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Ground-Based Gamma-Ray Astronomy

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Forschungsgemeinschaft



GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung



Outline

0. Introduction

I. Measurement Principles and Instruments

Lecture I

II. Galactic Gamma-Ray Astronomy

III. Extragalactic Gamma-Ray Astronomy

IV. Outlook/Future

Lecture II



CTAO
Cherenkov Telescope Array Observatory

Kathrin Egberts . Ground-Based Gamma-Ray Astronomy . Erice . August 2026 2



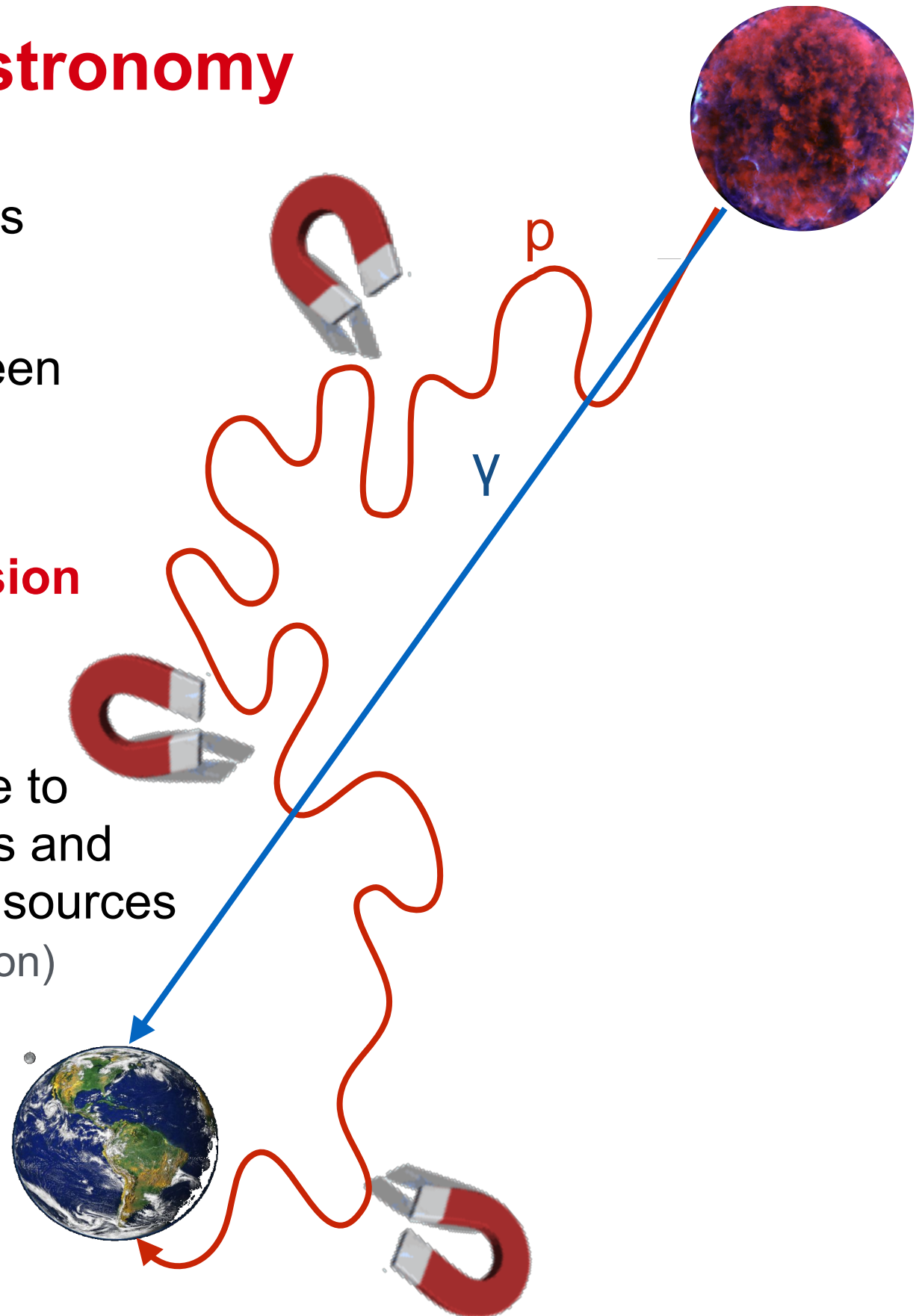
0. Introduction to TeV Astronomy

Observations of cosmic rays
via neutral messengers

Cosmic-ray accelerators seen
as **gamma-ray sources**

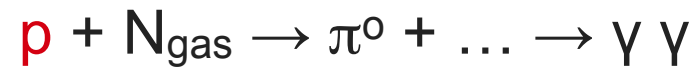
cosmic-ray propagation
as **diffuse gamma-ray emission**

At TeV energies, we are close to
the limit of Galactic accelerators and
the observational limit of extragal. sources
(due to gamma-gamma absorption)

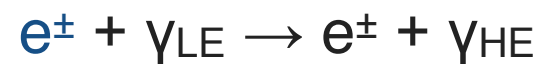


From Particles To Radiation

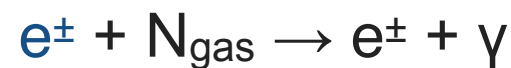
- **Pion production and decay**



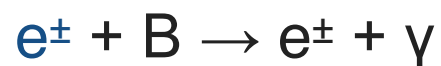
- **Inverse Compton scattering**



- **Bremsstrahlung**

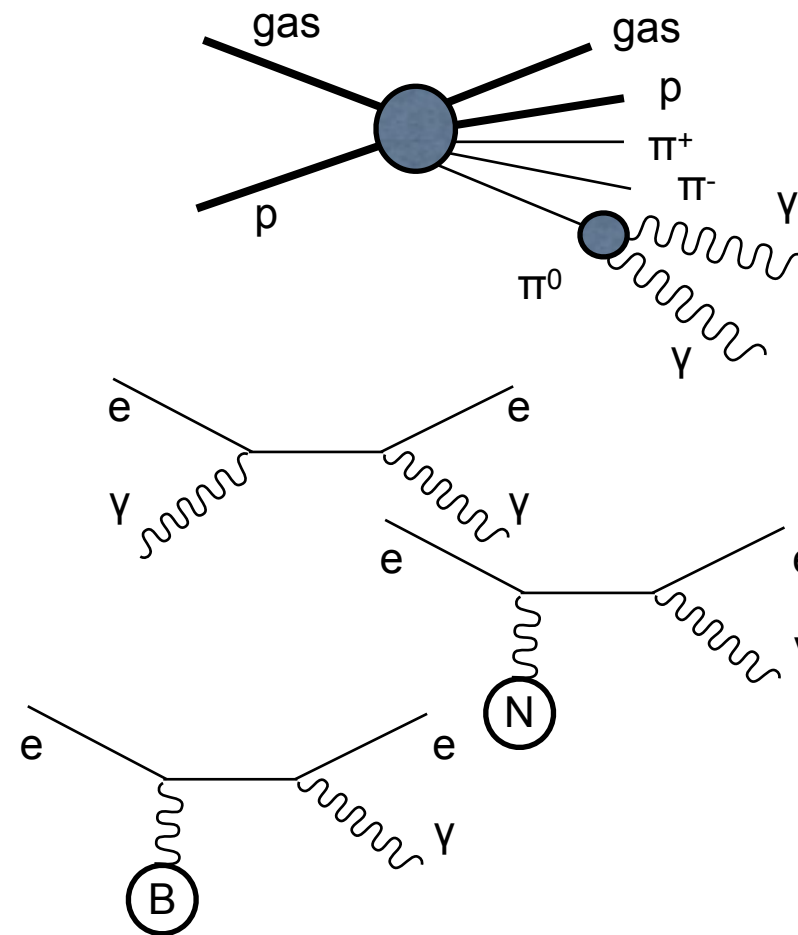


- **Synchrotron radiation**



hadronic
mechanism

leptonic
mechanisms

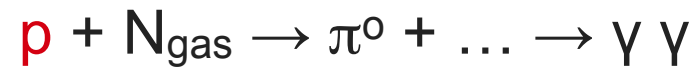


- Need for target “material”: interstellar medium, radiation fields, B fields
- γ-rays are the line-of-sight integral of CR density and target material:

$$F_\gamma(E_\gamma) = \int dl_d \int d\sigma_{\text{CR}+t \rightarrow \gamma} / dE_{\text{CR}} \cdot n_t(l, b, l_d) \cdot n_{\text{CR}}(l, b, l_d, E_{\text{CR}}) dE_{\text{CR}}$$

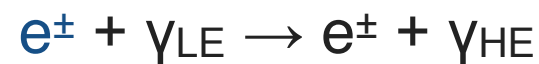
From Particles To Radiation

- Pion production and decay



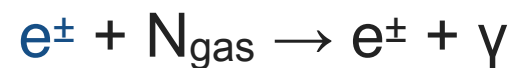
hadronic
mechanism

- Inverse Compton scattering

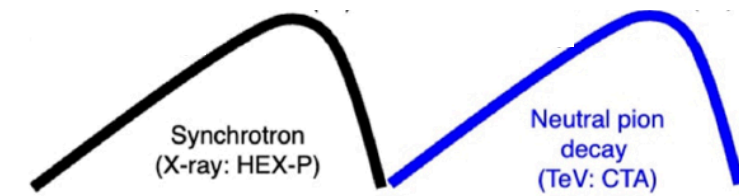
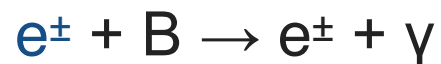


