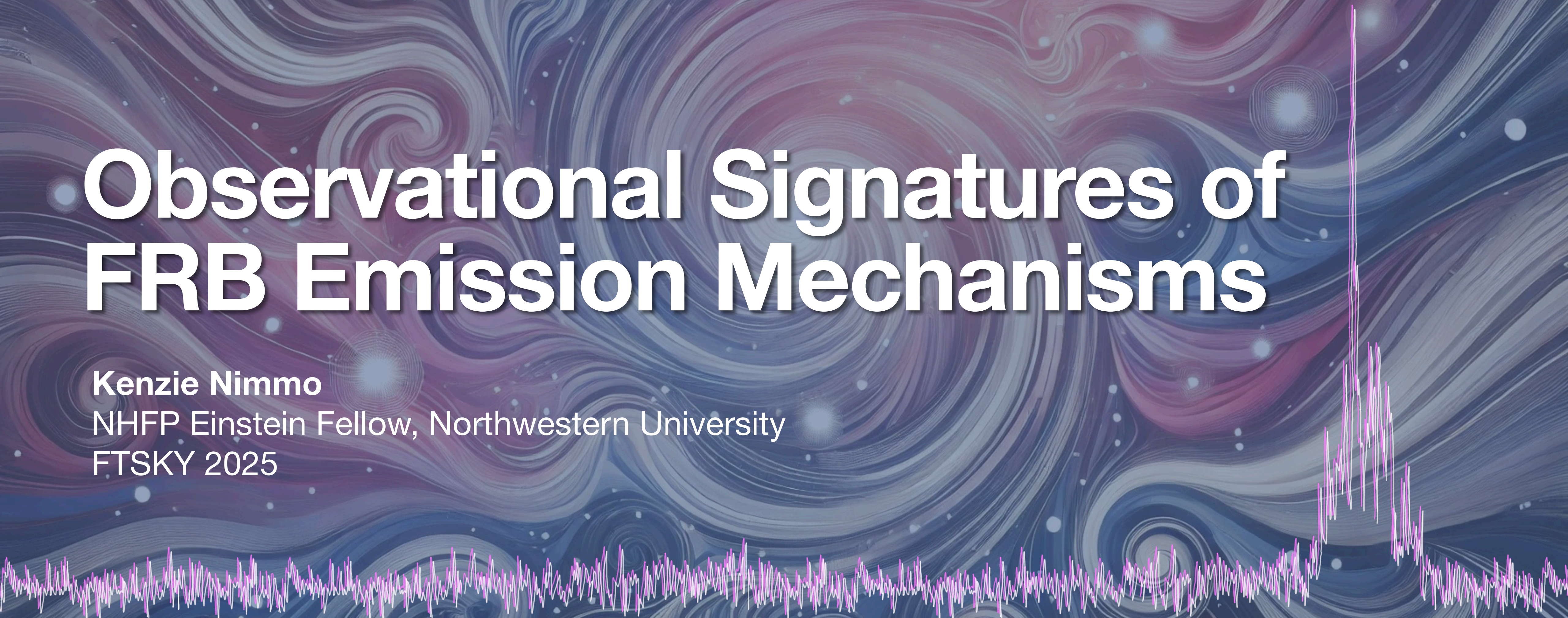


Observational Signatures of FRB Emission Mechanisms

Kenzie Nimmo

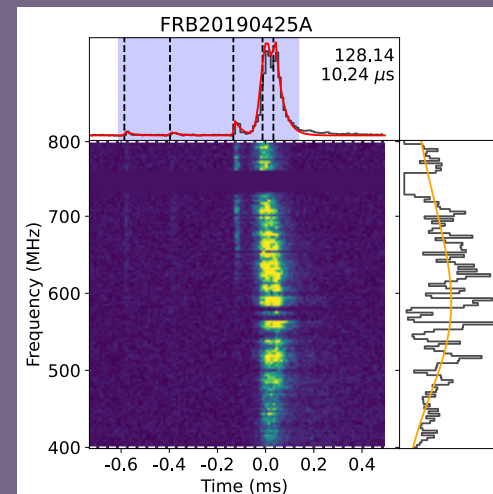
NHFP Einstein Fellow, Northwestern University

FTSKY 2025



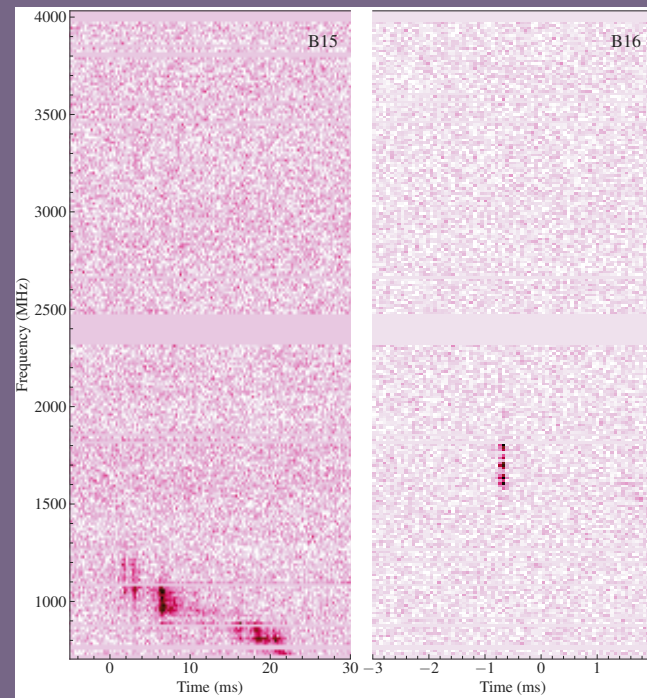
Diversity of radio properties

Broadband



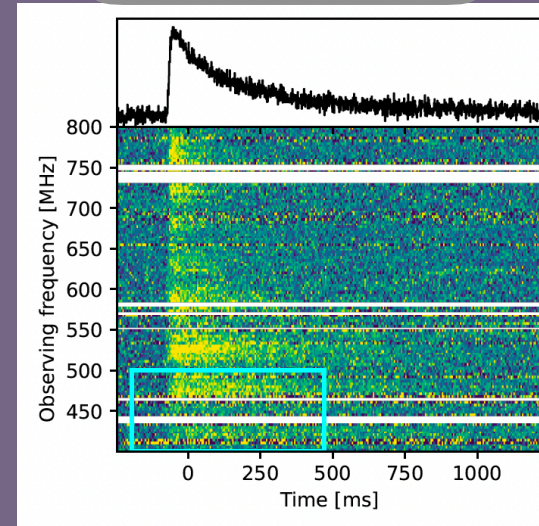
Sand et al. 2025

Narrowband



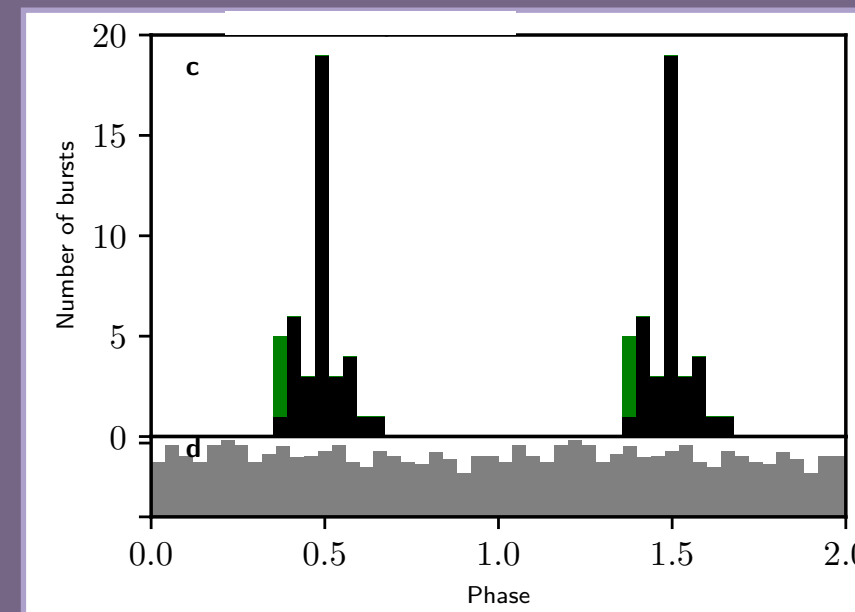
Kumar et al. 2023

Scattered



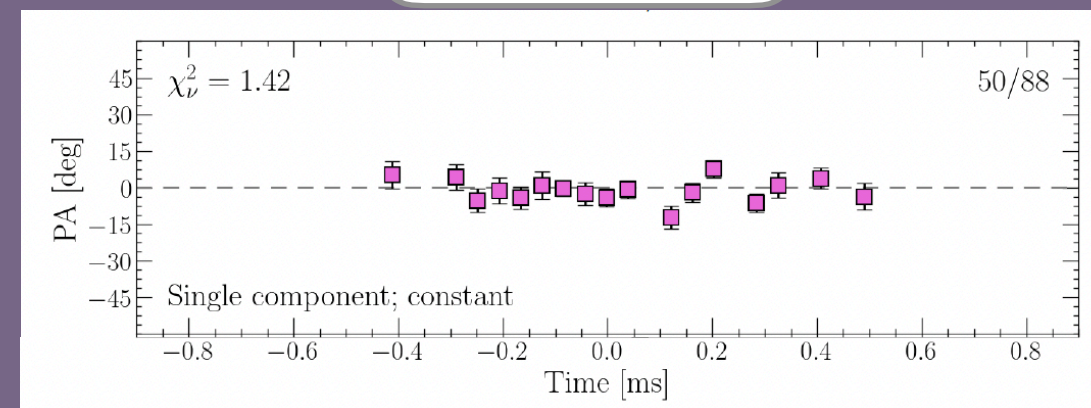
Shin et al. 2024

Periodic



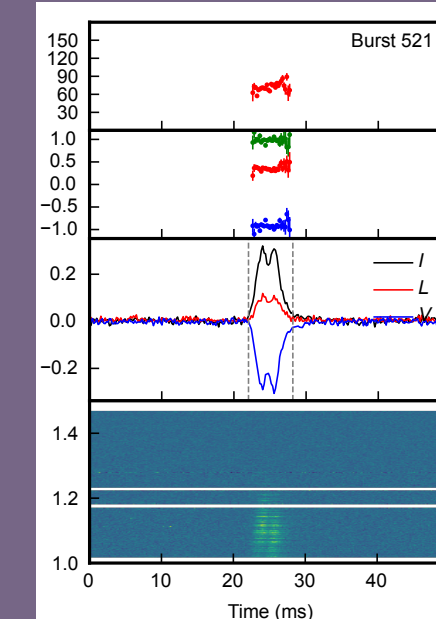
CHIME/FRB Collab. 2020

Flat PA



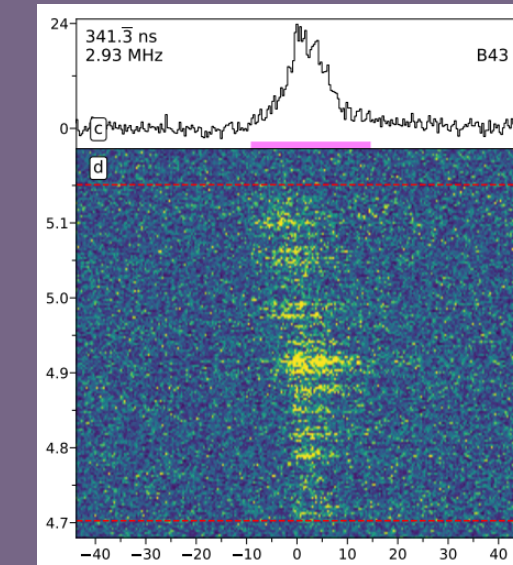
Pandhi et al. 2024

Circularly polarized



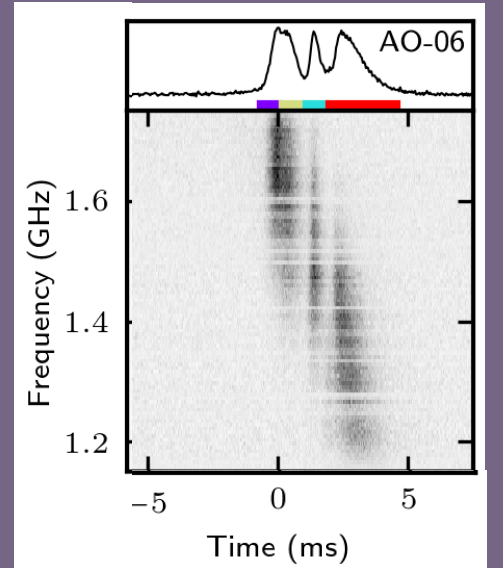
Jiang et al. 2024

Ultra-fast



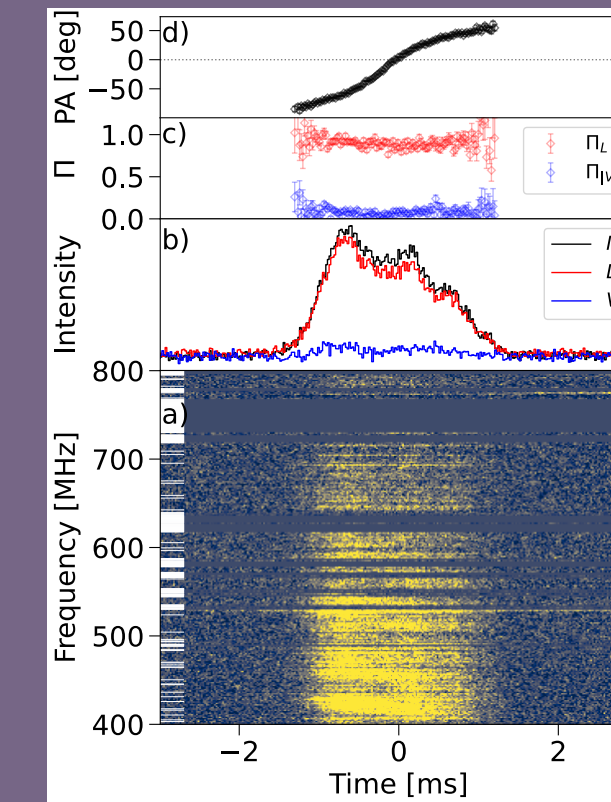
Snelders et al. 2023

Sad-trombone



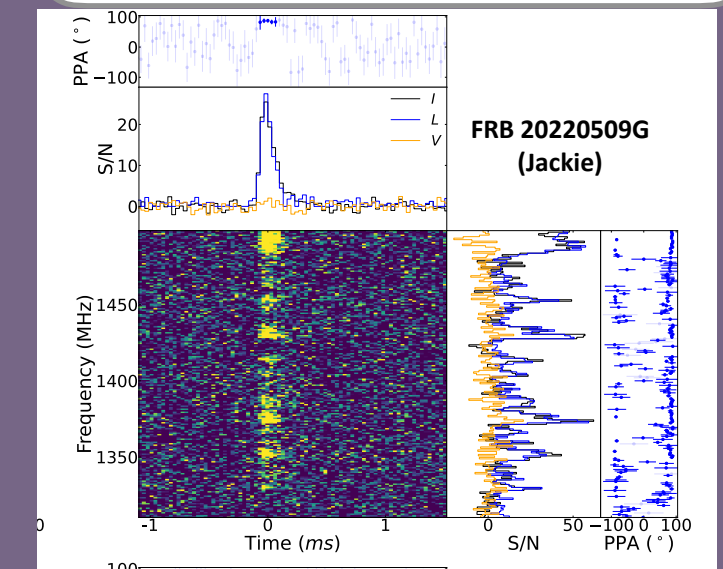
Hessels et al. 2019

PA swing



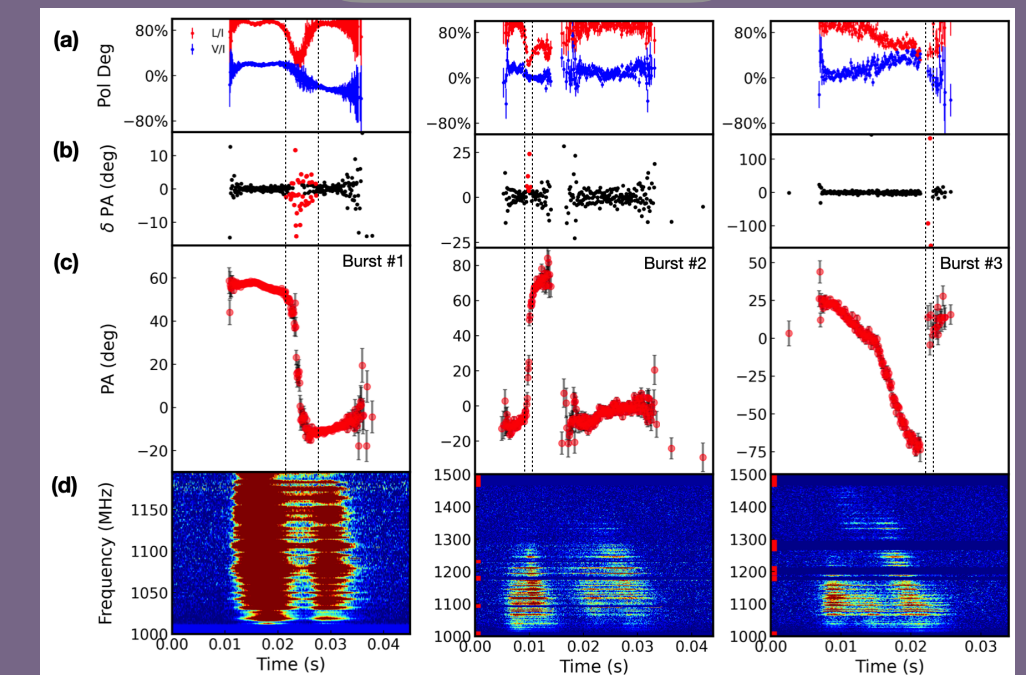
Mckinven et al. 2025

Linearly polarized



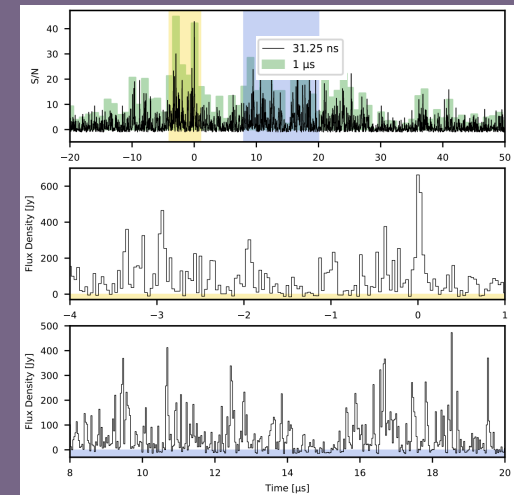
Sherman et al. 2024

PA jumps



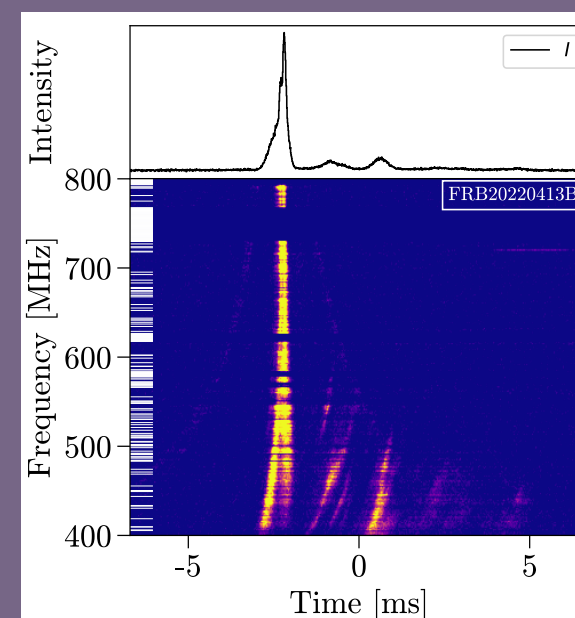
Niu et al. 2024

Temporal variability



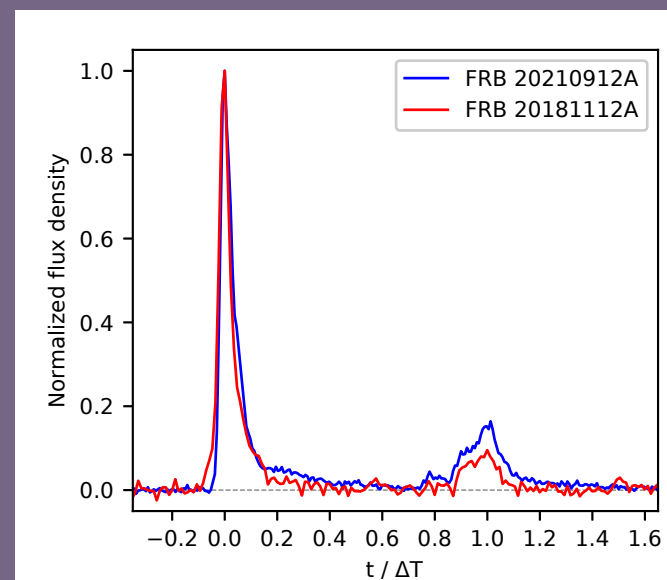
Nimmo et al. 2022

Complex variability



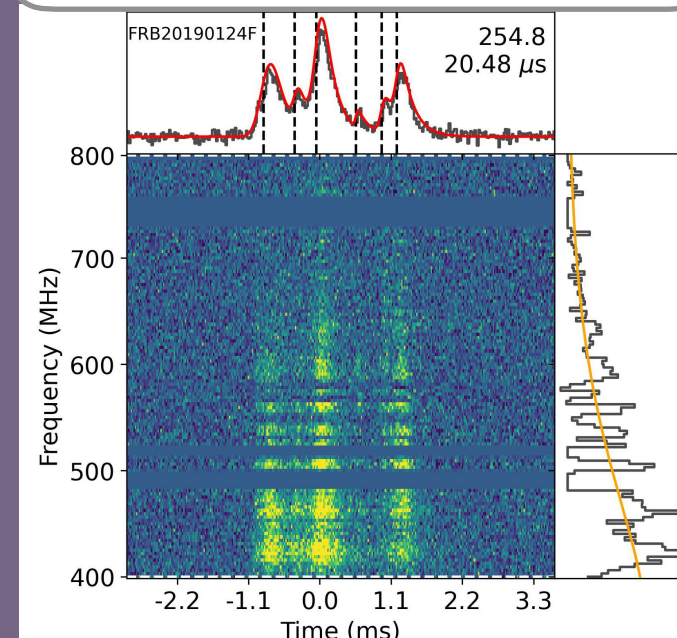
Faber et al. 2024

Twins



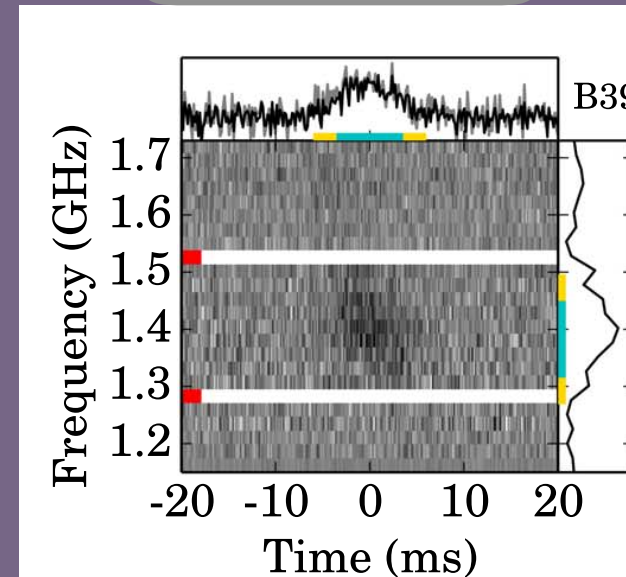
Bera et al. 2024

Multi-component



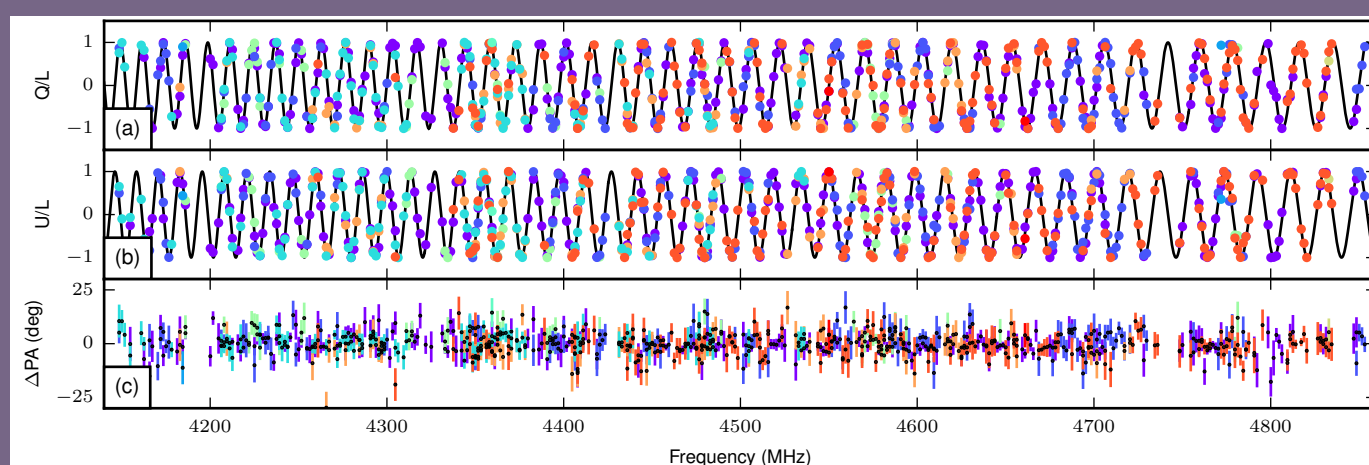
Sand et al. 2025

Smudgy



Gourdji et al. 2019

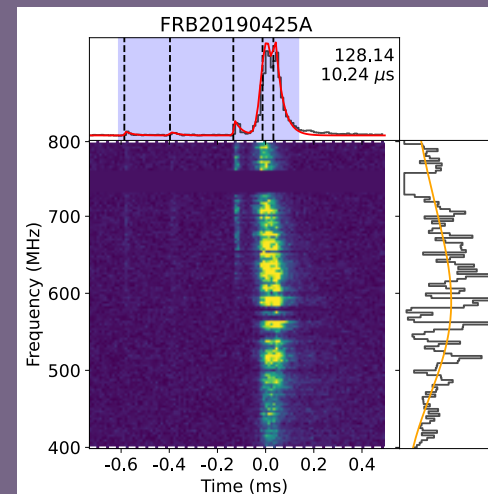
High RM



Michilli et al. 2018

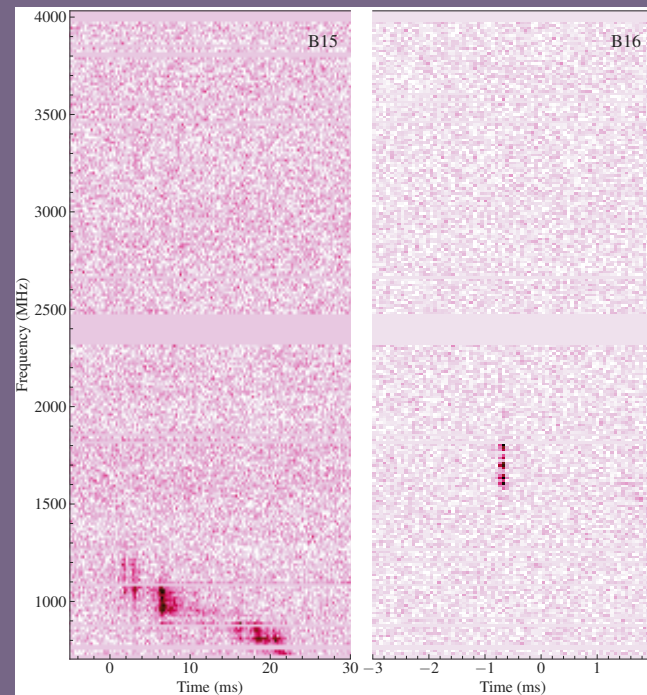
Diversity of radio properties

Broadband



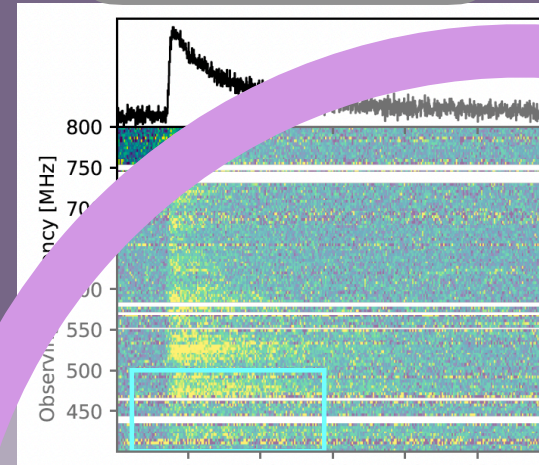
Sand et al. 2025

Narrowband

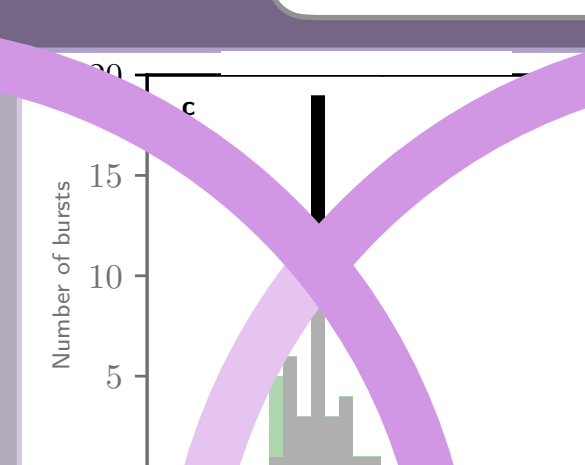


Kumar et al. 2023

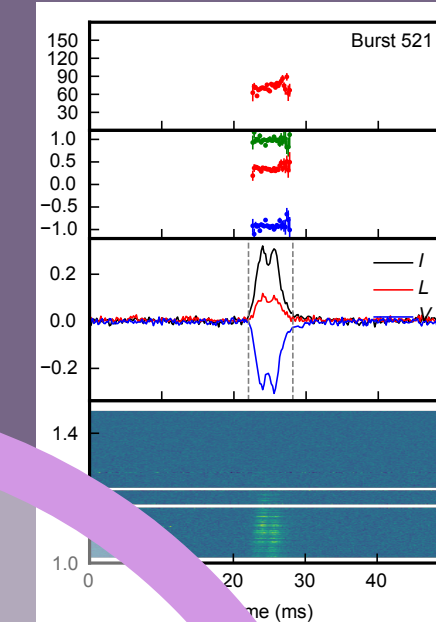
Scattered



Periodic

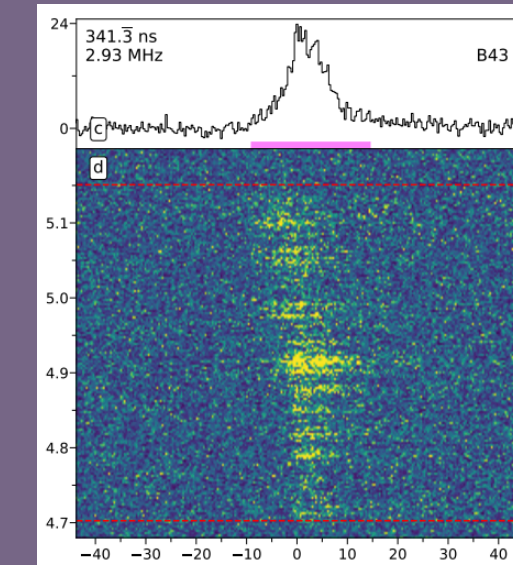


Circularly polarized



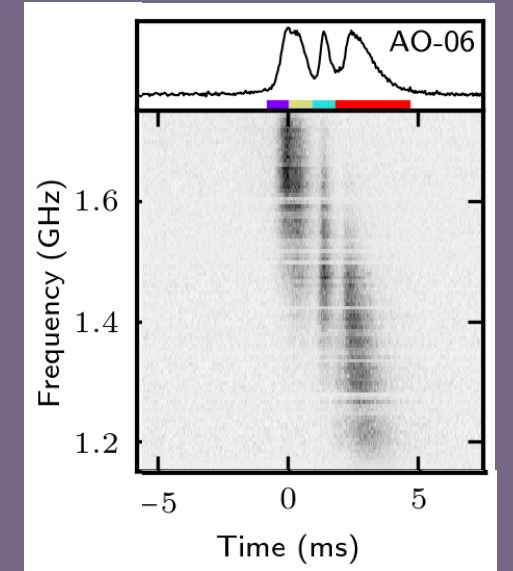
Jiang et al. 2024

Ultra-fast



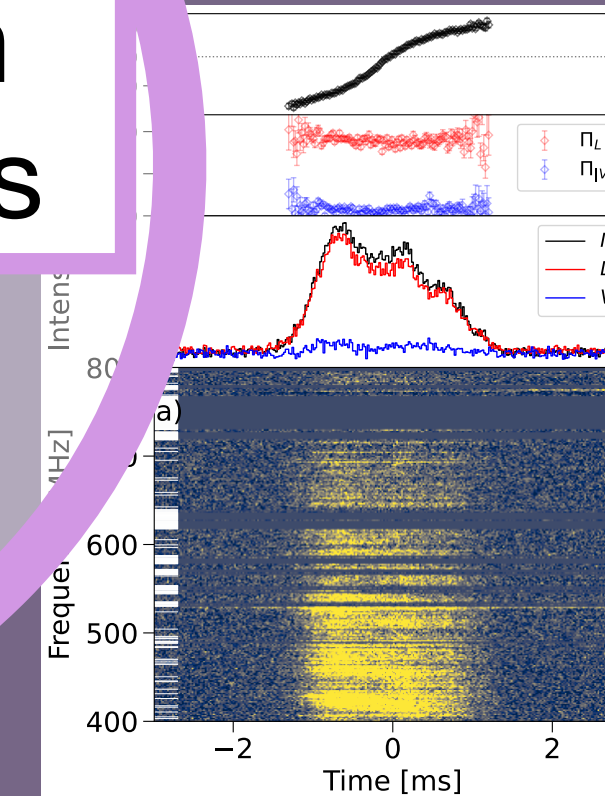
Snelders et al. 2023

Sad-trombone



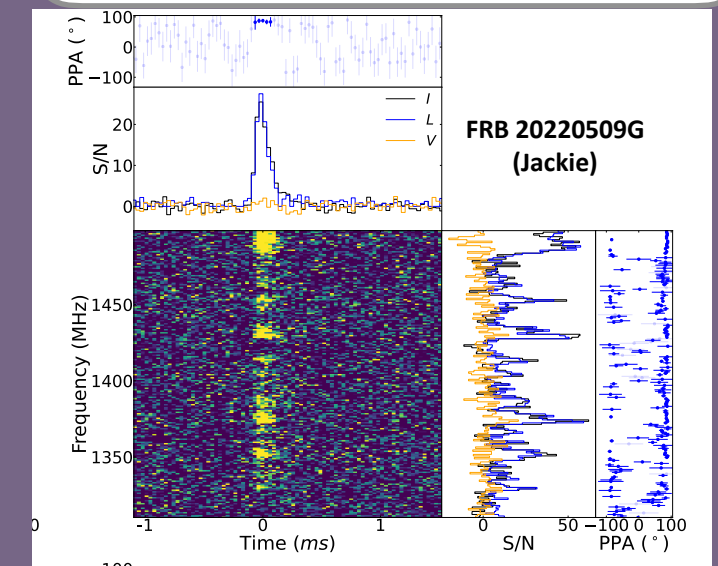
Hessels et al. 2019

PA swing



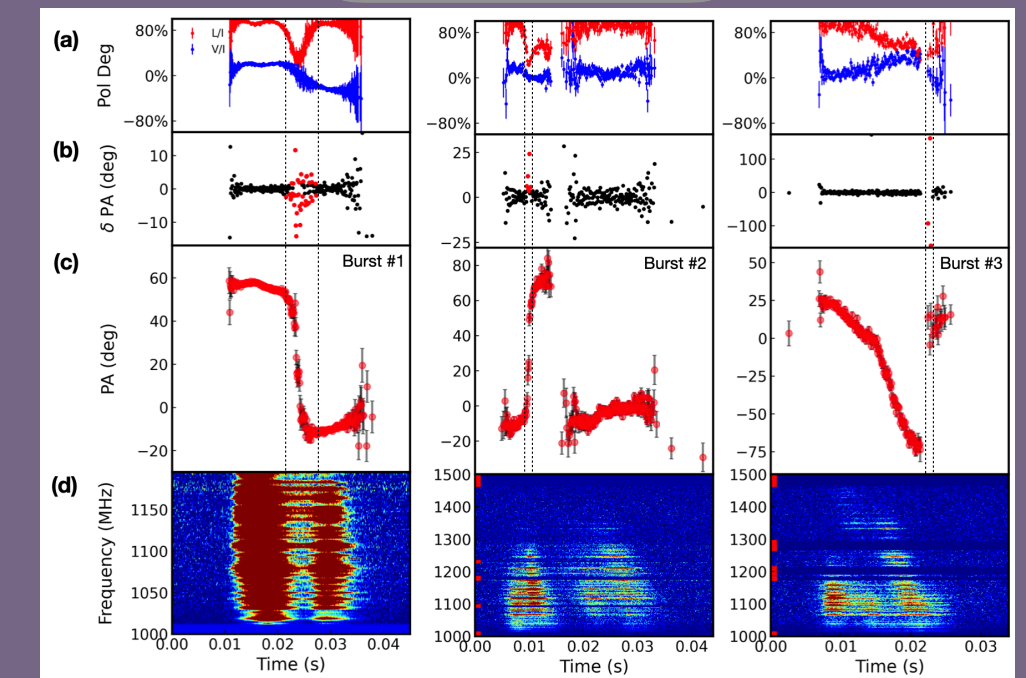
Mckinven et al. 2025

Linearly polarized



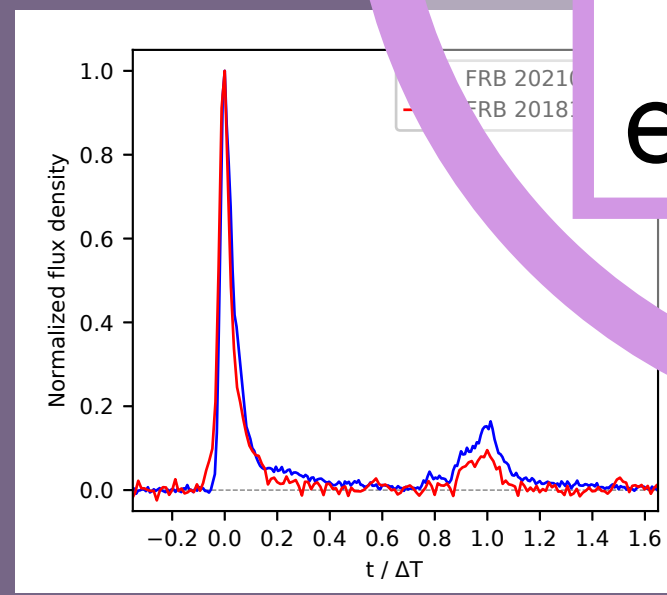
Sherman et al. 2024

PA jumps



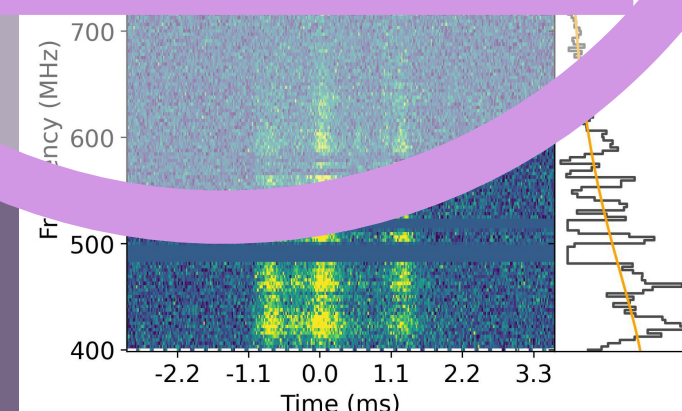
Niu et al. 2024

Twins



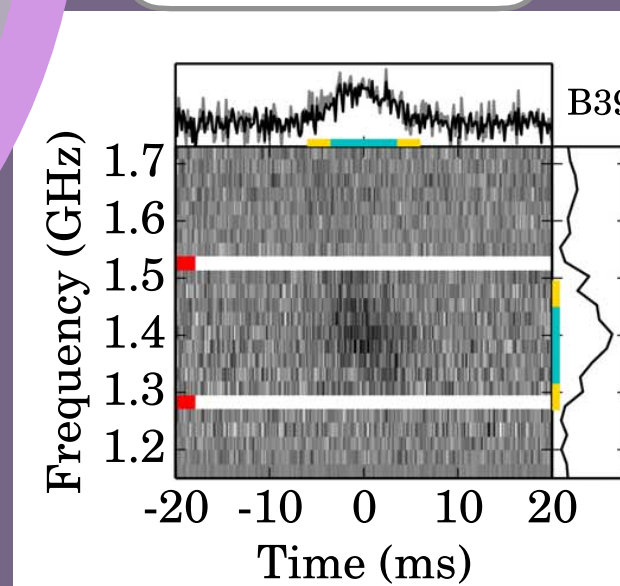
Bera et al. 2024

Immediate environments



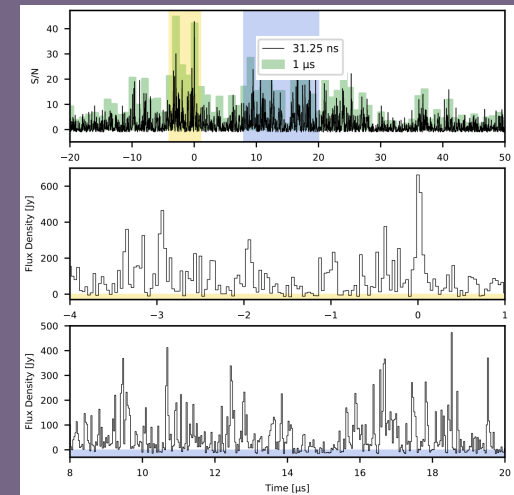
Sand et al. 2025

Smudgy



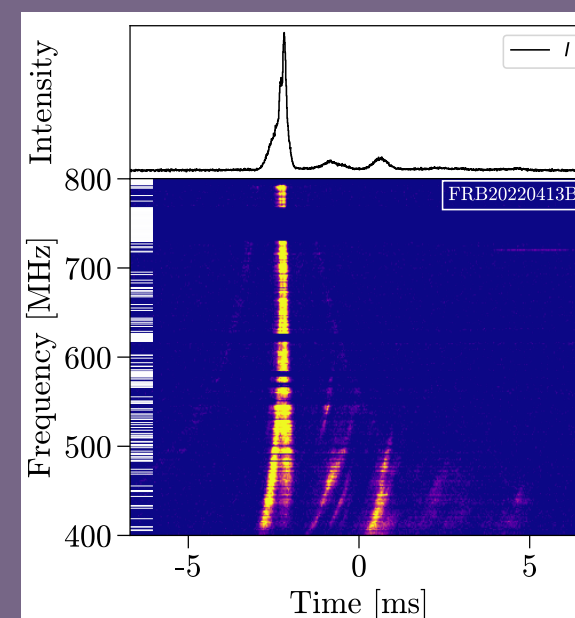
Gourdji et al. 2019

Temporal variability



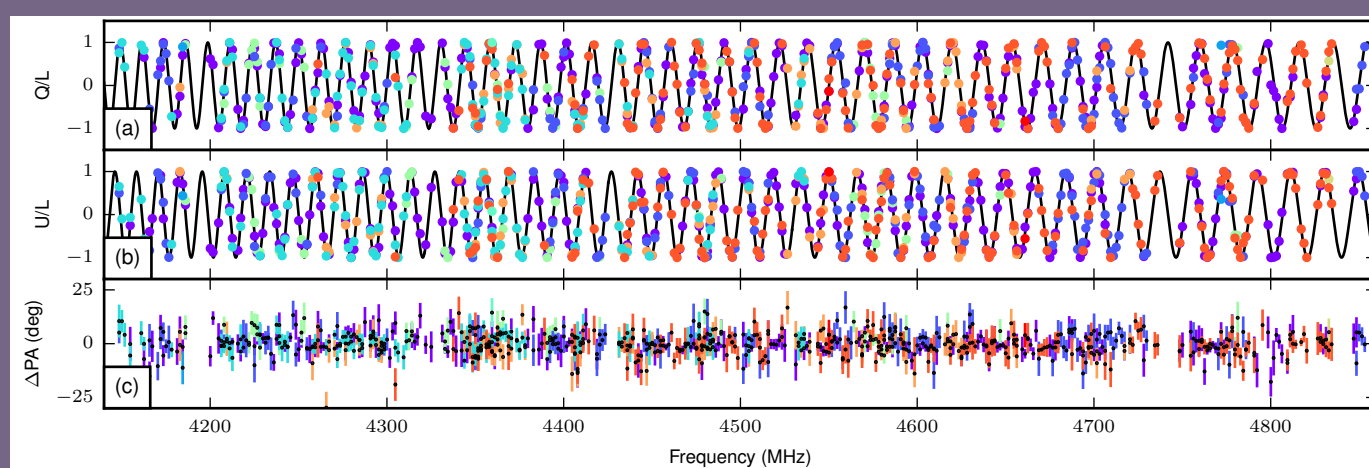
Nimmo et al. 2022

Complex variability



Faber et al. 2024

High RM

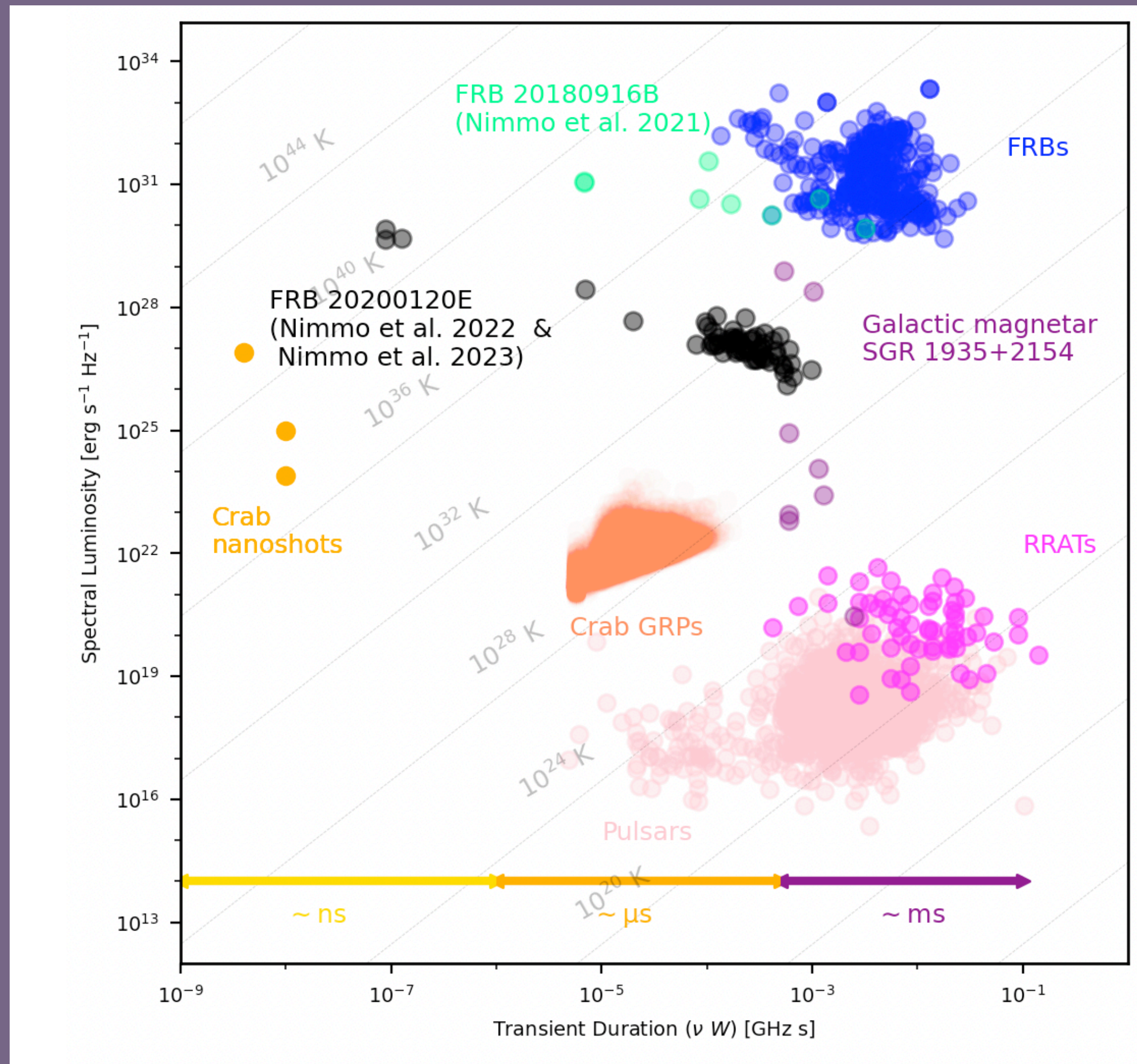


Michilli et al. 2018

Progenitors

Emission processes

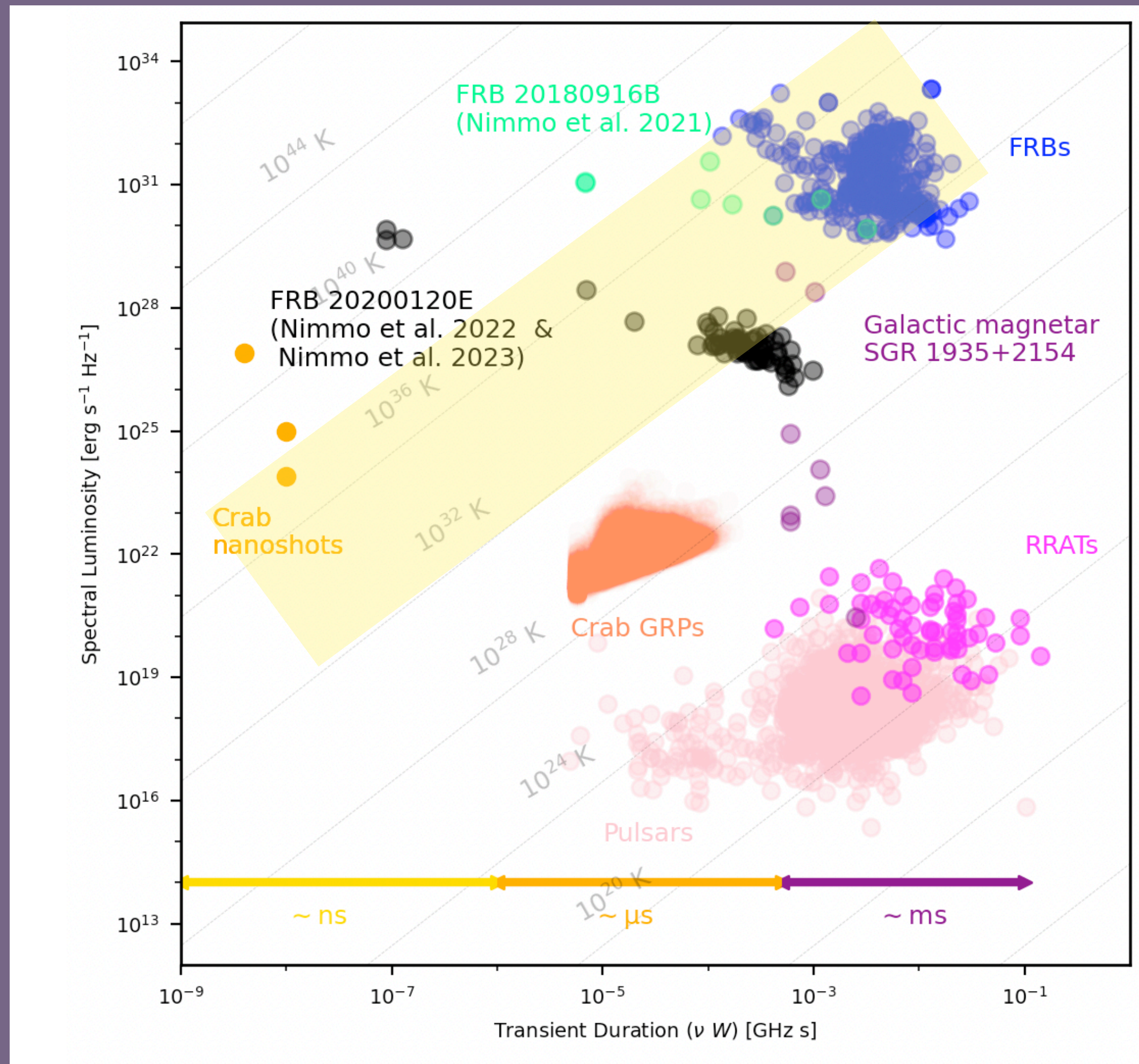
Broadly true FRB properties



Adapted from Nimmo et al. 2022

Broadly true FRB properties

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

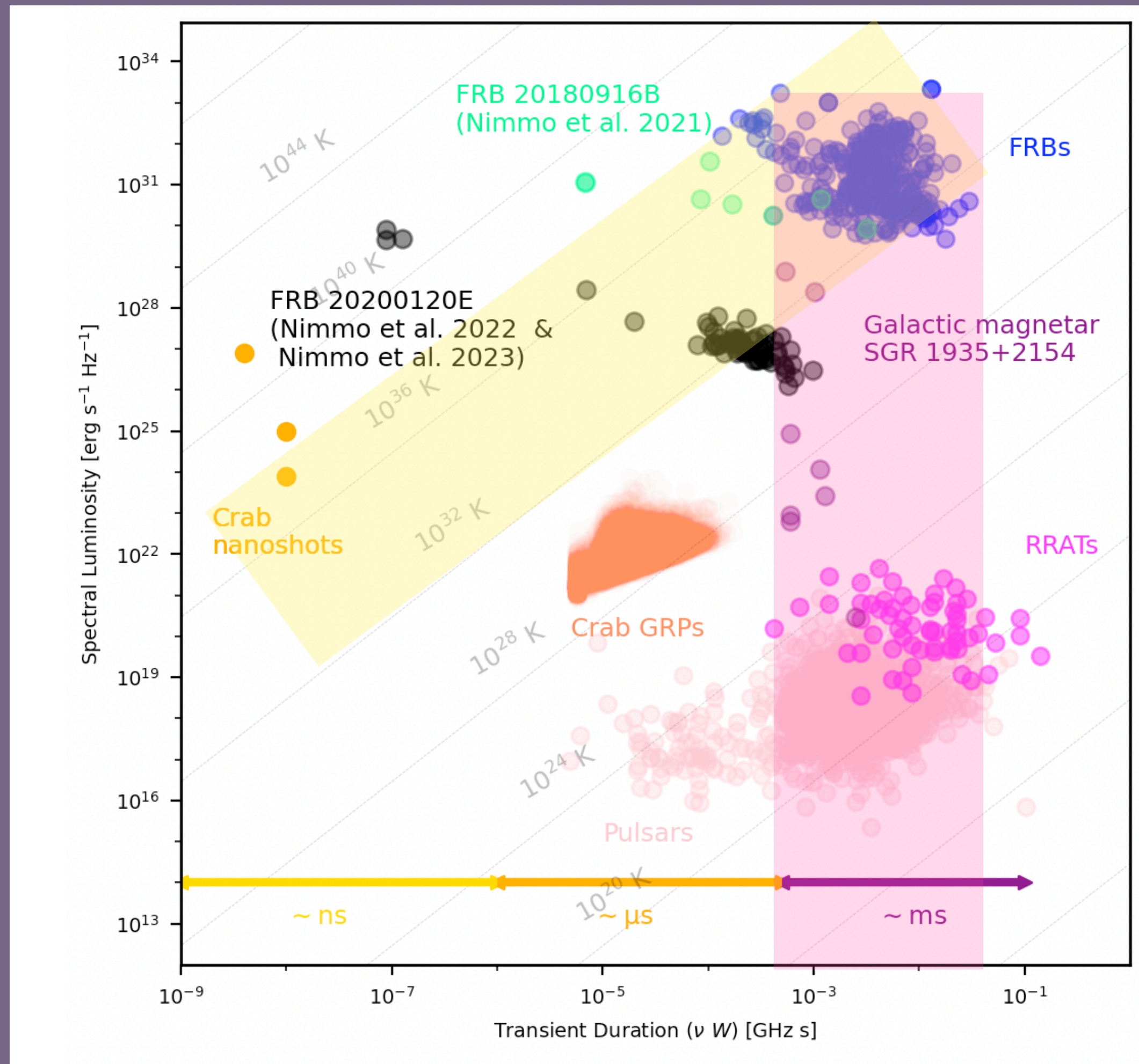


Adapted from Nimmo et al. 2022

Broadly true FRB properties

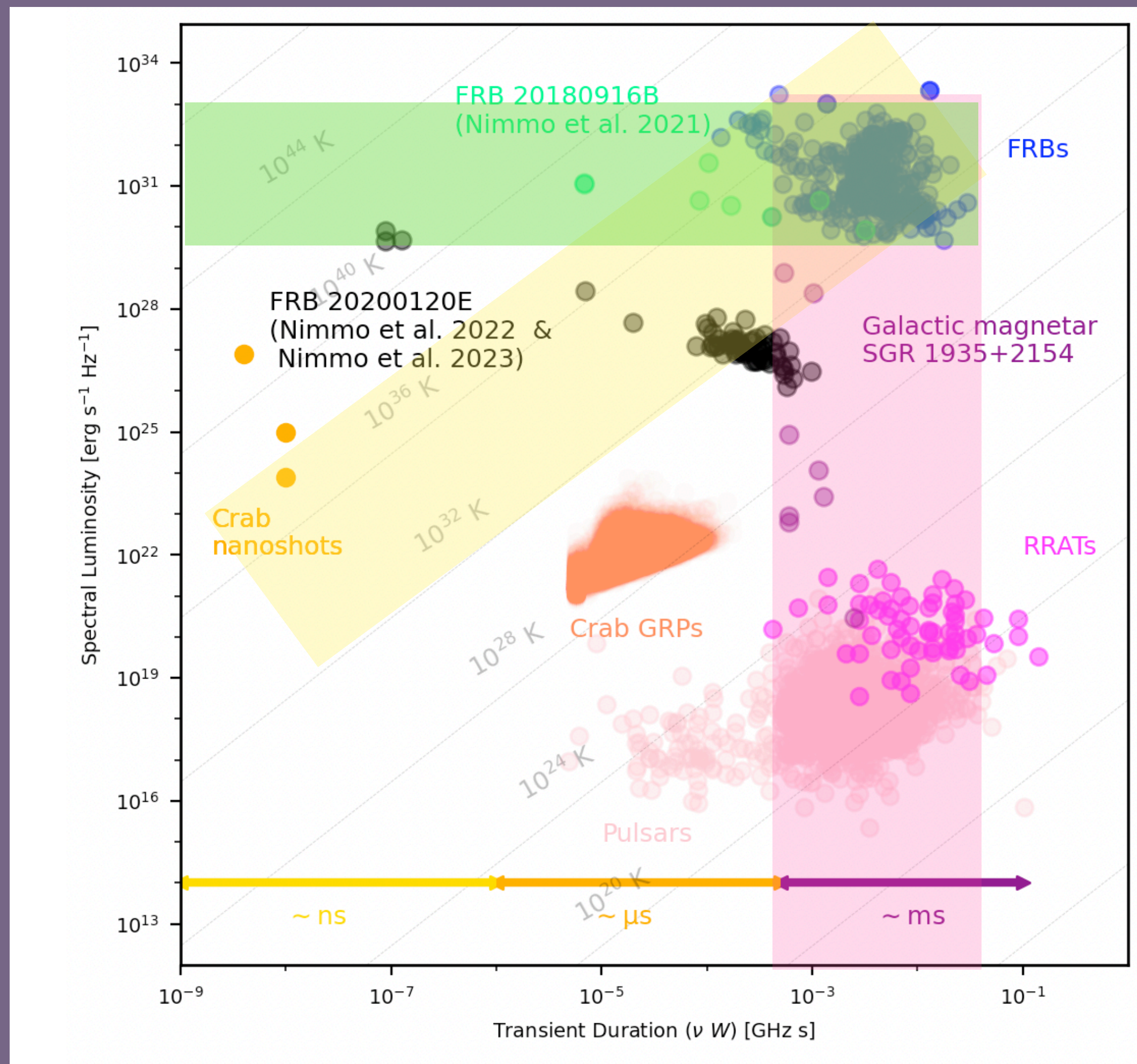
Coherent ($T_b \sim 10^{32} - 10^{36} \text{K}$)

