# Der Einfluss der Ionosphäre von Saturn auf die Polarisation der Radioemissionen von Saturnblitzen

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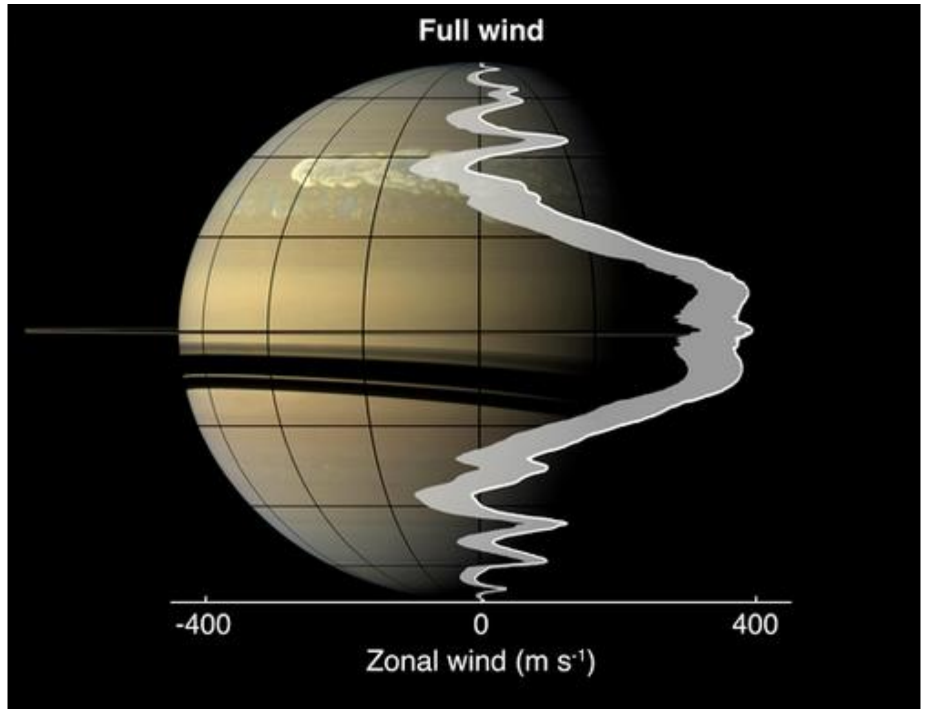
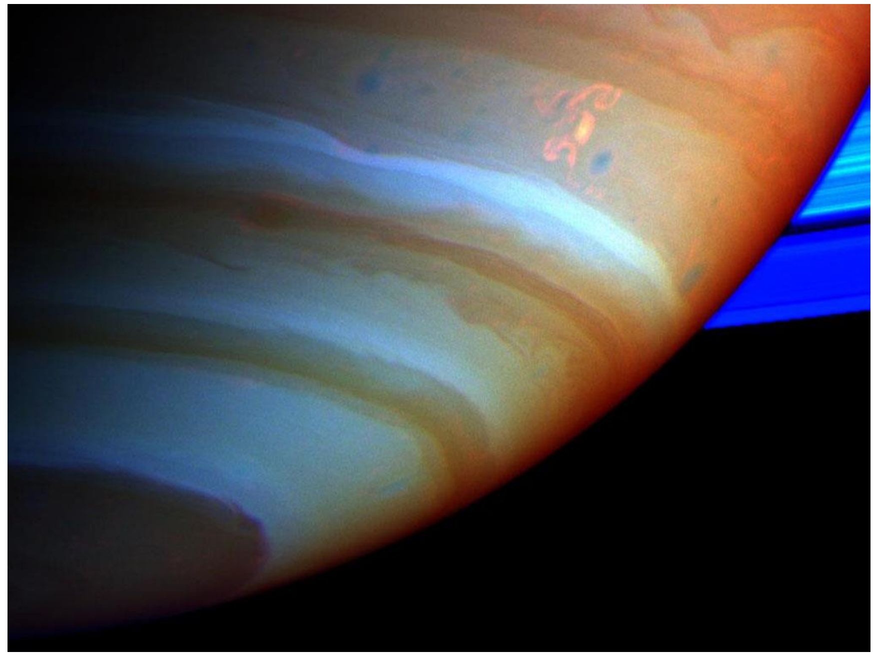
# Introduction: Lightning on Saturn or "SEDs"

- SEDs (Saturn Electrostatic Discharges) are the radio emissions of Saturn lightning, detected in a frequency range from a few hundred kHz (ionospheric cutoff) up to 16 MHz or 40 MHz (Cassini or Voyagers)
- Cassini s/c was in orbit around Saturn from 2004 to 2017
- Millions of SEDs were detected over the years by the antennas and receivers of the Cassini RPWS (Radio and Plasma Wave Science) instrument
- SEDs are so strong (10,000 times more intense than Earth lightning), and so they were also detected by the ground-based radio telescope UTR-2 in Ukraine
- SEDs are related to bright cloud systems in Saturn's atmosphere with diameters of ~2000 km or 10,000 km („Great White Spots") imaged by Cassini and by many professional & amateur astronomers on Earth



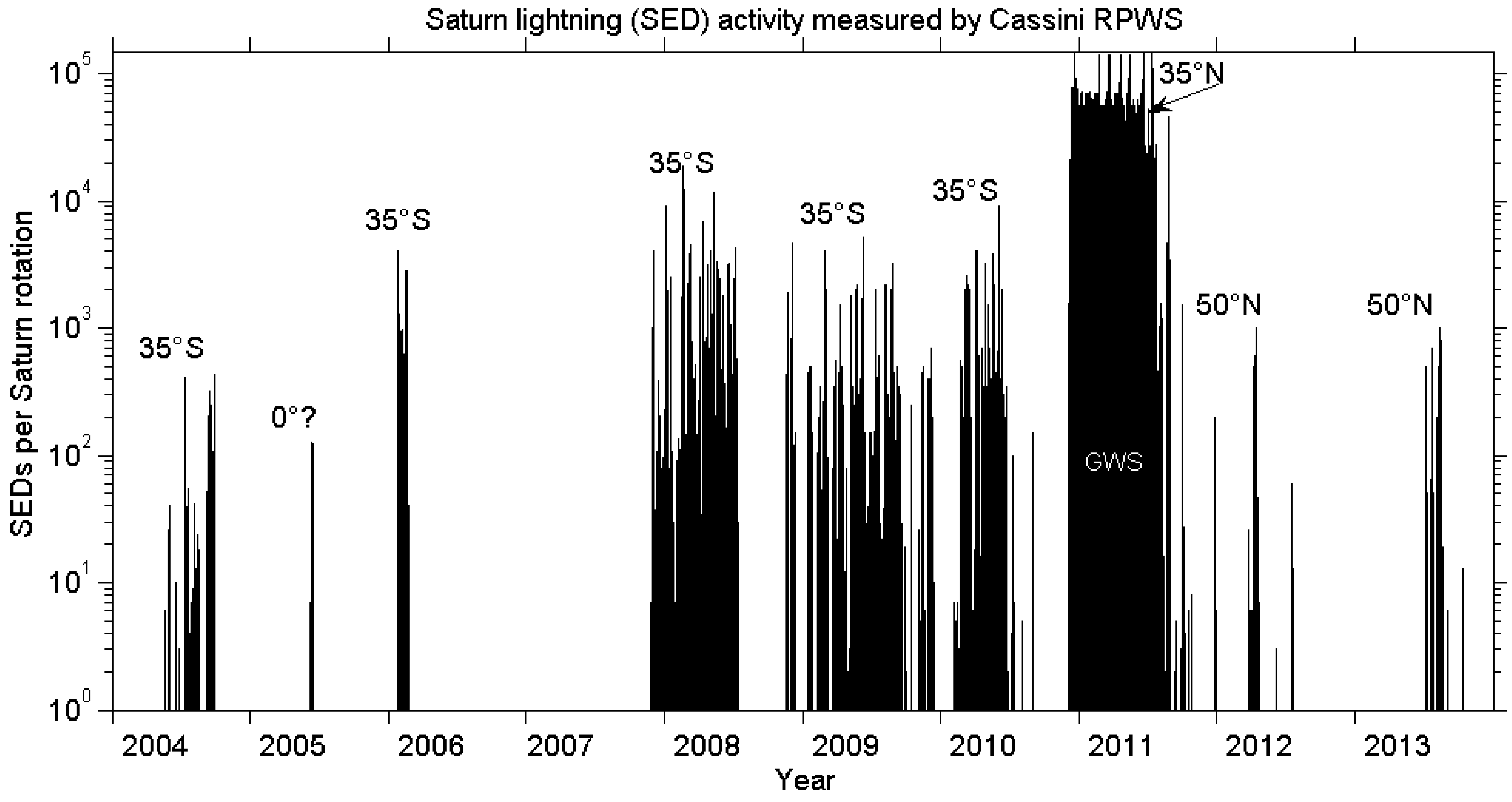

[Galanti et al., 2019]