leptonic
mechanisms

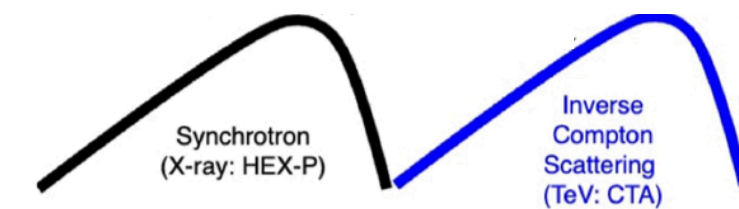
- Bremsstrahlung



- Synchrotron radiation

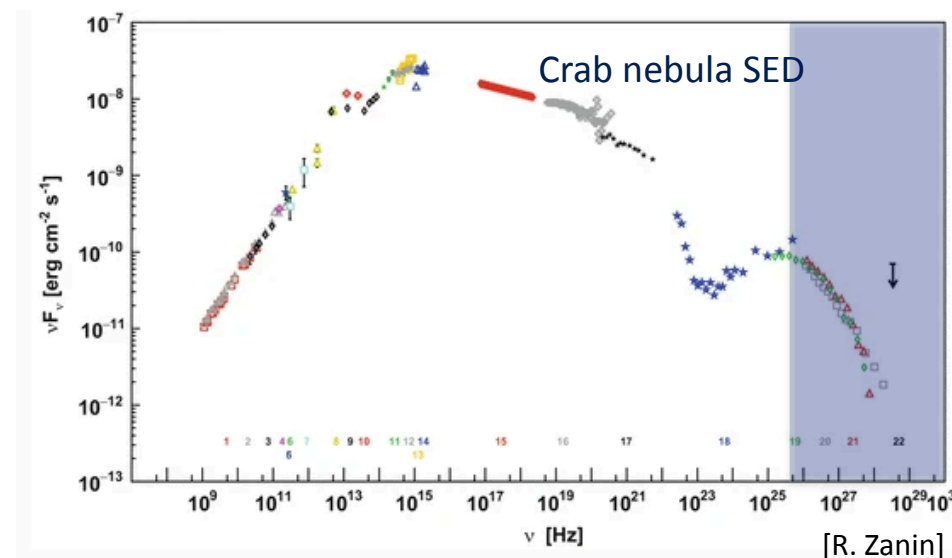


Hadronic accelerators

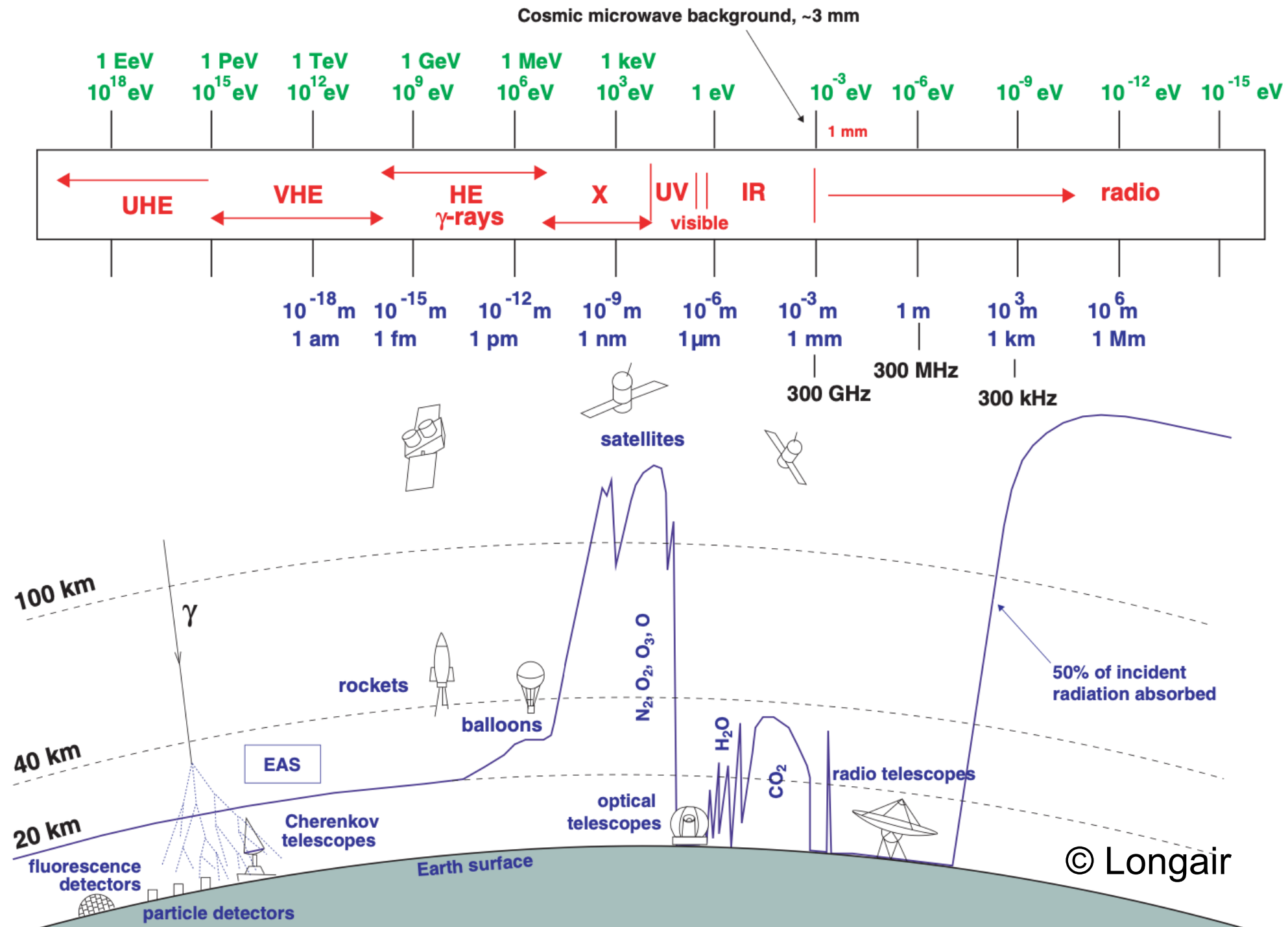


Leptonic accelerators

Mori et al.

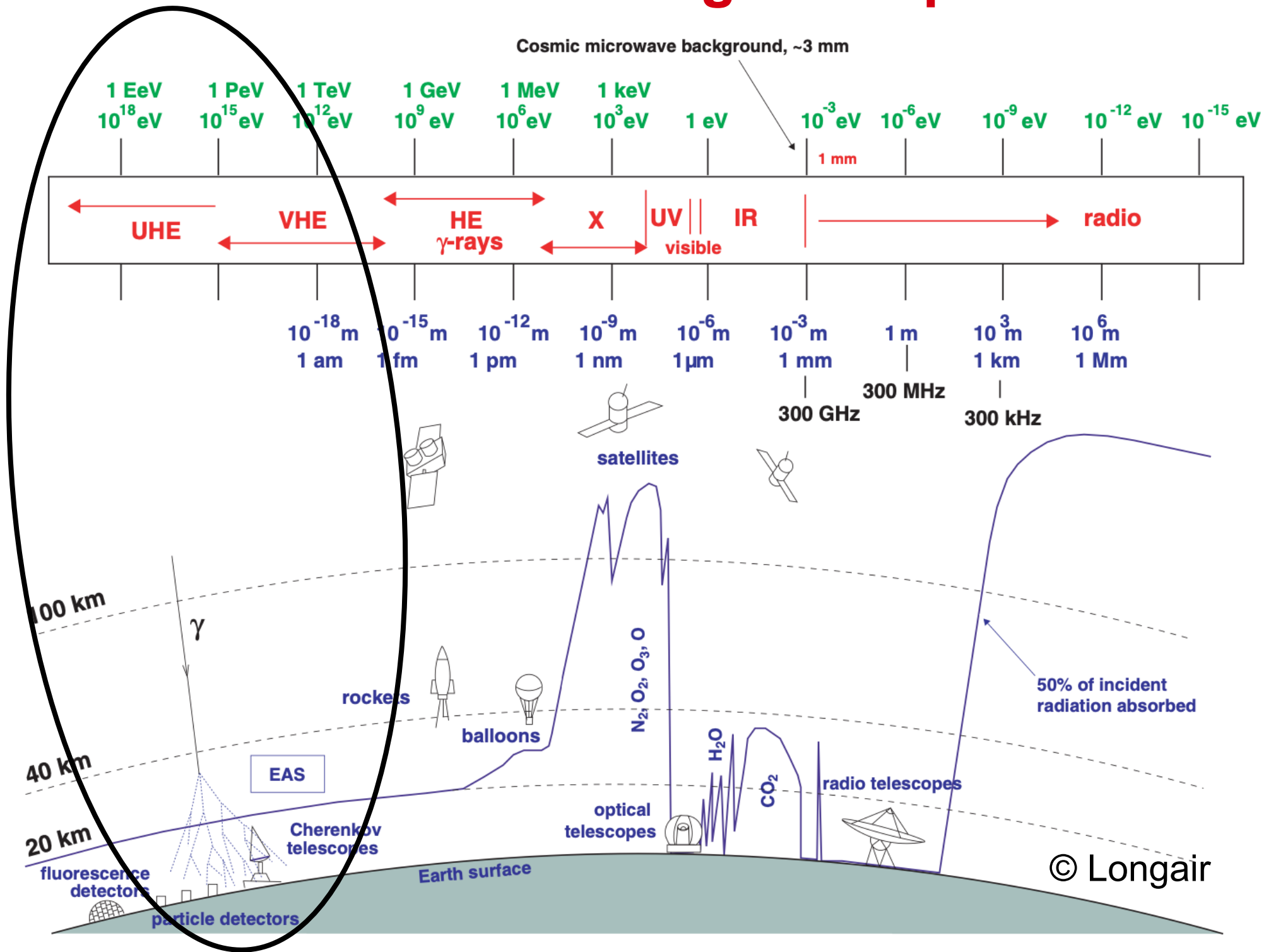


Observations in the electromagnetic spectrum



© Longair

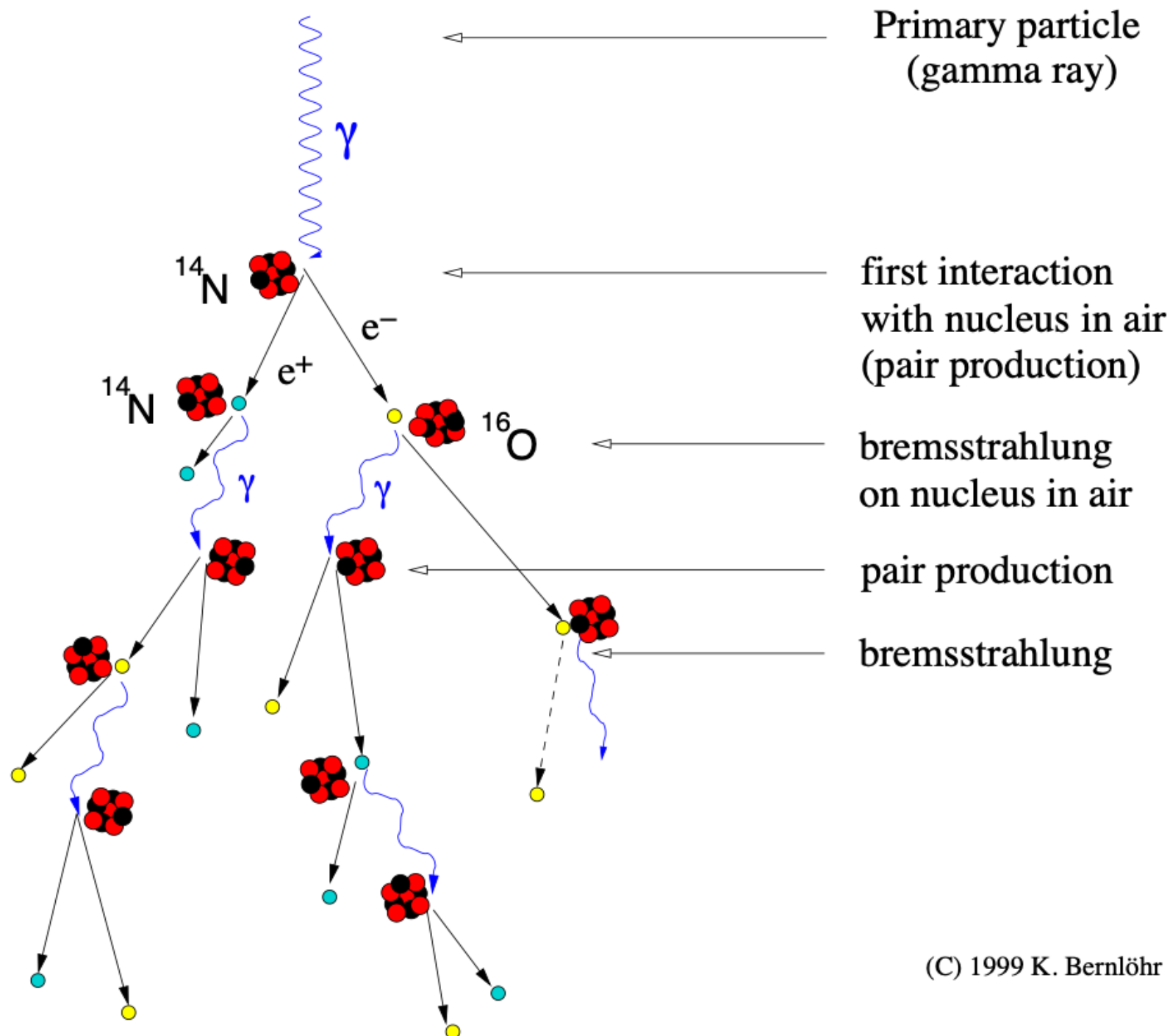
Observations in the electromagnetic spectrum



