CENTRO FERMI
Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

CENTRO RICERCHE ENRICOFERMI

INFN
Istituto Nazionale di Fisica Nucleare

Consiglio Nazionale delle Ricerche

CERN

INRiM
Istituto Nazionale di Ricerca Metrologica

Società Italiana di Fisica

PolarquEEEst

Cosmic rays from Italy to the North Pole

Luisa Cifarelli
University and INFN Bologna

CERN – 16 July 2024

Extreme Energy Events
Science inside Schools

P.9LARQUEST2018 81°14'N, 25°25'E

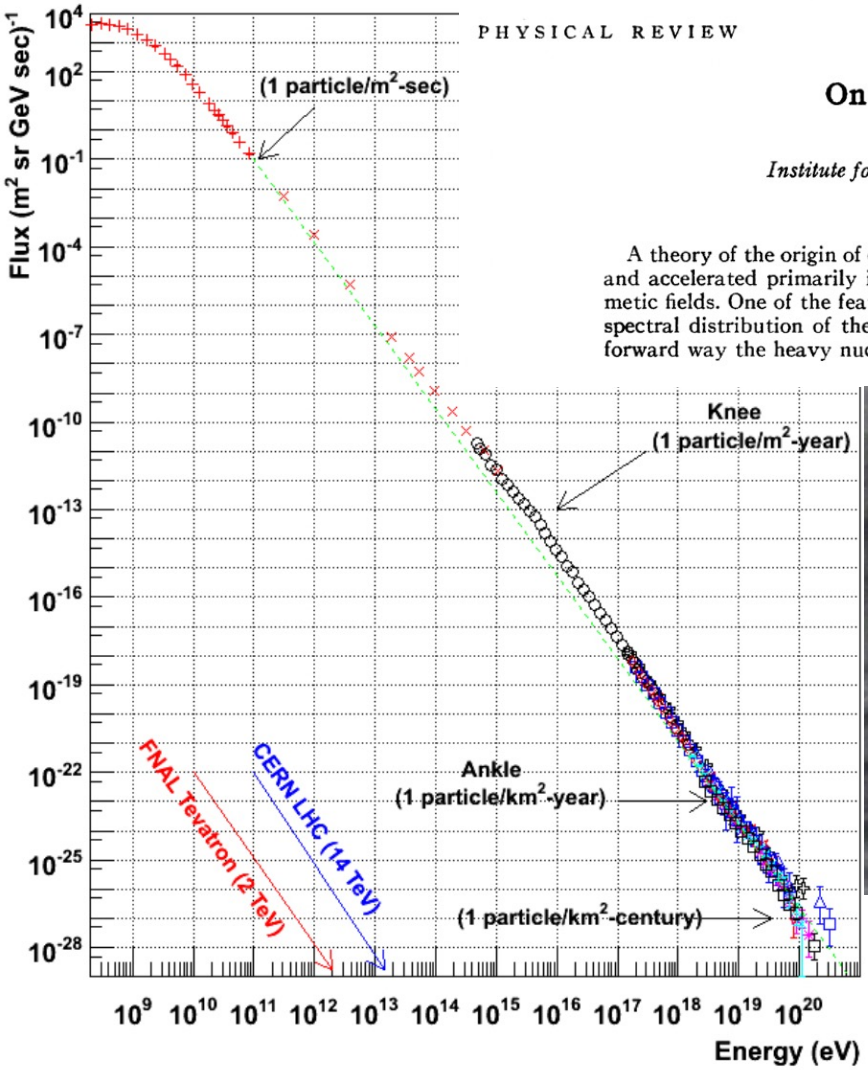
POLAR QUEEEst 2019 EEE@NyAlesund

Cosmic rays

- Every second each m^2 of the Earth is struck by several 10^3 **charged particles** travelling from **deep space** → **cosmic rays**
- Cosmic rays discovered more than a century ago but still very interesting and challenging to study
- Cosmic rays produced by astrophysical sources: stars (like the **Sun**), exploding stars … and even black holes
- Their origin is galactic and extra galactic
- The origin of extremely high-energy cosmic rays is a big mystery …

- But cosmic rays are also of interest beyond astrophysics
  → open questions
  - cosmic rays may influence cloud formation ?
    → implications for the evolution of Earth's climate ?
  - cosmic rays may allow to monitor the health of the atmosphere ?
  - …

Cosmic Ray Spectra of Various Experiments

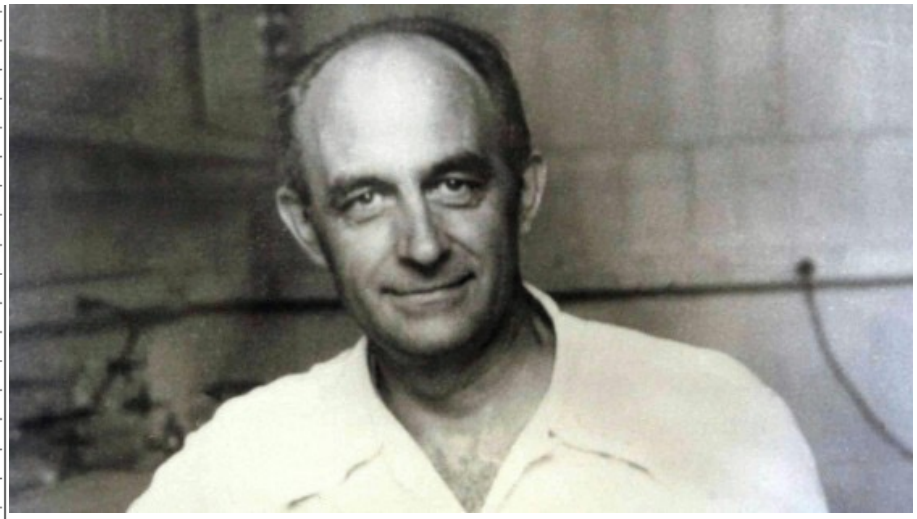


PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magmetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.



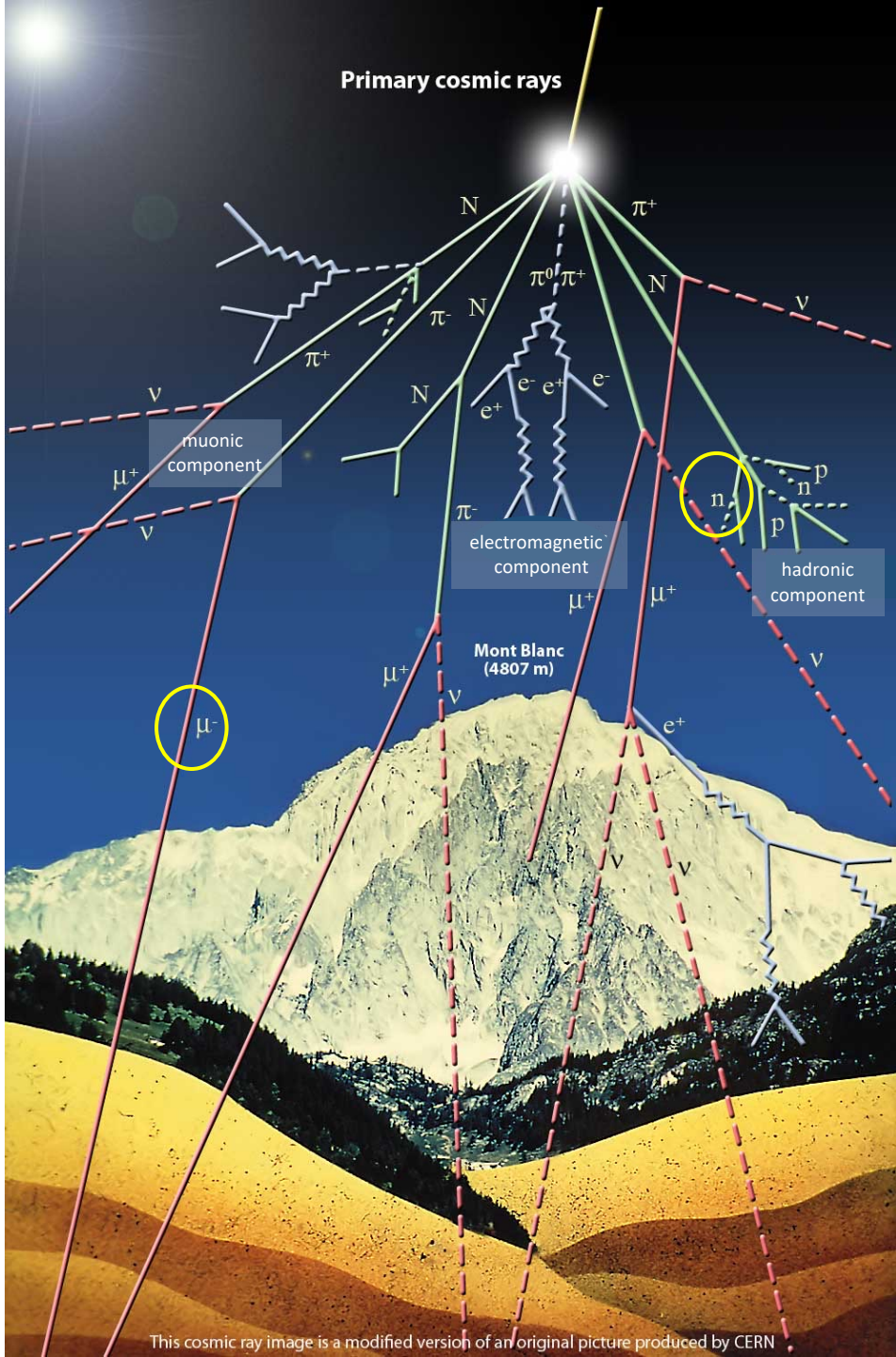
One of the many contributions!

Cosmic ray showers

Apart from solar flares, **primary** cosmic rays come from outside the solar system

Primary cosmic rays (e, p, N) are **charged** and **stable** particles interacting with atoms and molecules in the atmosphere

→ Showers (with 3 components) of **secondary** cosmic rays



Cosmic ray showers

The less energetic secondaries are attenuated by the atmosphere

→ At sea/ground level most of the cosmic rays are the **penetrating** secondary **muons**

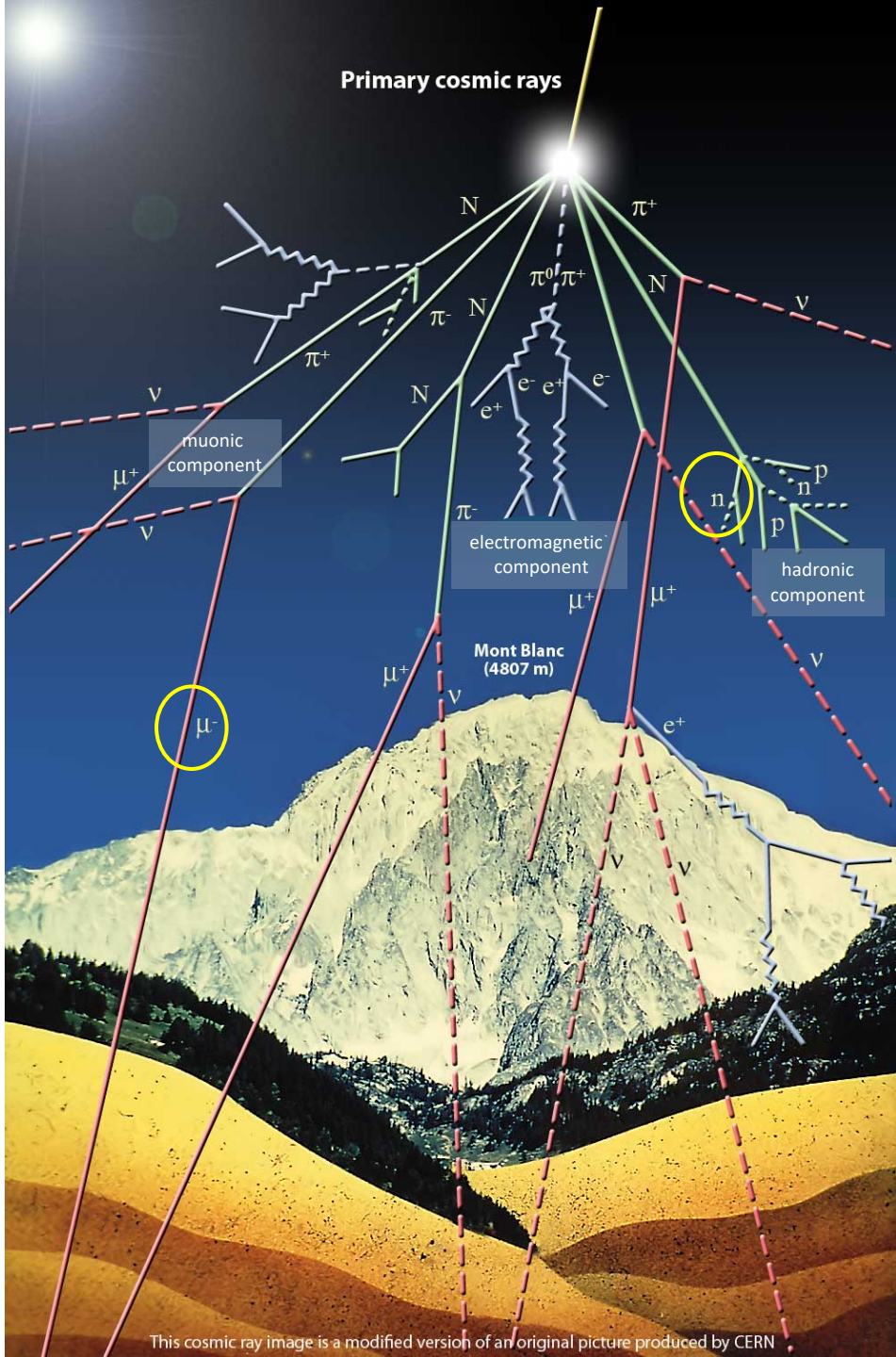
≈ 1 muon / cm^2 min

Muons are 200 times heavier than electrons

They are **unstable** and decay into electrons

They are **more penetrating** than electrons

Typically these muons at sea level have an **average** energy ≈ few GeV (muon energies > **few tens of MeV**)



The EEE Project

Observatory to study cosmic rays on ground in Italy

- Proposed by A. Zichichi (Centro Fermi) in 2004
- Presently coordinated by Centro Fermi and INFN in collaboration with CERN, INRIM, CNR, SIF and various universities

The EEE Project consists of about **60 telescopes** and allows unique studies of cosmic rays & cosmic showers including a search for very long distance correlations between cosmic showers

The EEE **telescopes** are each made of three **MRPCs** (Multigap Resistive Plate Chambers) **built at CERN by high-school students** which are installed and monitored in **high schools** by the students themselves

→ Extreme Energy Events – Science Inside Schools (EEE)

