Partial polarization and propagation of Saturn Kilometric Radiation (SKR) at low and very low frequencies

Georg Fischer[1], Ulrich Taubenschuss[2], Siyuan Wu[3], David Pisa[2], and Dorian Jost[1]

(1) Institute of Physics, University of Graz, Austria

(2) Institute of Atmospheric Physics, Czech Academy of Sciences, Prague, Czech Republic

(3) School of Physics and Astronomy, University of Southampton, UK

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Introduction: SKR polarization

- SKR is emitted from auroral magnetic field lines by the CMI (Cylotron Maser Instability) mechanism
- R-X mode SKR is mainly right-hand (RH) circularly polarized from the North and left-hand (LH) circularly polarized from the South; SKR can also be elliptic above ±25° in latitude
- Cassini around equatorial latitudes usually sees RH and LH SKR (from N and S), which experience incoherent superposition
- Coherence length L of SKR is usually small compared to Cassini distance, $L=c/(n*\Delta f)$: For c=3e8 m/s, refractive index $n\approx 1$ and bandwidth Δf=1 MHz we have L=300 m, even for Δf=1 kHz (SKR fine structure) it is just L=300 km.
- Incoherent superposition usually leads to depolarization. Stokes vectors have to be added, and we do this for two fully circularly polarized emissions of different sense (no linear component):

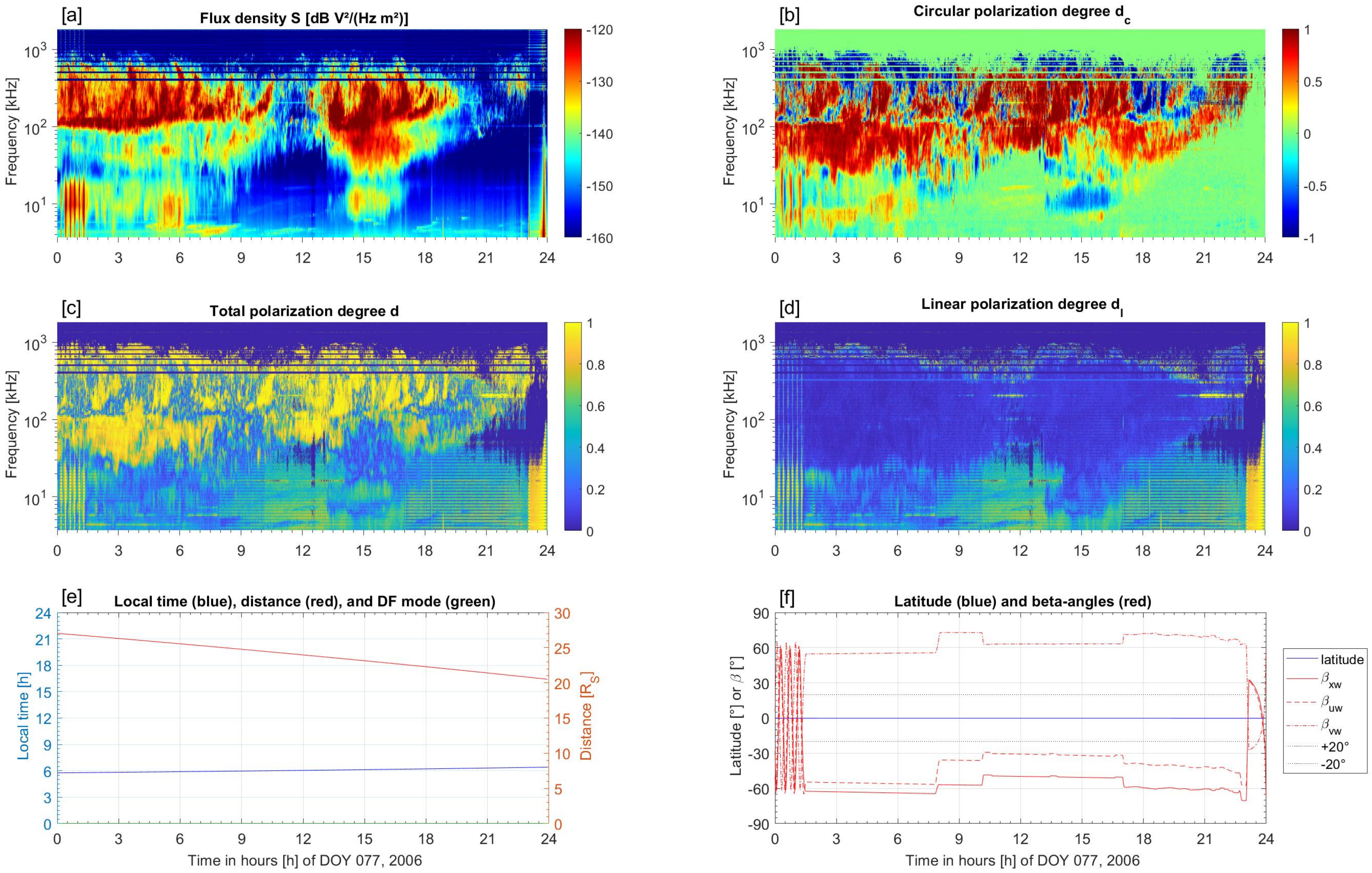
$$S \begin{pmatrix} 1 \\ q \\ u \\ v \end{pmatrix} = S_L \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix} + S_R \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix} = \begin{pmatrix} S_L+S_R \\ 0 \\ 0 \\ S_L-S_R \end{pmatrix}$$

<u>Superposed wave</u>:
Flux $S=S_L+S_R$
$d_c=d_{tot}=(S_L-S_R)/(S_L+S_R)$

$S_L=S_R$ -> $v=d_{tot}=0$ (0 dB or no difference)
$S_L=2*S_R$ -> $v=d_{tot}=1/3=0.33$ (3 dB difference)
$S_L=10*S_R$ -> $v=d_{tot}=9/11=0.81$ (10 dB difference)
$S_L=100*S_R$ -> $v=d_{tot}=99/101=0.98$ (20 dB diff.)

