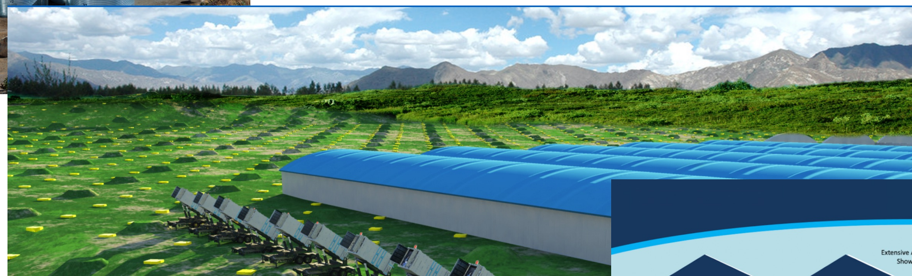
# Two-layer water Cherenkov detector array for measurement of cosmic ray electrons and gamma-ray observations

Andrii Neronov
APC Paris and EPFL

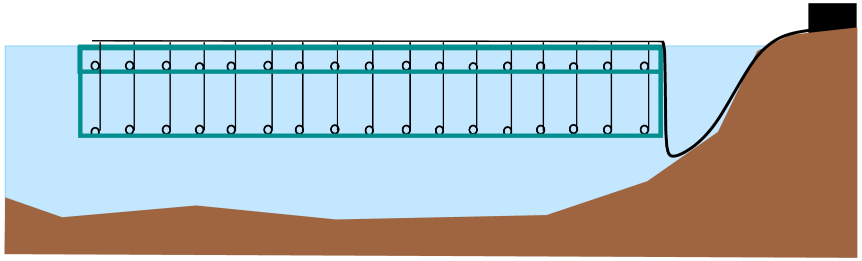
The technique of "Water Cherenkov Detector Arrays (WCDA)

MILAGRO

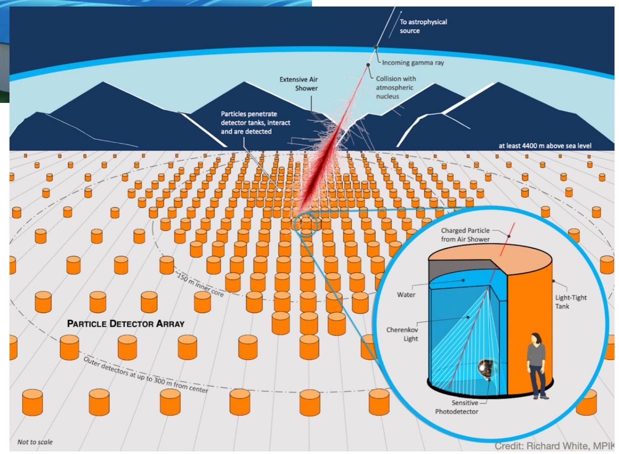
HAWC



LHAASO



$\mu WCDA$




SWGO

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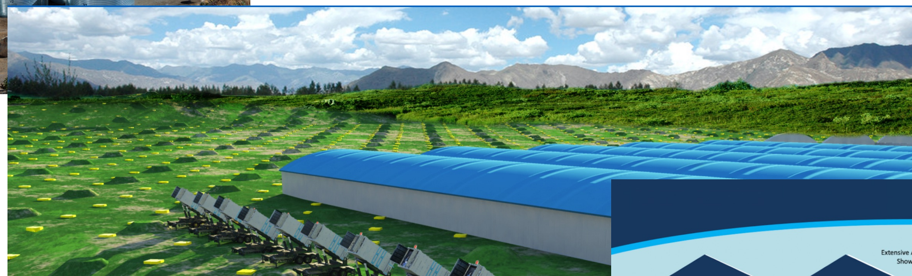
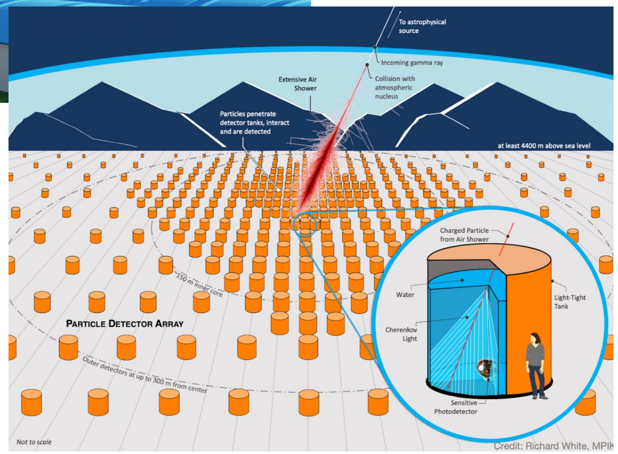
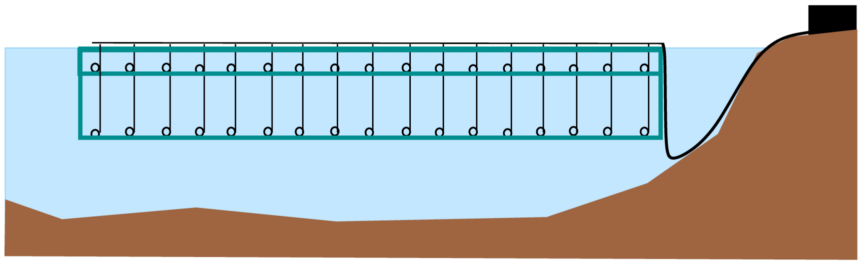

LHAASO



SWGO


$\mu WCDA$

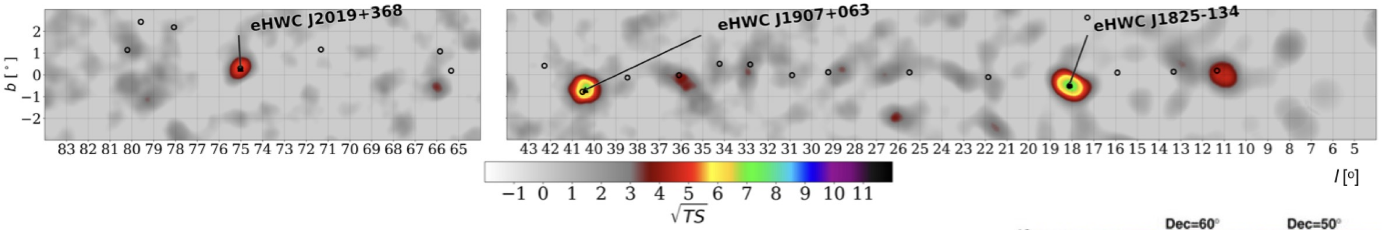
# Introduction: WCDA at the high-energy frontier of astronomy

Air shower arrays and, in particular, WCDA type detectors have been successfully used for gamma-ray observations up to the PeV energy range.

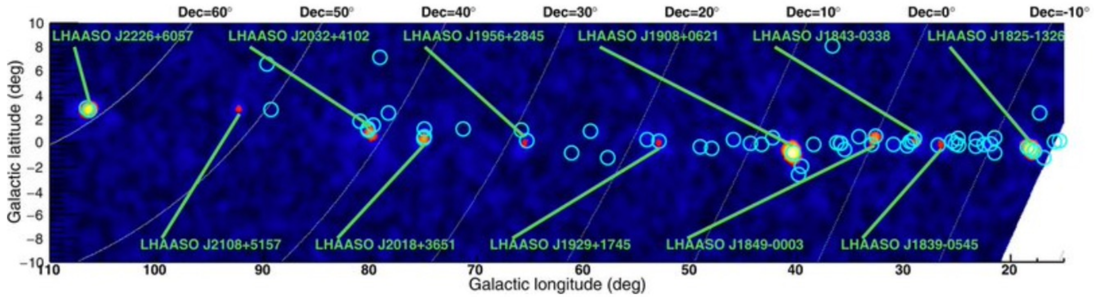
Isolated sources in the Milky Way galaxy are detected at E>100 TeV energy. Diffuse emission from the interstellar medium is detected up to PeV energy.

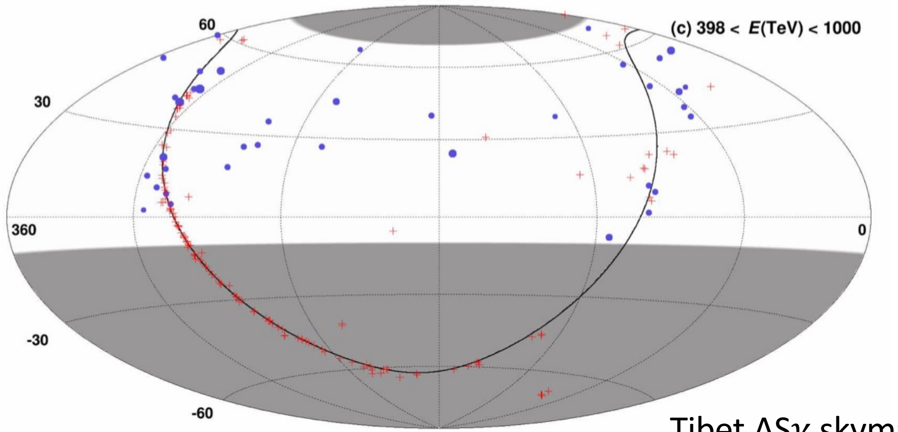
HAWC

HAWC skymap E>100 TeV

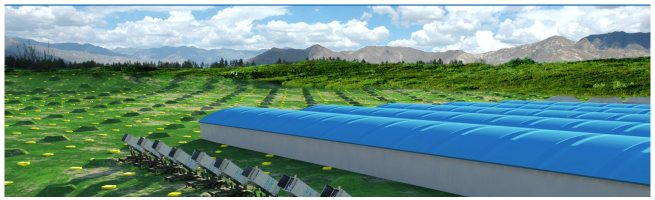



LHAASO skymap E>100 TeV



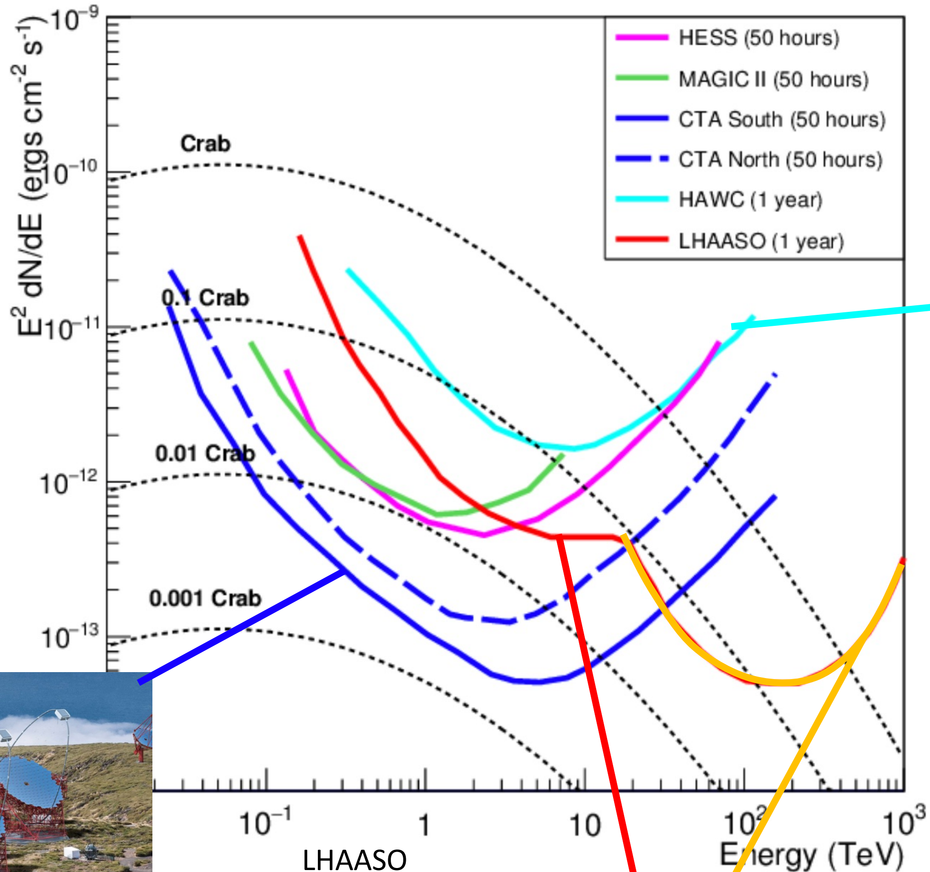

Tibet AS$\gamma$ skymap E>398 TeV



LHAASO

HAWC collab. https://arxiv.org/abs/1909.08609; Tibst AS$\gamma$ collab. https://arxiv.org/abs/2104.05181; LHAASO collab. https://ui.adsabs.harvard.edu/abs/2021Natur.594...33C/abstract

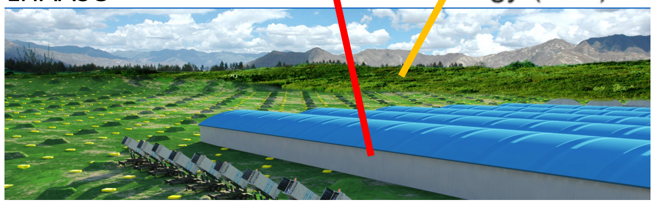
# Introduction: WCDA at the high-energy frontier of astronomy




