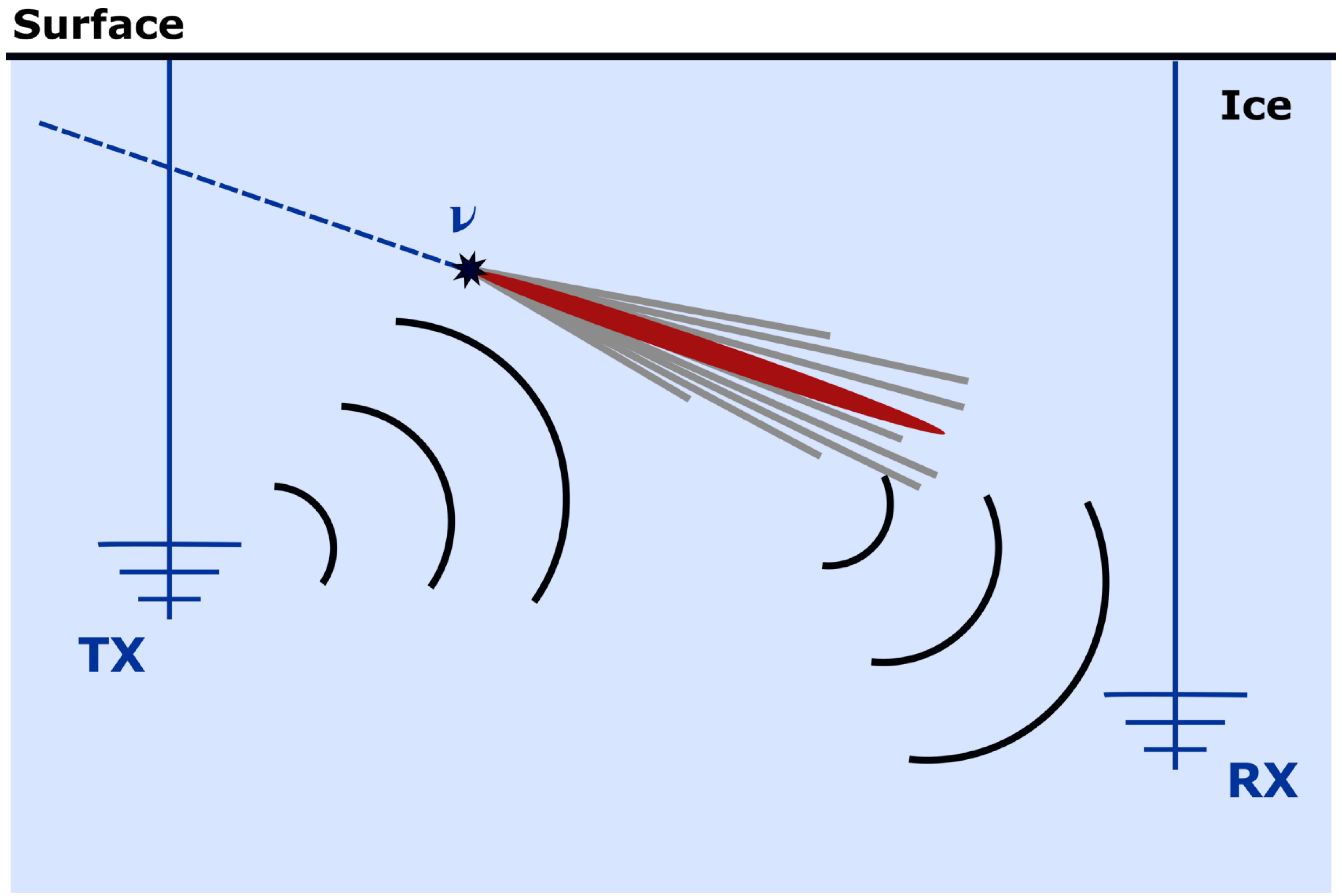
RADAR ECHO TELESCOPE

Event properties and Reconstruction for the Radar Echo Telescope

Jannes Loonen

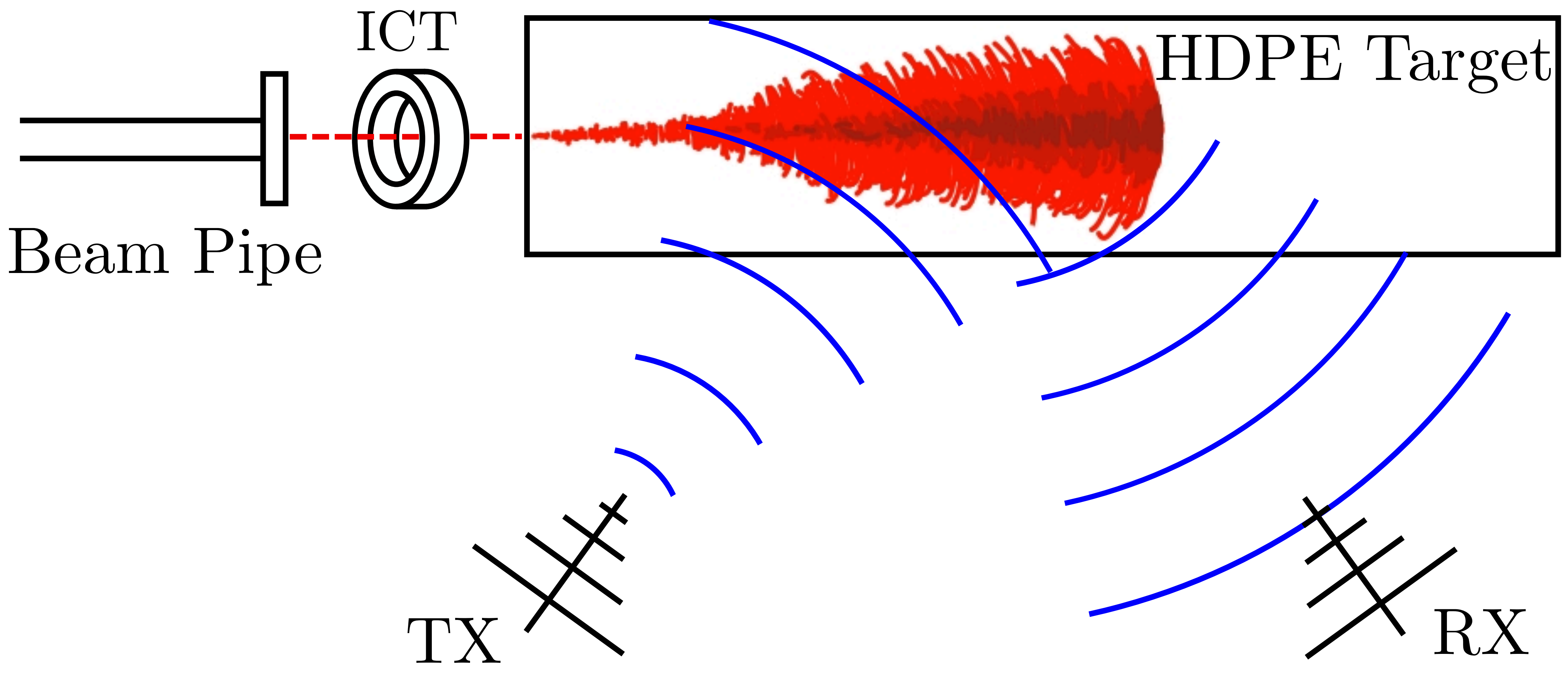
The Radar Echo Telescope

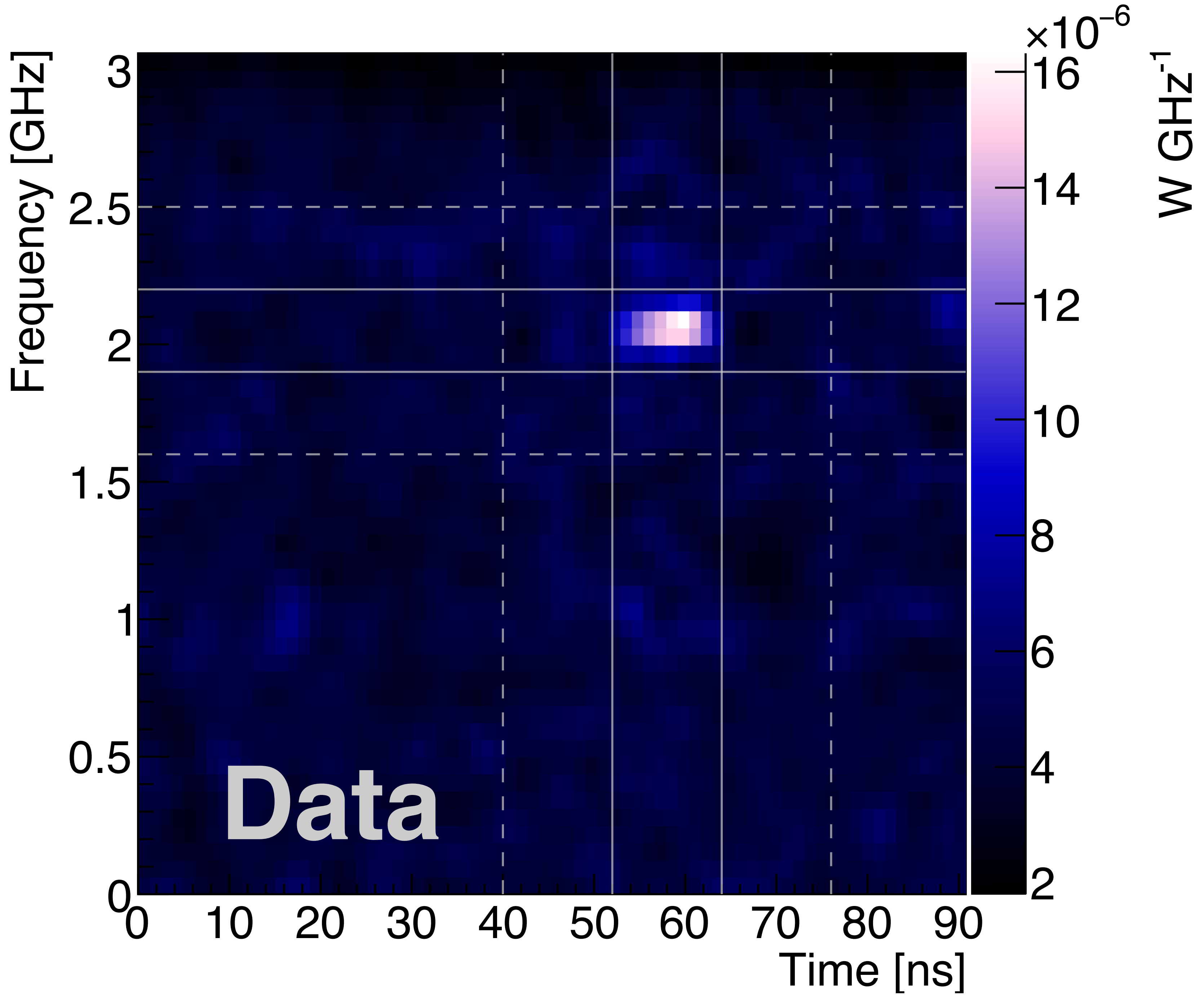
- **A future high-energy neutrino detector**
  - Detect cosmic neutrinos (> 10 PeV) using radar
  - Neutrino interaction creates trail of free ionised electrons $\longrightarrow$ macroscopic radar target



The Radar Echo Telescope

- **Validation of the radar echo method**
  - Experiment T-576 at SLAC demonstrated the feasibility in a laboratory environment

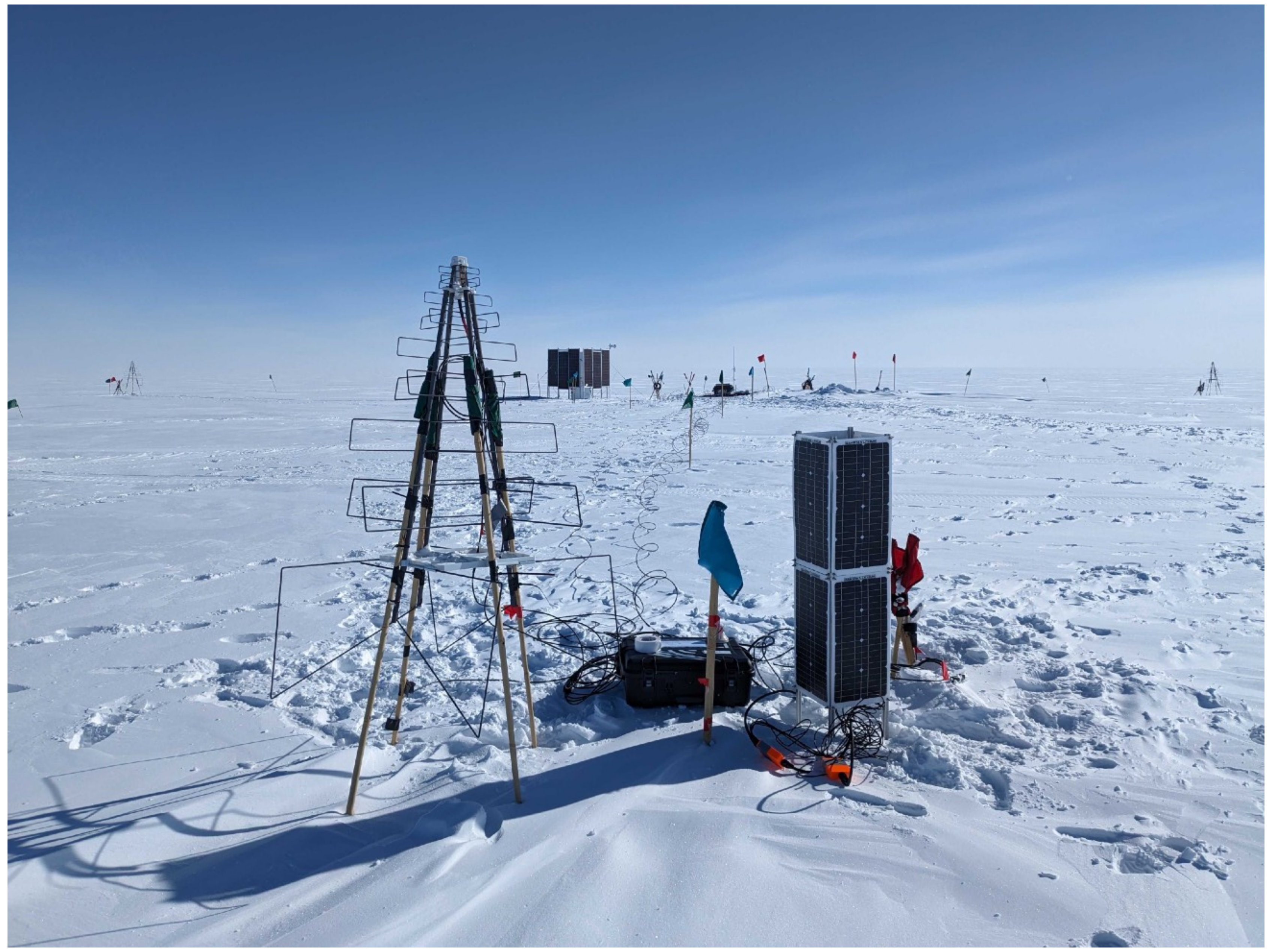


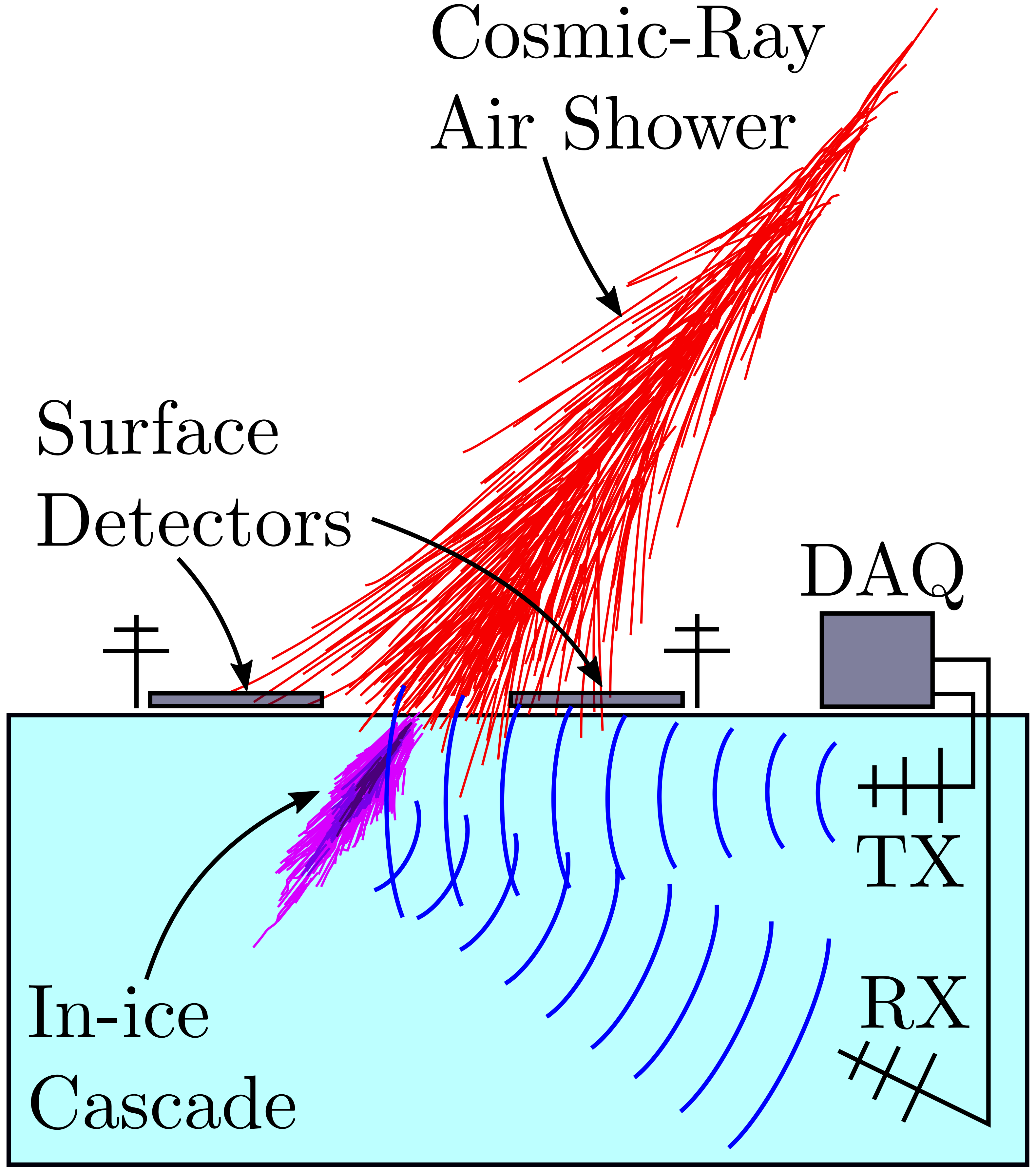


Observation of Radar Echoes from High-energy Particle Cascades, S. Prohira, K.D. de Vries et al. 2020

The Radar Echo Telescope

- **Validation of the radar echo method**
  - Prove in-nature feasibility with the Radar Echo Telescope for Cosmic Rays (RET-CR)
  - Target in-ice extension of CR air showers
  - **Data analysis is ongoing!**

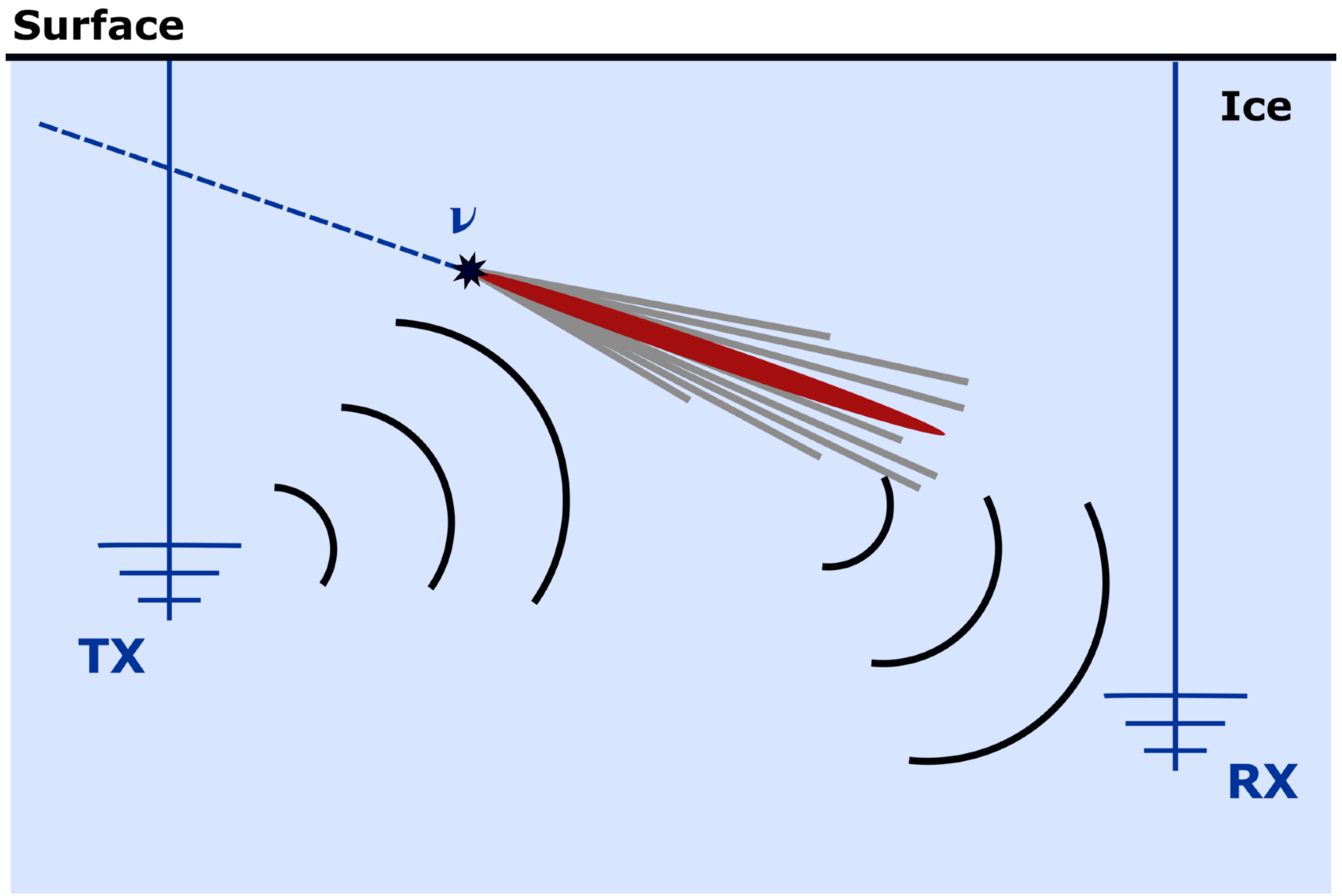




The Radar Echo Telescope for Cosmic Rays: Pathfinder Experiment for a Next-Generation Neutrino Observatory, S. Prohira, K.D. de Vries et al. 2020