Short-duration $\sim \text{ms}$



Adapted from Nimmo et al. 2022

Broadly true FRB properties



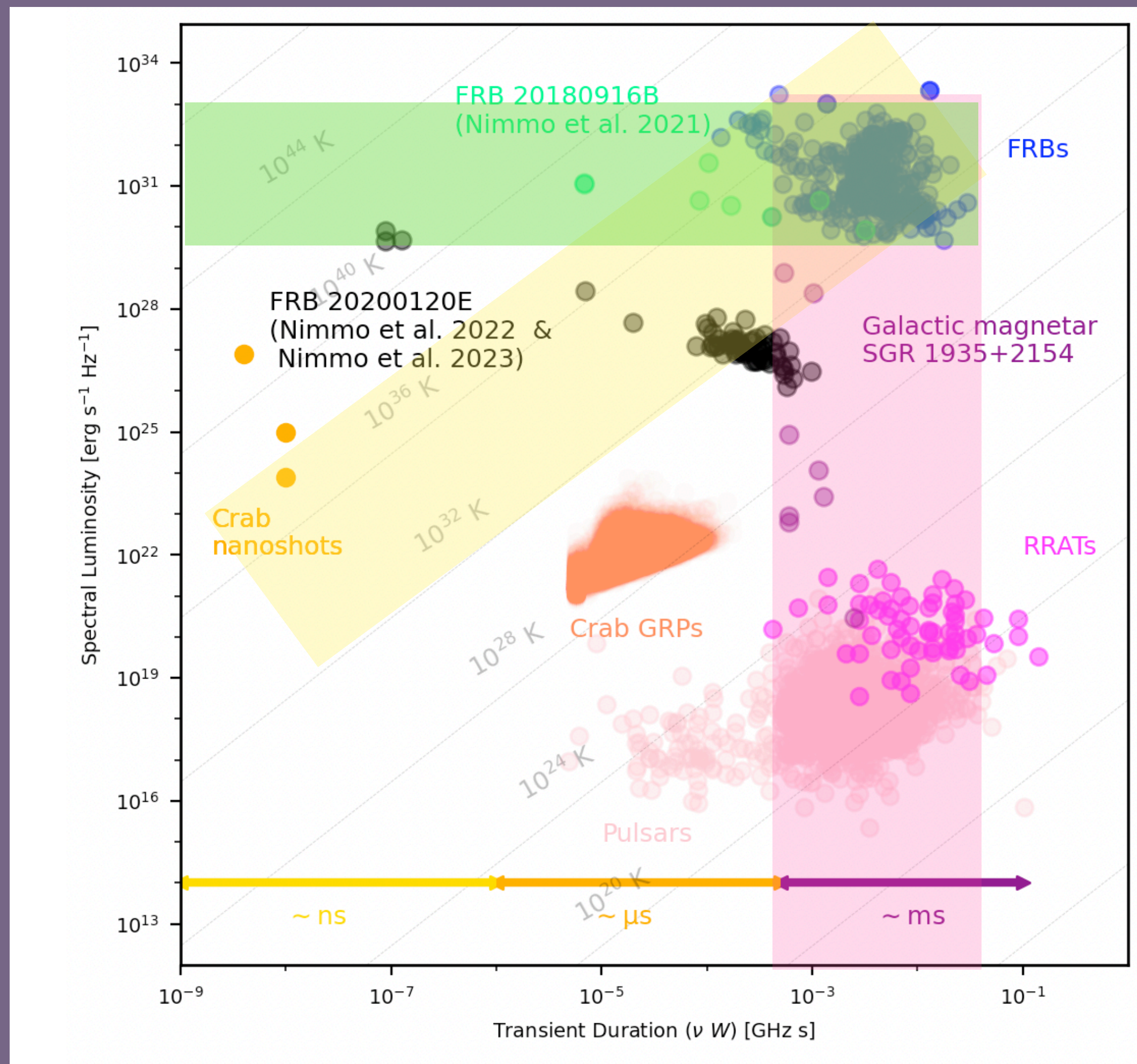
Adapted from Nimmo et al. 2022

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

Short-duration \sim ms

Luminous $\sim 10^{32}$ erg s⁻¹ Hz⁻¹

Broadly true FRB properties



Adapted from Nimmo et al. 2022

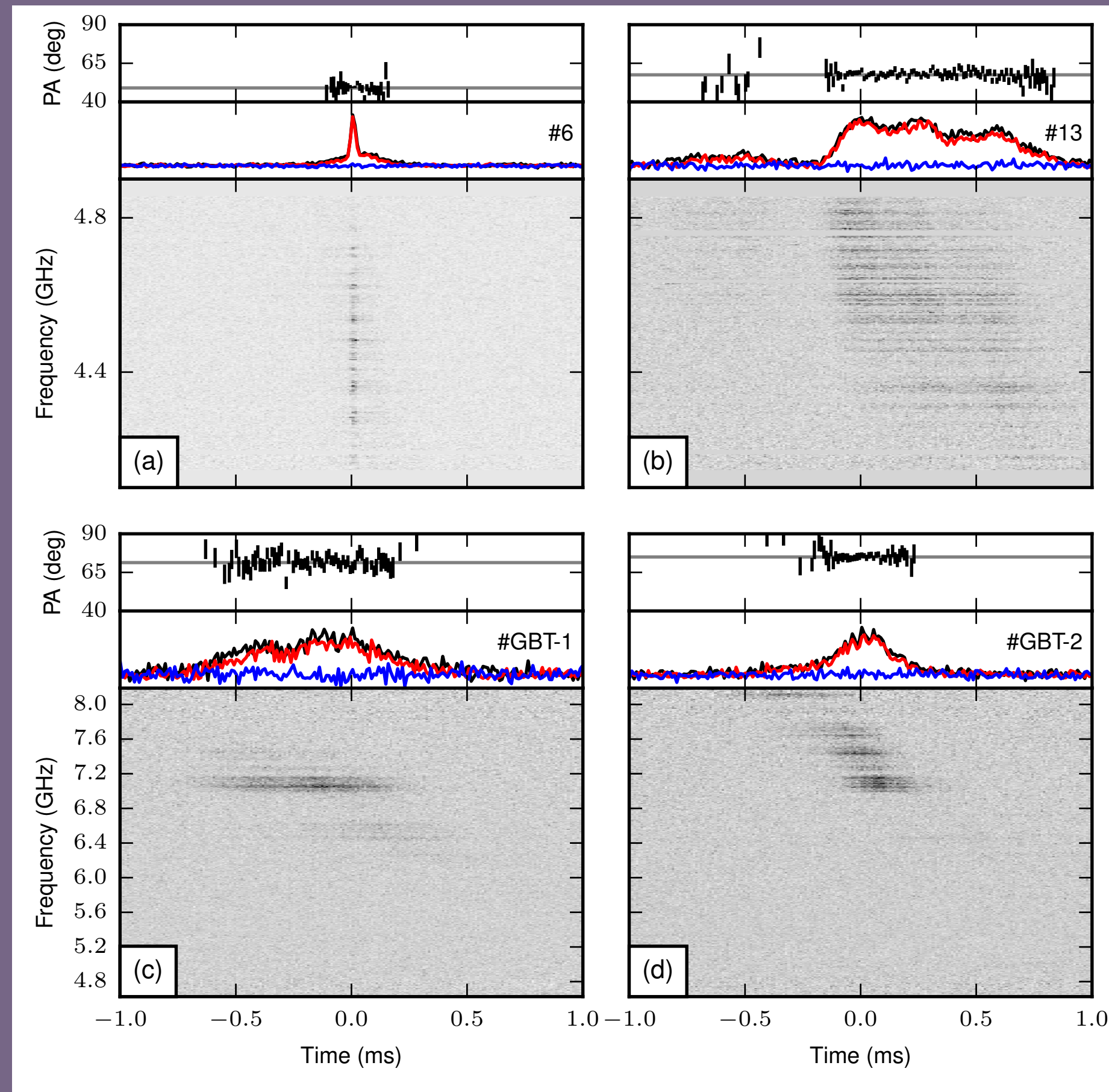
Coherent ($T_b \sim 10^{32} - 10^{36}$ K)

Short-duration \sim ms

Luminous $\sim 10^{32}$ erg s⁻¹ Hz⁻¹

Radio (110 MHz - 8 GHz)

Broadly true FRB properties



Michilli et al. 2018

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

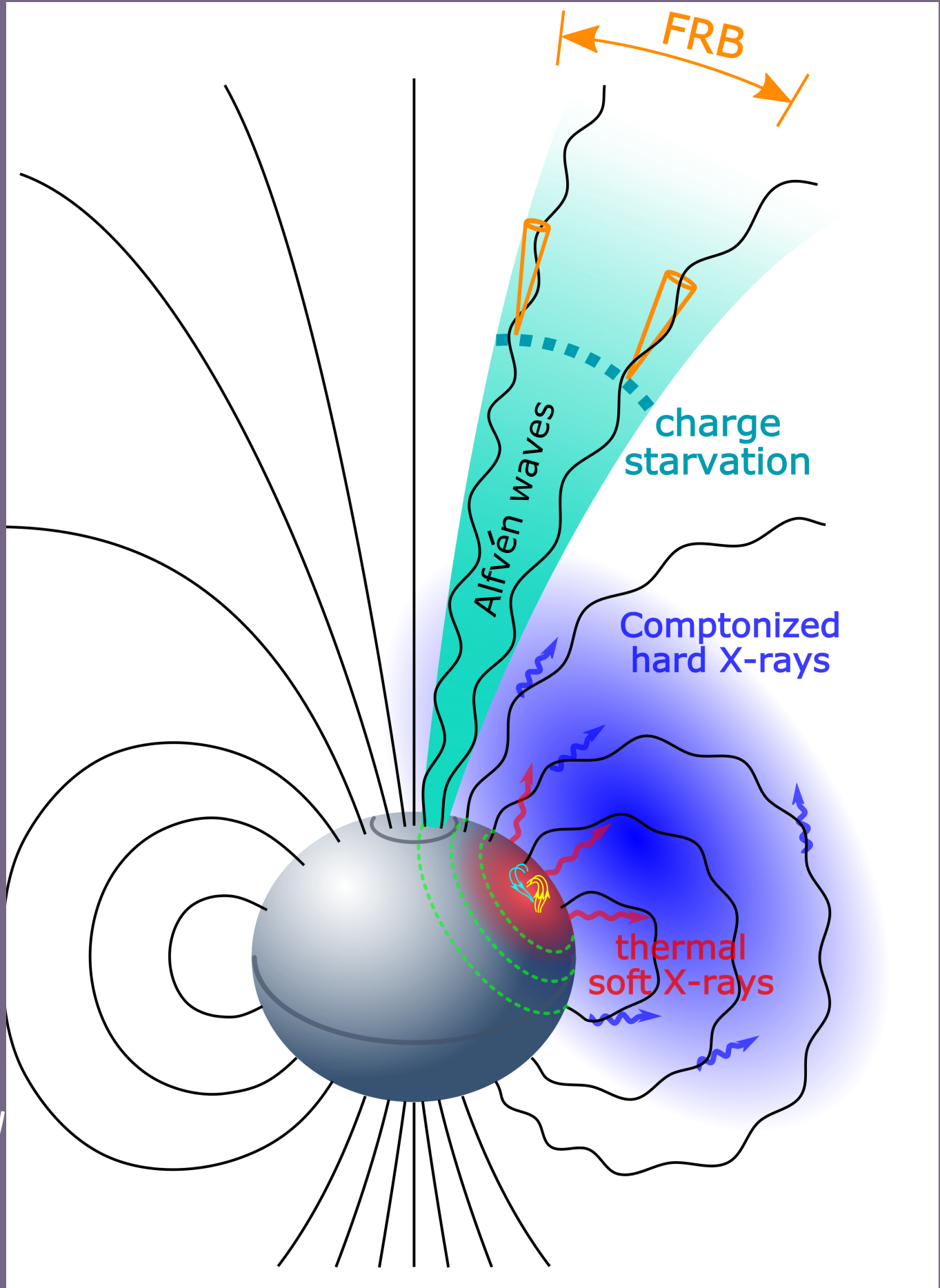
Short-duration \sim ms

Luminous $\sim 10^{32} \text{ erg s}^{-1} \text{ Hz}^{-1}$

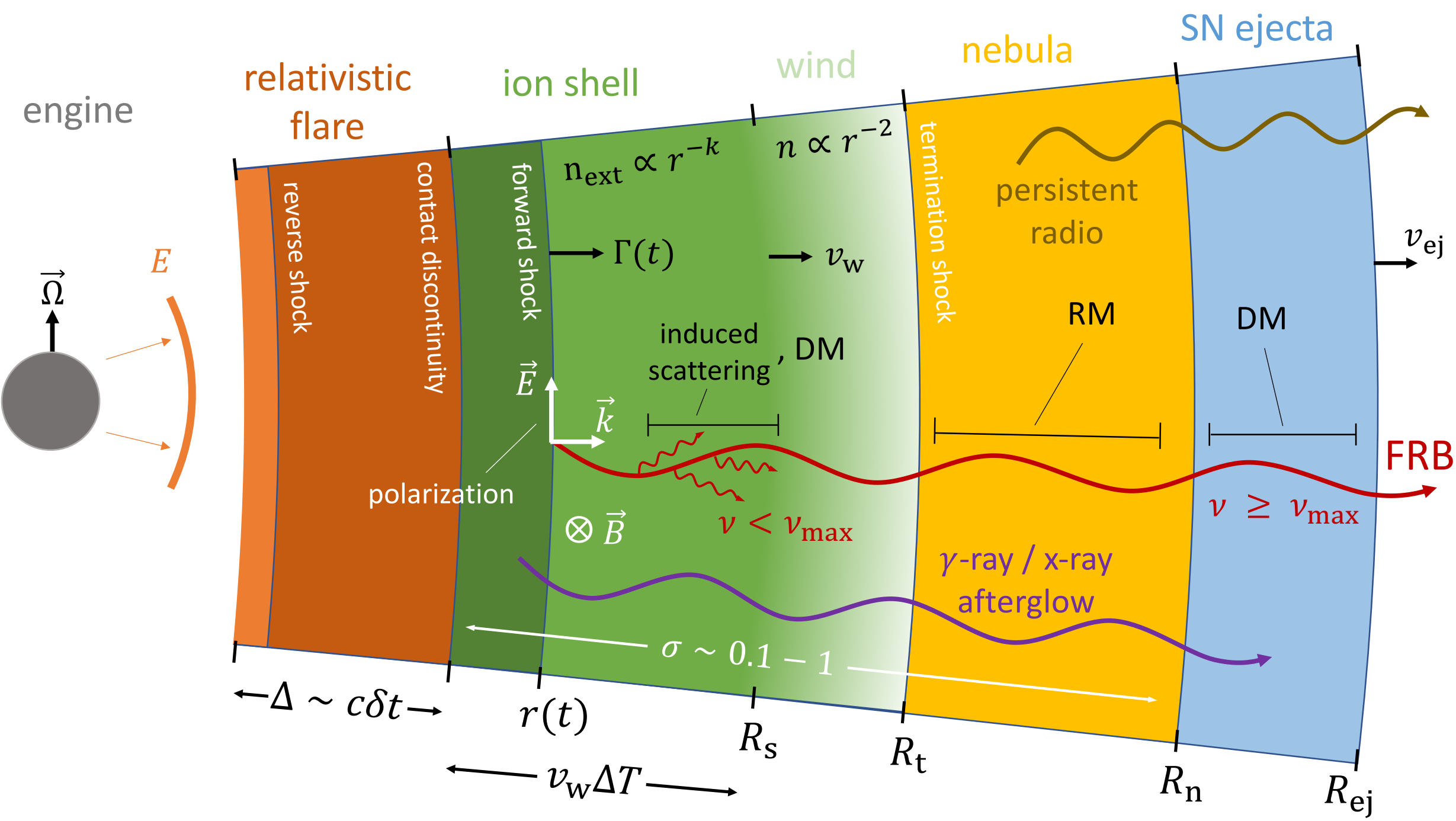
Radio (110 MHz - 8 GHz)

Highly polarized

The FRB emission mechanism

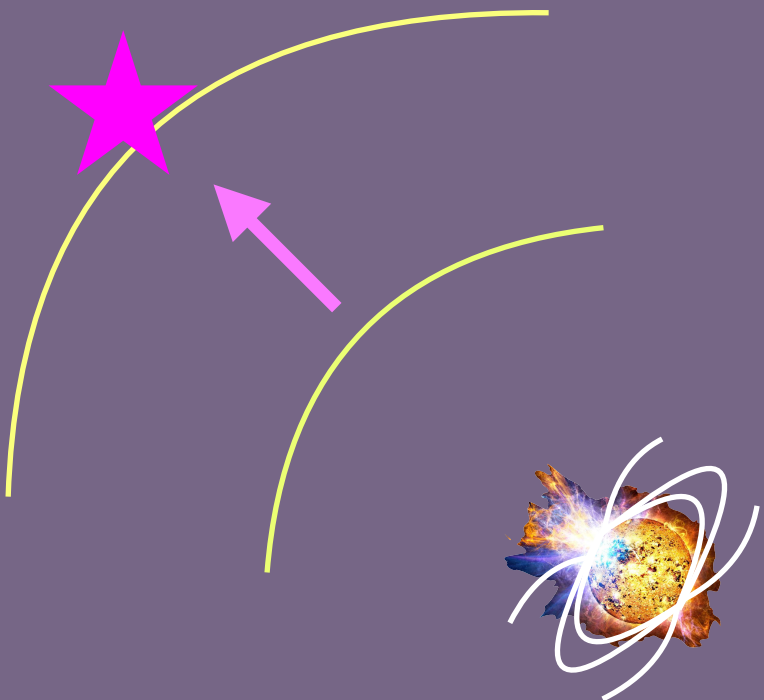


Lu et al. 2020

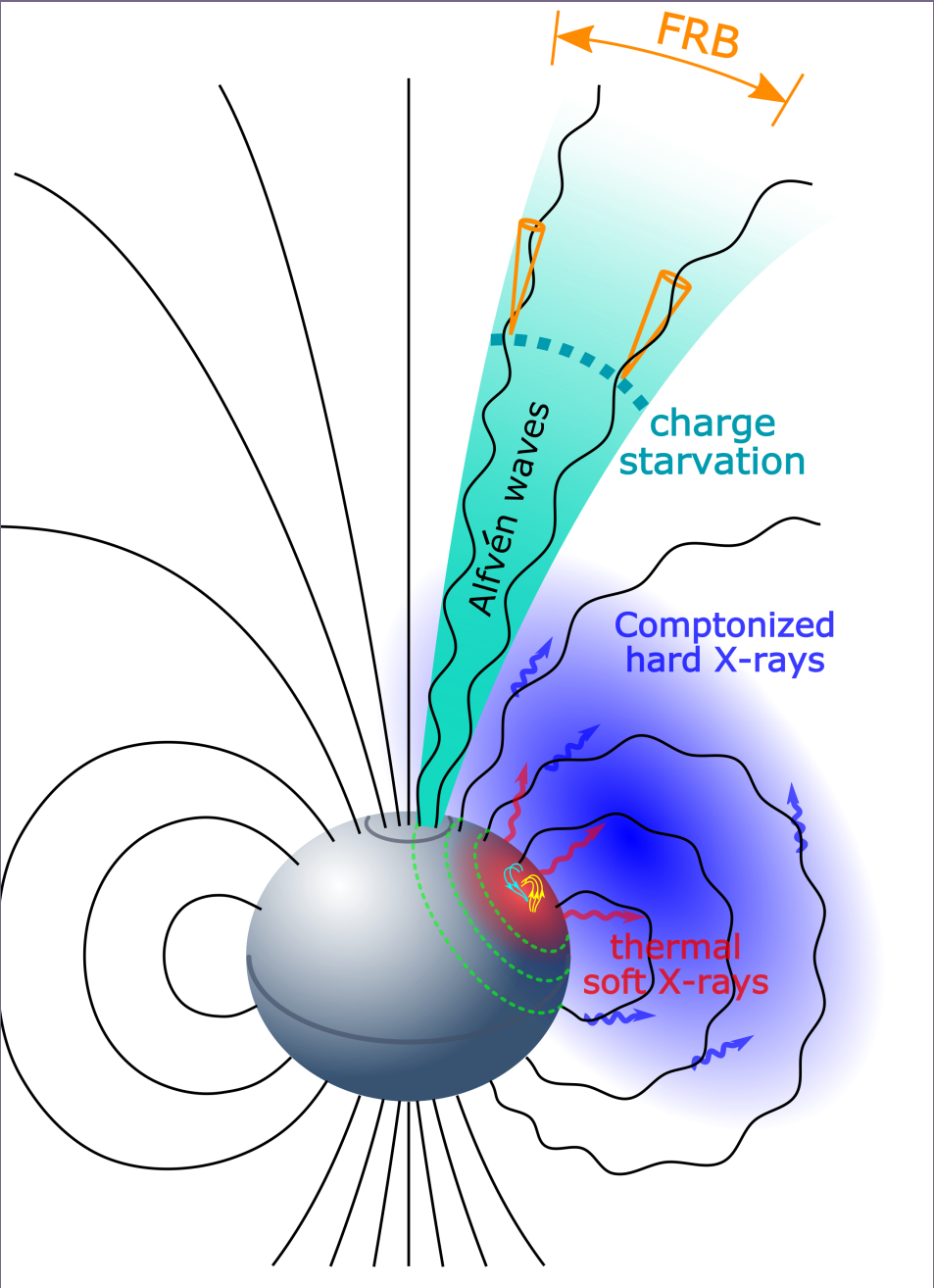


Metzger et al. 2019

Non-magnetospheric



The FRB emission mechanism



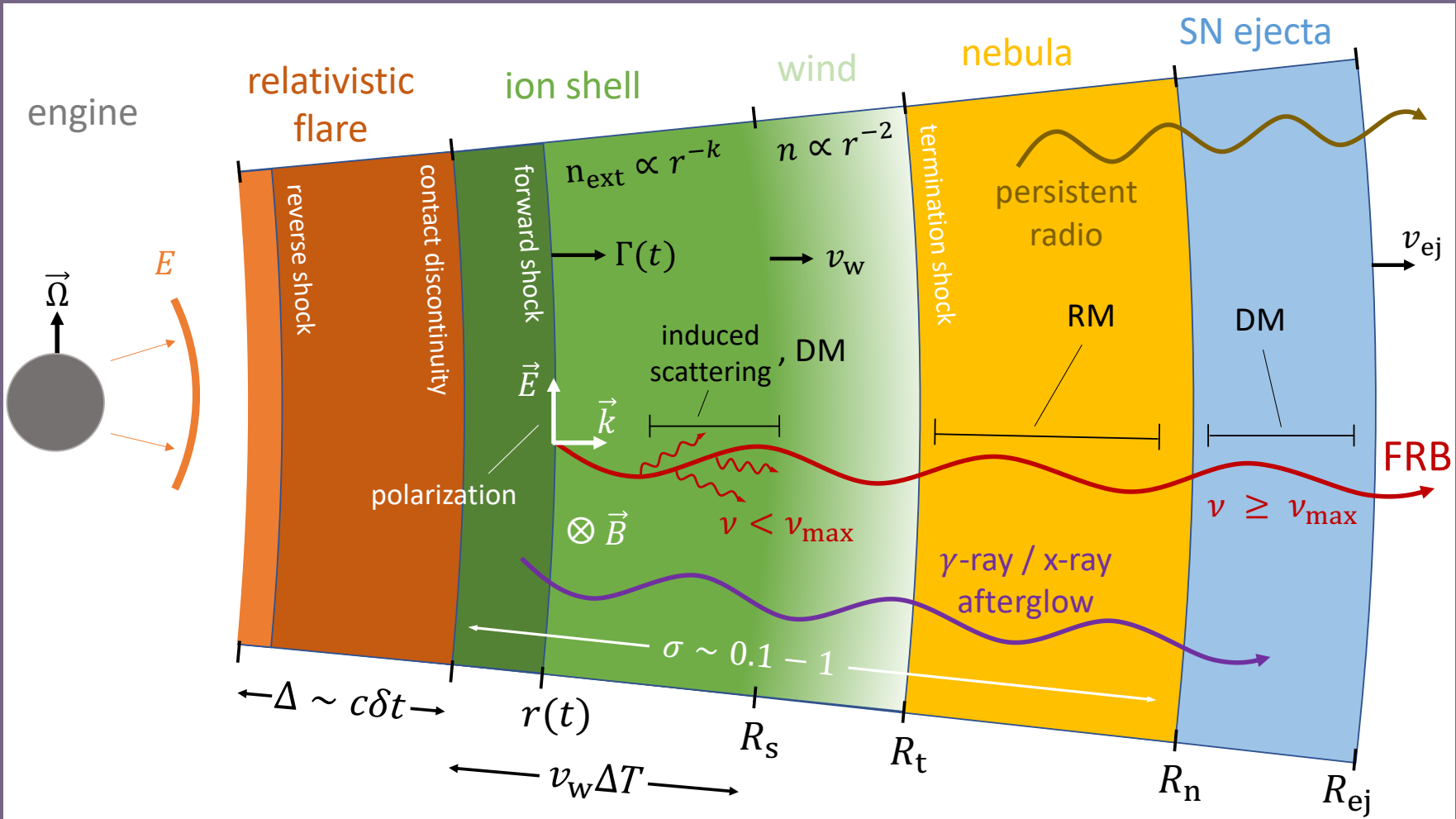
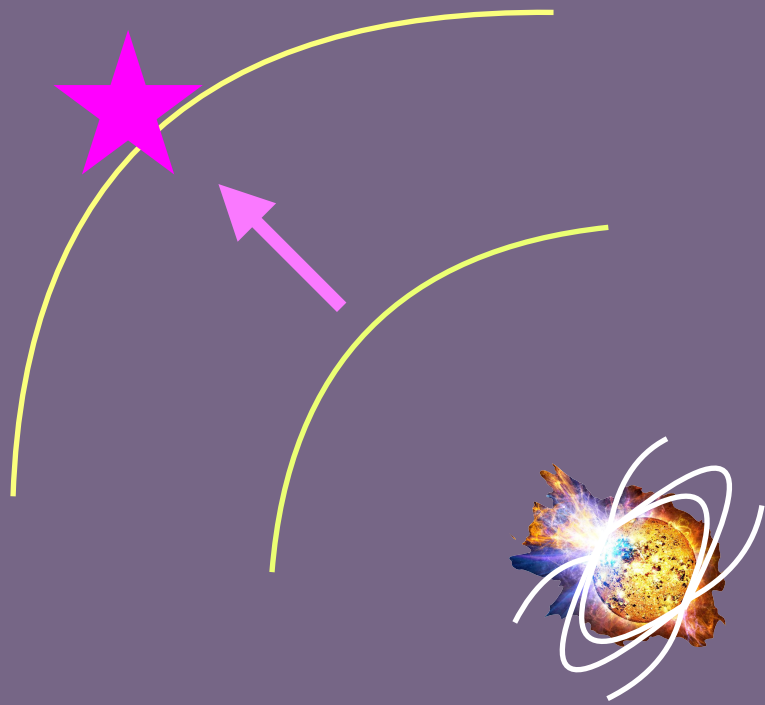
Lu et al. 2020

Magnetospheric



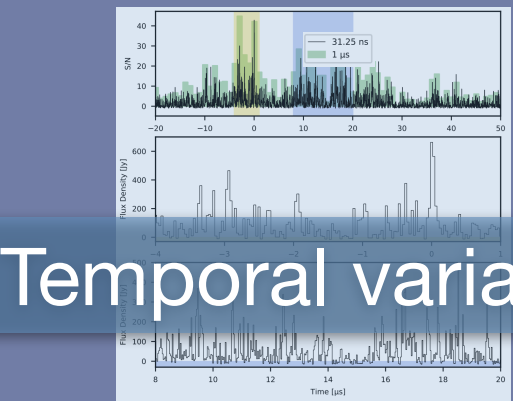
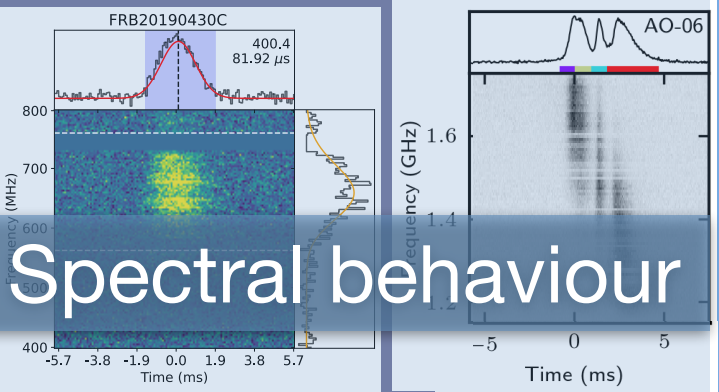
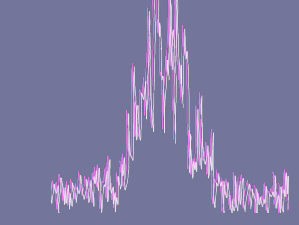
or?

Non-magnetospheric

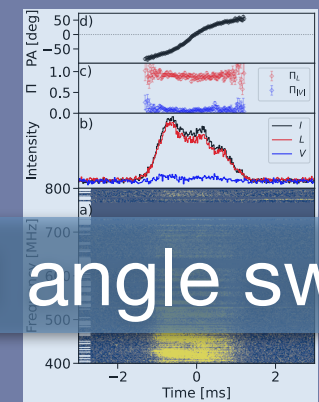


Metzger et al. 2019

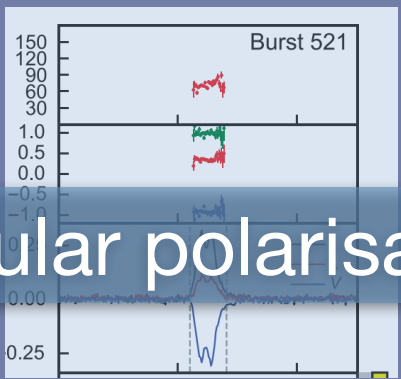
FRB property



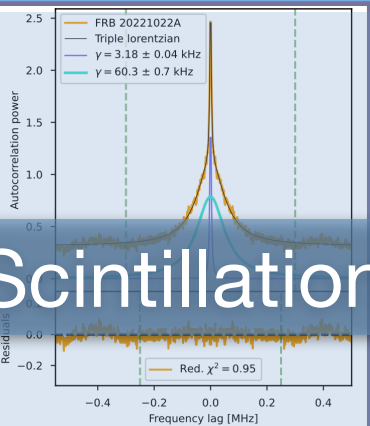
Temporal variability



Pol angle swing



Circular polarisation



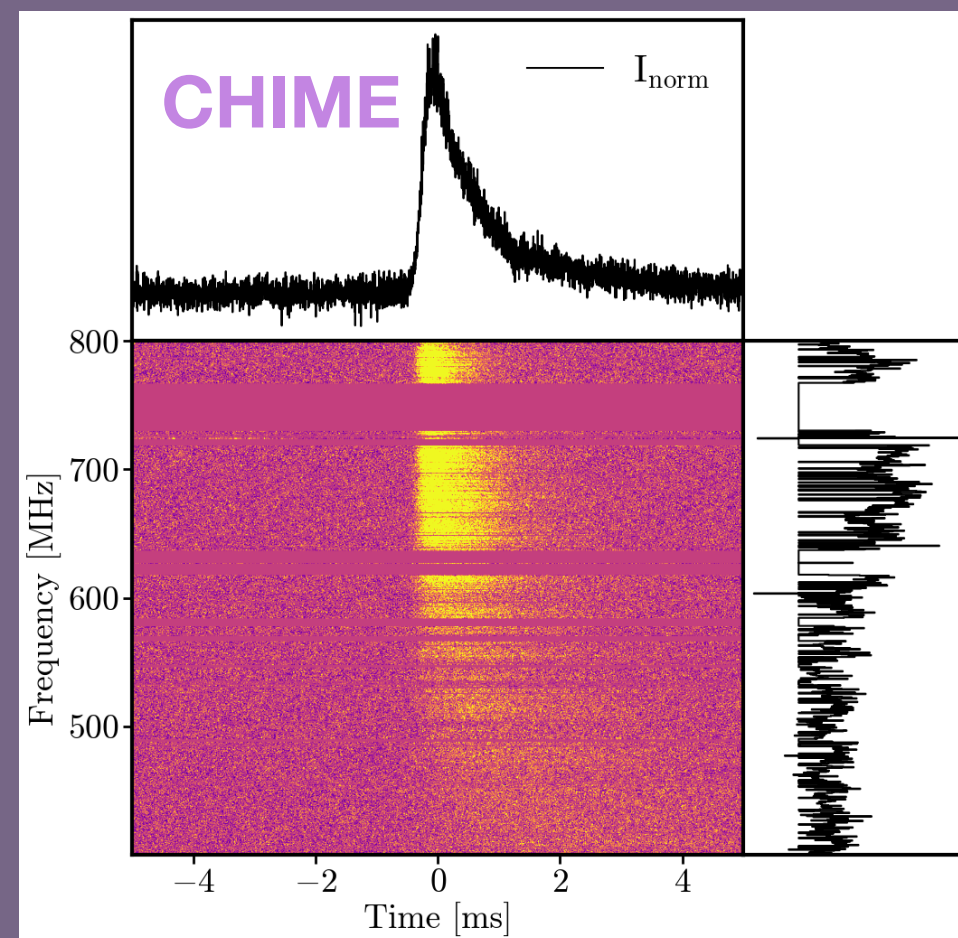
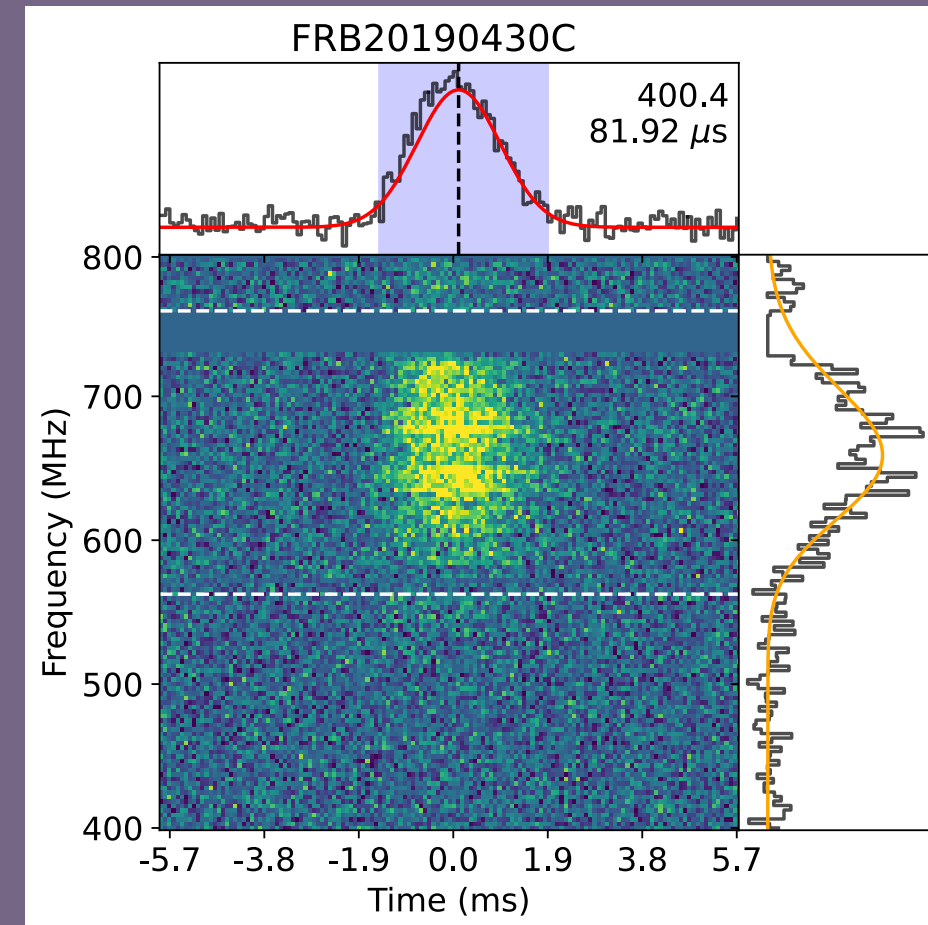
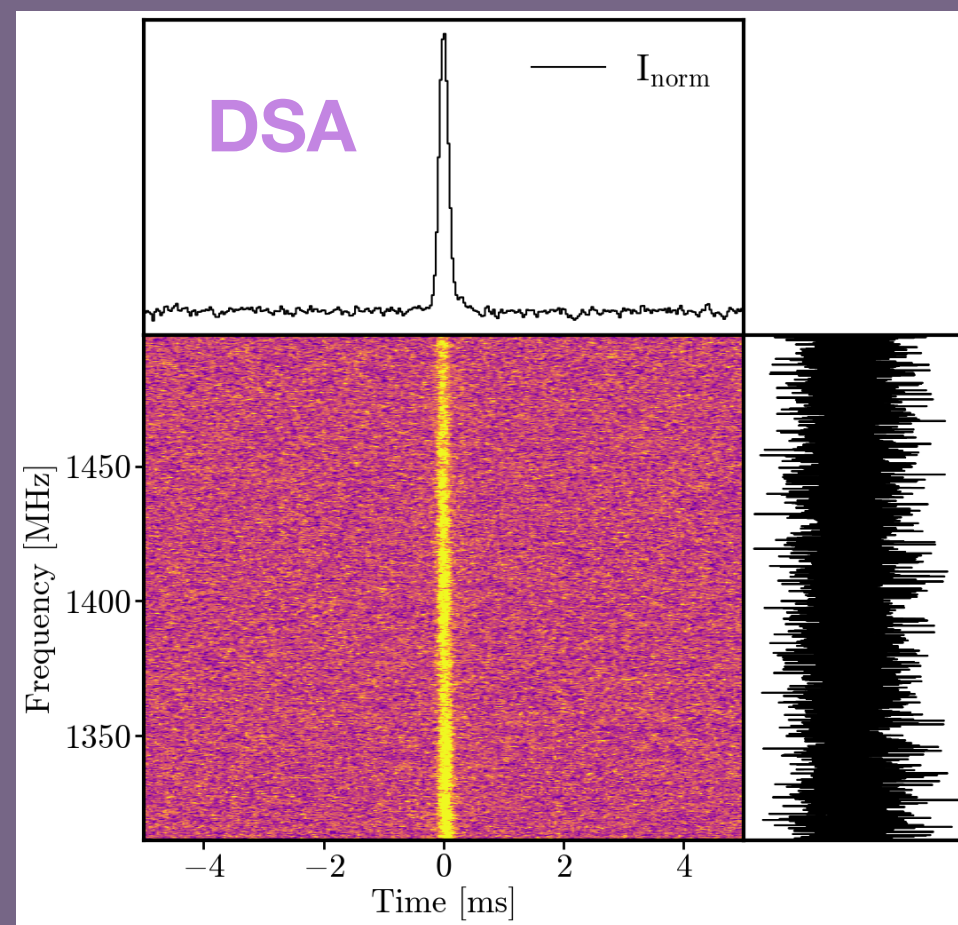
Scintillation

Spectral behaviour

Broadband

Narrowband

Pleunis et al. 2021
Sand et al. 2025

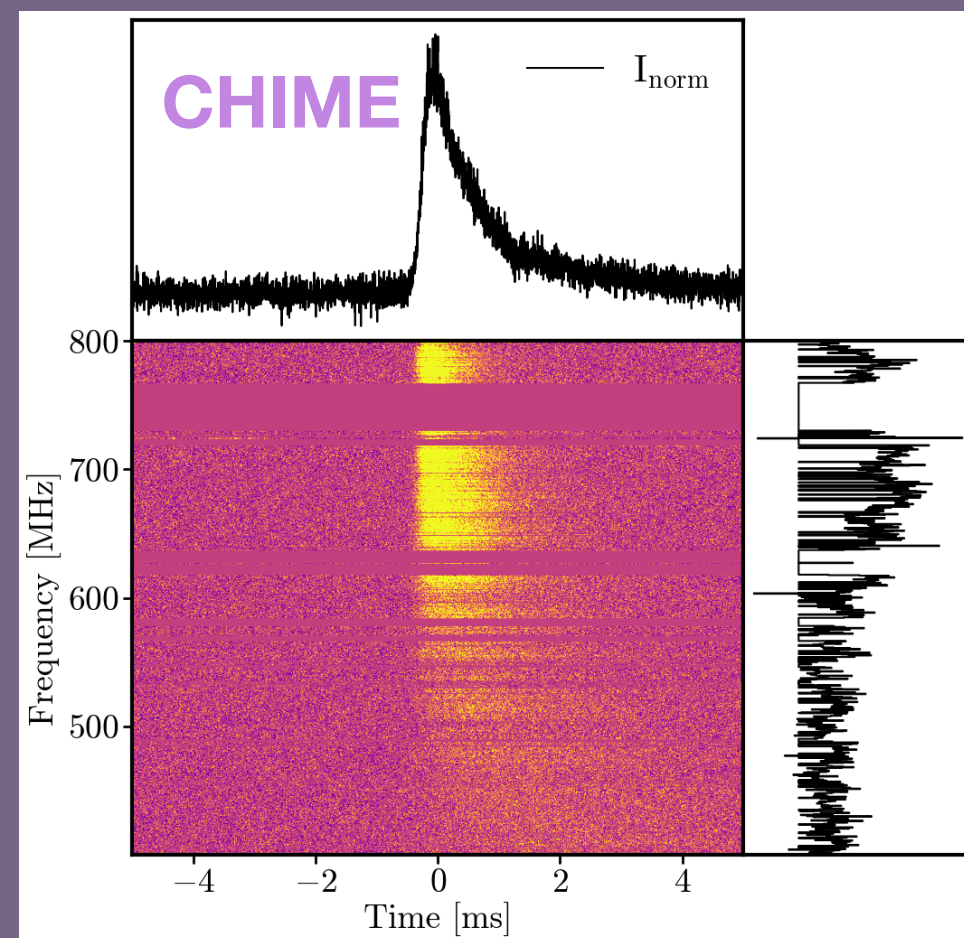
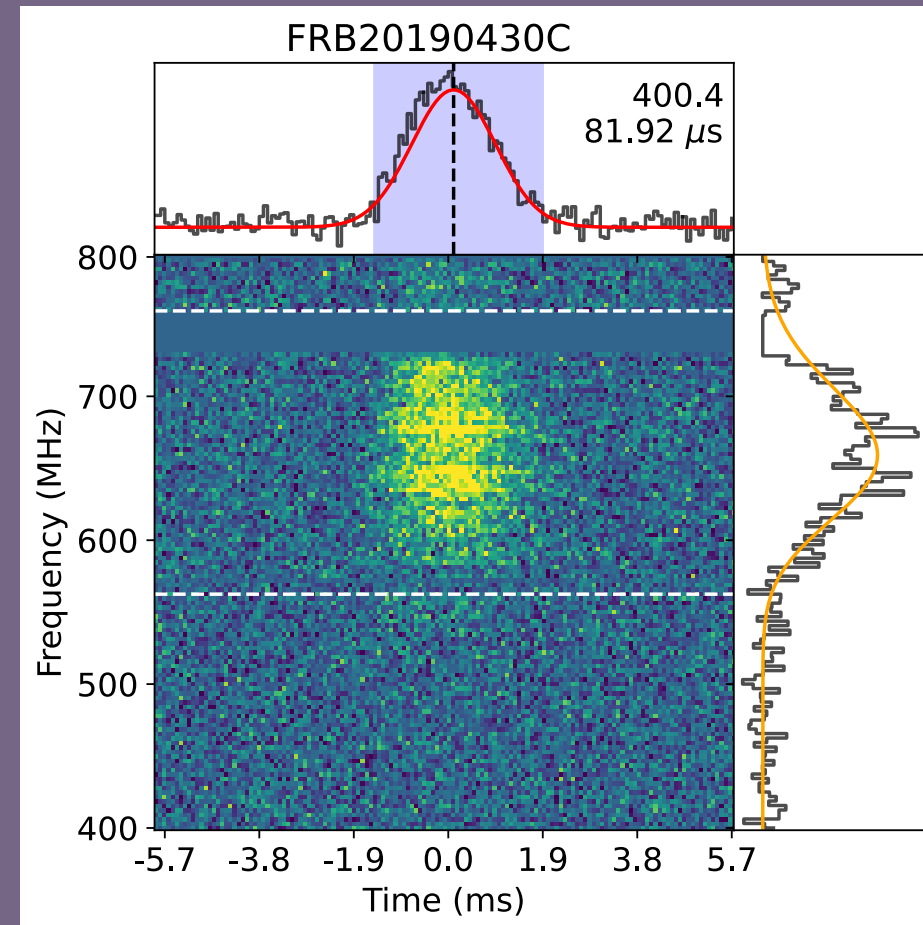
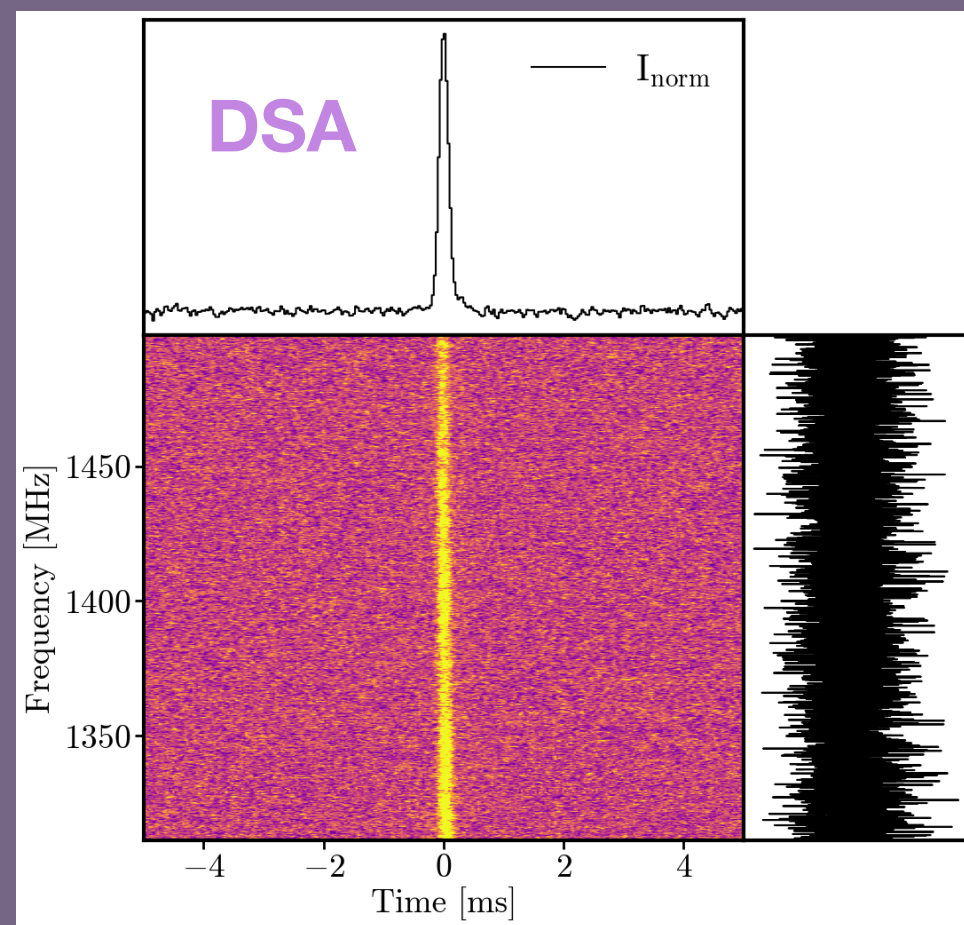


Spectral behaviour

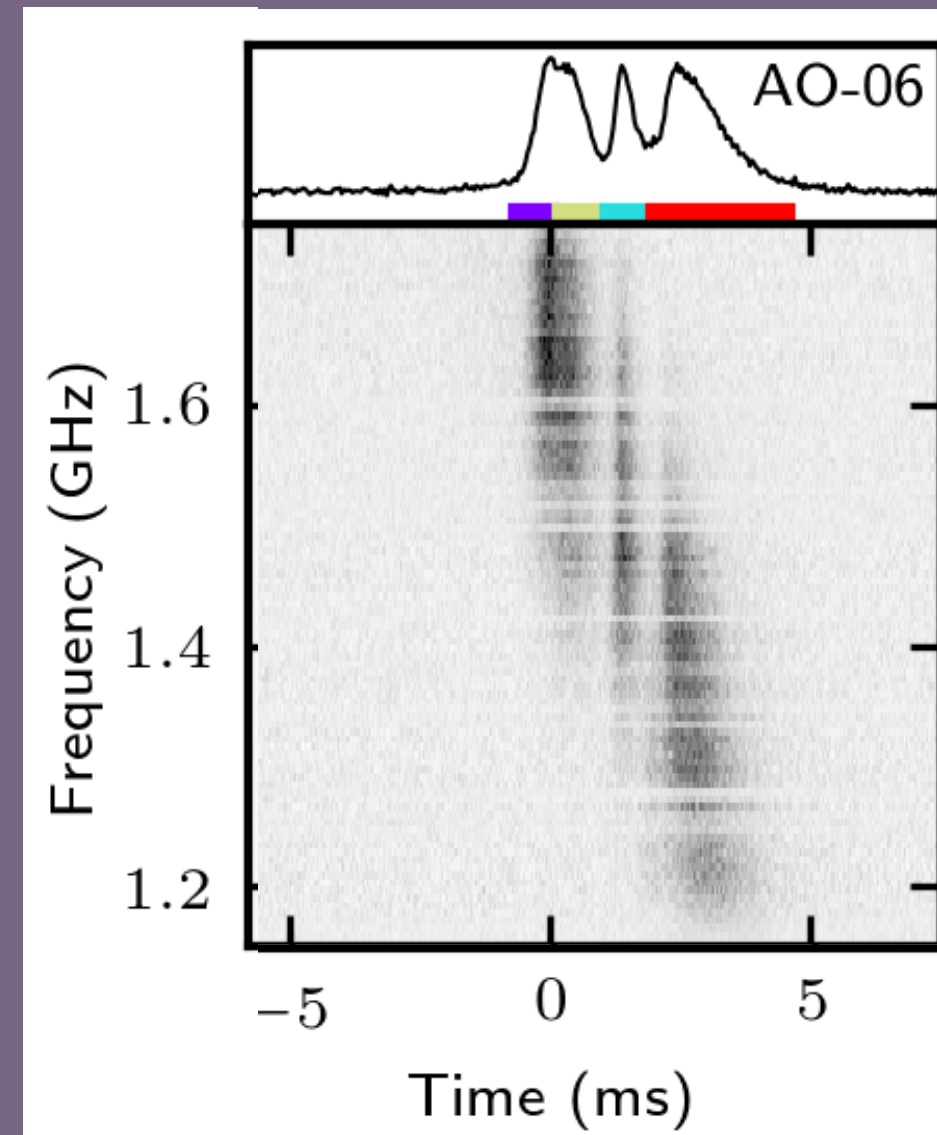
Broadband

Narrowband

Pleunis et al. 2021
Sand et al. 2025



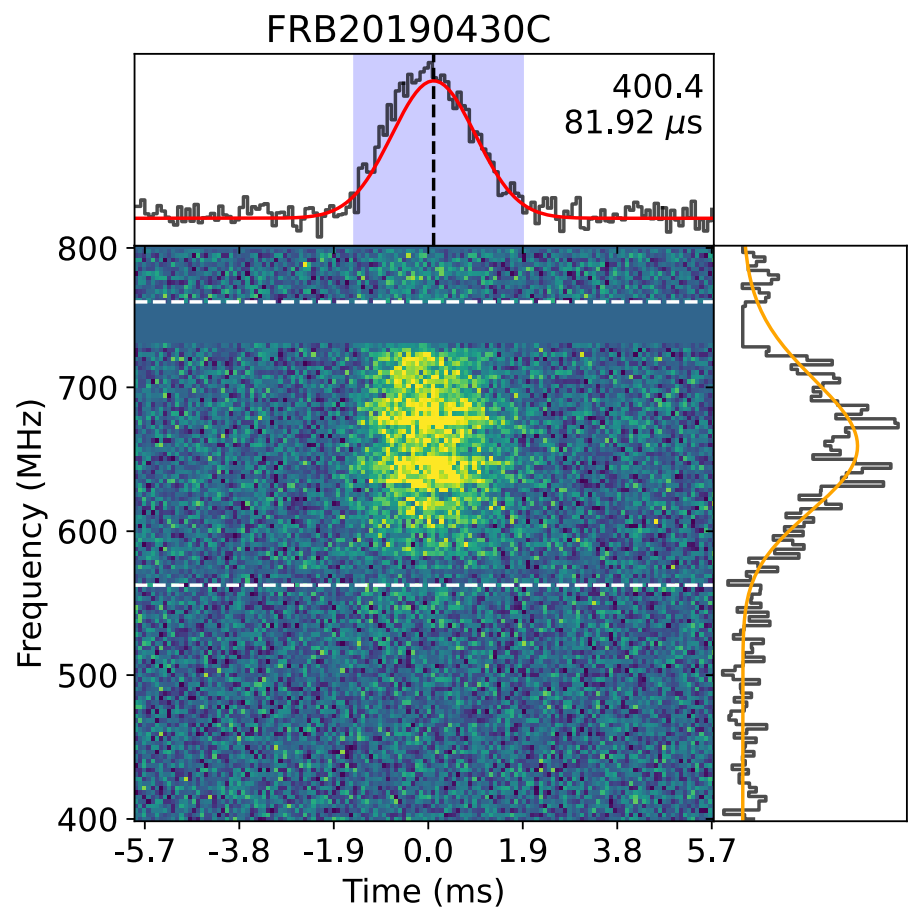
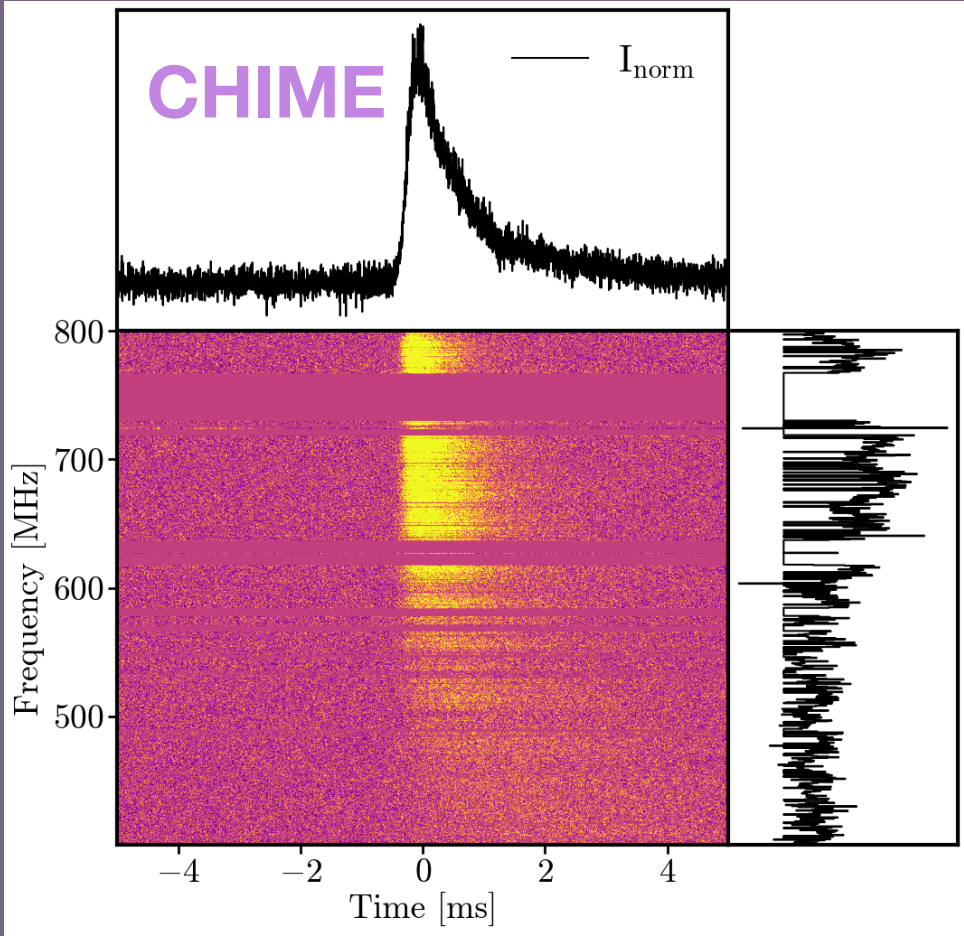
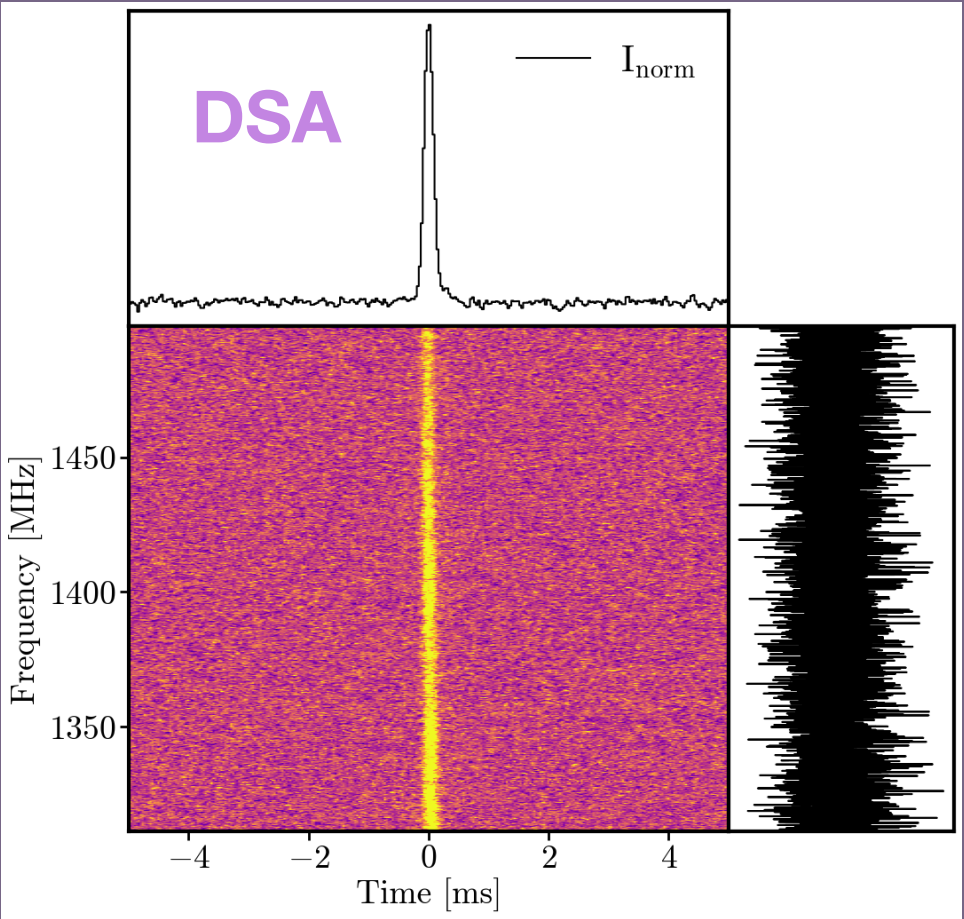
Sad-trombone



