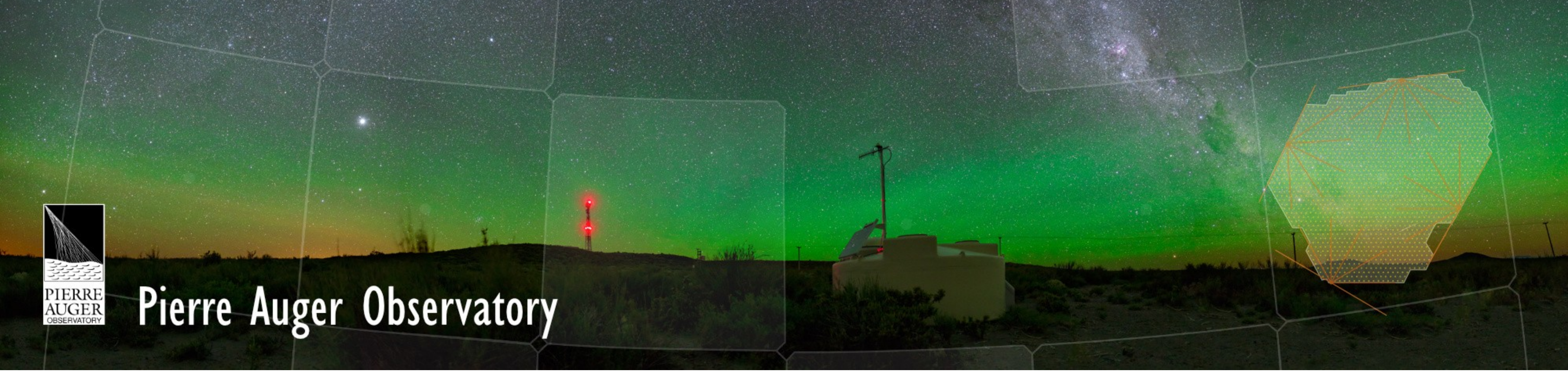


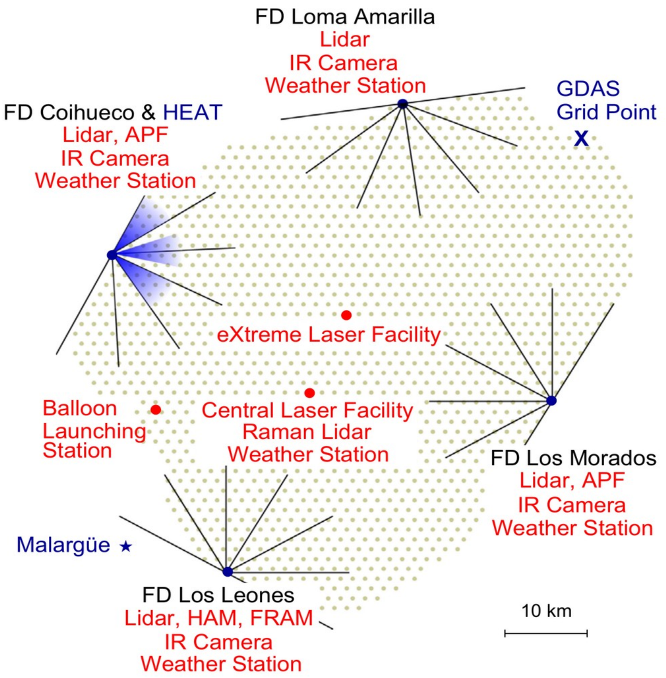
Simulation production and data storage at the Pierre Auger Observatory

Roberta Colalillo
Università "Federico II" & INFN, Napoli

INFN
Istituto Nazionale di Fisica Nucleare

Workshop sul Calcolo nell'INFN, Loano (SV), May 22, 2023

The Pierre Auger Observatory



Located in the Argentinian pampa (Malargüe), at ~1400 m above sea level.

SD detector:

1660 Water-Cherenkov Detectors (WCD), covering 3000 km^2 and arranged in a triangular grid with 1500 m spacing.

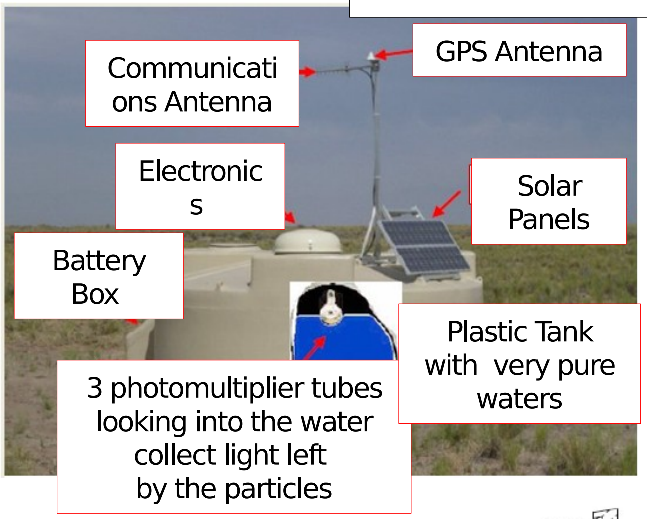
FD detector:

24 telescopes, 6 for each sites, arranged to overlook the area covered by the SD.

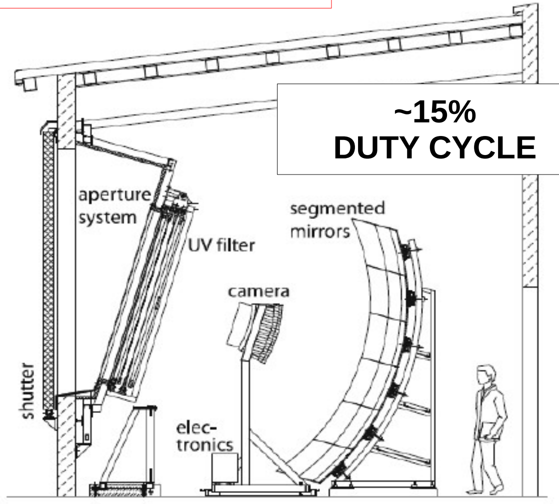
① **Large Aperture**
(about 7000 km^2 sr)

② **Hybrid Technique**

100% DUTY CYCLE



~15% DUTY CYCLE

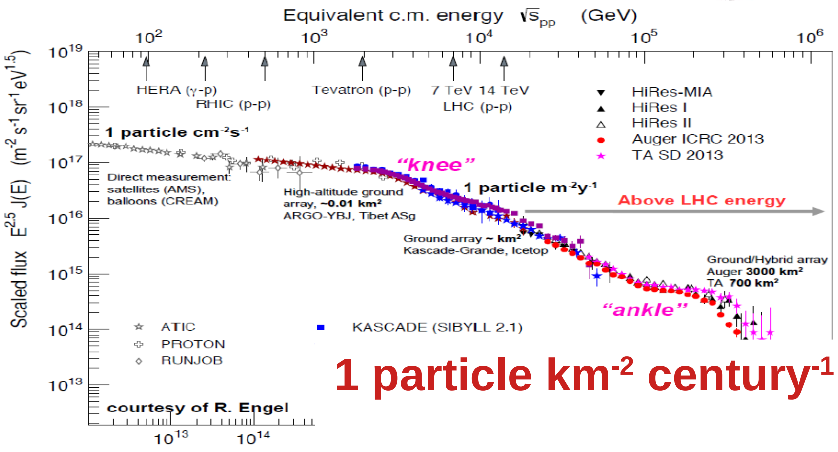


Goals of the Experiment:

