Radar Signal Properties from Neutrino-Induced Particle Cascades

Isha Loudon, on behalf of the
Radar Echo Telescope
collaboration

ARENA
10/06/26

fnrs LA LIBERTÉ DE CHERCHER

European Research Council
Established by the European Commission

ULB

iihe BRUXELLES BRUSSEL

NSF

RADAR ECHO TELESCOPE

The Radar Signal

Exploring the detection of >PeV neutrinos with in-ice radar: RADAR ECHO TELESCOPE

The Radar Signal

Exploring the detection of >PeV neutrinos with in-ice radar: RADAR ECHO TELESCOPE

⇒ Gain a detailed understanding of the emission mechanism and resulting signal features.

↳ Reconstruction methods, optimised detector layout, trigger studies…

MARES: semi-analytic code package
E. Huesca Santiago et al., 2024

The Radar Signal

Exploring the detection of >PeV neutrinos with in-ice radar: RADAR ECHO TELESCOPE

Gain a detailed understanding of the emission mechanism and resulting signal features.

→ Reconstruction methods, optimised detector layout, trigger studies...

→ In this talk: give a qualitative overview of the radar signal features in a global detector geometry

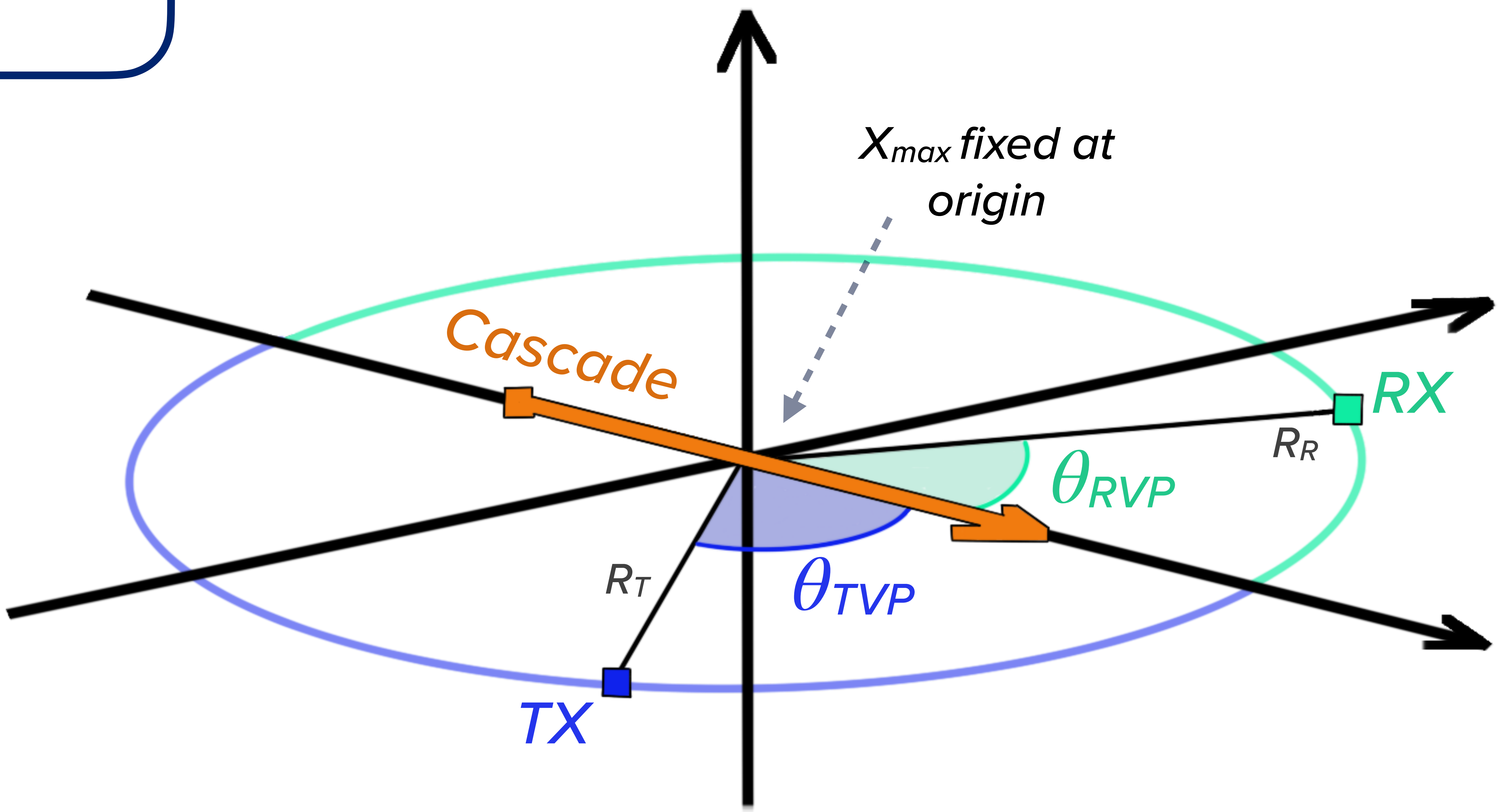
MARES: semi-analytic code package
E. Huesca Santiago et al., 2024

Detector Geometry

- *Simulate signals in an* ***ideal detector geometry***
- *Explore amplitude and frequency observables*
- *Obtain global descriptions*

Aim is to cover the full space of possible solutions from a single event:

- Place antennas (TX, RX) on circle surrounding the cascade
- Define radar frame angles $\theta_{RVP}, \theta_{TVP}$

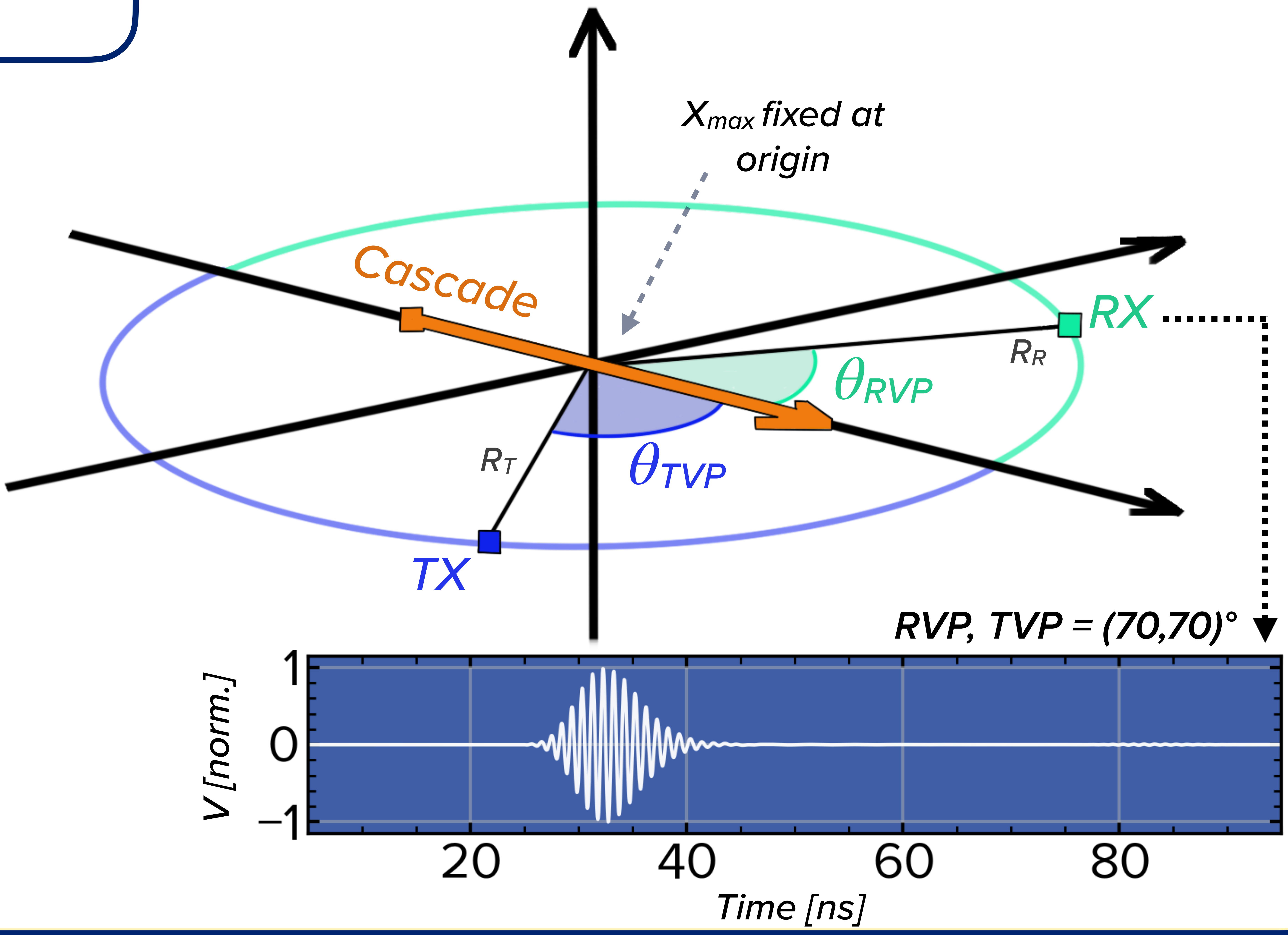


Detector Geometry

- *Simulate signals in an* ***ideal detector geometry***
- *Explore amplitude and frequency observables*
- *Obtain global descriptions*

Aim is to cover the full space of possible solutions from a single event:

- Place antennas (TX, RX) on circle surrounding the cascade
- Define radar frame angles $\theta_{RVP}, \theta_{TVP}$

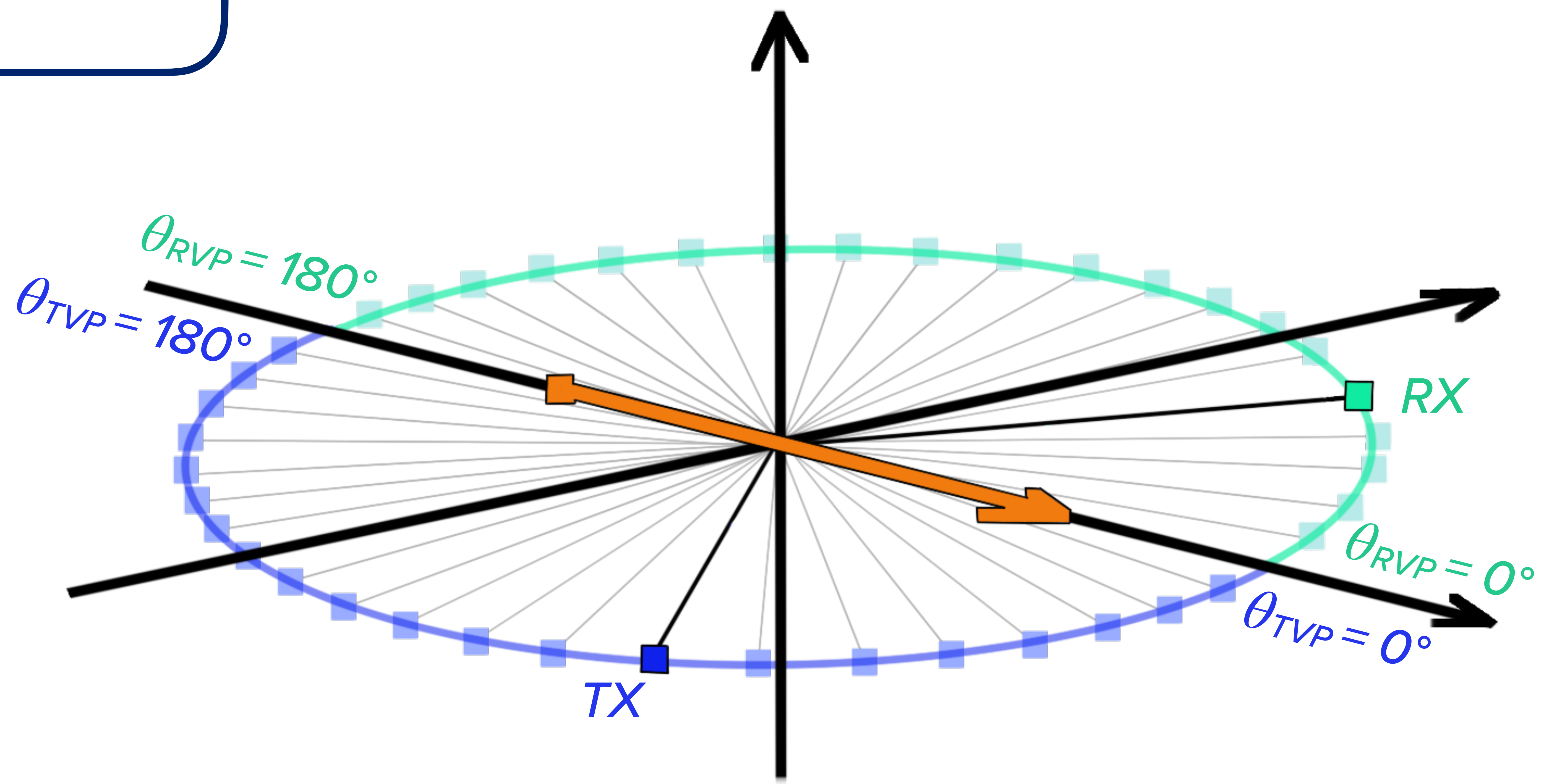


Detector Geometry

- *Simulate signals in an **ideal detector geometry***
- *Explore amplitude and frequency observables*
- *Obtain global descriptions*

Aim is to cover the full space of possible solutions from a single event:

- Place antennas (TX, RX) on circle surrounding the cascade
- Define radar frame angles $\theta_{RVP}, \theta_{TVP}$
- Obtain signal from each TX-RX combination, corresponding to a $\theta_{RVP}, \theta_{TVP}$ orientation within the detector



$\theta_{RVP} \in [5,175]°$; $\theta_{TVP} \in [5,175]°$

→ *Detector-independent coordinate system*

Detector Geometry

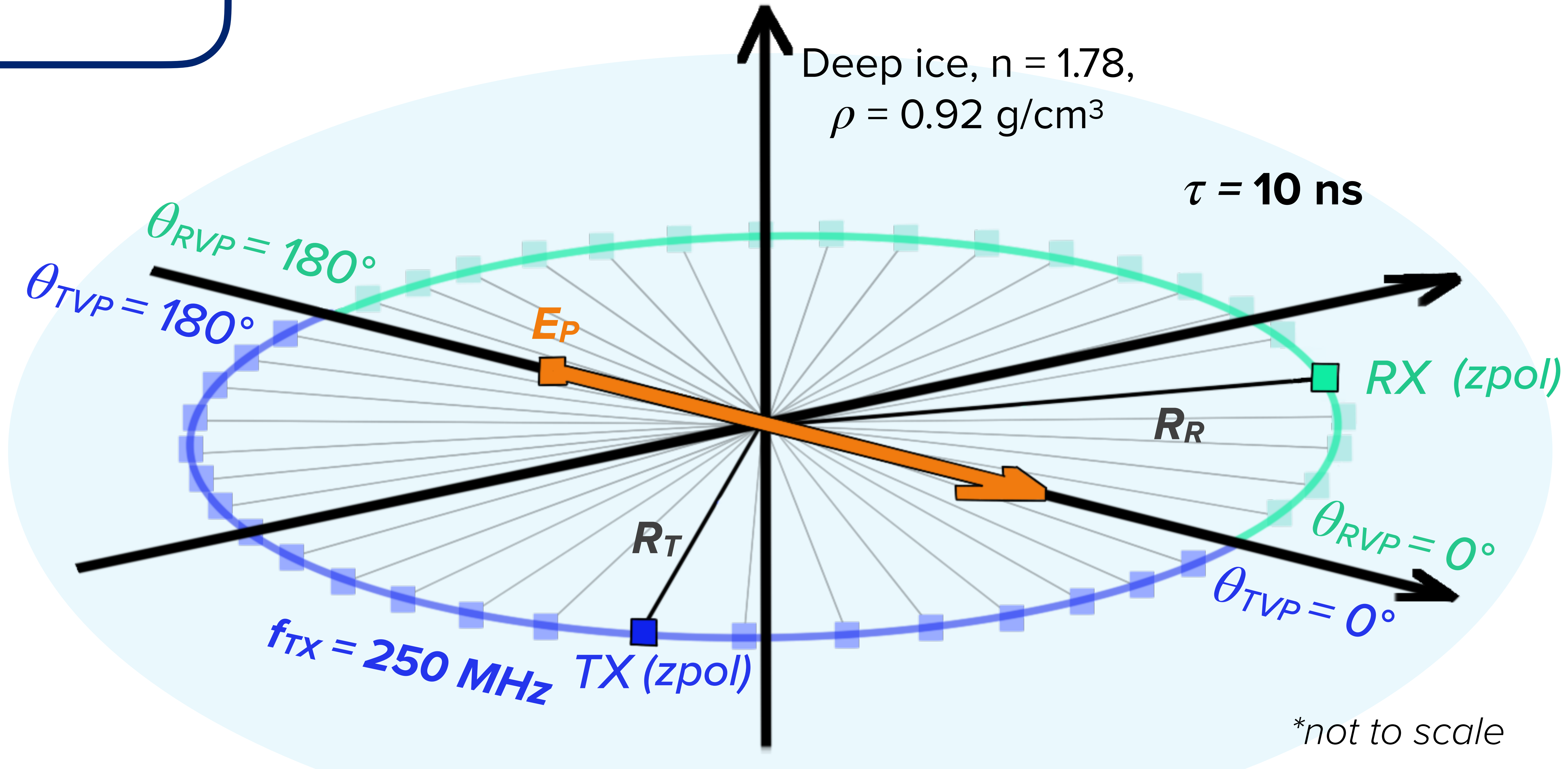
- *Simulate signals in an ideal detector geometry*
- *Explore **amplitude and frequency** observables*
- *Obtain global descriptions*

→ Aim is to cover the full space of possible solutions from a single event:

- Place antennas (TX, RX) on circle surrounding the cascade
- Define radar frame angles $\theta_{RVP}, \theta_{TVP}$
- Obtain signal from each TX-RX combination, corresponding to a $\theta_{RVP}, \theta_{TVP}$ orientation within the detector

$\theta_{RVP} \in [5,175]^\circ$; $\theta_{TVP} \in [5,175]^\circ$

→ *Detector-independent coordinate system*

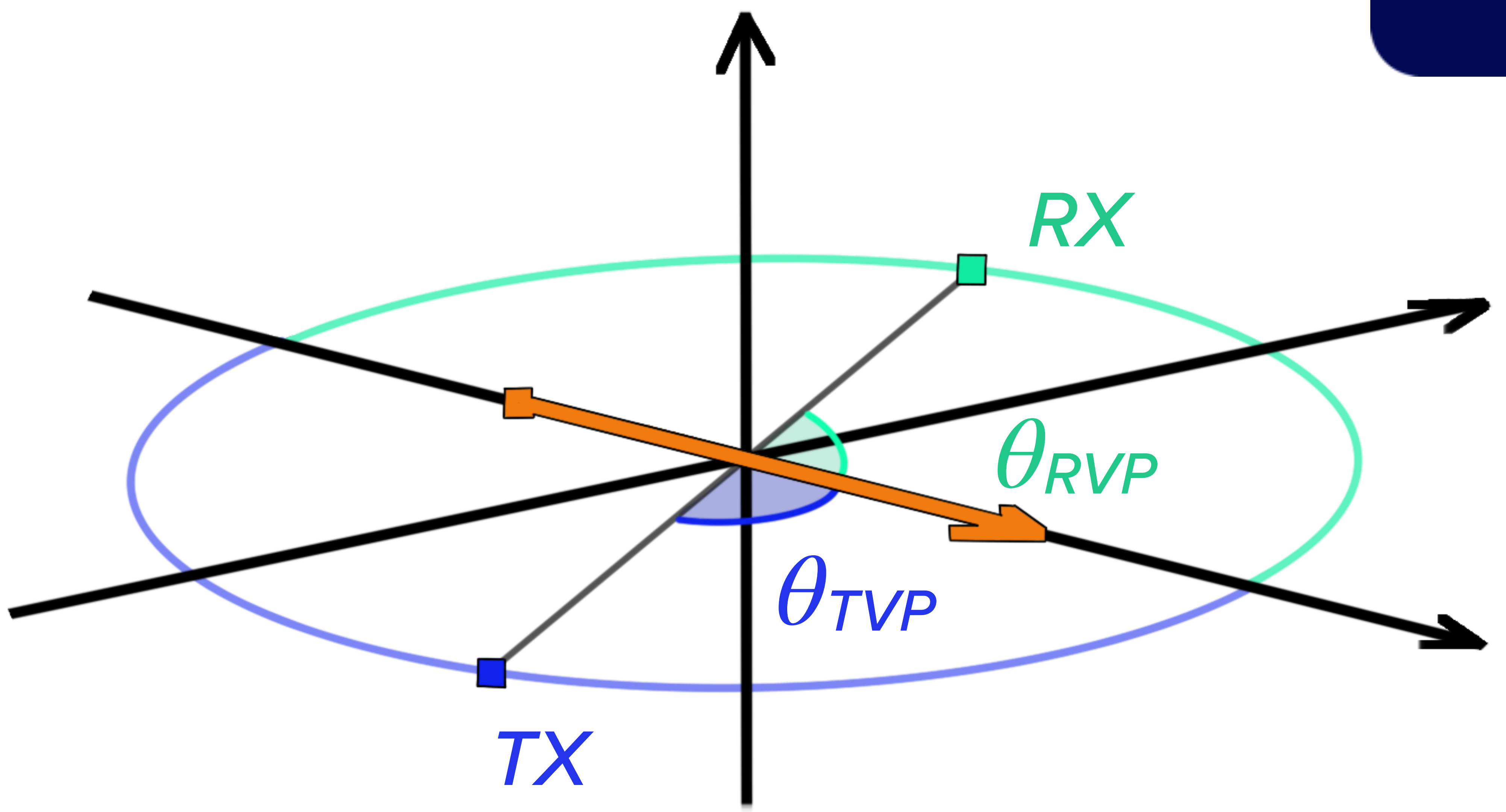


Simulation constants:
- Neutrino E_p = **100 PeV**
- Baselines $R_T = R_R$ = **400 m**

