Radar Echo Telescope

Enrique Huesca Santiago

on behalf of the RET Collaboration

VUB iihe BRUXELLES BRUSSEL ULB

Why am I here today?

RET-N: Radar Echo Telescope for Neutrinos

A telescope concept that probes the ultra-high-energy (> 10 PeV) cosmic neutrino flux via the radar echo technique in polar ice.

MARES: Macroscopic Approach to the Radar Echo Scatter

MARES is a macroscopic model to describe the radar echo from the ionization trail of a particle cascade induced by a ultra-high-energy neutrino in ice.

Key idea #1: Ultra-high-energy neutrinos

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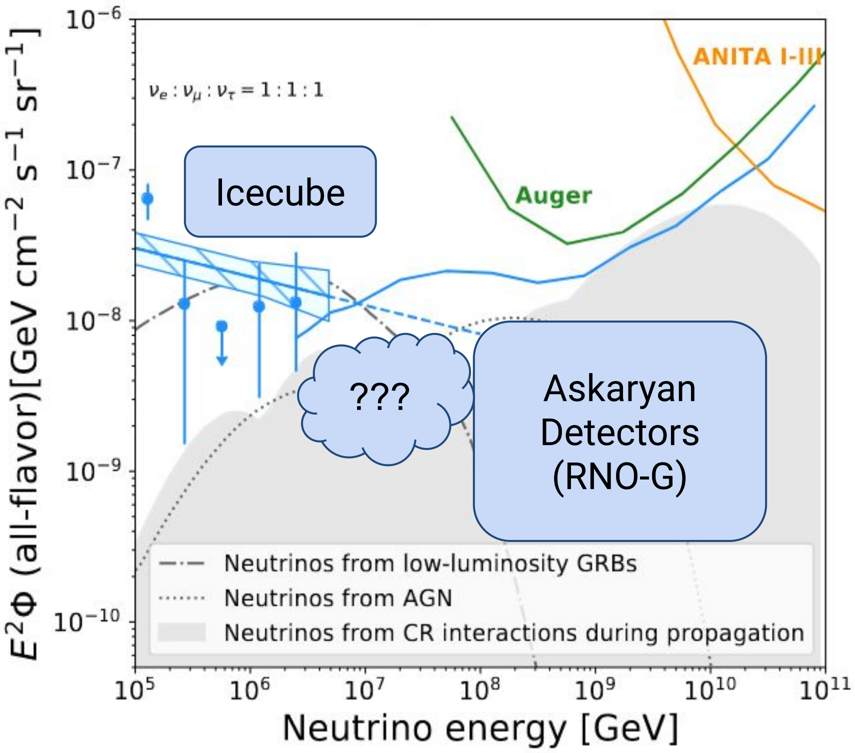
The case for RET-N



Adapted from: https://arxiv.org/abs/1903.04334

IceCube's measured flux reaches up to 10 PeV, while Askaryan detectors like RNO-G become effective at 100 PeV.

We need a different method to bridge the gap between the two detection systems → RET-N.

We expect RET-N to be compatible and complementary to current and future planned neutrino telescopes.

Key idea #2: Ionization trail in ice

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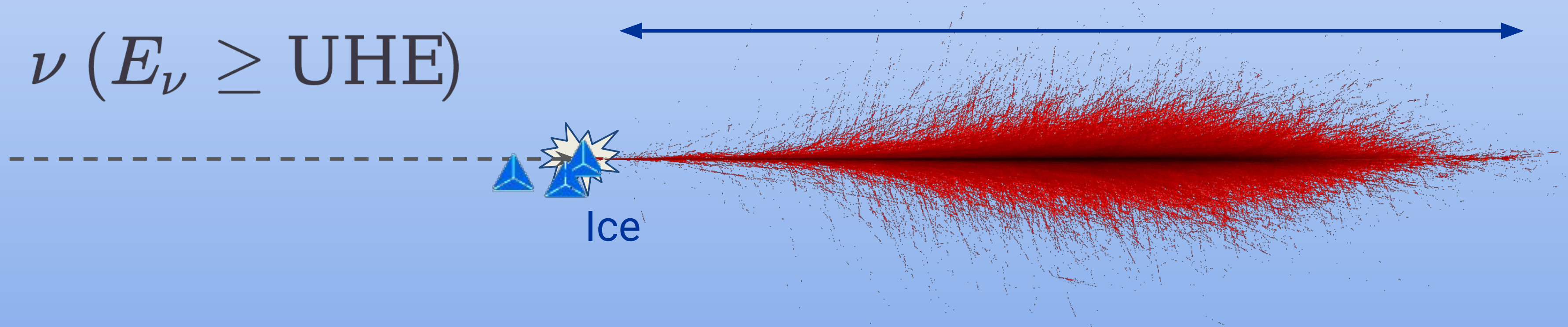
The in-ice particle cascade

