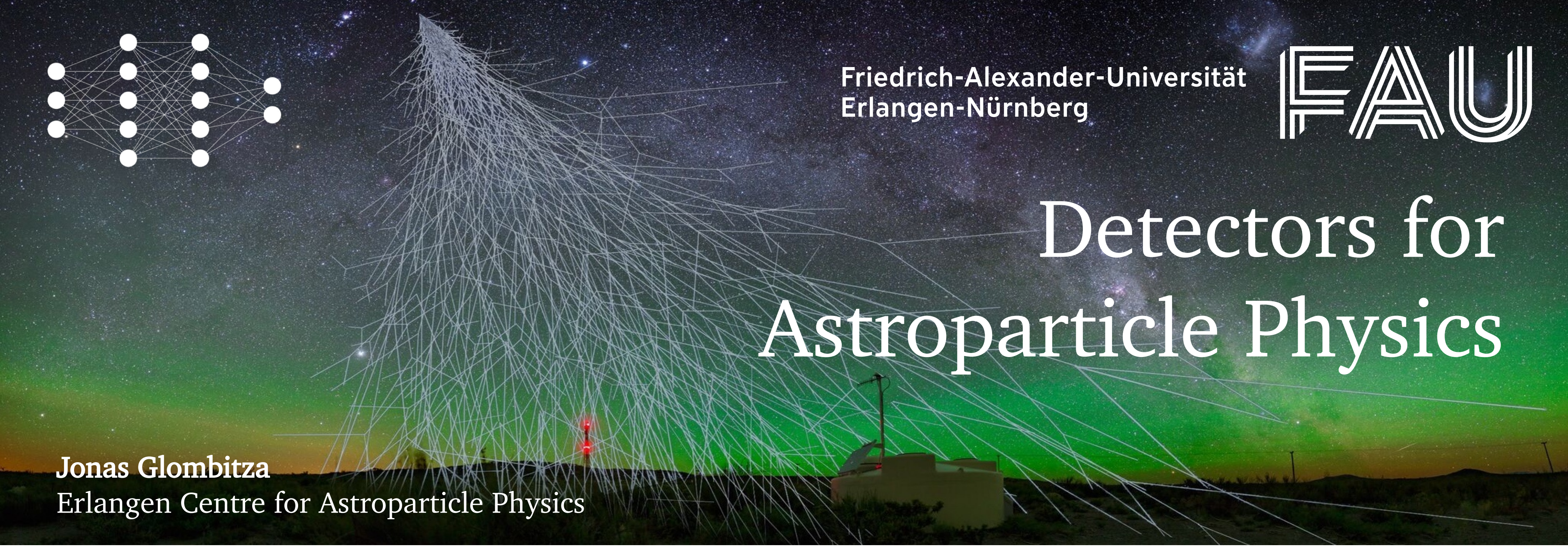
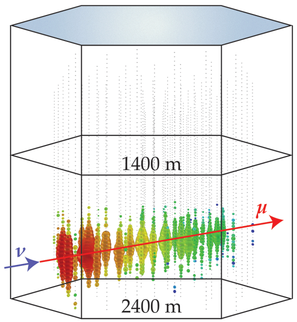


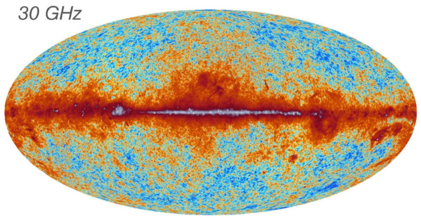
Friedrich-Alexander-Universität
Erlangen-Nürnberg

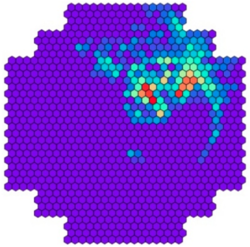
FAU

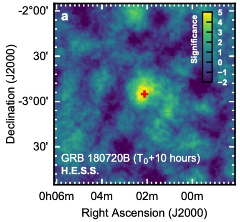
Detectors for Astroparticle Physics

Jonas Glombitza
Erlangen Centre for Astroparticle Physics









September 4, 2025

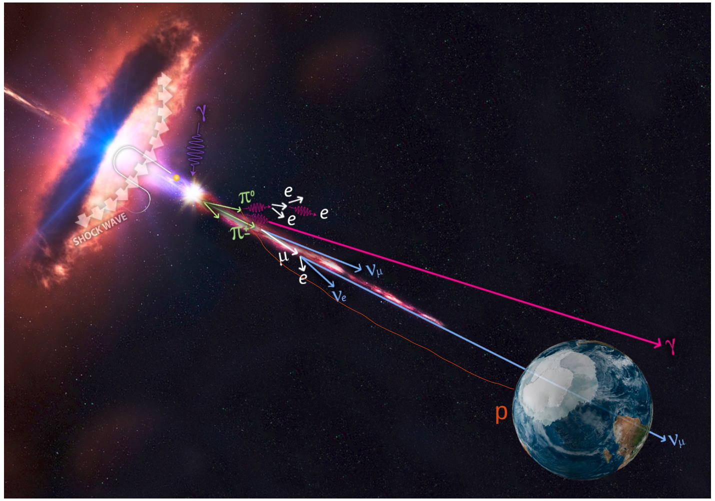
ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

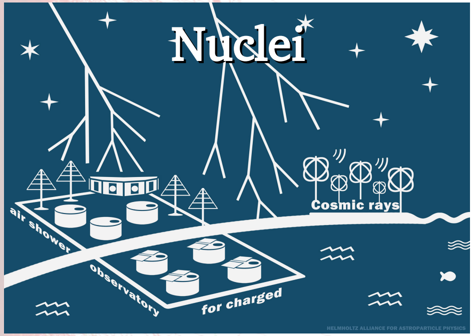
SPONSORED BY THE
Federal Ministry of Education and Research

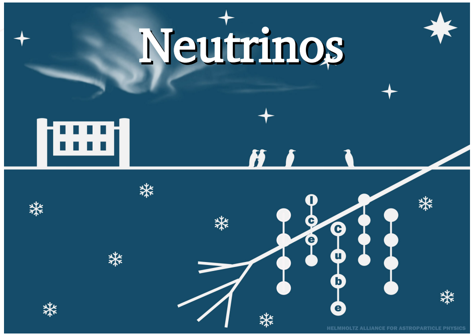
Astroparticle Physics

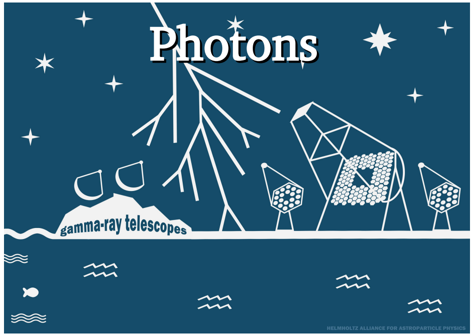
- Observation of particles with astronomical origin
- Search for their sources
  - Understand physics of astronomical objects
- Cosmic messengers: Photons, neutrinos, nuclei

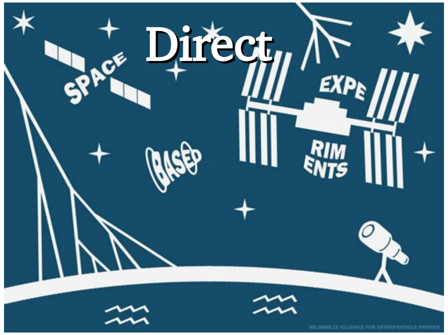
- Distant sources, high particle energies
  - Experiment often feature huge detector volumes











Origin of high-energy cosmic rays not known! (since >100 yrs)

Astroparticle Physics Experiments

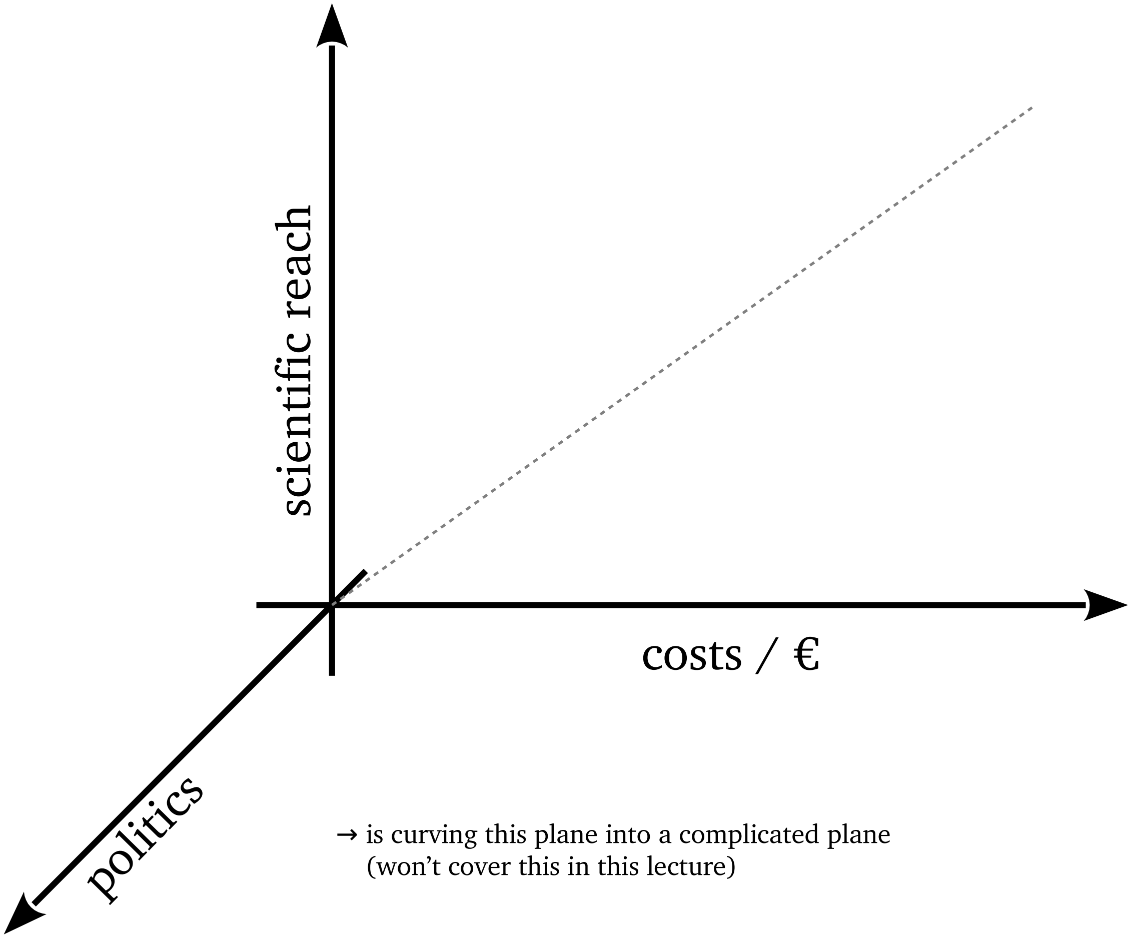
HOW TO DESIGN

Astroparticle Physics Experiments?

Experiment design

Designing experiments is complex and complicated

- politics may change the rules
- financial costs are crucial
  - ensure scientific goals can be reached
  - optimize performance / cost



→ is curving this plane into a complicated plane
(won't cover this in this lecture)

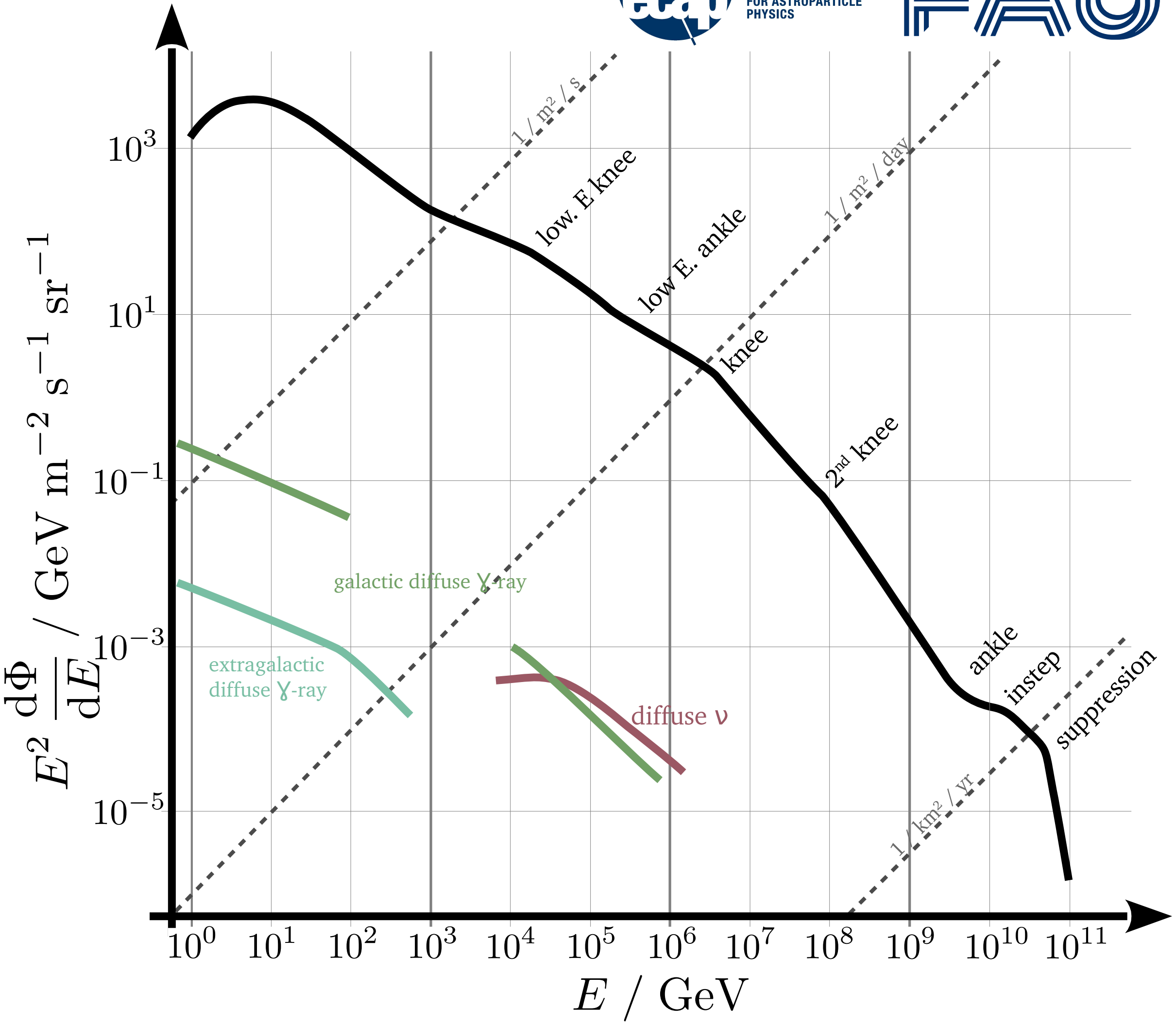
Astroparticle Physics

Want to explore astroparticles

- messengers from the cosmos

Messenger particles

- charge nuclei (cosmic rays)
- charged leptons (e^- / e^+)
- gamma-rays (ɣ's)
- neutrinos (ν's)
- gravitational waves (G?)



Instrument Performance

I. Instrument response functions (IRFs)
   i. Effective area
   ii. Angular resolution
   iii. Energy resolution
   iv. Particle type identification

Instrument Response Functions

Effective area

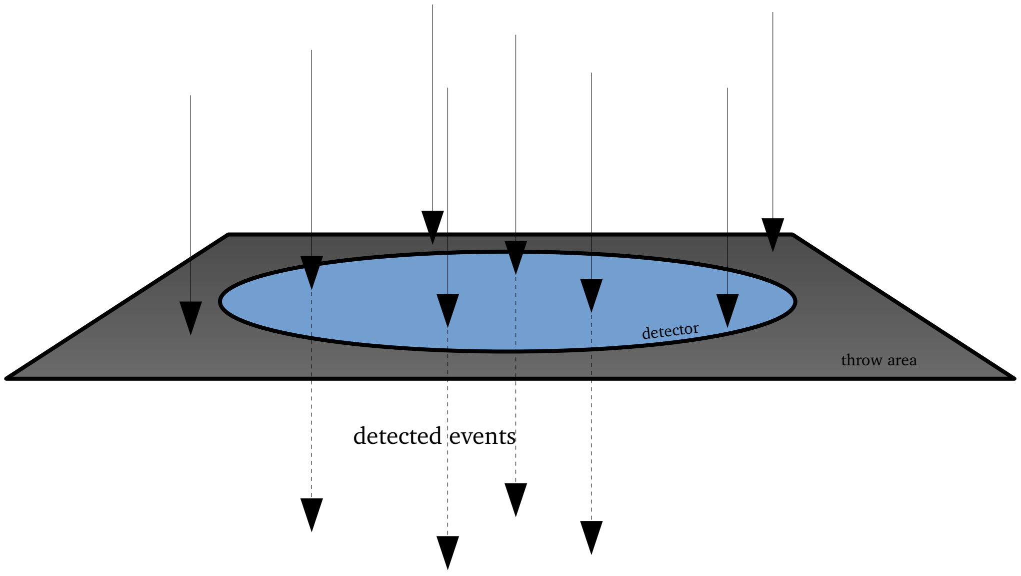
- Quantifies how sensitive my detector is (in terms of area)
  - assumption: area of a detector with 100% efficiency
  - strongly depends on trigger efficiency, event selection

$$\Phi_{\text{rec}}\ [\text{s}^{-1}] = A_{\text{eff}}(E, \vec{r}, \theta, \phi,) \times \Phi_{\text{phys}}\ [\text{m}^{-2}\,\text{s}^{-1}]$$

  - connects event rate with true flux
  - needed to reconstruct flux given the measured event(s) rate

Often estimated via MC simulations

$$A_{\text{eff}} = A_{\text{thrown}} \cdot \frac{N_{\text{det}}}{N_{\text{thrown}}}$$



Instrument Response Functions

Effective aperture

- Quantifies sensitivity (in terms of aperture) of detector
  - Assumption: aperture of a detector with 100% efficiency
  - for isotropic flux: $\mathcal{A}_{\text{eff}} = \int \vec{A}_{\text{eff}}\, \mathrm{d}\Omega$

$$\Phi_{\text{rec}}\ [\mathrm{s}^{-1}\,\mathrm{sr}^{-1}] = \mathcal{A}_{\text{eff}}(E, \vec{r}, \theta, \phi) \times \Phi_{\text{phys}}\ [\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}]$$

→ otherwise effective area binned in $\theta, (\phi)$

Often estimated via MC simulations

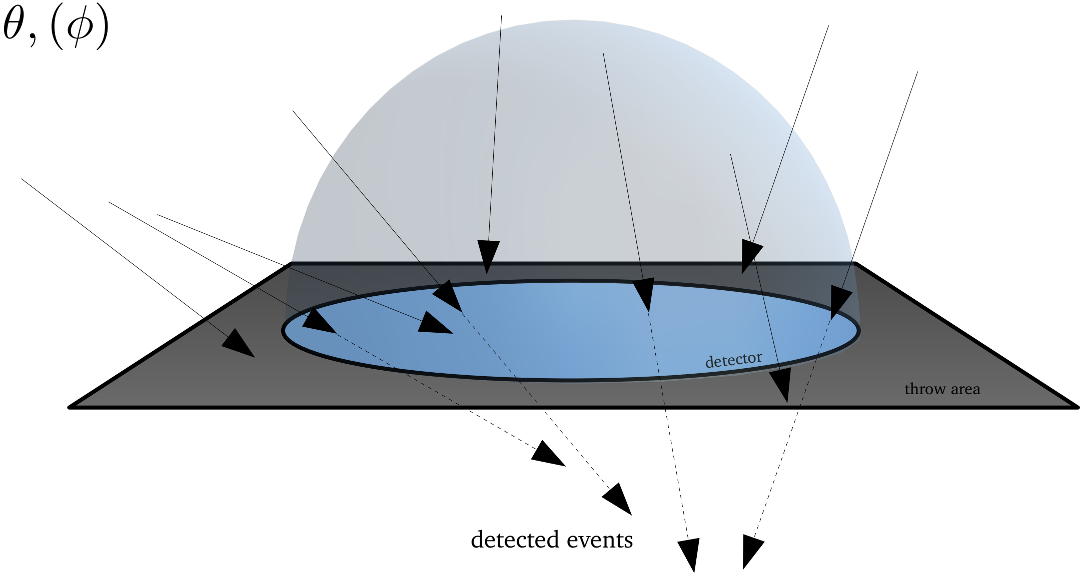
$$\mathcal{A}_{\text{eff}} = \mathcal{A}_{\text{thrown}} \cdot \frac{N_{\text{det}}}{N_{\text{thrown}}}$$

Example: UHECR observatory.
Detect showers up to 60°

$$\mathcal{A}_{\text{eff}} = \int \vec{A}_{\text{eff}}\, \mathrm{d}\Omega = \int A_{\text{eff}} \cos(\theta)\, \mathrm{d}\Omega$$

$$= 2\pi \int_0^{60^\circ} A_{\text{eff}} \cos(\theta) \sin(\theta)\, \mathrm{d}\theta$$

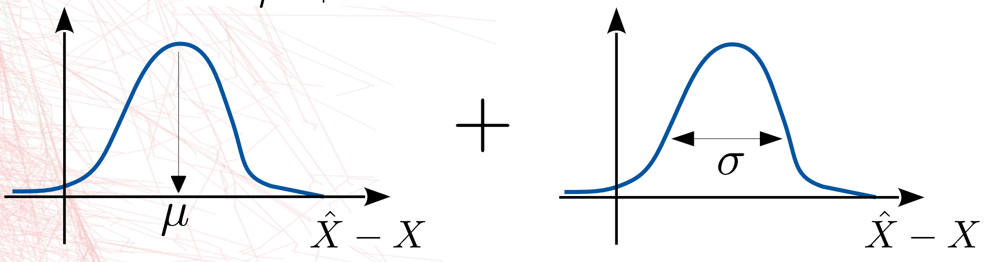
$$= 2\pi \cdot A_{\text{eff}} \left[\frac{\sin^2(\theta)}{2}\right]_0^{60^\circ} = \frac{3}{4}\pi \cdot A_{\text{eff}}$$



Reconstruction performance

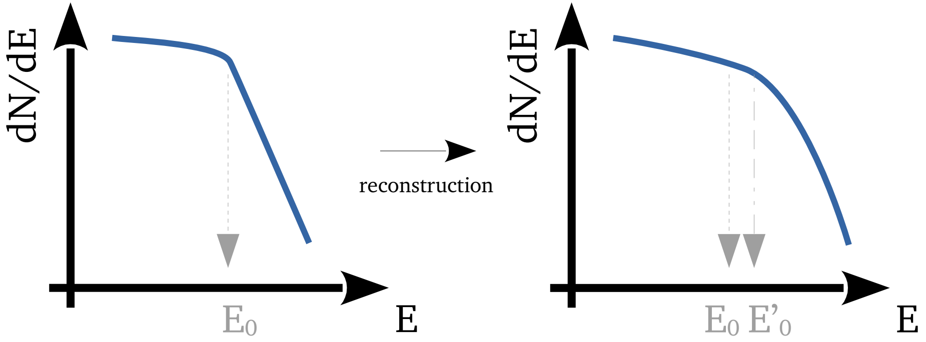
Performance: **Bias** + **Resolution**

$$\mathcal{L} = \langle \mathrm{Bias}(\hat{X}, X)^2 \rangle + \langle \mathrm{Var}(\hat{X} - X) \rangle$$
$$= \mu^2 + \sigma^2$$



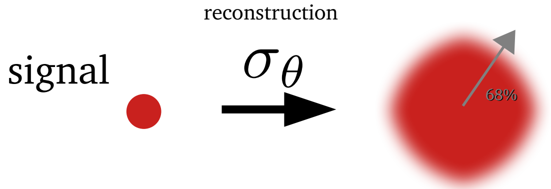
Bias

Variance → Resolution²



Reconstruction shifts breaks and 'wash out' sharp features

Angular resolution



Challenges to disentangle objects

Resolution (PSF): defined of 68% quantile of angular distance distribution

Bias:

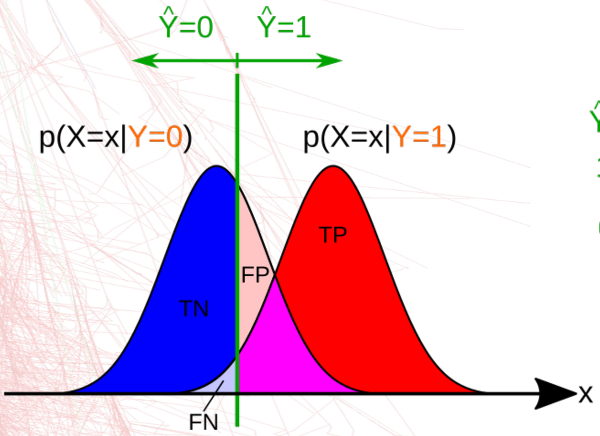
- Average displacement of reconstruction
  - often a systematic uncertainty

Resolution:

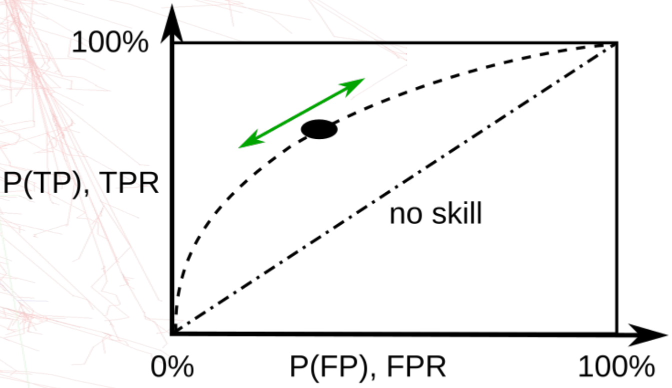
- How big is the spread

→ often combined in dispersion matrix

Particle type



Ŷ \ Y	1	0
1	TP	FP
0	FN	TN



Measuring messengers id challenging

- often significant backgrounds
- → reliable identification required

Performance metrics (binary case):

True positive rate (TPR), *signal efficiency*

- rate of correctly identified signal events

False positive rate (FPR)

- rate of wrongly classified background events

often cited: FPR for a fixed TPR

For categorical (>2 classes) cases

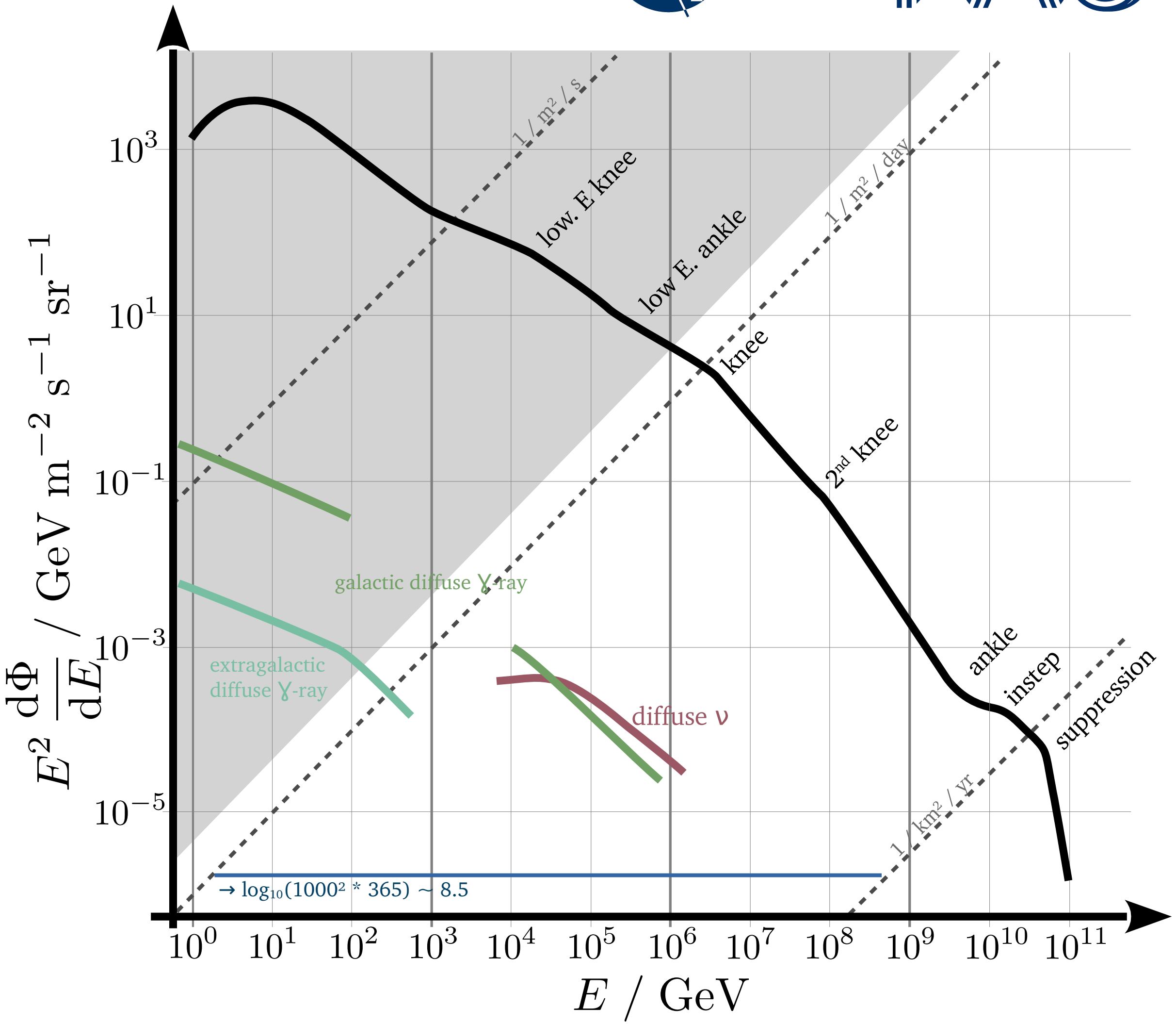
- confusion matrix

Direct detection

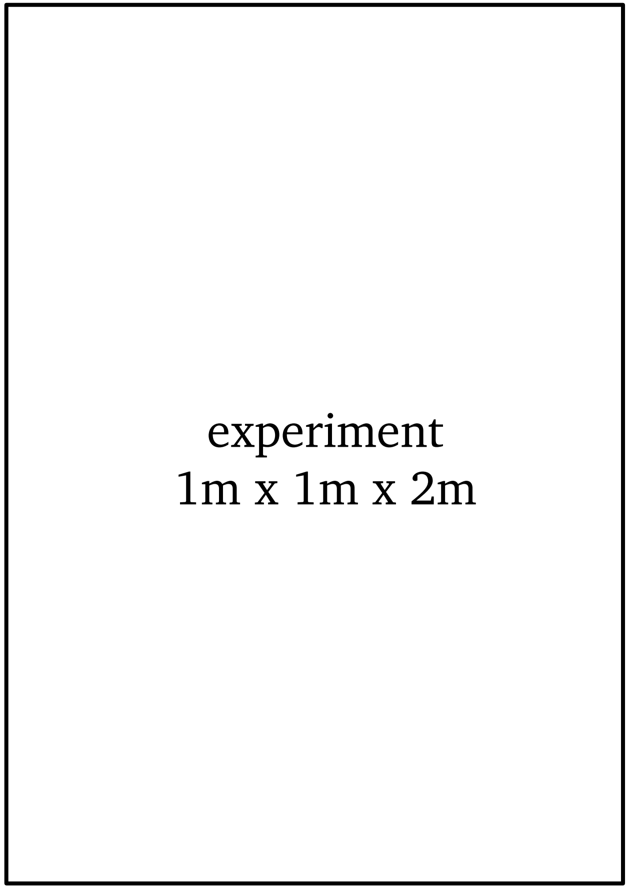
Low energy regime

- Direct experiments
- Balloon flights / space missions
- Very precise measurements
  - high statistics (up to low E ankle)
  - low systematics
    - tested / calibrated via test beams

- “light-weight” + small
  - space missions are expensive!

