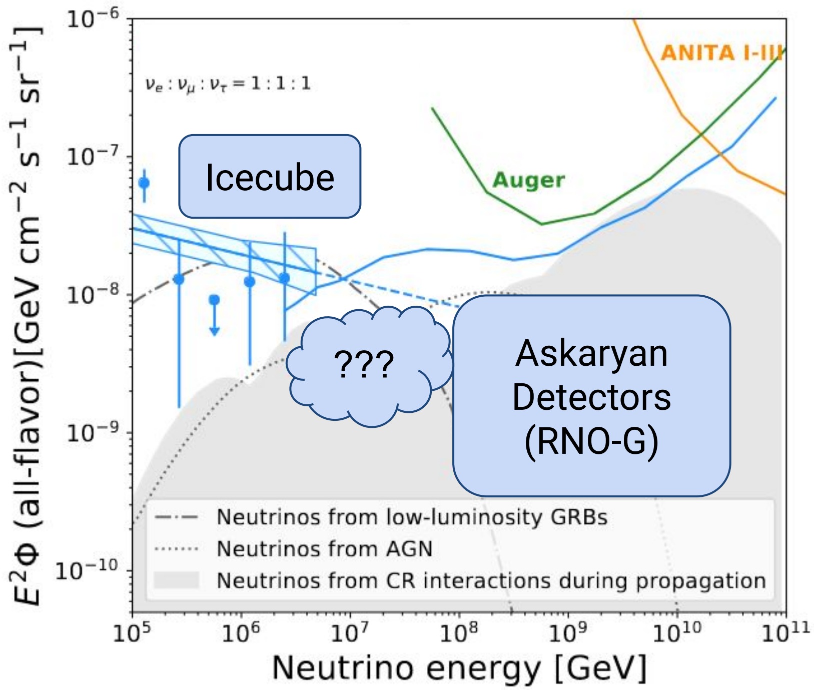
# RADAR ECHO TELESCOPE

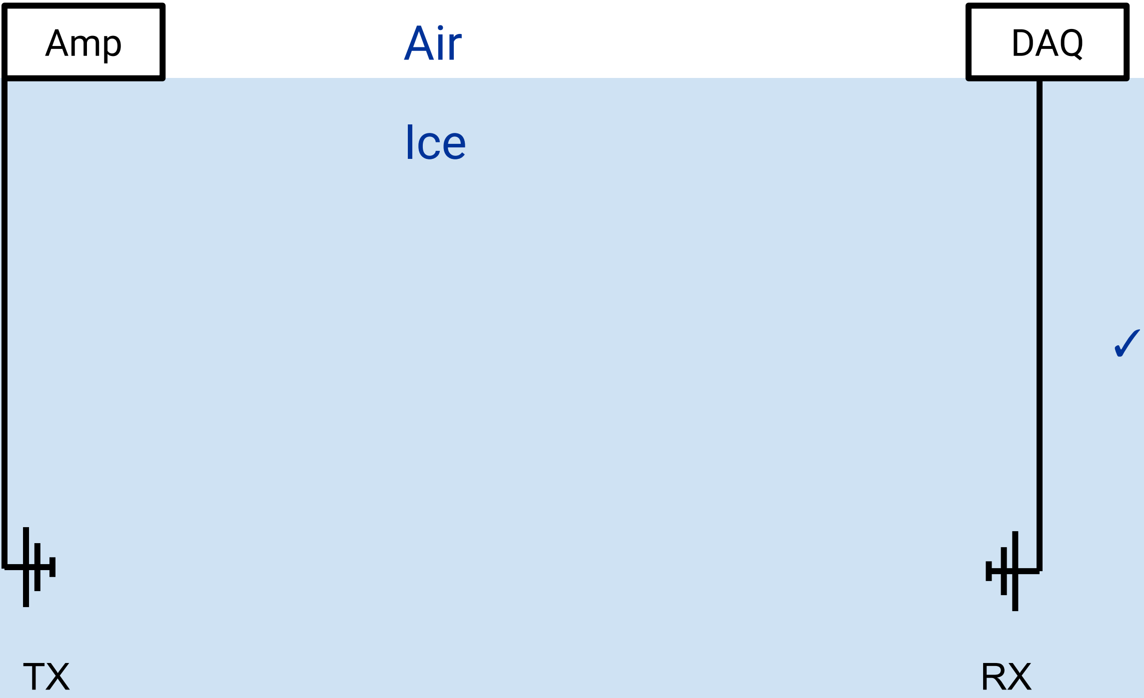
Enrique Huesca Santiago
on behalf of the RET Collaboration

**Probing the >10 PeV cosmic neutrino flux with the radar echo telescope for neutrinos**




- IceCube’s measured flux reaches up to 10 PeV, while Askaryan detectors become effective at 100 PeV.
- We need a different method to bridge the gap between the two detection systems.

# The Radar Echo Technique




✓ Instrument a large volume of ice with a radar system.

Credit: Rose Stanley

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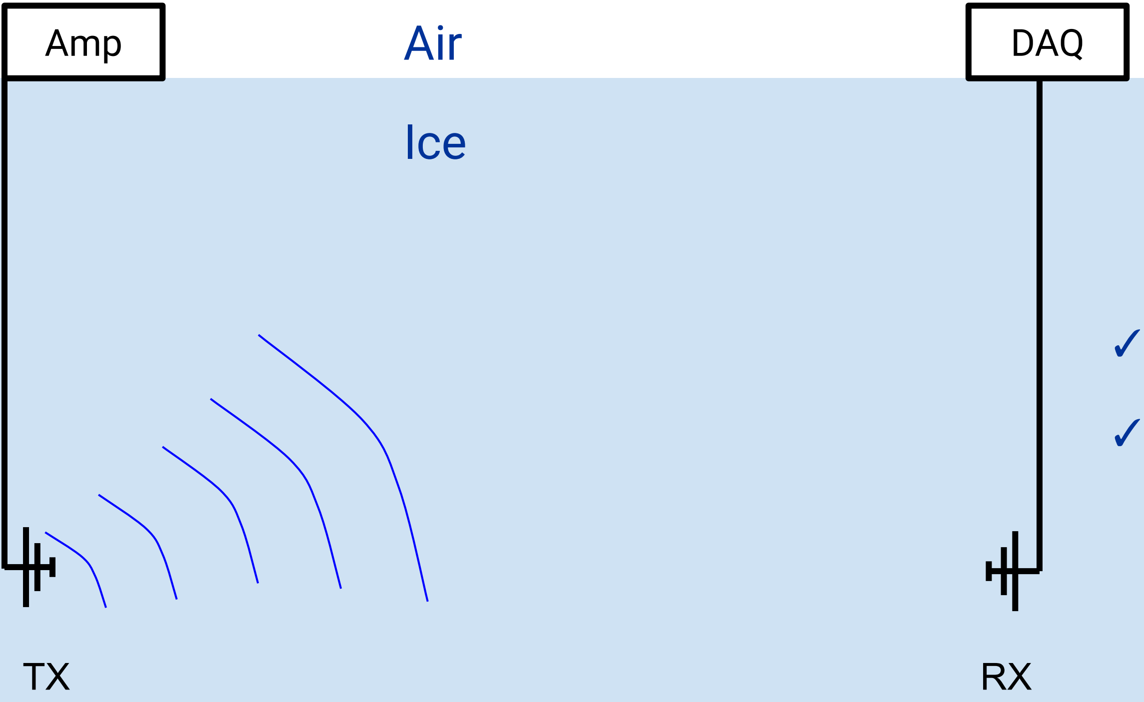
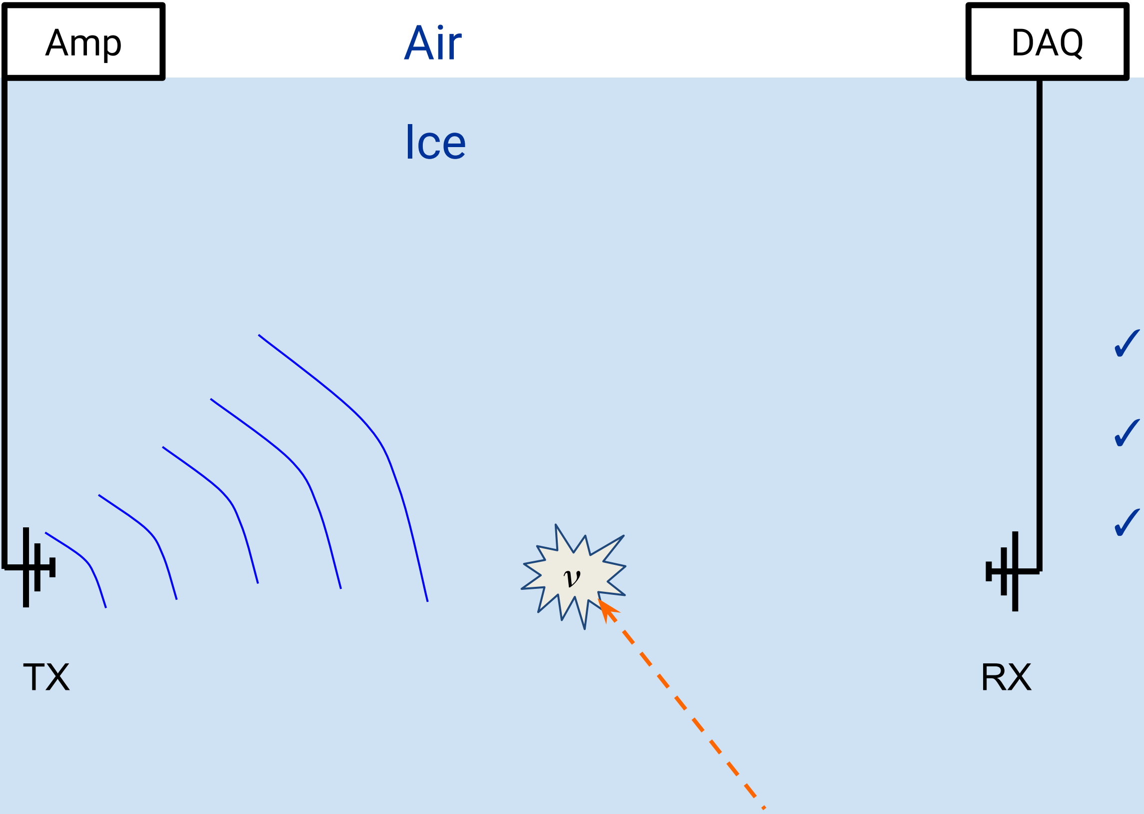



- ✓ Instrument a large volume of ice with a radar system.
- ✓ A radio transmitter (TX) constantly illuminates the ice.

Credit: Rose Stanley

# The Radar Echo Technique




- ✓ Instrument a large volume of ice with a radar system.
- ✓ A radio transmitter (TX) constantly illuminates the ice.
- ✓ A neutrino ($\nu$) interacts in the monitored volume

Credit: Rose Stanley

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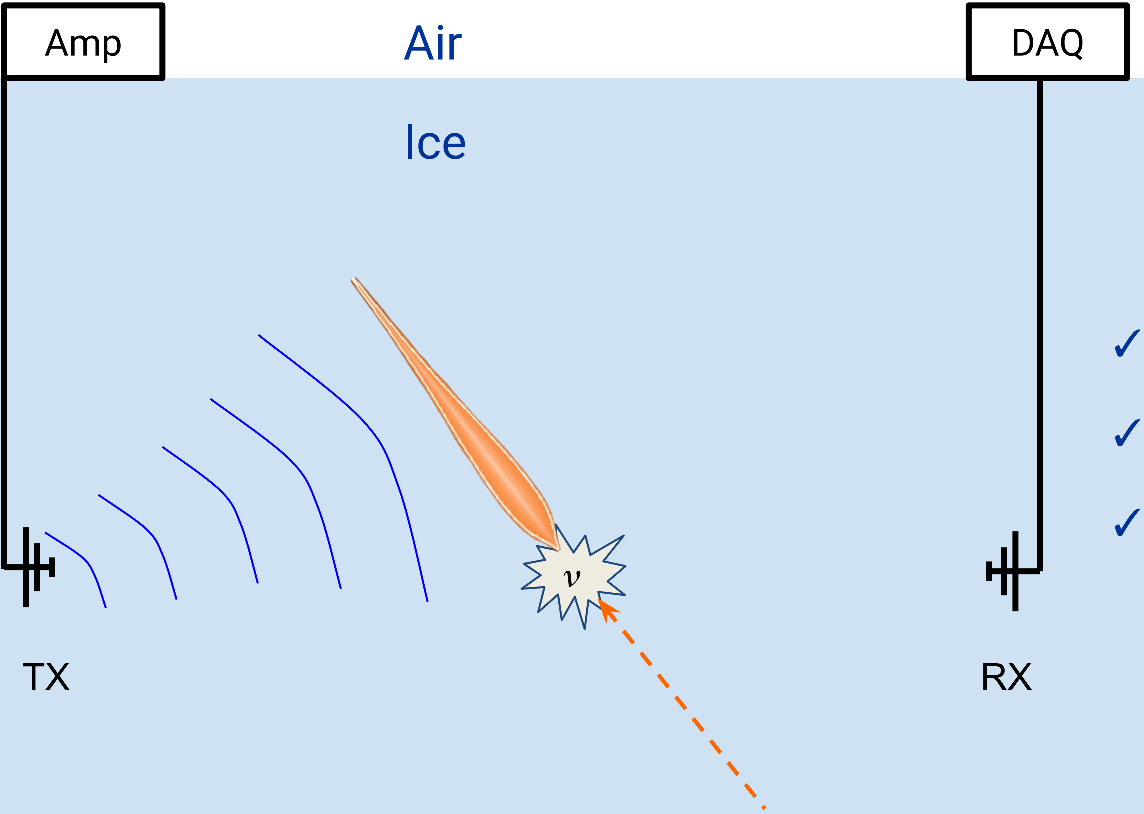