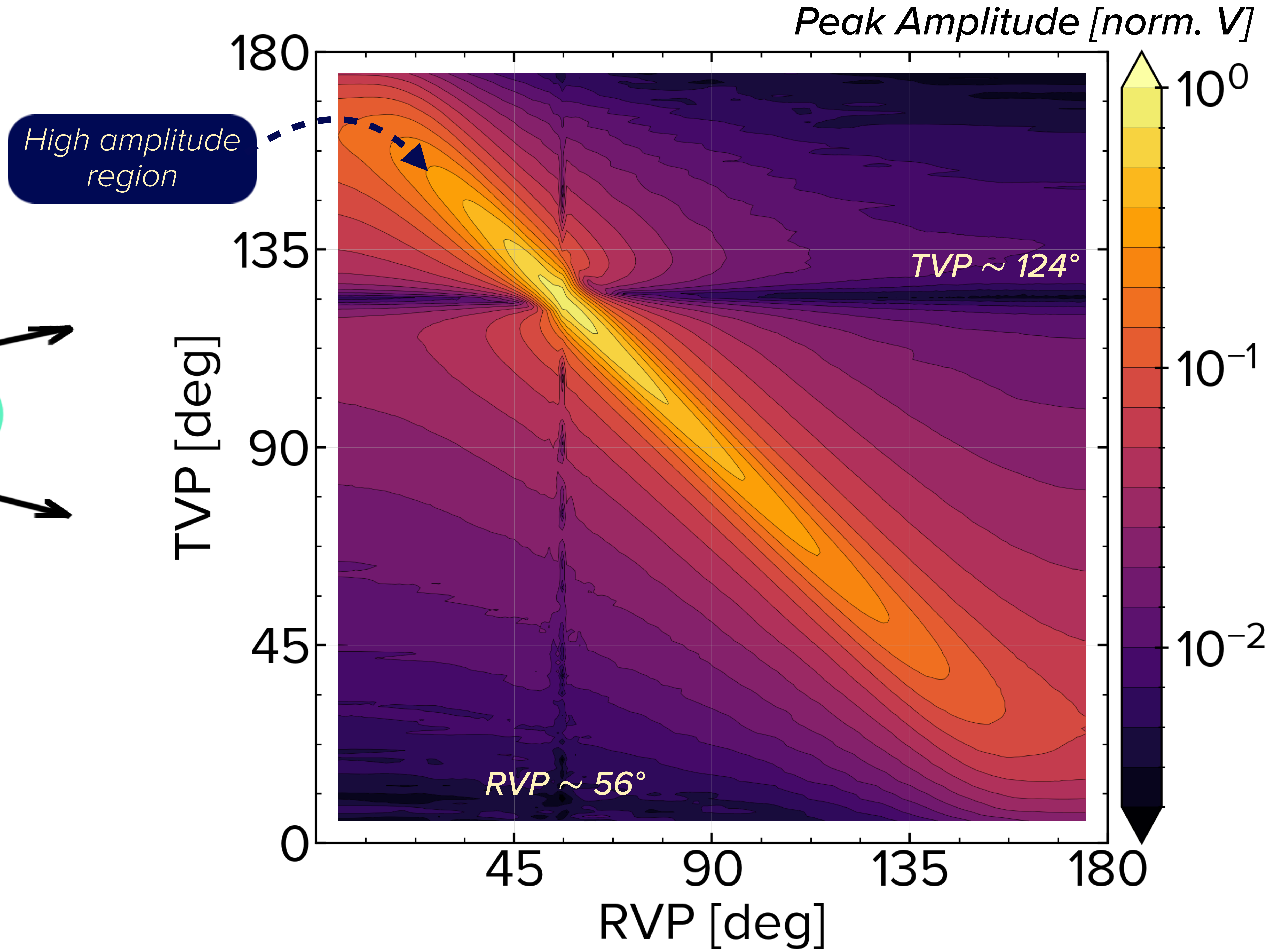
Radar-specific parameters:
- Plasma lifetime $\tau \in (1, 50)$ ns
- Transmit frequency $f_{TX} \in (50, 250)$ MHz

Peak Amplitude

- Exploring peak amplitude for the RVP TVP space:
  (f_{TX} = 250MHz, τ = 10ns)

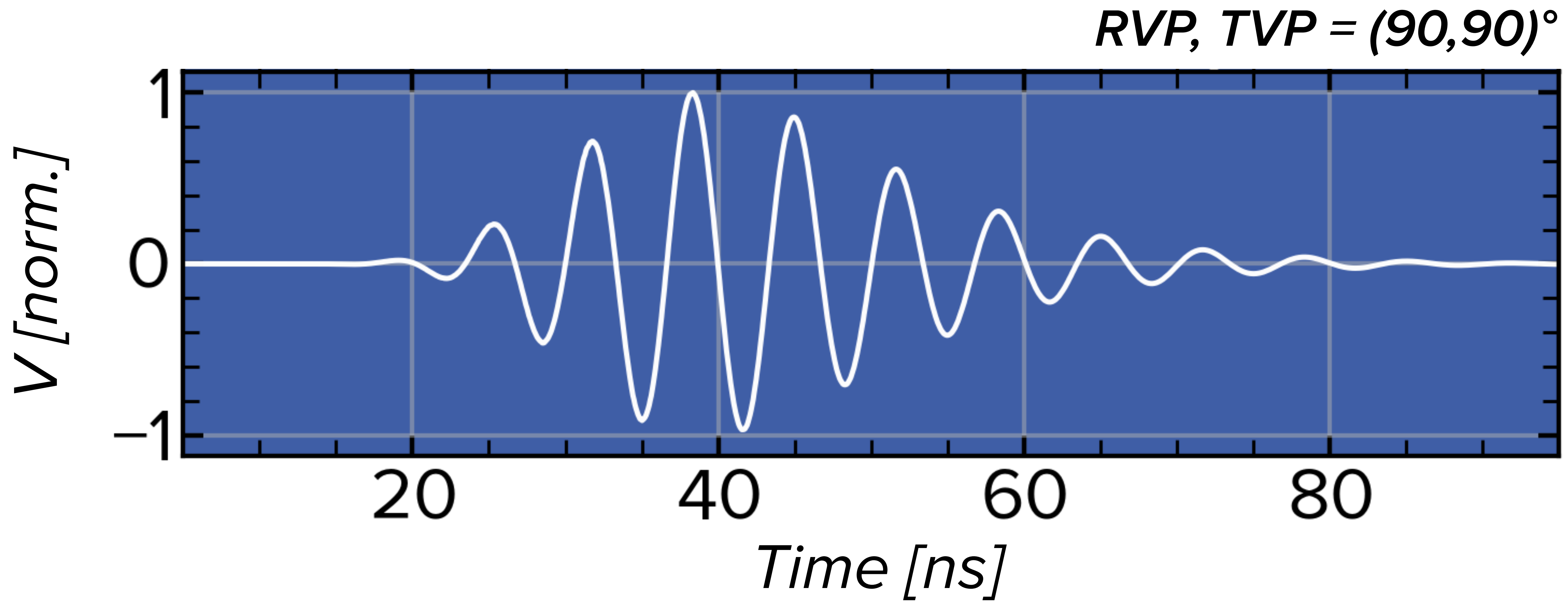


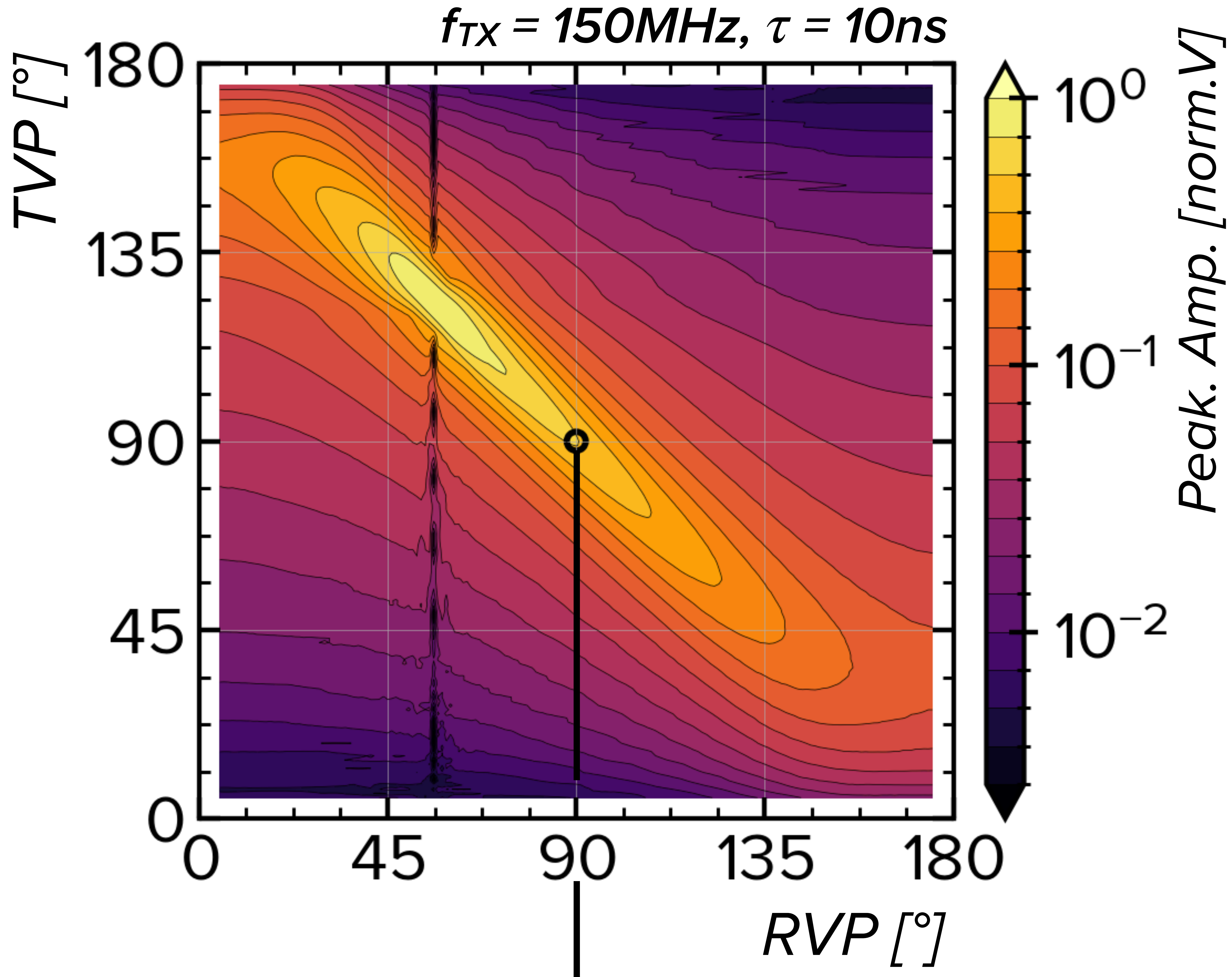
- Found to be well-described by *phase coherence* effect

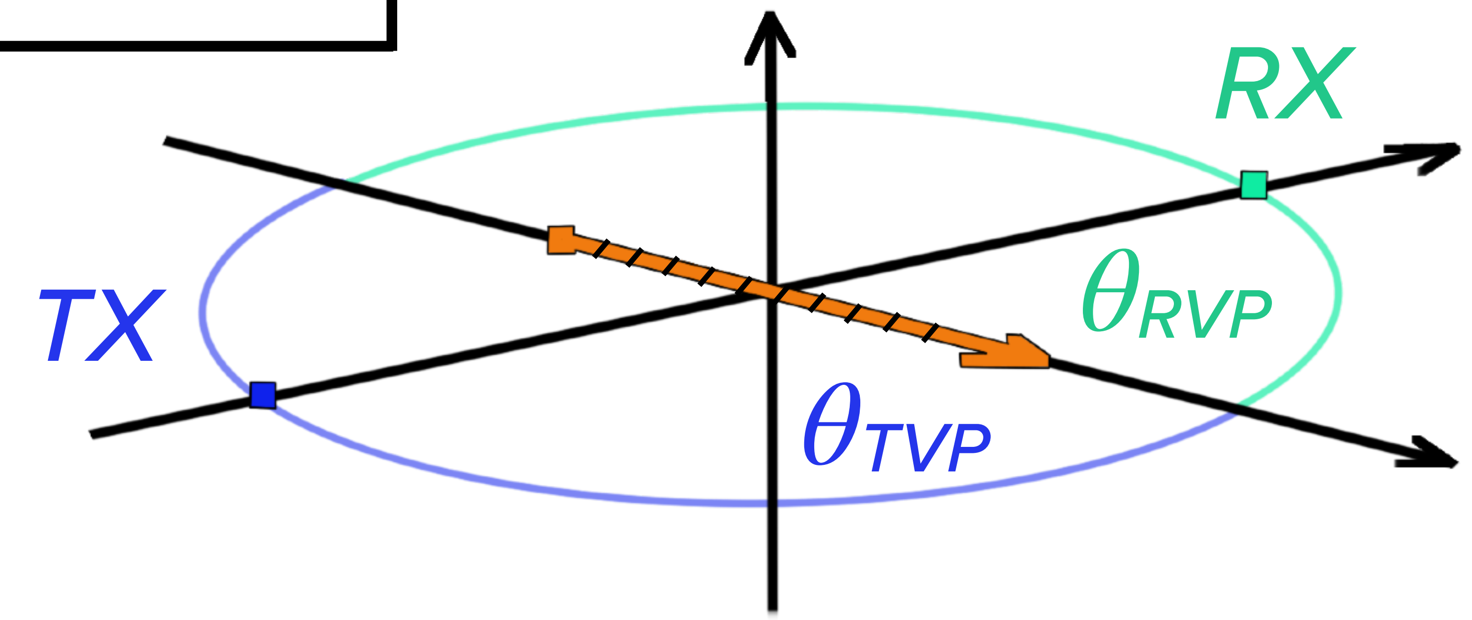


Phase Coherence

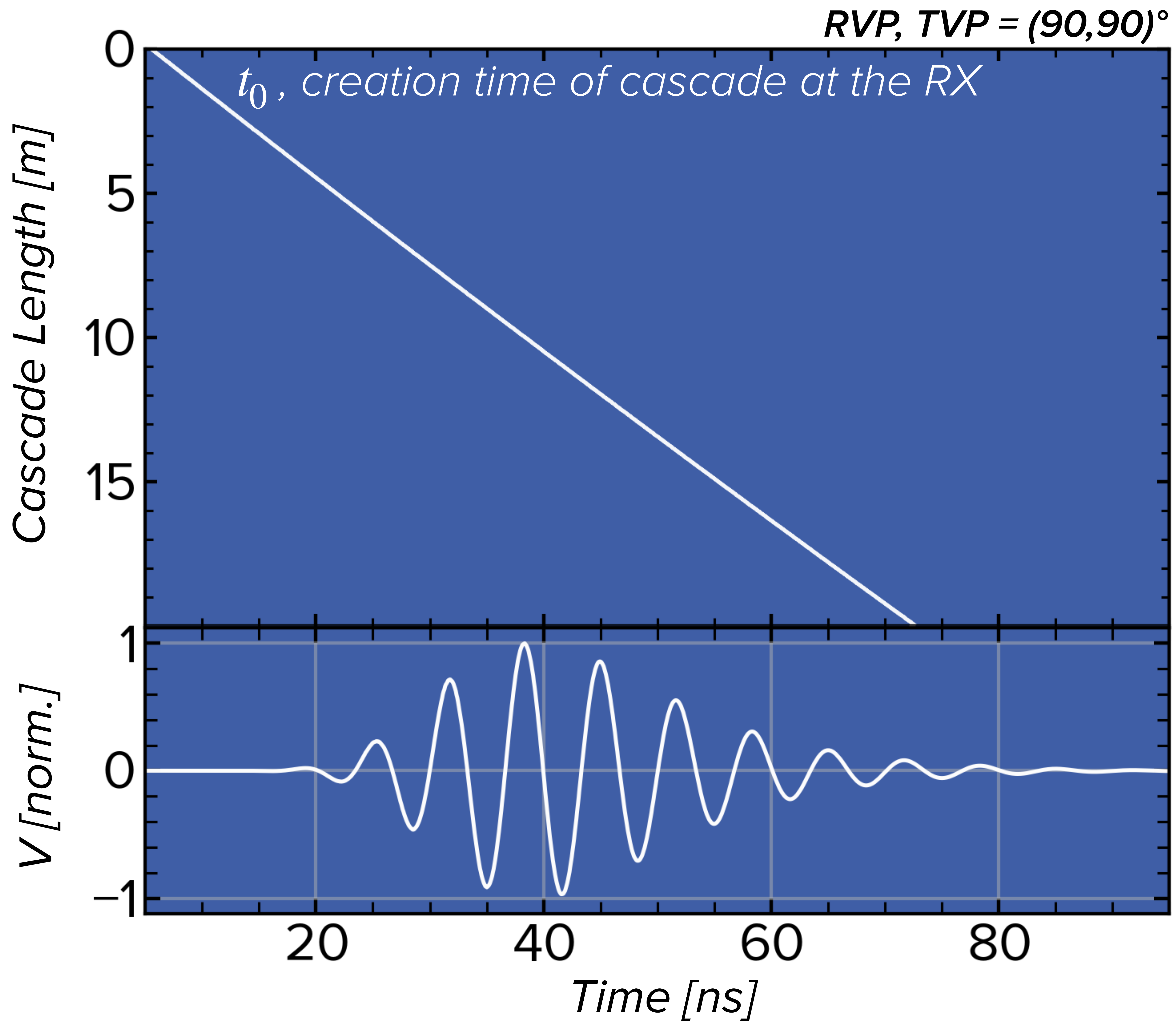
Signal contributions from adjacent parts of the cascade arrive at the RX with the same **phase**, boosting the final signal