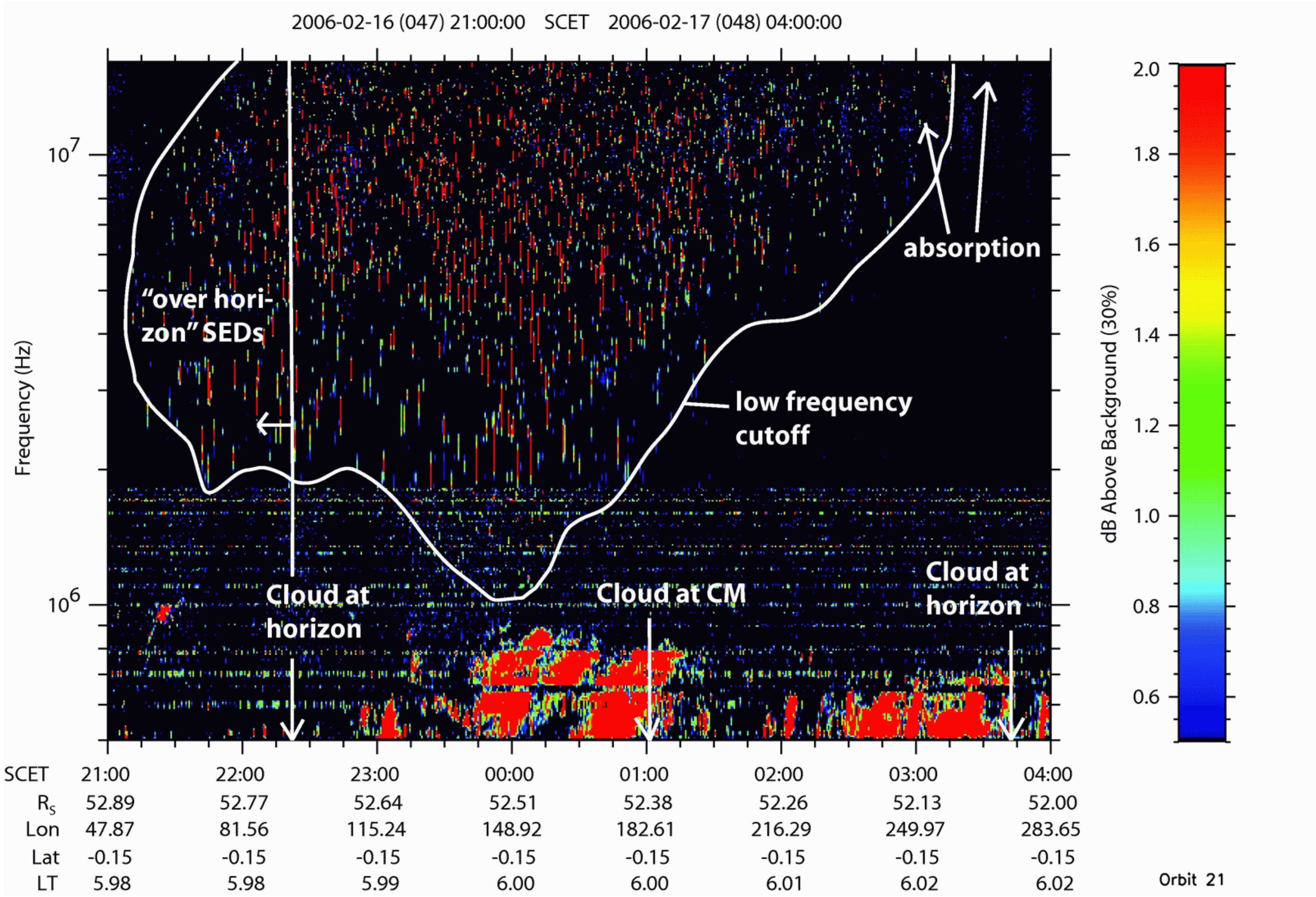
„Dragon storm"
© NASA

# Saturn lightning activity during Cassini mission

- Long-lasting SED storms (weeks to several months) and long periods of no lightning activity
- No more SEDs after November 2013
- Storms detected only at specific latitudes: 35°S, equator, 35°N, 50°N
- Storm locations at wind speed minima (10h40min) except for equator (10h10 min)



# A dynamic spectrum showing Saturn lightning

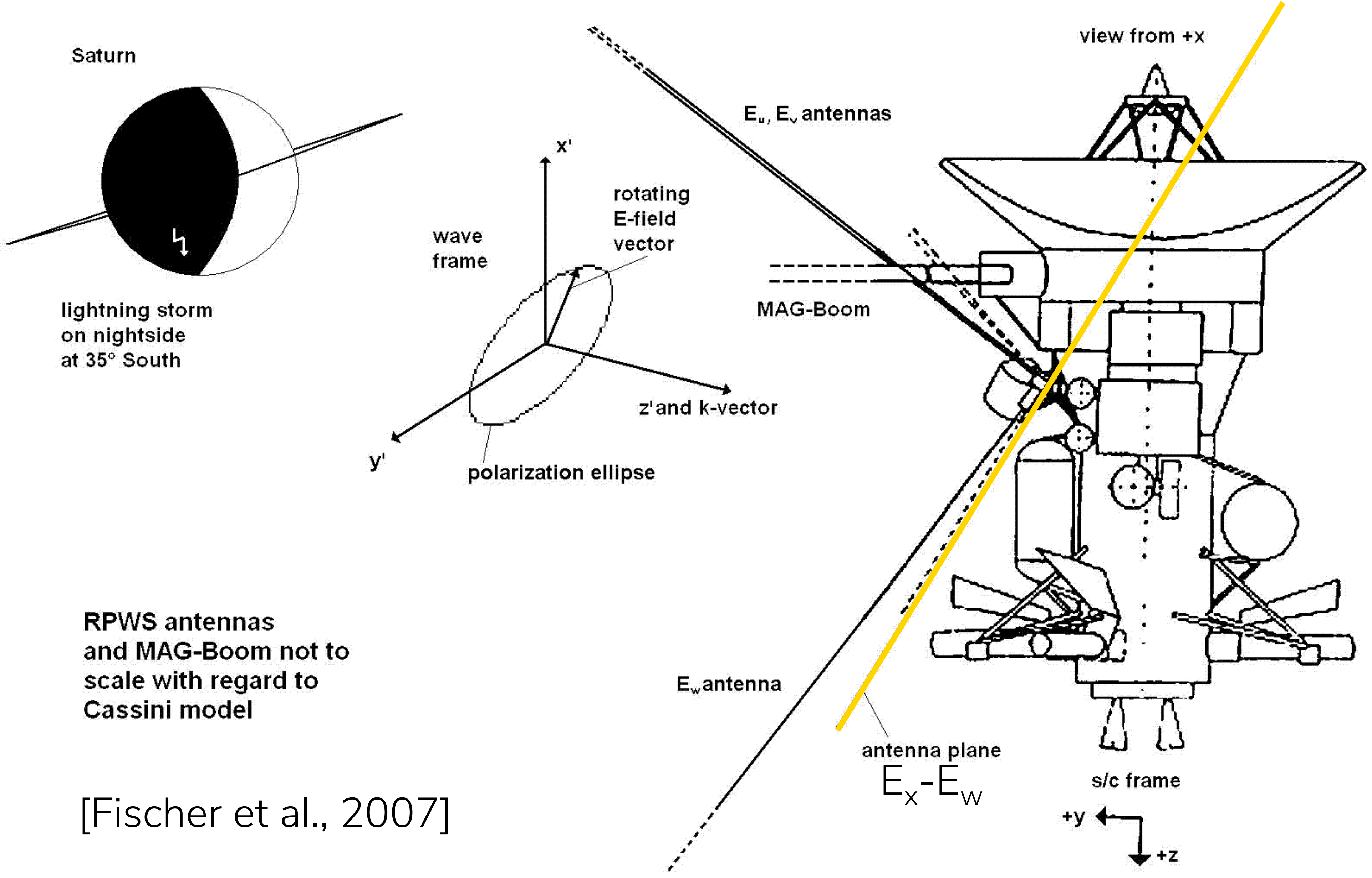



$$f_{cutoff} = \frac{f_{pe,\max}}{\cos(\alpha)} \qquad N_e = f_{pe,\max}^2 / 81$$

$f_{pe}$ in kHz, $N_e$ in cm$^{-3}$, typically $10^4$-$10^5$ cm$^{-3}$ (night- and day-side)

- Low-frequency cutoff of SED episodes can be used to determine peak electron density of Saturn's ionosphere
- Some SEDs are detected when storm is still beyond the visible horizon ("over horizon SEDs")

# How to measure SED polarization




[Fischer et al., 2007]

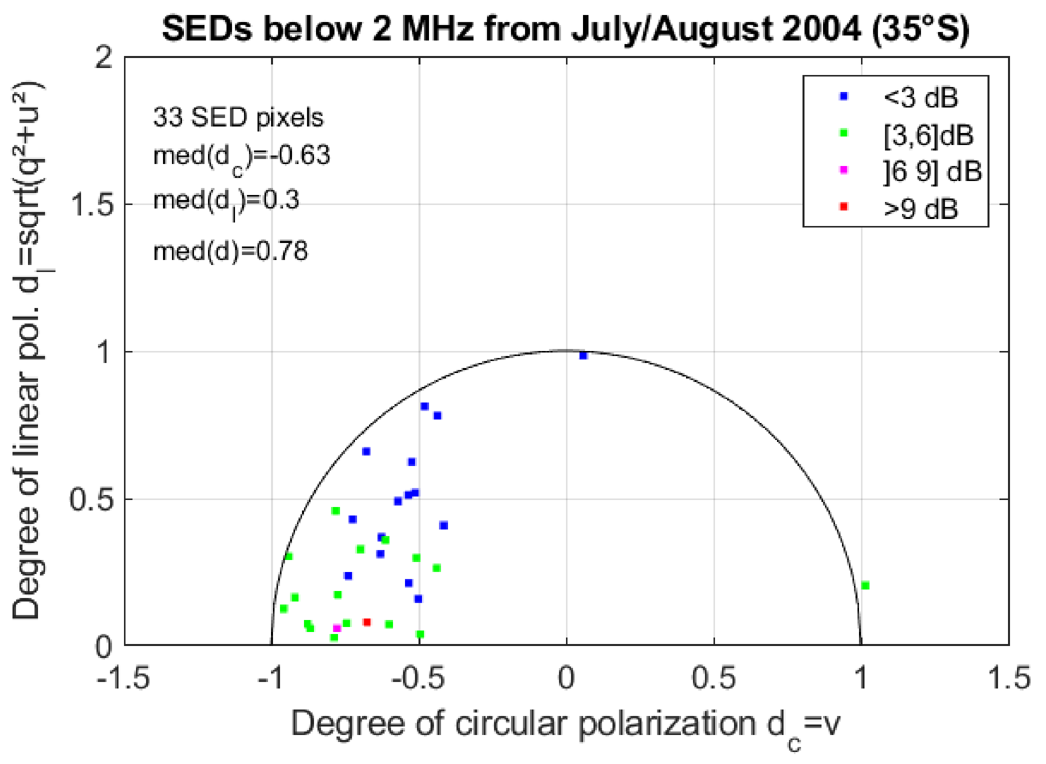
$$\begin{pmatrix} \langle V_w V_w^* \rangle \\ (h_w/h_x)^2 \langle V_x V_x^* \rangle \\ (h_w/h_x) Re \langle V_x V_w^* \rangle \\ (h_w/h_x) Im \langle V_x V_w^* \rangle \end{pmatrix} = \mathbf{M} \frac{S h_w^2}{2} \begin{pmatrix} 1 \\ q \\ u \\ v \end{pmatrix}$$