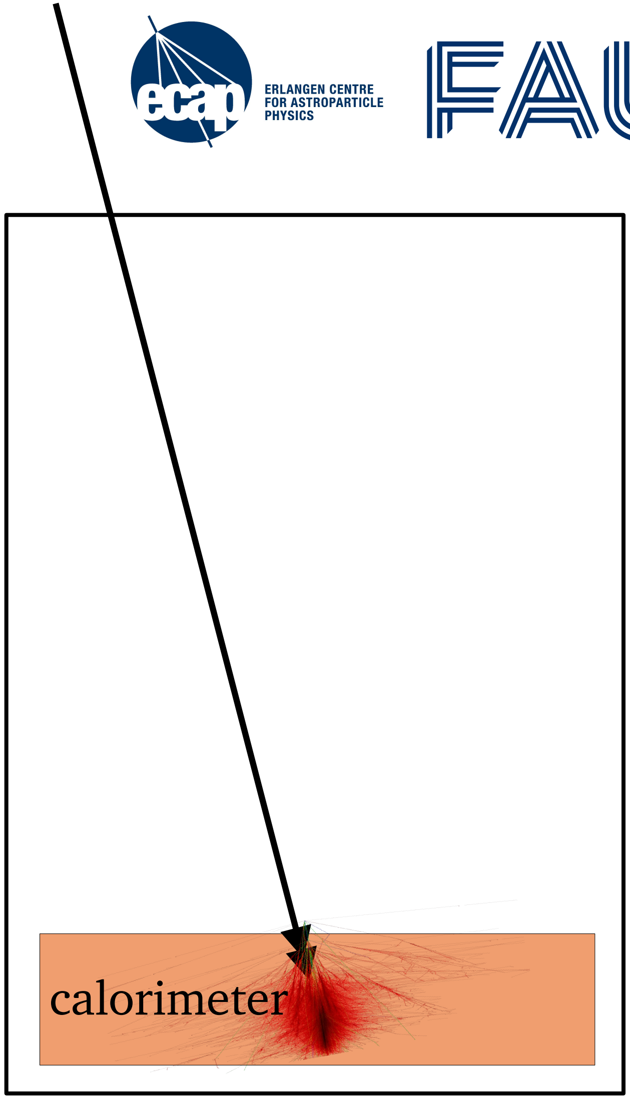


Design a direct cosmic-ray detector



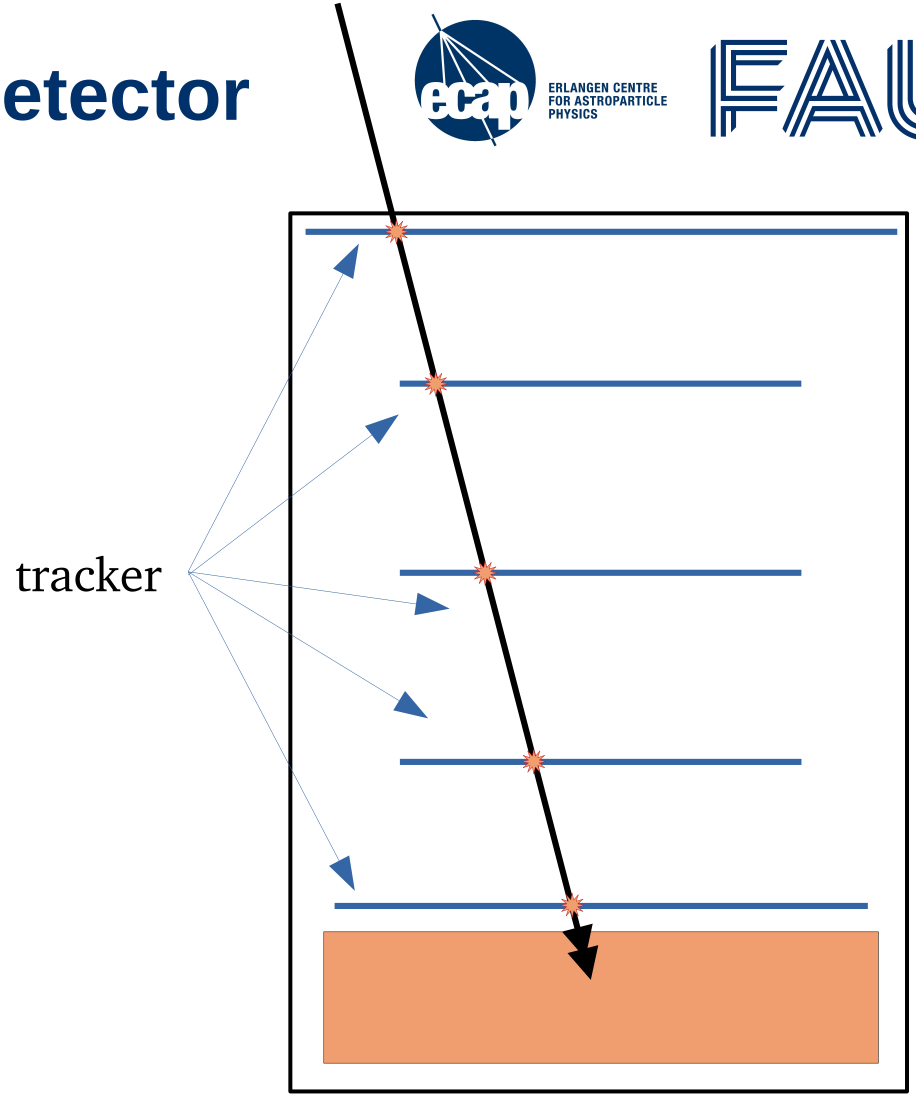
Design a direct cosmic-ray detector

- Energy measurement → calorimeter
  - full energy deposition → at the tail



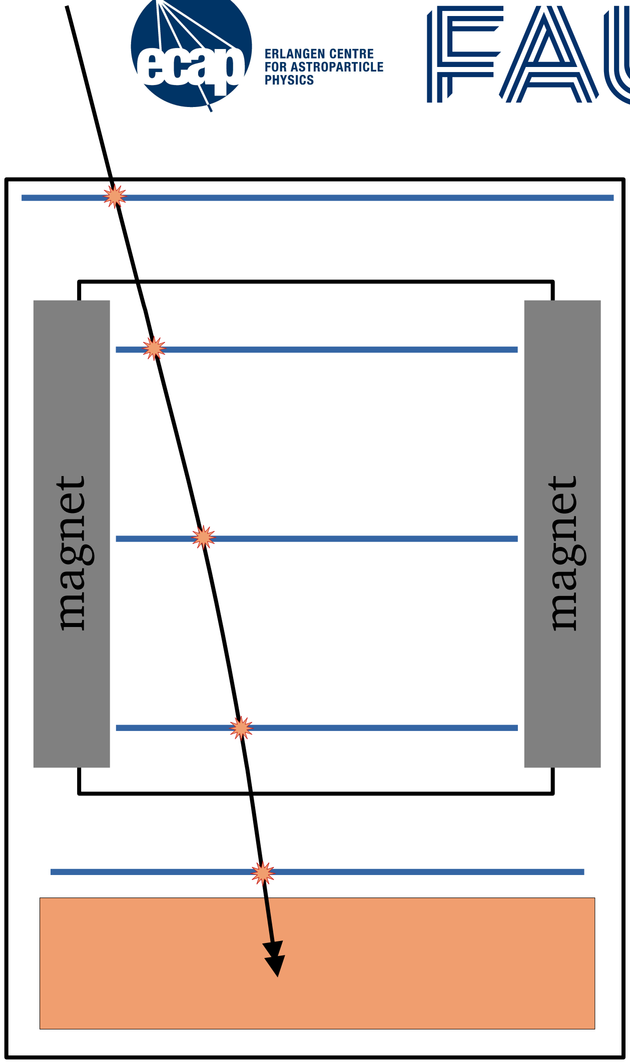
Design a direct cosmic-ray detector

- Energy measurement → calorimeter
  - full energy deposition → at the tail
- Direction (shower axis)
  - measure using tracker



Design a direct cosmic-ray detector

- Energy measurement → calorimeter
  - full energy deposition → at the tail
- Direction (shower axis)
  - measure using tracker
- Charge (particle type) measurement
  - add magnet to tracker system



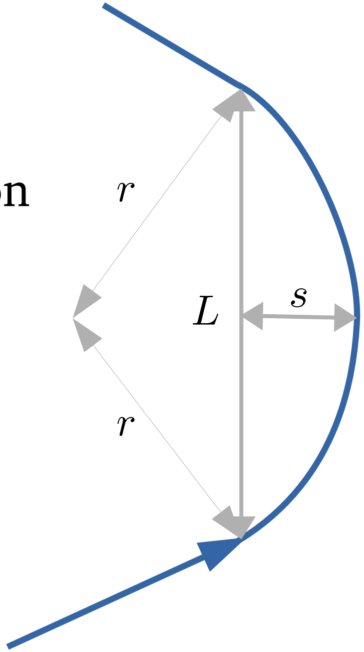
Design a direct cosmic-ray detector

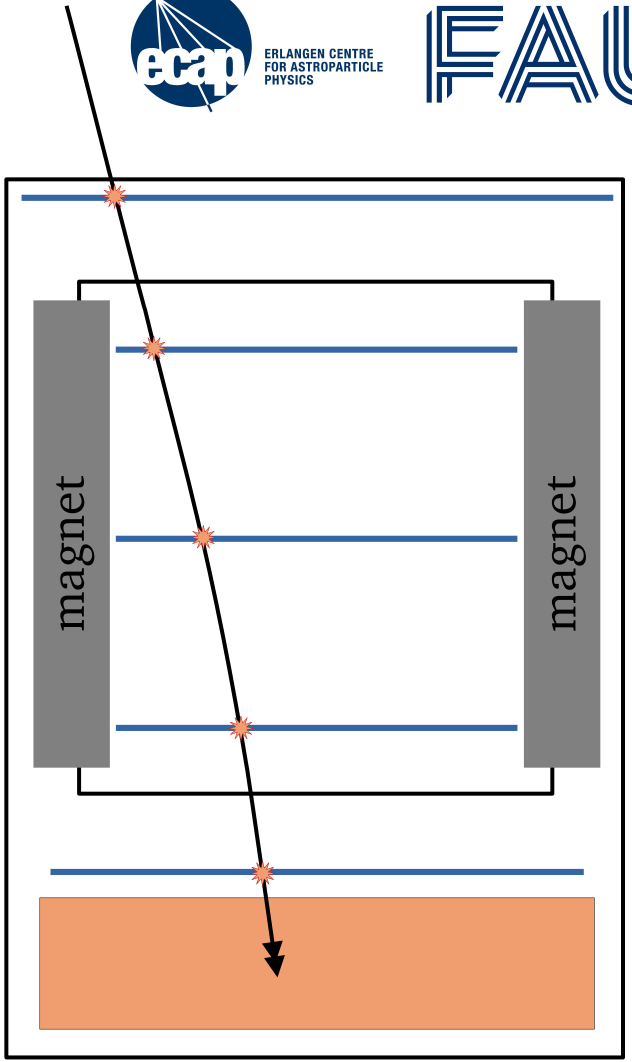
- Typical values for magnet: 0.15 T,
- Size of tracker ~? m, resolution ~5 µm

$$R \hat{=} \frac{E}{Z} = [\mathrm{GV}] = 0.3\, B\,[\mathrm{T}] \cdot r\,[\mathrm{m}]$$

Approximation of sagitta:

$$s \approx \frac{L^2}{8r}$$

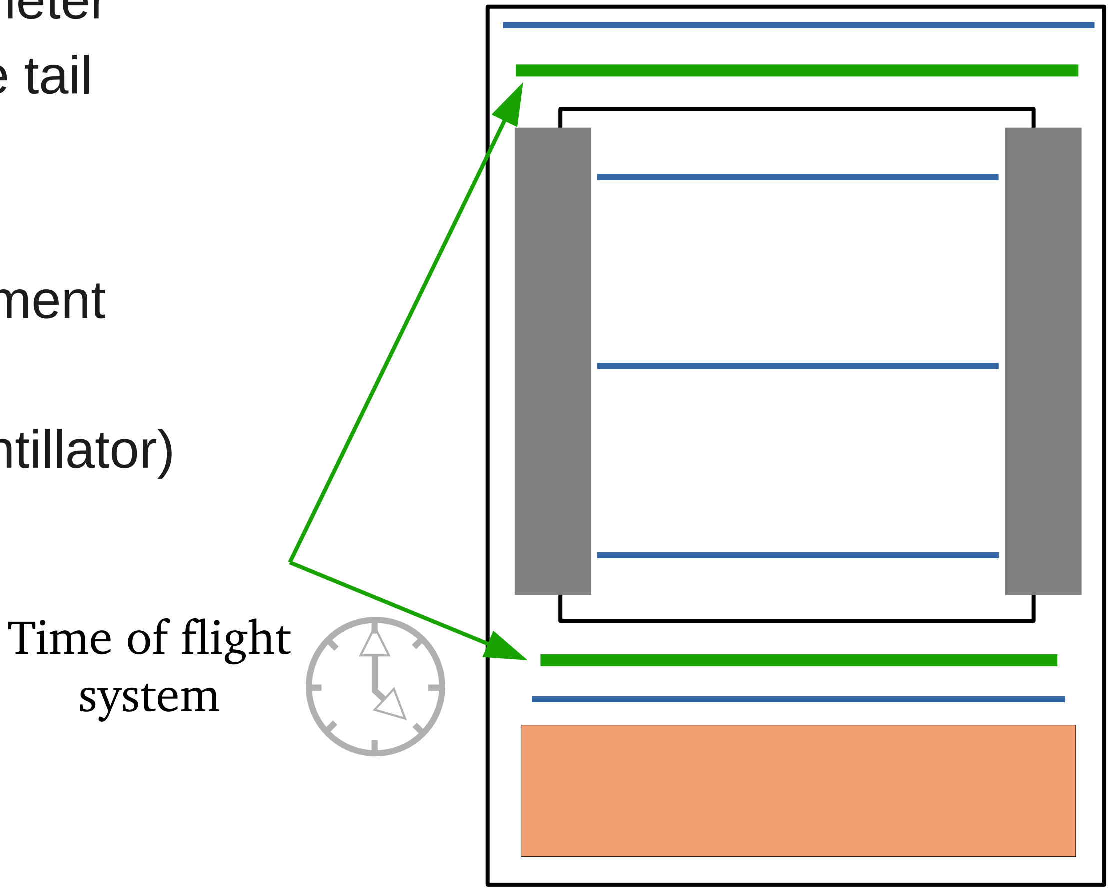




Up to which rigidity can we measure particles precisely?

Design a direct cosmic-ray detector

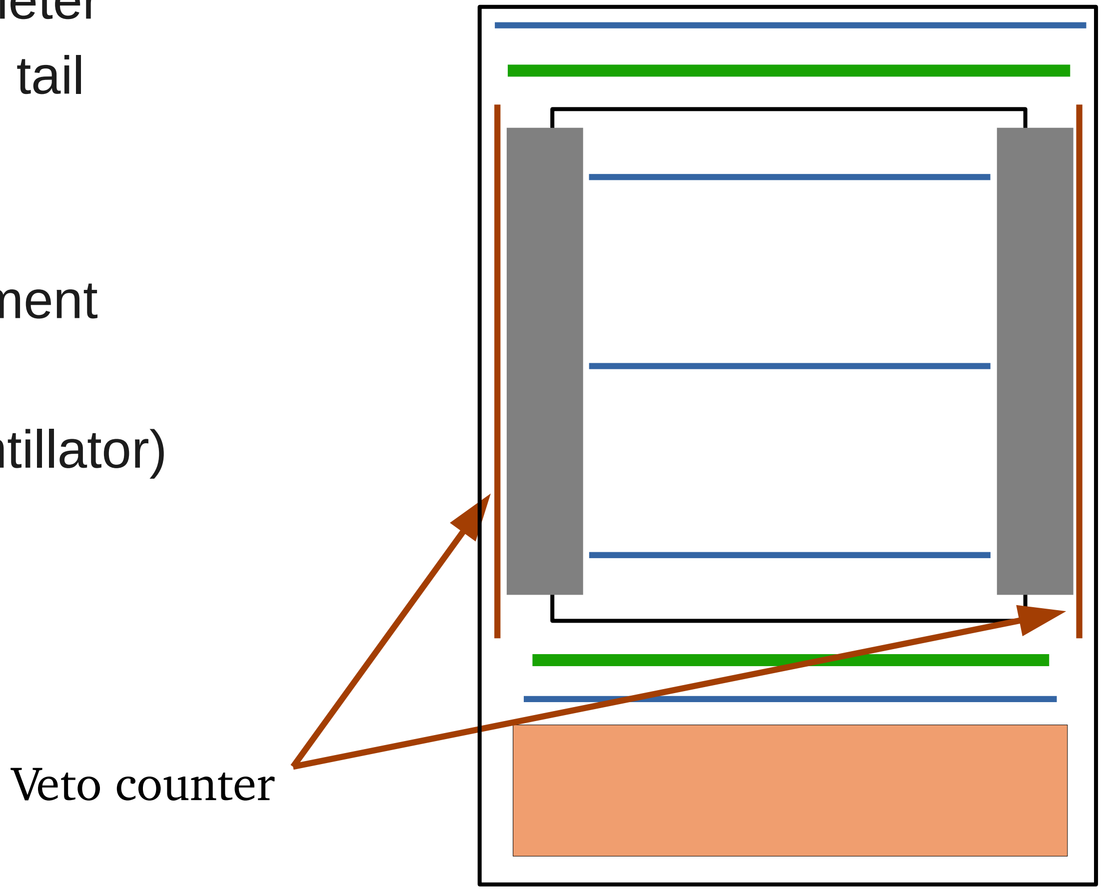
- Energy measurement → calorimeter
  - full energy deposition → at the tail
- Direction (shower axis)
  - measure using tracker
- Charge (particle type) measurement
  - add magnet to tracker system
- Momentum → time of flight (scintillator)
  - get isotope (particle type)



Design a direct cosmic-ray detector

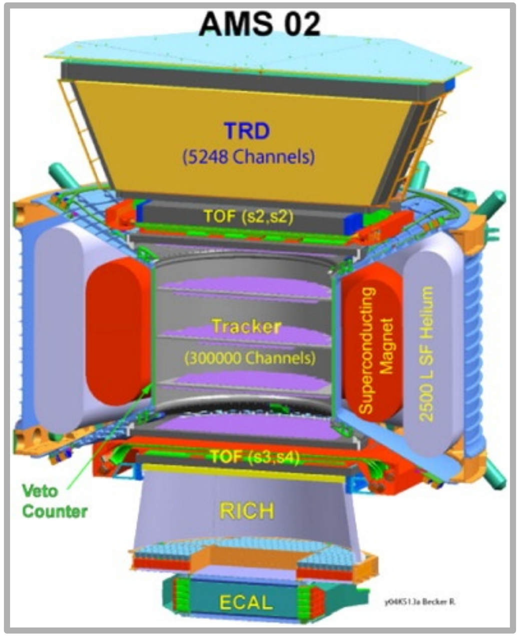
- Energy measurement → calorimeter
  - full energy deposition → at the tail
- Direction (shower axis)
  - measure using tracker
- Charge (particle type) measurement
  - add magnet to tracker system
- Momentum → time of flight (scintillator)
  - get isotope (particle type)

- Remove background
  - install veto detector

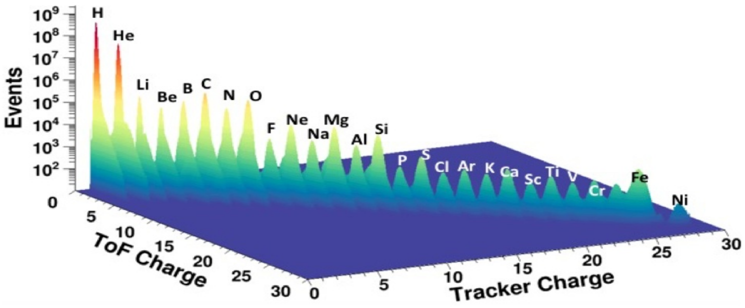


Example AMS

- Very similar to AMS-02



Gotta catch ‘em all!

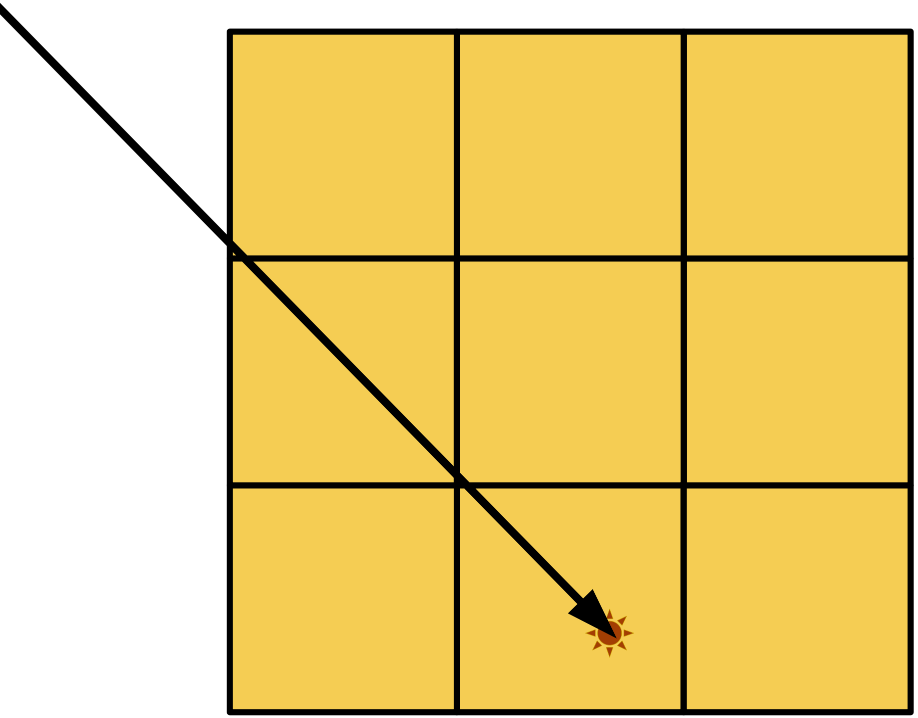


Key findings:

- Positron fraction: rising up to ~250 GeV with a sharp break, new sources, DM?
- Antiproton excess: Higher-than-expected antiproton-to-proton ratio above ~5 GeV,
- Spectral hardening in protons, helium, and heavier nuclei (~200–300 GV)
- So far no anti helium

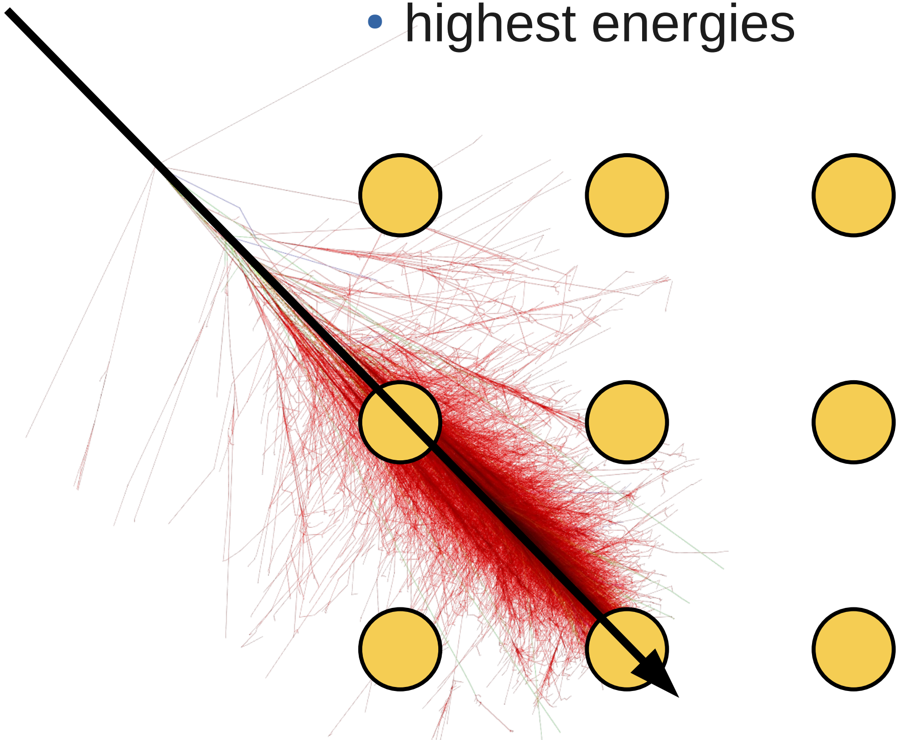
Astronomy at the highest energies

- Lower energies



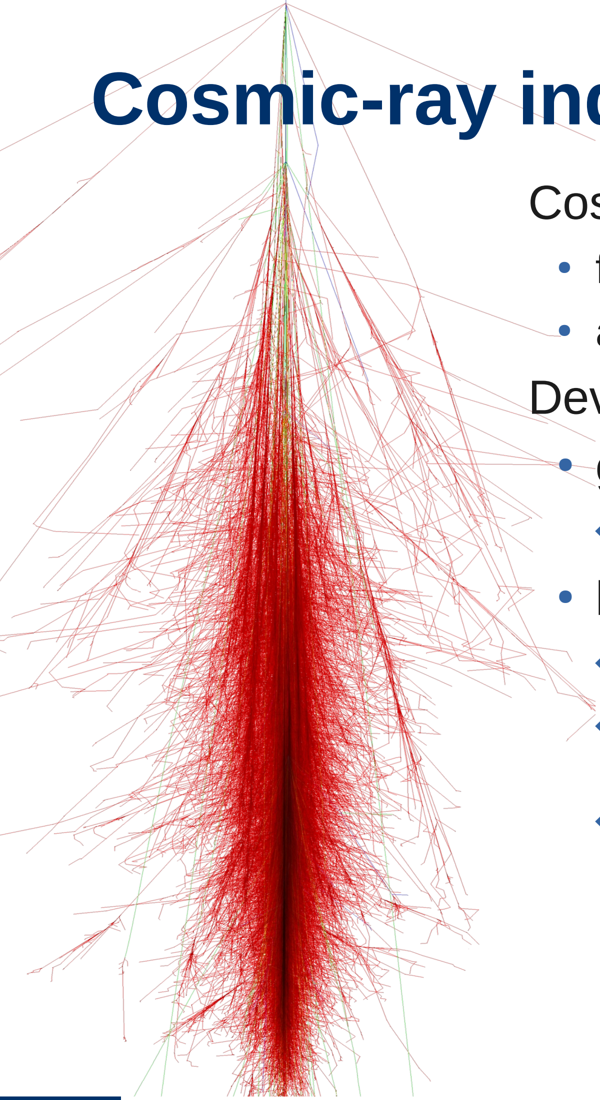
Direct
detection

- highest energies



- Low flux & indirect detection
  - Sparsely instrumented detectors
- Complex reconstruction
  (direction, energy, particle type)

