Broadband Lightning Radio Interferometry at the Pierre Auger Observatory

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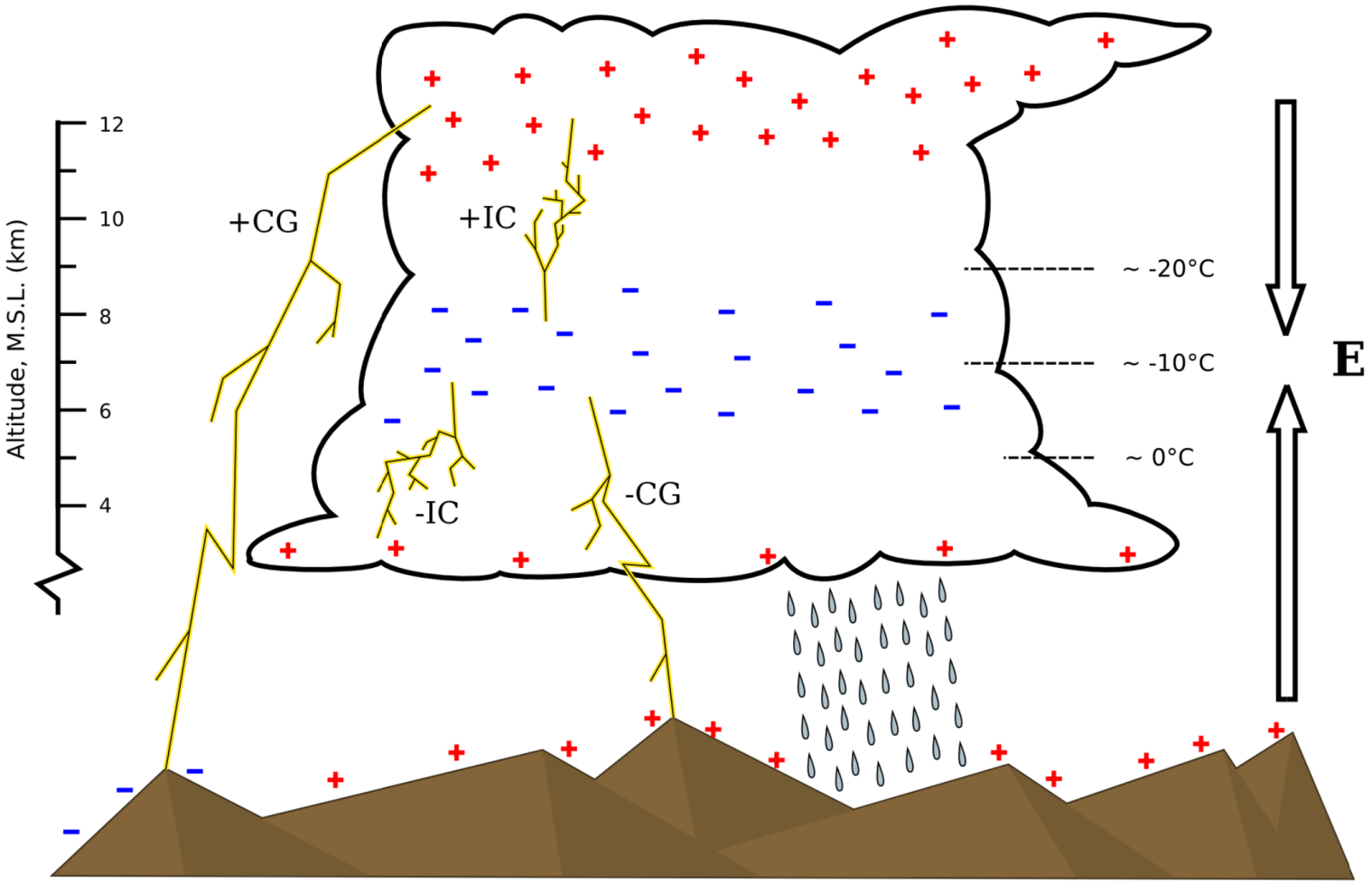
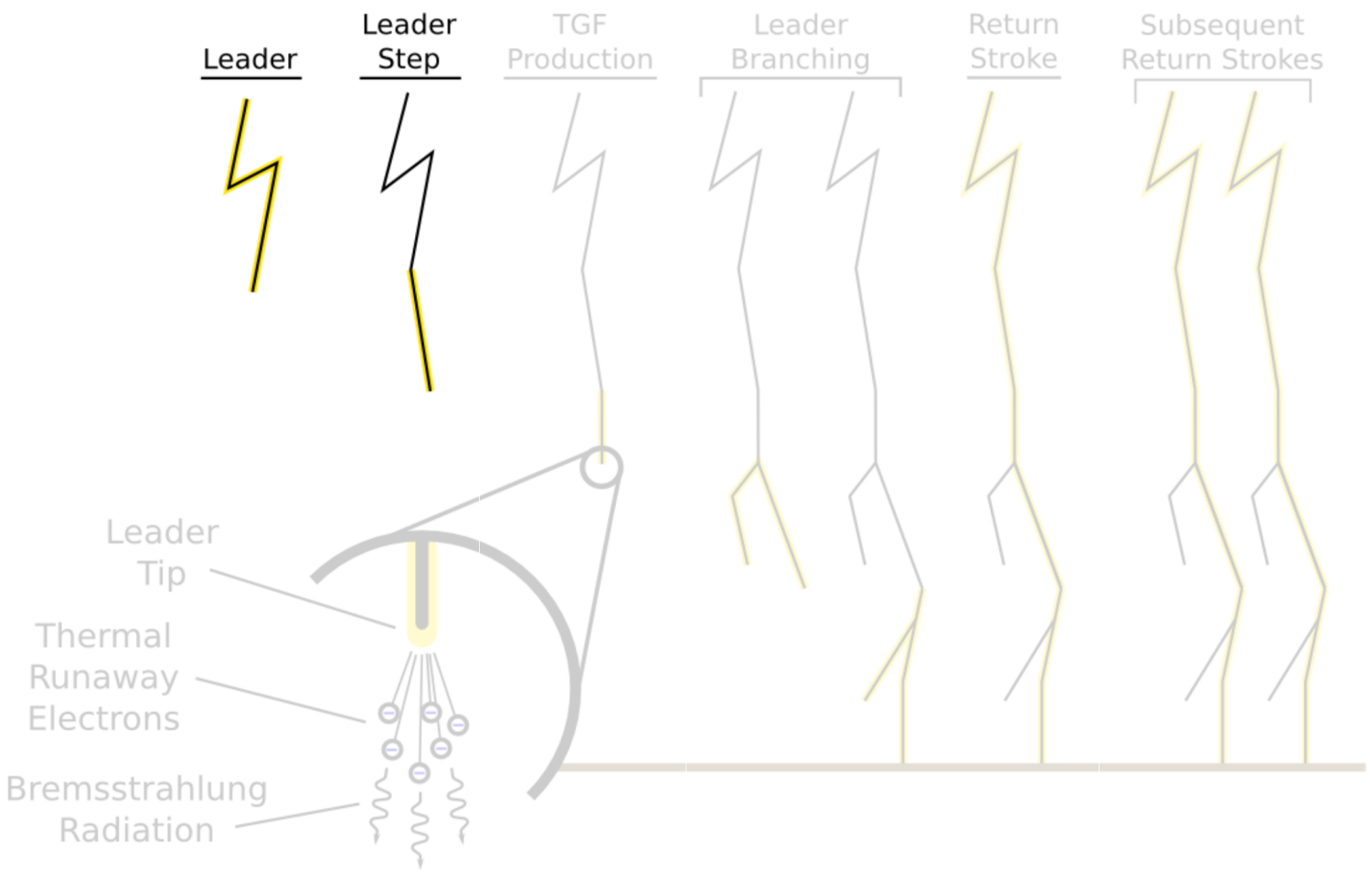
19th Erlangen School for Astroparticle Physics,
Obertrubach-Bärnfels,
October 08, 2024