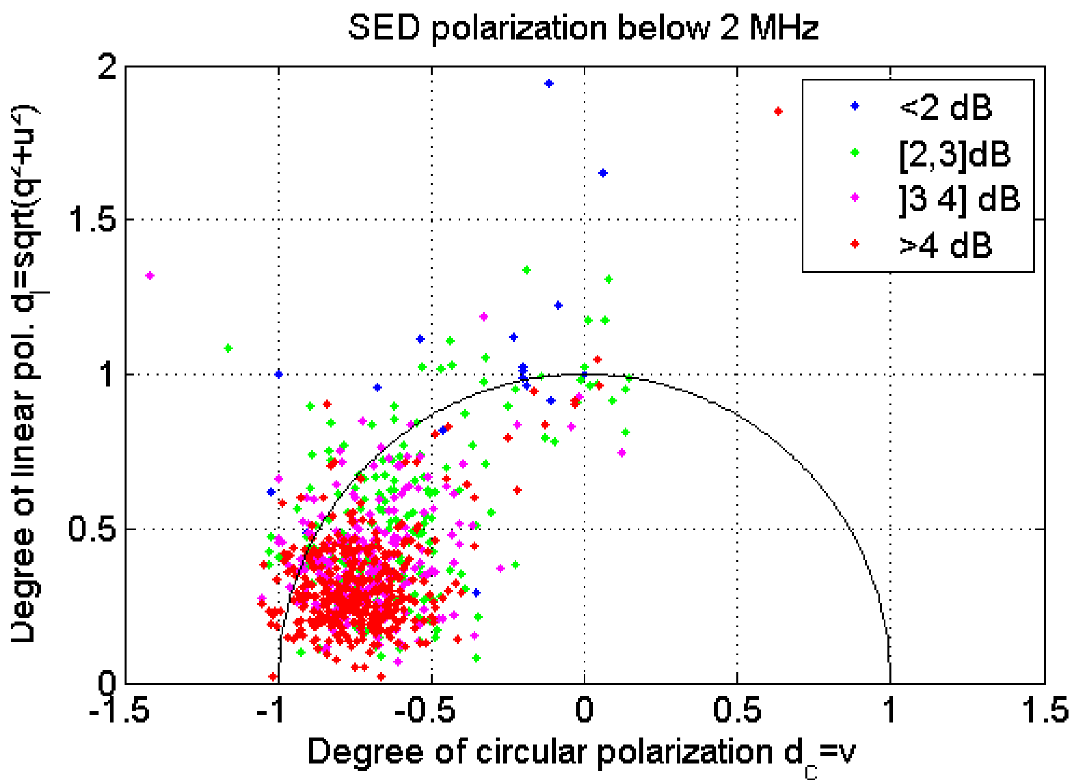
- <u>4 equations with 4 unknowns</u>: S (intensity), q, u, v (normalized Stokes parameters)
- <u>4 measurement values</u>: auto-correlations of $E_x$ & $E_w$ and real and imaginary part of cross-correlation
- $h_x$ and $h_w$ are effective length of antennas (known)
- Matrix **M** represents source-antenna geometry (also known)

Fully calibrated RPWS antenna system with 3 monopole antennas $E_u$, $E_v$, $E_w$ or $E_x$ ($E_u$-$E_v$) dipole. In survey mode antenna pair $E_x$-$E_w$ is often used.

$$d_l = \sqrt{q^2 + u^2} \qquad d_c = v$$

# SED polarization for storms at 35°S




<u>Storm Jan./Feb. 2006:</u>

665 SED pixels

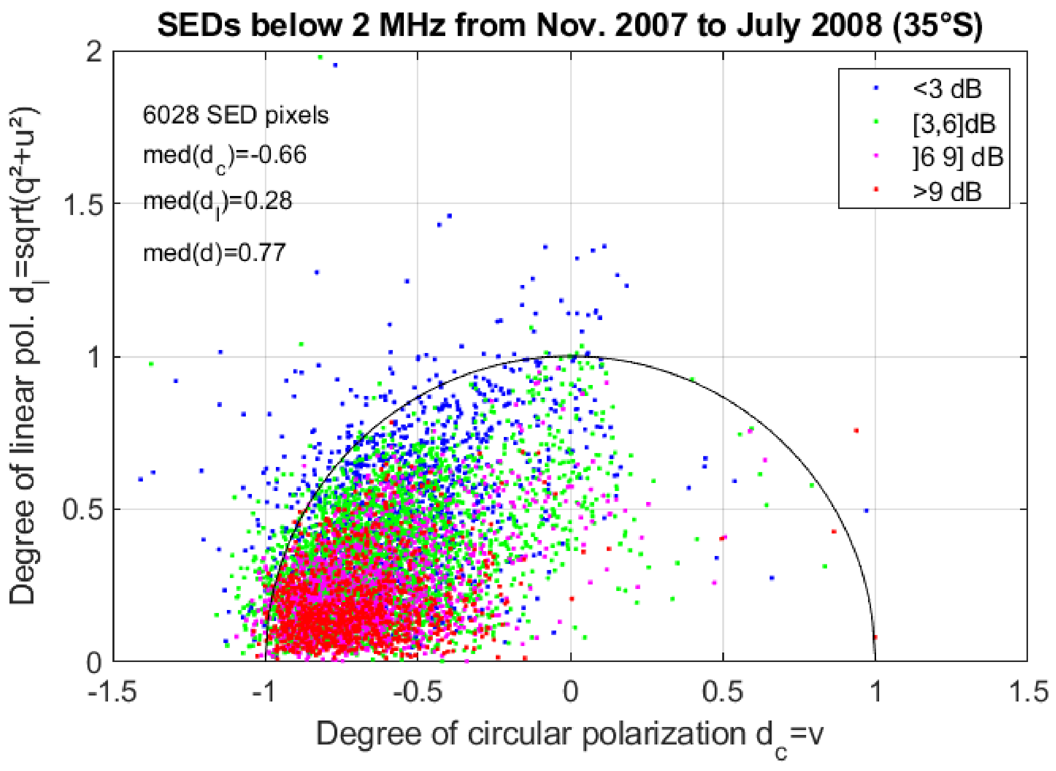
$med(d_c)=-0.73$

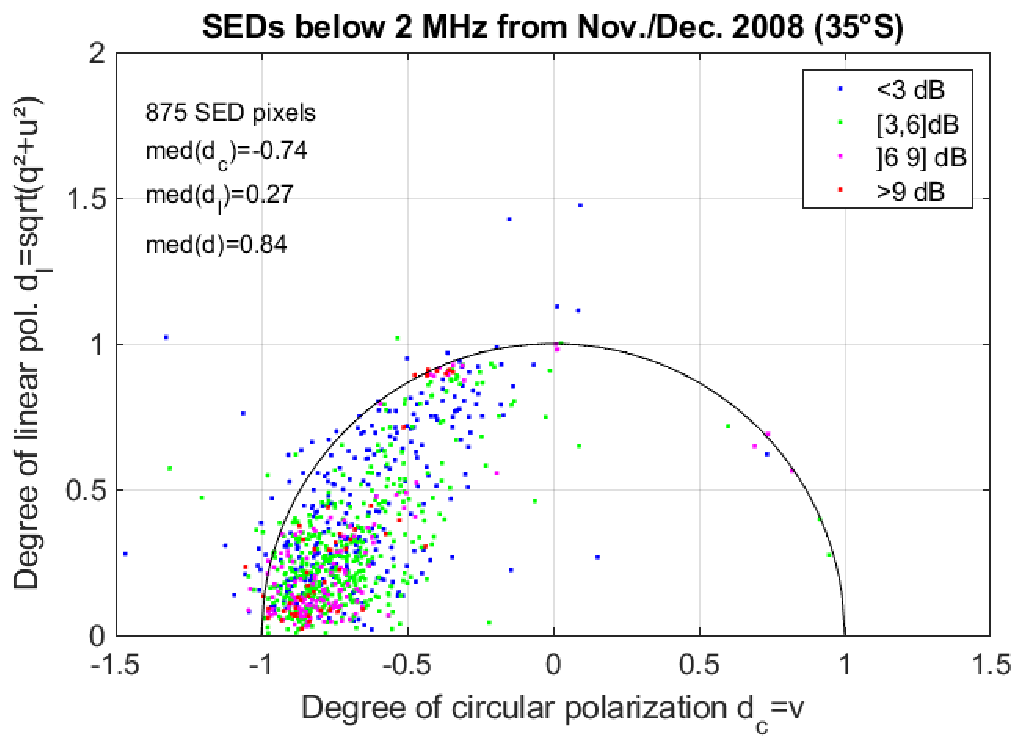
$med(d_l)=0.33$

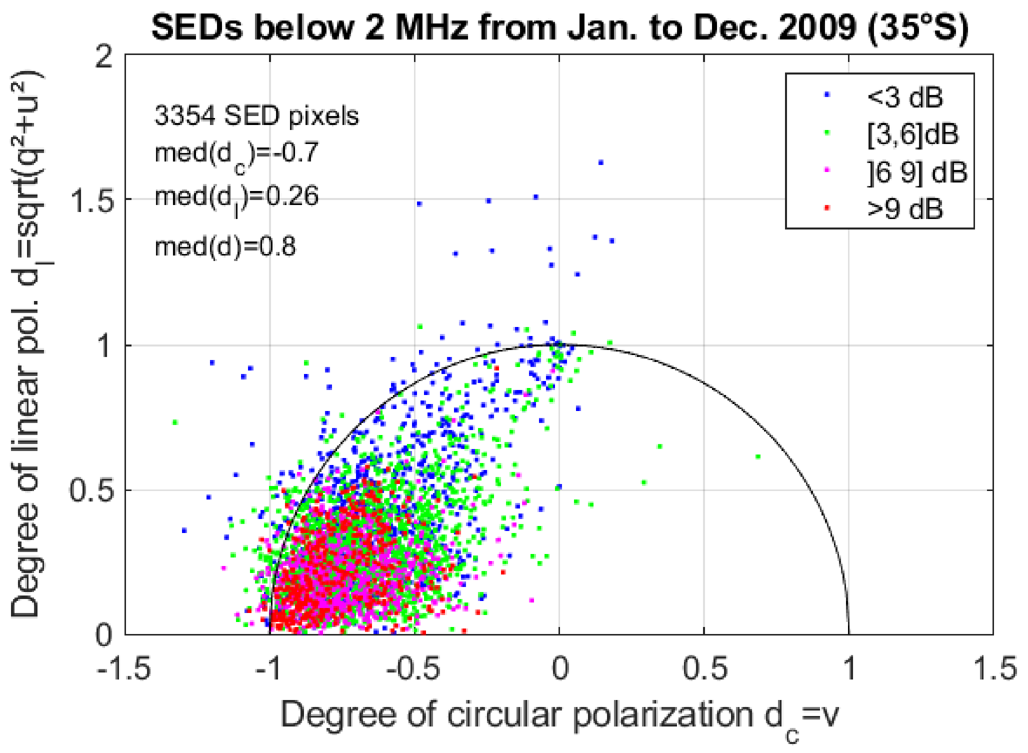
$med(d)=0.83$

[Fischer et al., 2007]

