



# Study on multi-ELVES in the Pierre Auger Observatory

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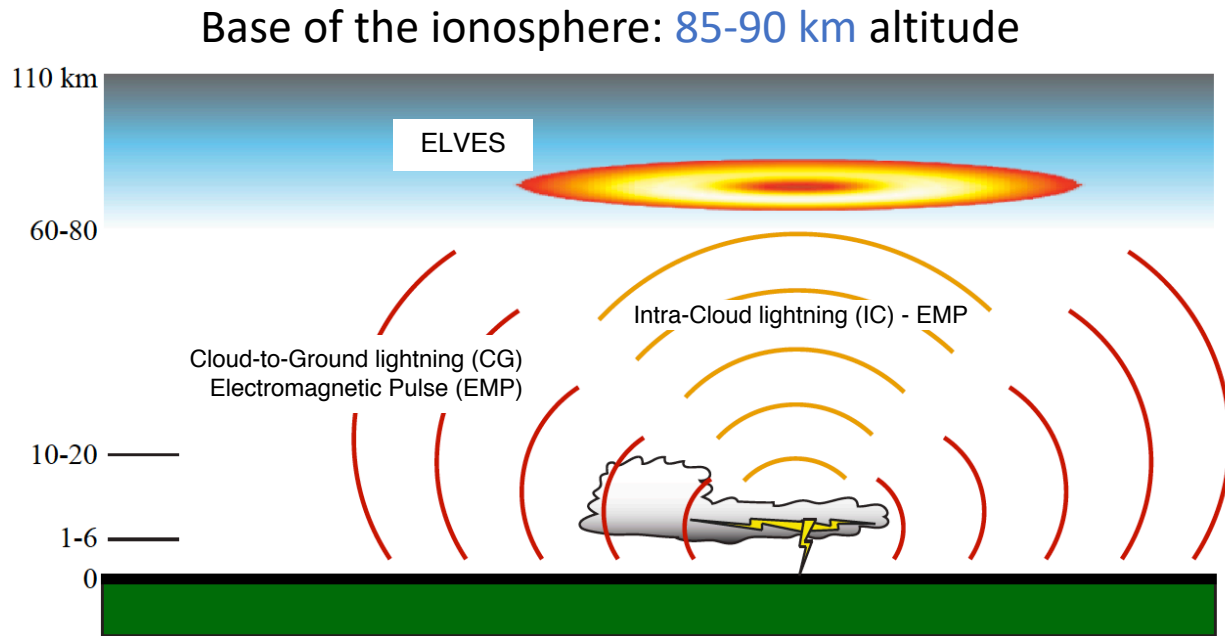
on behalf of the Pierre Auger Collaboration<sup>b</sup>

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<sup>b</sup>Observatorio Pierre Auger, Av. San Martín Norte 304, 5613 Malargüe, Argentina

# 1. ELVES

Emission of Light and Very low frequency perturbations due to Electromagnetic pulse Sources



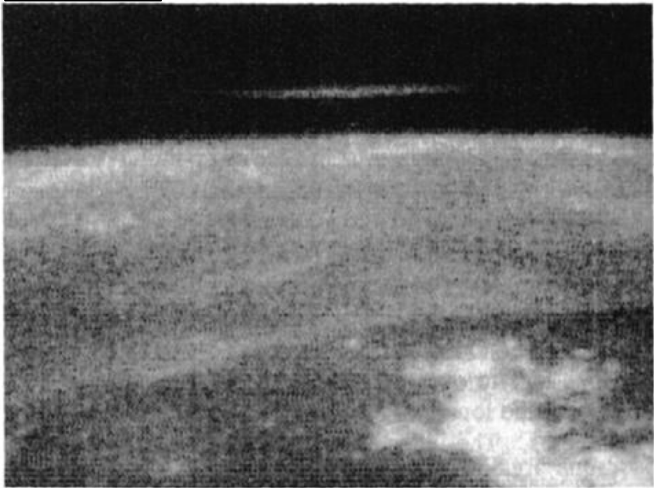
[https://agenda.infn.it/event/6244/contributions/62230/attachments/45129/53411/HILITE2013\\_elves\\_Blaes.pdf](https://agenda.infn.it/event/6244/contributions/62230/attachments/45129/53411/HILITE2013_elves_Blaes.pdf)



# The improvement of the time resolution of the detectors allowed the detection of multi-ELVES

First detection of ELVES:  
a very thin glow from the sky

17 ms

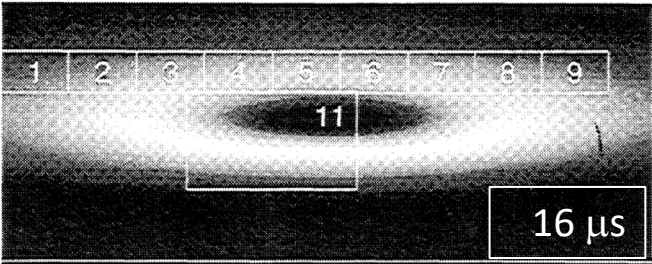


W. L. Boeck et al., *Geophysical R.L.* 19 (1992).

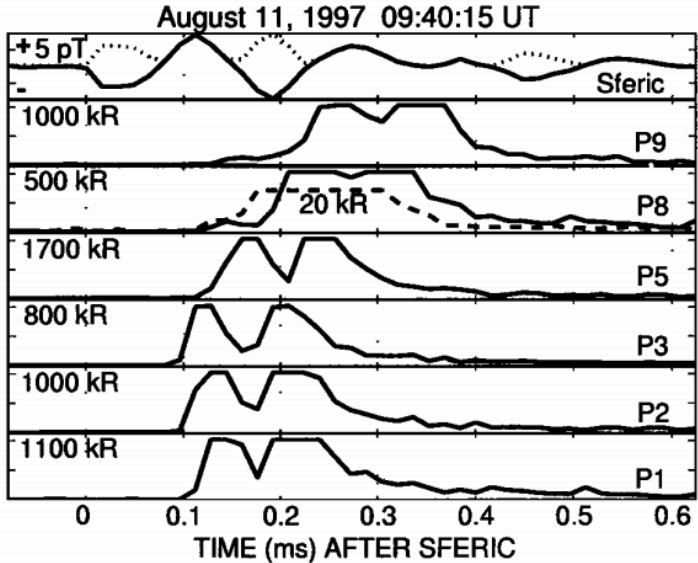
First detection of ELVES "doublets"

## Fly's Eye

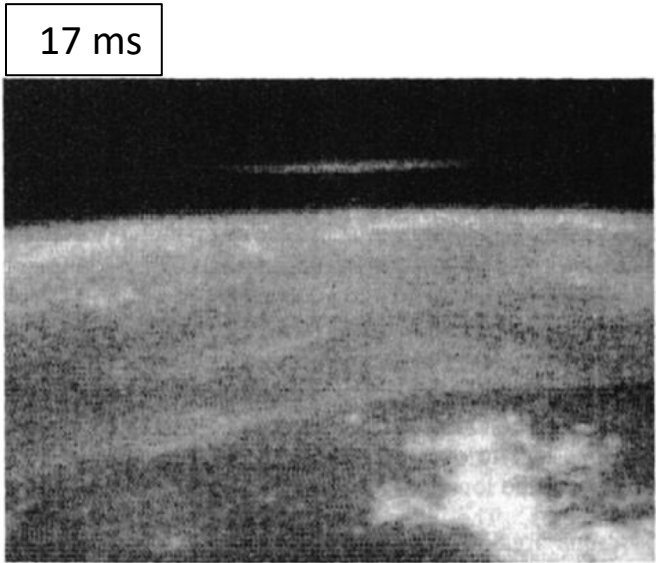
horizontal array of PMTs



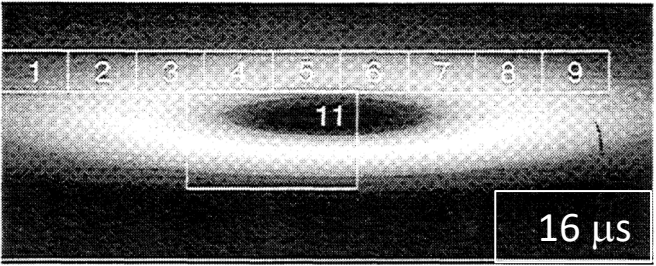
C. P. Barrington-Leigh and U. S. Inan (1999), *Geophysical R.L.* 26



