Classification and Reconstruction of Single and Multiple ELVES at the Pierre Auger Observatory

Roberto Mussa
INFN Torino

(Pierre Auger Collaboration)

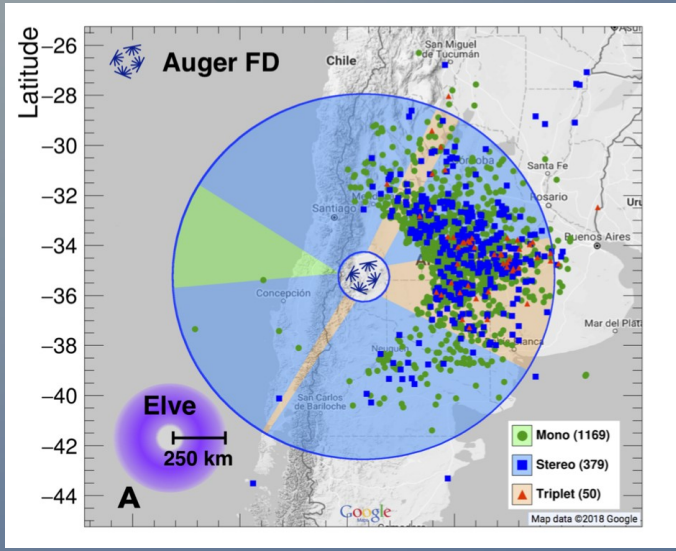
PIERRE AUGER OBSERVATORY

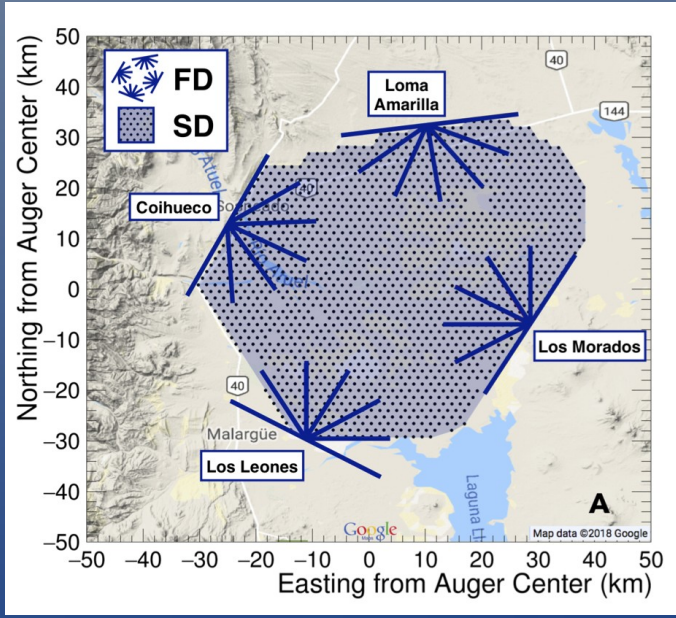
INFN Torino
Istituto Nazionale di Fisica Nucleare

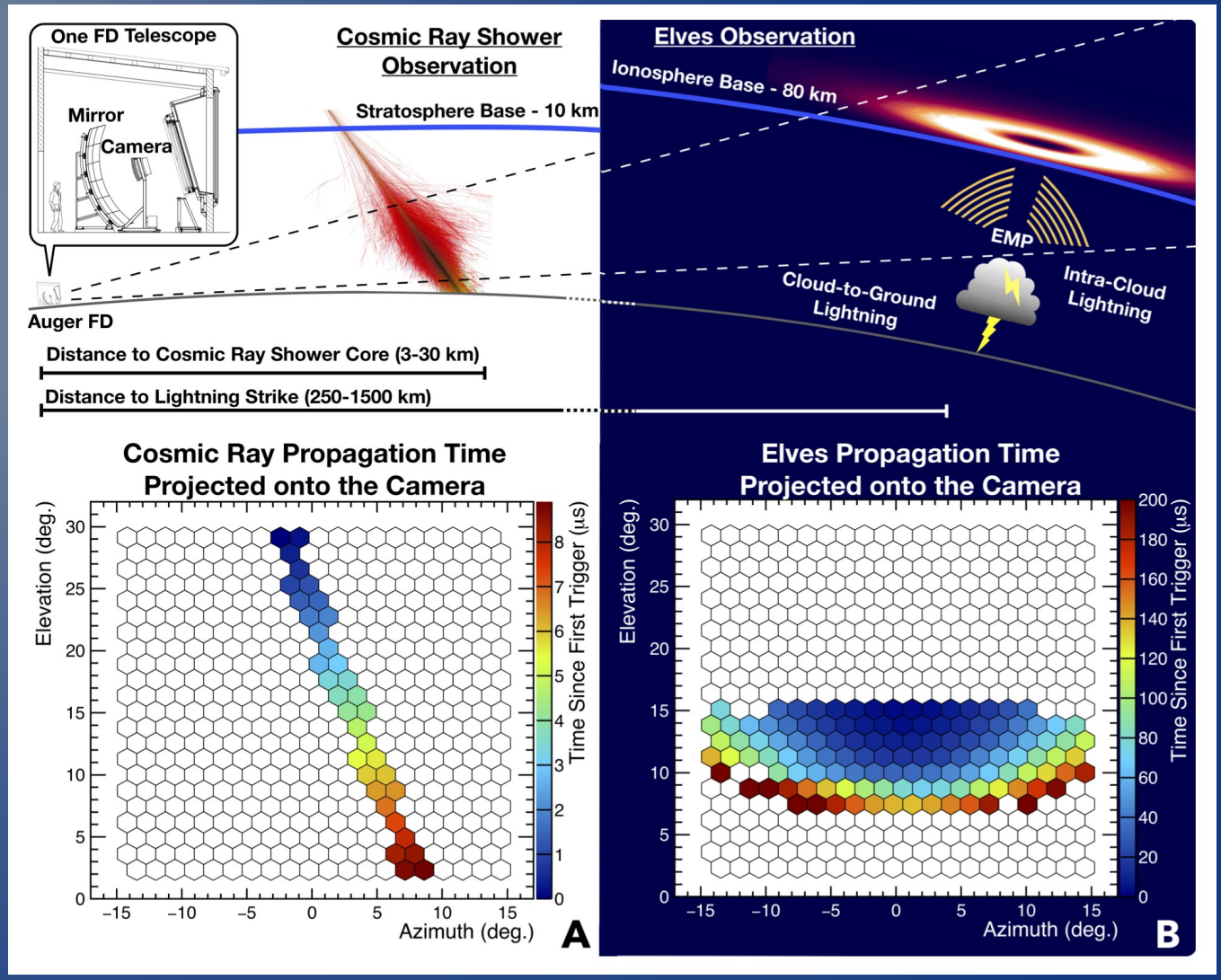
13-15/7/2022

AtmoHEAD

Observation of ELVES at the Auger Observatory



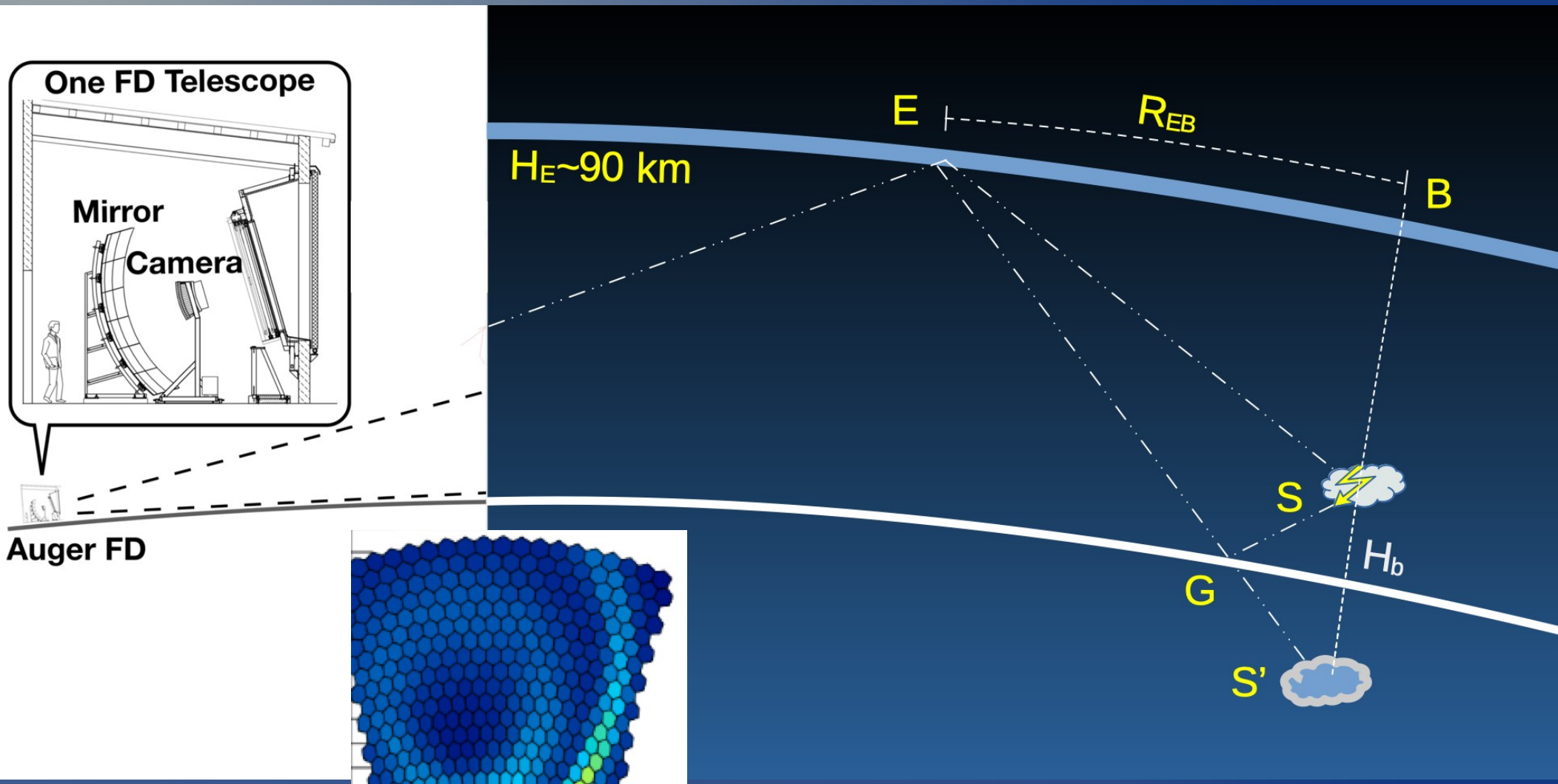


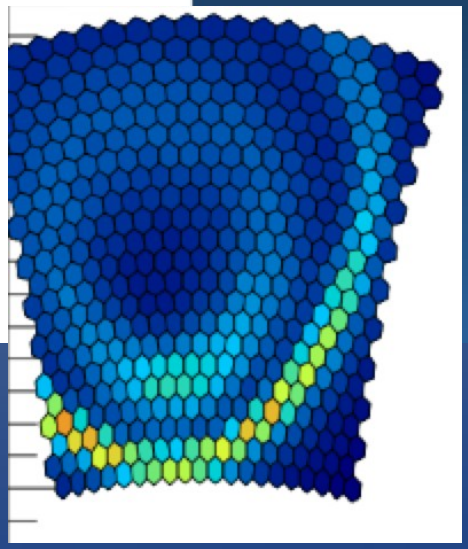


A.Aab et al,Earth Space Sci. 7 (2020) 4

DAQ: 100(x9) μs traces, 100(x20) ns bins

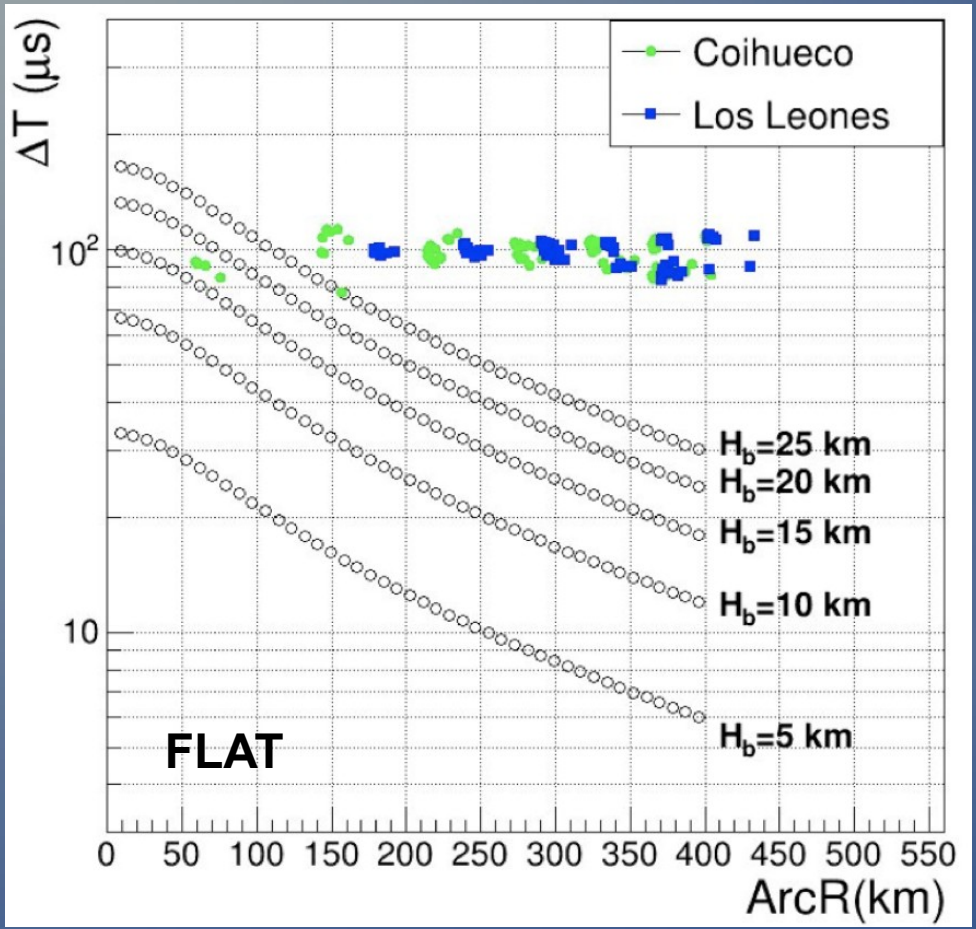
Modeling ground reflection in double ELVES

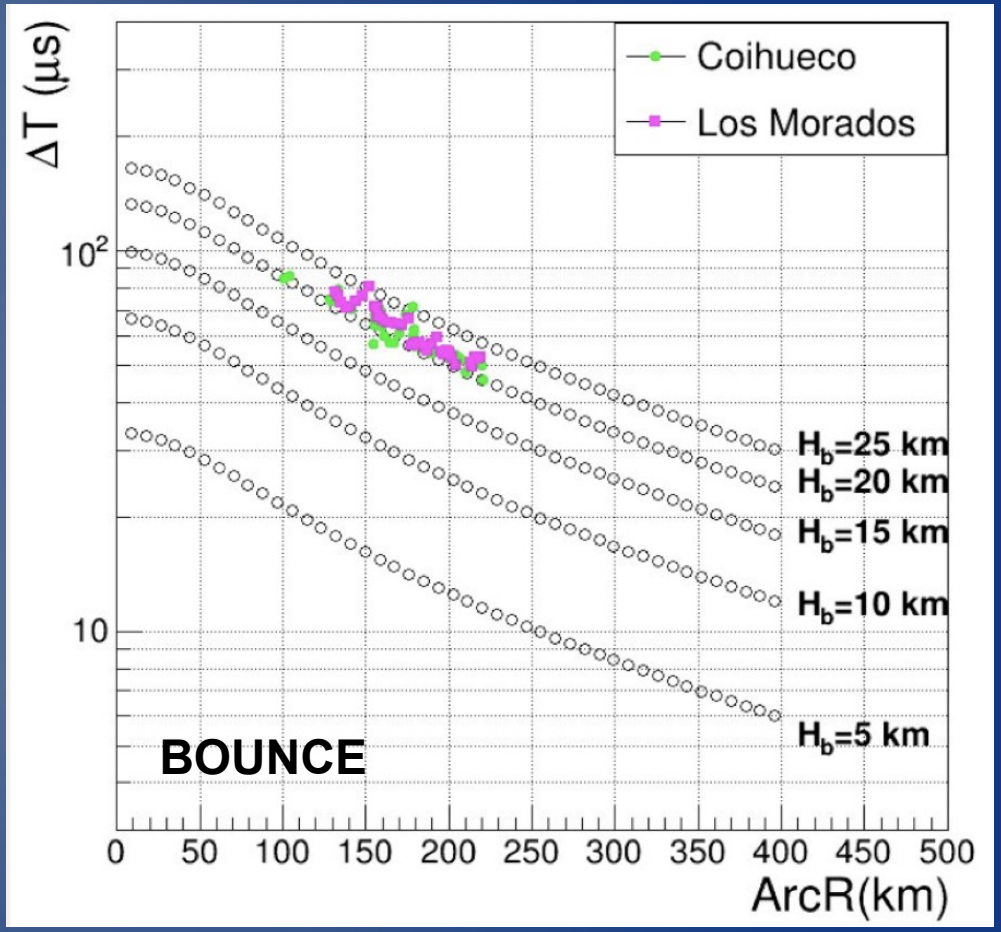




We originally thought that most double ELVES were caused by the ground relection of the EMP from intracloud discharges ....