- Energy Spectrum
- Mass Composition
- Arrival Directions

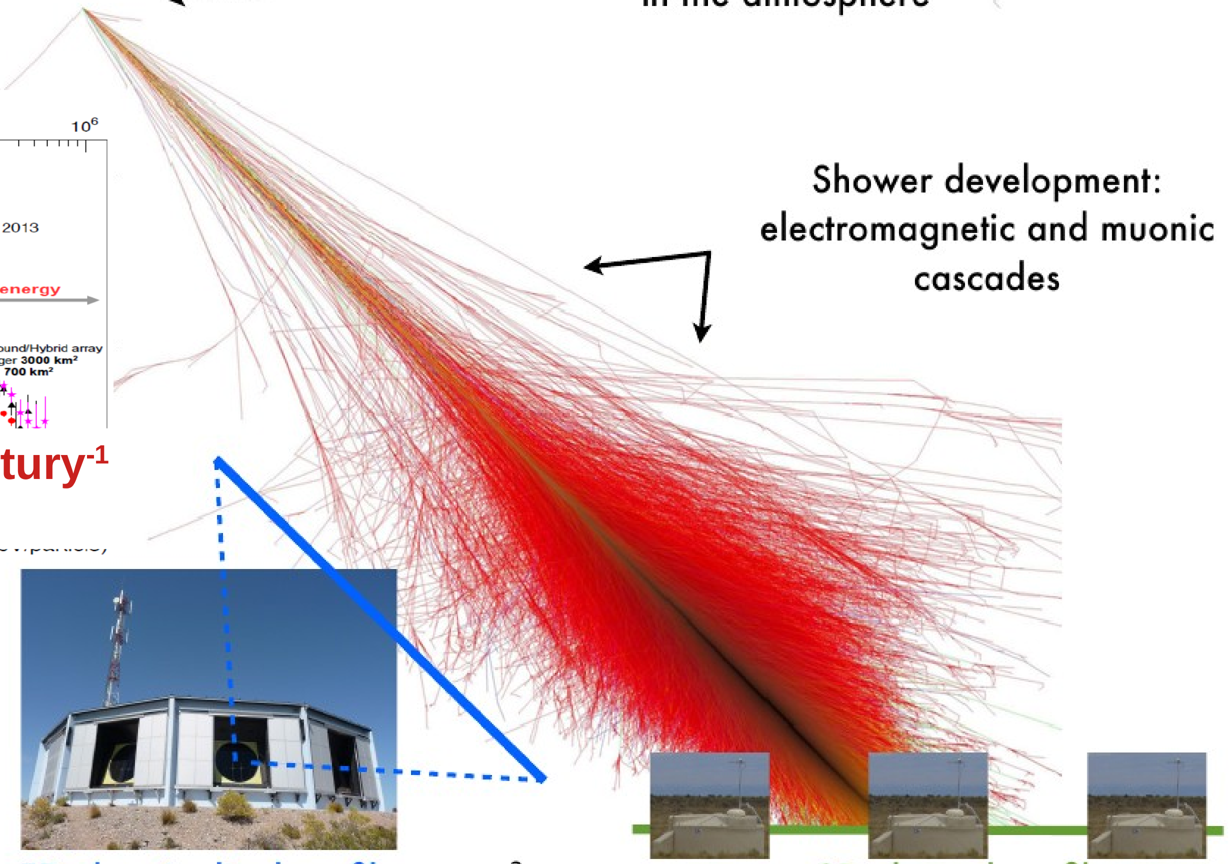
Indirect cosmic-ray measurements

Cosmic ray 1st interaction high in the atmosphere



1 particle km^{-2} $century^{-1}$

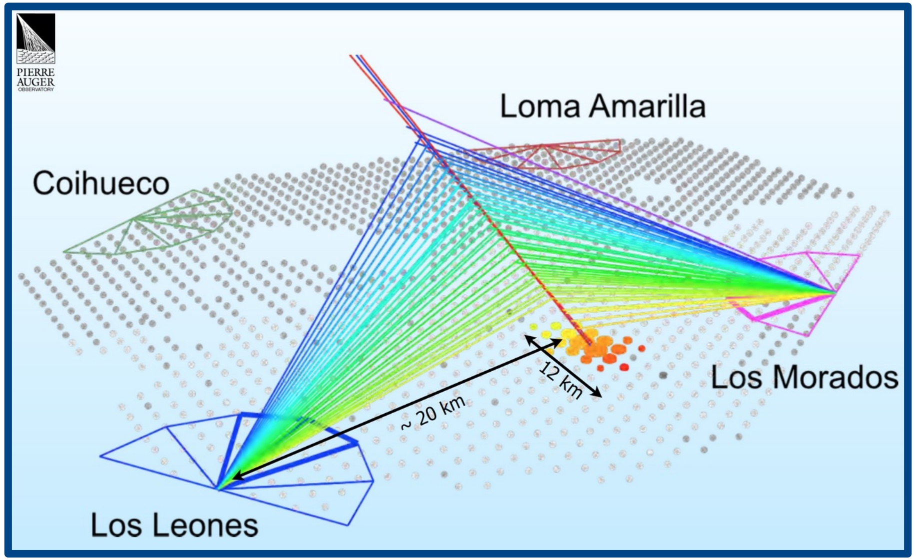
Shower development: electromagnetic and muonic cascades