Typical error of RPWS polarization measurement ~10%

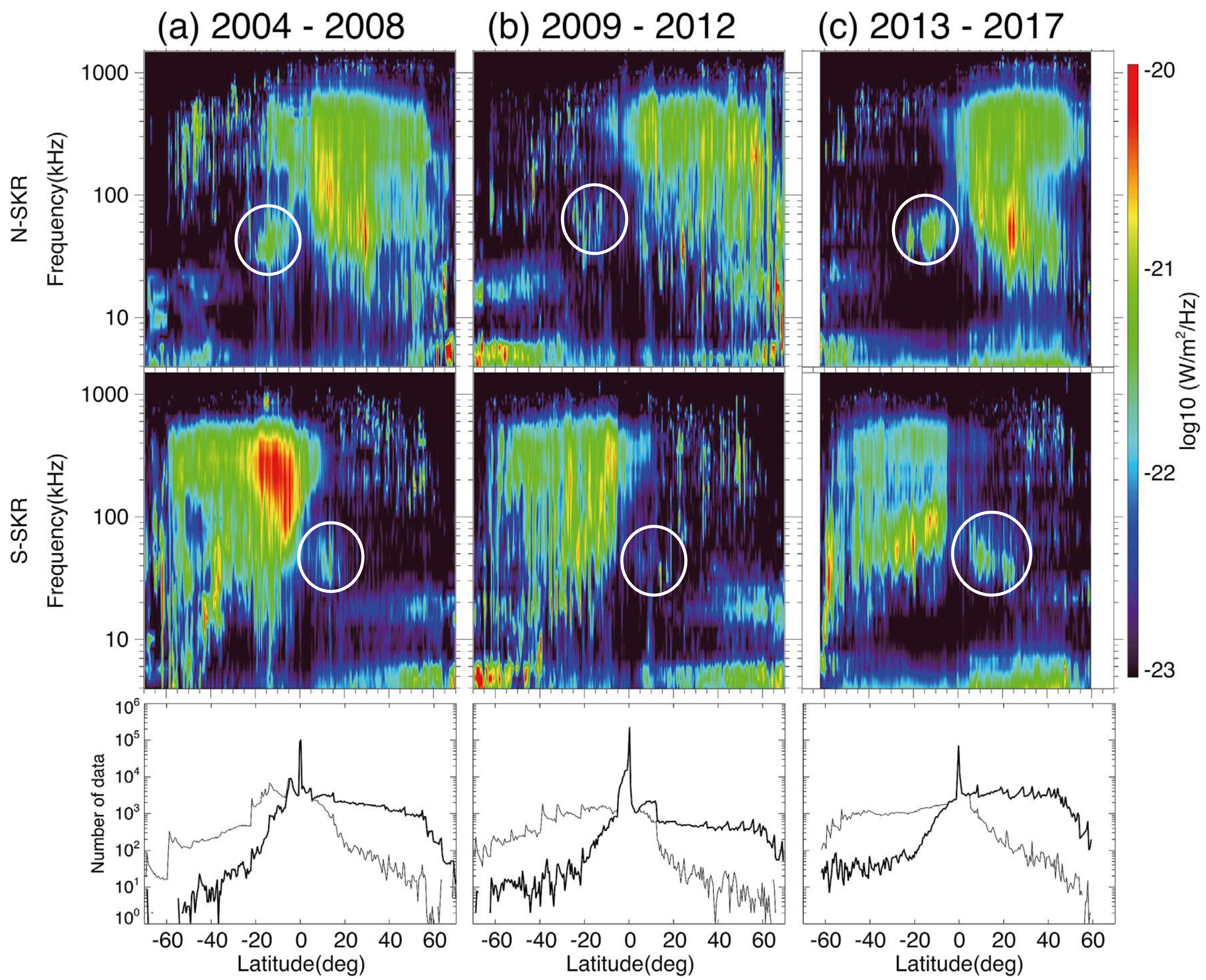
SKR polarization from equatorial latitudes



- SKR flux and polarization data from Meudon-n3d (preset source direction, Saturn's center)
- Cassini orbit (LT, distance, latitude), beta angles
- SKR incoherent superposition leads to depolarization
- SKR flux and total polarization look different above and below 100 kHz
- d_{tot}=0.8 below 100 kHz is a common SKR feature!
- SKR, caterpillar SKR, 5 kHz narrowband emissions