The Radar Echo Telescope

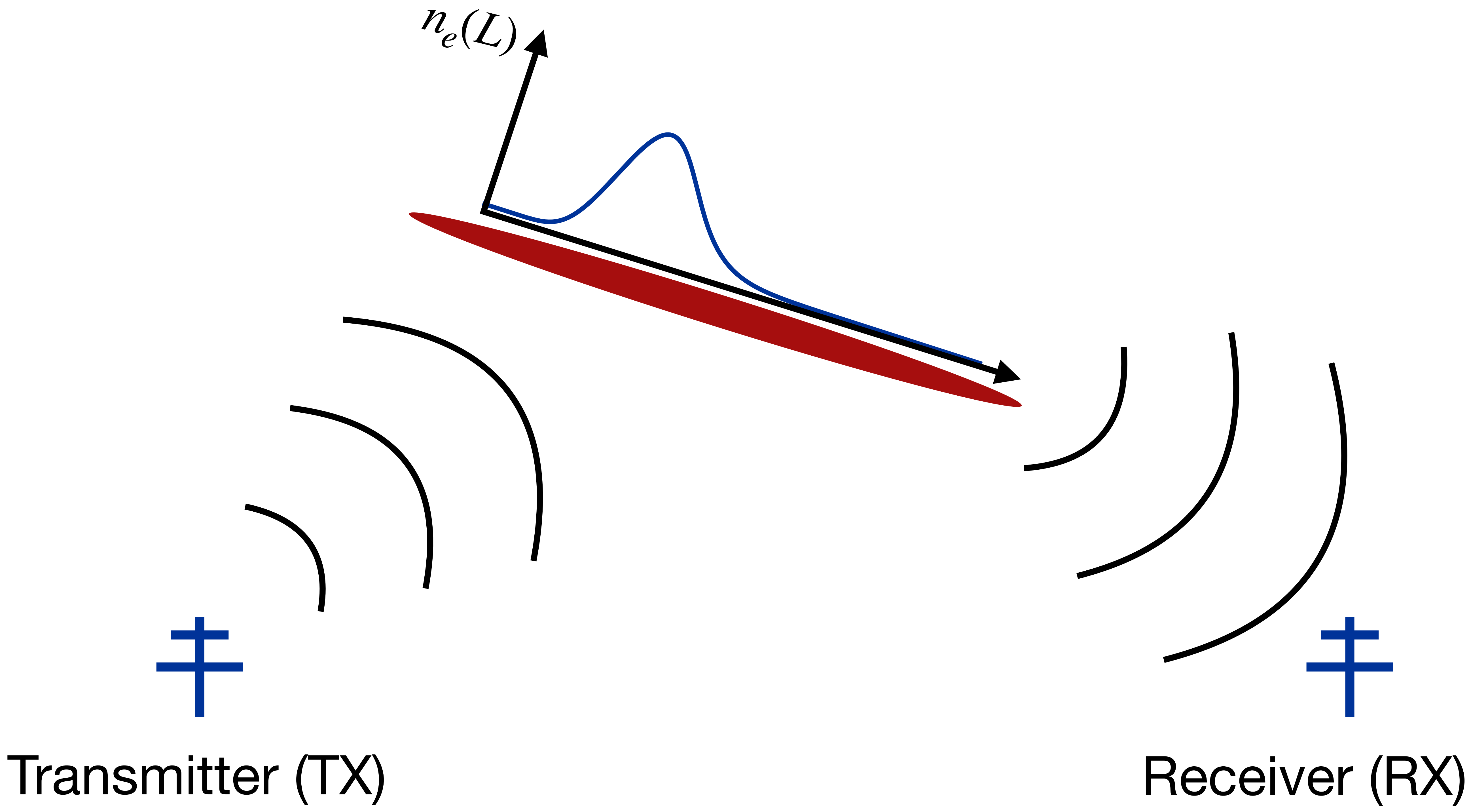
- **The Radar Echo Telescope for Neutrinos (RET-N)**
  - Understand the radar echo signal properties from neutrino induced particle cascade:
    1. Optimise RET-N detector layout
    2. Develop reconstruction algorithms



Radar Echo Signal Properties

Simulating Radar Echoes

- **Modelling radar echoes from neutrino induced particle cascades**
  - MARES (arXiv:2310.06731) ⟶ NKG profile to describe electron distribution



Simulating Radar Echoes

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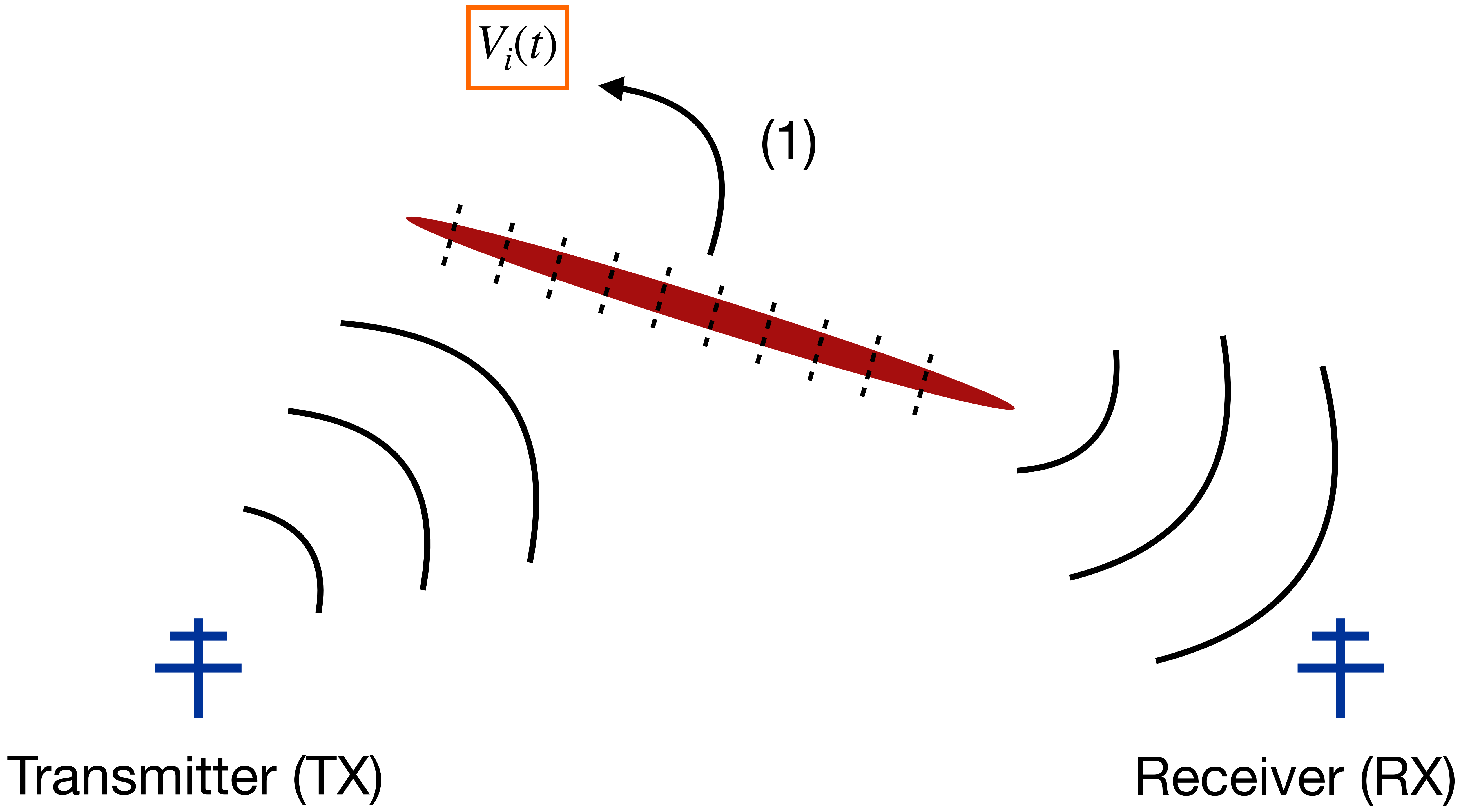
  - Calculate the individual contribution from each segment



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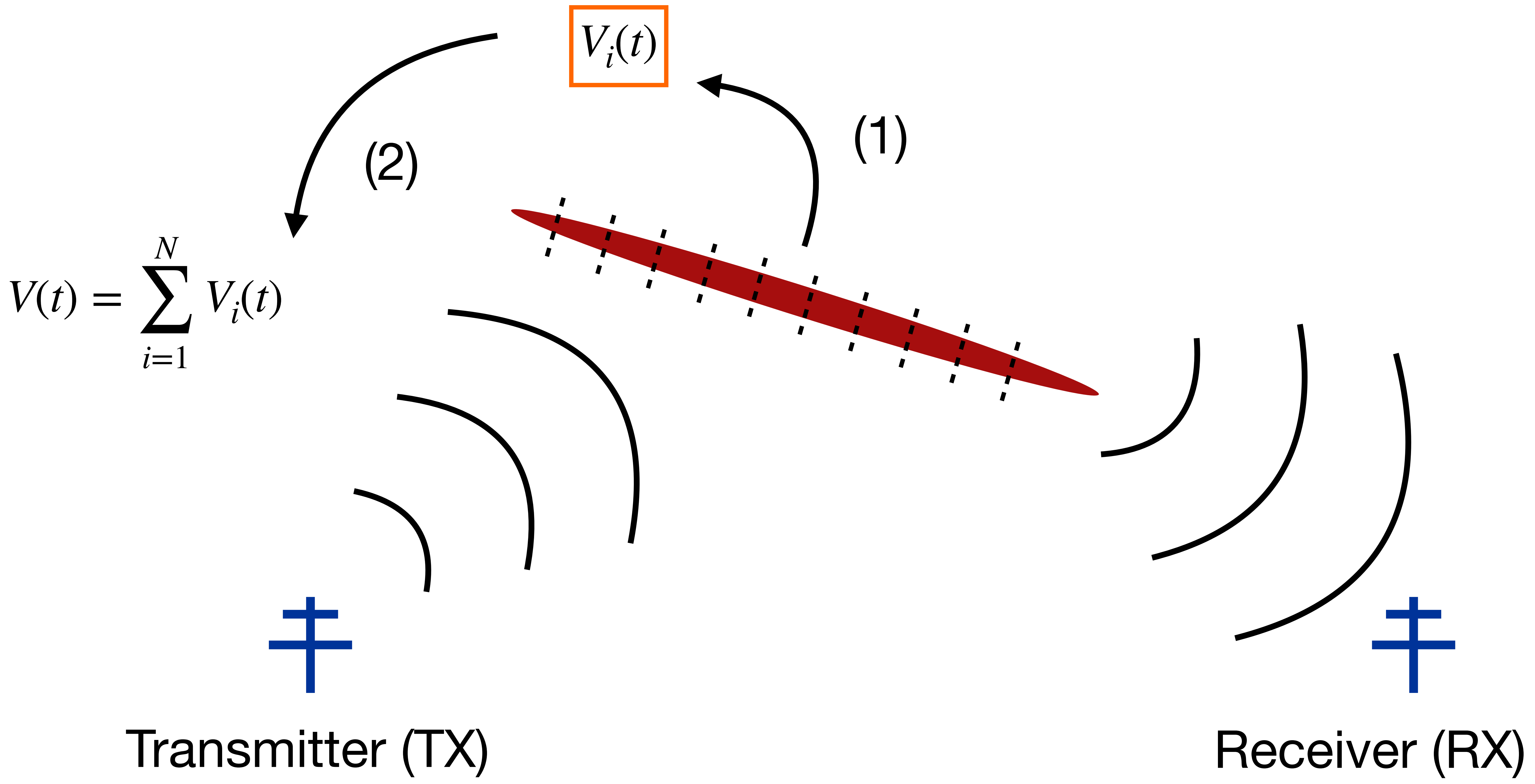

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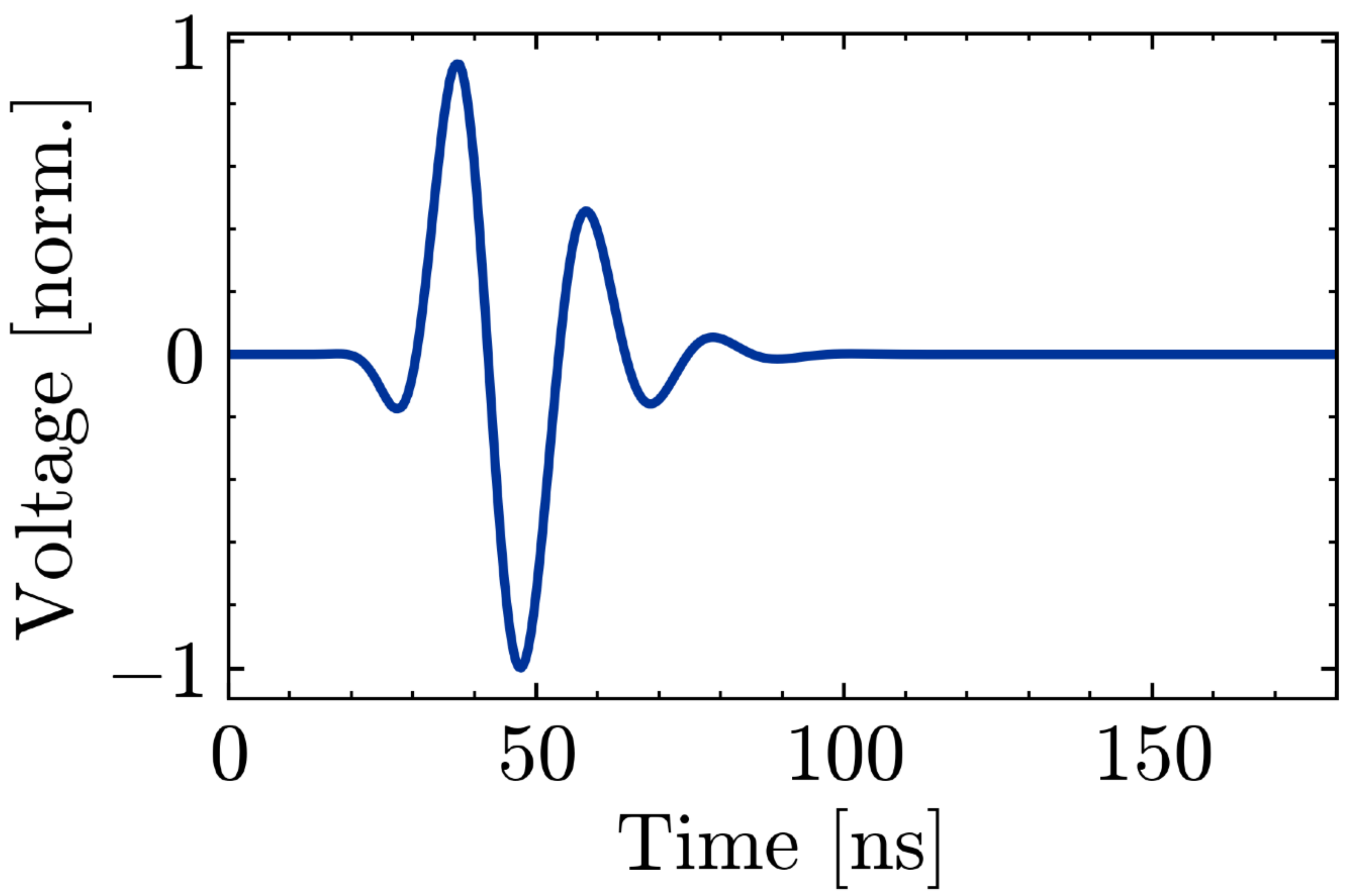
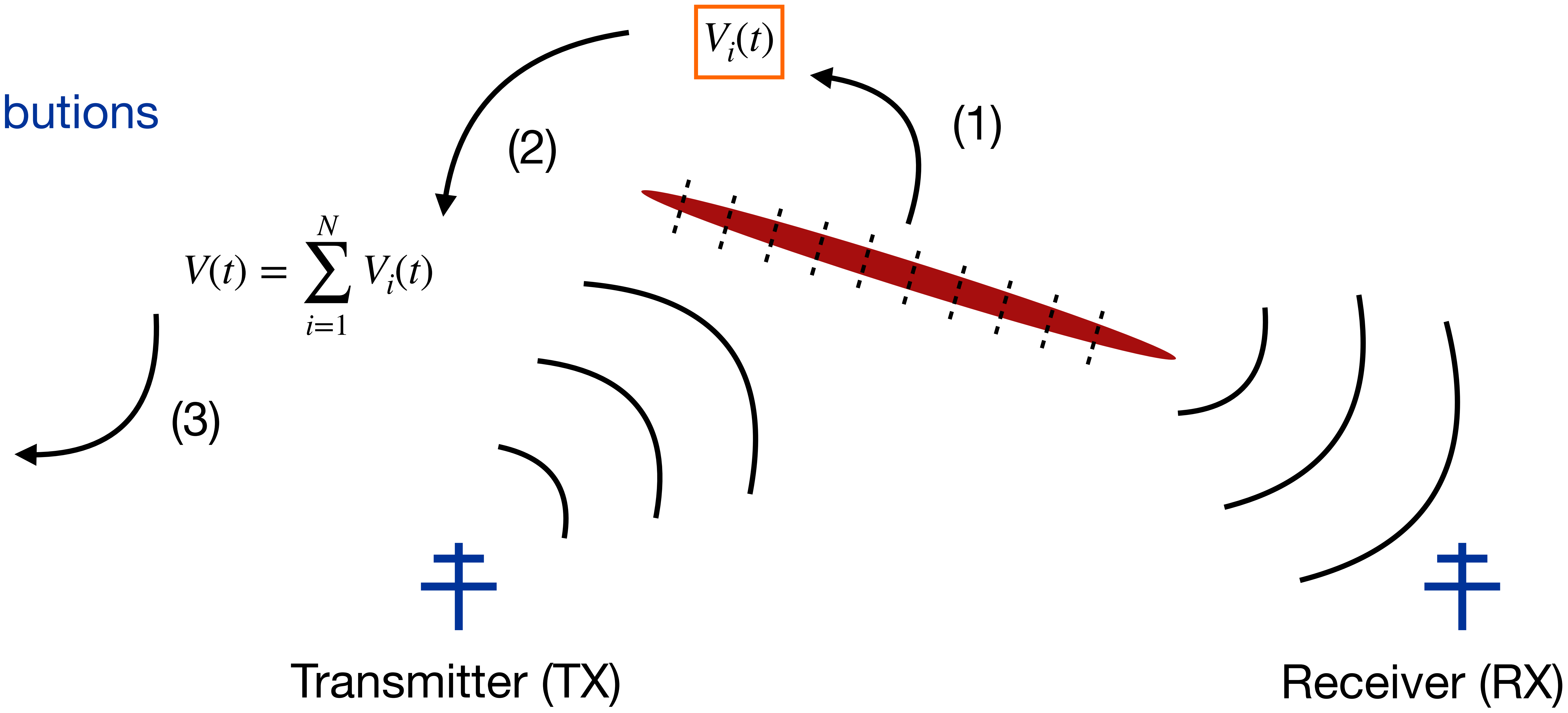
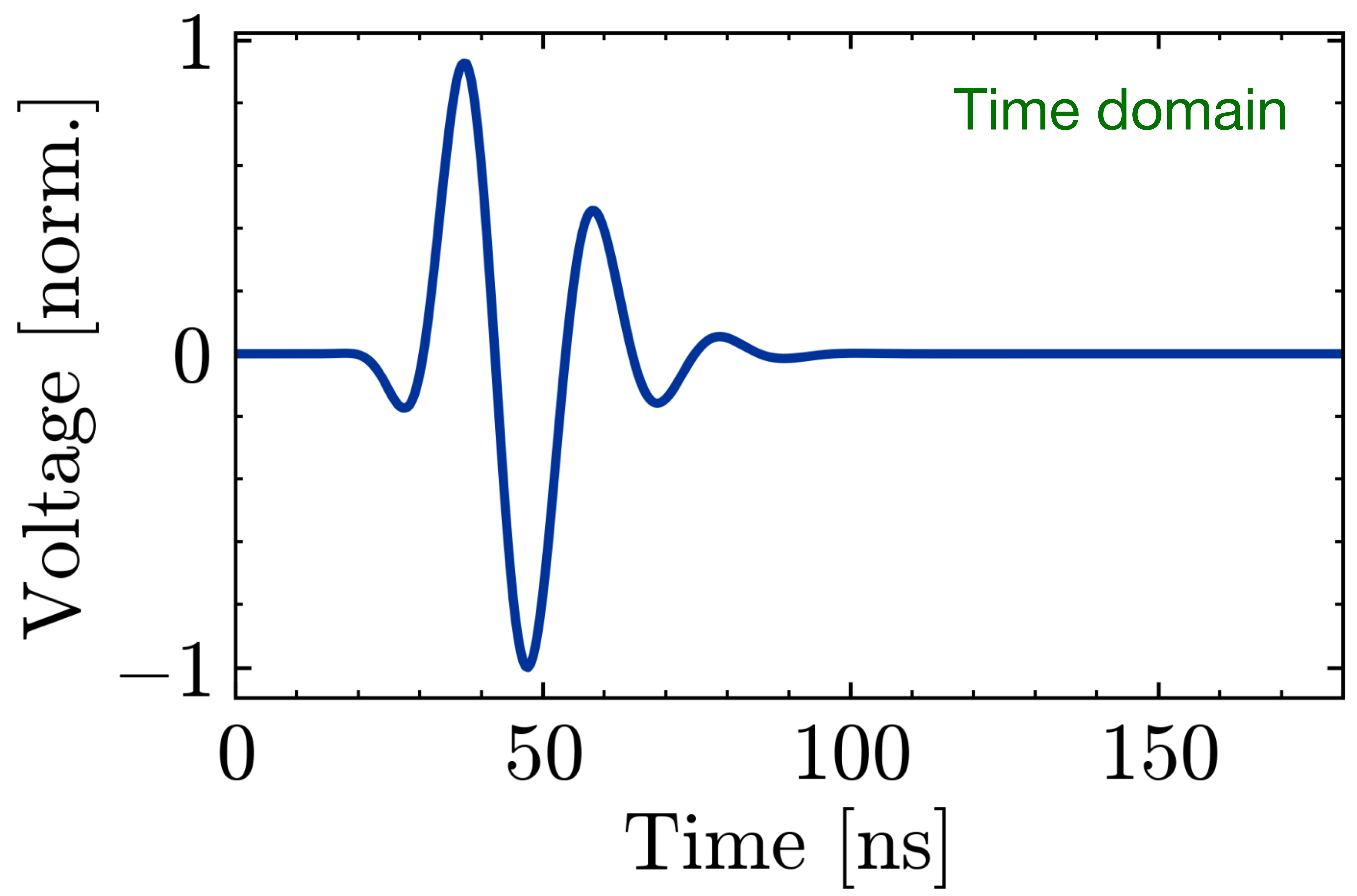
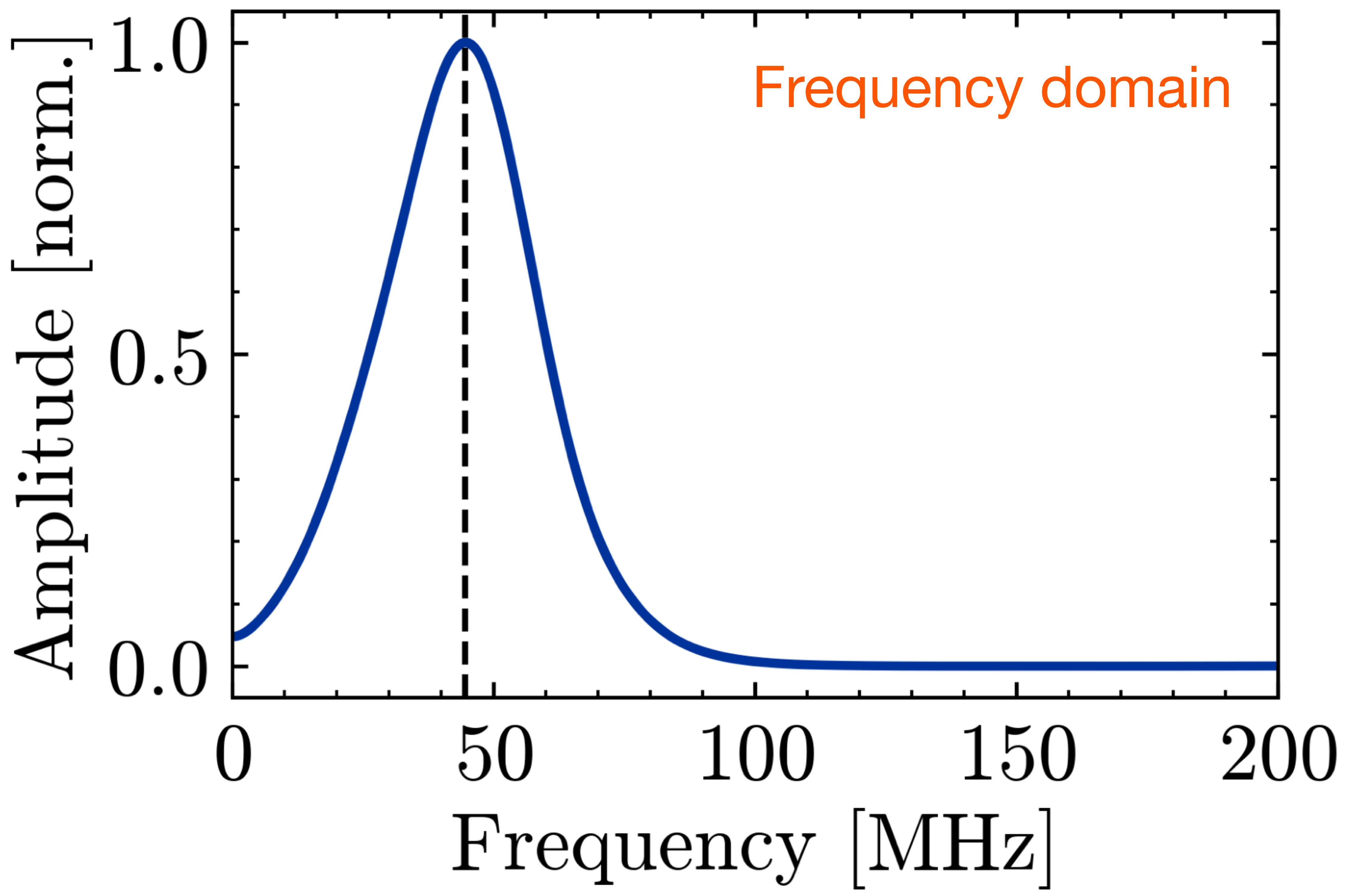




