RADAR ECHO TELESCOPE

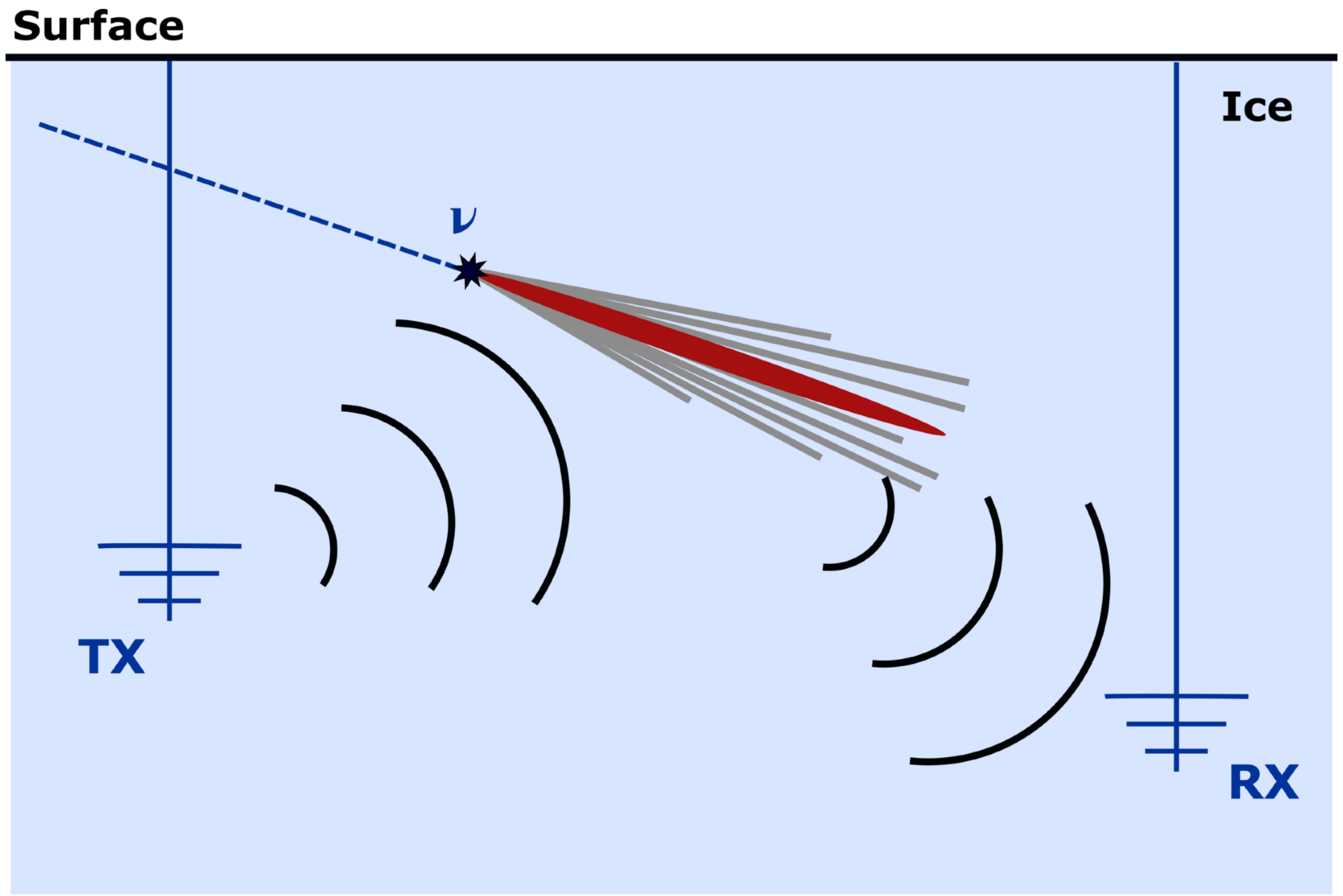
Explaining signal Properties in the Context of Reconstruction Methods for the Radar Echo Telescope for Neutrinos

Jannes Loonen

fwo VUB VRIJE UNIVERSITEIT BRUSSEL iihe BRUXELLES BRUSSEL NSF erc European Research Council Established by the European Commission

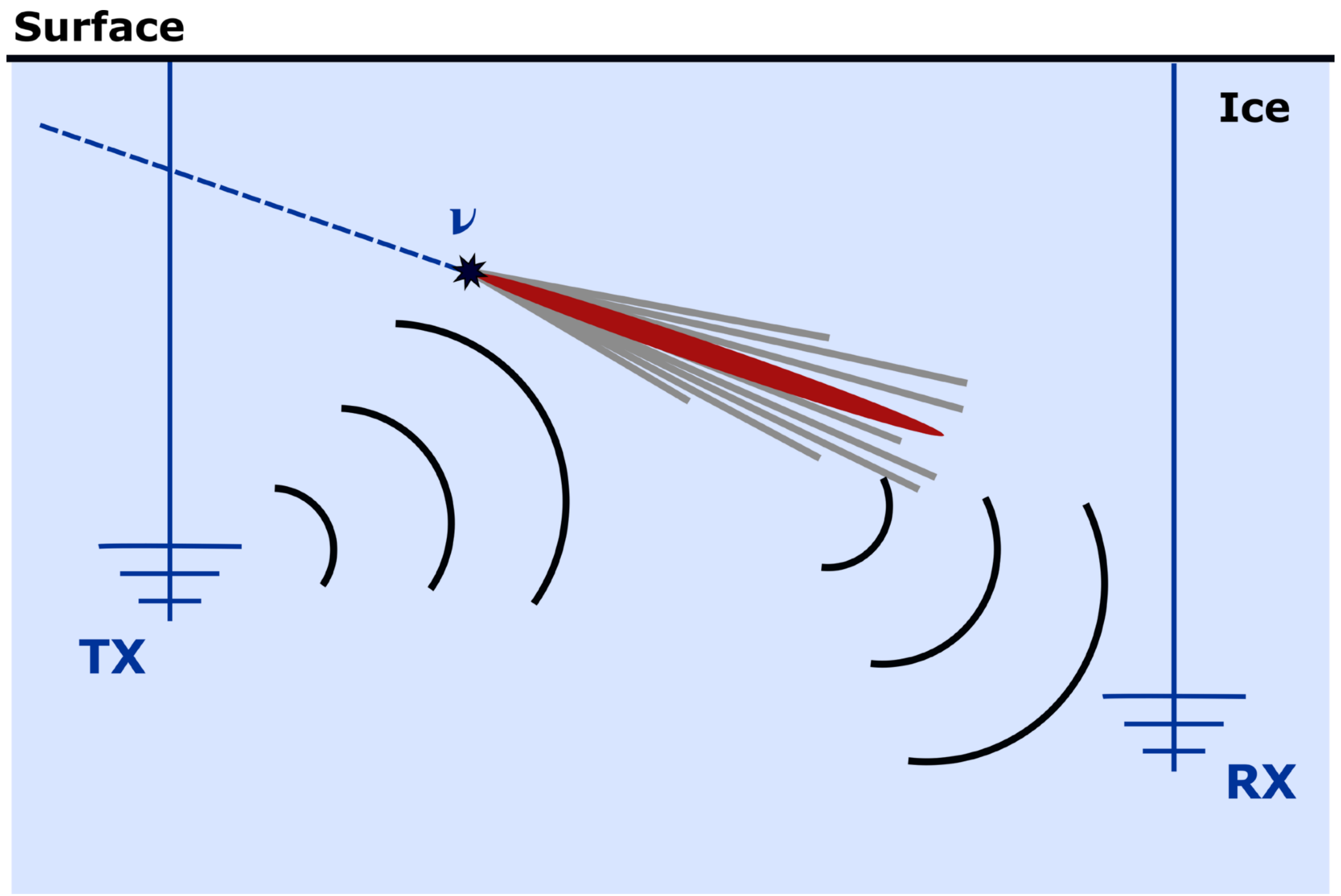
Introduction

- **The Radar Echo Telescope for Neutrinos: A future high-energy neutrino detector**
  - Detect cosmic neutrinos (> 10 PeV) using radar
  - Neutrino interaction creates trail of free ionised electrons $\longrightarrow$ macroscopic radar target



Introduction

- **Towards building a radar neutrino detector**
  - Detector layout
  - Radar triggers for in-ice neutrino-interactions
  - Reconstruction methods



Introduction

- **Towards building a radar neutrino detector**
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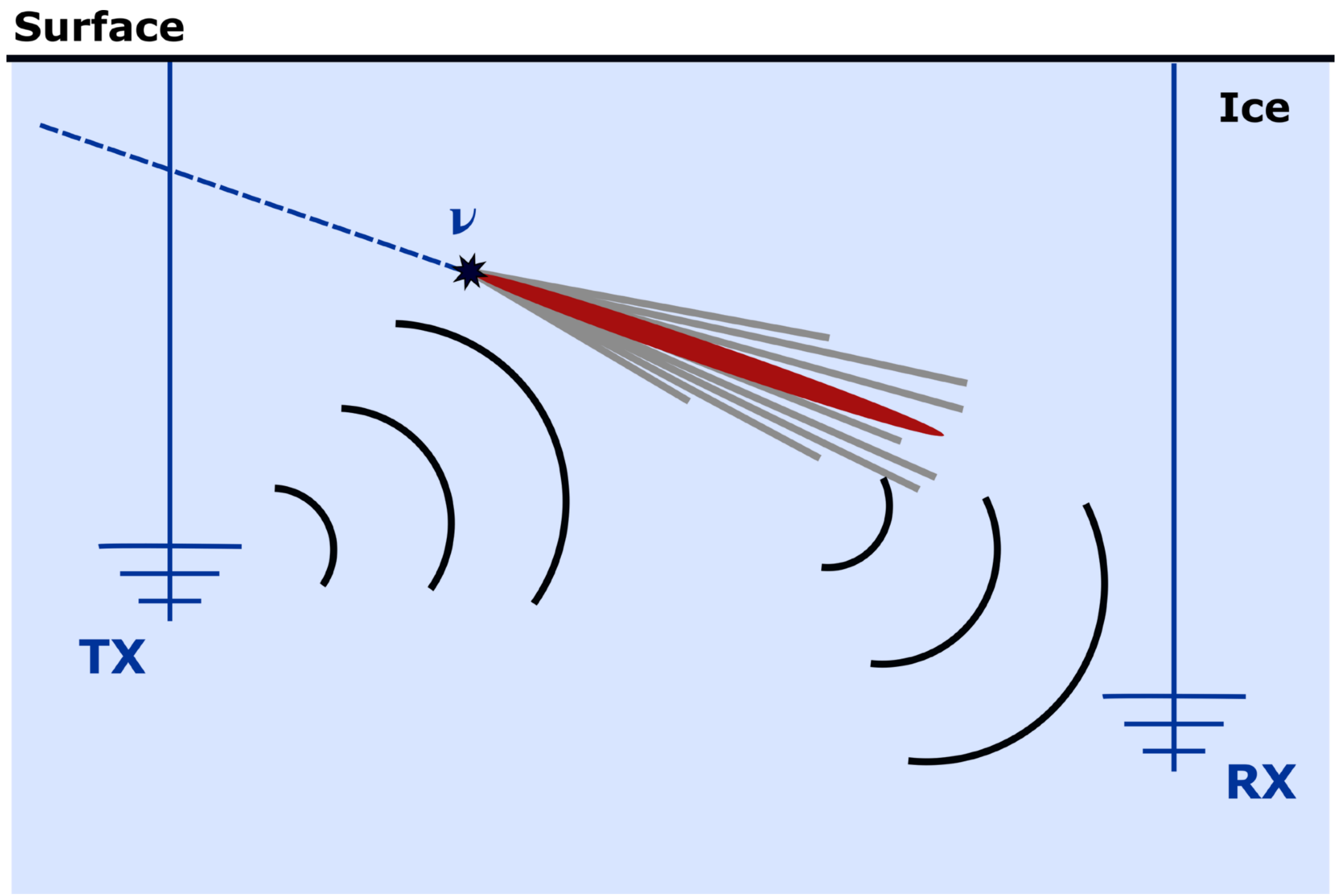
  - Radar triggers for in-ice neutrino-interactions
  - Reconstruction methods

→ Requires a thorough understanding of the **radar signal properties**

→ Deduce these properties from detailed simulations

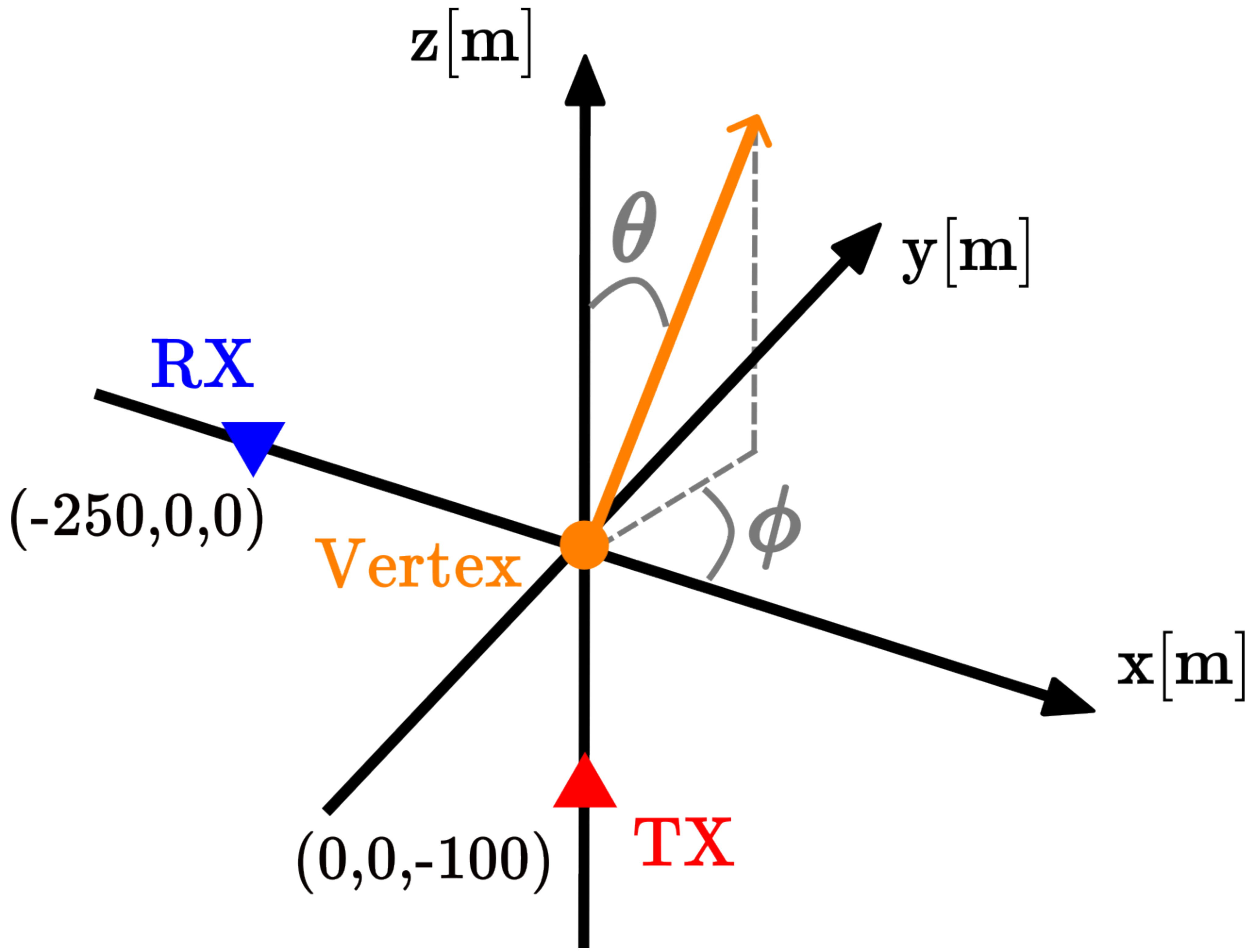


Two papers to be submitted to APS:

1. J. Loonen, I Loudon, et al., (RET Collaboration), *Phase Coherence, Relativistic Doppler Shifts and the Radar Echo Method of Ultrahigh Energy Neutrino Detection.*
2. I. Loudon, J. Loonen, et al., (RET Collaboration), *Exploring Signal Properties of Radar Echoes from High-Energy Particle Cascades.*

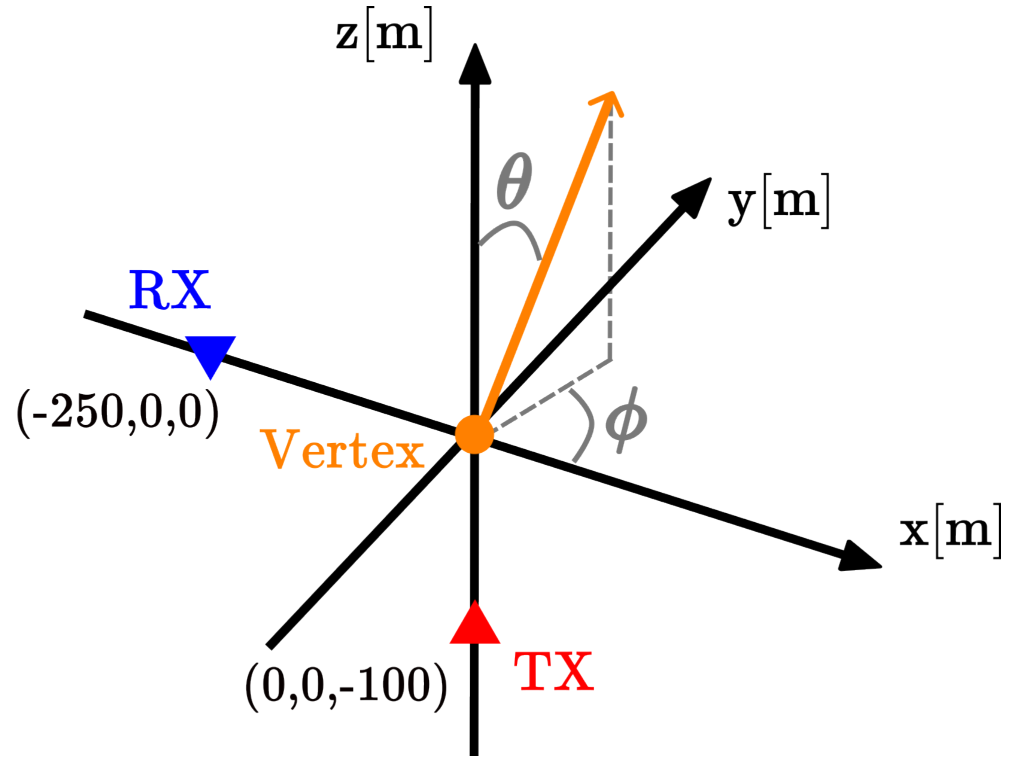
Radar Echo Signal Properties

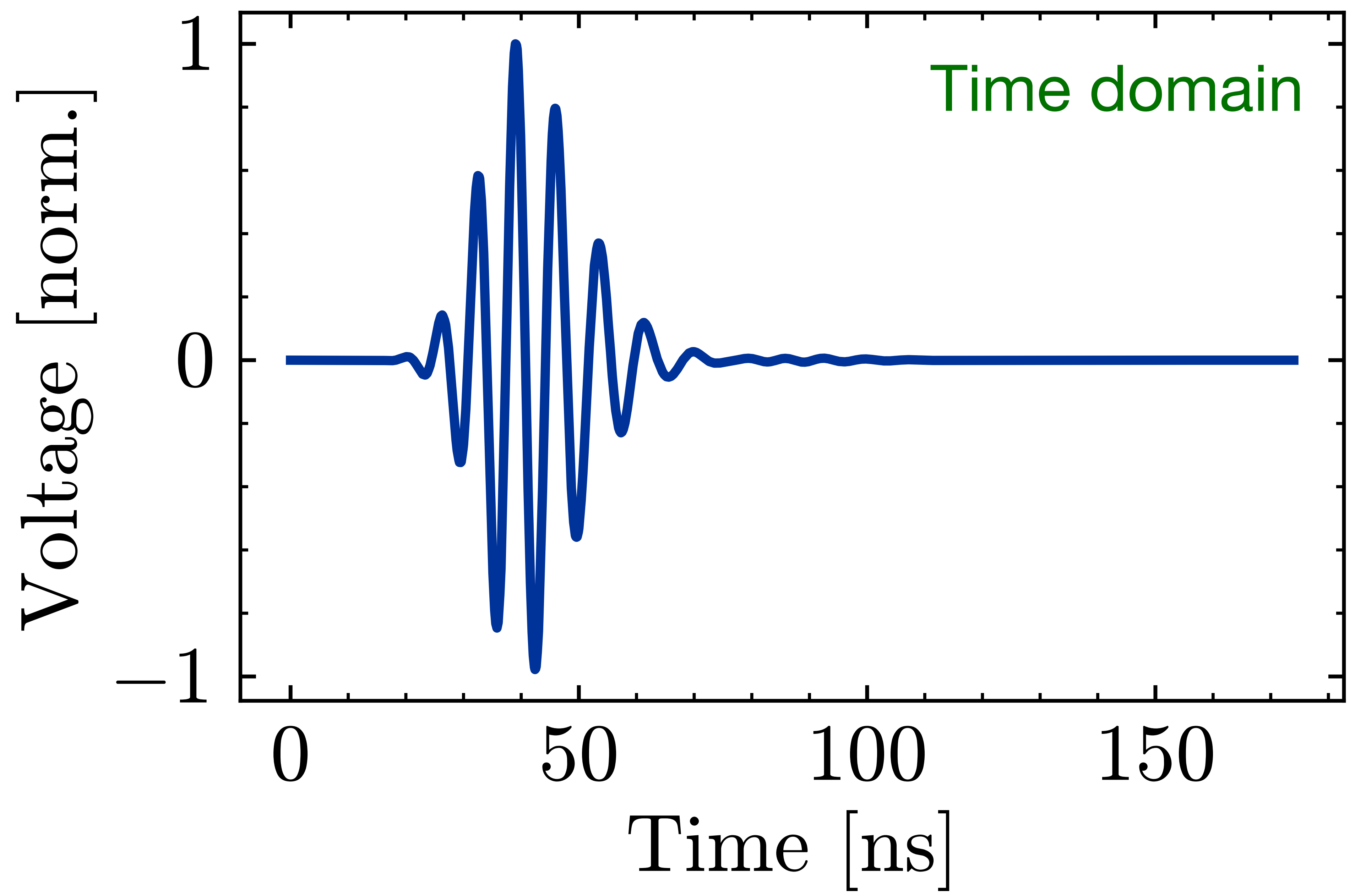
- **Antenna configuration**
  - Single transmitter (TX) and receiver (RX)
  - Neutrino interaction vertex at the origin
  - Neutrino arrival direction is a free parameter
  - Fixed simulation parameters:
    - f_{TX}= 200 MHz
    - Power = 1 kW
    - n = 1.78 (uniform ice)
    - E_ν = 1 EeV
  - Simulate radar echoes using MARES
    (E. Huesca Santiago, et.al., (RET collaboration), 2024)

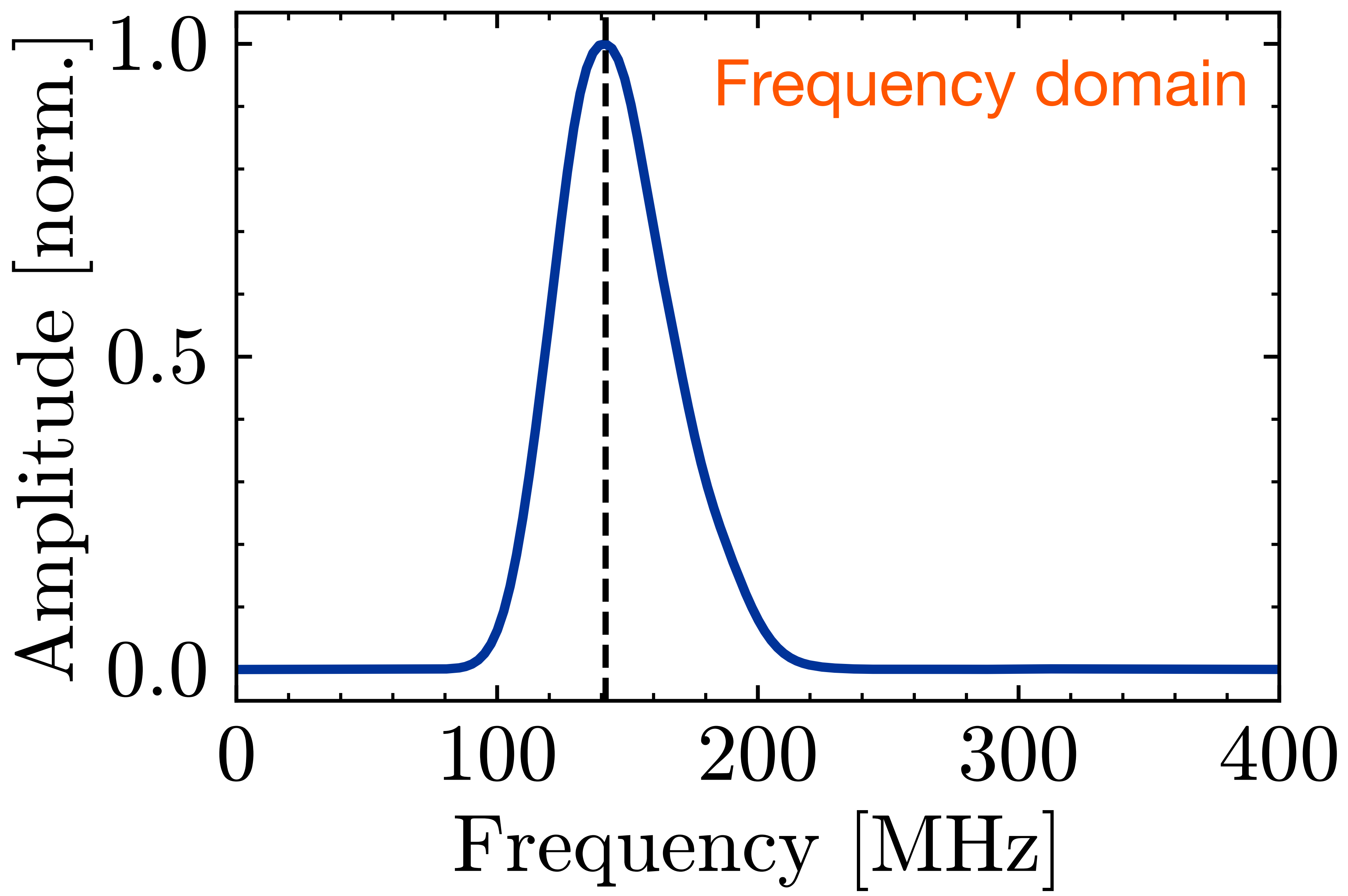


Radar Echo Signal Properties

- **Radar signals**
  - Time domain ⟶ When are the signals strong ⟶ optimise detector layout
  - Frequency domain ⟶ Doppler shifts ⟶ reconstruct arrival direction
  - **Investigate the radar echo signal properties in the time domain and frequency domain**



