INSTITUTO DE FÍSICA GLEB WATAGHIN

UNIVERSIDADE DE SÃO PAULO
Instituto de Física de São Carlos

Extensive air showers

simulation, analysis, and more

Luan Bonneau Arbeletche

luan.arbeletche@gmail.com

High-energy astrophysics in the multi-messenger era - Erlangen - May 2023

About me

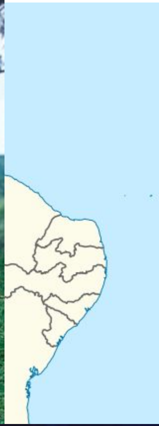
Pelotas, Rio Grande do Sul, Brazil

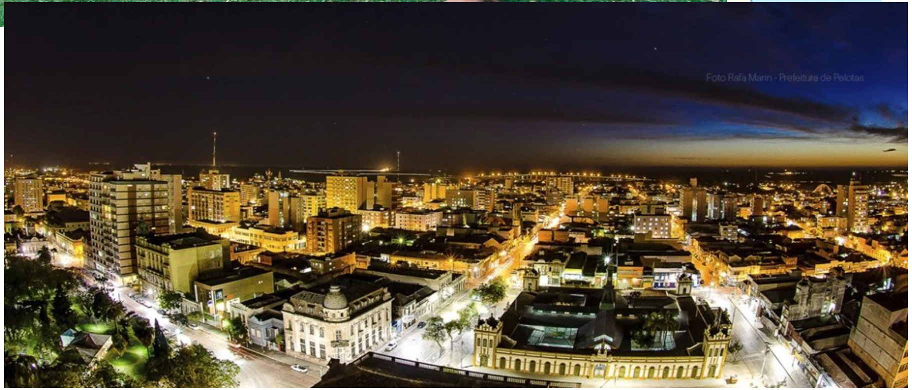
About me

Pelotas, Rio Grande do Sul, Brazil

About me

Pelotas, Rio Grande do Sul, Brazil

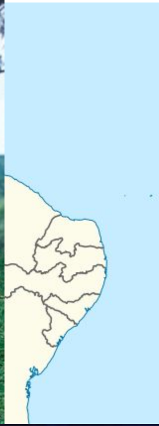


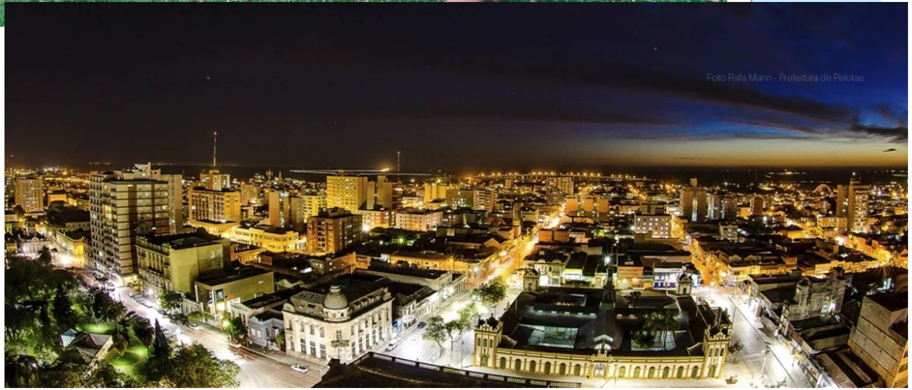


About me

Pelotas, Rio Grande do Sul, Brazil

2015 Physics (*licenciatura*) - Pelotas - UFPel



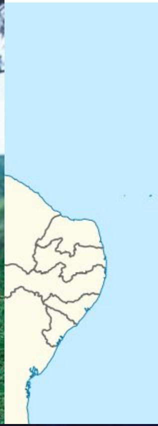


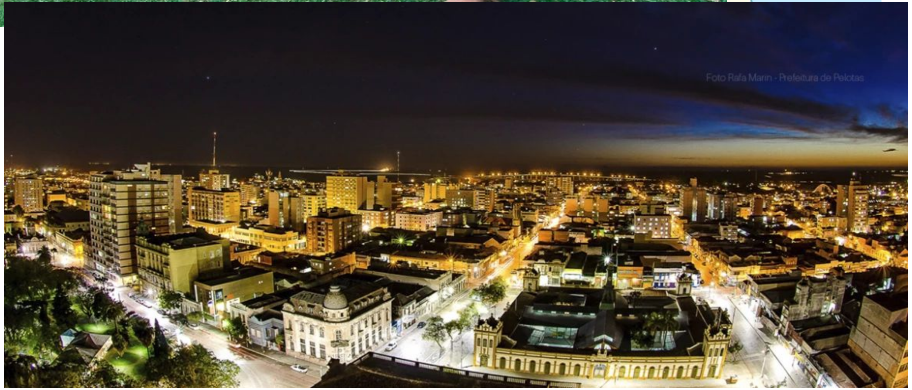
About me

Pelotas, Rio Grande do Sul, Brazil

<u>2015</u> Physics (*licenciatura*) - Pelotas - UFPel

<u>2017</u> MSc - Pelotas - UFPel
GAME - Grupo de Altas e Médias Energias





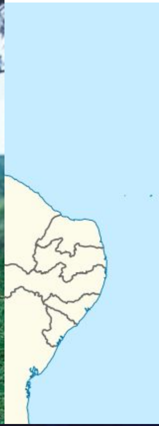
About me

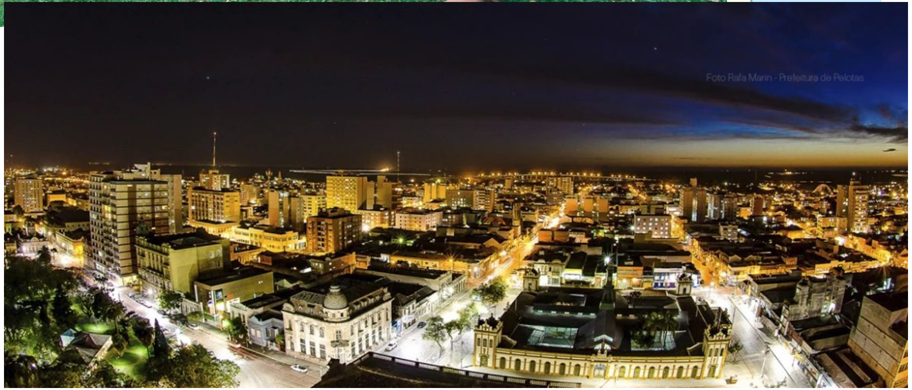
Pelotas, Rio Grande do Sul, Brazil

<u>2015</u> Physics (*licenciatura*) - Pelotas - UFPel

<u>2017</u> MSc - Pelotas - UFPel
GAME - Grupo de Altas e Médias Energias

<u>2021</u> PhD - São Carlos - IFSC/USP





About me

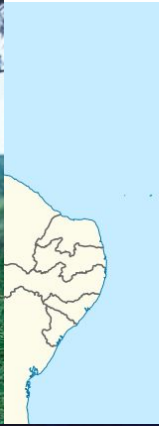
Pelotas, Rio Grande do Sul, Brazil

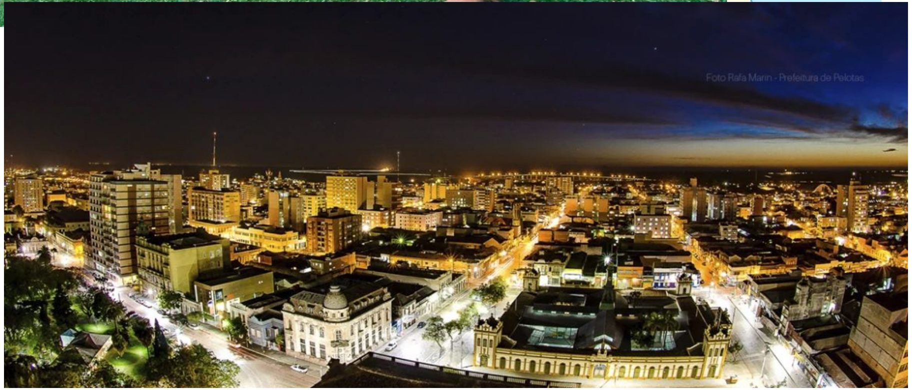
2015 Physics (*licenciatura*) - Pelotas - UFPel

2017 MSc - Pelotas - UFPel
GAME - Grupo de Altas e Médias Energias

2021 PhD - São Carlos - IFSC/USP

then six months as a SW developer





About me

Pelotas, Rio Grande do Sul, Brazil

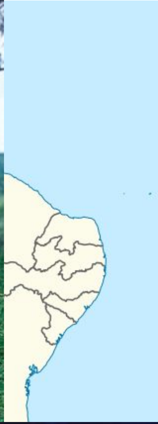
2015 Physics (*licenciatura*) - Pelotas - UFPel

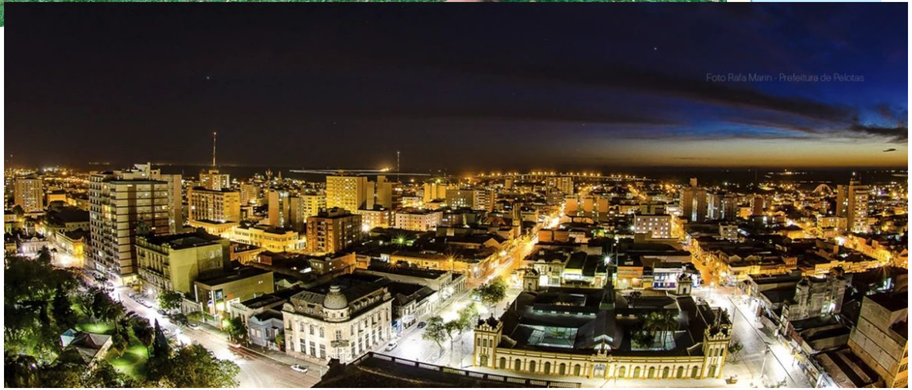
2017 MSc - Pelotas - UFPel
GAME - Grupo de Altas e Médias Energias

2021 PhD - São Carlos - IFSC/USP

then six months as a SW developer

now postdoc at IFSC/IFGW





Astrophysical context for air showers

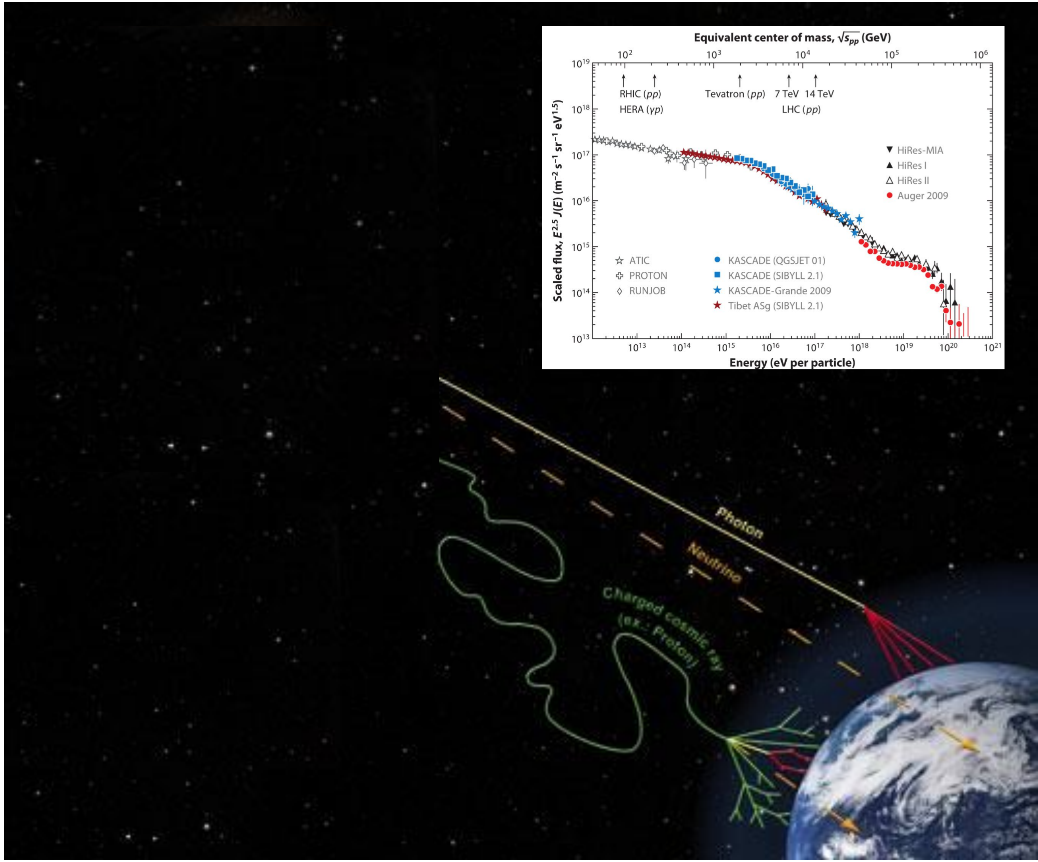
Multi messenger astrophysics

i. diversity of particles/messengers

Astrophysical context for air showers

<u>Multi messenger astrophysics</u>

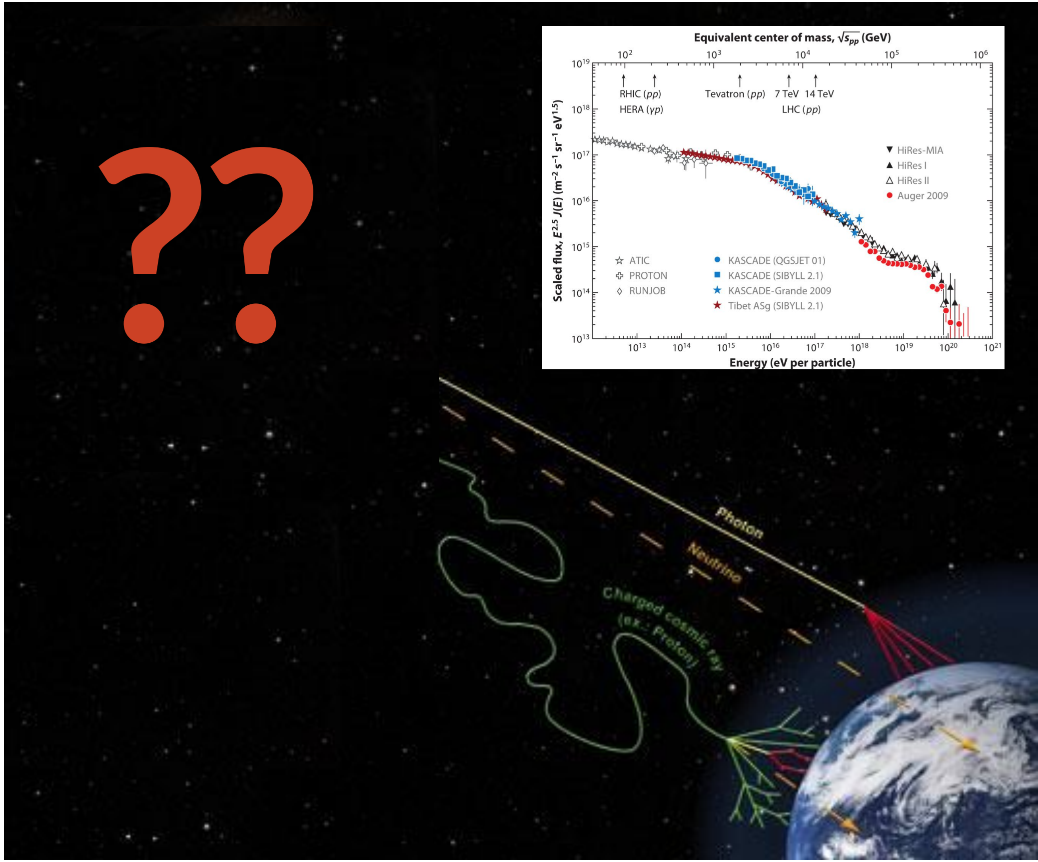
i. diversity of particles/messengers
ii. broad energy range/spectrum



Astrophysical context for air showers

Multi messenger astrophysics

i. diversity of particles/messengers
ii. broad energy range/spectrum
iii. unknown environments of propagation and acceleration

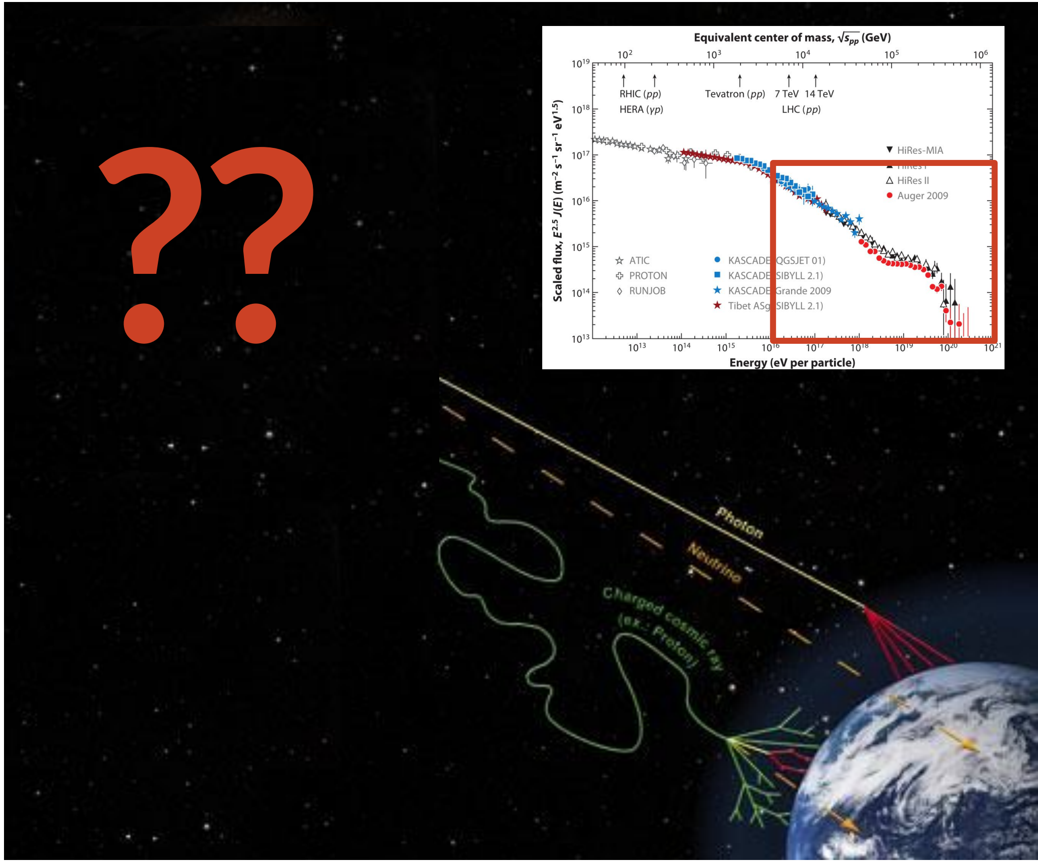


Astrophysical context for air showers

Multi messenger astrophysics

i. diversity of particles/messengers
ii. broad energy range/spectrum
iii. unknown environments of propagation and acceleration