Faber et al. *in prep*

Hessels et al. 2019

Spectral behaviour

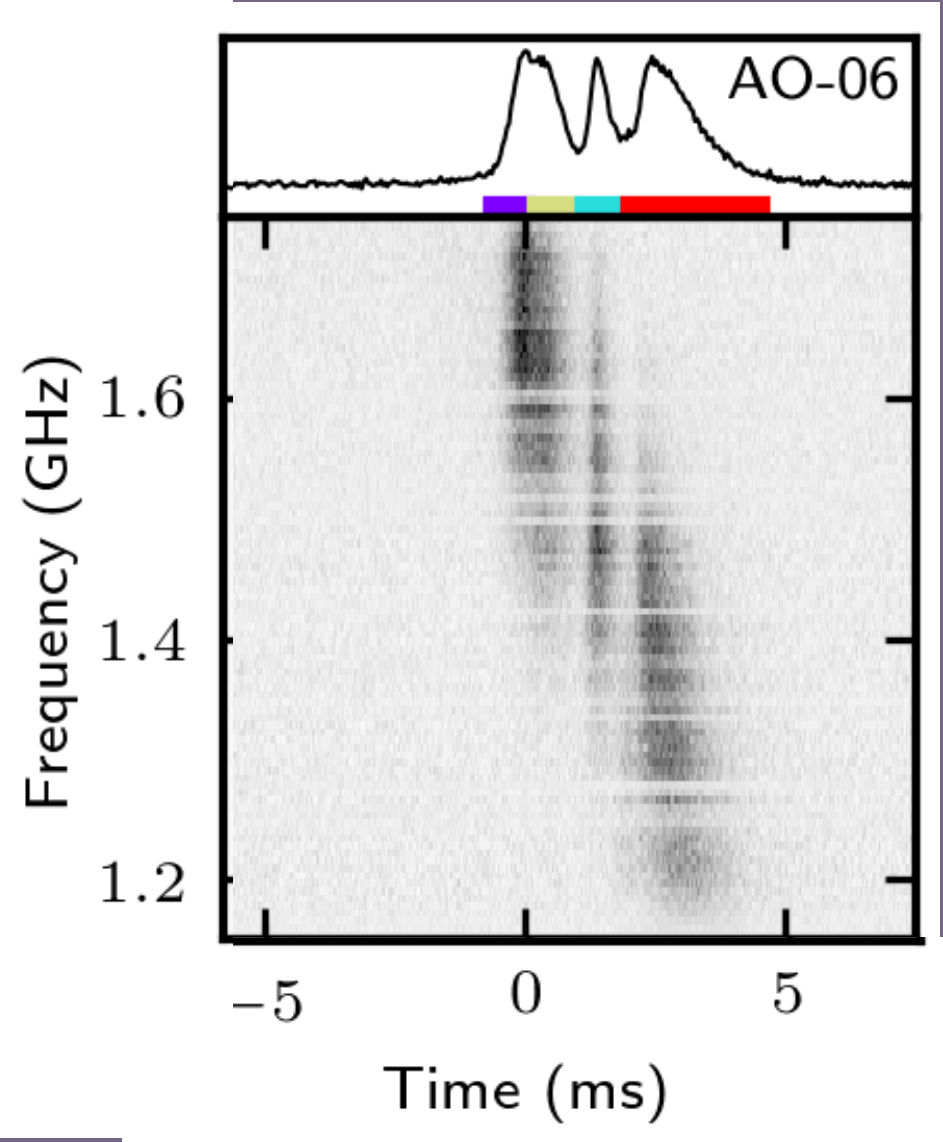


Pleunis et al. 2021
Sand et al. 2025

<p>FRB property</p>	<p>Magnetospheric</p>	<p>Non-magnetospheric</p>
<p>Spectral behaviour</p>		

Metzger et al. 2022

Sad-trombone



Faber et al. *in prep*

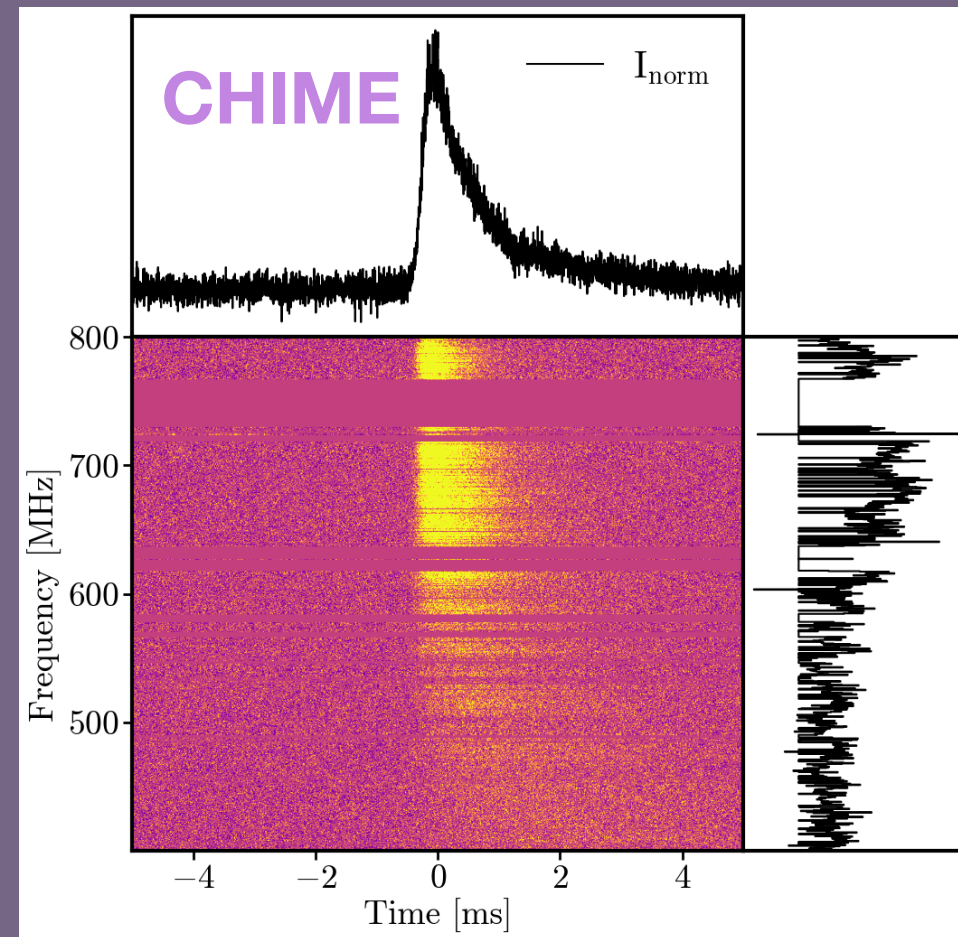
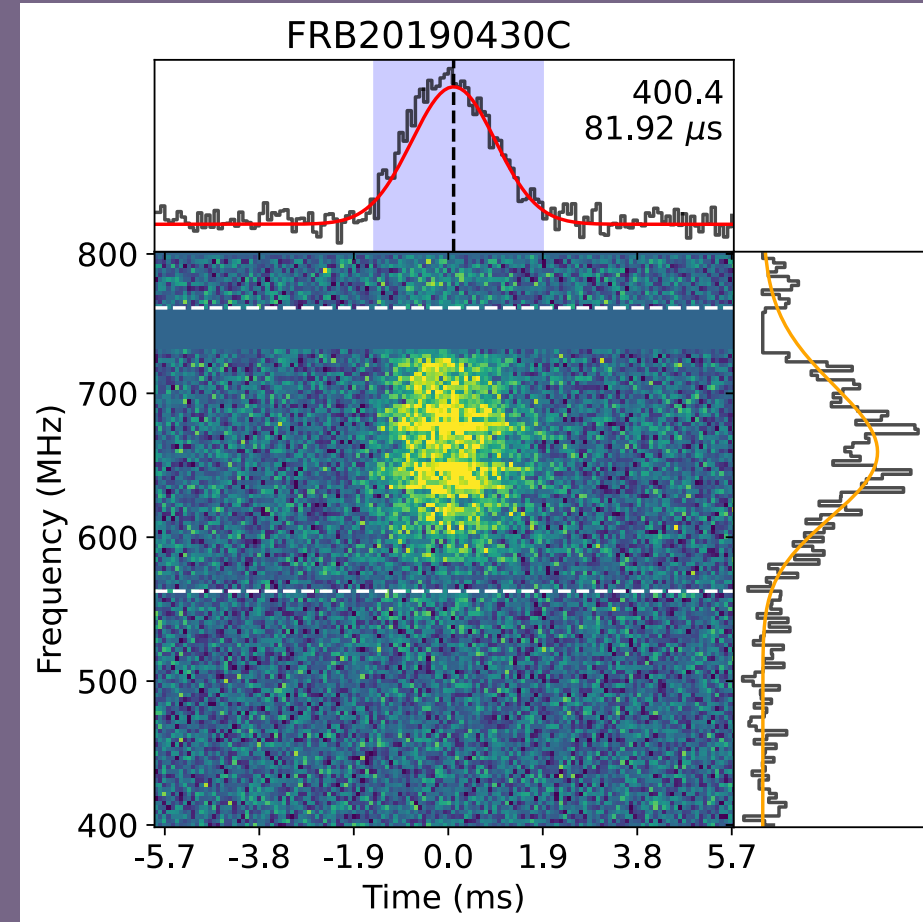
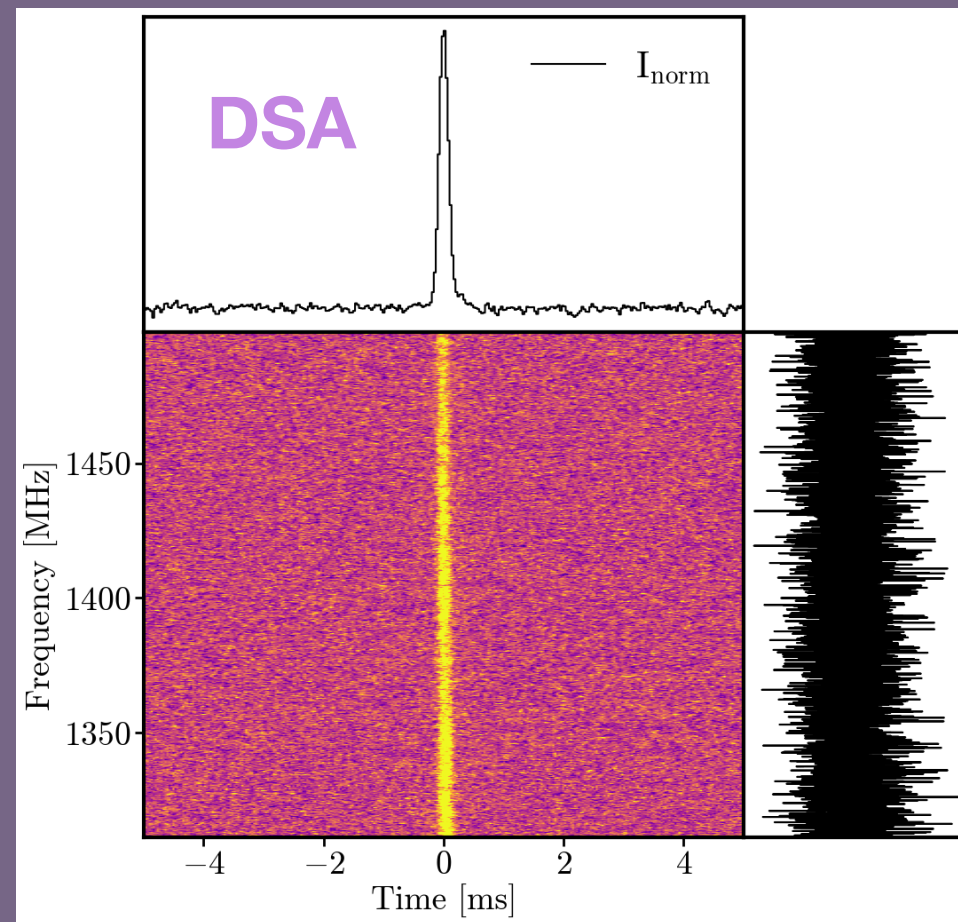
Hessels et al. 2019

Spectral behaviour

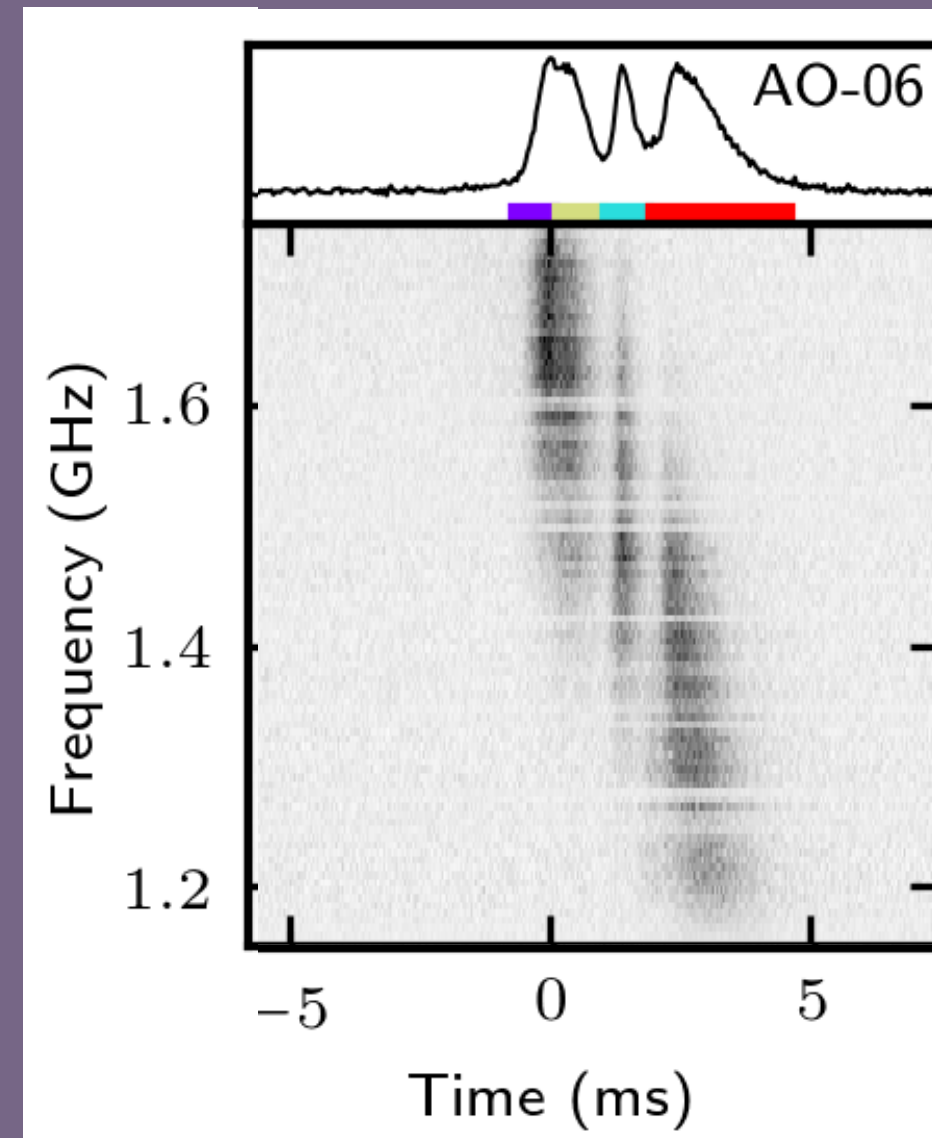
Broadband

Narrowband

Pleunis et al. 2021
Sand et al. 2025



Sad-trombone

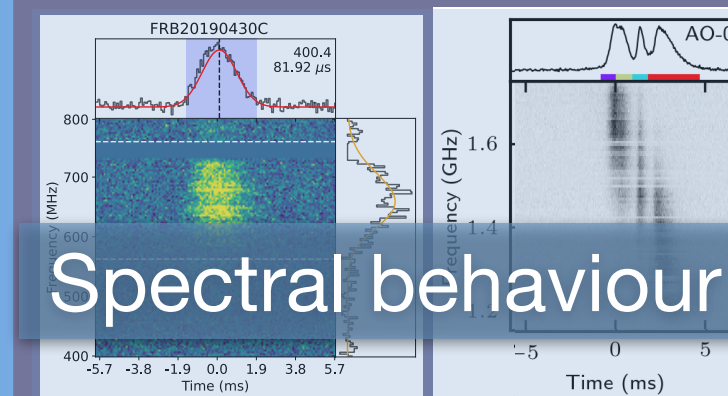


Hessels et al. 2019

FRB property

Magnetospheric

Non-magnetospheric



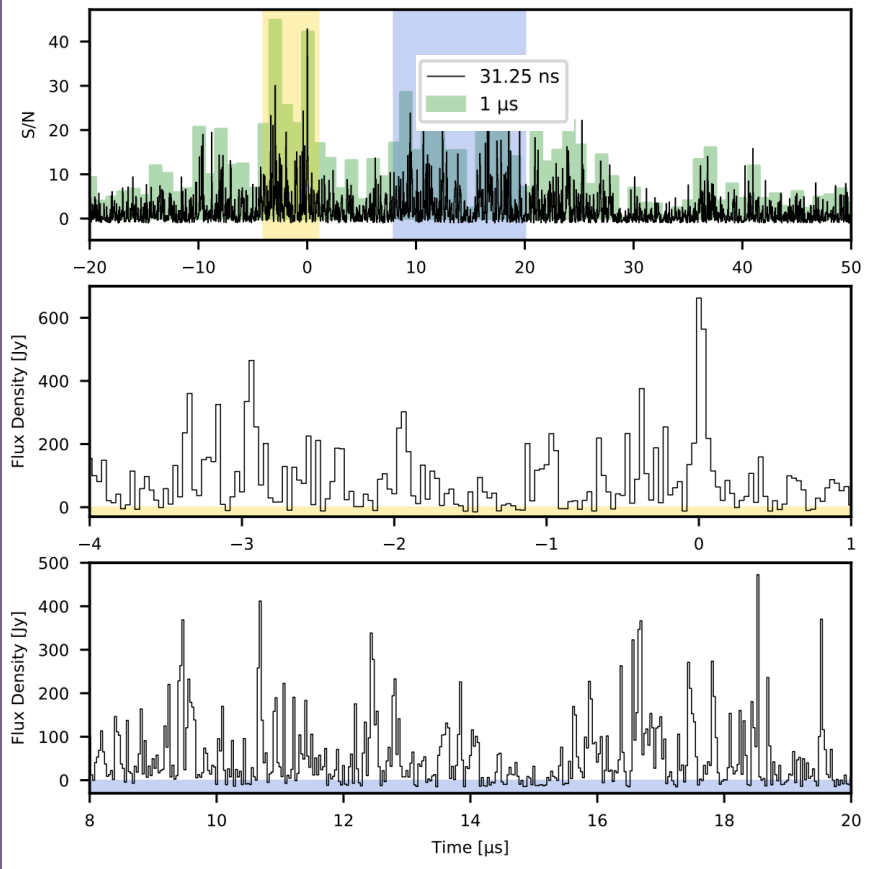
Spectral behaviour



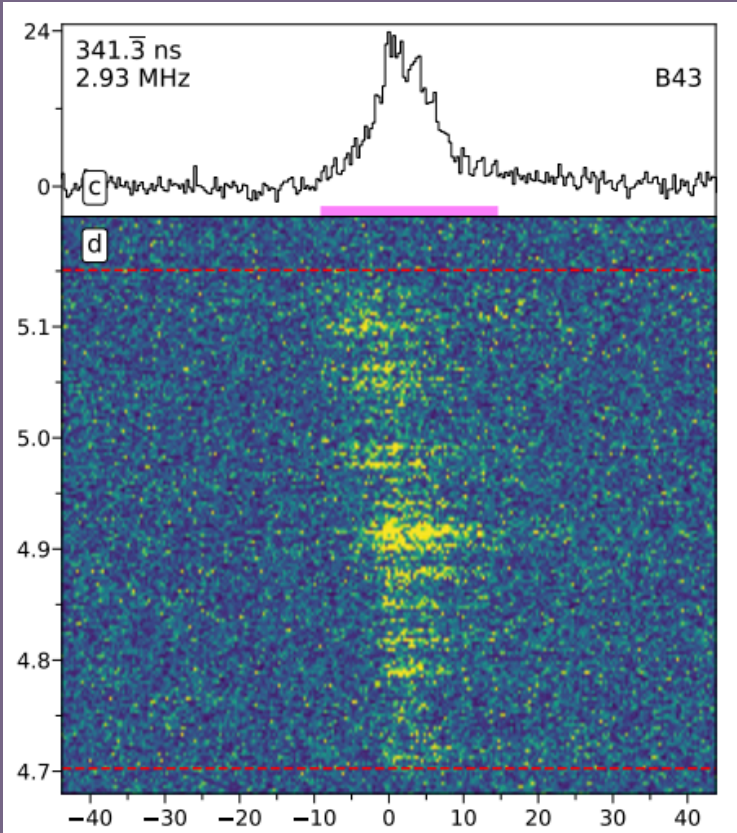
Metzger et al. 2022

Faber et al. *in prep*

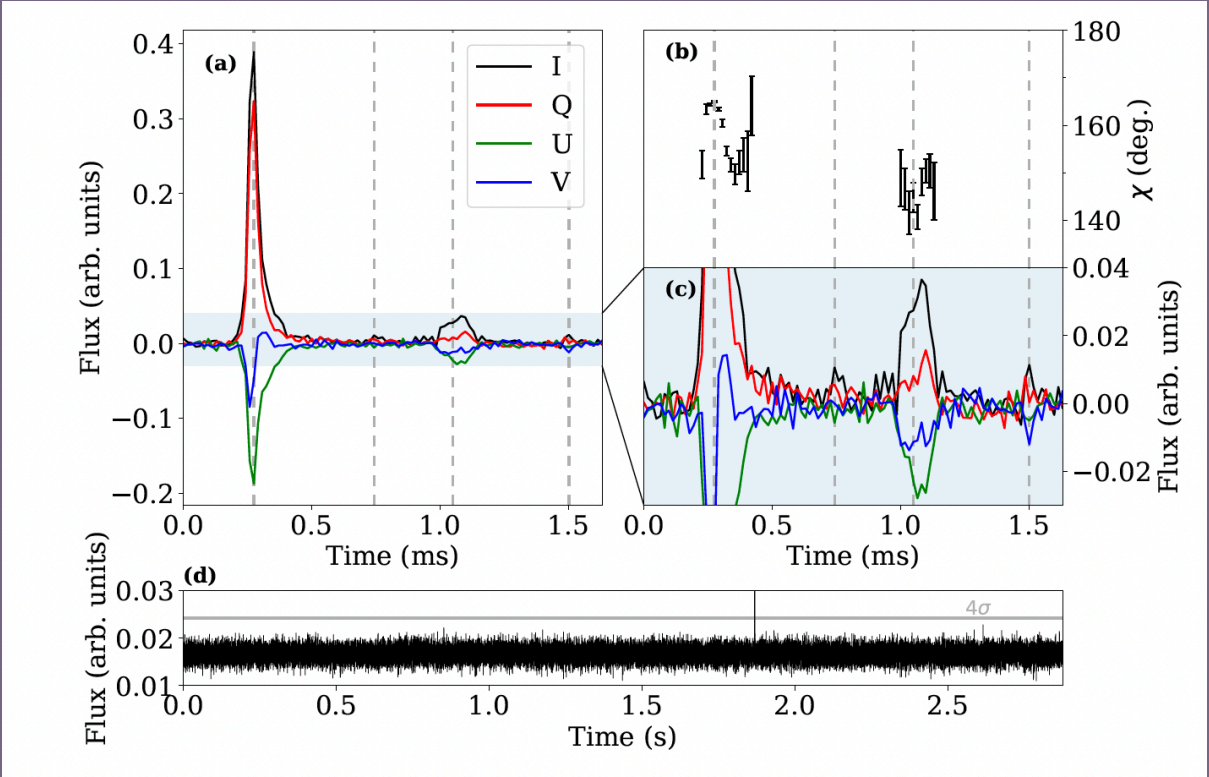
Temporal variability



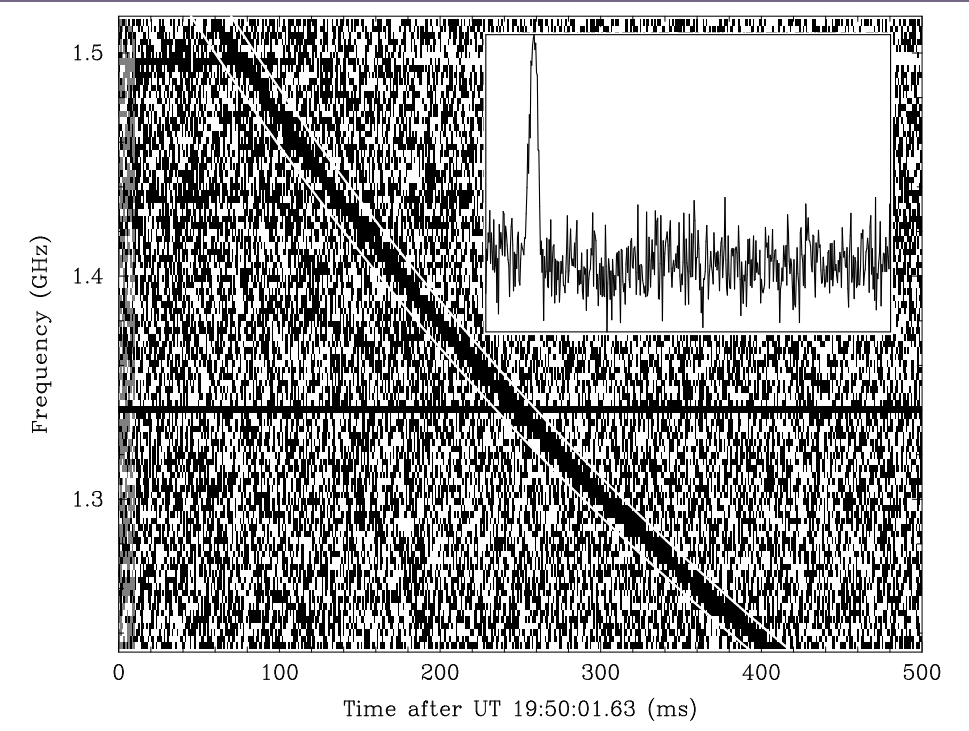
Nimmo et al. 2022



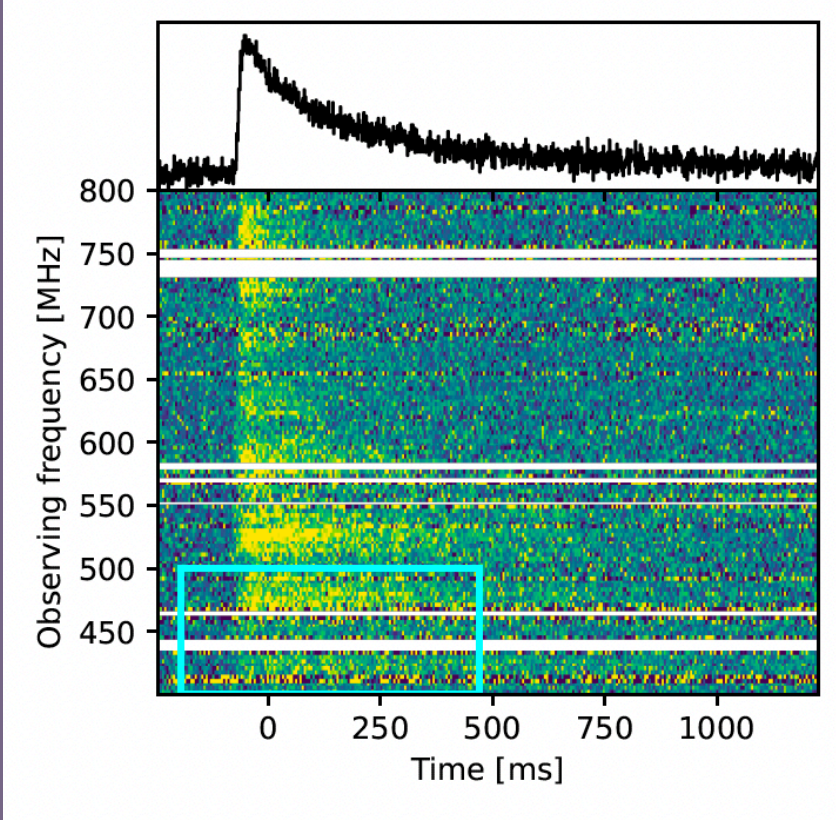
Snelders et al. 2023, Nimmo et al. 2021



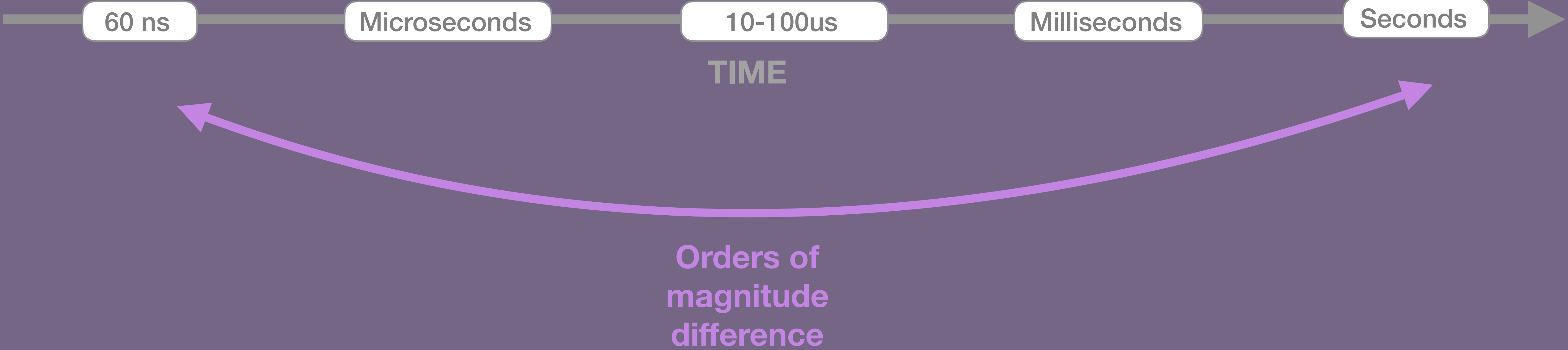
Cho et al. 2020



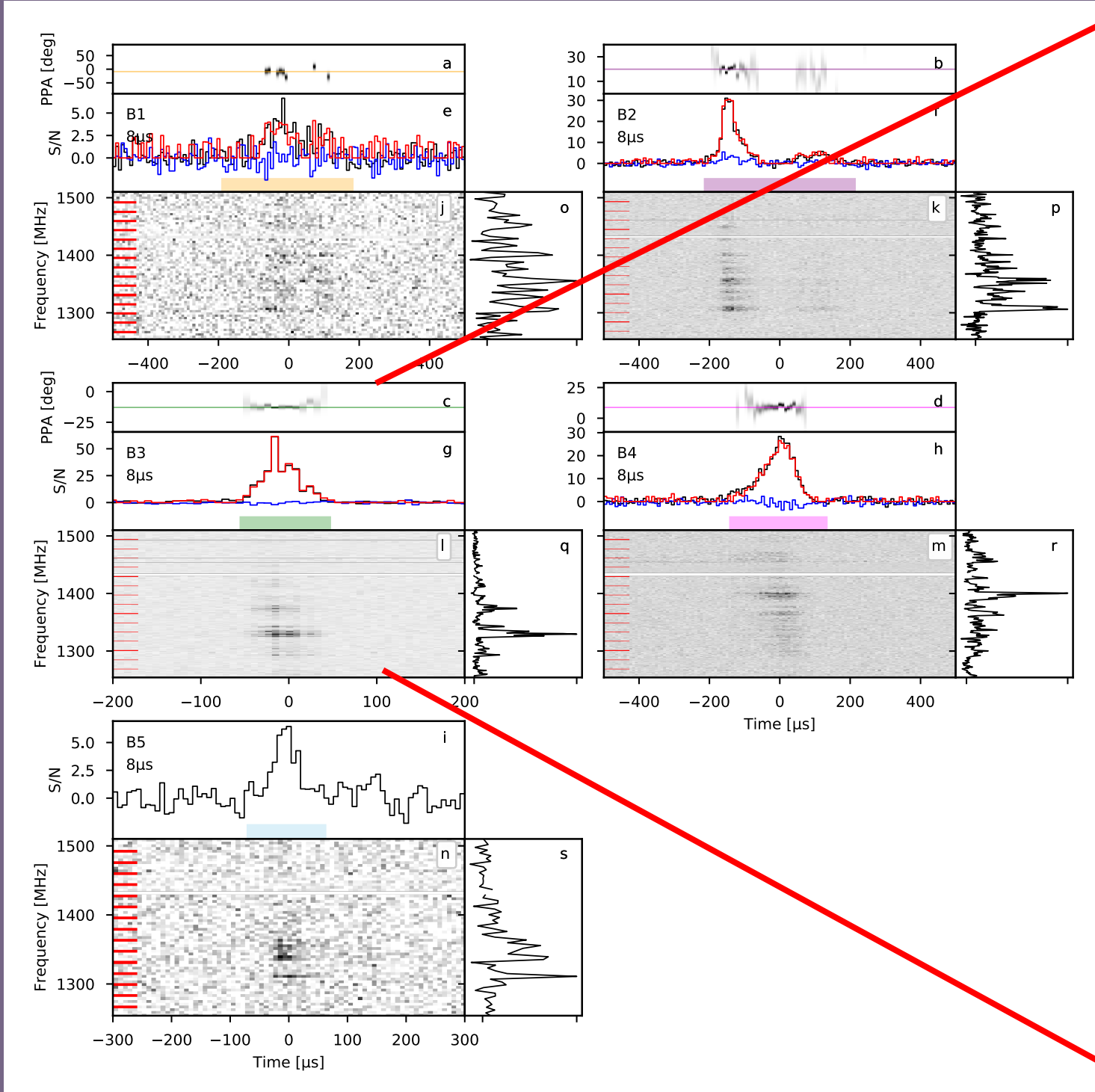
Lorimer et al. 2007



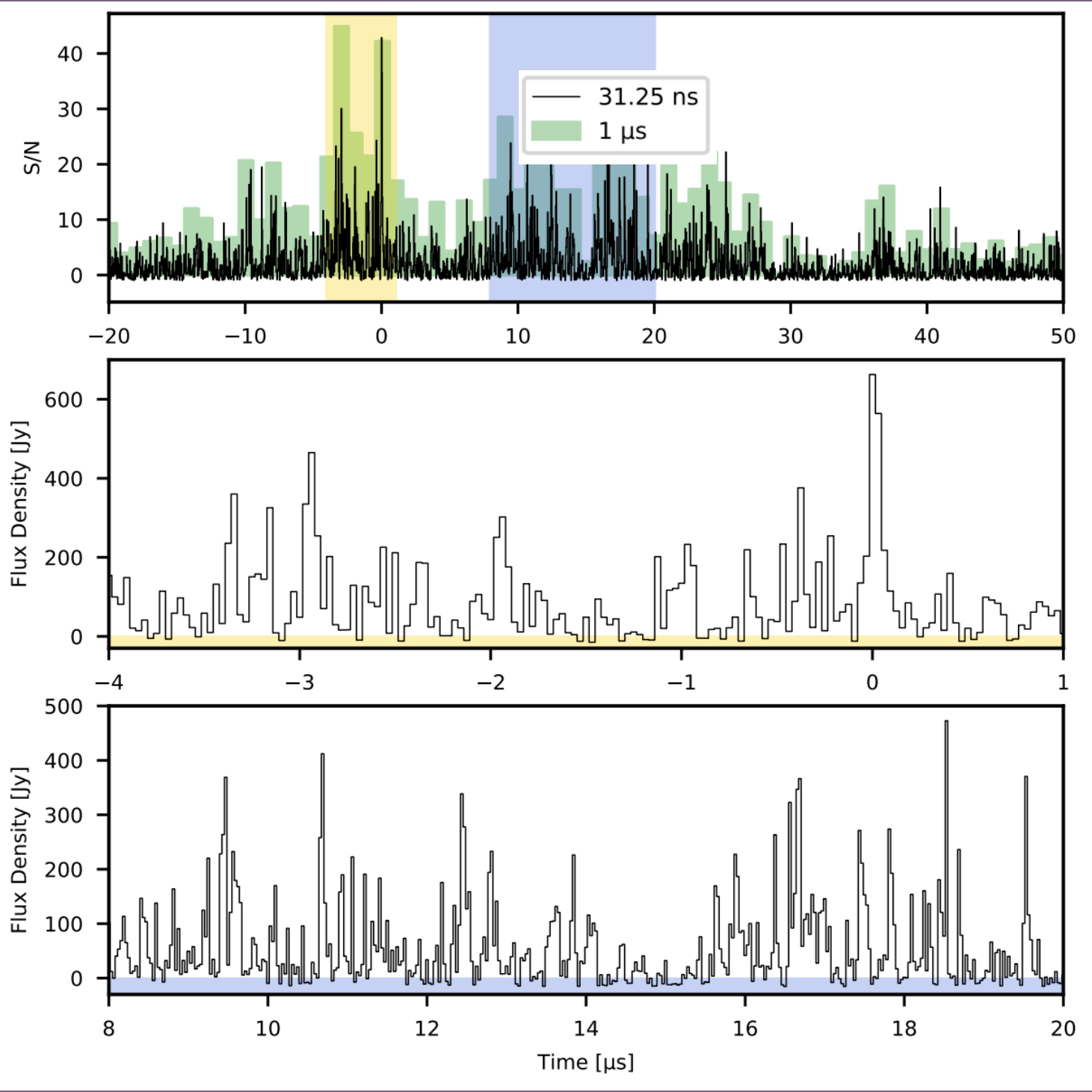
Shin et al. 2024



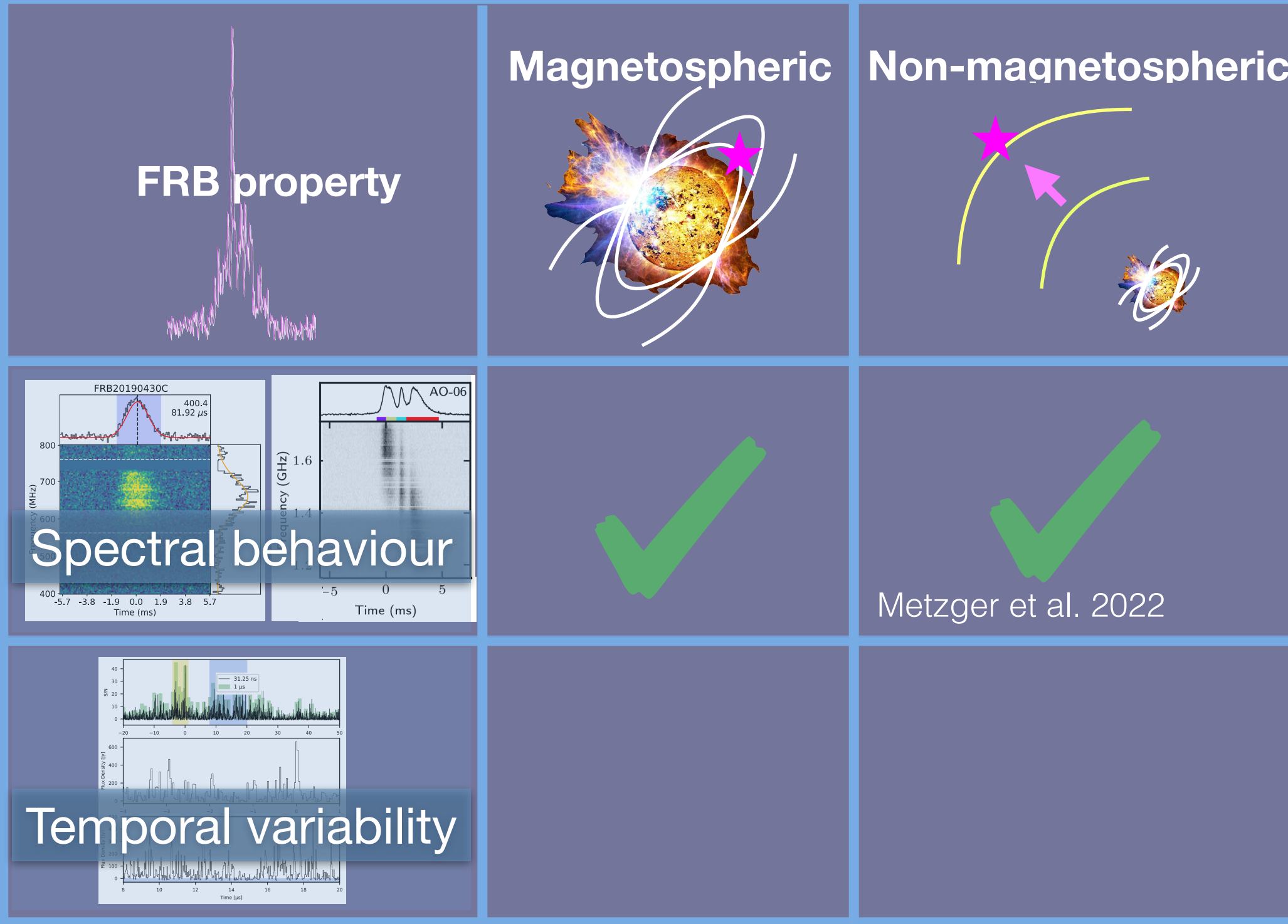
Temporal variability



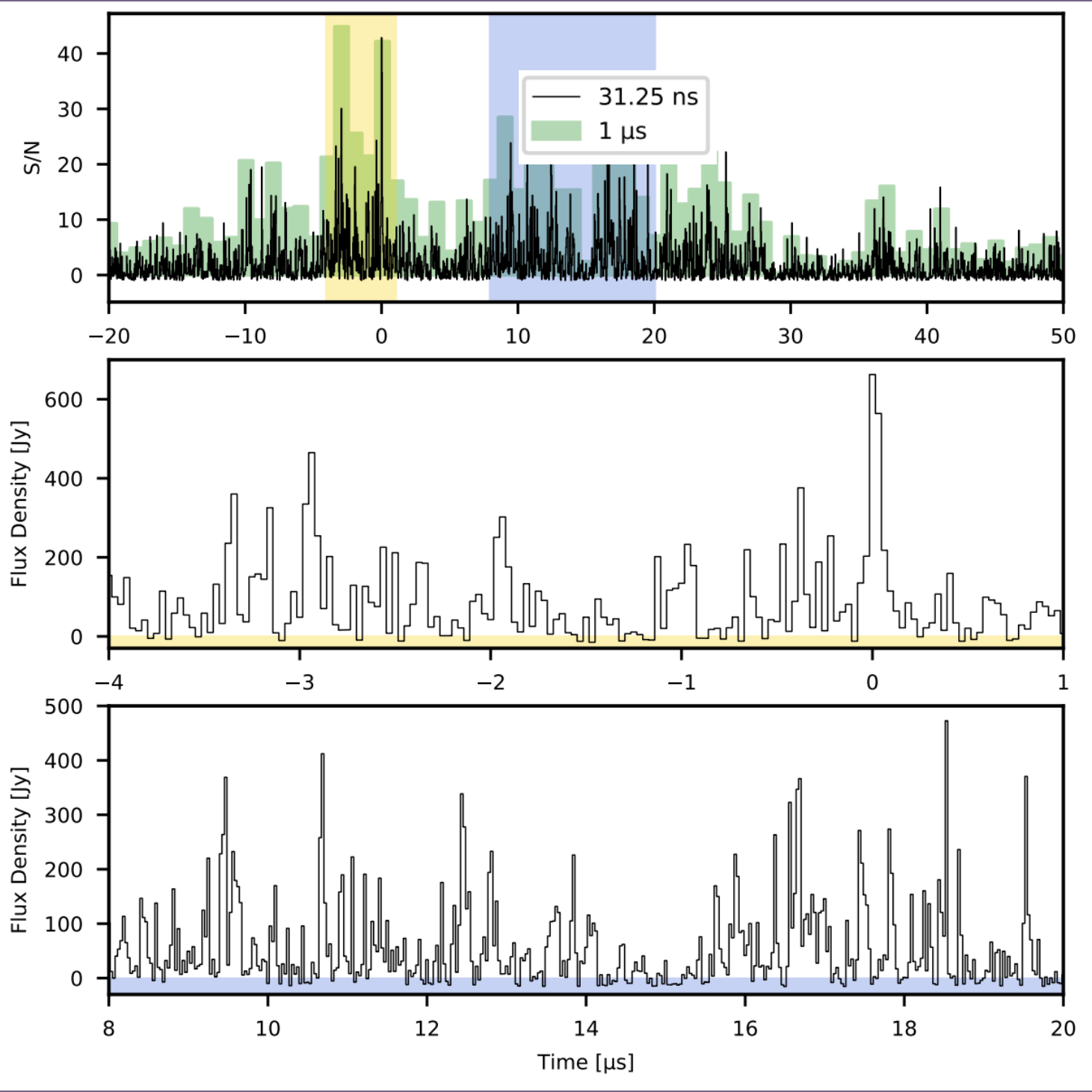
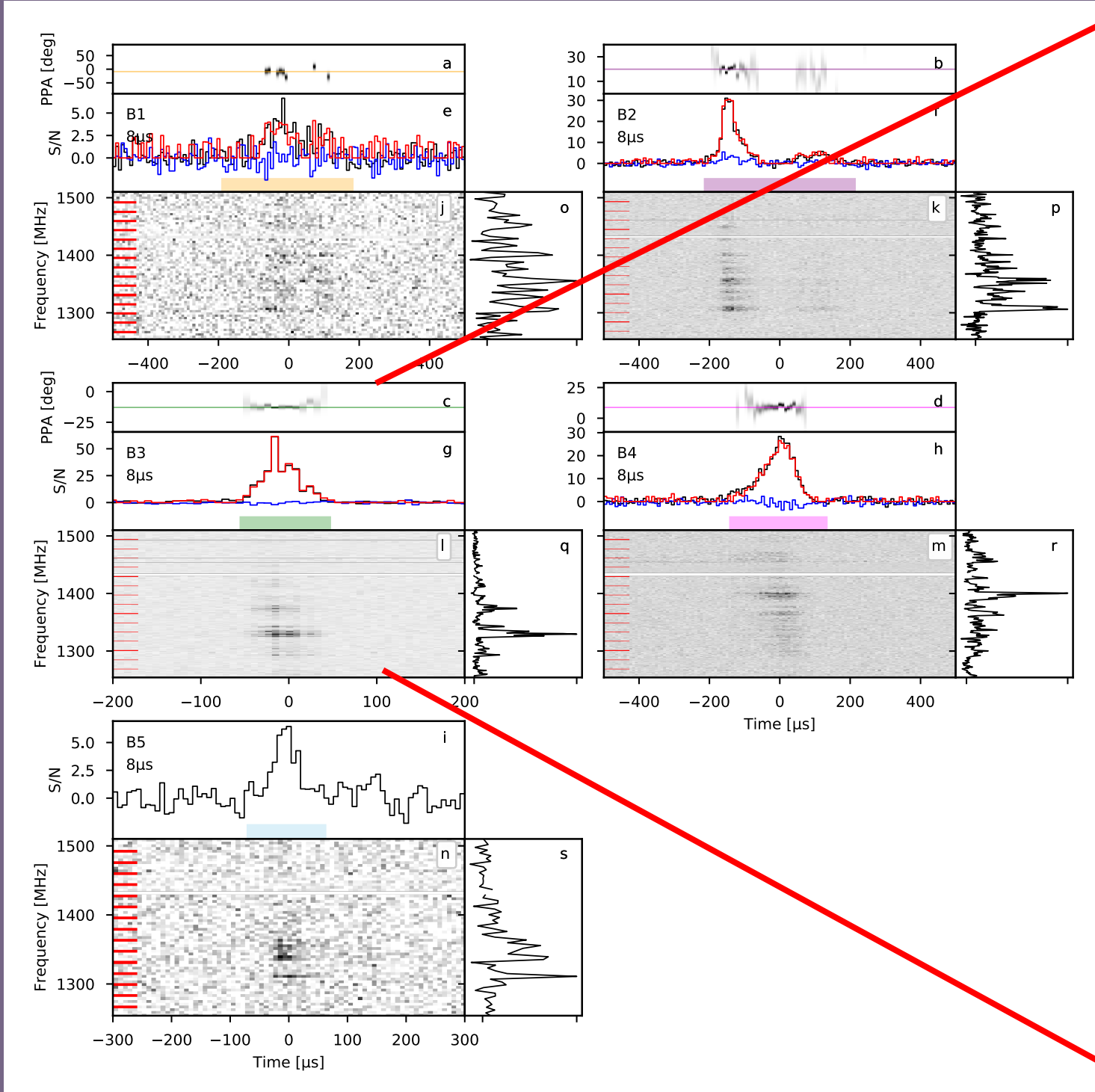
Nimmo et al. 2022a



Beniamini & Kumar 2020



Temporal variability



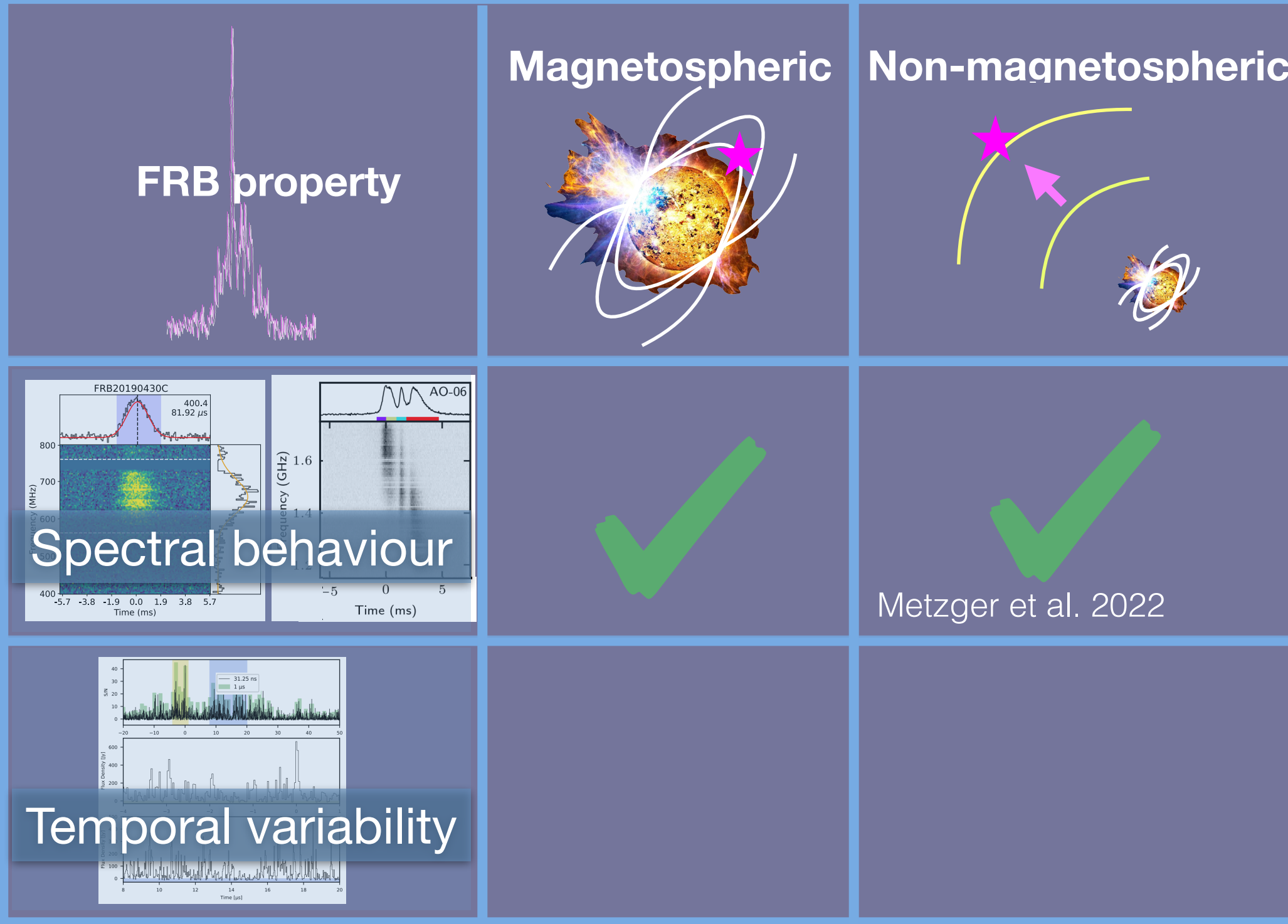
Nimmo et al. 2022a

Implies an emission size ~20m (excl. relativistic effects)

