Imaging Atmospheric Telescopes: Detection Principles

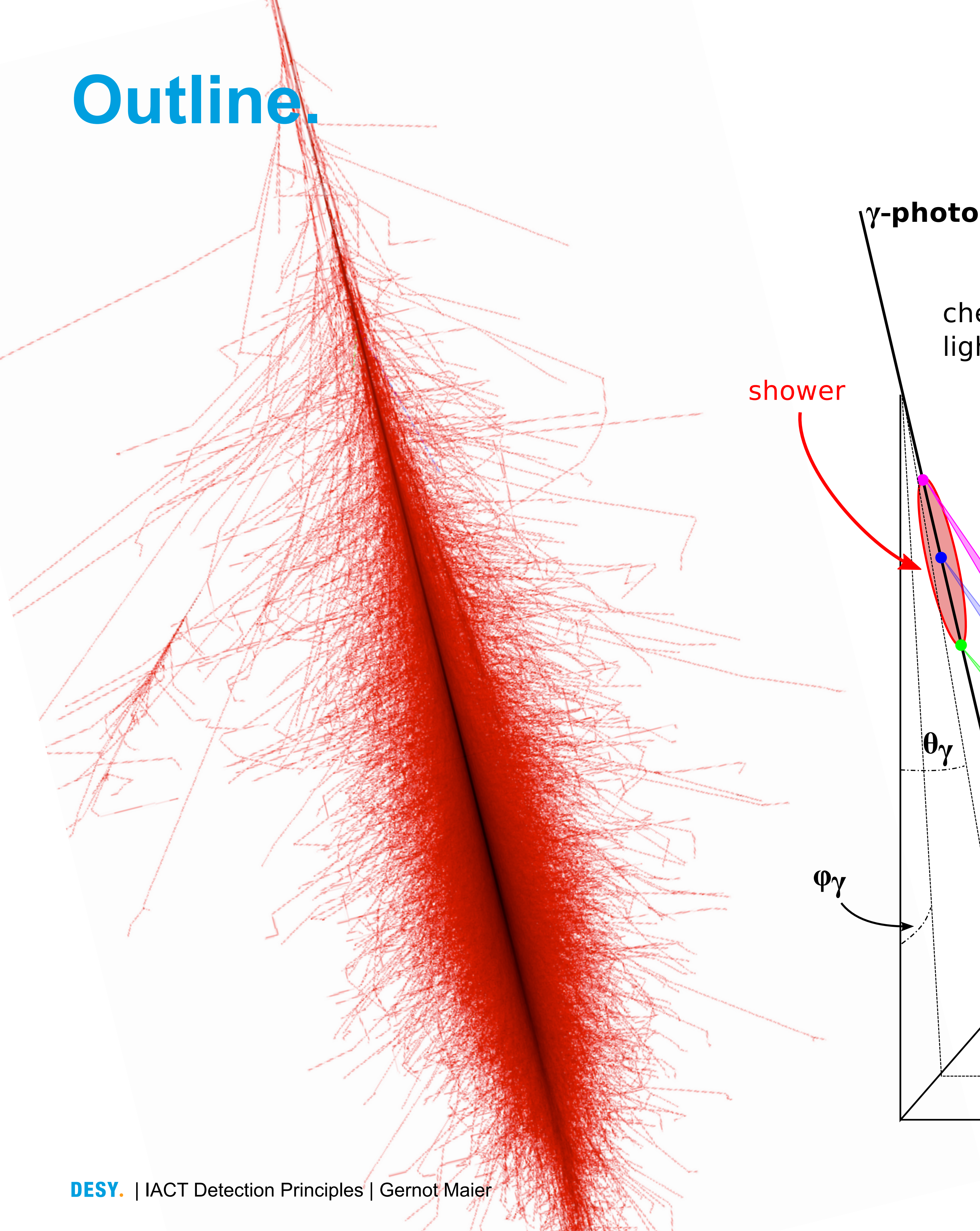
CTAO School 2025

Gernot Maier

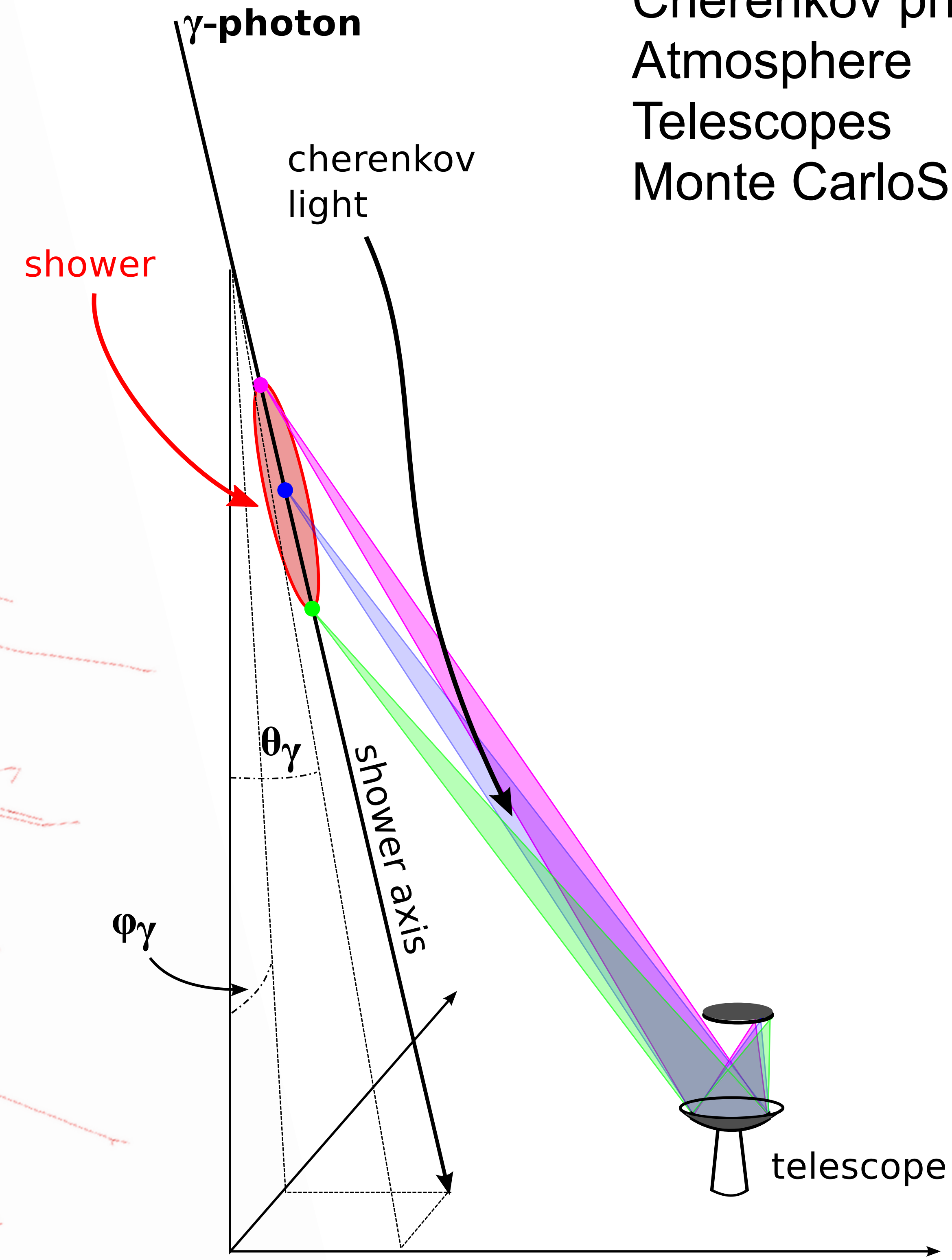
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Outline.



Extensive air showers
Cherenkov photons
Atmosphere
Telescopes
Monte CarloSimulations



C.Skole (Thesis)

What we want to measure.

