# SPHERE-3: tackling the problem of primary cosmic ray mass composition with a new approach

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# Problem

Particle astrophysics: mass composition of the primary cosmic rays (PCR), namely, the primary nuclei in $10^{15}$ eV — $10^{18}$ PeV range.
Knowledge of the partial energy spectra of the primary nuclei can help to understand the mechanisms of particle acceleration and propagation in the Galaxy.

# Method

Traditional method of the PCR study of such energies is the detection of Extensive Air Showers (EAS).

EAS Cherenkov light (CL) benefits:

1) Cherenkov photons are much more numerous than the shower particles,
2) they roughly follow the direction of the parent particles,
3) optical photon absorption length amounts to 10-20 km.

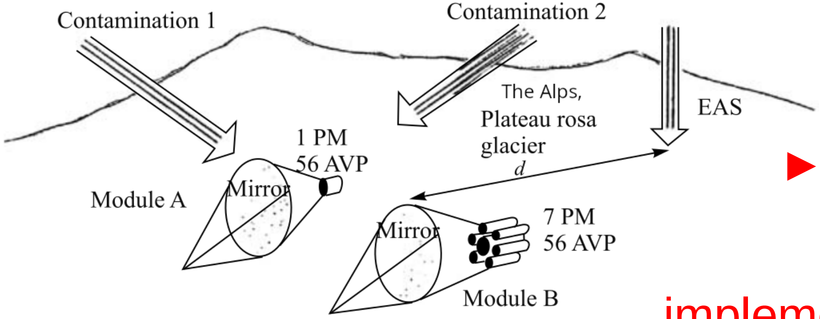
EAS CL drawback is the limited duty cycle: clear moonless nights only.

EAS CL may be detected

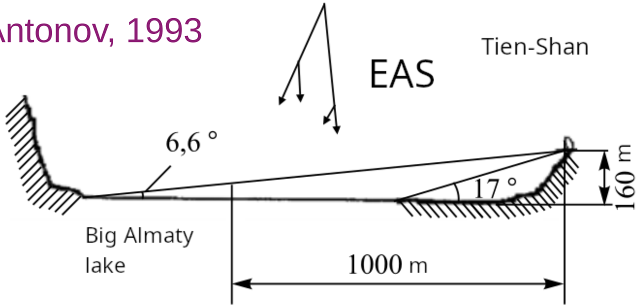
1) by the ground based detector arrays
2) by the elevated detectors ← our way

# Alexander Chudakov’s idea (1972)

Castagnoli & Navarra, 1983

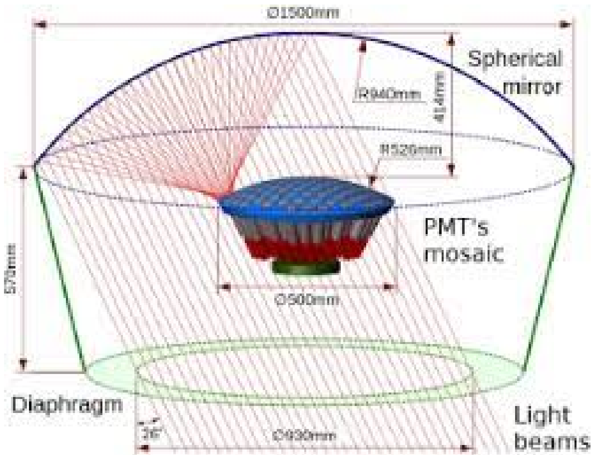



Antonov, 1993

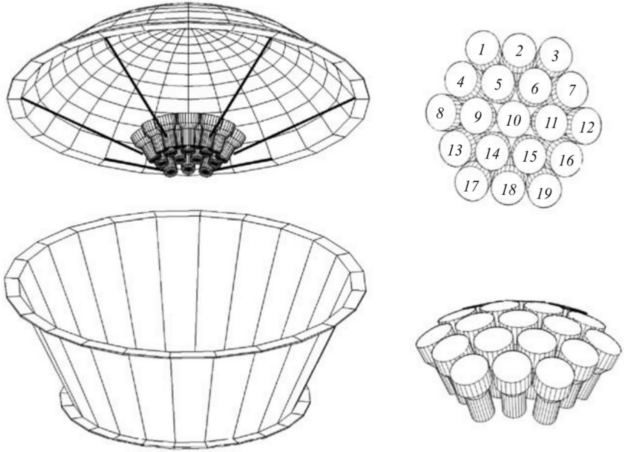



implementations

SPHERE-2




SPHERE-1




The second way is based on Alexander Chudakov’s idea to register EAS CL reflected from the snowed surface with an elevated telescope.

SPHERE-1 and SPHERE-2 were balloon-borne telescopes

# SPHERE Project

Cosmic rays $E_0$ > 3 PeV.

Detection of reflected EAS CL

**Balloon telescope SPHERE-2**:

Baikal Lake, 2008-2013.