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

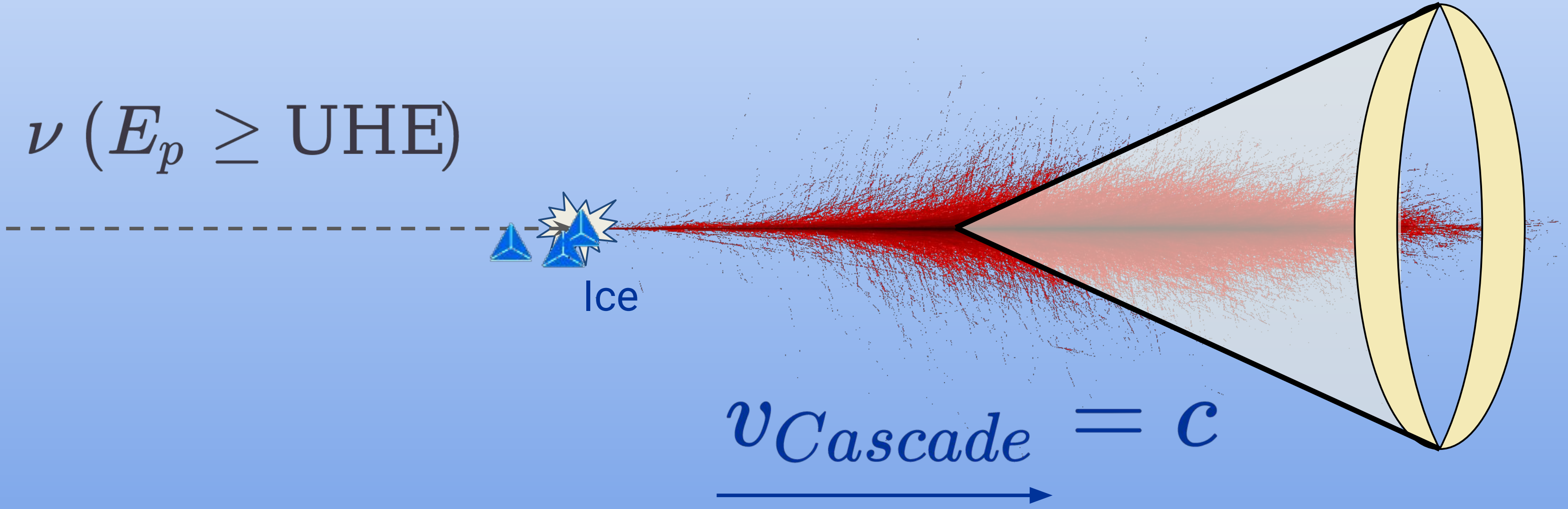
$$\nu\ (E_\nu \geq \mathrm{UHE})$$



$$v_{Cascade} = c$$

The in-ice particle cascade

The in-ice cascade radiation can be due to the Cherenkov or Askaryan effects

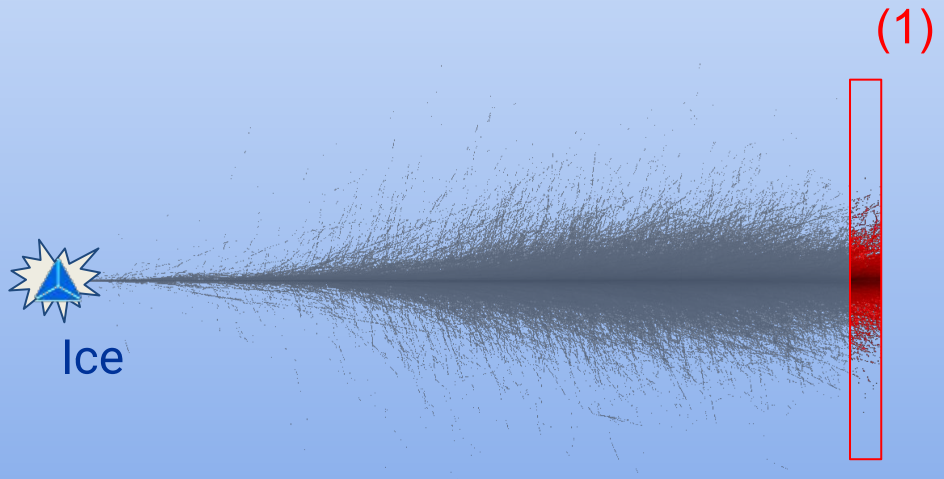


The in-ice cascade trail

(1) Cascade front

$E_p > E_{front} > E_{Critical} \sim 80$ MeV

The cascade develops



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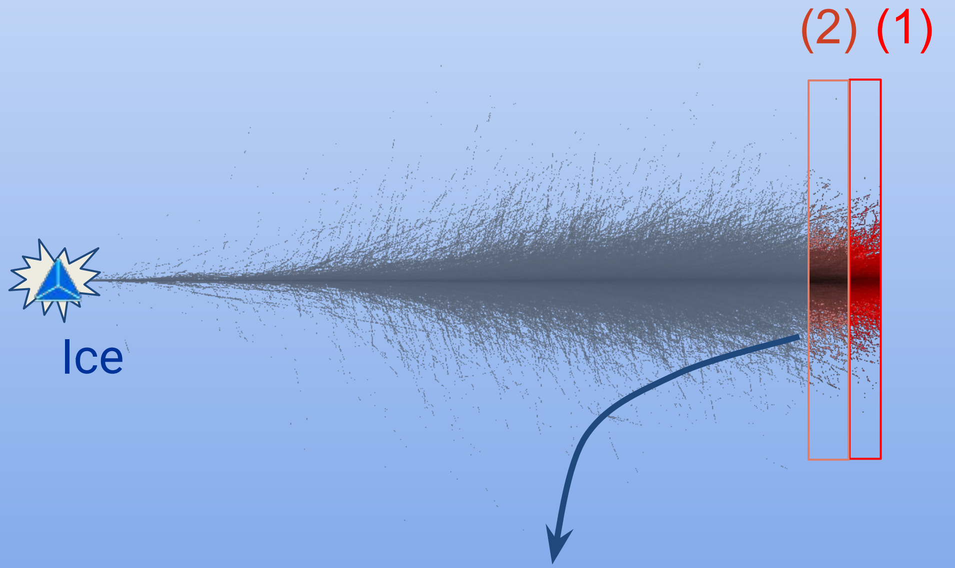
(2) Auger secondaries

$E_{Critical} > E_{Trail} > E_{ion} \sim 20$ eV

The ice is ionised



1 cascade, HE $e^- \sim 10^5$ ionisation e^-

The in-ice cascade trail

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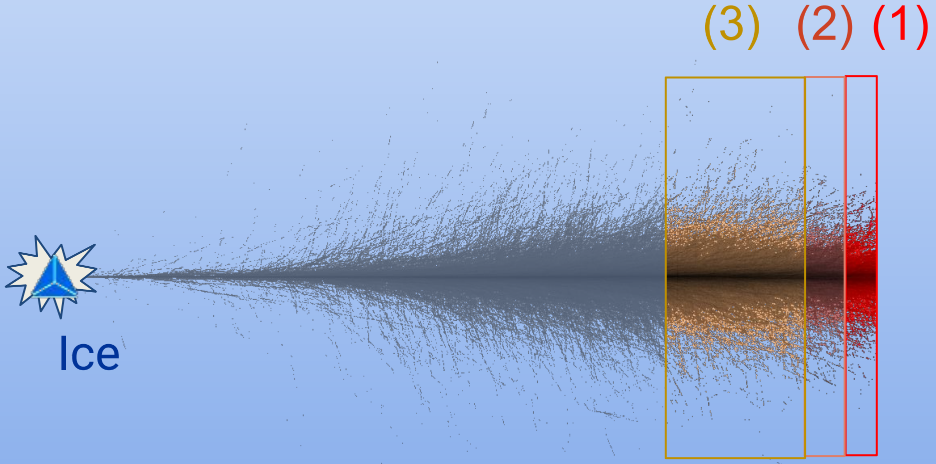
(3) Cascade trail

$\tau\,(e^-_{ionisation}) \sim O(10)$ ns.
Long-lived electron plasma



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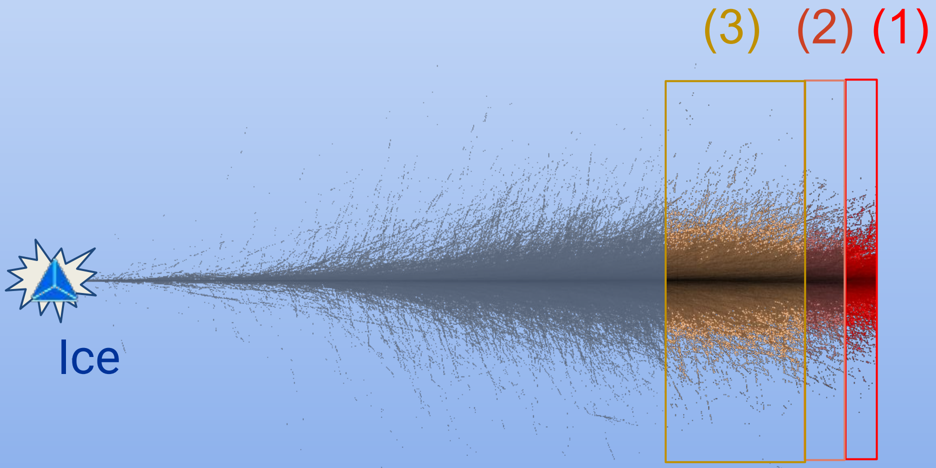
Long-lived electron plasma

$$L_{Trail} = c\,\tau_{e^-} \sim O(1)\ \mathrm{m}$$



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

Key idea #3: Radar echoes

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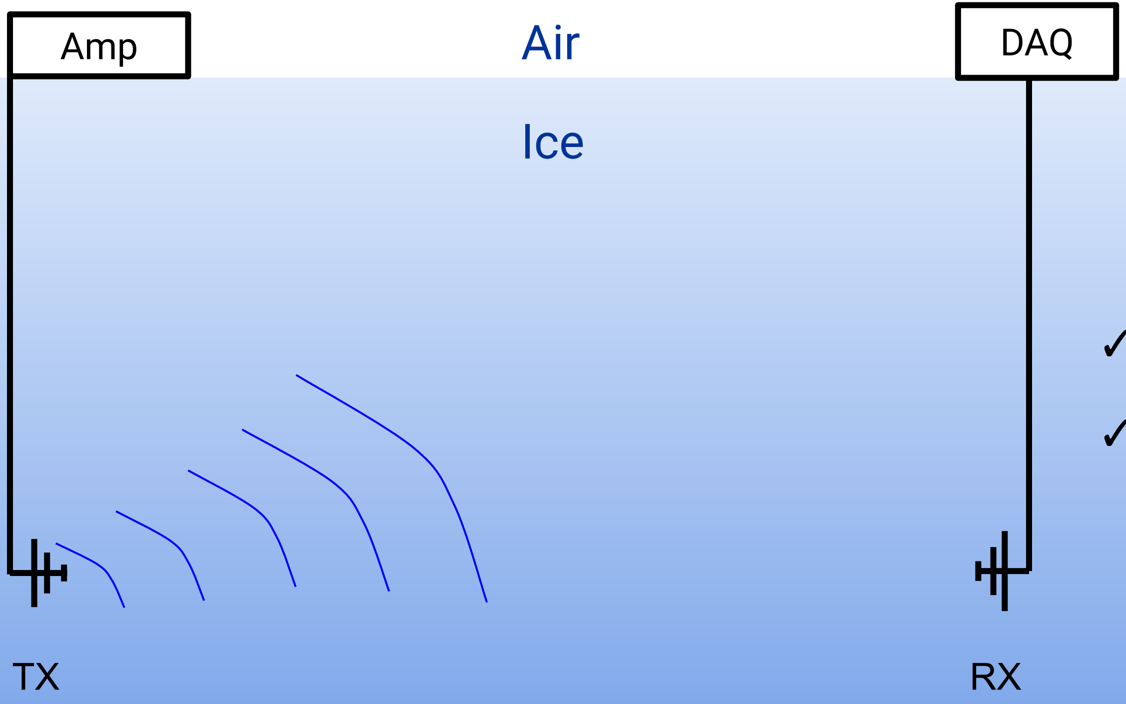
The Radar Echo Technique