- ✓ Instrument a large volume of ice with a radar system.
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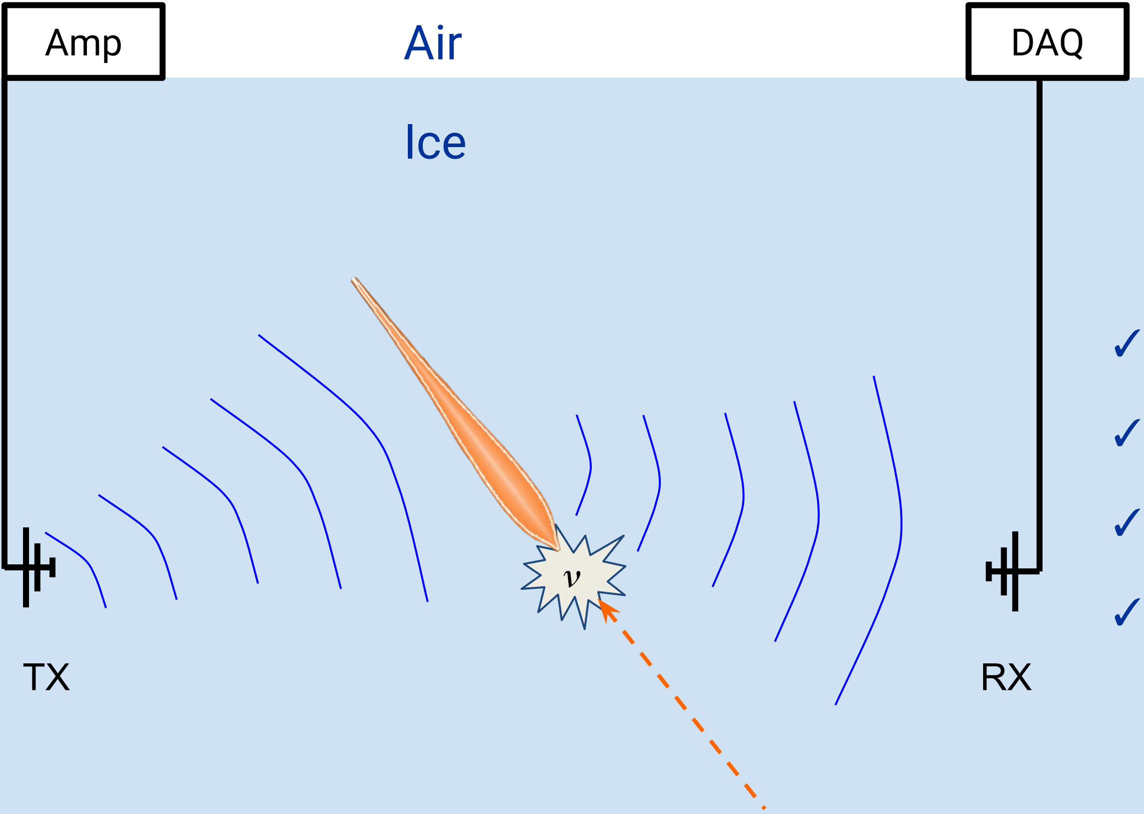


- ✓ Instrument a large volume of ice with a radar system.
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- ✓ The ionization trail will produce a **radar echo**

Credit: Rose Stanley

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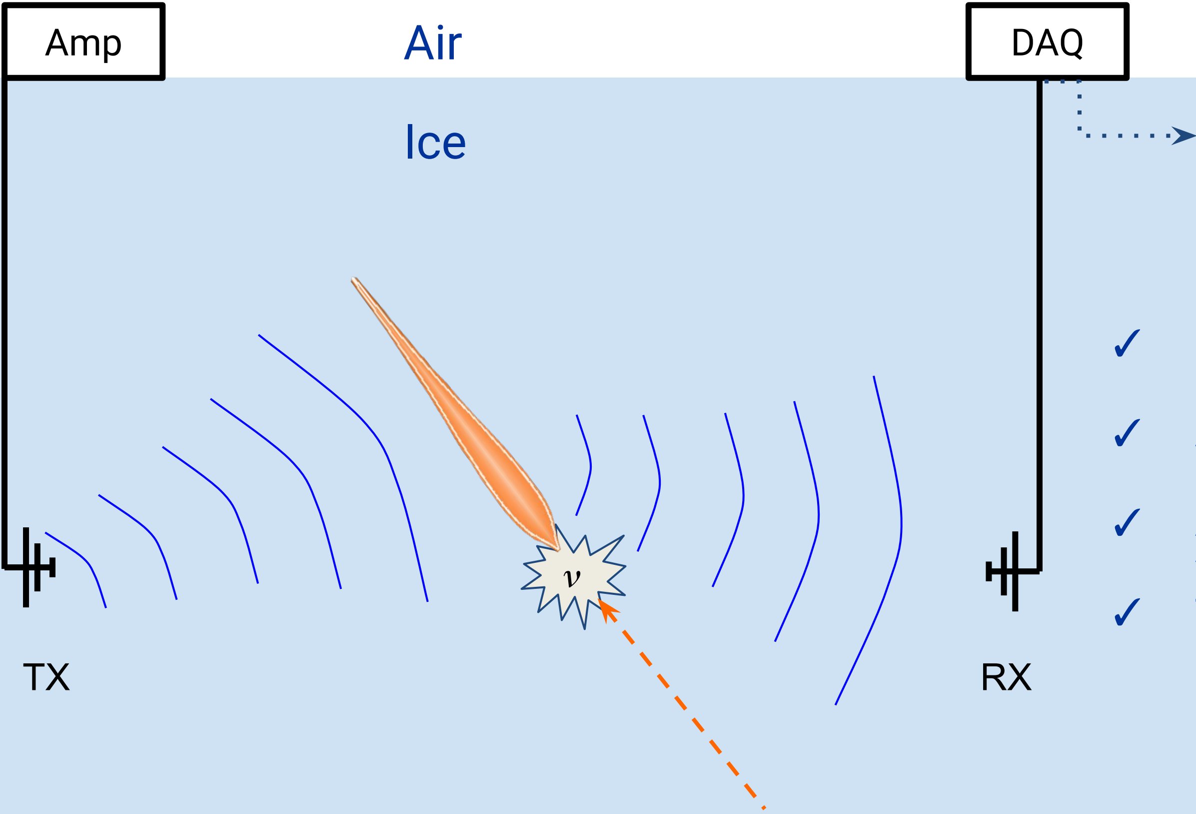
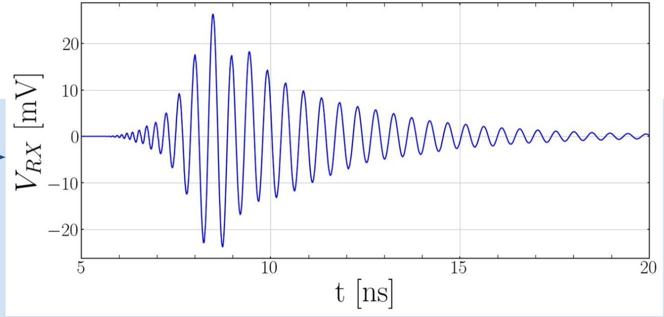



- ✓ Instrument a large volume of ice with a radar system.
- ✓ A radio transmitter (TX) constantly illuminates the ice.
- ✓ A neutrino ($\nu$) interacts in the monitored volume, leaving an ionization trail.
- ✓ The ionization trail will produce a **radar echo,** which is recorded by the receivers (RX).

Credit: Rose Stanley

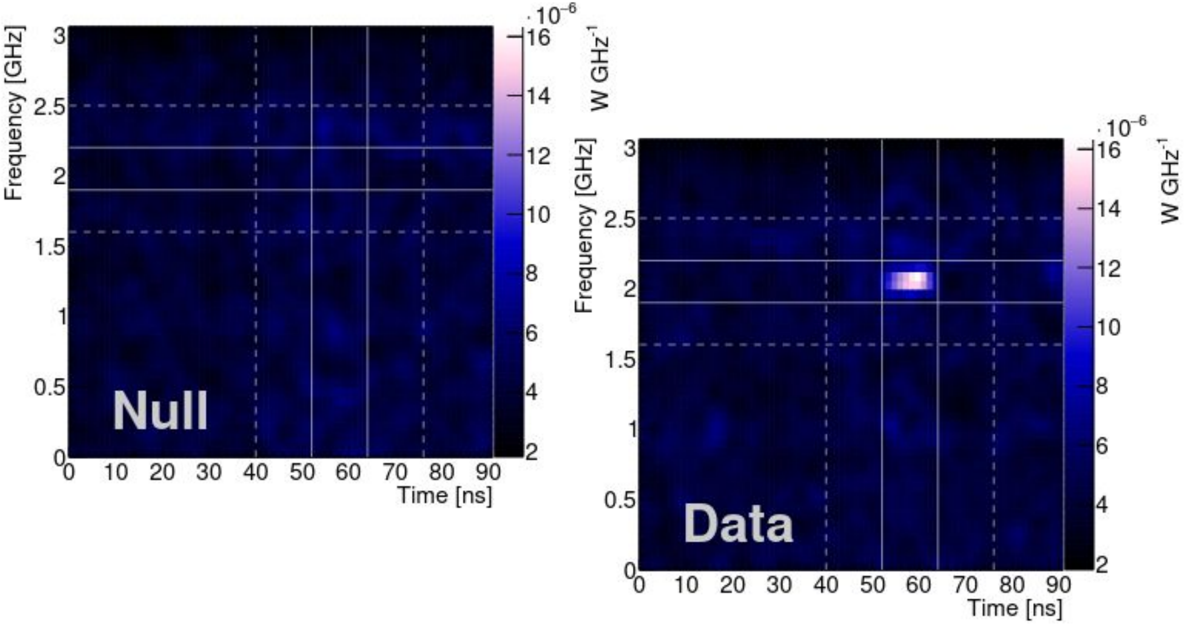
# Radar echoes have been confirmed in the lab!

