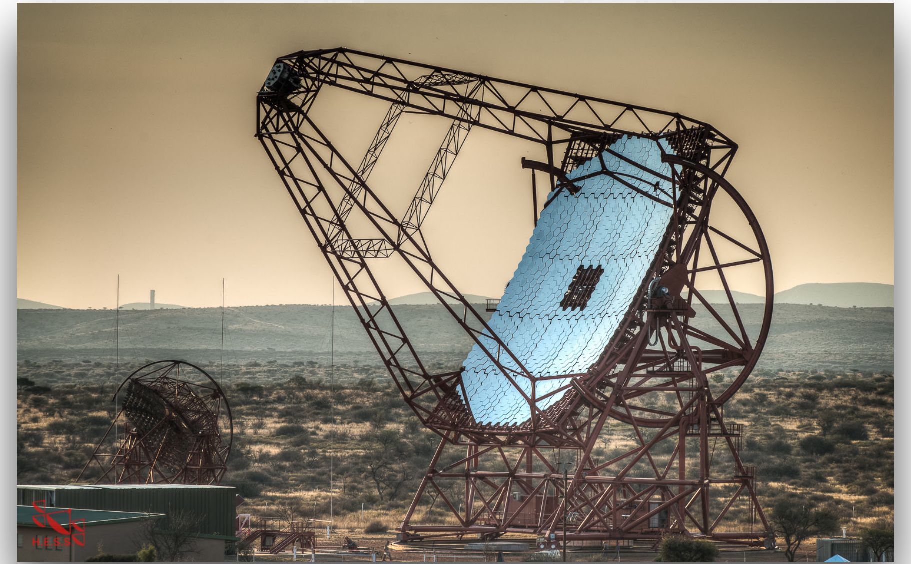
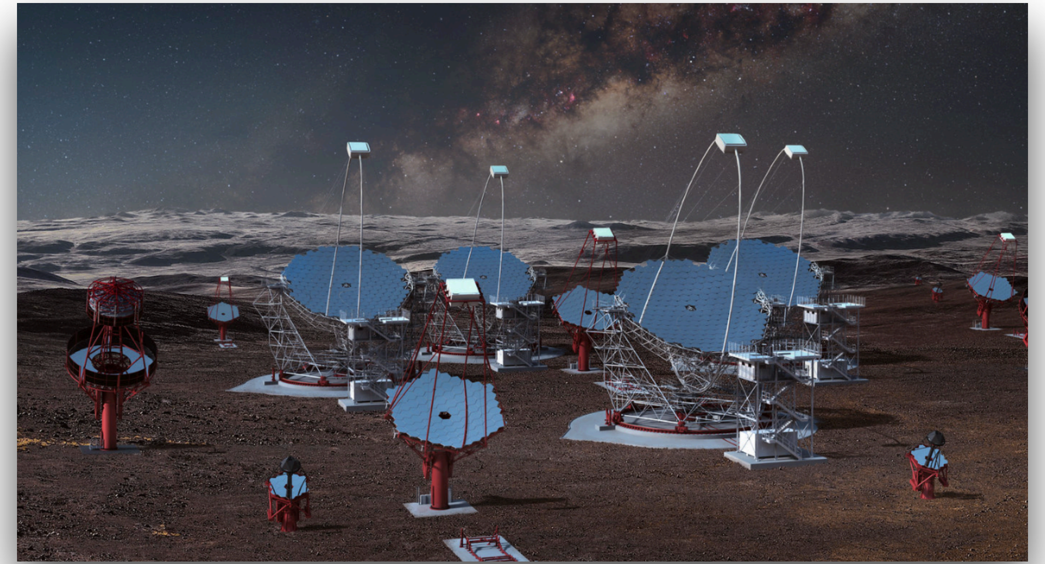
IACT Fundamentals & Air Showers

Kathrin Egberts, University of Potsdam

Who am I?

- Since 2005 H.E.S.S. member, since 2009 CTAO member
- Main passion: complex data analyses at the detection threshold
- Scientific focus: Galactic science, diffuse phenomena, cosmic rays, population synthesis
- Development of the software component responsible for transient follow-up observations with CTAO





Outline

Day 1: Introduction

- Basic considerations
- Detection principles
- Development of the field

Day 2: Everything about Air Showers

- Particle interactions in matter
- Electromagnetic & hadronic air showers
- Air-shower simulations

Day 3: IACTs

- The IACT principle
- Gamma-hadron separation & backgrounds
- Current and future instruments & their sensitivities

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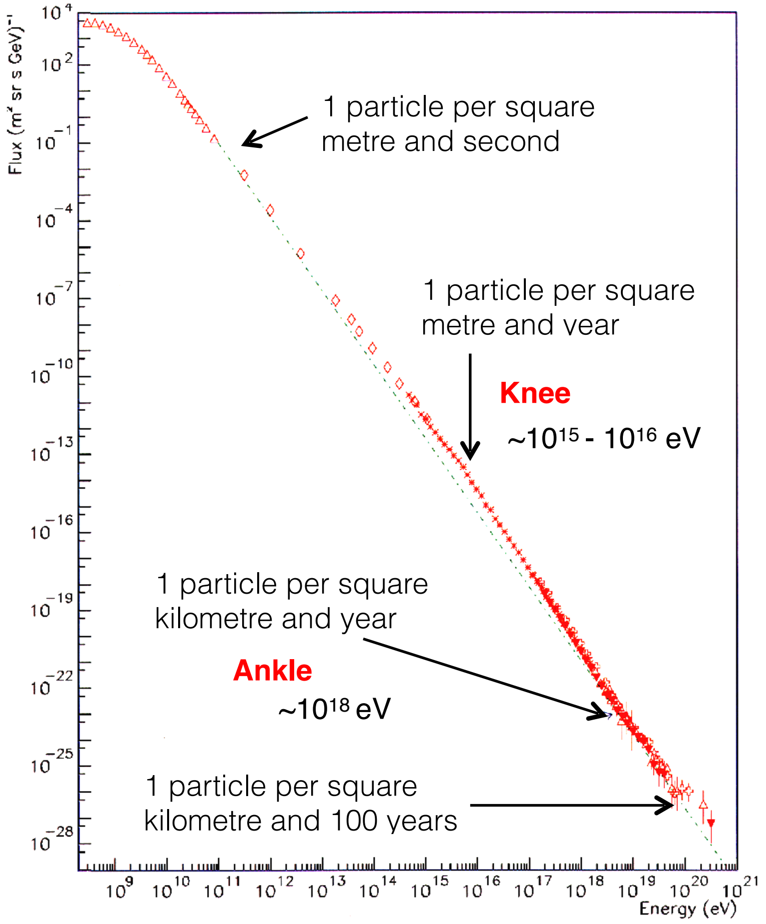
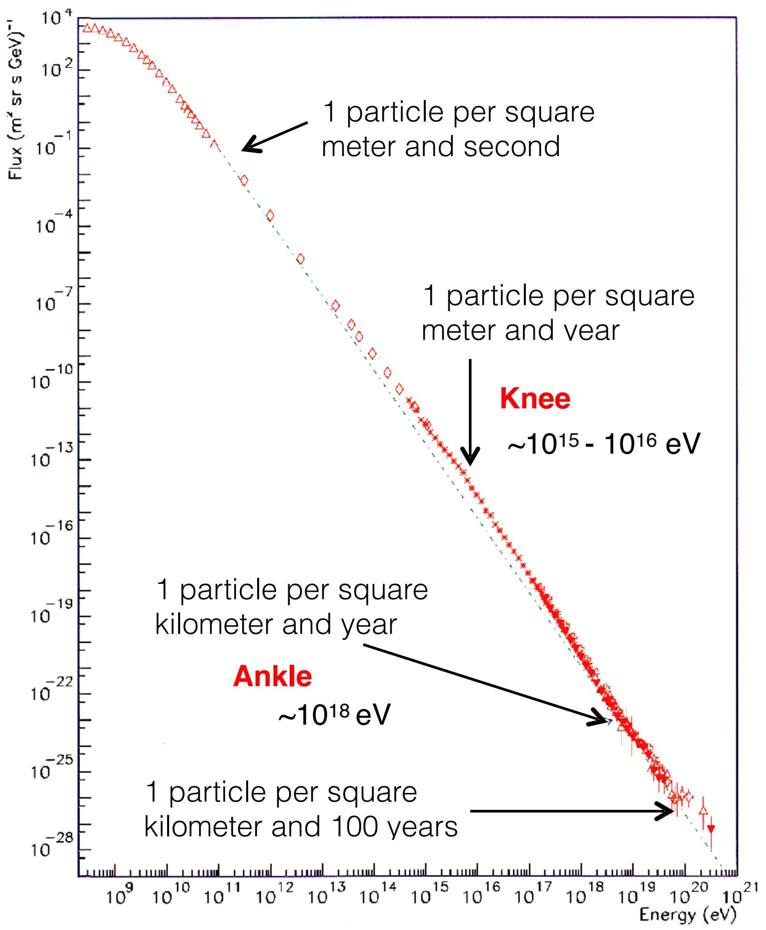
Fluxes & Counts



$$\Phi = \frac{d^4 N}{dA\, dt\, dE\, d\Omega} = C \left(\frac{E}{E_0} \right)^{-\alpha}$$

Fluxes & Counts



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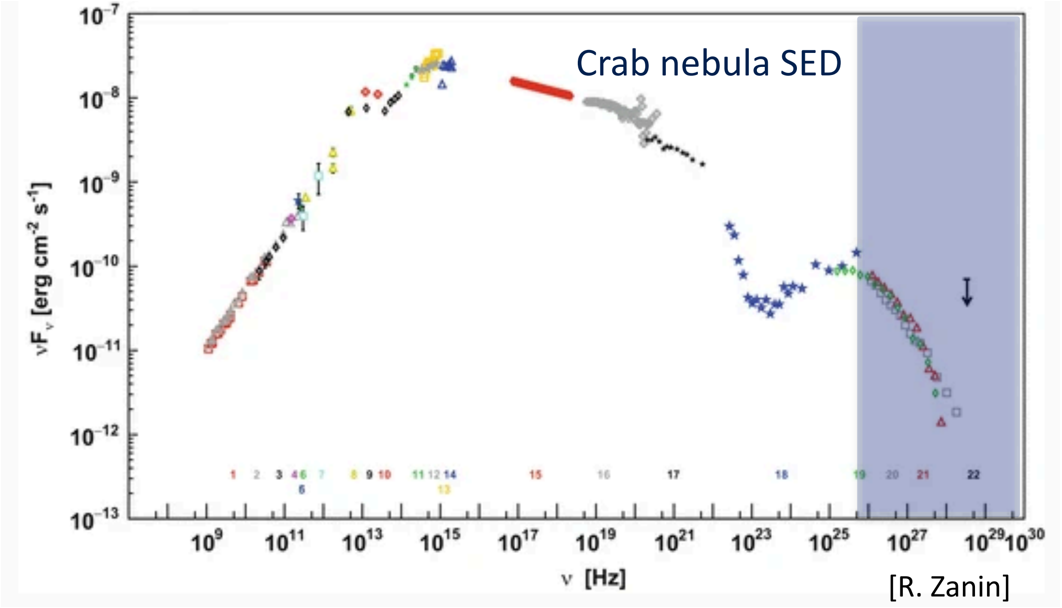


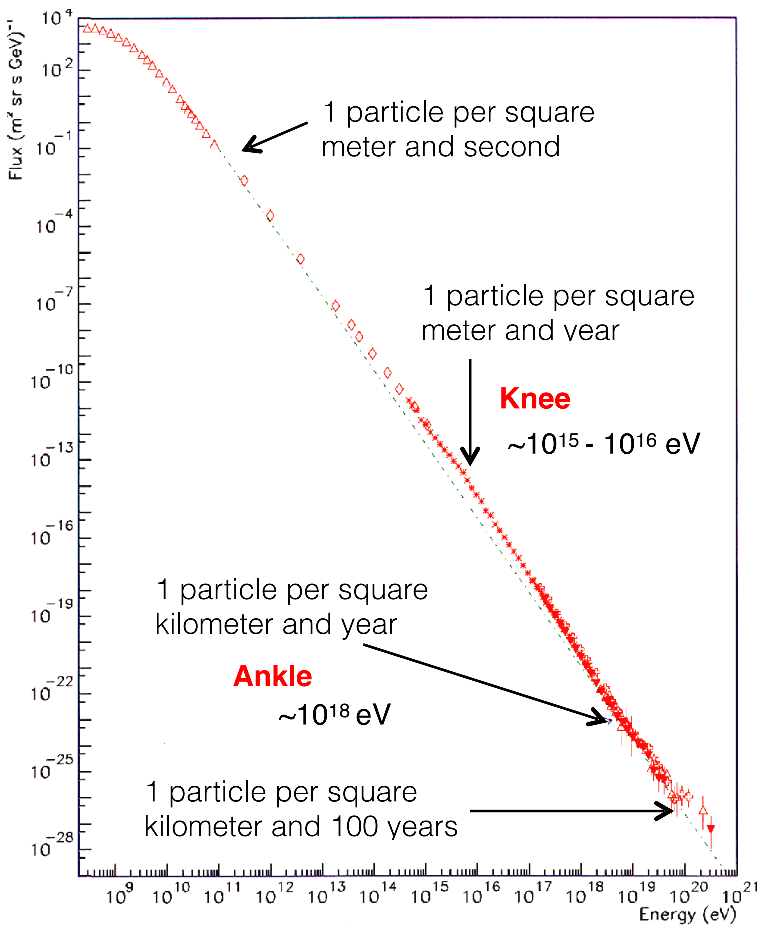
- spectral energy distribution (SED): energy flux per decade of energy

$$E^2\frac{dN}{dE} = E\frac{dN}{d\log E}$$

- sometimes also written as

$$\nu F_\nu(\nu) = \nu\frac{dE}{d\nu}$$

Fluxes & Counts



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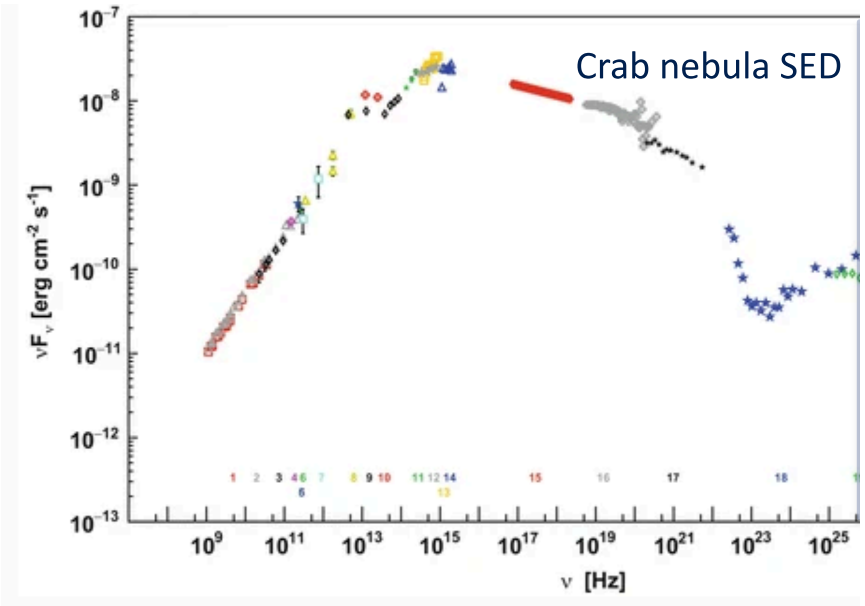
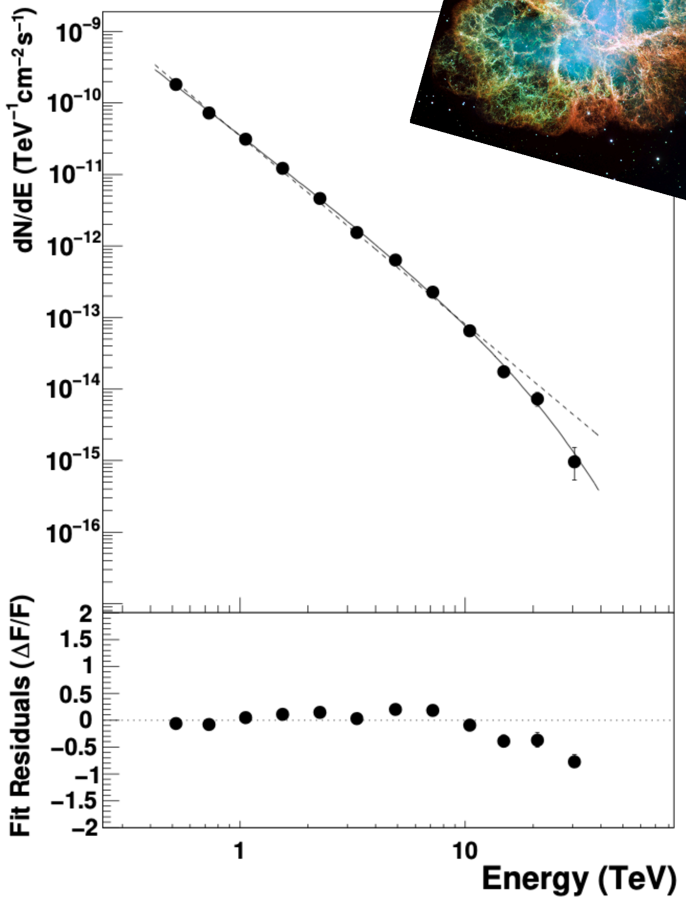
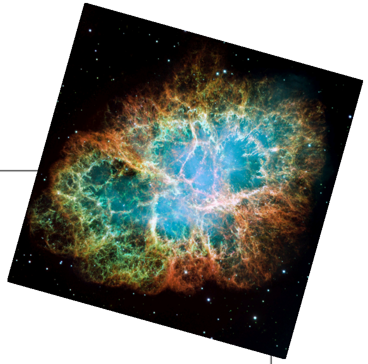


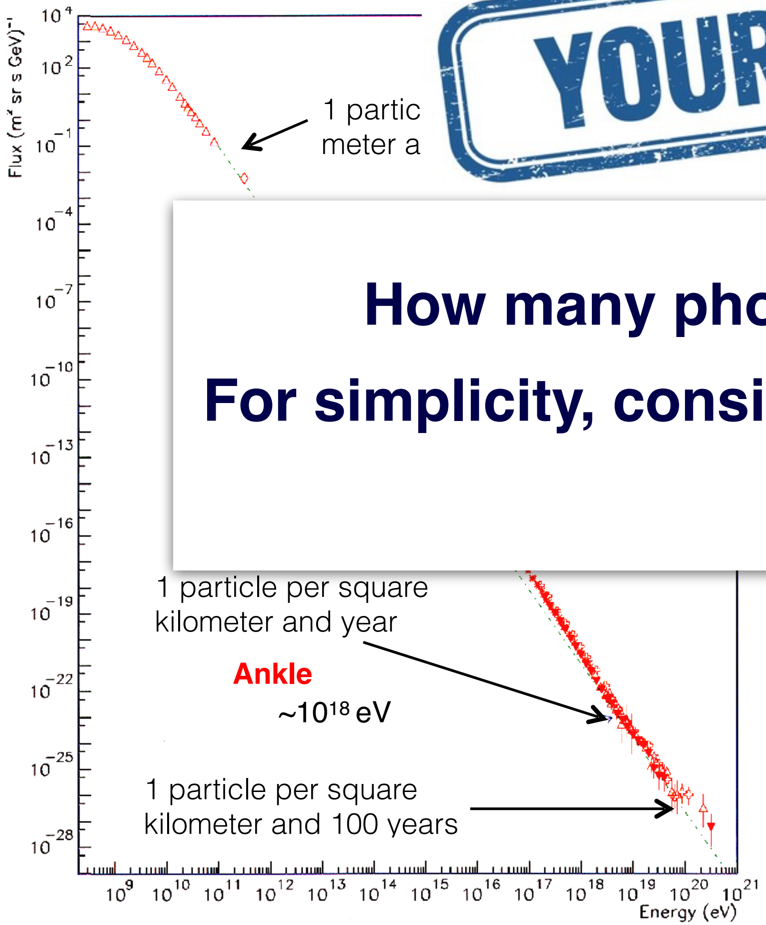




$$\Phi = \frac{d^3 N}{dA\, dt\, dE} = C \left(\frac{E}{E_0}\right)^{-\alpha}$$

Fluxes & Counts

YOUR TURN



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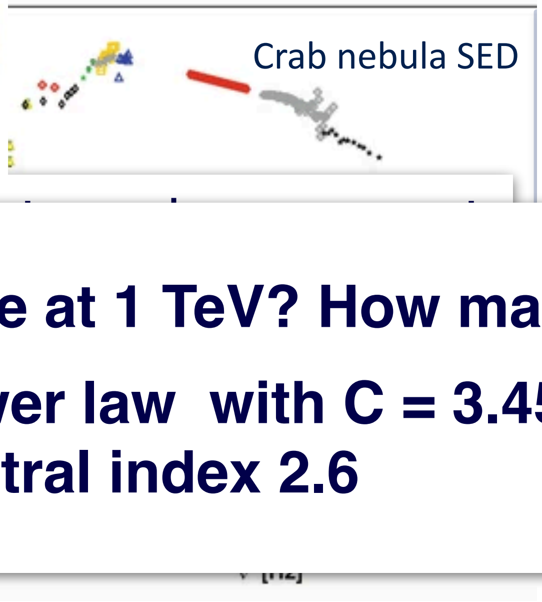

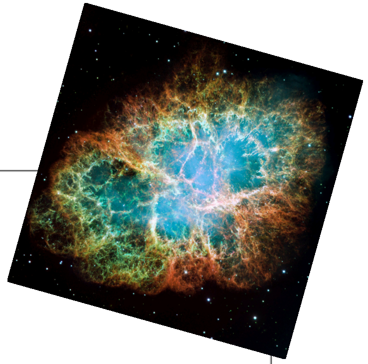

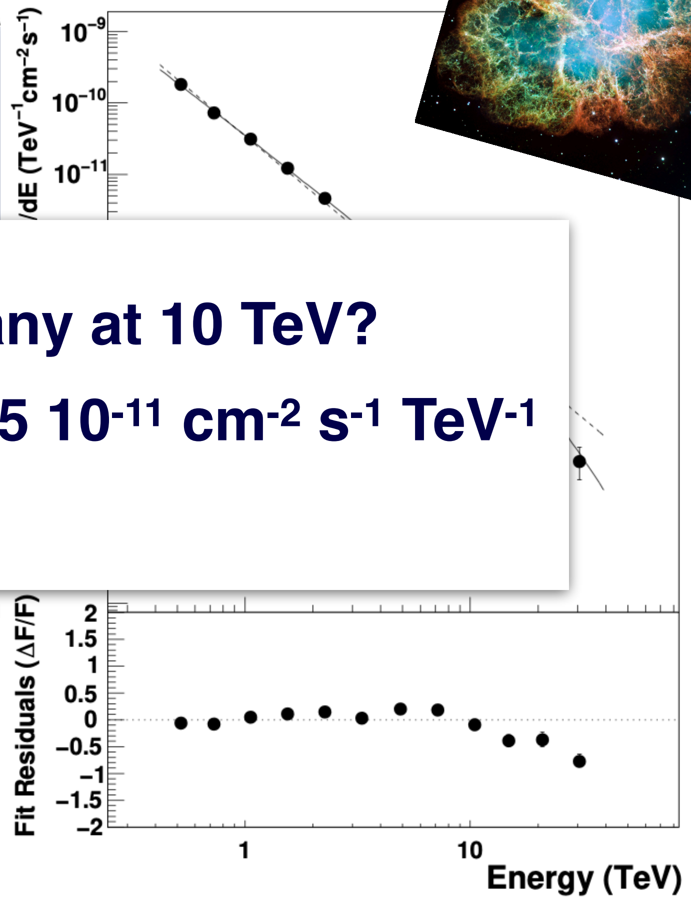

How many photons do we see at 1 TeV? How many at 10 TeV?

For simplicity, consider a pure power law with $C = 3.45\ 10^{-11}\ cm^{-2}\ s^{-1}\ TeV^{-1}$ and spectral index 2.6

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Fluxes & Counts

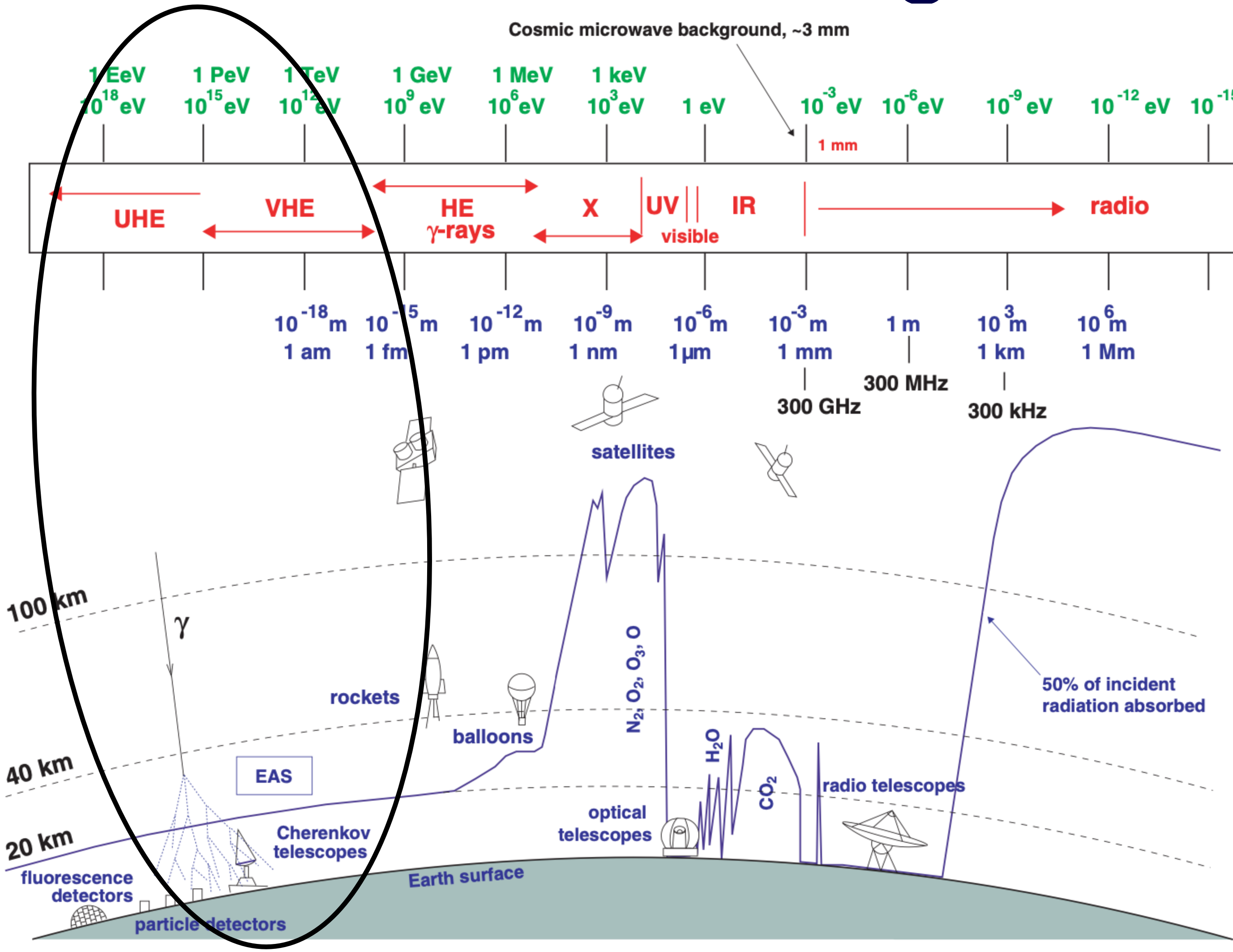
How many photons do we see at 1 TeV? How many at 10 TeV?