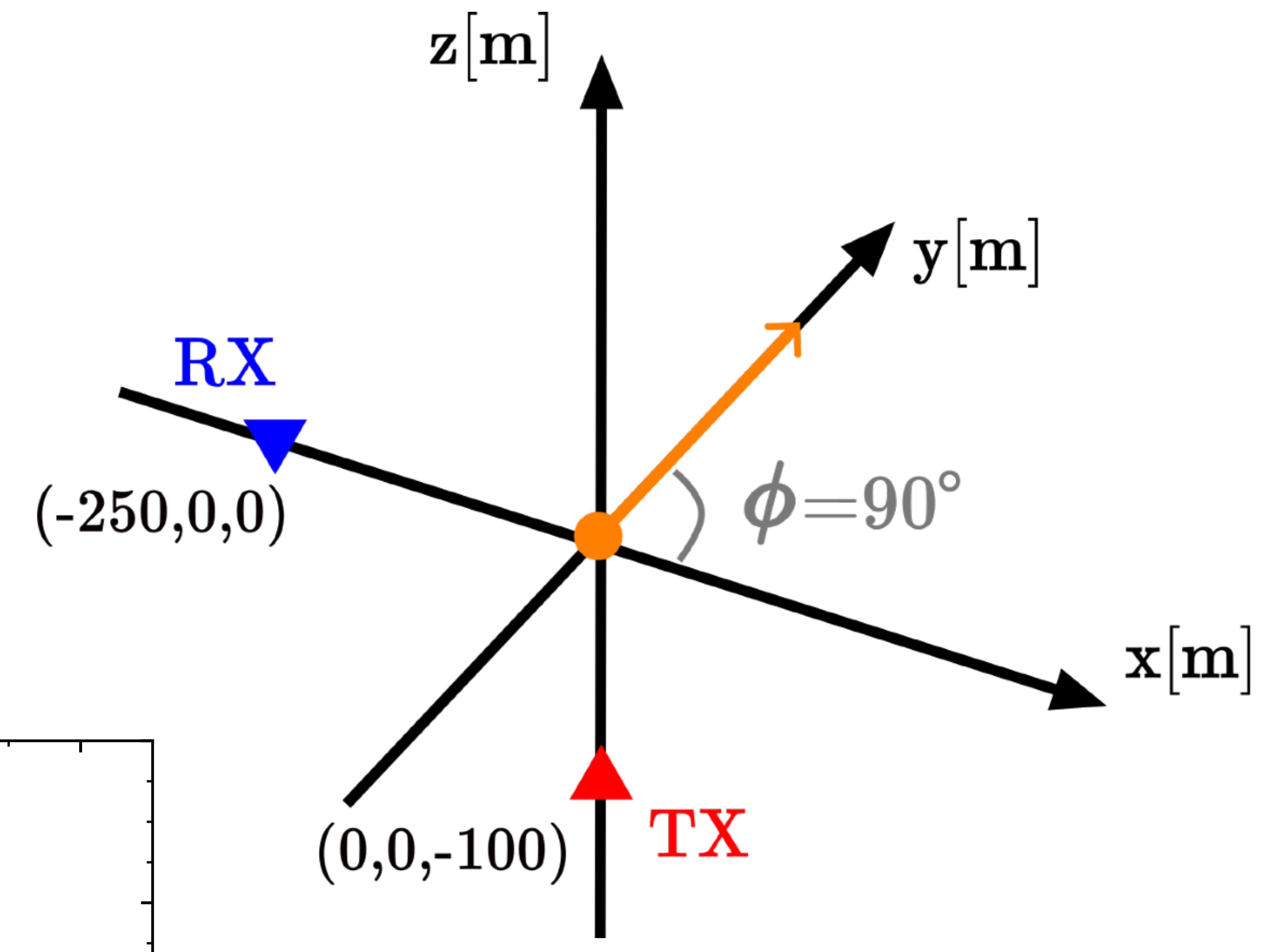


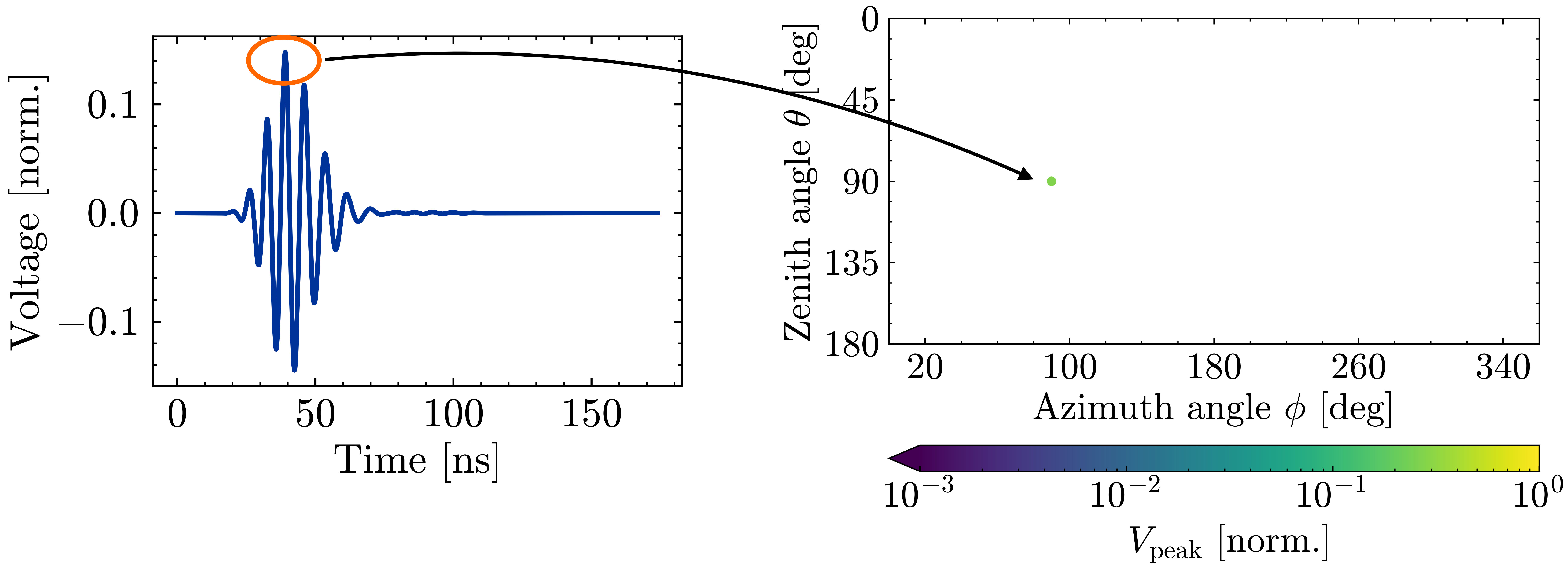


Time Domain Signal Properties

Radar Echo Signal Properties

- **Signal strength vs neutrino arrival direction**
  - Simulate the radar echo
  - Extract the peak amplitude of the waveform





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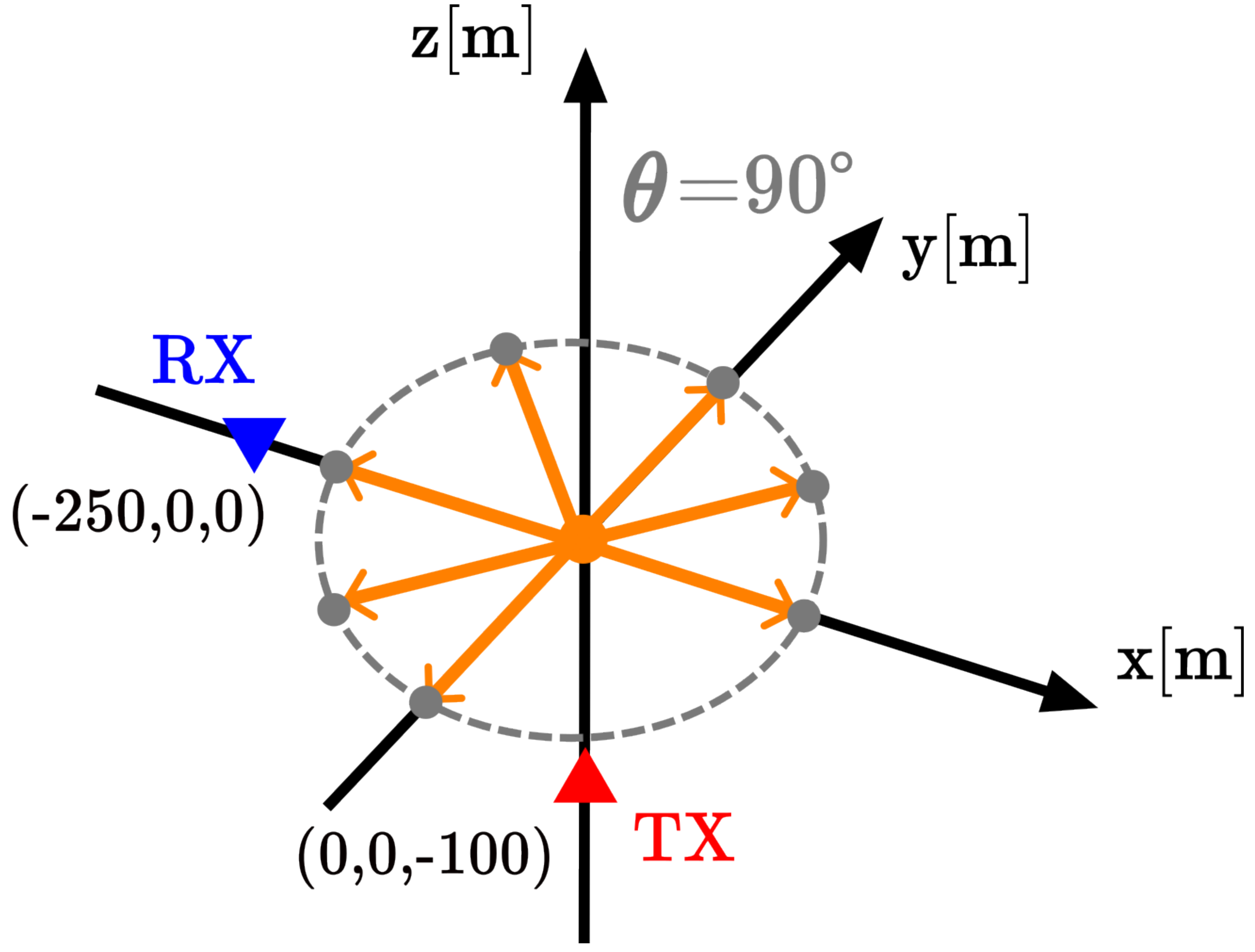

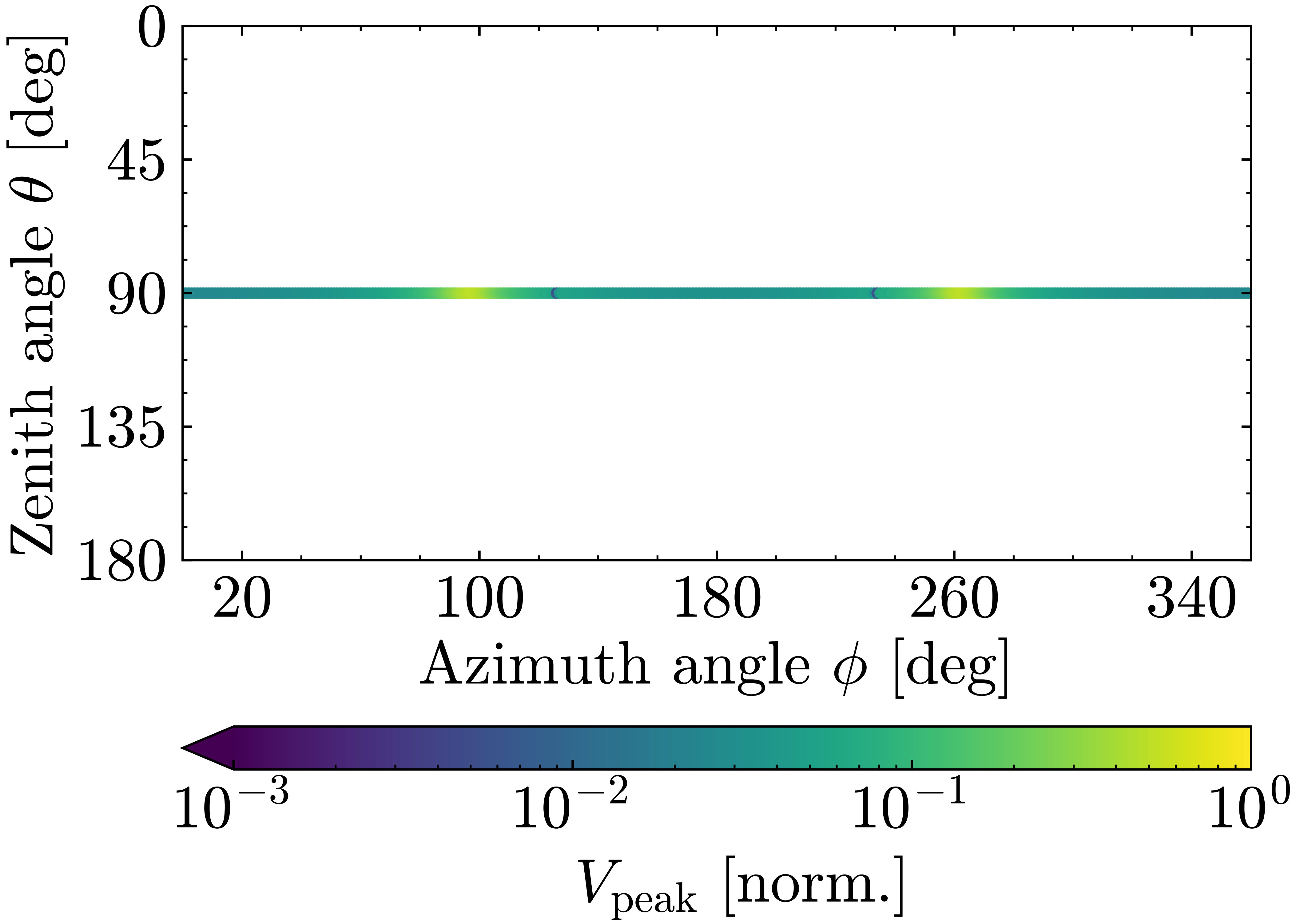

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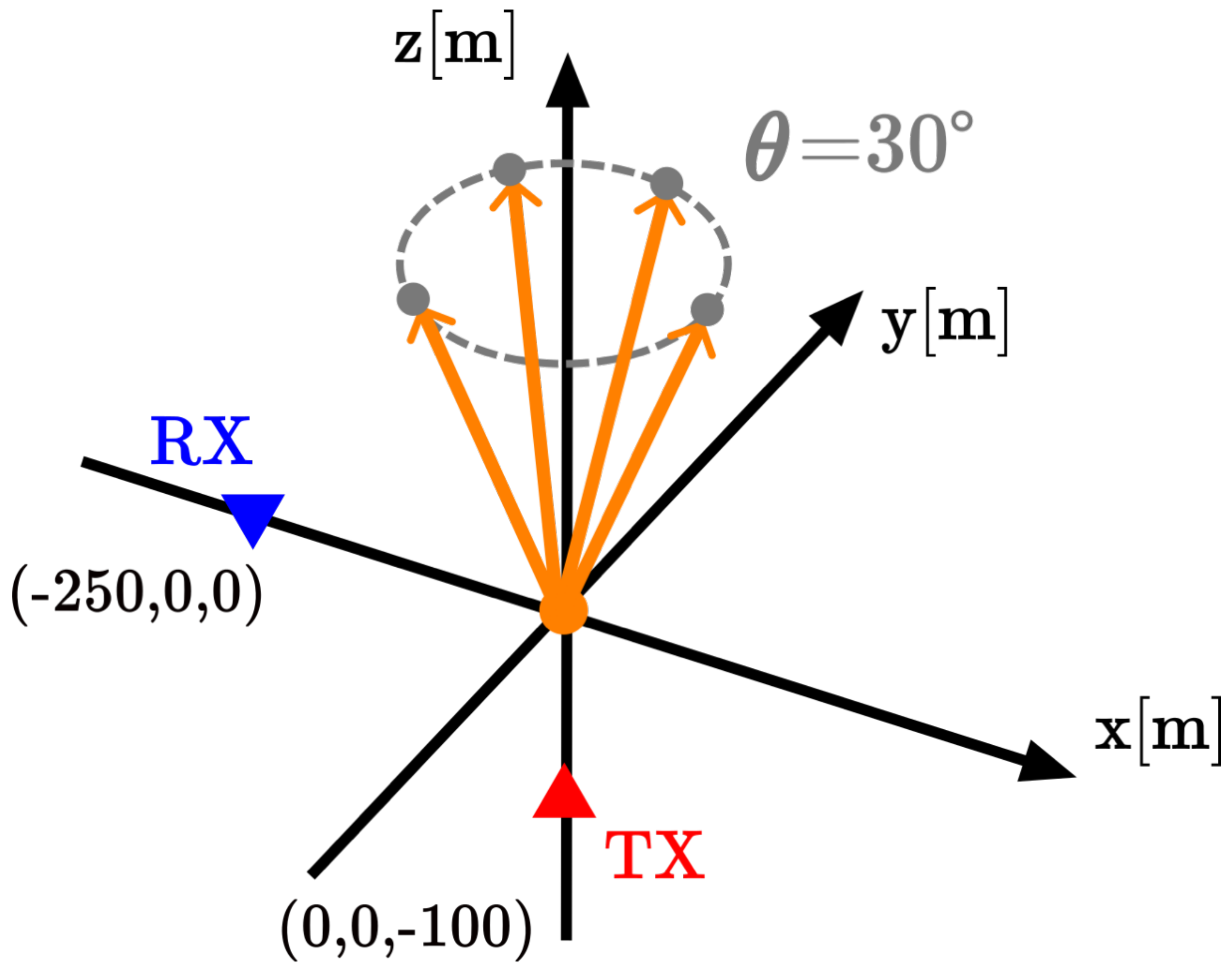
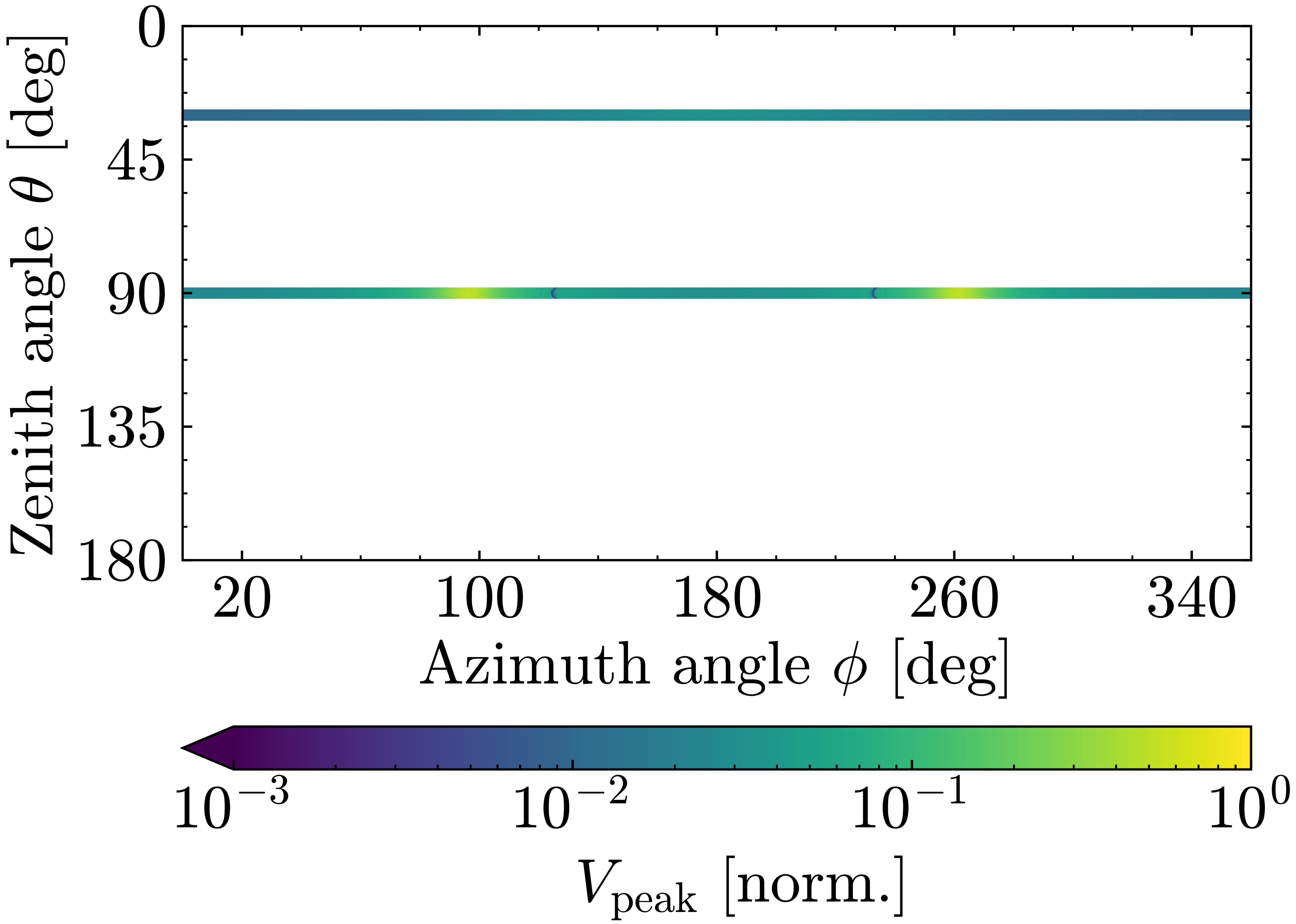
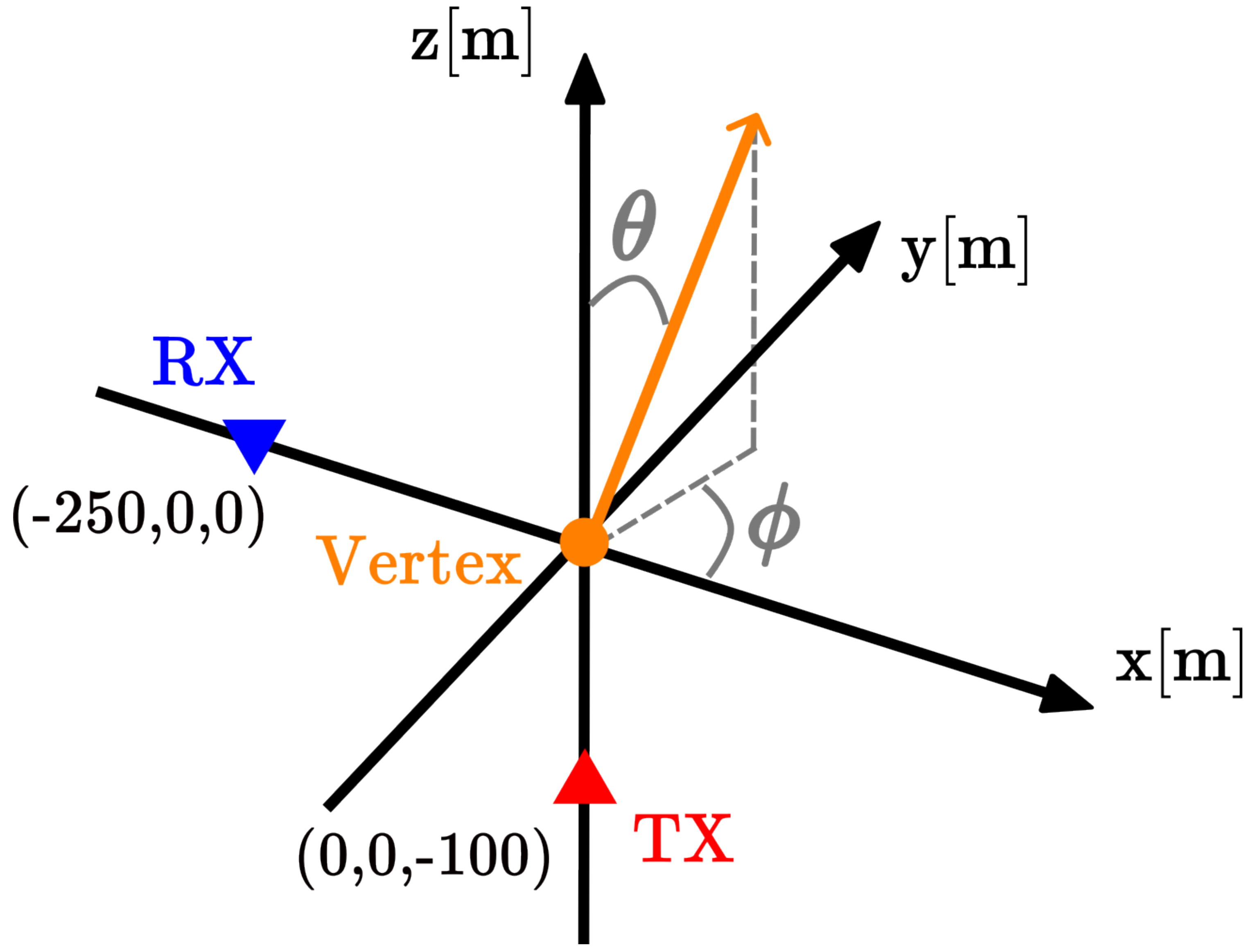
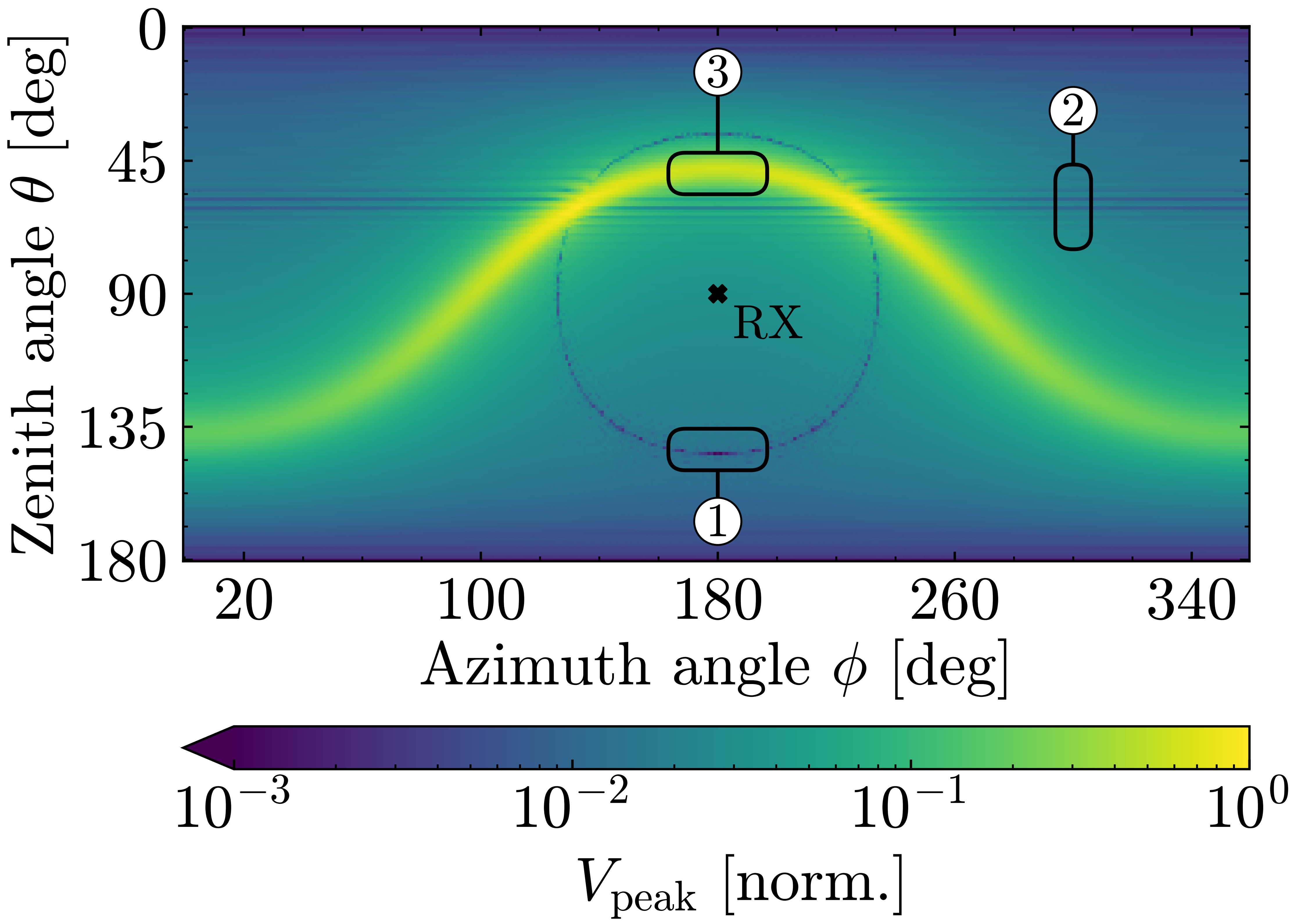