## T576 experiments @ SLAC (2018 - 2019)


PHYSICAL REVIEW LETTERS **124**, 091101 (2020)

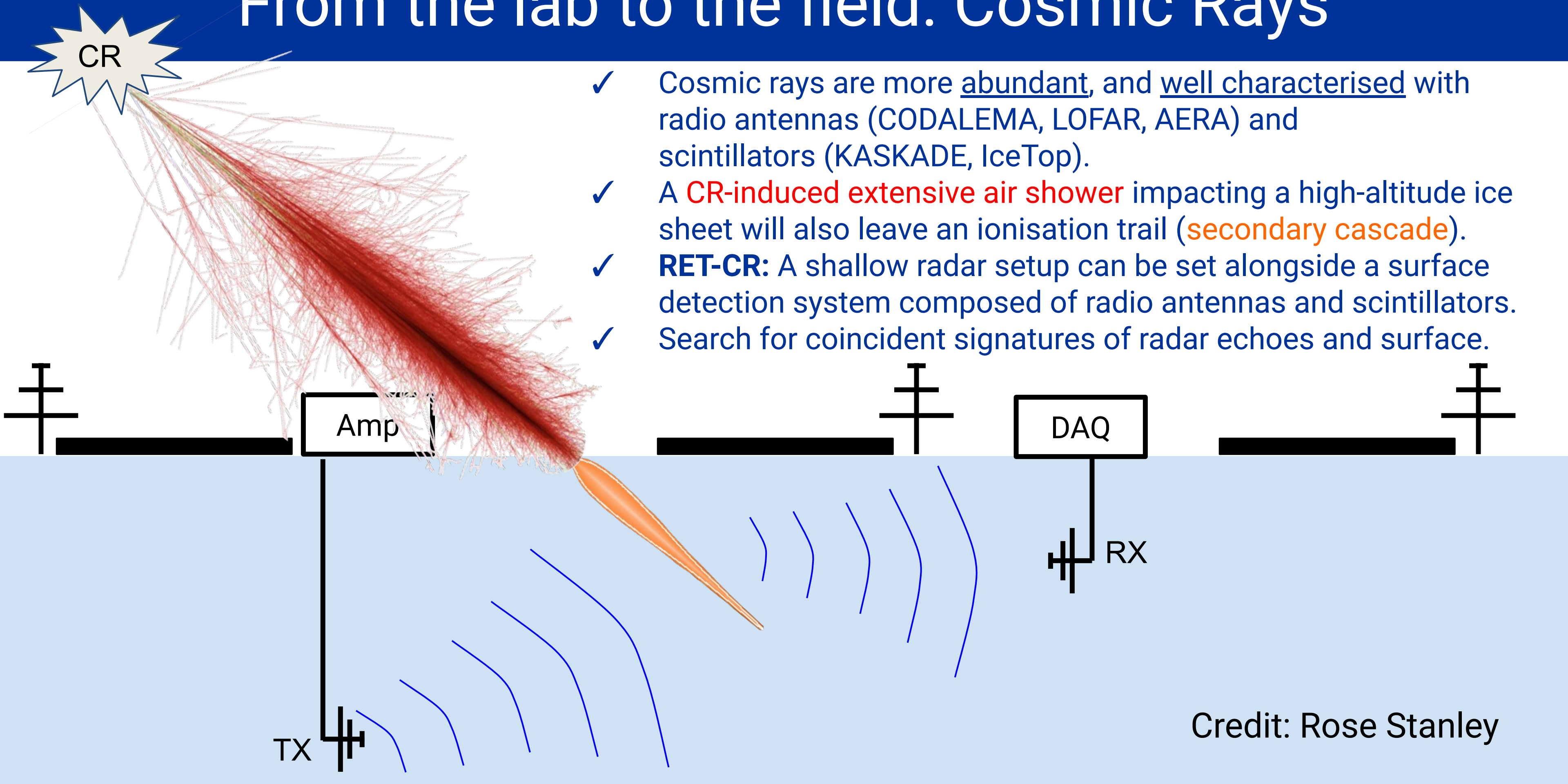
**Observation of Radar Echoes from High-Energy Particle Cascades**

S. Prohira,[1,*] K. D. de Vries,[2] P. Allison,[1] J. Beatty,[1] D. Besson,[3,4] A. Connolly,[1] N. van Eijndhoven,[2] C. Hast,[5] C.-Y. Kuo,[6] U. A. Latif,[3] T. Meures,[7] J. Nam,[6] A. Nozdrina,[3] J. P. Ralston,[3] Z. Riesen,[8] C. Sbrocco,[1] J. Torres,[1] and S. Wissel[8]



# From the lab to the field: Cosmic Rays

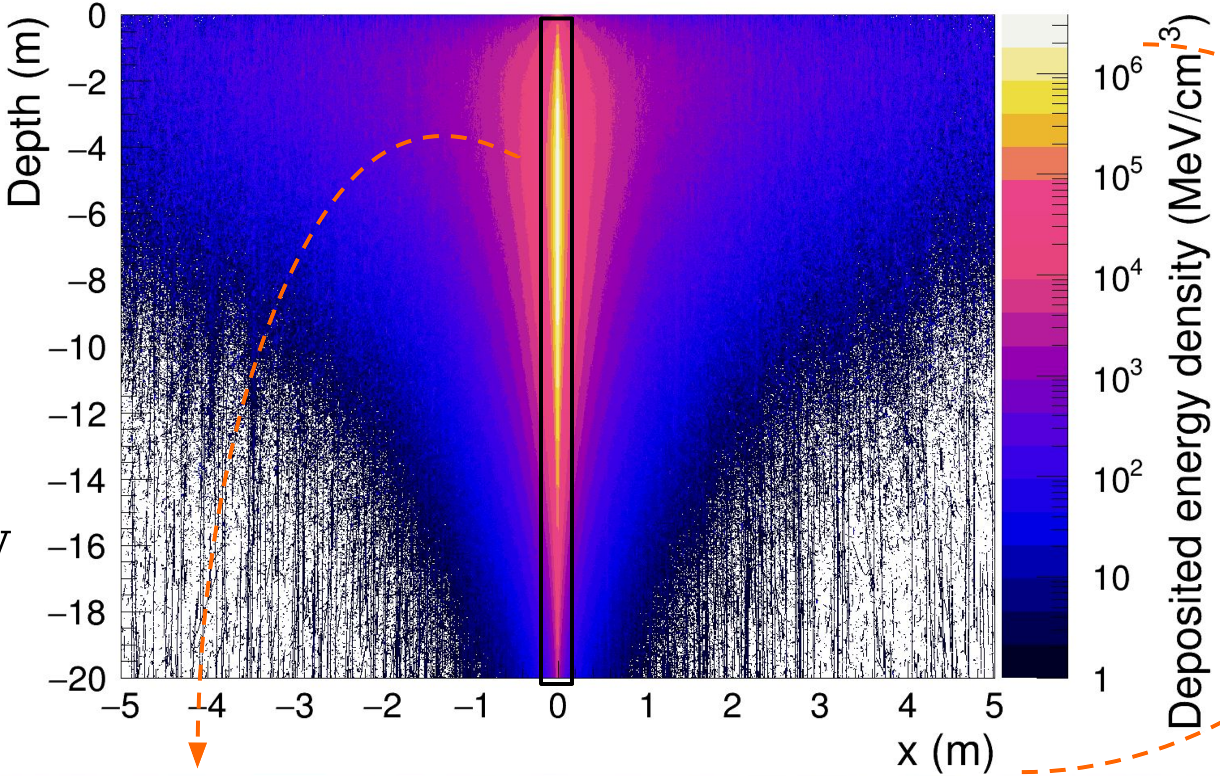
- ✓ Cosmic rays are more abundant, and well characterised with radio antennas (CODALEMA, LOFAR, AERA) and scintillators (KASKADE, IceTop).
- ✓ A CR-induced extensive air shower impacting a high-altitude ice sheet will also leave an ionisation trail (secondary cascade).
- ✓ **RET-CR:** A shallow radar setup can be set alongside a surface detection system composed of radio antennas and scintillators.
- ✓ Search for coincident signatures of radar echoes and surface.




Credit: Rose Stanley

# IIHE modelling efforts towards RET-CR

Credit: Simon de Kockere



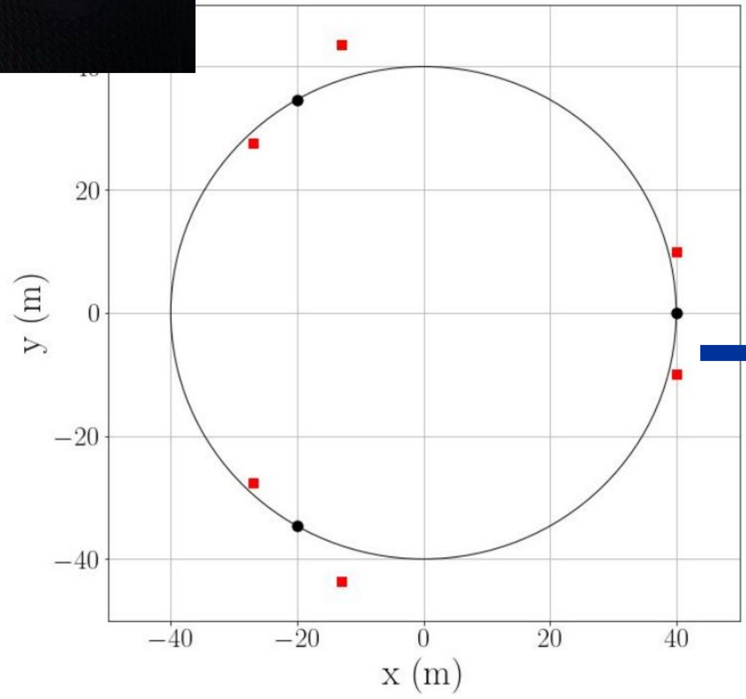

$$E_p = 0.1 \text{ EeV} = 10^8 \text{ GeV} = 10^{17} \text{ eV}$$

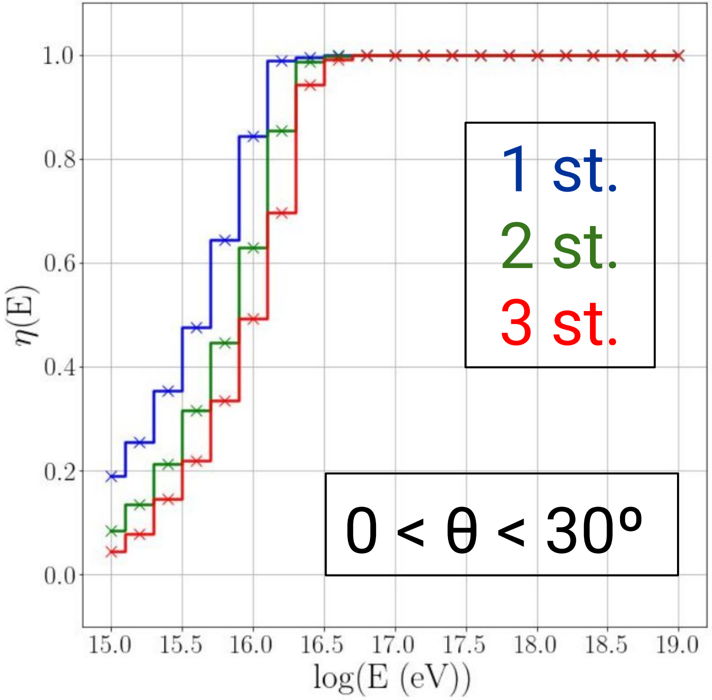
$$\frac{10^6 \frac{MeV}{cm^3}}{20 \frac{eV}{e^-}} = = 10^{11} \frac{e^-}{cm^3}$$

# IIHE modelling efforts towards RET-CR

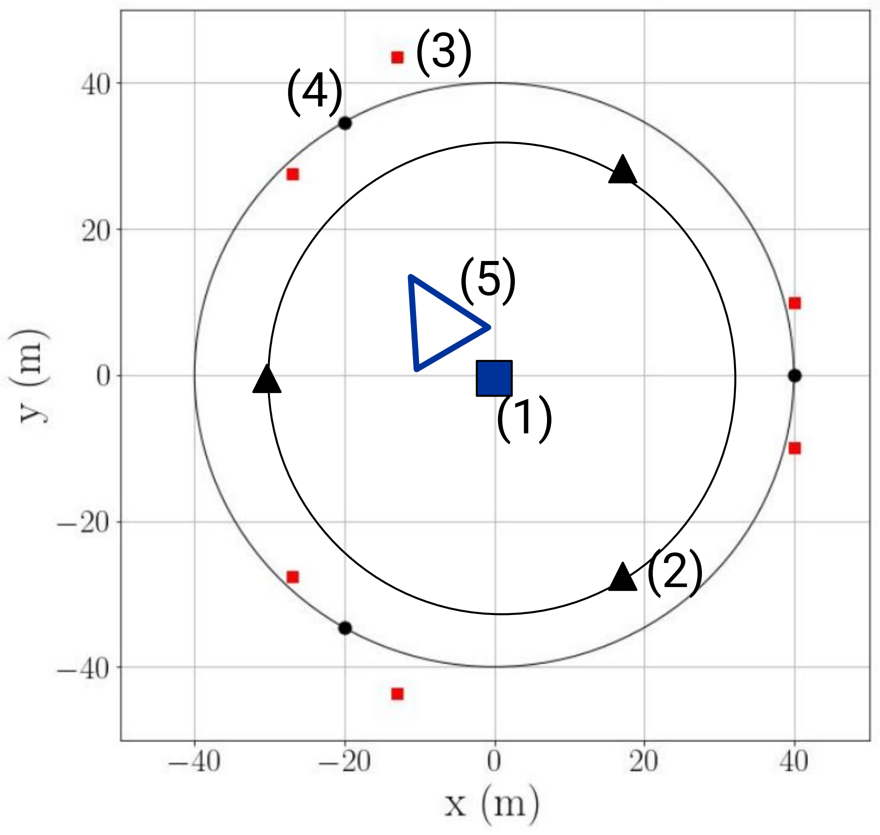
Rose Stanley:

Sensitivity studies on the surface component of RET-CR.



