RADAR DETECTION OF HIGH-ENERGY PARTICLE CASCADES

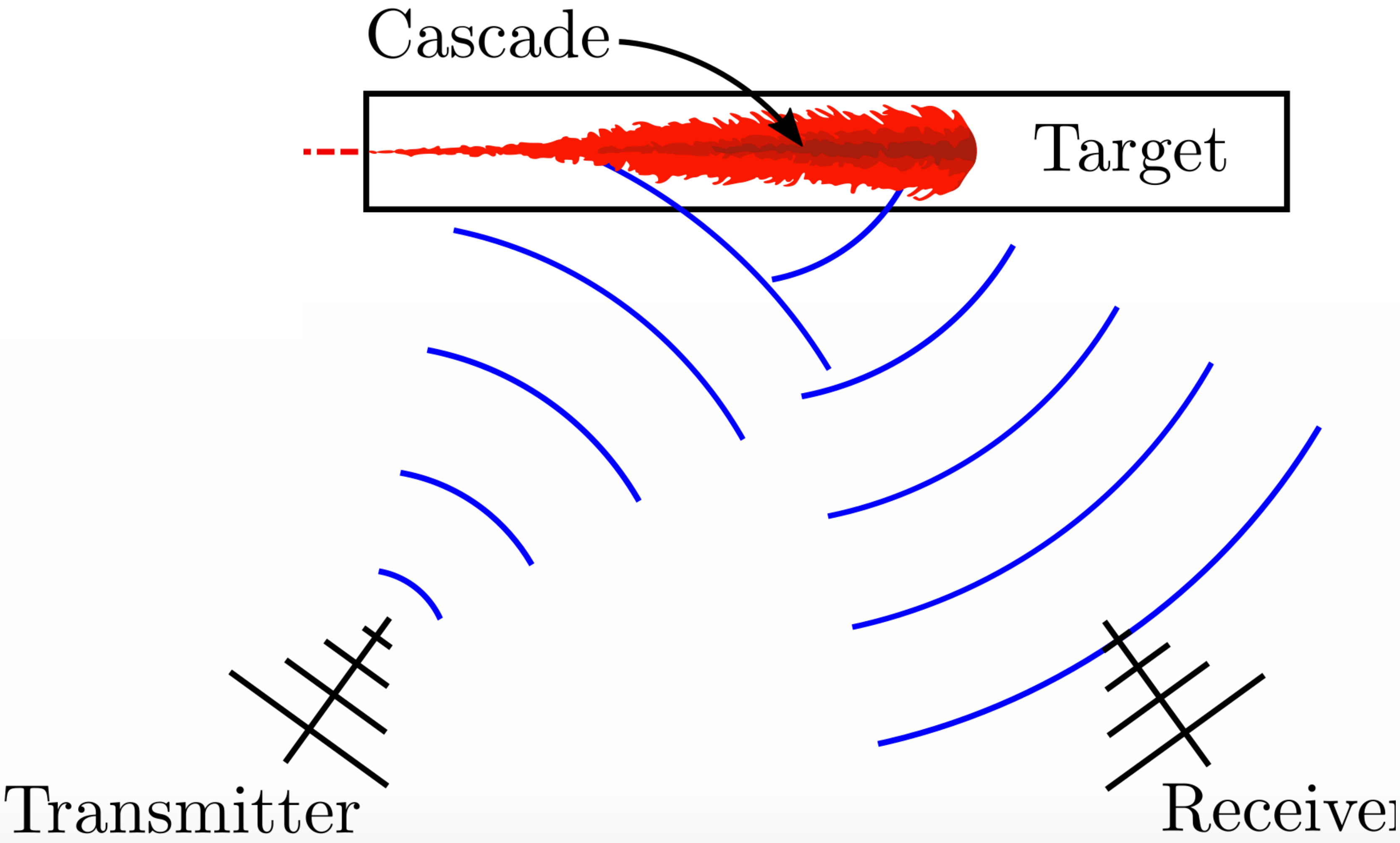
KRIJN D DE VRIES

VRIJE UNIVERSITEIT BRUSSEL

GCOS 2021 WORKSHOP

RADAR DETECTION OF HIGH-ENERGY PARTICLE CASCADES

THE MAIN IDEA



RADAR DETECTION OF HIGH-ENERGY PARTICLE CASCADES HISTORY

COSMIC-RAY AIR SHOWER DETECTION

- 1940's: Blacket and Lovell propose radar effort. Abandoned after detecting meteors. Eckersly discusses collisional damping.

- 1960: Air shower investigations were briefly picked by the Tokyo large air shower project, but no results published.

- 2000: Method revived by Peter Gorham.

- 2010-2015: Experimental (MARIACHI, TARA) and theoretical (Stasielak et al.) advances finally deemed the method not feasible for detecting air showers ~2010-2015.

Overview at:

www.radarechotelescope.org

Sir Bernard Lovell
https://history.nasa.gov/SP-4217/ch3.htm

Fig: http://www.telescopearray.org/tara/index.html

RADAR DETECTION OF HIGH-ENERGY PARTICLE CASCADES HISTORY

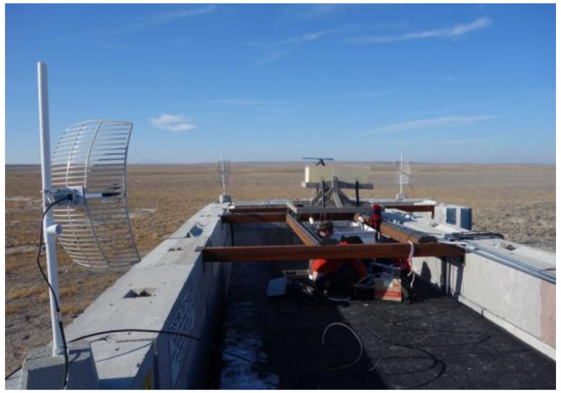
WHAT ABOUT NEUTRINO'S INTERACTING IN ICE?

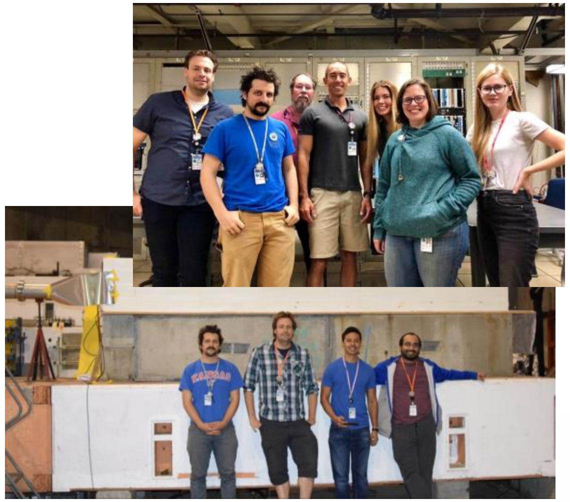
- 2012-2013: Chiba et al. (experiment); de Vries et al. (theory). Follow-up by Prohira et al.

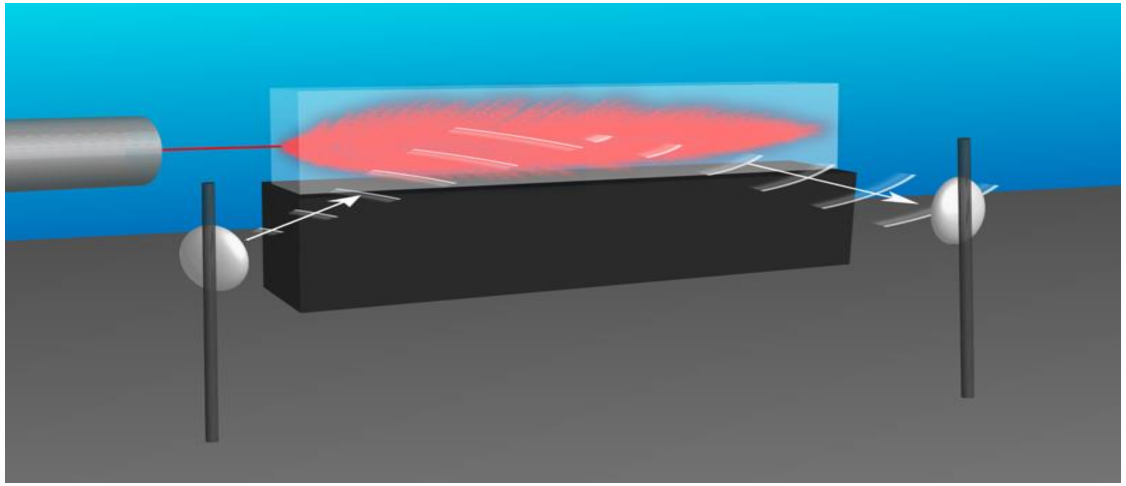
  →feasible due to high particle density in ice!!

- 2015-2019: Several beam test experiments performed at TA-ELS in Utah and SLAC. TA-ELS results inconclusive, final detection at SLAC.

- 2019 – ongoing: **The radar echo telescope** for cosmic-rays and neutrinos. Funded by EU Horizon 2020 and NSF.







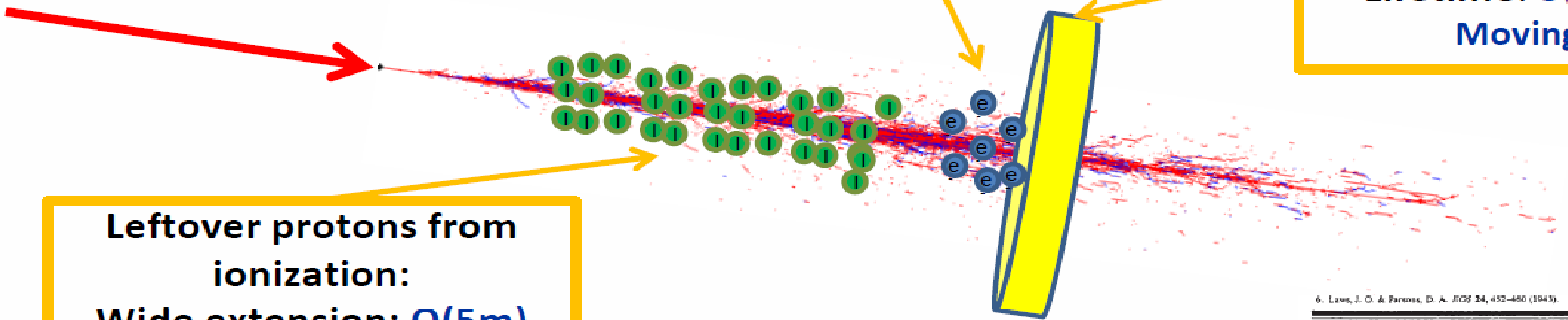
APS/**Alan Stonebraker**

RF SCATTERING FROM PARTICLE CASCADES

WHAT SCATTERS?

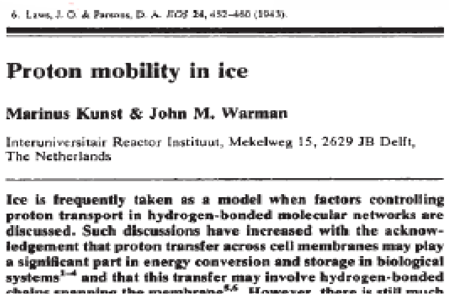
Leftover electrons from ionization:
Extension: O(30 cm)
Lifetime: O(1-20 ns)

Shower front electrons:
Extension: R_L = O(10 cm)
Lifetime: O(100ns)
Moving!



Leftover protons from ionization:
Wide extension: O(5m)
Lifetime: O(10-1000 ns)

Ionization numbers come from Physical Chemistry research!