Ground-based detection at VHE energies via extensive air showers

Air Showers

Development of gamma-ray air showers

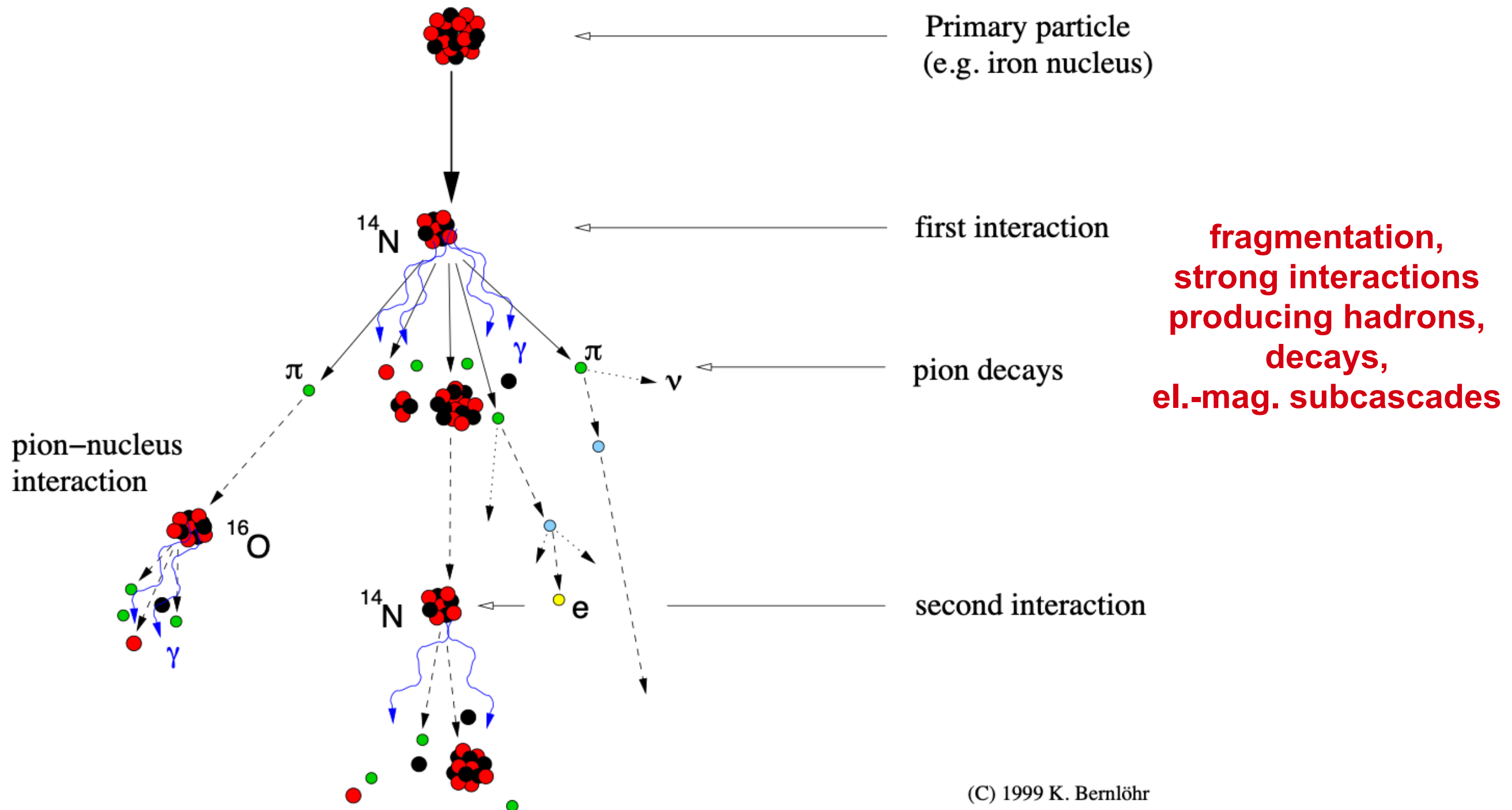


**pair production
and
bremsstrahlung**

(C) 1999 K. Bernlöhner

Air Showers

Development of cosmic-ray air showers



Air Showers

Electromagnetic shower

Hadronic shower

z

z

γ

p

x

x

Detailed air-shower simulations contain atmospheric information, possible interactions and decays

x axis exaggerated for visualisation purpose

y

y

x

x

Clear differences seen between electromag. and hadronic showers

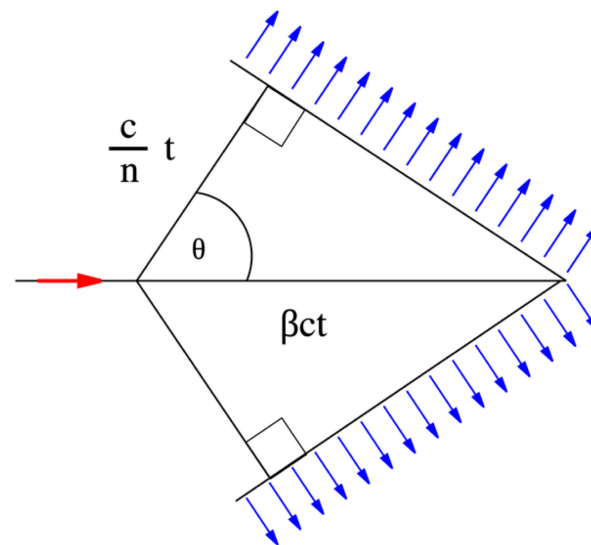
Cherenkov Radiation

*one of the favourite
techniques for detecting
relativistic air-shower particles*

- In a medium with refractive index n :
- Speed of light: c/n
- Charged particle moving with $v > c/n$ emits Cherenkov light
- Emission angle:

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

- $\sim 1^\circ$ in air, $\sim 40^\circ$ in water



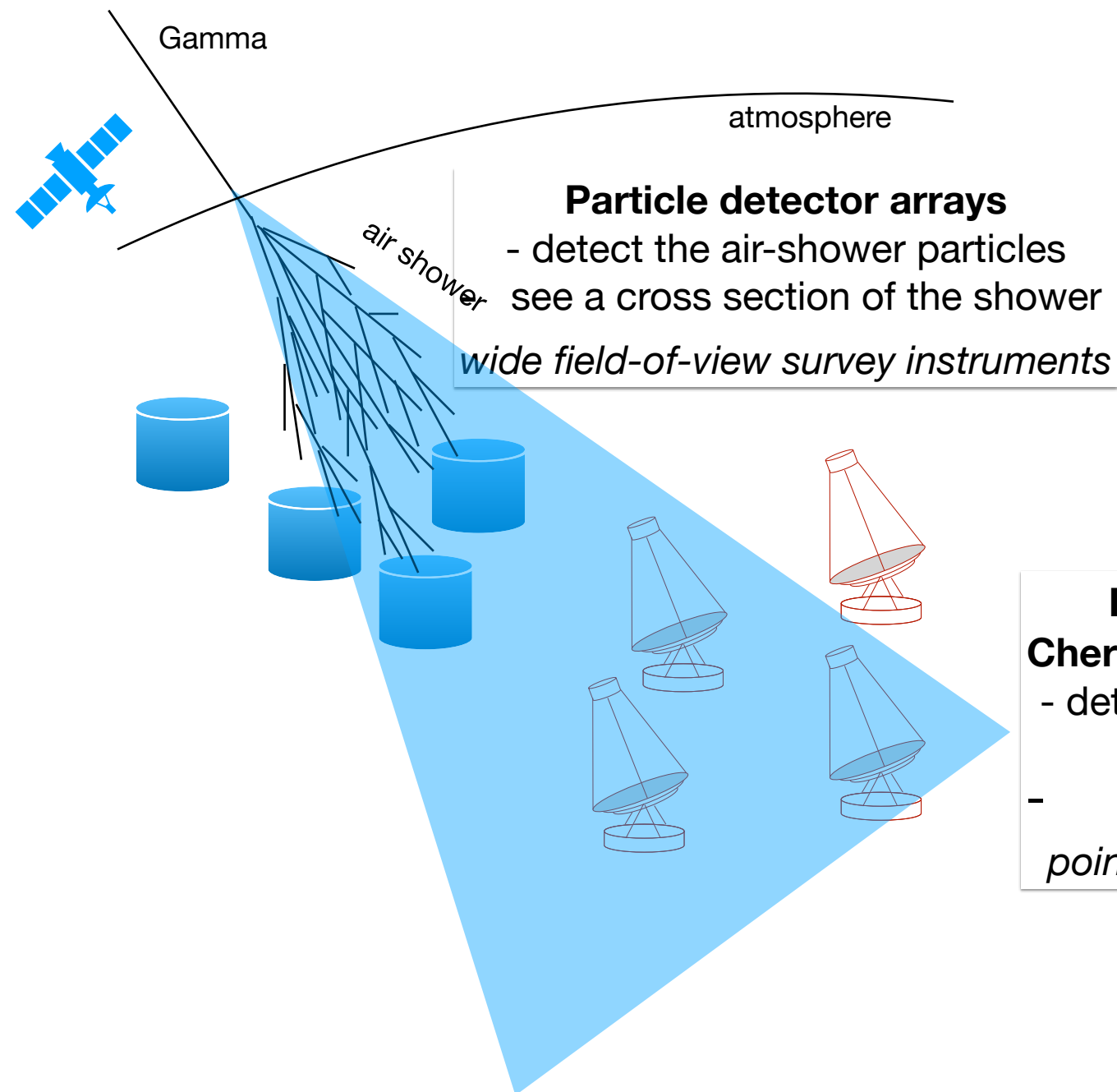
Pavel Alexeyevich Cherenkov
(Nobel Prize in 1958)