Multiple elves zoology



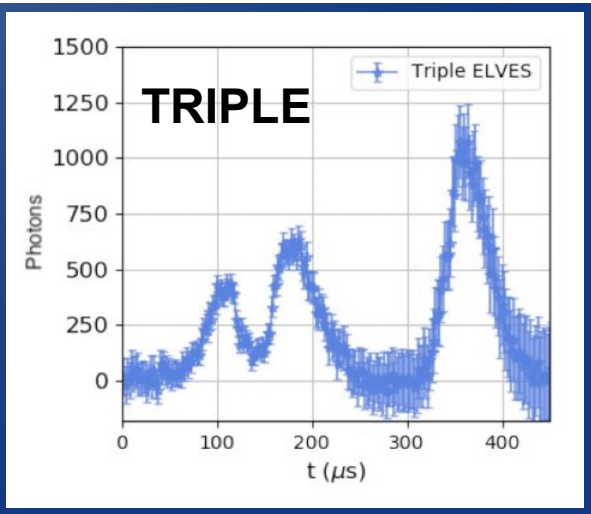


FLAT ΔT : time gaps from 80 to 250 μs , constant vs distance from source lightning

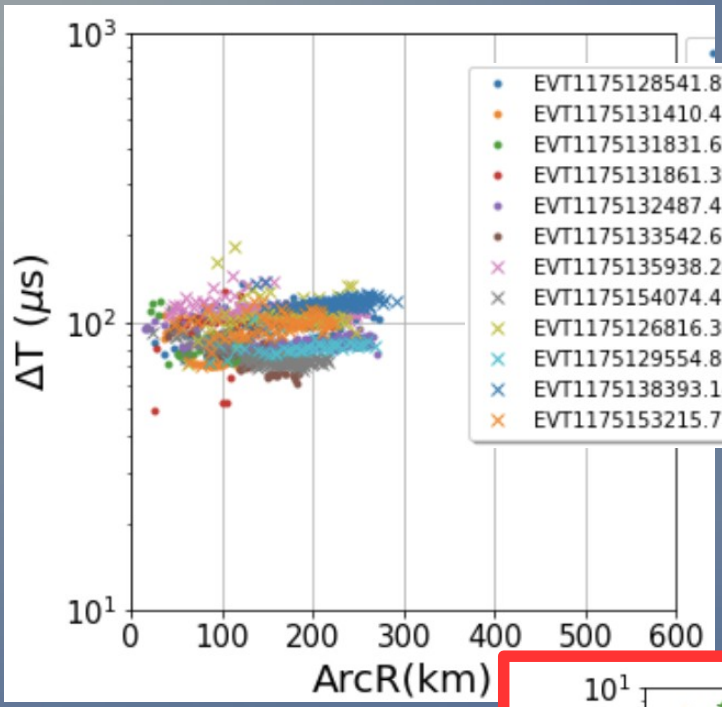
BOUNCE : time gaps decreases with distance

Hardly resolved from low clouds, in far lightning

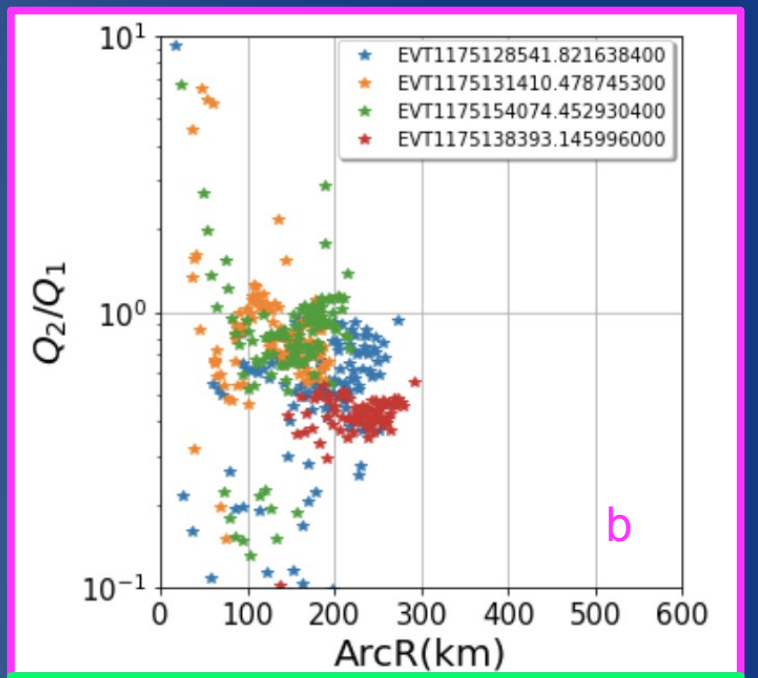
TRIPLE flashes: <2% of multiple elves: TGF?



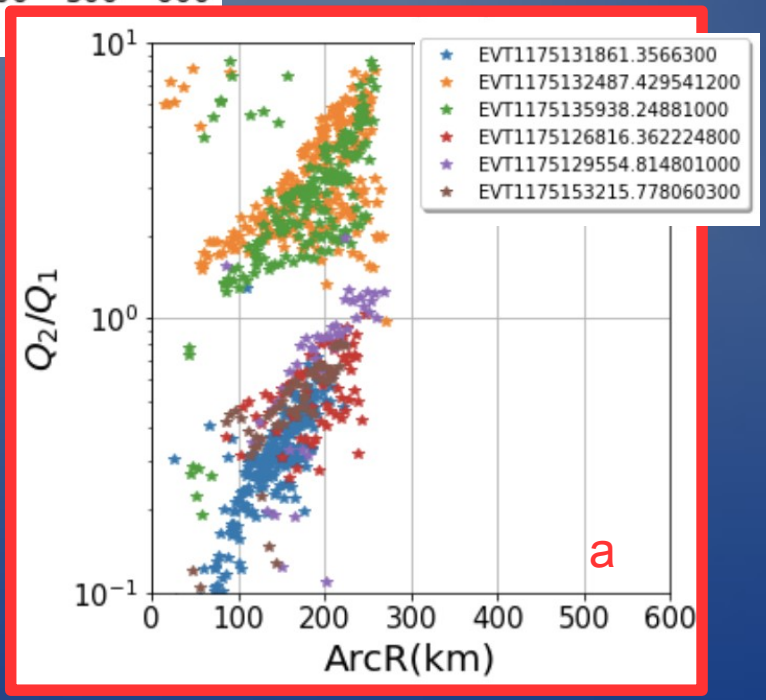
Classification of FLAT events: Light Flux ratio

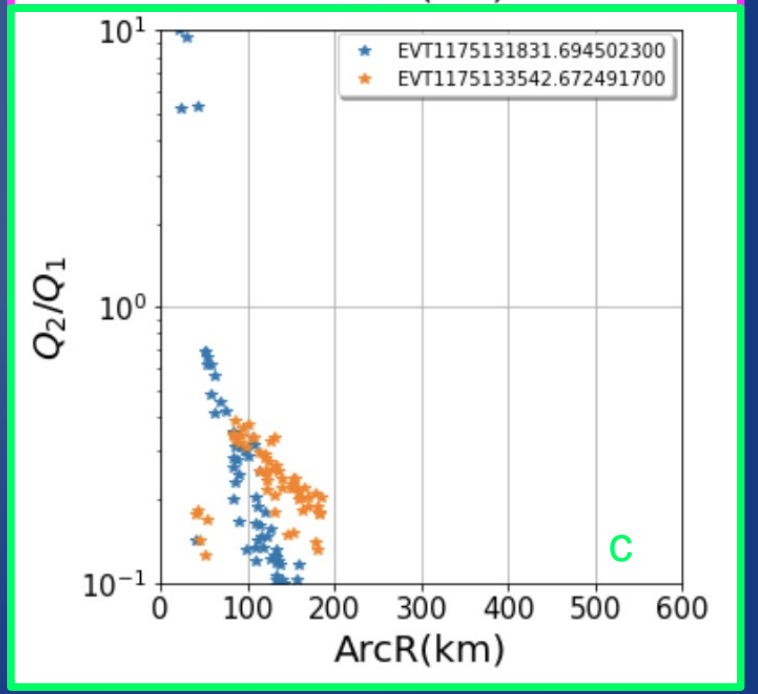


Double ELVES during 28/04/20



Even within the same storm, double elves with constant gap split in different classes based on flux ratio evolution vs distance from lightning source

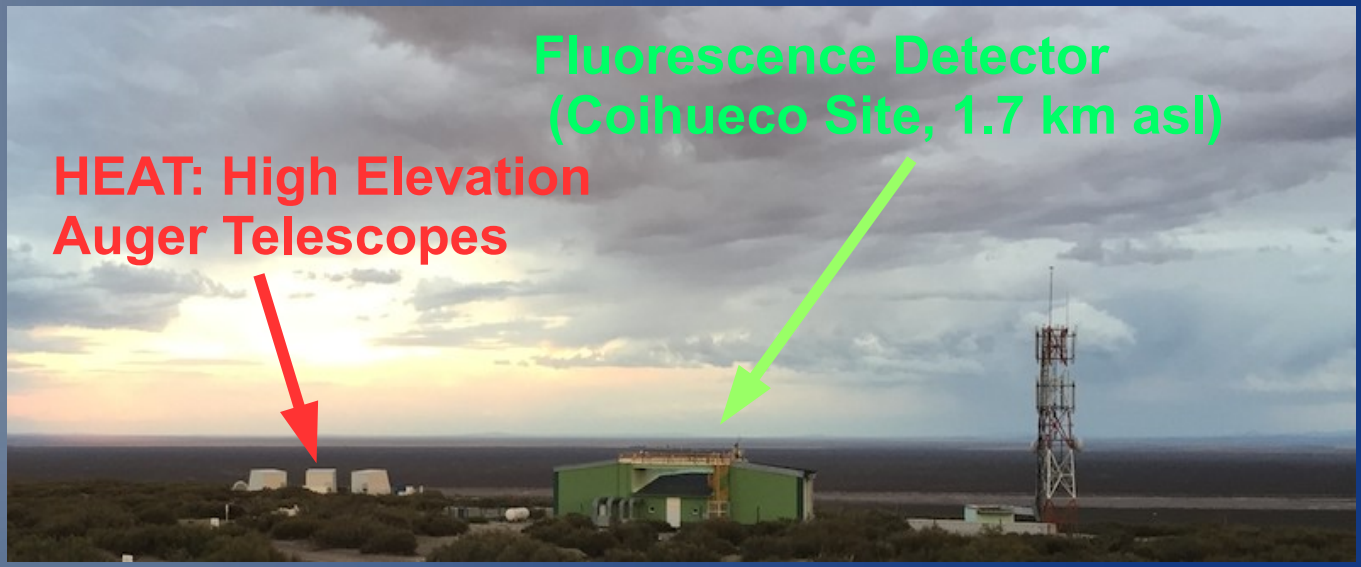




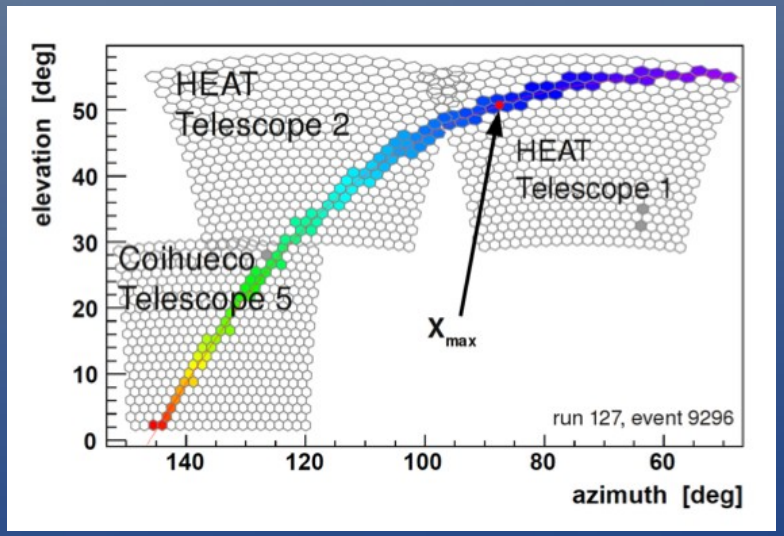
New: the HEAT telescopes in AUGER

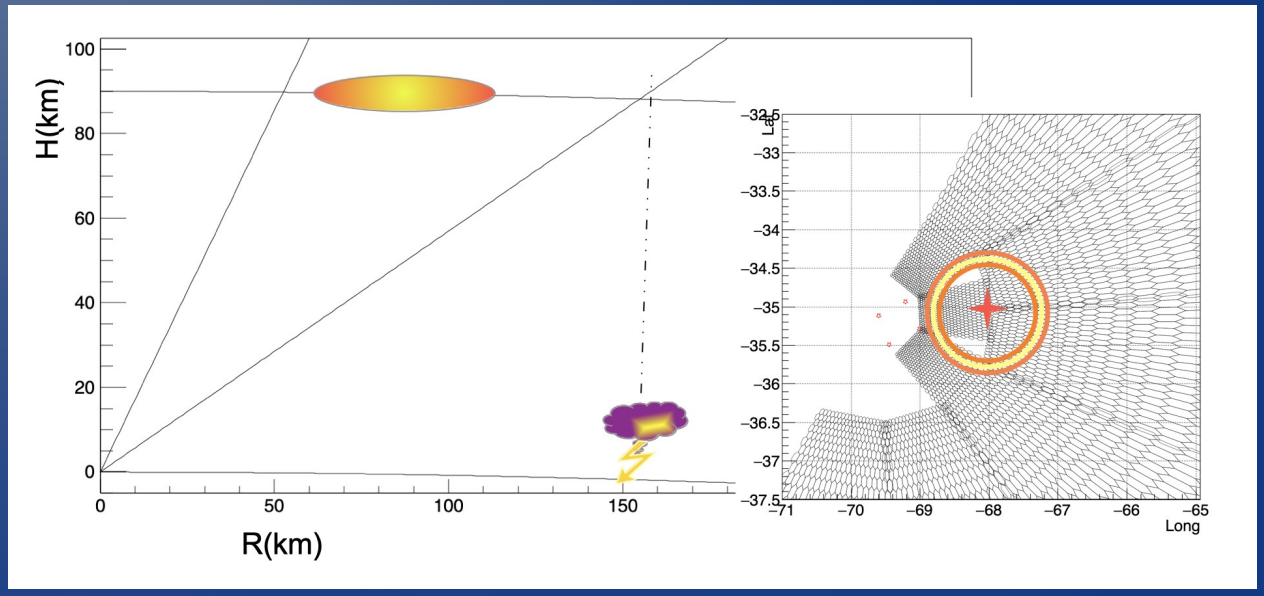
3 Fluorescence Detectors with :

