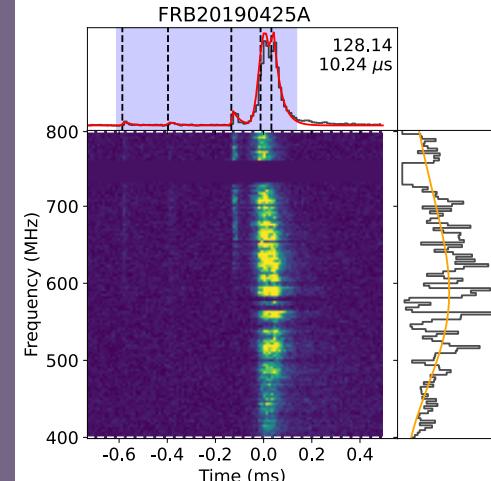


# Observational Signatures of FRB Emission Mechanisms

**Kenzie Nimmo**  
NHFP Einstein Fellow, Northwestern University  
FTSKY 2025

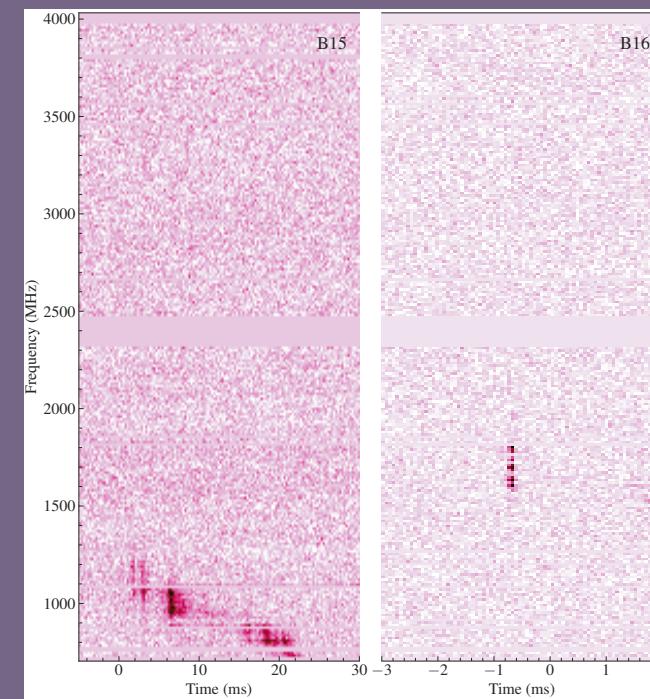
# Diversity of radio properties

## Broadband



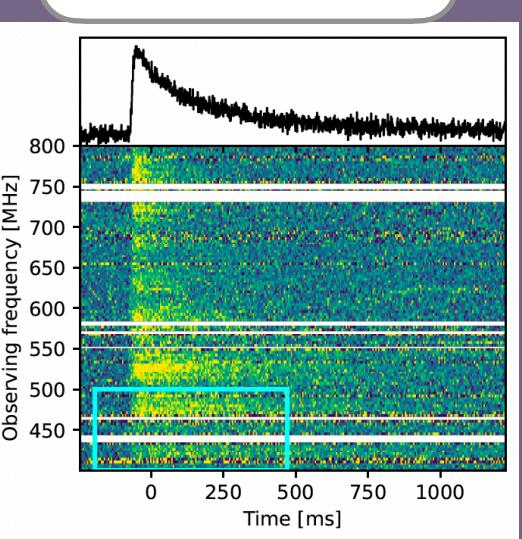
Sand et al. 2025

## Narrowband



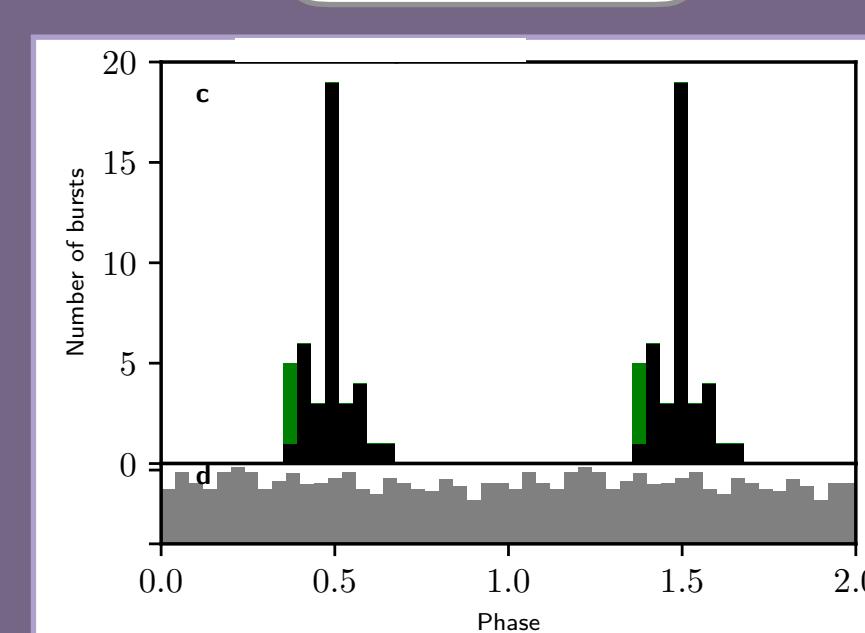
Kumar et al. 2023

## Scattered



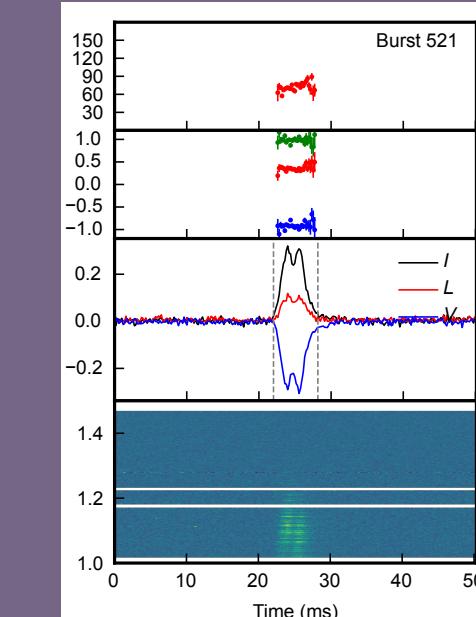
Shin et al. 2024

## Periodic



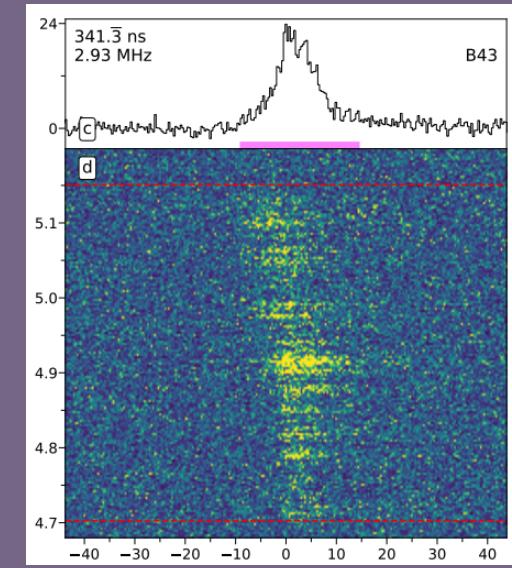
CHIME/FRB Collab. 2020

Circularly polarized



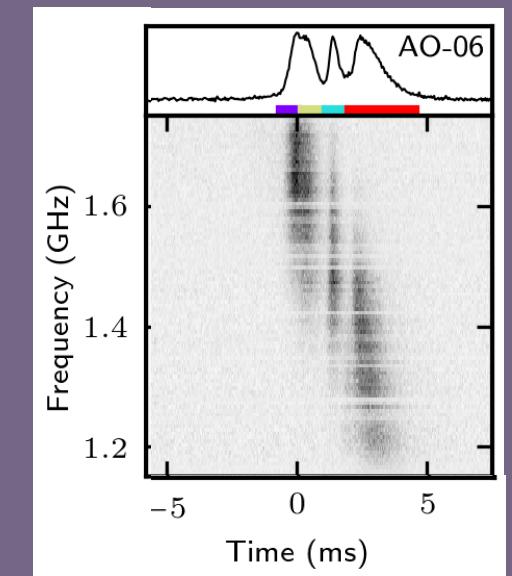
Jiang et al. 2024

Ultra-fast



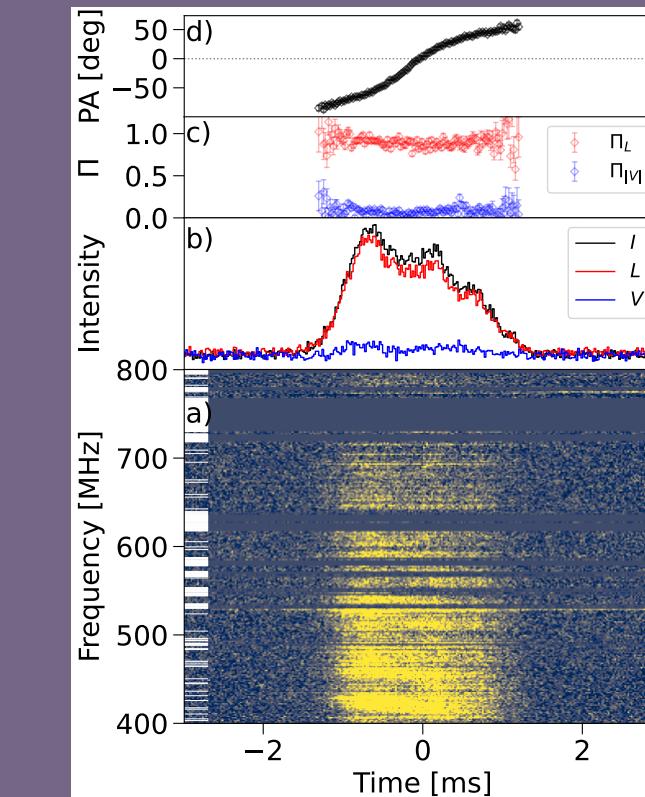
Snelders et al. 2023

Sad-trombone



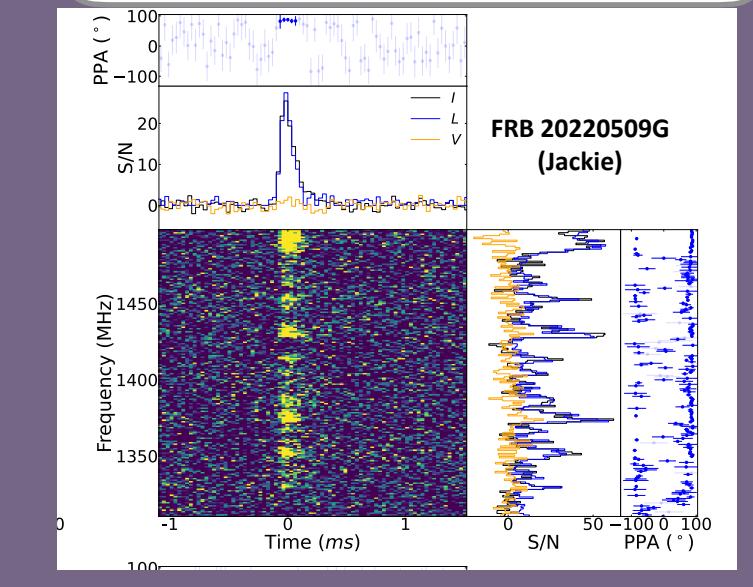
Hessels et al. 2019

PA swing



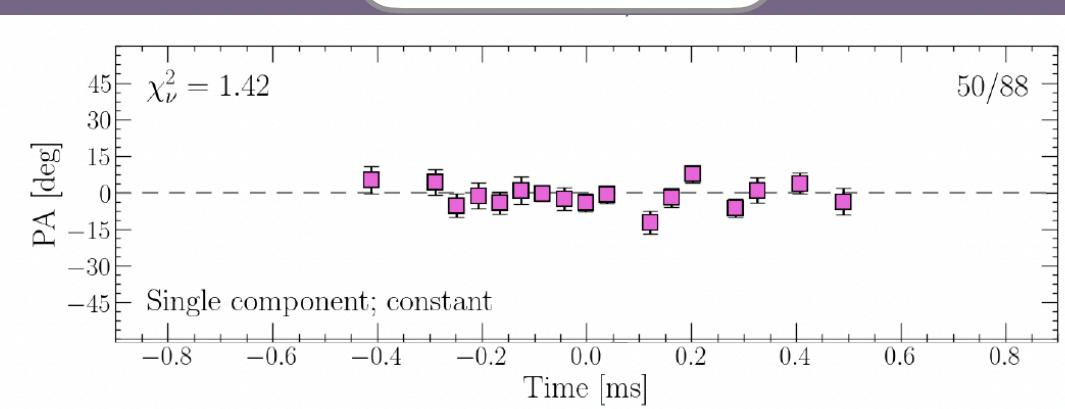
McKinven et al. 2025

Linearly polarized



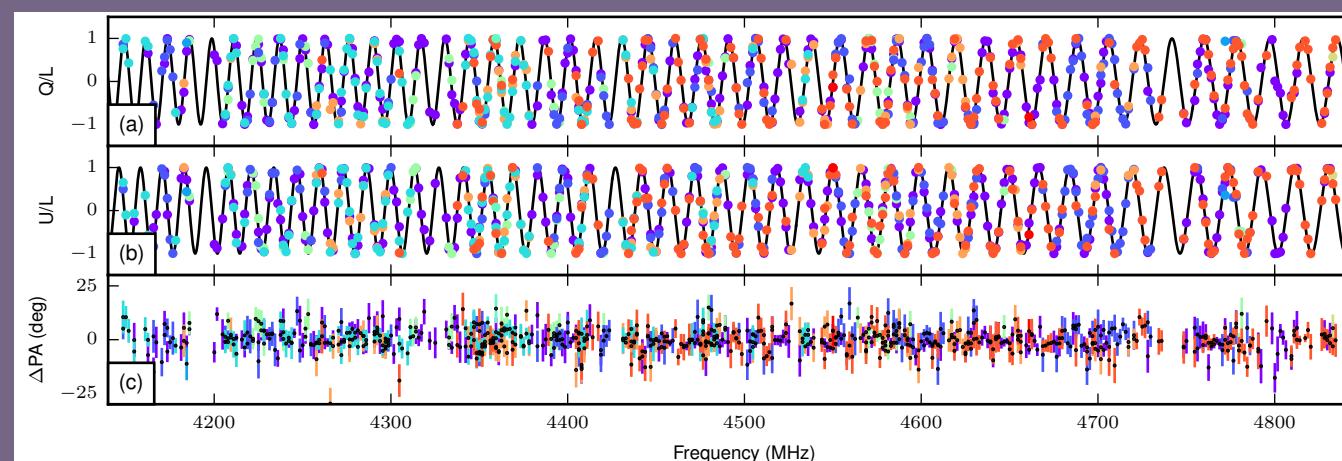
Sherman et al. 2024

## Flat PA



Pandhi et al. 2024

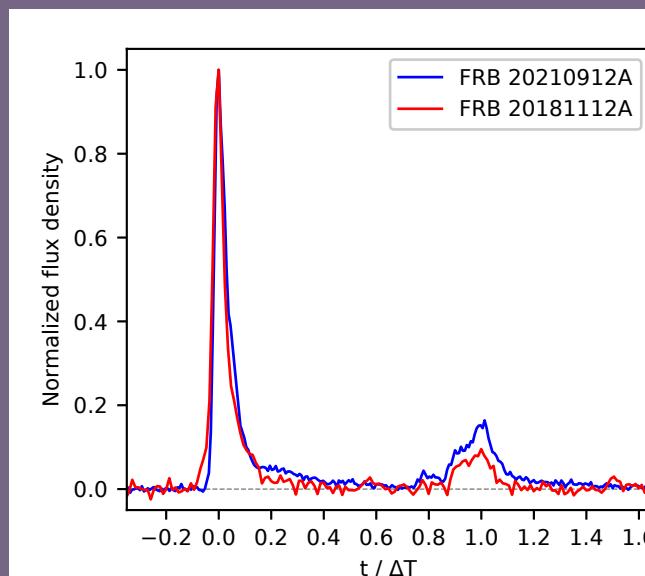
## High RM



Faber et al. 2024

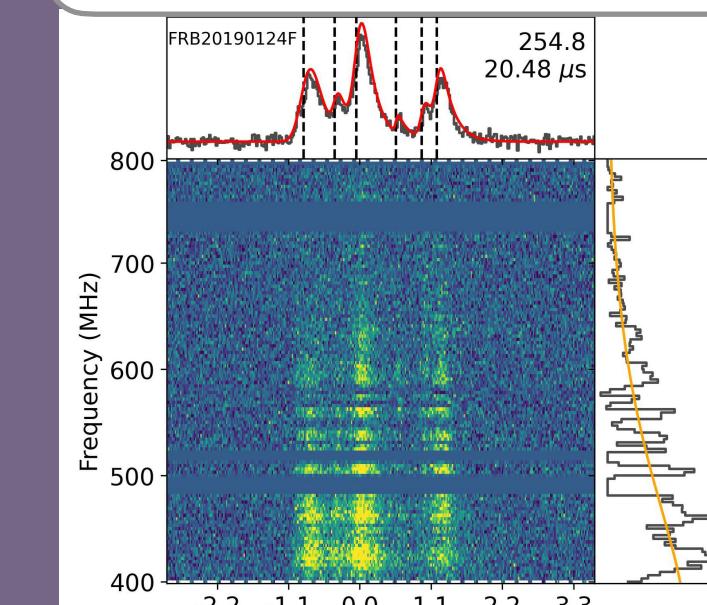
Michilli et al. 2018

## Twins



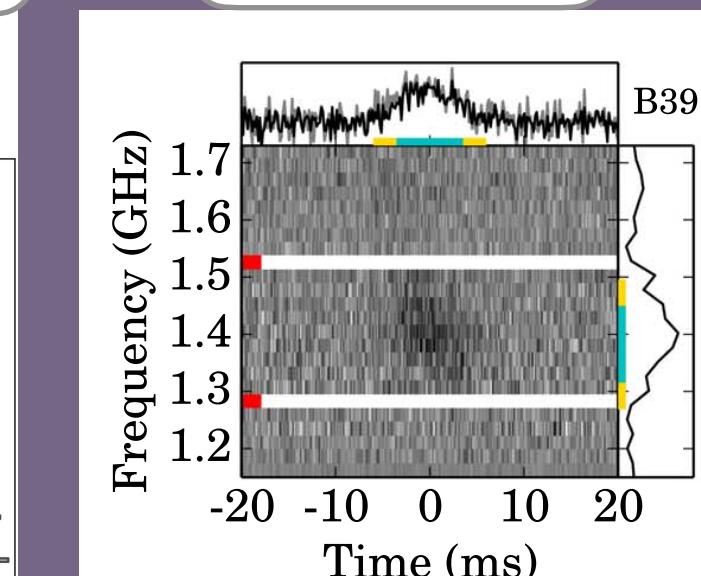
Bera et al. 2024

## Multi-component



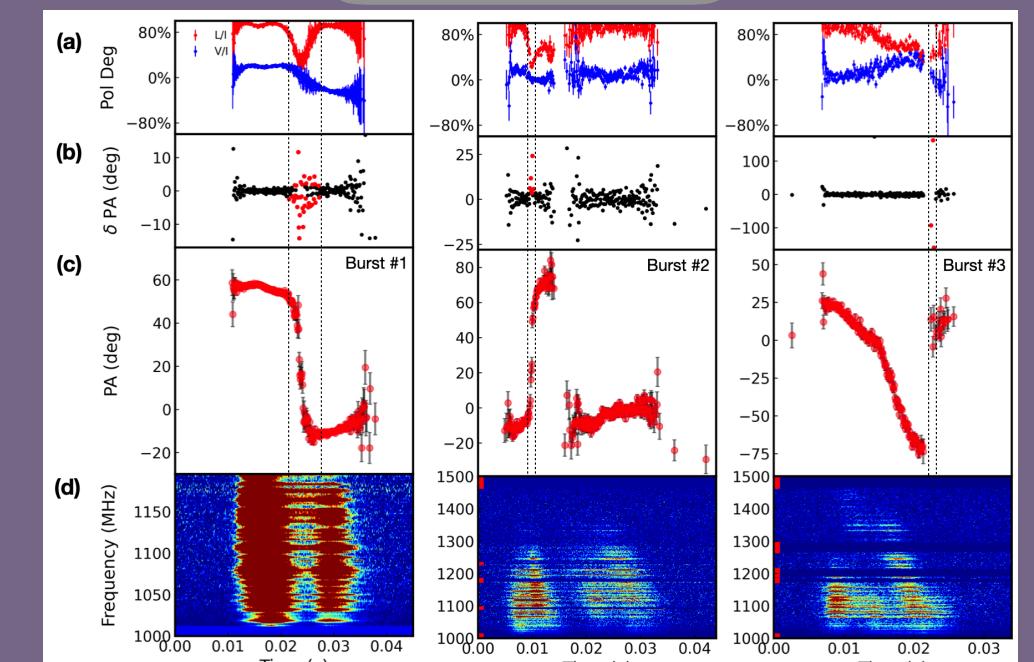
Sand et al. 2025

## Smudgy



Gourdji et al. 2019

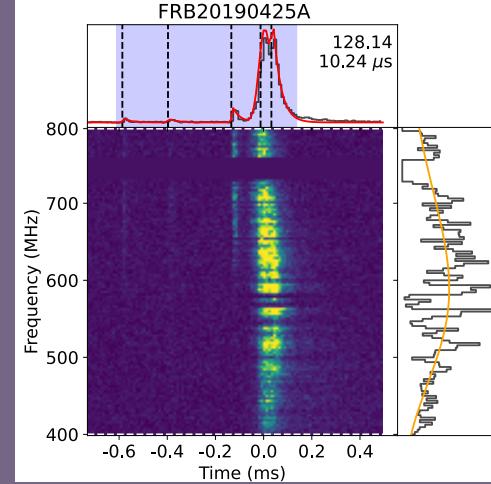
## PA jumps



Niu et al. 2024

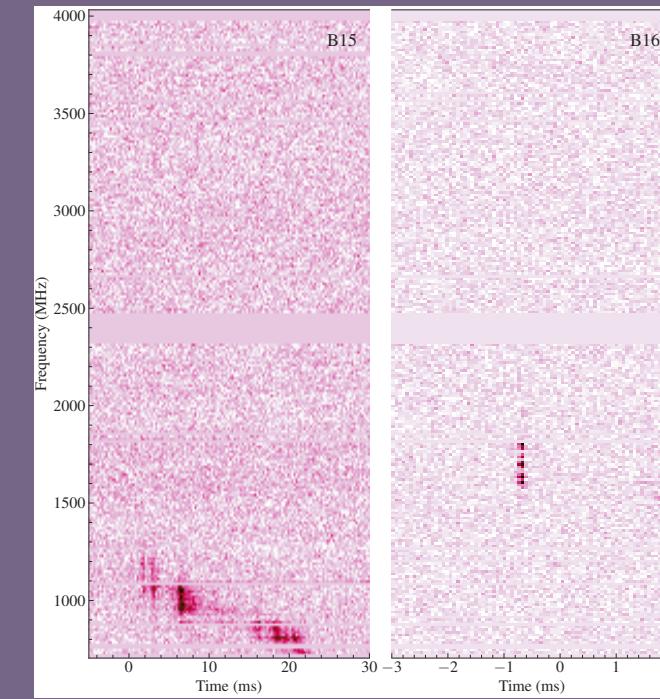
# Diversity of radio properties

## Broadband



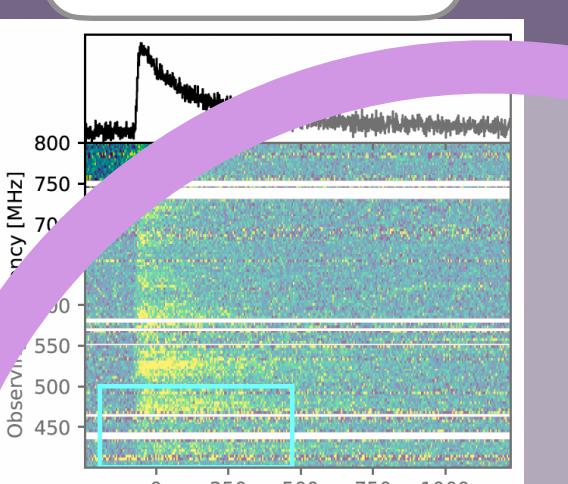
Sand et al. 2025

## Narrowband



Kumar et al. 2023

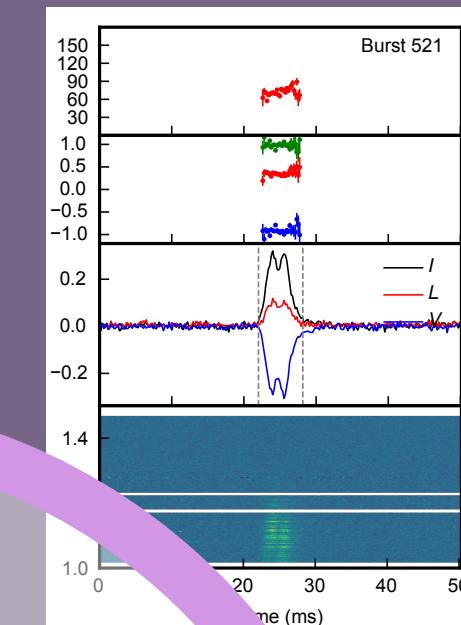
## Scattered



Progenitors

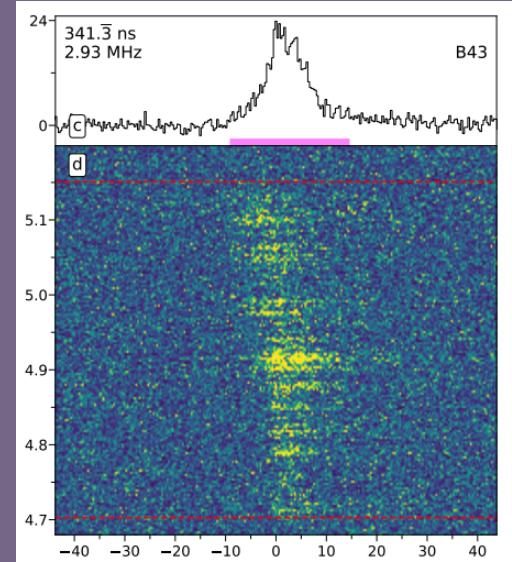
## Periodic

Circularly polarized



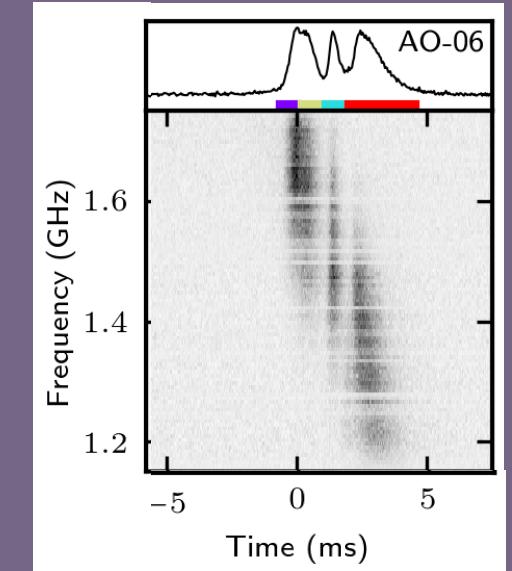
Jiang et al. 2024

Ultra-fast



Snelders et al. 2023

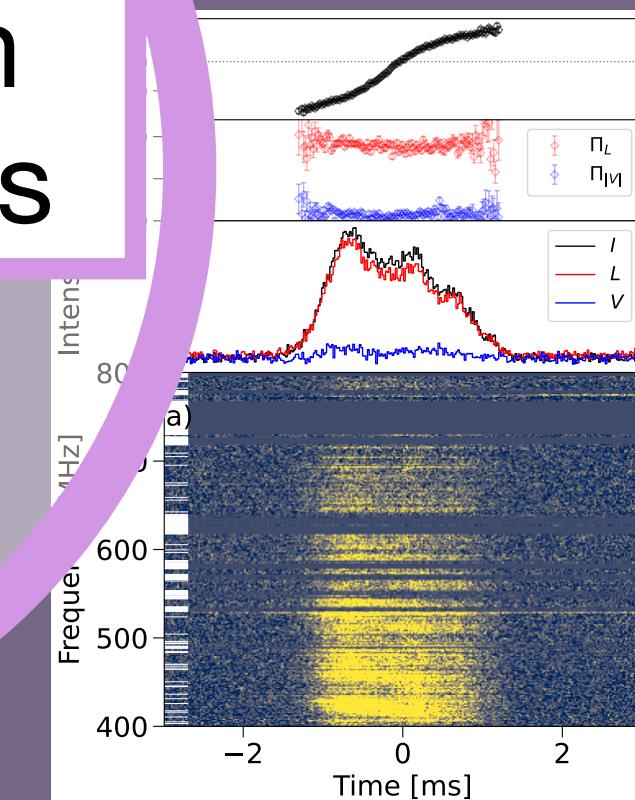
Sad-trombone



Hessels et al. 2019

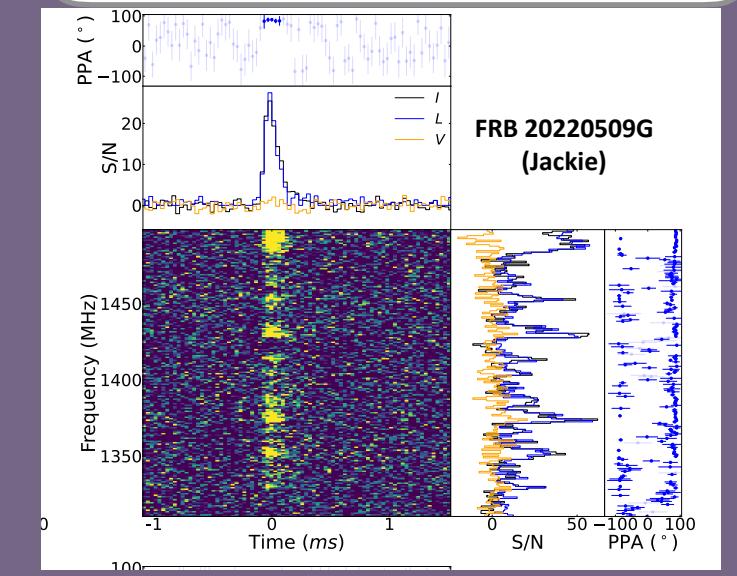
Emission processes

PA swing



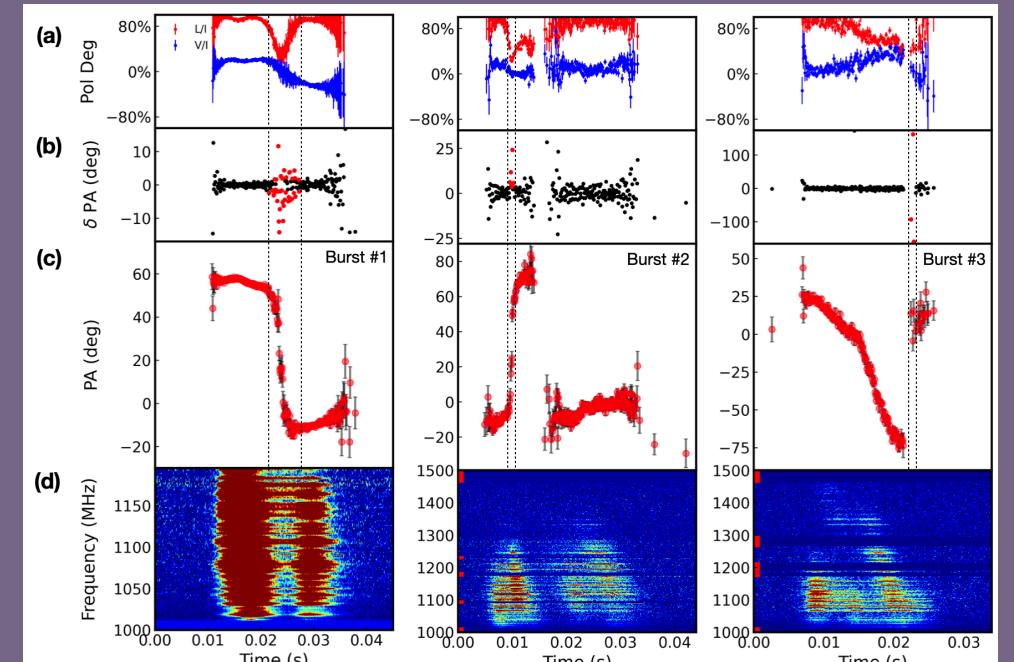
McKinven et al. 2025

Linearly polarized



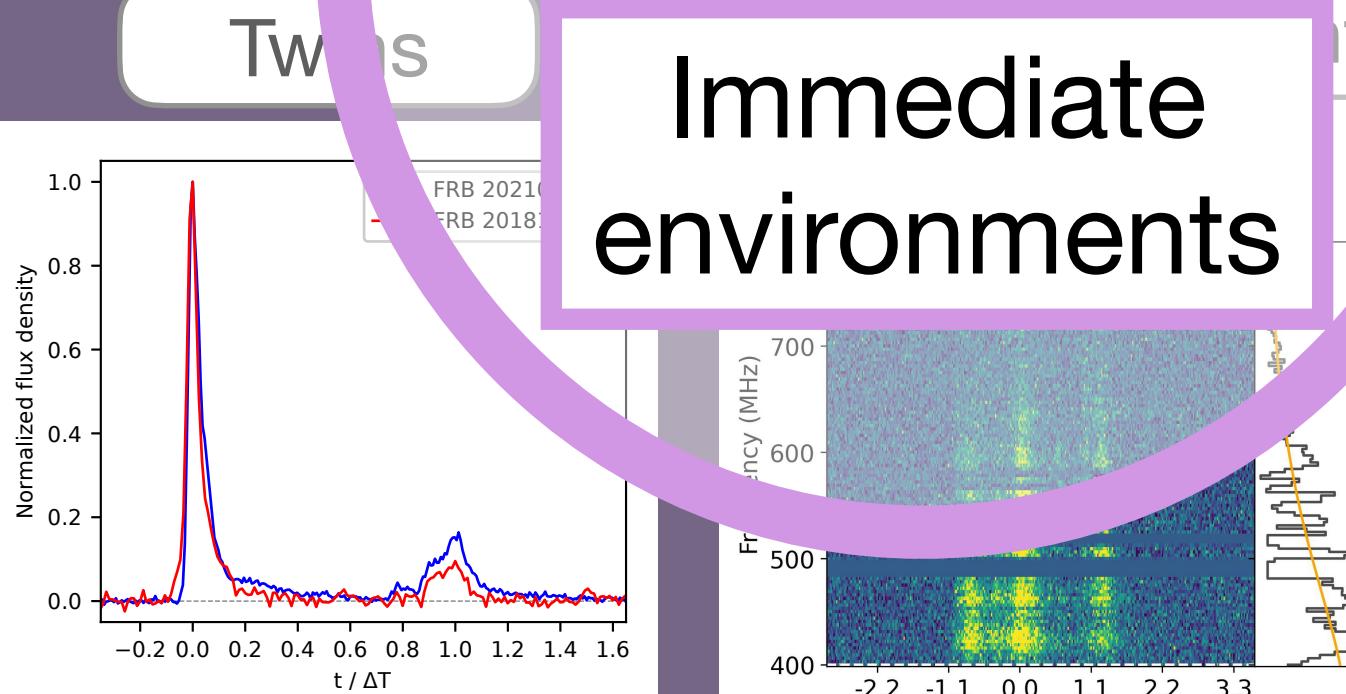
Sherman et al. 2024

PA jumps



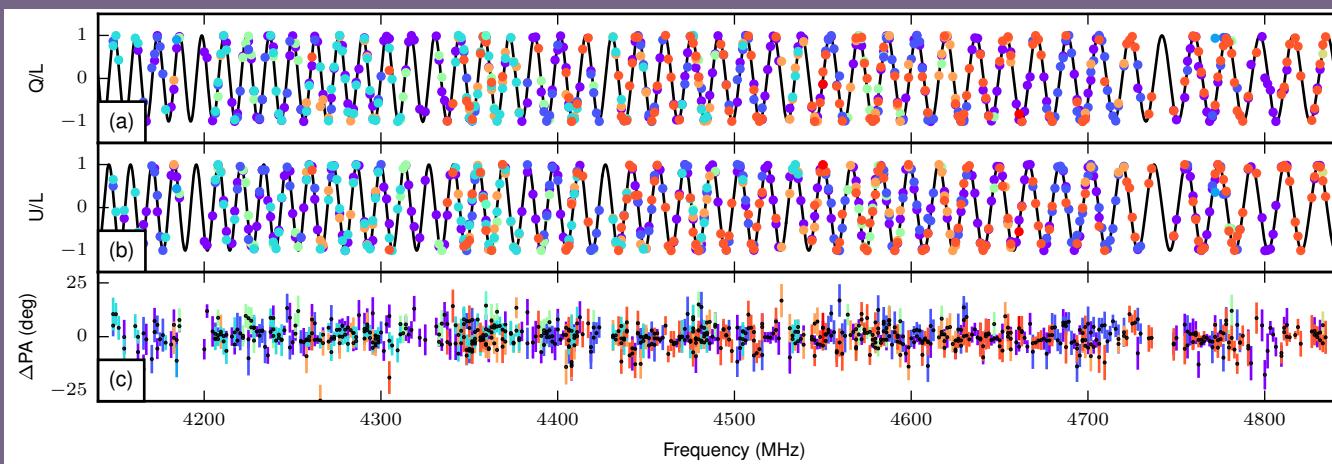
Niu et al. 2024

## Twins



Bera et al. 2024

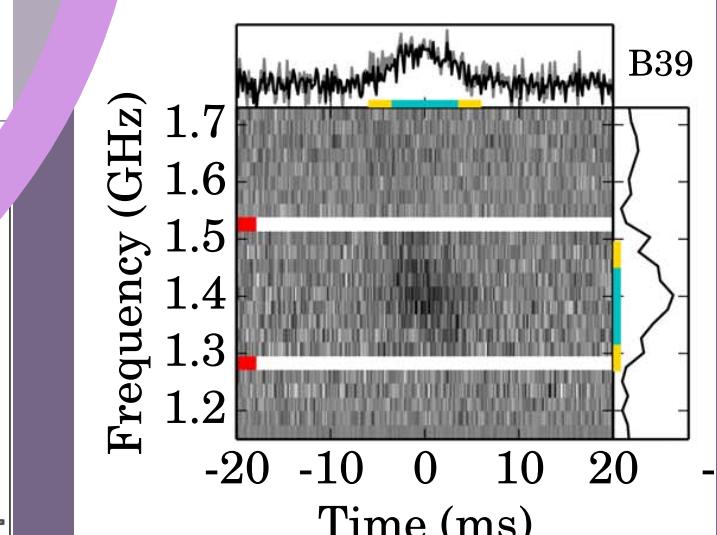
## High RM



Michilli et al. 2018

Immediate environments

## Smudgy

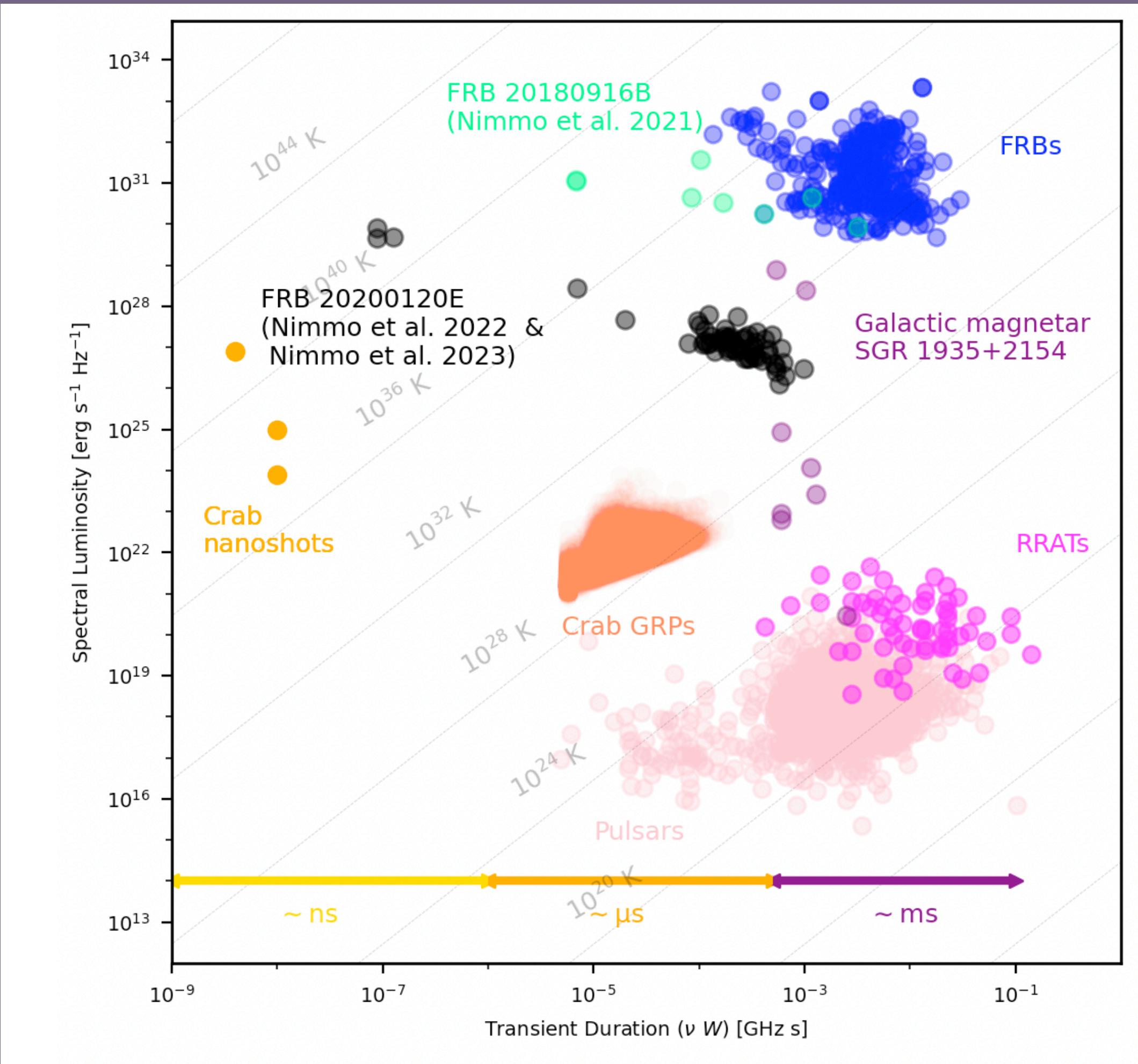


Gourdji et al. 2019

Sand et al. 2025

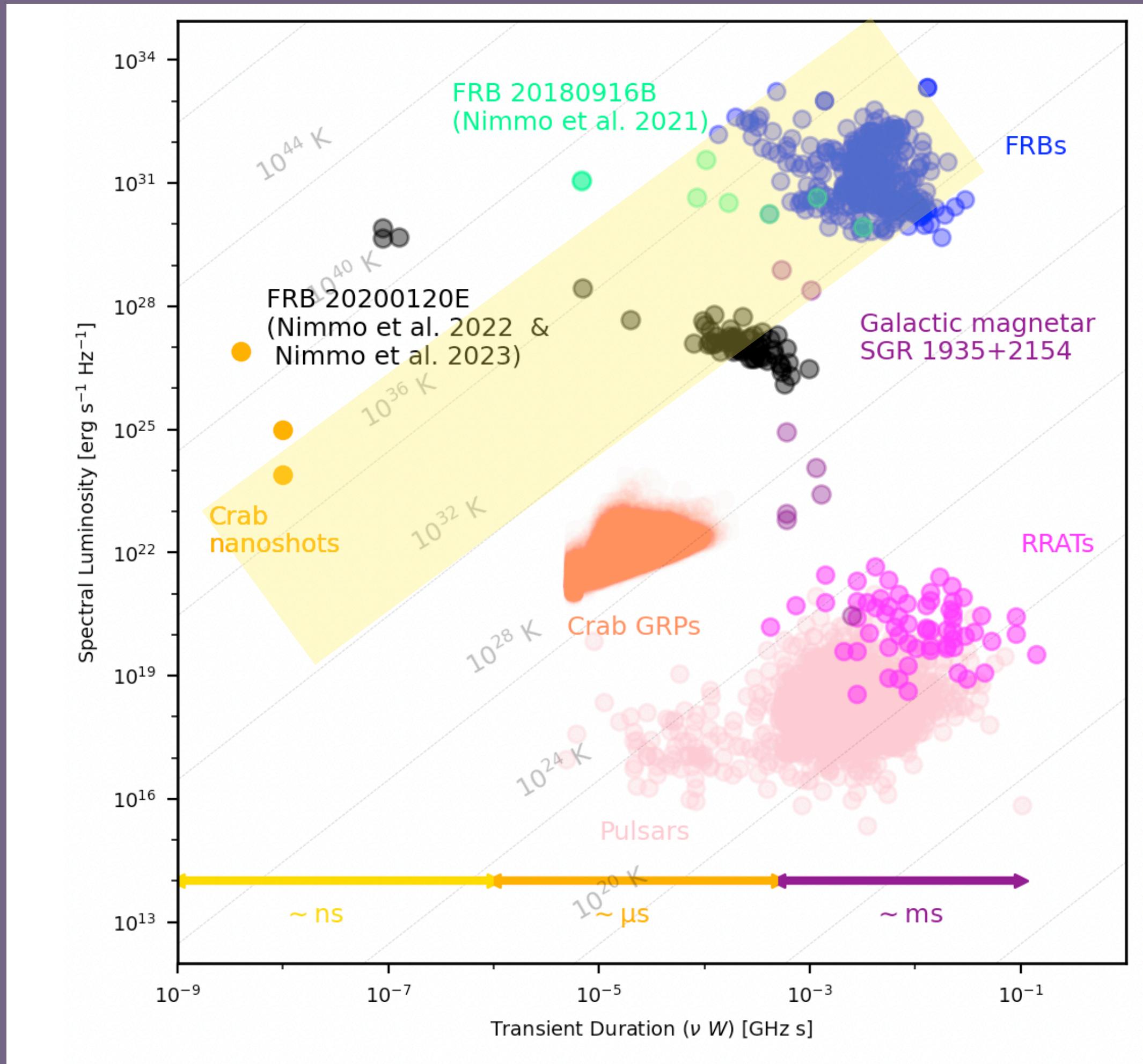
Environment

# Broadly true FRB properties



Adapted from Nimmo et al. 2022

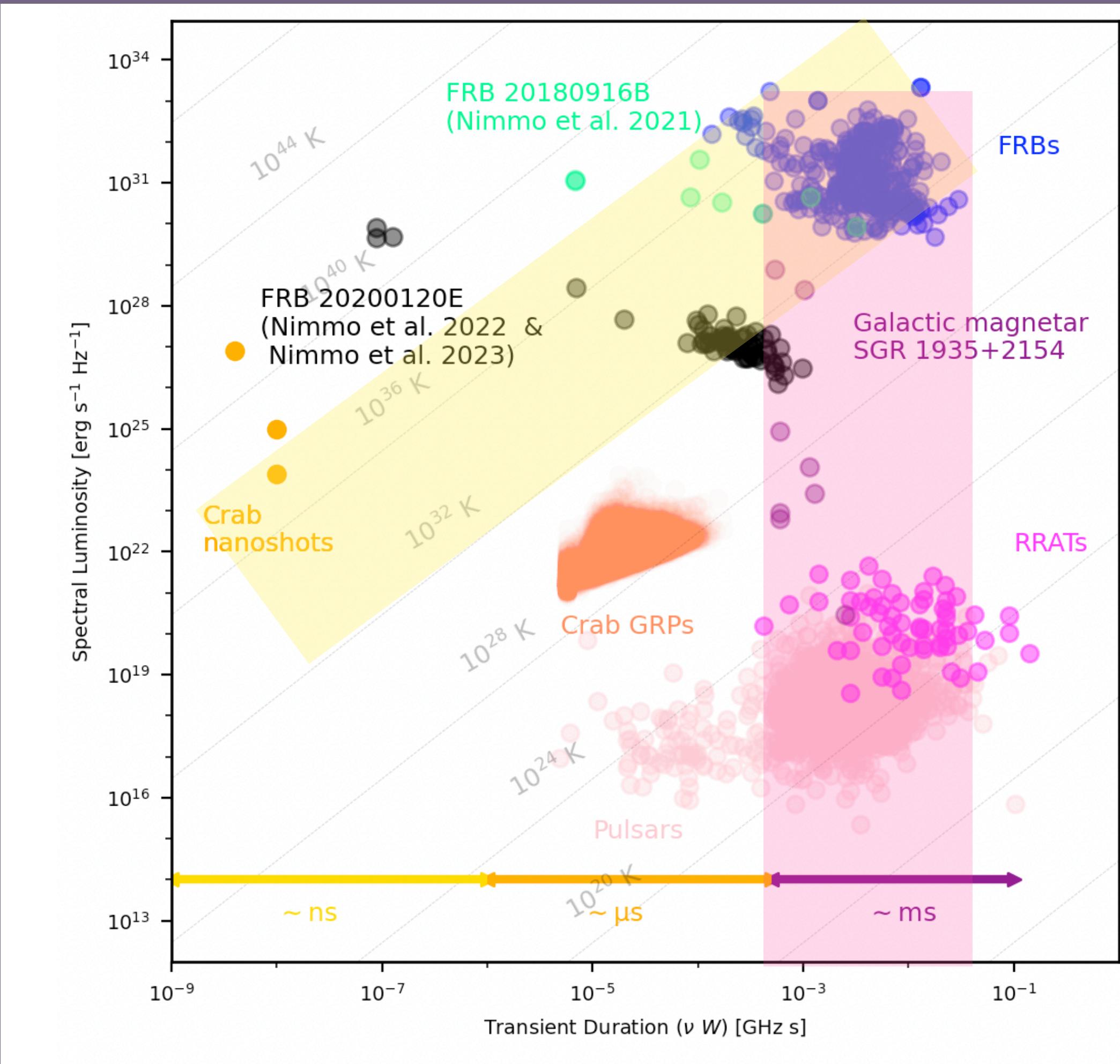
# Broadly true FRB properties



**Coherent ( $T_b \sim 10^{32} - 10^{36}$  K)**

Adapted from Nimmo et al. 2022

# Broadly true FRB properties

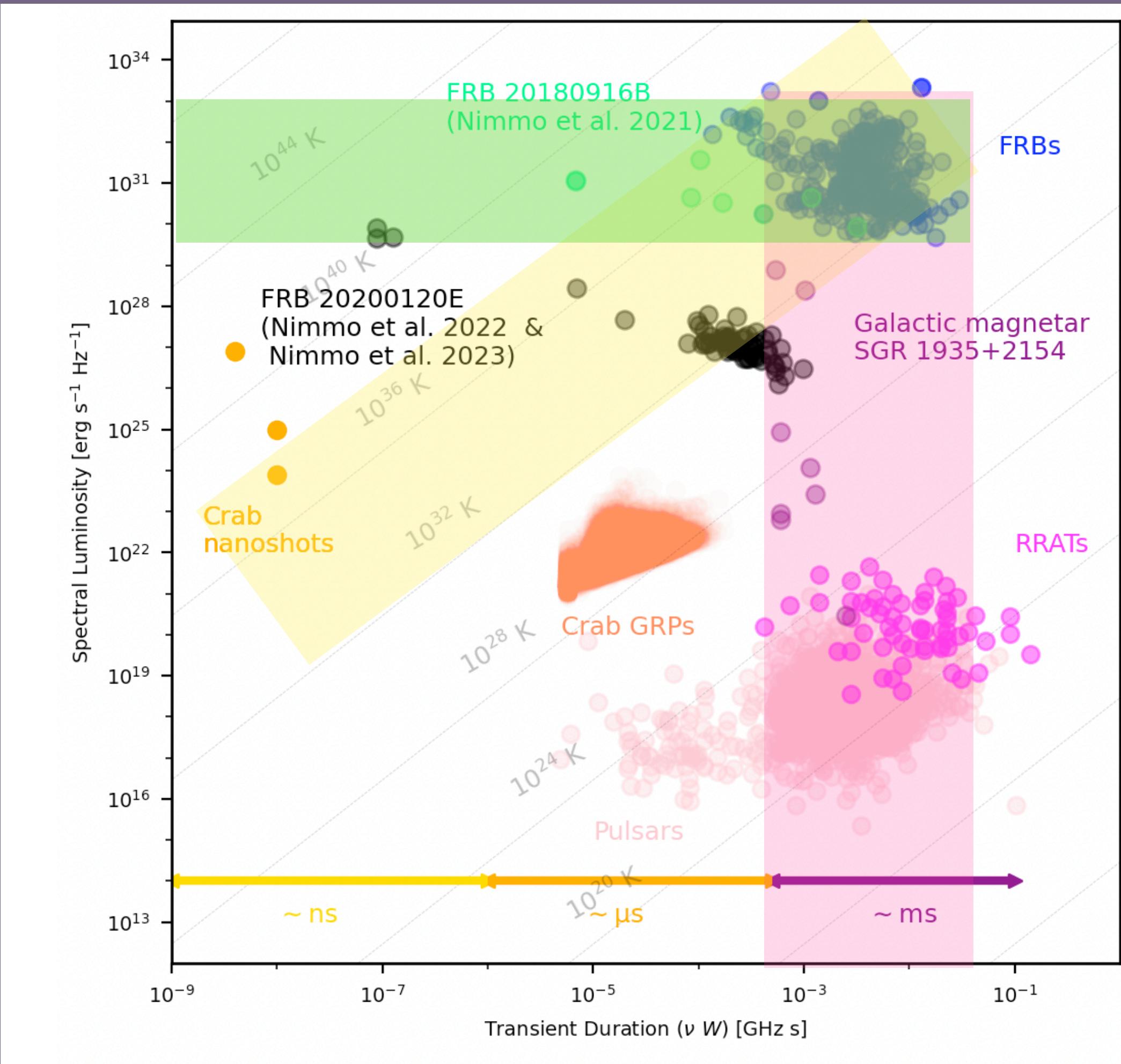


Adapted from Nimmo et al. 2022

**Coherent ( $T_b \sim 10^{32} - 10^{36}$  K)**

**Short-duration  $\sim$  ms**

# Broadly true FRB properties



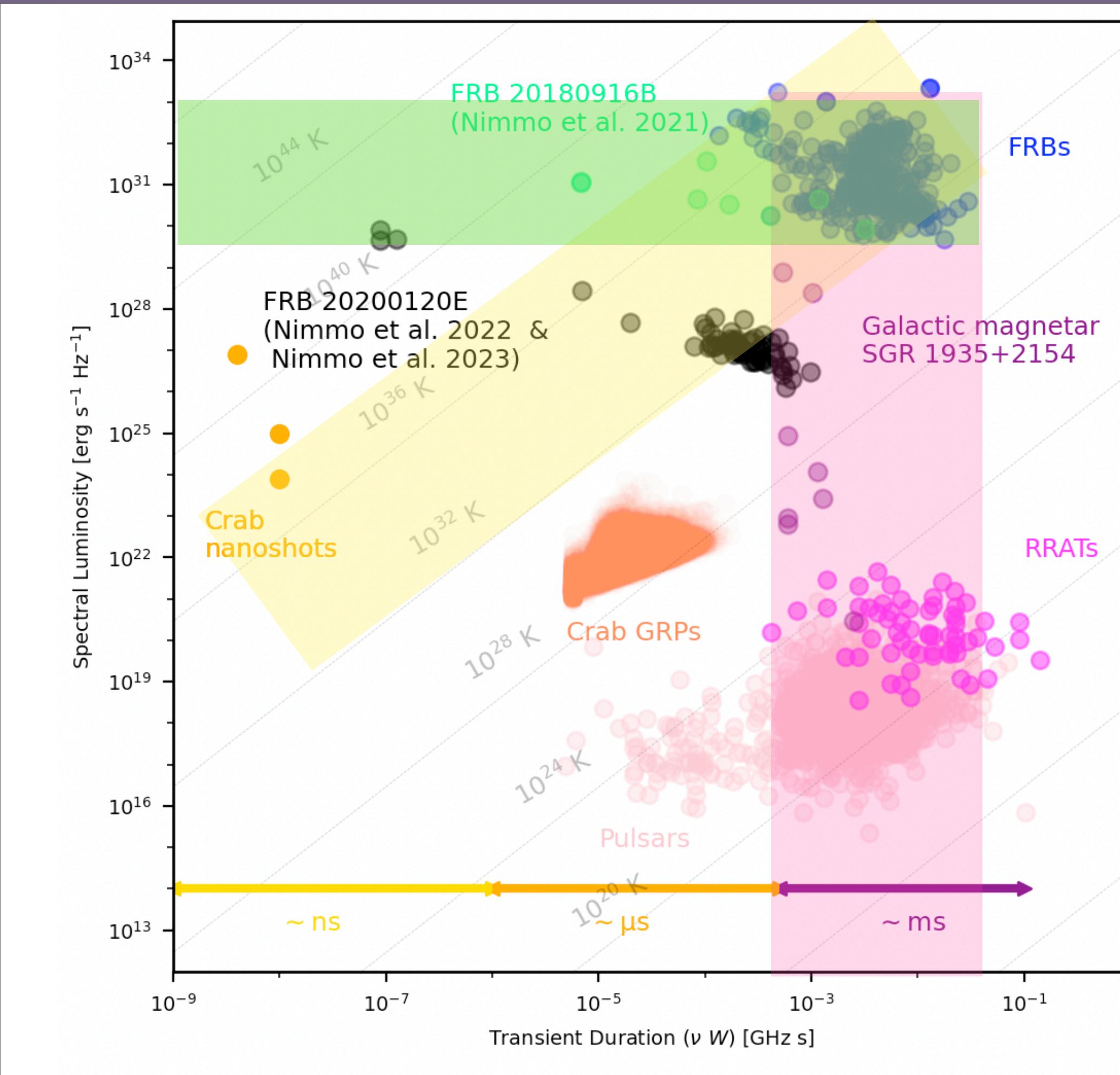
**Coherent** ( $T_b \sim 10^{32} - 10^{36}$  K)

**Short-duration**  $\sim$  ms

**Luminous**  $\sim 10^{32}$  erg s<sup>-1</sup> Hz<sup>-1</sup>

Adapted from Nimmo et al. 2022

# Broadly true FRB properties



Adapted from Nimmo et al. 2022

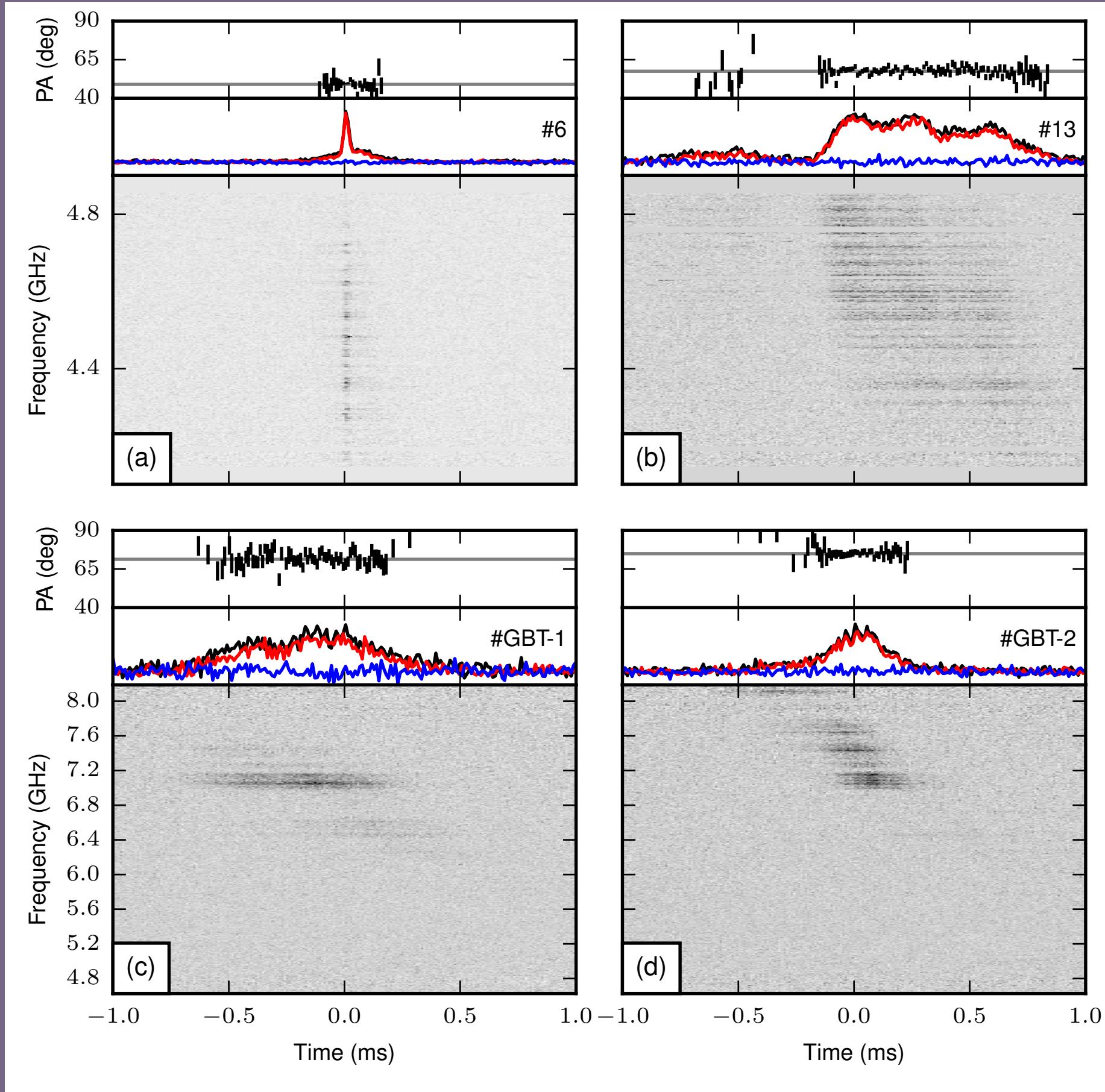
**Coherent ( $T_b \sim 10^{32} - 10^{36}$  K)**