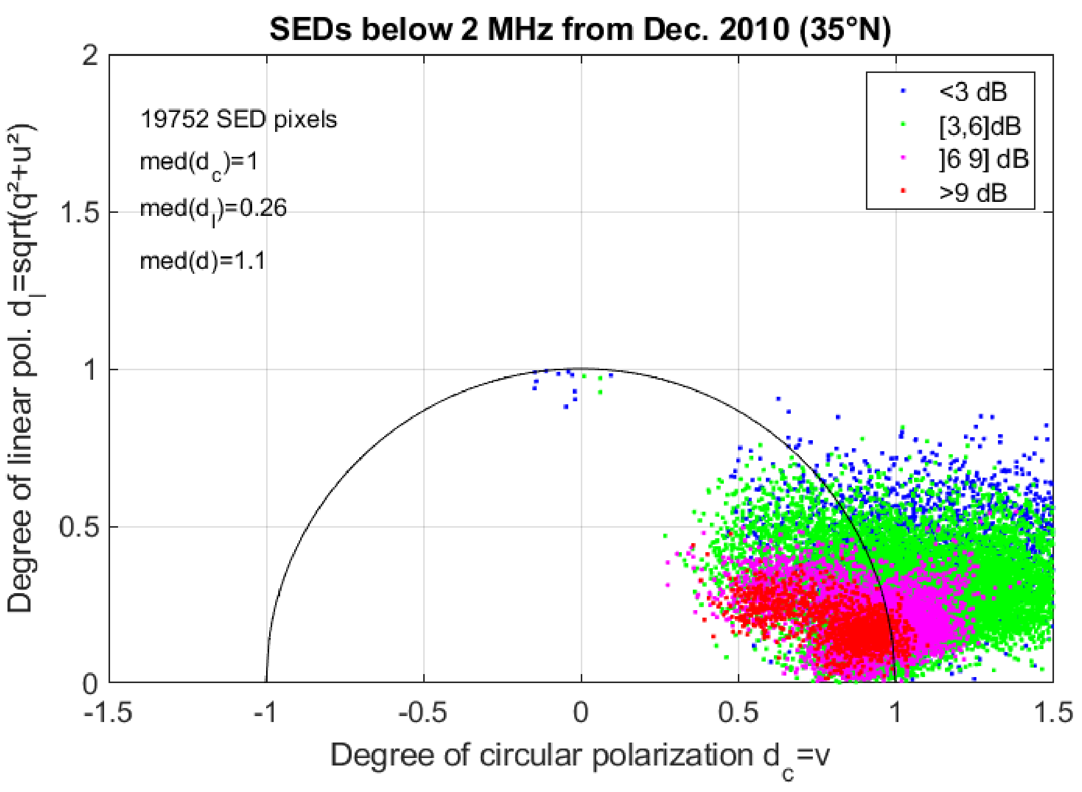
SEDs from southern storms are RH polarized ($d_c<0$)!