HAWC

CTA

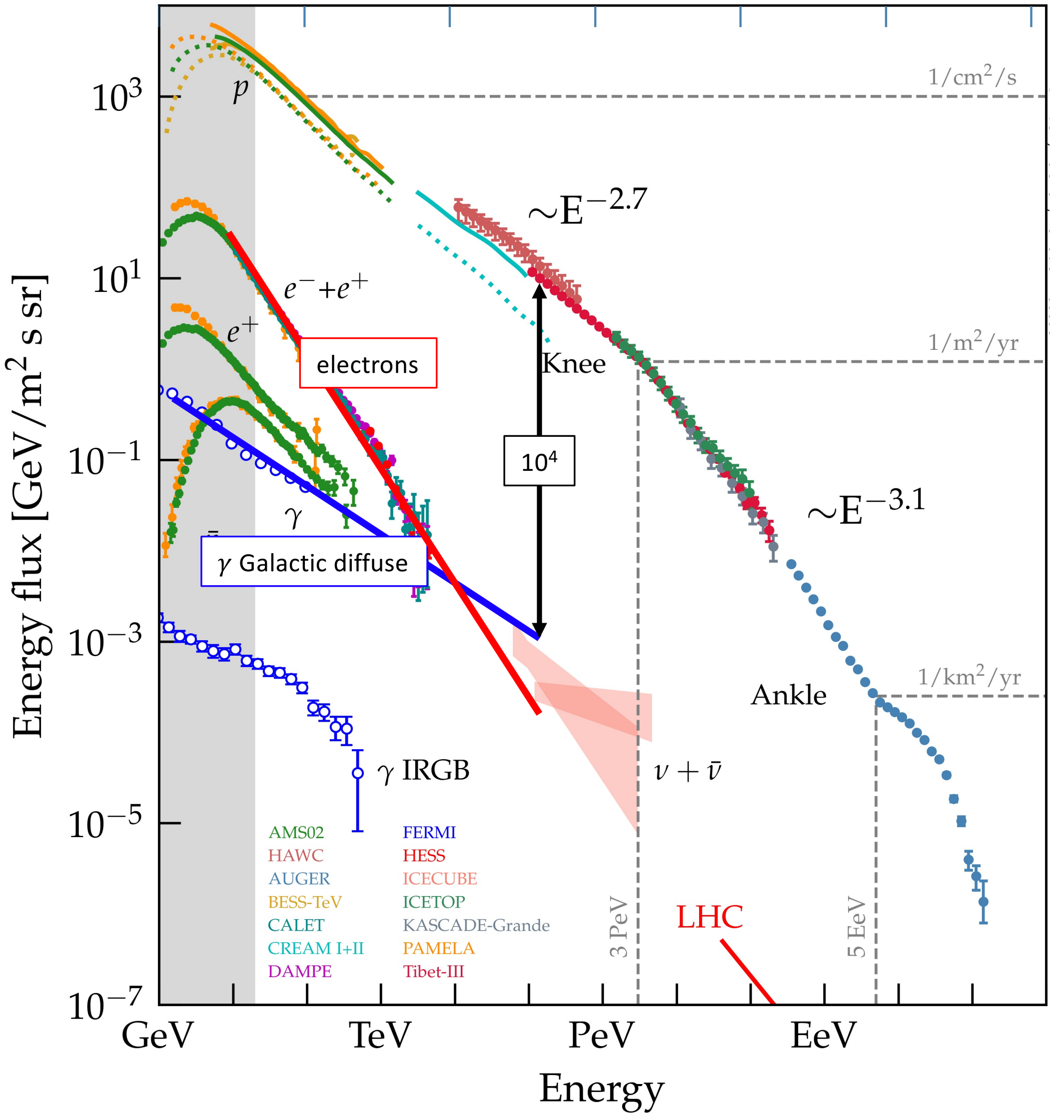
LHAASO

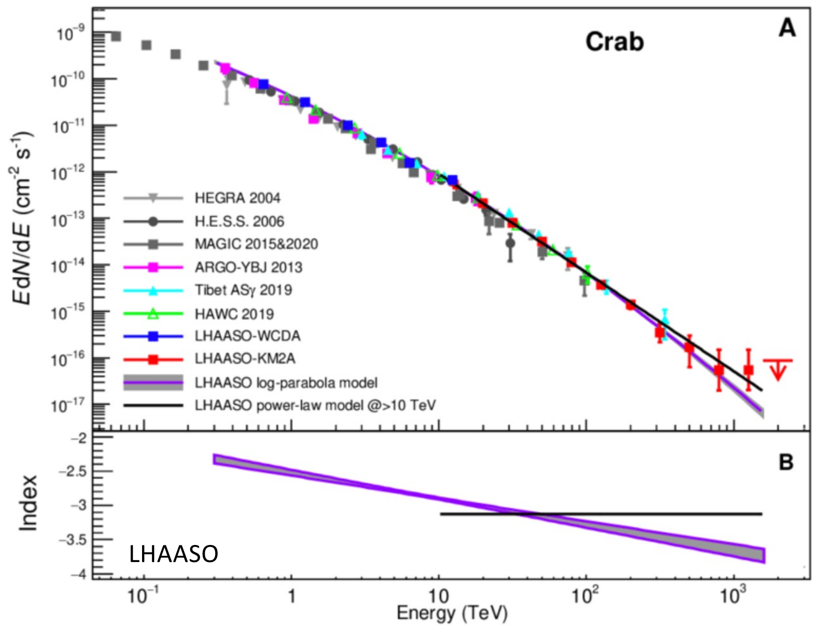


Compared to Cherenkov telescopes, WCDA have higher "duty cycle" (close to 100%), but lower efficiency of charged cosmic ray background suppresssion

……. unless muon counting is used to veto proton and nuclei induced Extensive Air Showers (EAS)

# Introduction: WCDA at the high-energy frontier of astronomy



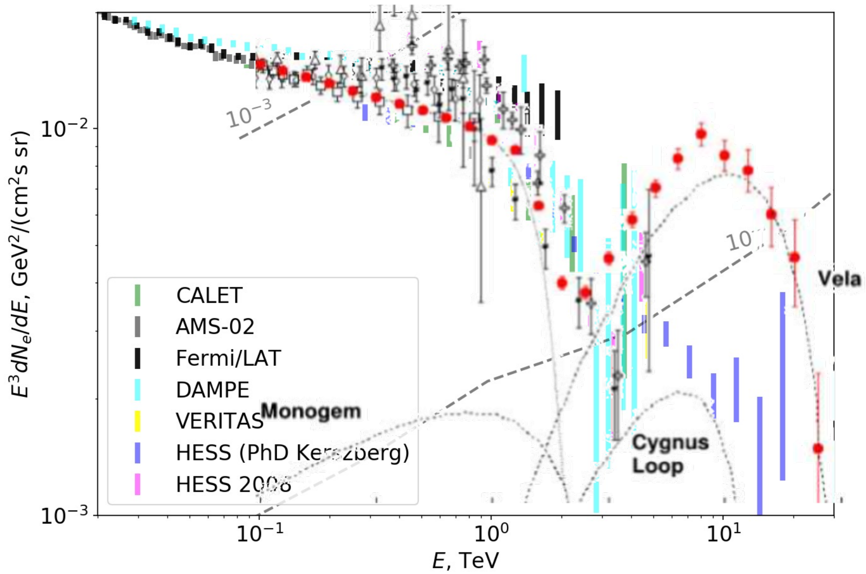




Point sources:

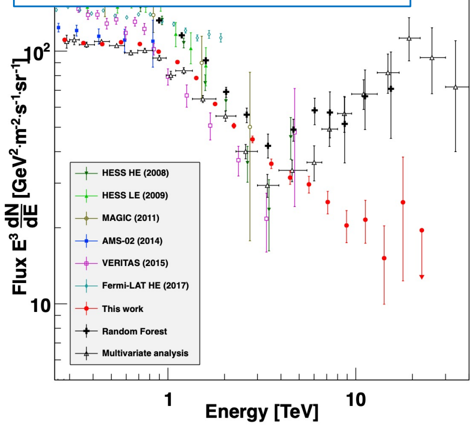
Example: Crab flux at PeV $10^{-16}\mathrm{cm}^{-2}\mathrm{s}^{-1}$; Signal statistics in a 300 m x 300 m detector is 3 events per year.

Cosmic ray flux: $3\times10^{-10}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}$; Background in 0.2º point spread function circular region on the sky is 100 events per year.

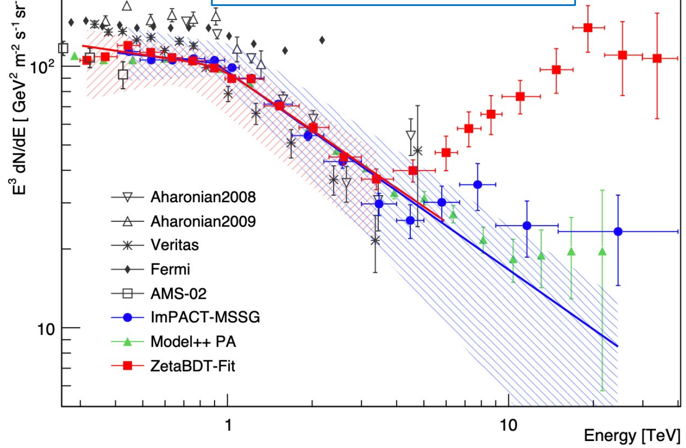
# Introduction: cosmic ray electron spectrum



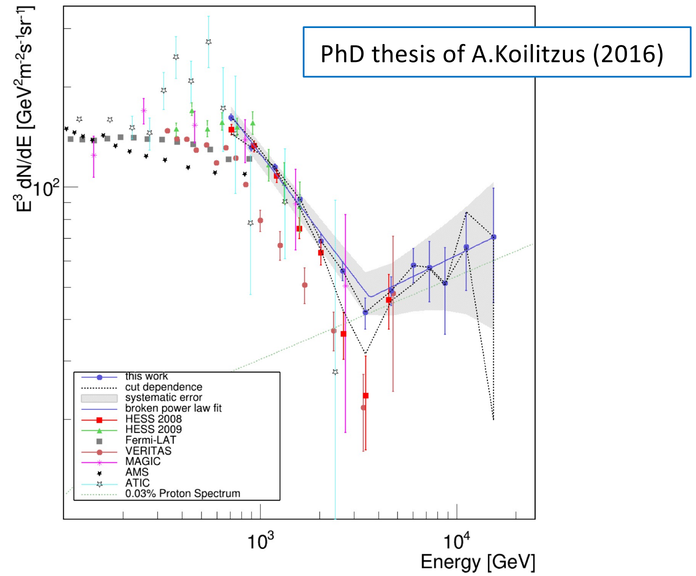

PhD thesis of D.Kerszberg (2017)




PhD thesis of M.Kraus (2018)




PhD thesis of A.Koilitzus (2016)



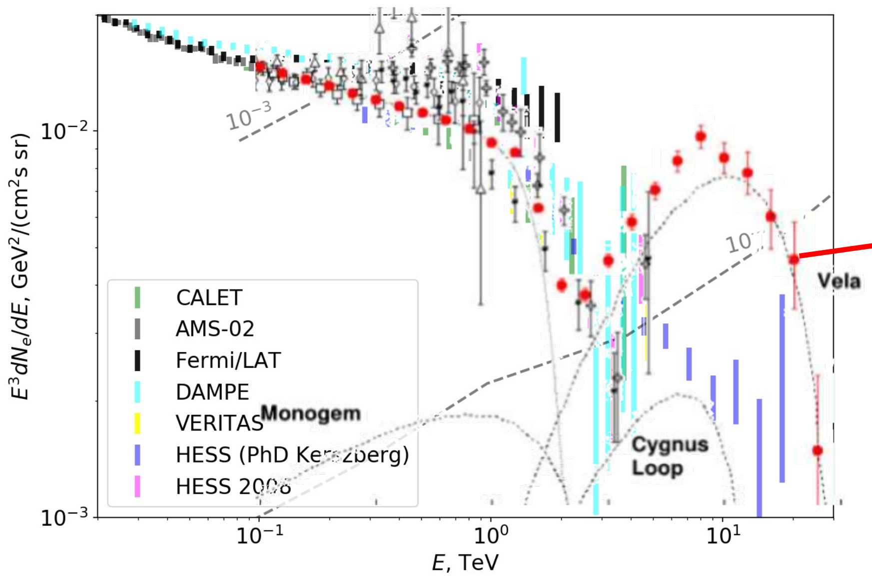

Electron spectrum is currently measured up to "several" TeV with space-based instruments (AMS-02, DAMPE, CALET).