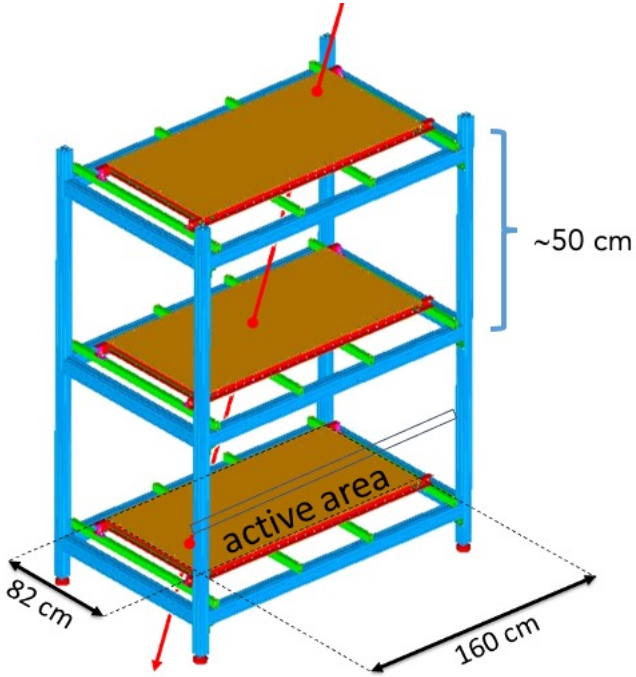
The EEE Project

Extreme Energy Events
Science inside Schools

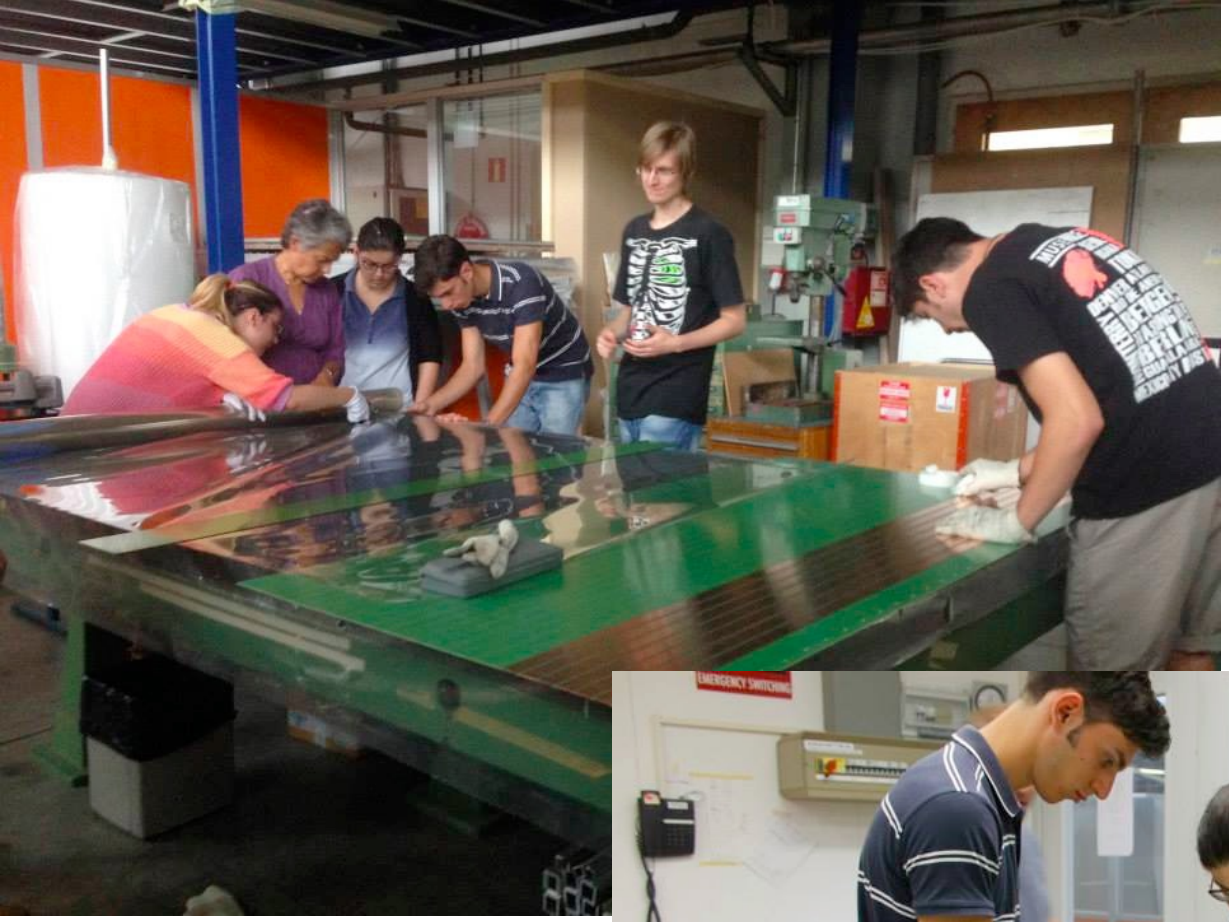
Dual role

- Cosmic ray **observatory**
- Scientific education tool

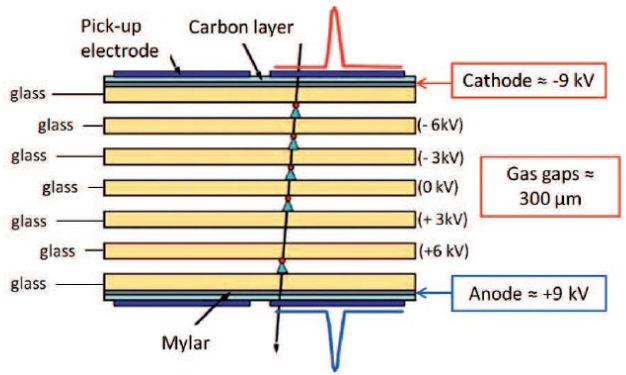
≈ 60 **MRPC** tracking telescopes in High Schools



≈ 0.5 x 10^6 km^2
≈ 10° of latitude/longitude



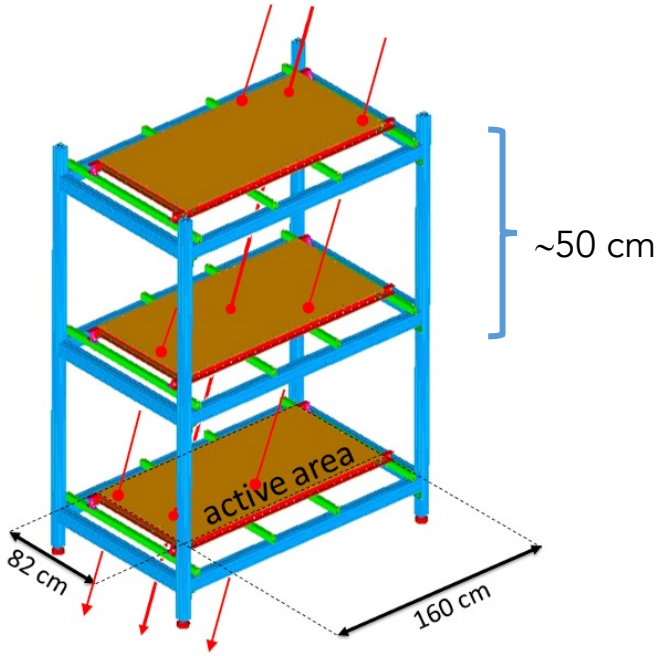
EEE Project
MRPC construction



The EEE Project

Extreme Energy Events
Science inside Schools

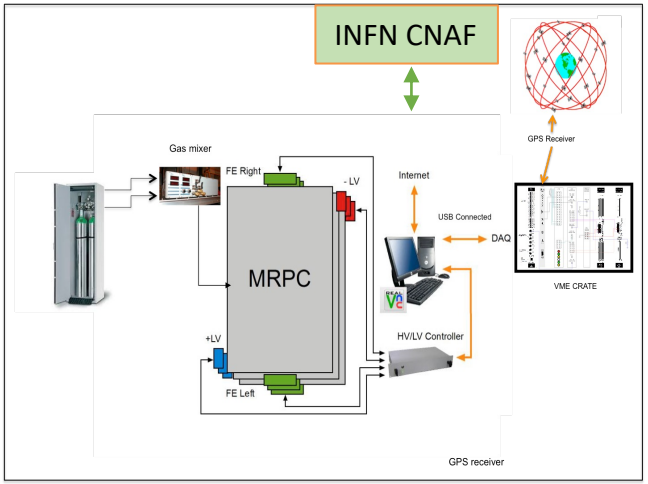
MRPC chambers are built by High School students at CERN (starting from 2004) and maintained by them under the supervision of EEE researchers



Acceptance
$\Omega = 1.6$ sr

3 MRPC planes with 24 strips each read at both ends → **144** readout channels
– Trigger requires a hit signal on each end of the 3 MRPCs within ±500 ns
– Cosmic muons are tracked & reconstructed

The EEE Project



- Time stamp via GPS
- Data taken an transferred to INFN CNAF for track reconstruction & storage
- Overall statistics **since 2015** (yearly data taking runs of ≈ 50 telescopes)

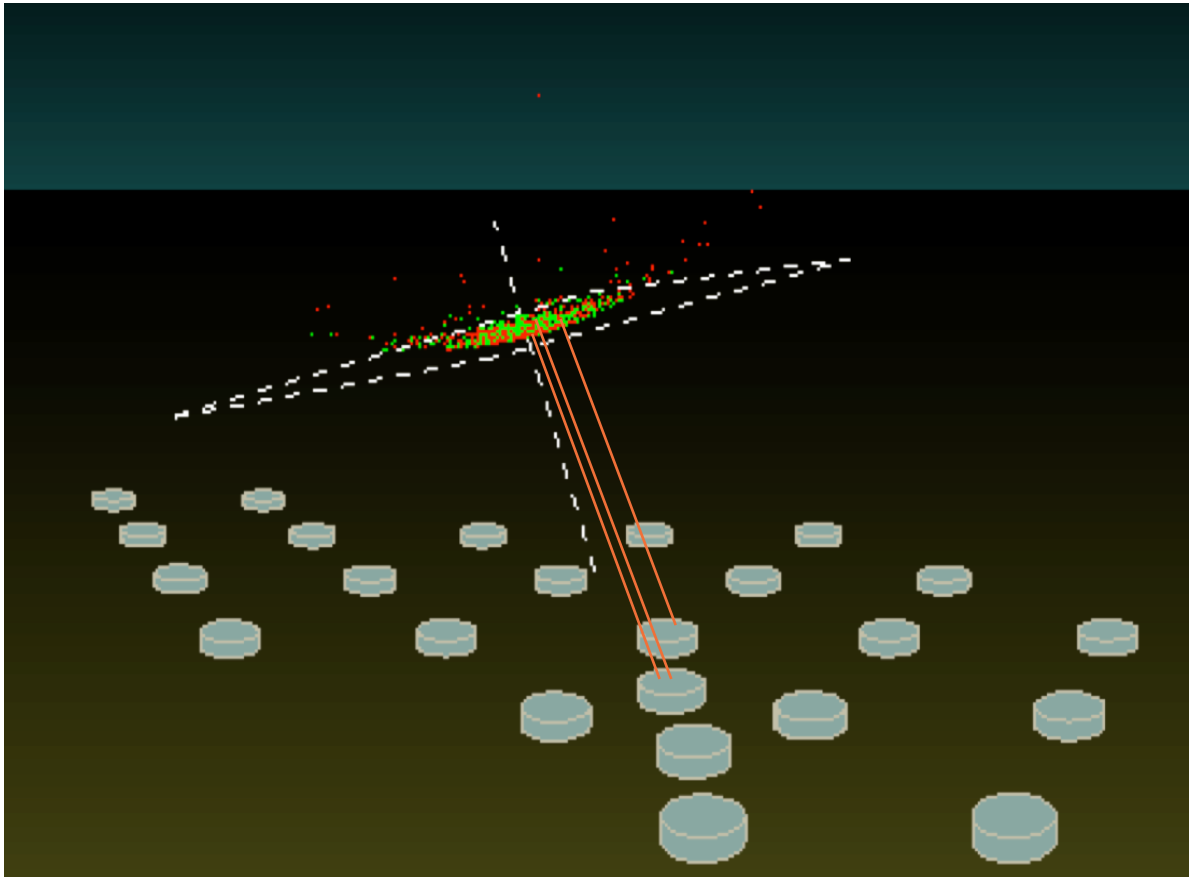
→ **over 110 billion cosmic rays reconstructed & analysed**

→ the EEE project allows many physics studies

Detection of atmospheric showers

- Search for time coincidences of ll muons in the same telescope or from near telescopes → **shower**

- Search for time correlations from distant showers

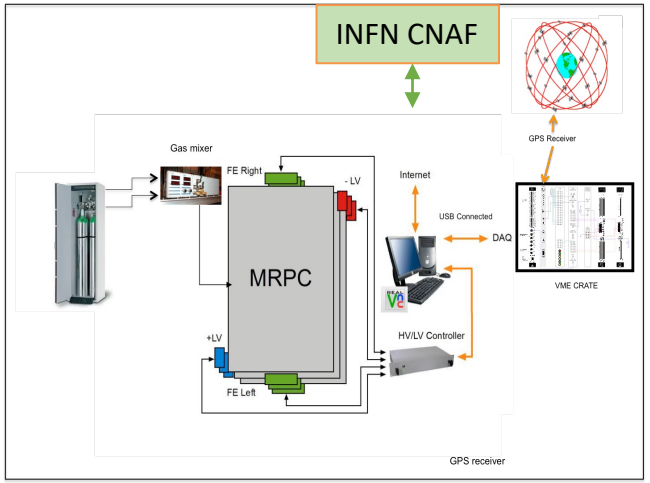


Physics goal of EEE Project

Detect atmospheric showers of very high or extreme energy by detecting secondary muons on ground coming from very high energy primary cosmic rays

The EEE Project

- Time stamp via GPS
- Data taken an transferred to INFN CNAF for track reconstruction & storage
- Overall statistics **since 2015** (yearly data taking runs of ≈50 telescopes)



→ **over 110 billion cosmic rays reconstructed & analysed**

→ the EEE project allows many physics studies

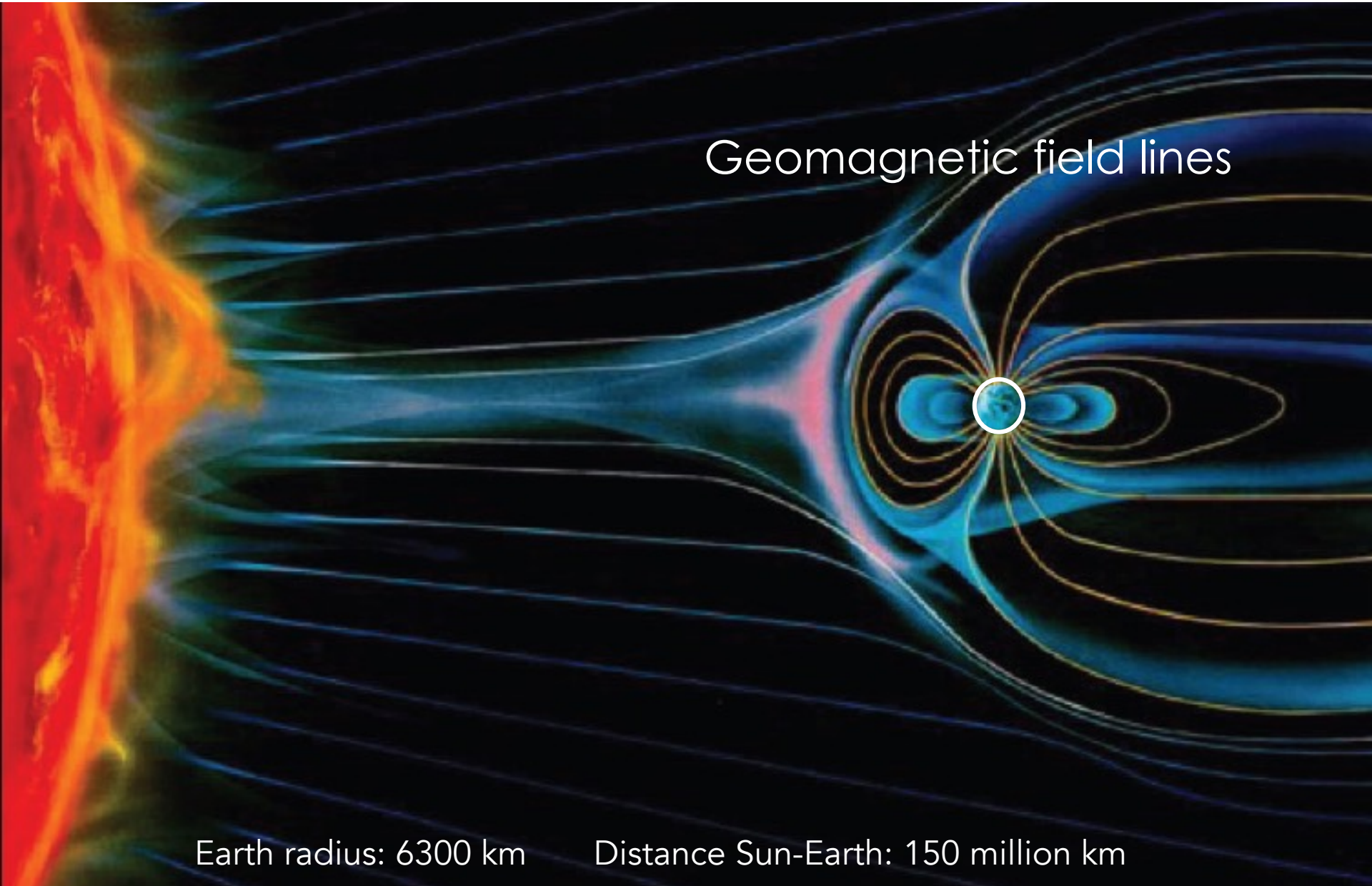
BUT to study

- the **effects of latitude** on cosmic ray flux over a large interval (≈50°)
- **very, very large distance** (several 10^3 km) shower correlations ...

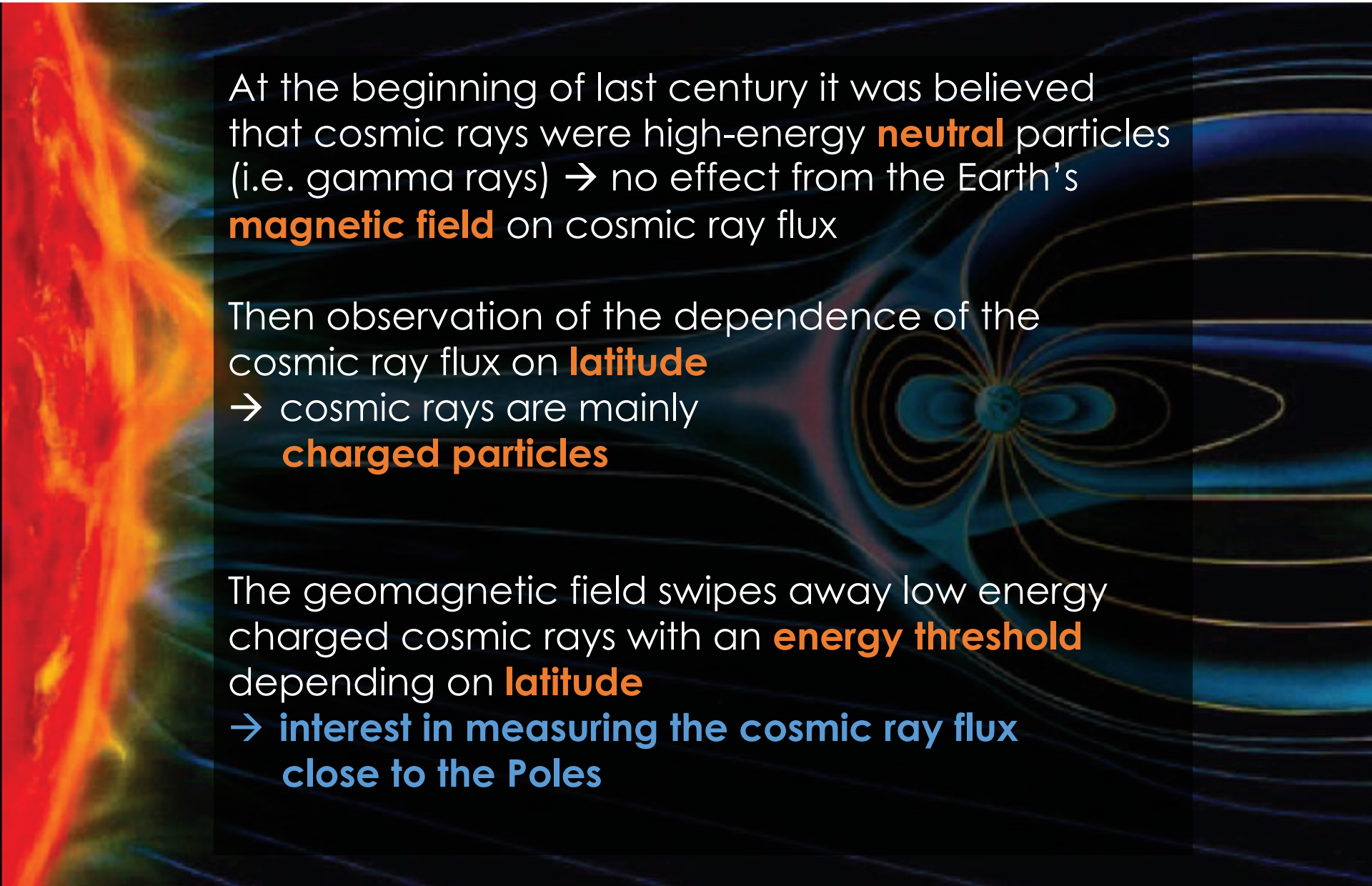
→ the EEE project sails to North Pole !