Radar Echo Signal Properties

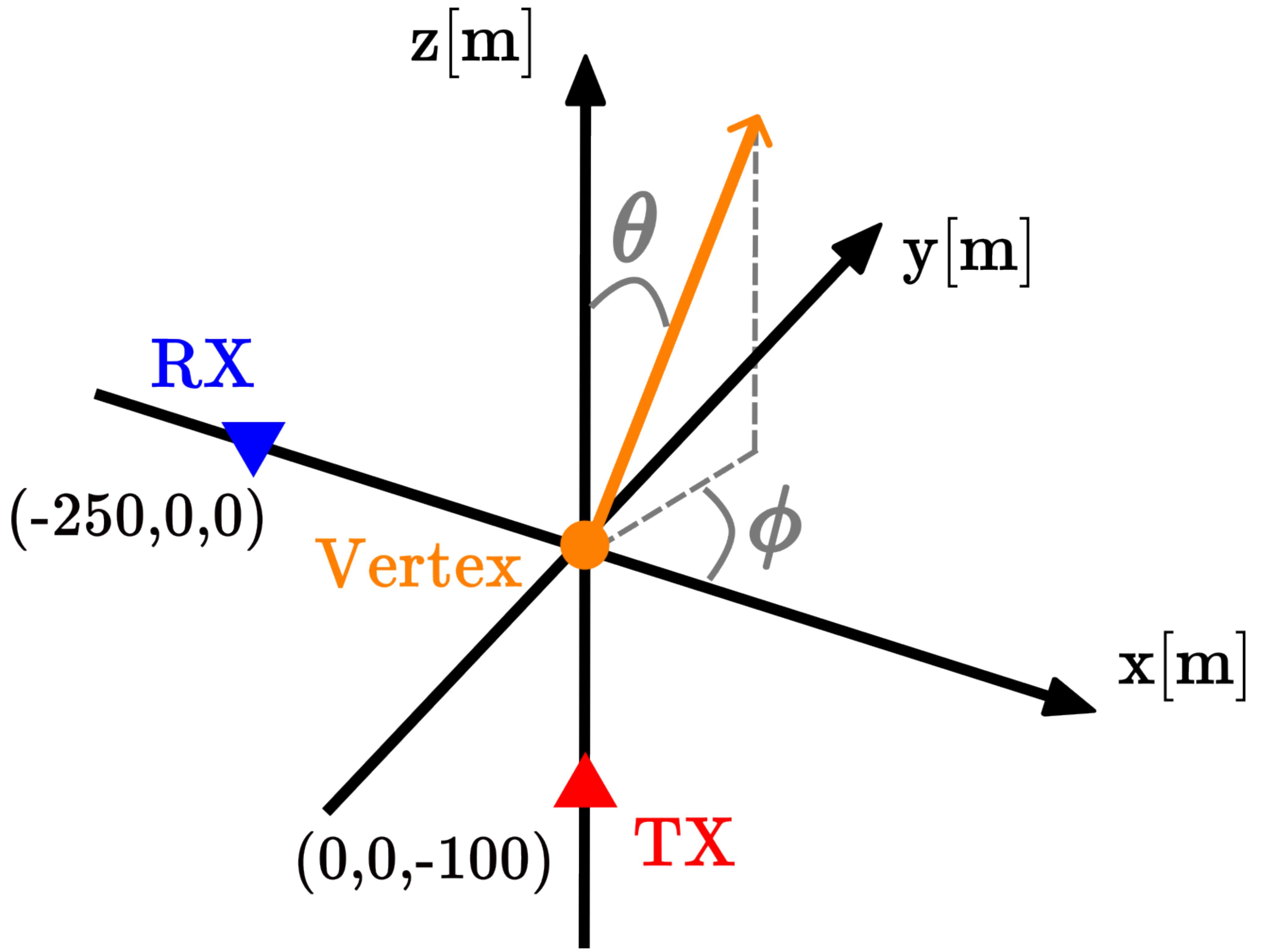
- **Radar signals**
  - Time domain ⟶ When are the signals strong ⟶ optimise detector layout
  - Frequency domain ⟶ Doppler shifts ⟶ reconstruct arrival direction





Radar Echo Signal Properties

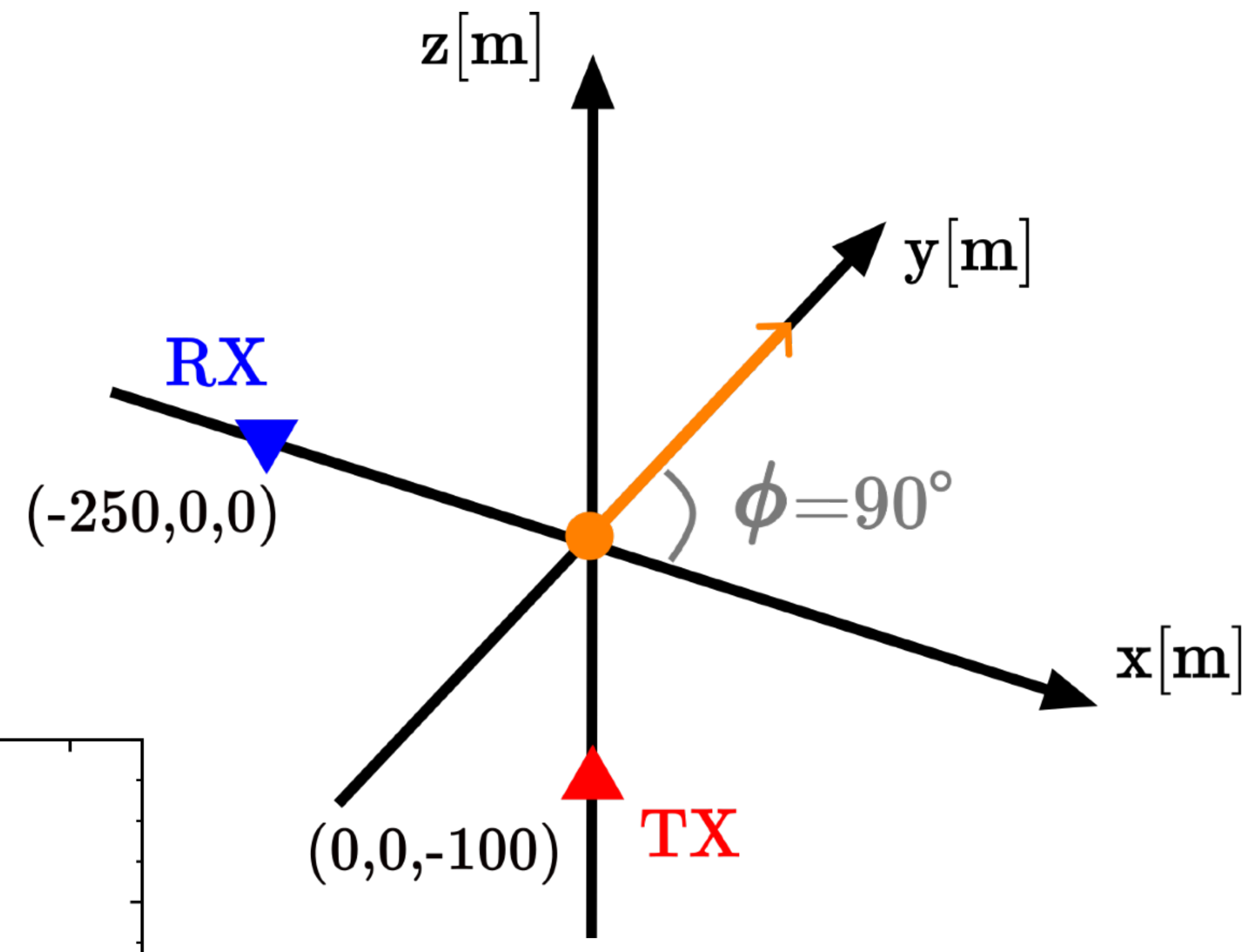
- **Antenna configuration**
  - Single transmitter (TX) and receiver (RX)
  - Neutrino interaction vertex at the origin
  - Neutrino arrival direction is a free parameter
  - Fixed simulation parameters:
    - f_{TX}= 50 MHz
    - Power = 1 kW
    - n = 1.78 (uniform ice)
    - E_ν = 1 EeV
  - **Investigate the effect of the neutrino arrival direction**

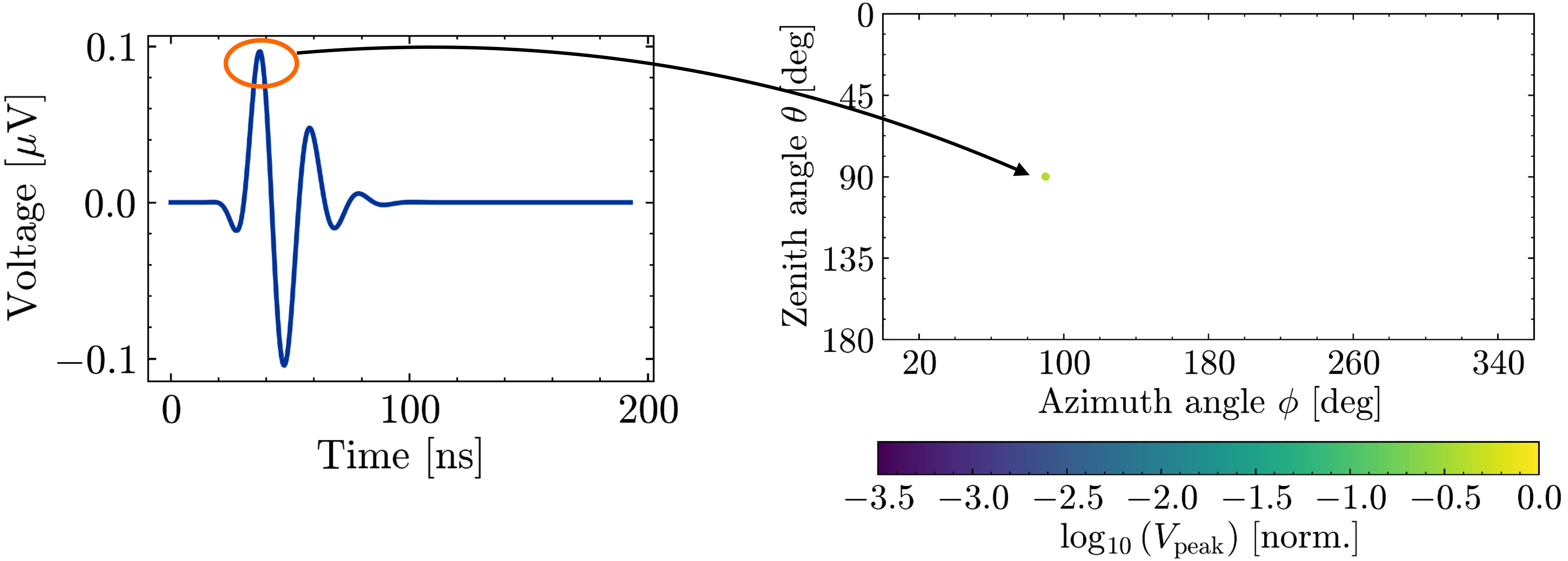


Time Domain Signal Properties

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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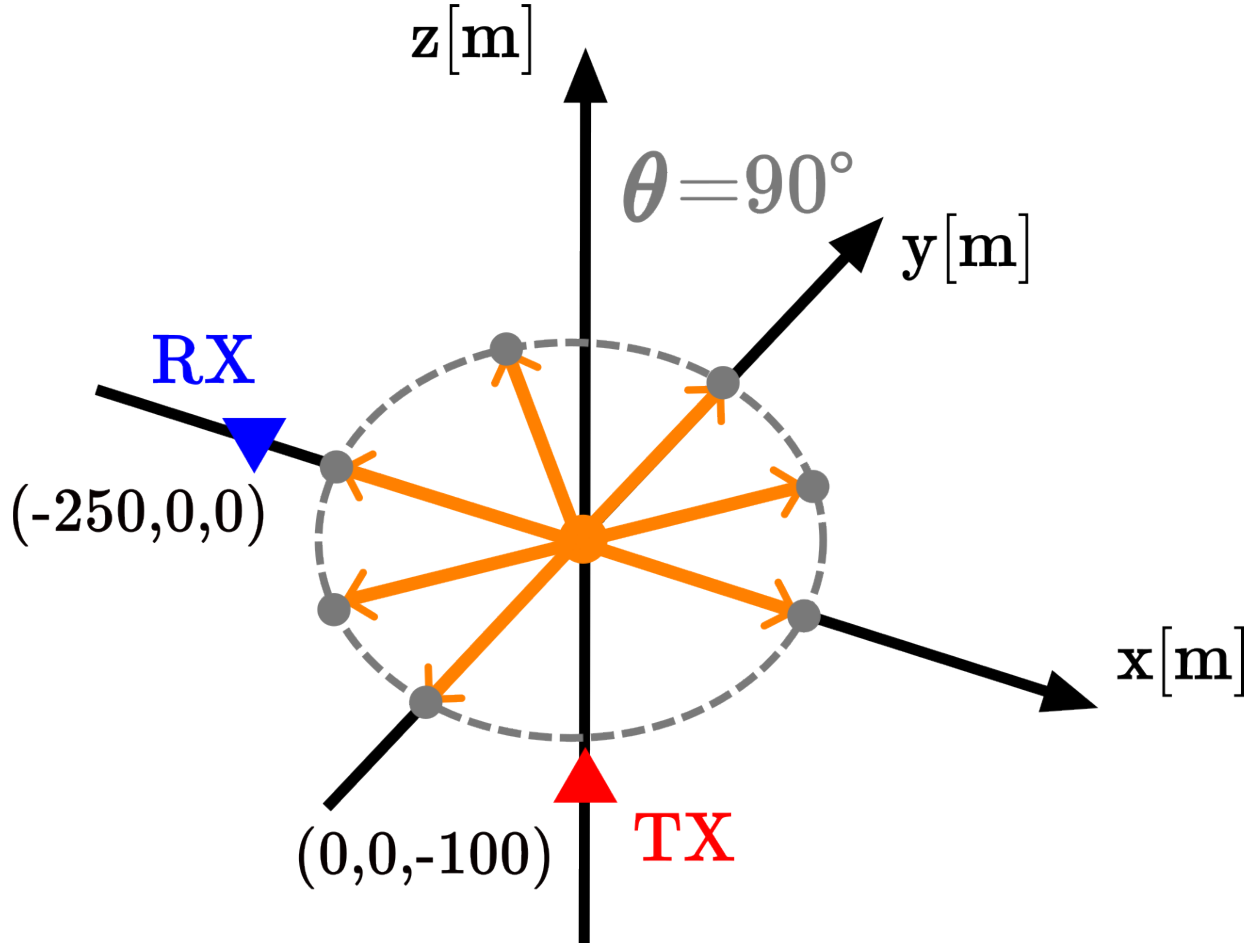