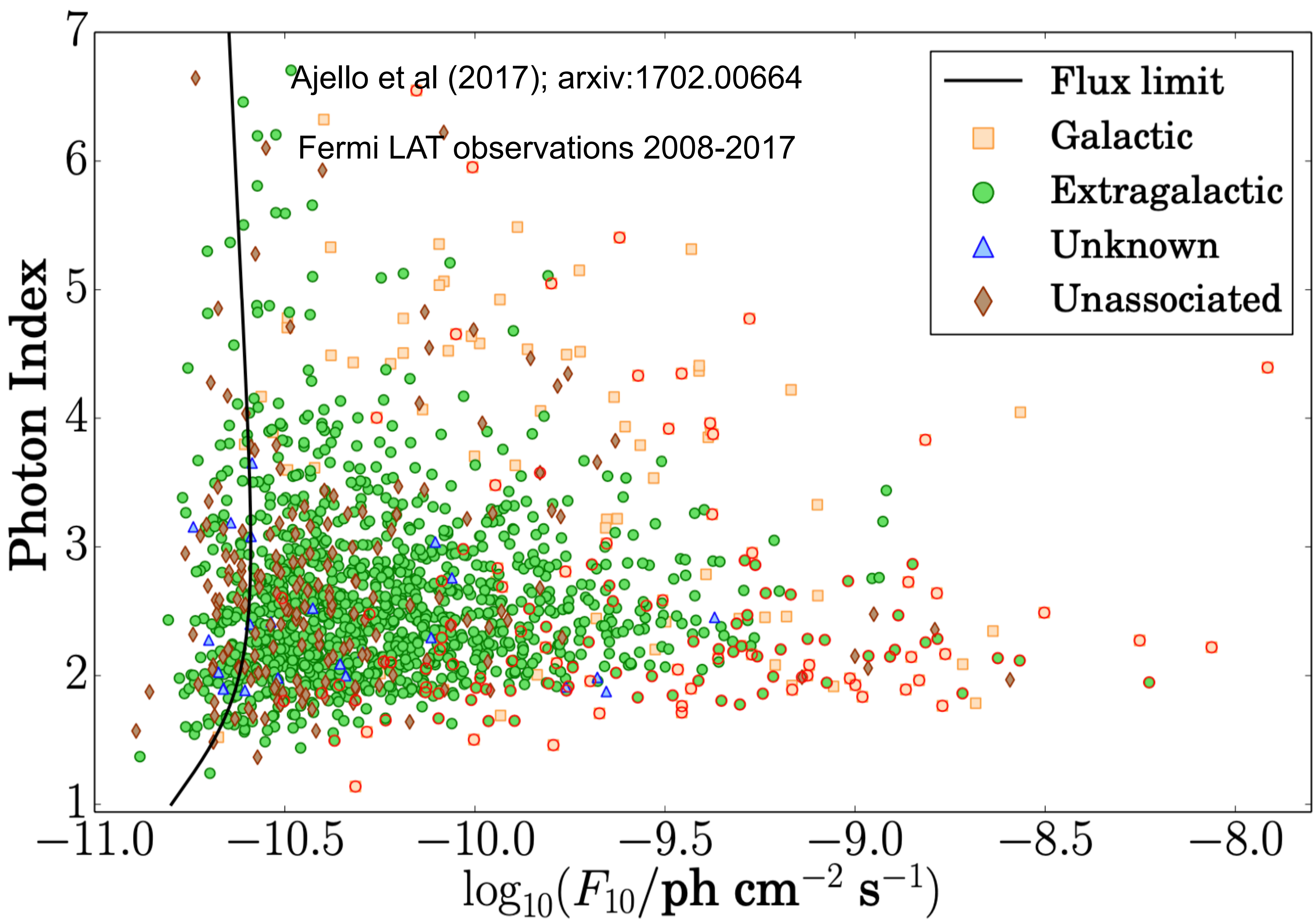
- For each event.
  - identification (probability that it is a gamma ray)
  - energy
  - direction
  - time
  - (do not measure photon polarization)

- (obviously we want to maximize number of events & precision)
- (replace "gamma ray" by the particle of interest)

Fluxes and spectra.

