Investigating radio-wave propagation in the heliosphere using multi-spacecraft observations of type III radio bursts

with Solar Orbiter, Parker Solar Probe, STEREO, Wind and Mars Express

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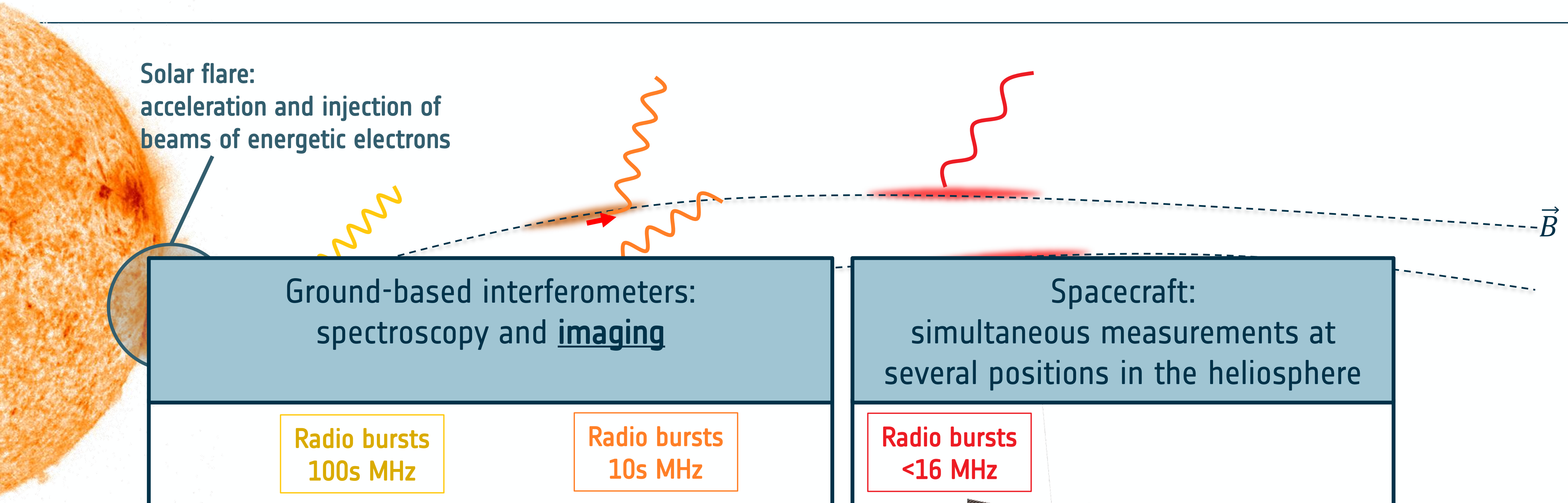
RPW consortium meeting – 2 October 2023

Observations of type III radio bursts



Solar flare:
acceleration and injection of
beams of energetic electrons

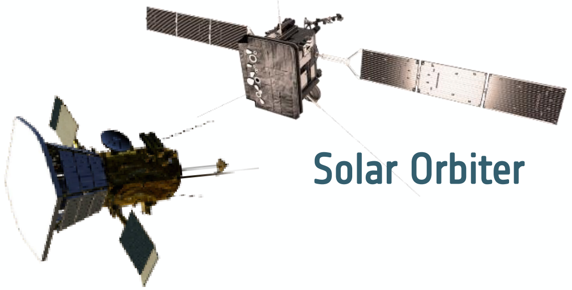
Ground-based interferometers:
spectroscopy and **imaging**

Radio bursts
100s MHz

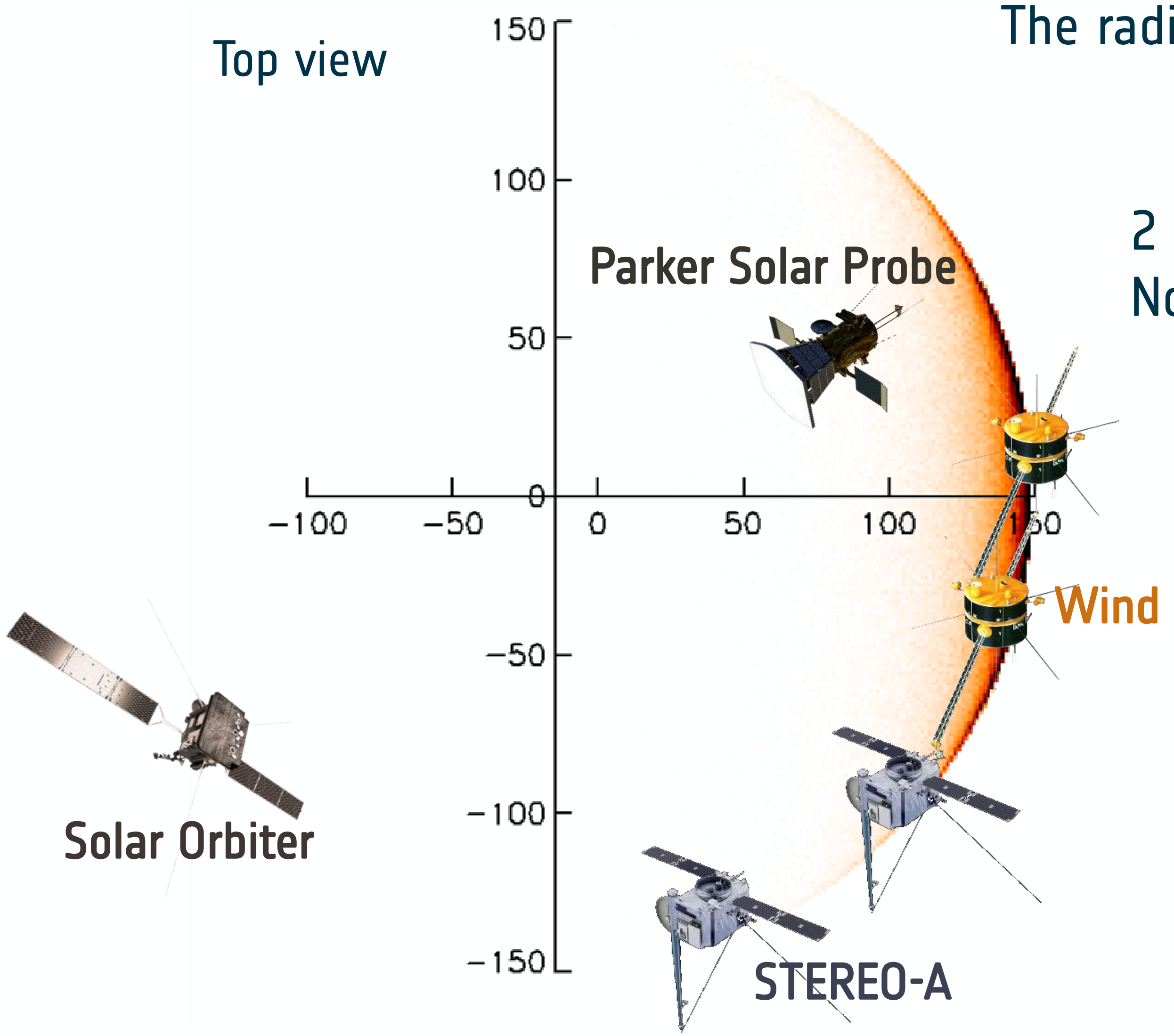
Radio bursts
10s MHz

Spacecraft:
simultaneous measurements at
several positions in the heliosphere

Radio bursts
<16 MHz

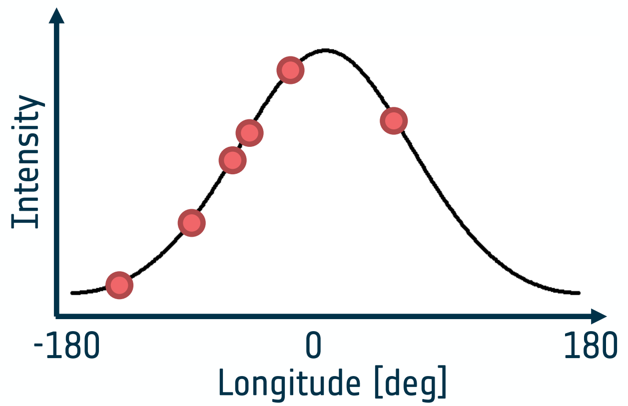


Directivity of radio emission



The radio emission is more intense when facing the source
→ **Directivity** of the radio emission

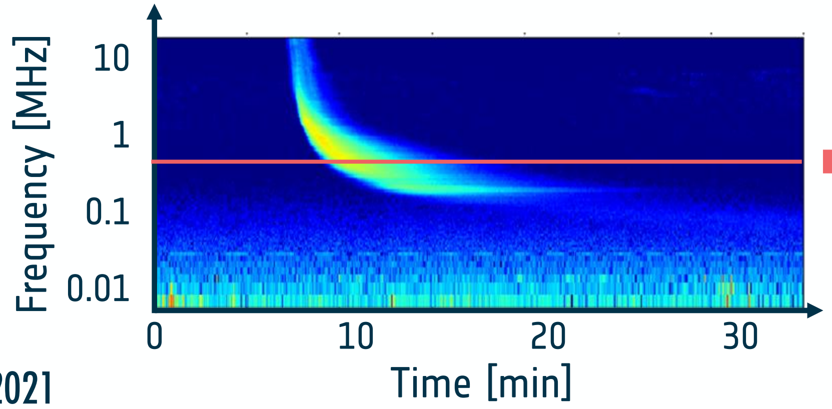
2 spacecraft = 1 ratio
Not enough to determine the shape of the directivity