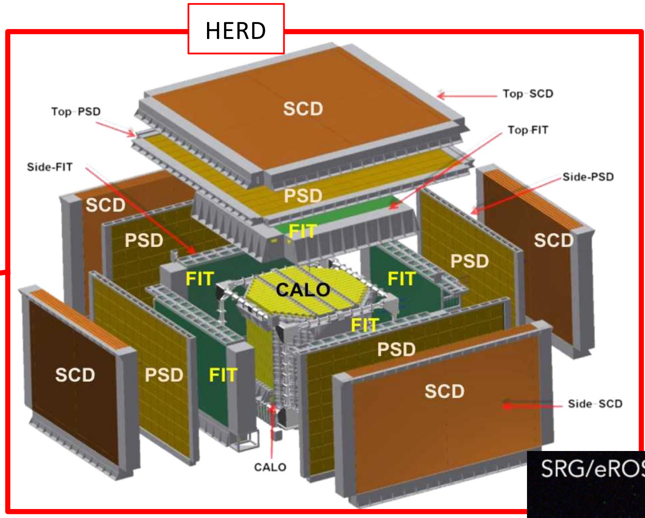
It has also been measured by HESS up to the same energy. Measurement up to 20 TeV has been tentatively reported (ICRC2017, no proceedings), but not published. Different versions of HESS analysis up to 10 TeV published in different PhD theses illustrate the challenge: different techniques of suppression of hadronic background give different results.

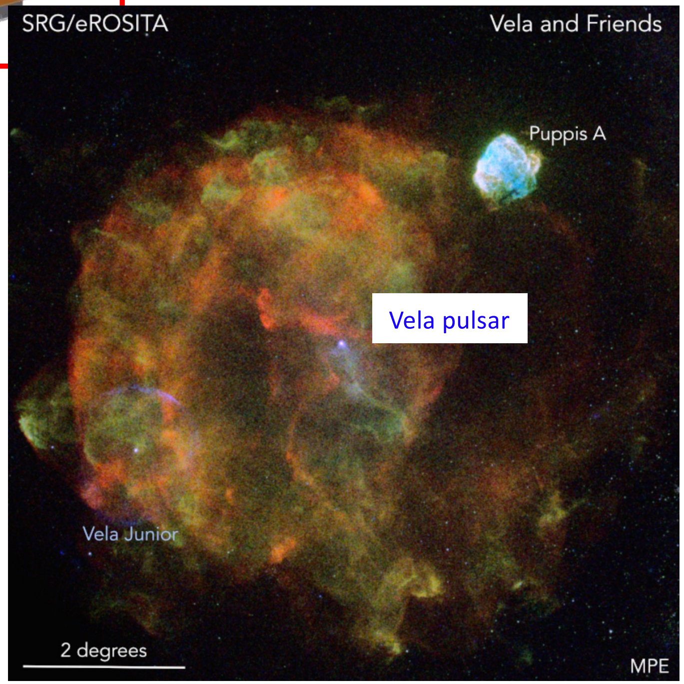
Main problem of ground-based measurements is high background of cosmic ray protons / nuclei: electron flux is $< 10^{-4}$ of the proton flux above 5 TeV.

https://arxiv.org/abs/2102.08456

# Introduction: cosmic ray electron spectrum



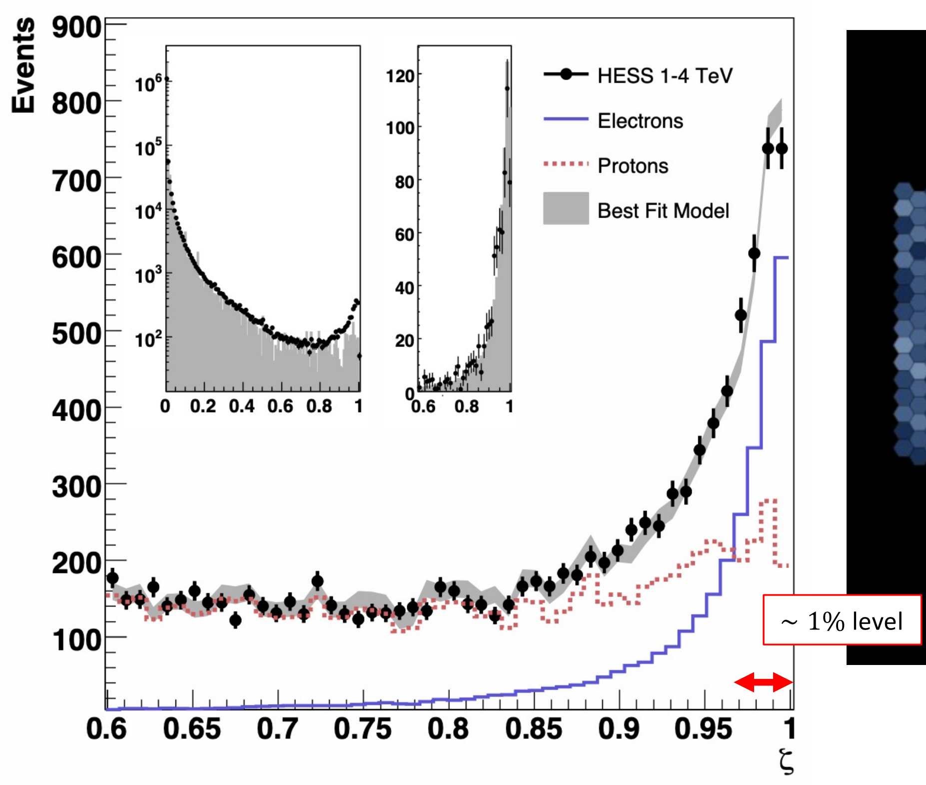

Origin of cosmic ray electrons is uncertain. They may be accelerated in the same sources as protons, but may also come from "electron-positron" sources, like pulsars and pulsar wind nebulae.

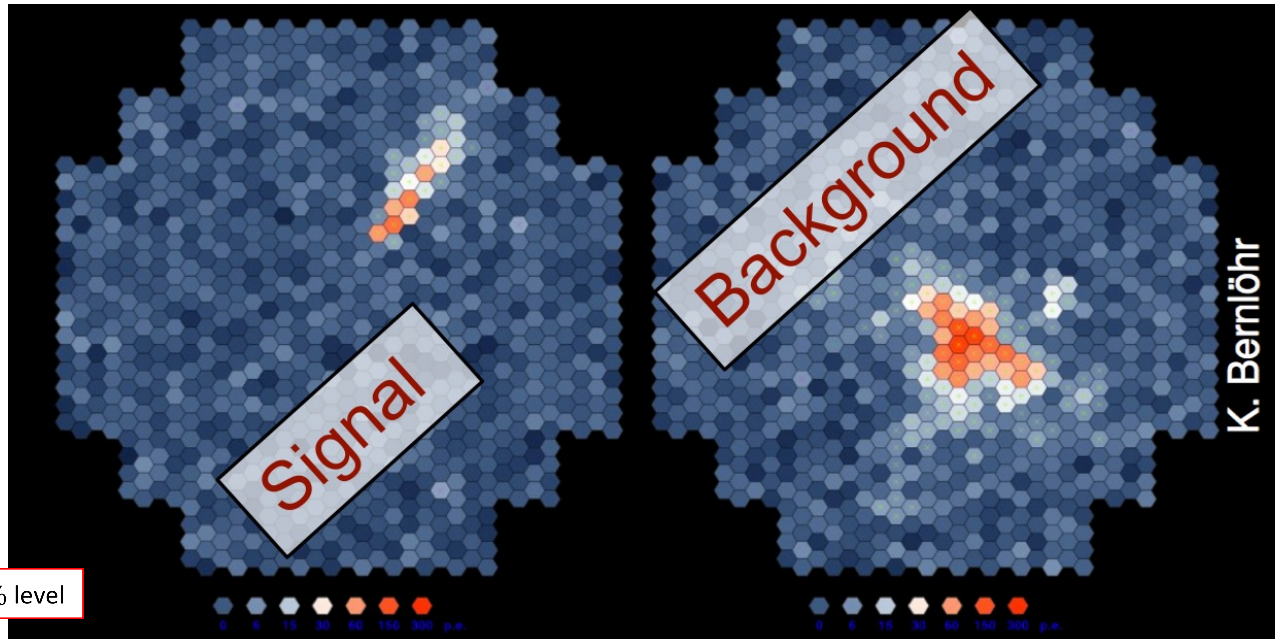
Electrons loose energy on synchrotron and inverse Compton scattering on time scale

$$t \sim 30 \left[\frac{E}{10\ \mathrm{TeV}}\right]^{-1} \left[\frac{U_{rad+B}}{1\frac{\mathrm{eV}}{\mathrm{cm}^3}}\right] \mathrm{kyr}$$

(compare with $> 10$ Myr for protons and atomic nuclei). They come from recent episodes of injection of high-energy particles in the "local Galaxy".

# Proton/nuclei cosmic ray particle background in Cherenkov telescopes




Air showers produced by protons and nuclei are wider, have multiple sub-showers. They also have larger amount of muons. This results in different pattern of Cherenkov light emission.

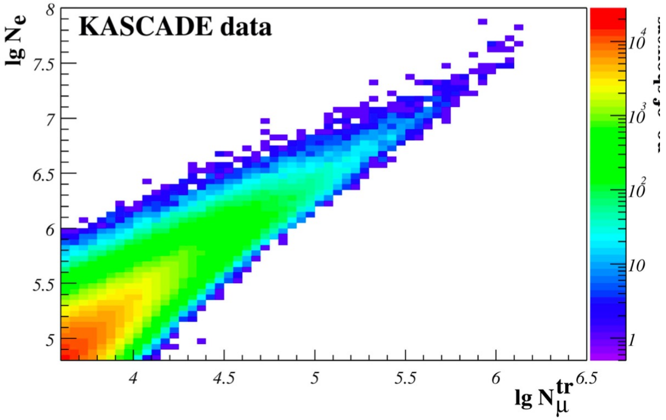
Boosted decision trees have been used to distinguish between proton / nuclei (background) and electron / positron (signal) images of extensive air showers. Alternative techniques, like "goodness of fit" of semi-analytical shower models were explored in PhD thesis works.

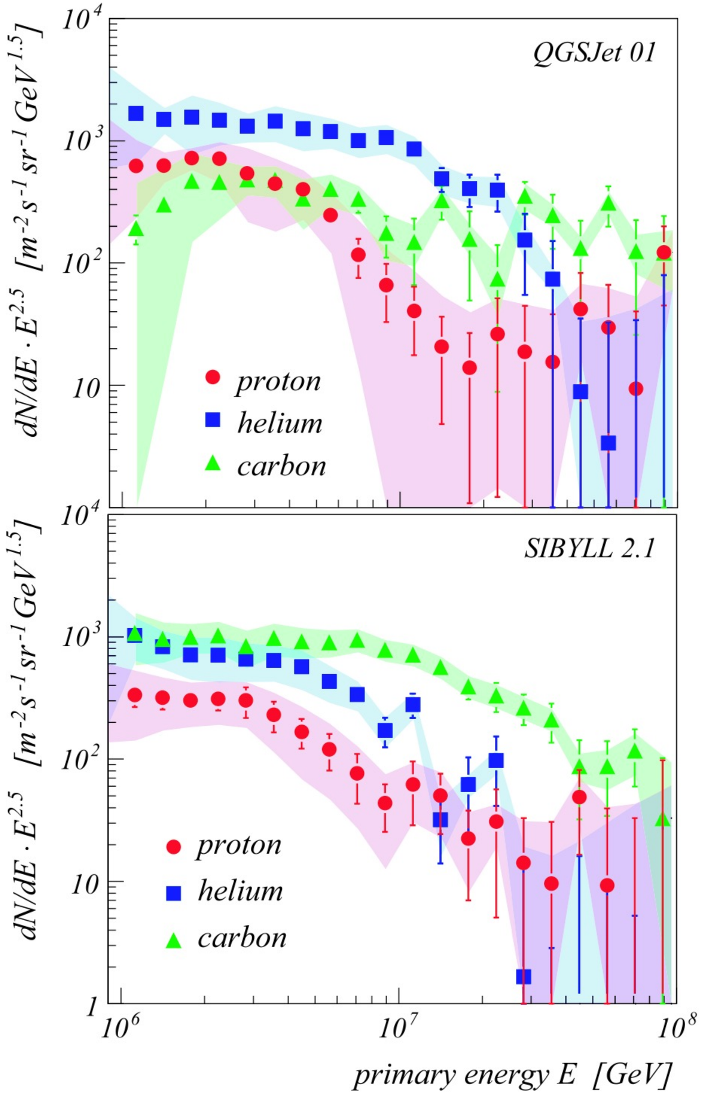
Electron showers are indistinguishable from gamma-ray showers and constitute "irreducible" background for gamma-ray observations.