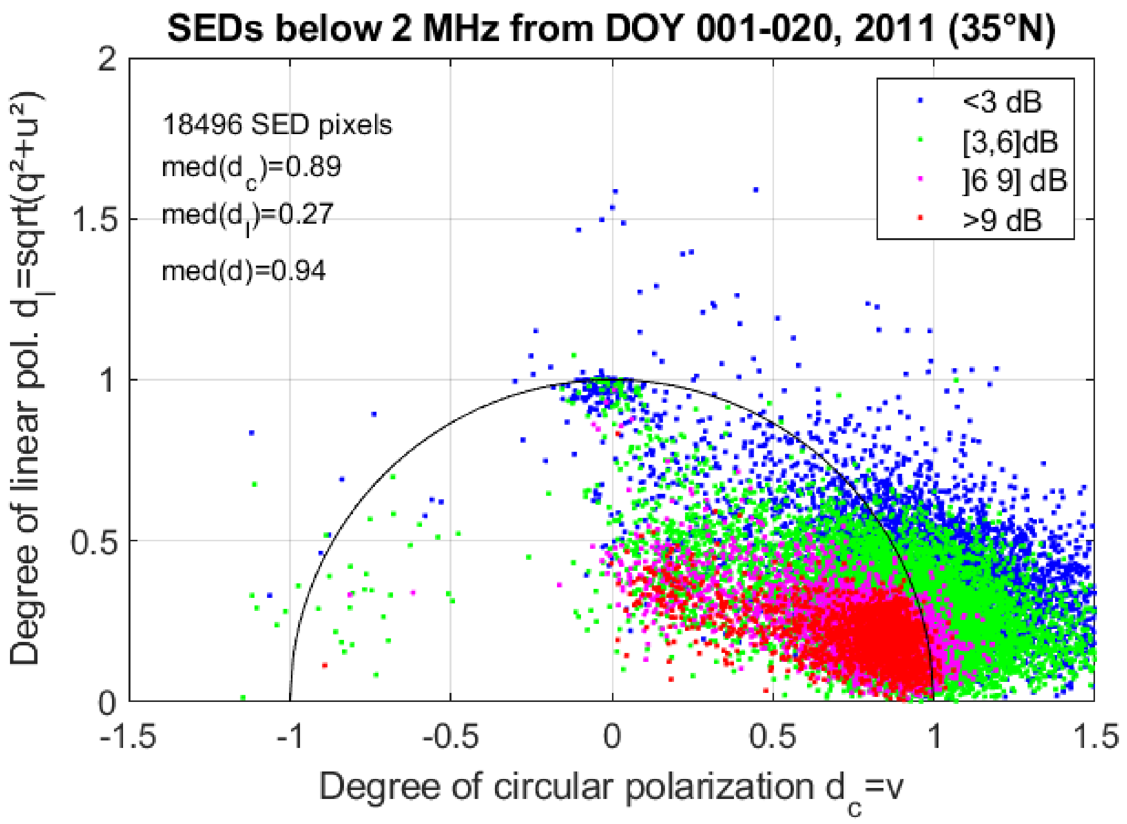


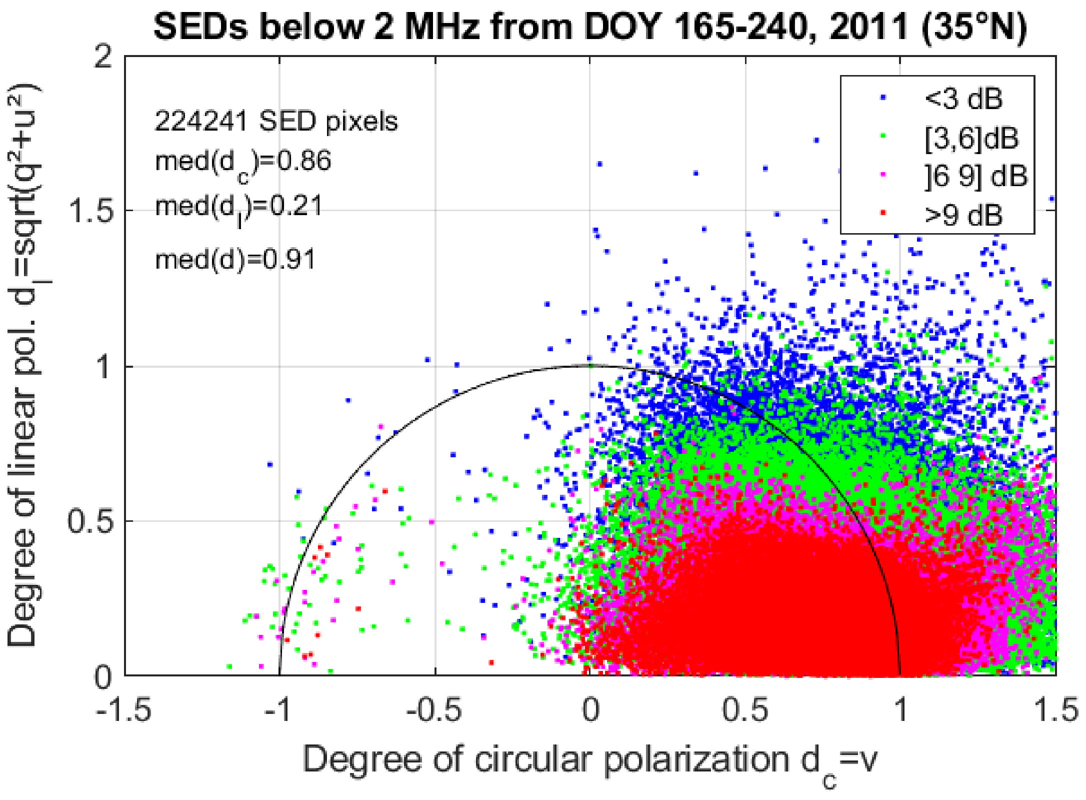



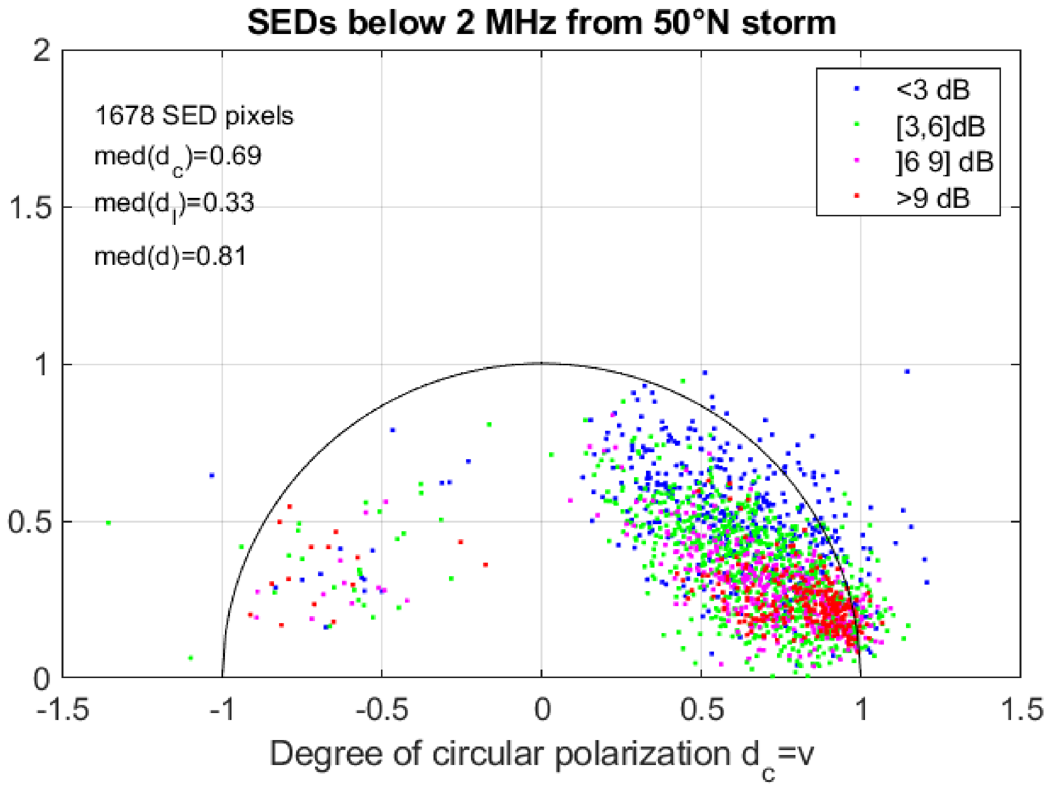



# SED polarization for storms at 35°N and 50°N



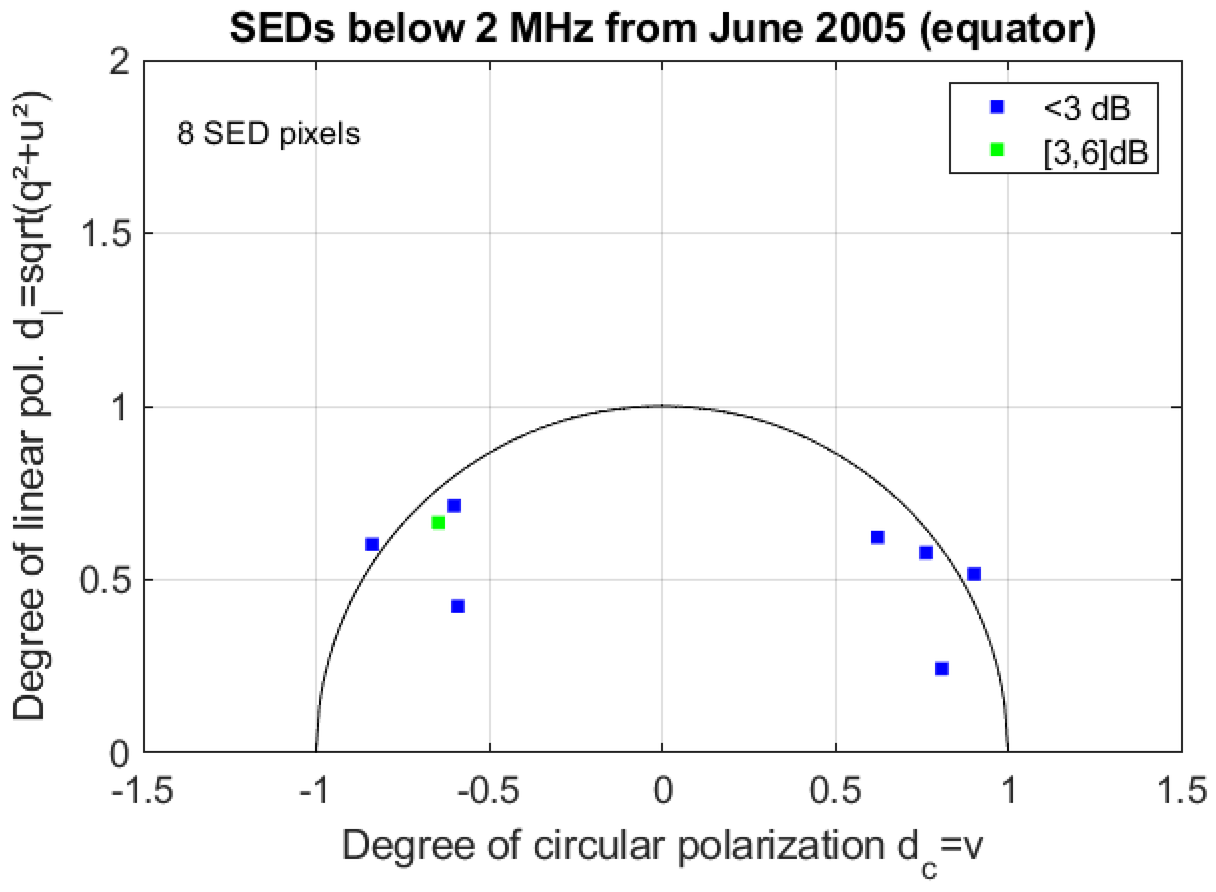



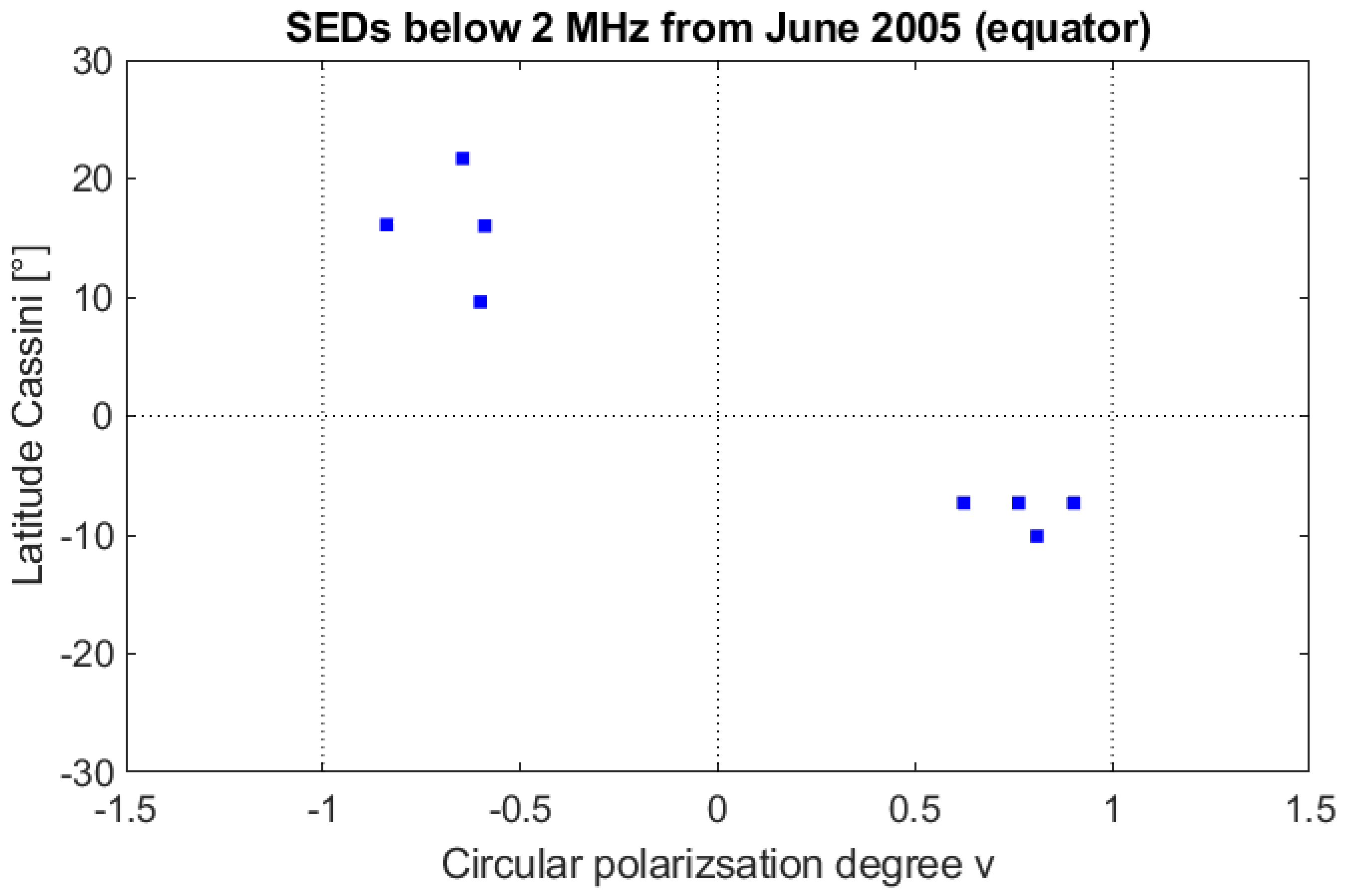




SEDs from northern storms are LH polarized ($d_c>0$)!