**Short-duration**  $\sim$  ms

**Luminous**  $\sim 10^{32}$  erg s<sup>-1</sup> Hz<sup>-1</sup>

**Radio (110 MHz - 8 GHz)**

# Broadly true FRB properties



**Coherent** ( $T_b \sim 10^{32} - 10^{36}$  K)

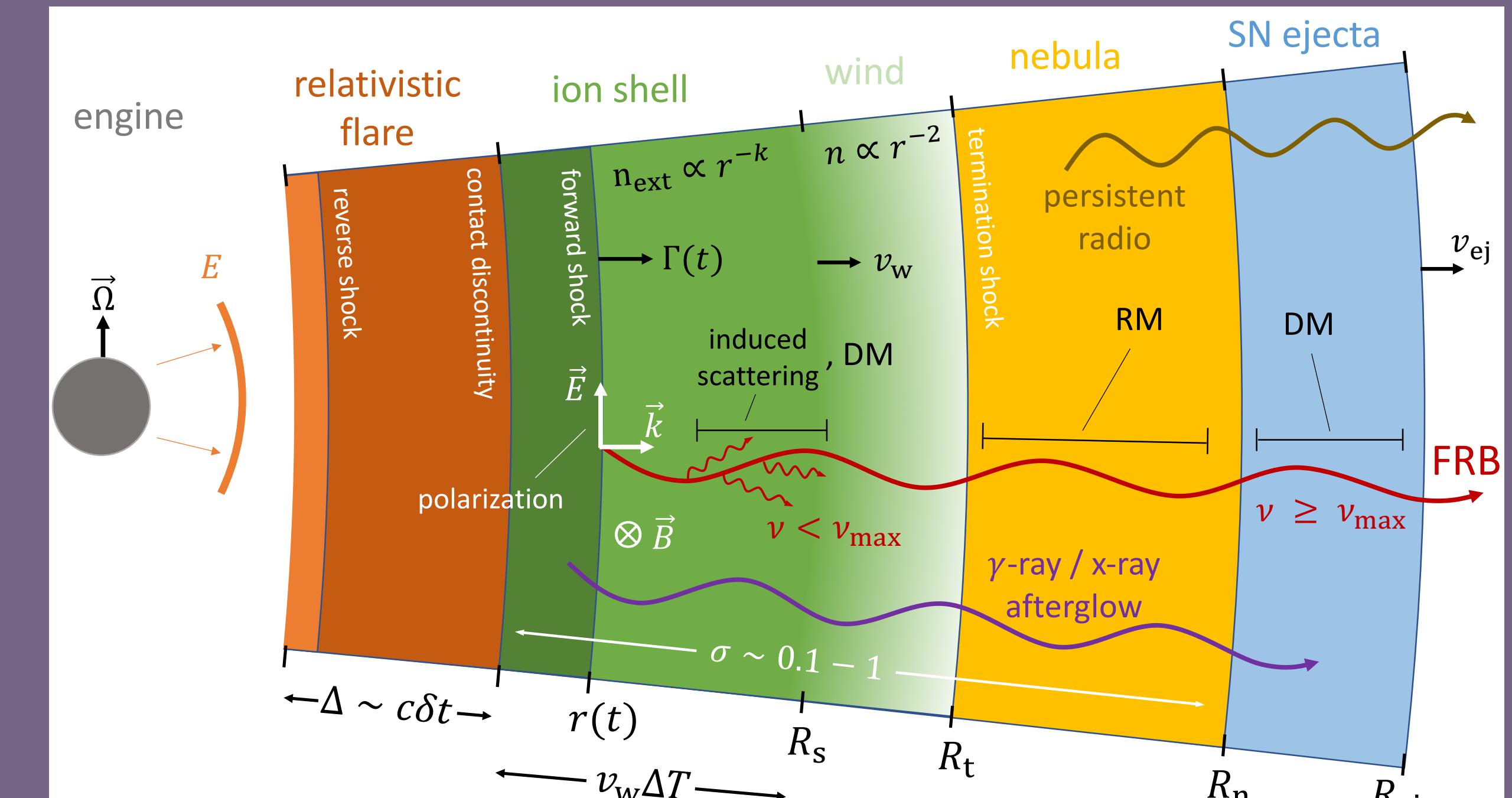
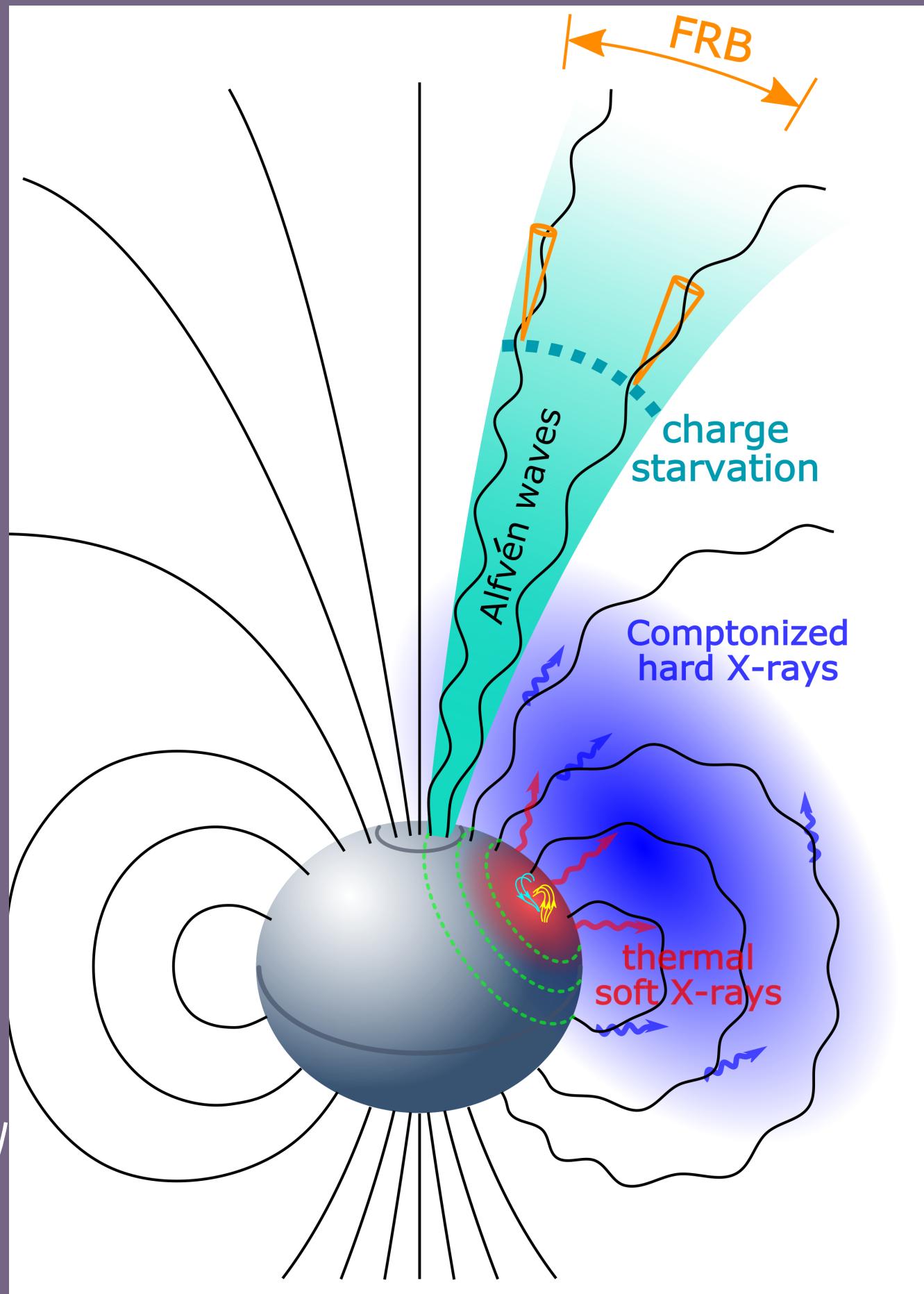
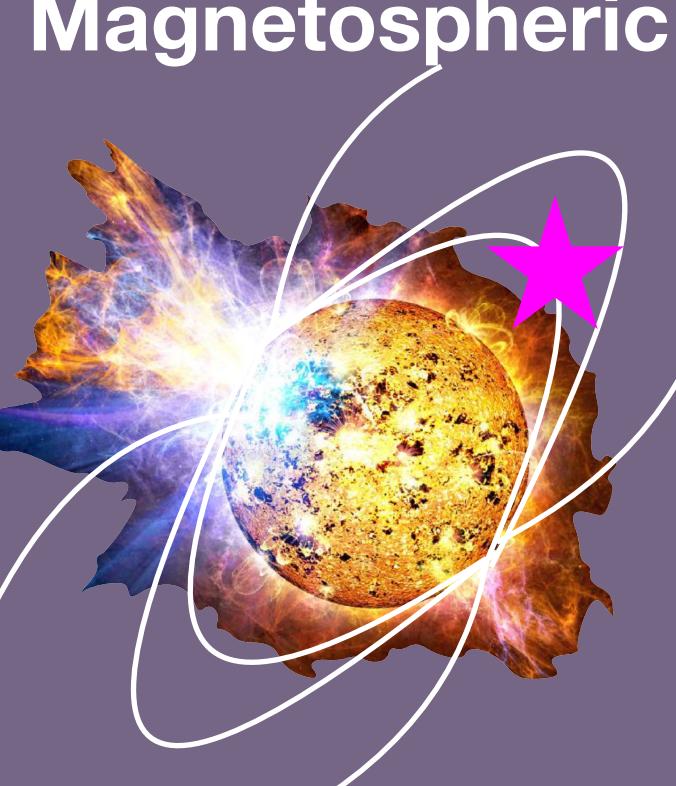
**Short-duration**  $\sim$  ms

**Luminous**  $\sim 10^{32}$  erg s<sup>-1</sup> Hz<sup>-1</sup>

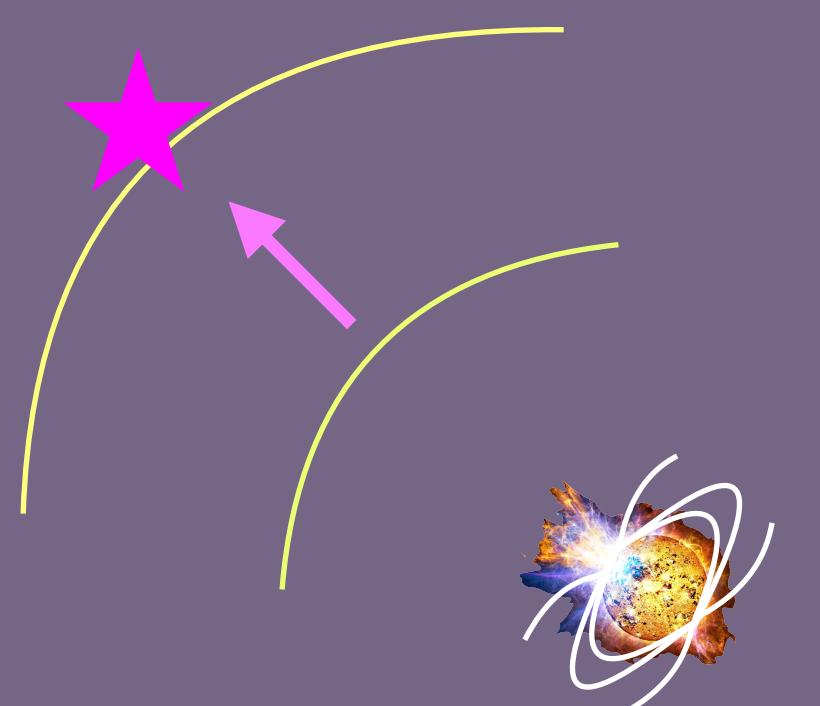
**Radio** (110 MHz - 8 GHz)

**Highly polarized**

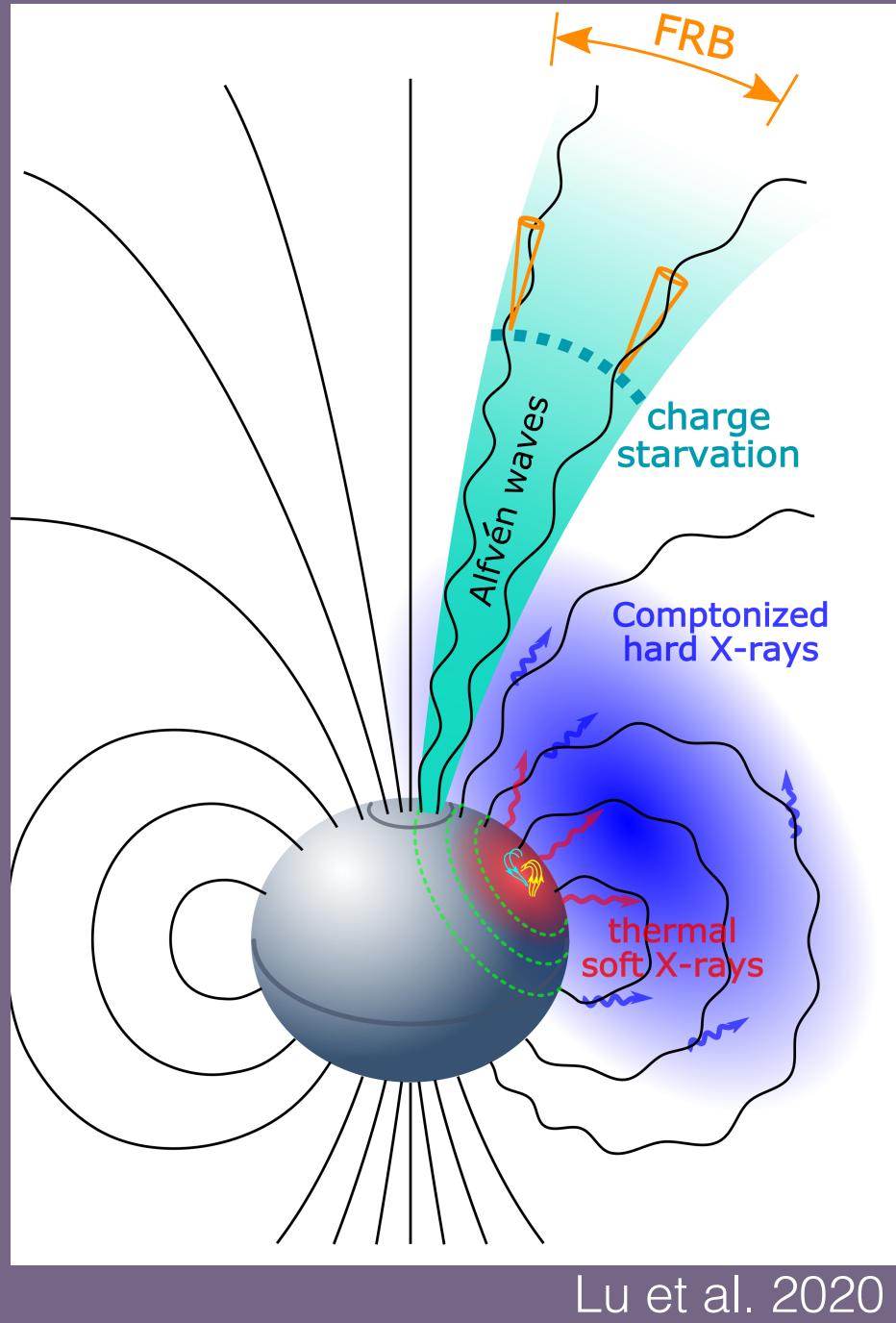
# The FRB emission mechanism



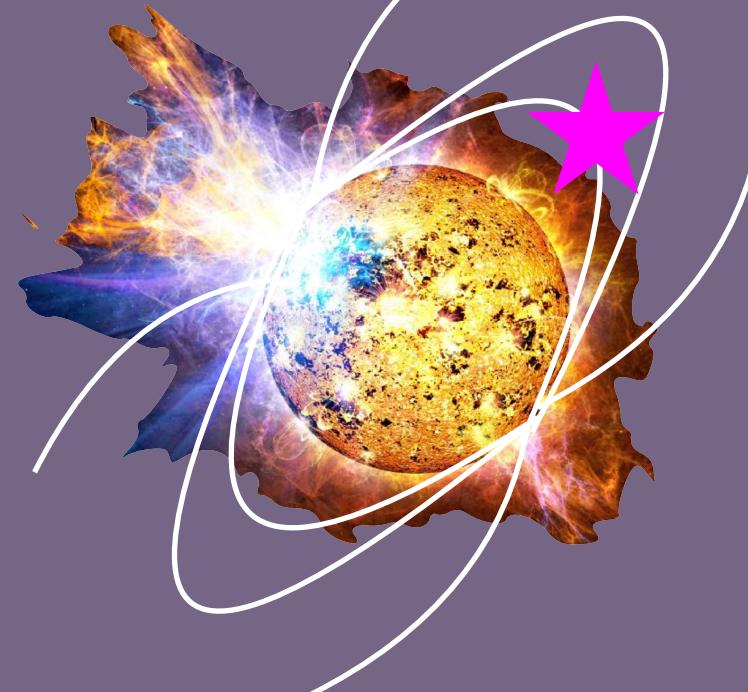
Non-magnetospheric



# The FRB emission mechanism

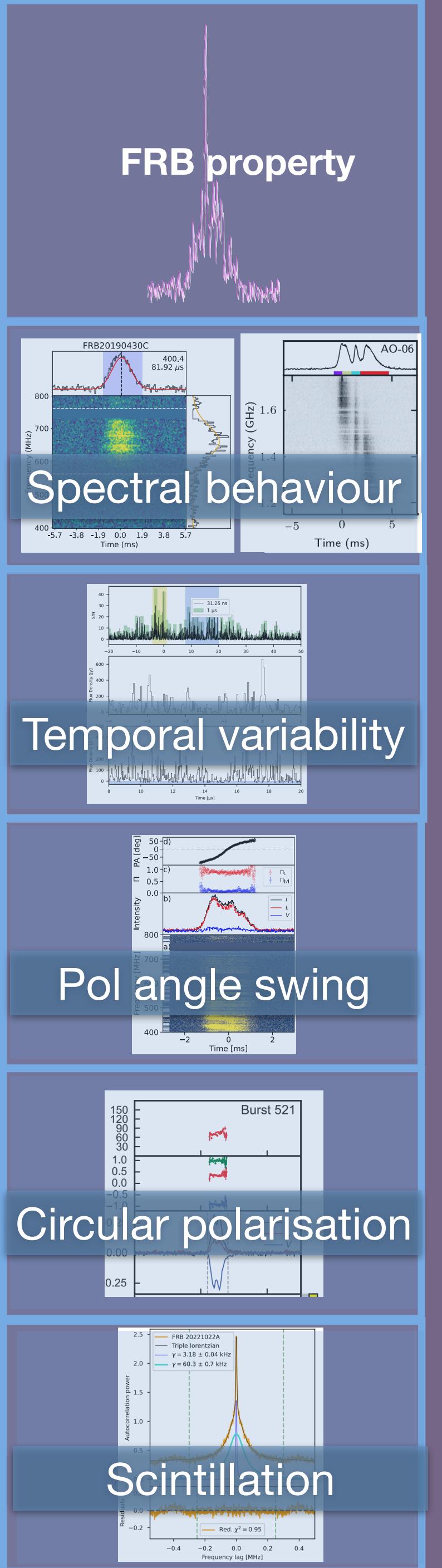
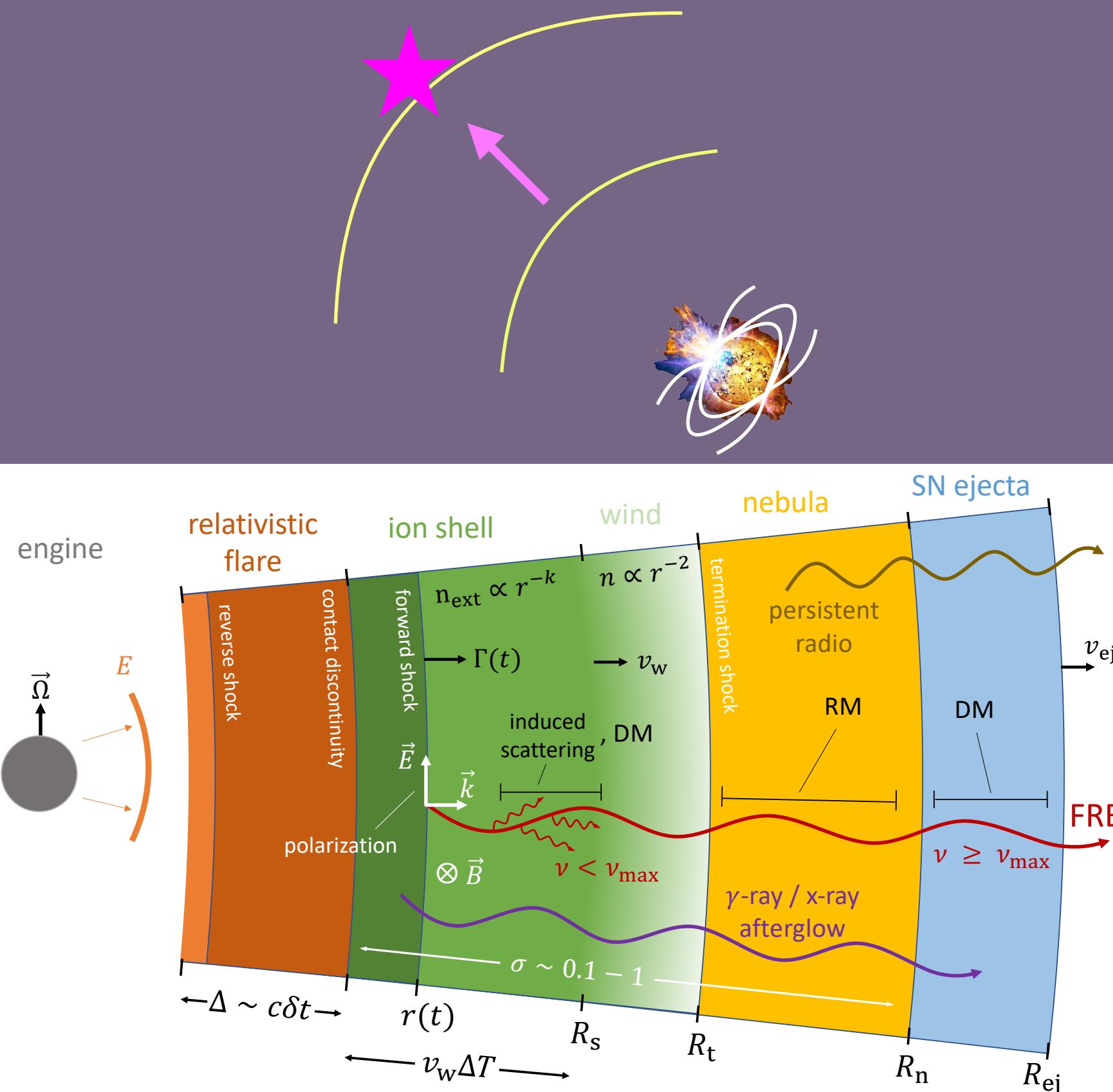


Magnetospheric



or?

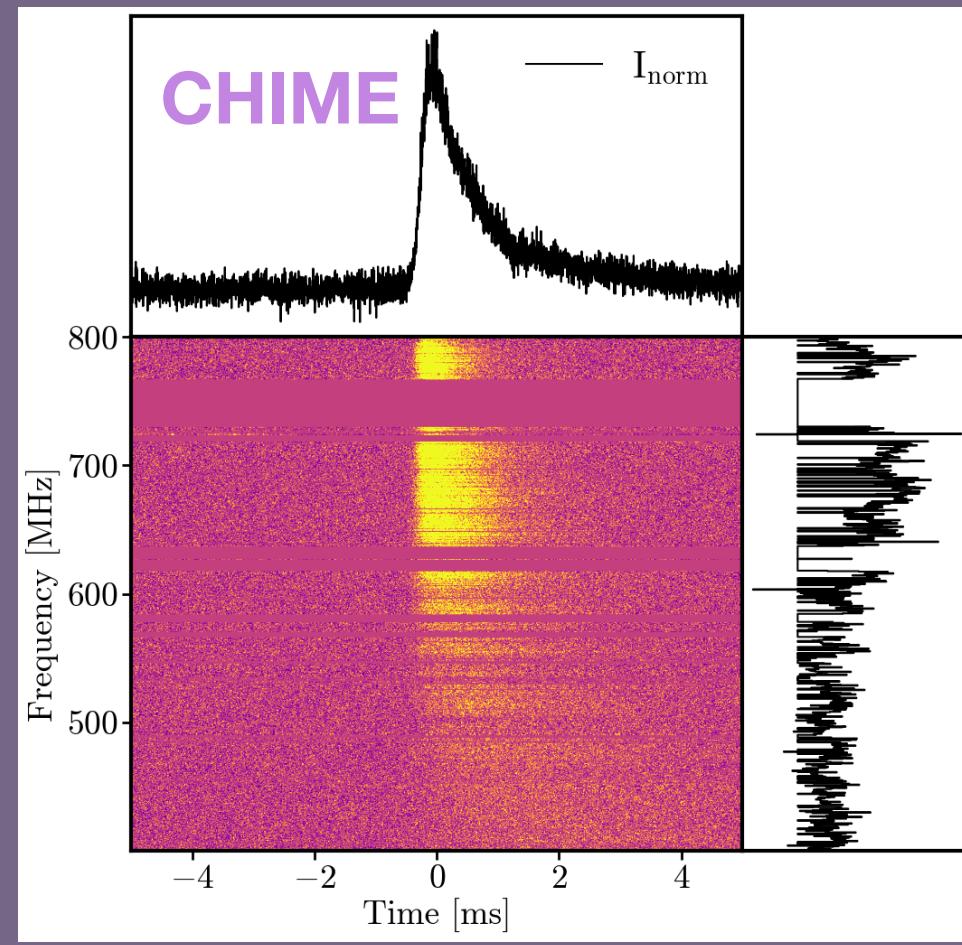
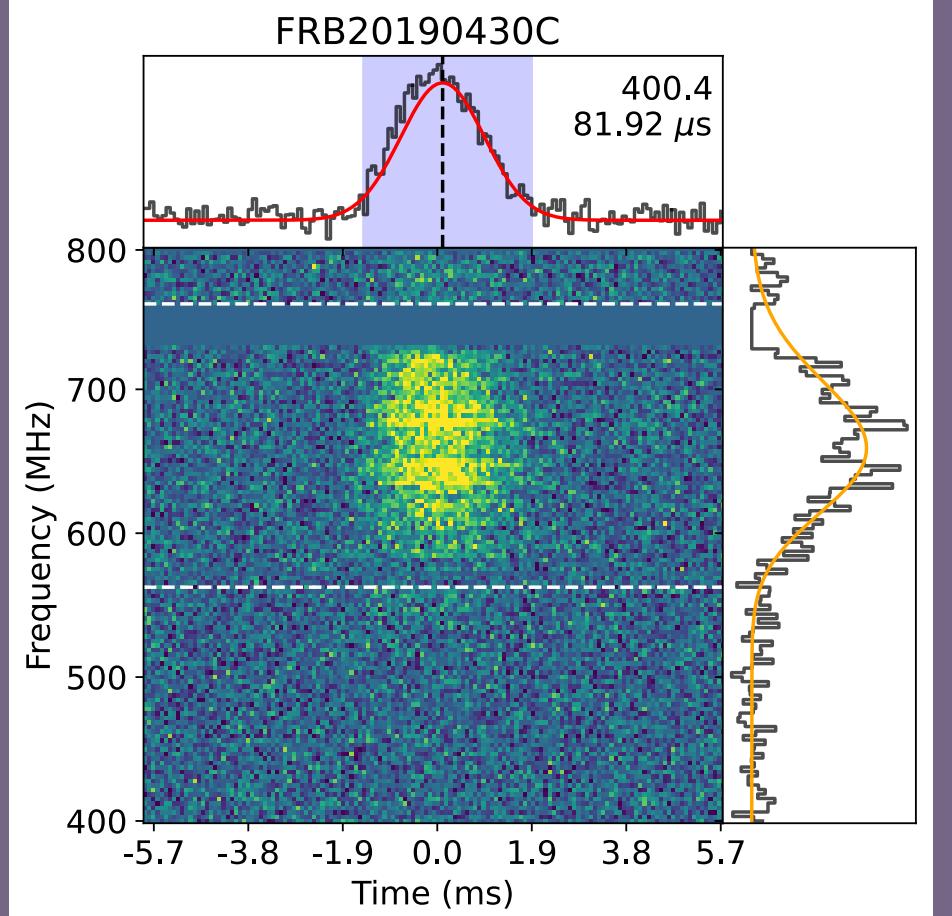
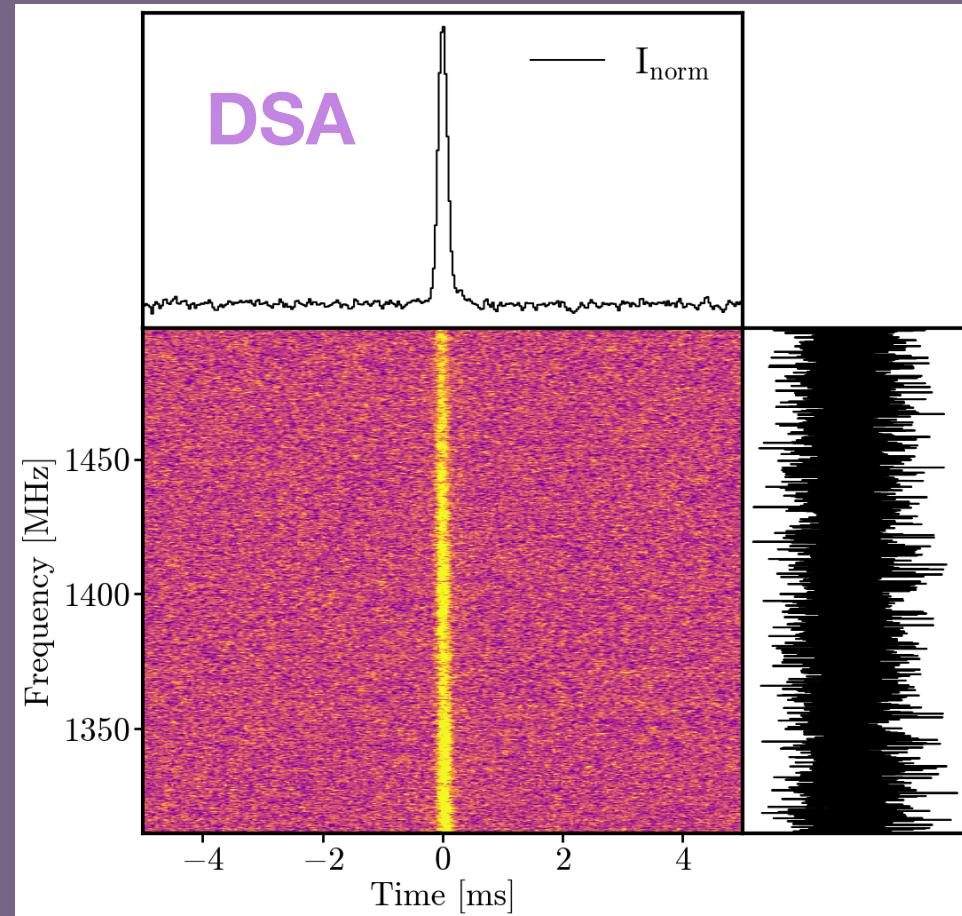
Non-magnetospheric



# Spectral behaviour

Broadband → Narrowband

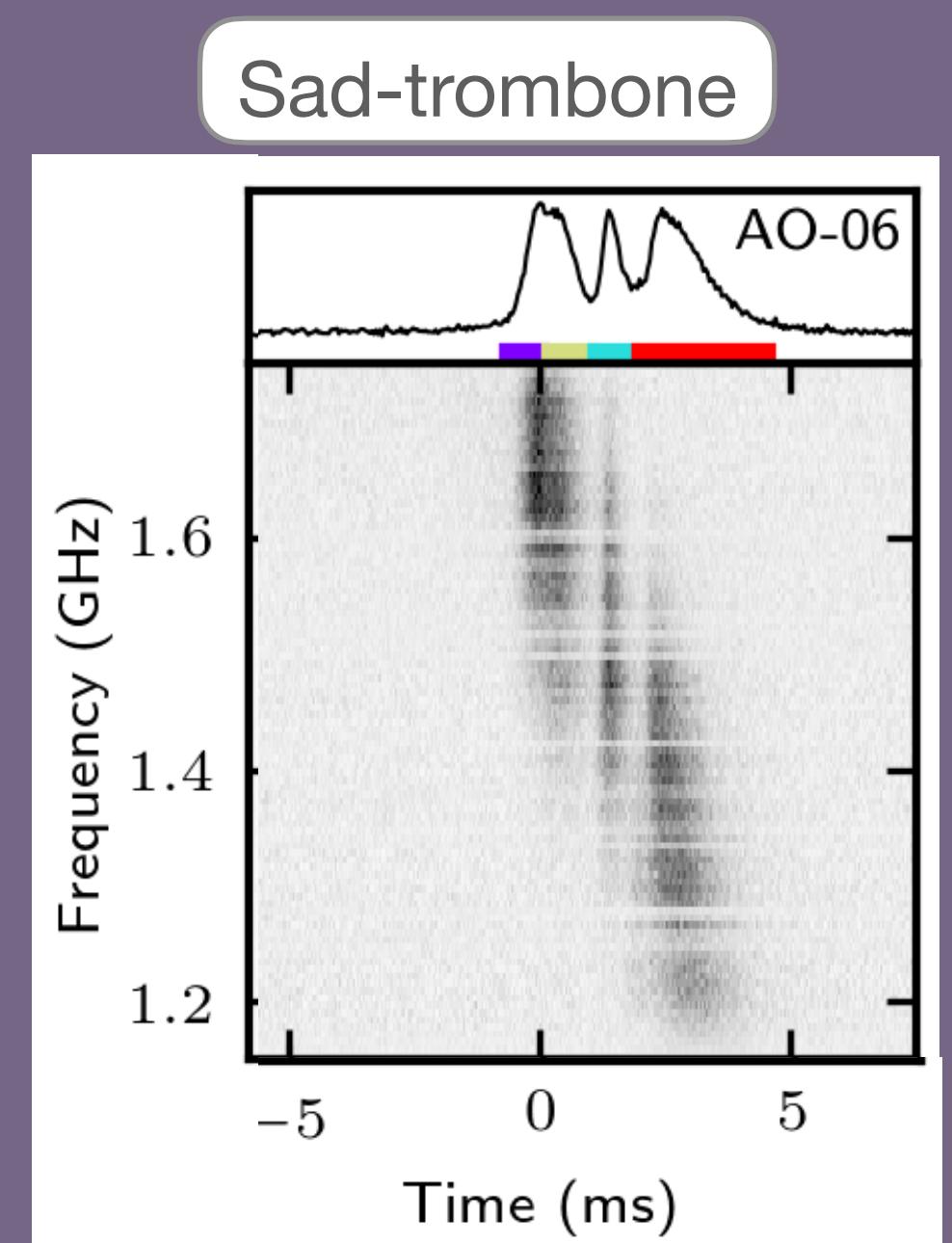
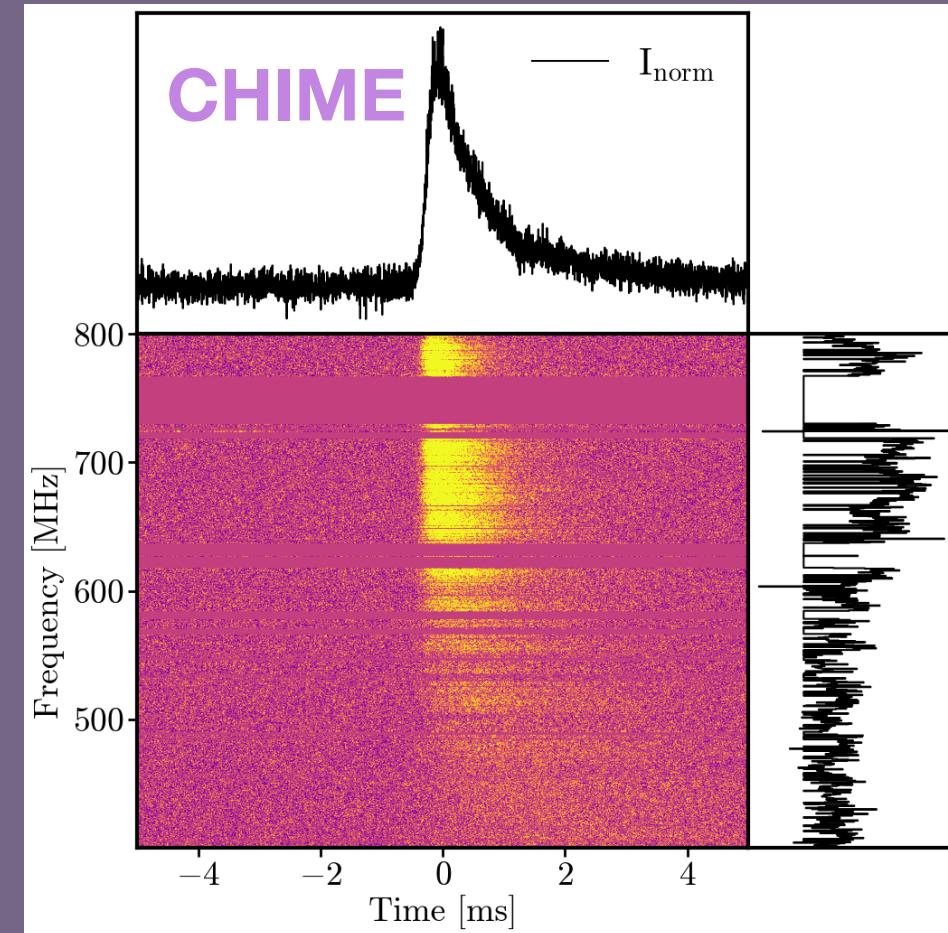
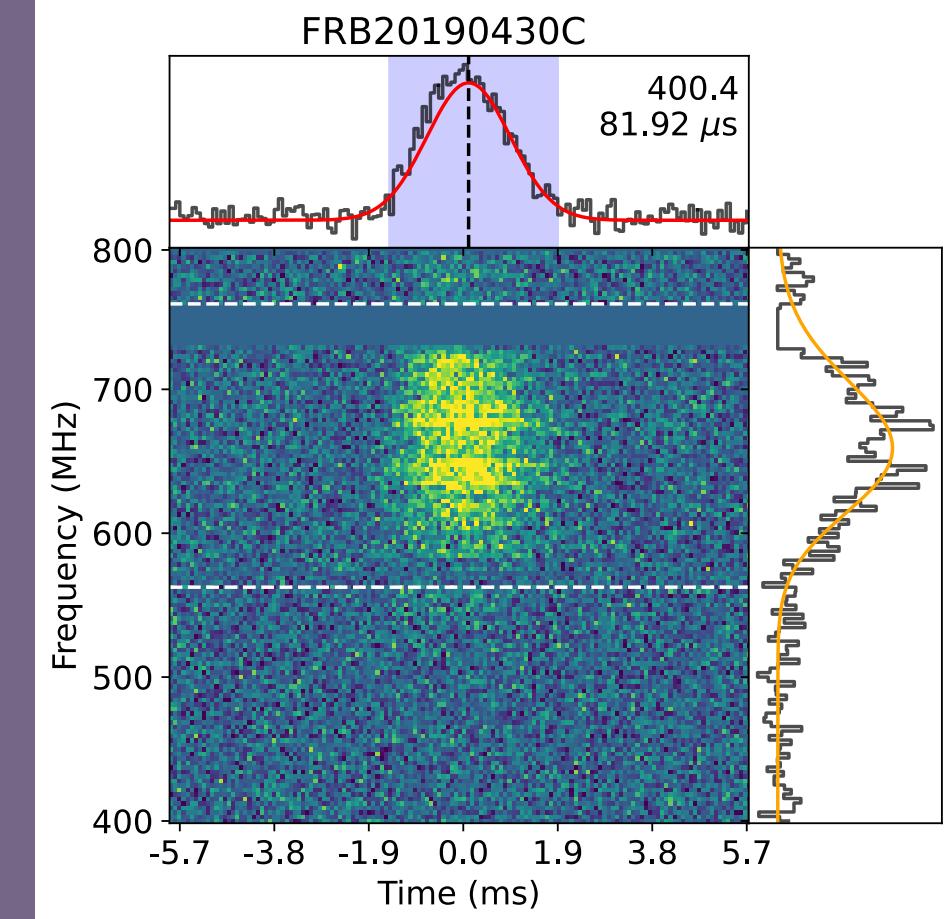
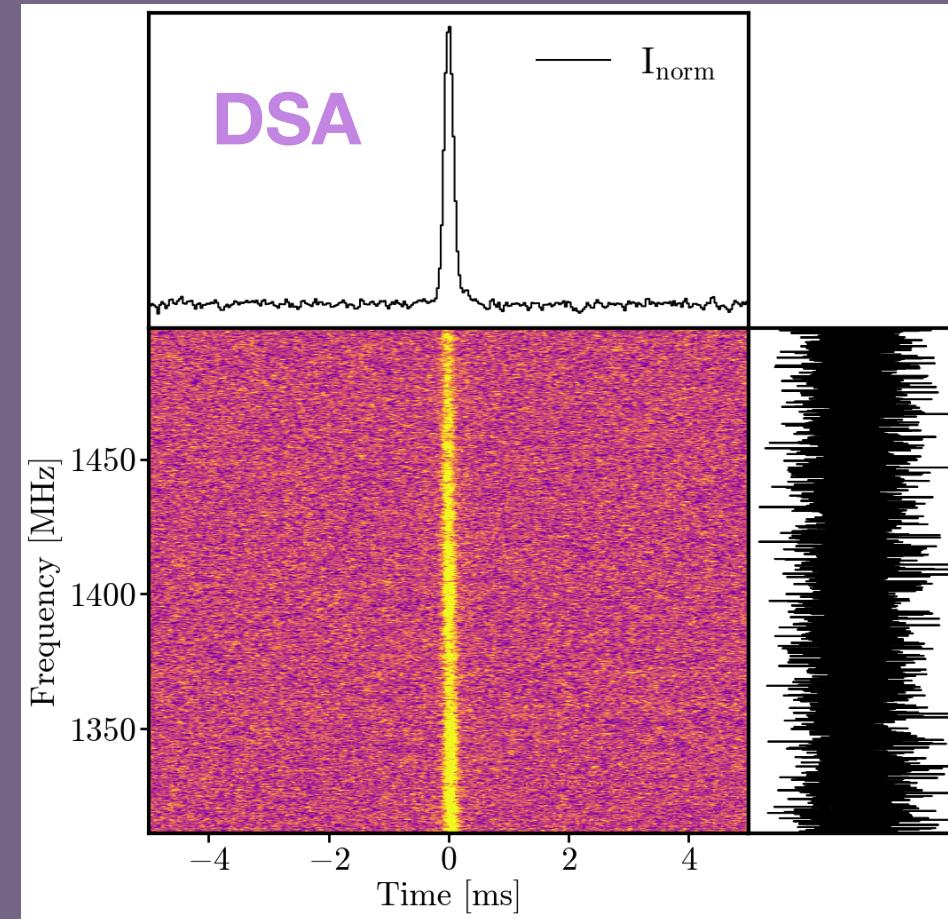
Pleunis et al. 2021  
Sand et al. 2025



# Spectral behaviour

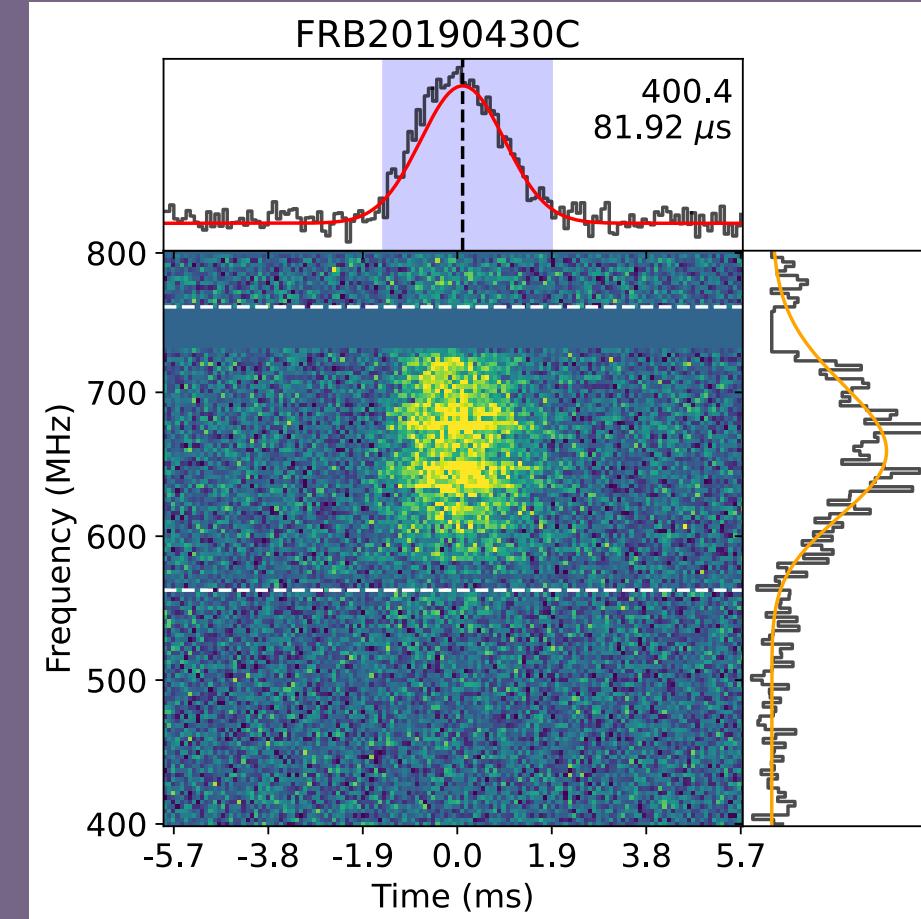
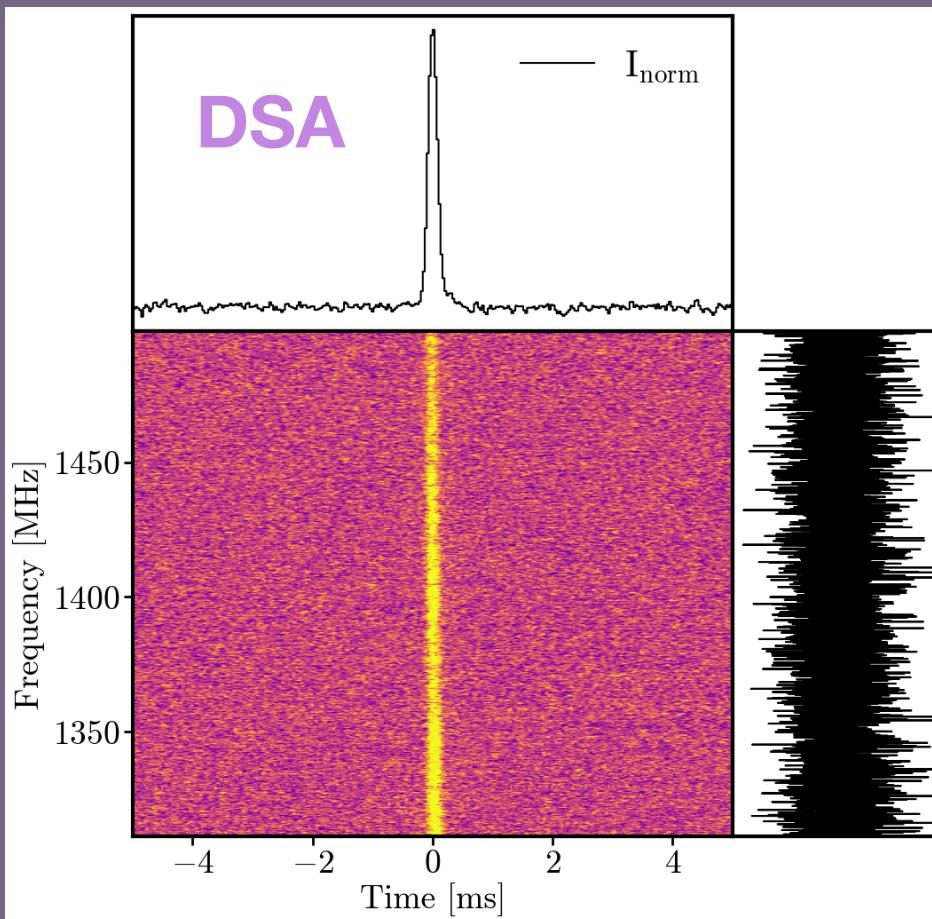
Broadband → Narrowband

Pleunis et al. 2021  
Sand et al. 2025



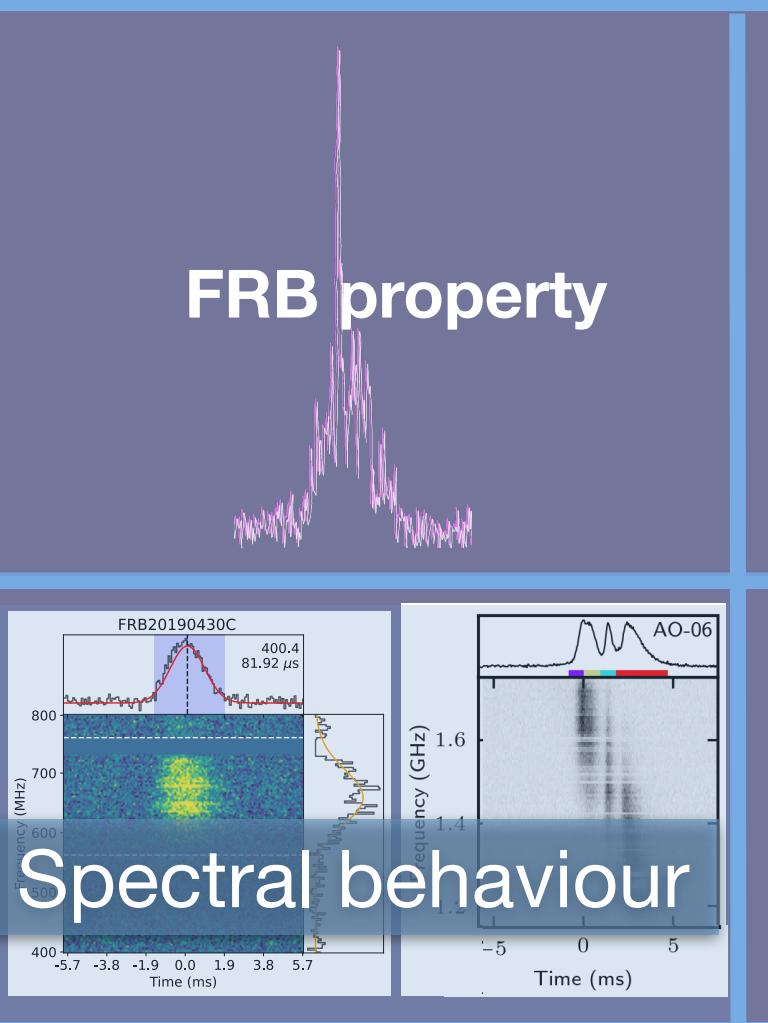
# Spectral behaviour

# Broadband



## Narrowband

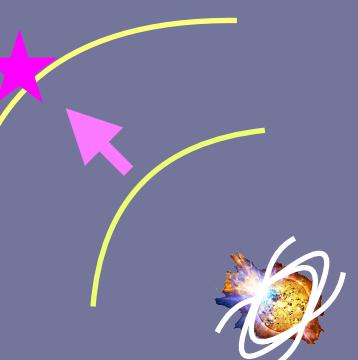
Pleunis et al. 2021  
Sand et al. 2025



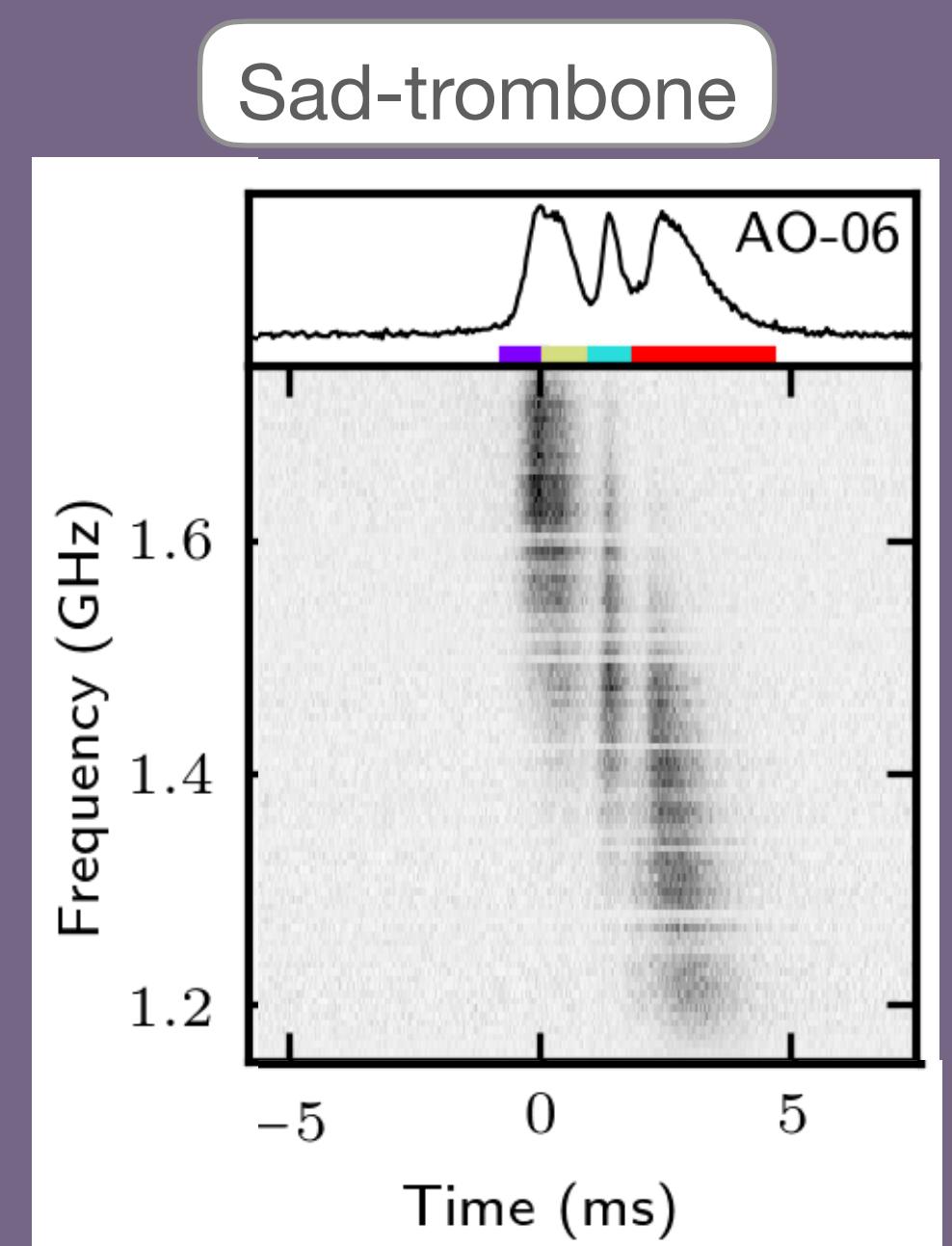
# Magnetospheric



## Non-magnetospheric



Metzger et al. 2022

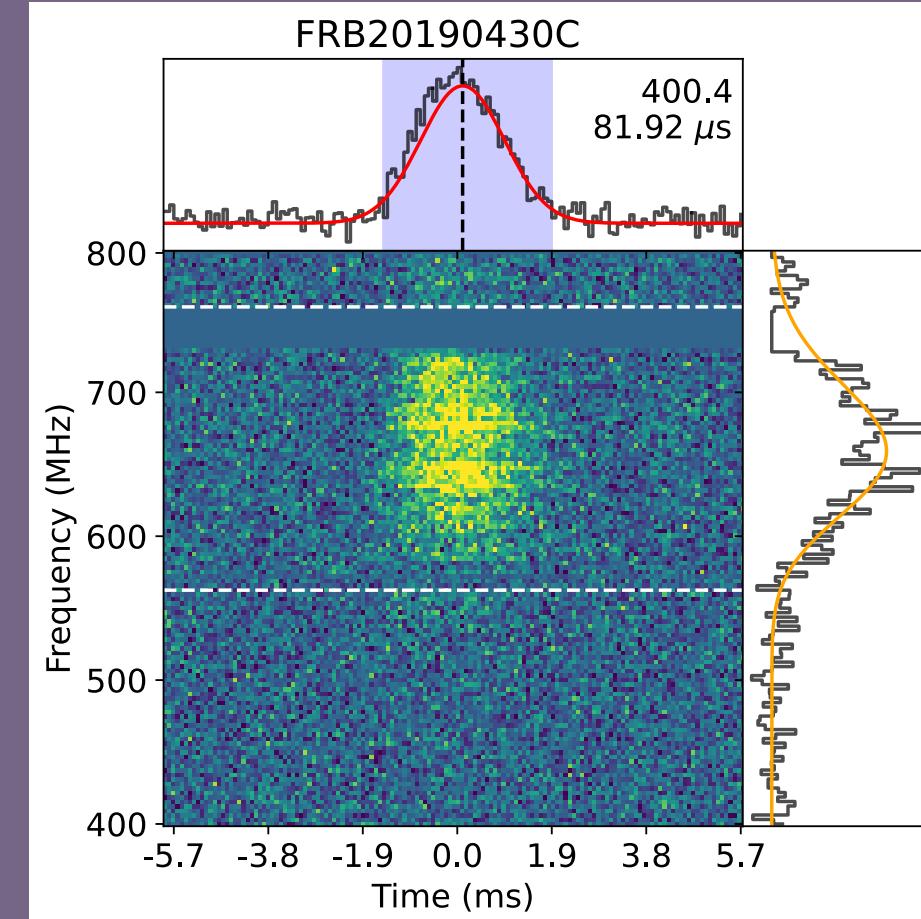
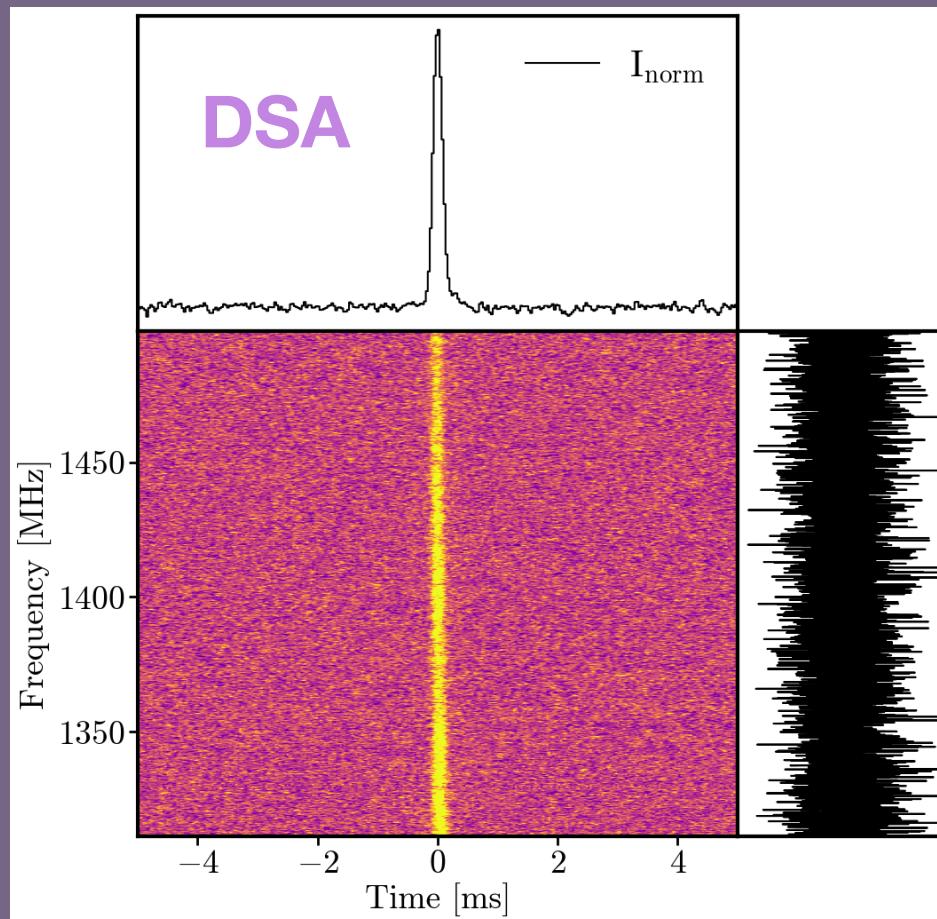