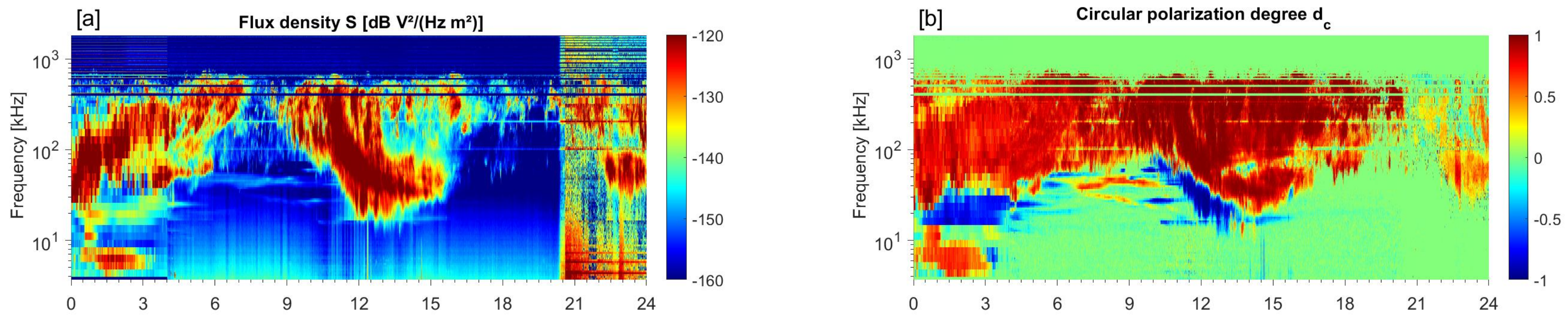
SKR visibility and L-O mode waves

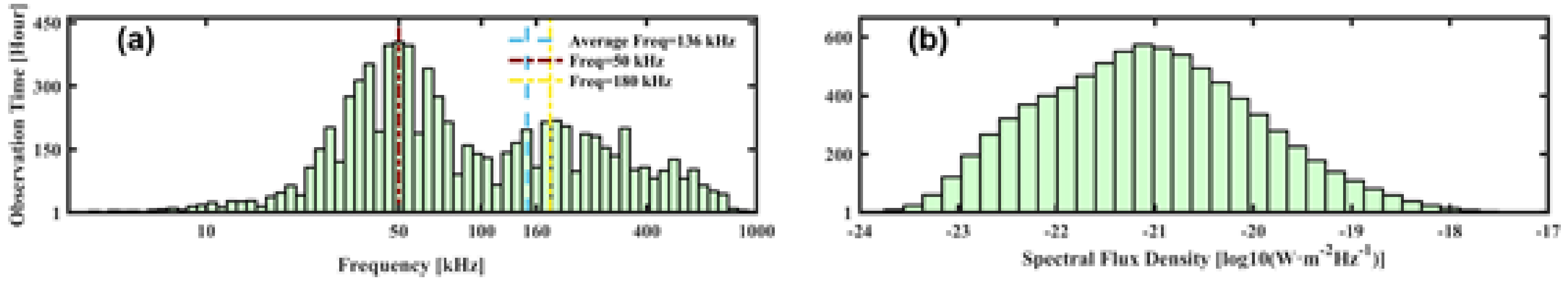
SKR north down to ~20°S, SKR south up to ~20°N -> mixed SKR polarization within ±20° latitude
White circles could be L-O mode waves



[Nakamura et al., 2019]

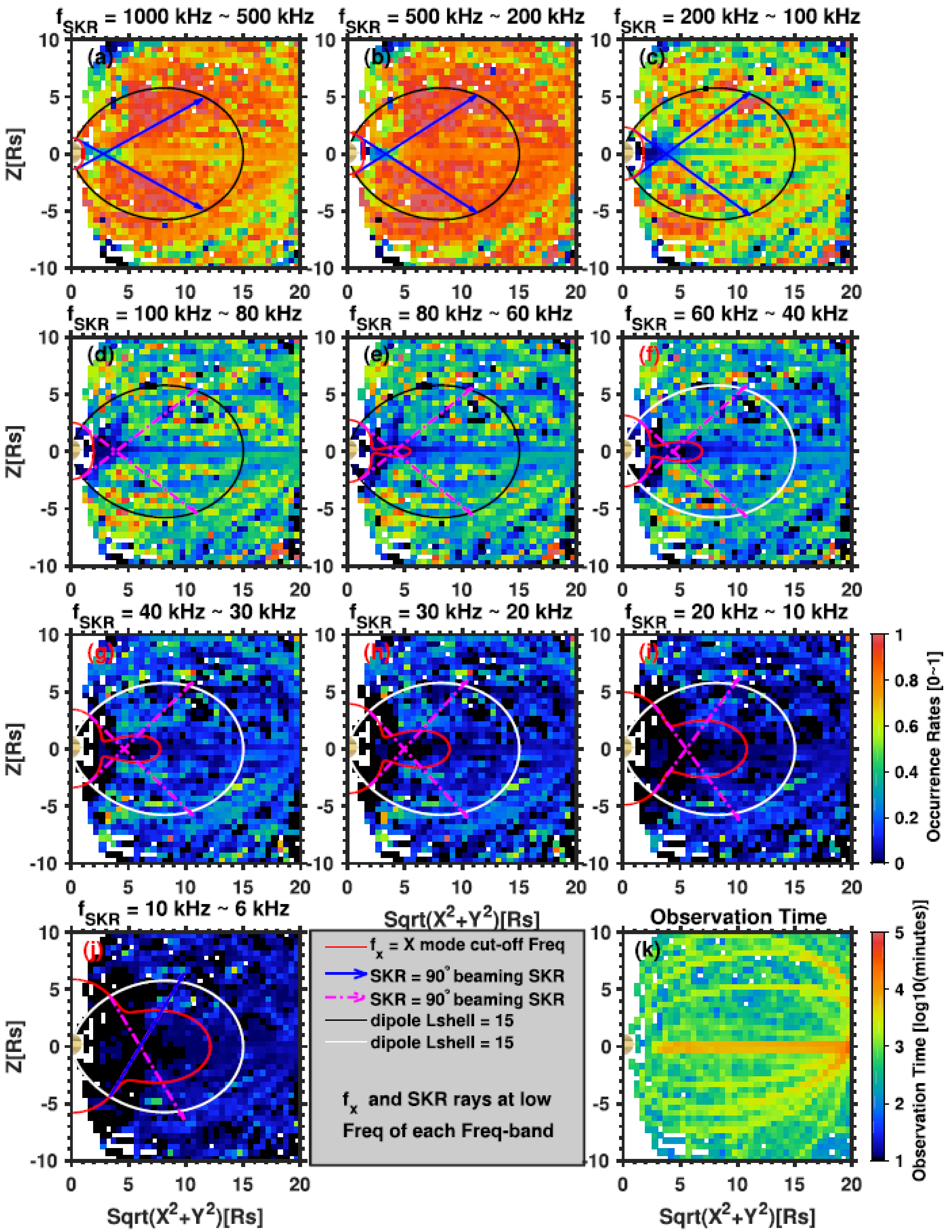
- L-O mode is RH from South and LH from North (opposite to R-X mode)
- L-O mode waves often seen at low frequencies at high s/c latitudes (most common around 50 kHz)
- their spectral flux (normalized to 1 AU) ranges over 5 orders of magnitude around 10^{-21} W/(m²Hz)
- Similar to flux of R-X mode SKR, only 1% level is larger by two orders of magnitude