Charged air-shower particles can emit Cherenkov light
either in the **air** or in a suitable medium like **water**

I. 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

Imaging atmospheric Cherenkov telescopes (IACTs)

- detect the Cherenkov light of the shower
- see the entire shower
- pointed precision instruments*

Two Techniques for Ground-Based Observations

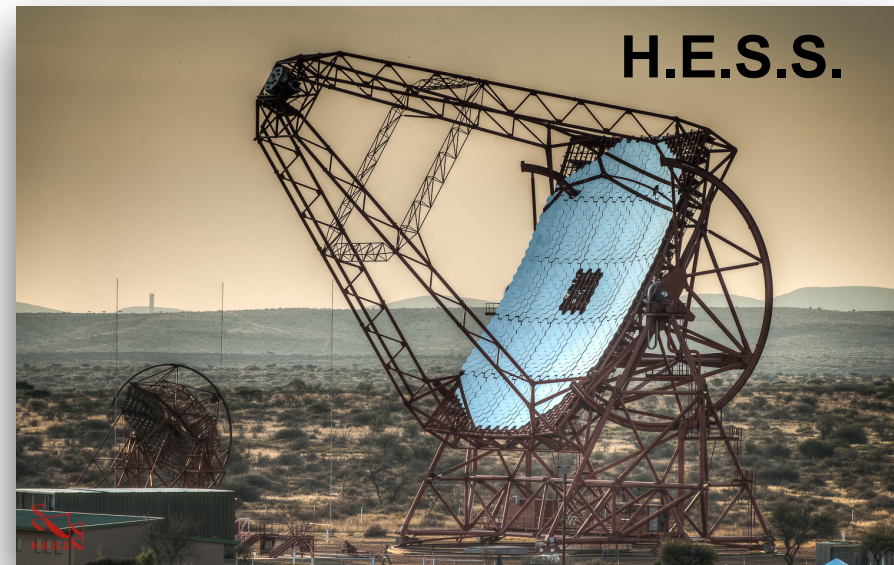


Particle Detector Arrays

Cherenkov light in water

24/7 observations

observation of full sky above detector



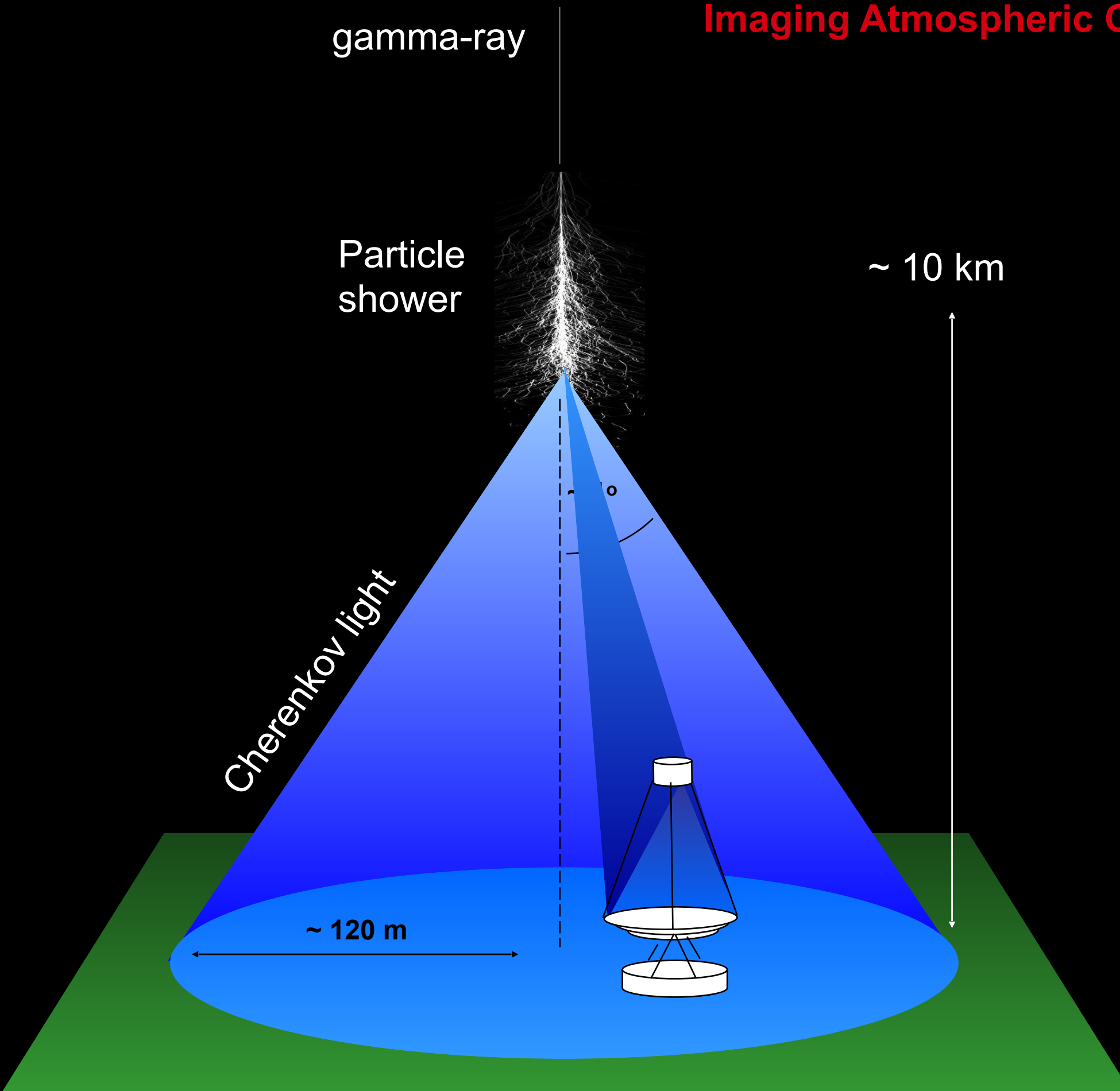
Imaging Atm. Cherenkov Telescopes

Cherenkov light in atmosphere

(moon-less) night observations

small field of view/
pointed observations

Imaging Atmospheric Cherenkov Telescopes

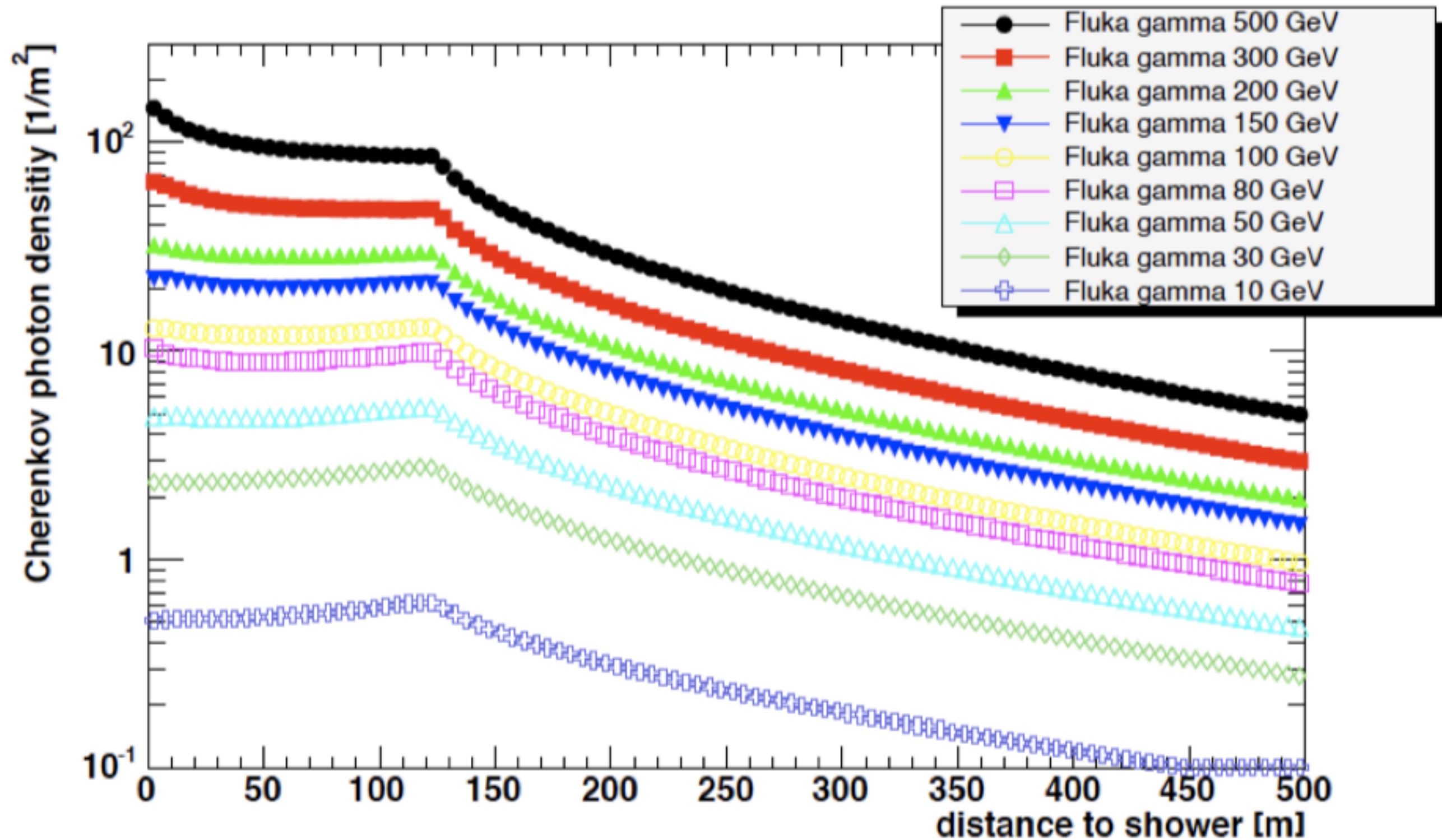


Cherenkov light on the ground

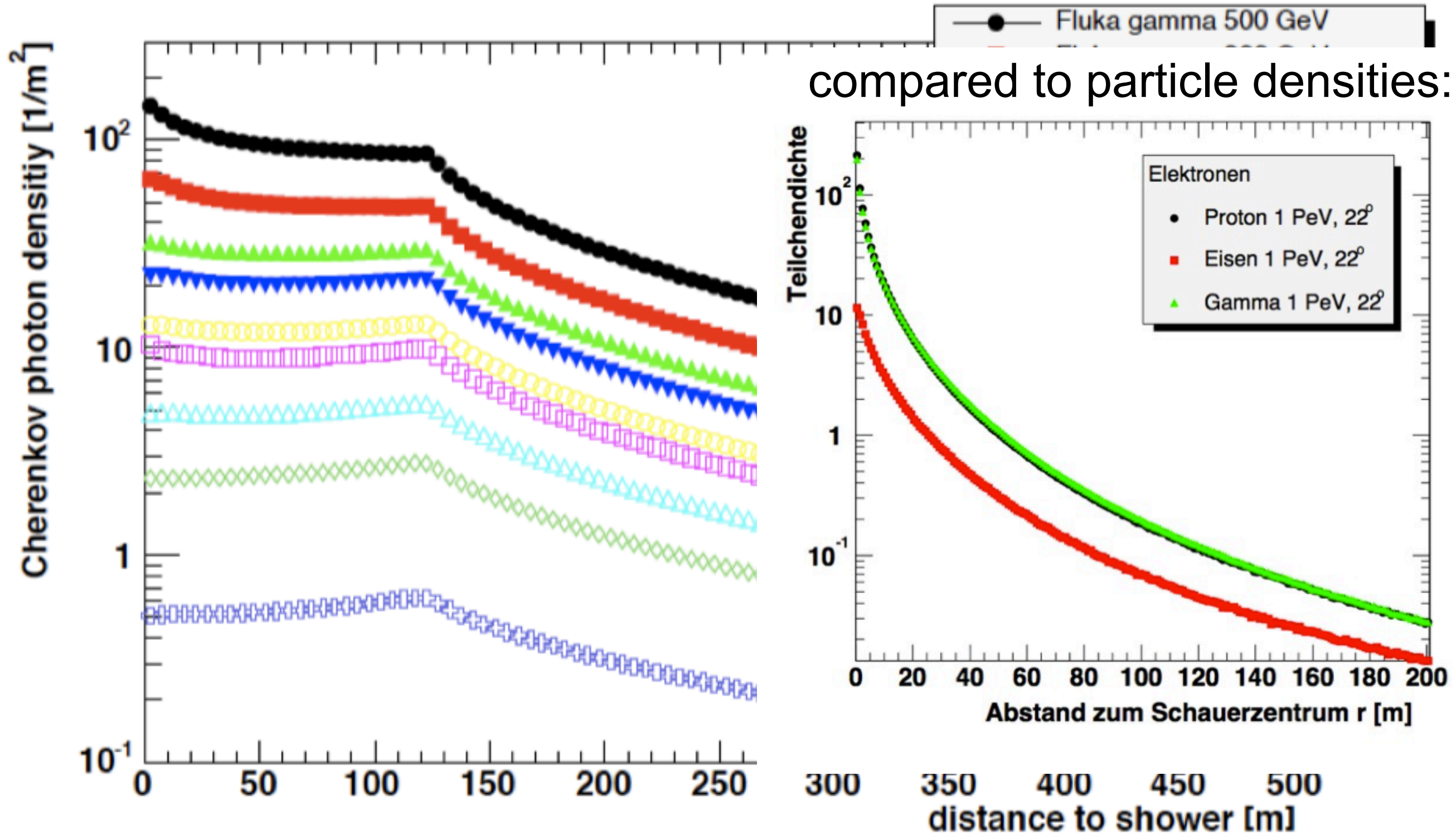
Gamma

- ~ 100 Photons per TeV and m^2
- large mirrors
- dark skies
- short exposures (~ 10 ns)

