ESA/ESTEC – University of Glasgow

# Multi-spacecraft observations of type III radio bursts

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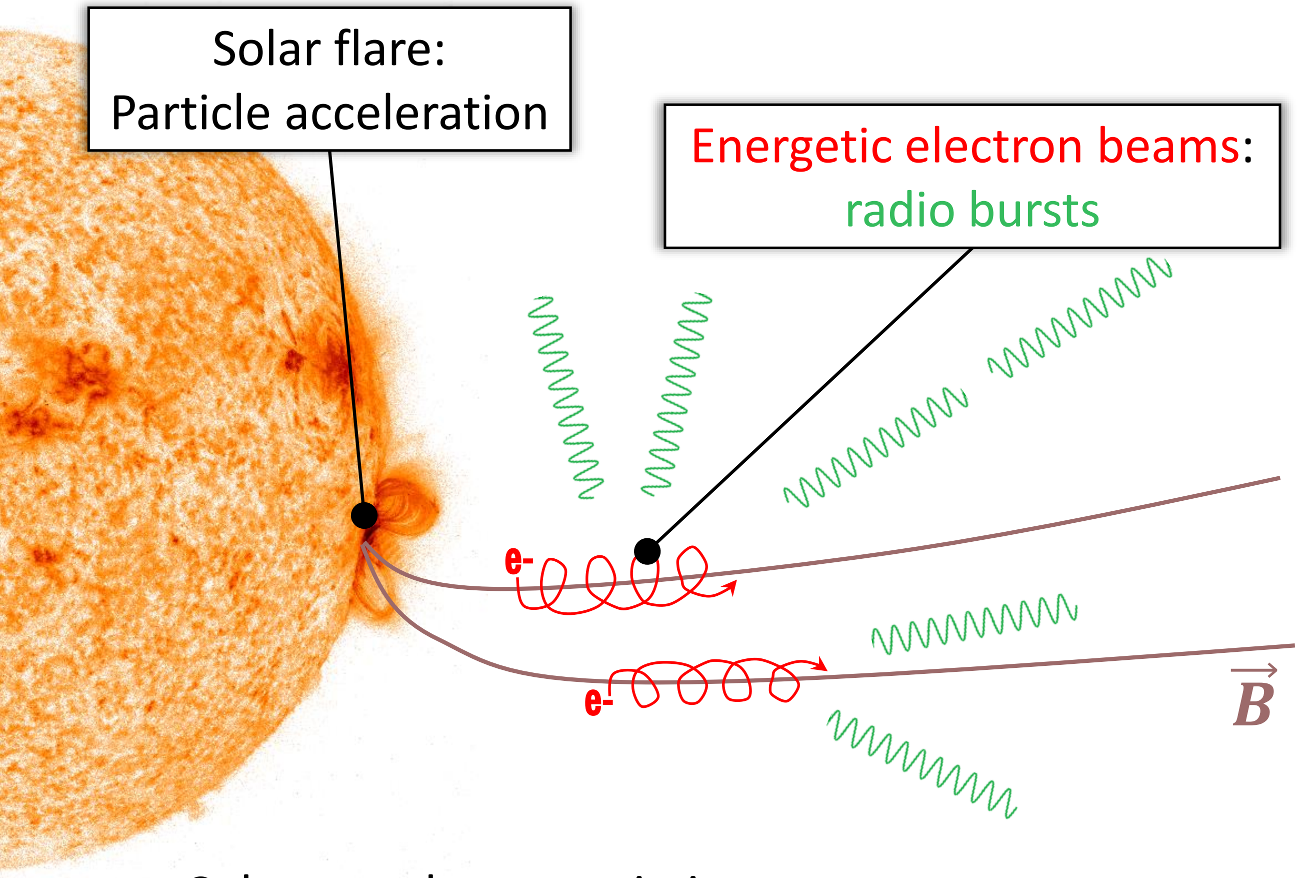
Astronomy & Astrophysics “Solar Orbiter first results (cruise phase)” special issue
In press

RPW Consortium Meeting – 30 Nov. 2021 – Meudon

# Outline

- Type III radio bursts: observed properties
- Radio-wave propagation in the heliospheric plasma
- Comparing ray-tracing simulation results to average properties of radio bursts
- Anisotropic scattering of radio-waves: implications for radio burst observed properties
- Observations of radio burst directivity: multi-spacecraft analysis of single bursts
- Conclusions, next steps

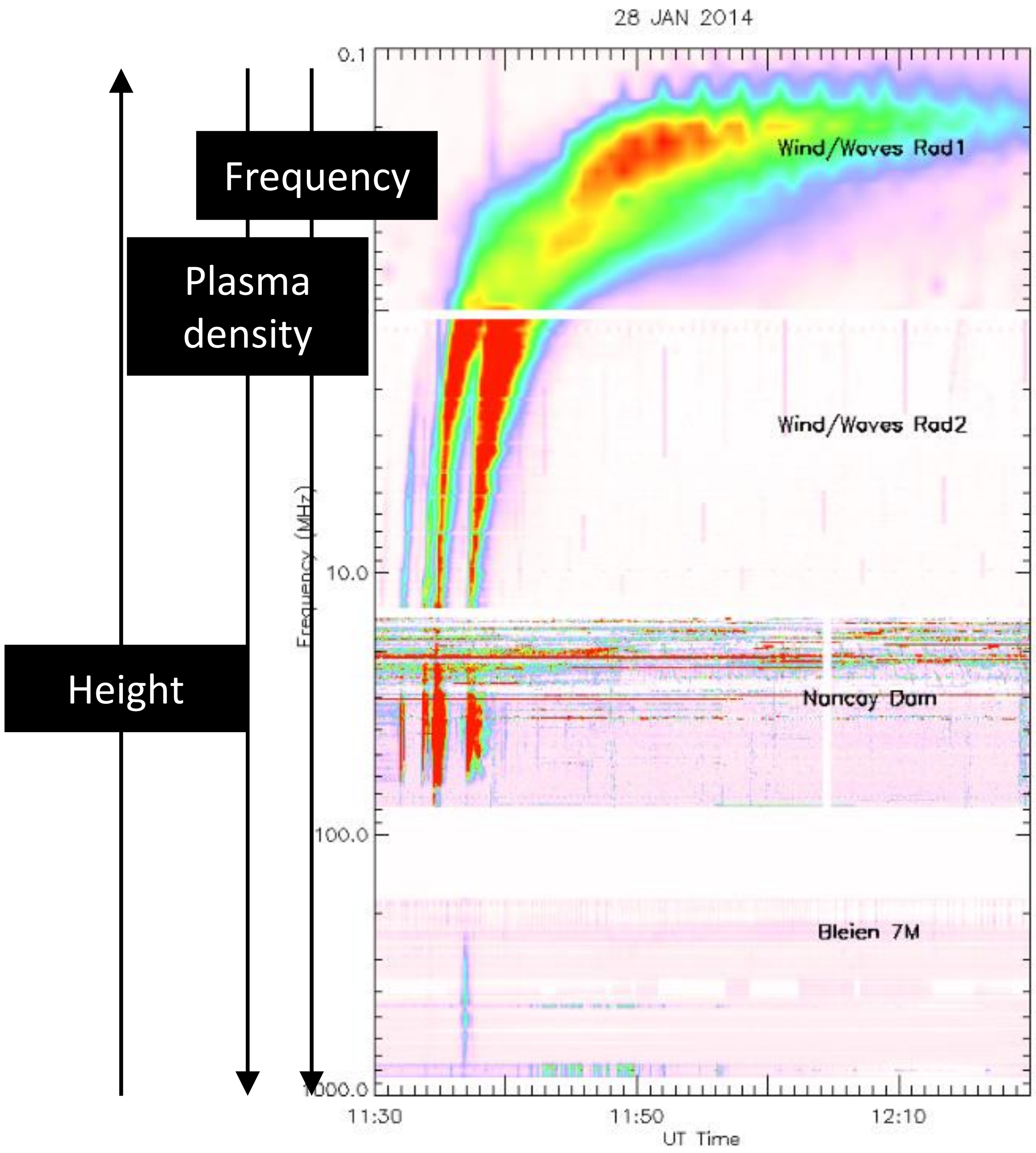
# Type III radio bursts




Coherent plasma emission:
frequency ∝ plasma frequency

Plasma frequency ∝ (plasma density)$^{1/2}$

Typical type III burst observation
*(Reid and Ratcliffe, 2014)*

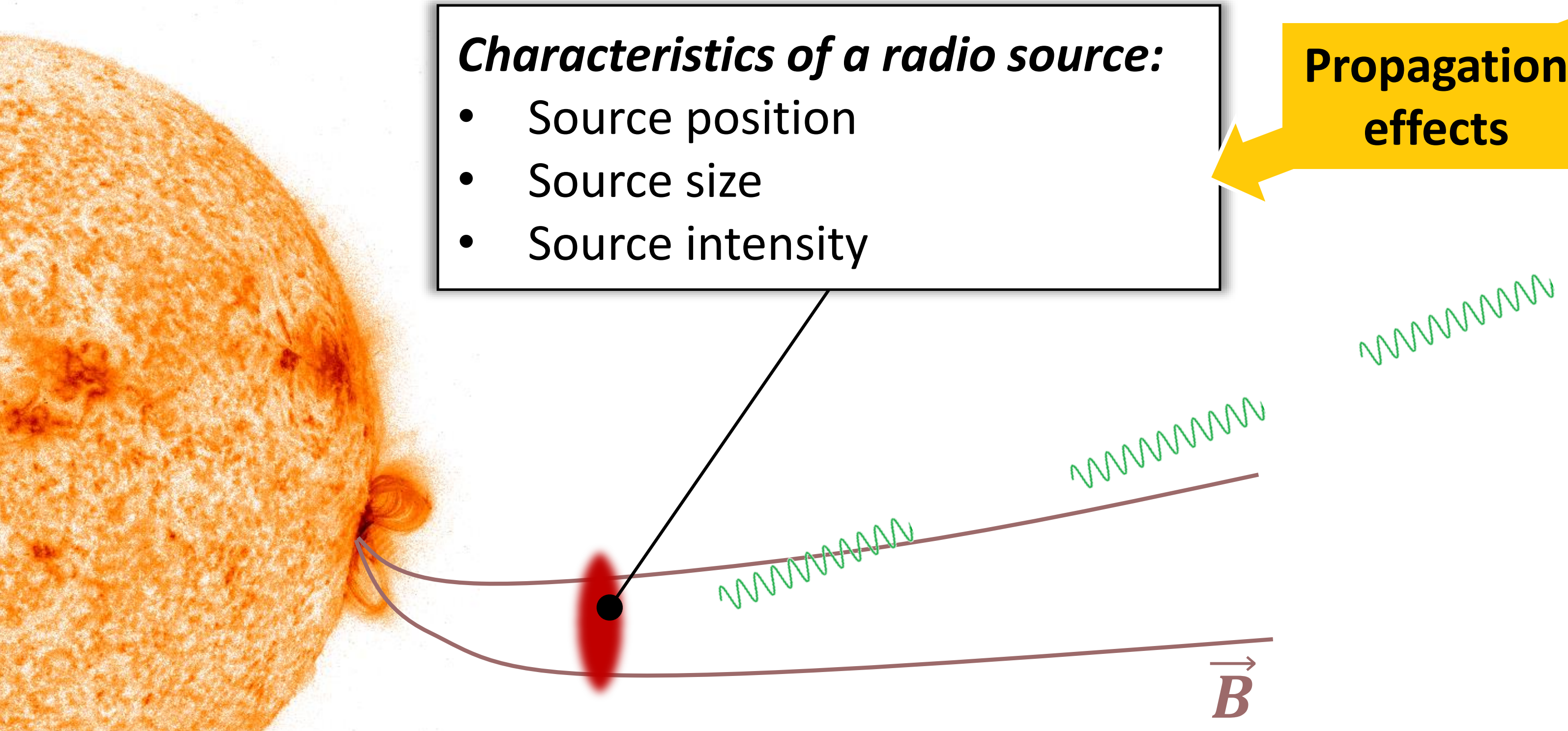


# Type III radio bursts

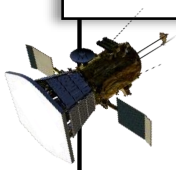
***Characteristics of a radio source:***
- Source position
- Source size
- Source intensity