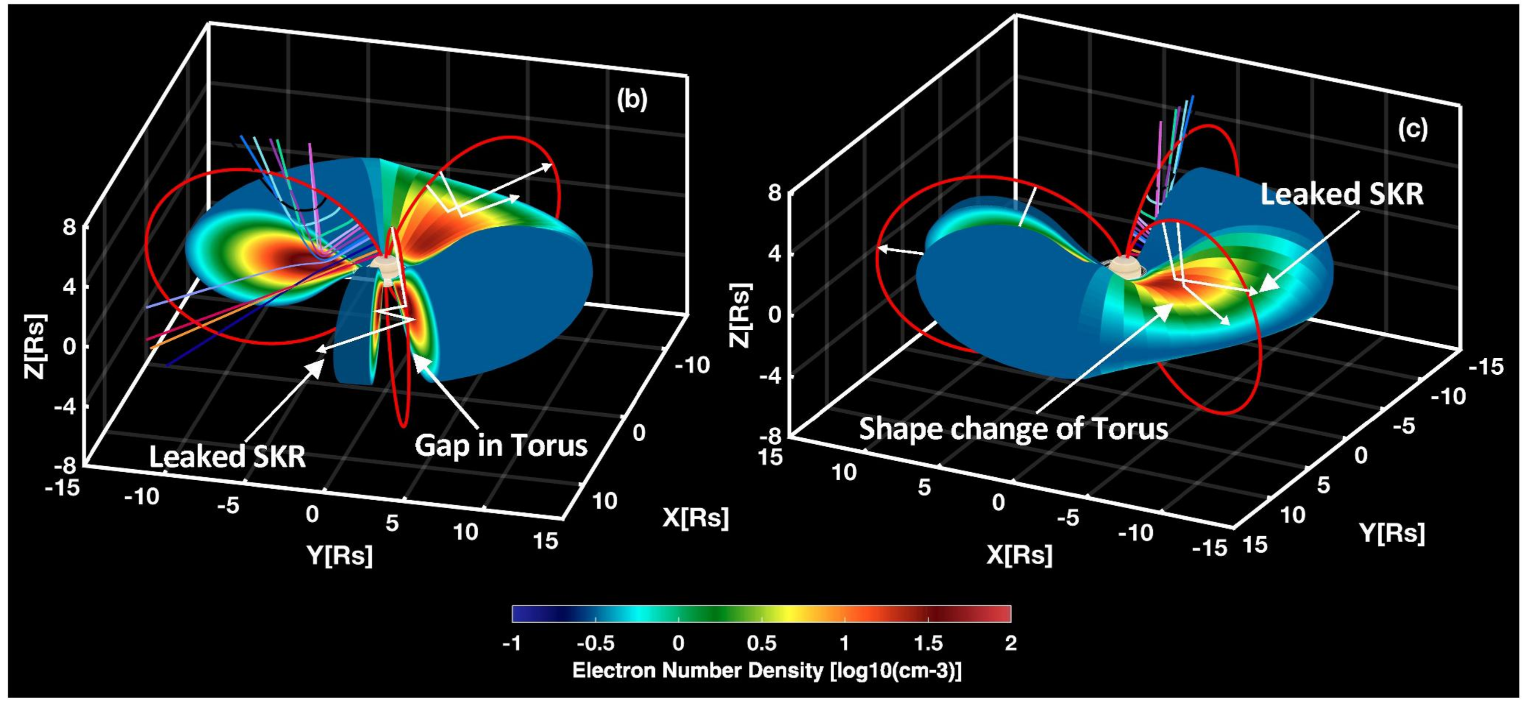
[Pan et al., 2025, GRL, submitted]