# Final RET-CR design




1) Central station:
   TX (phased array) and DAQ

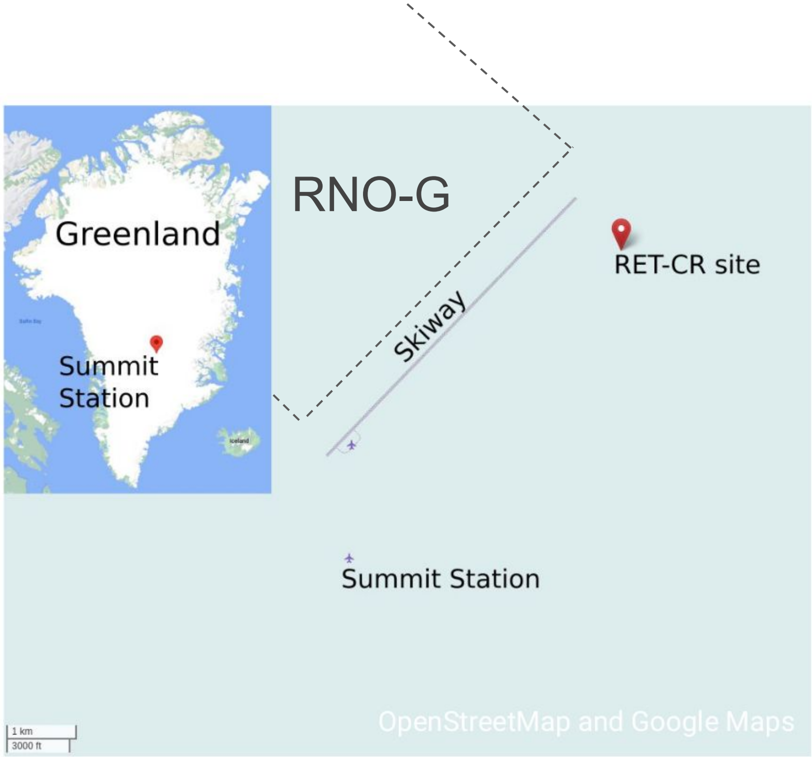
2) In-ice radio antenna

3) IceTop scintillators

4) Surface Radio Antennas:
   SKALA's LPDA +
   CODALEMA's DAQ

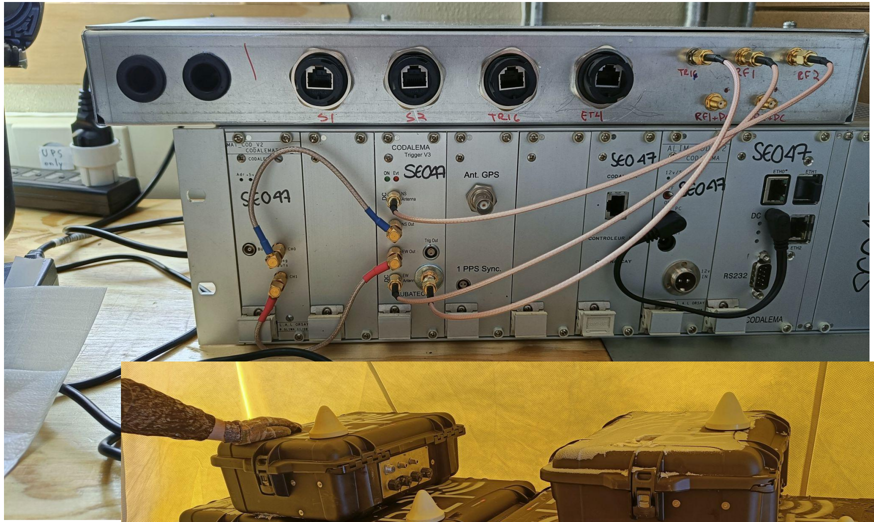
5) Solar array and batteries

# RET-CR Greenland deployment (May 2023)

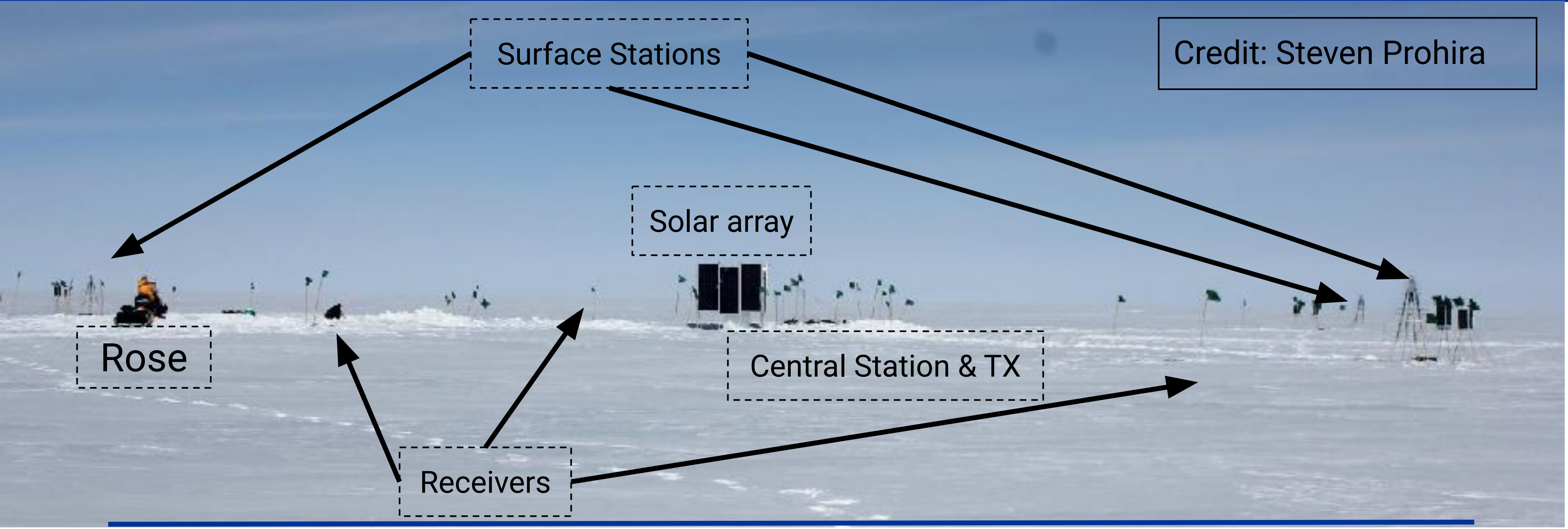



# RET-CR Greenland deployment (May 2023)

# IIHE experimental efforts towards RET-CR

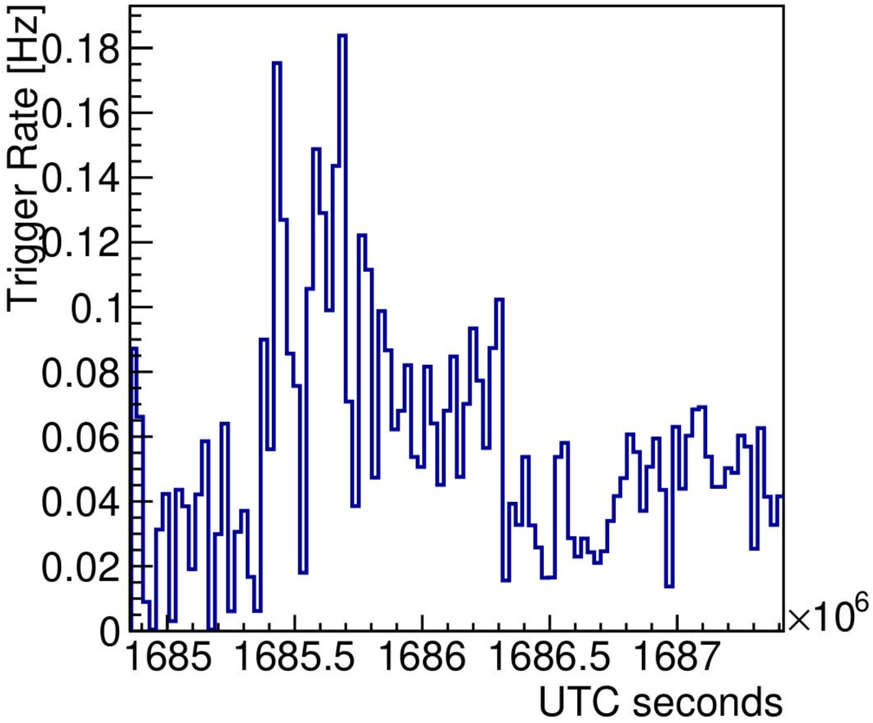


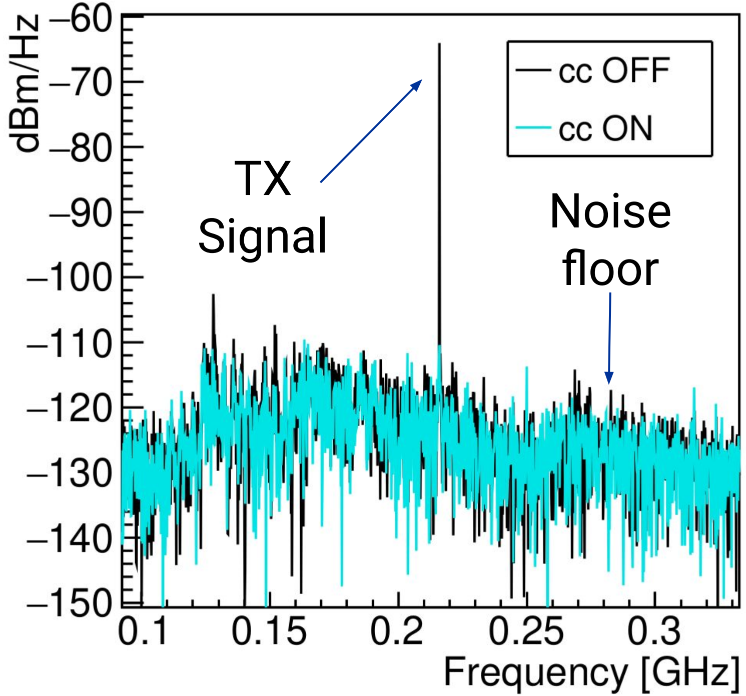

# RET-CR in Greenland



# RET-CR Performance

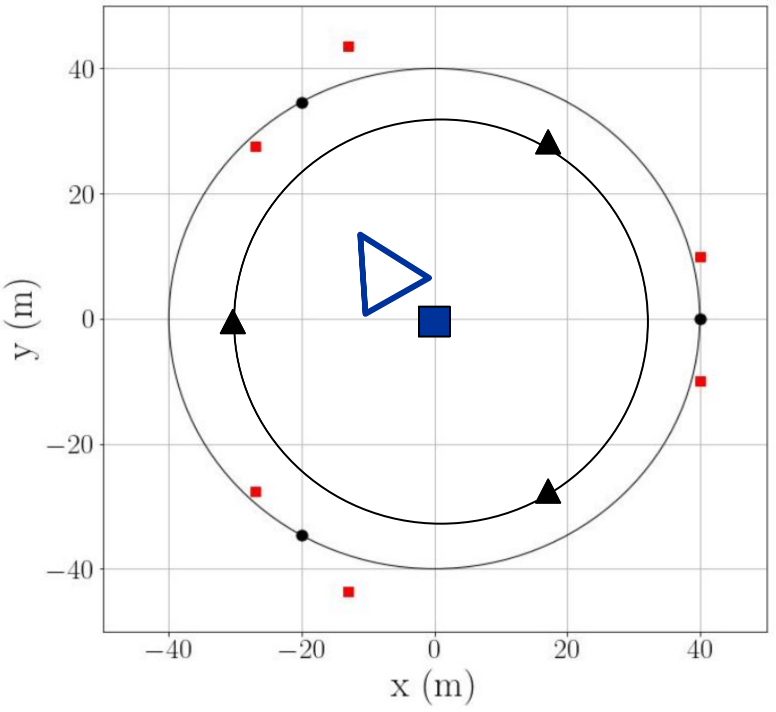
This is the first publicly released data (ICRC 2023) about the deployed system.