**Propagation effects**

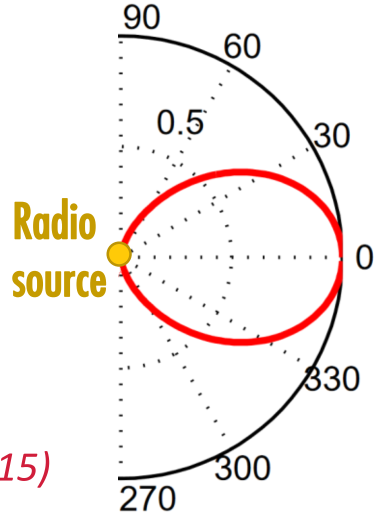
***Characteristics of a radio burst:***
- Source position and size (images)
- Time profile
- Directivity




*Radio-waves propagate in the plasma of the solar wind*
- Free-free absorption
- Refraction on large-scale, gradual variations of the density (e.g. ICME)
- ***Scattering on small-scale, turbulent density fluctuations***

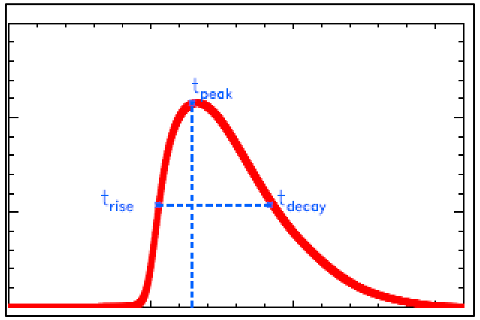


Emission ***directivity***




*(Thejappa & Macdowall, 2015)*

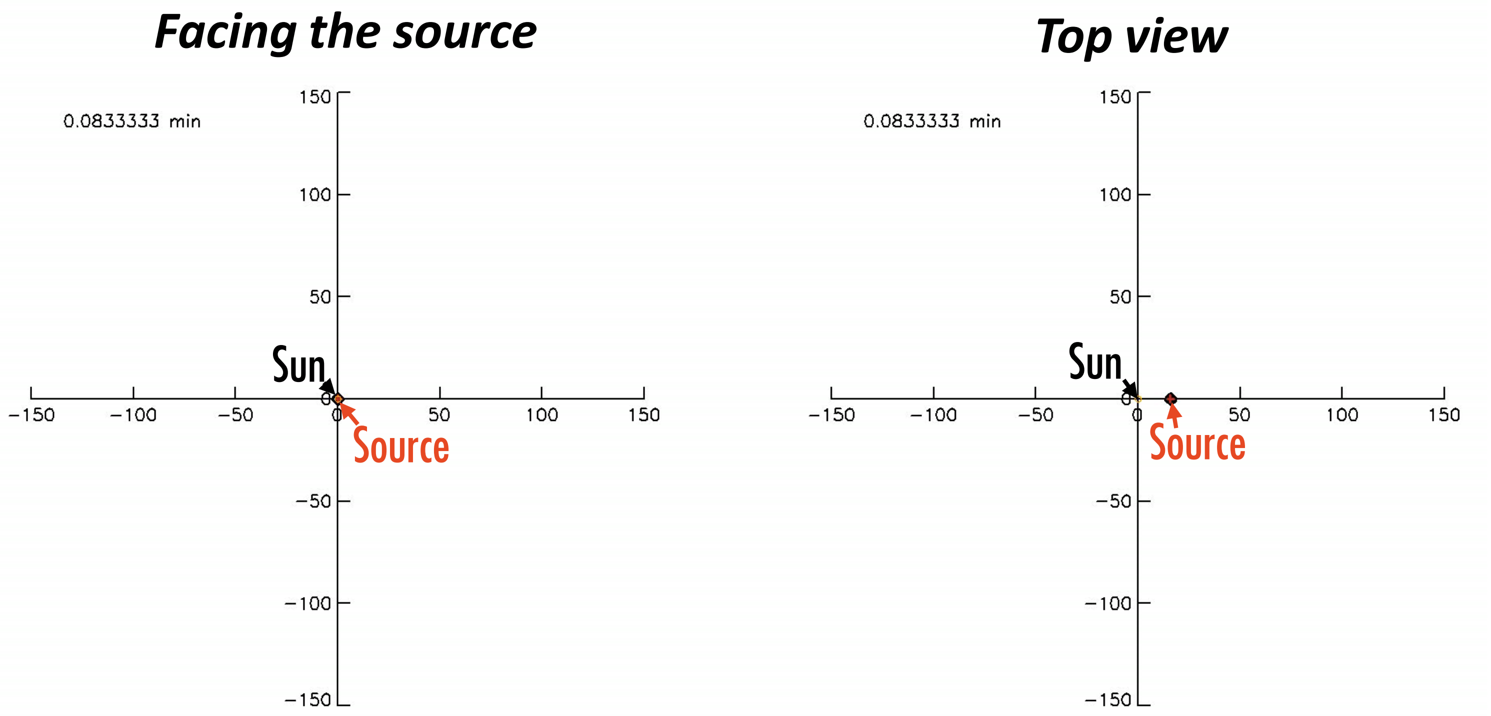
Emission ***time profile***

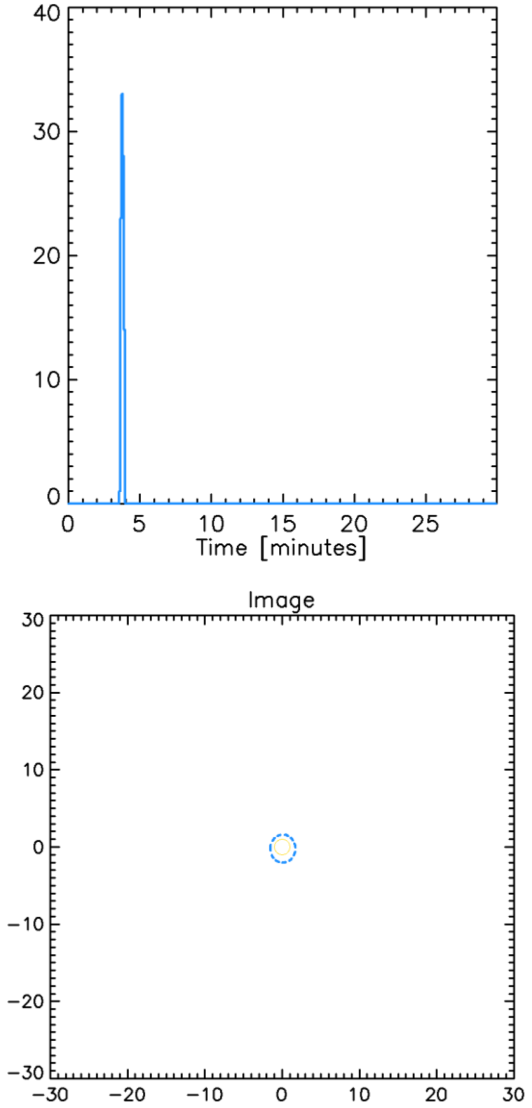



*(Reid & Kontar, 2018)*

# Ray-tracing simulations of radio-wave propagation

(Almost) no scattering

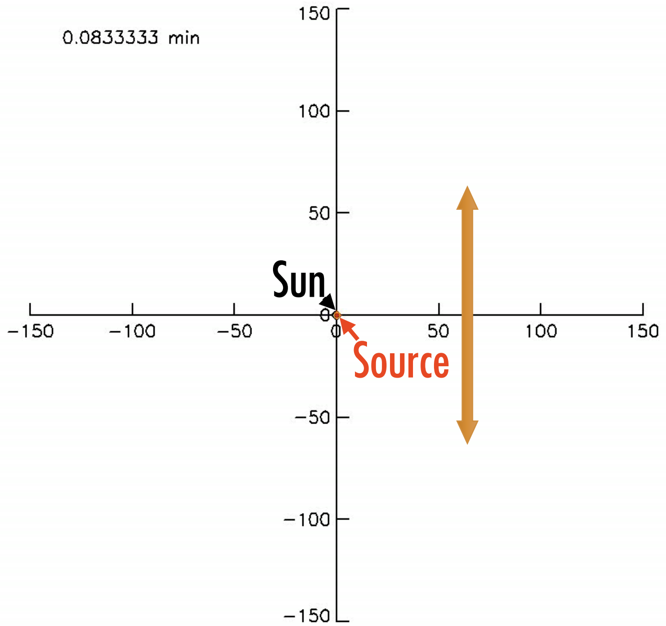


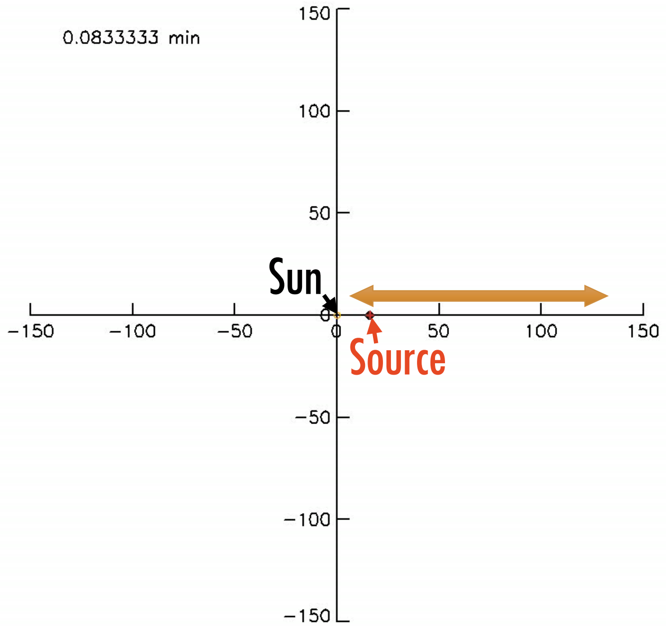
# Ray-tracing simulations of radio-wave propagation