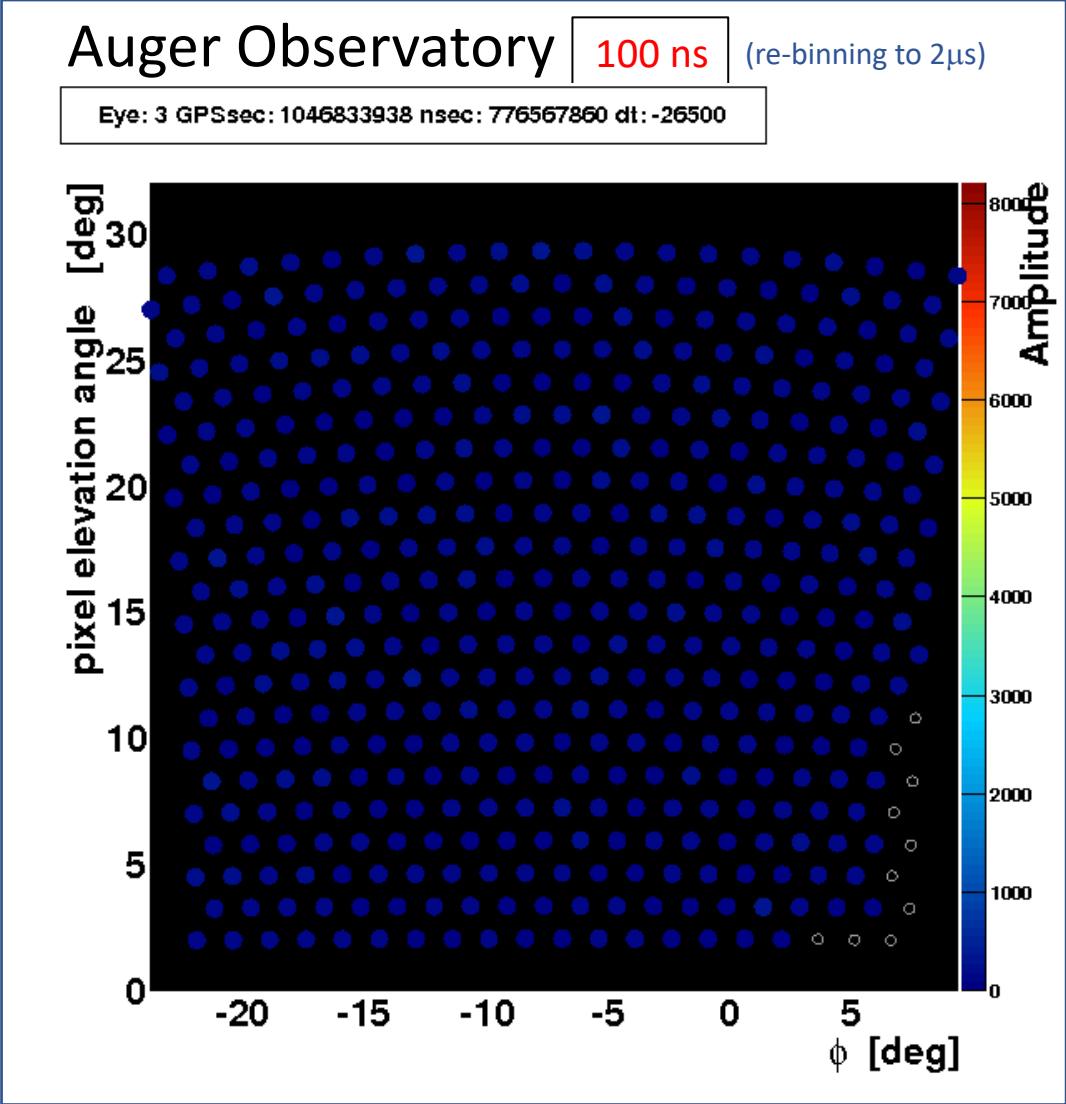
# The improvement of the time resolution of the detectors allowed the detection of multi-ELVES



W. L. Boeck et al., *Geophysical R.L.* 19 (1992).



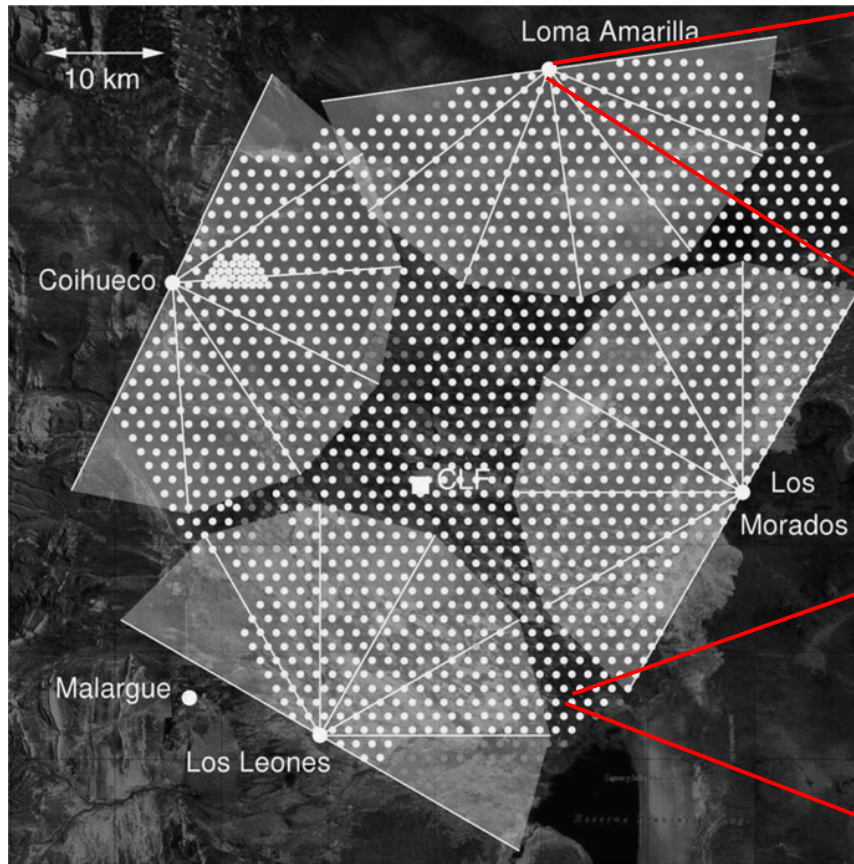
C. P. Barrington-Leigh and U. S. Inan (1999), *Geophysical R.L.* 26