Faber et al. *in prep*

Hessels et al. 2019

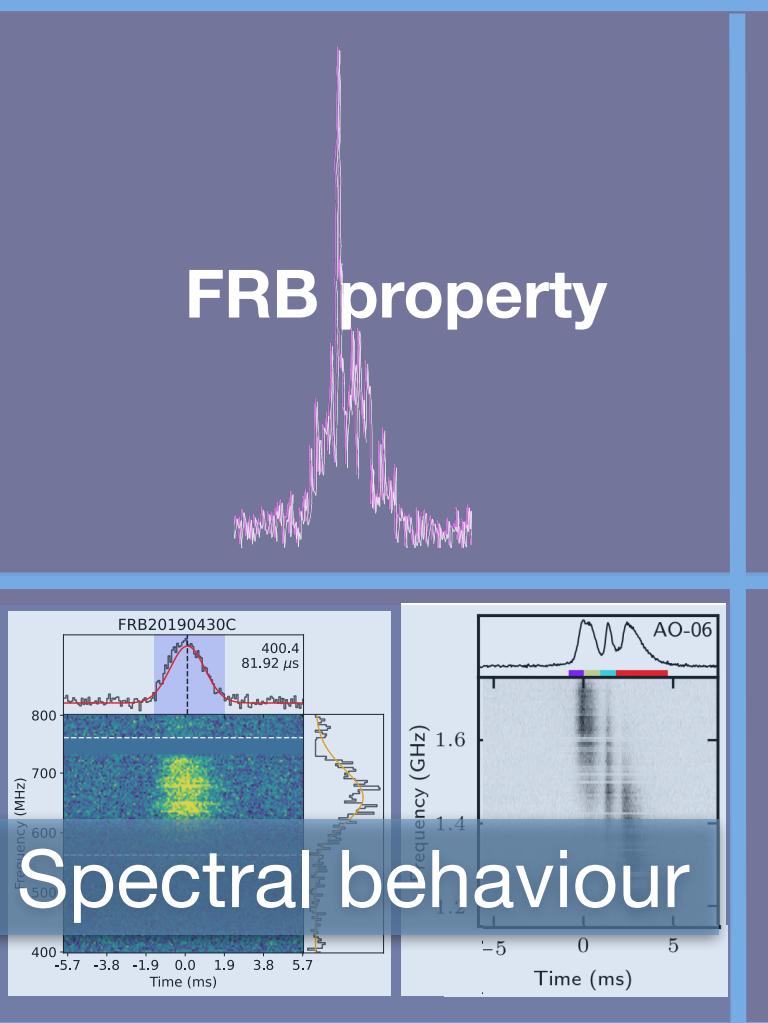
# Spectral behaviour

# Broadband



## Narrowband

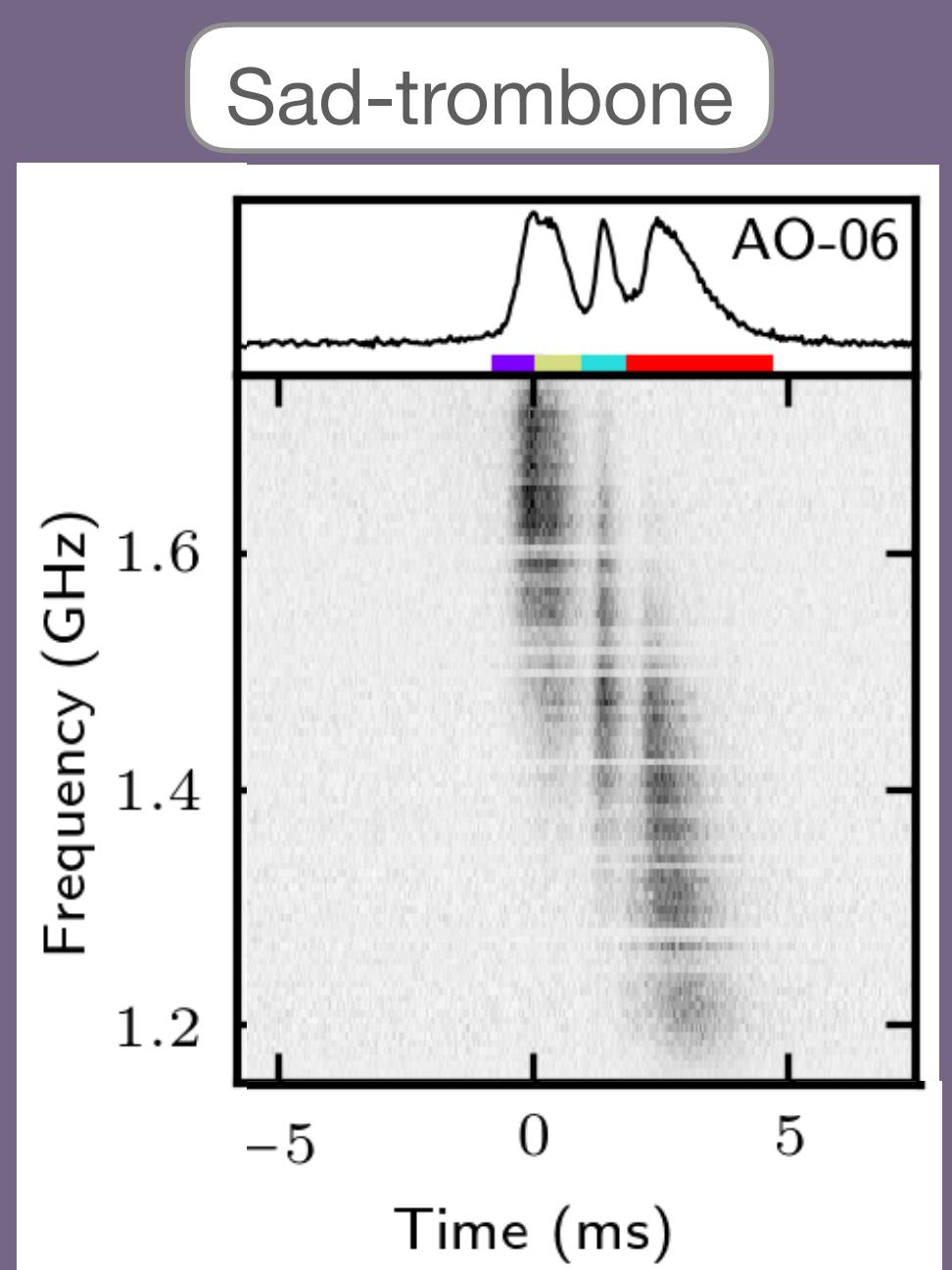
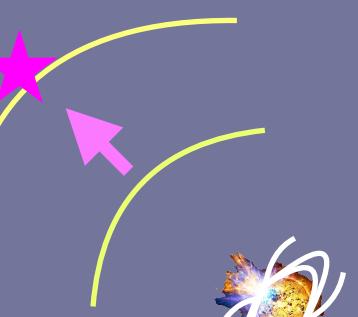
Pleunis et al. 2021  
Sand et al. 2025



# Magnetospheric



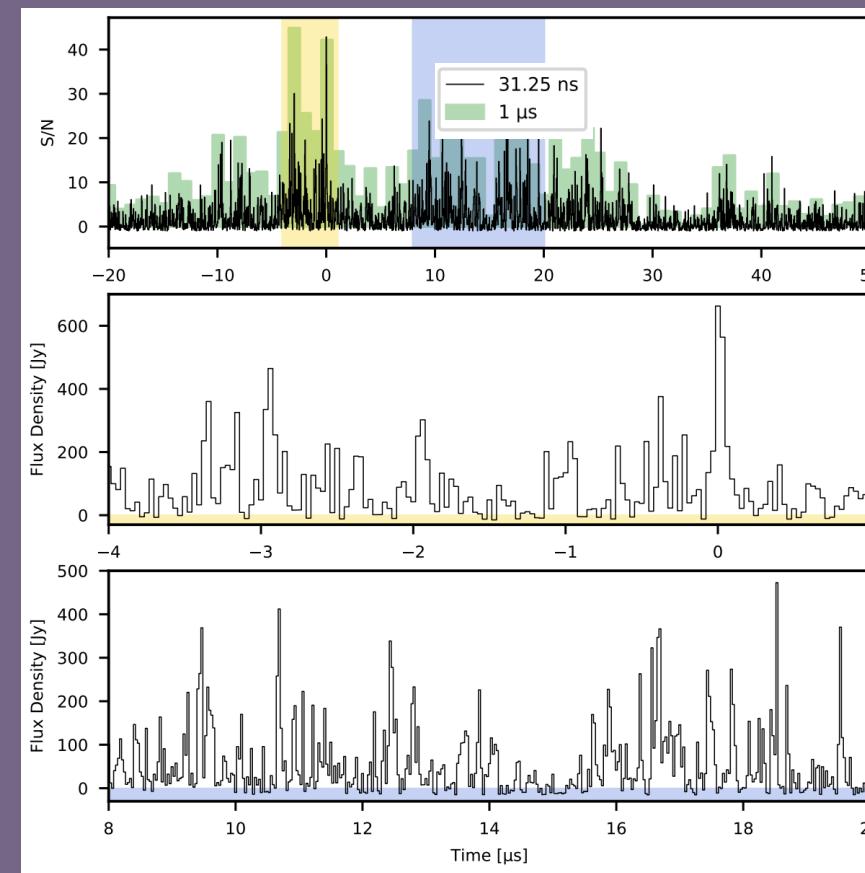
## Non-magnetospheric



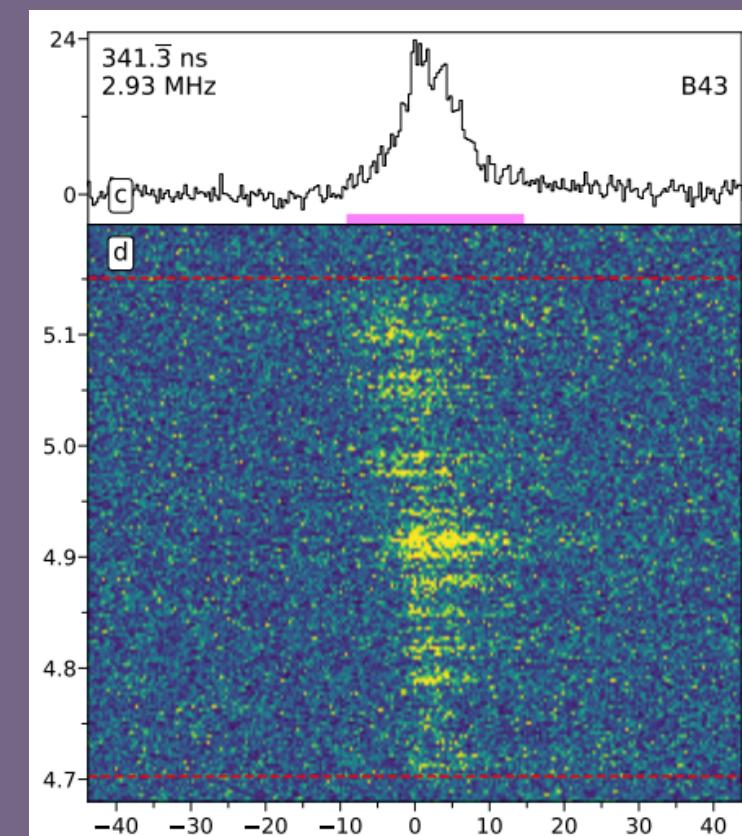
Faber et al. *in prep*

Hessels et al. 2019

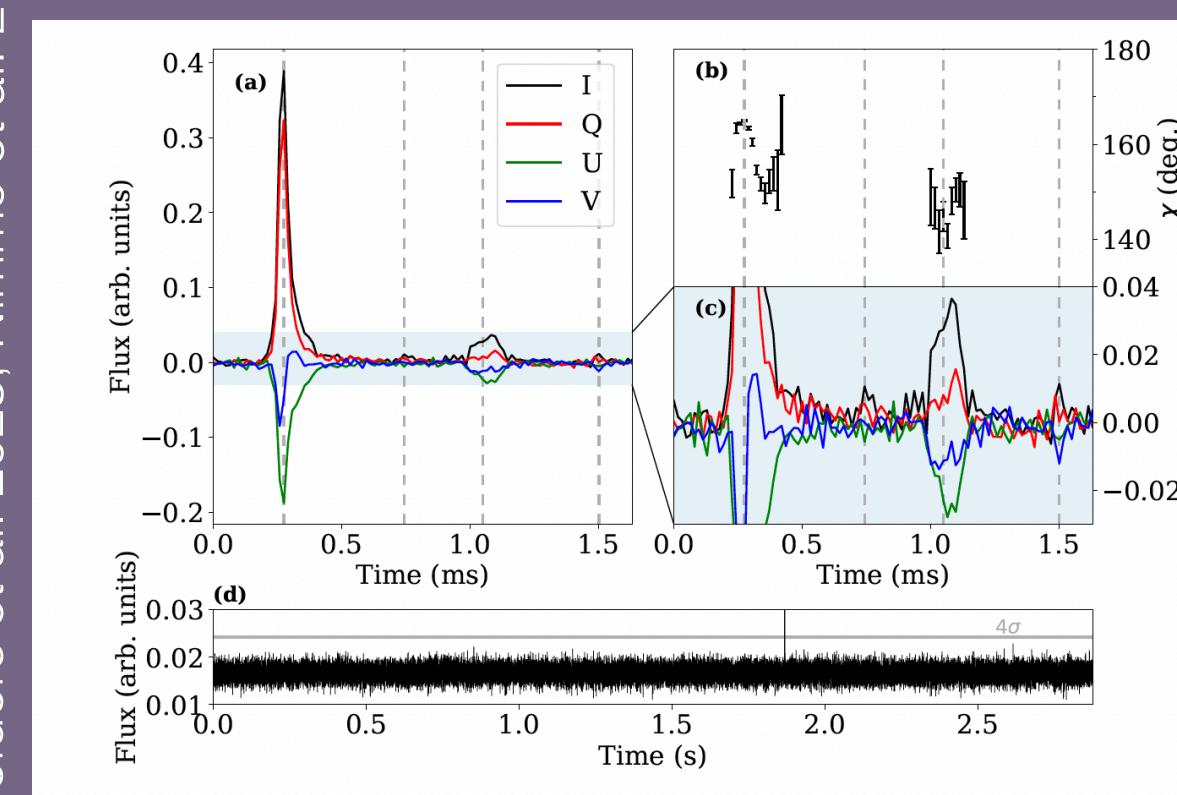
# Temporal variability



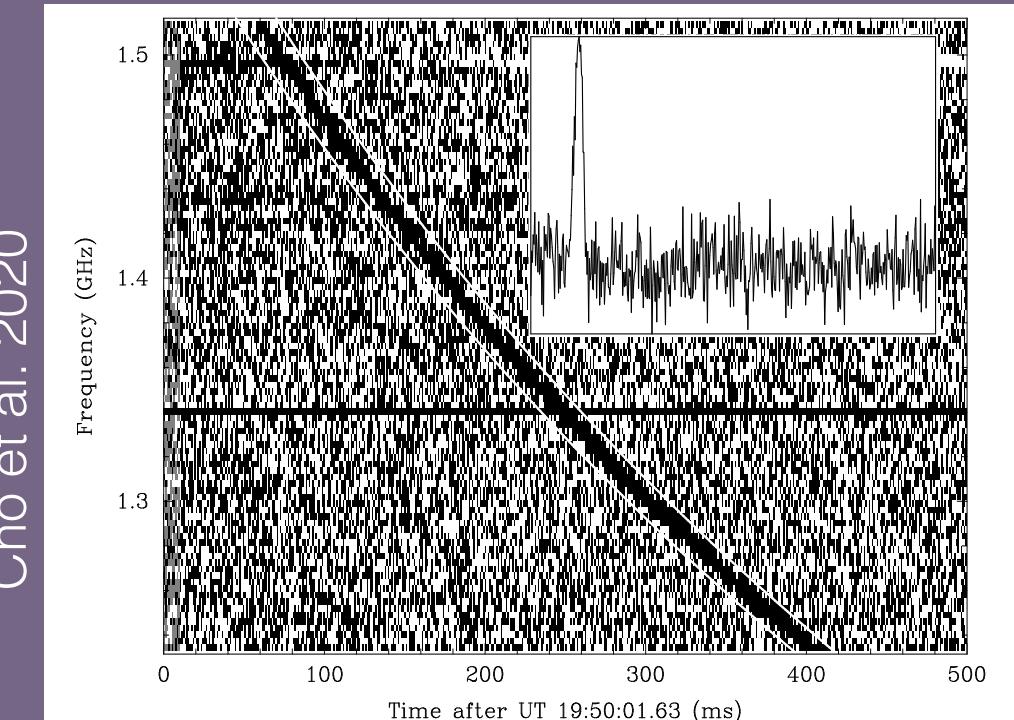
Nimmo et al. 2022



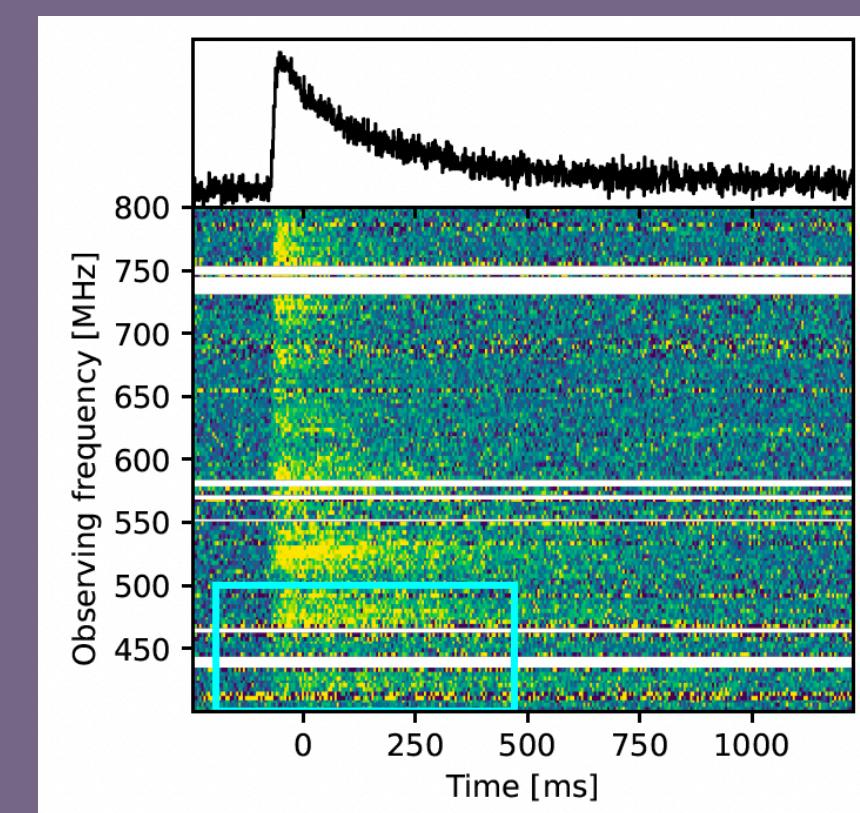
Snelders et al. 2023, Nimmo et al. 2021



Cho et al. 2020



Lorimer et al. 2007



Shin et al. 2024

60 ns

Microseconds

10-100us

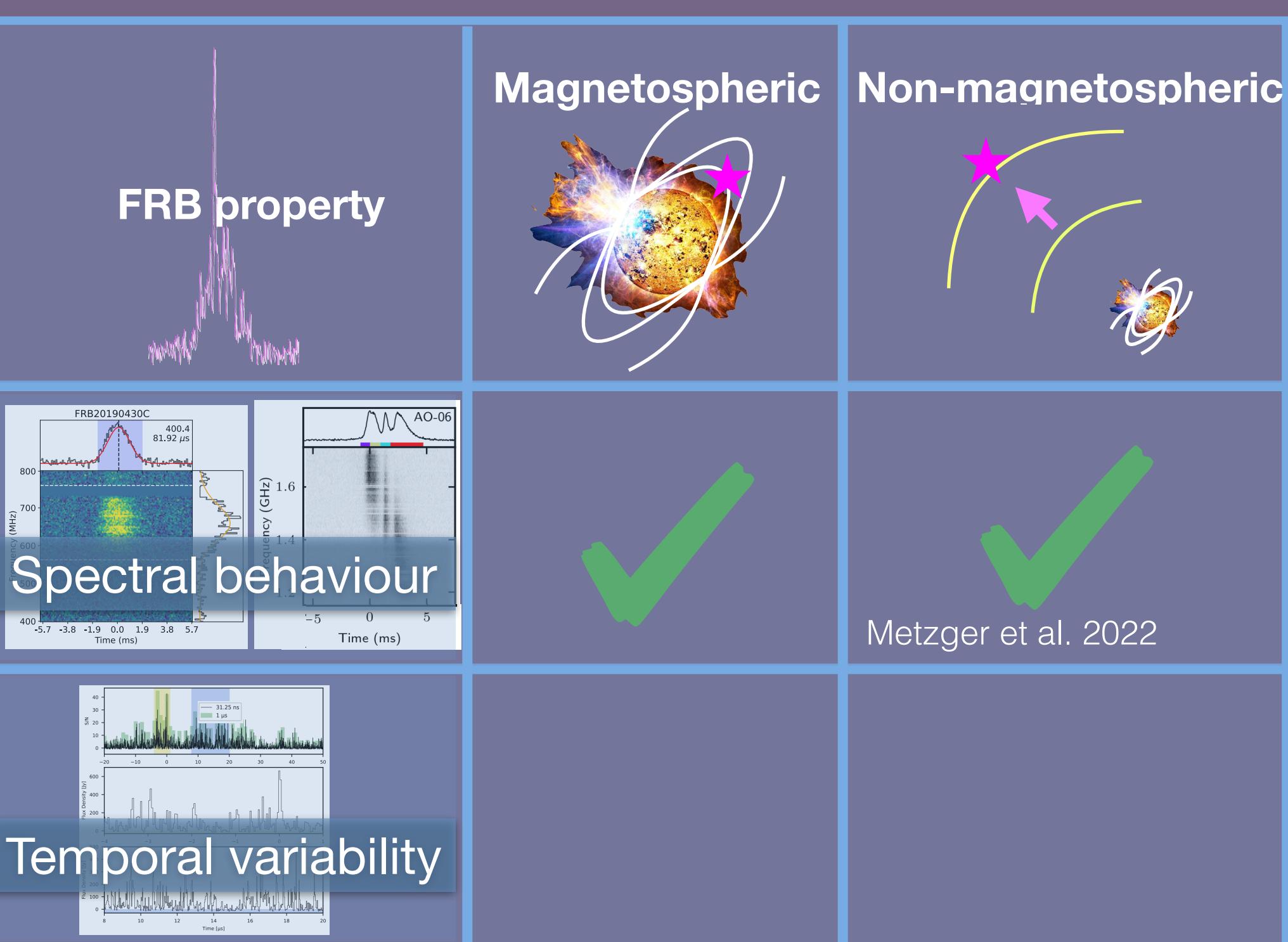
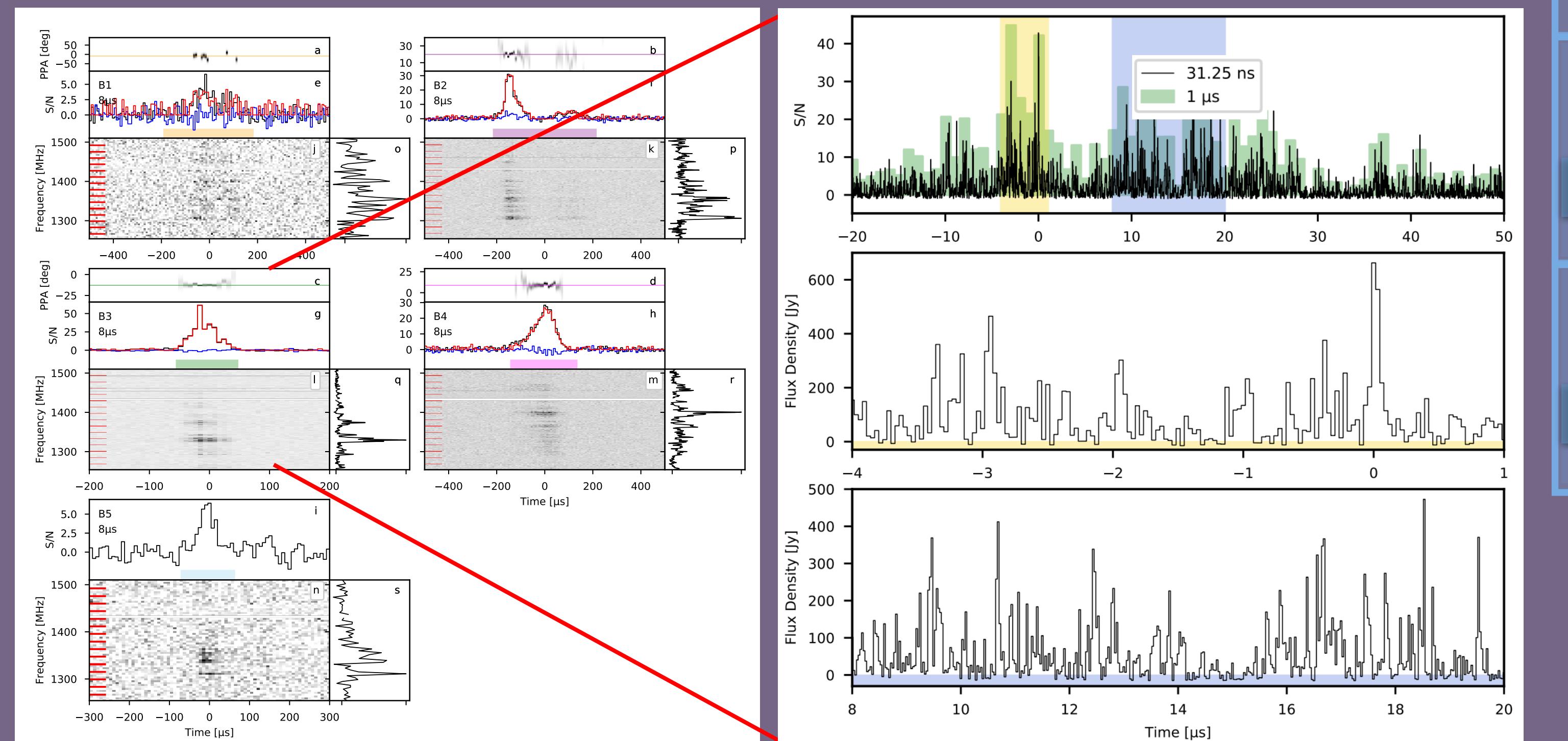
Milliseconds

Seconds

TIME

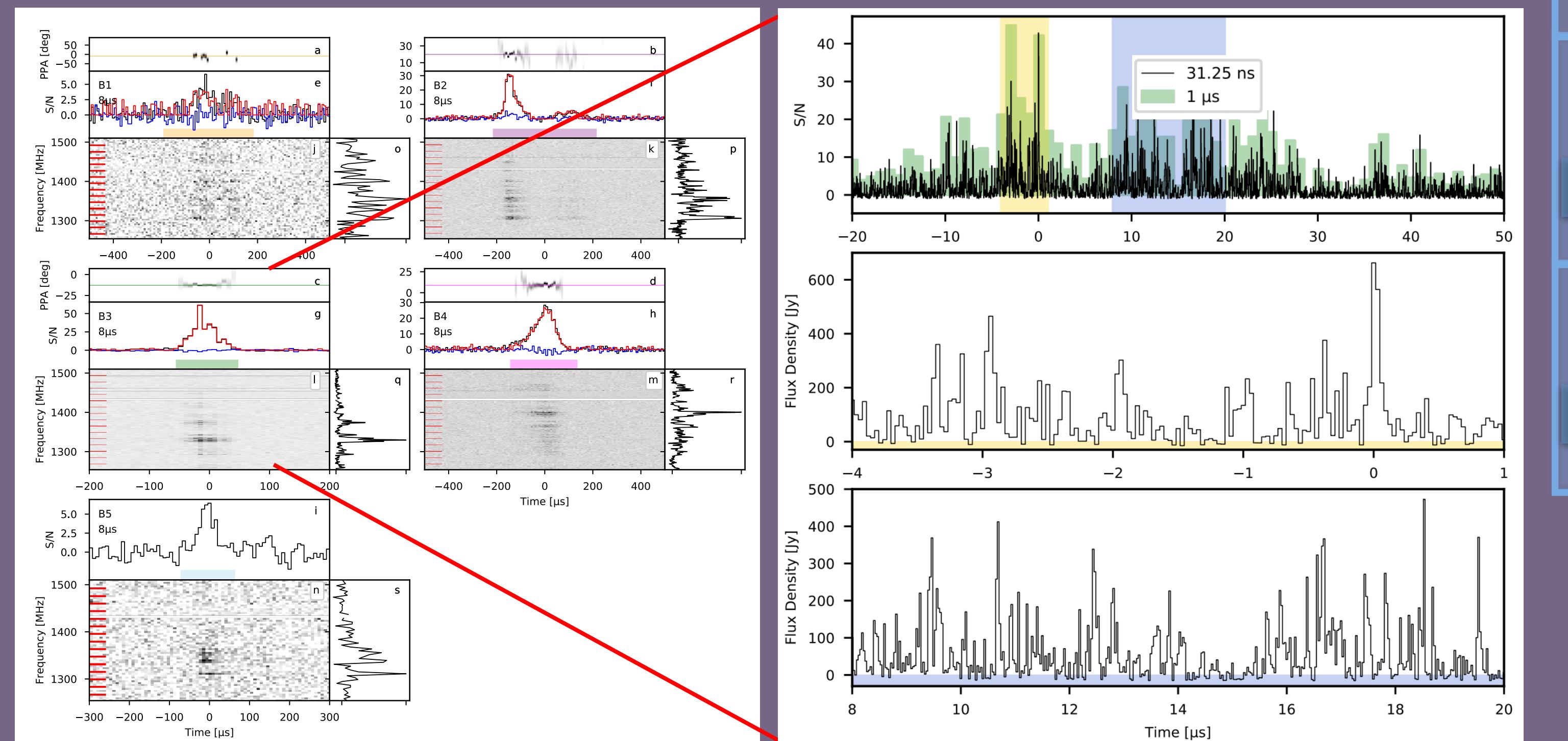
Orders of  
magnitude  
difference

# Temporal variability



Nimmo et al. 2022a

# Temporal variability

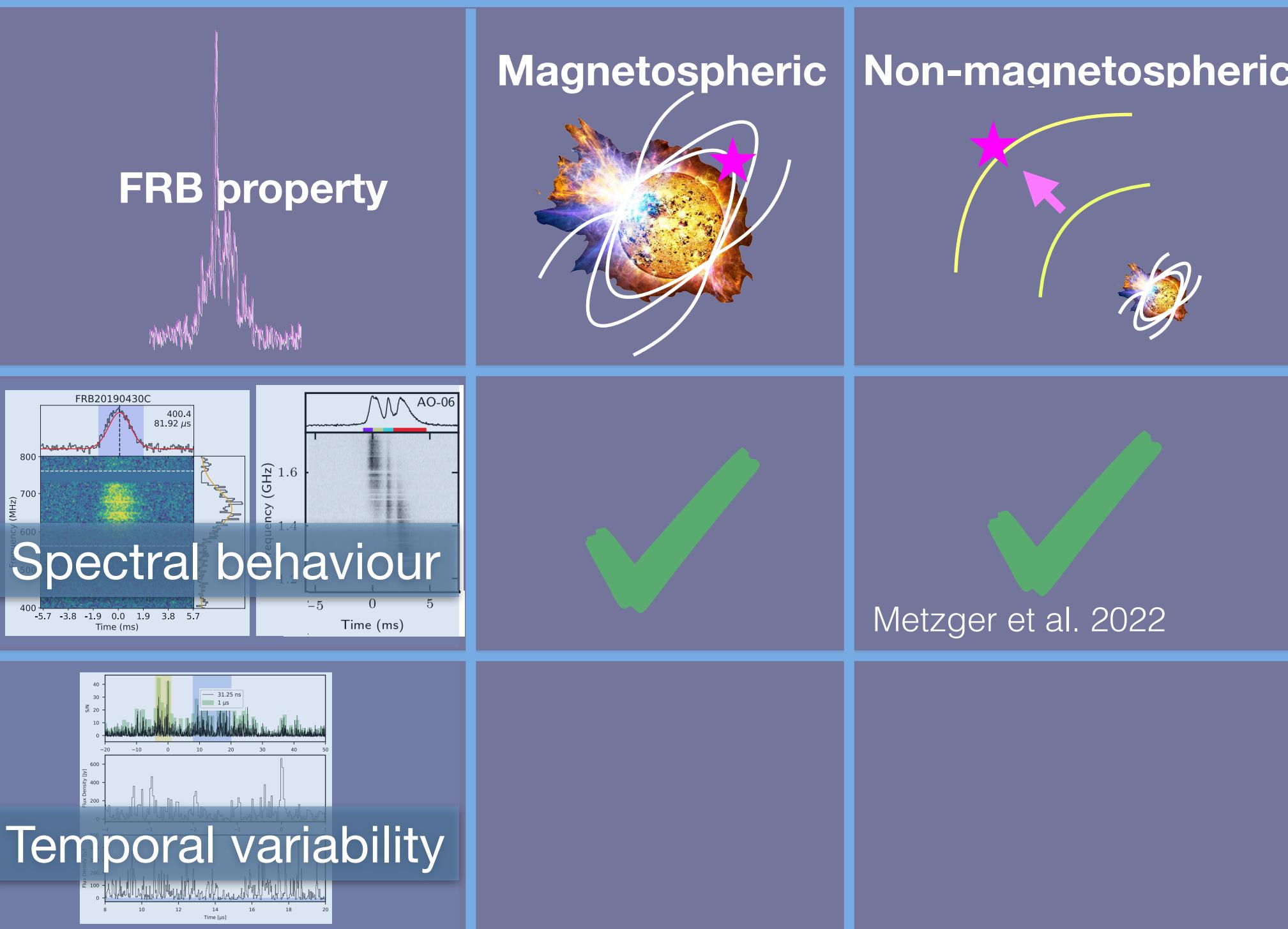


Nimmo et al. 2022a

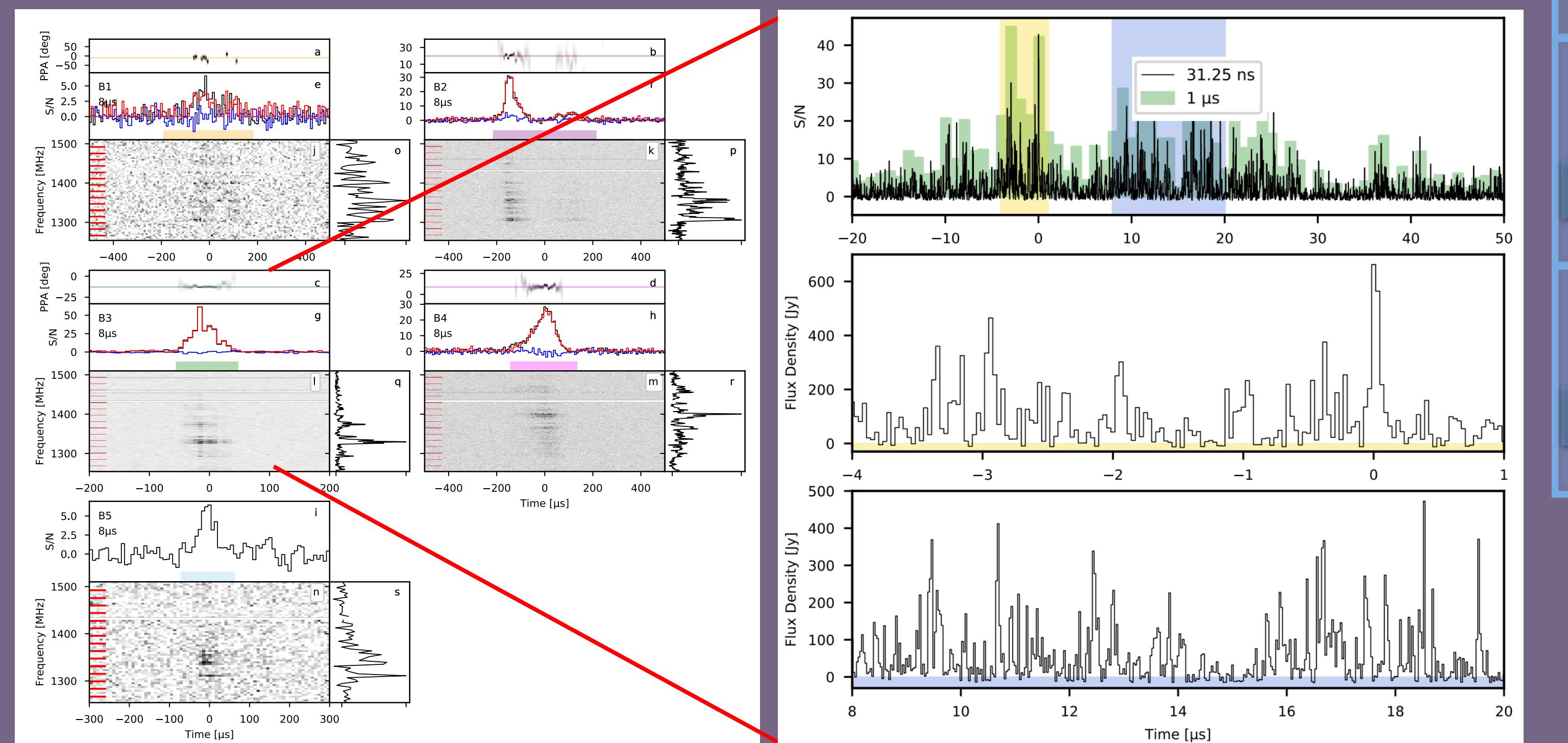
Implies an emission size  $\sim 20\text{m}$  (excl. relativistic effects)

With relativistic correction:

$$\delta t \sim \frac{R_{\text{em}}}{2c\Gamma^2}$$



# Temporal variability

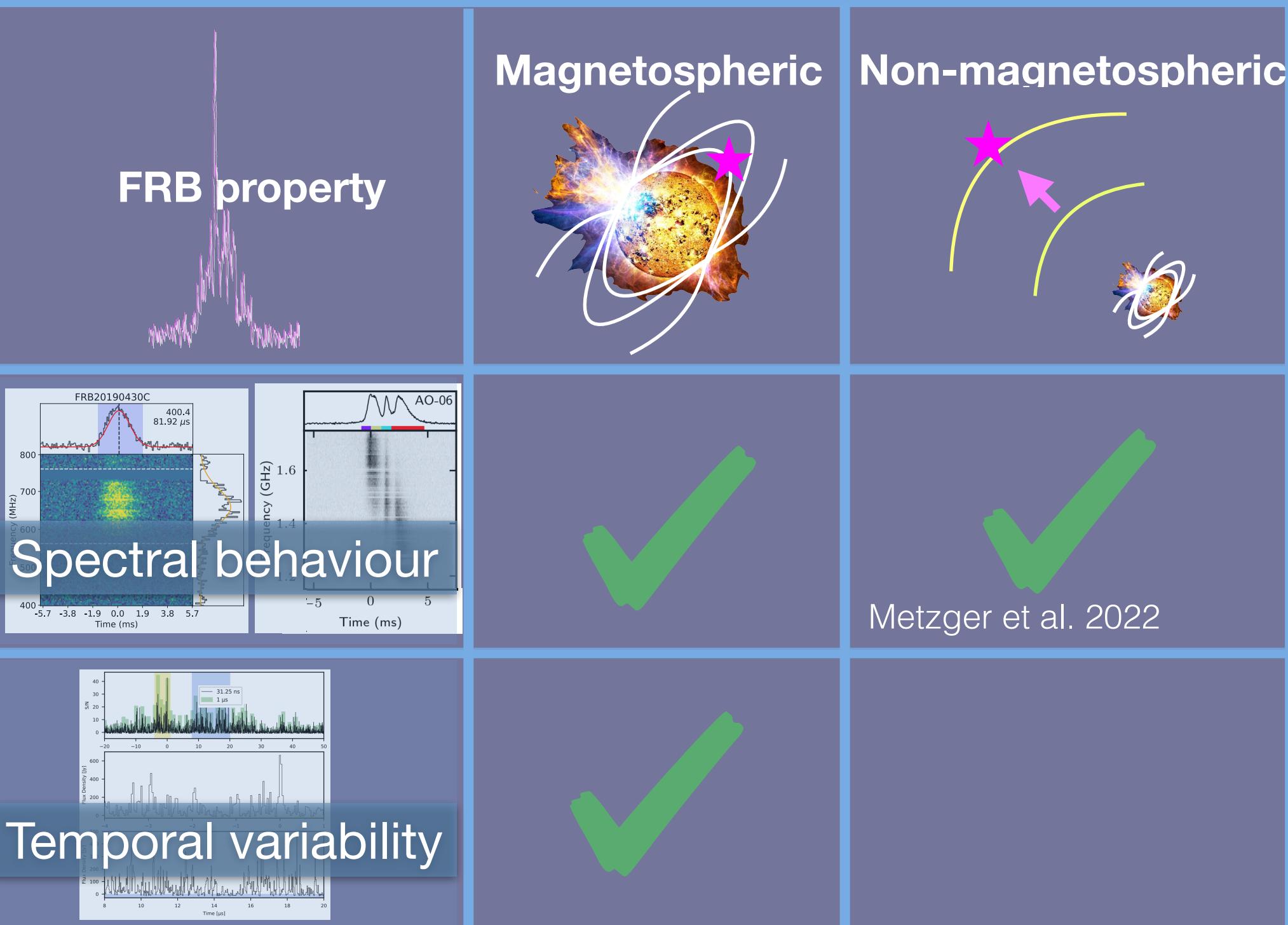


Nimmo et al. 2022a

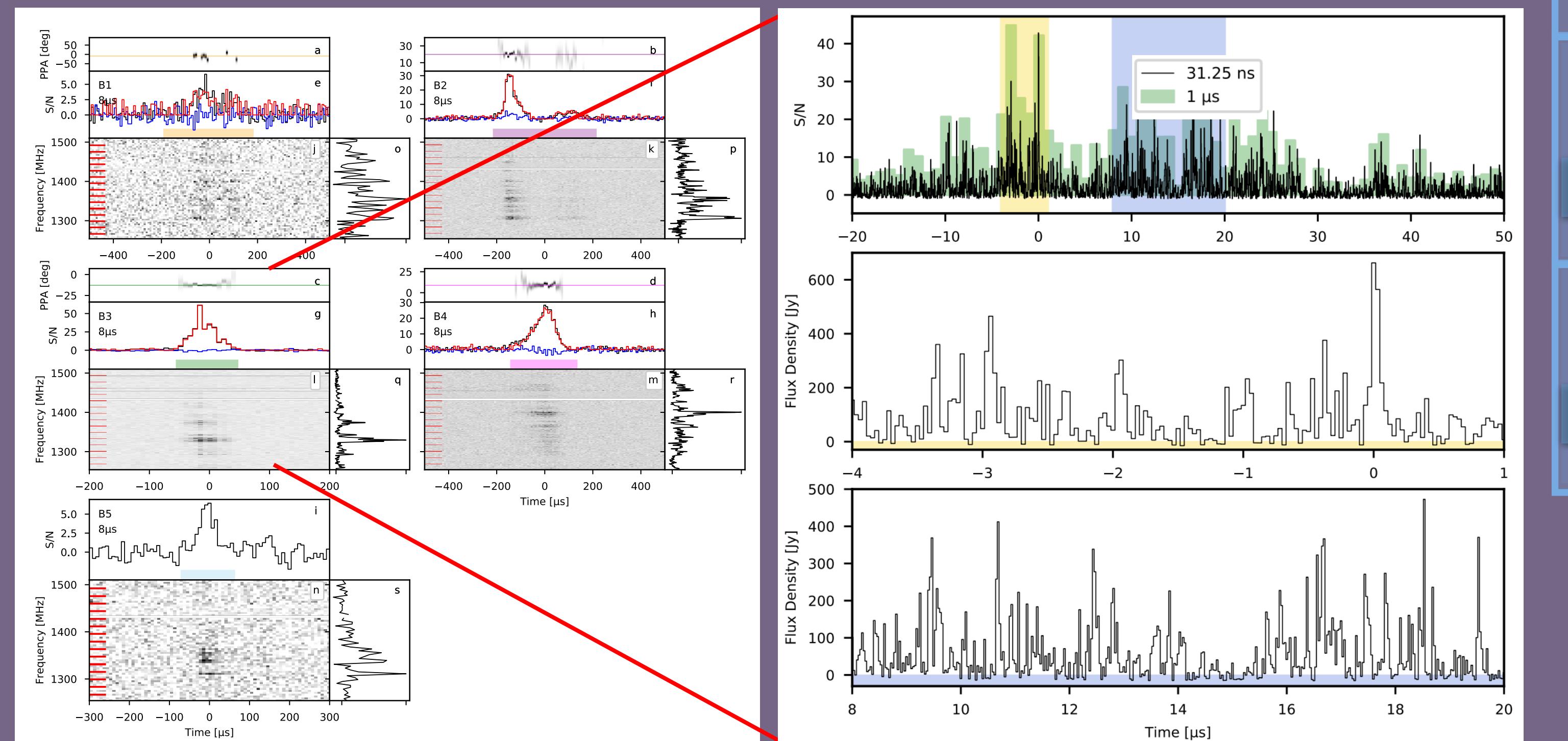
Implies an emission size  $\sim 20\text{m}$  (excl. relativistic effects)

With relativistic correction:

$$\delta t \sim \frac{R_{\text{em}}}{2c\Gamma^2}$$



# Temporal variability

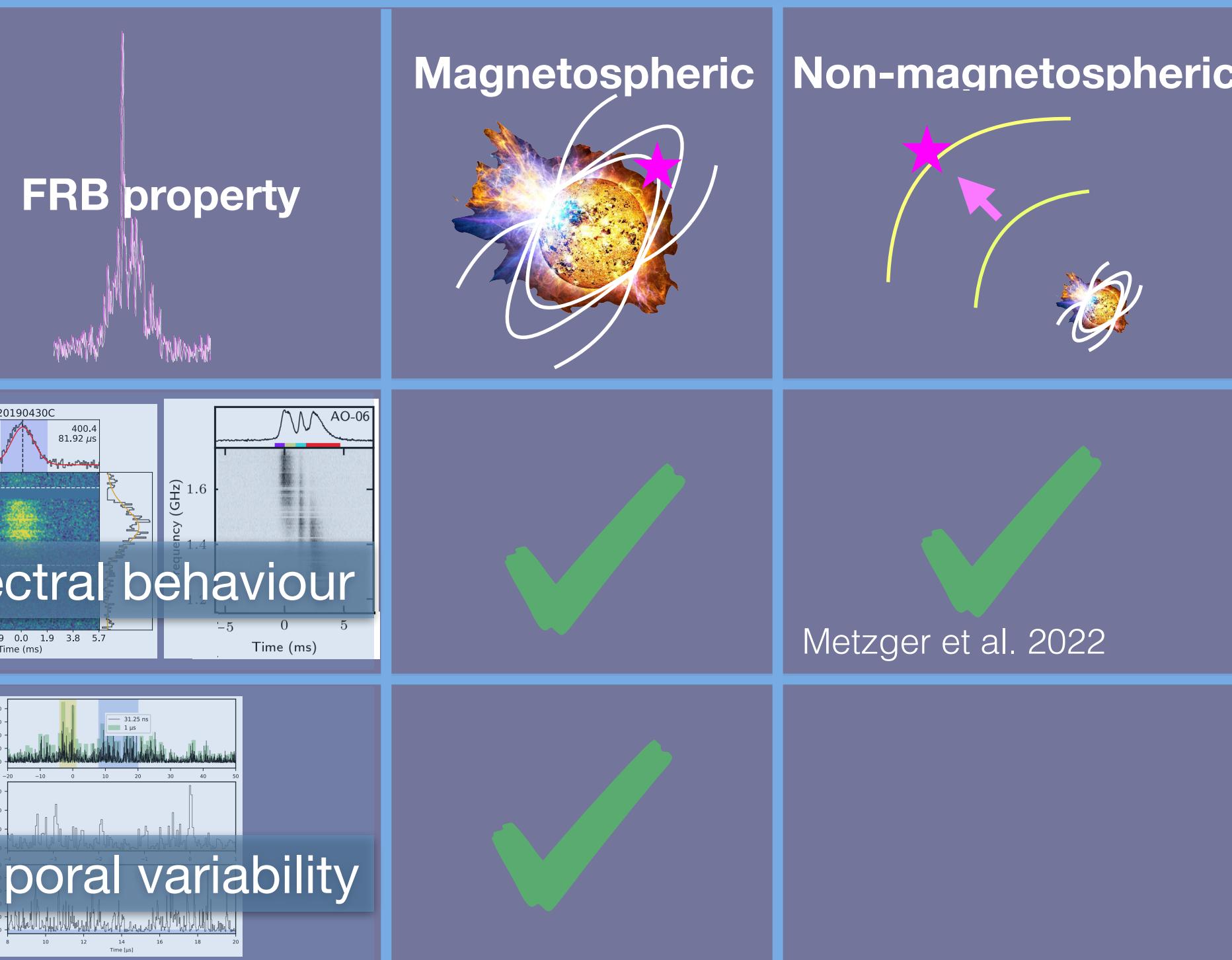


Nimmo et al. 2022a

Implies an emission size  $\sim 20\text{m}$  (excl. relativistic effects)

With relativistic correction:

$$\delta t \sim \frac{R_{\text{em}}}{2c\Gamma^2}$$



But for the non-magnetospheric shock models:

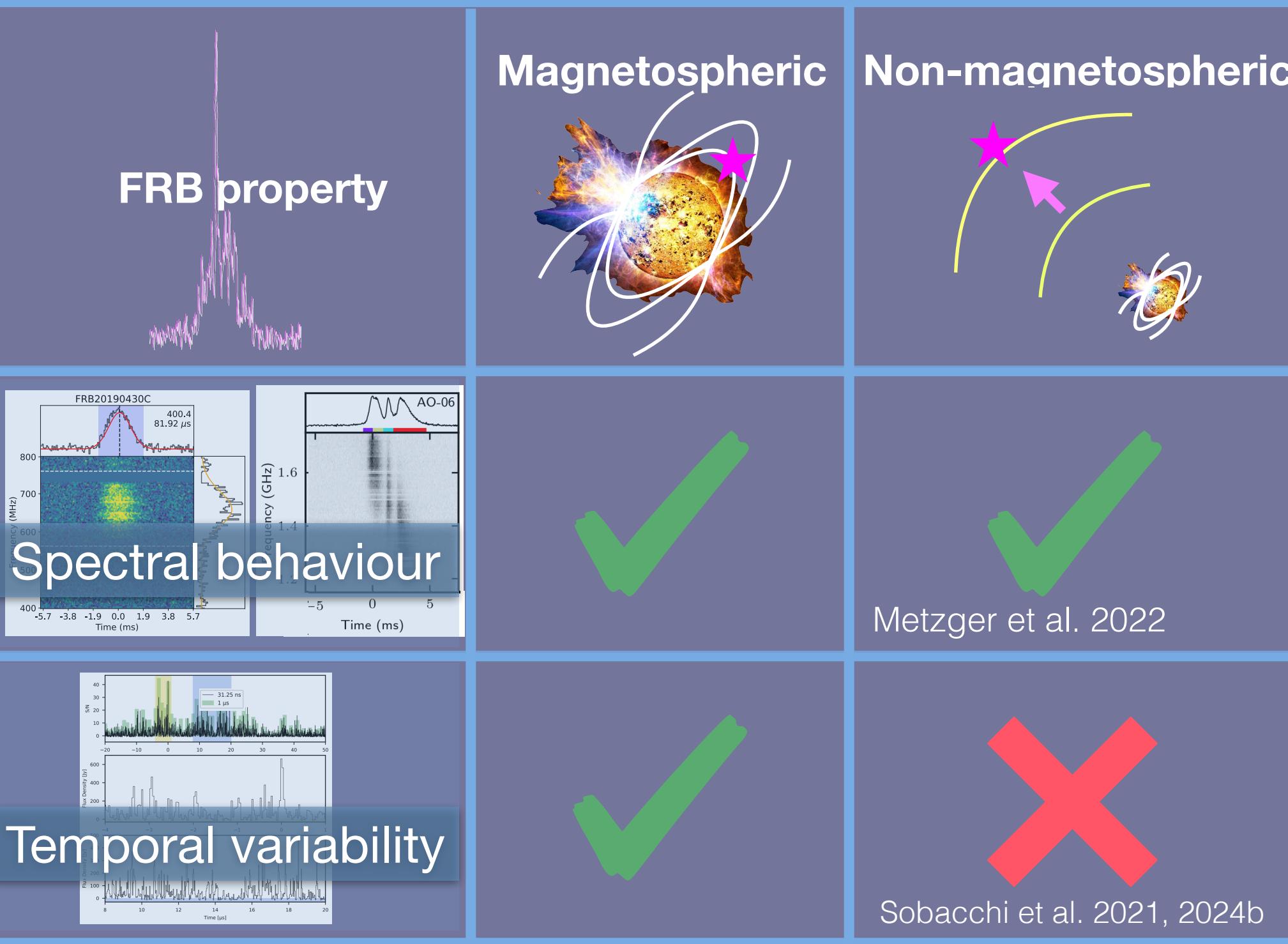
$$W \sim \frac{R_{\text{em}}}{c\Gamma^2}$$

Implying...

$W \simeq \delta t$

Metzger et al. 2019

# Temporal variability



But for the non-magnetospheric shock models:

$$W \sim \frac{R_{\text{em}}}{c\Gamma^2}$$

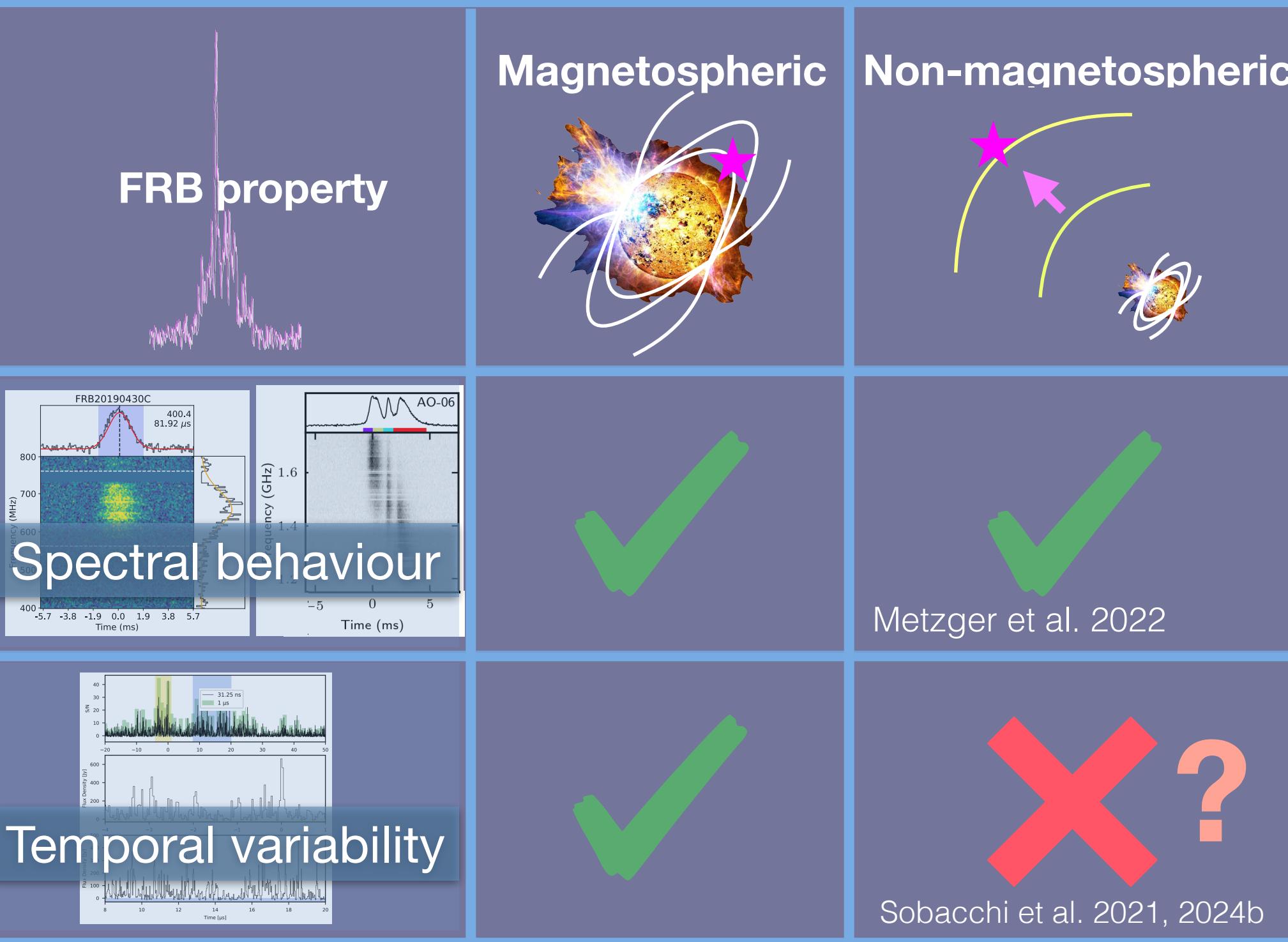
Implying...

$$W \simeq \delta t$$

Metzger et al. 2019

# Temporal variability

\* Caveat



But for the non-magnetospheric shock models:

$$W \sim \frac{R_{\text{em}}}{c\Gamma^2}$$

Implying...

$$W \simeq \delta t$$

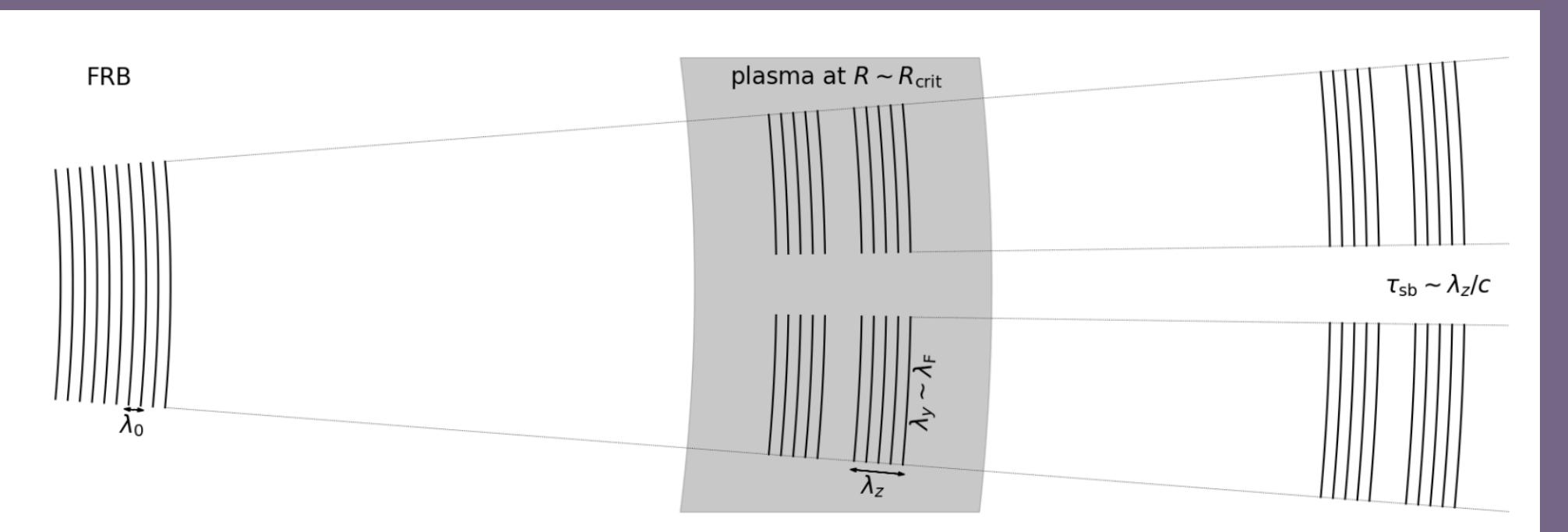
Metzger et al. 2019

# Temporal variability

\* Caveat

Propagation effects?