Proton mobility in ice

Marinus Kunst & John M. Warman

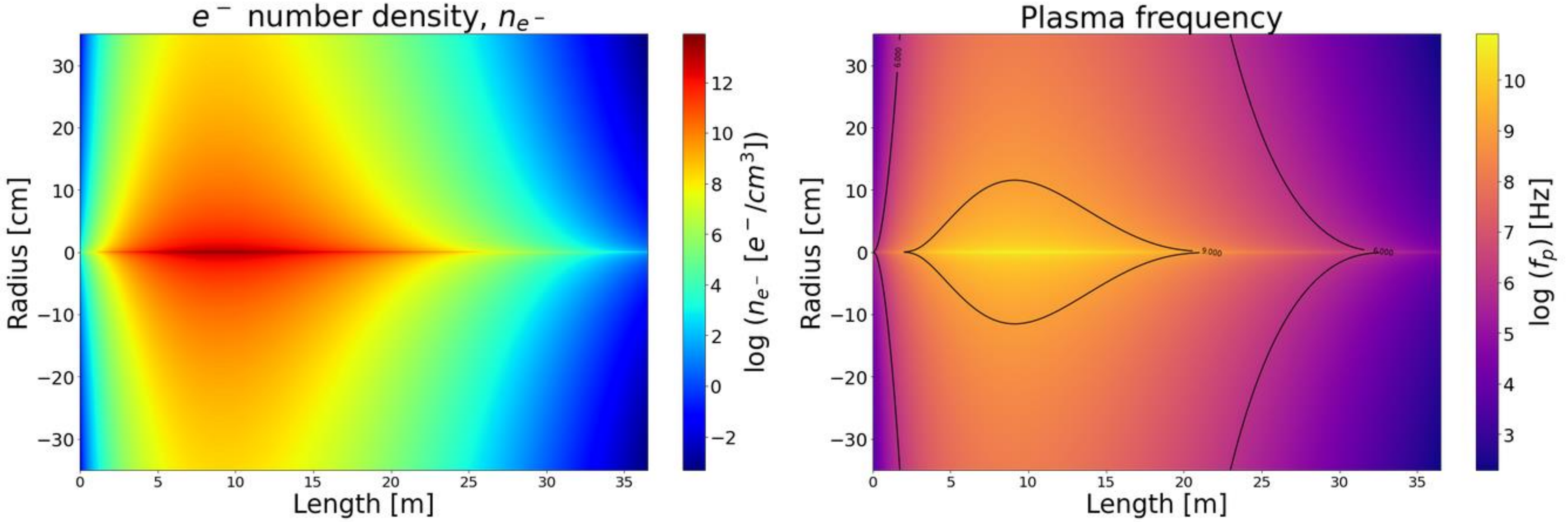
Interuniversitair Reactor Instituut, Mekelweg 15, 2629 JB Delft, The Netherlands

Ice is frequently taken as a model when factors controlling proton transport in hydrogen-bonded molecular networks are discussed. Such discussions have increased with the acknowledgement that proton transfer across cell membranes may play a significant part in energy conversion and storage in biological systems[1-4] and that this transfer may involve hydrogen-bonded

Figure from arXiv:1210.5140v2

RF SCATTERING FROM PARTICLE CASCADES

LENGTH/TIME SCALES



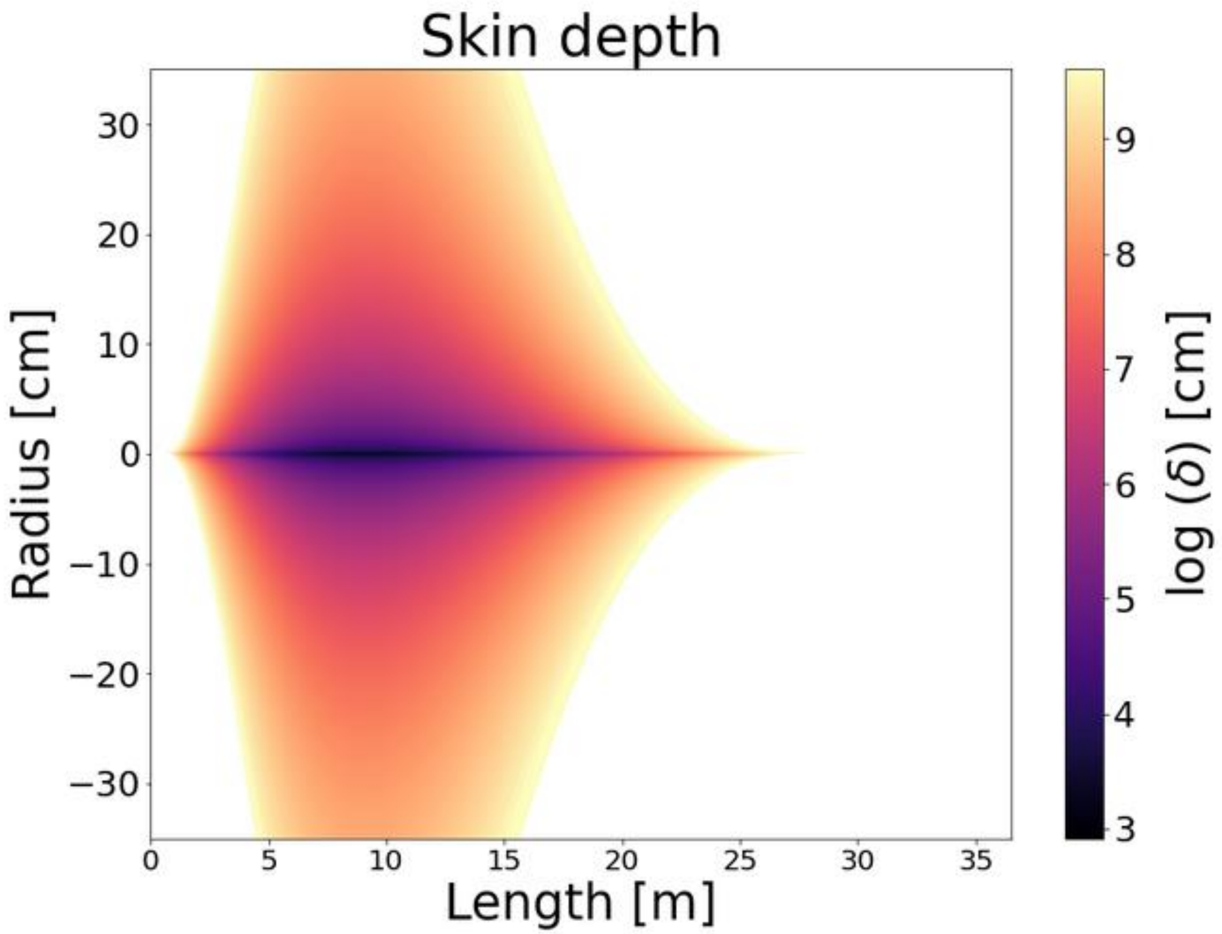
ω_p : Plasma frequency → ~ MHz up to 10's of GHz

ω : Detection frequency → ~ 100 MHz – 5 GHz

ν_c : Elastic collision rate → ~88 THz in ice

RF SCATTERING FROM PARTICLE CASCADES

SKIN DEPTH AND EFFECTIVE SCATTERING SIZE



→ Effective scattering size ~10-100 cm^2

Fig: Enrique Huesca Santiago ; 1 EeV shower energy

RF SCATTERING FROM PARTICLE CASCADES

SIMULATIONS: RADIOSCATTER + MACROSCATTER

RadioScatter:
S. Prohira and D. Besson, Nucl. Instrum. Meth.A922, 161(2019), arXiv:1710.02883

https://github.com/prchyr/RadioScatter

Individual particle level MC treatment including collisional effects.

Macroscatter:
K.D. de Vries, E.H. Santiago, RET collab., in preparation.

Fig. from: Nucl. Instrum. Meth.A922, 161(2019), arXiv:1710.02883

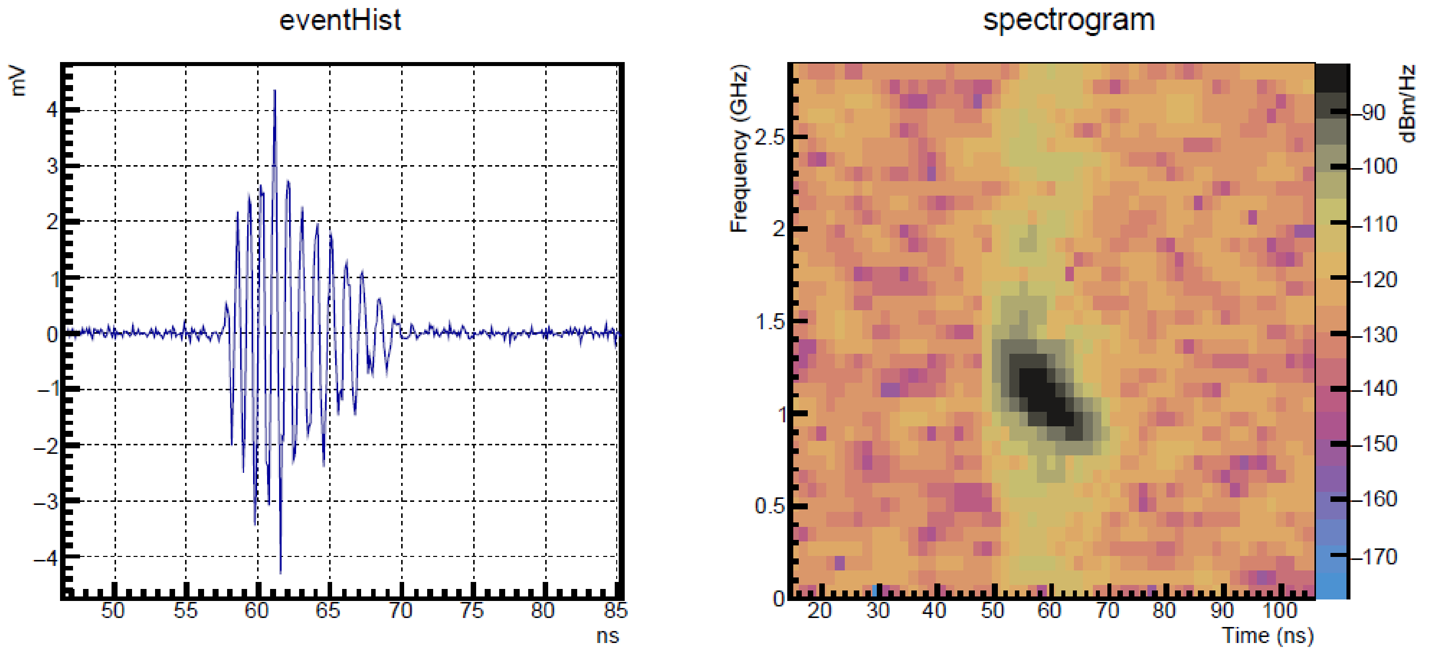


Figure 8: Simulated radio reflection for a 5 GHz bandwidth receiver, from an electron-initiated plasma consisting of 10^9 13.6 GeV primaries, superimposed upon thermal noise, with a sounding frequency of 1.15 GHz CW. The transmitter output power is 10 W and the plasma lifetime is 0.1 ns. The observed chirp-like signal is a function of the TX-PSP-RX geometry.

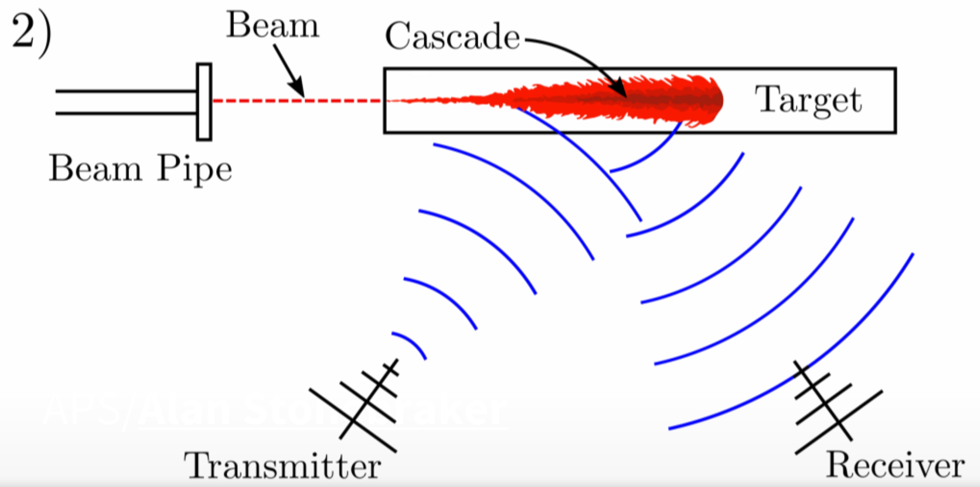
DETECTING HIGH-ENERGY PARTICLE CASCADES AT SLAC

Observation of Radar Echoes from High-Energy Particle Cascades

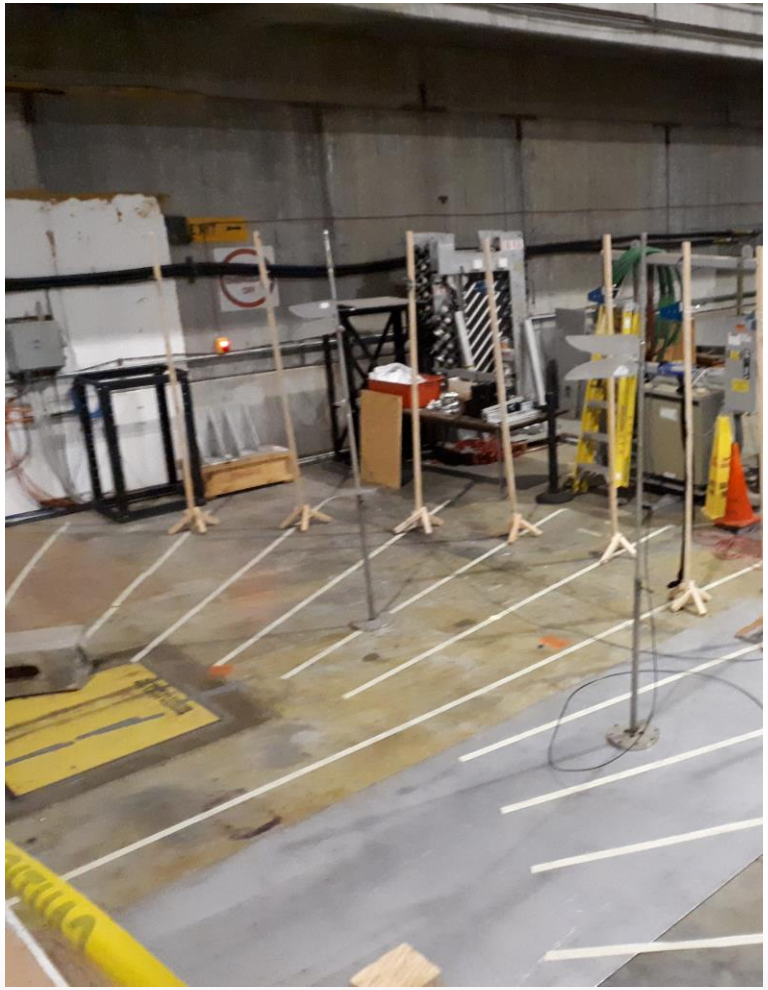
S. Prohira, K. D. de Vries, P. Allison, J. Beatty, D. Besson, A. Connolly, N. van Eijndhoven, C. Hast, C.-Y. Kuo, U. A. Latif, T. Meures, J. Nam, A. Nozdrina, J. P. Ralston, Z. Riesen, C. Sbrocco, J. Torres, and S. Wissel