**Multi-ELVES**  
Event with more than one peak in their photo-traces

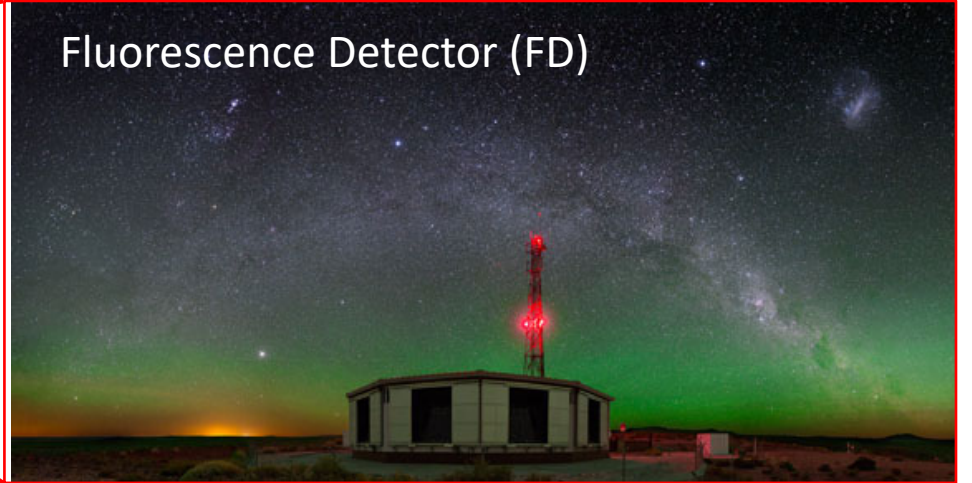


# ELVES at the Pierre Auger Observatory



J. Abraham et al. [Pierre Auger Coll.], *Nucl. Instrum. Meth. A* **620** (2010)

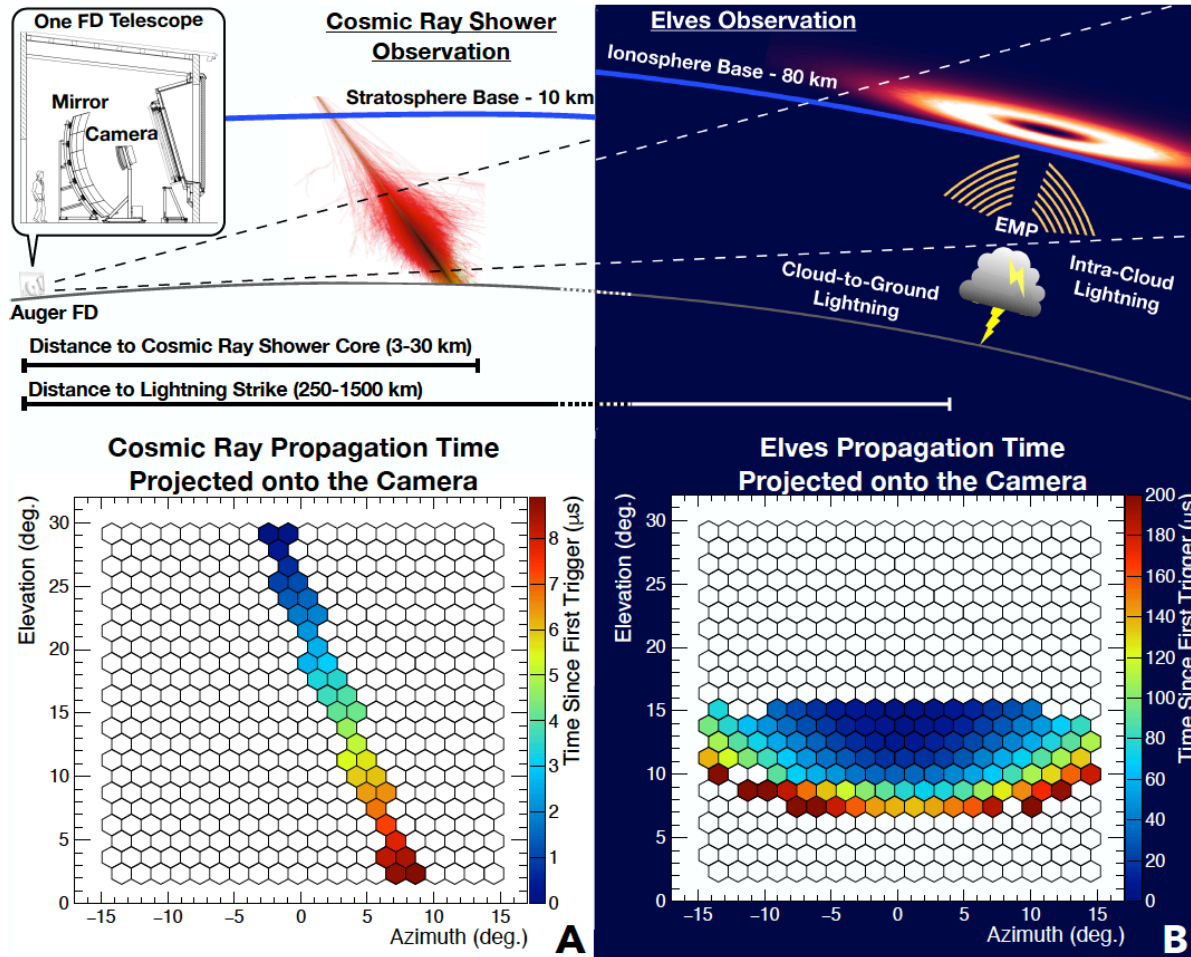
## Fluorescence Detector (FD)