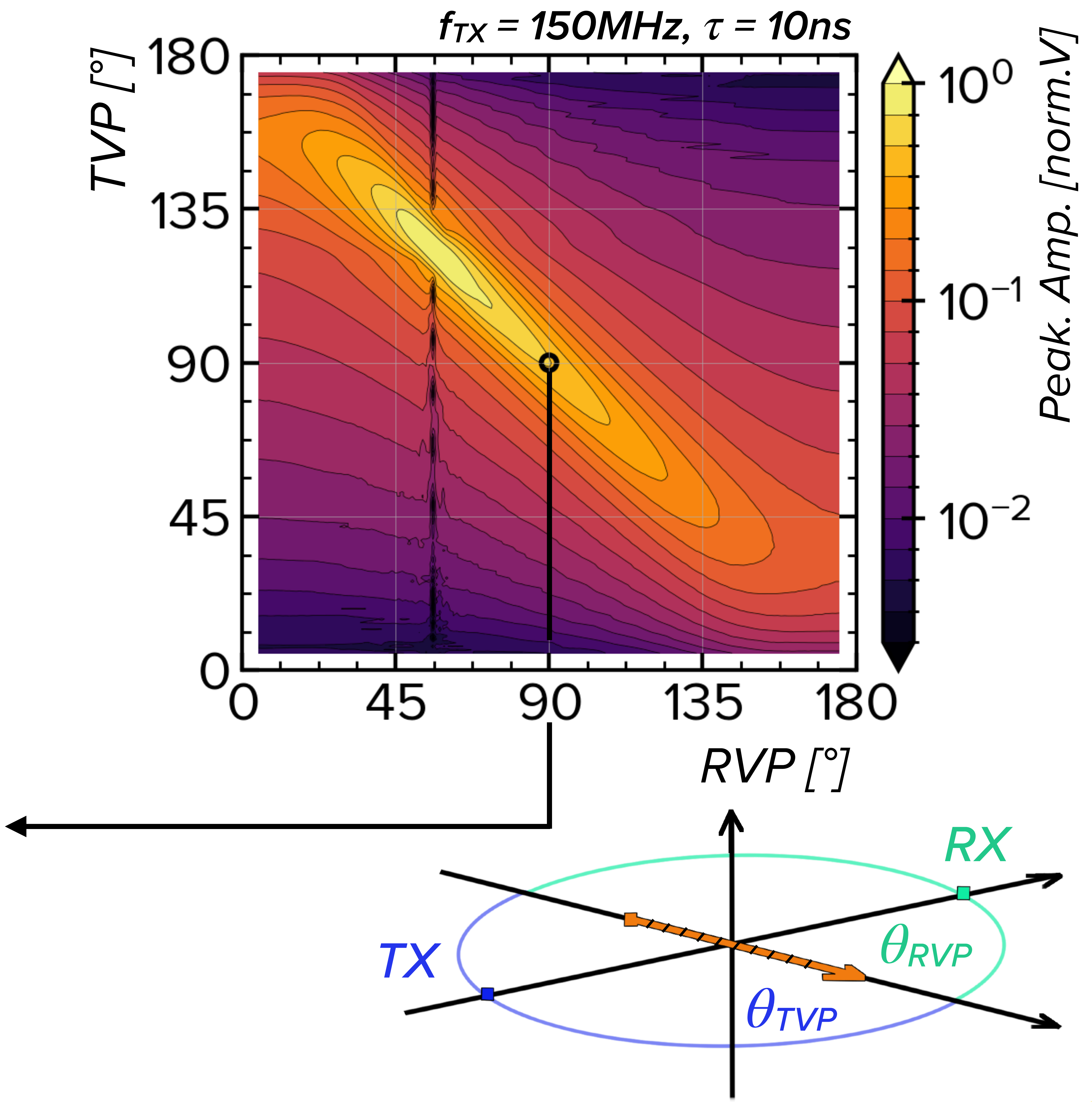




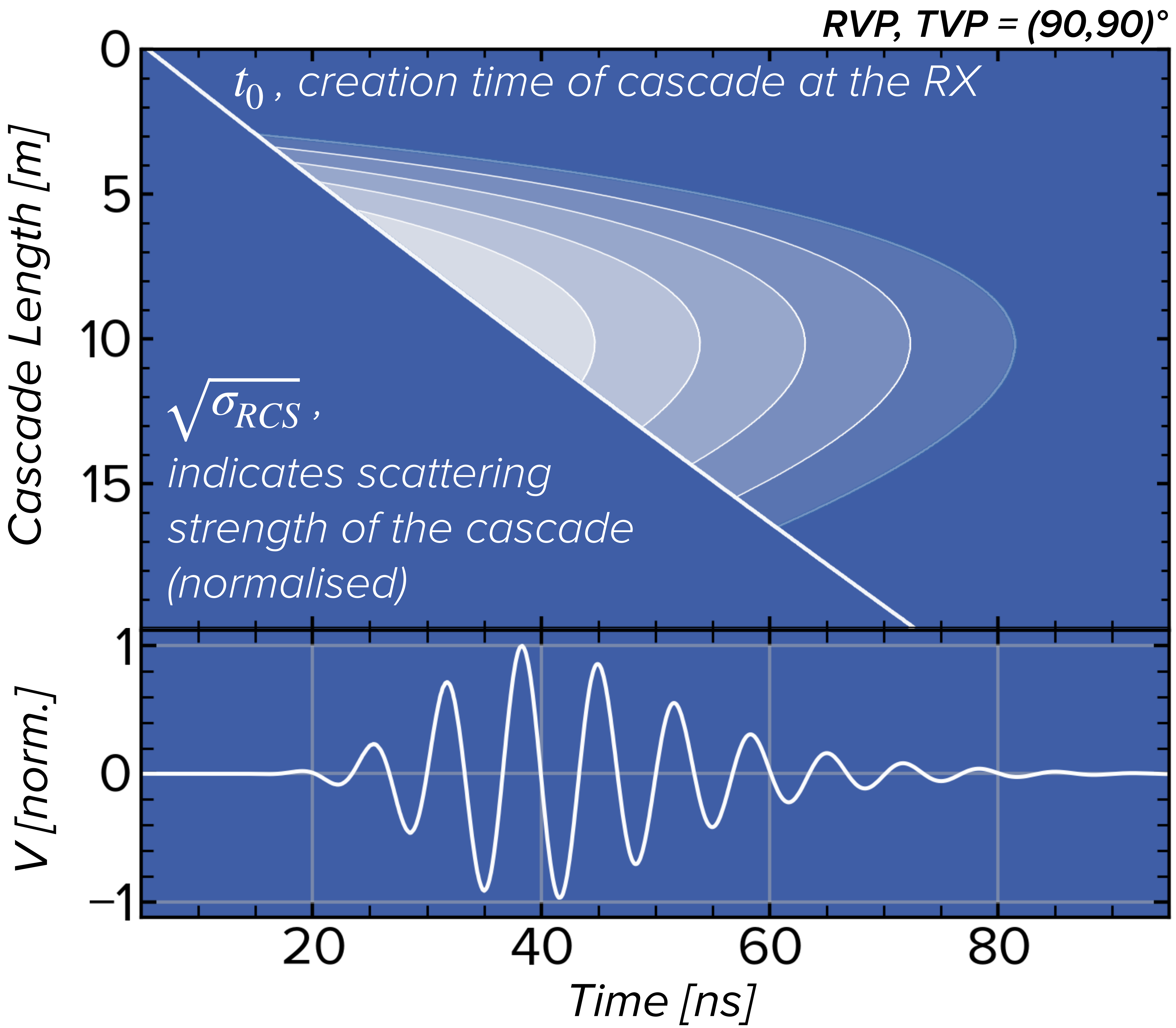


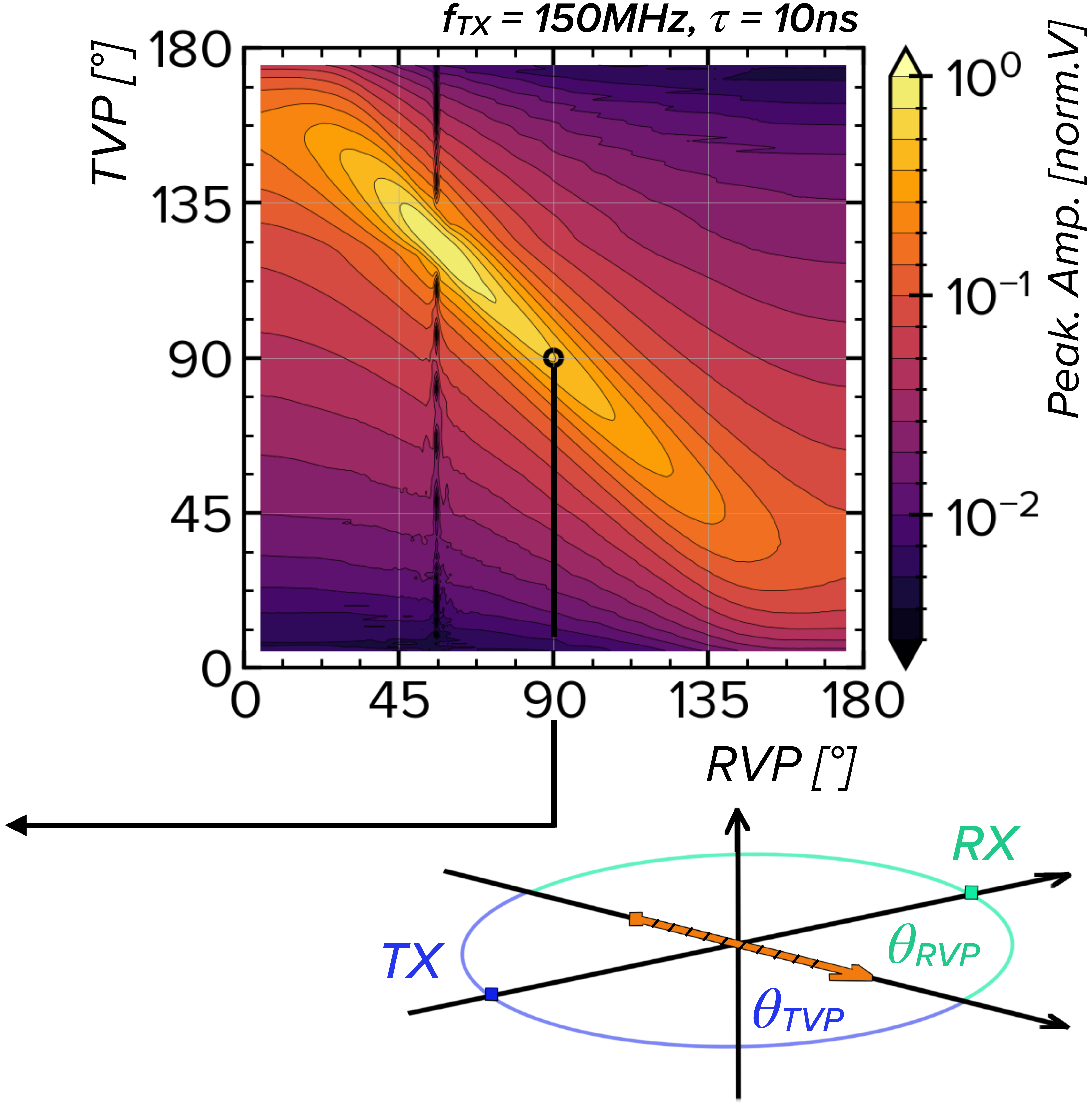
Phase Coherence



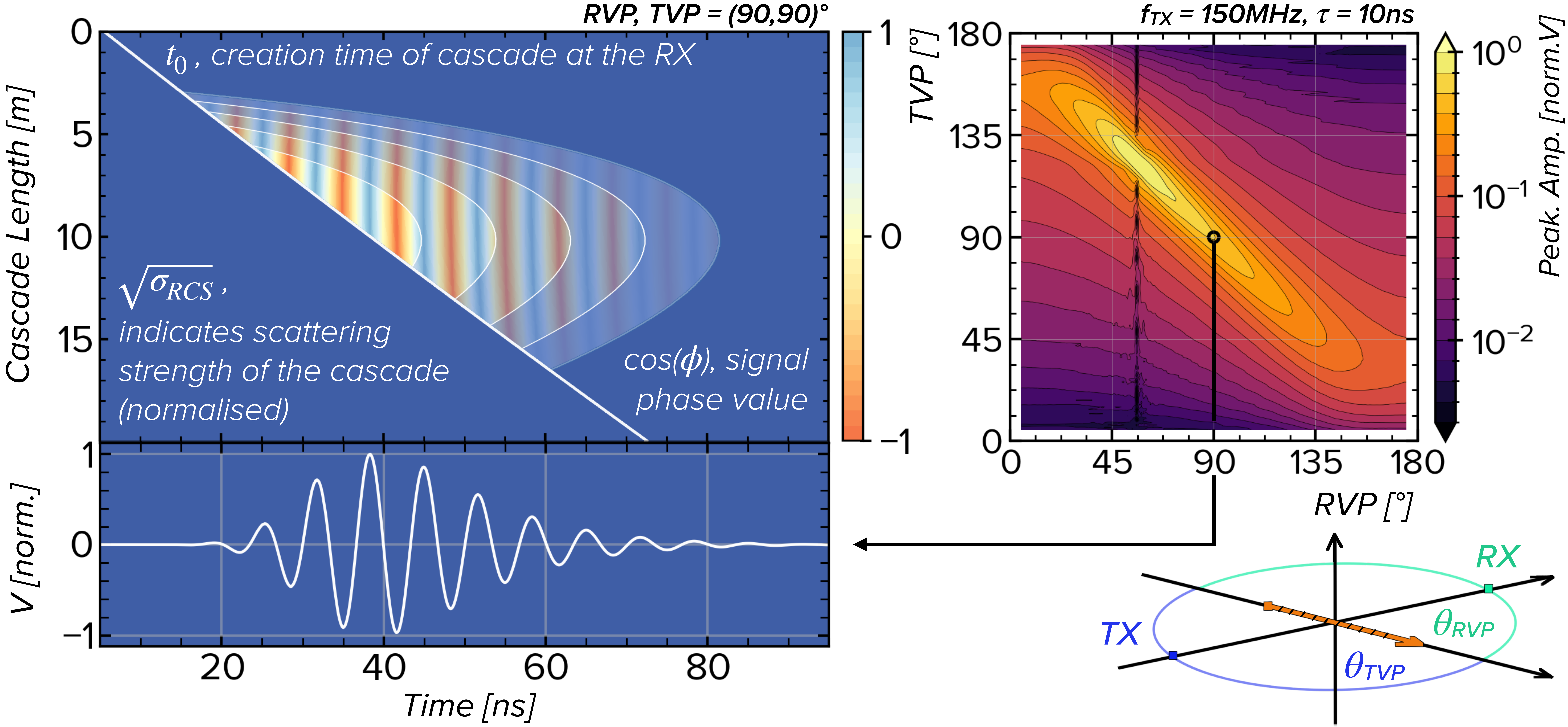


Phase Coherence

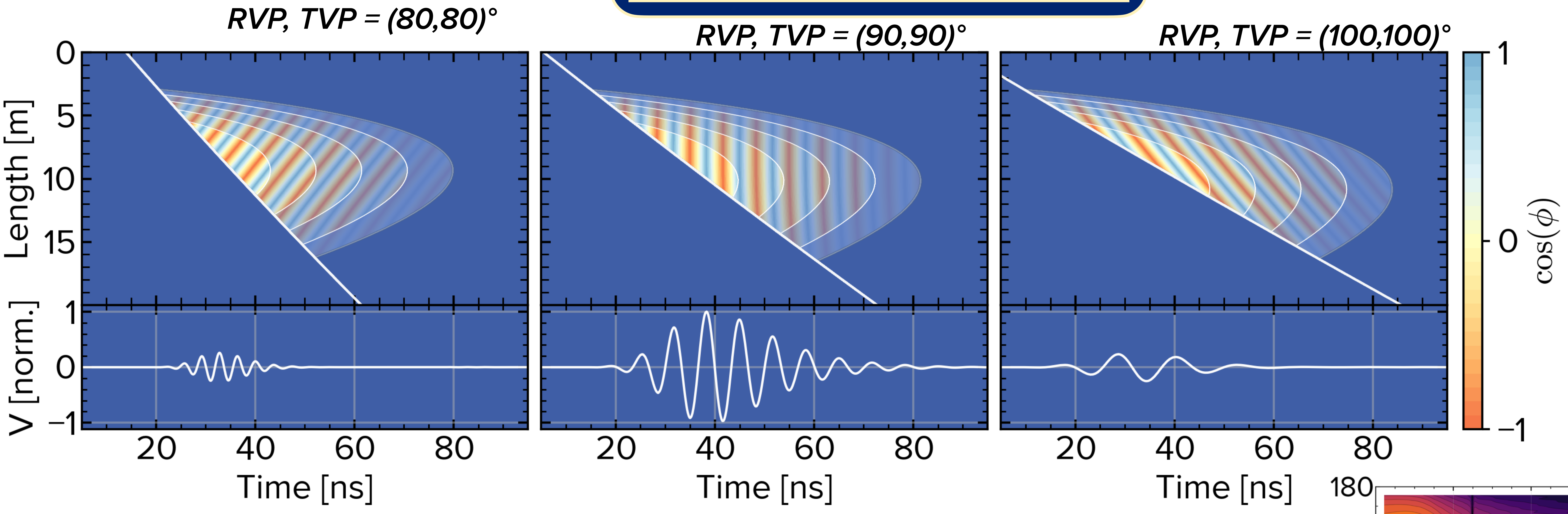




Phase Coherence



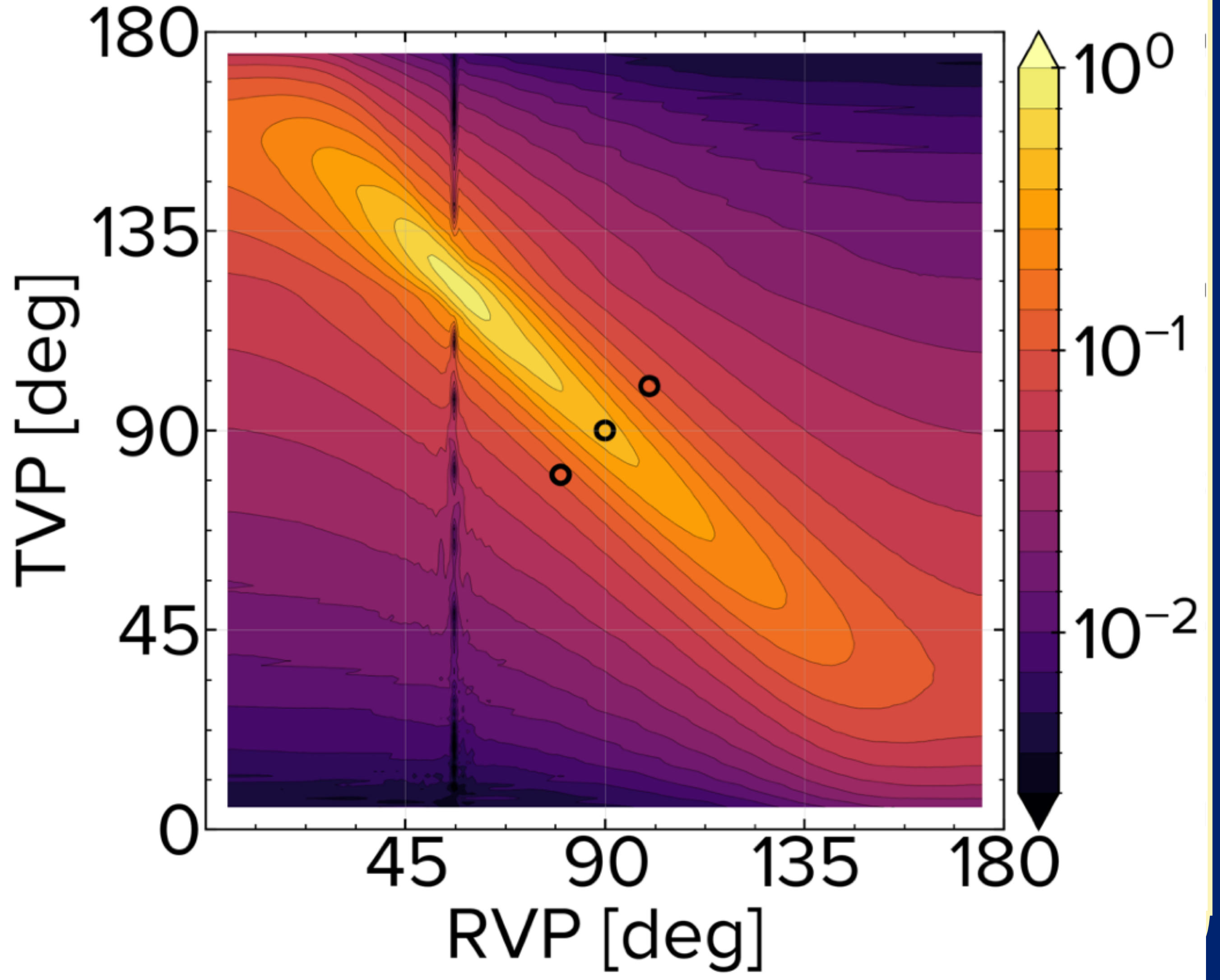
Phase Coherence



- We can define a phase coherence measure:

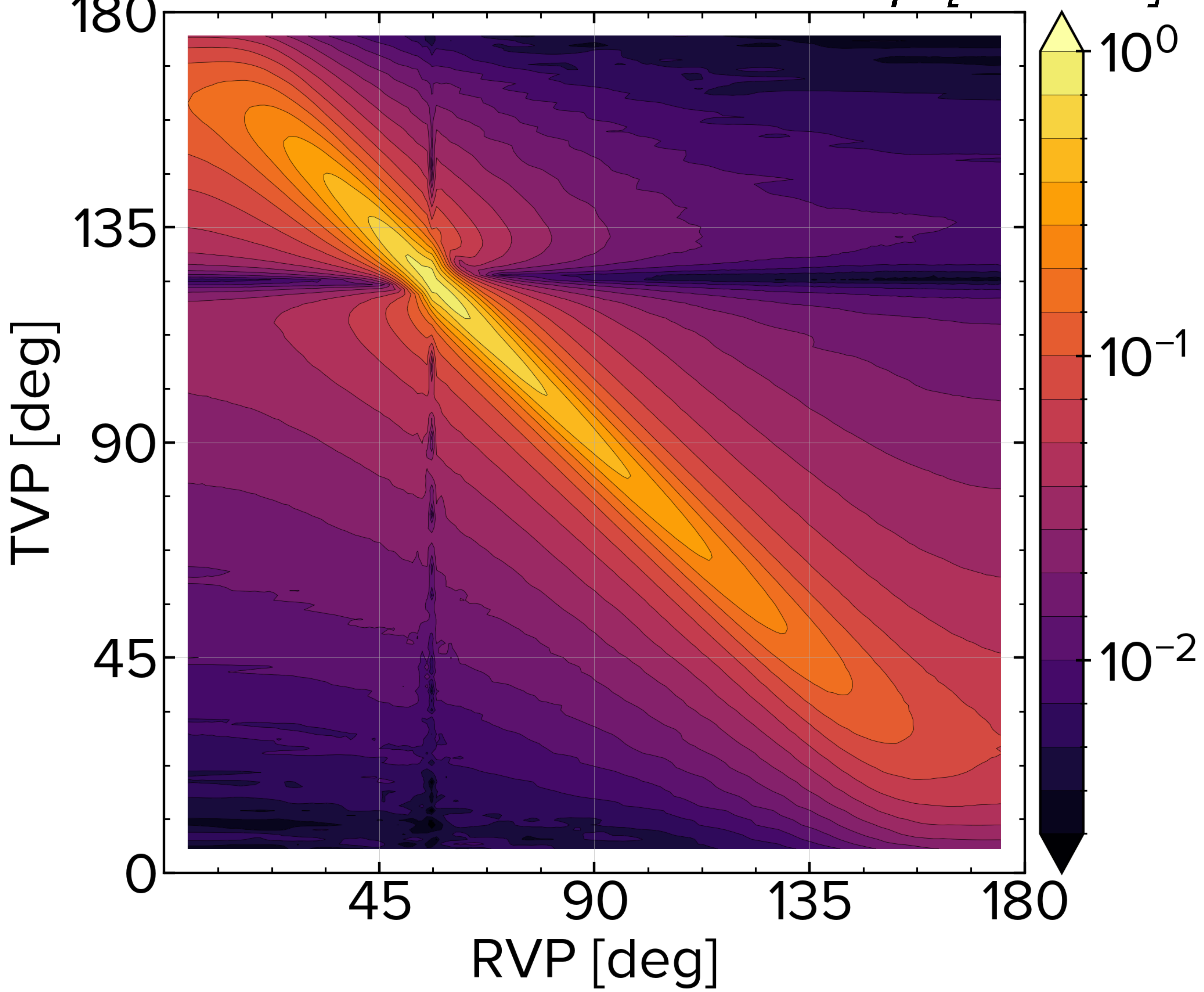
$$C = \sum_{j=1}^{M} \left(\cos(\phi_j(t)) \frac{n_j(t)}{n_{e^-,max}} \right) \Bigg|_{t_{peak}}$$