Thunderstorms and Lightning



Source: J. Remington's PhD thesis [1]

Thunderstorms and Lightning, very, very frightening..



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- Many radio pulses from Leaders in VHF (MHz) regime,

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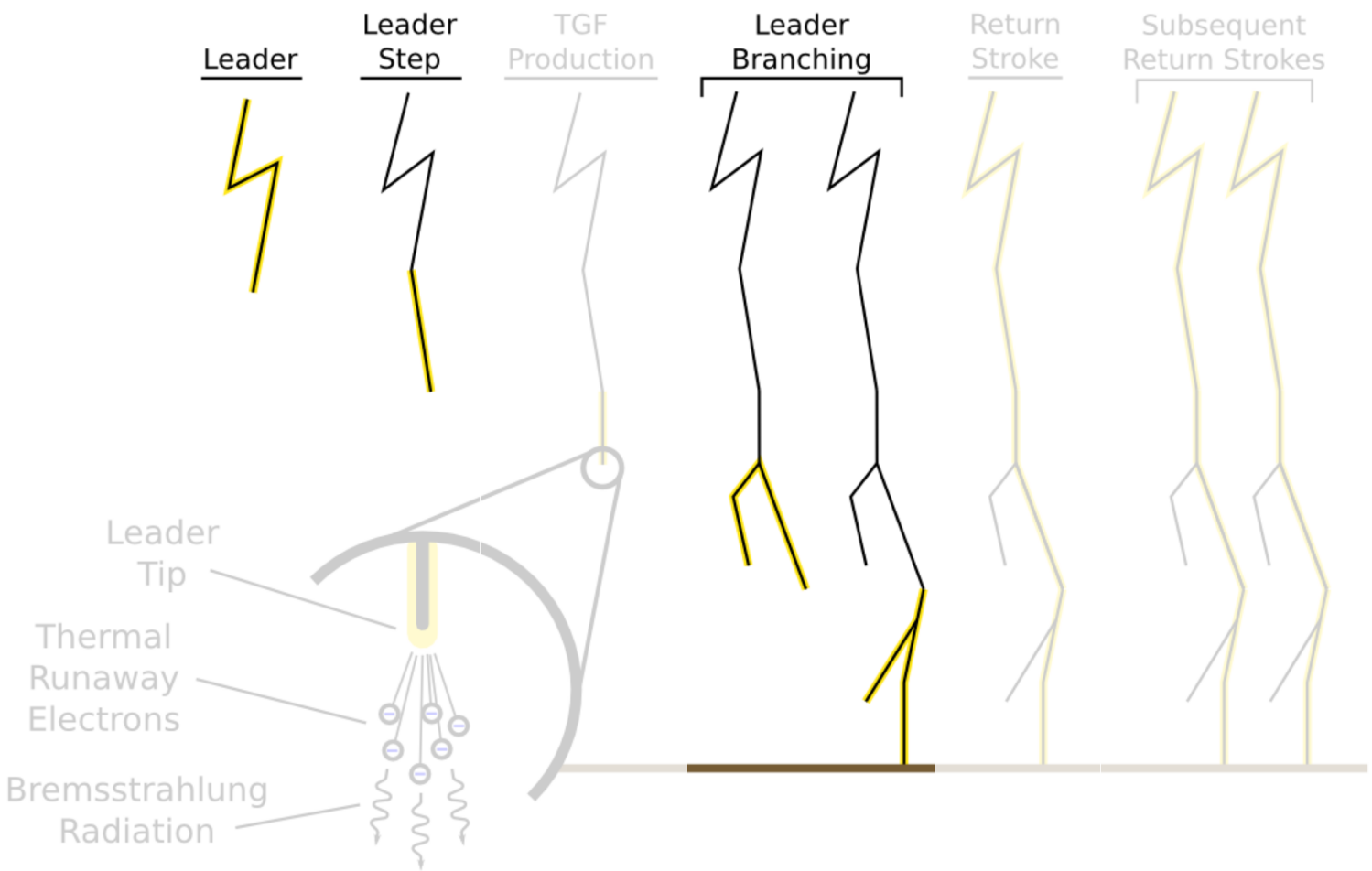