Hess Collab. https://arxiv.org/abs/0811.3894

# Proton/nuclei cosmic ray particle background in air shower arrays

KASCADE



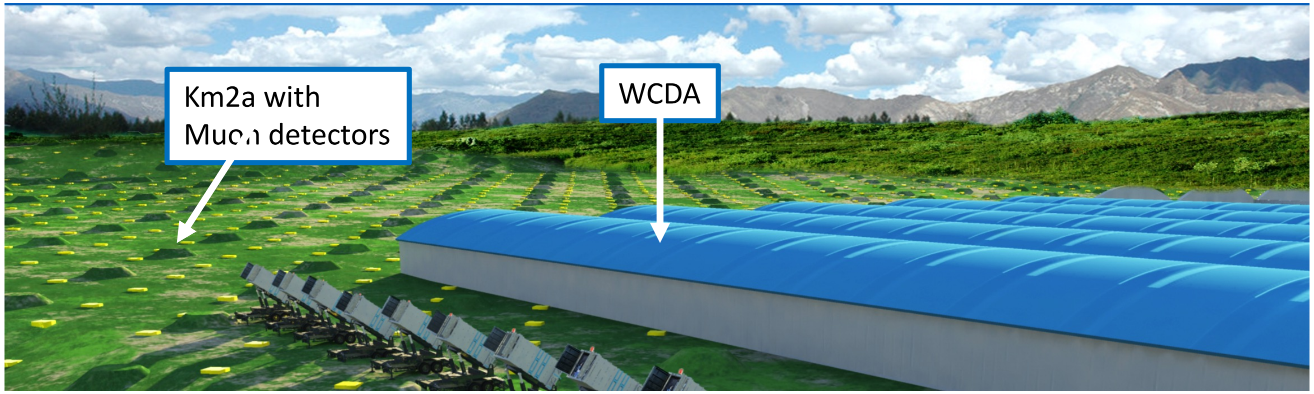

Identity of the primary particle of the air shower can be determined via sampling of muon content of the shower.

Showers produced by protons and atomic nuclei have much larger muon statistics, compared to showers produced by electrons / positrons / gamma-rays.

This technique has been used by KASCADE to measure cosmic ray composition changes across the knee of the cosmic ray spectrum.

Also used by Tibet AS$\gamma$, LHAASO km2a, …. but not by LHAASO WCDA and HAWC

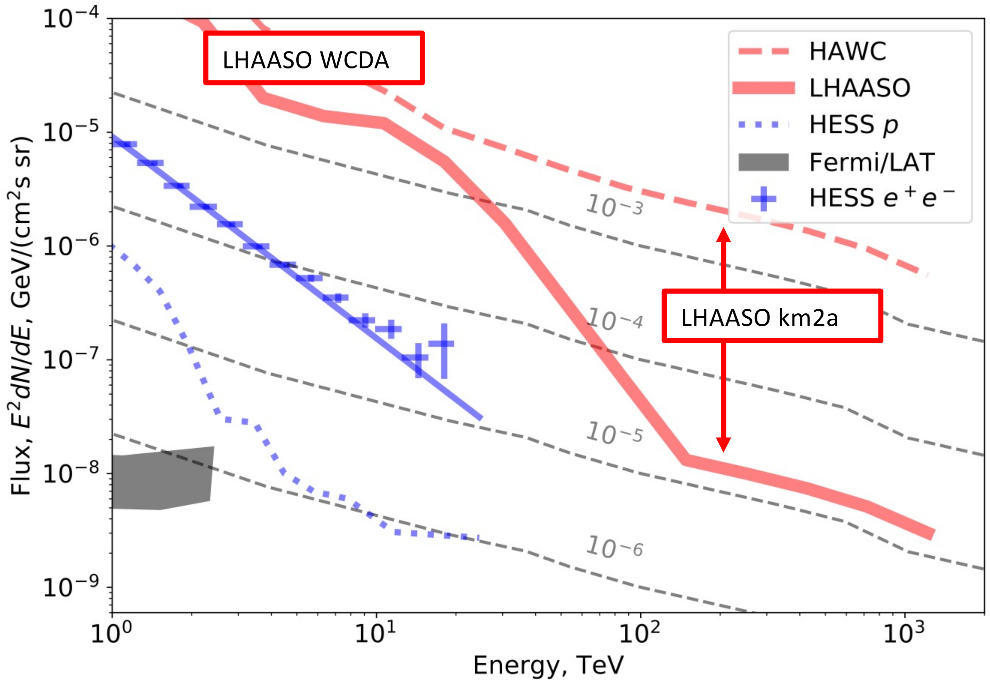
# Rejection of hadronic background using muon counting



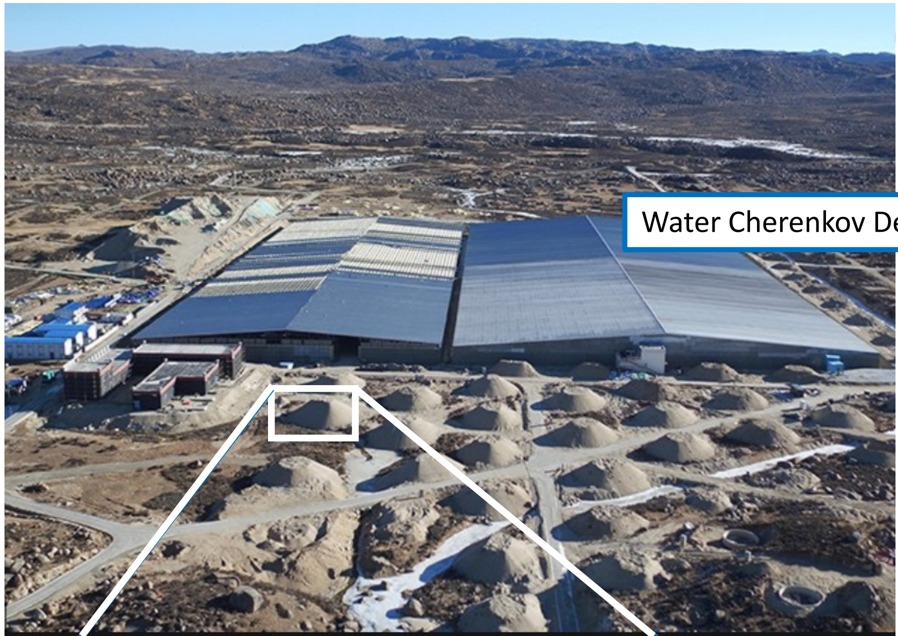

LHAASO

Muon detection technique is used by LHAASO km2a component to reject the background of hadronic air showers to increase sensitivity of gamma-ray observations above 100 TeV.

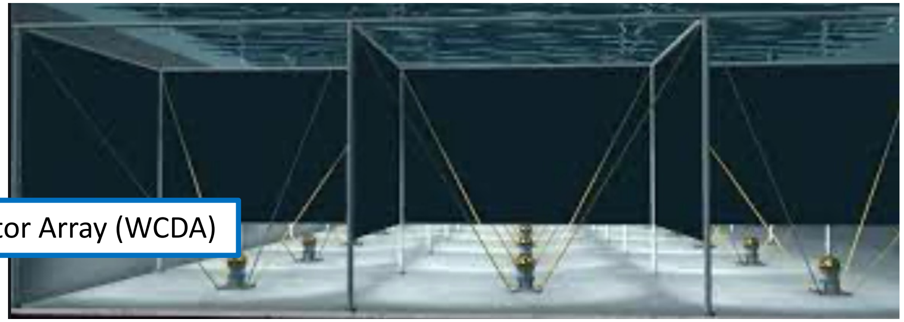
The improvement of background rejection (two orders of magnitude) works only above 100 TeV because LHAASO's muon detector catches only 4% of the air shower muon content. Efficiency of muon detection decreases below 100 TeV.

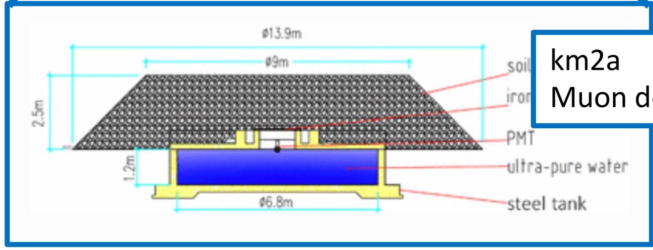


# Muon counting in LHAASO and SWGO



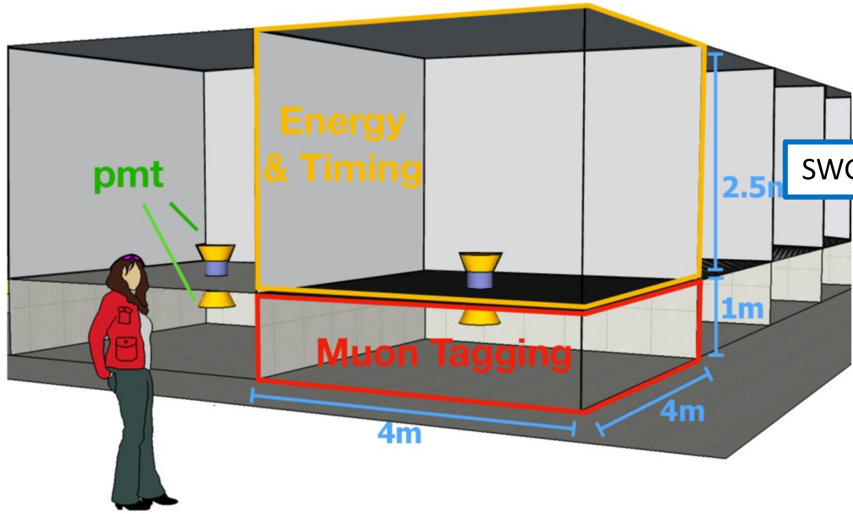
Water Cherenkov Detector Array (WCDA)






km2a
Muon detector(s) MD

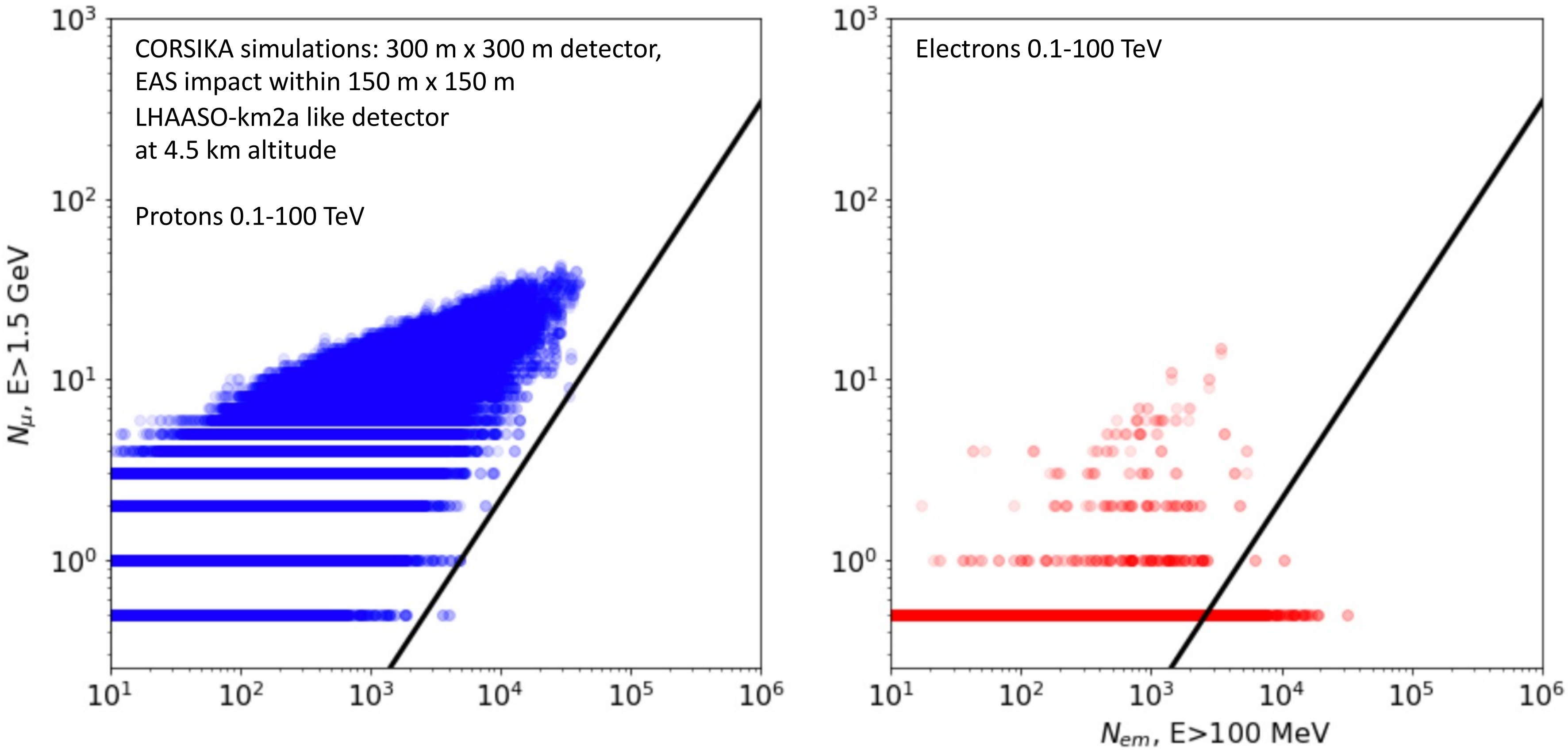
In LHAASO km2a (kilometre square array), muon detector (buried water tanks) loose efficiency below 100 TeV because of small number of muons in the air showers.