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

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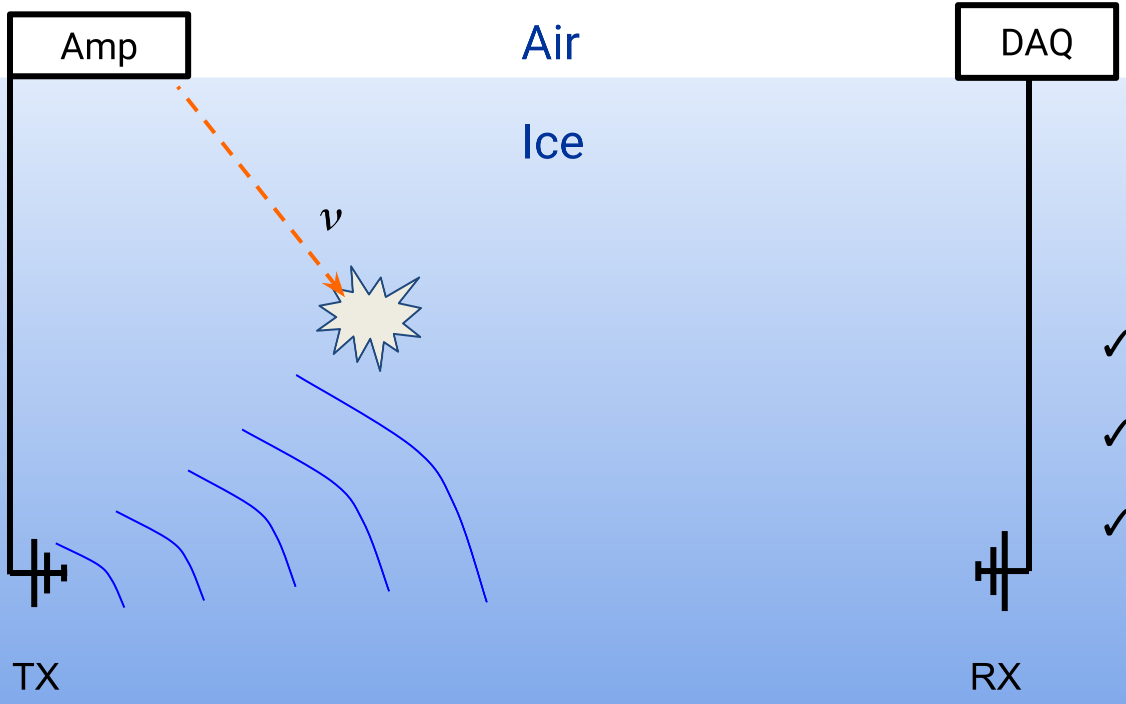

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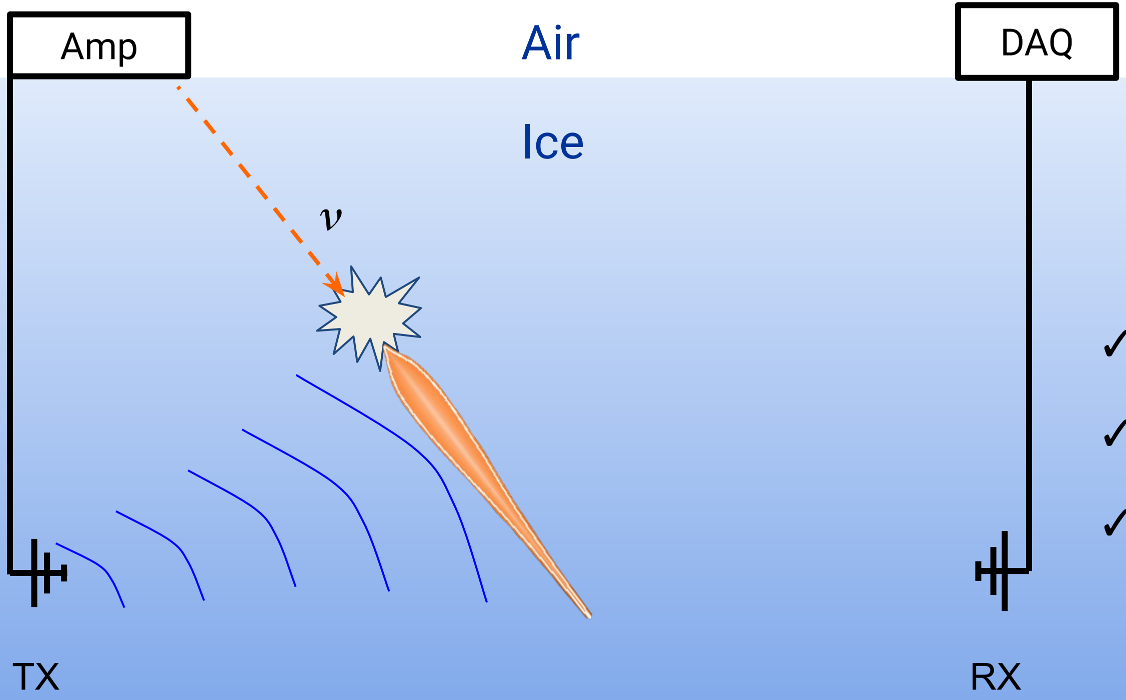

- ✓ Instrument a large volume of ice with a radar system.
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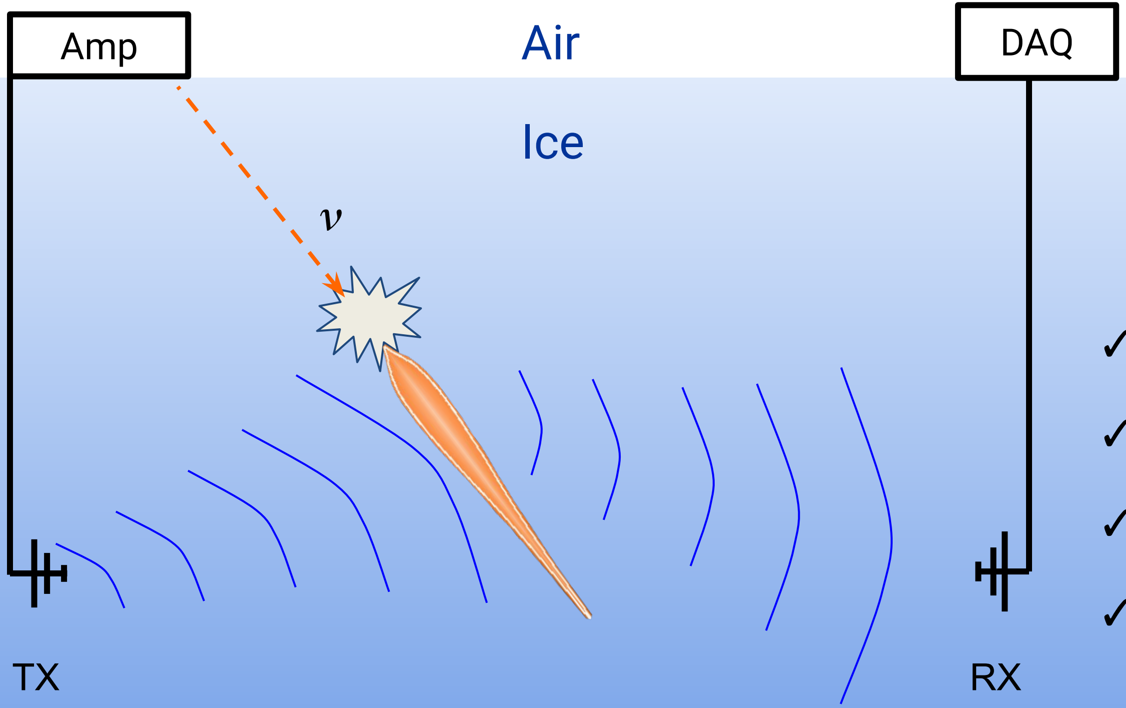