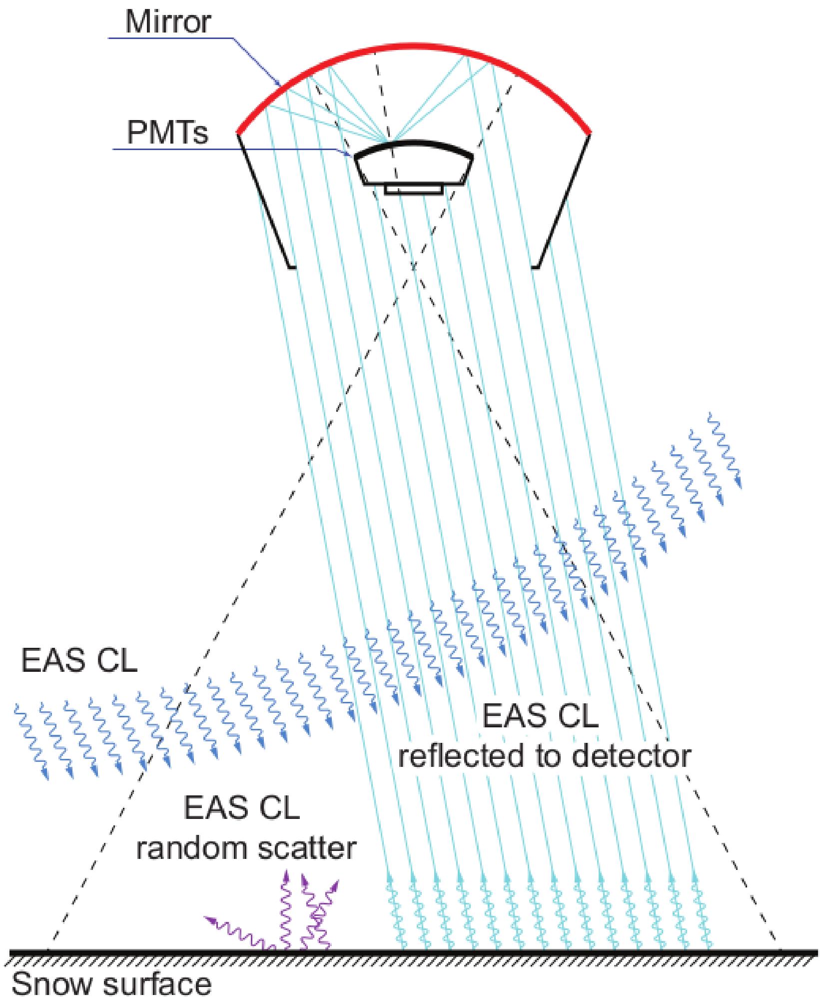
Detector altitude: 300-900 m

Mirror diameter - 1.5 m

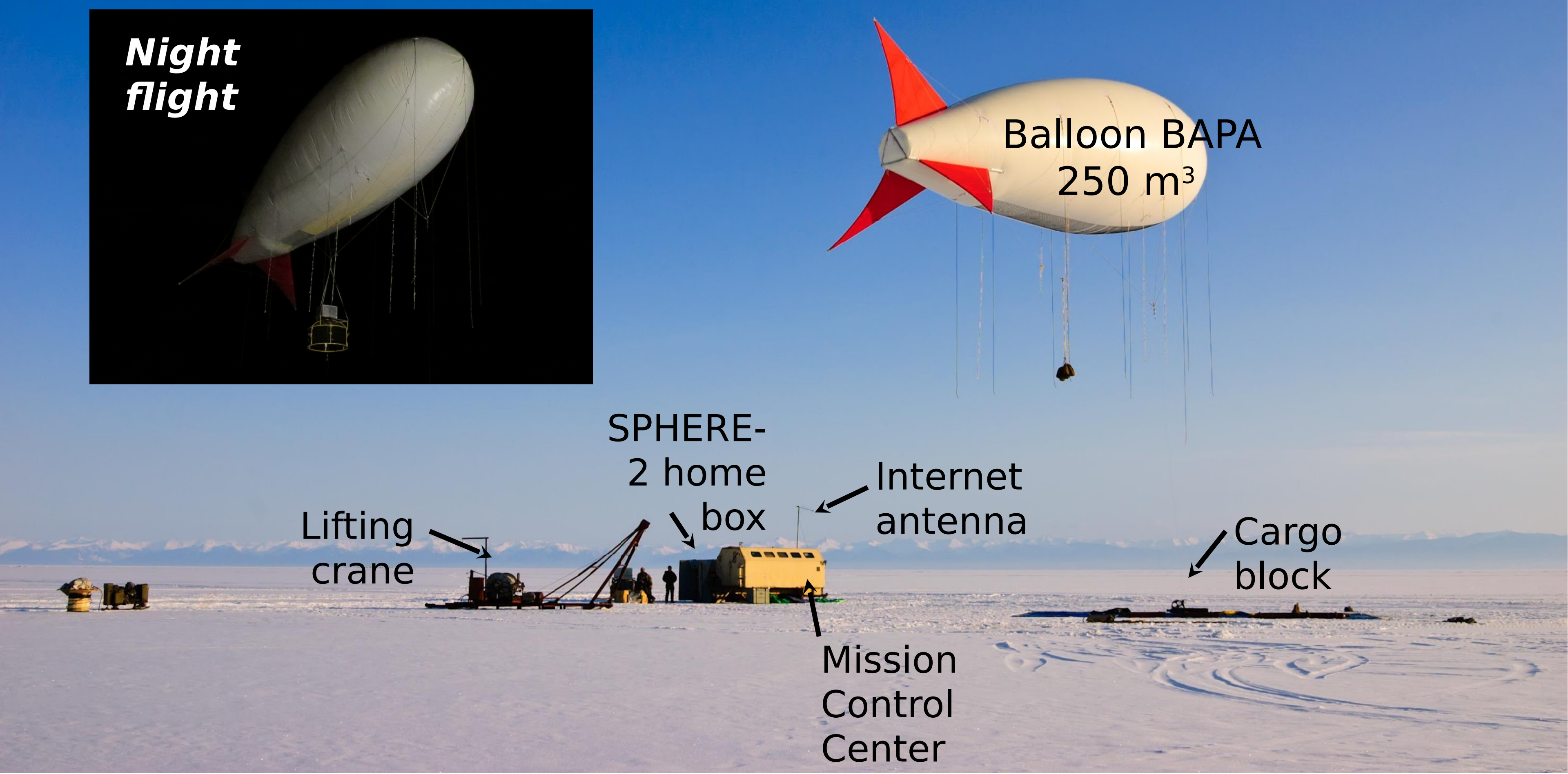
Retina 109 FEU-84-3

Time digitation 12.5 ns

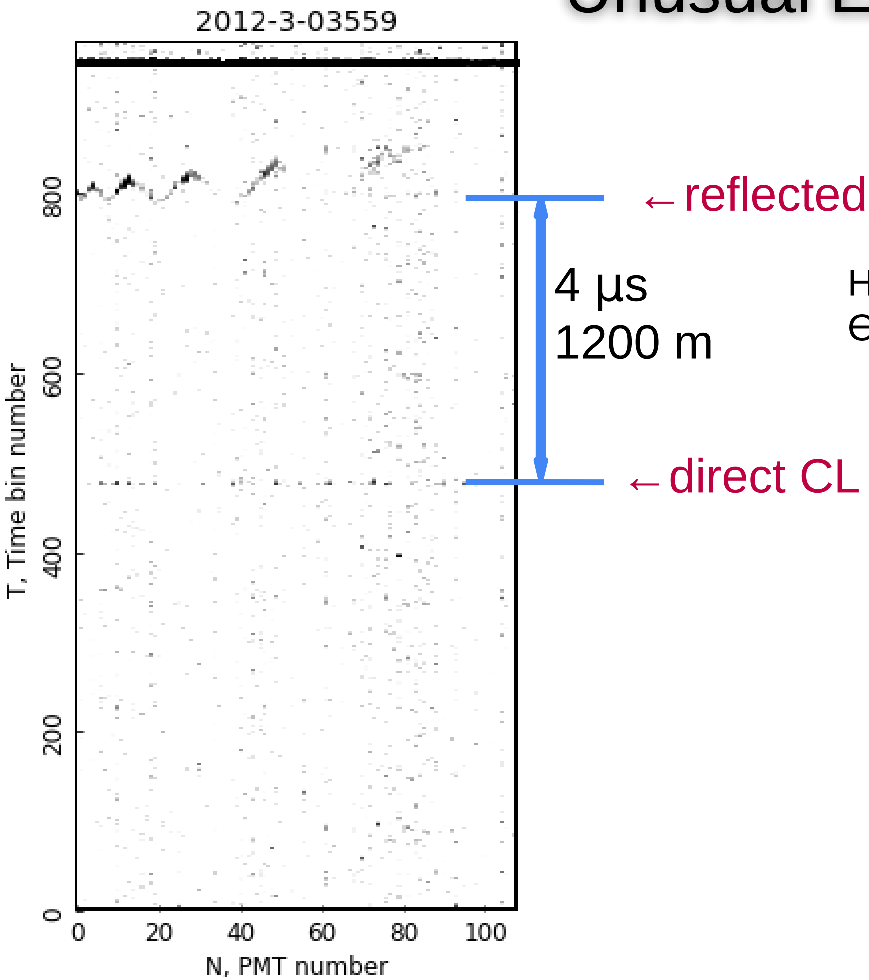
2011-2013: EAS events: 1040



# SPHERE-2 launch pad



# Unusual EAS event




H = 603 m
Θ = 17°

During the SPHERE-2 data analysis an unusual event was discovered with usual reflected Cherenkov image preceded by an unusual one identified as direct image.

# New SPHERE-3 Project

To be designed with the main goal to fight the uncertainty of the PCR mass composition in 1-100 PeV energy range