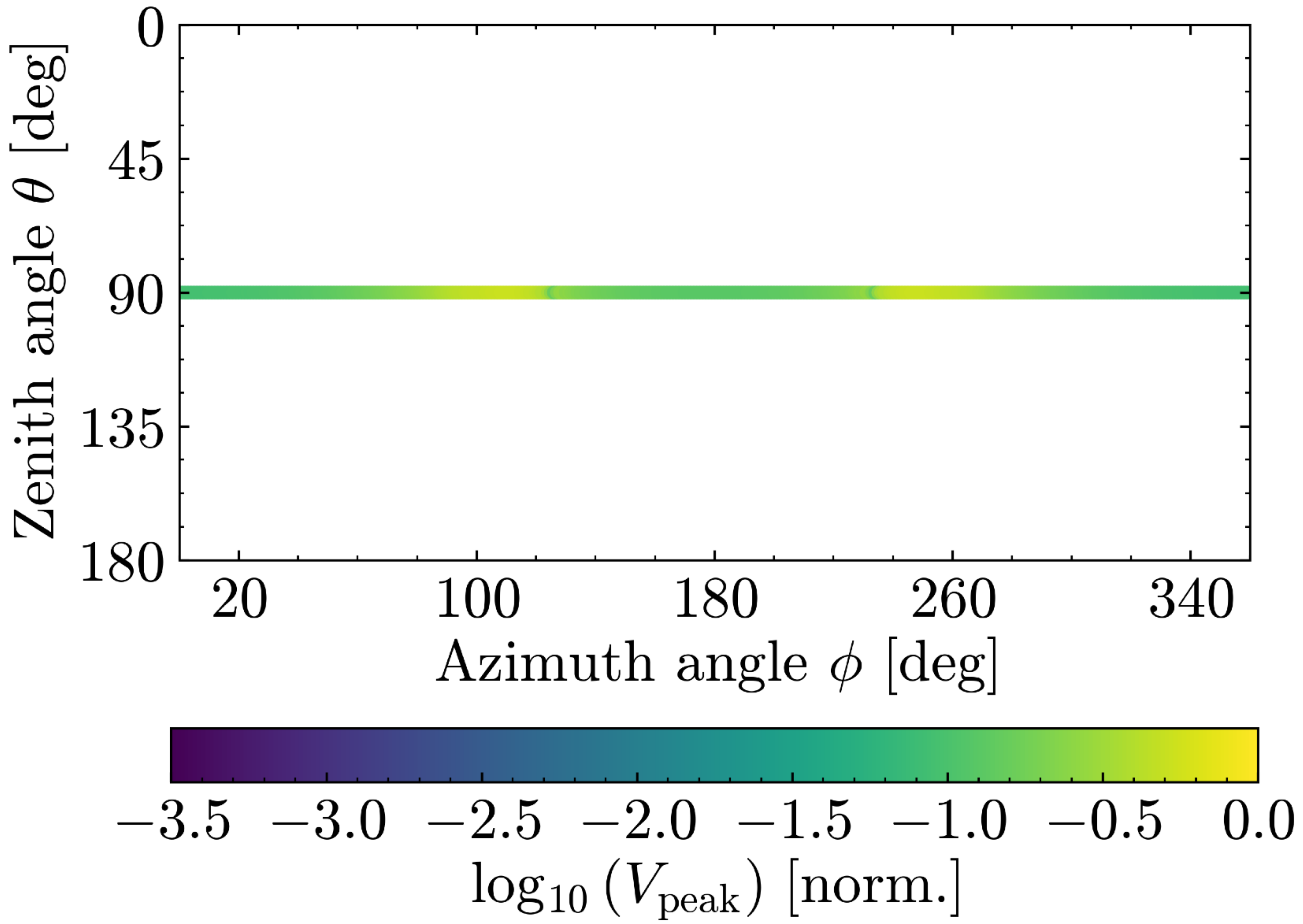

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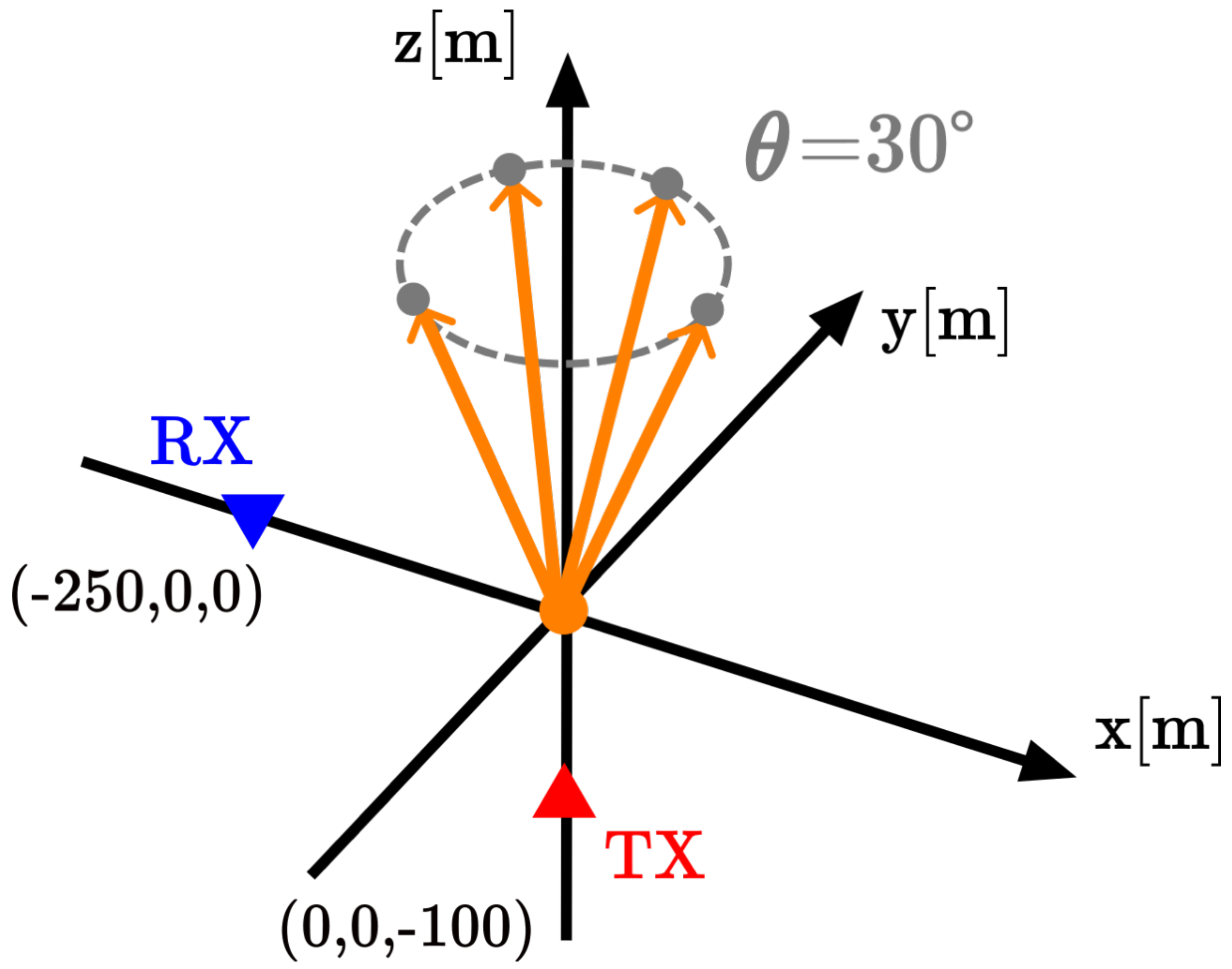
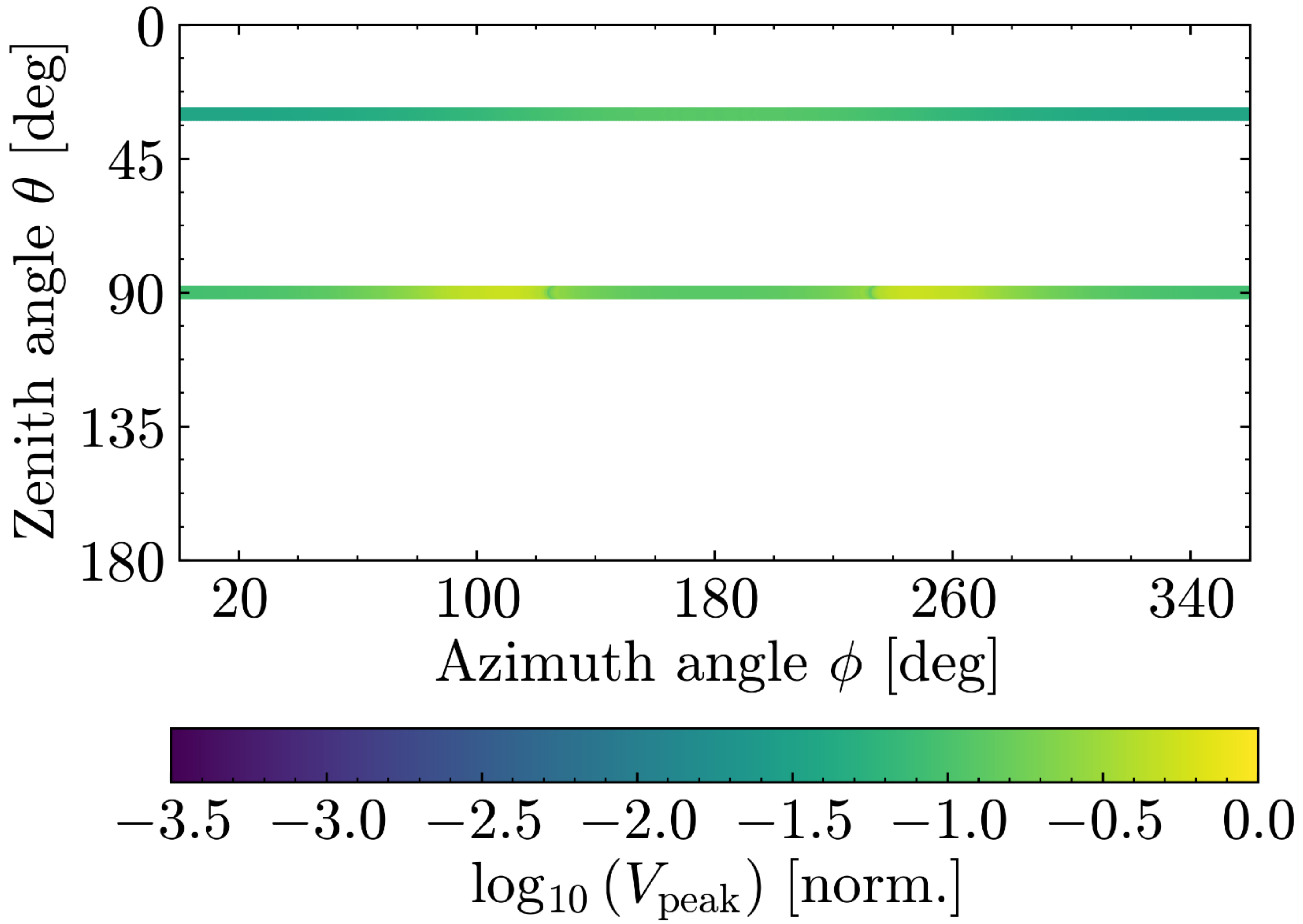
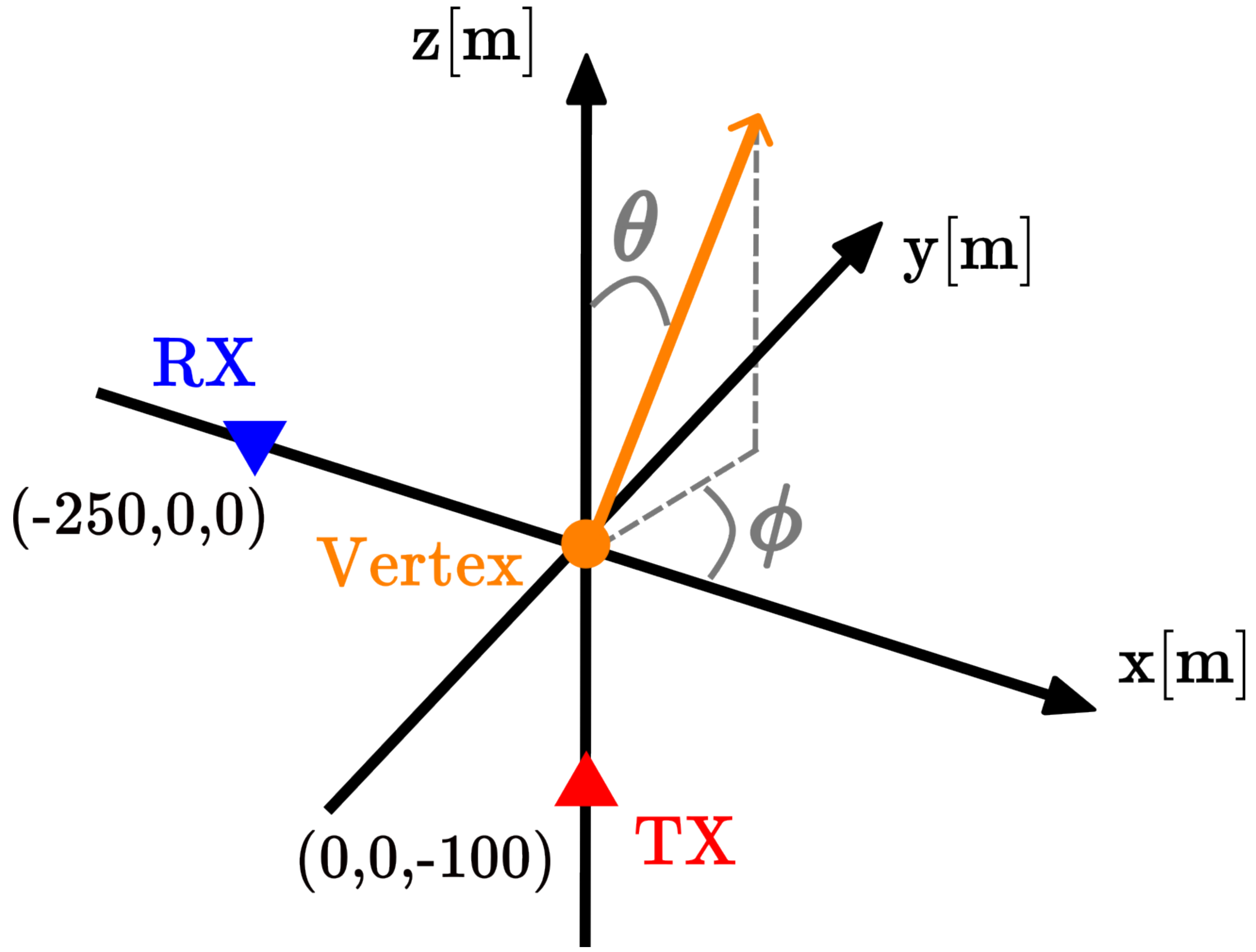
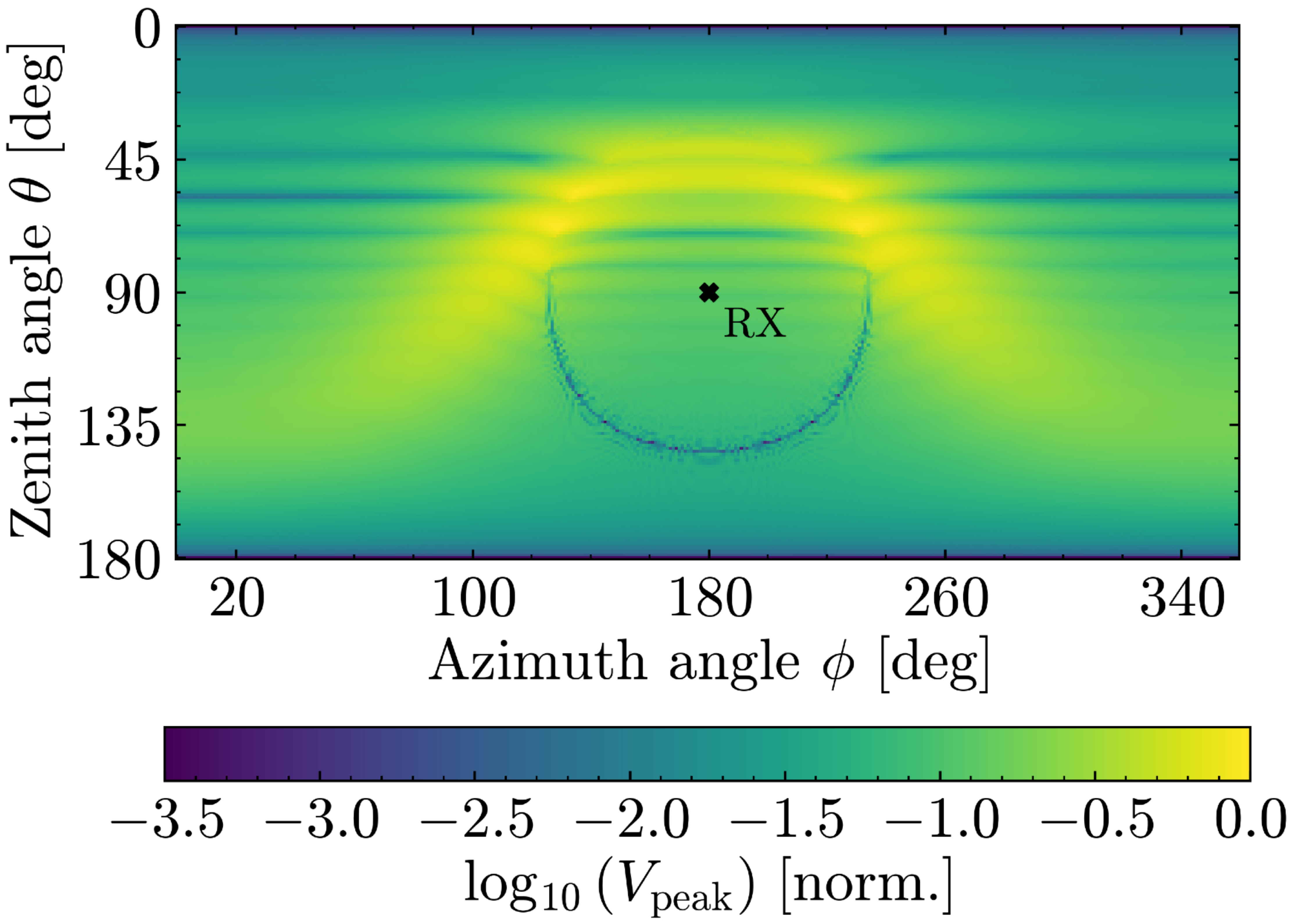




Radar Echo Signal Properties

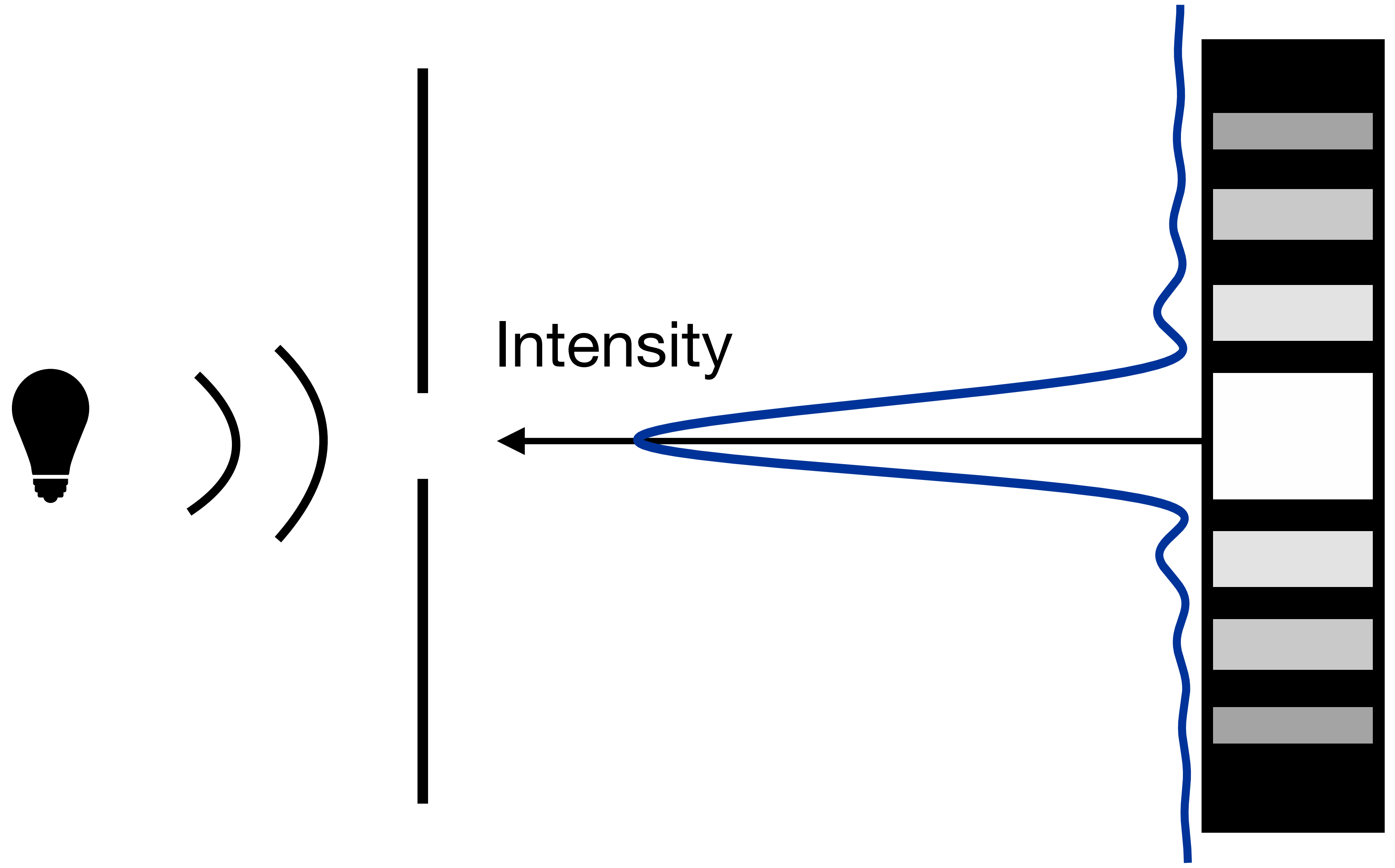
- **Signal strength vs neutrino arrival direction**
  - Three distinct features:
    - Horizontal bands
    - Low-amplitude half-ring
    - High-amplitude region