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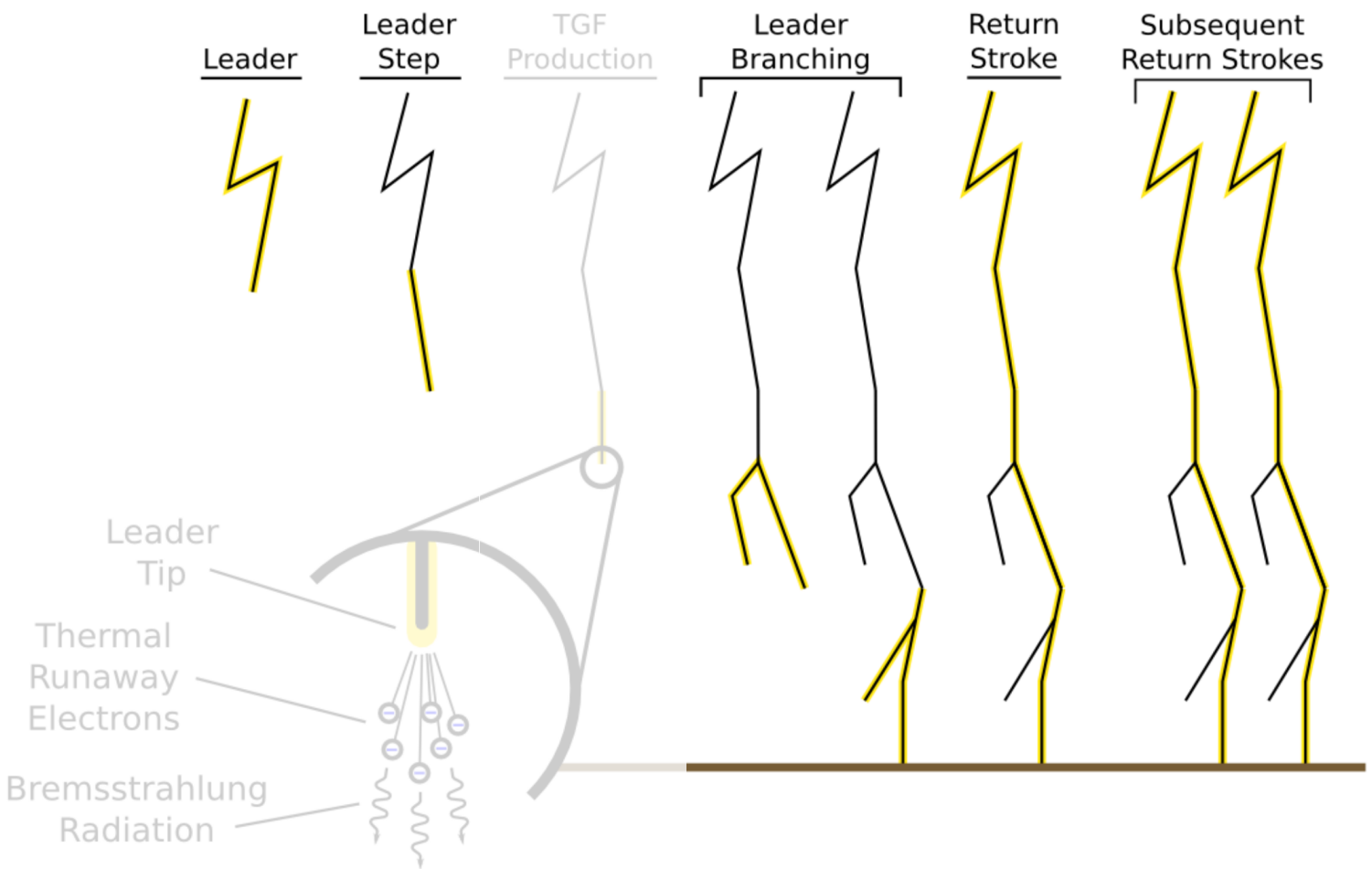