For simplicity, consider a pure power law with C = 3.45 10^{-11} cm^{-2} s^{-1} TeV^{-1} and spectral index 2.6

- at 1 TeV: ~0.03 photons per square metre and day / 1 photon per square metre and month!
- at 10 TeV: ~0.0001 photons per square metre and day
- in comparison, a CR proton has C ~ 10^{-5} cm^{-2} s^{-1} sr^{-1} TeV^{-1}, giving 10 000 particles per square metre and day
- within 0.1 deg radius: 0.1 particle per square metre and day

→ Requires large detectors

Absorption in the Electromagnetic Spectrum



low fluxes + absorption in the atmosphere = indirect measurements via air showers

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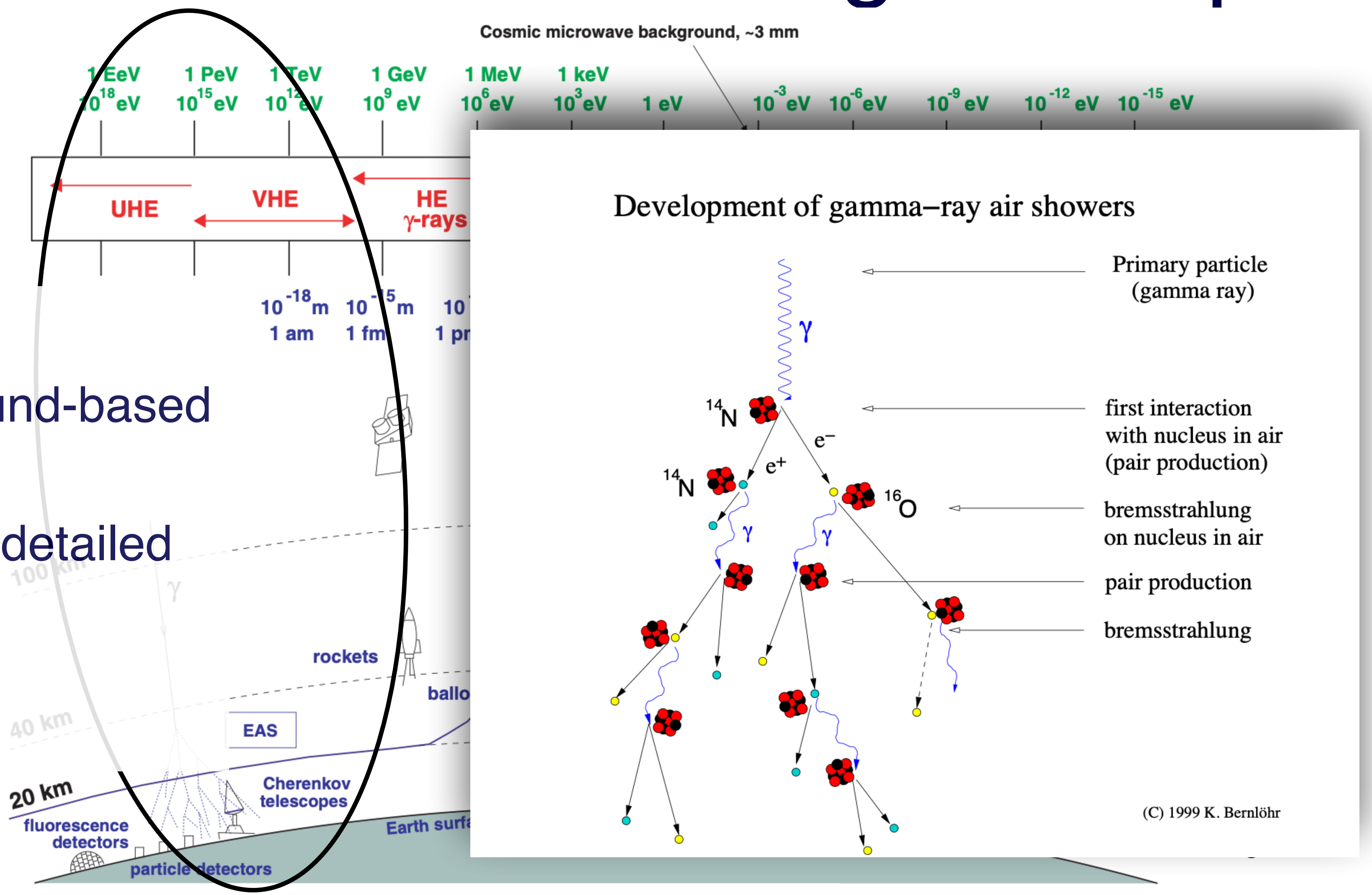
Absorption in the Electromagnetic Spectrum



Air Showers

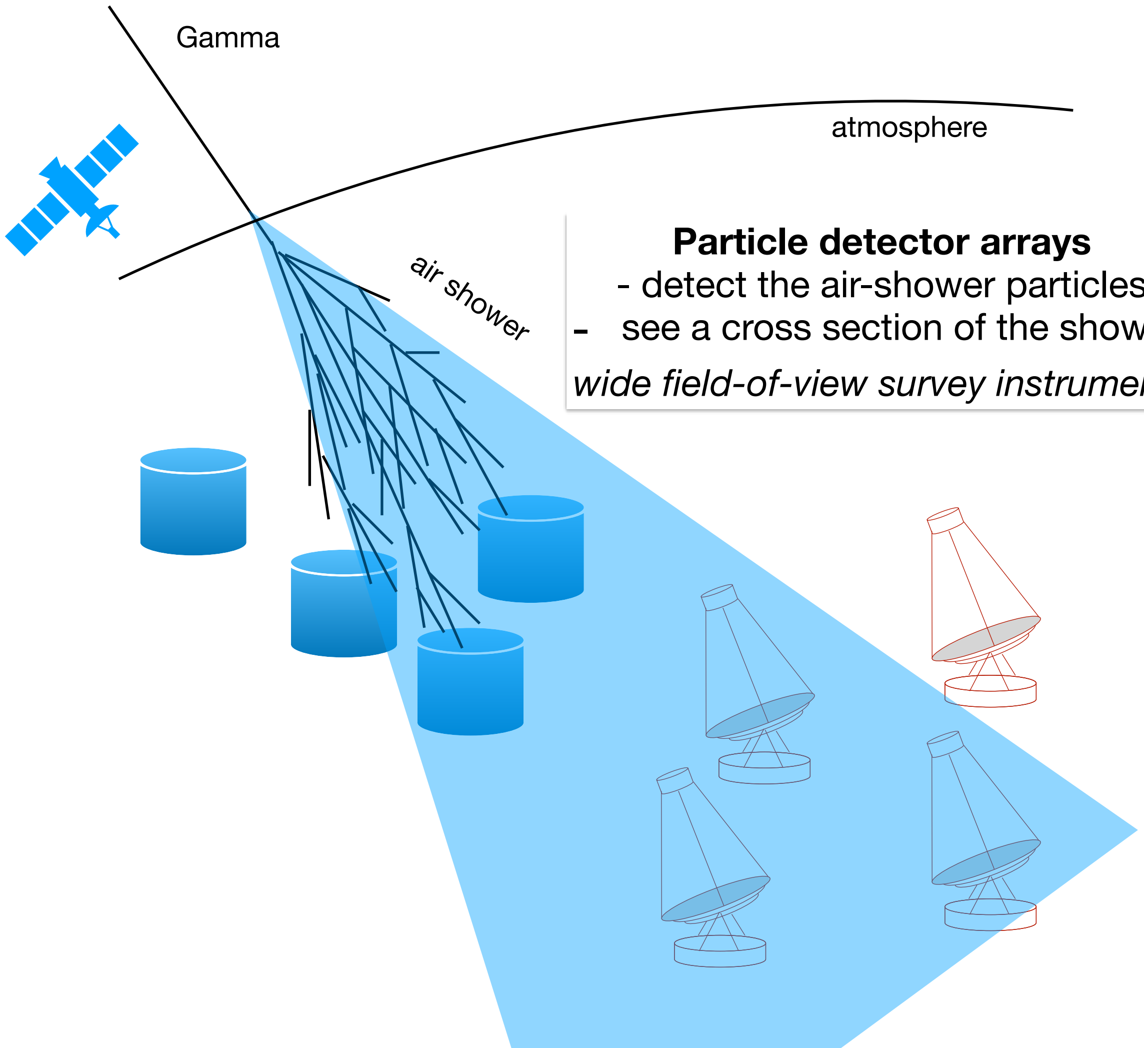
- Crucial for ground-based measurements
- We will have a detailed look tomorrow

low fluxes + absorption in the atmosphere = indirect measurements via air showers

Measurement Principles & Instruments

Satellite instruments
- direct detection
- excellent particle ID and energy reconstruction

lower energies up to ~1 TeV



Particle detector arrays
- detect the air-shower particles
- see a cross section of the shower

wide field-of-view survey instruments

Imaging atmospheric Cherenkov telescopes (IACTs)
- detect the Cherenkov light of the shower
- see the entire shower

pointed precision instruments

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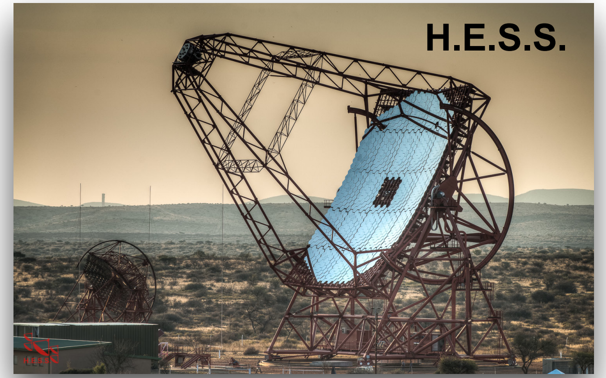
Two Techniques for Ground-Based Observations

Particle Detector Arrays

Cherenkov light in water

24/7 observations

observation of full sky above detector



Imaging Atm. Cherenkov Telescopes

Cherenkov light in atmosphere

(moon-less) night observations

pointed observations

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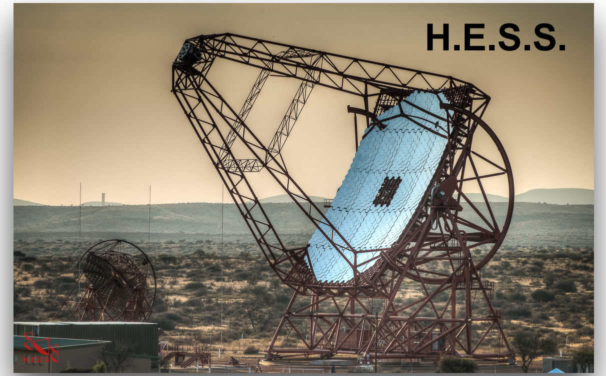
Two Techniques for Ground-Based Observations

Particle Detector Arrays

Angular resolution of ~0.5 deg

Wide fields of view

Large duty cycle



Imaging Atm. Cherenkov Telescopes

Angular resolution of ≲0.1 deg

Small fields of view

Larger instantaneous sensitivity (put into perspective by small FoV and low duty cycle)

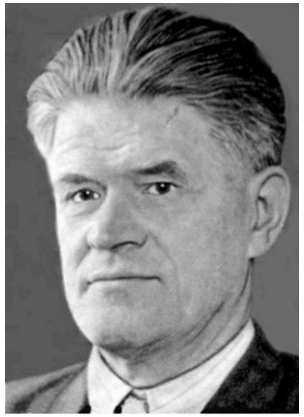
Survey instruments at somewhat higher energies

Very strong complementarity!

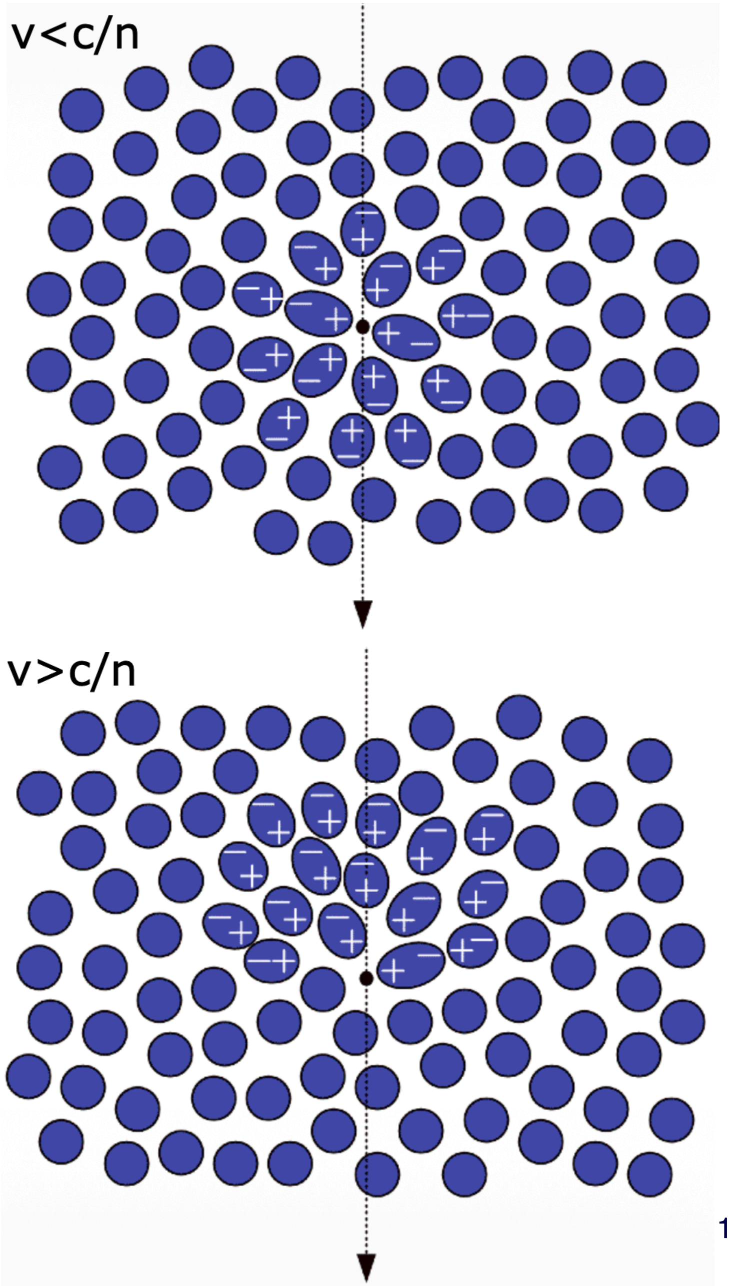
Pointed precision instruments with somewhat lower energy threshold

Cherenkov Radiation

- A charged particle moves faster than the speed of light through a dielectric medium ($c_n = c/n$)
- Atoms get polarised. These atoms emit photons when they return to the ground state
- When the particle moves quickly, the polarisation is not symmetrical along the axis of motion, resulting in constructive interference



Pawel Alexeyevich Cherenkov
(Nobel Prize in 1958)



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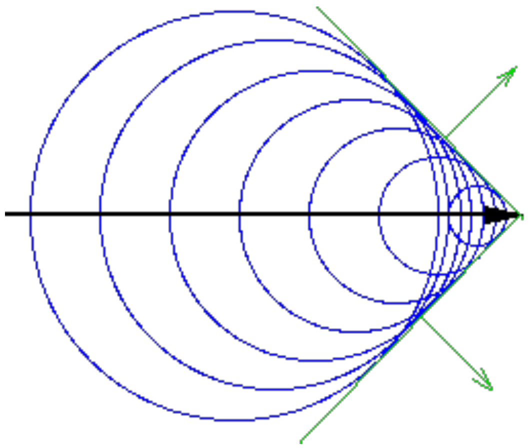
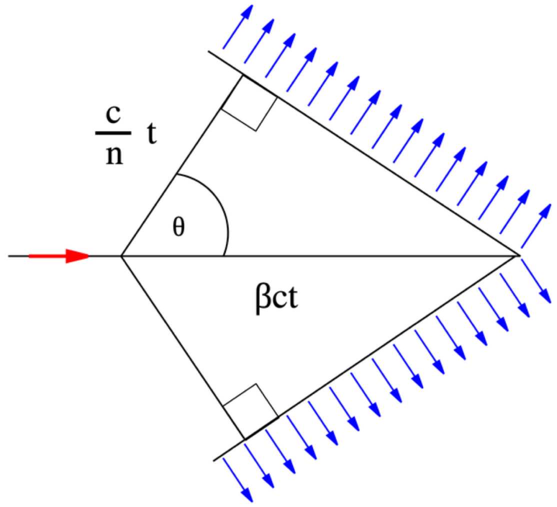
Cherenkov Radiation

- Charged particle moving with v>c/n emits Cherenkov light
- Emission angle:

$$\cos \theta_c = \frac{1}{n\beta}$$





- Charged air-shower particles can emit Cherenkov light either in the air or in a suitable medium like water
- ϑ_C ~1° in air, ~40° in water

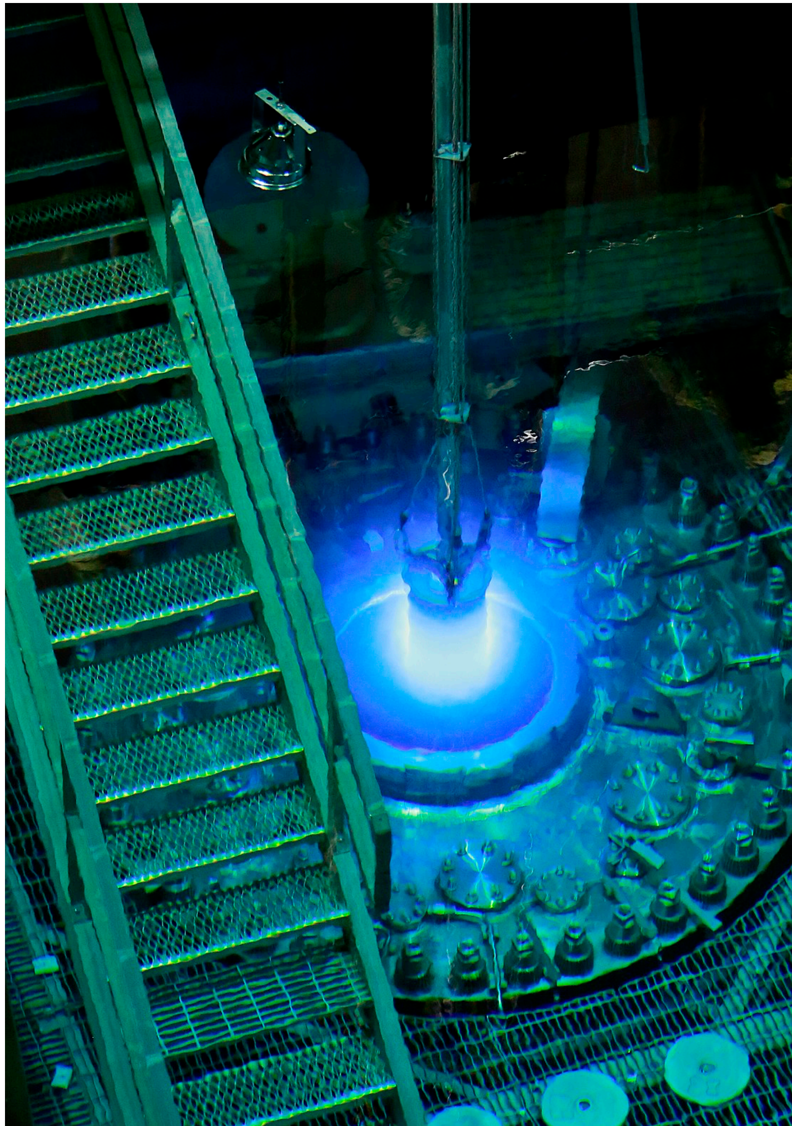
optical equivalent to sonic boom

Cherenkov Radiation

- Dominated by small wavelengths
  → blue light

$$\frac{d^2N}{dx\,d\lambda} \propto \lambda^{-2}$$

- No emission in X-rays because refractive index depends on wavelength



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Cherenkov Radiation in the Atmosphere

Refractive index changes with altitude h:

$$n = 1 + 0.000283\ \rho(h)/\rho(0)$$

YOUR TURN

What is the threshold for Cherenkov emission for electrons at sea level (h = 0 m)? Consider that to emit Cherenkov radiation, the electrons have to move faster than the speed of light in the medium ($c_n = c/n$).

Cherenkov Radiation in the Atmosphere

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What is the threshold for Cherenkov emission for electrons at sea level (h = 0 m)? Consider that to emit Cherenkov radiation, the electrons have to move faster than the speed of light in the medium ($c_n = c/n$).

$$\beta = \frac{v}{c} = \frac{c/n}{c} = 1/n$$

$$\gamma = \sqrt{\frac{1}{1-\beta^2}}$$

$$E = \gamma m_0 c^2 = 42 * 0.511 MeV \approx 20 MeV$$

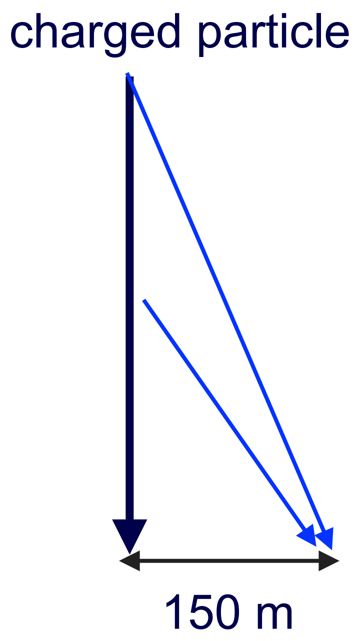
At sea level, the threshold is E = 20 MeV

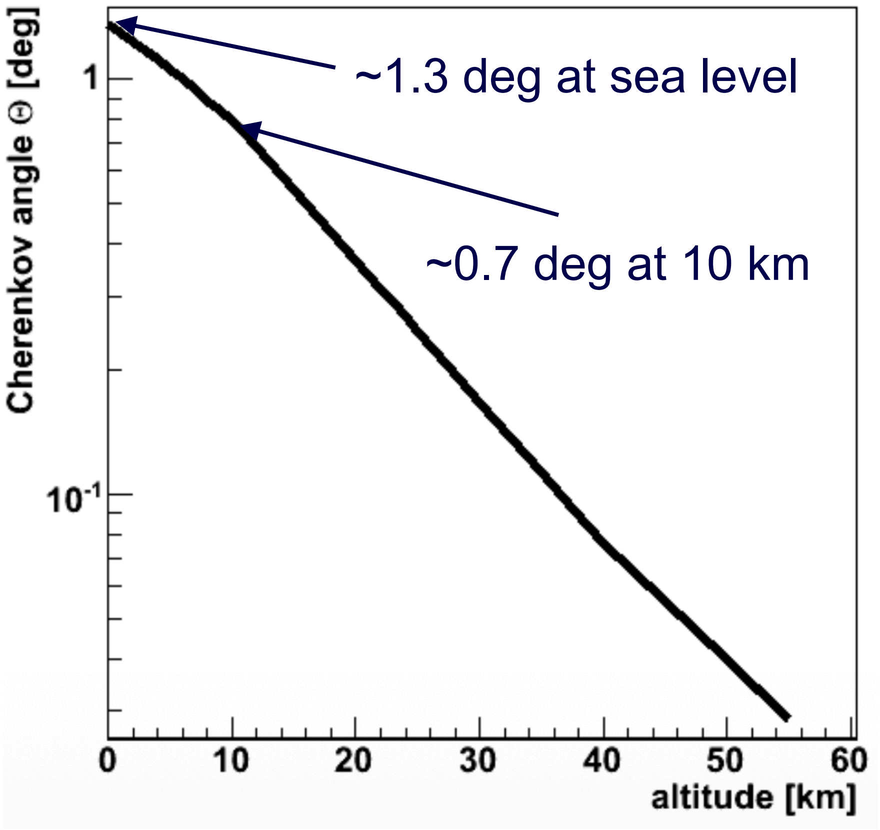
At 10 km height (where we have our air showers): 40 MeV

Cherenkov Radiation in the Atmosphere

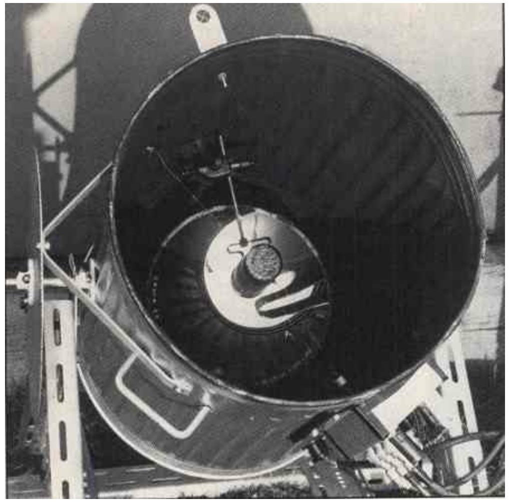
Opening angle changes due to density changes in the atmosphere

$$n = 1 + 0.000283\ \rho(h)/\rho(0)$$



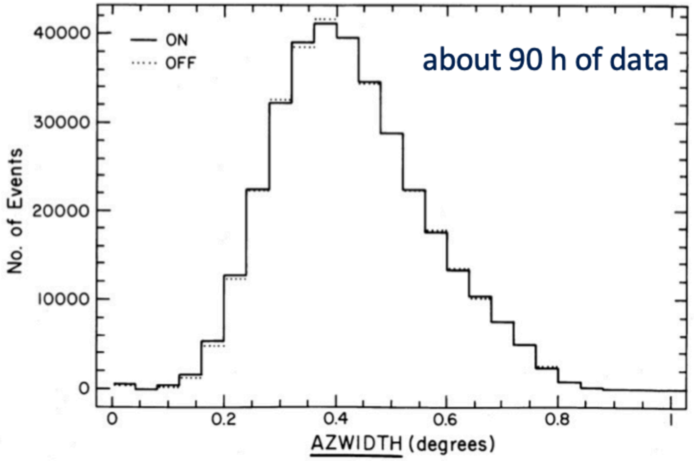


The Beginning…



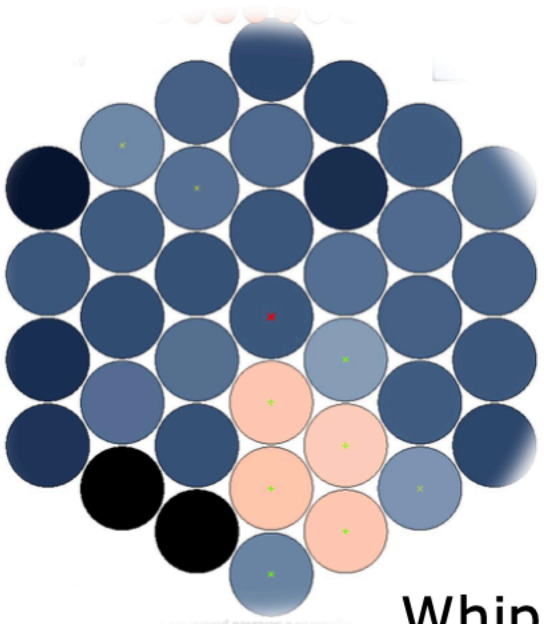
1953: with a garbage can and a 60 cm Ø mirror first measurement of atmospheric Cherenkov light

1968: Whipple telescope (10 m Ø mirror)

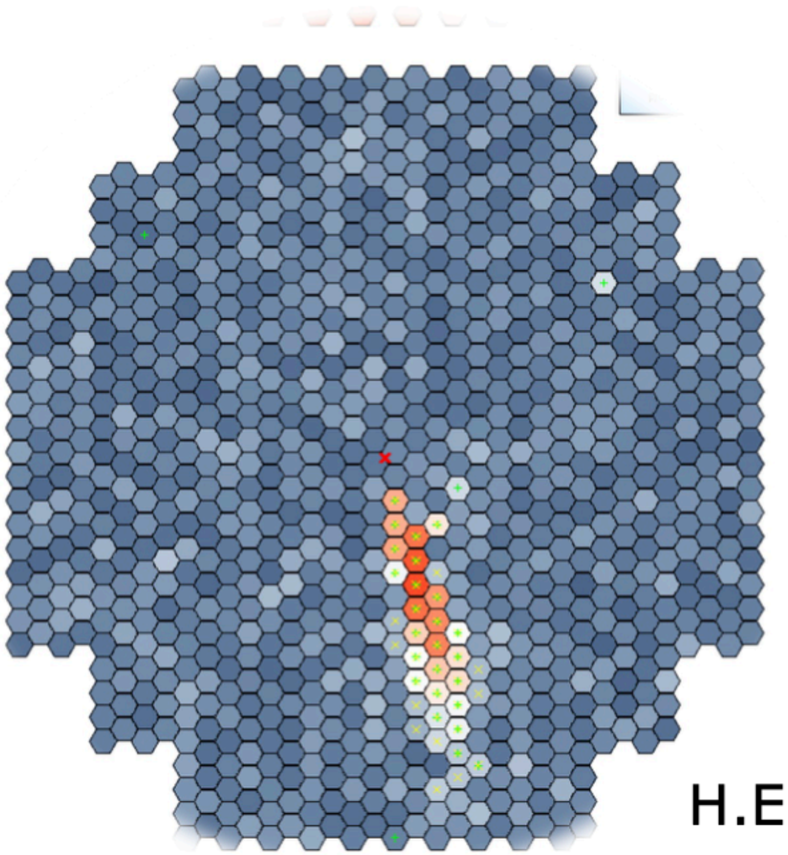


1989: First detection of the Crab nebula at 5σ

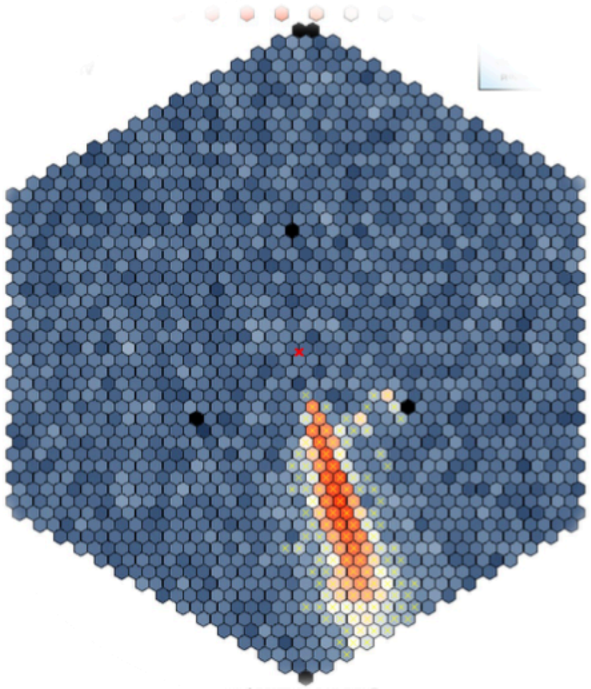
Technology Advances



Whipple
1989



H.E.S.S. I



H.E.S.S. II

from K. Bernlöhr

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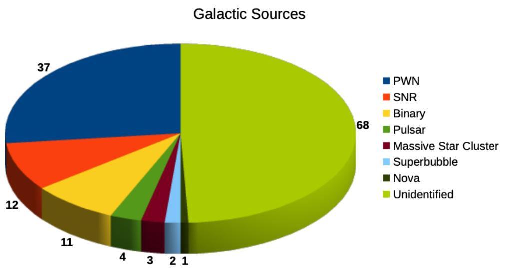
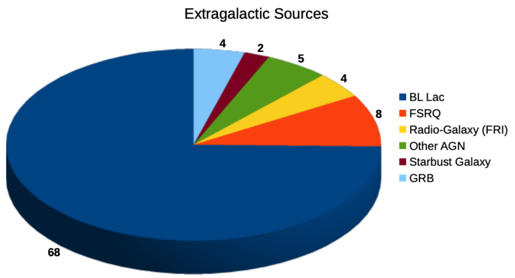
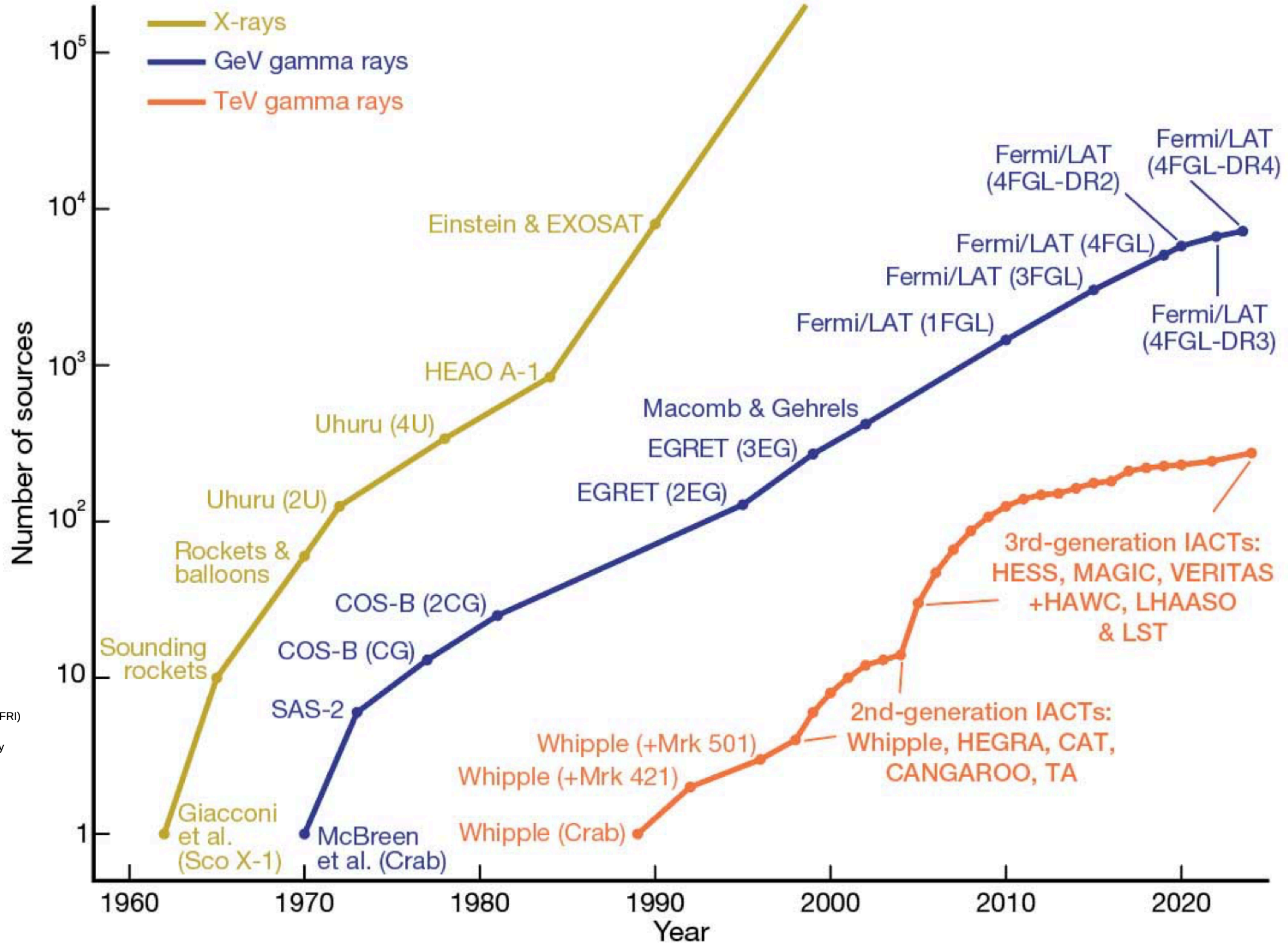
Rapid Development in the Past Years







with a large variety in sources!