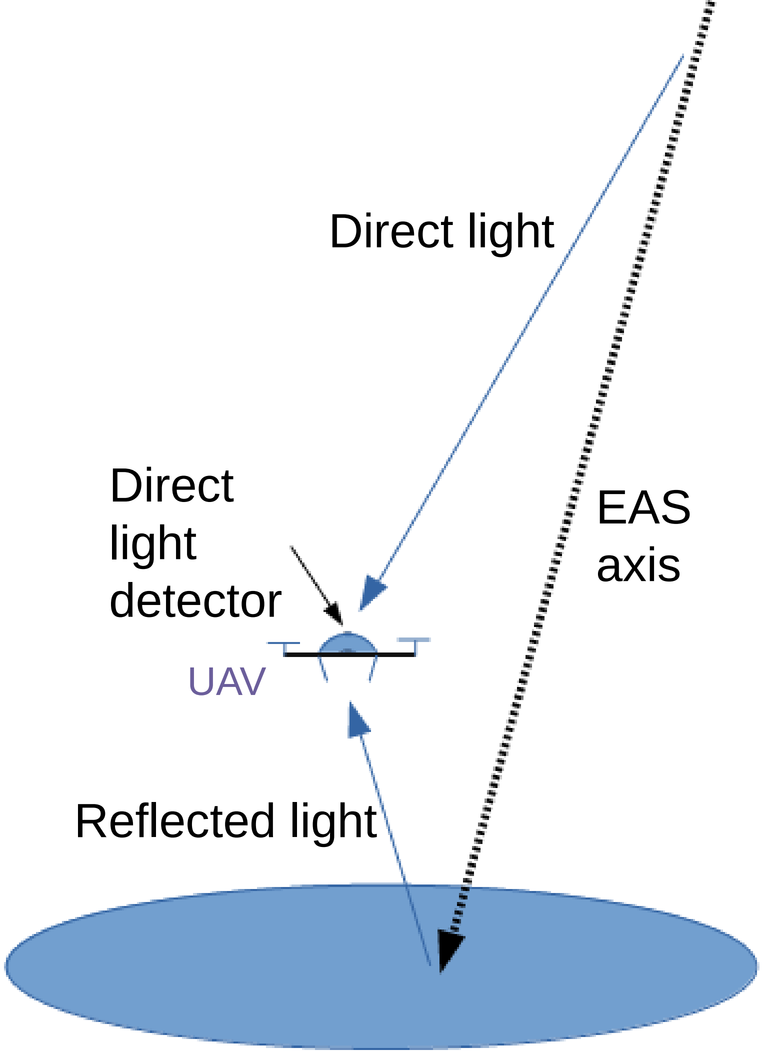
Airmobile detector

An unmanned aerial vehicle as a carrier

Large mirror up to 2.5 m in diameter
Light sensors: SiPM > 2000

**Detection**:

Direct Cherenkov light
Reflected Cherenkov light



# Preliminary version of the SPHERE-3 optical scheme

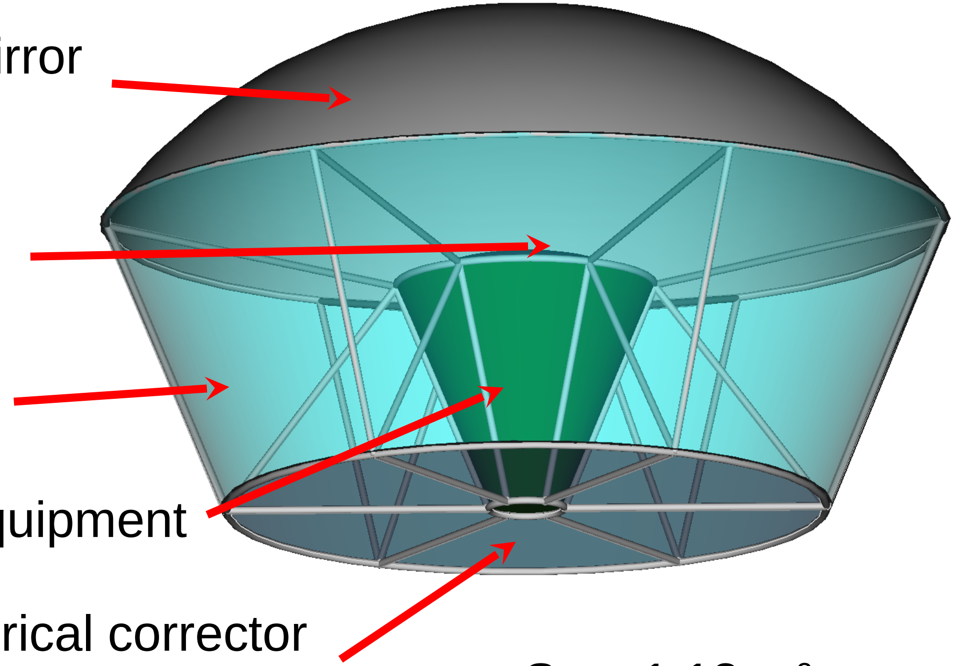
Aspherical mirror
⌀ 2160 mm

SIPM mosaic
⌀ 550 mm

Blend

Measuring equipment

Acrylic aspherical corrector
⌀ 1344 mm

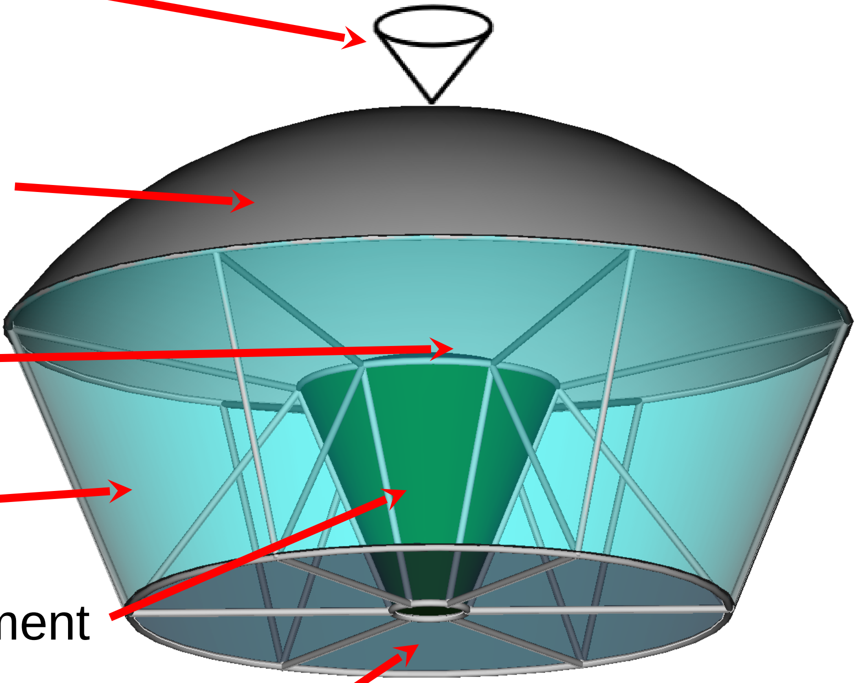


$S_{eff} = 1.18\ m^2$

to be optimized:

- optical scheme
- mosaic scheme
- electronics
- trigger algorithm
- off-line processing algorithms

# Preliminary version of the SPHERE-3 optical scheme



Direct light collector

Aspherical mirror
⌀ 2160 mm

SIPM mosaic
⌀ 550 mm

Blend

Measuring equipment

Acrylic aspherical corrector
⌀ 1344 mm

$S_{eff} = 1.18\ m^2$

to be optimized:

- optical scheme
- mosaic scheme
- electronics
- trigger algorithm
- off-line processing algorithms

# Primary mass estimation with reflected CL

With the SPHERE-2 telescope [*] it is possible to distinguish between EAS coming from different primary nuclei. The shape of the CL lateral distribution function is used as a measure of the primary mass.

SPHERE-2 image and its approximation

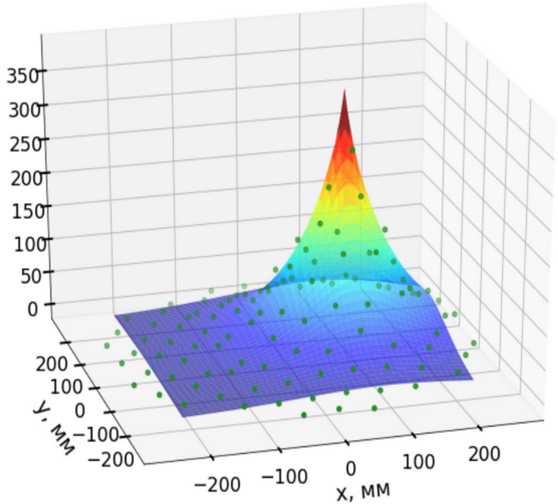
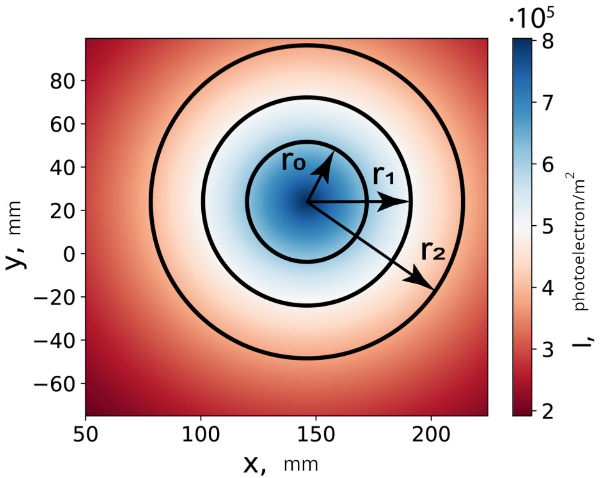



Image integration




Criterion:

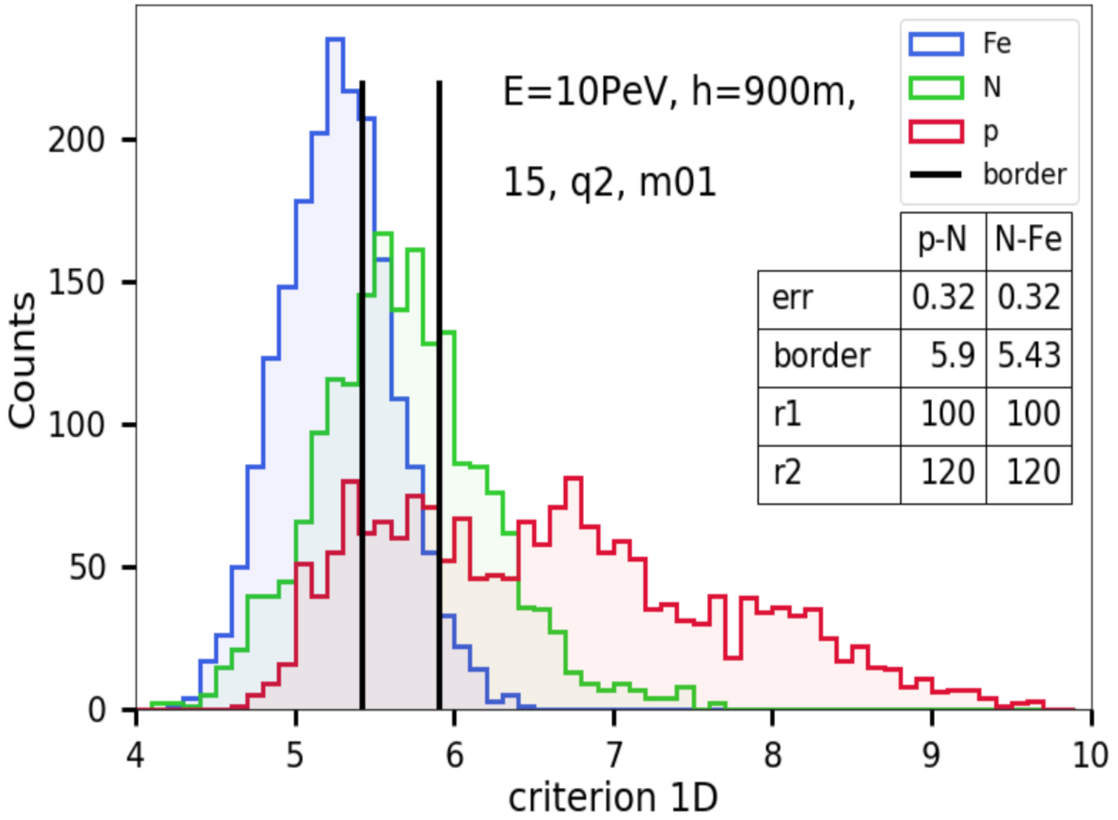
$$cri_1 = \frac{\int_0^{r1} F_{LDF} dr}{\int_{r1}^{r2} F_{LDF} dr}$$

* -- V. Latypova, Memoirs of the Faculty of Physics 2023, No.m14513, to be published

# Primary mass estimation with reflected CL

SPHERE-2: it is not possible to make accurate primary mass estimates on event-by-event basis [*] but one can assess the average mass dependence on $E_0$.