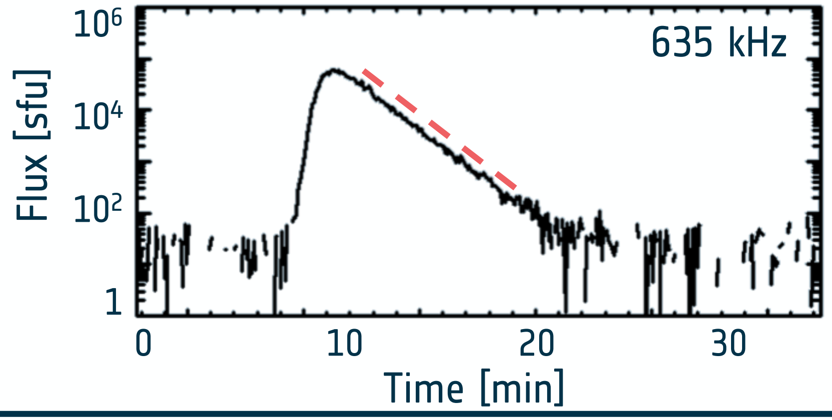


Now: 4 spacecraft
Simultaneous observations
→ Measure of the directivity

Observational properties of type III radio bursts

Timing



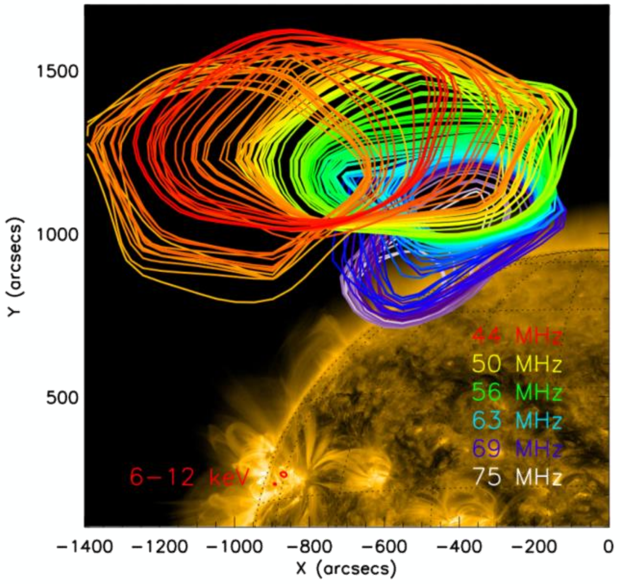


Decay fitted with an exponential model
→ Decay time

Musset et al, 2021

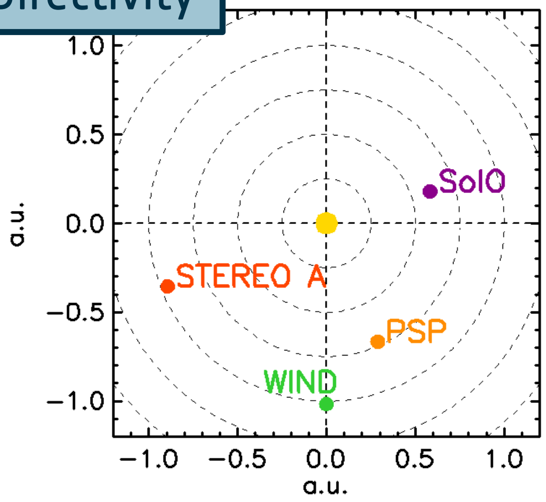
Imaging

→ Source position
→ Source size

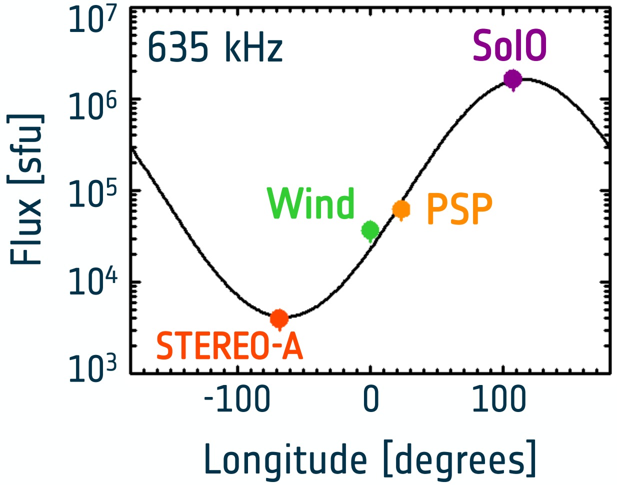


Reid & Kontar, 2017

Directivity



Model for the directivity



Musset et al, 2021

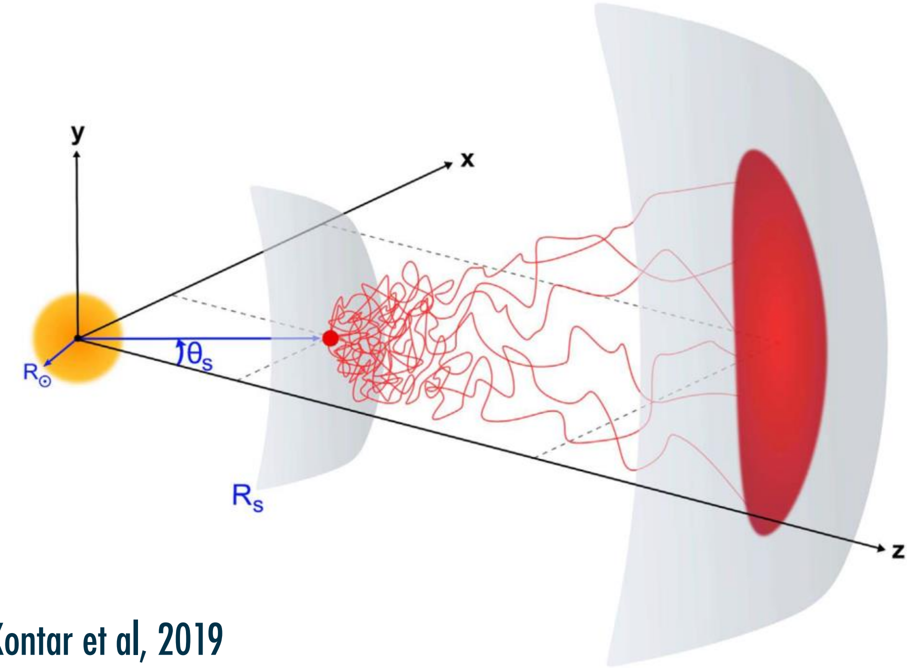
+ indication on source position

Observations of type III radio bursts

Observational properties of type III radio bursts:

- Decay time
- Source position
- Source size
- Directivity profile

→ Intrinsic properties of the radio source?
→ Constrain properties of energetic electron beam?



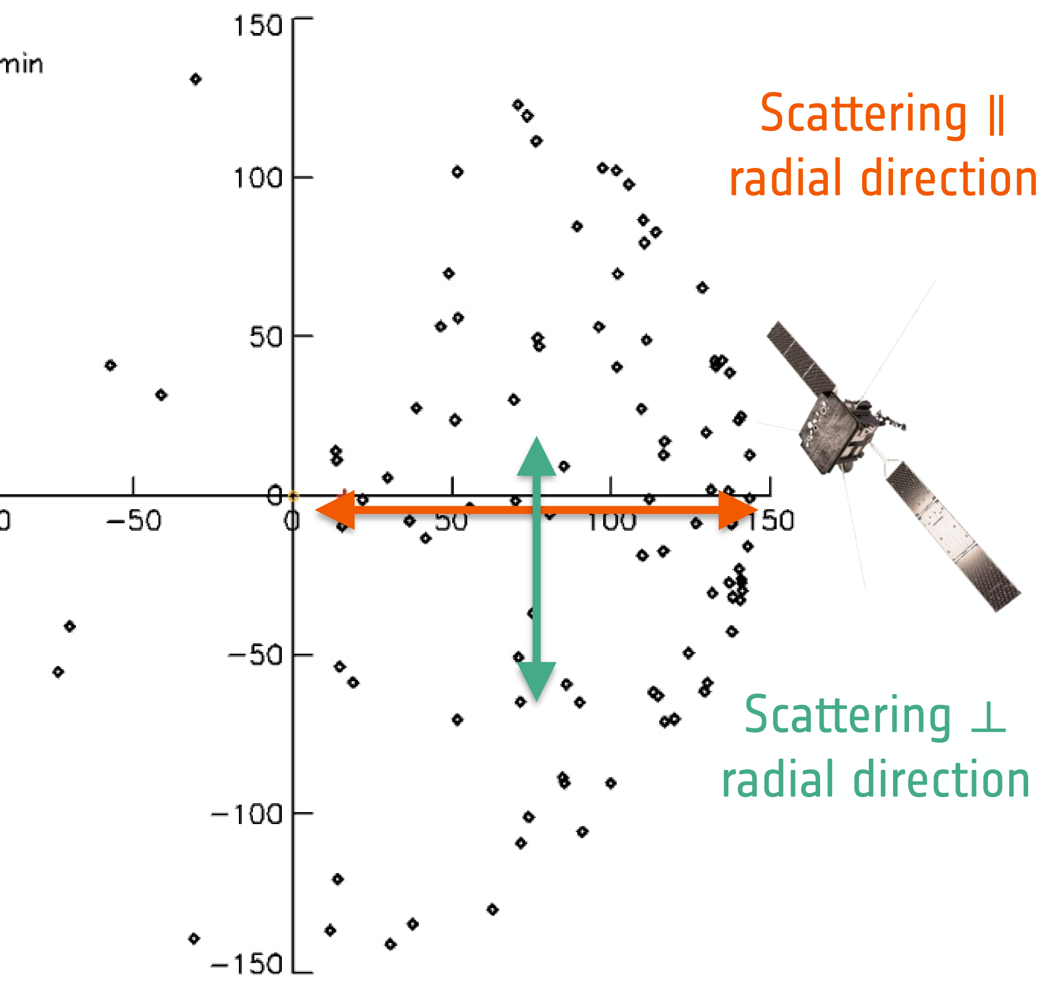
Kontar et al, 2019

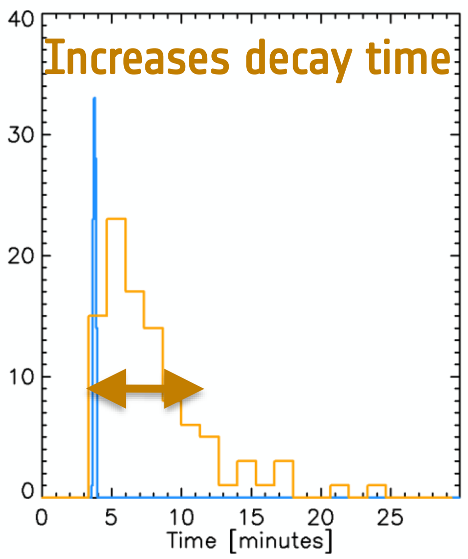
Radio-wave propagation effects in the heliosphere:

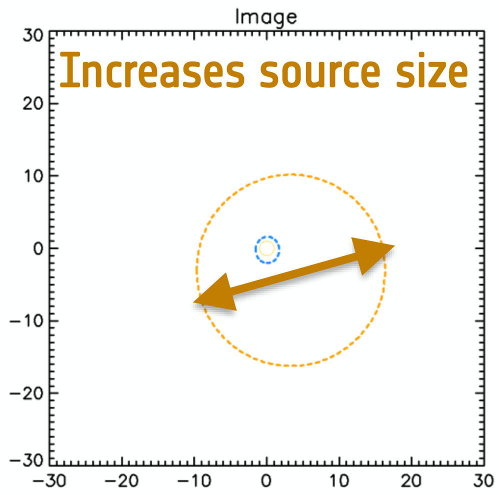
- Free-free absorption
- Large scale refraction (gradual variation of plasma density)
- Scattering on small scale, turbulent density fluctuations