Credit: J.Loonen

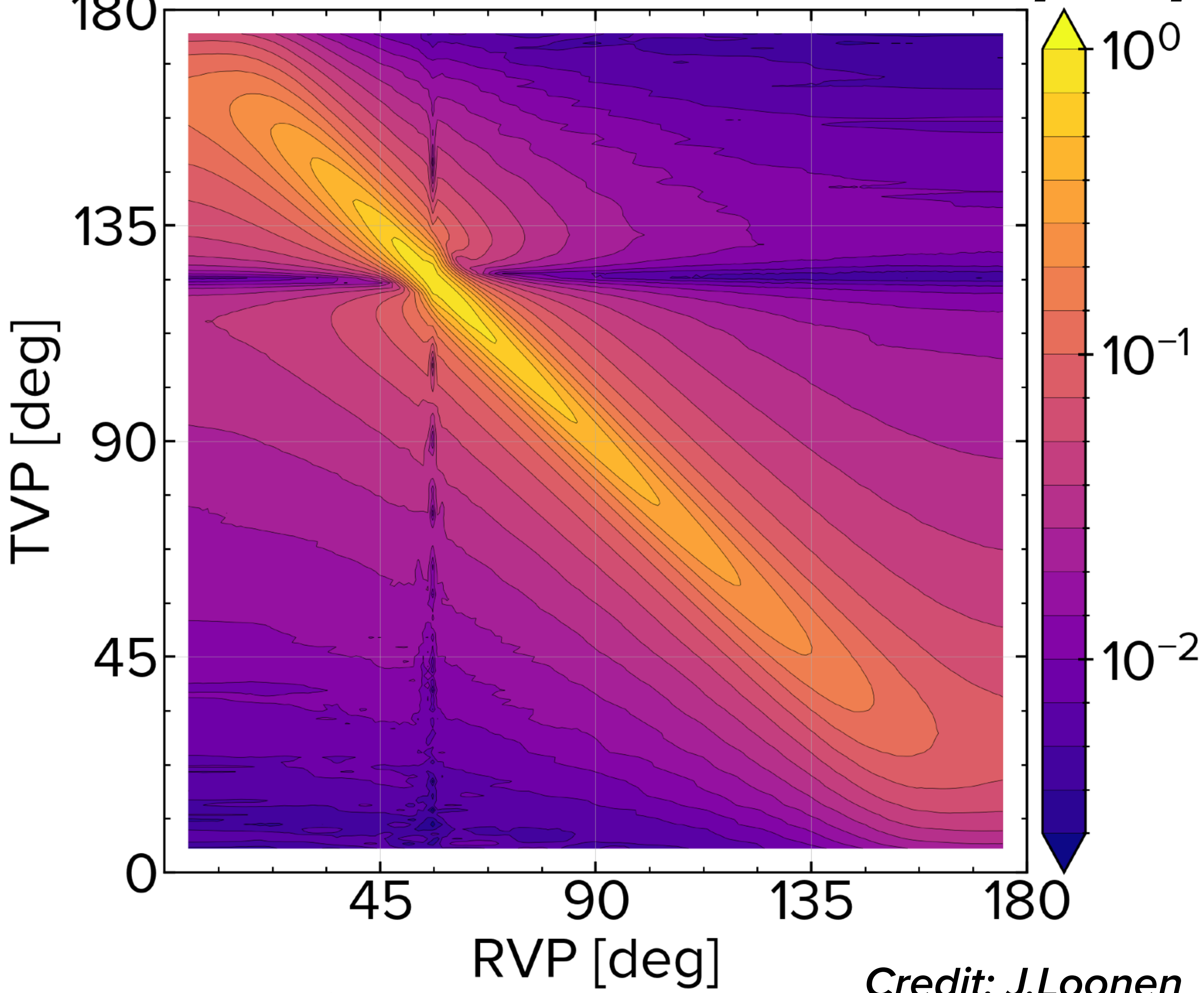


Phase Coherence

MARES simulations:



Phase Coherence Measure:



Credit: J.Loonen

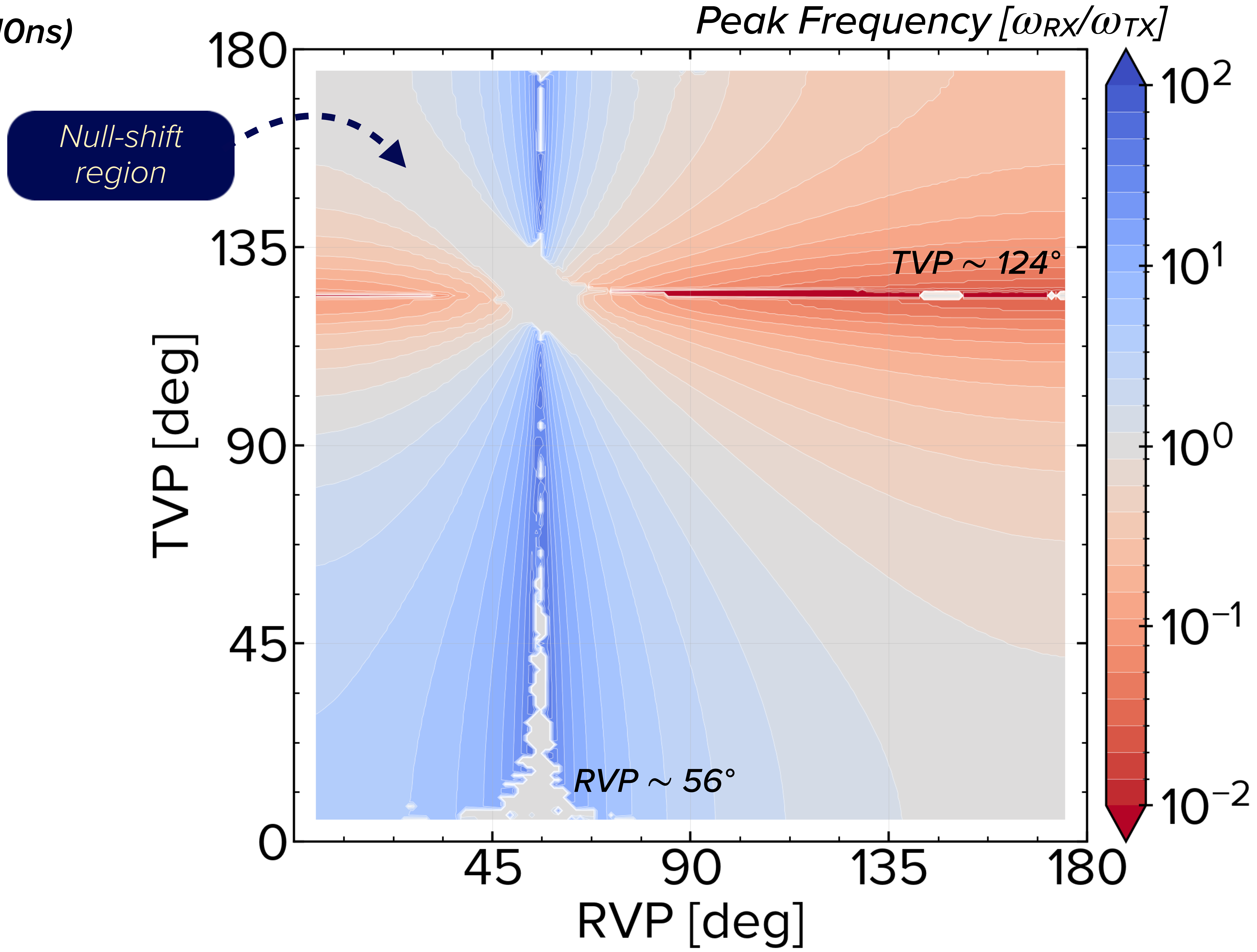
$$C = \sum_{j=1}^{M} \left(\cos(\phi_j(t)) \frac{n_j(t)}{n_{e^-,max}} \right) \Bigg|_{t_{peak}}$$

(f_{TX} = 250MHz, τ = 10ns)

Peak Frequency

- Exploring peak frequency for the RVP TVP space:

(f_{TX} = 250MHz, τ = 10ns)



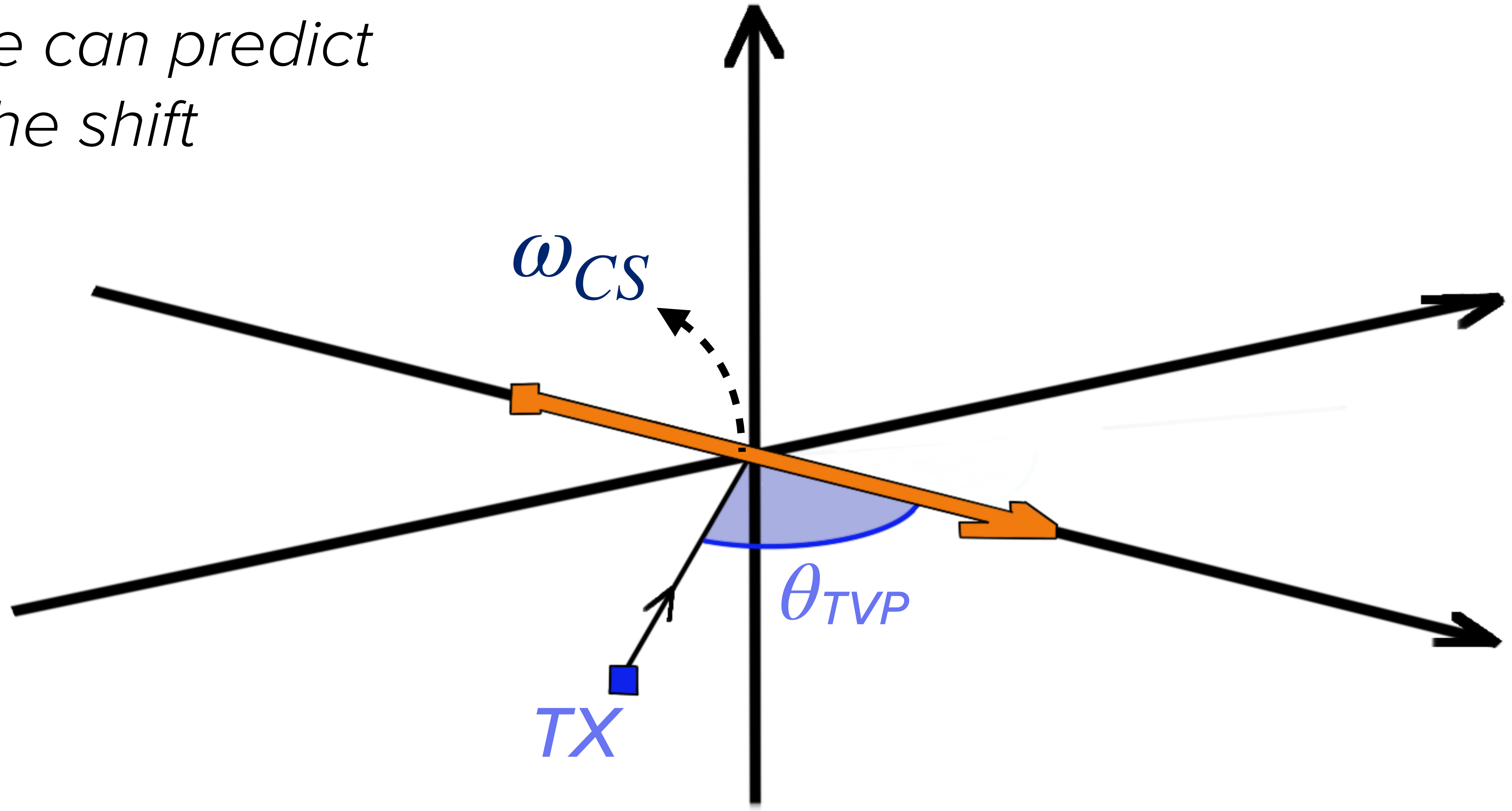
- Exhibits relativistic Doppler shifts

Doppler Shifts

Doppler shifts expected in the radar system, with two caveats:

- Relativistic appearance, n > 1
- Double Doppler system (bistatic)

→ *By combining the two, we can predict the magnitude of the shift*



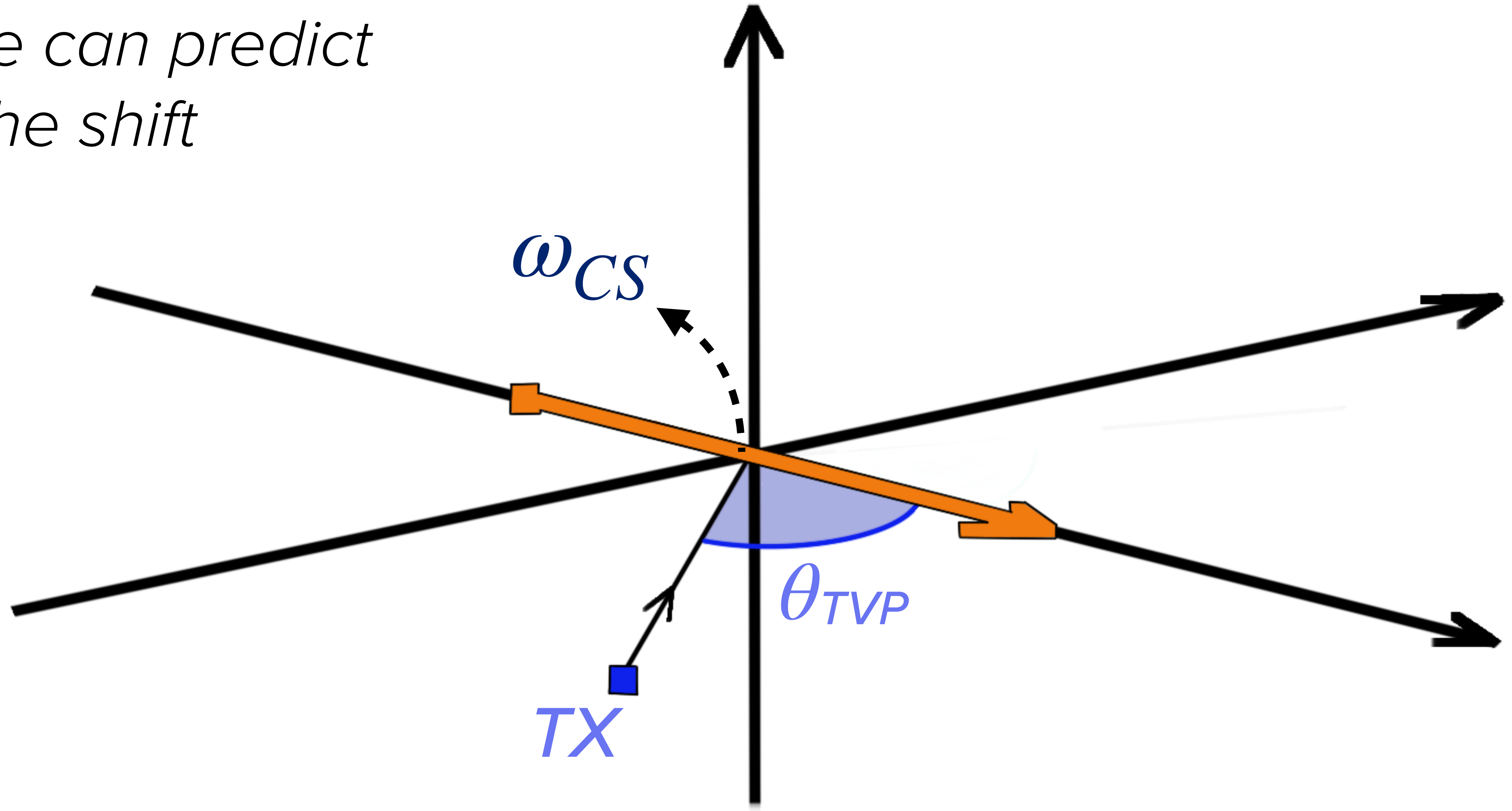
Doppler Shifts

Doppler shifts expected in the radar system, with two caveats:

- Relativistic appearance, n > 1
- Double Doppler system (bistatic)

→ *By combining the two, we can predict the magnitude of the shift*

(1) ω_{CS} → the observed frequency of the radio wave from the **TX** at the **cascade**



Doppler Shifts

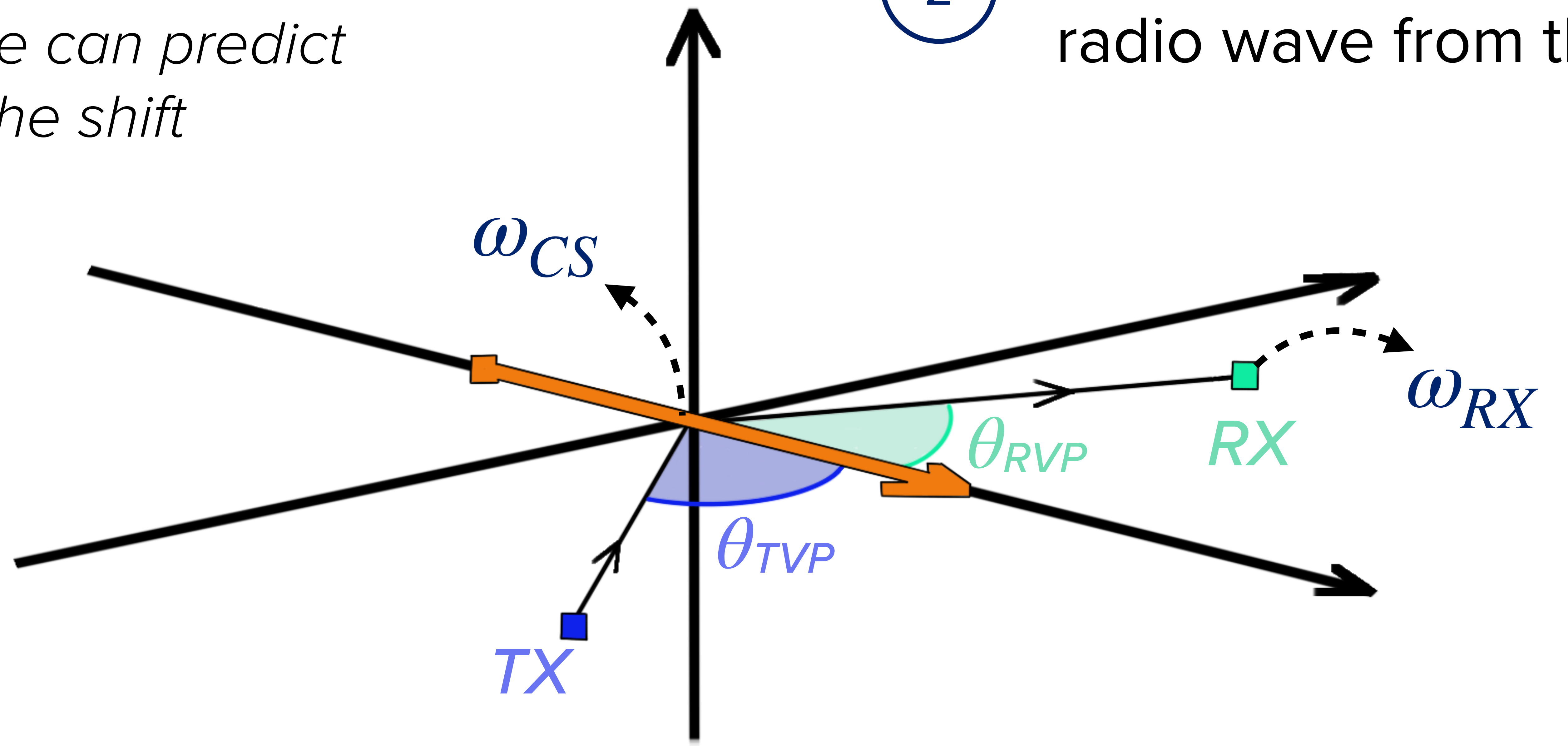
Doppler shifts expected in the radar system, with two caveats:

- Relativistic appearance, n > 1
- Double Doppler system (bistatic)

→ *By combining the two, we can predict the magnitude of the shift*

1 ω_{CS} → the observed frequency of the radio wave from the **TX** at the **cascade**

2 ω_{RX} → the observed frequency of the radio wave from the **cascade** at the **RX**