Few pixels with RH polarization could be due to contamination by SKR (Saturn Kilometric Radiation) or other emissions

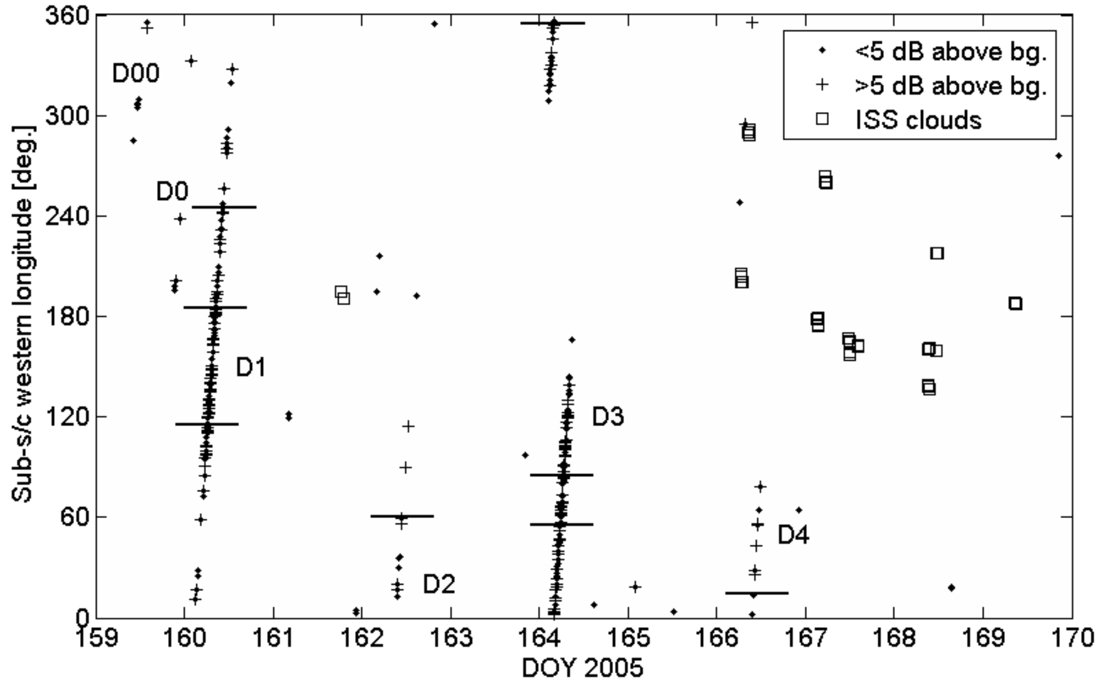
# SED polarization for storm at equator



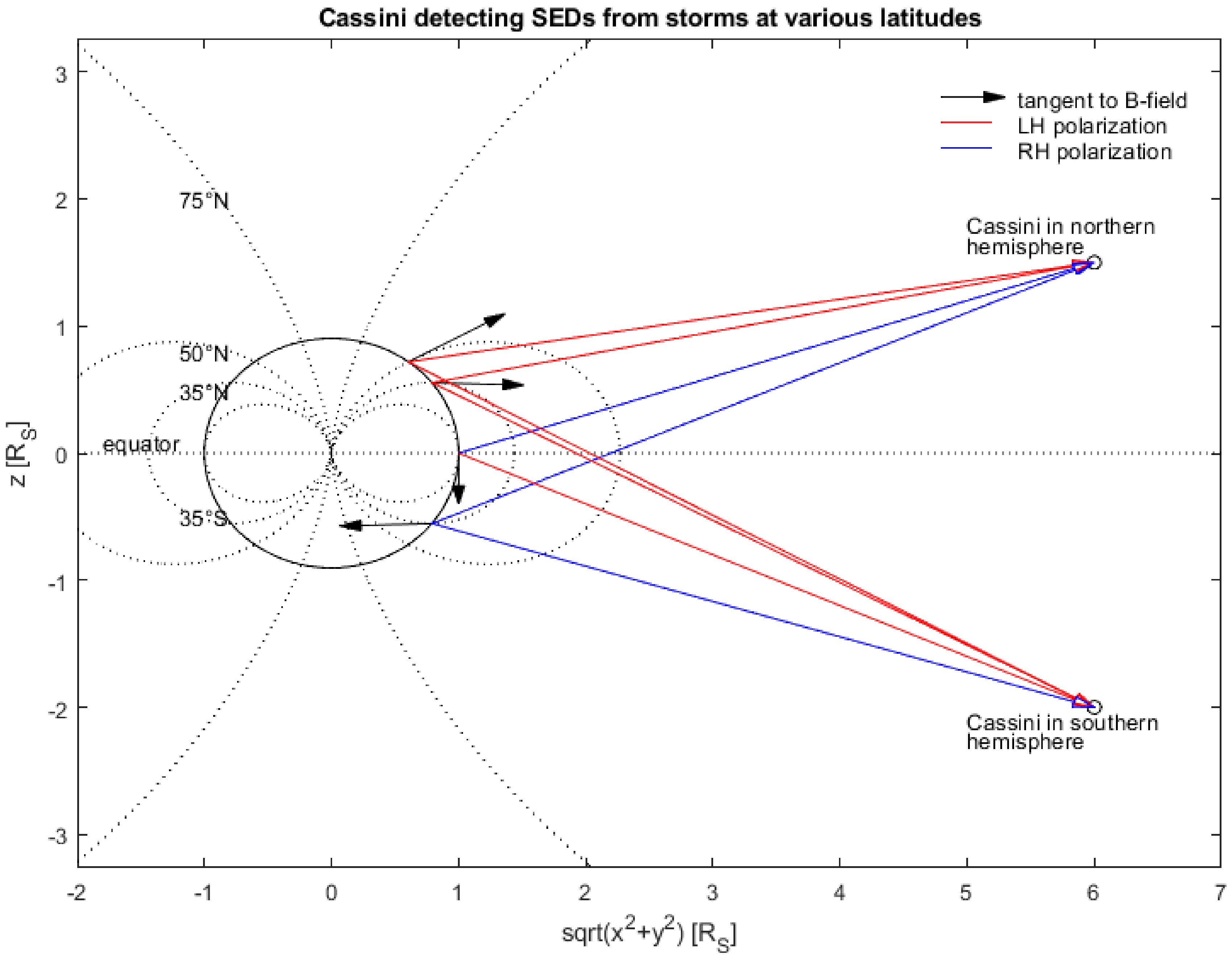




Eastward drift of episodes in longitude w.r.t to Voyager radio period suggests storm at equator, no clear cloud sytem observed visually [Fischer et al., 2007]

- Short storm (about one week) led to only 8 SED pixels, 4 of them are RH (v<0) and 4 of them are LH (v>0).
- RH ones were detected when Cassini was at northern latitudes, and LH ones when Cassini was at southern latitudes