## Surface Detector (SD)



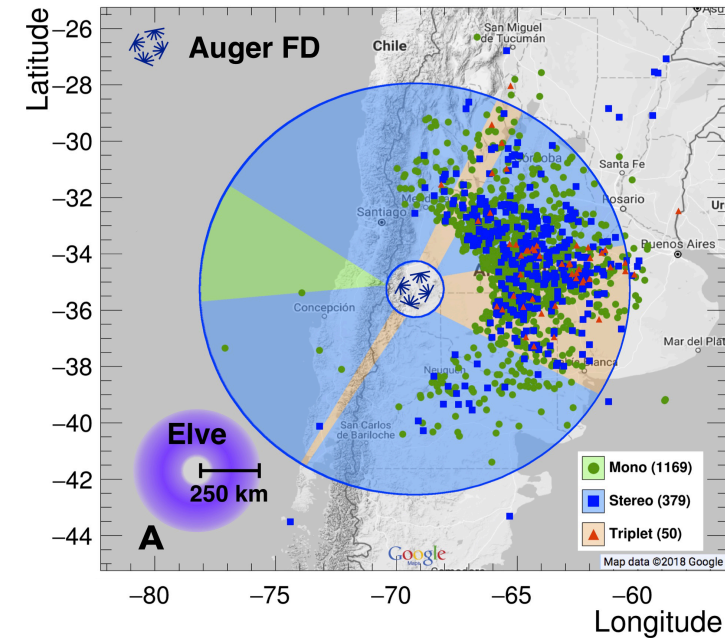
# ELVES at the Pierre Auger Observatory



CRs  $\sim 8 \mu\text{s}$

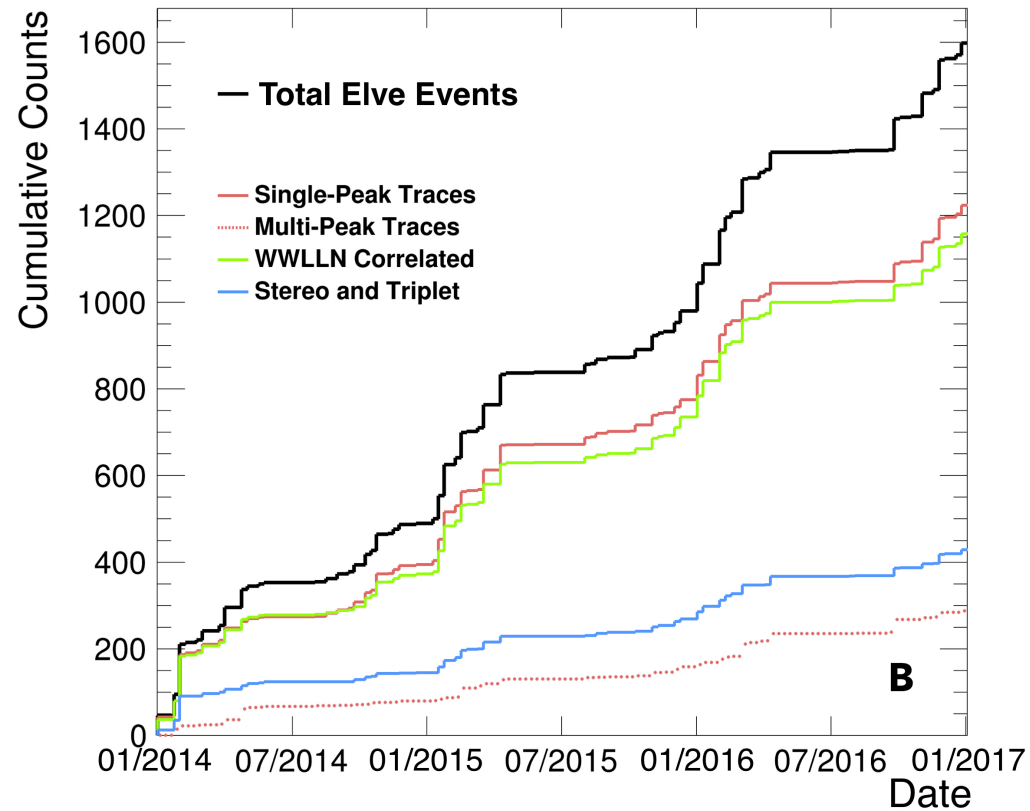
ELVES  $\sim 200 \mu\text{s}$

A. Aab et al. [Pierre Auger Coll.], *Astr. Soc. P.* 7 (2020).

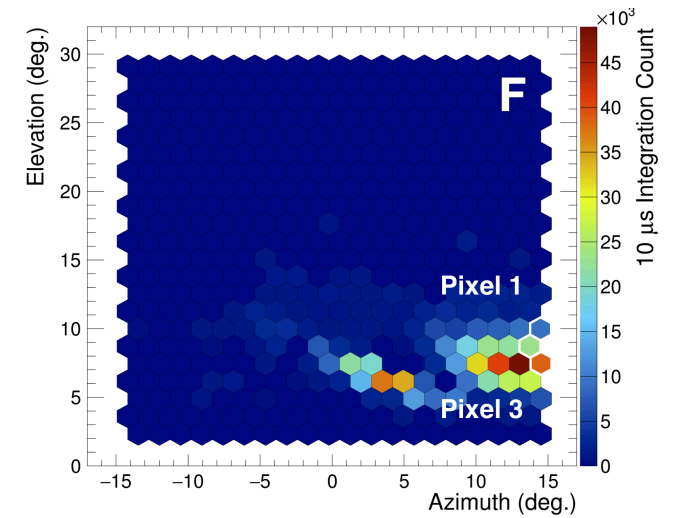
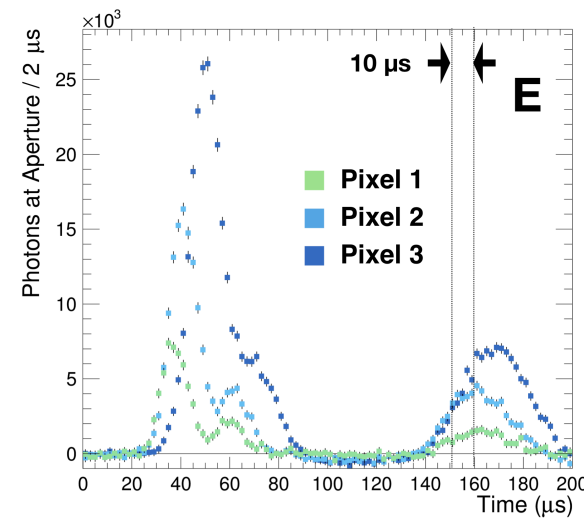


- Since 2014 the FD readout and triggering system were updated to detect ELVES with a high efficiency.
- Trace length extended from  $300 \mu\text{s}$  to  $900 \mu\text{s}$  in 2017.
- Viewing footprint for ELVES:  $3 \times 10^6 \text{ km}^2$

# ELVES at the Pierre Auger Observatory



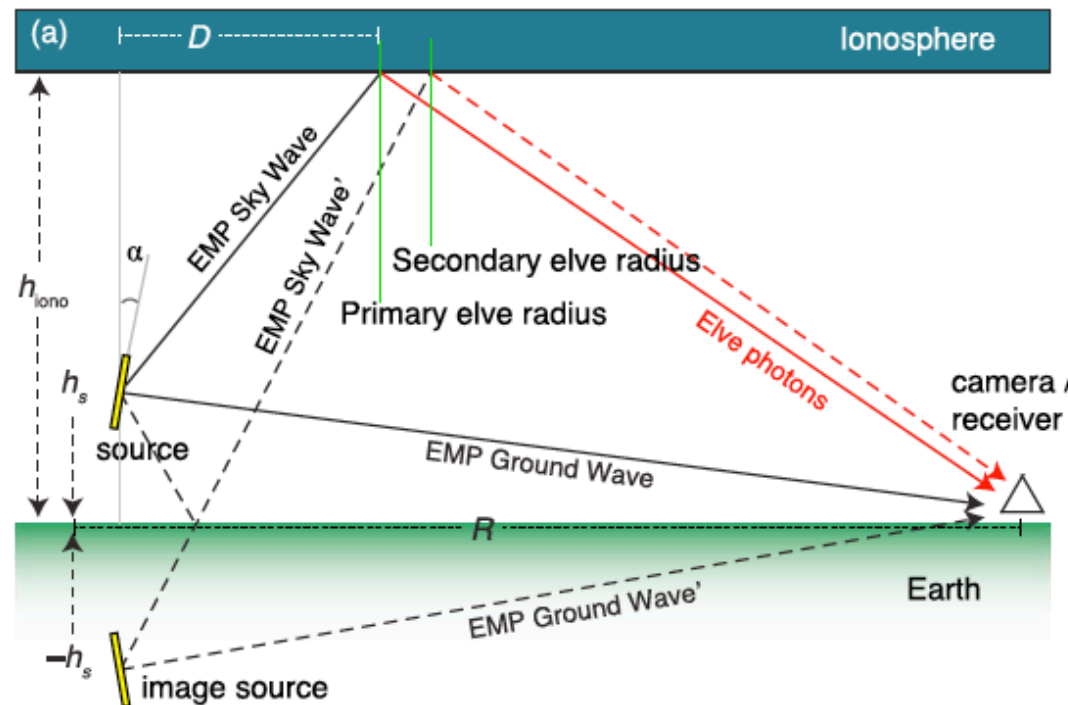
- 1600 well reconstructed ELVES were detected in the period 2014-2016
- 72% are correlated with WWLLN
- Many ELVES show **multiple-peak traces**: first reported observation of ELVES with **three peaks**



