MARES: A MACROSCOPIC APPROACH TO THE RADAR ECHO SCATTER FROM HIGH-ENERGY PARTICLE CASCADES

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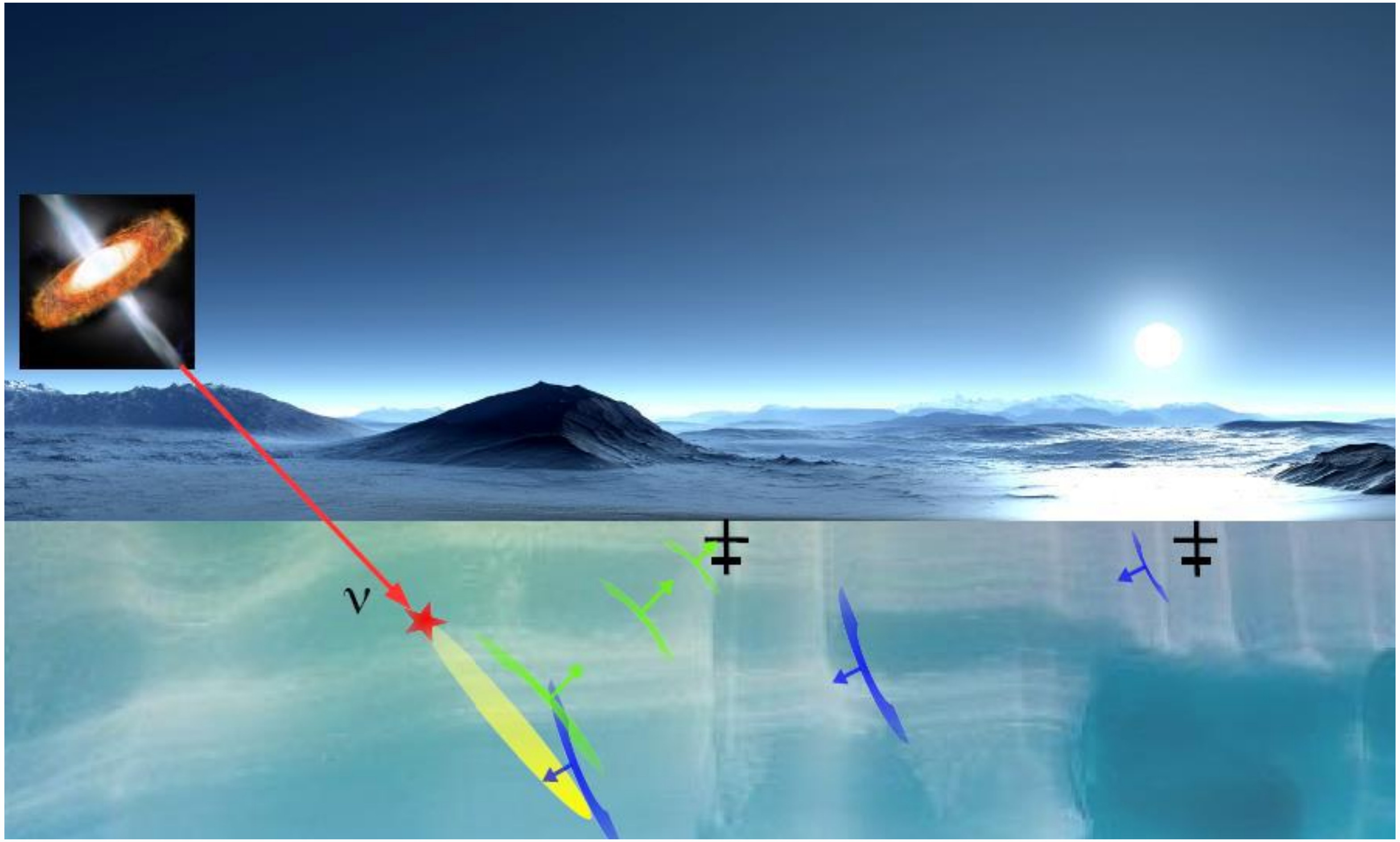
ON BEHALF OF THE RADAR ECHO TELESCOPE COLLABORATION

VRIJE UNIVERSITEIT BRUSSEL
INTERUNIVERSITY INSTITUTE FOR HIGH ENERGIES

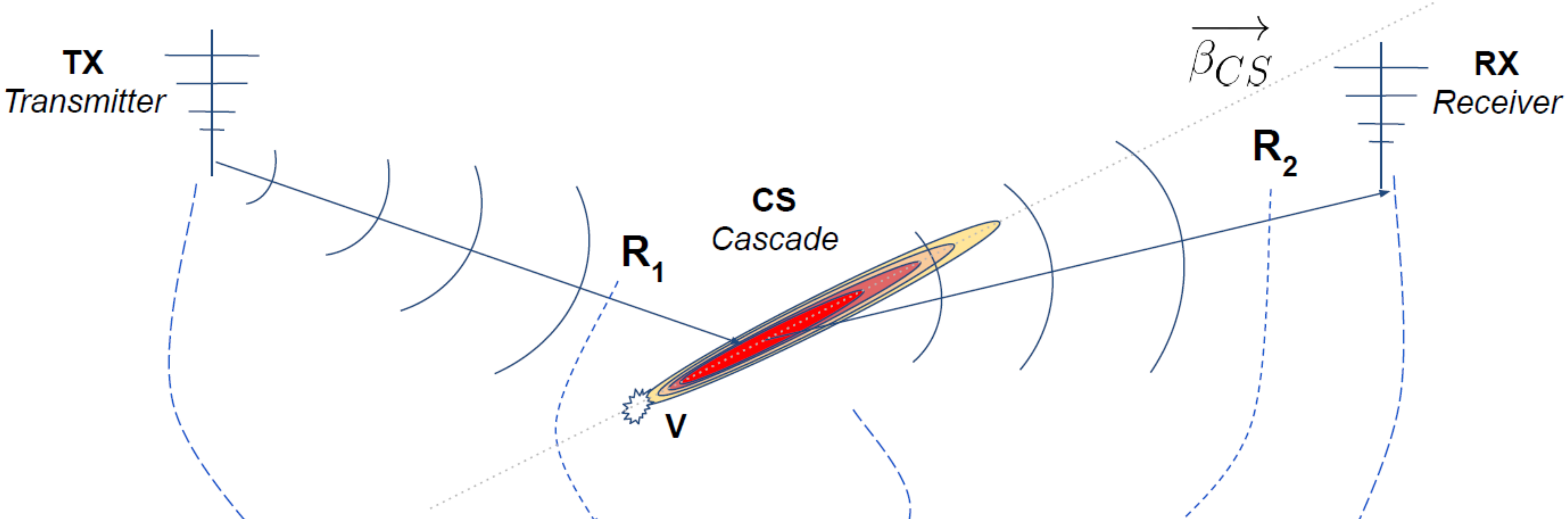
RADAR DETECTION OF HIGH-ENERGY PARTICLE CASCADES IN ICE

THE MAIN IDEA



MODELING AND UNDERSTANDING RADAR ECHOS FROM PARTICLE CASCADES

THE RADAR RANGE EQUATION



$$P_r = \eta P_t G_1 \frac{e^{-2R_1/L}}{4\pi R_1^2} \sigma_{rad} \frac{e^{-2R_2/L}}{4\pi R_2^2} G_2$$