.. in general:
- low fluxes (10^{-10} photons/cm^2/s)
- spectra with power-law like shape

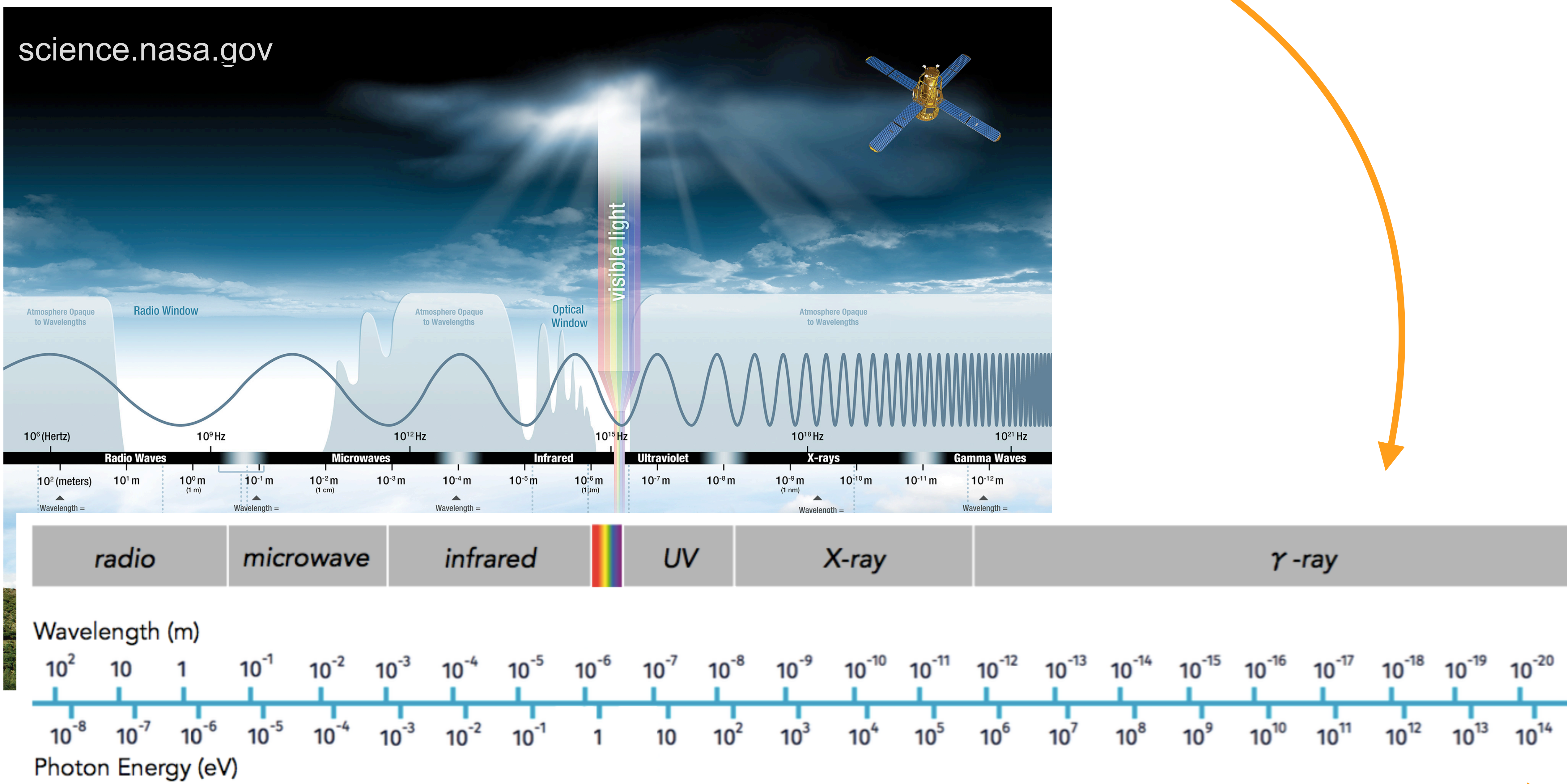
$$\frac{dN}{dE} \propto E^{-\gamma}$$