We hope to improve the mass sensitivity of the telescope by
1) the optimization of its design in this respect,
2) simultaneous use of both direct and and reflected CL characteristics.




| | p-N | N-Fe |
|---|---|---|
| err | 0.32 | 0.32 |
| border | 5.9 | 5.43 |
| r1 | 100 | 100 |
| r2 | 120 | 120 |

# SPHERE-3 simulations

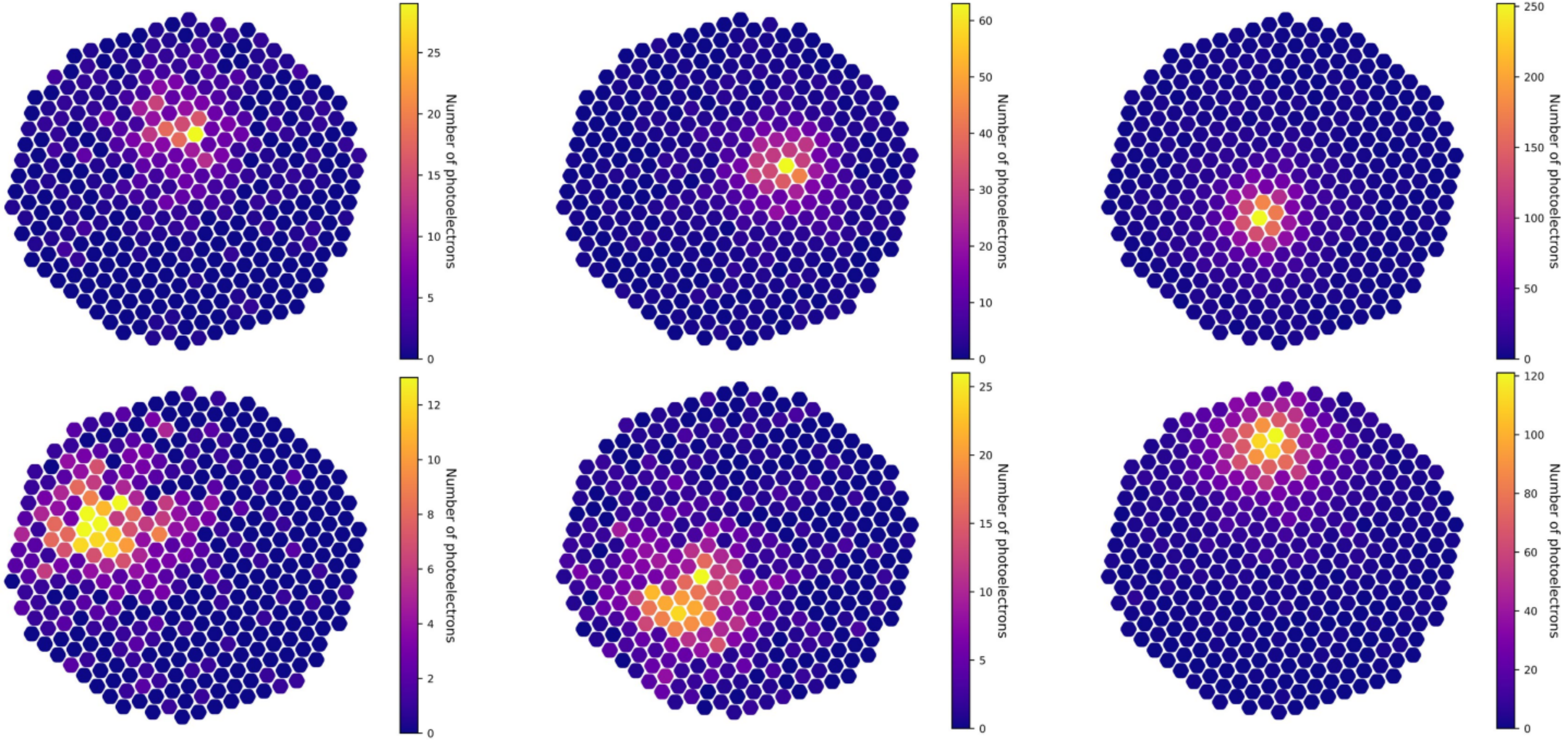
To develop the method we make simulations of CL from EAS at different levels with CORSIKA code.

For the ground level (lake Baikal snowed ice) it is important to know the spacial-temporal distribution of CL in order to estimate the primary parameters (i.e. the primary energy, direction and mass).

For the flight altitudes (0.5, 1.0 and 2.0 km) the CL spacial-angular distribution is calculated to estimate the primary direction and mass.

Joint detection of the reflected and direct Cherenkov images (~30% of all events) will probably reduce the uncertainty of the primary mass estimates.