Cosmic-ray induced Air Showers

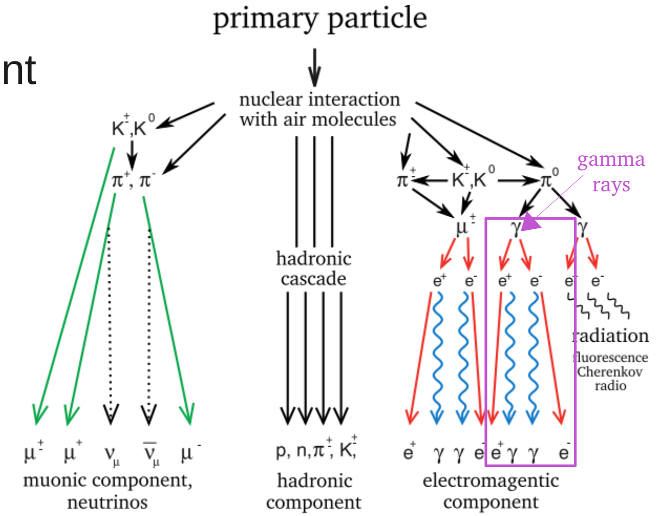


Cosmic rays induce extensive particle cascades

- first interaction: hadrons = strong force // gamma-rays: pair production
- additional fluctuations during shower development (stochastic)

Development determined by particle type and energy

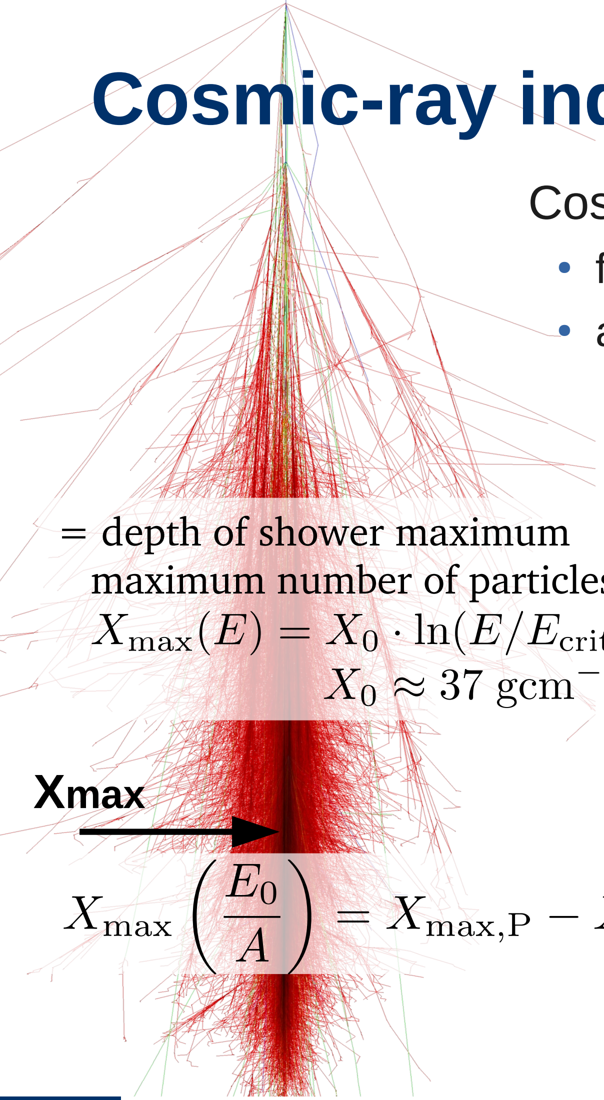
- **gamma-rays**: pair production + bremsstrahlung // inference at UHE
  - Nucleon scattering only at higher energies → few muons
- **hadrons**: significant pion production $\pi^0\pi^+\pi^-$
  - π^0 ~1/3 energy deposition in EM shower
  - $\pi^+\pi^-$ + other mesons → muonic component
  - $N^{\mu}_{\max} = A^{1-\beta}\left(\frac{E_0}{E^{\pi}_{\mathrm{crit}}}\right)^{\beta}, \quad \beta \approx 0.85$



Cosmic-ray induced Air Showers

Cosmic rays induce extensive particle cascades

- first interaction: hadrons = strong force // gamma-rays: pair production
- additional fluctuations during shower development (stochastic)

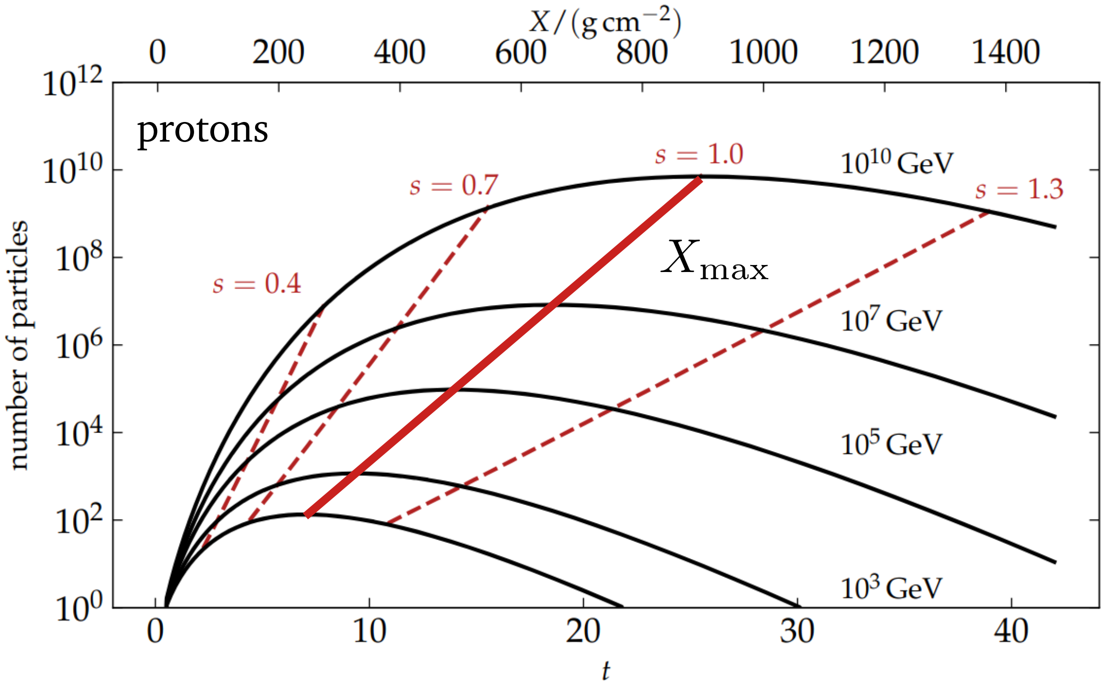


= depth of shower maximum
maximum number of particles

$$X_{\max}(E) = X_0 \cdot \ln(E/E_{\text{crit}})$$

$$X_0 \approx 37\ \text{gcm}^{-2}$$

$$X_{\max}\left(\frac{E_0}{A}\right) = X_{\max,\mathrm{P}} - X_0 \ln(A)$$



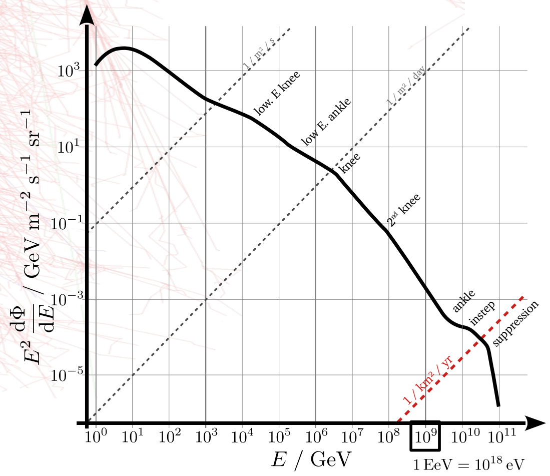
Shower universality: scaled profiles are ~universal at UHE!

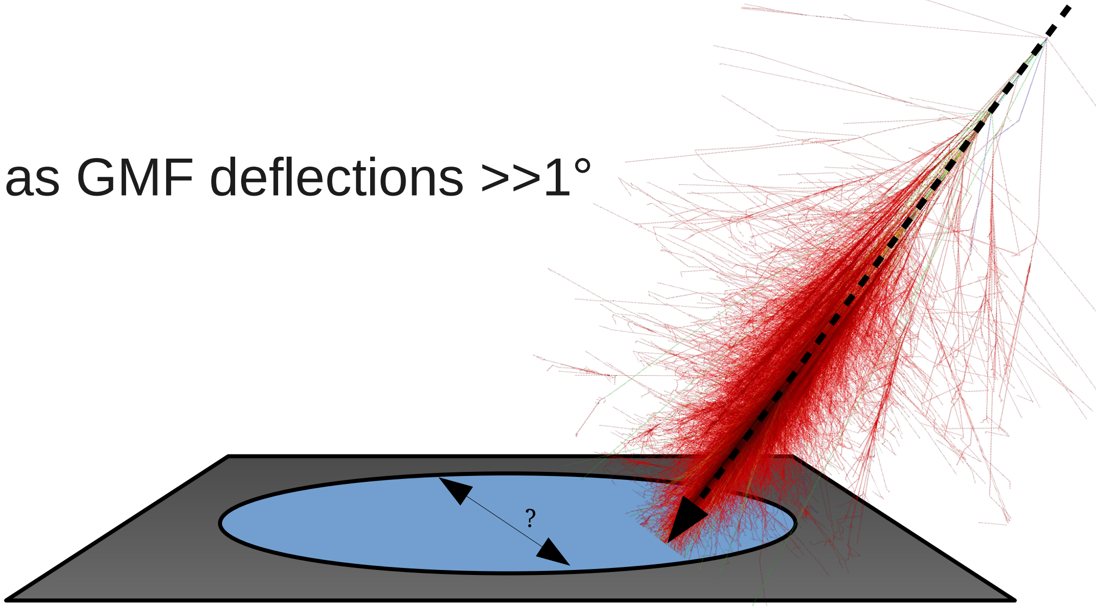
How to design an UHECR observatory

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

Precise measurements required (high statistics, low systematics)

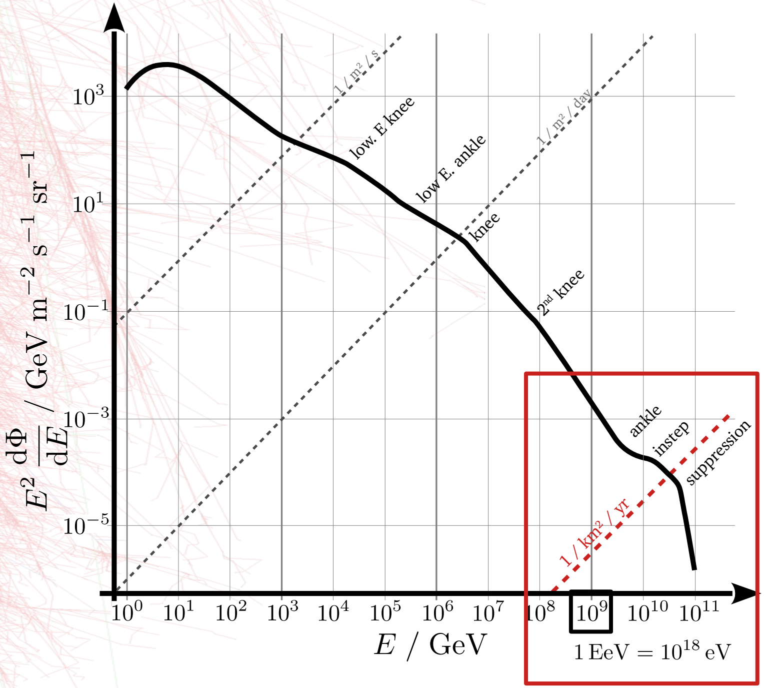
- Energy spectrum, number of particles correlates with energy → straight-forward
  → biggest challenge: absolute calibration
- Mass composition, very challenging
- Anisotropy with high statistics
  - search for cosmic-ray sources
    - angular resolution, <1° sufficient, as GMF deflections >>1°

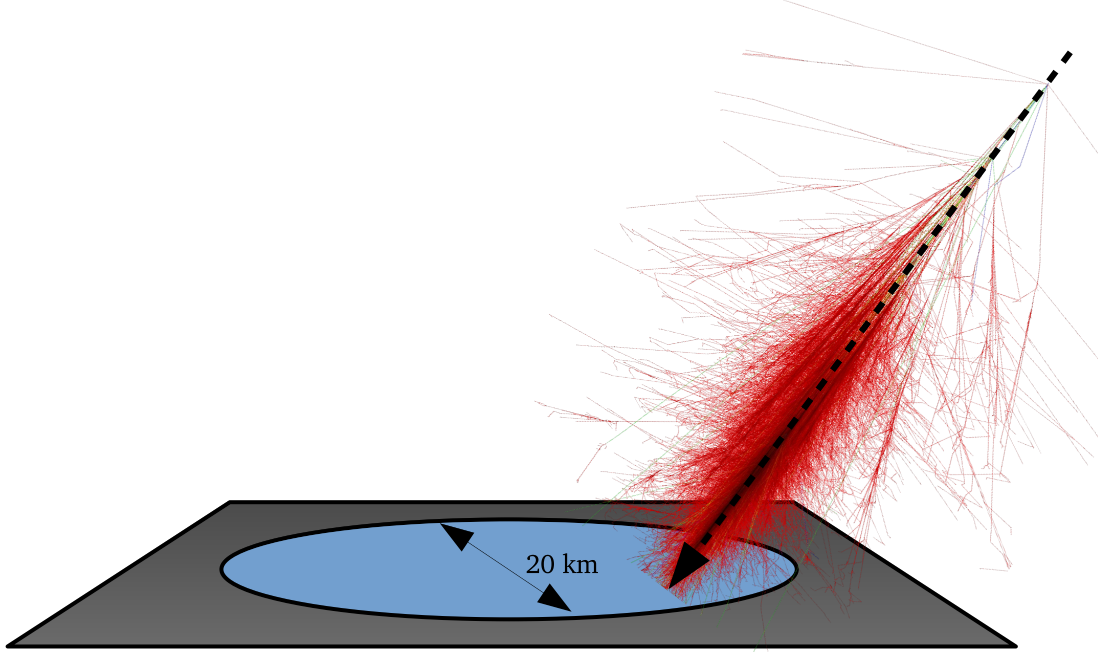




How to design an UHECR observatory

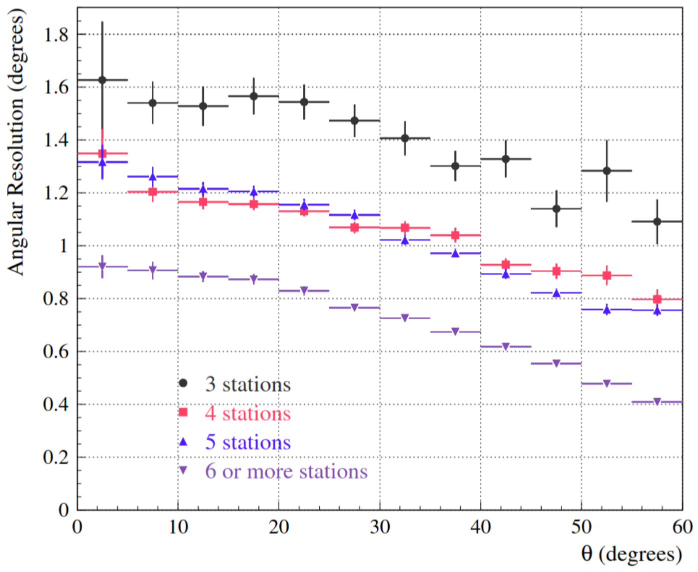
- Detector design of an UHECR observatory:
  - study particles above the ankle (extra-galactic?!) at ~30 EeV
  - flux → 1 / km² / year → for thousands per year → size: 1,000 km² !

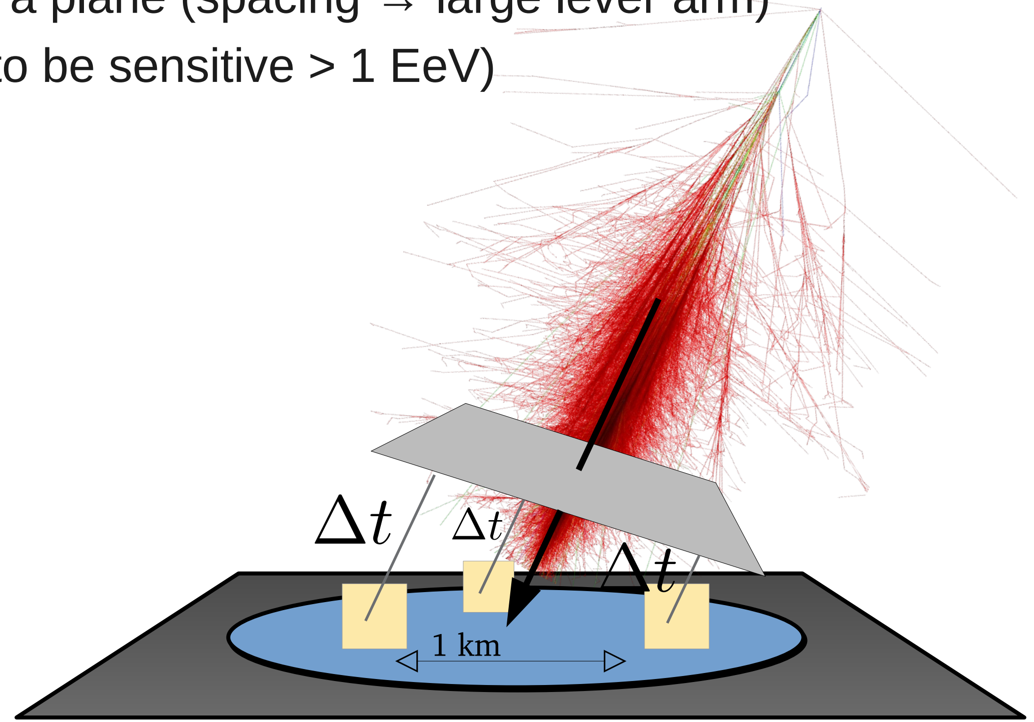




How to design an UHECR observatory

- Angular resolution:
  - angular resolution, <1° sufficient, GMF deflections >>1°
  - at least 3 triggered stations needed: fit a plane (spacing → large lever arm)
  - requires spacing of about 1 – 1.5 km (to be sensitive > 1 EeV)



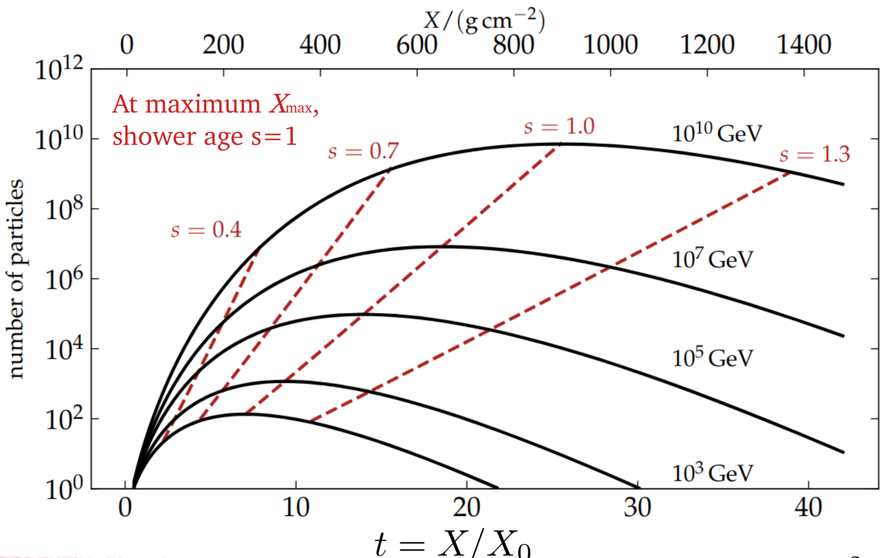


How to design an UHECR observatory

At which altitude to place the observatory?

Best performance:

- Measure at shower maximum X_{max} → relative fluctuations are small, large multiplicity
- Below X_{max}, number of particles reduces → shower dampens

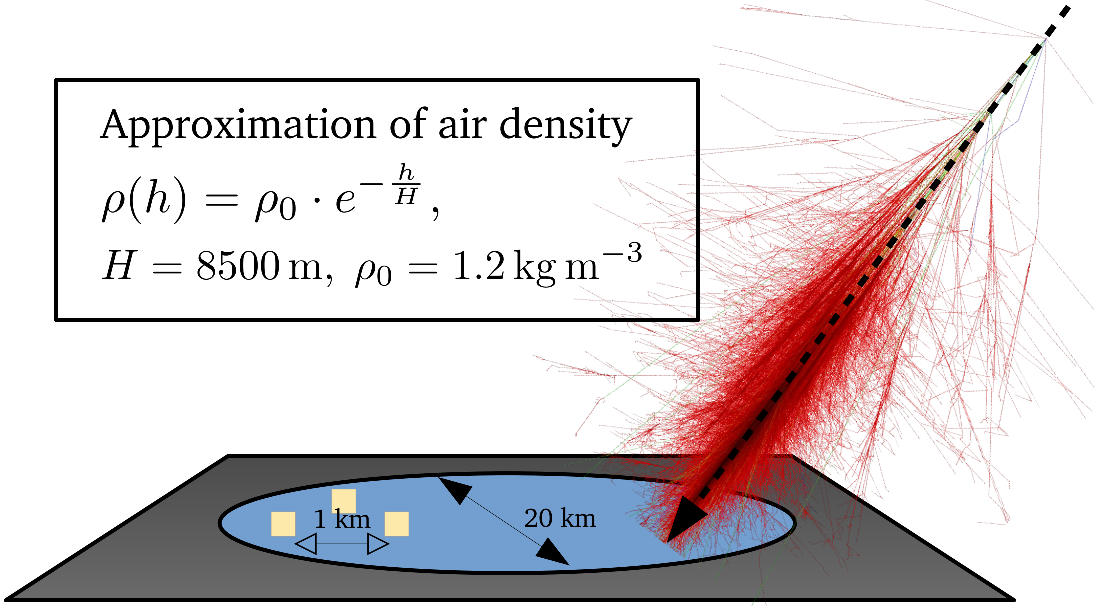


$X_{0,\mathrm{air}} \approx 37\,\mathrm{g\,cm^{-2}}$

Approximation of air density

$$\rho(h) = \rho_0 \cdot e^{-\frac{h}{H}},$$

$$H = 8500\,\mathrm{m},\ \rho_0 = 1.2\,\mathrm{kg\,m^{-3}}$$



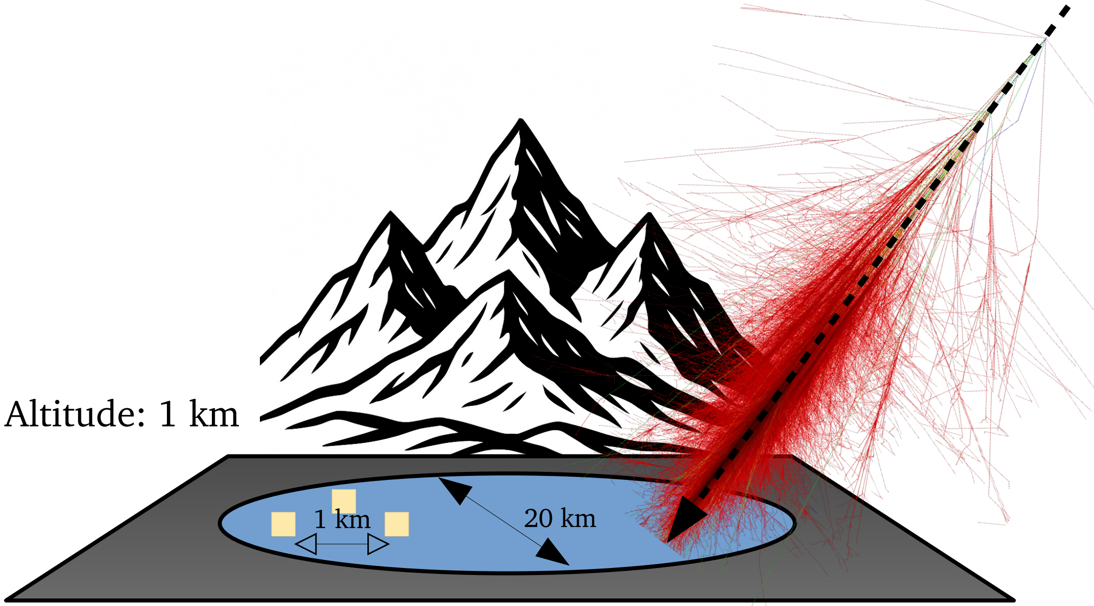
How to design an UHECR observatory

Detector design of an UHECR observatory:

- study particles above the ankle (extra-galactic?!) at ~30 EeV

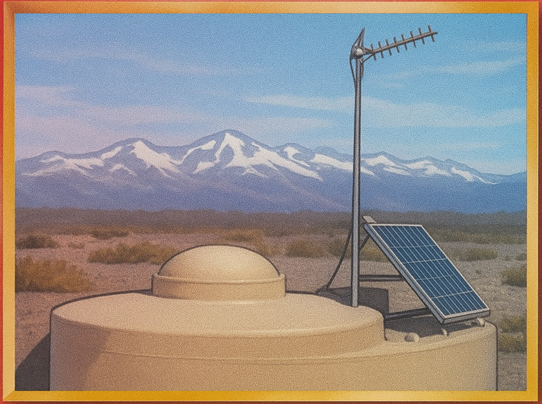
Typical UHECR observatory

- at altitude of 1,000 m
- size: thousand km²
- detector spacing 1,000 – 1,500 m
- angular resolution: 1° → 0.5°
- energy resolution 20% – 5%
- Calibration (bias) challenging
  - Extrapolated simulations additional detector needed



Gotta catch 'em all!