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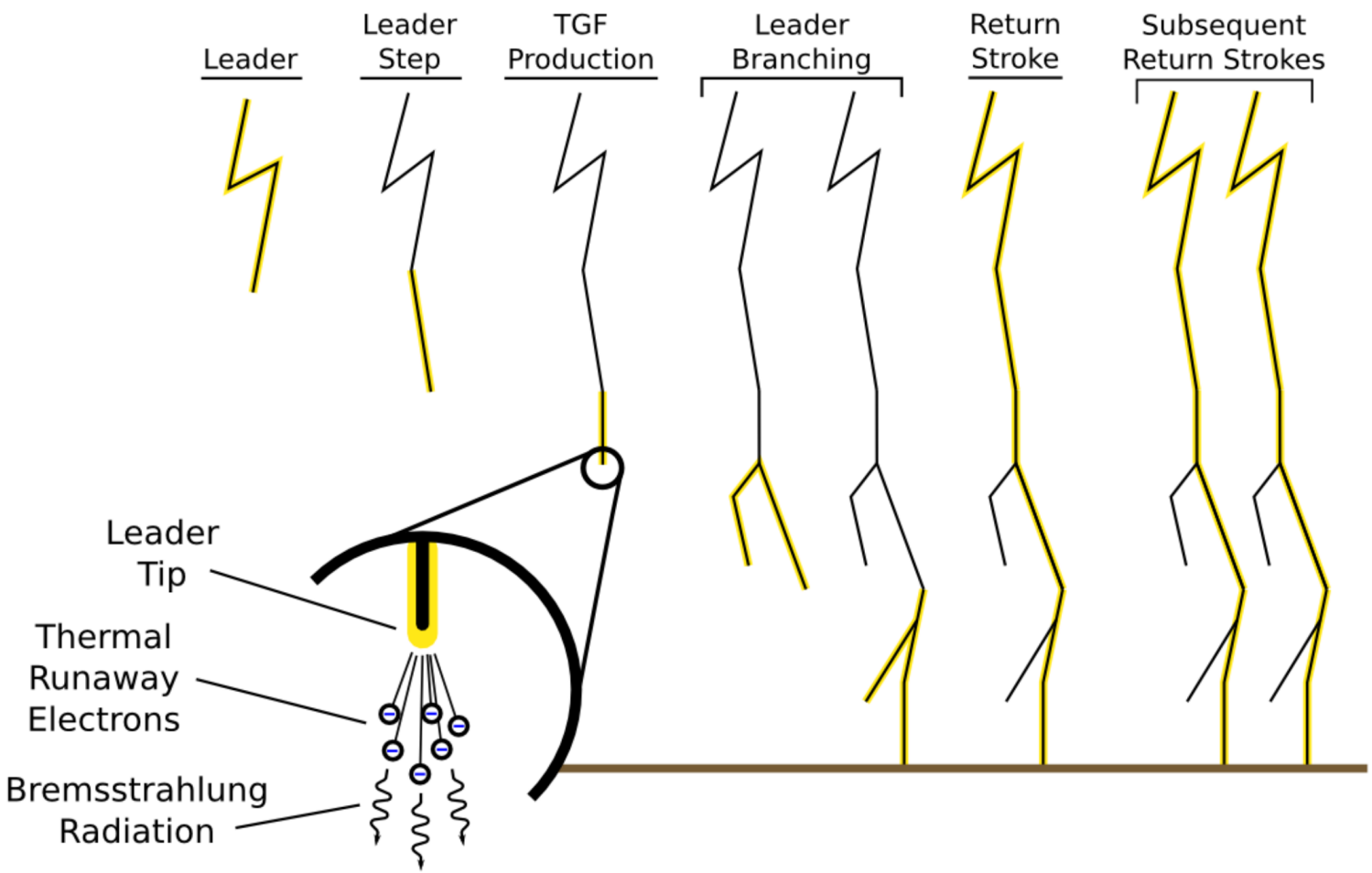

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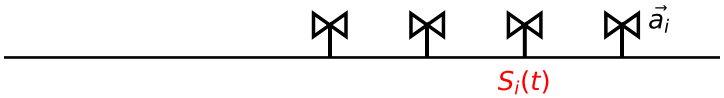
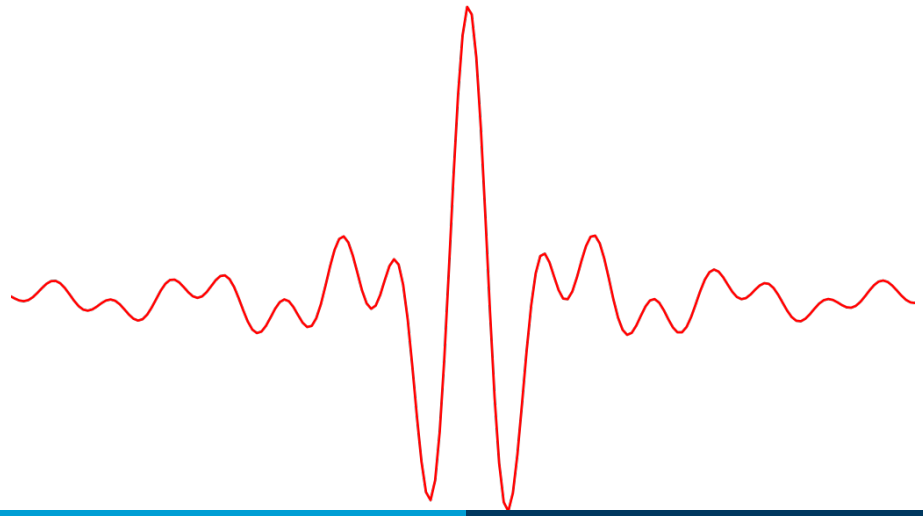
Radio Interferometry