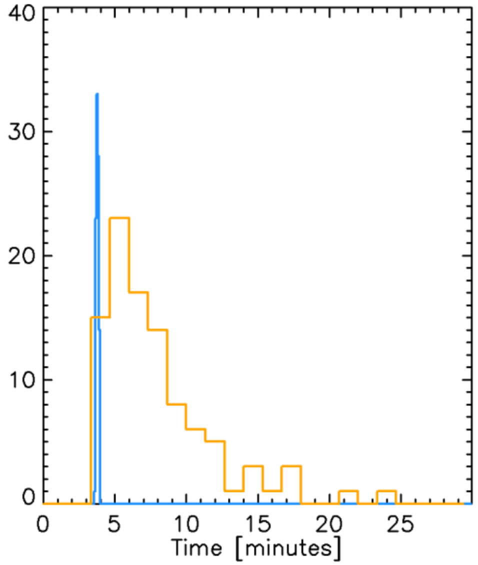
**Radio-wave propagation with scattering**

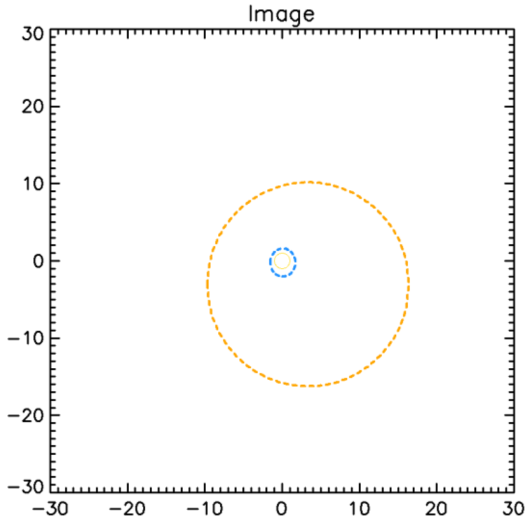
***Facing the source***




***Top view***




Scattering ⊥ radial direction

⬇

Increase spatial distribution

Scattering || radial direction

⬇

Increase time distribution

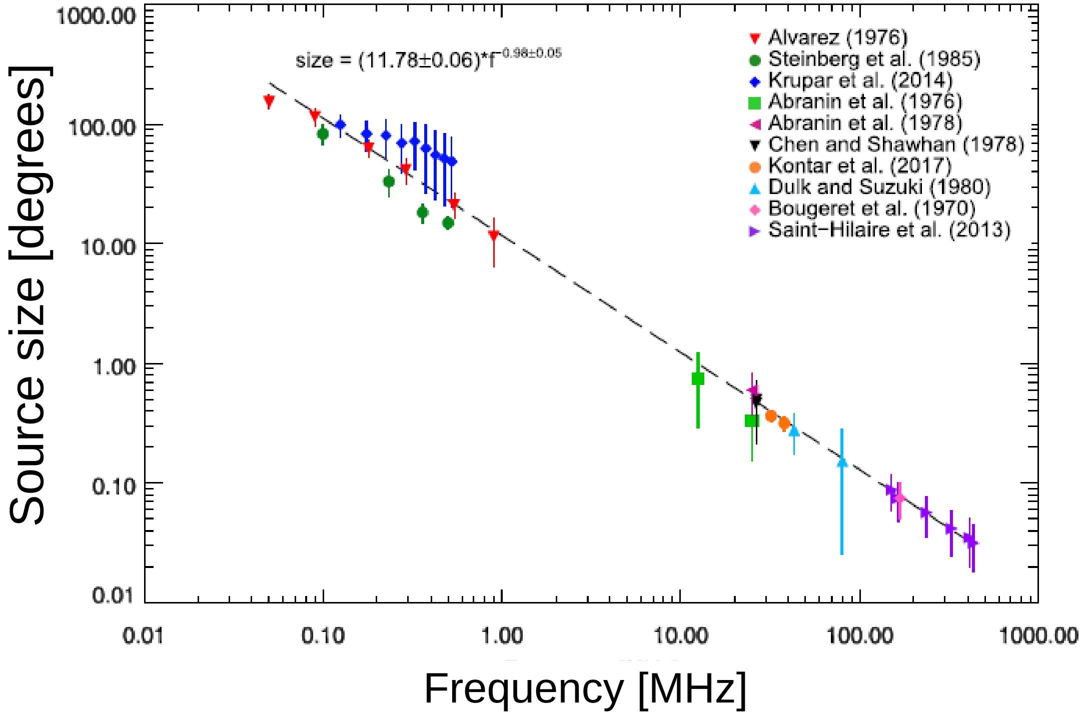
# Simulations vs. observations

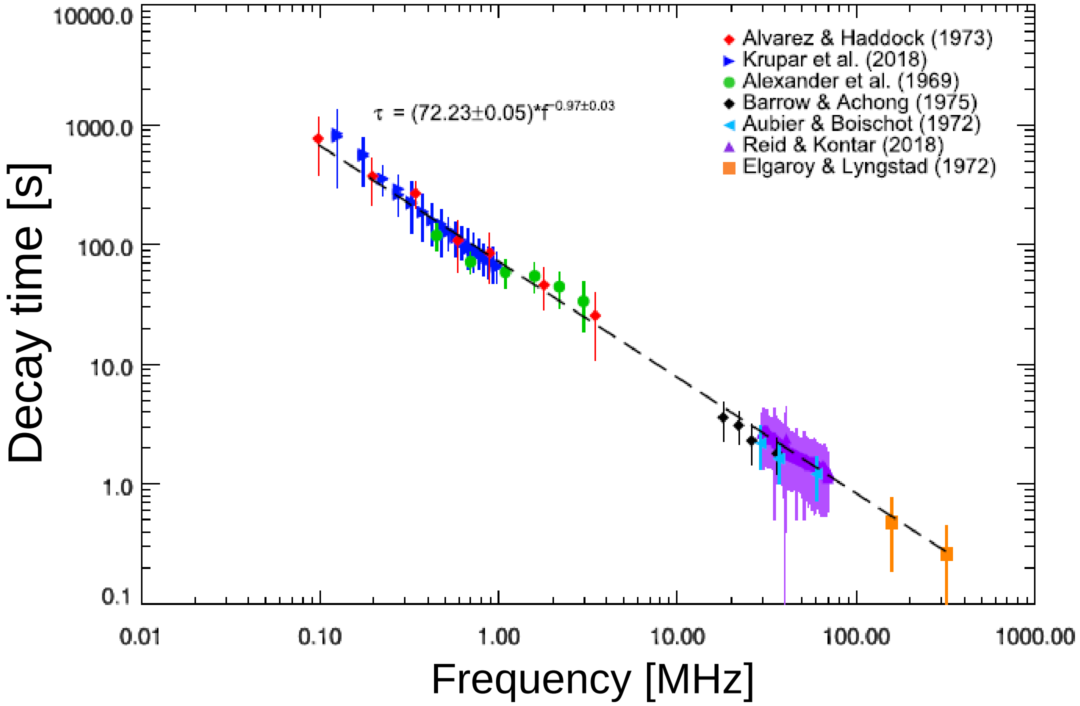
- Level of density fluctuations ("amount" of scattering)

- Source sizes
- Decay times
- *Directivity*

**Compilation of type III burst observations**

*(Kontar et al, 2019)*



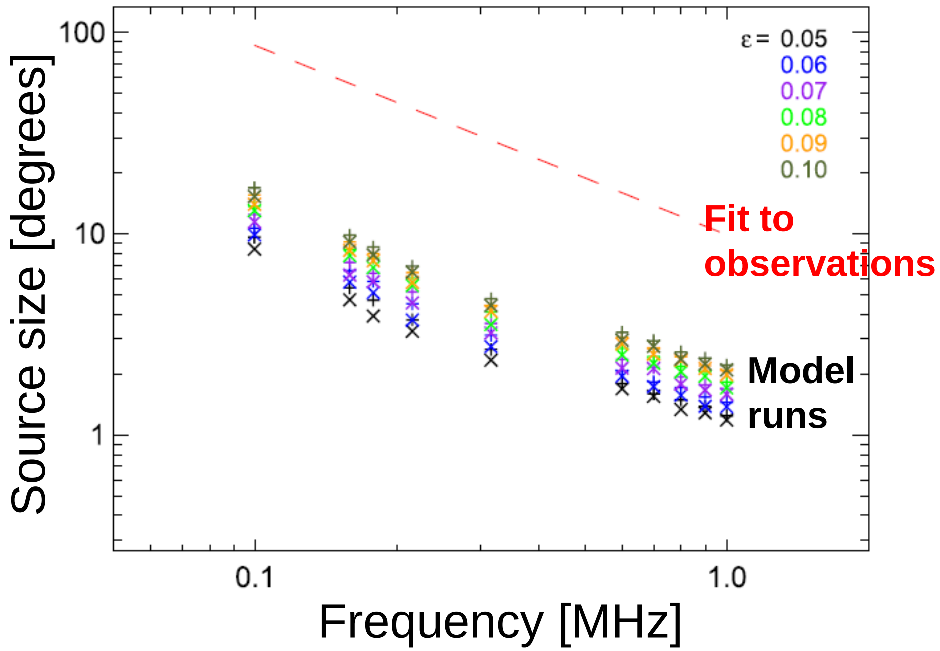



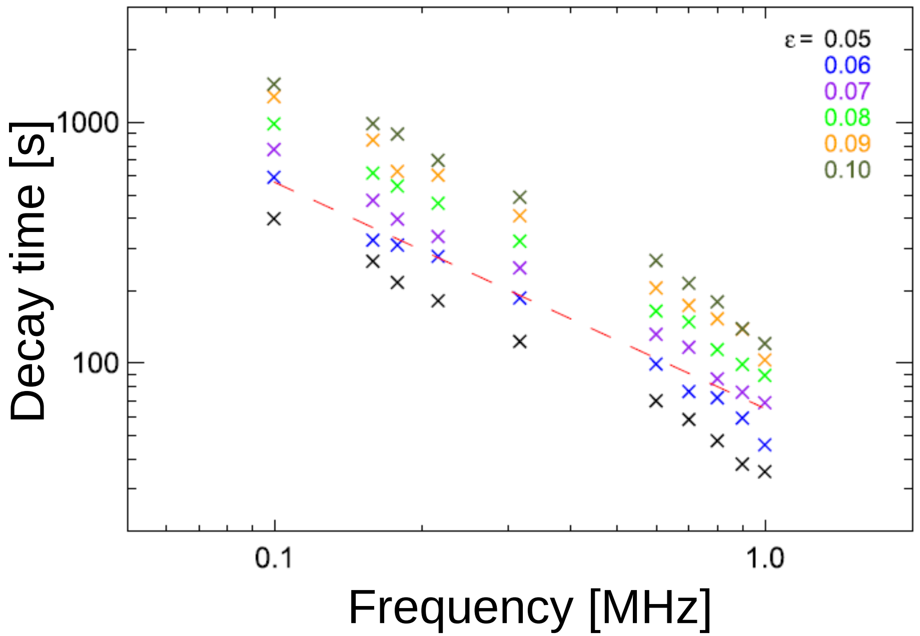

Scattering models should explain the frequency dependence of **source size** and **decay time**