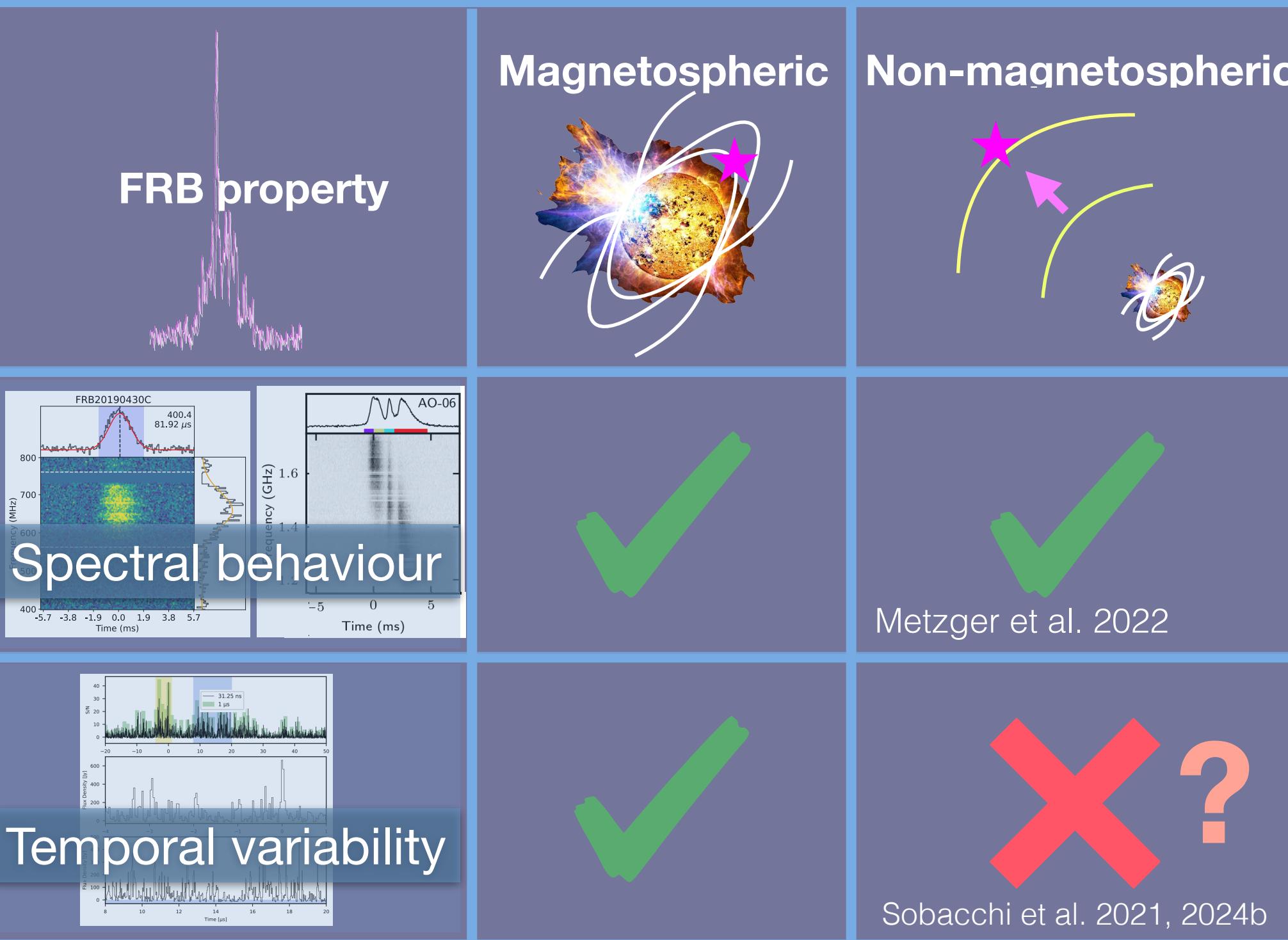
Self-modulation



Sobacchi et al. 2021

Propagation through electron-proton shell introduces non-linear effects which can create the observed microstructure

Sobacchi et al. 2024b



But for the non-magnetospheric shock models:

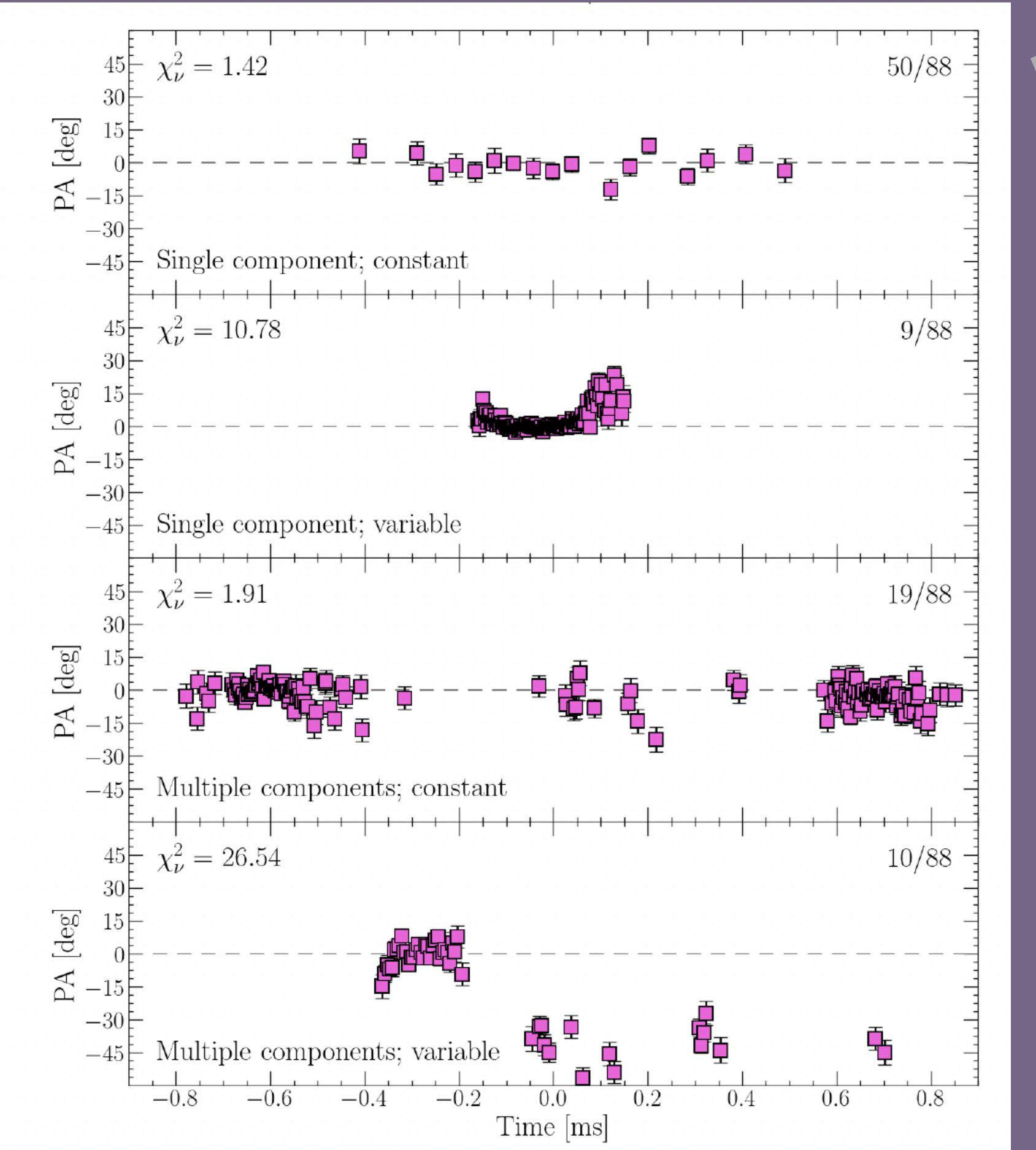
$$W \sim \frac{R_{\text{em}}}{c \Gamma^2}$$

Implying...

$$W \simeq \delta t$$

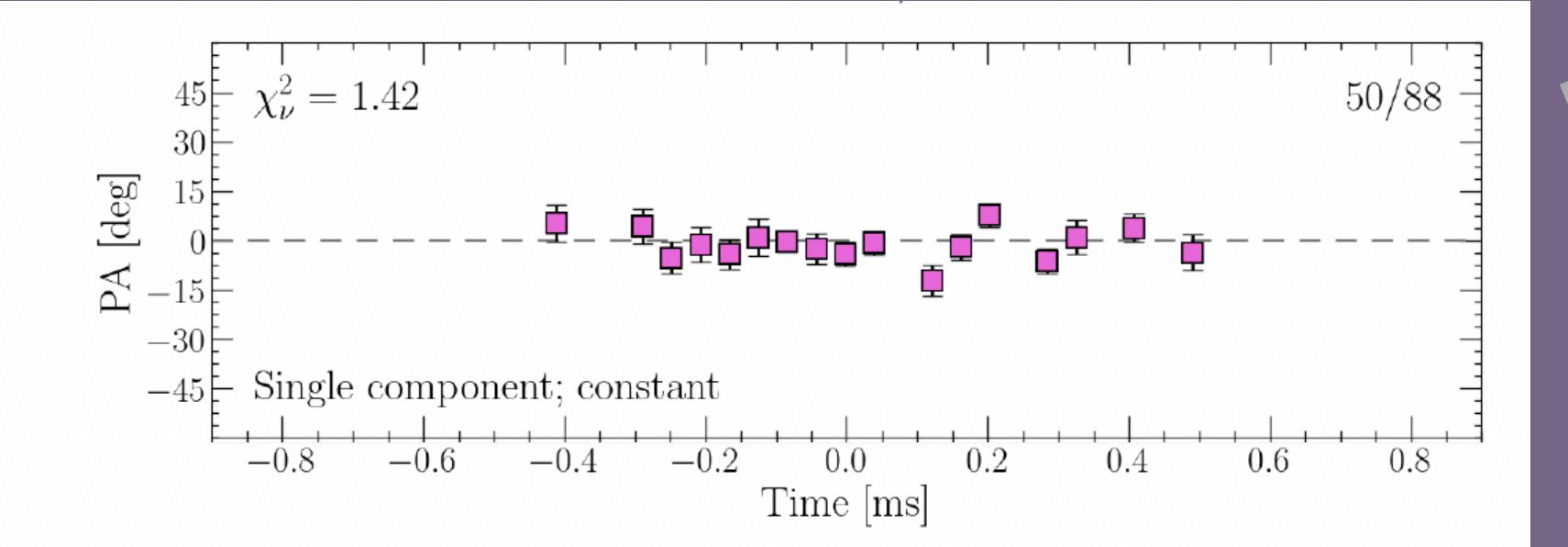
Metzger et al. 2019

# Polarization



highly structured magnetic  
field configurations

# Polarization

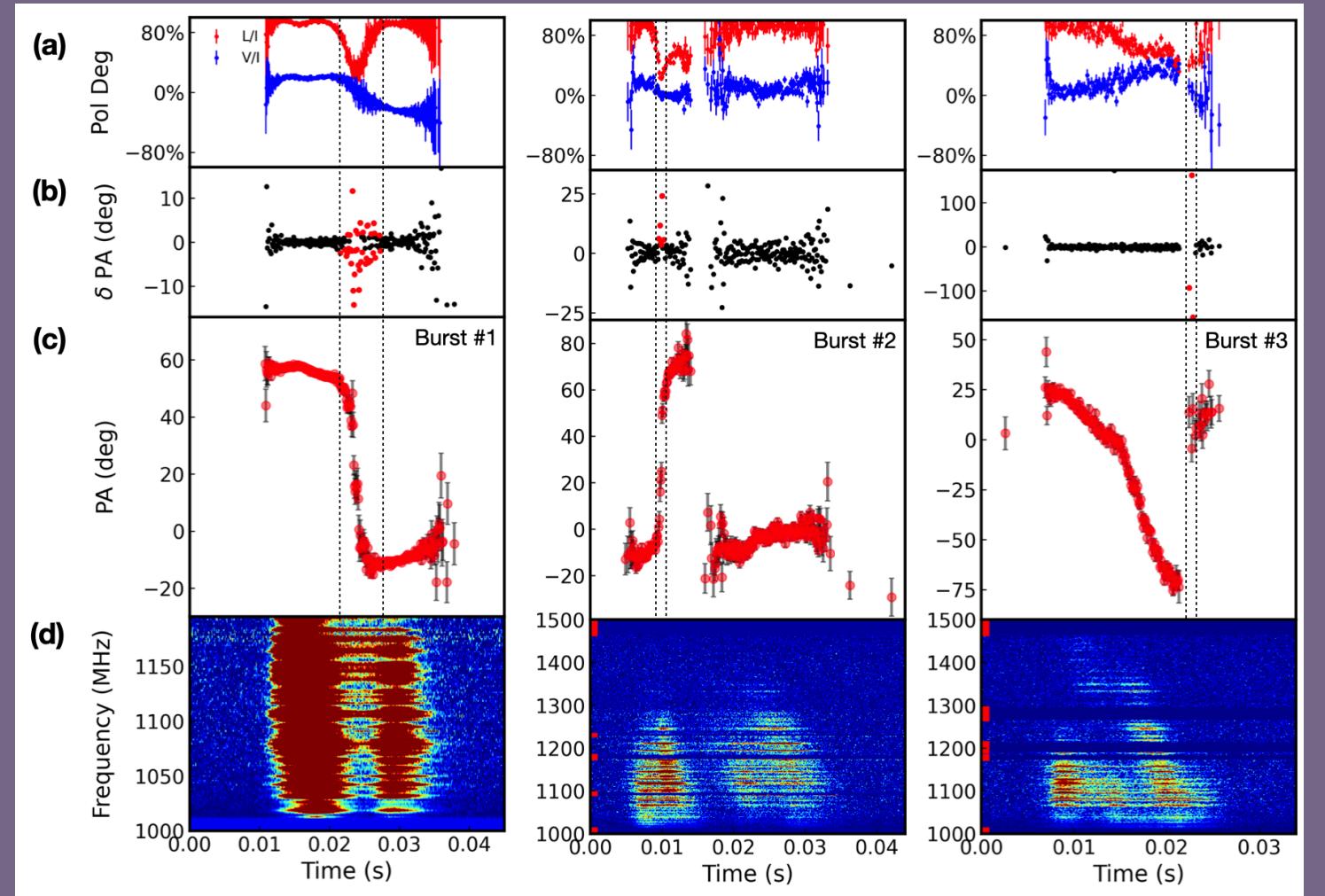


Pandhi et al. 2024

highly structured magnetic field configurations

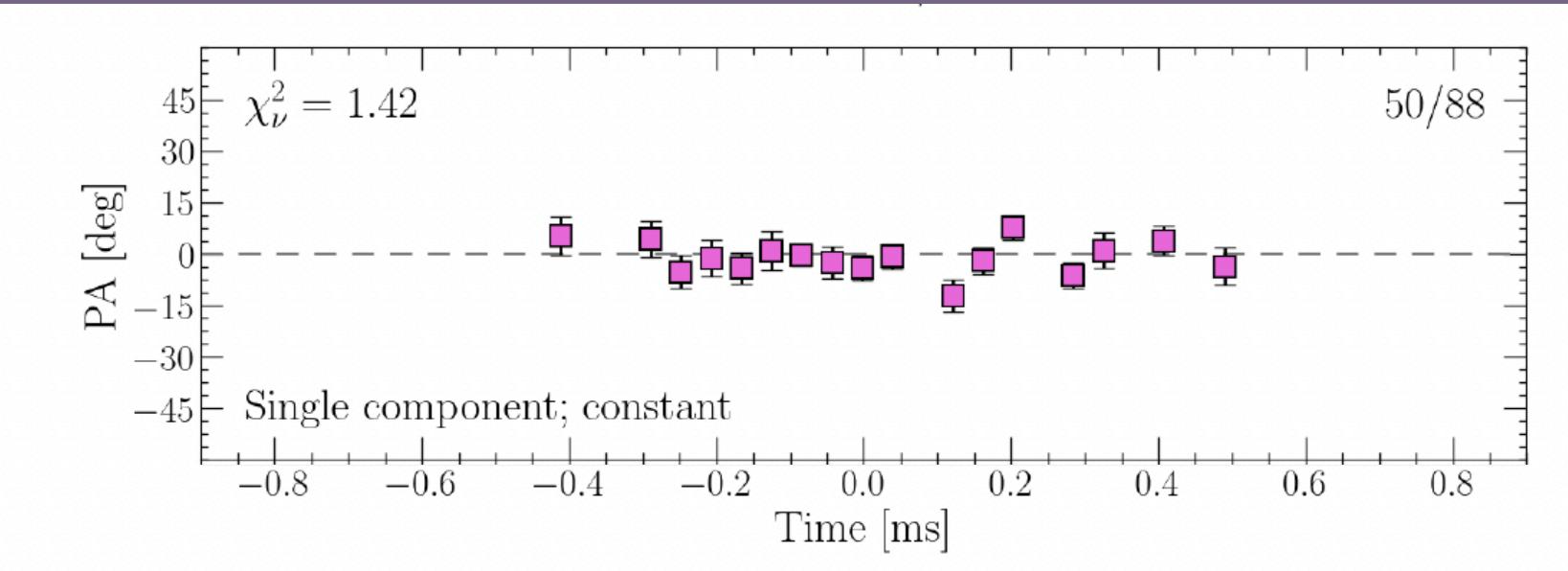
But sometimes...

## JUMPS



Niu et al. 2024

# Polarization



Pandhi et al. 2024

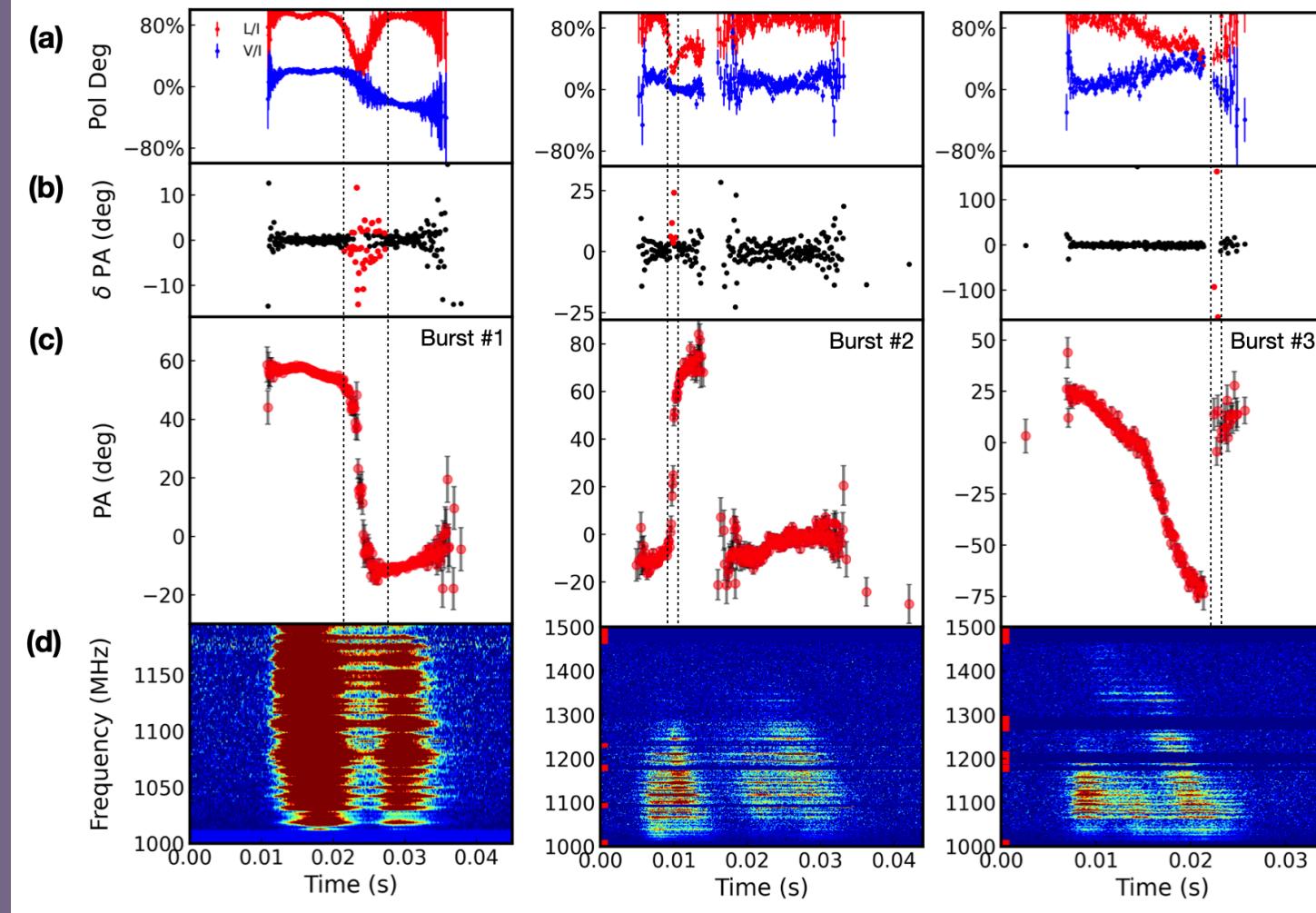


Difficult to explain without having a beam of light sweeping across our line of sight.

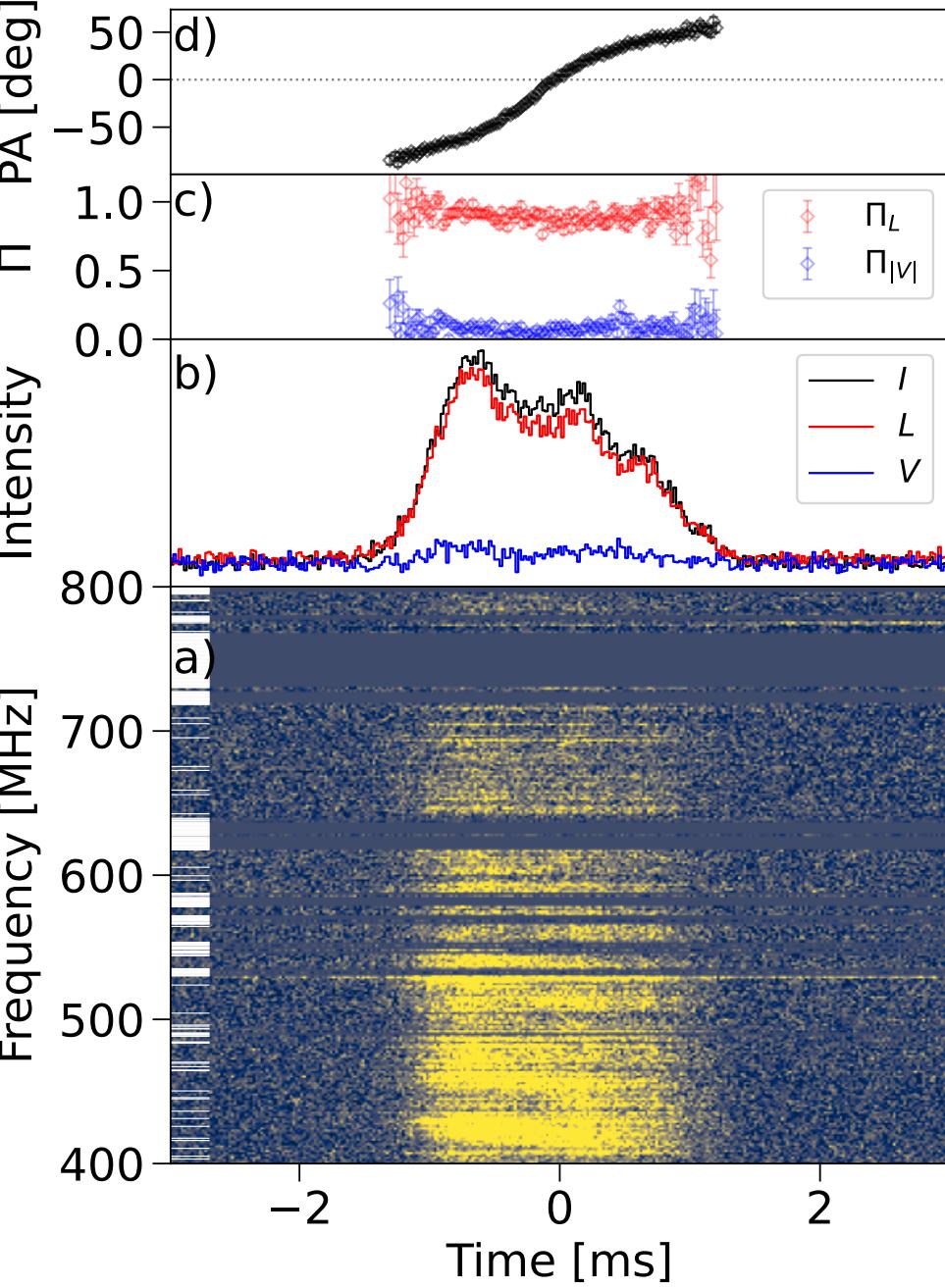
highly structured magnetic field configurations

But sometimes...

## JUMPS



Niu et al. 2024



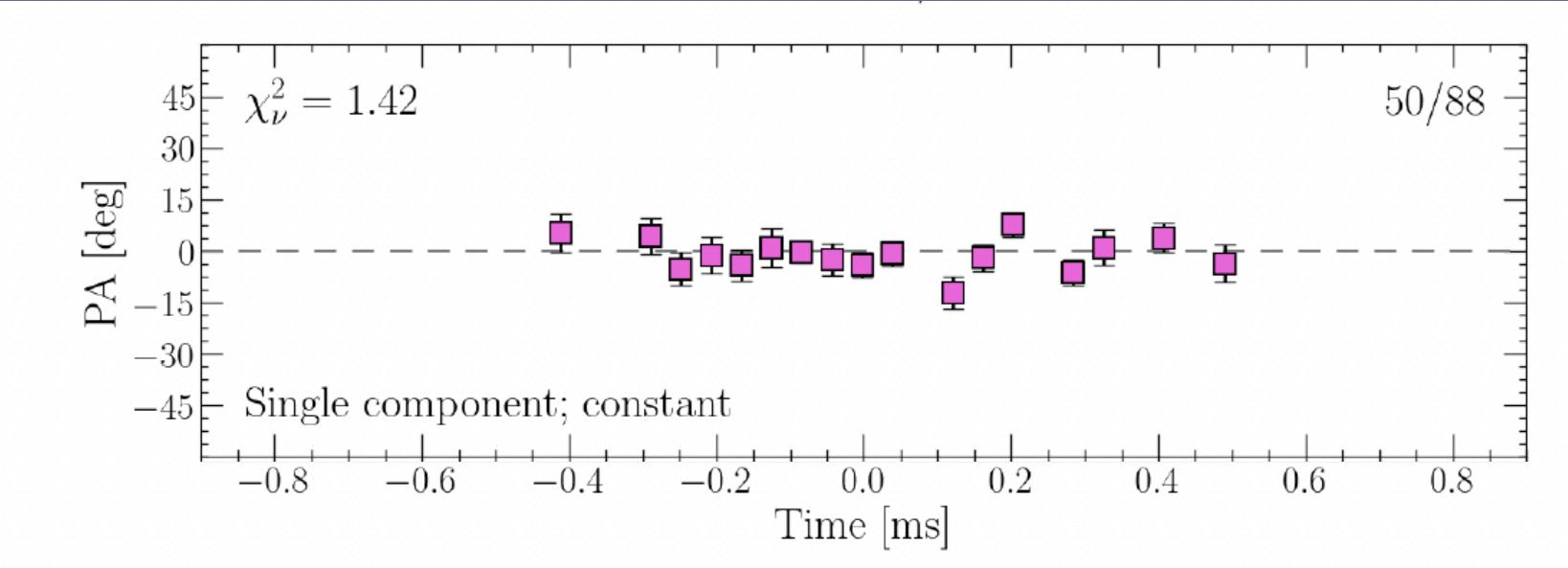
McKinven et al. 2025



Credit: van Leeuwen

...and therefore the emission is tied to the rotation of an object.

# Polarization



Pandhi et al. 2024

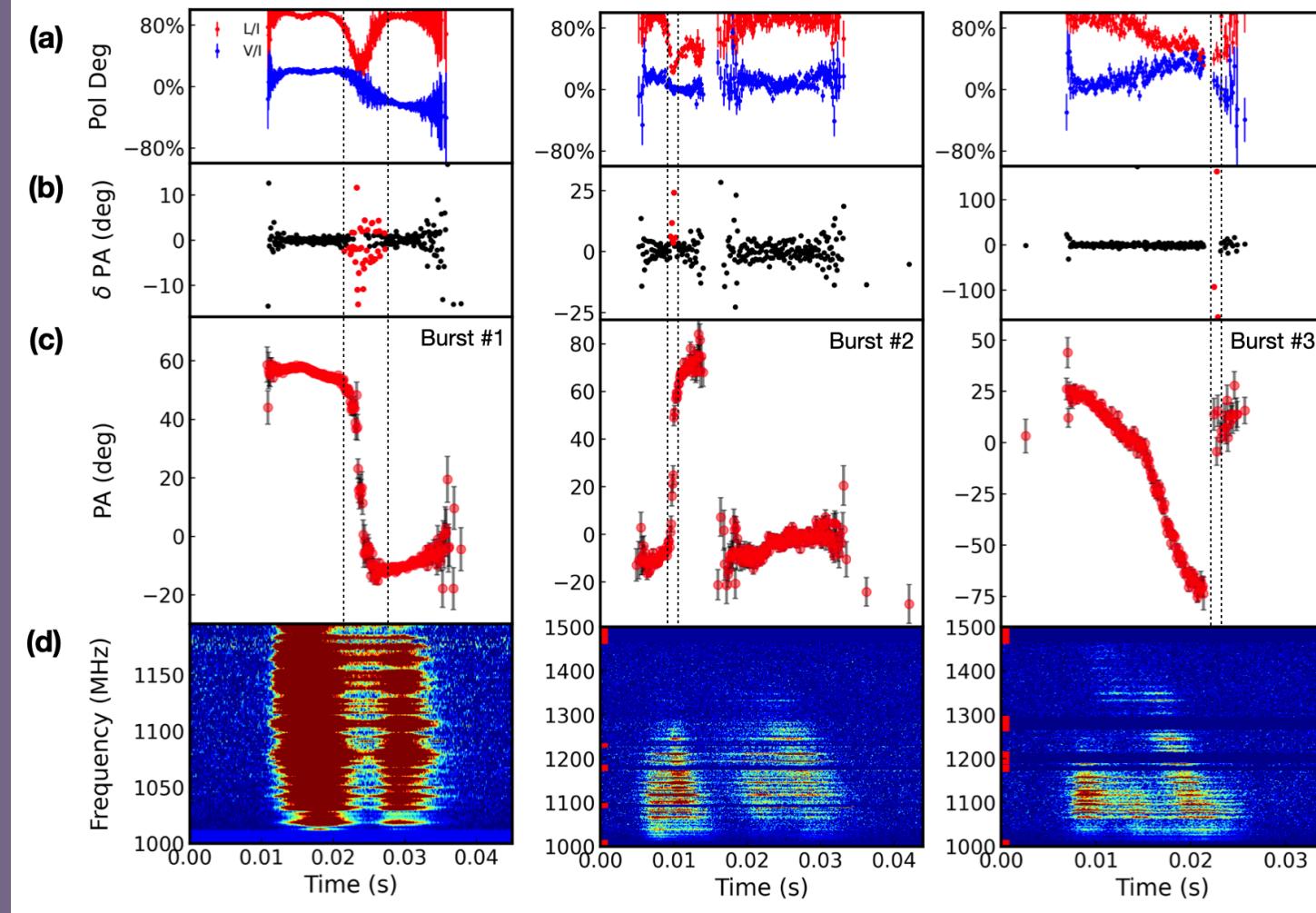


Difficult to explain without having a beam of light sweeping across our line of sight.

highly structured magnetic field configurations

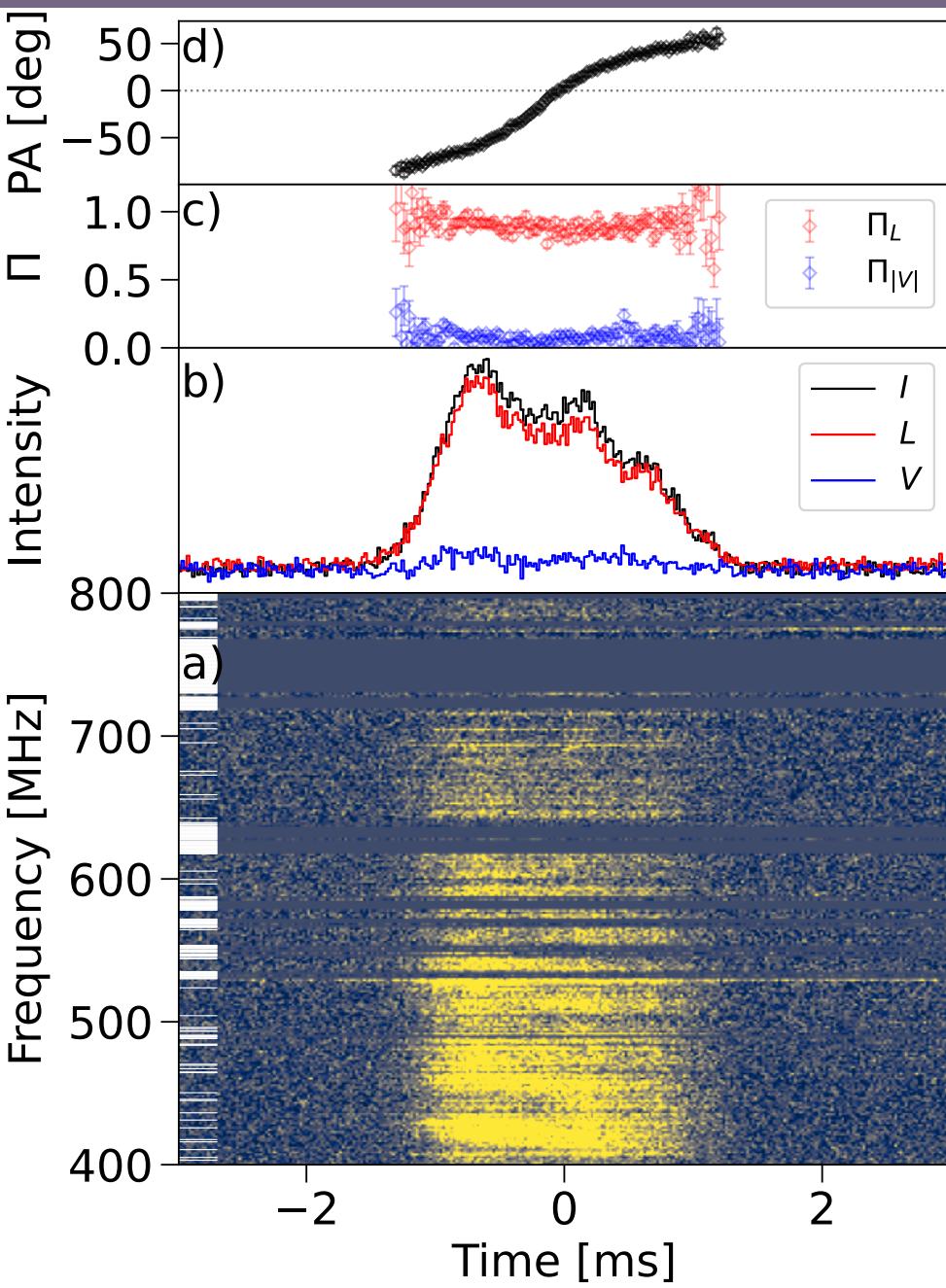
But sometimes...

## JUMPS



Niu et al. 2024

## SWINGS

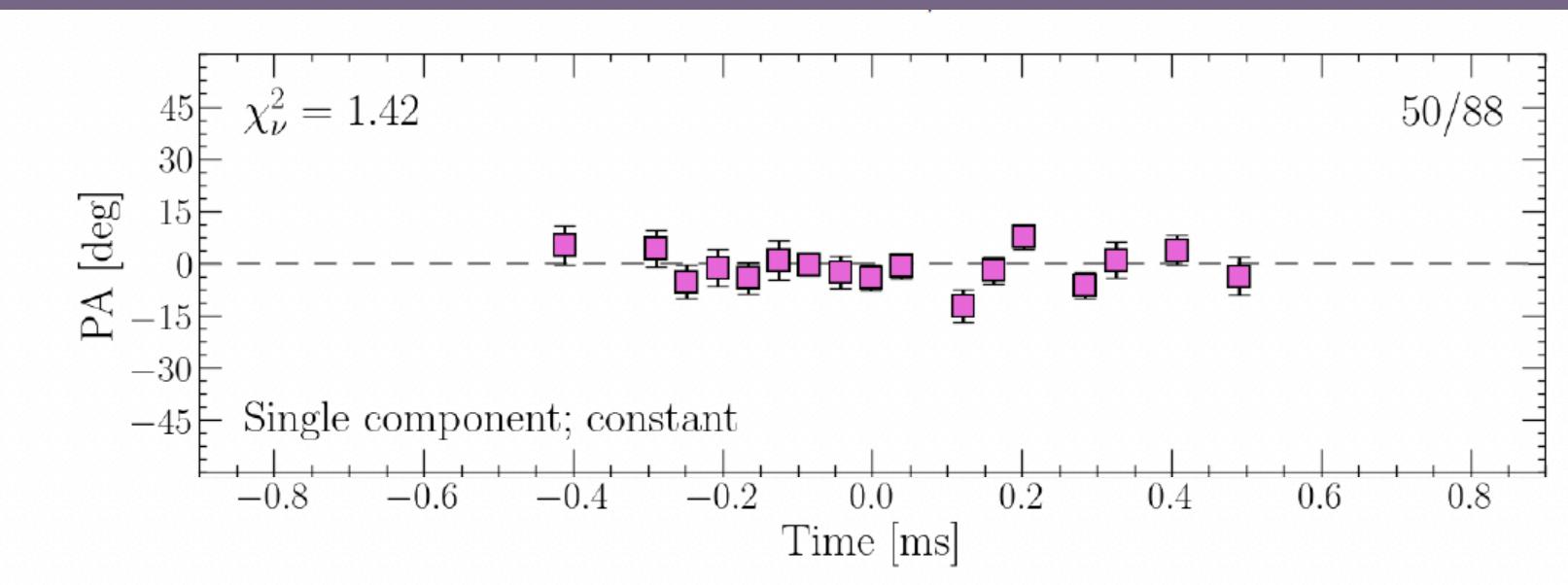


McKinven et al. 2025



...and therefore the emission is tied to the rotation of an object.

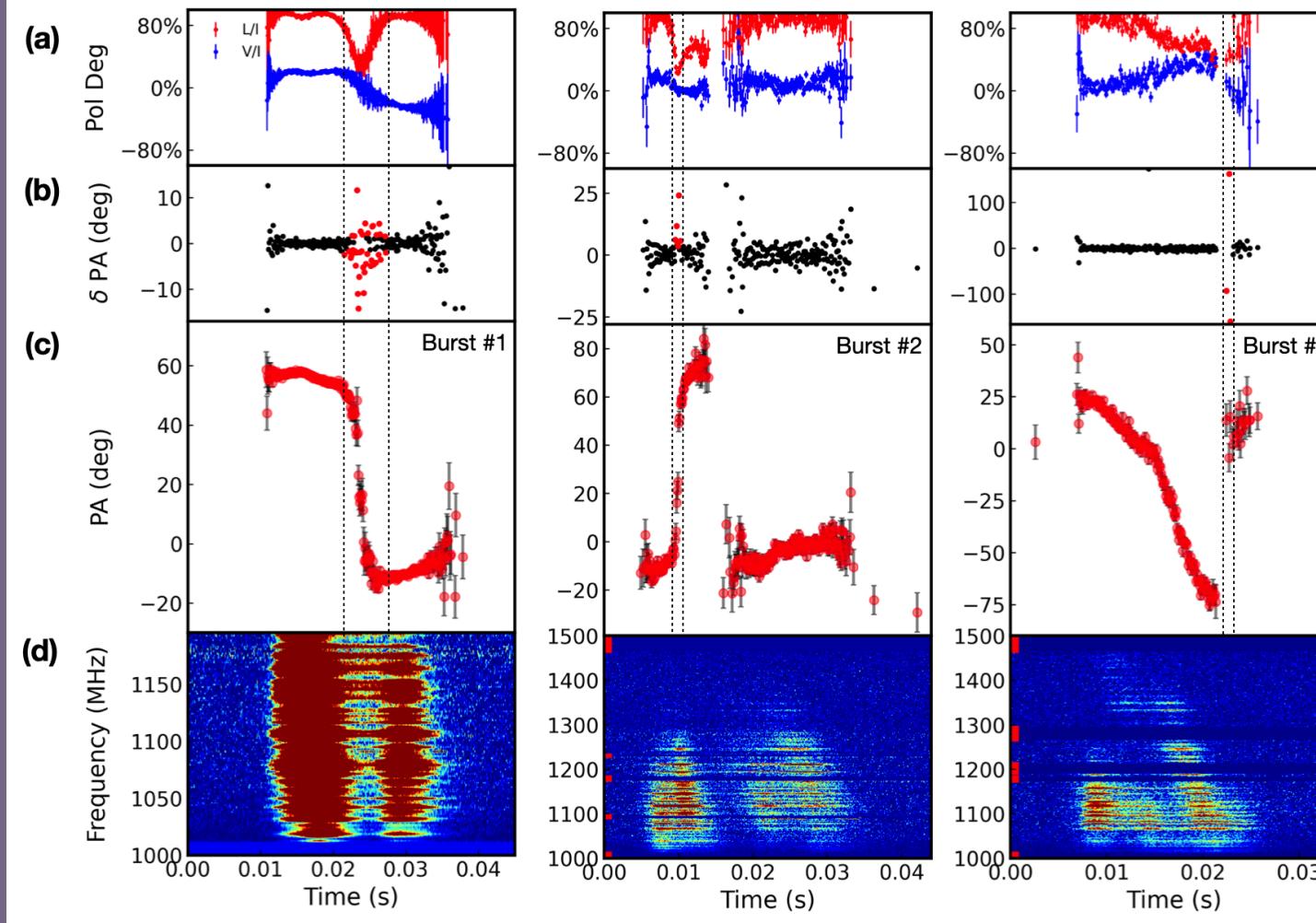
# Polarization



Pandhi et al. 2024

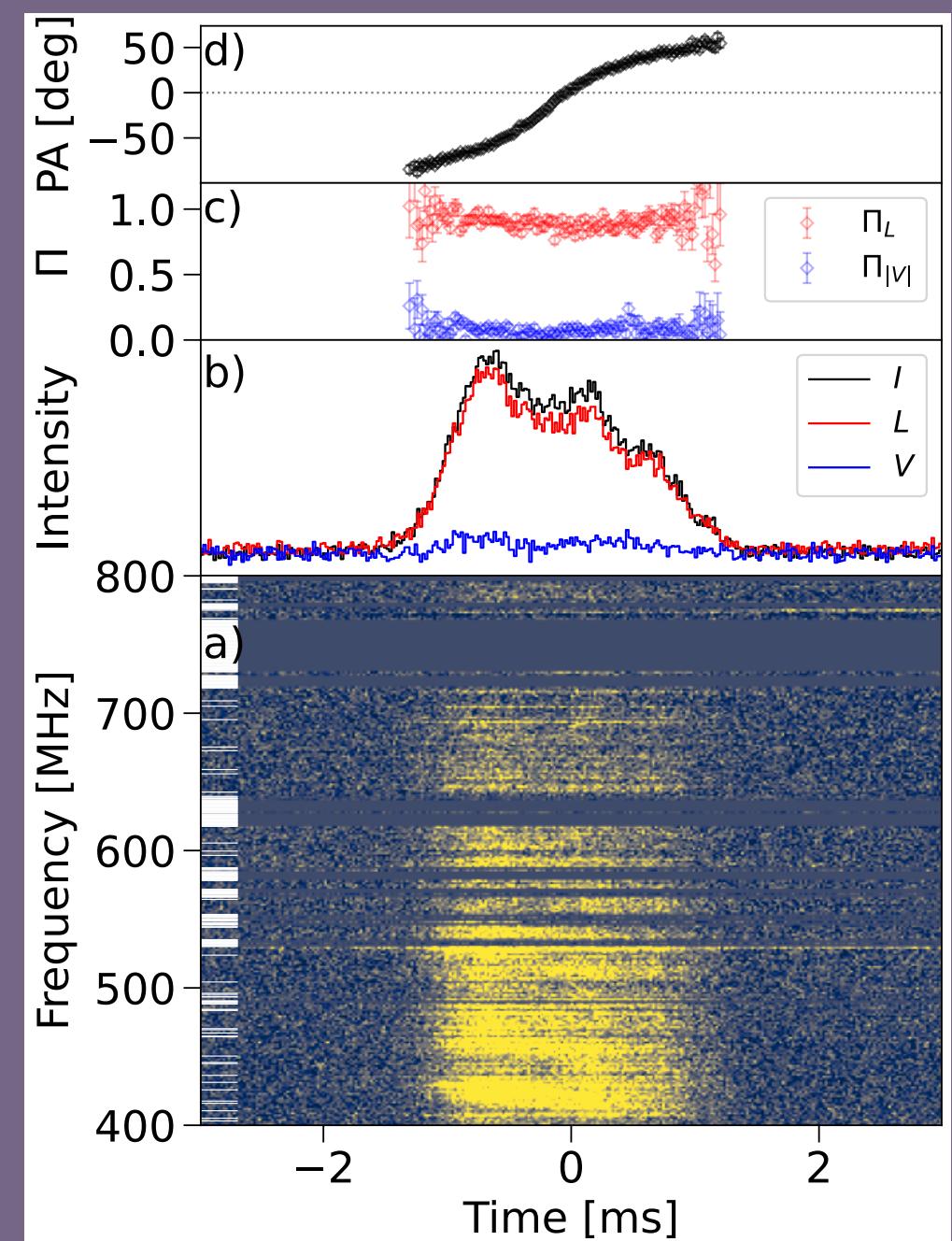
But sometimes...

## JUMPS



Niu et al. 2024

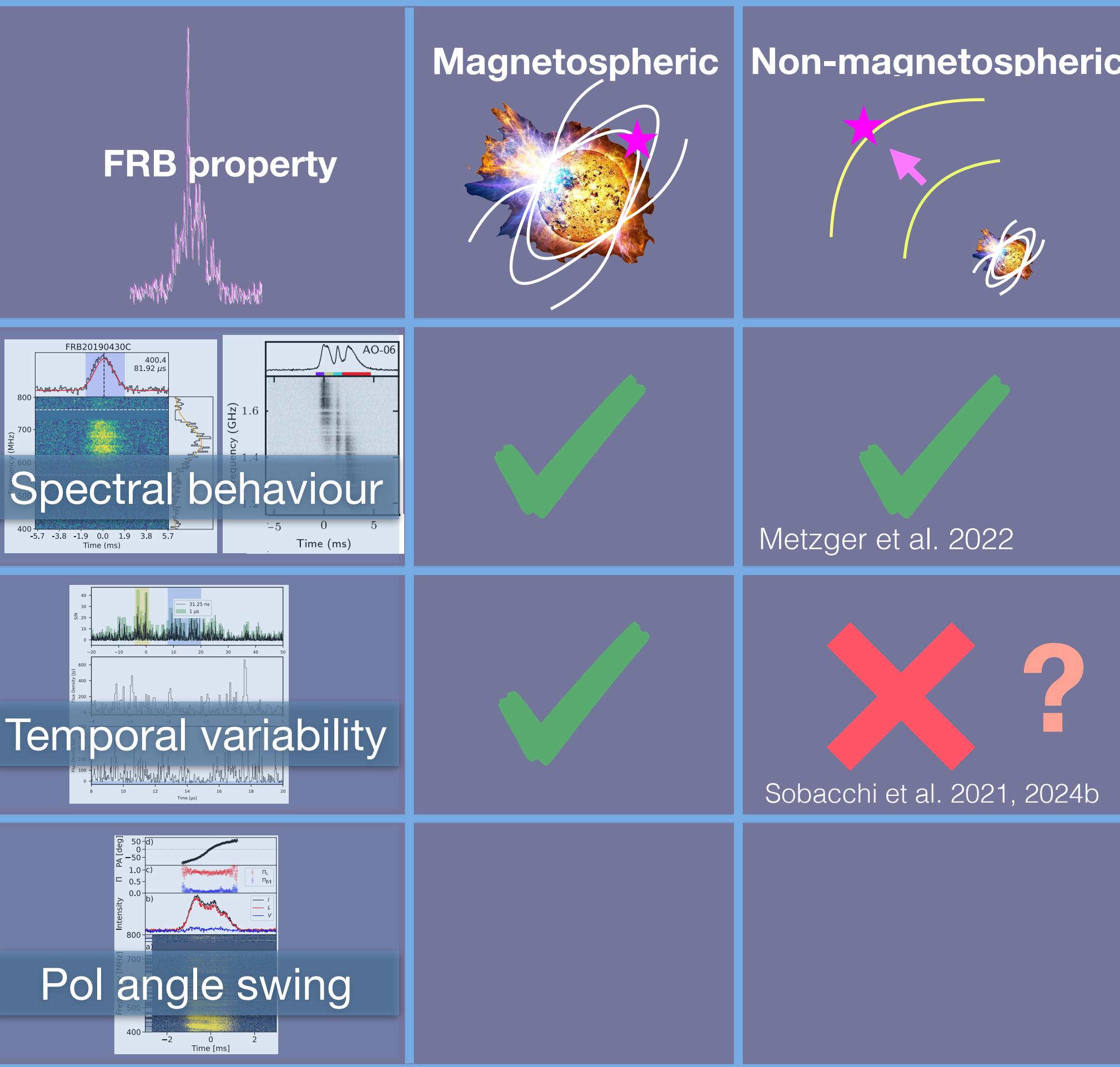
## SWINGS



McKinven et al. 2025



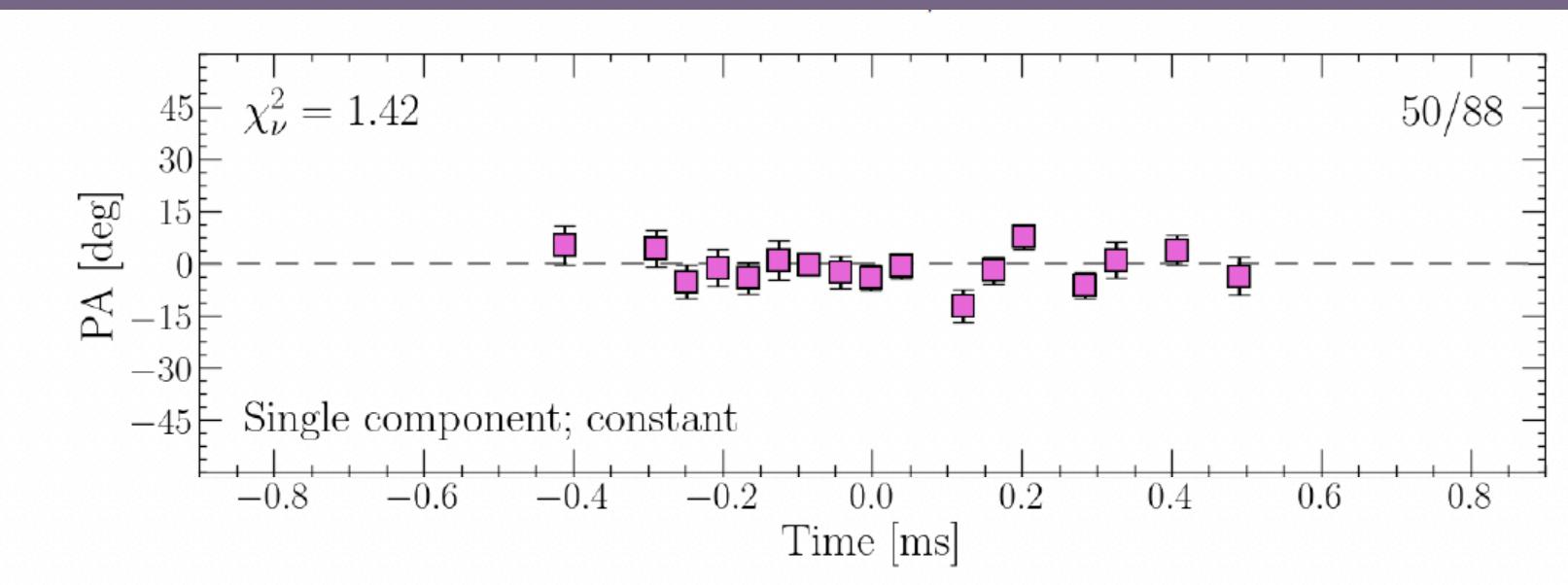
highly structured magnetic field configurations



Metzger et al. 2022

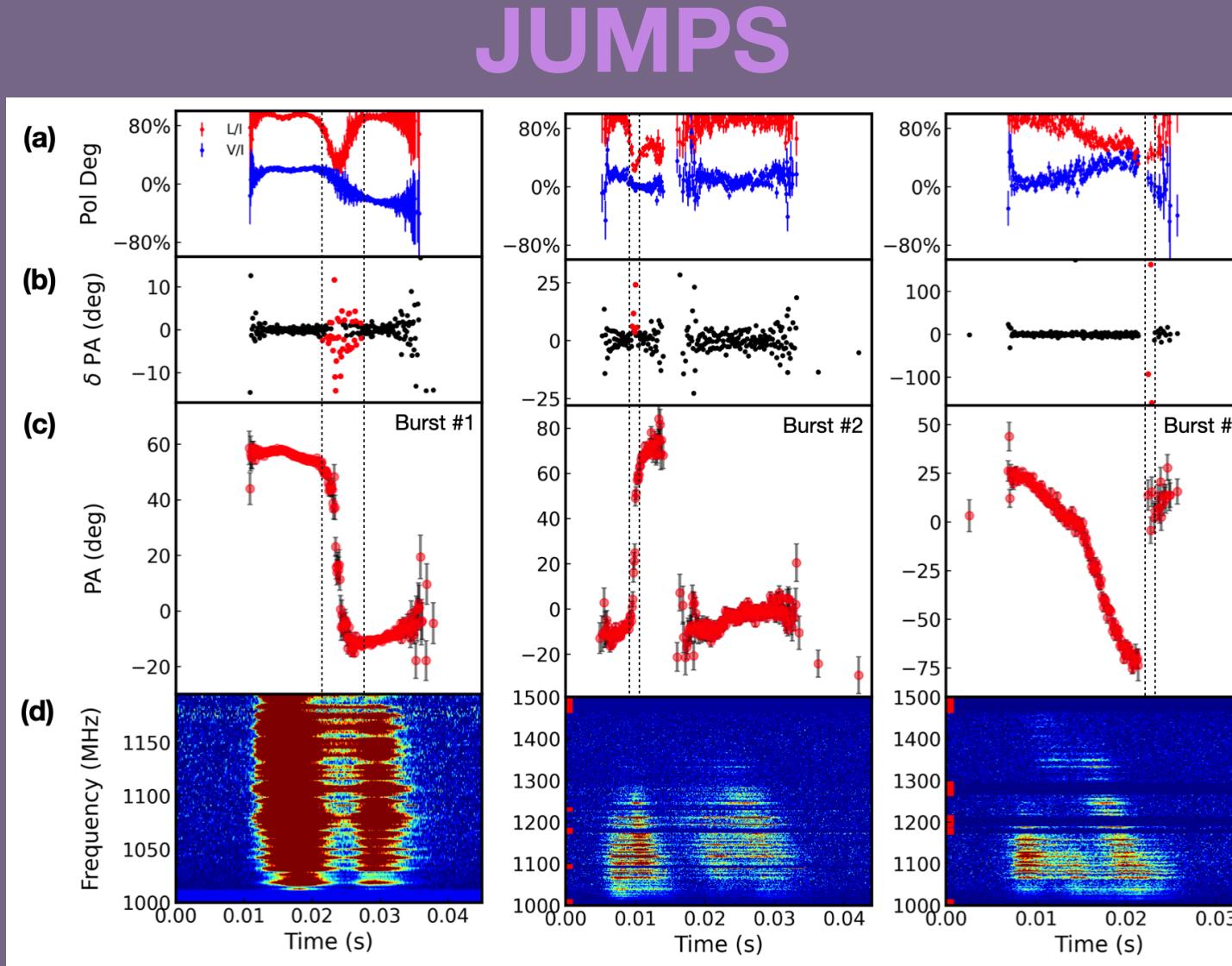
Sobacchi et al. 2021, 2024b

# Polarization



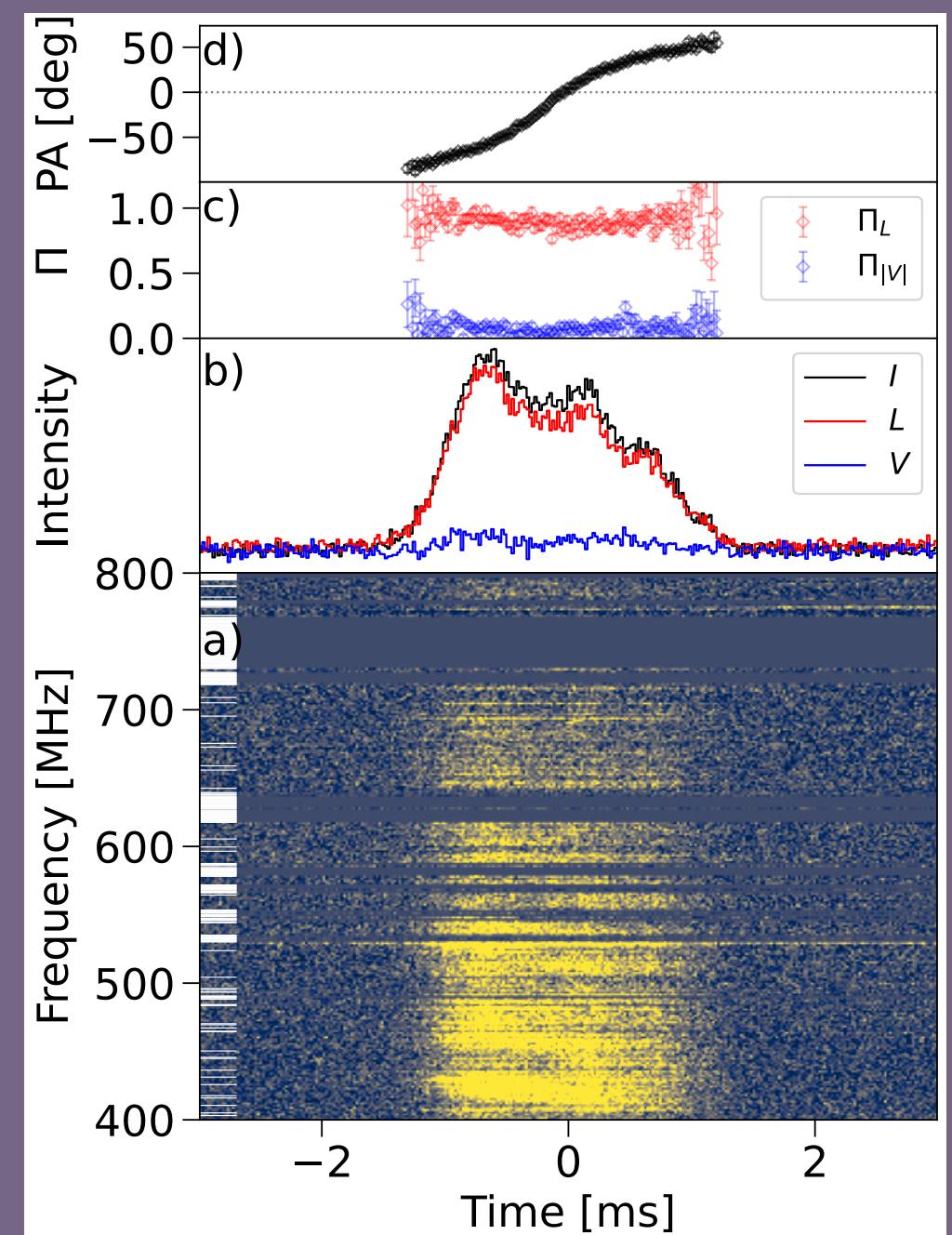
Pandhi et al. 2024

But sometimes...