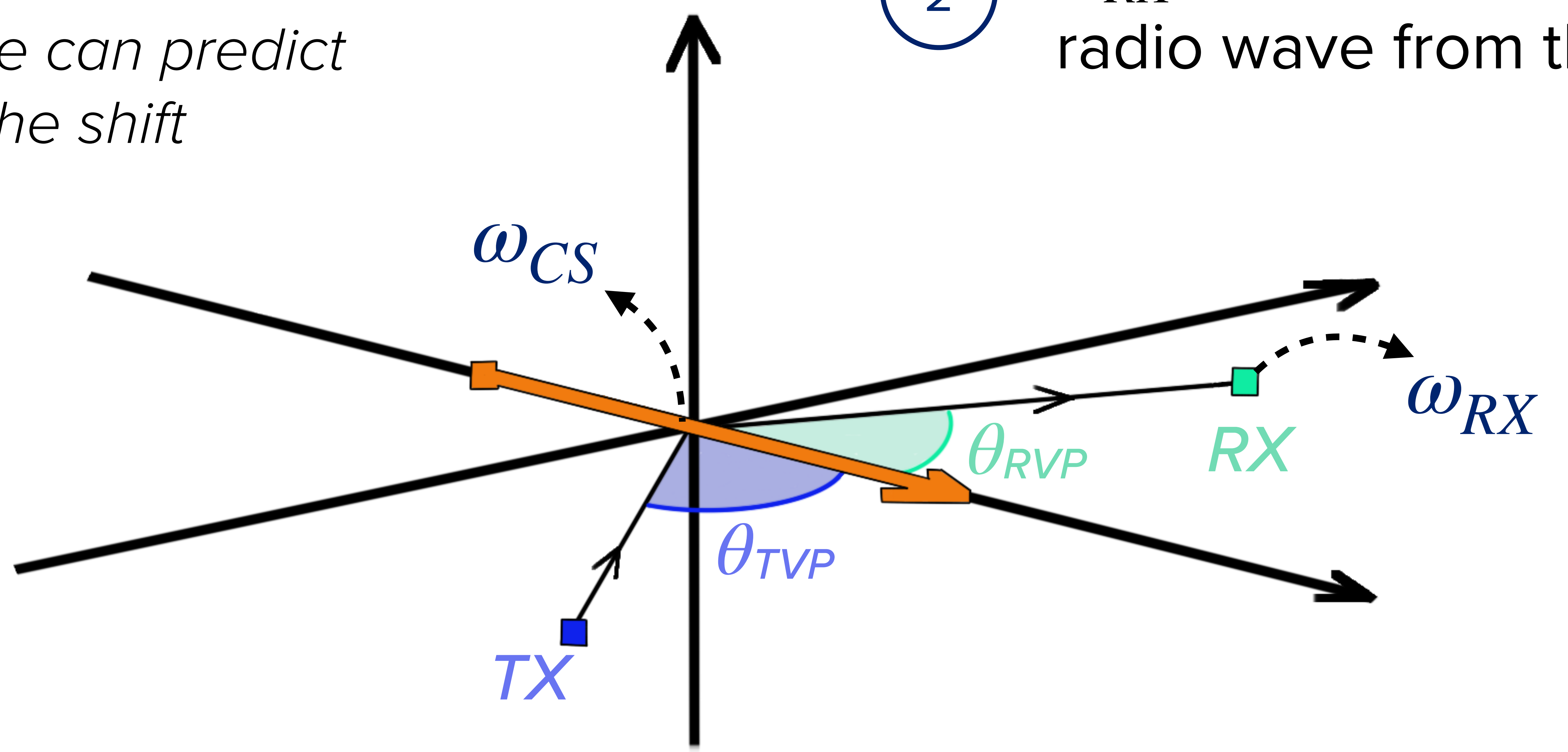
Doppler Shifts

Doppler shifts expected in the radar system, with two caveats:

- Relativistic appearance, n > 1
- Double Doppler system (bistatic)
- → *By combining the two, we can predict the magnitude of the shift*

1. ω_{CS} → the observed frequency of the radio wave from the **TX** at the **cascade**

2. ω_{RX} → the observed frequency of the radio wave from the **cascade** at the **RX**



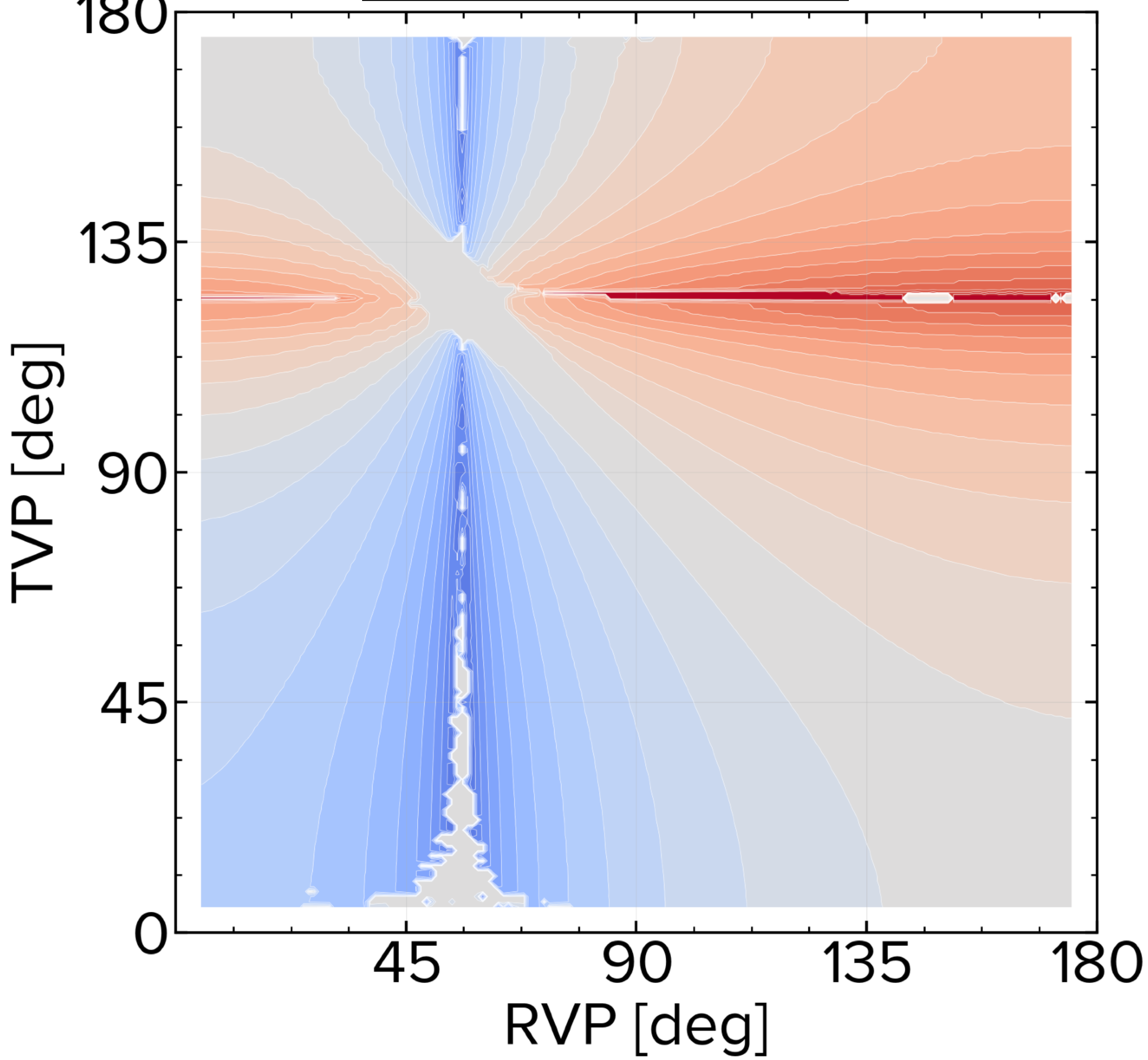
Final Doppler shift observed → $$\frac{\omega_{RX}}{\omega_{TX}} = \frac{|1 + n\beta\cos\theta_{TVP}|}{|1 - n\beta\cos\theta_{RVP}|}$$

(Assuming moving point source)

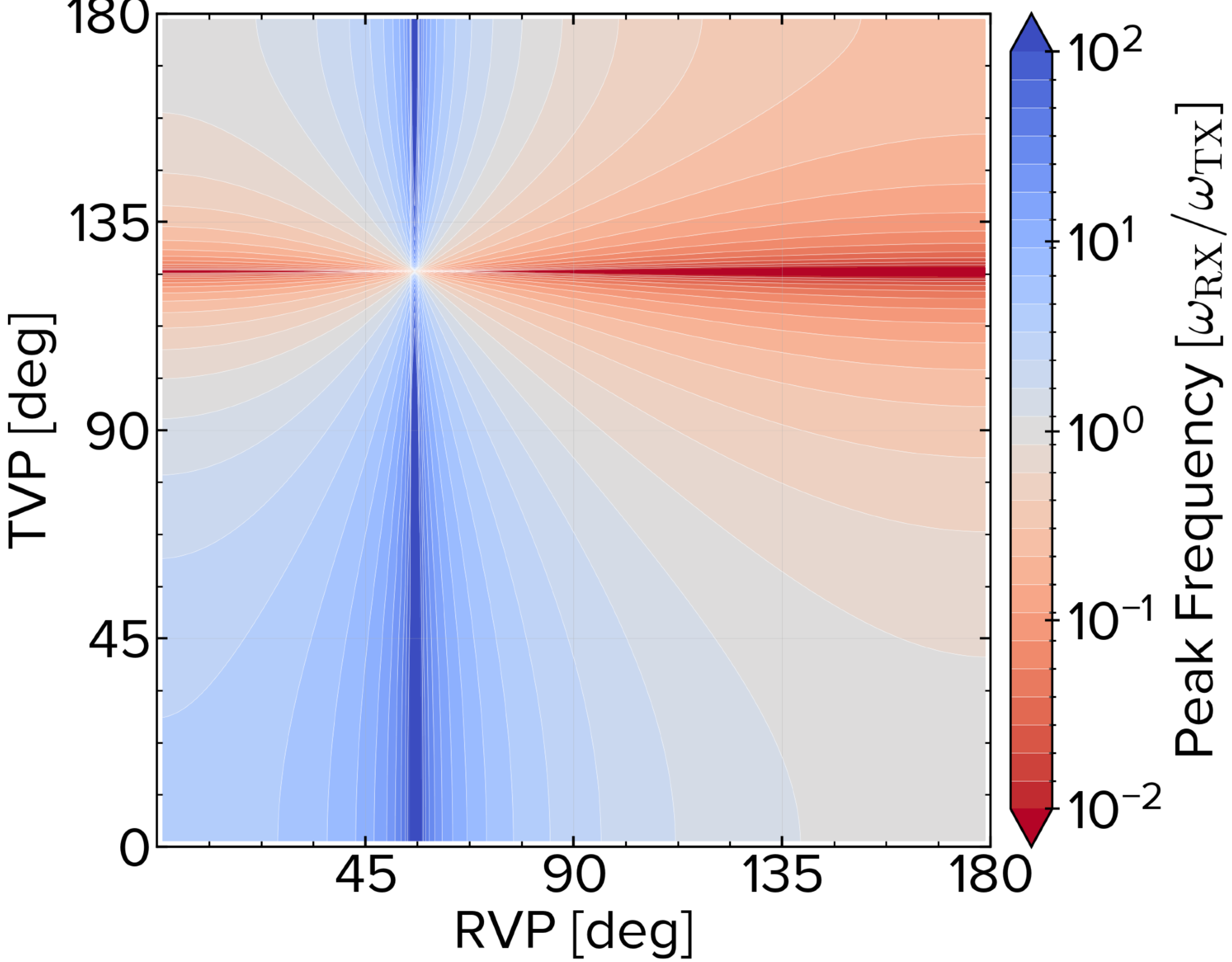
Doppler Shifts

$$\frac{\omega_{RX}}{\omega_{TX}} = \frac{|1 + n\beta\cos\theta_{TVP}|}{|1 - n\beta\cos\theta_{RVP}|}$$

MARES simulations:

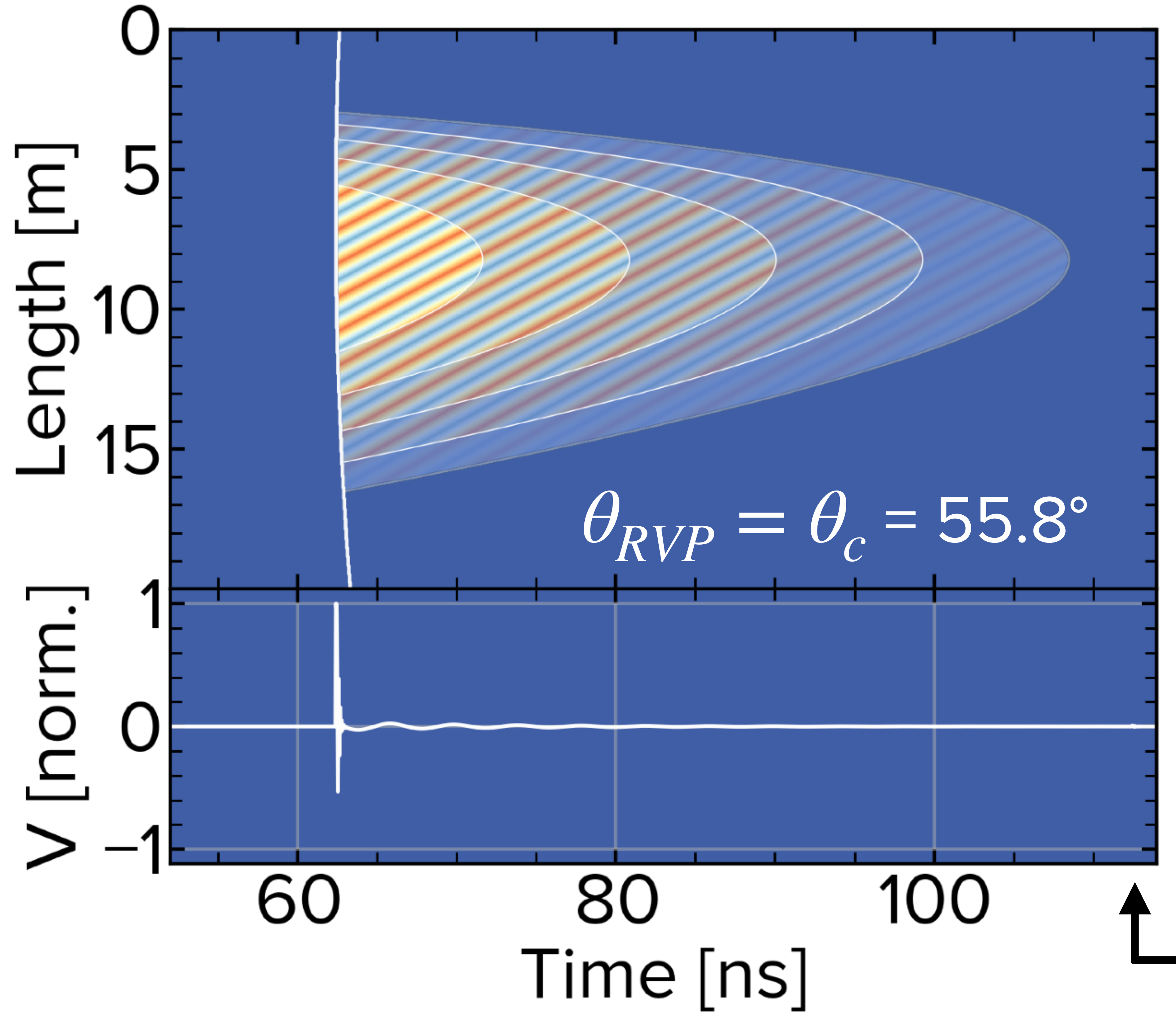


Predicted Doppler shifts:



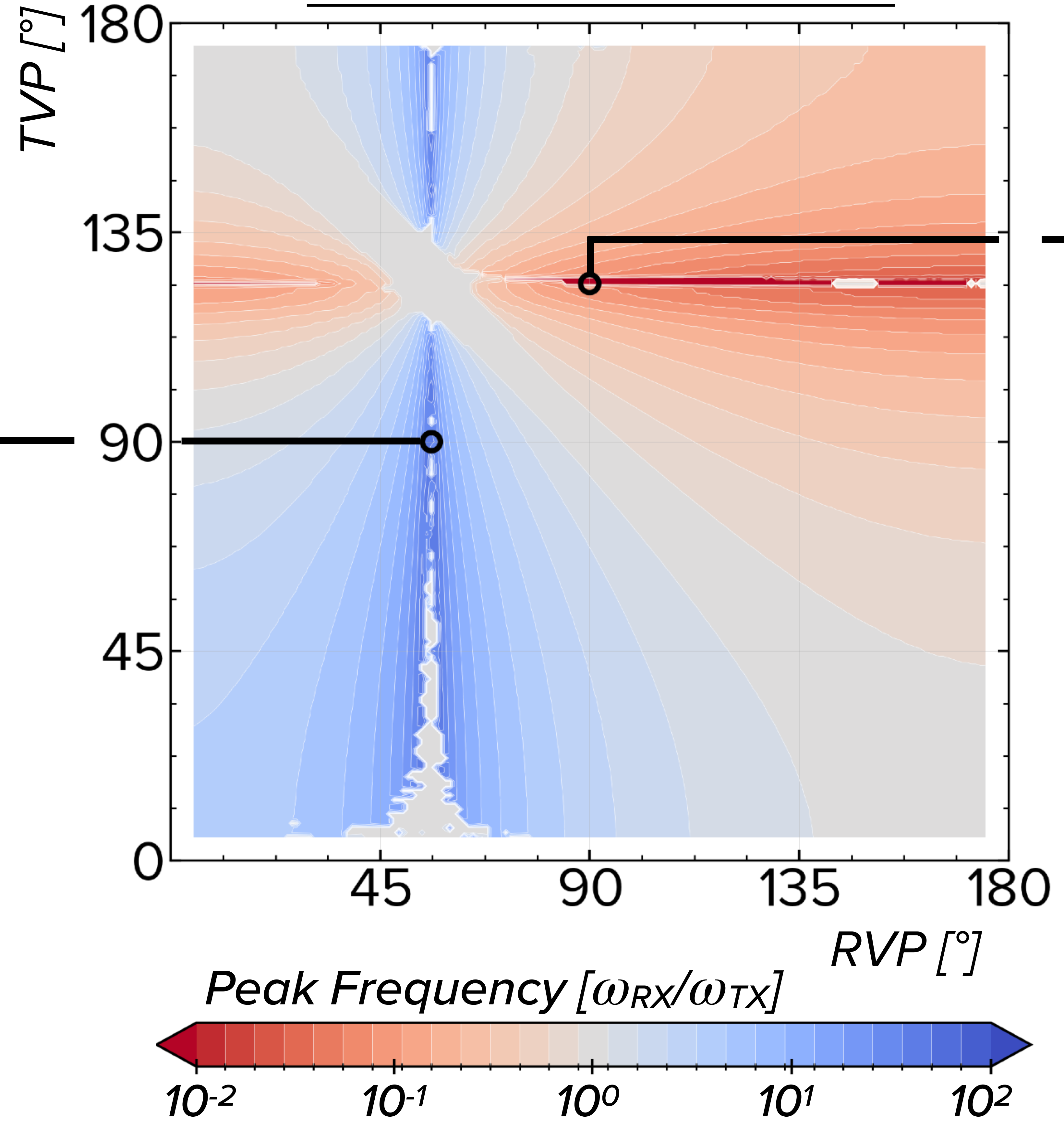
Cherenkov Cones

$$\frac{\omega_{RX}}{\omega_{TX}} = \frac{|1 + n\beta\cos\theta_{TVP}|}{|1 - n\beta\cos\theta_{RVP}|}$$

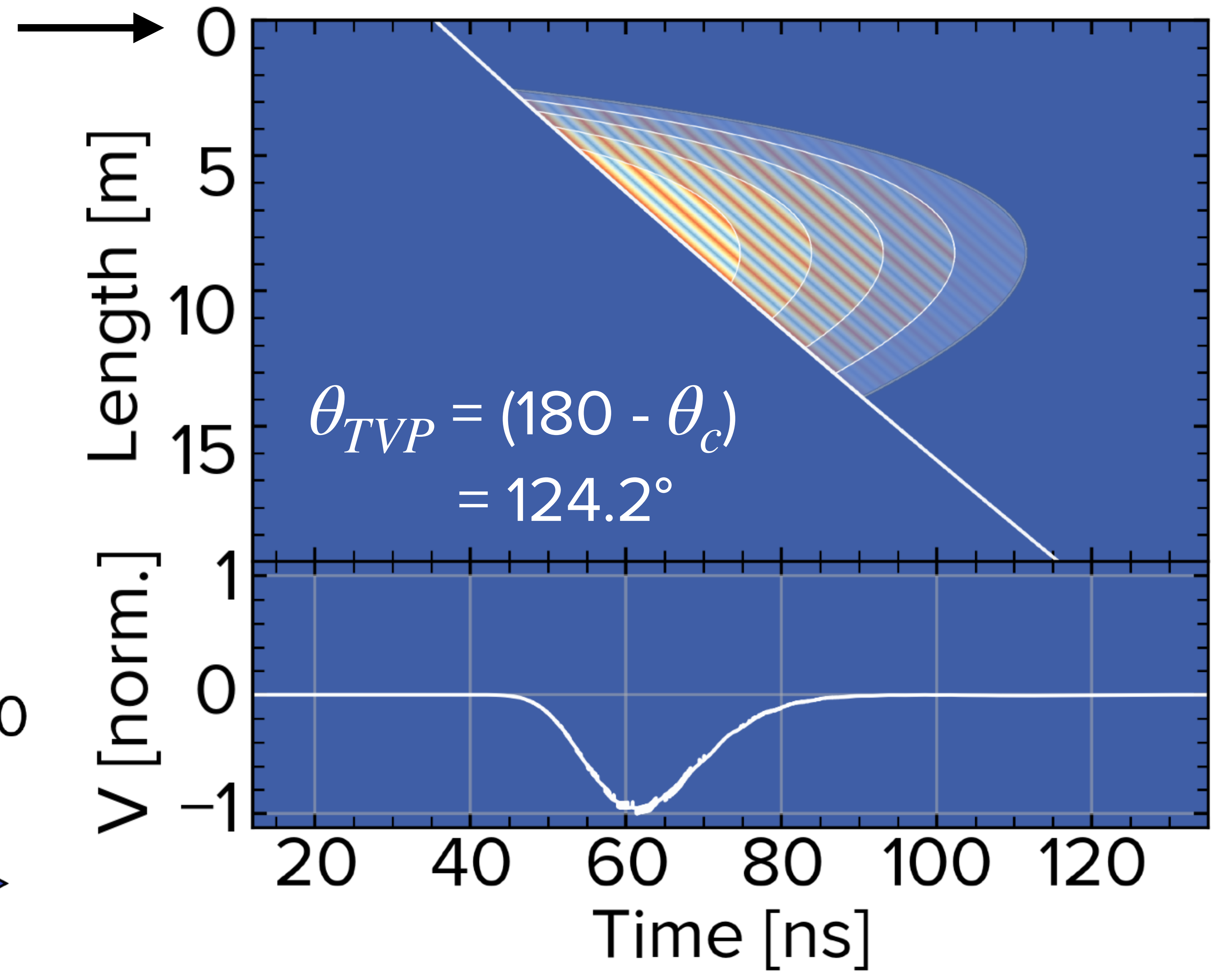


- *RX Cherenkov cone;* signals arrive simultaneously at the RX: $\frac{\omega_{RX}}{\omega_{TX}} \rightarrow \infty$
- Inside the cone, signals display time-reversal