At the highest energies



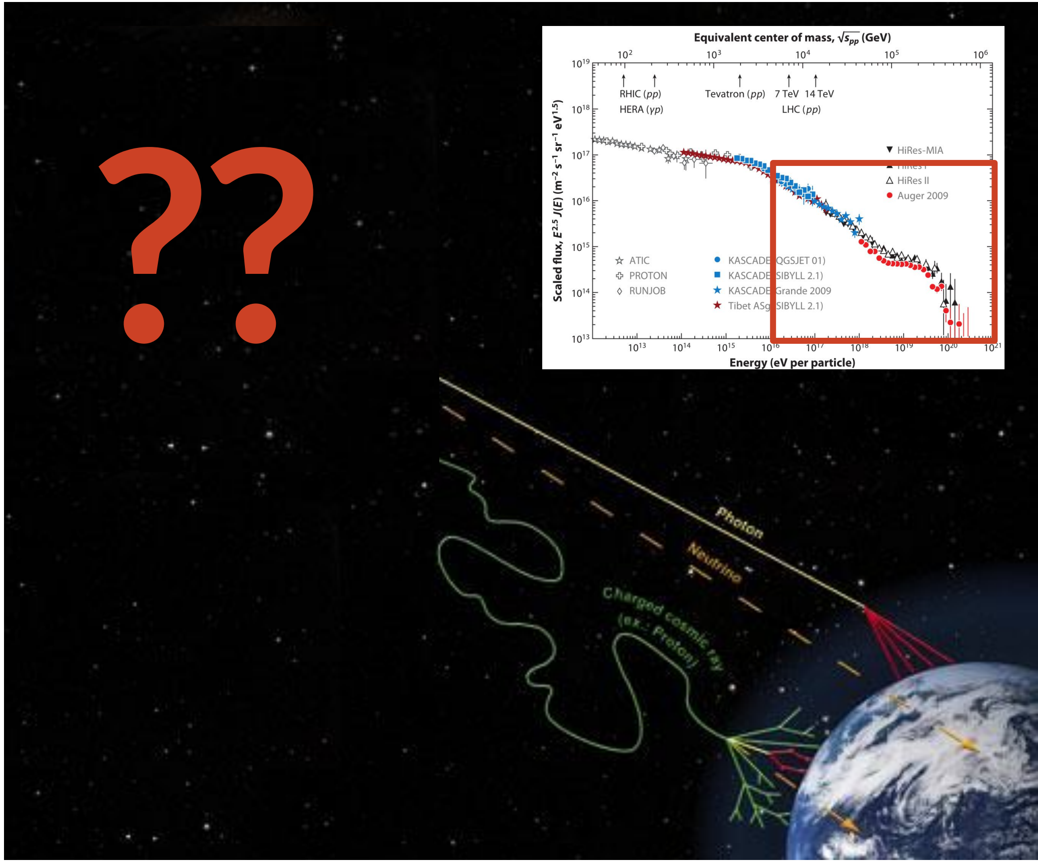
Astrophysical context for air showers

Multi messenger astrophysics

i. diversity of particles/messengers
ii. broad energy range/spectrum
iii. unknown environments of propagation and acceleration

At the highest energies

iv. the flux of particles is too small for direct detectors



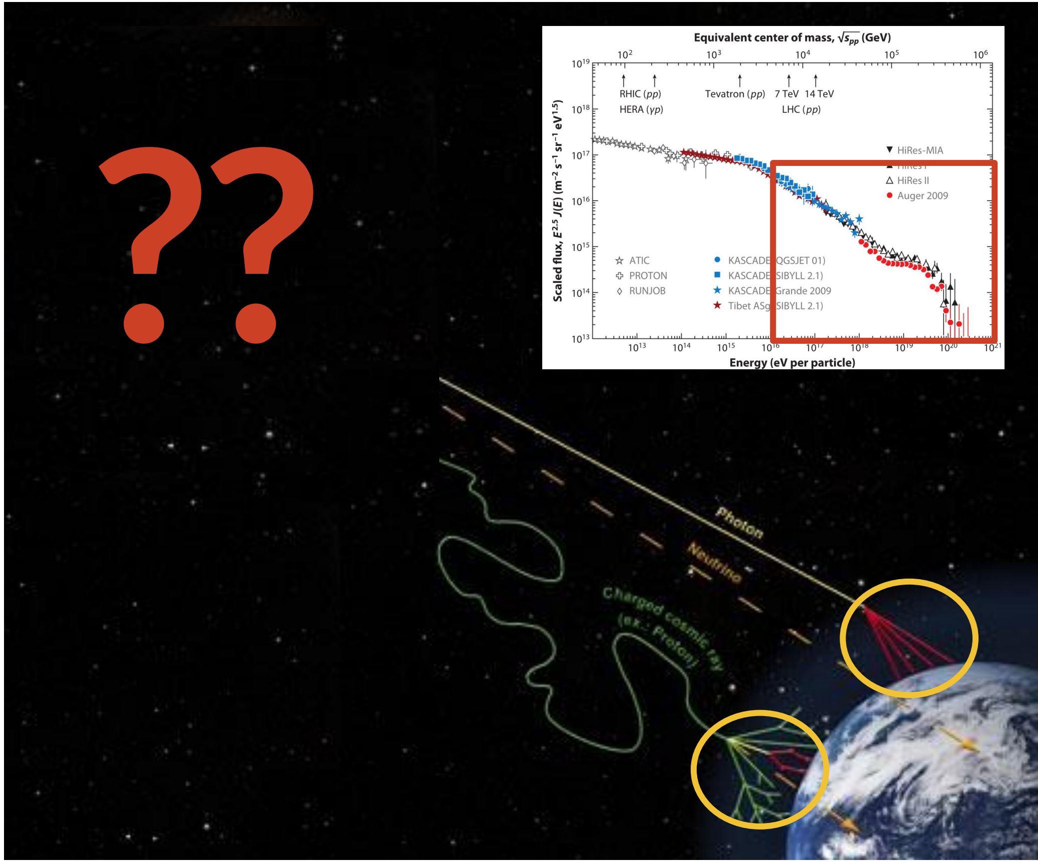
Astrophysical context for air showers

<u>Multi messenger astrophysics</u>

i. diversity of particles/messengers
ii. broad energy range/spectrum
iii. unknown environments of propagation and acceleration

<u>At the highest energies</u>

iv. the flux of particles is too small for direct detectors
v. the energy is enough to generate an observable cascade in the atmosphere



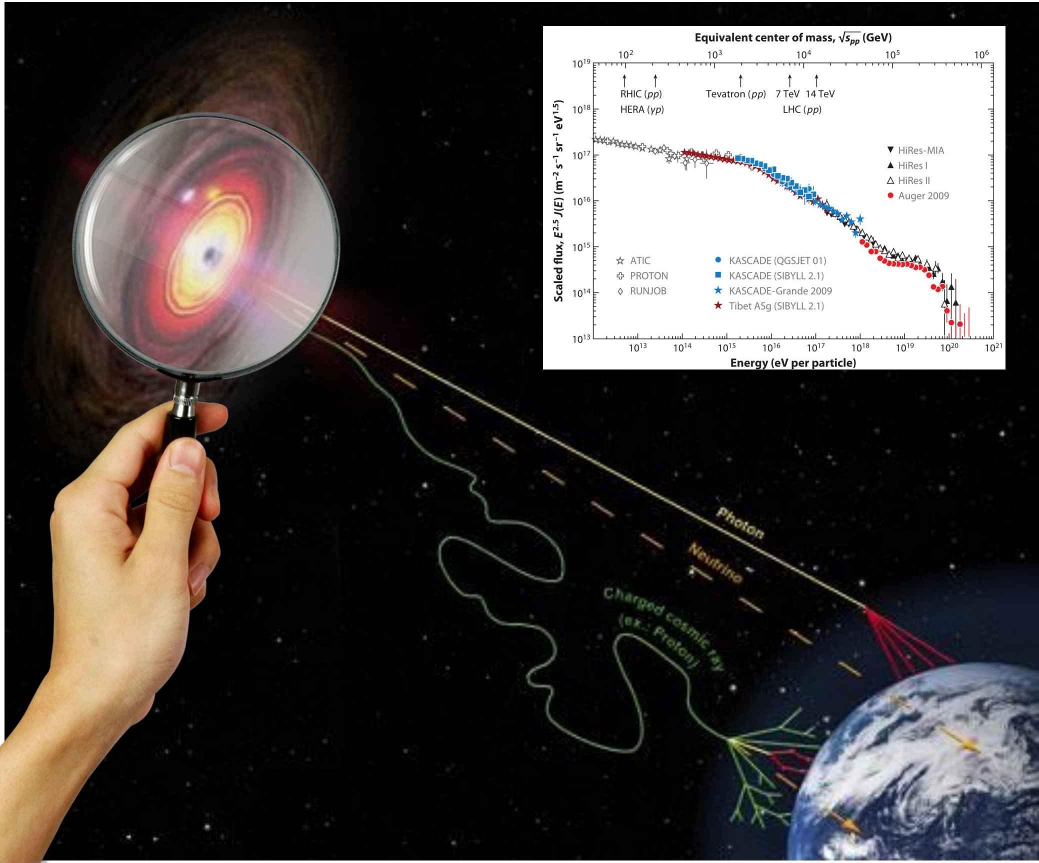
Astrophysical context for air showers

<u>Multi messenger astrophysics</u>

i. diversity of particles/messengers
ii. broad energy range/spectrum
iii. unknown environments of propagation and acceleration

<u>At the highest energies</u>

iv. the flux of particles is too small for direct detectors
v. the energy is enough to generate an observable cascade in the atmosphere



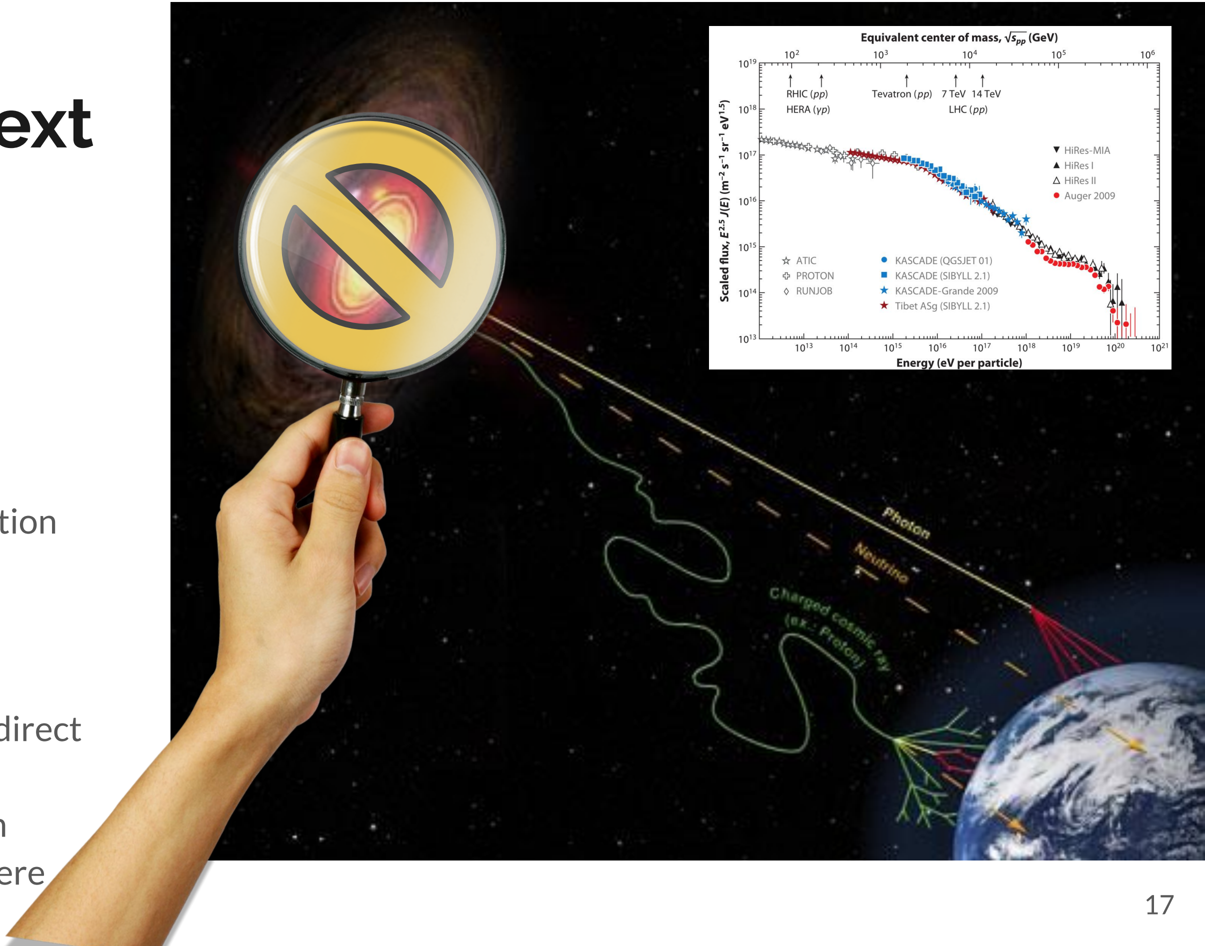
Astrophysical context for air showers

<u>Multi messenger astrophysics</u>

i. diversity of particles/messengers
ii. broad energy range/spectrum
iii. unknown environments of propagation and acceleration

<u>At the highest energies</u>

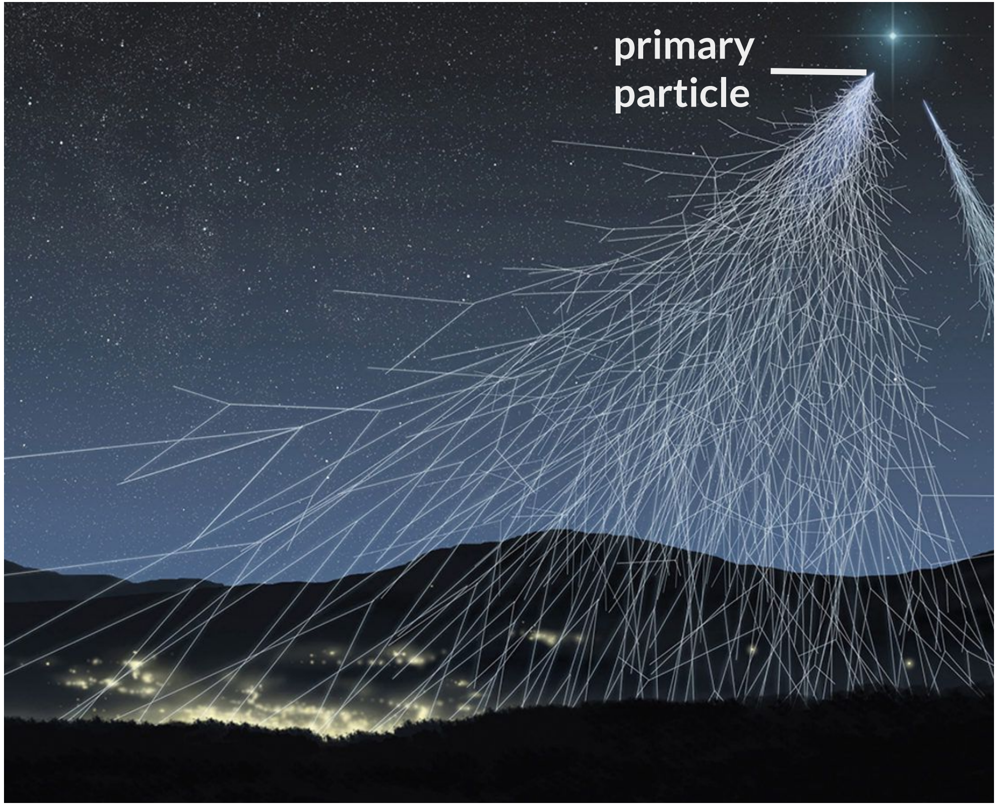
iv. the flux of particles is too small for direct detectors
v. the energy is enough to generate an observable cascade in the atmosphere