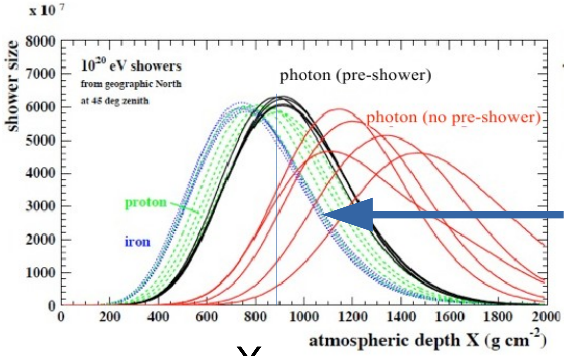


FD - longitudinal profile

SD - lateral profile

An Auger event

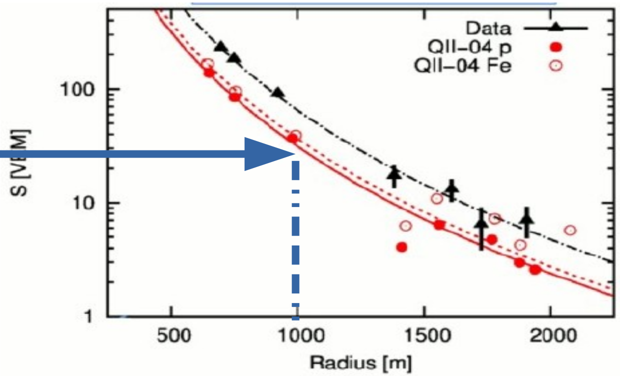




Xmax

$E_{cal} = \int dE/dX \, dX$

S1000



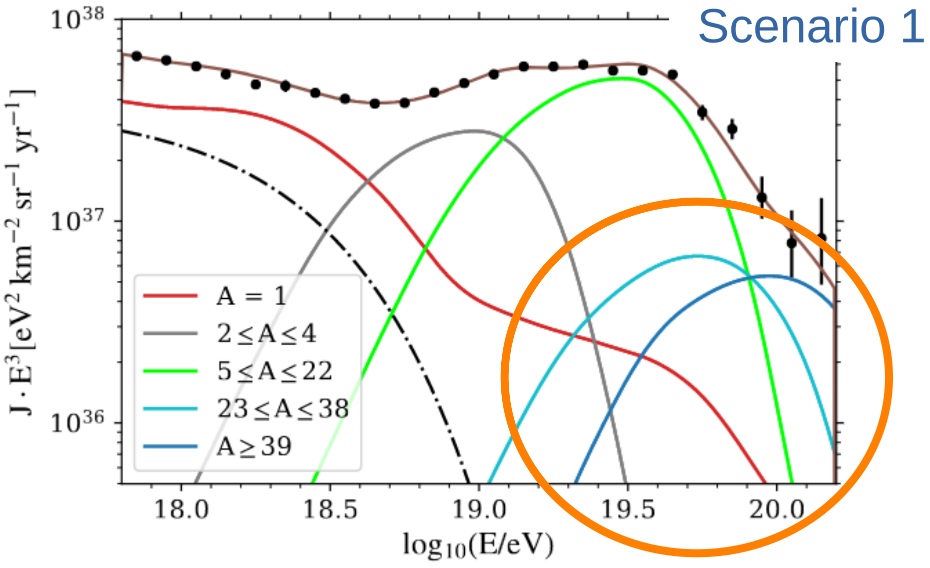
$E_{surface} = f(S_{1000}, \theta)$

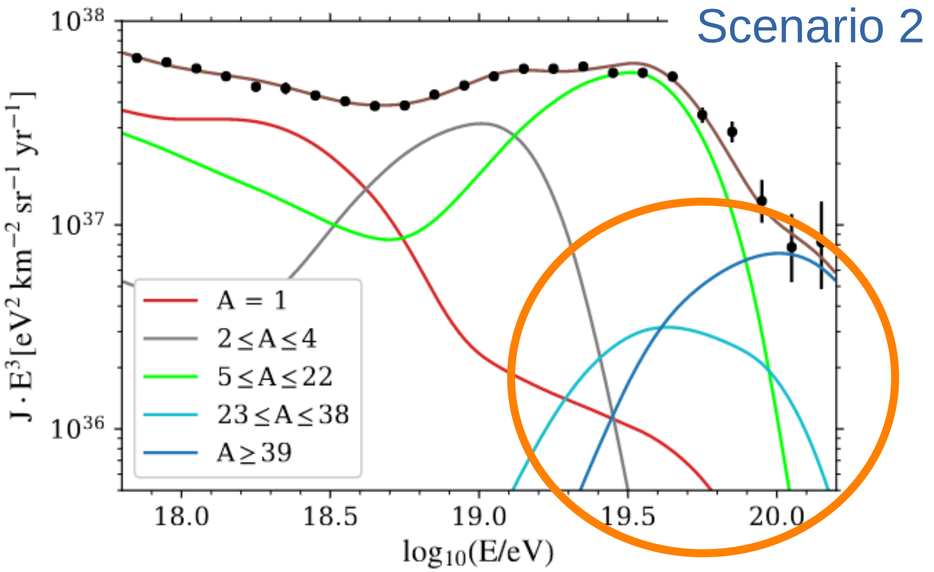
longitudinal profile

lateral profile

Spectrum and Composition

It is possible to reproduce the Auger energy spectrum using different astrophysical models as input for simulations.





The composition can help to distinguish one model from another.
FD provides important information about composition but **at the highest energies, the statics is too low**. We want to use data collected by the SD, which has a 100% duty cycle e we want to measure the **muonic component** of the shower.

Auger Prime: the major upgrade of the Auger SD

- A complementary measurement of the shower particles will be provided by plastic Surface Scintillator Detectors (SSD) placed above the existing 1660 WCDs.
- The SD stations will be upgraded with new electronics that will process both WCD and SSD signals.
- To increase the dynamic range, each WCD will be equipped with an additional smaller low gain photomultiplier tube.

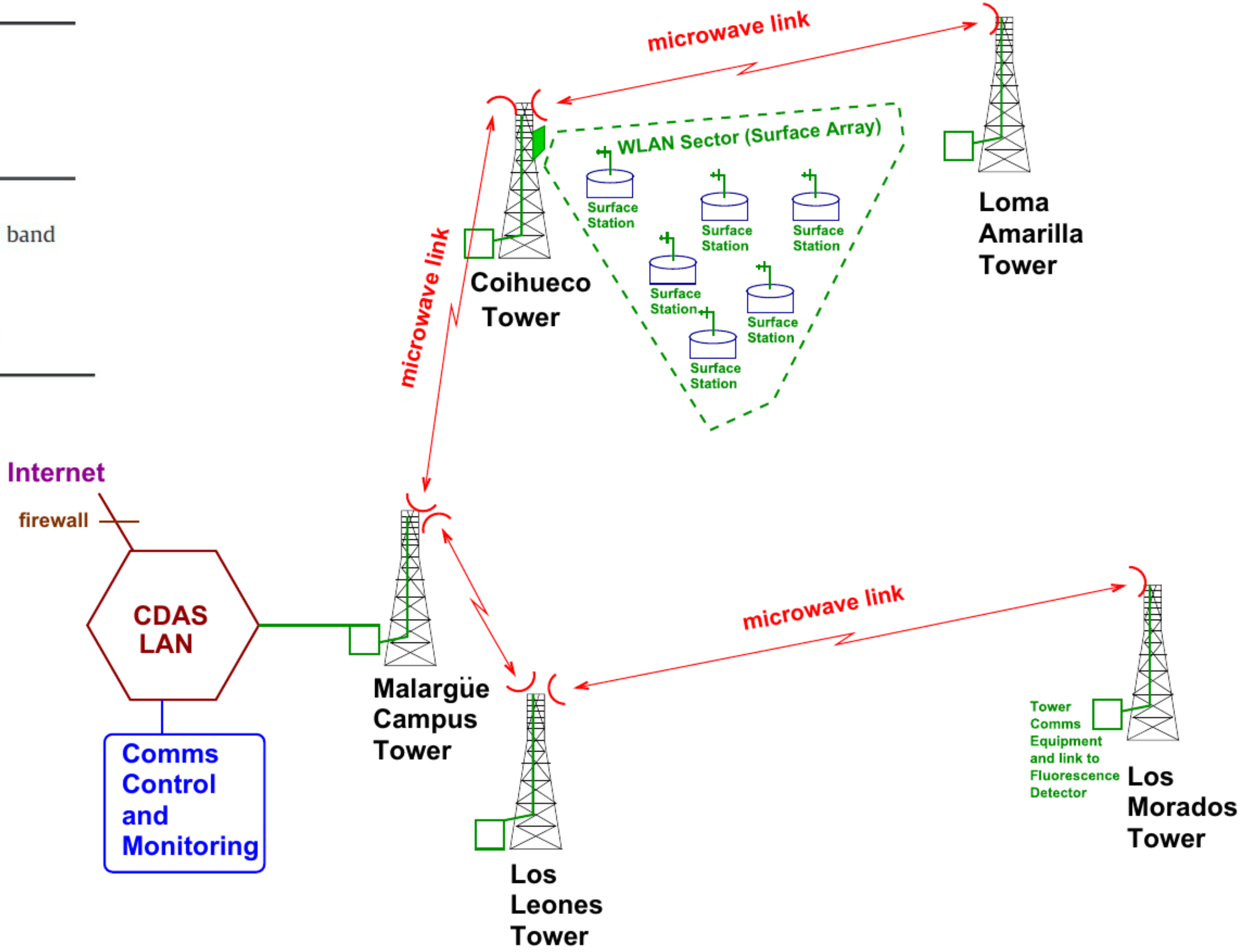
- An Underground Muon Detector (UMD) will provide important direct measurements of the shower muon content.
- Each SD station will be complemented with an antenna for the detection of radio signal produced by cosmic-ray showers.