Phys. Rev. Lett. 124, 091101 (2020)

https://arxiv.org/pdf/1910.12830.pdf

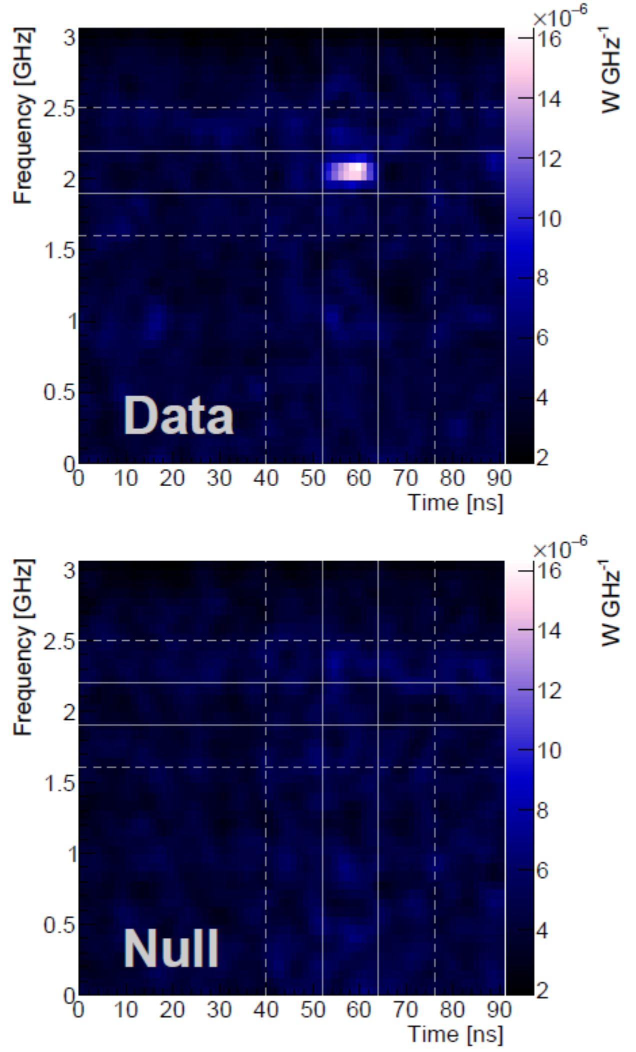


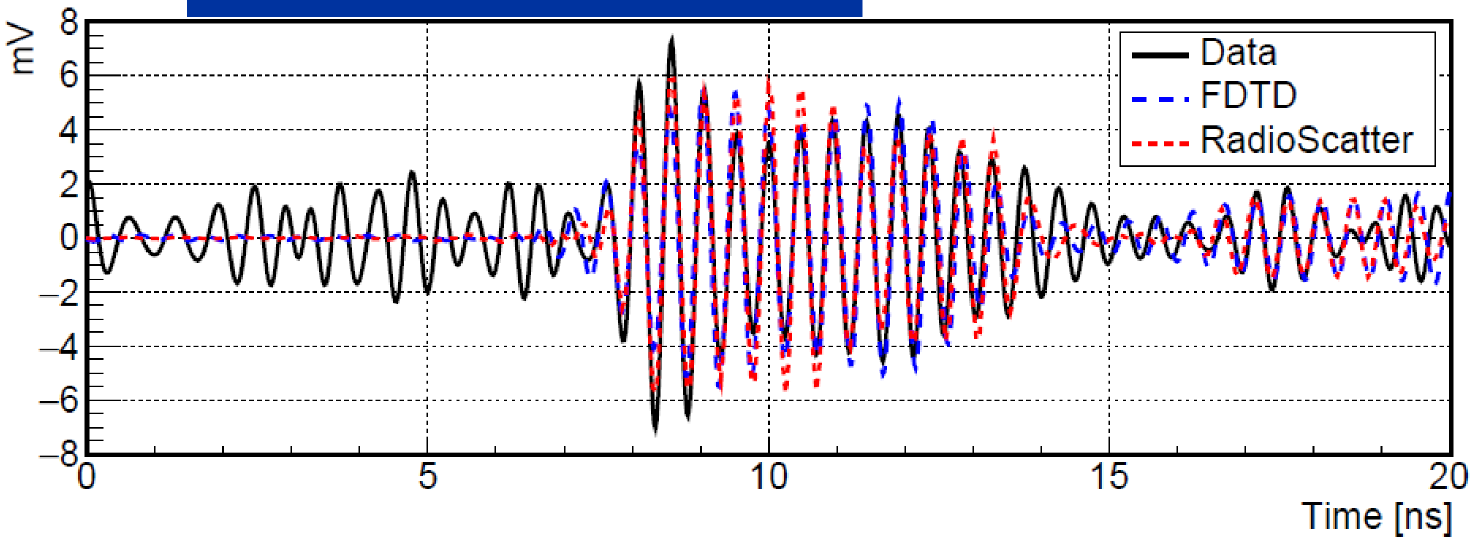
SLAC T-576 EXPERIMENT



DETECTING HIGH-ENERGY PARTICLE CASCADES AT SLAC

SLAC T-576 EXPERIMENT





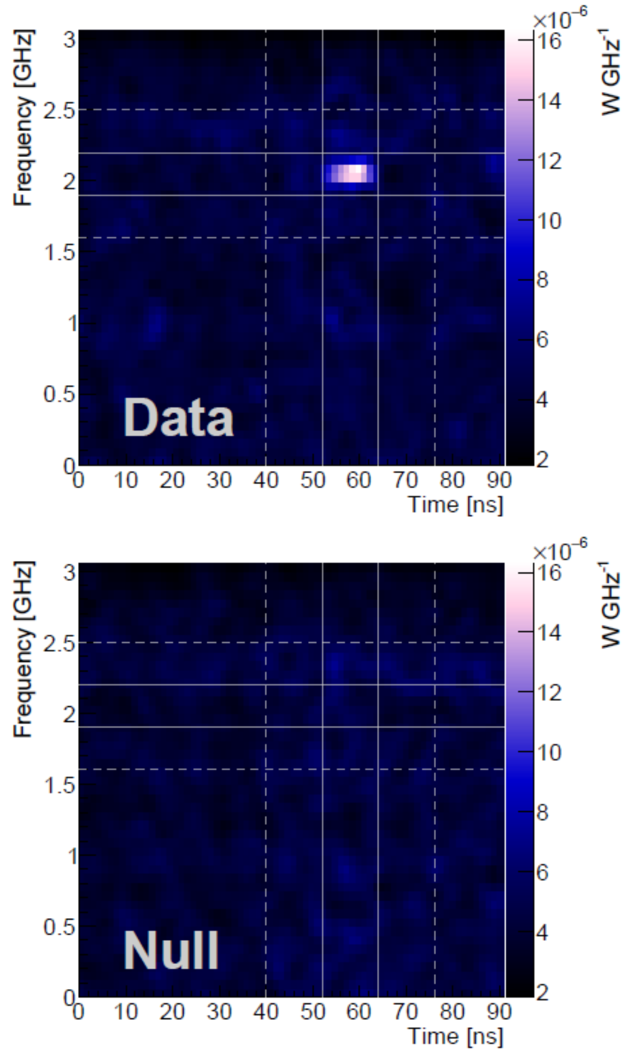
Difficult analysis due to **Askaryan and Transition radiation** backgrounds → Singular Value Decomposition to filter.

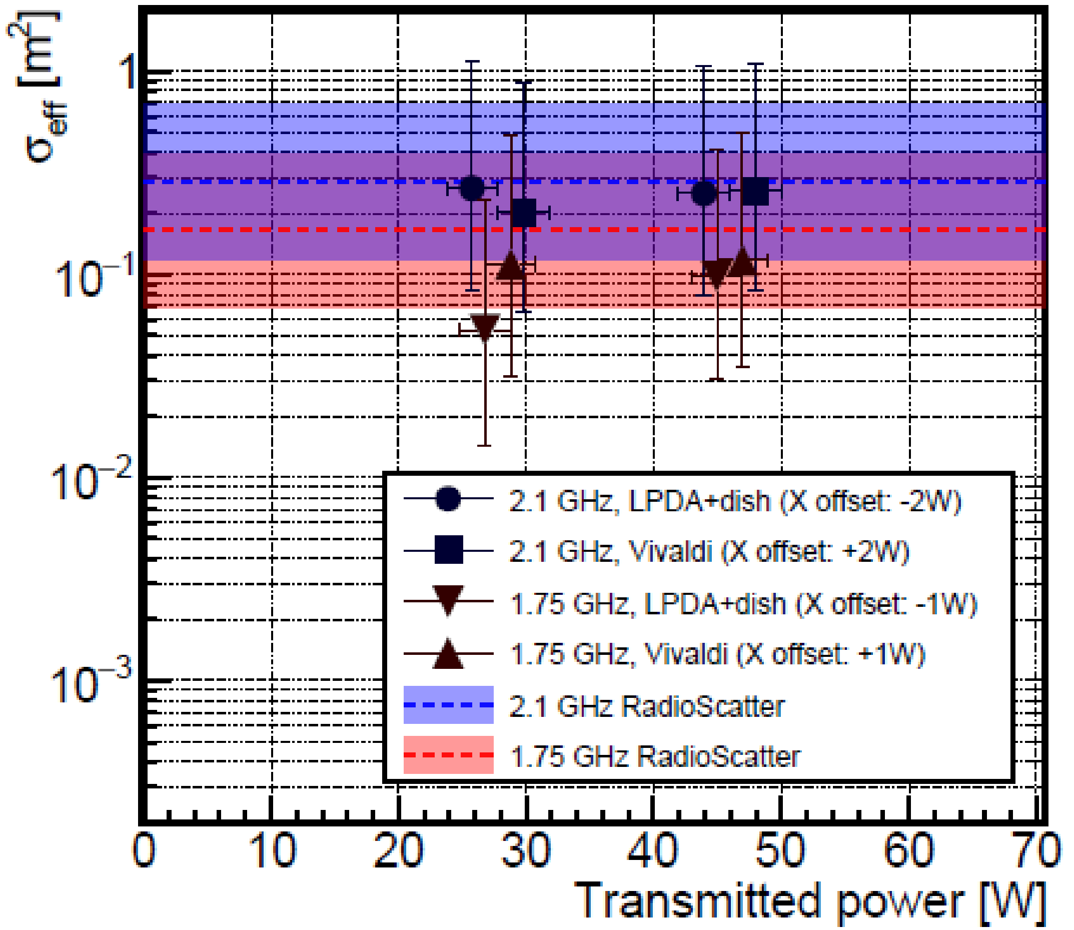
→ **Excellent agreement between data and simulations**

Method: S. Prohira, et al., Phys. Rev. D 100, 072003 (arxiv:1810.09914) || S. Prohira, 2020 J. Phys.: Conf. Ser. **1525** 012119 (arxiv:1910.11314)