Radar Echo Signal Properties

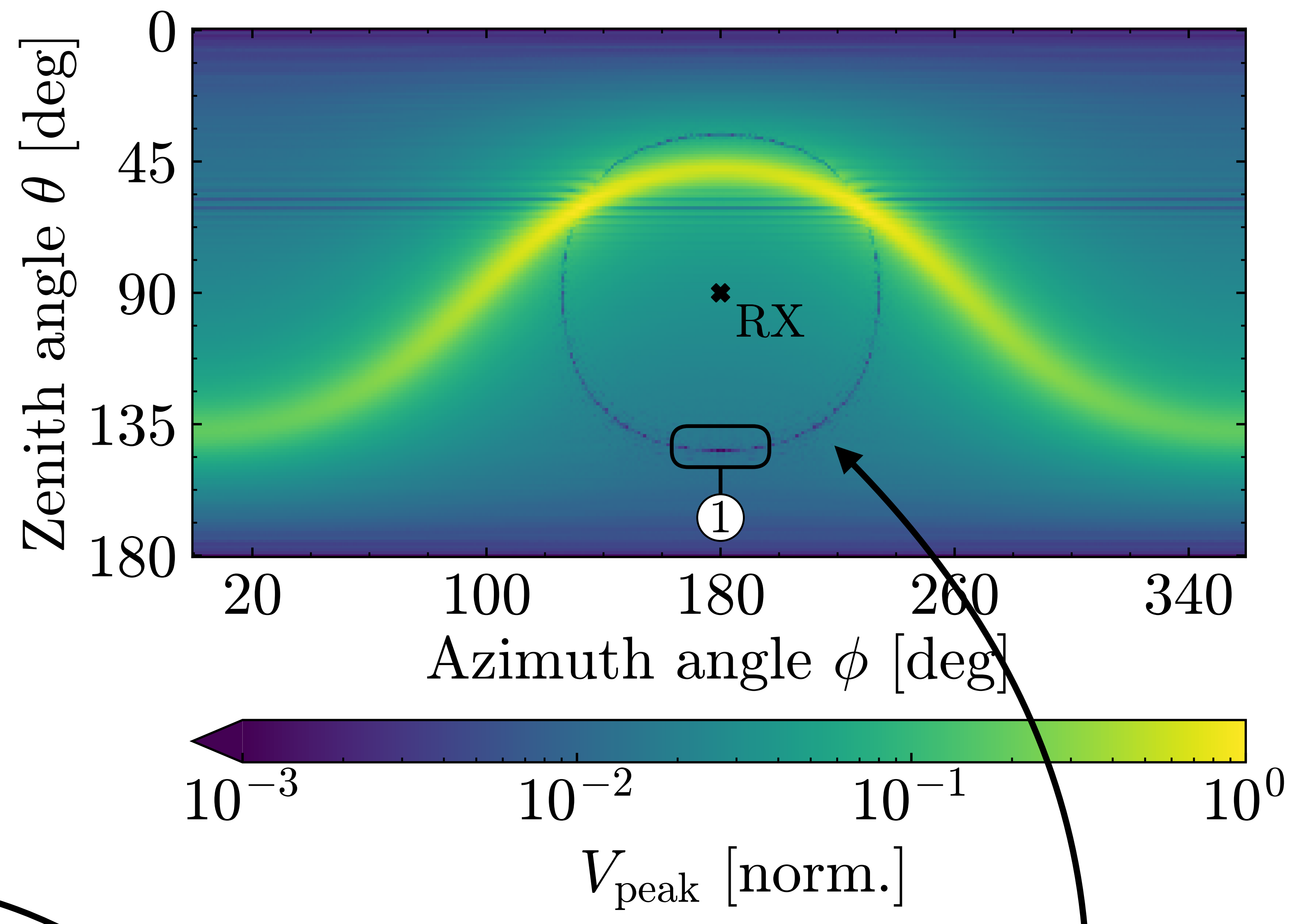
- **Signal strength vs neutrino arrival direction**
  - Three distinct features:
    1. Low-amplitude ring
    2. Horizontal bands
    3. High-amplitude region

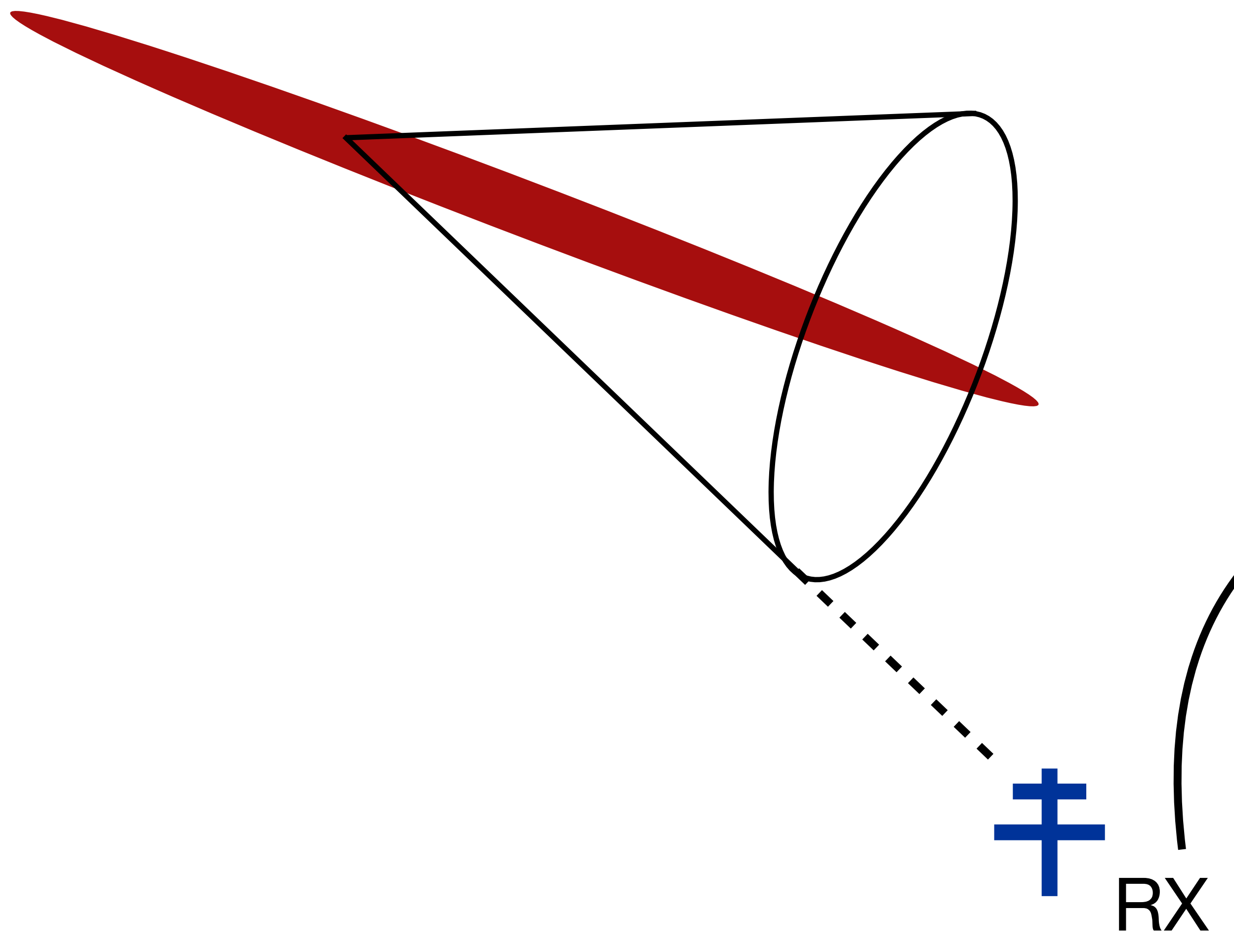


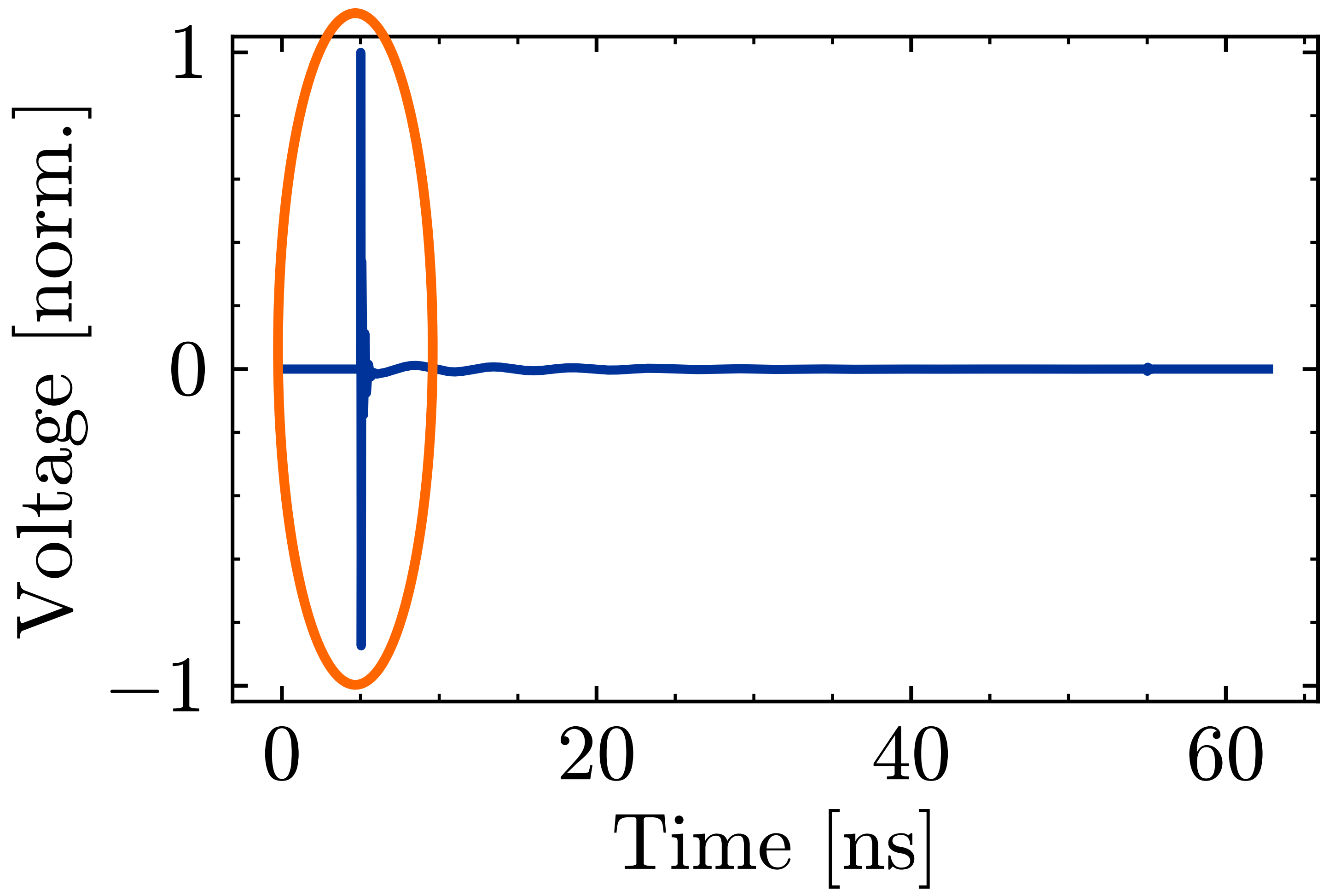


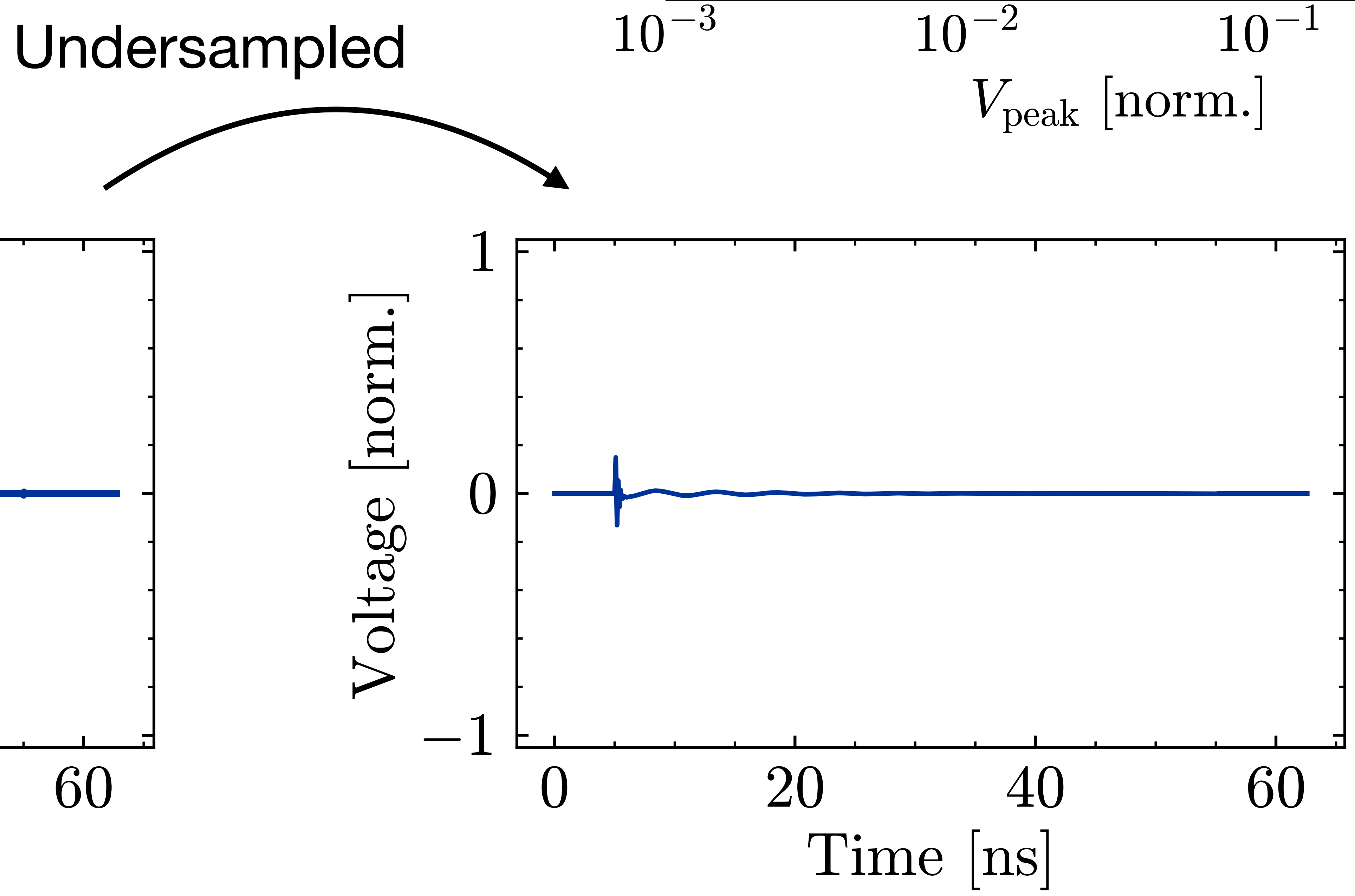
Radar Echo Signal Properties

- **1) Low-amplitude ring**
  - Cherenkov cone
  - Radio waves are time compressed on the cone
    - High-intensity radio burst
  - Undersampling effect artificially lowers the amplitude



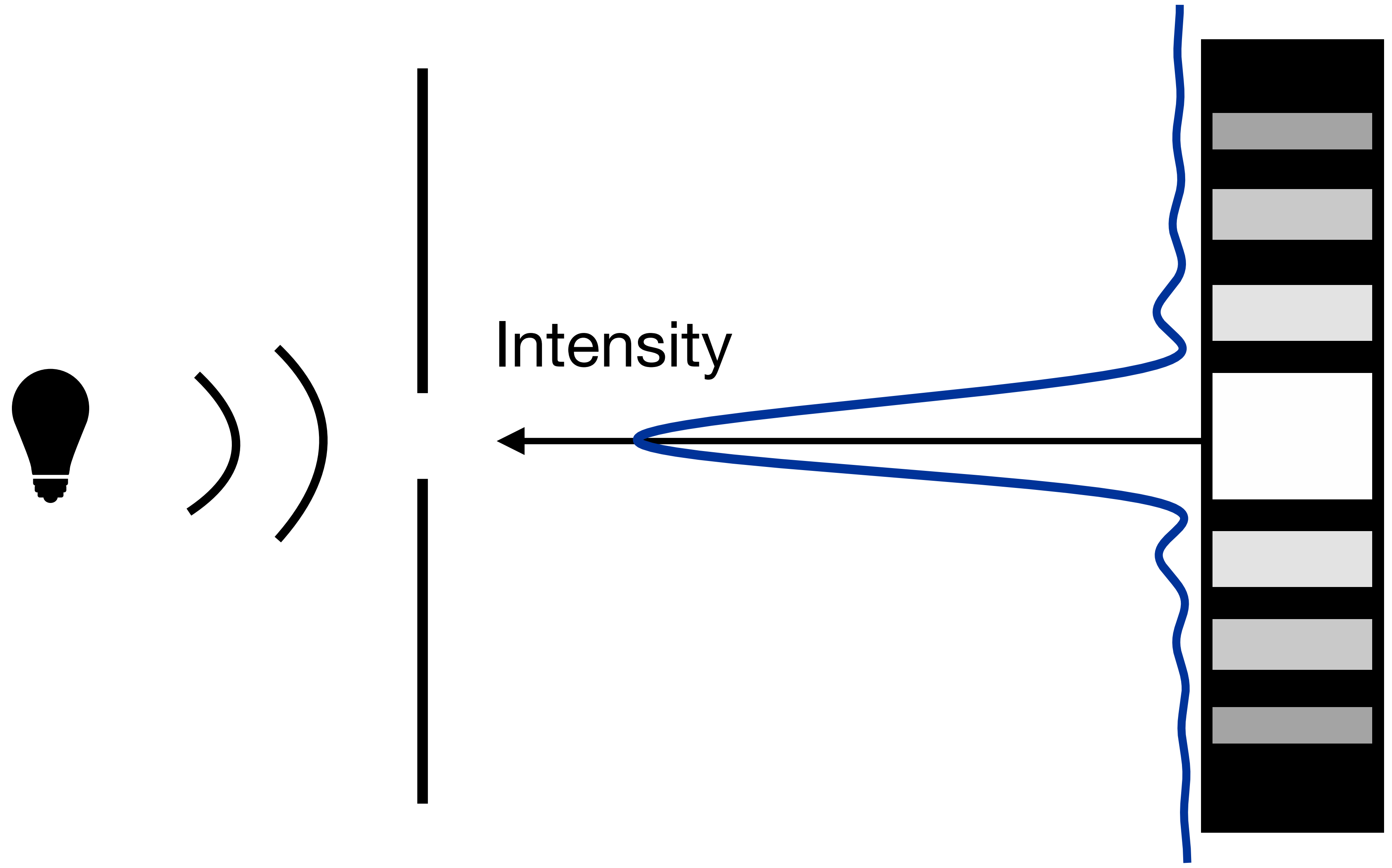


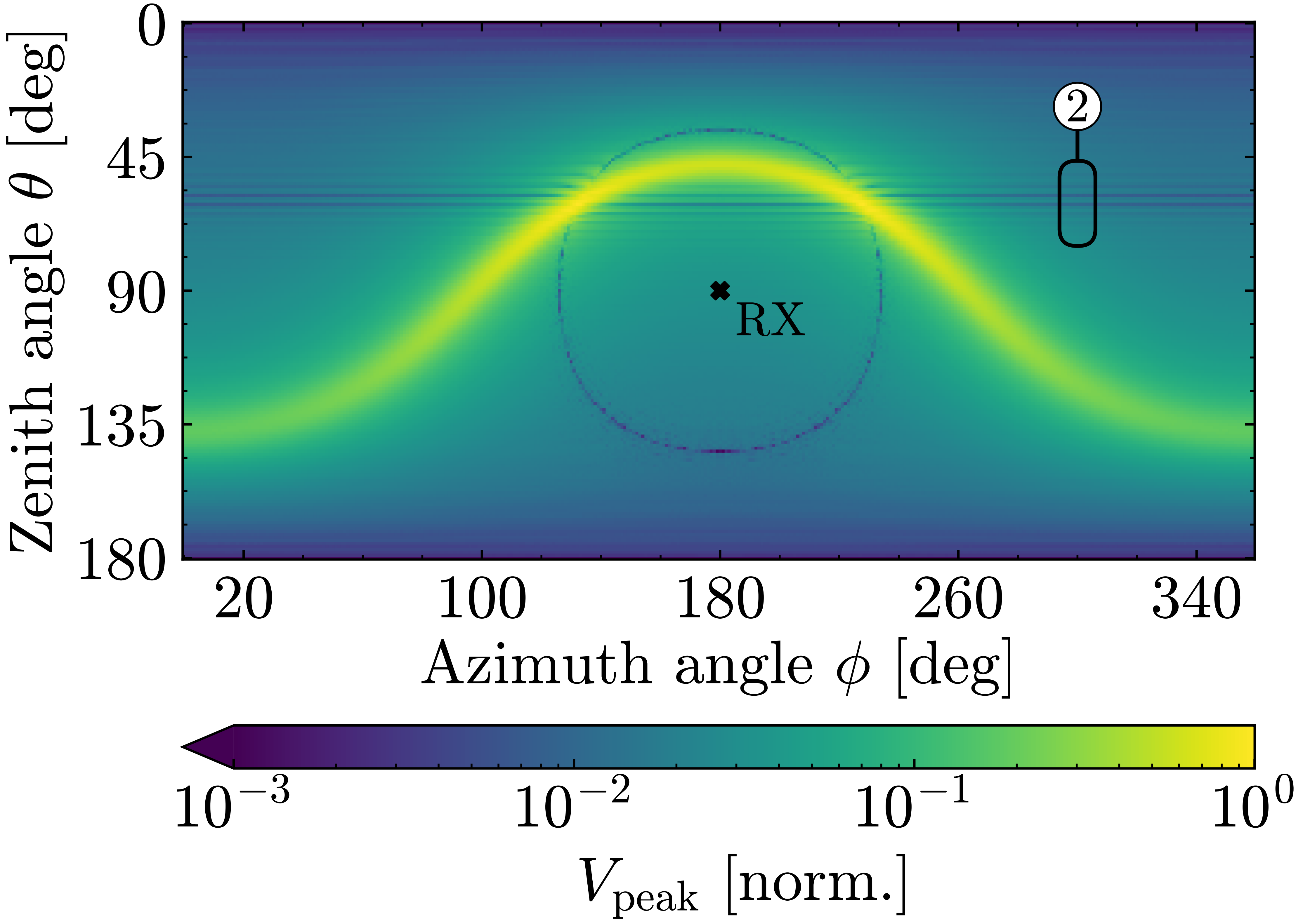




Radar Echo Signal Properties

- **2) Horizontal bands**
  - A diffraction pattern
  - Analogous to a single slit experiment





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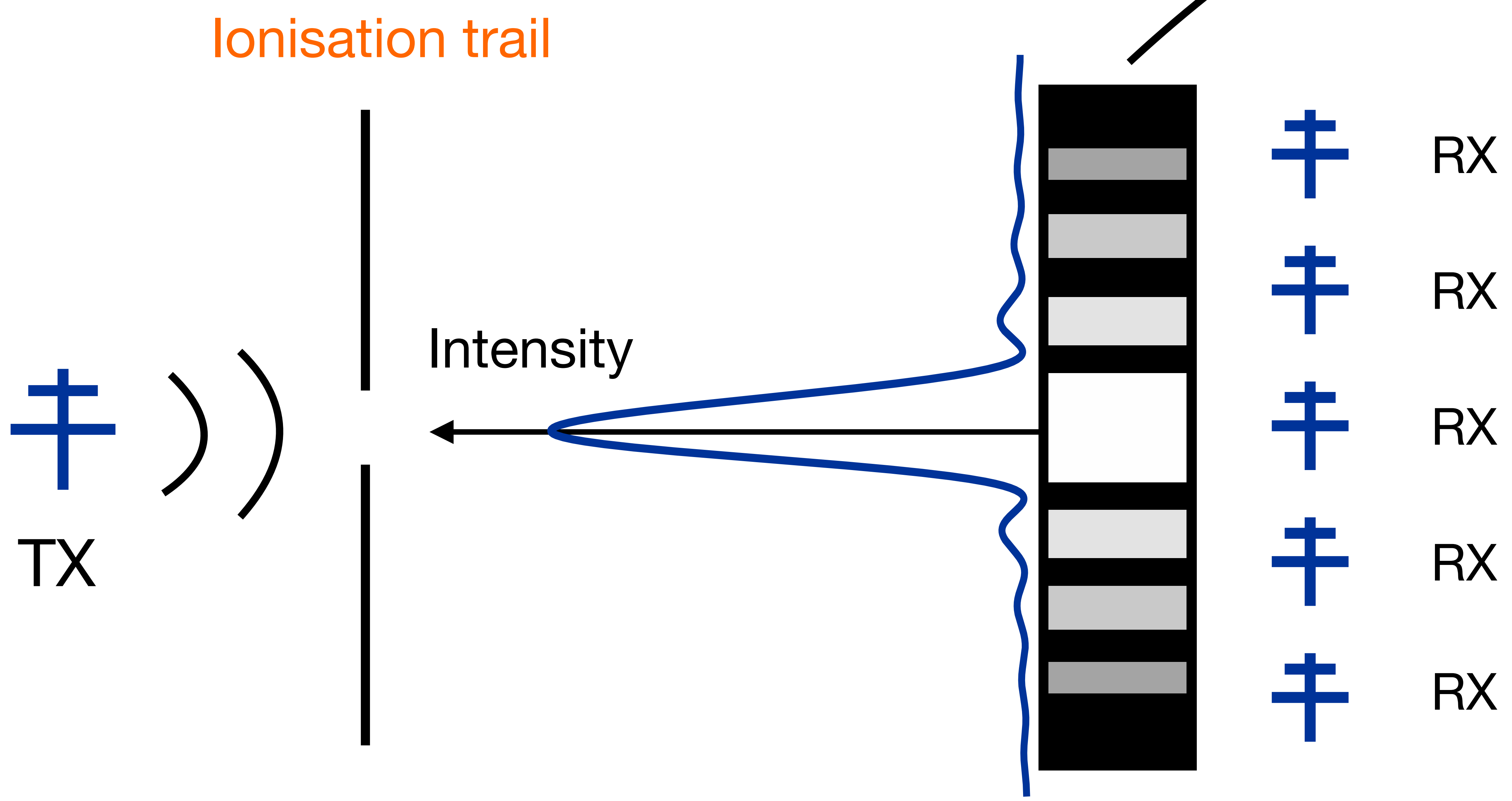
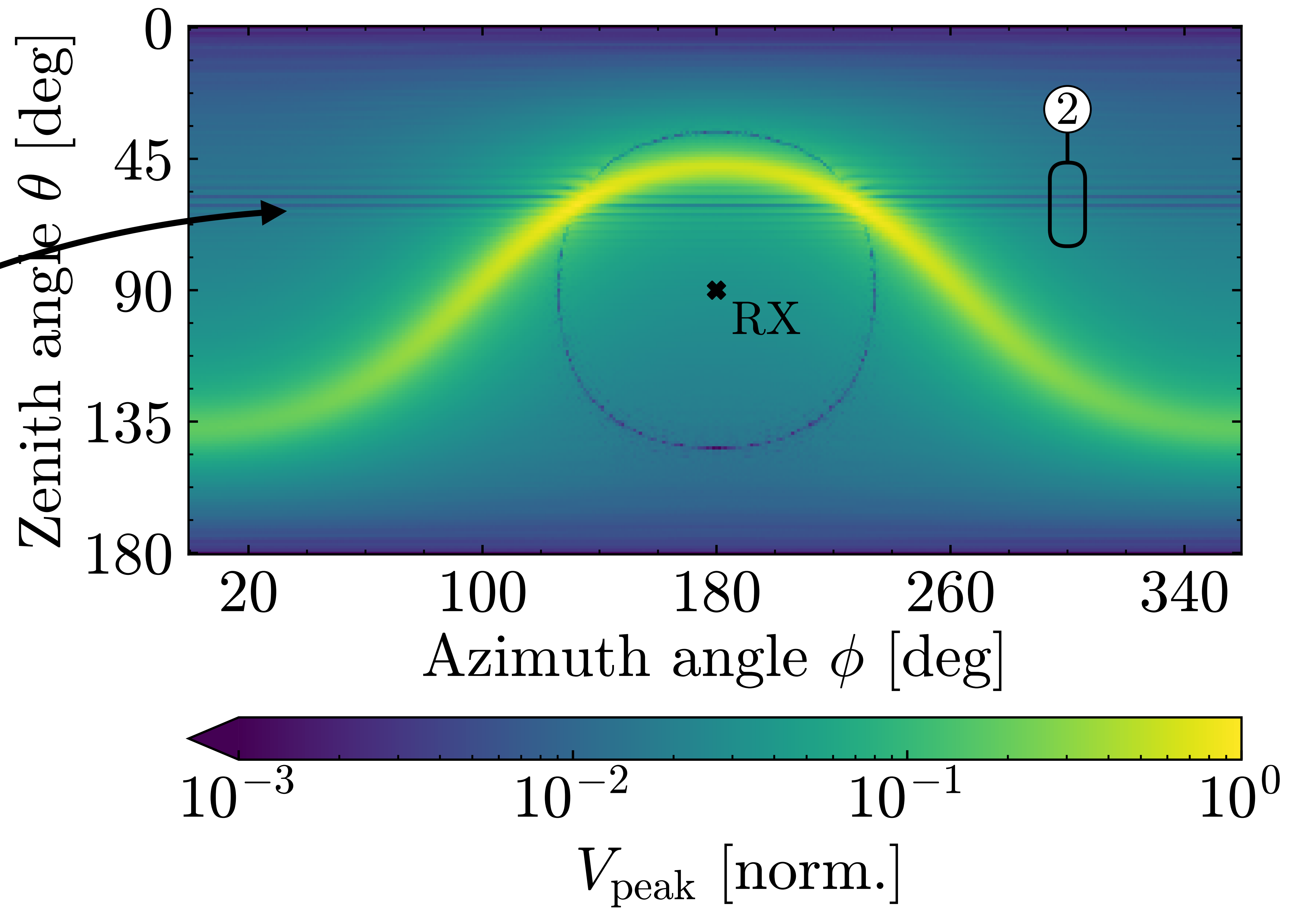
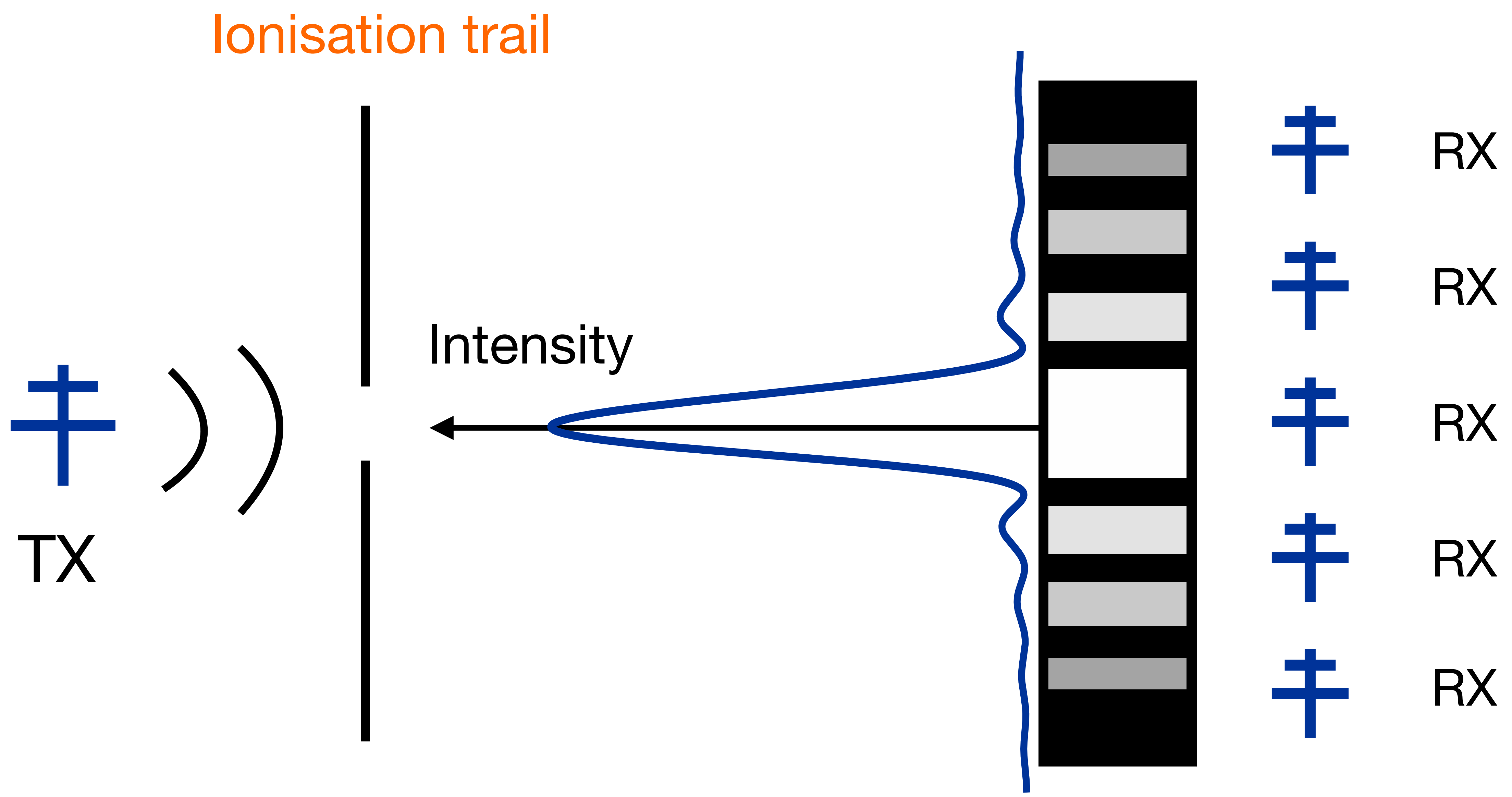
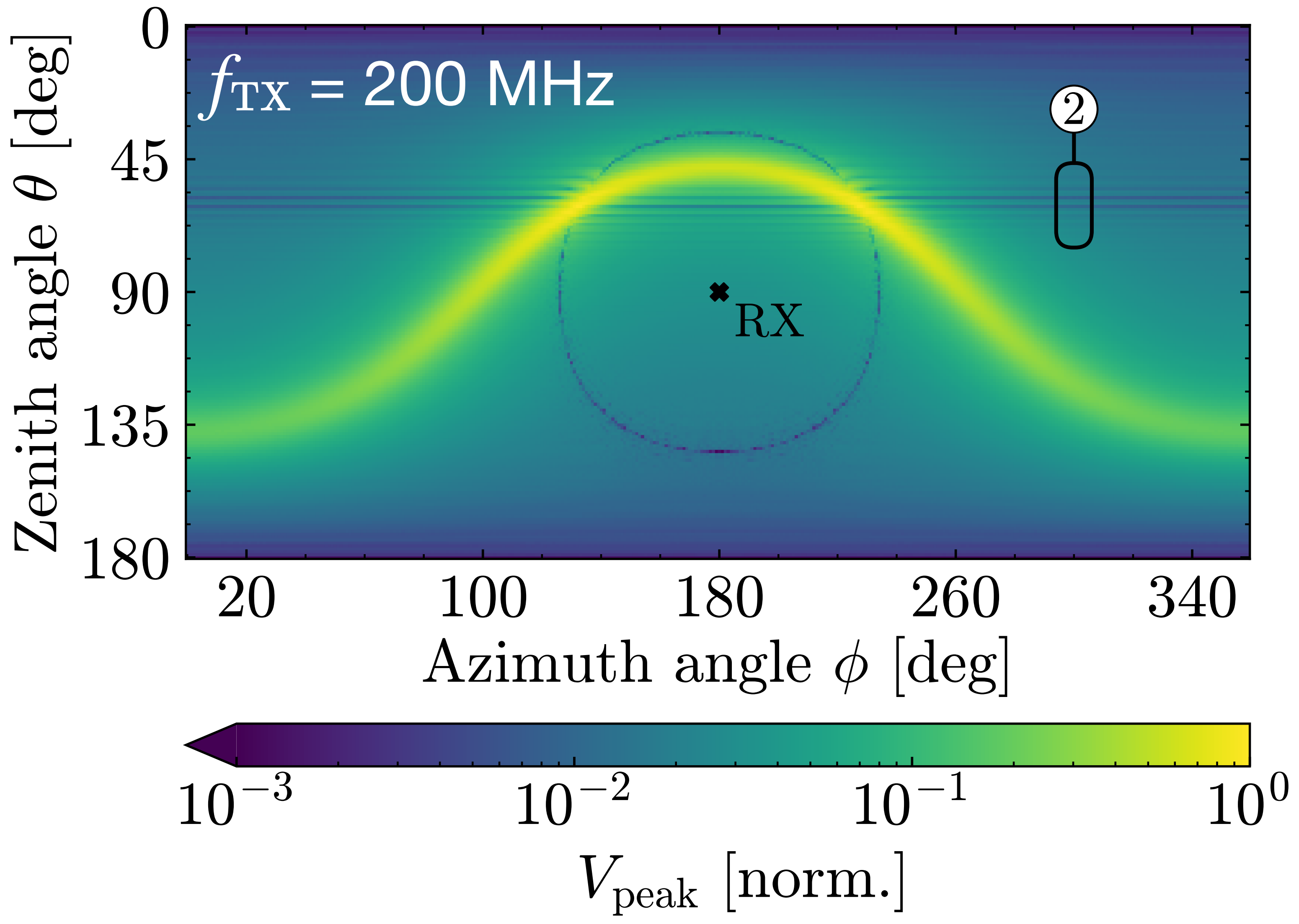