Flux above 10 GeV

Fermi LAT
~1 m^2 of effective area

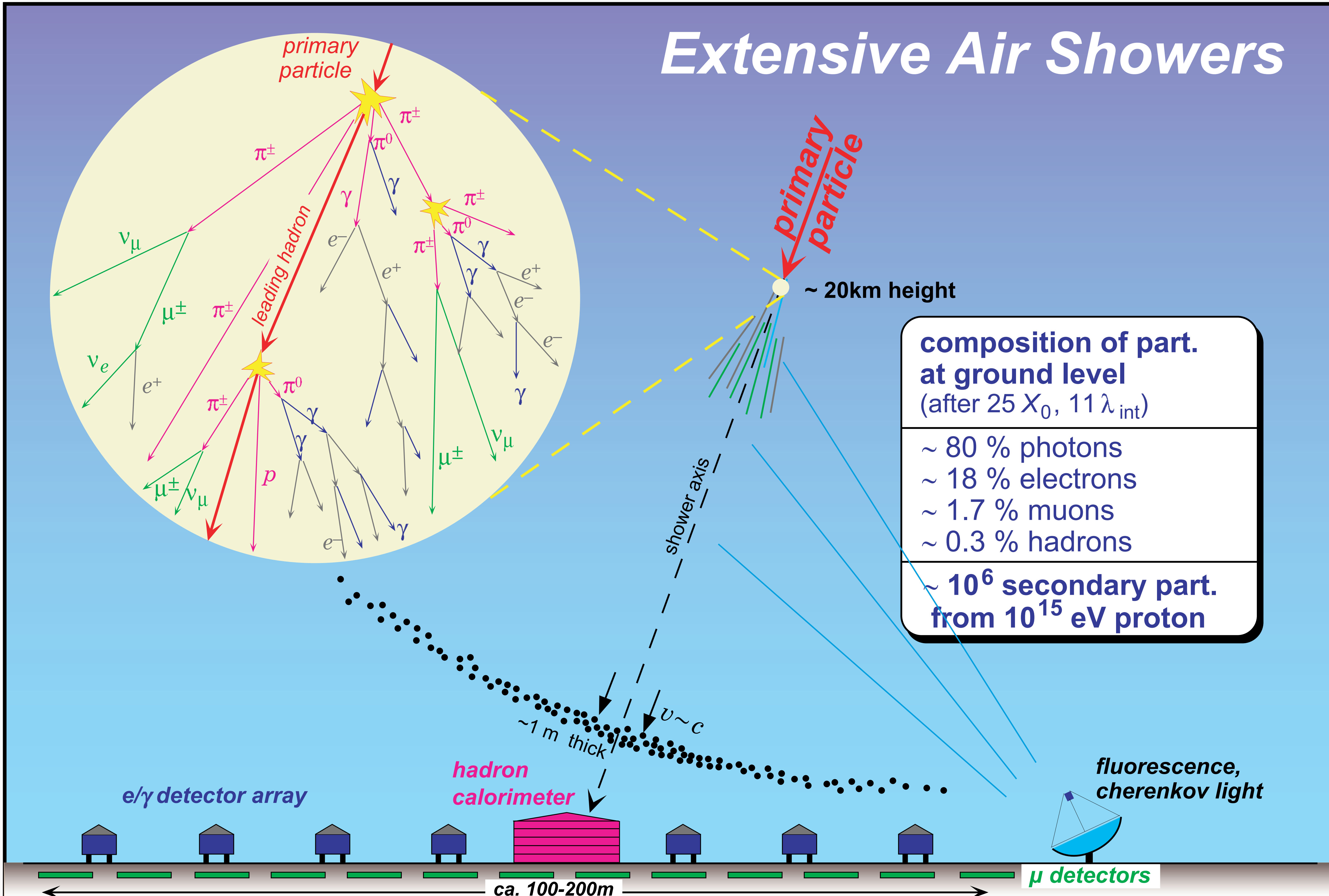
Very-High Energy Gamma-ray Astronomy.