DETECTING HIGH-ENERGY PARTICLE CASCADES AT SLAC

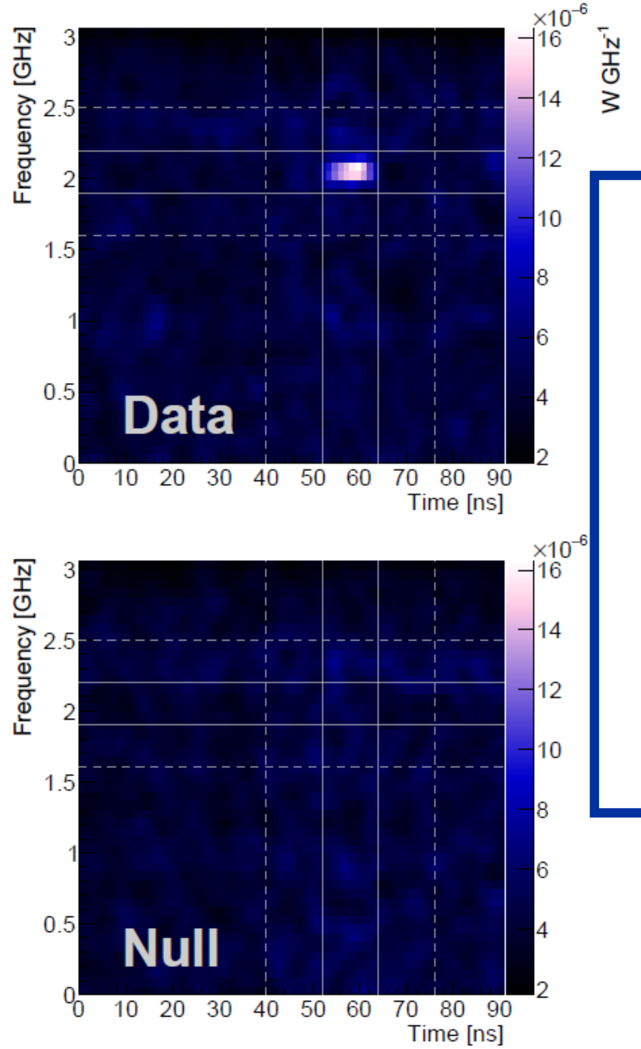
SLAC T-576 EXPERIMENT

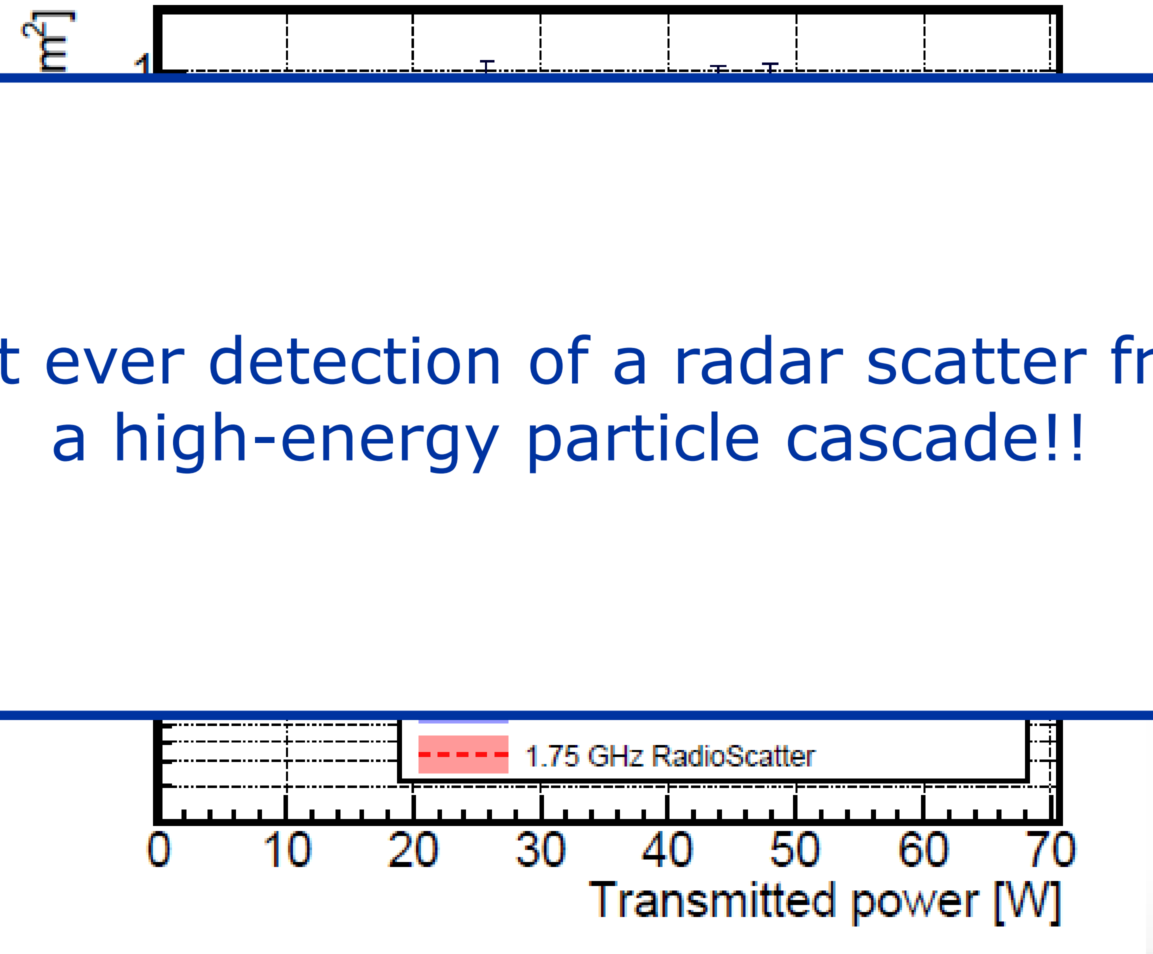




DETECTING HIGH-ENERGY PARTICLE CASCADES AT SLAC

SLAC T-576 EXPERIMENT

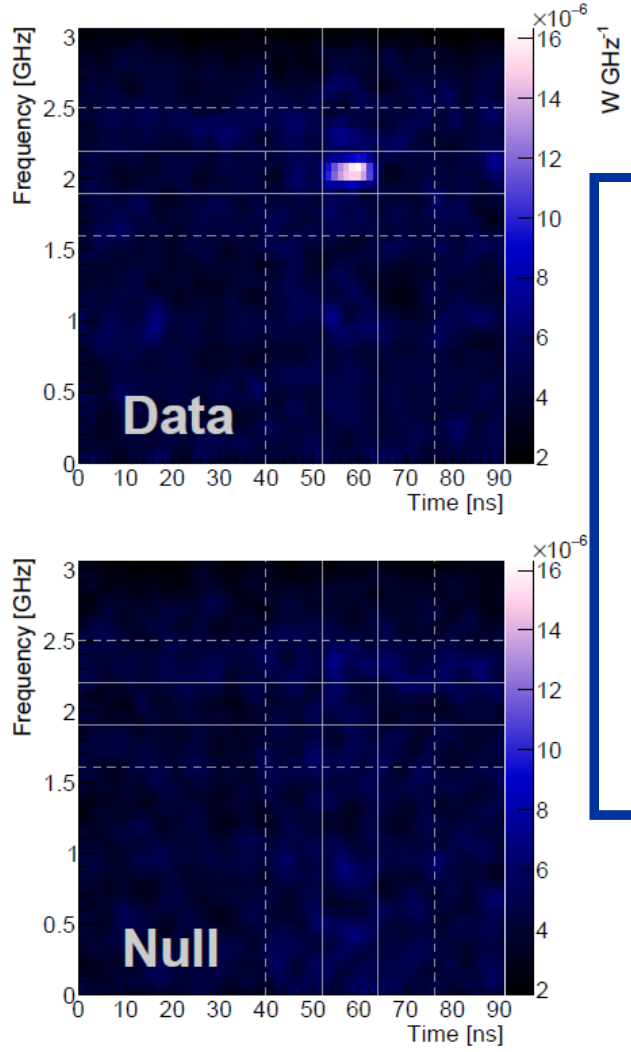


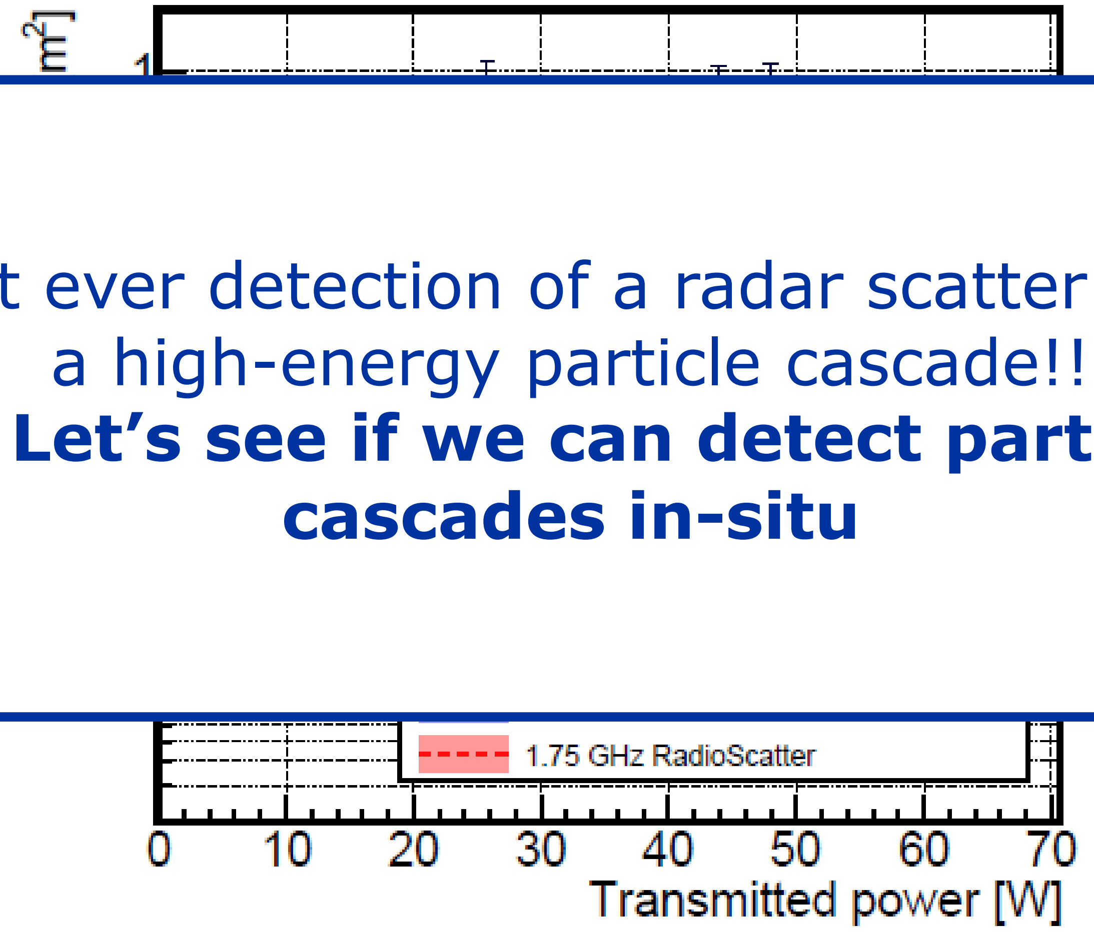


First ever detection of a radar scatter from a high-energy particle cascade!!

DETECTING HIGH-ENERGY PARTICLE CASCADES AT SLAC

SLAC T-576 EXPERIMENT





First ever detection of a radar scatter from a high-energy particle cascade!!

→ **Let's see if we can detect particle cascades in-situ**

DETECTING HIGH-ENERGY PARTICLE CASCADES AT SLAC

FROM SLAC TO IN-SITU: WHAT TO EXPECT?