<u>*MARES simulations:*</u>



- *TX Cherenkov cone;* signals arrive maximally extended at the RX: $\frac{\omega_{RX}}{\omega_{TX}} \rightarrow 0$



Outlook

- *Have explored **amplitude** and **frequency** properties of the radar signal → global descriptions that can be applied to realistic geometries*
  - *amplitude → Phase Coherence*
  - *frequency → Relativistic Doppler shifts*

- *Leads to insight into signal features, as well as timing, radar parameters (τ, f_{TX}) and more complex frequency responses (chirp signals)*

- *Next steps → applying properties (optimised detector layout, trigger studies, **reconstruction methods**...*
  - *→ Thu 16:15 - Jannes Loonen*

ULB

iihe BRUXELLES BRUSSEL

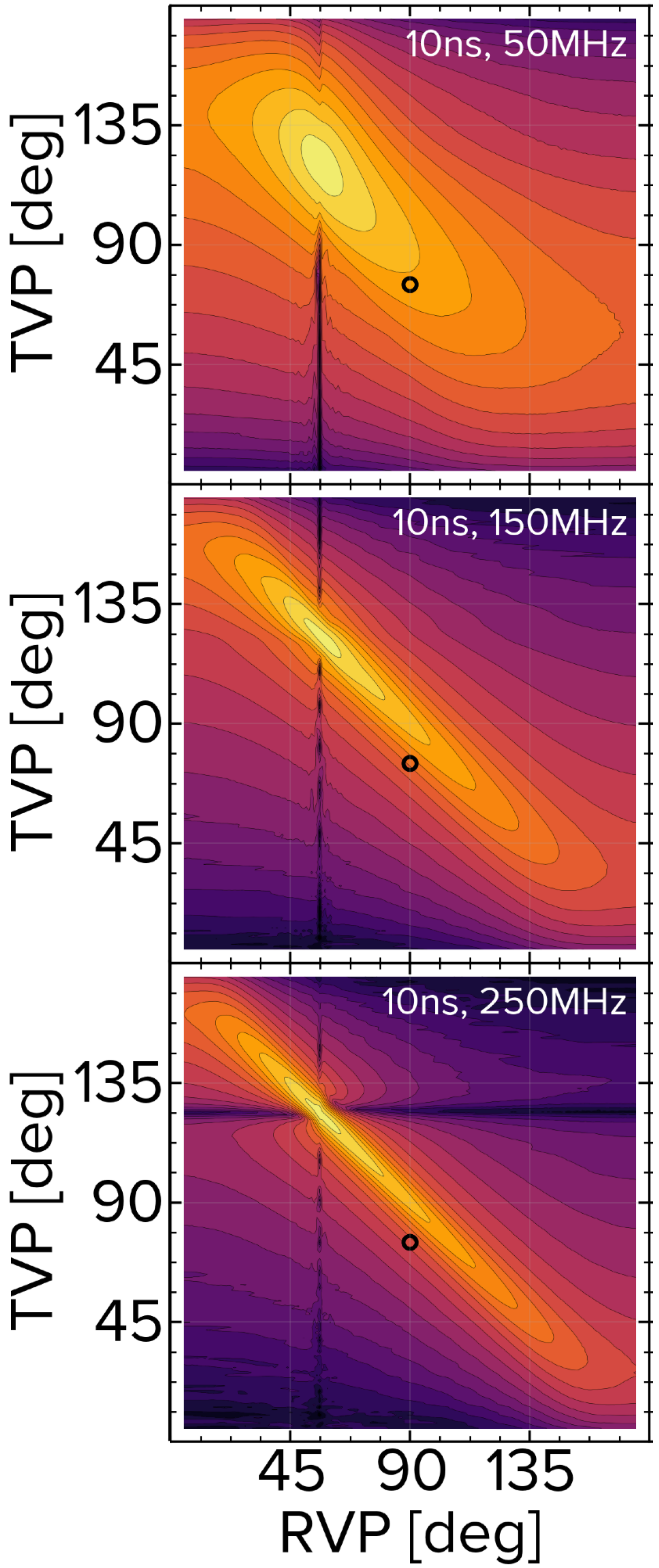
NSF

erc European Research Council Established by the European Commission

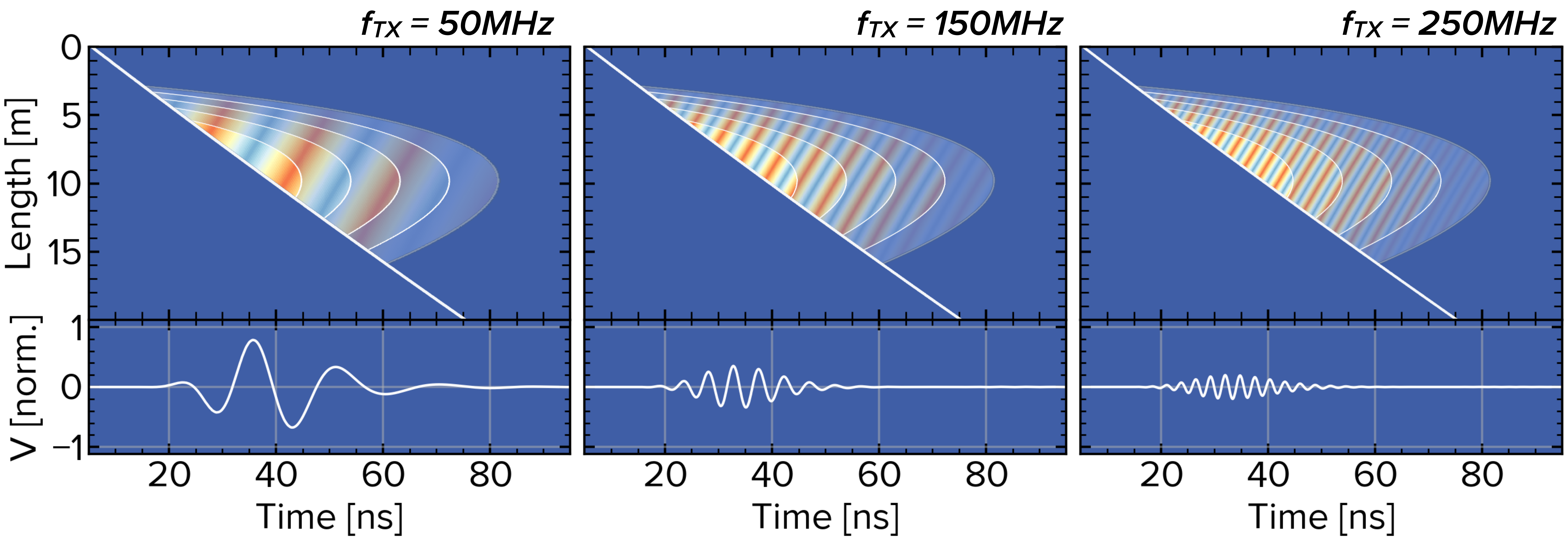
fnrs LA LIBERTÉ DE CHERCHER

RADAR ECHO TELESCOPE

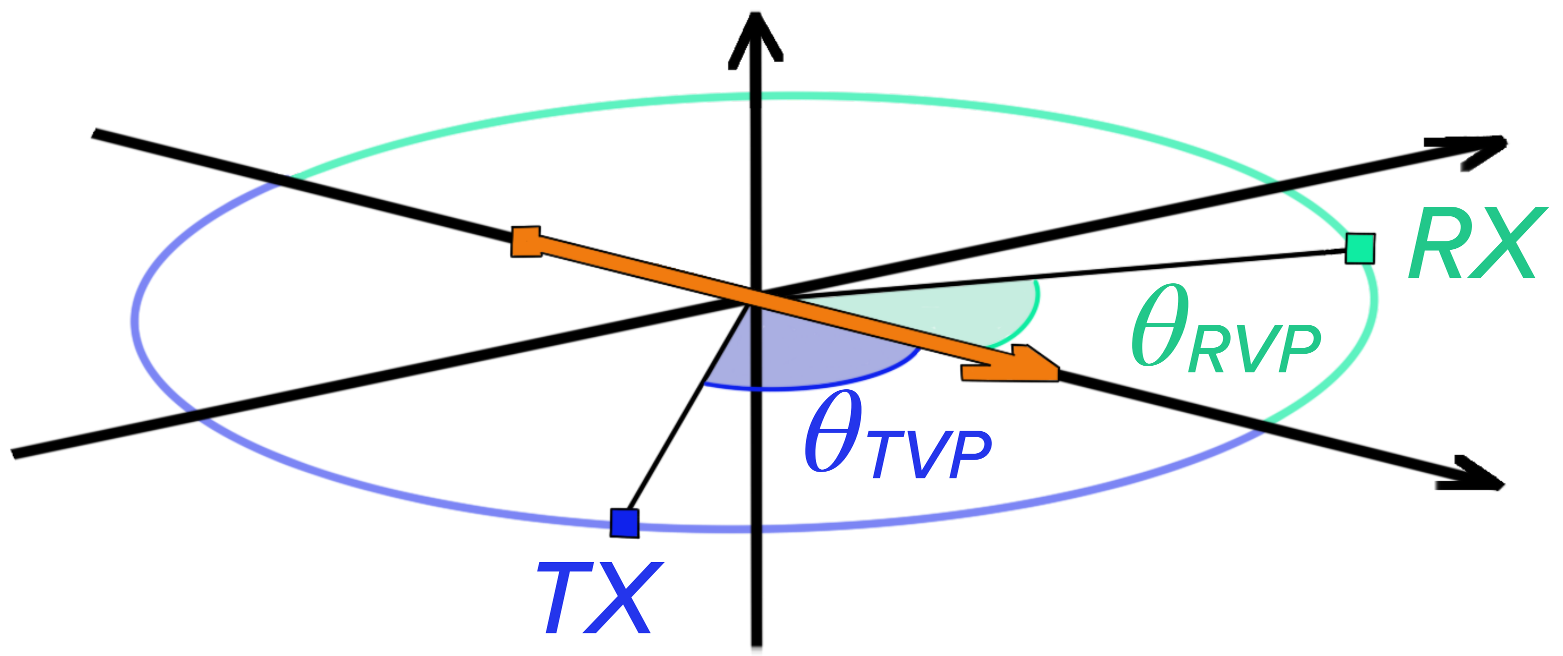
Transmit Frequency



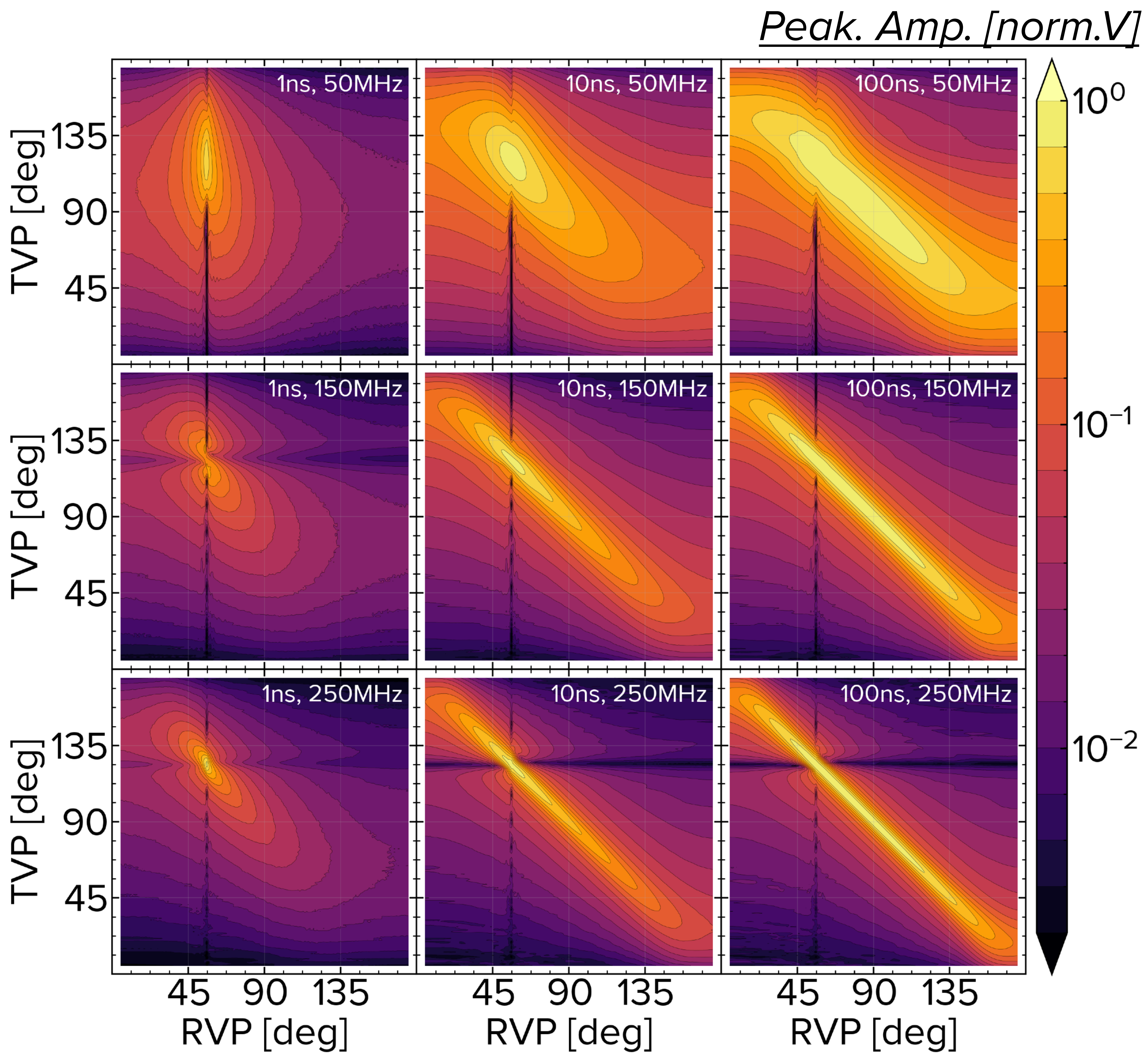
RVP, TVP = (90,75)°

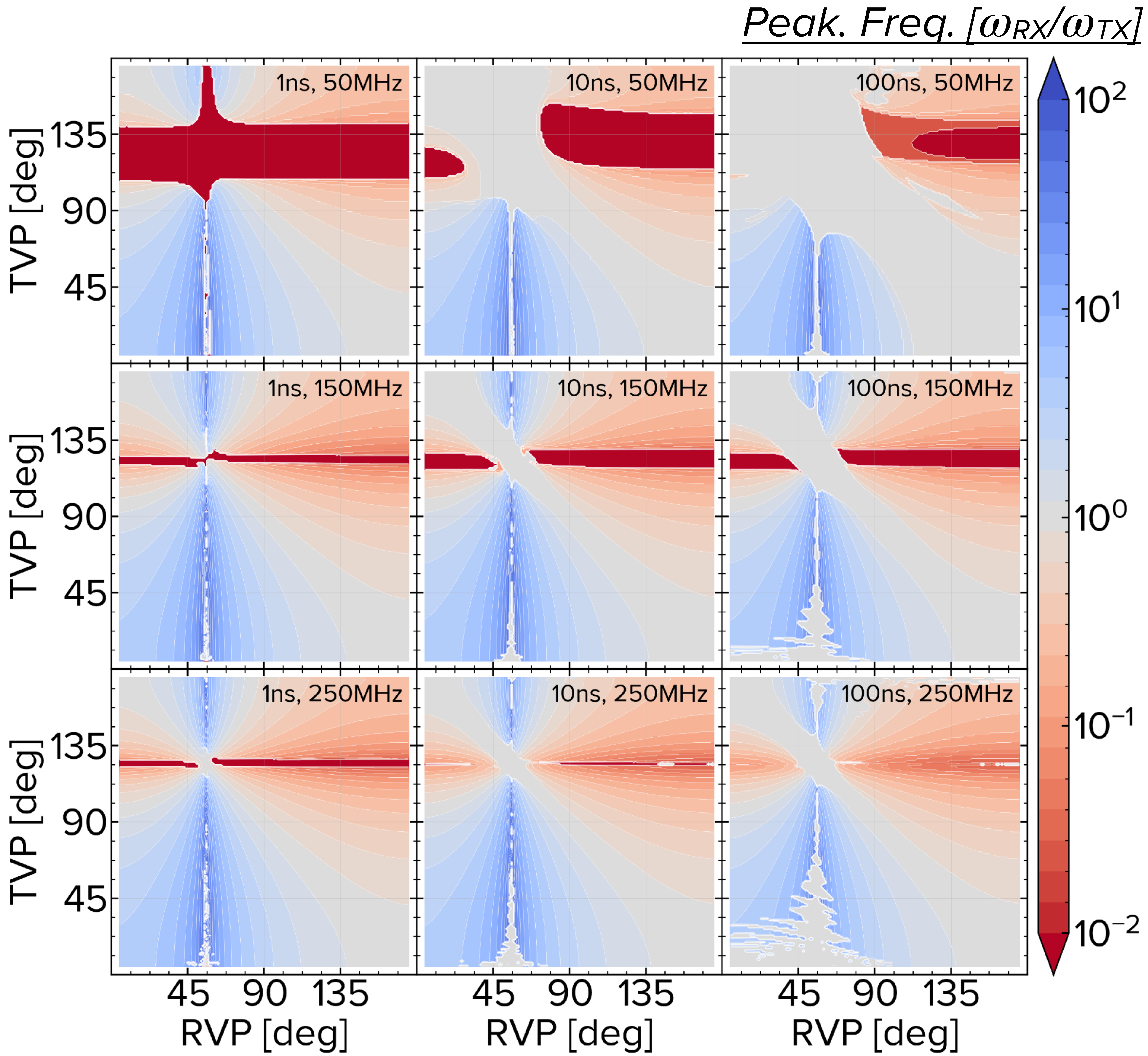


- f_{TX} modifies the width of the phase striping
- Affects the acceptance region for strong phase coherence →controls width of the high-amplitude region

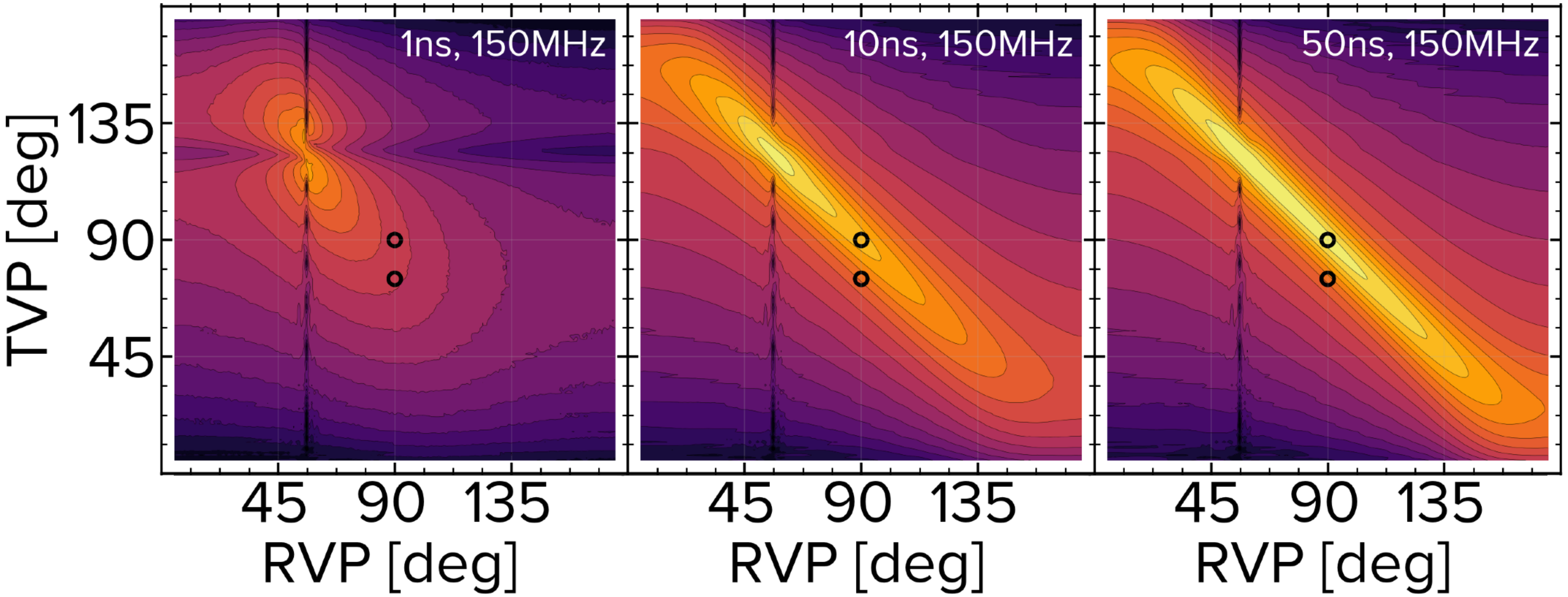


Signal Properties





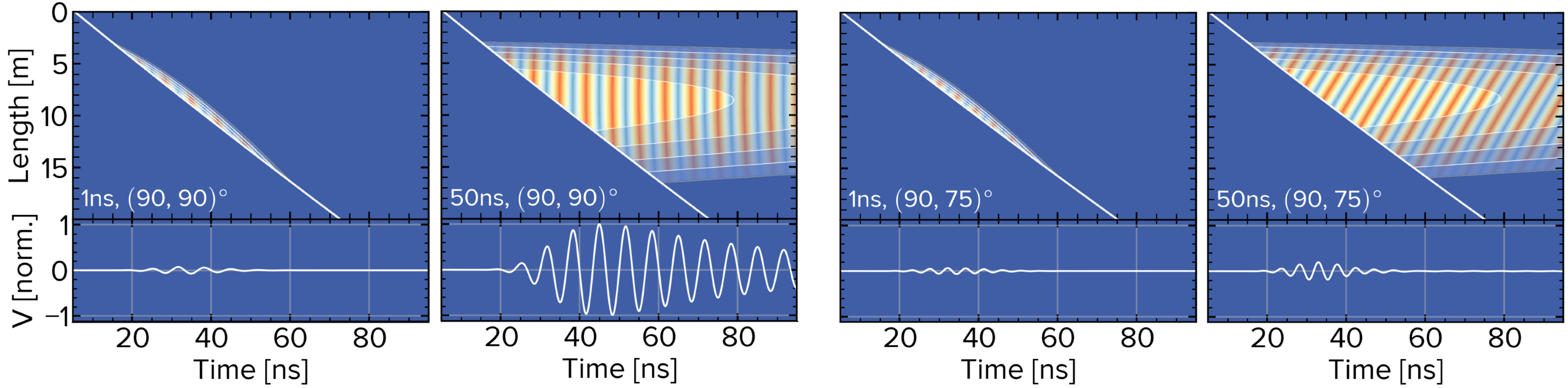
Plasma Lifetime



- τ extends the cascade available for scattering
- Causes high-amplitude region to increase over full possible acceptance, and extends duration of the signal