SKR extended equatorial shadow zone and torus

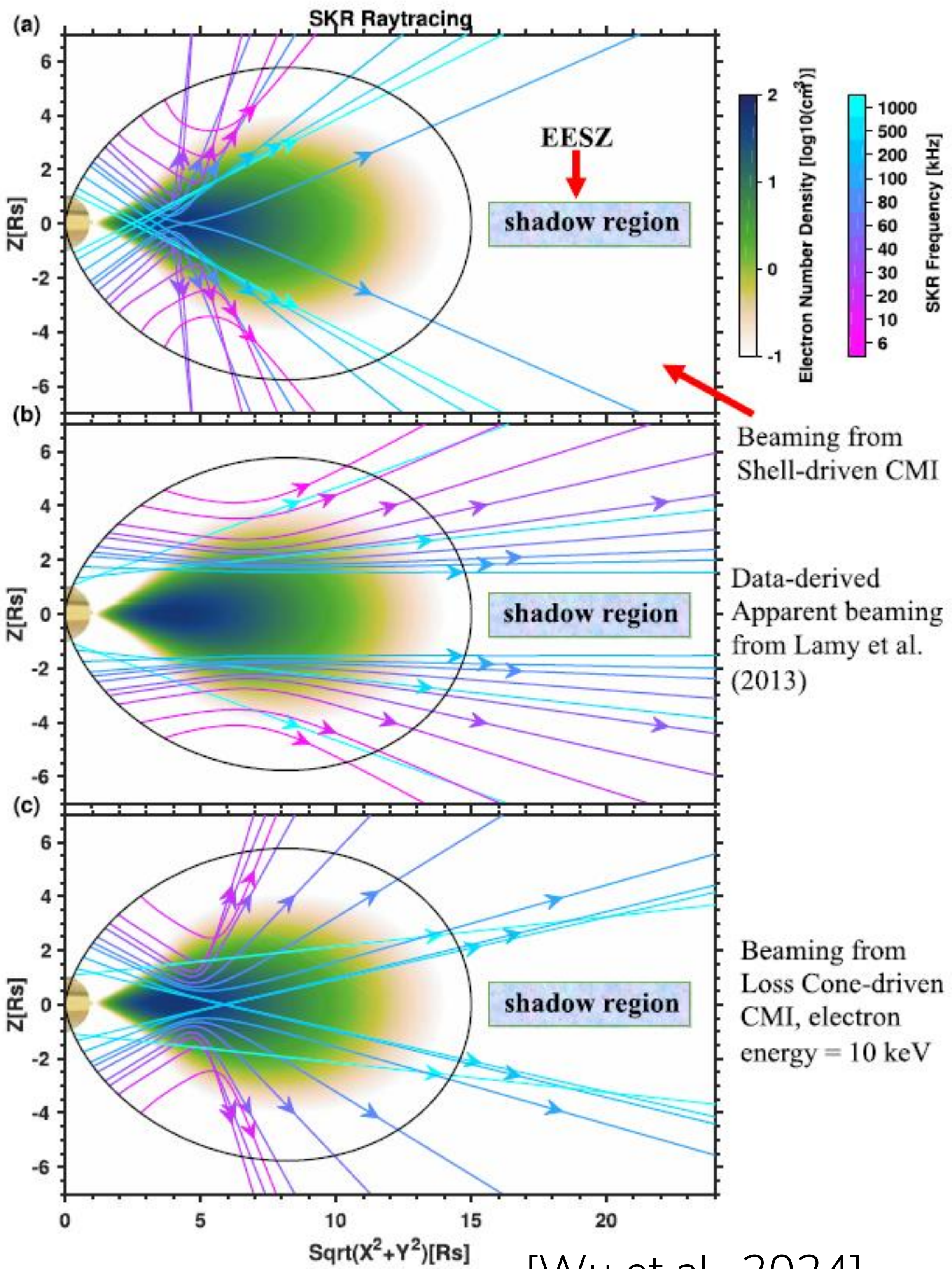


- SKR above 100 kHz has only small equatorial shadow zone due to beaming (up to Enceladus orbit), usually fully polarized, very common
- SKR from 40-100 kHz starts to have a more extended equatorial shadow zone out to 20 R_S, typical polarization of 0.8, lower occurrence
- SKR below 40 kHz is even less common, has a broader shadow zone, and usually a low polarization (region of “caterpillar” SKR)
- Beaming of SKR to low latitudes might be explained by torus leakage, SKR magnetosheath reflection like for 5 kHz narrowband emissions is rather unlikely due to too low electron density in sheath

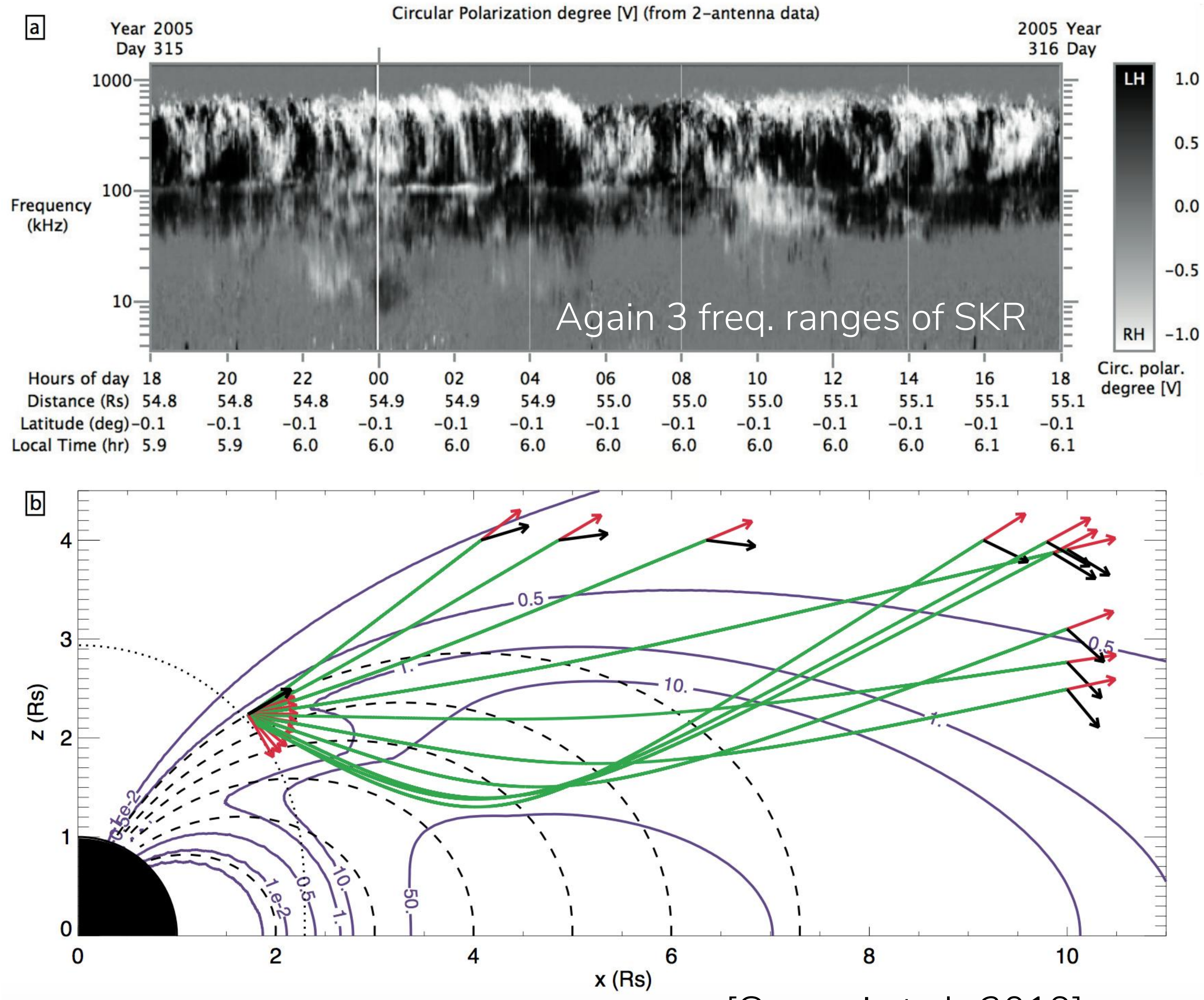
[Figures from Wu et al., 2024]