THE CASCADE

(1)Relativistic cascade front

$E_p > E_{front} > E_{rel} \sim O(1\text{ MeV})$

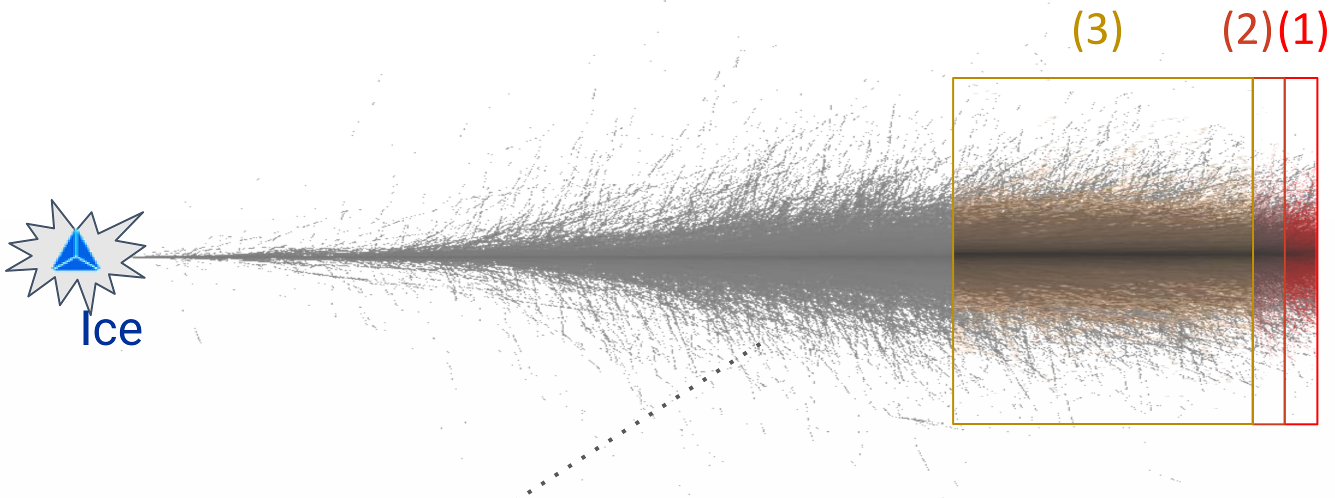
(2) Auger secondaries

$E_{rel} > E_{trail} > E_{ion}$

(3) Cascade trail

τ ($e^-_{ionisation}$) $\sim O(10)$ ns.

Long-lived electron plasma



$$\max(n_{e^-,Trail}) \sim 10^{10}\left[\frac{e^-}{\text{cm}^3}\right]\log\left(\frac{E_p}{10\text{ PeV}}\right) \ll N_{Avogadro}$$

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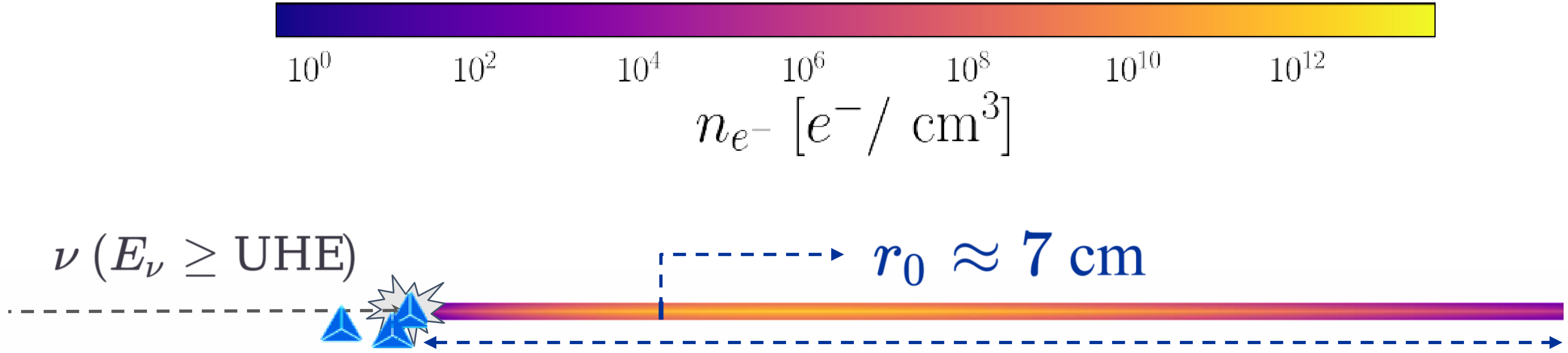
Credit: E.H. Santiago

MARES: THE CASCADE



$$L_{Cascade} \sim O(10\text{ m}) \propto \log(E_\nu)$$

$$\max(n_{e^-,\,Trail}) \sim 10^{10}\left[\frac{e^-}{\text{cm}^3}\right]\log\left(\frac{E_p}{10\text{ PeV}}\right) \ll N_{Avogadro}$$

Credit: E.H. Santiago

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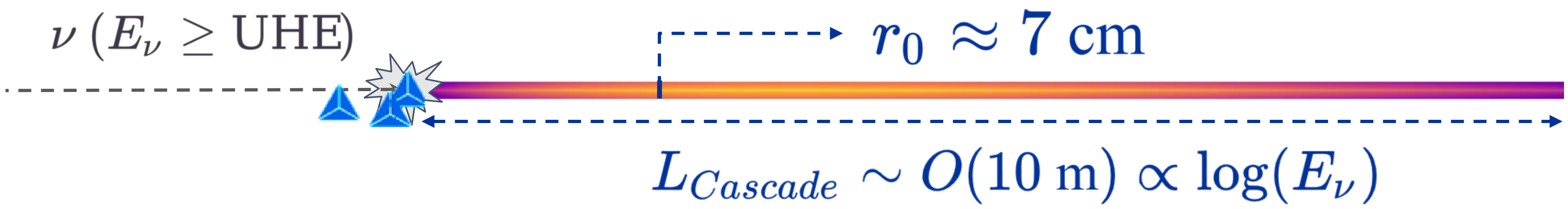
MARES: THE CASCADE SEGMENTATION



Cascade shape very "line-like" → Allows integration along radial dimension and considering line-segments:

Take segments small enough to preserve coherence

MARES:
arXiv:2310.06731
Phys. Rev. D 109, 083012 (2024)

Credit: E.H. Santiago

MARES: THE RADAR ECHO CROSS-SECTION

$$[6.65 \cdot 10^{-25}\mathrm{cm}^2] \quad [10^{-10} \rightarrow 10^{-14}] \quad [\tfrac{3}{2}\sin^2(\theta)]$$

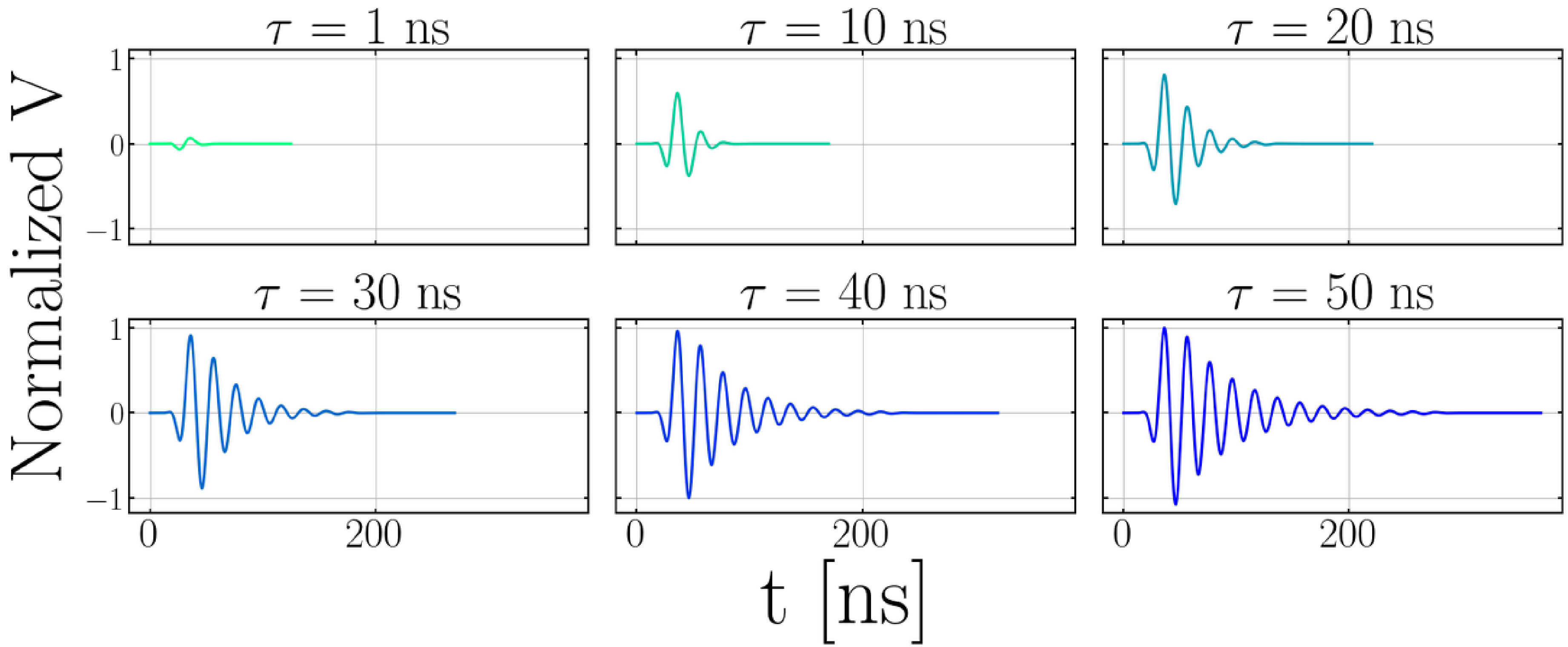
$$\sigma_{RCS,e^-} \simeq \sigma_{Thomson} \cdot \left(\frac{\omega}{\nu_c}\right)^2 \cdot G_{Hertz}$$

$$\sigma_{RCS,dV} = \sigma_{RCS,e^-} \cdot N_e^2 \cdot \mathfrak{T} \cdot [\Theta(t - t_0)e^{-2t/\tau_e}]_{t=t_{ret}}$$