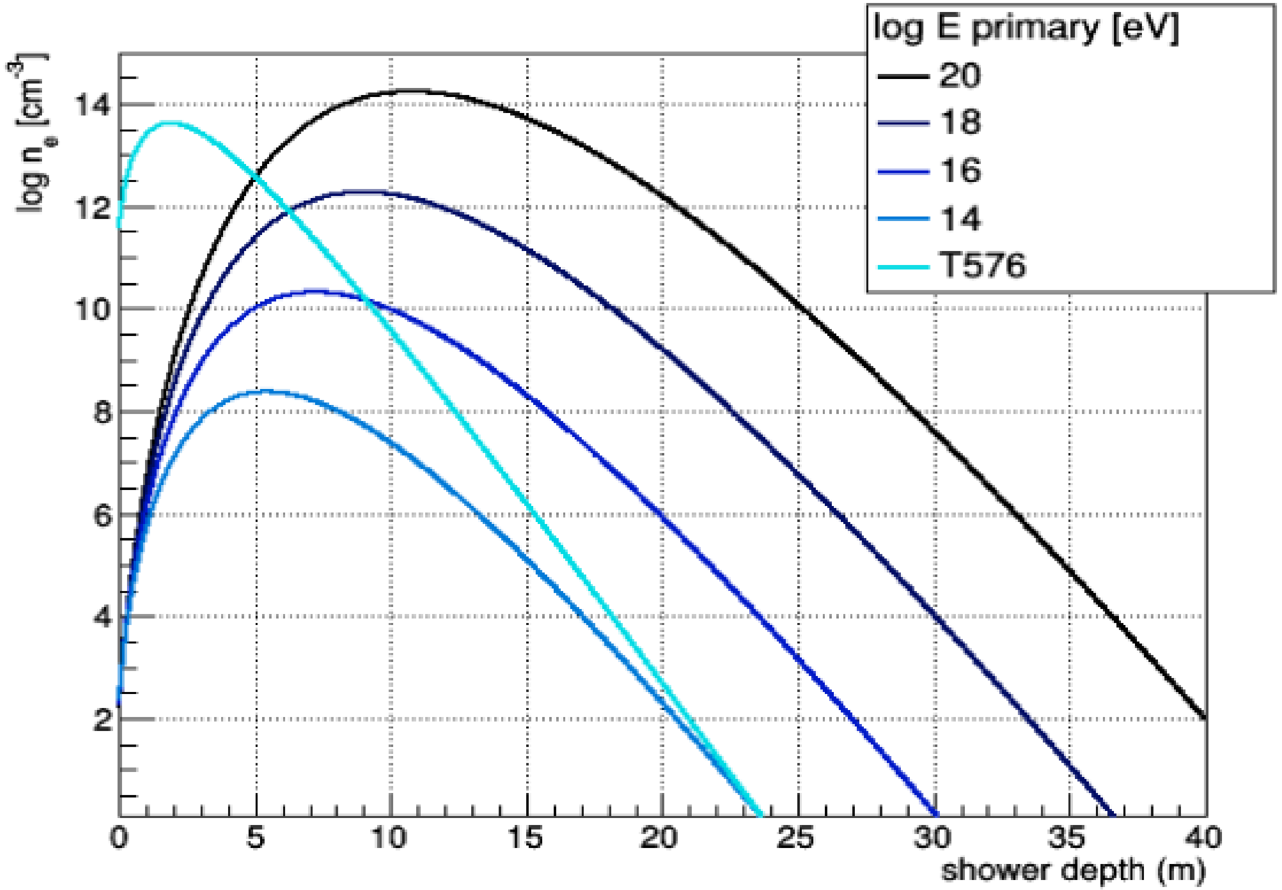
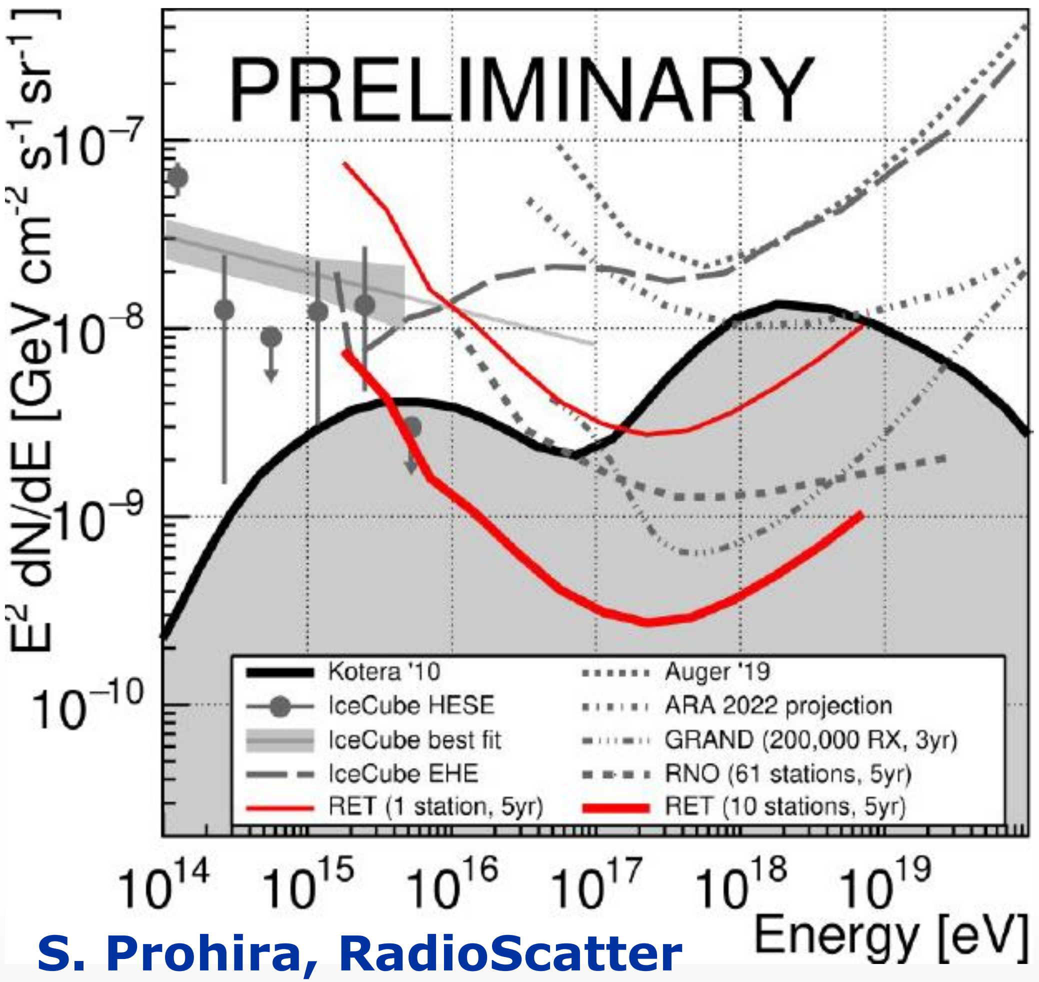


Fig: S. Prohira

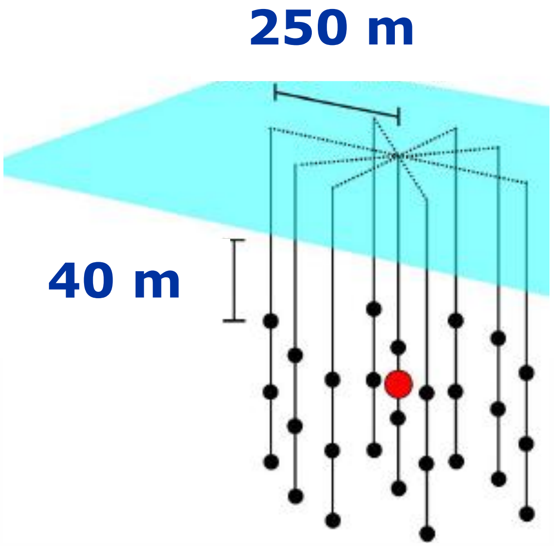
THE RADAR ECHO TELESCOPE FOR NEUTRINOS

WHY RADAR? PROBING THE PEV-EEV COSMIC NEUTRINO FLUX

- **40 kW, 1.5 km deep transmitter** (similar to typical radio broadcast station). → **Phased transmitters** to not push all power in a single antenna.
- **27** receivers on 9 **radial 250m** out strings. **Vertical** separation **40m**.
- Vertices simulated in **2.5 km x 5 km x 5km volume**.
- **Trigger at 0 dB noise**.



S. Prohira, RadioScatter



DETECTING PARTICLE CASCADES IN NATURE

THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

the RADAR ECHO TELESCOPE for COSMIC RAYS

DETECTING PARTICLE CASCADES IN NATURE

the RADAR ECHO TELESCOPE for COSMIC RAYS

The Radar Echo Telescope for Cosmic Rays: Pathfinder Experiment for a Next-Generation Neutrino Observatory

S. Prohira,[1,*] K.D. de Vries,[2,†] P. Allison,[1] J. Beatty,[1] D. Besson,[3,4] A. Connolly,[1] P. Dasgupta,[5] C. Deaconu,[6] S. De Kockere,[2] D. Frikken,[1] C. Hast,[7] E. Huesca Santiago,[2] C.-Y. Kuo,[8] U.A. Latif,[3,2] V. Lukic,[2] T. Meures,[9] K. Mulrey,[2] J. Nam,[8] A. Nozdrina,[3] E. Oberla,[6] J.P. Ralston,[3] C. Sbrocco,[1] R.S. Stanley,[2] J. Torres,[1] S. Toscano,[5] D. Van den Broeck,[2] N. van Eijndhoven,[2] and S. Wissel[10,11]
(Radar Echo Telescope)

RET-CR paper: arXiv: 2104.00459

Funded by NSF (NSF/PHY-2012980) and the EU/ERC HORIZON2020 PROGRAM.

THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

IN-ICE AIR SHOWER CORES: A BRIEF HISTORY

In-Ice radio detection of air shower cores

DAVID SECKEL[1], SURUJ SEUNARINE[2], JOHN CLEM[1], AMIR JAVAID[1]
[1]*Deptartment of Physics and Astronomy, University of Delaware, Newark DE 19716*
[2]*Department of Physics, Canterbury University, Christchurch NZ.*
seckel@bartol.udel.edu

Proc. 30th ICRC, V5 (2007) p1029-1032

The cosmic-ray air-shower signal in Askaryan radio detectors

Krijn D. de Vries[a], Stijn Buitink[a], Nick van Eijndhoven[a], Thomas Meures[b], Aongus Ó Murchadha[b], Olaf Scholten[a,c]

[a]*Vrije Universiteit Brussel, Dienst ELEM, B-1050 Brussels, Belgium*
[b]*Université Libre de Bruxelles, Department of Physics, B-1050 Brussels, Belgium*
[c]*University Groningen, KVI Center for Advanced Radiation Technology,Groningen, The Netherlands*

Astropart.Phys. 74 (2016) 96-104
arXiv:1503.02808

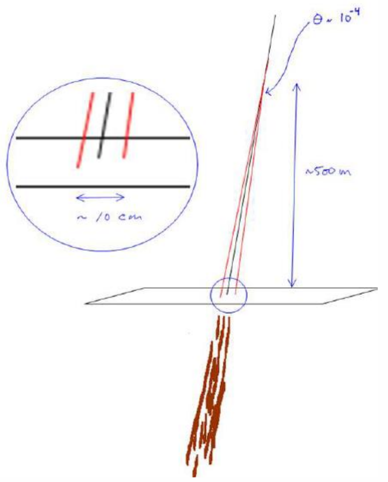


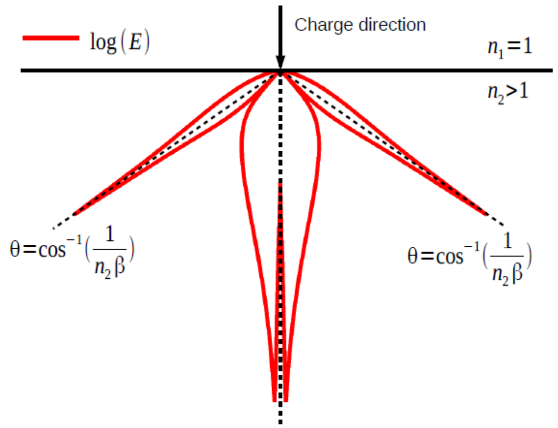
Fig: D. Seckel

The Radar Echo Telescope for Cosmic Rays: Pathfinder Experiment for a Next-Generation Neutrino Observatory

S. Prohira,[1,*] K.D. de Vries,[2,†] P. Allison,[1] J. Beatty,[1] D. Besson,[3,4] A. Connolly,[1] P. Dasgupta,[5] C. Deaconu,[6] S. De Kockere,[2] D. Frikken,[1] C. Hast,[7] E. Huesca Santiago,[2] C.-Y. Kuo,[8] U.A. Latif,[3,2] V. Lukic,[2] T. Meures,[9] K. Mulrey,[2] J. Nam,[8] A. Nozdrina,[3] E. Oberla,[6] J.P. Ralston,[3] C. Sbrocco,[1] R.S. Stanley,[2] J. Torres,[1] S. Toscano,[5] D. Van den Broeck,[2] N. van Eijndhoven,[2] and S. Wissel[10,11]
(Radar Echo Telescope)

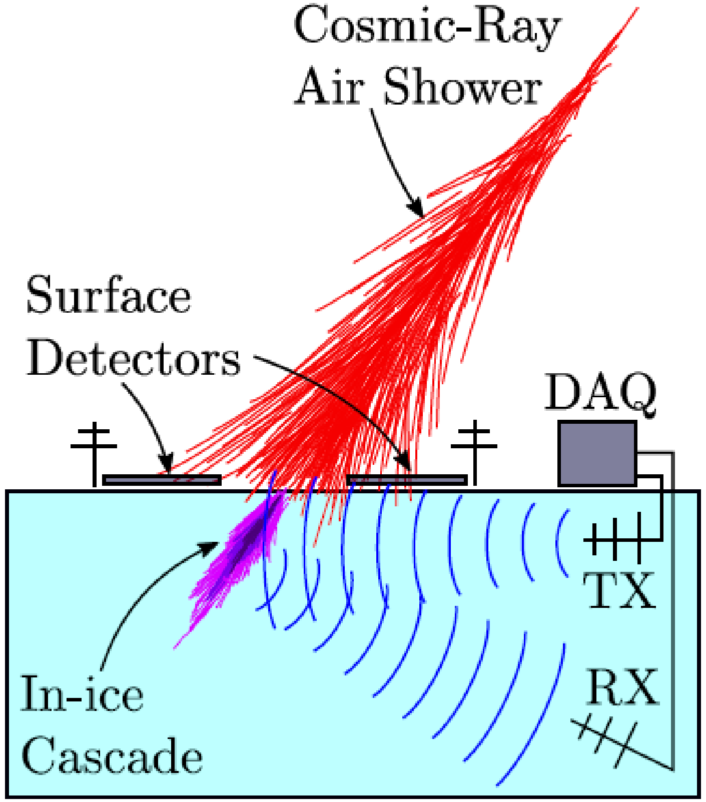
arXiv:2104.00459(2021)