- Elevation axis : 45°
- FoV = 30° – 60°
- Goal: detect low energy cosmic ray showers
- DAQ: 100(x3) μs traces, 50(x40) ns bins



Since Jan. 2021 we can observe ELVES from closer storms



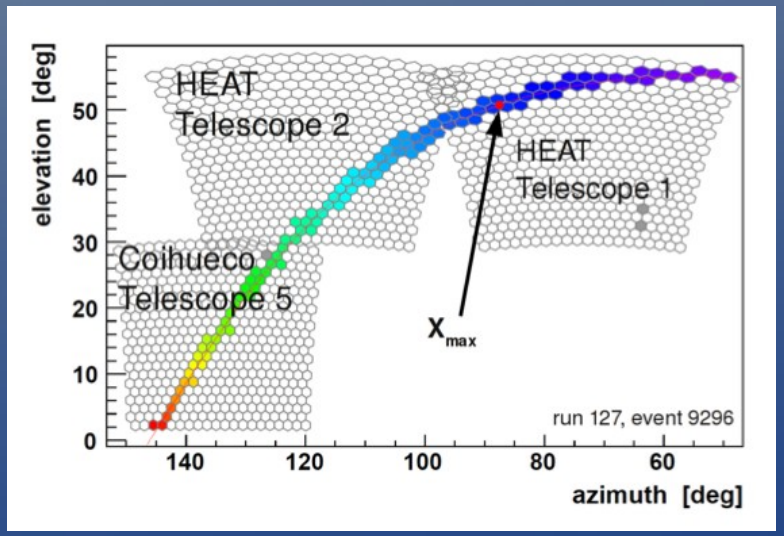


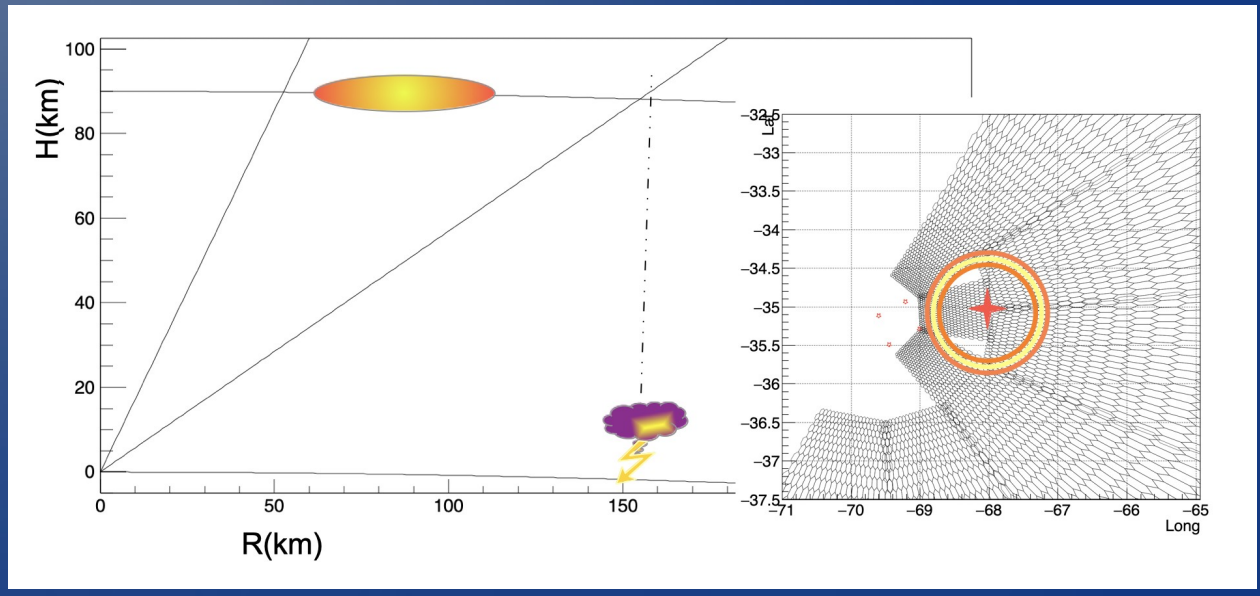
New: the HEAT telescopes in AUGER

3 Fluorescence Detectors with :

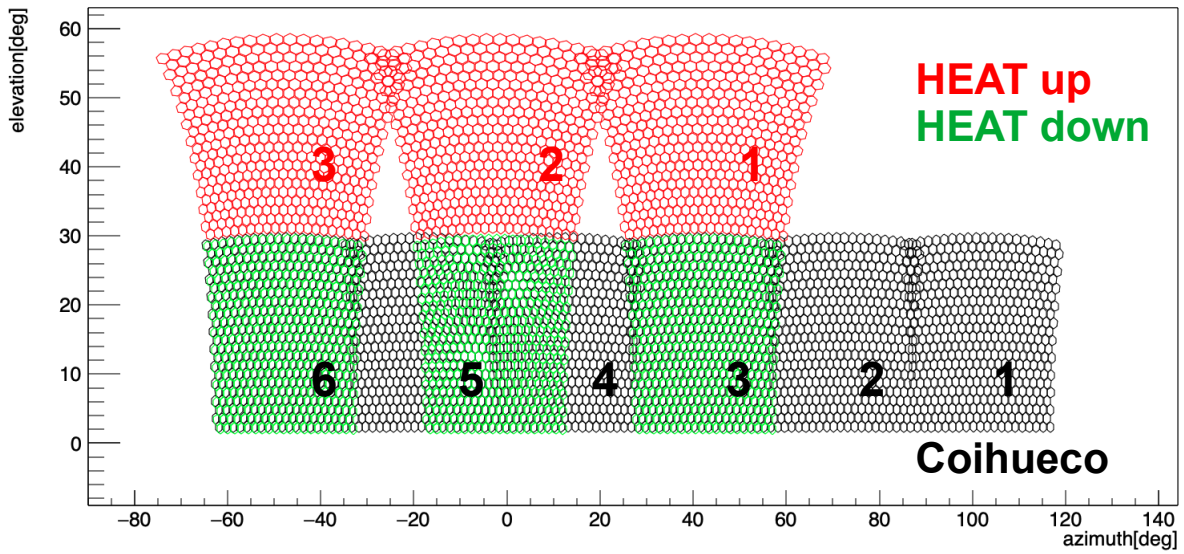
- Elevation axis : 45°
- FoV = 30° – 60°
- Goal: detect low energy cosmic ray showers
- DAQ: 100(x3) μs traces, 50(x40) ns bins

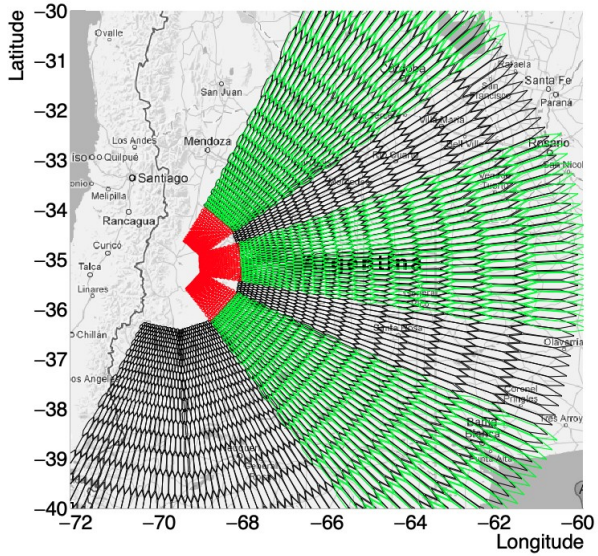
Since Jan. 2021 we can observe ELVES from closer storms





HEAT statistics in 2021





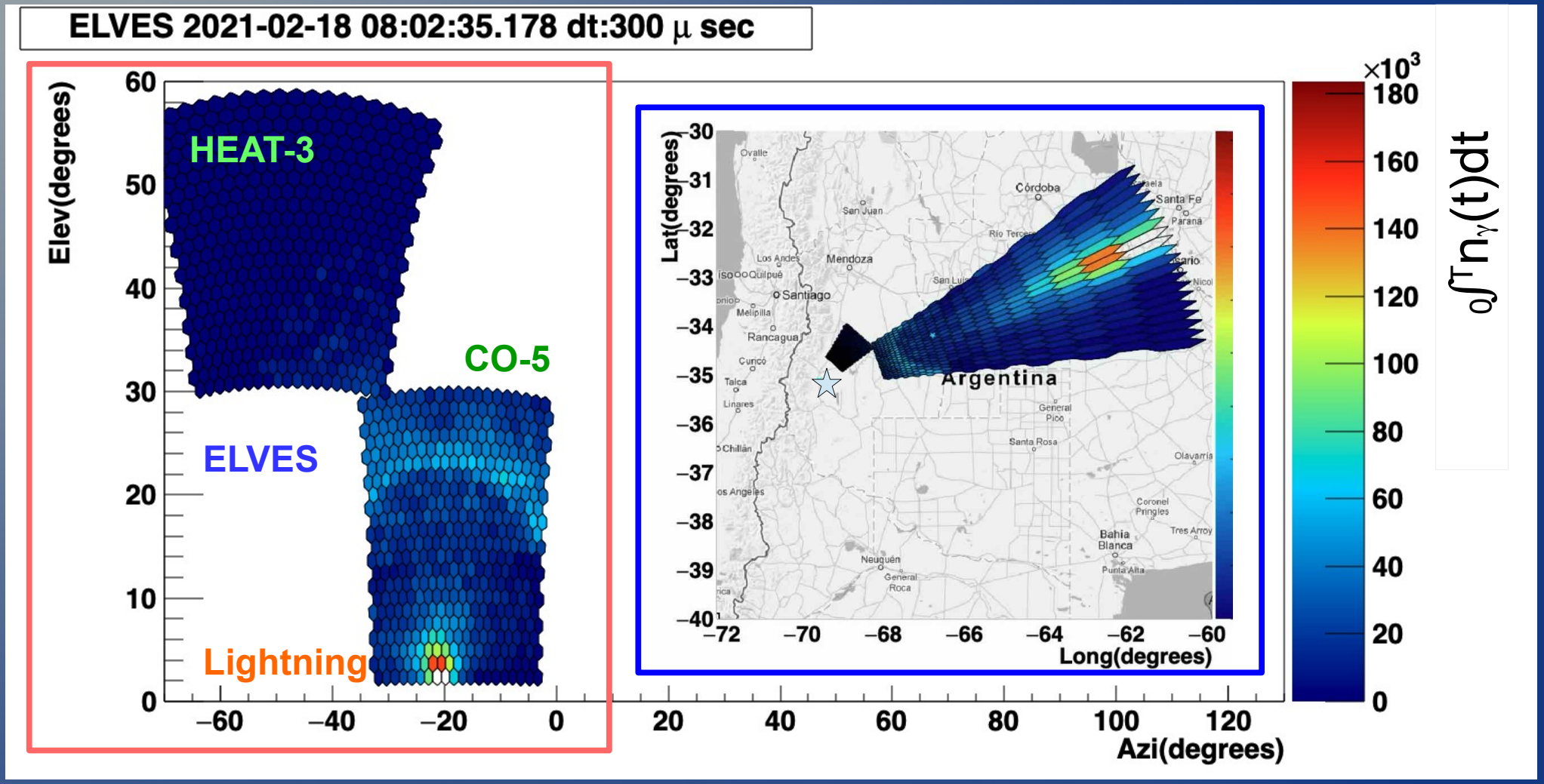
HEAT Telescopes in UP position

Tel#	3	3*2	2	2*1	1
Totals	88	22	47	-	8
Best storms:					
15/1	4	5	6	-	-
7/3	-	-	13	-	-
14/3	54	16	10	-	-

HEAT Telescopes in DOWN position

Tel#	3	3*2	2	2*1	1
Totals	46	4	73	-	4
Best storms:					
14/7	34	-	9	-	-
7/7	3	4	3	-	-

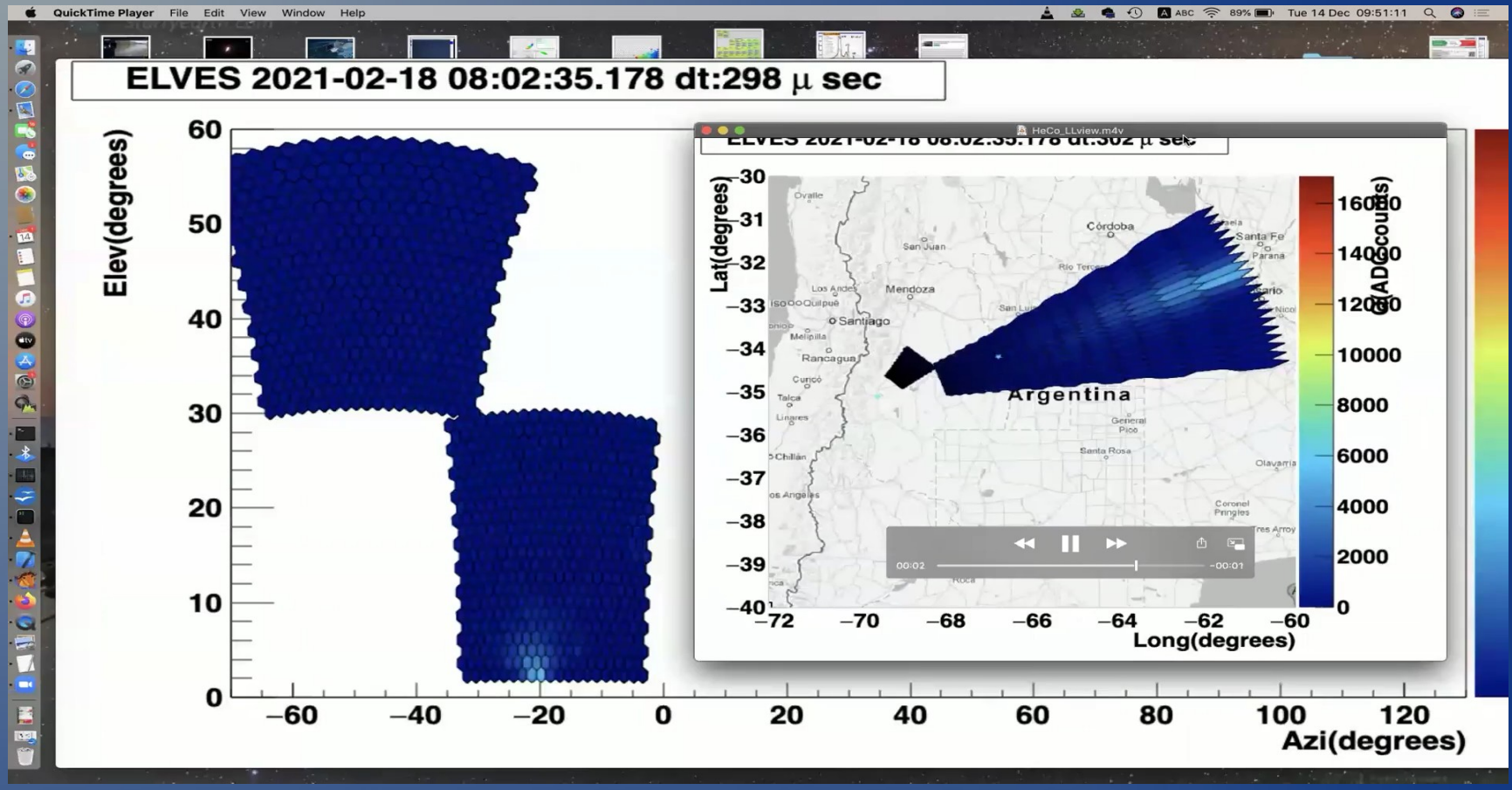
ELVES observed by 3 eyes: HEAT, Coihueco, Los Leones