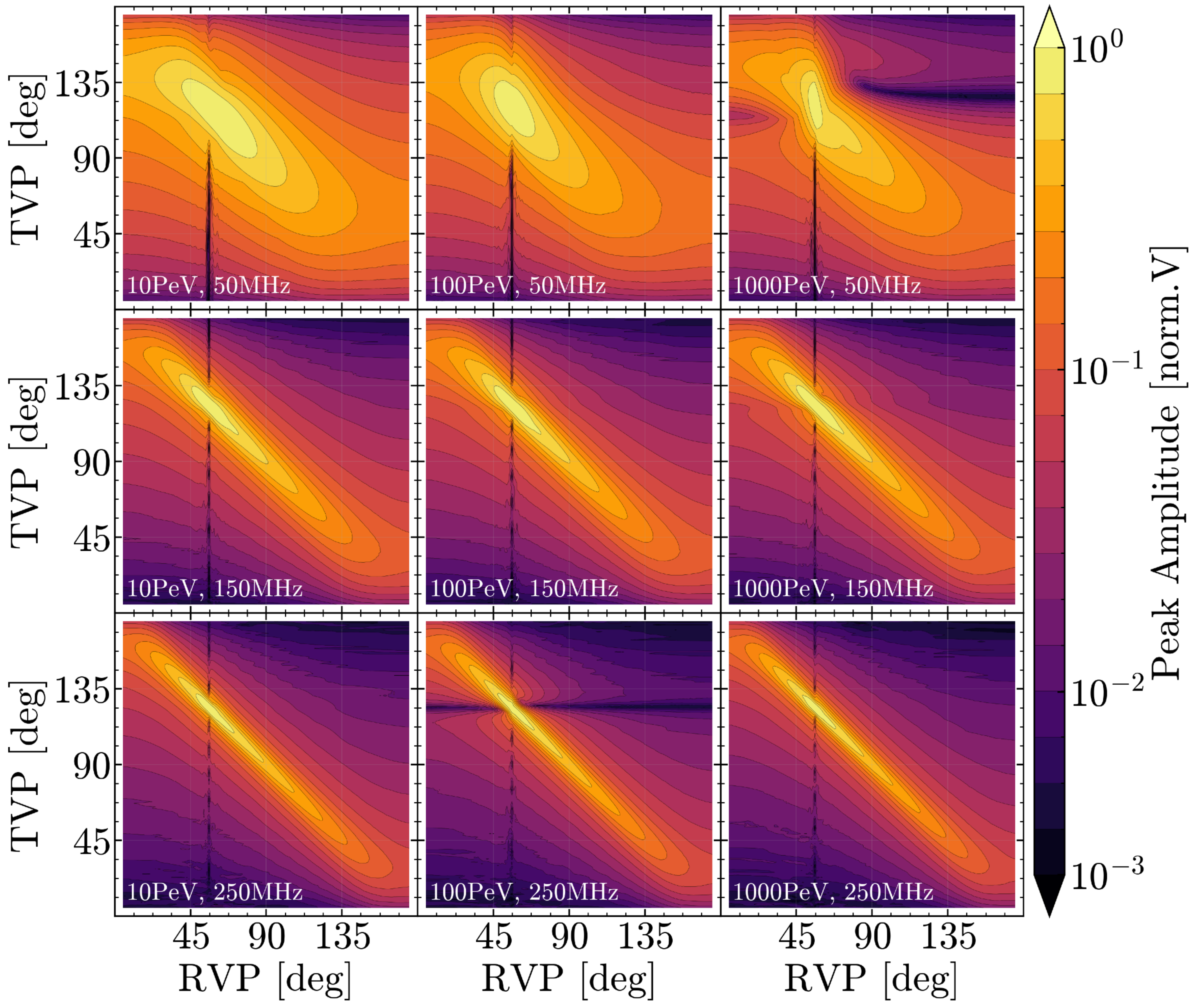
RVP, TVP = (90,90)° *τ = 1 ns* *τ = 50 ns*

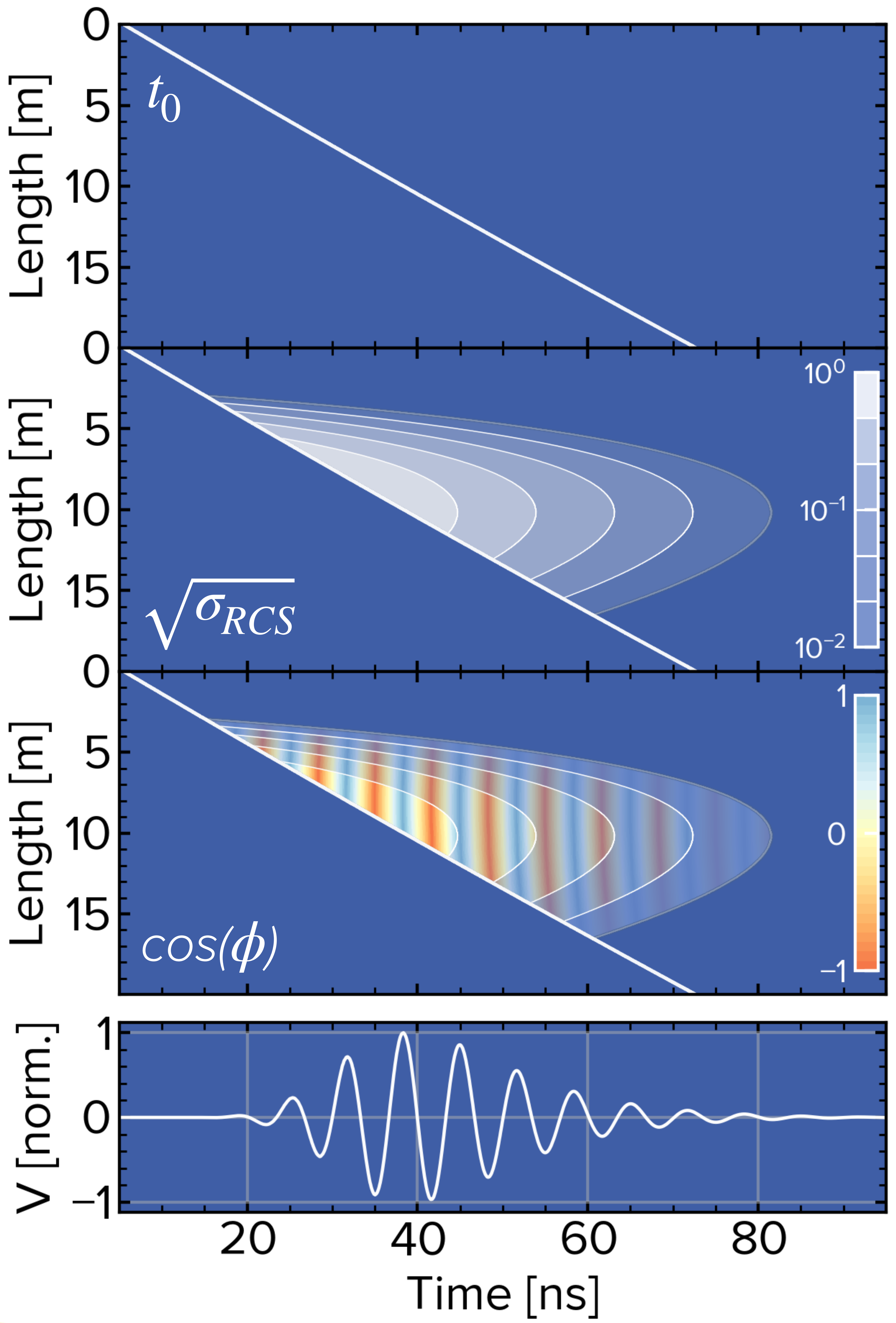
RVP, TVP = (90,75)° *τ = 1 ns* *τ = 50 ns*



Primary Energy

- τ = 10ns
- Individually normalised





Phase Profile

Cascade creation time

Radar cross section:

$$\sigma_{\mathrm{RCS},i}(t,t_0) = \sigma_{\mathrm{Th}} N_{e,i}^2 (\omega^2 W)^2 \cdot G_{\mathrm{Hz}} \cdot \mathcal{T} \cdot e^{-\frac{2(t-t_0)}{\tau}} \Theta(t-t_0)$$

(Normalised)

Time-dependent phase of each cascade segment:

$$\cos\phi_i = kR_i - \omega t - \pi/2$$

Final signal:

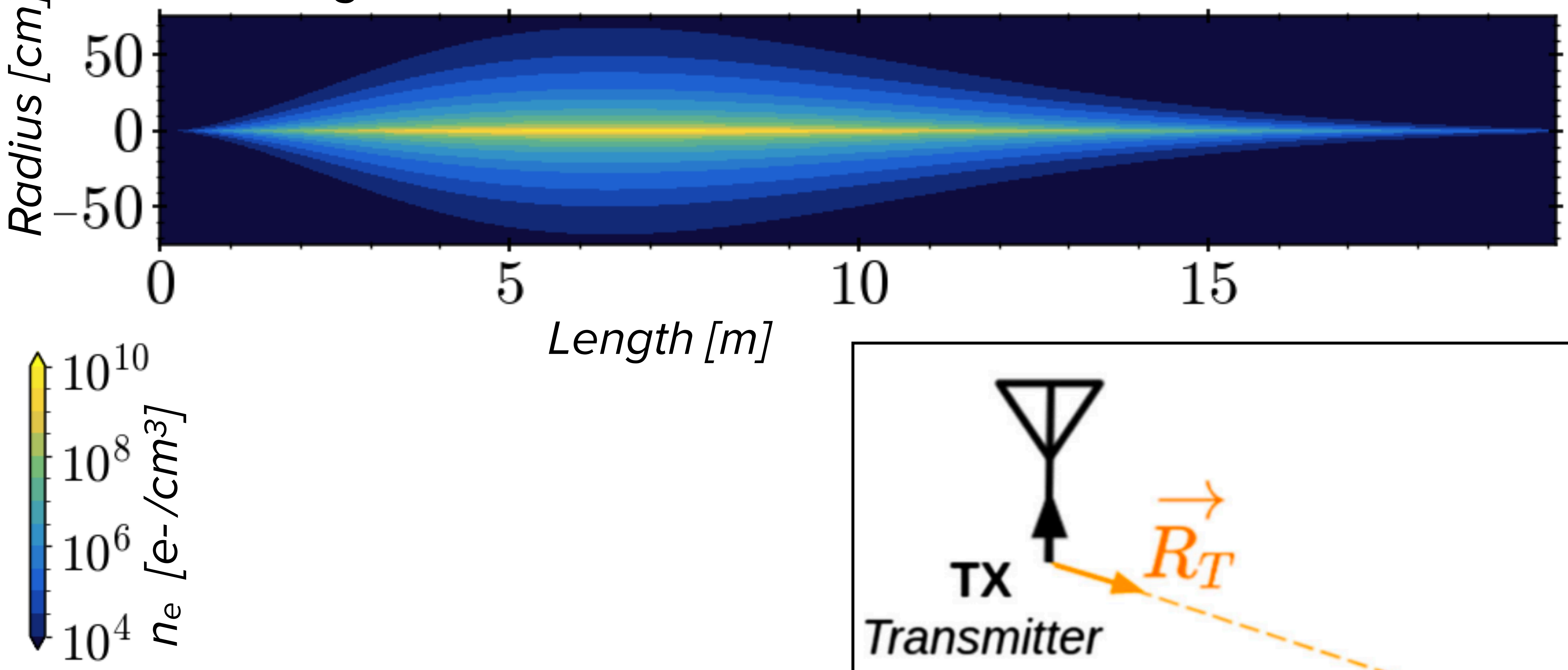
$$V(t) \propto \sum \sqrt{\sigma_{RCS,i}} \cdot \frac{1}{R_{R,i} R_{T,i}} \cdot \cos\phi_i$$

MARES

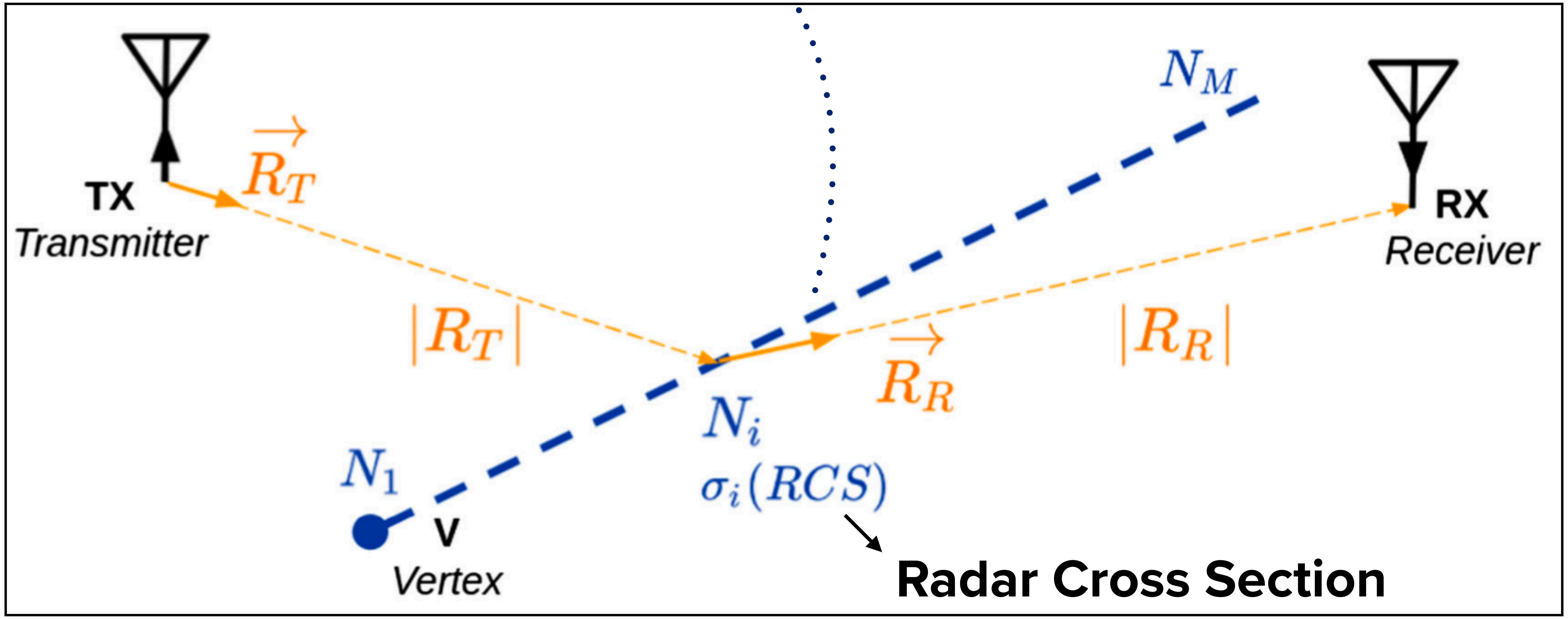
MARES - Macroscopic Approach to the Radar Echo Scatter

E. Huesca Santiago et al. 2024

→ *Modelling a CC electron electron ν interaction*



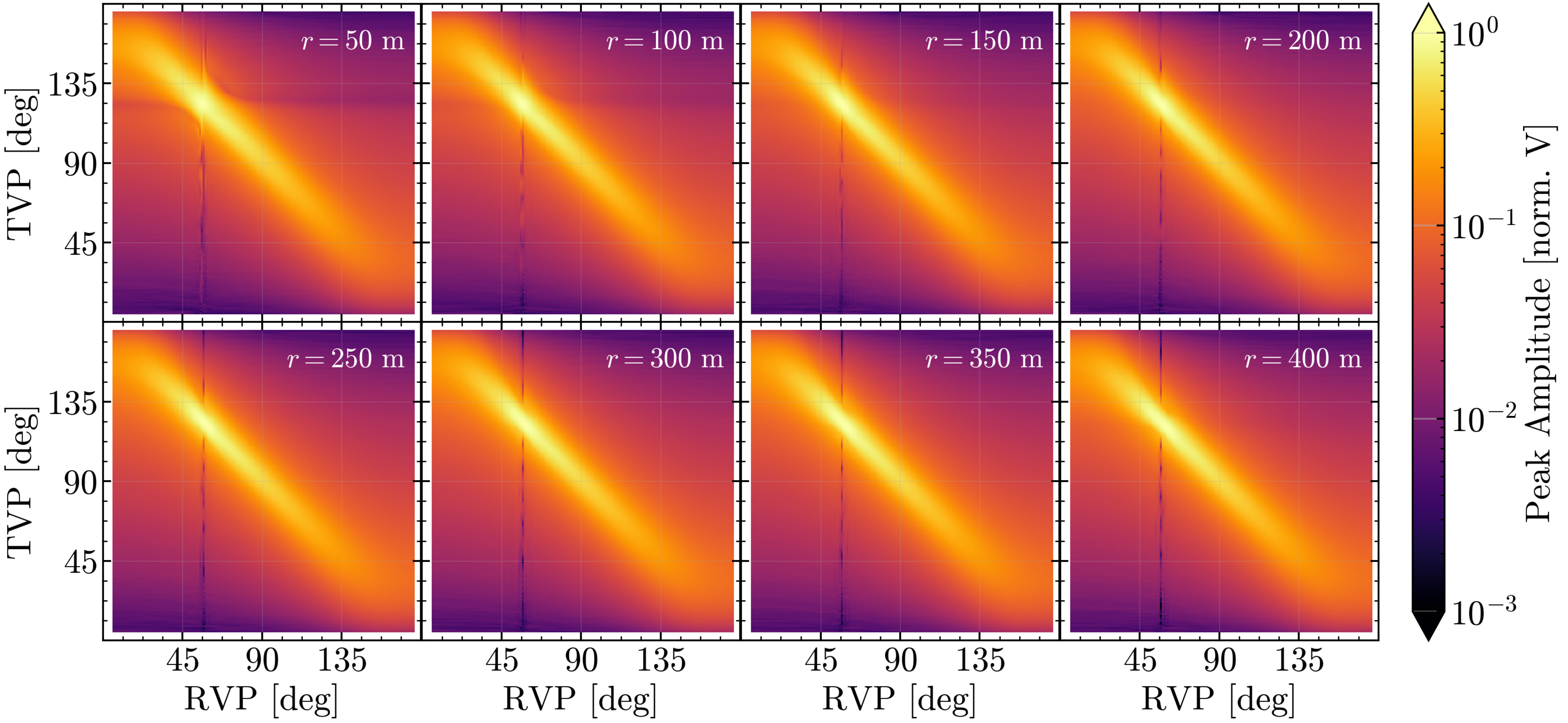
- Semi-analytic, deterministic C++ code package
- Splits cascade into segments
- Estimates scattered field from each segment



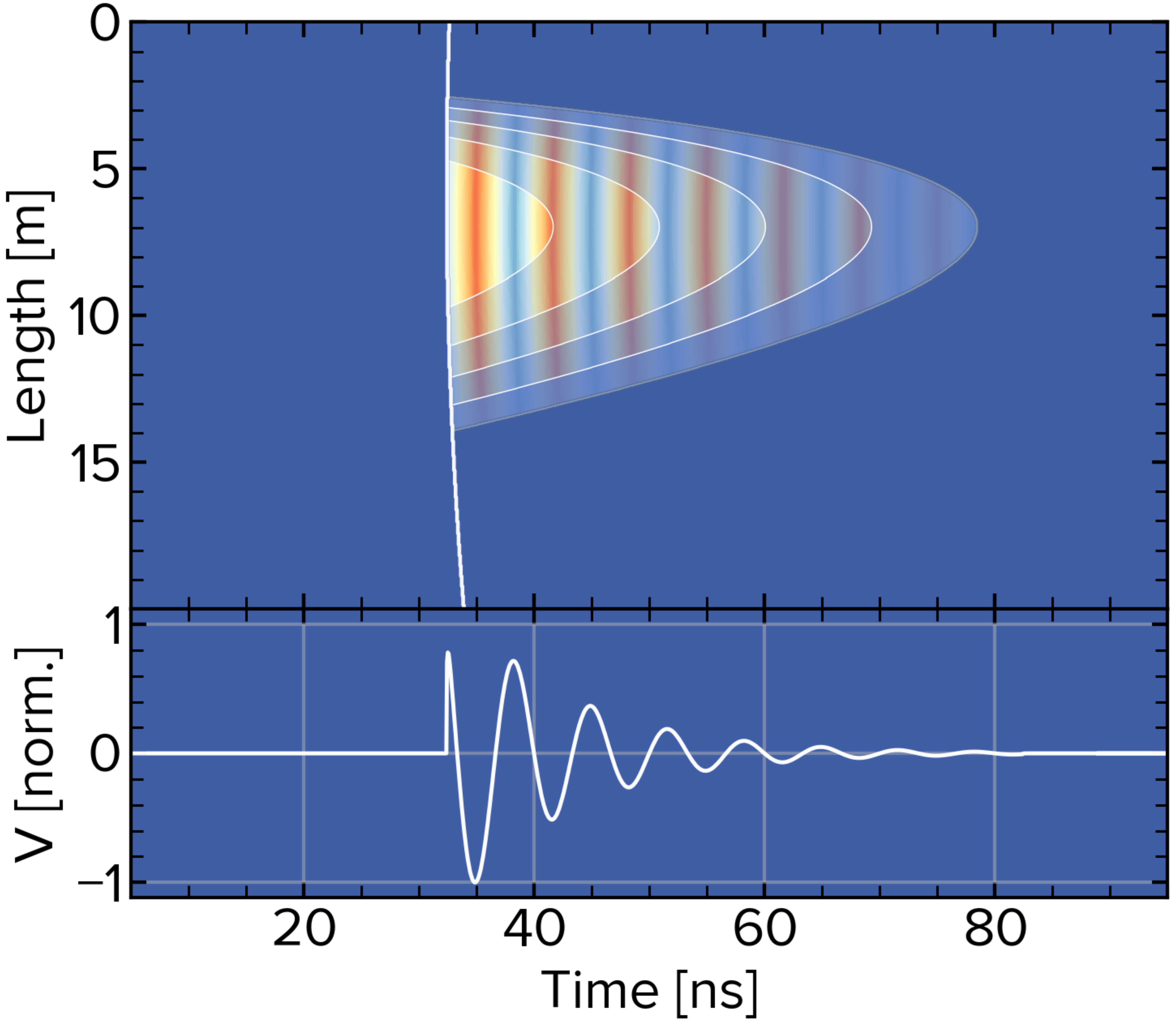
Final signal at receiver = sum of contributions of each segment