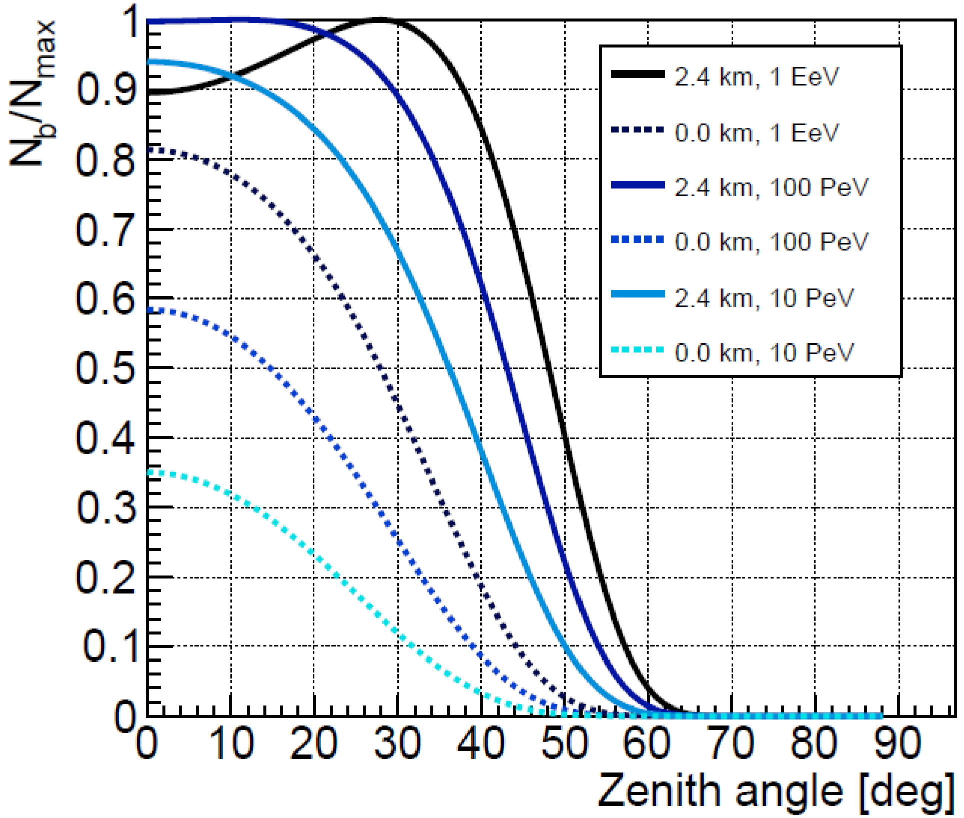
the RADAR ECHO TELESCOPE for COSMIC RAYS



THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

DETECTING PARTICLE CASCADES IN NATURE

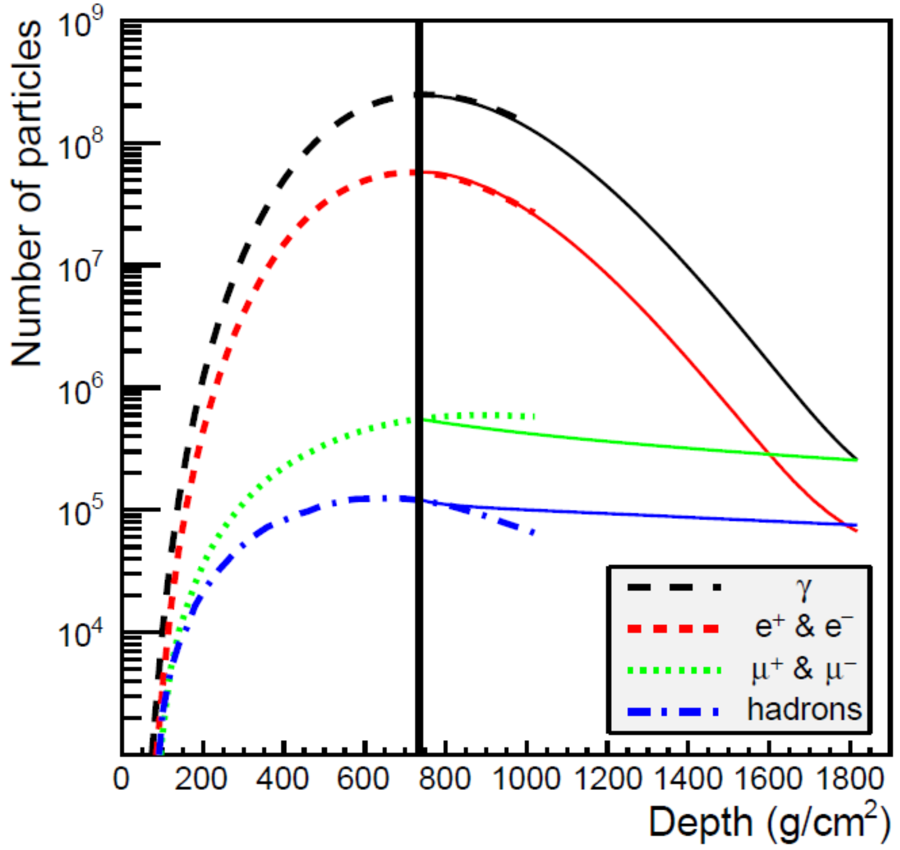




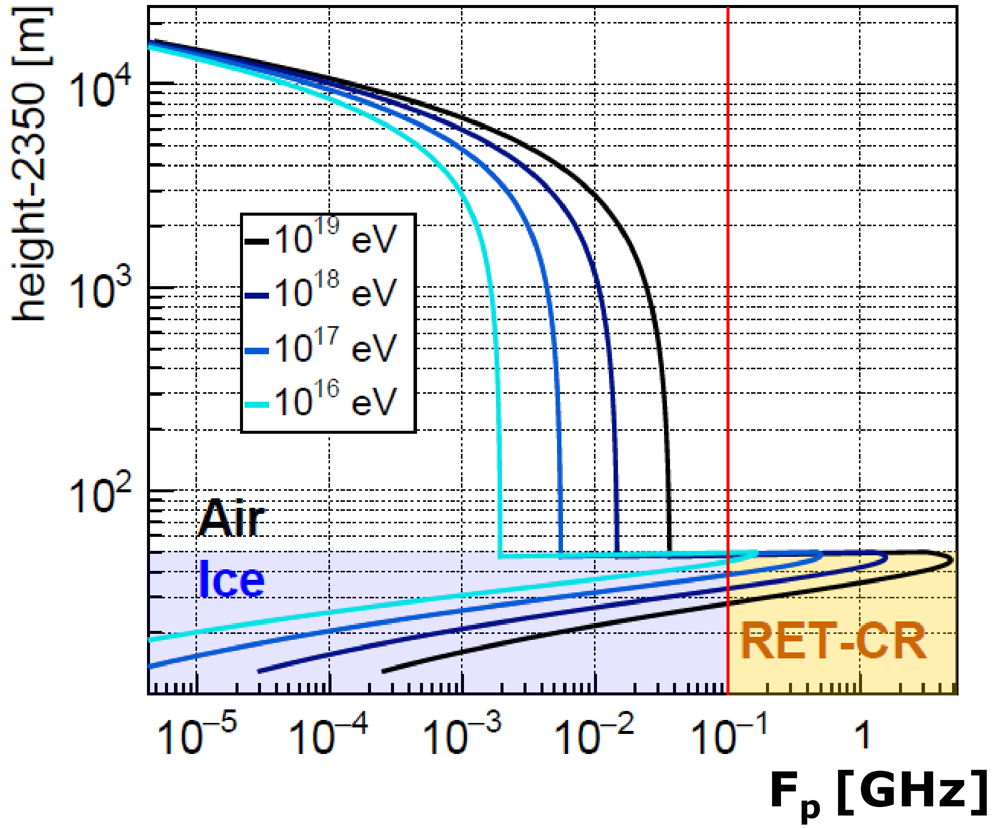
RET-CR paper: arXiv: 2104.00459

THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

DETECTING PARTICLE CASCADES IN NATURE



Simon de Kockere
→Propagate showers from **CORSIKA into ice using GEANT4**

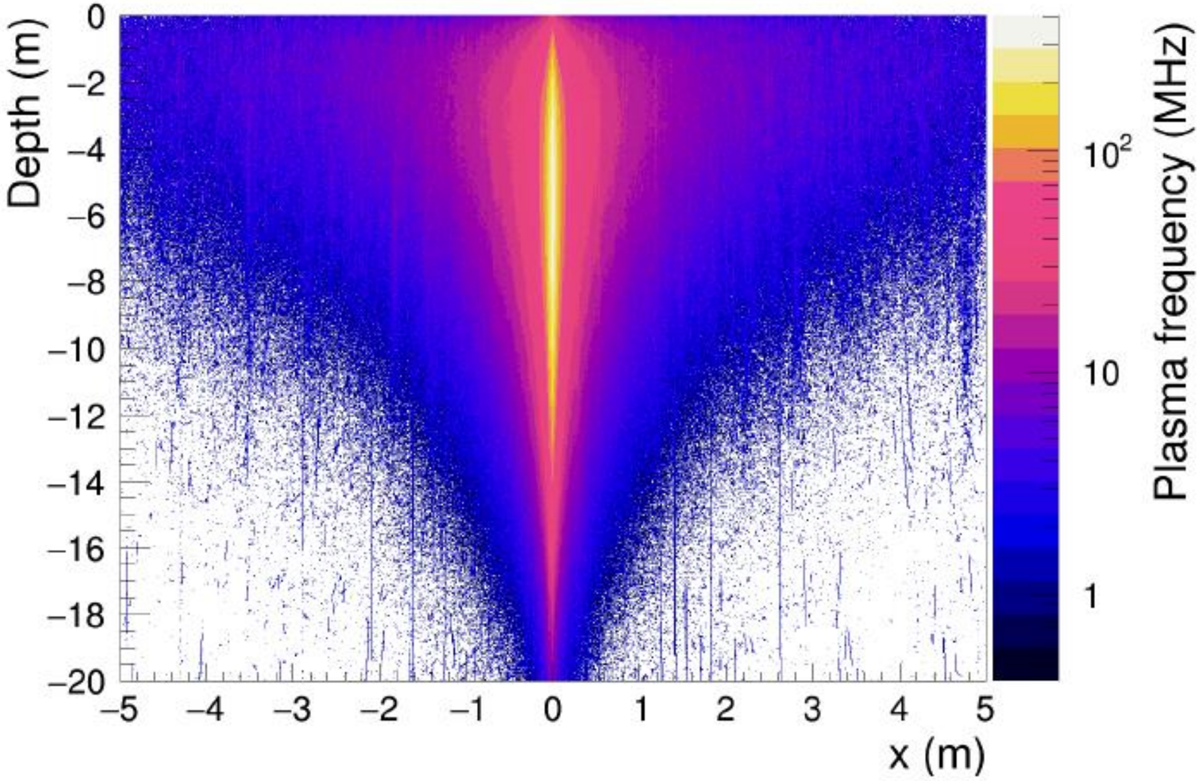


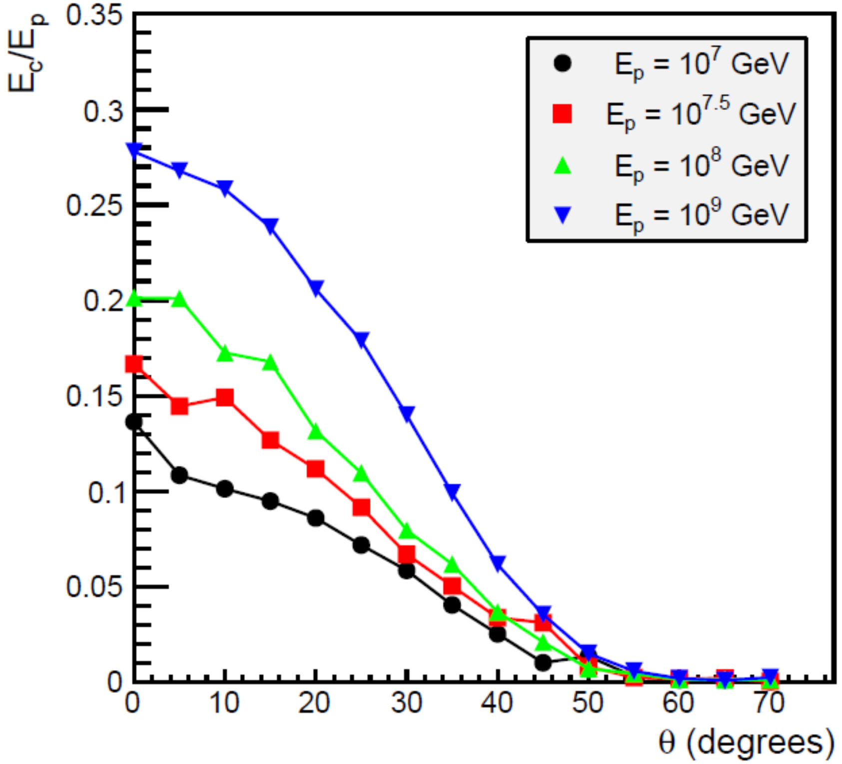
RET-CR paper: arXiv: 2104.00459

THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

DETECTING PARTICLE CASCADES IN NATURE

10^{17} eV primary cosmic-ray moving into ice. **Credit: Simon de Kockere**



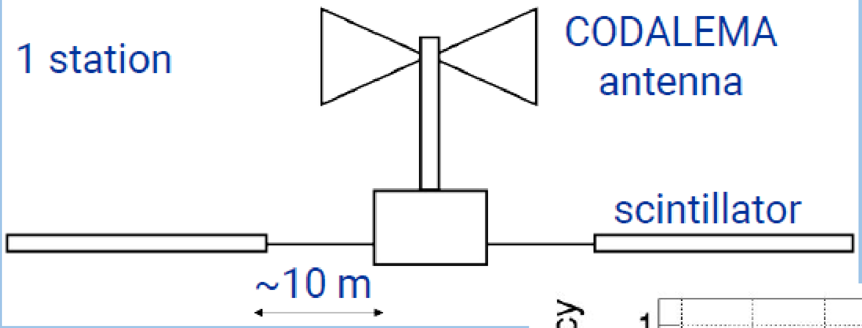


RET-CR paper: arXiv: 2104.00459

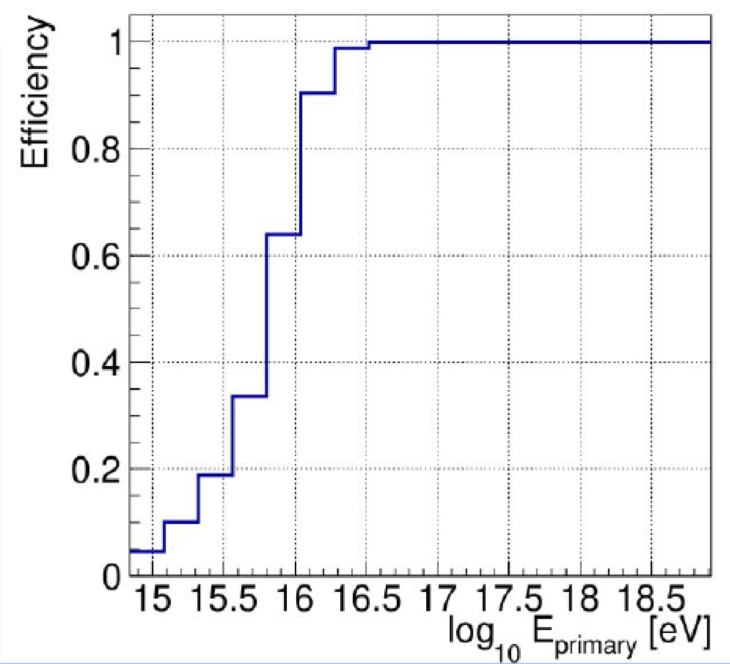
THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