Credit: E.H. Santiago

MODELING AND UNDERSTANDING RADAR ECHOS FROM PARTICLE CASCADES

SIGNAL PROPERTIES: LIFETIME



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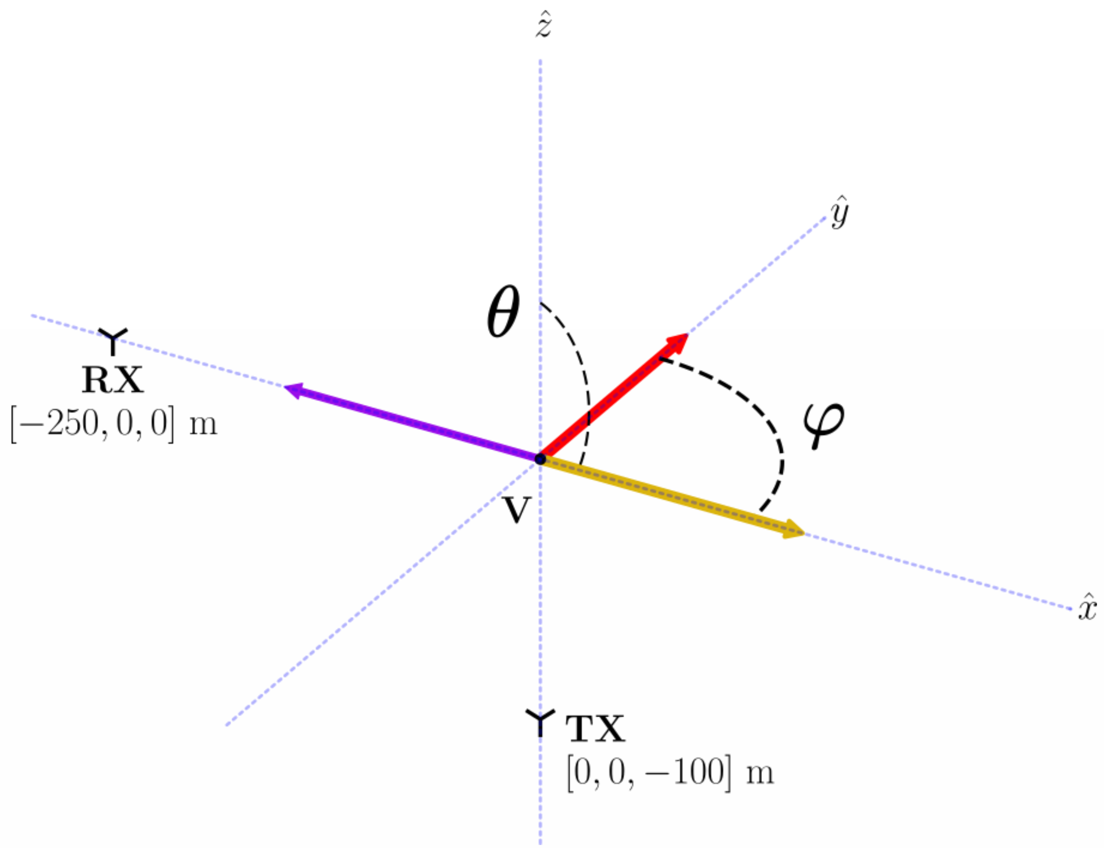
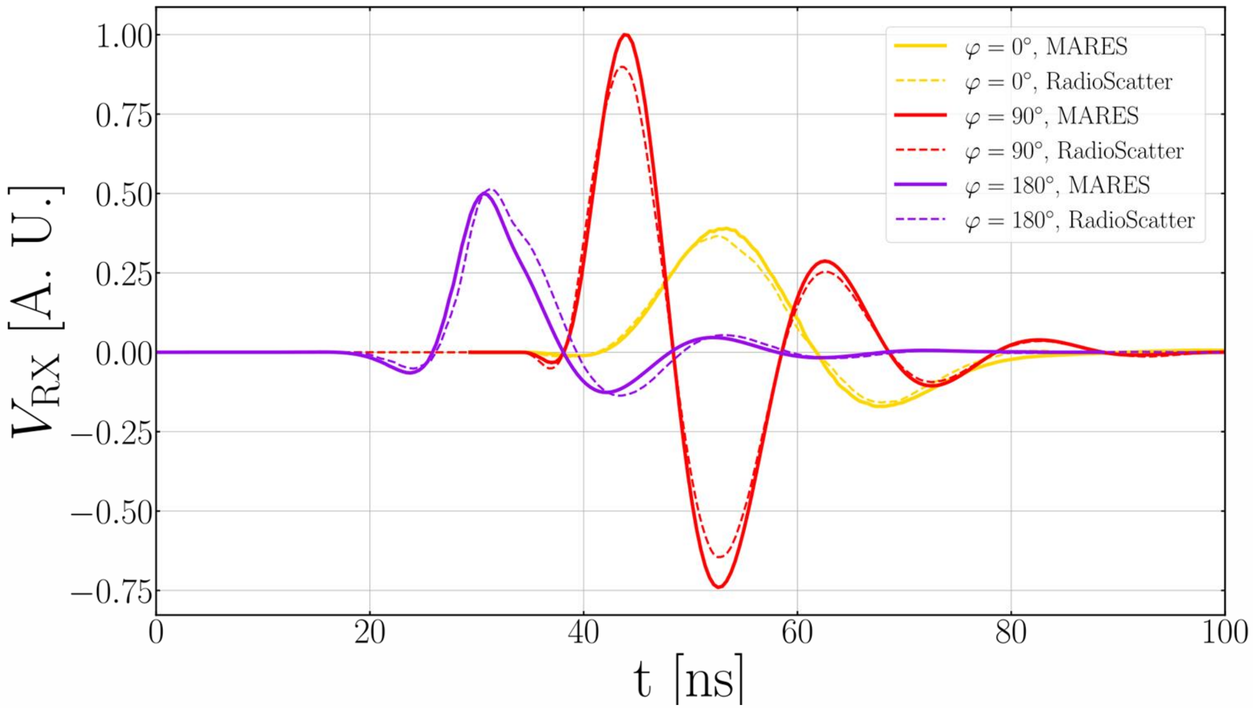
SIGNAL PROPERTIES: PULSE SHAPE





Excellent agreement between RadioScatter + GEANT4 Microscopic Monte-Carlo simulation and MARES Macroscopic deterministic RET simulation codes

RadioScatter: arXiv:1710.02883 ; NIM-A 922 (2019) 161-170
MARES: arXiv:2310.06731 ; Phys. Rev. D 109, 083012 (2024)