A. Aab et al. [Pierre Auger Coll.], *Astr. Soc. P.* 7 (2020).

## 2. Sources that may produce multi-ELVES

### Mechanism of an IC lightning producing double-ELVES



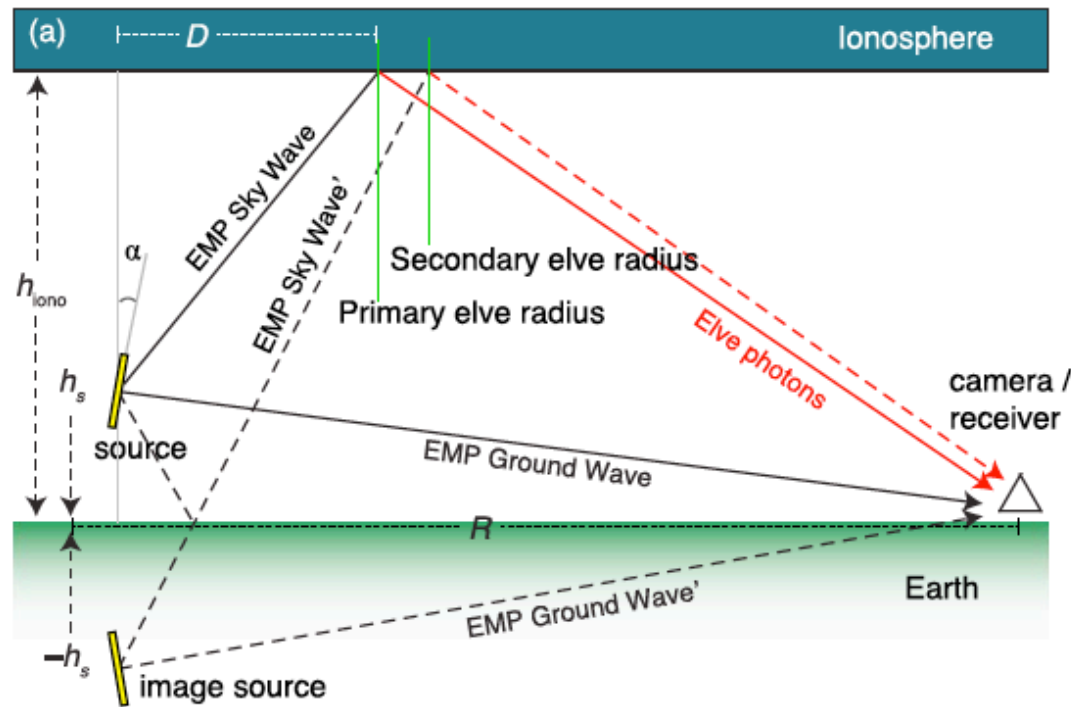
R. A. Marshall et al., *Geophys. Res. Lett.*, **42** (2015)

- The **altitude of the lightning** source inducing elves is directly proportional to the **time delay** between peaks.
- The **inclination of the lightning** with respect to the vertical can produce **different amplitudes** between peaks.

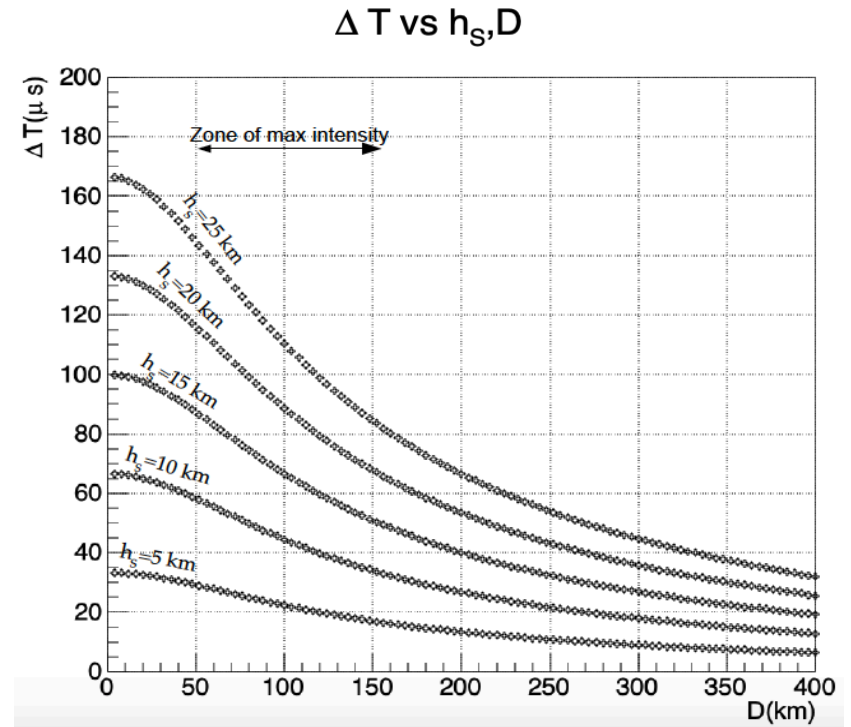


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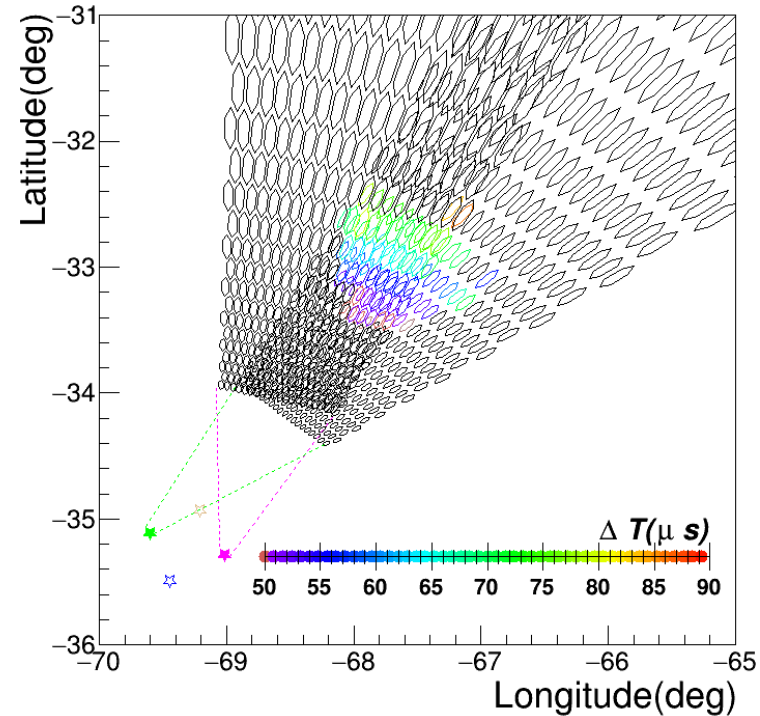
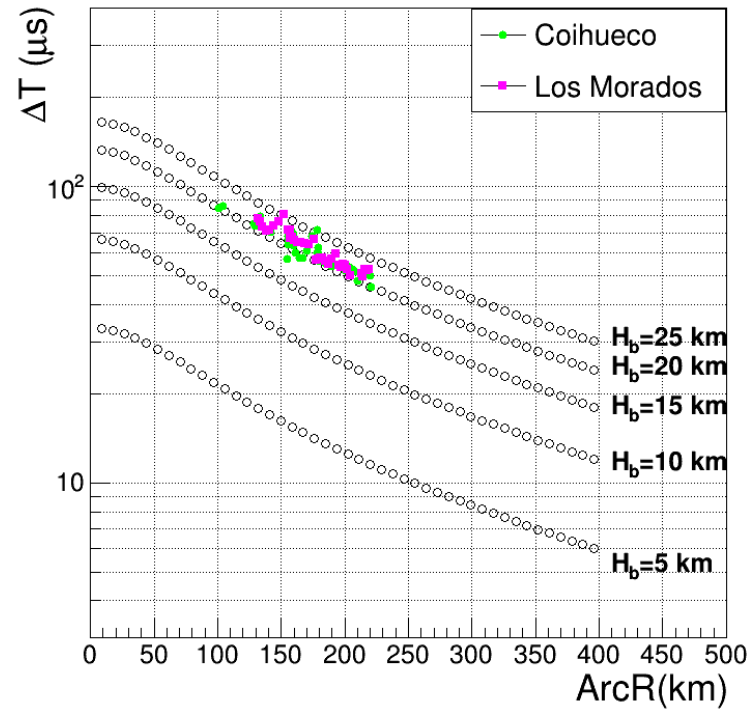
R. A. Marshall et al., *Geophys. Res. Lett.*, **42** (2015)