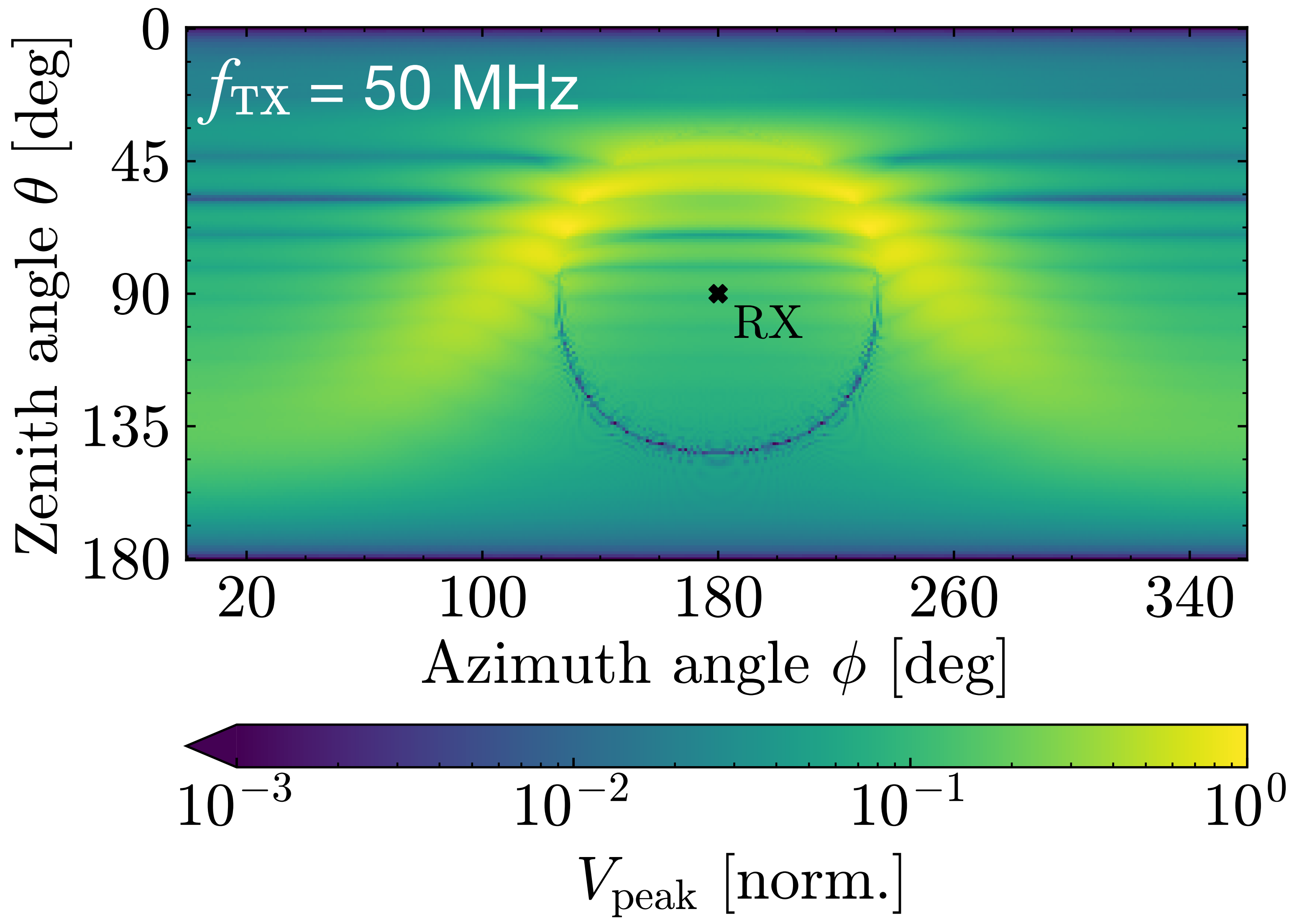


Radar Echo Signal Properties

- **2) Horizontal bands**
  - A diffraction pattern
  - Analogous to a single slit experiment
  - Width of the bands $\propto 1/f_{\mathrm{TX}}$

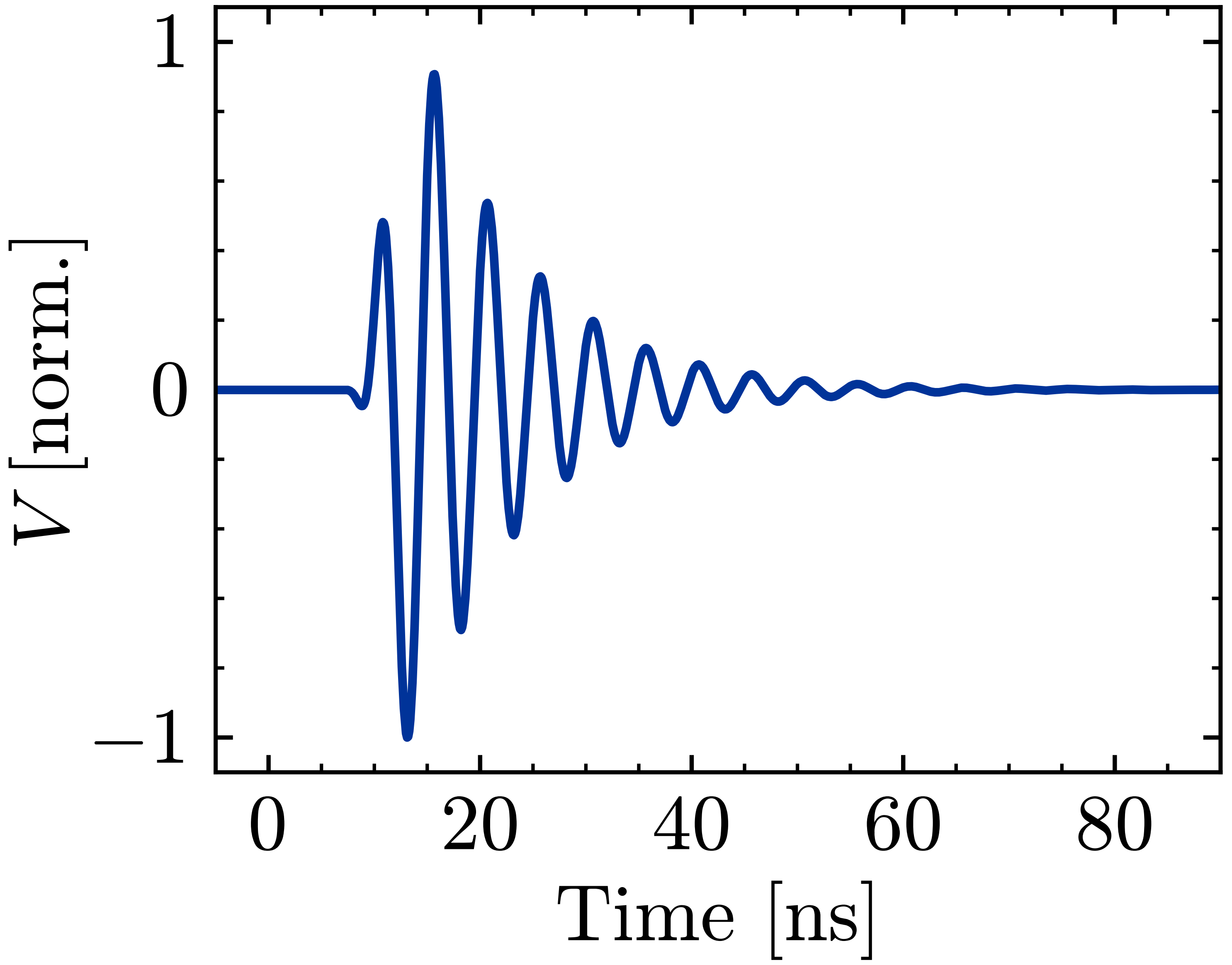


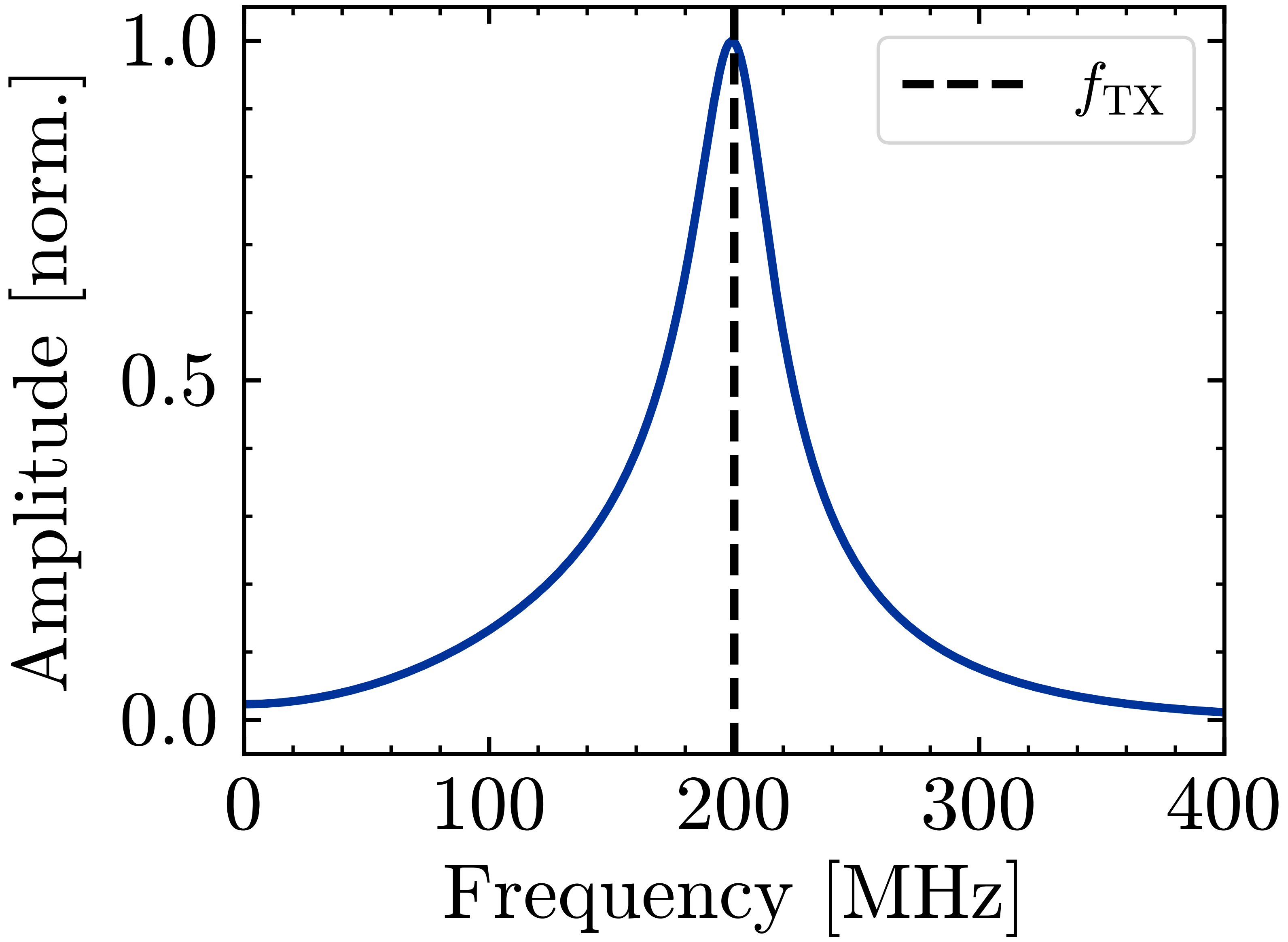


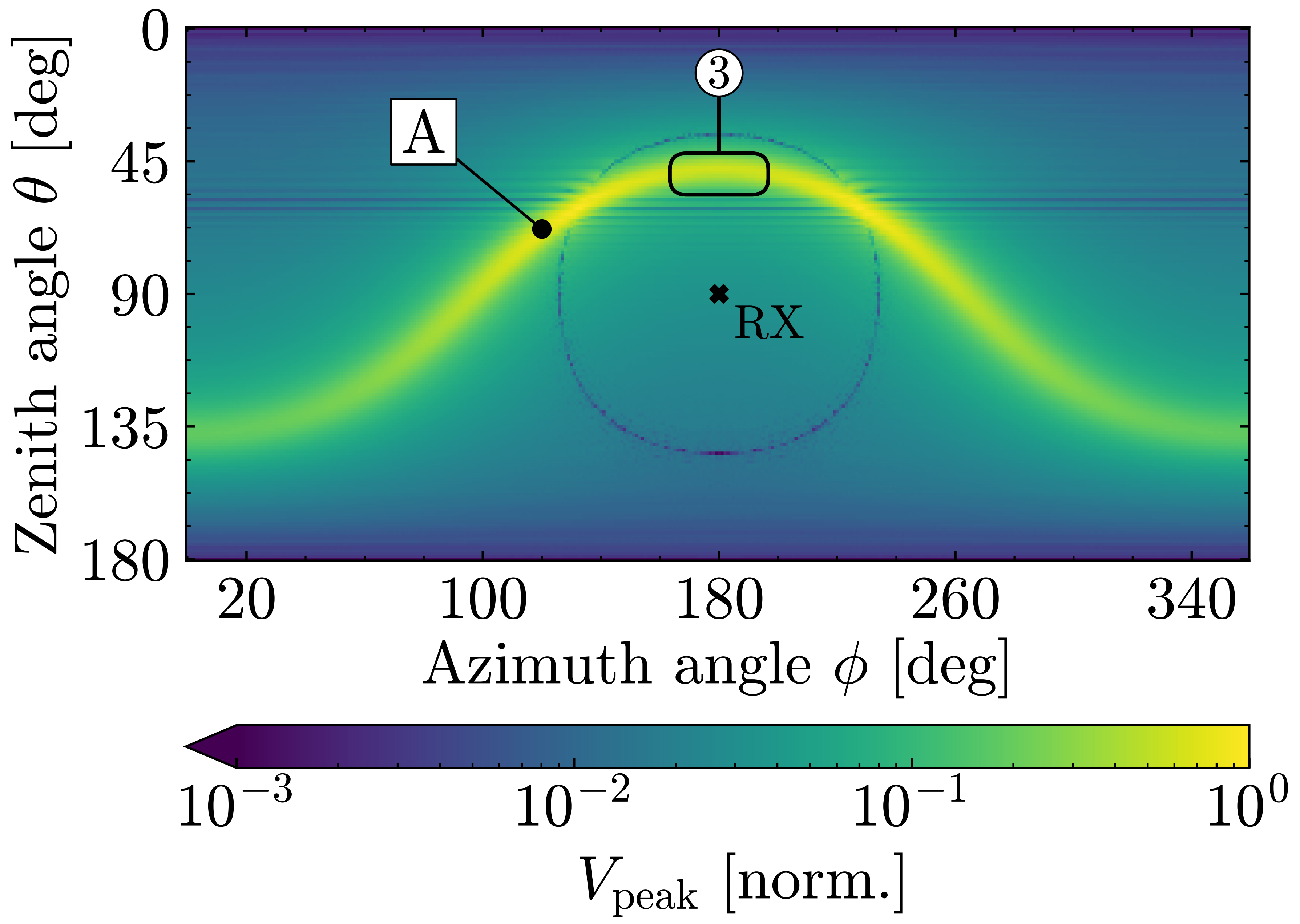


Radar Echo Signal Properties

- **3) High-amplitude region**
  - Unique to the radar detection method
  - No Cherenkov time-compression effect

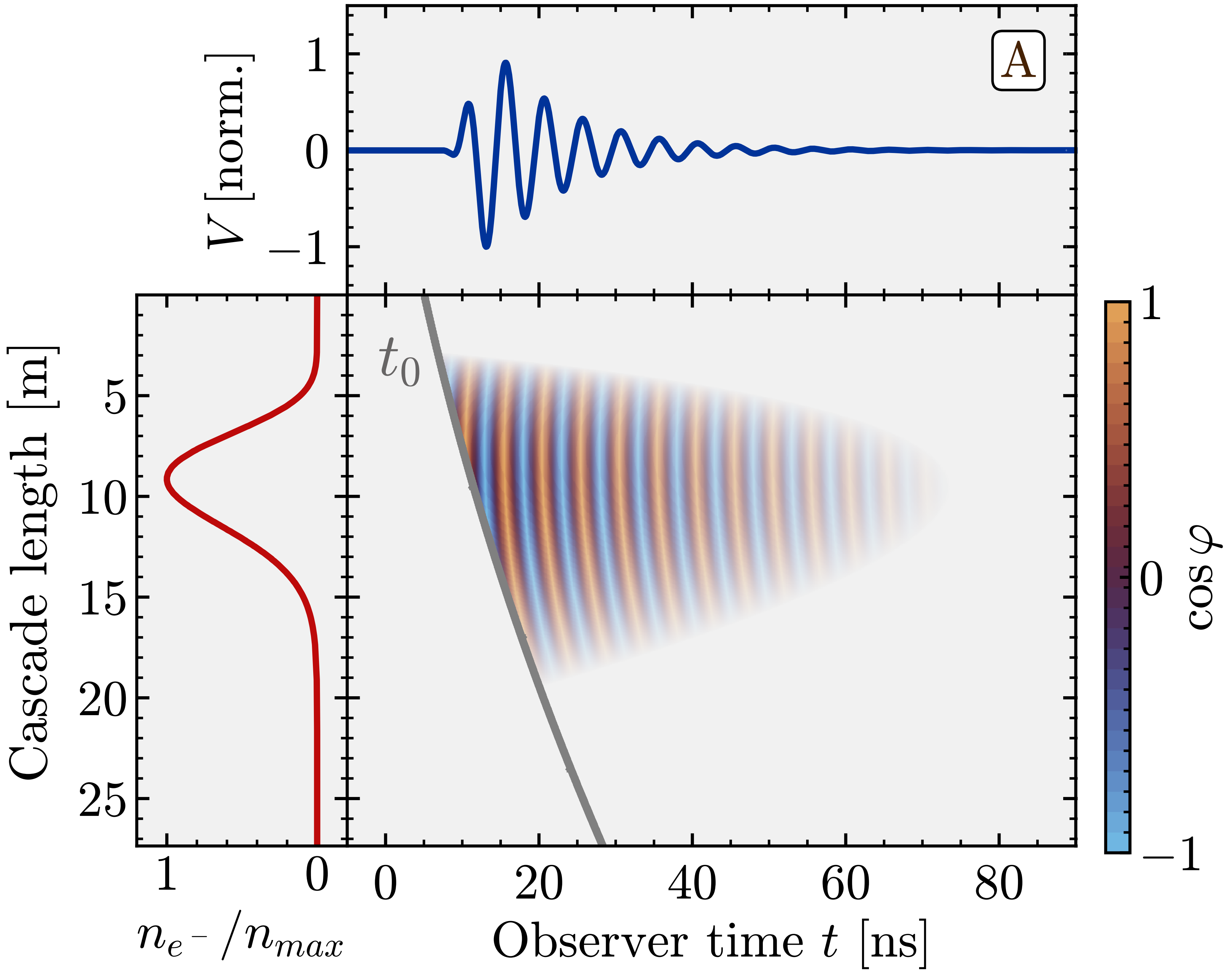


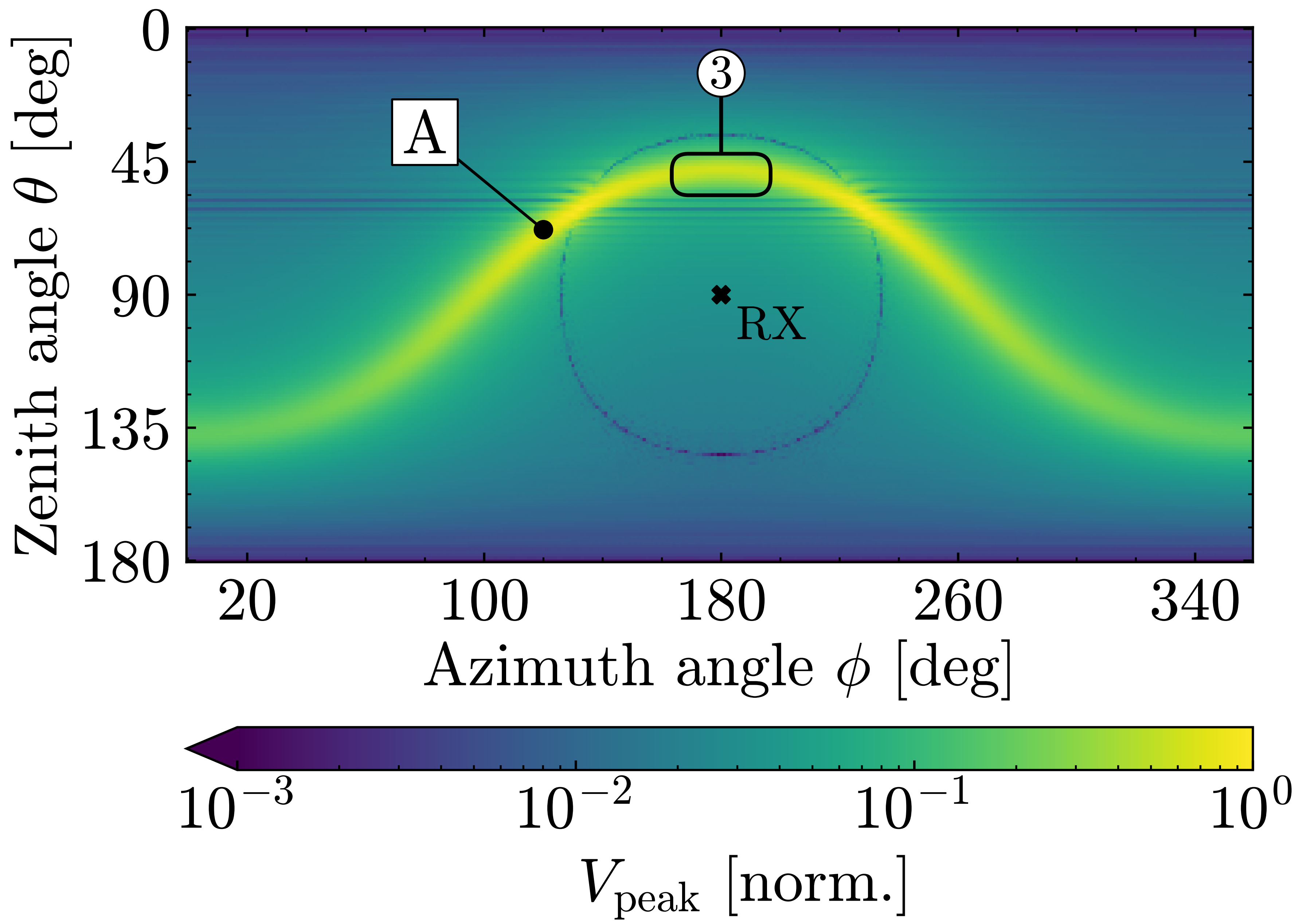




Radar Echo Signal Properties

- **3) High-amplitude region**
  - Unique to the radar detection method
  - Amplification of the signal due to phase alignment between different parts of the trail