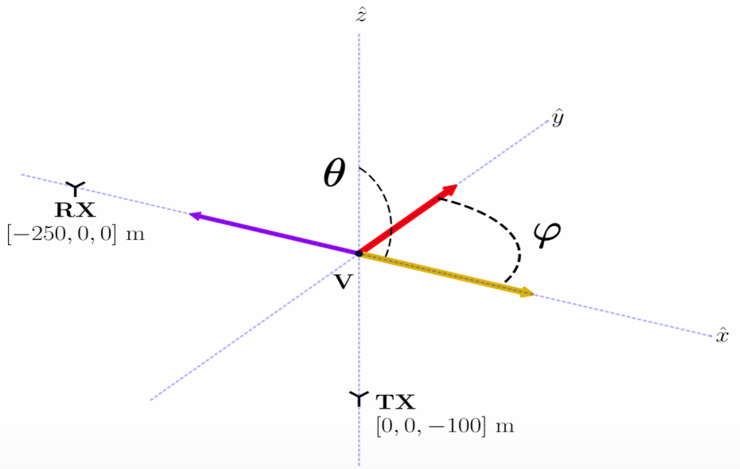
SIGNAL PROPERTIES: INTENSITY

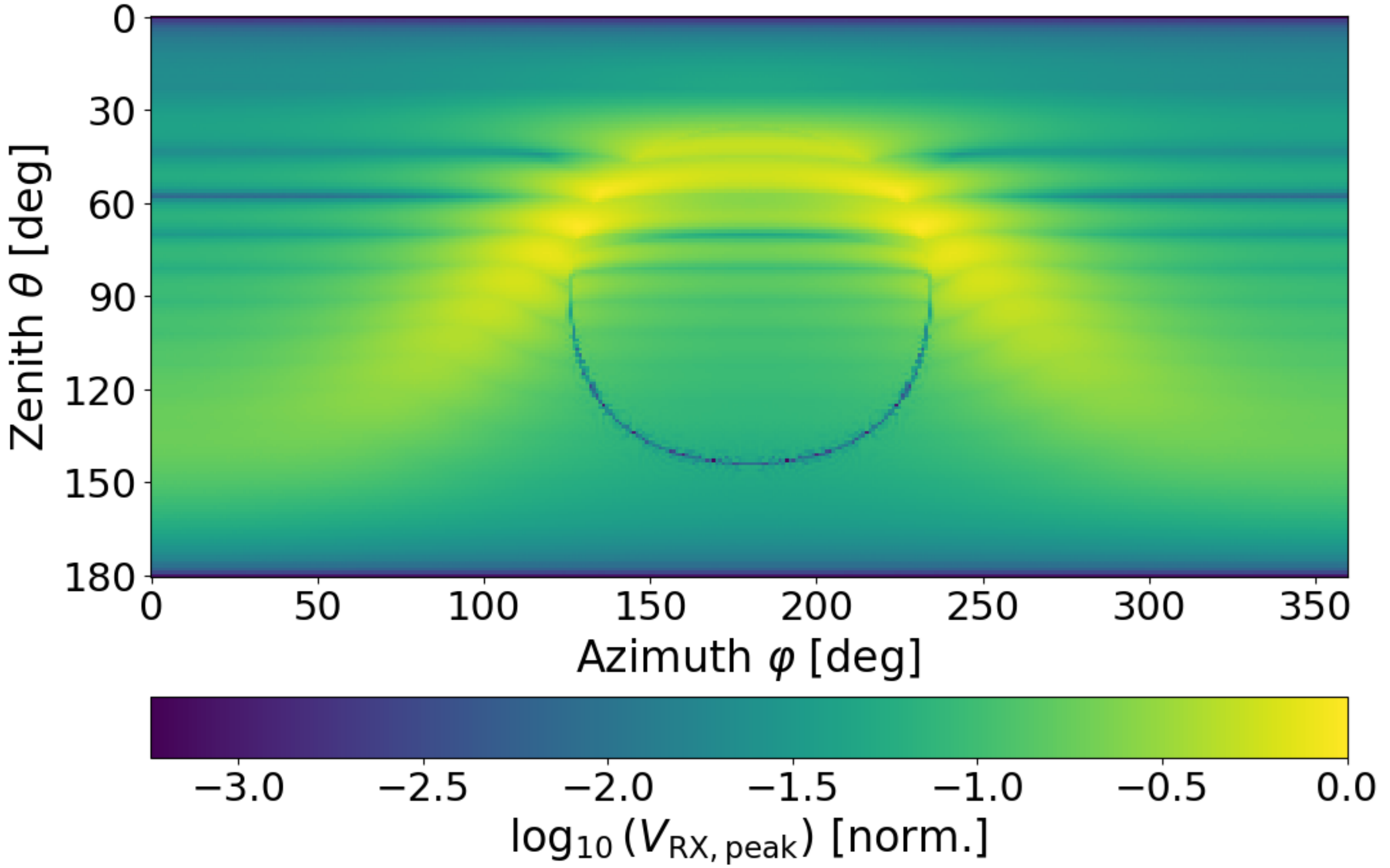
Features:

1) Cherenkov-like effect

2) Diffraction bands

3) High-intensity swirl





**Credit: I. Loudon, J. Loonen
E. Huesca-Santiago, D. Frikken**

MODELING AND UNDERSTANDING RADAR ECHOS FROM PARTICLE CASCADES

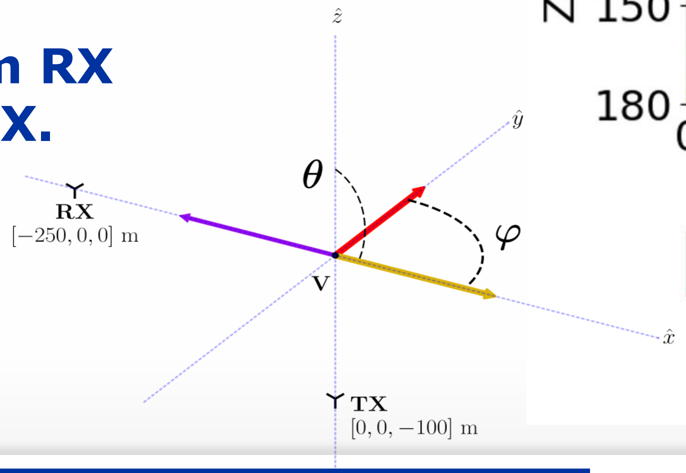
SIGNAL PROPERTIES: FREQUENCY

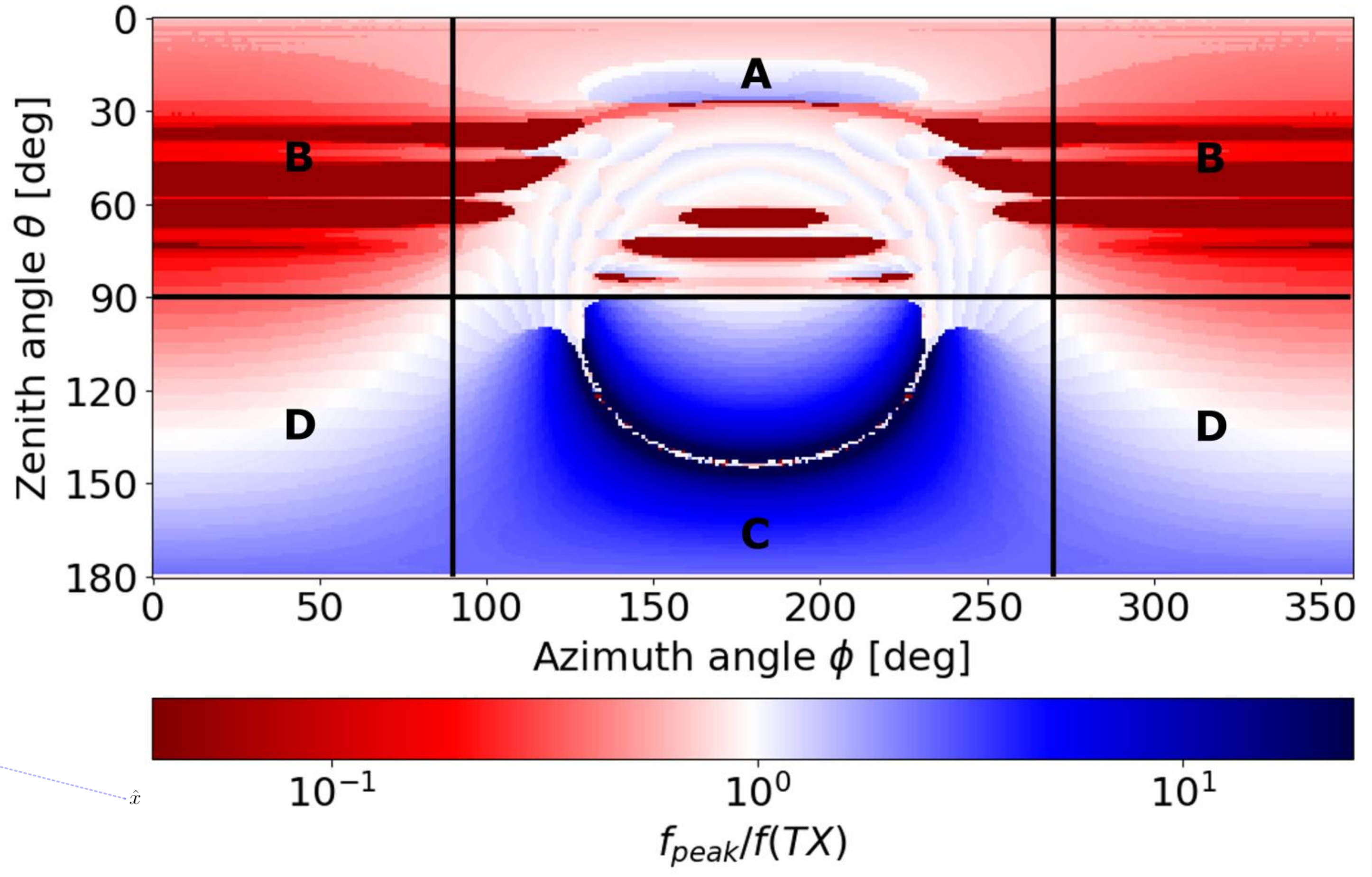
A: Towards RX,
Away from TX.