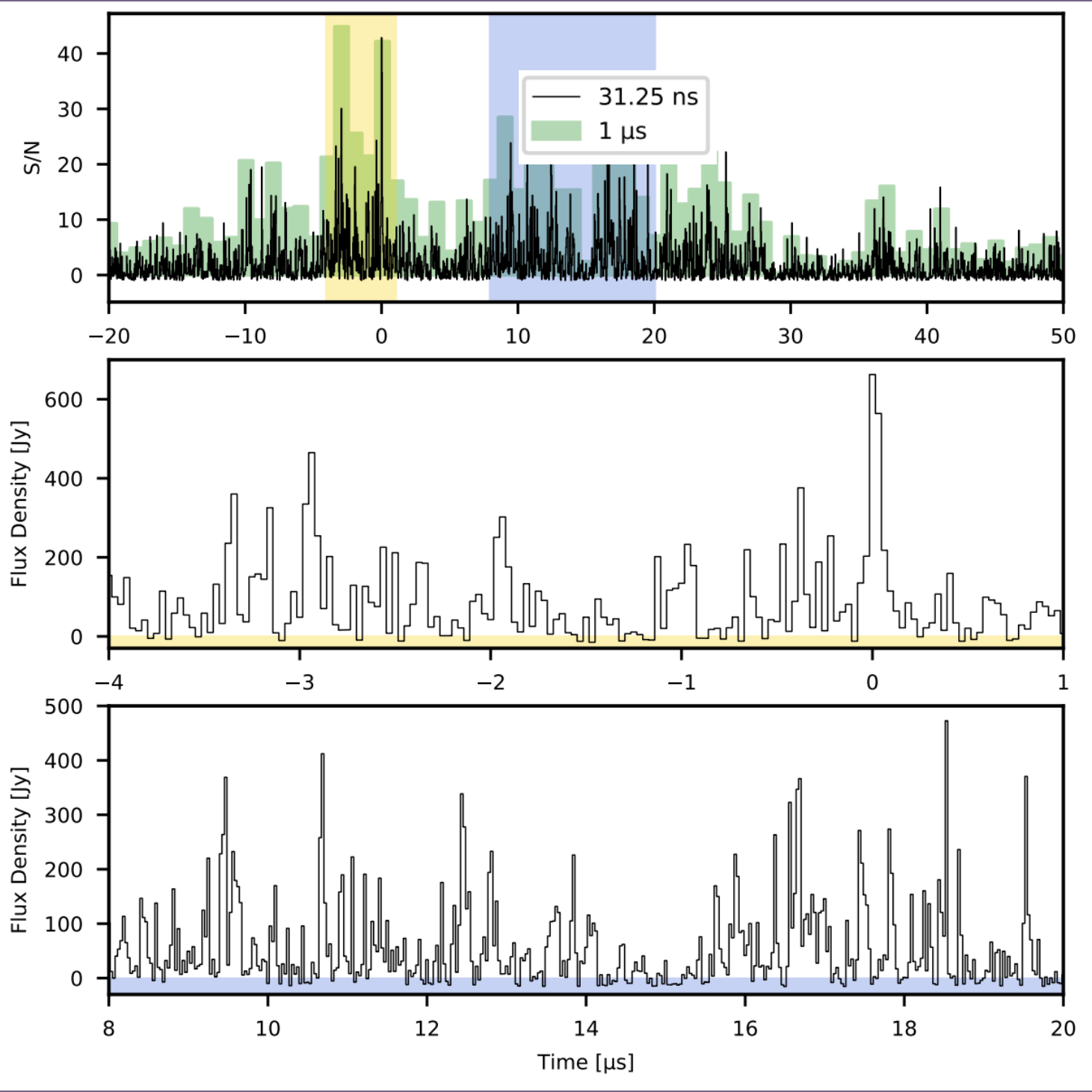
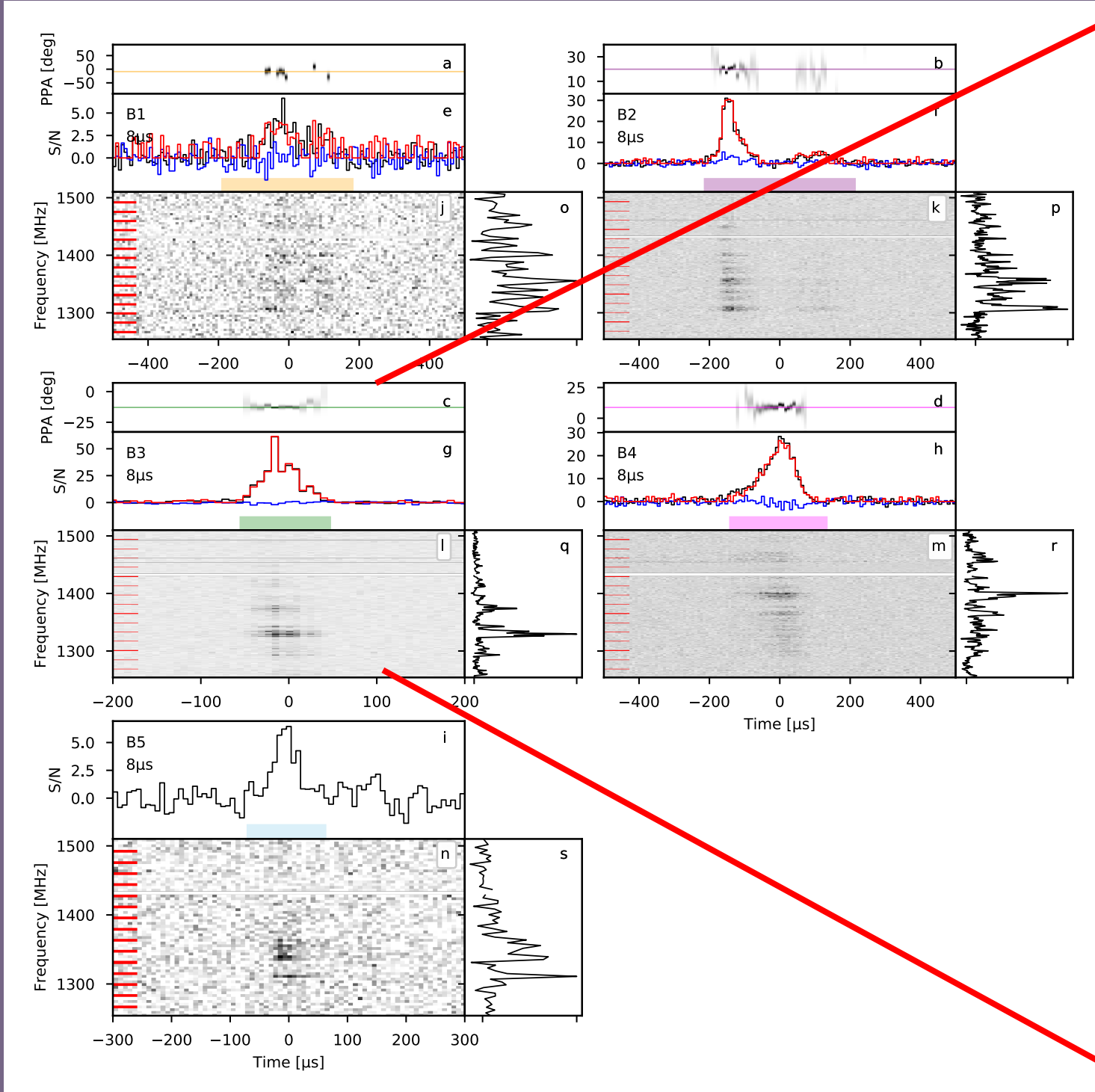
With relativistic correction:

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

Beniamini & Kumar 2020



Temporal variability



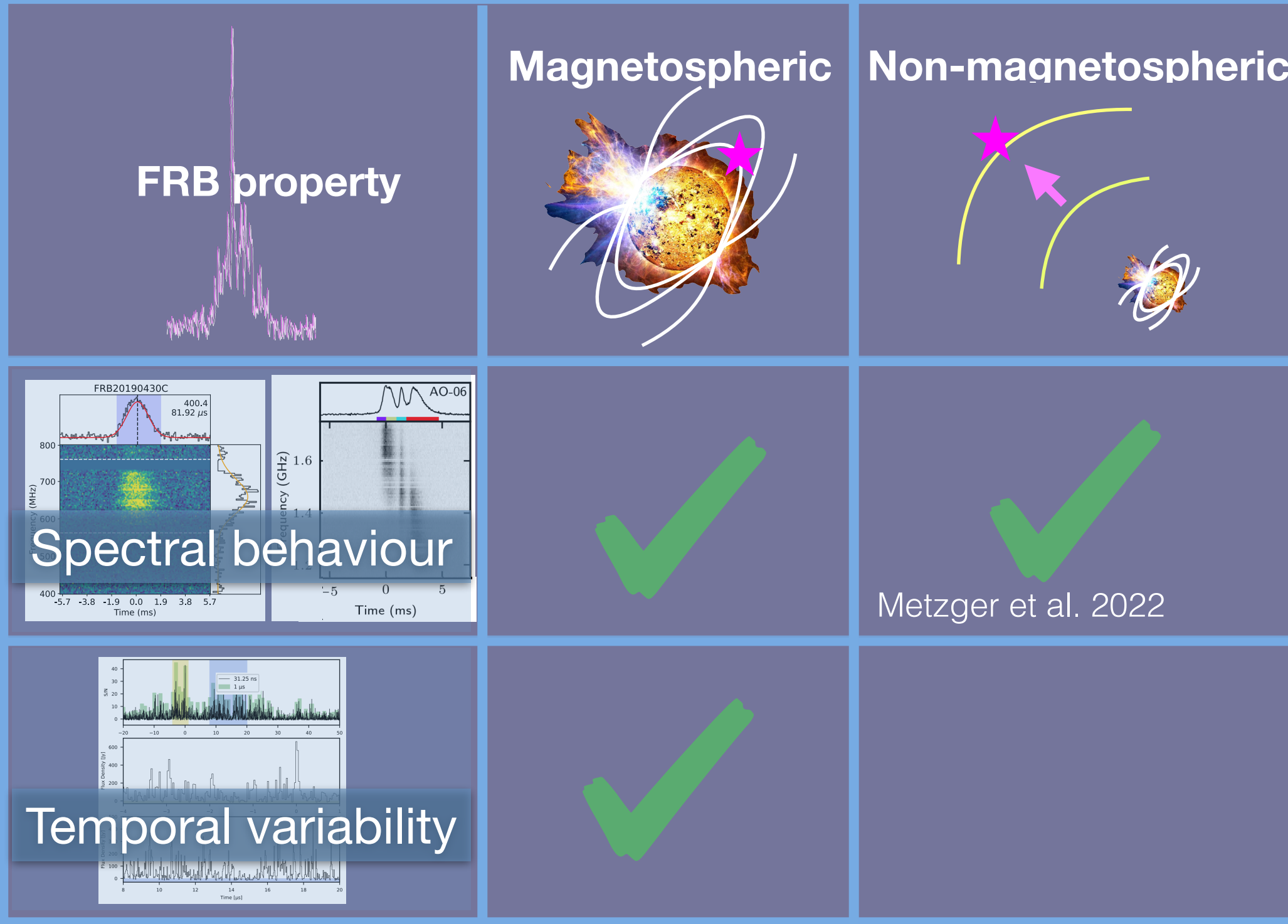
Nimmo et al. 2022a

Implies an emission size ~20m (excl. relativistic effects)

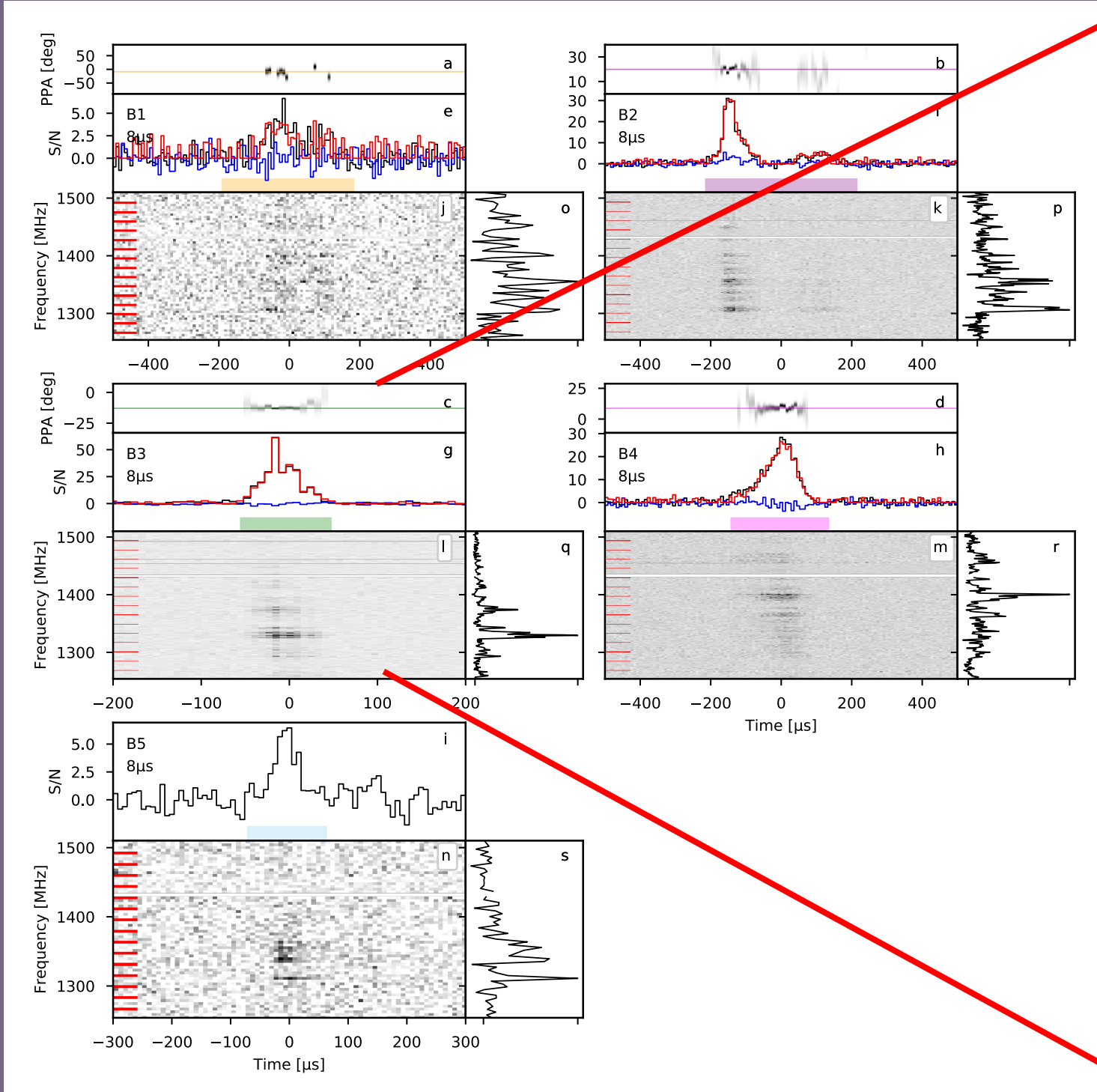
With relativistic correction:

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

Beniamini & Kumar 2020



Temporal variability



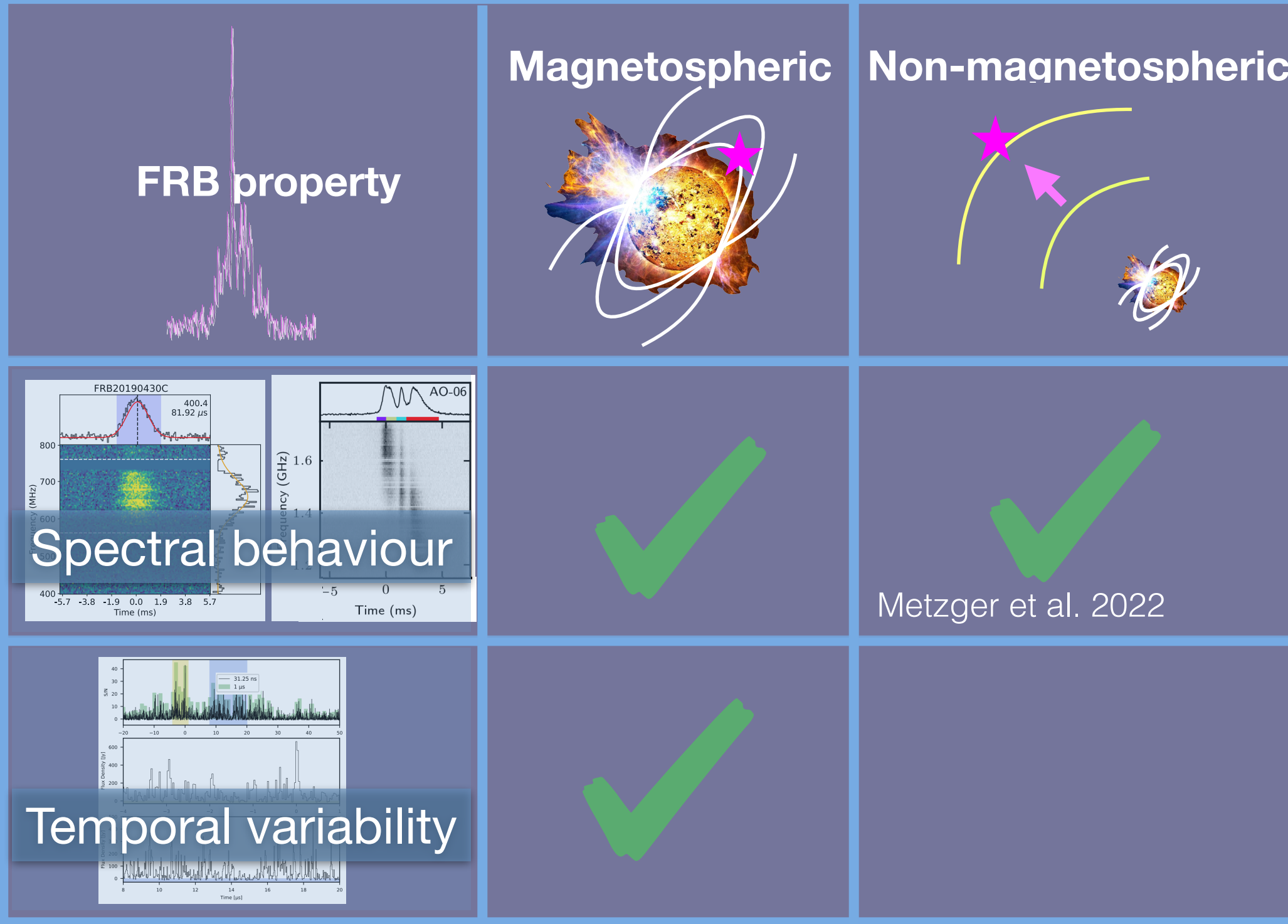
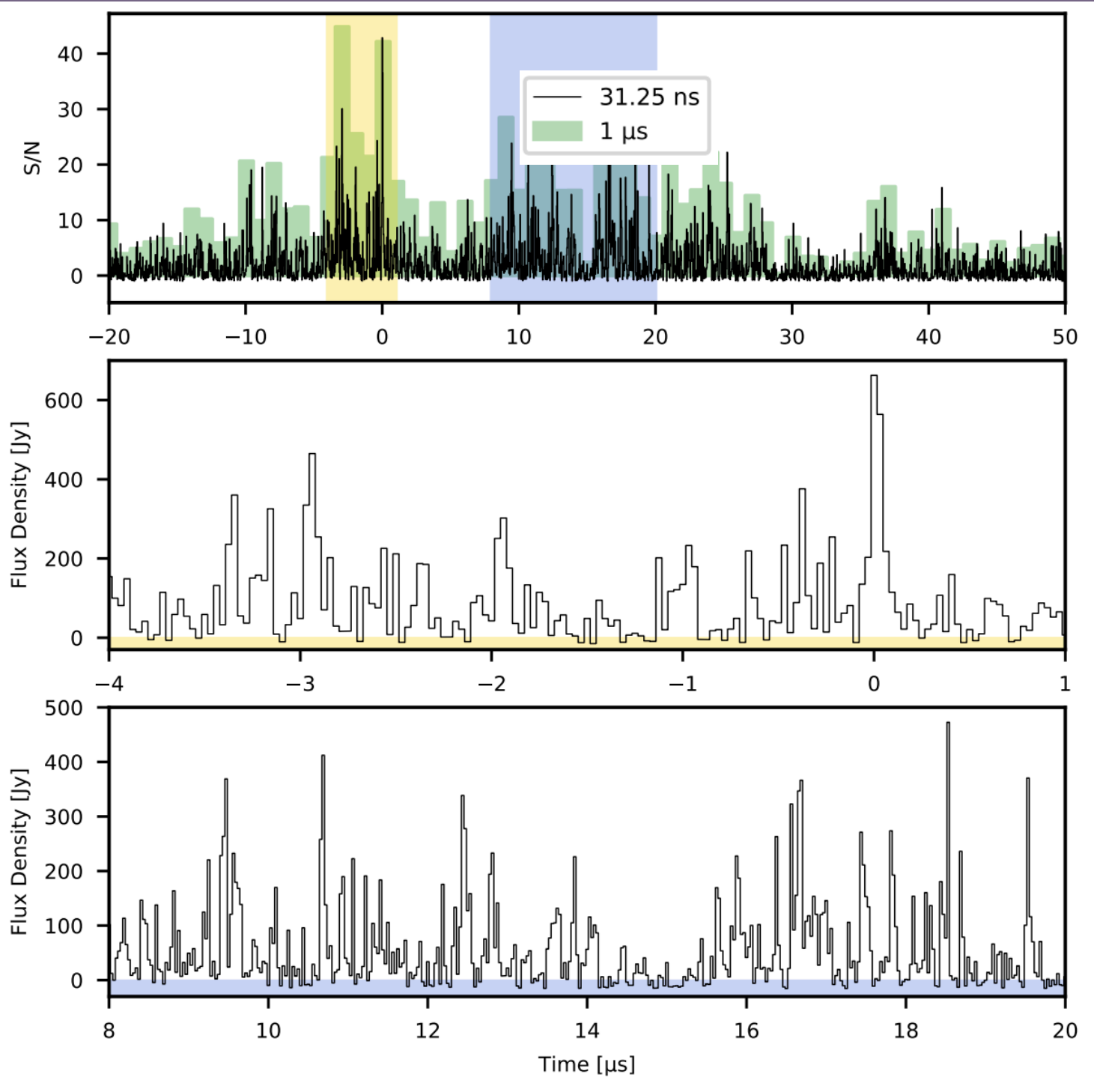
Nimmo et al. 2022a

Implies an emission size ~20m (excl. relativistic effects)

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Beniamini & Kumar 2020



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

FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour	Metzger et al. 2022	
Temporal variability	Sobacchi et al. 2021, 2024b	

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* Caveat

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Spectral behaviour	Metzger et al. 2022	
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Implying...

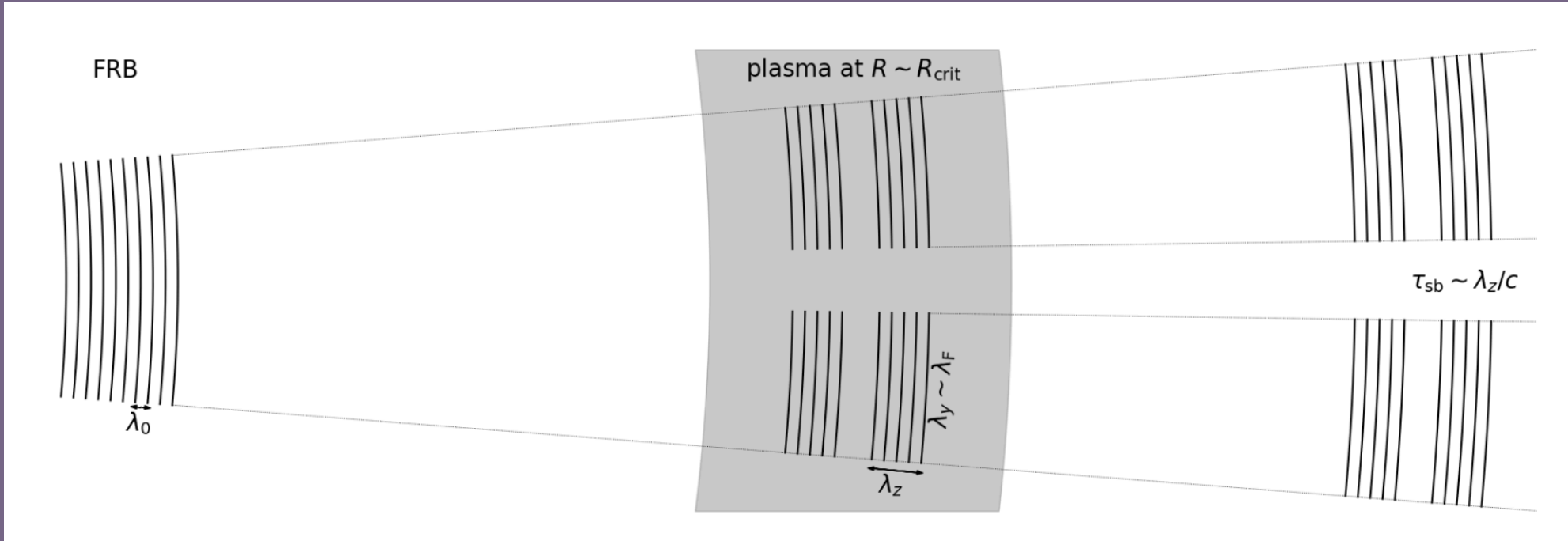
$$W \simeq \delta t$$

Temporal variability

* Caveat

Propagation effects?

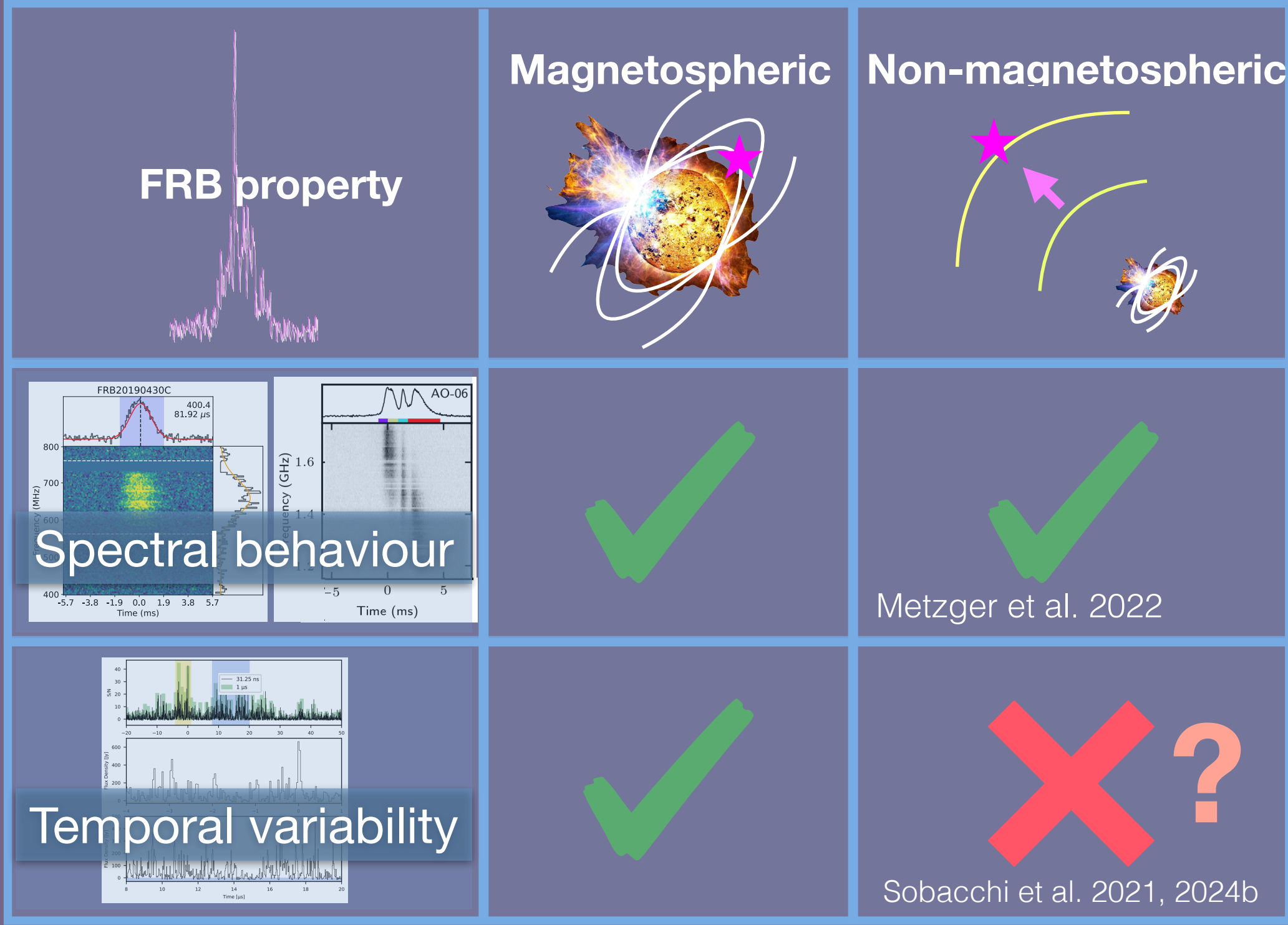
Self-modulation



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:

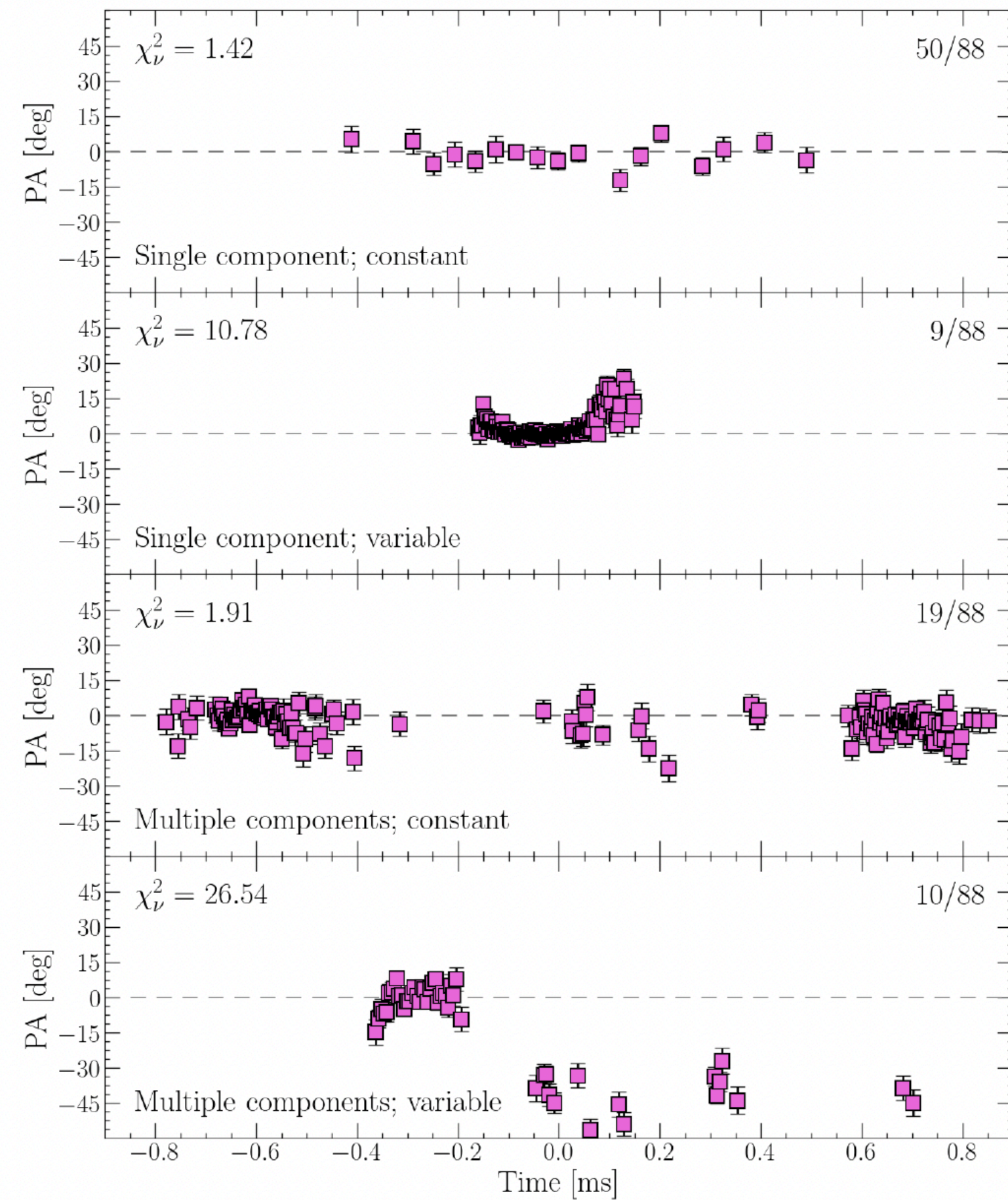
$$W \sim \frac{R_{\text{em}}}{c\Gamma^2}$$

Implying...

$$W \simeq \delta t$$

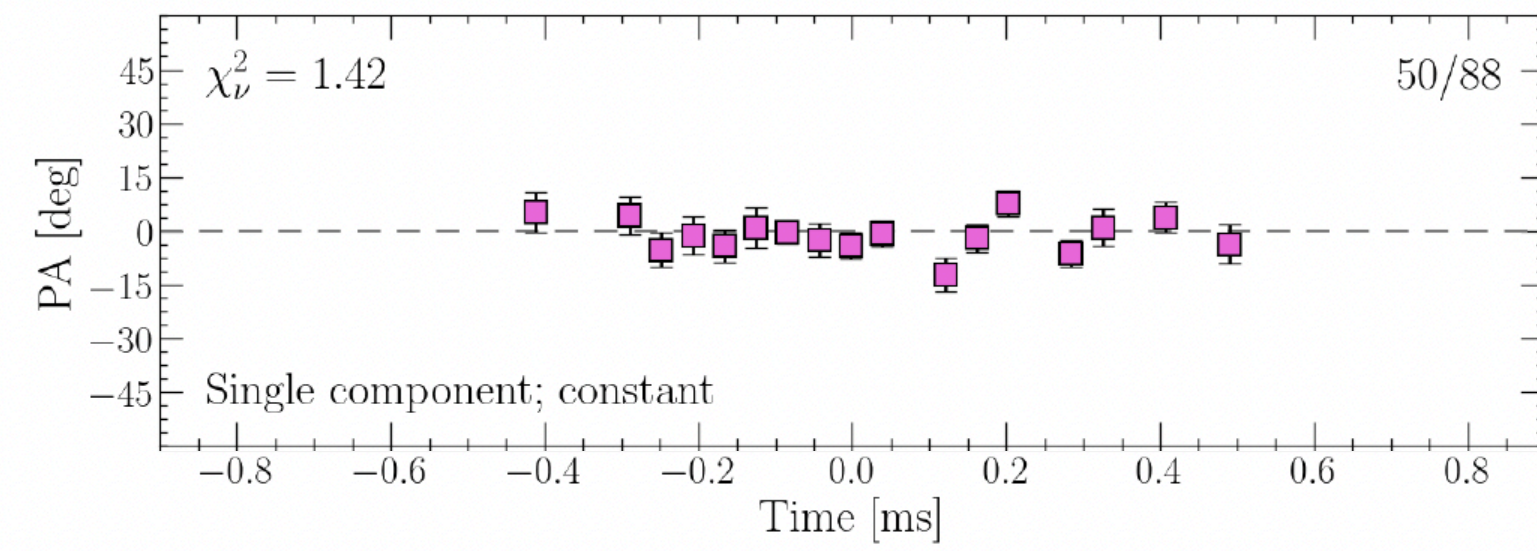
Metzger et al. 2019

Polarization



highly structured magnetic
field configurations

Polarization

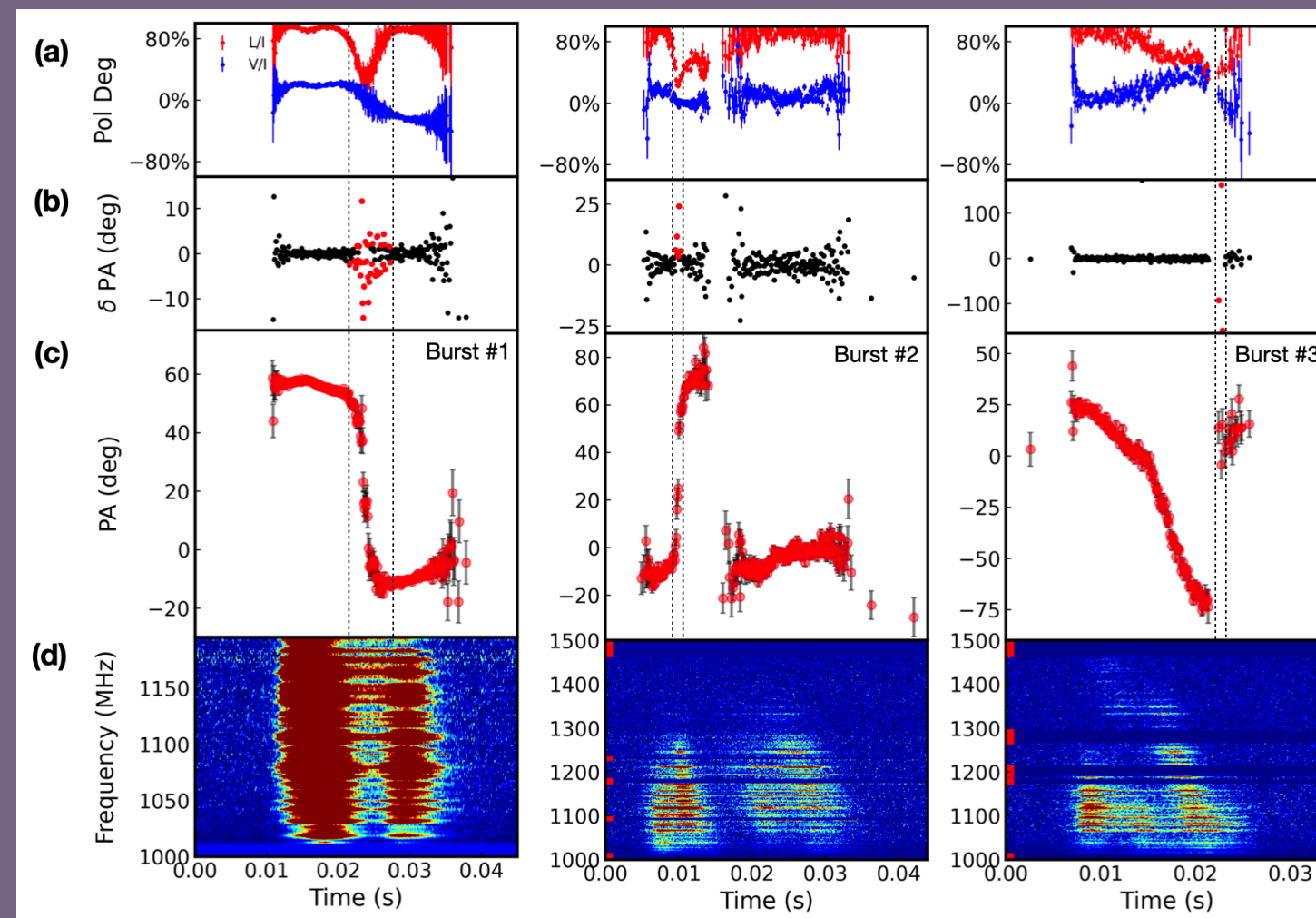


Pandhi et al. 2024

highly structured magnetic
field configurations

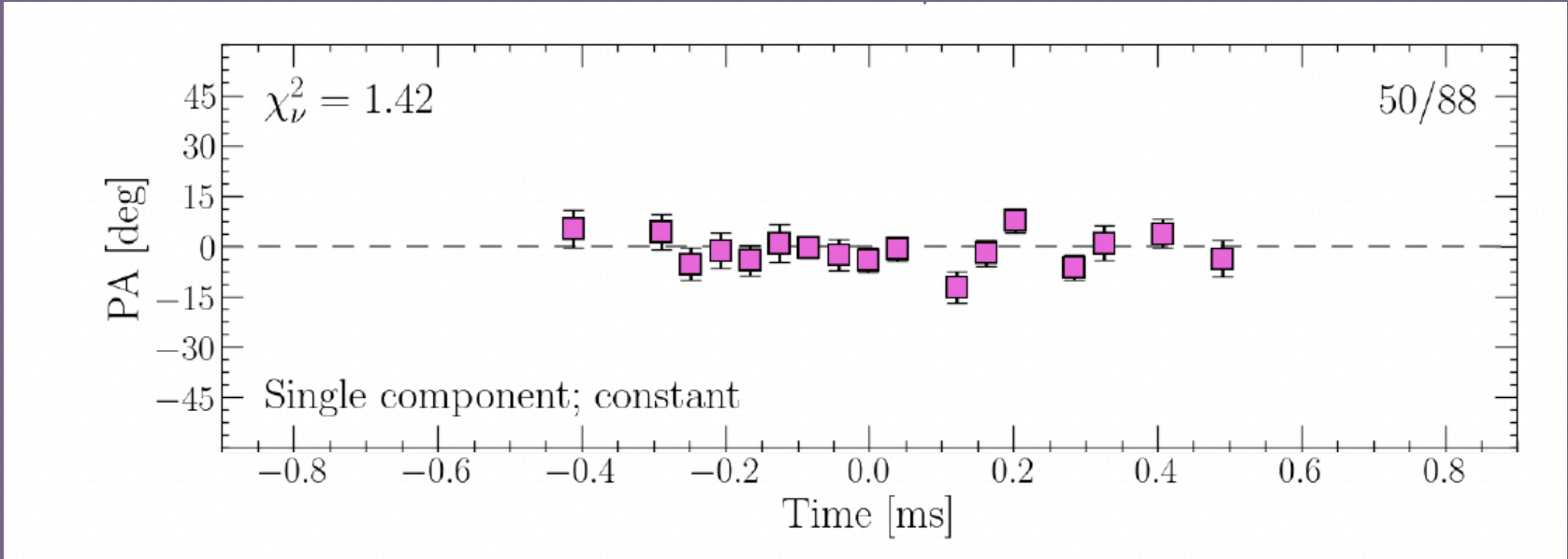
But sometimes...

JUMPS



Niu et al. 2024

Polarization



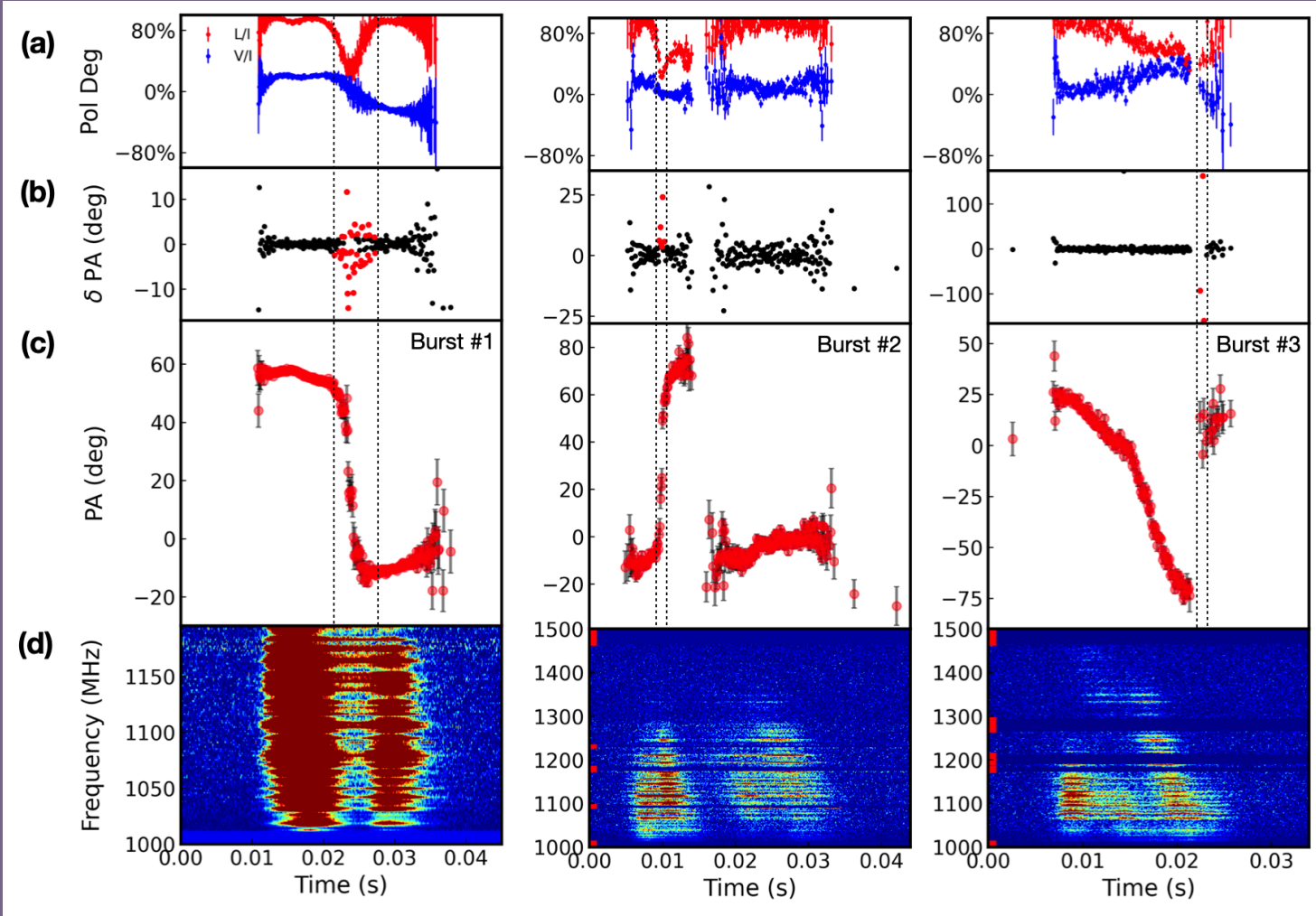
Pandhi et al. 2024

highly structured magnetic field configurations

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

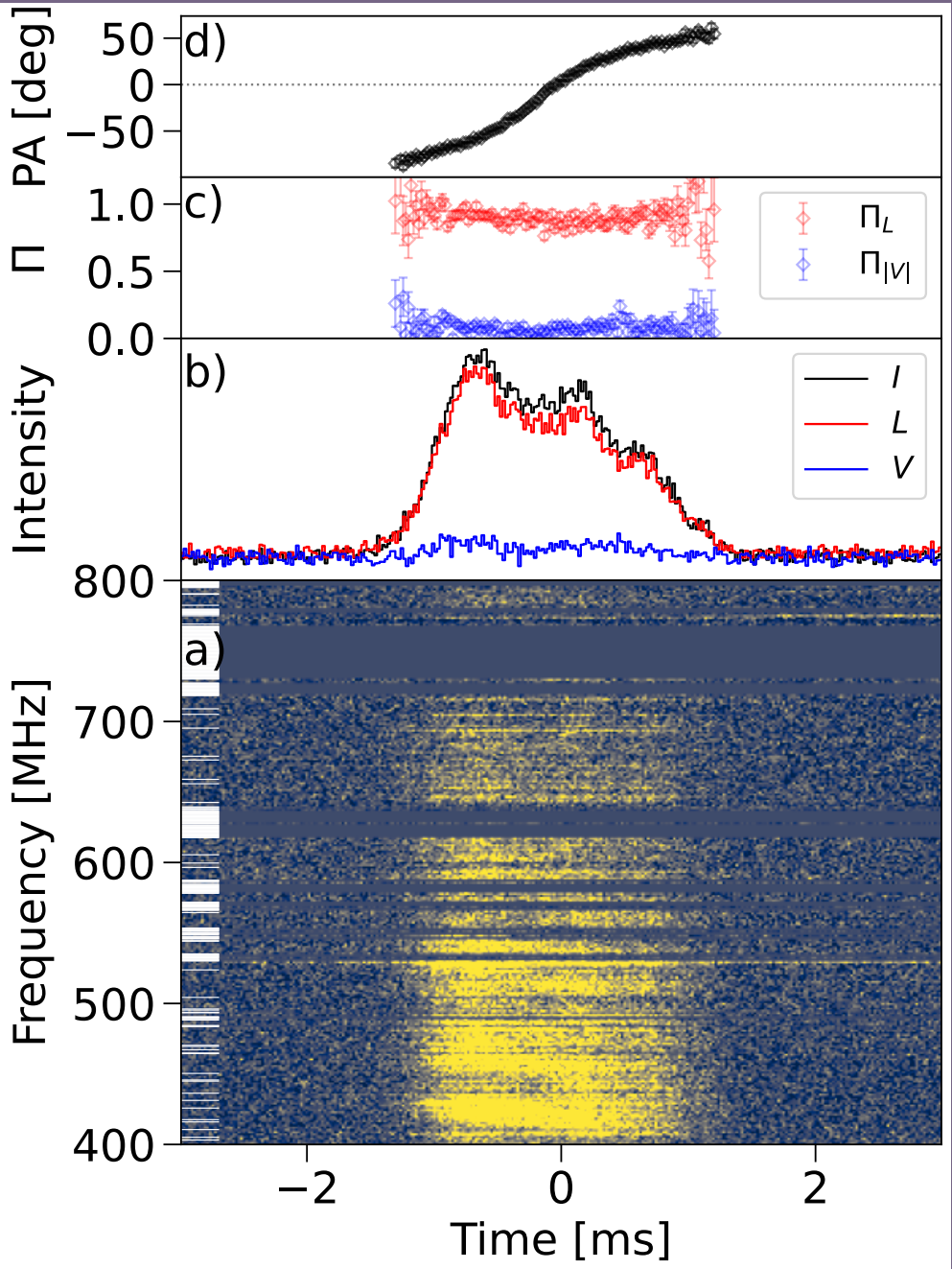
But sometimes...