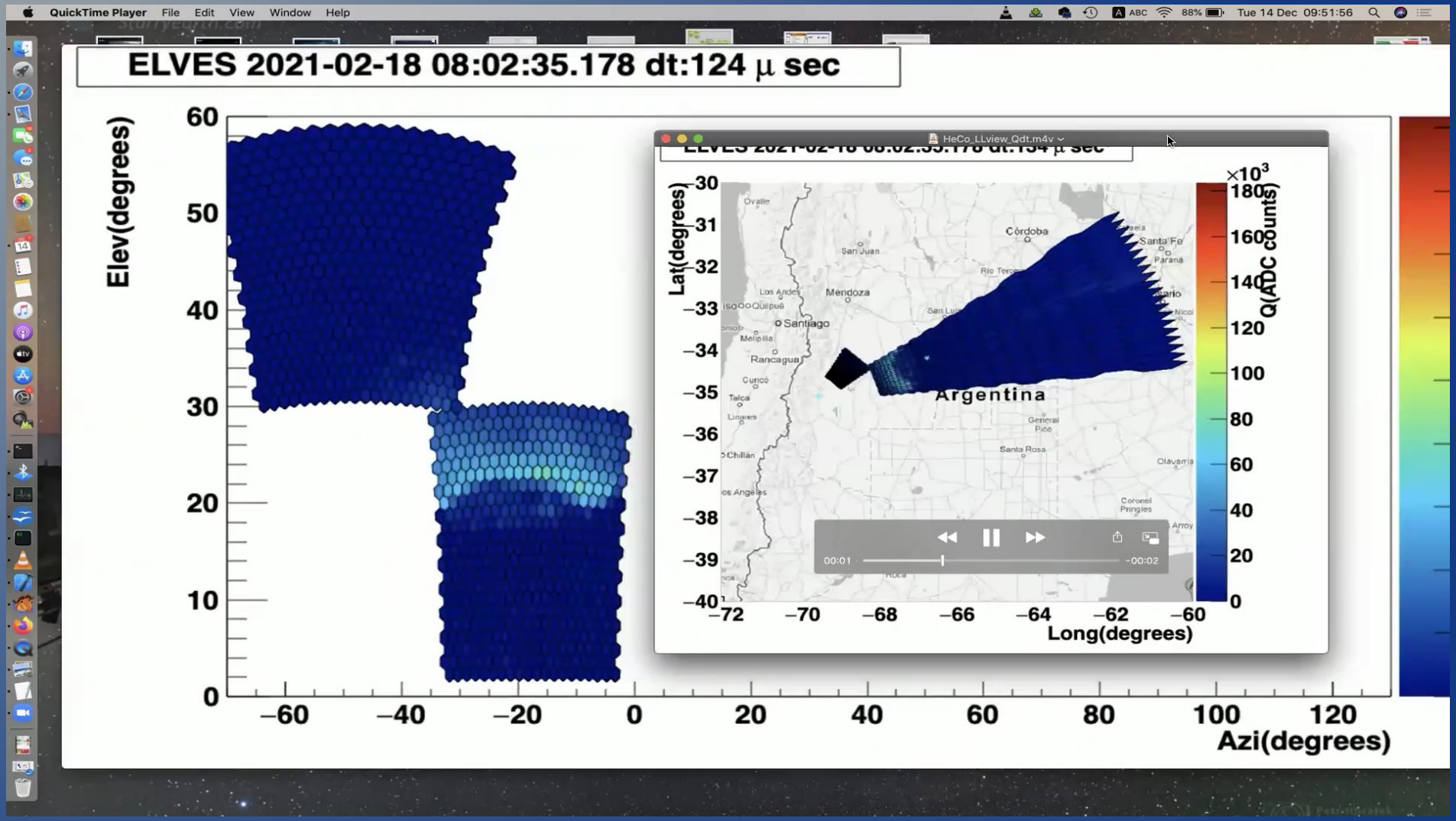
FD CAMERA VIEW

PROJECTION TO THE BASE OF IONOSPHERE

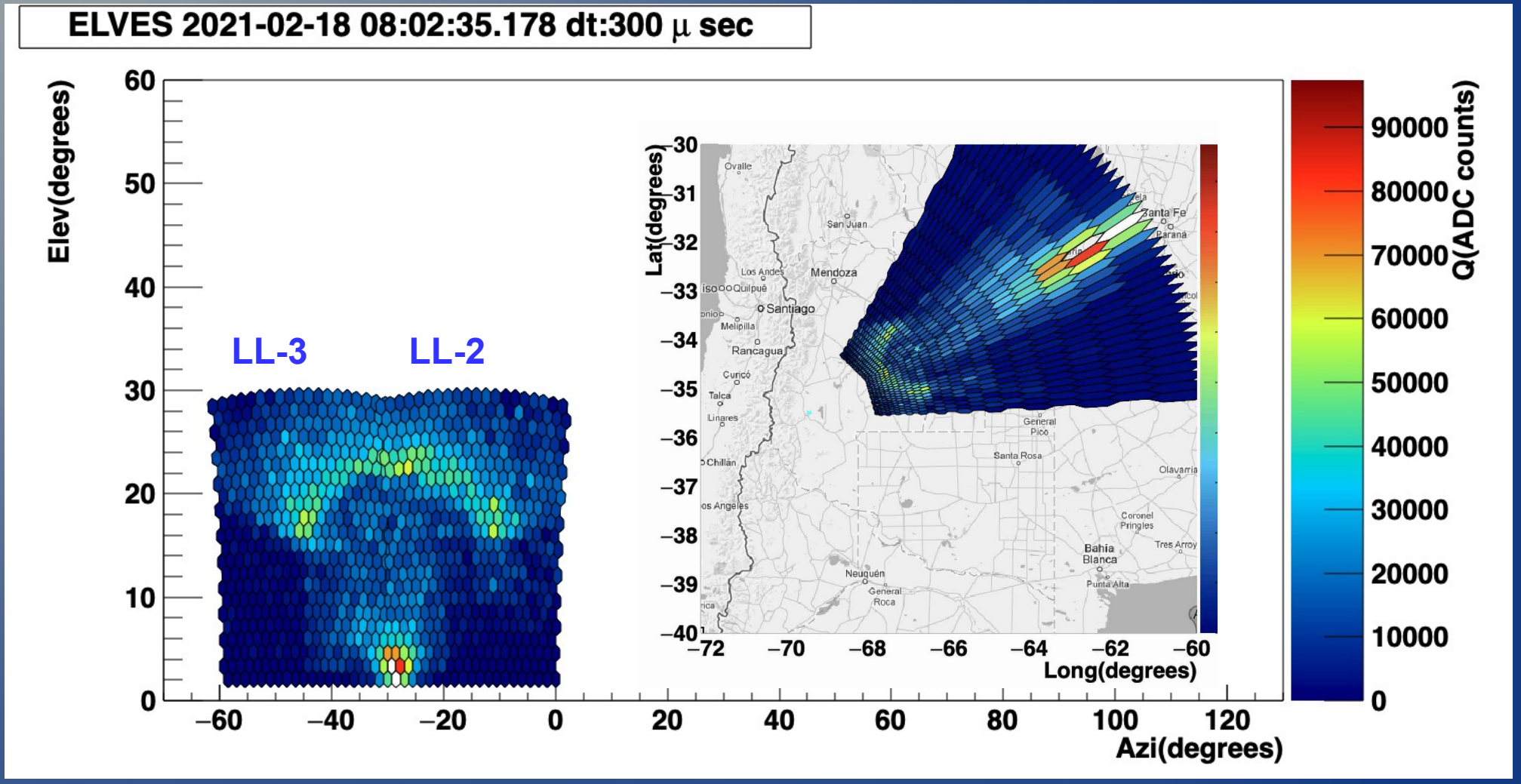
ELVES observed by 3 eyes: HEAT, Coihueco, Los Leones



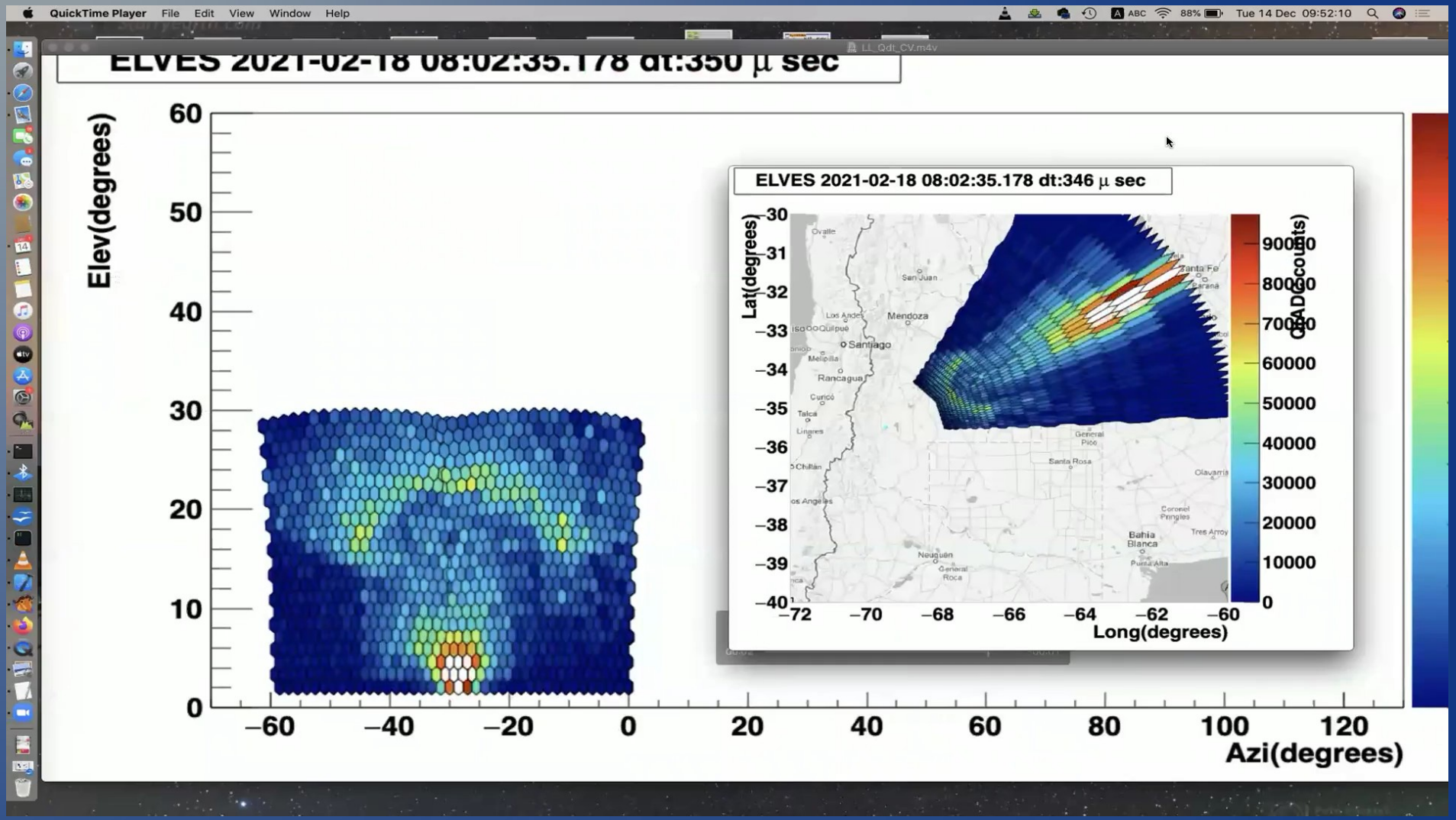
ELVES observed by 3 eyes: HEAT, Coihueco, Los Leones



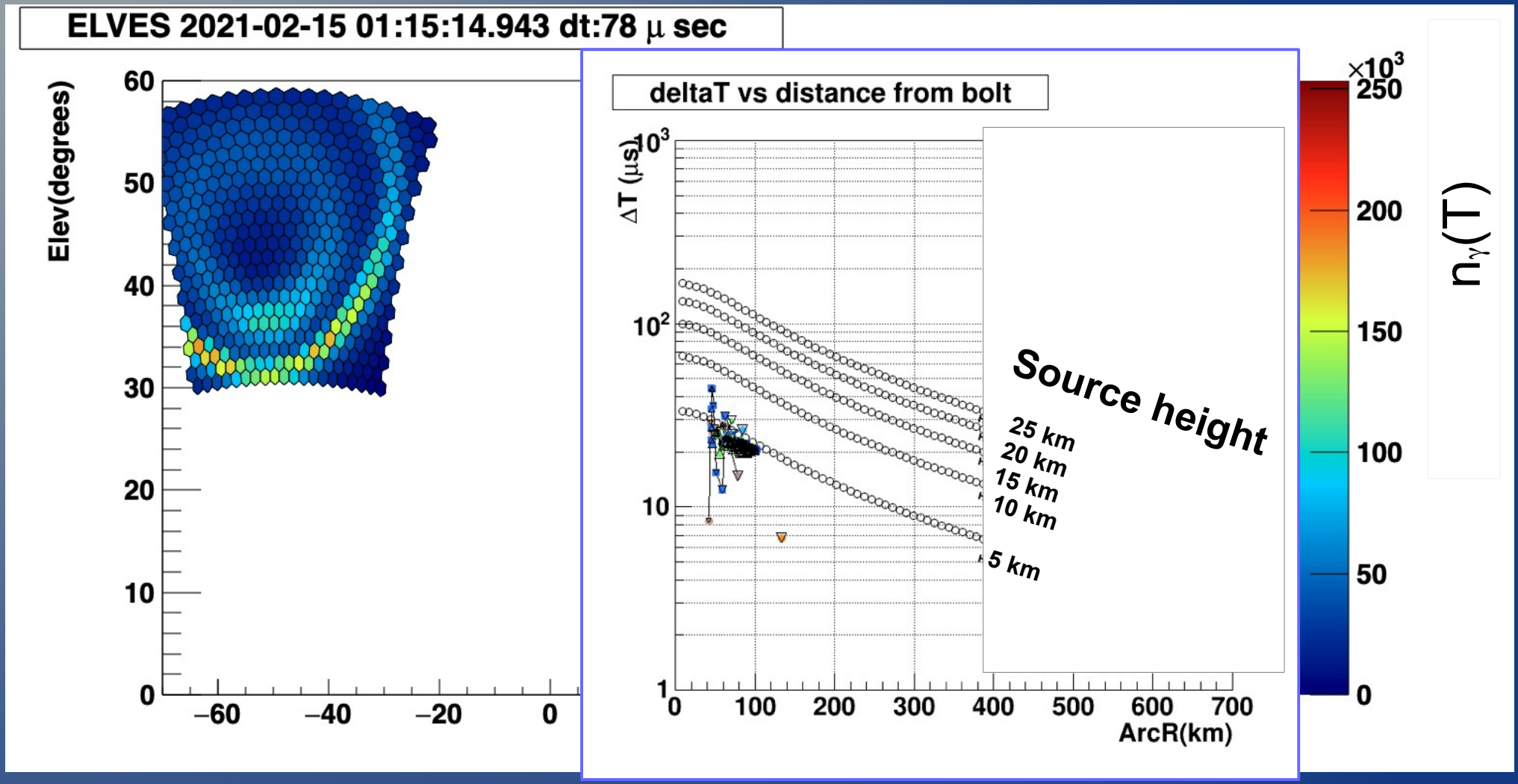
ELVES observed by 3 eyes: HEAT, Coihueco, Los Leones