→ PolarquEEEst

Cosmic ray flux on Earth



Cosmic ray flux on Earth



At the beginning of last century it was believed that cosmic rays were high-energy **neutral** particles (i.e. gamma rays) → no effect from the Earth's **magnetic field** on cosmic ray flux

Then observation of the dependence of the cosmic ray flux on **latitude**
→ cosmic rays are mainly **charged particles**

The geomagnetic field swipes away low energy charged cosmic rays with an **energy threshold** depending on **latitude**
→ **interest in measuring the cosmic ray flux close to the Poles**

The EEE project sails to North Pole !

Polar QuEEEst 1928 – 2018

Airship Italia mission – 1928

Sailboat Nanuq mission – 2018
Proposed by L. Cifarelli (Centro Fermi) and P. Catapano (CERN)

To measure cosmic ray flux
with 3 detectors
40° in latitude span
5000 km distance

CENTRO FERMI
MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

Extreme Energy Events
Science inside Schools

POLAR QUEST 1928 2018

The eco-friendly vessel Nanuq was used, especially designed for the Arctic, with passive technology, low consumption, low waste etc.

On board of Nanuq, a diverse team of researchers, science communicators, and sailors, carried out valuable scientific investigations about the Arctic environment and the impact of human activity on its fragile ecosystems

The expedition crossed the 80th parallel North, into uncharted waters in the Northeast of the Svalbard archipelago

→ Complex expedition, with scientific and technological challenges and a sense for adventure

Thanks to Paola Catapano (CERN) Expediton Leader

The scientific motivation of the POLARQUEST expedition performed in 2018 on board of Nanuq around the Svalbard Archipelago was:

– measurement of cosmic rays at unprecedented northern latitudes where no systematic and accurate sea-level measurements have ever been performed → PolarquEEEst

– investigation of the Arctic environment threatened nowadays by many factors, such as macro/microplastic pollution or temperature growth

– air (with drone) and water (with multibeam sonar) exploration of unknown Artic areas

In addition the mission had a **celebration** purpose and gathered at the Svalbard Islands the descendants of the participants of the **airship Italia** tragic expedition of 1928

→ POLARQUEST was a polar expedition melting adventure, science and history

PolarquEEEst

GOAL: Measure cosmic rays at extreme latitudes

2018

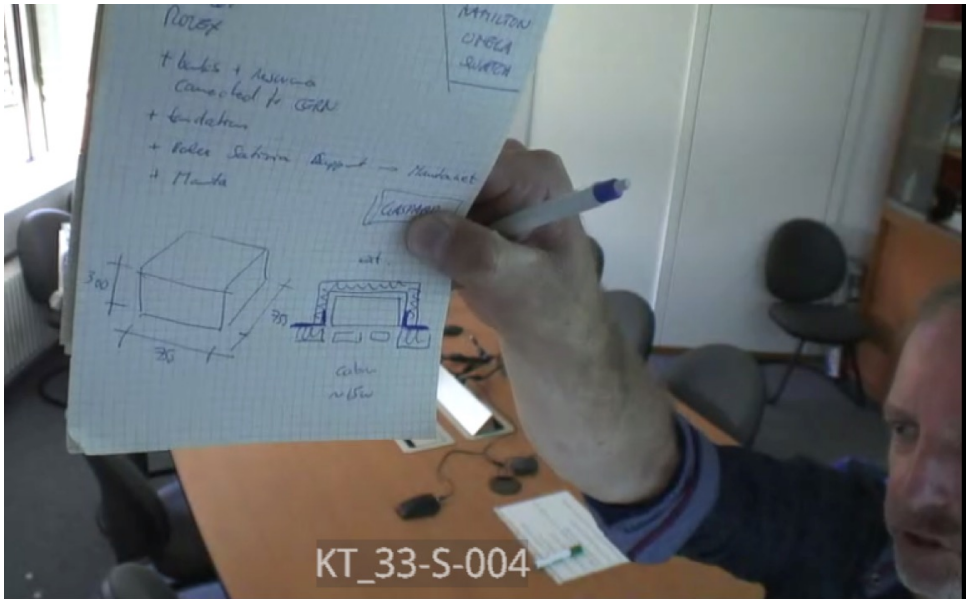
PolarquEEEst2018

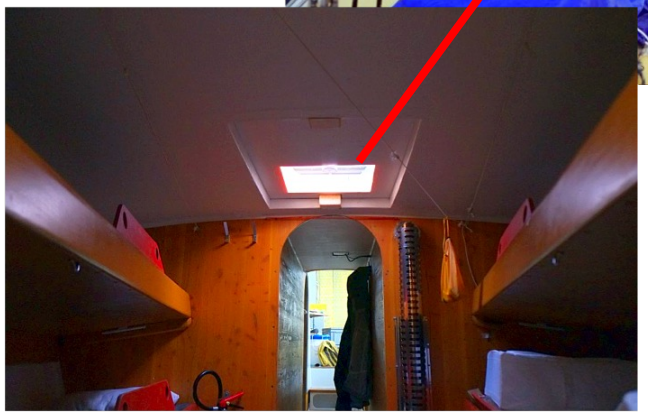
- 3 detectors (POLA-01, POLA-02, POLA-03)
- PolarquEEEst2018 → mission on board of sailboat Nanuq (Jul – Sept 18) +
  2 detectors at fixed sites: Bra (Italy) and Nessoden (Norway)

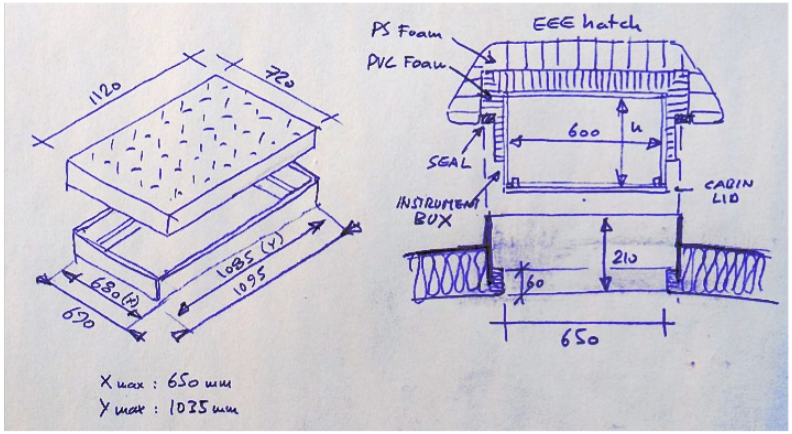
2019

- (Dec 18 – Apr 19) → measurements at different latitudes (Italy, Germany, CERN)
- Construction of 4th detector (POLA-04)
- PolarquEEEst2019 → installation of 3 detectors at Ny Ålesund (Svalbard)

Requirements for PolarquEEEst detector → POLA-R





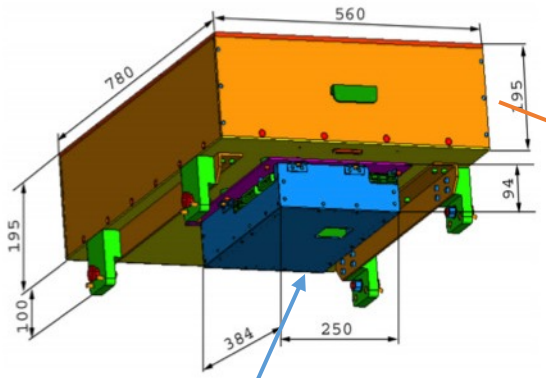


The detector on Nanuq sailship has been designed to fulfill stringent requests on:

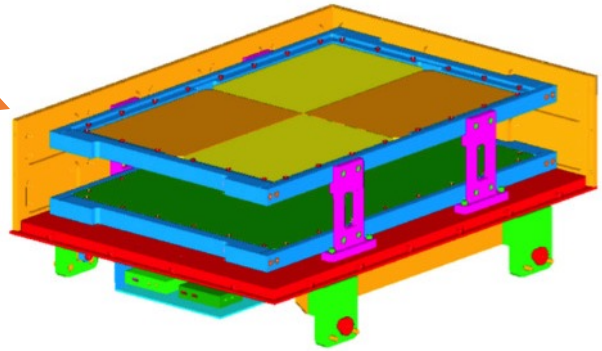
- dimension
- weight (~ 50 kg)
- power consumption (< 15 W)

POLA-R detector

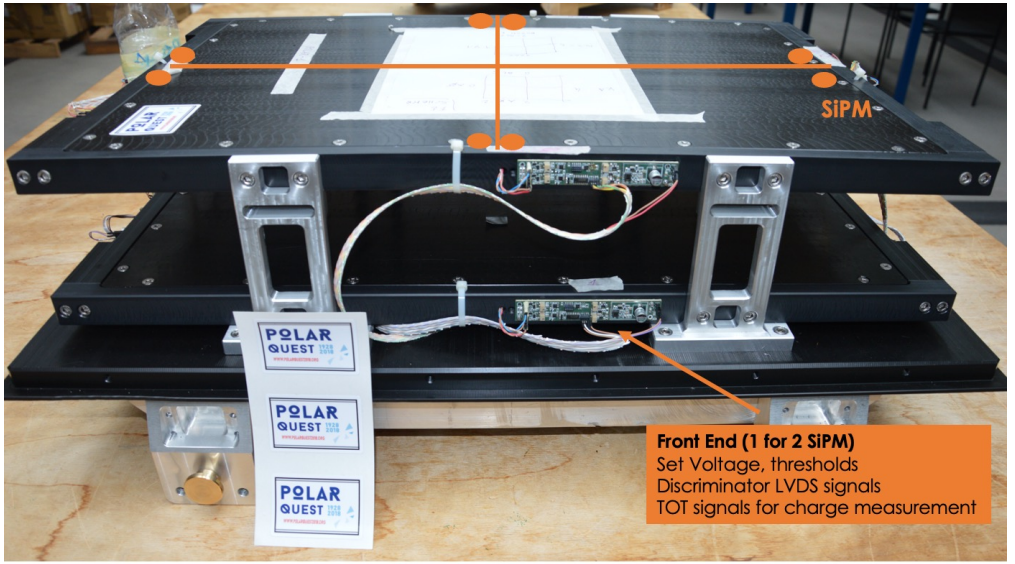
- 2 planes of plastic scintillators
- 4 tiles/plane: 30 x 20 cm^2
- Distance between planes: 11 cm
- 2 SiPMs/tile
- Efficiency > 96%
- Trigger: coincidence of signals from both planes (signals from at least 3 SiPMs)



Electronics box

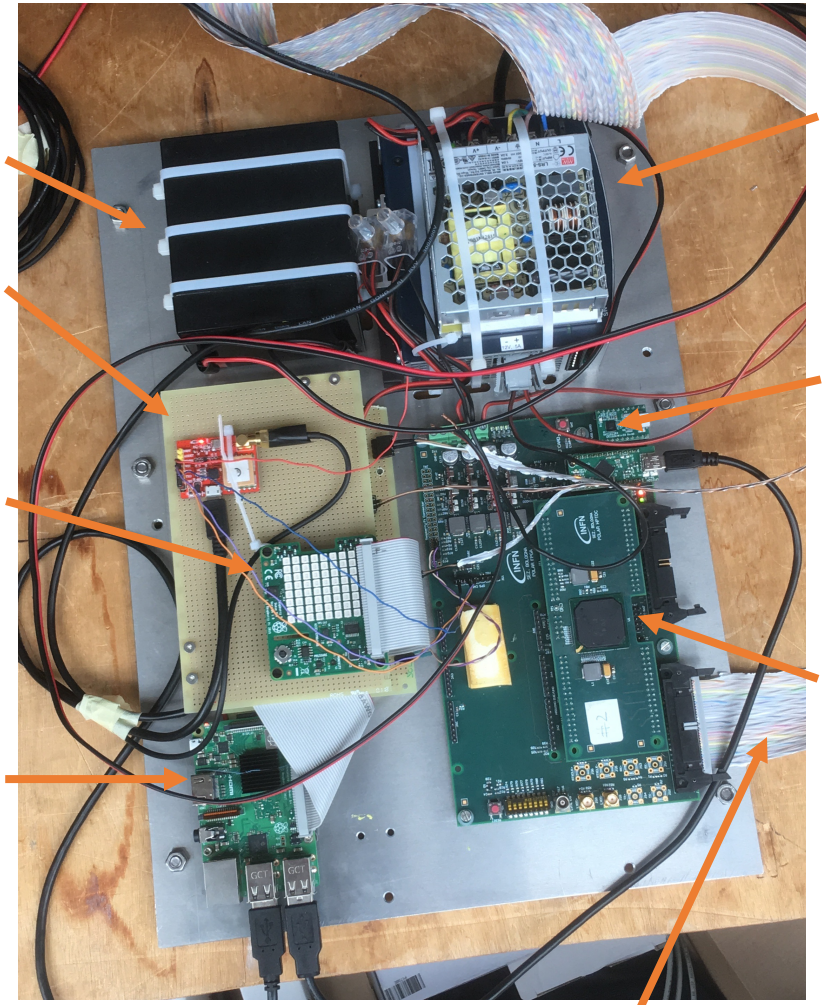


Students from the Italian, Swiss and Norwegian schools involved in the detector assembly at CERN



POLA-R detector electronics

(overall power consumption: **12-13 W**)



Back-up Battery

GPS
GNSS-Ublox

Sense HAT
Gyroscope
Accelerometer
Magnetometer
Temperature
Barometric pressure
Humidity

Raspberry PI
Control readout

Power box

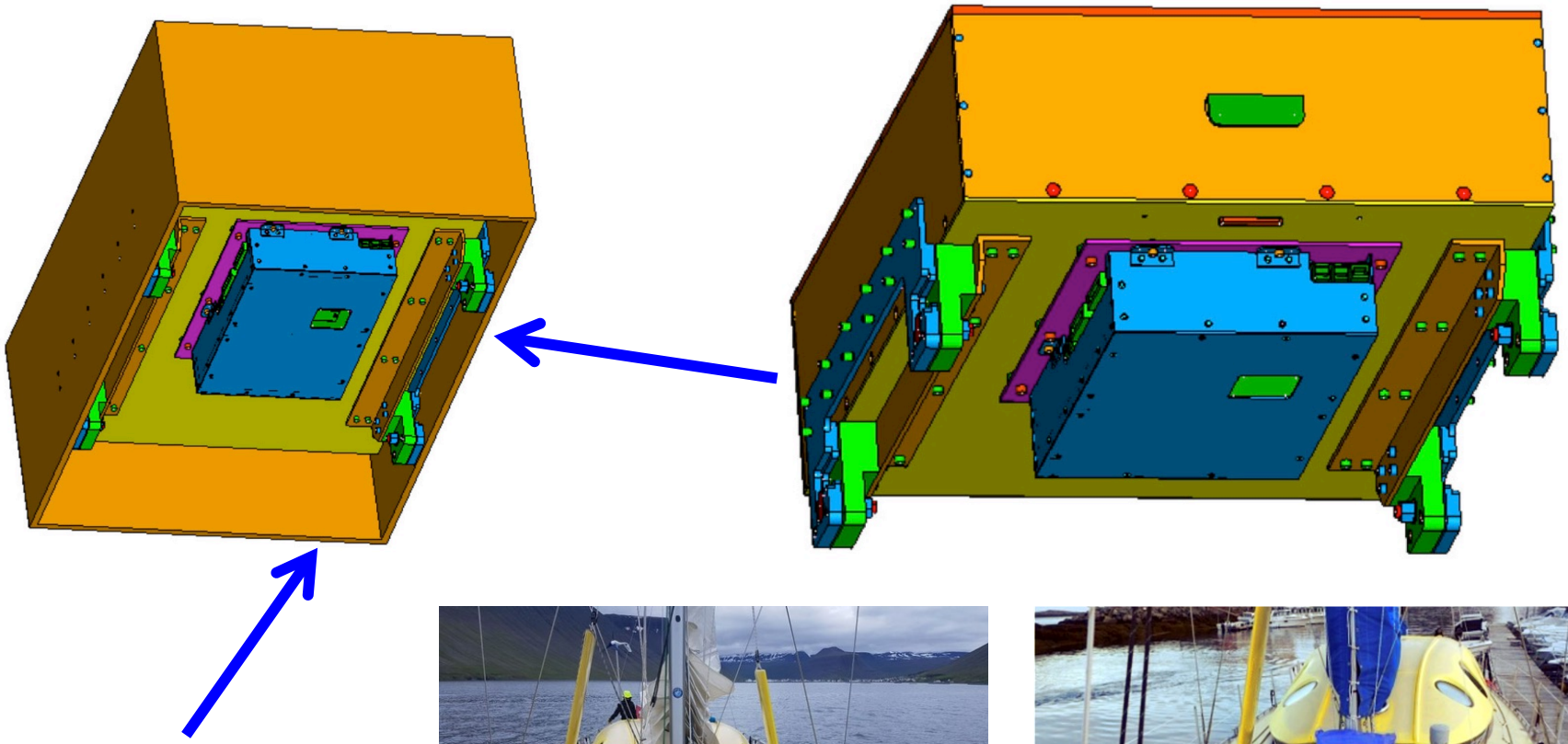
Readout board
FPGA Altera Cyclone 5
For Trigger and TDC readout