Pierre Auger Observatory



World's largest cosmic-ray observatory located in Argentina

Operation
since 2005, AugerPrime since 2024, at 1200 m altitude

Energy range
10^18 – 10^21 eV, with extensions down to 10^16.5 eV

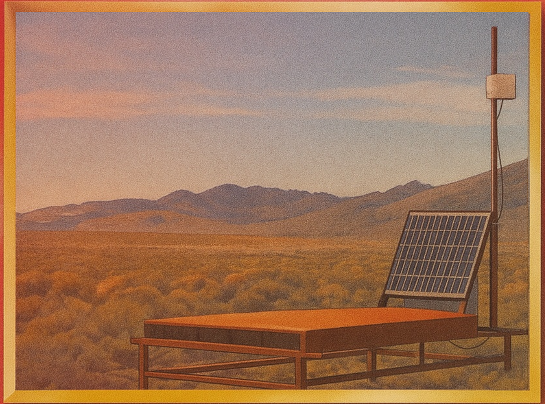
Size
3,000 km², 1550 WCD stations, 27 telescopes

Angular resolution
Below 1°, up to 0.5° (at the highest energies)

Energy resolution
From 20% to 7%, 15% energy scale uncertainty

Strange habit
Analyses are like wine, let them age (before publishing)

Telescope Array Project



UHECR observatory located in Utah

Operation
Since 2008, deployed using helicopters, 1400 m altitude

Energy range
10^17 – 10^21 eV

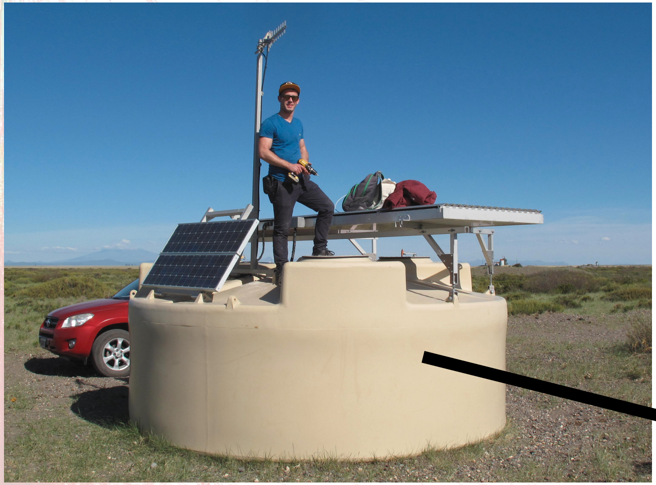
Size
760 km², 500 scintillators, ~30 telescopes

Angular resolution
Below 1.5°, up to 1°

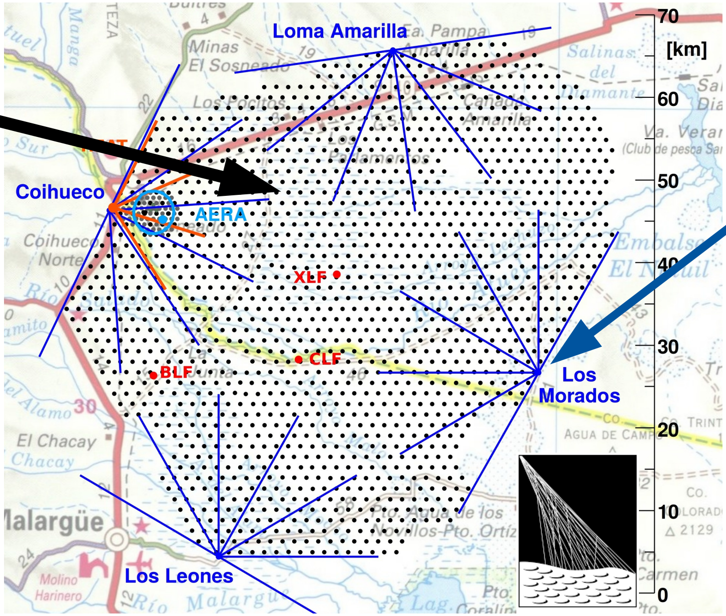
Energy resolution
From 15%, 21% energy scale uncertainty

Strange habit
Still loves outdated hadronic interaction models

The Pierre Auger Observatory



- largest cosmic-ray observatory
  - located in Argentina
- **hybrid** measurements



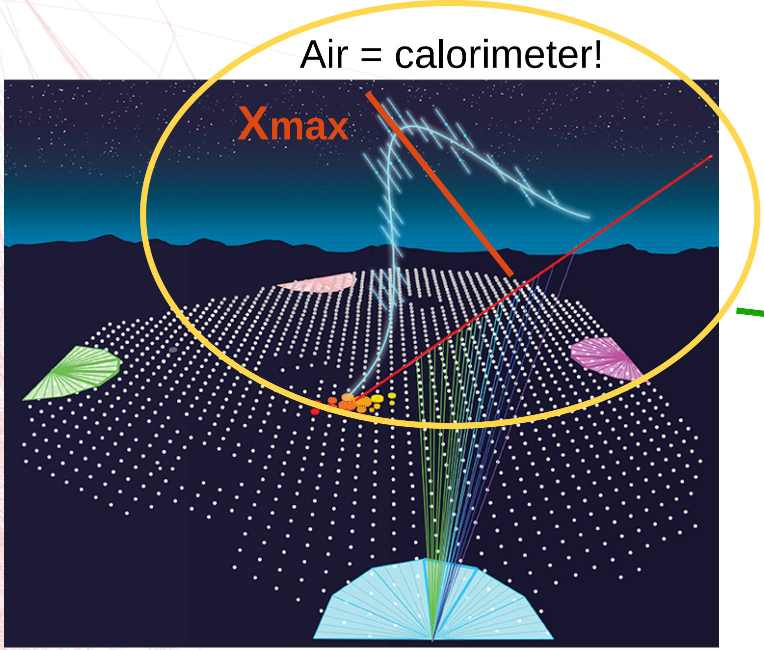
Surface Detector (SD)

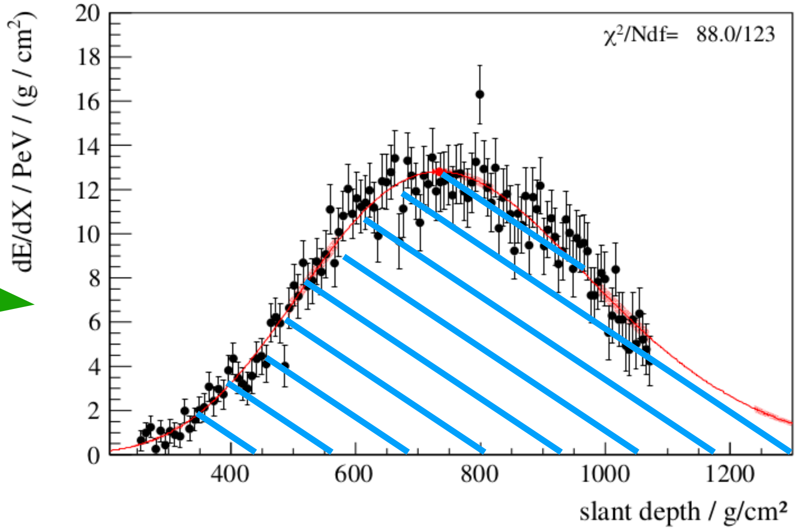
- 1660 water-Cherenkov detector stations
  - 3000 km² array
  - <u>~100% duty cycle</u>

Fluorescence Detector (FD)

- 27 telescopes
  - located at 4 sites
  - <u>~15% duty cycle</u> (dark, moonless nights)

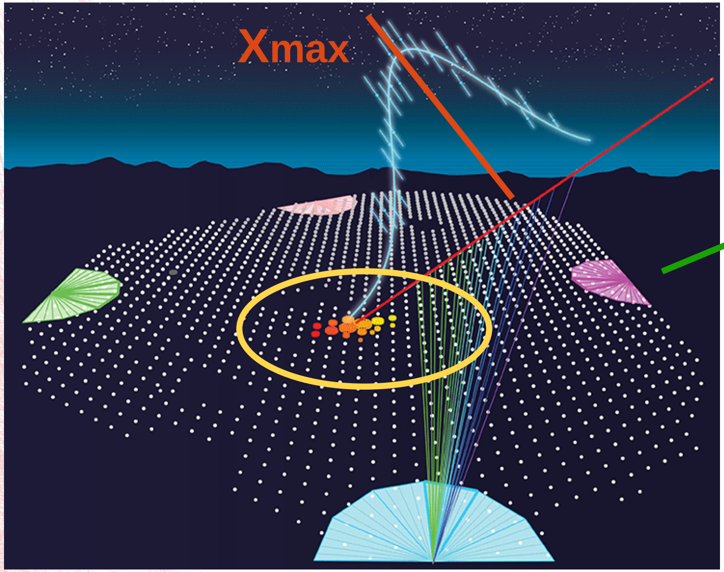
Fluorescence Detector & Reconstruction

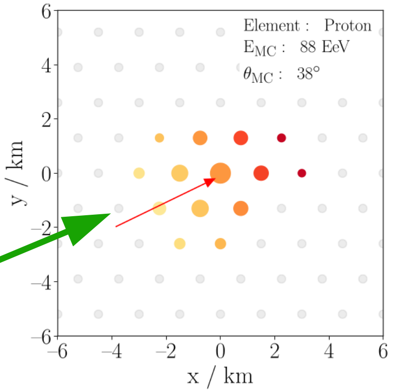


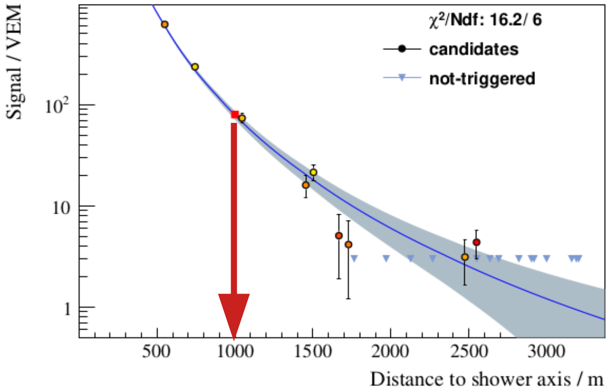


- Reconstruct shower geometry (axis + core)
- Reconstruct profile as function of slant depth
  - Fit Gaisser-Hillas profile
  - → Integrate → estimator for Fluorescence yield
  - → Fluorescence yield → deposited Energy
    → absolute Energy

Surface Detector & Reconstruction

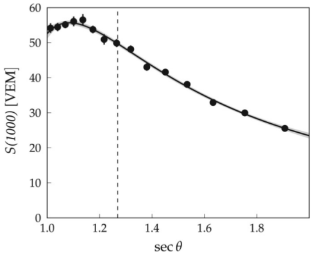






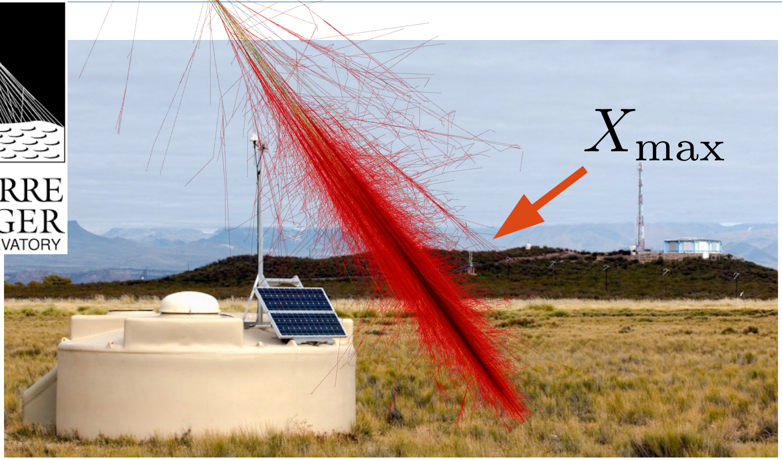
- SD measures signal footprint
  - fit signal footprint (Lateral Distribution Function)
- Parameterized as **S(1000)**
  - Signal measured for shower at 1000m distance
  - Corrected on atmospheric attenuation → **S38**
  - Signal measured at 1000m distance & 38° zenith

→ Signal = energy estimator dependent on **MC**

S(1000) →  → **S38**

Ultra-high-energy cosmic rays (UHECRs)

PIERRE AUGER OBSERVATORY

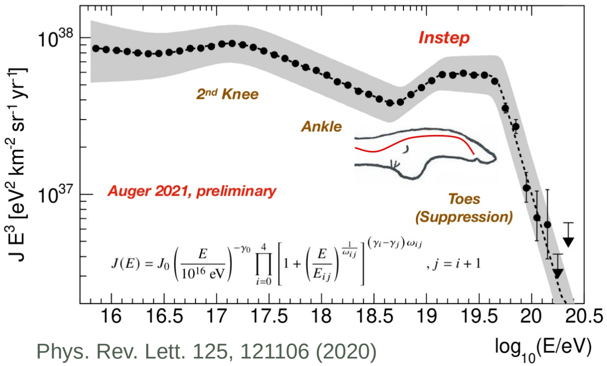


The Pierre Auger Observatory

- world's largest observatory to study ultra-high-energy cosmic rays
- hybrid detection of air showers
  - 1,660 water-Cherenkov detectors
  - 27 fluorescence telescopes
    - can precisely observe Xmax

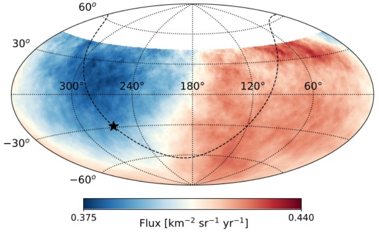
Key findings

Characteristics of the energy spectrum at ultra-high energies >10[18] eV

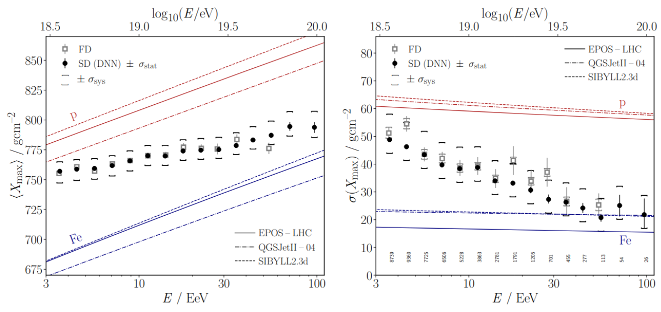


Phys. Rev. Lett. 125, 121106 (2020)

Science 357 (2017) 1266



Discovery: large-scale anisotropy pointing away from galactic center
Hint: UHECRs are extragalactic



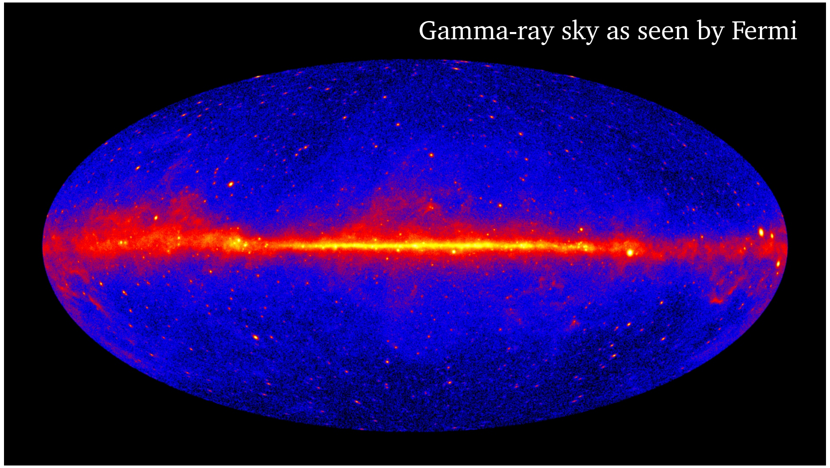
Mass composition
Towards heavier and purer composition

Cutoff not caused by GZK only

Phys. Rev. Lett. 134, 021001 (2025)

Gamma-Ray Astronomy

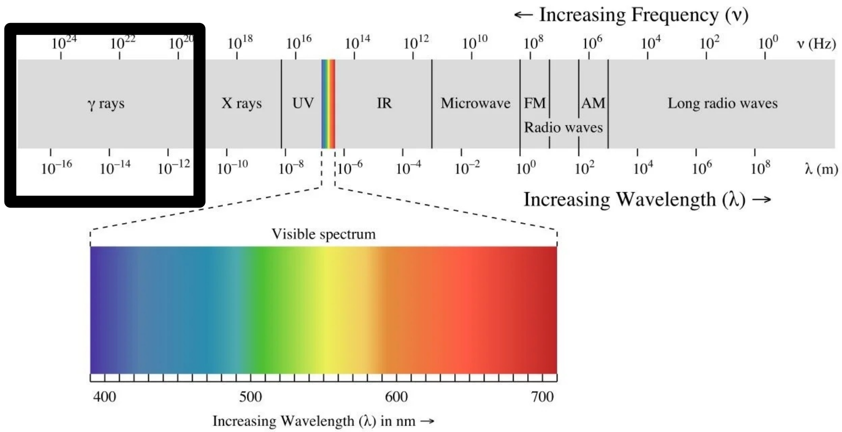
Observing the highest-energy photons (> 100 keV to PeV)



- Smoking gun of cosmic-ray acceleration
  → direct search for CR accelerators

- Probe violent astrophysical environments:
  supernova remnants, black holes,
  active galactic nuclei, gamma-ray bursts

- At low energies:
  - comprehensive sky surveys (e.g. Fermi-LAT)



gamma-rays

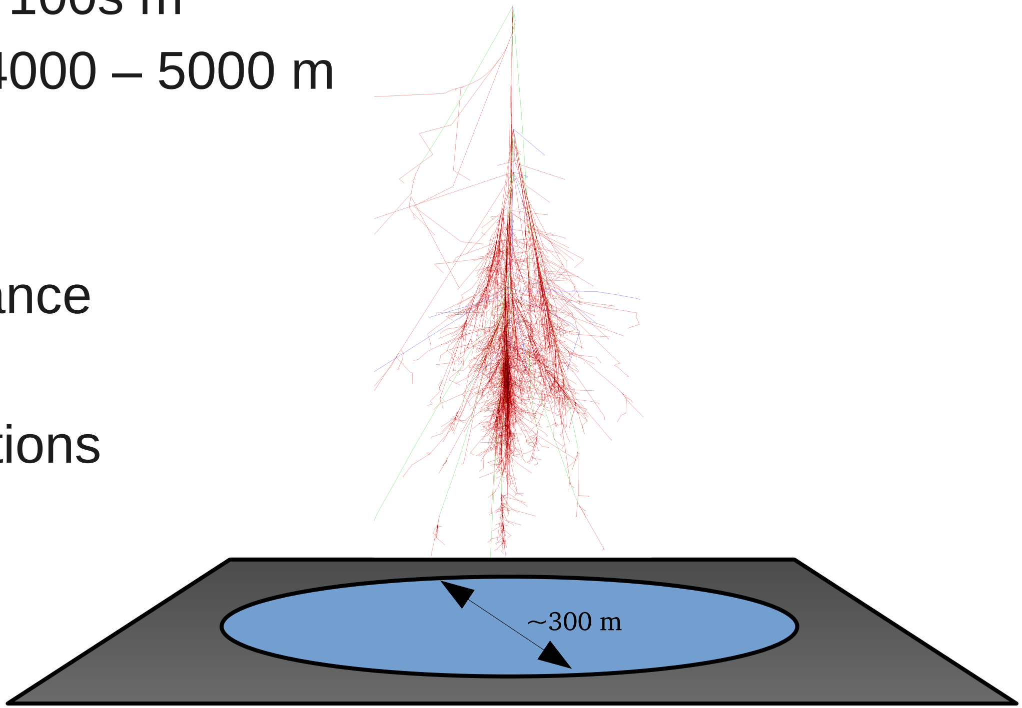
Catching gamma-rays

Air showers start to develop, featuring a few generations

- number of particles small → high fill factors required
- size of footprint at ~TeVs of scale 10s – 100s m
- to be sensitive to showers → altitude ~4000 – 5000 m

Typical instrument reconstruction performance

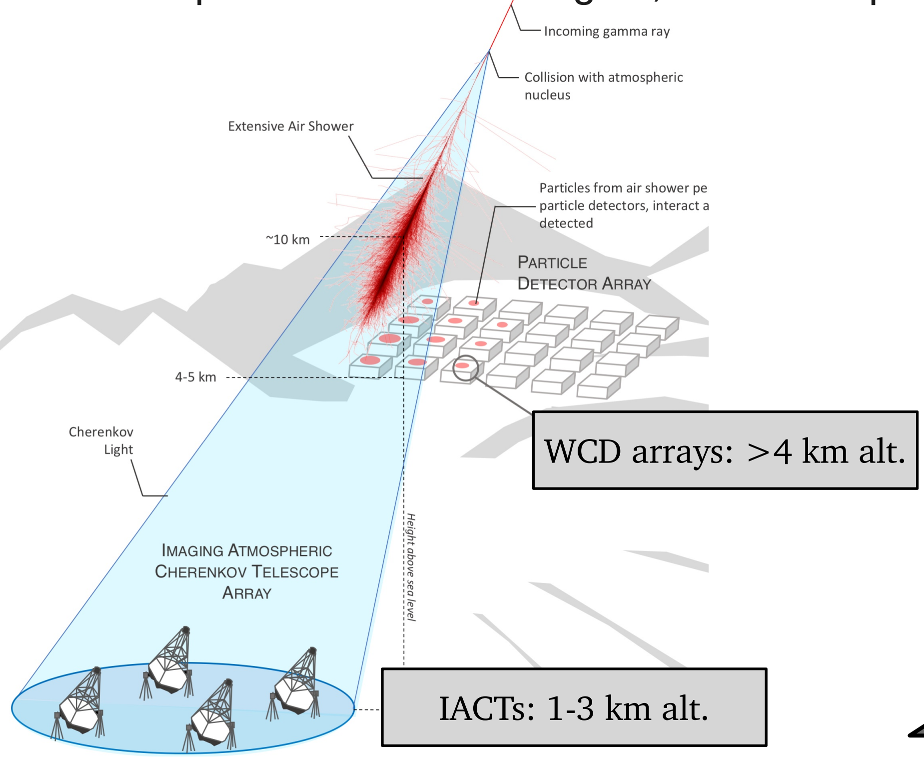
- Energy resolution is modest
  - small number of particle, huge fluctuations
- good angular resolution
  - driven by multiplicity, high fill factors

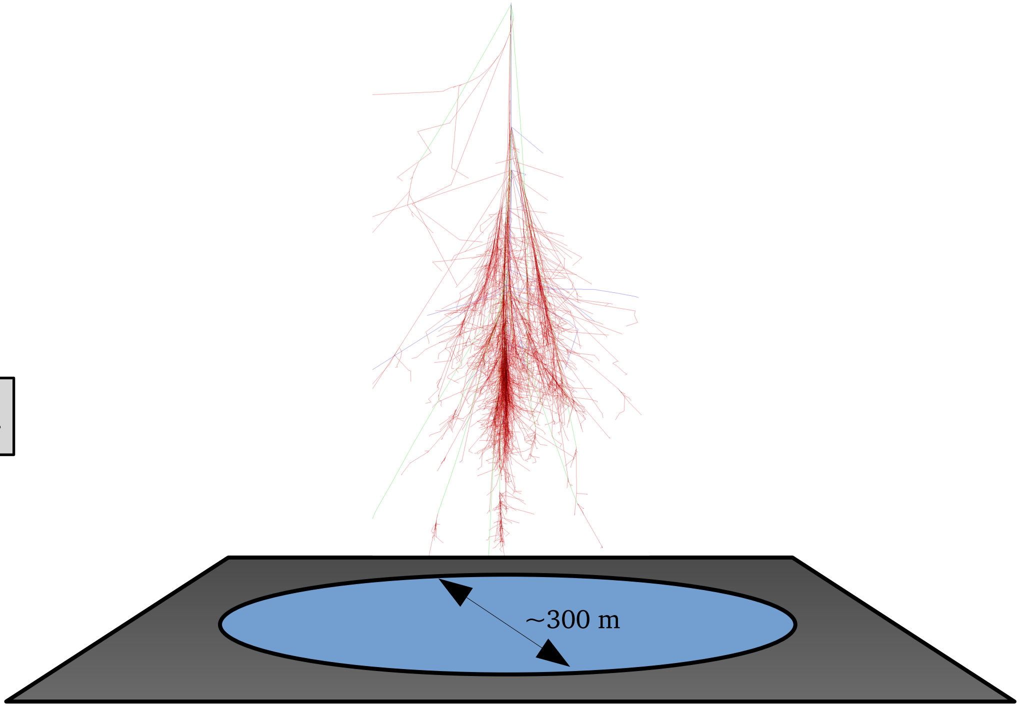


How to design a gamma-ray observatory?

Low energies

- ➔ we need to get high up the mountains
- ➔ IACTs can operate at lower energies, less absorption



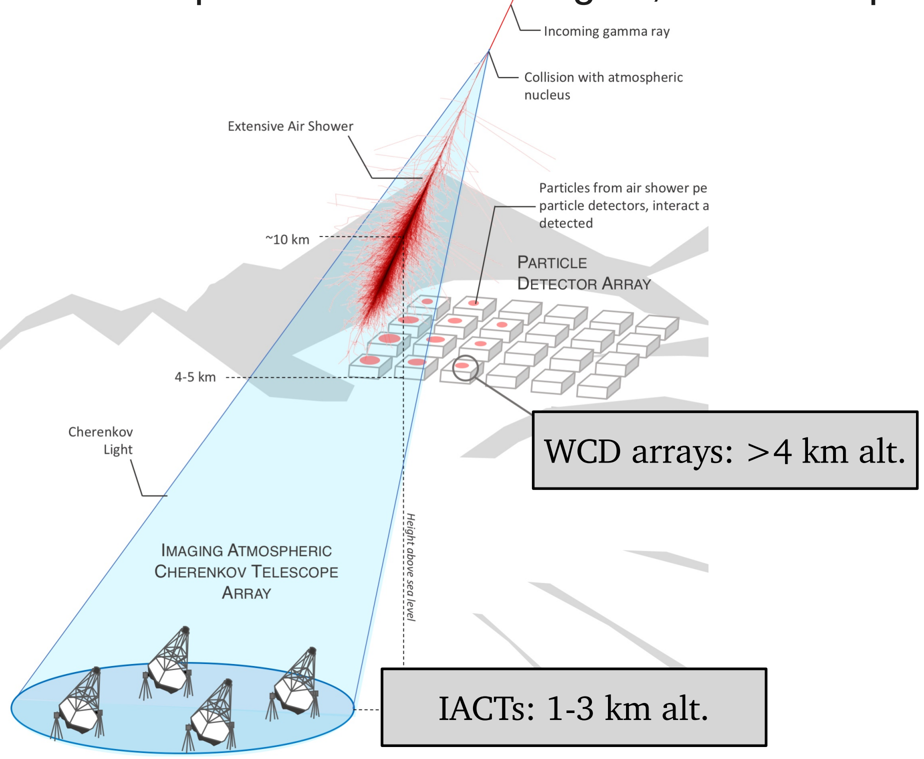


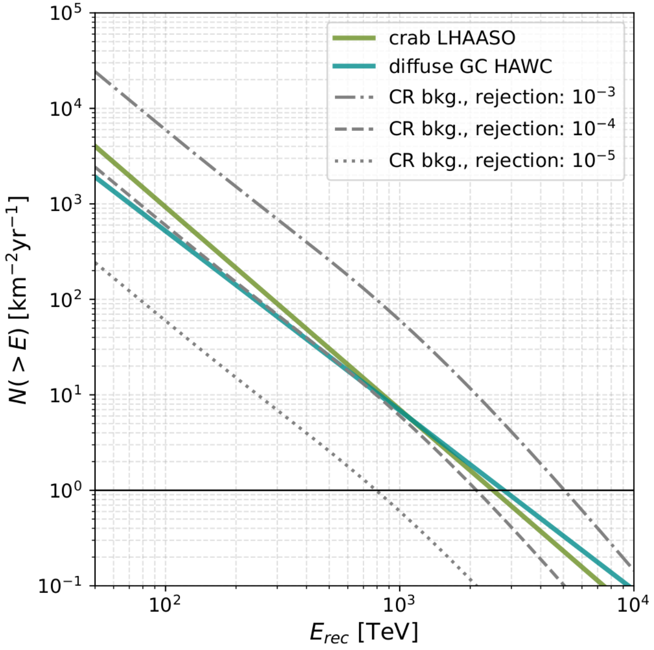
←space-borne ~30 GeV ~100 GeV TeV regime PeV regime

How to design a gamma-ray observatory?

Low energies

- we need to get high up the mountains
- IACTs can operate at lower energies, less absorption





High energies

- Falling gamma-ray spectrum → low flux
- Large array is needed (~1 km²)

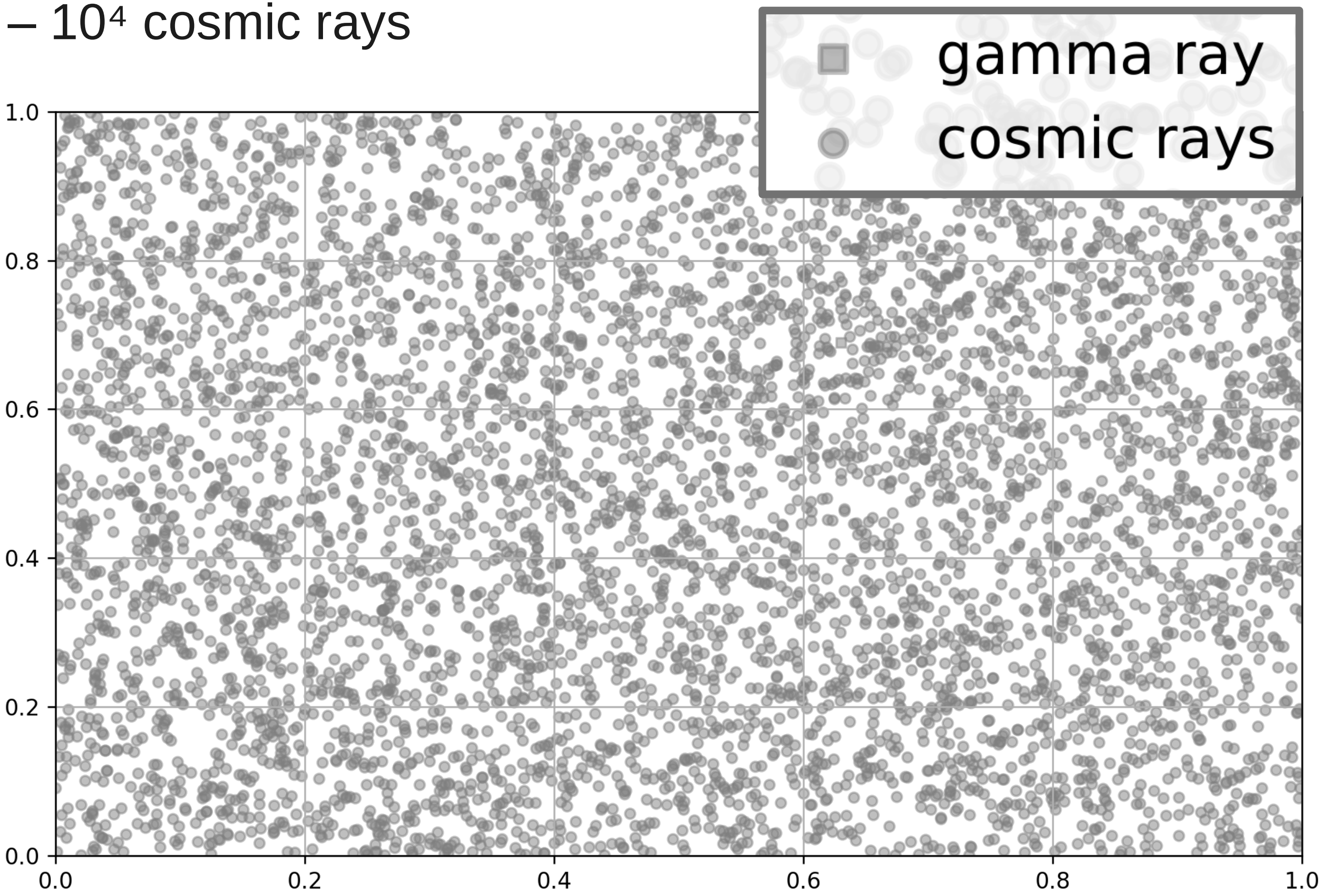
←space-borne ~30 GeV ~100 GeV TeV regime PeV regime

Rejecting the cosmic-ray background

- Only 1 gamma per 10^3 – 10^4 cosmic rays

challenging background!