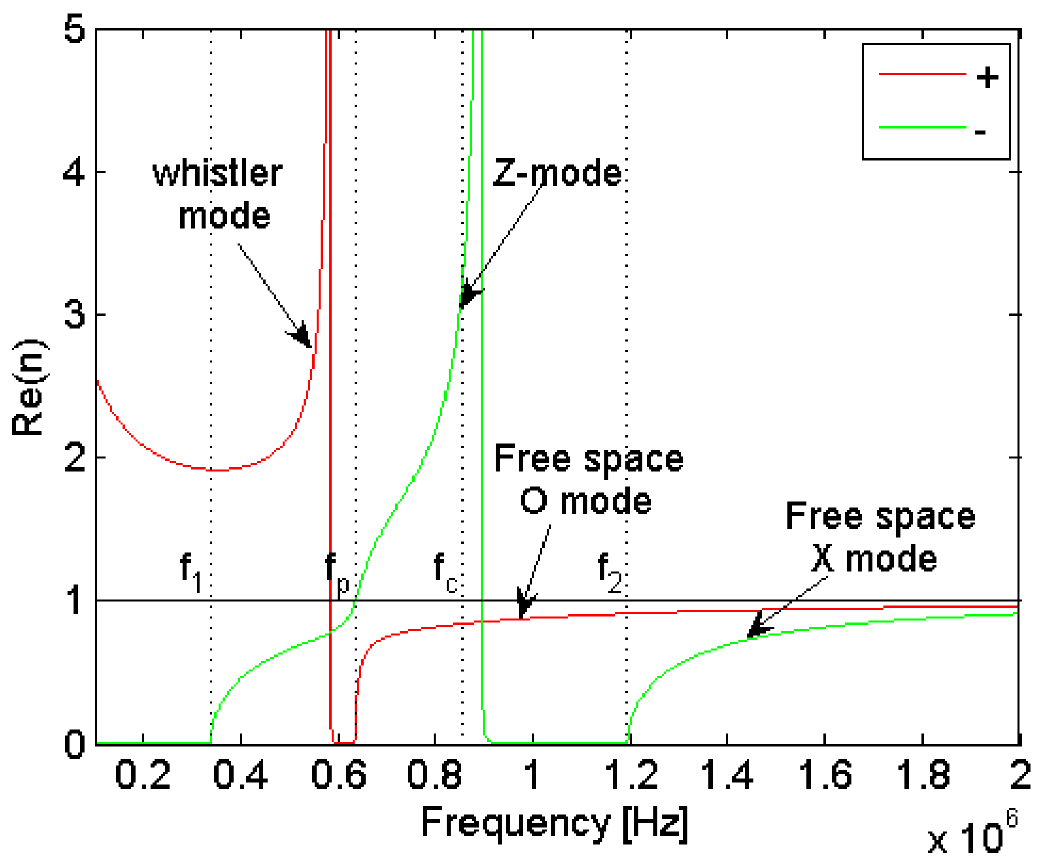


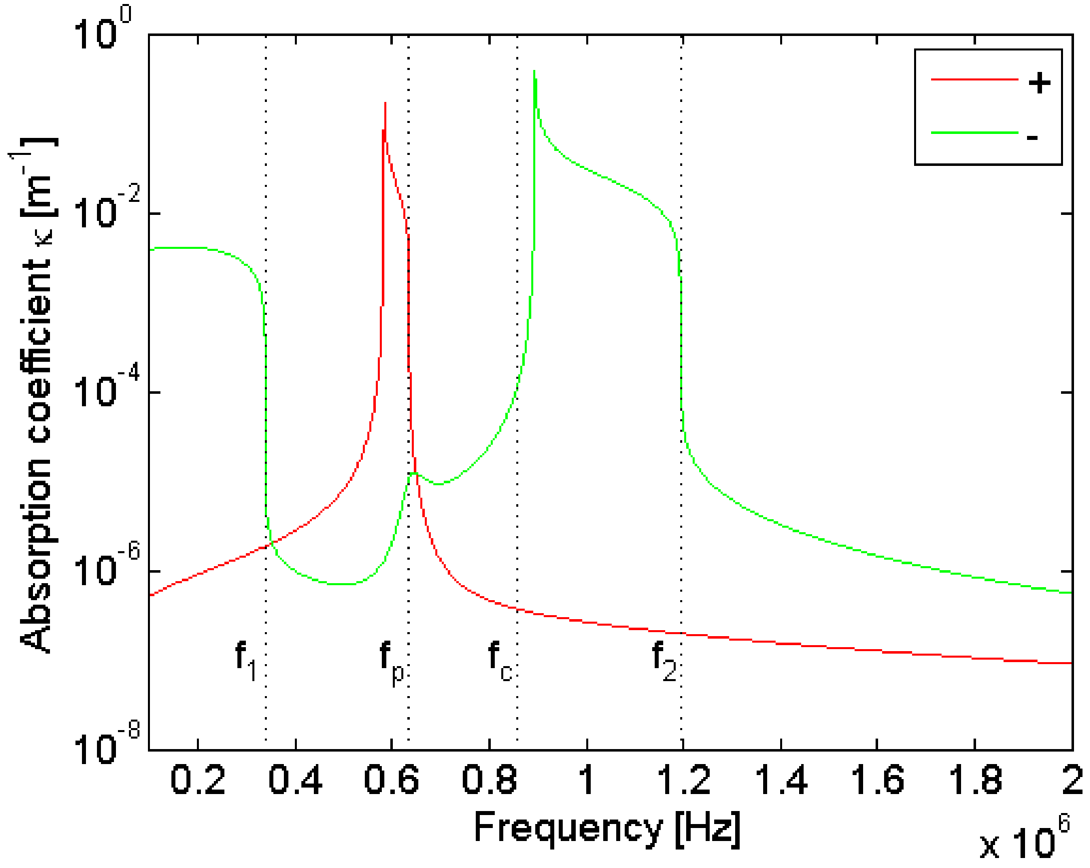
# Dependence of sign of circular polarization on the hemisphere of the storm




- Saturn's axisymmetric magnetic field goes from north to south (field lines drawn at equator, ±35°, ±50°, and ±75°)
- SEDs propagate through magnetoplasma of Saturn's ionosphere
- Modes (L-O, R-X) are defined w.r.t. magnetic field direction **B** in plasma
- L-O mode waves are LH for ∠ (**k**, **B**)<90° and RH for ∠ (**k**, **B**)>90°
- SEDs below 2 MHz appear as L-O mode waves, oppositely polarized to R-X mode Saturn Kilometric Radiation (SKR, at ±75°).
- Where is the R-X mode for SEDs?

# Dispersion relation for typical plasma in Saturn‘s ionosphere



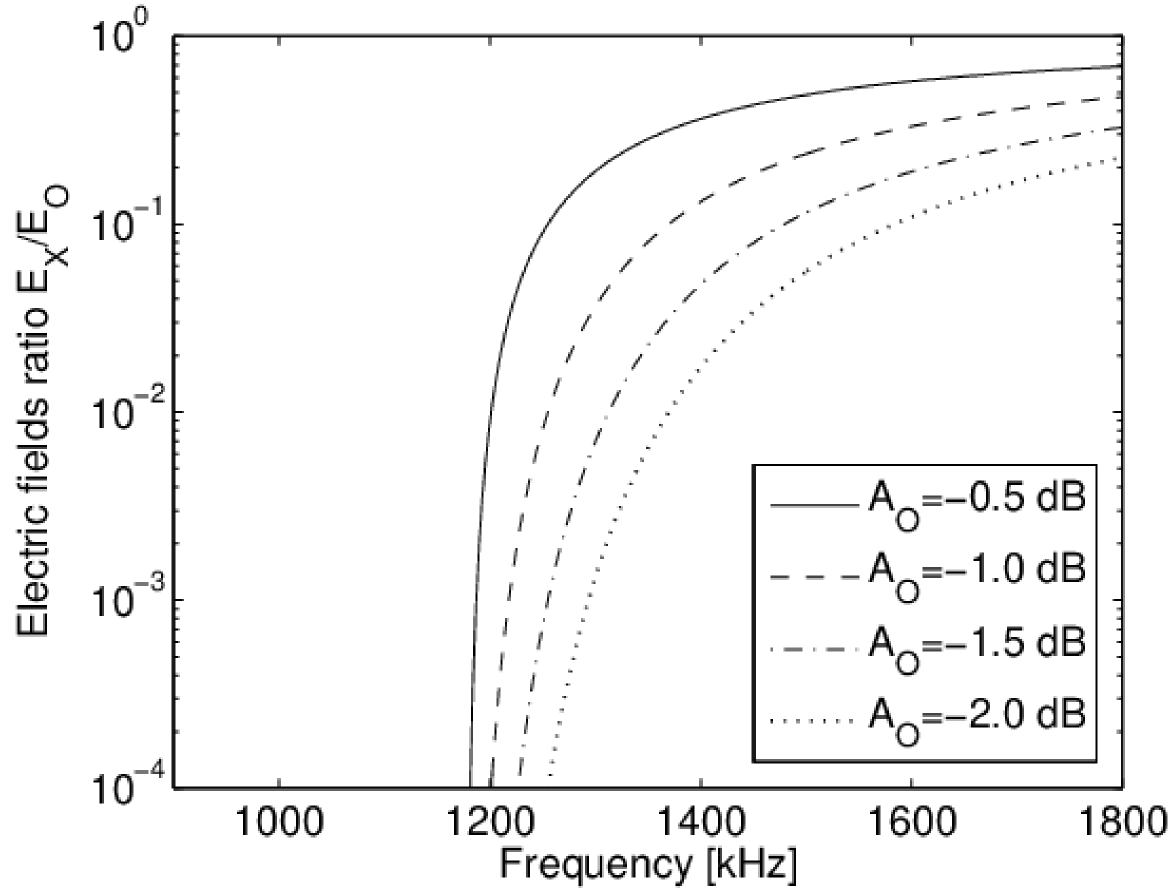



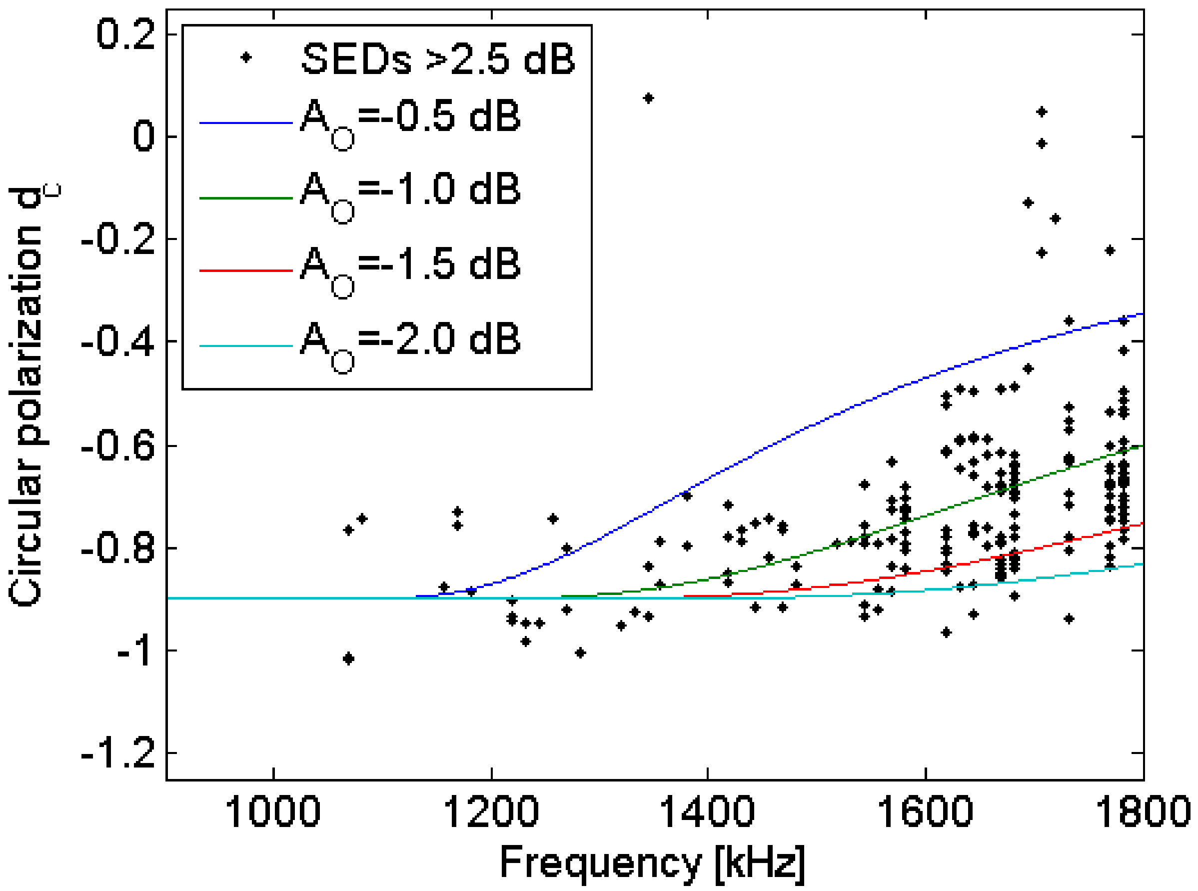

$$n^2 = (\mu - j\chi)^2 = n^2(N, f, f_c, \nu, \theta)$$

Appleton‘s equation for refractive index n with real part $\mu$ and imaginary part $\chi$, the latter related to absorption coefficient $\kappa$