SWGO design

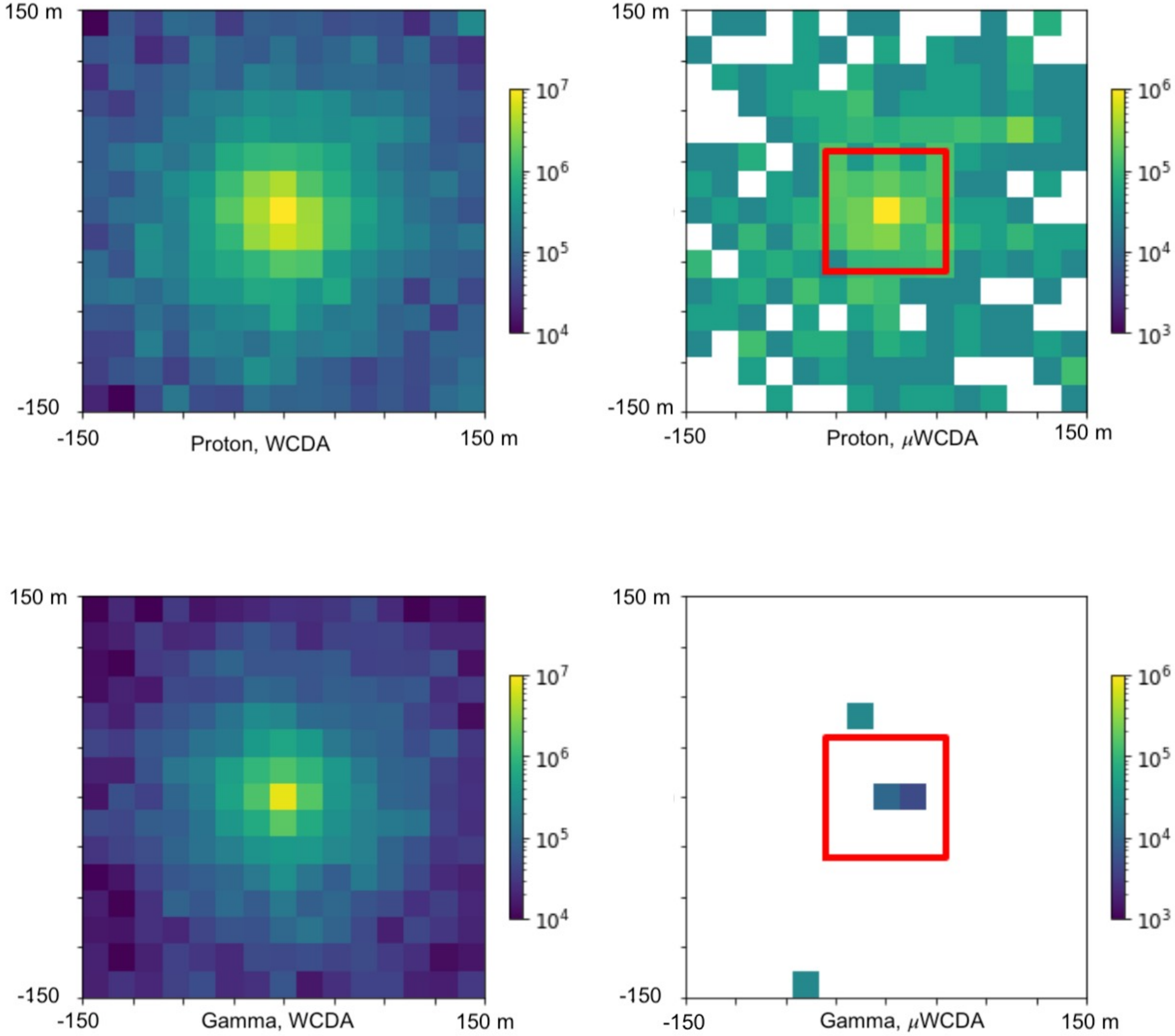
SWGO (HAWC successor in Southern hemisphere) plans to add second layer in WCDA, to do “muon tagging”.

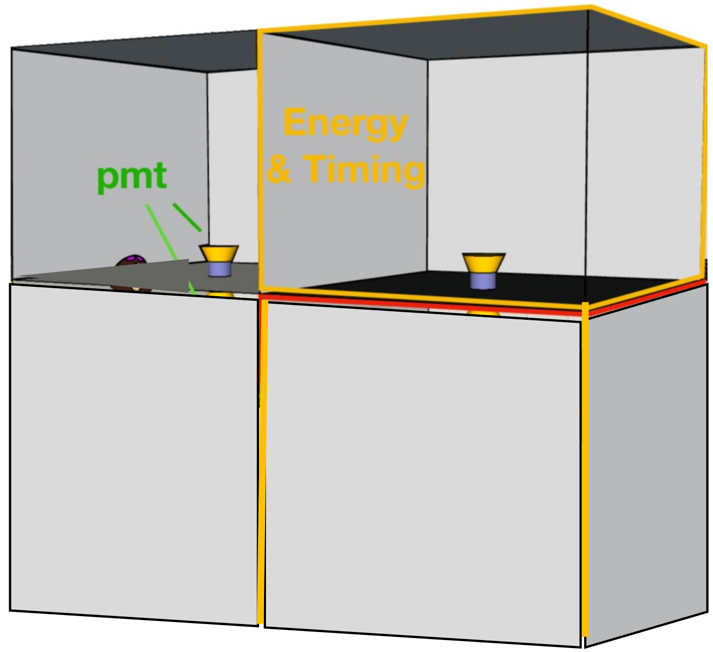
# Muon counting in LHAASO




The efficiency of hadronic background rejection in LHAASO-km2a like detector drops because of low statistics of muons.

# Electron / gamma / hadron discrimination in two-layered “pool”

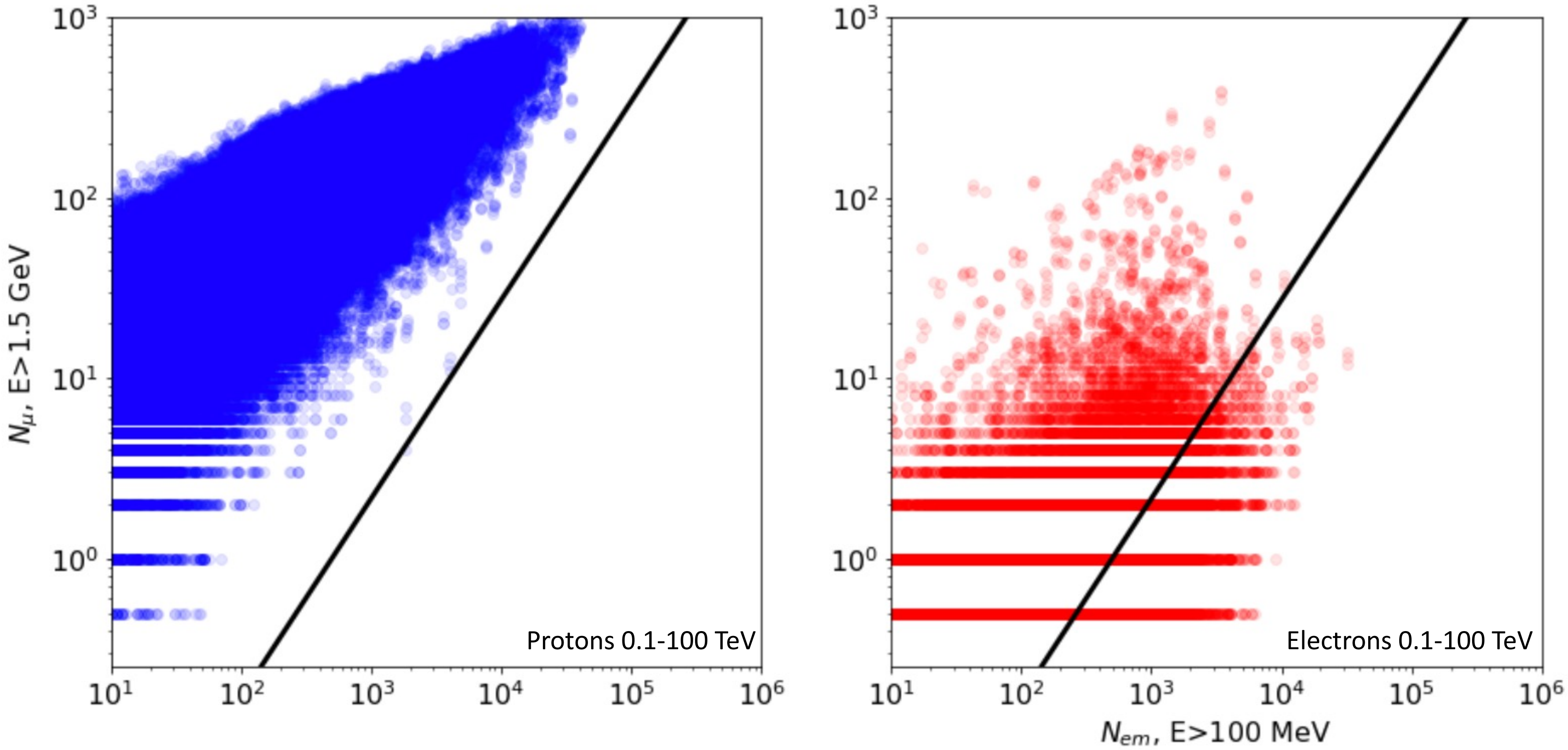



Gamma-electron / hadron separation can be improved in 10 TeV band if muons are counted by continuous detector (rather than sampled by a detector covering 4% of the area)

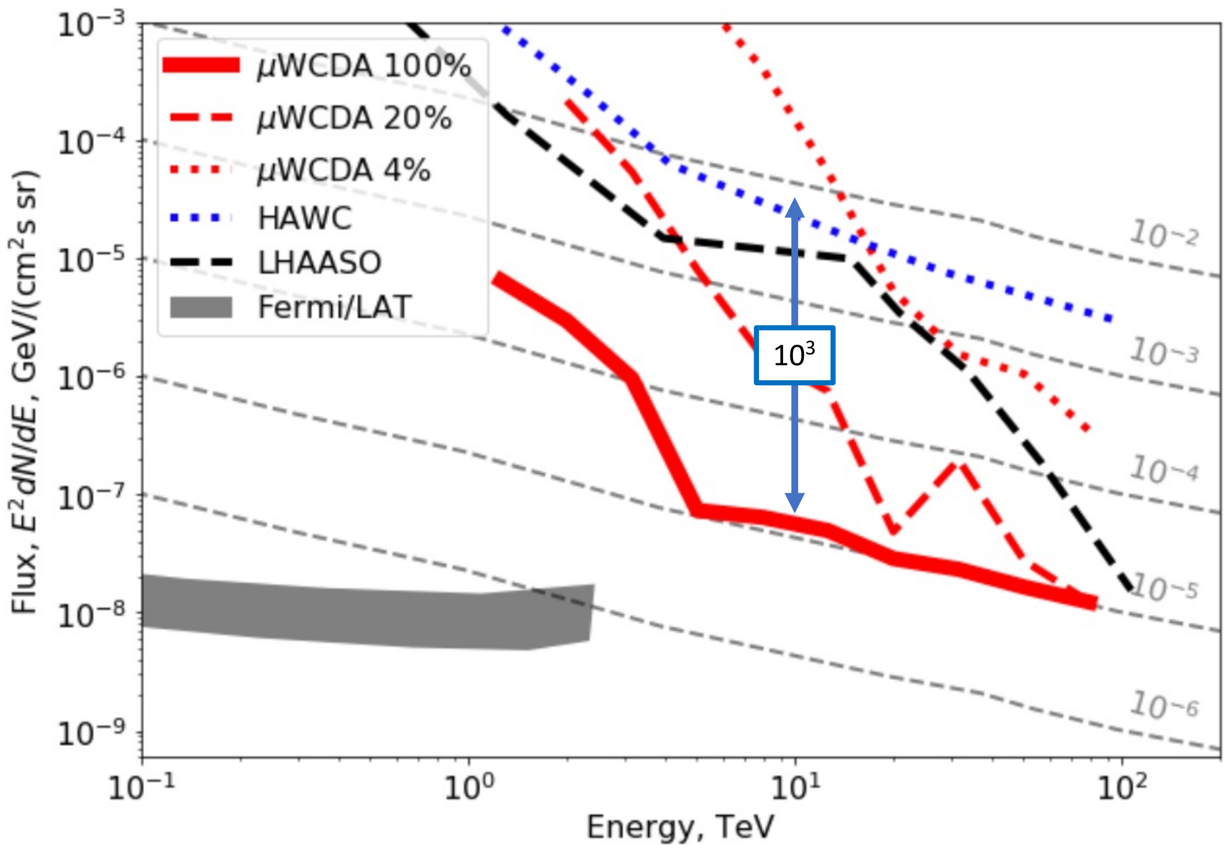
Simulation: CORSIKA+CORSIKA-water, 5m depth each layer (LHAASO-like)