- Excellent separation is essential

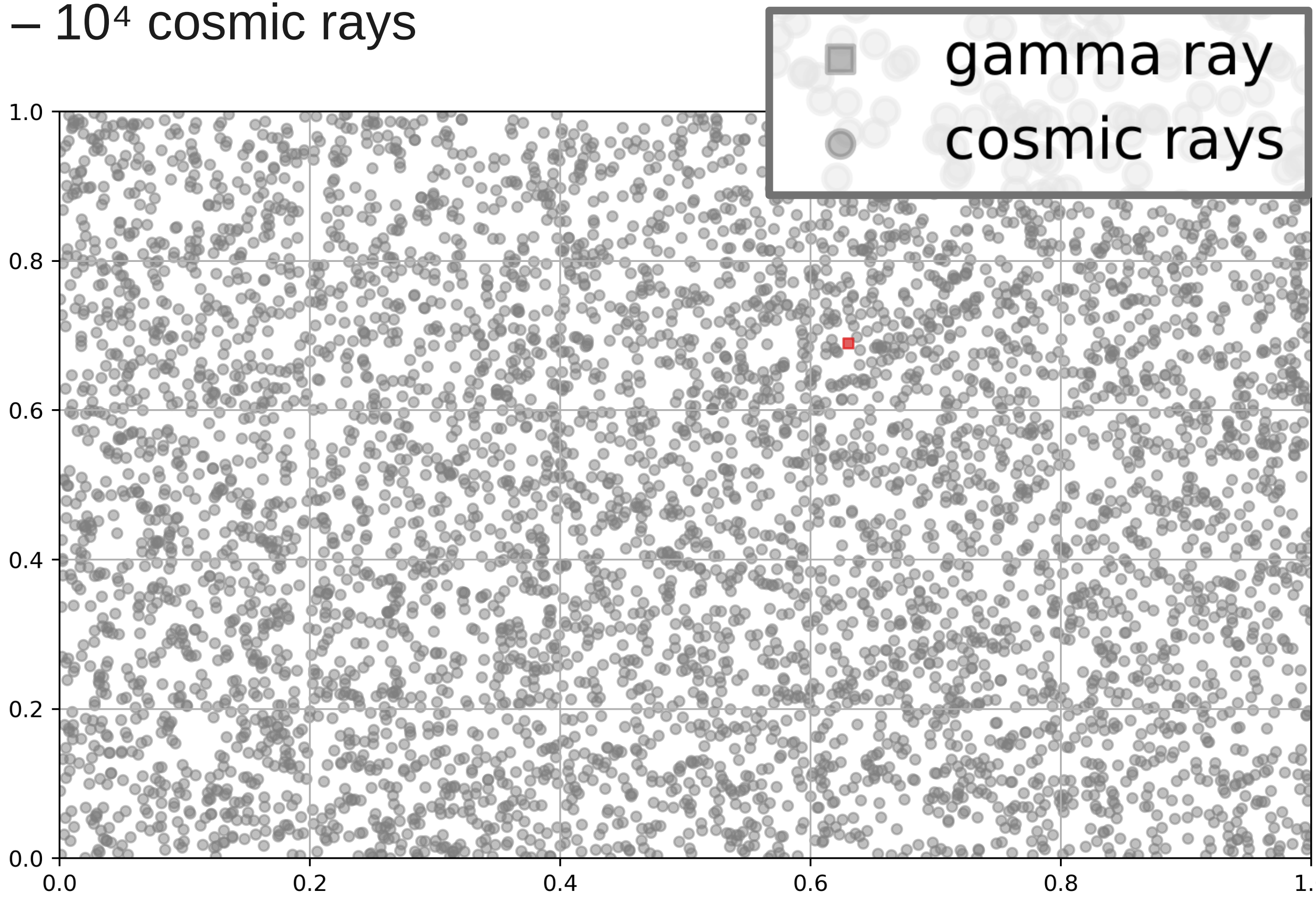


Rejecting the cosmic-ray background

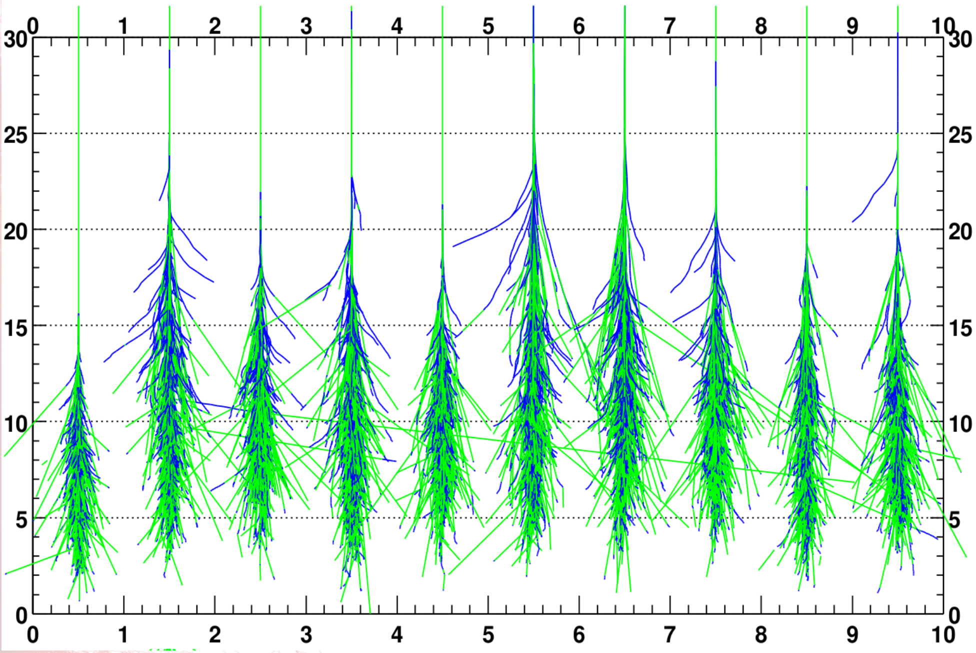
- Only 1 gamma per 10^3 – 10^4 cosmic rays

challenging background!

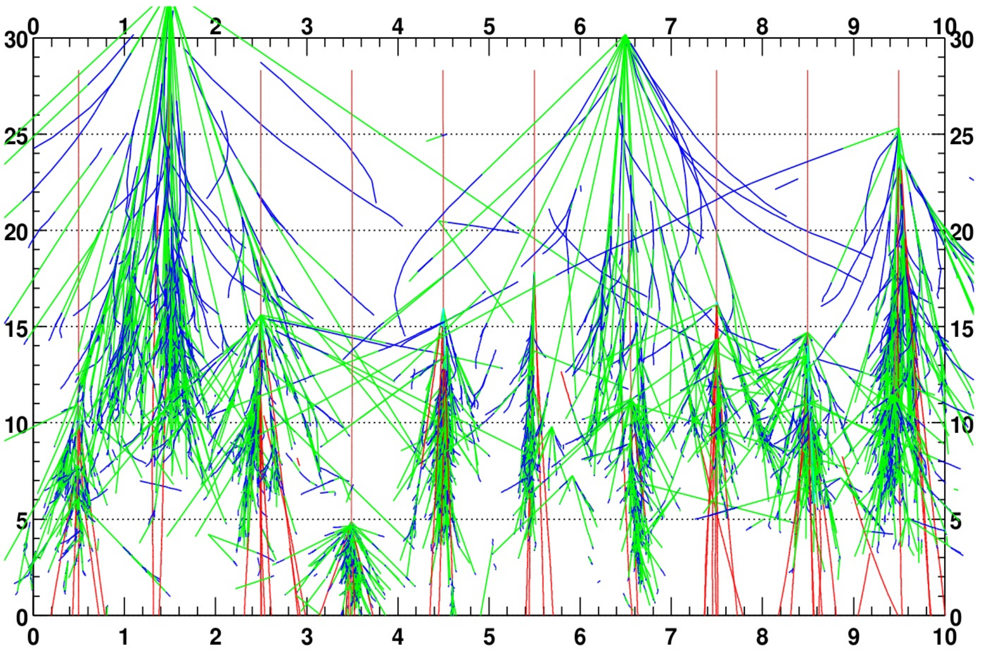
- Excellent separation is essential



Gamma- vs hadron-induced showers



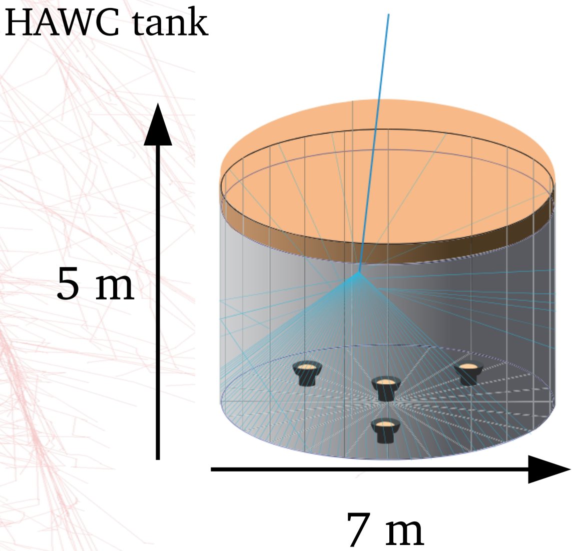
gamma-ray showers (300 GeV)



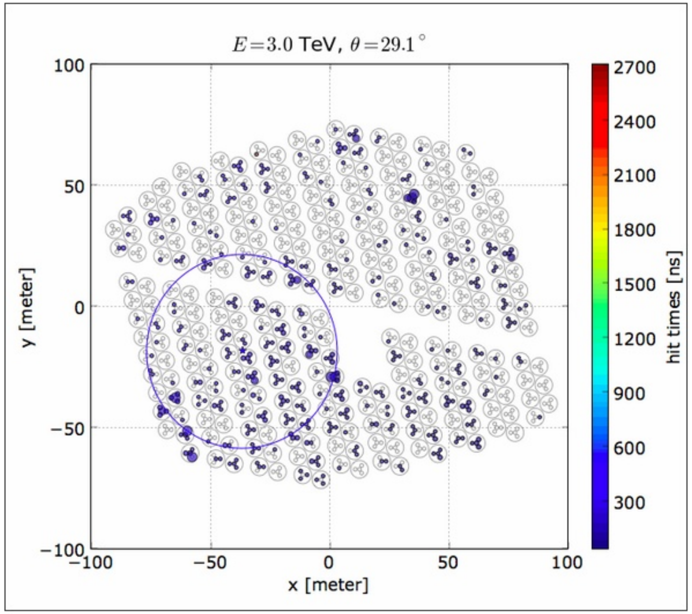
proton showers (300 GeV)

de Naurois, M., Ph.D. thesis, Université Pierre et Marie Curie - Paris VI (2000).

Gamma-ray WCDs



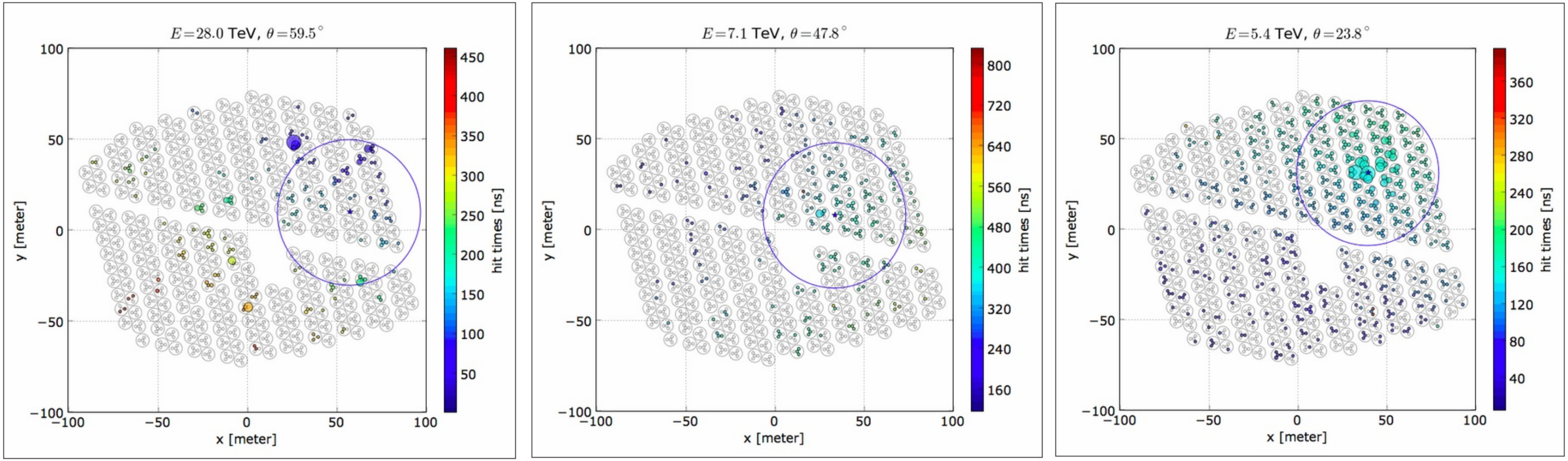
Depth of 5 m:
Cosmic muons (MIP) induce large signals



Ability to tag muons!

https://www.hawc-observatory.org/observatory/ghsep.php

Gamma / hadron separation

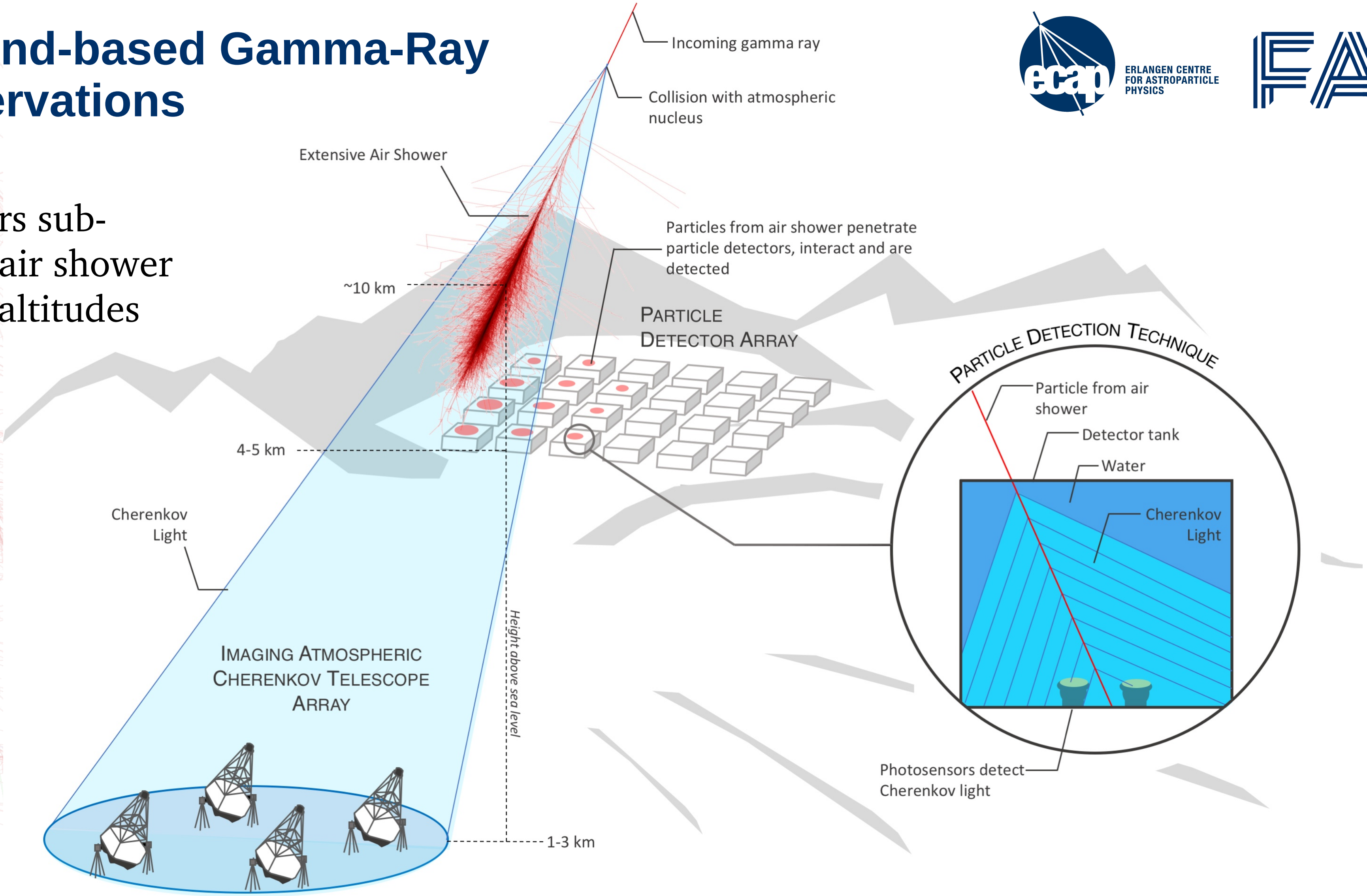


Which event is a gamma, which event is a proton?

Star = reconstructed shower core (shower center)
Blue = early, red = later, large markers indicate huge signals
https://www.hawc-observatory.org/observatory/ghsep.php

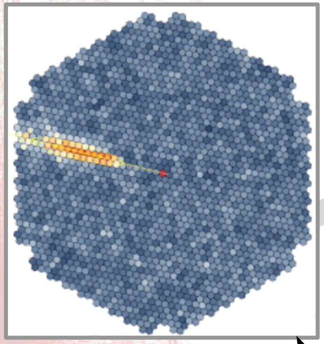
Ground-based Gamma-Ray Observations

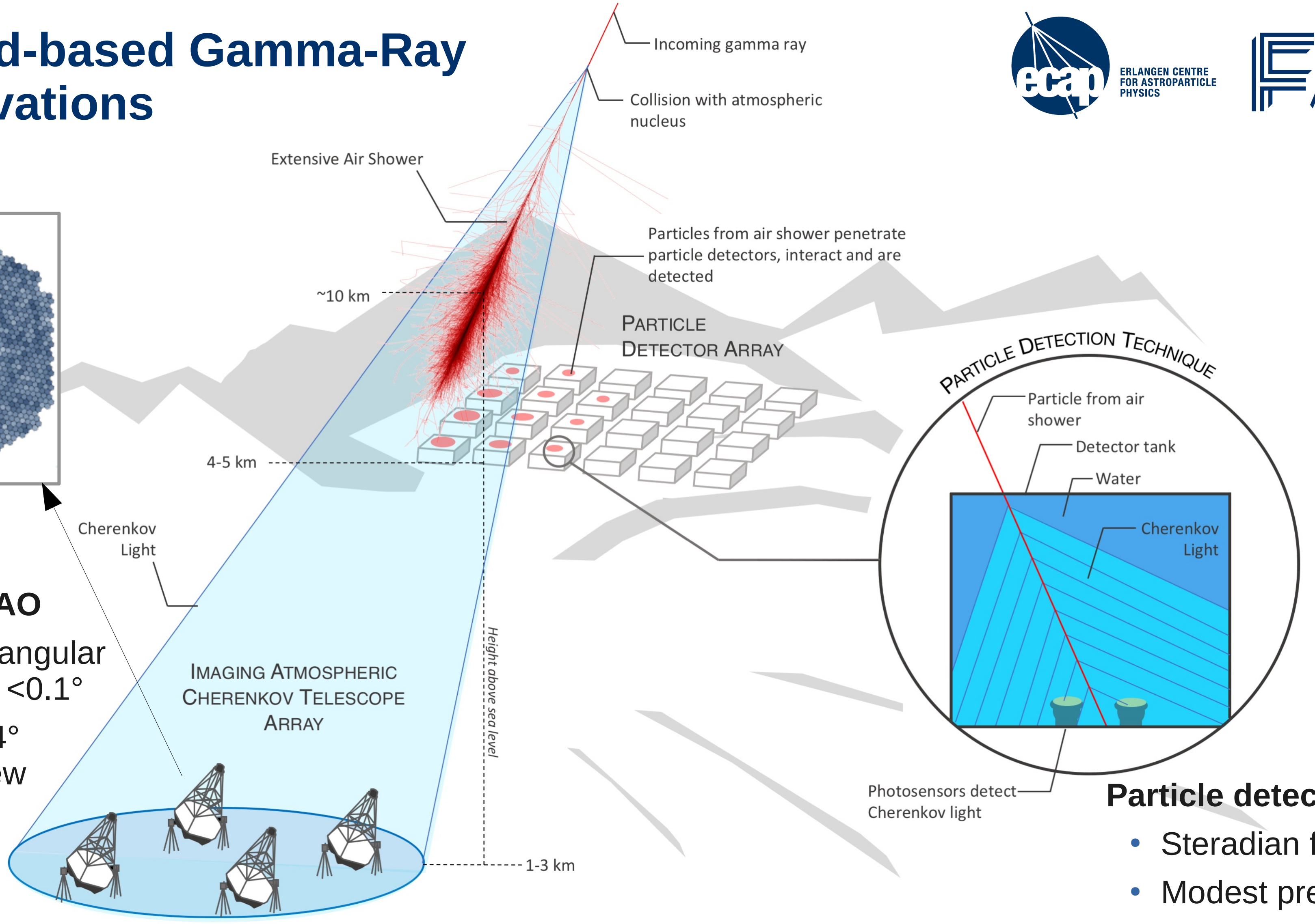
Detectors sub-sample air shower
→ high altitudes



Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Ground-based Gamma-Ray Observations





Shower image, 100 GeV γ-ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

IACTs → CTAO

- Excellent angular resolution <0.1°
- Limited ~4° field of view
- Low duty cycle

Particle detectors

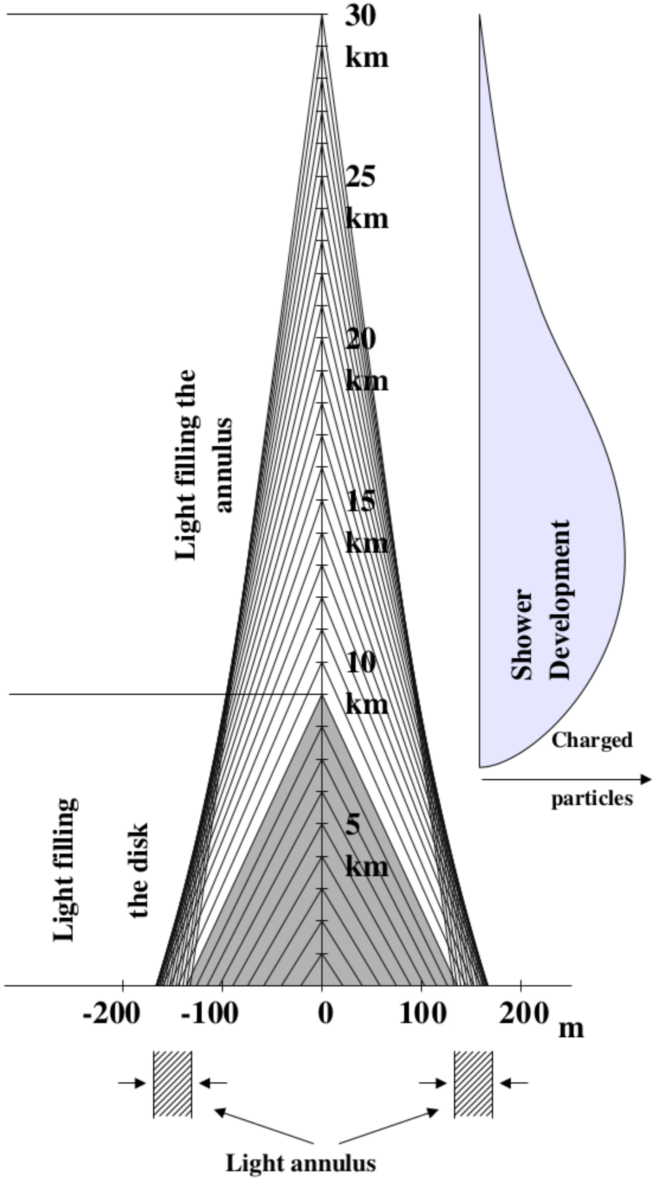
- Steradian field of view
- Modest precision
- 100% duty cycle

Imaging Air Cherenkov Telescopes

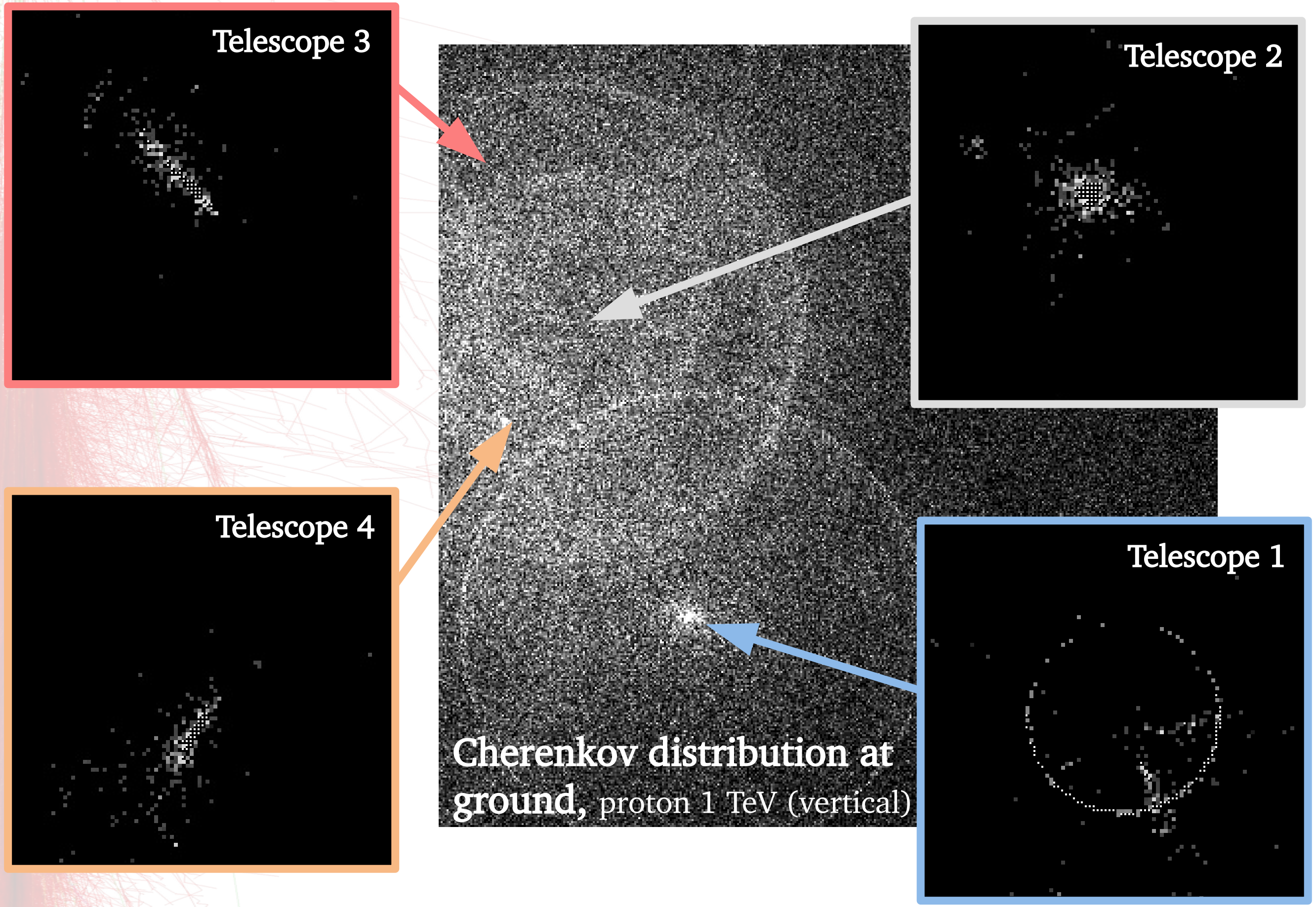
Cherenkov light emission in air showers

- produced by charged particles (e^-, e^+) in the cascade.
- particle velocity v > c/n (speed of light in medium)
- angle ~1° in atmosphere $\cos(\theta_c) = \frac{1}{\beta n}$
  - gets wider during propagation
  - density increases, particles scatter + loose energy