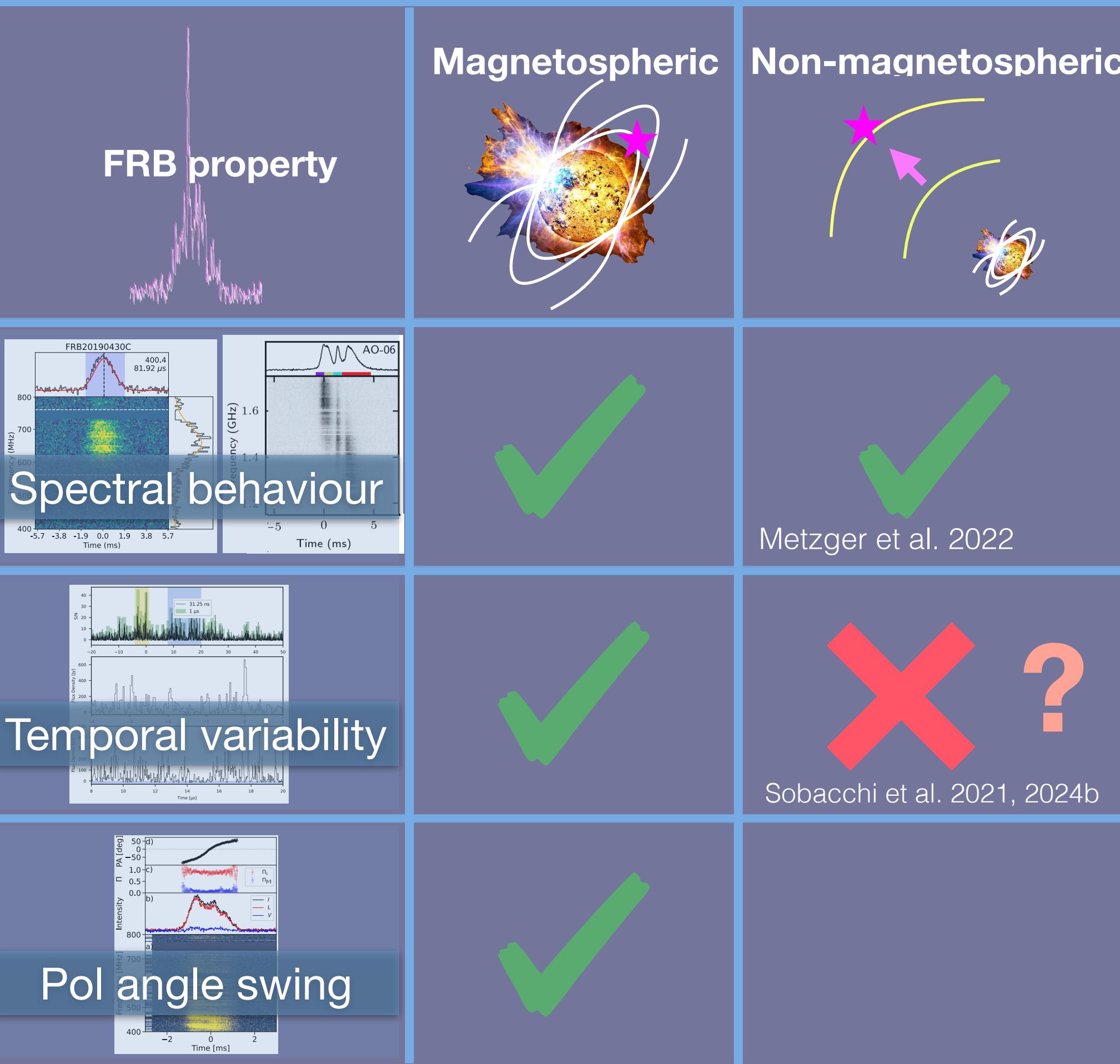


Niu et al. 2024

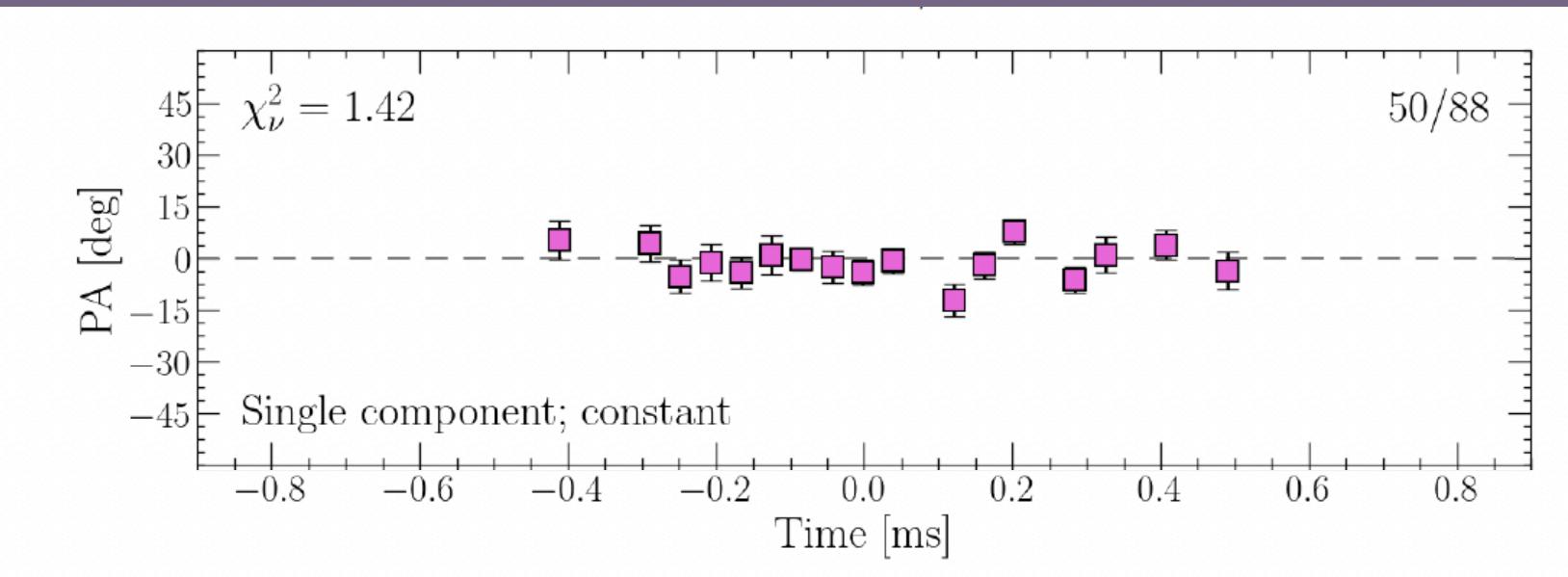
## SWINGS



highly structured magnetic field configurations

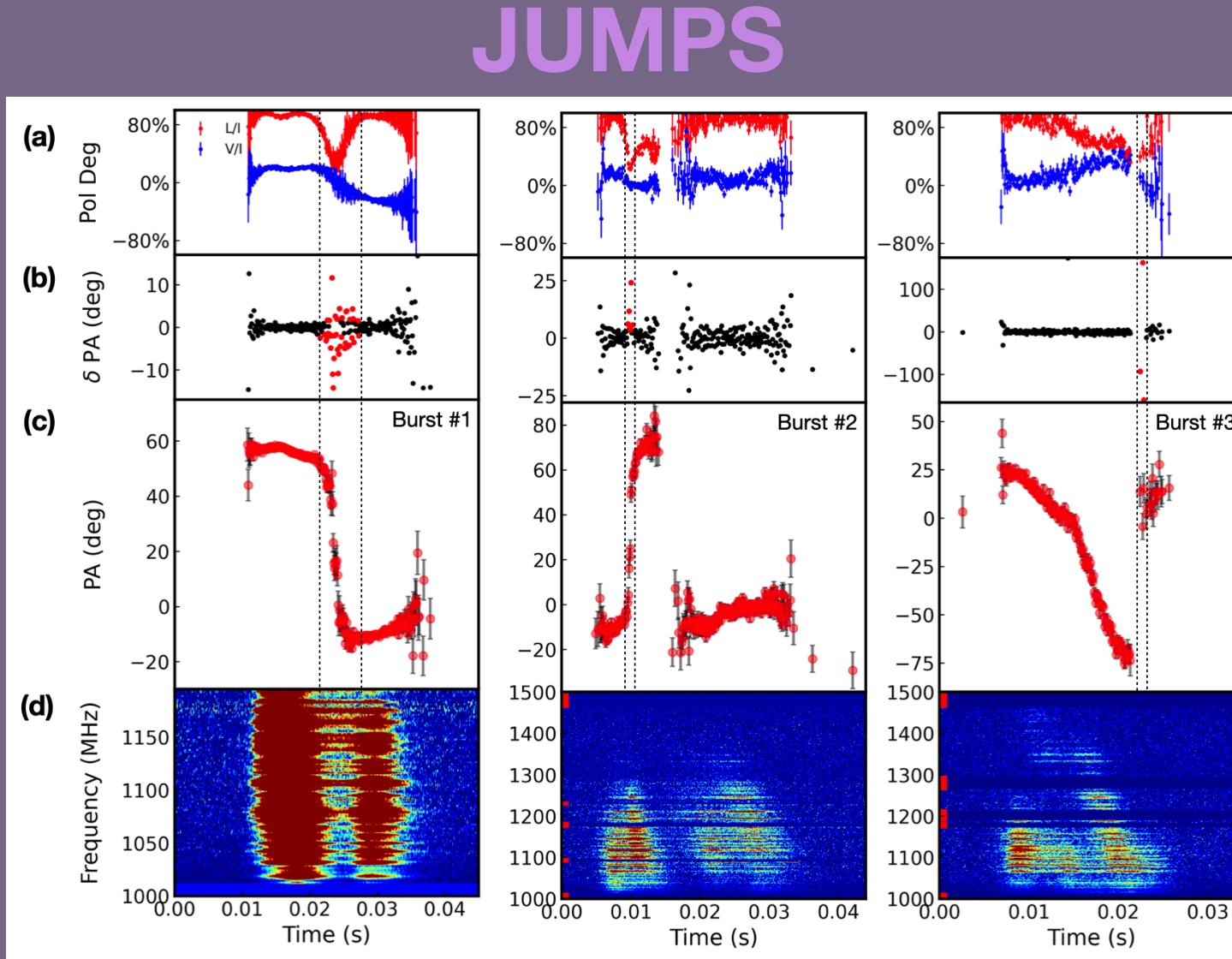


# Polarization



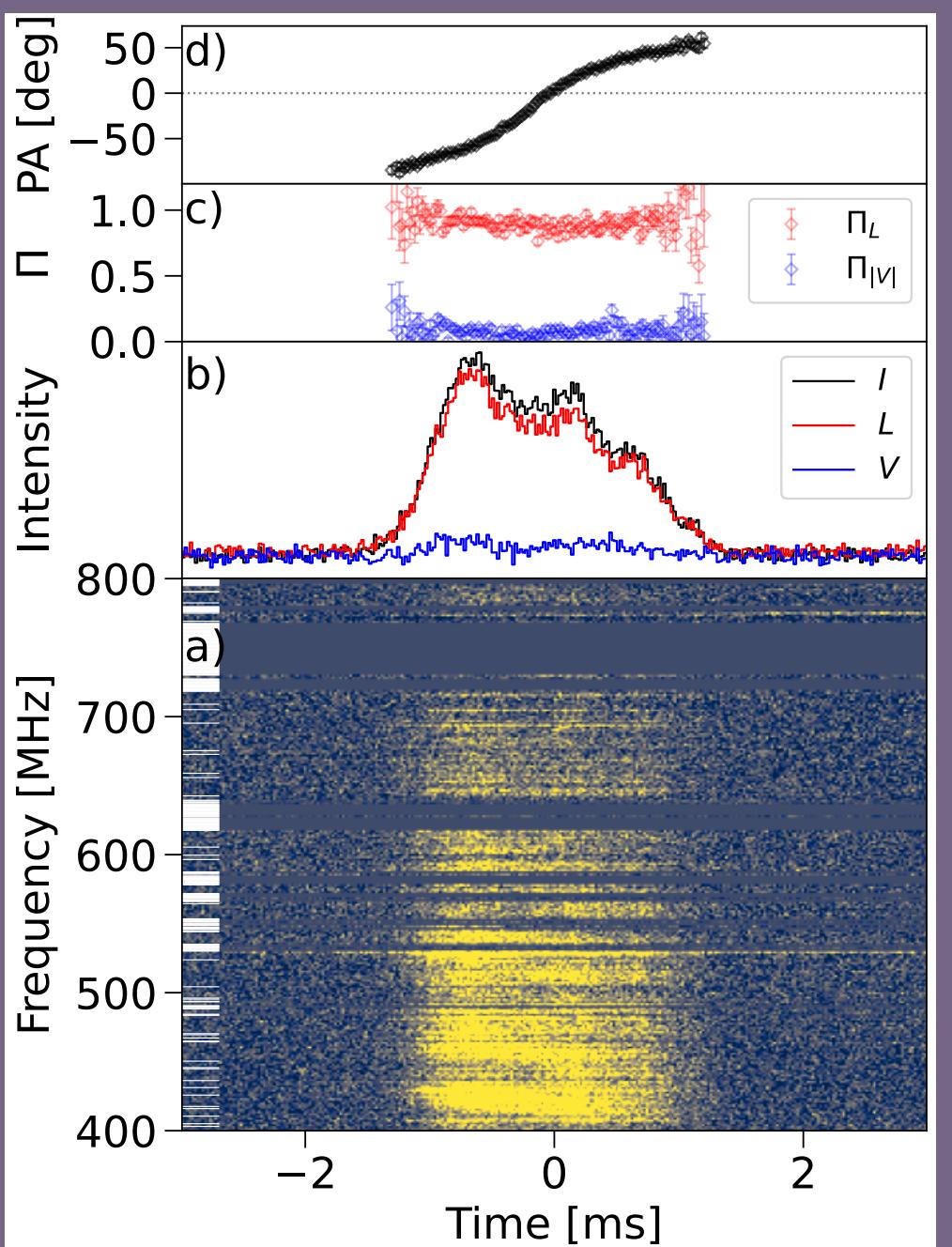
Pandhi et al. 2024

But sometimes...



Niu et al. 2024

## SWINGS

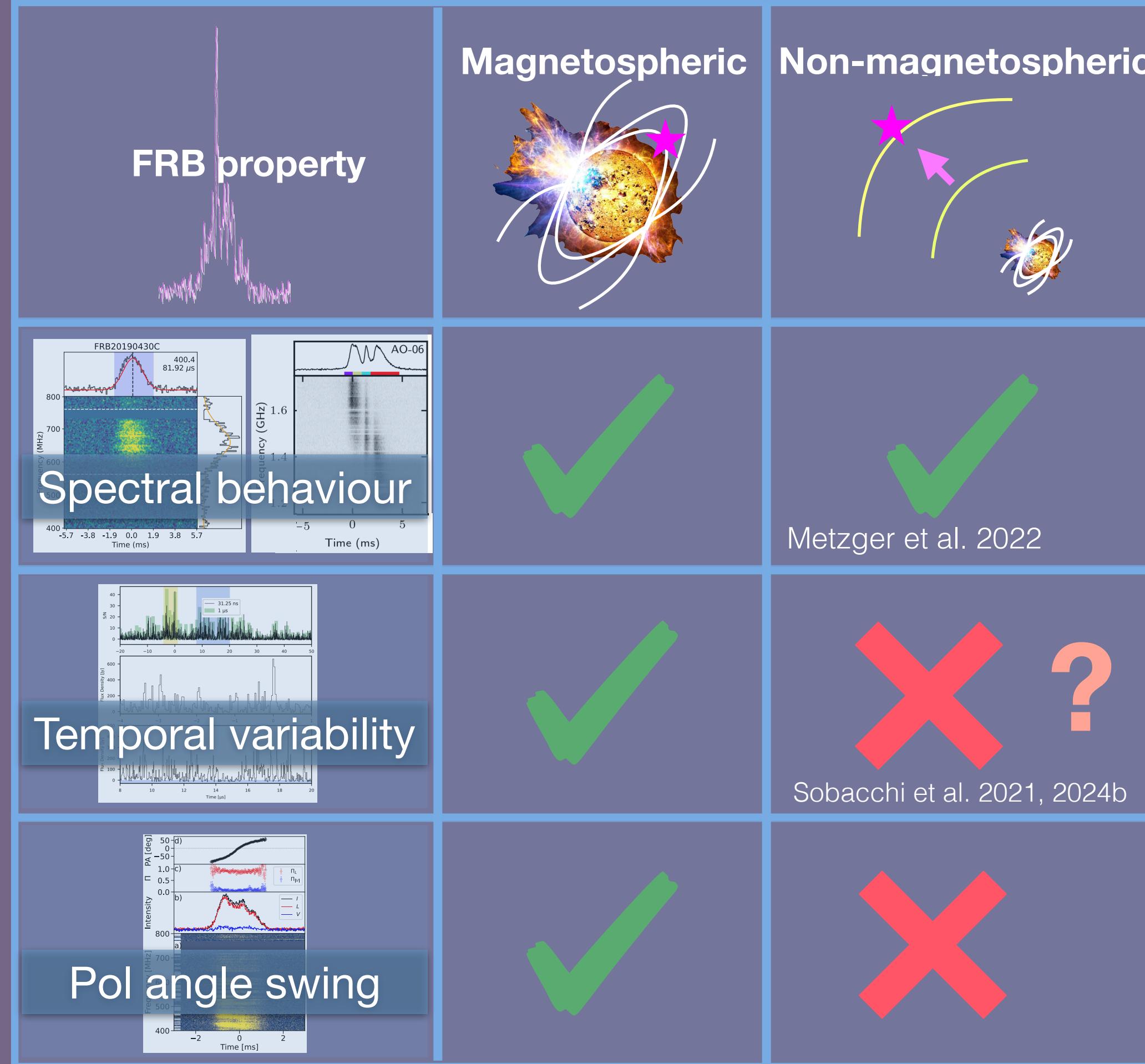
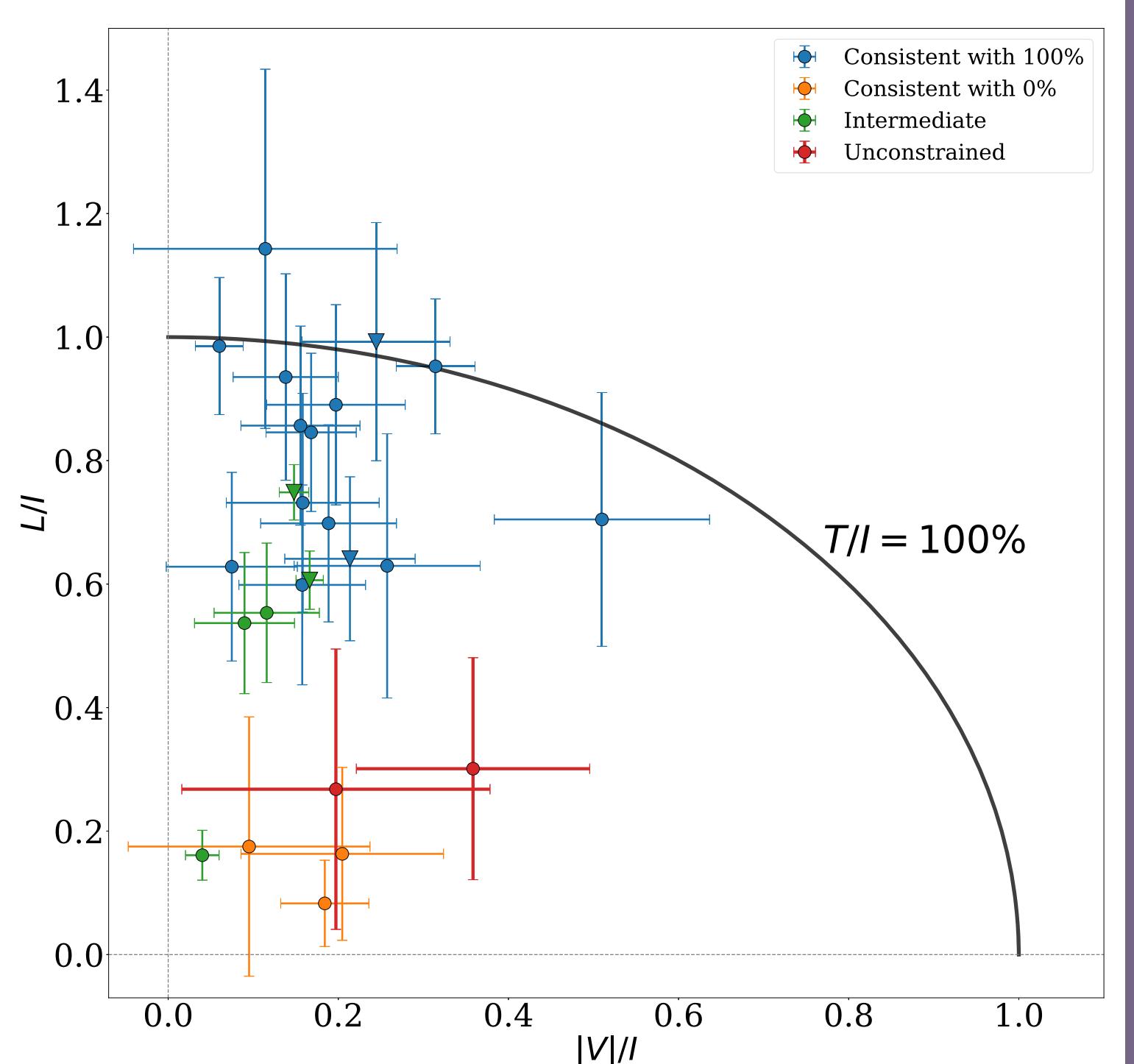


highly structured magnetic field configurations



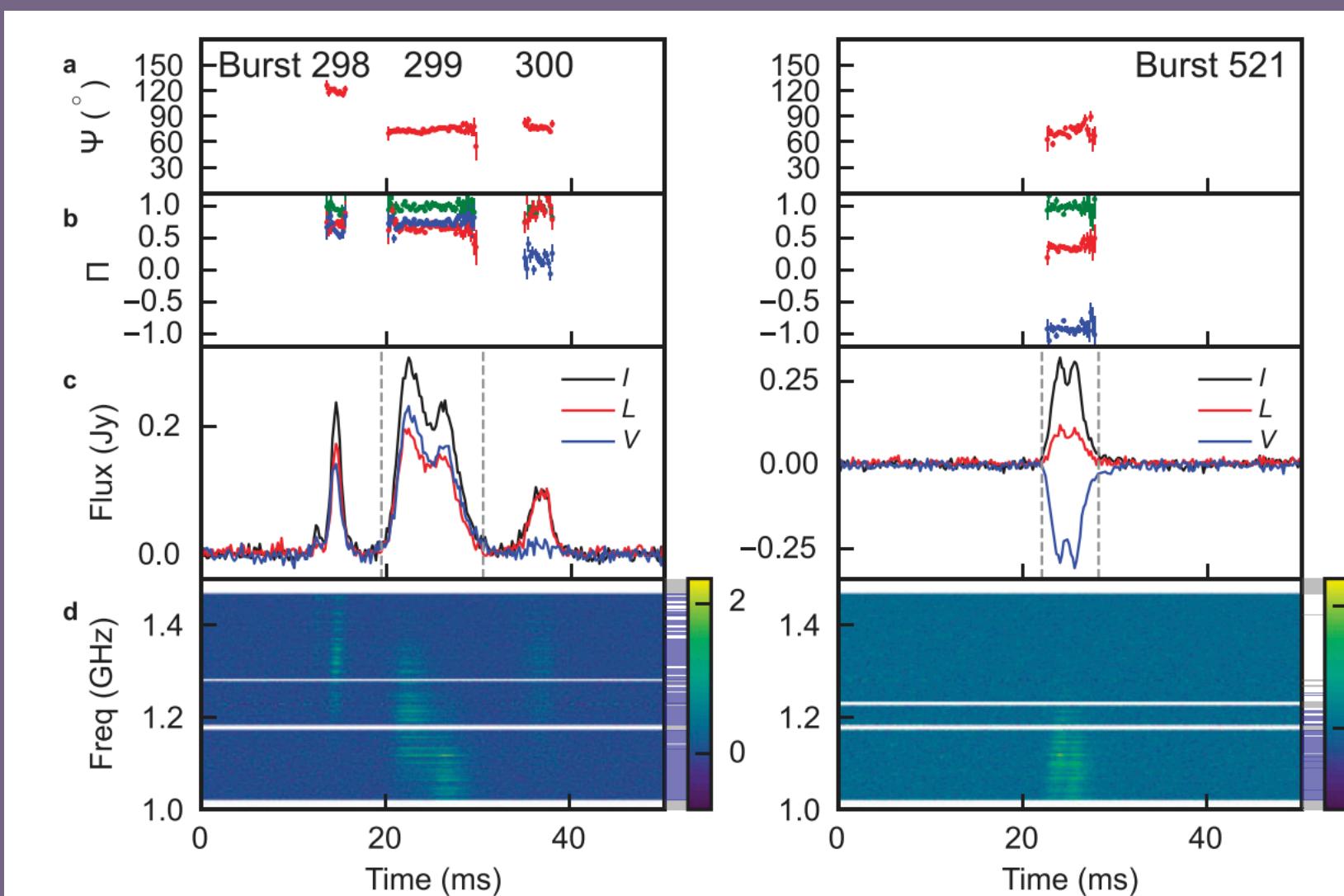
# Polarization

Sherman et al. 2024



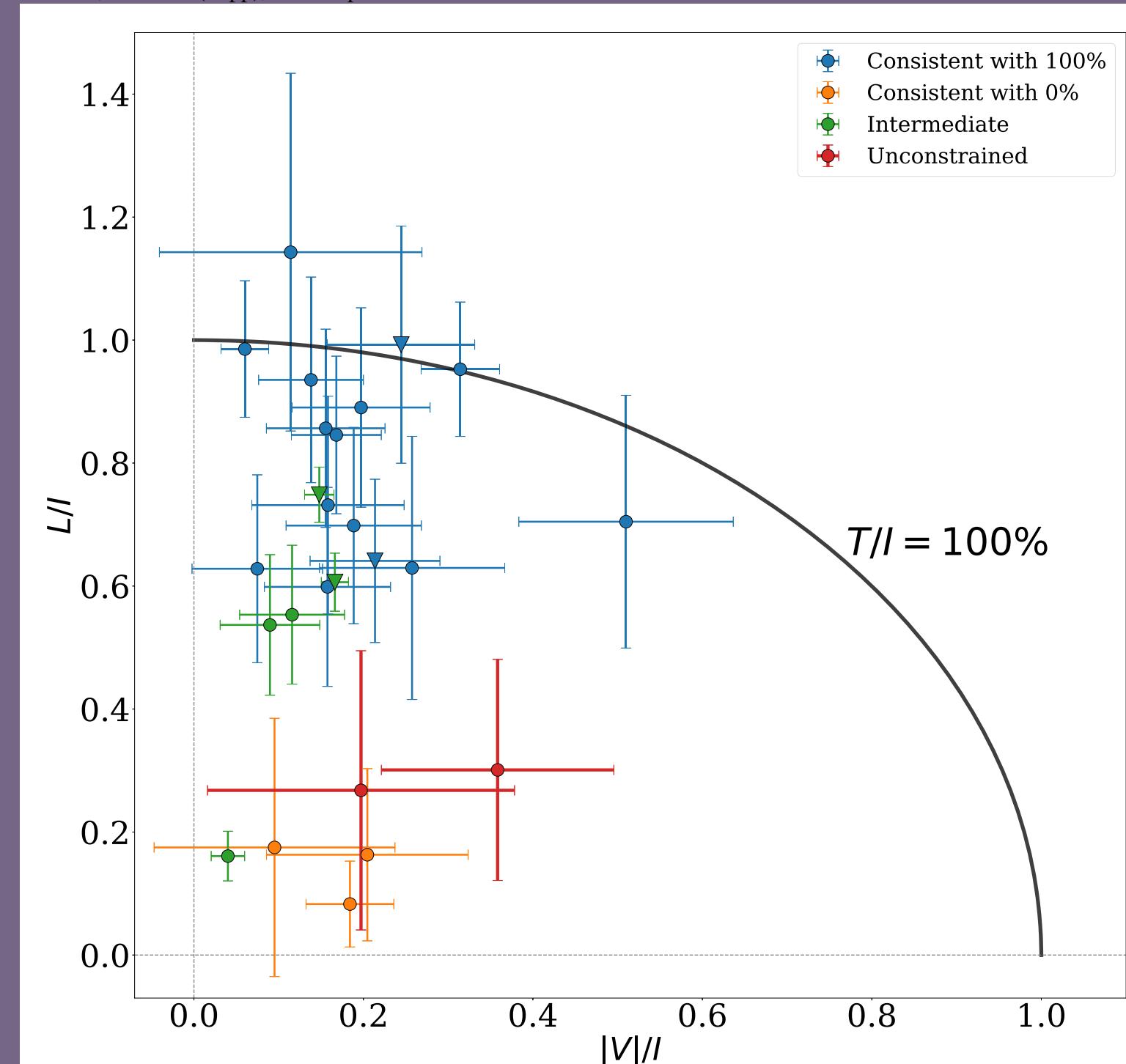
# Polarization

But sometimes...

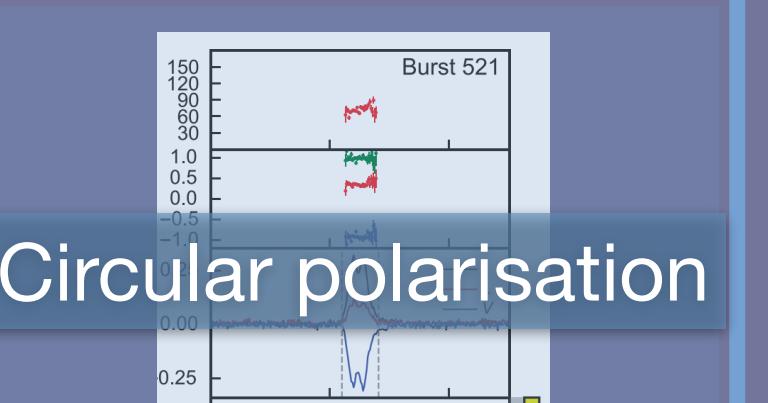
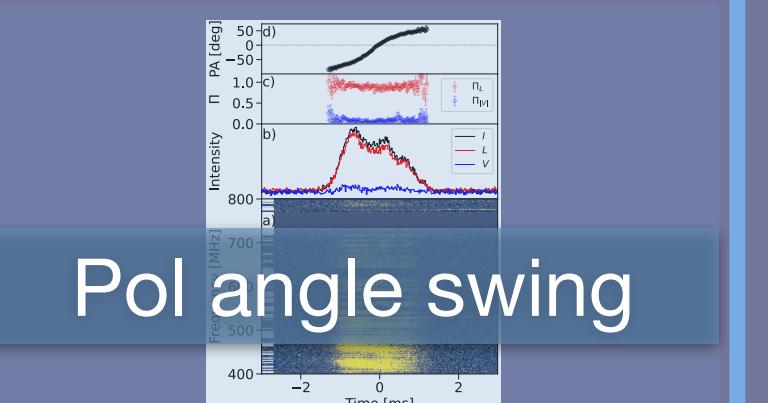
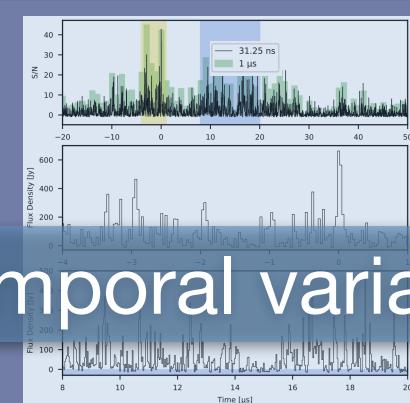
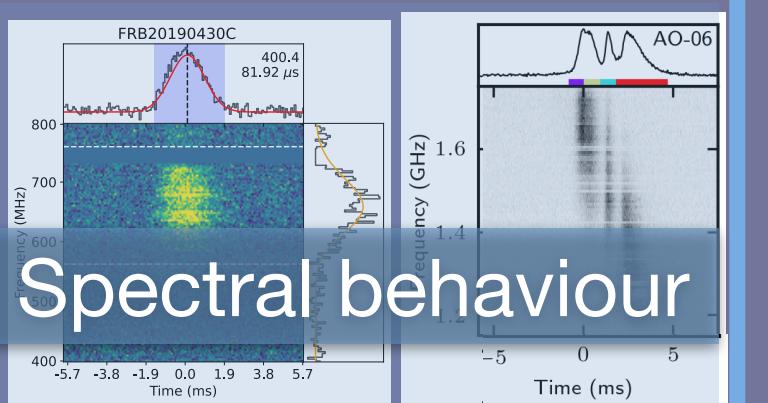


Up to 90%  
circular

Jiang et al. 2024

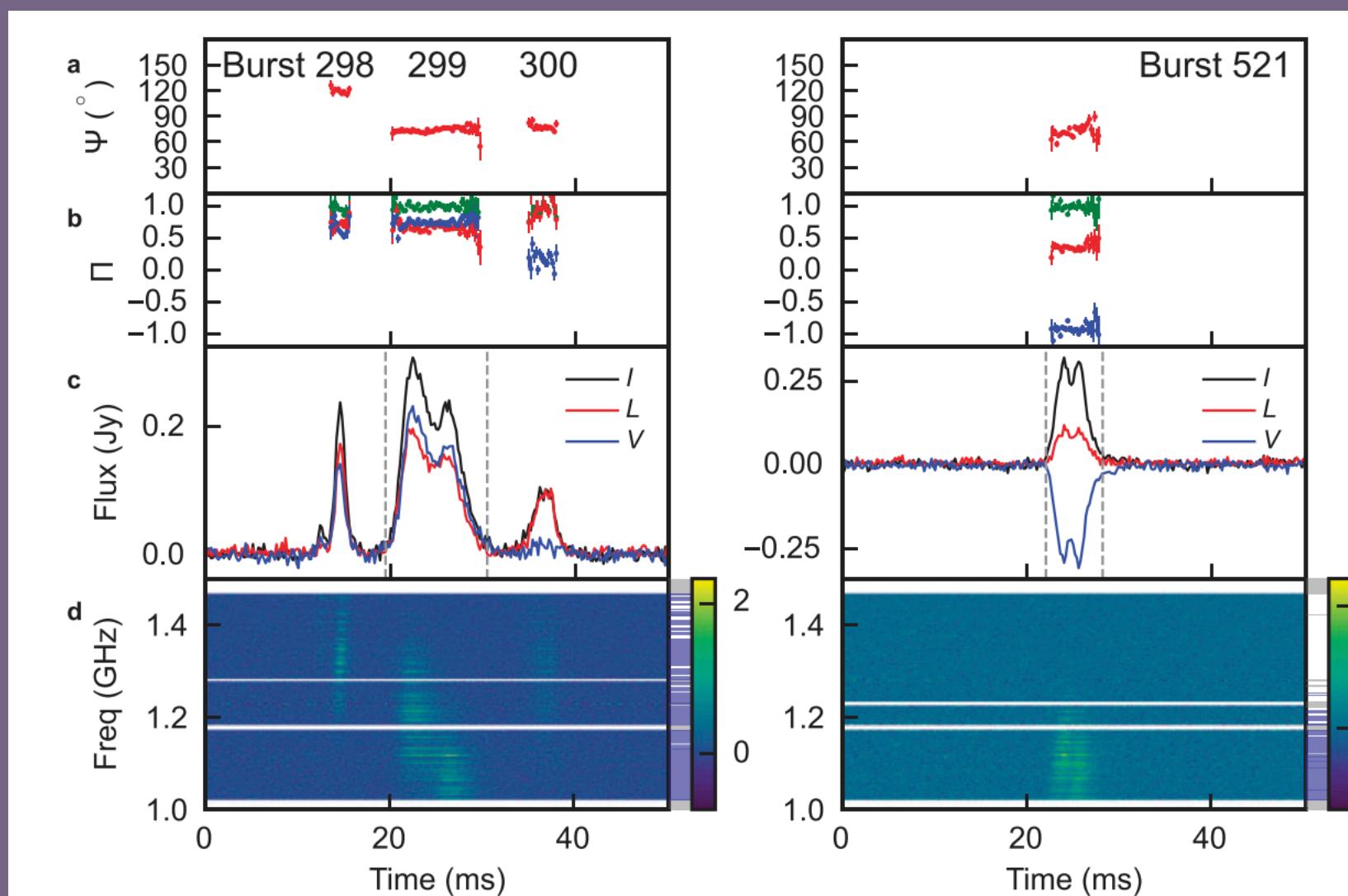


Sherman et al. 2024

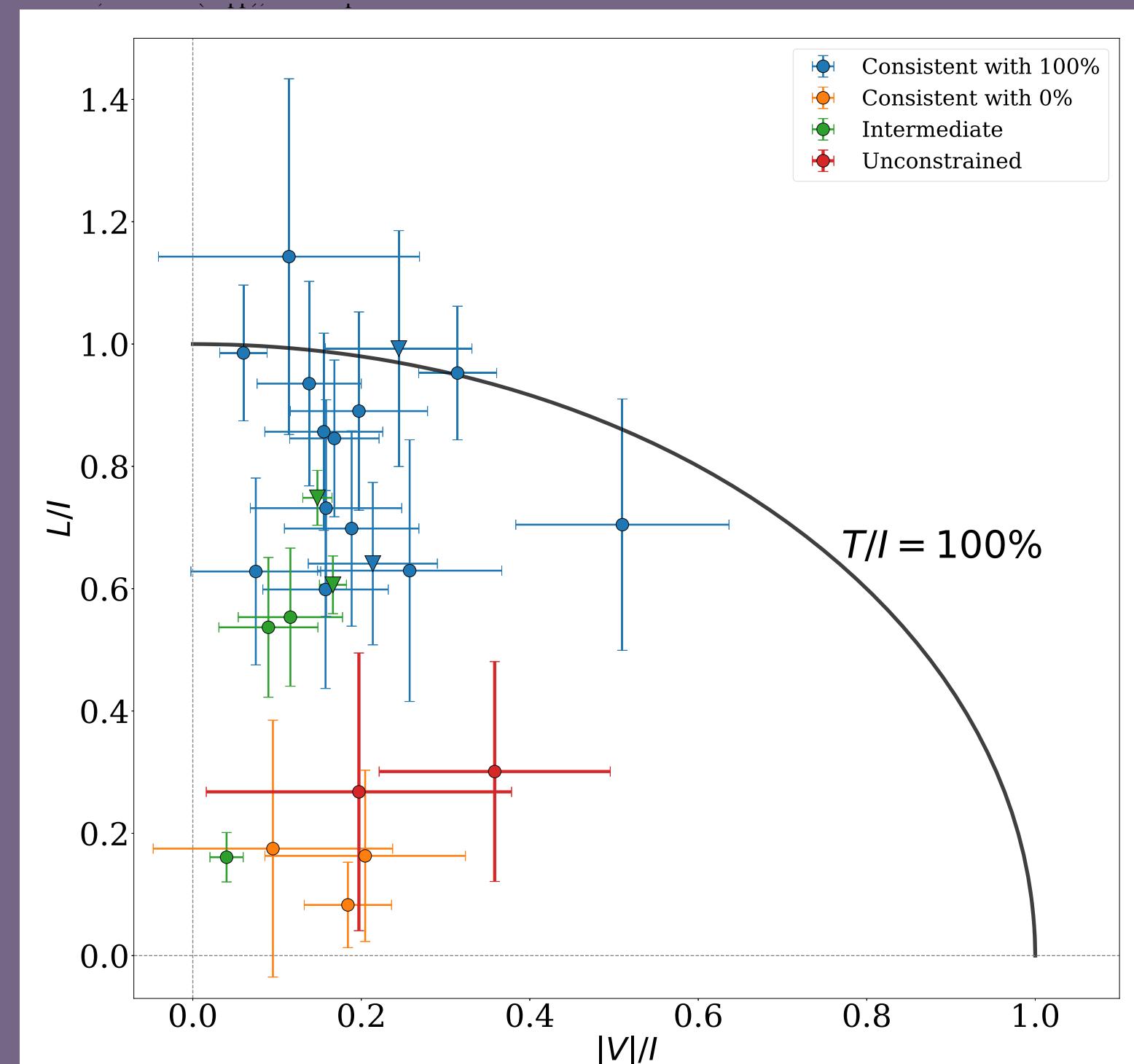


# Polarization

But sometimes...



Up to 90%  
circular



Sherman et al. 2024

Jiang et al. 2024

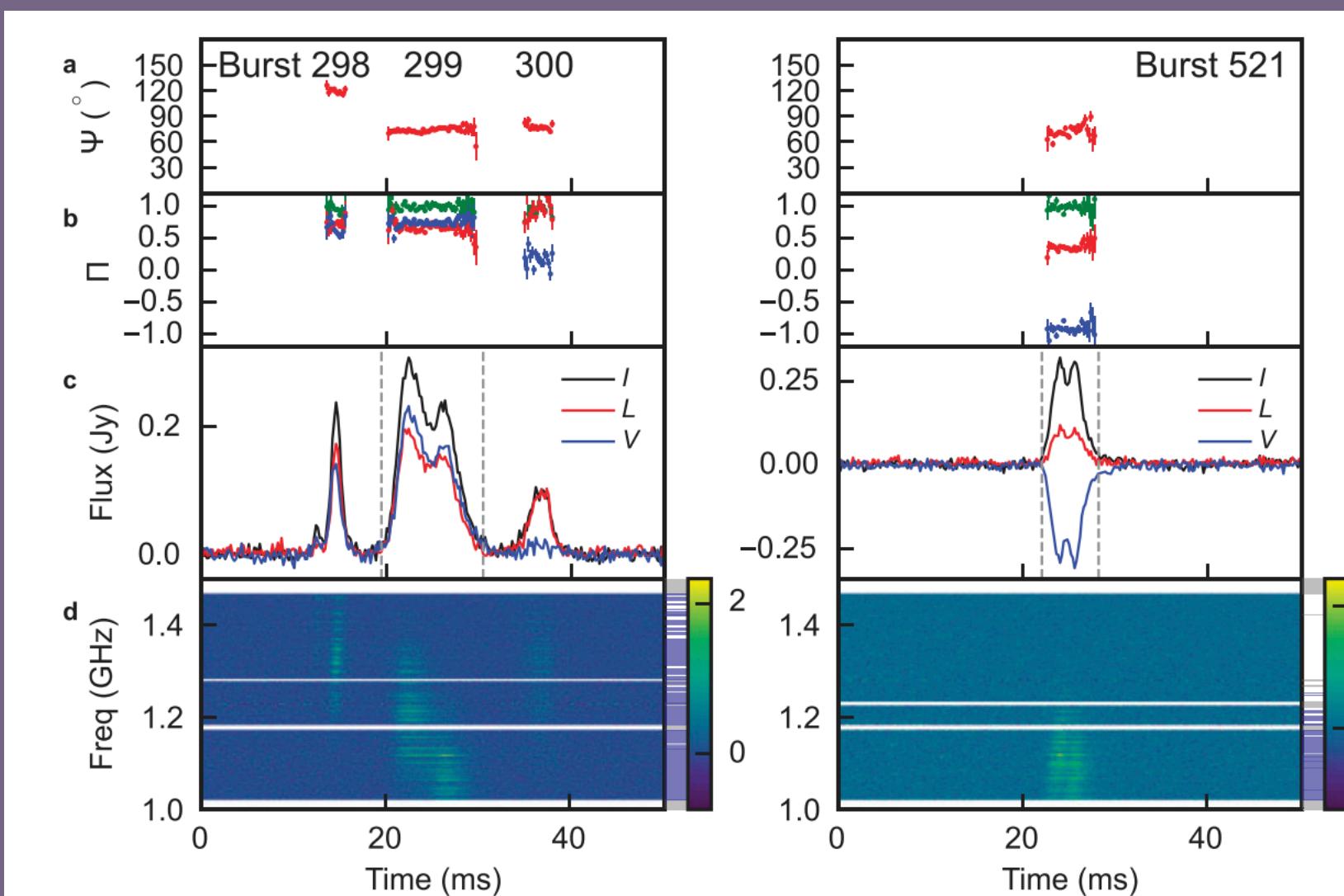


Metzger et al. 2022

Sobacchi et al. 2021, 2024b

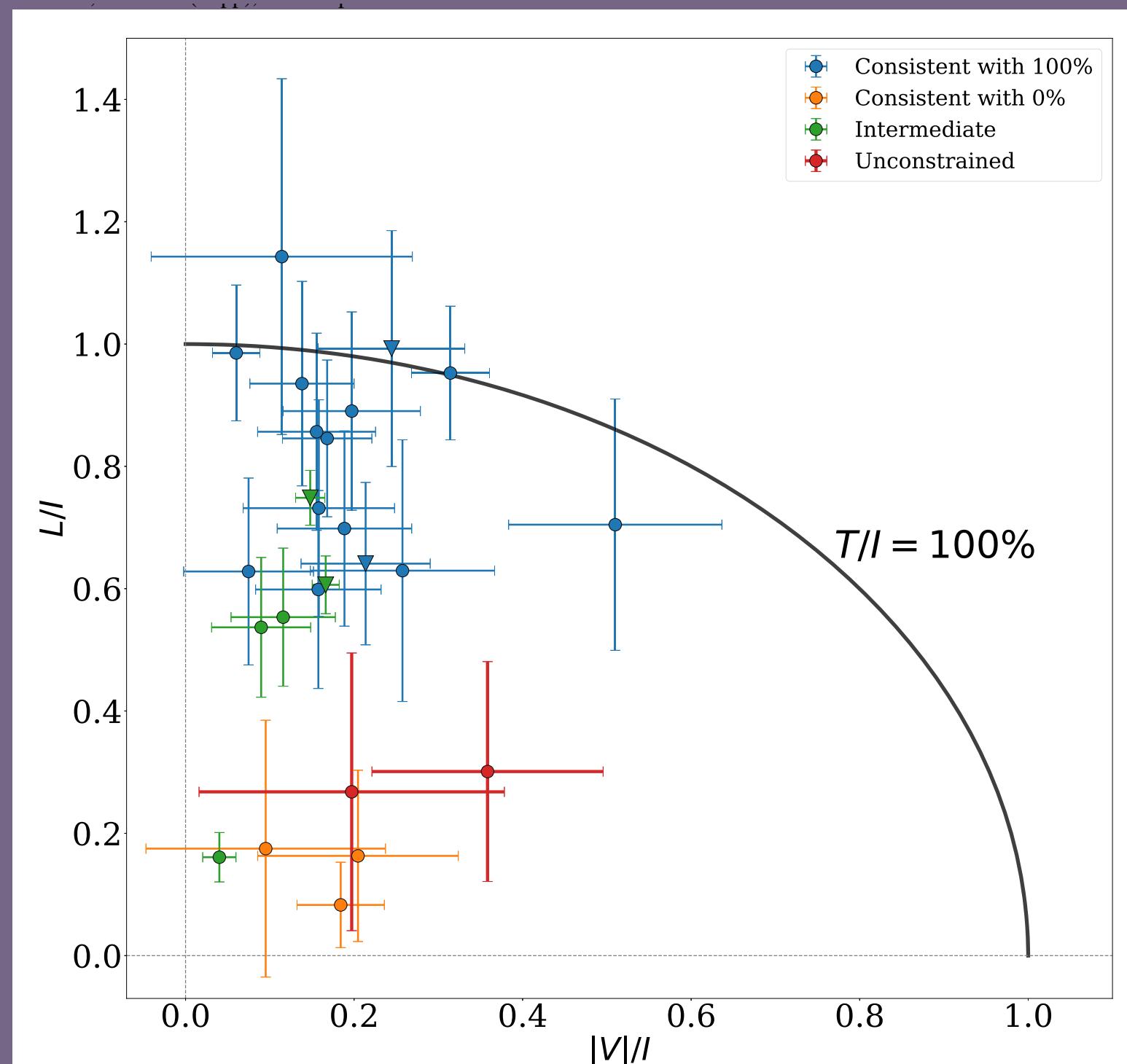
# Polarization

But sometimes...



Up to 90%  
circular

Jiang et al. 2024



Sherman et al. 2024



?

Qu et al. 2023

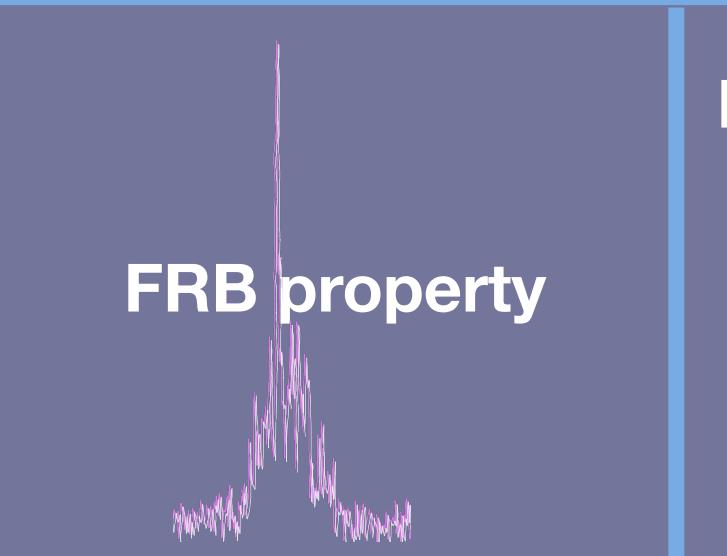
Metzger et al. 2022

?