Anisotropic scattering

Top view







Need more scattering to explain observed source sizes
Than to explain decay times

Anisotropic scattering:
More efficient in the ⊥direction than in the ∥ direction

Ray-tracing simulations

Simulation settings

Kontar et al, 2019

- Point source emitting radio-waves instantaneously

- Two parameters to describe scattering:

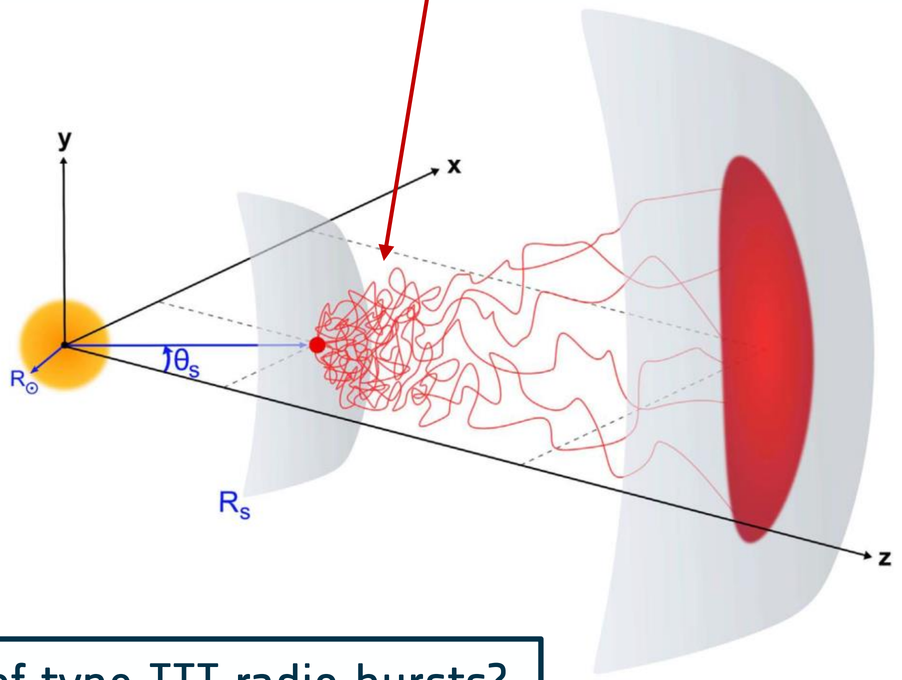
  - Level of density fluctuations

$$\epsilon = \frac{\langle n_e^2 \rangle}{n_e^2}$$

  - Anisotropy of density fluctuations

$$\alpha = \frac{h_\perp}{h_\parallel}$$ Ratio of correlation lengths

Most of the scattering happens near the radio source



How do simulation parameters affect the observed properties of type III radio bursts?

Simulation vs. Observations

Simulation

Two parameters to describe scattering:

- Level of density fluctuations $\epsilon = \frac{\langle n_e^2 \rangle}{n_e^2}$
- Anisotropy of density fluctuations $\alpha = \frac{h_\perp}{h_\parallel}$

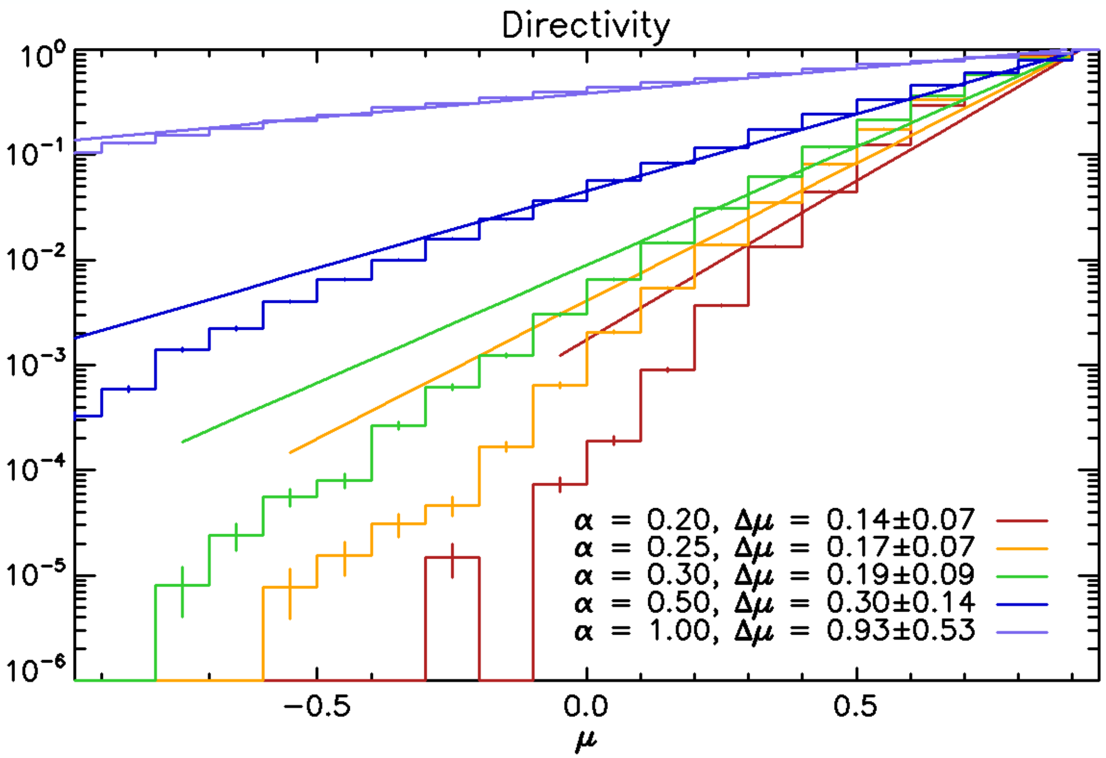
Observations

Multi-spacecraft analysis of radio burst:

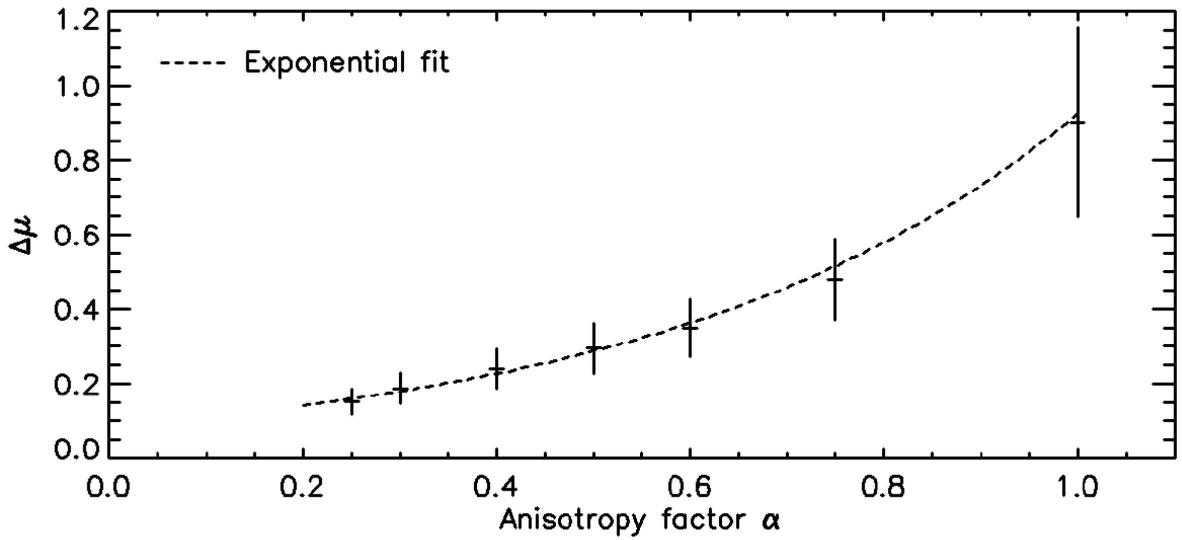
- Directivity profile $\Delta\mu$
- Decay time (time profile) τ

Simulations: directivity

Musset et al, 2021



Ray-tracing simulation:
Evolution of directivity profiles
with anisotropy of density fluctuations



Evolution of directivity ($\Delta\mu$) with anisotropy

Fit of the profile with model:

$$F(\mu) = C_0 \exp\left(-\frac{(1-\mu)}{\Delta\mu}\right)$$

$$\mu = \cos(\theta)$$

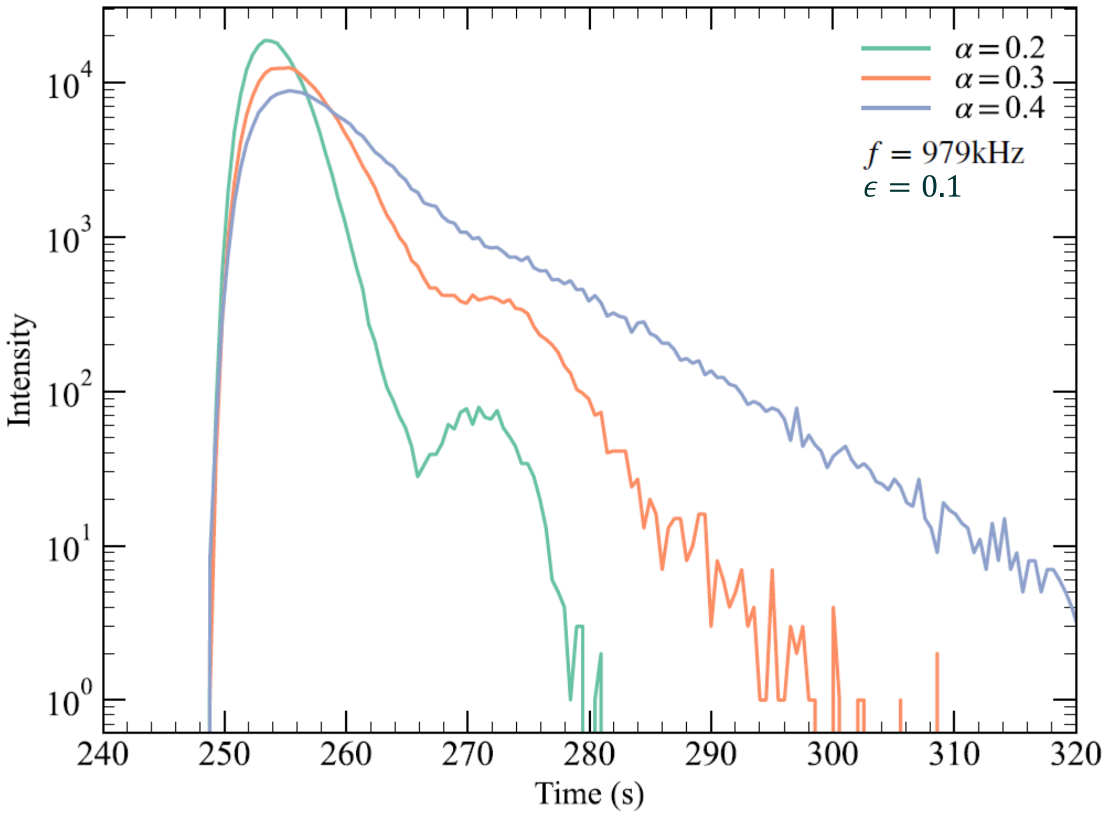
Cosine of longitude

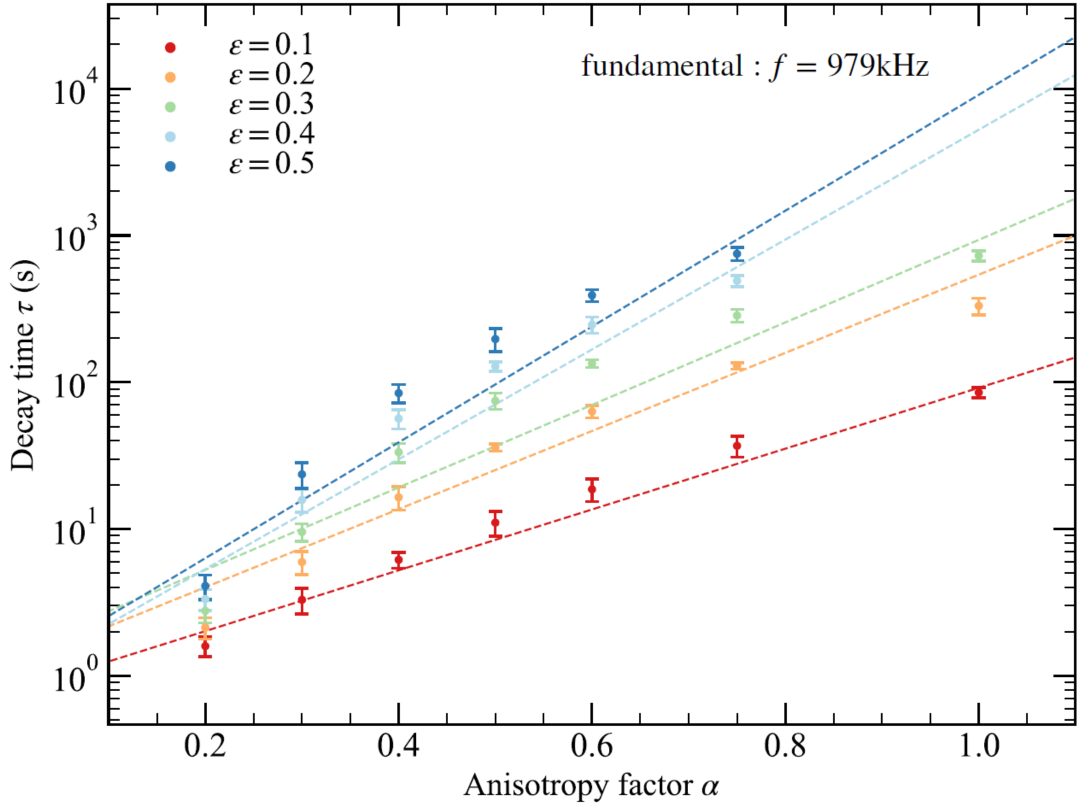
Simulations: decay times

Decay time (τ) of radio emission

Master thesis of Louis Siebenaler

As a function of the level and anisotropy of the fluctuations





Echo in time profiles

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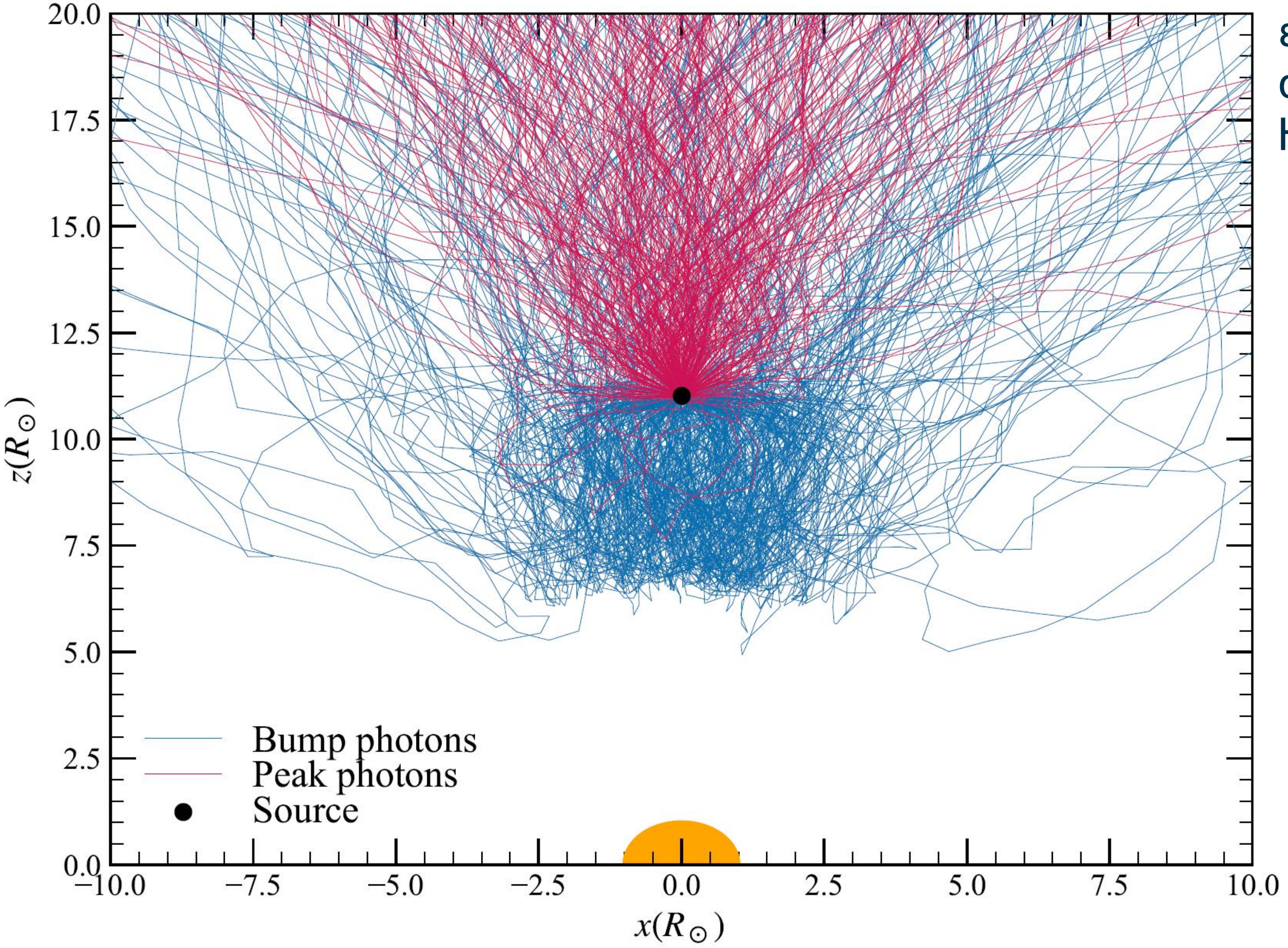
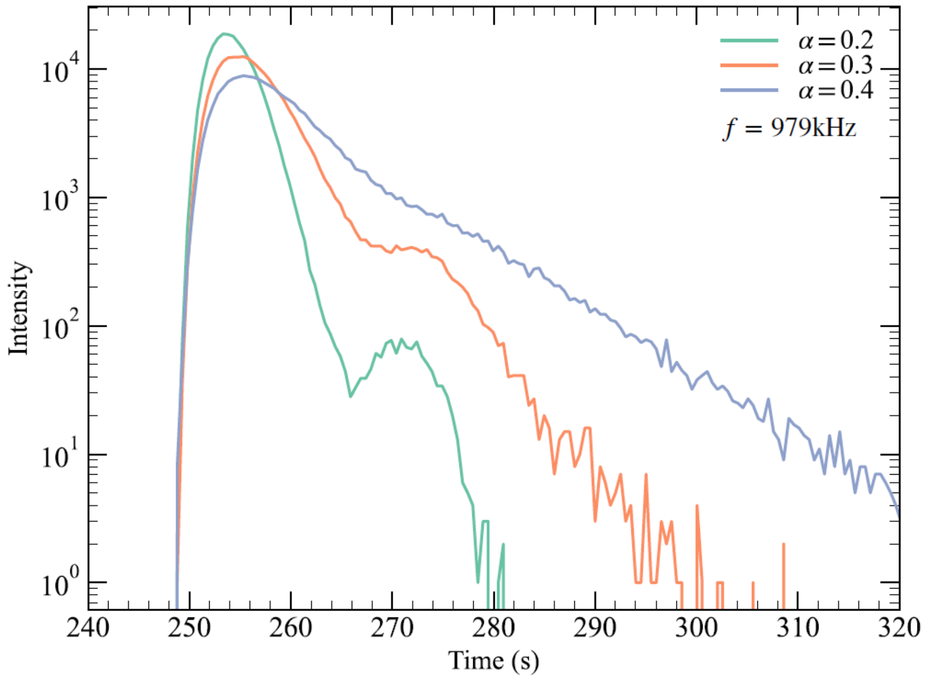