# Simulations vs. observations

- Level of density fluctuations ("amount" of scattering)

- Source sizes
- Decay times
- *Directivity*




The evolution decay time and source size with frequency **can not be both reproduced** with ***isotropic*** scattering

*(Kontar et al, 2019)*

# Anisotropic radio-wave scattering

**Need "more" perpendicular scattering than parallel scattering:** **anisotropic scattering**

*Description*

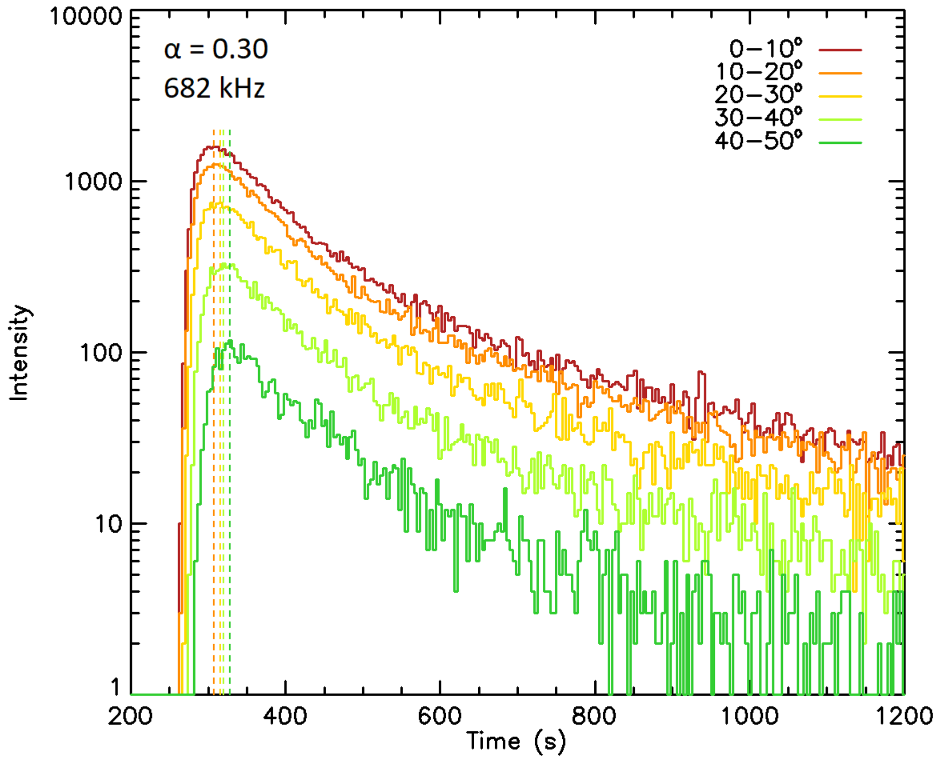
Spectrum of density fluctuations parameterized as $$S(\mathbf{q}) = S\left(\sqrt{q_\perp^2 + \alpha^{-2} q_\parallel^2}\right)$$ *(Kontar et al, 2019)*

With the anisotropy factor $\alpha = h_\perp / h_\parallel$
(ratio of correlation lengths)

α = 1 : isotropic scattering
α ~ 0.3 explains observations *(Kontar et al. 2019)*

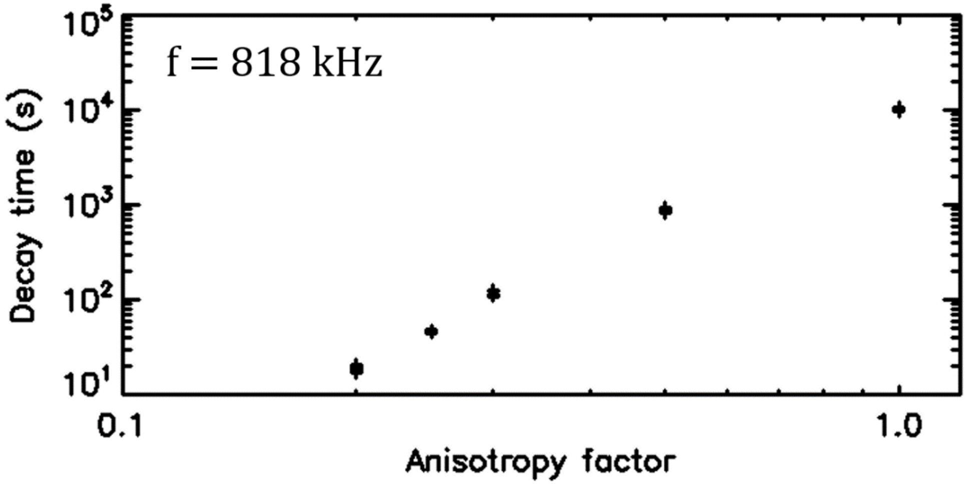
# Anisotropy and decay times of radio bursts

Time profiles from the simulation (at different angles from the source)

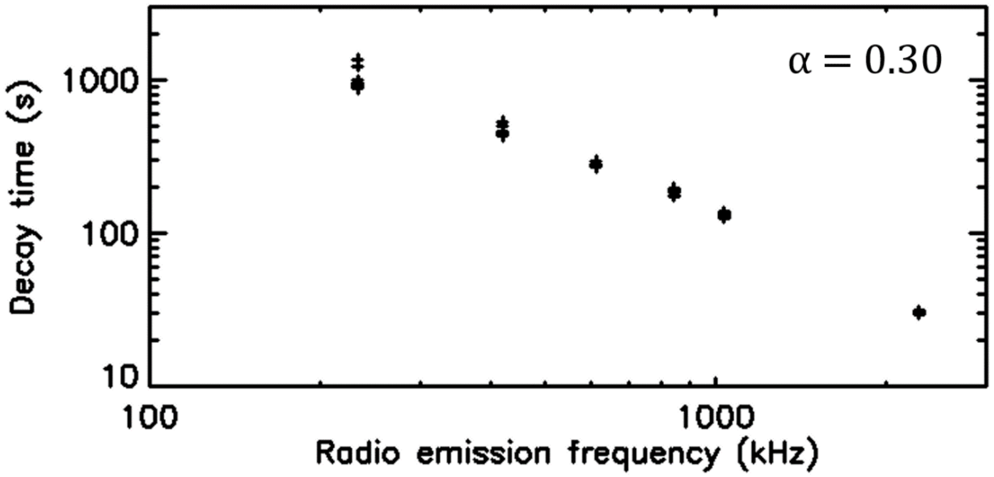



Decay: slight deviation from exponential shape (due to the anisotropy)

Decay time vs anisotropy factor




Decay time vs frequency



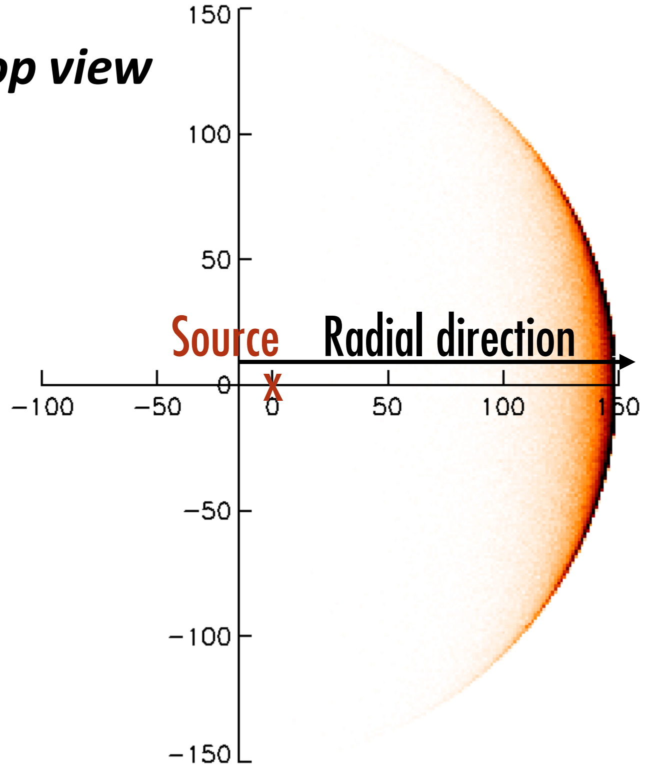
# Simulations vs. observations

- Level of density fluctuations ("amount" of scattering)
- Anisotropy

- Source sizes
- Decay times
- *Directivity*

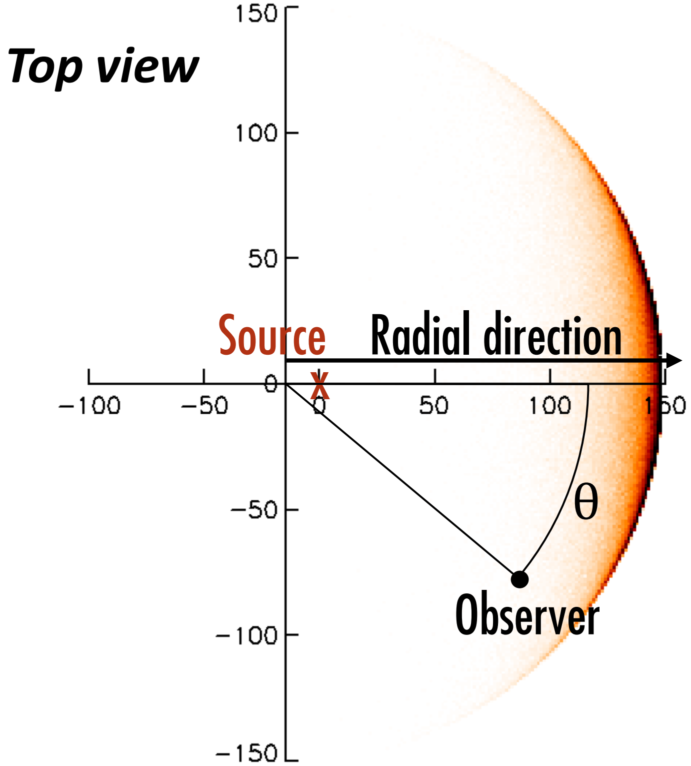
Anisotropy factor of ~0.3 ➔ Source size and lightcurve decay times (statistically) *(Kontar et al, 2019)*