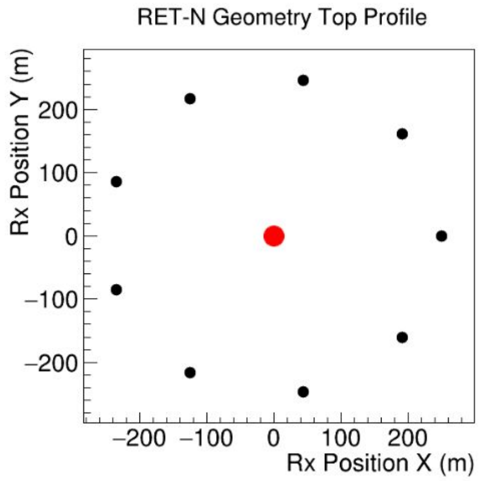



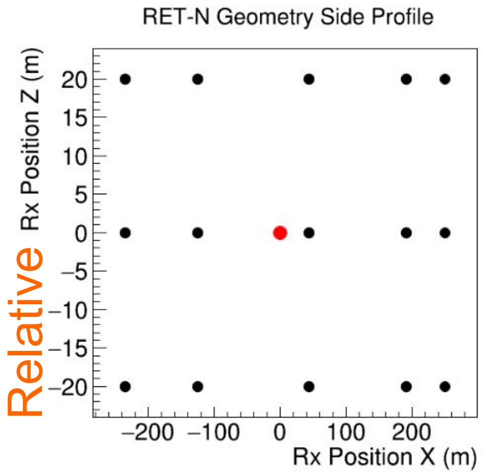
# From RET-CR to RET-N

## RET - CR




## (PRELIMINARY) RET - N



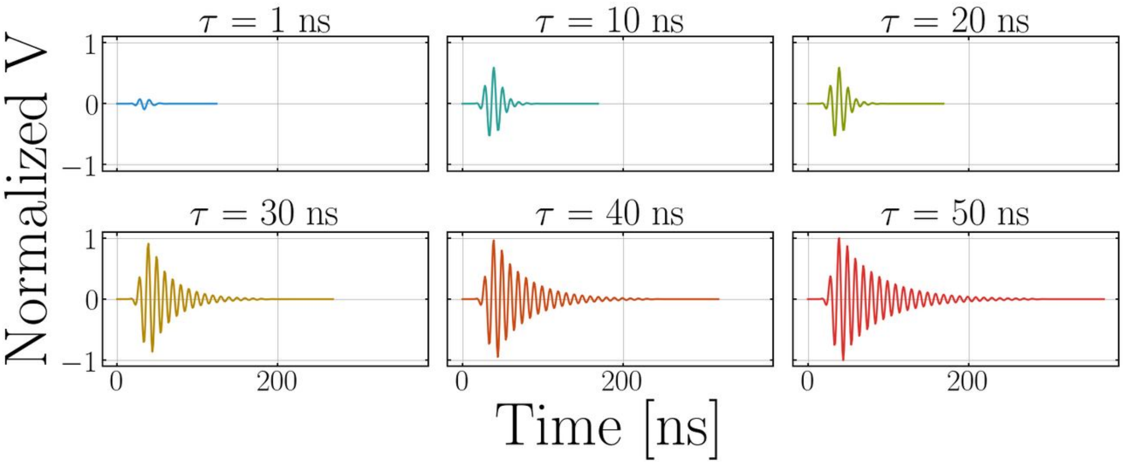



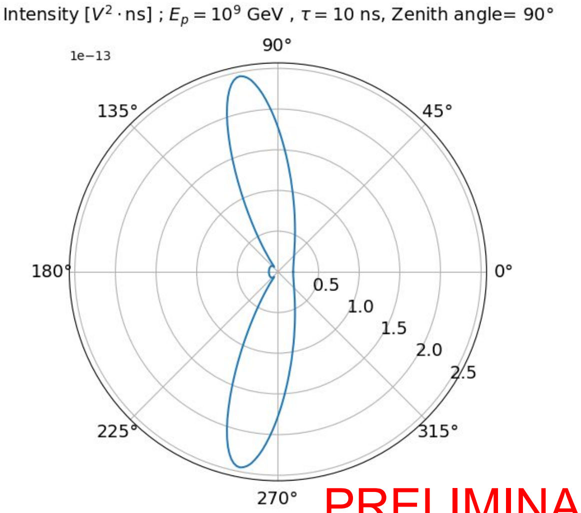

RET-N stations will be deeper than RET-CR, $O$(1 km) vs $O$(10 m); and much more sparse.

# How can we simulate the radar scatter?

## MARES: A Macroscopic Approach to the Radar Echo Scatter

https://arxiv.org/abs/2310.06731



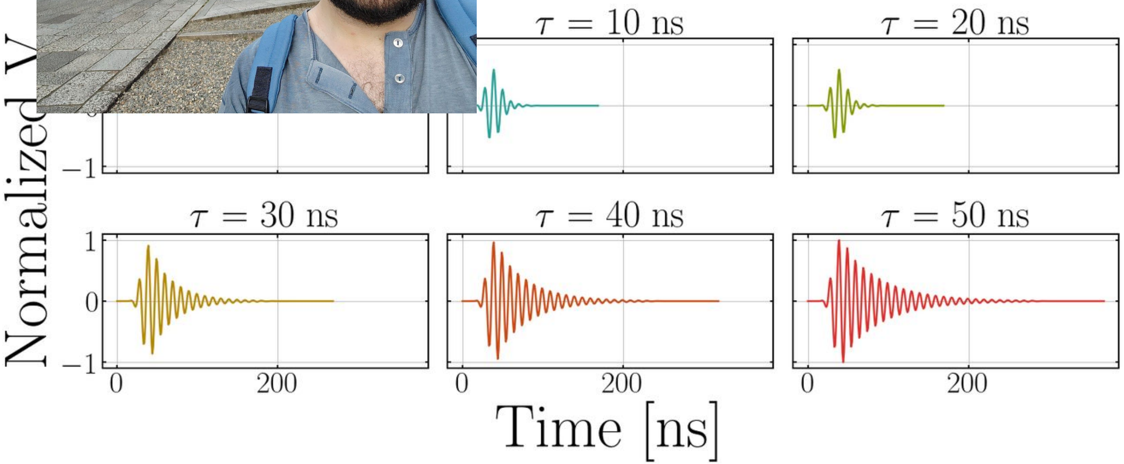

PRELIMINARY

# How can we simulate the radar scatter?

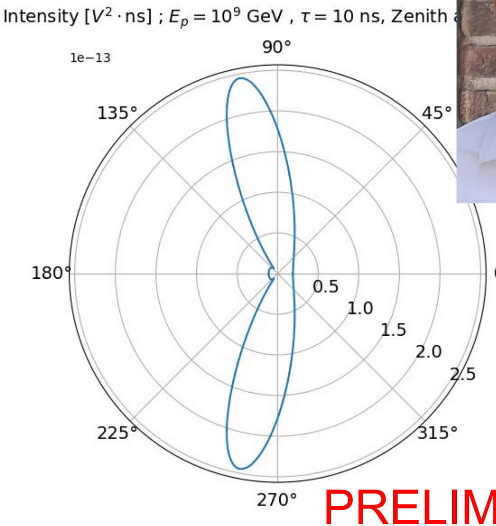
## MARES: A Macroscopic Approach to the Radar Echo Scatter

://arxiv.org/abs/2310.06731

(Me)



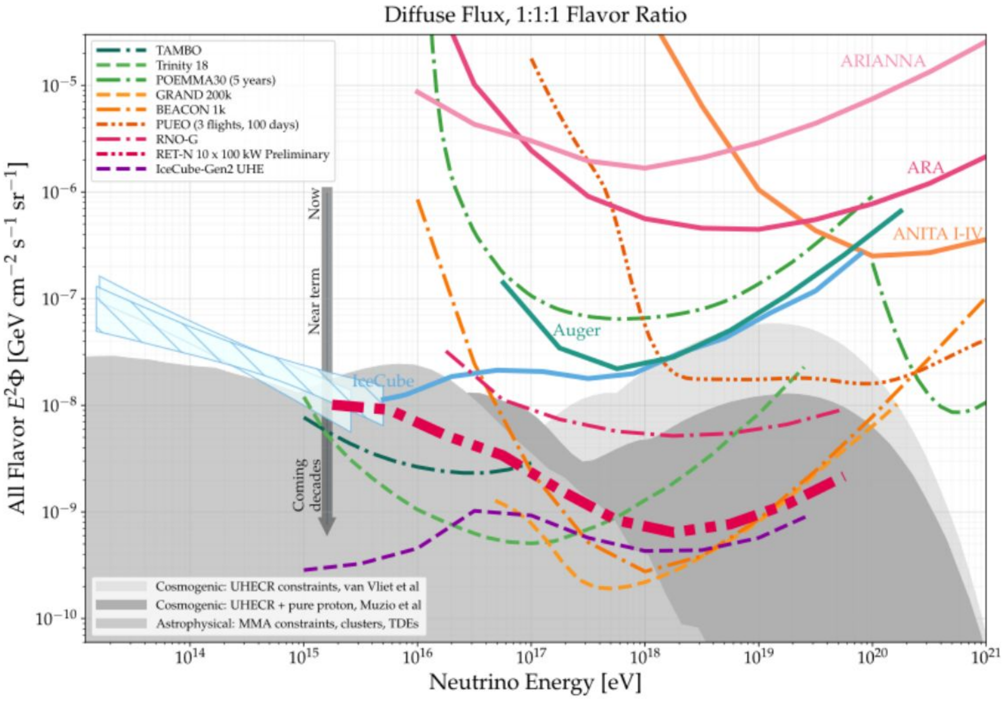

Jannes Loonen




PRELIMINARY

# The Goal of the Radar Echo Telescope

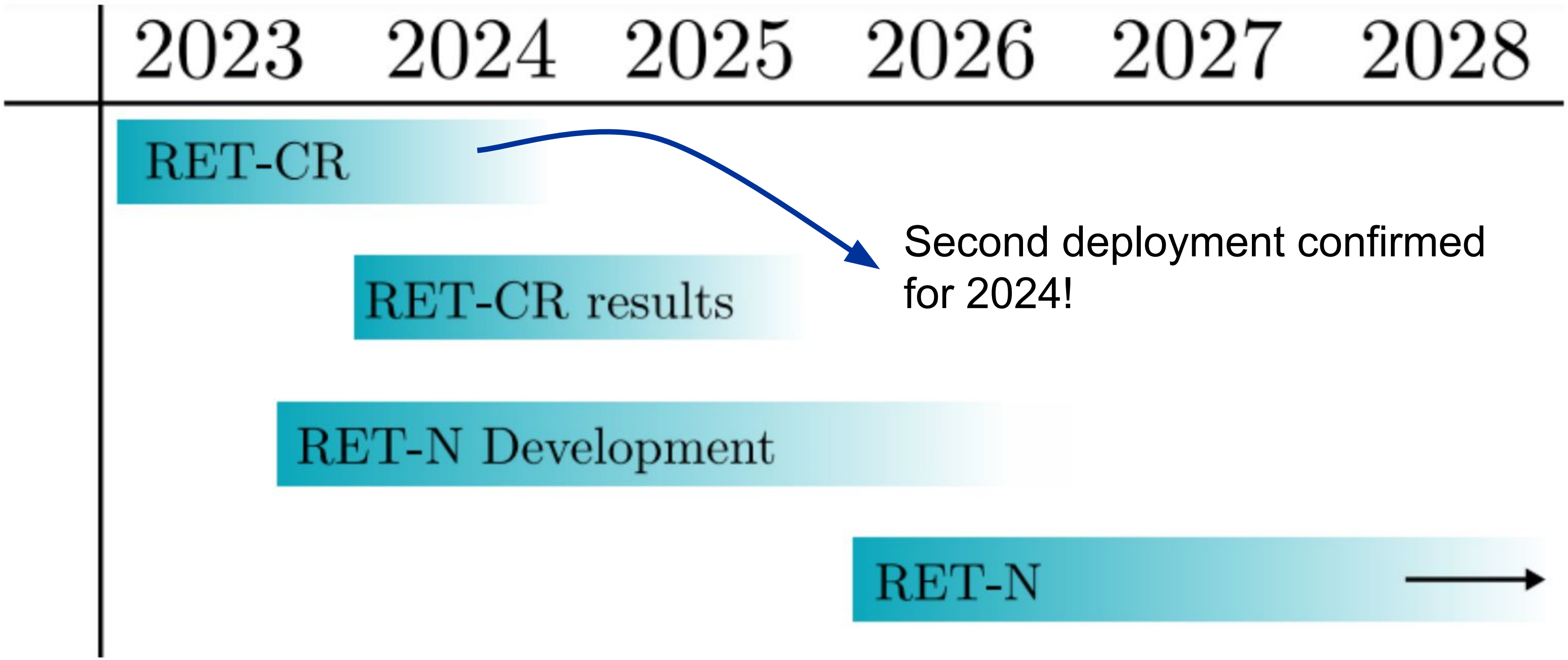
**Probing the >10 PeV cosmic neutrino flux with the radar echo telescope for neutrinos**




Adapted from "High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper" arXiv:2203.08096, RET-N curve highlighted in thickened dashed red line

- RET-N (red highlight) will have comparable sensitivity with other experiments.
- RET-N will have a broad energy range, therefore making it <u>complementary</u> with current and planned experiments.

# Outlook




Second deployment confirmed for 2024!