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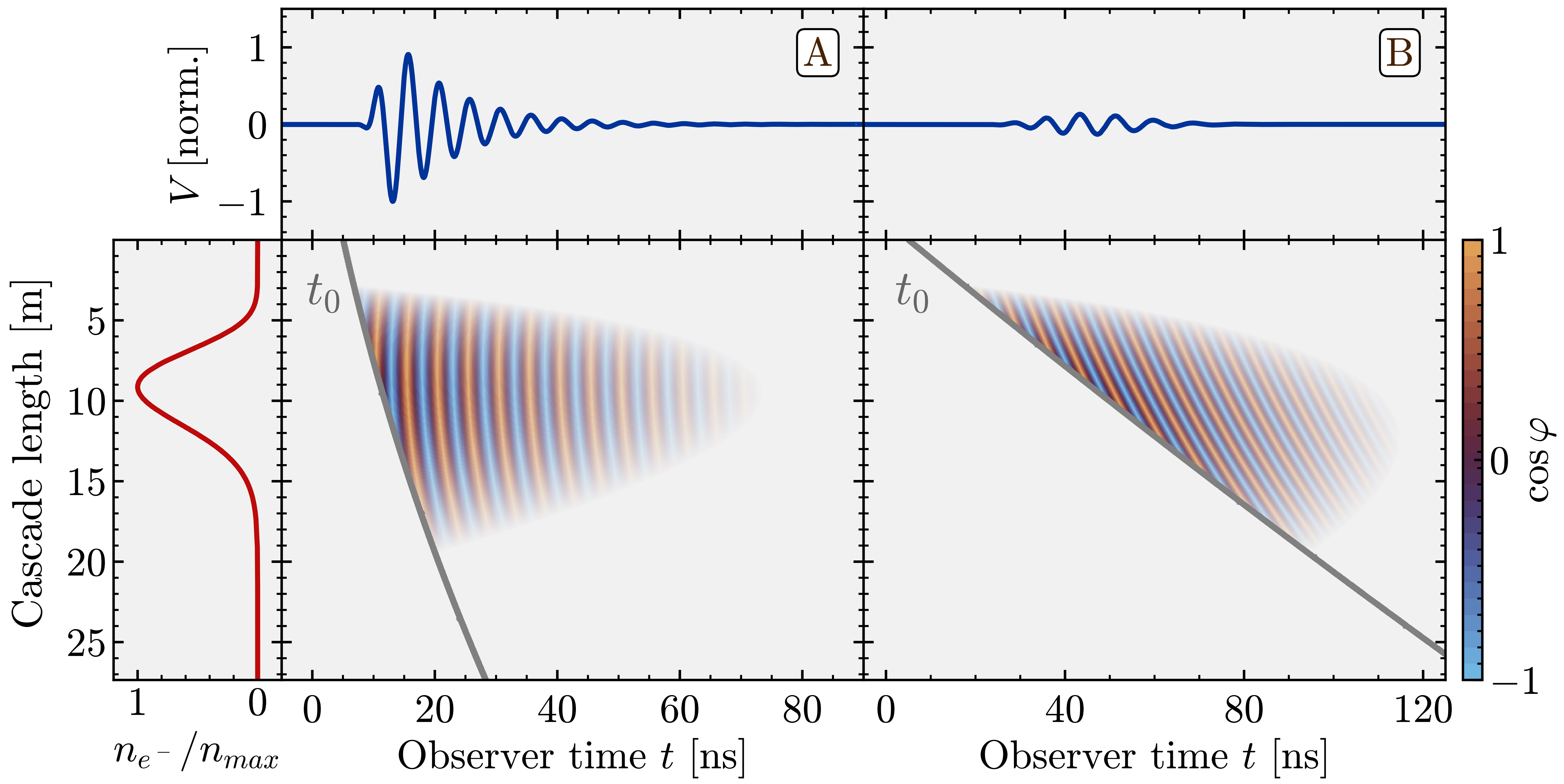
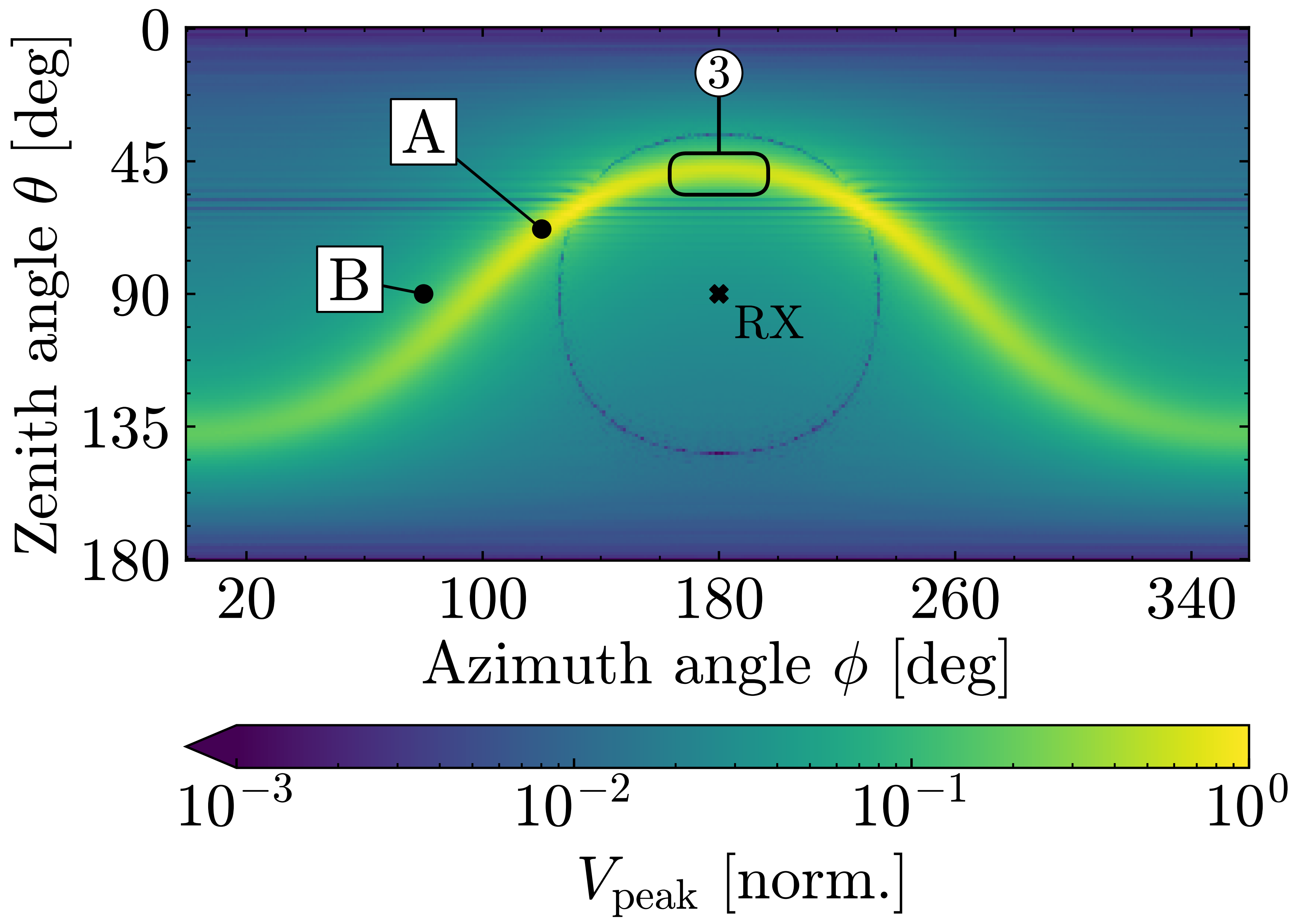
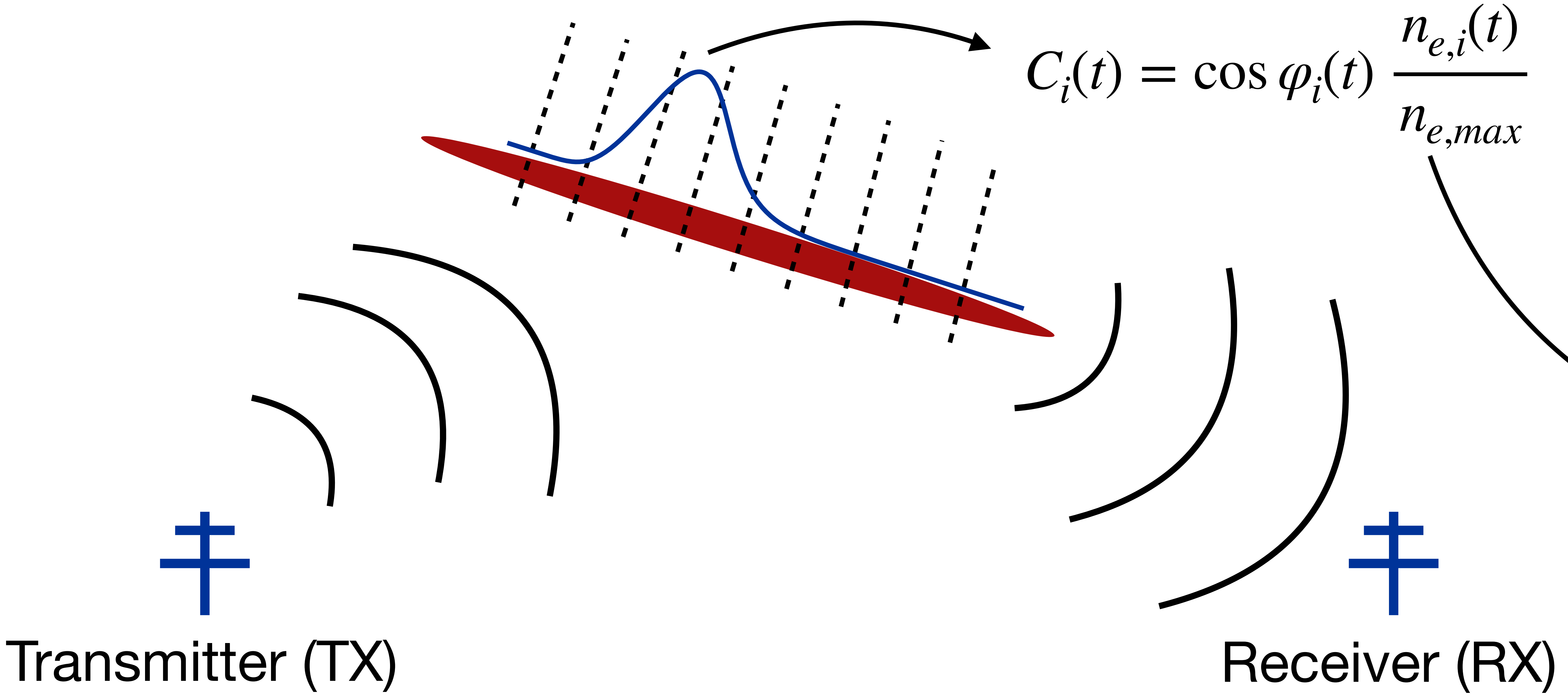




- **3) High-amplitude region**
  - The amount of phase coherence $\longleftrightarrow$ Quantify the vertical orientation of the bands



$$C_i(t) = \cos\varphi_i(t)\,\frac{n_{e,i}(t)}{n_{e,max}}$$

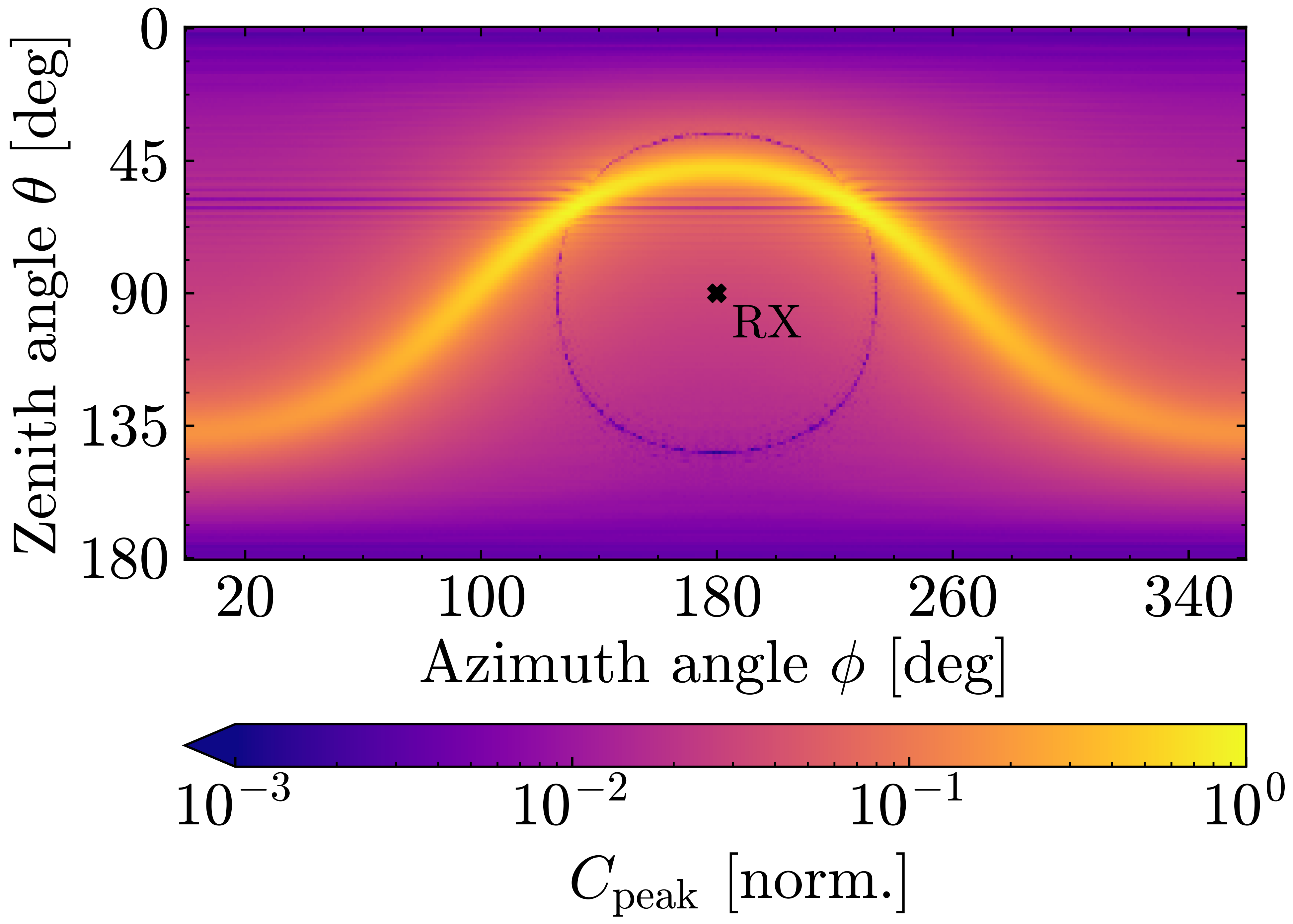
$$C(t) = \left|\sum_{i=1}^{N}\cos\varphi_i(t)\,\frac{n_{e,i}(t)}{n_{e,max}}\right|$$

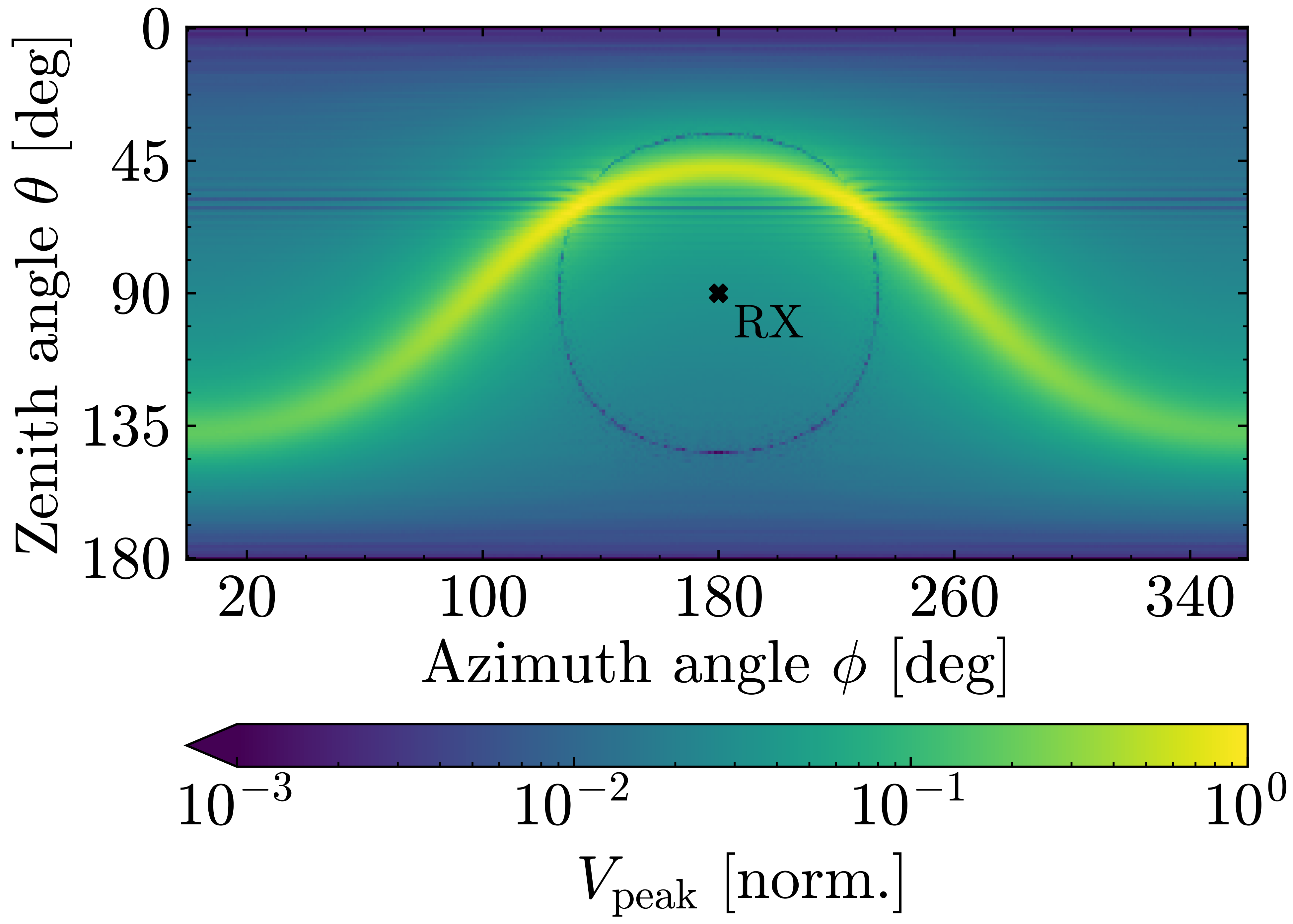
$$\boxed{C_{\text{peak}} = \left.\left|\sum_{j=1}^{M}\left(\frac{n_j(t)}{n_{e^-,max}}\cos\varphi_j(t)\right)\right|\right|_{t=t_{\text{peak}}}}$$

Radar Echo Signal Properties

- **3) High-amplitude region**
  - High-amplitude band is reproduced by C_{peak}
  - All features are described by the concept
  - Phase coherence drives description of radar signals

$$C_{\text{peak}} = \left| \sum_{j=1}^{M} \left(\frac{n_j(t)}{n_{e^-,max}} \cos \varphi_j(t) \right) \right|_{t=t_{\text{peak}}}$$

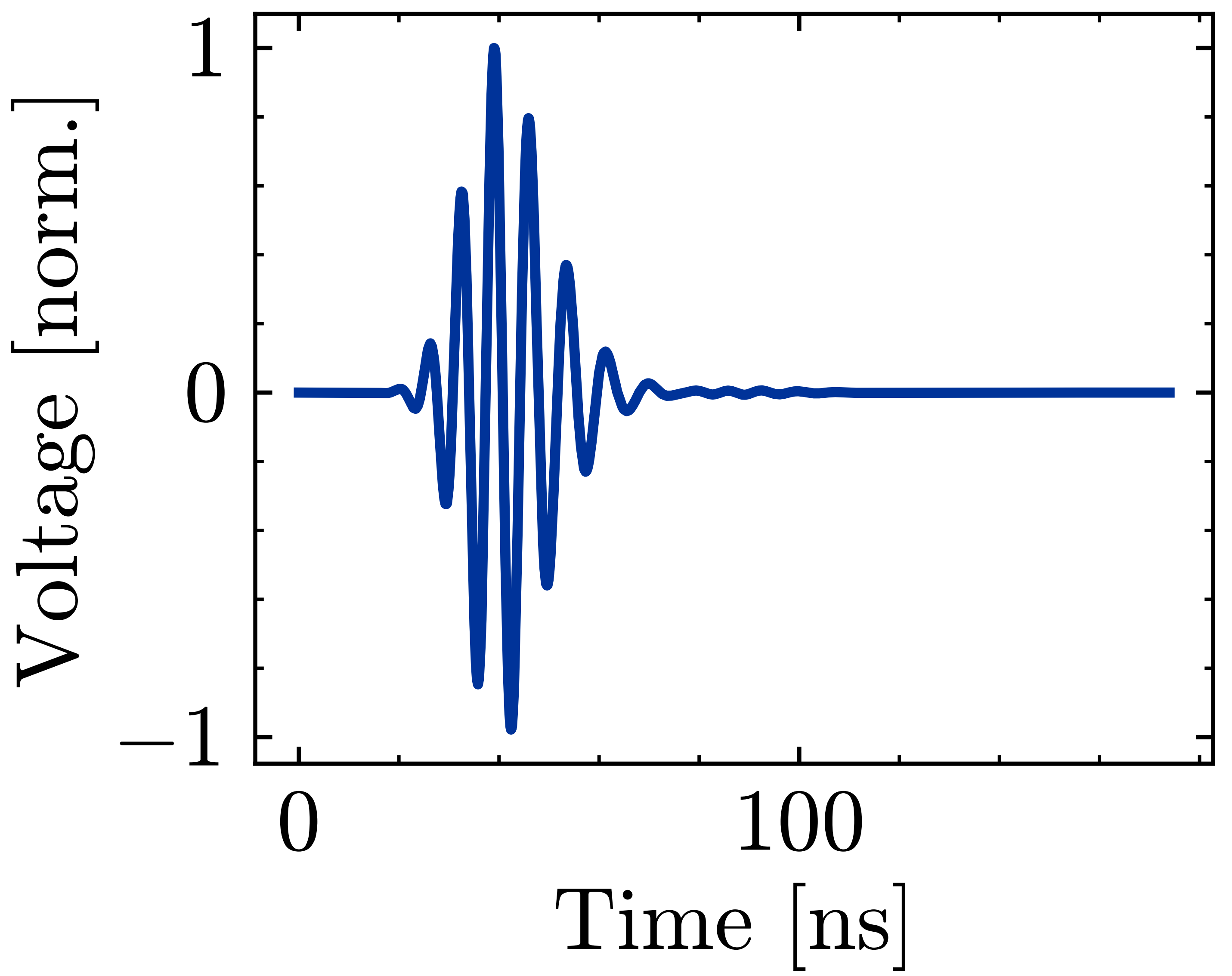


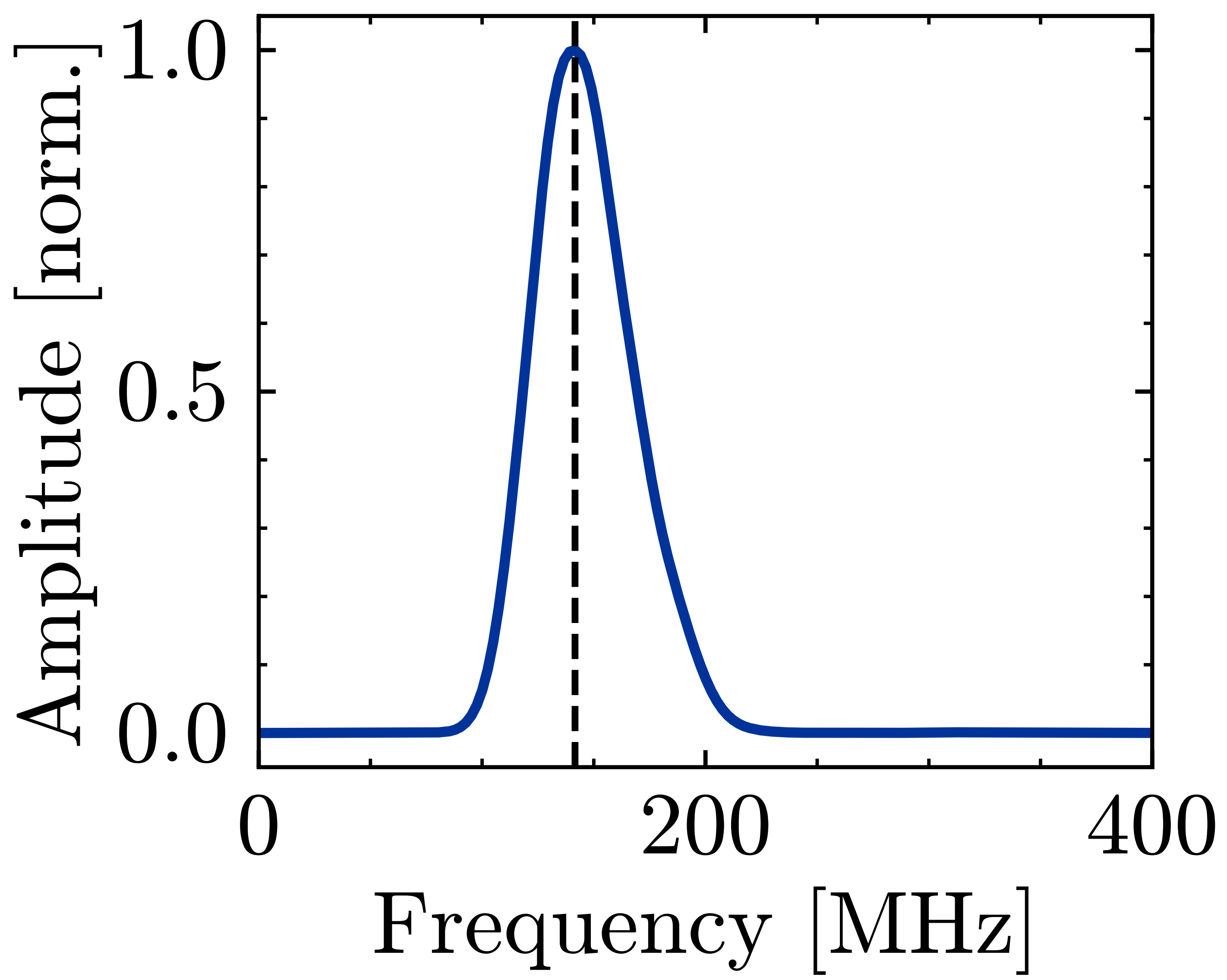


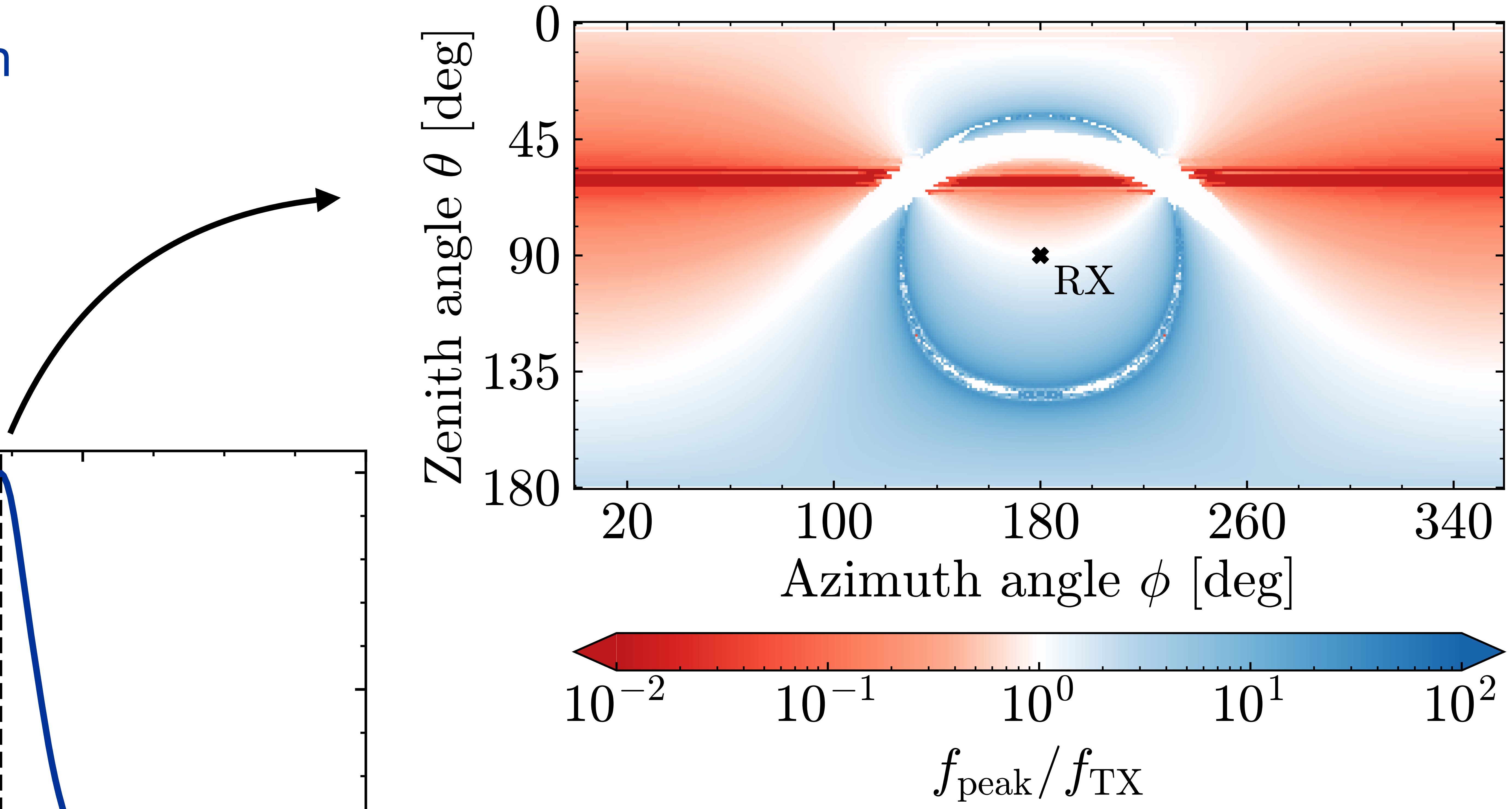
Frequency Domain Signal Properties

Radar Echo Signal Properties

- **The frequency domain**
  - Transform the signals to the frequency domain
  - Extract the peak frequency
  - Strong frequency shifts observed