***Top view***




**What about the directivity?**

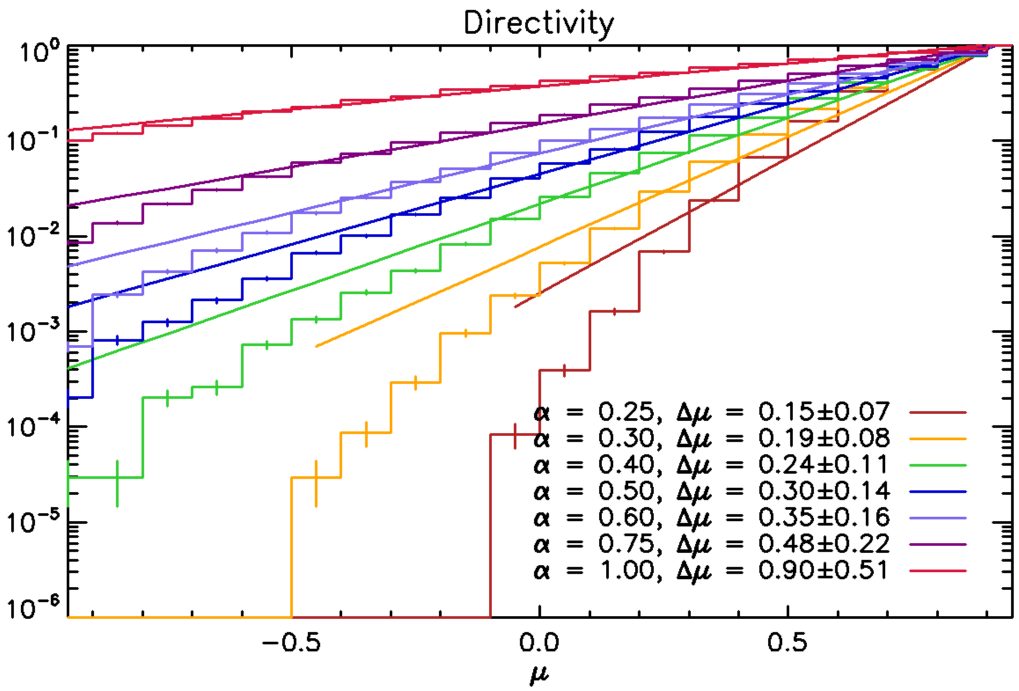
# Simulations vs. observations



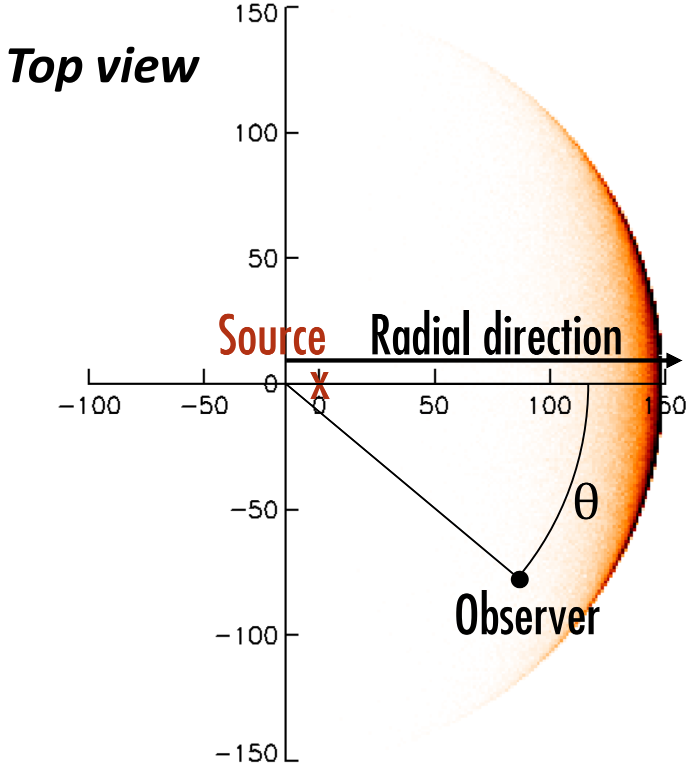

Directivity as a function of μ = cos(θ)

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

Evolution of directivity with anisotropy of density fluctuations (parameter α)



# Simulations vs. observations

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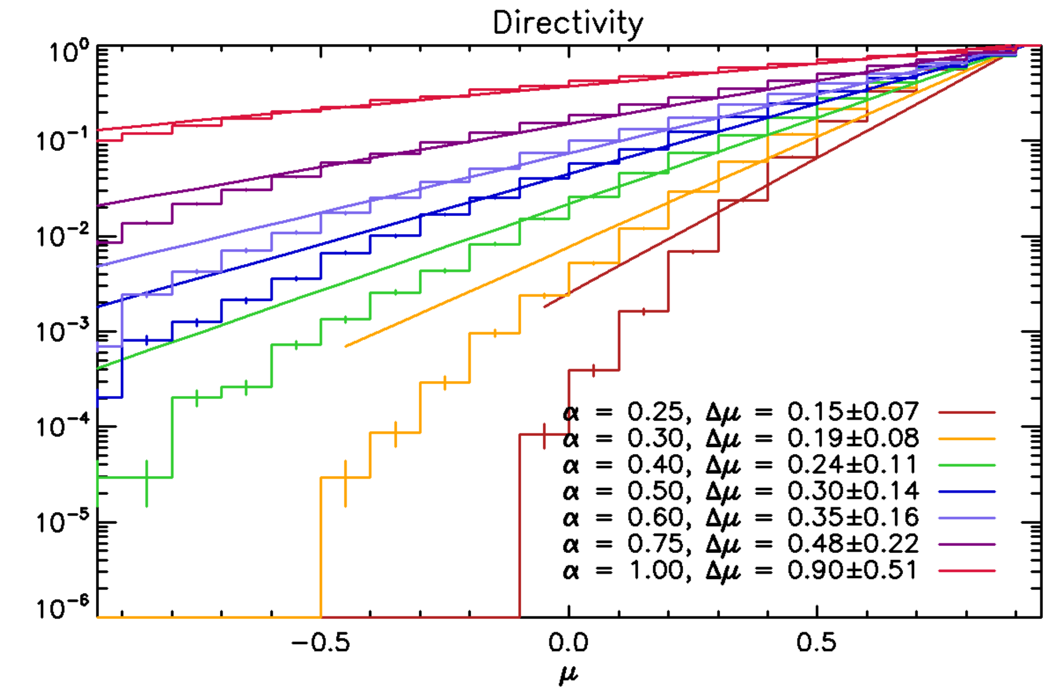
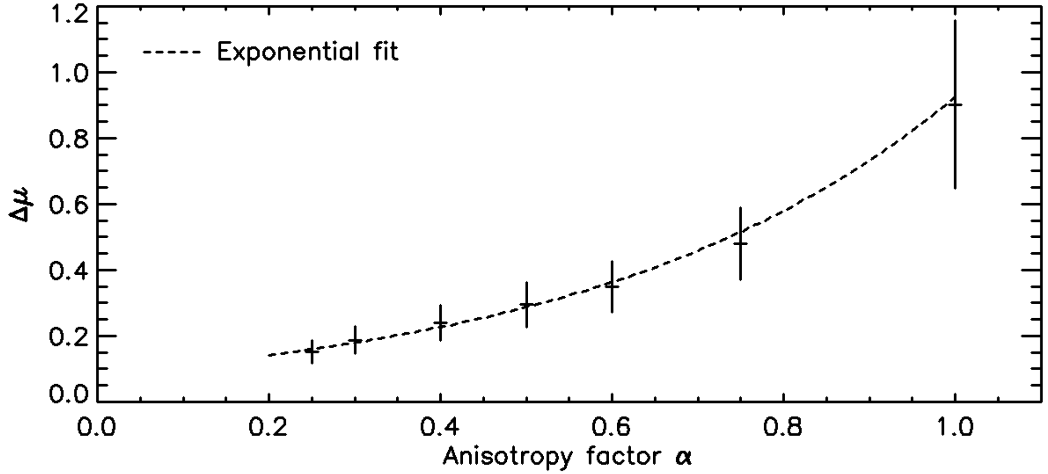
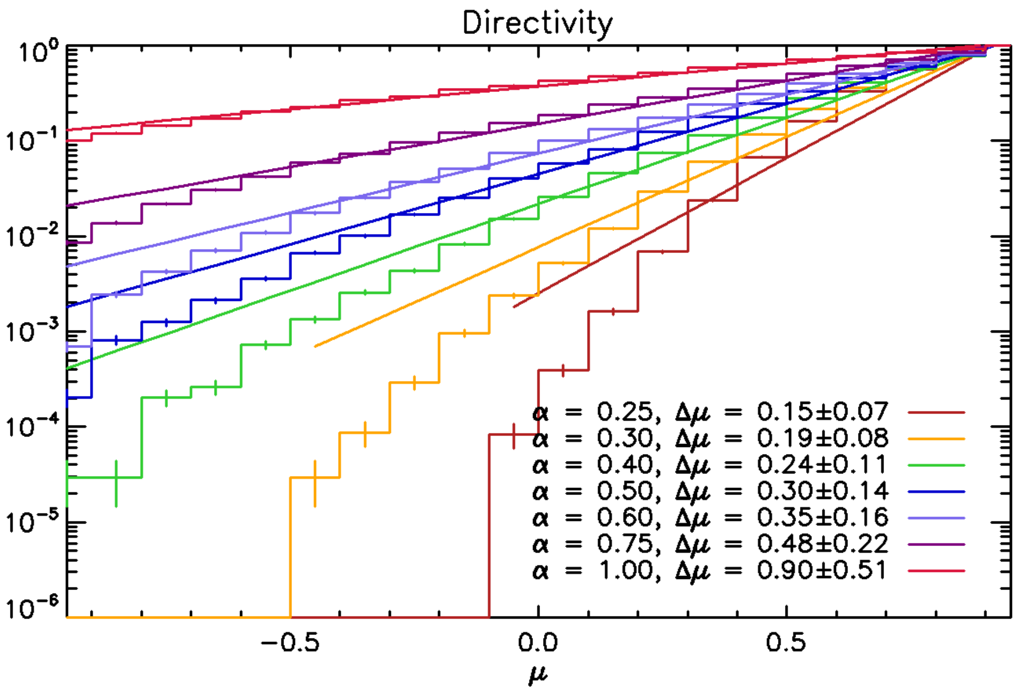
Evolution of directivity with anisotropy of density fluctuations (parameter α)