# RET @ IIHE

THANK YOU FOR LISTENING

# Let’s go have lunch!

# Extra slides

# Why MARES?

## MARES: A Macroscopic Approach to the Radar Echo Scatter

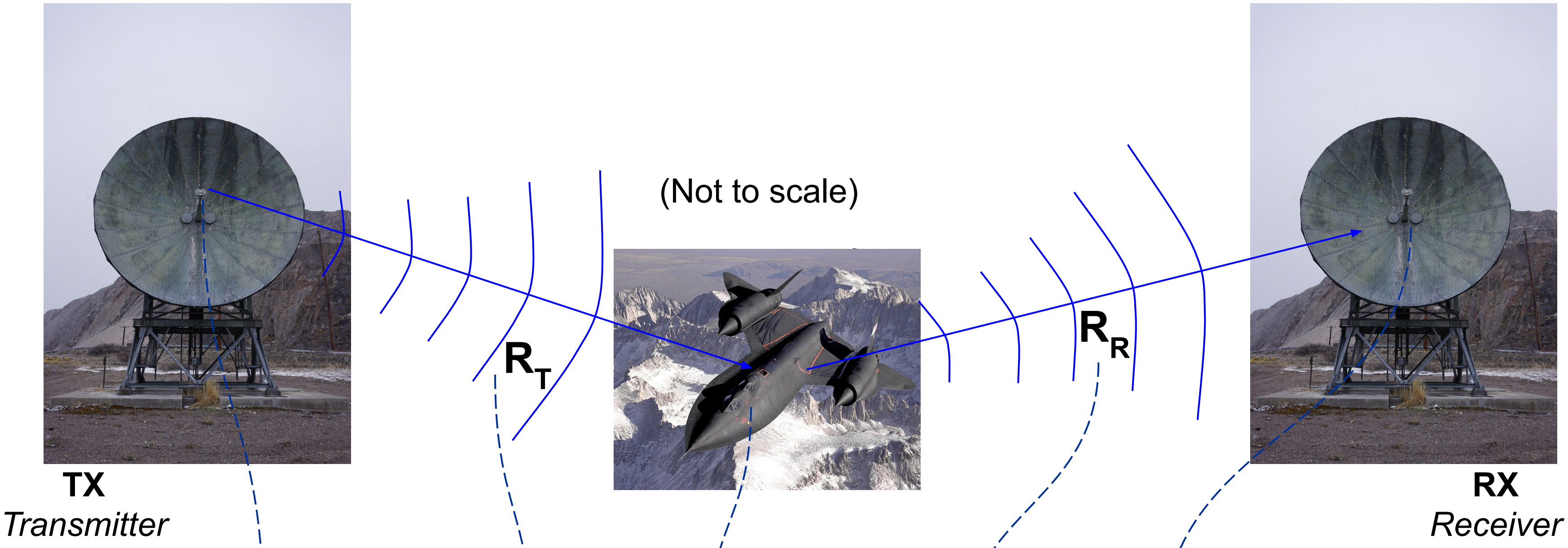
1. Are radar systems not well understood already?
   ↳ The particle cascade is a *relativistic, non-uniform, non-perfect conductor.*

2. Can you not simulate the event?
   ↳ Sure! Radioscatter (2017). (arXiv:1710.02883)
   ↳ Particle-level simulations are difficult: $\mathcal{O}(10^{13}\ e^{-})$ @ 1 PeV.

3. What else is there to gain?
   ↳ We want a complementary, deterministic approach to the existing method.
   ↳ A deeper understanding of the radar scatter features from the global cascade properties ⟶ Event reconstruction.

# Key concept 1:
# Radar cross section

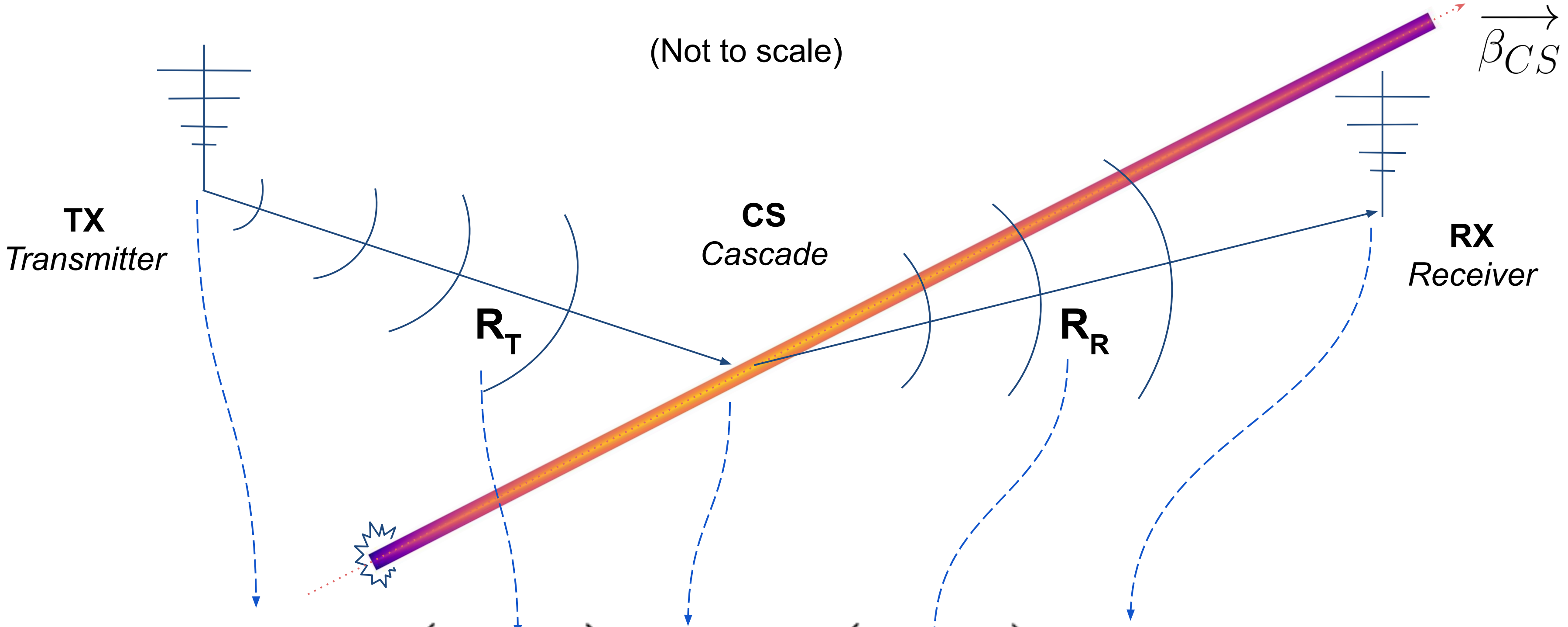
# How does radar work?




$$P_R = P_T \left( \frac{G_T}{4\pi R_T^2} \right) \sigma_{RCS} \left( \frac{1}{4\pi R_R^2} \right) A_{eff,R} [f_{att} \ldots]$$

# Key concept 2:
# Collisional electron plasma

# The radar scatter

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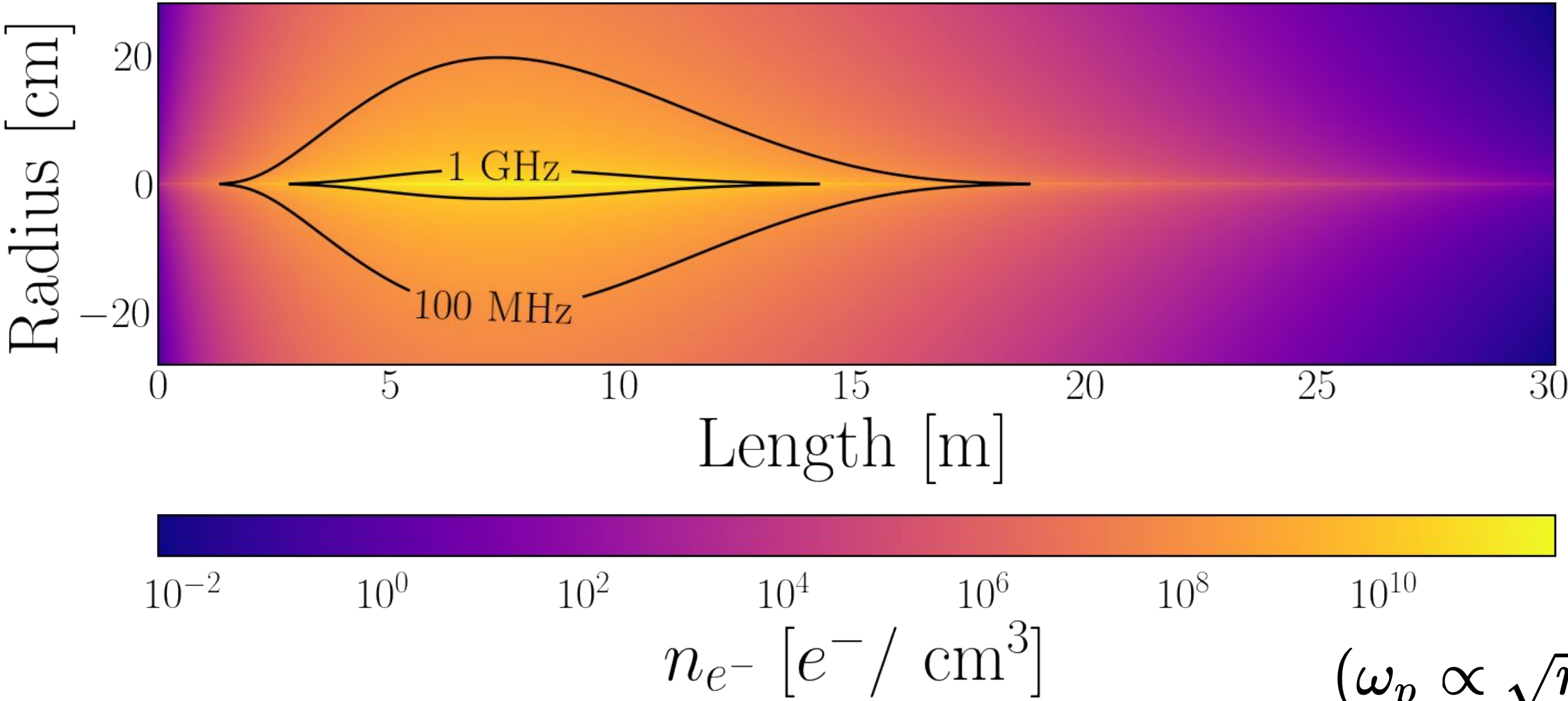
# How can we describe the cascade's core?

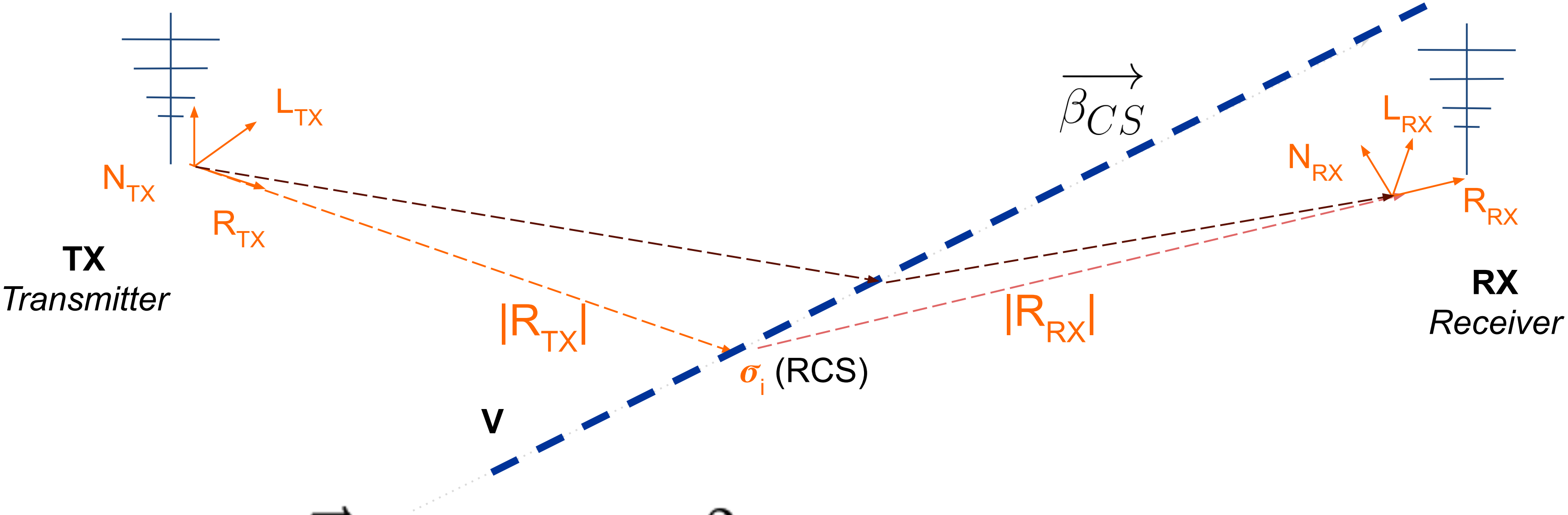



$(\omega_p \propto \sqrt{n_e})$

Nishimura, Kamata & Greisen: Air showers (Progr. Theoret. Phys. 6, 93 (1958) & Prog. Cosmic Ray Phys., vol. III (1965) )
K. Werner, K. de Vries, O. Scholten: In-ice neutrino cascade (arxiv:1312.4331)
Simon de Kockere, *et al.* : Air shower cores from CR that propagate through ice (arXiv:2202.09211)