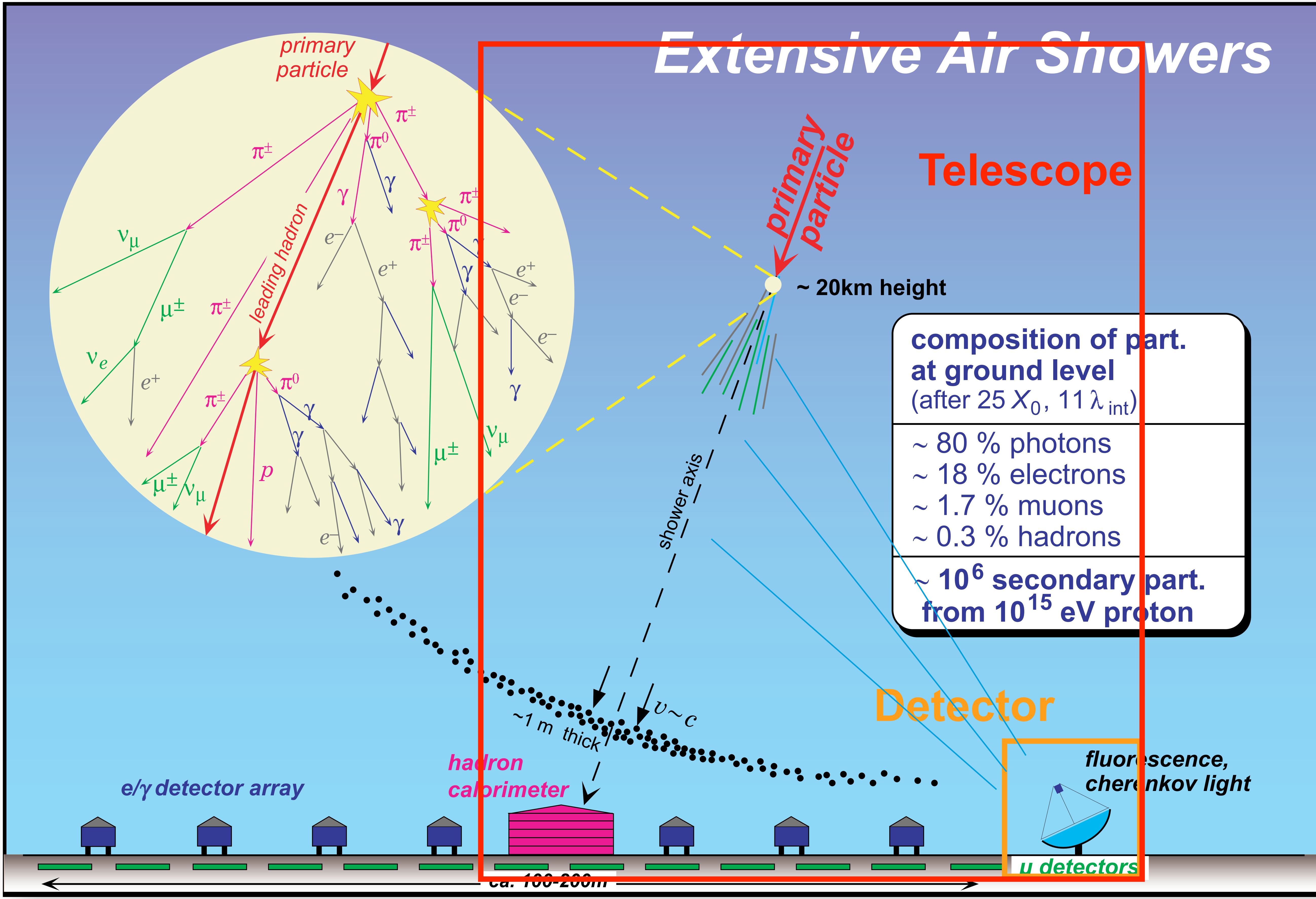


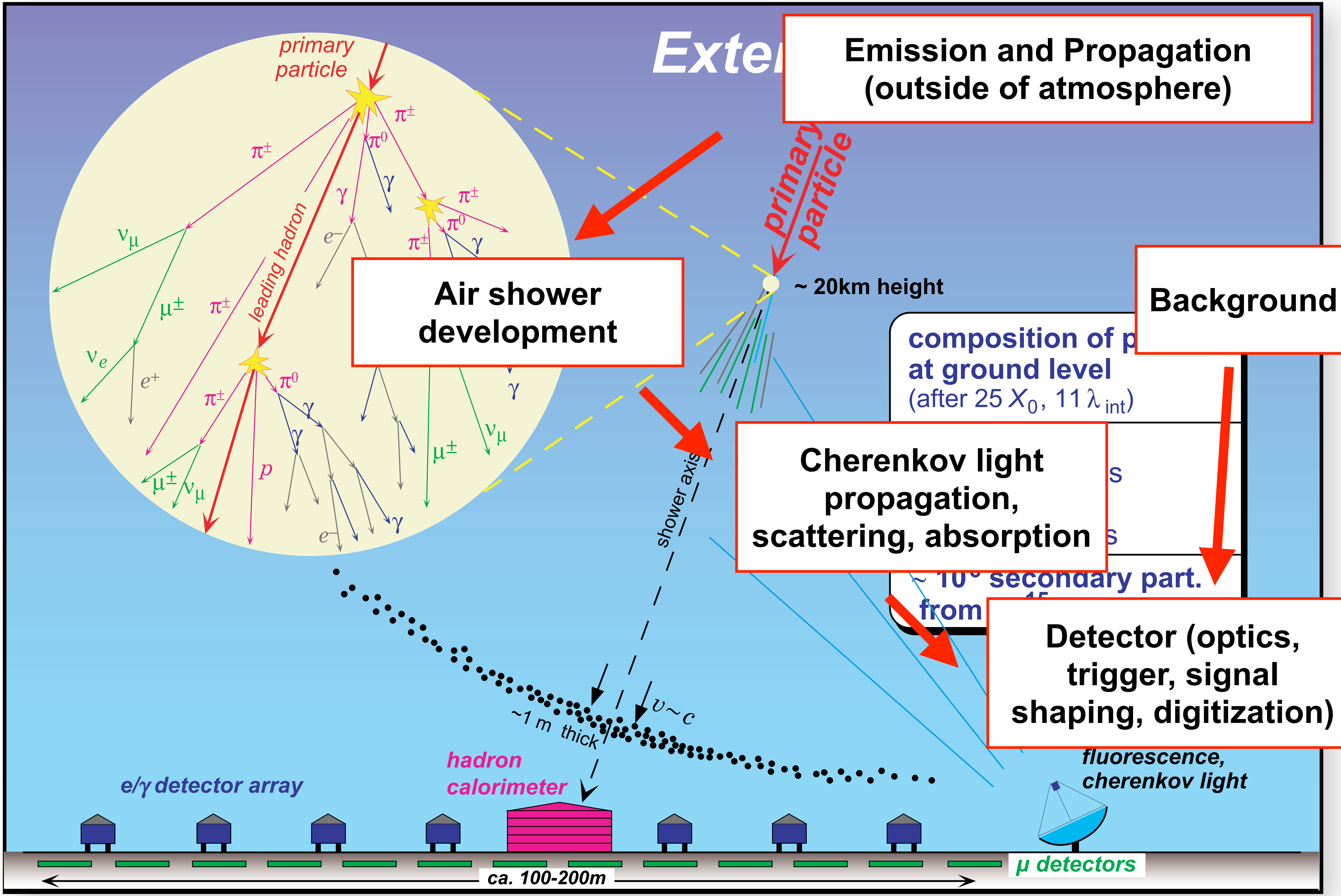
GeV …PeV

10^9 - 10^{15} eV

Extensive Air Showers




Extensive Air Showers
primary particle
leading hadron
Telescope
primary particle
~ 20km height
composition of part. at ground level
(after 25 X_0, 11 λ_{int})
~ 80 % photons
~ 18 % electrons
~ 1.7 % muons
~ 0.3 % hadrons
~ 10^6 secondary part. from 10^{15} eV proton
shower axis
$\upsilon \sim c$
~1 m thick
Detector
fluorescence, cherenkov light
hadron calorimeter
e/γ detector array
μ detectors
ca. 100-200m



Air showers are complicated: use Monte Carlo simulations.

Atmosphere.
Nature's calorimeter.

Atmosphere.