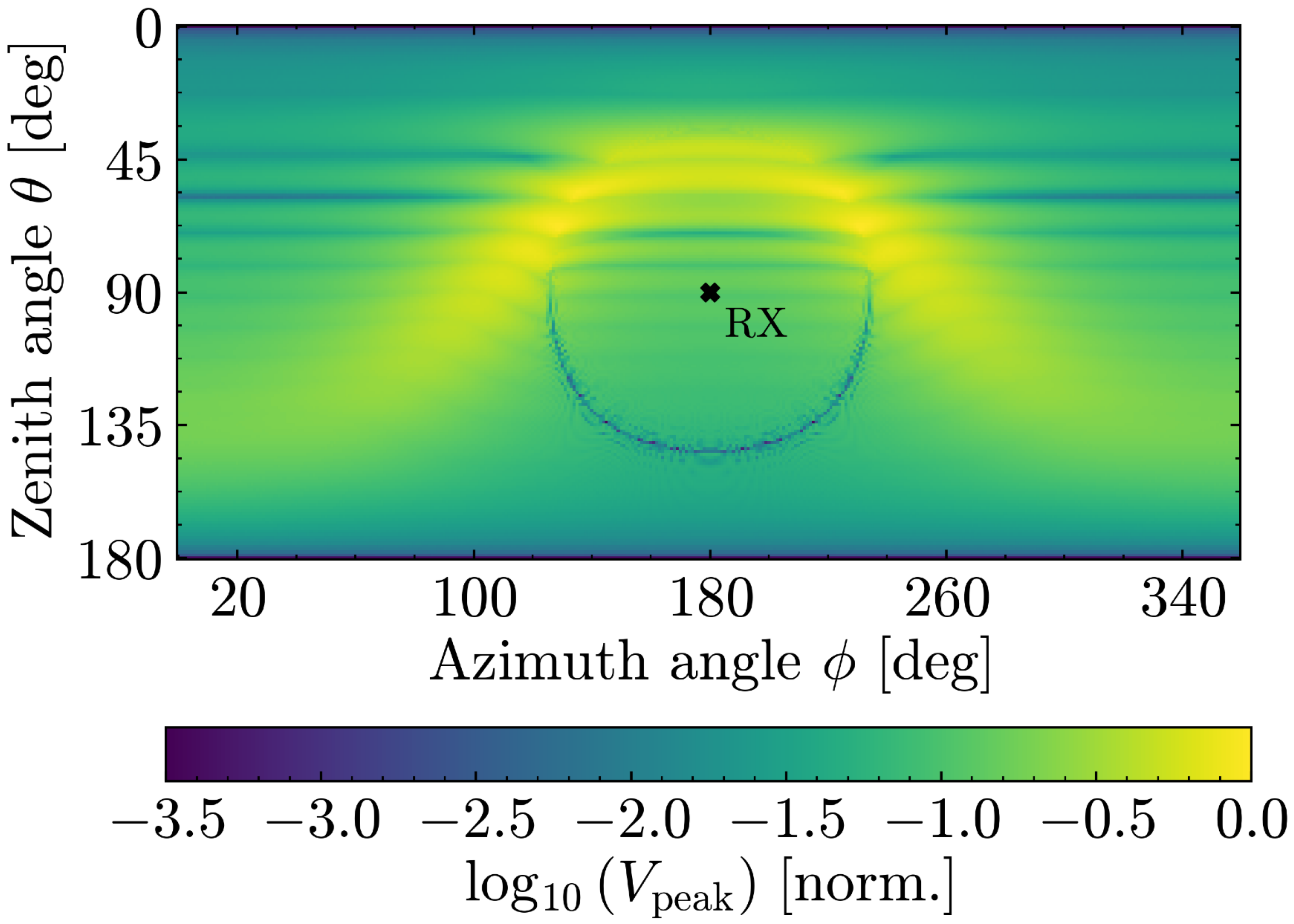




Radar Echo Signal Properties

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





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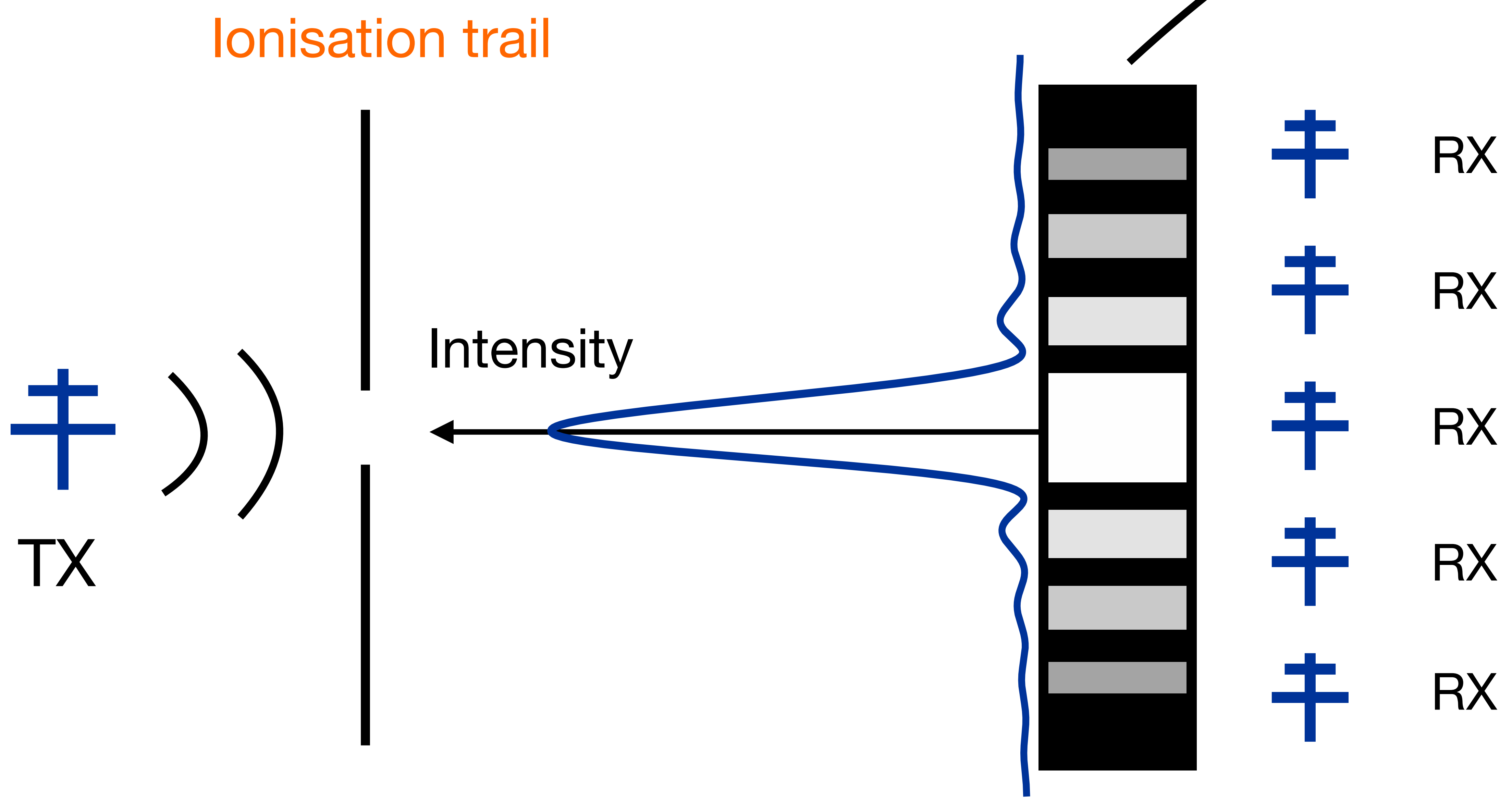
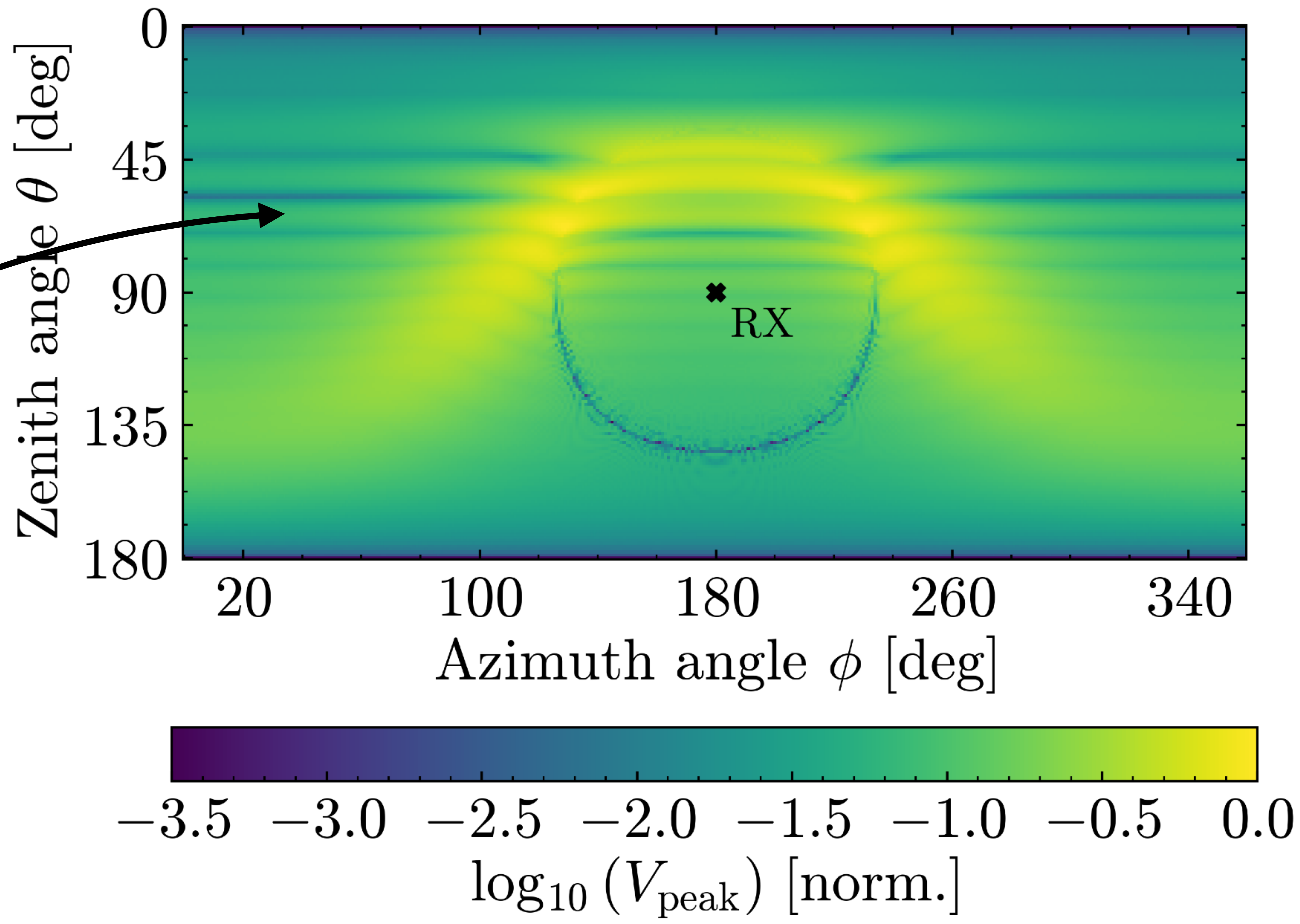
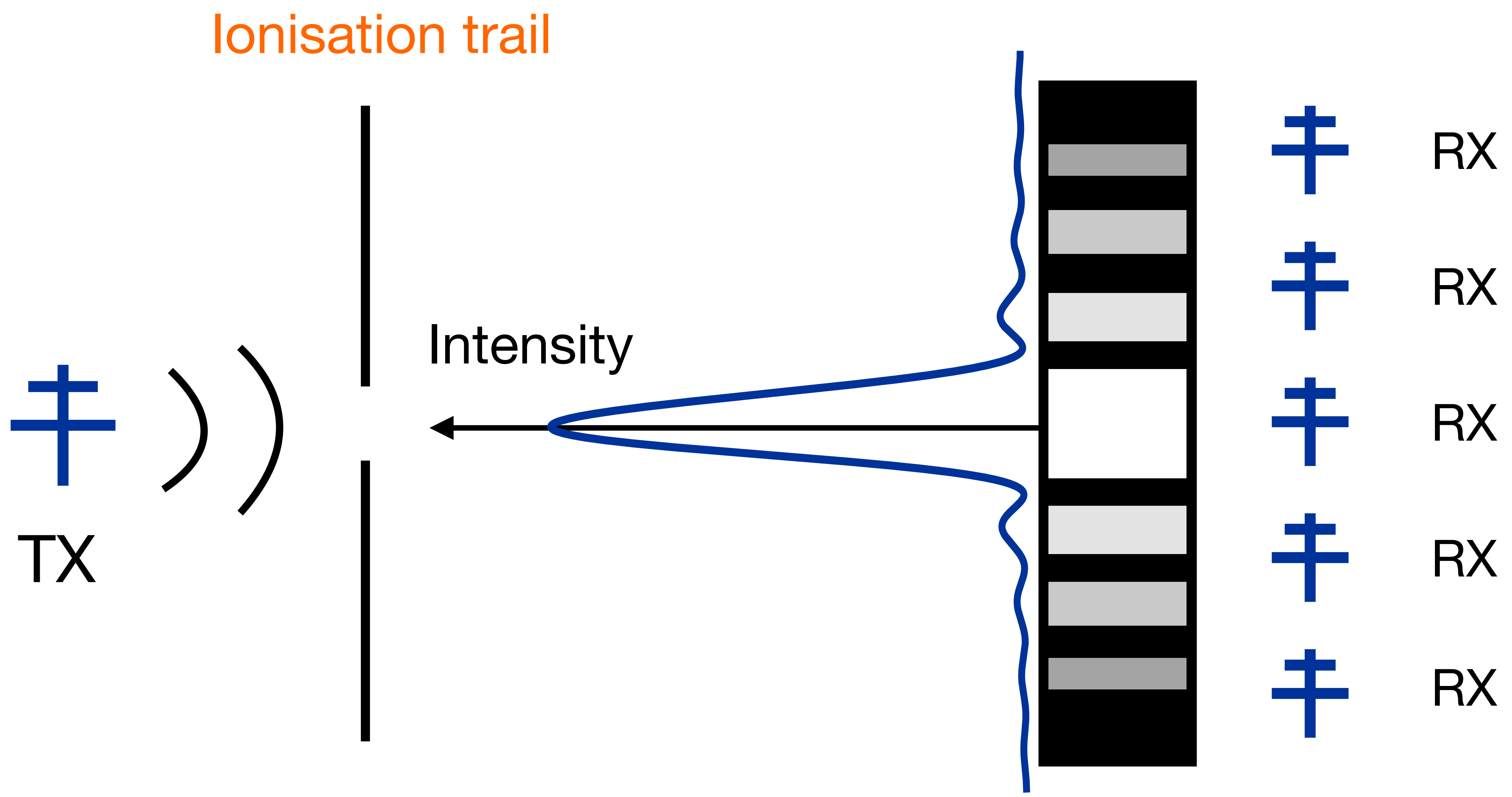
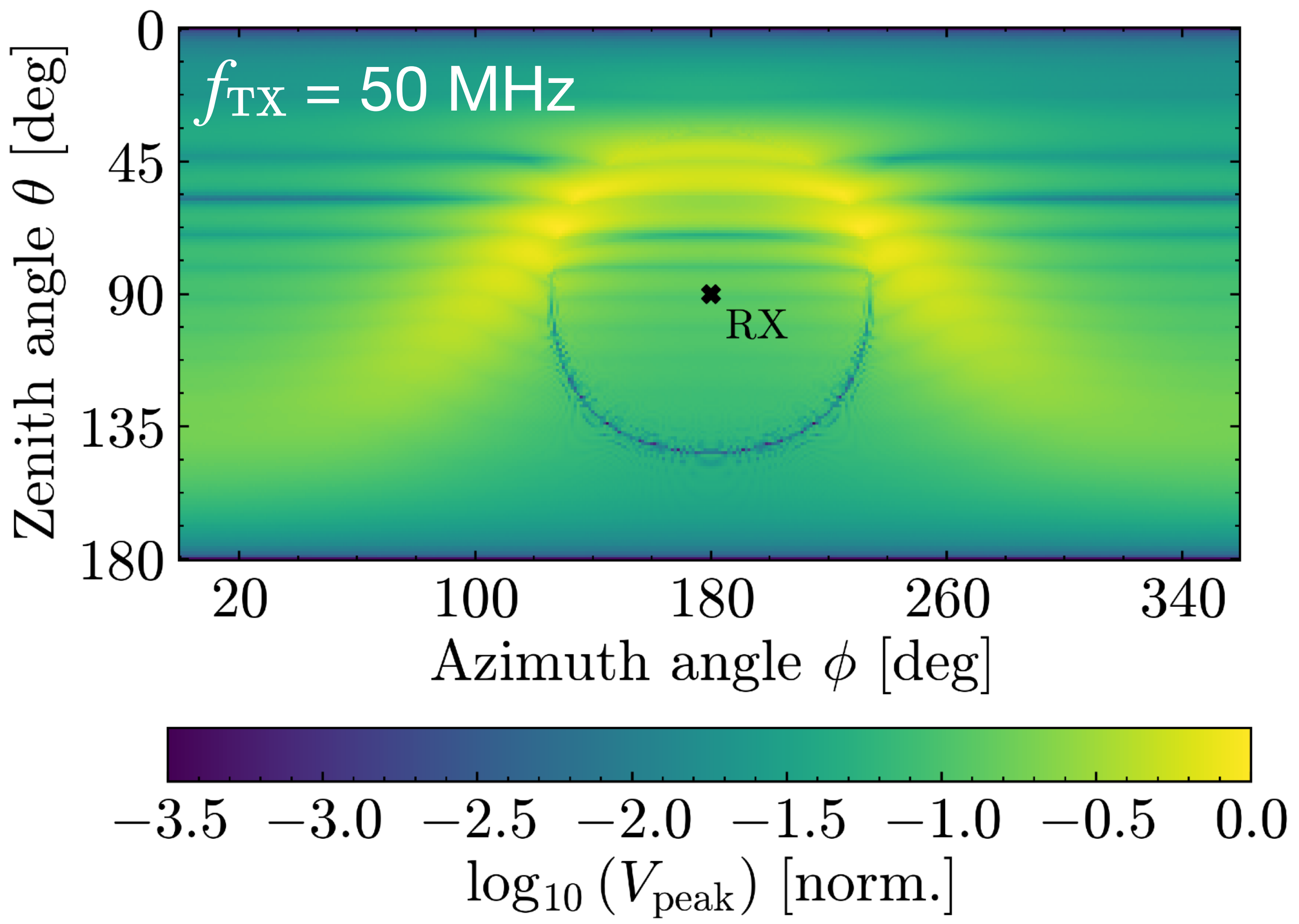


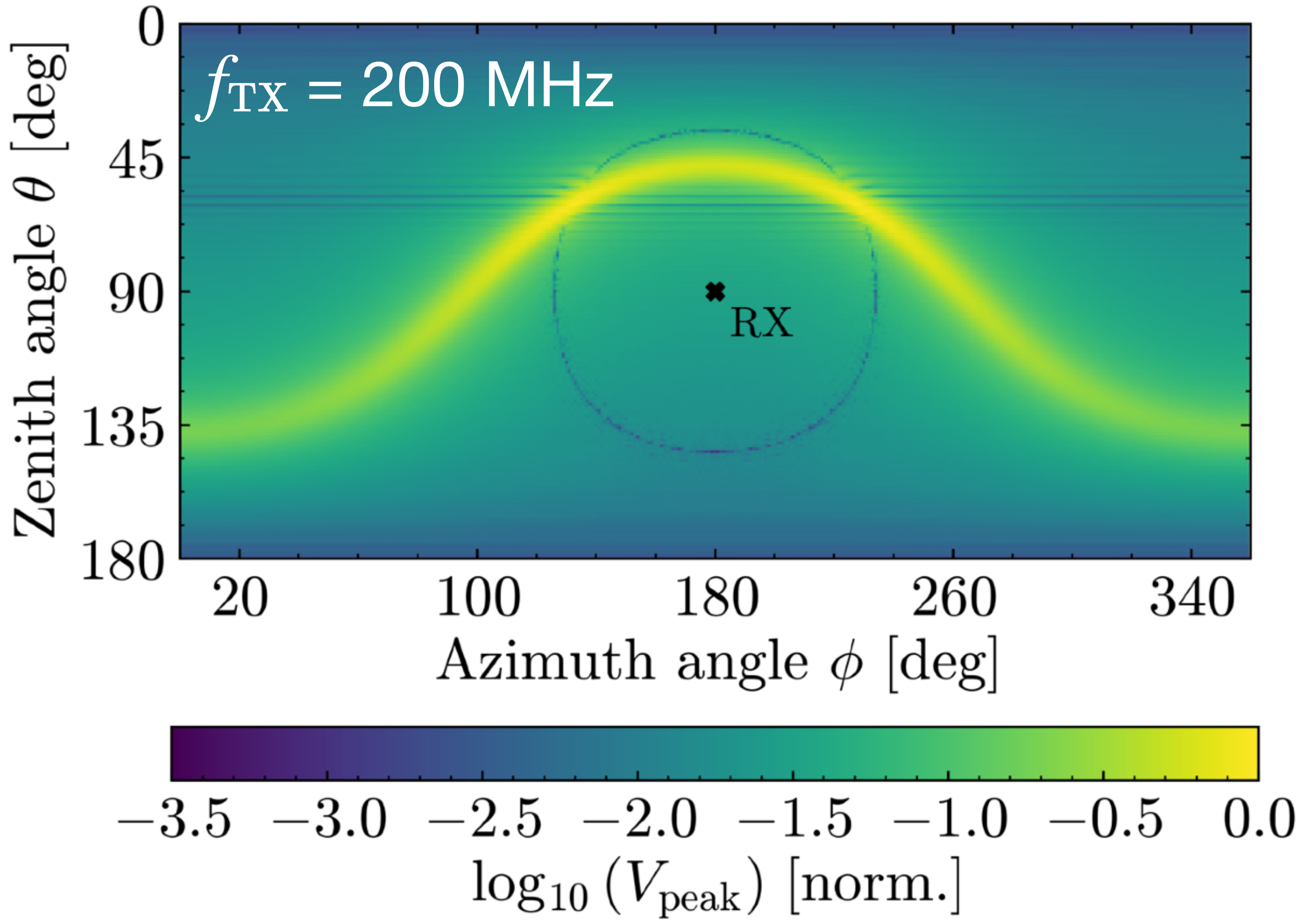


Radar Echo Signal Properties

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

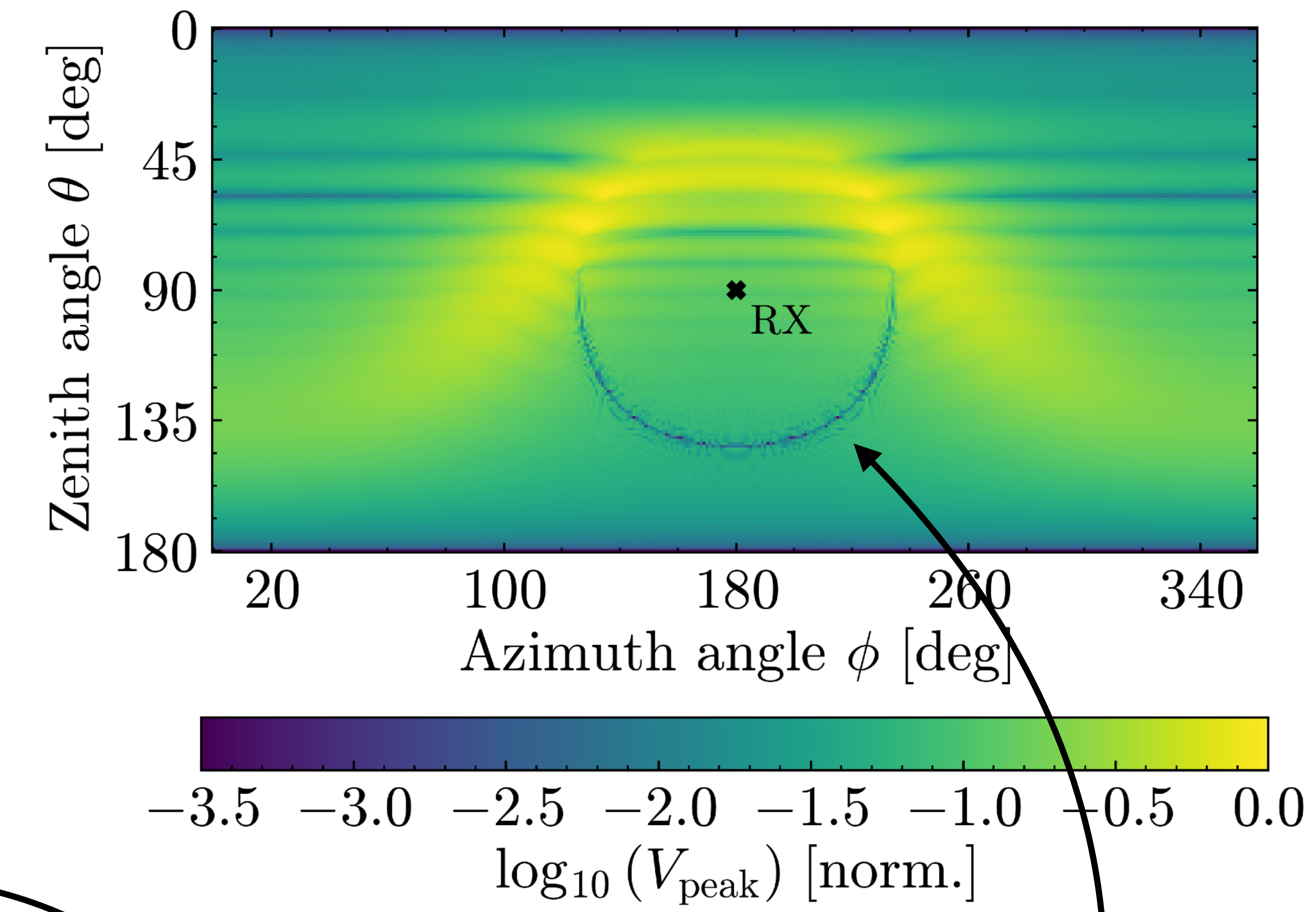


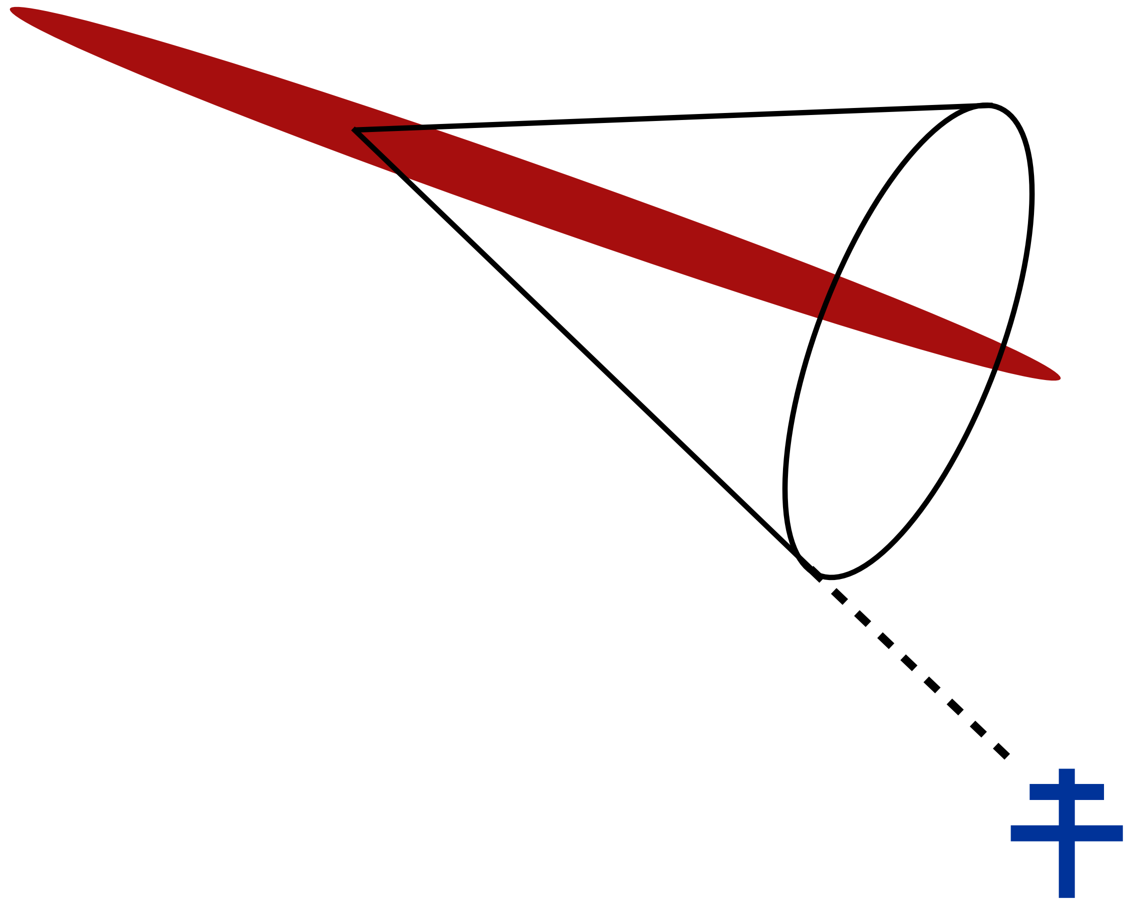


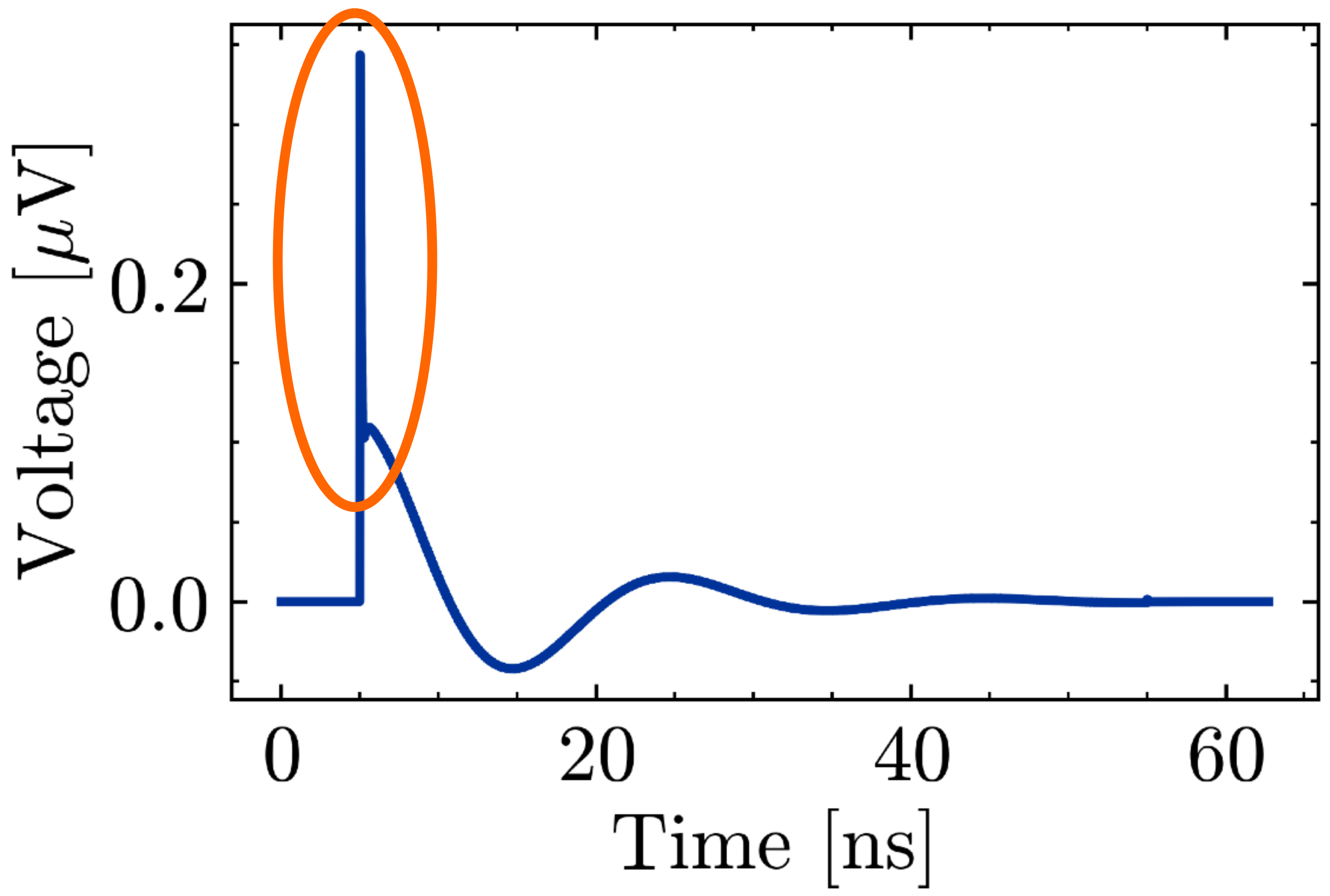


Radar Echo Signal Properties

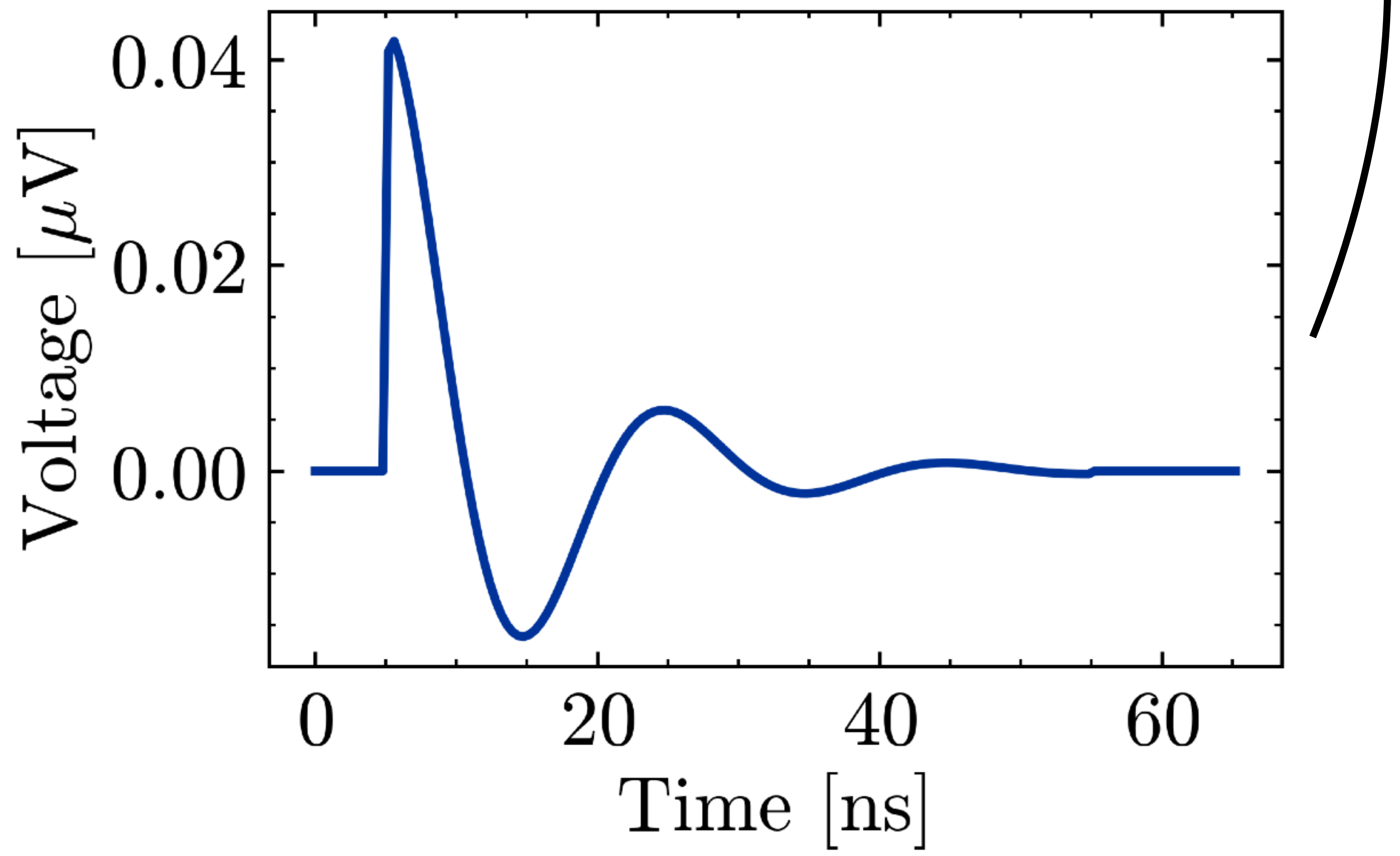
- **Low-amplitude half-ring**
  - Cherenkov ring
  - Radio waves are time compressed on the cone
    - high intensity radio burst
  - Undersampling effect artificially lowers the amplitude