- ✓ Instrument a large volume of ice with a radar system.
- ✓ A radio transmitter (TX) constantly illuminates the ice.
- ✓ A neutrino (ν) interacts in the monitored volume, leaving an ionization trail.
- ✓ The ionization trail will produce a **radar echo,**

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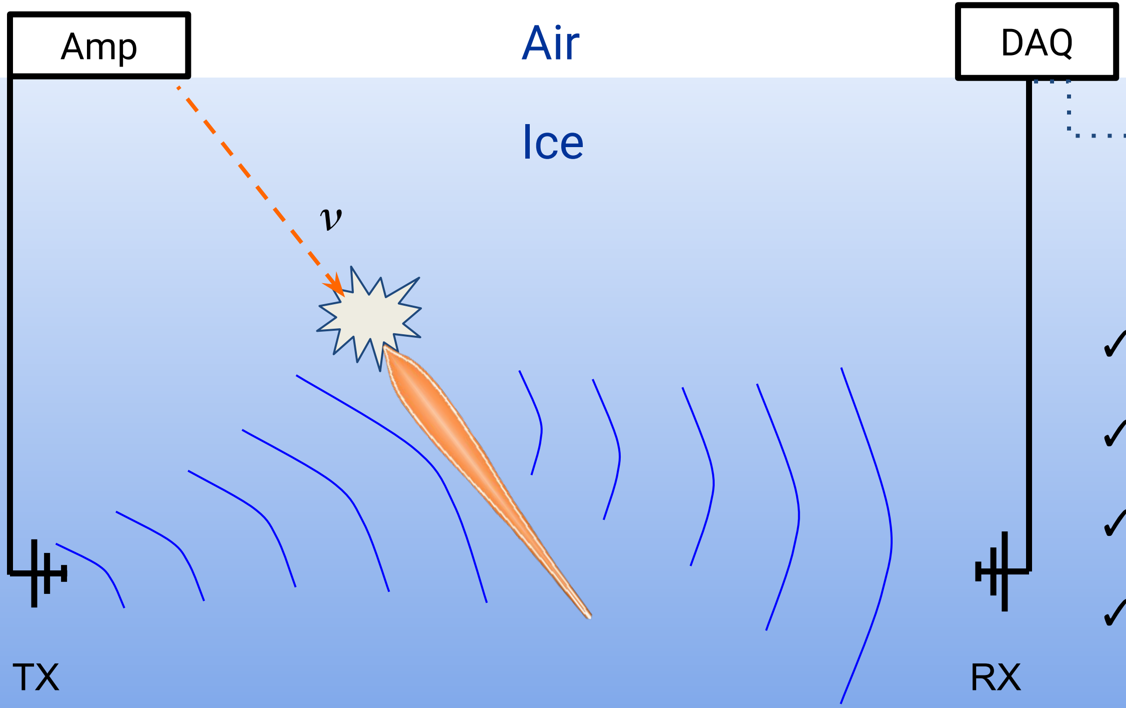
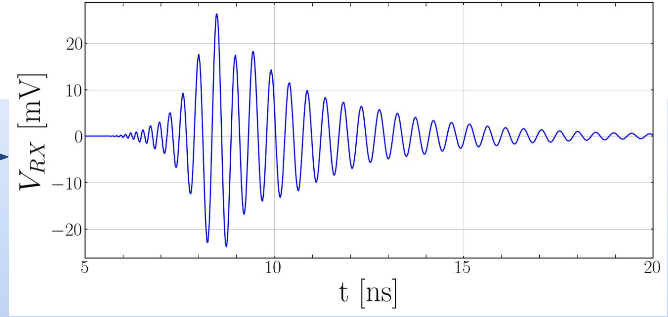
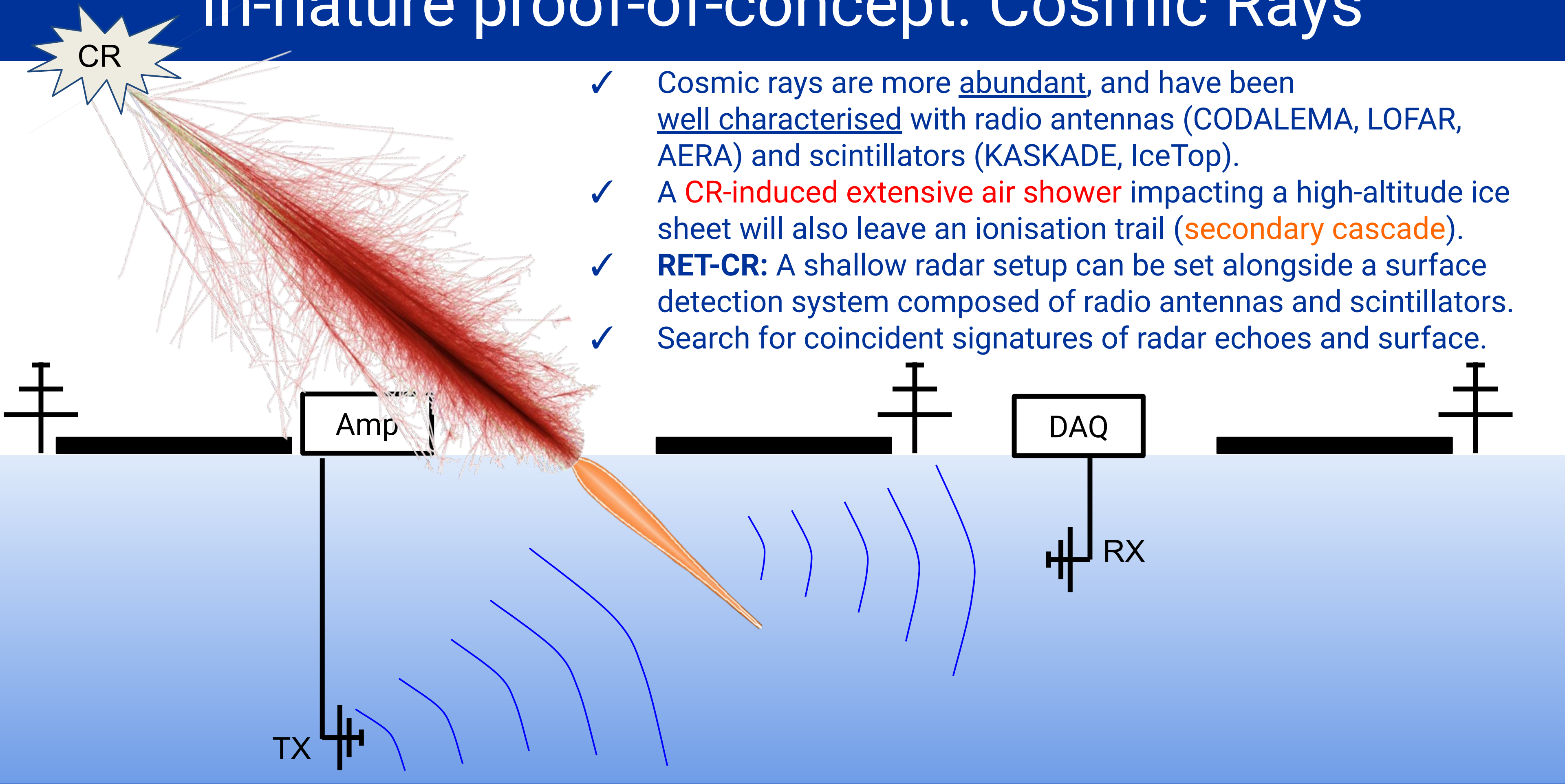