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Day 1: Introduction
- Basic considerations
- Detection principles
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Day 2: Everything about Air Showers
- Particle interactions in matter
- Electromagnetic & hadronic air showers
- Air-shower simulations

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- The IACT principle
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Particle Interactions in Matter

Particle interactions give rise to

- change of energy
- change of direction
- secondary particles

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Particle Interactions in Matter

Interactions with electrons (atomic shell):

- Ionisation: μ- + atom → μ- + atom+ + e- **energy loss**
- Excitation: μ- + atom → μ- + atom* **scintillation light emission**

  atom* → atom + γ

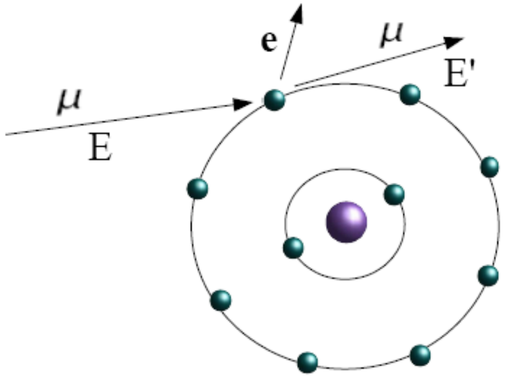
Interactions with nuclei:

- Bremsstrahlung **energy loss/light emission**

Polarisation:

- Cherenkov radiation **light emission**
- Transition radiation **light emission**

Ionisation

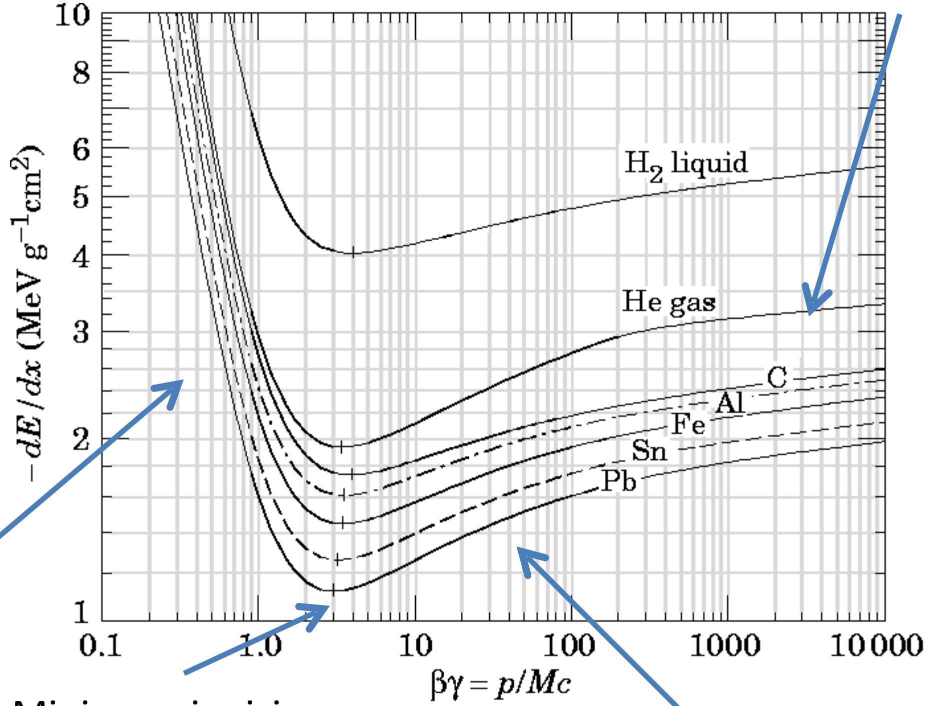


- $\mu^- + \text{atom} \rightarrow \mu^- + \text{atom}^+ + e^-$

- Average energy loss described by Bethe-Bloch formula:

$$-\frac{dE}{dx} = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A} \frac{1}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2} - \beta^2 - \frac{\delta}{2}\right]$$

- dE/dx in [MeV g^{-1} cm^2]:
  Distance dx measured in g/cm^2,
  dx = ρ·**ds** (grammage)



Fermi plateau

Kinematic term

$$\frac{dE}{dx} \propto \frac{1}{\beta^2}$$

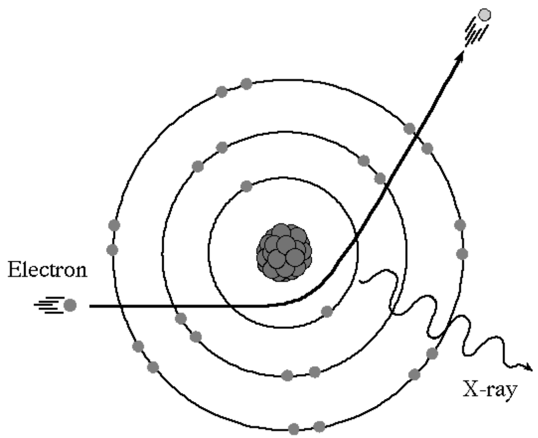
Minimum ionising particles: βγ≈4

Relativistic rise

$$\frac{dE}{dx} \propto \ln \beta^2\gamma^2$$

[Formula valid for “heavy” particles ($m \geq m_\mu$), electrons require modifications because of the equal masses of the collision partners]

Bremsstrahlung



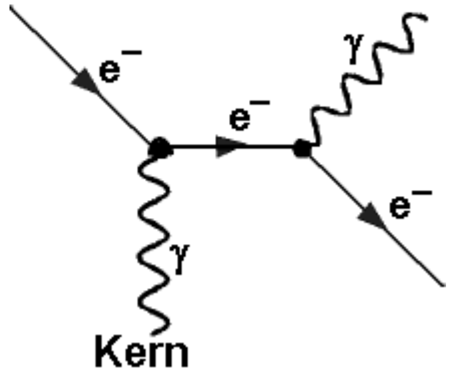
- Deceleration in the Coulomb field of the nucleus
- dE/dx ∝ E:

$$\frac{dE}{dx} = \frac{E}{X_0} \Rightarrow E = E_0 \exp(-\frac{x}{X_0})$$

where X_0 is radiation length, $X_0 \propto m^2$

- The radiation length depends on the target properties and is usually defined for electrons

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$



- Distance over which the energy is reduced by a factor of 1/e
- $X_0 \propto m^2 \rightarrow$ important for small masses, electrons

in the atmosphere:
$X_o (N_2)$ = 716.4 g/cm^{-2} * 14 / (7 * (1+7) * ln(287/sqrt(7))) = ~37 g/cm^2

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Critical Energy

- Energy dependence of ionisation at high energies is ∝ ln γ^2 → basically flat!
- Energy dependence of bremsstrahlung is ∝ E

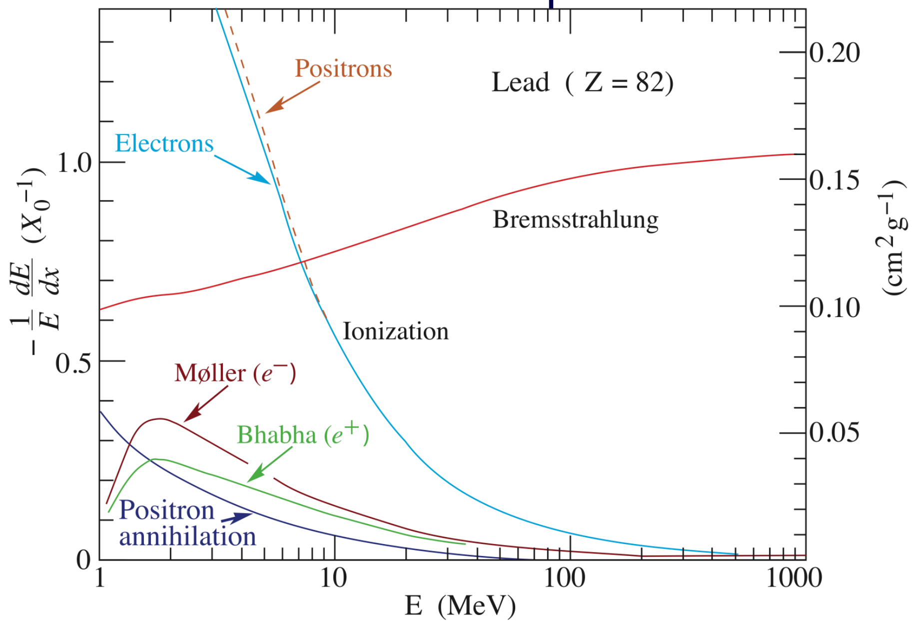
→ bremsstrahlung takes over at some point

critical energy E_c: energy at which energy losses of ionisation and bremsstrahlung are the same:

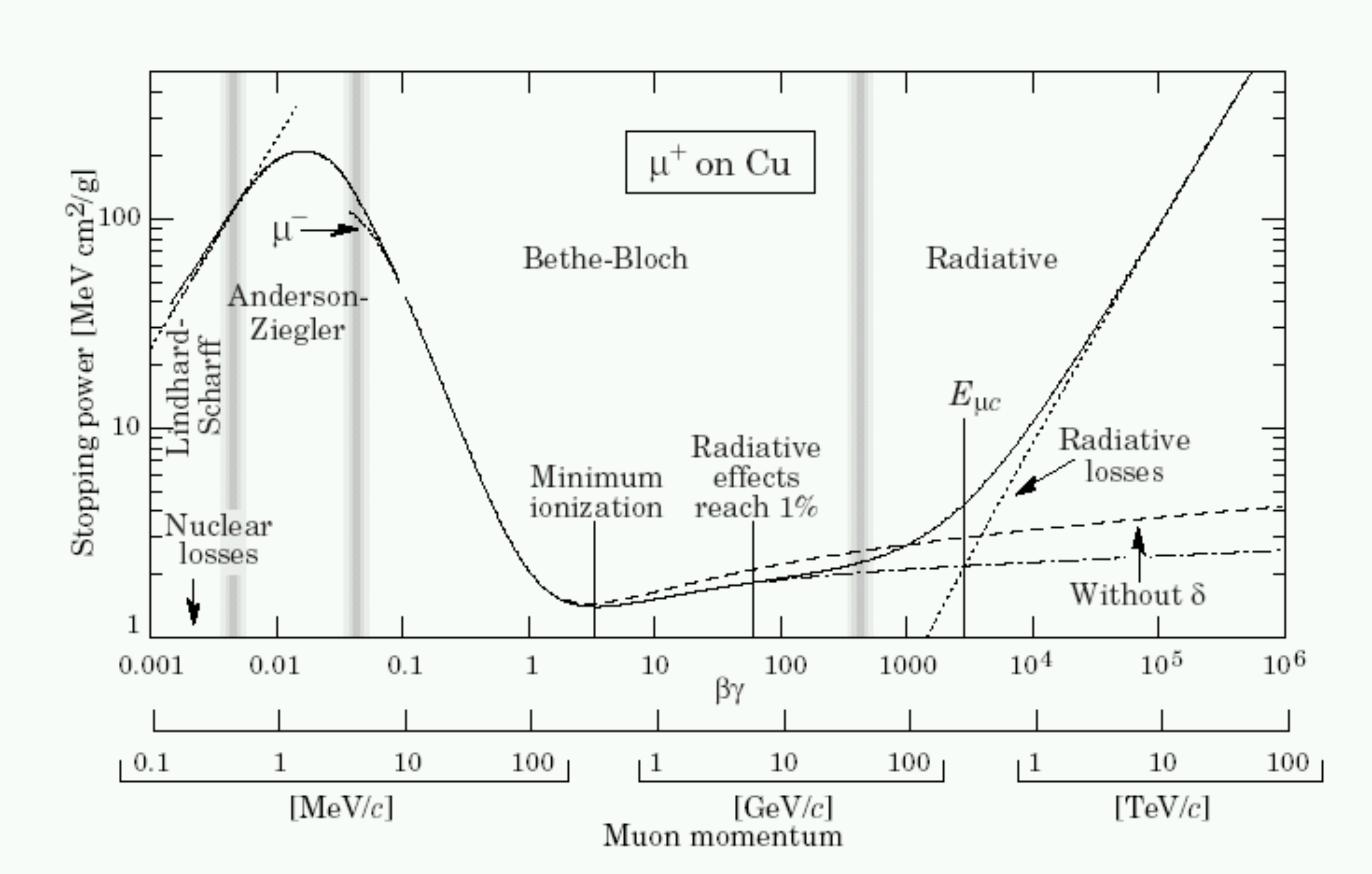
$$\left.\frac{dE}{dx}(E_c)\right|_{Ionisation} = \left.\frac{dE}{dx}(E_c)\right|_{bremsstrahlung}$$

for electrons: $E_c \sim 560$ MeV/Z

electrons and positrons

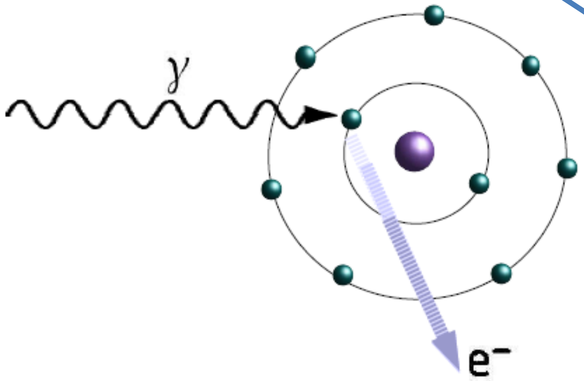


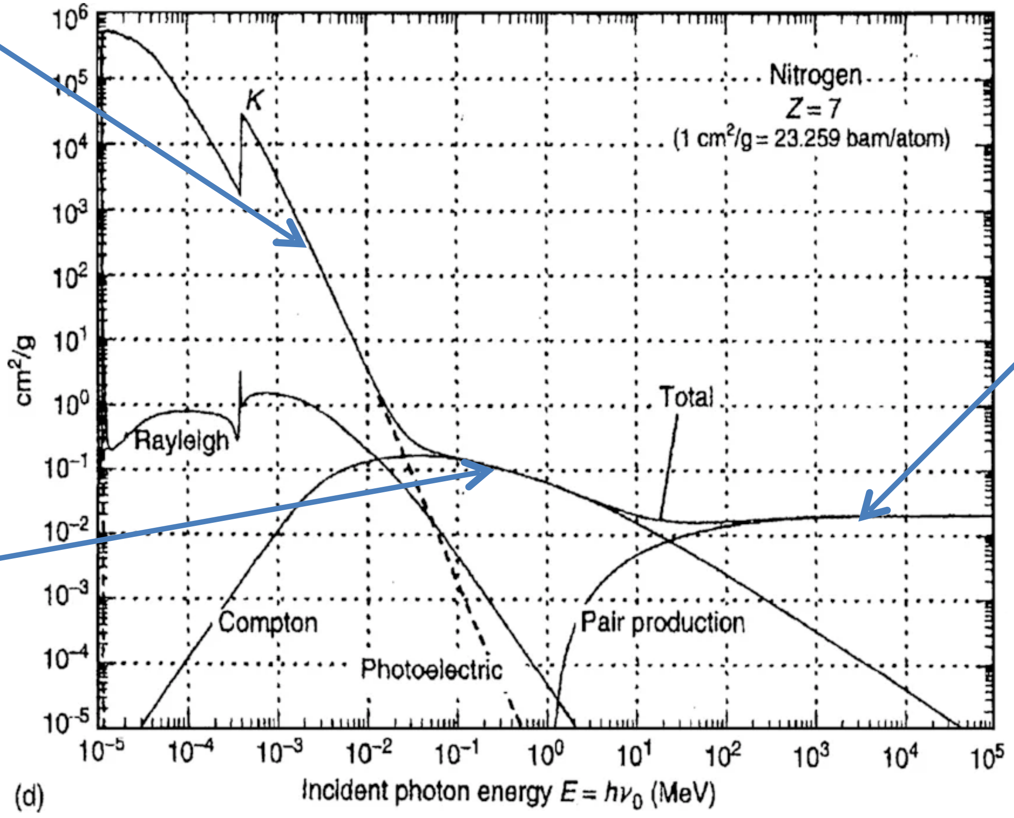
electrons in the atmosphere:
$E_c \sim 560$ MeV/7 = 80 MeV


μ+ on Cu
Bethe-Bloch
Radiative
Anderson-
Ziegler
Lindhard-
Scharff
Nuclear
losses
Minimum
ionization
Radiative
effects
reach 1%
Eμc
Radiative
losses
Without δ
Stopping power [MeV cm2/g]
βγ
[MeV/c]
[GeV/c]
[TeV/c]
Muon momentum

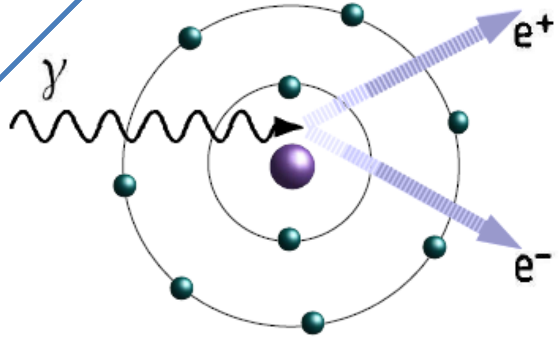
Photon Interactions with Matter

photoelectric effect

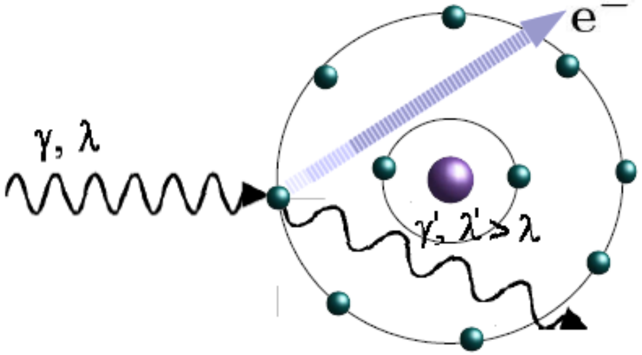




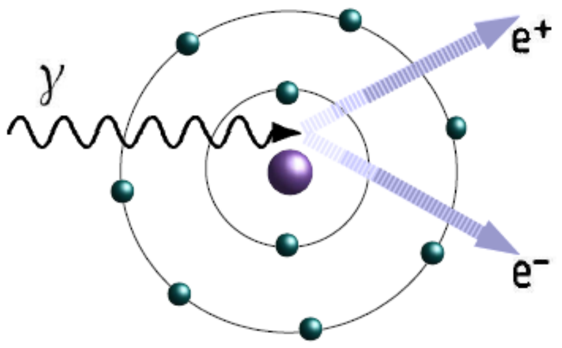
pair production



Compton scattering



Pair Production



- γ + nucleus → nucleus + e^- + e^+
- Threshold energy: $$E_\gamma \geq 2m_e c^2 + 2\frac{m_e^2}{m_{nucleus}}c^2$$
- After an attenuation length $\lambda \cong 7/9\ X_0$, a photon beam intensity has dropped to I_0/e
- Notice the difference to the definition for electrons, where the energy is reduced by a factor of 1/e! Photon loss is catastrophic

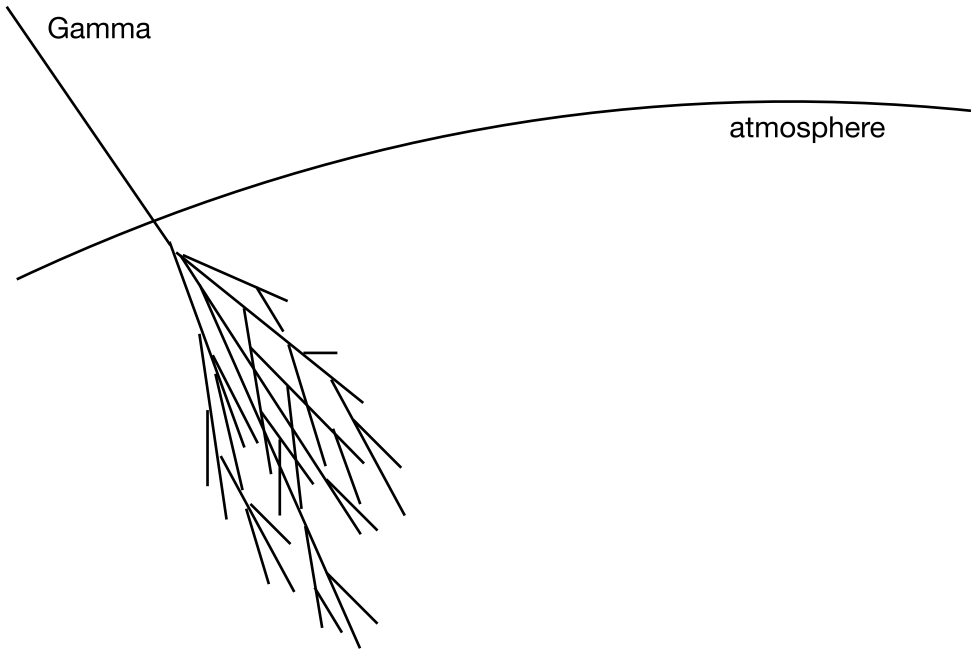
That's what energetic gamma rays do in the atmosphere!

Air Showers

When a charged particle or a photon enters the atmosphere, it interacts and produces a cascade of secondary particles

→ an air shower

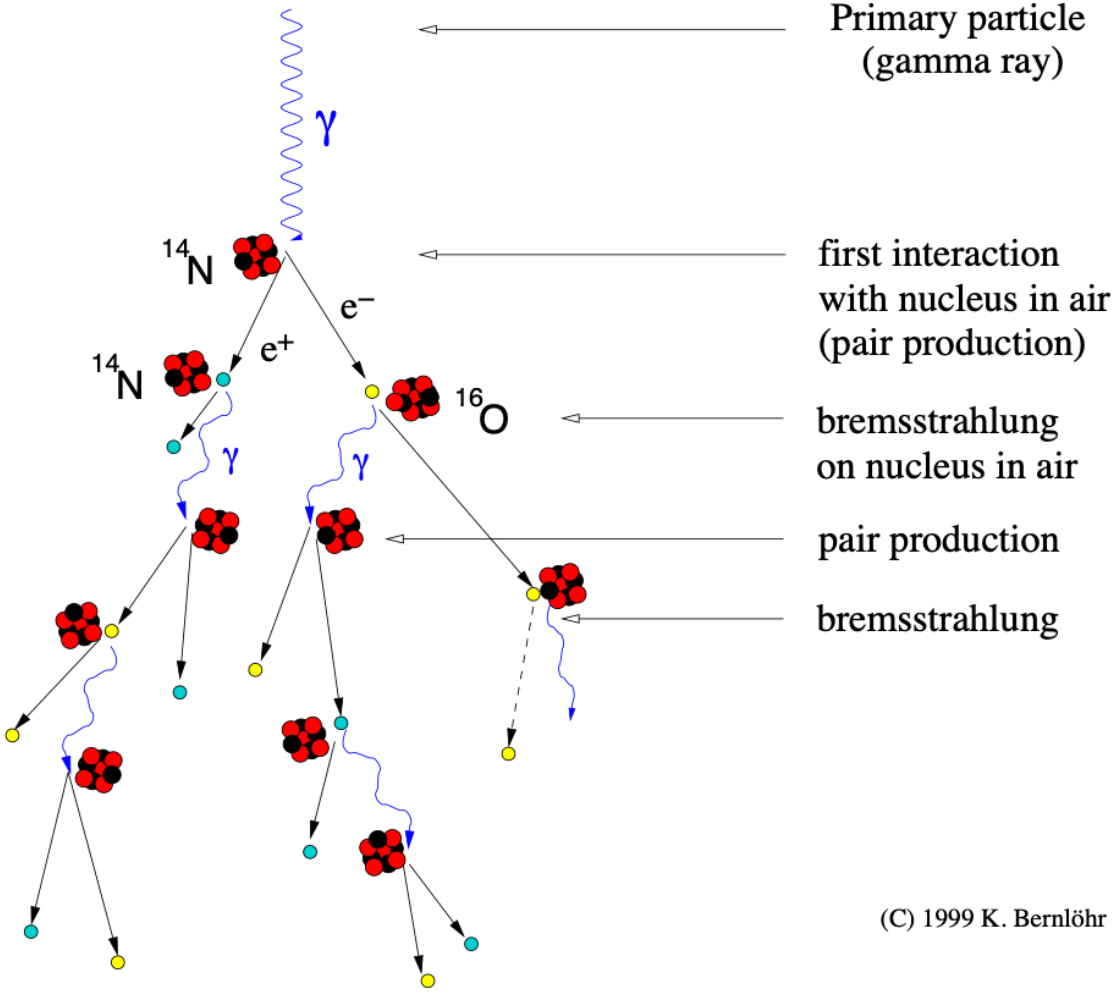
Succession of particle interactions that give the observable quantity



Electromag. Air Showers

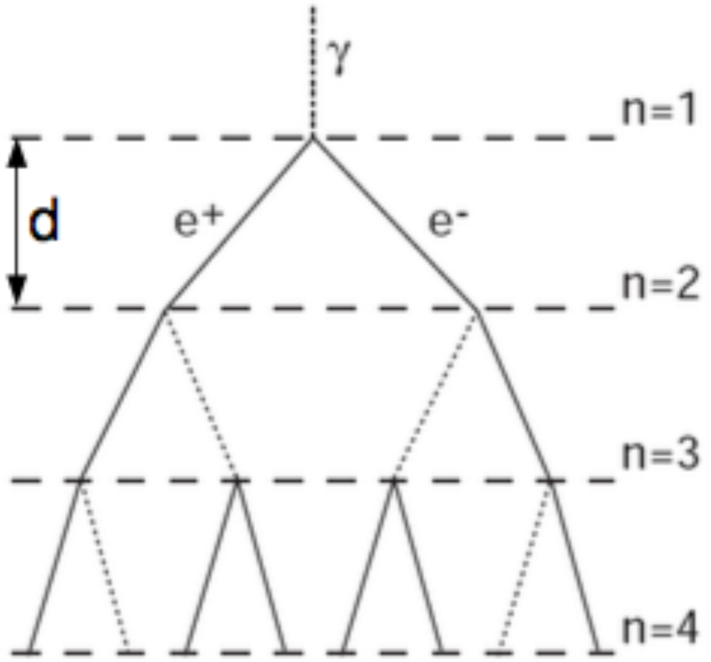
- Iteration of pair production
  γ + nucleus → e^- + e^+ + nucleus

  and bremsstrahlung
  e^- + nucleus → e^- + γ + nucleus
- Increase in particle counts in every interaction
- Until ionisation starts to dominate, then air shower fades out



Heitler Model

- Every interaction happens after one splitting length d
- The energy is split into half: $E_{n=1} = E_{n=0} /2$
- Process stops when the individual particle's energy drops below E_c



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Heitler Model

YOUR TURN

$$\frac{dE}{dx} = \frac{E}{X_0} \Rightarrow E = E_0 \exp\left(-\frac{x}{X_0}\right)$$

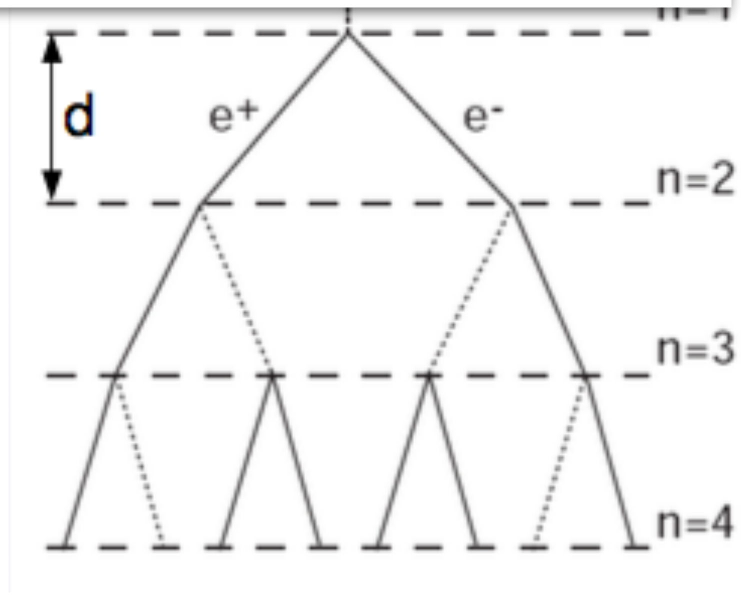
What is the splitting length d expressed in radiation length X_0?