# Artificial images of reflected EAS Cherenkov light

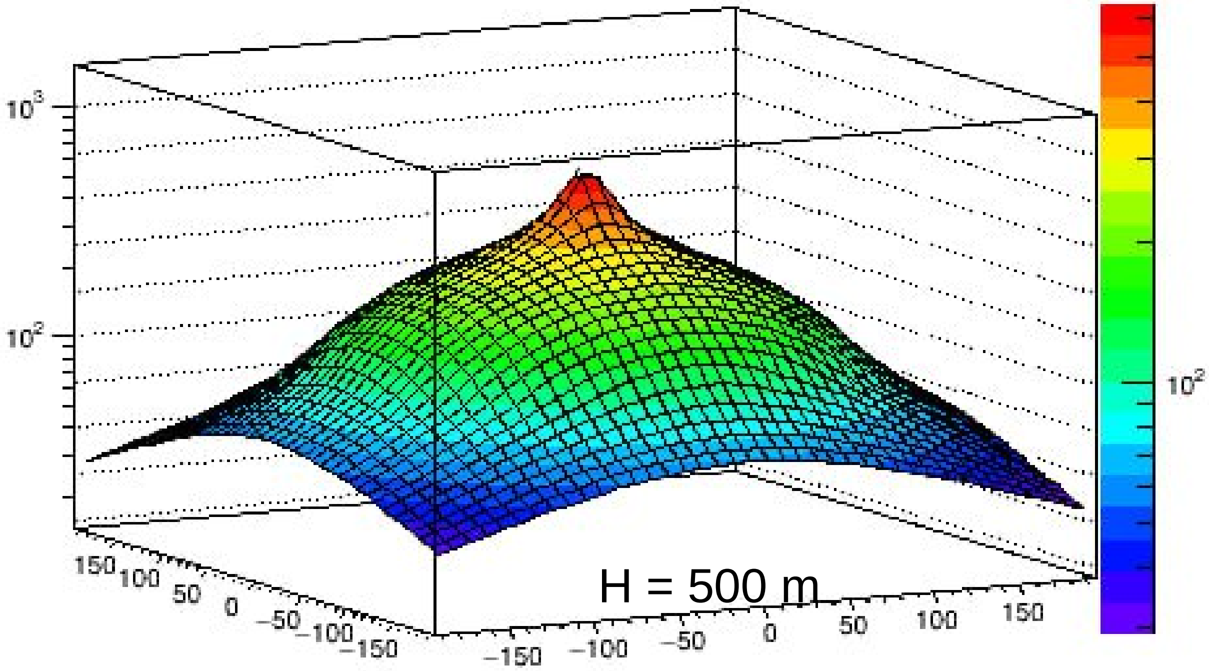



5 PeV, p

10 PeV, p

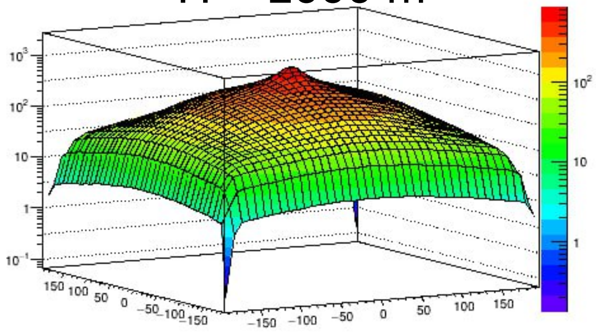
30 PeV, p

# Direct Cherenkov light:
# integral over the upper detector field of view = lateral distribution

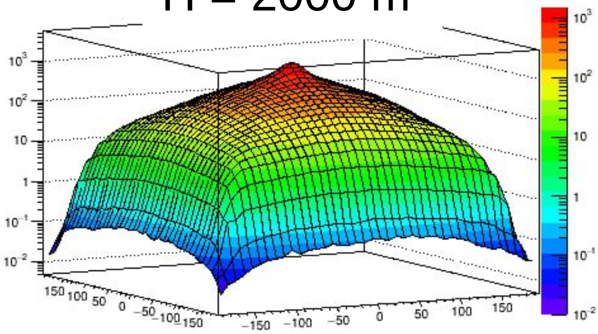



H = 500 m

H = 1000 m



H = 2000 m



*Photoelectrons / S = 1 dm²*

**EAS**: Proton 1 PeV, ϴ=15°

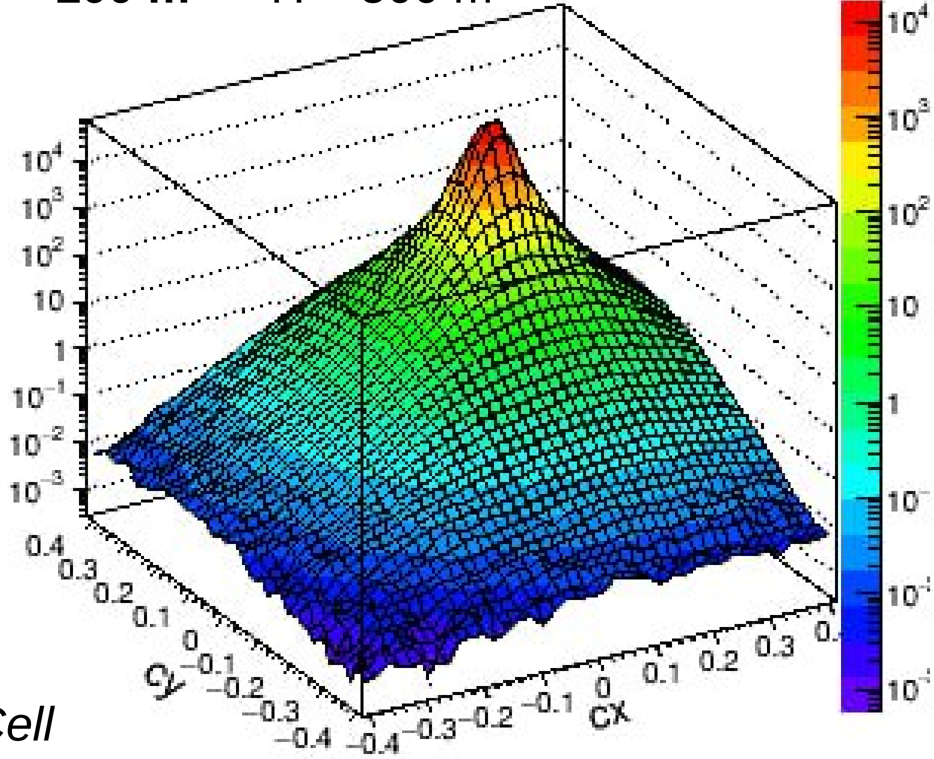
# Direct Cherenkov light: Angular distribution

**Detector**:
View: 50 X 50°
Cell: 1° x 1°
S = 1 dm²
R = 100 m

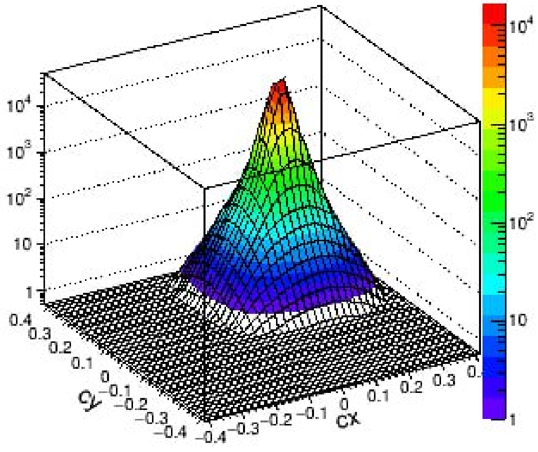
**EAS**:
Proton 1 PeV,
ϴ=15°

*Ph.el. / 1 dm² / Cell*

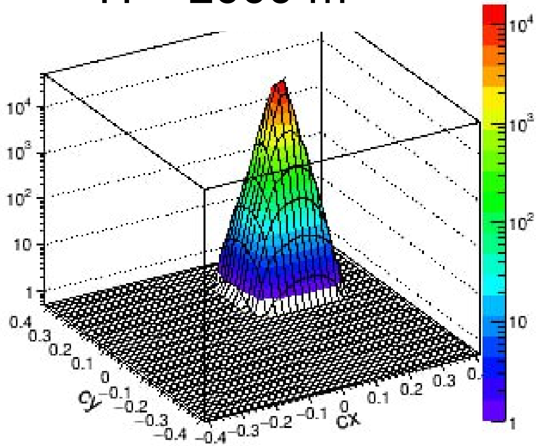
**R = 100 m**     H = 500 m



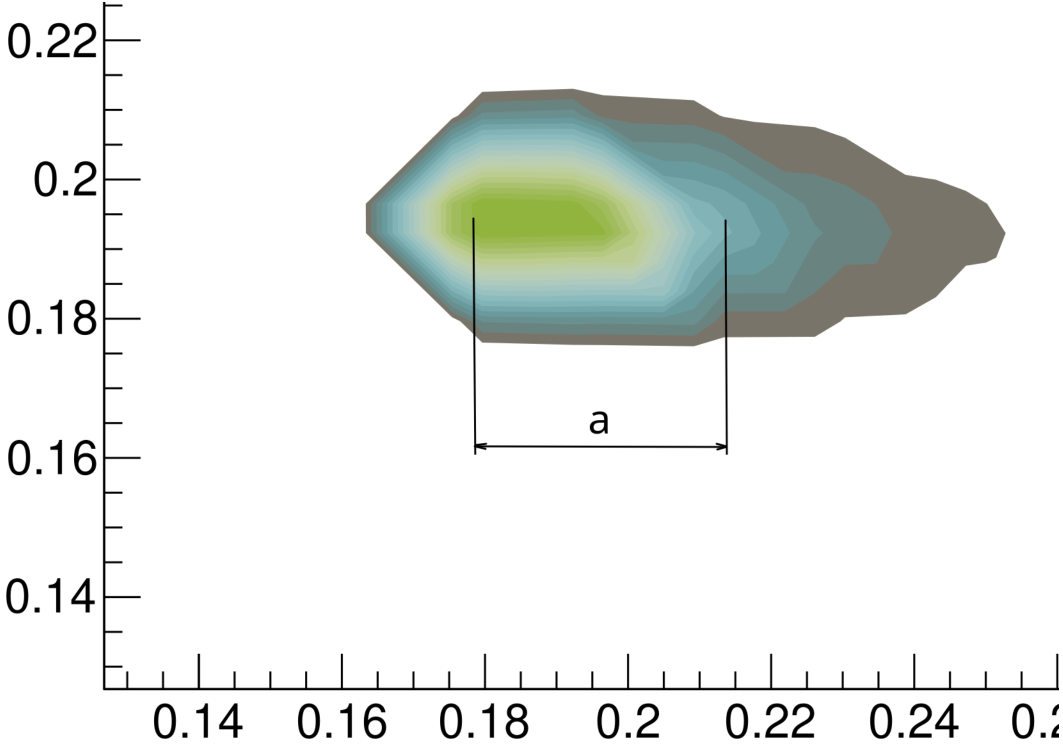

H = 1000 m




H = 2000 m



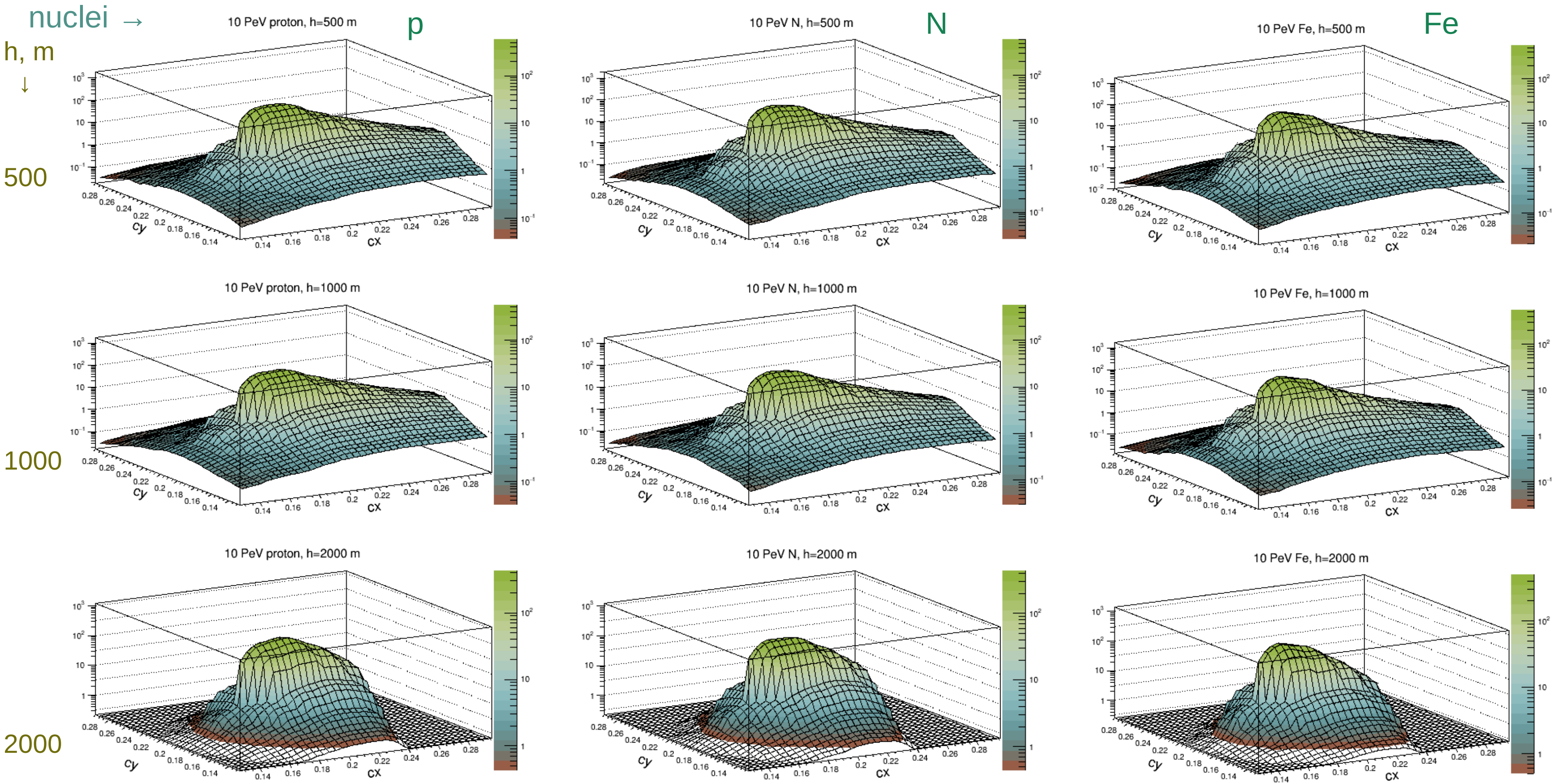
# Primary mass separation with the direct CL