B: Away from RX
Away from TX.

C: Towards RX
Towards TX.

D: Away from RX
Towards TX.





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MODELING AND UNDERSTANDING RADAR ECHOS FROM PARTICLE CASCADES

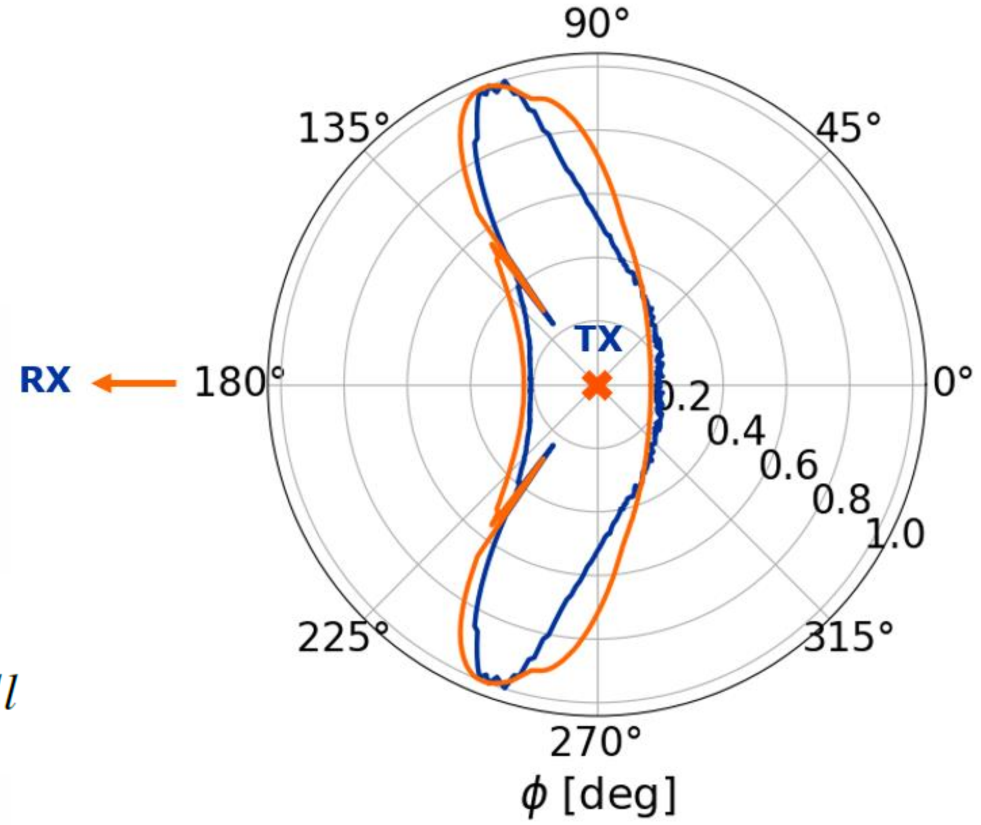
SIGNAL PROPERTIES: PHASE ALIGNMENT

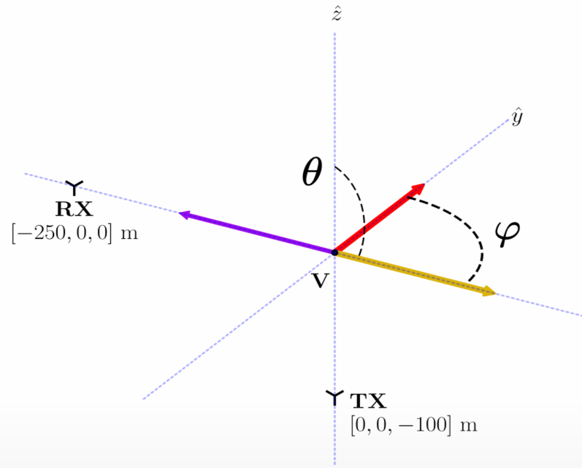
PRELIMINARY

Orange: Simulation at fixed zenith angle of 90 degrees

Blue: Phase alignment measure:

$$C = \int \left(\cos(\varphi) \cdot \frac{n_{e^-}}{n_{max}} \right)_{norm} dl$$





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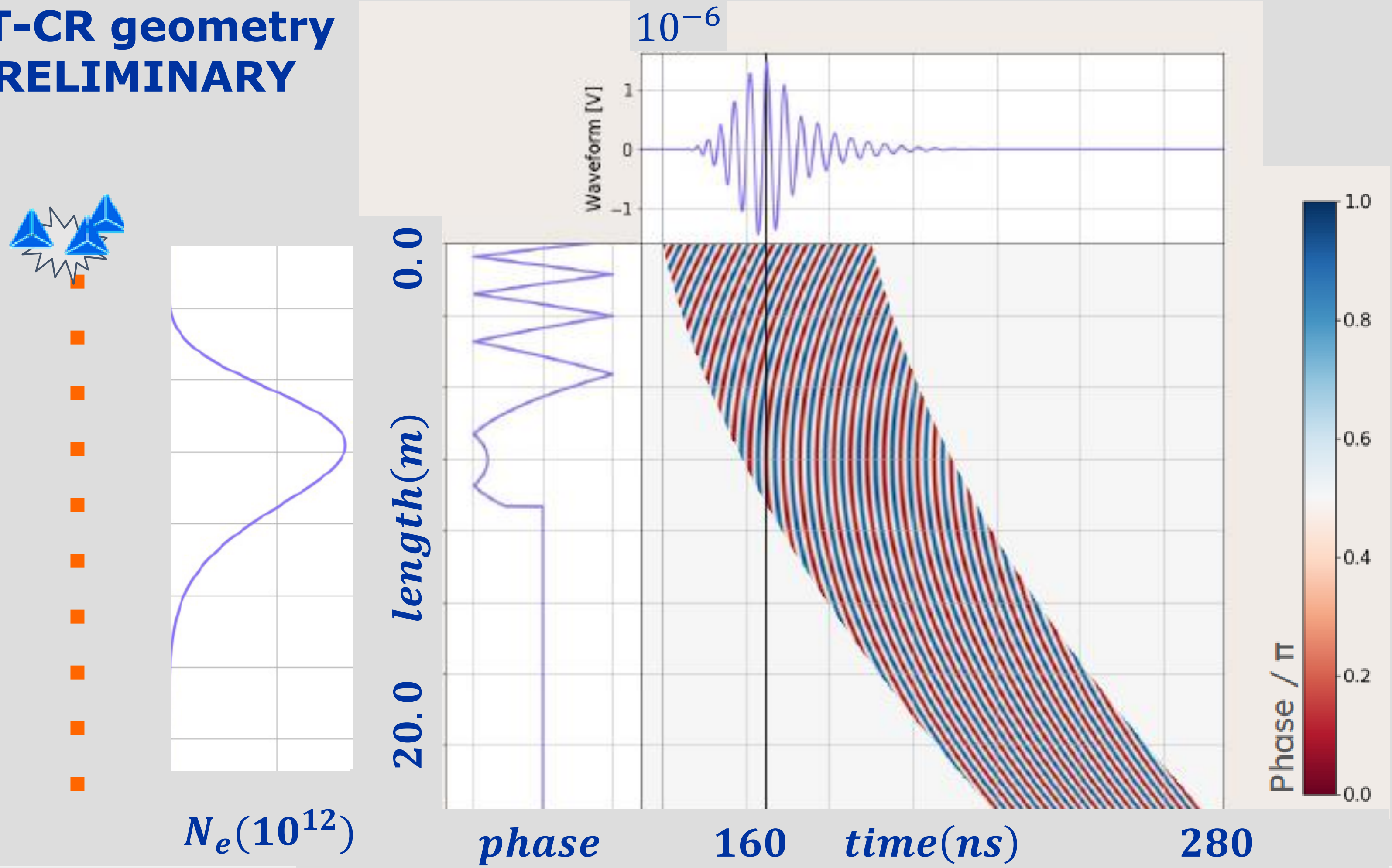
MODELING AND UNDERSTANDING RADAR ECHOS FROM PARTICLE CASCADES