HPTDC piggy-back
for TDC readout

Signals from SiPMs

→ Data stored on SSD memory or transmitted via internet

Anchoring POLA-R detector on Nanuq



Cosmic hutch and anchoring system

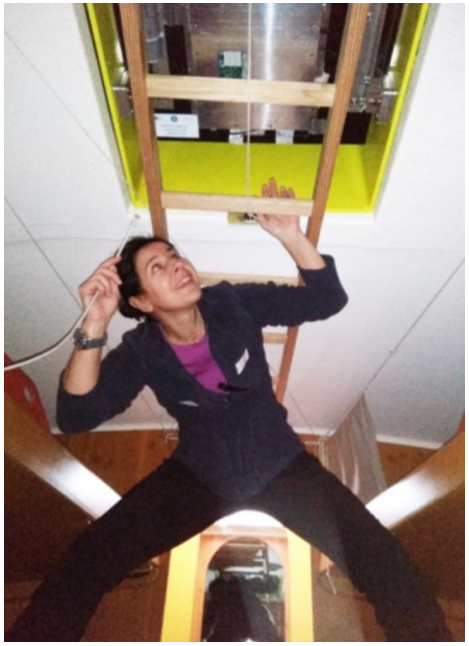
Installation

All POLA-R detectors installed by the end of July 2018

POLA-01 @ Isafjordur

POLA-02 @ Oslo (Nesodden)

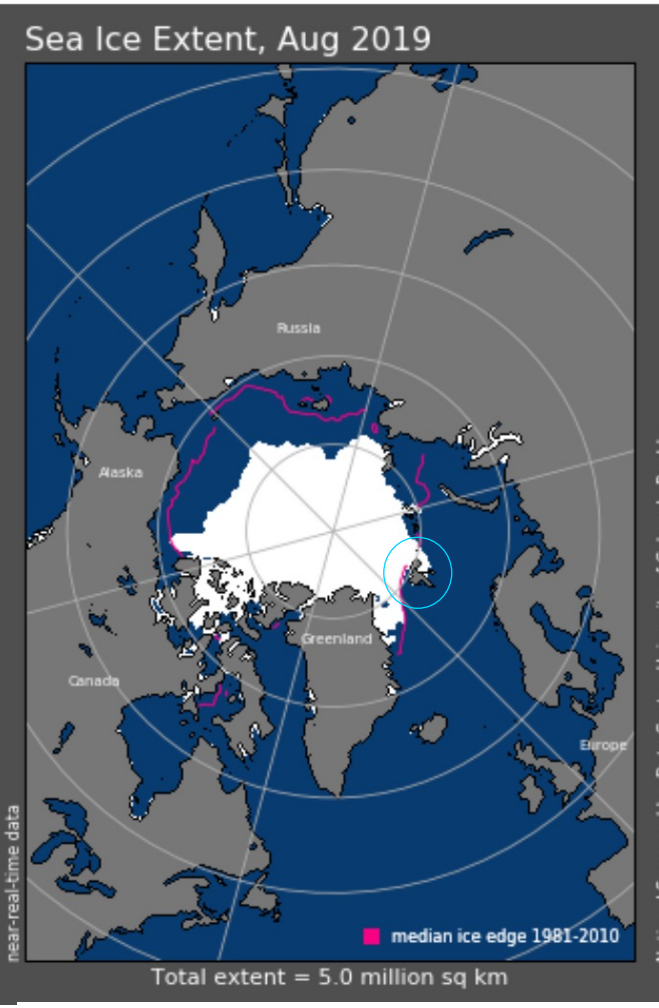
POLA-01 on board



POLA-03 @ Torino (Bra)


Sea Ice Extent, Aug 2017
Russia
Alaska
Greenland
Canada
Europe
median ice edge 1981-2010
Total extent = 5.5 million sq km


Sea Ice Extent, Aug 2018
Russia
Alaska
Greenland
Canada
Europe
median ice edge 1981-2010
Total extent = 5.6 million sq km

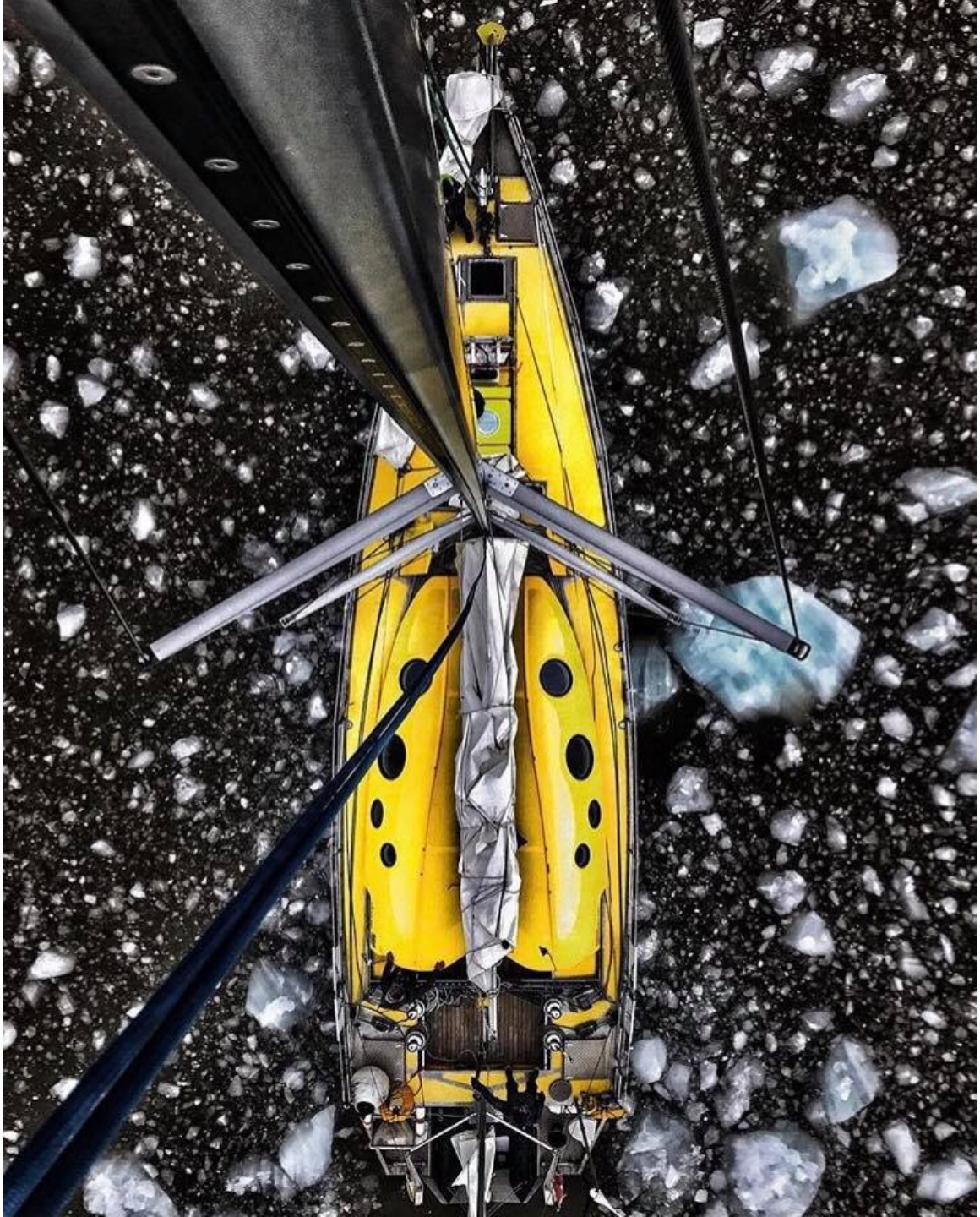

Sea Ice Extent, Aug 2019
Russia
Alaska
Greenland
Canada
Europe
median ice edge 1981-2010
Total extent = 5.0 million sq km

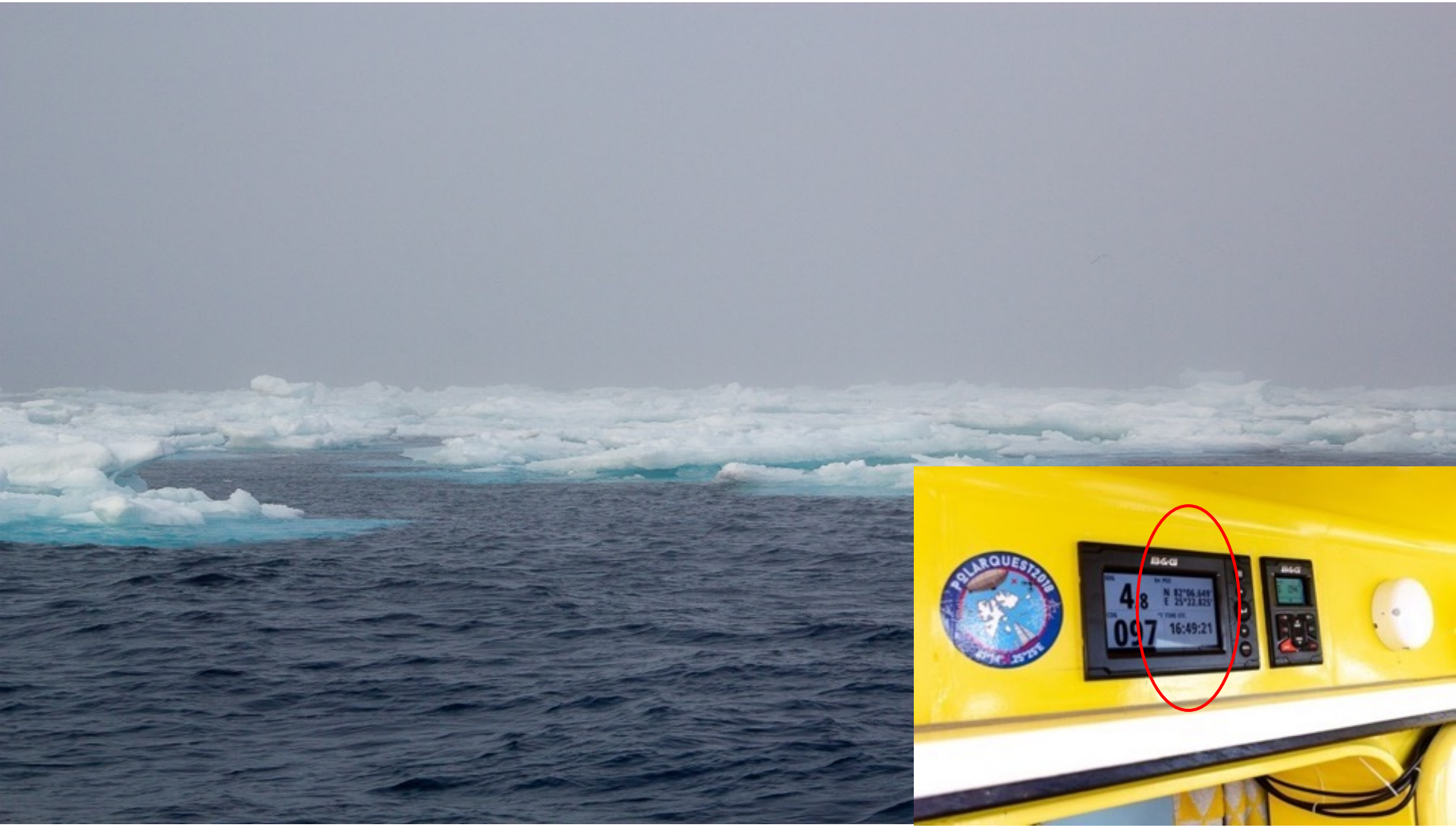
Nanuq en route to the Svalbard Islands

Nanuq at the Svalbard Islands

Nanuq at the Svalbard Islands

approaching a glacier





Nanuq reaching the limit of the polar pack ice
82° 07'N 25° 23' E

On board of Nanuq

Navigation shift on Nanuq

PolarquEEEst Statistics

Extreme Energy Events
Science inside Schools

Trip length

Nanuq sailed for **45 days** covering about **3500 NM (≈ 6500 km)**

Duty cycle

The POLA-01 cosmic ray detector has taken data almost continuously for about **984 hours**

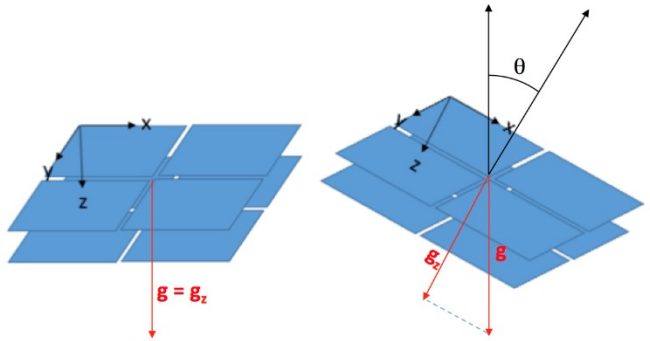
Detector efficiency

- for **POLA-01: about 91%** efficiency due to various reasons (main power down, difficult weather conditions, detector reset ….)
- for POLA-02 and POLA-03: essentially 100% efficiency (they were functioning during the whole period)

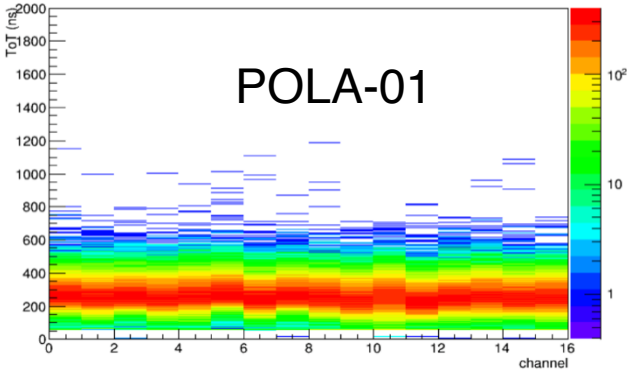
Collected muons

In total, more than **100.000.000 muon tracks per detector** were collected

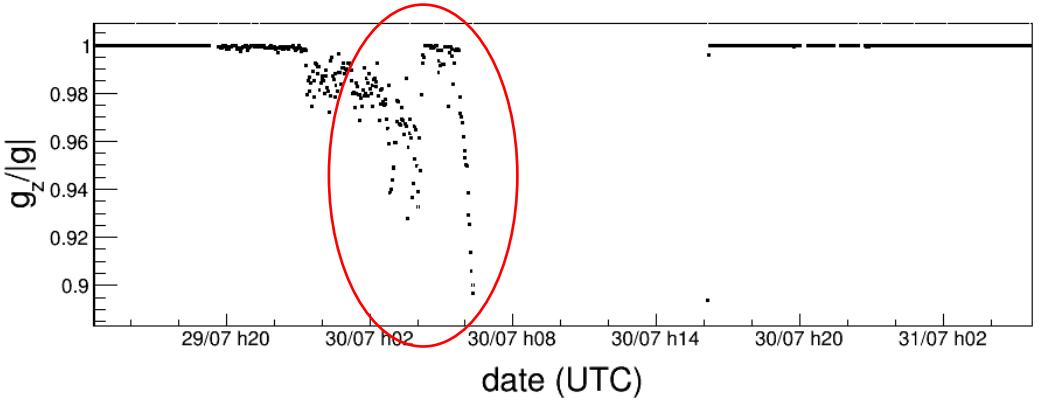
Detector performance



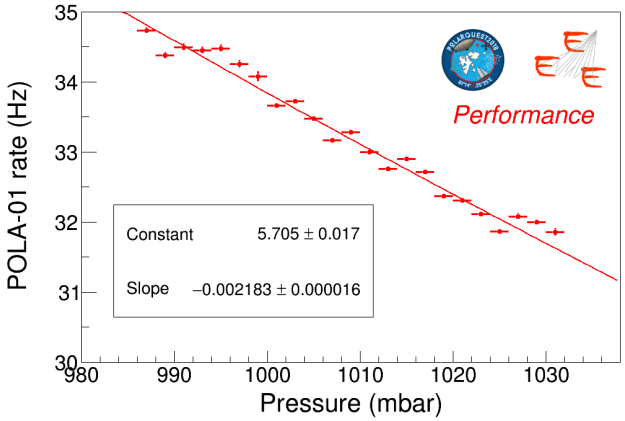
Channel equalization (thresholds)



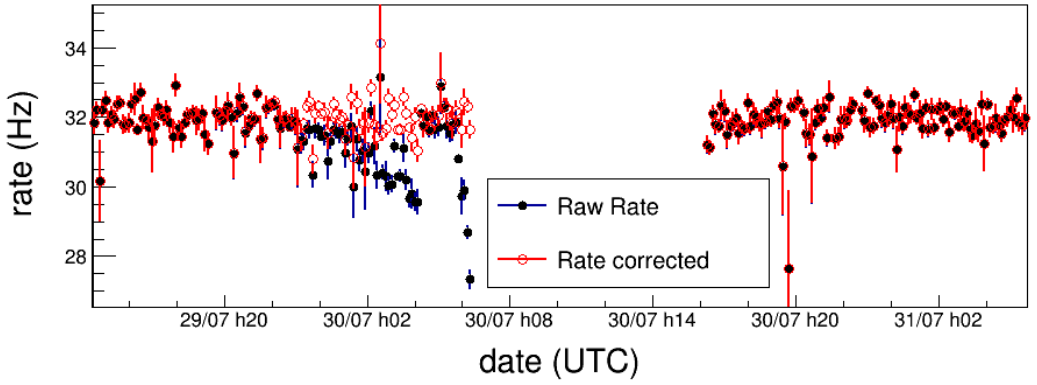
Correction for inclination (POLA-01)