Ray-tracing of SKR around plasma torus

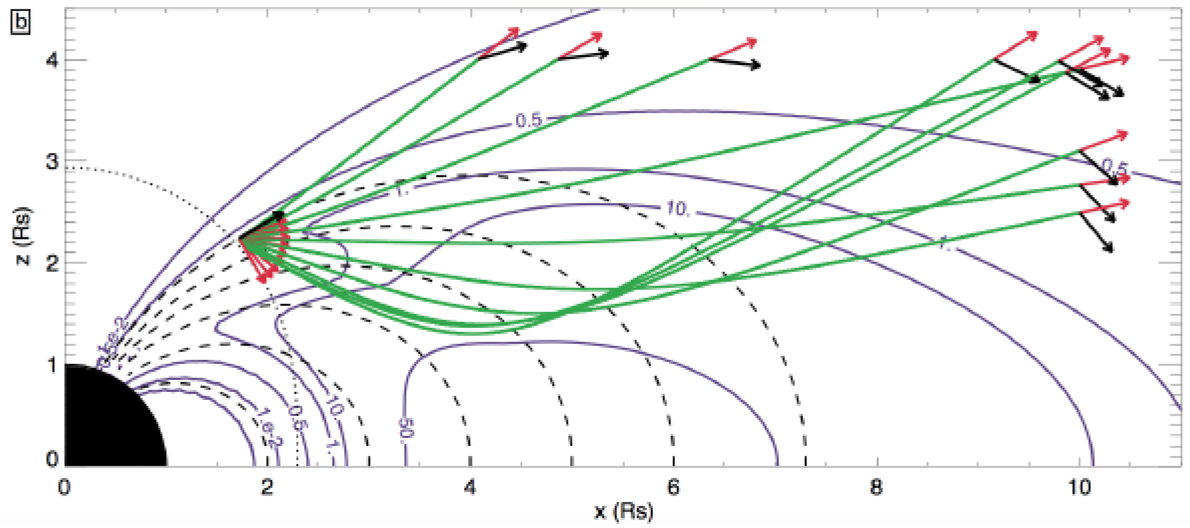


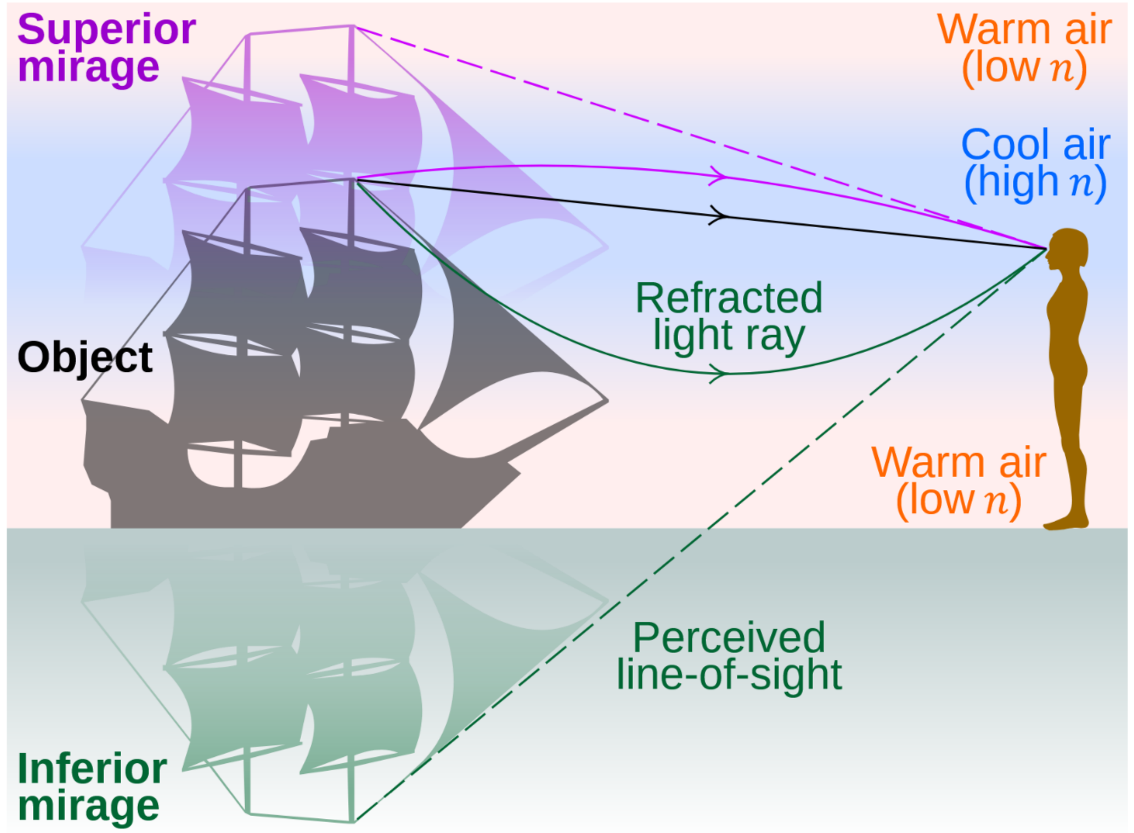
[Wu et al., 2024]