Extensive air showers

<u>Facts</u>

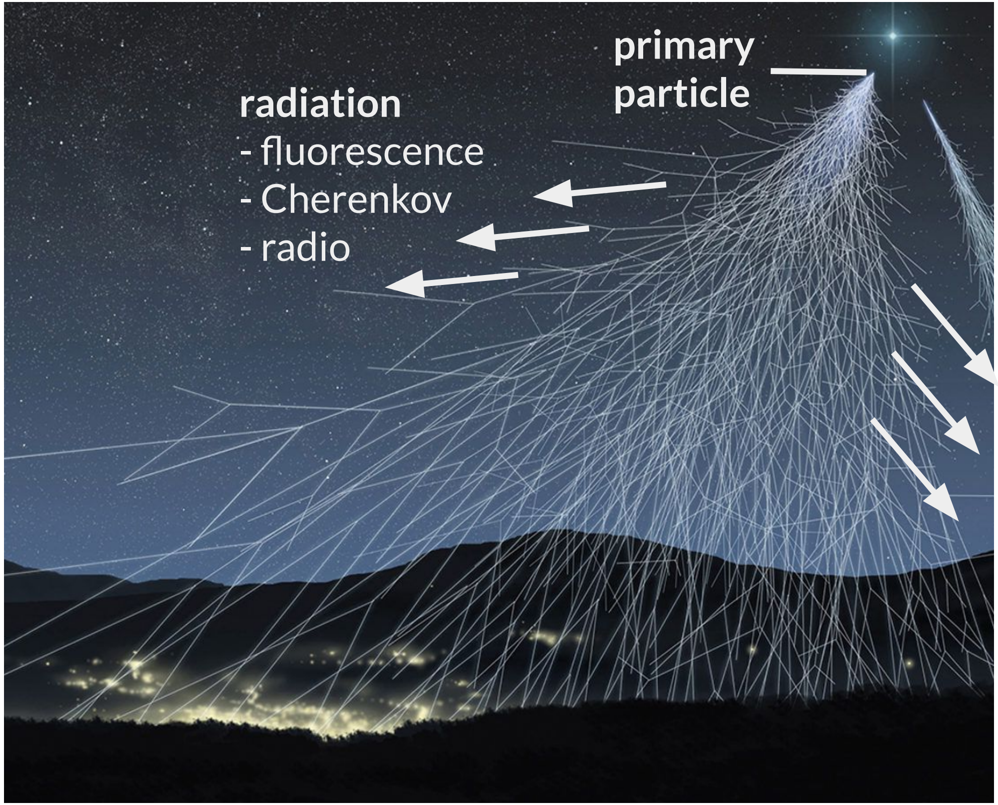
i. started by extraterrestrial particle



Extensive air showers

<u>Facts</u>

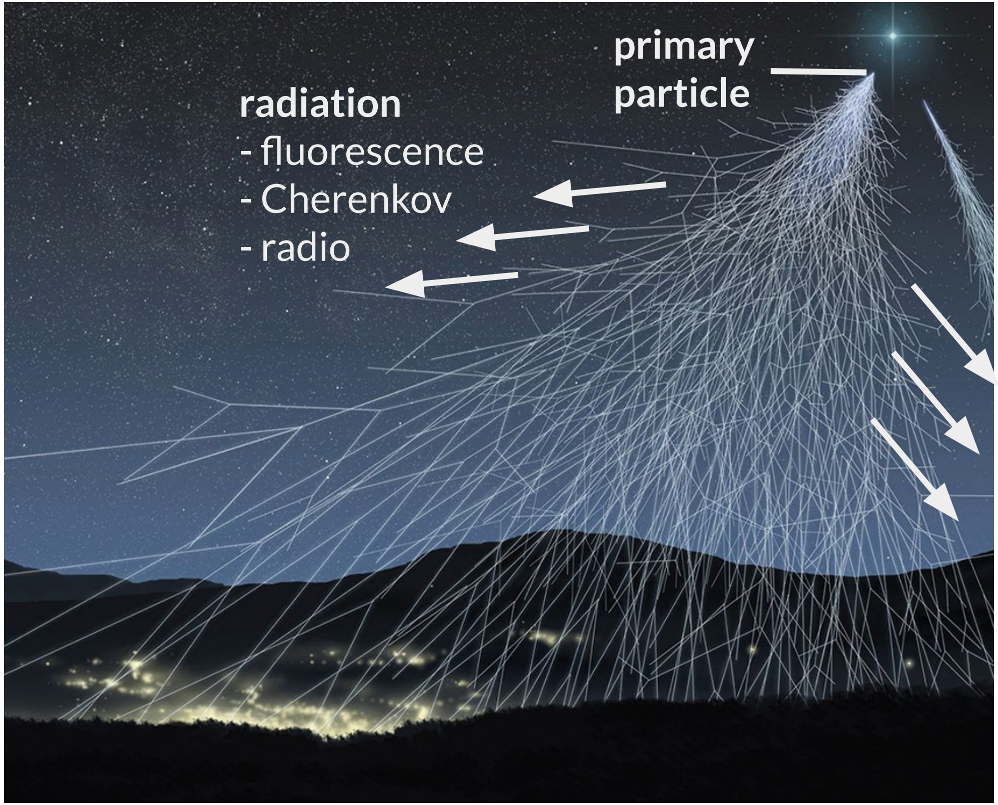
i. started by extraterrestrial particle
ii. cascade of particles and radiation



Extensive air showers

<u>Facts</u>

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

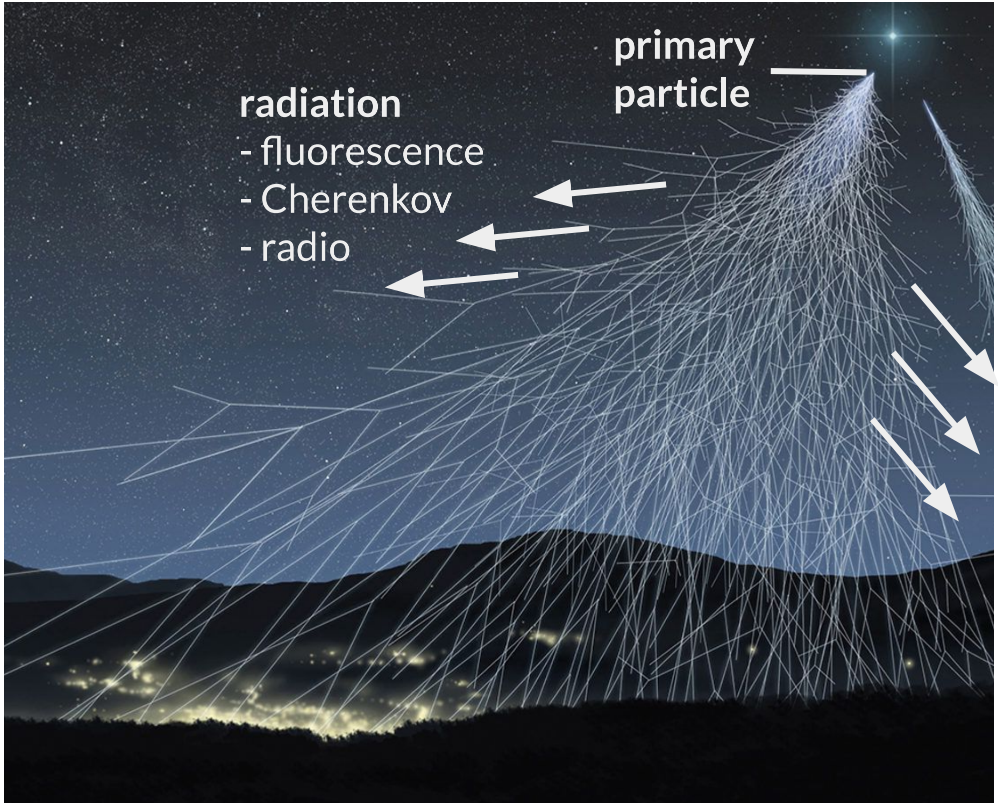


Extensive air showers

Facts

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

Why care about them?

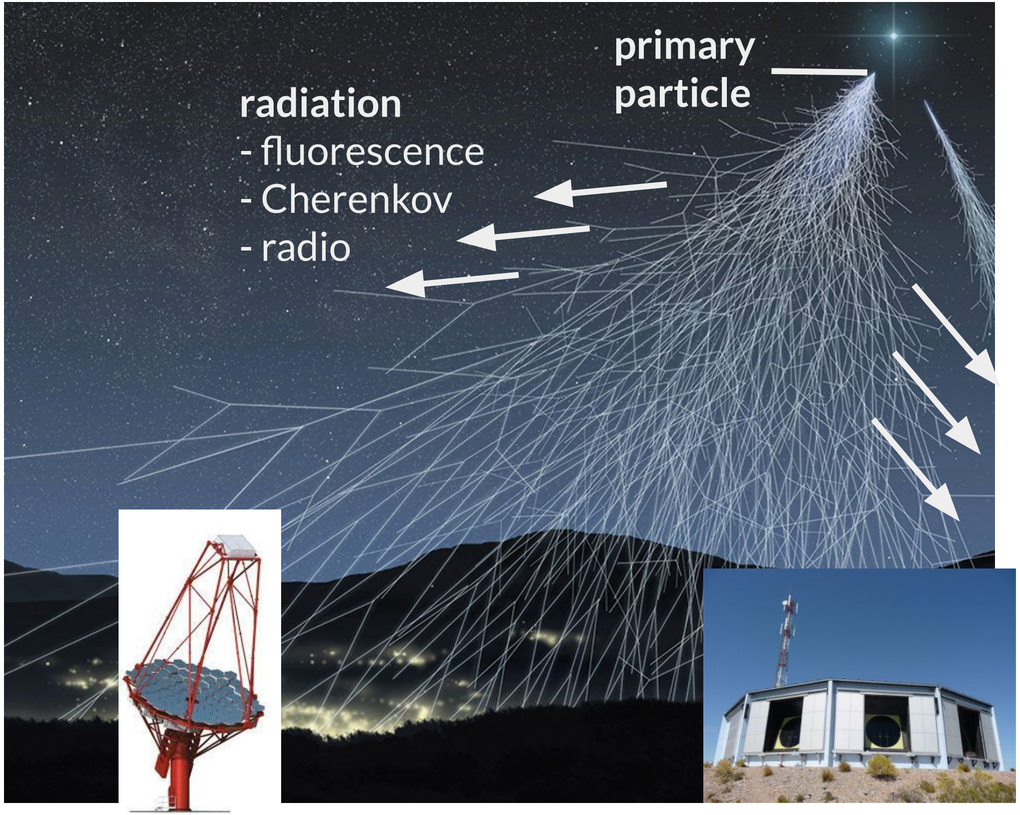


Extensive air showers

<u>Facts</u>

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

<u>Why care about them?</u>



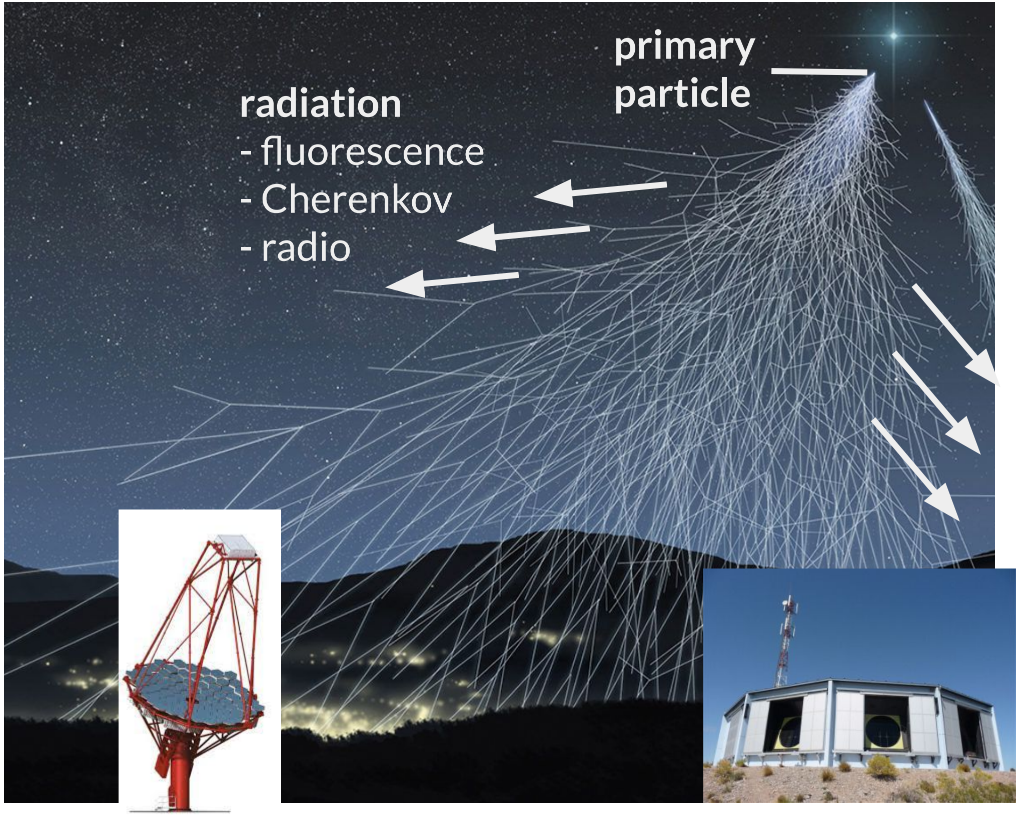
Extensive air showers

<u>Facts</u>

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

<u>Why care about them?</u>

i. interesting per se, beyond astrophysics



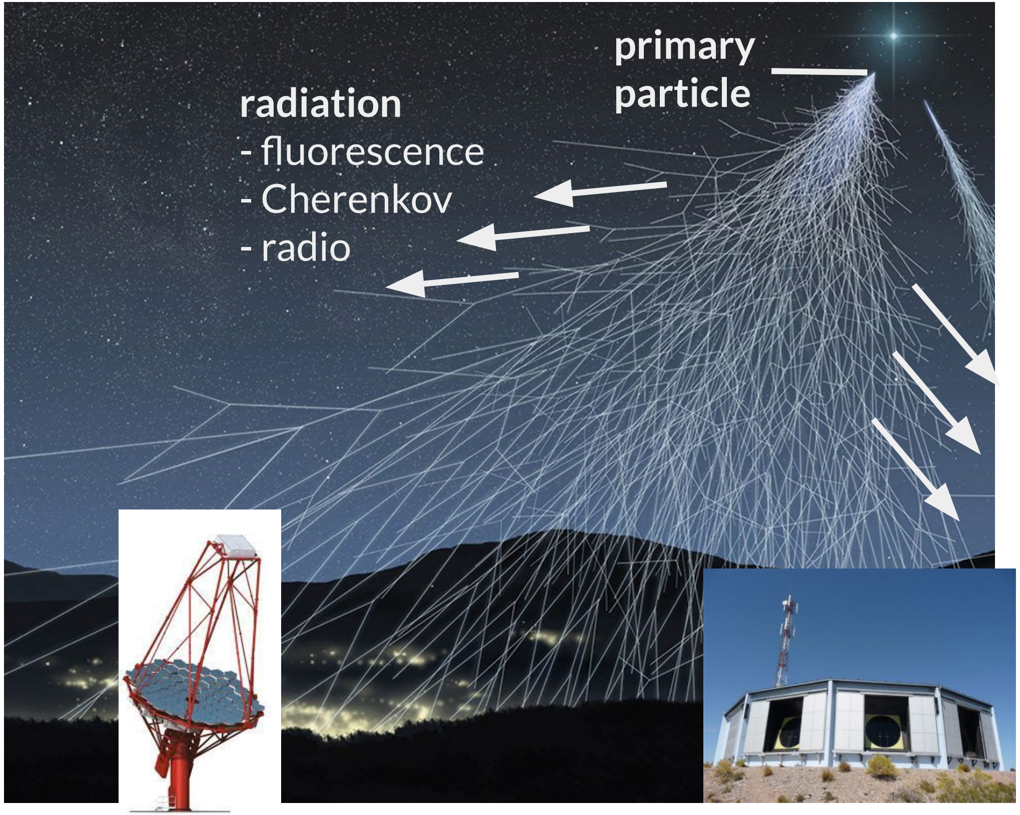
Extensive air showers

Facts

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

Why care about them?

i. interesting per se, beyond astrophysics
ii. interactions up to ~10^{20} eV
(LHC is 10^{17} lab. energy)



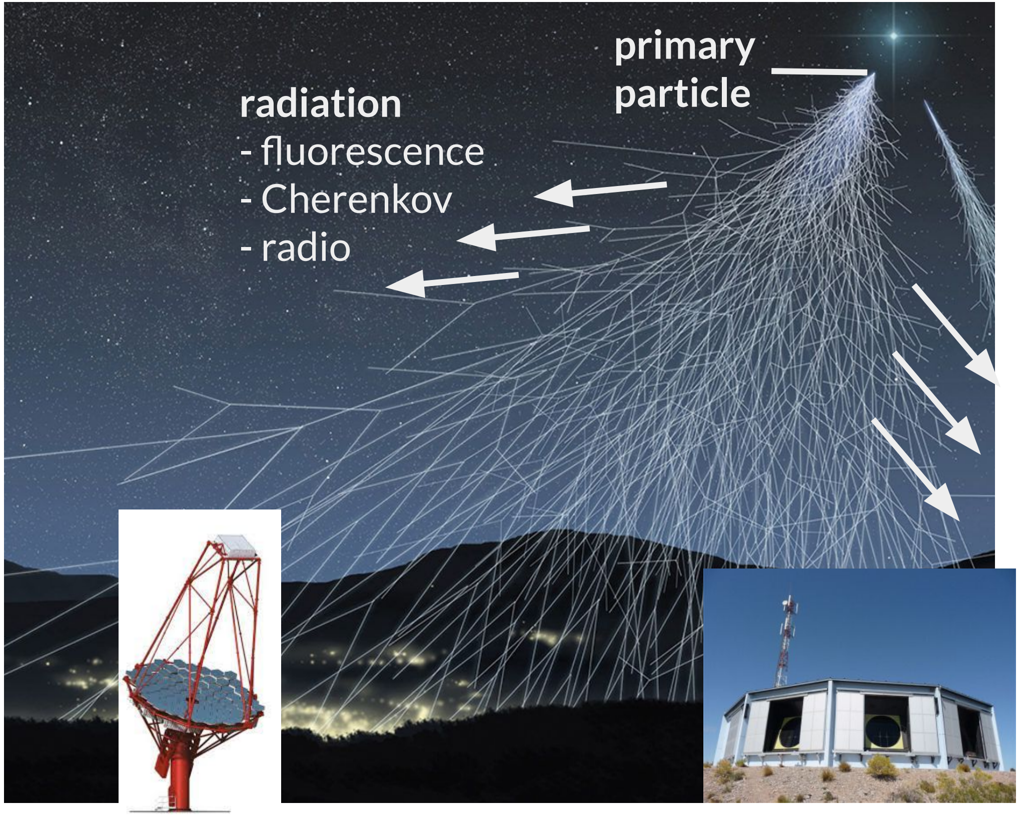
Extensive air showers

<u>Facts</u>

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

<u>Why care about them?</u>

i. interesting per se, beyond astrophysics
ii. interactions up to ~10^{20} eV
    (LHC is 10^{17} lab. energy)
iii. up to ~10^{12} electrons in few μs