JUMPS

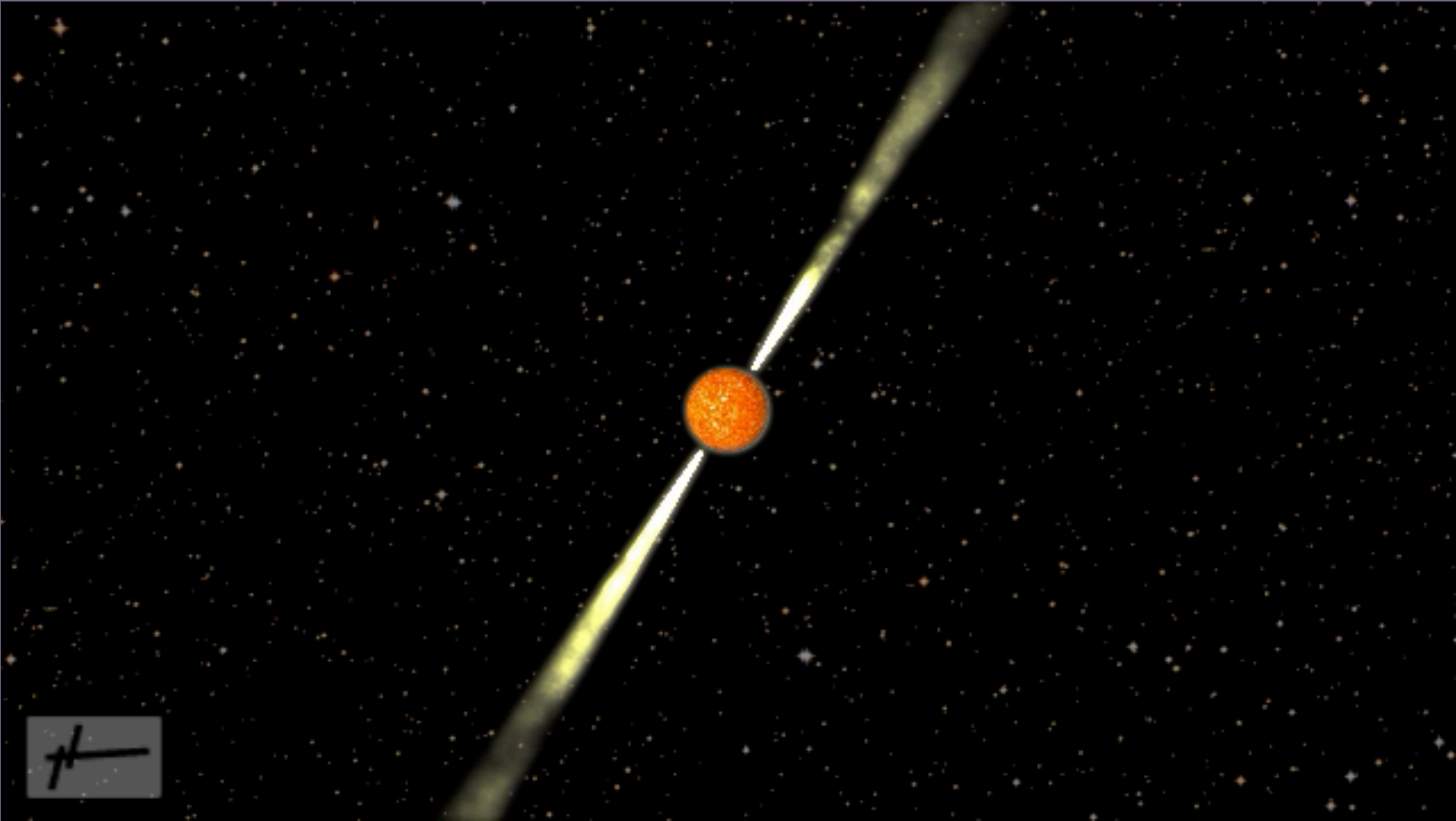


Niu et al. 2024

SWINGS



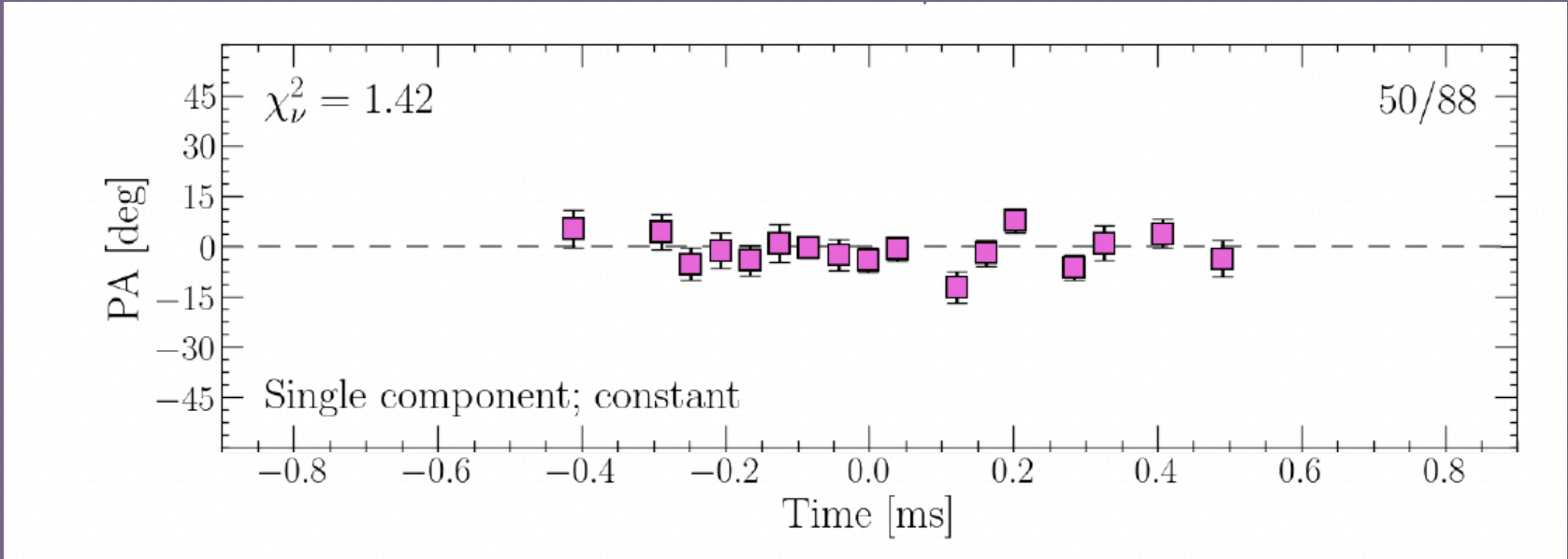
Mckinven et al. 2025



Credit: van Leeuwen

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

Polarization



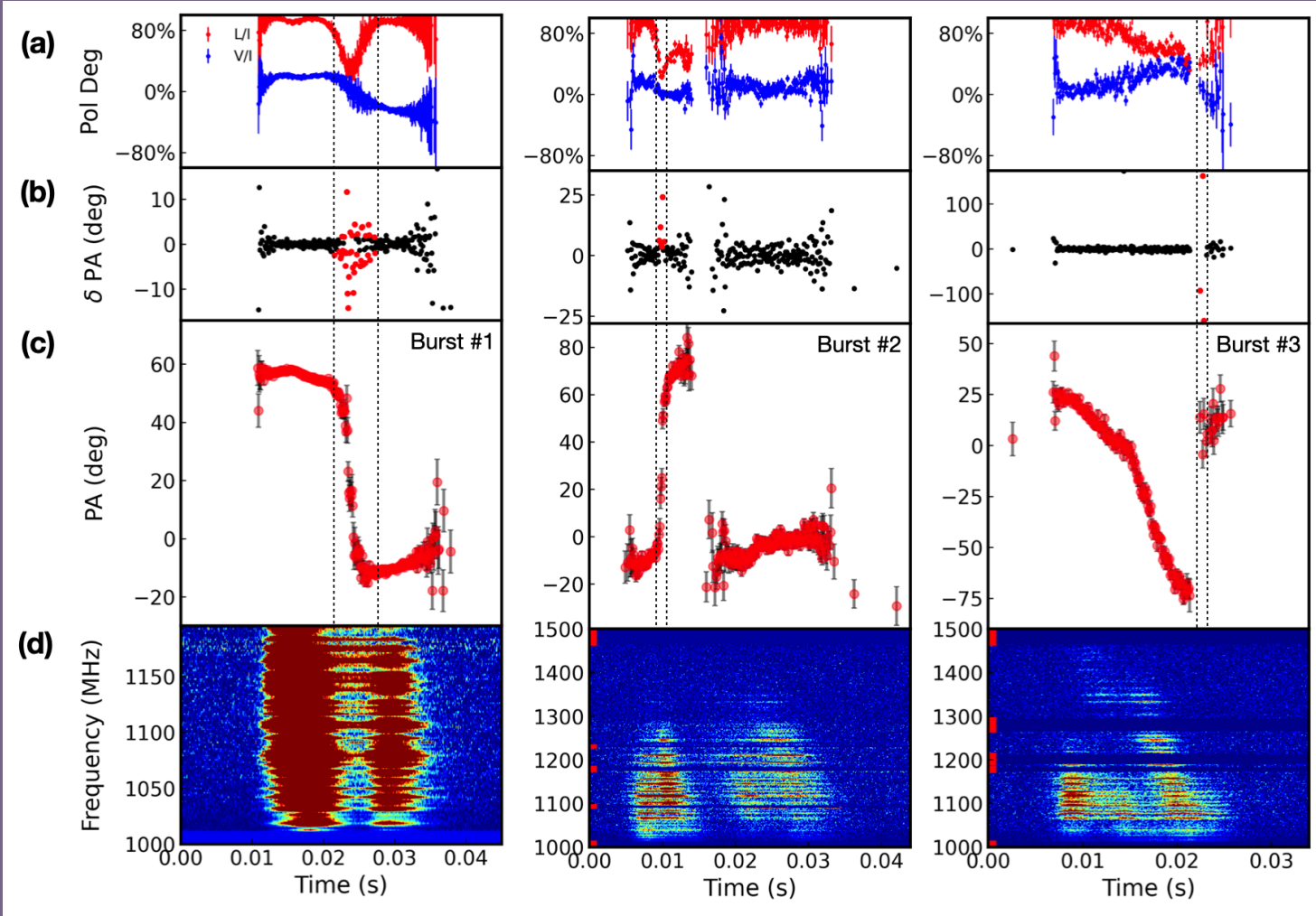
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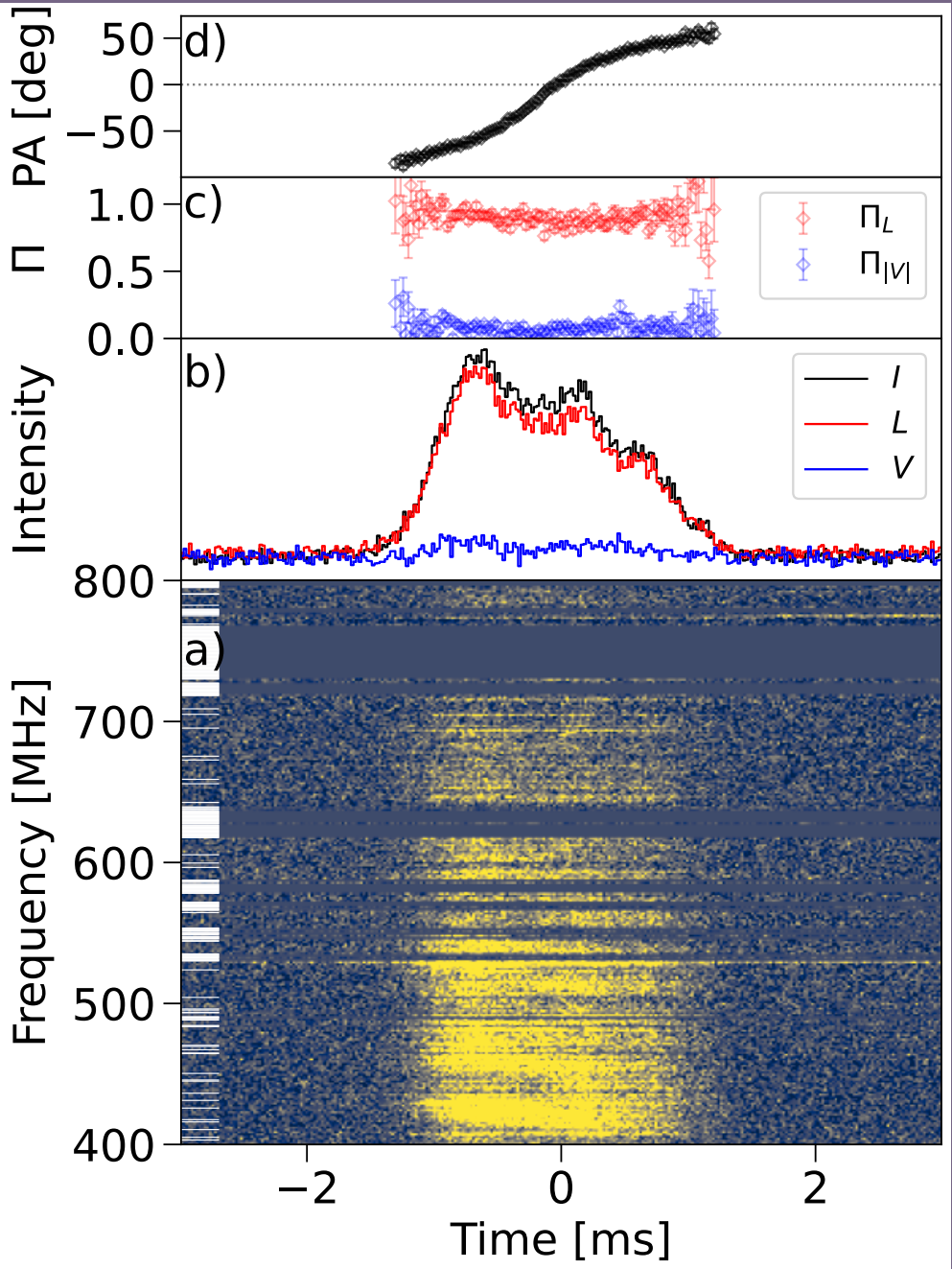
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JUMPS

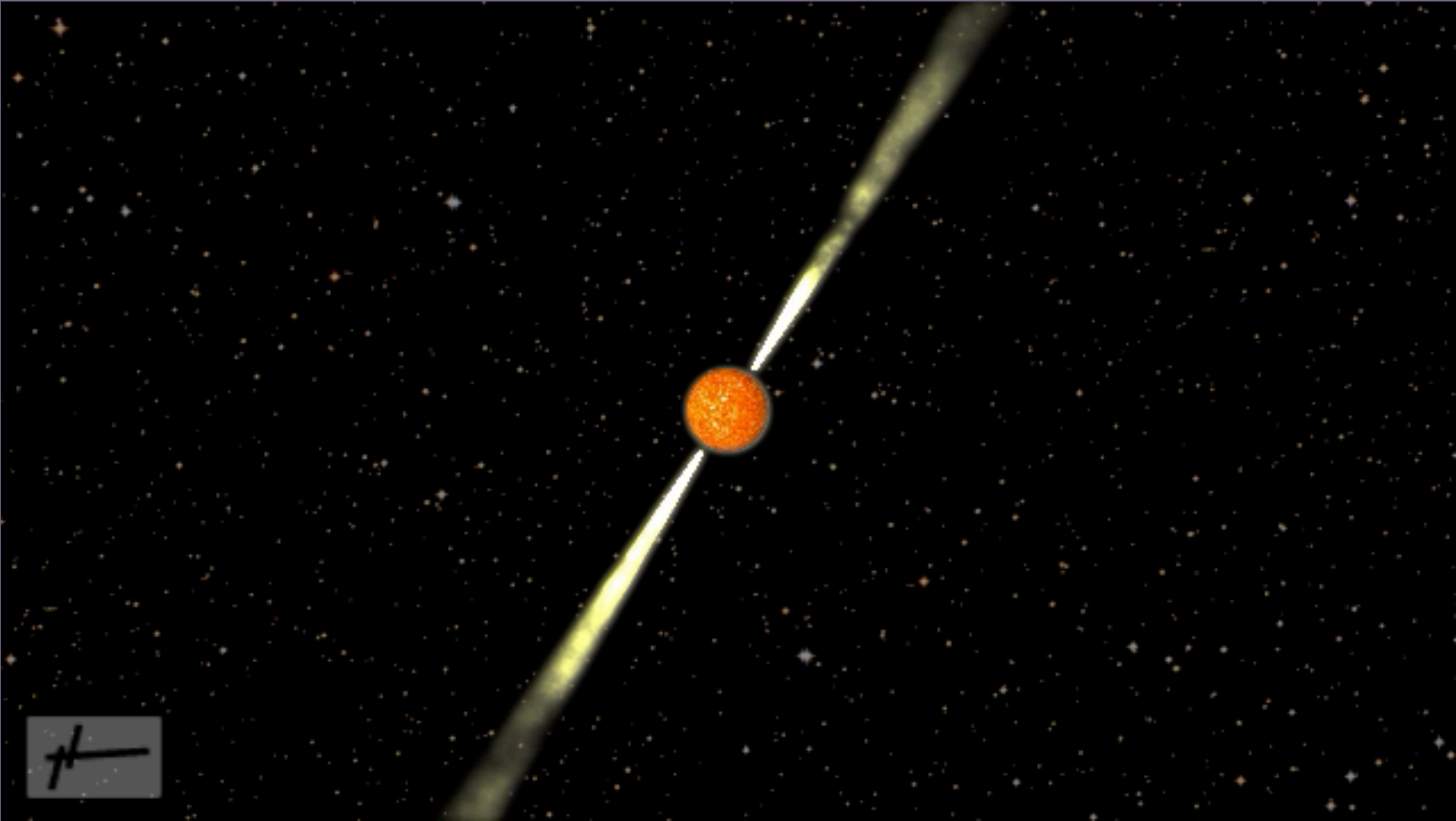


Niu et al. 2024

SWINGS



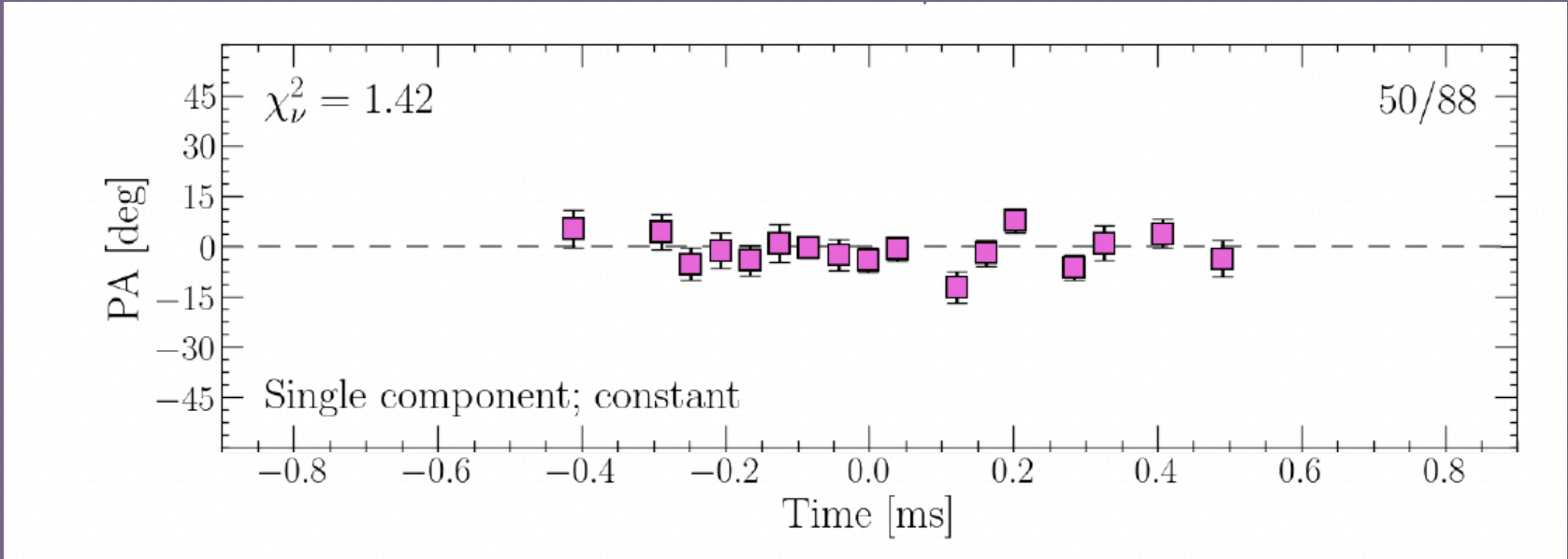
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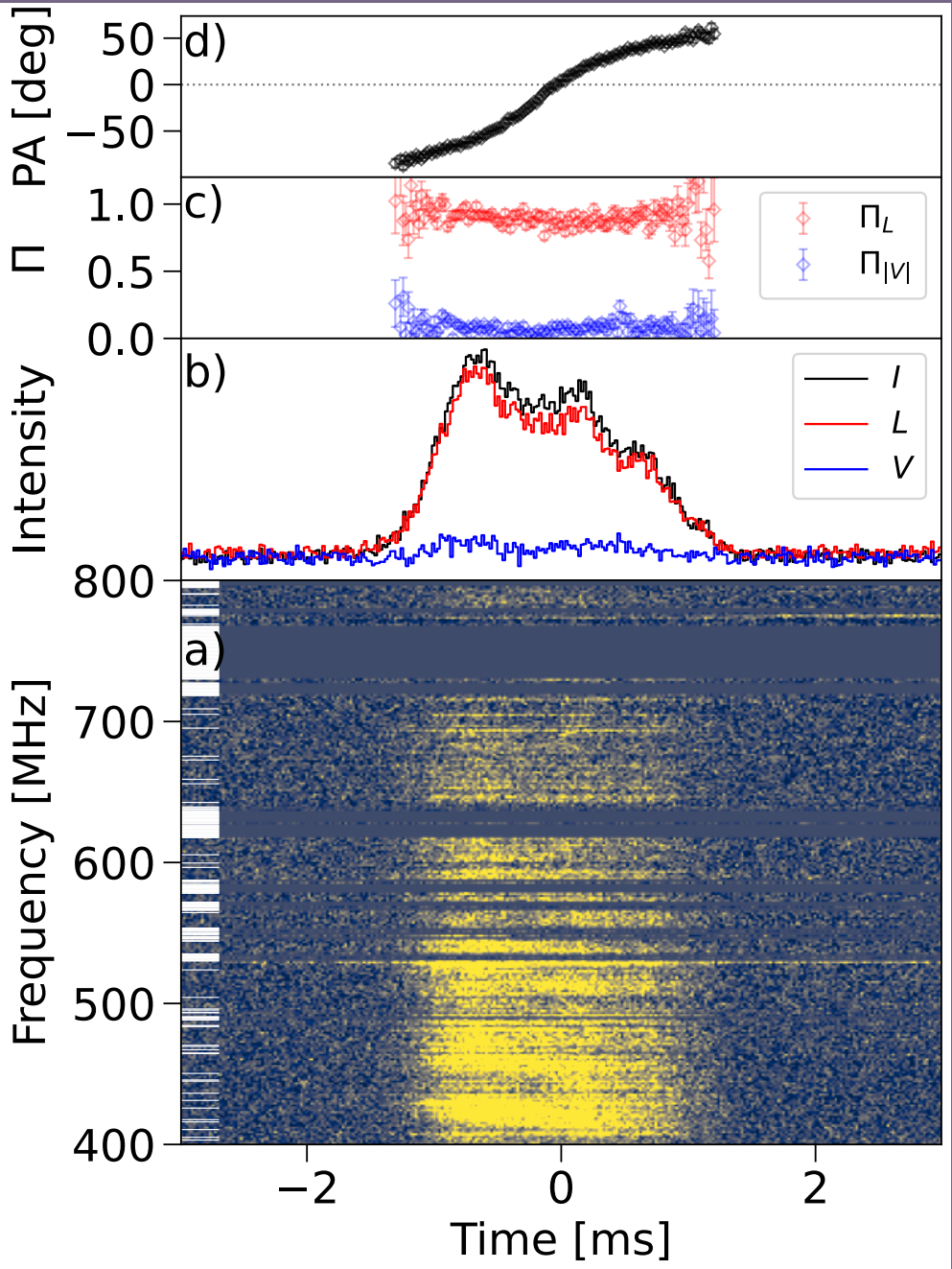
Polarization



Pandhi et al. 2024

highly structured magnetic field configurations

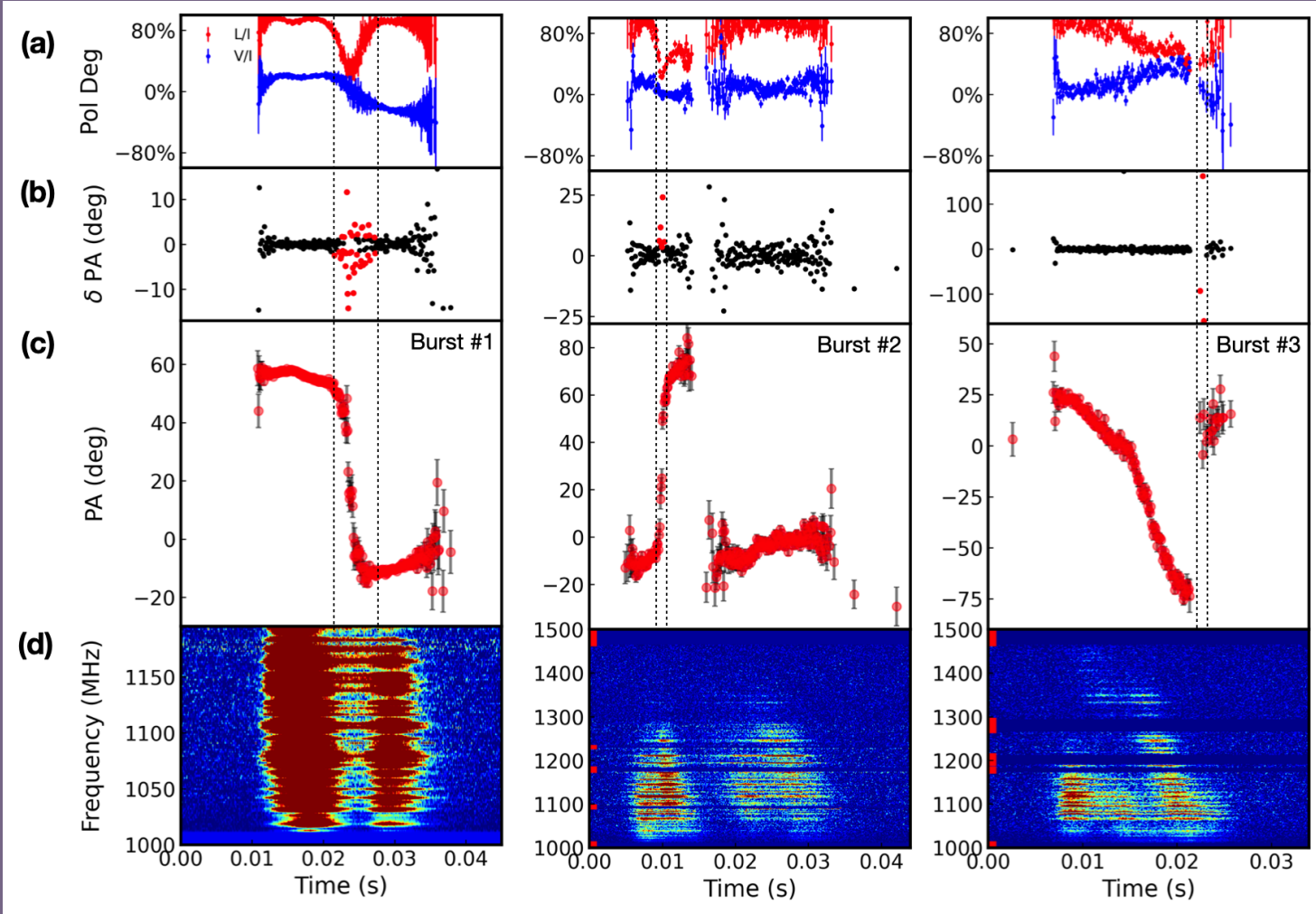
SWINGS





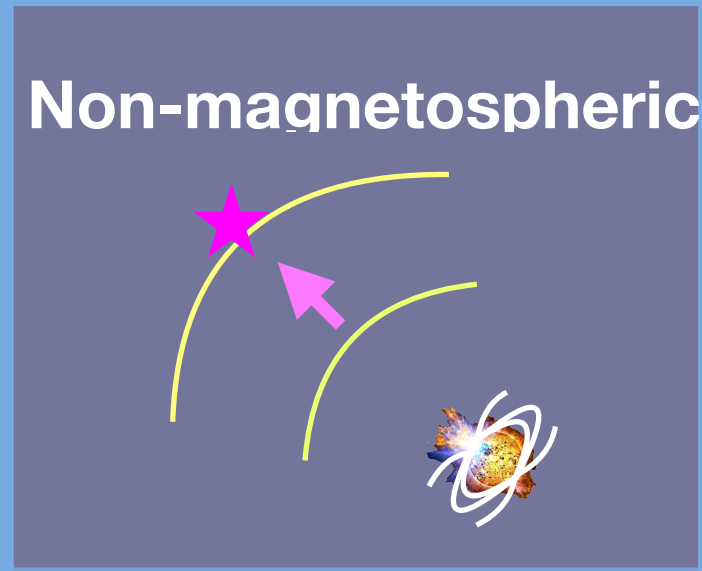
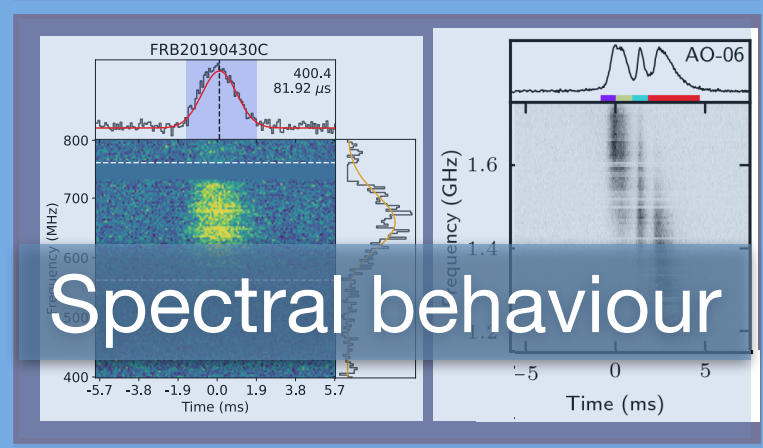


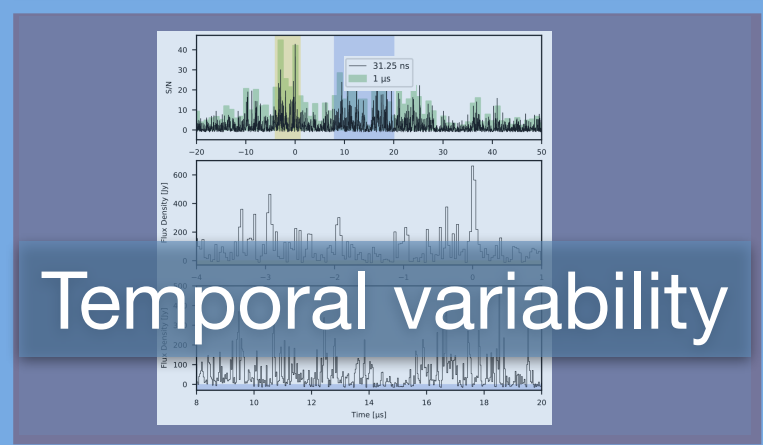

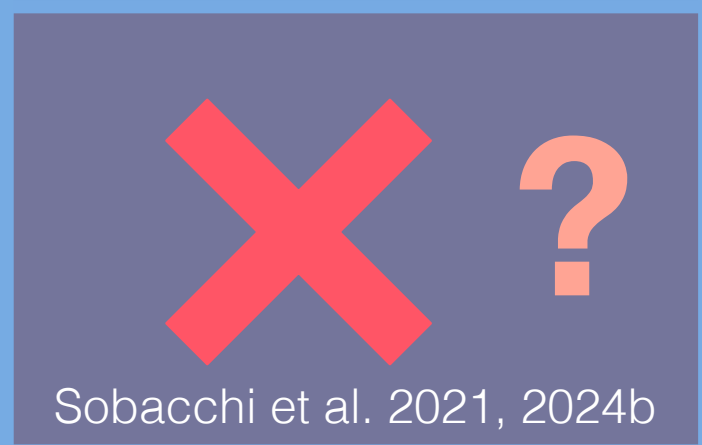
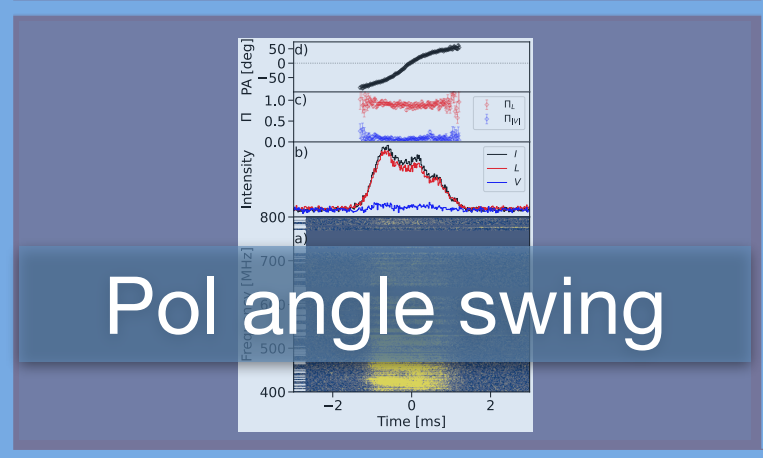
Mckinven et al. 2025

But sometimes...

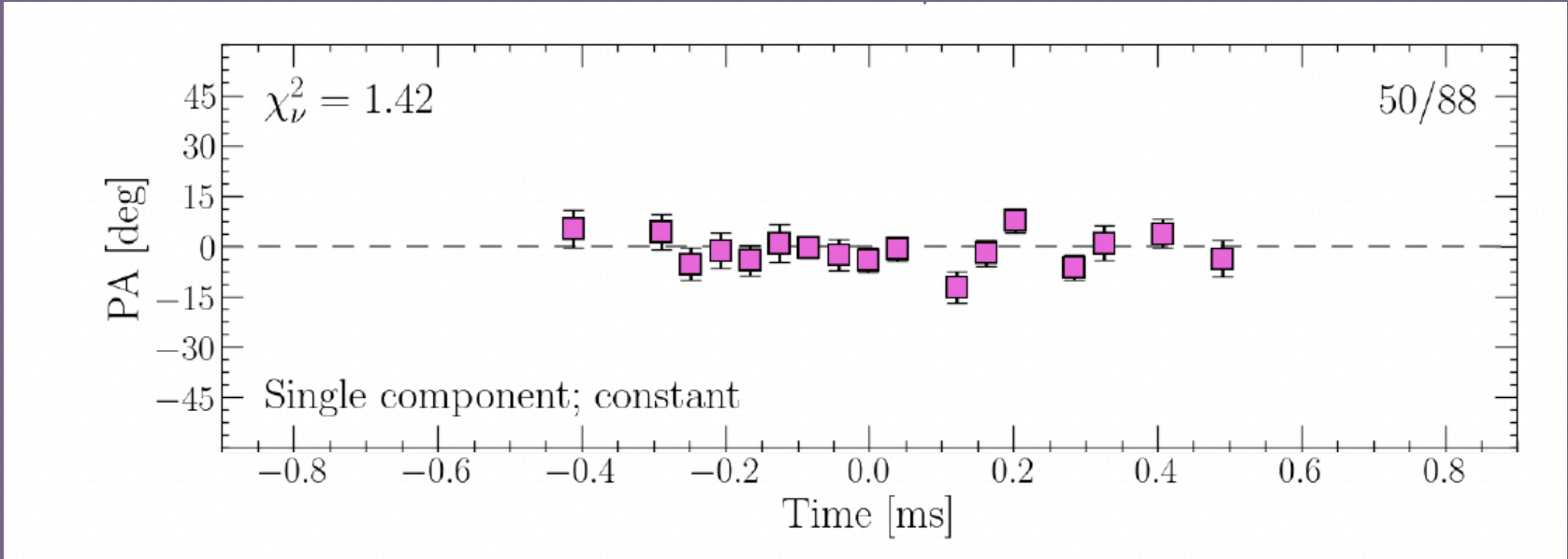
JUMPS



Niu et al. 2024

 <p>FRB property</p>	 <p>Magnetospheric</p>	 <p>Non-magnetospheric</p>
 <p>Spectral behaviour</p>		 <p>Metzger et al. 2022</p>
 <p>Temporal variability</p>		 <p>Sobacchi et al. 2021, 2024b</p>
 <p>Pol angle swing</p>		

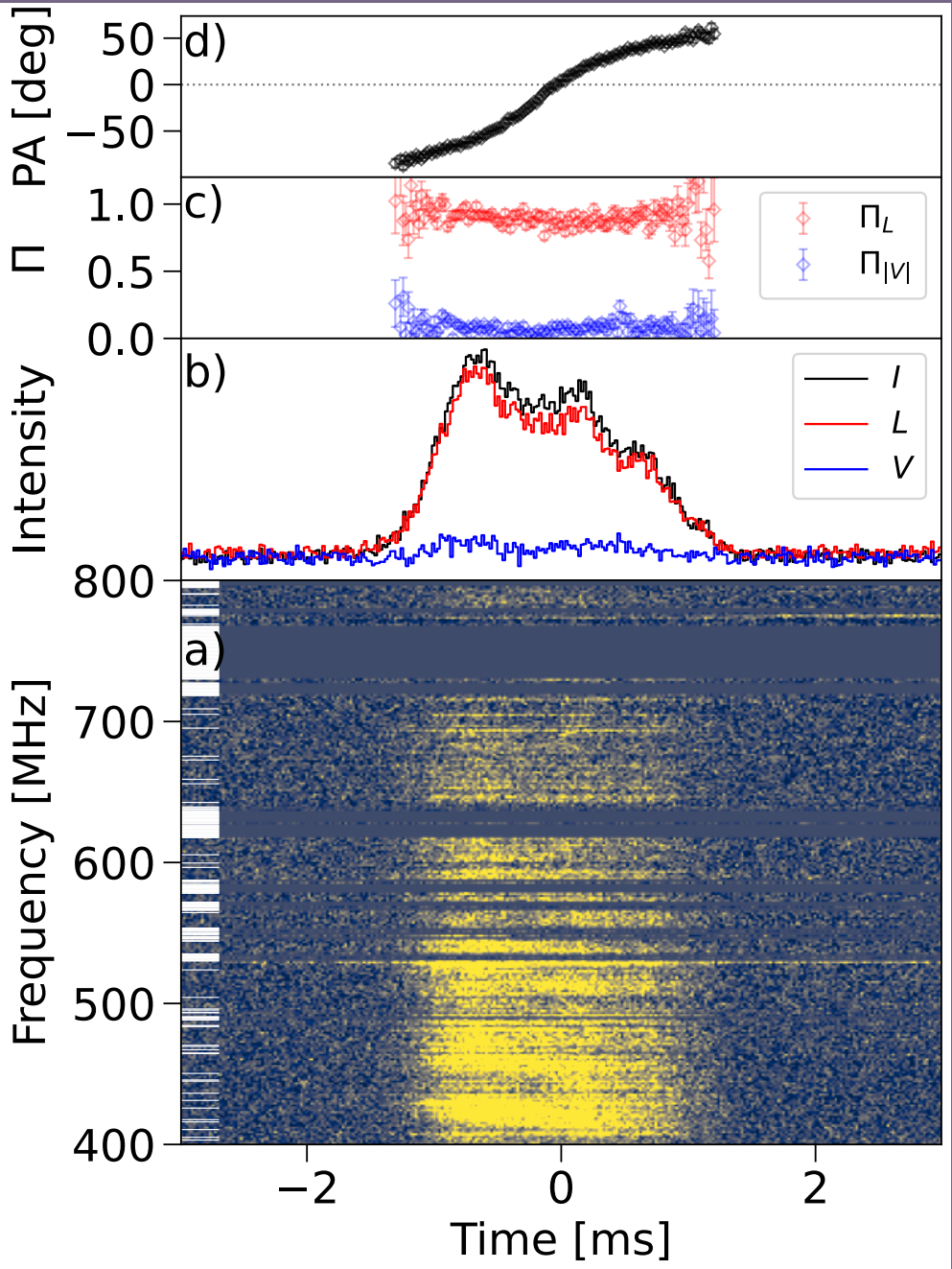
Polarization



Pandhi et al. 2024

highly structured magnetic field configurations

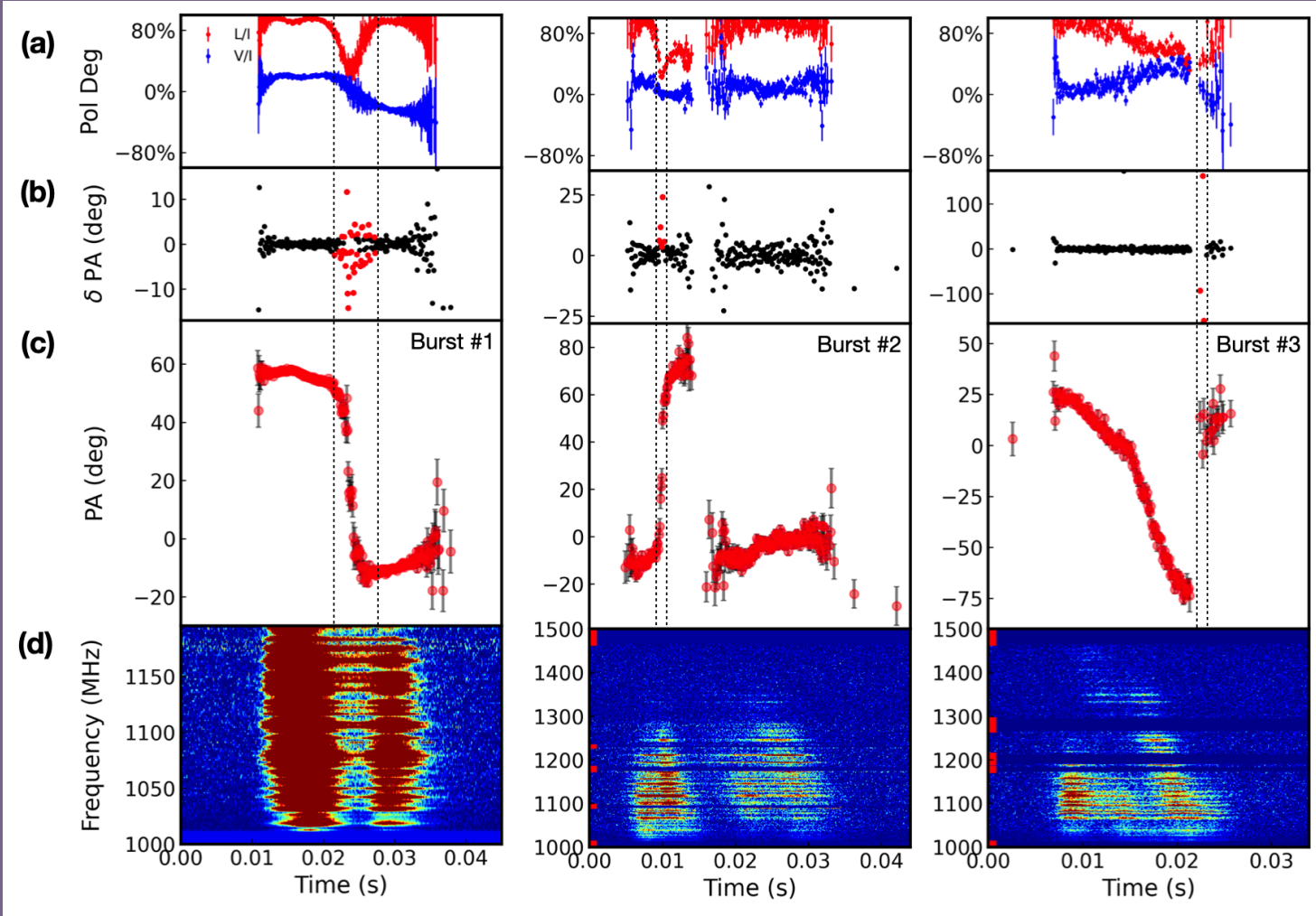
SWINGS




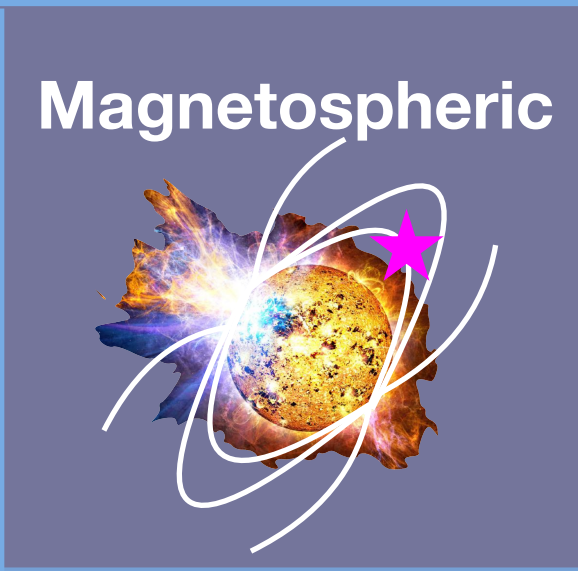
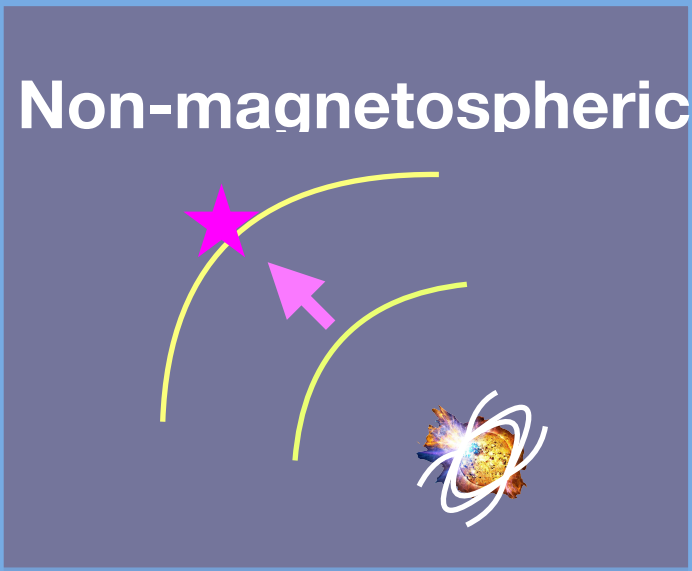
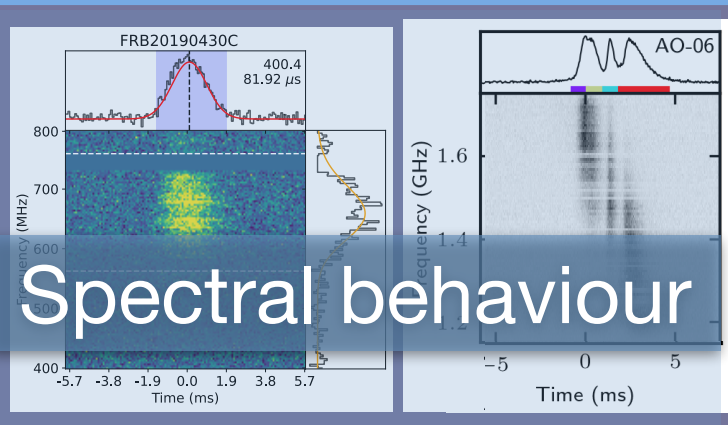


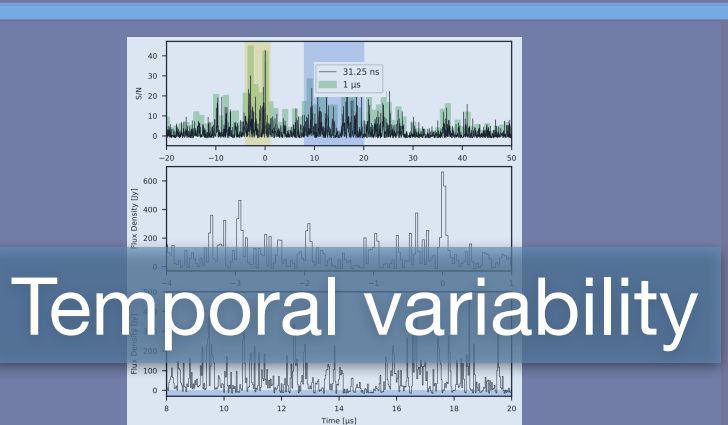


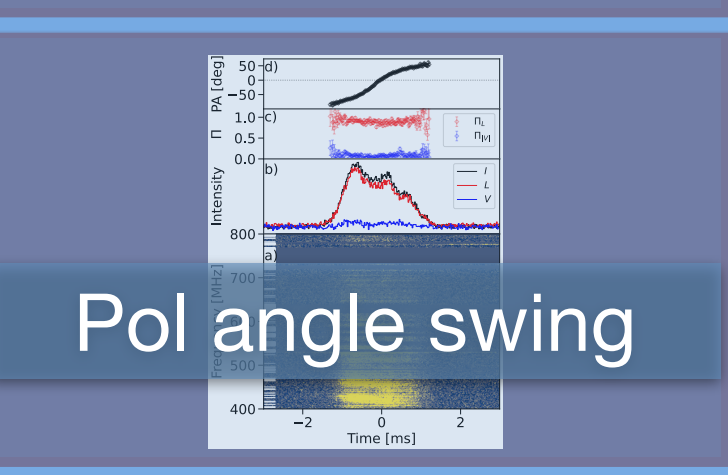

Mckinven et al. 2025

But sometimes...

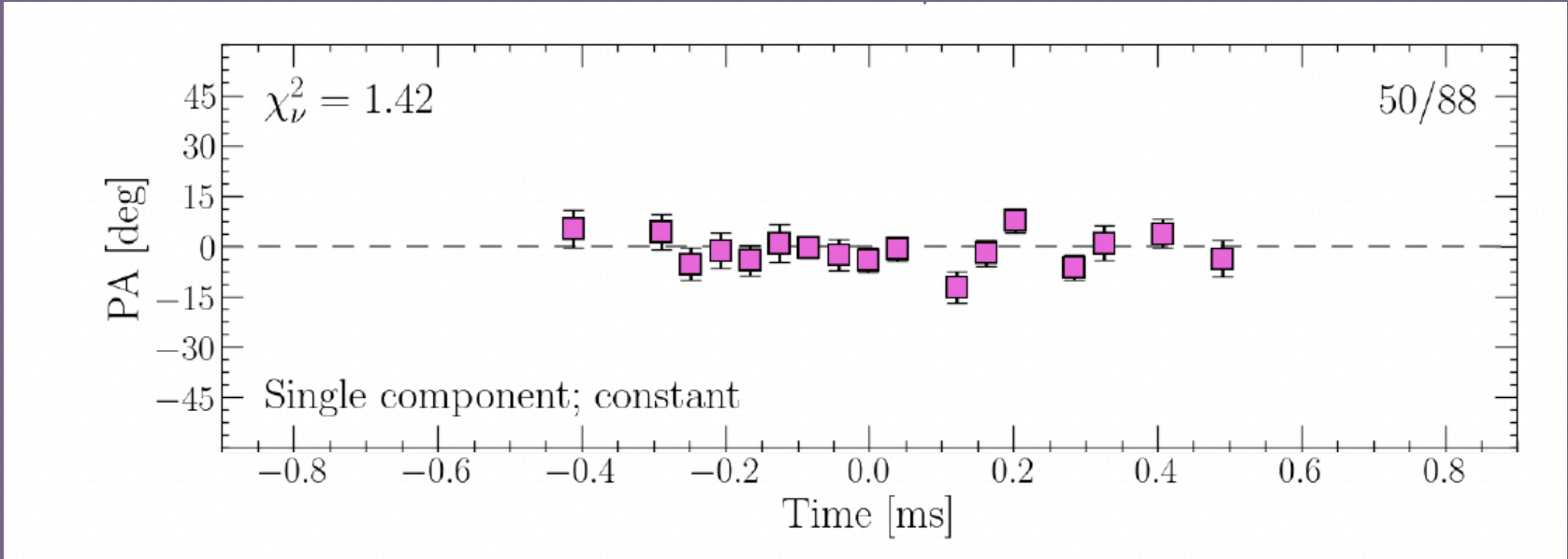
JUMPS



Niu et al. 2024

 <p>FRB property</p>	 <p>Magnetospheric</p>	 <p>Non-magnetospheric</p>
 <p>Spectral behaviour</p>		 <p>Metzger et al. 2022</p>
 <p>Temporal variability</p>		 <p>Sobacchi et al. 2021, 2024b</p>
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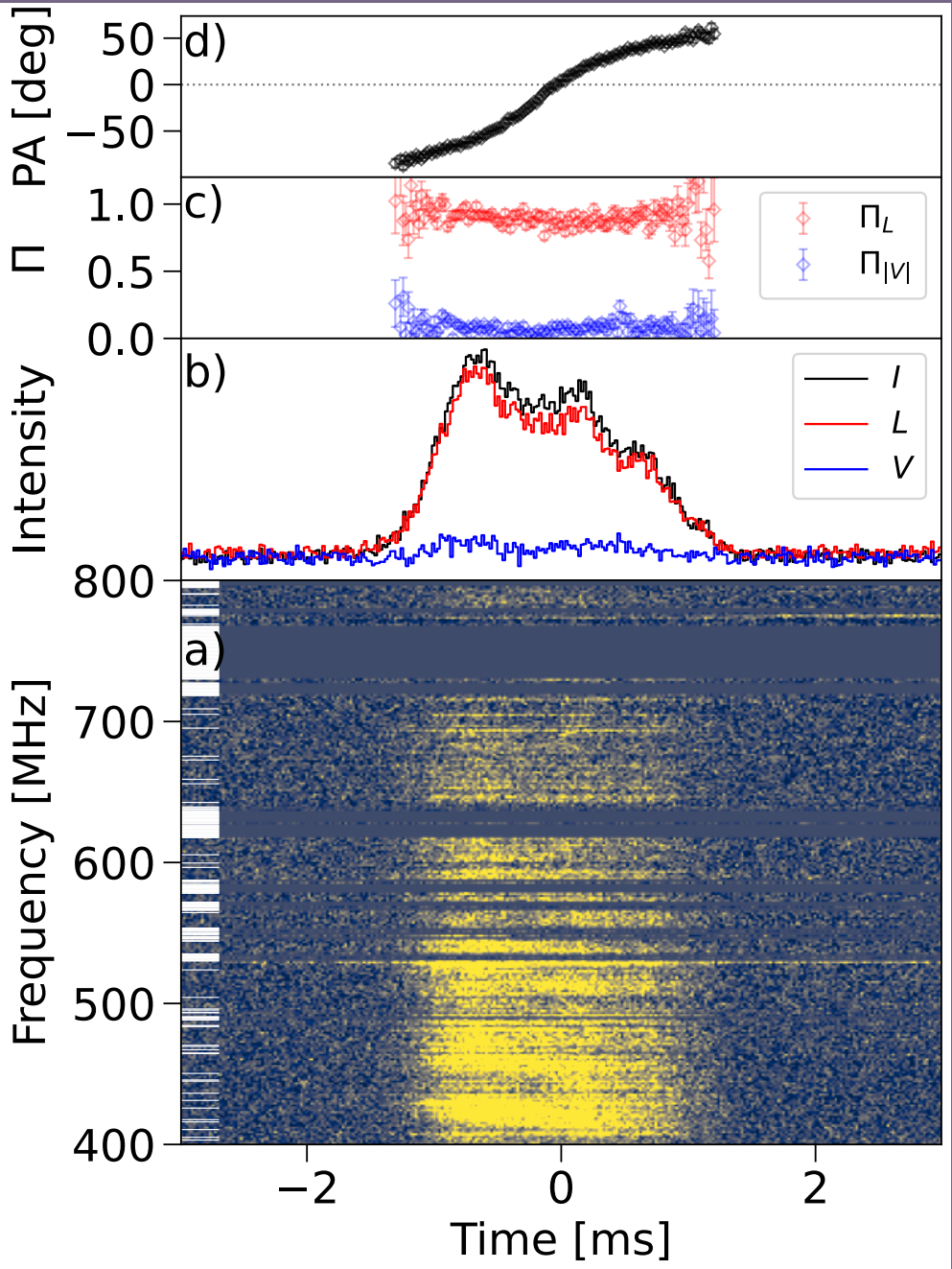
Polarization



Pandhi et al. 2024

highly structured magnetic field configurations

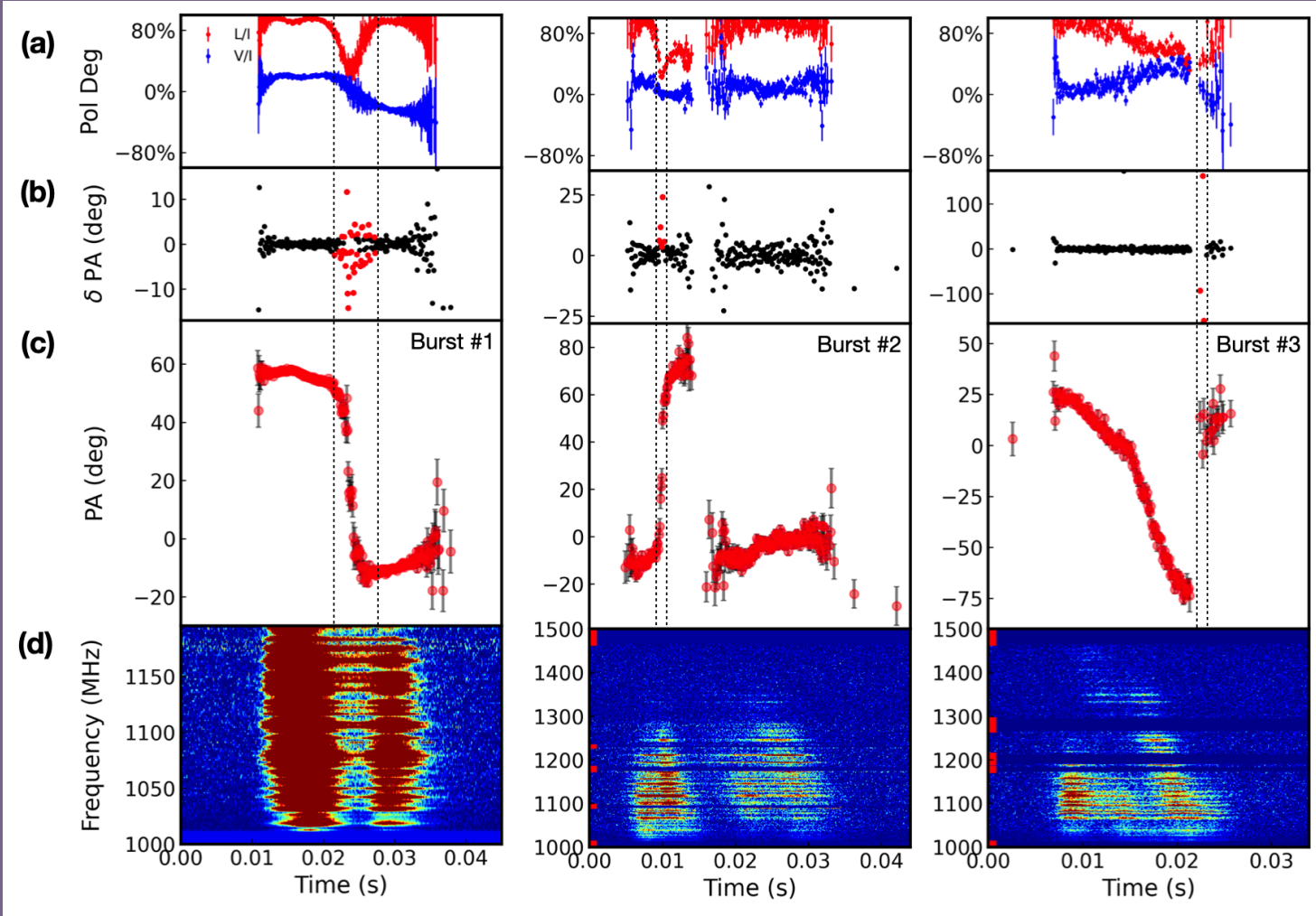
SWINGS





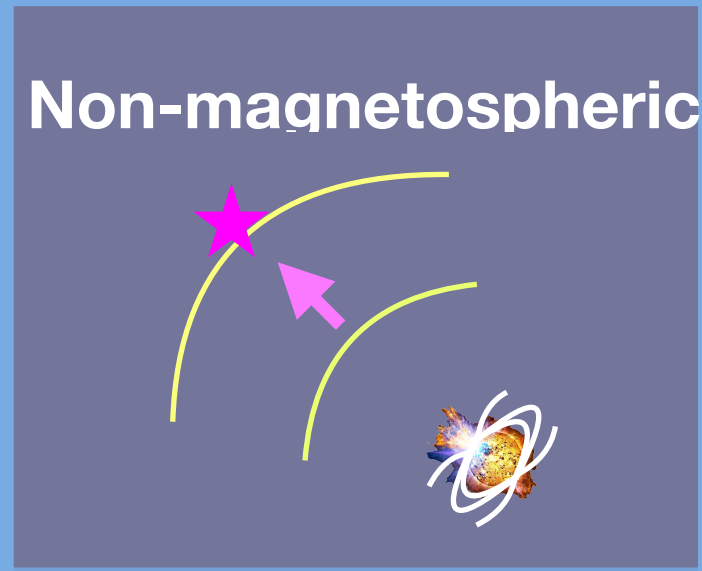
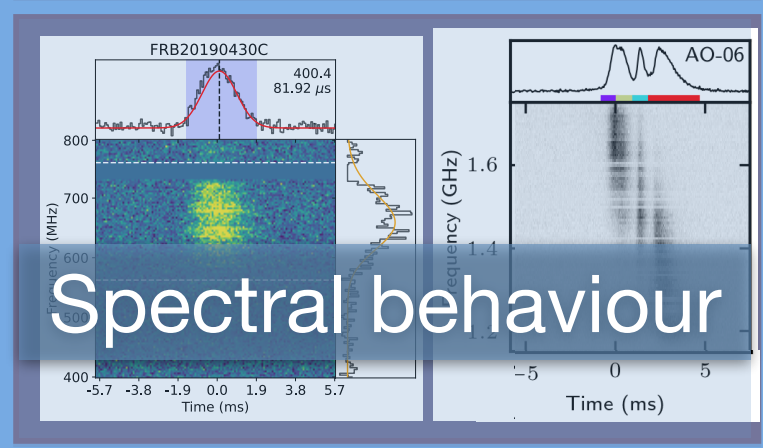


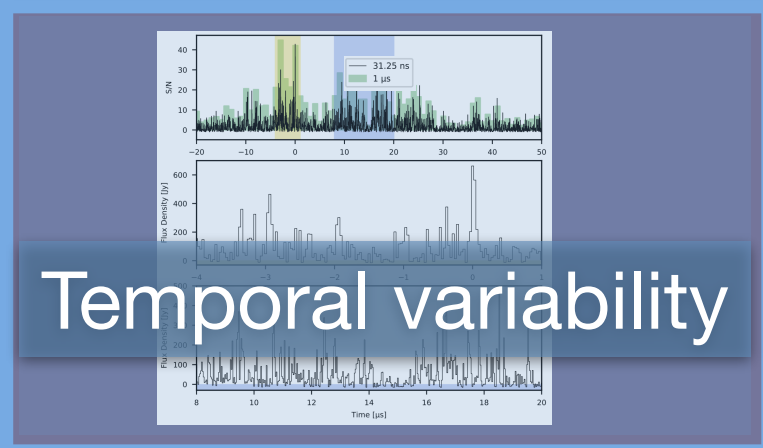


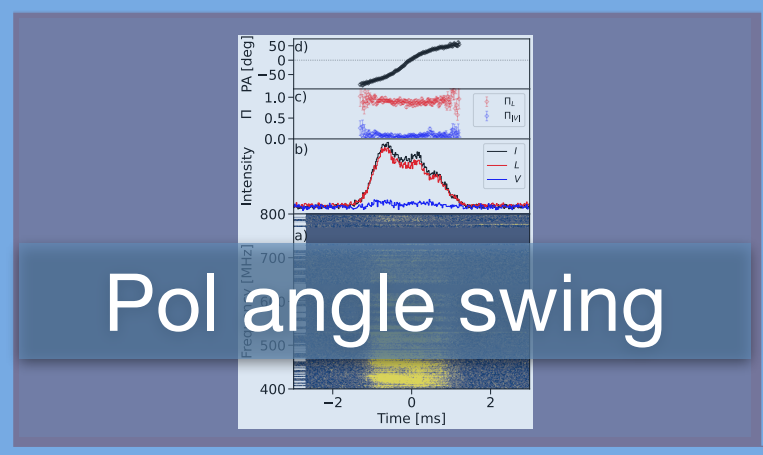


Mckinven et al. 2025

But sometimes...