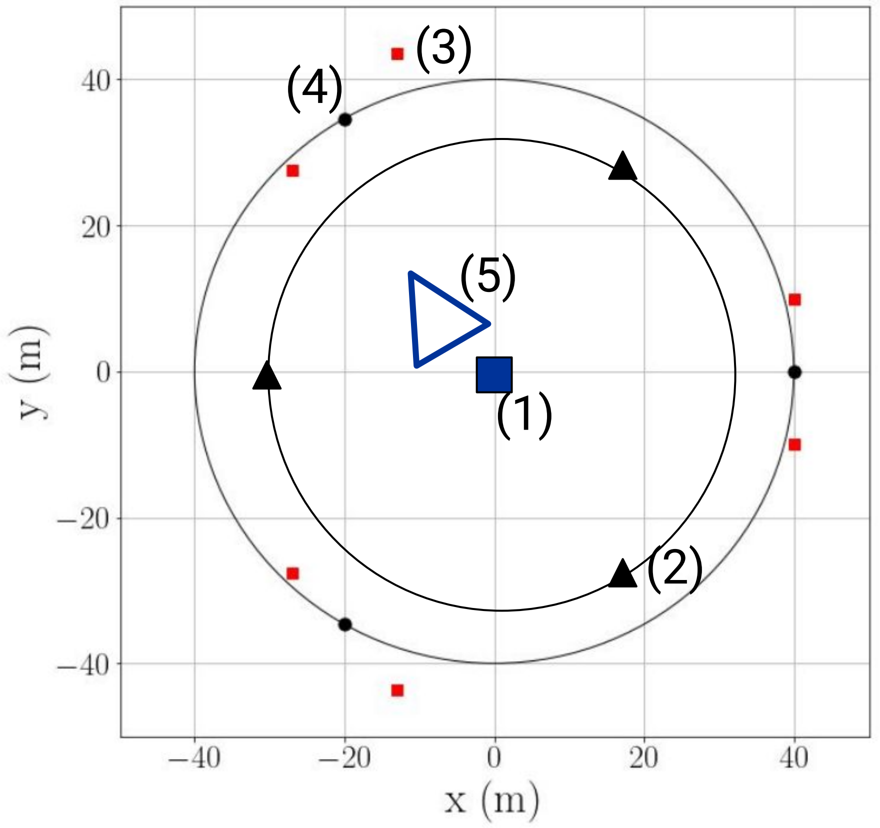
- ✓ Instrument a large volume of ice with a radar system.
- ✓ A radio transmitter (TX) constantly illuminates the ice.
- ✓ A neutrino (ν) interacts in the monitored volume, leaving an ionization trail.
- ✓ The ionization trail will produce a **radar echo,** which is recorded by the receivers (RX).

In-nature proof-of-concept: Cosmic Rays

- ✓ Cosmic rays are more abundant, and have been 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.



Final RET-CR design



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

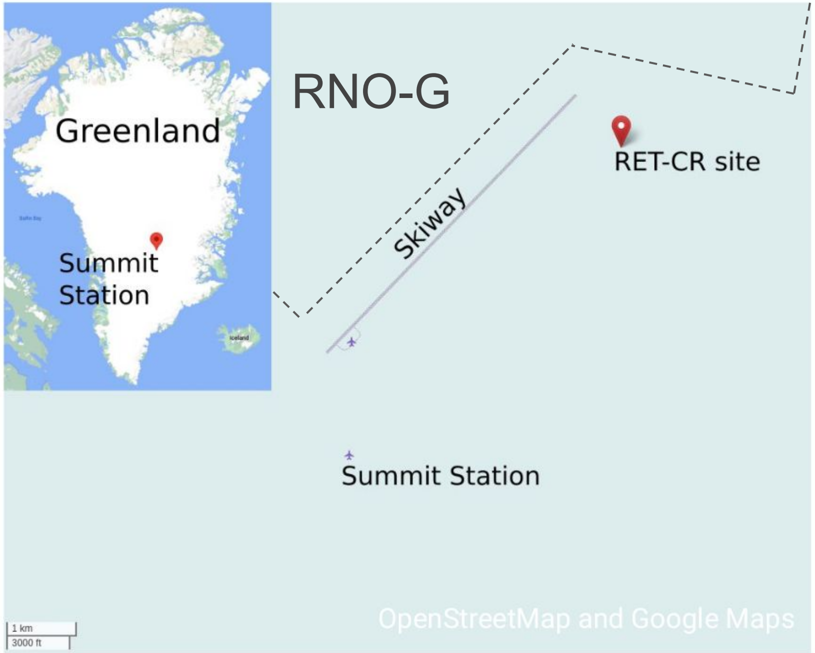
2) In-ice radio antenna

3) IceTop scintillators

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

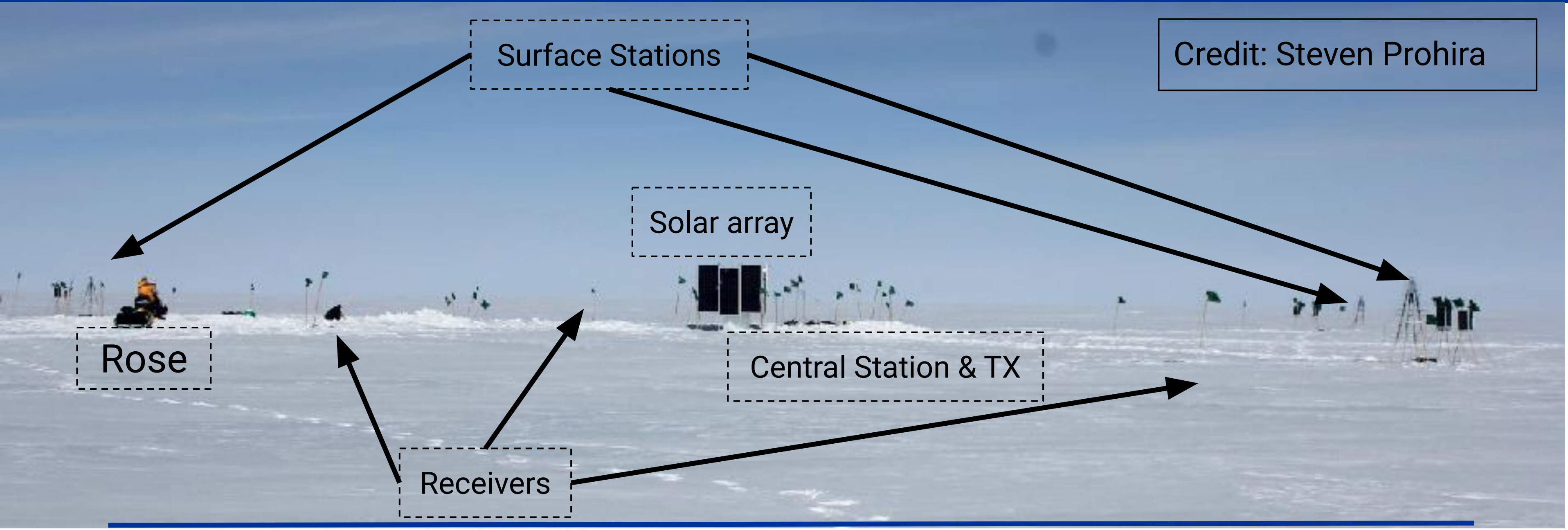
5) Solar array and batteries

RET-CR Greenland deployment (May 2023)



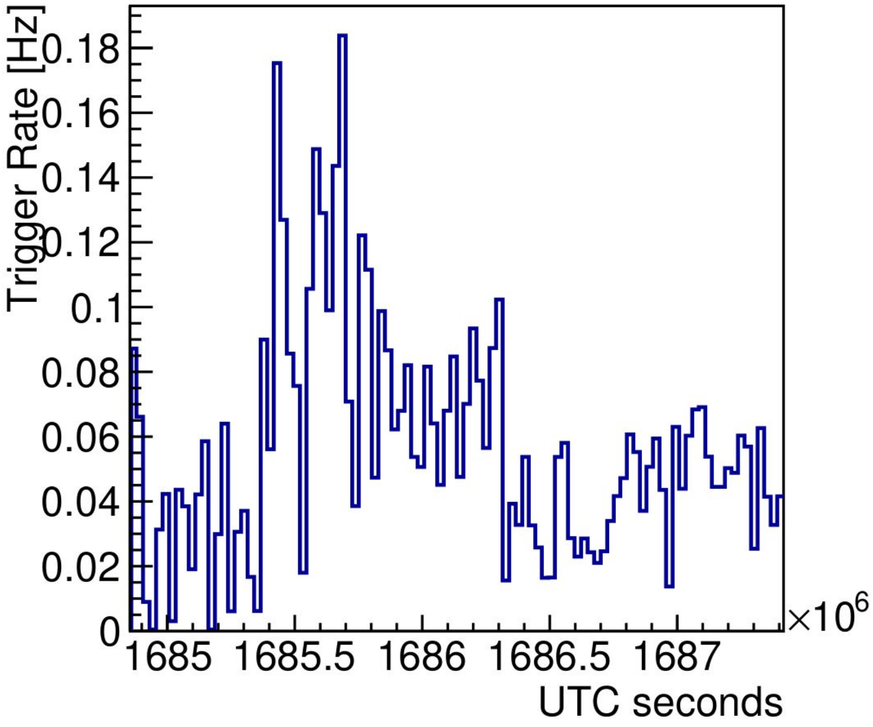
RET-CR Greenland deployment (May 2023)