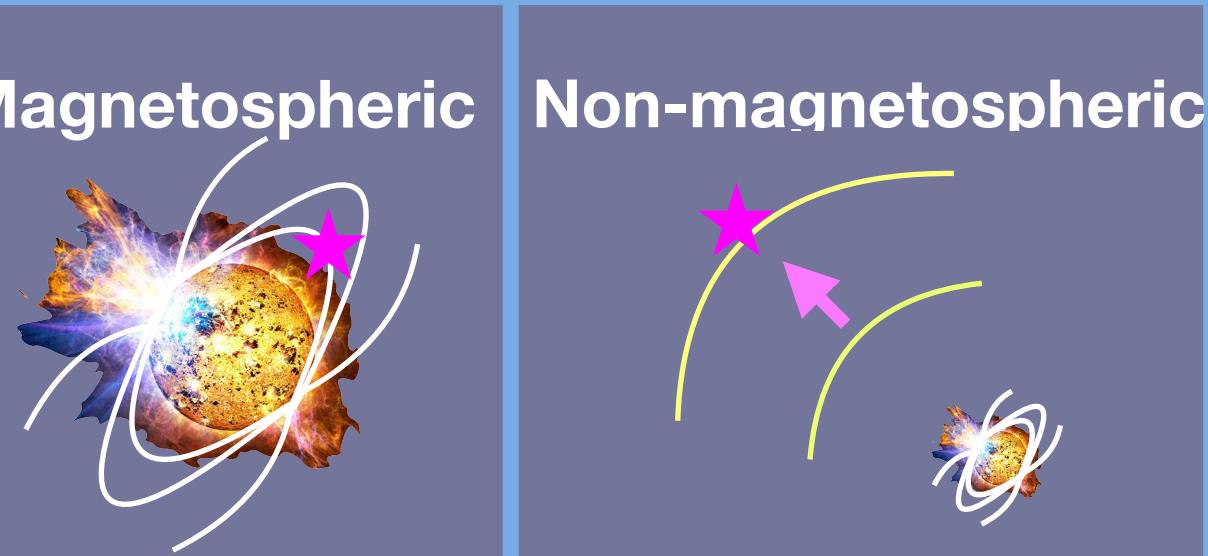
Sobacchi et al. 2021, 2024b

# Scintillation\*

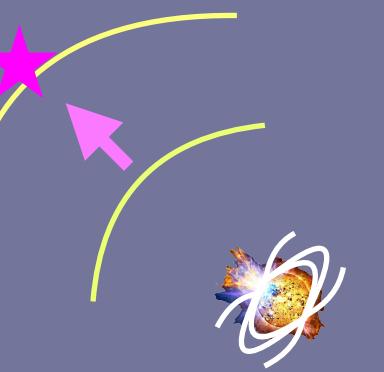
\* from the host galaxy



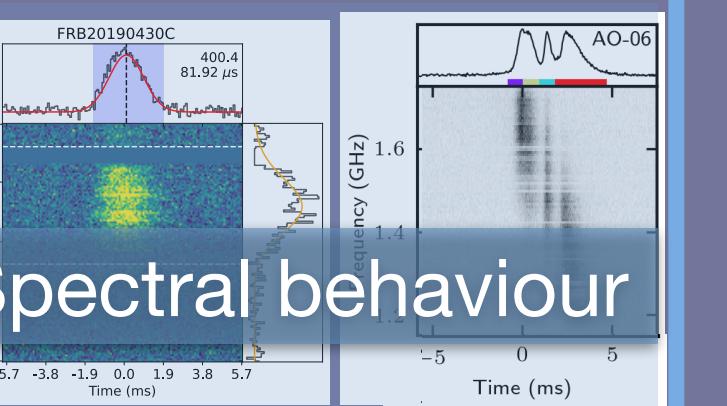
FRB property



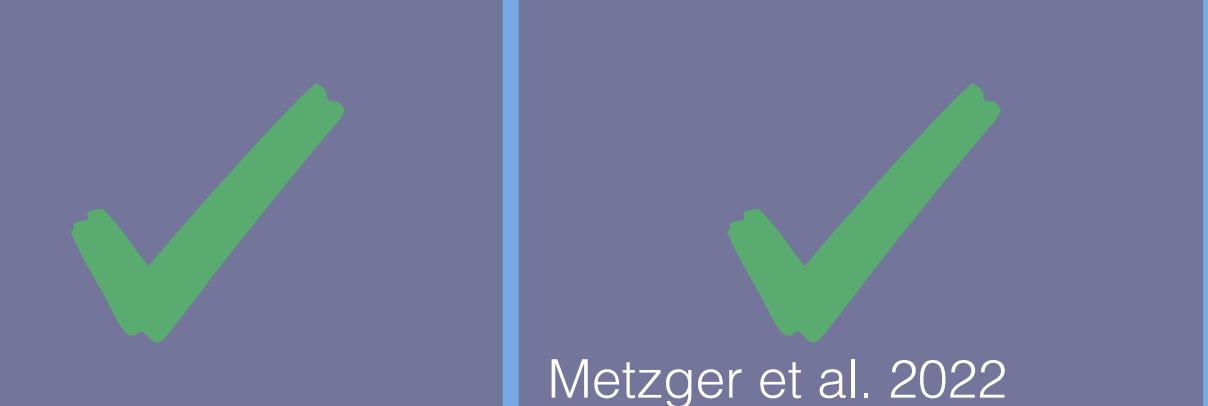
Magnetospheric



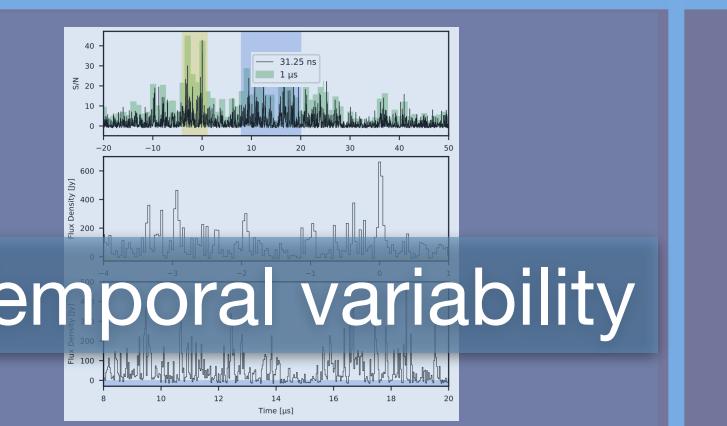
Non-magnetospheric



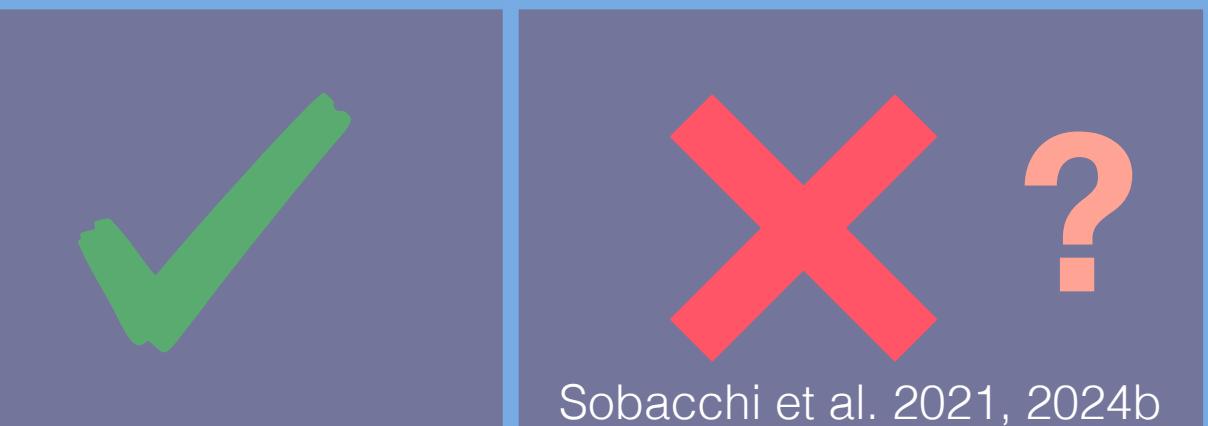
Spectral behaviour



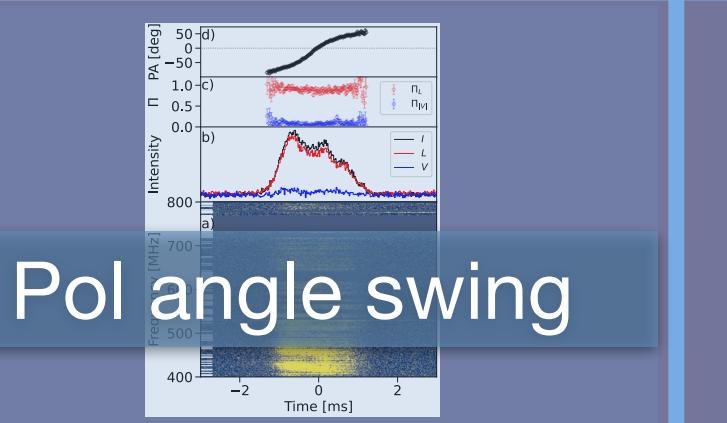
Metzger et al. 2022



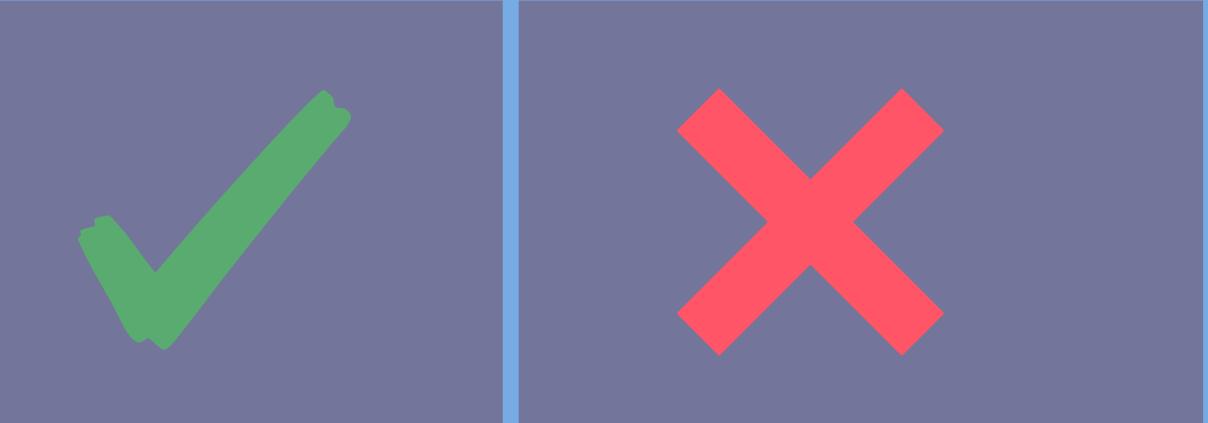
Temporal variability



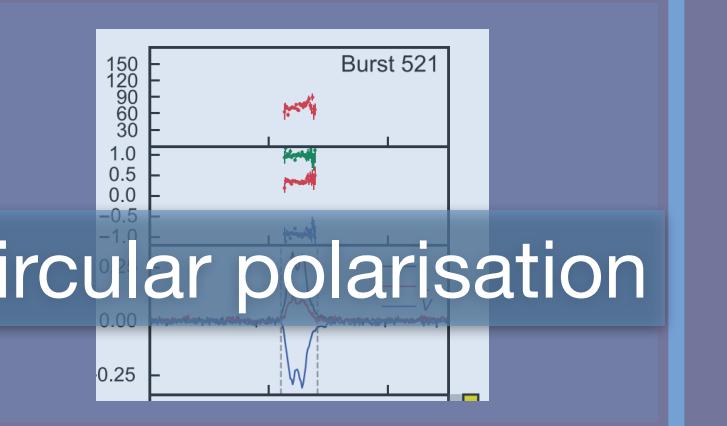
Sobacchi et al. 2021, 2024b



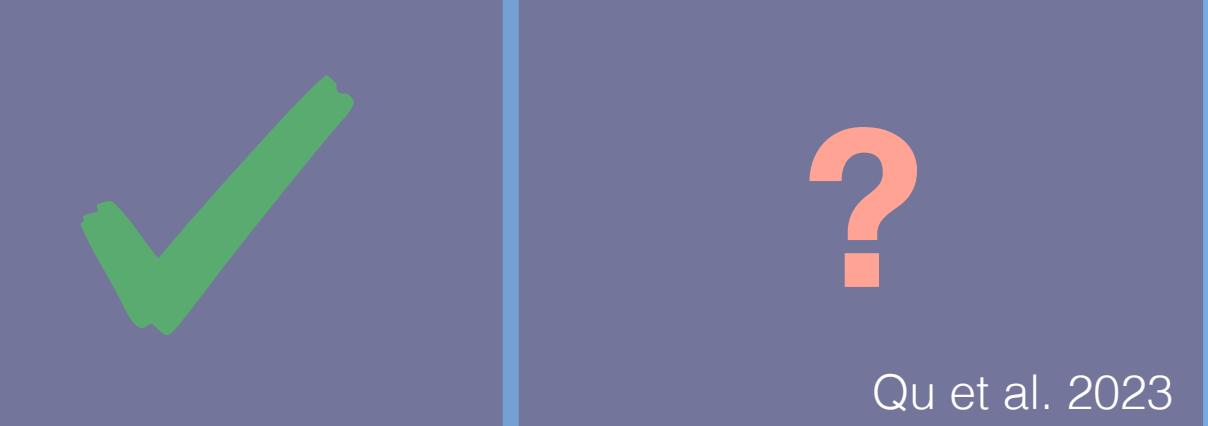
Pol angle swing



Metzger et al. 2022



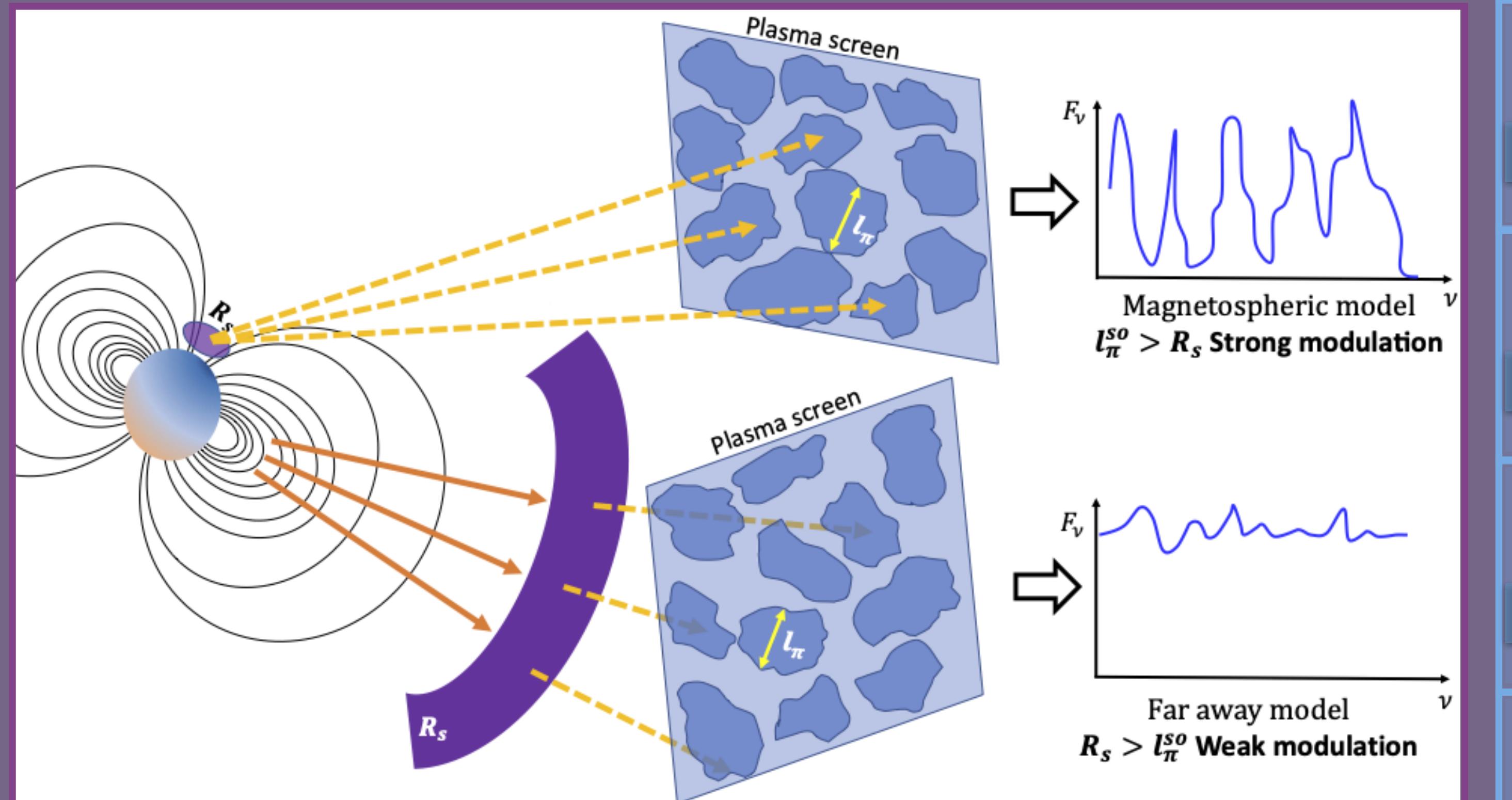
Circular polarisation



Qu et al. 2023

# Scintillation\*

\* from the host galaxy

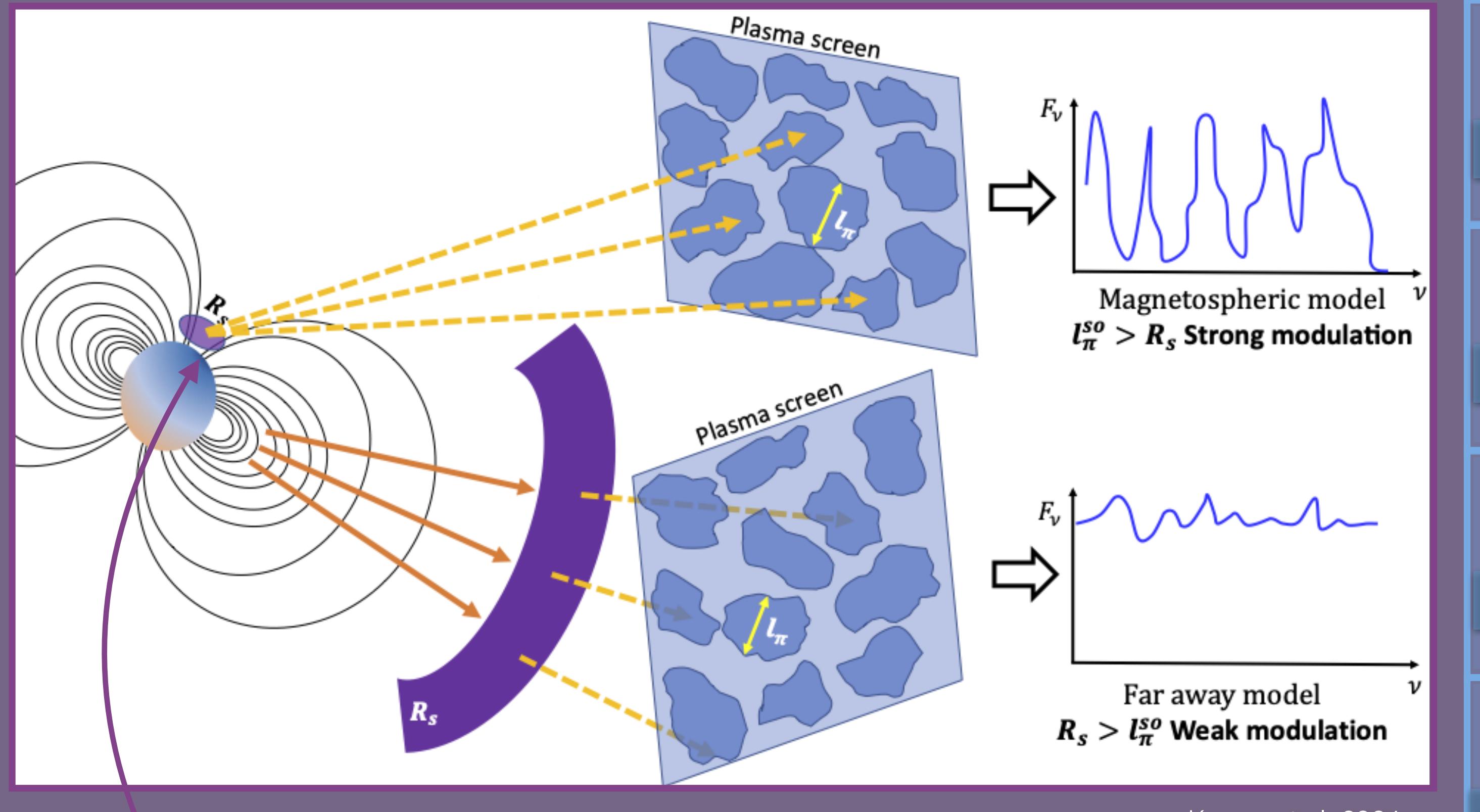


Kumar et al. 2024



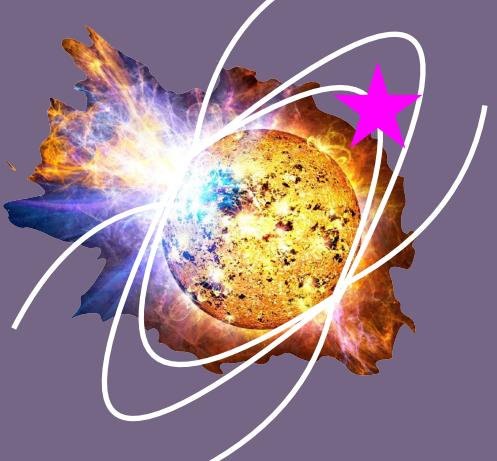
# Scintillation\*

\* from the host galaxy



Kumar et al. 2024

Magnetospheric



Metzger et al. 2022

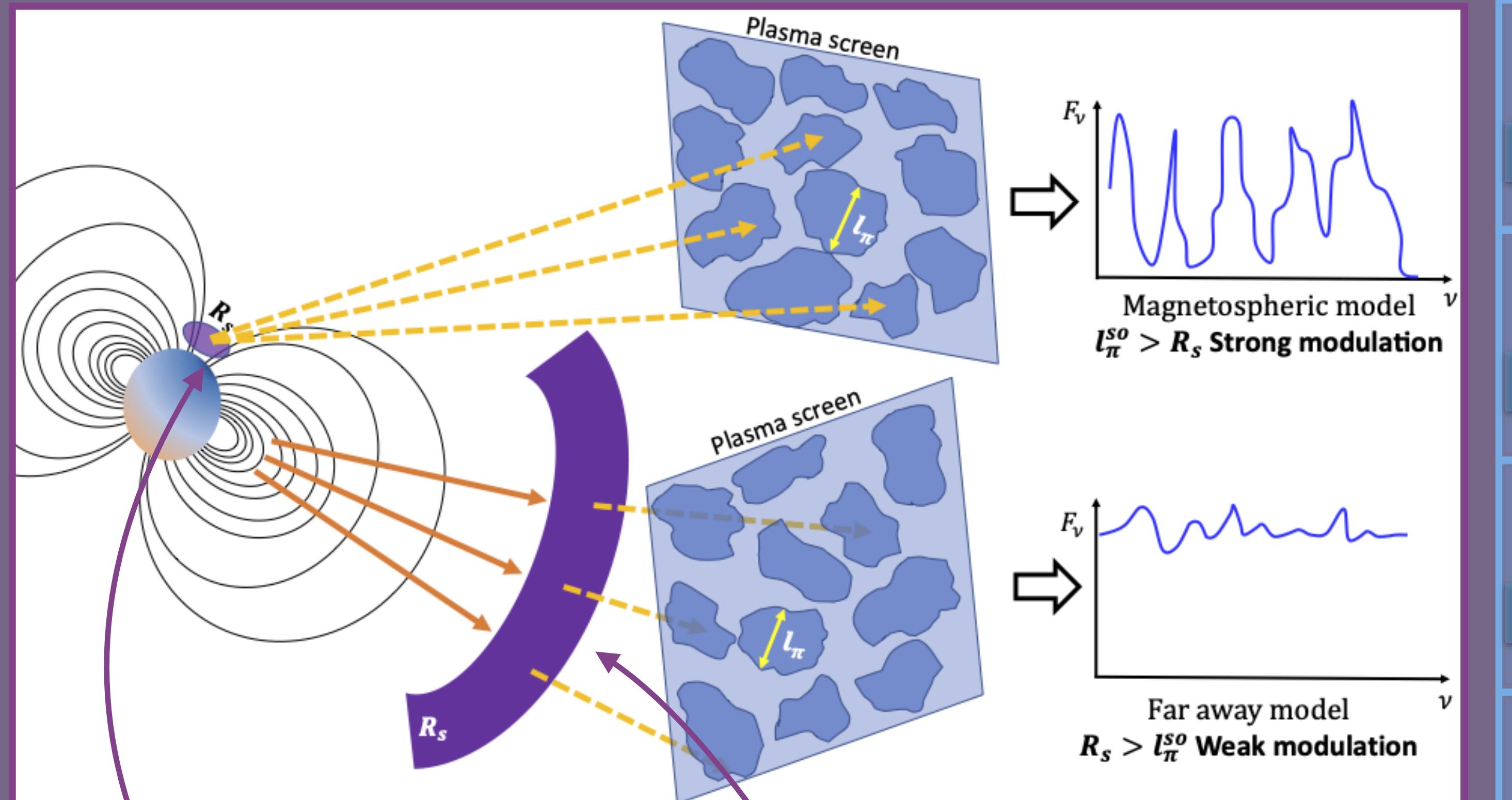
Sobacchi et al. 2021, 2024b

?

Qu et al. 2023

# Scintillation\*

\* from the host galaxy



Kumar et al. 2024

Magnetospheric

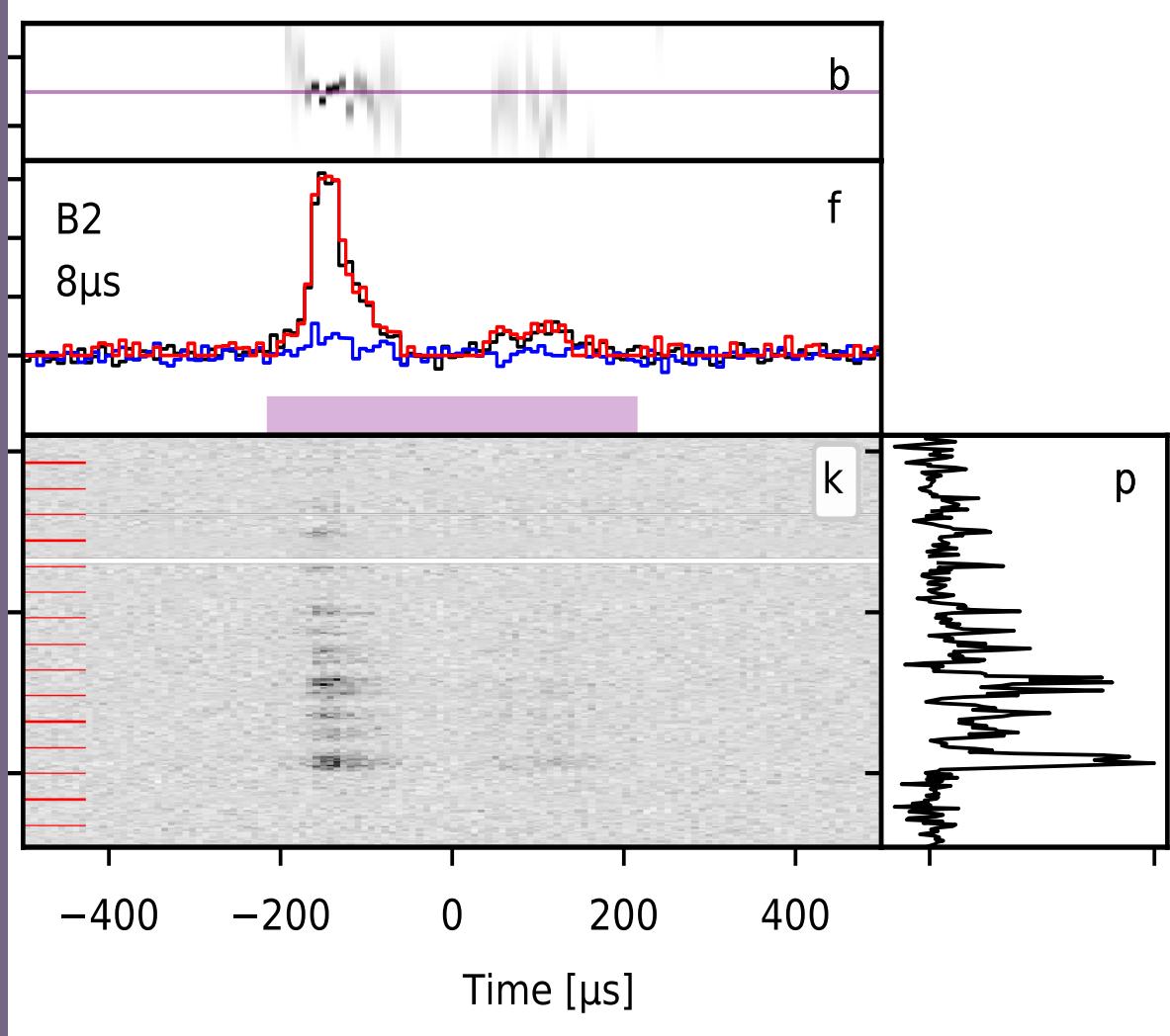


Non-magnetospheric

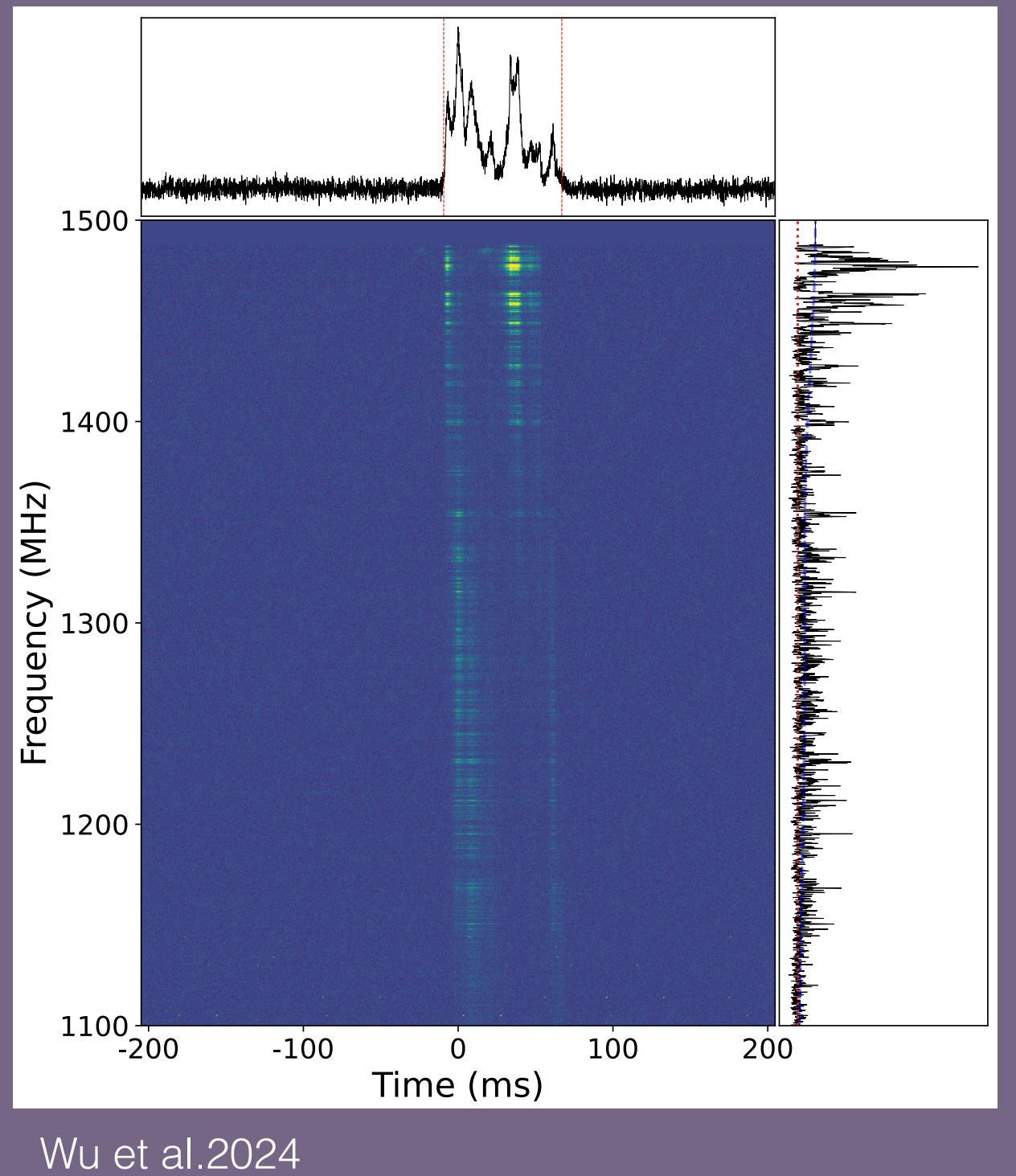


# Scintillation\*

\* from the host galaxy



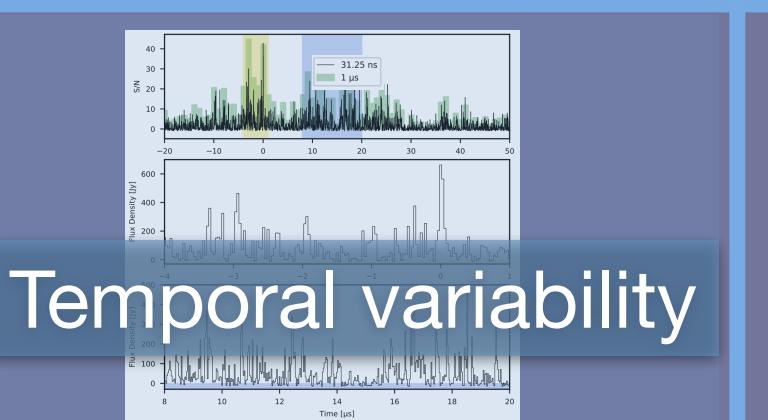
Nimmo et al. 2022



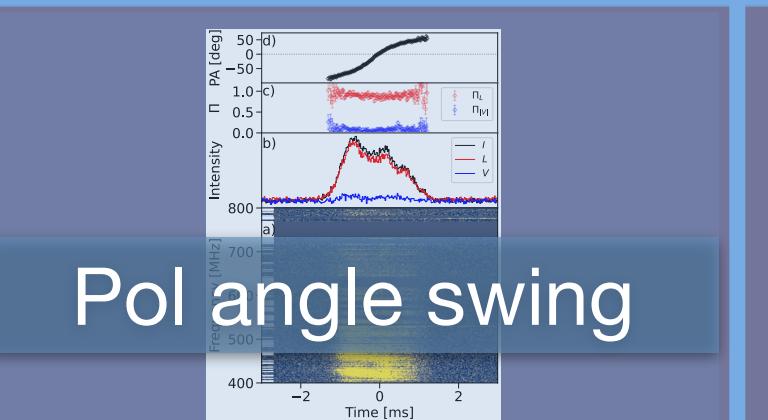
Wu et al. 2024



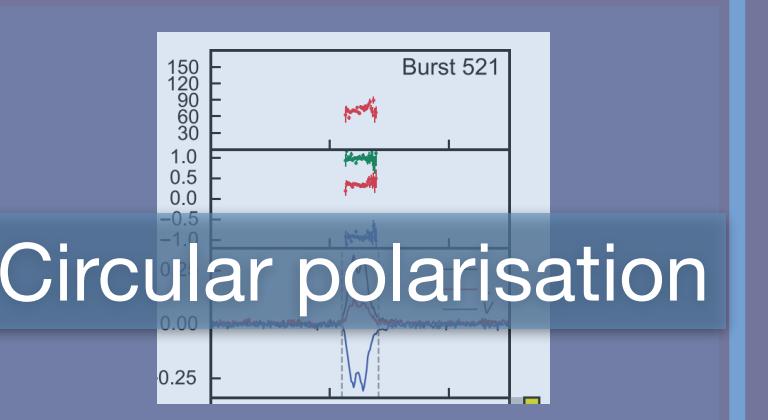
Spectral behaviour



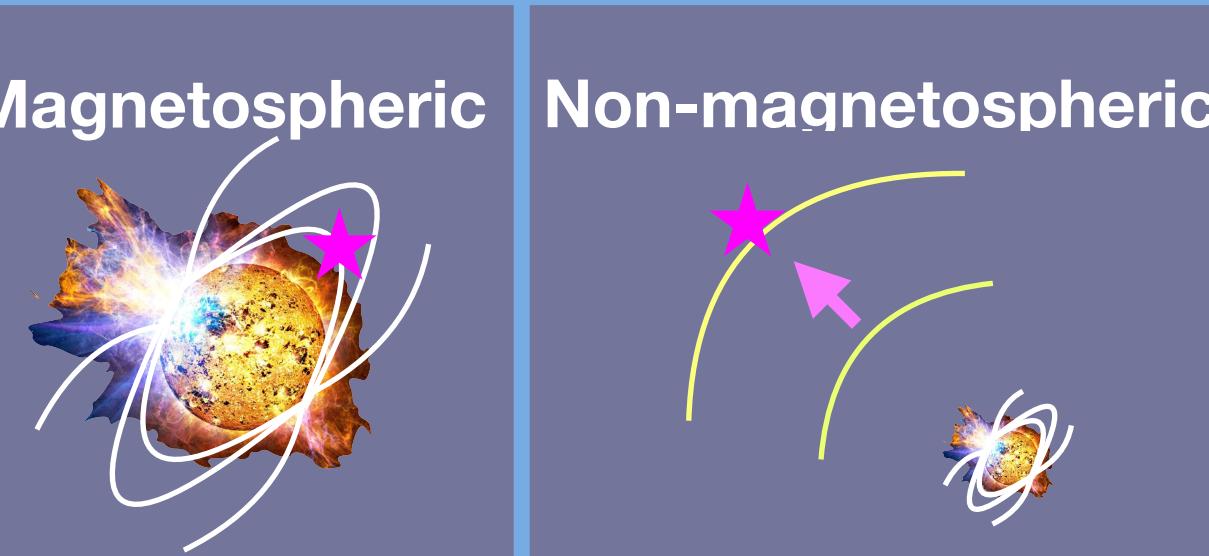
Temporal variability



Pol angle swing



Circular polarisation



Magnetospheric

Non-magnetospheric

Metzger et al. 2022

?

Sobacchi et al. 2021, 2024b

?

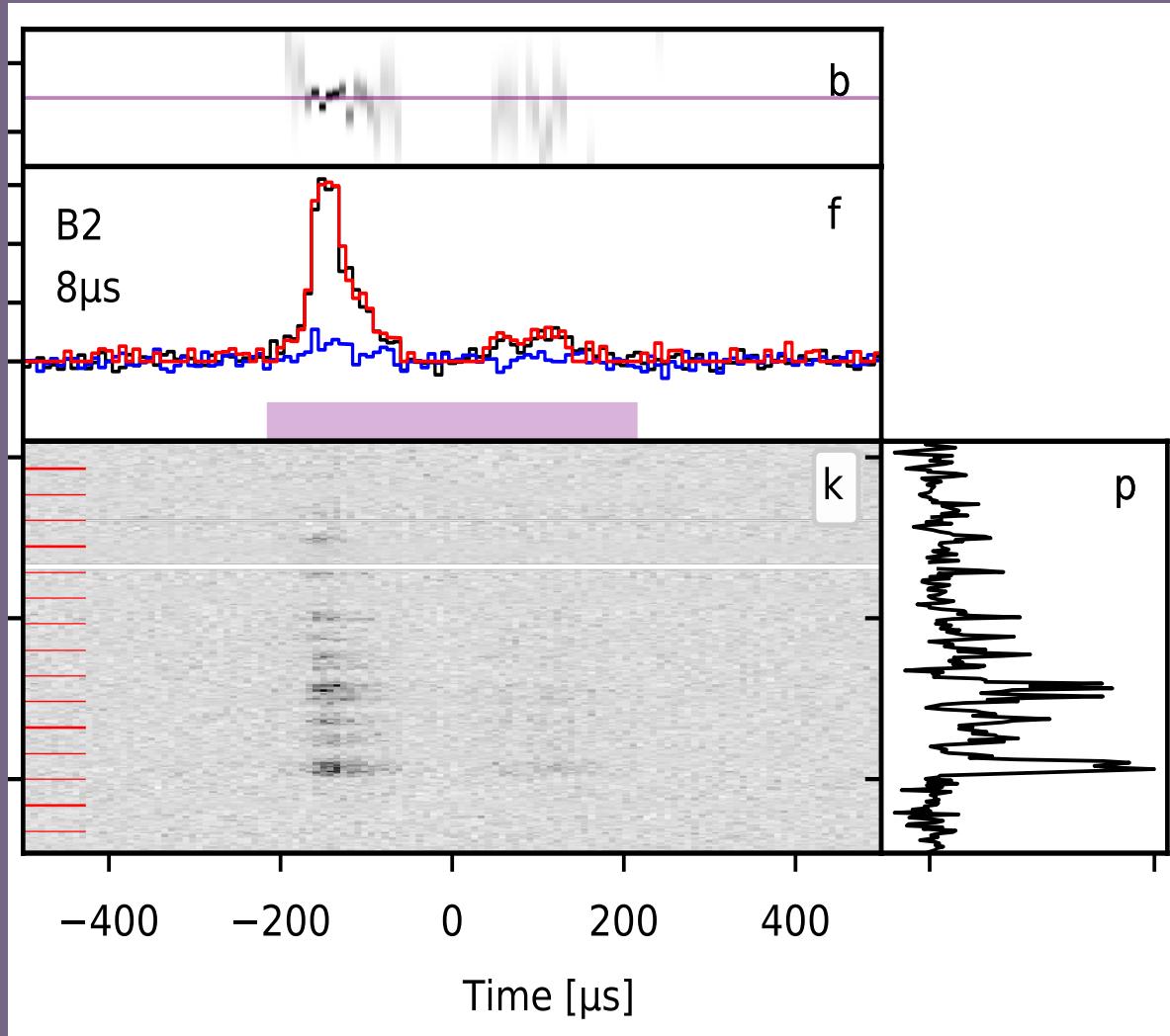
?

?

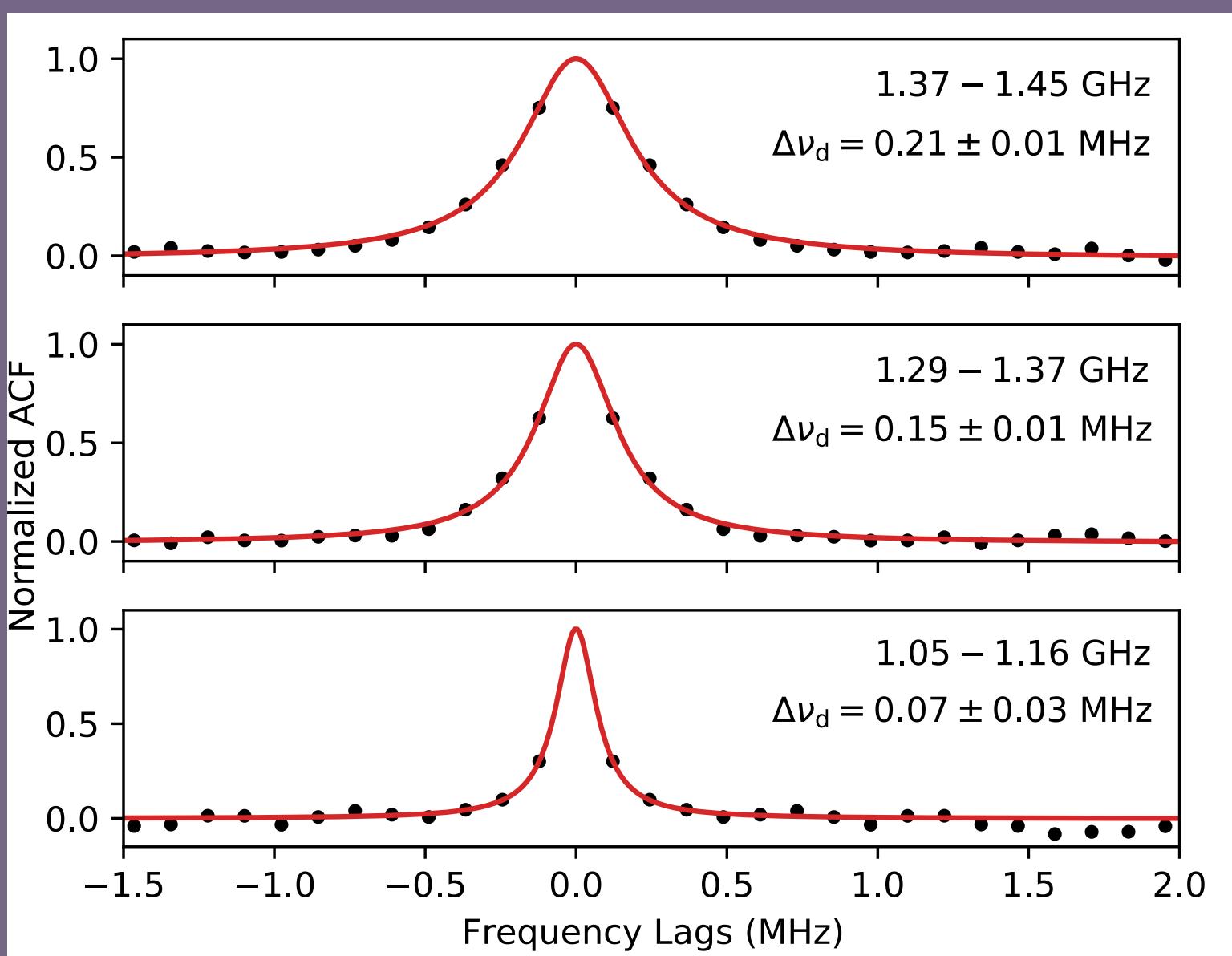
Qu et al. 2023

# Scintillation\*

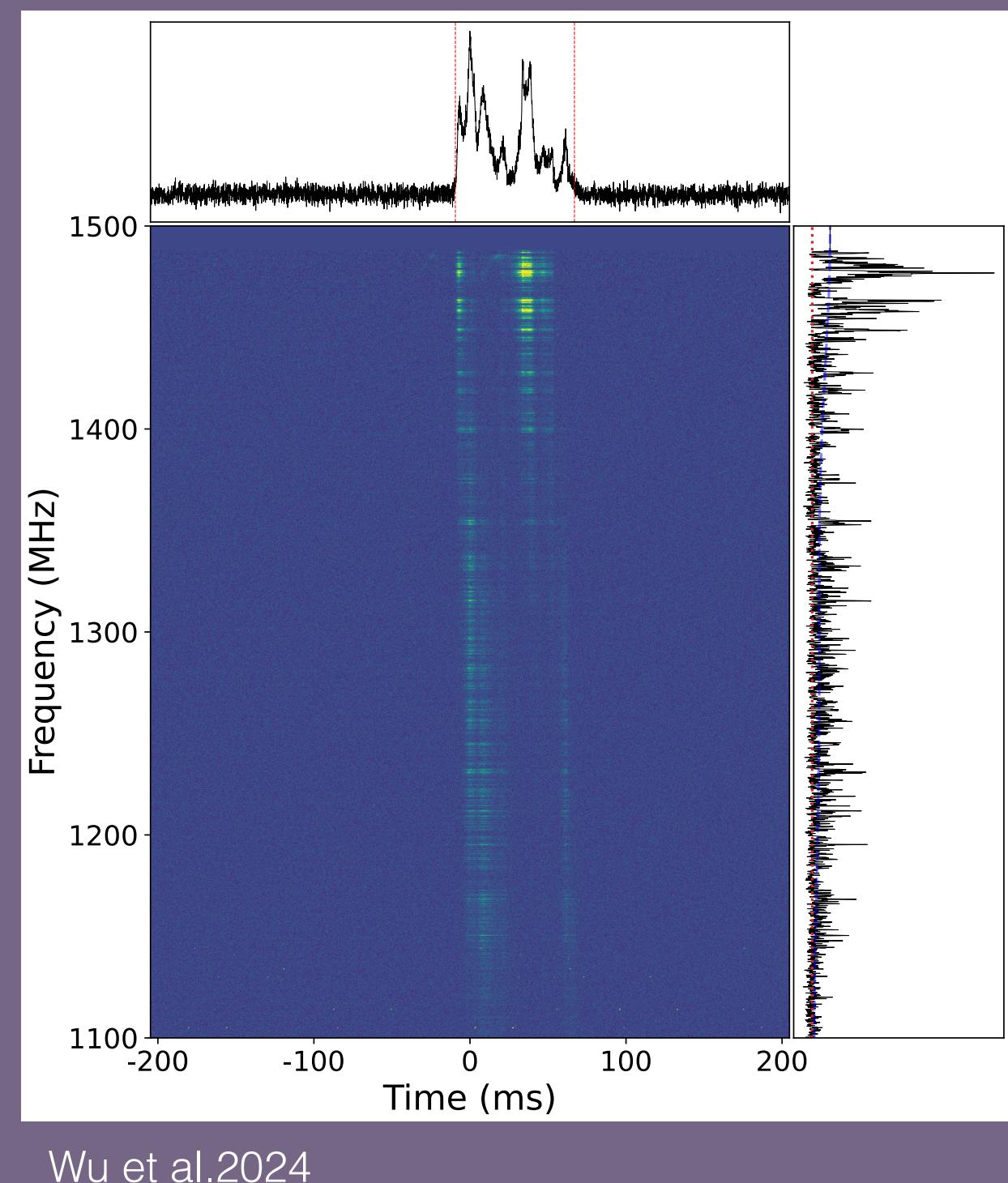
\* from the host galaxy



Nimmo et al. 2022



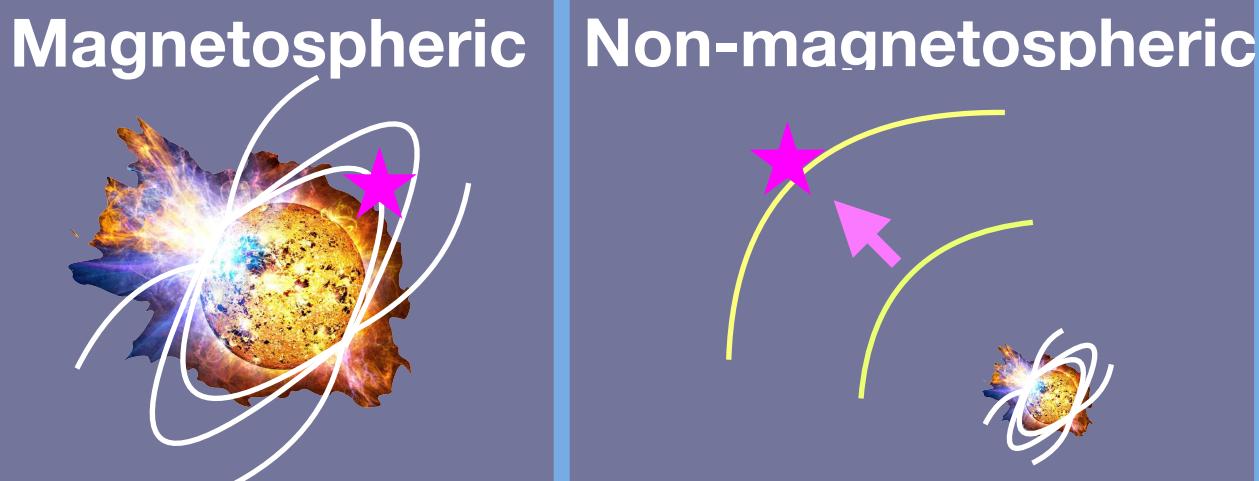
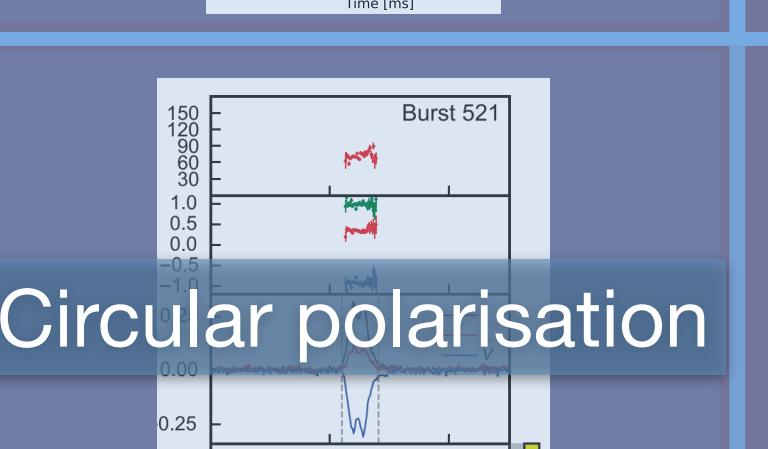
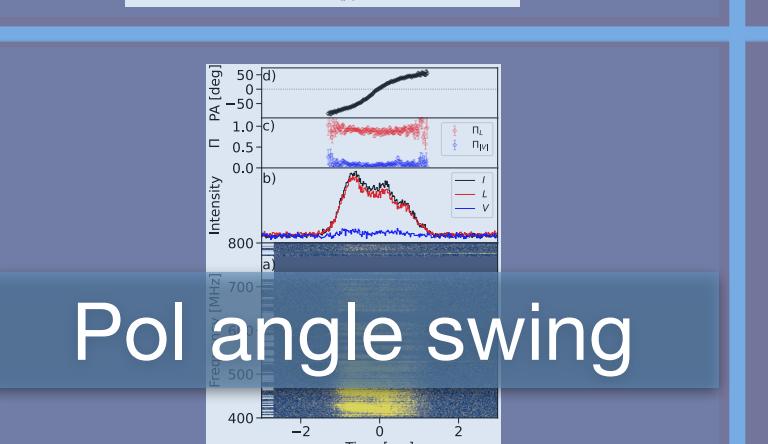
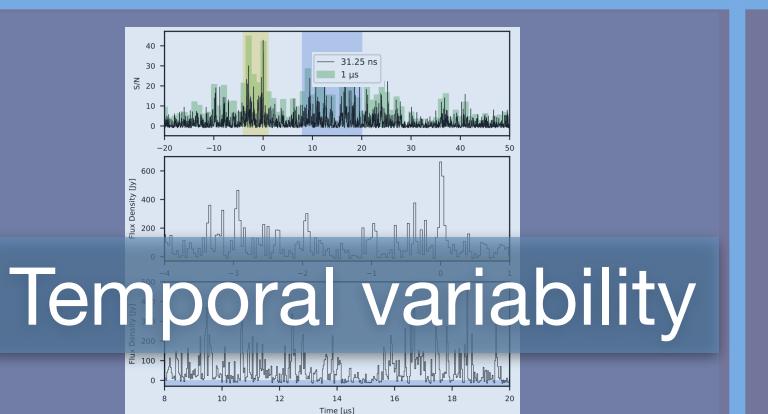
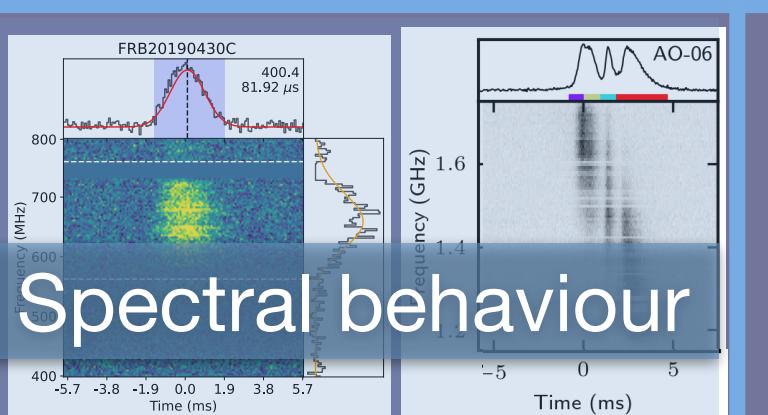
Ocker et al. 2022a



Wu et al. 2024

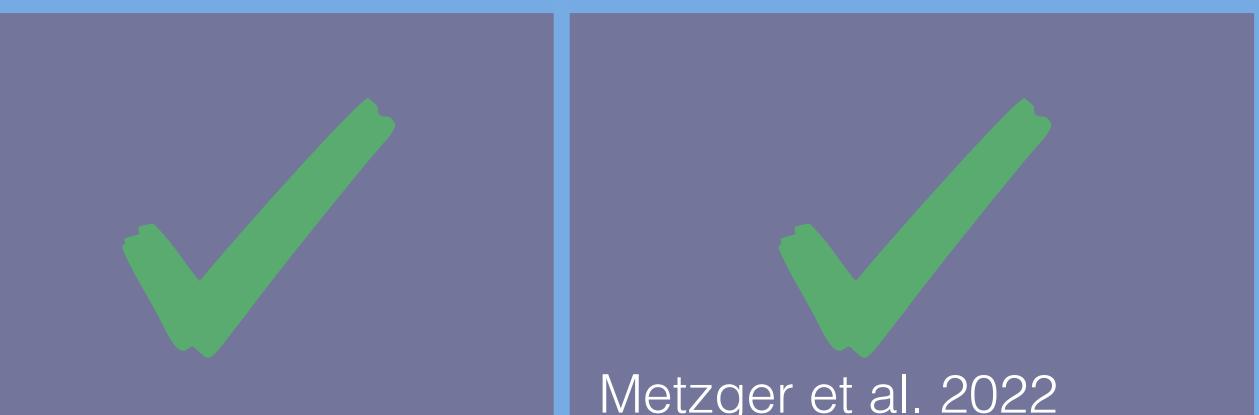


FRB property



Magnetospheric

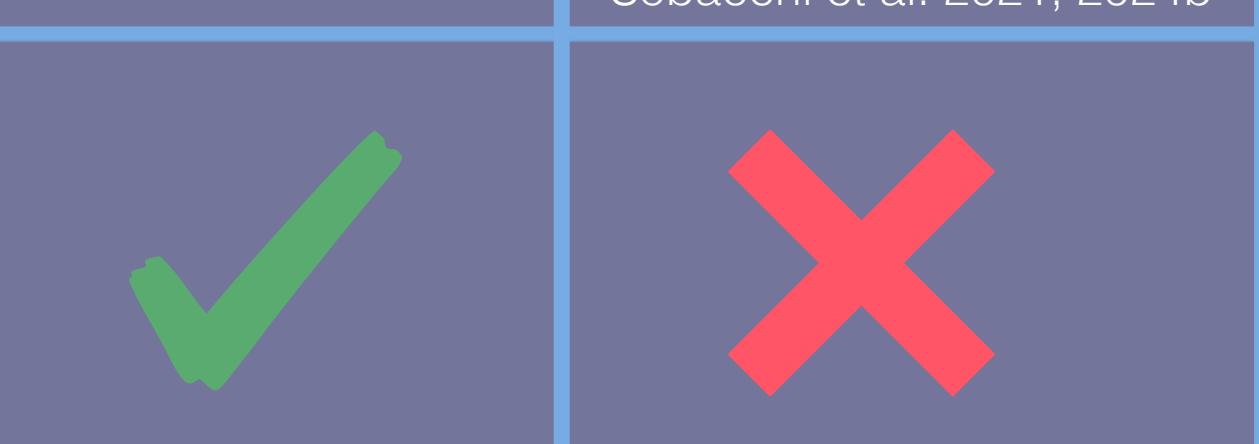
Non-magnetospheric



Metzger et al. 2022



Sobacchi et al. 2021, 2024b



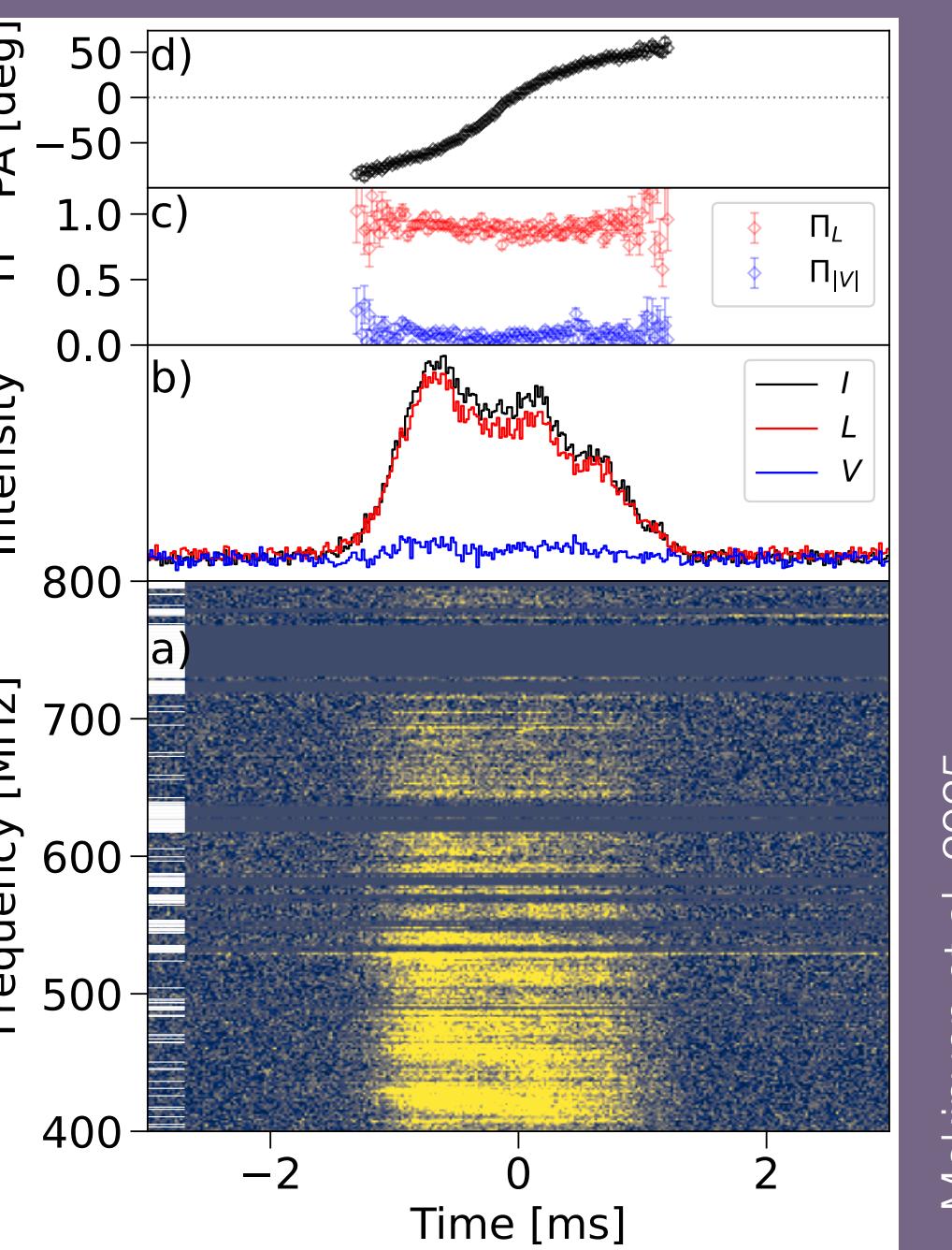
?

Qu et al. 2023

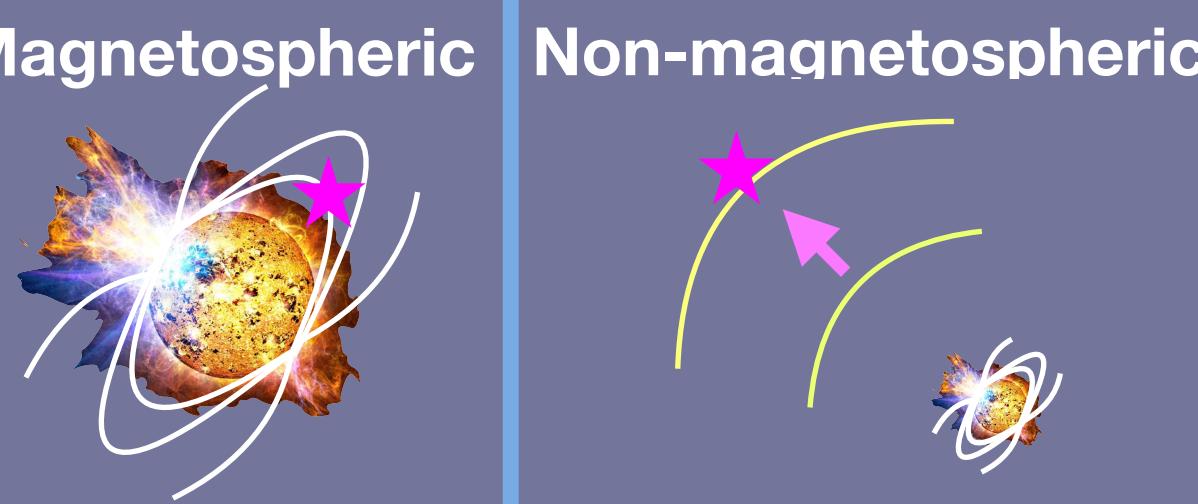
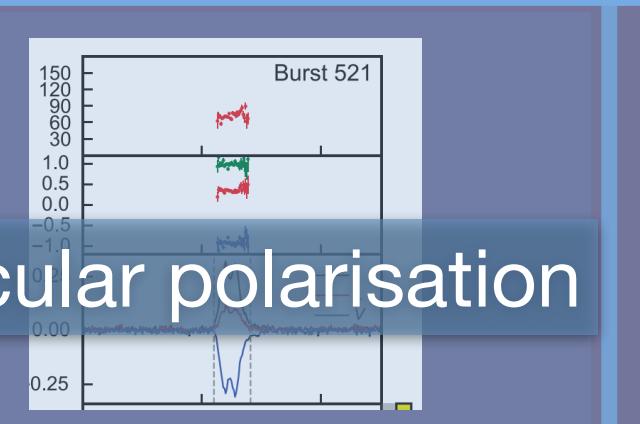
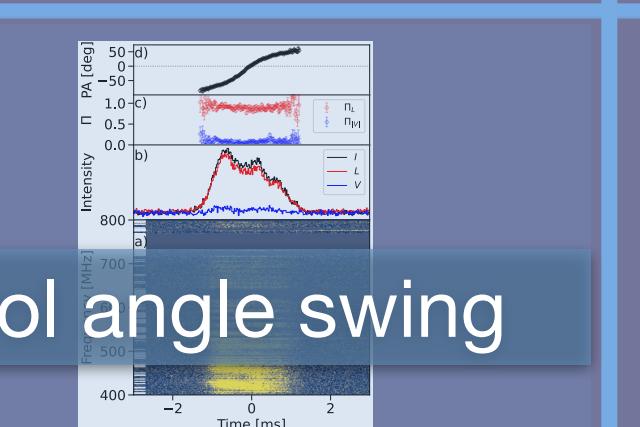
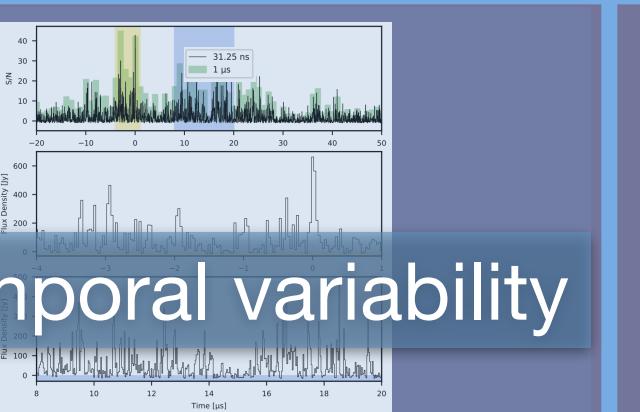
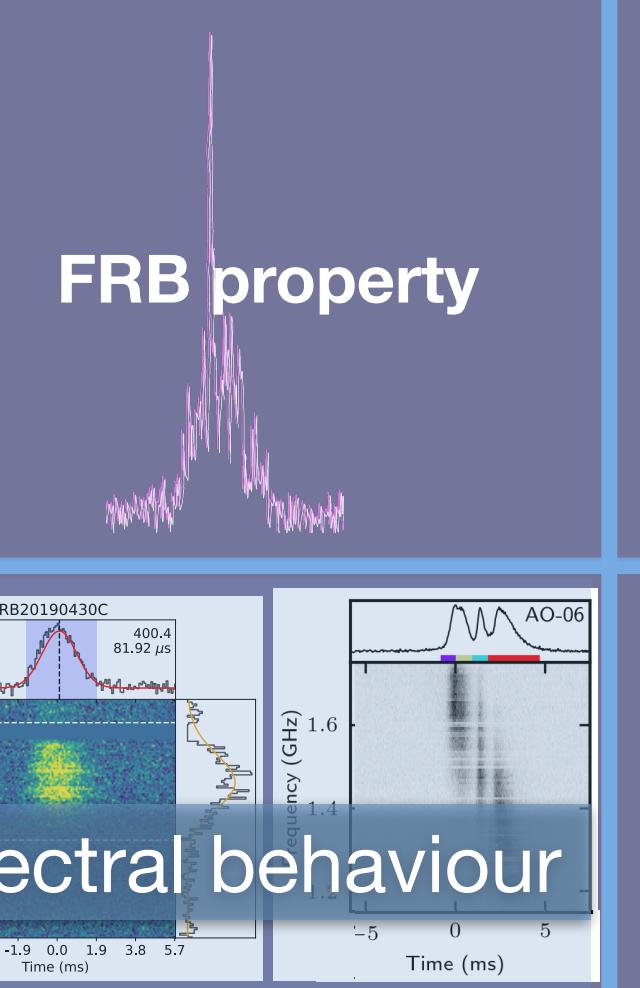
# Scintillation\*

\* from the host galaxy

## SWINGS



McKinven et al. 2025



Metzger et al. 2022

?

Sobacchi et al. 2021, 2024b

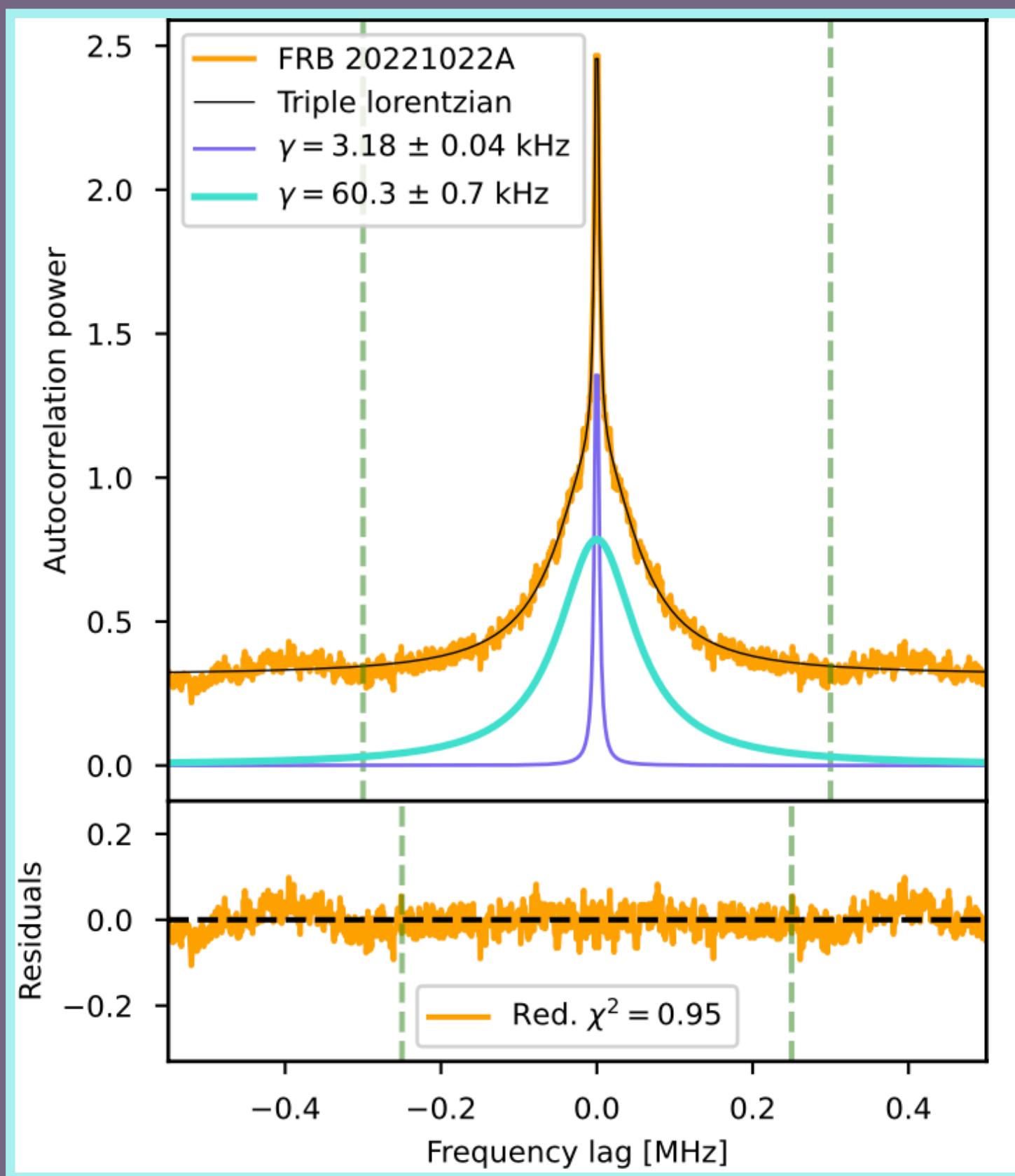


?