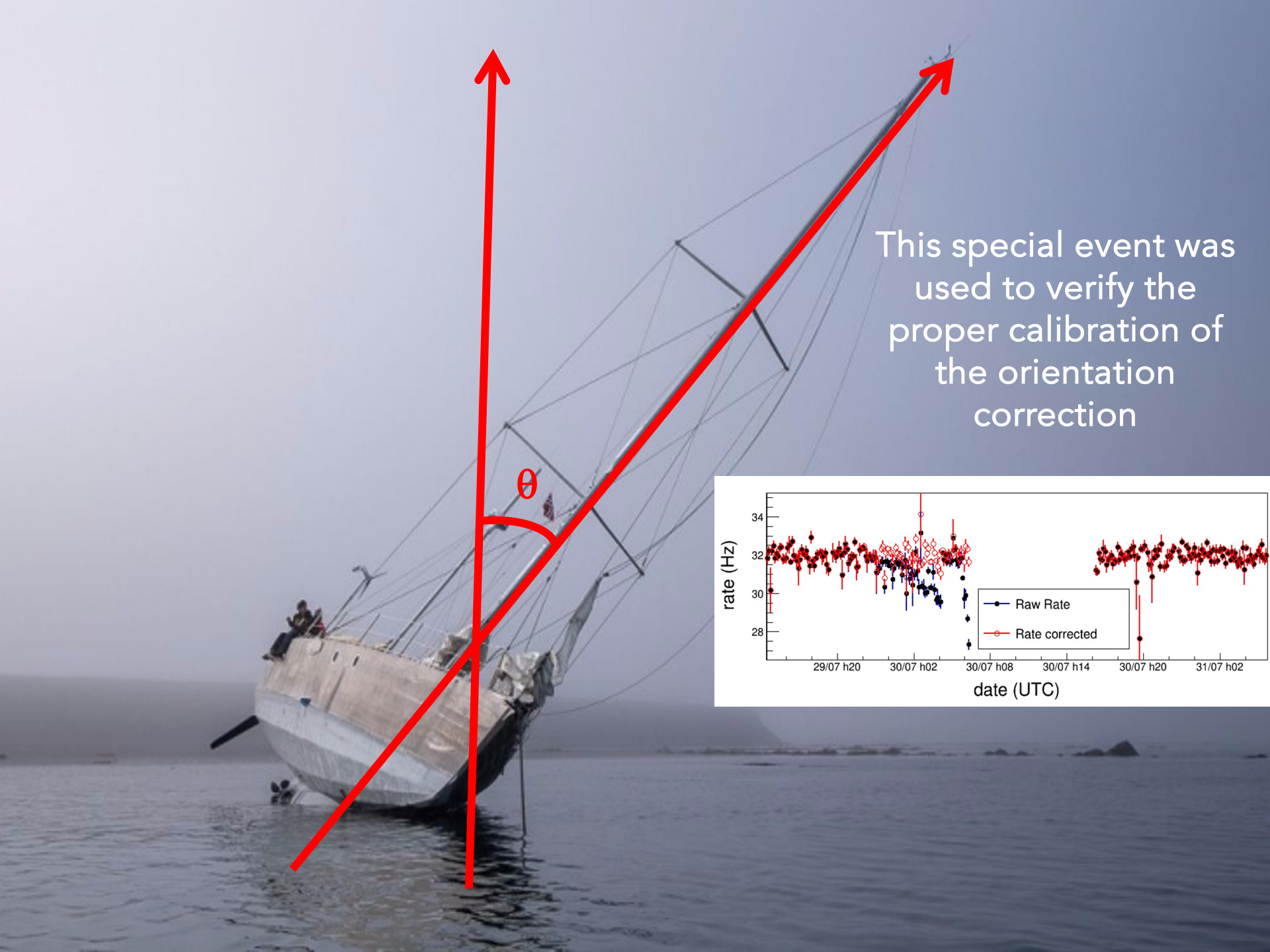
Correction for pressure



"Calibration run" on 30/07/18

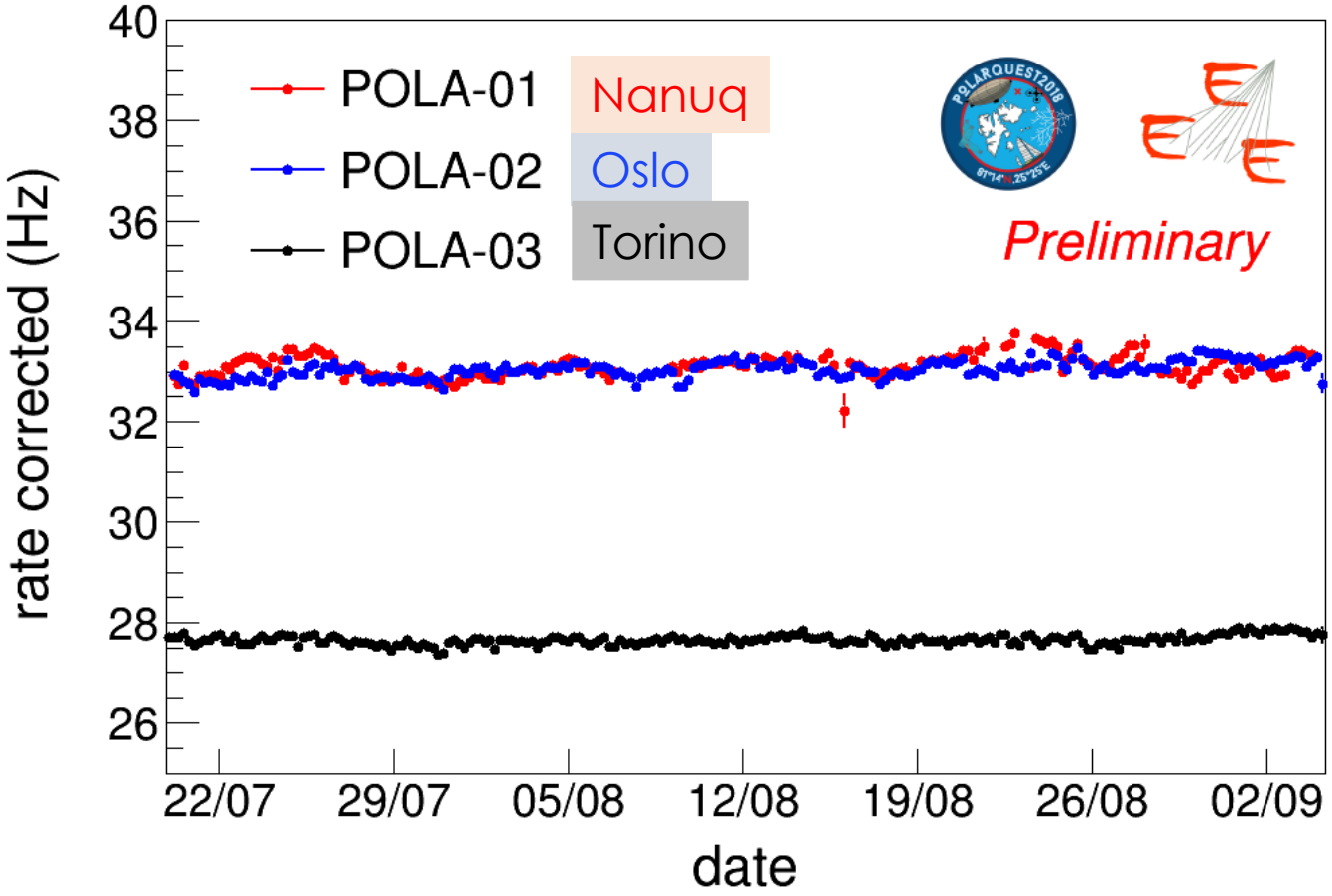



Any event (unexpected!?) can be an opportunity
On 30 July 2018 a problem occurred for Nanuq (during low tide) …
Data were nevertheless collected before reaching this “exotic” position



This special event was used to verify the proper calibration of the orientation correction

Rate (corrected)

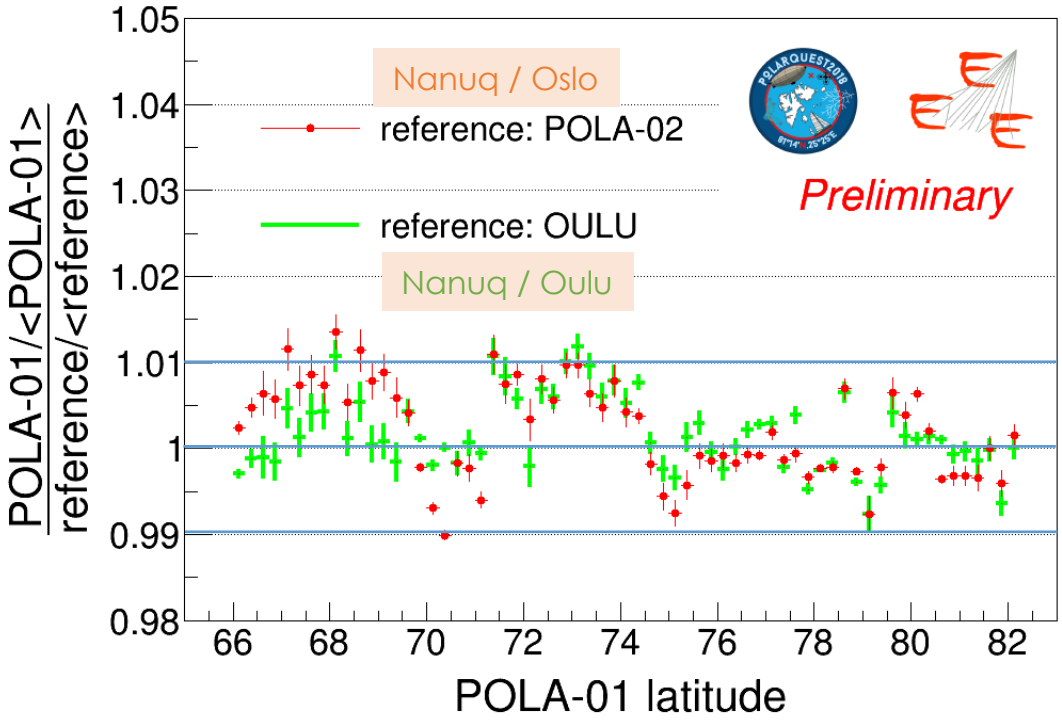


Difference of POLA-03 w.r.t. POLA-01/02 is ≈ **20%** and is due to:

- material budget on top of detector (mostly)
- latitude

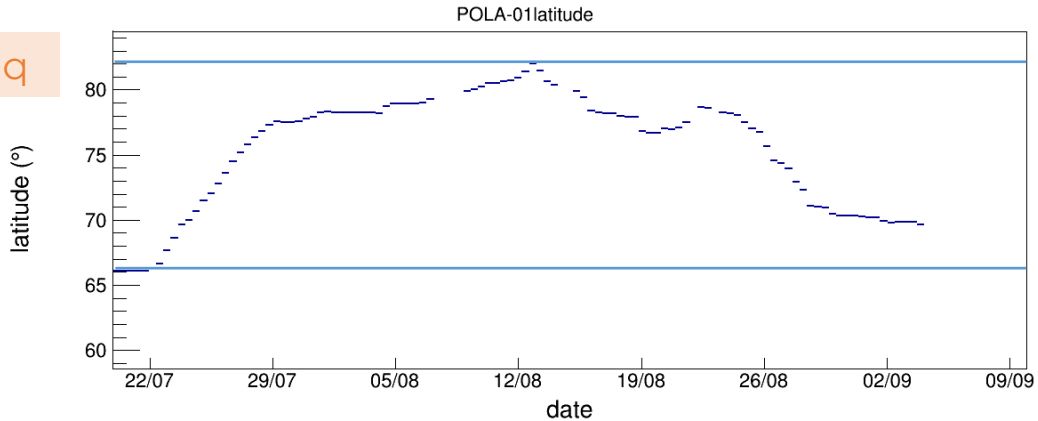
Rate vs. latitude

POLA-02 (in Oslo @ 59° N) used as reference since closer in latitude than POLA-03 (in Torino @ 45° N)



No significant effect observed
→ possible variation < 1%

Nanuq



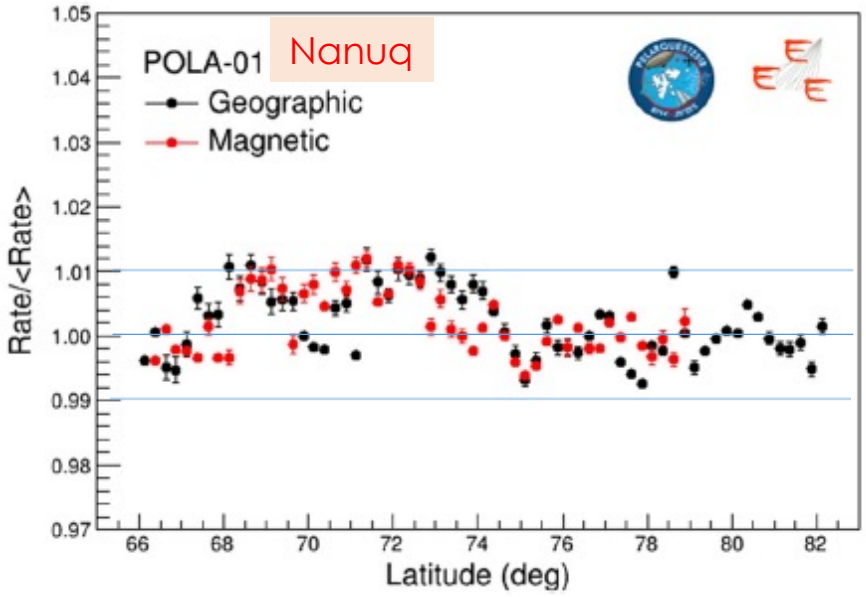
82° N (max) – North of Svalbard

POLA-01 on Nanuq

66° N (min) – Iceland

Thanks to PolarquEEEst

- **an extreme and unprecedented latitude reached at sea level (82° 07' N)** by an efficient cosmic ray detector
- **high precision measurements** of cosmic rays achieved with the **same kind of detectors** over a very large latitude range up to **Arctic latitudes → unprecedented (± 1%)**



"New high precision measurements of the cosmic charged particle rate beyond the Arctic Circle with the PolarquEEEst experiment", EEE Collaboration, Eur. Phys. J. C (2020) 80: 665

The arrival in Longyearbyern after Svalbard circumnavigation

Extreme Energy Events
Science inside Schools

Gianluca Casagrande, Paola Catapano, Peter Gallinelli, Alwin Courcy, Safiria Buono, Mathilde Gallinelli Gonzalez, Dolores Gonzalez, Mike Struik, Ombretta Pinazza, Rémy Andrean

PolarquEEEst

GOAL: Measure cosmic rays at extreme latitudes

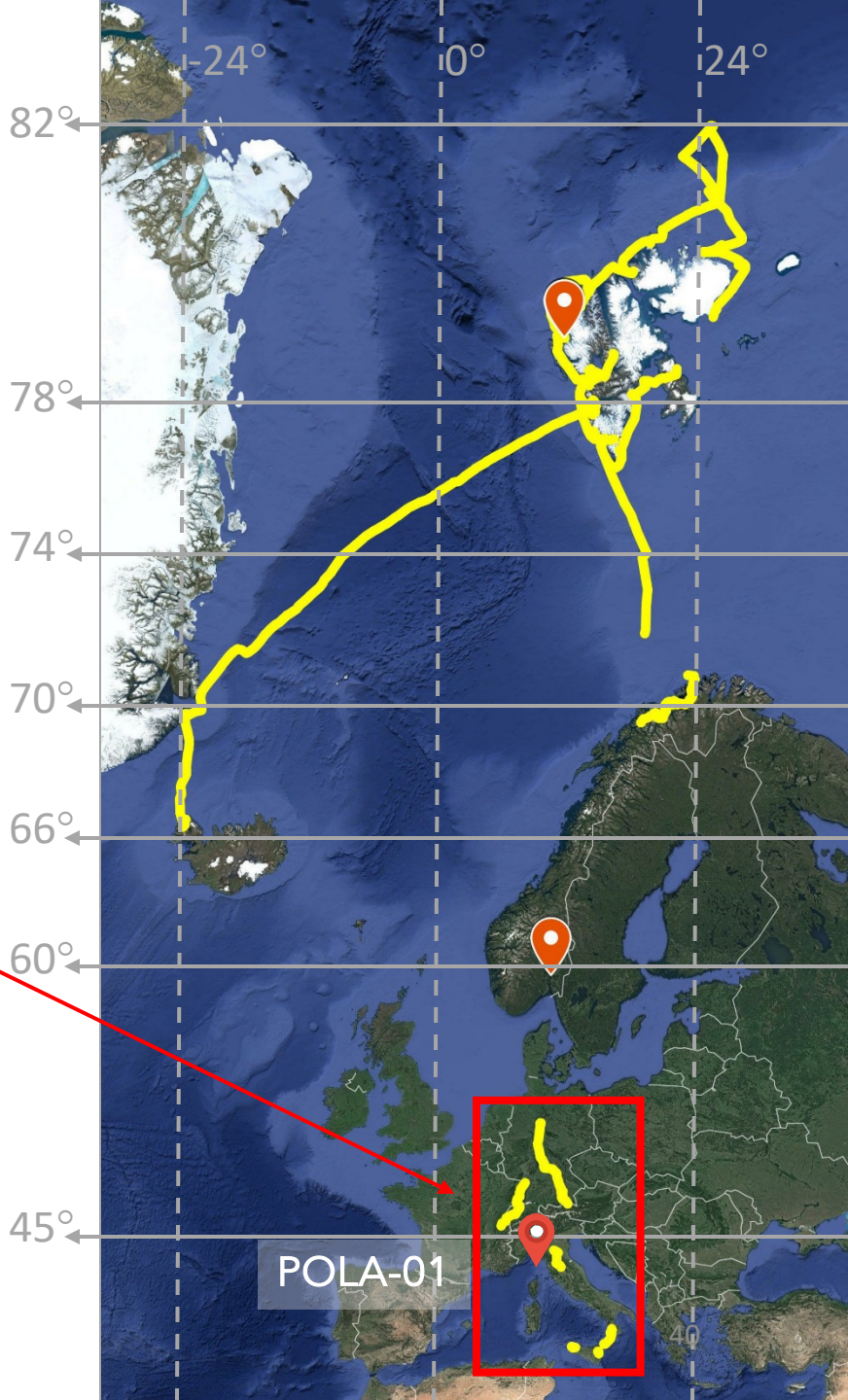
2018

- 3 detectors (POLA-01, POLA-02, POLA-03)
- PolarquEEEst2018 → mission on board of sailboat Nanuq (Jul – Sept 18) + 2 detectors at fixed sites: Bra (Italy) and Nessoden (Norway)