# Muon counting in two-layer WCDA



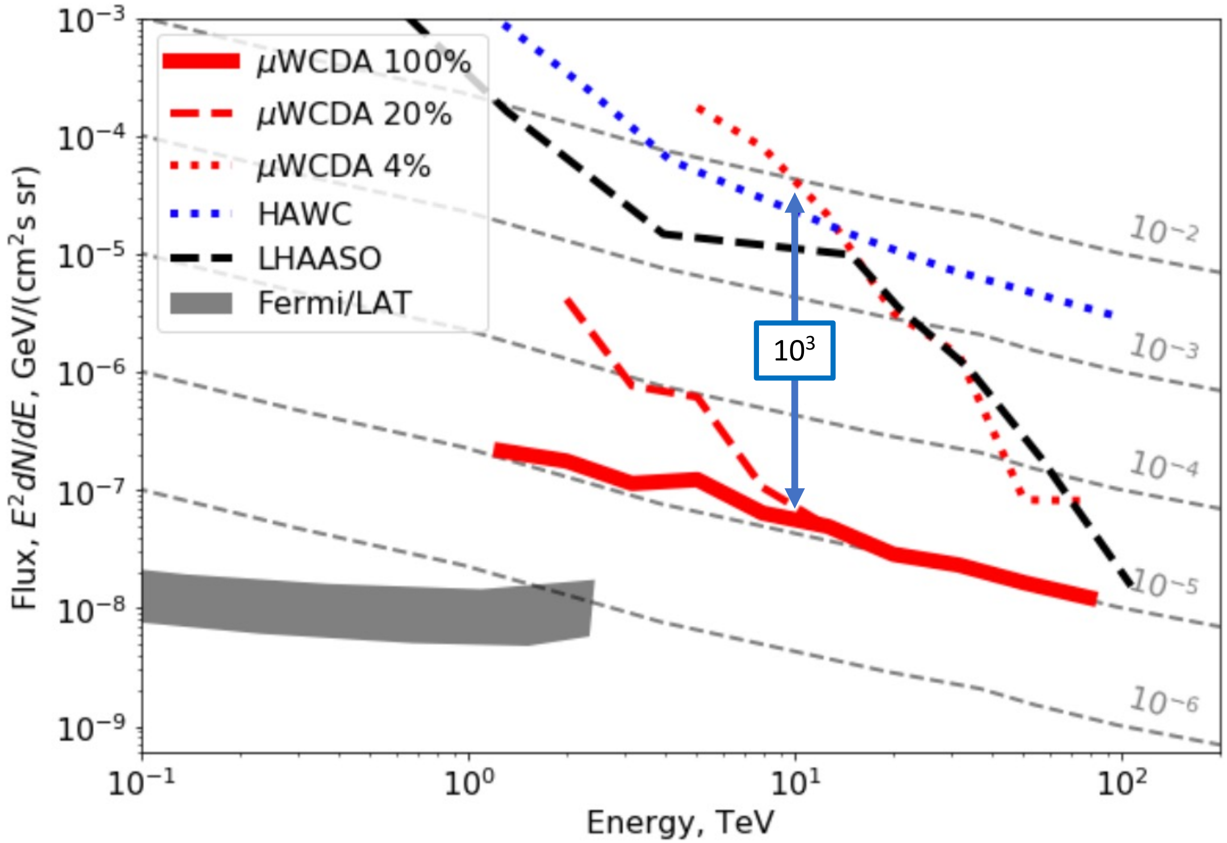

The statistics of muon counts can be improved with muon detector with larger surface filling factor.

# Large 100% efficient muon detector at 4.5 km altitude



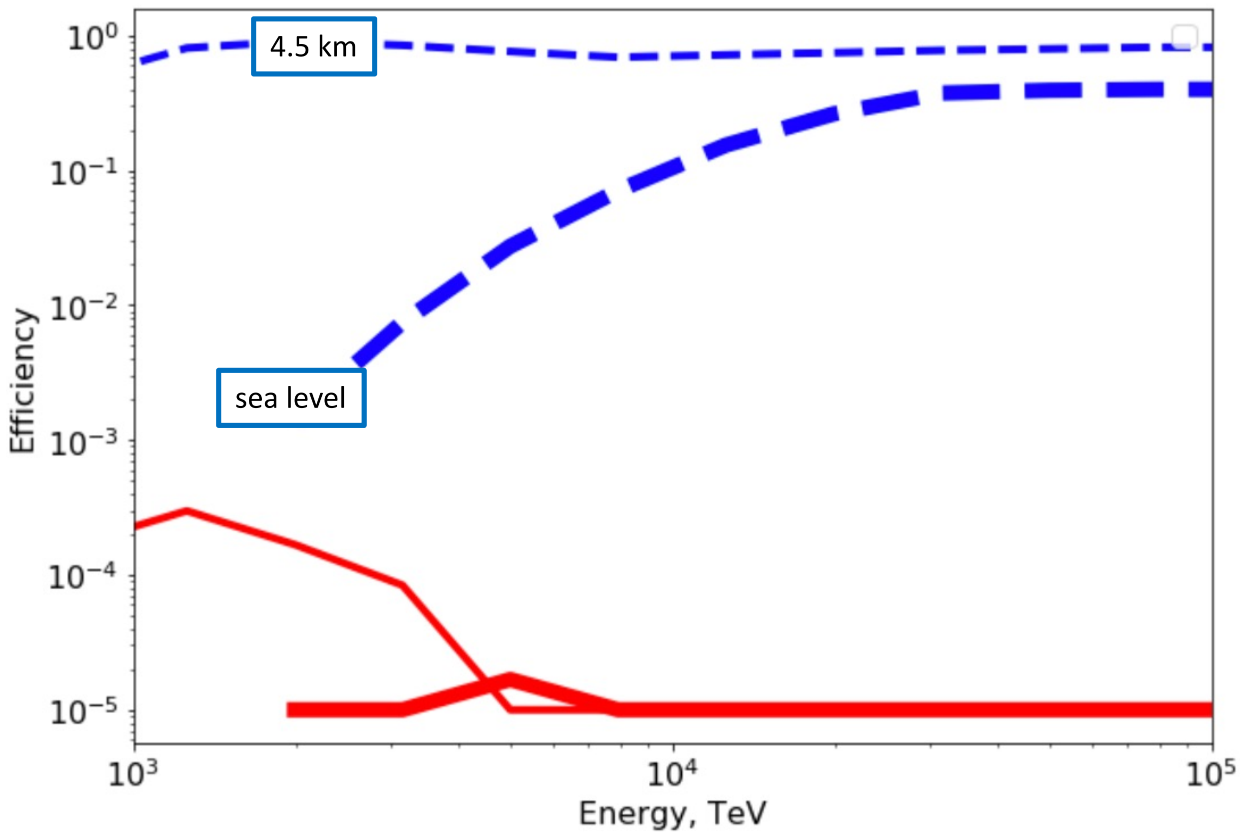

Increase of muon statistics with continuous muon detector of the size comparable to HAWC / LHAASO WCDA / SWGO allows to achieve suppression of hadronic background down to $10^{-5}$ already at 5 TeV.

# Large 100% efficient muon detector at sea level altitude




Muon flux is not significantly attenuated down to the sea-level altitude. Muon counting with large continuous detector can be used for suppression of hadronic background also with a sea-level detector

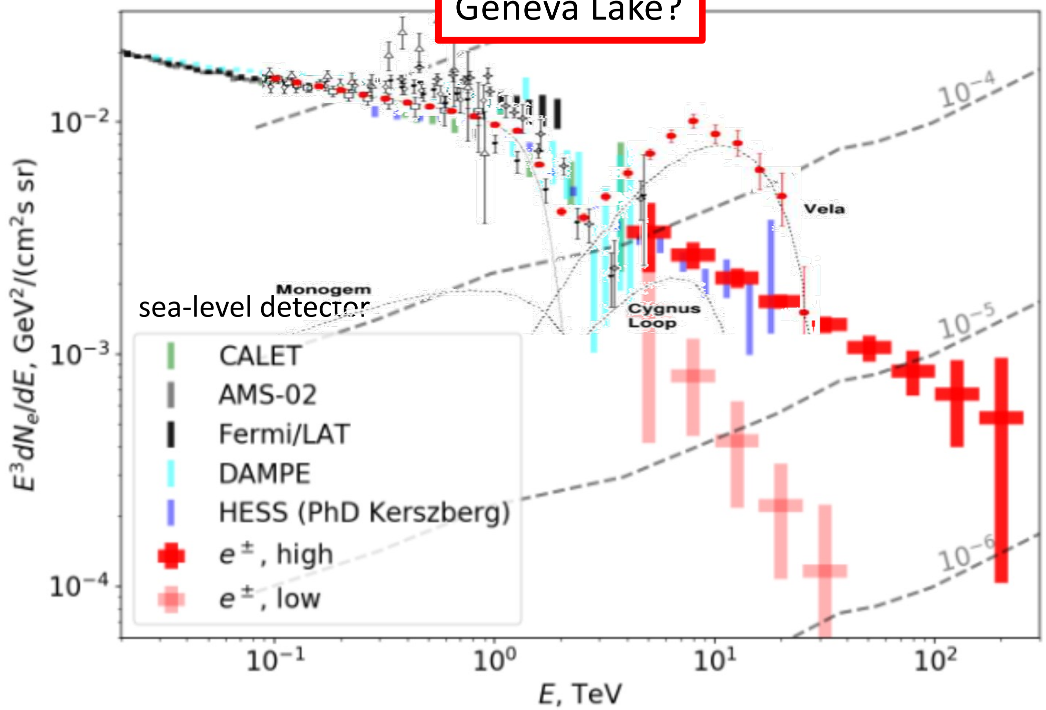
# Sea level vs high-altitude detector

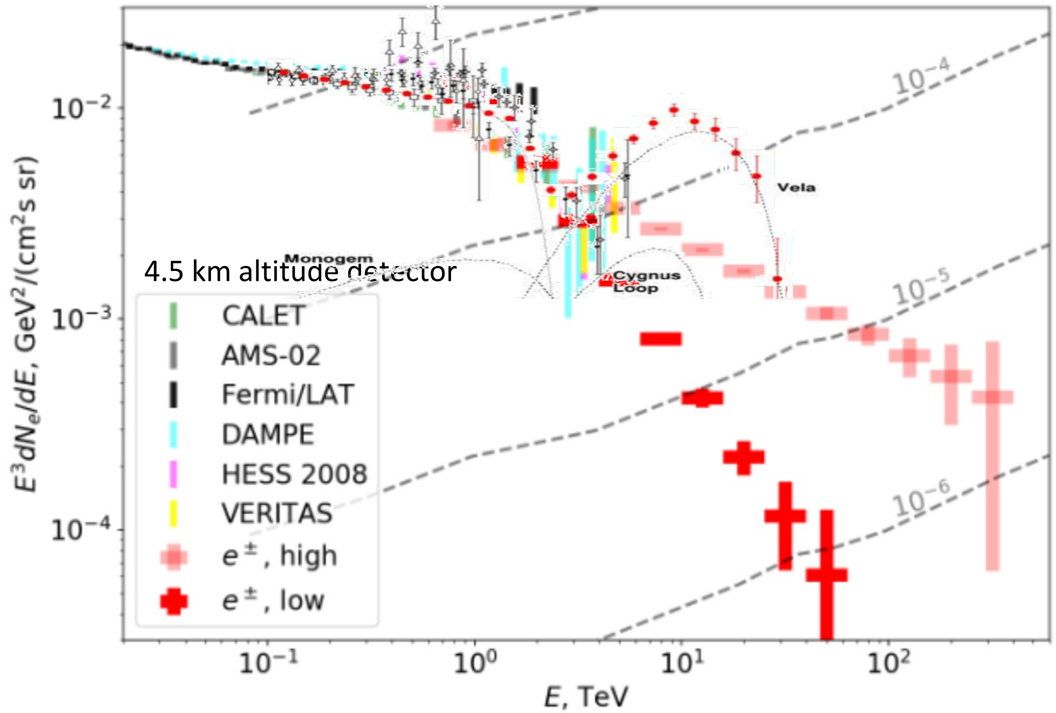



Contrary to the muon component, the electromagnetic component of the air showers is attenuated in the troposphere. This increases the energy threshold of the sea level detector.

However, even the sea-level detector becomes fully efficient toward 100 TeV range.