If double ELVES is a ground reflection, the time gap should vary with the distance from the vertical of the lightning as shown



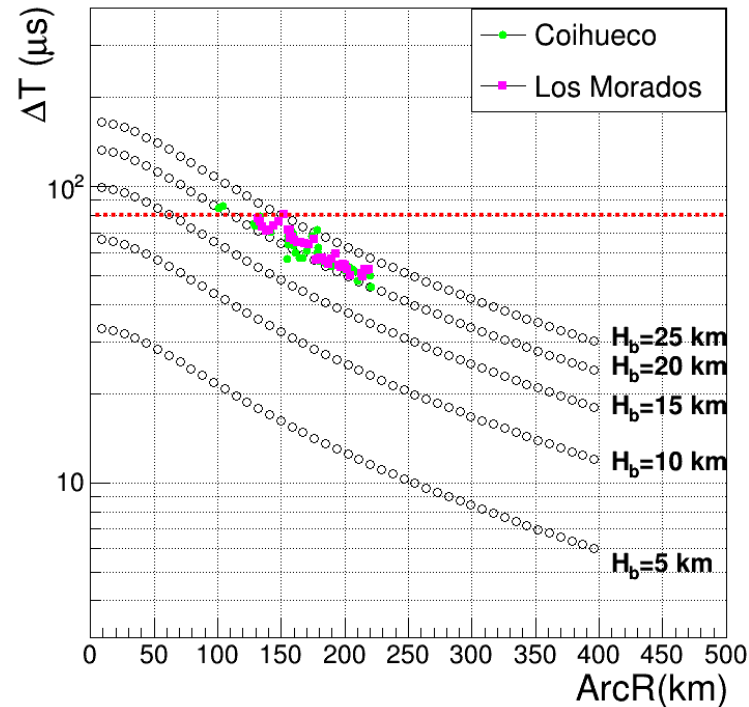
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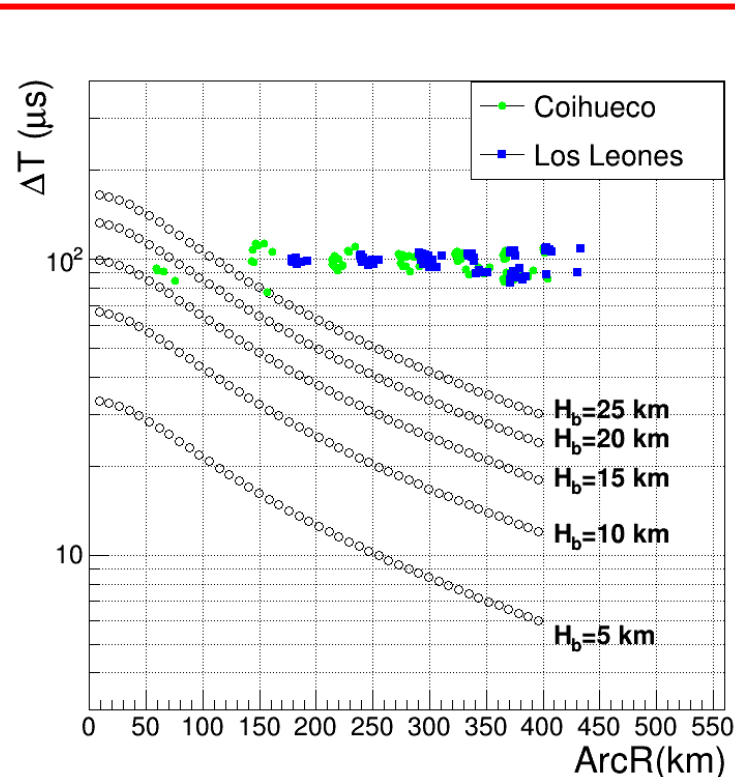
- Very few events follow this production mechanism.

**Figure 1:** Multi-ELVES event on the night of February 09, 2018, possibly produced through the EMP ground reflection mechanism, detected from Los Morados and Coihueco FD sites.

## 2. Sources that may produce multi-ELVES



**Figure 1:** Multi-ELVES event on the night of February 09, 2018, possibly produced through the EMP ground reflection mechanism, detected from Los Morados and Coihueco FD sites.



**Figure 2:** Multi-ELVES event on the night of April 28, 2020, with constant  $\Delta T > 80 \mu\text{s}$  from Coihueco and Los Leones FD sites.

- Very few events follow this production mechanism.
- Between 2018 and 2020 there are **only about 16** ground reflection mechanism candidates, while a **large number** of events shows **constant  $\Delta T > 80 \mu\text{s}$** .
- Different EMPs sources may produce a diversity of ELVES that depends on the **properties of the lightning**.