2019

PolarquEEEst2018-9

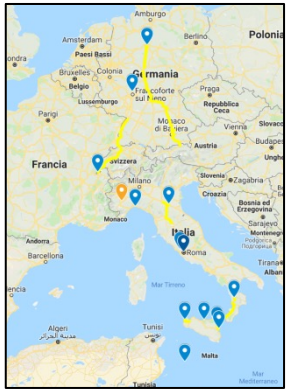
- (Dec 18 – Apr 19) → measurements at different latitudes (Italy, Germany, CERN)
- Construction of 4th detector (POLA-04)
- PolarquEEEst2019 → installation of 3 detectors at Ny Ålesund (Svalbard)



Cosmic ray flux vs latitude

Travel "on the road" of POLA-01 in Italy/Germany

POLA-01 at Cosenza



Other stops:

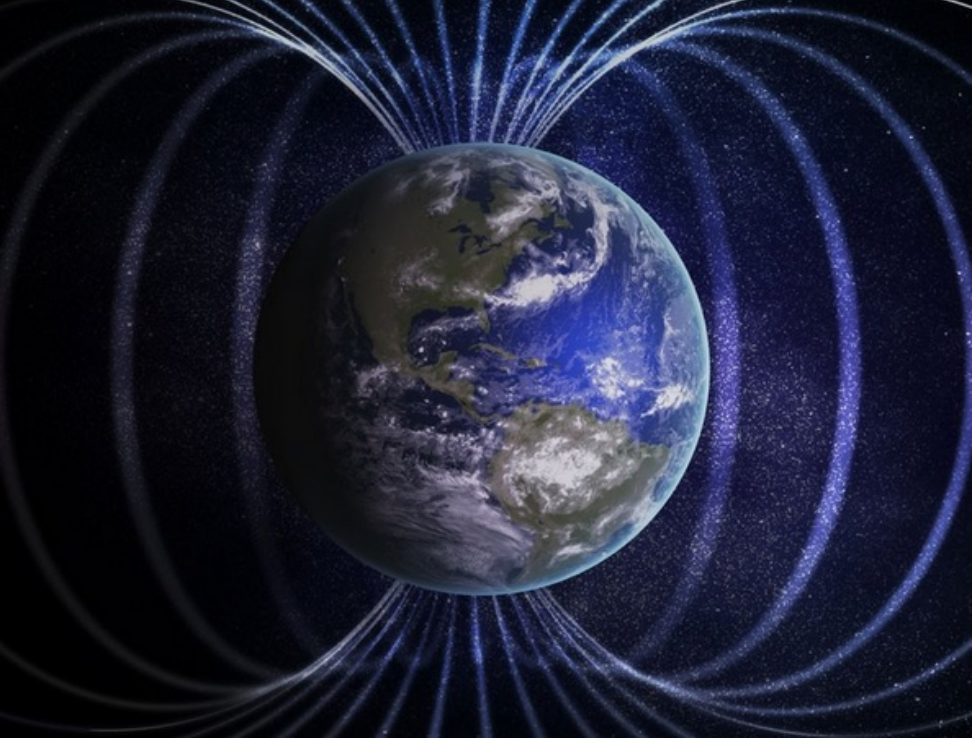
- Bologna
- Vigna di Valle
- Erice
- Catania

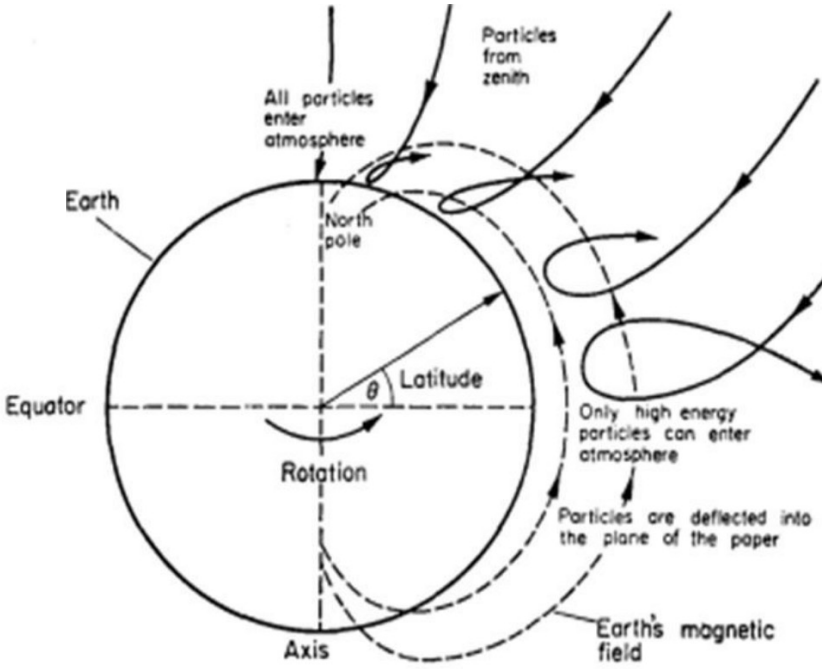
POLA-01 at Lampedusa
(reached by ferry boat)

POLA-01 on the Etna

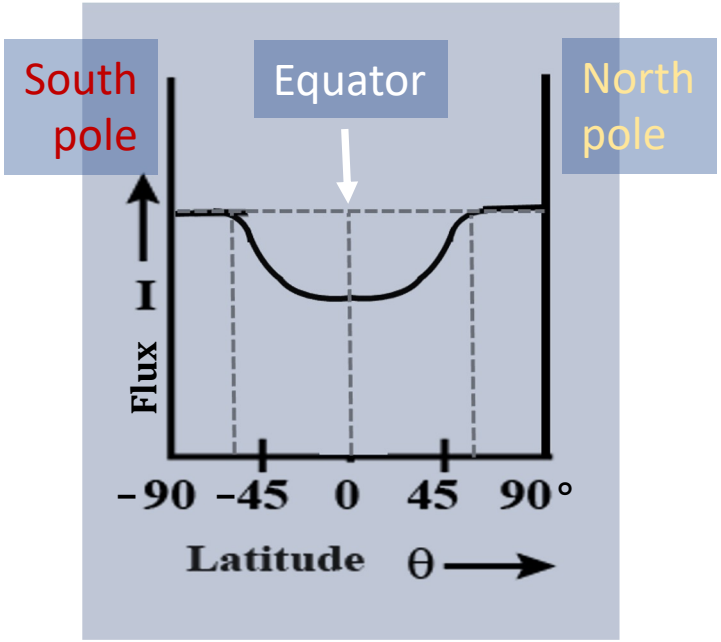
POLA-01 at Cefalù

POLA-01 in Germany:
Frankfurt, Hannover



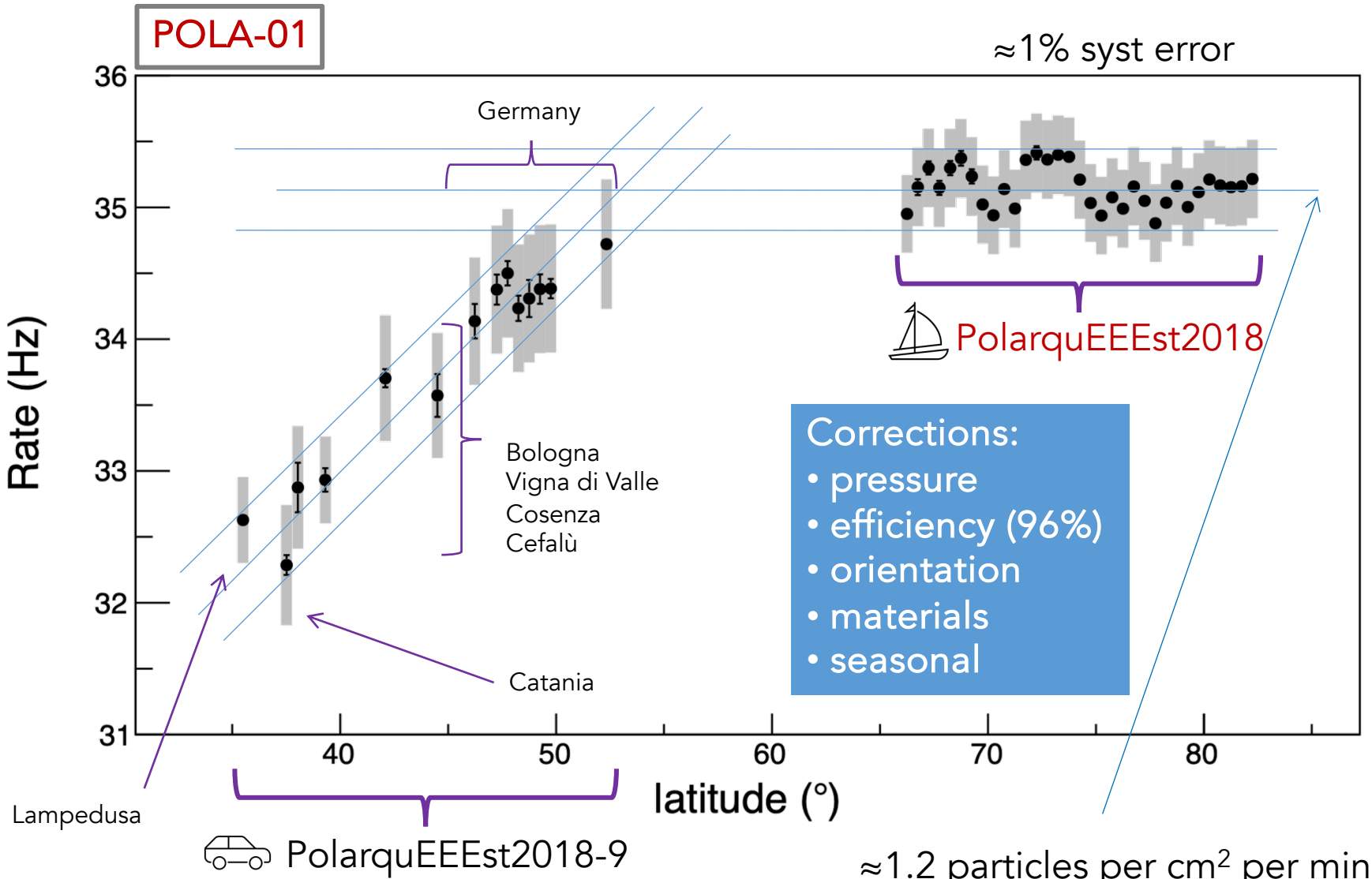


Geomagnetic field effect



Acceptance (assuming $\cos^2\theta$ distribution) = 0.741 x (40x60 cm^2)

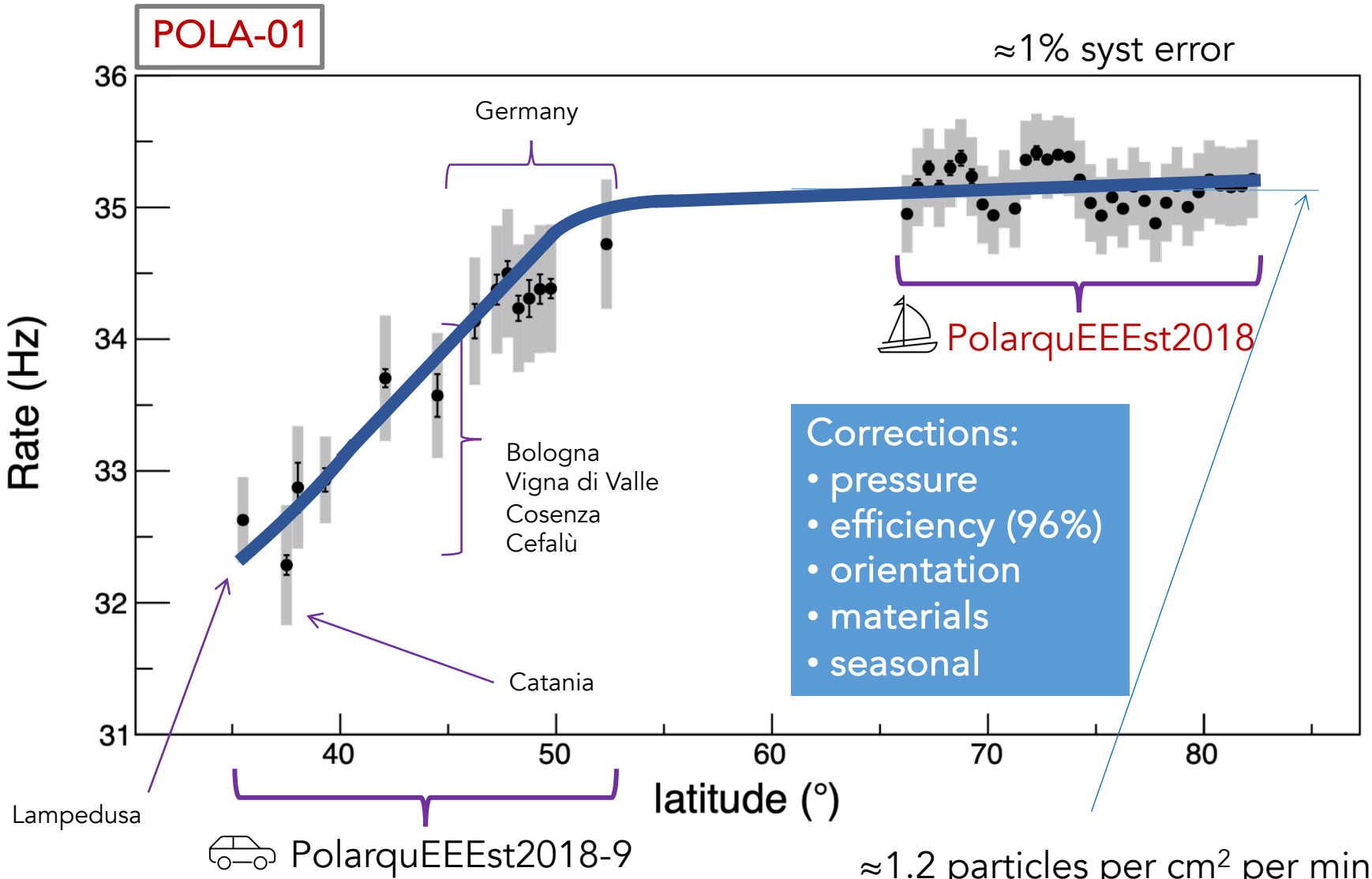
Cosmic ray flux vs latitude



≈1.2 particles per cm^2 per minute
consistent with PDG value for muons

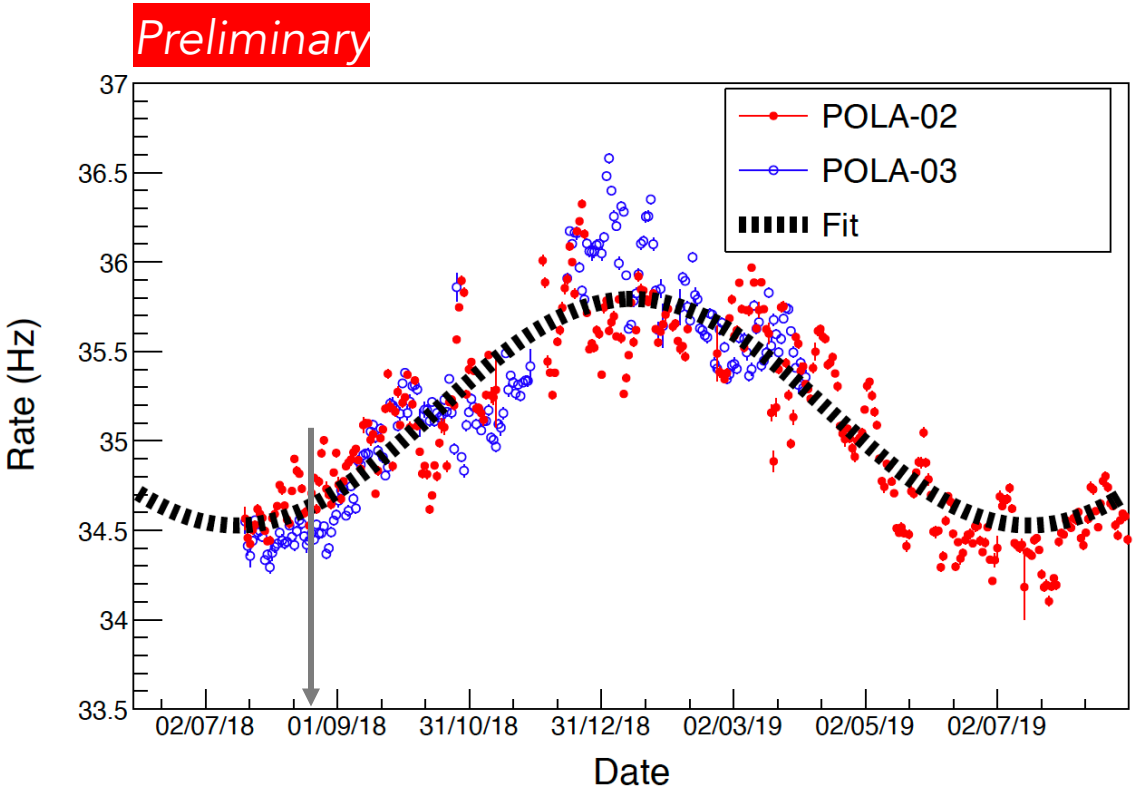
Acceptance (assuming $\cos^2\theta$ distribution) = 0.741 x (40x60 cm^2)