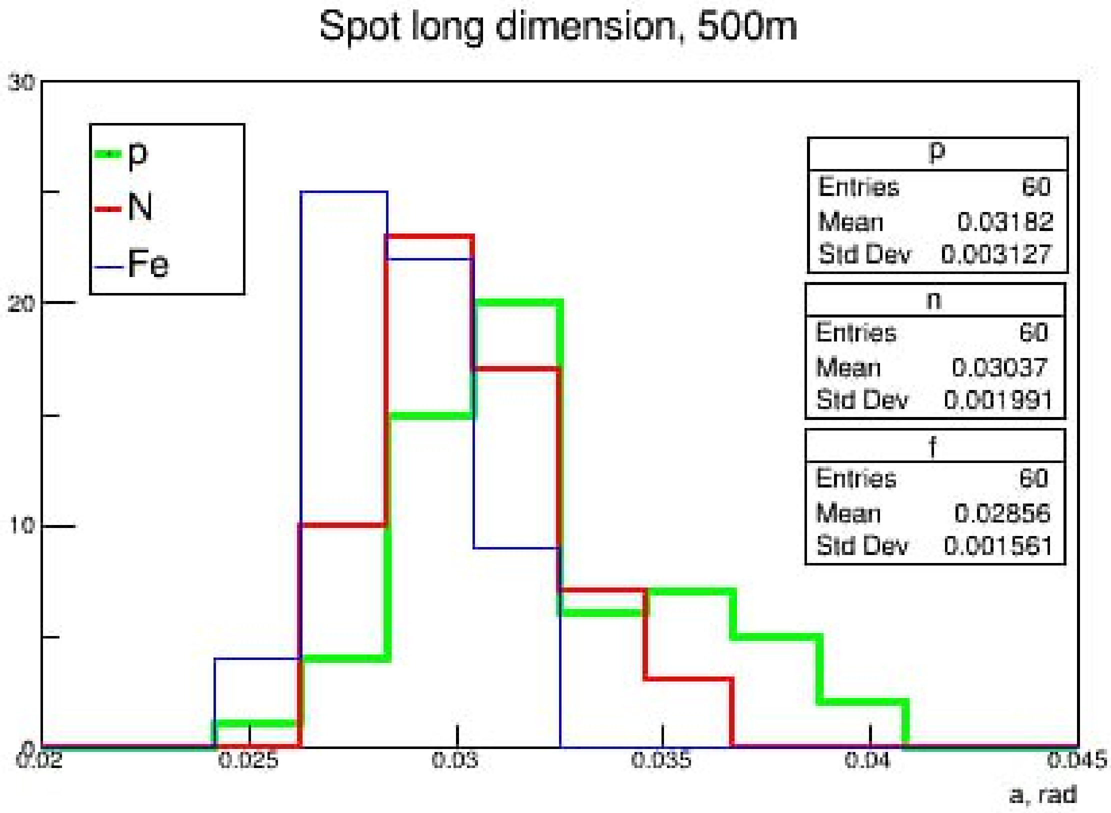

Primary mass separation with the direct CL image using one simple parameter of the spot — long dimension (widely used in Cherenkov γ-ray astronomy).

Certainly, we can find some other parameters which are more sensitive to the primary mass.

# Direct CL images of 10 PeV EAS



# Direct CL angular distribution: long spot size **a** is sensitive to the primary nucleus mass




$E_0$=10 PeV, R=95 m, h=500 m

Classification with **a** parameter

Misclassification probabilities:

p-N pair:

P{p → N}=0.35, P{N → p}=0.40;

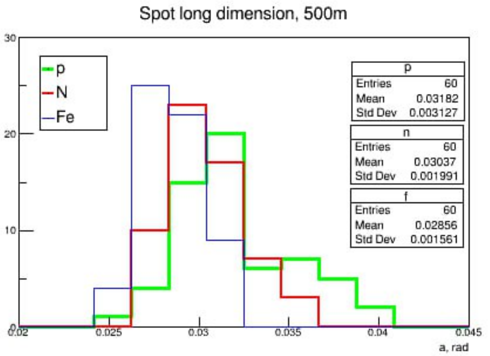
N-Fe pair:

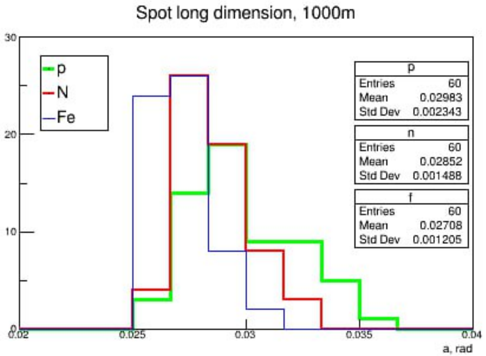
P{N → Fe}=0.30, P{Fe → N}=0.35.

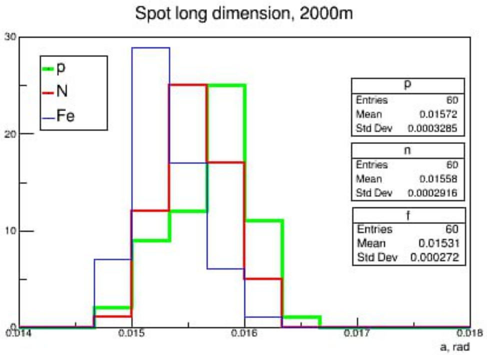
Classification errors resemble these in the reflected CL but the latter were obtained with the optimized criterial paramer while here we use no optimization.

# Direct CL angular distribution: long spot size **a** is sensitive to the primary nucleus mass

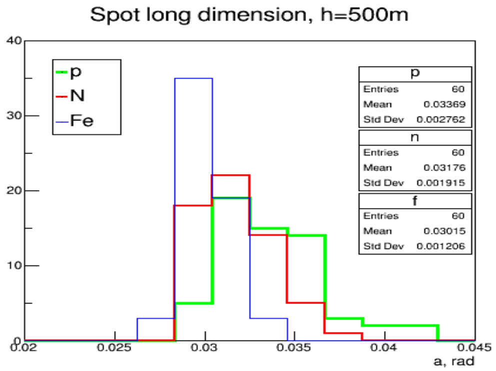
## $E_0$=10 PeV, R=95 m

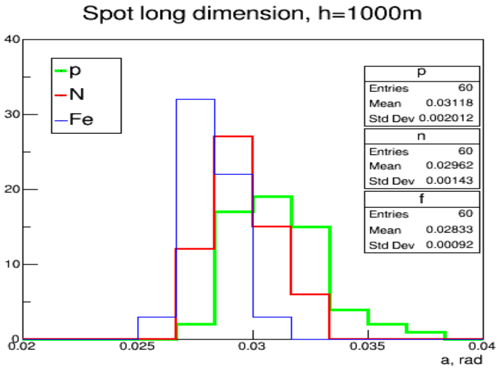


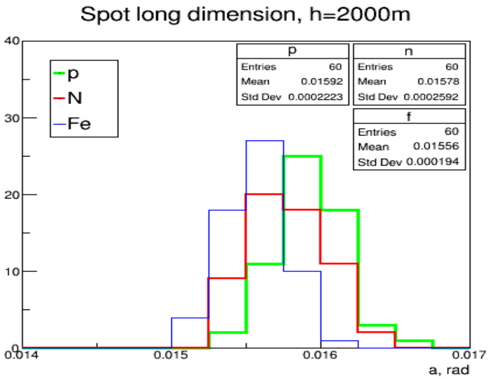




## $E_0$=30 PeV, R=95 m



# Conclusions

1. The main goal of the current stage of our work is to find the optimal design of the new telescope with respect to the primary mass resolution.
2. We have already developed a procedure for such optimization of the traditional part of the SPHERE telescope acquiring the reflected CL.
3. Now that we have perceived the possibility to detect also the direct CL (= to ensure the EAS detection at two levels) we are going to extend the optimization to the upper part of the telescope.
4. Direct CL of EAS definitely shows sensitivity toward the primary mass.
5. Combined with the sensitivity provided by the reflected CL (e.g., the reflected CL image steepness parameter) it can substantially reduce the uncertainty of the individual shower primary mass estimate.