Relationship between directivity (Δμ) and the anisotropy factor α



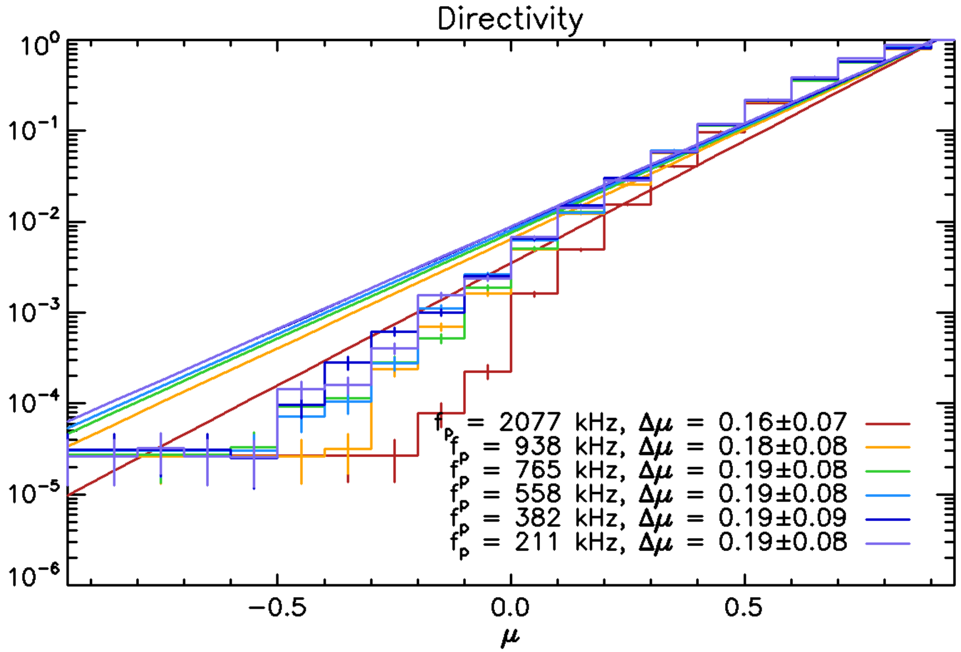



# Directivity and anisotropic scattering



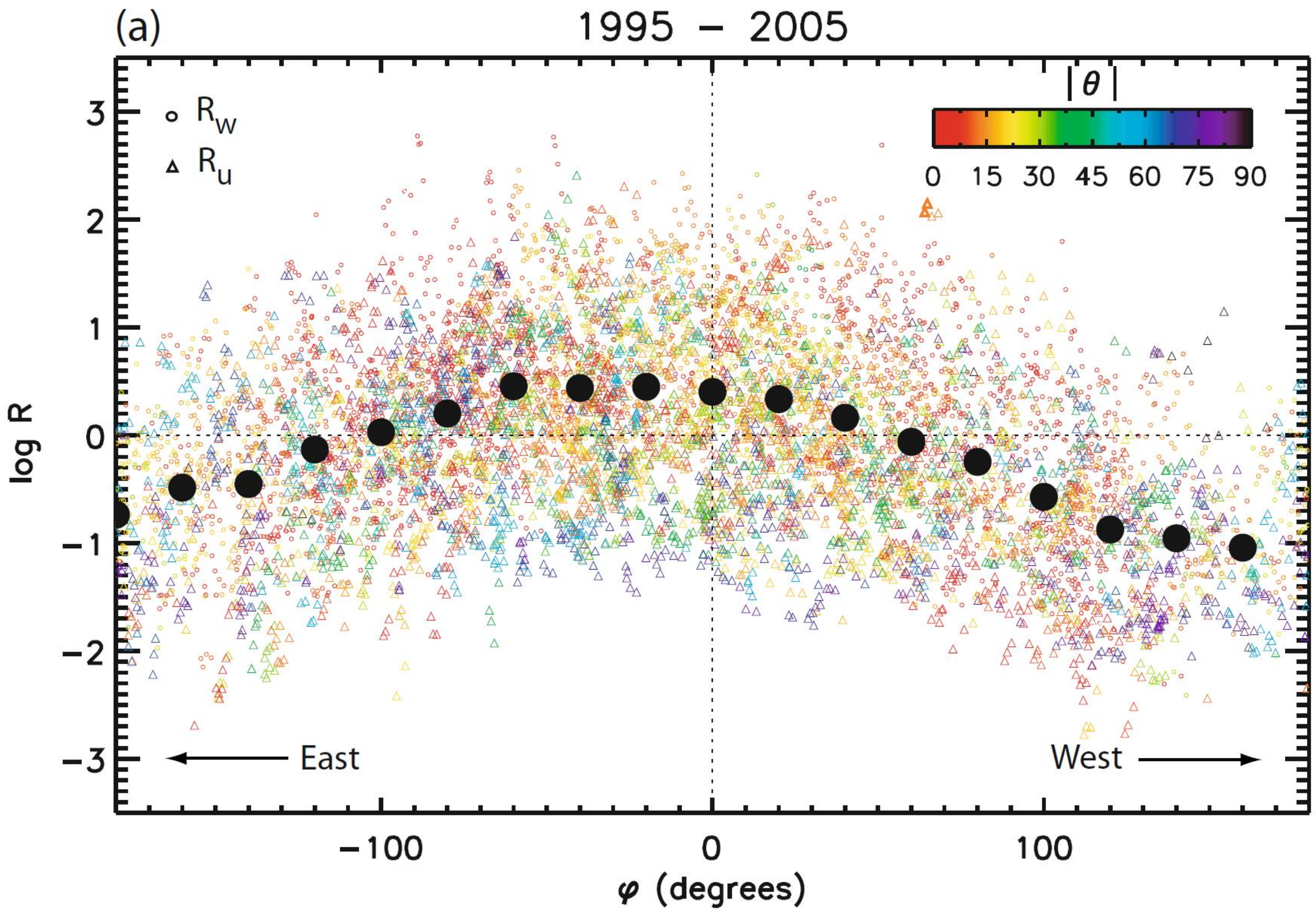

Evolution of directivity pattern with anisotropy of density fluctuations (parameter α)

Evolution of directivity with frequency




The directivity does not change significantly with frequency

# Measuring the radio burst directivity



Angle between source and spacecraft

**Past studies: directivity from flux ratios (2 spacecraft measurements)**

*e.g. Bonnin et al (2008)*

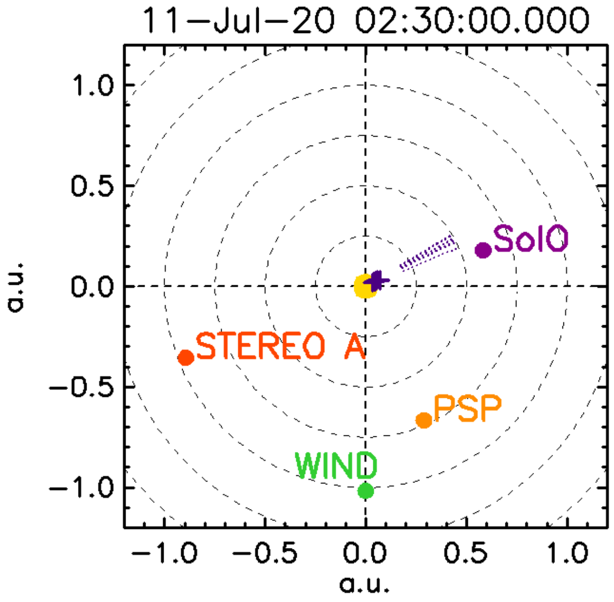
Distribution of radio flux ratios observed at two spacecraft (Ulysses and Wind)

Use of thousands of events to study "***averaged***" directivity of radio bursts

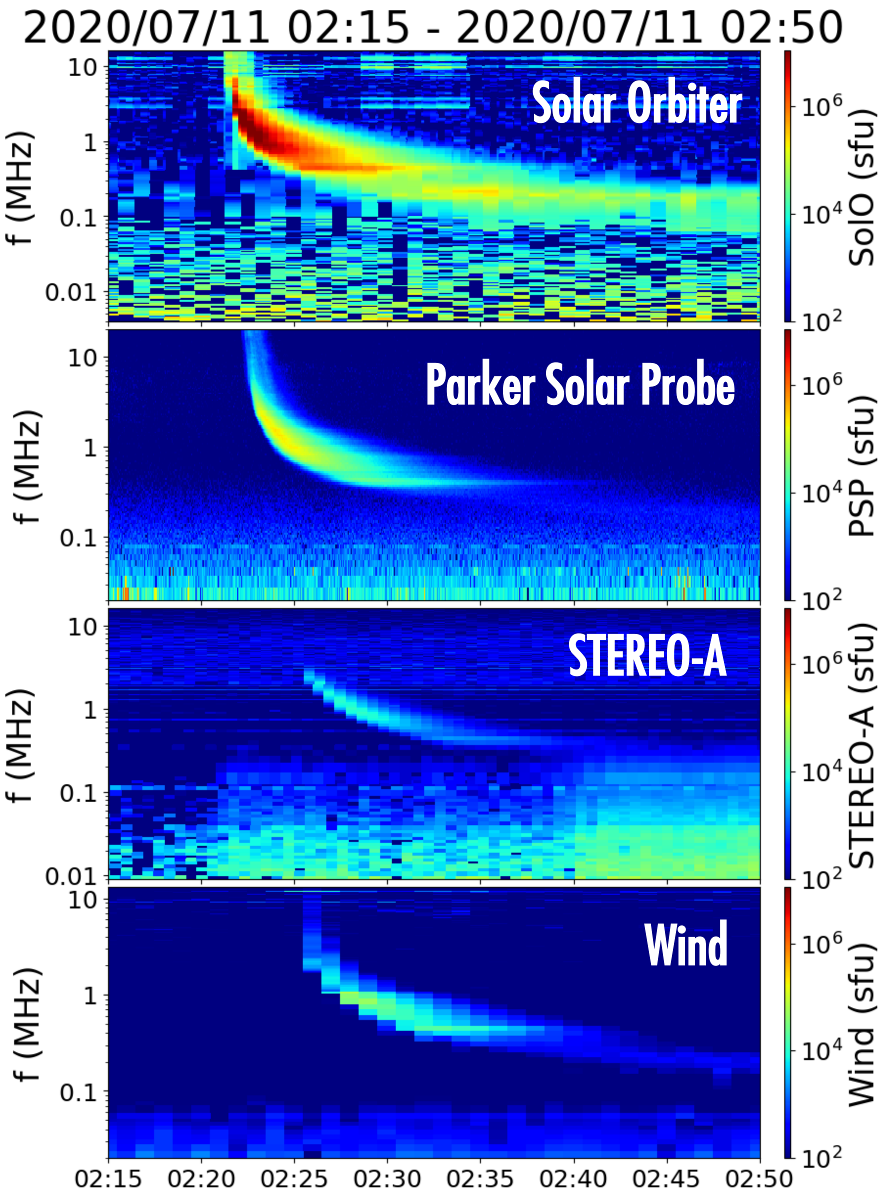
Using measurements at 4 spacecraft
→ analyse directivity of ***single*** type III radio bursts