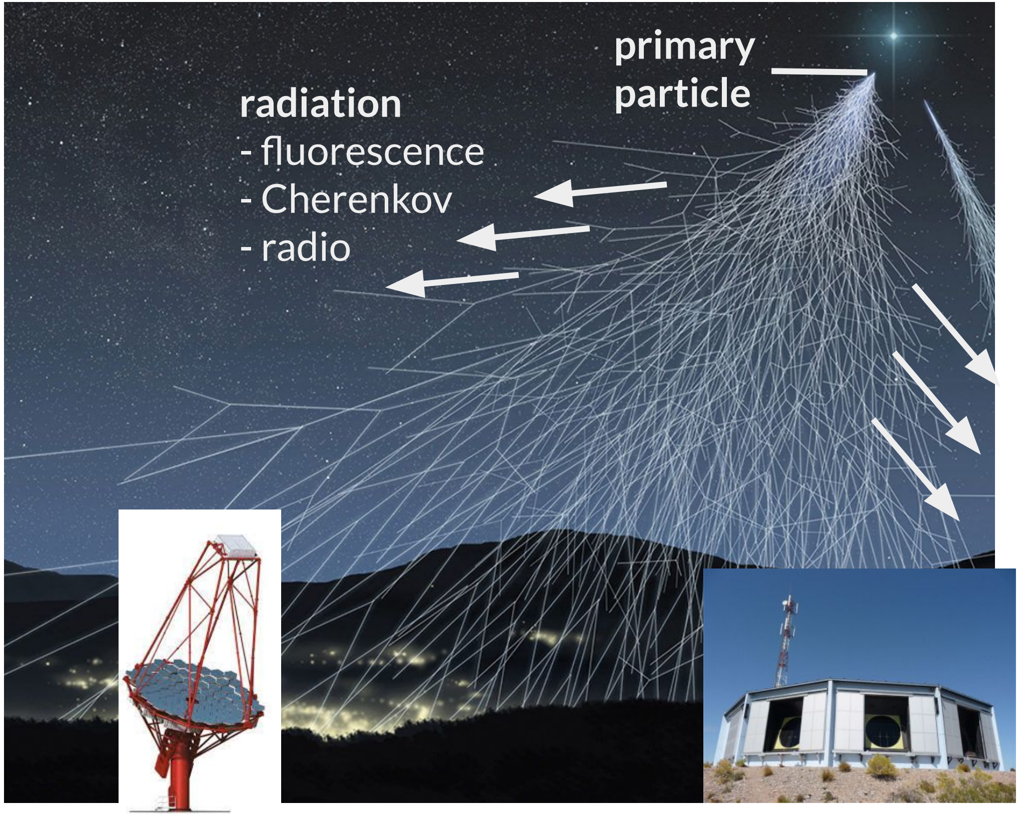
Extensive air showers

Facts

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

Why care about them?

i. interesting per se, beyond astrophysics
ii. interactions up to ~10^{20} eV (LHC is 10^{17} lab. energy)
iii. up to ~10^{12} electrons in few μs
iv. early experimental particle physics



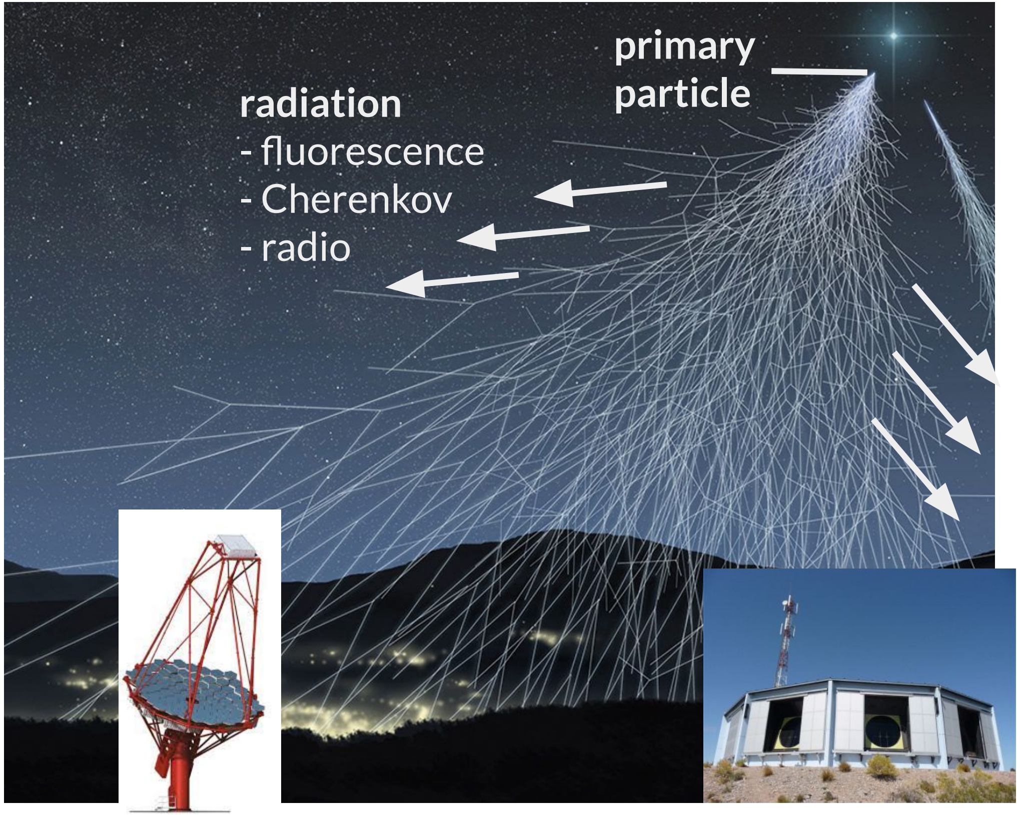
Extensive air showers

Facts

i. started by extraterrestrial particle
ii. cascade of particles and radiation
iii. stochastic process in nature

Why care about them?

i. interesting per se, beyond astrophysics
ii. interactions up to ~10^{20} eV
(LHC is 10^{17} lab. energy)
iii. up to ~10^{12} electrons in few μs
iv. early experimental particle physics
v. great scenario for machine learning



Reconstruction of the primary particle

1 Arrival direction

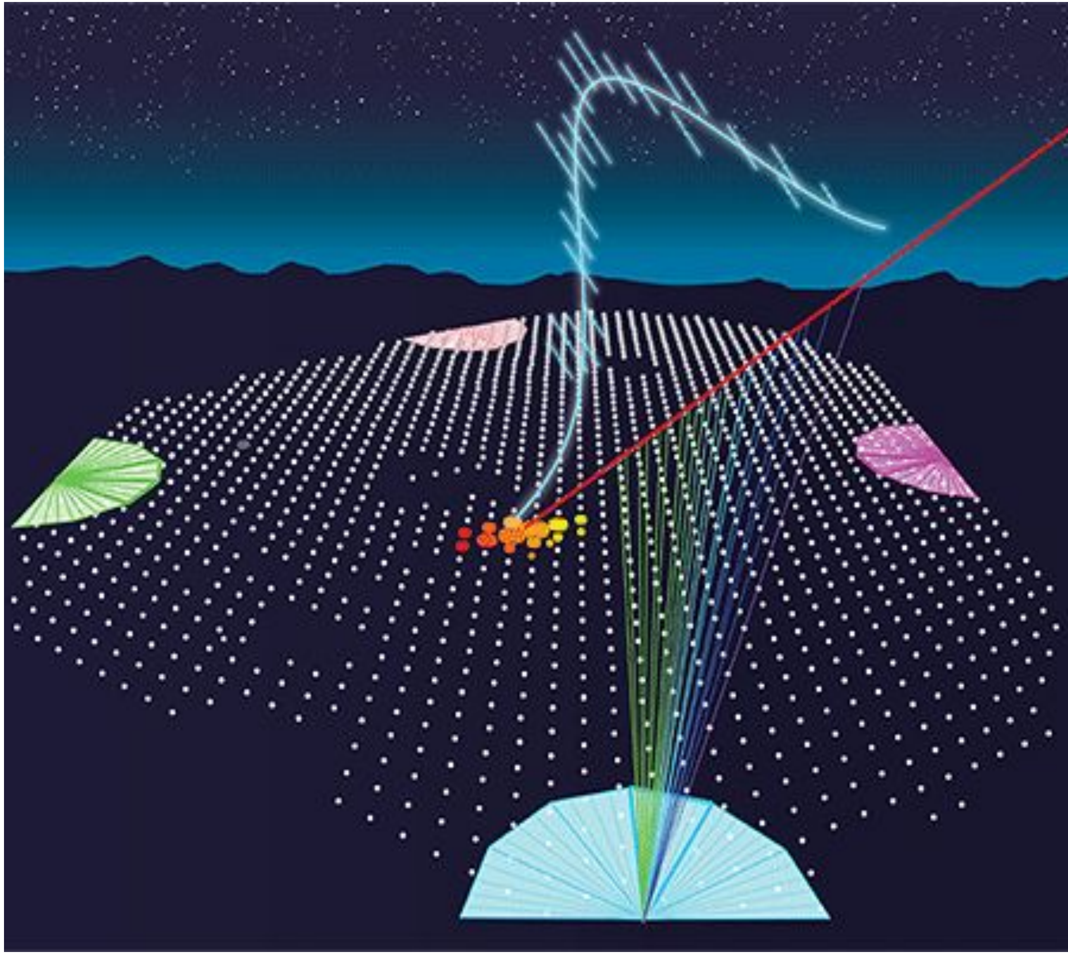
- ✓
- ✓

2 Primary energy

- ✓
- ✓

3 Species or mass composition

- ✓
- ✓



Reconstruction of the primary particle

1 Arrival direction

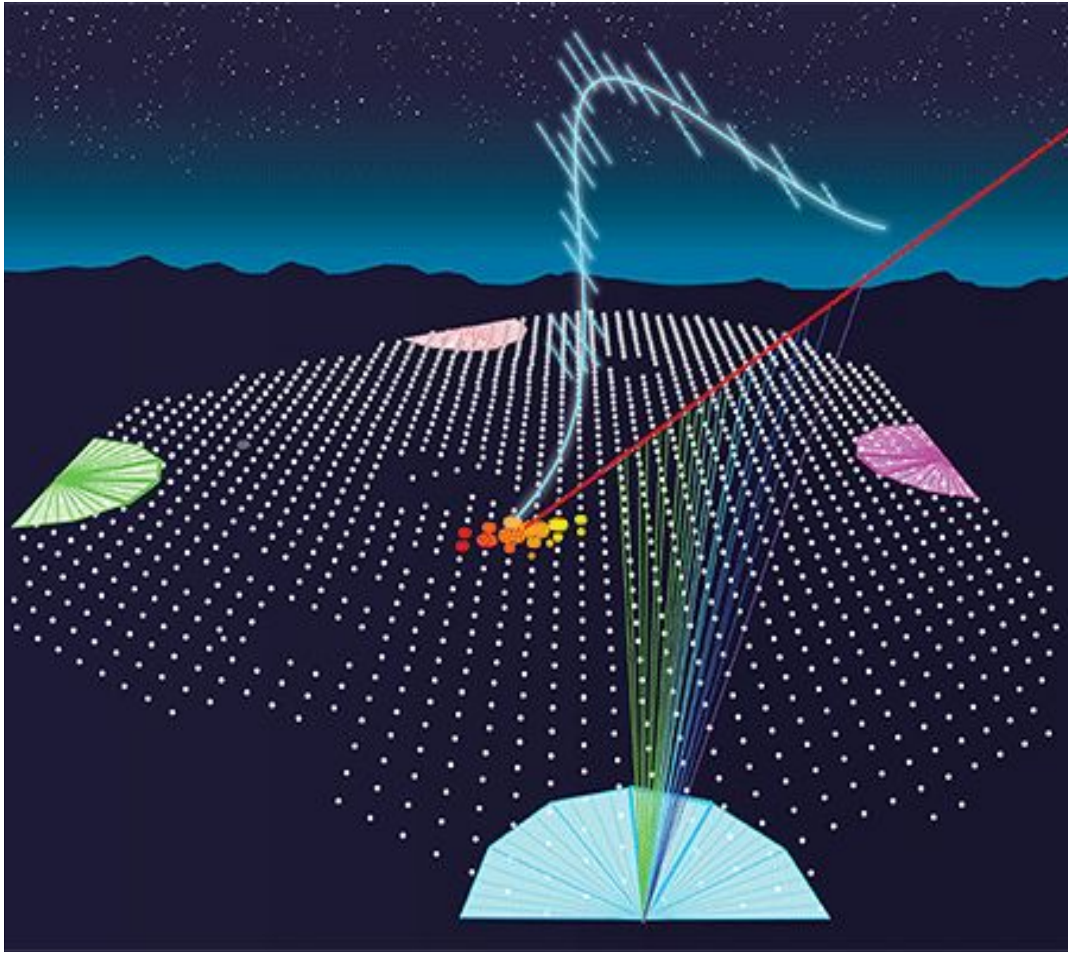
- ✓ momentum conservation
- ✓ shower geometry

2 Primary energy

- ✓
- ✓

3 Species or mass composition

- ✓
- ✓



Reconstruction of the primary particle

1 Arrival direction

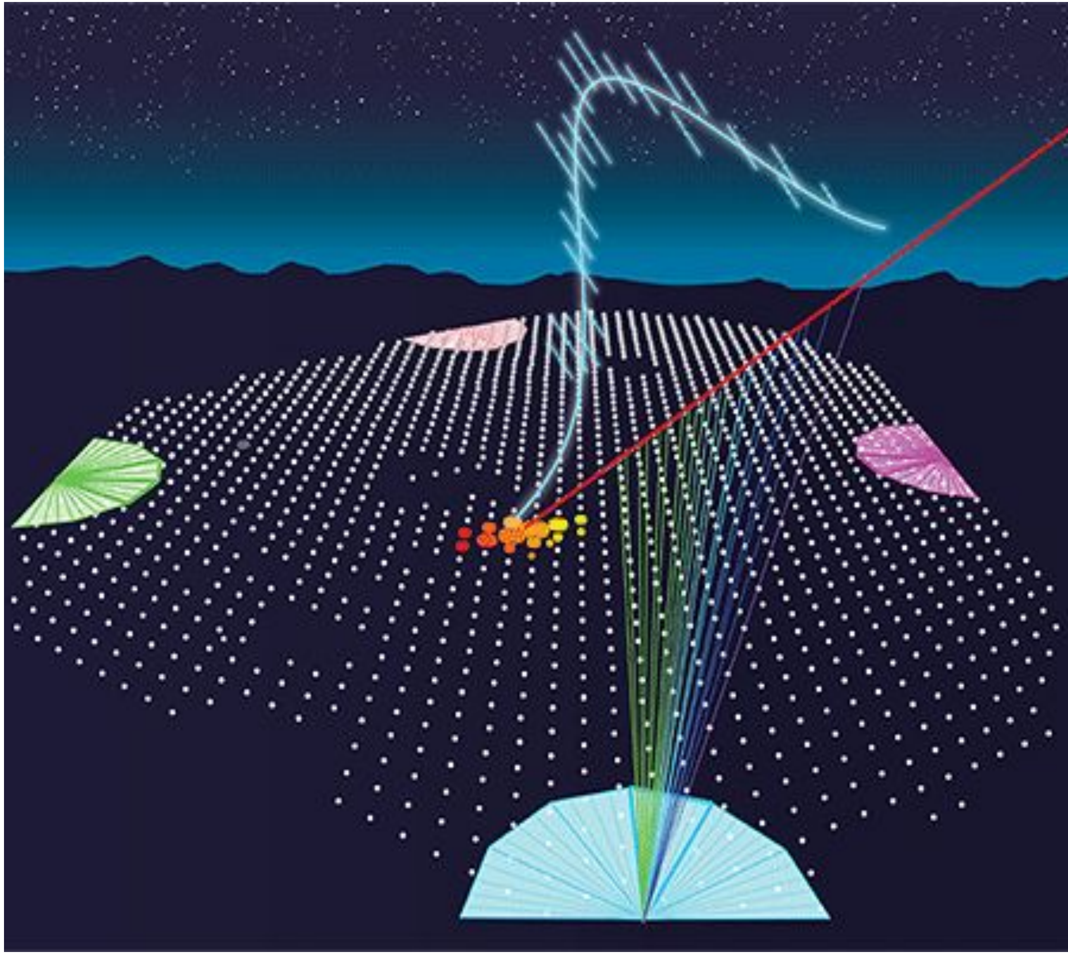
✓ momentum conservation
✓ shower geometry

2 Primary energy

✓ proportional to the signal
✓ calorimetric energy, amplitude, etc.