Cosmic ray flux vs latitude



≈1.2 particles per cm^2 per minute
consistent with PDG value for muons

Seasonal variation



The cosmic ray flux seems to be sensitive to atmospheric & climate parameters such as the **temperature**

→ The study and observation of cosmic rays could be **a nice tool to investigate and monitor atmospheric & climate changes**

±1.8% modulation (max in winter, min in summer)
consistent with
R.R.S. de Mendonça *et al*, The Astrophysical Journal, 830:88 (2016)

PolarquEEEst

GOAL: Measure cosmic rays at extreme latitudes

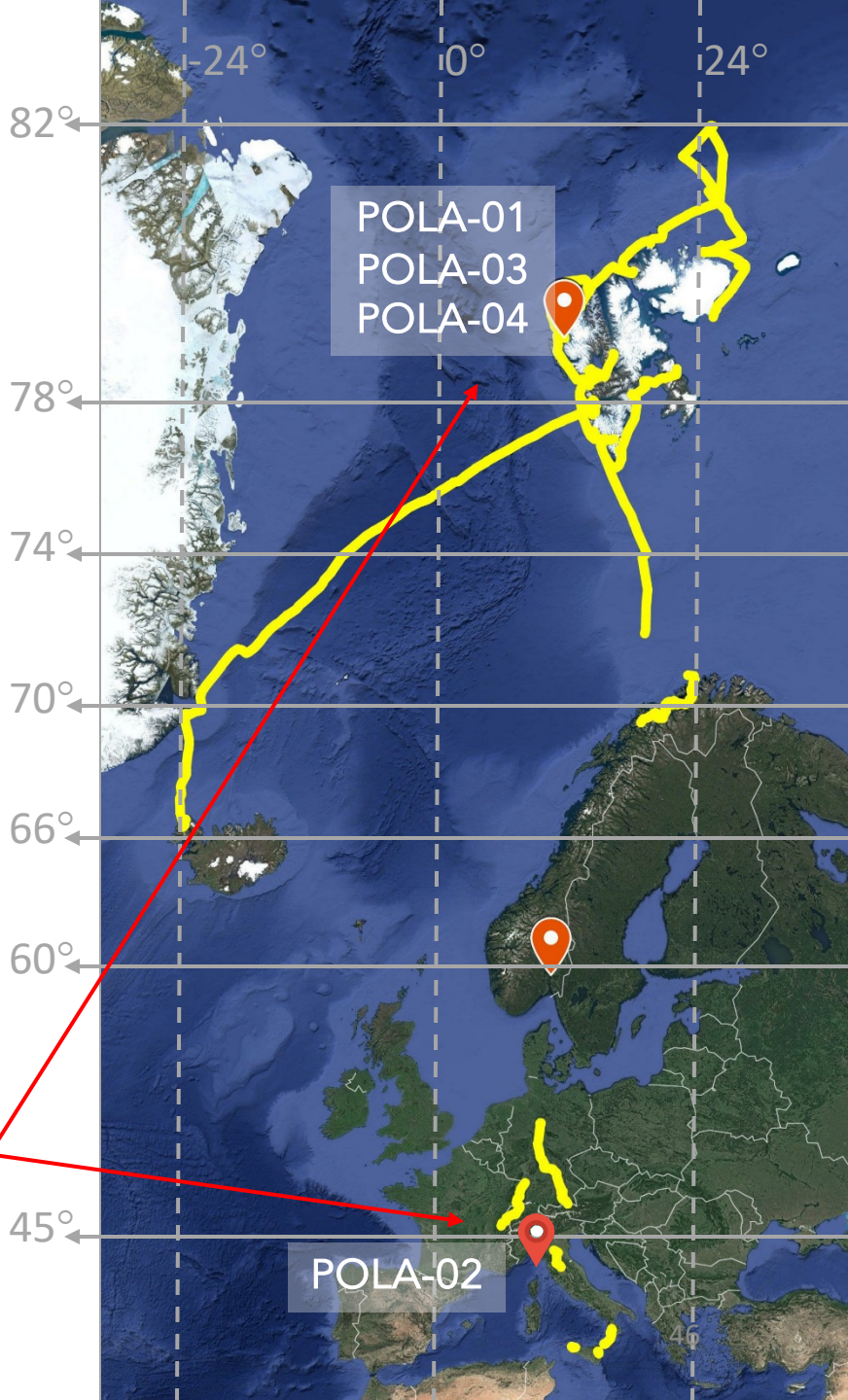
2018

- 3 detectors (POLA-01, POLA-02, POLA-03)
- PolarquEEEst2018 → mission on board of sailboat Nanuq (Jul – Sept 18) + 2 detectors at fixed sites: Bra (Italy) and Nessoden (Norway)

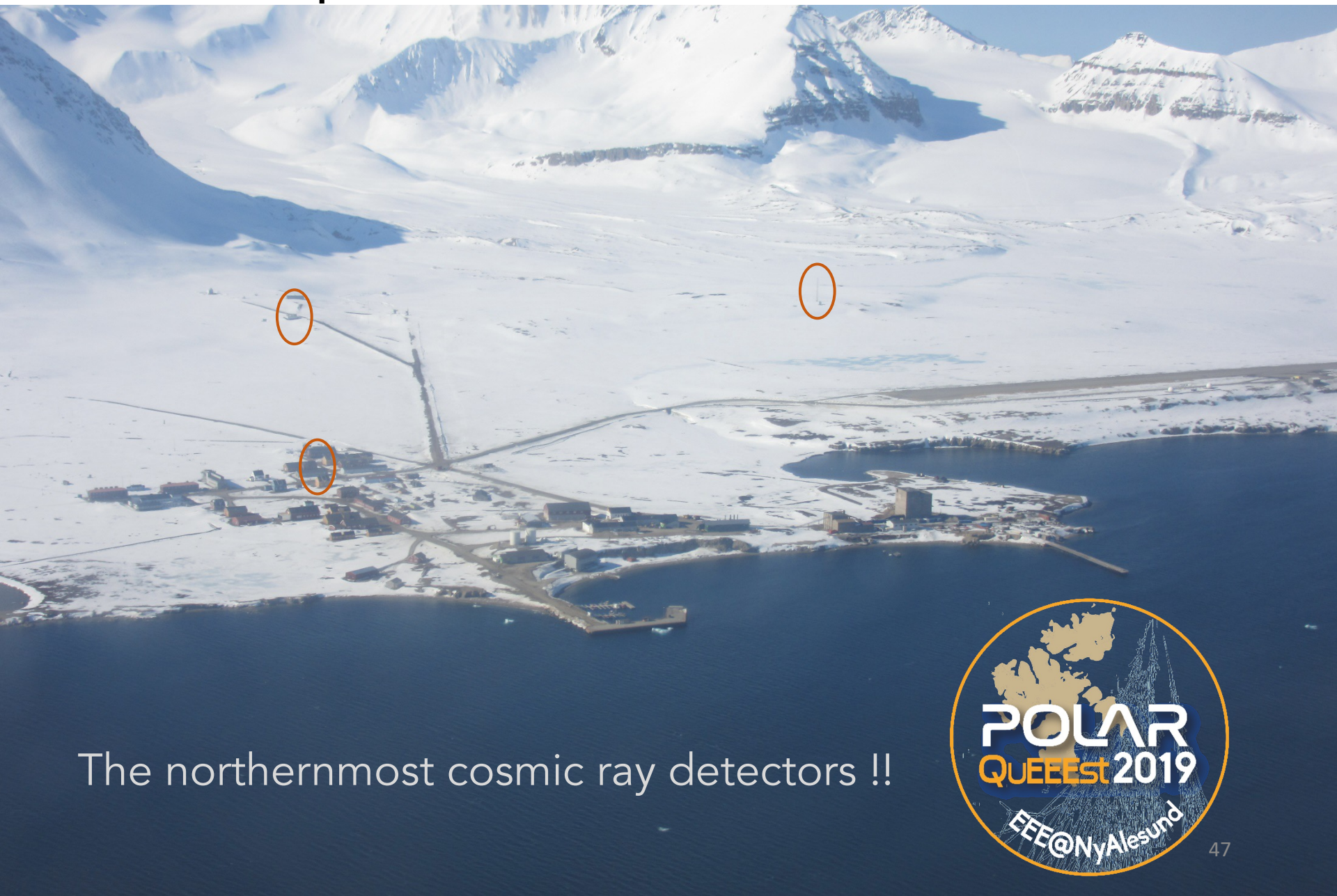
2019

- (Dec 18 – Apr 19) → measurements at different latitudes (Italy, Germany, CERN)
- Construction of 4th detector (POLA-04)
- PolarquEEEst2019 → installation of 3 detectors at Ny Ålesund (Svalbard)

PolarquEEEst2019



PolarquEEEst2019@Ny Ålesund



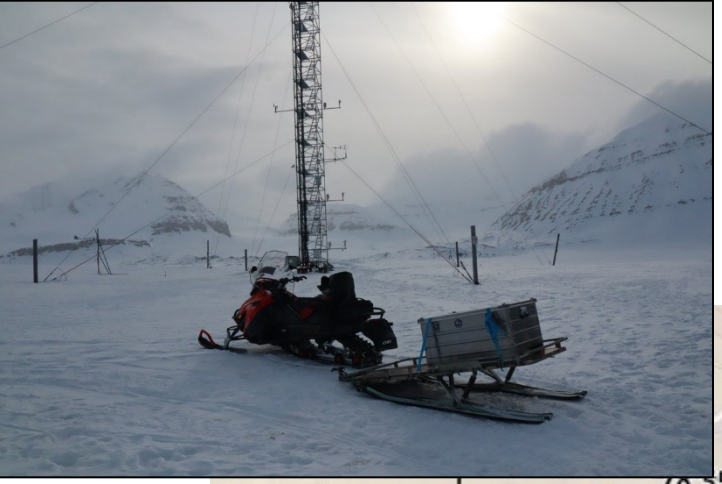
The northernmost cosmic ray detectors !!

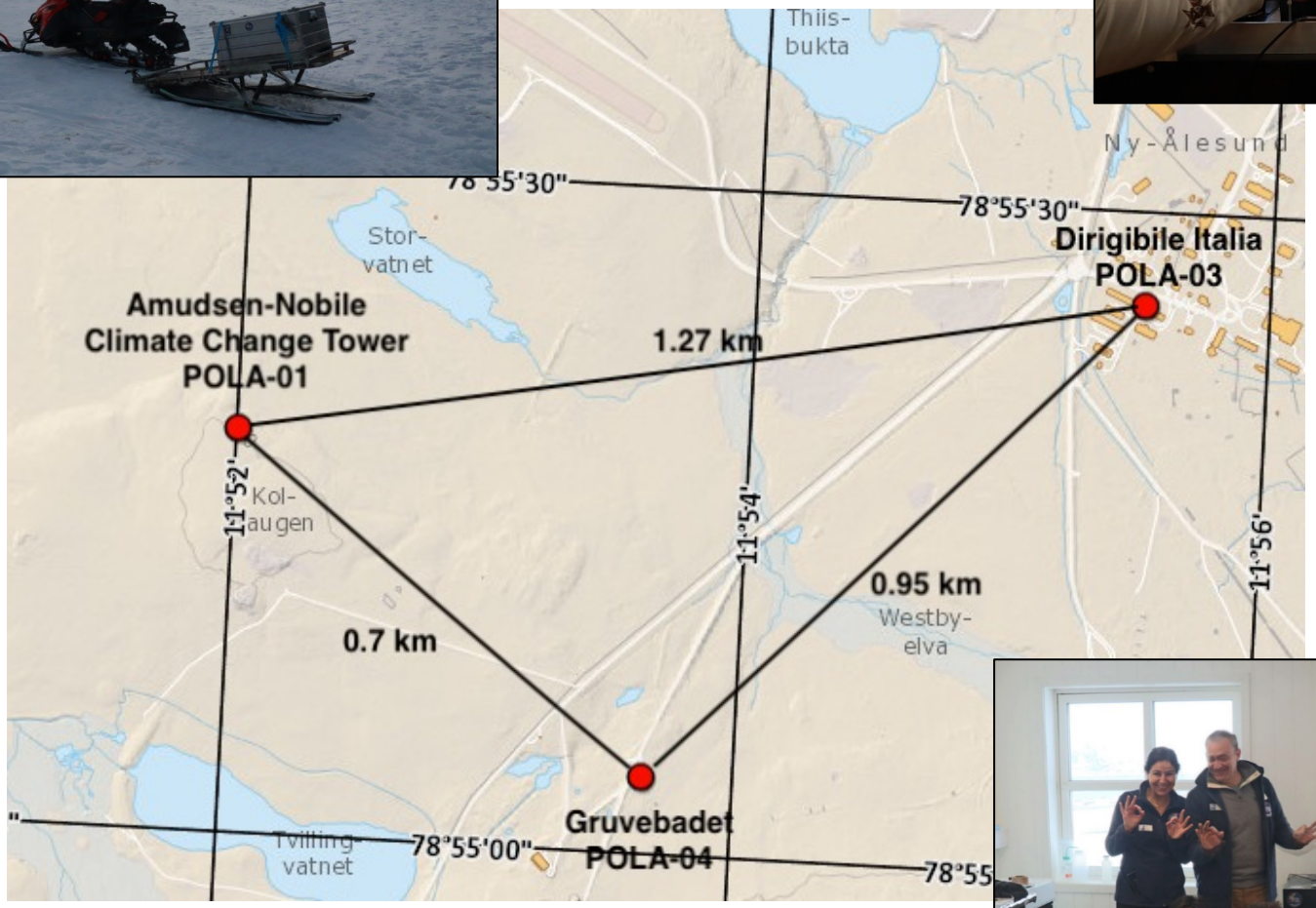
Installation at Ny Ålesund

The Polar task arriving at Ny Ålesund

At the *Dirigibile Italia* (*Italia Airship*) station with the CNR staff

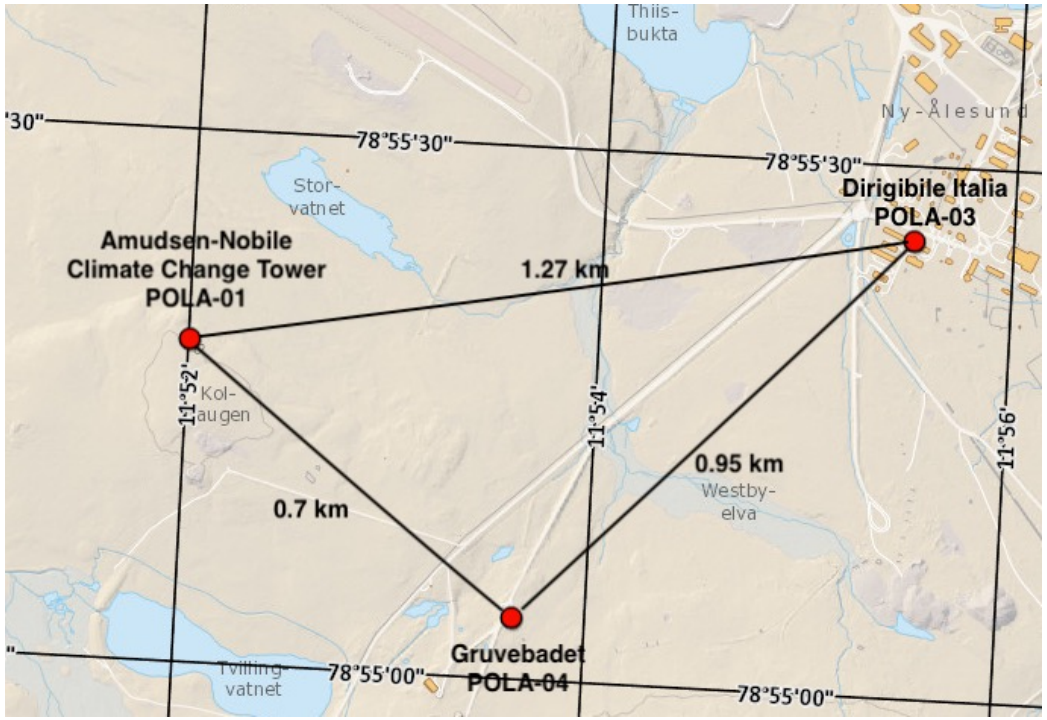
POLA-01 on its way to the CNR "Climate Change Tower"





Installation in 2019

Maintenance check in 2021



PolarquEEEst2019@Ny Ålesund

Maintenance check after COVID lockdown in September 2021

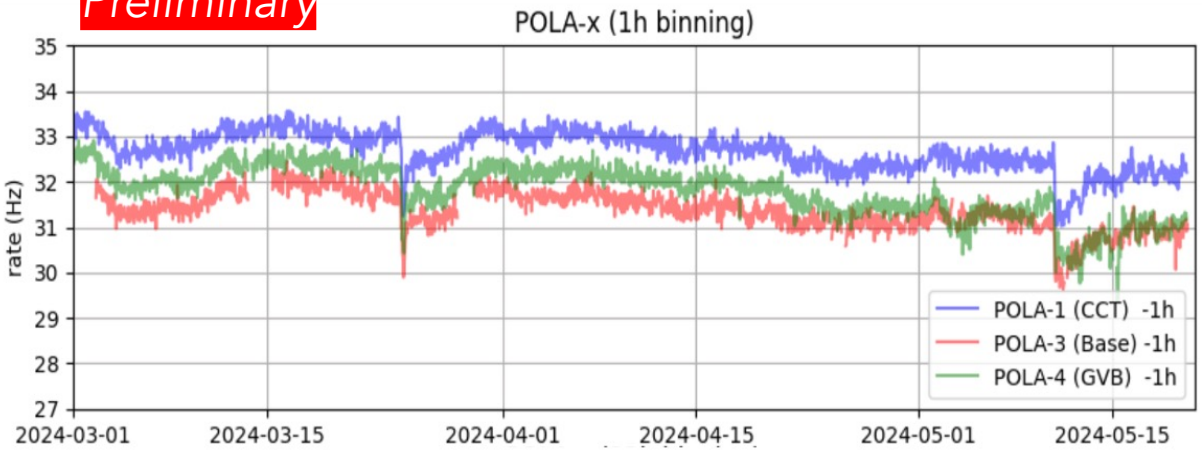
Since then data taking nicely ongoing

→ Shower coincidences
→ Seasonal modulation effects
→ Solar activity

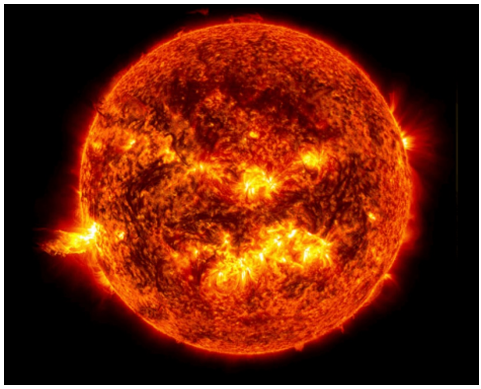
New maintenance checks in May 2023 then in May 2024

The northernmost cosmic ray detectors !!