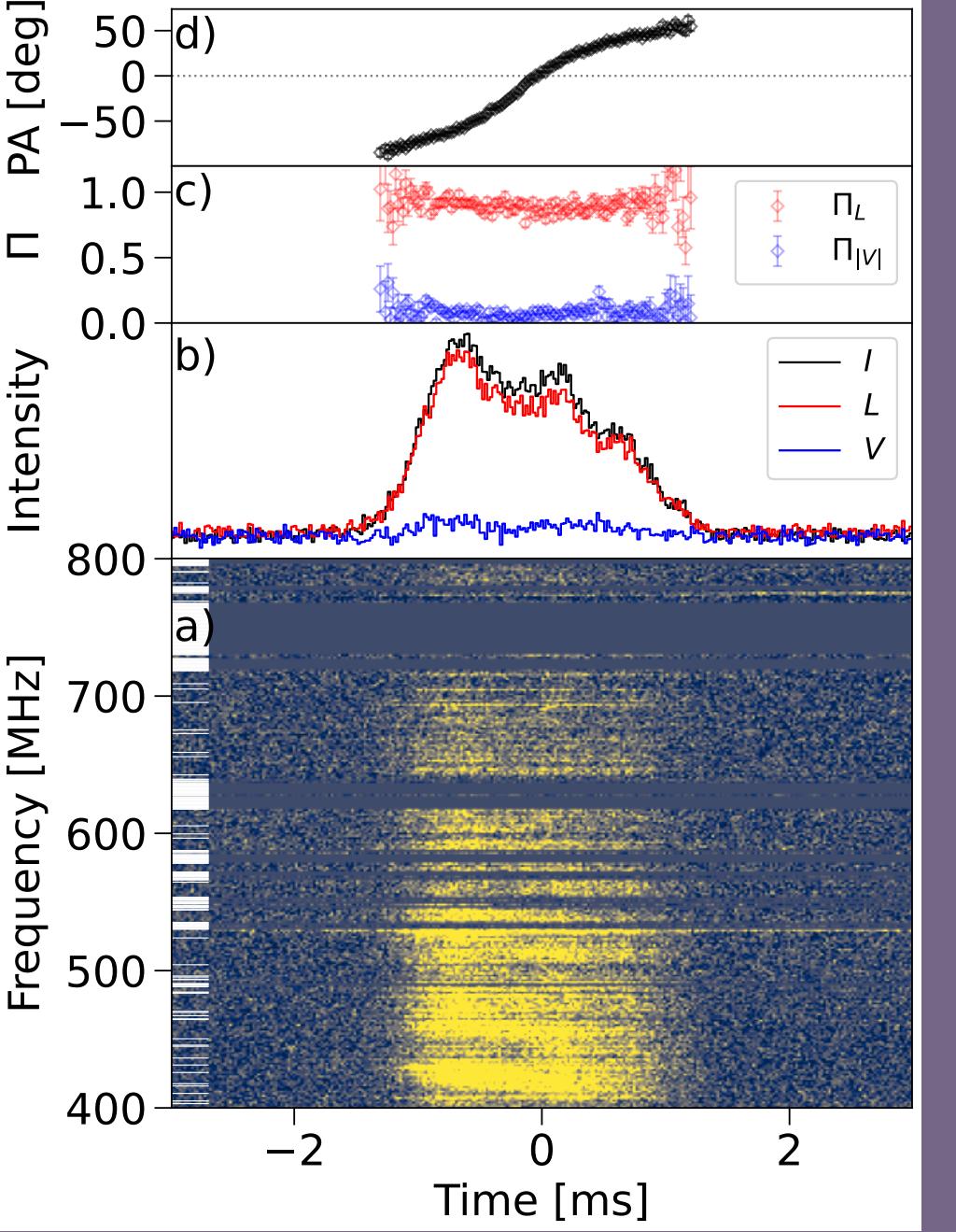
Qu et al. 2023

# Scintillation\*

\* from the host galaxy



Nimmo et al. 2025



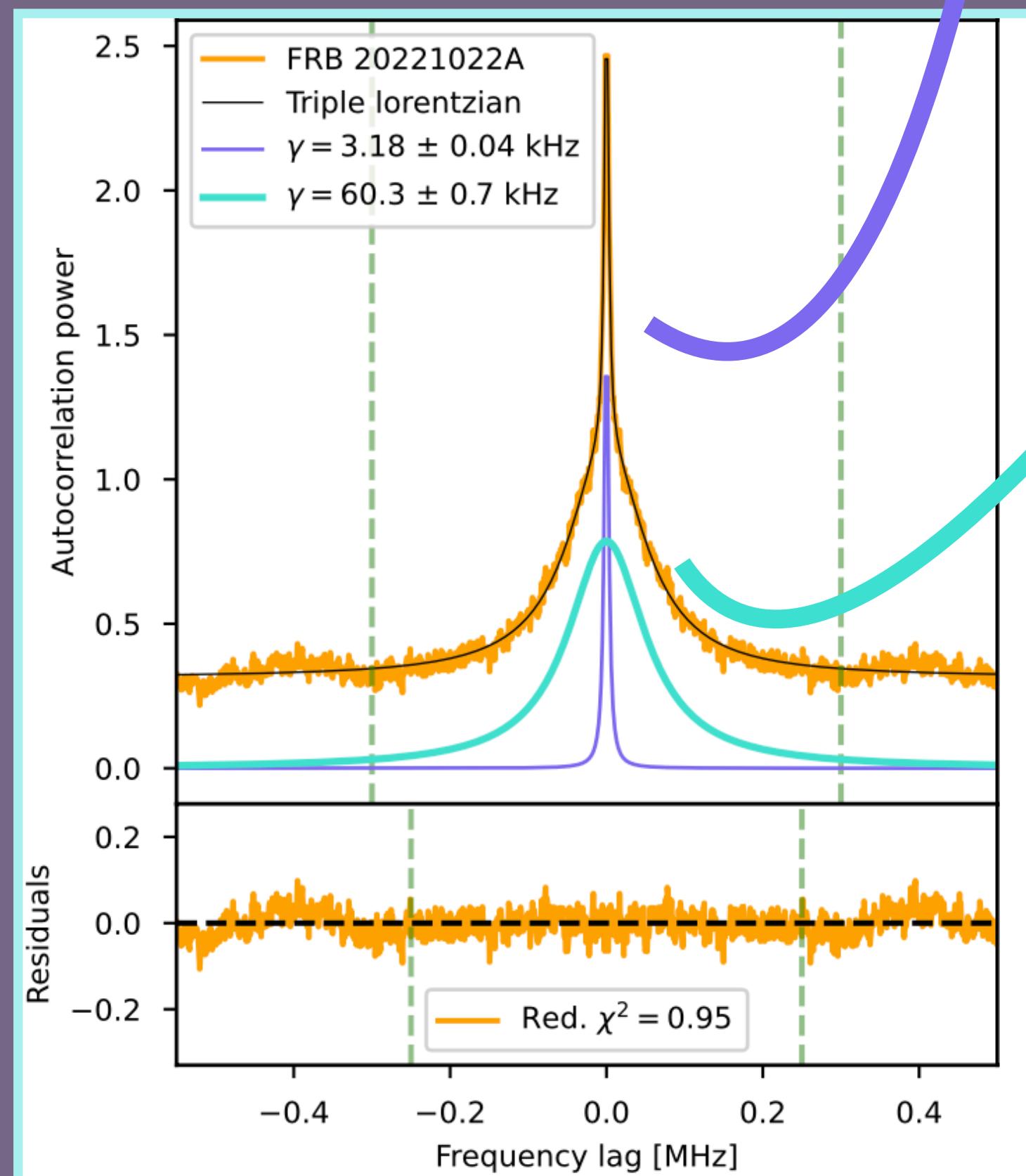
McKinven et al. 2025



# Scintillation\*

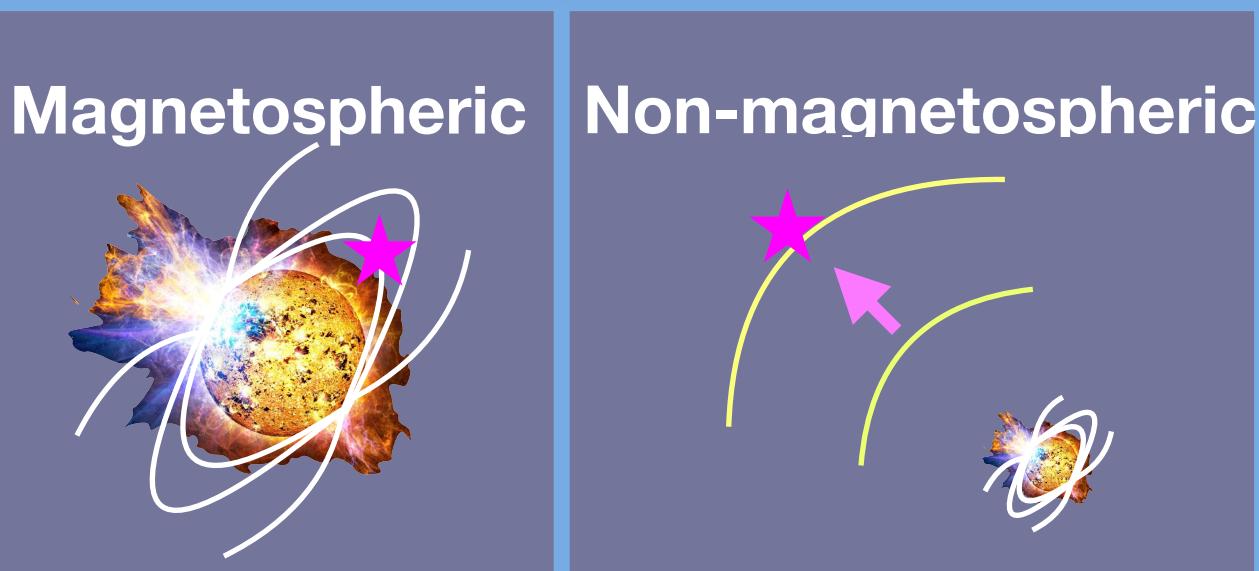
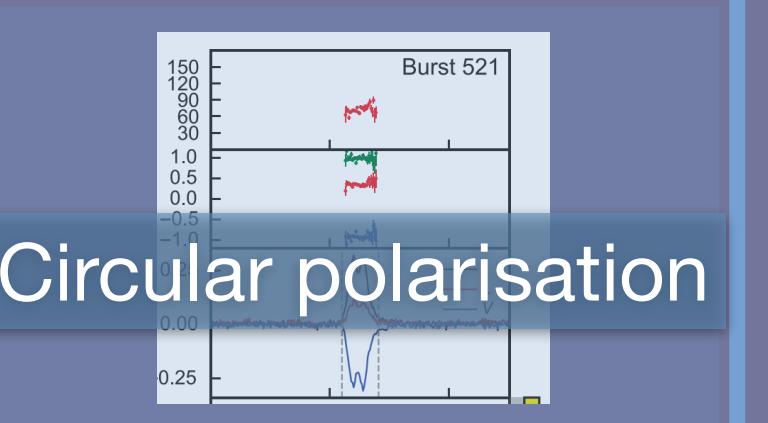
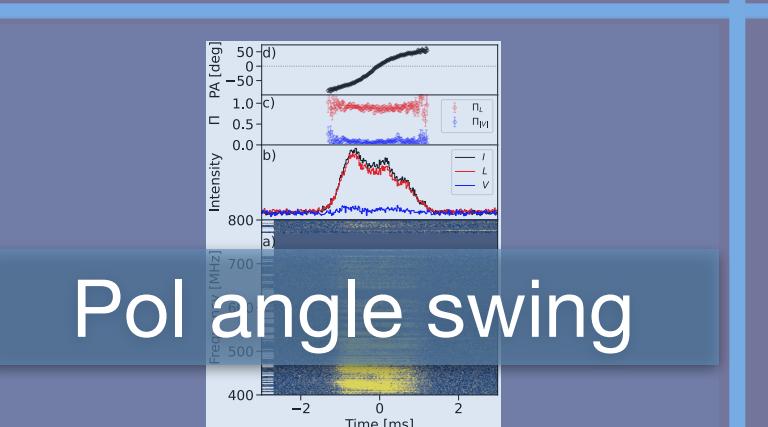
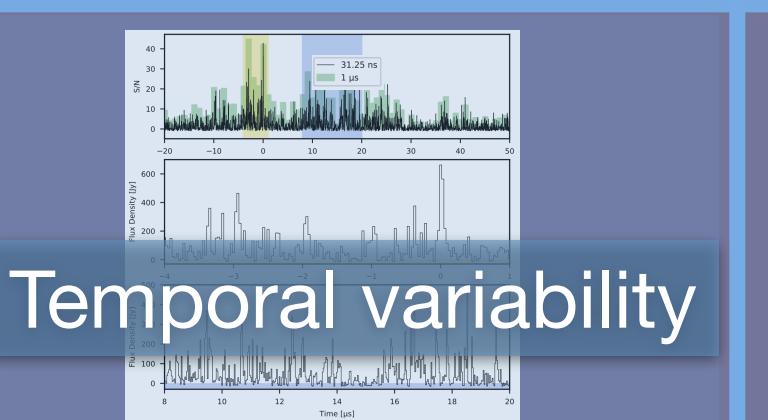
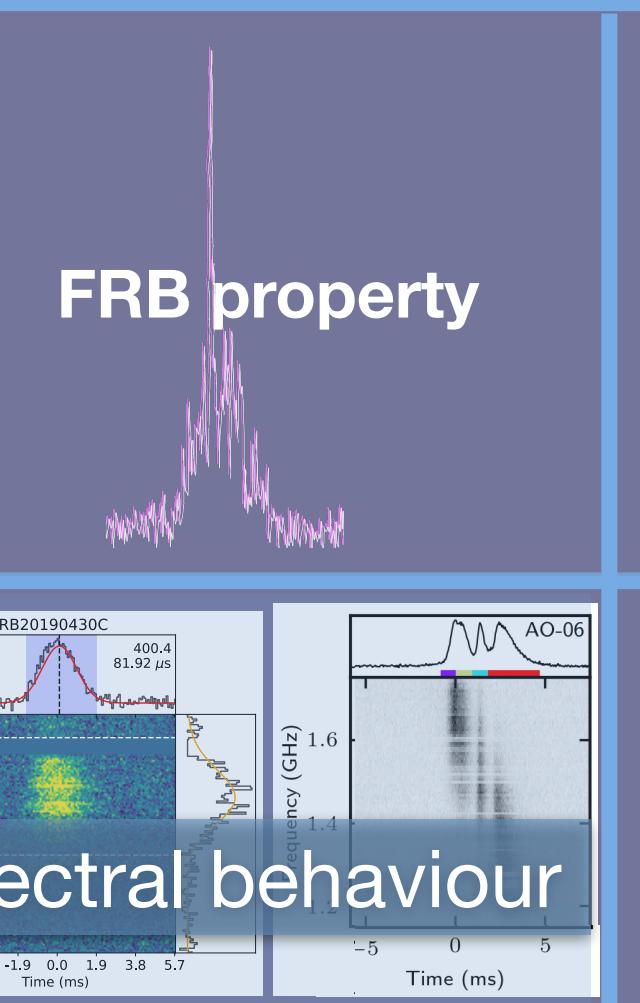
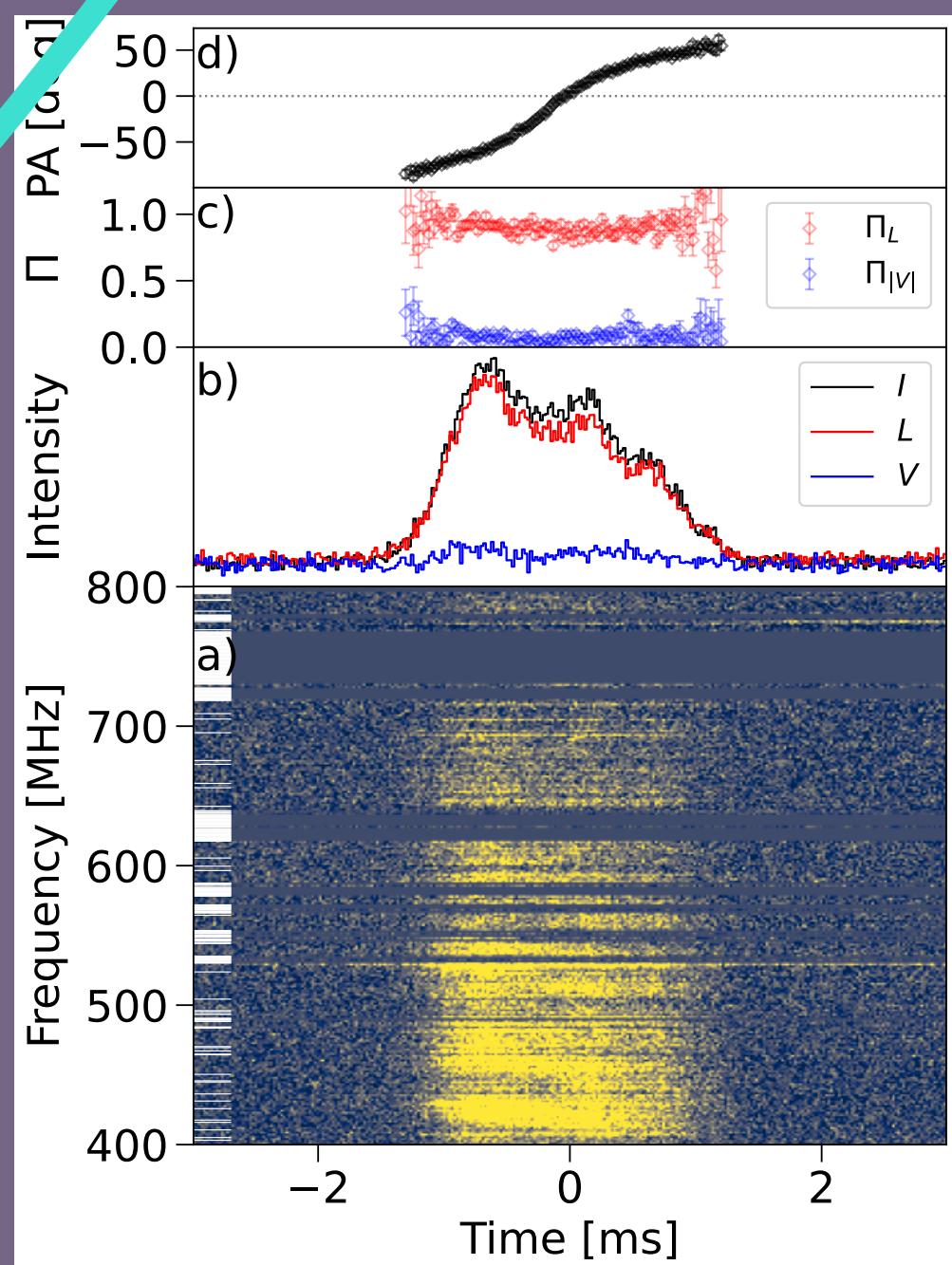
\* from the host galaxy

## Scintillation screen in Milky Way



## Scintillation screen in FRB host galaxy

### SWINGS



Metzger et al. 2022

Sobacchi et al. 2021, 2024b

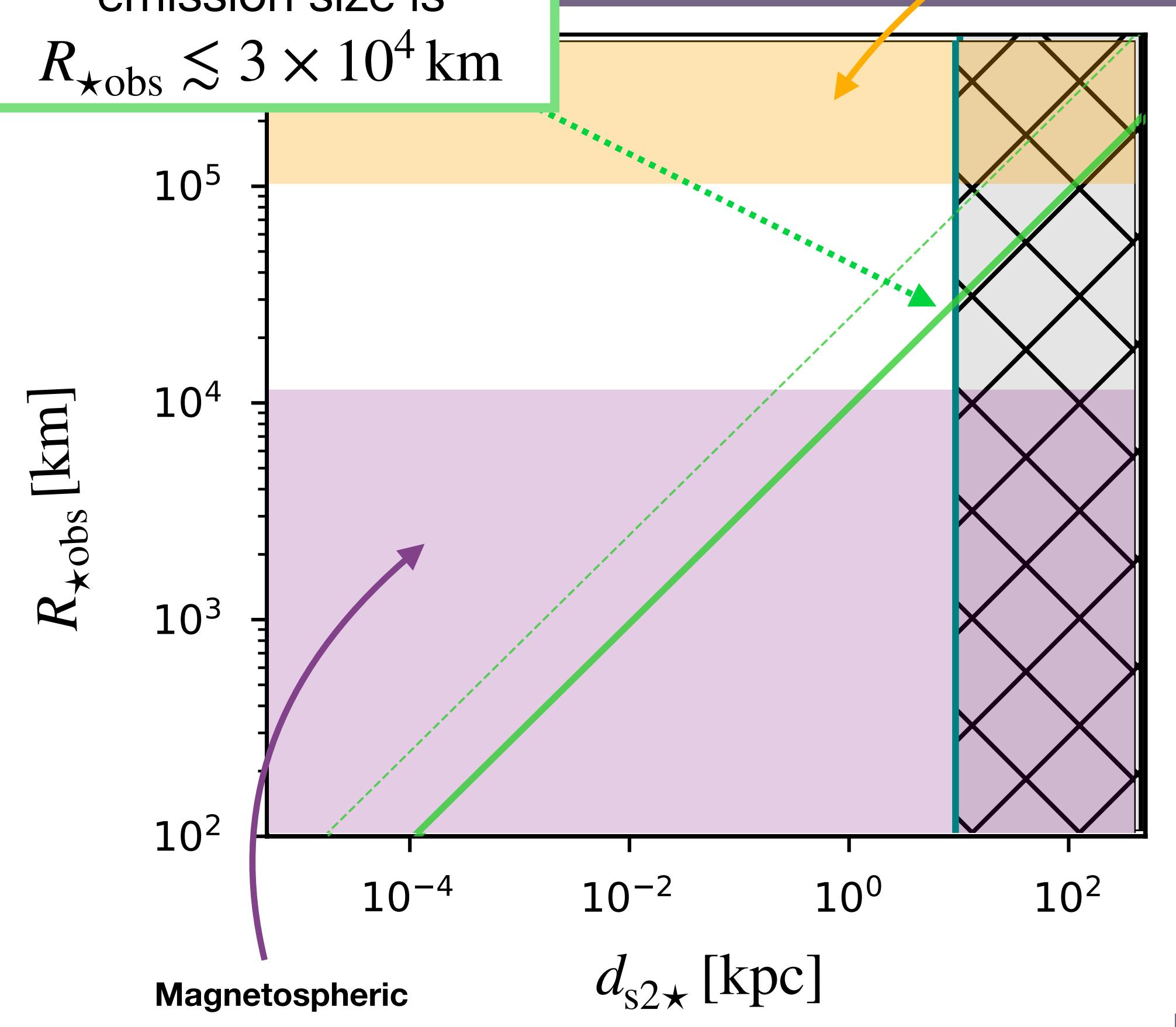
Qu et al. 2023

# Scintillation\*

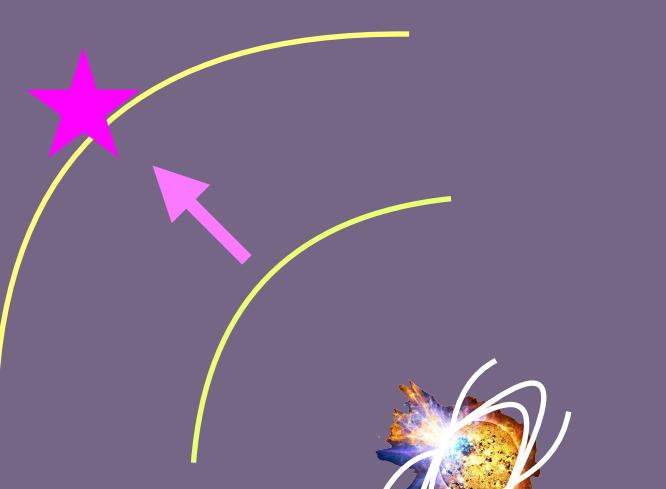
\* from the host galaxy

# Upper limit on the emission size is

$$R_{\star\text{obs}} \lesssim 3 \times 10^4 \text{ km}$$



## Non-magnetospheric



# FRB property



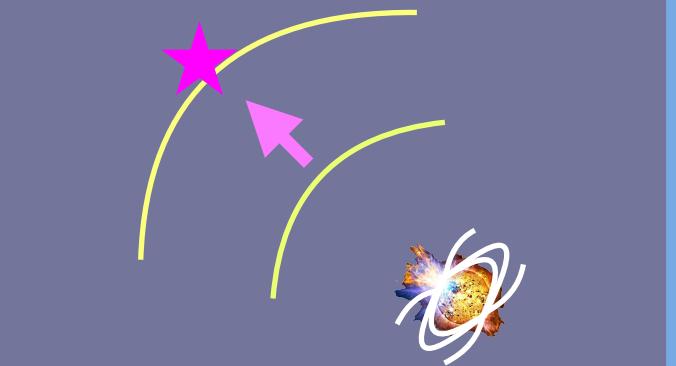
# Temporal variability

The figure shows a plot of circular polarisation parameters for Burst 521. The vertical axis represents the Stokes parameters, with values ranging from -0.25 to 1.50. The horizontal axis represents time. The plot displays four data series:   
 - **Stokes I (Red line):** Shows a sharp peak reaching approximately 0.8 at the end of the burst.   
 - **Stokes Q (Green line):** Shows a peak reaching approximately 0.6 at the end of the burst.   
 - **Stokes U (Blue line):** Shows a peak reaching approximately 0.25 at the end of the burst.   
 - **Stokes V (Dashed line):** Shows a peak reaching approximately 0.1 at the end of the burst.   
 The plot is titled "Burst 521" and includes a legend in the bottom right corner.

# Magnetospheric



# Non-magnetospheric



Metzger et al. 2022

Sobacchi et al. 2021, 2024b

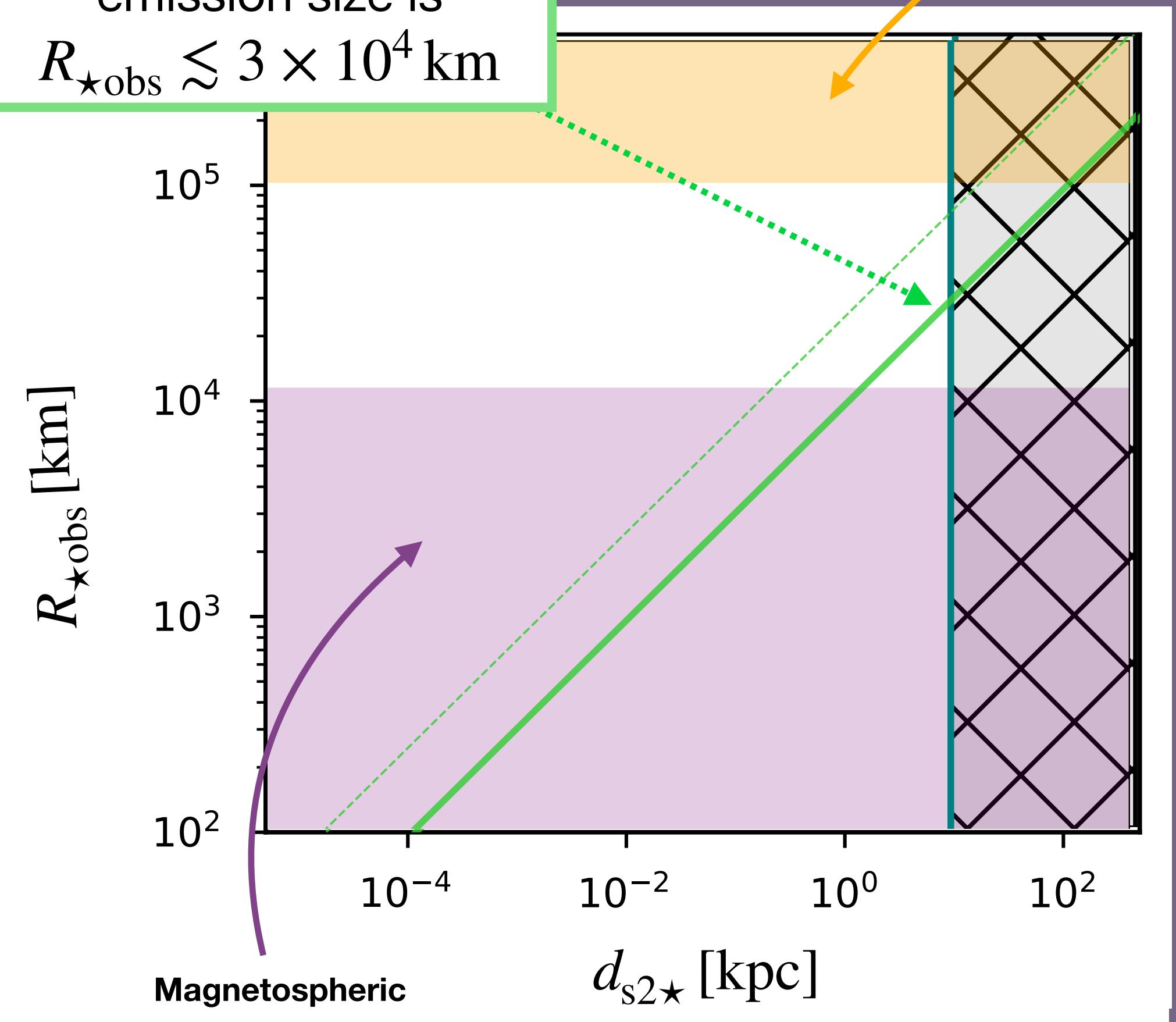
# ?

# Scintillation\*

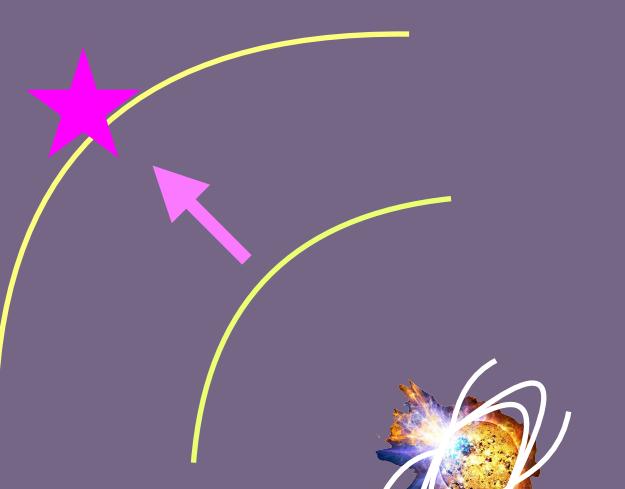
\* from the host galaxy

# Upper limit on the emission size is

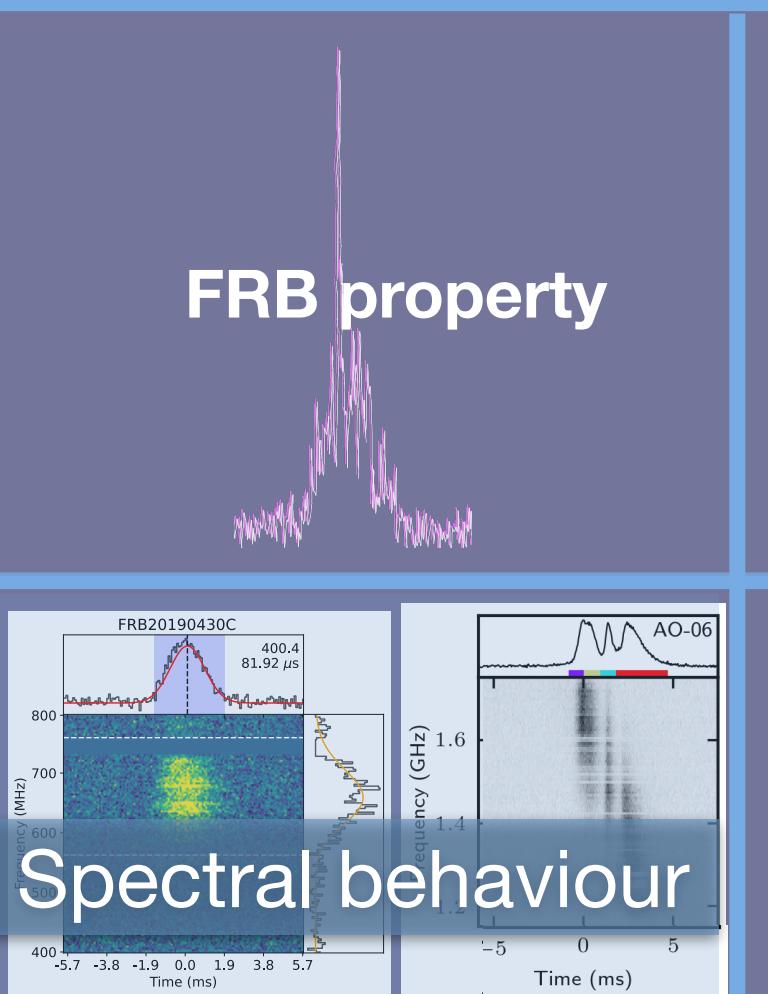
$$R_{\star\text{obs}} \lesssim 3 \times 10^4 \text{ km}$$



## Non-magnetospheric



# FRB property

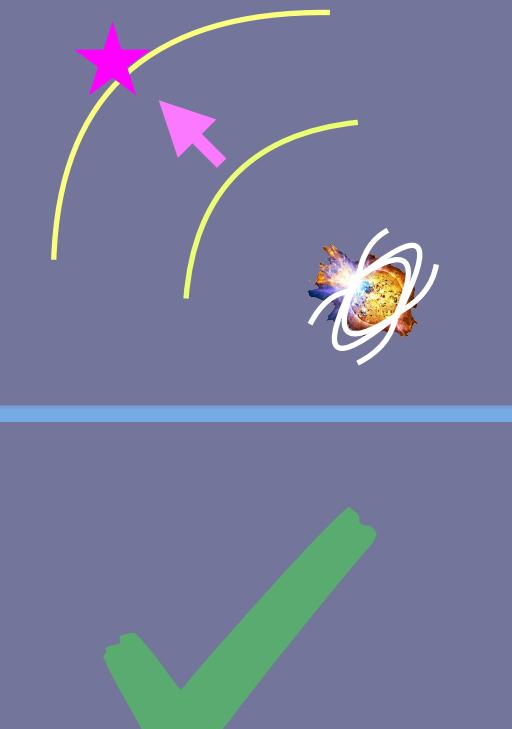


# Temporal variability

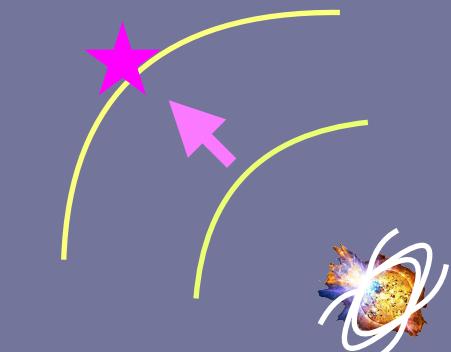
The figure shows a plot of circular polarization parameters for Burst 521. The top panel displays the Stokes parameter  $Q$  (red line) and  $U$  (green line) in arbitrary units, with a horizontal reference line at 1.0. The  $Q$  signal shows a sharp peak reaching approximately 80, while the  $U$  signal peaks around 10. The bottom panel shows the Stokes parameter  $V$  (blue line) in arbitrary units, with a horizontal reference line at 0.00. The  $V$  signal exhibits a deep negative minimum reaching about -0.25, indicated by a dashed line. The x-axis represents time, and the y-axis represents the Stokes parameter values.

# Magnetospheric





The image is a composite figure. The top half features a dark blue background with a white title 'Non-magnetospheric' in a large, bold, sans-serif font. Below the title is a diagram consisting of a yellow star at the top left, a pink arrow pointing towards it from the bottom left, and two yellow curved lines that meet at a central point. To the right of this central point is a small, colorful illustration of a celestial body with a ring system, resembling a planet like Saturn. The bottom half of the image is a solid light blue color. In the bottom right corner, there is a large, solid green checkmark.



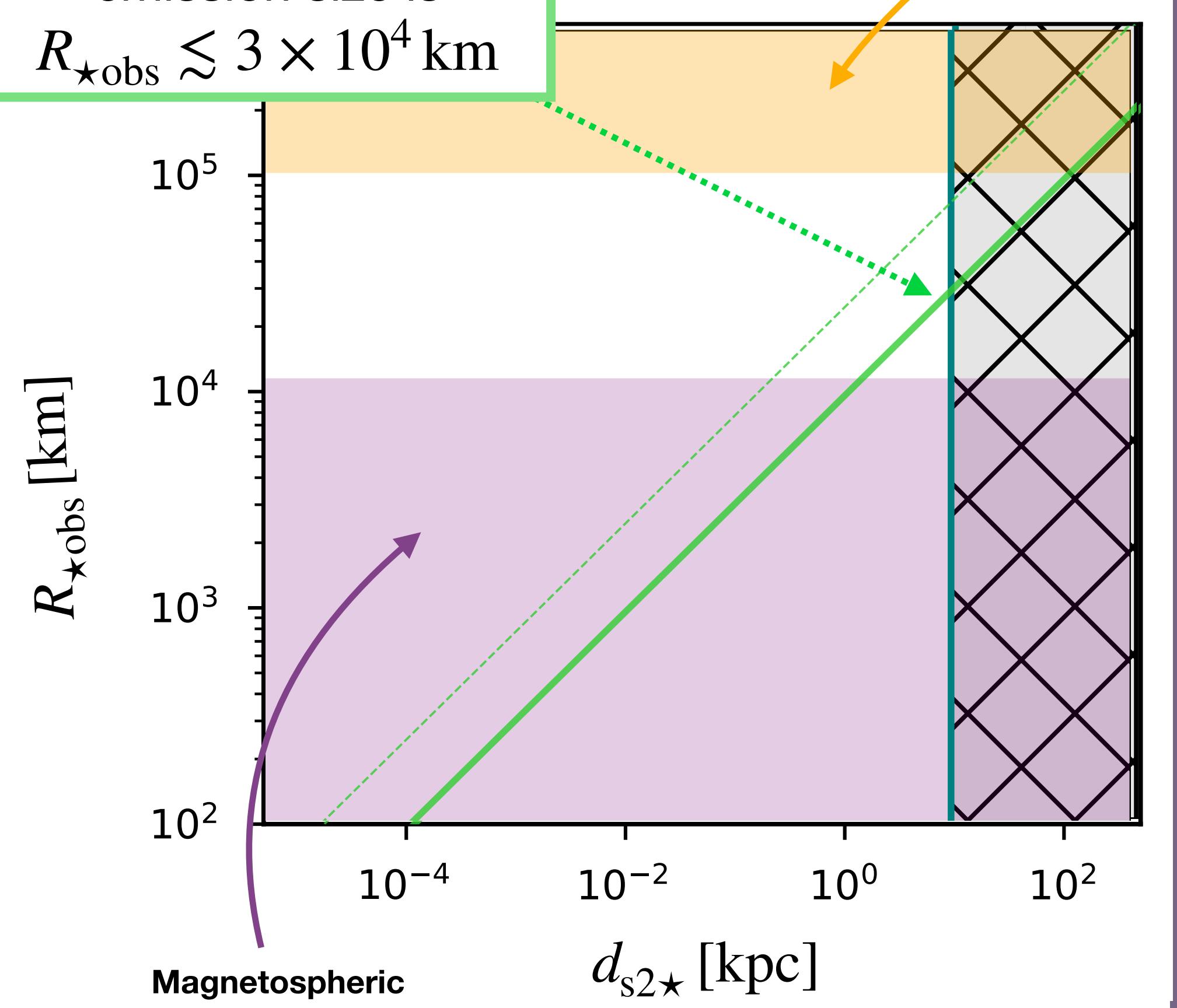
A large red 'X' is positioned on the left side of the slide, and a large question mark is on the right side. The background is a solid blue color.

# ?

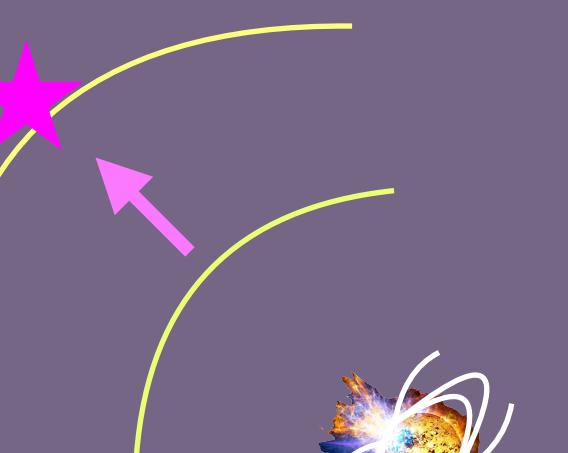
# Scintillation\*

\* from the host galaxy

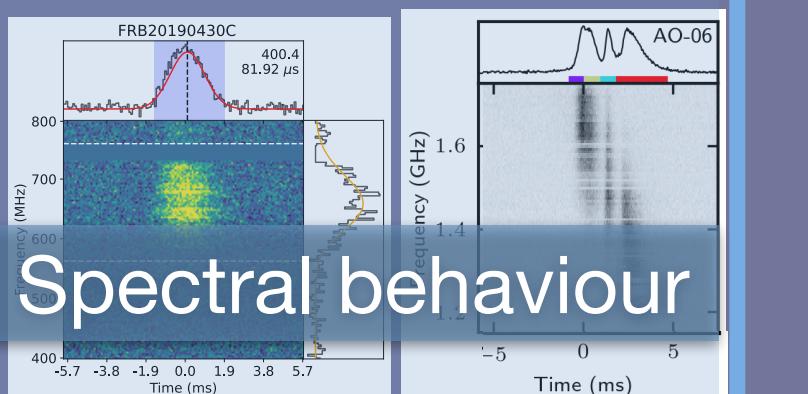
Upper limit on the emission size is  
 $R_{\star\text{obs}} \lesssim 3 \times 10^4 \text{ km}$



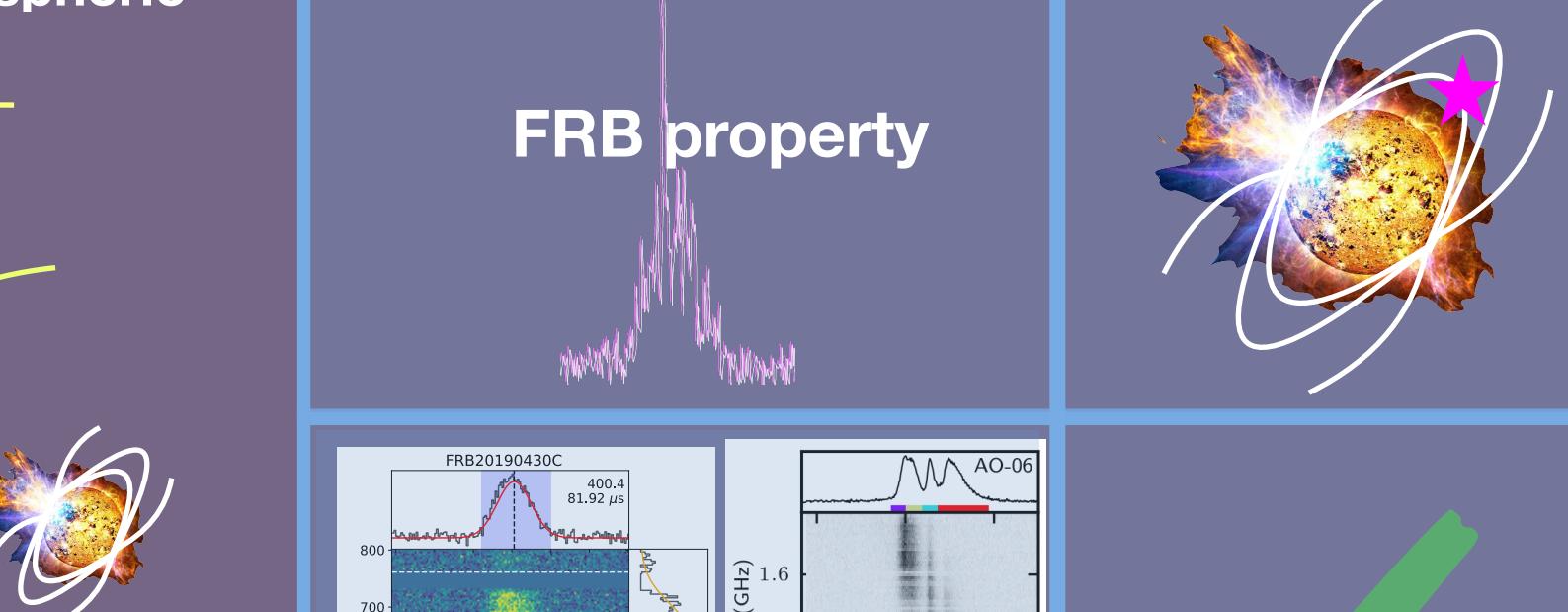
Non-magnetospheric



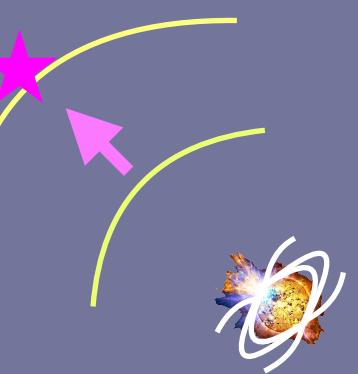
FRB property



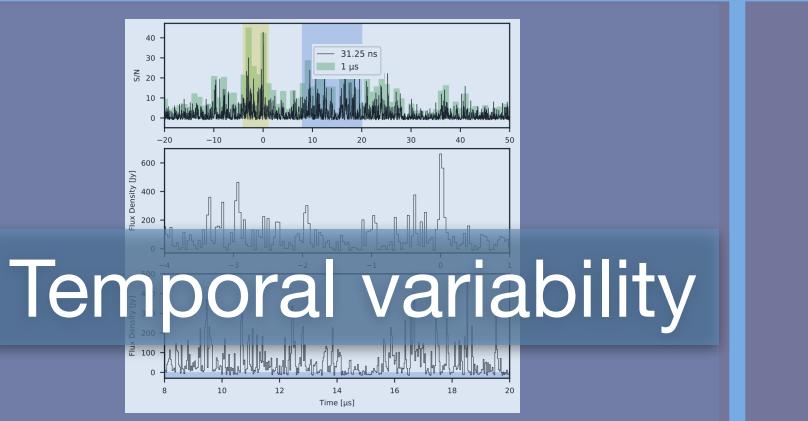
Magnetospheric



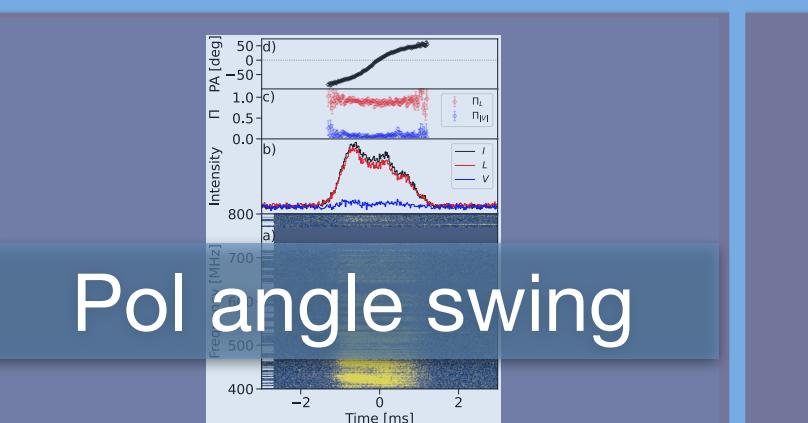
Non-magnetospheric



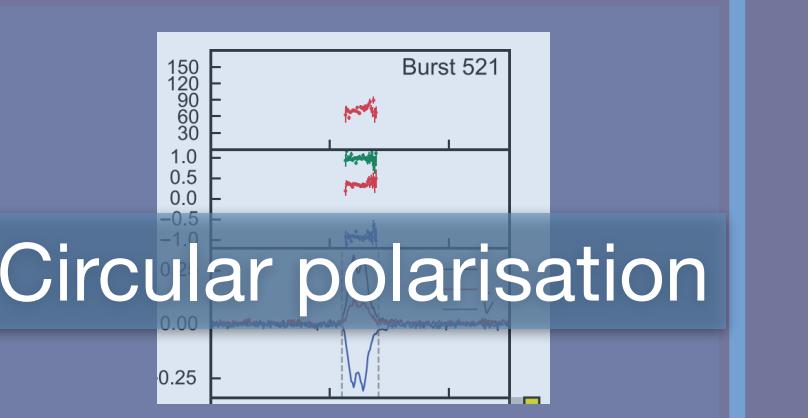
Metzger et al. 2022



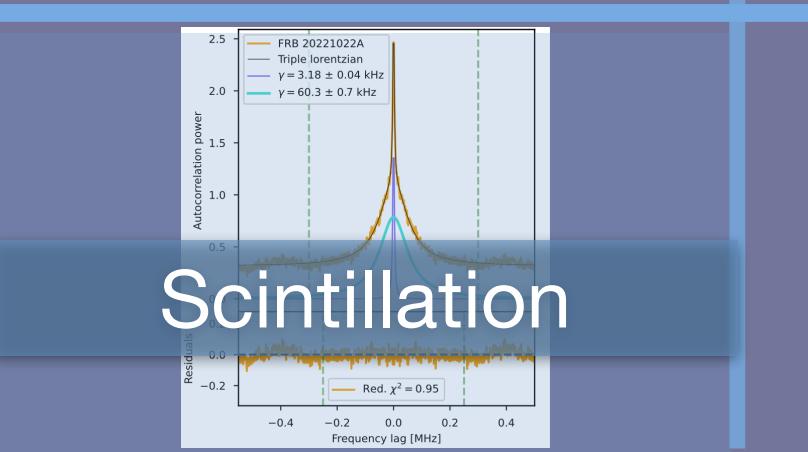
Sobacchi et al. 2021, 2024b



?

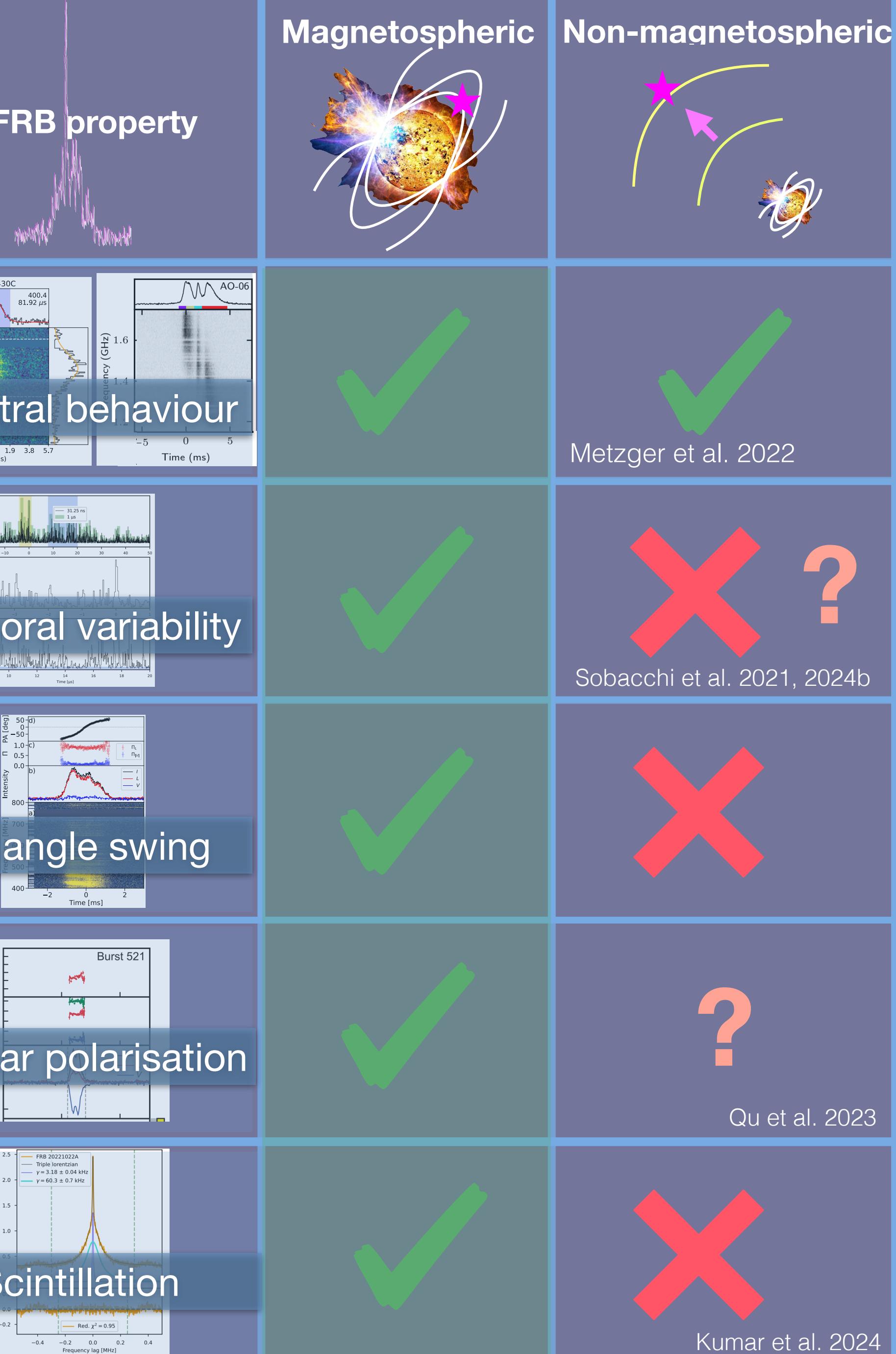


Qu et al. 2023

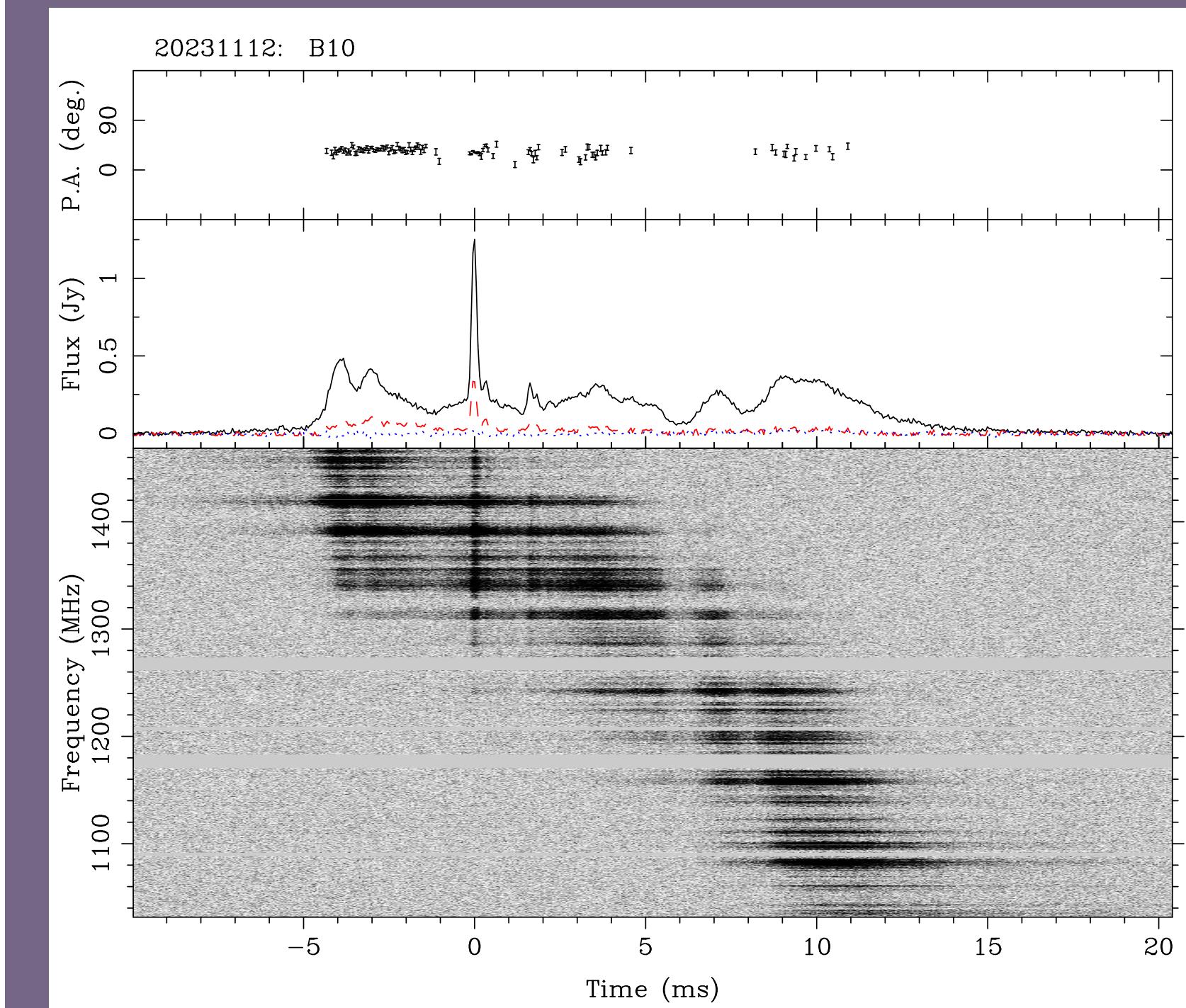
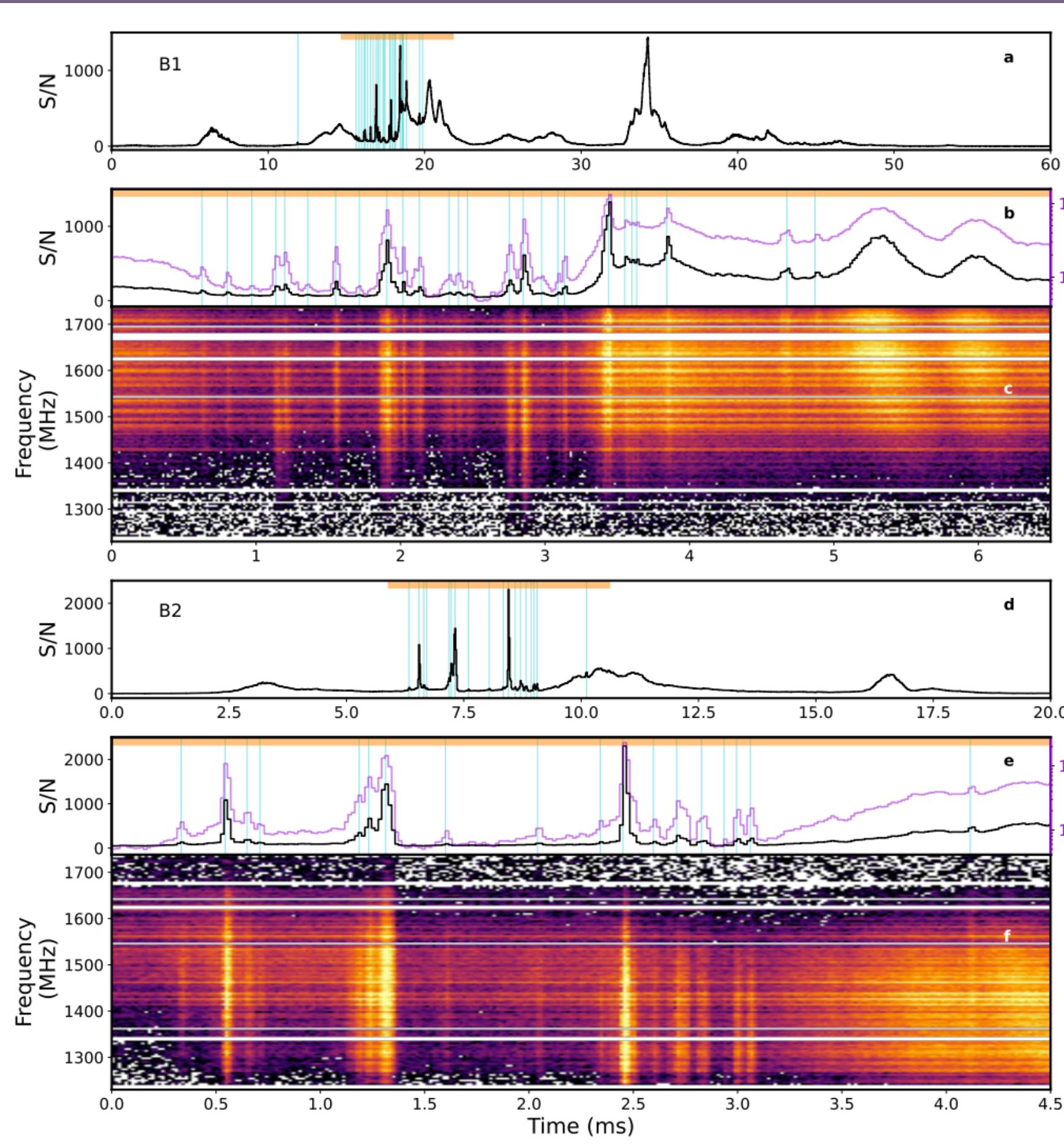


Kumar et al. 2024

# Growing support for magnetospheric models



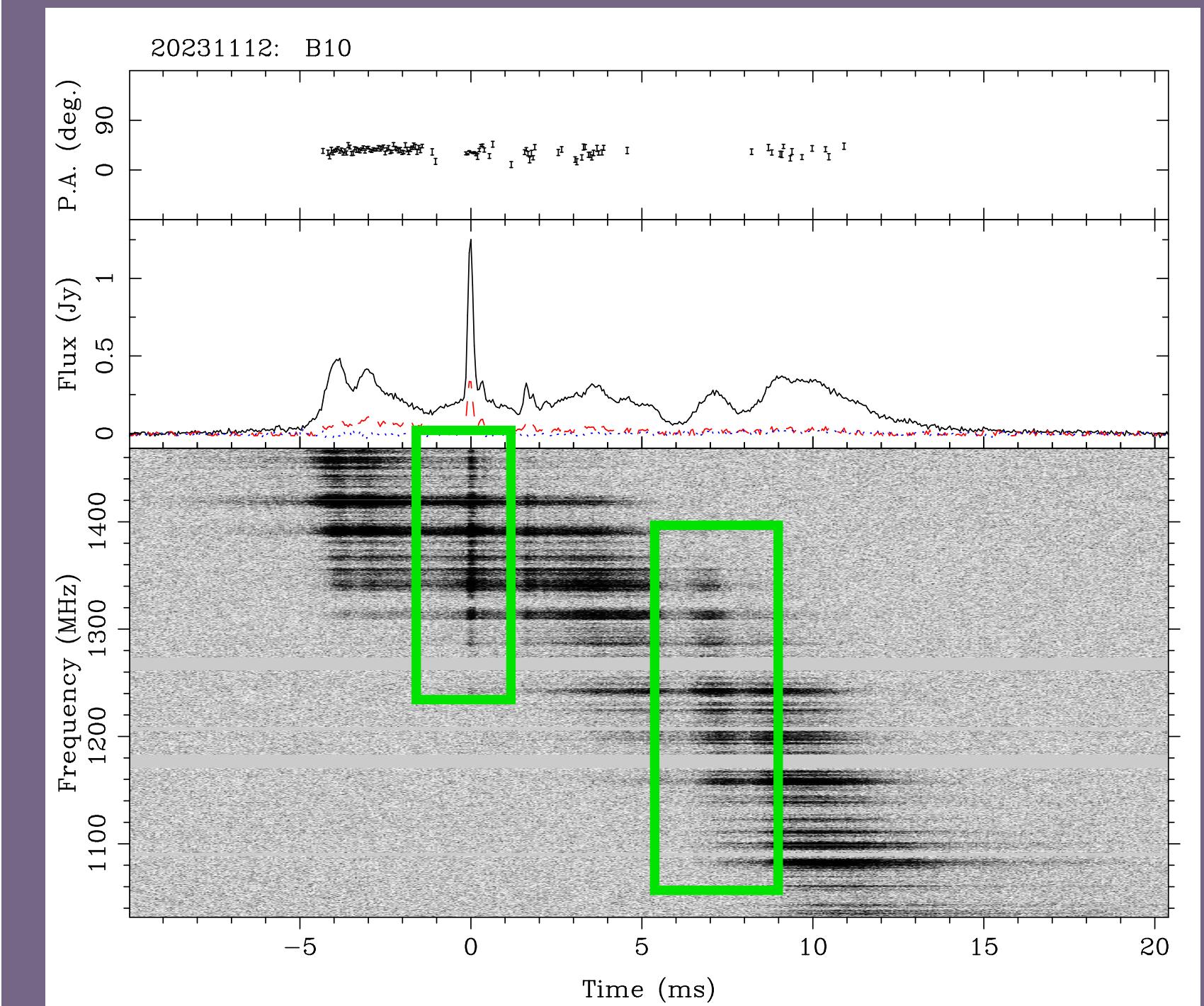
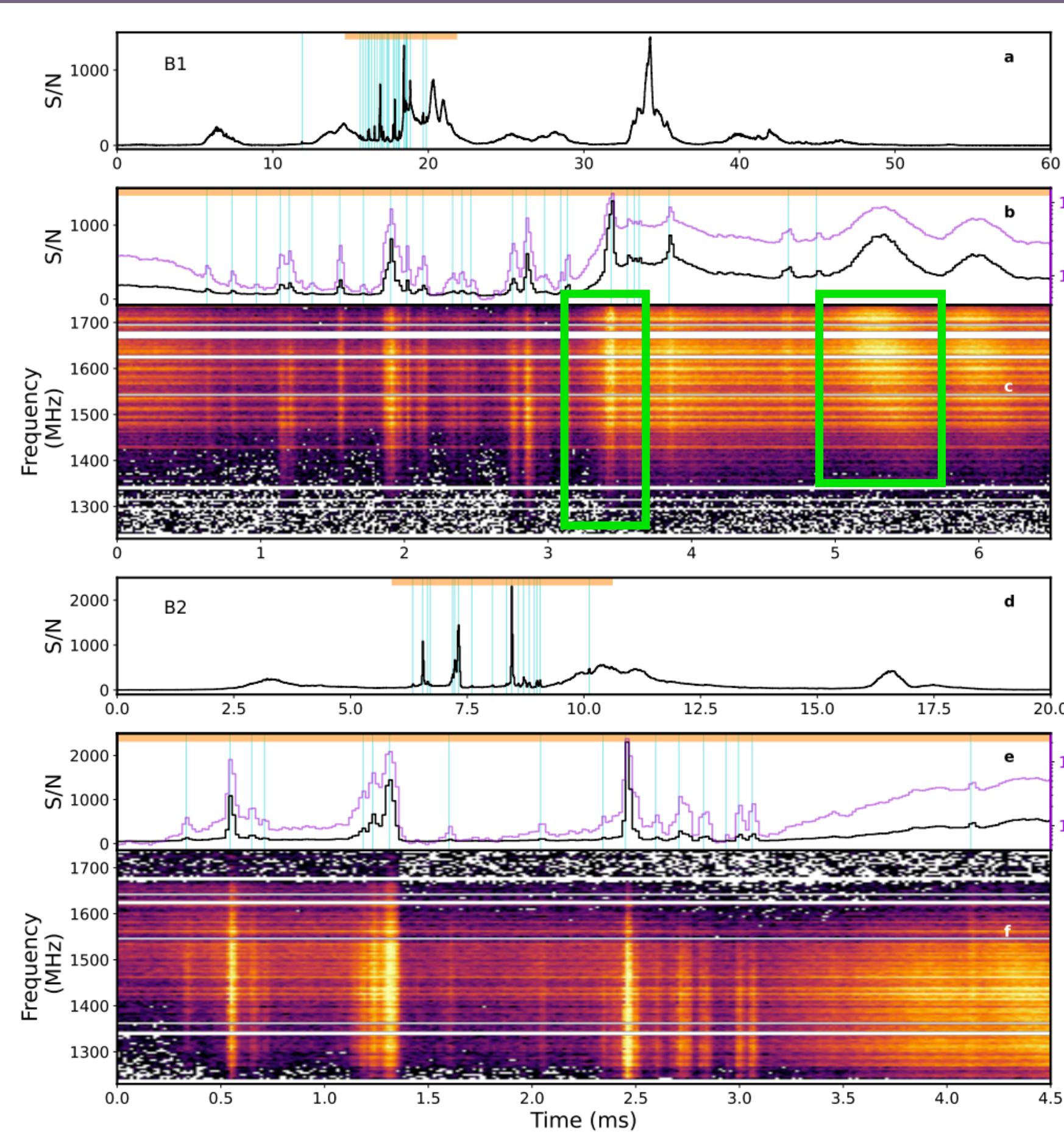
# Evidence for multiple emission processes?