3 Species or mass composition

✓
✓



Reconstruction of the primary particle

<u>1 Arrival direction</u>

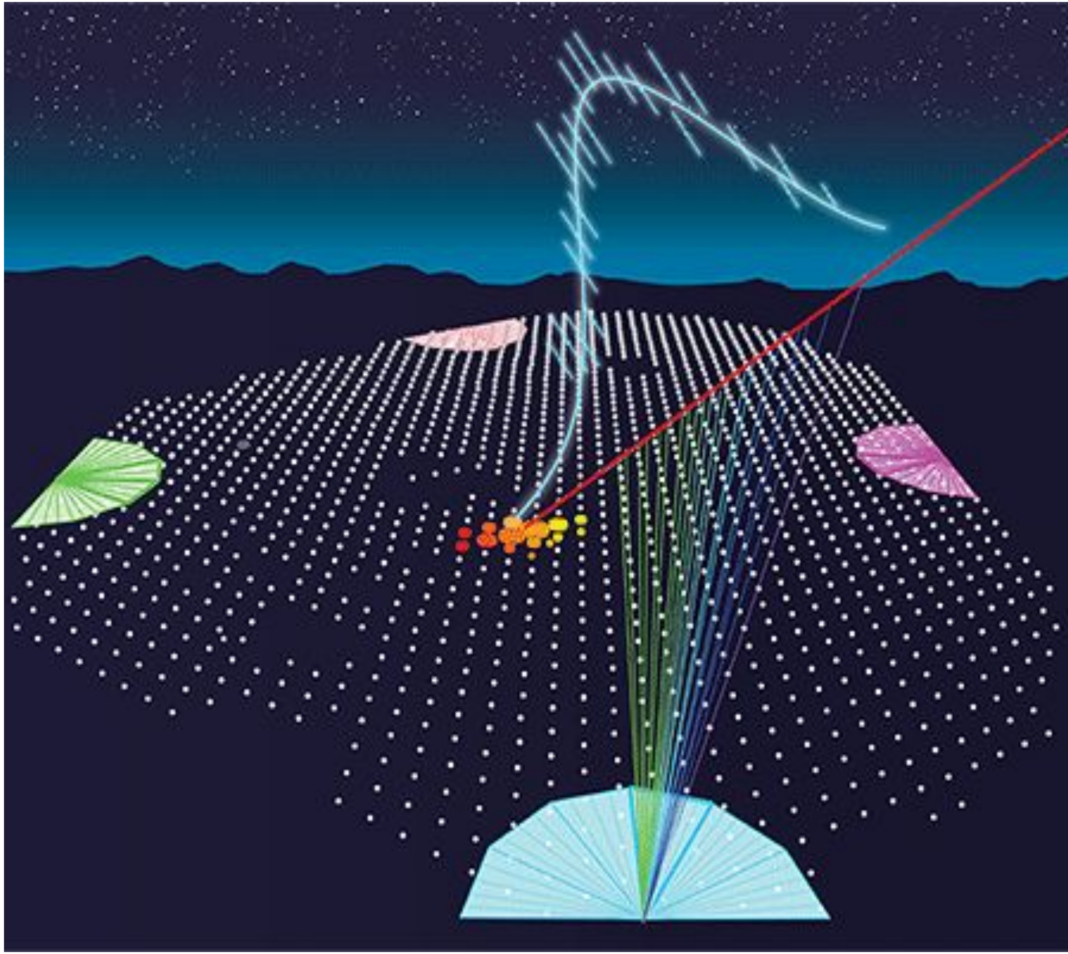
- ✓ momentum conservation
- ✓ shower geometry

<u>2 Primary energy</u>

- ✓ proportional to the signal
- ✓ calorimetric energy, amplitude, etc.

<u>3 Species or mass composition</u>

- ✓ difficult, typically Xmax
- ✓ shower-to-shower typically not possible



Reconstruction of the primary particle

1 Arrival direction

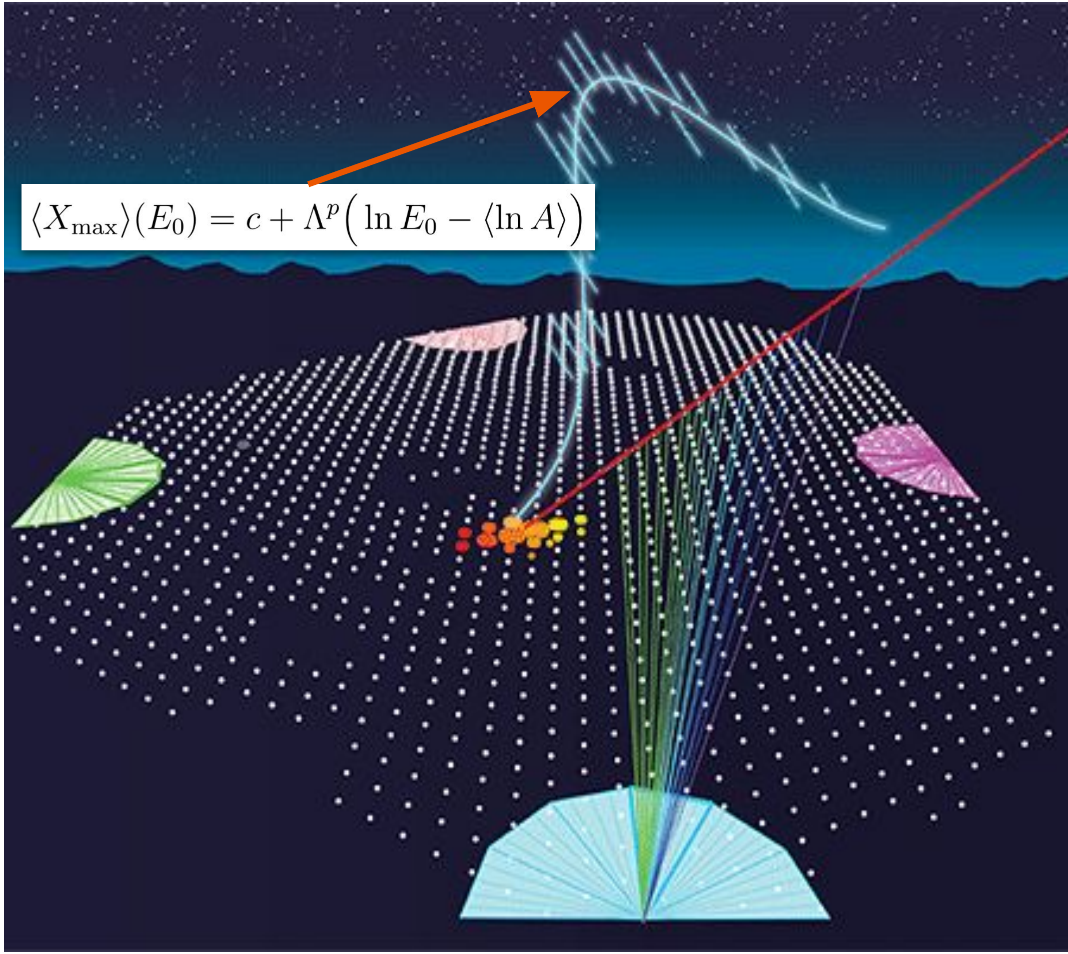
- ✓ momentum conservation
- ✓ shower geometry

2 Primary energy

- ✓ proportional to the signal
- ✓ calorimetric energy, amplitude, etc.

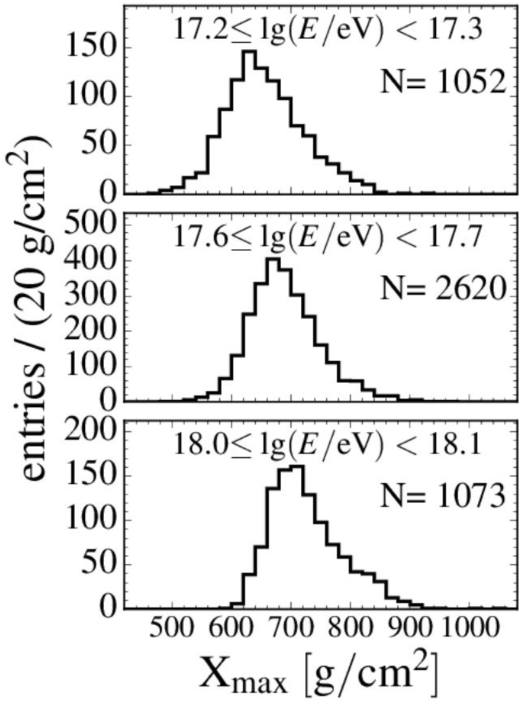
3 Species or mass composition

- ✓ difficult, typically Xmax
- ✓ shower-to-shower typically not possible



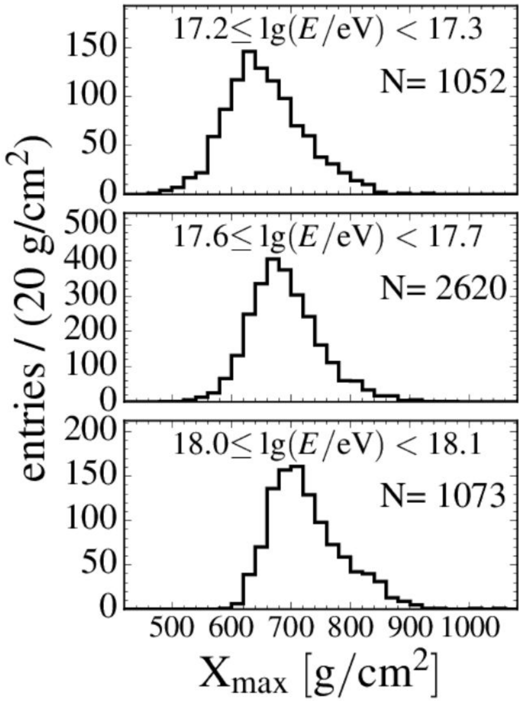
X_{max} and the mass composition at ultra-high energies

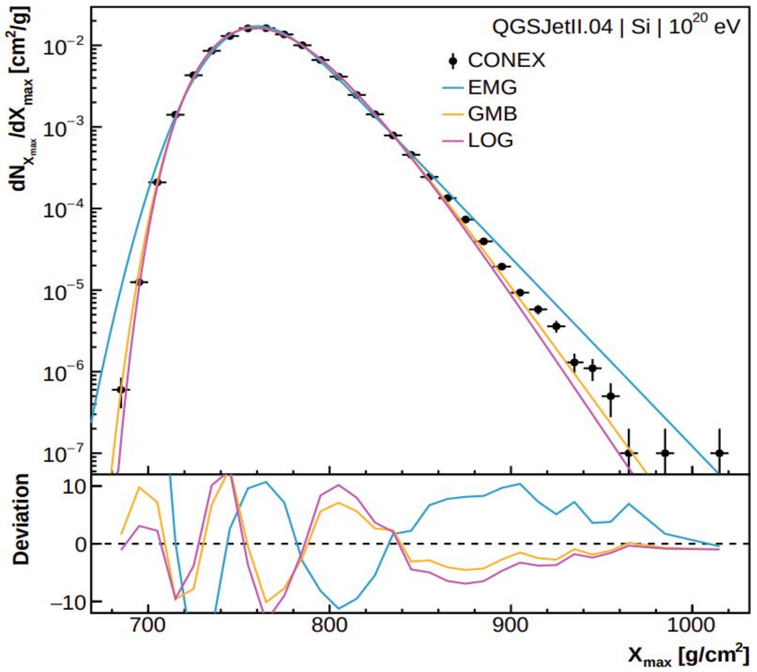
Auger 2017



X_{max} and the mass composition at ultra-high energies

Auger 2017



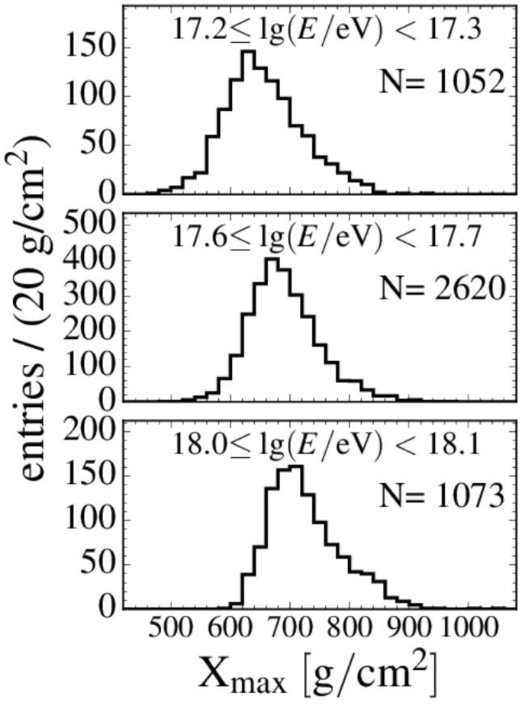


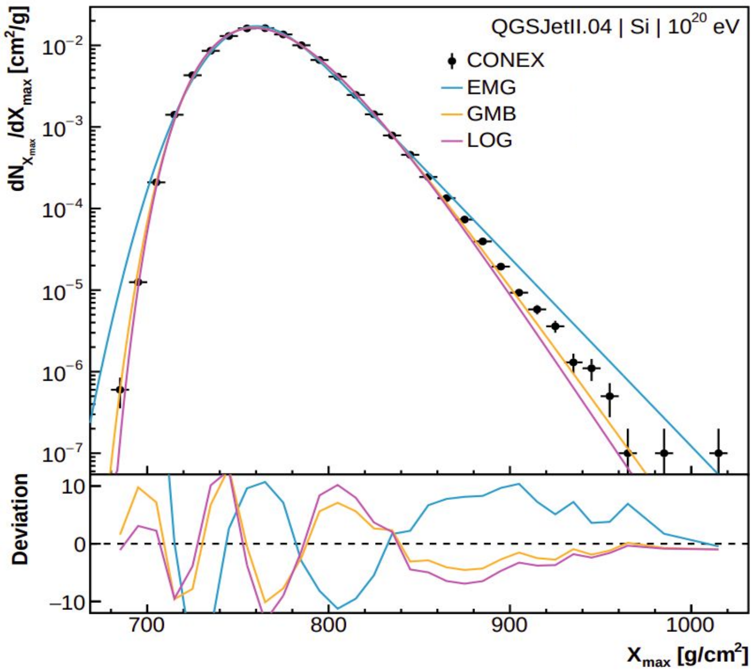
Contribution in São Carlos

- ✓ parametric description of X_{max}
- ✓ ~10^7 simulated showers
- ✓ Gumbel distribution is OK
- ✓ mass composition analysis

Xmax and the mass composition at ultra-high energies

Auger 2017





Contribution in São Carlos

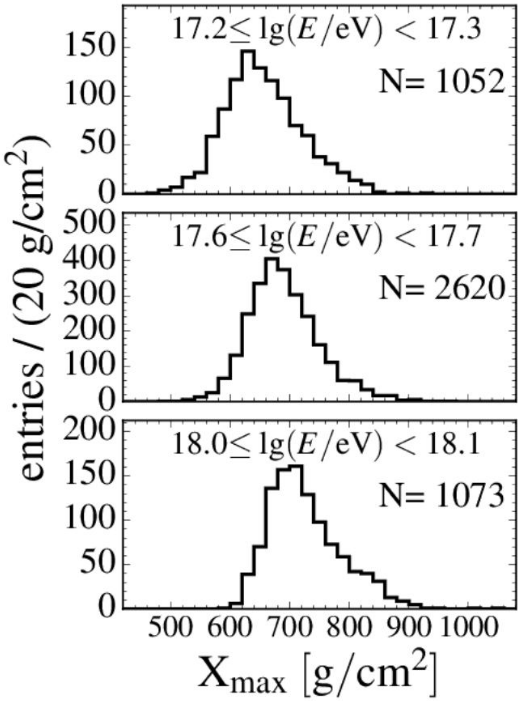
- ✓ parametric description of Xmax
- ✓ ~10^7 simulated showers
- ✓ Gumbel distribution is OK
- ✓ mass composition analysis

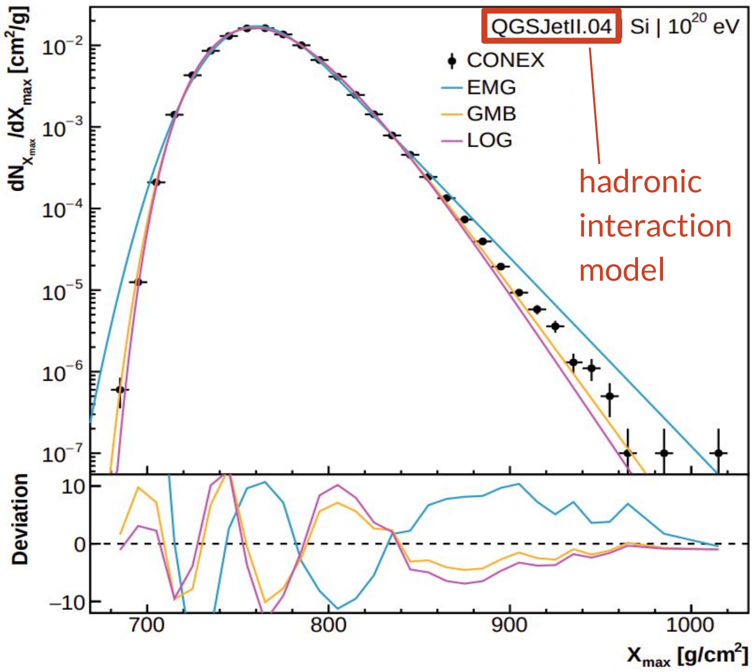
Archetype of my work

a) idea
b) *ad hoc* simulation
c) data analysis
d) results

X_{max} and the mass composition at ultra-high energies

Auger 2017





Contribution in São Carlos

- ✓ parametric description of X_{max}
- ✓ ~10^7 simulated showers
- ✓ Gumbel distribution is OK
- ✓ mass composition analysis