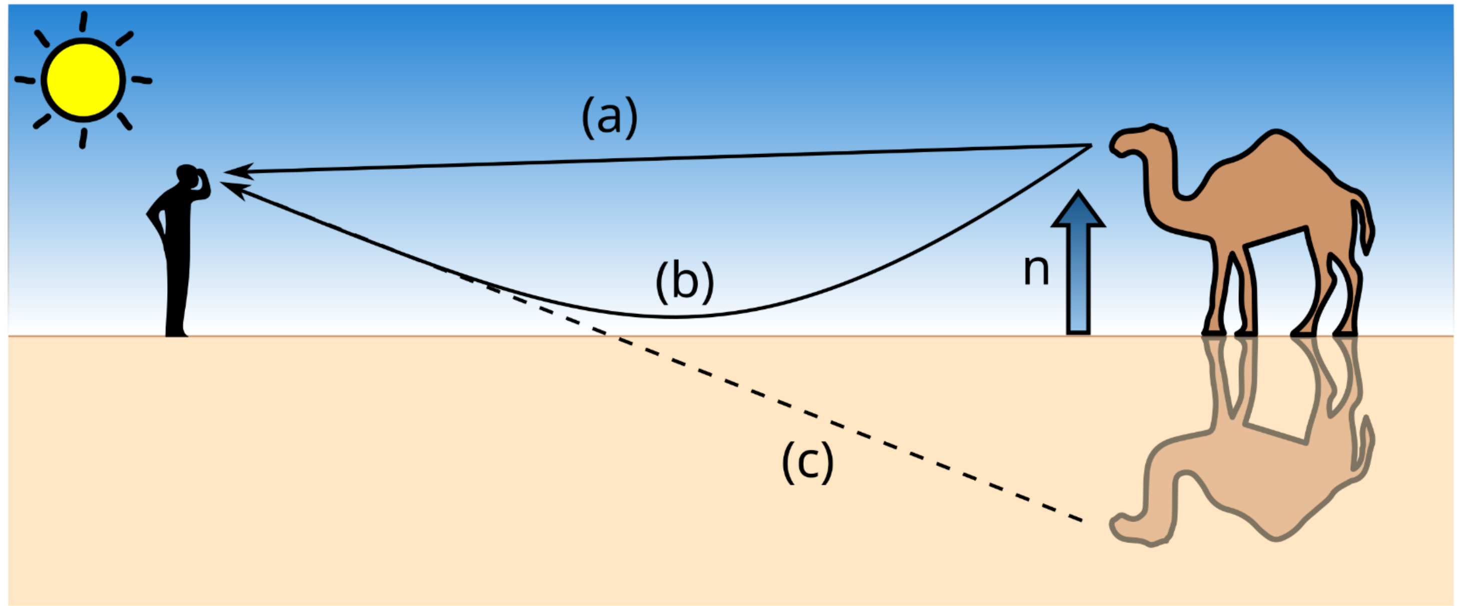
[Cecconi et al., 2019]

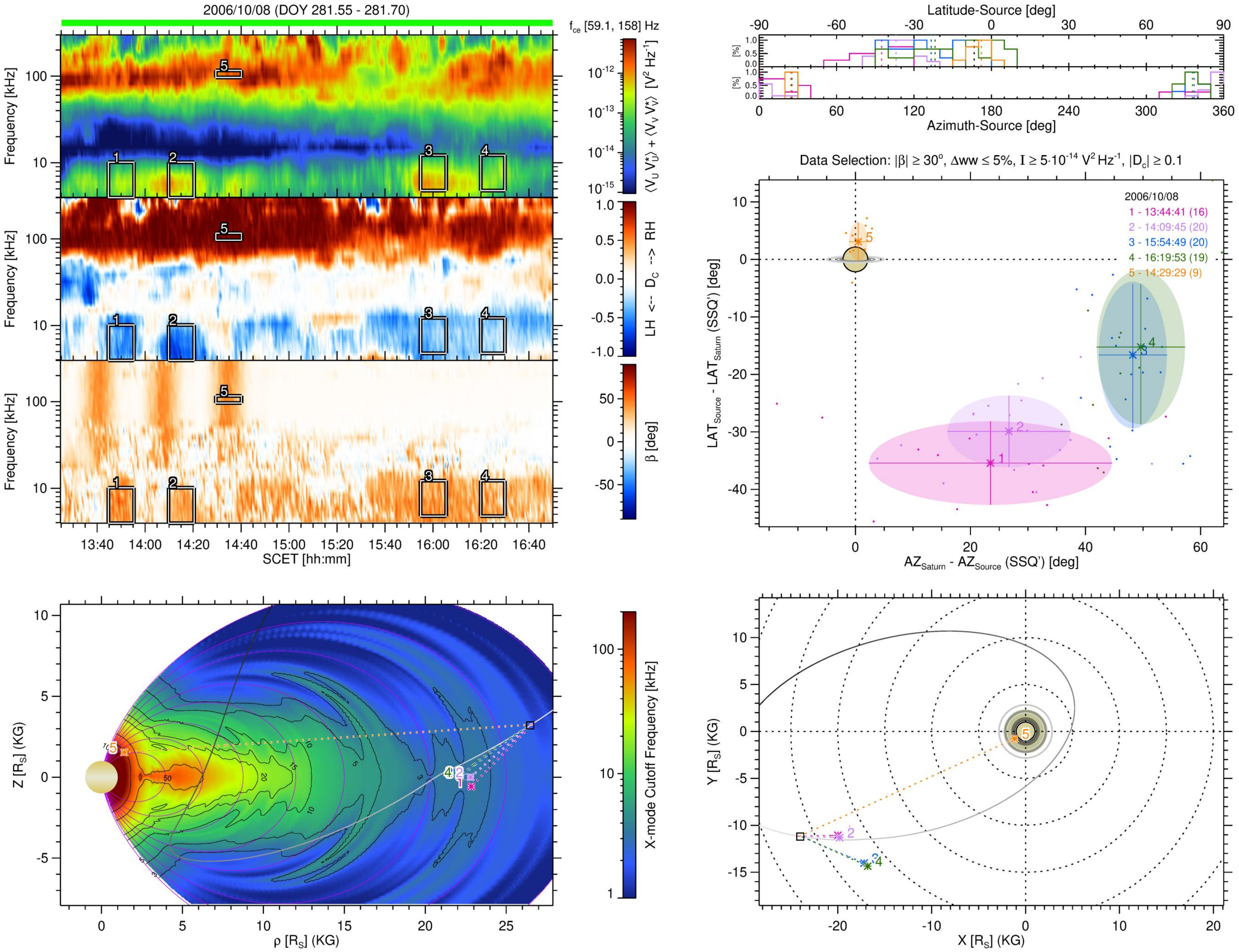
Assume we could see the radio waves: "Inferior mirage" image of SKR





- Mirage images can be seen at Earth in a desert or at the sea under special conditions
- Direct ray through n≈1 region (magnetosphere of Saturn, no plasma). Cool air at Earth: n=1.0003
- Refracted ray through n<1 region (plasma torus at Saturn). Hot air close to surface at Earth: n=1.0002
- Refractive index of plasma $n^2 \approx 1 - f_{pe}^2/f^2$ (without **B**) or precise Appleton-Hartree equation





Direction-finding for SKR at low frequencies:

Example:
$d_{tot}=0.6$
$S_{pol}=0.6*S_{tot}$
$S_{rand}=0.4*S_{tot}\equiv S_{noise}$

Interpret unpolarized part as background noise!