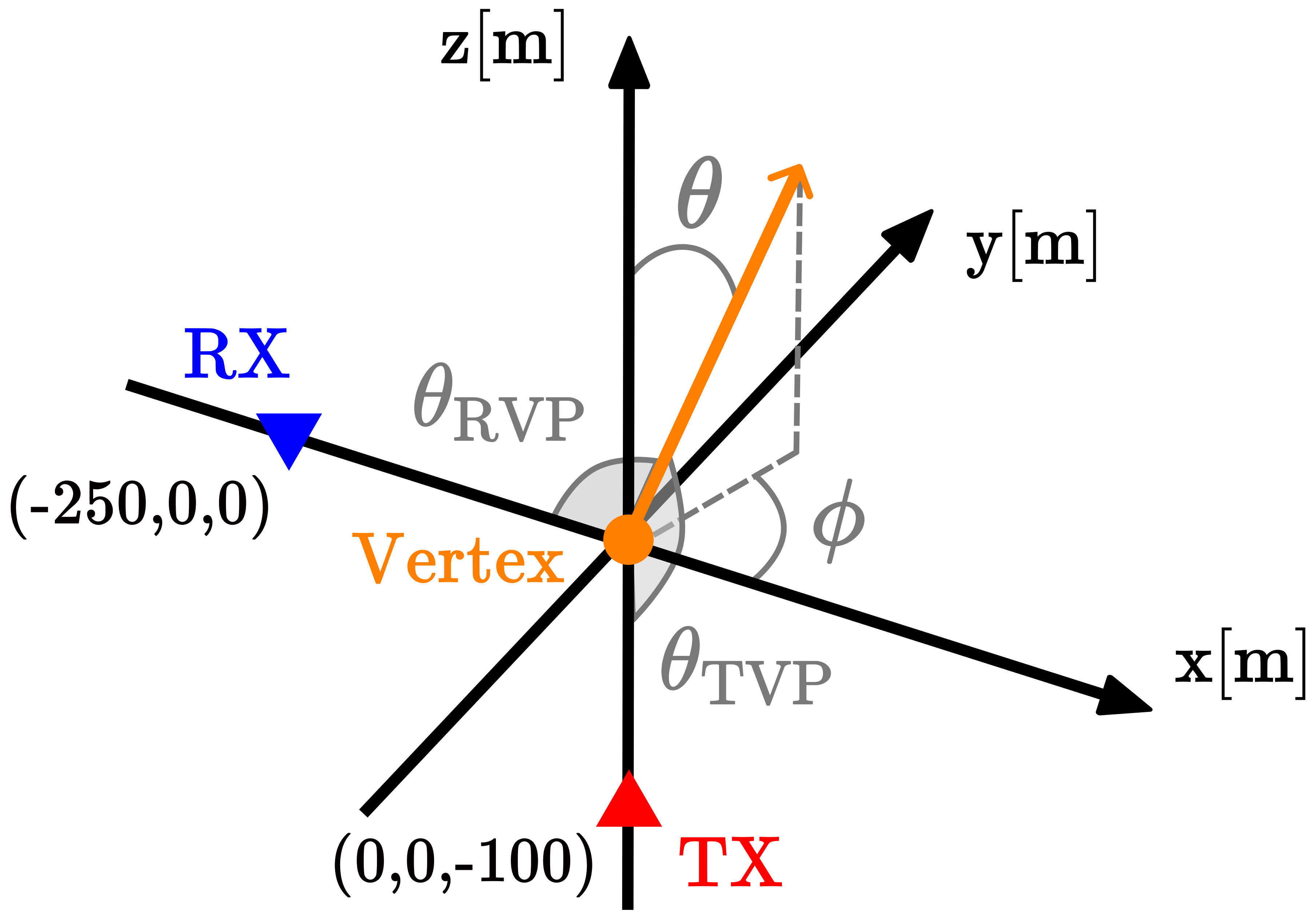






Radar Echo Signal Properties

- **The frequency domain**
  - The shifts can be predicted from first principles
  - Doppler shifts in classical bistatic radar systems are well-understood
    - $$\frac{f_{\mathrm{RX}}}{f_{\mathrm{TX}}} = 1 - \frac{v}{c}\left(\cos\theta_{\mathrm{RVP}} + \cos\theta_{\mathrm{TVP}}\right)$$



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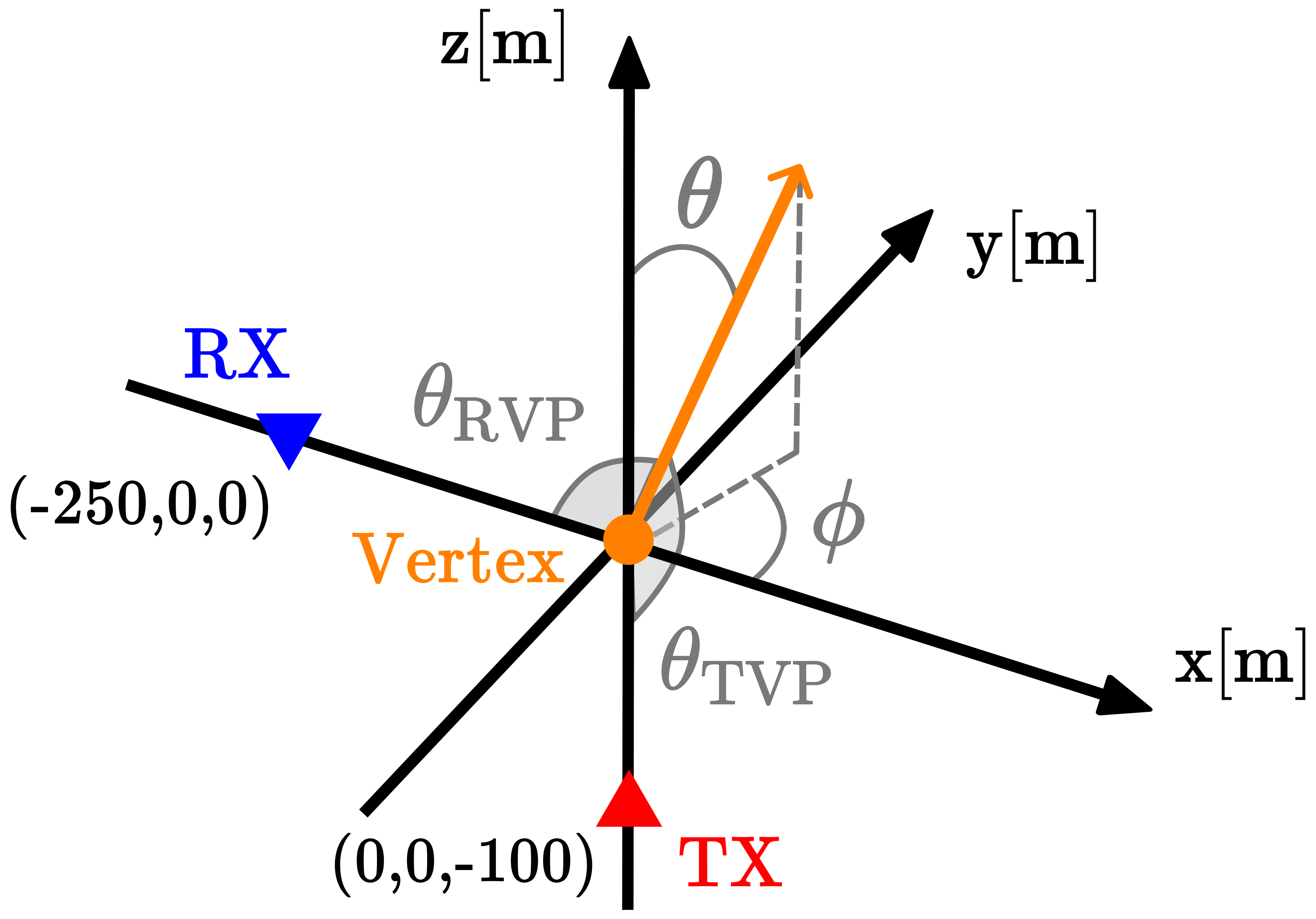
    - $$\cancel{\frac{f_{\mathrm{RX}}}{f_{\mathrm{TX}}} = 1 - \frac{v}{c}\left(\cos\theta_{\mathrm{RVP}} + \cos\theta_{\mathrm{TVP}}\right)}$$
  - Our system moves relativistically
    - $$\frac{f_{\mathrm{RX}}}{f_{\mathrm{TX}}} = \left|\frac{1 + n\beta\cos\theta_{\mathrm{TVP}}}{1 - n\beta\cos\theta_{\mathrm{RVP}}}\right|$$

I. Loudon, J. Loonen, et al., (RET Collaboration), *Exploring Signal Properties of Radar Echoes from High-Energy Particle Cascades.*



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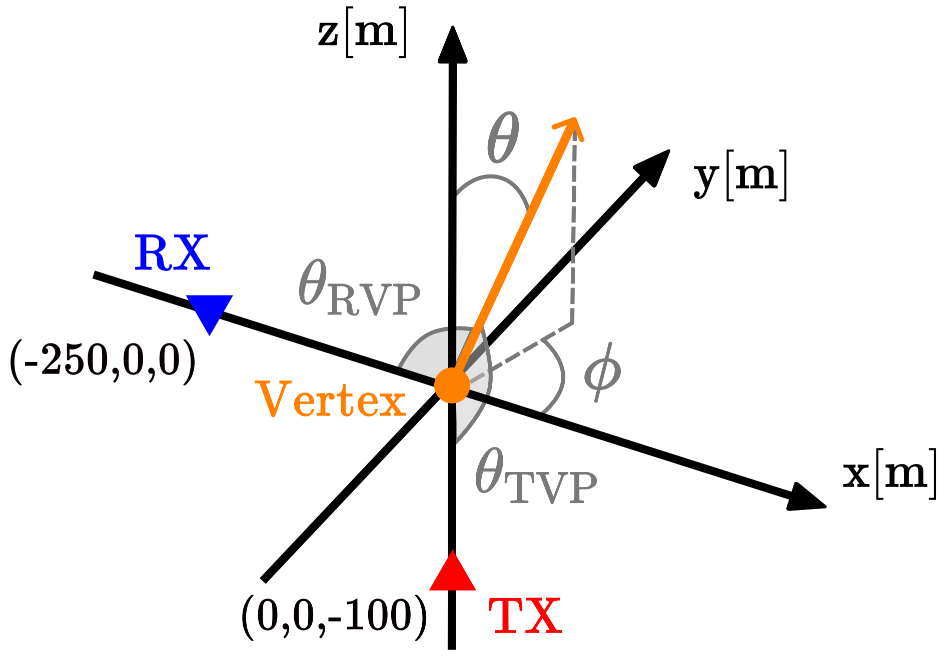
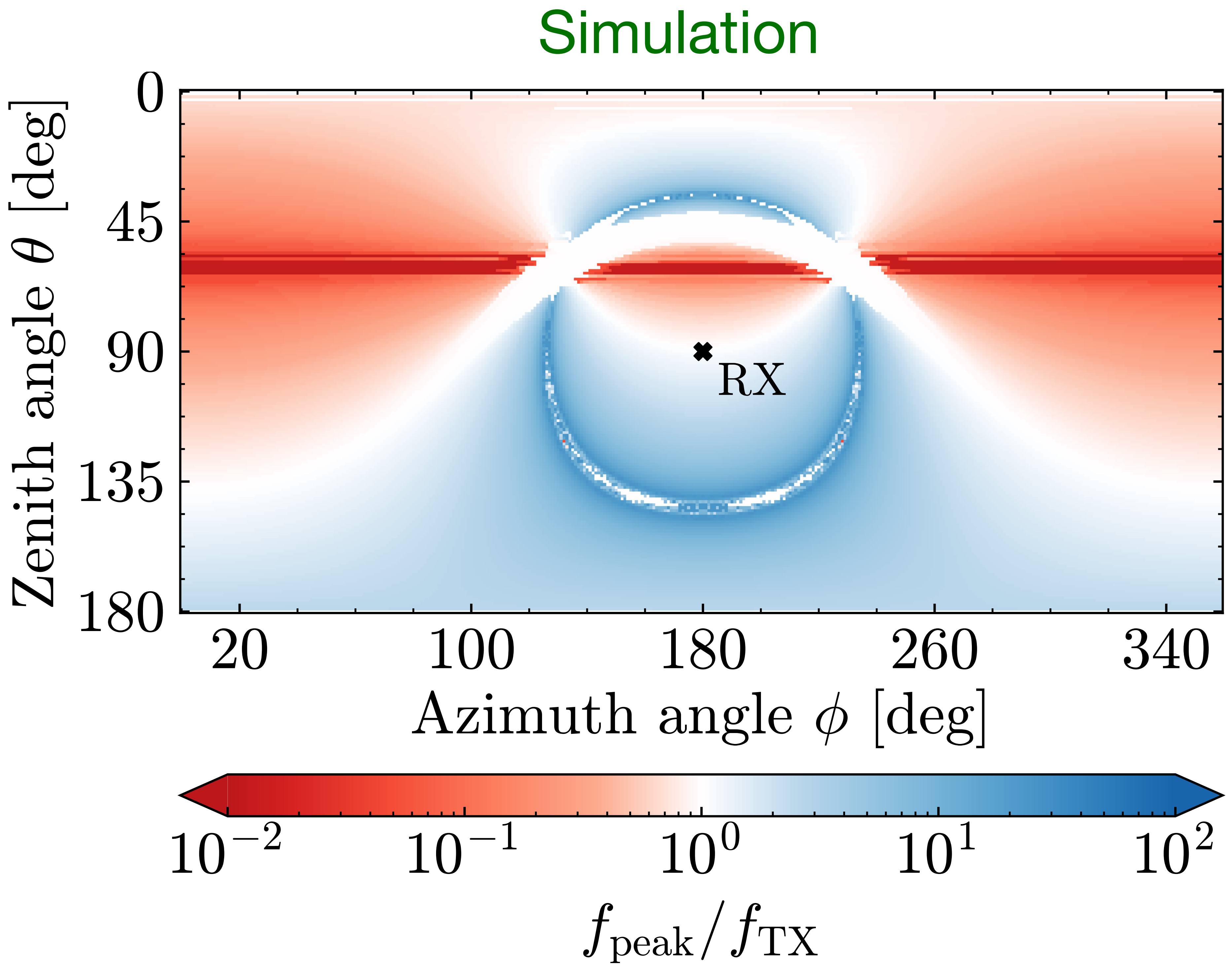
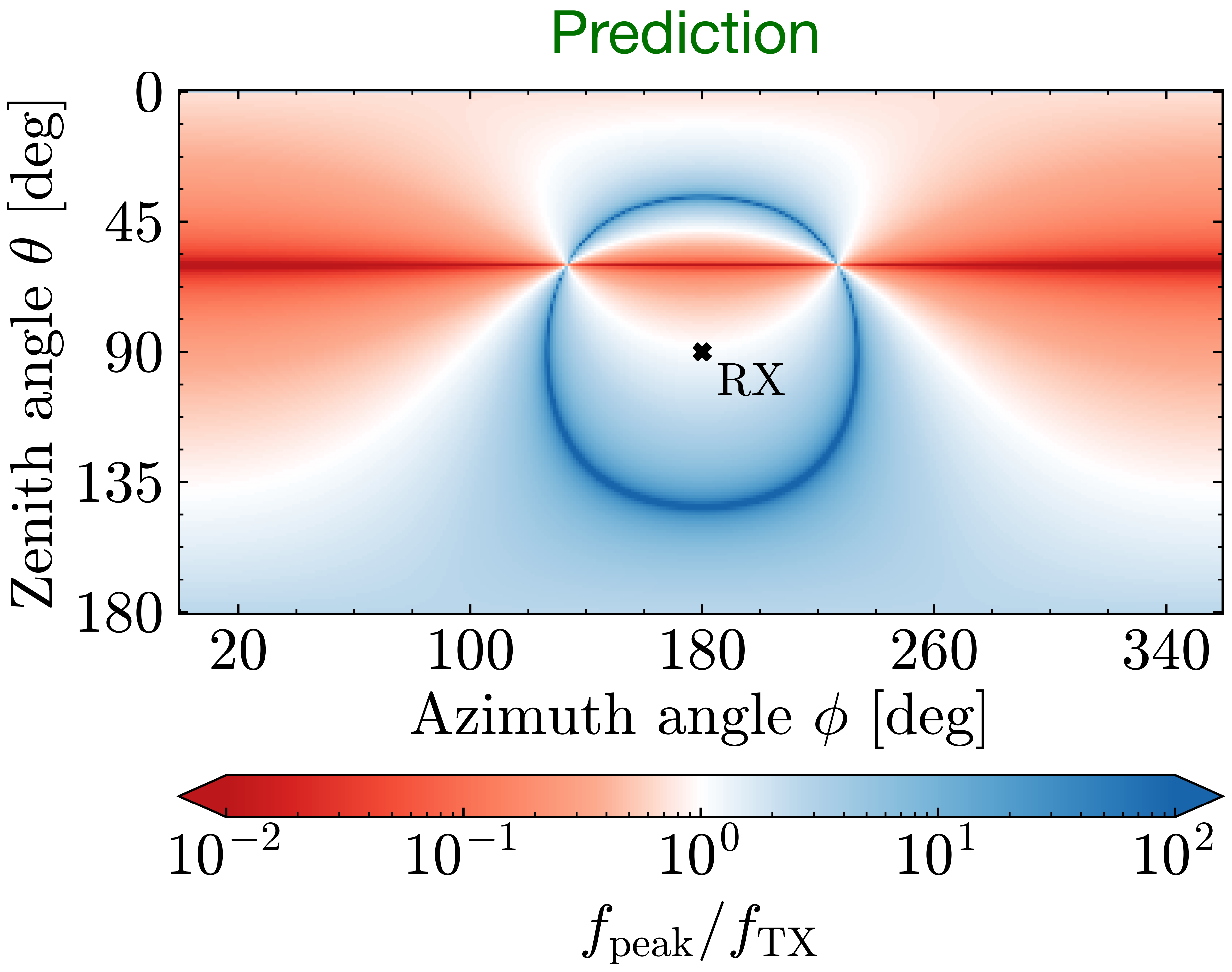
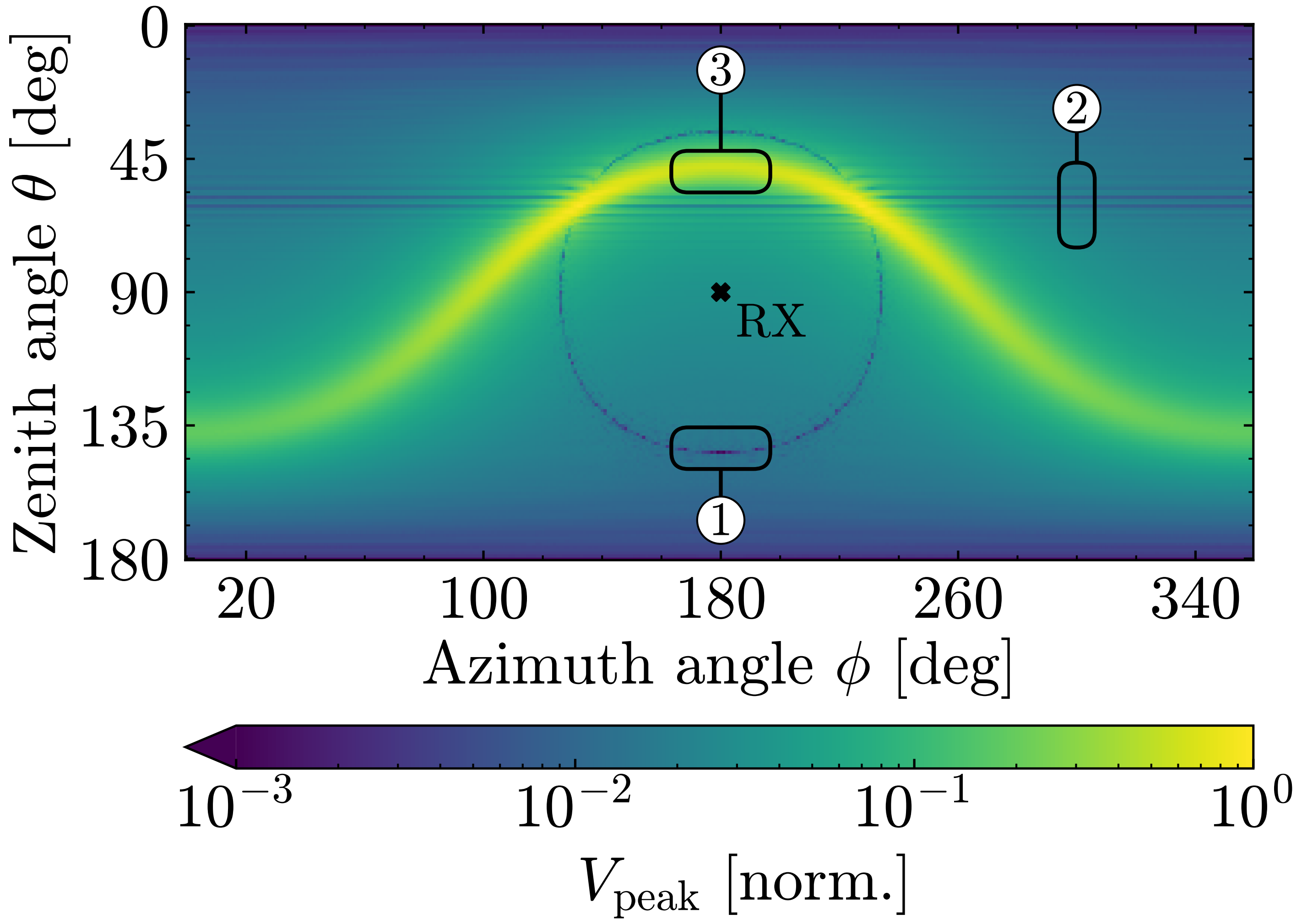