JUMPS

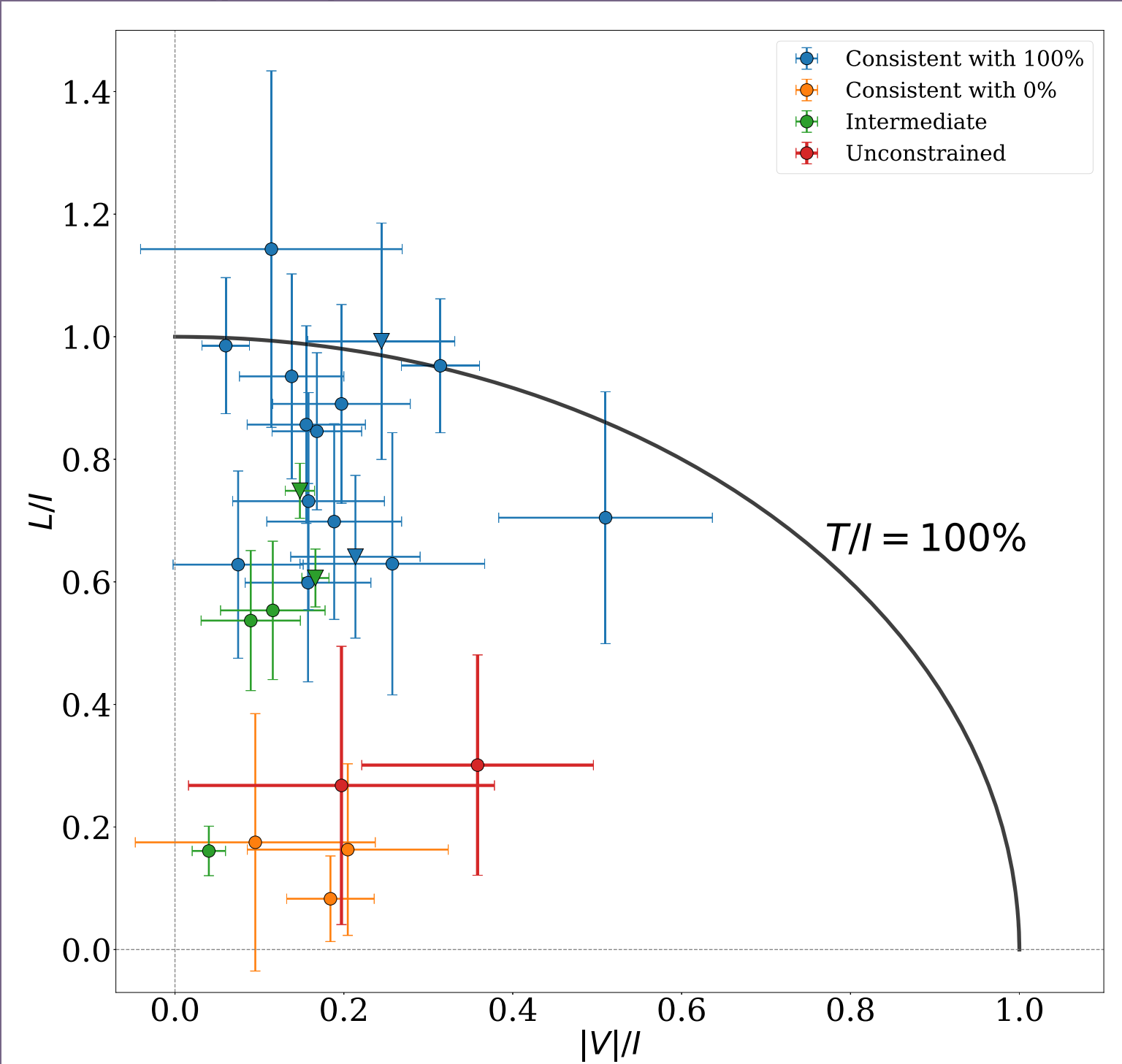


Niu et al. 2024

 <p>FRB property</p>	 <p>Magnetospheric</p>	 <p>Non-magnetospheric</p>
 <p>Spectral behaviour</p>		 <p>Metzger et al. 2022</p>
 <p>Temporal variability</p>		 <p>Sobacchi et al. 2021, 2024b</p>
 <p>Pol angle swing</p>		

Polarization

Sherman et al. 2024

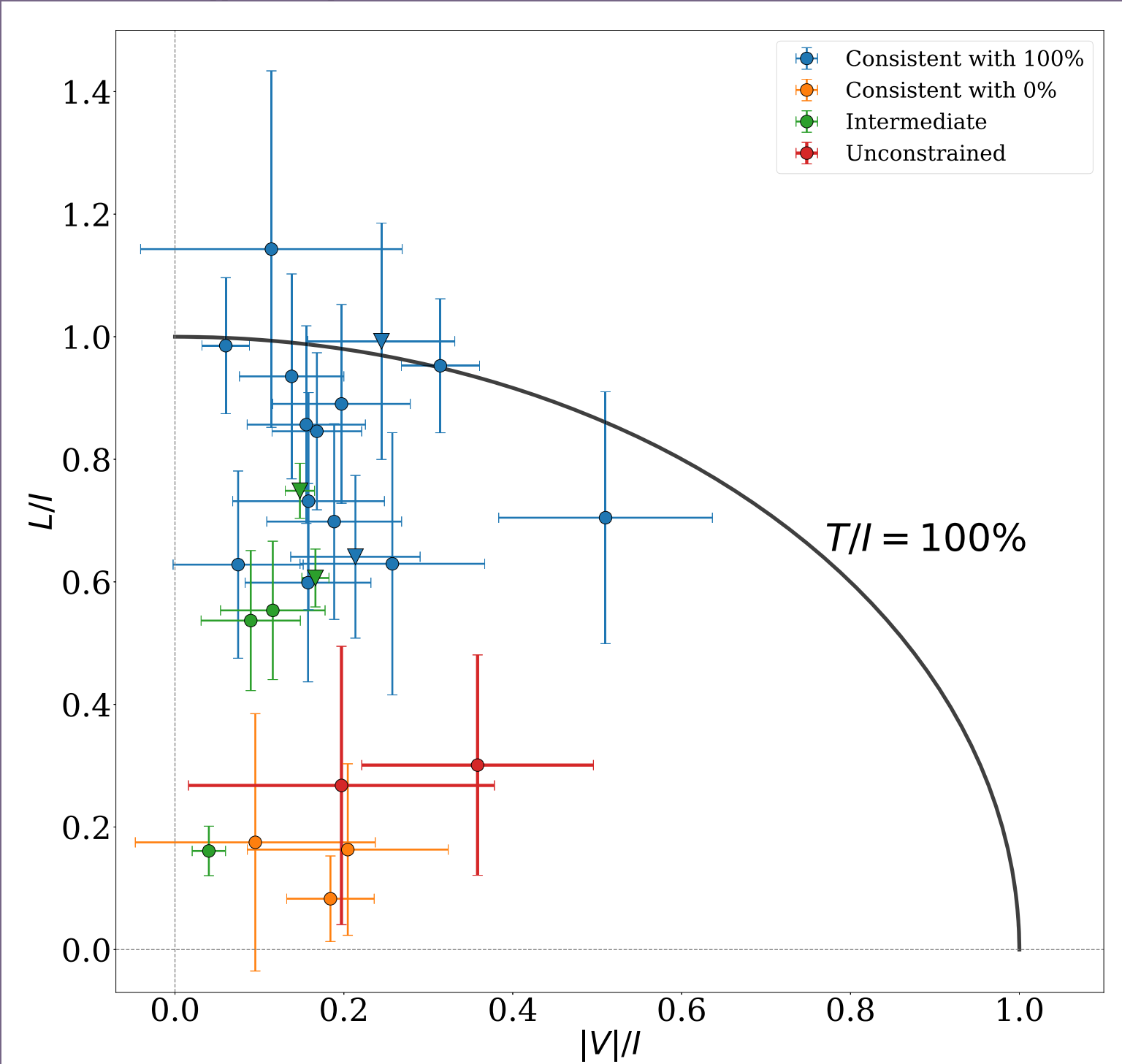


	Magnetospheric	Non-magnetospheric
FRB property		
Spectral behaviour		
Temporal variability		
Pol angle swing		

Metzger et al. 2022

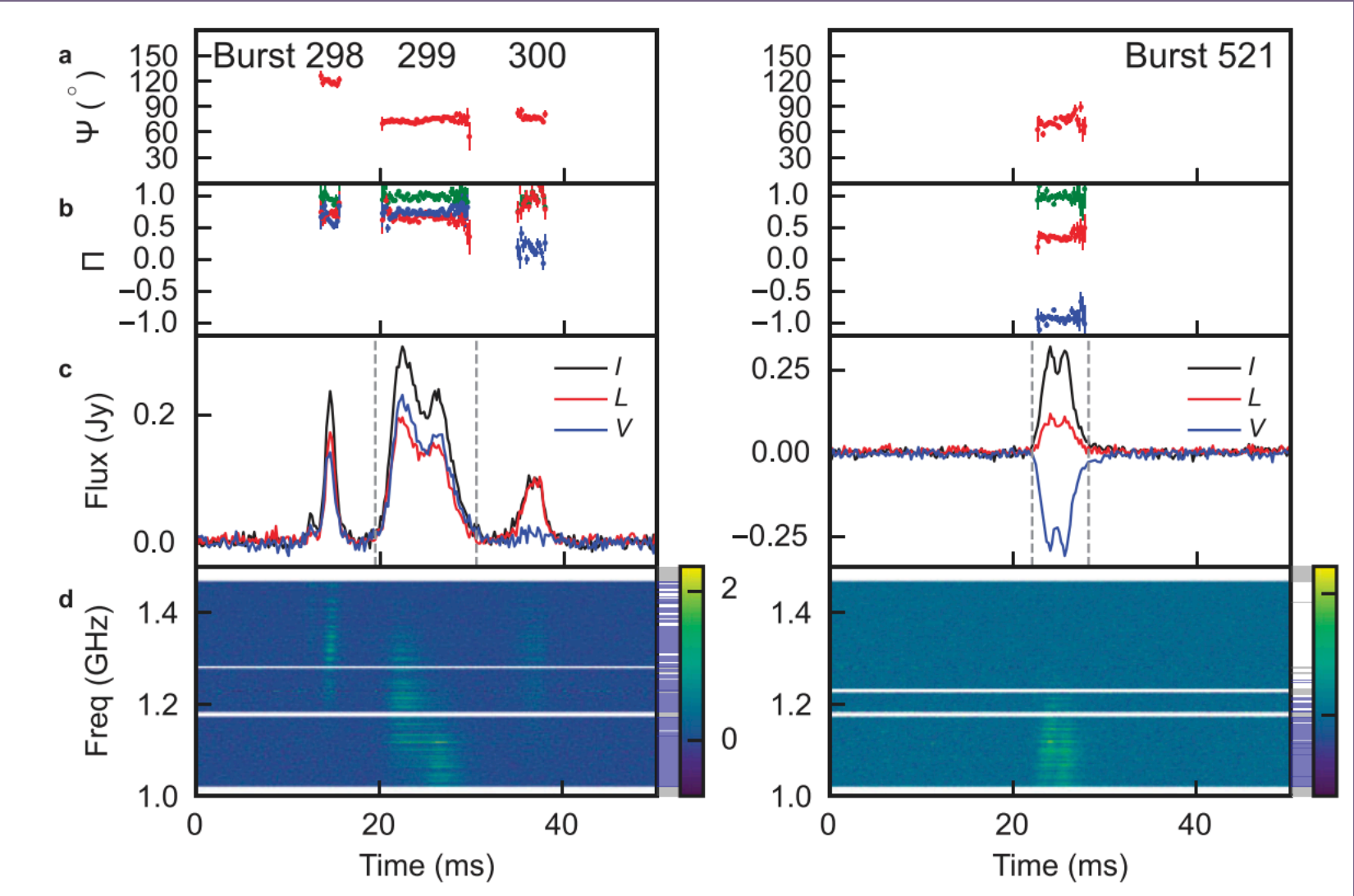
Sobacchi et al. 2021, 2024b

Polarization



Sherman et al. 2024

But sometimes...



Jiang et al. 2024

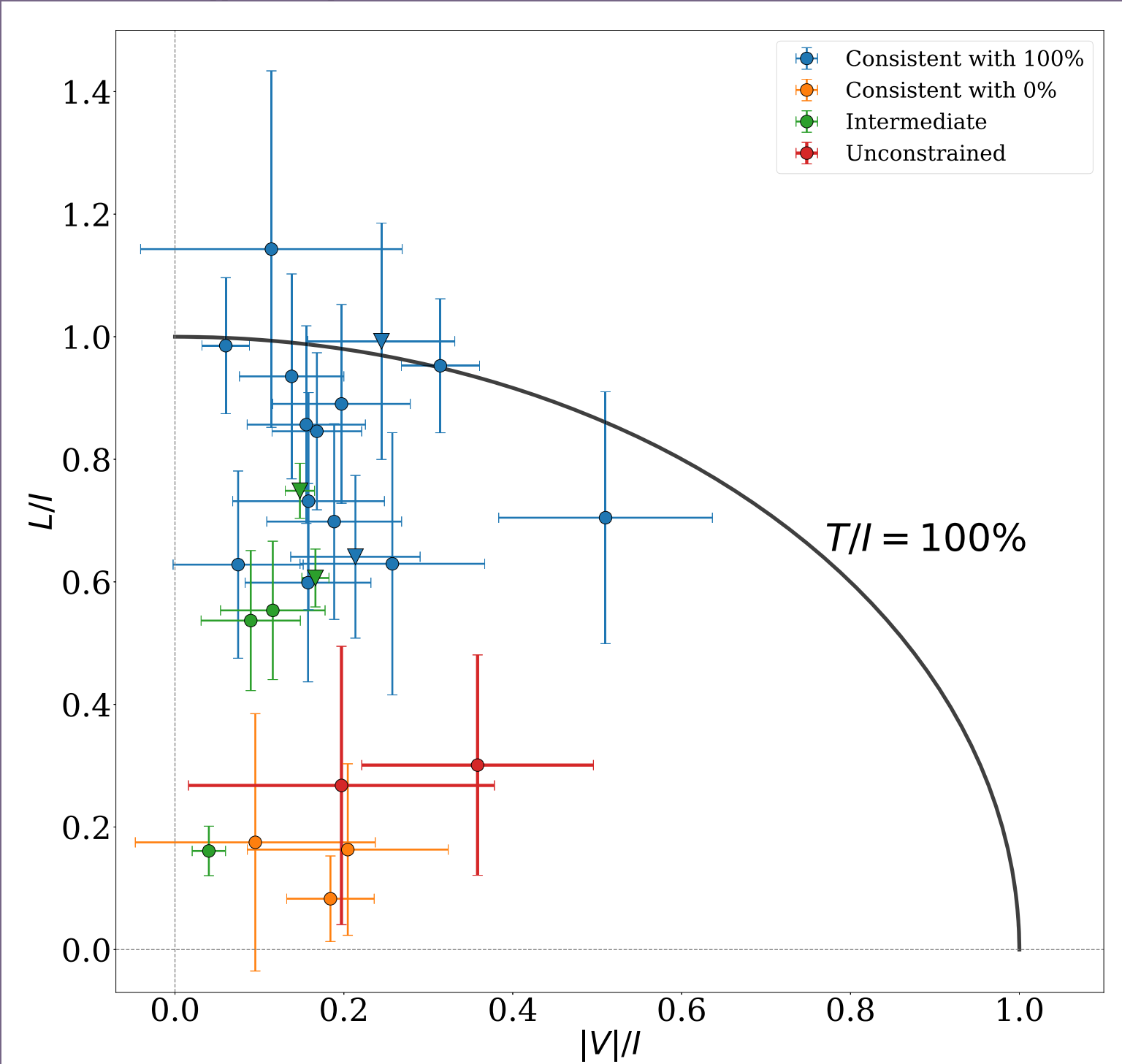
FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour		
Temporal variability		
Pol angle swing		
Circular polarisation		

Metzger et al. 2022

Sobacchi et al. 2021, 2024b

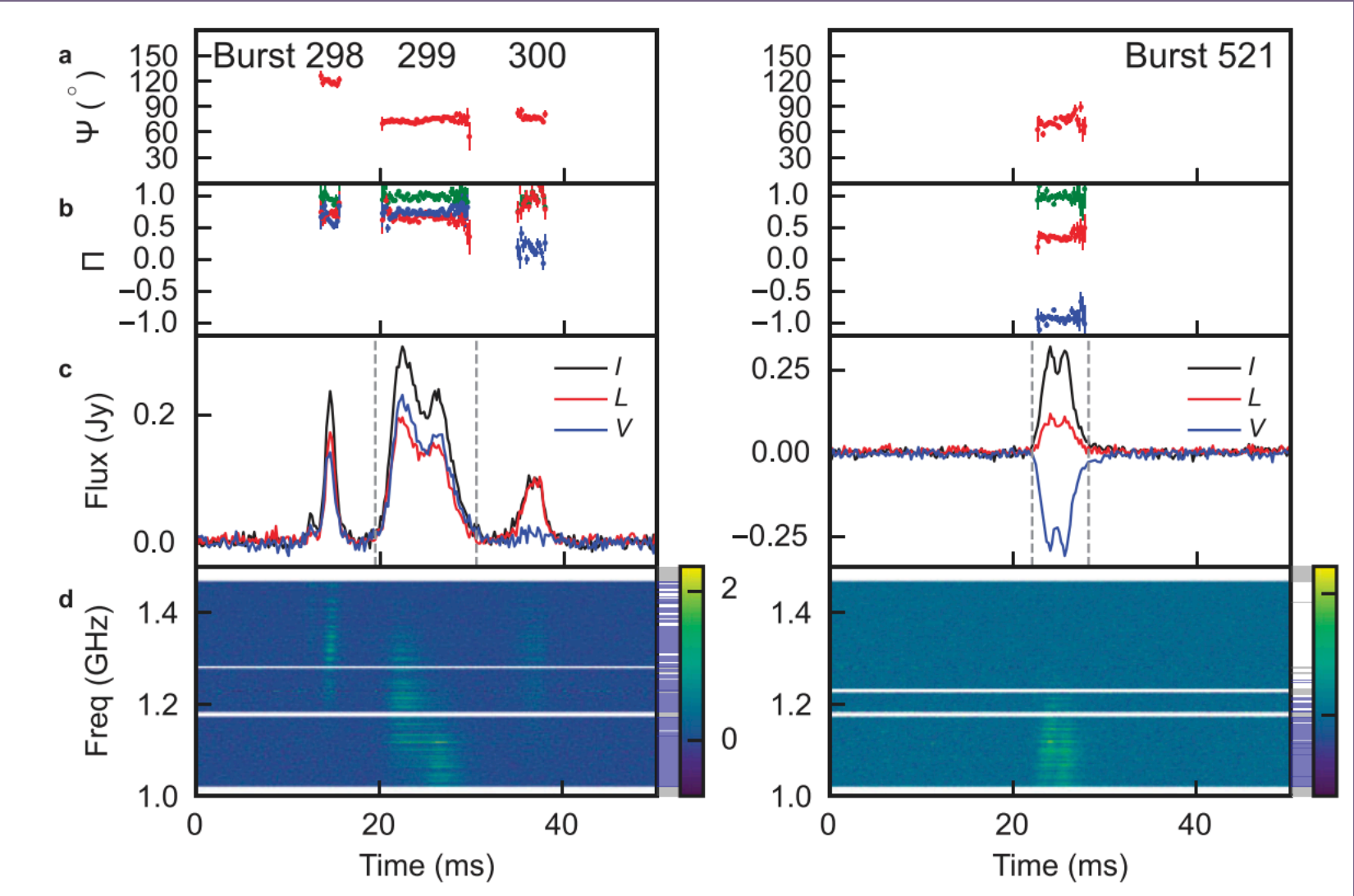
Up to 90% circular

Polarization


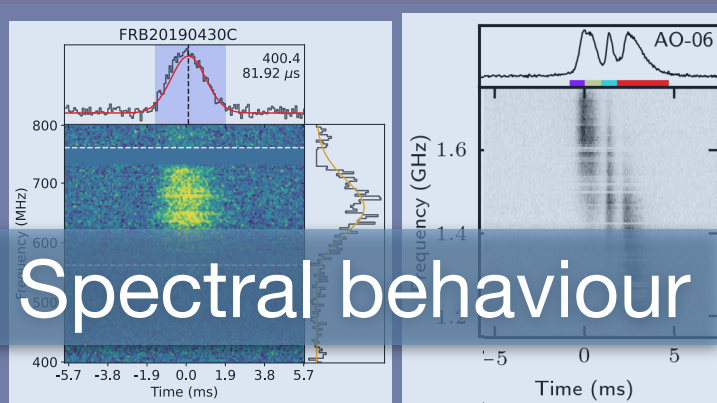


Sherman et al. 2024

But sometimes...

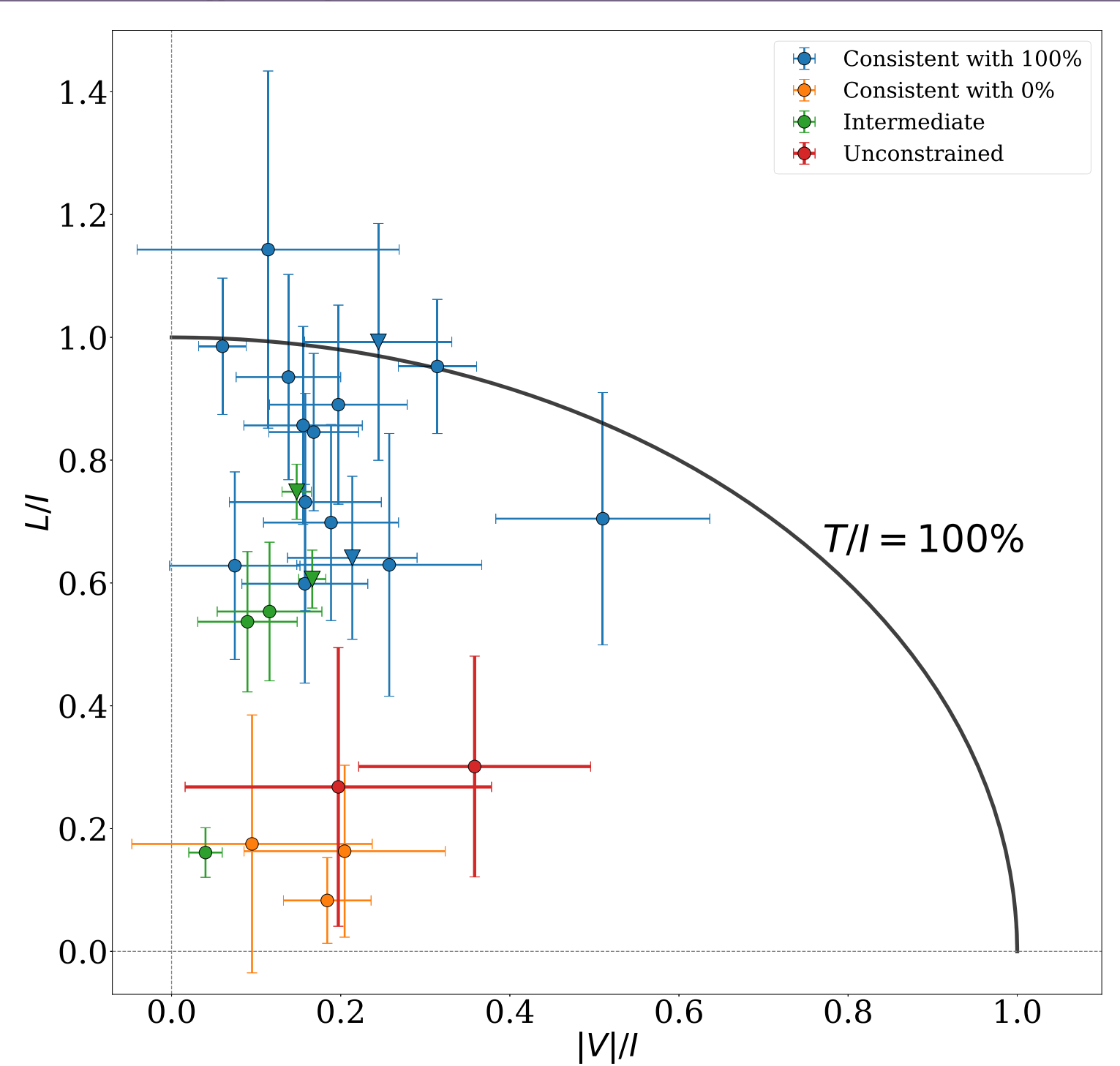


Jiang et al. 2024

 <p>FRB property</p>	 <p>Magnetospheric</p>	 <p>Non-magnetospheric</p>
 <p>Spectral behaviour</p>		 <p>Metzger et al. 2022</p>
 <p>Temporal variability</p>		 <p>Sobacchi et al. 2021, 2024b</p>
 <p>Pol angle swing</p>		
 <p>Circular polarisation</p>		

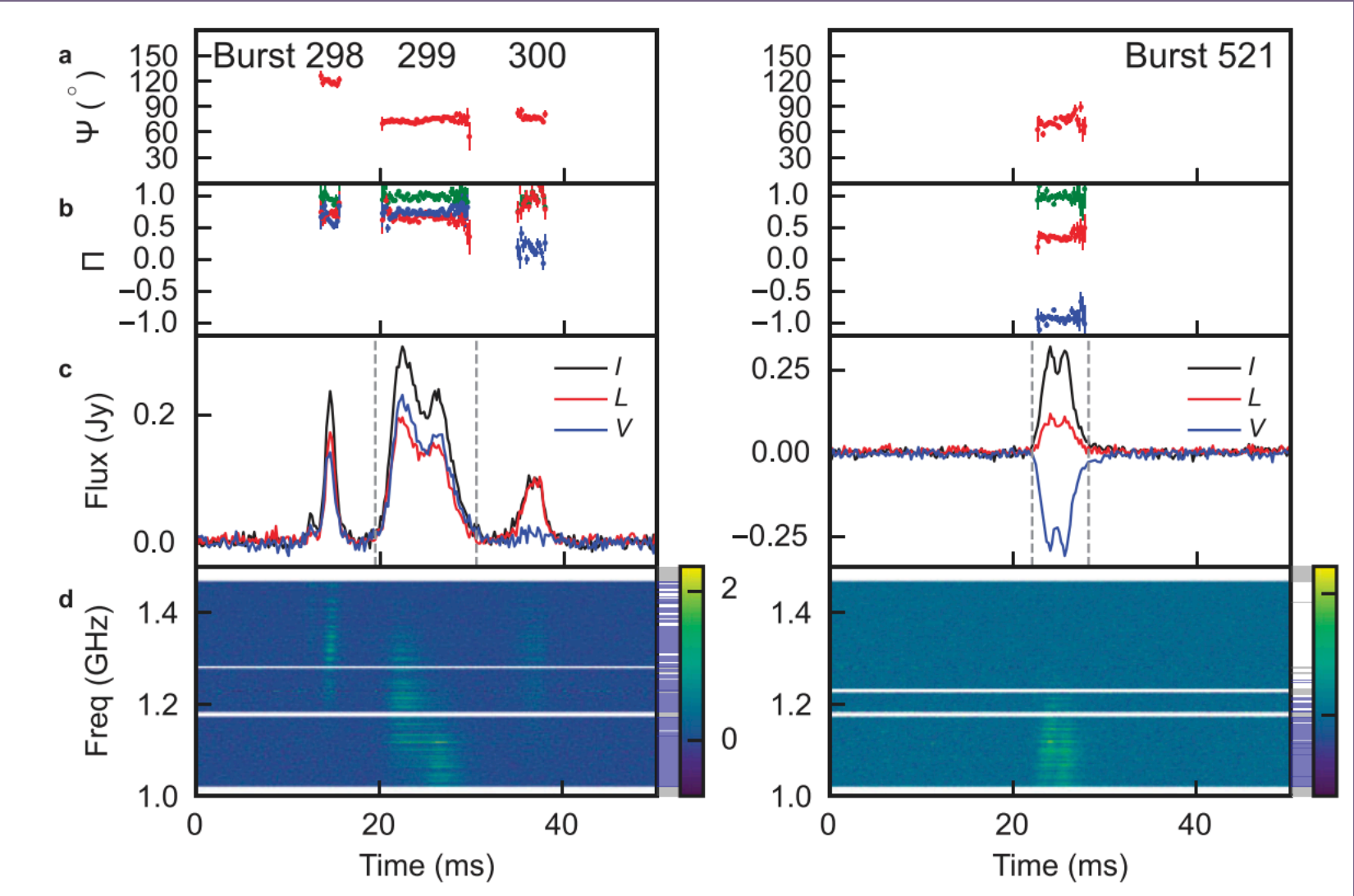
Up to 90% circular

Polarization



Sherman et al. 2024

But sometimes...





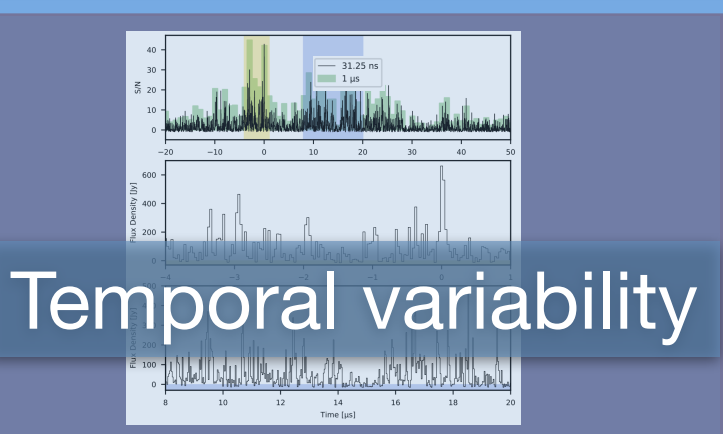

Jiang et al. 2024

Up to 90% circular

 <p>FRB property</p>	 <p>Magnetospheric</p>	 <p>Non-magnetospheric</p>
 <p>Spectral behaviour</p>		 <p>Metzger et al. 2022</p>
 <p>Temporal variability</p>		 <p>Sobacchi et al. 2021, 2024b</p>
 <p>Pol angle swing</p>		
 <p>Circular polarisation</p>		 <p>Qu et al. 2023</p>

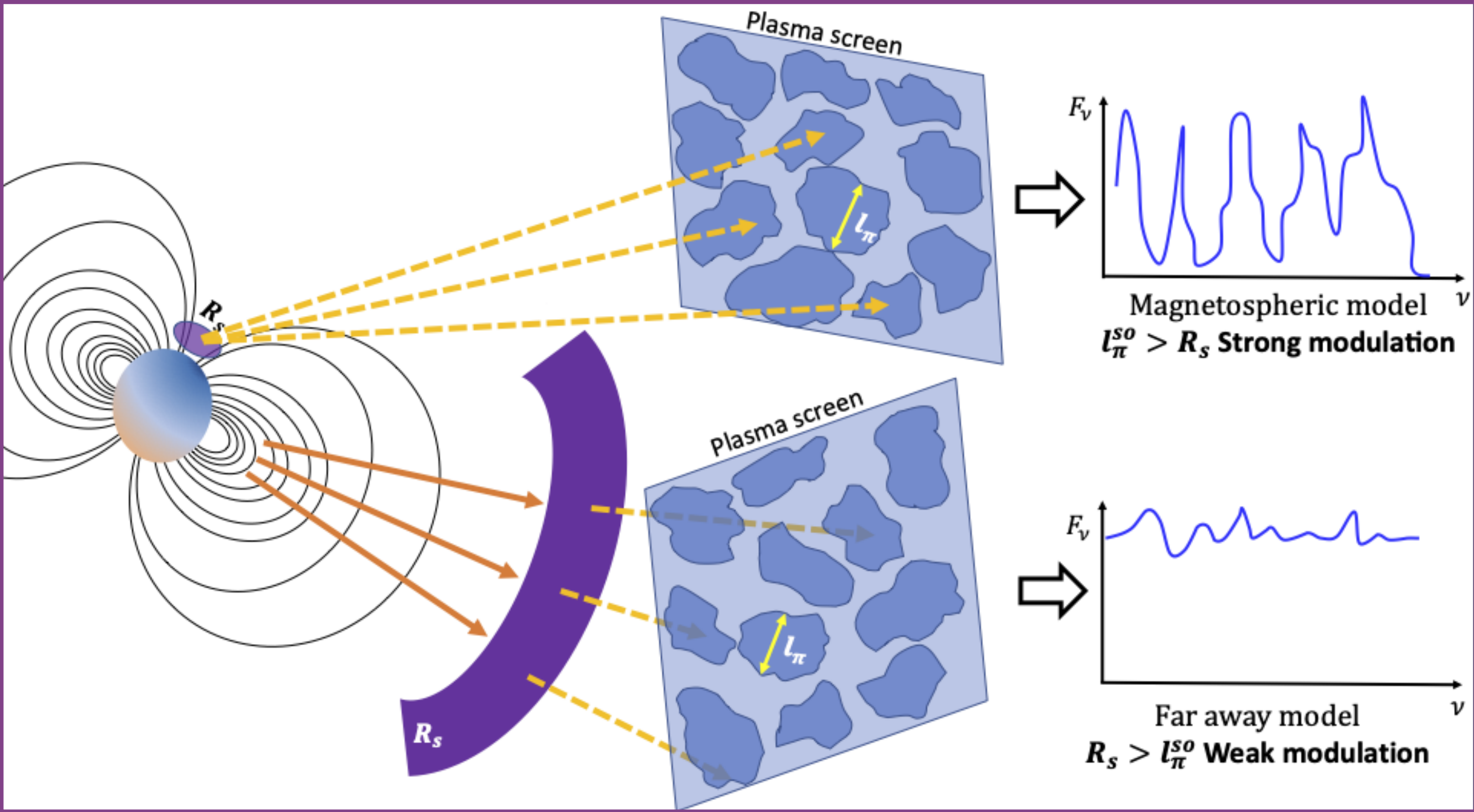
Scintillation*

* from the host galaxy

 <p>FRB property</p>	 <p>Magnetospheric</p>	 <p>Non-magnetospheric</p>
 <p>Spectral behaviour</p>		 <p>Metzger et al. 2022</p>
 <p>Temporal variability</p>		 <p>Sobacchi et al. 2021, 2024b</p>
 <p>Pol angle swing</p>		
 <p>Circular polarisation</p>		 <p>Qu et al. 2023</p>

Scintillation*

* from the host galaxy



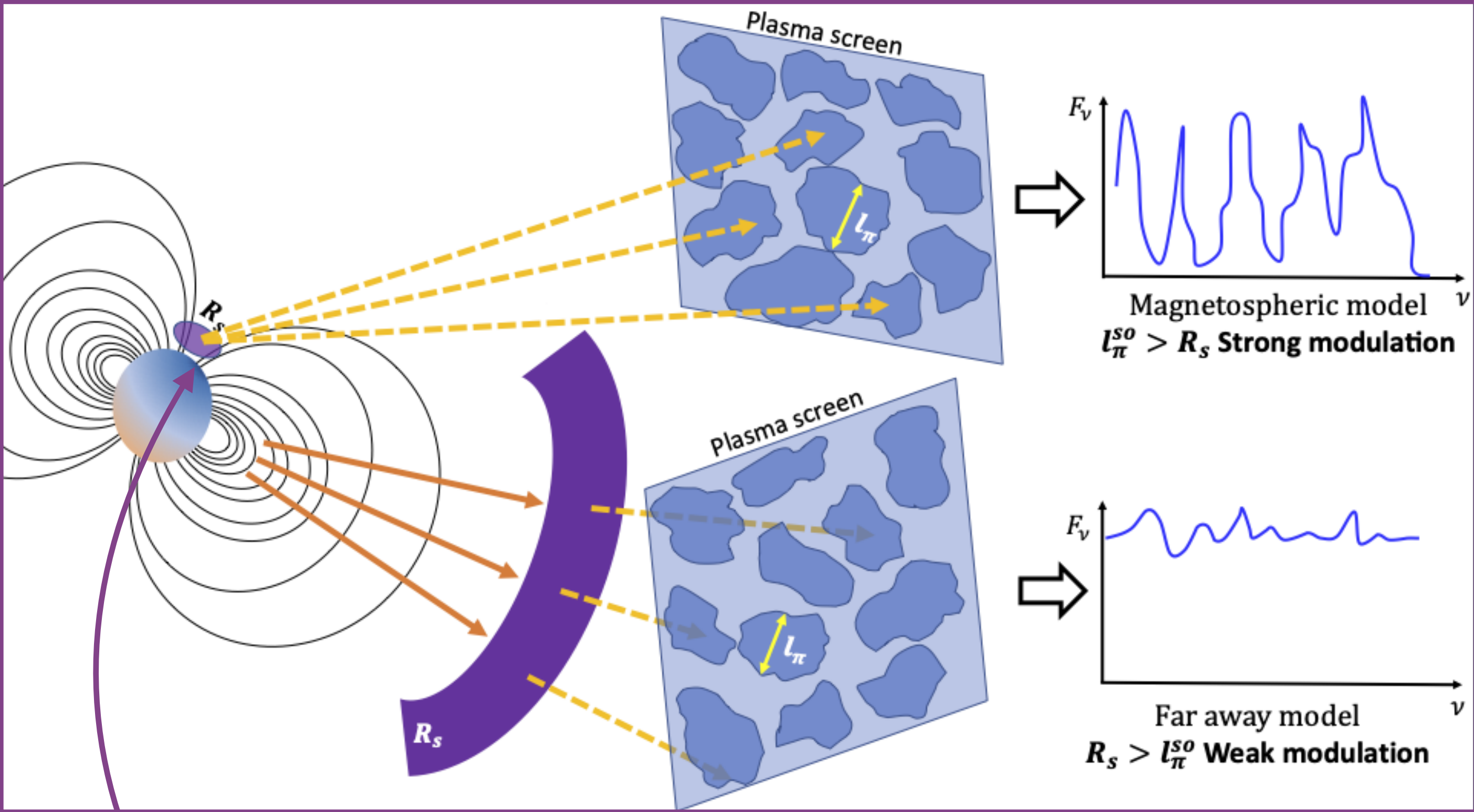
Kumar et al. 2024

	Magnetospheric	Non-magnetospheric
FRB property		
Spectral behaviour		
Temporal variability		
Pol angle swing		
Circular polarisation		

Qu et al. 2023

Scintillation*

* from the host galaxy



Kumar et al. 2024

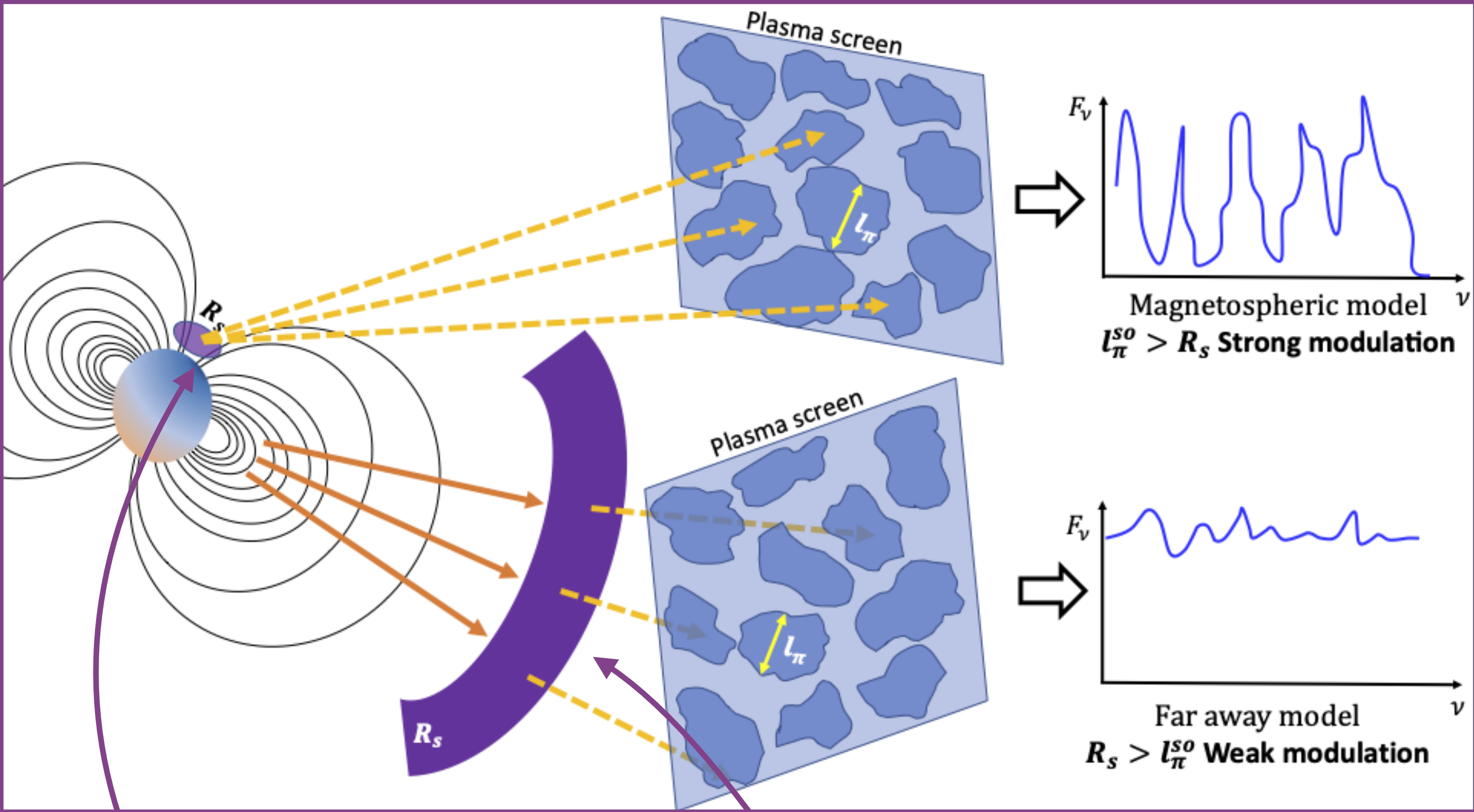
Magnetospheric



FRB property	Magnetospheric	Non-magnetospheric
		Metzger et al. 2022
		Sobacchi et al. 2021, 2024b
		Qu et al. 2023

Scintillation*

* from the host galaxy



Magnetospheric

Non-magnetospheric

Kumar et al. 2024

FRB property	Magnetospheric	Non-magnetospheric
		Qu et al. 2023

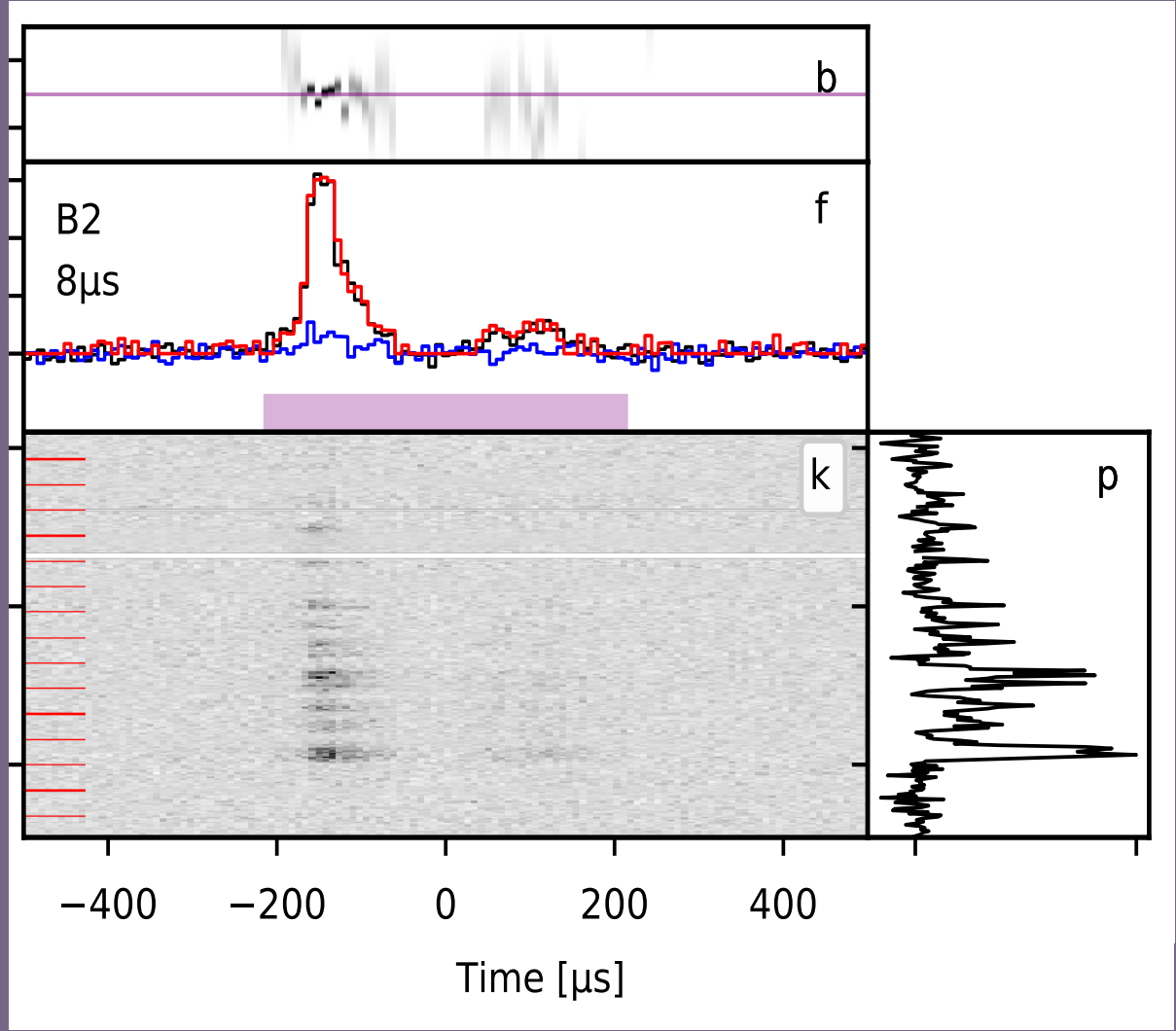
Metzger et al. 2022

Sobacchi et al. 2021, 2024b

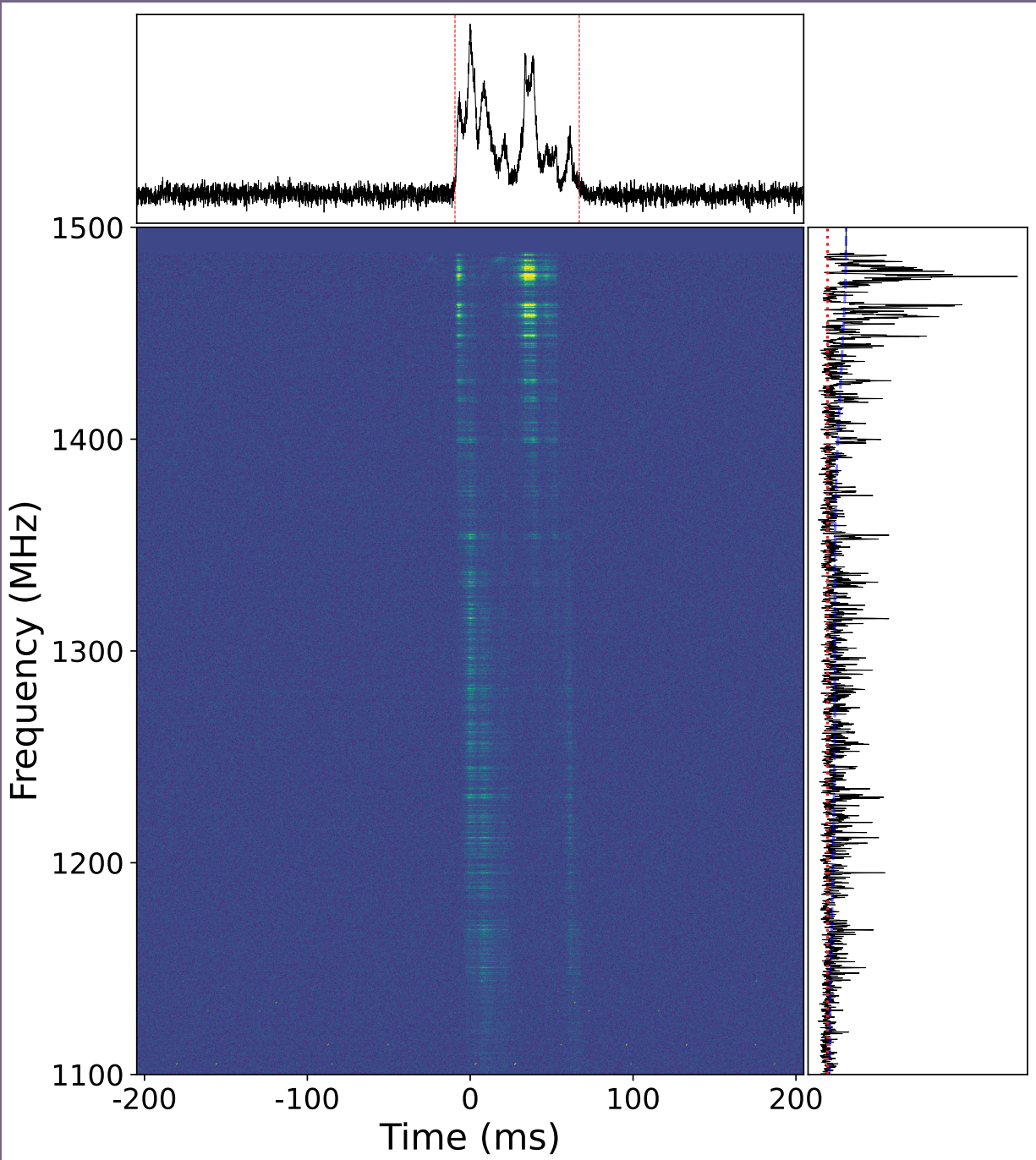
Qu et al. 2023

Scintillation*

* from the host galaxy



Nimmo et al. 2022



Wu et al.2024

FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour	✓	✓
Temporal variability	✓	✗ ?
Pol angle swing	✓	✗
Circular polarisation	✓	?

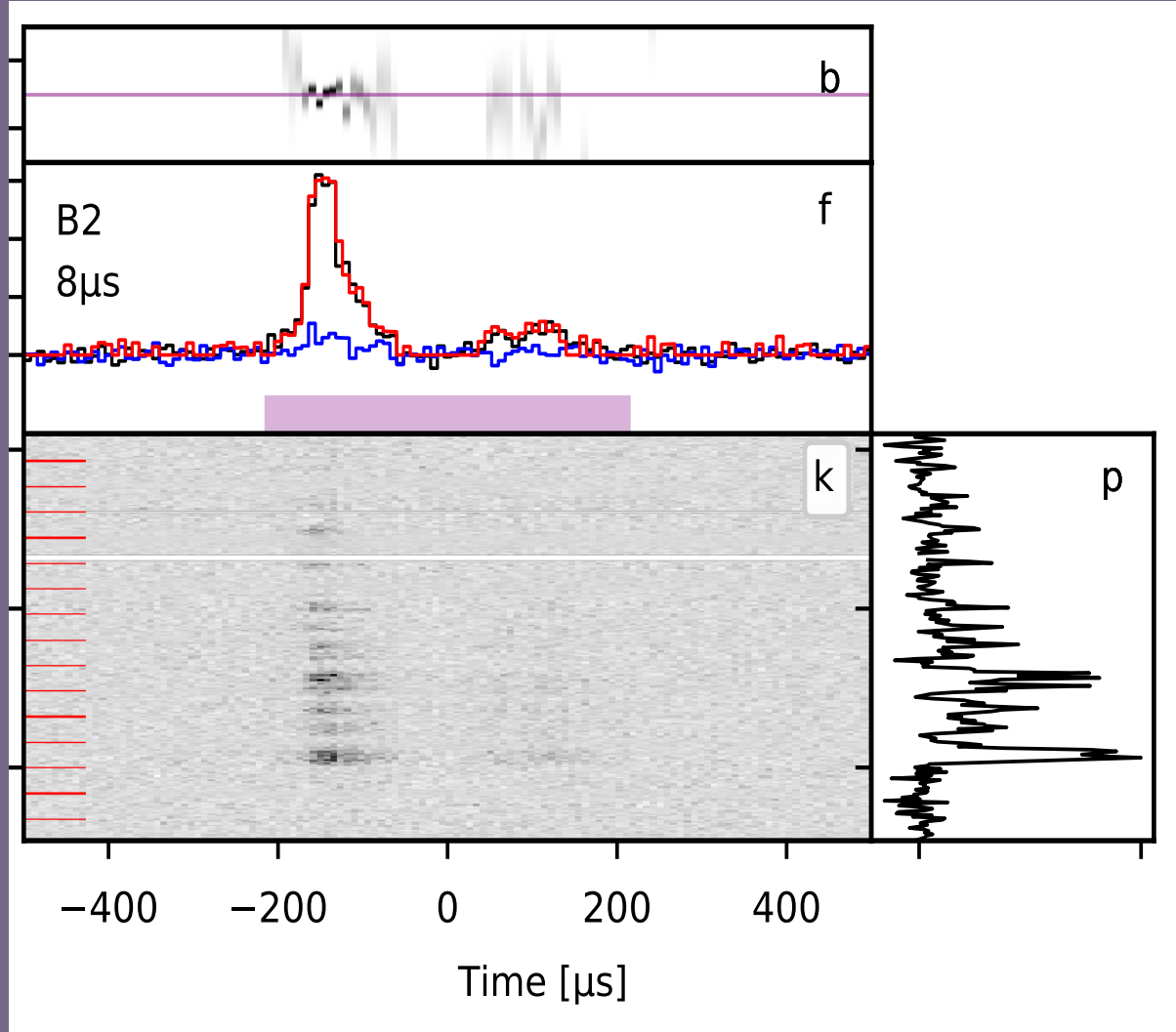
Metzger et al. 2022

Sobacchi et al. 2021, 2024b

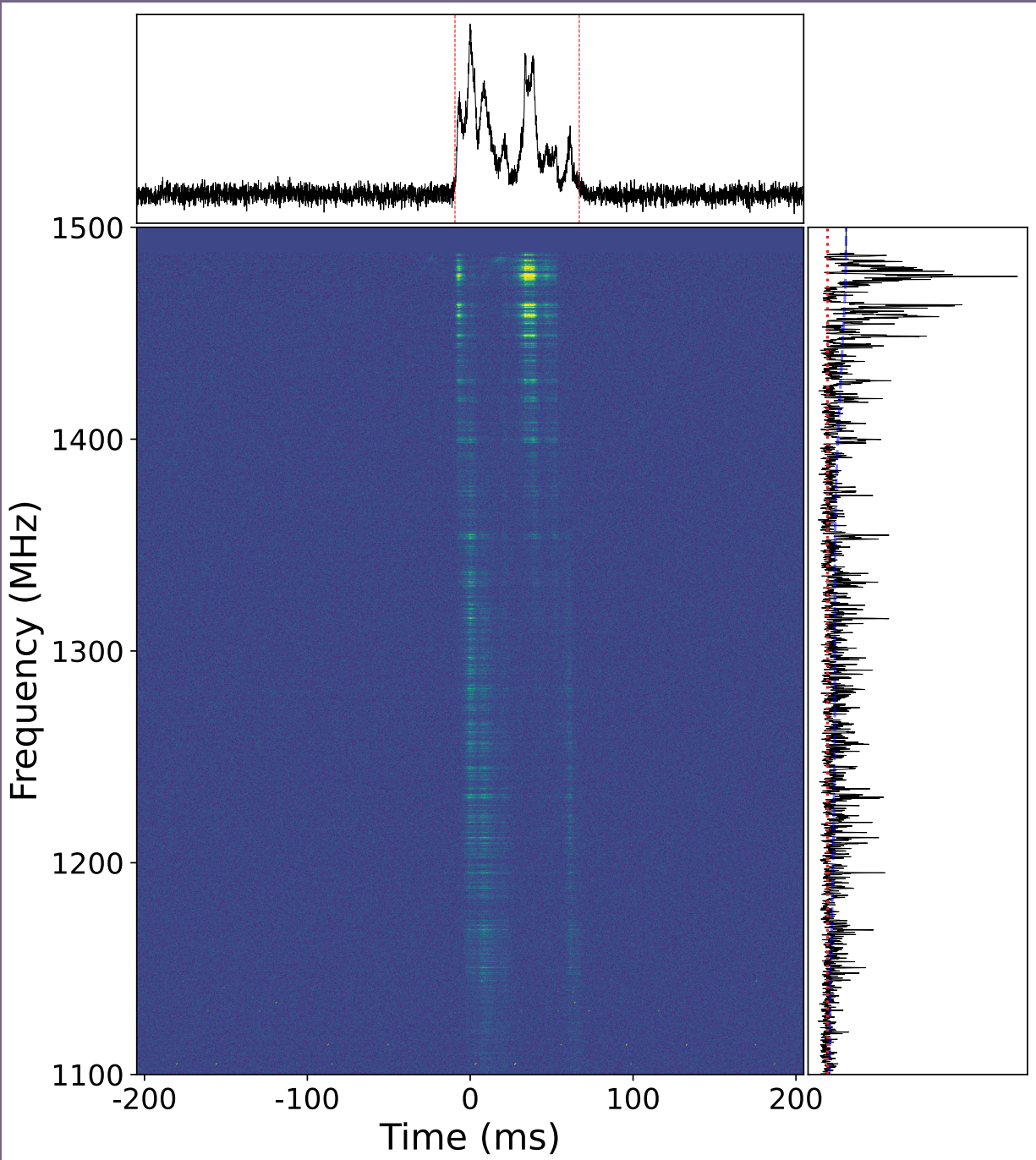
Qu et al. 2023

Scintillation*

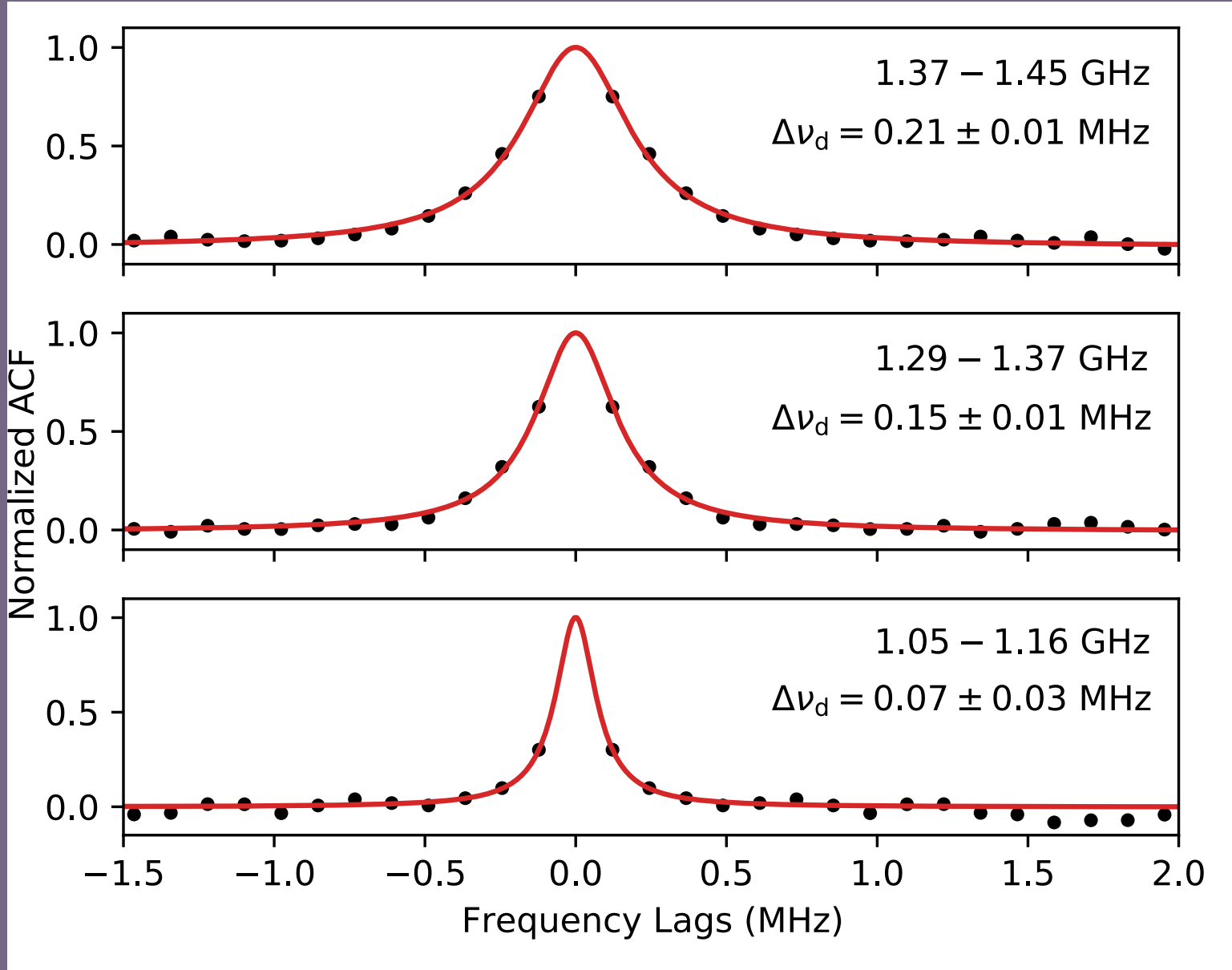
* from the host galaxy



Nimmo et al. 2022



Wu et al.2024



Ocker et al. 2022a

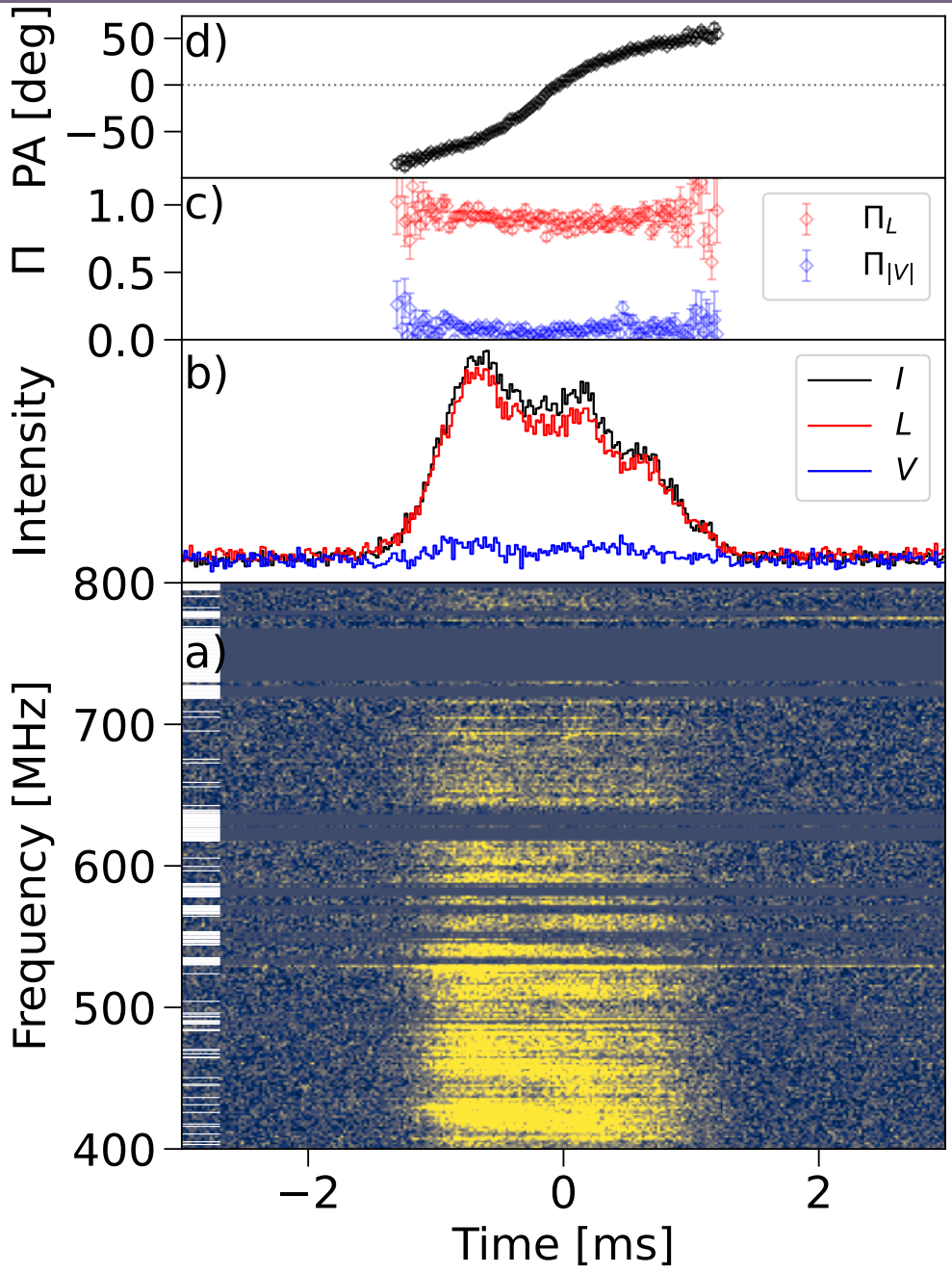
<p>FRB property</p>	<p>Magnetospheric</p>	<p>Non-magnetospheric</p>
<p>Spectral behaviour</p>		
<p>Temporal variability</p>		
<p>Pol angle swing</p>		
<p>Circular polarisation</p>		