Data communications system

Microwave backbone network	
Links	4
Frequency	7 GHz
Data rate	24 Mbps
Wireless LAN	
Nodes	1660
Frequency	902–928 MHz ISM band
Protocol	TDMA, custom
Subscriber unit over-air rate	200 kbps
Effective payload rate	1200 bps uplink
Typical daily data packet loss rate	Less than 0.002%

Each SD station communicates through a **bidirectional WLAN** customs radio network.

Four concentrators located at the FD buildings collect the data from the field and transfer it through a dedicated **microwave link** to the Central Station. This microwave link also transports the FD data.



Central Data Acquisition System (CDAS)

The CDAS has been running since March 2001. It was designed:

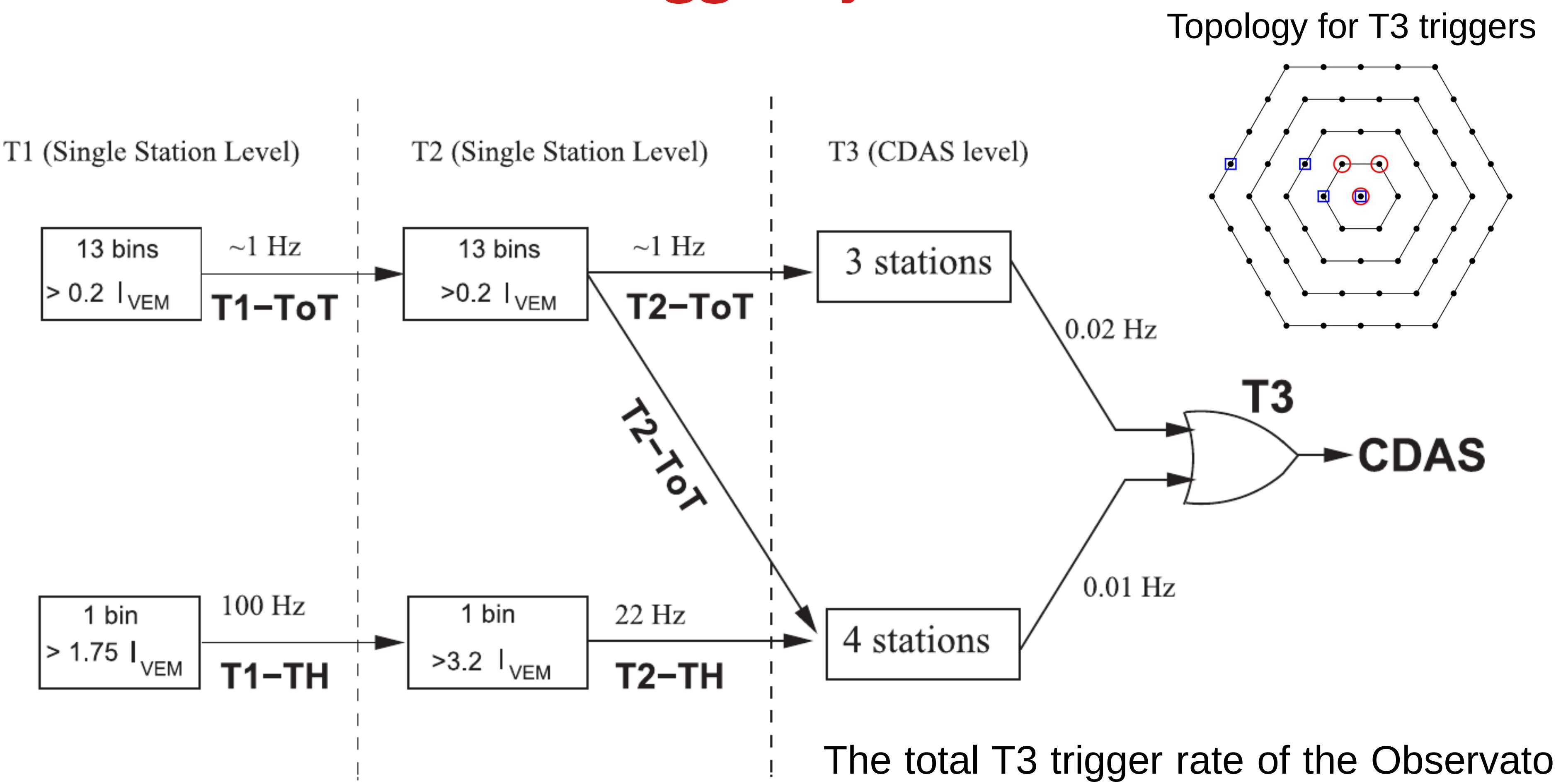
- to assemble the triggers from the SD detectors;
- to allow control of these detectors;
- to organize the storage of data.

Data from the FD are recorded separately at the FD locations and transferred daily to the Computer Center at Malargüe.
Hybrid coincidences are identified online within the SD data stream.

The primary role for the **CDAS** is to **combine local trigger information from the SD stations in order to identify potential physical events** generating an SD higher level trigger (T3). These triggers combined with the T3 from FD sites (FD T3) are used to generate a request for the relevant data from SD stations for these events.

Except for triggering information, the CDAS and the FD data acquisition systems are completely independent. The merging of FD and SD data is made offline during the daytime following an FD run. **Data are synchronized** on the **central storage hardware** after each night of observation. The newly acquired data within the central storage **are mirrored** at the **primary data mirror** located at the **IN2P3 HEP Computer Center in Lyon** (France) every 3 h.

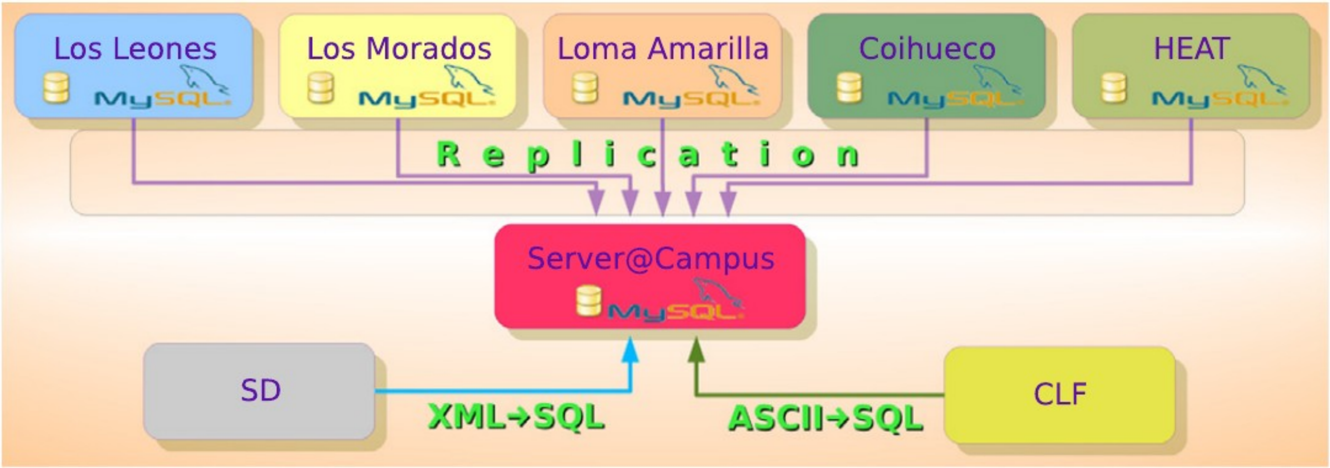
SD trigger system



The total T3 trigger rate of the Observatory is of the order of **0.1 Hz** and about **3 million SD events are recorded yearly**.