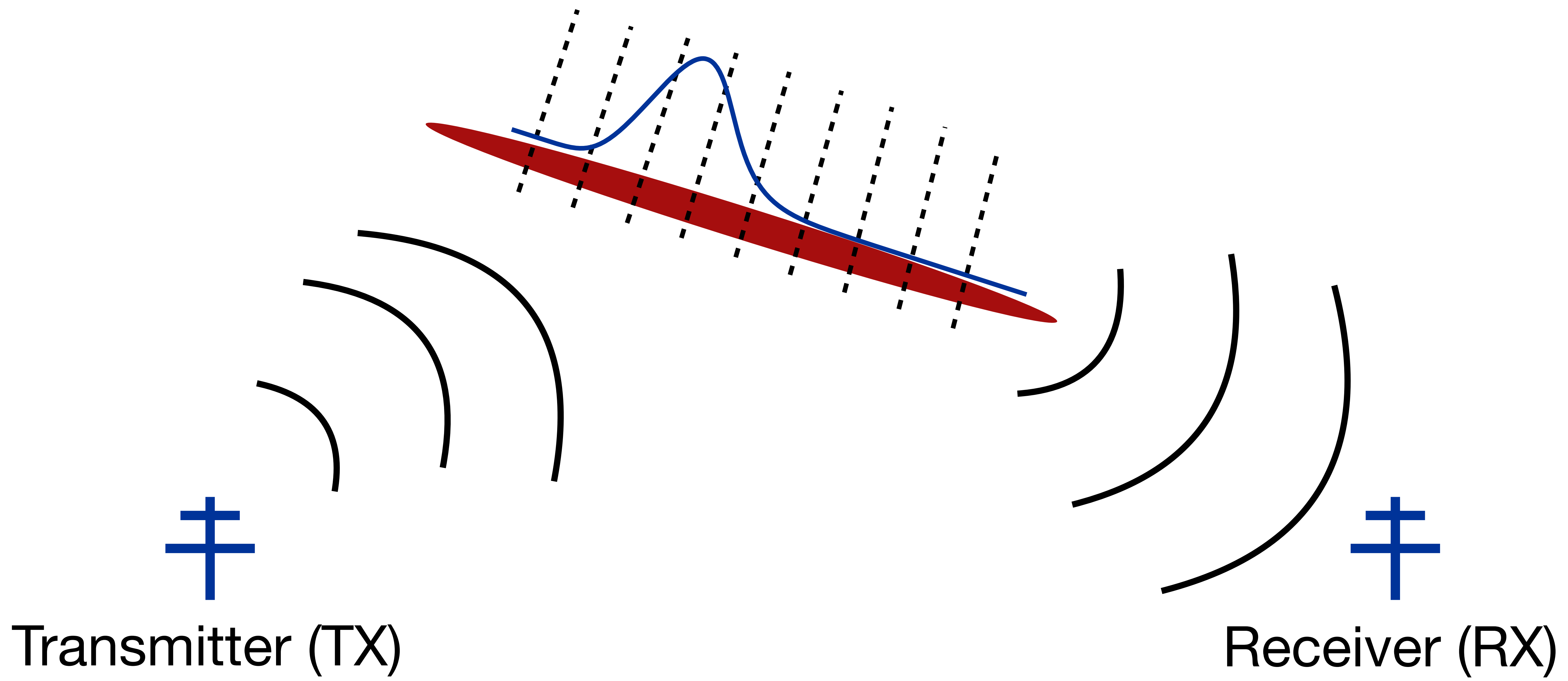


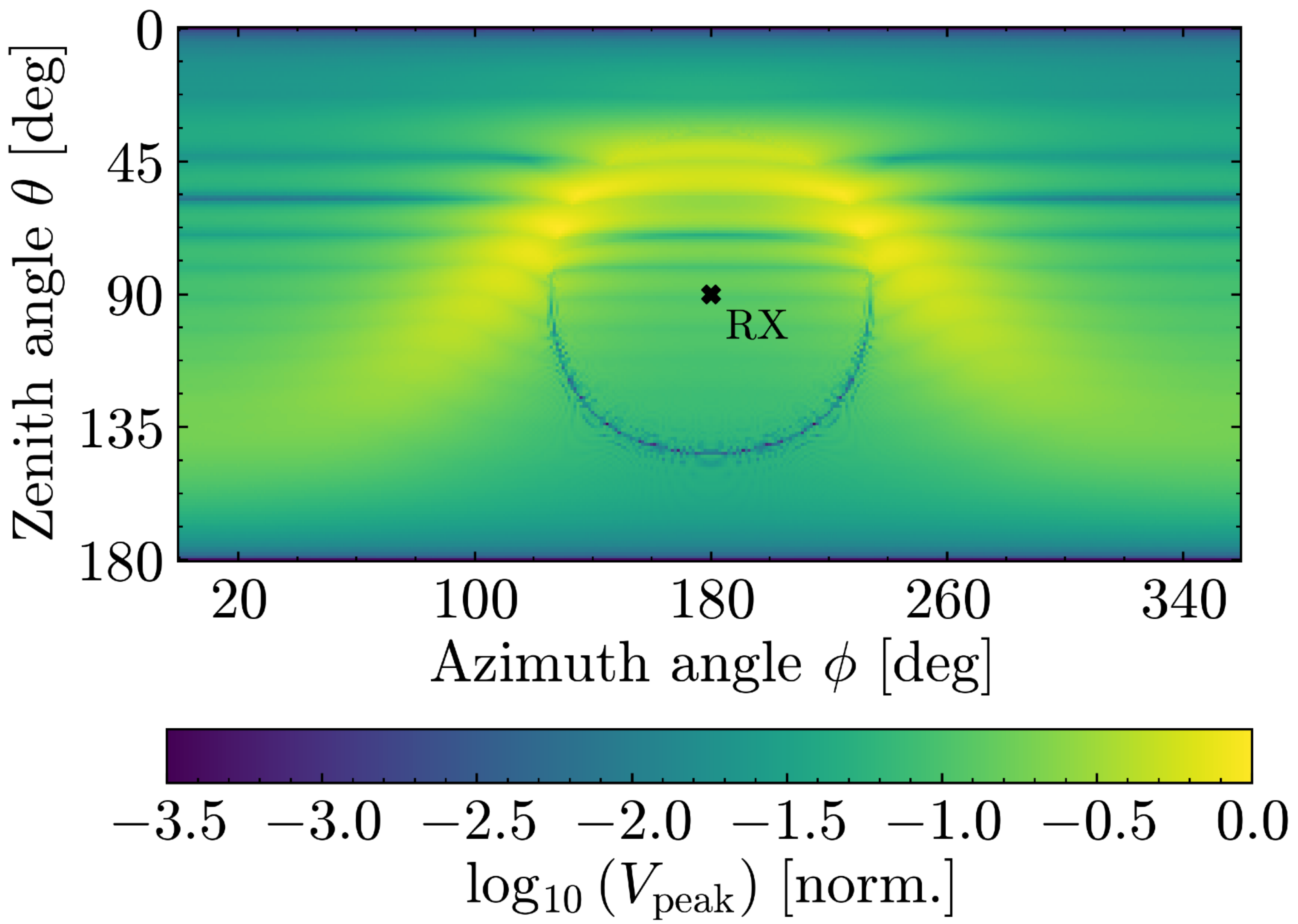
Undersampled



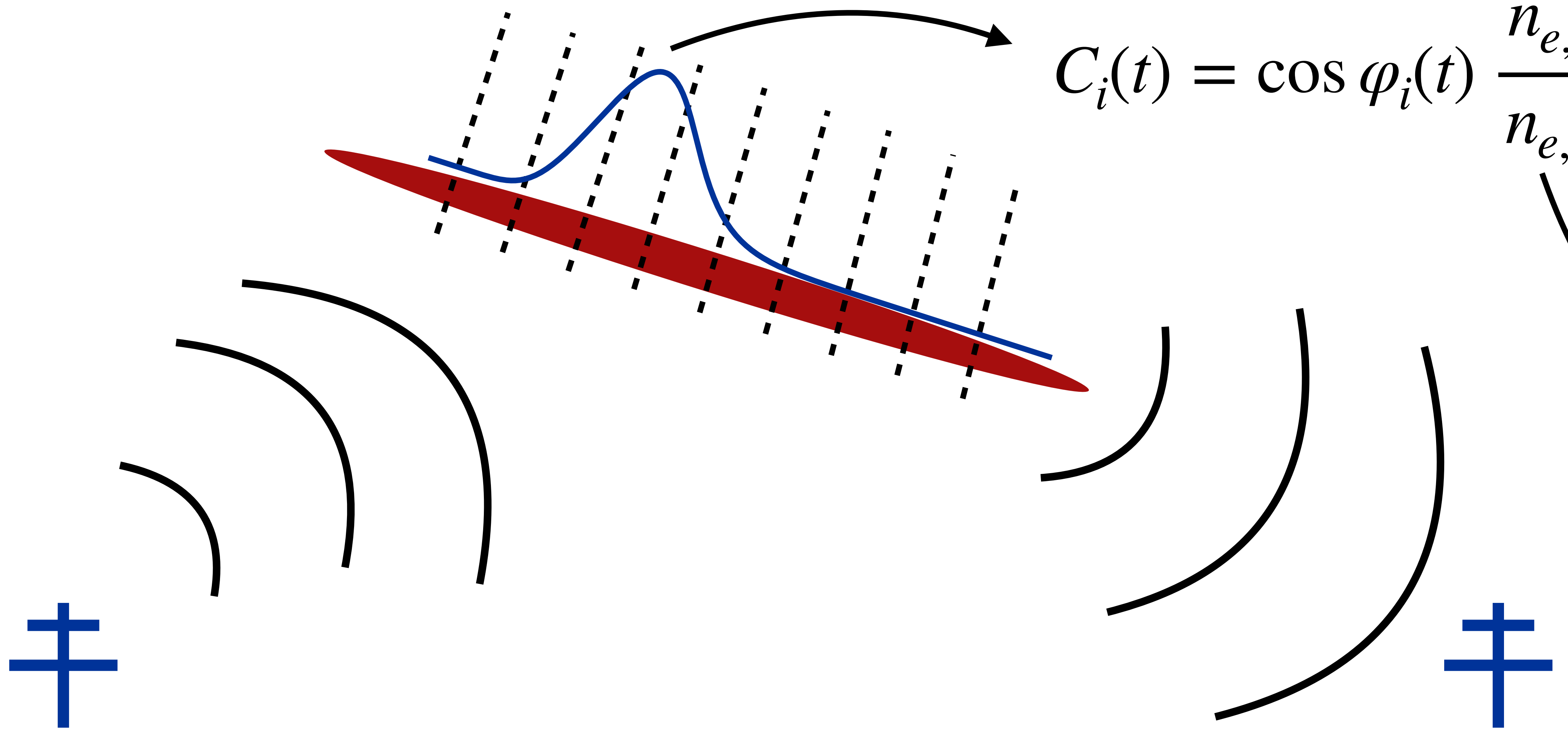
Radar Echo Signal Properties

- **High-amplitude region**
  - Unique to the radar detection method
  - Amplification of the signal due to phase alignment between the segments
  - Described by what we call phase coherence $C(t)$
  - $C(t)$ describes how strong the phases are aligned





Radar Echo Signal Properties



Transmitter (TX)

Receiver (RX)

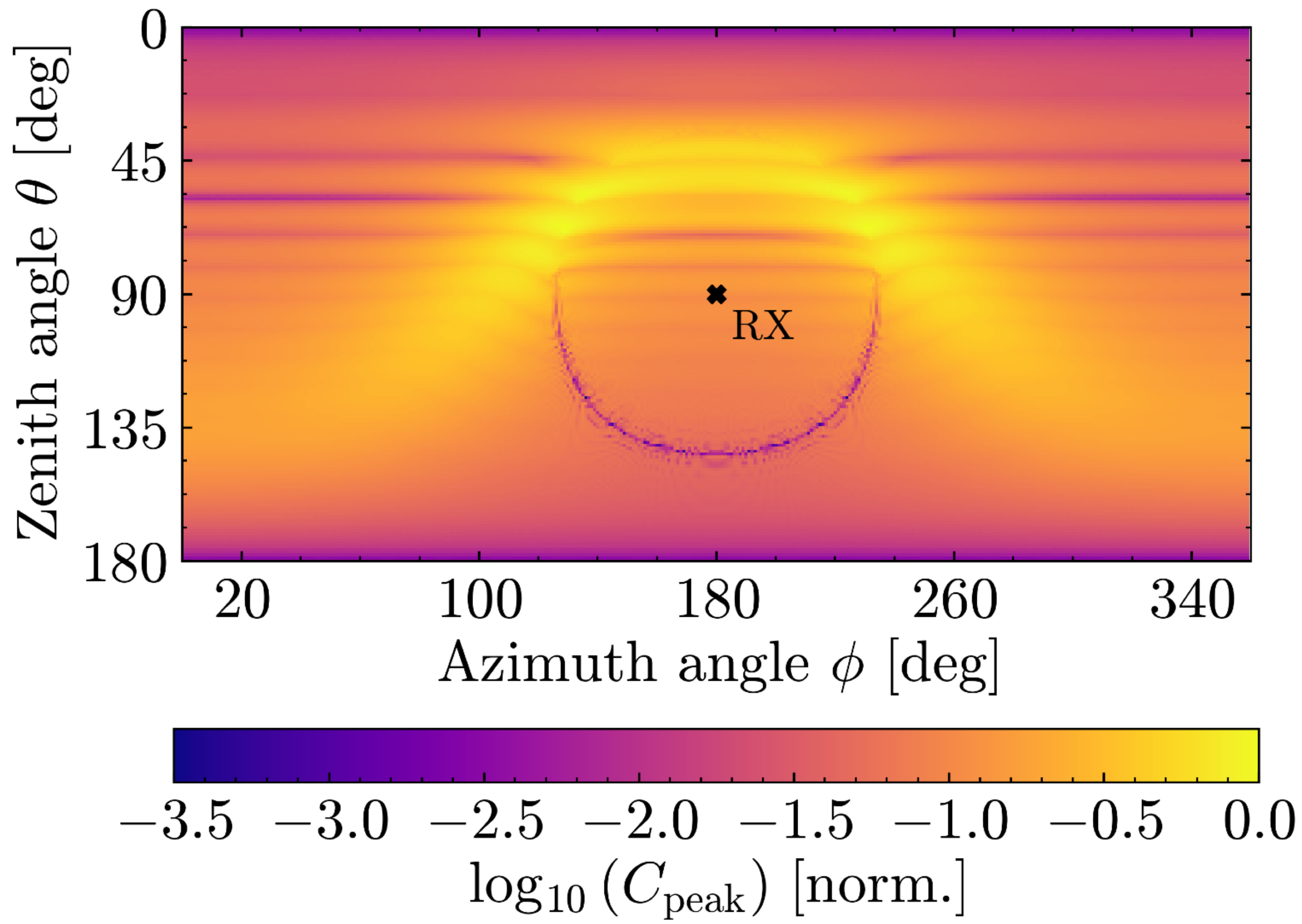
$$C_i(t) = \cos \varphi_i(t)\, \frac{n_{e,i}(t)}{n_{e,max}}$$

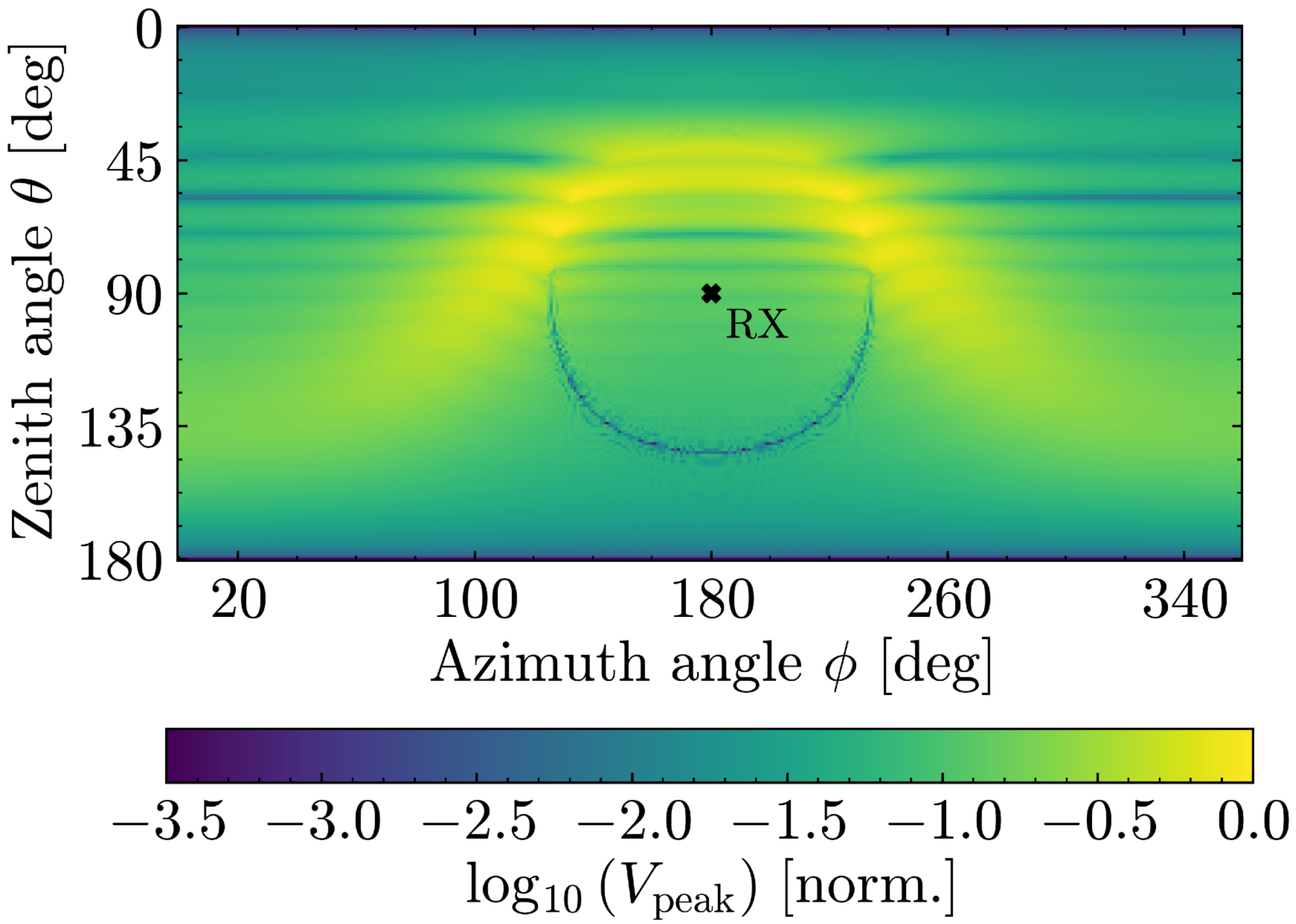
$$C(t) = \left| \sum_{i=1}^{N} \cos \varphi_i(t)\, \frac{n_{e,i}(t)}{n_{e,max}} \right|$$

$$\boxed{C_{peak} = \left| \sum_{i=1}^{N} \cos \varphi_i(t)\, \frac{n_{e,i}(t)}{n_{e,max}} \right|_{t=t_{peak}}}$$

- **High-amplitude region**
  - High-amplitude band is reproduced by $C(t)$
  - All features are described by the concept
  - Phase coherence drives description of radar signals