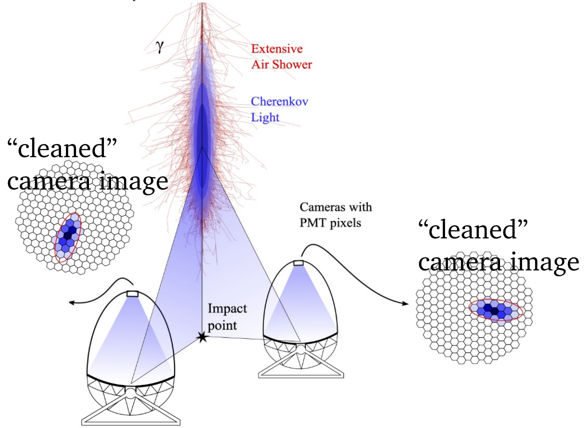
- Cherenkov angle wides during cascade:
  - change of air density
  - scattering of particles (lower energy)
- Cherenkov radius ~150 m on ground
  - light is NOT a ring!
    → superposition of emission of the whole cascade



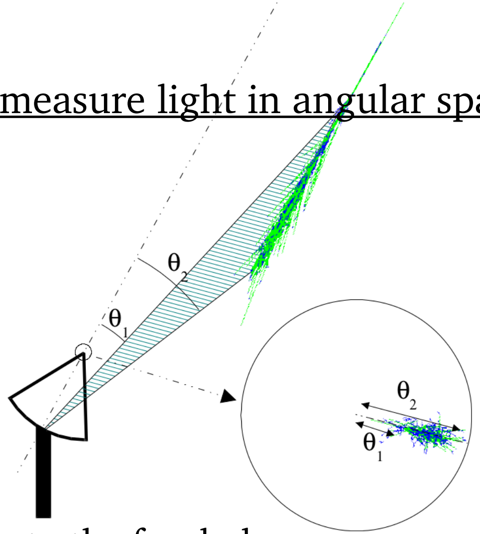
Stereoscopic reconstruction



Cherenkov distribution at ground, proton 1 TeV (vertical)



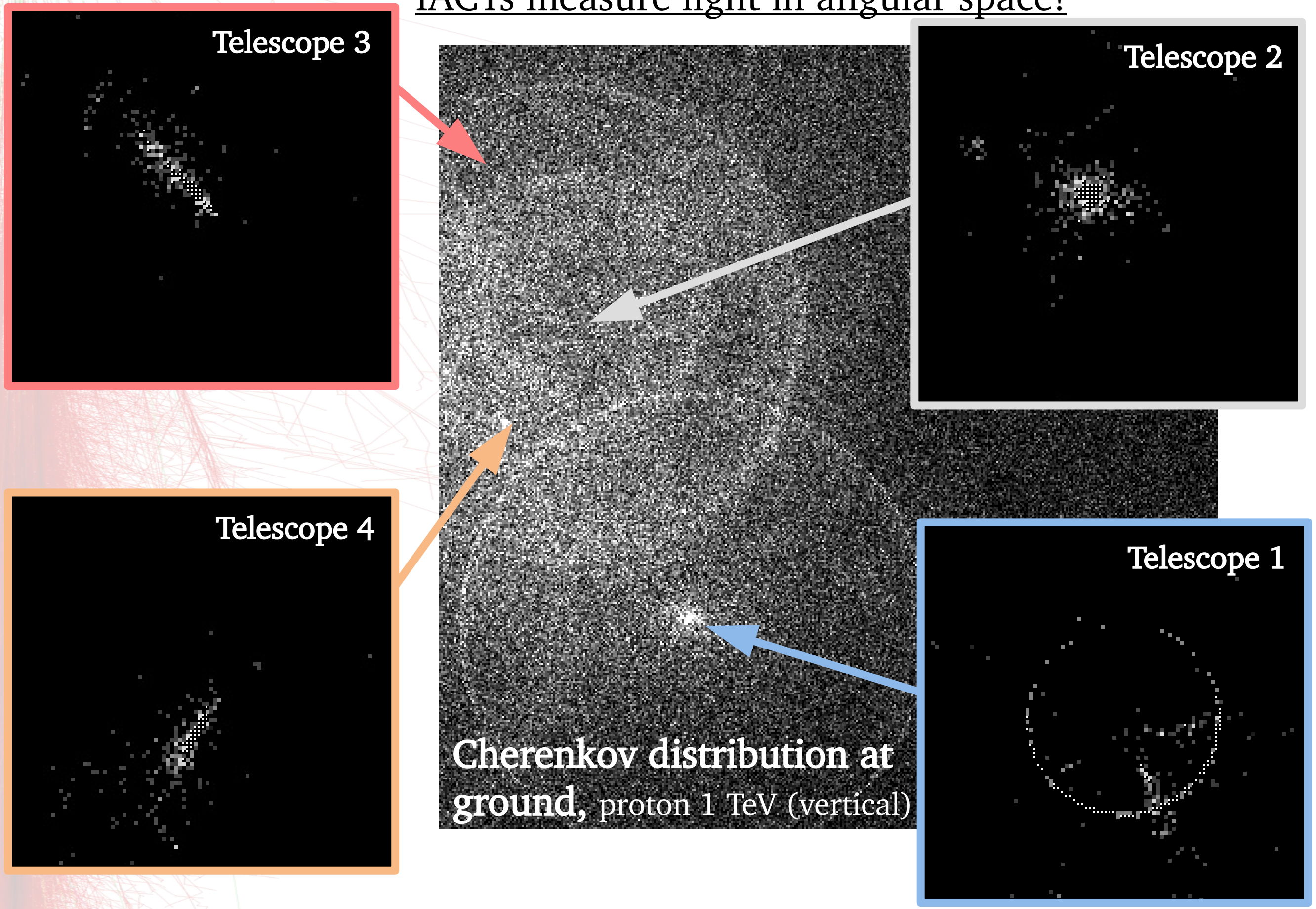
IACTs measure light in angular space!

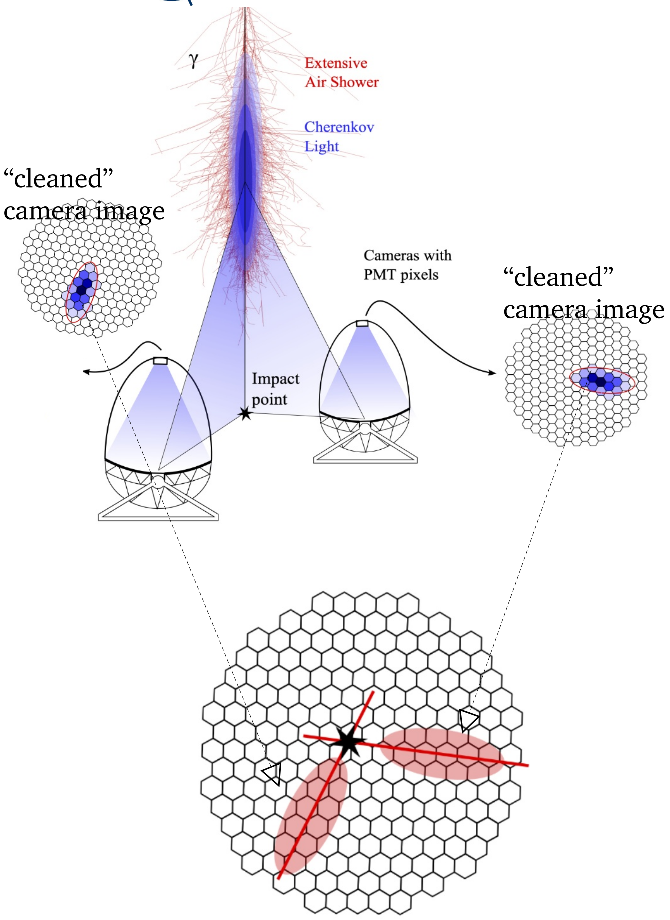


IACT maps angular distribution onto the focal plane

Stereoscopic reconstruction

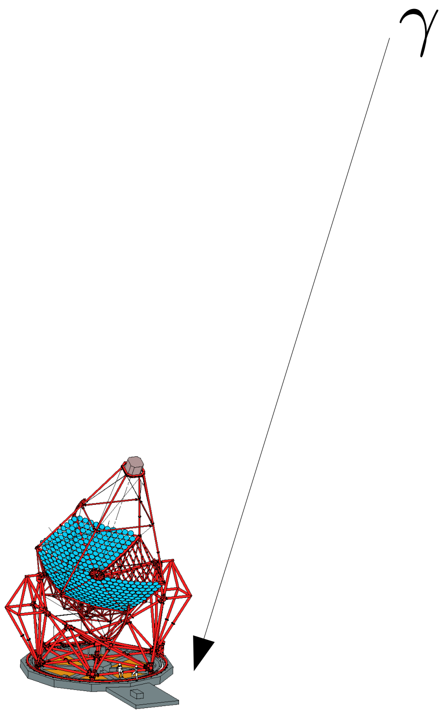
<u>IACTs measure light in angular space!</u>



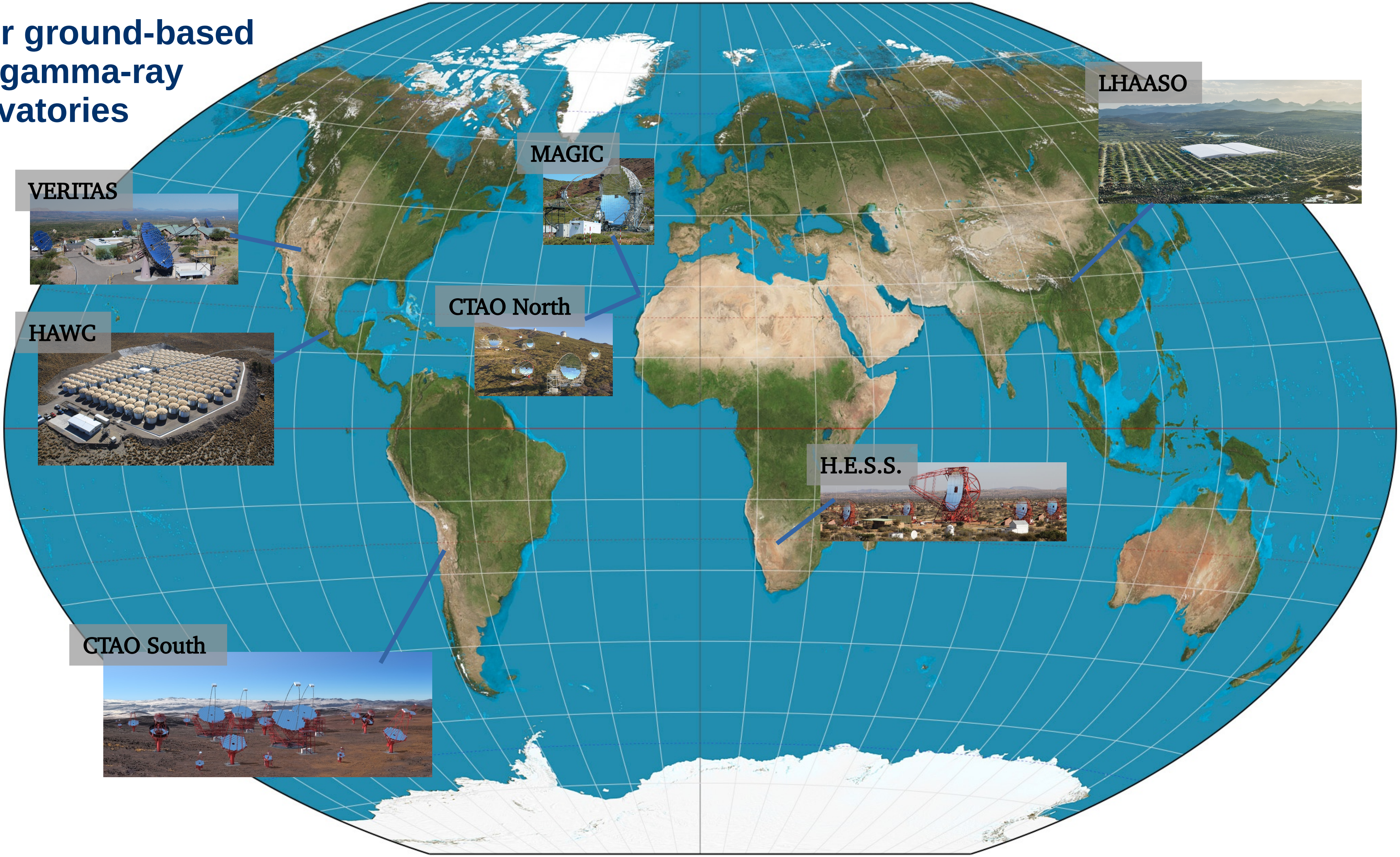


Intersect reconstructed ellipses
→ arrival direction of cosmic ray

What is the effective area of an IACT?

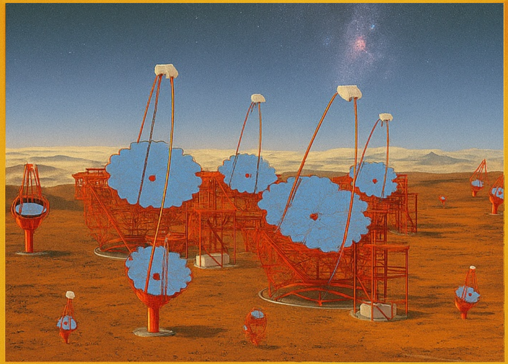


Major ground-based gamma-ray observatories



Gotta catch 'em all!

Cherenkov Telescope Array



Future flagship IACT array with a Southern and Northern Site

Operation at ~2000 m
In 2027? Sites: Chile (Atacama Desert), Spain (La Palma)

Energy range
~10 GeV to 300 TeV

Size
60 telescopes, larger array (smaller telescopes) in Chile

Angular resolution
Below 0.1° to 0.01° (sub arcmin!)

Energy resolution
From 10% to 5%, 15%?! energy scale uncertainty

Strange habit
After 10 yrs should we start construction?! No, wait, let's...

LHAASO

Largest gamma-ray observatory to date

Operation at 4400 m
In 2020, Sites: China (Sichuan Province, Daocheng)

Energy range
~100 GeV to 1 PeV

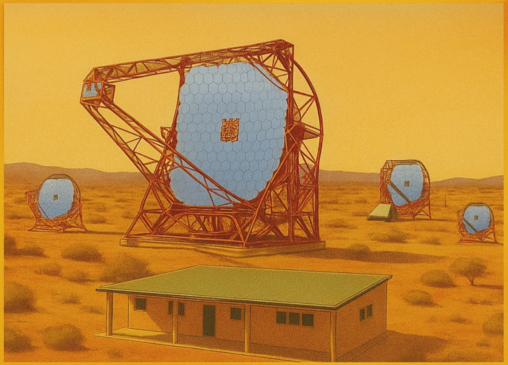
Size
1100 KM2A detectors, 1200 muon detectors, 3 ponds

Angular resolution
1° up to 0.1°

Energy resolution
From 50% to 15%

Strange habit
What again are systematic uncertainties?

H.E.S.S.



Currently the only IACT array observing the Southern Sky

Operation at 1800 m
Since 2004 (H.E.S.S. Phase II, big telescope, since 2012)

Energy range
30 GeV to 100 TeV

Size
4x 12 m, and a 28 m telescopes, square with 120 m sides

Angular resolution
Below 0.1° (100 GeV) to 0.04° (100 TeV)

Energy resolution
From 20% to 10%, 15% energy scale uncertainty

Strange habit
Let's build 5 telescopes but use only 4 or better: just one!

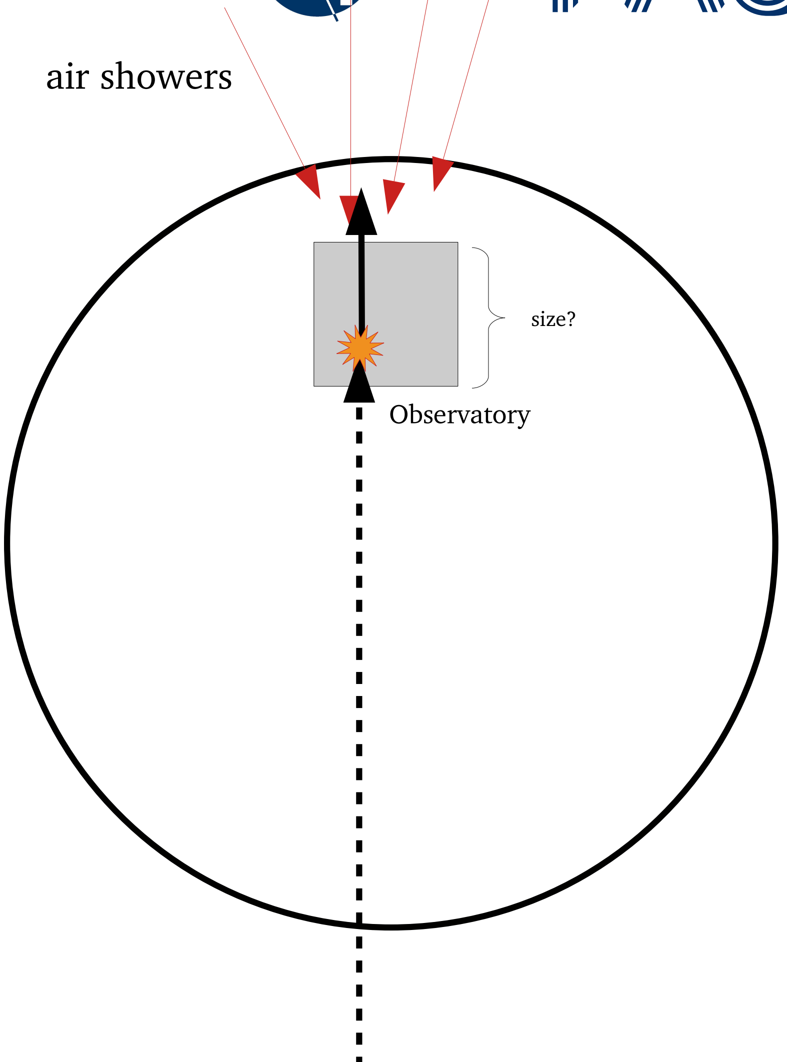
Neutrino astronomy

Observatory needs large effective volume

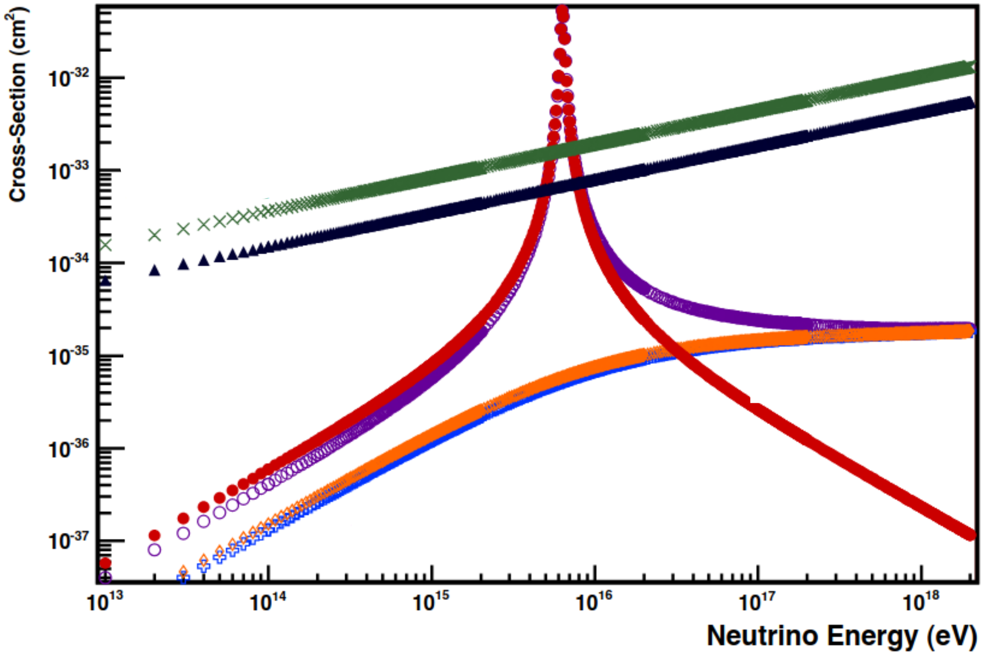
- first order assumption: to be contained in volume

- **How big is the flux?**

- **How big is the crosssection?**



Neutrino interactions at high energies



Draw the most important
Feynman diagrams for neutrino detection at UHE!

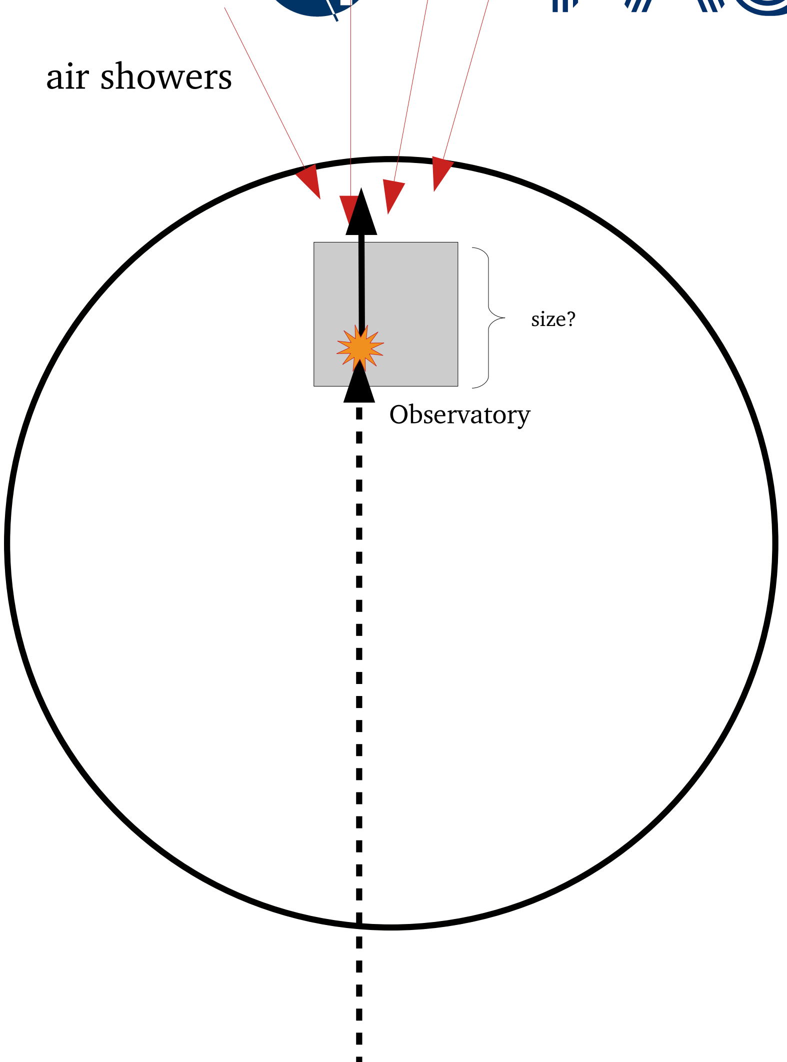
Exercise neutrino detection at 1 PeV

Observatory needs large effective volume

- First order assumption: to be contained in volume

Needed size to measure ~1 neutrino per year?

$$\lambda_{\mathrm{int}} = \frac{1}{\rho\, N_A\, \sigma_{\mathrm{int}}} = 16{,}000\,\mathrm{km}$$



Exercise neutrino detection at 1 PeV

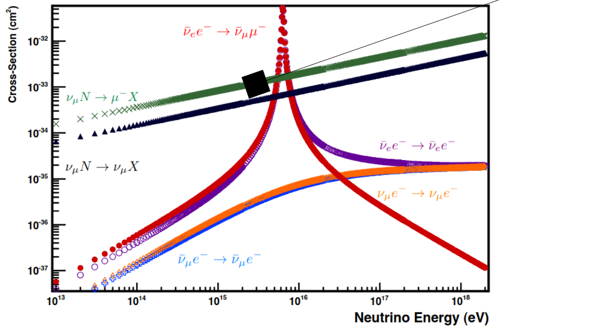
Observatory needs large effective volume

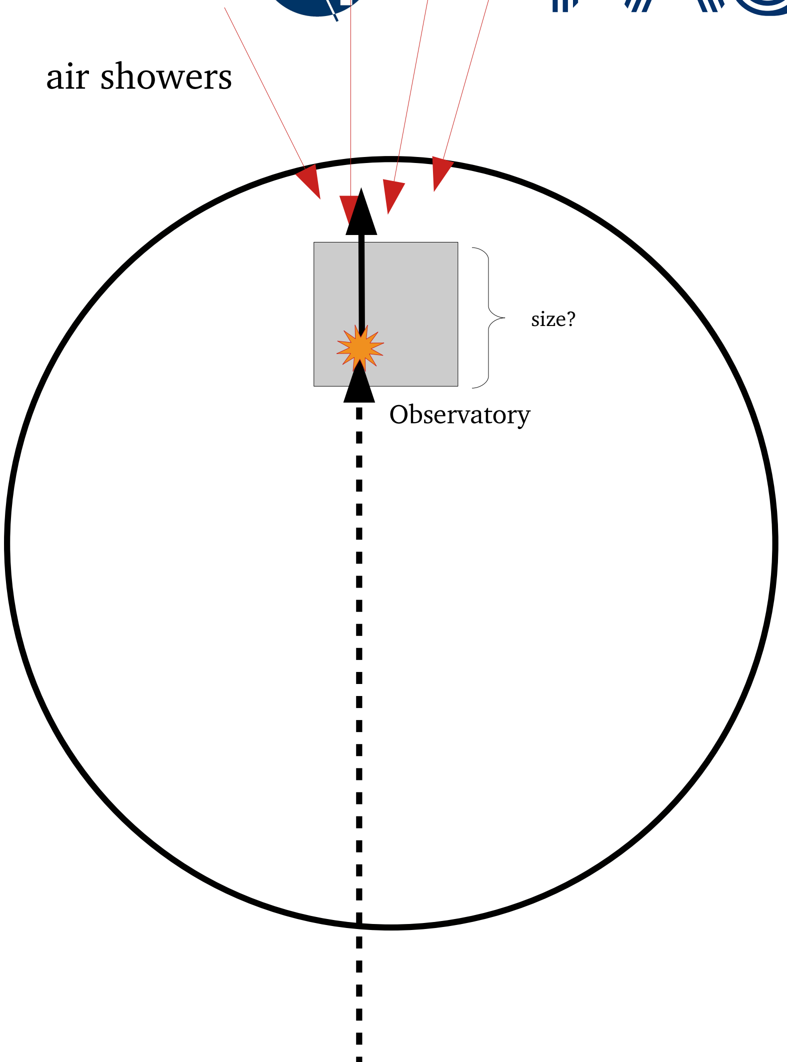
- First order assumption: to be contained in volume

Needed size to measure ~1 neutrino per year?

$$\lambda_{\text{int}} = \frac{1}{\rho\, N_A\, \sigma_{\text{int}}} = 16{,}000\,\text{km}$$

$$P_{\text{int}}(l) = 1 - \exp^{-l/\lambda} \approx \frac{l}{\lambda_{\text{int}}} \approx 6 \cdot 10^{-5}$$