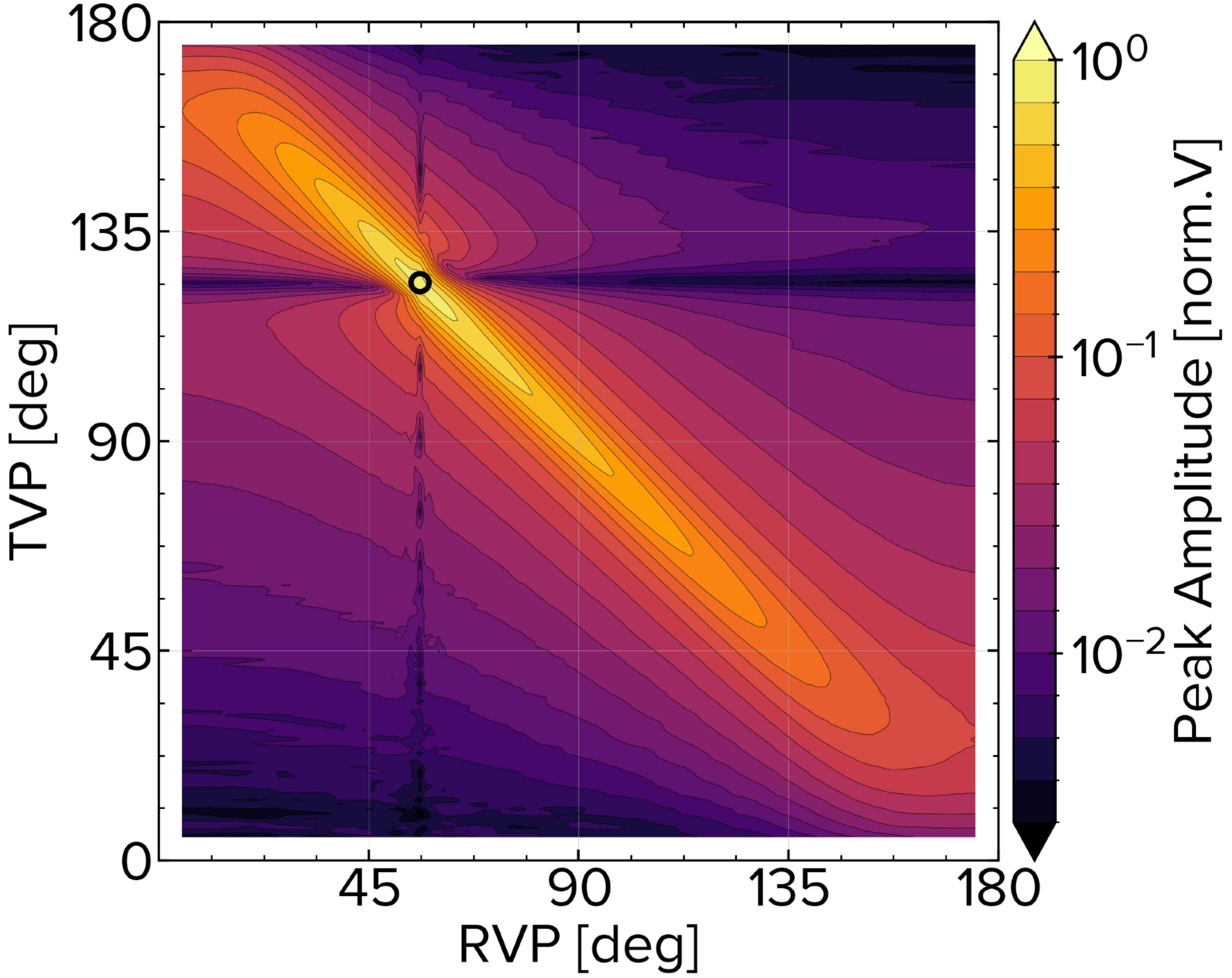
Radial distance

Credit: J.Loonen

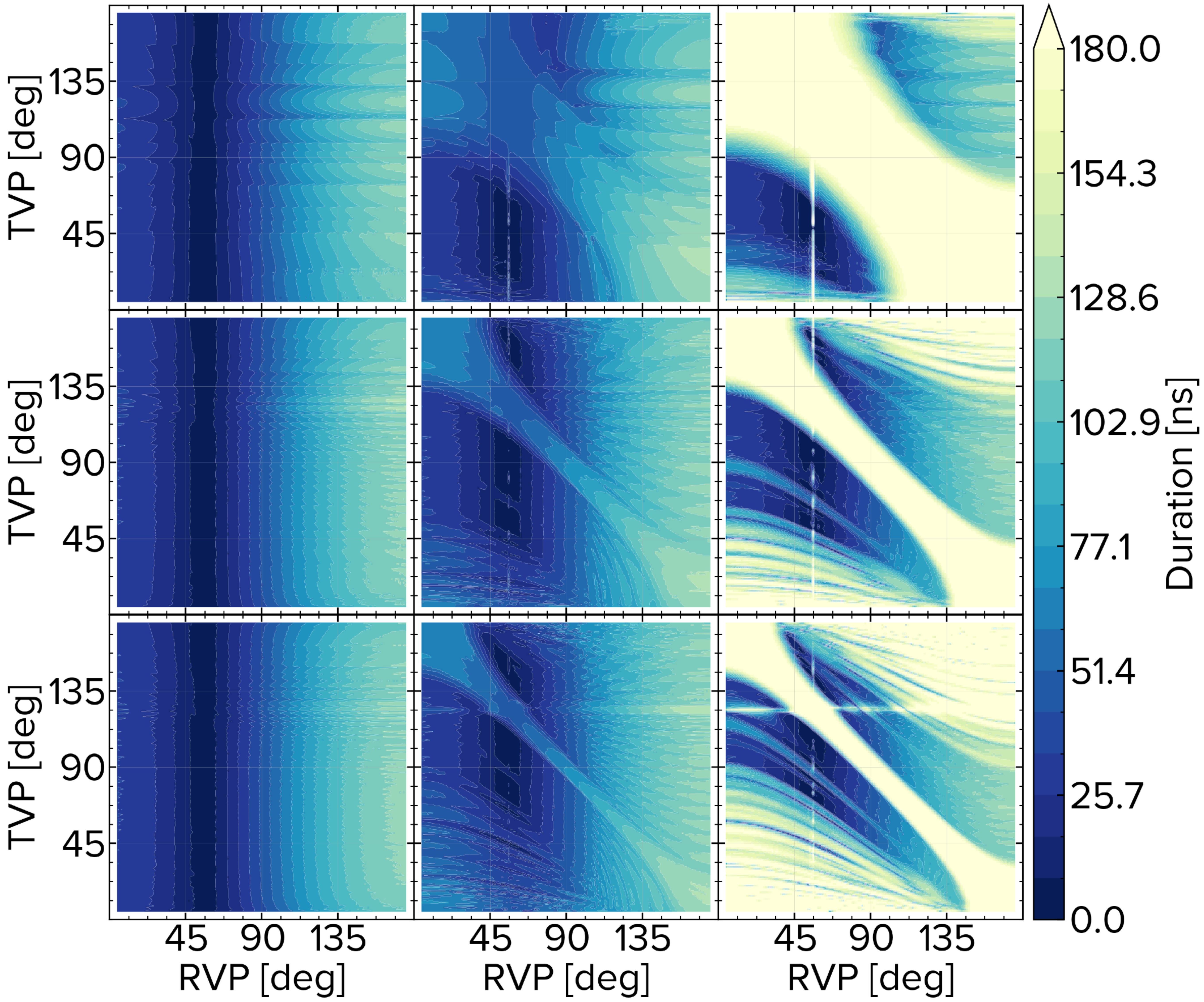


$RVP = 56°,\ TVP = 124°$





Duration

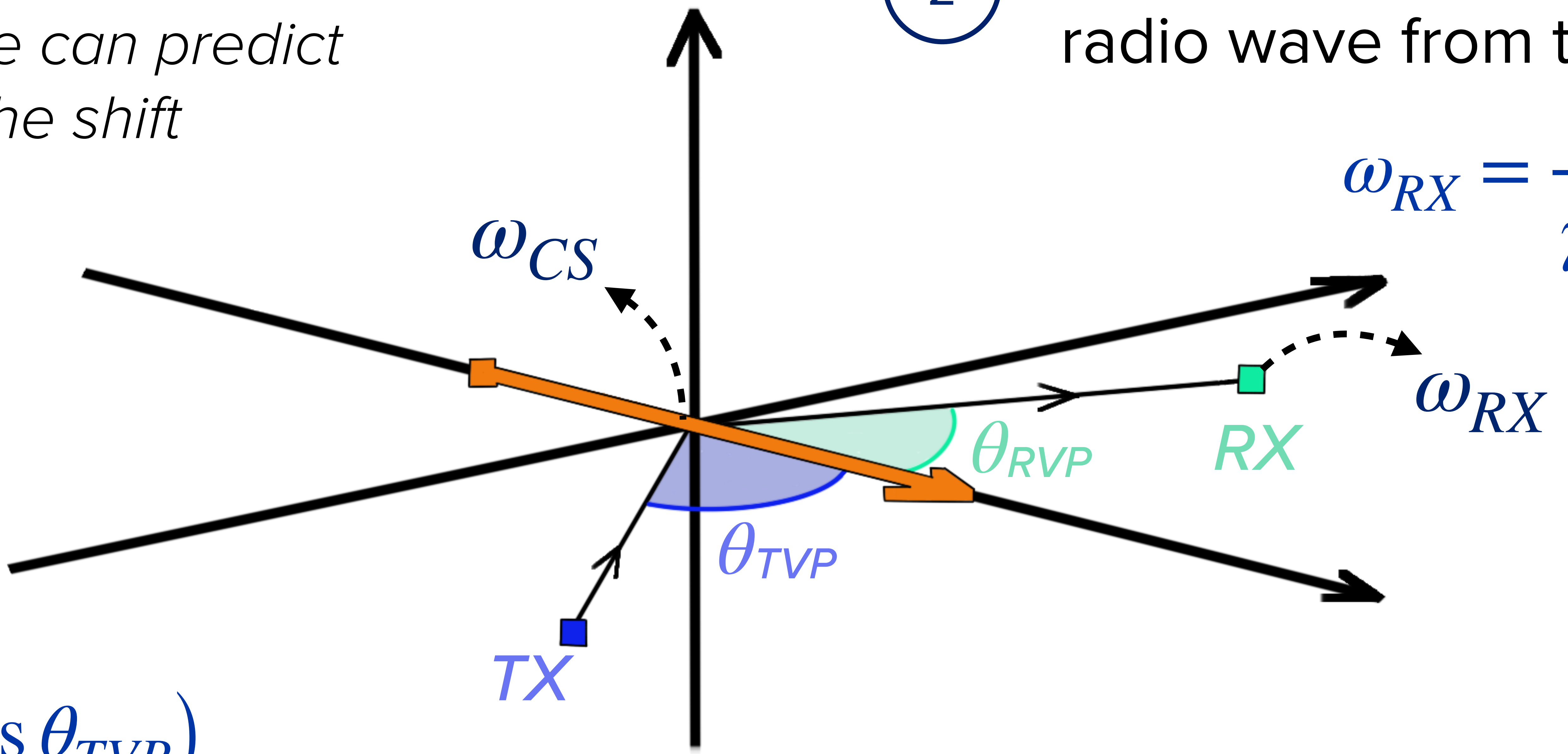

135
90
45
TVP [deg]
45 90 135
RVP [deg]
180.0
154.3
128.6
102.9
77.1
51.4
25.7
0.0
Duration [ns]

Doppler Shifts

Doppler shifts expected in the radar system, with two caveats:

- Relativistic appearance, n > 1
- Double Doppler system (bistatic)

→ *By combining the two, we can predict the magnitude of the shift*



1 ω_{CS} → the observed frequency of the radio wave from the **TX** at the **cascade**:

$$\omega_{CS} = \gamma \omega_{TX} \left(1 + n\beta_{TX} \cdot \cos \theta_{TVP}\right)$$

2 ω_{RX} → the observed frequency of the radio wave from the **cascade** at the **RX**:

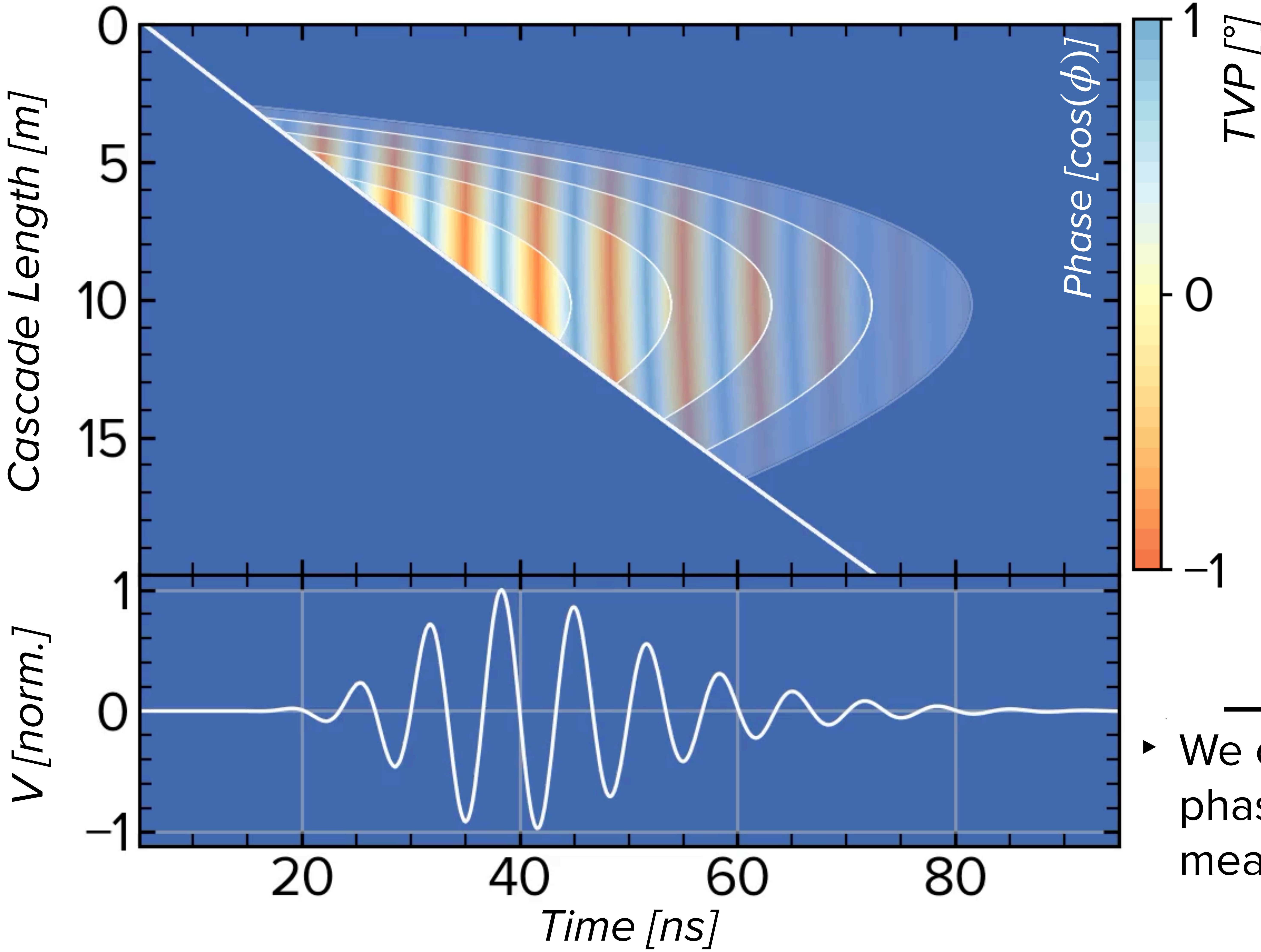
$$\omega_{RX} = \frac{\omega_{CS}}{\gamma \left(1 - n\beta_{TX} \cdot \cos \theta_{RVP}\right)}$$

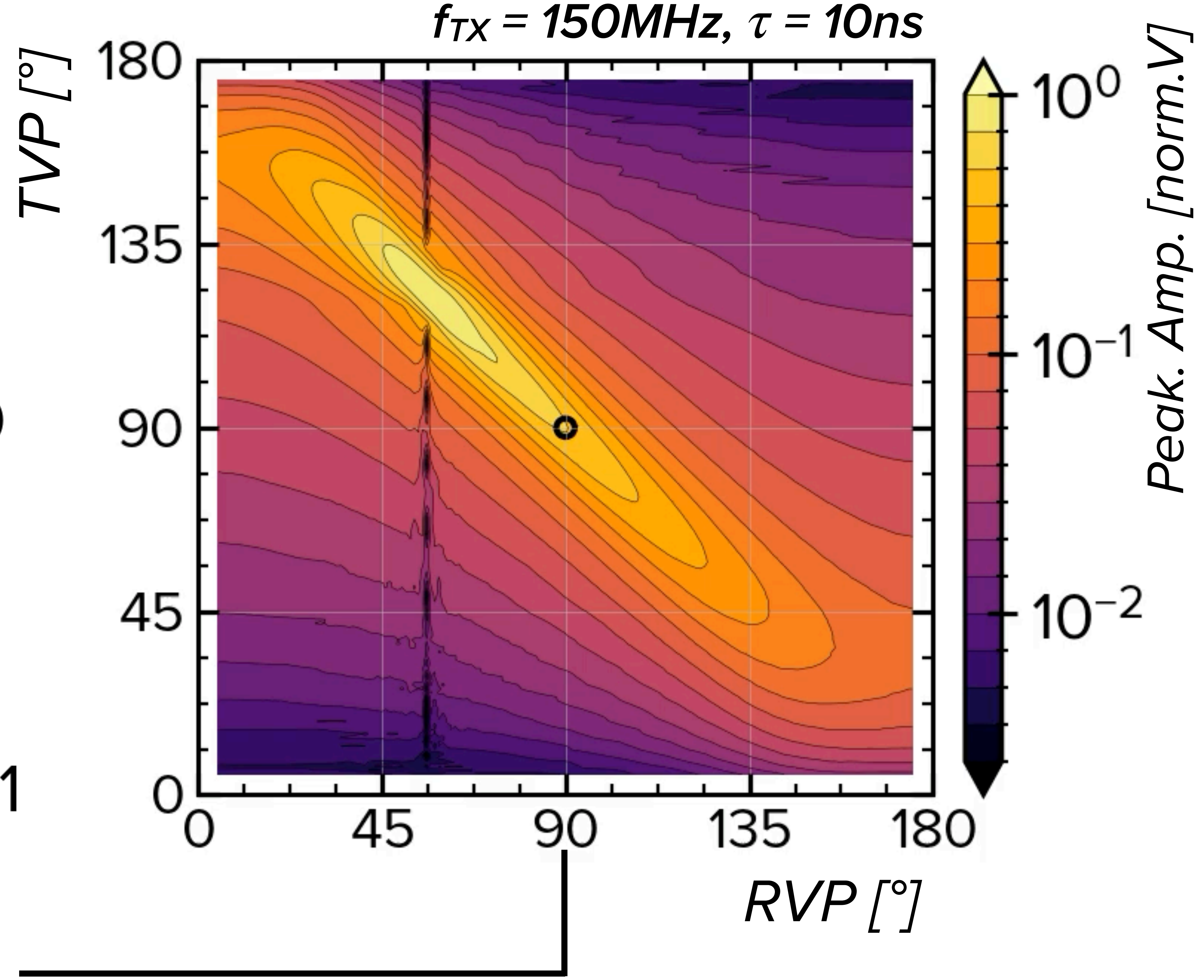
(Shifted to TX frame)

Final Doppler shift observed → $$\frac{\omega_{RX}}{\omega_{TX}} = \frac{|1 + n\beta \cos \theta_{TVP}|}{|1 - n\beta \cos \theta_{RVP}|}$$

(Assuming moving point source)

Phase Coherence





- We can define a phase coherence measure:

Credit: J.Loonen

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