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

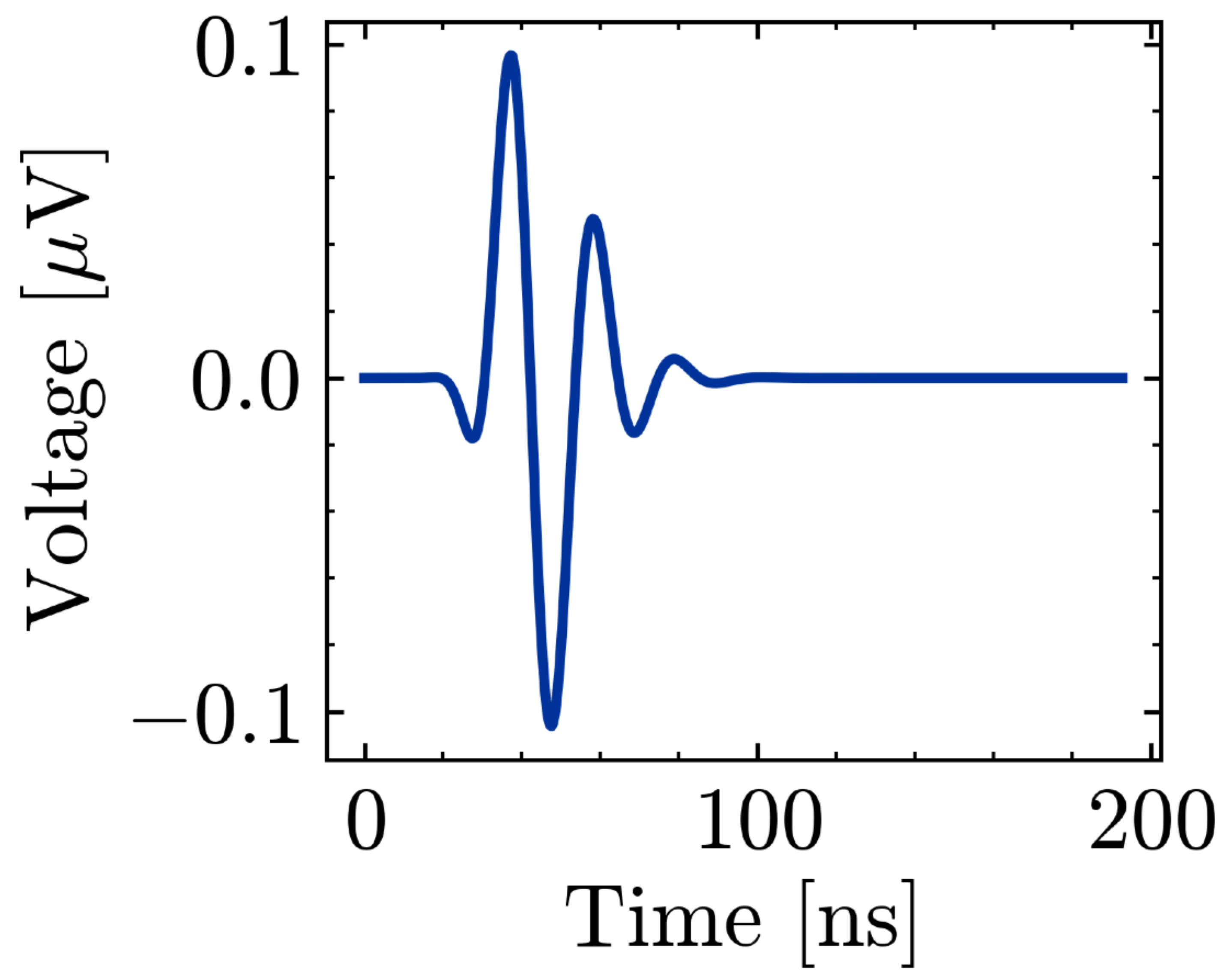


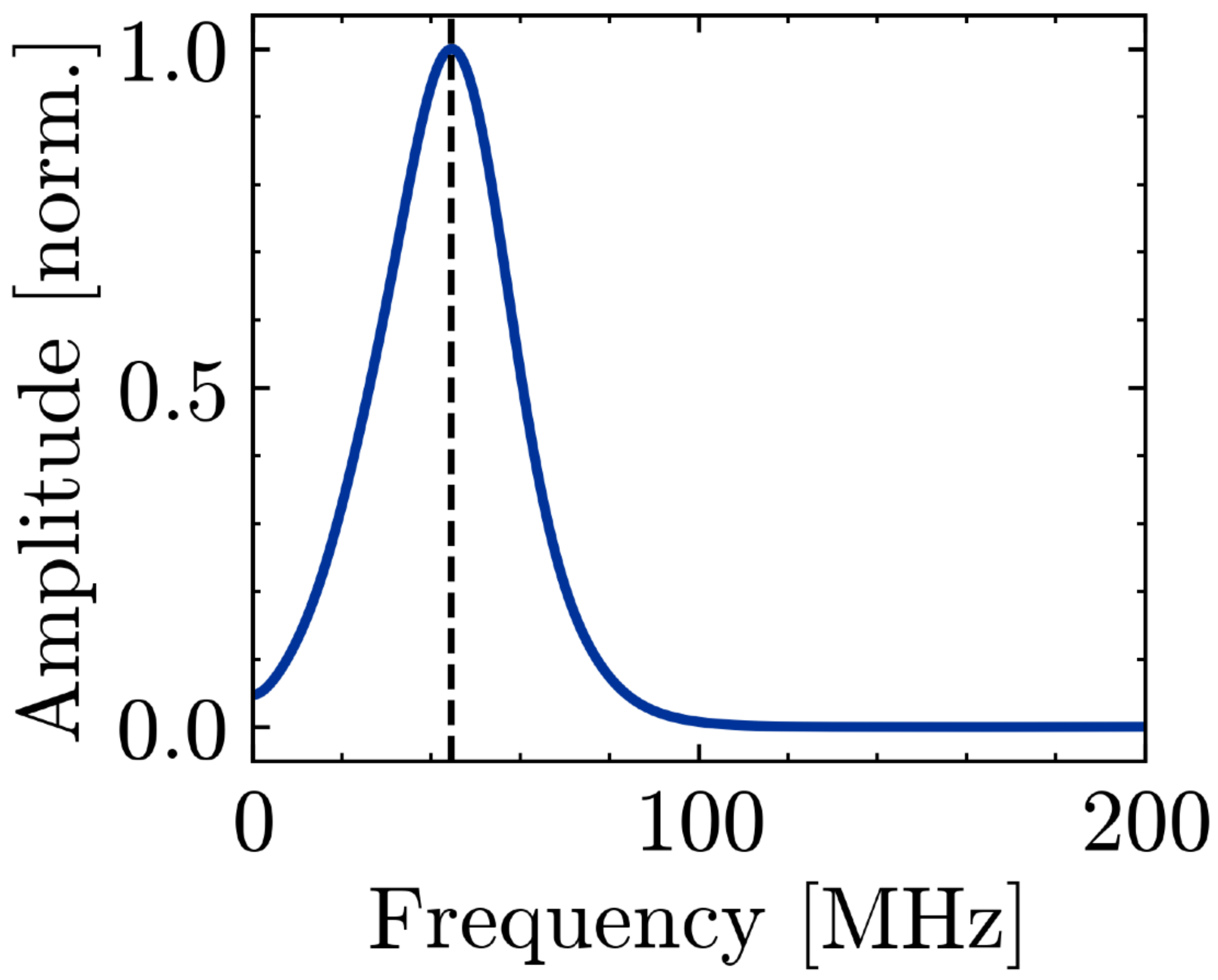


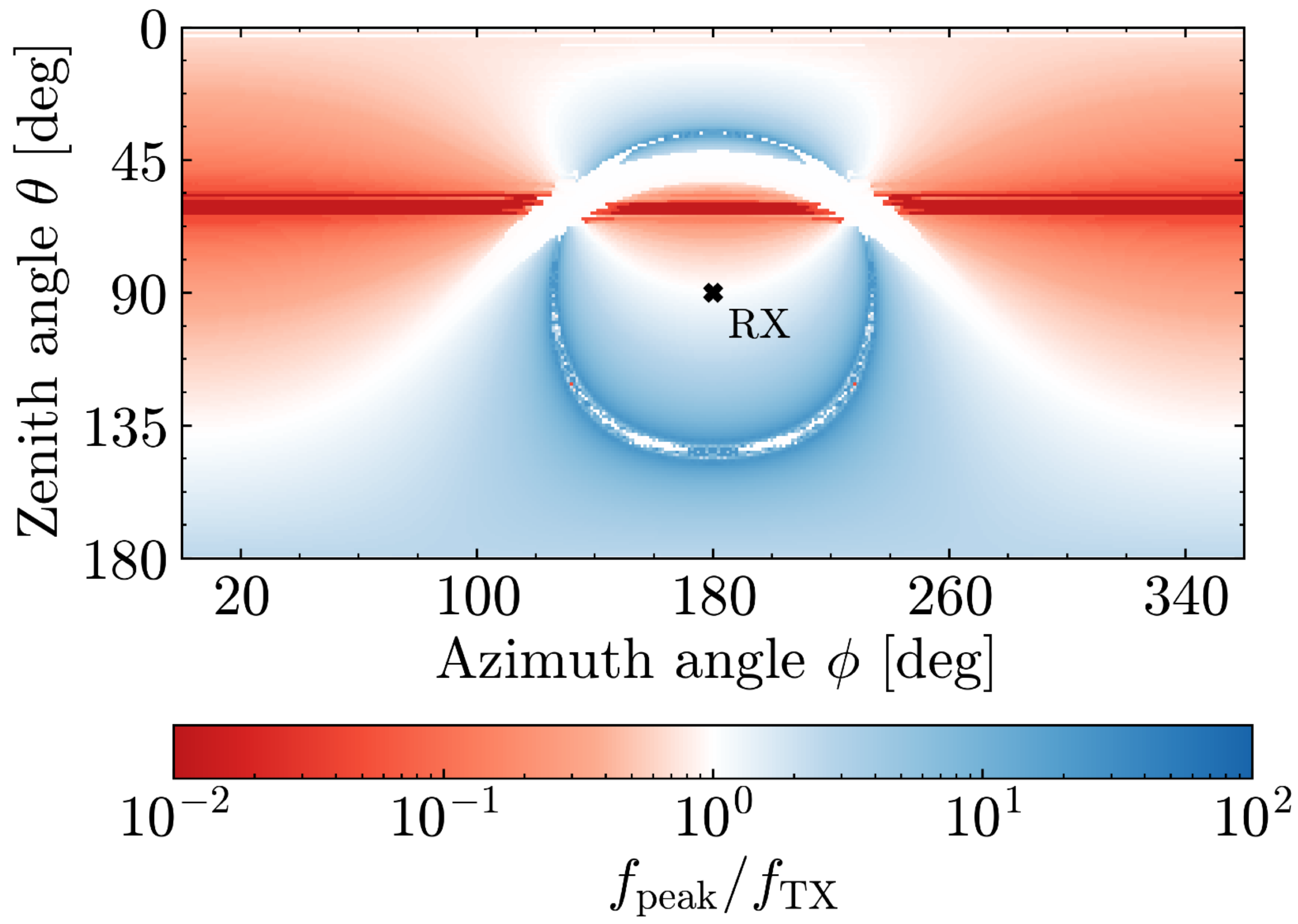
Frequency Domain Signal Properties

Radar Echo Signal Properties

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





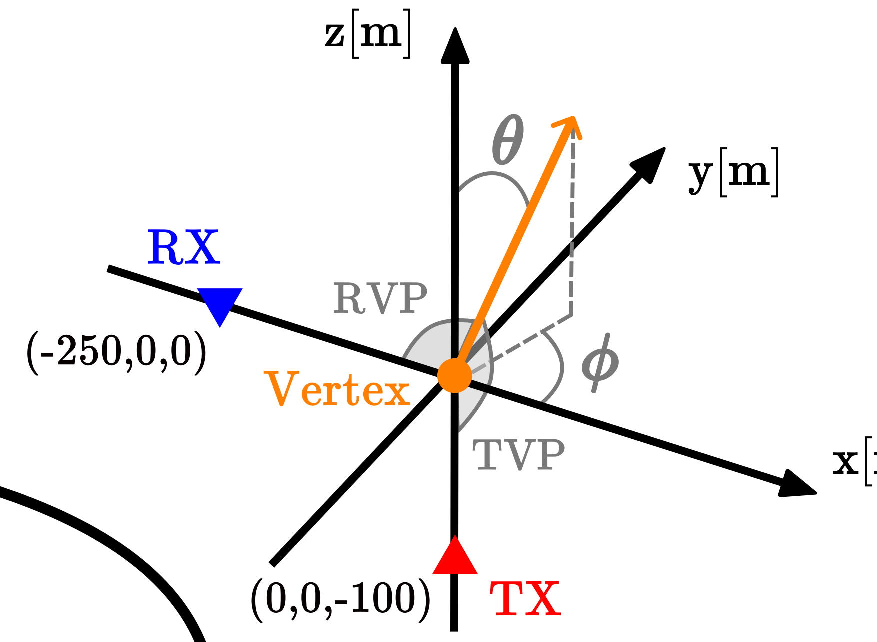


Radar Echo Signal Properties

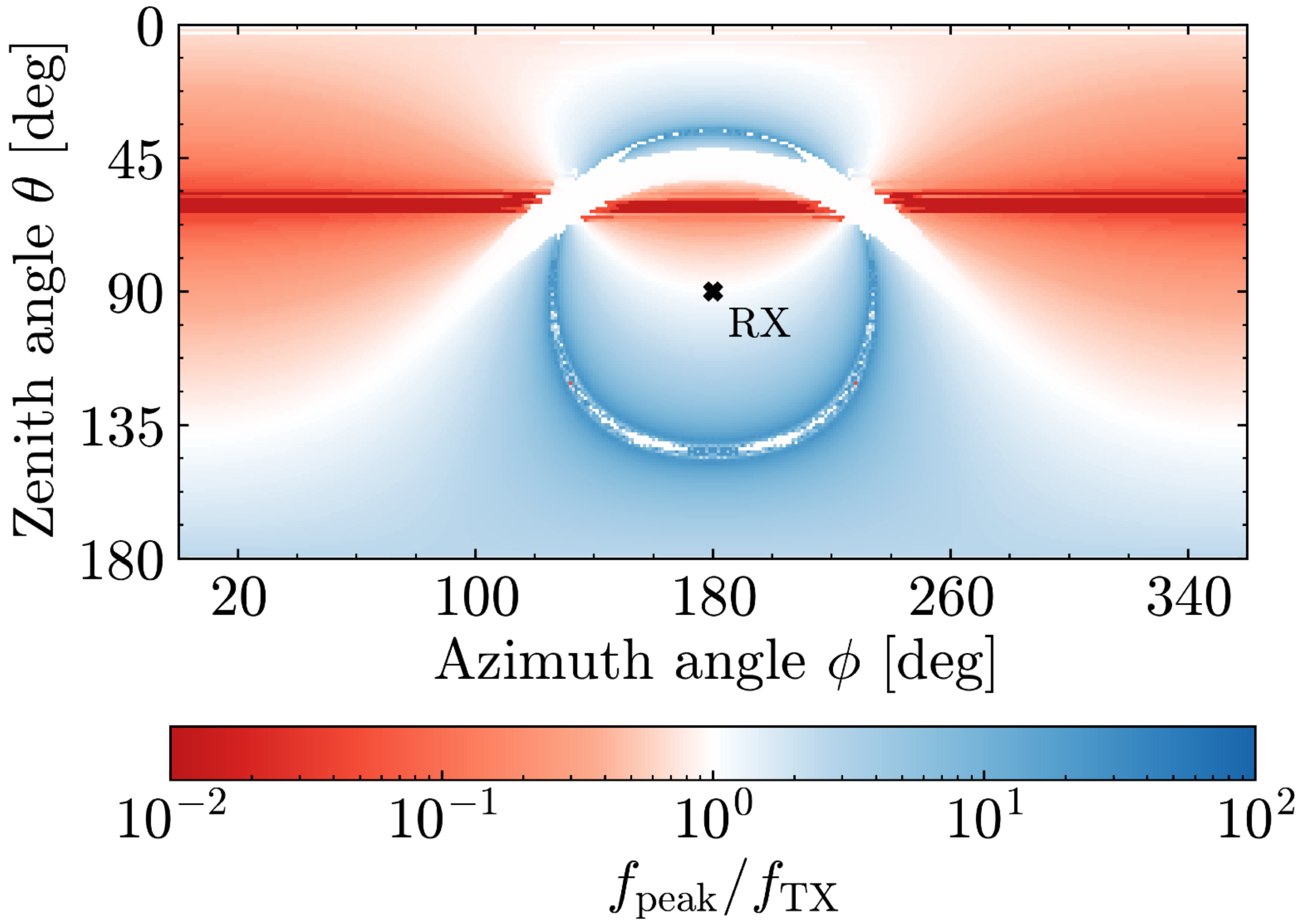
- **The Frequency Domain**
  - The shifts can be predicted from first principles
  - Ionisation trail moves relativistically
  - Double Doppler shift due to radar setup

Collaboration Isha Loudon

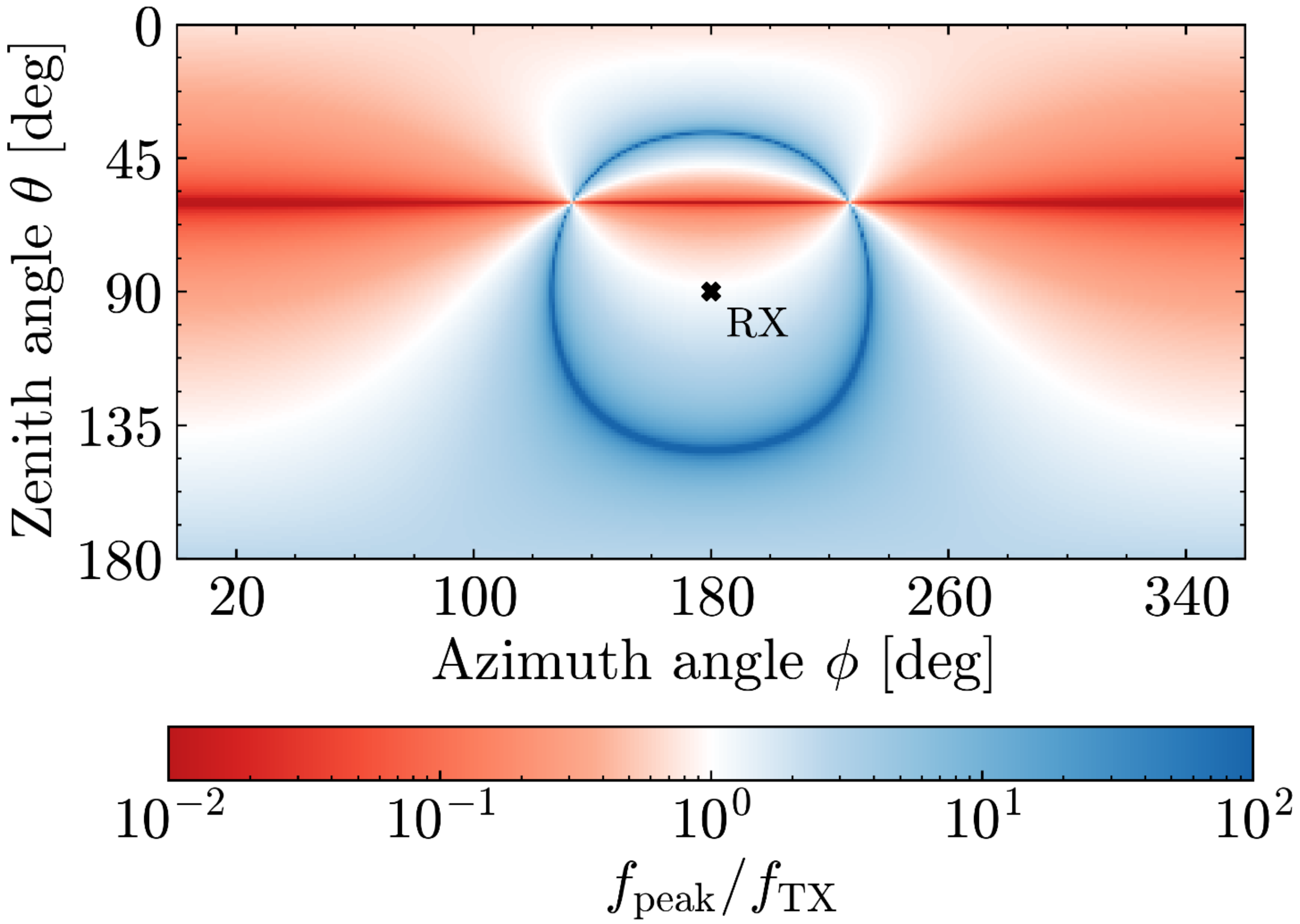
$$\frac{f_{RX}}{f_{TX}} = \frac{|\,1 + n\beta\cos(TVP)\,|}{|\,1 - n\beta\cos(RVP)\,|}$$