Qu et al. 2023

Scintillation*

* from the host galaxy

SWINGS

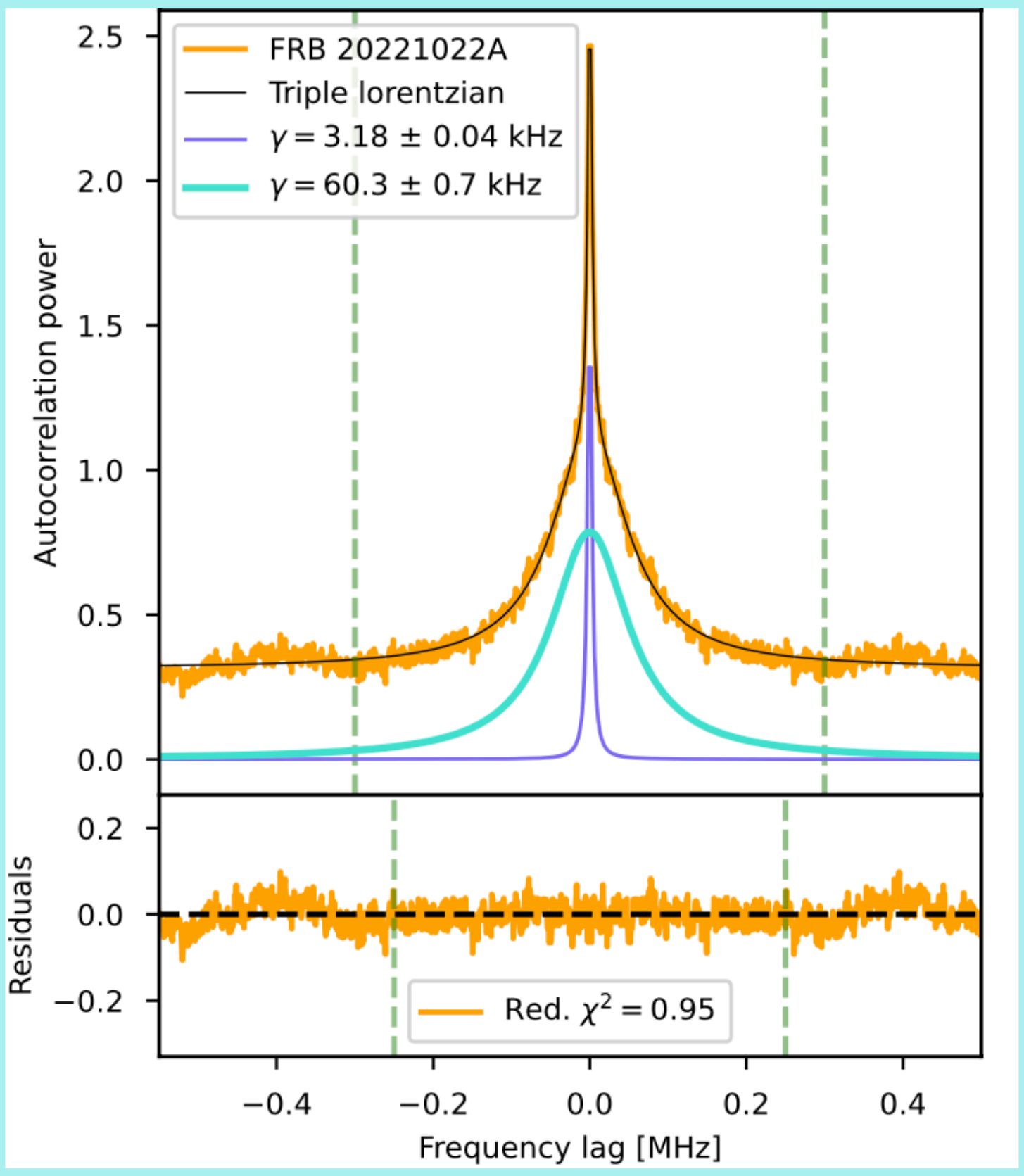


Mckinven et al. 2025

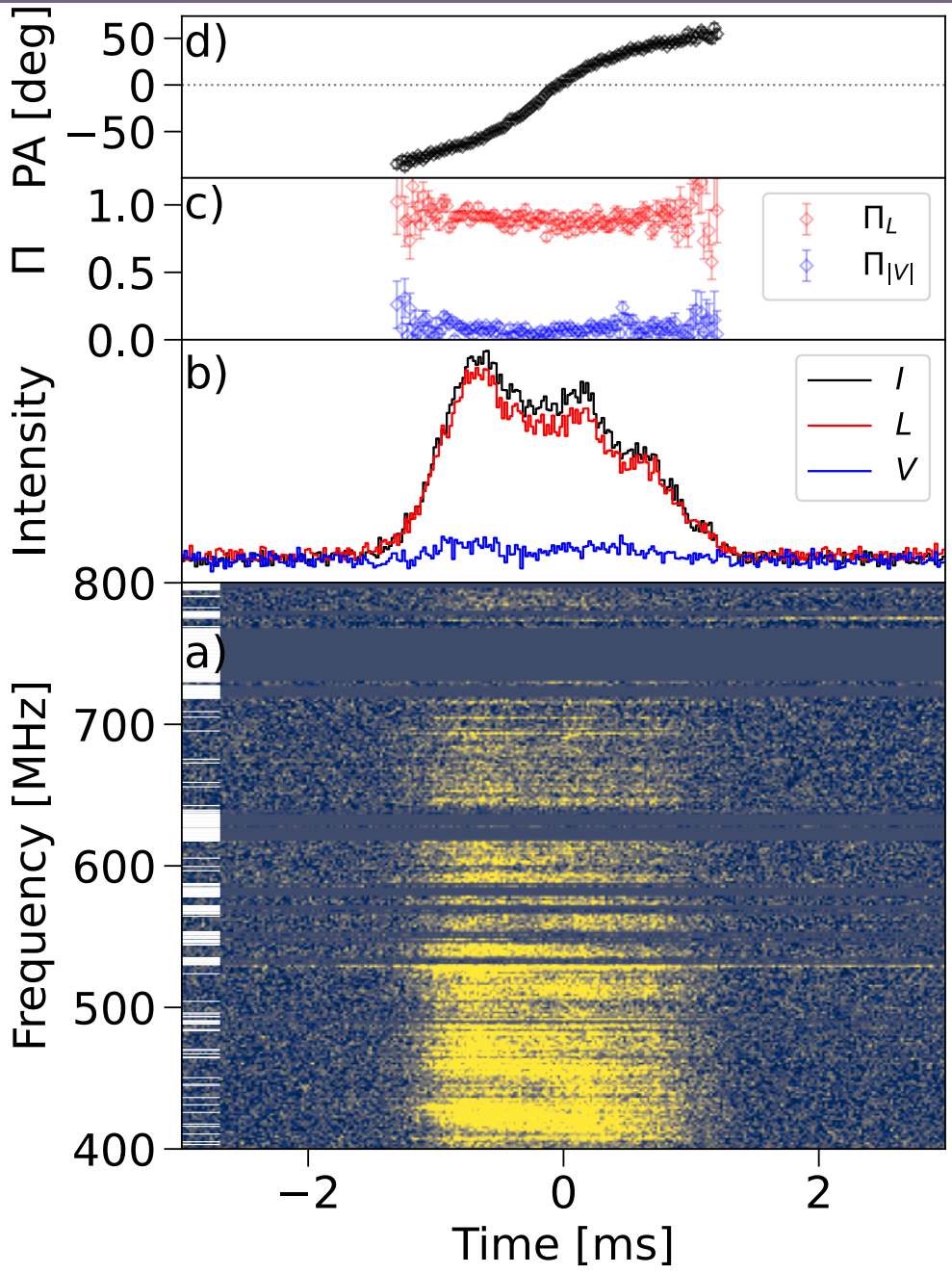
FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour		Metzger et al. 2022
Temporal variability		Sobacchi et al. 2021, 2024b
Pol angle swing		
Circular polarisation		Qu et al. 2023

Scintillation*

* from the host galaxy



Nimmo et al. 2025



Mckinven et al. 2025

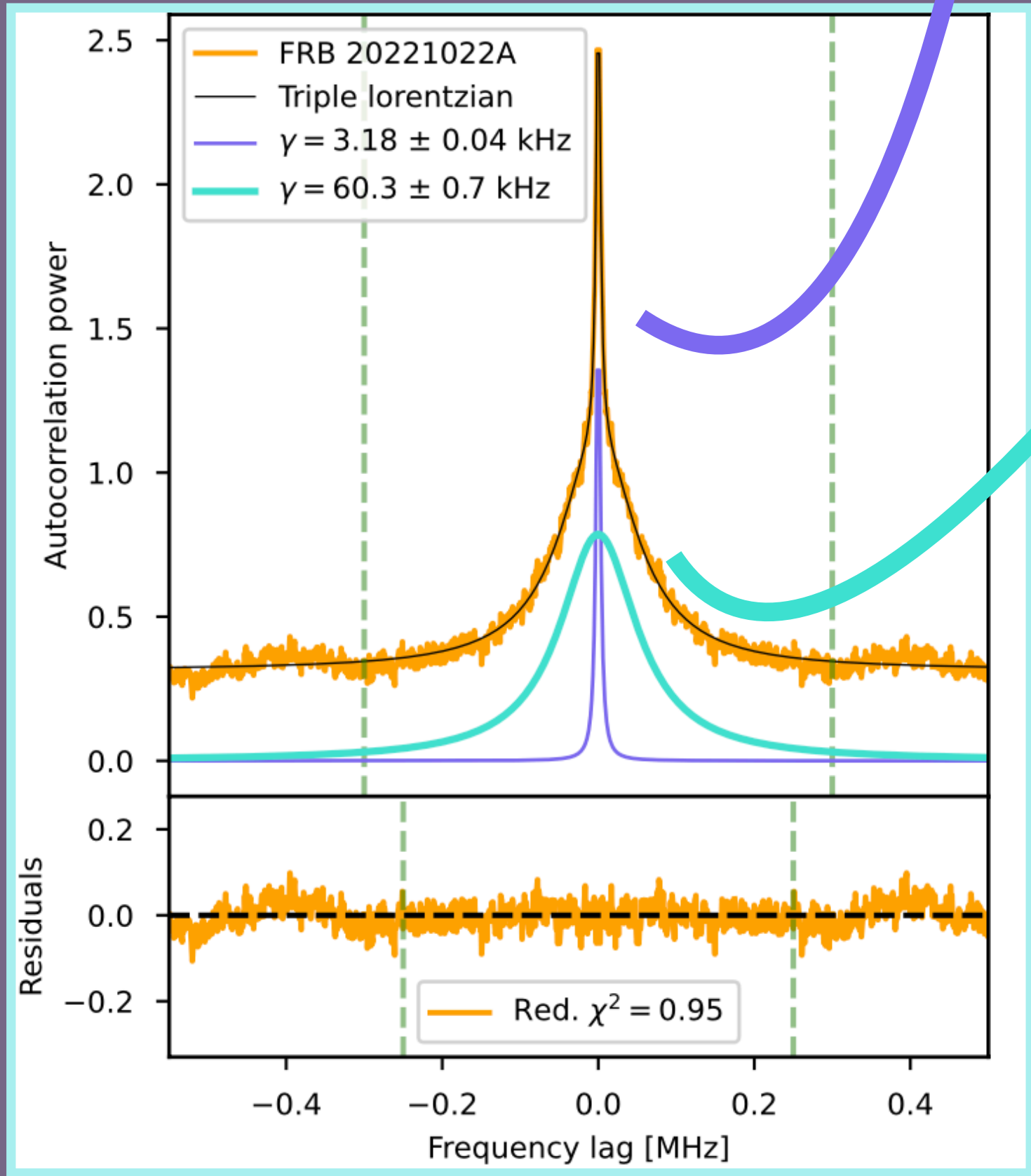
FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour	✓	✓ Metzger et al. 2022
Temporal variability	✓	✗ ? Sobacchi et al. 2021, 2024b
Pol angle swing	✓	✗
Circular polarisation	✓	? Qu et al. 2023

Scintillation*

* from the host galaxy

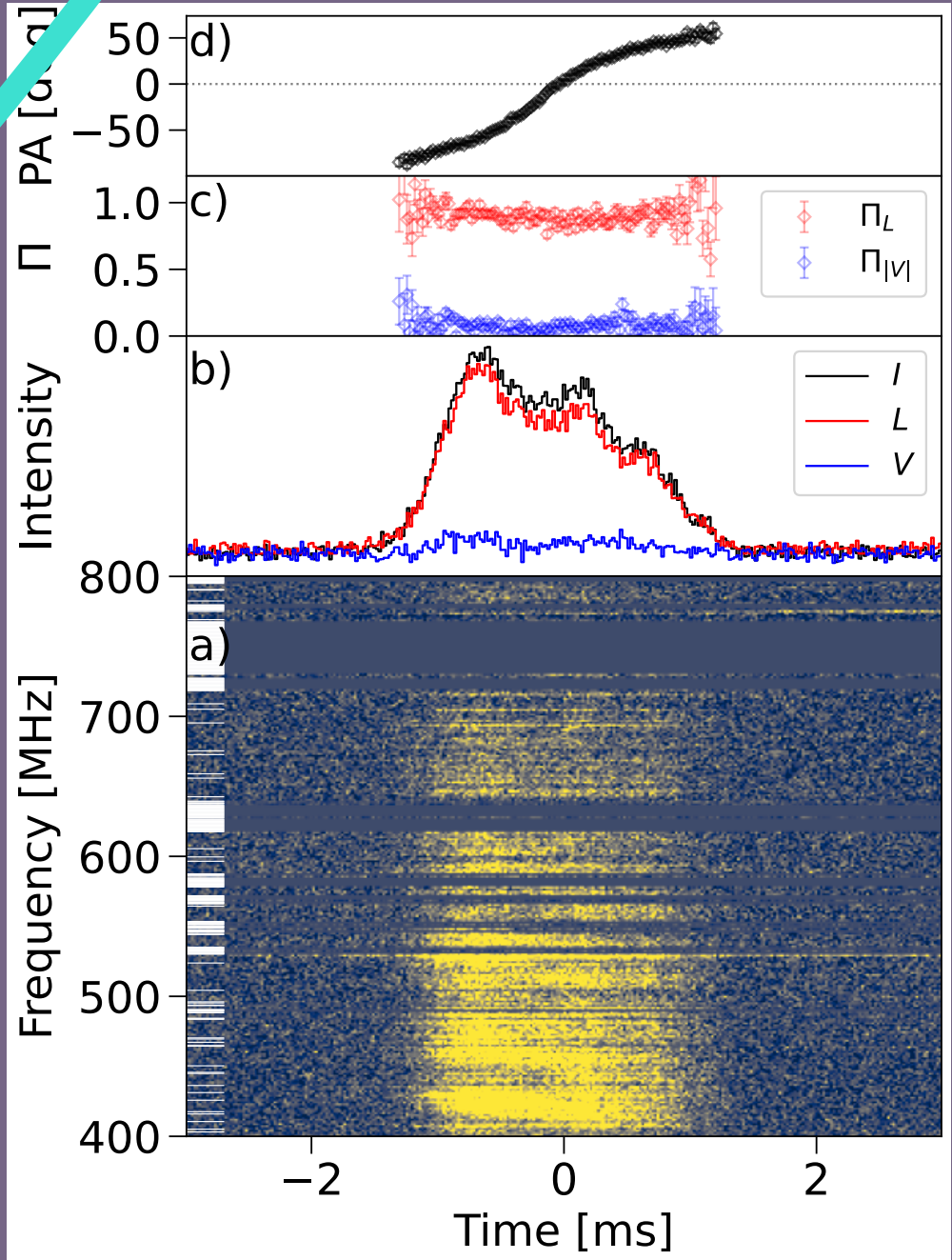
Scintillation screen in Milky Way

Scintillation screen in FRB host galaxy



Nimmo et al. 2025

SWINGS



Mckinven et al. 2025

FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour	✓	✓
Temporal variability	✓	✗ ?
Pol angle swing	✓	✗
Circular polarisation	✓	?

Metzger et al. 2022

Sobacchi et al. 2021, 2024b

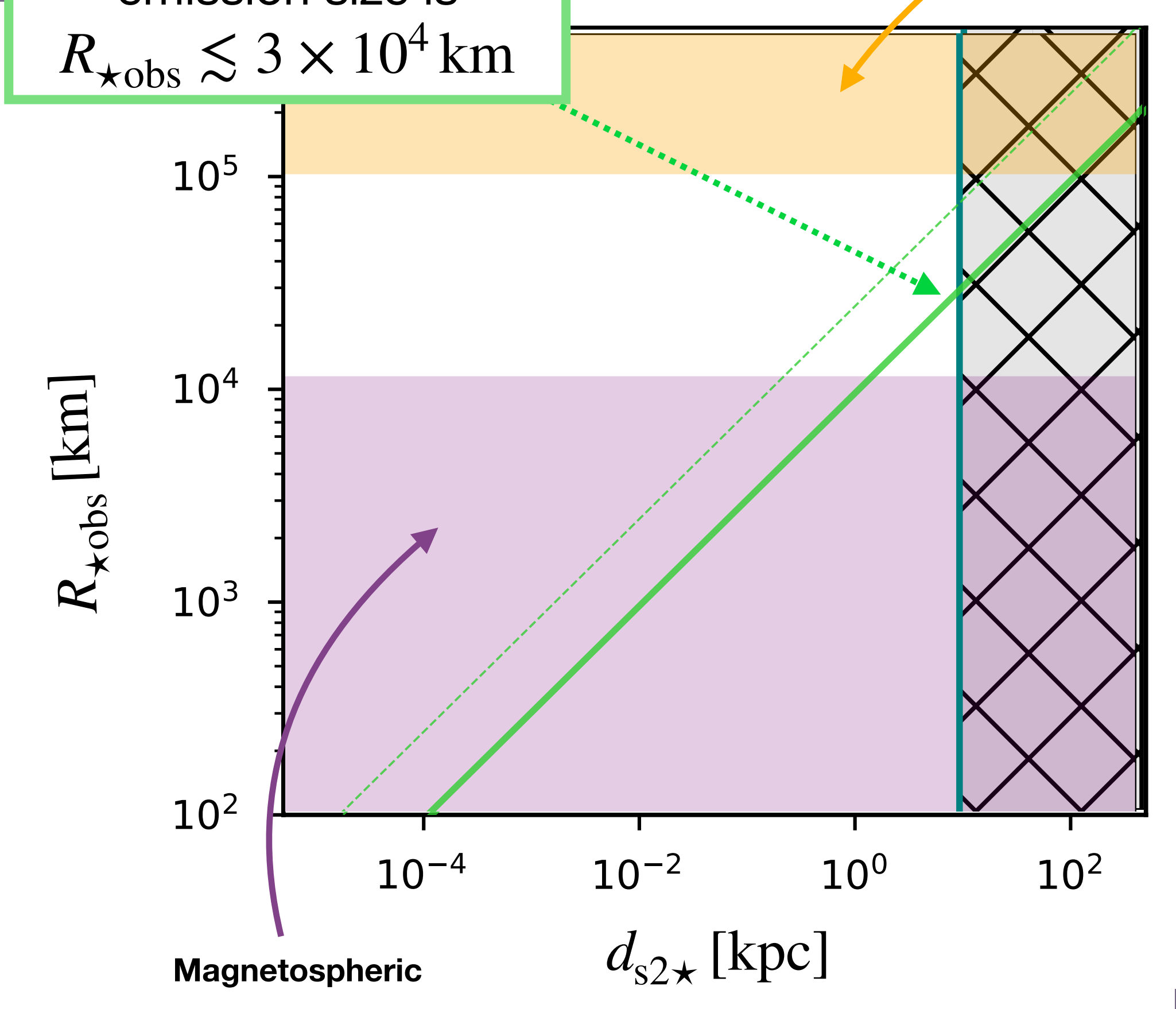
Qu et al. 2023

Scintillation*

* from the host galaxy

Upper limit on the emission size is

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



Nimmo et al. 2025



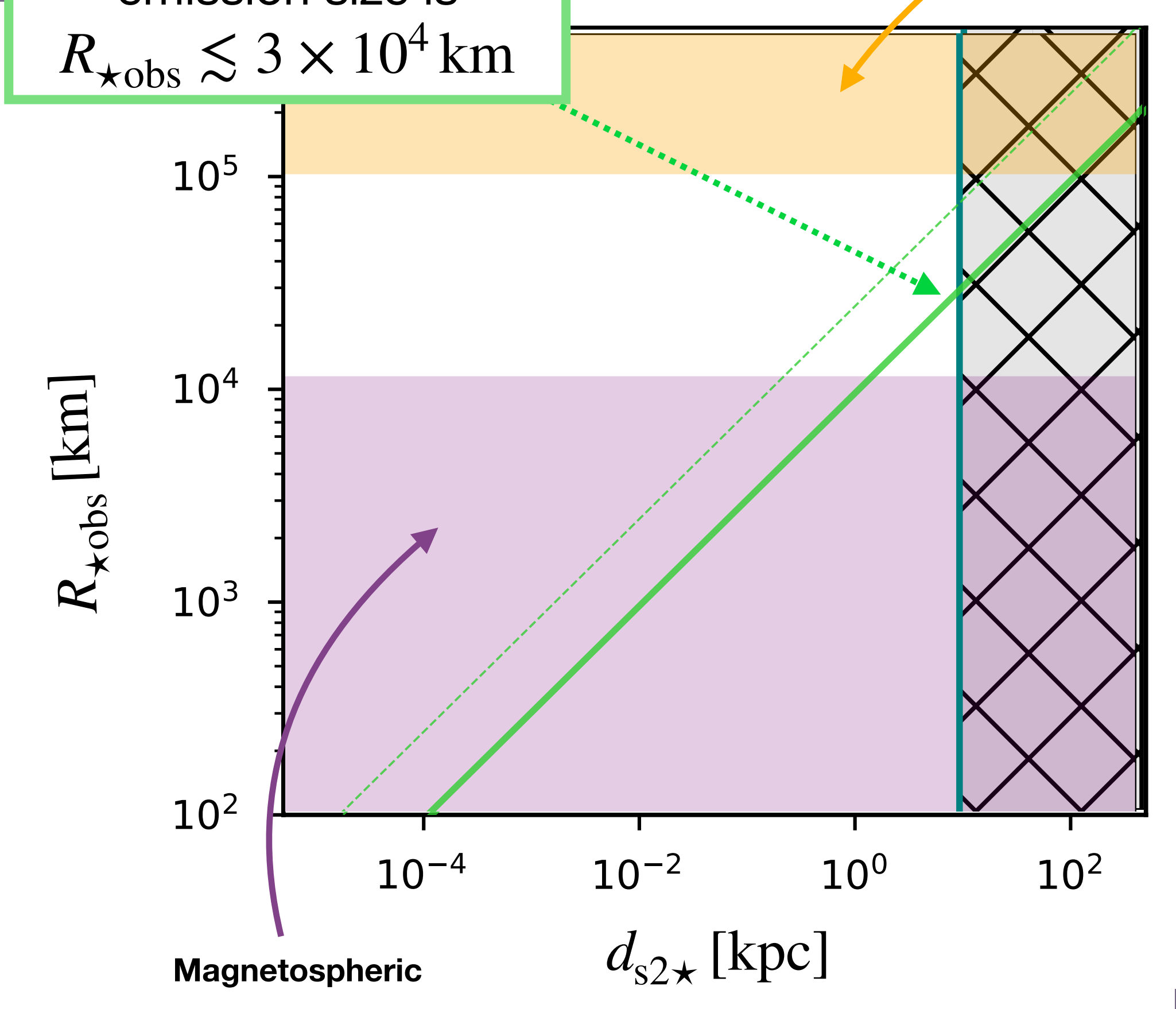
FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour	✓	✓ Metzger et al. 2022
Temporal variability	✓	✗ ? Sobacchi et al. 2021, 2024b
Pol angle swing	✓	✗
Circular polarisation	✓	? Qu et al. 2023
Scintillation		

Scintillation*

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



Nimmo et al. 2025



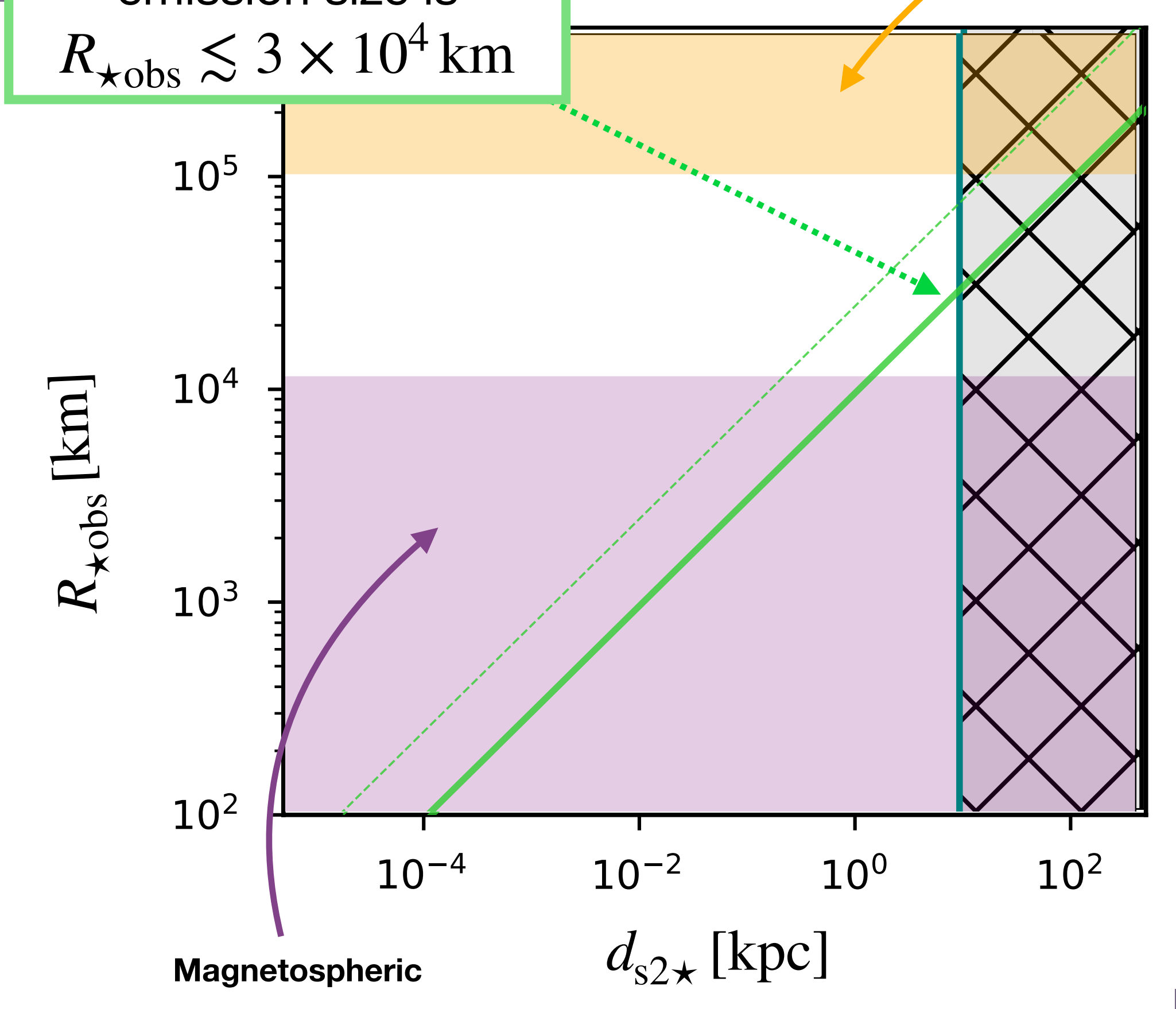
FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour	✓	✓ Metzger et al. 2022
Temporal variability	✓	✗ ? Sobacchi et al. 2021, 2024b
Pol angle swing	✓	✗
Circular polarisation	✓	? Qu et al. 2023
Scintillation	✓	

Scintillation*

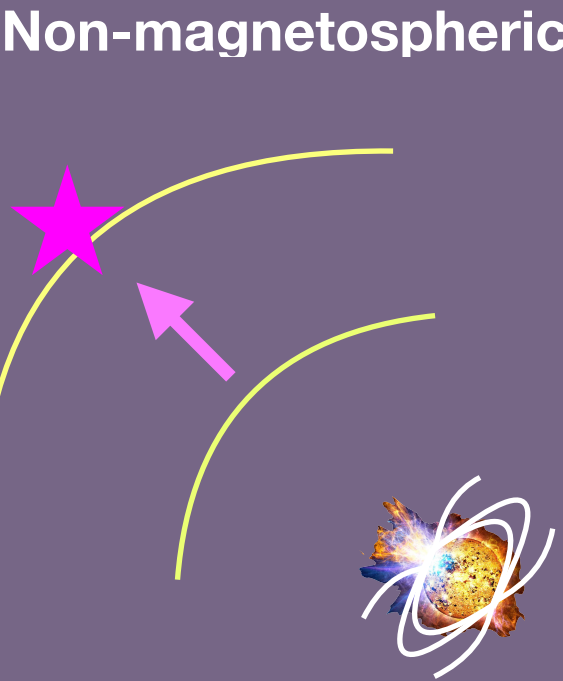
* from the host galaxy

Upper limit on the emission size is

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



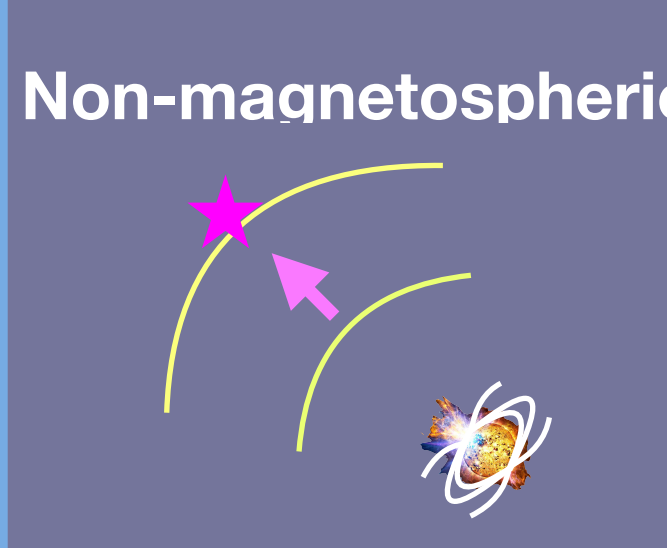
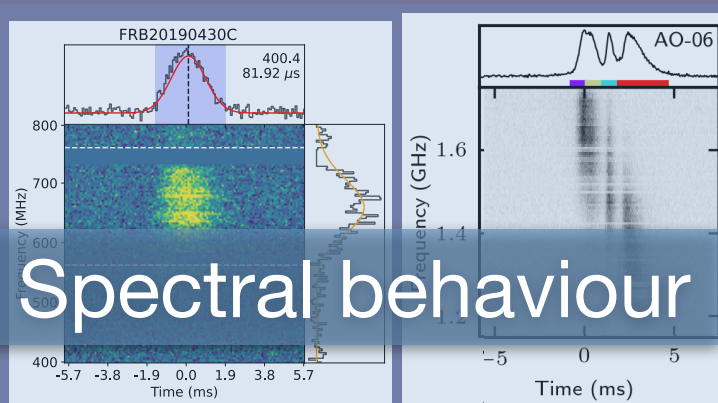


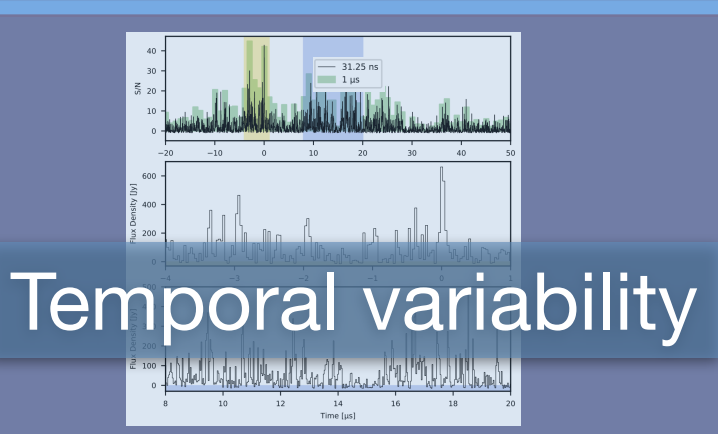

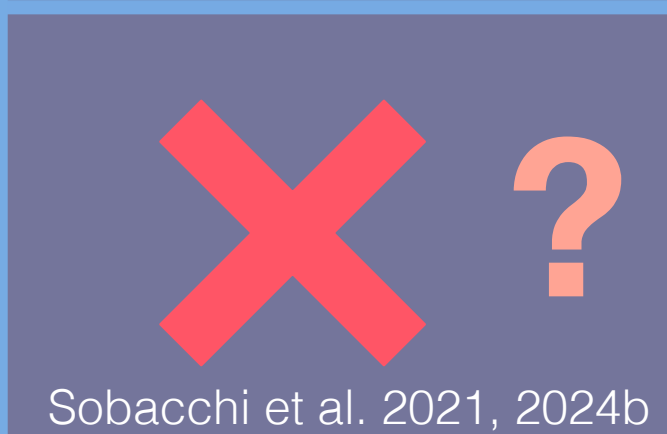
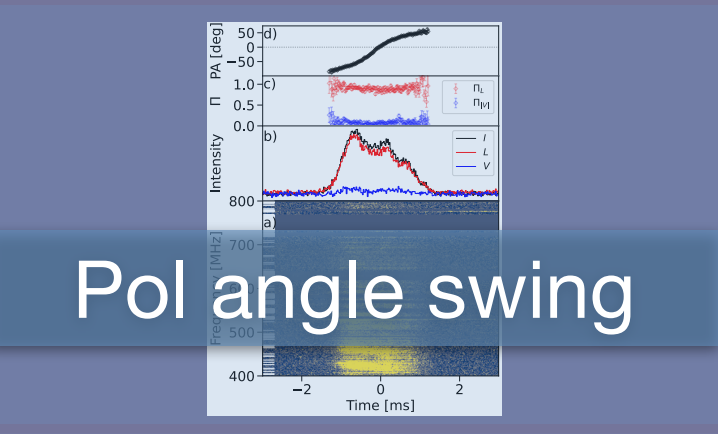


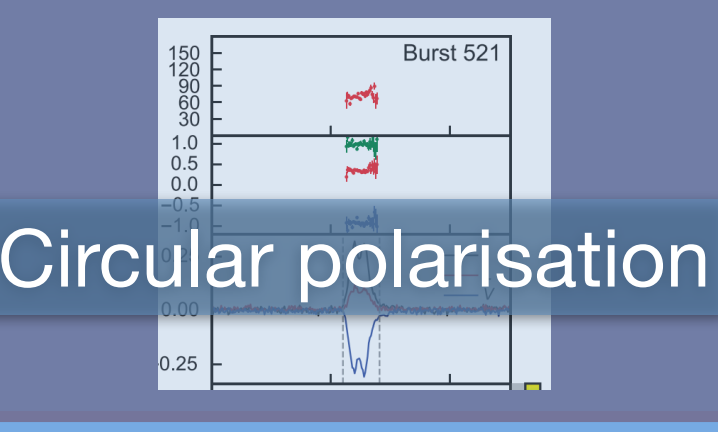


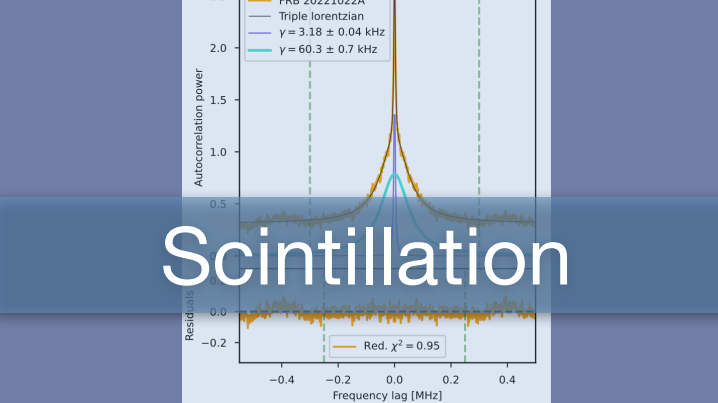




Nimmo et al. 2025

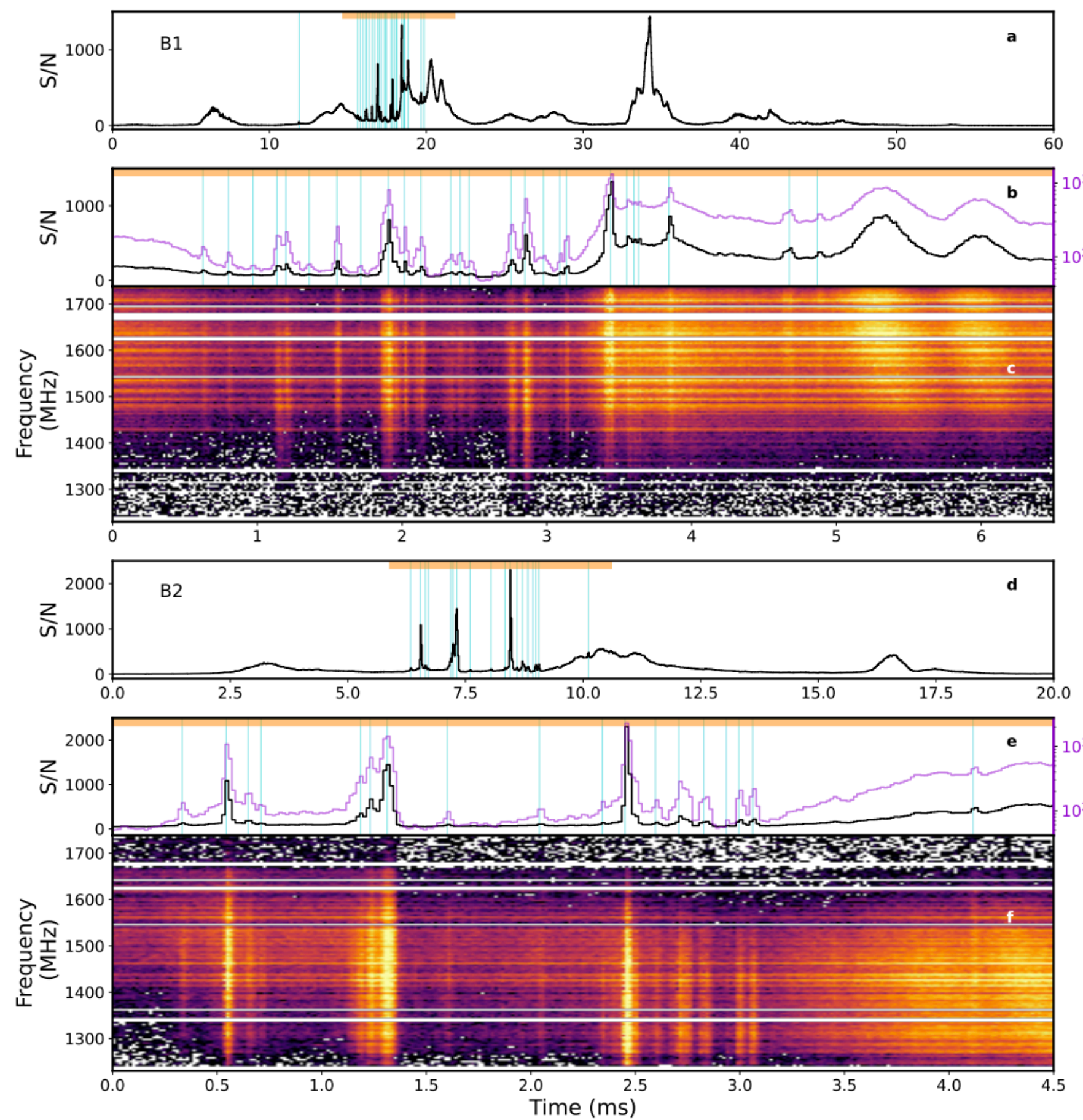


FRB property	Magnetospheric	Non-magnetospheric
Spectral behaviour	✓	✓ Metzger et al. 2022
	✓	✗ ? Sobacchi et al. 2021, 2024b
	✓	✗
	✓	? Qu et al. 2023
	✓	✗ Kumar et al. 2024

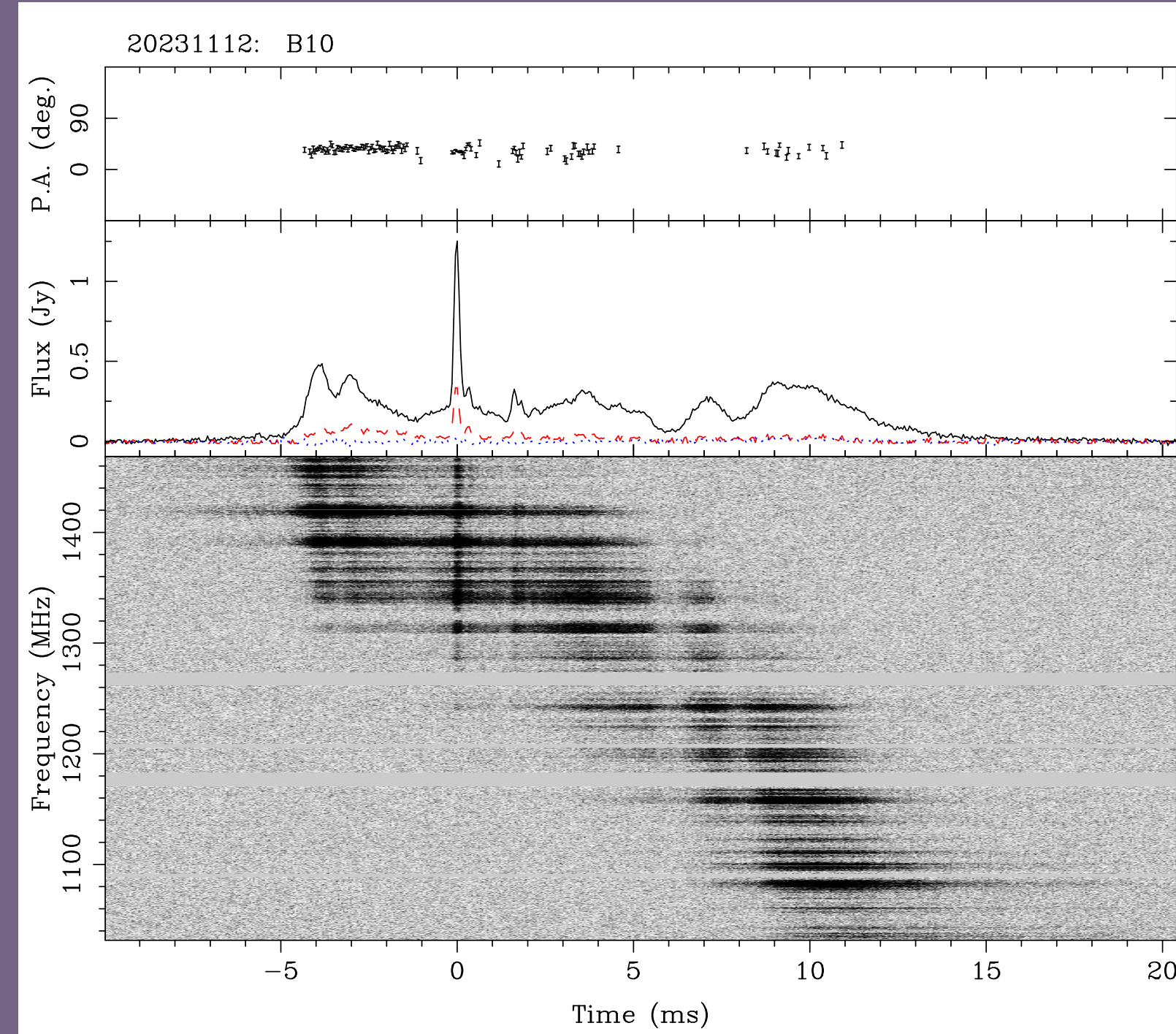
Growing support for magnetospheric models

<p>FRB property</p> 	<p>Magnetospheric</p> 	<p>Non-magnetospheric</p> 
<p>Spectral behaviour</p> 		 <p>Metzger et al. 2022</p>
<p>Temporal variability</p> 		 <p>Sobacchi et al. 2021, 2024b</p>
<p>Pol angle swing</p> 		
<p>Circular polarisation</p> 		 <p>Qu et al. 2023</p>
<p>Scintillation</p> 		 <p>Kumar et al. 2024</p>

Evidence for multiple emission processes?



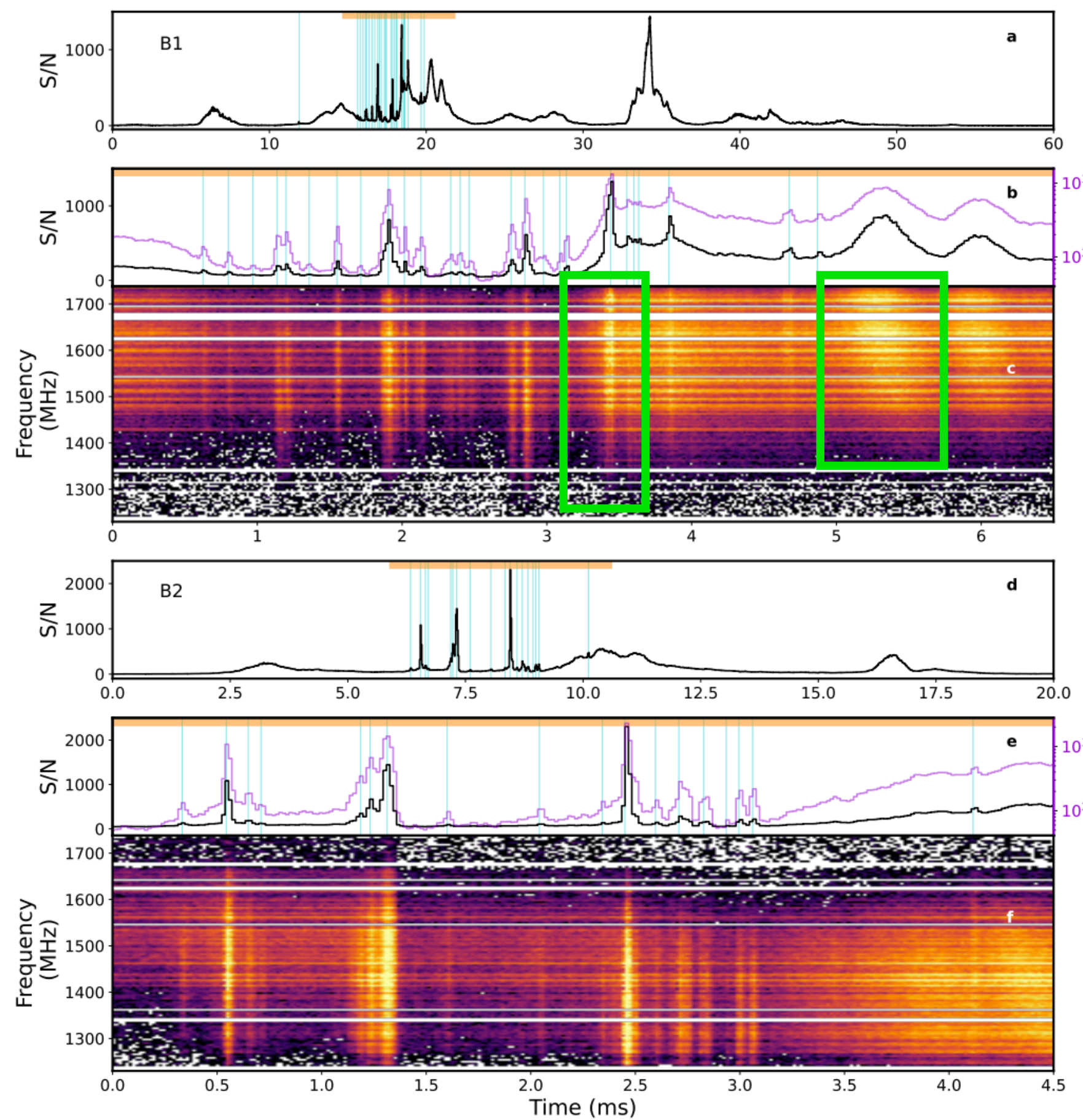
Hewitt et al. 2023



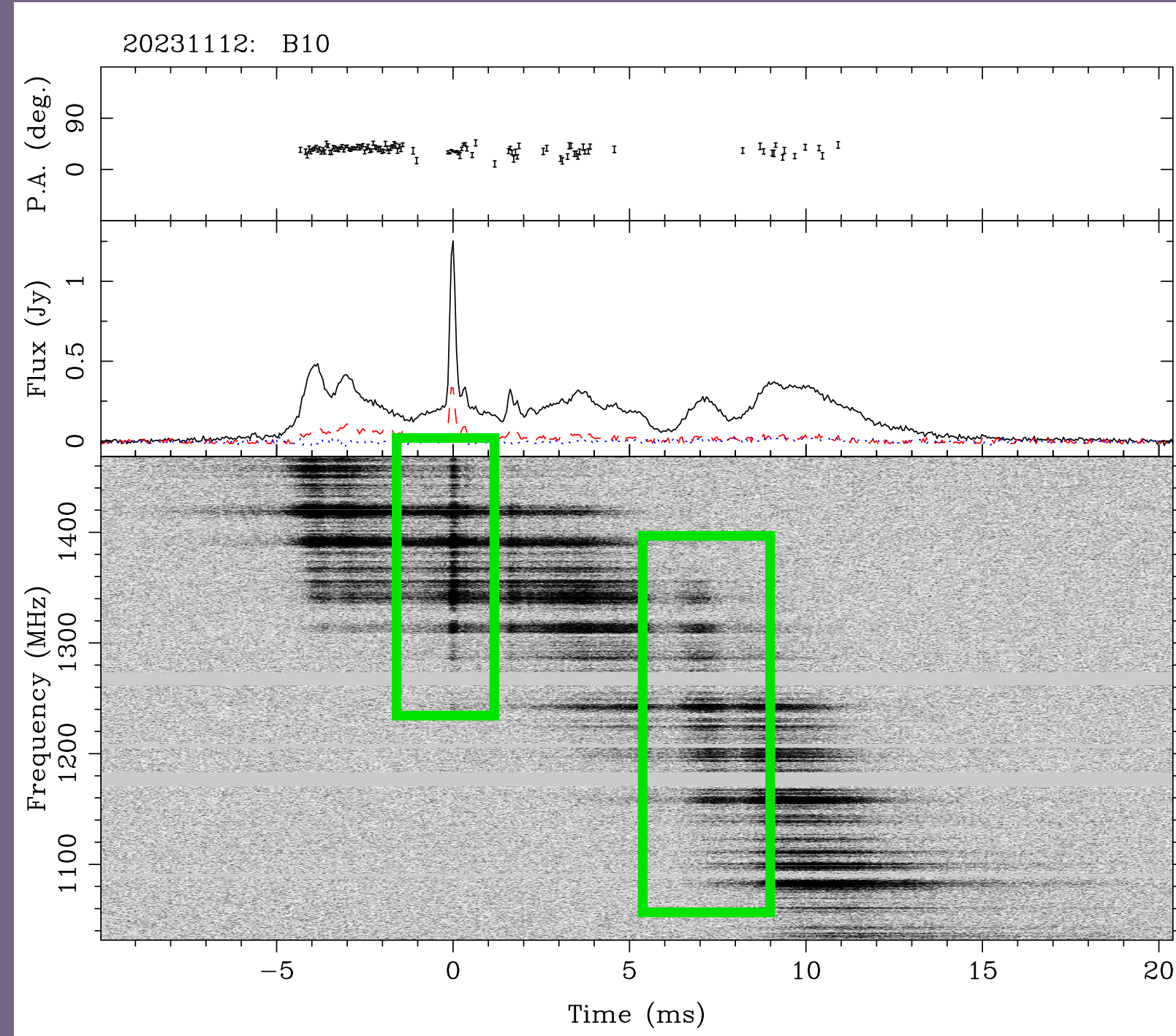
Zhou et al. 2025

Evidence for multiple emission processes?