ELVES observed by 3 eyes: HEAT, Coihueco, Los Leones

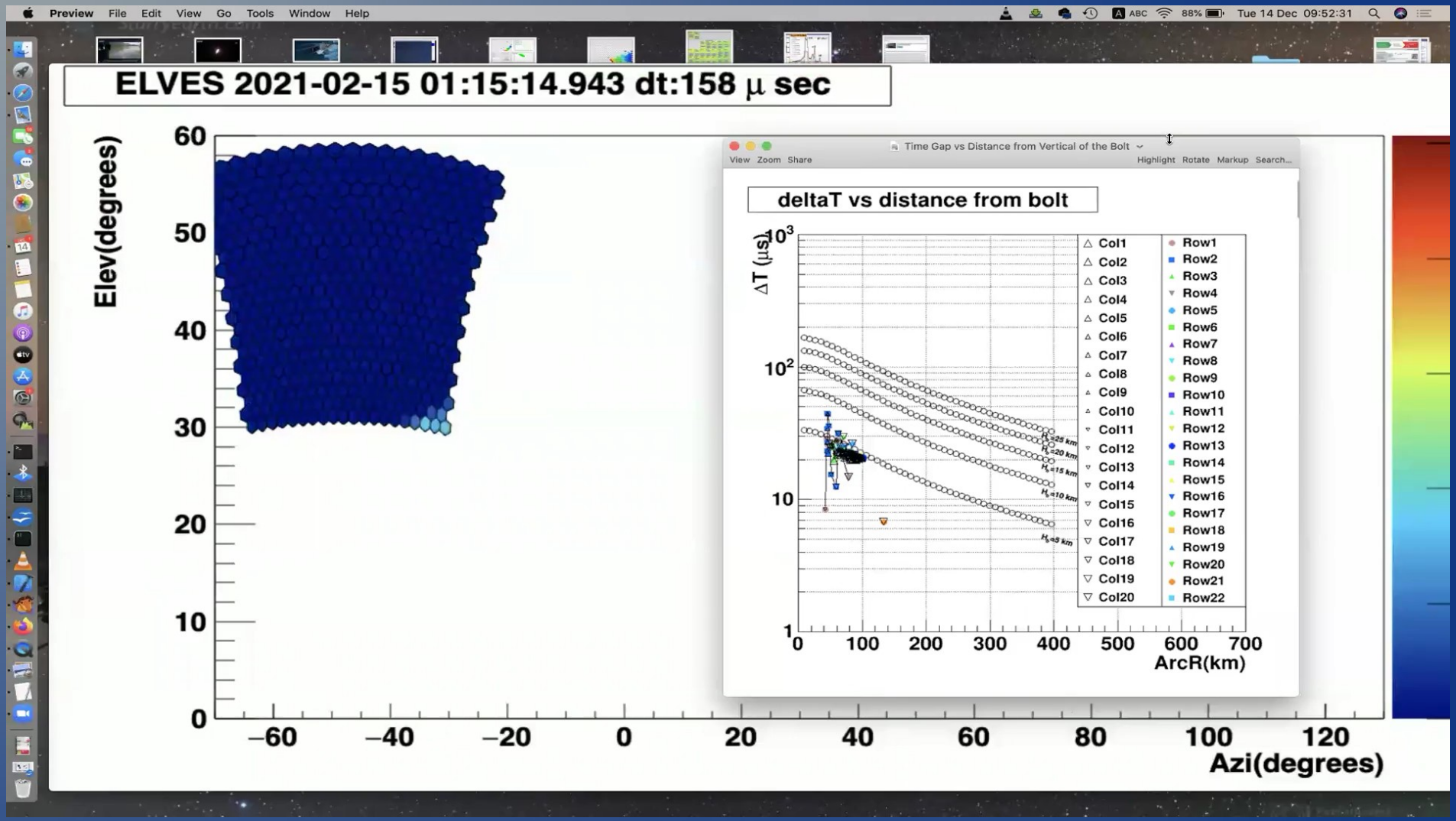


DOUBLE ELVES in HEAT-3



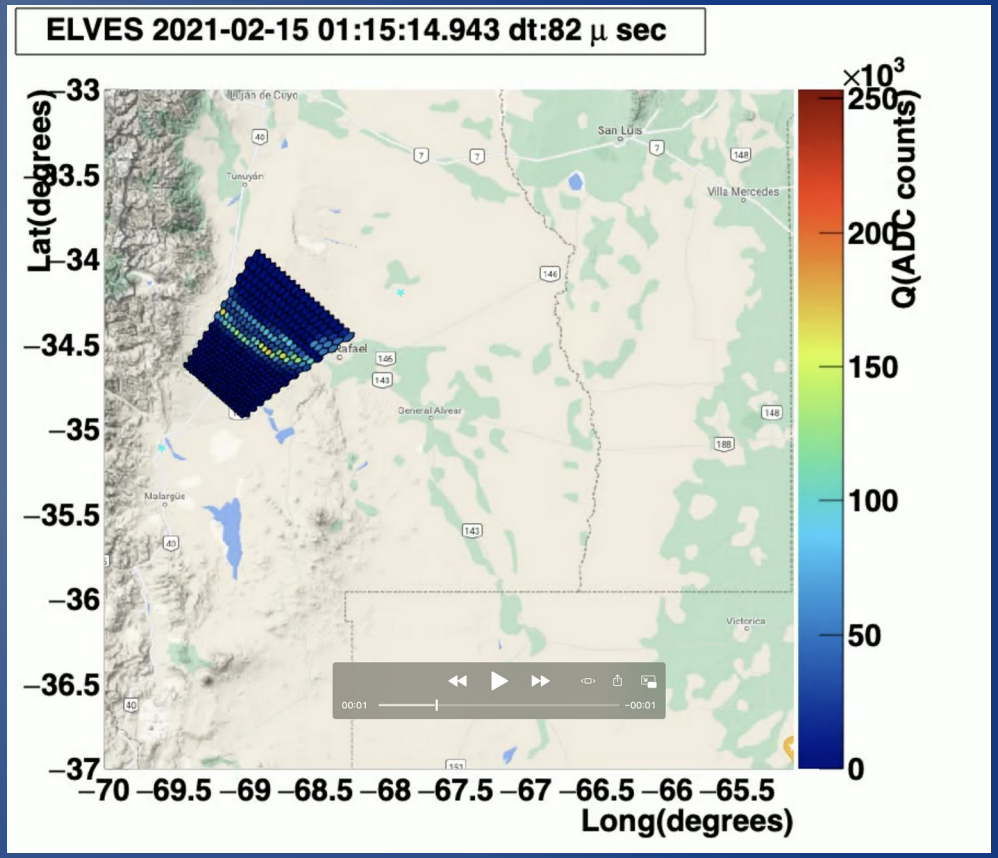
The small time gap between flashes in BOUNCE elves from low altitude clouds is hardly resolved in standard FD telescopes, but is well separated in HEAT field of view. Then, double ELVES from closer lightning can be better resolved in HEAT events.

DOUBLE ELVES in HEAT-3



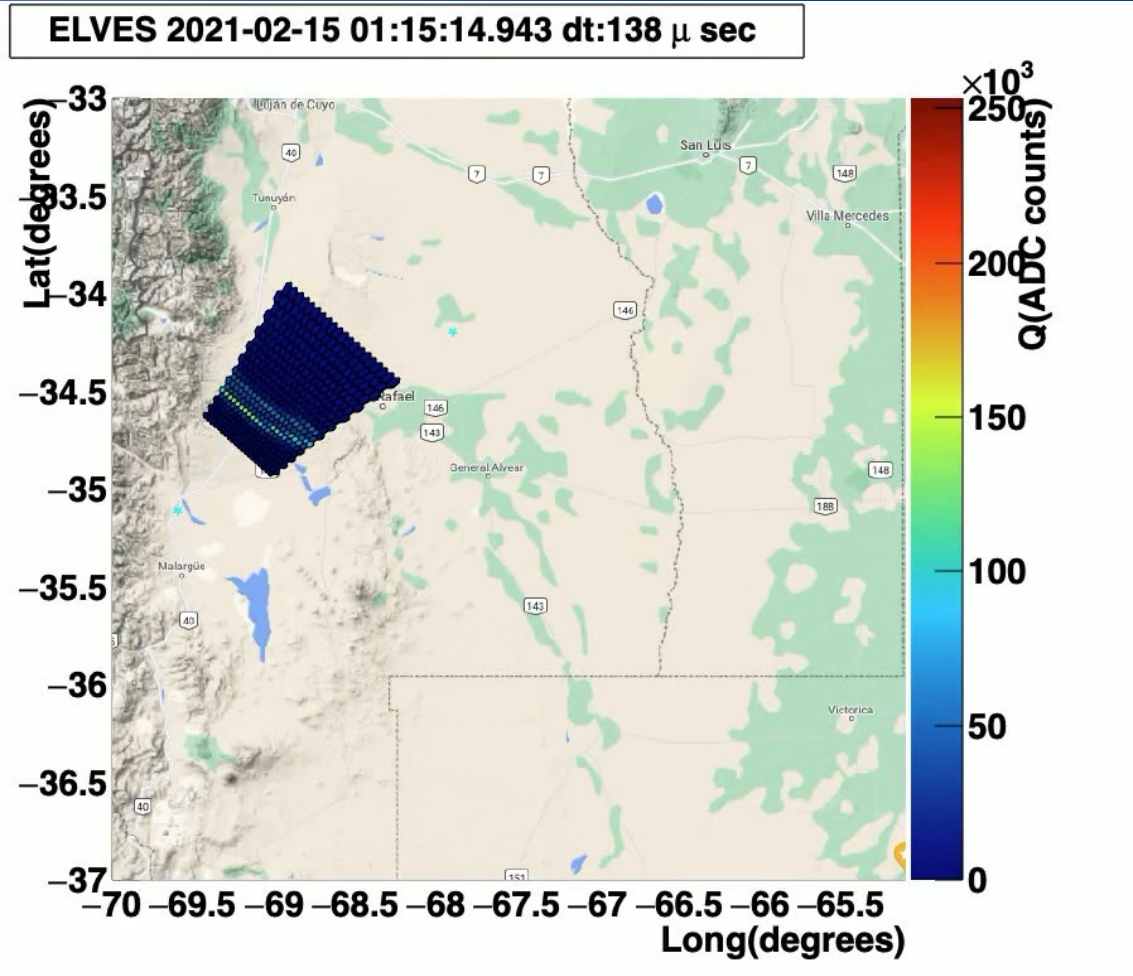
DOUBLE ELVES in HEAT-3

The animation of the event from the base of the ionosphere should be corrected by the time delay between the emission point and the FD.
Accounting for this, the light wave changes direction, as we expect, showing expanding rings, centered at the lightning source

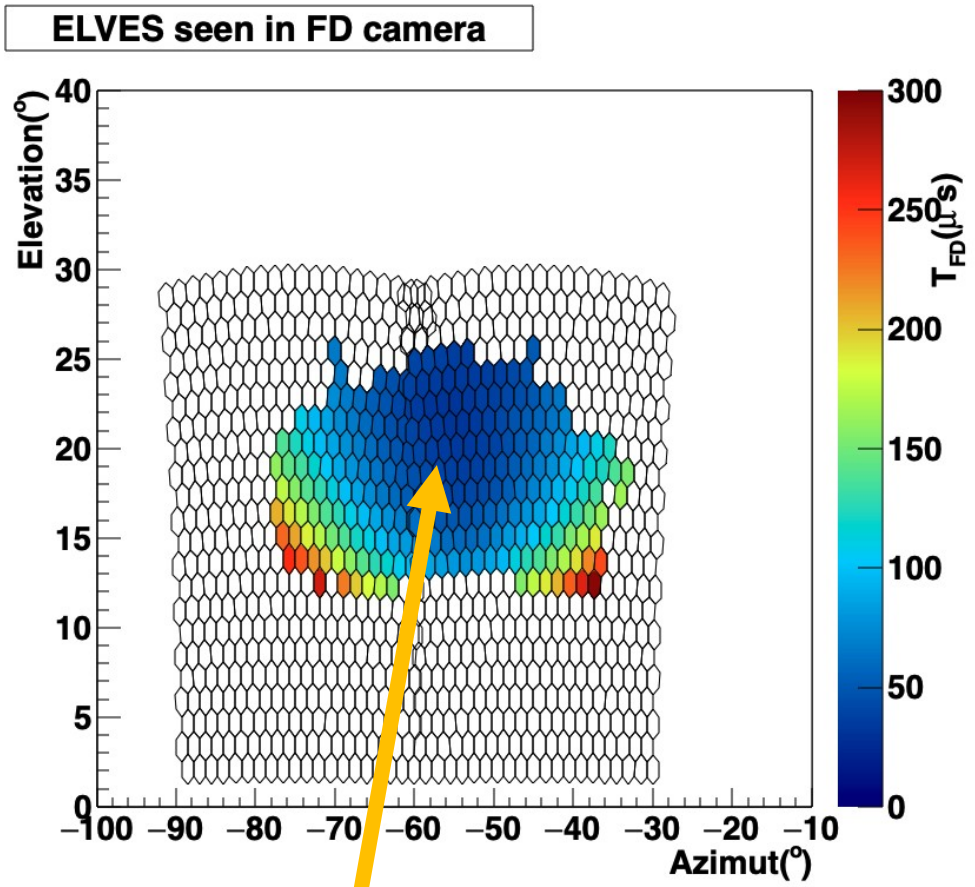


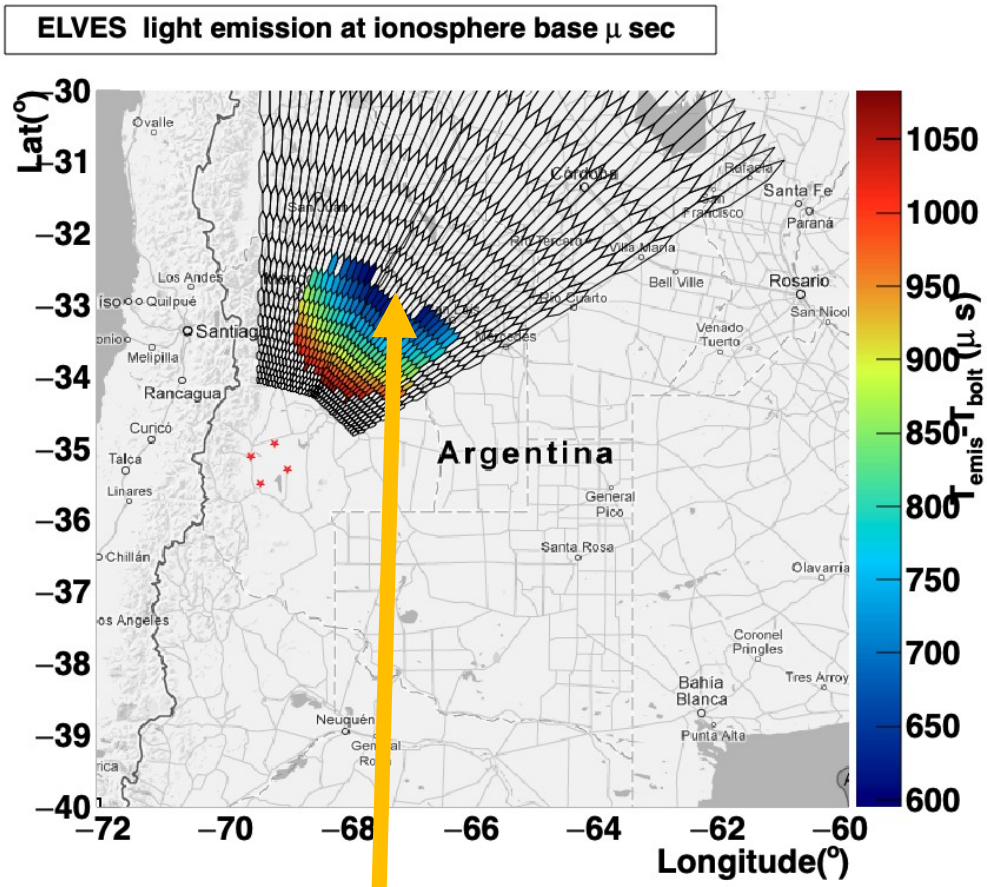
DOUBLE ELVES in HEAT-3

The animation of the event from the base of the ionosphere should be corrected by the time delay between the emission point and the FD.
Accounting for this, the light wave changes direction, as we expect, showing expanding rings, centered at the lightning source