RET-CR paper: arXiv: 2104.00459 Slide from Rose Stanley

Cosmic Ray Surface Detector



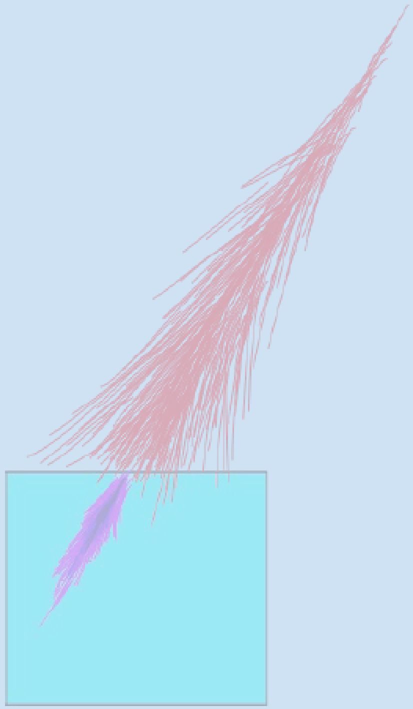
Simulations
- CORSIKA 7.7400 with QGSJETII-04 and URQMD 1.3cr
- CoREAS 1.4
- Geant4 9.6



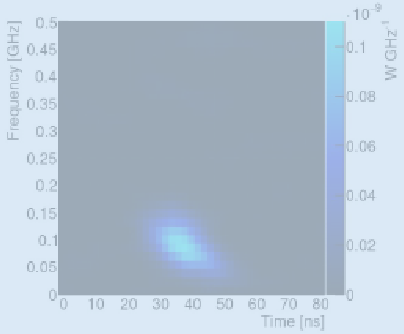
- ➔ Stations trigger independently
- ➔ 6 MeV threshold
- ➔ L0 trigger: both scintillators in one station
- ➔ L1 trigger: all stations within one cluster
- ➔ Trigger sent to radar detector