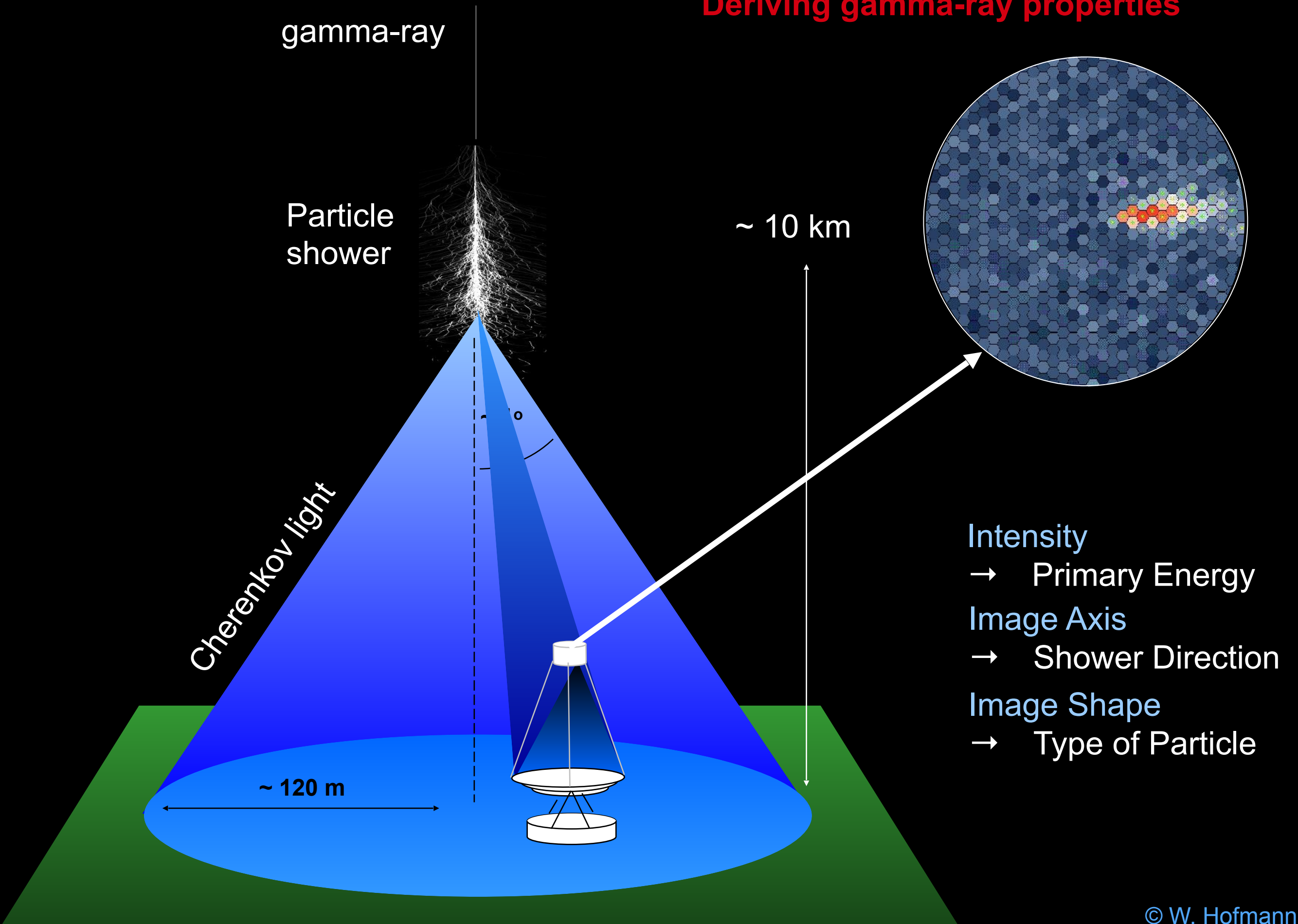
Cherenkov light on the ground



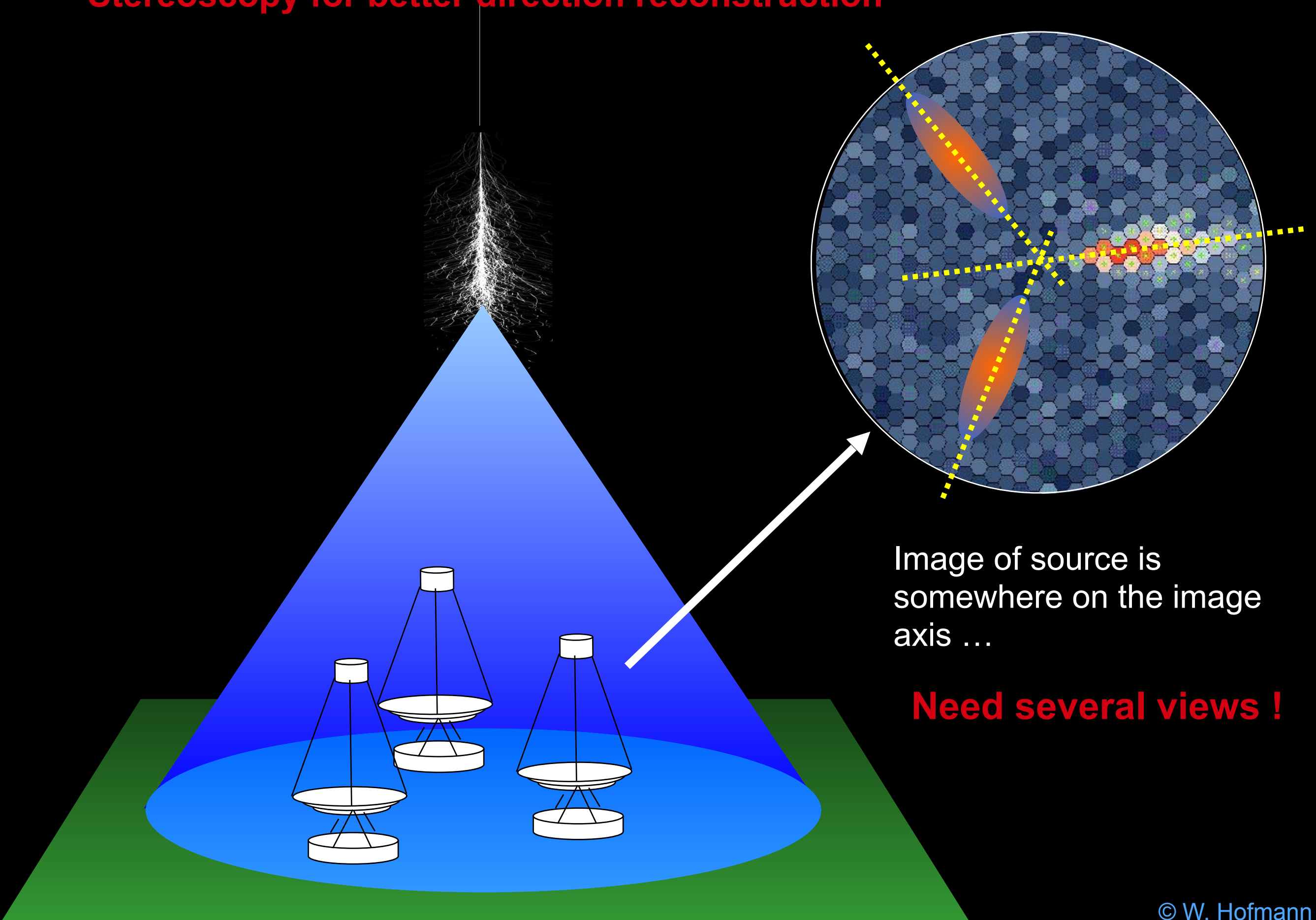
Cherenkov light on the ground



Deriving gamma-ray properties



Stereoscopy for better direction reconstruction



Background discrimination / γ -hadron separation

Electromagnetic shower

Hadronic shower

z

γ

z

p

x

x

Difference between elmag. and hadronic showers used for classification

y

x

y

x

Background discrimination / γ -hadron separation

Electromagnetic shower

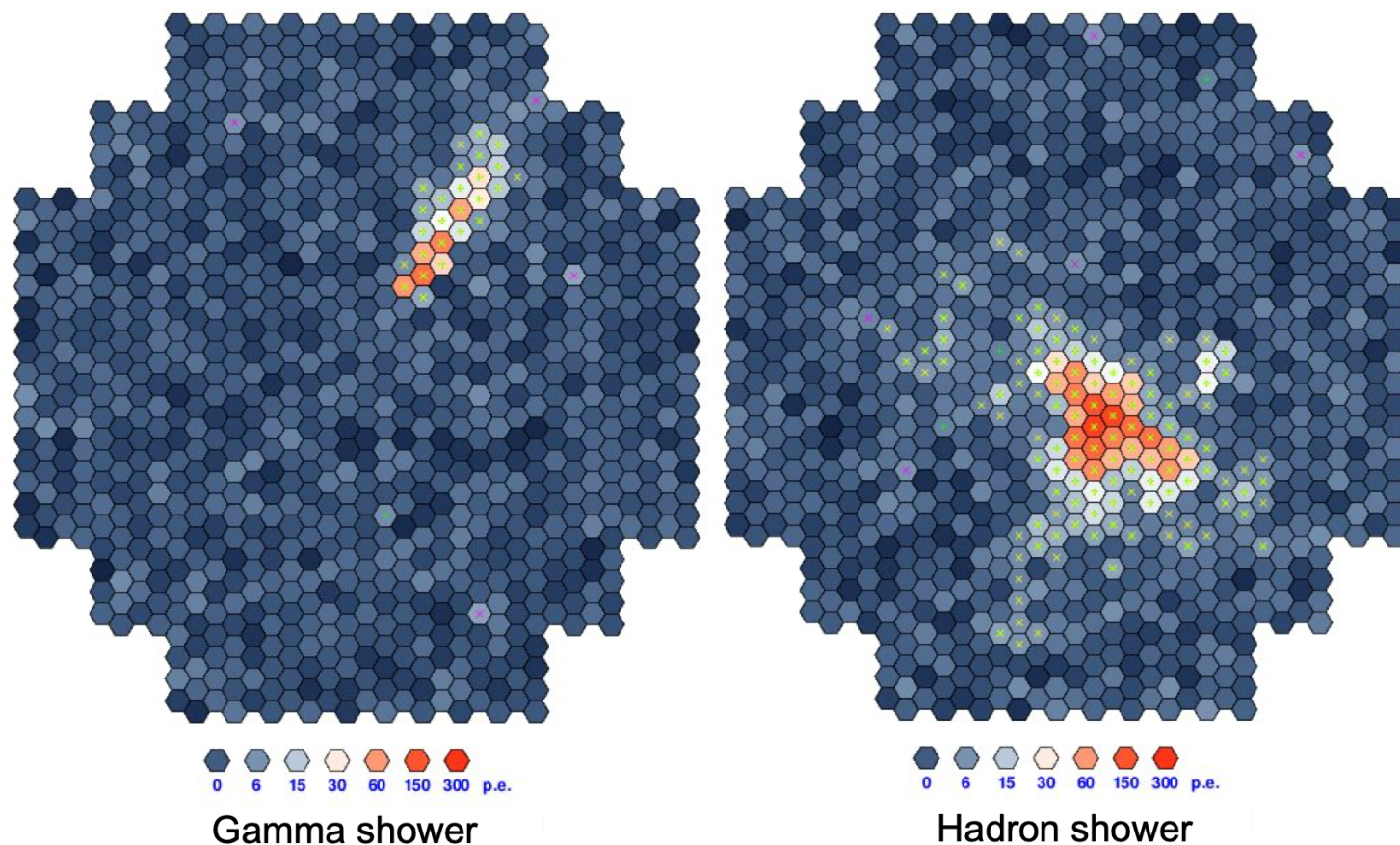