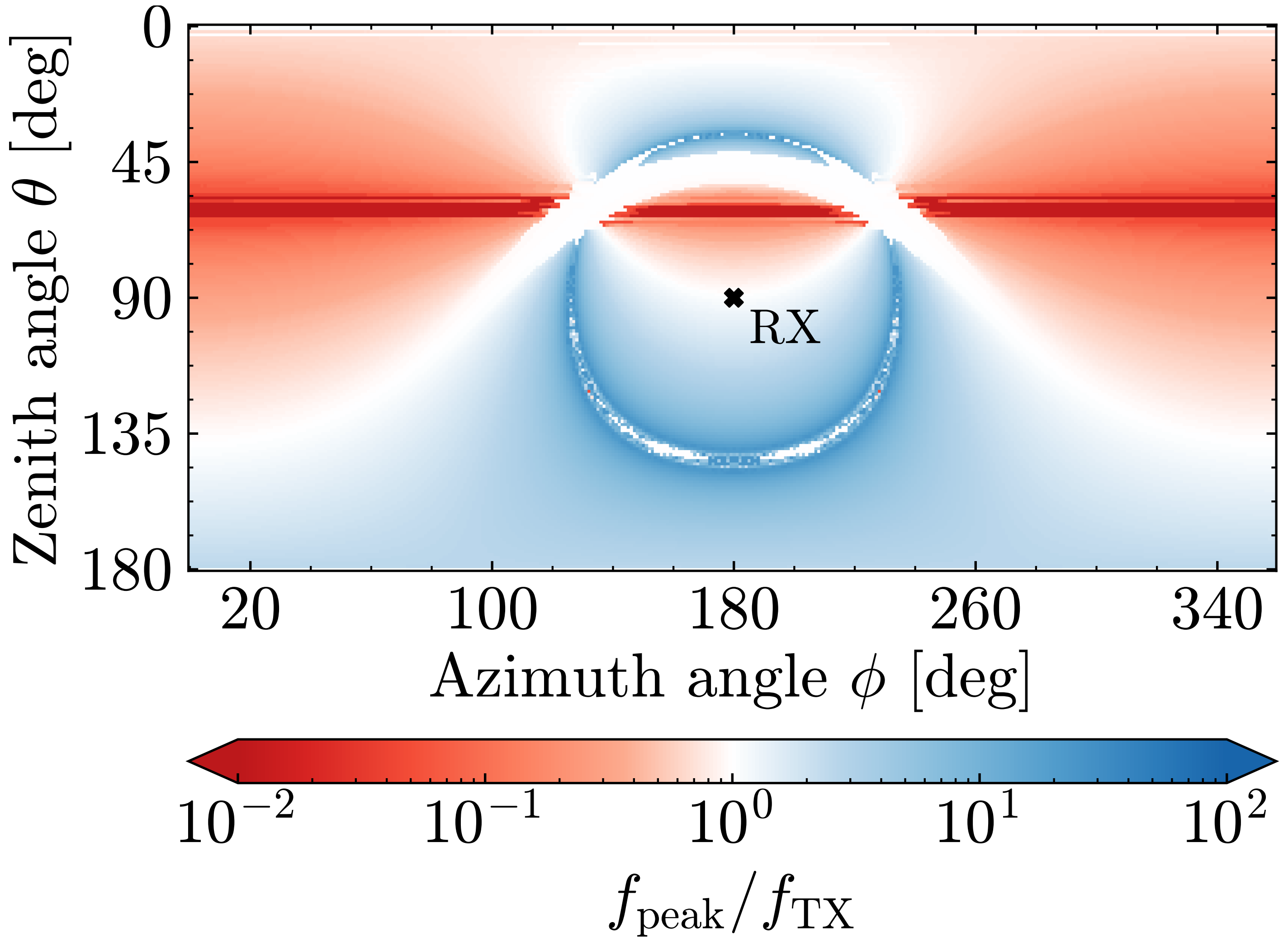




Radar Echo Signal Properties

MARES model

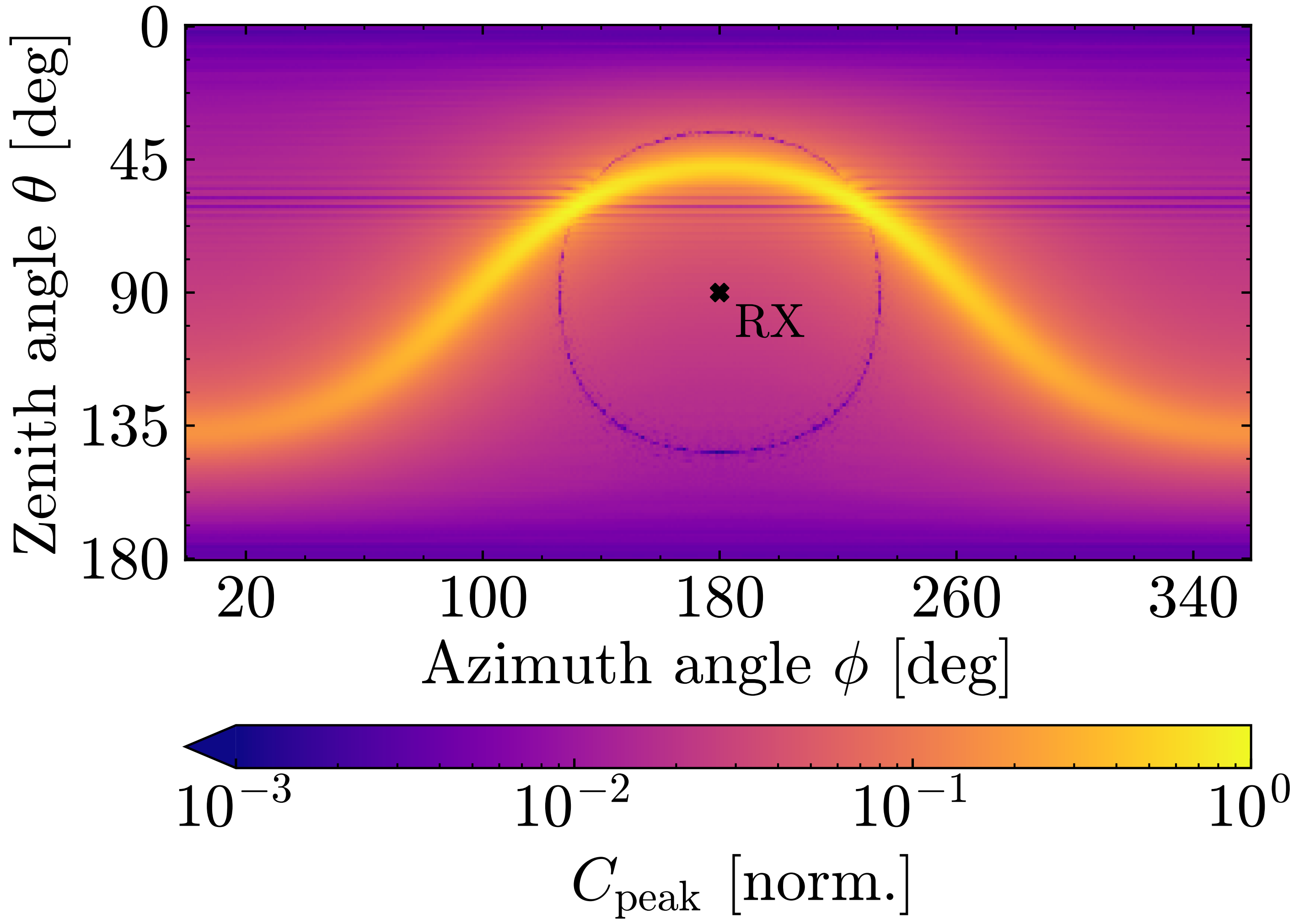


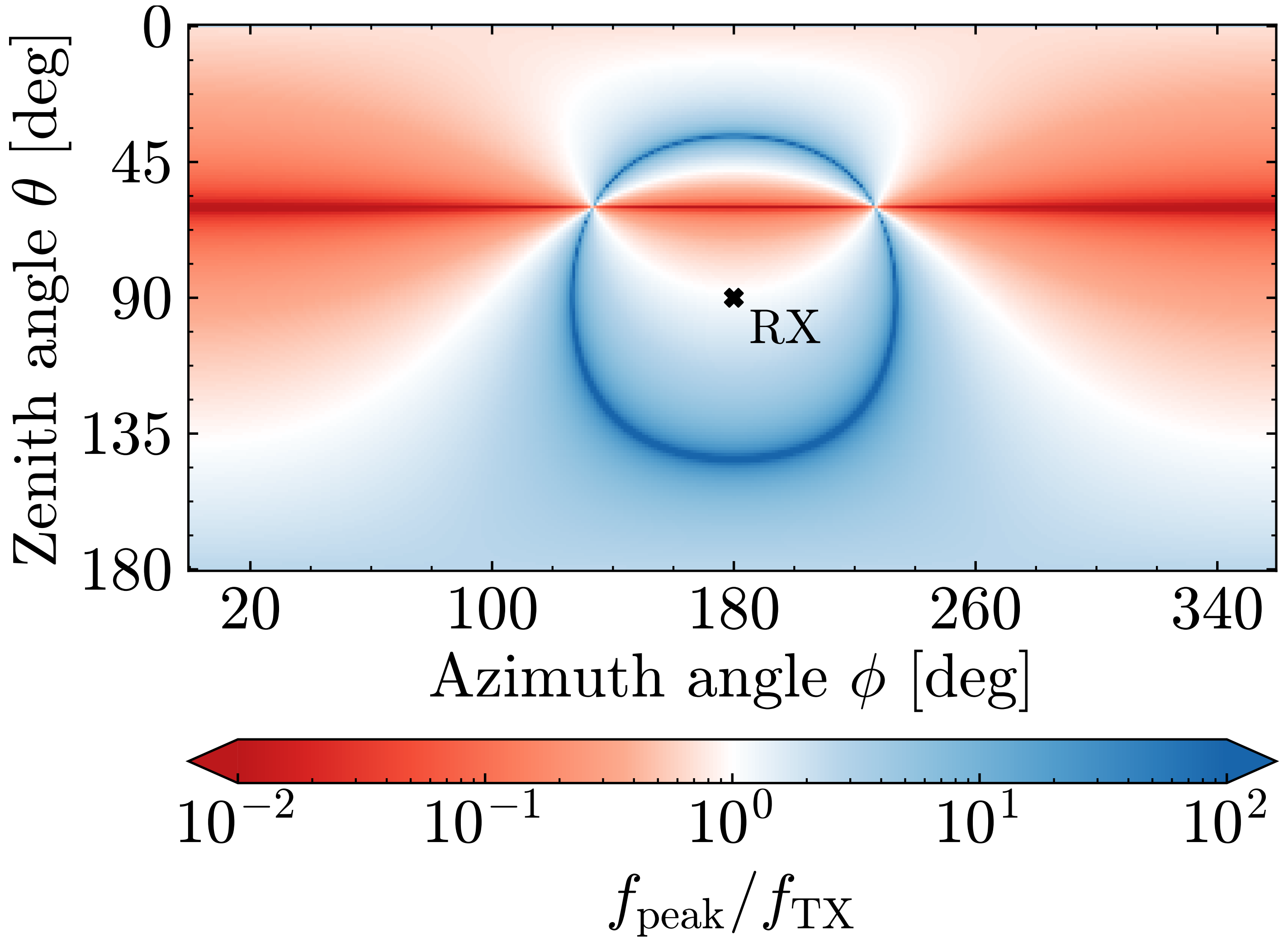


$$C_{\text{peak}} = \left| \sum_{j=1}^{M} \left(\frac{n_j(t)}{n_{e^-,max}} \cos \varphi_j(t) \right) \right|_{t=t_{\text{peak}}}$$

$$\frac{f_{\text{RX}}}{f_{\text{TX}}} = \left| \frac{1 + n\beta \cos \theta_{\text{TVP}}}{1 - n\beta \cos \theta_{\text{RVP}}} \right|$$

Analytical formula

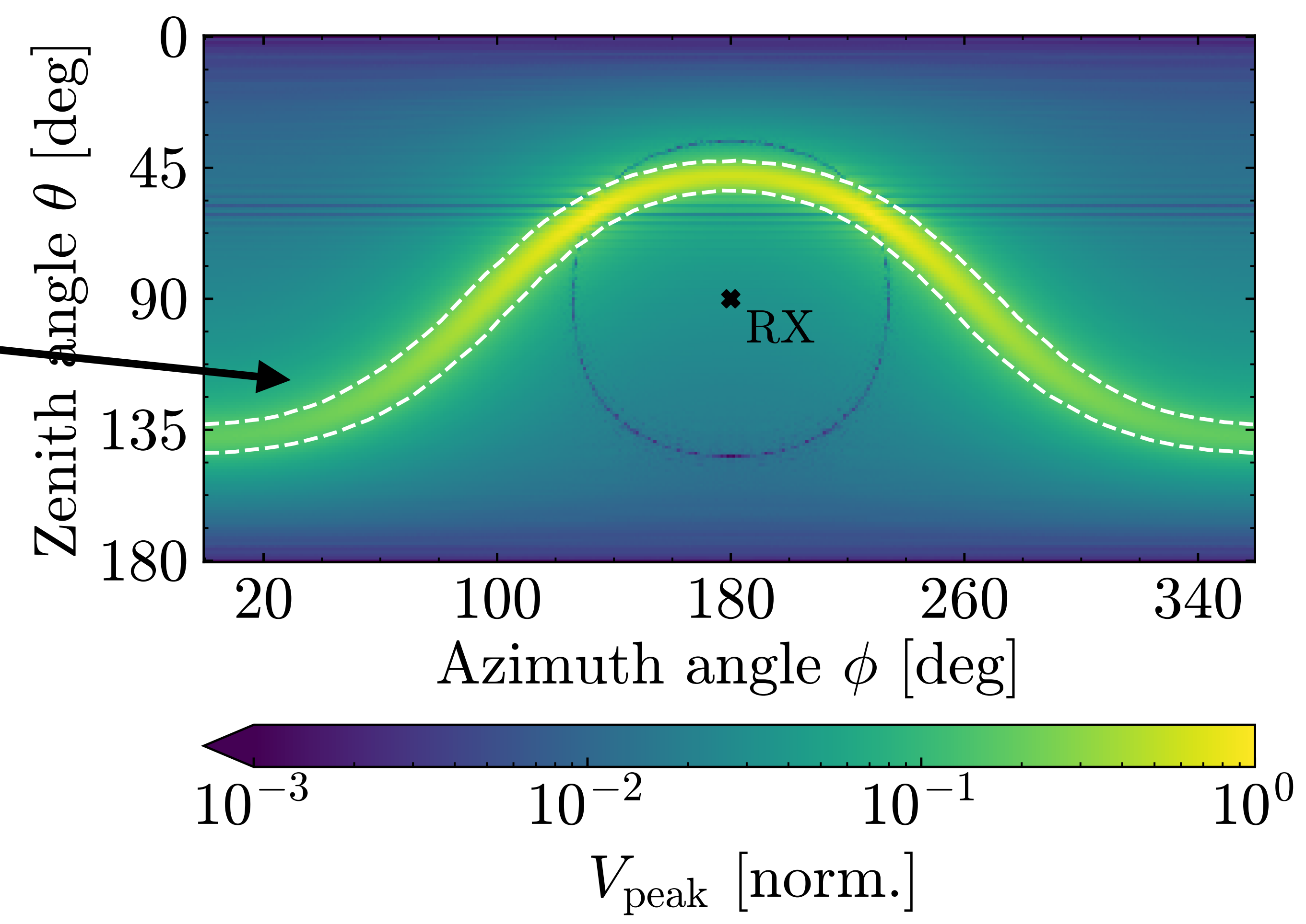


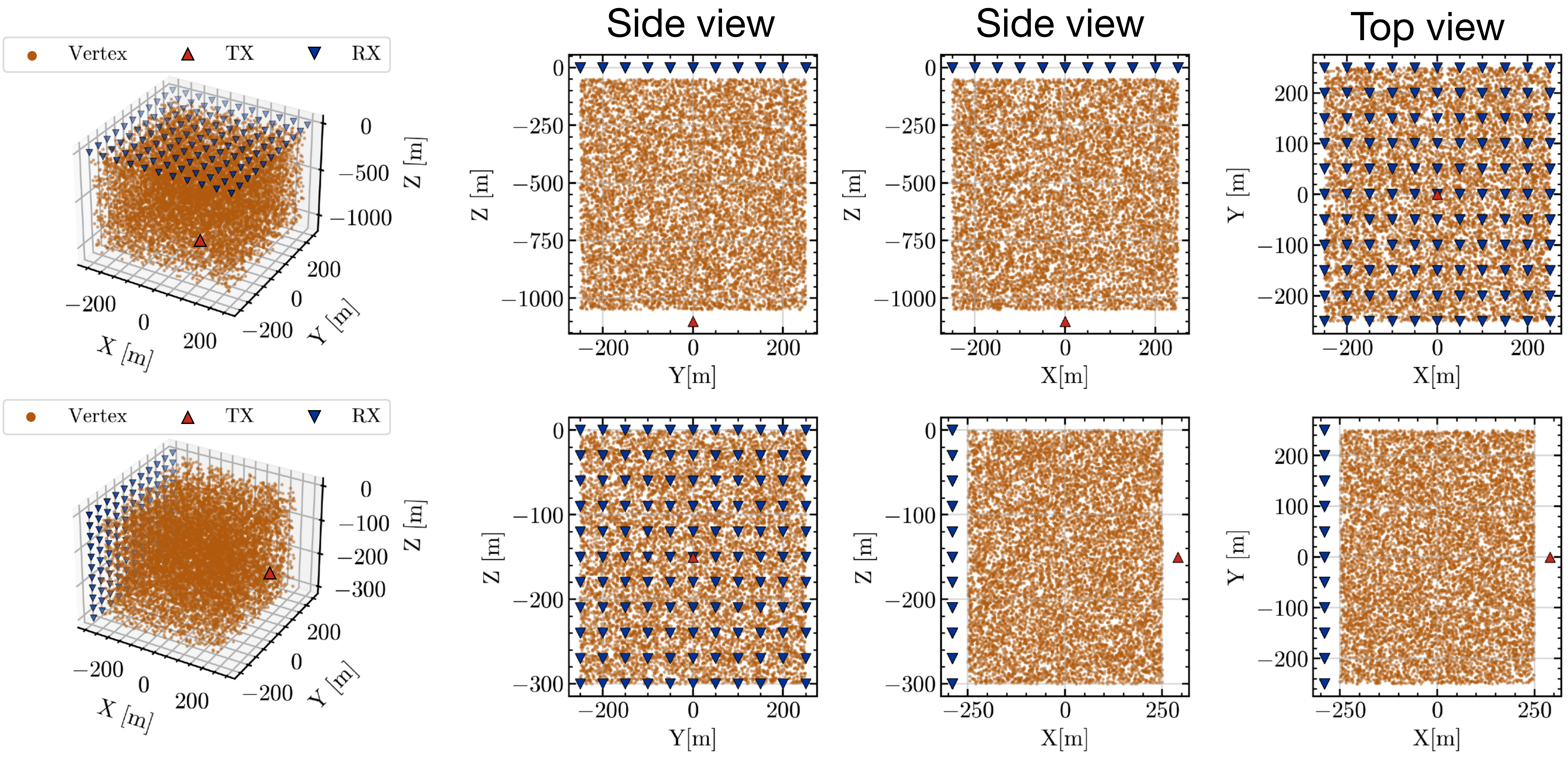


Signal Properties and Detector Optimisation

Detector Optimisation

- **Signal properties and detector optimisation**
  - Arrival directions in strong coherence band are favourable
    - Large peak amplitude and reflection at the transmit frequency





- Random vertex position ($N = 10^4$)
- Realistic arrival directions
- **Back of the envelope estimate**

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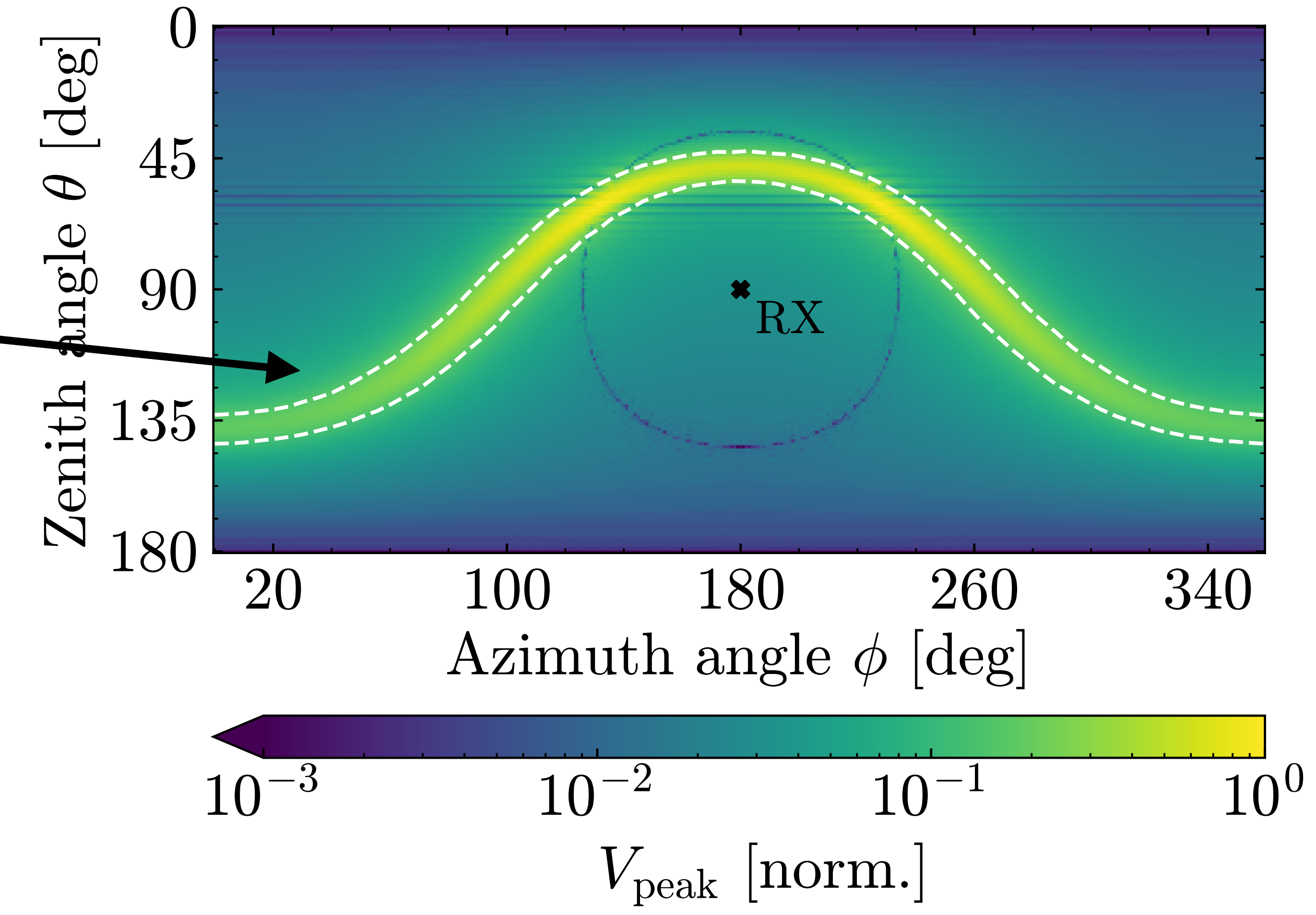
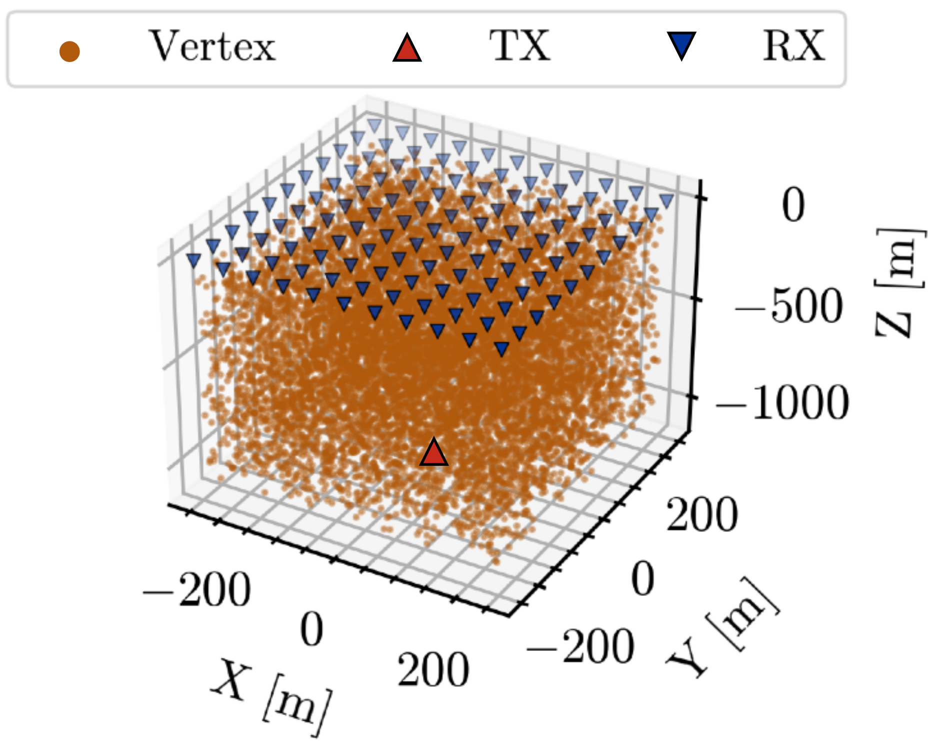
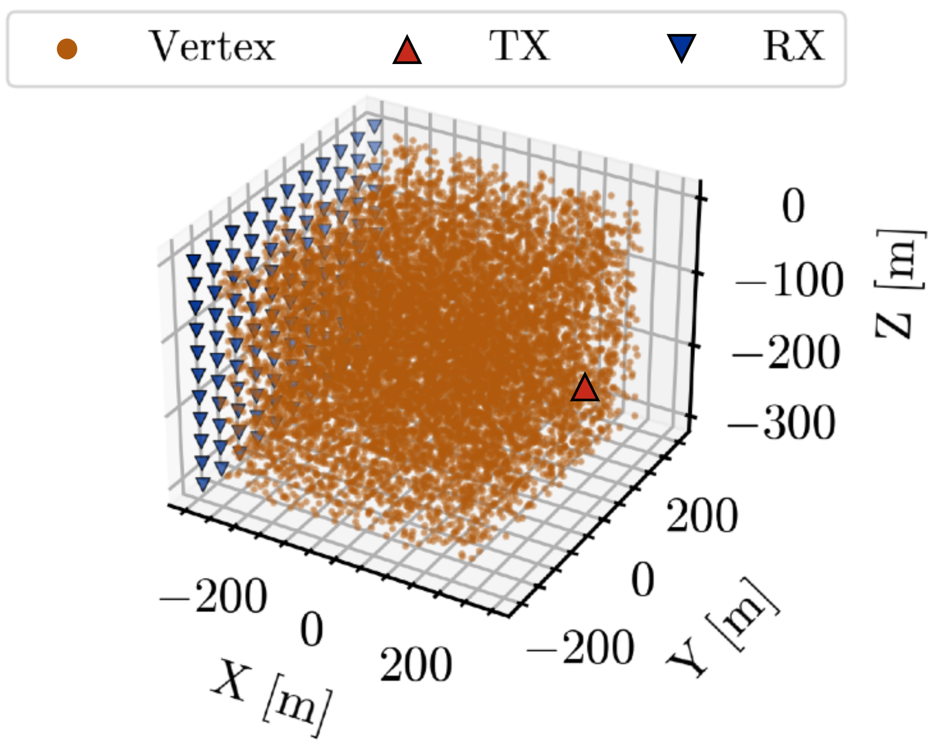
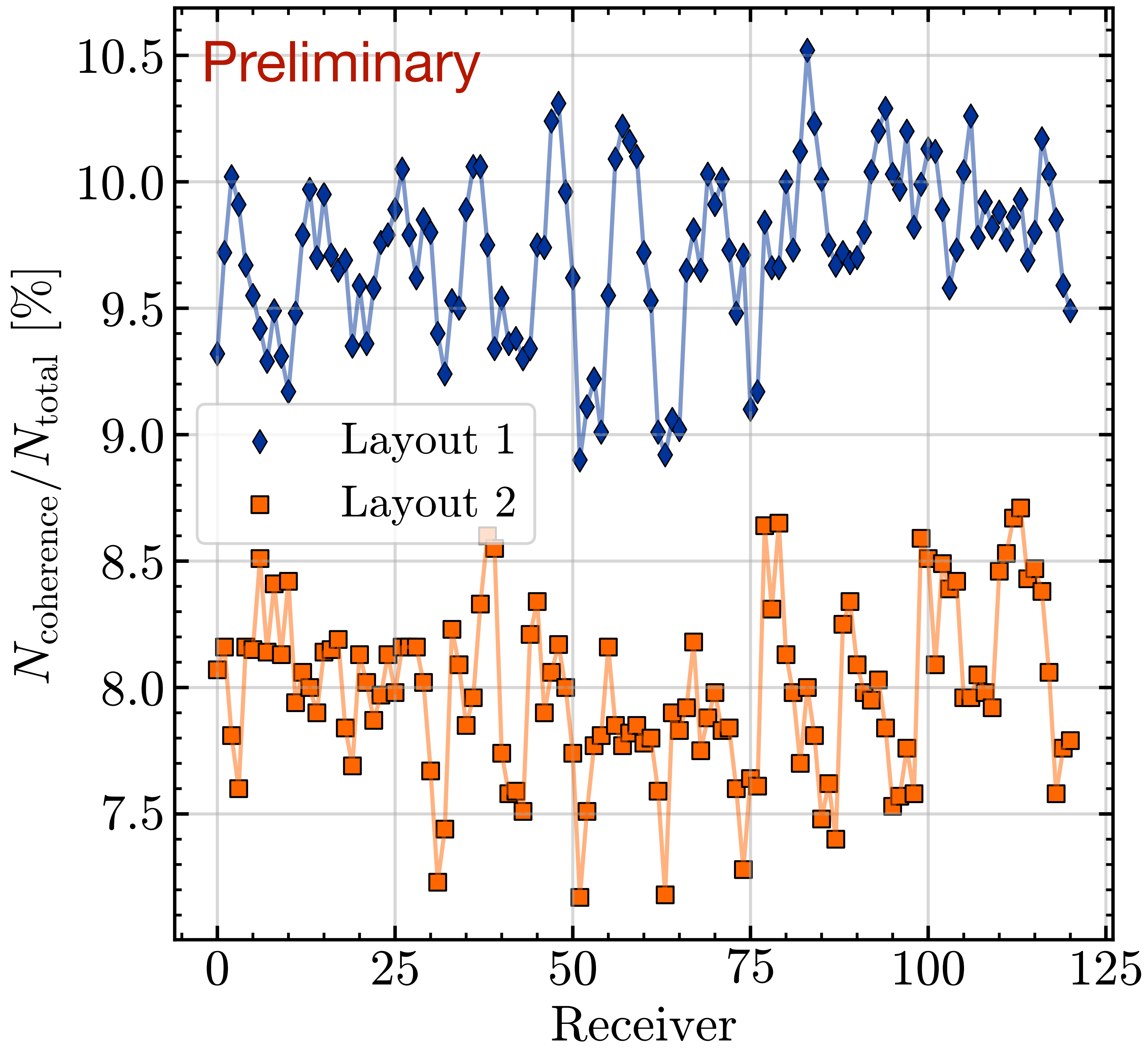








- Random vertex position ($N = 10^4$)
- Realistic arrival directions
- **Back of the envelope estimate**

RADAR ECHO TELESCOPE

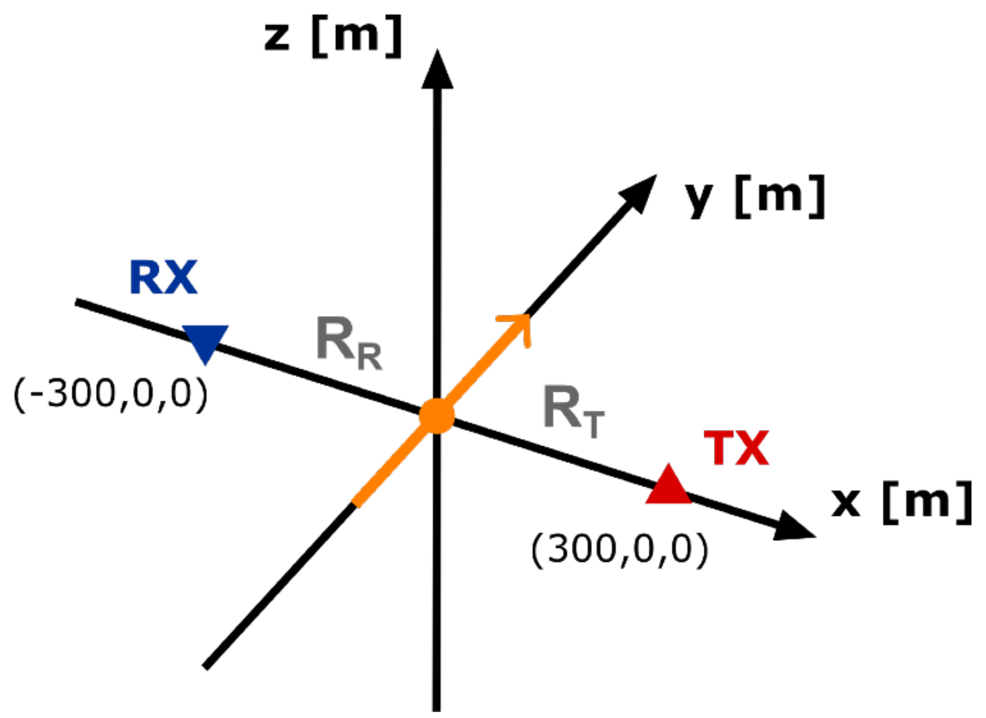
THANK YOU!