After n splitting lengths, what is the energy E_n of the particles and what is the number N_n of particles?

What is the number of particles at the shower maximum N_{max}? What is the depth of the shower maximum X_{max} expressed in X_0?

With $E_c \sim$ 80 MeV, what are N_{max} and X_{max} for a 1 TeV gamma ray?

- Every interaction happens after one splitting length d
- The energy is split into half: $E_{n=1} = E_{n=0}/2$
- Process stops when the individual particle's energy drops below E_c



CTAO

Heitler Model

YOUR TURN

What is the splitting length d expressed in radiation length X_0?

After n splitting lengths, what is the energy E_n of the particles and what is the number N_n of particles?

What is the number of particles at the shower maximum N_{max}?
What is the depth of the shower maximum X_{max} expressed in X_0?

With E_c ~ 80 MeV, what are N_{max} and X_{max} for a 1 TeV gamma ray?

- one splitting length d is:

$$\frac{dE}{dx} = \frac{E}{X_0} \Rightarrow E = E_0 \exp(-\frac{x}{X_0})$$

$$E(d) = E_0/2$$

$$d = \ln 2 \cdot X_0$$

- after n splitting lengths:

$$N_\mathrm{n} = 2^n$$

$$E_\mathrm{n} = E_0/N_\mathrm{n}$$

$$X_\mathrm{n} = n \ln 2 \cdot X_0$$

- at shower maximum:

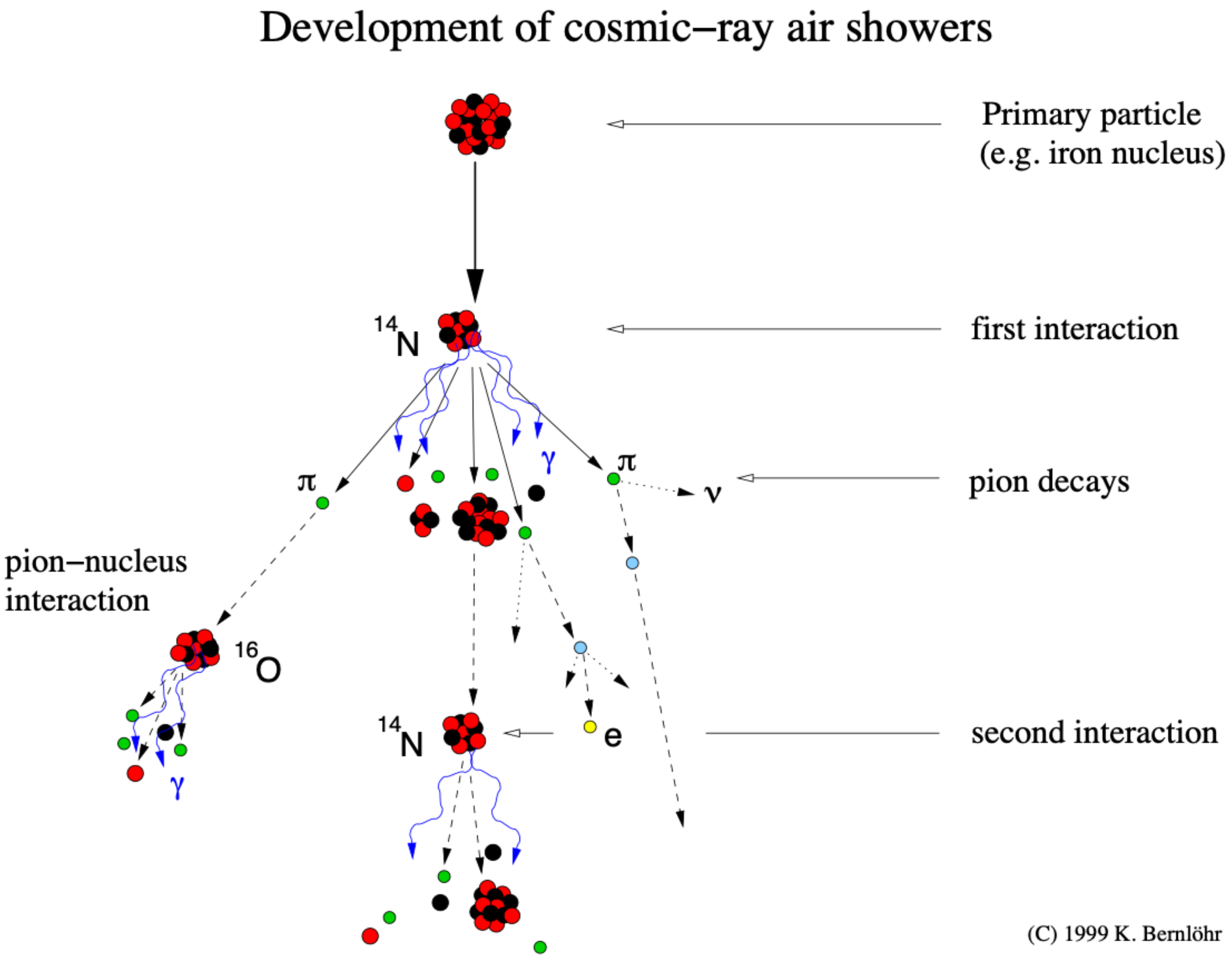
$$N_\mathrm{max} = E_0/E_c$$

$$X_\mathrm{max} = \log_2 N_\mathrm{max} \cdot \ln 2 \cdot X_0 = \log_2 \frac{E_0}{E_c} \cdot \ln 2 \cdot X_0 = \ln \frac{E_0}{E_c} \cdot X_0$$

At 1 TeV: N_{max} ~ 12500 particles and X_{max} ~ 9 X_0 ~ 300 g/cm^2

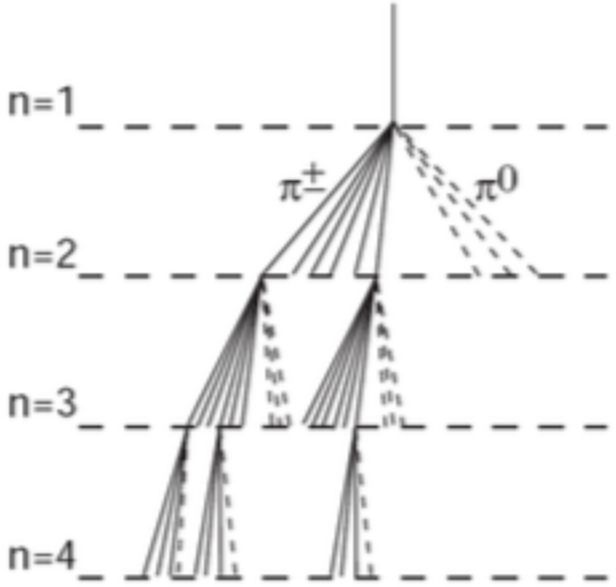
Hadronic Air Showers

- Fragmentation
- Strong interactions producing hadrons (pions, but also heavier particles), which will decay/ interact further
- El.-mag. sub-cascades from neutral pions



Matthews-Heitler Model

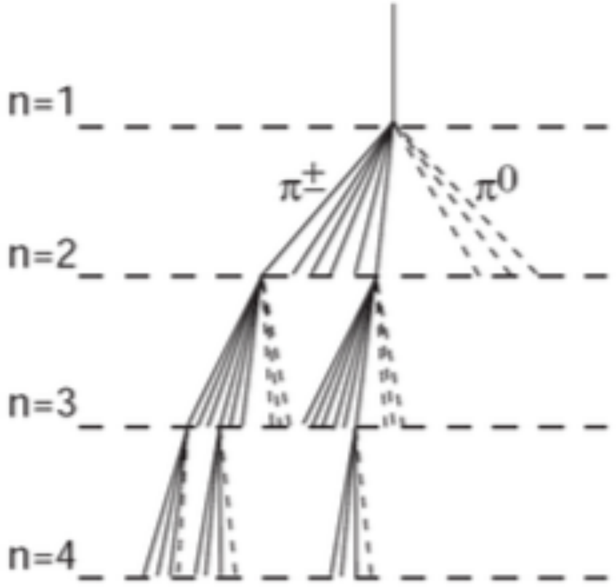
- Every interaction produces M pions (π^+, π^-, π^0 in equal quantities)
- Charged pions interact and initiate a secondary cascade
- Neutral pions decay immediately and initiate electromagnetic shower
- Cascade stops when decay length is reached, i.e. the pions decay into muons



Matthews-Heitler Model

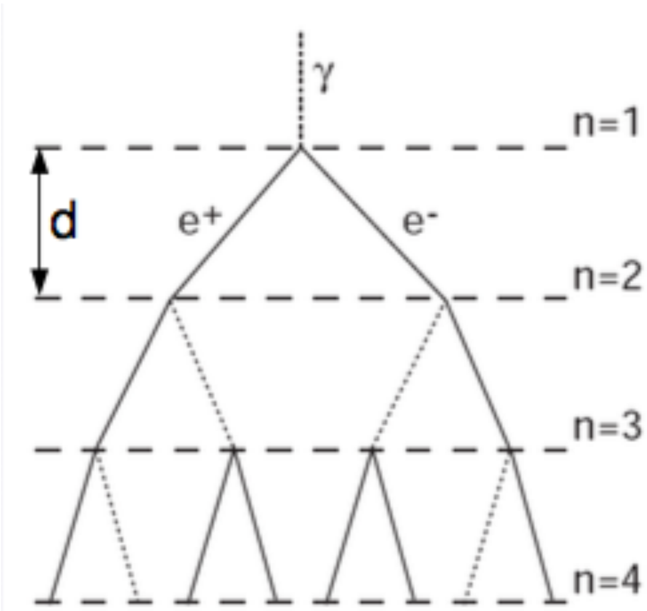
- Number of charged pions at level n:
  $N_n = (2/3\ M)^n$
- Energy of charged pion at level n:
  $E_n = E_0/M^n$
- Total energy in charged pions:
  $E_\pi = (2/3)^n\ E_0$
- Total energy in elmag component:
  $E_{elmag} = (1-(2/3)^n\ )E_0$

- Elmag. component larger with larger initial energy (corresponding to larger n_{max})
- At IACT energies around 70% of energy in elmag. sub-showers



Comparison Elmag/Hadronic Showers

Electromagnetic

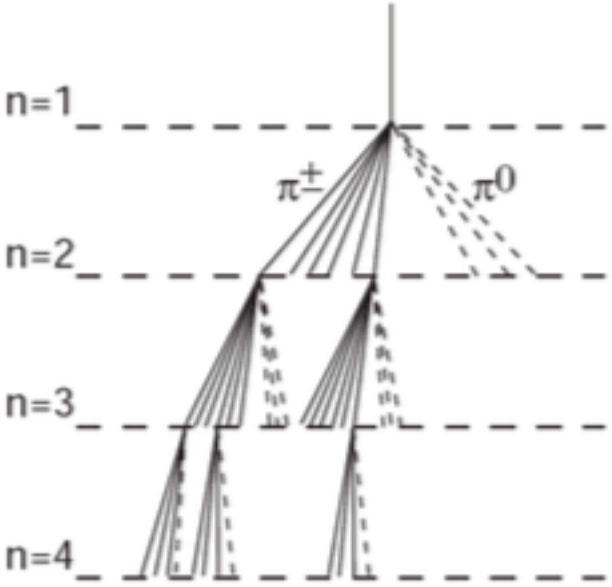


Radiation length

$X_0 = 37$ g/cm^2

$X_{atm} = 27\ X_0$

Hadronic



Nuclear interaction length

$\lambda_I = 90$ g/cm^2

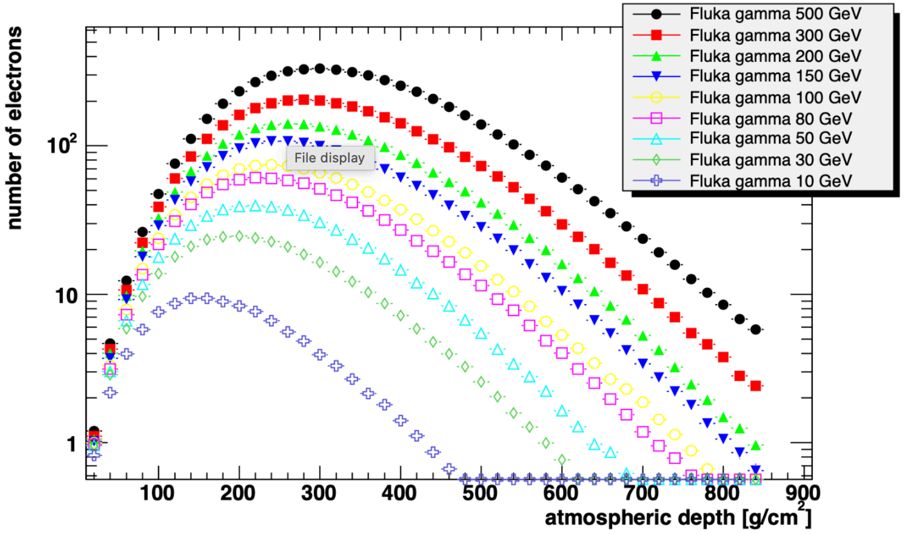
$X_{atm} = 11\ \lambda_I$

$X_{atm} \approx 1000$ g/cm^2

Analytical models vs. reality

Analytical models describe qualitative behaviour of air showers

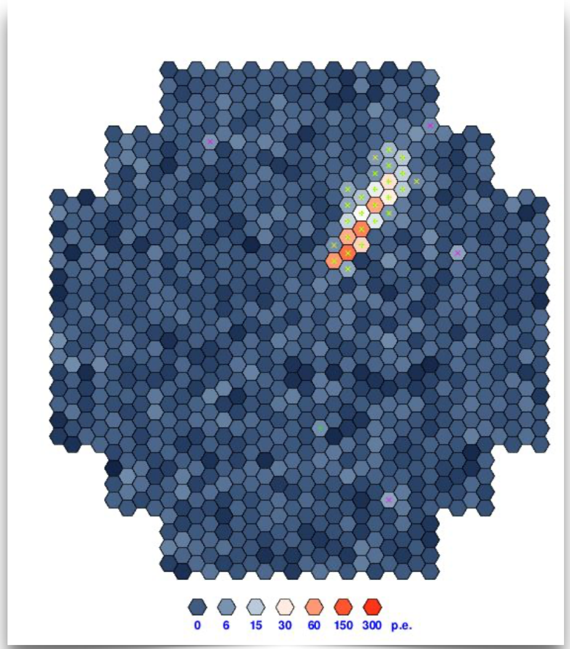
- For elmag. showers:
  - $X_{max} \sim \ln E_0$
  - $N_{max} \sim E_0$
- For hadronic showers:
  - Elmag component larger with larger initial energy (corresponding to larger n_{max})
  - At IACT energies around 70% of energy in elmag sub showers



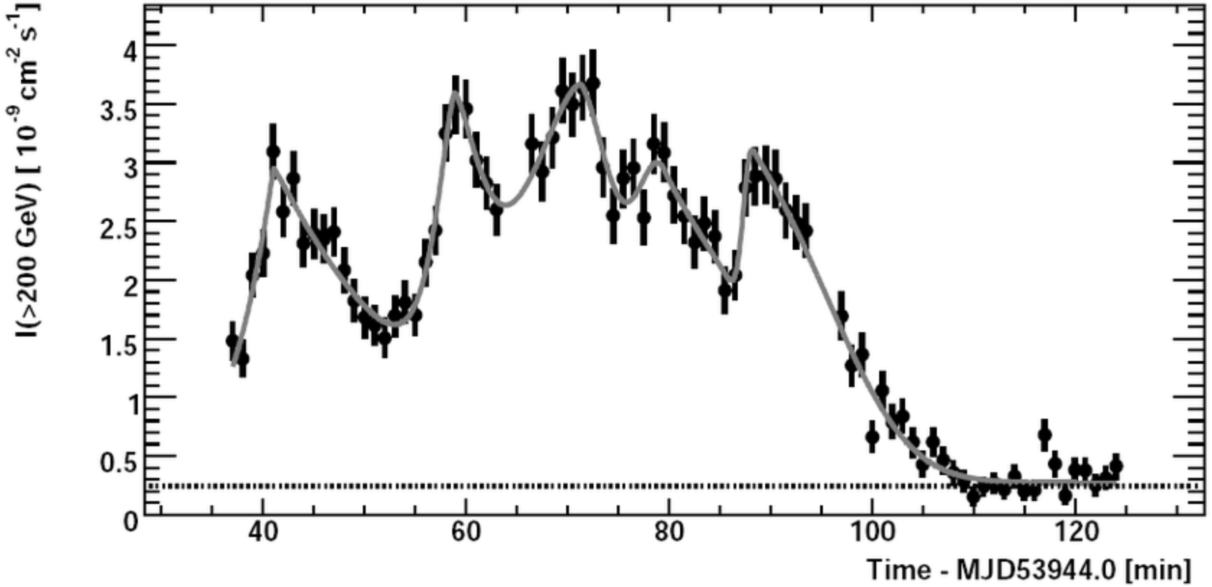
© G. Maier Gamma Picturebook

Details require the simulation of all processes in the atmosphere

Why do we need air-shower simulations?



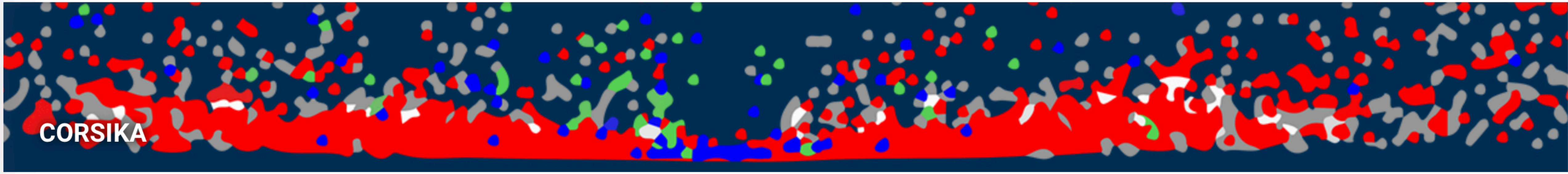
?



Determine from secondary products
primary-particle properties (reconstruction) and physical quantities

Often for air showers CORSIKA is used, for telescope response Sim_telarray

CORSIKA



- CORSIKA (COsmic Ray SImulations for KAscade) is a program for detailed simulation of extensive air showers
- Particles are tracked through the atmosphere until they undergo reactions with the air nuclei or decay
- Plug-in of interaction models

Electromagnetic interactions can be modelled to high precision (QED),
for hadronic interactions (QCD) interaction models are required:
GEISHA, FLUKA, UrQMD (low energies) and
VENUS, QGSJET, DPMJET, SIBYLL, EPOS (high energies)

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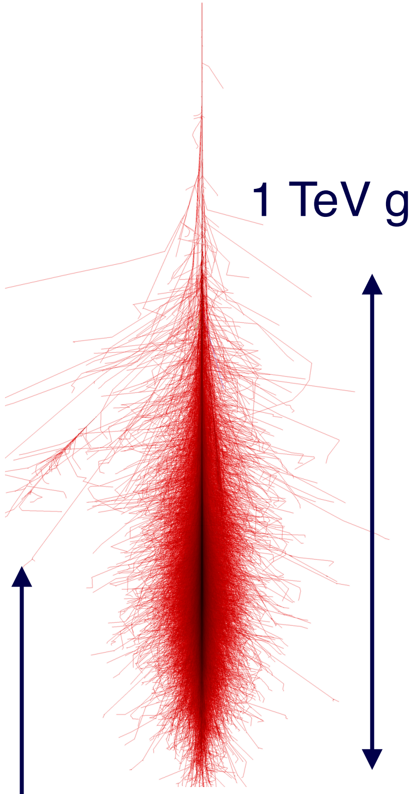
Shower Simulations

1 TeV gamma-ray

longitudinal projection



~5 km

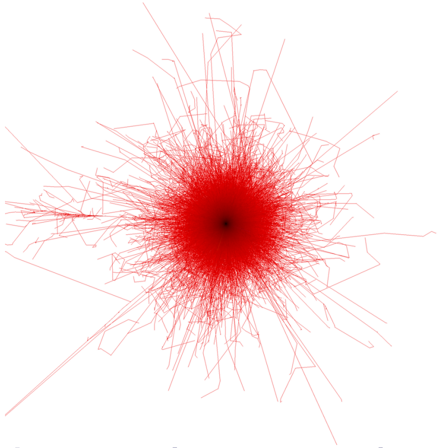
~20 m

x axis exaggerated
for visualisation purpose

~10 km
above sea level

Particle type is encoded in track color:

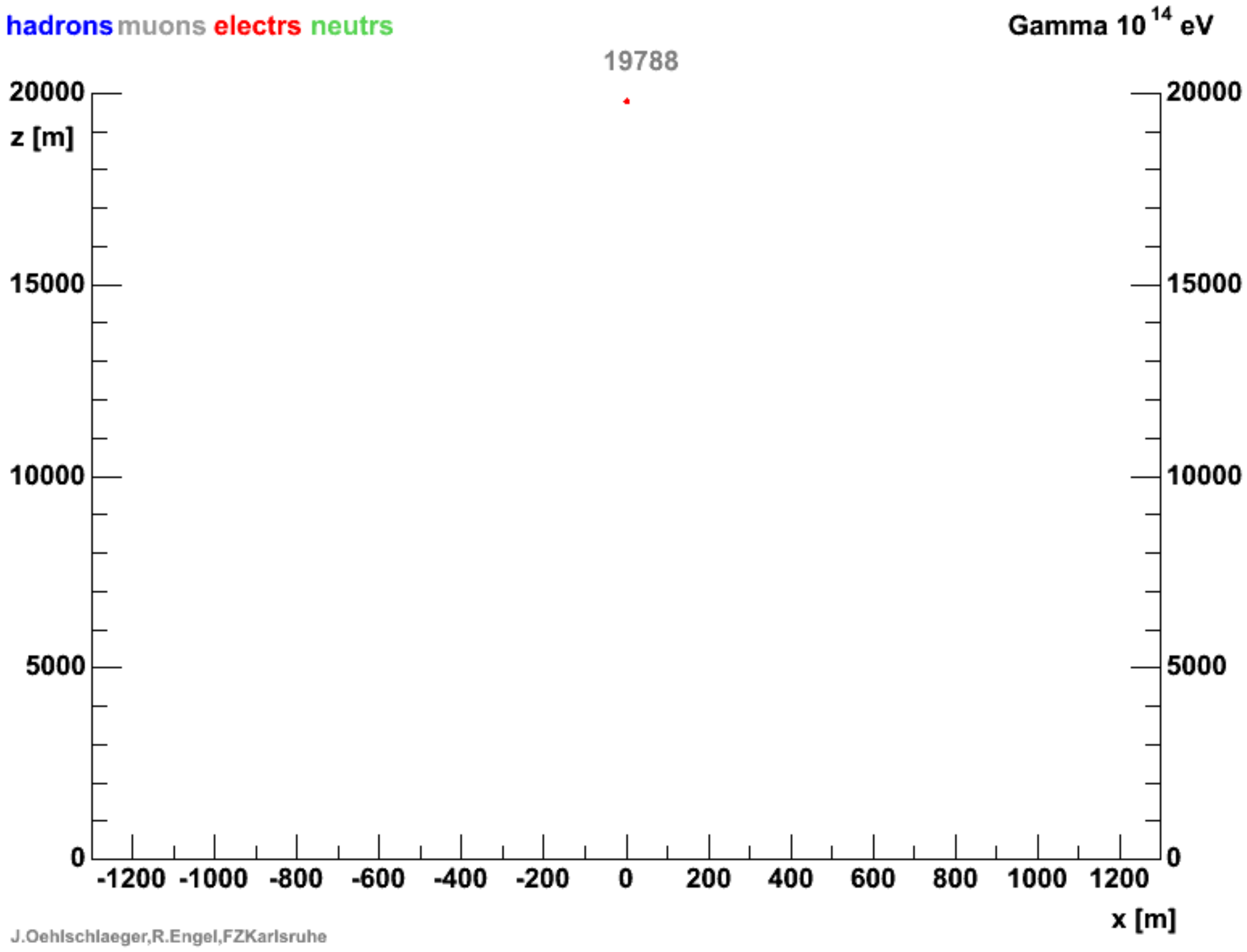
- red = electrons, positrons, gammas
- green = muons
- blue = hadrons