Monitoring

For the optimal scientific output of the Observatory, the status of the detector array as well as its measured data have to be monitored.
The basis of the monitoring system is a MySQL database.

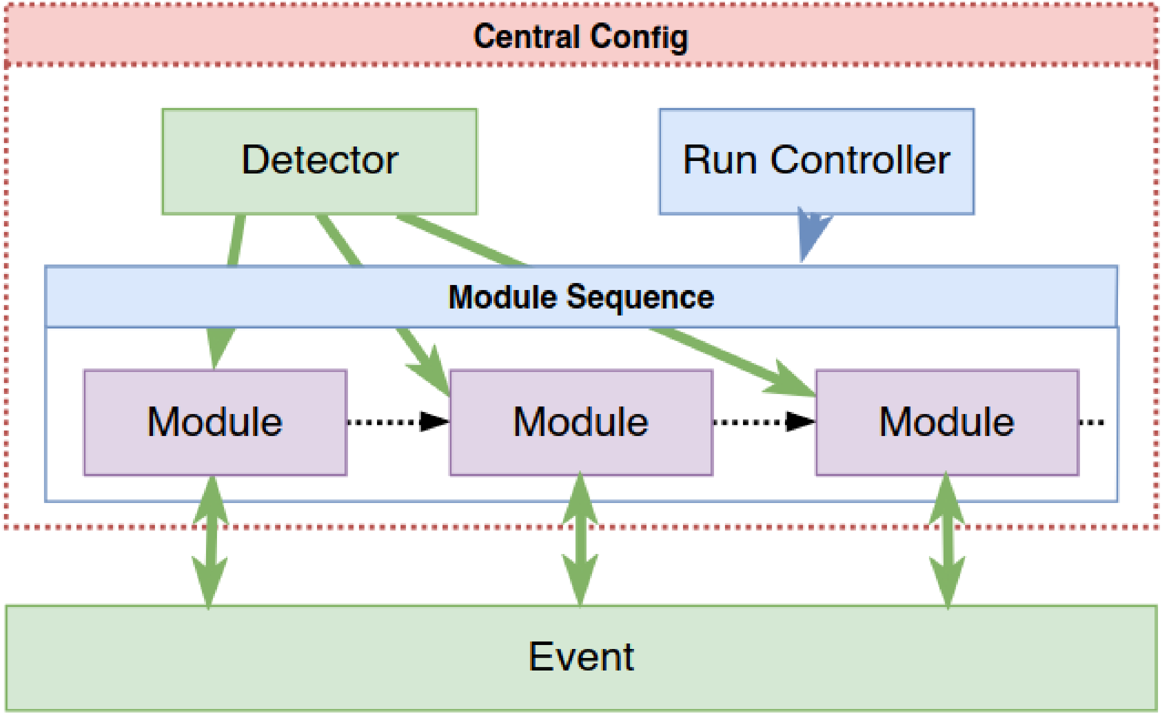


The data acquisition for the FD telescopes is organized by site to insure against disruption of data collection.
The data transport for FD monitoring is organized via a database internal replication mechanism.

Online monitoring server in Malargüe + European mirror in Wuppertal (DE)

Data processing and Offline framework

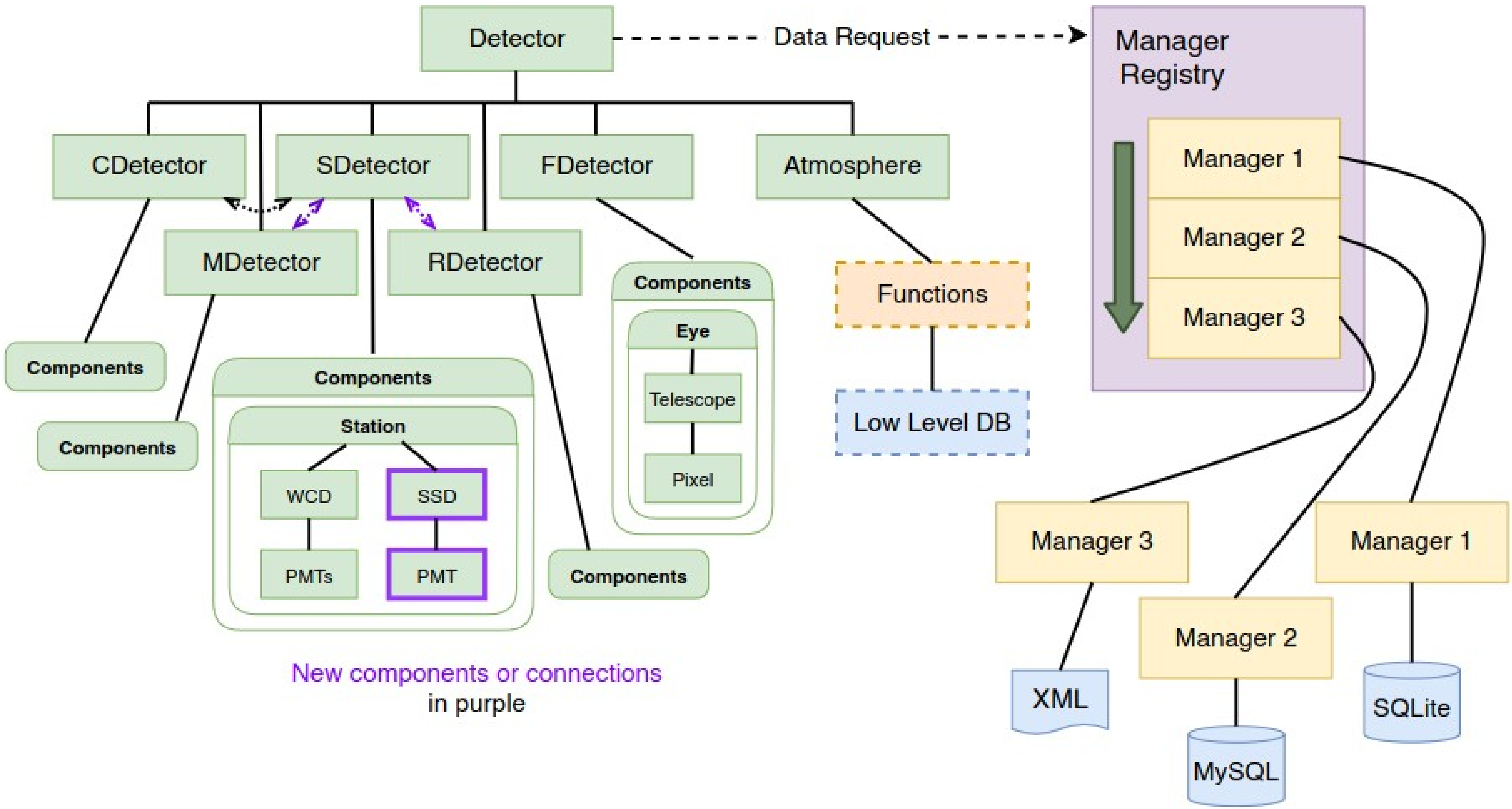
The Offline software of the Pierre Auger Observatory provides both an implementation of simulation and reconstruction algorithms to assure a complete simulation, reconstruction and analysis pipeline.