Interferometry: Amplitude + Timing information of the signal

- Measure signal $S_i(t)$ at antenna $\vec{a}_i$





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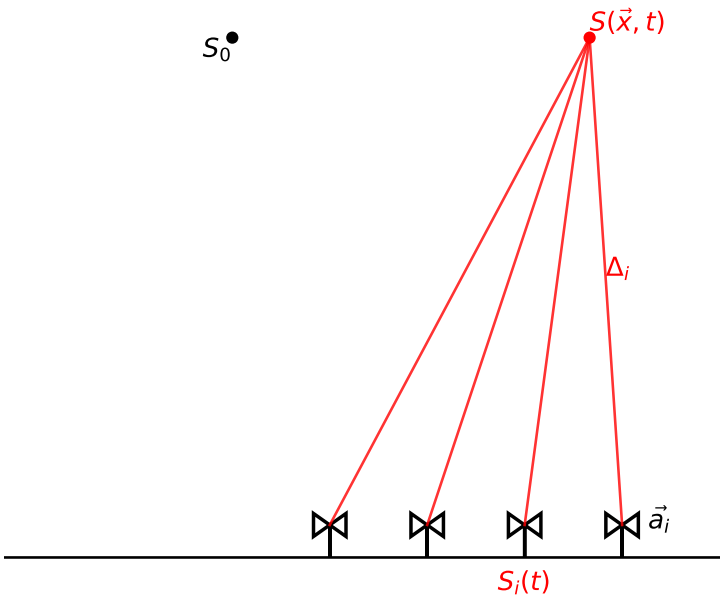
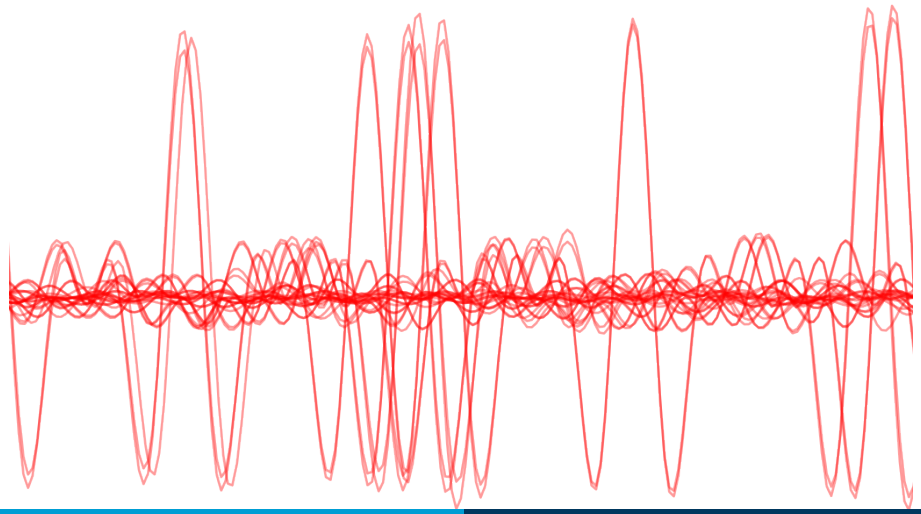


- Measure signal $S_i(t)$ at antenna $\vec{a}_i$
- Calculate light travel time

$$\Delta_i(\vec{x}) = \frac{|\vec{x} - \vec{a}_i|}{c} n_{eff}$$

- Sum/Multiply waveforms accounting for time delay

$$S(\vec{x}, t) = \sum S_i(t + \Delta_i(\vec{x}))$$



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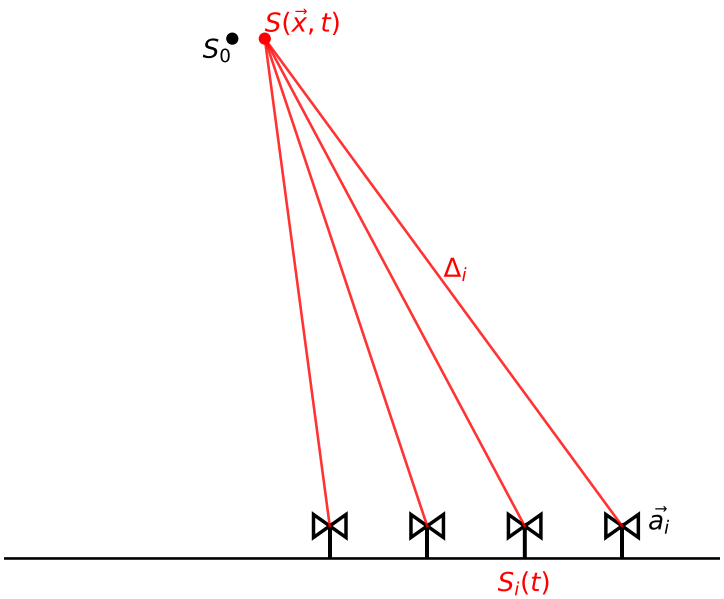