SIGNAL PROPERTIES: PHASE ALIGNMENT

RET-CR geometry
PRELIMINARY



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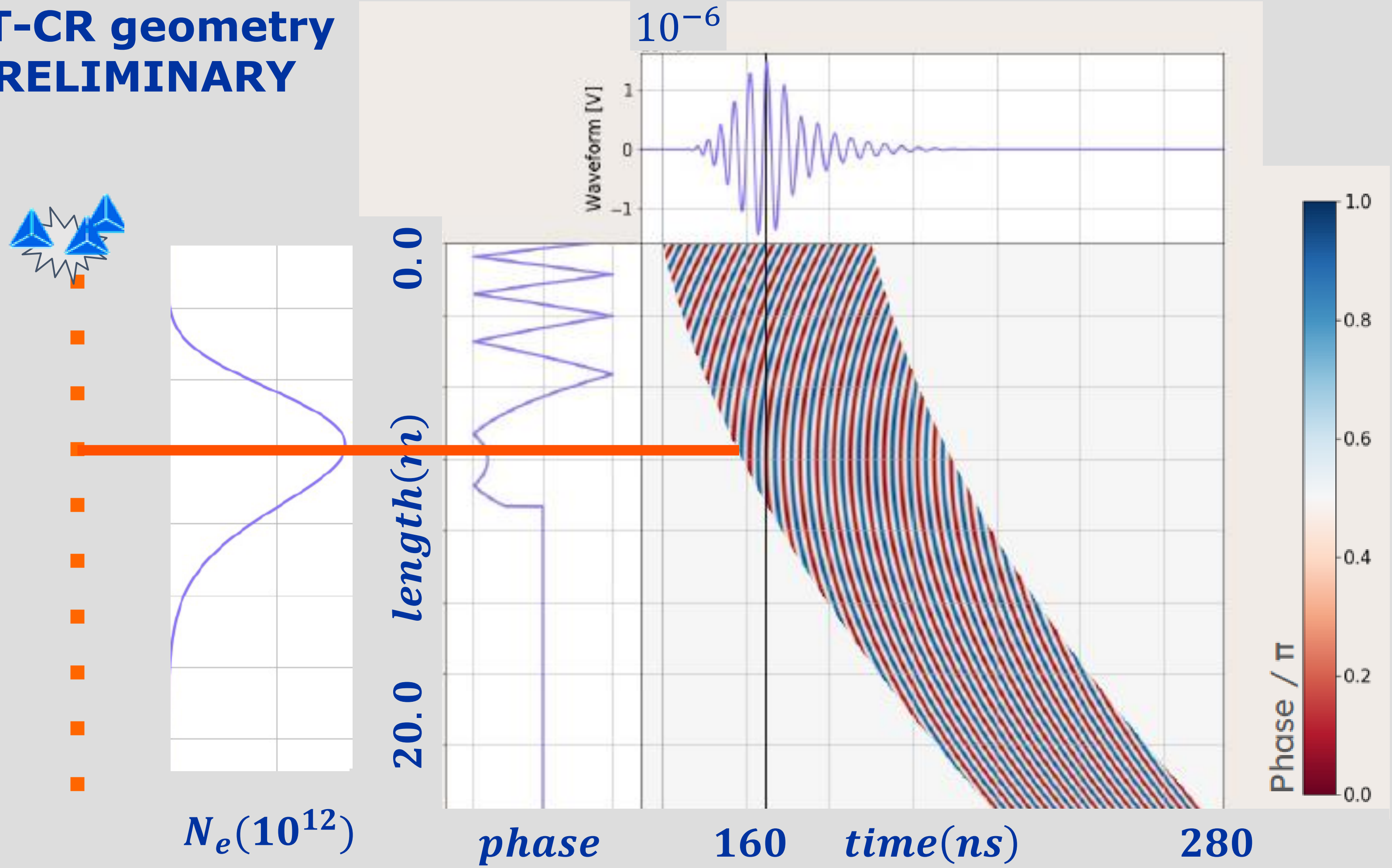

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SIGNAL PROPERTIES: PHASE ALIGNMENT

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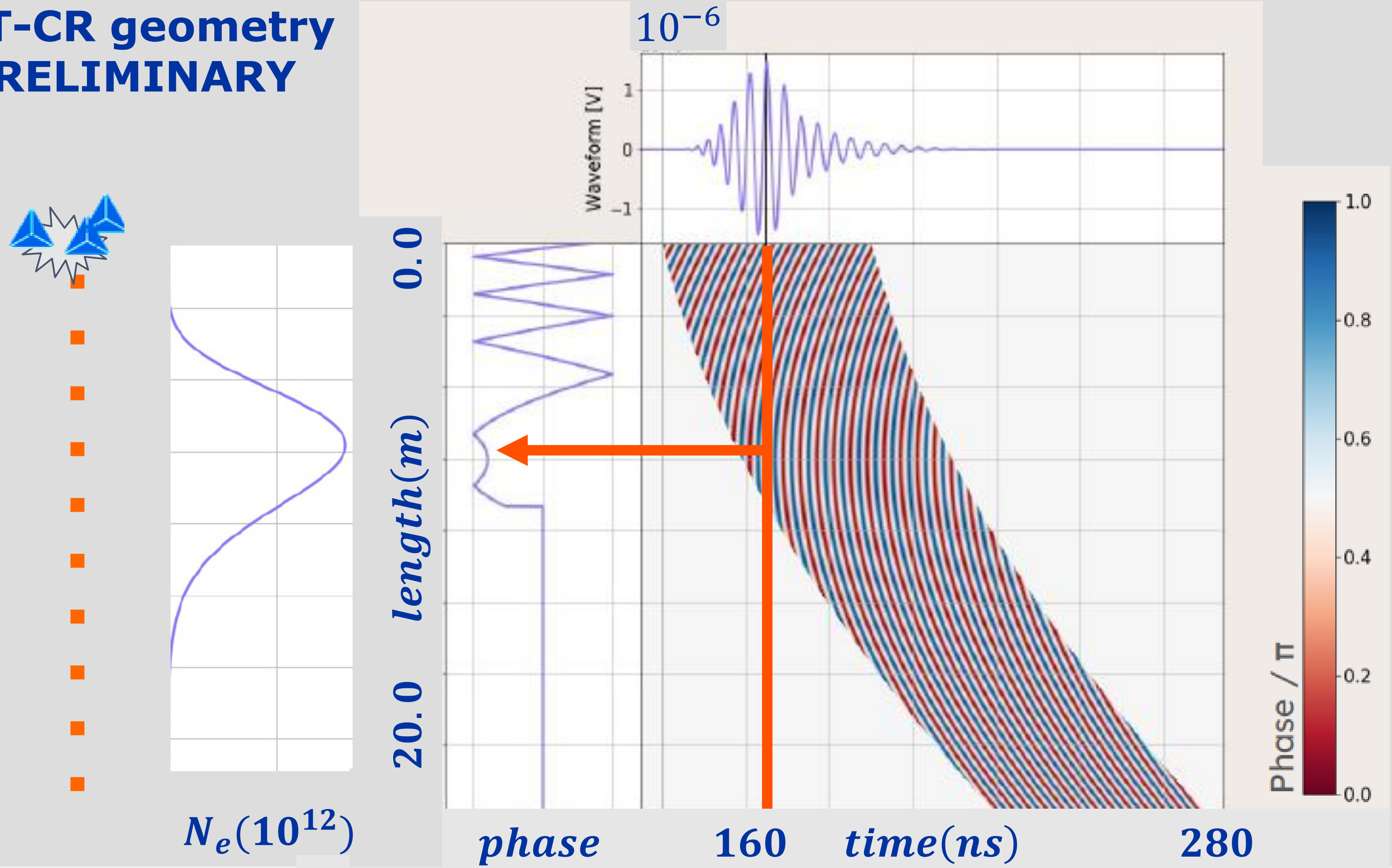