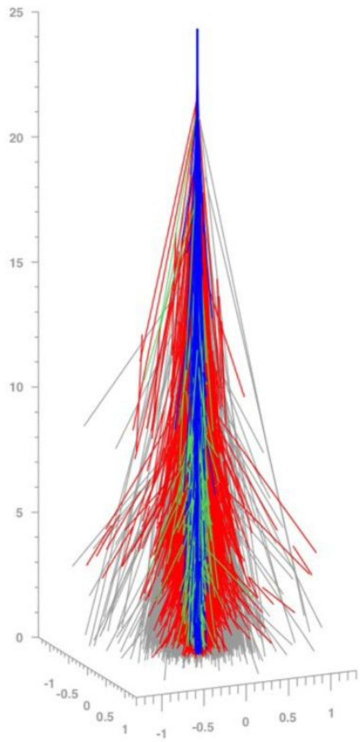
Archetype of my work

a) idea
b) *ad hoc* **simulation**
c) data analysis
d) results

Hadronic interactions

Simulation of EAS

i. CORSIKA - detailed, but not fast
ii. CONEX - fast, but not detailed

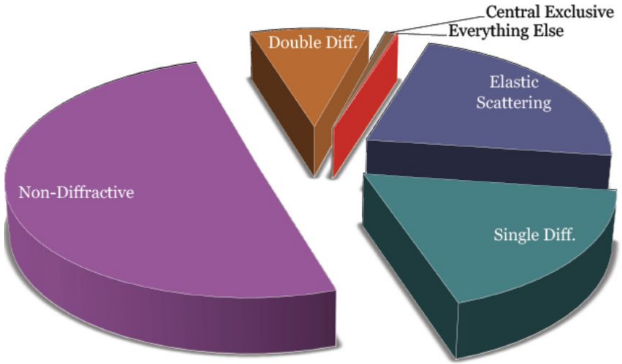


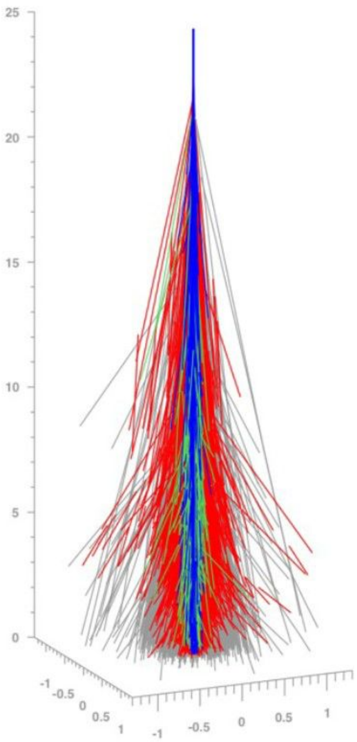
Hadronic interactions

Simulation of EAS

i. CORSIKA - detailed, but not fast
ii. CONEX - fast, but not detailed

Hadron-hadron cross section



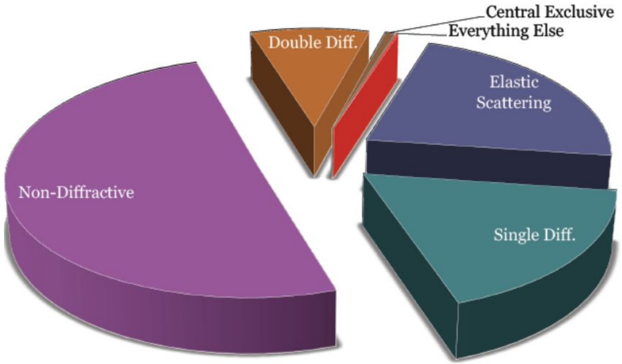


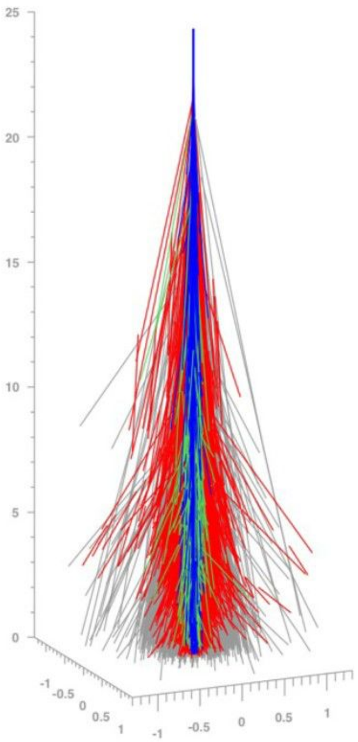
Hadronic interactions

Simulation of EAS

i. CORSIKA - detailed, but not fast
ii. CONEX - fast, but not detailed

Hadron-hadron cross section





Diffractive interactions

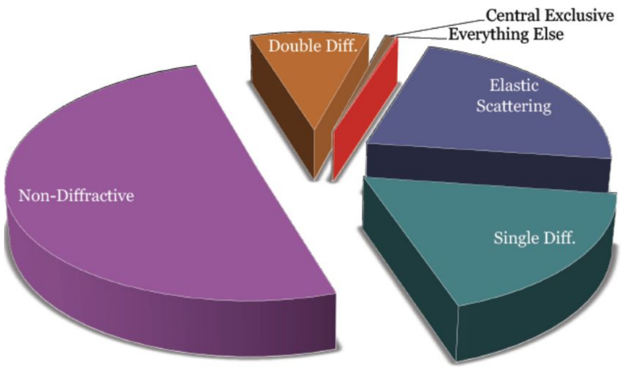
i. no exchange of quantum numbers
ii. non-perturbative regime of QCD
iii. phenomenological models diverge

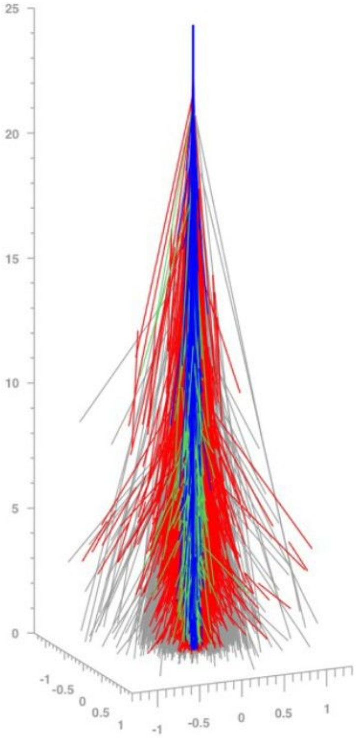
Hadronic interactions

Simulation of EAS

i. CORSIKA - detailed, but not fast
ii. CONEX - fast, but not detailed

Hadron-hadron cross section

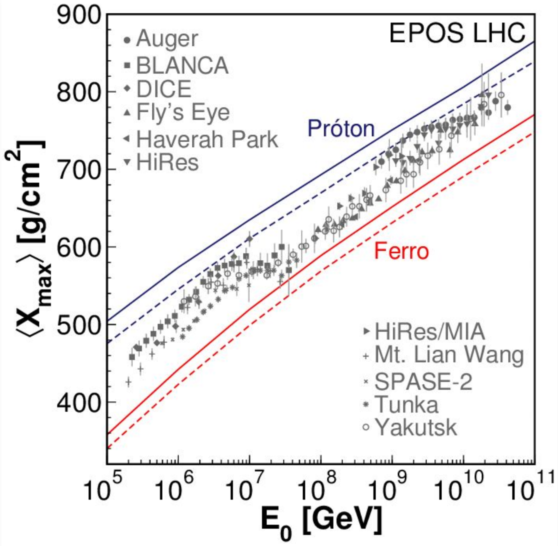




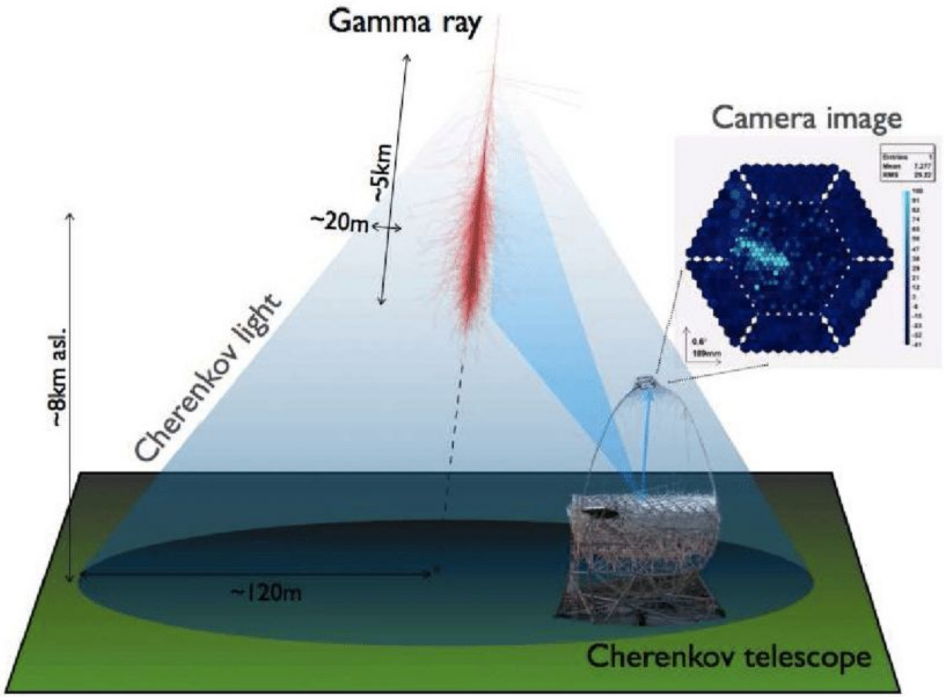
Diffractive interactions

i. no exchange of quantum numbers
ii. non-perturbative regime of QCD
iii. phenomenological models diverge

Impact over the depth of shower maximum



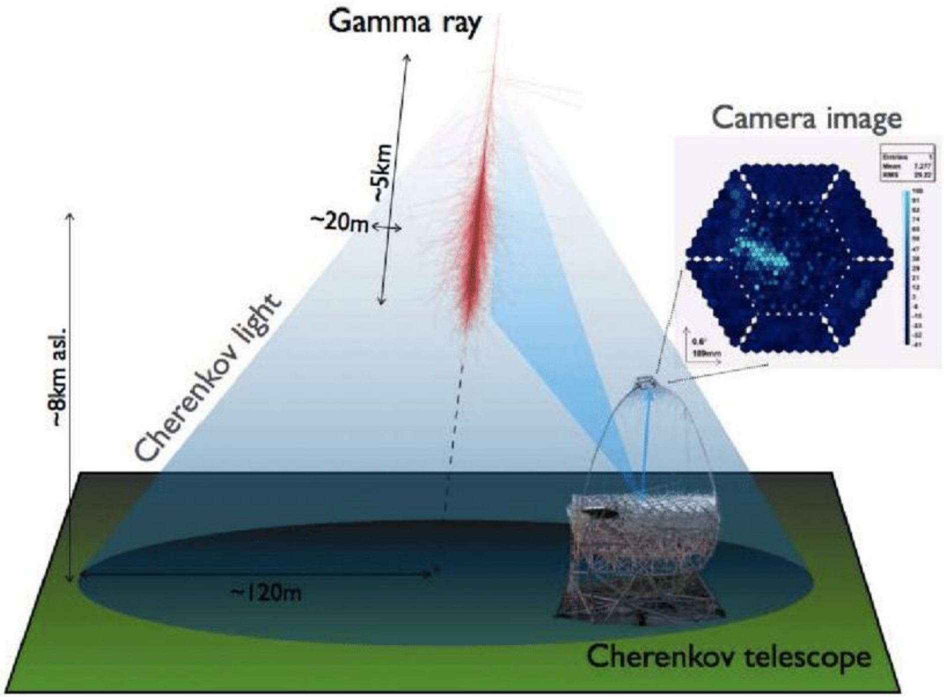
They are important even at lower energies in CTA



Background rejection

- ✓ sensitivity is constrained by background rejection power
- ✓ gamma-like-shower rates are different between models

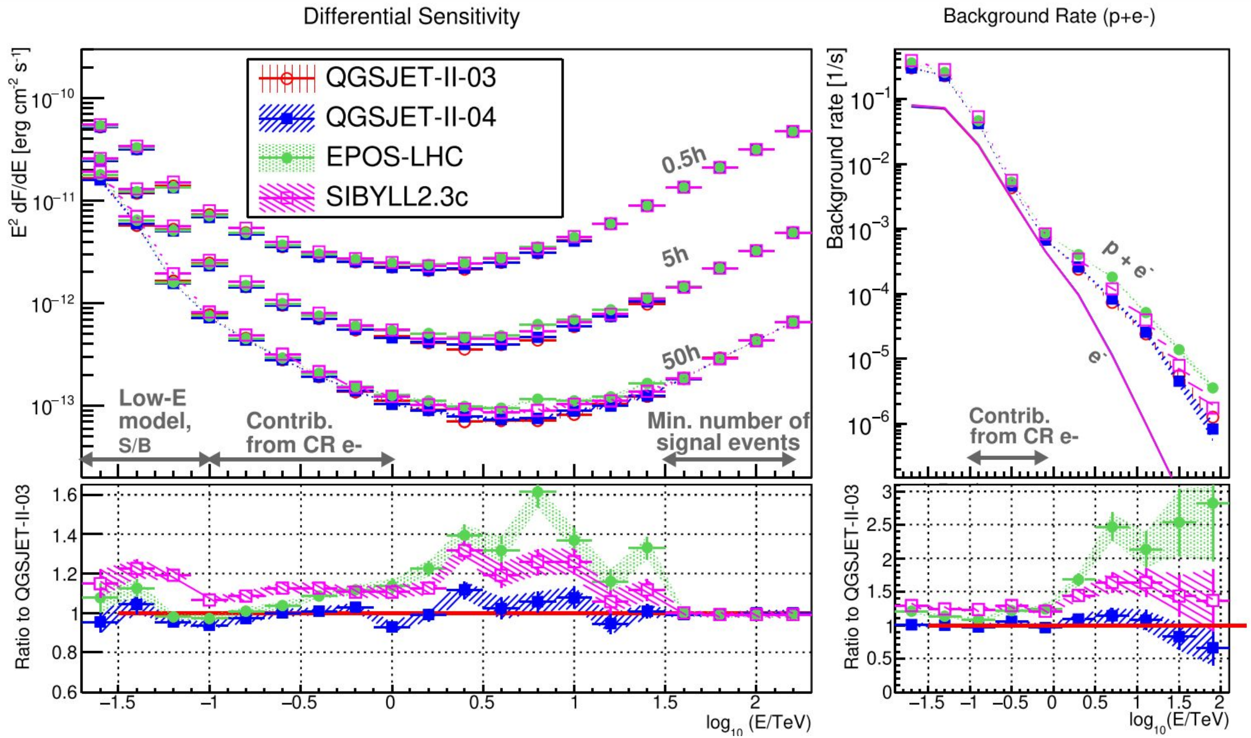
They are important even at lower energies in CTA



Background rejection

- ✓ sensitivity is constrained by background rejection power
- ✓ gamma-like-shower rates are different between models
- ✓ M. Ohishi et al

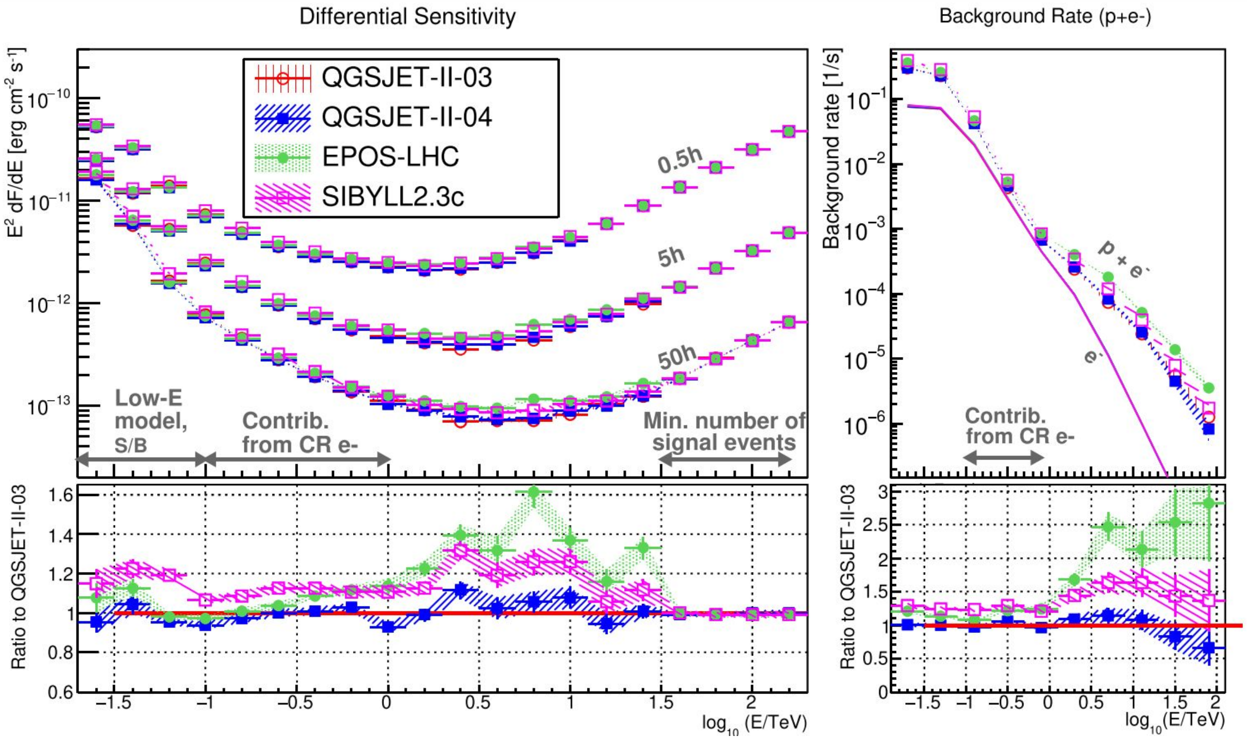
They are important even at lower energies in CTA