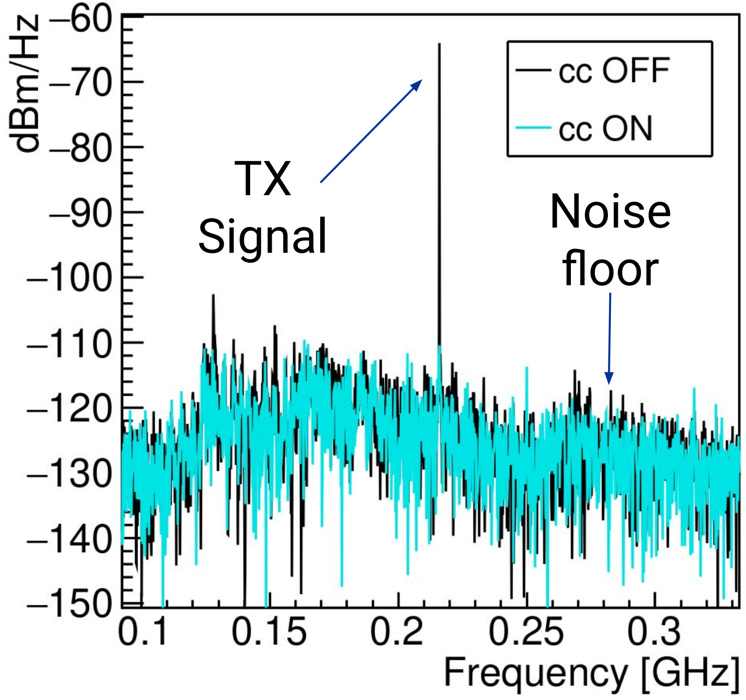
RET-CR in Greenland



RET-CR Performance

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





MARES

A Macroscopic Approach to the Radar Echo Scatter

Why do we need MARES?

1. The ionisation trail is a relativistic, non-uniform, non-perfect conductor.
   - ↪ Commercial radar solutions are not designed for this case.
   - ↪ Analytical solutions to the scatter are not feasible.

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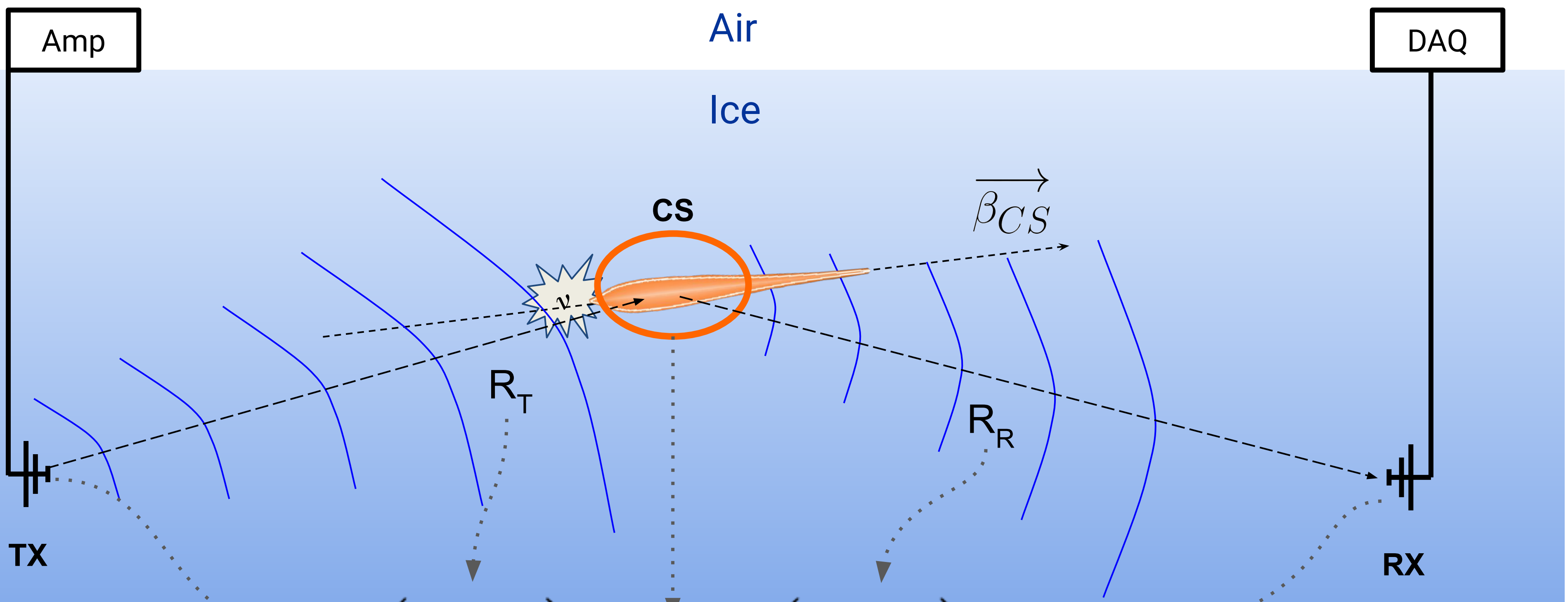
3. MARES uses the macroscopic parametrisations of the particle cascade.
   - ↪ This is a semi-analytical, deterministic and complementary approach.
   - ↪ We can use it to learn the radar scatter features
     from the global cascade properties ⟶ Event reconstruction.

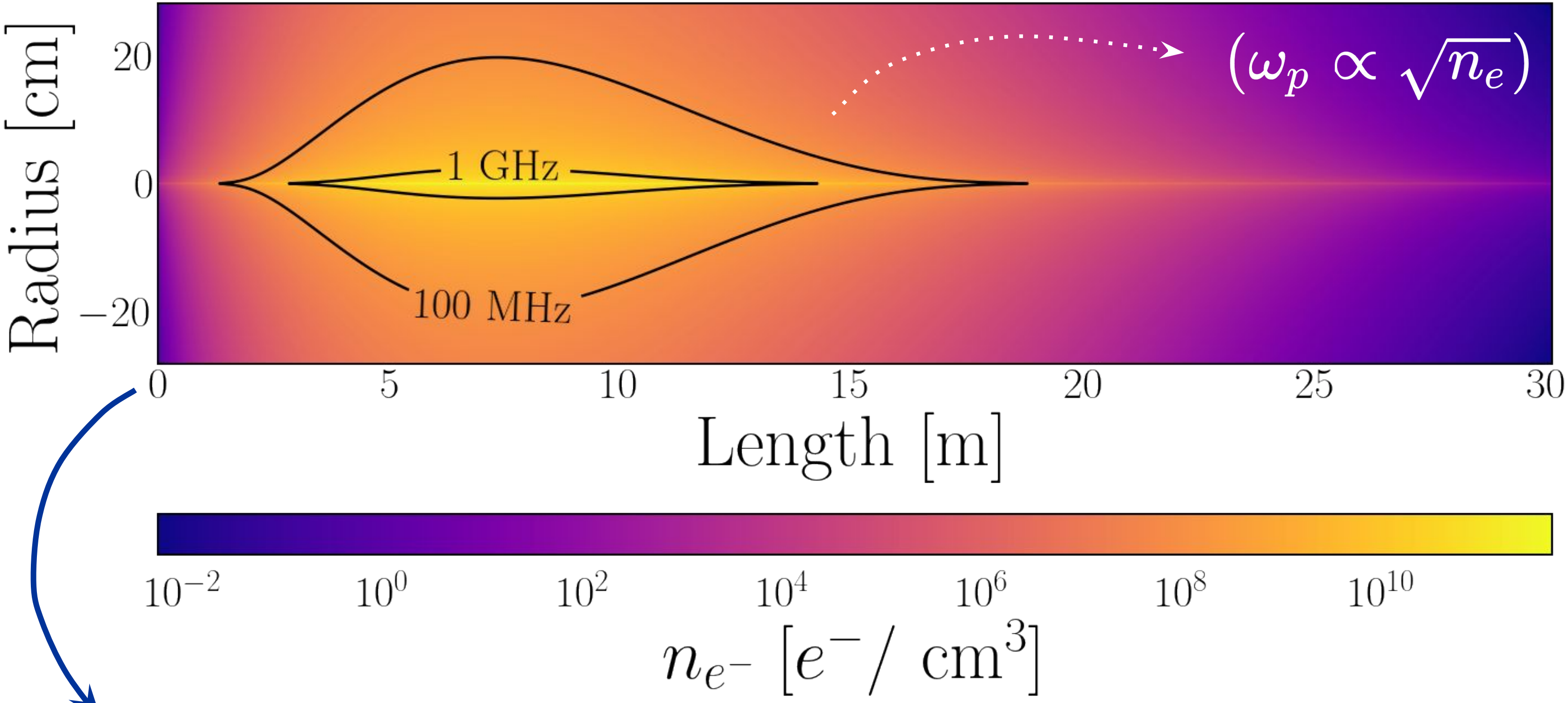
MARES' Fundamental Principles: https://arxiv.org/abs/2310.06731

The Radar Echo Technique



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

How can we describe the ionisation trail?