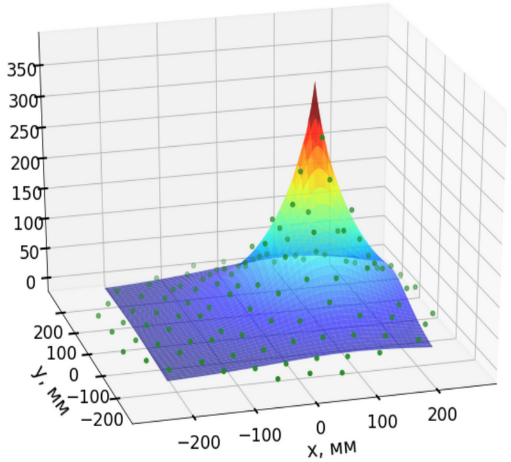
# Thanks!

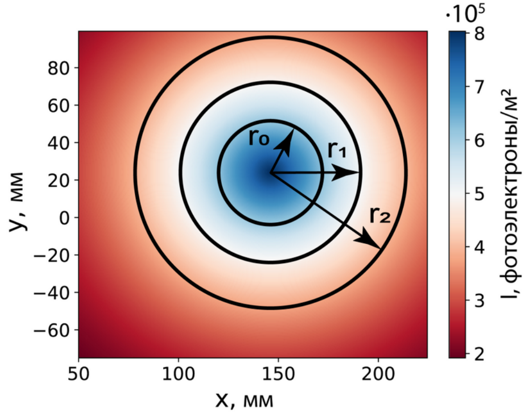
The research is carried out at the expense of a grant from the Russian Science Foundation No 23-72-00006, https://rscf.ru/project/23-72-00006/

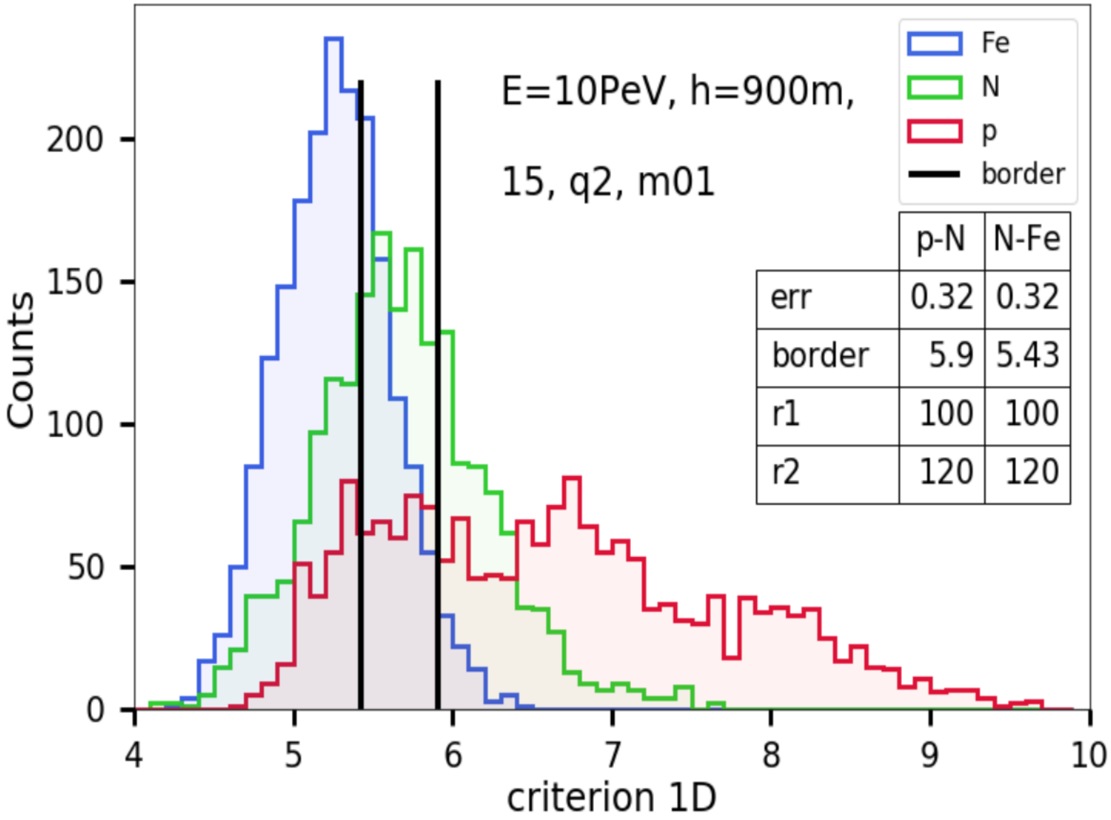
The research is carried out using the equipment of the shared research facilities of HPC computing resources at Lomonosov Moscow State University

**e-mail: v_i_galkin@mail.ru**

# Reflected CL: EAS separation by primary mass using the steepness of the lateral distribution of the image



# Reflected and Direct Cherenkov light calculations

1. Primary: p, He, N, Fe
2. Energy: 1, 3, 10, 30, 100 PeV
3. Zenith angles: 10°, 15°, 20°
4. Hadron interaction models:
   QGSJET01, QGSJETII-04
5. Atmosphere: 3 models
6. Detector altitudes: 500m, 1000m, 2000m

Calculations are performed on the Lomonosov-2 supercomputer cluster of the Moscow State University.

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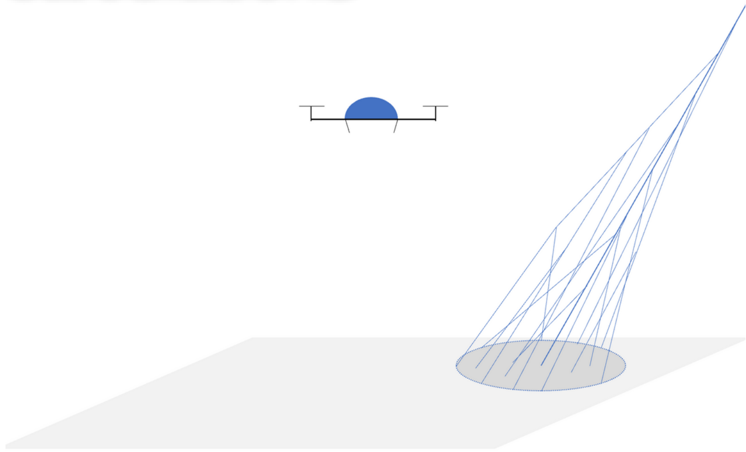