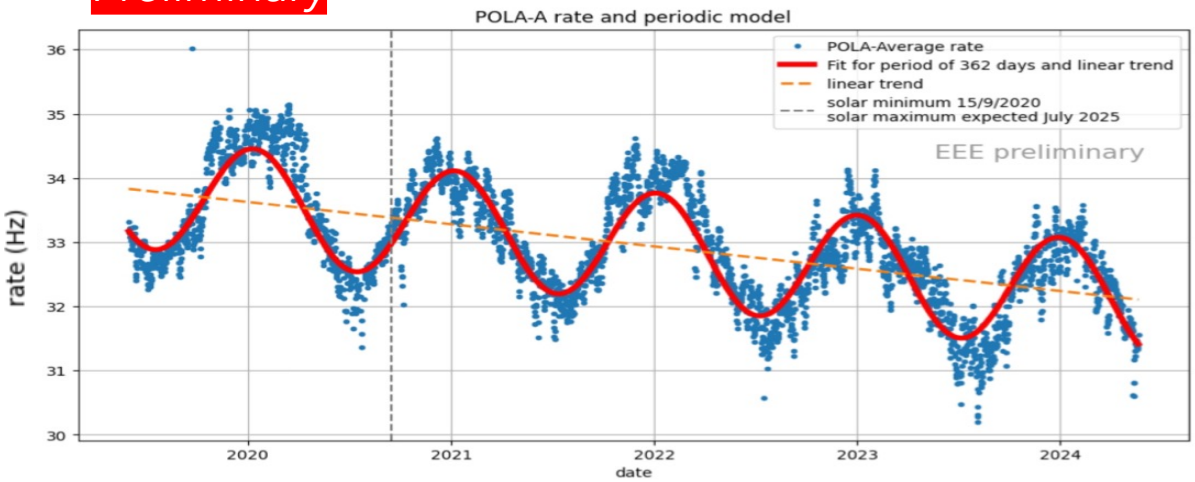
Preliminary



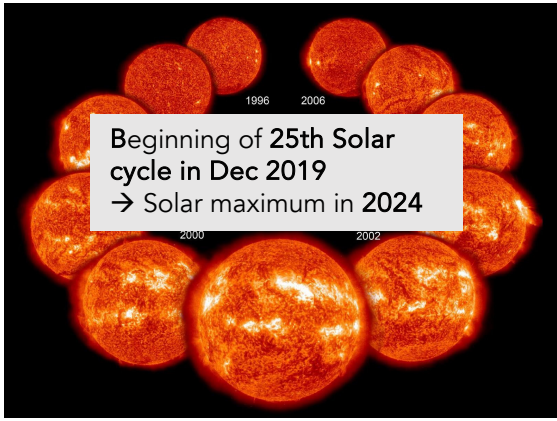
Intense solar flares
(Forbush effects)



Preliminary



Annual modulation
+ Solar cycle effect



Measurement of cosmic-ray flux time dependence
→ potential monitoring tool for spotting changes related to environment, solar activity or other causes

At the North Pole we are more sensitive!

PolarquEEEst

GOAL: Measure cosmic rays at extreme latitudes

2018

- 3 detectors (POLA-01, POLA-02, POLA-03)
- PolarquEEEst2018 → mission on board of sailboat Nanuq (Jul – Sept 18) + 2 detectors at fixed sites: Bra (Italy) and Nessoden (Norway)

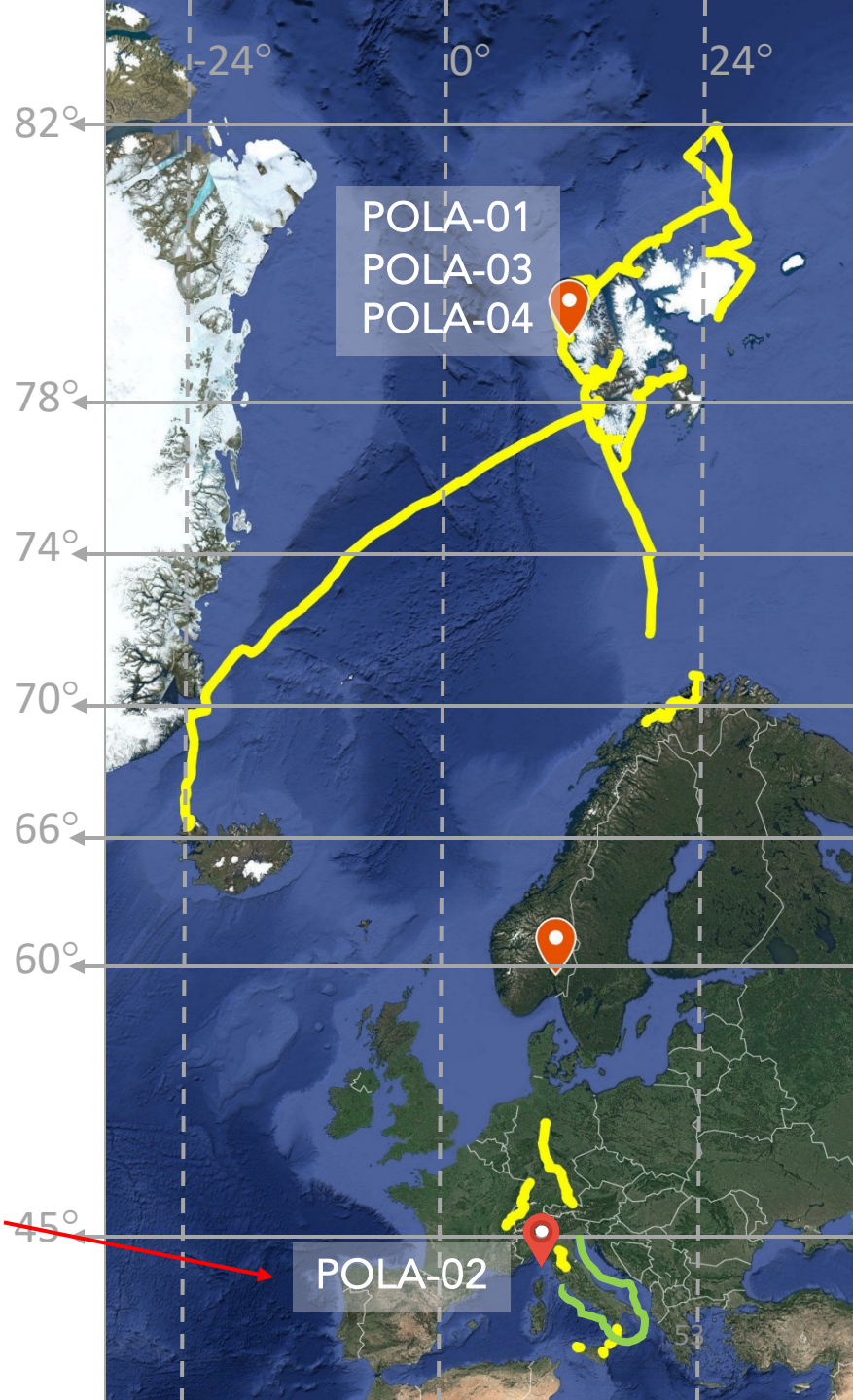
2019

- (Dec 18 – Apr 19) → measurements at different latitudes (Italy, Germany, CERN)
- Construction of 4th detector (POLA-04)
- PolarquEEEst2019 → installation of 3 detectors at Ny Ålesund (Svalbard)

2022

PolarquEEEst2022

- (Oct 22) → measurements at different latitudes (Italy) on board of Amerigo Vespucci tall ship

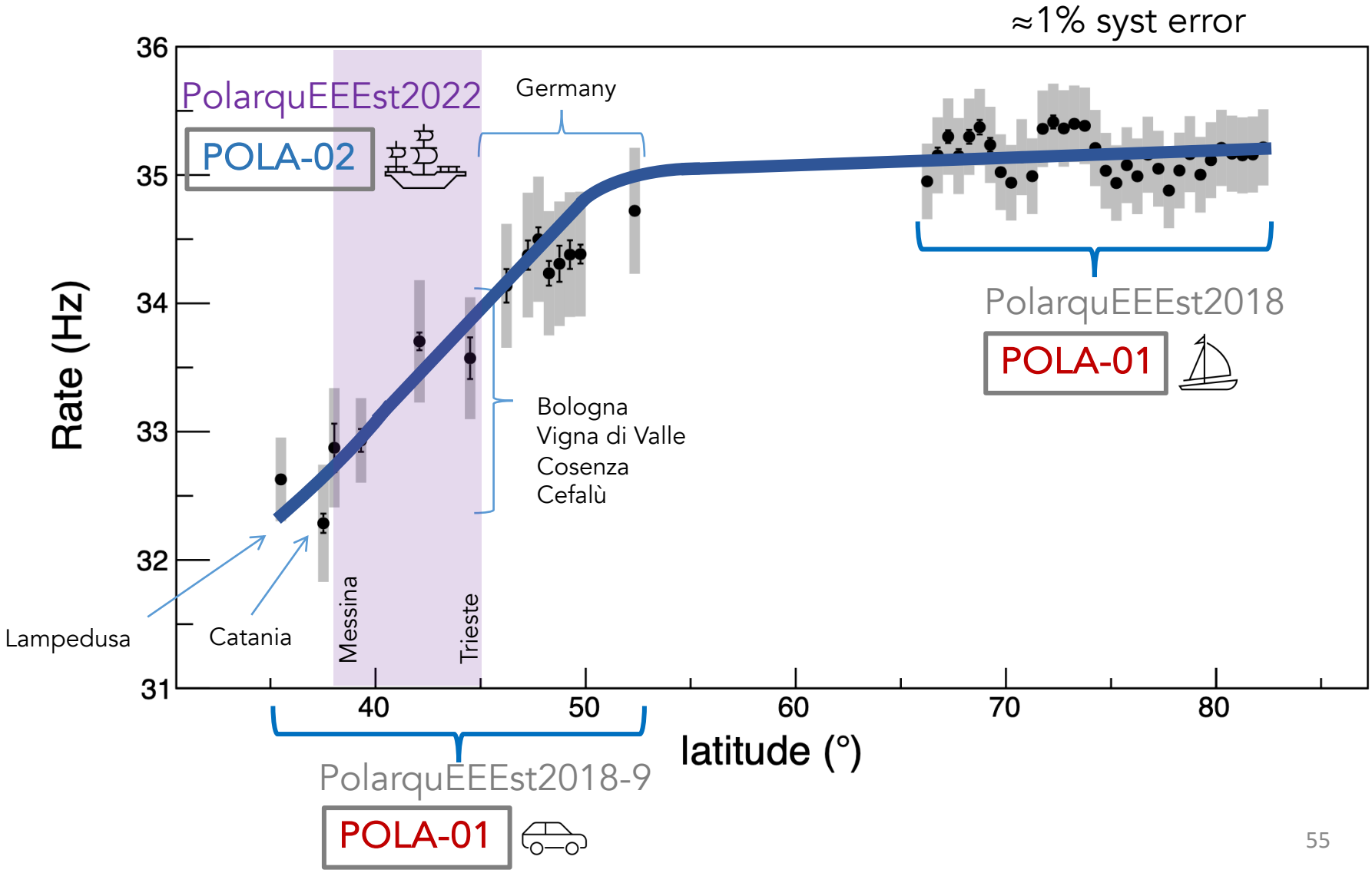


PolarquEEEst 2022

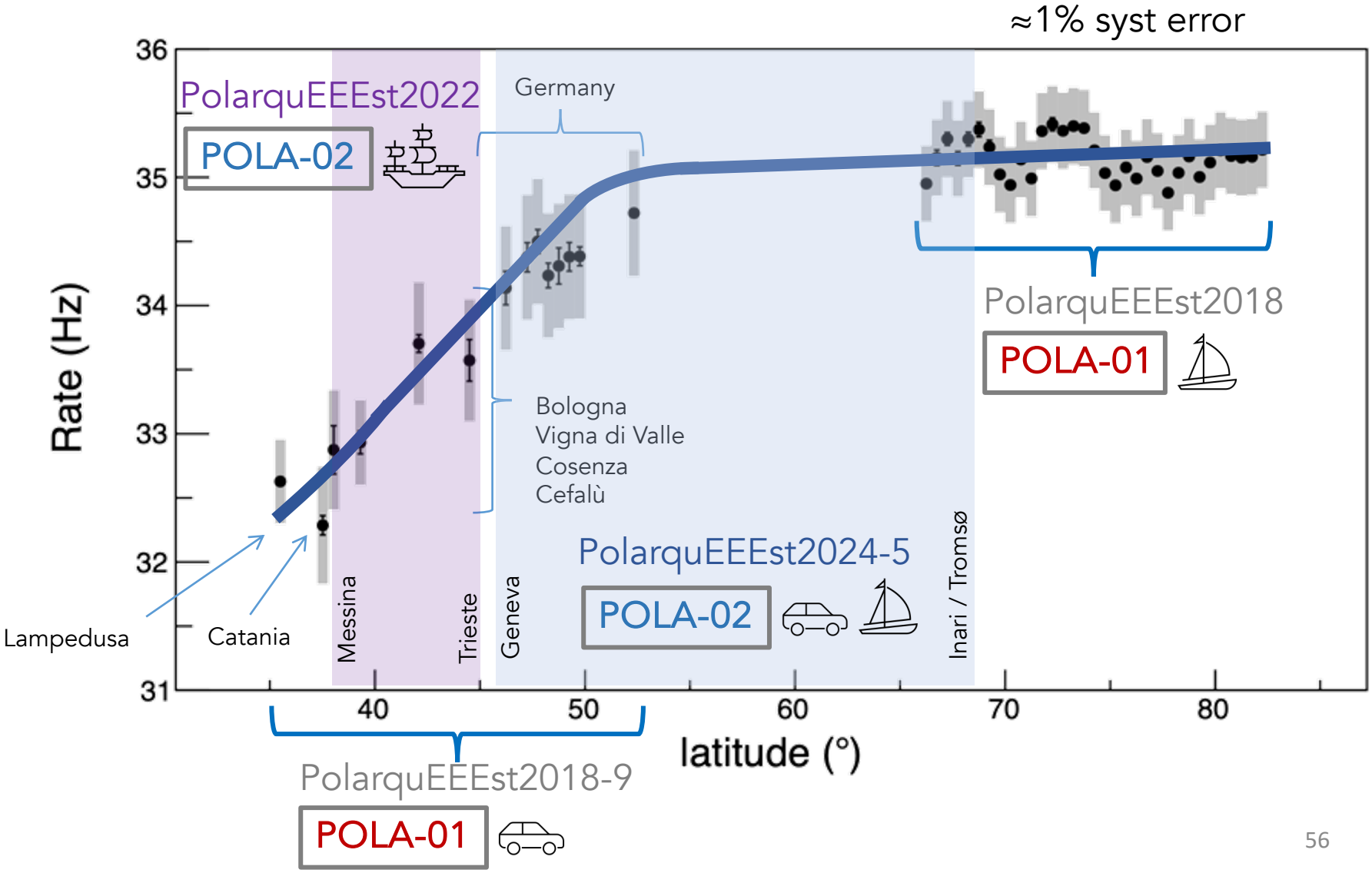
Aboard the Amerigo Vespucci to measure particles from the Cosmos

Crediti: marina.difesa.it

Cosmic ray flux vs latitude



Cosmic ray flux vs latitude



Extreme Energy Events
Science inside Schools

- Thanks to PolarQuEEEst

→ **Precision study of the cosmic ray intensity at high latitudes up in the Arctic polar region where no published data exist**

→ **Check of the saturation of the cosmic ray intensity at higher latitudes and of the suppression of the intensity at lower latitudes**

→ **Very useful probe to monitor the configuration of the Earth magnetic field, the primary cosmic ray energy spectrum affected by the Sun activity and maybe the status of the Earth atmosphere**

Thank you
for your kind attention