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Thanks!!

www.radarechotelescope.org

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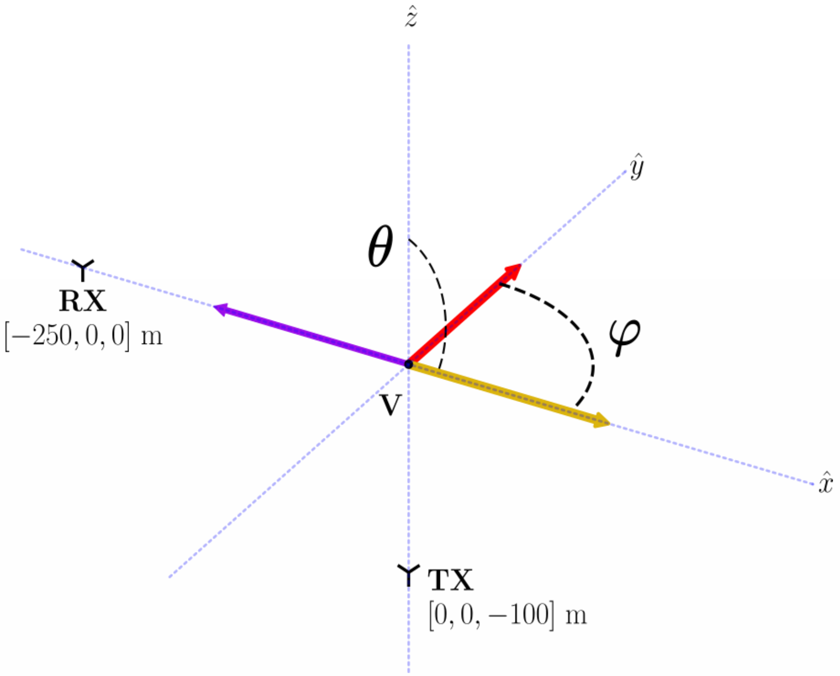
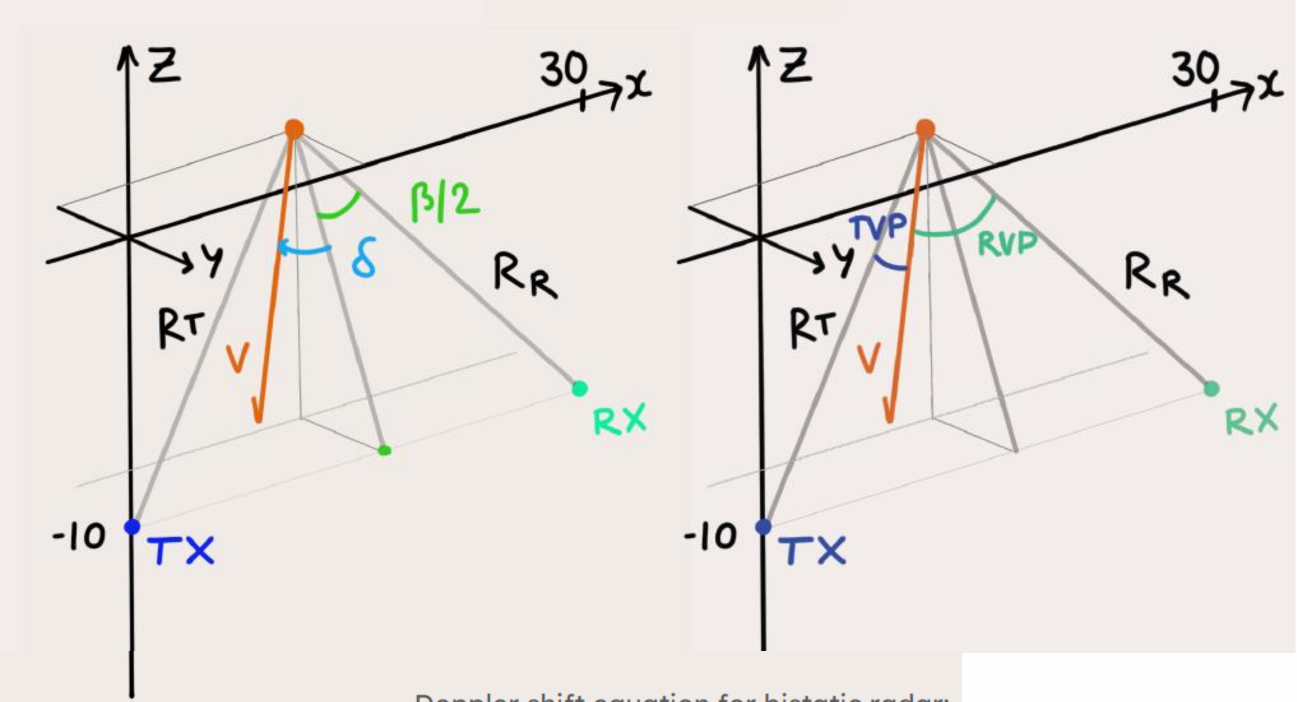
the RADAR ECHO TELESCOPE for COSMIC RAYS

MODELING AND UNDERSTANDING RADAR ECHOS FROM PARTICLE CASCADES

COORDINATES





Doppler shift equation for bistatic radar:

- Bistatic angle β
- Aspect angle δ

→ $$f_d = \frac{2V}{\lambda}\cos(\beta/2)\cos(\delta)$$

N.J. Willis, Bistatic Radar (2005)

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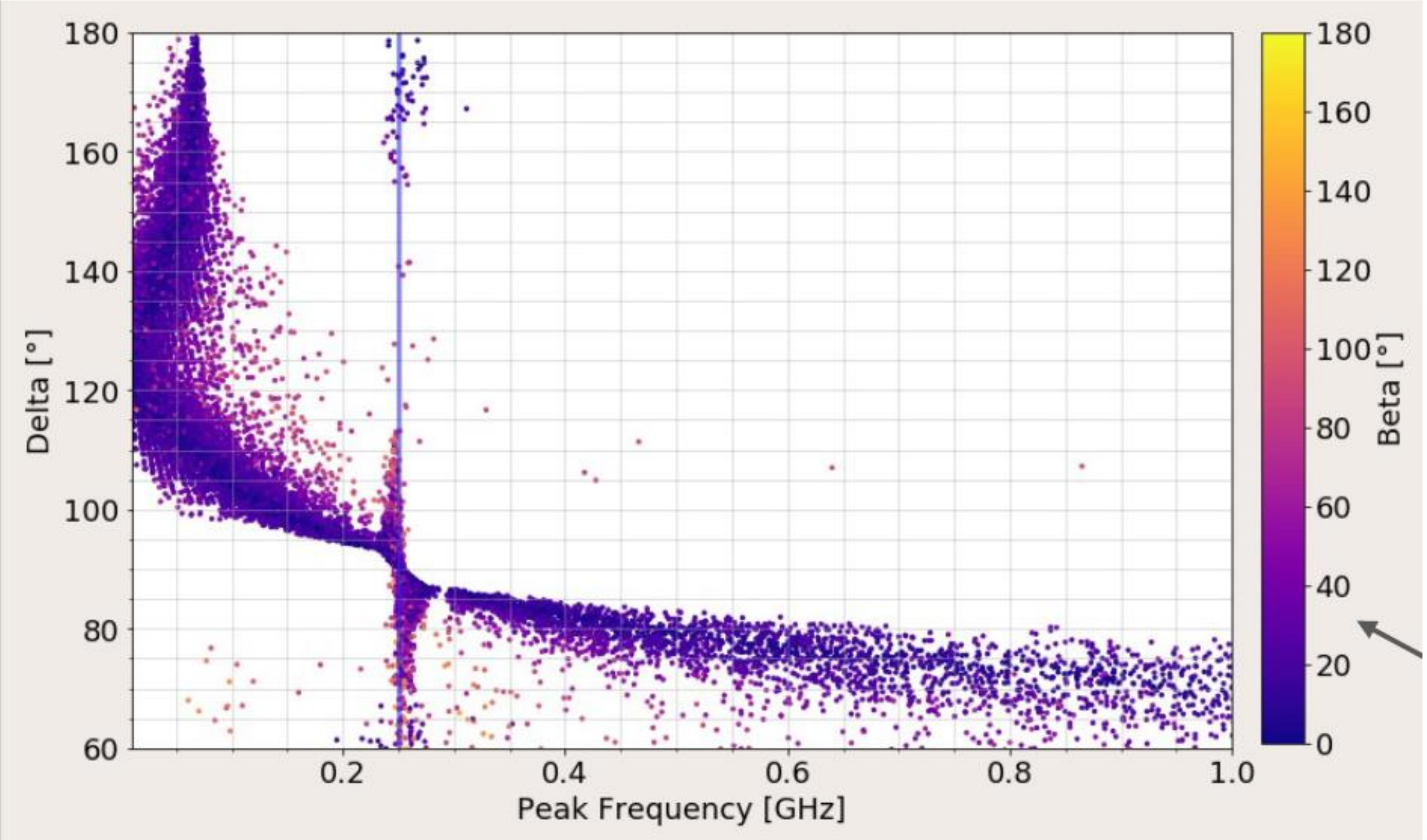