Changing DM? Changing drifting?



Hewitt et al. 2023

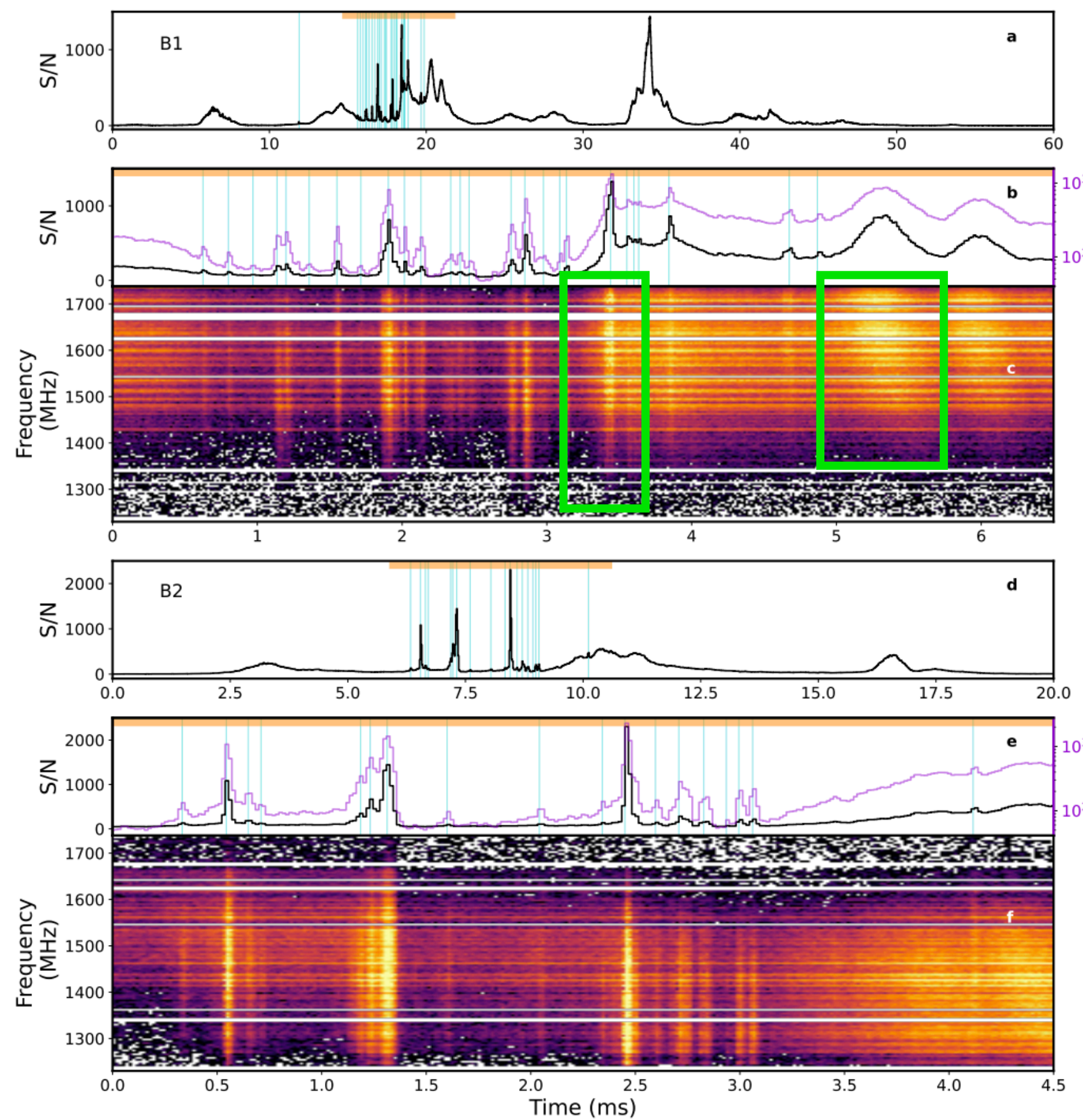


Zhou et al. 2025

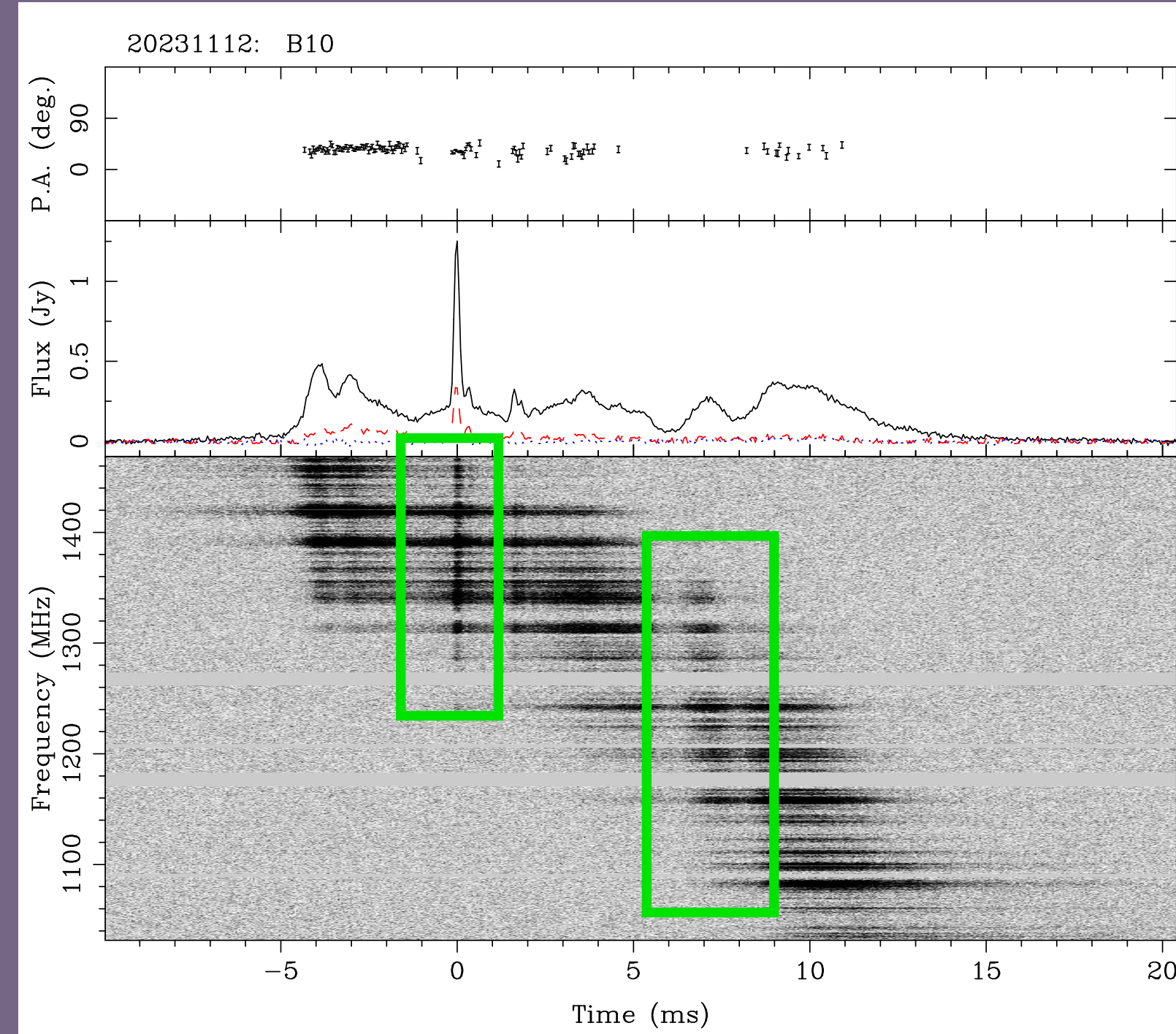
Evidence for multiple emission processes?

Changing DM? Changing drifting?

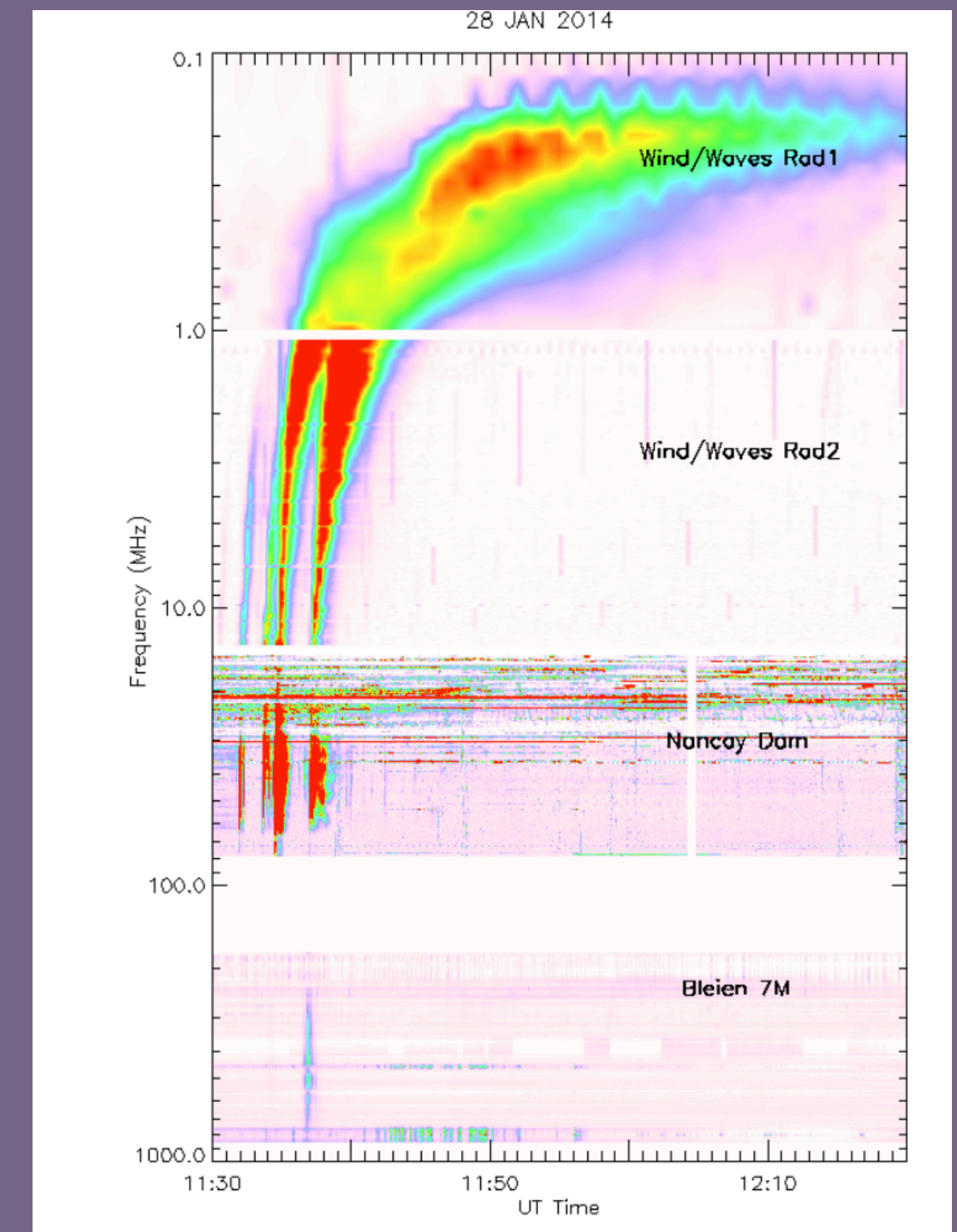
Analogous to solar flares?



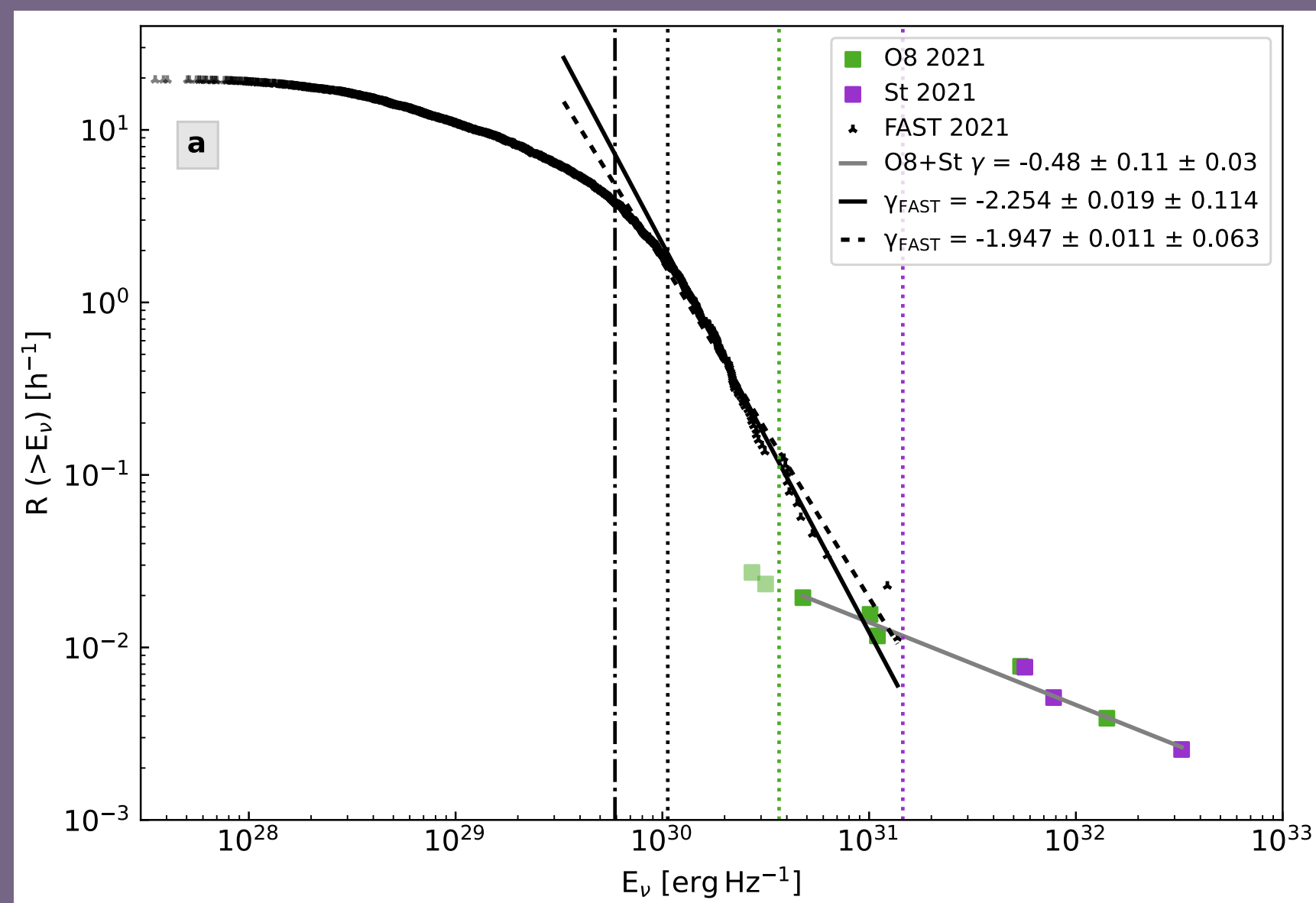
Hewitt et al. 2023



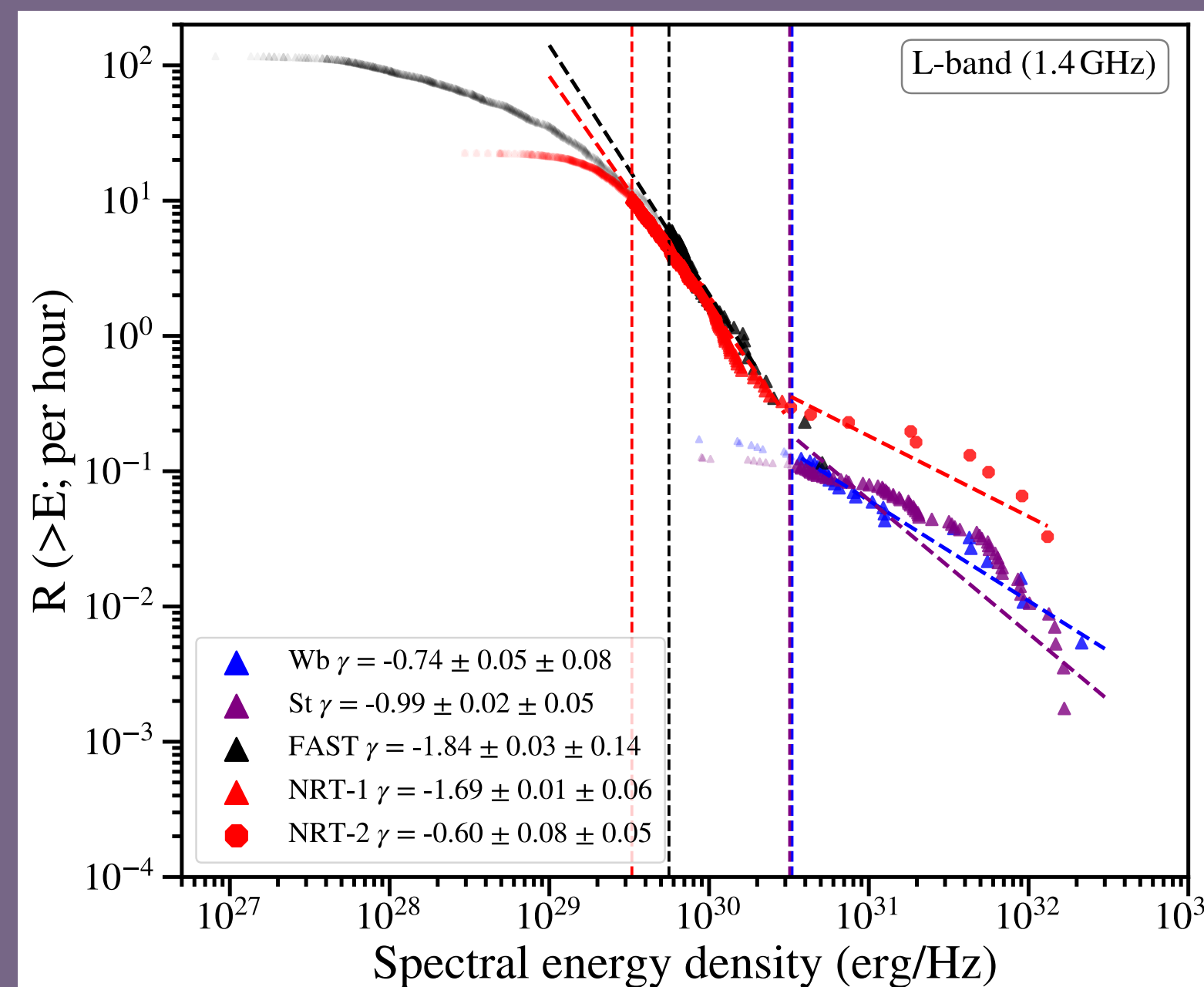
Zhou et al. 2025



Evidence for multiple emission processes?

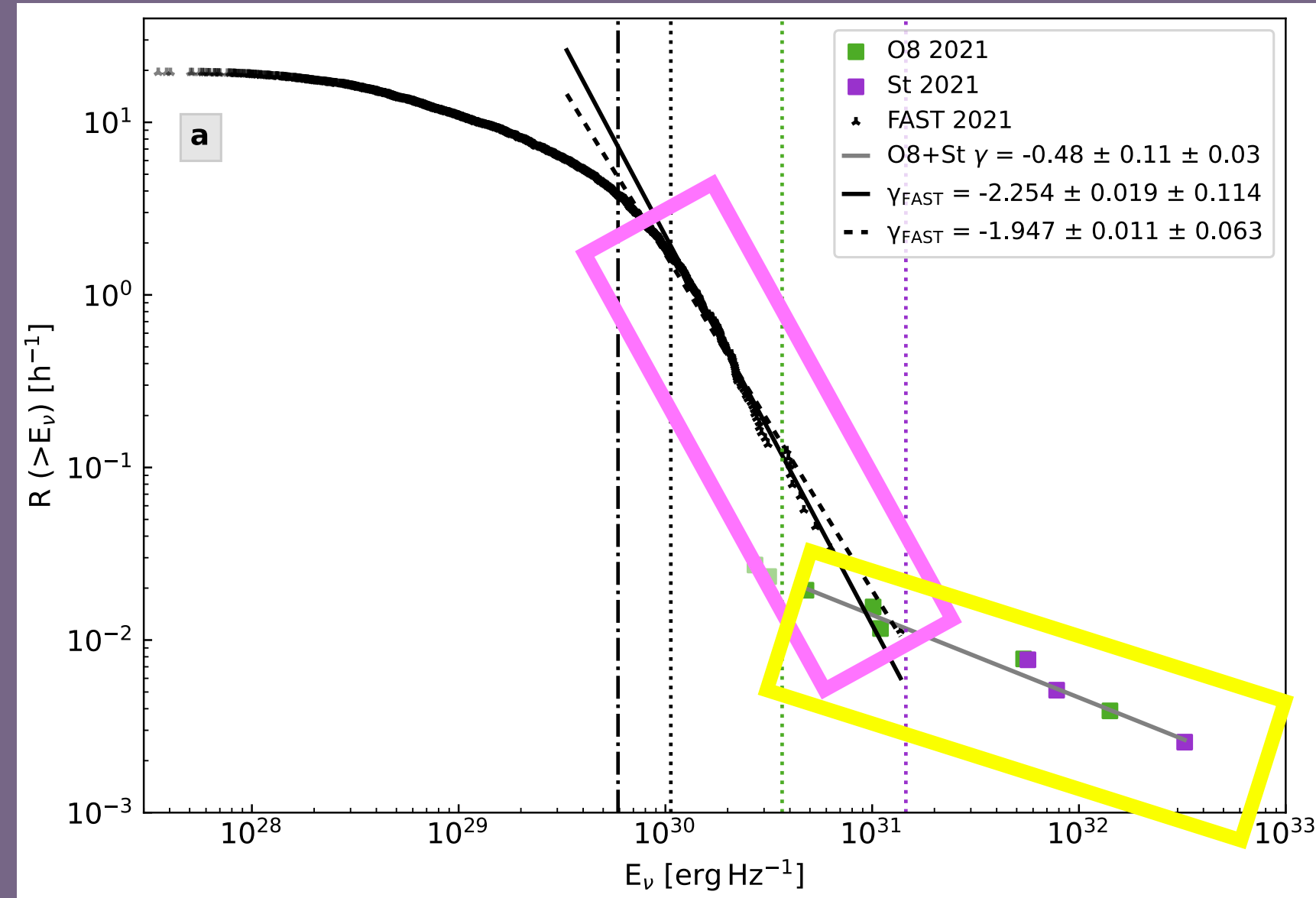


Kirsten et al. 2024

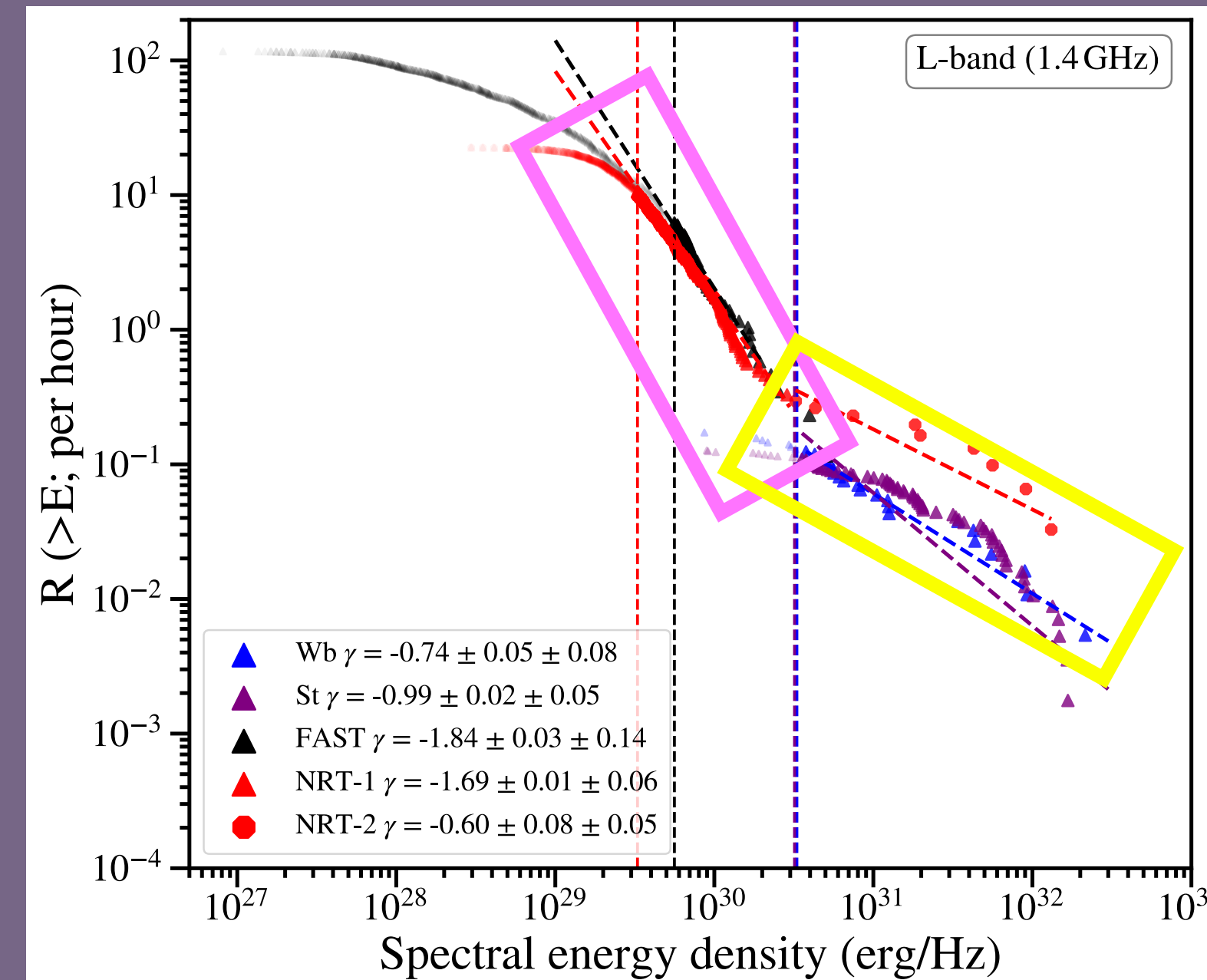


Ould-Boukattine et al. 2024

Evidence for multiple emission processes?



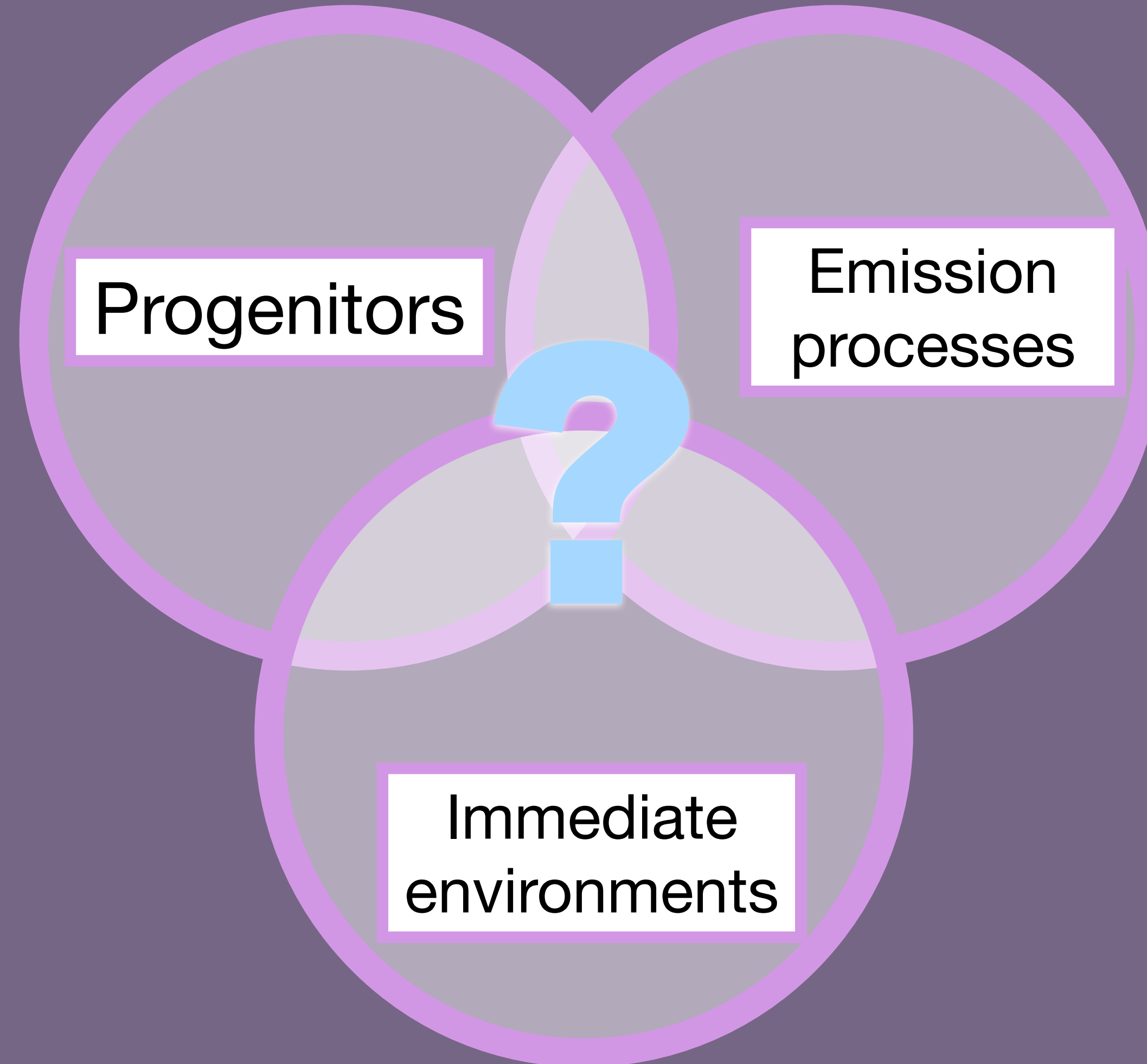
Kirsten et al. 2024



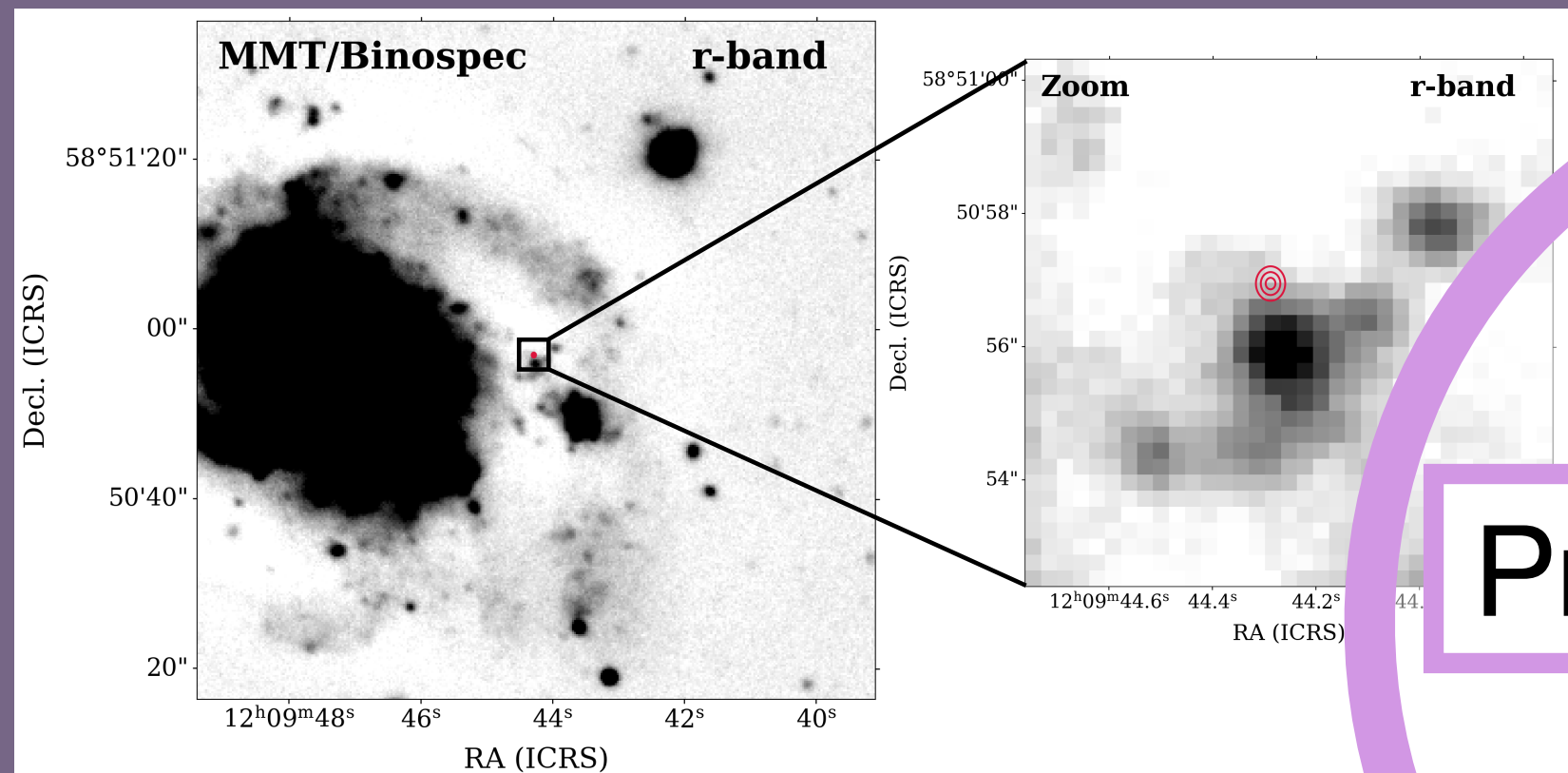
Ould-Boukattine et al. 2024

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

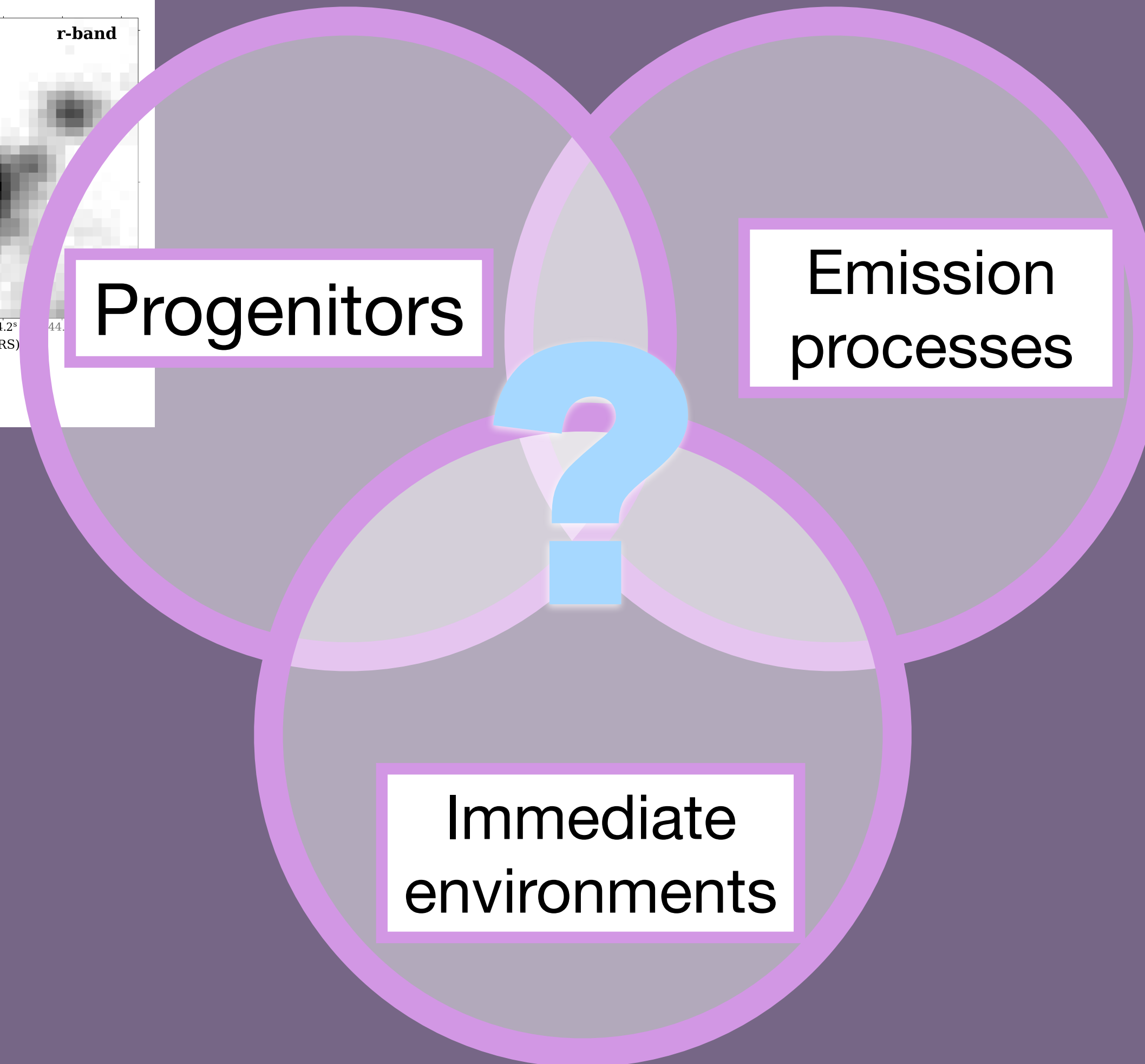
Summary



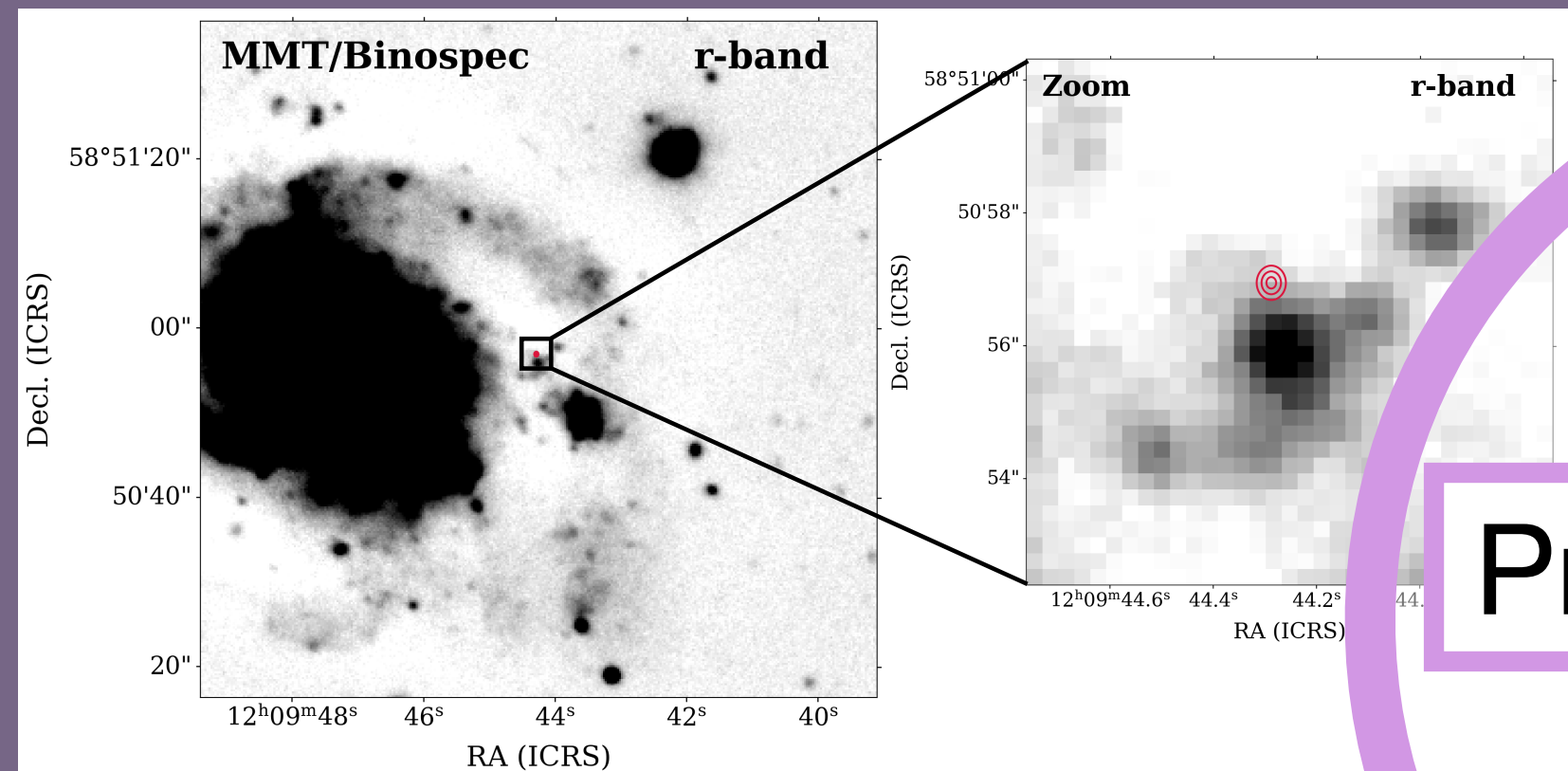
Summary



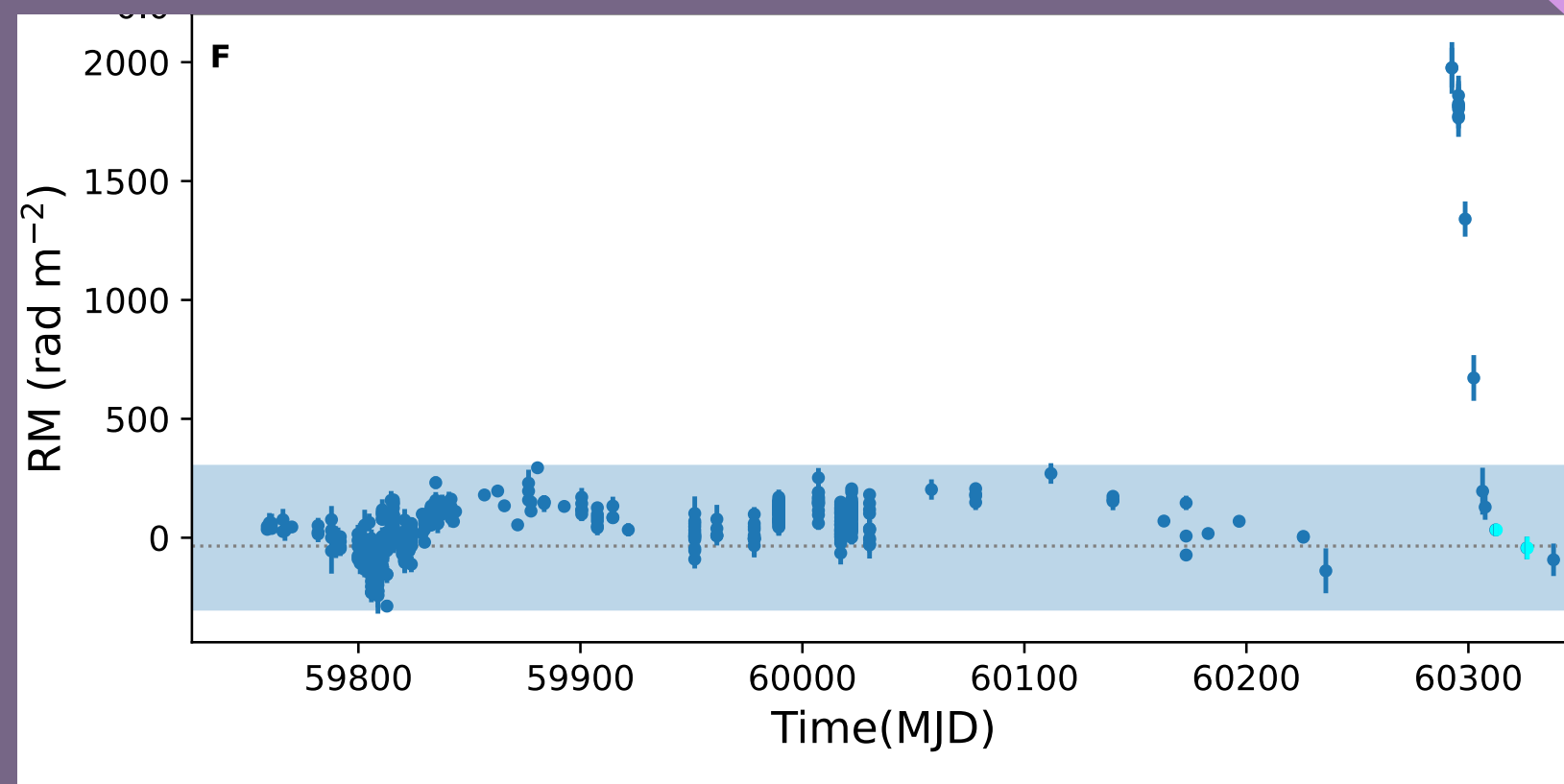
CHIME/FRB Collab. et al. 2025



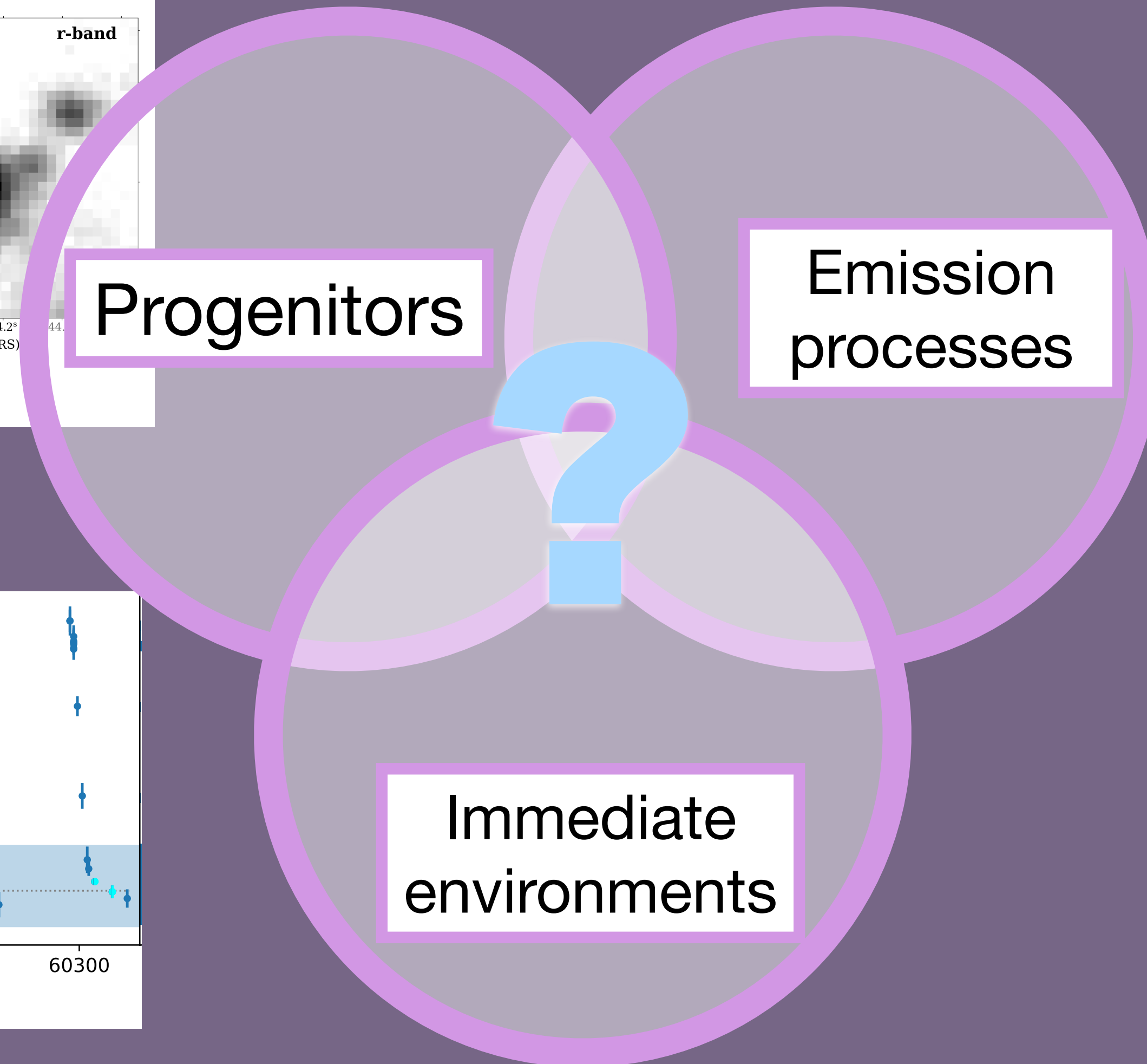
Summary



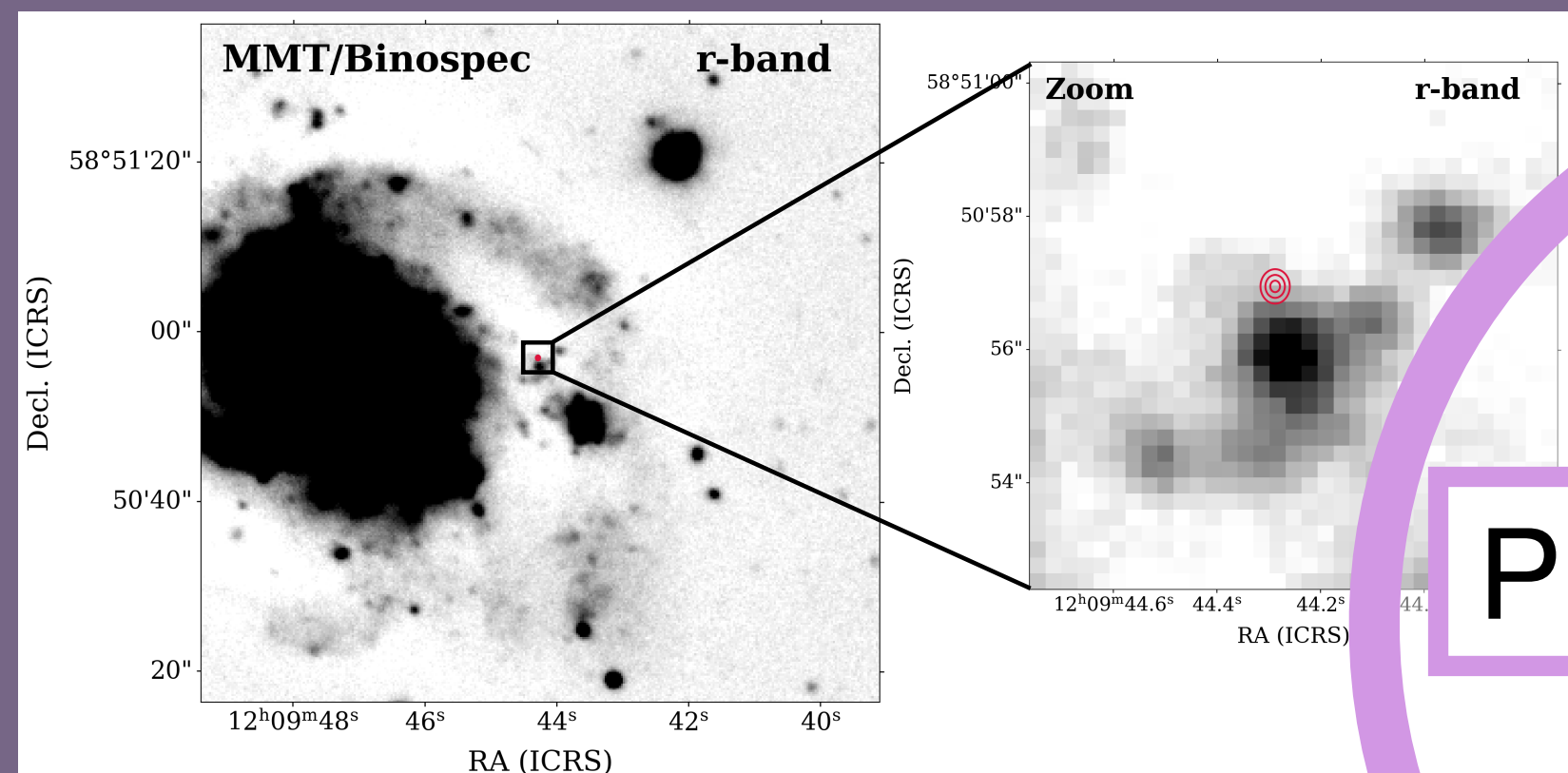
CHIME/FRB Collab. et al. 2025



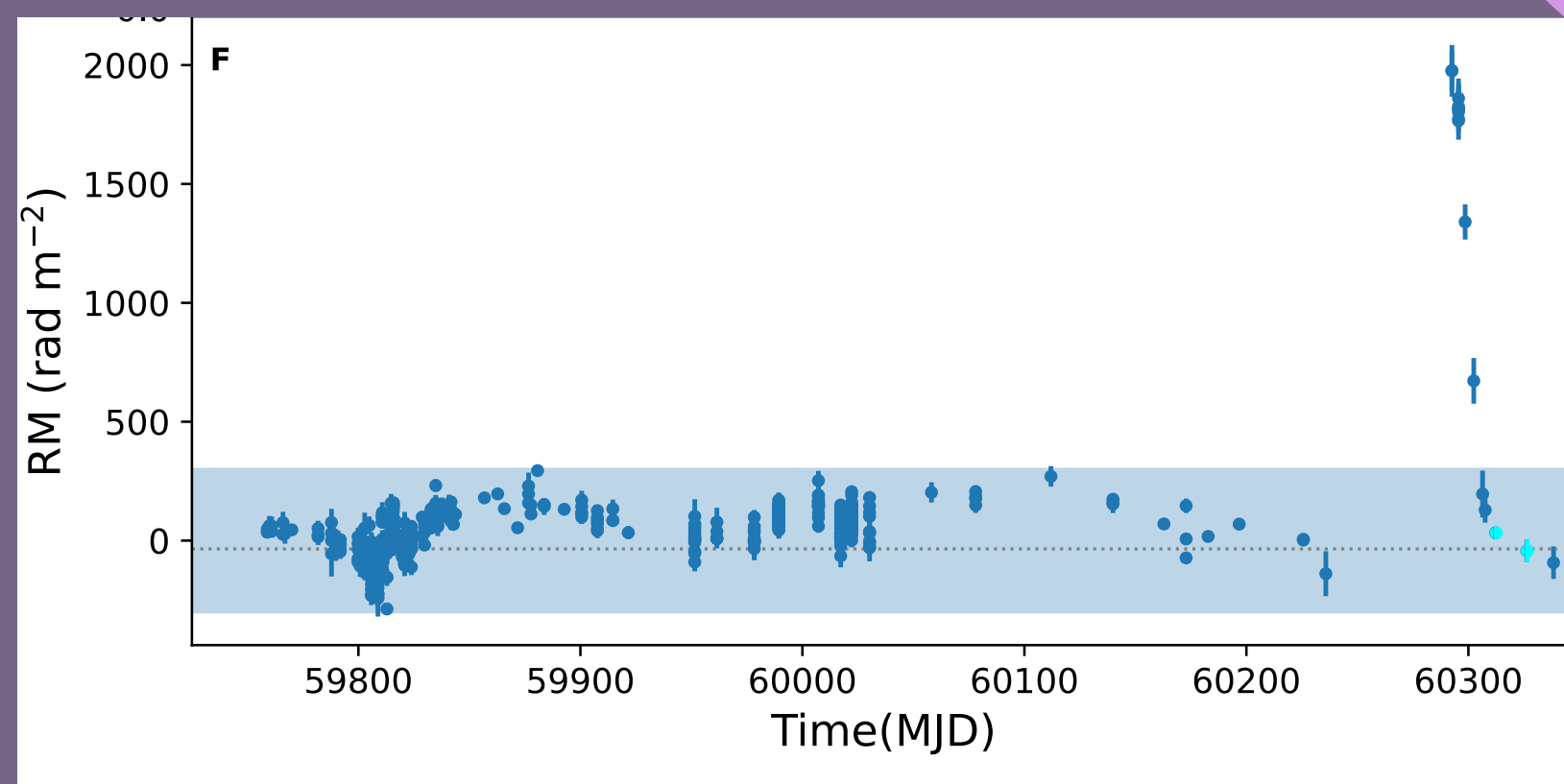
Li et al. 2025



Summary



CHIME/FRB Collab. et al. 2025



Li et al. 2025

Progenitors

Emission processes

Immediate environments

FRB property

Magnetospheric

Non-magnetospheric