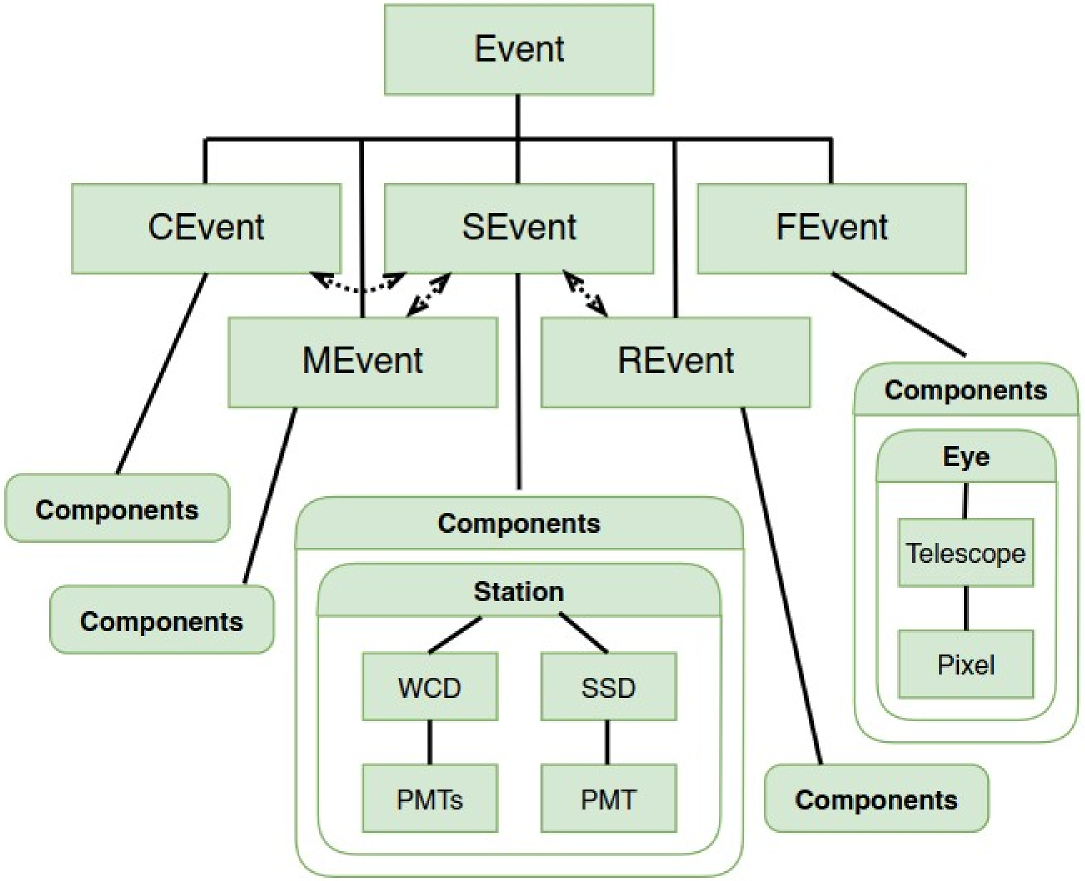

```
<sequenceFile>
  <loop numTimes="unbounded">
    <module> SimulatedShowerReader </module>
    <loop numTimes="10">
      <module> EventGenerator   </module>
      <module> TankSimulator    </module>
      <module> TriggerSimulator </module>
      <module> EventExporter    </module>
    </loop>
  </loop>
</sequenceFile>
```

Simulation Module Sequence

Data processing and Offline framework



Data processing and Offline framework



Data Storage

Primary data mirror: **IN2P3 HEP Computer Center in Lyon.**
The total data volume required to store all data produced at the Pierre Auger Observatory is of the **order of 50 TB.**

Data are divided in 3 main categories:
① Raw data;
② Monitoring;
③ Offline.

→ Monitoring data account for ~5 TB.
→ The Offline data, the high-level data, acciunt for the tiniest fraction of disk space since typical file sizes are of the order of 1 MB.

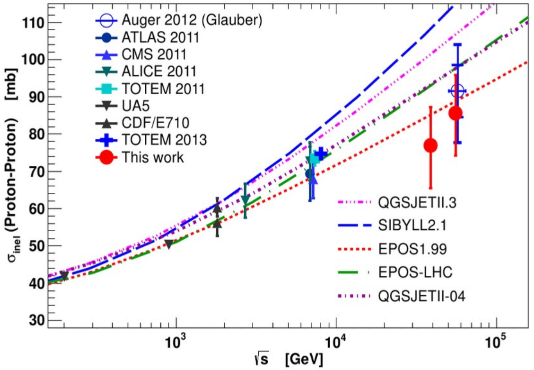
CNAF is one of the secondary data mirrors.

Monte Carlo Simulations

Simulation of Extensive Air Shower produced by the interaction of primary cosmic rays with the atmosphere.

CORSIKA (**CO**smic **R**ay **SI**mulations for **KA**scade) is the tool used to simulate showers initiated by protons, light nuclei up to iron, photons, neutrinos, and many other particles. The particles are tracked through the atmosphere until they undergo reactions with the air nuclei or, in the case of instable secondaries, decay.

The **hadronic interactions at high energies** may be described by several models:
EPOS-LHC;
QSJet-II.04;
Sibyll2.3d.



Hadronic interactions at lower energies are described by FLUKA-INFN.

CoREAS (**Co**rsika-based **R**adio **E**mission from **A**ir **S**howers) can be used for radio emission and it can be linked by CORSIKA.

VO Auger

The VO auger was created in 2006 by the Czech group in cooperation with the **CESNET Metacentrum**.

It provides and maintains the central resources such as the registration portal and the VOMS server.

As of May 2023, the VO auger has 21 valid users.

The VO auger comprises several grid sites:

Brazil: EGI.CBPF.br

Czech Republic: EGI.PRAGUE.cz; EGI.CESNET.cz

France: EGI.IN2P3-CC.fr; EGI.M3PEC.fr; EGI.GRIF.fr; DIRAC.LSST.fr

Germany: EGI.GRIDKA.de

Italy: EGI.CNAF.it; EGI.CATANIA.it

Mexico: EGI.UNAM.mx

Portugal: EGI.INGRID.pt

Romania: EGI.ROISS.ro

The Netherlands: EGI.NIKHEF.nl; EGI.SARA.nl

DIRAC interware and CVMFS

In 2014 the VO auger adopted the DIRAC (Distributed Infrastructure with Remote Agent Control) interware for the job submission, monitoring, and file catalog management.

The DIRAC server, at https://dirac.france-grilles.fr/DIRAC/, runs on the France Grilles Infrastructure.

The job submission is made via python scripts using the DIRAC-API.

The main software to run simulations is available in the Auger CVMFS repository, whose name is “auger.egi.eu”.

In the past, simulations were produced in local computing farms, now the bulk of the productions is transferred to the grid.

The local computing farms will be free for processing CPU-time demanding jobs that cannot run on the grid mainly due to walltime limitations (ex.: radio simulations).