ELVES timing at FD site vs Ionosphere base

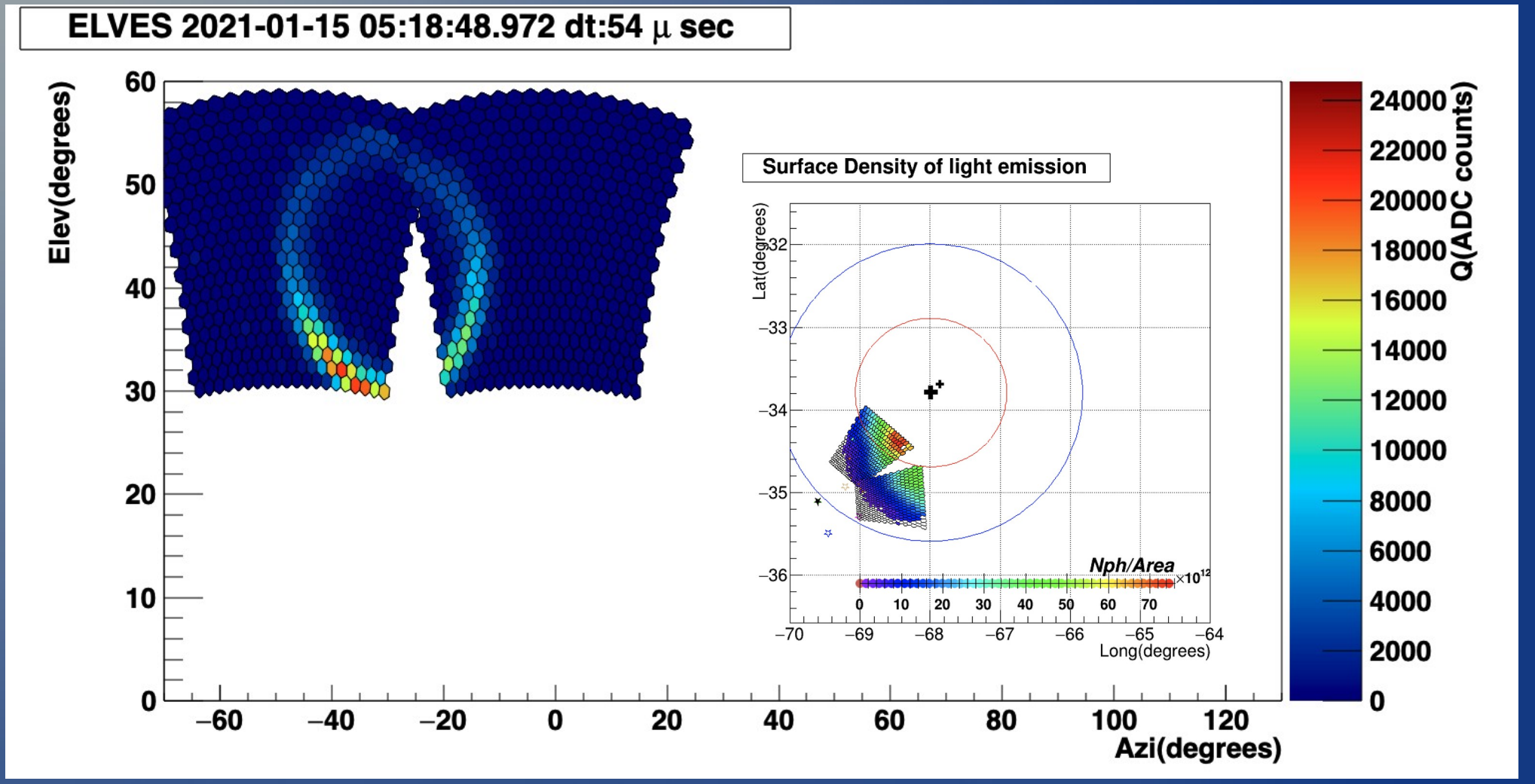




Here the center is in the direction with the shortest path between source and FD

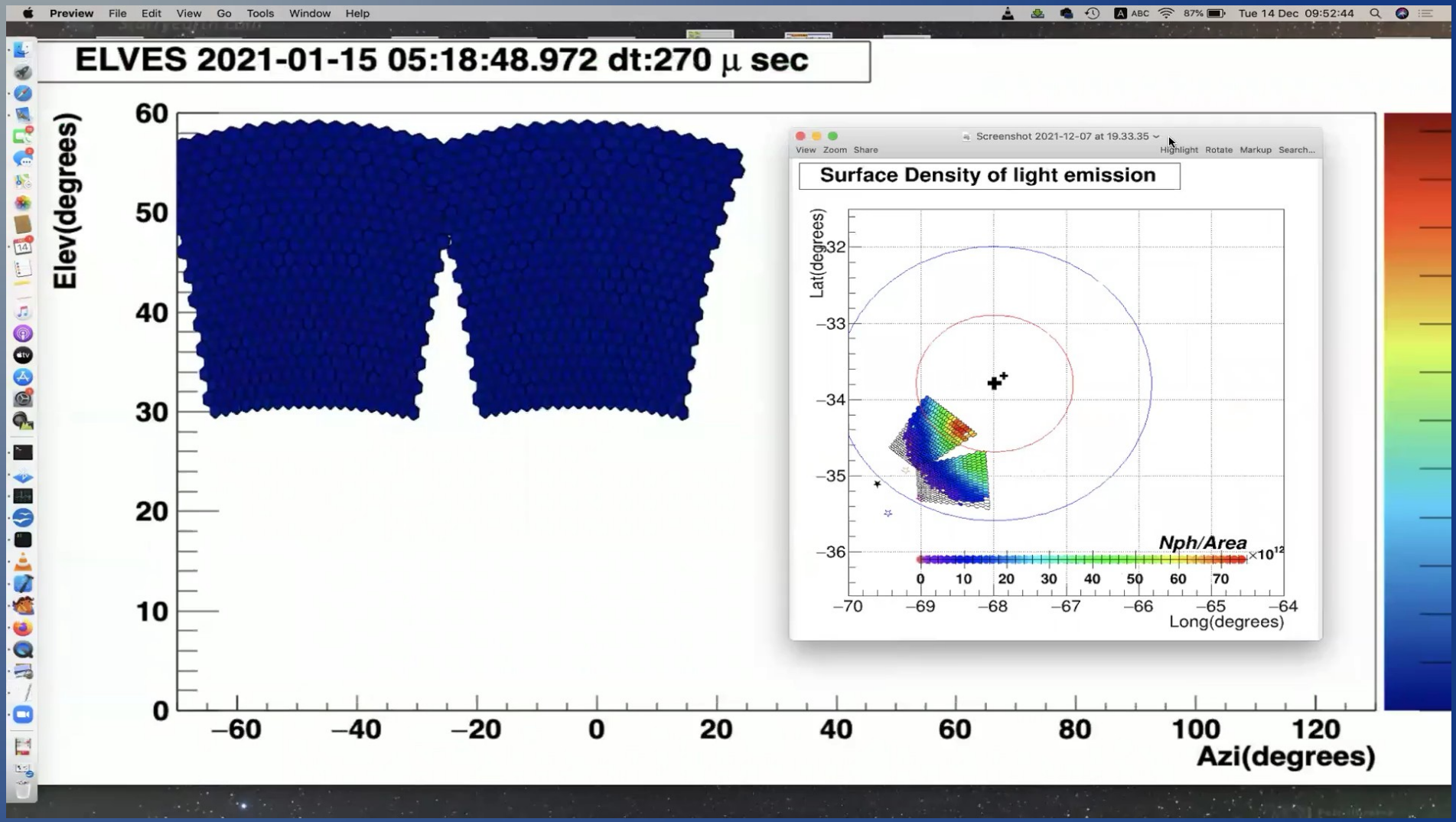
After correcting for time delays, the center is at the lightning source location

ELVES seen by HEAT 2&3



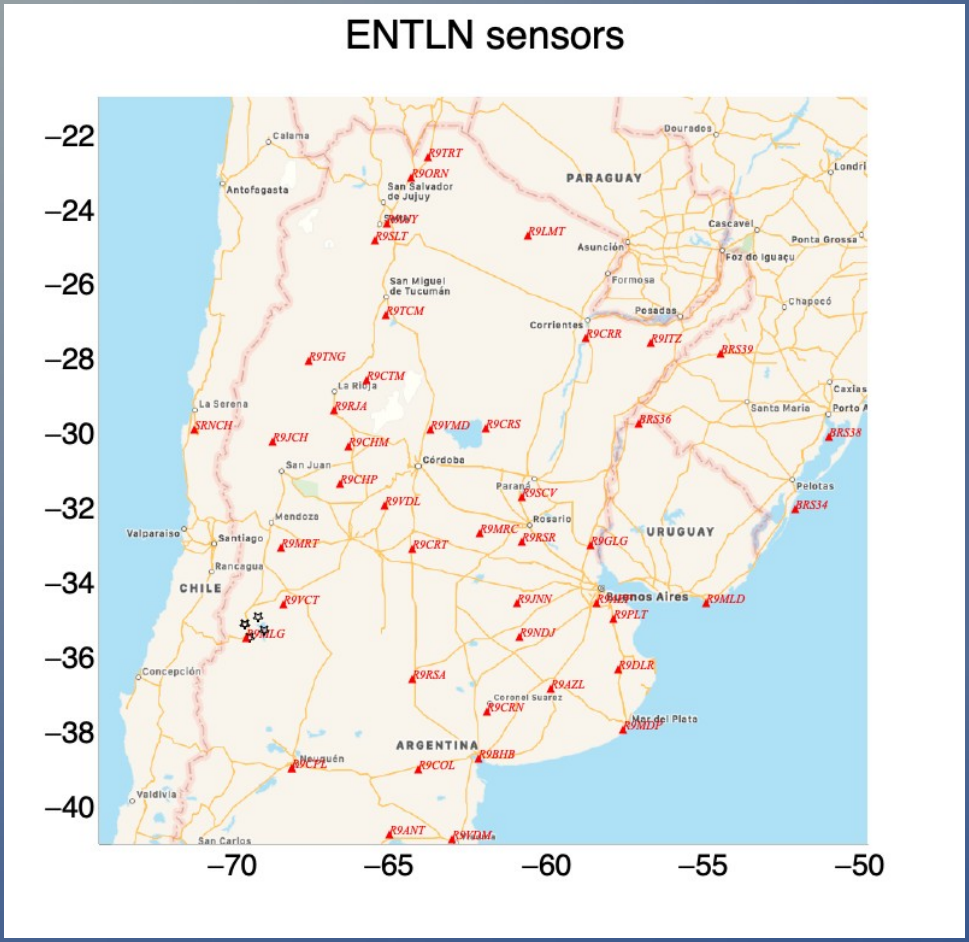
In many events we gain access to fine details of the light emission in the region of maximum intensity , but only in a fraction of the whole ring.

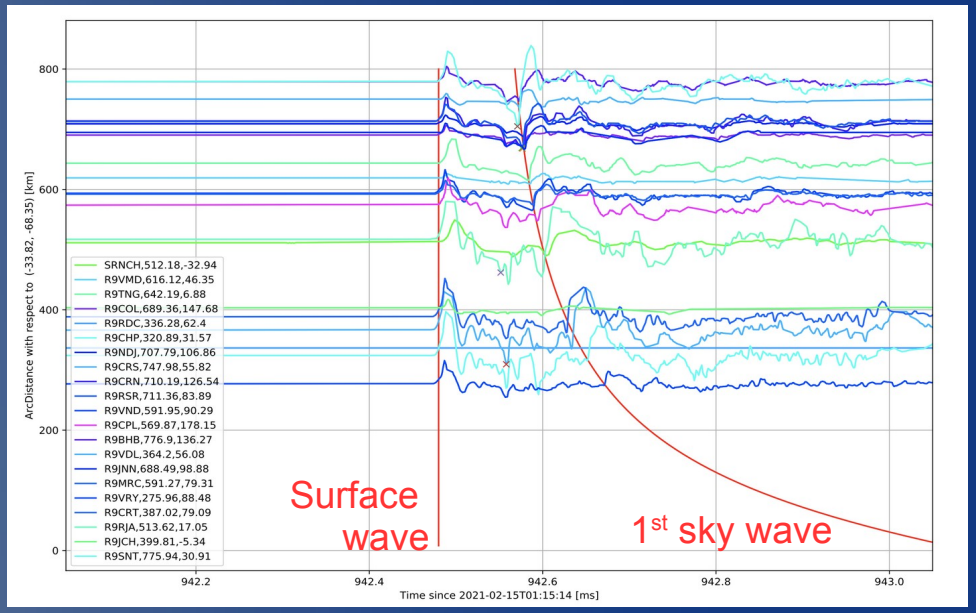
ELVES seen by HEAT 2&3



ELVES signals vs Radio signals

(Work in collaboration with J.Lapierre)



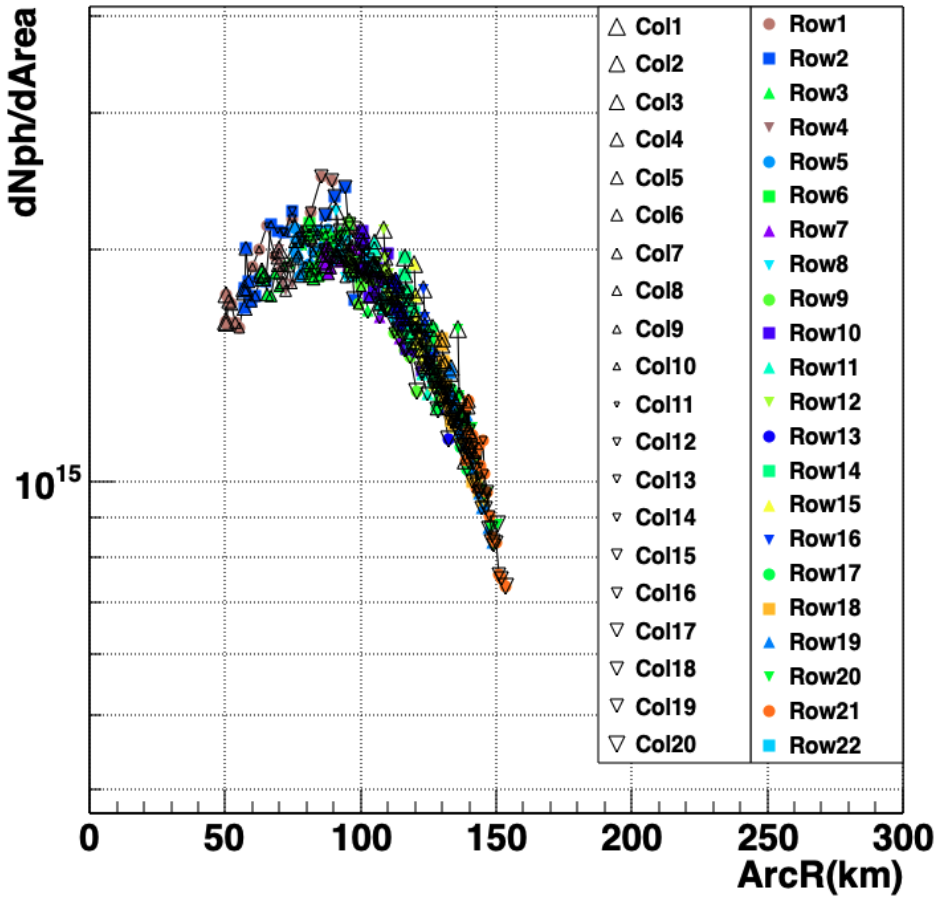


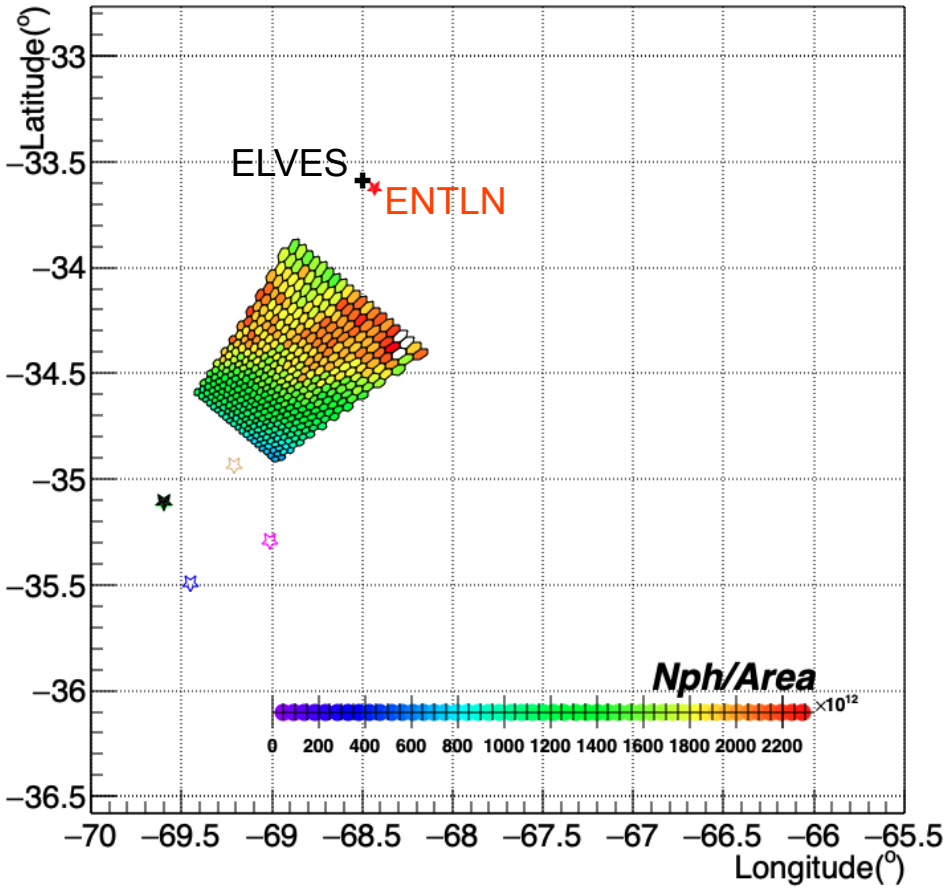
Semi-automated python scripts to align ENTLN traces: time axis corrected for delay from source lightning, calculated from results of elves reconstruction.