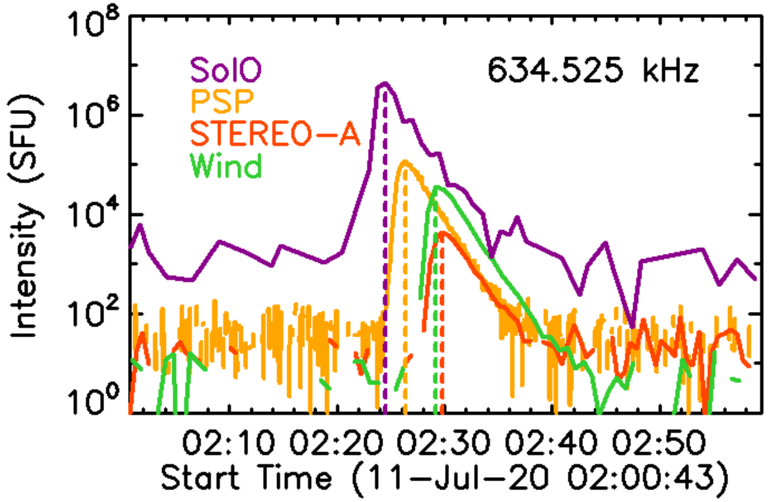
# Type III radio bursts at SOLO, PSP, STEREO and Wind

Example of a type III radio burst observed on July 11 2020

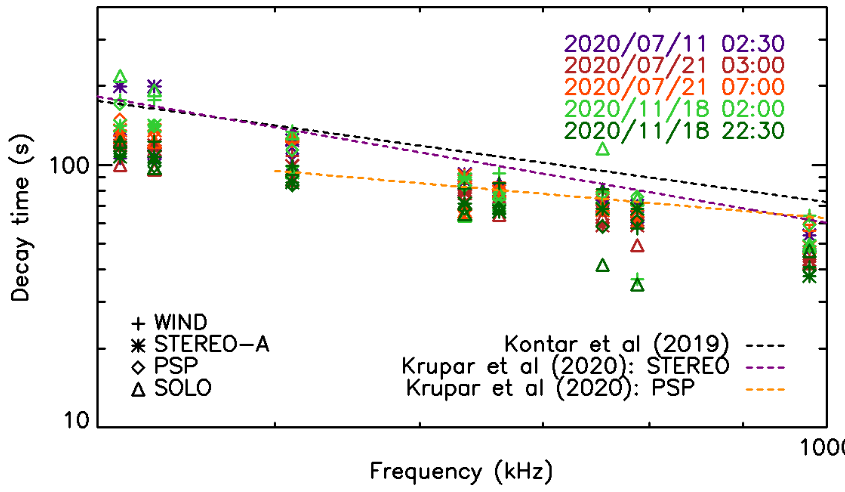



*5 events selected in July and November 2020*

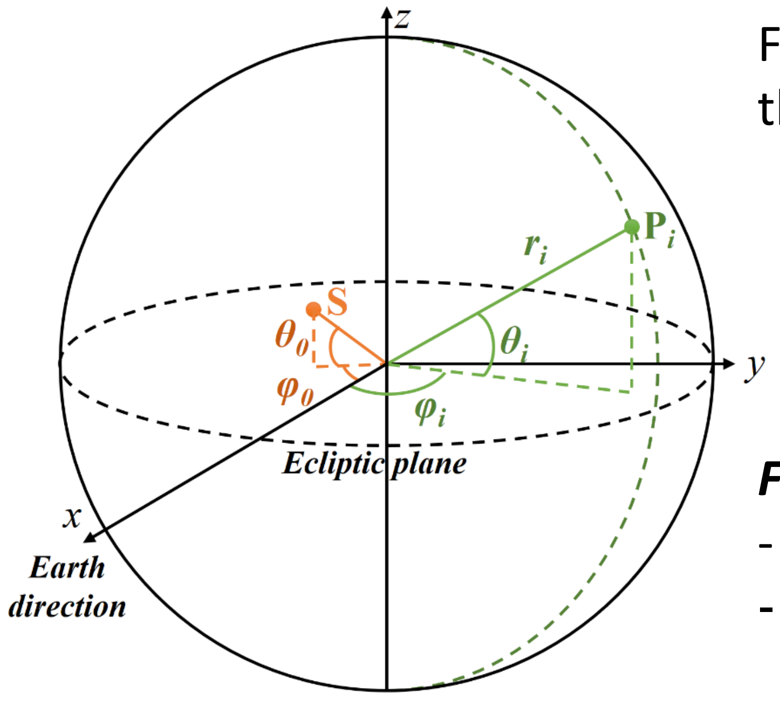



Evaluation of decay times at different frequencies



# Directivity fit to radio fluxes at 4 positions




Fitting the radio fluxes at the 4 spacecraft with an exponential model for the directivity:

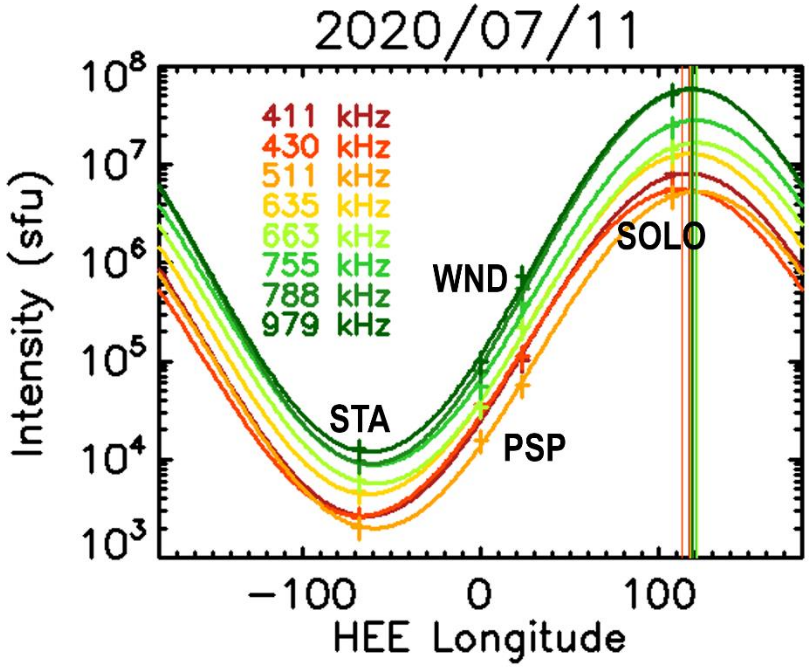
$$D(\mu) = C_0 \exp\left(\frac{\mu - 1}{\Delta\mu}\right)$$

where $\mu = \cos(\varphi_i - \varphi_0)\cos(\theta_i - \theta_0)$

$(\varphi_0, \theta_0)$ is the position of the radio source

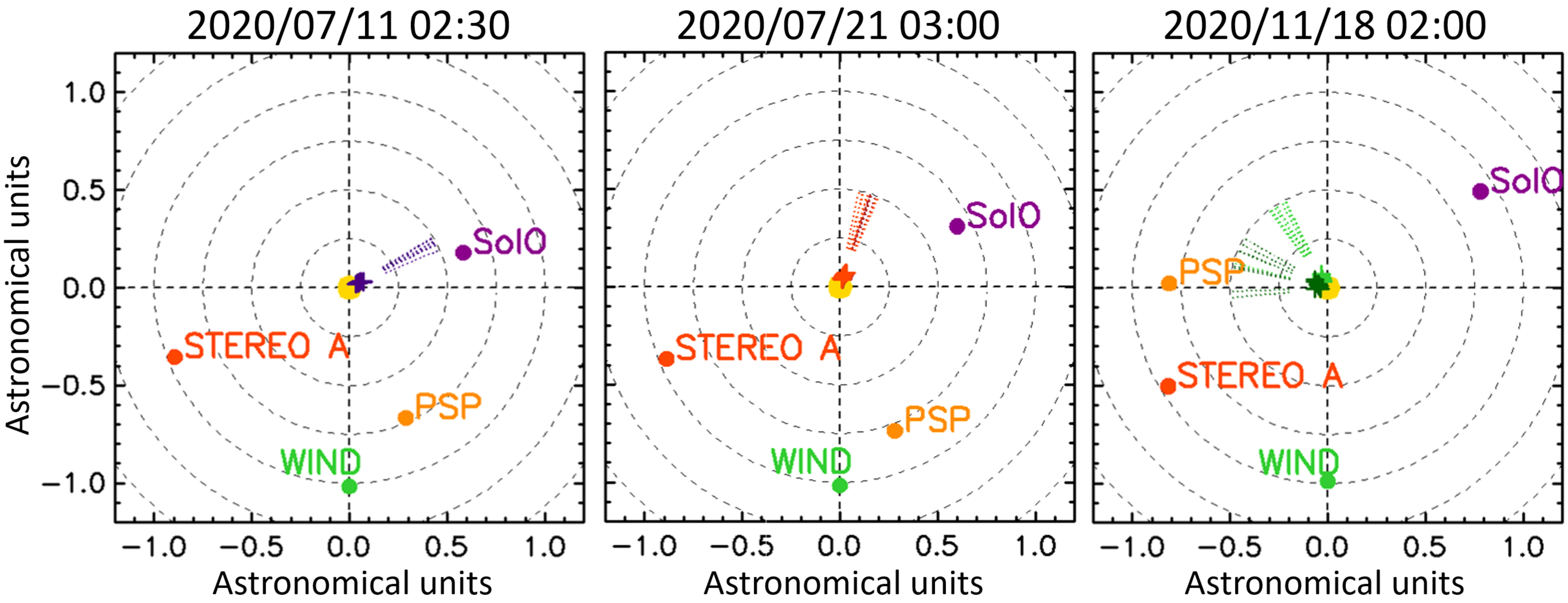
***Free parameters are***:

- Position of the source
- $\Delta\mu$ describing the shape of the directivity
- $C_0$ (maximum flux)




*In the presented cases, the spacecraft are close to the ecliptic plane so we cannot constrain the elevation of the radio source (therefore it is assumed to be in the plane as well)*