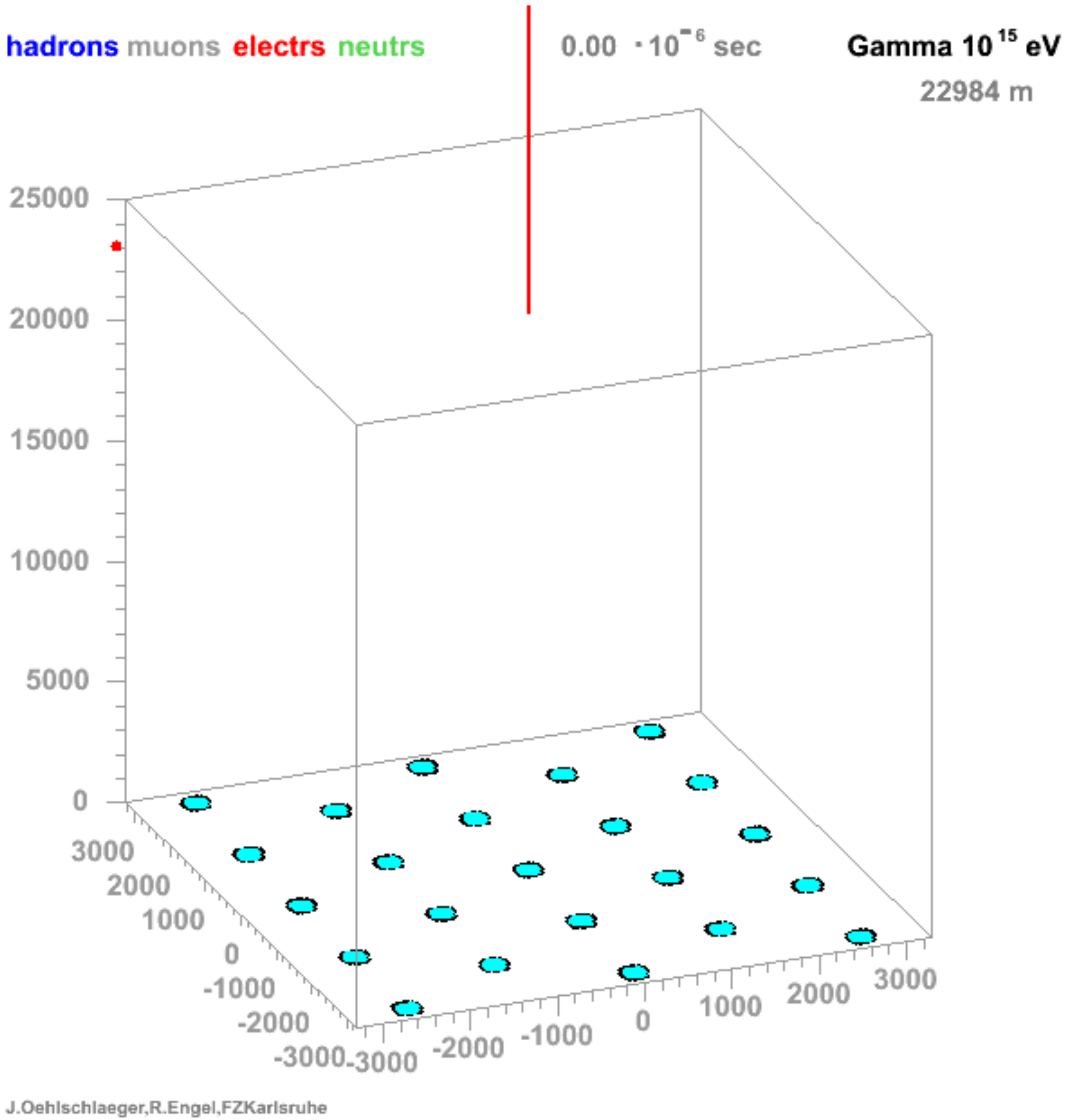
projection on the ground plane

F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Gamma Shower Development

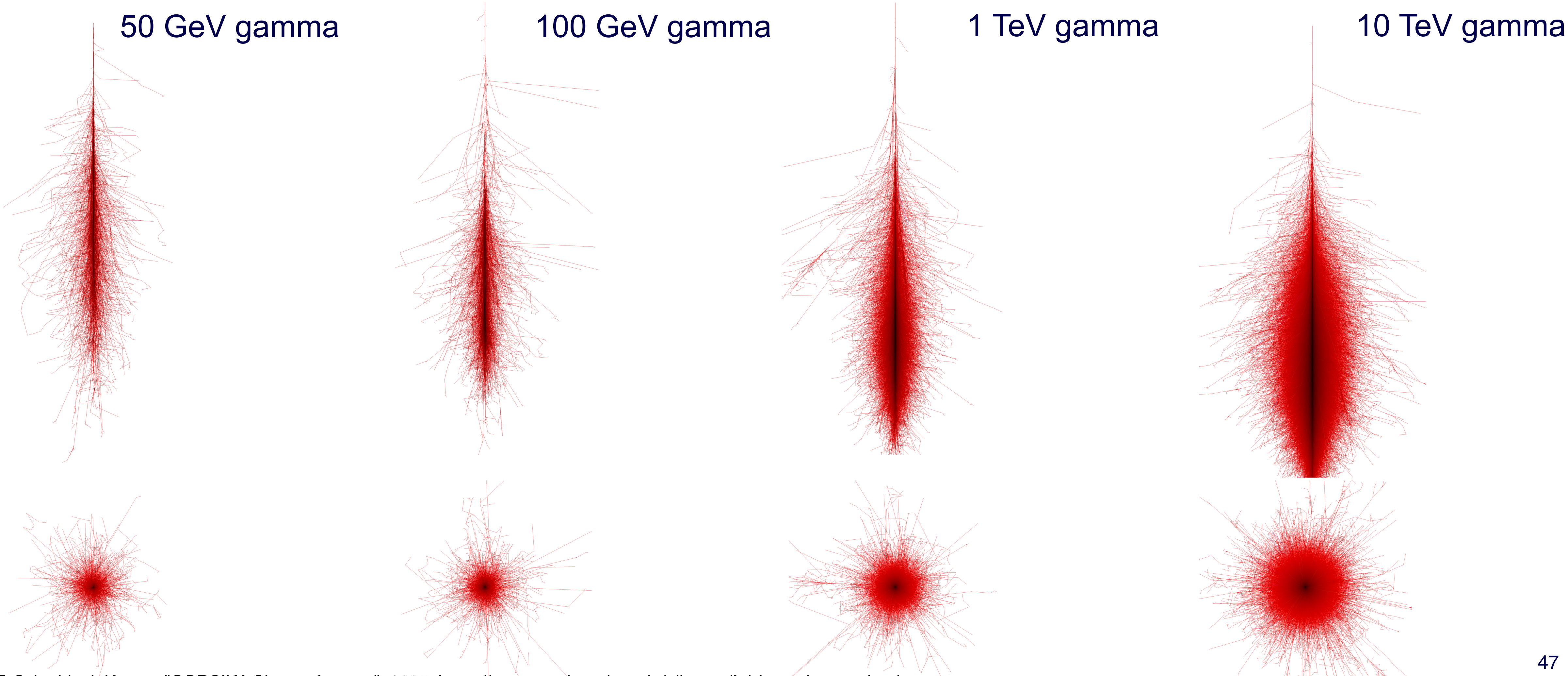


100 TeV gamma-ray



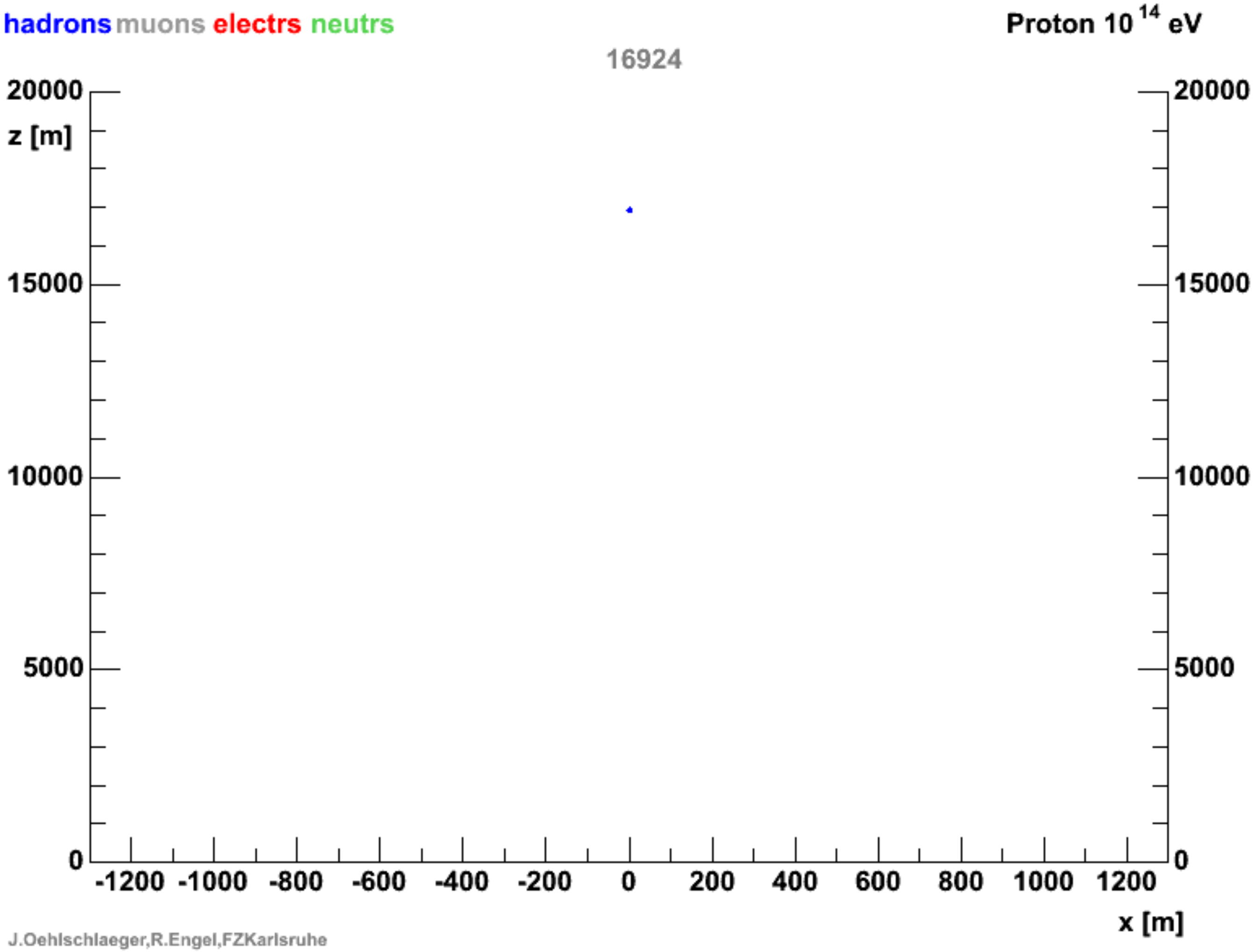
1 PeV gamma-ray

Gamma Simulations

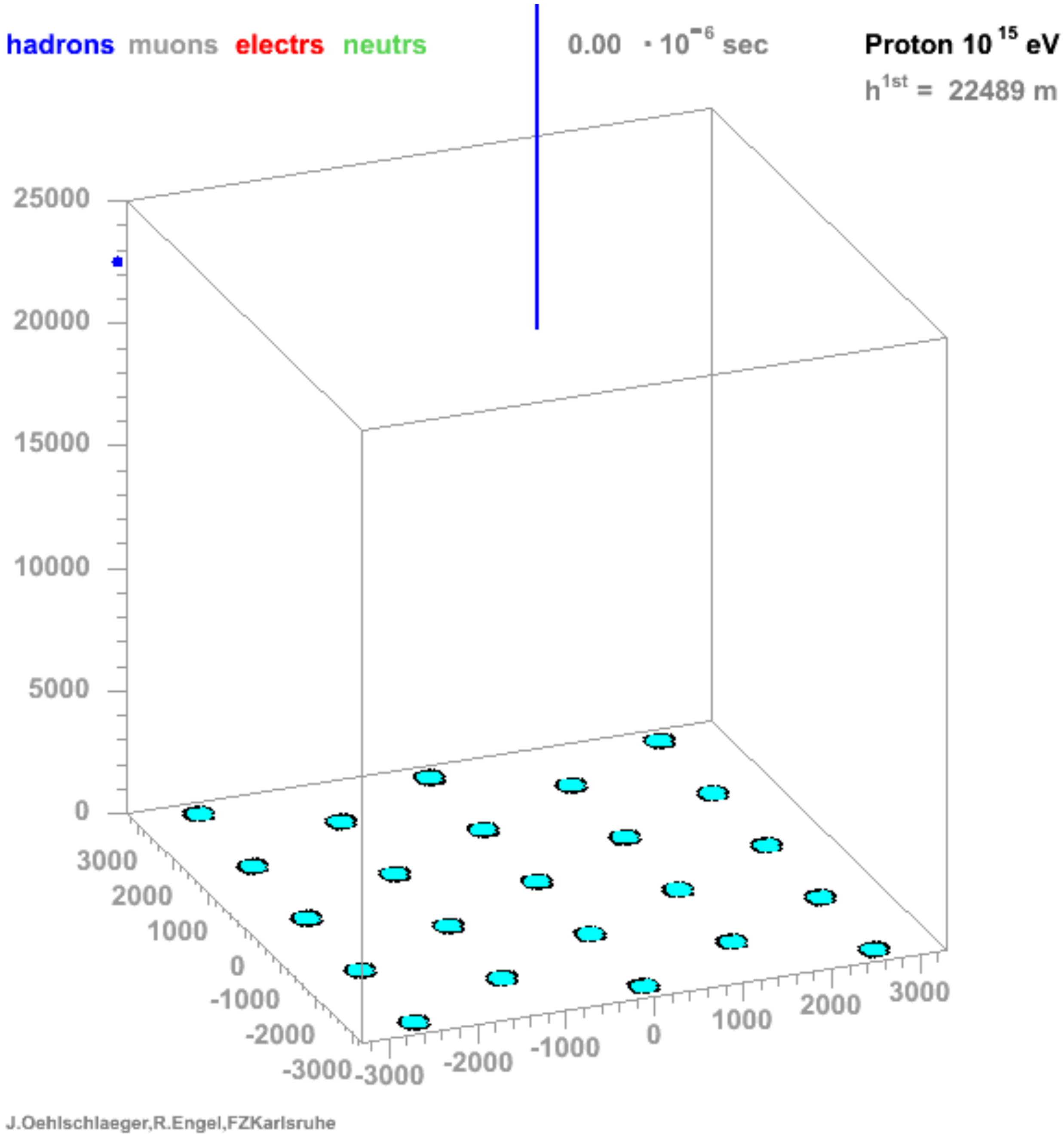


F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

Proton Shower Development



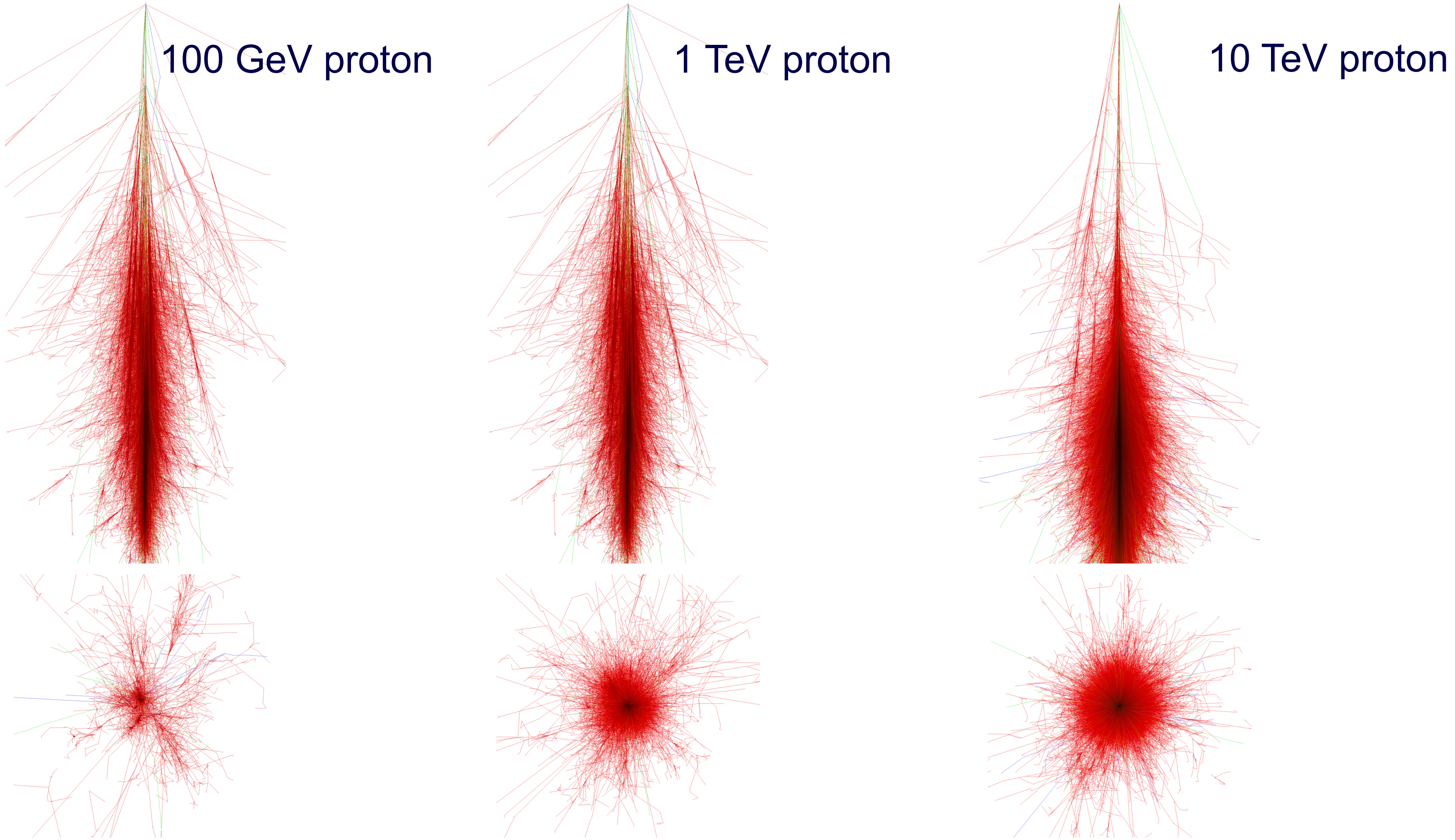
100 TeV proton



hadrons muons electrs neutrs
0.00 · 10⁻⁶ sec
Proton 10 15 eV
h1st = 22489 m
25000
20000
15000
10000
5000
0
3000
2000
1000
0
-1000
-2000
-3000
-3000
-2000
-1000
0
1000
2000
3000
J.Oehlschlaeger,R.Engel,FZKarlsruhe

1 PeV proton

Proton Simulations



F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

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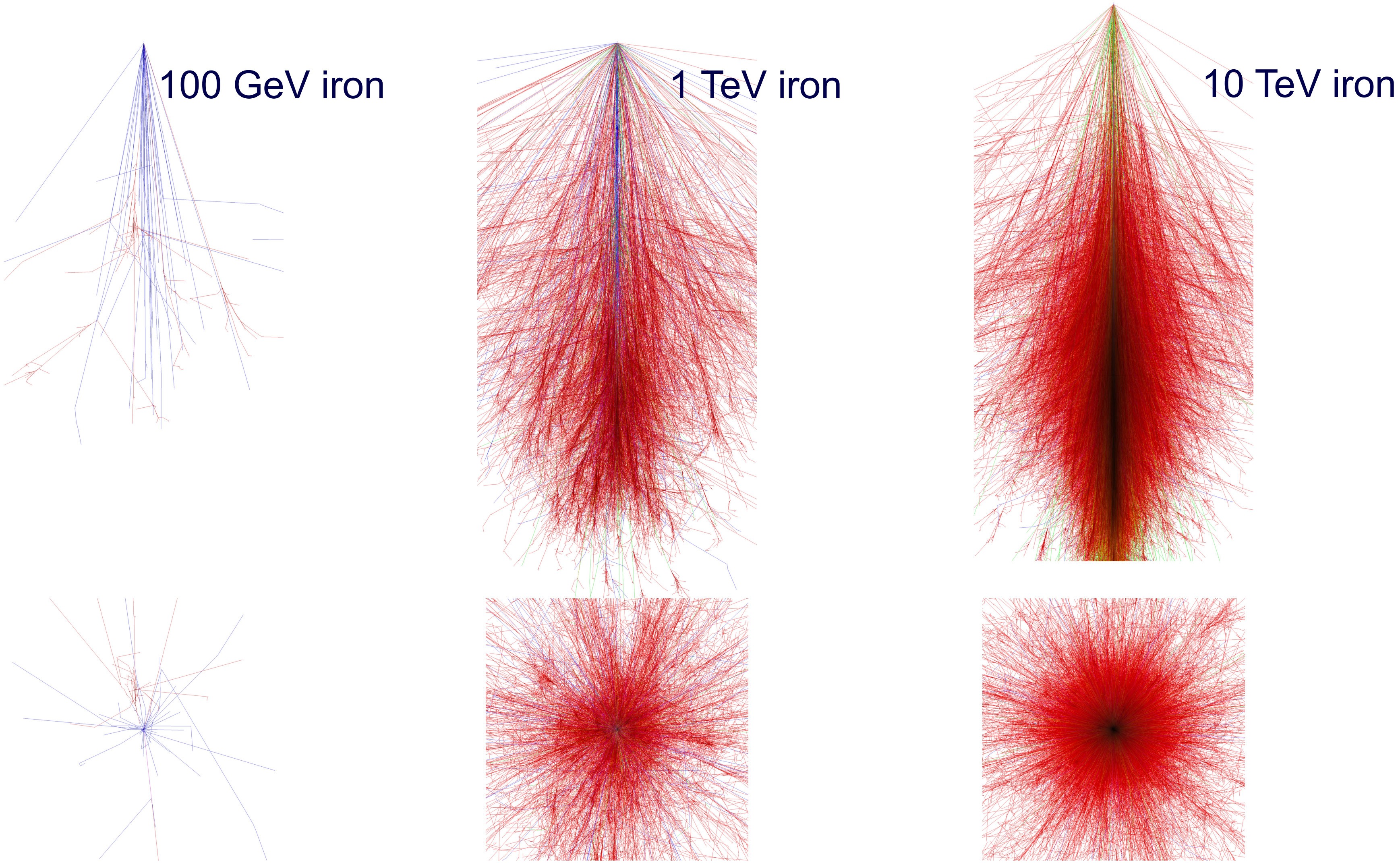
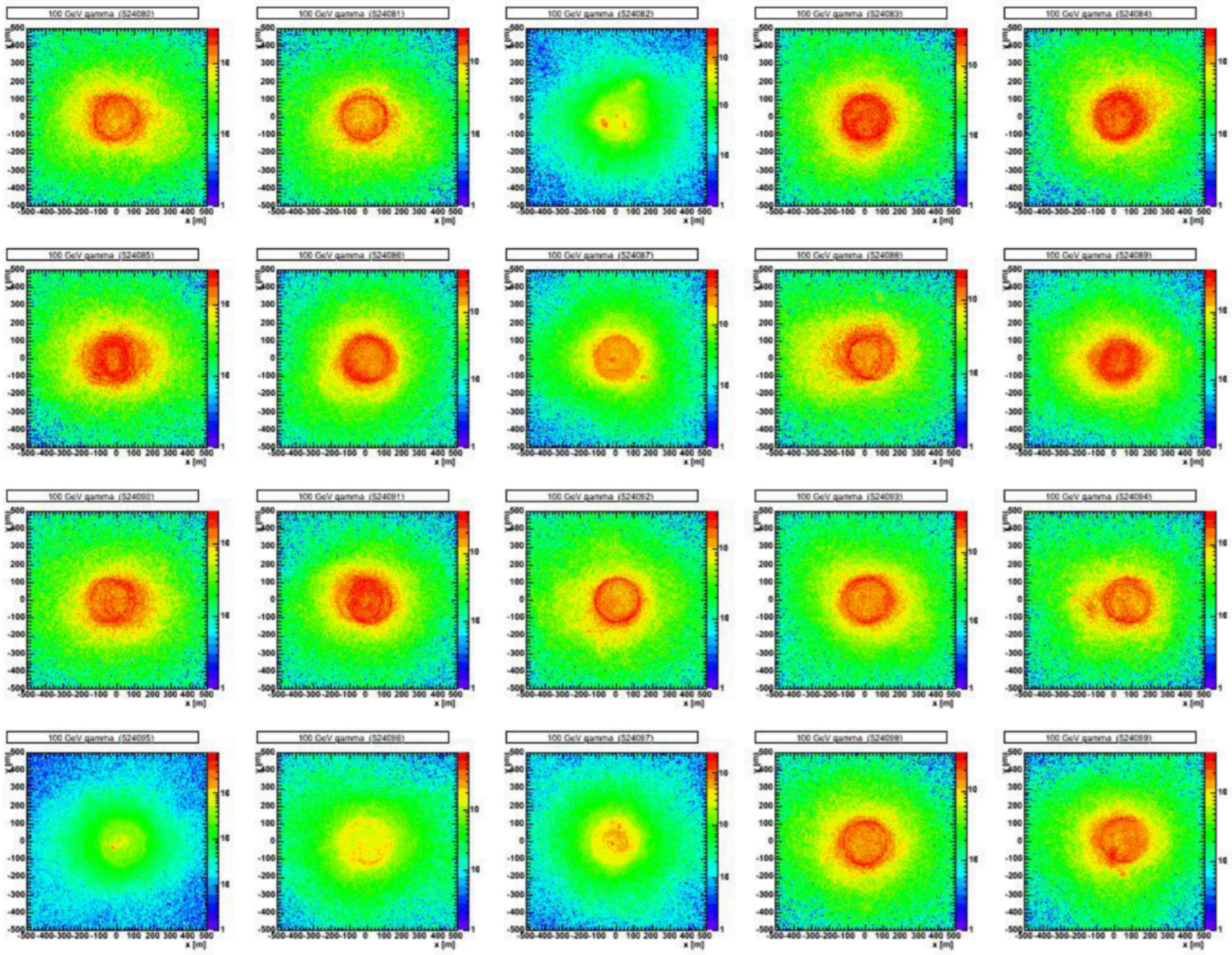
Iron Simulations



F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005, https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html

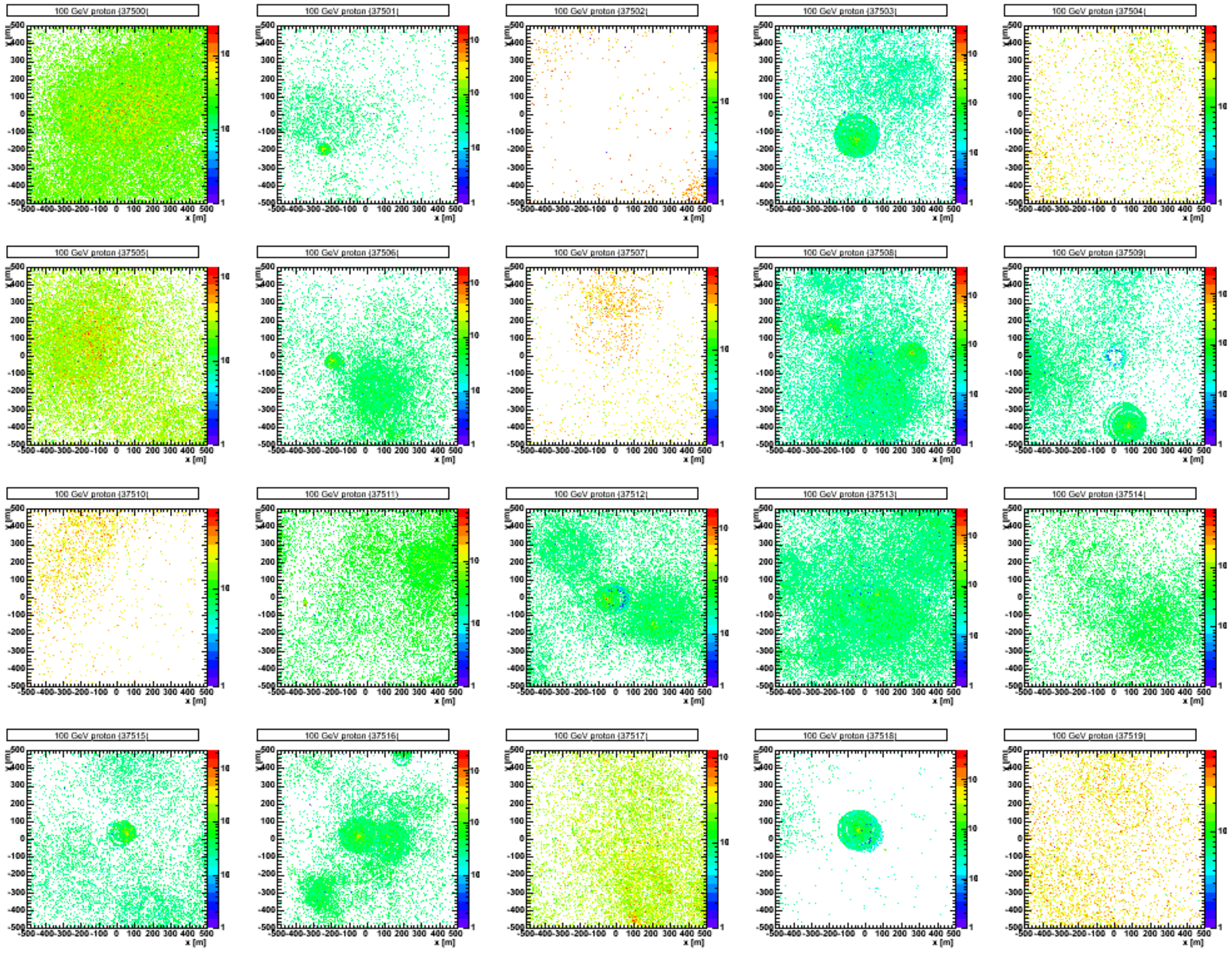
Cherenkov light on the ground

100 GeV gamma-ray



Cherenkov light on the ground

100 GeV proton



© G. Maier Gamma Picturebook

Outline

Day 1: Introduction

- Basic considerations
- Detection principles
- Development of the field

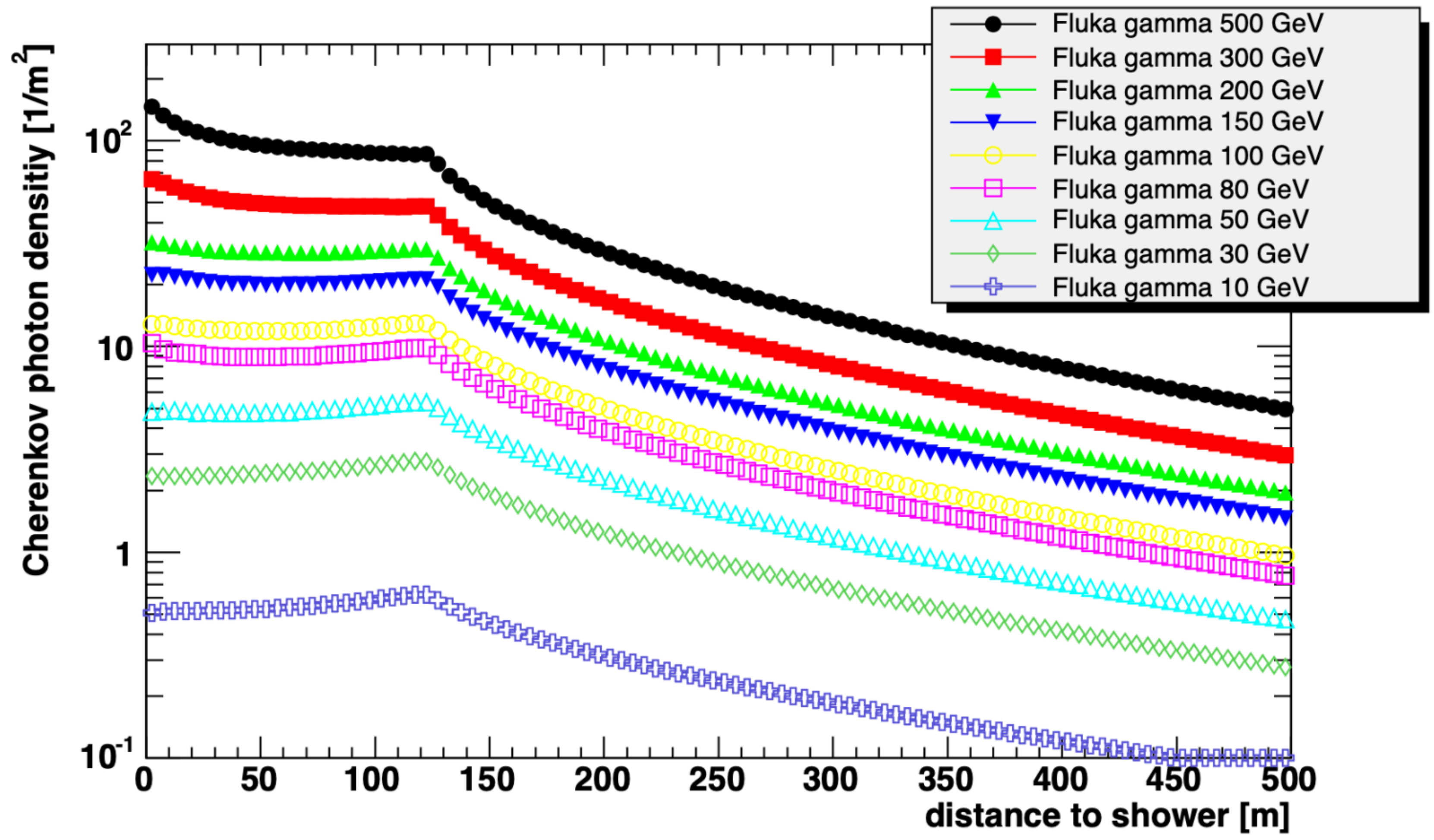
Day 2: Everything about Air Showers

- Particle interactions in matter
- Electromagnetic & hadronic air showers
- Air-shower simulations