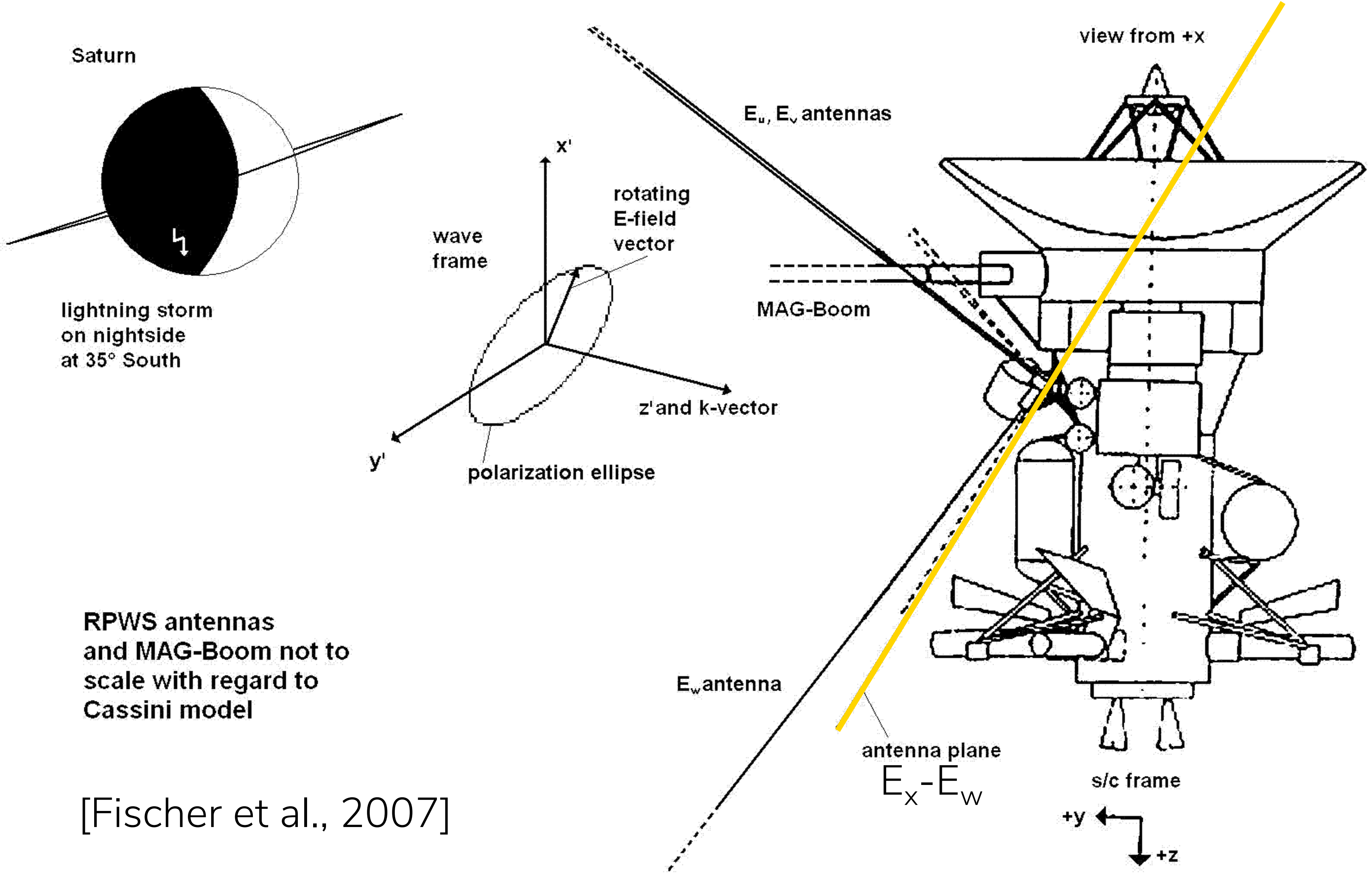
SNR=0.6/0.4=3/2≡1.8 dB
DF does not work for such a low SNR

Might be possible for d_{tot}=0.9, SNR=13 dB

Summary: SKR depolarization

- SKR total polarization around 0.8 is quite common below 100 kHz, even less pol. below ~40 kHz
- Depolarization could be due to Enceladus plasma torus in which $f_{pe,max} \approx 100$ kHz
- Incoherent superposition of R-X mode SKR from North (RH) and South (LH) leads to depolarization (addition of Stokes vectors and not electric field vectors) with Cassini around equatorial plane
- Incoherent superposition of R-X mode SKR with L-O mode SKR from the same hemisphere can also lead to depolarization. However, if L-O mode is 15 dB (and more) less intense than the R-X mode, one would not recognize and the R-X mode would remain fully polarized
- Depolarization of SKR below 100 kHz could be due to L-O mode waves or another not yet identified mechanism in the Enceladus plasma torus (**k** rather parallel to **B**, not close to 90°)
- Direction-finding (DF) of depolarized SKR impossible when unpolarized part is viewed as noise
- n3d-spectra could be made available for the public throughout Cassini Saturn tour (2004-2017)

Appendix: How to measure SKR polarization



[Fischer et al., 2007]

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

- 4 equations with 4 unknowns: S (intensity), q, u, v (normalized Stokes parameters)
- 4 measurement values: 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.

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