Electron density $N_e$=5000 cm$^{-3}$ or $f_p$=635 kHz (can be retrieved from SED low frequency cutoff!), frequency f is variable, electron cyclotron frequency $f_c$=830 kHz (B=0.3 G), collision frequency $\nu=10^3$ Hz [Zarka, 1985], angle $\theta$ (**k**,**B**)≈160° (storm at 35°S). R-X mode starts at $f_2$=1.2 MHz, and absorption $\kappa$ is still high up to 2 MHz $\rightarrow$ „**differential absorption effect**“ of O and X-mode

# Differential absorption effect



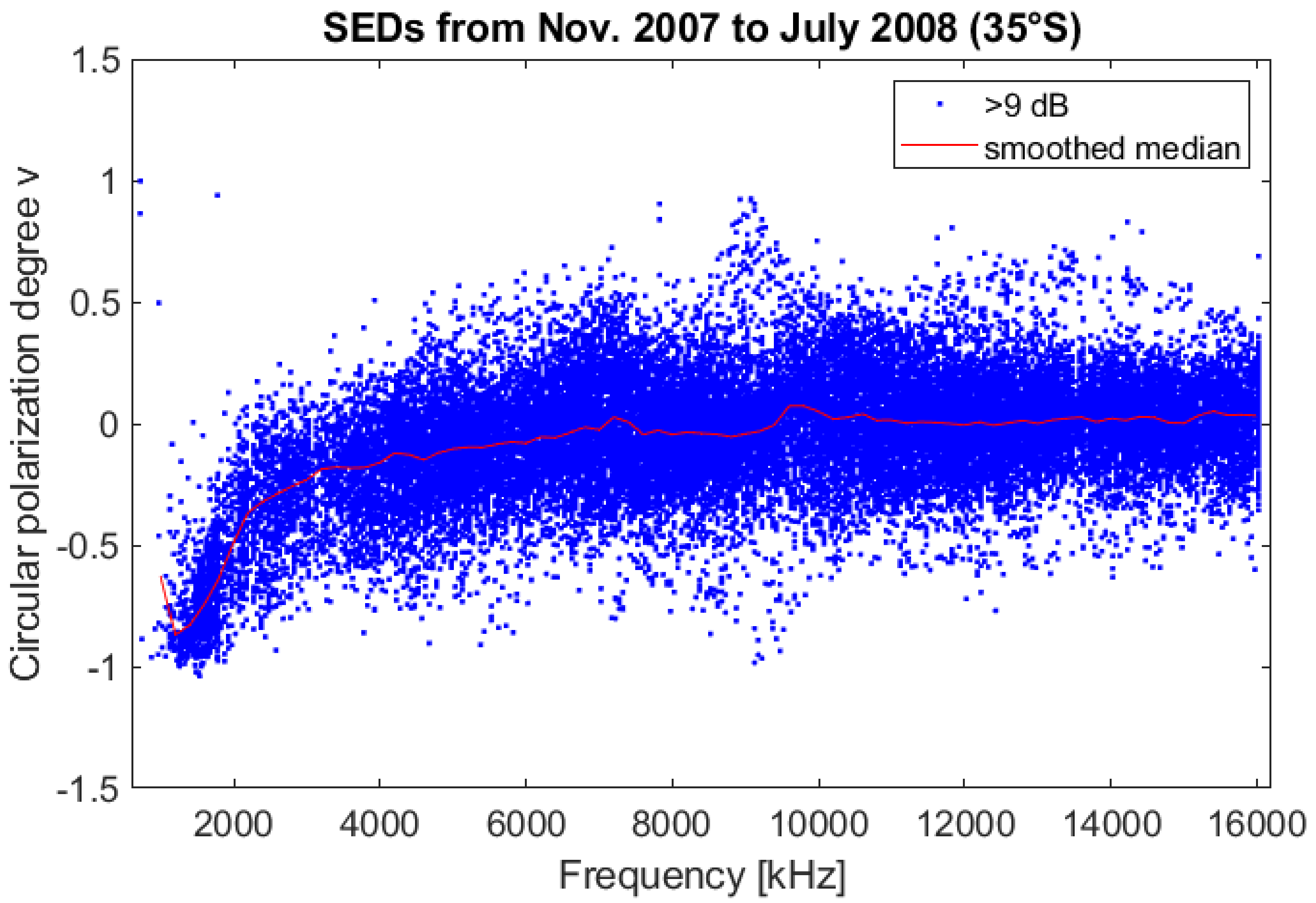

$$\frac{E_X}{E_O} = 10^{\frac{A_O(\frac{\kappa_X}{\kappa_O}-1)}{20}}$$

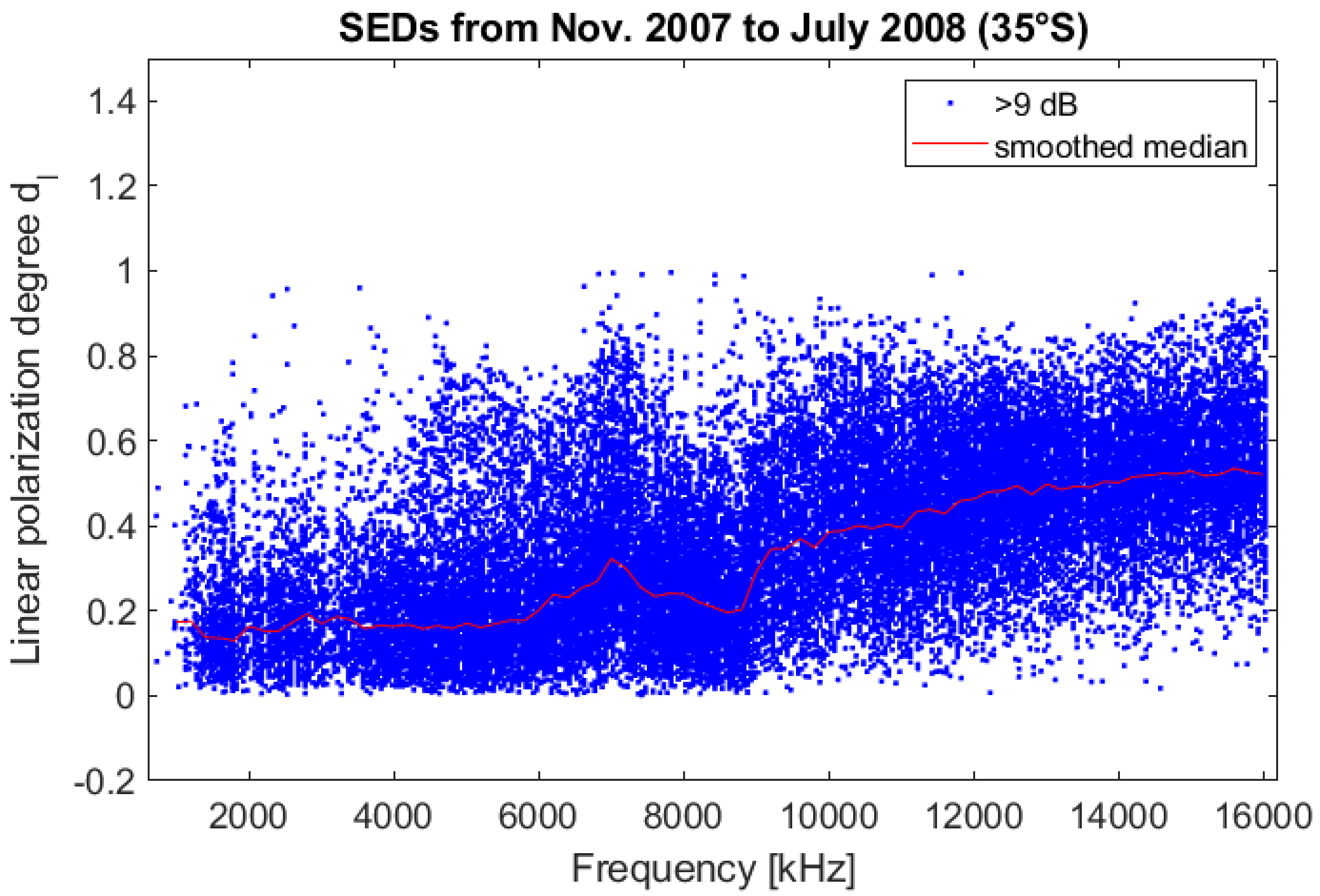
$$f_X = \frac{f_c}{2} + \sqrt{\frac{f_c^2}{4} + f_p^2}$$

$$f_O = -\frac{f_c}{2} + \sqrt{\frac{f_c^2}{4} + f_p^2}$$

- Differential absorption: Ratio of the absorption coefficients of X-mode to O-mode
- Enables the calculation of electric field ratios of X-mode to O-mode (with total absorption $A_O$ of O-mode as parameter)
- X-mode cutoff frequency $f_X$ (here at 1200 kHz) higher than O-mode cutoff $f_O$
- Increasing frequency leads to similar electric field of O-mode and X-mode

# SED polarization at frequencies above 2 MHz




- Circular polarization tends to zero around 7 MHz, linear polarization starts to rise at 9 MHz
- Polarization determination above 2 MHz: tricky since effective length of antennas become complex quantities depending on frequency and wave direction (here: quasi-static values)
- No more circular polarization due to superposition of L-O mode with R-X mode of equal power

# Summary

- Saturn lightning below 2 MHz is highly polarized (~80%) with high degree of circular polarization
- It is right-handed (RH) from a storm in the south and left-handed (LH) from a storm in the north
- Storm at equator (June 2005) showed LH polarization with Cassini at southern latitudes and RH polarization with Cassini at northern latitudes
- This suggests emission in the L-O mode, and the R-X mode is mainly absorbed below 2 MHz („differential absorption effect“)
- Sense of circular polarization below 2 MHz can be used as indicator for hemispherical origin of the Saturn lightning storm (RH from south, LH from north, opposite to „SKR“)
- Circular polarization goes to zero towards ~7 MHz and linear polarization starts to rise, which could be due to superposition of L-O with R-X mode of equal power