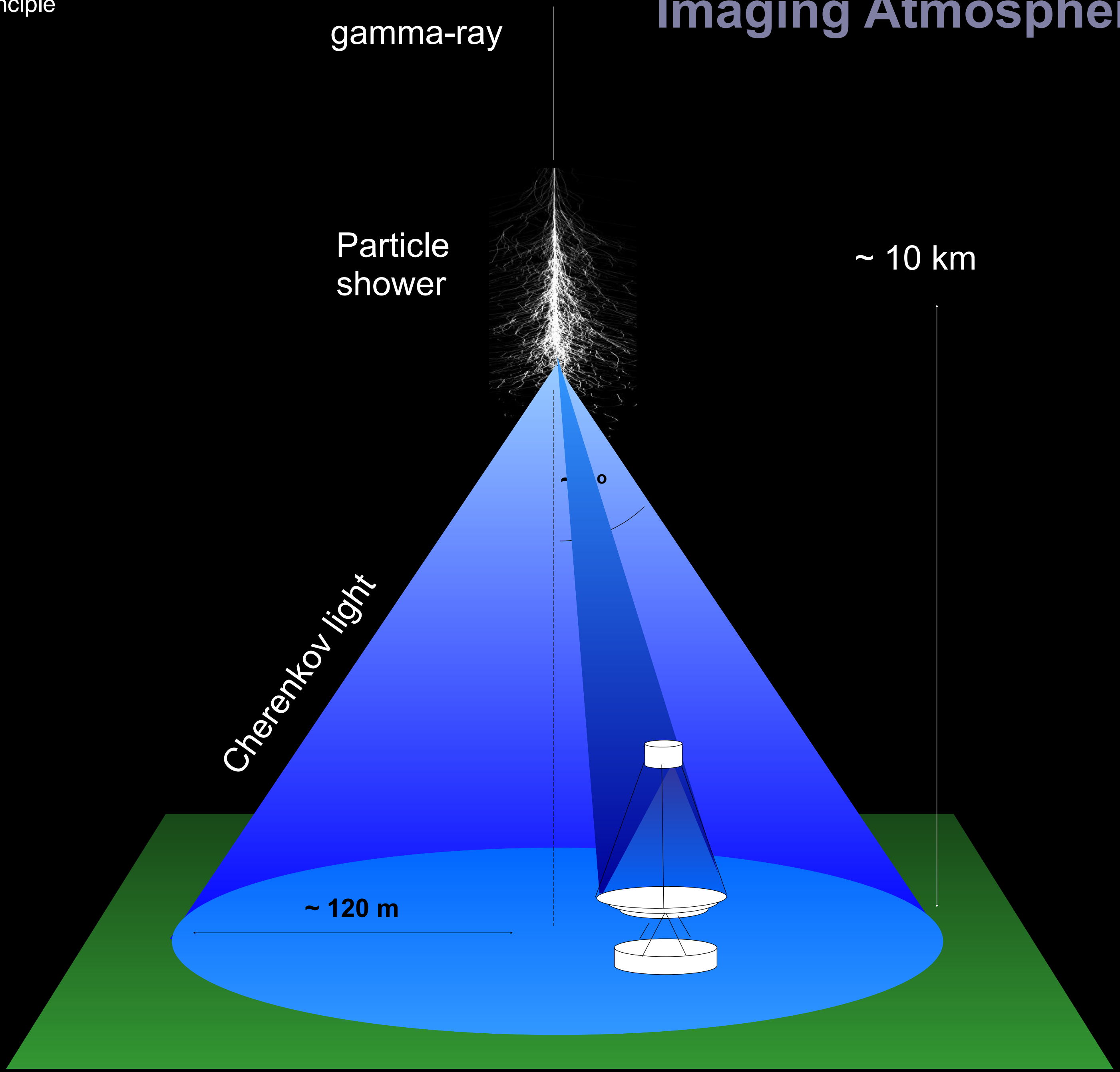
Day 3: IACTs

- The IACT principle
- Gamma-hadron separation & backgrounds
- Current and future instruments & their sensitivities

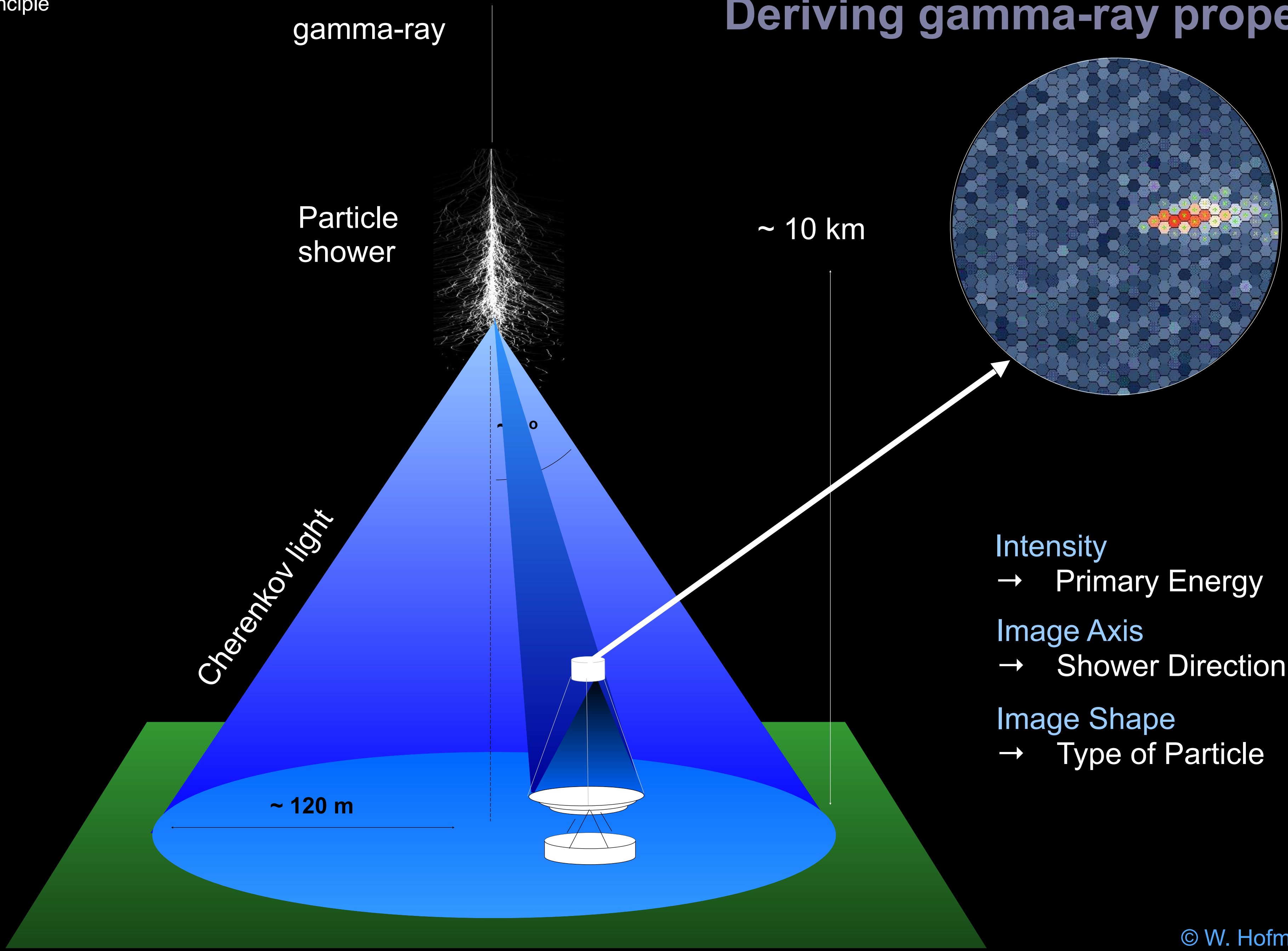
Cherenkov light on the ground



Imaging Atmospheric Cherenkov Telescopes



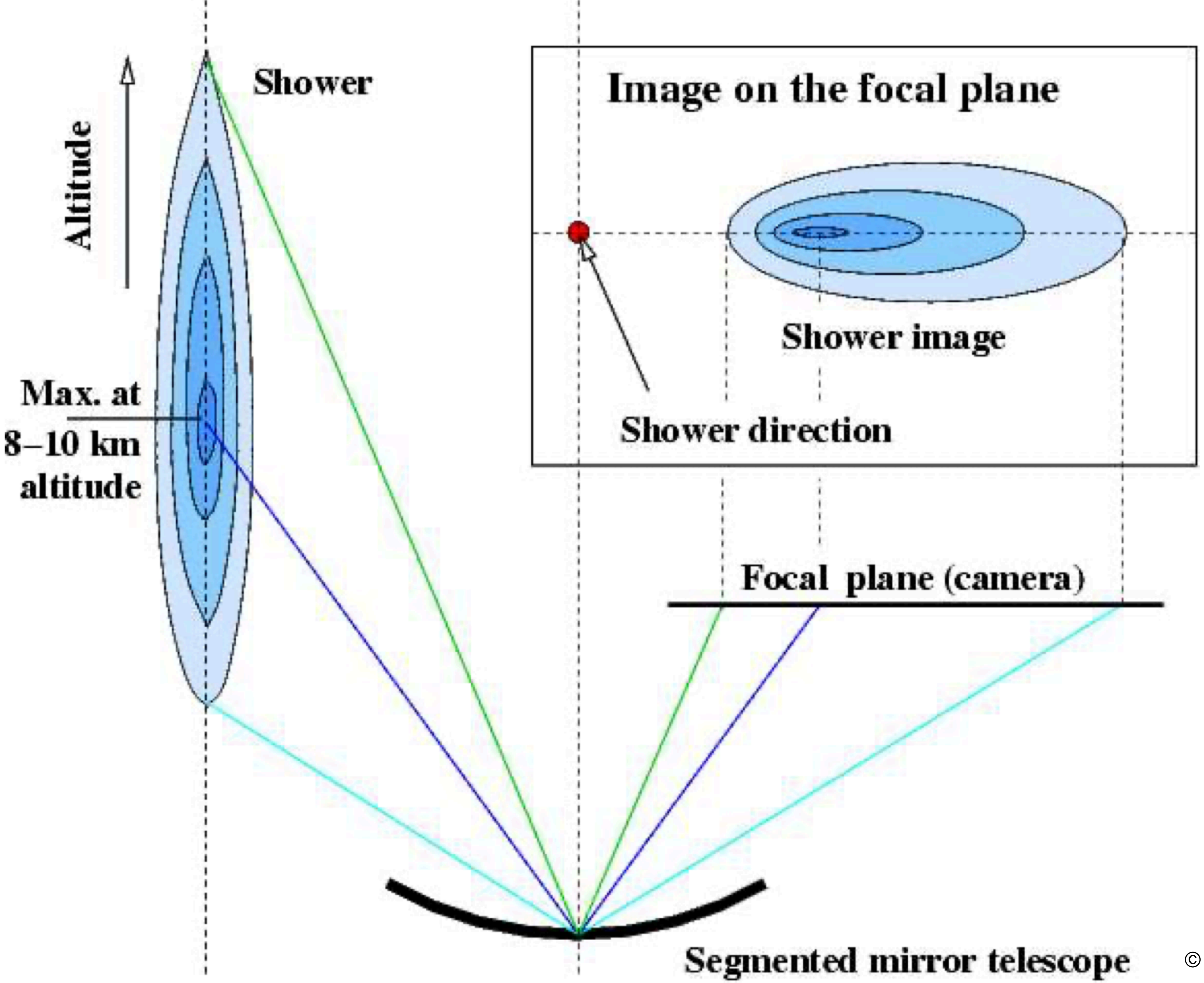
Deriving gamma-ray properties



Intensity
→ Primary Energy

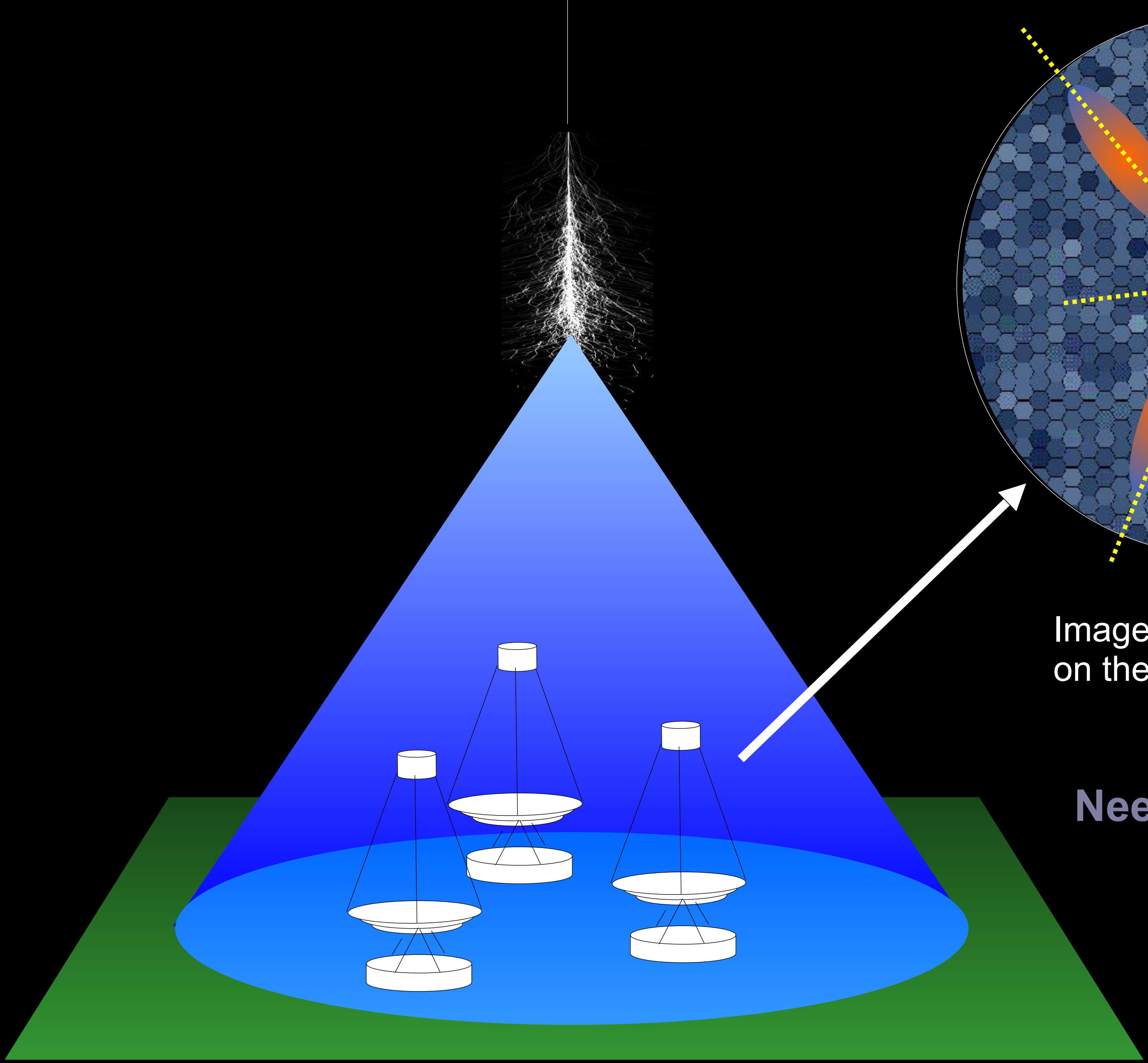
Image Axis
→ Shower Direction

Image Shape
→ Type of Particle


Shower
Altitude
Max. at
8–10 km
altitude
Image on the focal plane
Shower image
Shower direction
Focal plane (camera)
Segmented mirror telescope

© K. Bernlöhr

Stereoscopy for better direction reconstruction



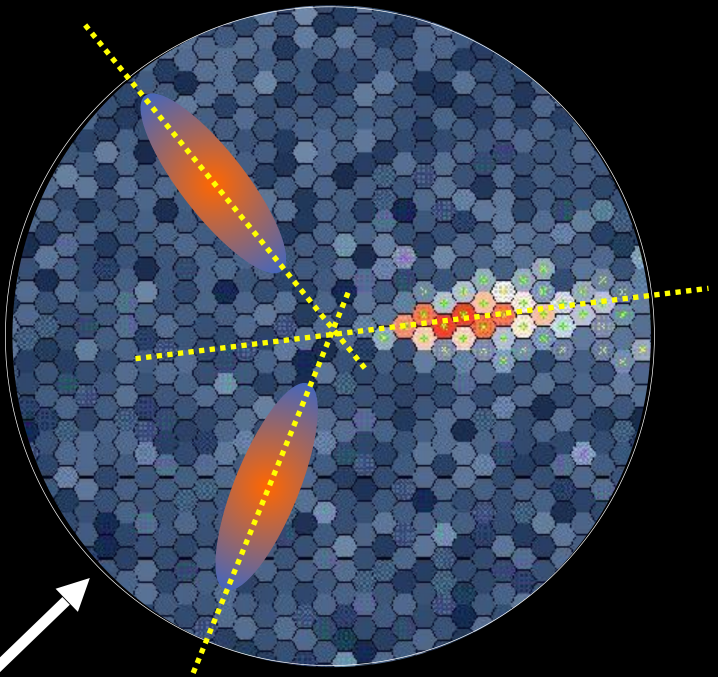
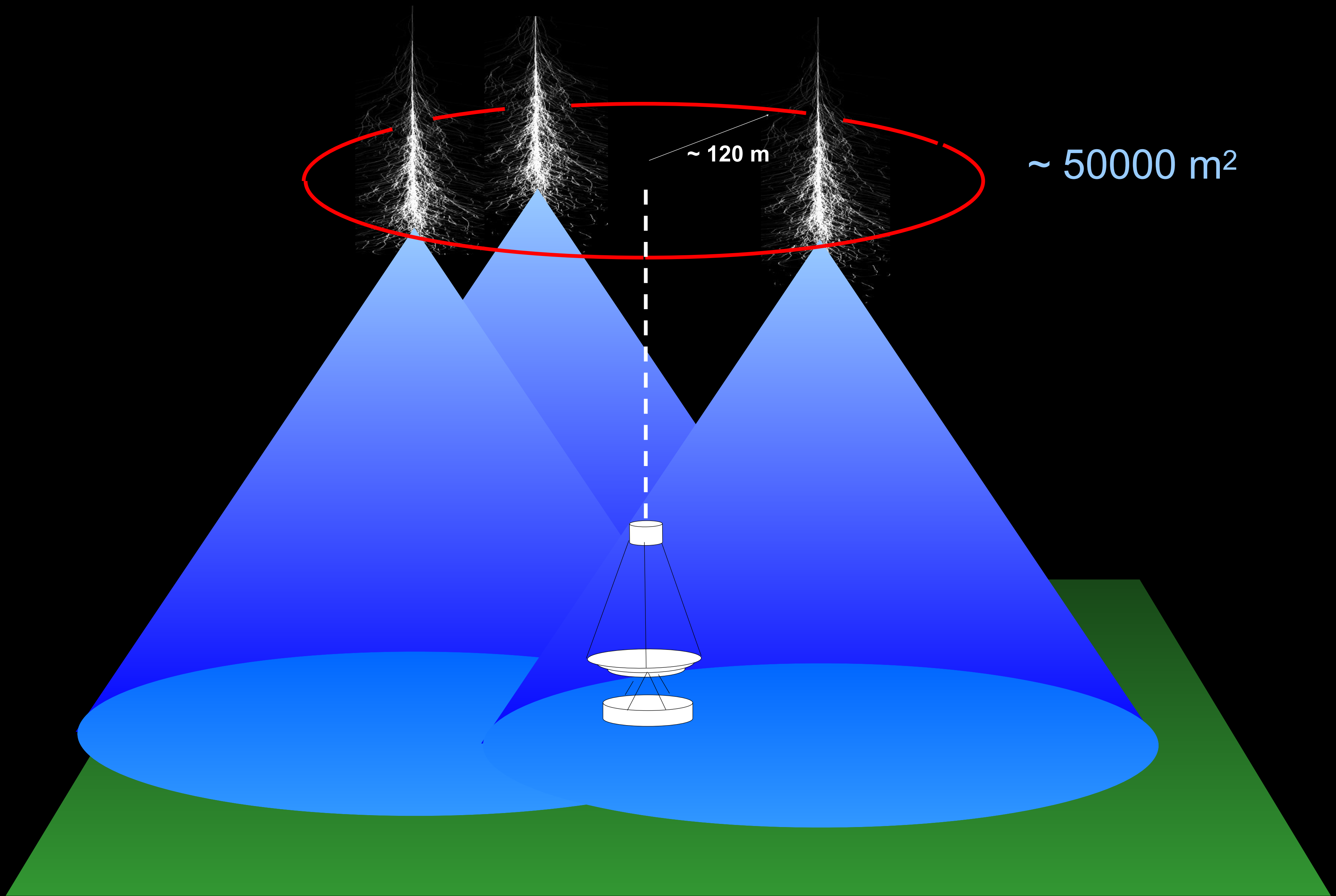


Image of source is somewhere on the image axis …

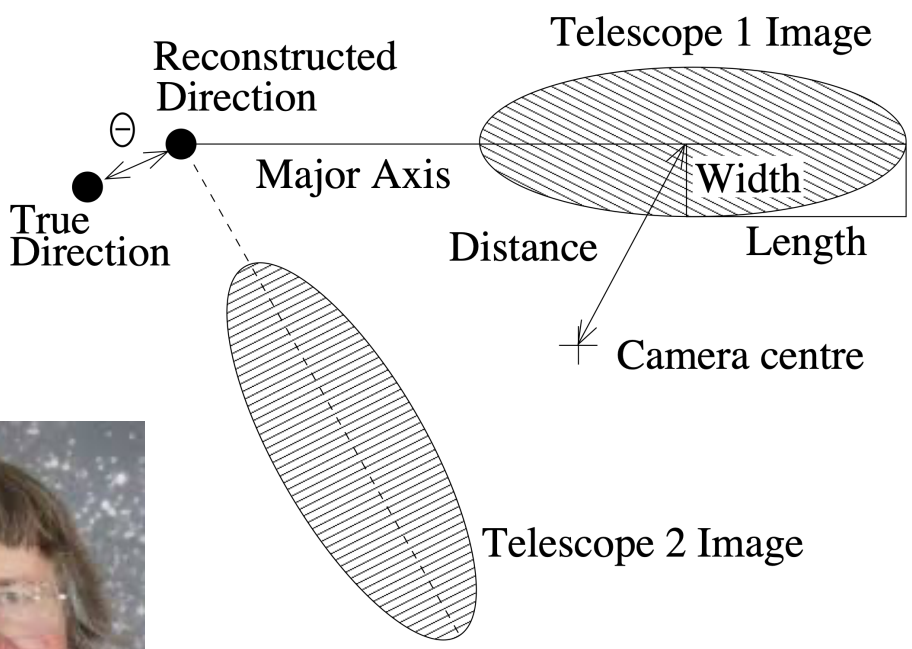
Need several views !

Detection area for Cherenkov telescopes



Reconstruction: Hillas Parameters

[the classical approach, robust and simple]



Michael Hillas
1932 - 2017

- In first approximation, elmag shower images are elliptical
- Fit gives width, length, distance, size

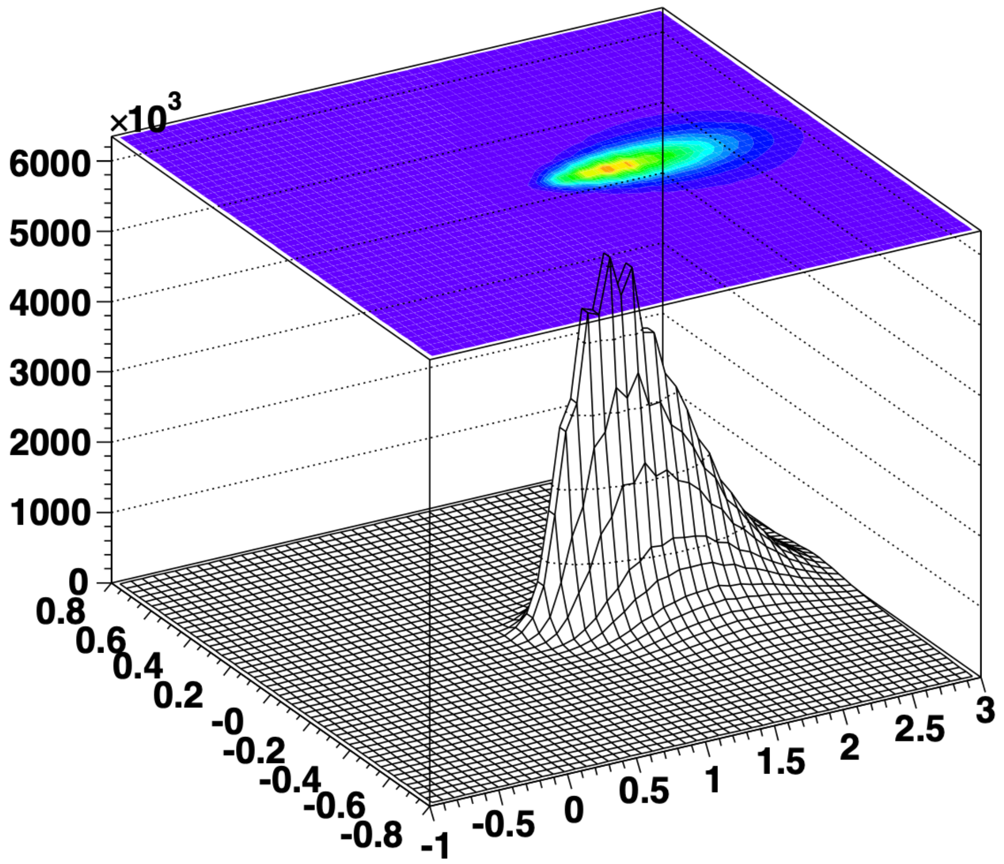
Reduction of shower image to a few parameters

- Comparison with (tabulated) simulations gives derived parameters like *mean scaled width*

$$MSCW = \frac{1}{N_{tel}} \sum \frac{width_i - \langle width_i \rangle_{MC}}{\sigma_i}$$

Models of Shower Development

[the modern approach, computationally expensive and more sensitive]



With increasing computing power, we aim to make use of
all image information available

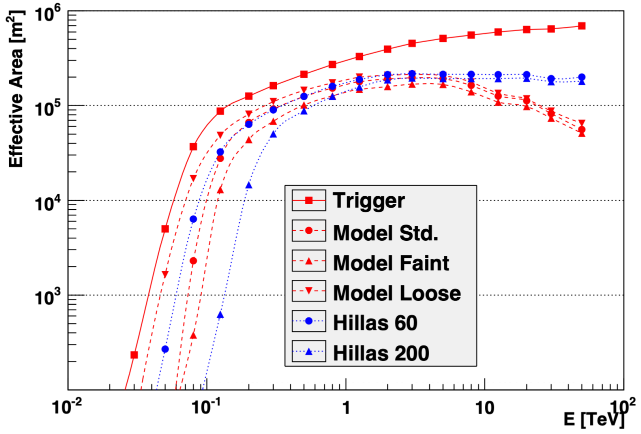
use models: either semi-analytical or entirely simulation based

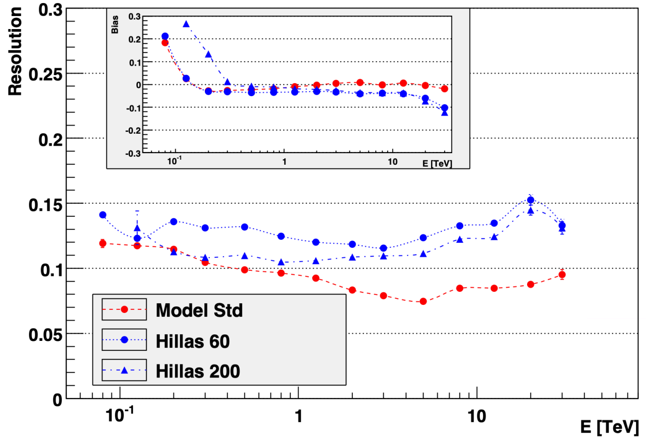
Shower templates as function of energy, impact distance, primary interaction depth and zenith angle (interpolate)

Pixel per pixel comparison of observed intensity with shower model in a likelihood fit

Models of Shower Development

[the modern approach, computationally expensive and more sensitive]





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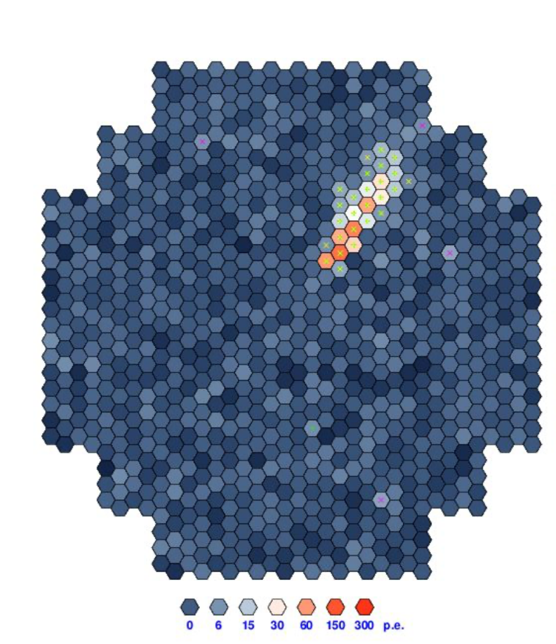
Shower templates as function of energy, impact distance, primary interaction depth and zenith angle (interpolate)

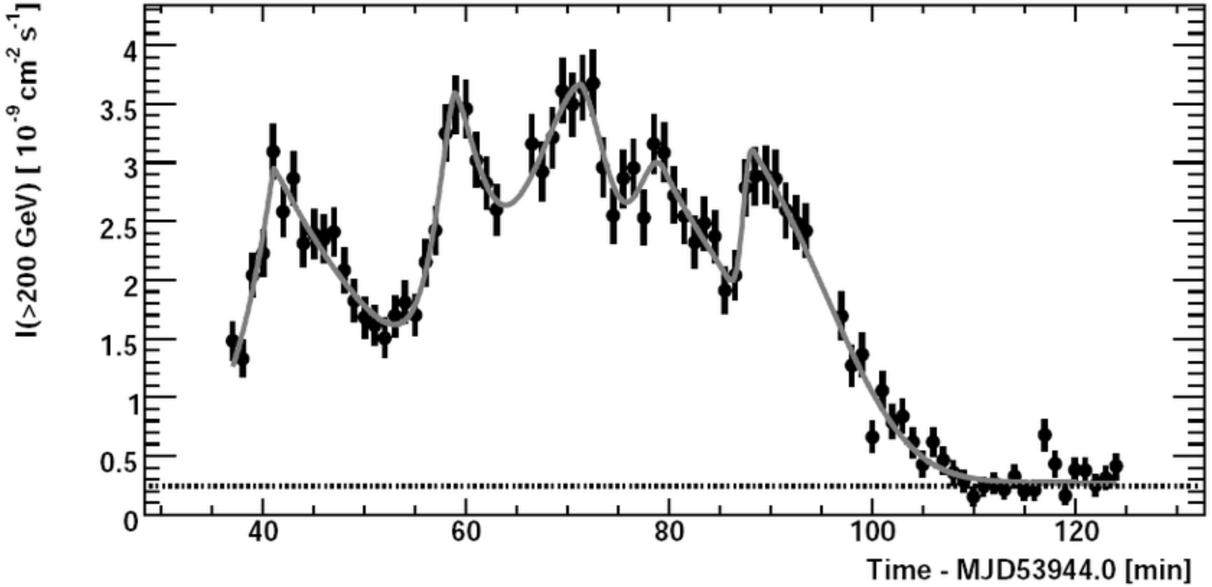
Pixel per pixel comparison of observed intensity with shower model in a likelihood fit

From Measurement to Physics



Counts as function of reconstructed energy, direction and time

?