GRID statistics

Countries — Elapsed time * Number of Processors (months) by VO and Month (TOP 10 VOs)

VO	Sep 2022	Oct 2022	Total	Percent
alice	155,511	140,642	296,152	18.17%
atlas	342,046	331,660	673,706	41.33%
auger	4,026	7,276	11,303	0.69%
belle	19,692	8,835	28,527	1.75%
cms	204,072	192,888	396,960	24.35%
eucliduk.net	307	3,052	3,359	0.21%
gridpp	2,425	1	2,426	0.15%
ilc	3,124	856	3,980	0.24%
lhcb	88,901	119,527	208,428	12.79%
virgo	2,657	2,614	5,271	0.32%
Total	822,760	807,350	1,630,111	
Percent	50.47%	49.53%		

1 - 10 of 10 results ‹ 1 › Number of rows per page 30

Auger production used more than 7000 cores on average during October 2022.

GRID statistics

VO Admin — Elapsed time * Number of Processors (months) by Resource Centre and Month

Resource Centre	Sep 2022	Oct 2022	Total	Percent
FZK-LCG2	25	143	169	1.5%
GRIF	0	40	40	0.35%
IN2P3-CC	46	142	188	1.66%
INFN-T1	1,017	481	1,497	13.24%
NCG-INGRID-PT	0	14	14	0.12%
NIKHEF-ELPROD	208	149	358	3.17%
RO-13-ISS	42	38	80	0.71%
SARA-MATRIX	968	1,268	2,237	19.79%
prague_cesnet_lcg2	832	919	1,751	15.49%
praguelcg2	887	4,082	4,969	43.96%
Total	4,026	7,276	11,303	
Percent	35.62%	64.37%		

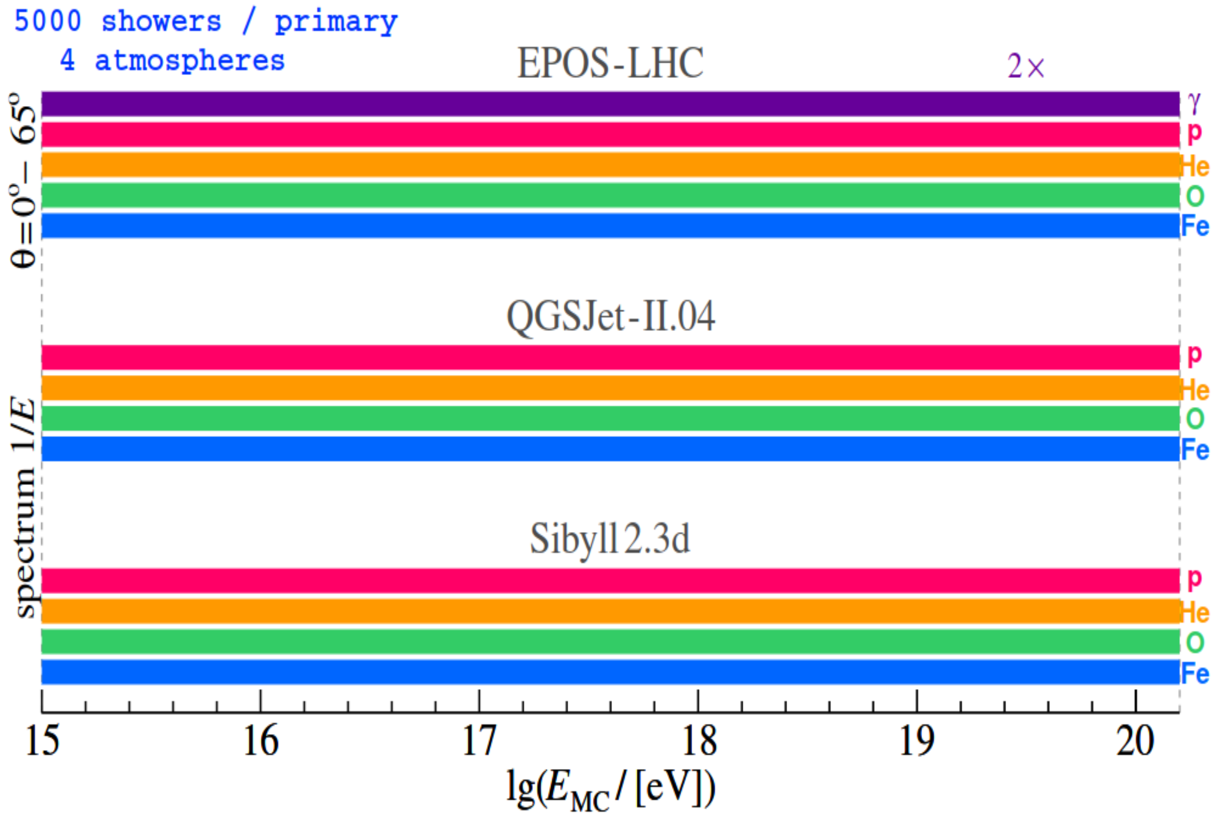
Fig. 2: Resource centers used for 2022 production.

SARA (Tier1), **INFN** and Czech sites CESNET and FZU are the main contributors.

The standard Auger library

Napoli + Praha - Vertical shower library ($\theta < 65°$)

CORSIKA 7.7420 + FLUKA-INFN 2021.2.6



Typical file sizes are of the order of ∼ 1 GB!

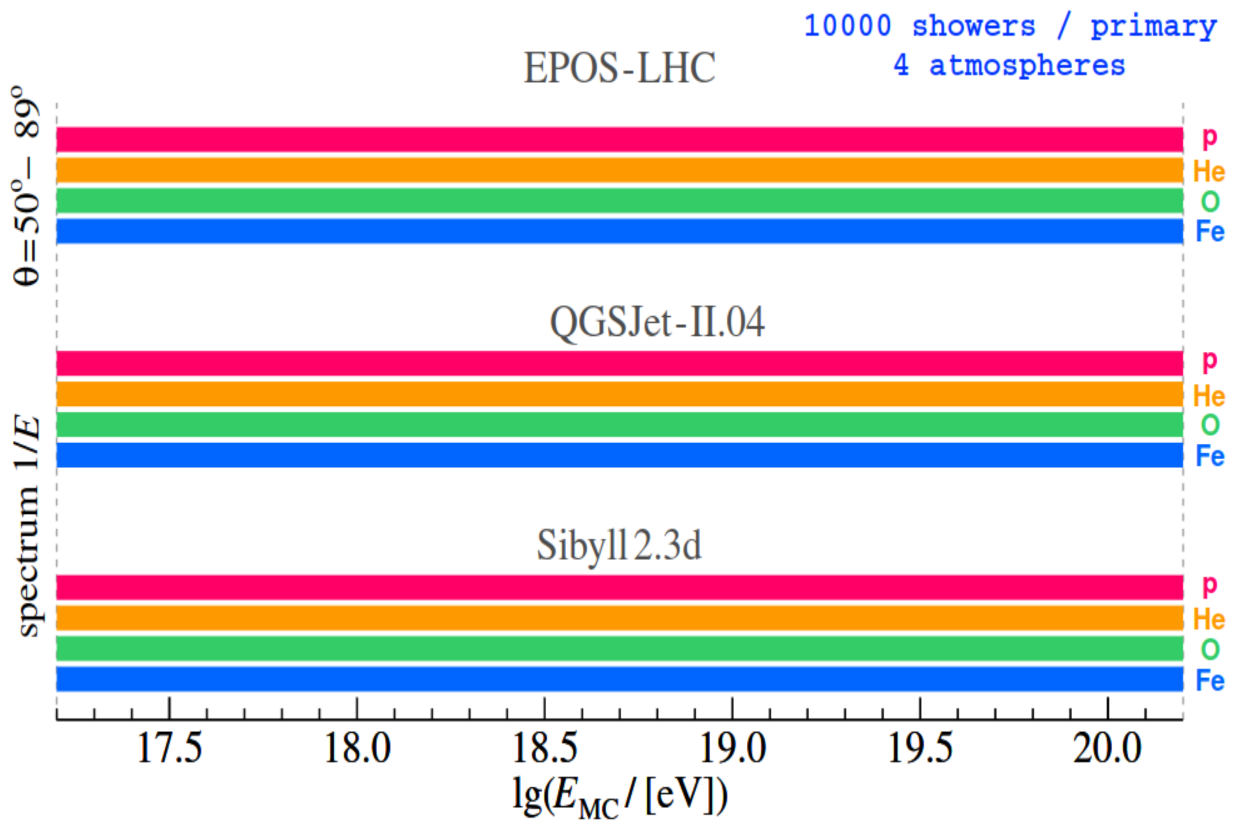
Full photon library is available via iRODS.