# MARES:
# The macroscopic scatter model

# The line approximation




$$P_{RX} \propto |\vec{E}_{RX}(R,t)|^2 =$$

$$|\sum_{i=1}^{N} E_{sc,i}(R_i,t) * e^{i(kR_i - \omega t|_{RX} + \psi_i)}|^2$$

# The radar cross section

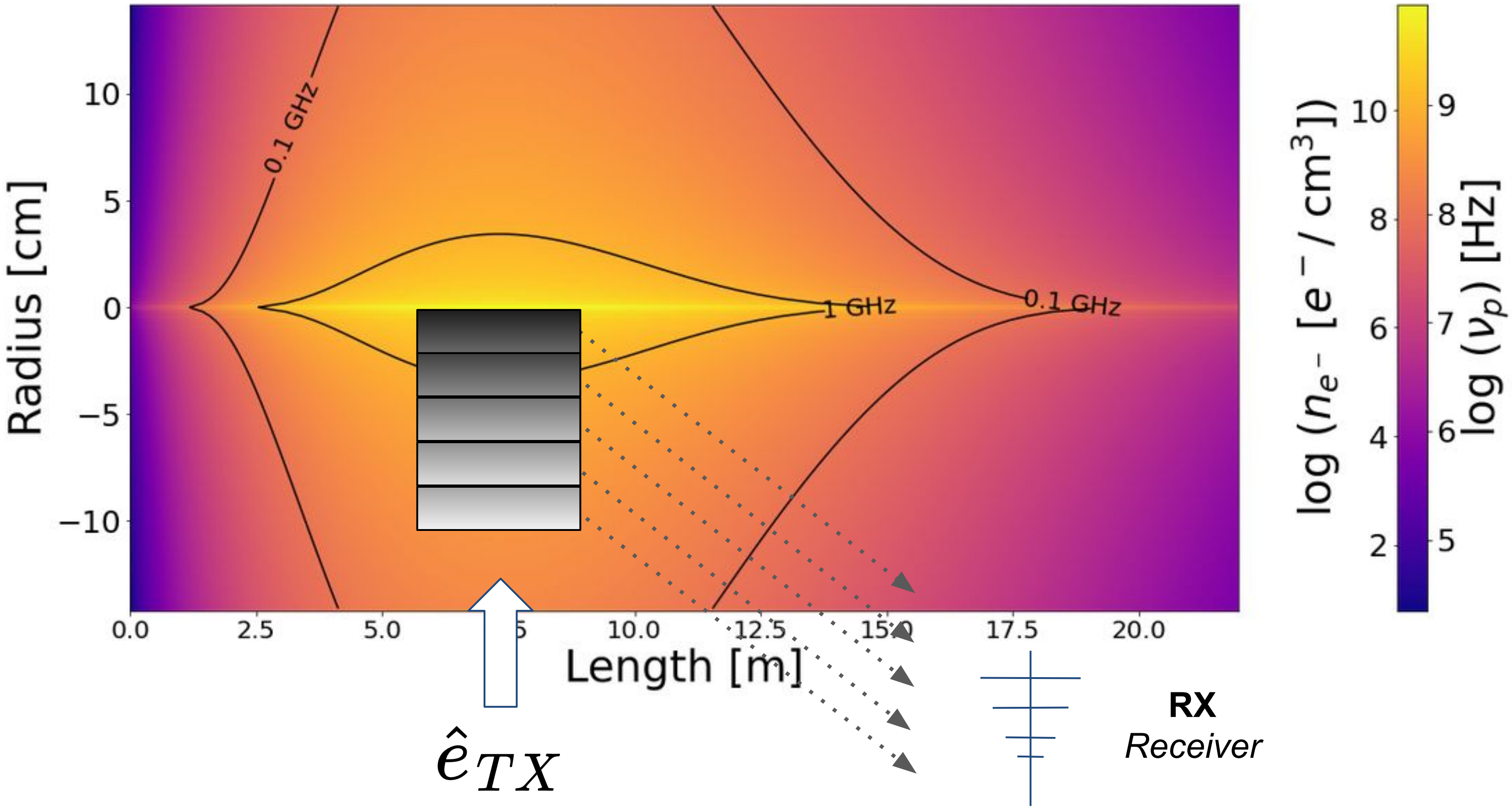
$$E_{sc,i} = \frac{\sqrt{2ZP_T G_T}}{4\pi R_{T,i} R_{R,i}} \sqrt{\sigma_{RCS,i}}$$

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

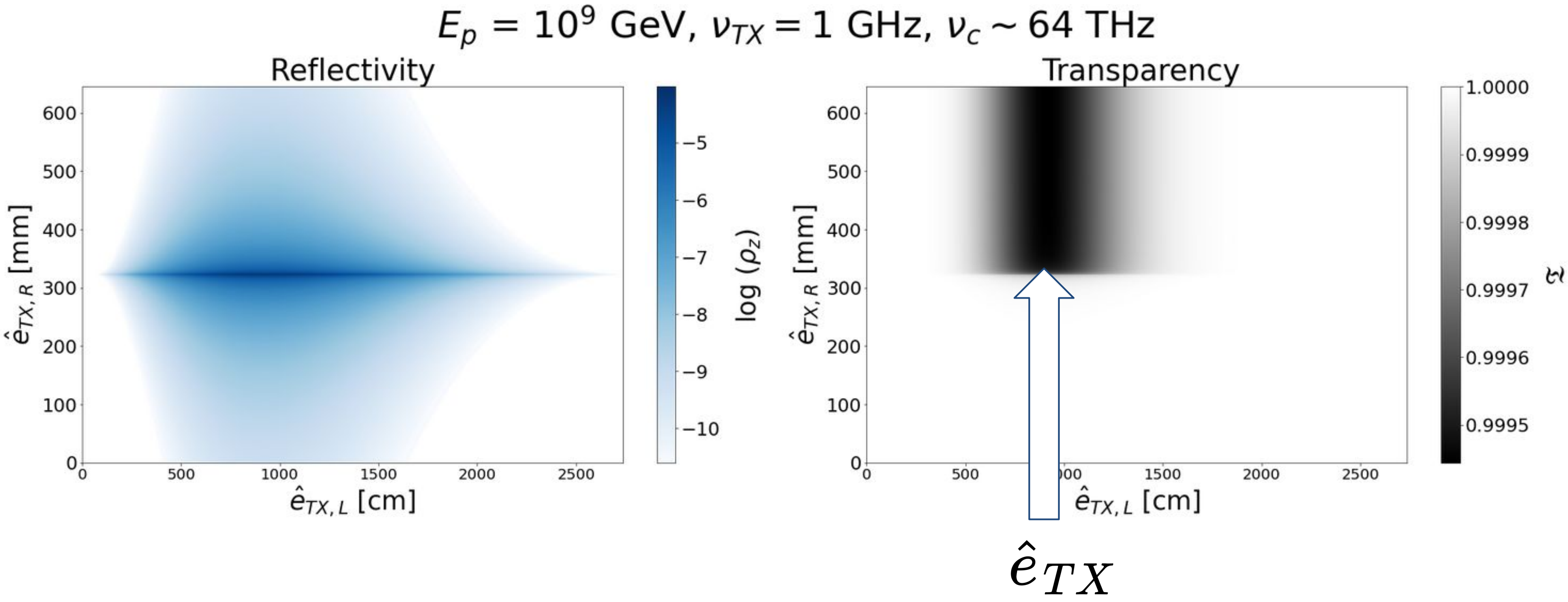
$$\sigma_{RCS,e^-} \simeq \sigma_{Thomson} \cdot \left(\frac{\omega}{\omega_c}\right)^2 \cdot G_{Hertz}$$

$$6.65 \cdot 10^{-25} cm^2 \qquad \sim 10^{-13} \rightarrow 10^{-10} \qquad \frac{3}{2}\sin^2(\theta)$$