# Positions of radio bursts resulting from the directivity fit



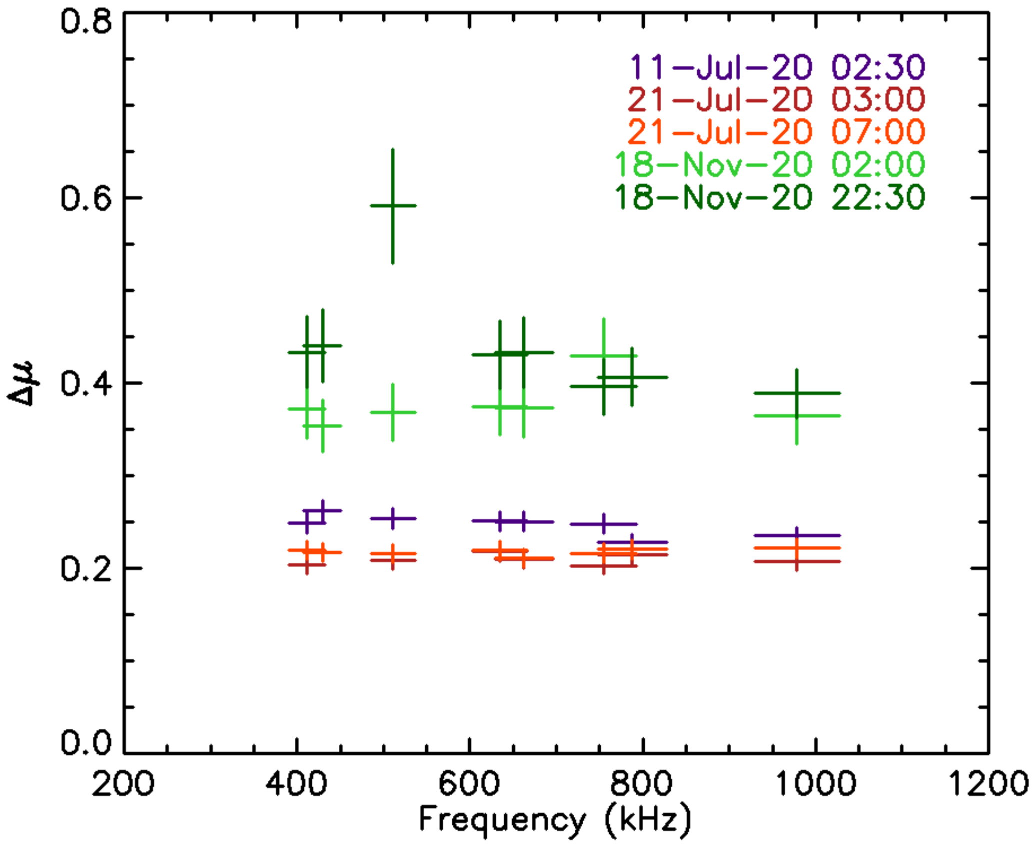

Positions of the radio sources at different frequencies is a result of the directivity fitting
– these results are in agreement with other methods for source localisation

# Directivity of observed radio bursts

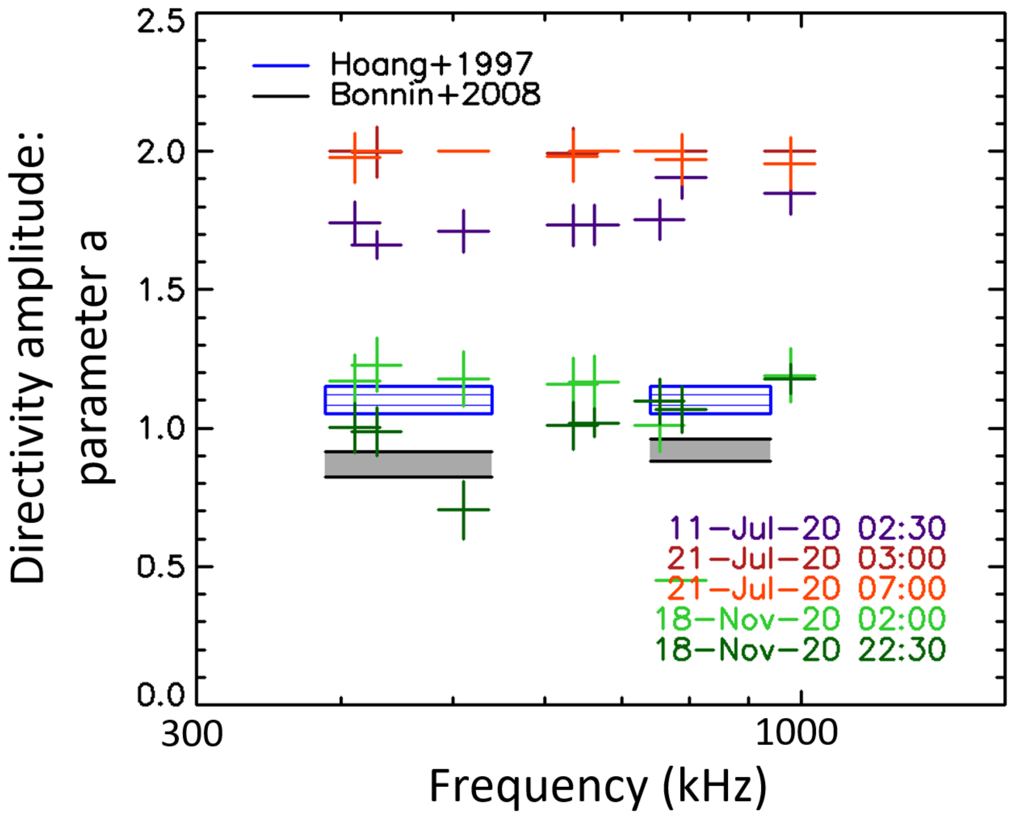
**Directivity does not evolve significantly with frequency**

Distribution of the parameter Δμ with frequency for the 5 type III radio bursts studied:
*Compatible with anisotropy factors between 0.3 and 0.6*

| event | Mean value of $\Delta\mu$ | Standard deviation |
|---|---|---|
| 2020/07/11 02:30 | 0.25 | 0.01 |
| 2020/07/21 03:00 | 0.21 | 0.01 |
| 2020/07/21 07:00 | 0.22 | 0.01 |
| 2020/11/18 02:00 | 0.4 | 0.2 |
| 2020/11/18 22:30 | 0.4 | 0.4 |



# Directivity of observed radio bursts




Comparison of the directivity found in our events with previous results derived from the analysis of radio flux ratios on many events by *Bonnin et al (2008*) and *Hoang et al (1997)*

Directivity measurements on single radio bursts
→ agreement with past results deduced from statistical studies of radio bursts

A significant difference is found between events from July 2021 and events from November 2021
→ Indication that the anisotropy factor or the size of the density fluctuation can vary significantly – due to solar wind conditions?

# Summary of findings

**<u>In simulations:</u>**

***Decay times of radio bursts***
- Decreases with increasing frequency
- Increases with increasing anisotropy factor
- Depends only weakly on the angle between the source direction and the observer

***Directivity of radio bursts***
- Does not evolve significantly with frequency
- Depends on the anisotropy factor

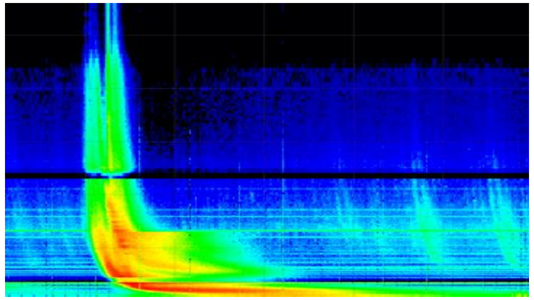
**<u>Observations:</u>**

***Decay times of radio bursts***
- Consistent with anisotropic scattering
- *Detailed comparison with simulation results still ongoing*

***Directivity of radio bursts***
- Consistent with anisotropic scattering
- Anisotropy factor between 0.3 and 0.6 with significant variations between events

# Next steps

- Better constraints on directivity measurements:
    - Add other spacecraft, e.g. MarsExpress
    - Constraint out of the ecliptic as Solar Orbiter goes out of the plane



*Radio burst measured at MarsExpress*
*Courtesy of O. Witasse (ESA/ESTEC)*

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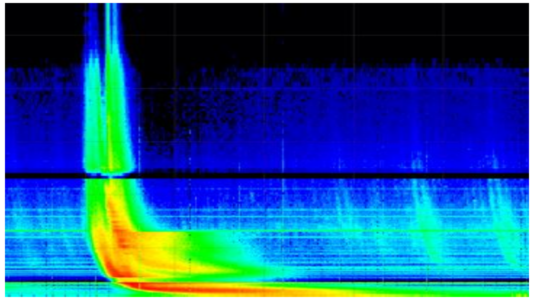

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❖ What is the influence of the level of density fluctuations on the directivity? *Ongoing study*

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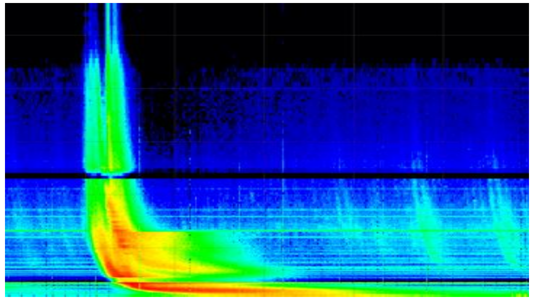

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- ❖ What is the influence of the level of density fluctuations on the directivity? *Ongoing study*

- ❖ How well is the agreement between simulations and observations of decay times? *Ongoing study*

# Next steps

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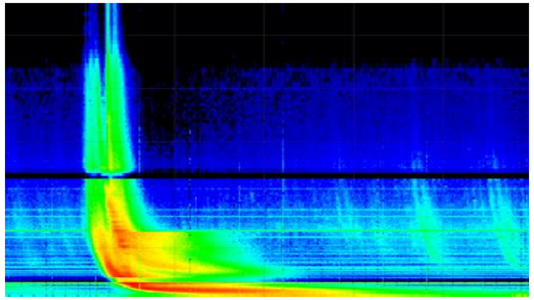

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- ❖ What is the influence of the level of density fluctuations on the directivity? *Ongoing study*

- ❖ How well is the agreement between simulations and observations of decay times? *Ongoing study*

- ❖ How can these measurements of properties of the density fluctuations be compared to in-situ diagnostics of the plasma from PSP and SOLO?

# Take home messages

Radio-wave propagation effects dominate the observed properties of radio bursts
→ Needs to be understood to get information on the radio source, and the electron beams at its origin

Multi-spacecraft observations of radio bursts → **directivity** of ***single*** bursts

**Directivity measurements**:
→ Radio source position
→ Anisotropy (and level?) of density fluctuations of ambient plasma at radio source
→ Complementary with in-situ plasma measurements