Full library is available in the grid.

The standard Auger library

Napoli + Praha - Horizontal shower library $(50^\circ < \theta < 89^\circ)$

CORSIKA 7.7420 + FLUKA-INFN 2021.2.6

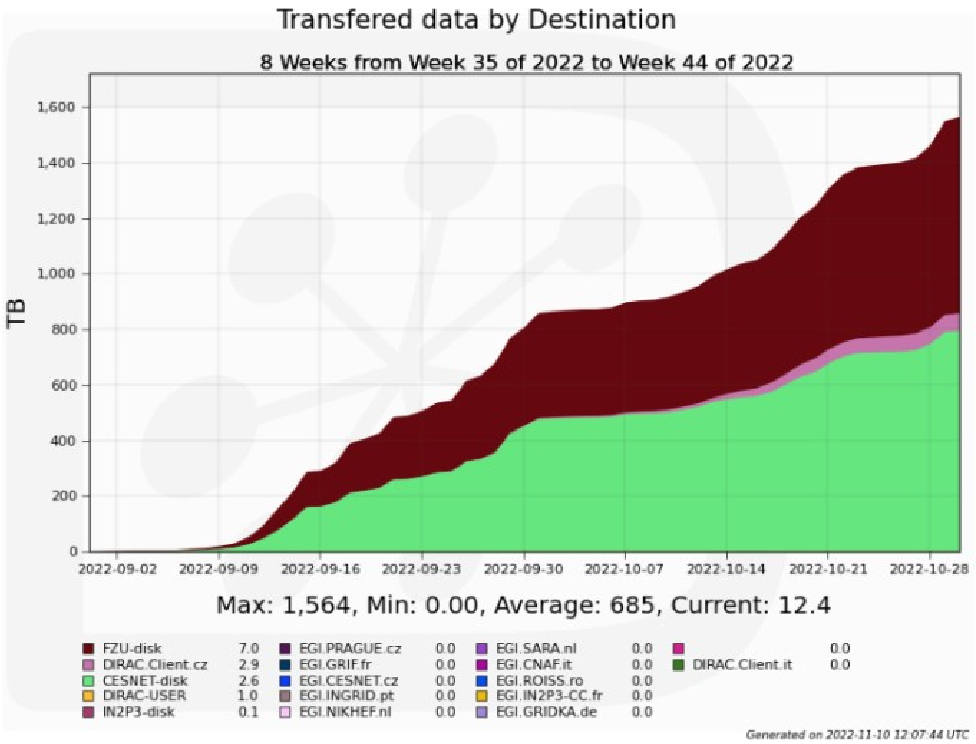


Typical file sizes are of the order of ∼ 1 GB!

Full library is available in the grid.

A small drop in the ocean!!!

Grid storage status



As of November 7th 2022, 6.7 million files were registered in the DIRAC File Catalog, with a **total size of ~ 1 PB**.

The bulk of the production is stored in the Czech CESNET and FZU disks.

```
Storage according to the DIRAC File Catalog (DFC)
  (listing only sites with > 100 Replicas)

        Status from March 13, 2023

   StorageElement Size                      Replicas
=====================================================
  3 CESNET-disk       537,009,738,982,615   3255424
  4 DIRAC-USER          1,965,497,269,317     27882
  5 FZK-disk               12,167,699,408       347
  6 FZU-disk          502,373,235,999,187   3555335
  7 FZU-proddisk        6,206,339,939,430     90058
 10 NIKHEF-disk         2,553,953,749,103     18580
 11 ROISS-disk         14,469,908,682,299     46739
 13 UNAM-disk              13,806,536,906      5341
    Total           1,064,611,289,502,435   6999894
------------------------------------------------------
```

Conclusions

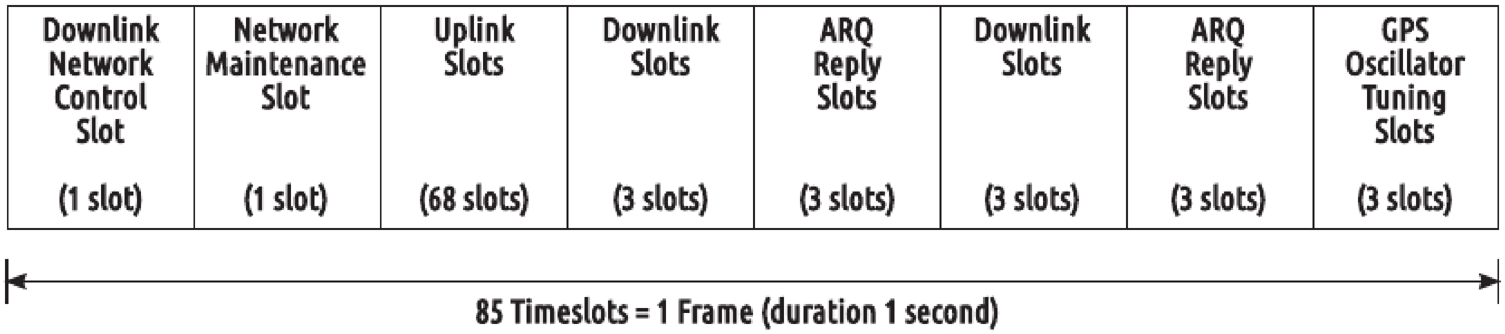
New simulations and new challenges await us!!!

Backup

Data communications system

Communications with the individual WCDs is bidirectional, so that the full trigger information can be requested from the WCD by the Central Data Acquisition System (CDAS) on demand, and software updates and reset commands can be sent to the individual detectors.

Transmissions to and from the stations are synchronized by GPS timing so that each station is assigned a particular time slot during which it is available to send and receive data. This time division multiple access (TDMA) scheme provides a contention free communication environment within the array.



CDAS

Since the beginning of 2013, the CDAS runs on a virtual machine using resources within a private Cloud installation.

The Cloud is composed of 6 servers, summing up 42 CPUs and 112 GB of RAM. CPUs are 2 GHz or faster. This scheme allows the live migration and automatic failover of virtual machines, to minimize the impact of critical failures. The disk storage system is comprised of redundant disk arrays installed in each server plus some standalone devices, making a total storage space near 8.5 TB, using a shared, replicated and distributed scheme. A Network Time Protocol (NTP) GPS clock is used to synchronize the system times.

We have adopted the GNU/Linux Debian latest stable distribution as the operating system, currently v6.0r4. Only a very small fraction of the CPU power is used by the CDAS application processes. Most of the software was developed in C or C++.

The whole system is installed in a Computer Center at the Observatory campus, with controlled temperature and redundant uninterruptible power supply.