Background rejection

- ✓ sensitivity is constrained by background rejection power
- ✓ gamma-like-shower rates are different between models
- ✓ M. Ohishi et al

They are important even at lower energies in CTA



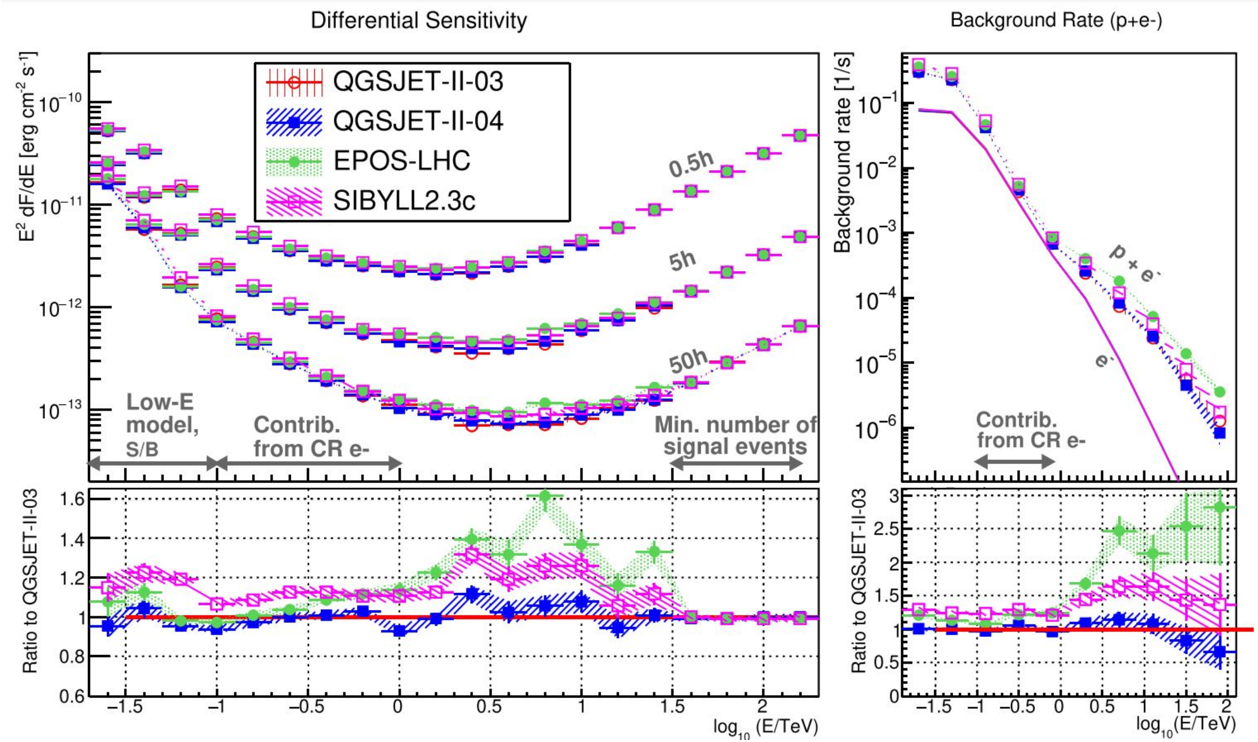
Background rejection

- ✓ sensitivity is constrained by background rejection power
- ✓ gamma-like-shower rates are different between models
- ✓ M. Ohishi et al

Computed sensitivity

- ✓ up to 30% different in the 1 TeV to 30 TeV region

They are important even at lower energies in CTA



Background rejection

- ✓ sensitivity is constrained by background rejection power
- ✓ gamma-like-shower rates are different between models
- ✓ M. Ohishi et al

Computed sensitivity

- ✓ up to 30% different in the 1 TeV to 30 TeV region
- ✓ problem or opportunity?

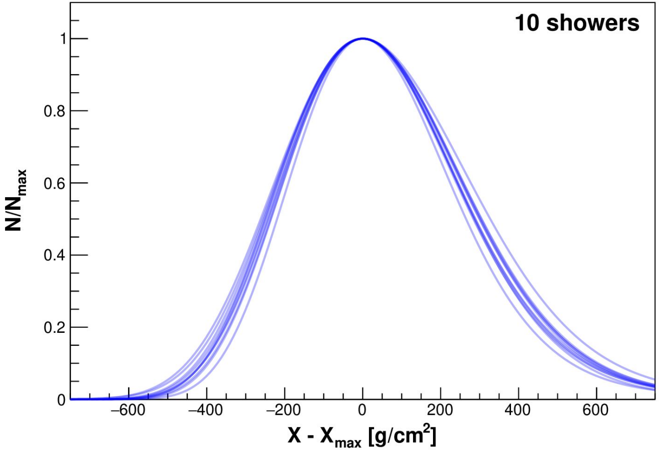
Parameterizations & reconstruction

lookup tables, signal subtraction of Cherenkov, template-based reco, etc.

Parameterizations & reconstruction

lookup tables, signal subtraction of Cherenkov, template-based reco, etc.

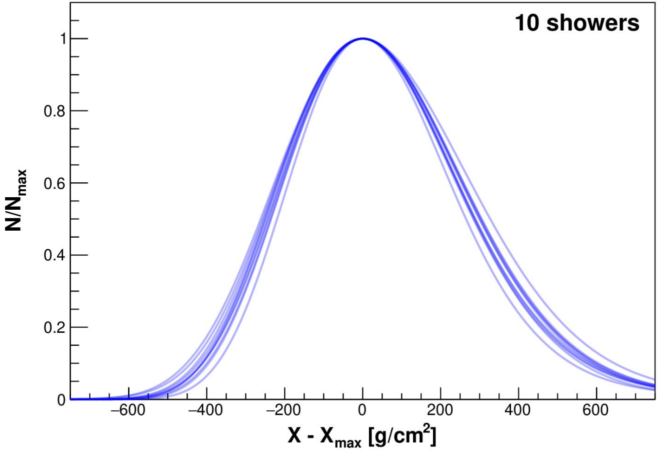
Shower universality



Parameterizations & reconstruction

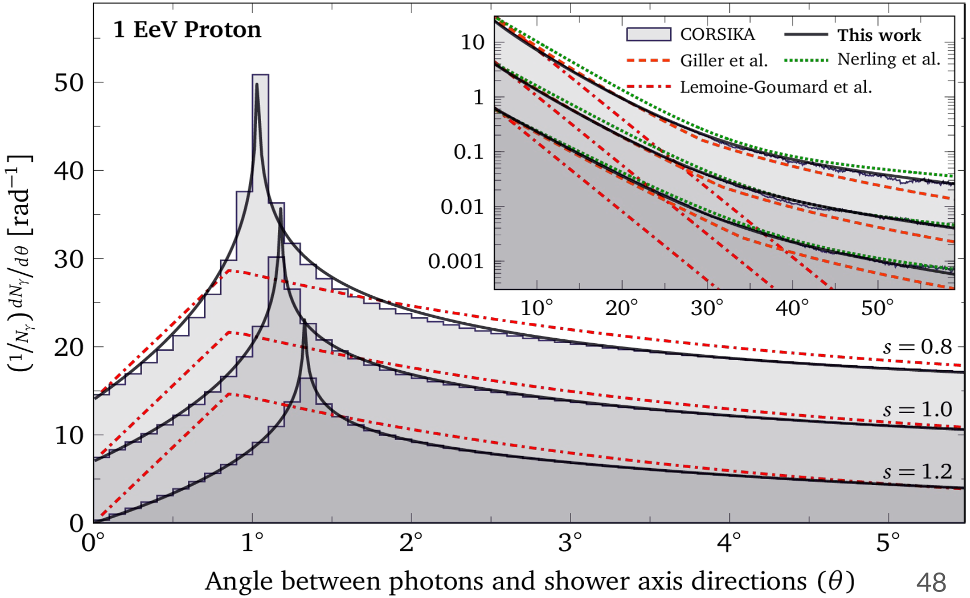
lookup tables, signal subtraction of Cherenkov, template-based reco, etc.

Shower universality



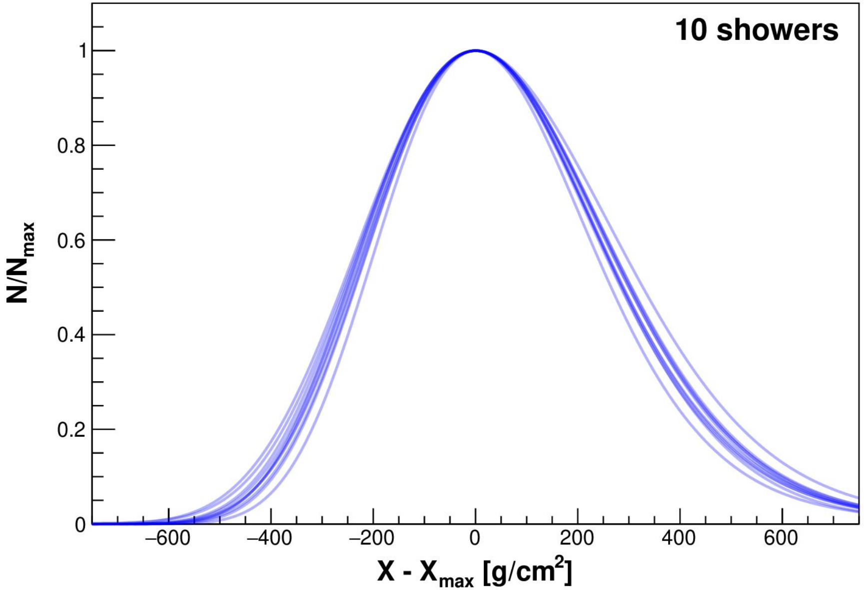
Cherenkov-light signal

✓ phenomenological description of photon angular distr.
✓ parametrization vs shower age and atmospheric height



Revisiting shower universality: anomalous showers

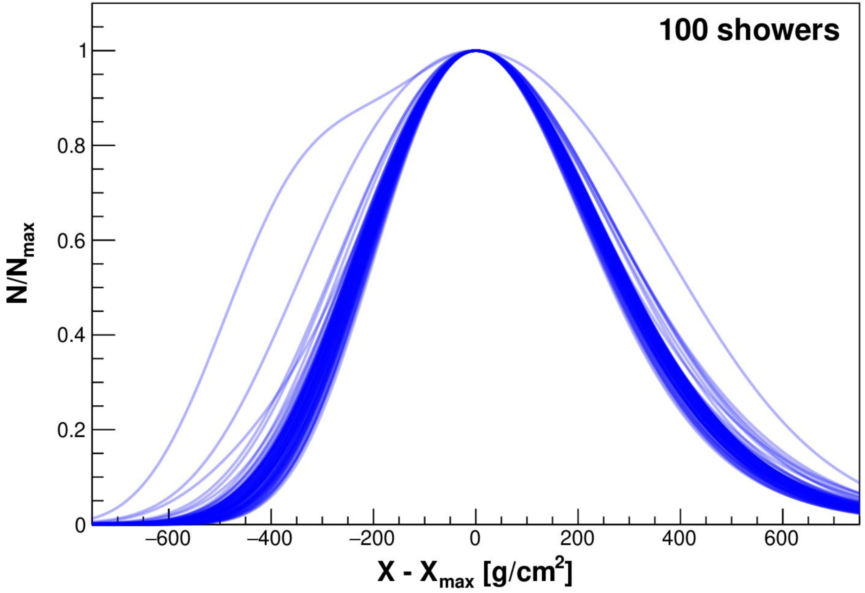
Extreme fluctuations



PROTON

Revisiting shower universality: anomalous showers

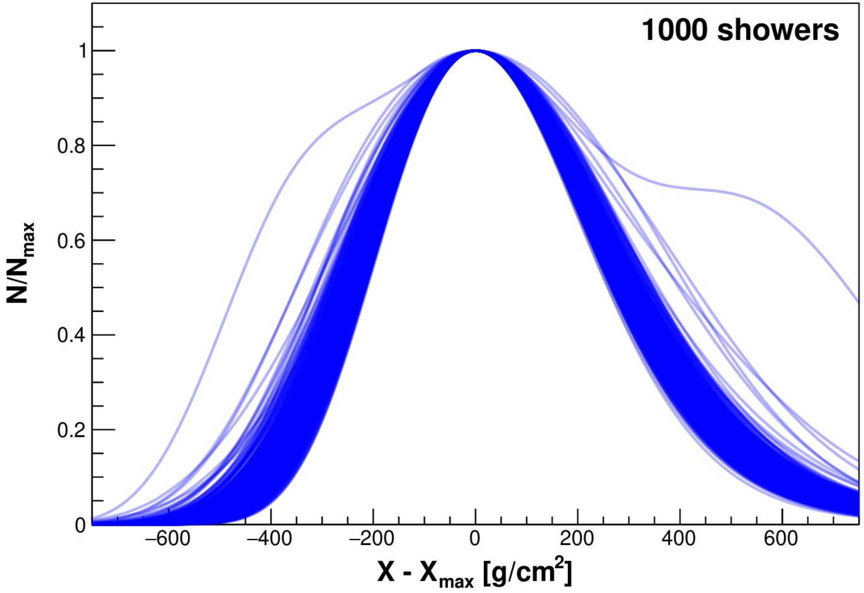
Extreme fluctuations



PROTON

Revisiting shower universality: anomalous showers

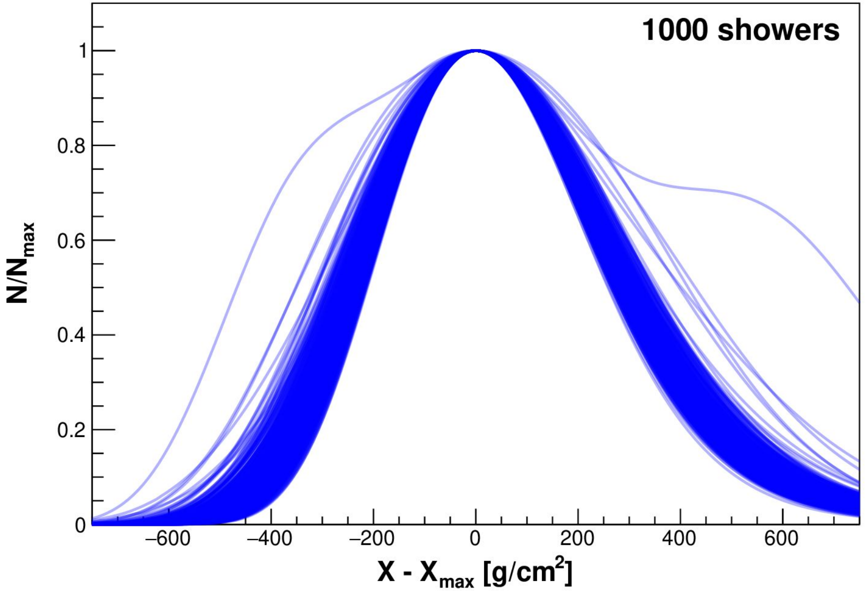
Extreme fluctuations



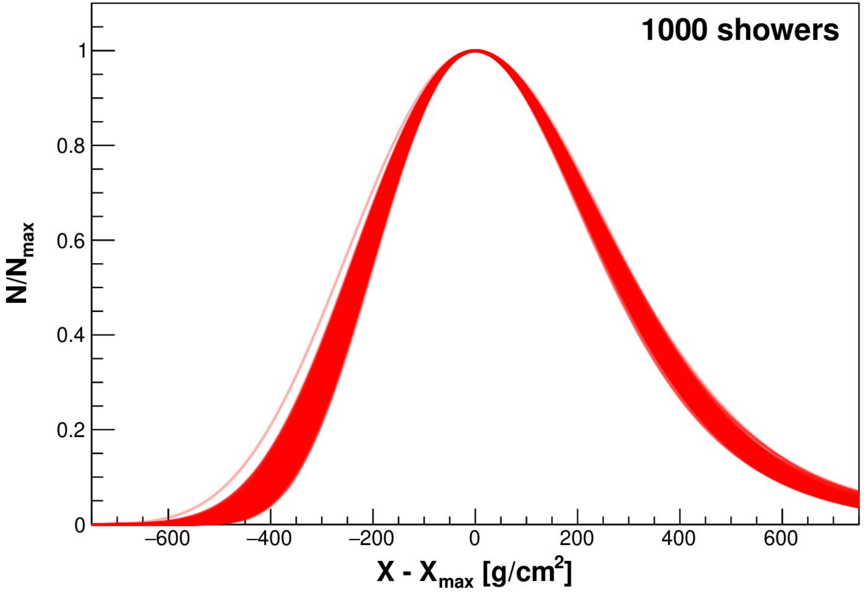
PROTON

Revisiting shower universality: anomalous showers

Extreme fluctuations are mass dependent



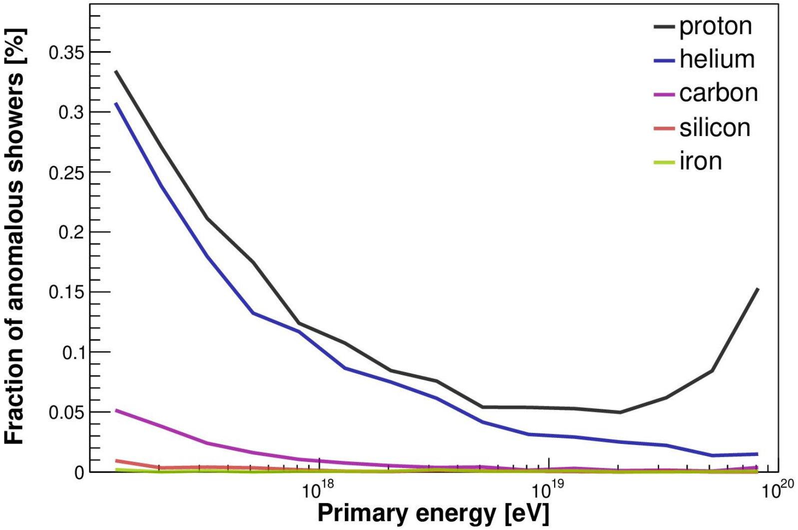
PROTON



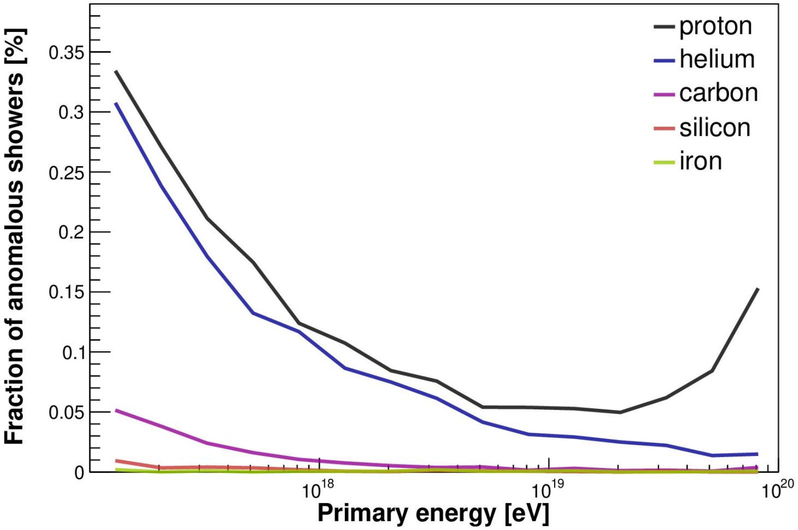
IRON

Can we probe mass composition using double-bump showers?