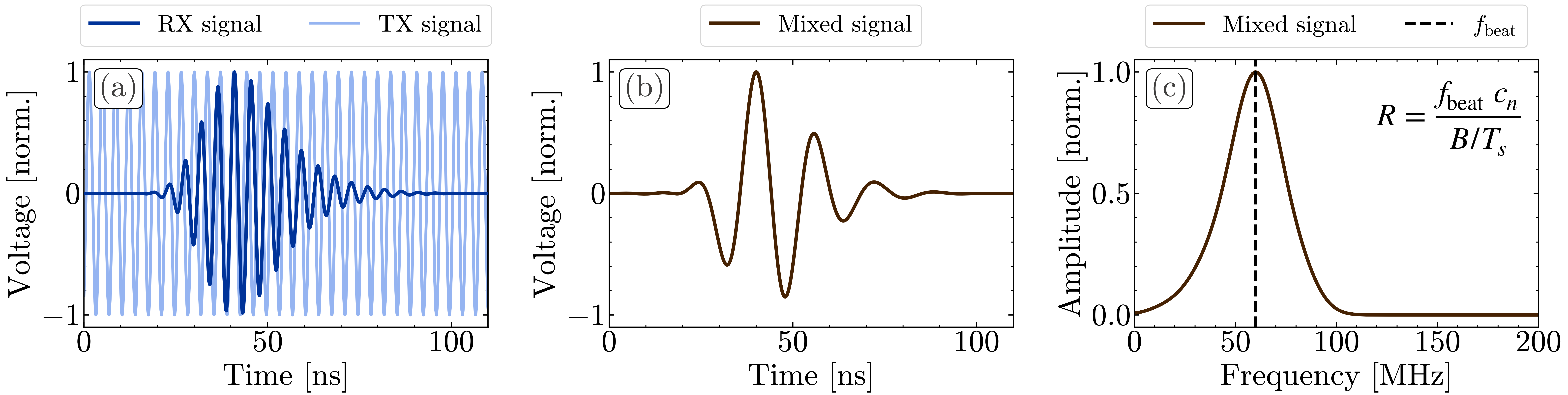
Jannes Loonen

fwo VUB VRIJE UNIVERSITEIT BRUSSEL iihe BRUXELLES BRUSSEL NSF European Research Council Established by the European Commission

- **Frequency-modulated continuous-wave radar**
  - Reconstruct distance to the neutrino vertex
  - Heterodyning as signal processing technique
  - Promising results in preliminary study: PoS(ARENA2026)040

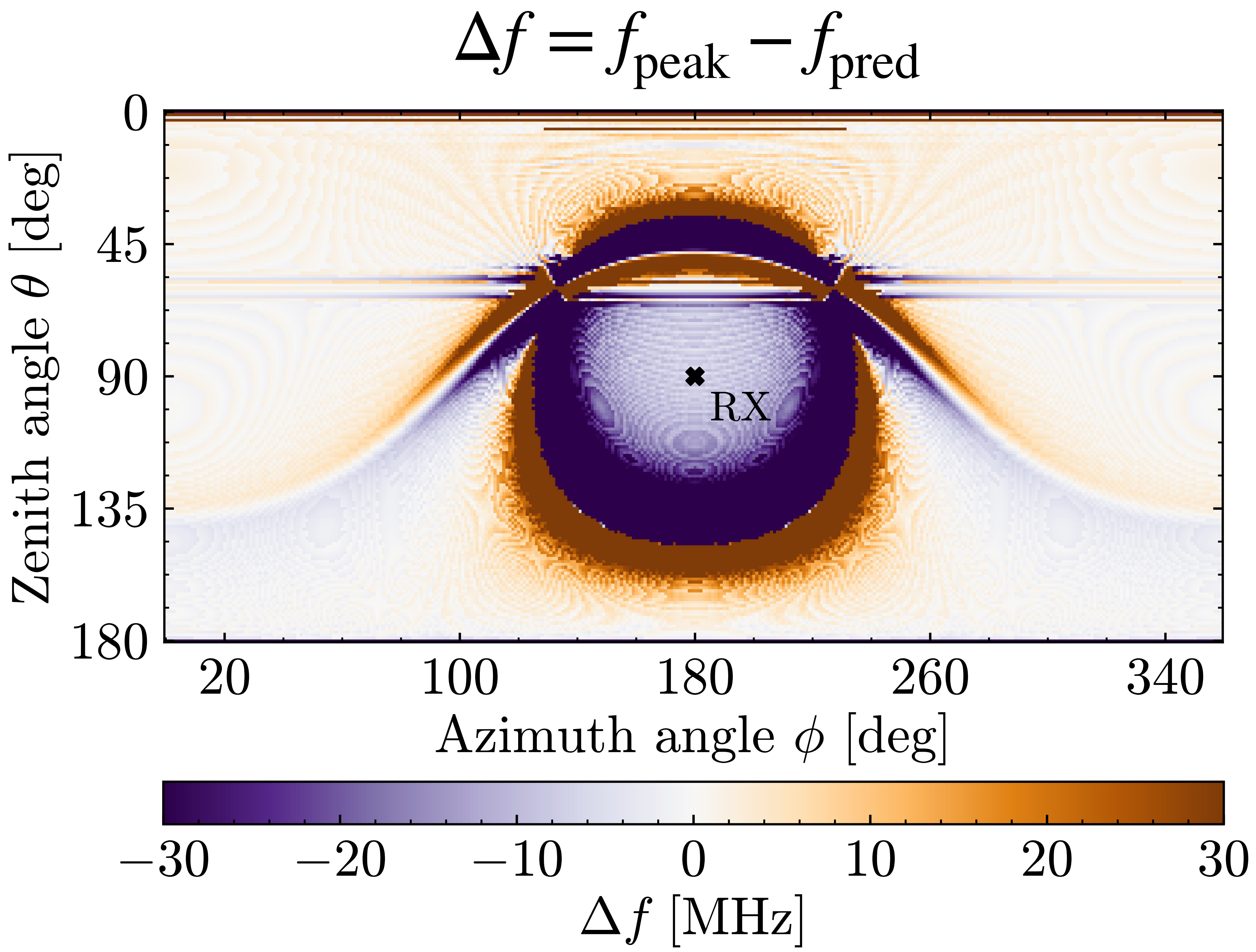
$R_{\text{true}} = 600$ m
$R_{\text{reco}} \approx 605$ m

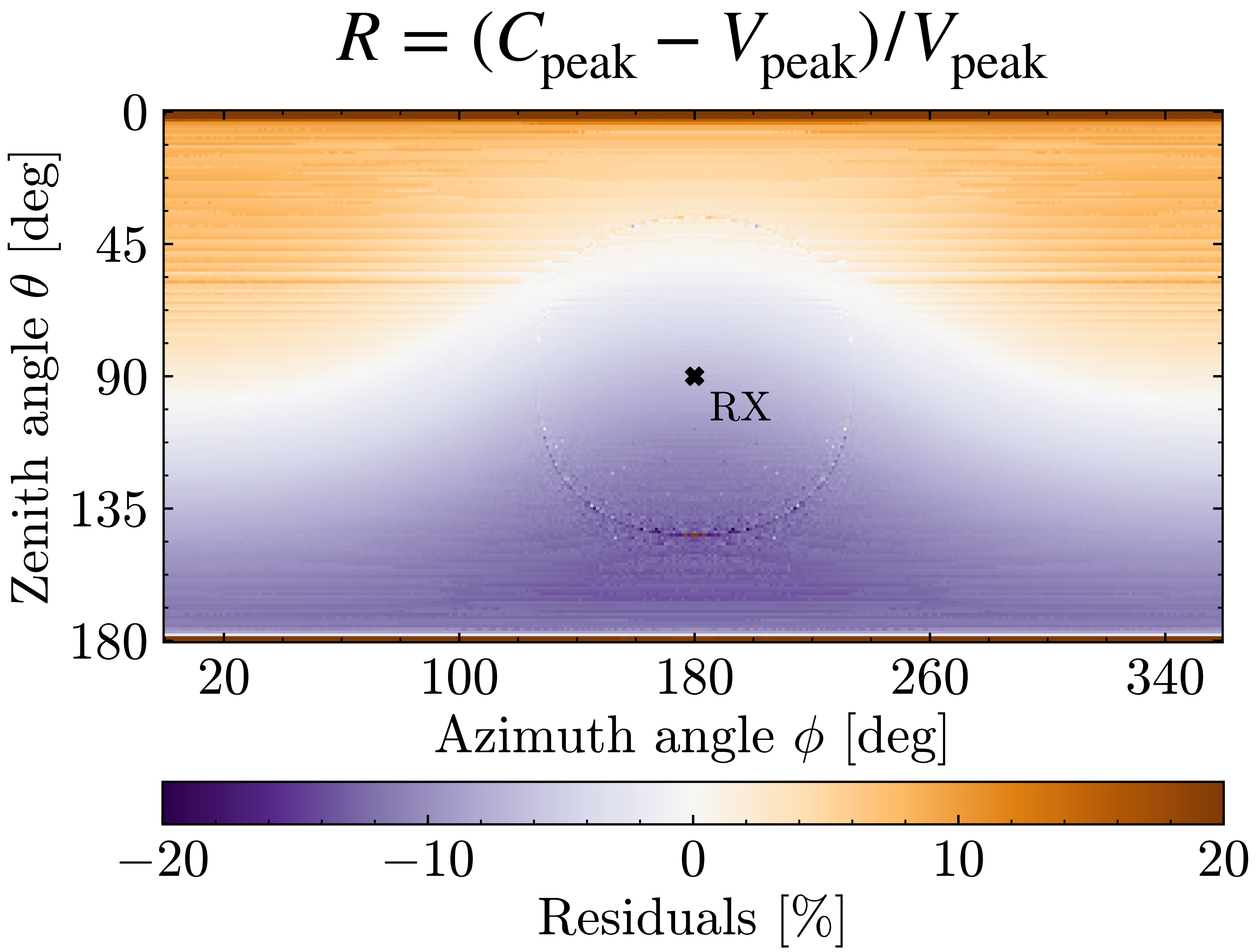




Accuracy Analytical descriptions

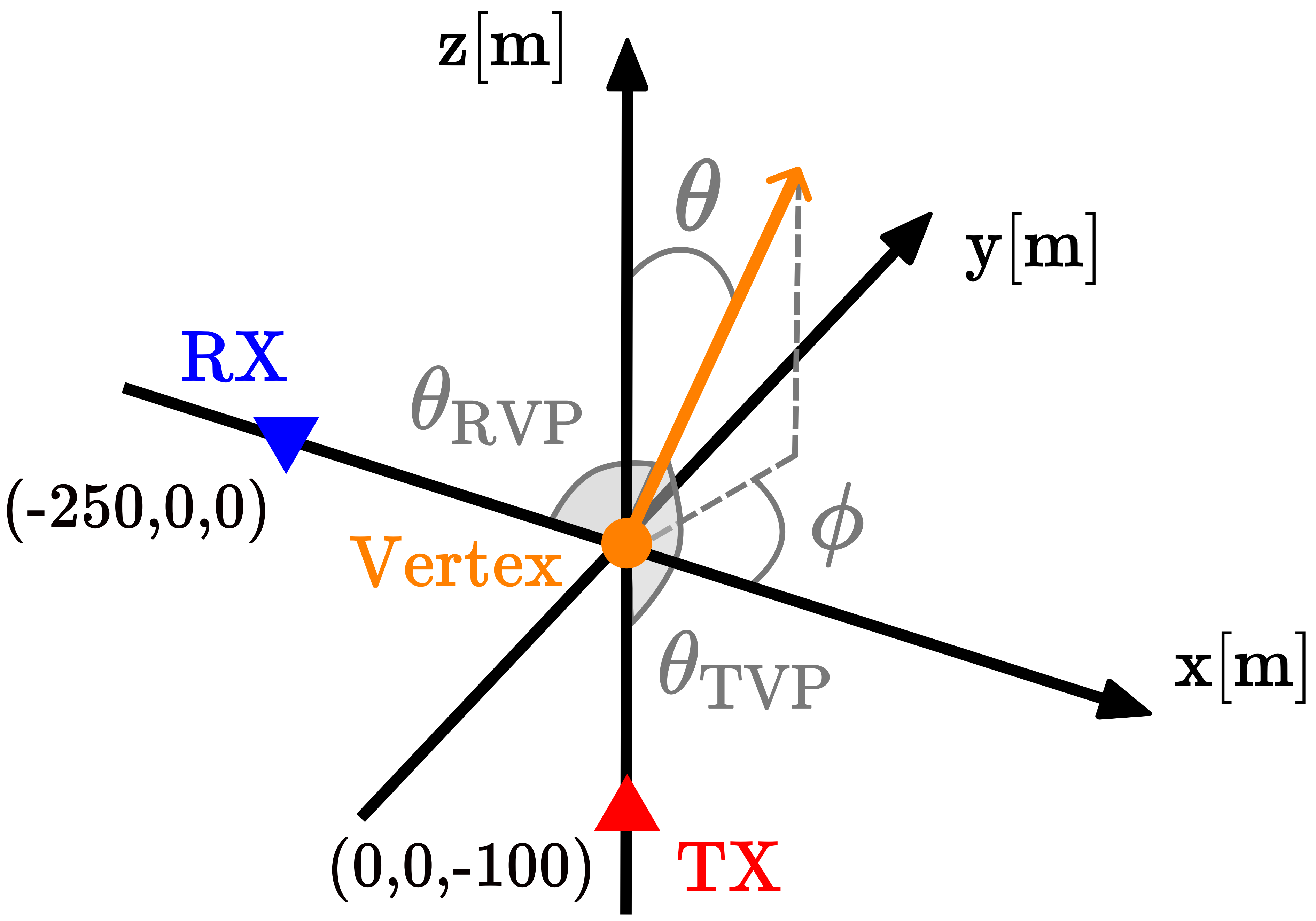
- **Residuals and absolute difference**
  - $\Delta f_{\text{med}} = 2.3$ MHz
  - $R_{\text{med}} = 6.6\,\%$

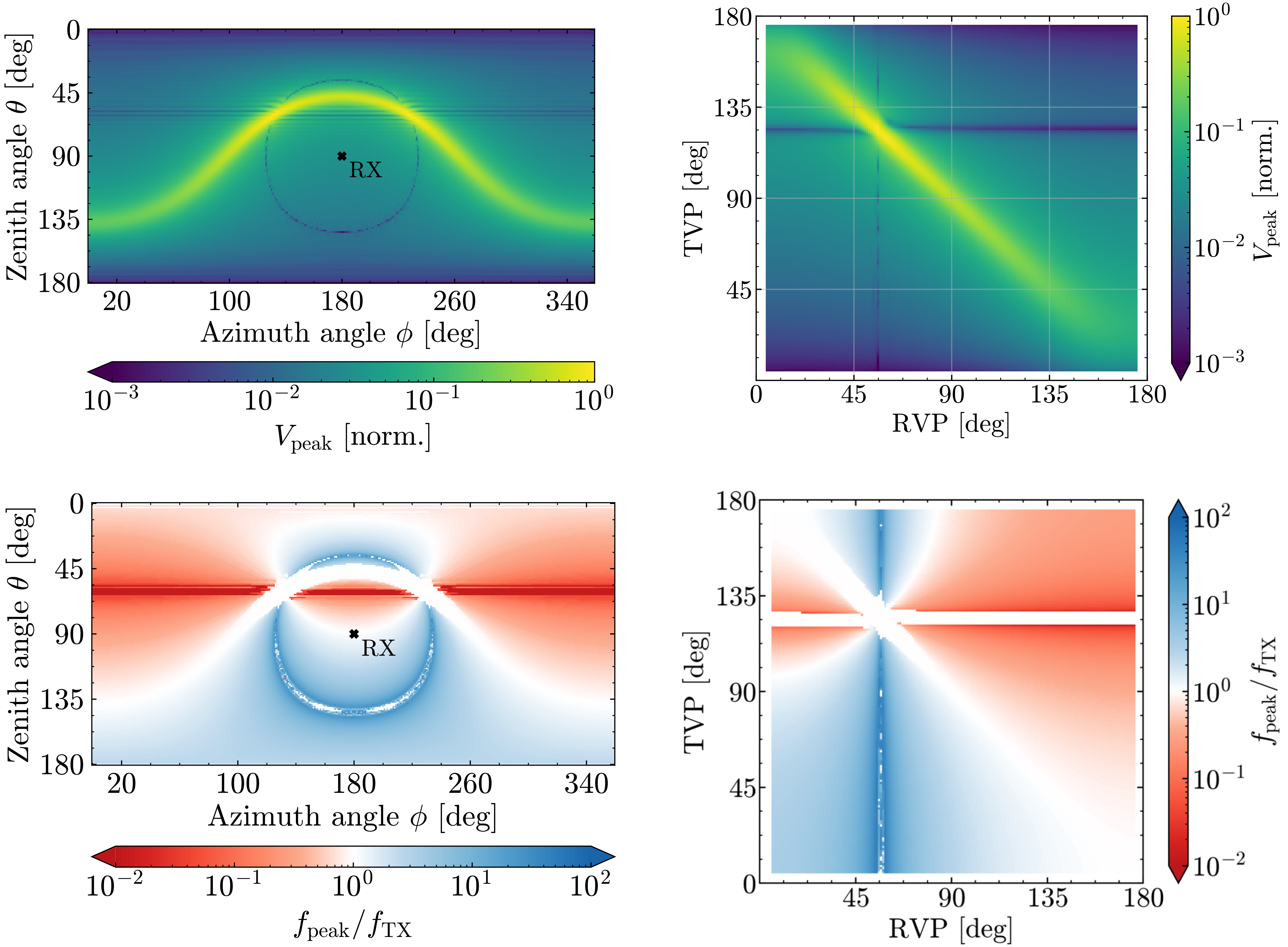




Radar specific coordinates

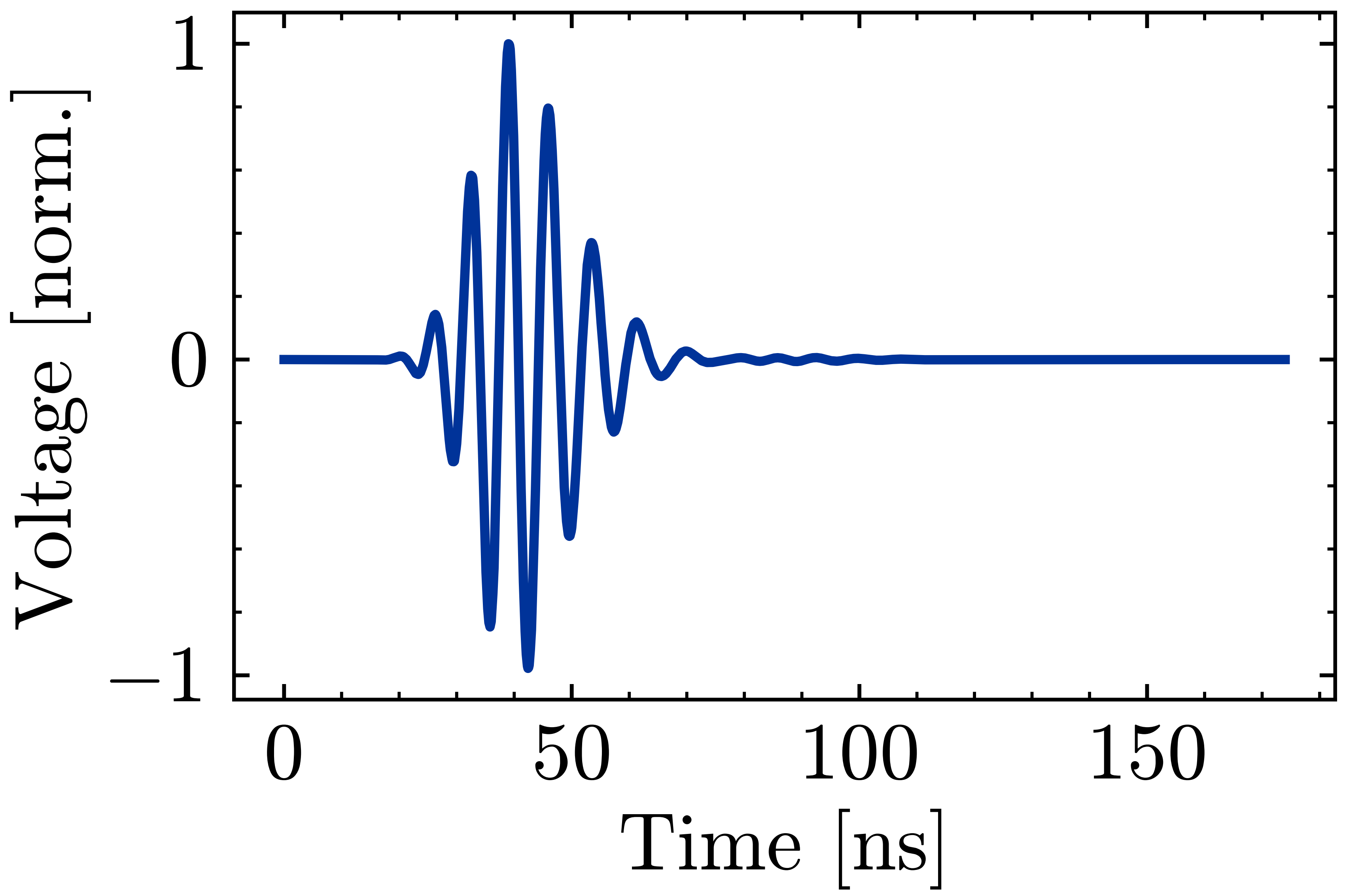
- **RVP and TVP vs (θ, ϕ)**

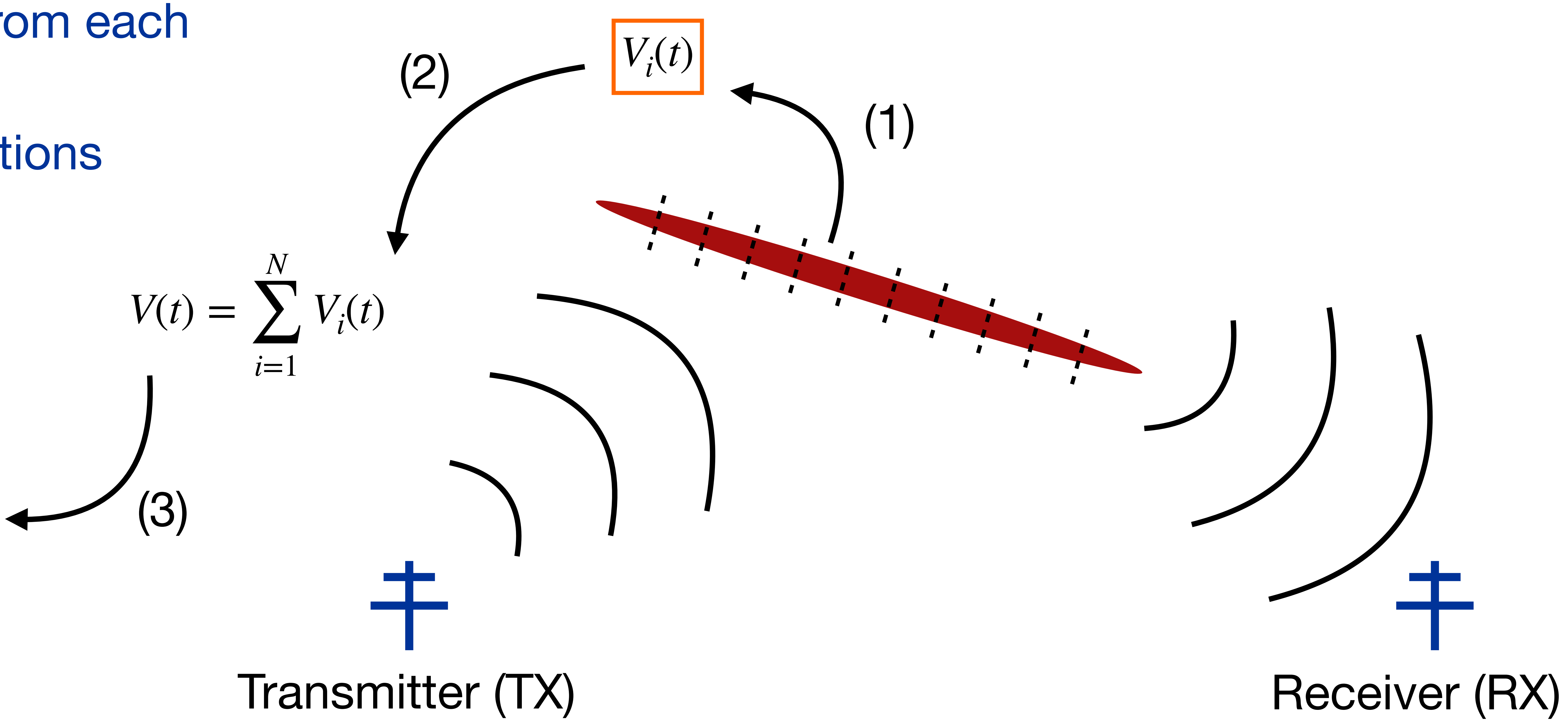




Simulating Radar Echoes

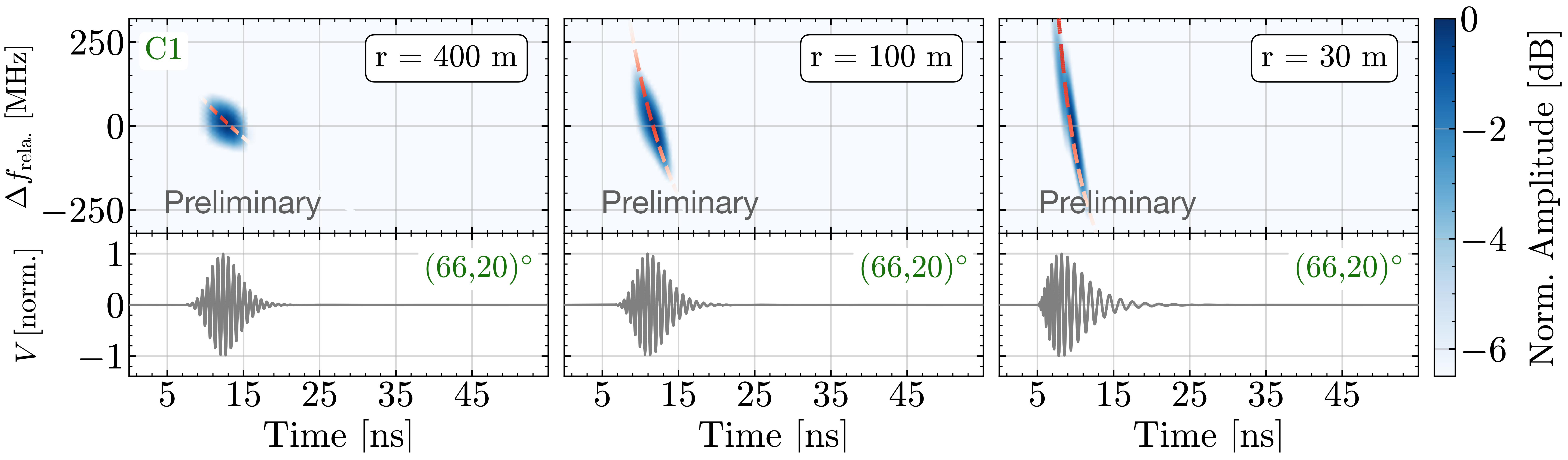
- **Modelling radar echoes from neutrino induced particle cascades**
  - MARES (arXiv:2310.06731) ⟶ NKG profile to describe electron distribution
  - Segment the ionisation trail
  - Calculate the individual contribution from each segment
  - Observed signal is sum of all contributions





Radar Triggers

- **Developing radar triggers for in-ice neutrino detection**
  - Radar echoes show frequency chirps
  - These chirps can be used for triggering (first proposed and implemented for radar detection of CR air showers, S. Kunwar et. Al. arXiv:1504.00779v2 and S. Prohira et. al. arXiv:1709.08587v2)



$$\frac{f_{\mathrm{RX}}}{f_{\mathrm{TX}}} = \left| \frac{1 + n\beta\cos\theta_{\mathrm{TVP}}}{1 - n\beta\cos\theta_{\mathrm{RVP}}} \right|$$

Radar Echo Signal Duration

- **The signal duration and arrival direction**
  - $T_{0.5}$ defined as the time window in which the signal exceeds 50% of the signal peak amplitude
  - Yields additional information to break degeneracies on peak frequency distribution

I. Loudon, J. Loonen, et al., (RET Collaboration), *Exploring Signal Properties of Radar Echoes from High-Energy Particle Cascades.*