ε = 0.6
α = 0.3
Harmonic emission ~ 1 MHz



Simulations: exploring the parameter space

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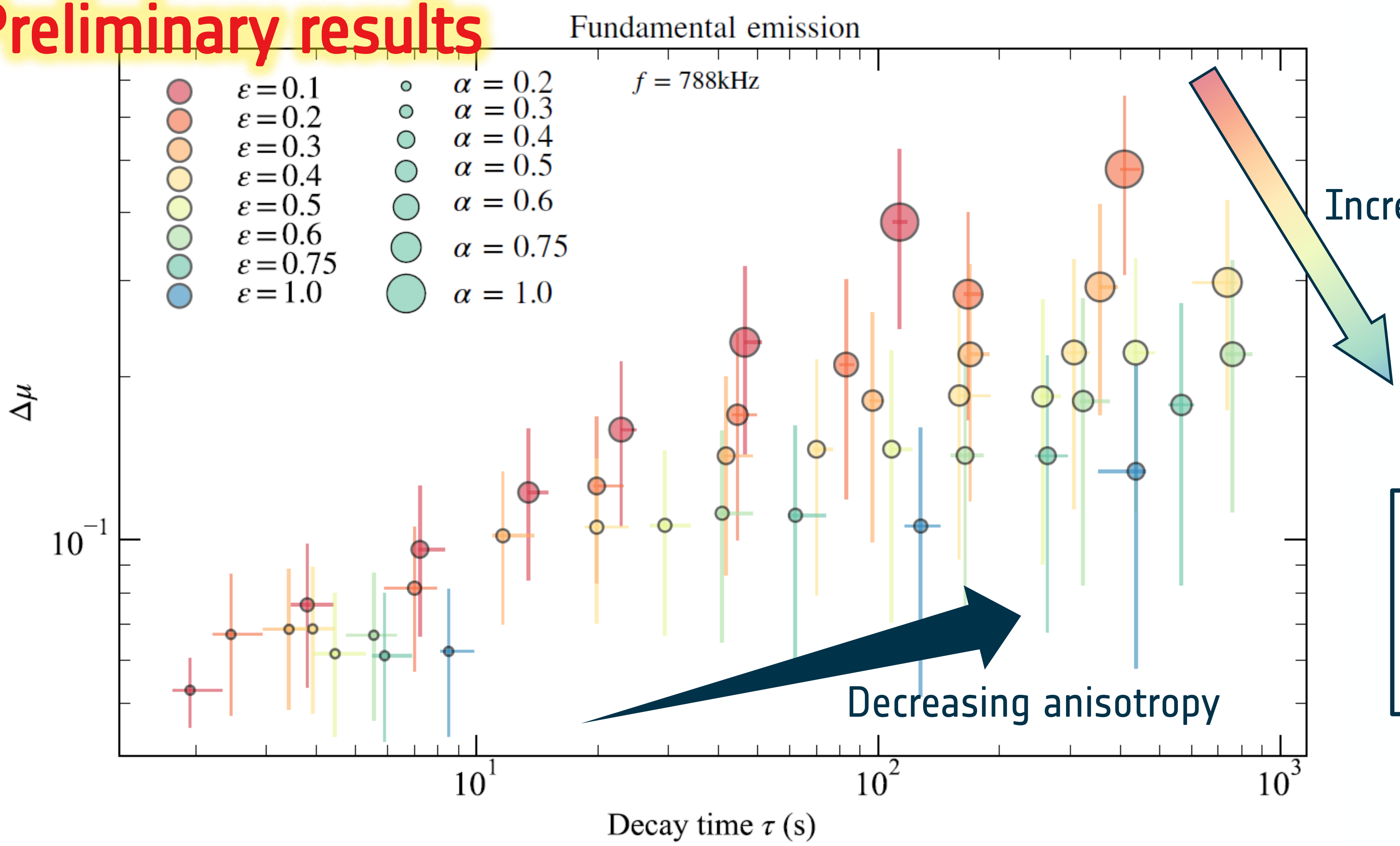
Preliminary results

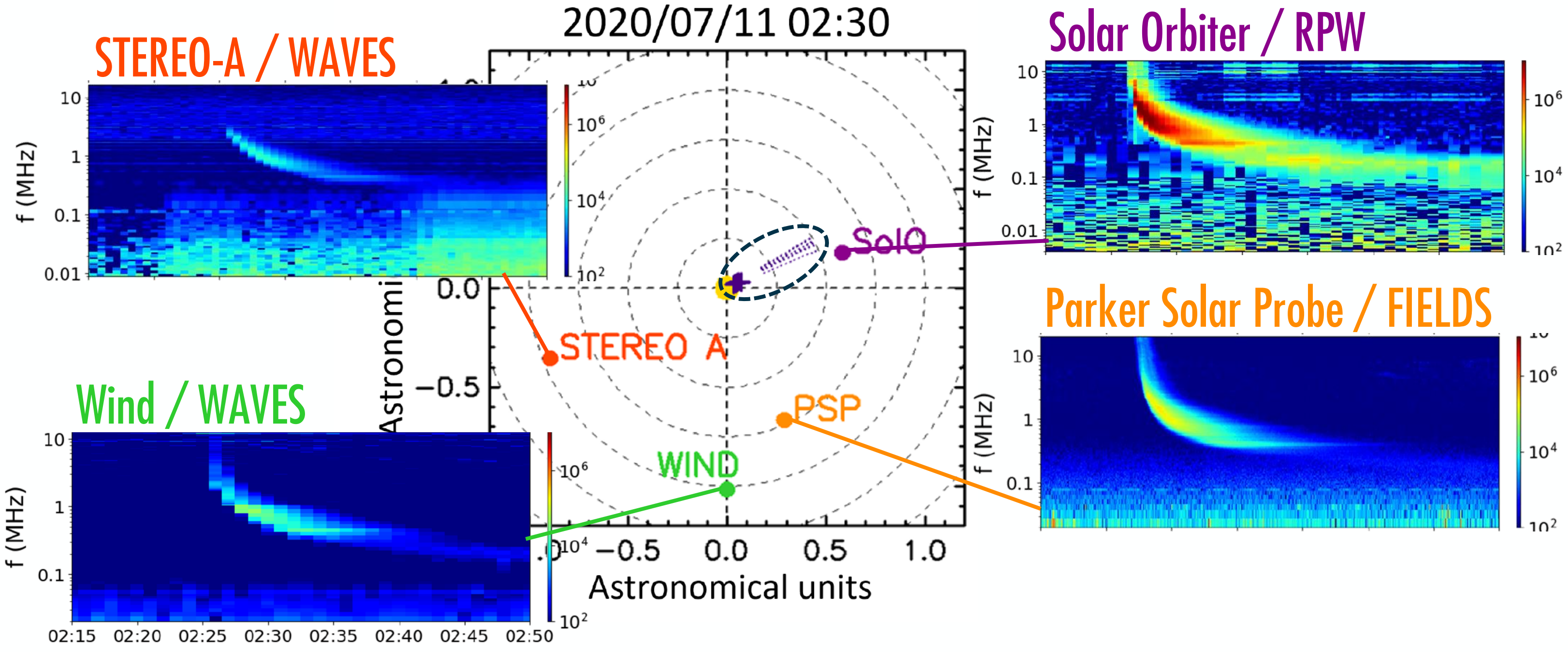


Measuring the decay time and directivity of type III burst could constrain both plasma parameters

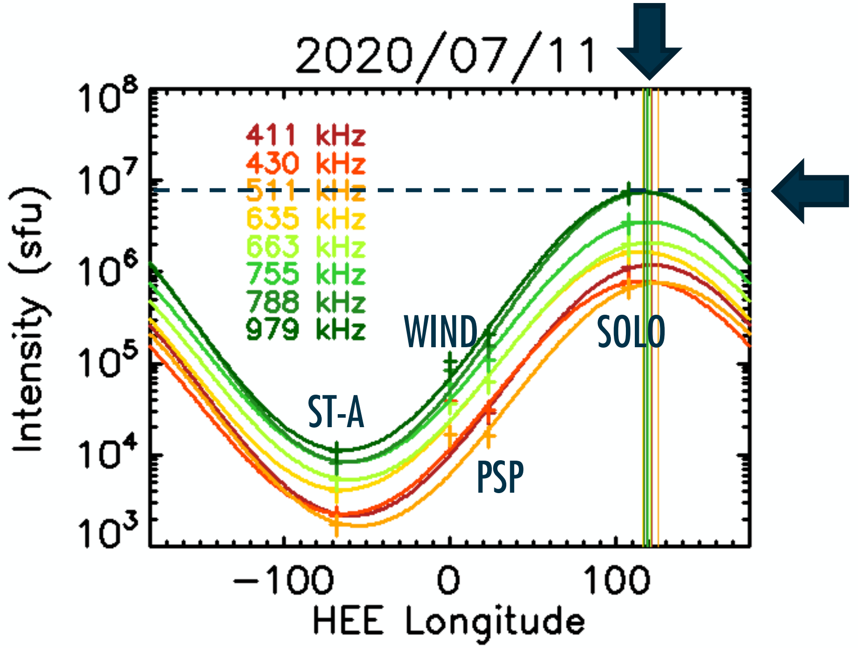
Multi-spacecraft analysis of radio bursts

First multi-spacecraft study of single solar radio bursts

Musset et al, 2021

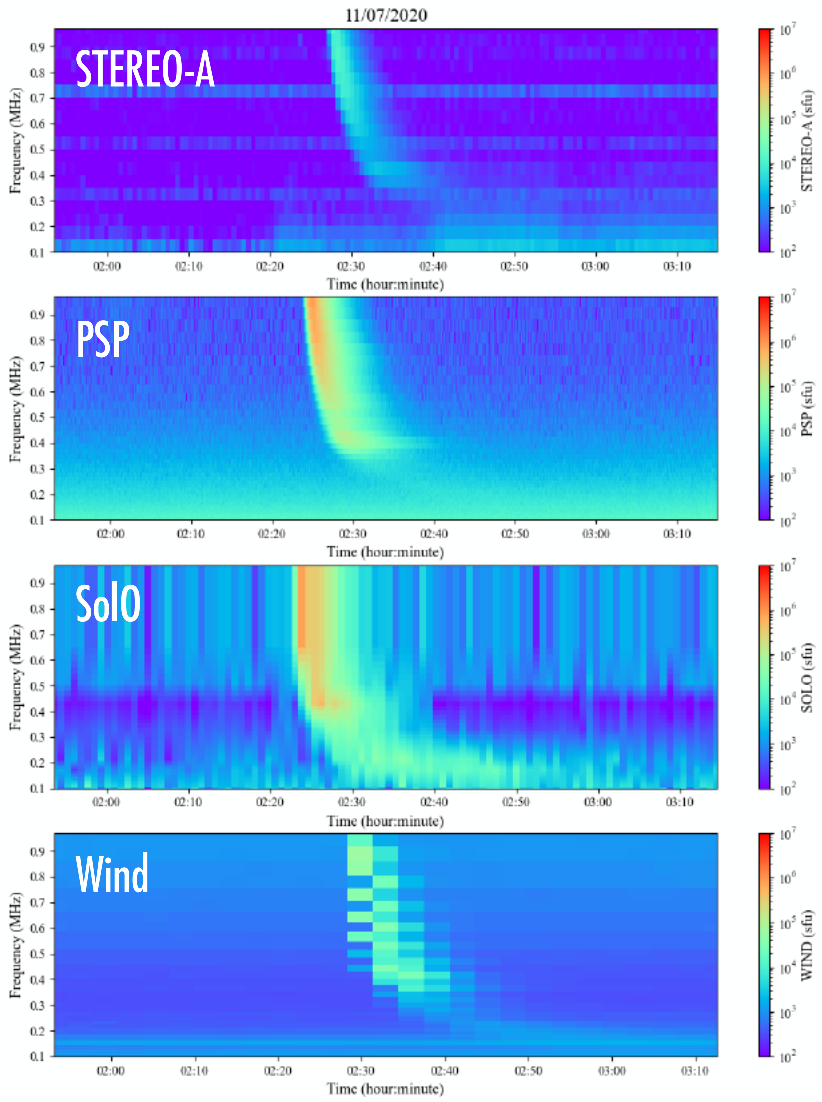


Study of 5 type III bursts observed simultaneously by 4 spacecraft



For individual type III bursts:
directivity profile
+ longitudinal position of source
+ intrinsic intensity of burst