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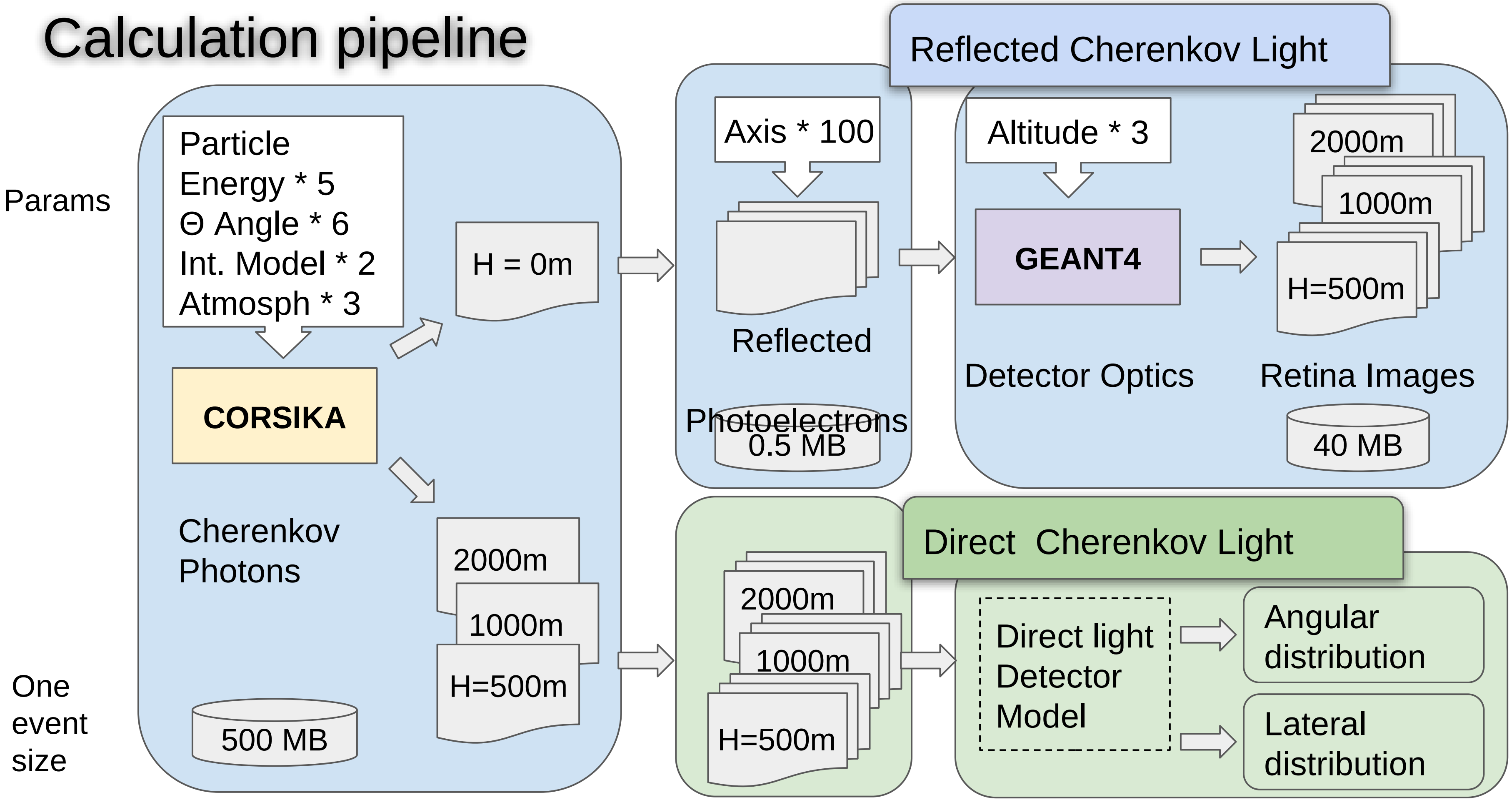
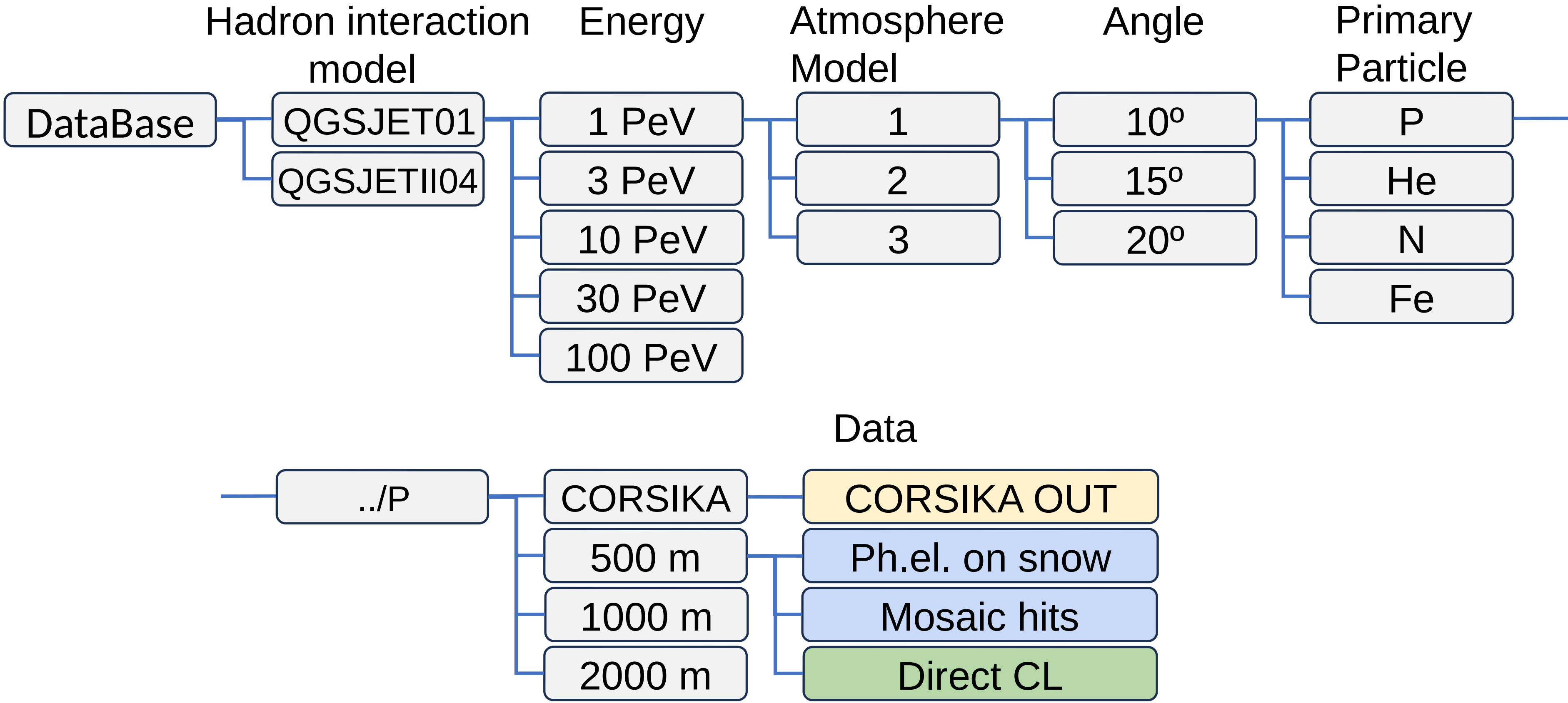
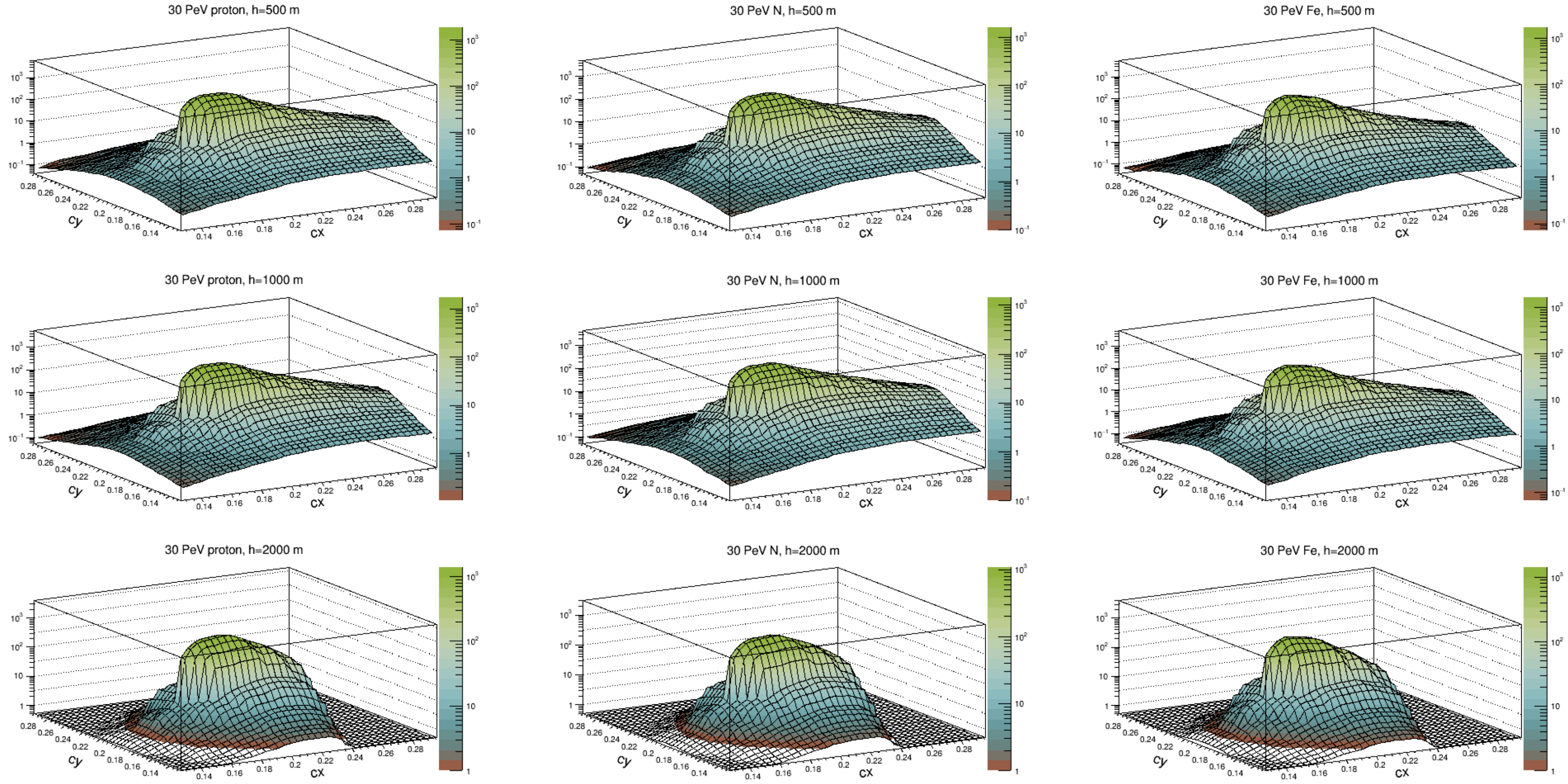
# Calculation pipeline



# Database structure



# Direct CL images of 30 PeV EAS



# Direct Cherenkov light:  Pulses on detector level

**Detector**:

H = 500 m

View angle 50° X 50°

S = 1 $dm^2$

dt = 2 ns

No electronics

**EAS**:

Proton 1 PeV, ϴ=15°