Hadronic shower

z

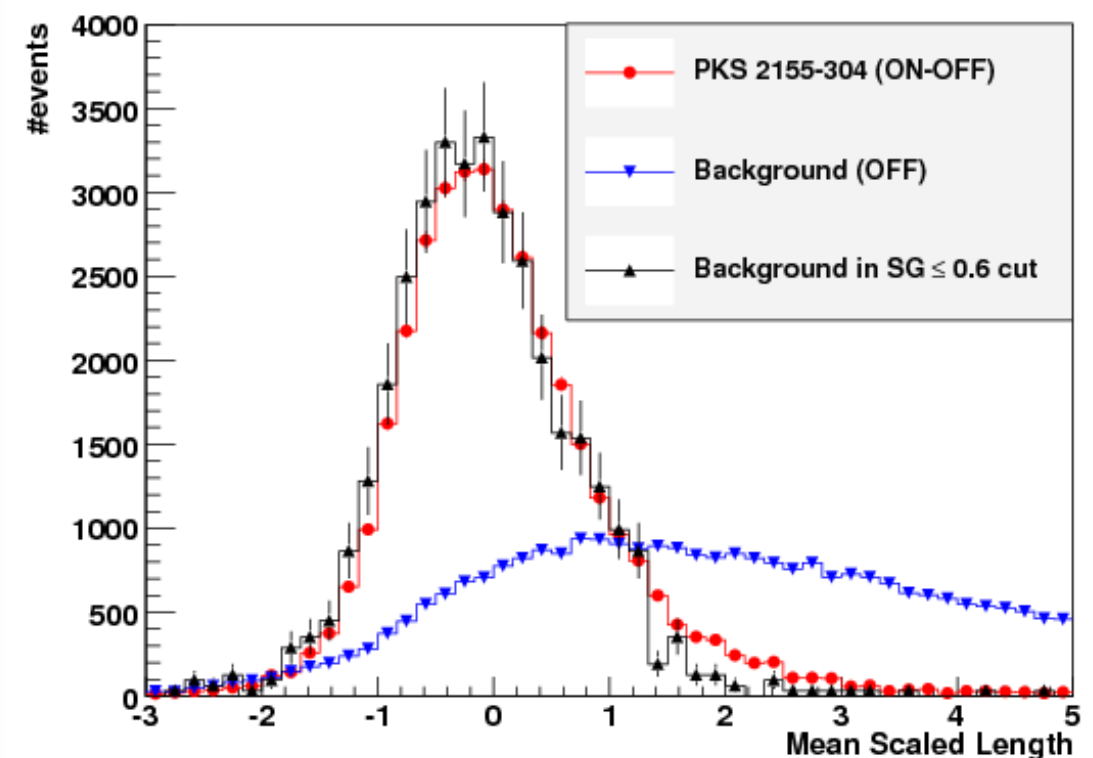
z

γ

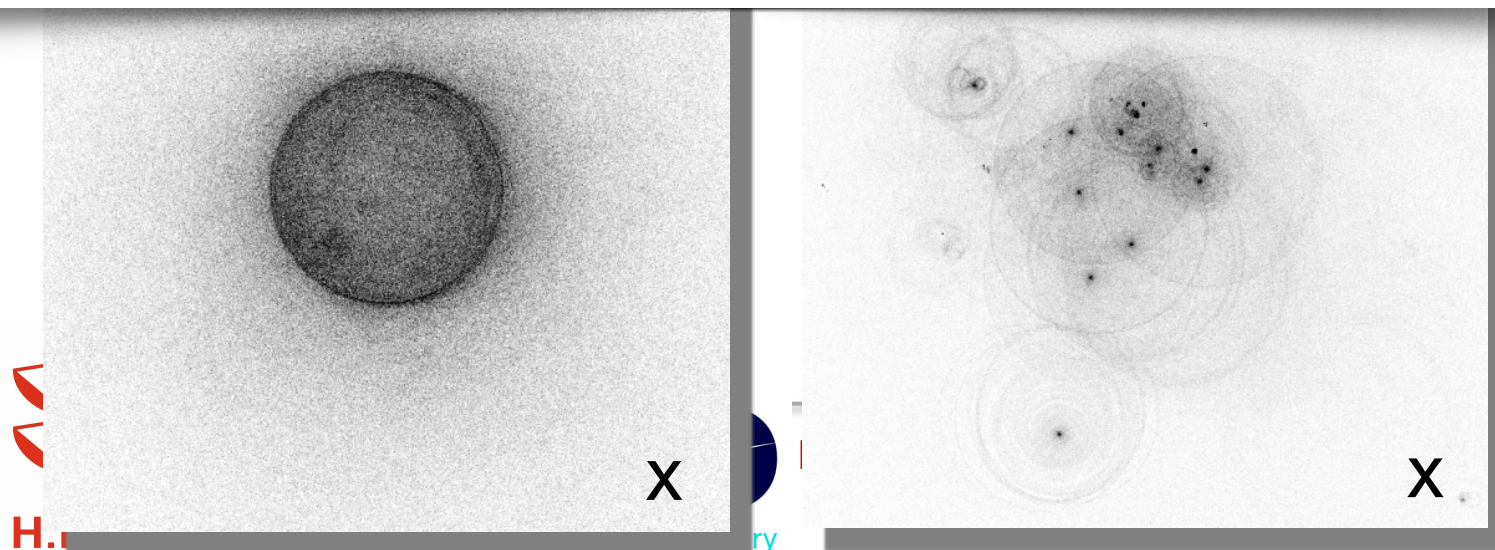
p



Difference between elmag. and hadronic showers used for classification

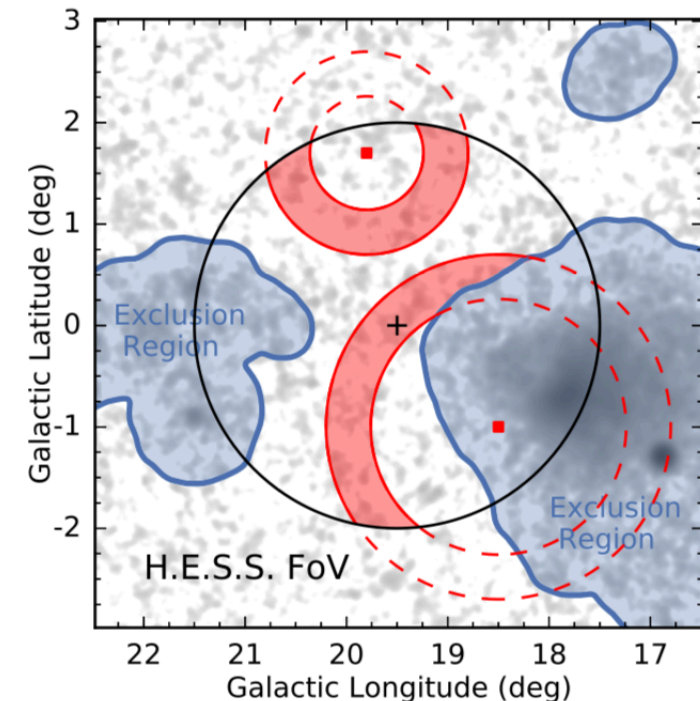


Width of the camera image
normalised to width of
 γ -distribution



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*: Results in subtraction of any large-scale gamma-ray emission together with the background
- method optimised for sources much smaller than the field of view