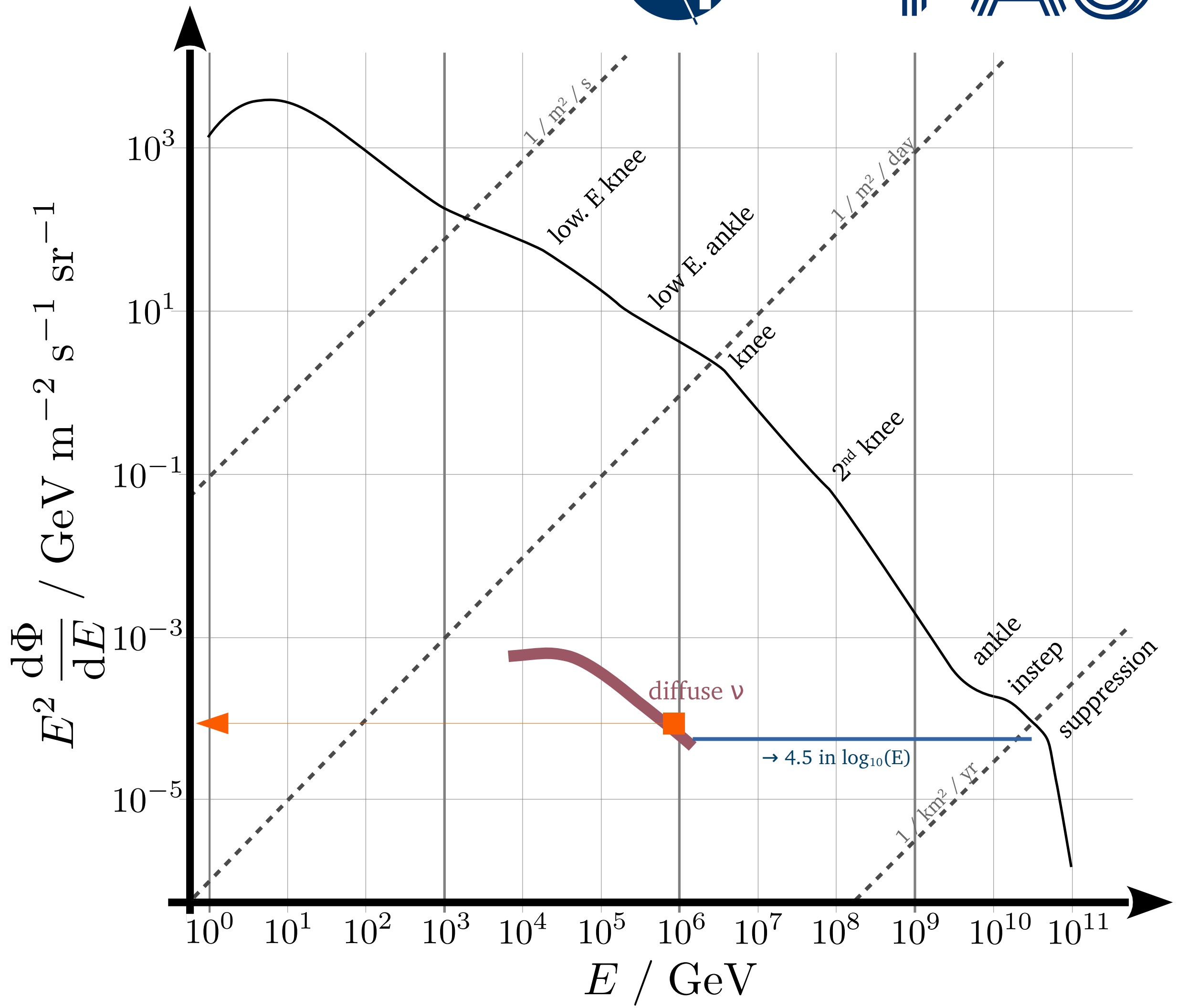
Neutrino flux

$$E^2 \cdot dJ/dE = 10^{-4}\ \mathrm{GeV\,m^{-2}\,s^{-1}\,sr^{-1}}$$

$$E \cdot dJ/dE = 10^{-4}\ \mathrm{GeV/PeV\,m^{-2}\,s^{-1}\,sr^{-1}}$$

$$\Phi \approx 100\ \mathrm{km^{-2}\,day^{-1}}$$

4,5 in logE
→ 30,000 per year per km²
→ ~100 per day per km²



Exercise neutrino detection at 1 PeV

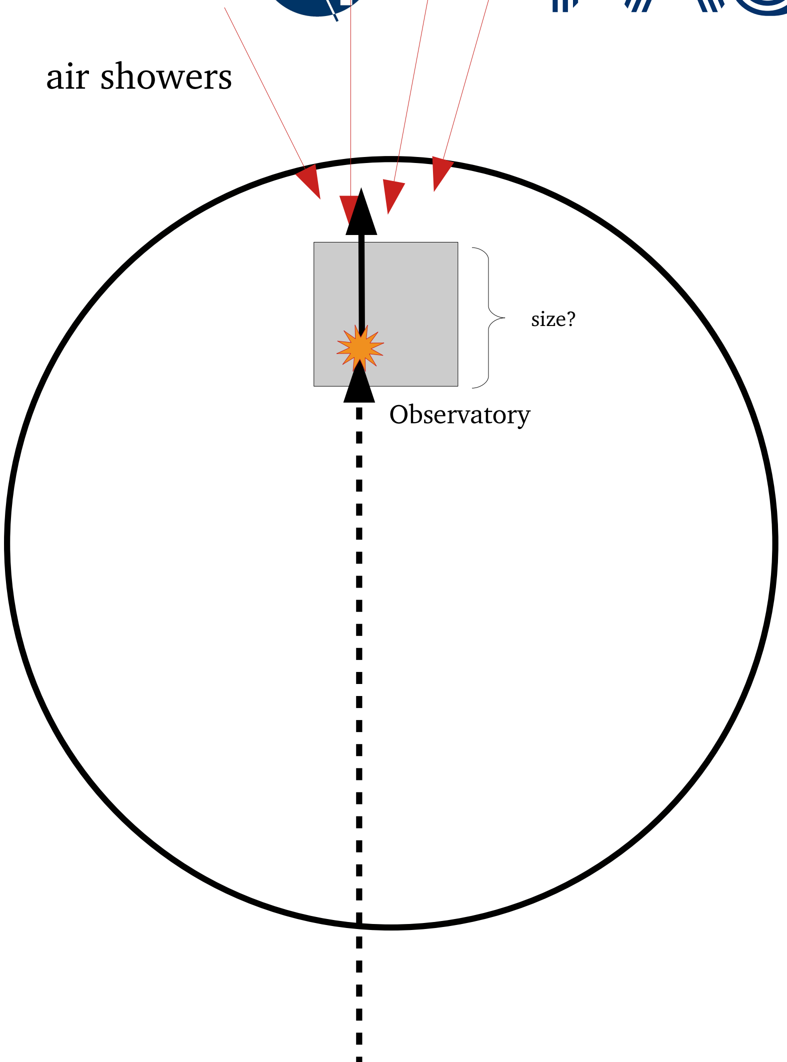
Observatory needs large effective volume

- First order assumption: to be contained in volume

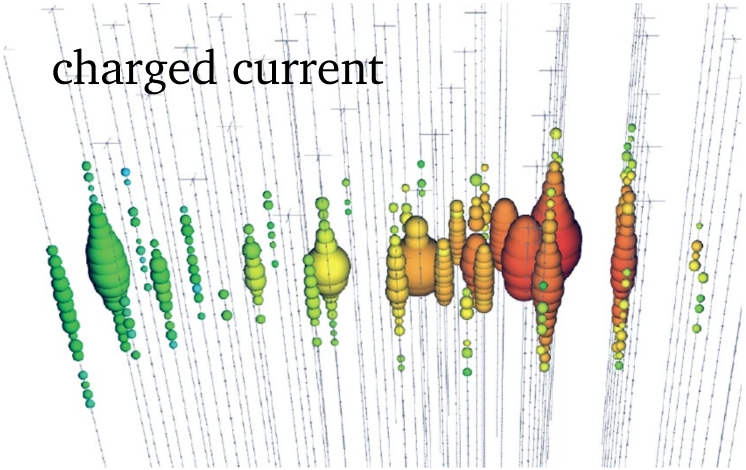
$$\lambda_{\text{int}} = \frac{1}{\rho\, N_A\, \sigma_{\text{int}}} = 16{,}000\,\text{km}$$

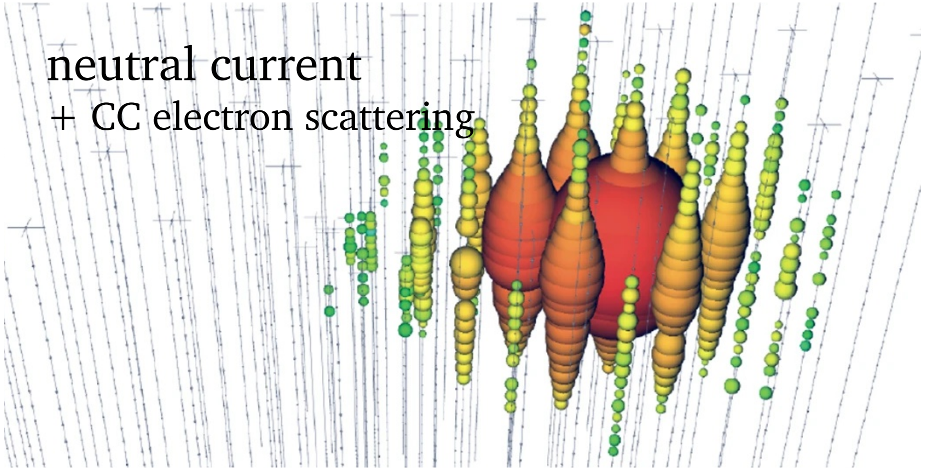
$$P_{\text{int}}(l) = 1 - \exp^{-l/\lambda} \approx \frac{l}{\lambda_{\text{int}}} \approx 6 \cdot 10^{-5}$$

$$\Phi \approx 100\ \text{km}^{-2}\,\text{day}^{-1}$$



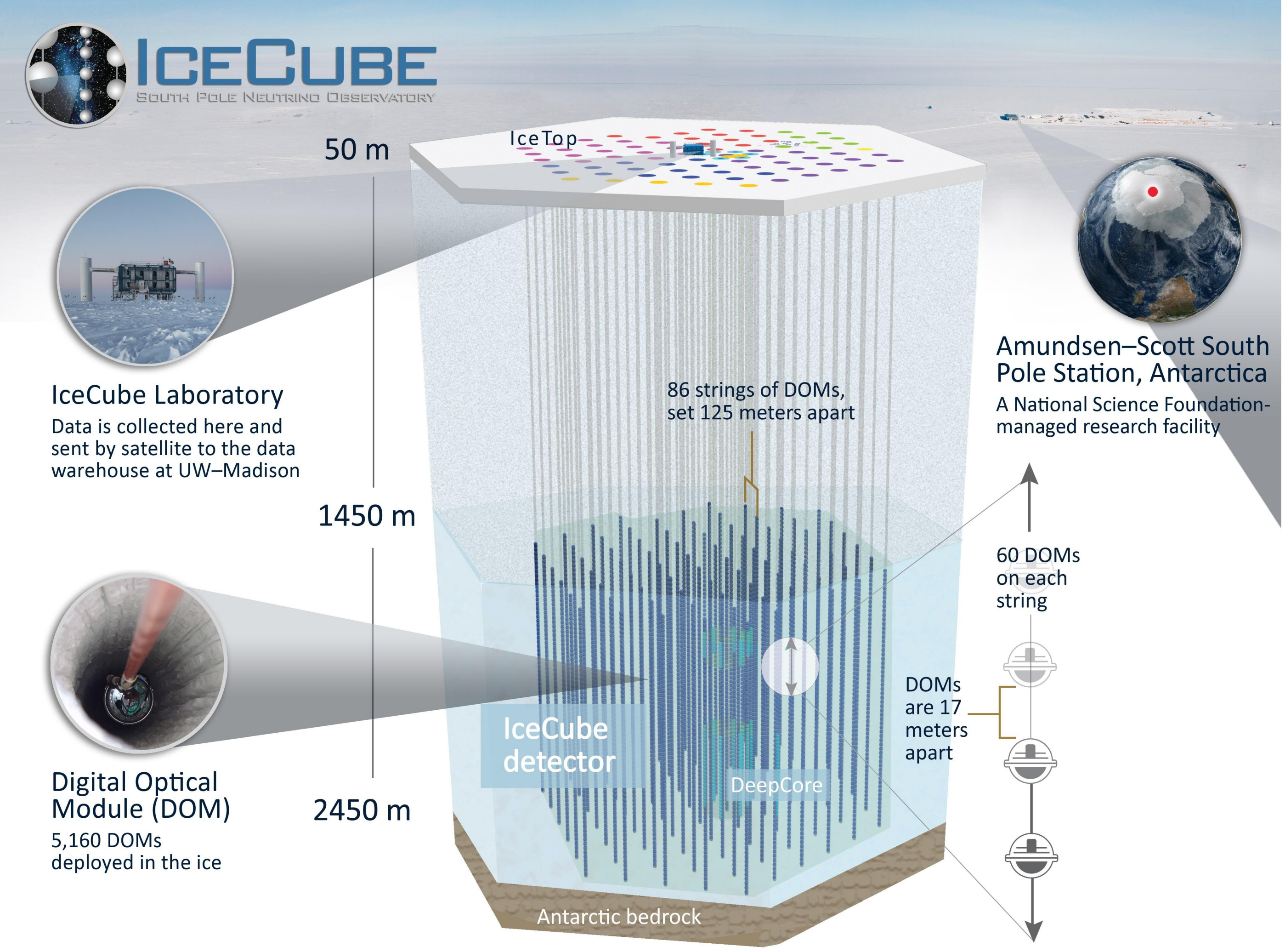
Event geometries





Tracks
Interactions that cause a muon
Muon track lengths long
(down-going events oft atmospheric)

Cascades
Interactions that induced a shower (cascade)
Mostly, DIS and fully contained

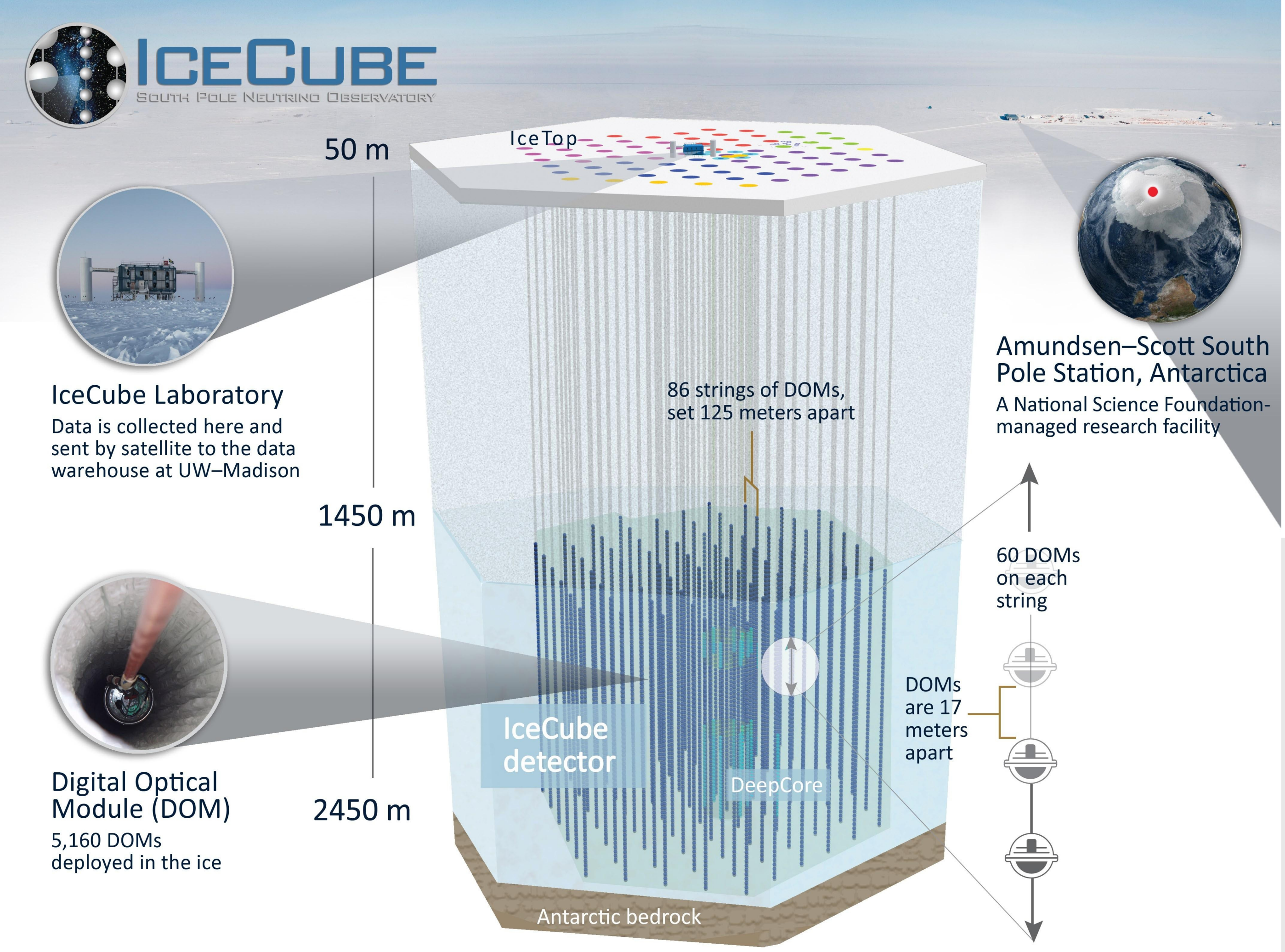


- instrumented km³ of ice
- detect astrophysical neutrinos (>1TeV)
- DOMs detect time resolved signals (Cherenkov light)

Key findings

- Discovery of astrophysical neutrinos
- Discovery of neutrinos from the galactic plane (5.7σ)
- Evidence for neutrinos from Blazars (3.5σ), active galaxy (4.2σ)
- Indication for astrophysical antineutrinos 2.3σ (Glashow)

Science 361, 147-151 (2018)
Science 378, 538-543 (2022)
Nature 591, 220-224 (2021)
Astrophys.J. 833 (2016) no.1, 3

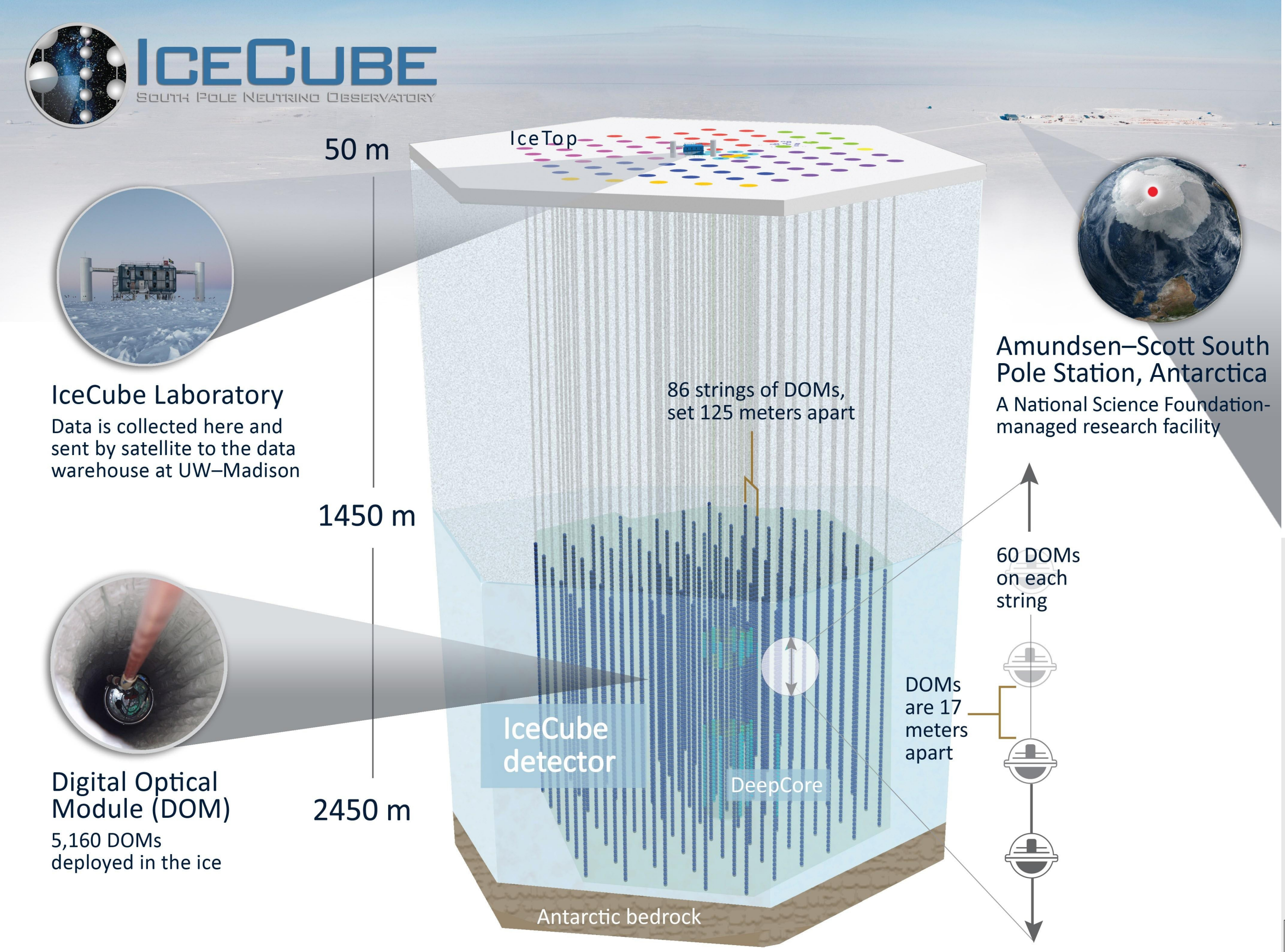


- instrumented km³ of ice
- detect astrophysical neutrinos (>1TeV)
- DOMs detect time resolved signals (Cherenkov light)

Challenging background

Example: Cascade events

- Atmospheric muons/neutrinos
- Per single astrophysical neutrino → 10^8 bkg. events
- After selection: 7% signal purity



- instrumented km³ of ice
- detect astrophysical neutrinos (>1TeV)
- DOMs detect time resolved signals (Cherenkov light)

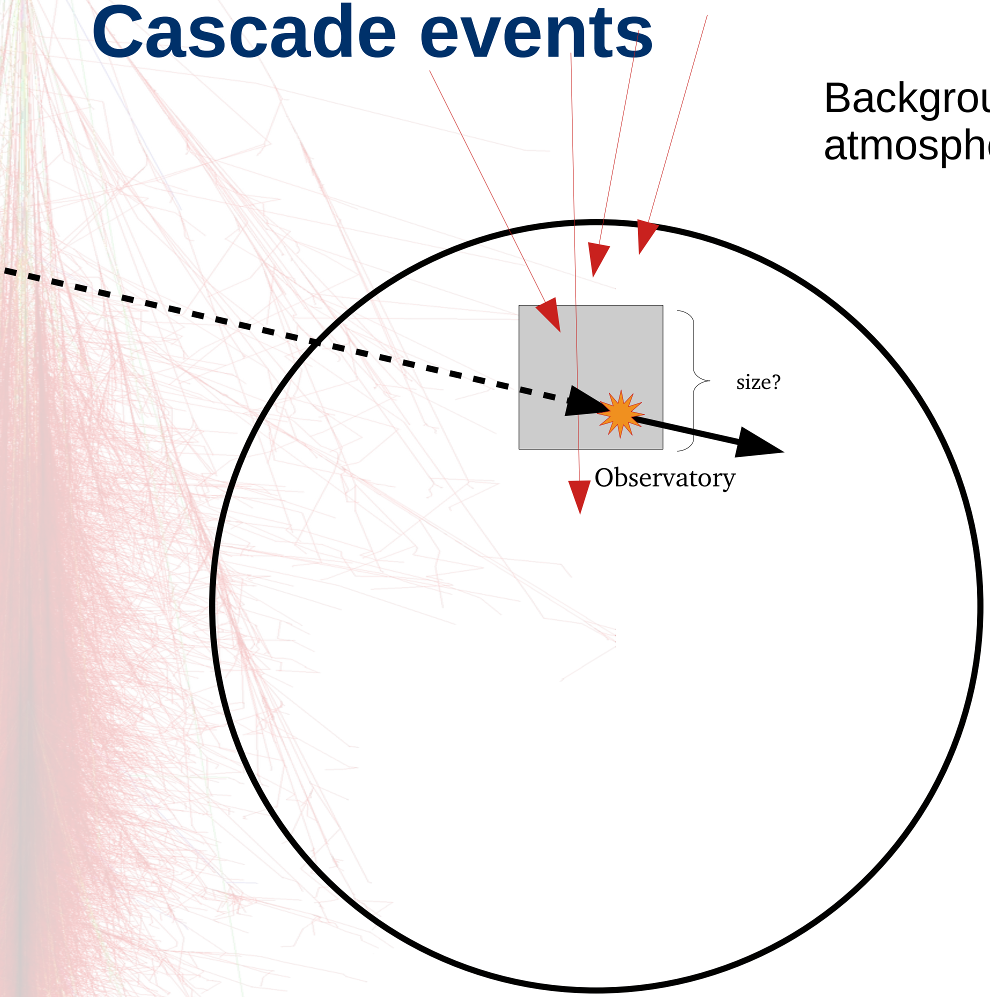
Challenging background

Example: Cascade events

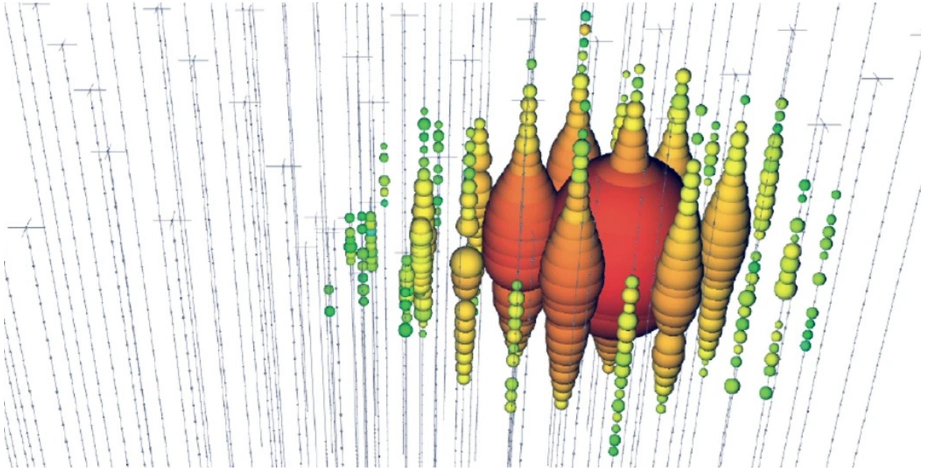
- Atmospheric muons/neutrinos
- Per single astrophysical neutrino → 10^8 bkg. events
- After selection: 7% signal purity

Odds for being killed by a vending machine: 1.2 * 10^8

Cascade events



Background: atmospheric neutrinos and atmospheric muons (stochastic depositions)



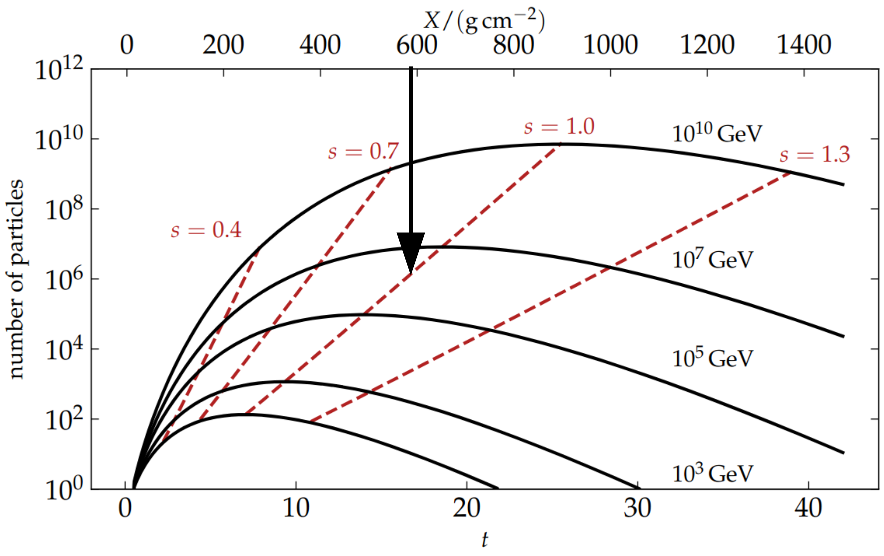
Cascades: fully contained in detector
Good energy resolution ~15%
- calorimetric deposition

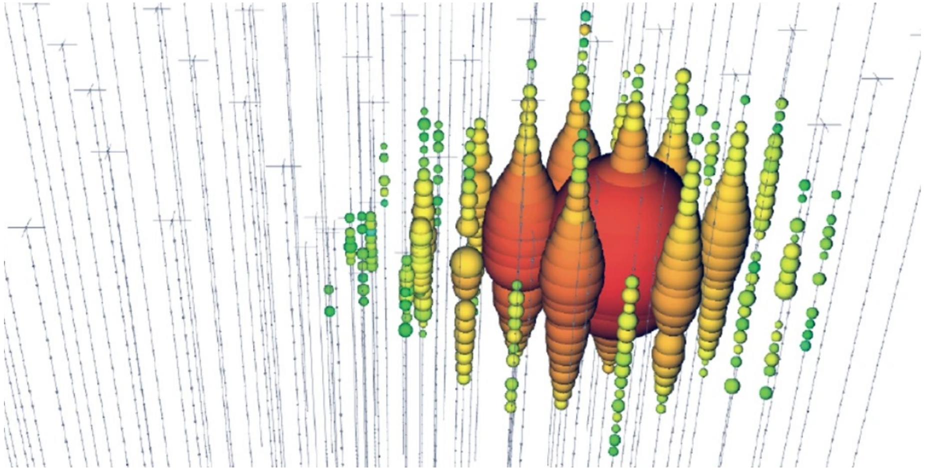
Bad angular resolution ~10°
- very compact shower, only small asymmetries, bad for axis reconstruction