WWLLN bandwidth: 1-24 kHz 40 μs time resolution

ENTLN bandwidth : 1 Hz – 1.2 Mhz <1 μs time resolution
>35 antennas in Argentina, installed in summer 2018-9

Lightning source location in HEAT: ELVES vs ENTLN

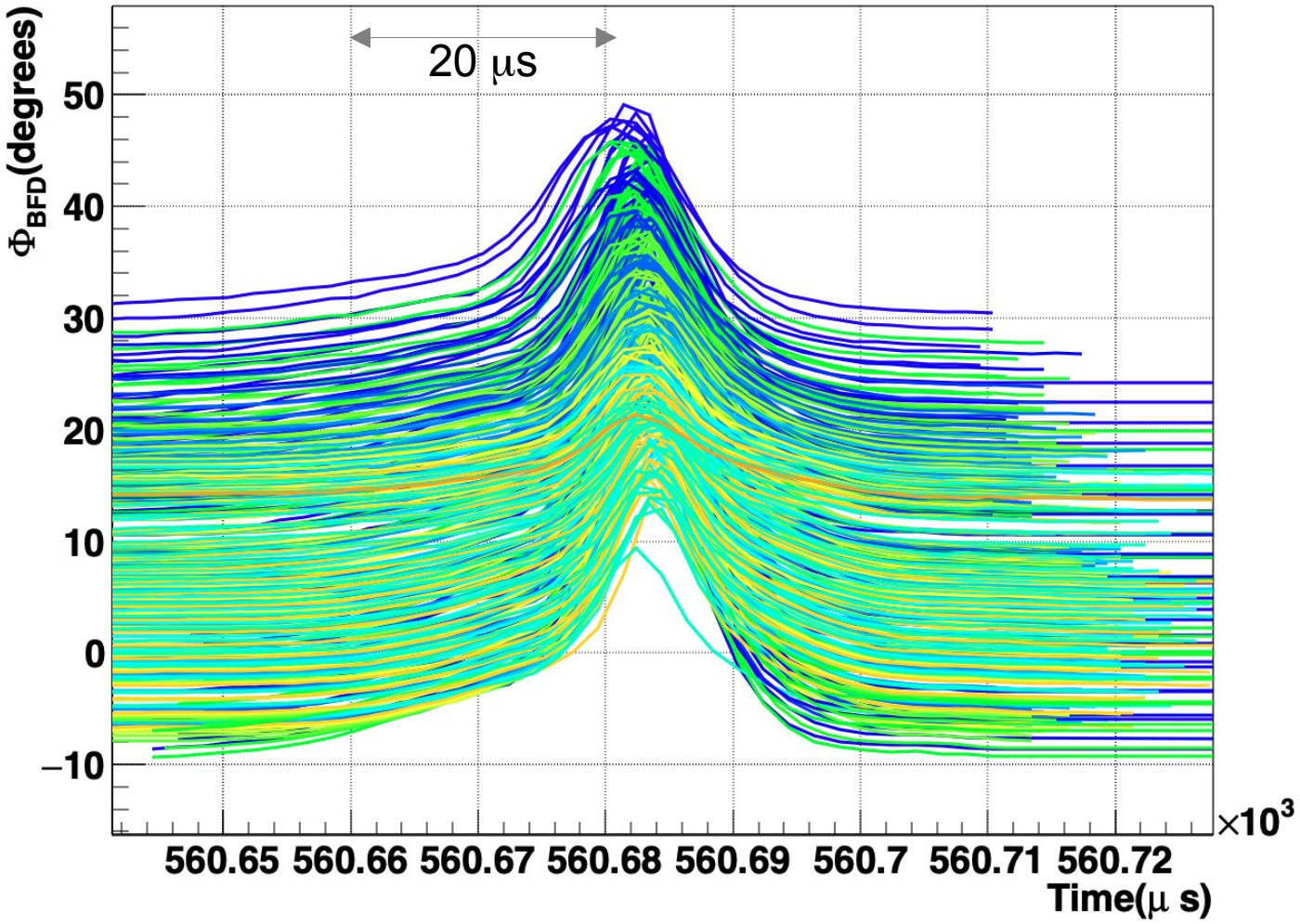


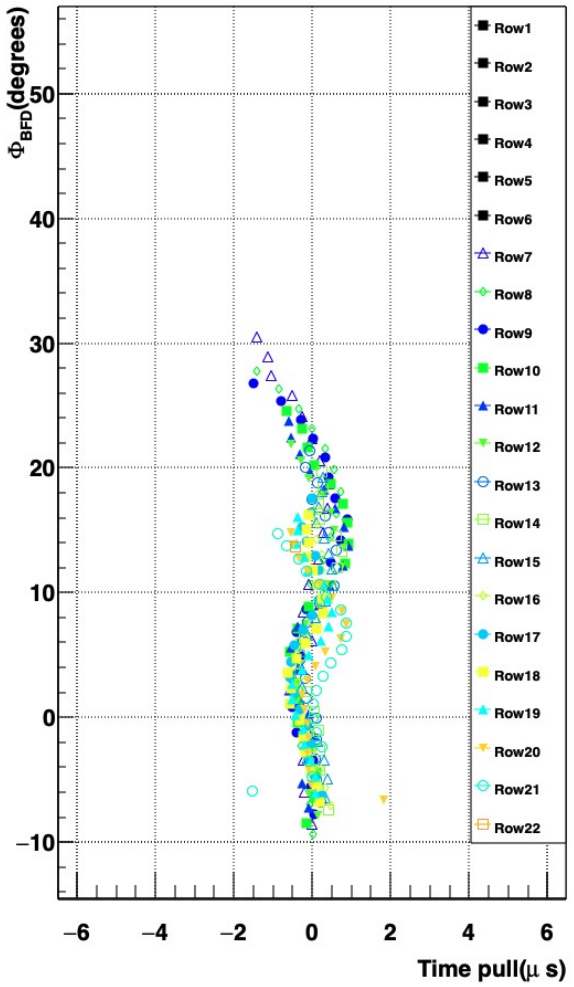


The light intensity distribution is NOT used to reconstruct the lightning source location: 3D time fit is used to locate lightning source

ELVES and ENTLN reconstructions differ by 5.5 km in this case

Lightning source location in HEAT: ELVES vs ENTLN

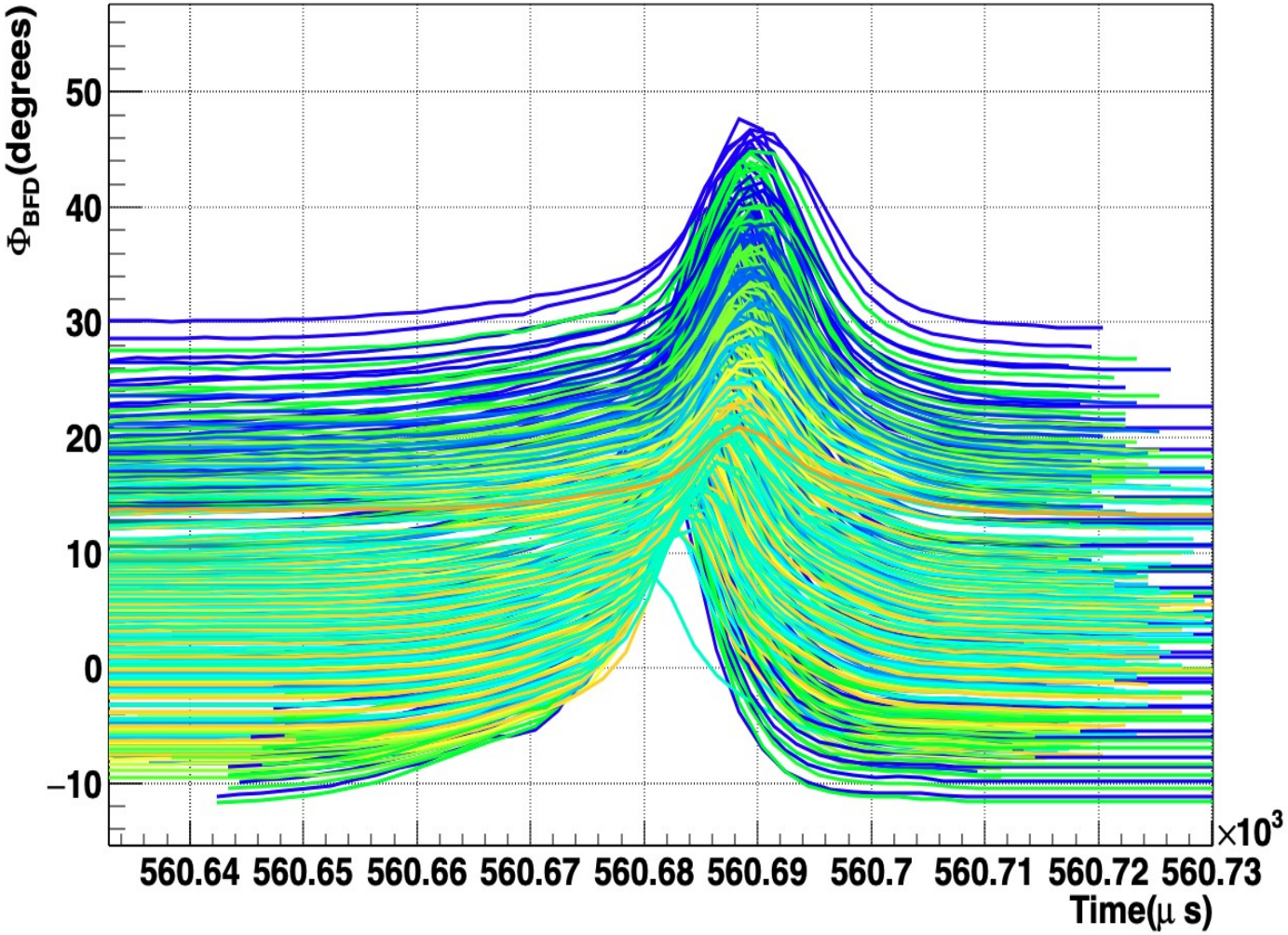


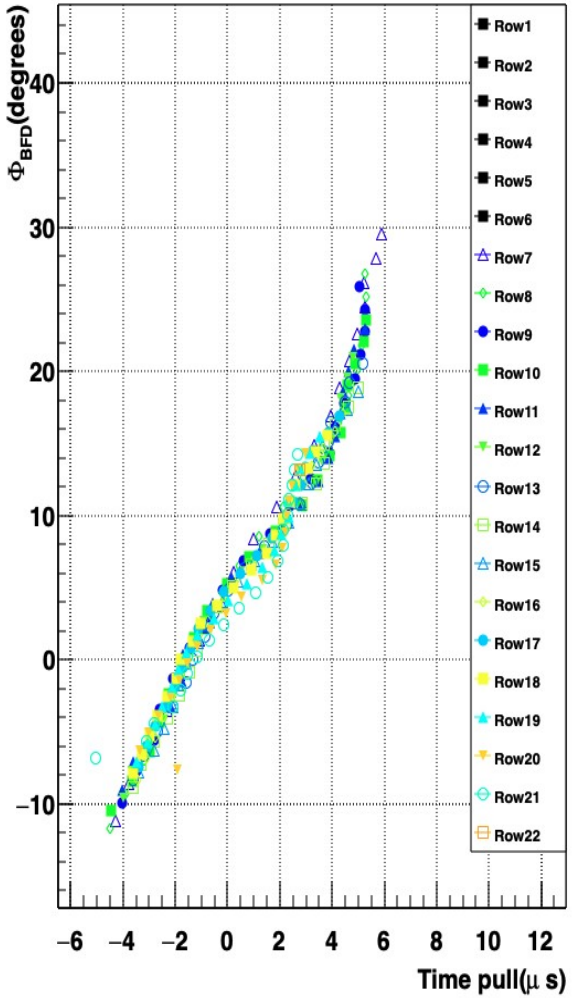


ELVES traces for all pixels realigned at source location, vs azimuth with respect to the vertical plane joining FD and lightning source location from ELVES reconstruction.
3D time fit is used to locate lightning source

Difference between measured time and expected time .