# Electron spectrum measurement up to 100 TeV ?



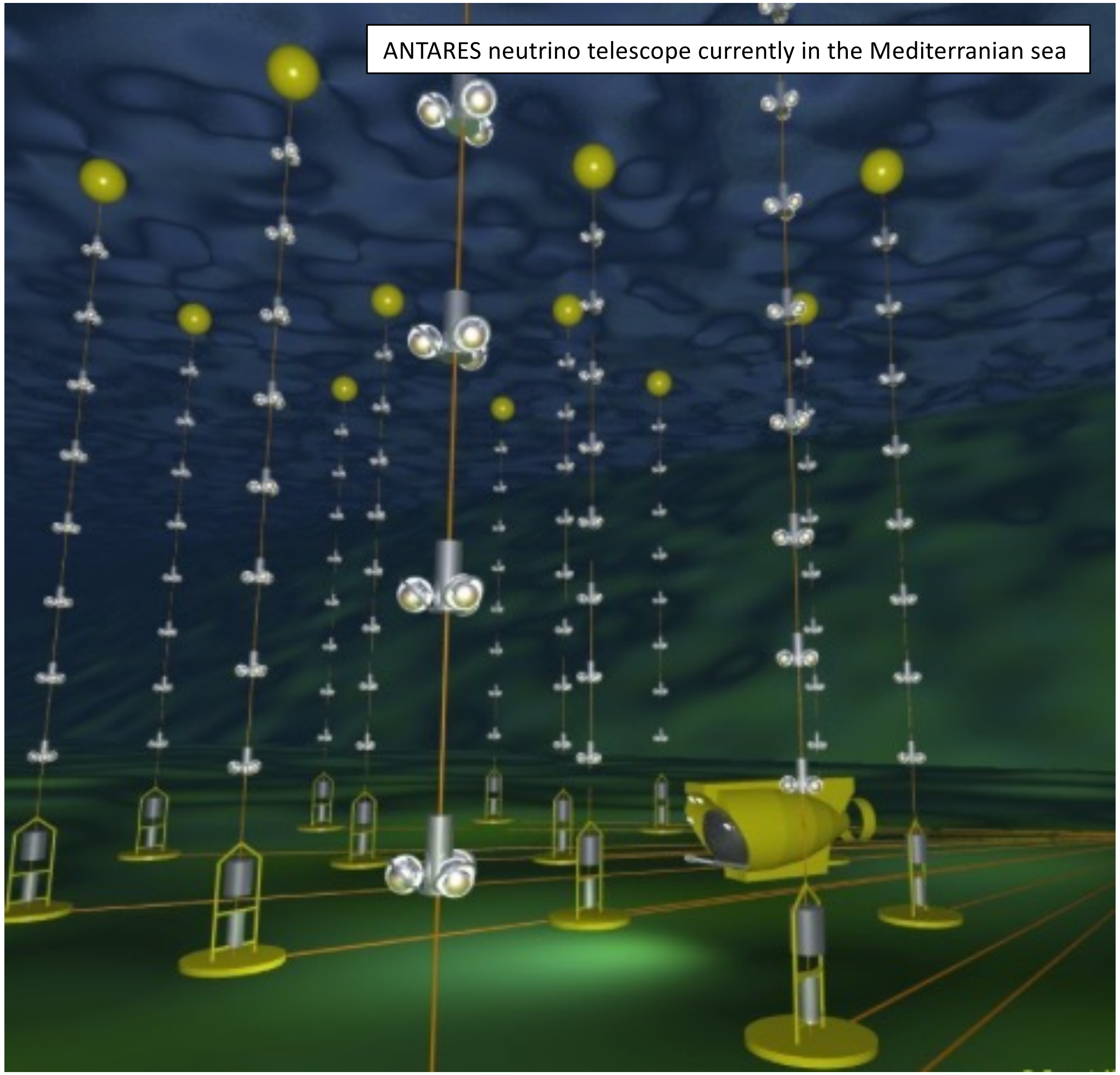




Simulation of electron(+positron) spectrum measurements with 1-year exposure (acceptance 30 degrees around zenith) for different powerlaw extrapolations of TeV band measurements.

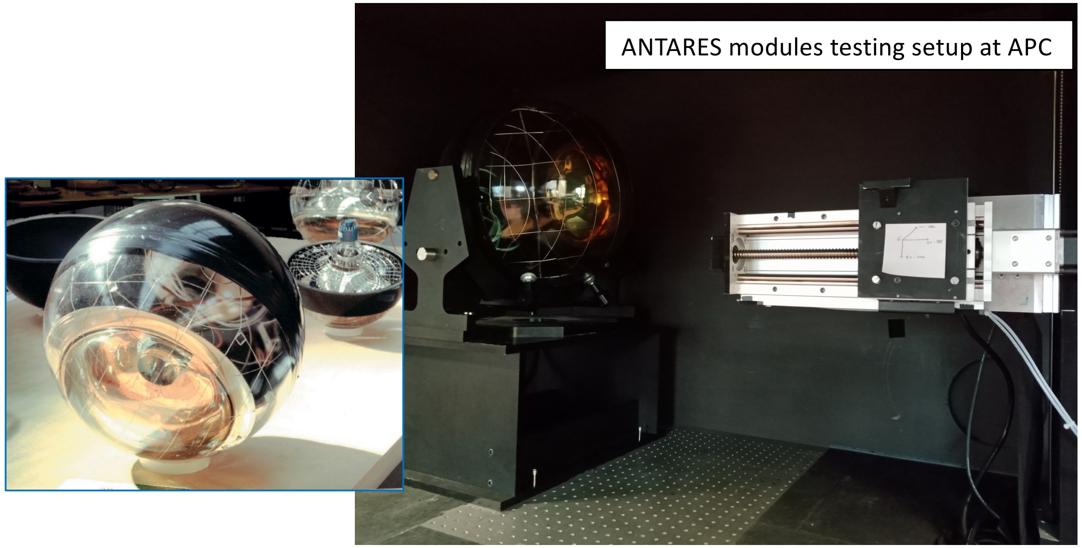
If electron spectrum is a powerlaw with the slope / normalisation suggested by HESS (2017, PhD Kerszberg) results, the spectrum is readily measurable with sea-level detector. If the TeV softening would be much sharper, the sea-level detector measurements would be dominated by the systematic uncertainty of the residual proton (nuclei) background.

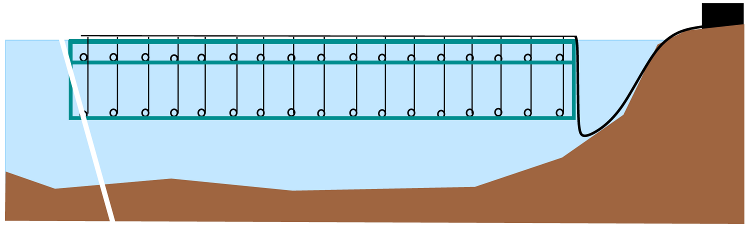
High-altitude detector can provide high-statistics measurements also for the electron flux also under "very soft spectrum" hypothesis.

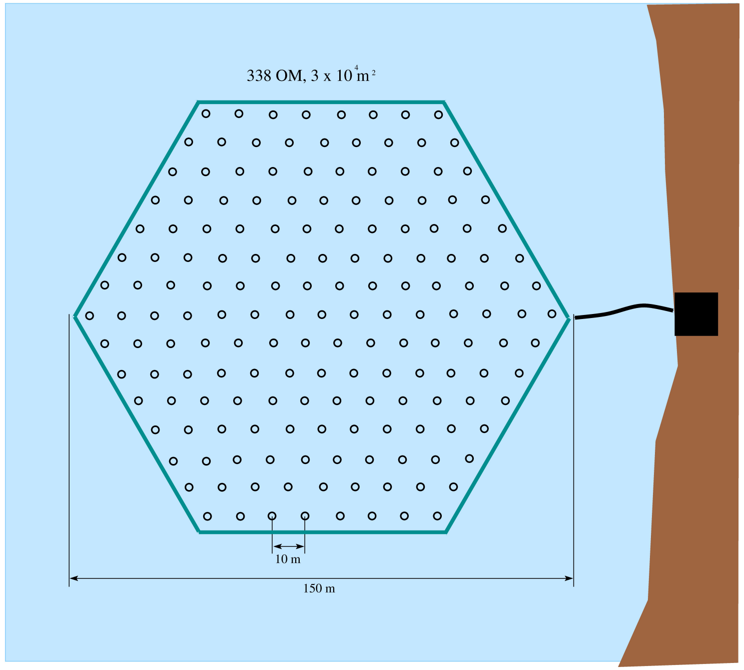
# ”Second life” for ANTARES optical modules



# "Second life" for ANTARES optical modules






ANTARES detector will soon be dismantled this summer (2022). Its optical modules can be re-used for a double-layer WCDA (alternative: an "engineering array for SWGO?)

Cherenkov signal from a muon track passing by the 12'' PMT at a distance d is

$$n_{p.e.} \simeq Y_{ch} \frac{d_{pmt}^2}{8\, R \tan\theta_{Ch}} \simeq 5 \left[\frac{\kappa}{0.3}\right] \left[\frac{d_{pmt}}{25\ \mathrm{cm}}\right]^2 \left[\frac{R}{10\ \ \mathrm{m}}\right]^{-1}$$

($Y_{Ch} \simeq 200/cm$ is the Cherenkov yield in 400-700 nm in water). Deployment of optical modules on a rather sparse grid with $R \sim 10-15\ m$ is sufficient for efficient muon detection in the bottom layer of WCDA.

A setup with $\sim 3{\times}10^2$ modules can form a 150 m large double-layer WCDA. Can be implemented in a lake.

Different possibilities for the muon detection layer geometry: wide shallow depth tanks with walls scattering light vs. $\sim 10\ m$ deep continuous volume.

# Test setup on Geneva lake

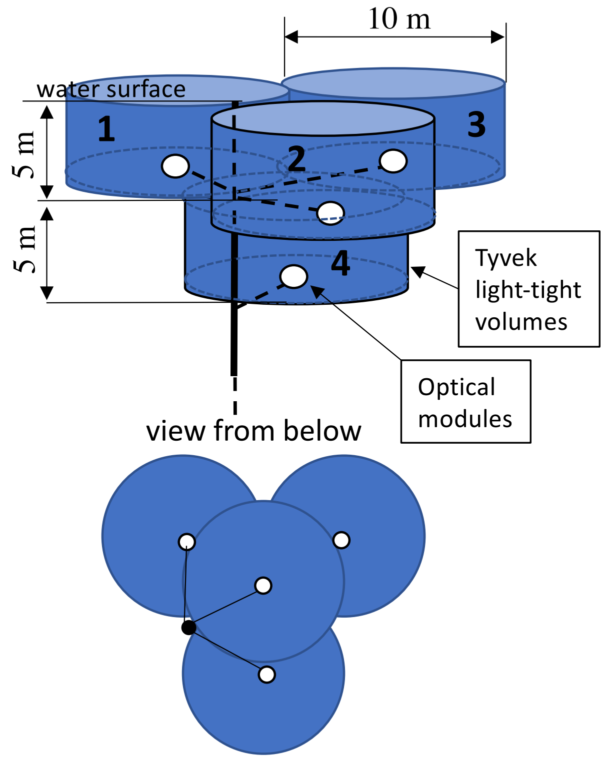
L'Explore platform on Geneva lake (372 m a.s.l.)

Initial deployment of a test setup can be done with several modules (available right now at APC), at L'EXPLORE platform of EPFL: 140 m diameter secured area in front of Pully, depth up to 110 m.

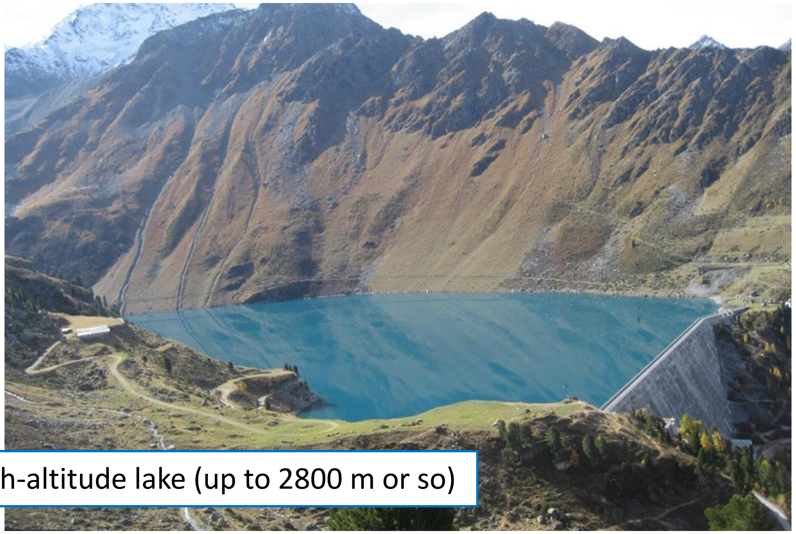
Minimal WCDA can be 3-4 modules.

Can be used for student lab works.