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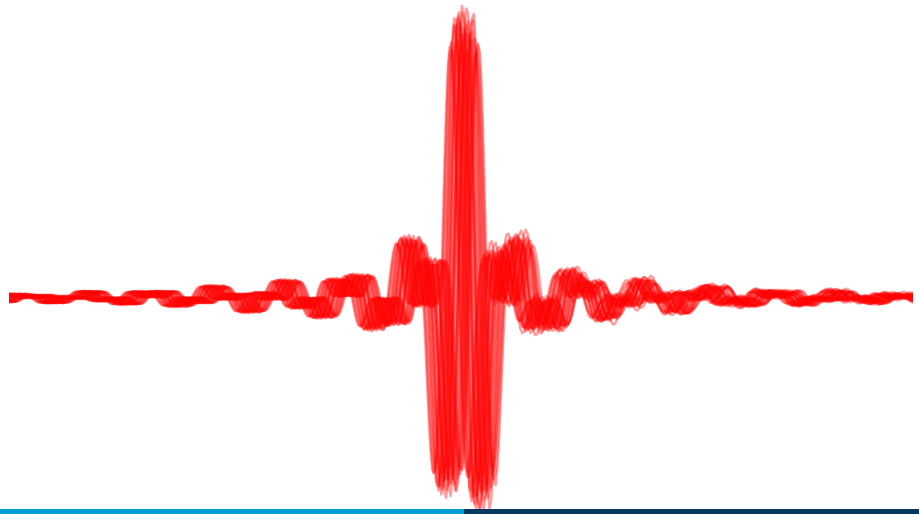

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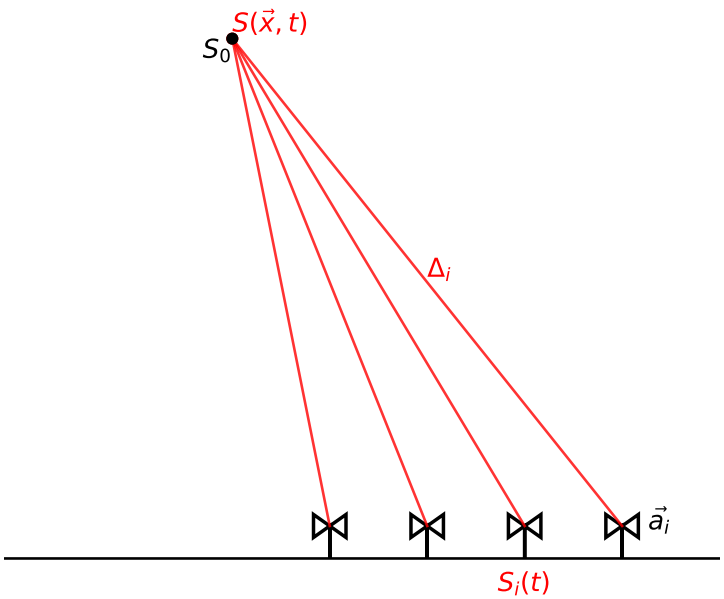

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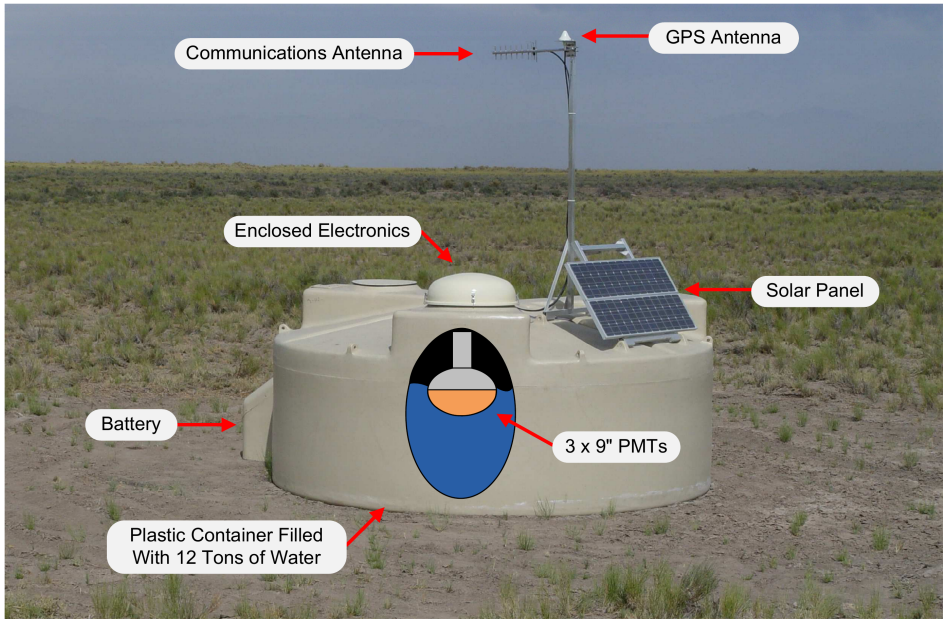
The Pierre Auger Observatory