Alternative: modelling of the background

Current IACT Instruments

VERITAS

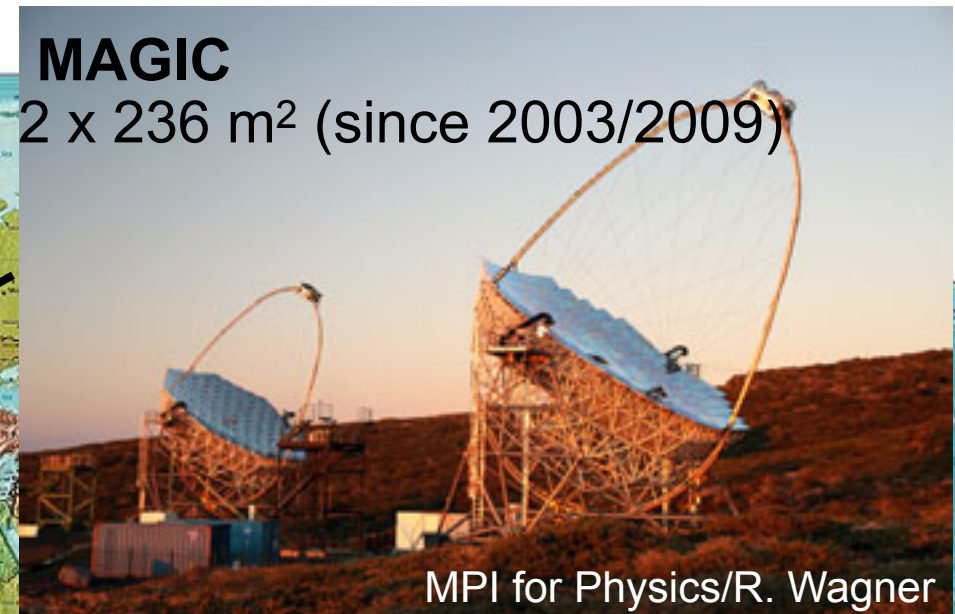
4 x 110 m² (since 2007)



VERITAS Coll.

MAGIC

2 x 236 m² (since 2003/2009)



MPI for Physics/R. Wagner

Effective area: ~10⁵ m²
Field of view: few degrees
Duty cycle: ~1000 hours/year
Background separation: imperfect
Angular resolution: <1'
Energy resolution: ~15%

H.E.S.S.

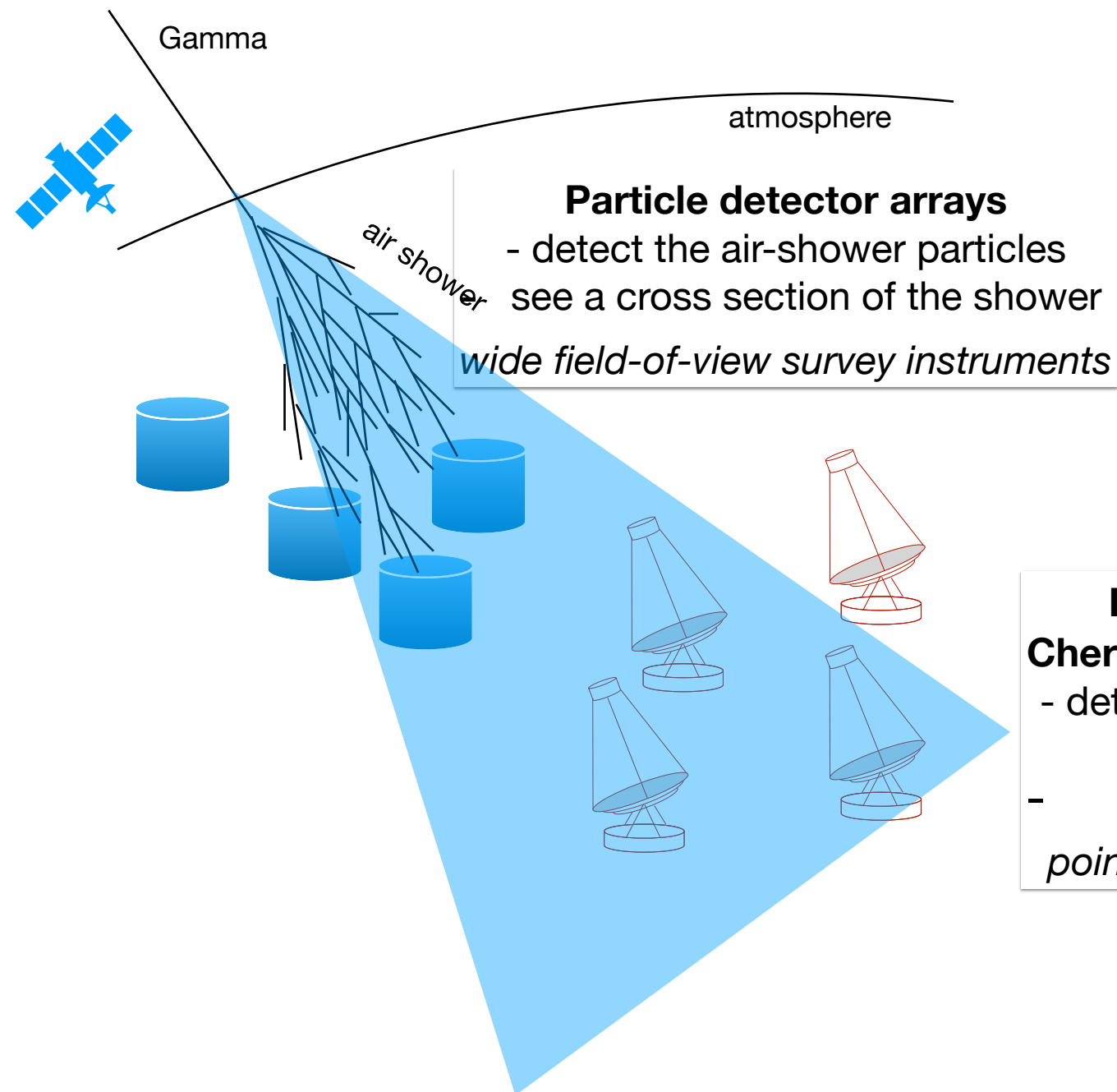


4 x 108 m² (since 2002)
1 x 614 m² (since 2012)

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

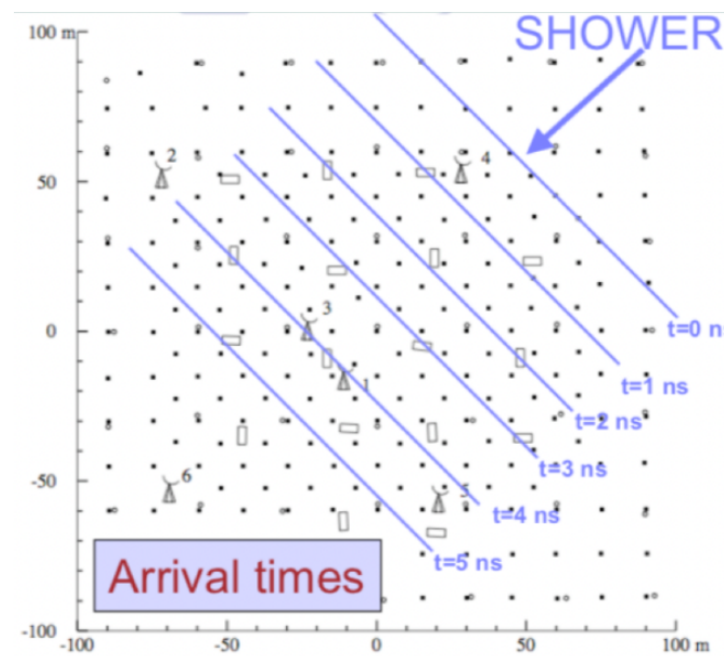
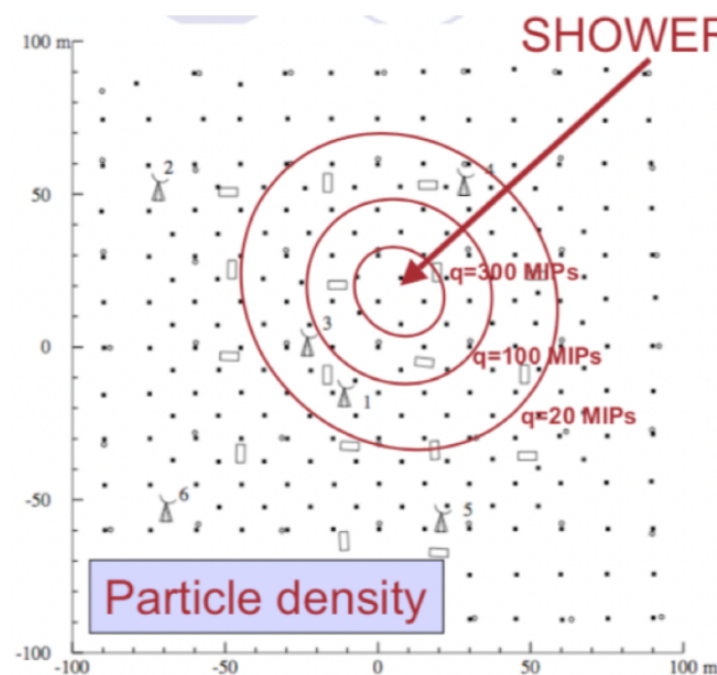
Imaging atmospheric Cherenkov telescopes (IACTs)