Lightning source location in HEAT: ELVES vs ENTLN

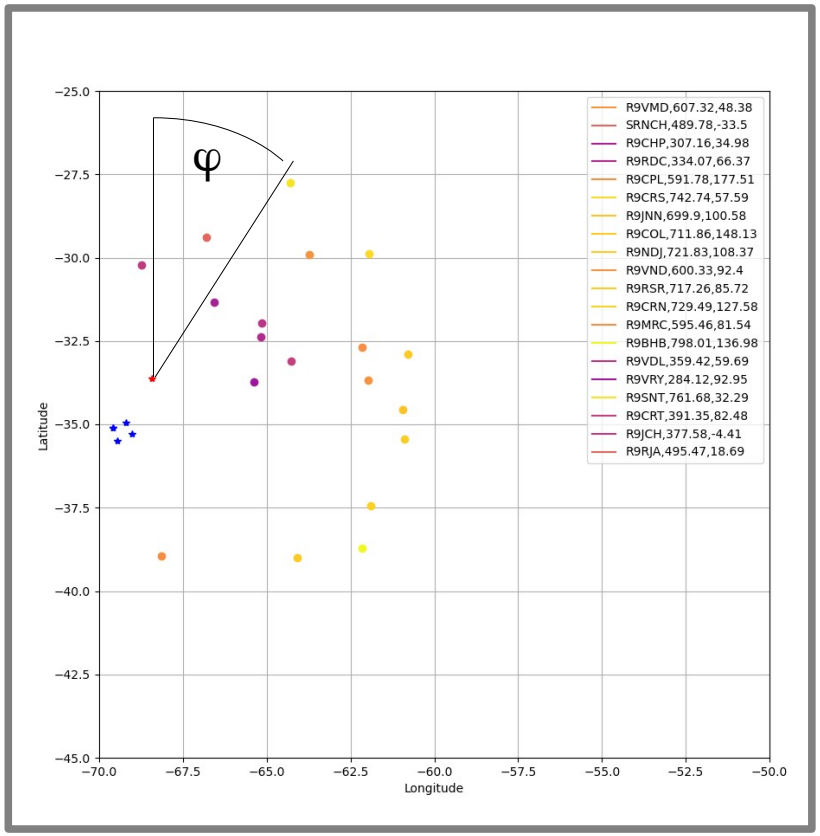


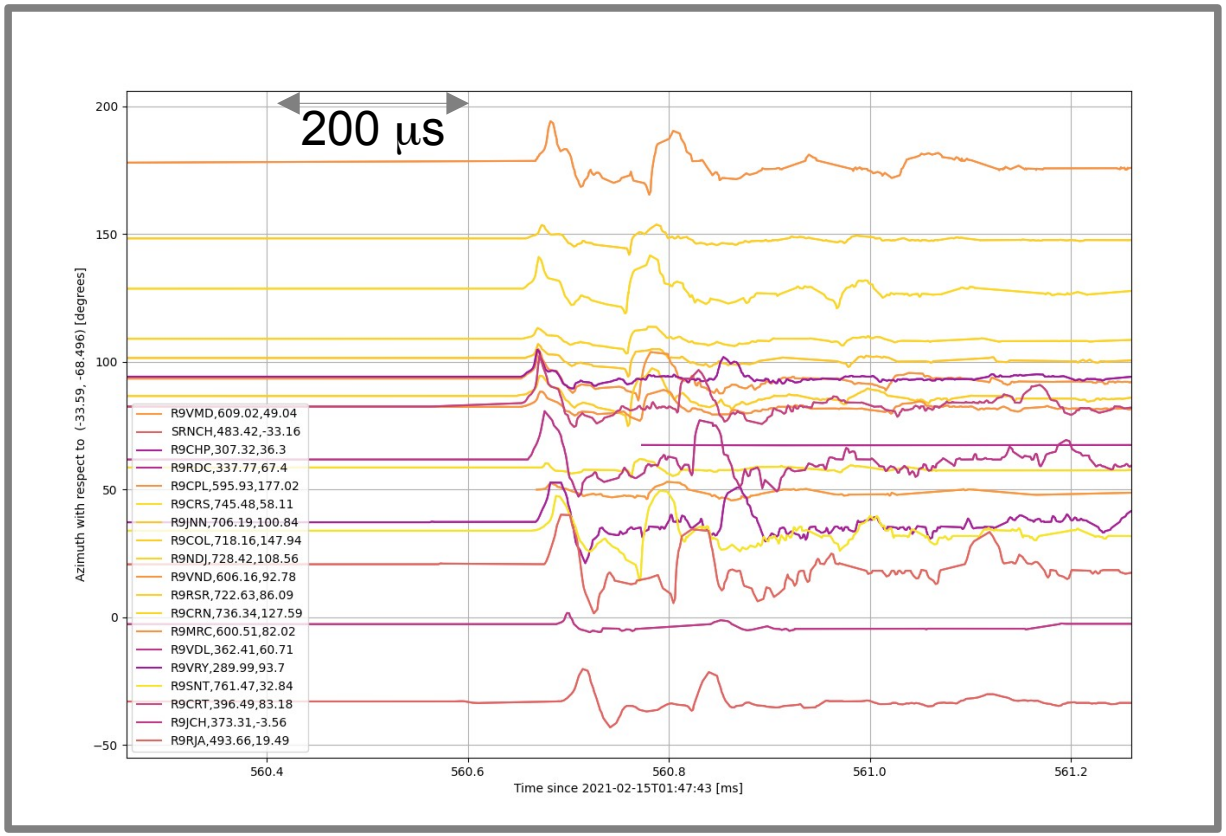


ELVES traces for all pixels realigned at source location, vs azimuth with respect to the vertical plane joining FD and lightning source location from ENTLN.

Difference between measured time and expected time .

Lightning source location in HEAT: ELVES vs ENTLN

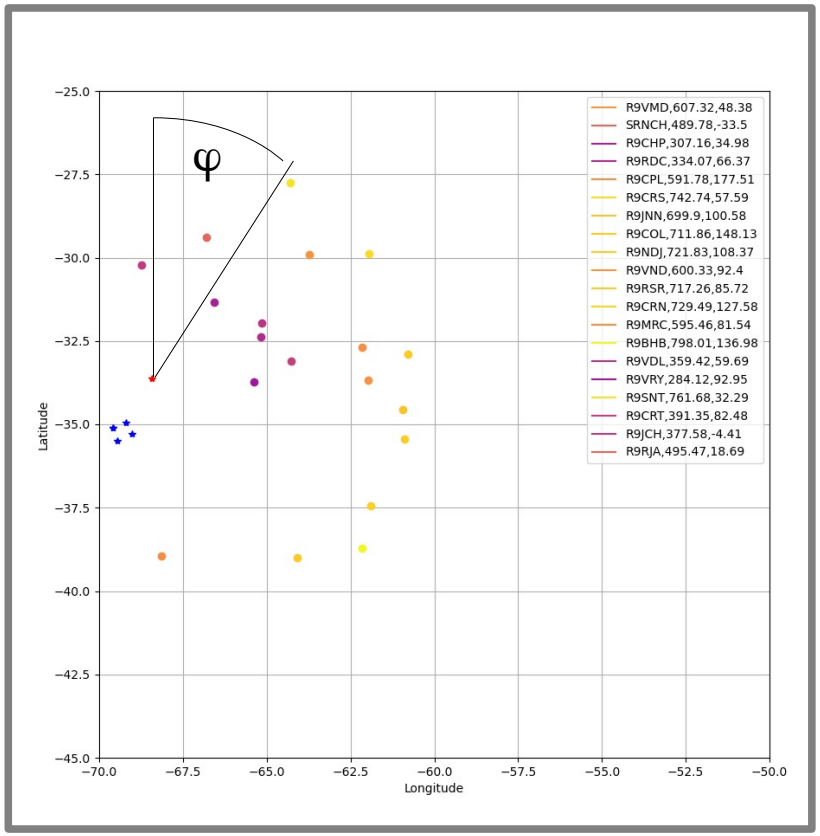


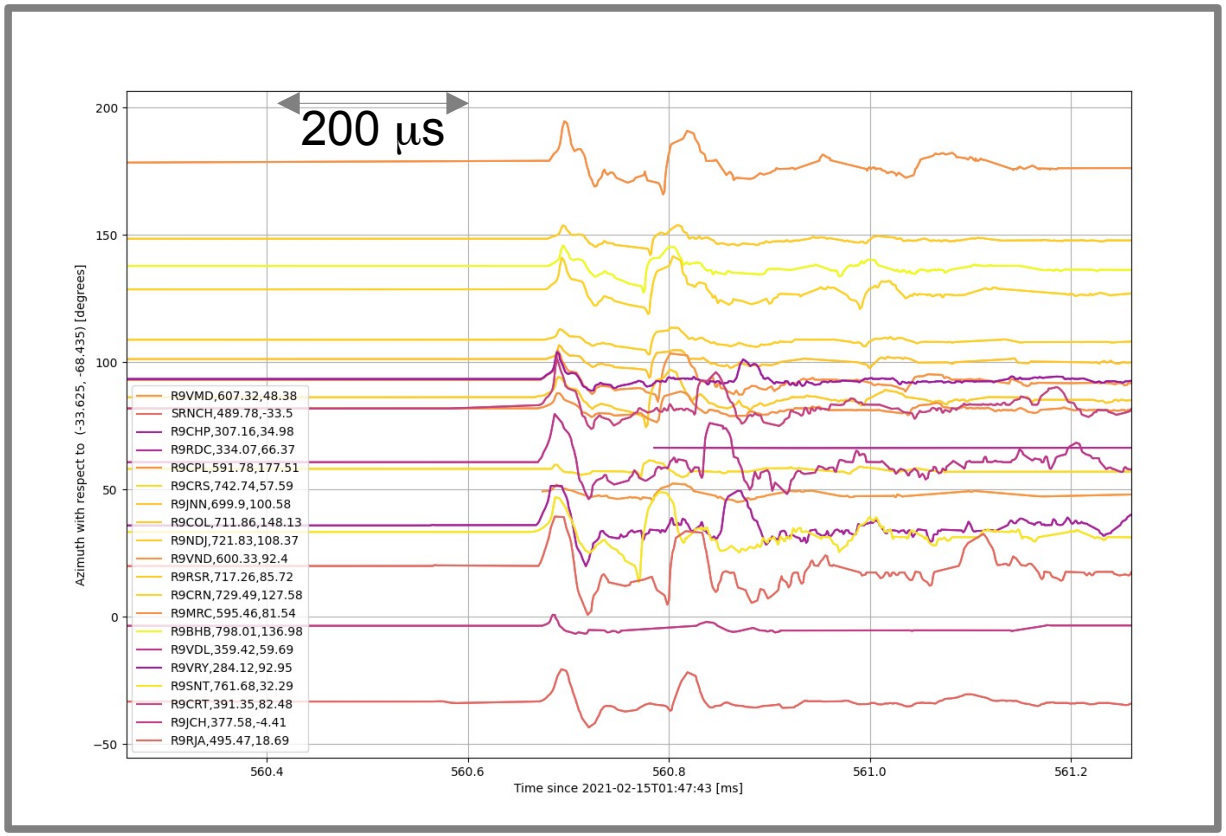


Location of the ENTLN antennas within 800 km around the lightning source location from ELVES reconstruction. Violet (yellow) stations are the closest (farthest).

Waveforms in the ENTLN stations. Baseline offsets are given by the azimuth of each antenna relative to the source location from ELVES reconstruction. Trace times are shifted to correct for the signal delay between source and antenna. Alignment is not ideal...

Lightning source location in HEAT: ELVES vs ENTLN

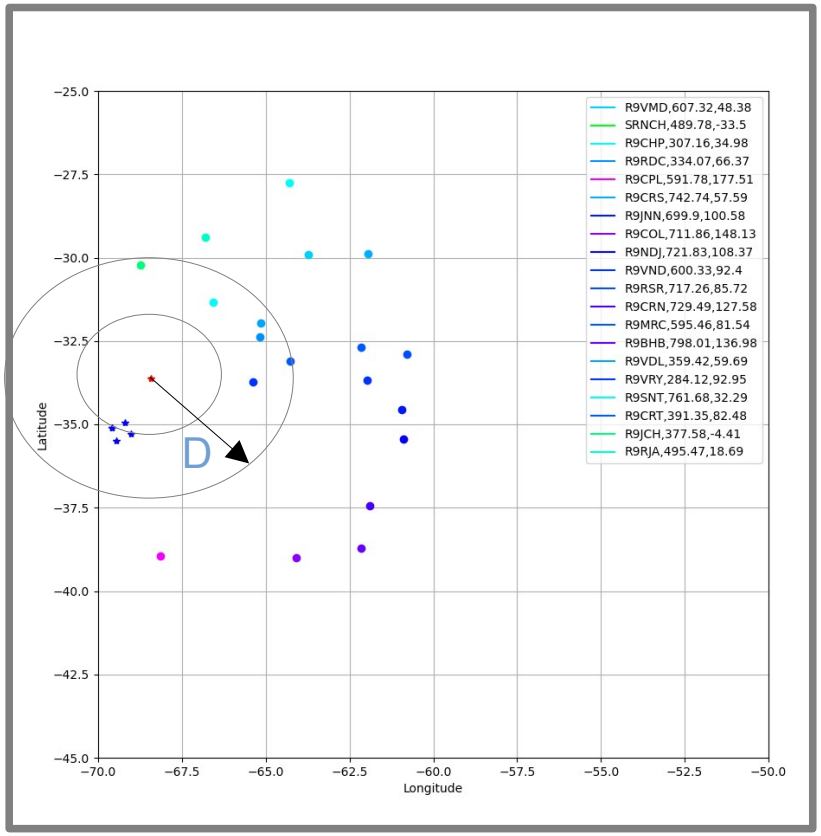


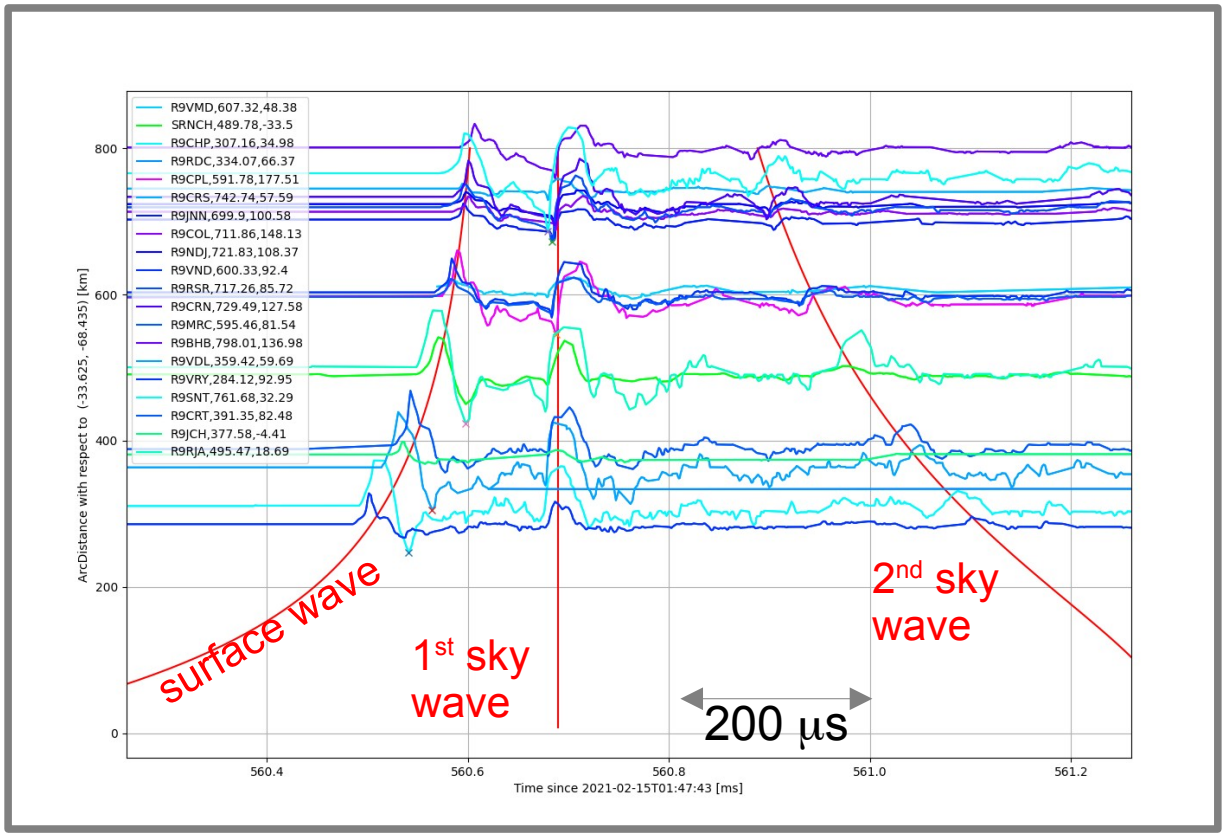


Location of the ENTLN antennas within 800 km around the lightning source location from ELVES reconstruction. Violet (yellow) stations are the closest (farthest).

Waveforms in the ENTLN stations. Baseline offsets are given by the azimuth of each antenna relative to the source location from ENTLN reconstruction. The source location is defined as the one which minimize the spread of the 1st peak. But the following peaks do not look aligned ...

Lightning source location in HEAT: ELVES vs ENTLN





Location of the ENTLN antennas within 800 km around the lightning source location from ENTLN reconstruction. Colors are now used to represent the azimuth.

Waveforms in the ENTLN stations. Baseline offsets are now given by the distance of each antenna relative to the source location from ENTLN reconstruction. The time correction accounts for the bounce at the base of the ionosphere (1st sky wave). The second reflection is also visible.

Summary

Auger Observatory takes data with an ELVES trigger regularly since 2014.

Since Jan.2021, the three additional HEAT telescopes allow detection of ELVES from closer lightning detecting features with unprecedented detail.

The origin of most double ELVES is still unclear: ground reflection accounts for a small fraction of double elves observed. For FLAT double ELVES, comparing the ratio of light emissions, we observe different behaviors which may hint to different mechanisms.

We have developed python code to directly compare ELVES trace to ENTLN waveforms with proer time corrections. Results are encouraging and will further help in clarifying the different mechanisms at the origin of the ELVES.

Thank you for you attention!

Bibliography

R.Mussa et al, Eur.Phys.J.Plus 127 (2012) 94
A.Tonachini et al., Proc. ICRC 2011, 401
A.Tonachini et al., Proc. ICRC 2013, 0676

R.Mussa et al, EPJ Web Conf. 197 (2019) 03004. AtmoHEAD2018
R.Mussa et al, PoS ICRC2019 (2020) 1131 Proc.ICRC2019
A.Vasquez et al., PoS ICRC2021 (2021) 327 Proc.ICRC2021

A.Aab et al, A Three Year Sample of Almost 1600 Elves Recorded Above South America by the Pierre Auger Cosmic-Ray Observatory, *Earth Space Sci.* 7 (2020) 4, https://doi.org/10.1029/2019EA000582

K.-D.Merenda, R.Mussa, L.Wiencke (2020), Catching elves in Argentina, EOS, 101, https://doi.org/10.1029/2020EO145248.