Hybrid cosmic ray experiment located in the Pampa Amarilla in Argentina

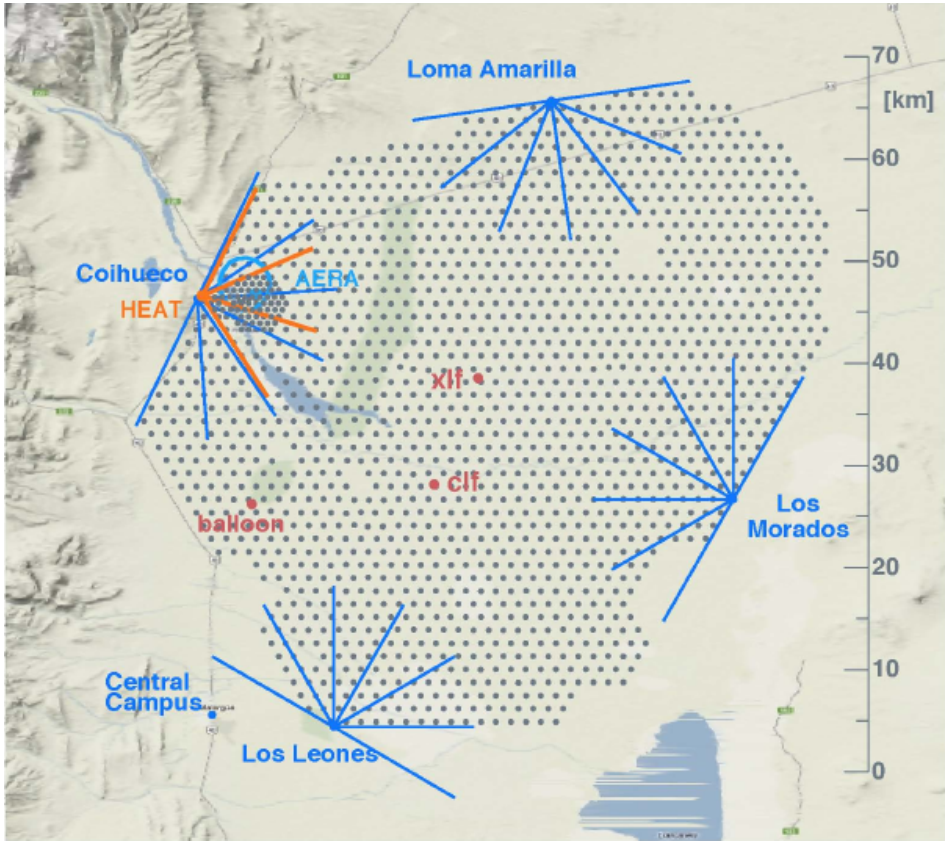
Surface Detectors (x1660)



Source: L. Niemietz's PhD thesis [2]

Fluorescence Detectors (x4)

AERA: Auger Engineering Radio Array



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Phase I: LPDA (x24)

Phase II/III: Butterfly (x130)

Sensitivity:	30 MHz to 80 MHz
Sampling Rate:	180 MHz
Tracelength:	2048x5.5 ns $\sim$ 11 µs

Radio detection for Lightning versus Air Showers

Rule of Thumb for Radio Interferometry:

'Timing accuracy must be better than 1/4 (1/12) of the period.'

.. but we are doing (digital) broadband interferometry.

Air Showers

- relativistic emitter
- single pulse ($\lesssim 10\,\text{ns}$)
- localised footprint (projected around shower axis)

Lightning

- extended emitter
- multiple pulses / substructure (10 ns to 10 µs, $\Delta \sim 10\,\text{ms}$)
- large footprint

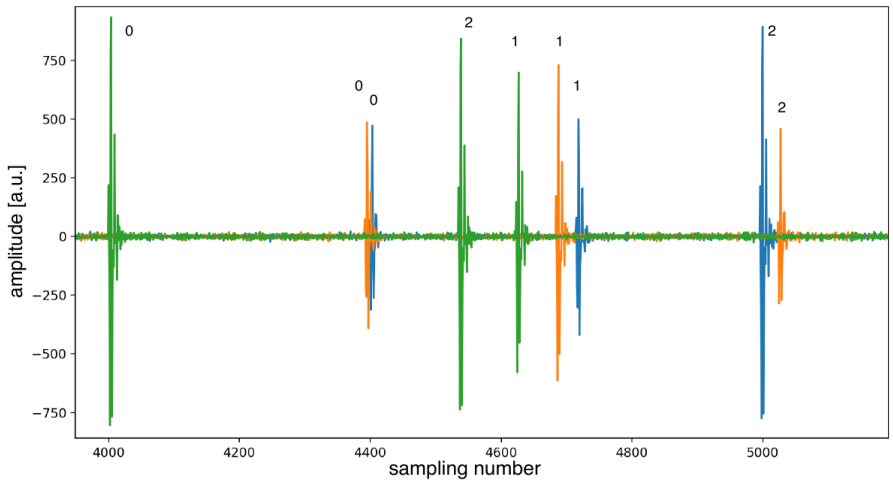
Lightning Interferometry: reusing AERA

Requirements:

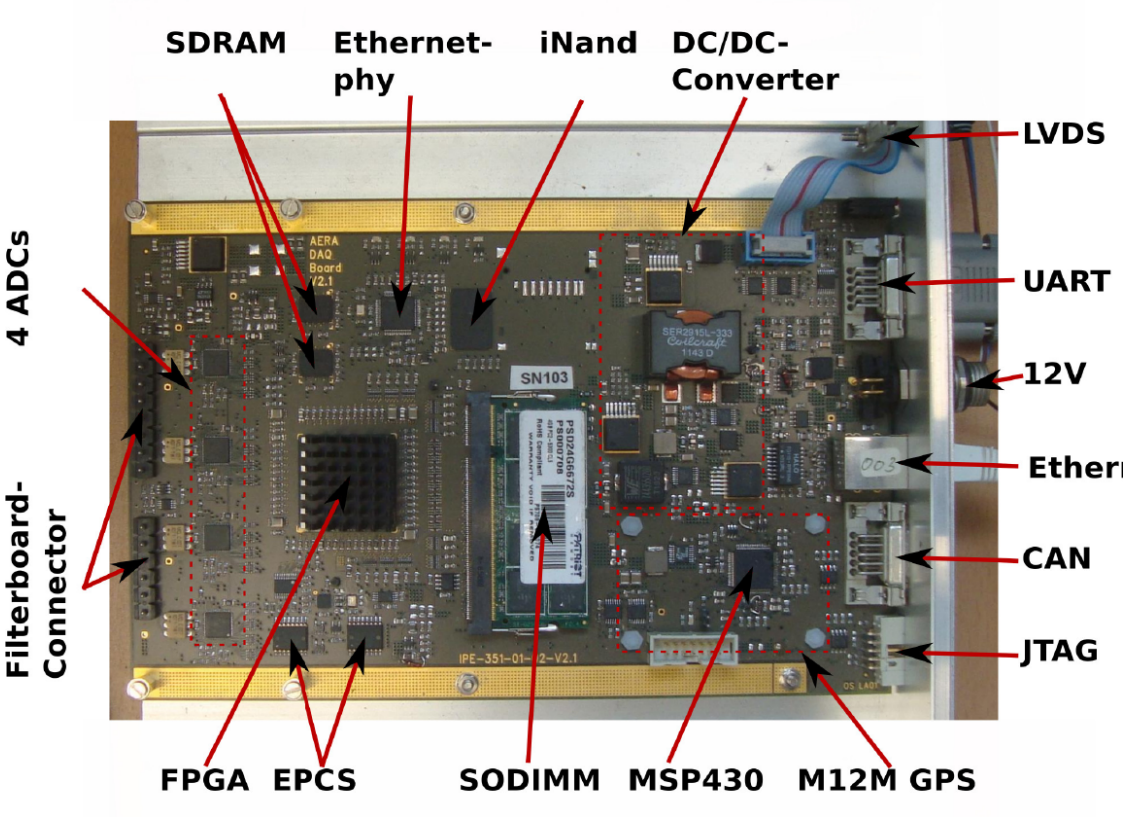
- modifications for AERA stations:
  - extending trace lengths from 11 µs to the order of 1 s,
  - transmitting the data from the stations.
- trigger development
- nanosecond synchronisation across stations with distances up to several kilometers

Planned configuration:

- 4 Core stations, baselines 58 m to 127 m (for pulse identification/ separation)
- 3 Medium range, baselines 1 km to 2.5 km
- 4 Remote stations, baselines 3.5 km to 66 km



AERA Digitizer



Source: B. Zimmermann's PhD thesis [3]

- custom FPGA gateware for continuous sampling
- uClinux for high-level coordination

- last development 2017
- FPGA Cyclone III, and NIOS II CPU, unsupported...

Summary and Outlook

- Geophysical sources of high-energy particles correlated with lightning.
- Idea: hybrid lightning measurements at the Pierre Auger Observatory, using SD, FD, E-field mills and repurposed AERA stations.
- AERA requires modification for lightning interferometry.

Outlook:

First repurposed AERA station to feature extended trace lengths by November 2024

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Thank you!

Bibliography I

Jackson Remington. *Analysis of Downward Terrestrial Gamma-ray Flashes Using a Large-Area Cosmic Ray Scintillation Detector*. PhD thesis, University of Utah, December 2021. arXiv: 2308.05662 [astro-ph.HE].

Lukas Niemietz. *Lightning Detection at the Pierre-Auger-Observatory*. PhD thesis, Bergische Universität Wuppertal, June 2017. URL: https://nbn-resolving.org/urn:nbn:de:hbz:468-20171012-105730-3.

Benedikt Hermann Zimmermann. *Radio-detection of ultra-high energy cosmic rays: multi-channel data acquisition and combined analysis of timing and energy information*. PhD thesis, Karlsruher Institut für Technologie (KIT), 2017. 105 pages. DOI: 10.5445/IR/1000076009. 51.03.03; LK 01.