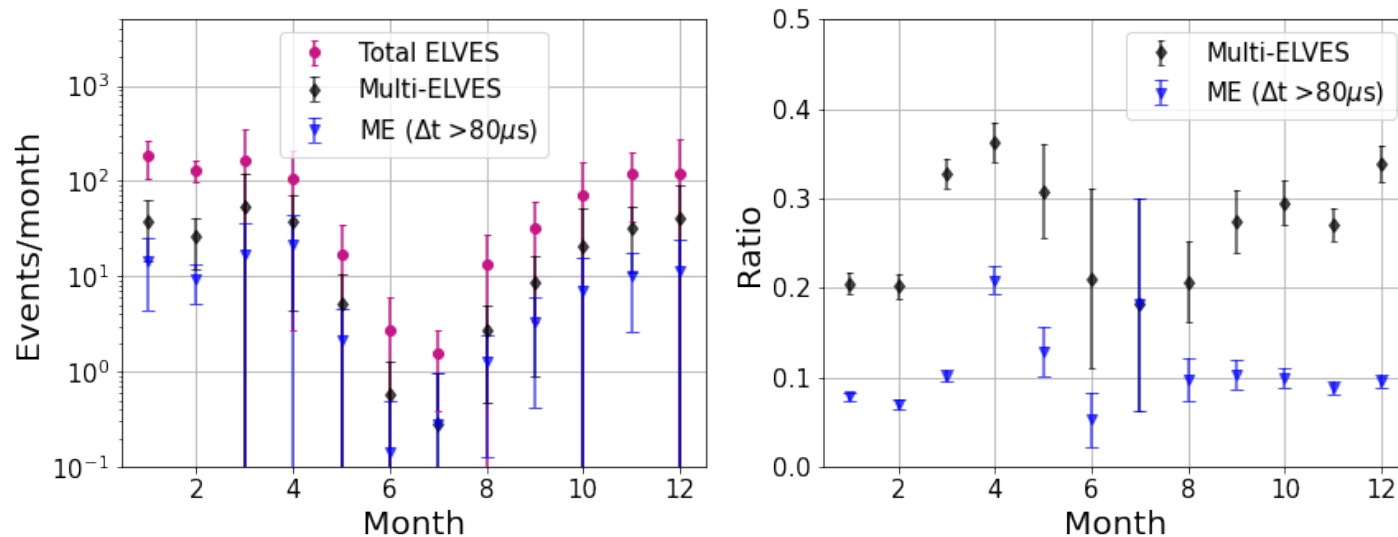
### 3. Seasonal and daily distribution of multi-ELVES

Trace length ( $\mu s$ )	Year	Total events	Total ME	Ratio (ME/Total)
300	2014	508	115	0.226
300	2015	673	201	0.299
300	2016	695	190	0.273
900	2017	1140	323	0.283
900	2018	875	233	0.266
900	2019	1689	500	0.296
900	2020	1157	311	0.269

**Table 1:** The total number of events and the total number of multi-ELVES detected by the FD in the period 2014-20.

- From 2017 onwards the number of detected events increases compared to the years 2014-2016, this is due to the improved trigger implemented in 2017.
- With the extension of the readout system we could expect an increase in the number of detected multi-ELVES, however, the annual ratio remains more or less constant (around  $0.273 \pm 0.023$ ).

### 3. Seasonal and daily distribution of multi-ELVES

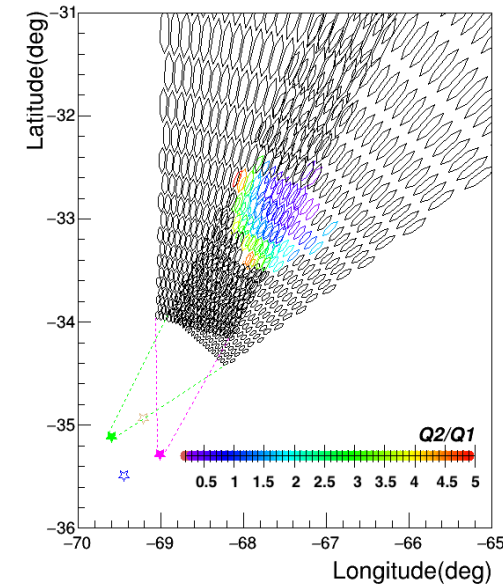
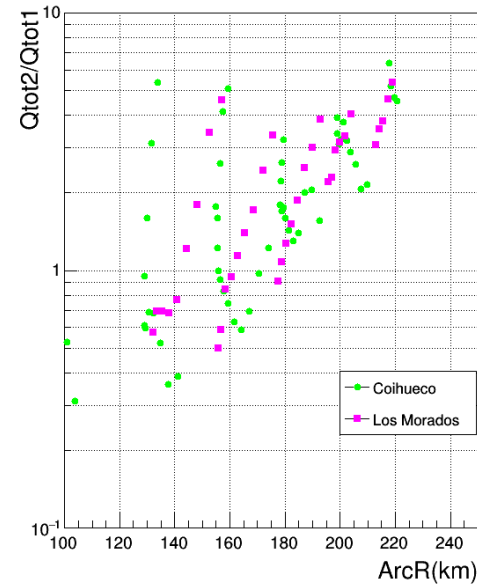


**Figure 3:** Left panel: total number per month of ELVES, multi-ELVES, and those with  $\Delta T > 80\mu s$  (ME) during the period 2014-20. Right panel: ratio of multi-ELVES, and ME to total number of ELVES per month.

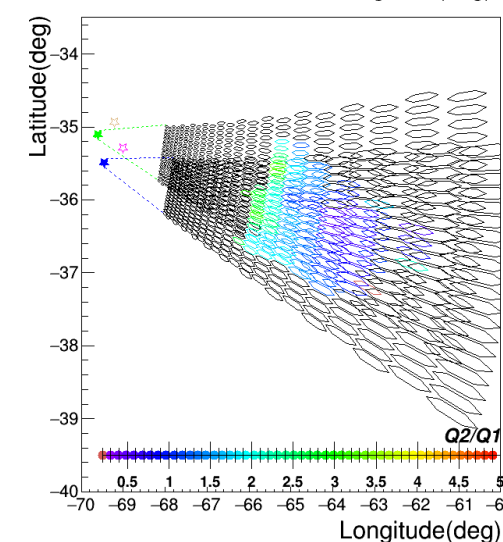
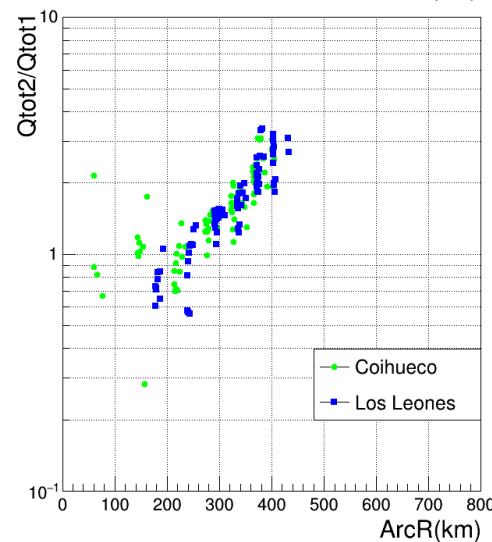
- The highest frequencies of events occur around the **southern summer and autumn**.
- We observed that the ratio of multi-ELVES to total is higher during **early summer (December)** and **autumn (March-May)**, while for multi-ELVES with  $\Delta T > 80\mu s$  (ME) the ratio is **higher in April**.

# 4. Analysis of multi-ELVES with constant time difference

- April 28, 2020 is the night with more  $\Delta T > 80 \mu s$  events during the period 2014-2020.
- 144 ELVES: 1 ground reflection candidate and 33 with constant  $\Delta T > 80 \mu s$ .
- The  $Q_{2tot}/Q_{1tot}$  ratio profile is different from a EMP ground reflection mechanism candidate profile.