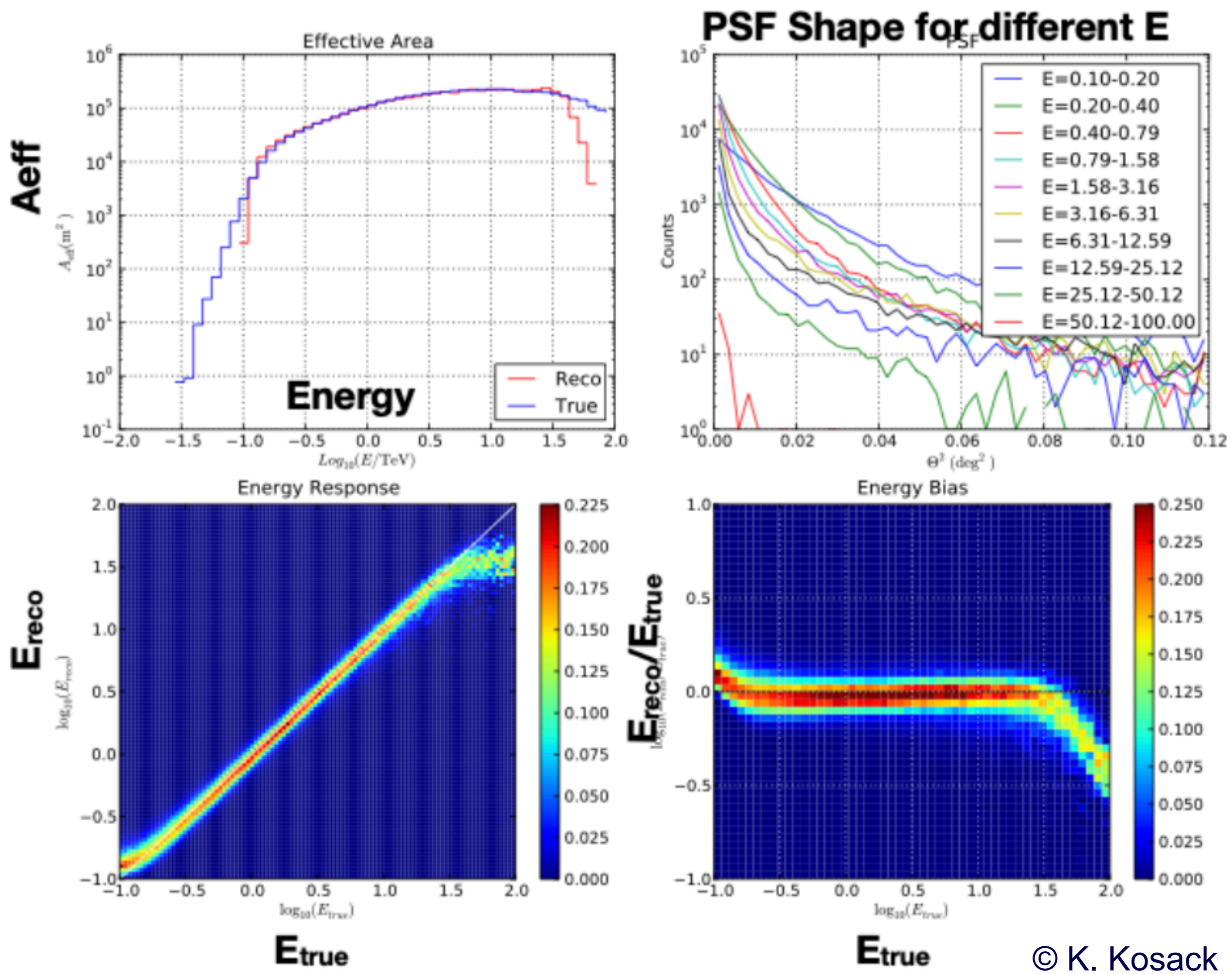
Flux as function of true energy, direction and time

Instrument Response Functions enable transition from measured to true quantities

Generated from air-shower simulations where you have both the measured and the true quantities!

Instrument Response Functions

- Point Spread Function
  - what is the system response to a perfect point in space?
- Energy Migration Matrix
  - what is the system response to a mono-energetic source?
  - consists of energy bias and energy resolution
- Effective Area
  - how many gamma-rays are really detected in a certain area?



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Cosmic-Ray Background

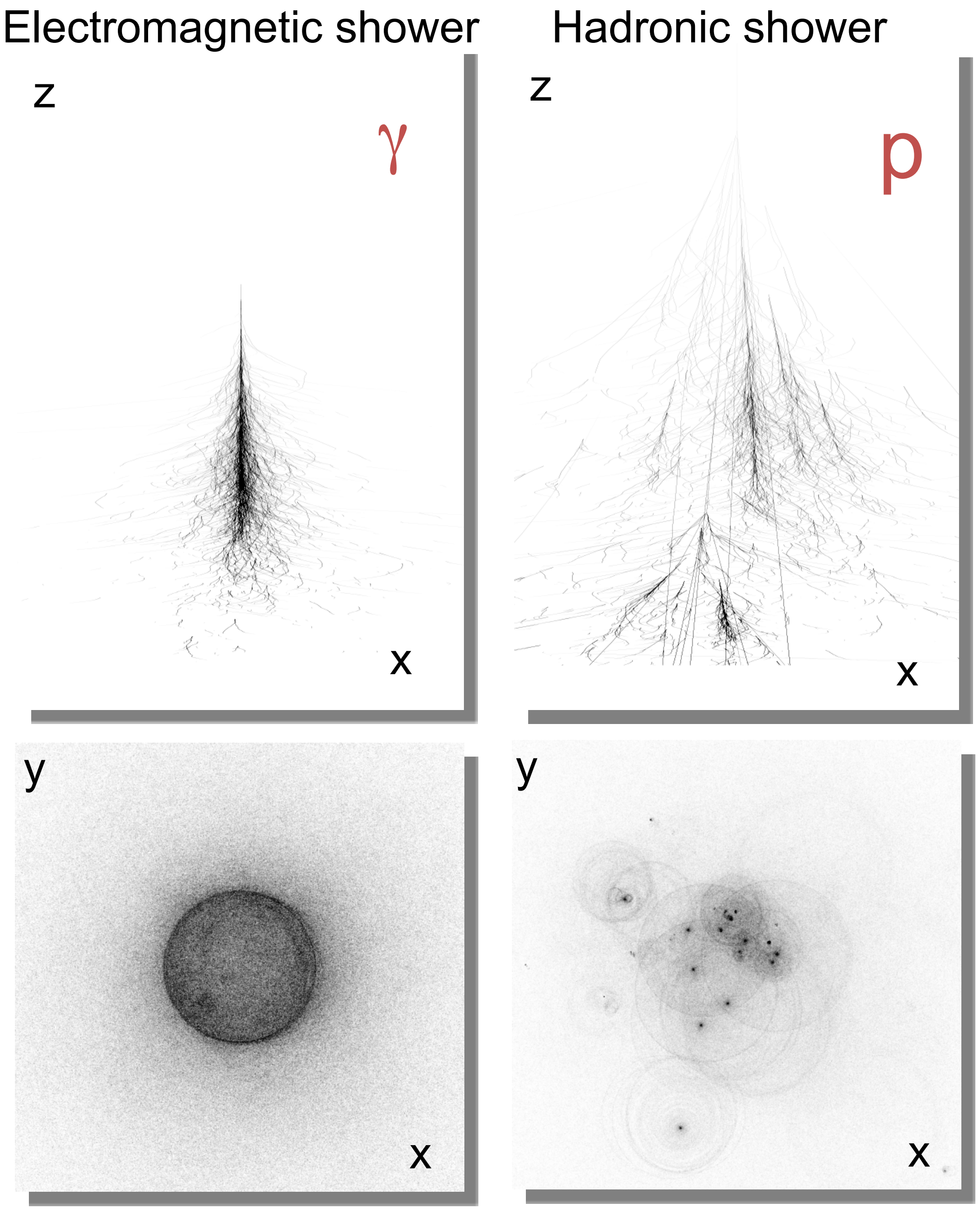
How many photons do we see at 1 TeV? How many at 10 TeV?

For simplicity, consider a pure power law with C = 3.45 10^{-11} cm^{-2} s^{-1} TeV^{-1} and spectral index 2.6

- at 1 TeV: **~0.03 photons per square metre and day**!
- at 10 TeV: ~0.0001 photons per square metre and day
- in comparison, a CR proton has C ~ 10^{-5} cm^{-2} s^{-1} sr^{-1} TeV^{-1}, giving **10 000 particles per square metre and day**
- within 0.1 deg radius: **0.1 particle per square metre and day**

The number of cosmic-ray showers in a given region of the sky can be orders of magnitude more than for gamma rays

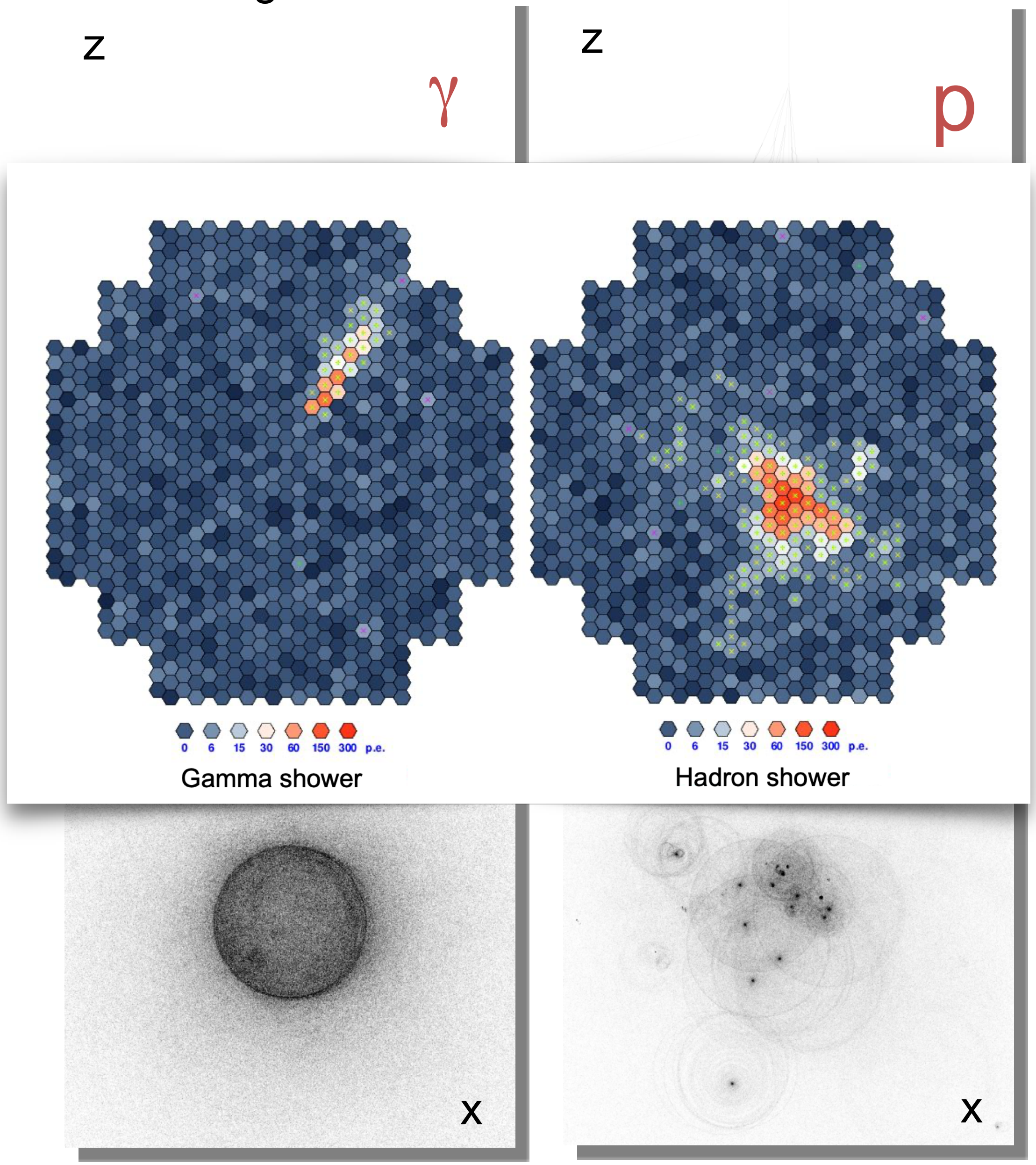
Rejecting them is critical

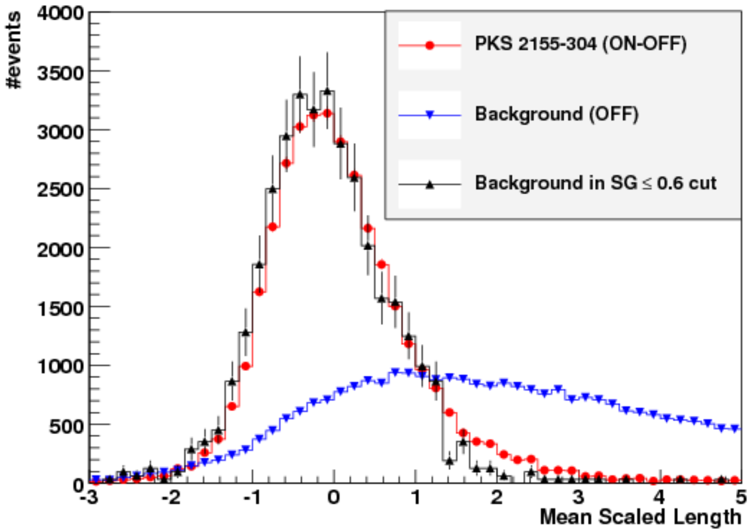


Electromagnetic and hadronic showers look on average different

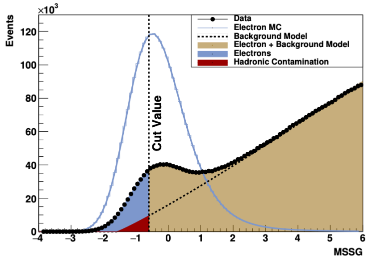
Use this difference to separate them

Electromagnetic shower | Hadronic shower

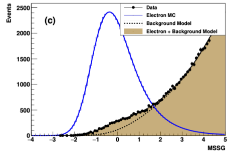




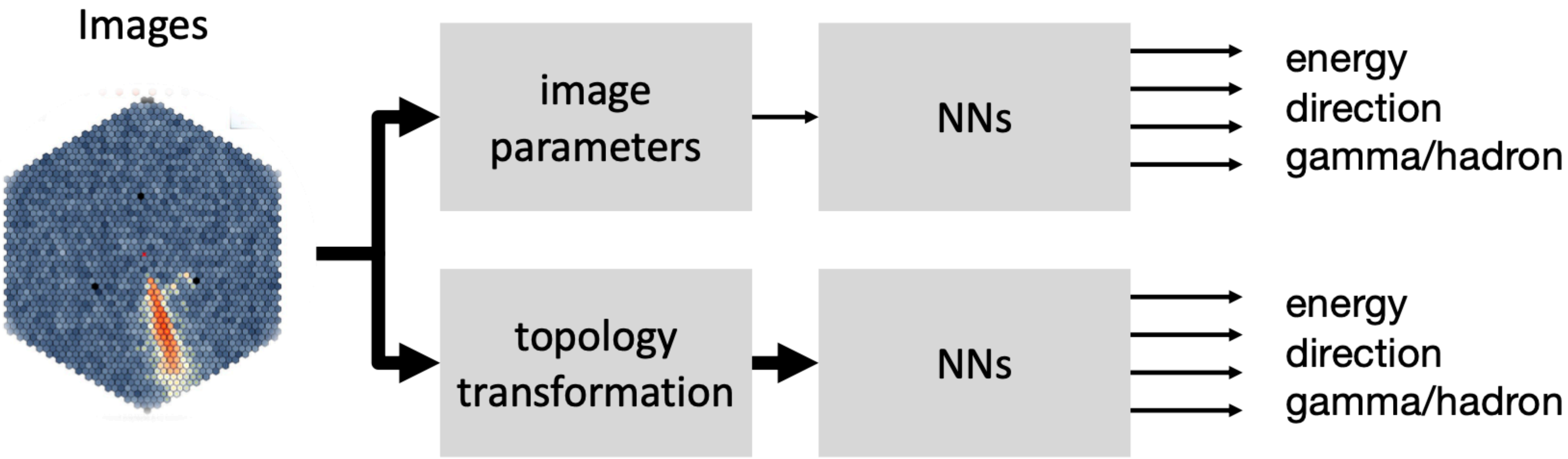
Width of the camera image (or the goodness of fit) normalised to corresponding value in simulations



Gamma-hadron separation

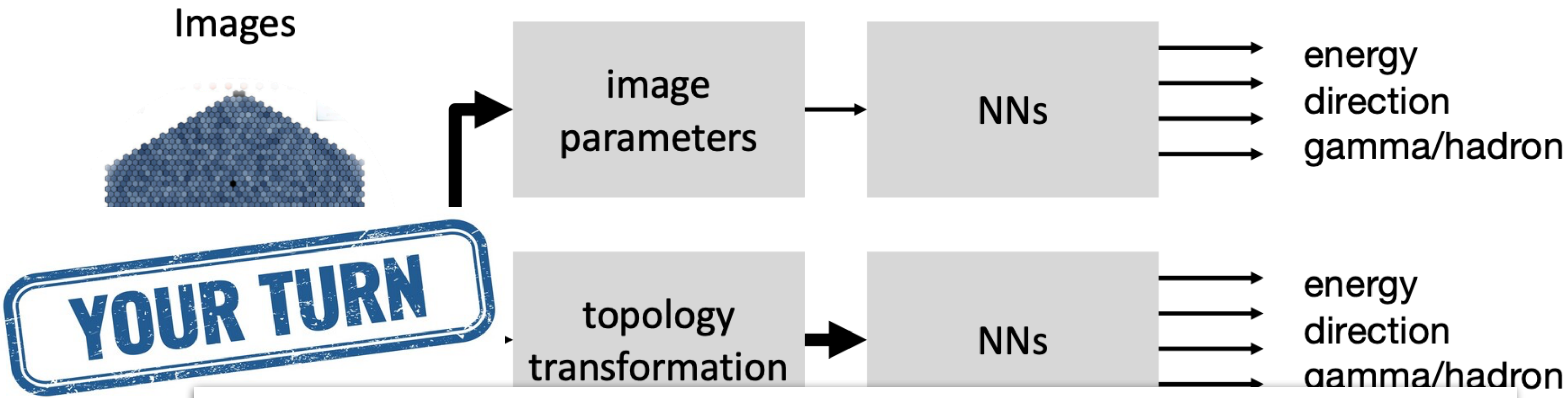


MACHINE LEARNING EVERYWHERE



- Setting up a NN and getting some output is easy
- Making it perform at least as well as classical methods is non-trivial
- Making it perform reliably and stable on real-world data is very hard work

MACHINE LEARNING EVERYWHERE



What do you think makes it so hard to apply a neural network to real-world data?

Which of the two approaches is more promising in terms of
(a) information content used
(b) reliability?

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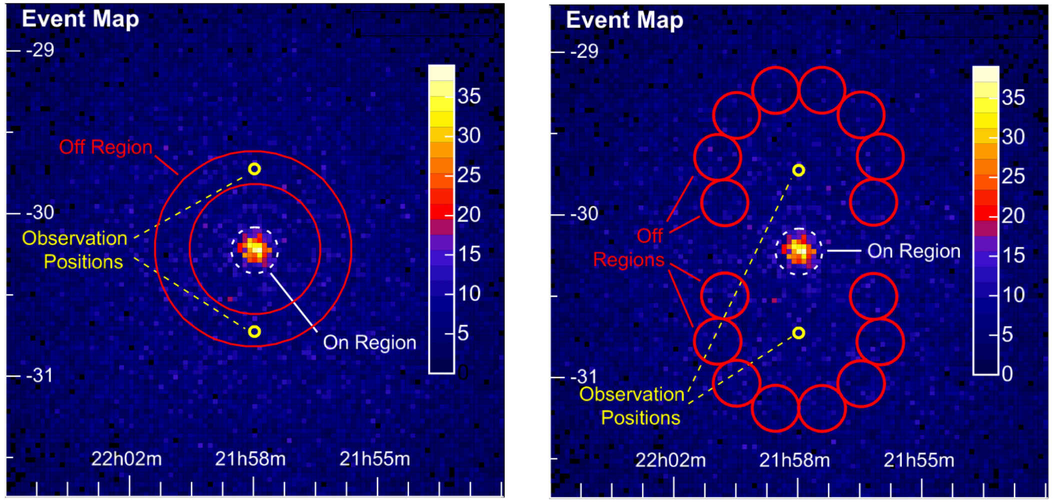
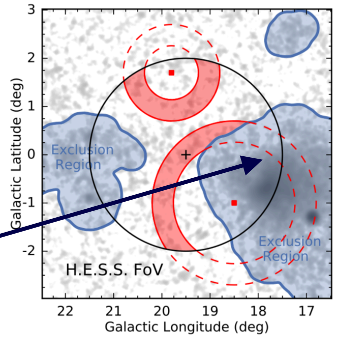
Background Subtraction

- Necessary because of imperfect gamma/hadron separation
- Performed in background measurements in the FoV (+ assumption on system response)
- Iterative exclusion of regions with gamma-ray emission
- *Advantage*: 1st order cancelation of systematics related to condition of instrument and atmosphere
- *Disadvantage*: Only moderately suited for larger regions, results in subtraction of signal together with the background



Background Modelling in Very-High-Energy γ-ray Astronomy

D. Berge[1,2], S. Funk[1,3], and J. Hinton[1,4,5]

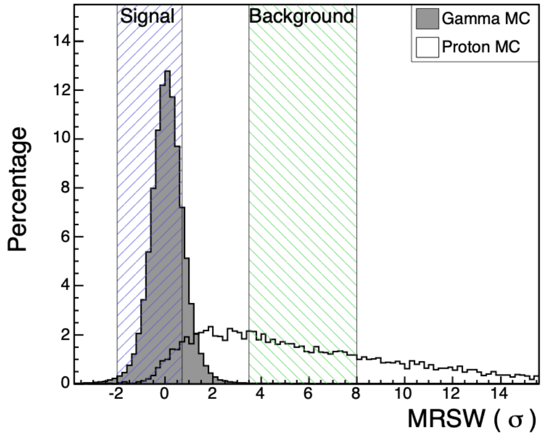


exclusion regions
= regions with gamma-ray emission

Alternatives

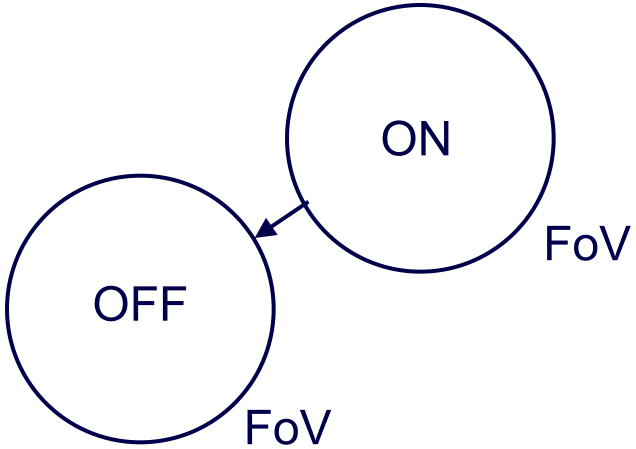
OFF regions in parameter space:

- still requires regions to determine the shape of the background distribution
- simulations? not very reliable



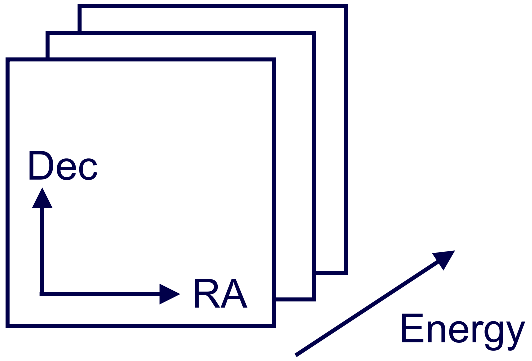
ON-OFF observations:

- go back in RA to observe dedicated OFF field
- duplicates observation time



Background Models

- Usage of old observations with no/easily excludable sources
- Use atmosphere calibration info and average over many blank fields in zenith and azimuth
- Control region in the field of view for verification/fitting
- Have a binned background model in 3D:
  2 spatial coordinates and energy

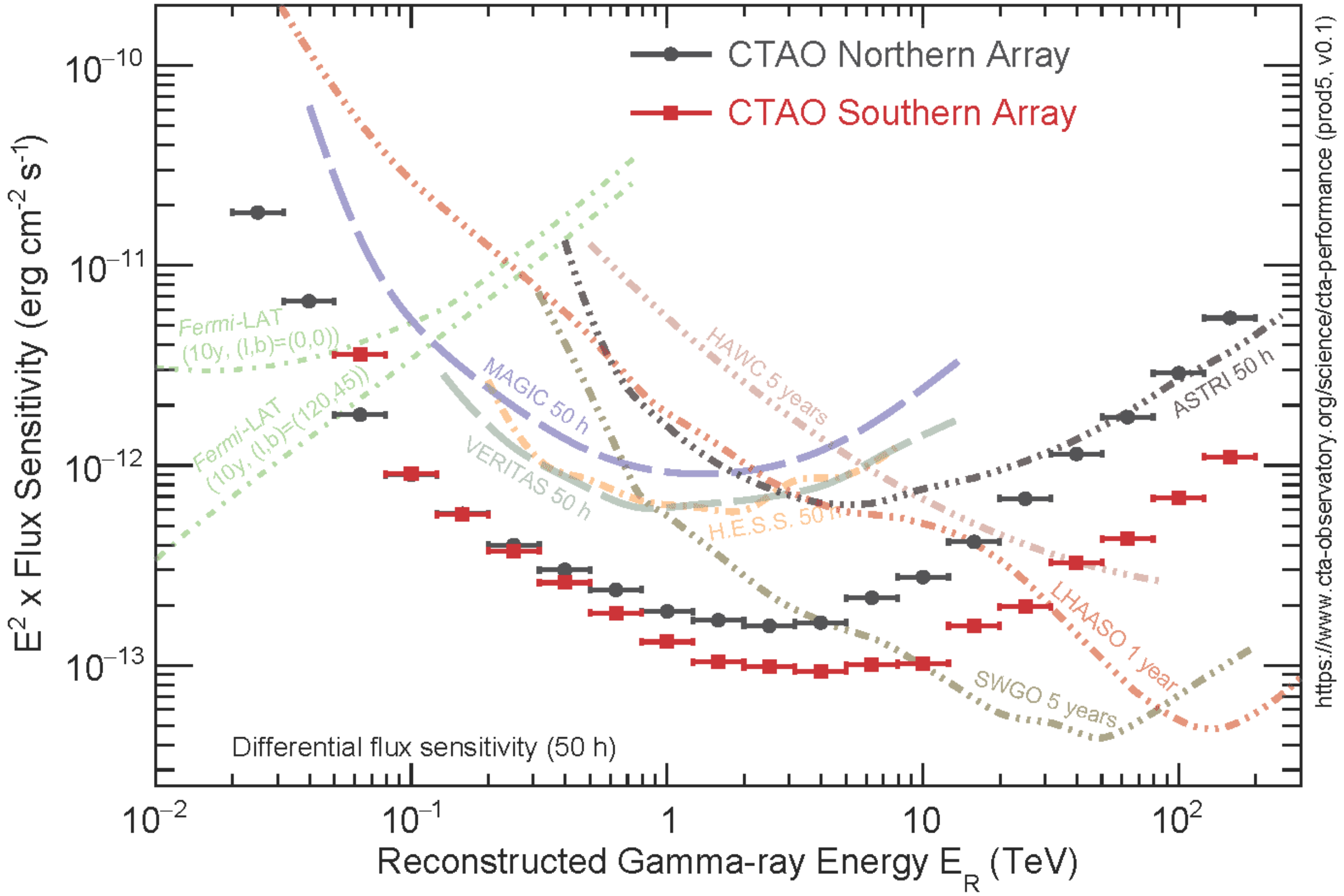


Sensitivities

Sensitivity curves serve as easy figure to compare between instruments

Which minimum flux is still significantly detectable in a certain time of observation