Zhou et al. 2025

# Evidence for multiple emission processes?

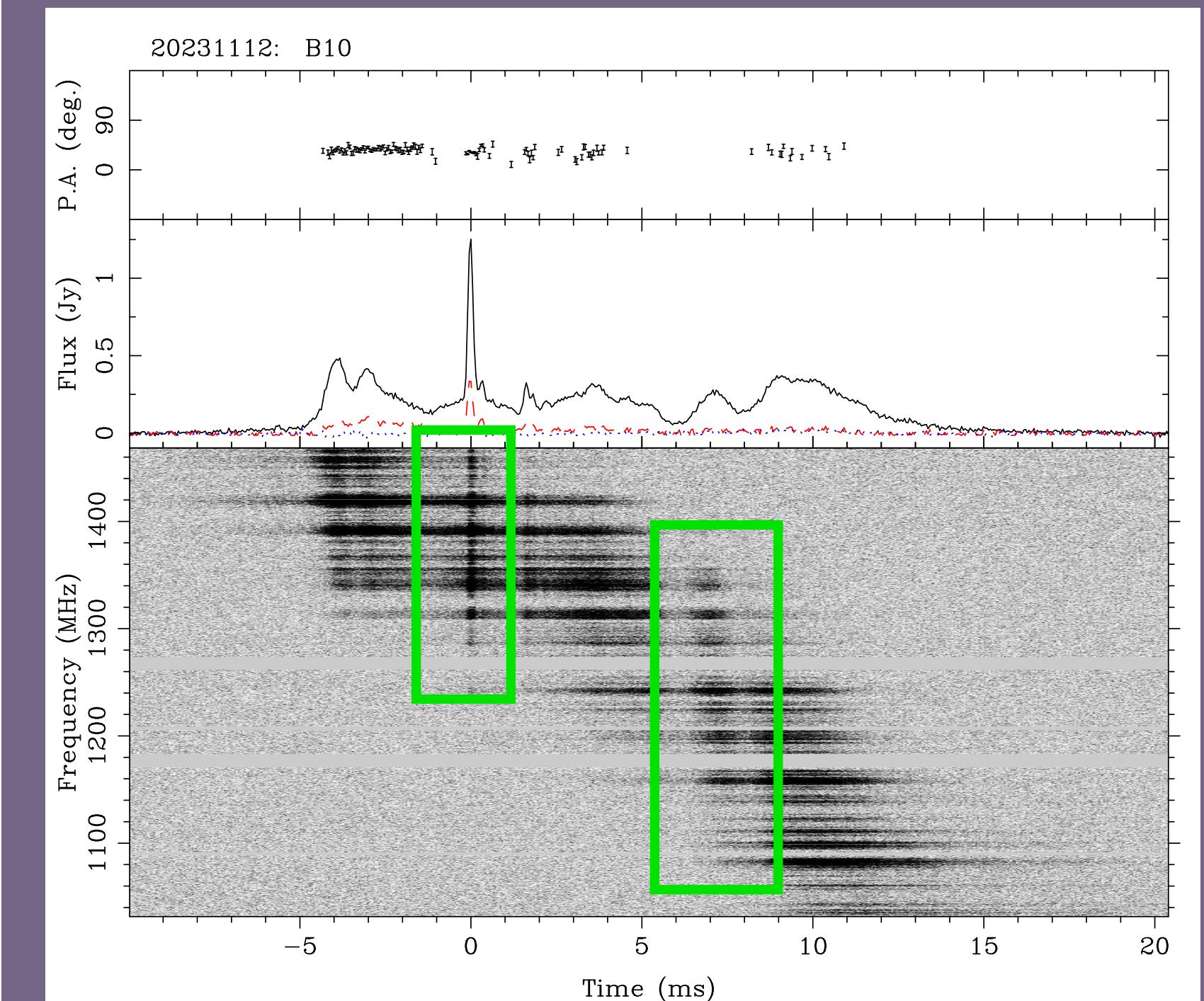
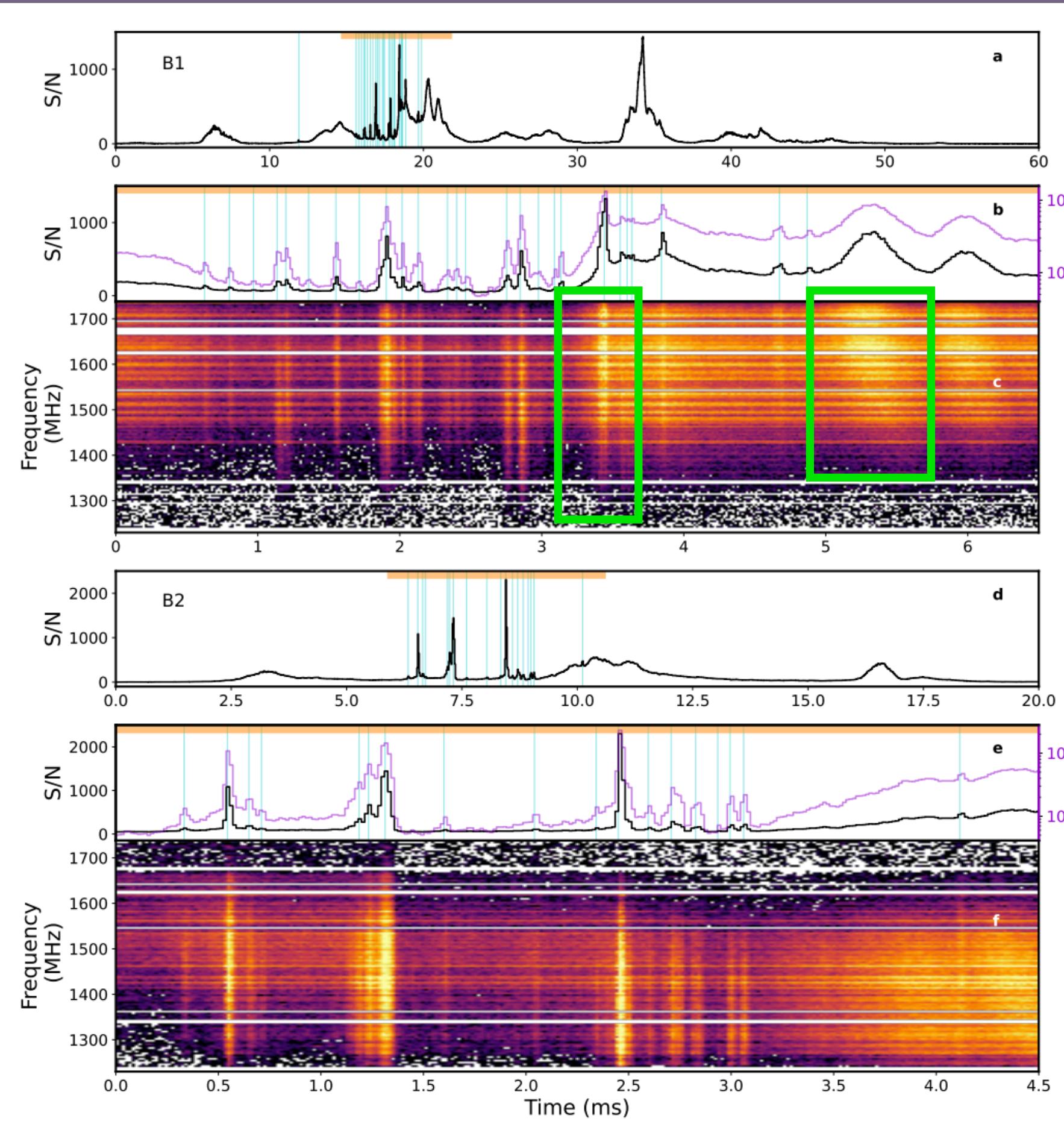
Changing DM? Changing drifting?



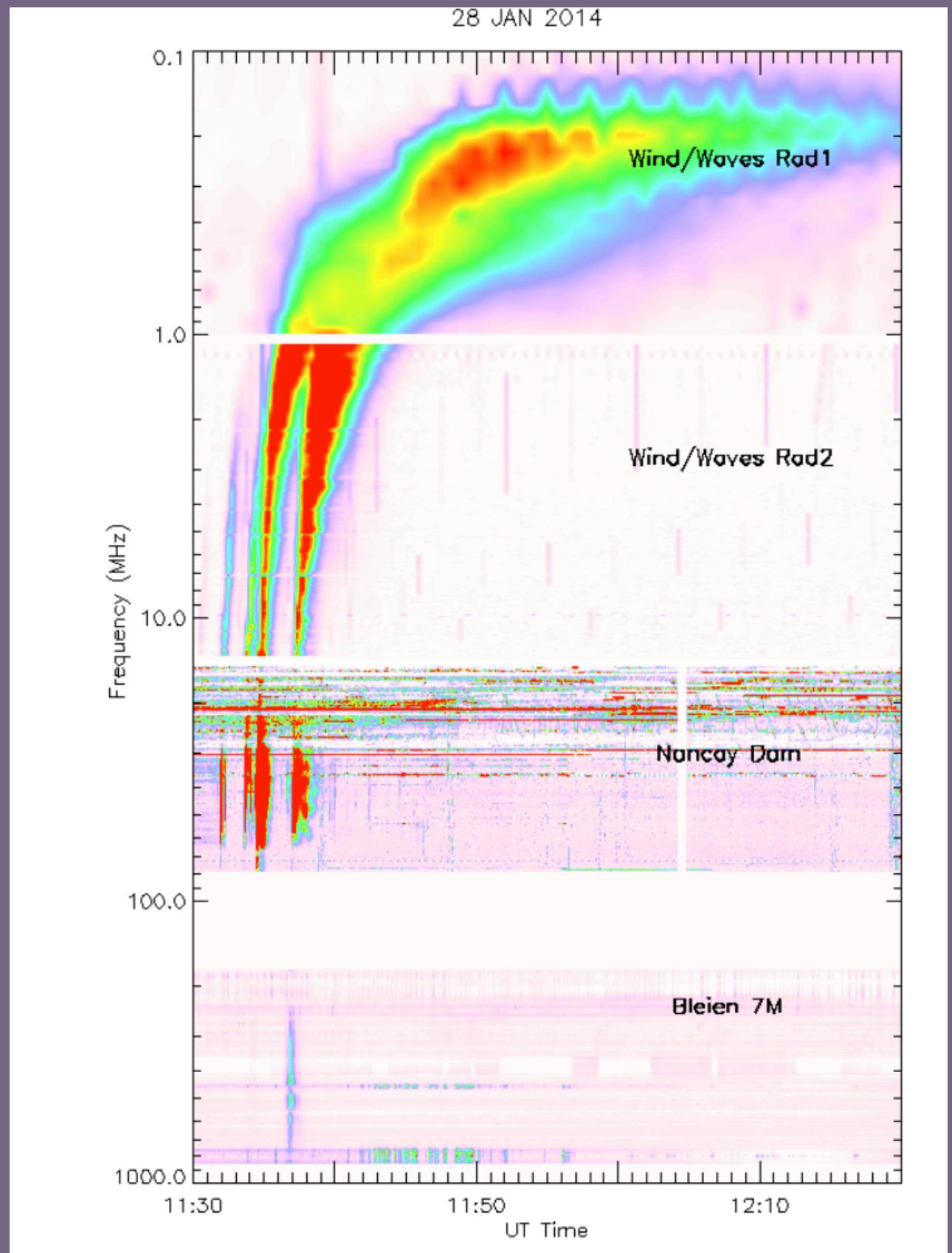
Zhou et al. 2025

# Evidence for multiple emission processes?

Changing DM? Changing drifting?

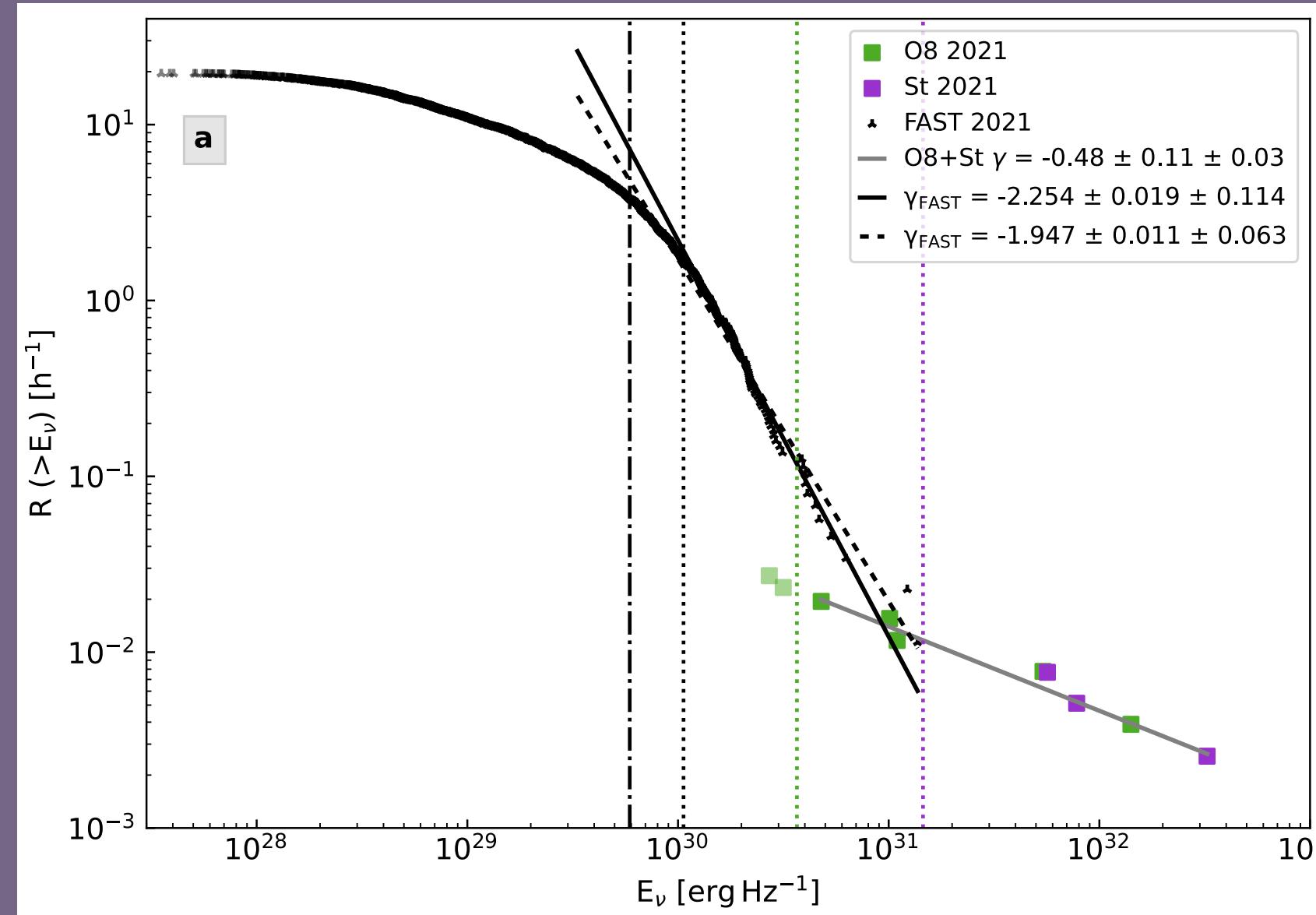


Zhou et al. 2025

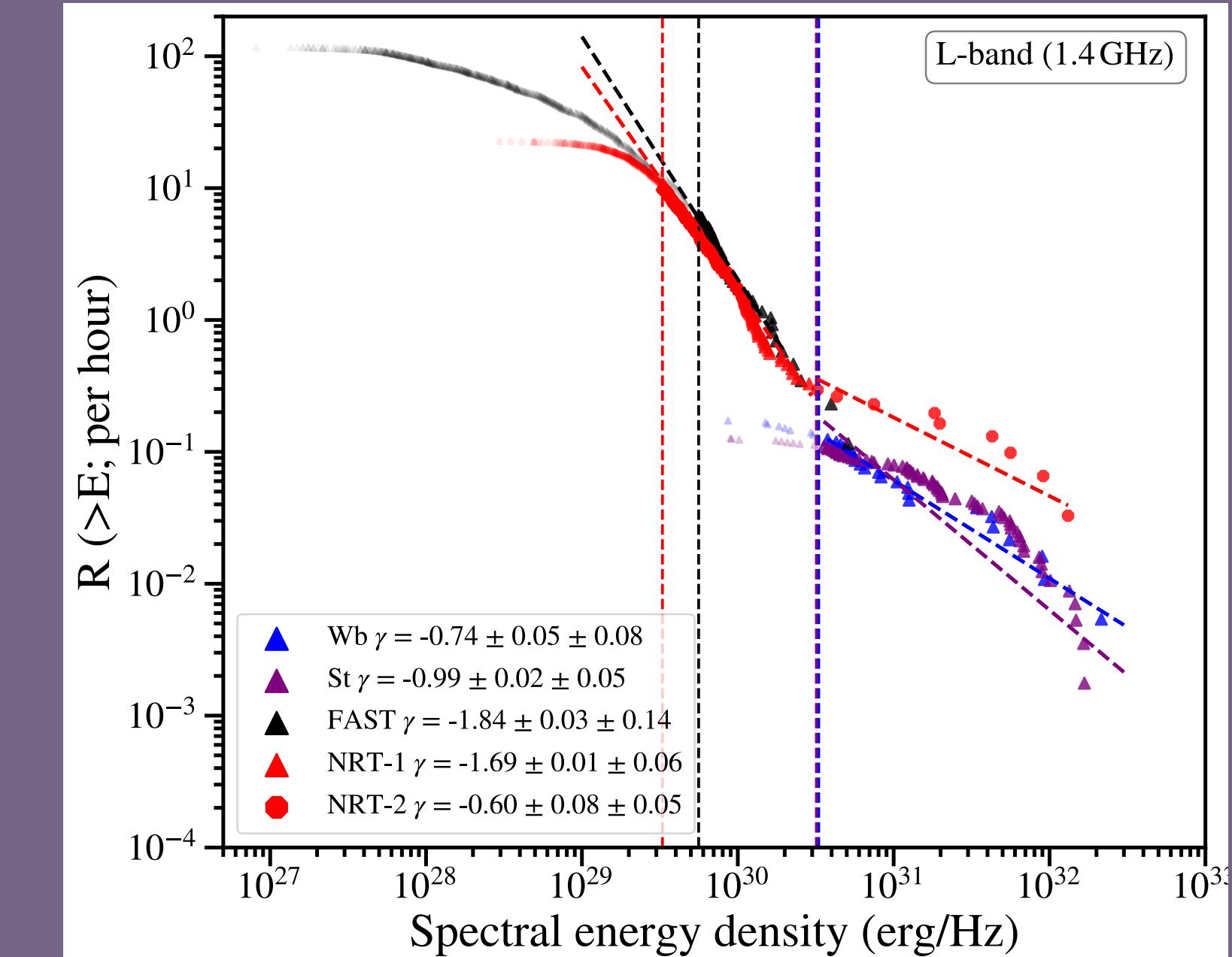


Hewitt et al. 2023

# Evidence for multiple emission processes?

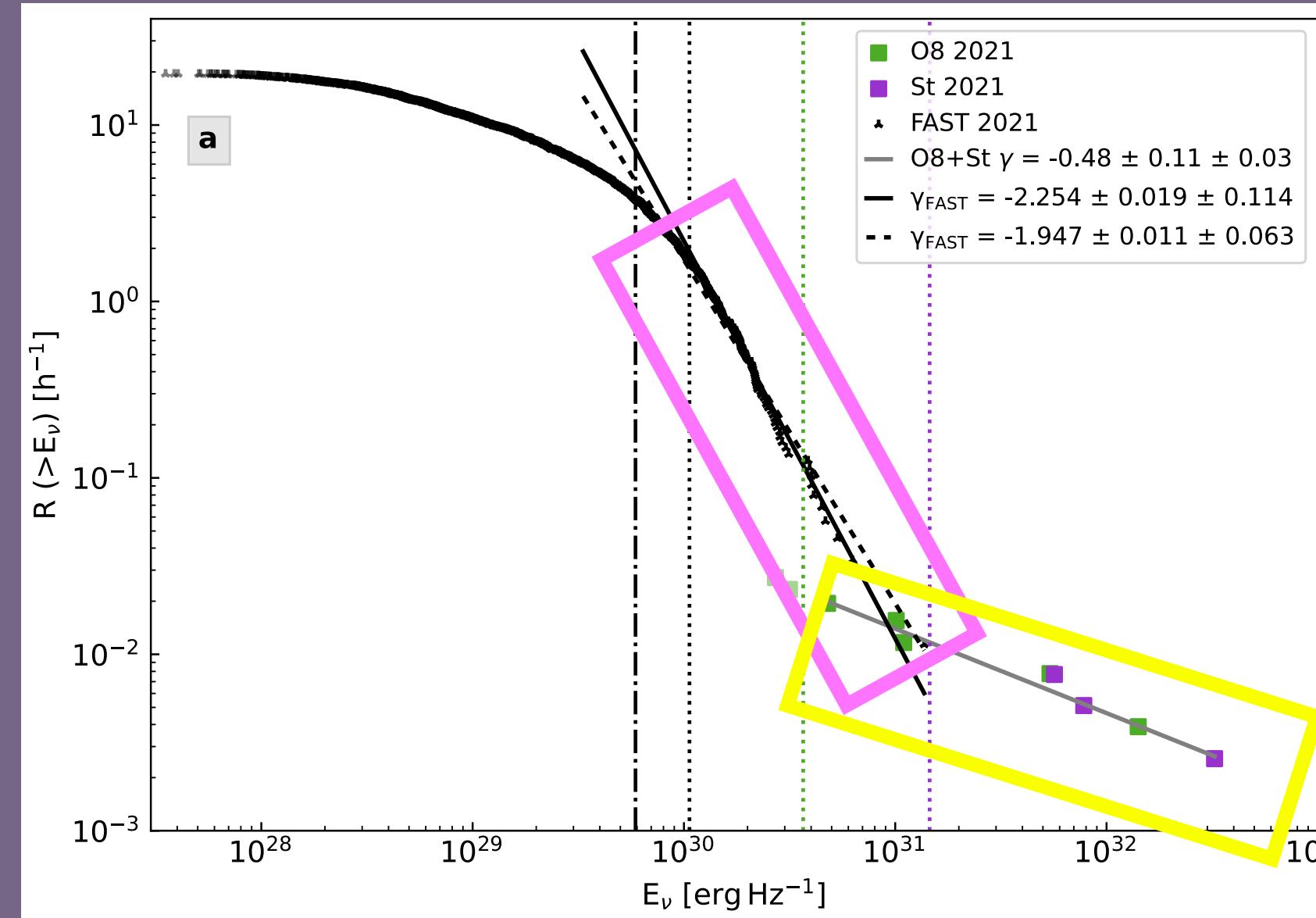


Kirsten et al. 2024

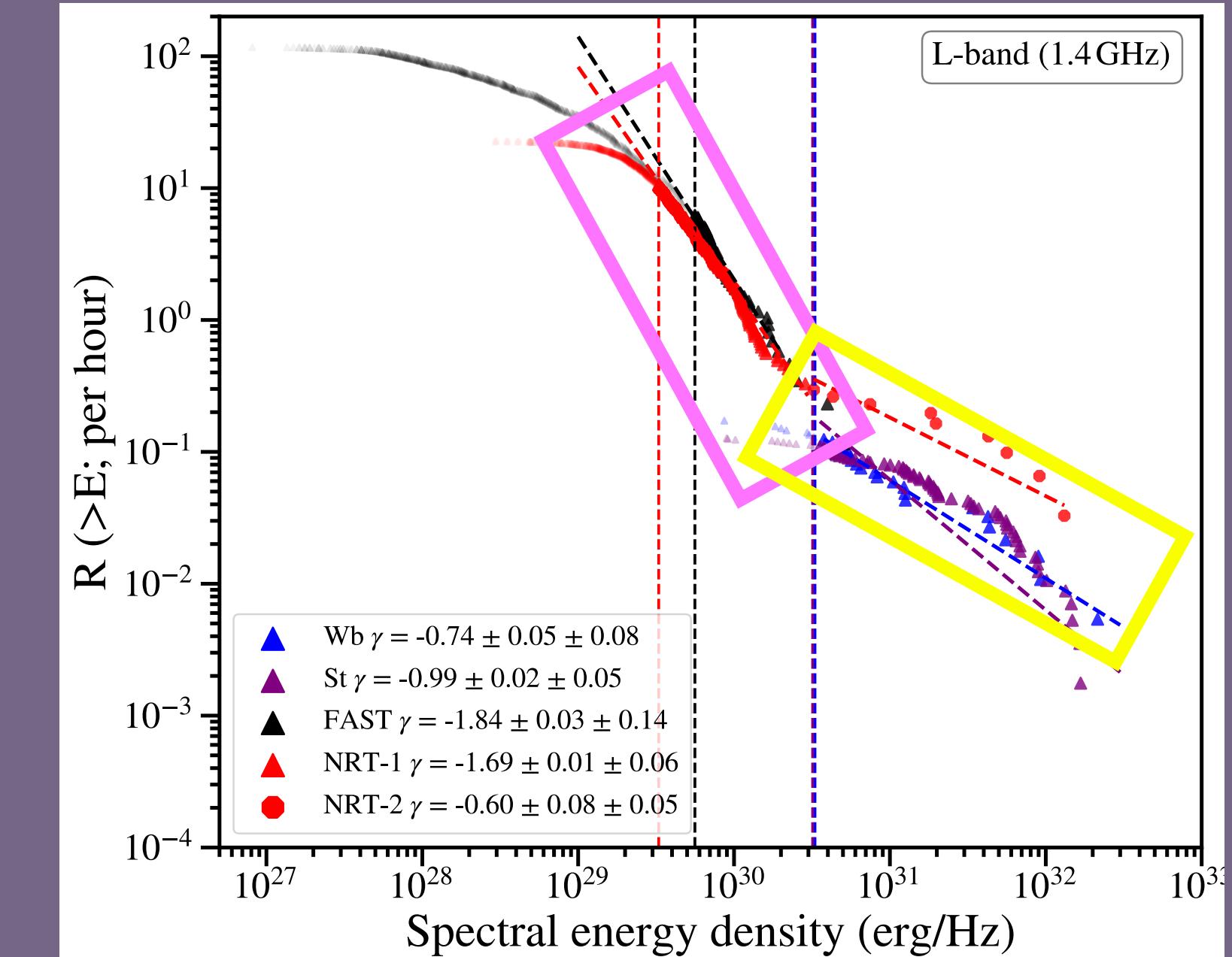


Ould-Boukattine et al. 2024

# Evidence for multiple emission processes?



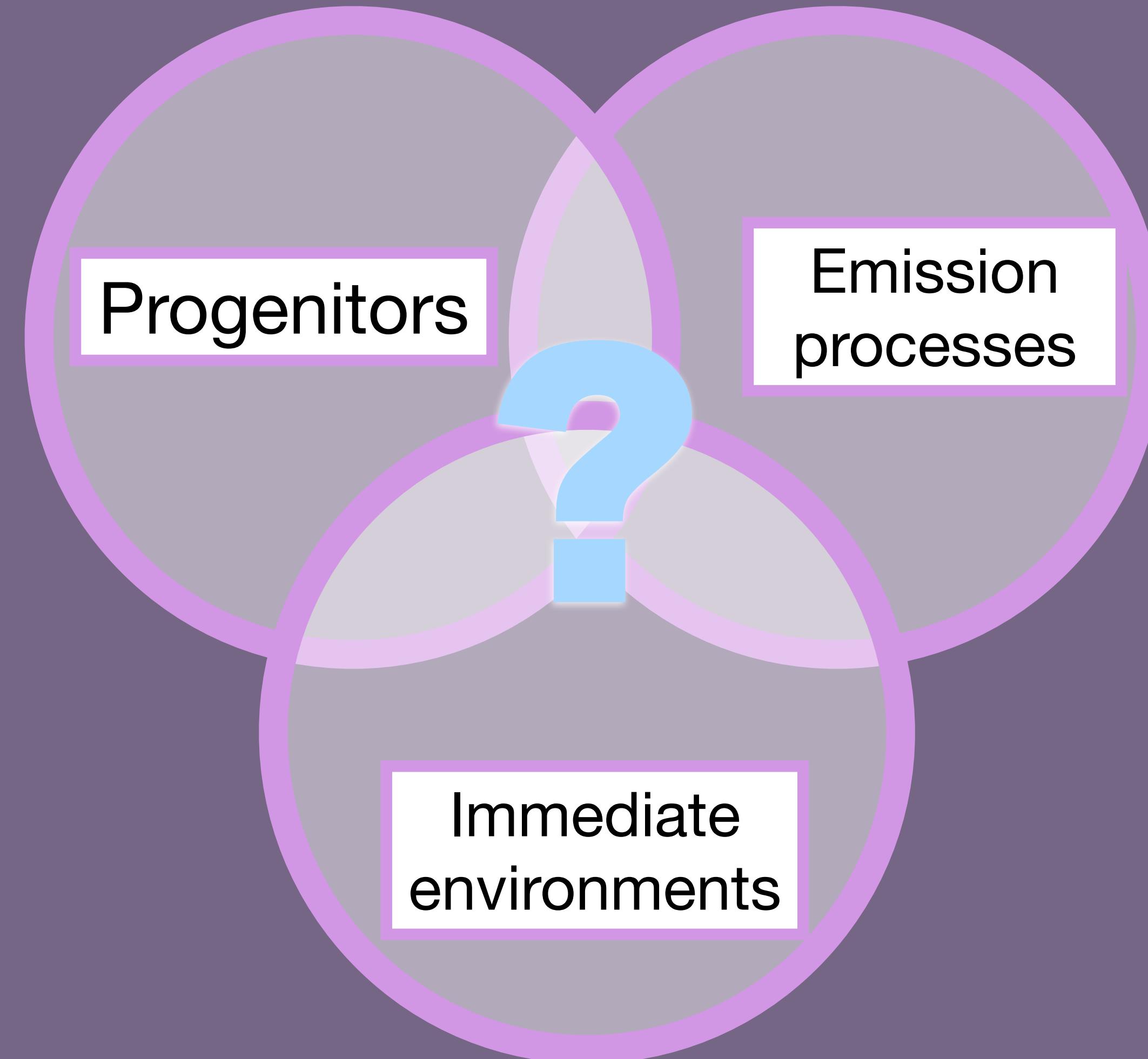
Kirsten et al. 2024



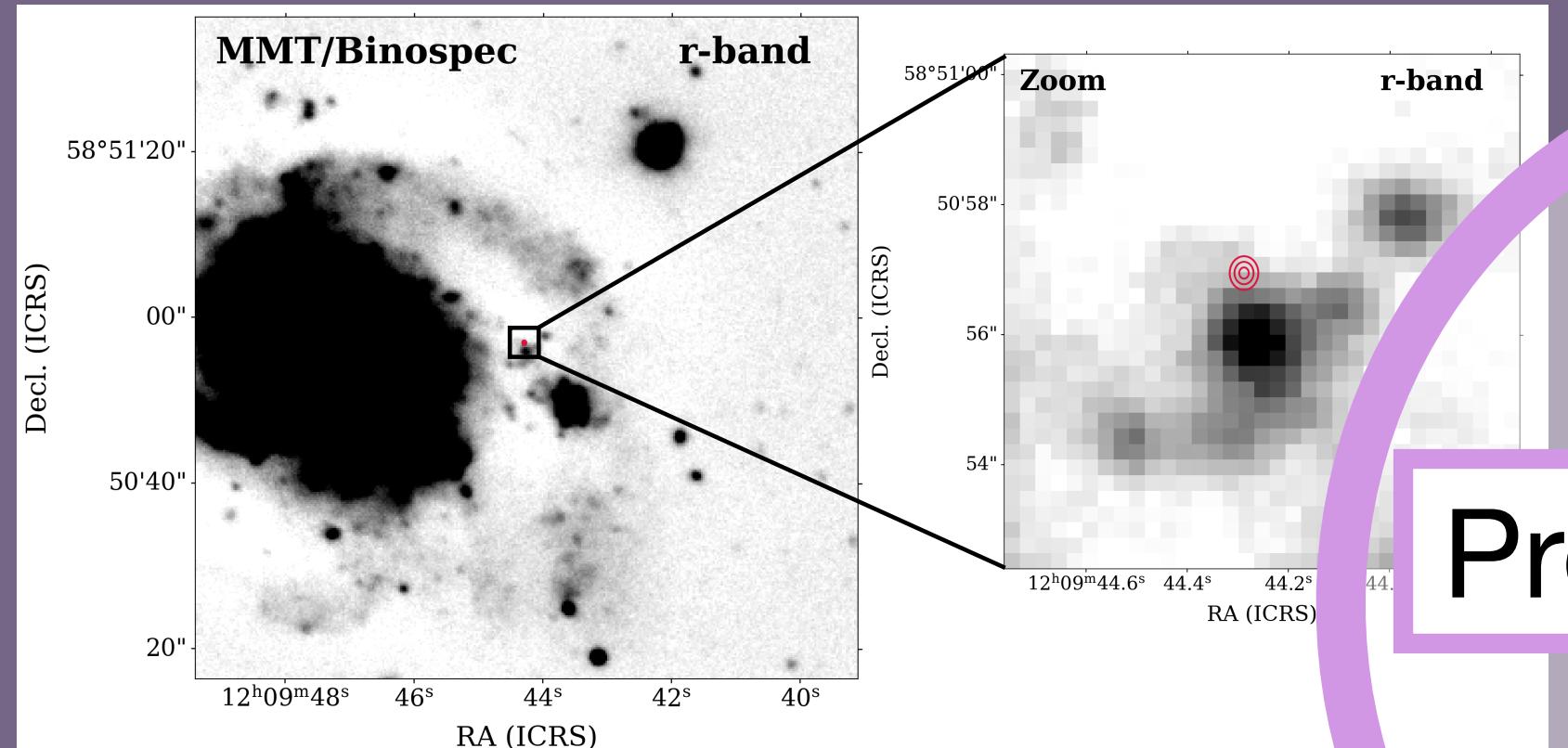
Ould-Boukattine et al. 2024

Is the emission physics for the *low energy bursts* the same as those in the *high energy tail*?

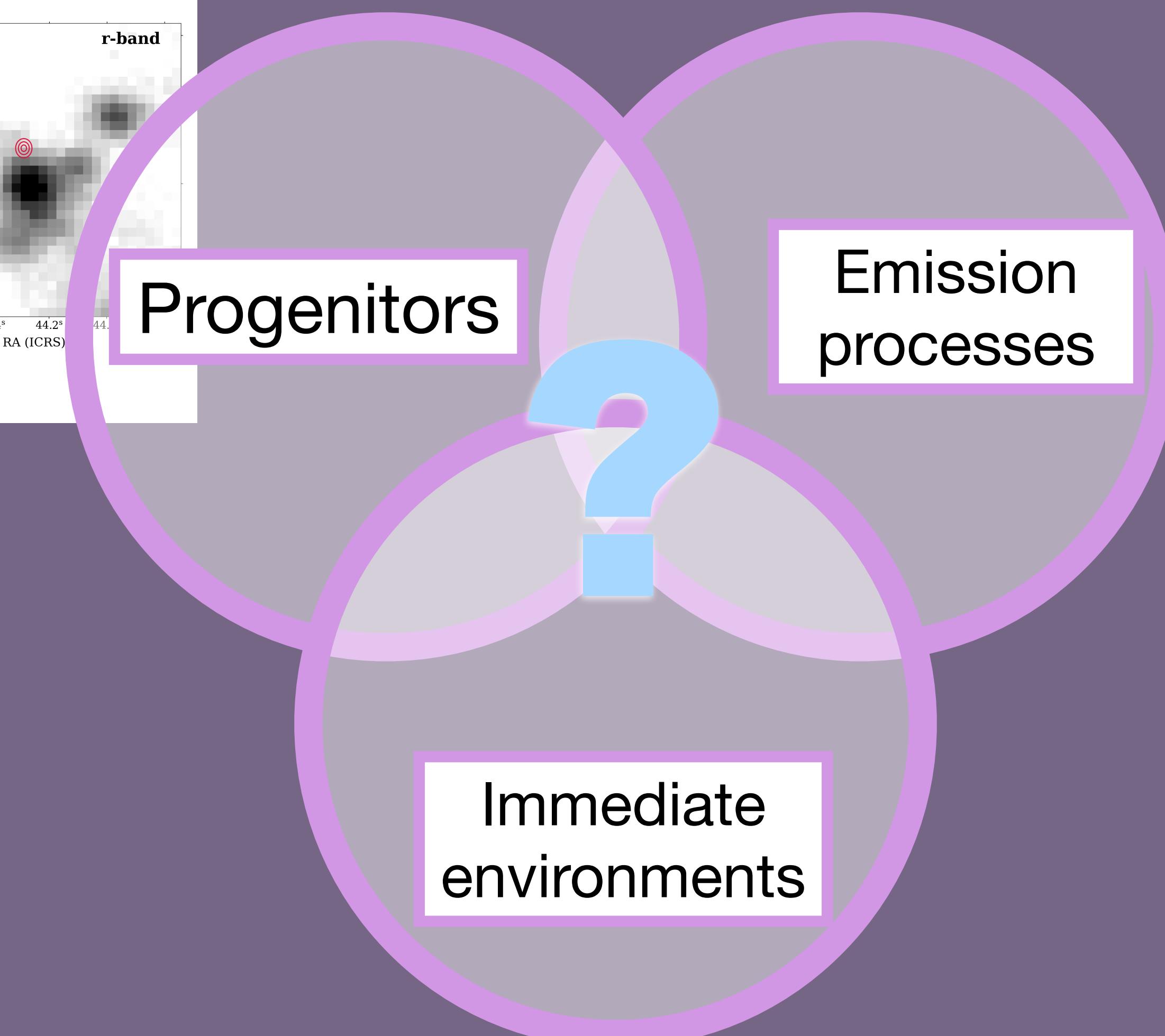
# Summary



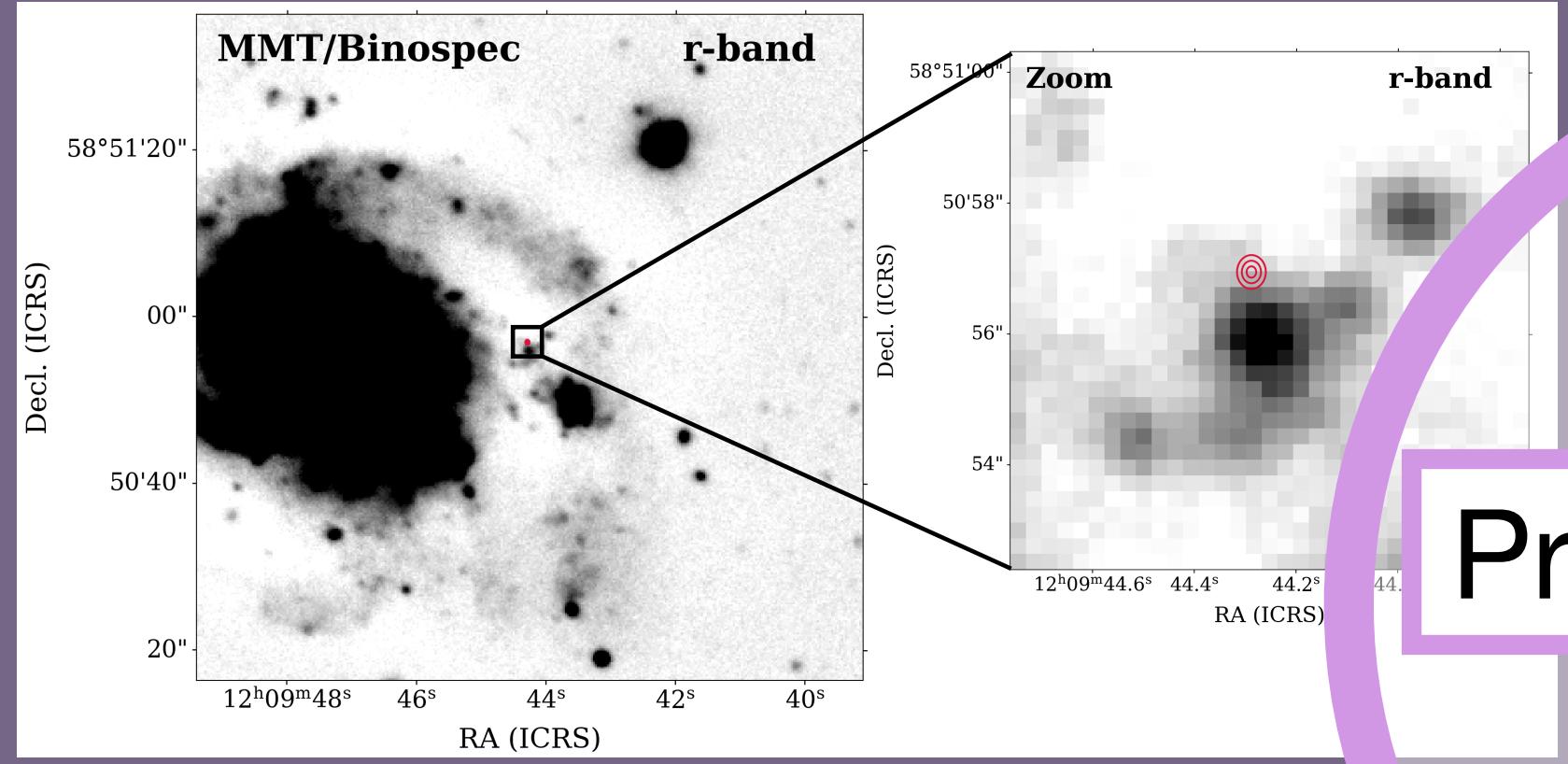
# Summary



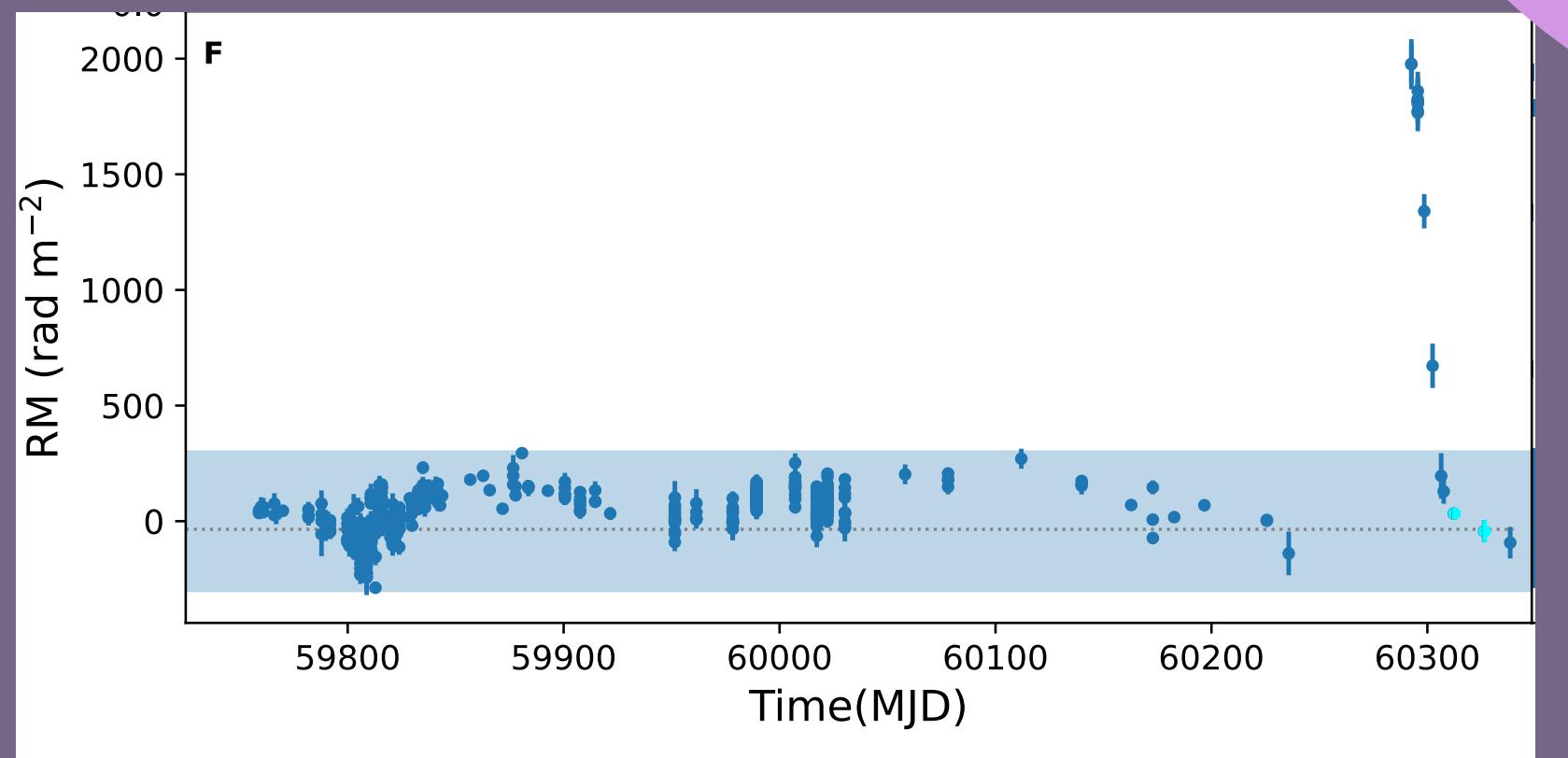
CHIME/FRB Collab. et al. 2025



# Summary



CHIME/FRB Collab. et al. 2025



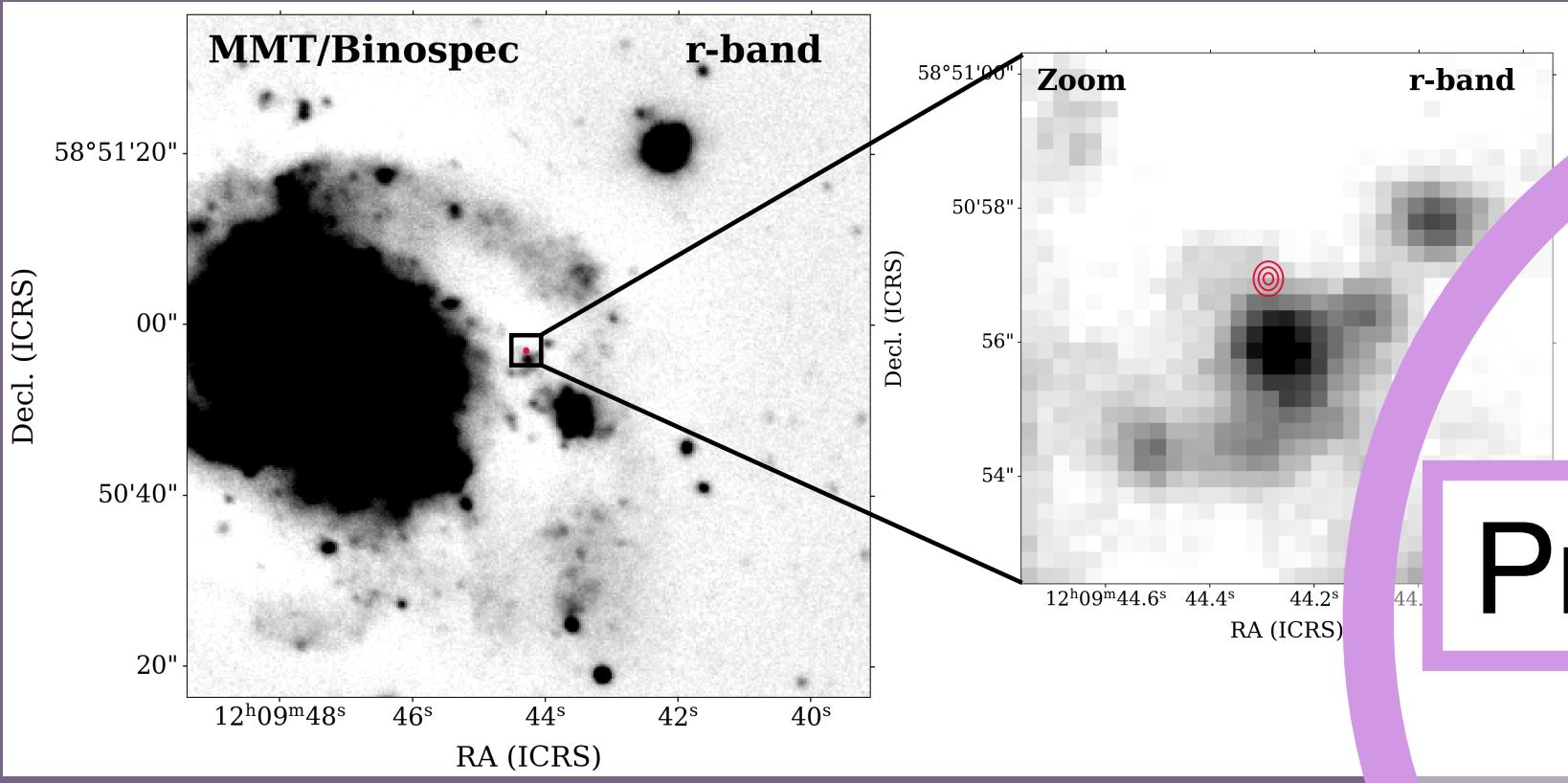
Li et al. 2025

# Progenitors

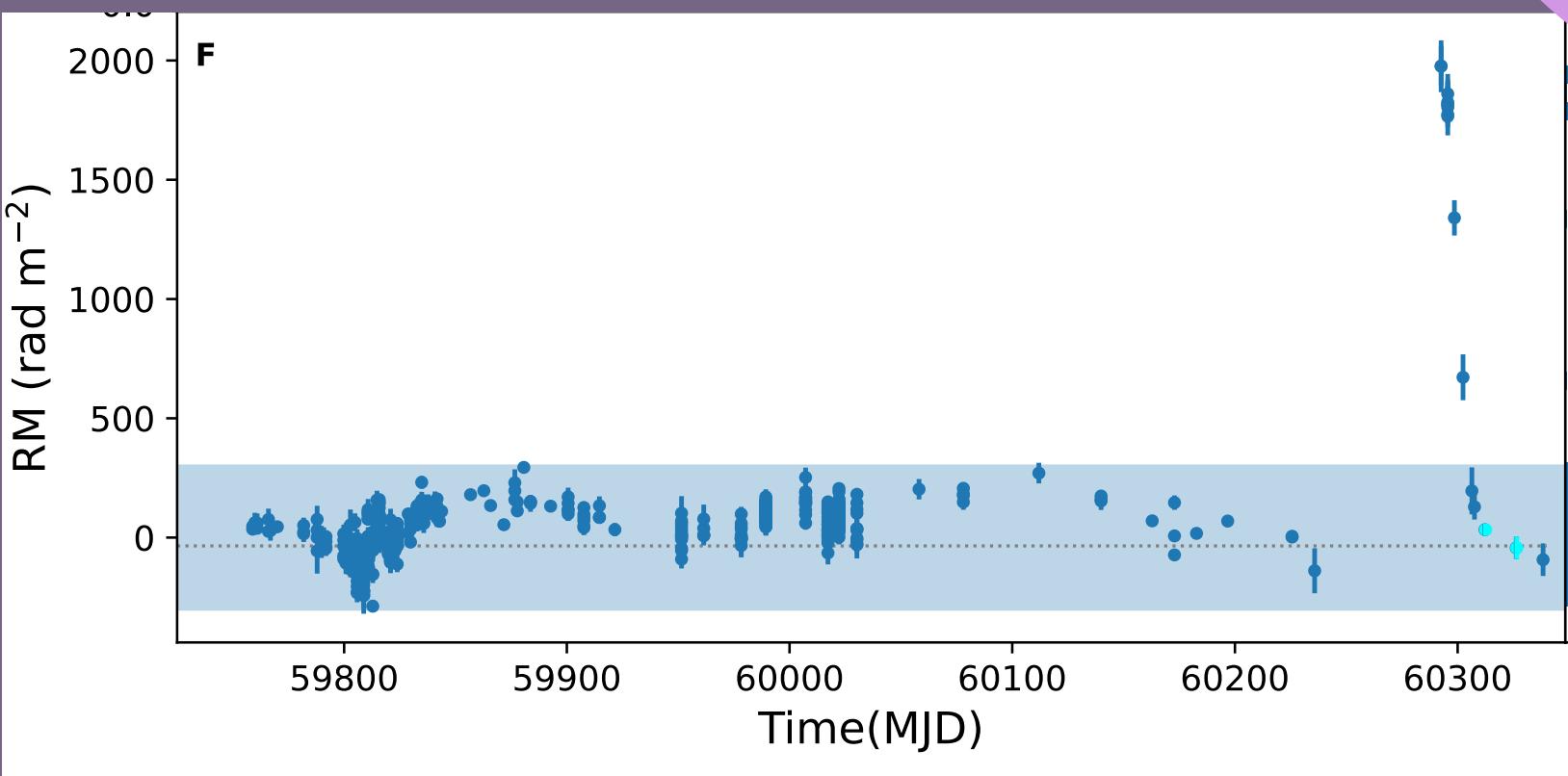
# Emission processes

# Immediate environments

# Summary



CHIME/FRB Collab. et al. 2025



Li et al. 2025

Progenitors

Emission processes

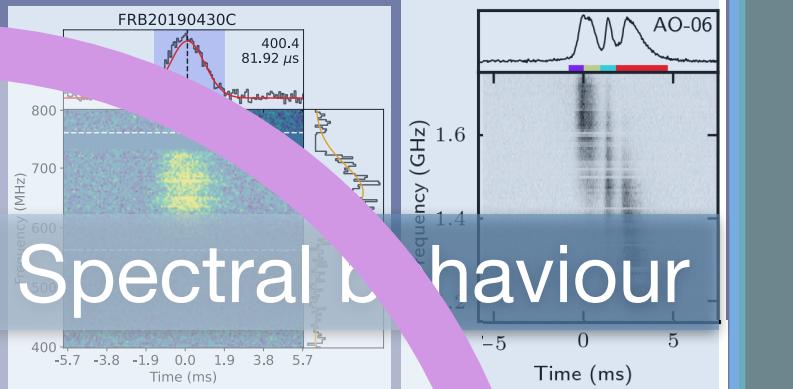
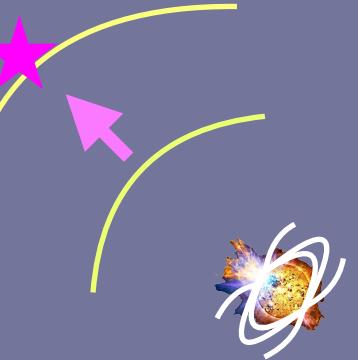
Immediate environments

FRB property

Magnetospheric



Non-magnetospheric



Spectral behaviour

Reliability

Parangle swing

Circular polarisation

Scintillation