Multi-spacecraft study of radio bursts



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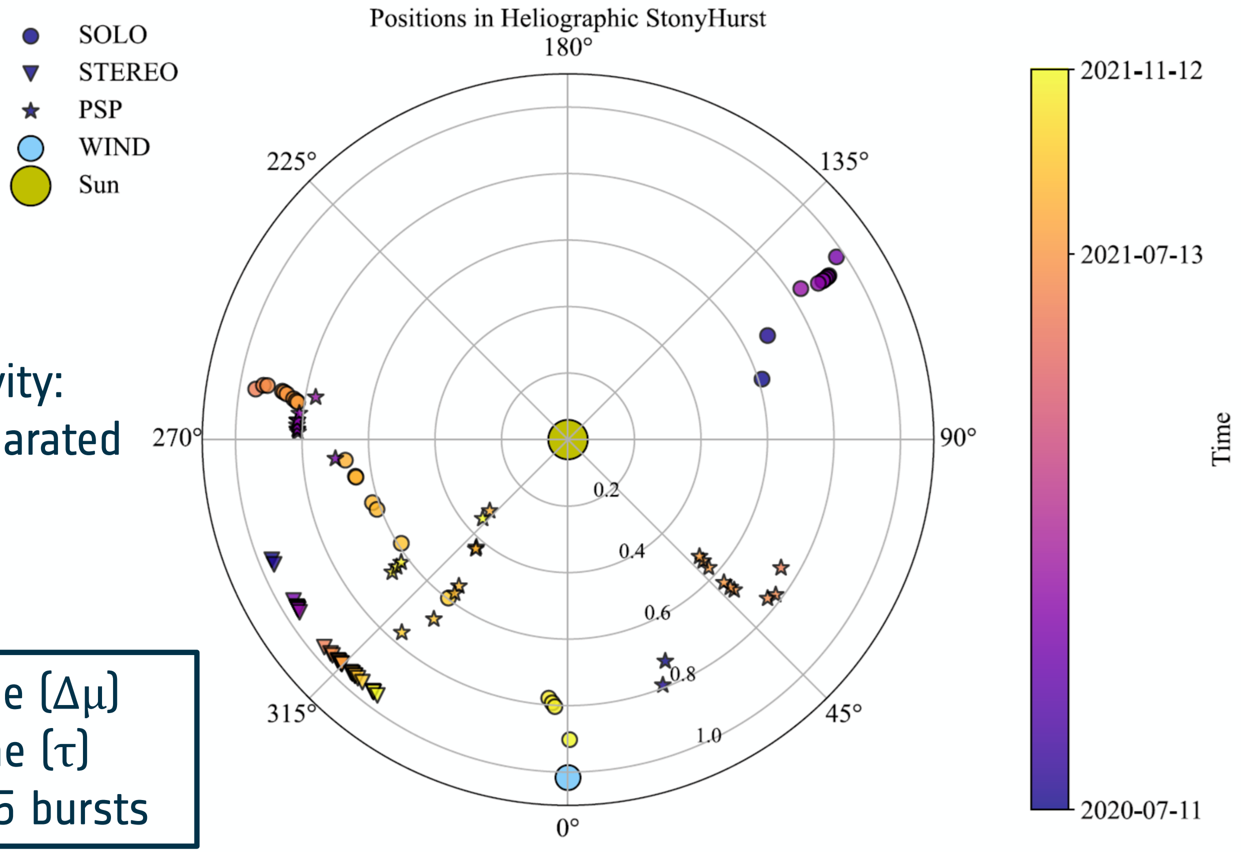
Selection of “clean” radio bursts observed by the four spacecraft in 2020-2021

To calculate directivity:
Spacecraft well separated
→ 25 bursts

Directivity profile (Δμ) and decay time (τ) derived for the 25 bursts



Observations and simulations

Preliminary results

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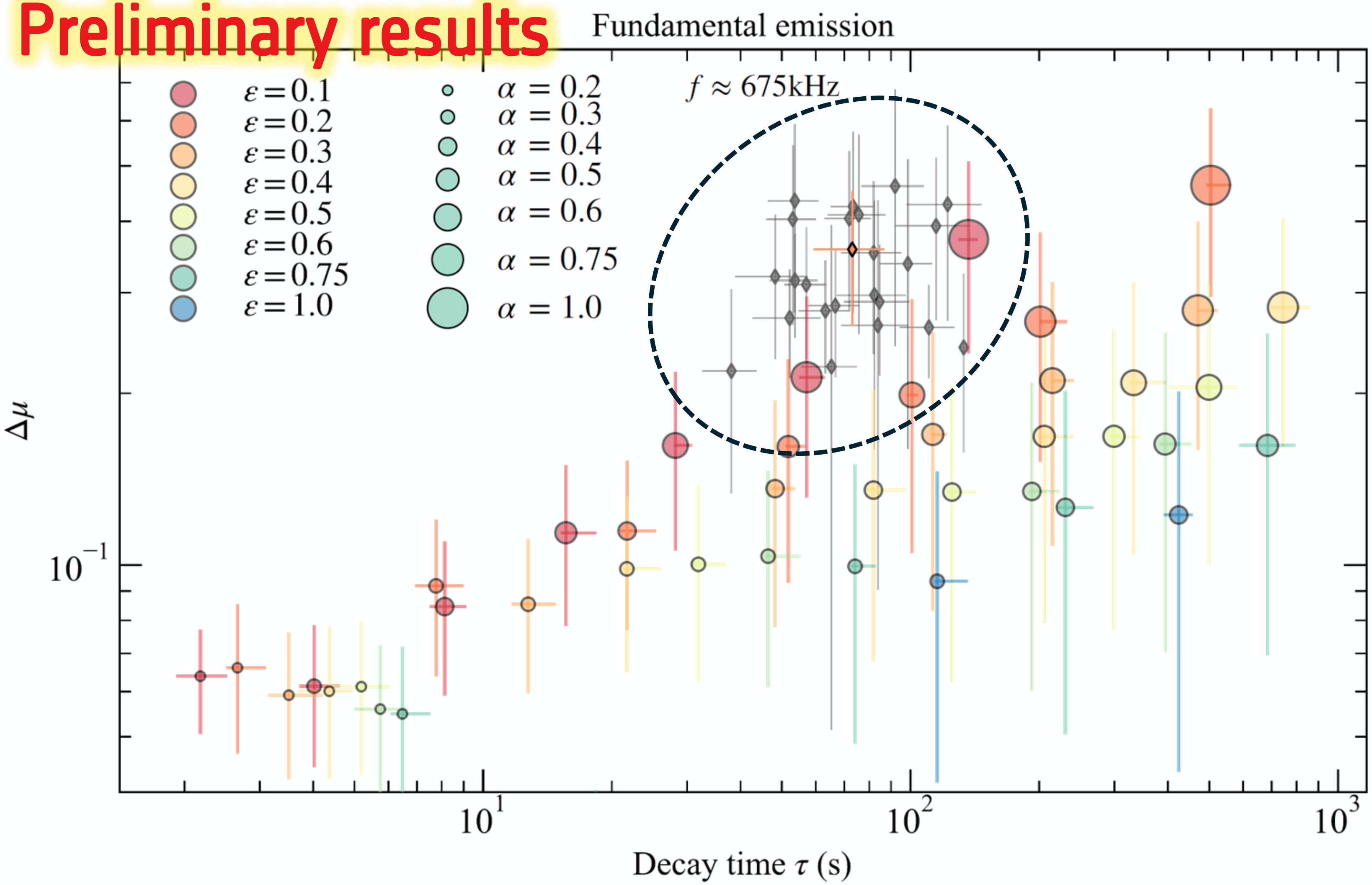

Directivity and decay time measured for 25 bursts compared to directivity and decay time inferred from simulations

Measurements compatible with level of density fluctuations

$\epsilon \sim 0.1$

And with anisotropy factor

$\alpha \sim 0.7\text{-}1.0$

Fundamental vs harmonic emission

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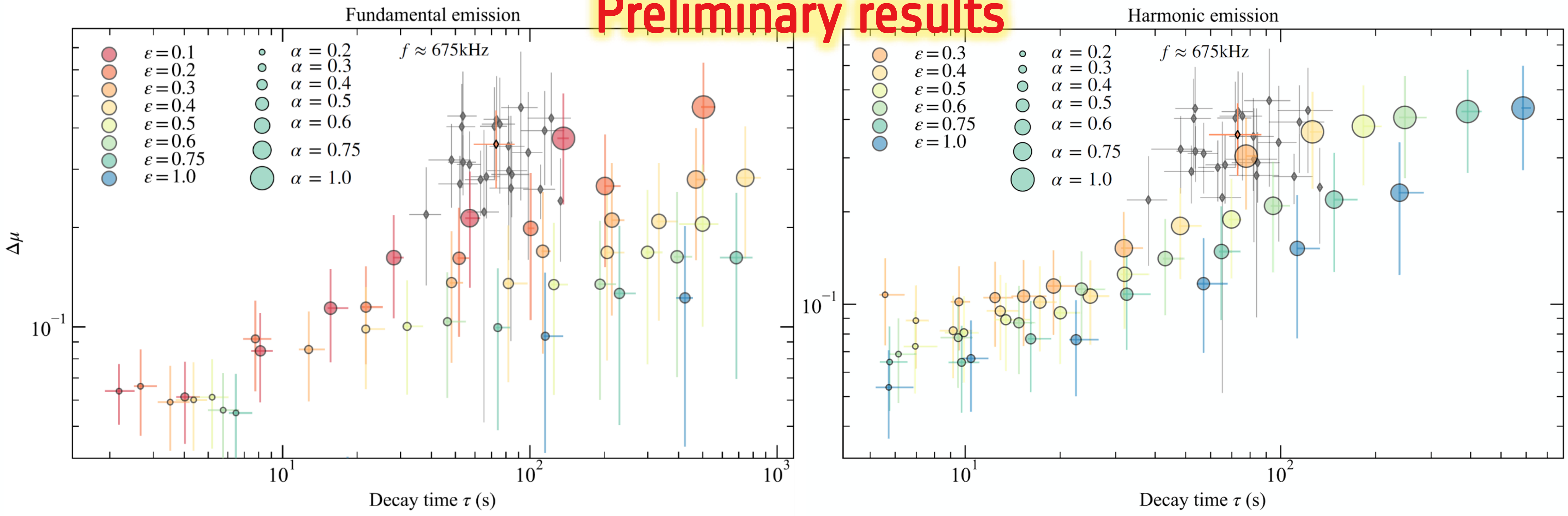
Preliminary results