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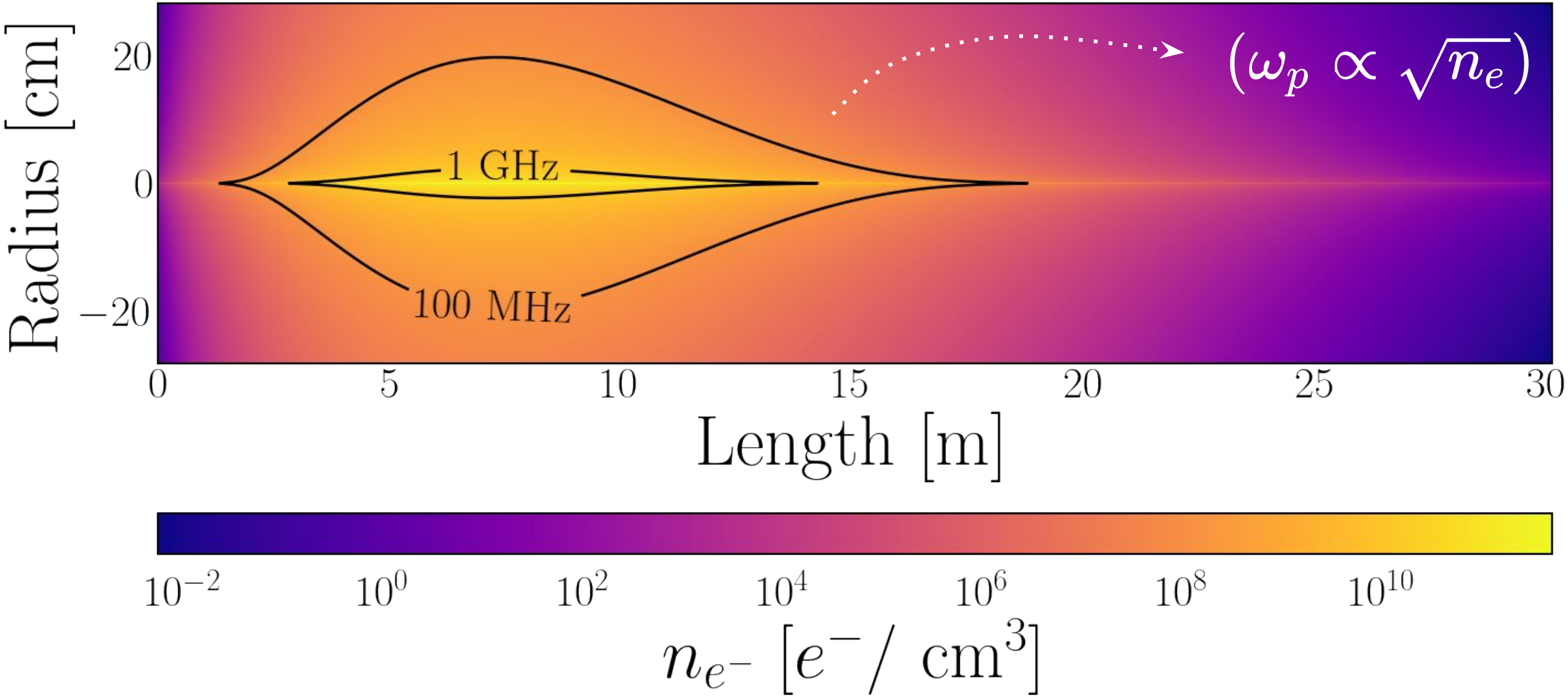


Nishimura, Kamata & Greisen: Air showers (Progr. Theoret. Phys. 6, 93 (1958) & Prog. Cosmic Ray Phys., vol. III (1965))
K. Werner, K. de Vries, O. Scholten: In-ice neutrino cascade (arxiv:1312.4331)
Simon de Kockere, *et al.* : Air shower cores from CR that propagate through ice (arXiv:2202.09211)

The radar cross section

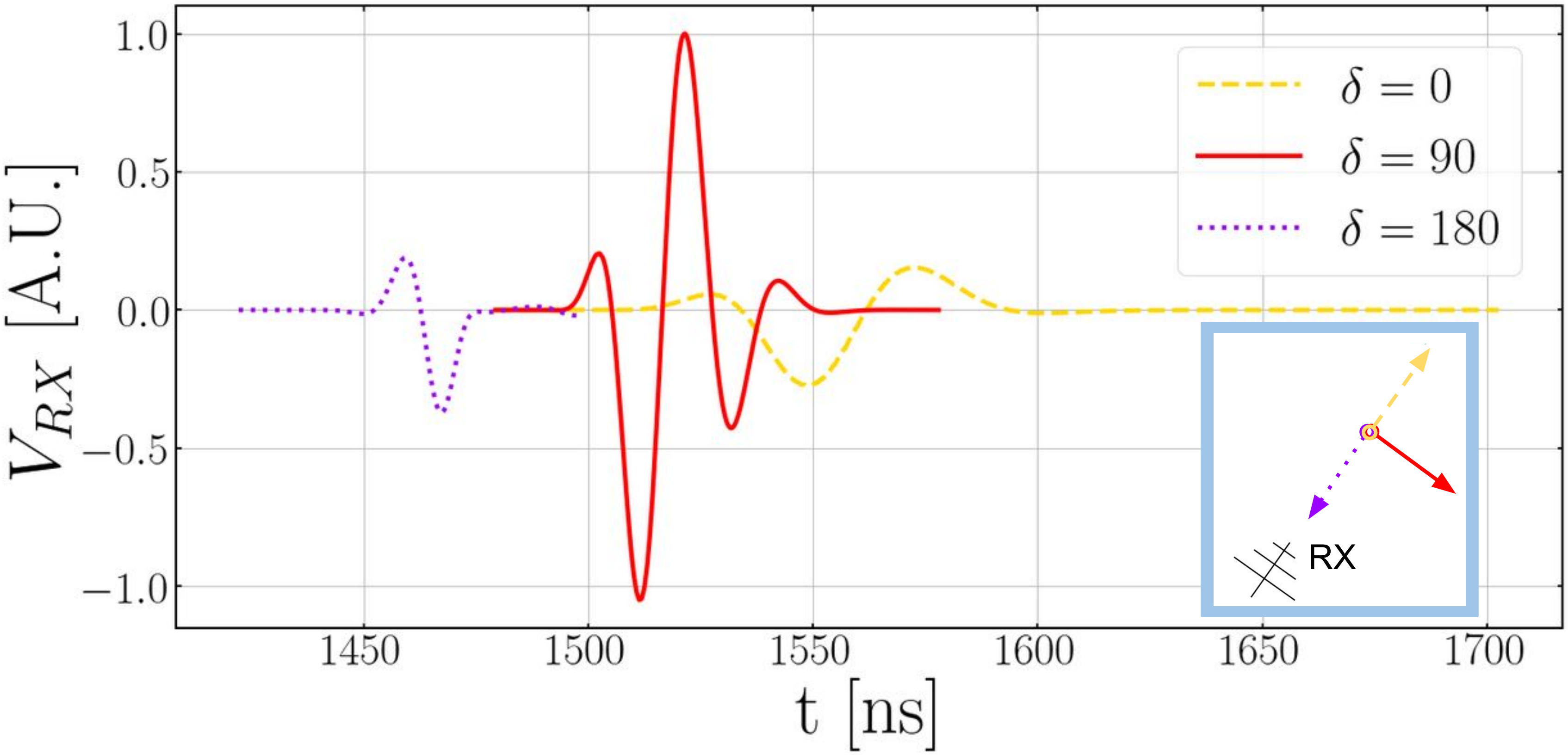
$$P_R \propto E_{sc} = \frac{\sqrt{2ZP_TG_T}}{4\pi R_T R_R}\sqrt{\sigma_{RCS}}$$