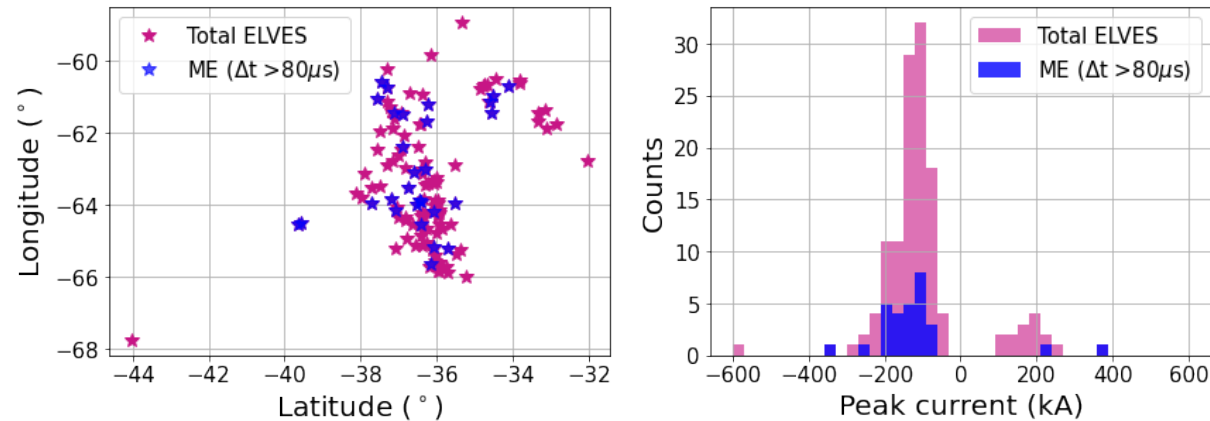
Ground reflection candidate  
(February 09, 2018)



Multi-ELVES with  $\Delta T > 80 \mu s$   
(April 28, 2020)



## 4. Analysis of multi-ELVES with constant time difference

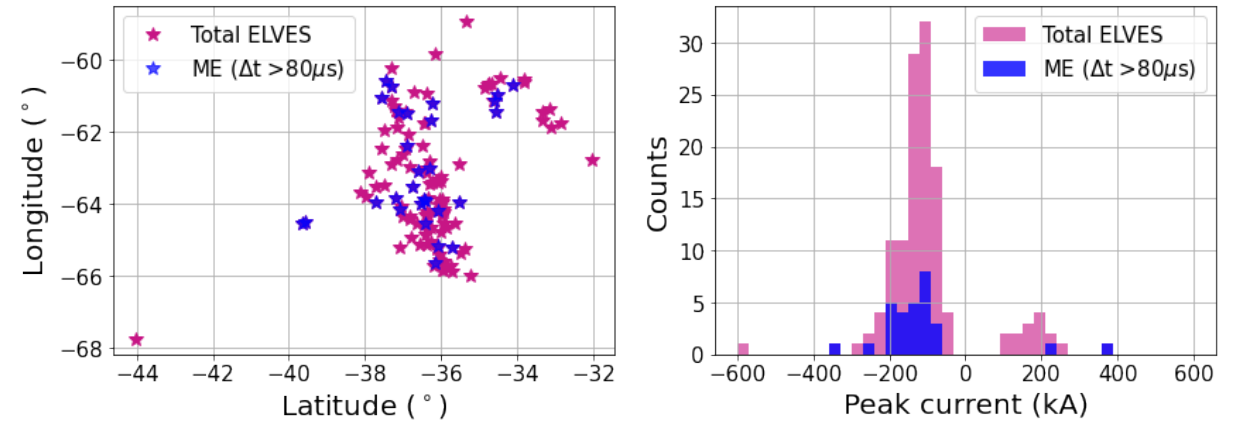
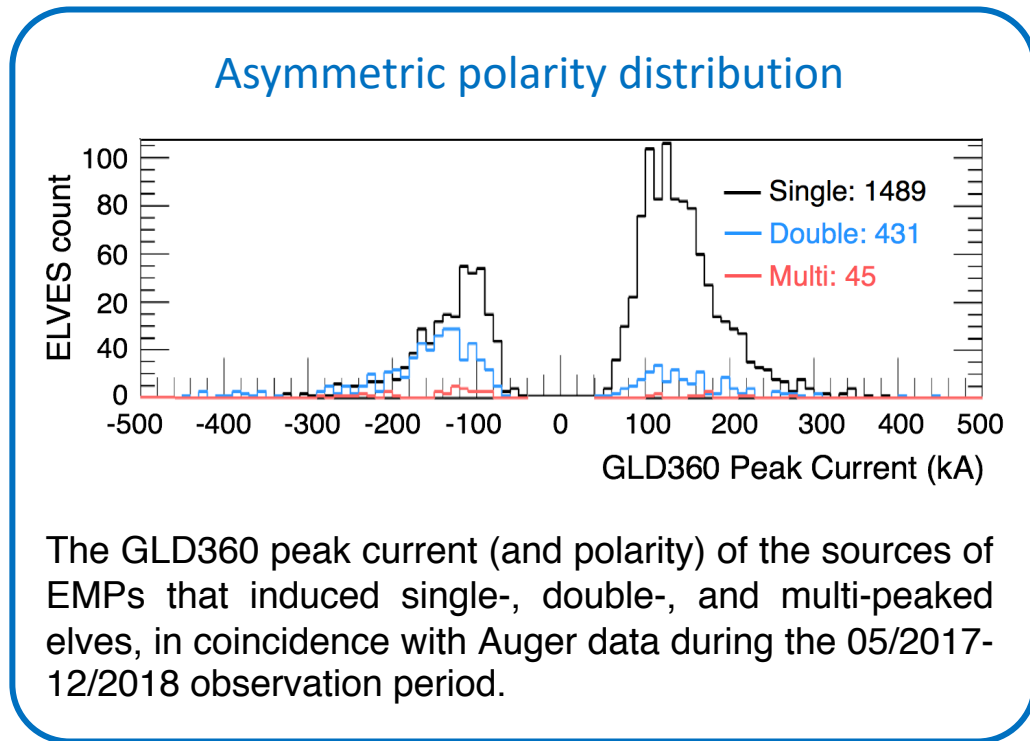


**Figure 5:** Events correlated with the Earth Networks Total Lightning Network (ENTLN) and the World Wide Lightning Location Network (WWLLN) data.

- April 28, 2020:

Out of a total of 144 elves, 128 were correlated with ENTLN and WWLLN data.

# 4. Analysis of multi-ELVES with constant time difference



**Figure 5:** Events correlated with the Earth Networks Total Lightning Network (ENTLN) and the World Wide Lightning Location Network (WWLLN) data.

## 5. Final remarks

- The **technical capabilities** of the P. Auger observatory's FD, especially its high temporal resolution of **200 ns**, allow the study of **multi-ELVES traces in great detail**.
- During 2014-20 we observe **some multi-ELVES candidates** to be explained by the **EMP ground reflection mechanism**. But, there is a **very frequent type of multi-ELVES (constant  $\Delta T > 80 \mu s$ )** that does not fit this mechanism.
- The ratio of multi-ELVES with constant  $\Delta T > 80 \mu s$  to total shows an **increase in April**.
- Finally, we show the analysis of the events detected at **the night with more multi-ELVES of constant  $\Delta T$  (April 28, 2020)**.

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- The ratio of multi-ELVES with constant  $\Delta T > 80 \mu s$  to total shows an **increase in April**.
- Finally, we show the analysis of the events detected at **the night with more multi-ELVES of constant  $\Delta T$**  (April 28, 2020).
- The  **$Q_{2tot}/Q_{1tot}$  ratio** profile of a multi-ELVES with constant  $\Delta T > 80 \mu s$  is **different** from a EMP ground reflection mechanism multi-ELVES profile.
- Out of 144 ELVES **128 were correlated** with ENTLN and WWLLN data.
- The **peak current distribution of this thunderstorm differs** from the distribution obtained in the correlation of Auger data **with the GLD360**, during the 05/2017-12/2018 observation period.
- **Future work:** analysis of the peak current distribution for **each type of storm**, as well as other **characteristics of lightning**, such as the type of lightning or the waveform of the electric field variation signal.

Thank you!