R. Stanley, K. Mulrey

Air-ice transition



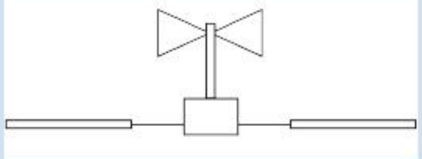
In-ice Radar Detector

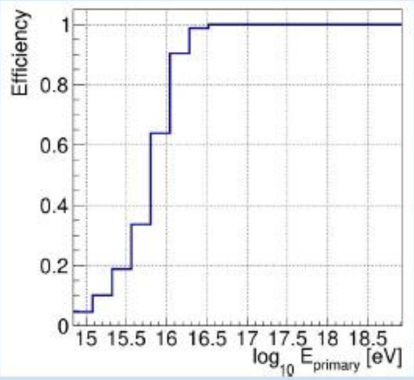


THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

RET-CR paper: arXiv: 2104.00459 **Slide from Rose Stanley**

CR Surface Detector

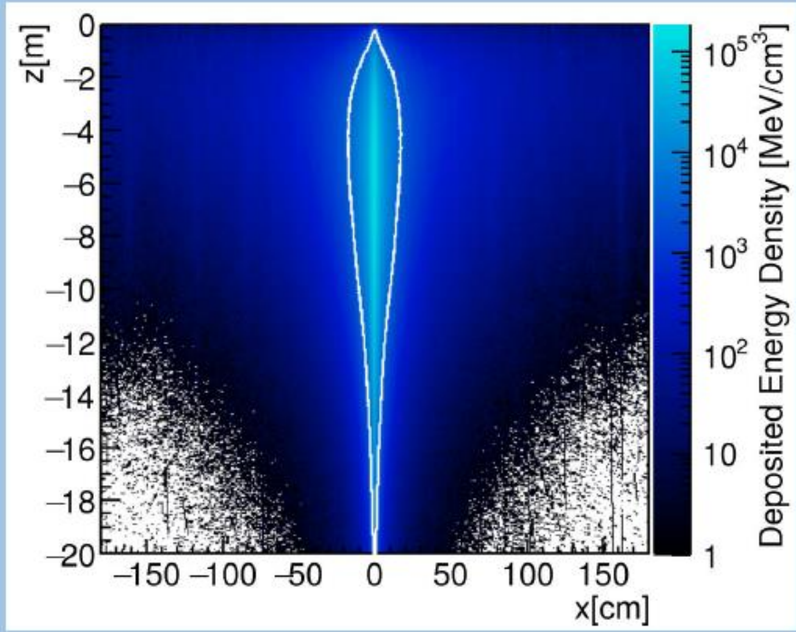




100% efficiency at $10^{16.5}$ eV

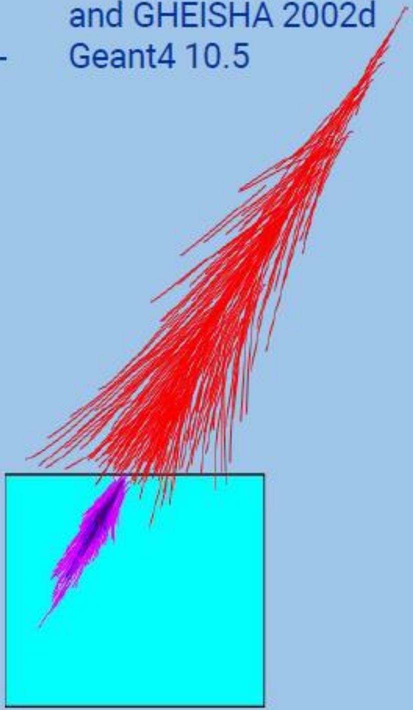
R. Stanley, K. Mulrey

Air-ice transition



Simulations

- CORSIKA 7.7100 with QGSJETII-04 and GHEISHA 2002d
- Geant4 10.5

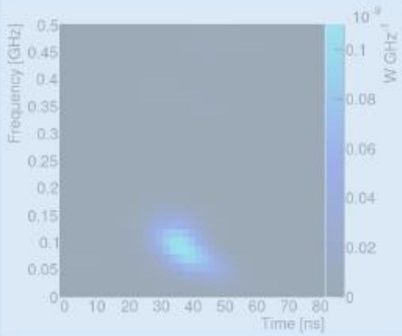


→ Approximately 10% of primary energy deposited into the ice at 2400 m

→ Secondary cascade in high elevation ice sheet

S. de Kockere

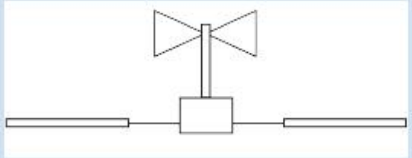
In-ice Radar Detector

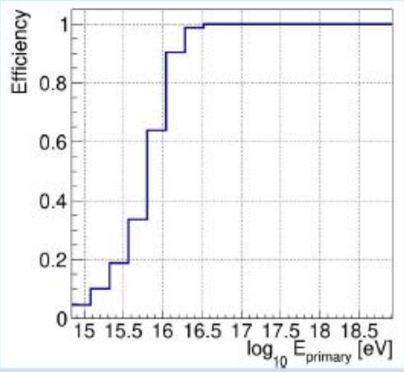


THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

RET-CR paper: arXiv: 2104.00459 Slide from Rose Stanley

CR Surface Detector

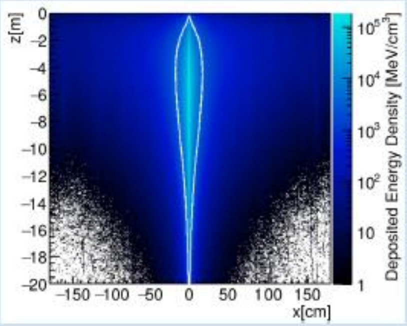




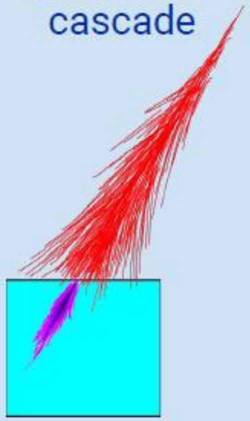
100% efficiency at $10^{16.5}$ eV

R. Stanley, K. Mulrey

Air-ice transition

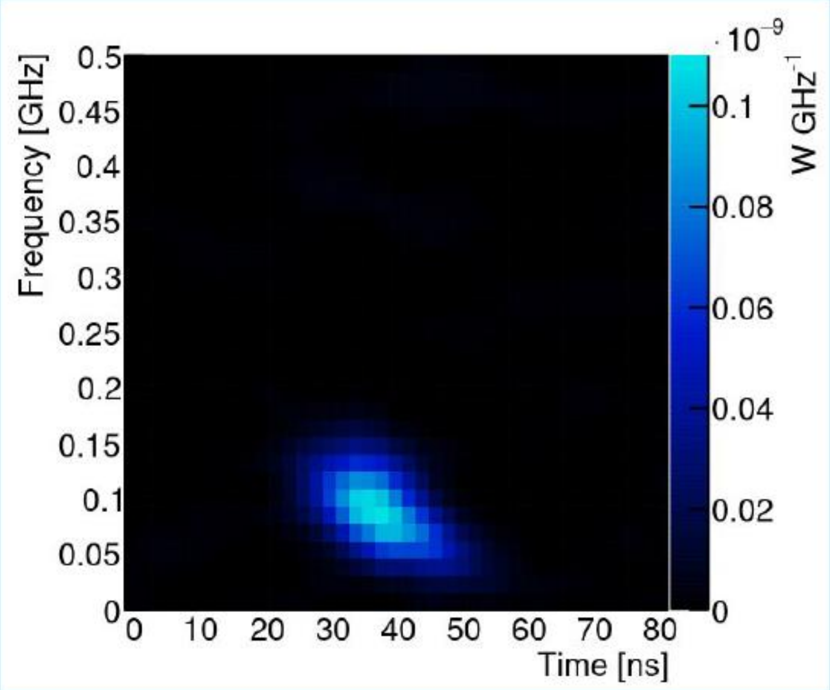


10% of primary energy in secondary cascade



S. de Kockere

In-ice Radar Detector



Simulations
- Radio Scatter 1.1.0

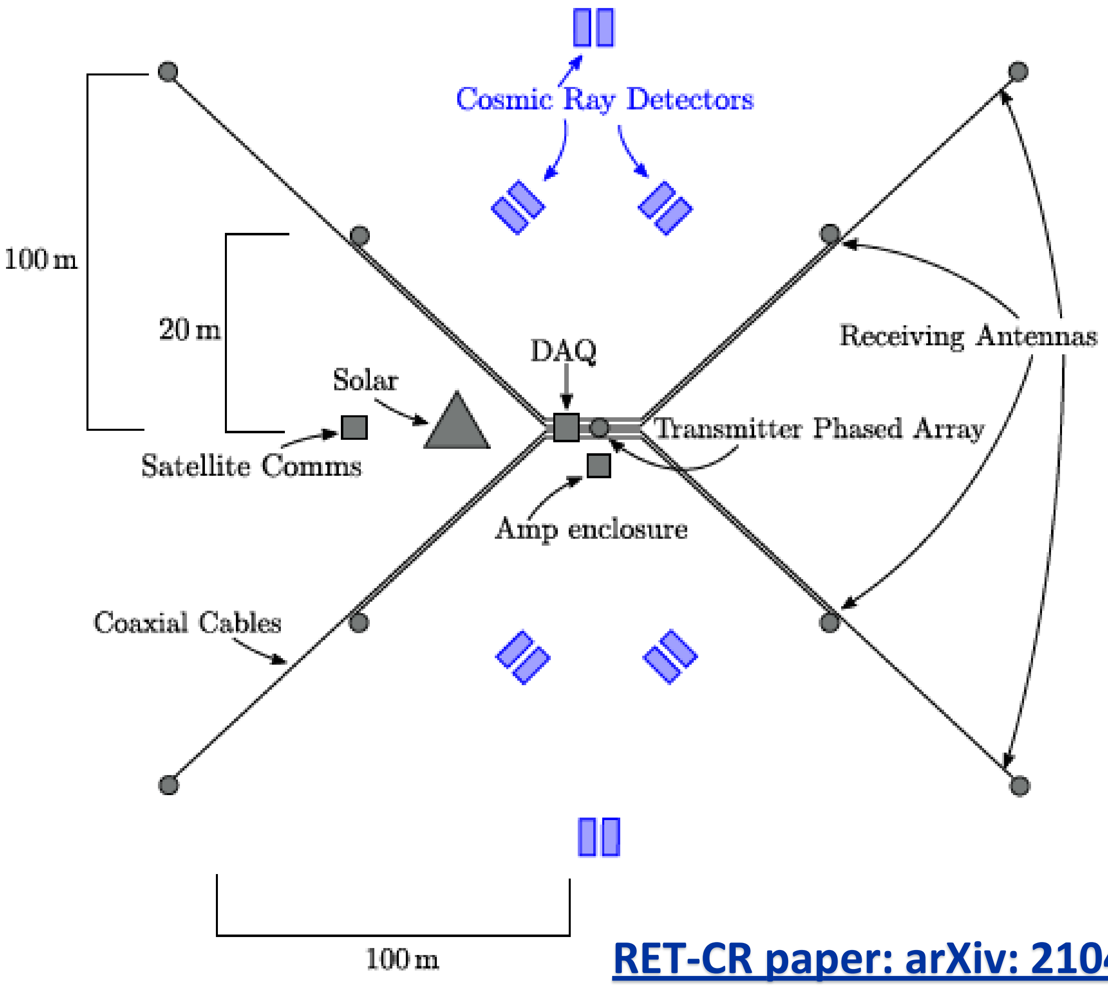
RadioScatter
- particle-level C++ code
- simulates radio scattering from ionization deposit

→ Interrogating frequency of 100 MHz
→ Data readout triggered by surface detector

S. Prohira

THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

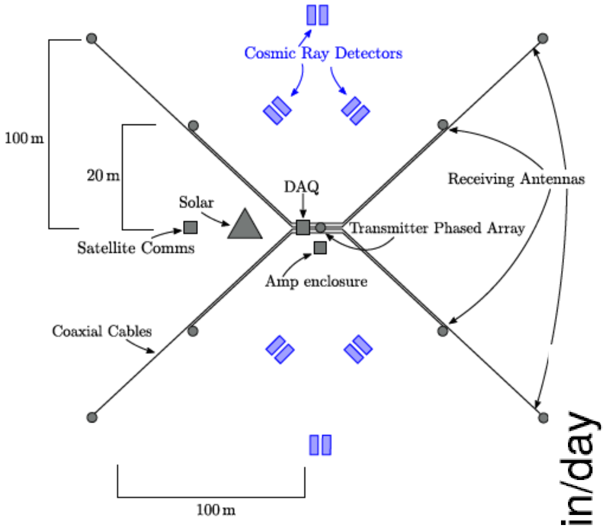
DETECTING PARTICLE CASCADES IN NATURE



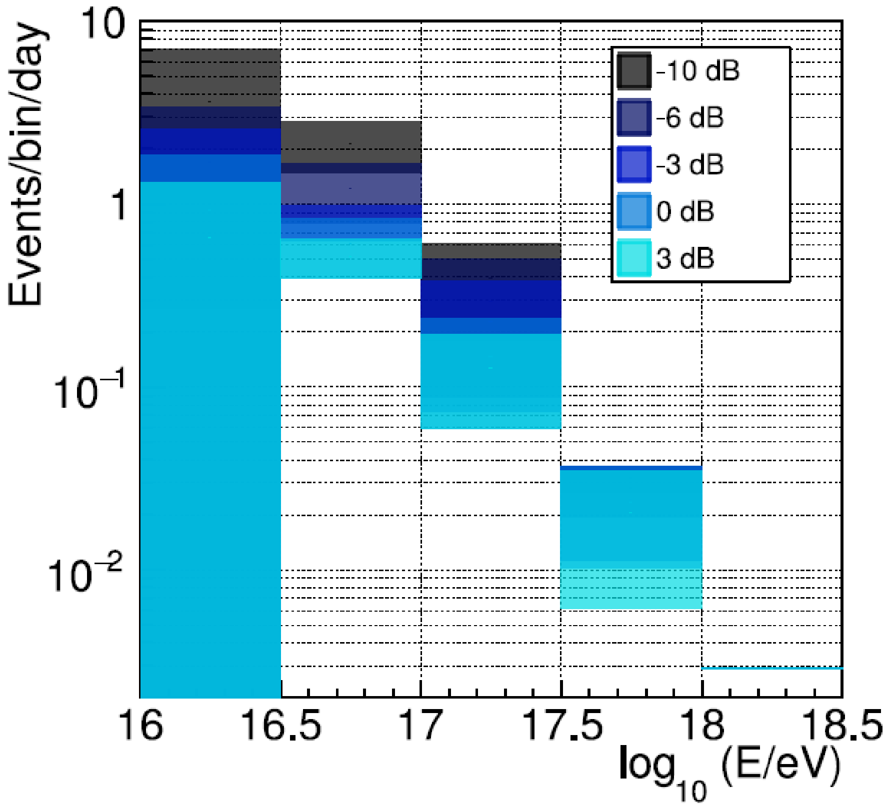
RET-CR paper: arXiv: 2104.00459

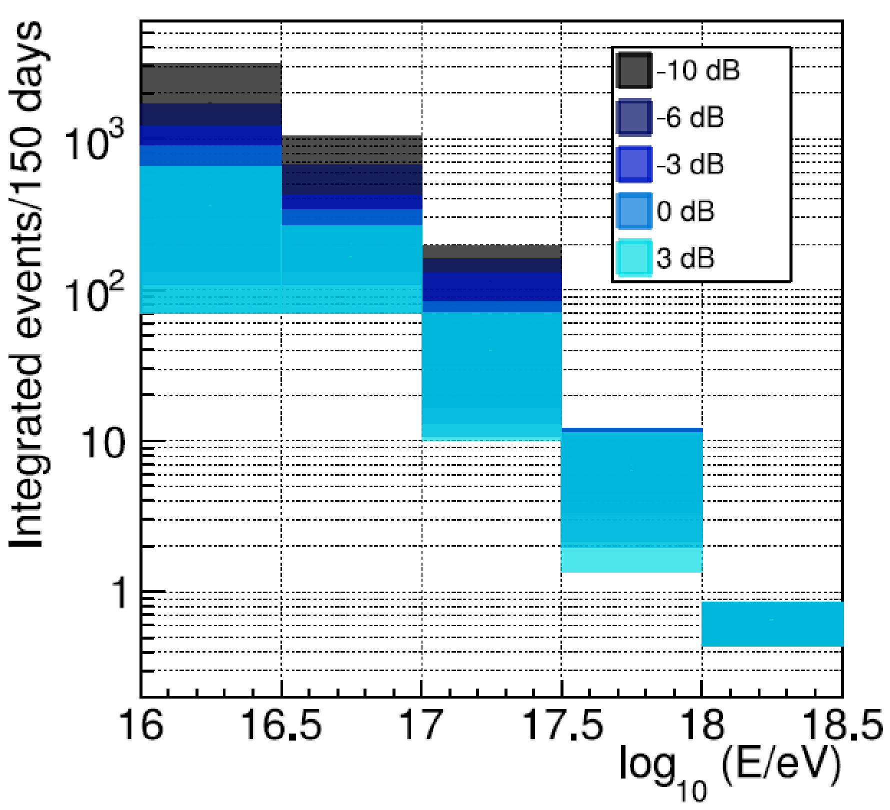
THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

DETECTING PARTICLE CASCADES IN NATURE



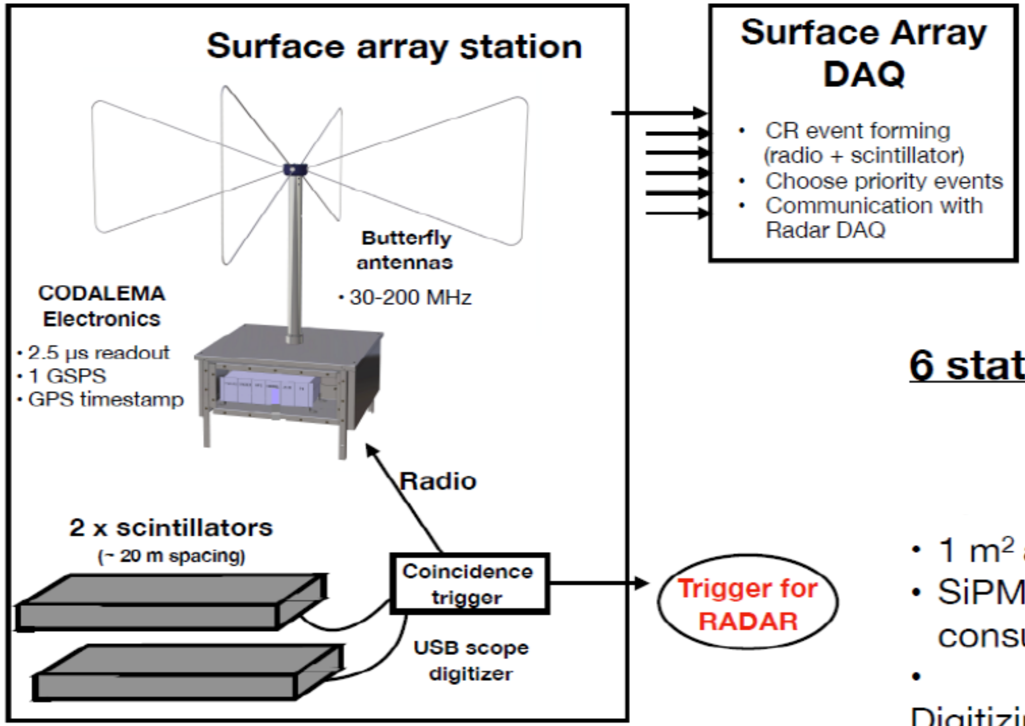
RET-CR paper: arXiv: 2104.00459





THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

RET-CR: COSMIC-RAY SURFACE STATIONS



Design based on CR energy cross-calibration array (K. Mulrey)

6 stations x 2 scintillators

- 1 m^2 area
- SiPM optimal (power consumption + cost)
-

Digitizing + trigger forming:

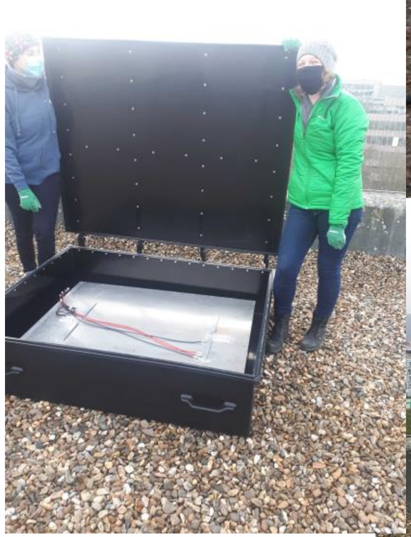
- Currently using Picoscope
- Should function in cold weather

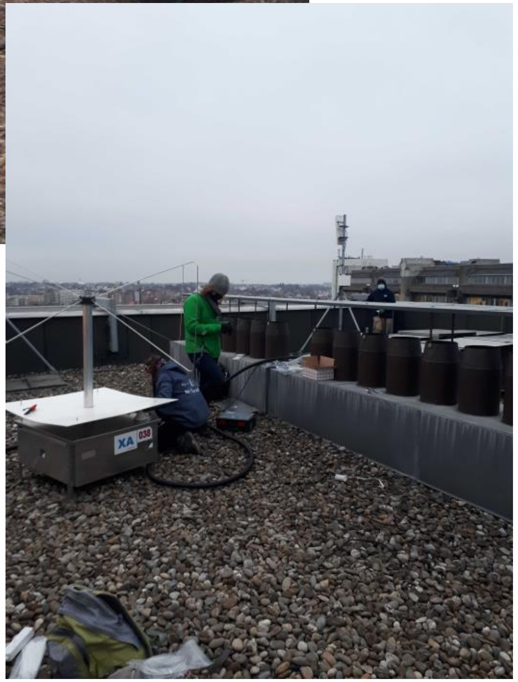
K. Mulrey, R. Stanley,
E.H. Santiago, K.D. de Vries

RET-CR paper: arXiv: 2104.00459

THE RADAR ECHO TELESCOPE FOR COSMIC RAYS

SURFACE SET-UP AT VUB INSTALLED AND TAKING DATA





Thanks!!