Cascade events

$$L = \frac{X_{\max}}{\rho} \approx 600\,\mathrm{cm} = 6\,\mathrm{m}$$

Shower itself → almost point-like
→ Cherenkov light distribution larger





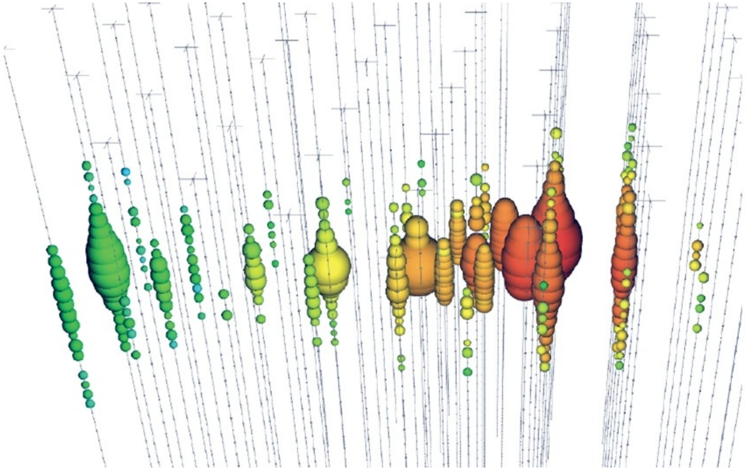
Cascades: fully contained in detector
Good energy resolution ~15%

- calorimetric deposition

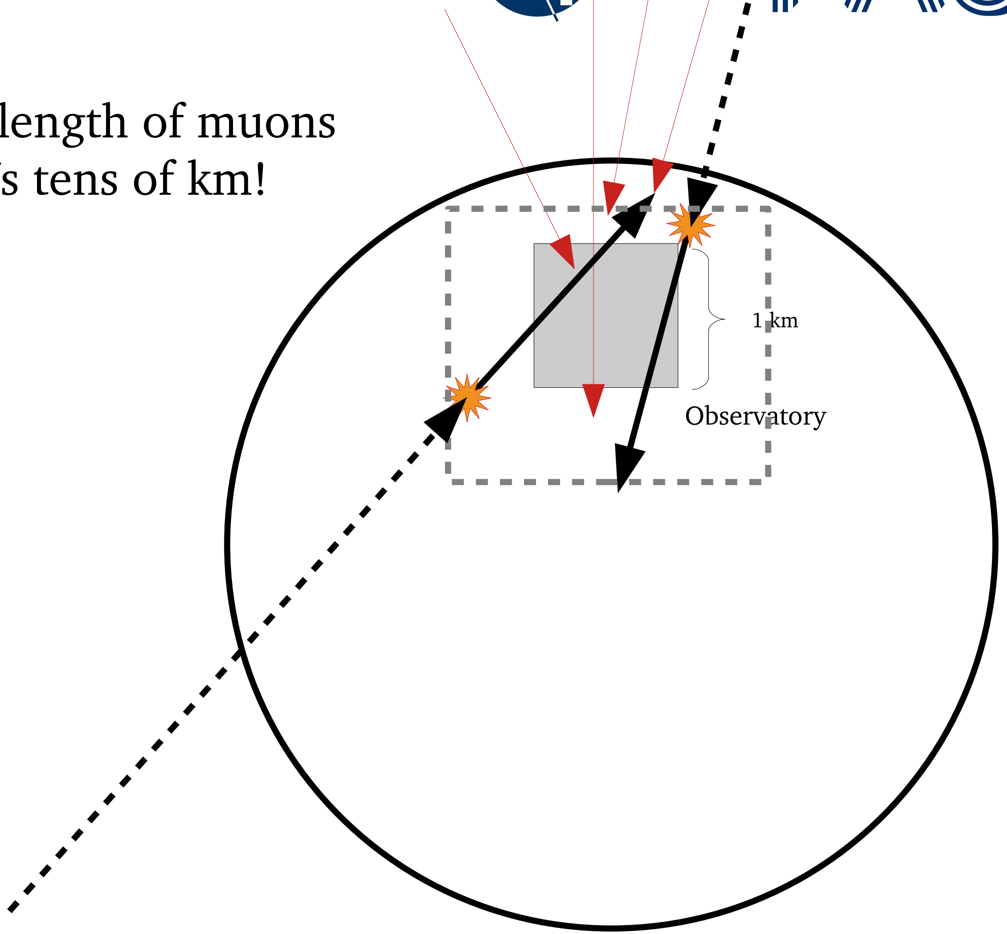
Bad angular resolution ~10°

- very compact shower, only small asymmetries, bad for axis reconstruction

Track events



Track length of muons at PeVs tens of km!



Tracks: (muons crossing the detector)

Bad energy resolution (100%)

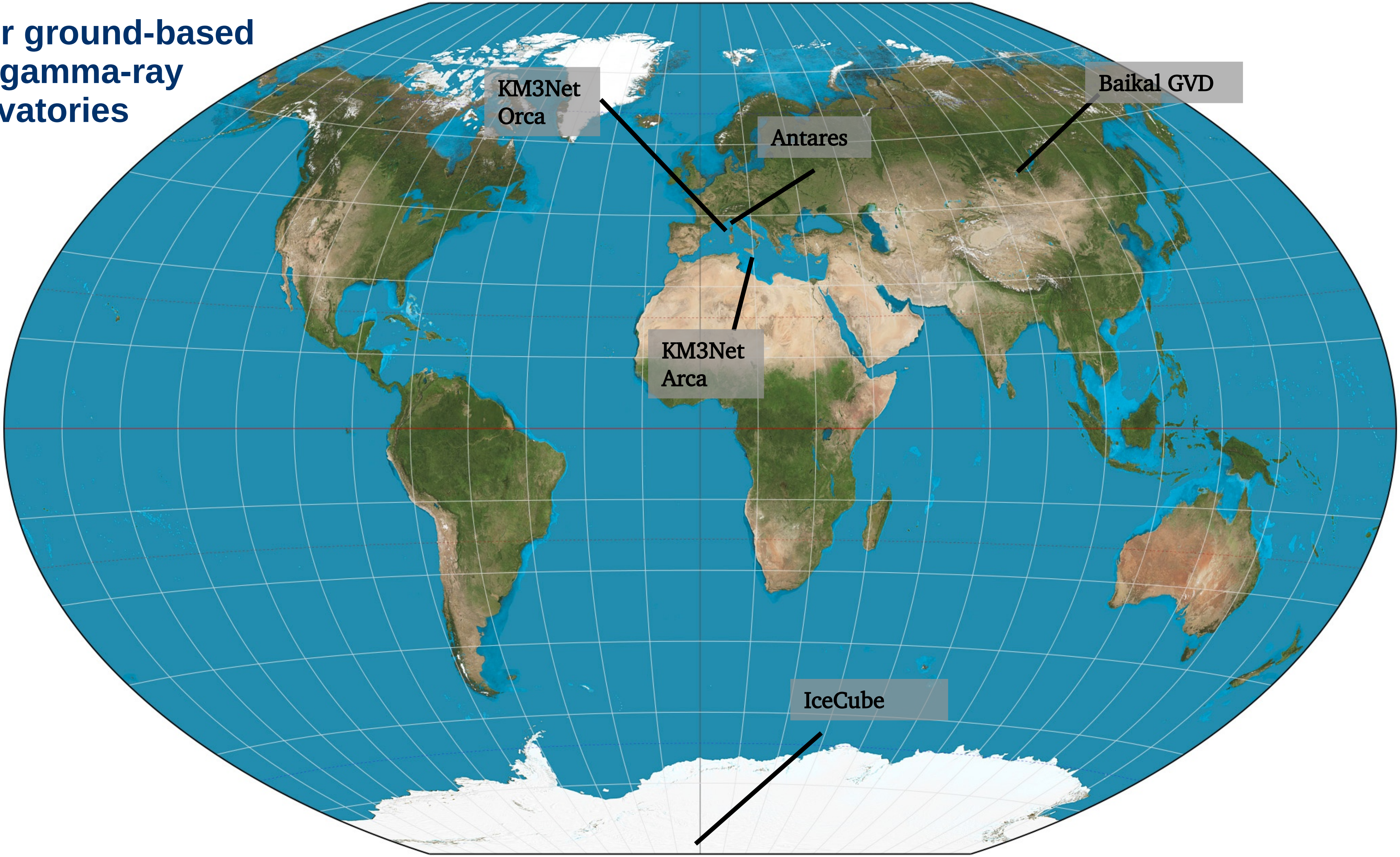
- vertex (often) outside detector, MIPs

Excellent angular resolution → <1°

- very clear muon track

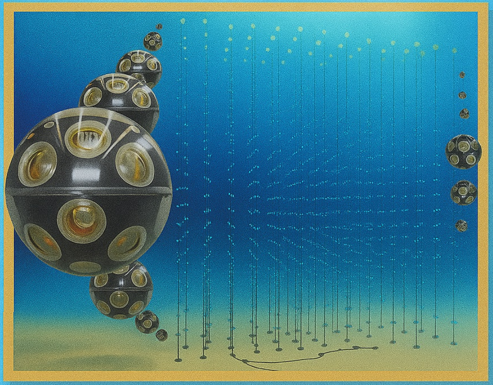
Low background for up-going events only

Major ground-based gamma-ray observatories



Gotta catch 'em all!

KM3Net



Future neutrino observatory in the Mediterranean Sea

Operation at -3500 m
Under construction since 2015

Energy range
1 GeV – 1 EeV

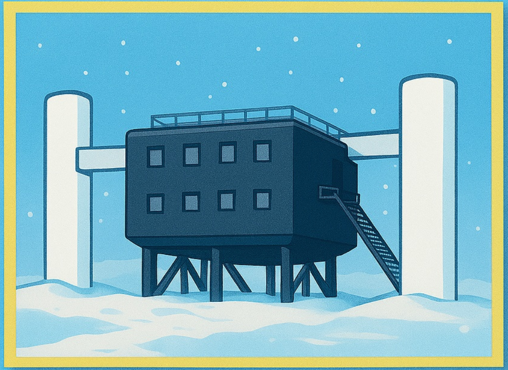
Size
1 km^2, 2x 1km diameter arrays, 6000 MPMTs, 243 strings

Angular resolution
Below 2° (cascades), ~0.3 – 0.1° (tracks)

Energy resolution
Around 6% (cascade), 100% (tracks)

Strange habit
Half detector, claims most energetic neutrino – cheers!

IceCube



Famous neutrino observatory located in Antarctica

Operation at -2,450 m
Since 2015

Energy range
10 GeV – 1 EeV

Size
1 km^3, deep core: 0.01 km^3, 86 strings (5000 PMTs)

Angular resolution
Below 10° (cascades), below 1° (tracks)

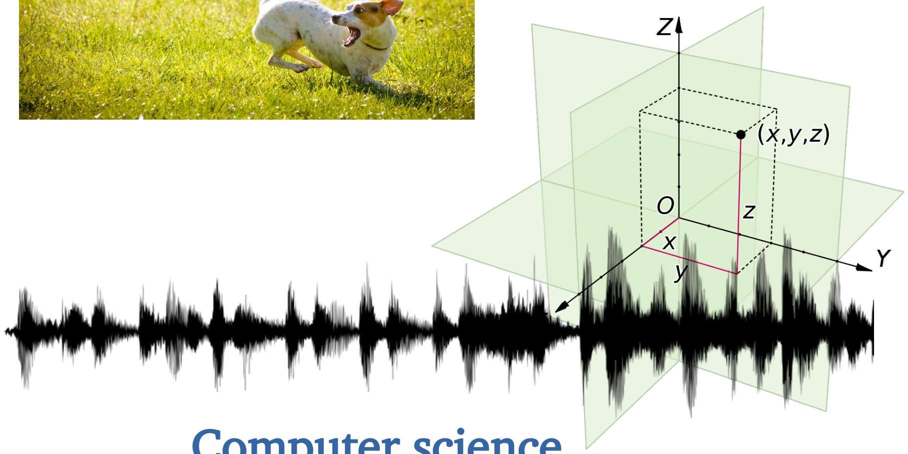
Energy resolution
Around 20% (cascade), 100% (tracks)

Strange habit
Calls everything above 3σ an "observation"

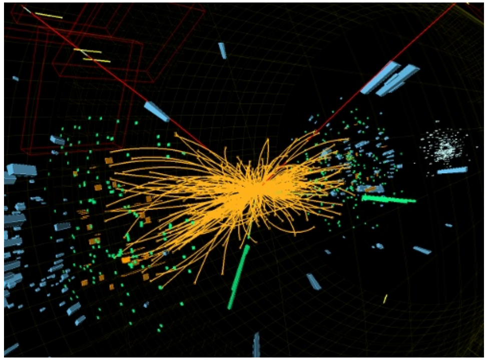
Application in Physics

Physics feature different data
Challenge: adapt algorithms from computer science to physics research

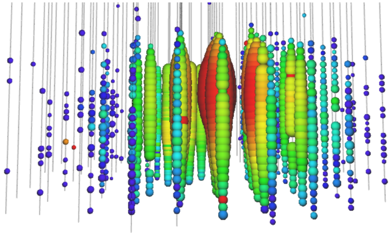
source: wikipedia



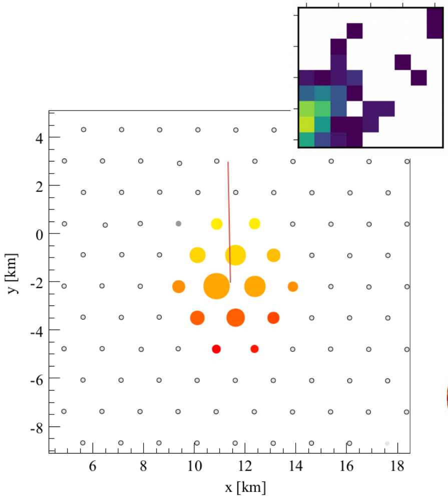
Computer science



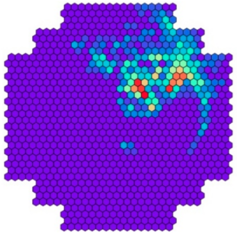
https://cds.cern.ch/record/2711418



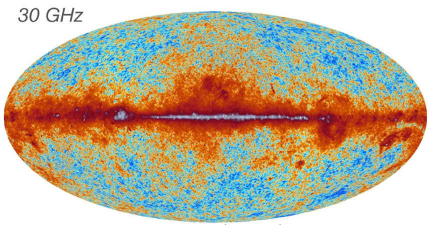
https://arxiv.org/abs/1309.7003



10.1016/j.nima.2015.06.058



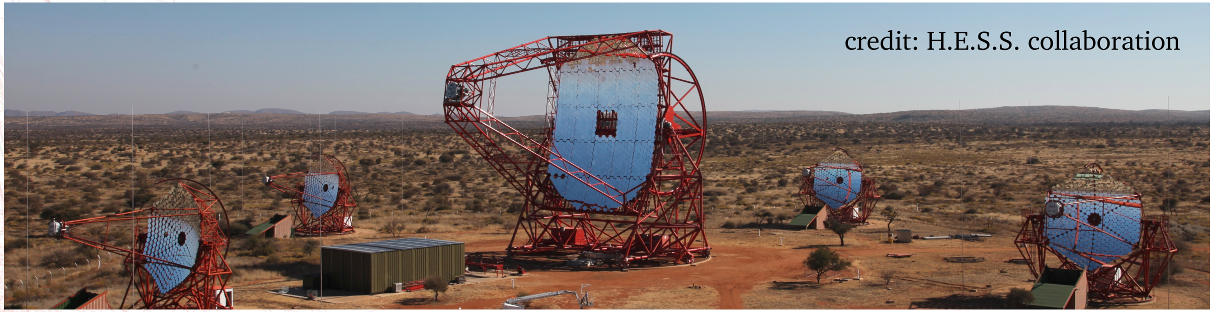
10.1016/j.astropartphys.2018.10.003

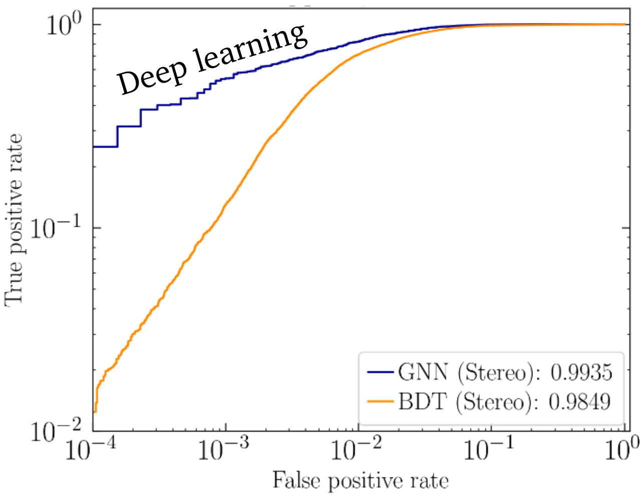


Astronomy and Astrophysics 641, p. 1 (2018)

Physics

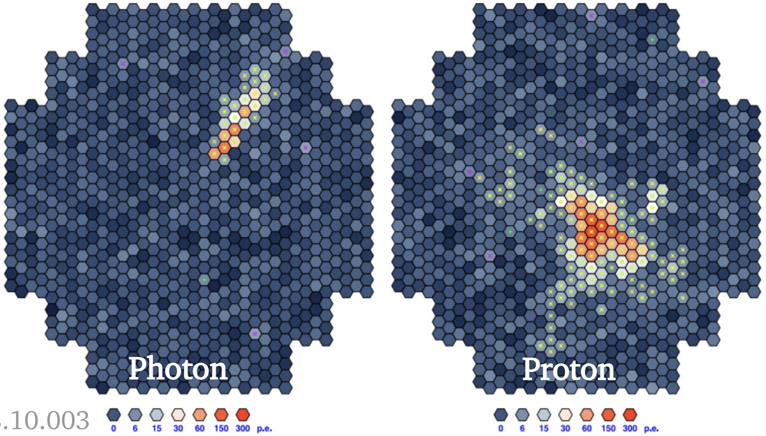
Deep Learning for IACTs





- Gamma ray telescopes in Namibia
- For each photon ~ $10^3 \rightarrow 10^4$ protons
  - Powerful rejection needed
- First promising results on simulations
  - Neural networks outperforms BDTs

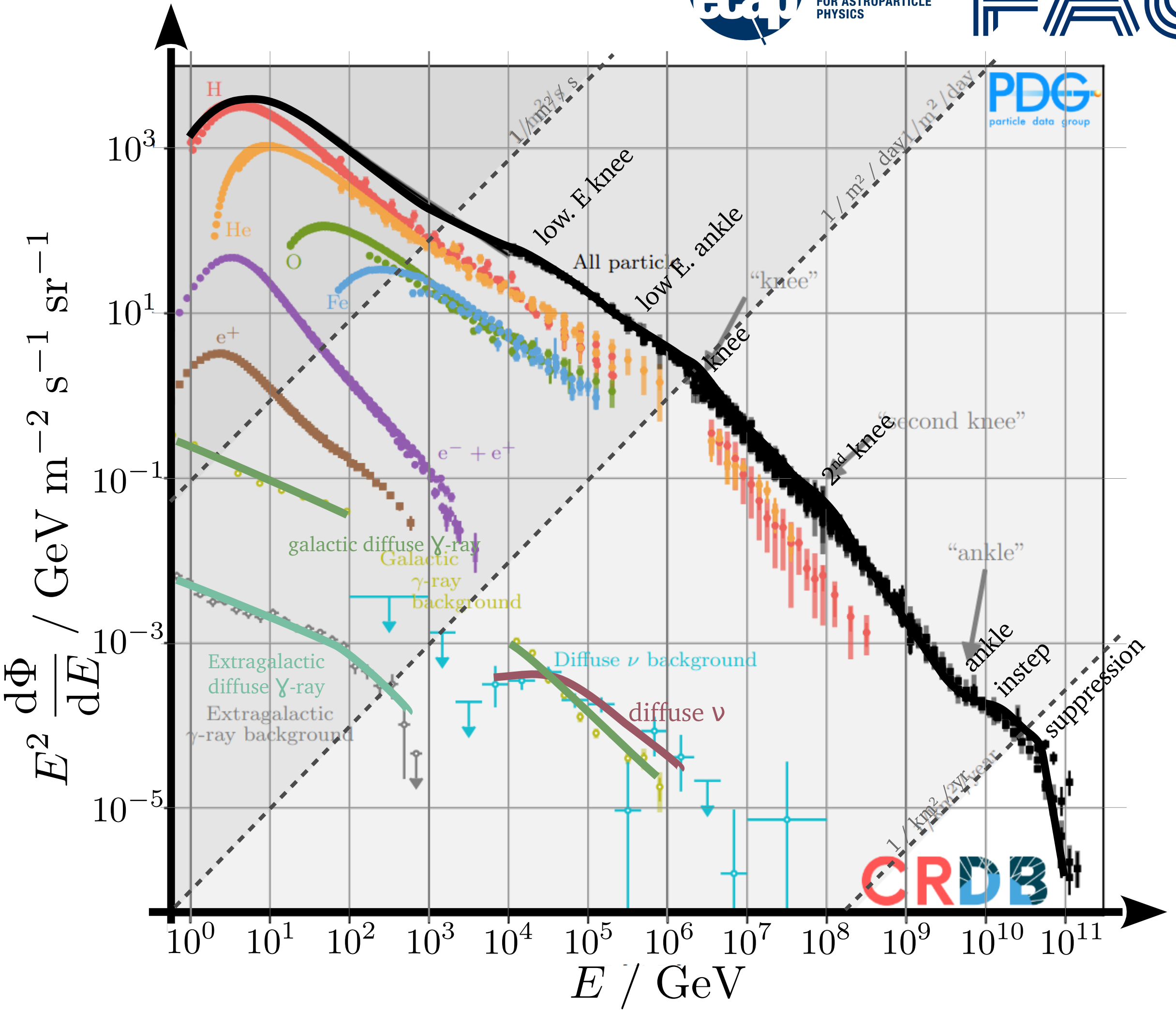
- Currently investigating stereoscopic models exploit telescope-telescope correlations
  - Standard reconstructions outperform DNNs



Shilon et al., 10.1016/j.astropartphys.2018.10.003
Glombitza et al, PoS(ICRC2023)715

BACKUP

Direct detection

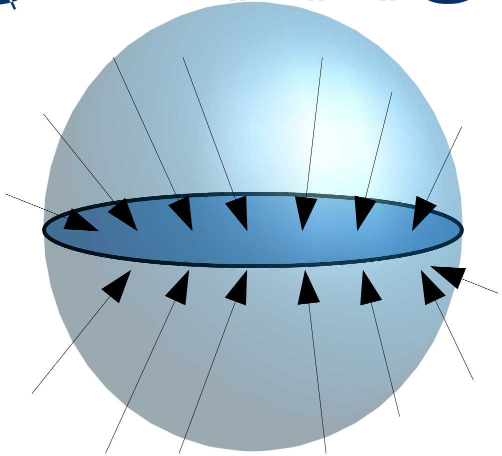


Cosmic-ray Flux

- Cosmic-ray flux is isotropic

$$J(E) = \frac{\mathrm{d}^4 N}{\mathrm{d}E\ \mathrm{d}A\ \mathrm{d}\Omega\ \mathrm{d}t}$$

diffuse flux



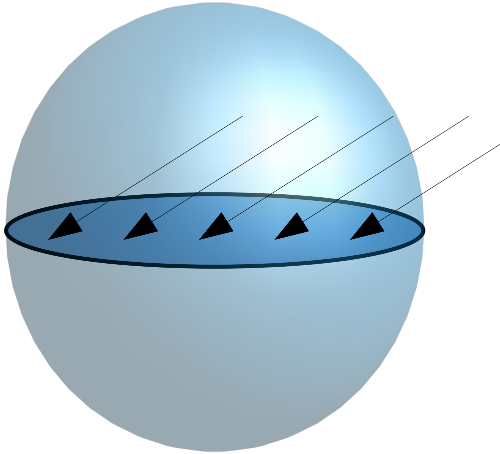
  - Integral flux
    (energy-integrated above certain threshold)

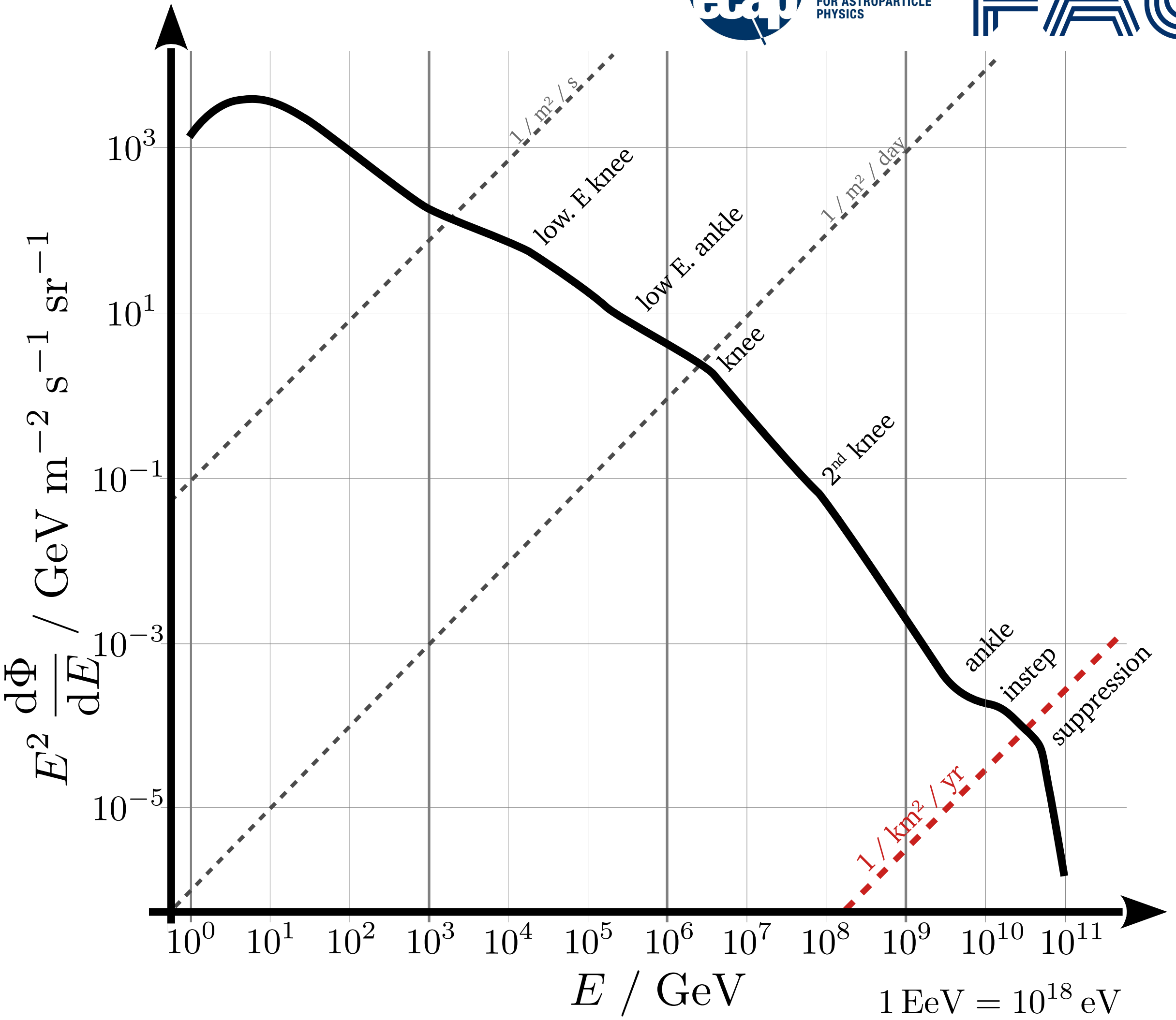
$$E \cdot J(E) = \frac{\mathrm{d}^3 N}{\mathrm{d}A\ \mathrm{d}\Omega\ \mathrm{d}t}$$

- Flux
  (from a point source, far away)

$$J(E) = \frac{\mathrm{d}^3 N}{\mathrm{d}E\ \mathrm{d}A\ \mathrm{d}t}$$

point source flux





$E^2 \frac{d\Phi}{dE}$ / GeV m^{-2} s^{-1} sr^{-1}
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
1 / m² / s
1 / m² / day
1 / km² / yr
low. E knee
low E. ankle
knee
2nd knee
ankle
instep
suppression
10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
E / GeV
$1\,\mathrm{EeV} = 10^{18}\,\mathrm{eV}$