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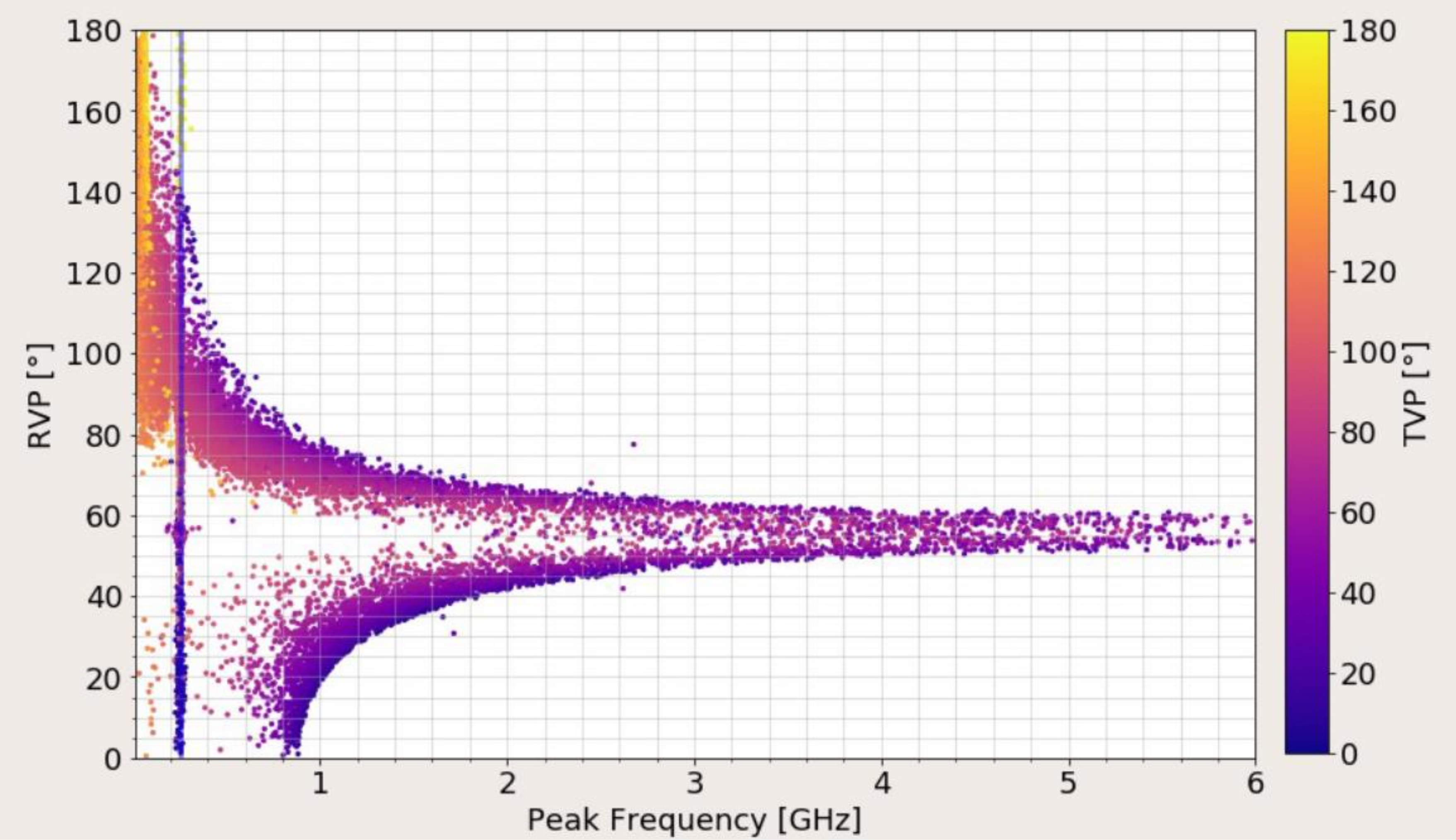

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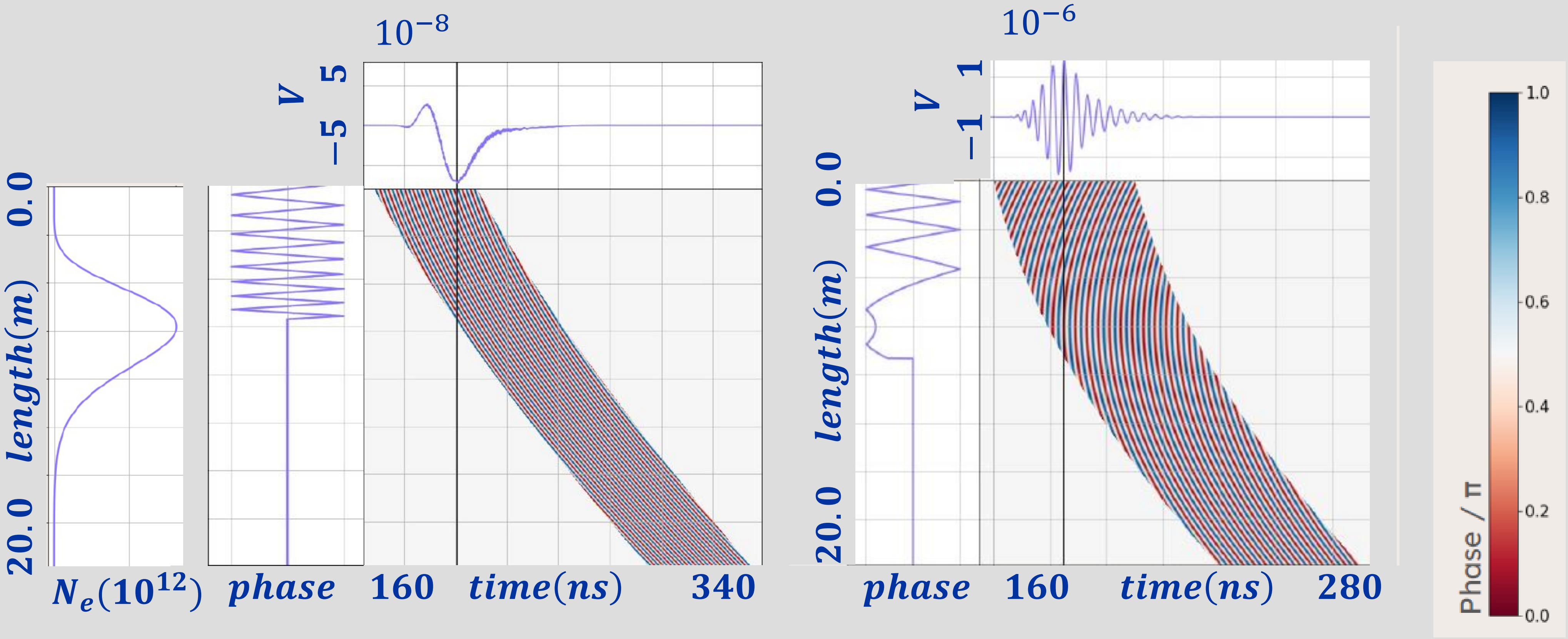
MODELING AND UNDERSTANDING RADAR ECHOS FROM PARTICLE CASCADES

SIGNAL PROPERTIES: PHASE ALIGNMENT



Phase coherence determines pulse strength

Dealignment away from high-intensity swirl

Alignment at high-intensity swirl

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