Intensity of radio bursts – first statistics

Preliminary results

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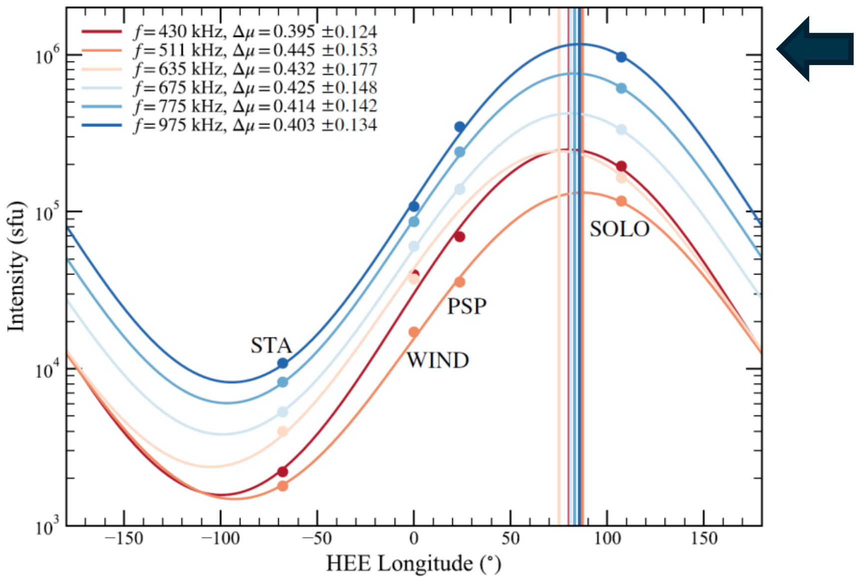
Selection of 25 bursts with well-separated spacecraft to derive radio emission directivity

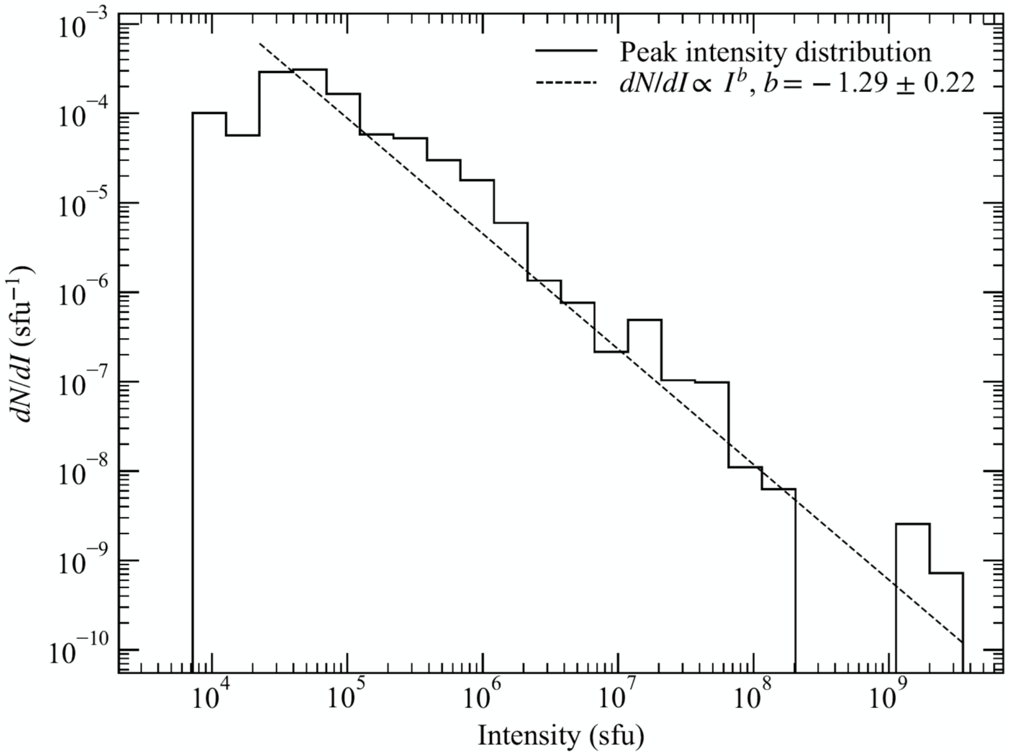


For each burst:

Directivity profile

→ **Intrinsic intensity** of radio bursts (e.g. peak of the profile)

Power-law distribution of radio burst intensities (index: -1.3)



Power-law distribution of flares: index -1.8 (Aschwanden et al, 2000)

Mars Express / MARSIS radio bursts observations

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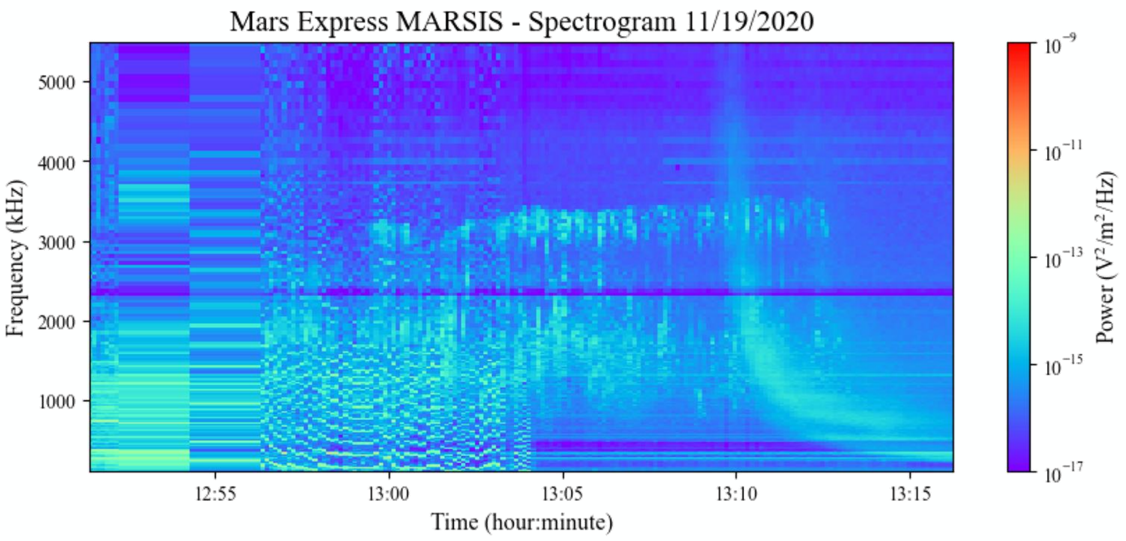
Mars Express, launched in 2003
MARSIS instrument (radar):
100 kHz – 5.5 MHz



In some operation modes, MARSIS detects solar radio bursts
→ Additional point for directivity profiles!

MARSIS calibration: event selection

Preliminary results

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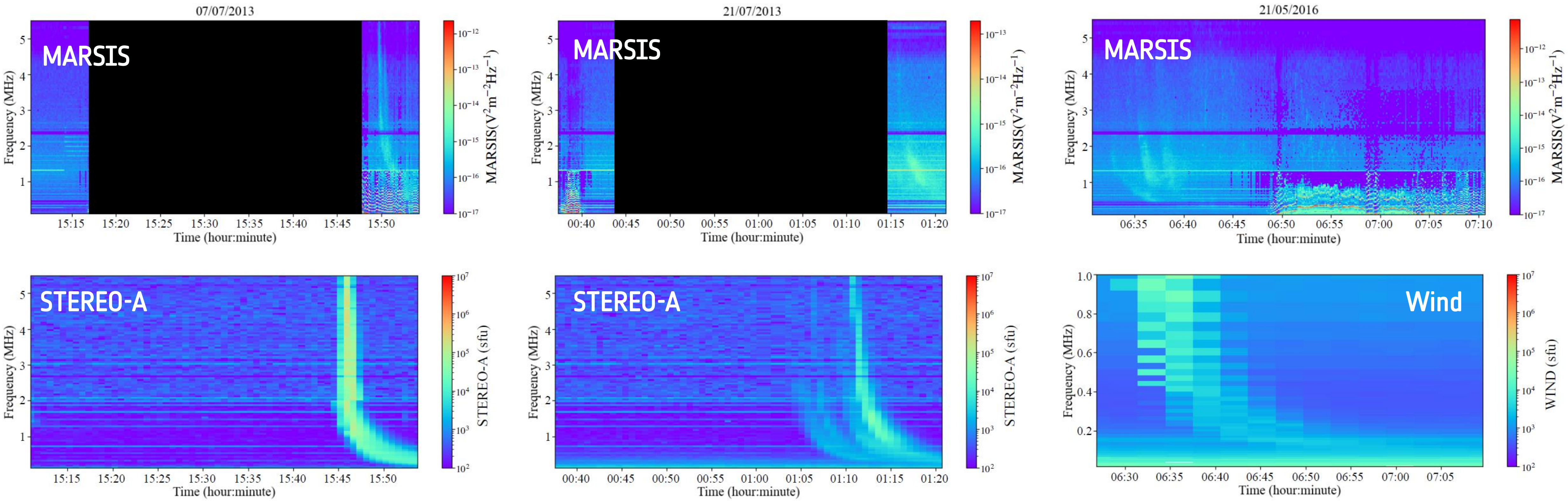