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

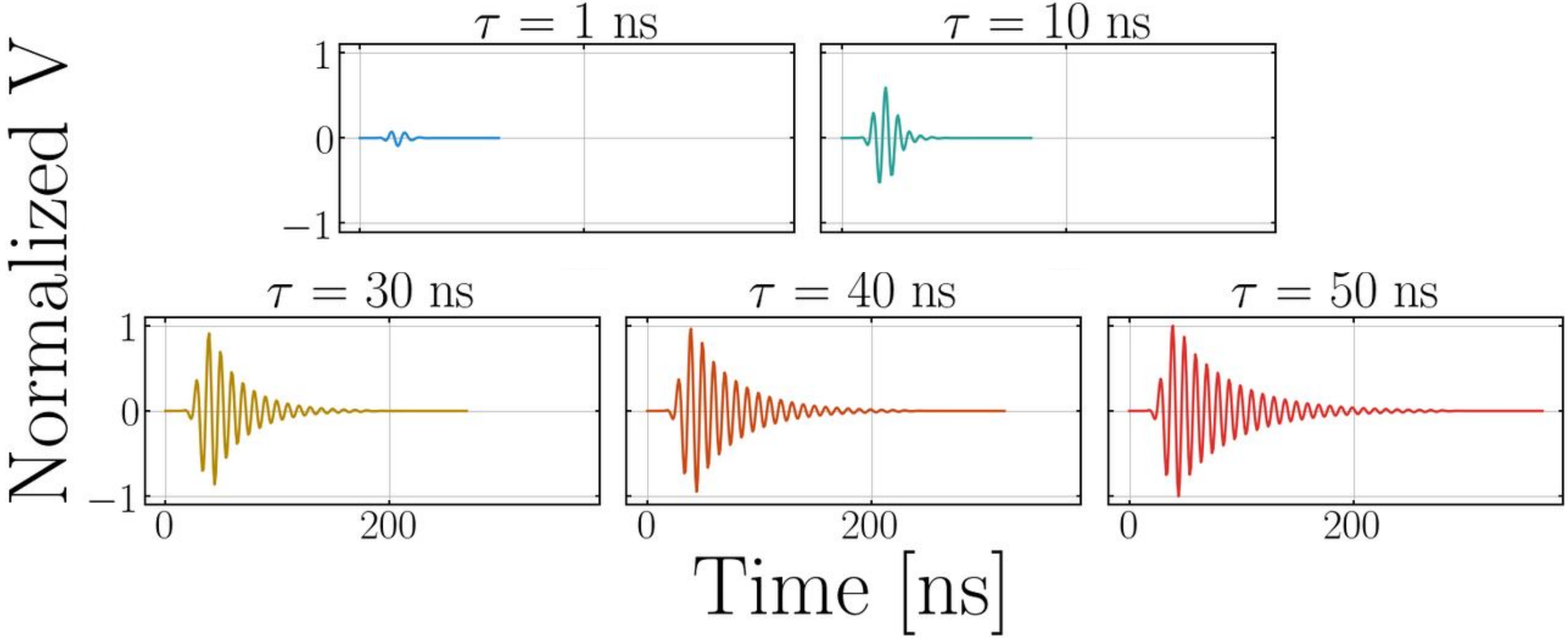
$$\sigma_{RCS,e^-} \simeq \sigma_{Thomson} \cdot \left(\frac{\omega}{\omega_c}\right)^2 \cdot G_{Hertz}$$

$$[6.65 \cdot 10^{-25}\,\mathrm{cm}^2] \quad [\sim 10^{-13} \rightarrow 10^{-10}] \quad [\tfrac{3}{2}\sin^2(\theta)]$$

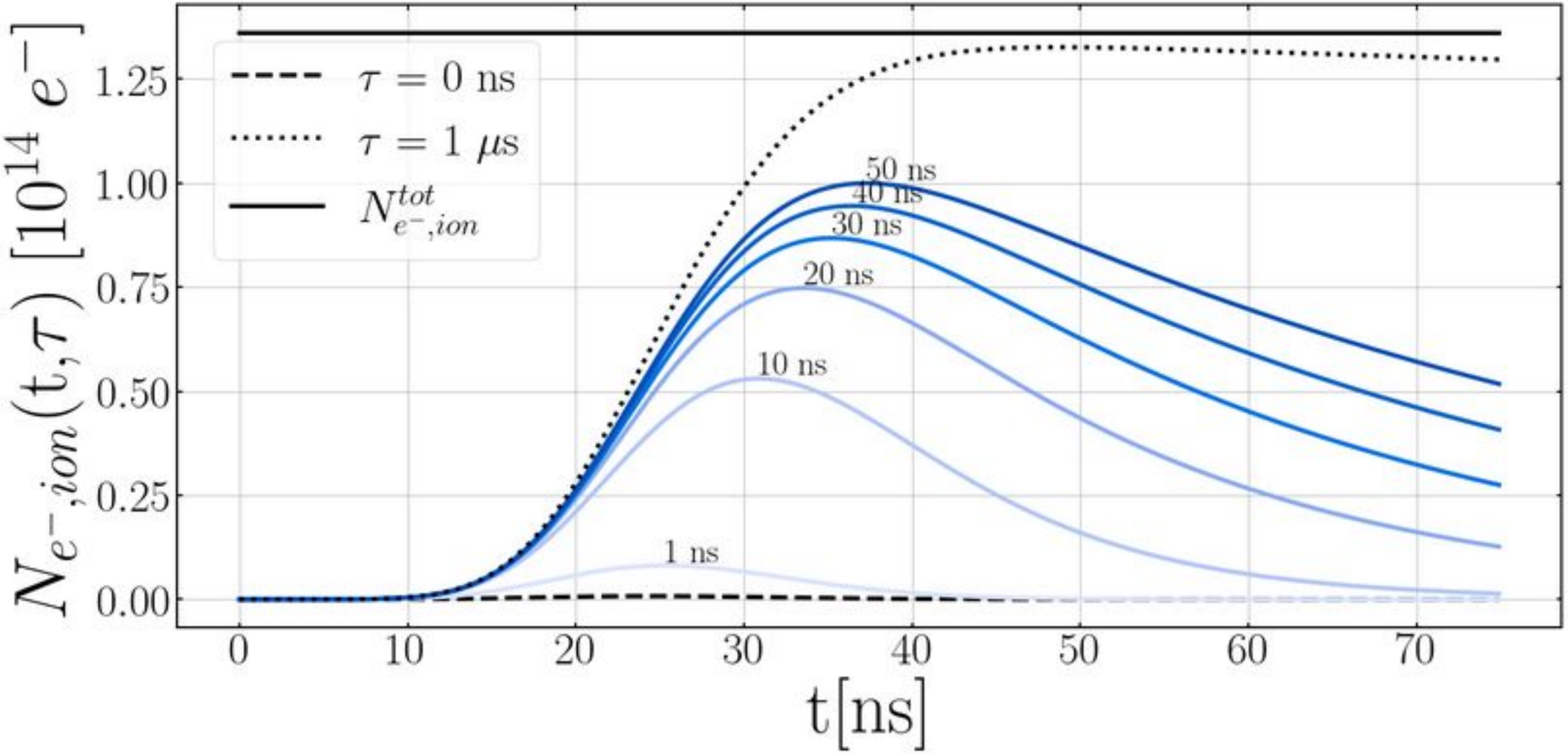
MARES' first simulated signals



The impact of the free electron lifetime



Understanding the impact of the lifetime



Summary

1. RET's Goal: Probing the >10 PeV cosmic neutrino flux (RET-N) with the radar echo echoes from the ionisation trails of neutrino-induced particle cascades.

2. The Radar Echo Telescope for Cosmic Rays (RET-CR) is a pathfinder project that was deployed near Summit Station during the summer season of 2023.

   ↪ There will be a second RET-CR campaign in the spring-summer of 2024!

3. MARES is a new way to model the radar scatter which uses the cascade parametrisations.
   ↪ The MARES code is available for the use of the RET collaboration.
   ↪ A public release is expected very soon, along the official publication in PRD. (Stay tuned!).

THANK YOU FOR LISTENING.