Can we probe mass composition using double-bump showers?



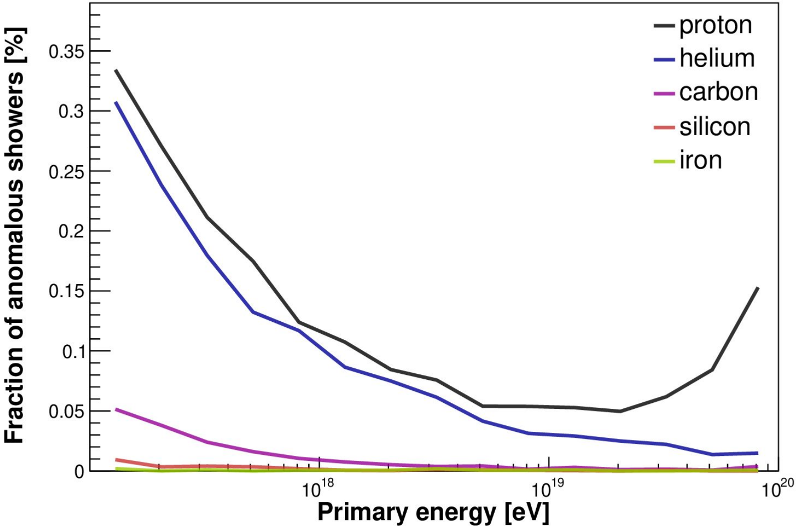
Can we probe mass composition using double-bump showers?



Can we measure those showers?

i. previous work on fluorescence shows statistics is too low
ii. alternative techniques have never been explored
iii. radio signal is sensitive to the longitudinal evolution

Can we probe mass composition using double-bump showers?



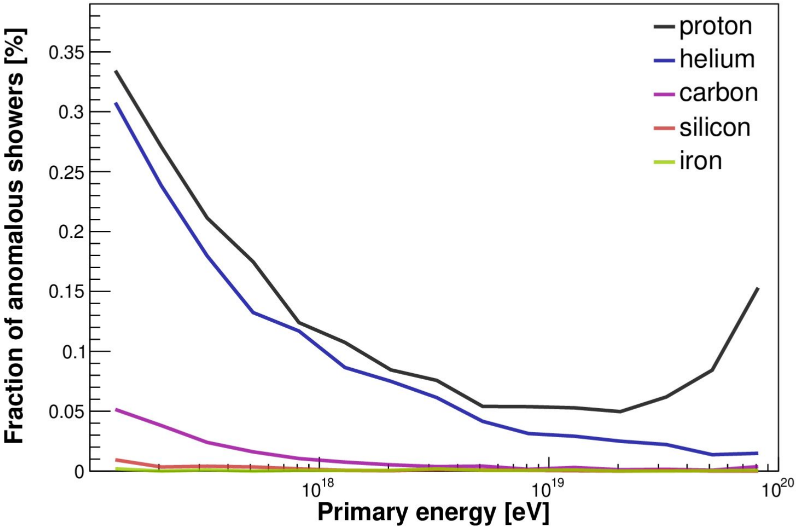
Can we measure those showers?

i. previous work on fluorescence shows statistics is too low
ii. alternative techniques have never been explored
iii. radio signal is sensitive to the longitudinal evolution

Detailed 3D simulations are required. Our strategy:

i. CONEX simulation of ~10^7 showers (0.05% are double bump)
ii. reprocessed the anomalous ones in 3D CORSIKA
iii. extracted the radio signal (electric field vs time)

Can we probe mass composition using double-bump showers?



<u>Can we measure those showers?</u>

i. previous work on fluorescence shows statistics is too low
ii. alternative techniques have never been explored
iii. radio signal is sensitive to the longitudinal evolution

<u>Detailed 3D simulations are required. Our strategy:</u>

i. CONEX simulation of ~10^7 showers (0.05% are double bump)
ii. reprocessed the anomalous ones in 3D CORSIKA
iii. extracted the radio signal (electric field vs time)

<u>We need a classification algorithm! Maybe machine learning?</u>

i. still ongoing, no conclusive results yet
ii. hopefully RNNs will be able to identify the outliers

ML: reconstruction of the depth of 1st interaction

<u>Motivation</u>

i. X_{max} is X_{first} + ΔX_{max} (convolved)
ii. Reconstruction of X_{first} would allow us for a direct access the properties of the primary

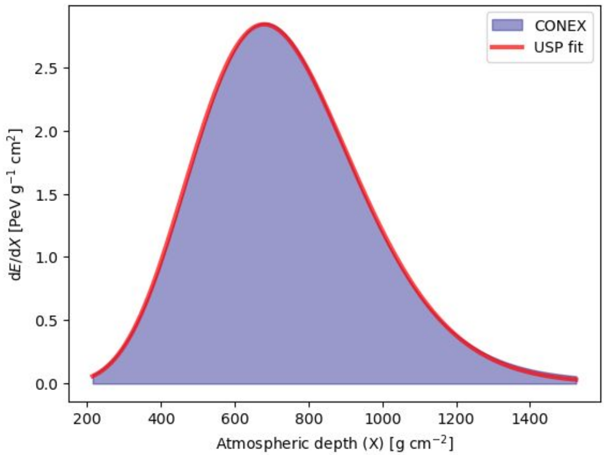
ML: reconstruction of the depth of 1st interaction

Motivation

i. X_{max} is X_{first} + ΔX_{max} (convolved)
ii. Reconstruction of X_{first} would allow us for a direct access the properties of the primary

Benchmark model: Gaisser-Hillas parameters

$$N' = \left(1 + \frac{RX'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{LR}\right)$$



ML: reconstruction of the depth of 1st interaction

Motivation

i. X_{max} is X_{first} + ΔX_{max} (convolved)
ii. Reconstruction of X_{first} would allow us for a direct access the properties of the primary

Benchmark model: Gaisser-Hillas parameters

$$N' = \left(1 + \frac{RX'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{LR}\right)$$

ML: reconstruction of the depth of 1st interaction

Motivation

i. X_{max} is X_{first} + ΔX_{max} (convolved)

ii. Reconstruction of X_{first} would allow us for a direct access the properties of the primary

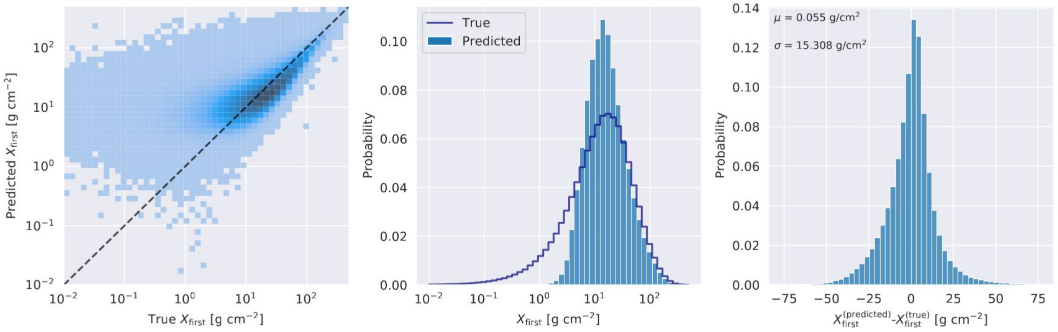
Benchmark model: Gaisser-Hillas parameters

$$N' = \left(1 + \frac{RX'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{LR}\right)$$

Benchmark MLP

i. trained on 9 x 10^6 showers (p, He, C, Si, Fe from 10^{17-20} eV)

ii. two layers with 64 nodes each



ML: reconstruction of the depth of 1st interaction

Motivation

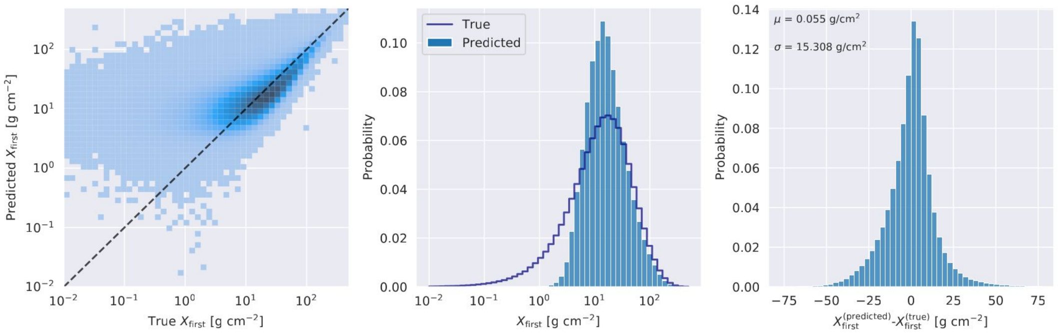
i. X_{max} is X_{first} + ΔX_{max} (convolved)
ii. Reconstruction of X_{first} would allow us for a direct access the properties of the primary

Benchmark model: Gaisser-Hillas parameters

$$N' = \left(1 + \frac{RX'}{L}\right)^{R^{-2}} \exp\left(-\frac{X'}{LR}\right)$$

Benchmark MLP

i. trained on 9 x 10^6 showers (p, He, C, Si, Fe from 10^{17-20} eV)
ii. two layers with 64 nodes each



Ongoing

i. networks analyzing directly the shower profile
ii. more complex networks, different types of layers
iii. effect of limiting the observed profile range

Preliminary results on X_{first} reconstruction using MLPs

Network configuration

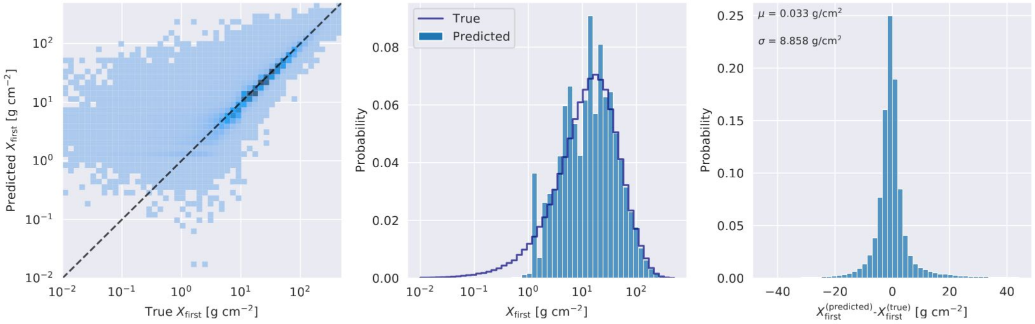
i. three dense layers with 1024 nodes
ii. trained on 9×10^5 showers
iii. p, He, C, Si, Fe from 10^{17-20} eV

Preliminary results on X_{first} reconstruction using MLPs

Network configuration

i. three dense layers with 1024 nodes
ii. trained on 9 x 10^5 showers
iii. p, He, C, Si, Fe from 10^{17-20} eV

Full profile range (0 to 2000 g/cm²)

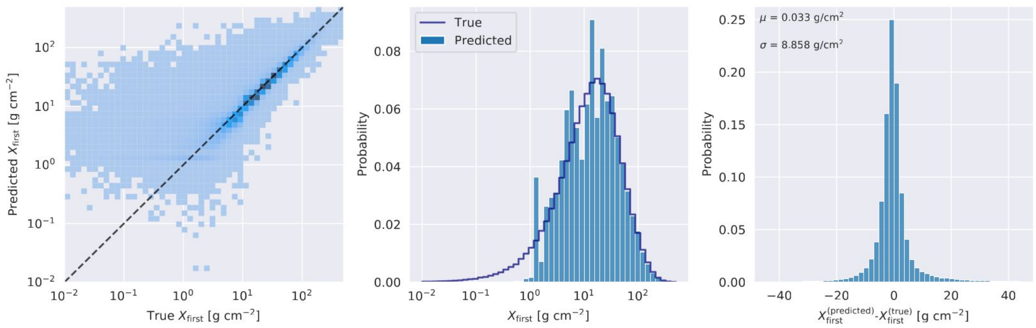


Preliminary results on X_{first} reconstruction using MLPs

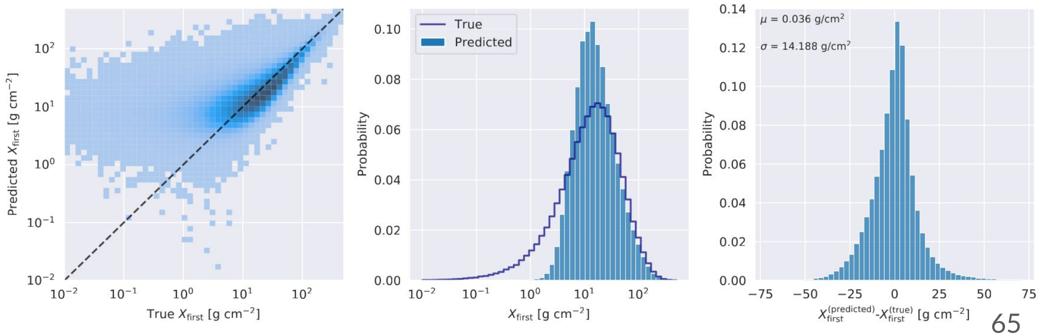
Network configuration

i. three dense layers with 1024 nodes
ii. trained on 9 x 10^5 showers
iii. p, He, C, Si, Fe from 10^{17-20} eV

Full profile range (0 to 2000 g/cm²)



600 g/cm² around Xmax



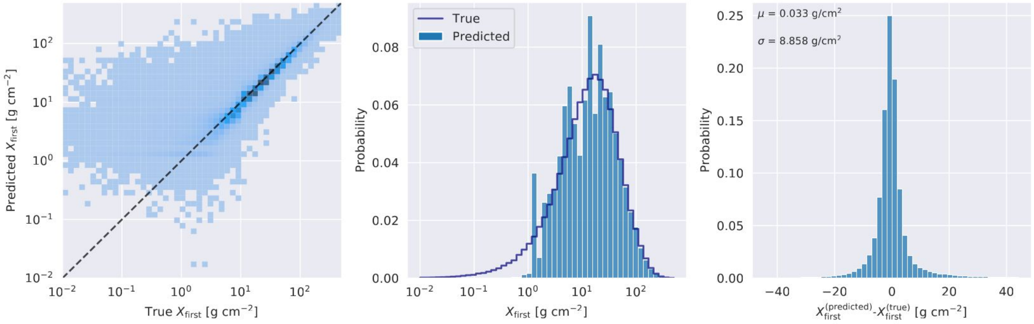
Preliminary results on X_{first} reconstruction using MLPs

<u>Network configuration</u>

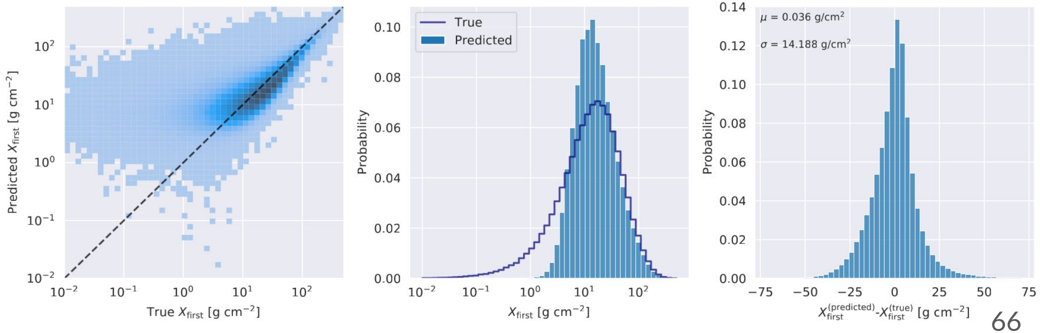
i. three dense layers with 1024 nodes
ii. trained on 9×10^5 showers
iii. p, He, C, Si, Fe from 10^{17-20} eV

<u>Overall</u> - improvement over our benchmark model

<u>Full profile range (0 to 2000 g/cm²)</u>



<u>600 g/cm² around Xmax</u>



Summary & closing remarks

- ✓ from Pelotas, but living in São Carlos, working as a postdoc at USP
- ✓ our group is interested in many aspects related to extensive air showers
  - Cherenkov detection, fluorescence detection, radio detection, and so on
  - air shower physics, shower modelling, and proposing new techniques
  - hadronic interactions and systematic uncertainties
- ✓ some expertise in simulation and understandment of analysis tools
- ✓ interest in applying Machine Learning (Andrés, Bruna)
- ✓ search for exotic particles (Tales)