Sun, STEREO-A and Mars aligned

Sun, Earth and Mars aligned

MARSIS calibration: conversion factor

Preliminary results

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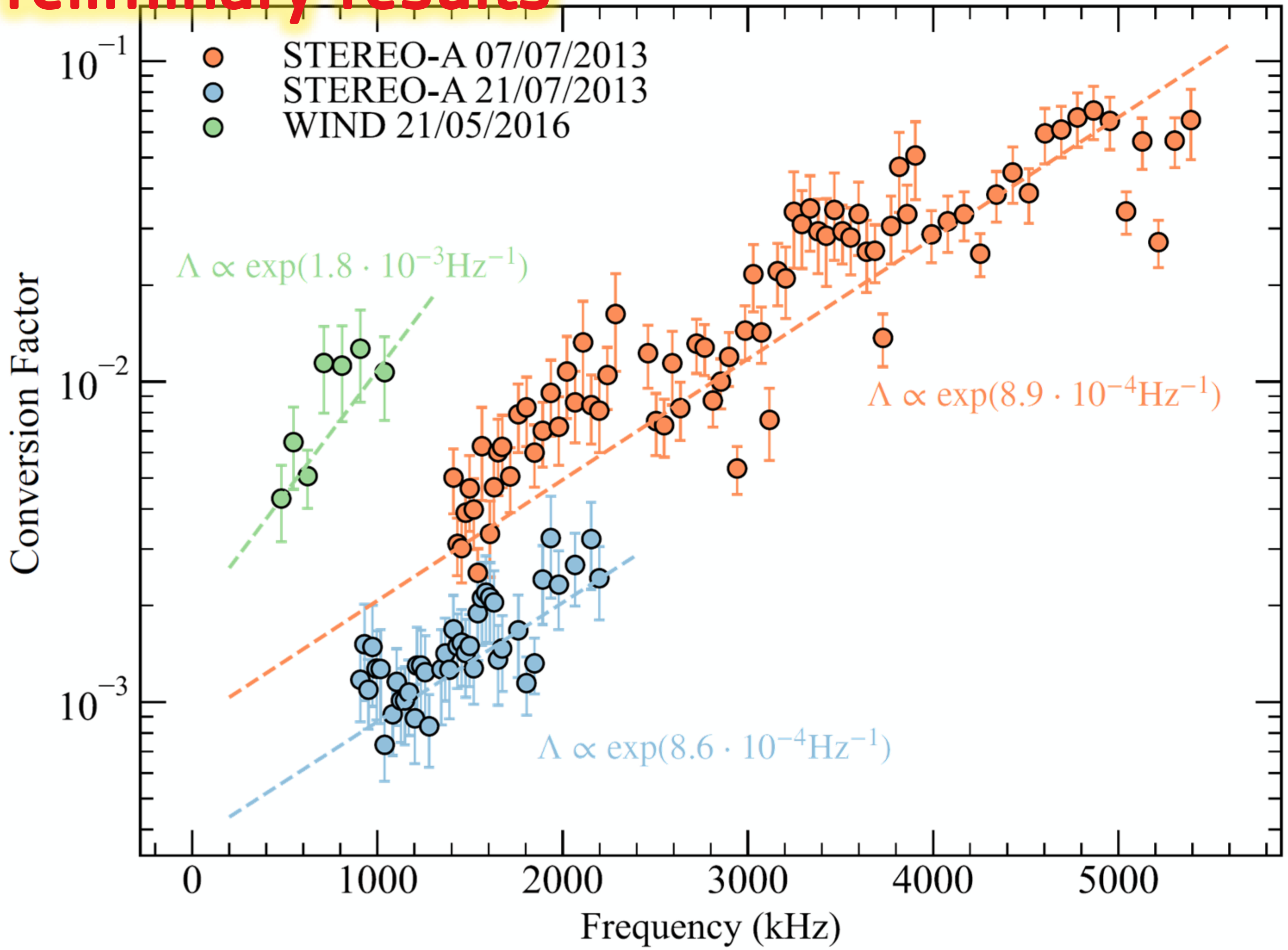

The conversion factor is different for each of the 3 events.

Best guess: the orientation of the antenna is different
→ We are investigating this

Nonetheless, we have a ballpark figure!

Mars Express / MARSIS radio bursts observations

Preliminary results

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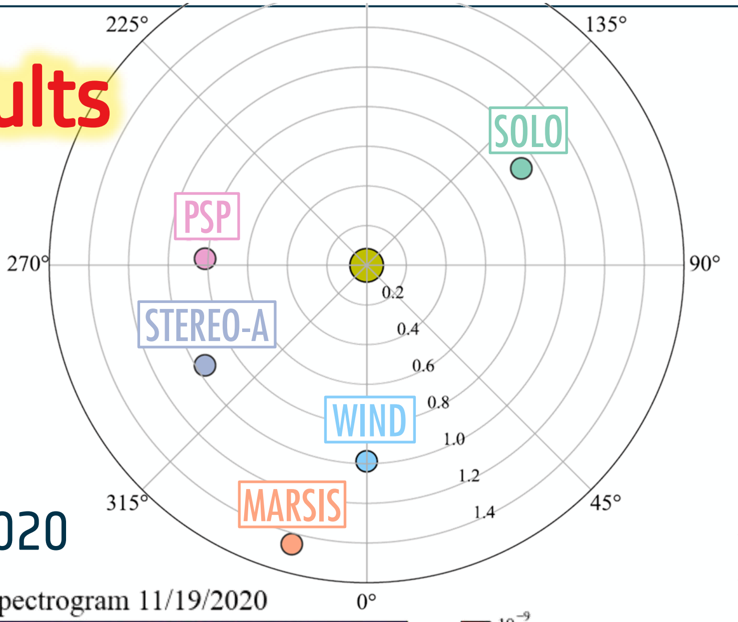
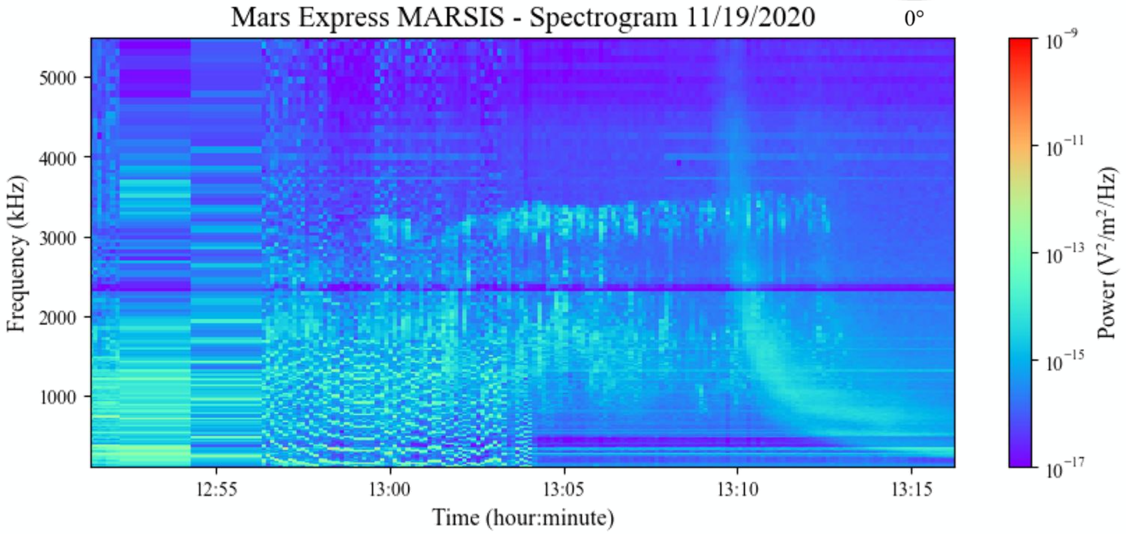
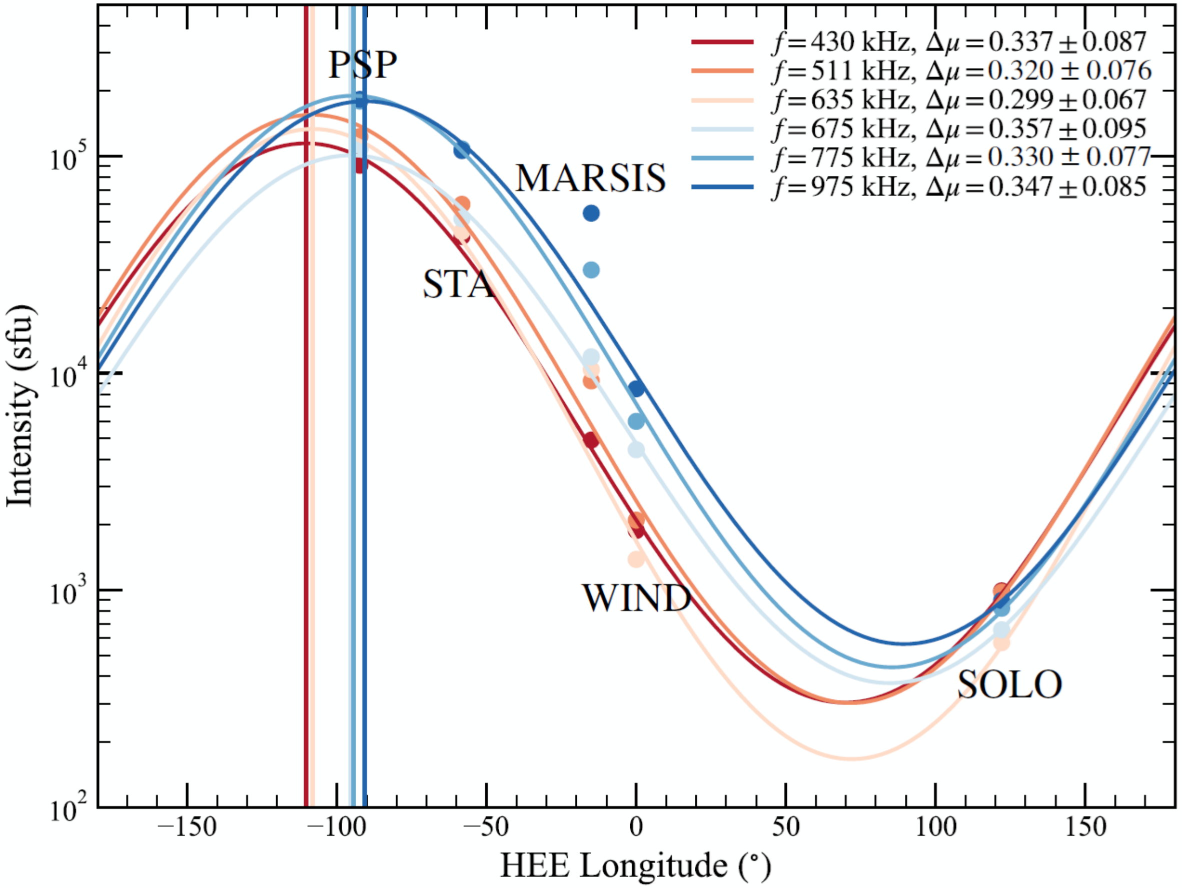


Radio burst on 19 Nov 2020





Conclusions

- Multi-spacecraft measurements allow to quantify the directivity profile of **single** radio bursts for the first time
- **Planetary missions** can be used to add data points in the heliosphere! We demonstrated the use of MARSIS on Mars Express: this could be done also with Juno, Juice…
- Comparing radio burst observations to ray-tracing simulations, we can determine the level and anisotropy of density fluctuations around the source, **and how it varies from event to event**
- Ray-tracing simulations must explain all observational signatures: decay time, directivity profile, source position and size.
  - → In this work we looked at directivity and decay time together
  - → Imaging at these frequencies would be amazing: interferometry in space!
  - → On the simulation side, need to address the hypothesis of point source instantaneous radio emission
- Next step: compare our findings on plasma density fluctuations to in-situ measurements near the Sun (Parker Solar Probe) to further validate our approach
- Multi-spacecraft observations of radio bursts could be a way to characterize the plasma at distances below what can be reached by Parker Solar Probe

Additional slides