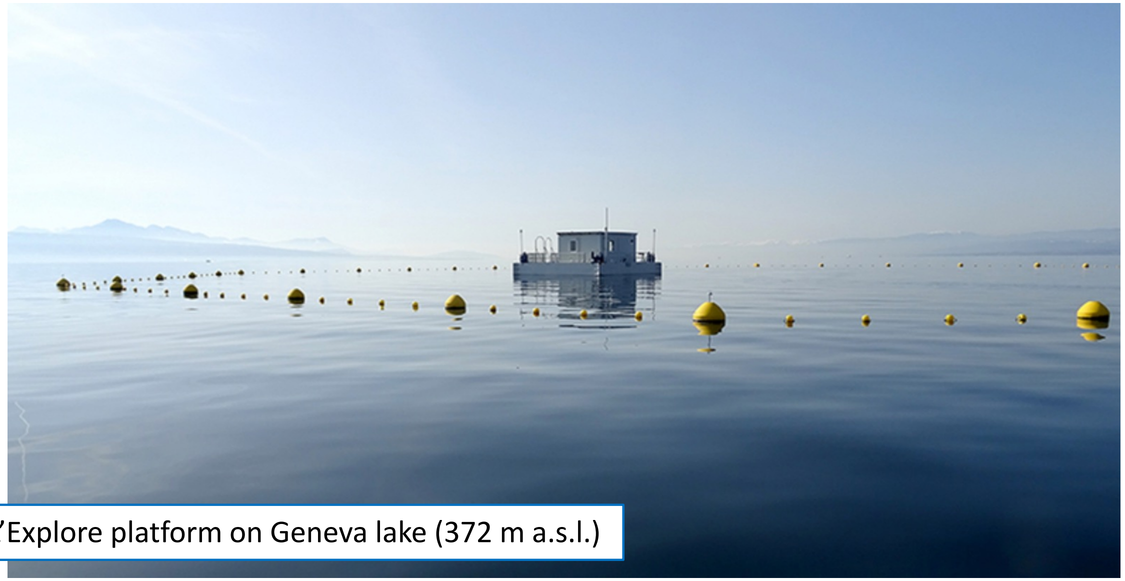
Complementary science: biology (bioluminescence), ecology (water scattering properties)



# ”Second life” for ANTARES optical modules



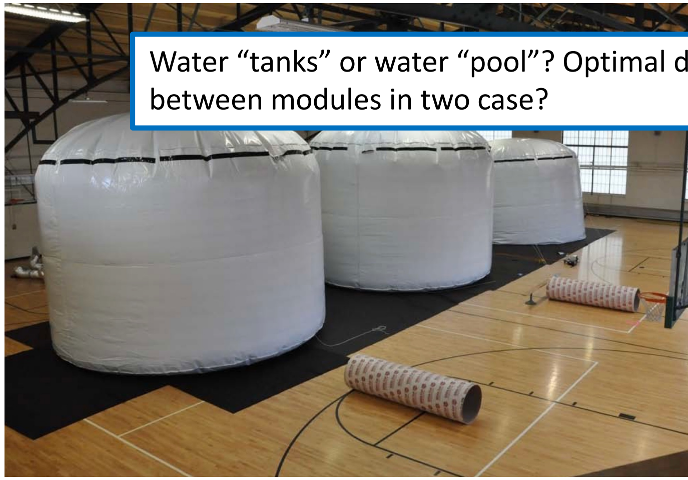
high-altitude lake (up to 2800 m or so)



L’Explore platform on Geneva lake (372 m a.s.l.)

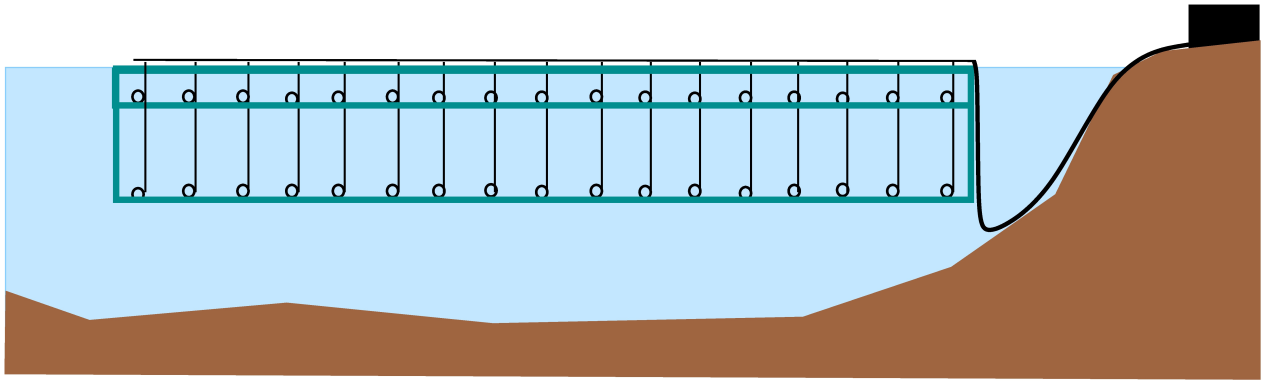
Advanced setup: several hundred modules, in a lake, possibly higher altitude.

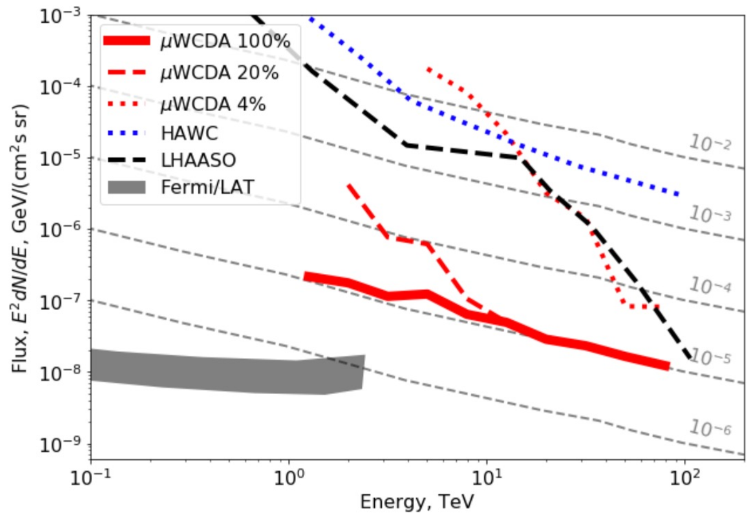

Water purification system?

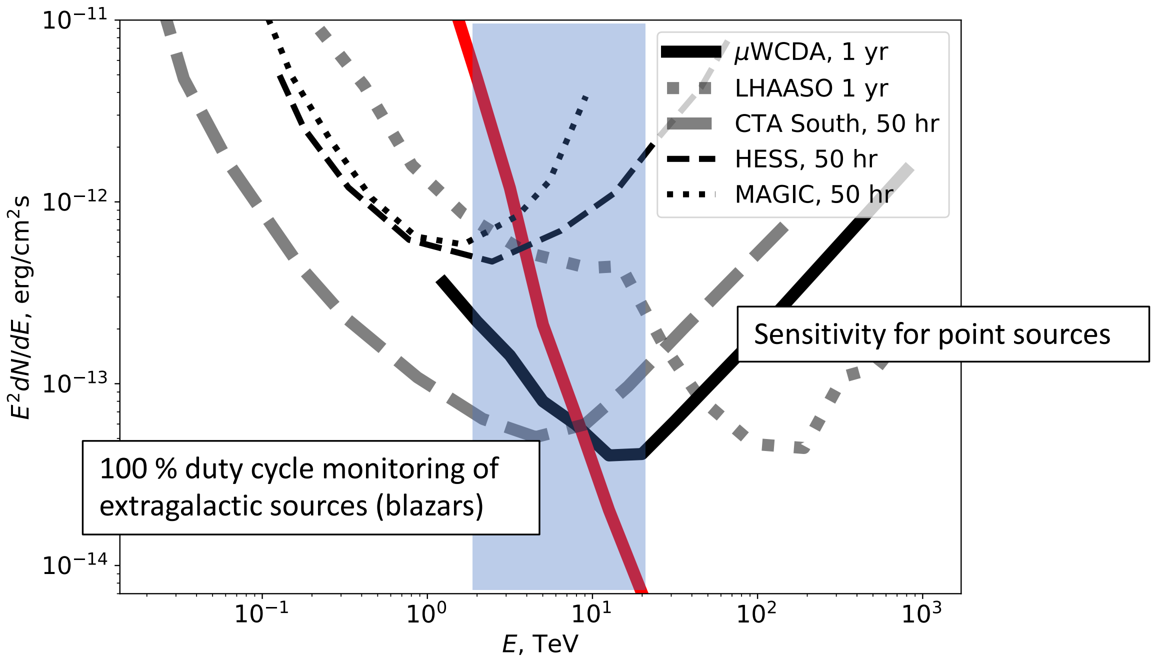


Water “tanks” or water “pool”? Optimal distance between modules in two case?

# Gamma-ray astronomy in 10-100 TeV range



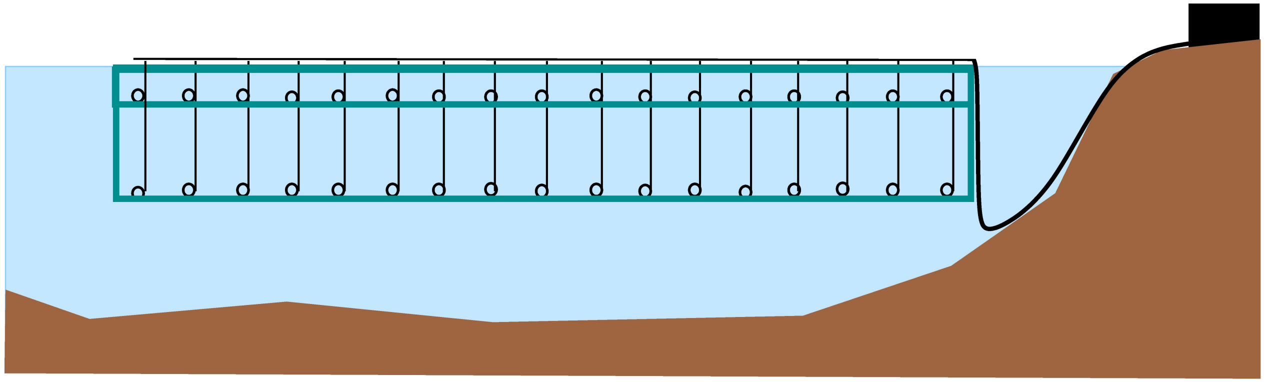


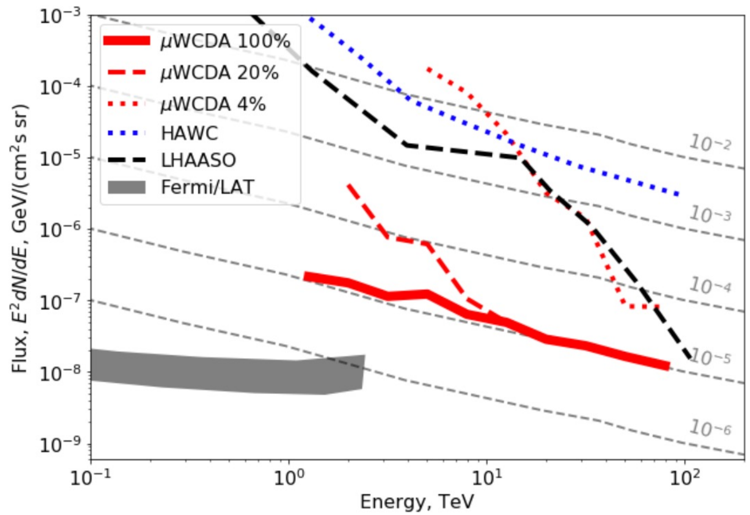



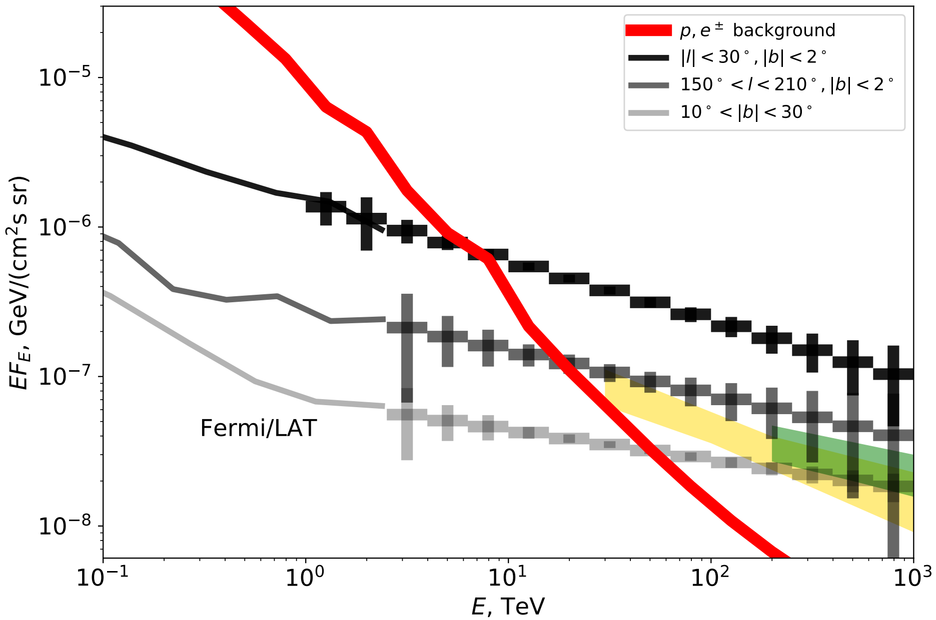

The two-layered WCDA will have better gamma-hadron separation than LHAASO in 10-100 TeV range.

At 10 TeV the EAS reach sea level with $\geq 10^3$ charged particle statistics, enough for detection with WCDA (factor-of-10 lower electron-positron statistics, compared to LHAASO, same or better muon number on the ground, much better muon signal statistics compared to LHAASO)

# Gamma-ray astronomy in 10-100 TeV range






Diffuse gamma-ray flux is currently measured only up to 3 TeV. Two-layer WCDA can extend diffuse flux measurements. Up to PeV range.

# Summary

Two-layer water Cherenkov detection array can be used for better suppression of proton and nuclei cosmic ray background:

- measurement of electron spectrum at the high-energy end above 10 TeV
- improved sensitivity for gamma-ray observations in 10 TeV range
  - diffuse emission from the Galaxy
  - 100% duty cycle monitoring of galactic and extragalactic sources.

Optical modules of ANTARES neutrino telescope can be re-used (will become available this summer)

A test setup in Geneva lake can be an interesting multi-disciplinary project:

- air shower detector
- biology / ecology
- student training