Simulation

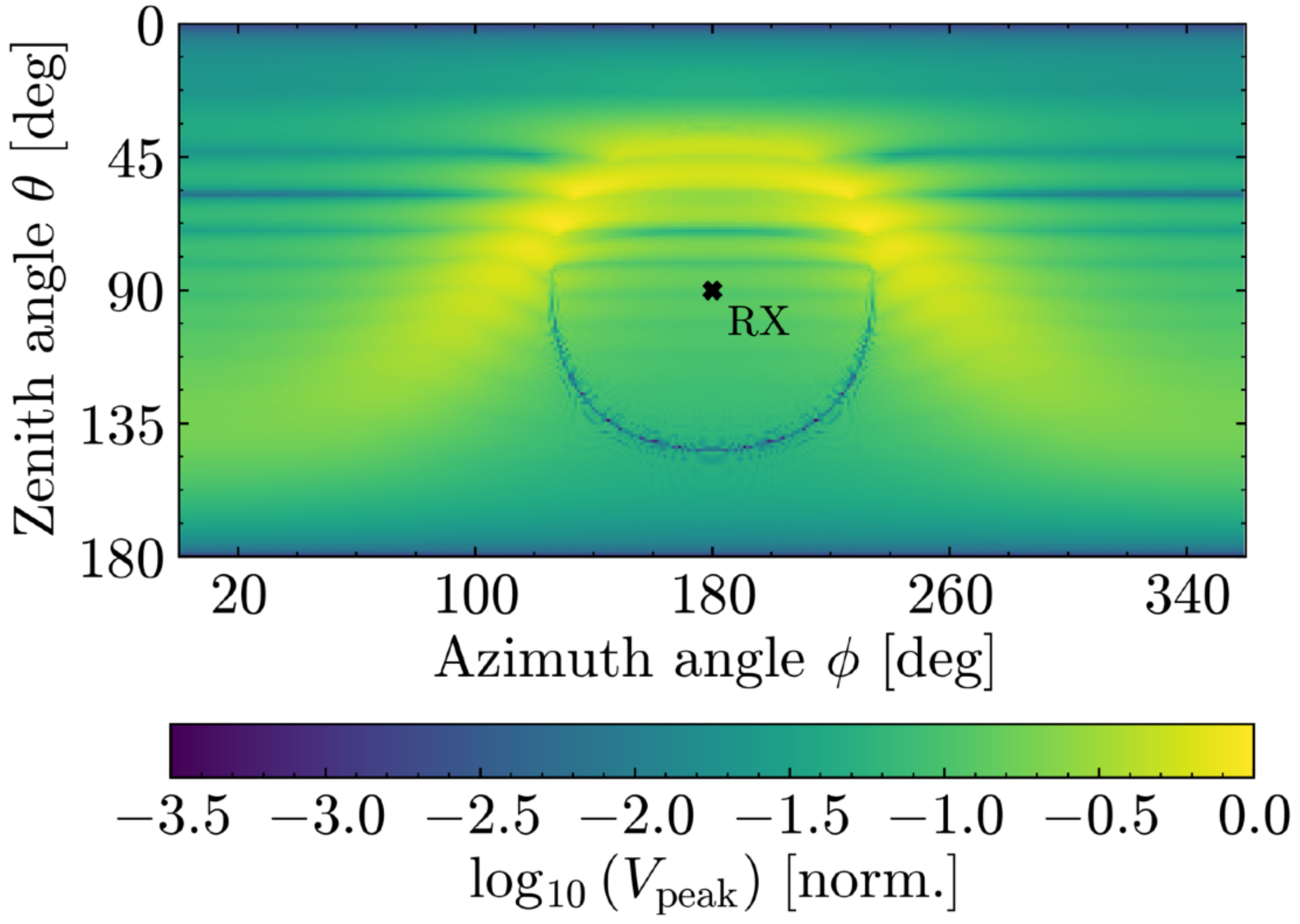


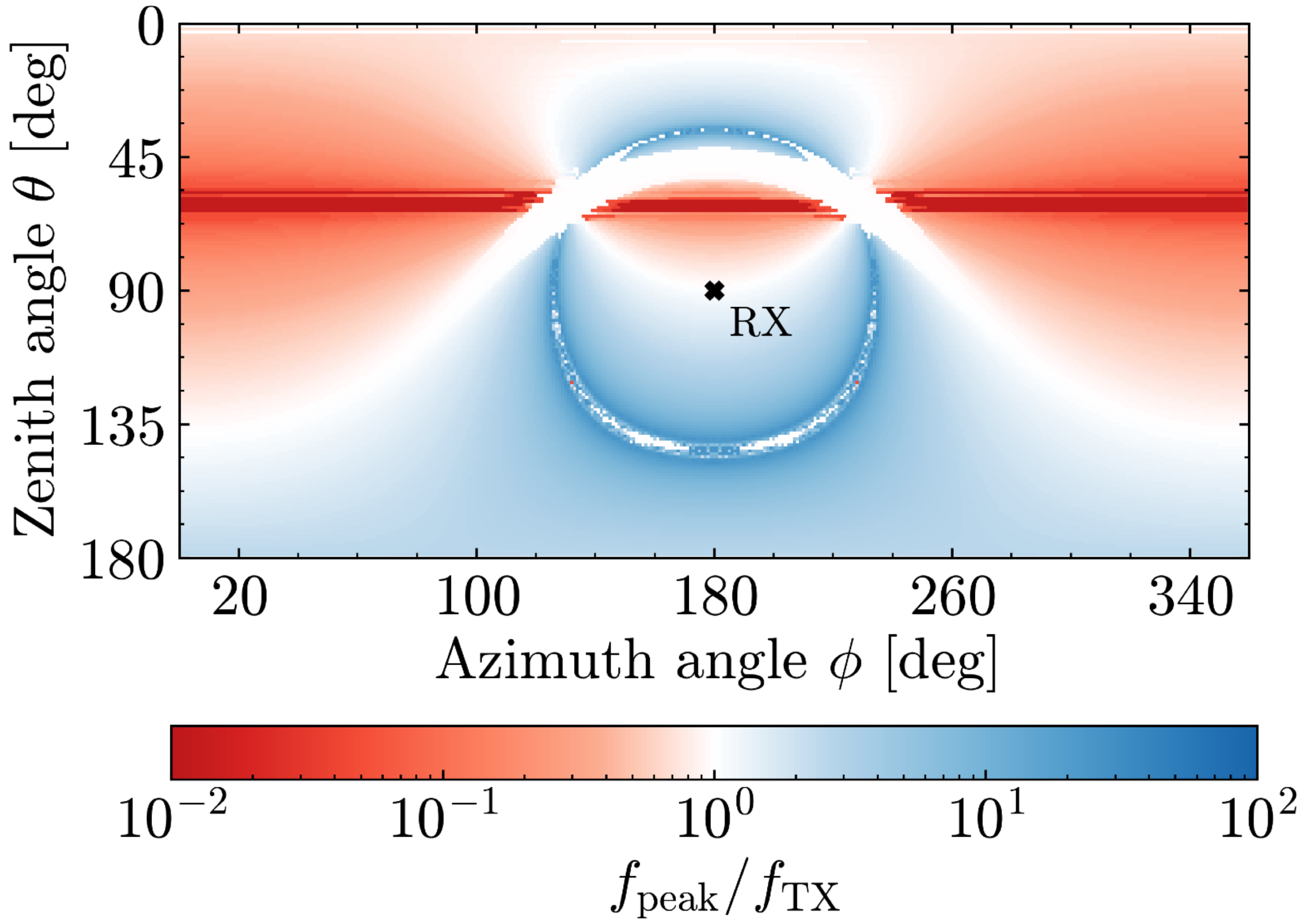
Prediction



Conclusion

MARES model





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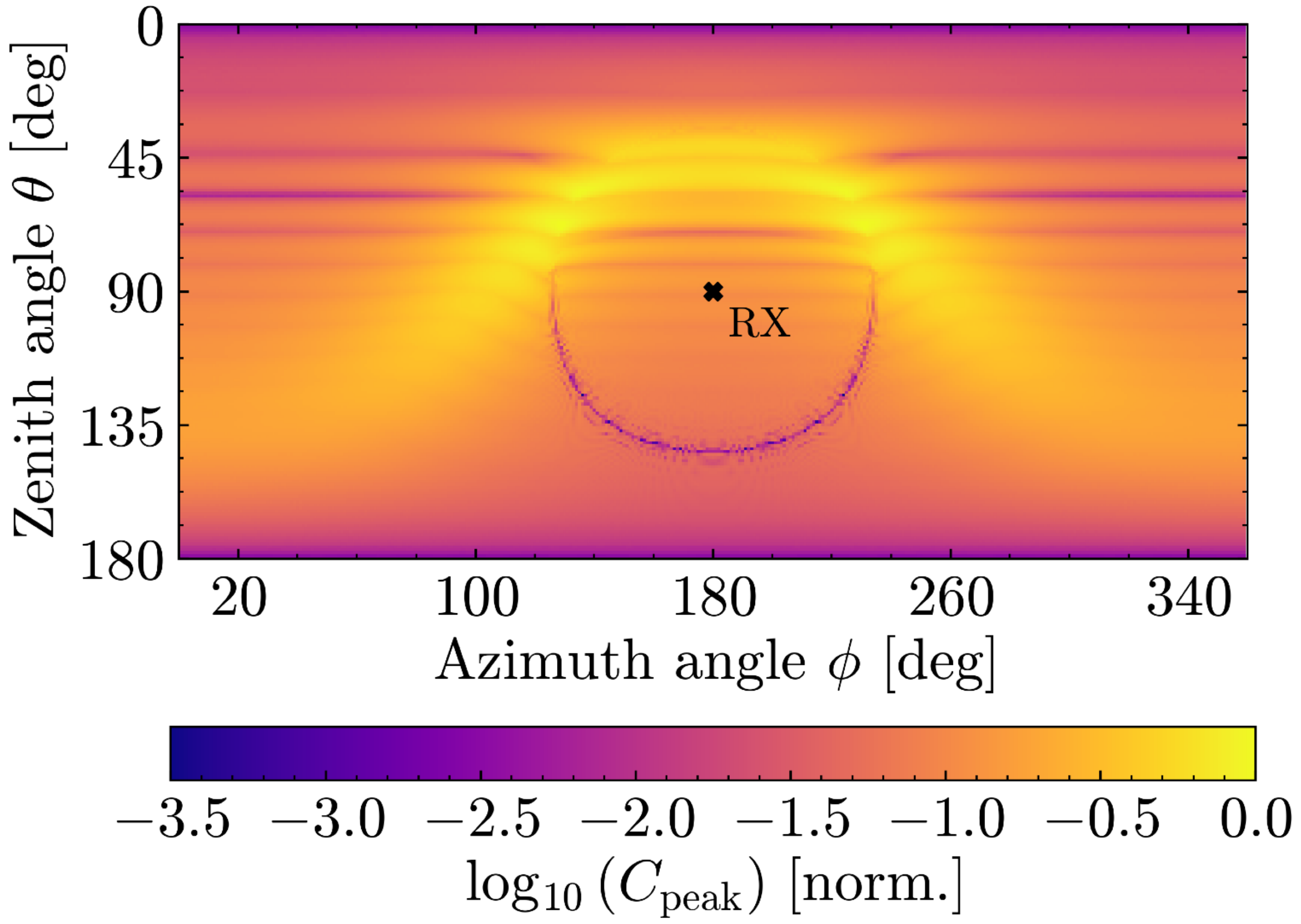
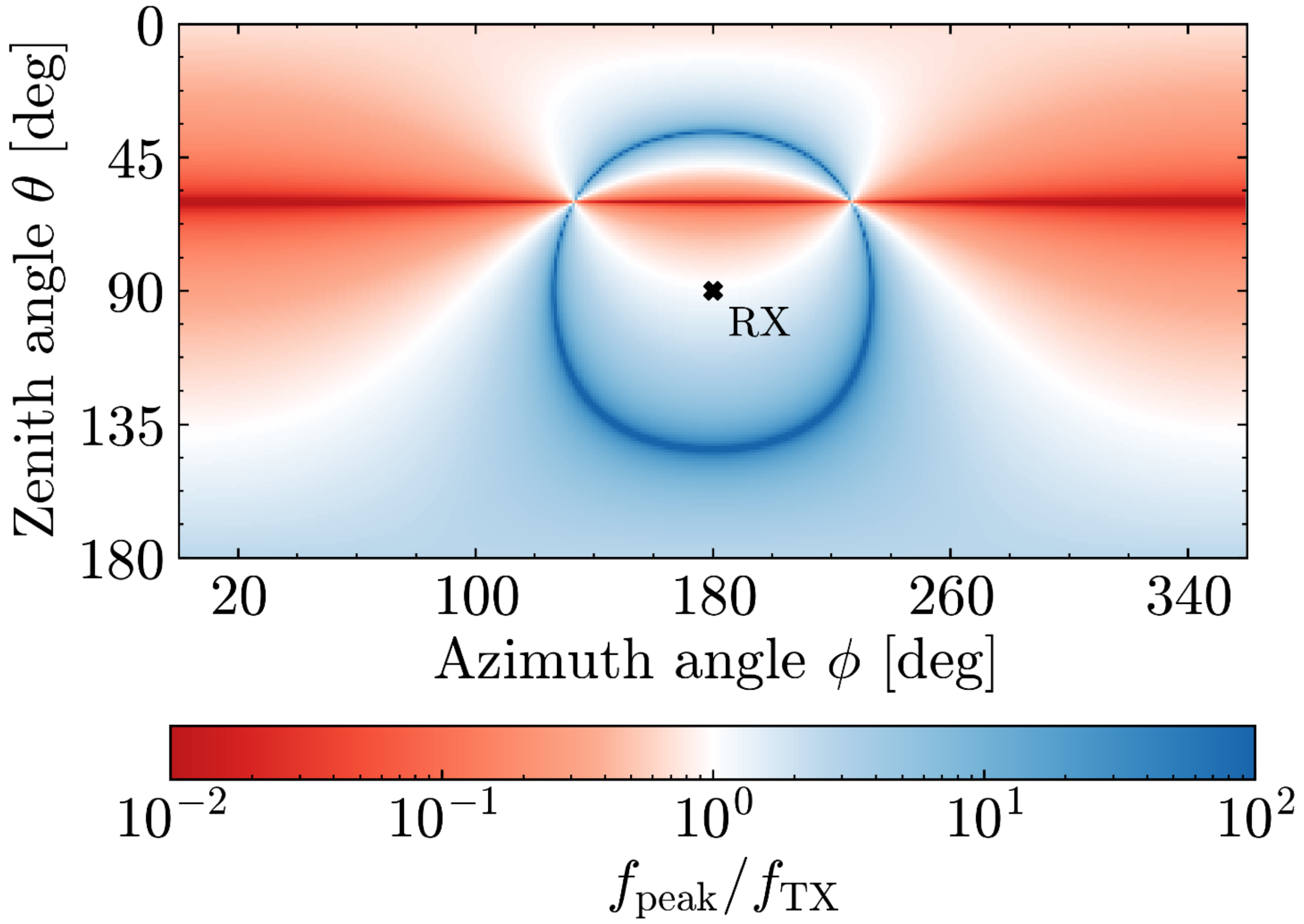
Analytical formula





RADAR ECHO TELESCOPE

THANK YOU!

Jannes Loonen

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VUB VRIJE UNIVERSITEIT BRUSSEL

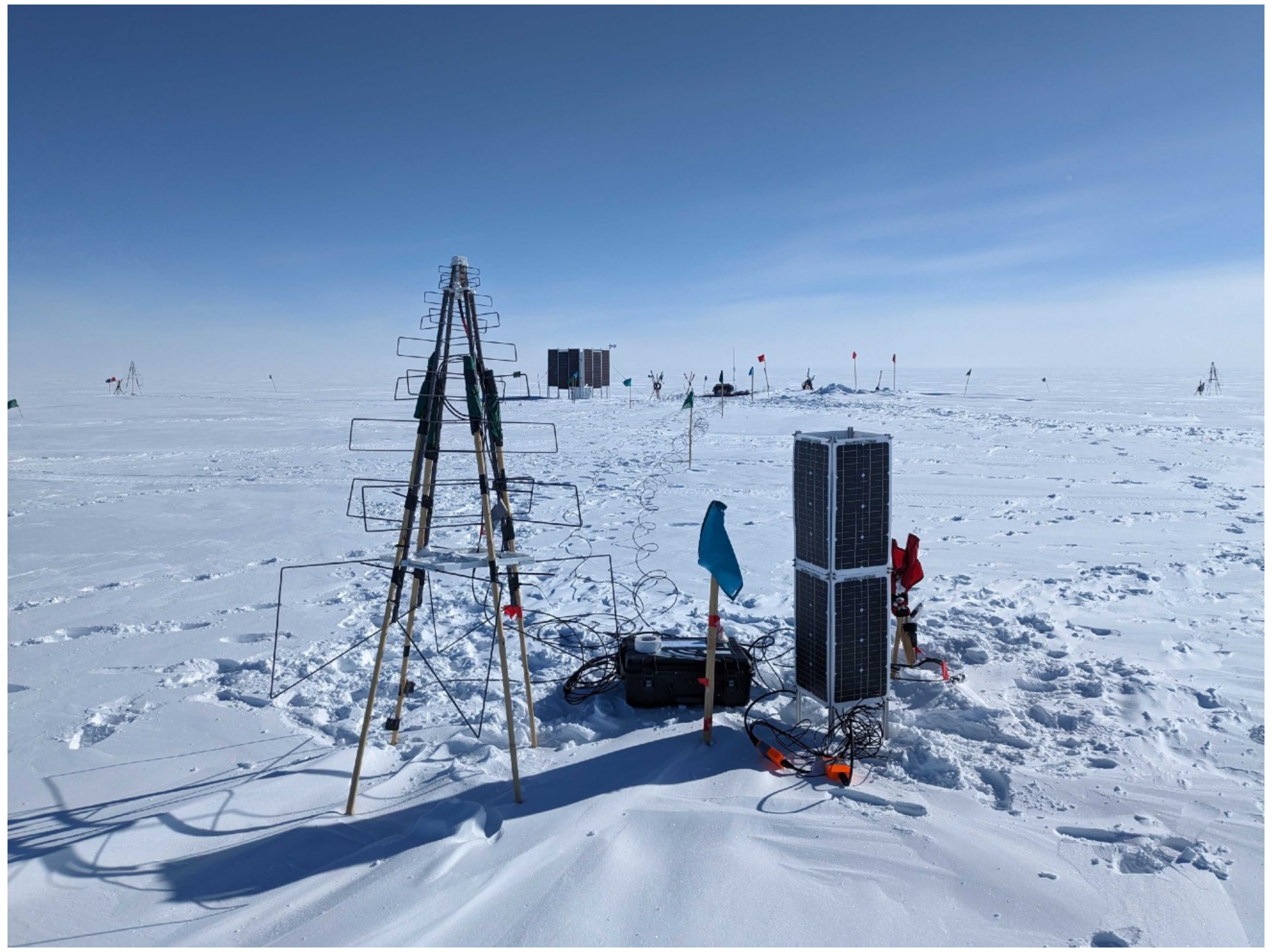
iihe BRUXELLES BRUSSEL

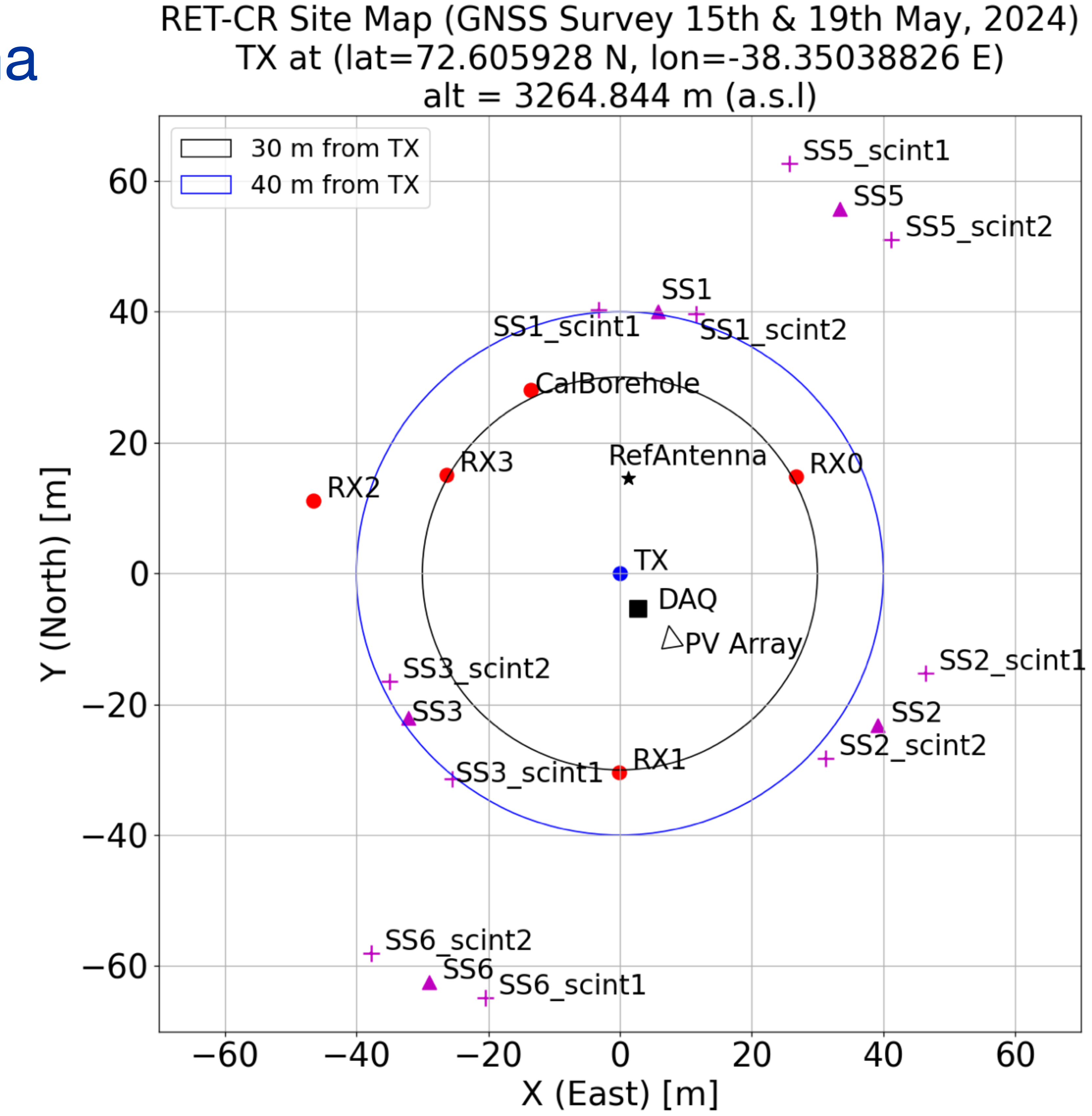
NSF

erc European Research Council Established by the European Commission

RET-CR

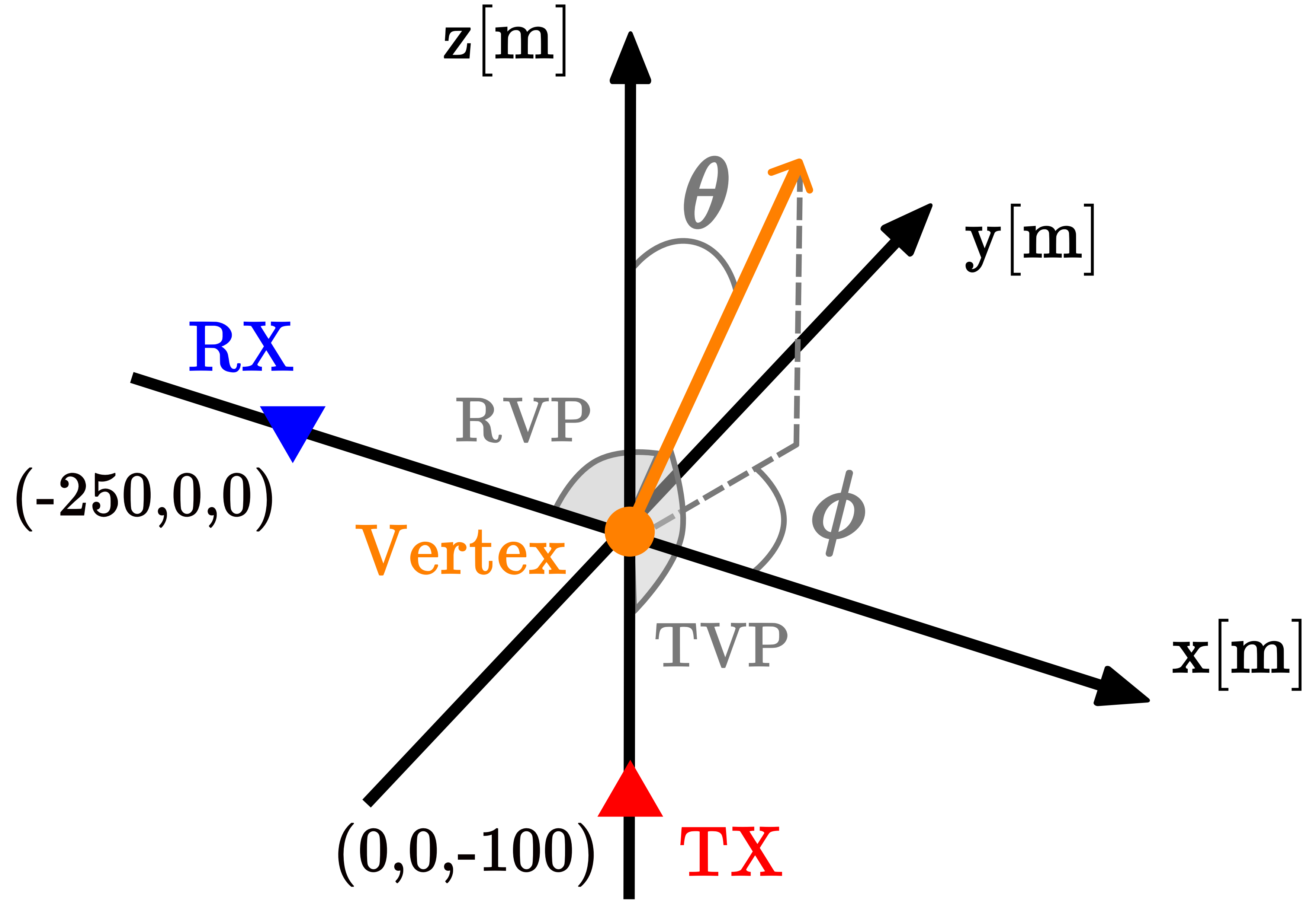
- **The Radar Echo Telescope for Cosmic Rays**
  - Purple: Surface station → Two scintillator panels single radio antenna
  - Blue: The transmitter antenna
  - Red: The receiver antennas (distance to central TX 30 m)

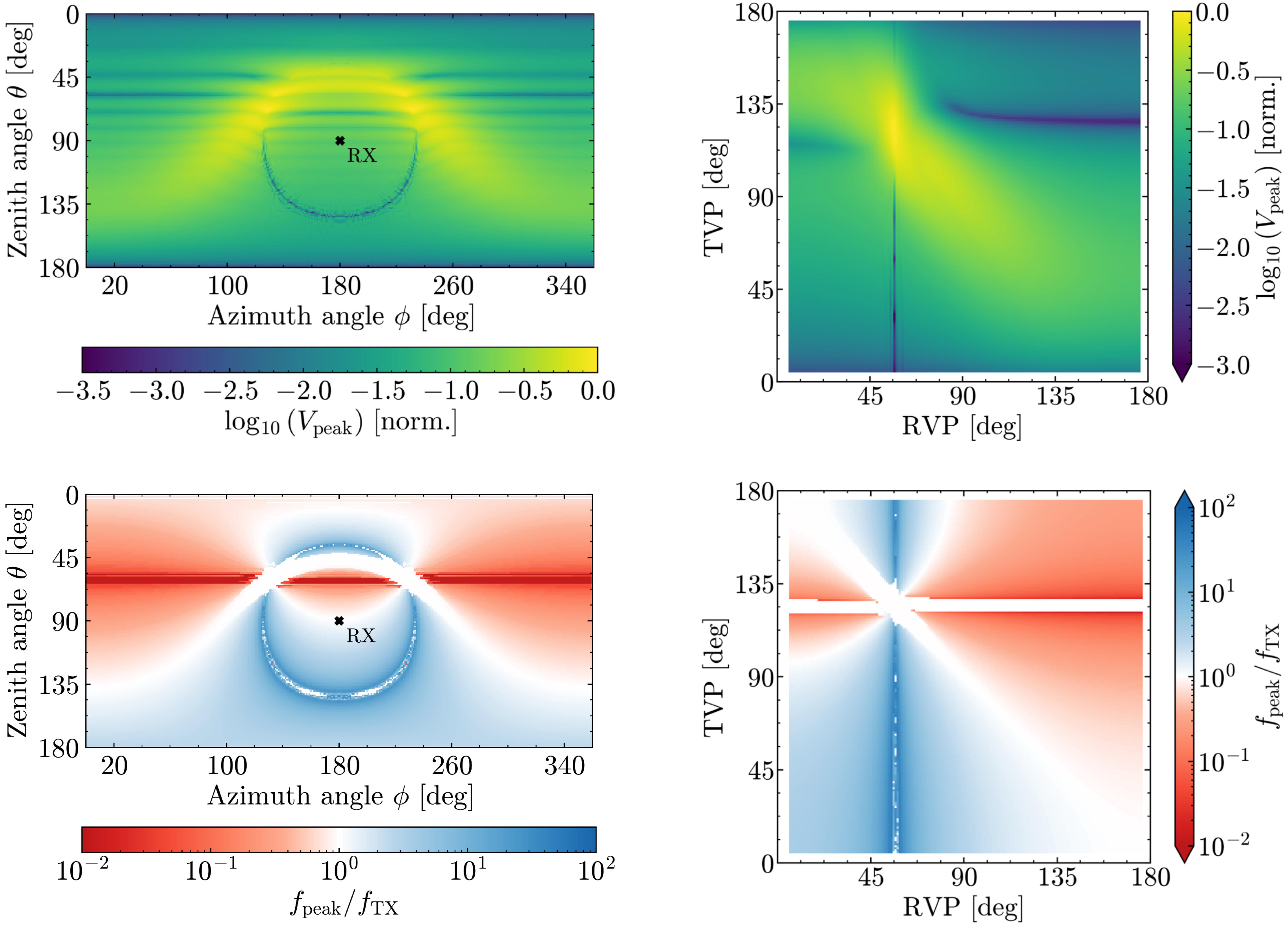




Radar specific coordinates

- **RVP and TVP vs (θ, ϕ)**





Accuracy Analytical descriptions

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