- detect the Cherenkov light of the shower
- see the entire shower

pointed precision instruments

Particle Detector Arrays

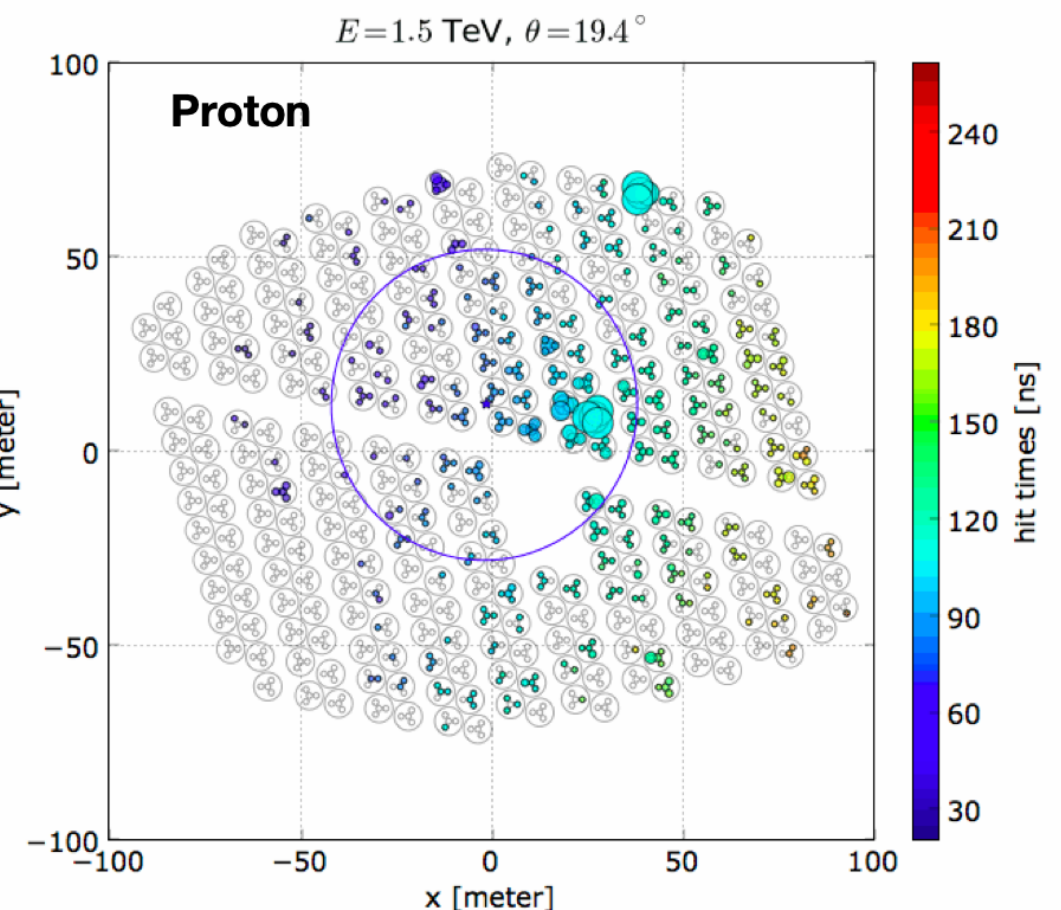
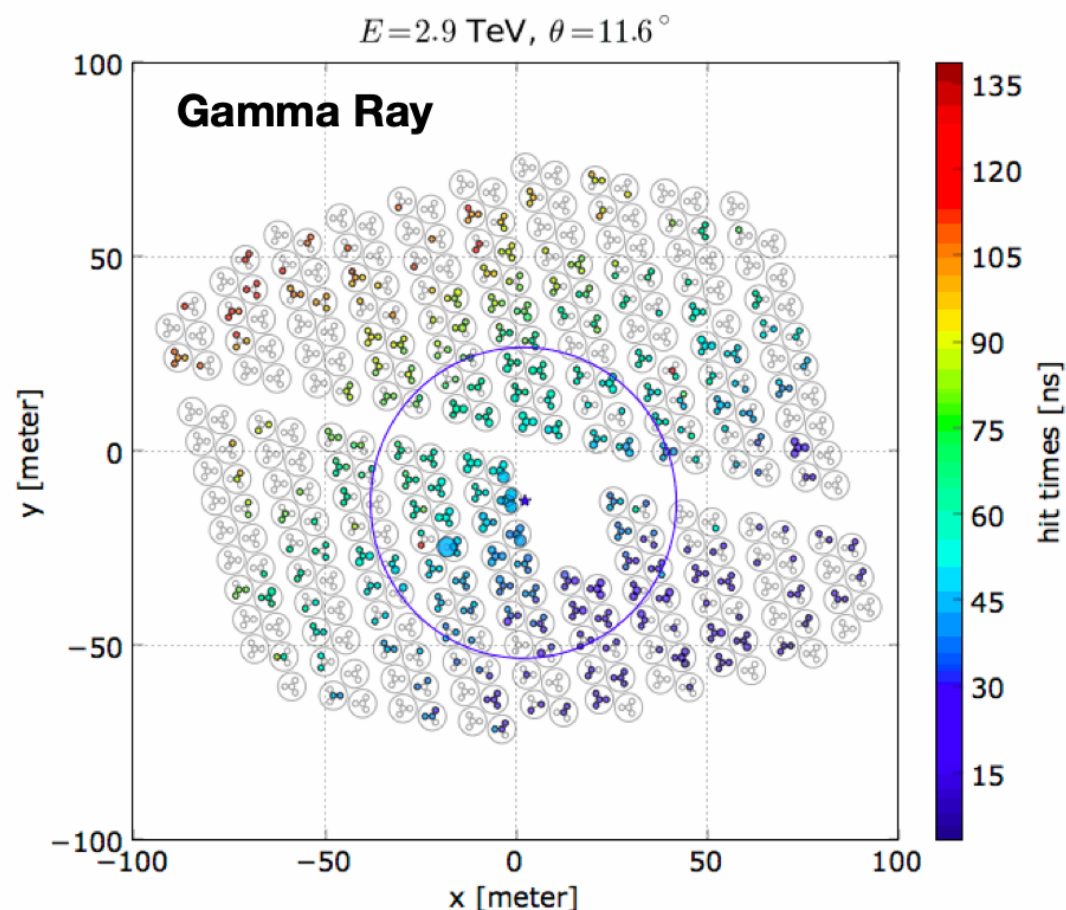
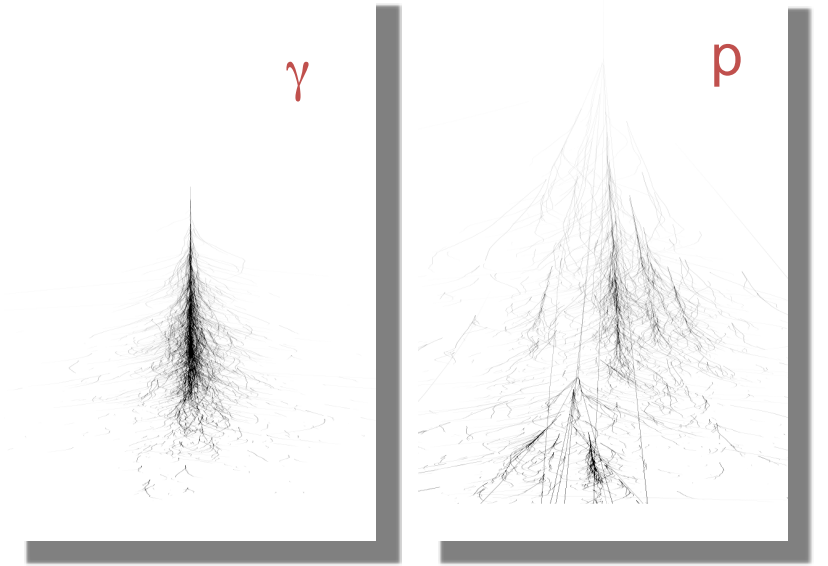
- Particle detectors can be *scintillators* or *water tanks*
- Detection of the tail of the air shower reaching the ground
→ preferably in *high locations* / higher energy threshold
- Observables: *Particle density* and *time of arrival* at each detector position



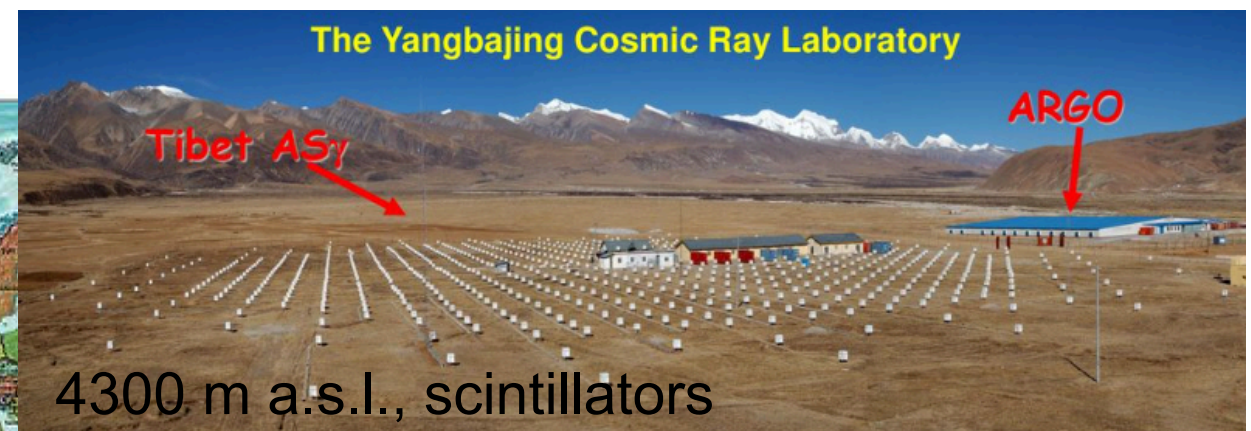
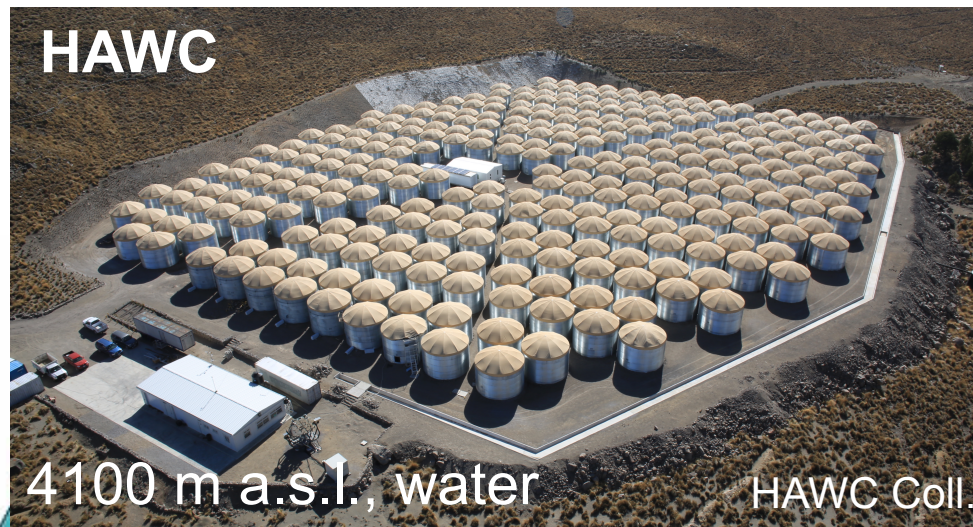
- Time gradient and center of gravity used for direction
- Energy from total signal
- Uniformity for gamma/hadron separation

Hadron Background

- Patchiness of the signal → compactness parameter
- Subtraction of remaining background: Direct integration from the data collected prior to and after the source transited in local coordinates (θ, ϕ)



Current Particle Detector Array Instruments



Field of view: sky above detector

Duty cycle: 24/7

Background separation: modest

Angular resolution: $\sim 0.5^\circ$

Energy resolution: $\sim 50\%$

LHAASO

4410 m a.s.l.
water & scintillators

IHEP

Two Techniques for Ground-Based Observations



Particle Detector Arrays

Angular resolution of ~ 0.5 deg

Wide fields of view

Large duty cycle

Survey instruments
at somewhat higher
energies



Imaging Atm. Cherenkov Telescopes

Angular resolution of $\lesssim 0.1$ deg

Small fields of view

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

Pointed precision
instruments with
somewhat lower energy
threshold

Very strong complementarity!