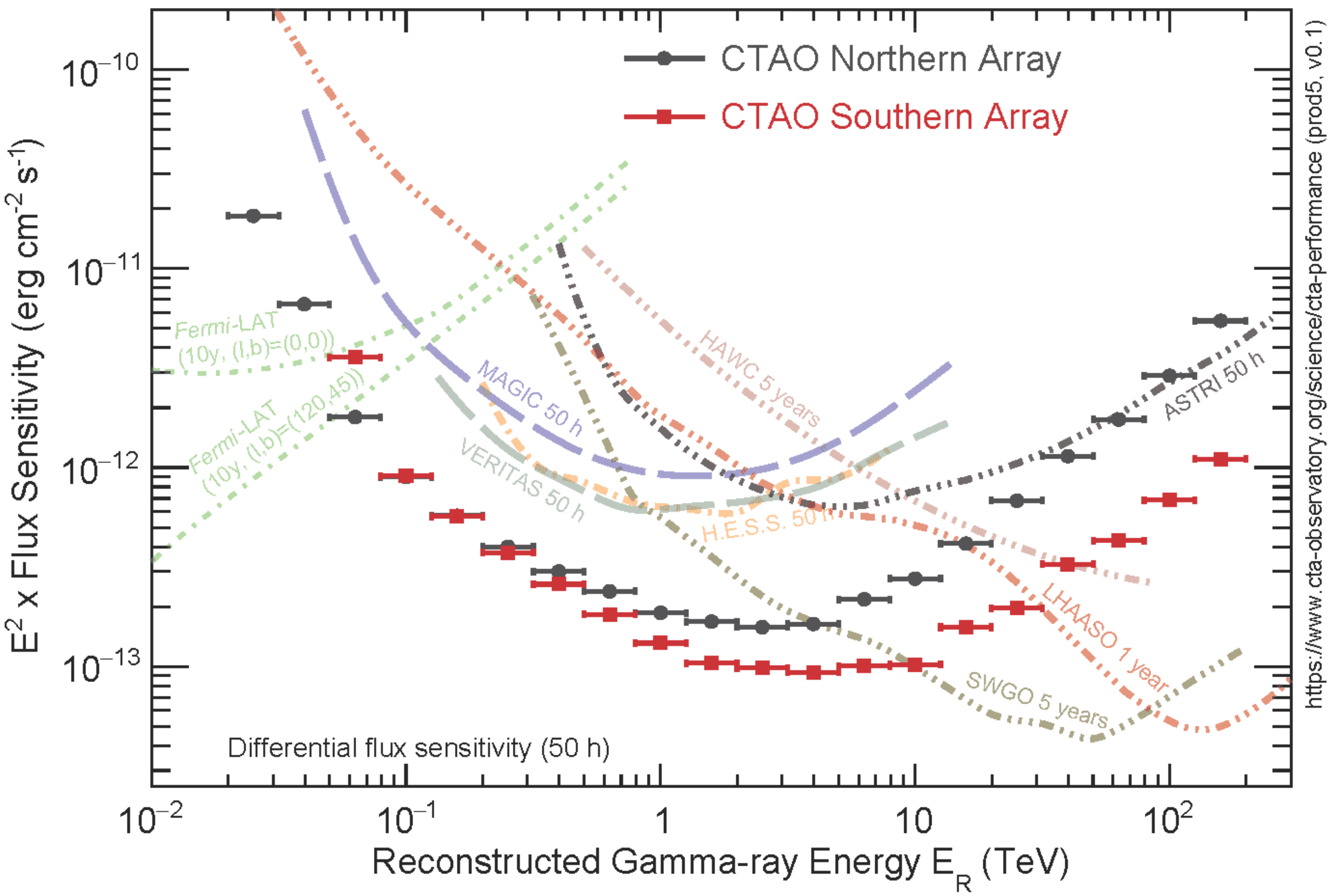
the lower, the better!



Sensitivities

Careful in the comparison of different instrument types → some element of arbitrariness

Does not reflect other performance indicators like resolution



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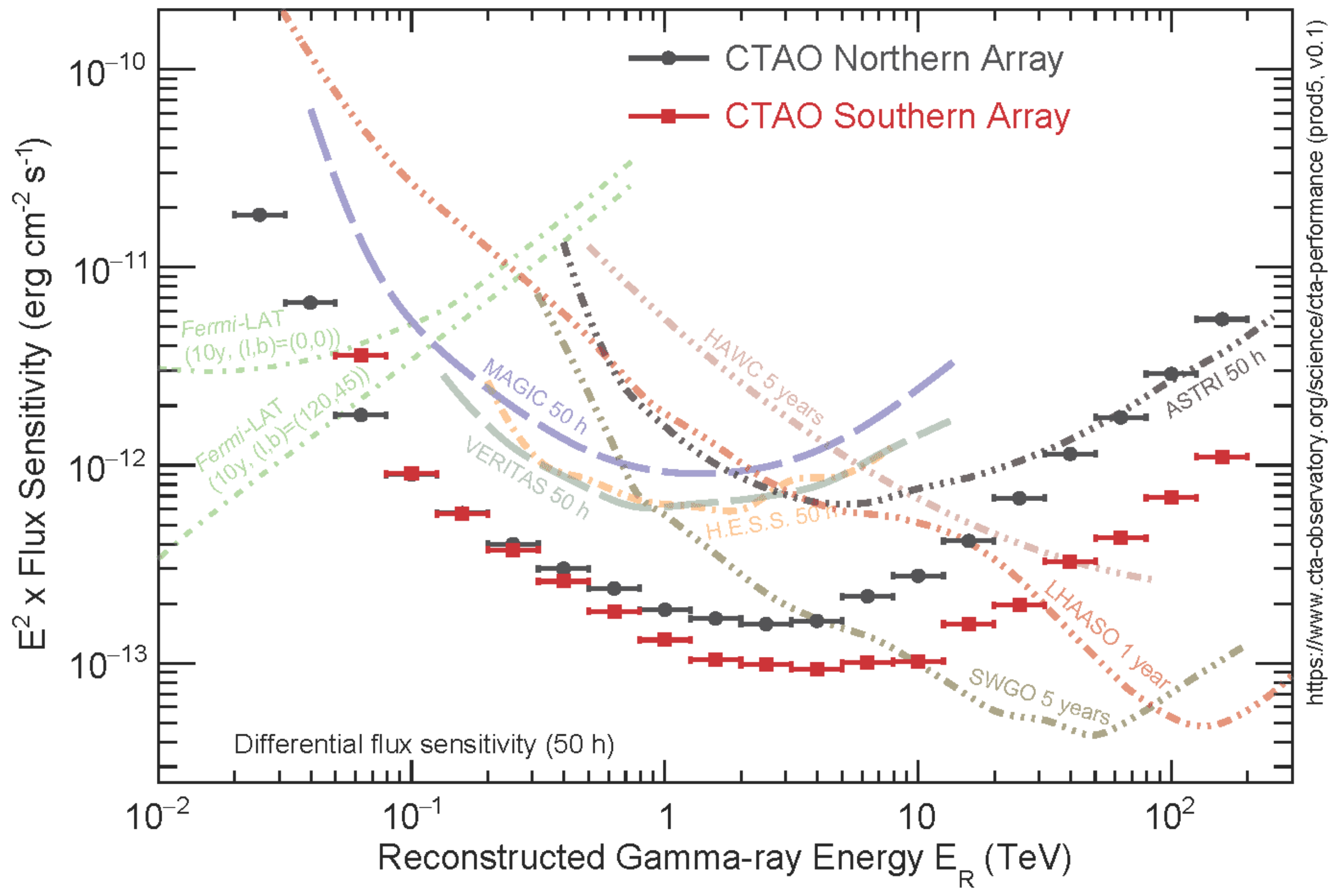
Sensitivities

at low energies: trigger on upward fluctuations

at intermediate energies: background-limited region

in first order S ~ signal/bkg$^{1/2}$

at high energies: statistics-limited region



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Sensitivity for IACTs and PDAs

YOUR TURN

Assume that in 20 hours we can detect a point-like source significantly in the background-limited regime with an angular resolution of 0.1deg. How does this time change if we have an angular resolution of 0.5 deg like many particle detector arrays?

Is this relevant, given the different observation modes of IACTs and PDAs?

Discuss: Which advantages do you see for IACTs for the observation of time-variable point-like sources and for steady and extended sources?

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Sensitivity for IACTs and PDAs

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Discuss: Which advantages do you see for IACTs for the observation of time-variable point-like sources and for steady and extended sources?

- The new background count per time is $n_{bkg} = (0.5deg/0.1deg)^2\ n_{bkg,0} = 25\ n_{bkg,0}$
- If $n_{signal,0}/sqrt(n_{bkg,0})$ is not supposed to change, we need to increase the time by factor of x: $n_{signal,0}/sqrt(n_{bkg,0})\ != n_{signal,0}*x\ /\ sqrt(25\ n_{bkg,0}\ *x)$
- Solving for x gives x/sqrt(x) = sqrt(25) -> x = 25, t = x*20 hours = 500 hours

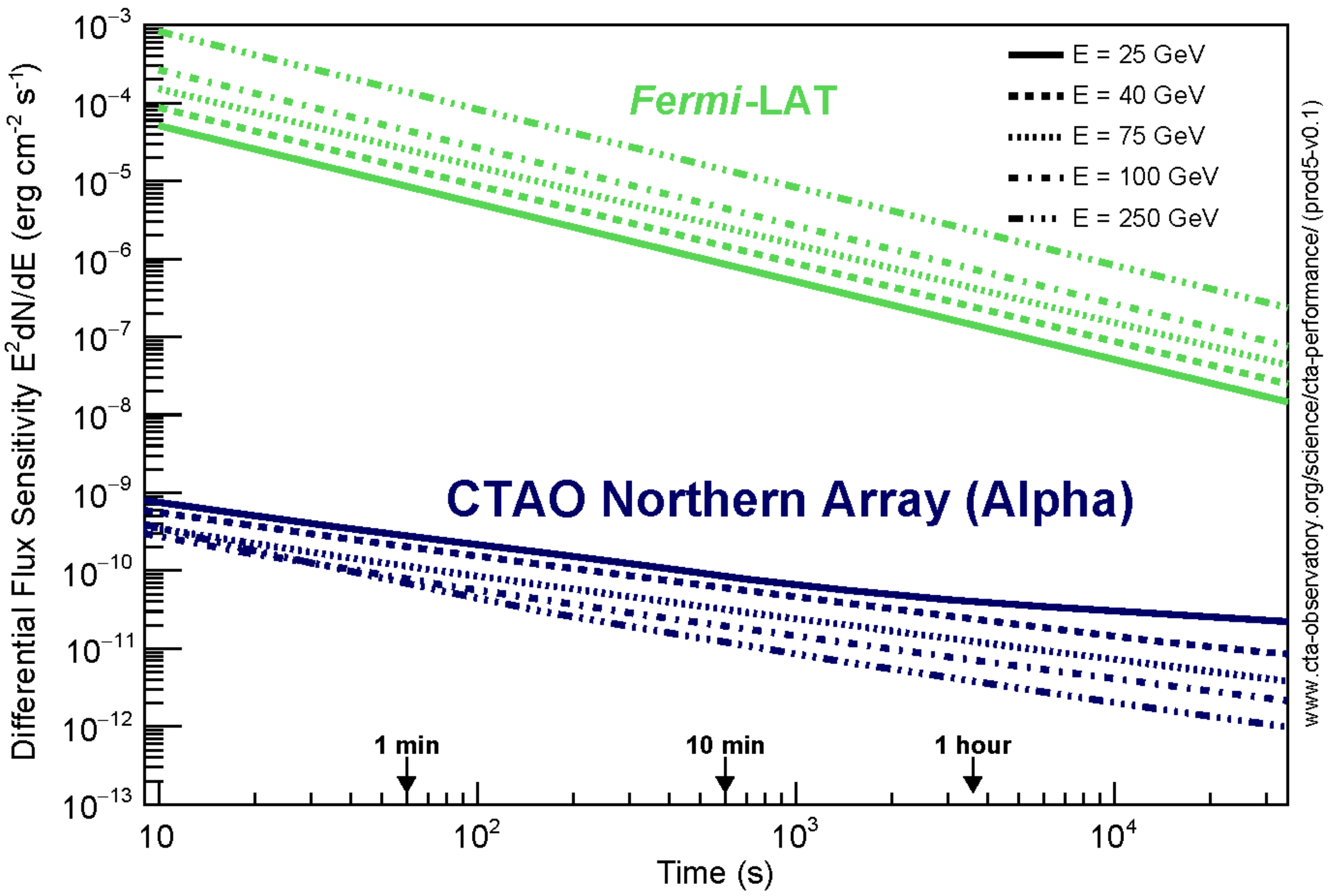
Sensitivities

Alternative way of looking at things:

sensitivity vs. time

Demonstrates the possibilities to do time-resolved astrophysics at a fixed energy

transient phenomena



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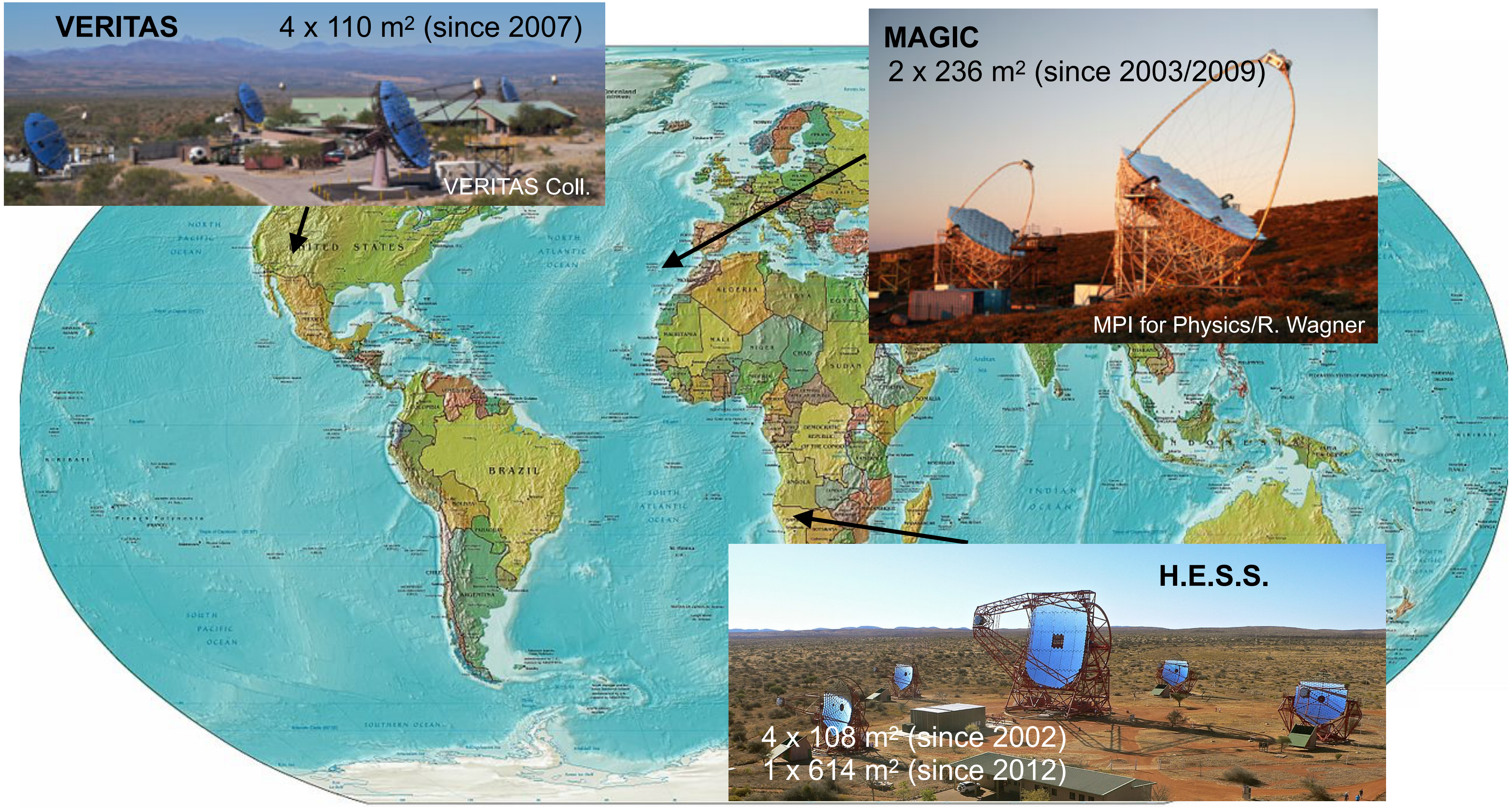
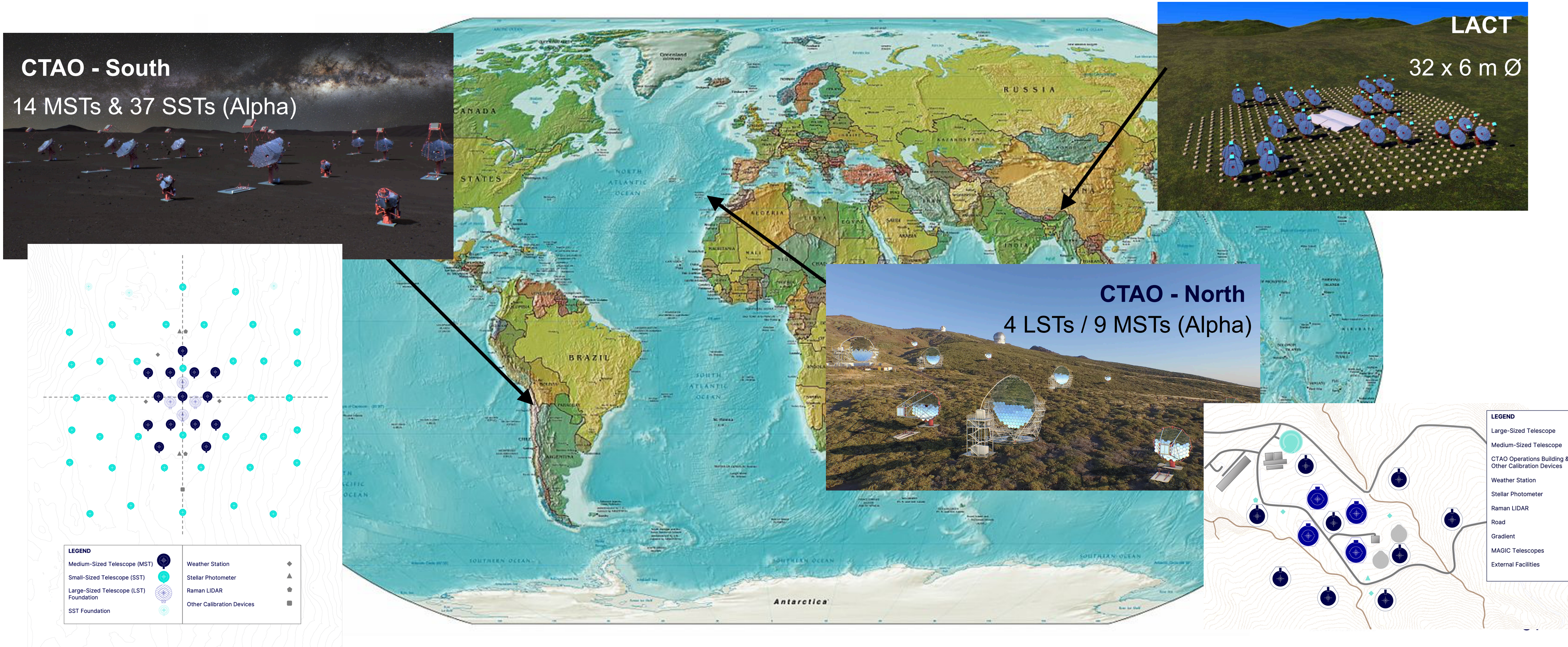
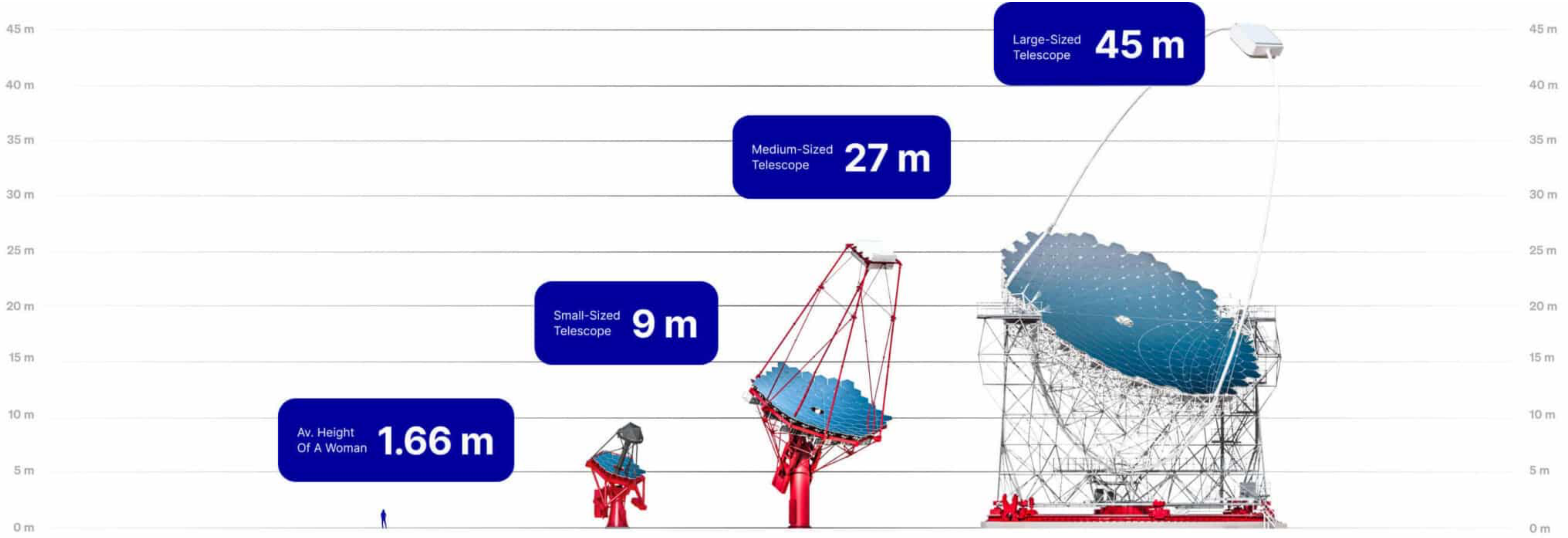
Current IACT Instruments



Next-Generation IACT Instruments



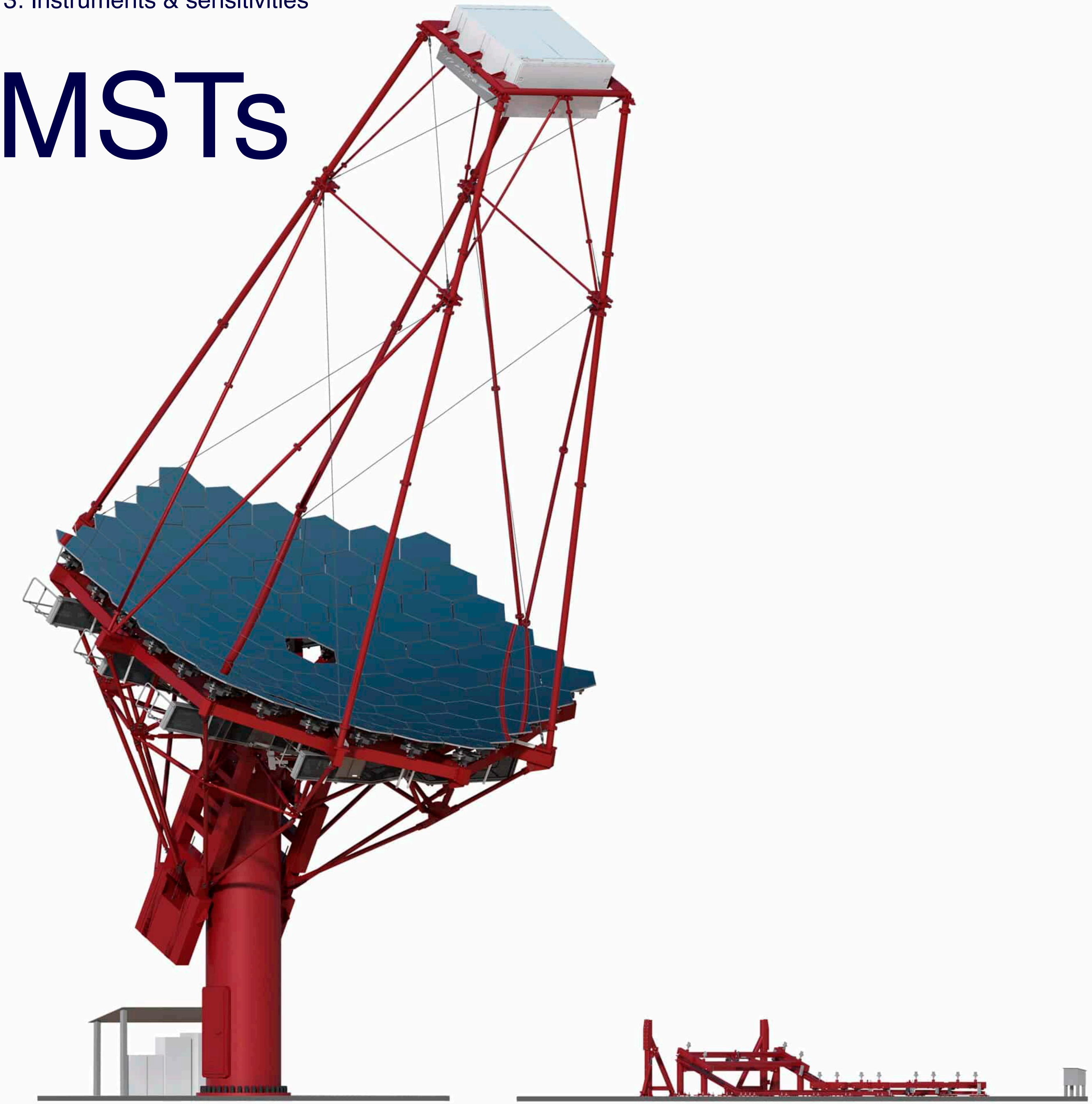
Different telescopes for a larger dynamical range



SSTs

	Small-Sized Telescope (SST)
Energy range (in which sensitivity is optimized)	2 TeV – 300 TeV
Number of SST telescopes	37 (South)
Optical design	Modified Schwarzschild-Couder
Primary reflector diameter	4.3 m
Secondary reflector diameter	1.8 m
Effective mirror area (including shadowing)	>5 m^2
Focal length	2.15 m
Total weight	17.5 t
Field of view	8.8 deg
Number of pixels	2048
Pixel size (imaging)	0.16 deg
Photodetector type	SiPM
Telescope readout event rate (before array trigger)	600 Hz
Telescope data rates (readout of all pixels; before array trigger)	2.55 Gb/s
Positioning time to any point in the sky (>30° elevation)	70 s
Pointing precision	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees

MSTs



	Medium-Sized Telescope (MST)
Energy range (in which sensitivity is optimized)	80 GeV – 50 TeV
Number of MST telescopes	14 (South) 9 (North)
Optical design	Modified Davies-Cotton
Reflector diameter	11.5 m
Effective mirror area (including shadowing)	88 m^2
Focal length	16 m
Total weight	89 t
Field of view (FlashCam / NectarCAM)	7.5 deg / 7.7 deg
Number of pixels (FlashCam / NectarCAM)	1764 / 1855
Pixel size (imaging)	0.17 deg
Photodetector type	PMT
Telescope readout event rate before array trigger (FlashCam / NectarCAM)	>6 kHz / >7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	12 Gb/s
Positioning time to any point in the sky (>30° elevation)	90 s
Pointing precision	<7 arcseconds
Observable sky	Any astrophysical object with elevation > 20 degrees

LSTs

	Large-Sized Telescope (LST)
Energy range (in which sensitivity is optimized)	20 GeV – 3 TeV
Number of LST telescopes	4 (North)
Optical design	Parabolic
Primary reflector diameter	23.0 m
Effective mirror area (including shadowing)	370 m^2
Focal length	28 m
Total weight	103 t
Field of view	4.3 deg
Number of pixels	1855
Pixel size (imaging)	0.1 deg
Photodetector type	PMT
Telescope readout event rate after array trigger	>7.0 kHz
Telescope data rates (readout of all pixels; before array trigger)	24 Gb/s
Positioning time to any point in the sky (>30° elevation)	30 s
Pointing precision	<14 arcseconds
Observable sky	Any astrophysical object with elevation > 24 degrees

Thank you for your attention

and my apologies for all the topics I had to leave out and that you would have liked to learn more about

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