# The radial integration



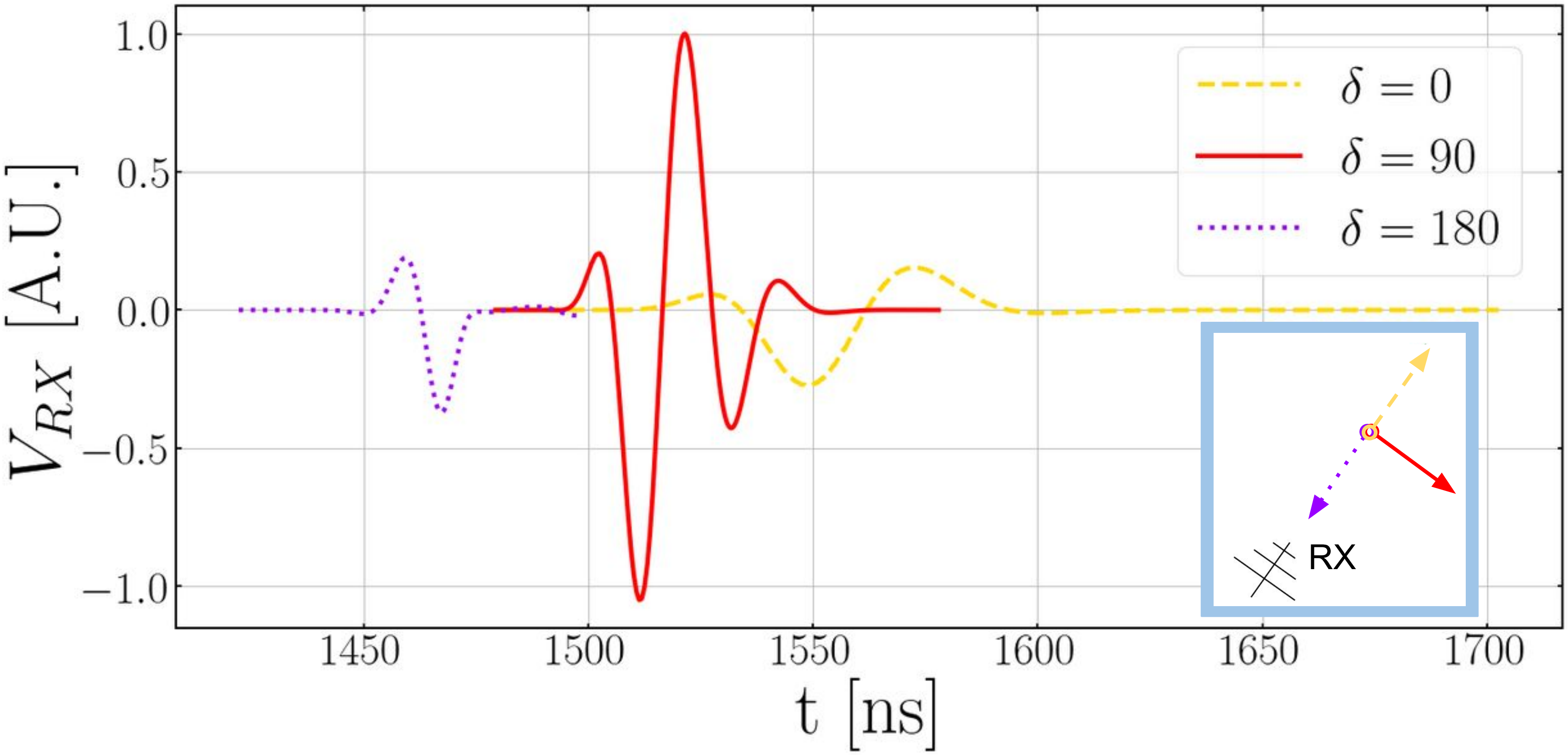
# The transparency



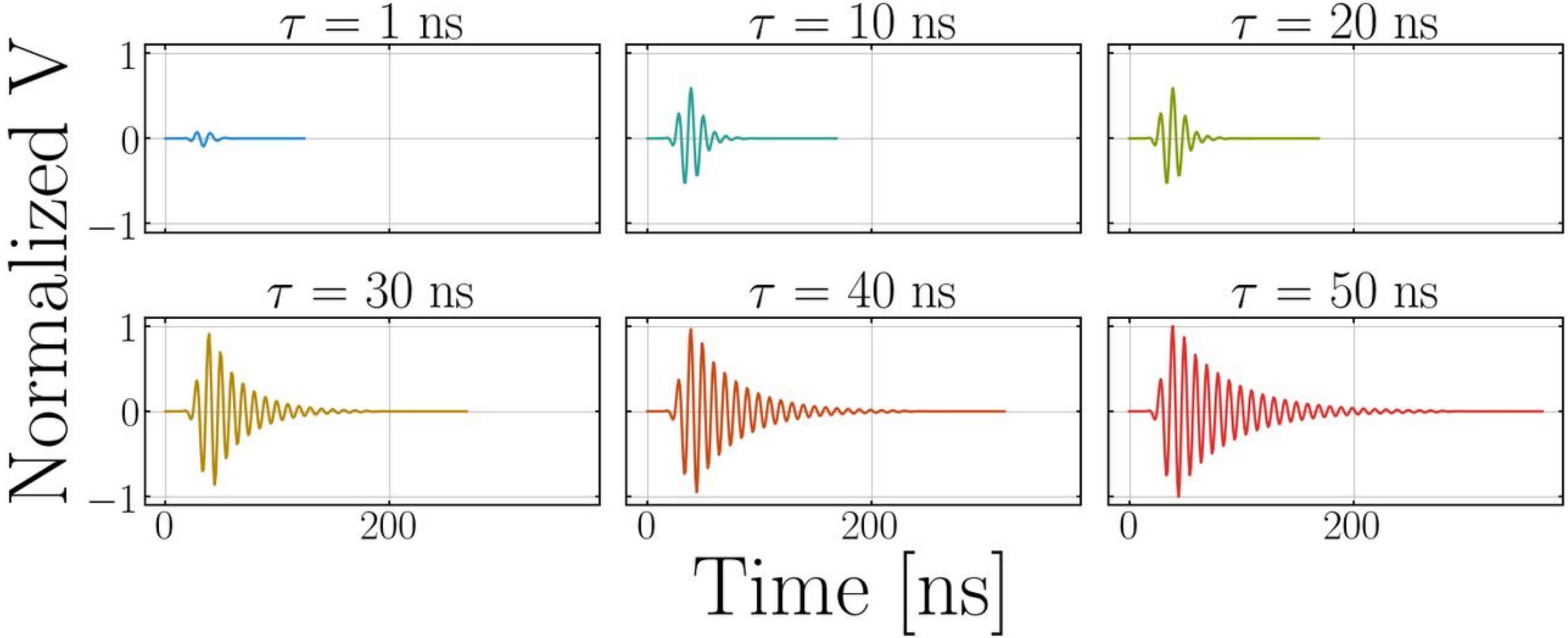
# Results:

## What does the signal look like?

# The MARES received signal



# The effect of the free electron lifetime



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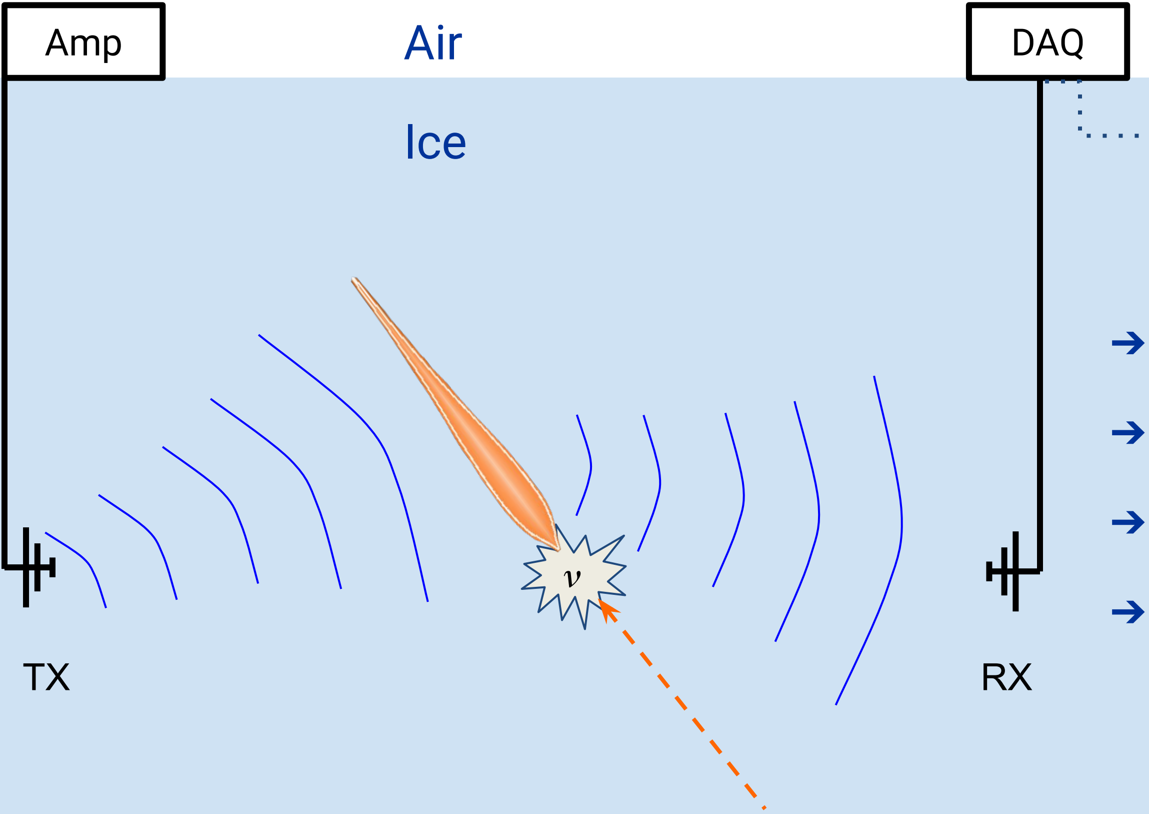


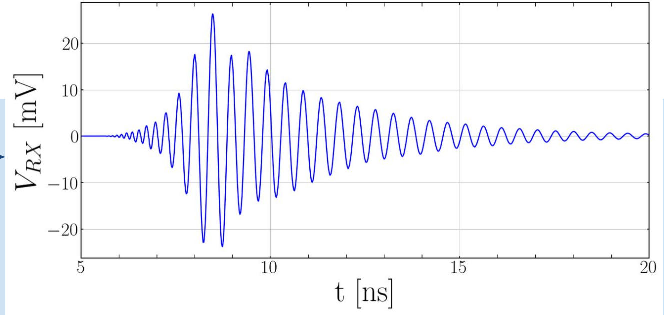


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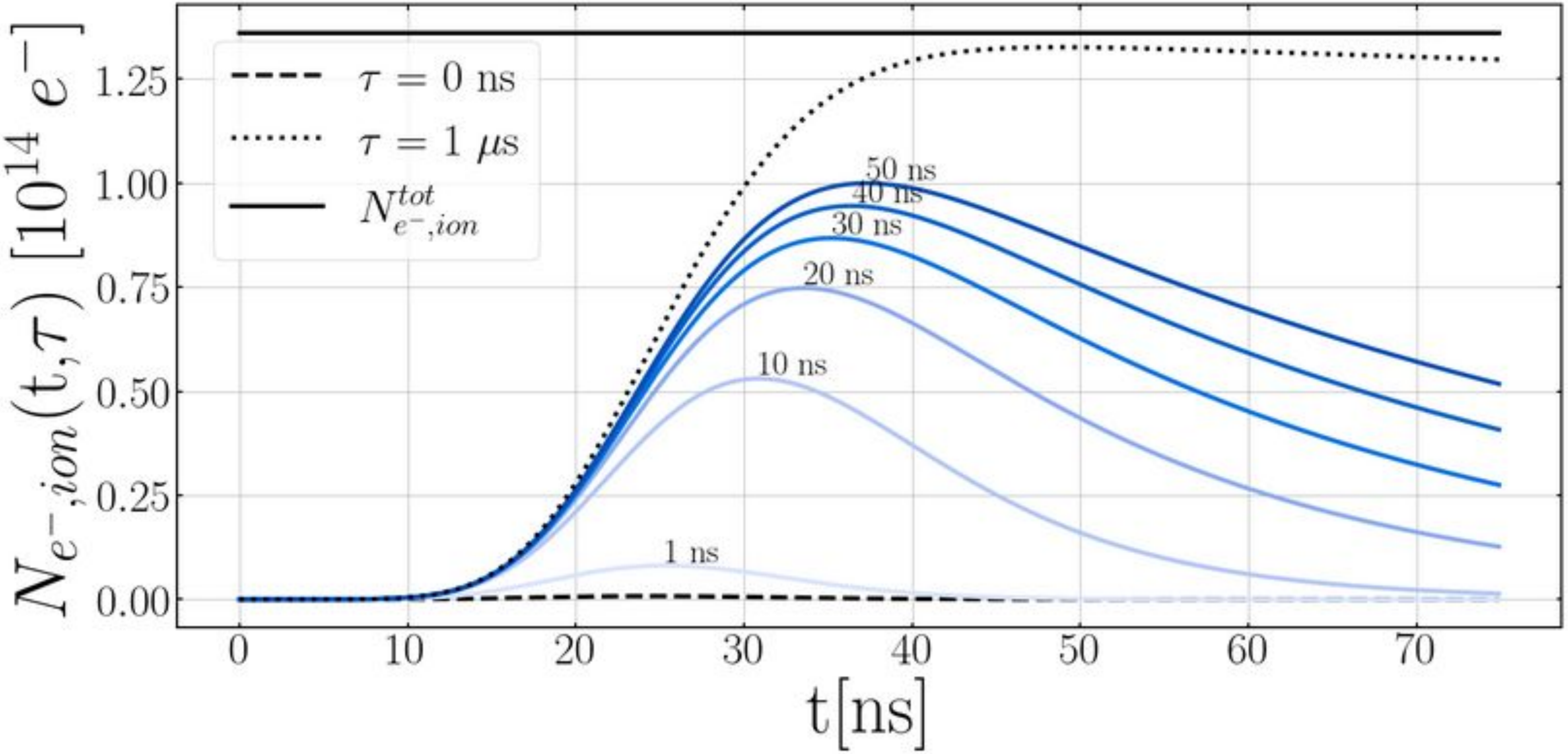
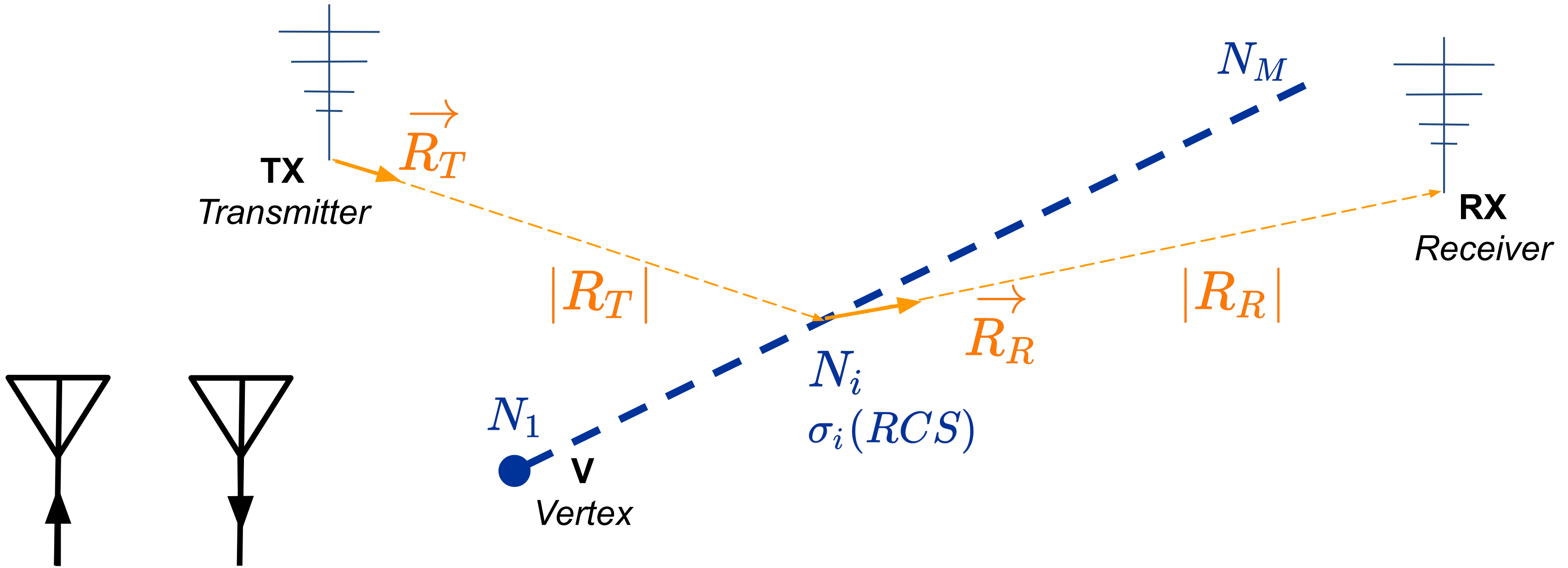
- ➔ The particle cascade will produce a **radar echo**, which is recorded by one or multiple receivers (RX).

Credit: Rose Stanley

# Analytic estimate of $N_e$



# The line approximation



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