Tomorrow: detailed view on the atmosphere

- composition: 78% N_2, 21% O_2, 0.9% Ar.
- density (isothermal approximation):

$$\rho_{\mathrm{atm}}(h) \approx \rho_0 \mathrm{e}^{-h/h_0}$$

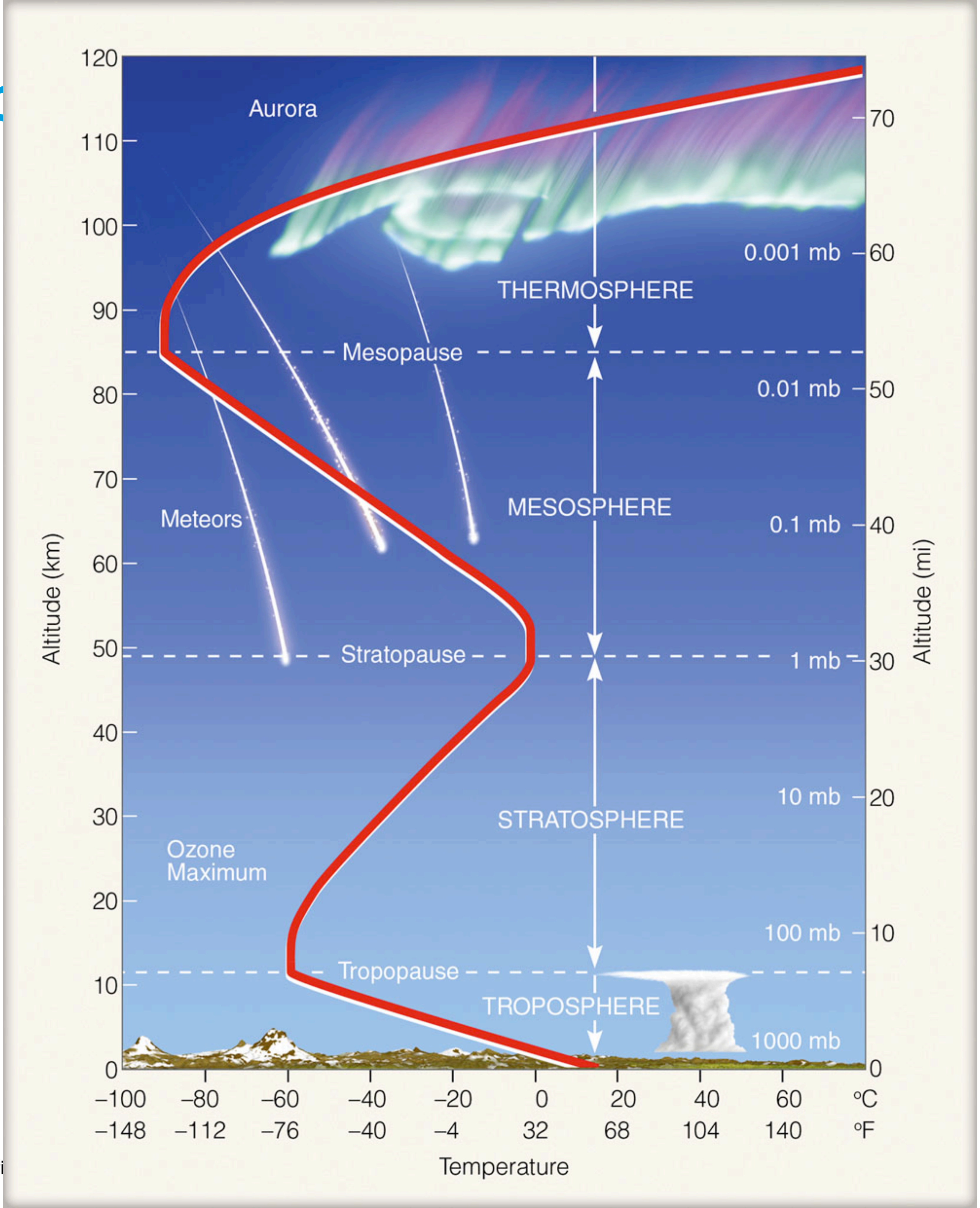
$\rho_0 \approx 1.225\ \mathrm{kg/m^3}$ scale height: $h_0 = RT/(\mu g) \approx 8.4\ \mathrm{km}$

- (for air shower simulations: need to be better than isothermal approximation)
- actual matter traversed by air shower: slant depth / thickness

$$X_v(h) = \int_h^\infty \rho_{\mathrm{atm}}(z)\,\mathrm{d}z$$

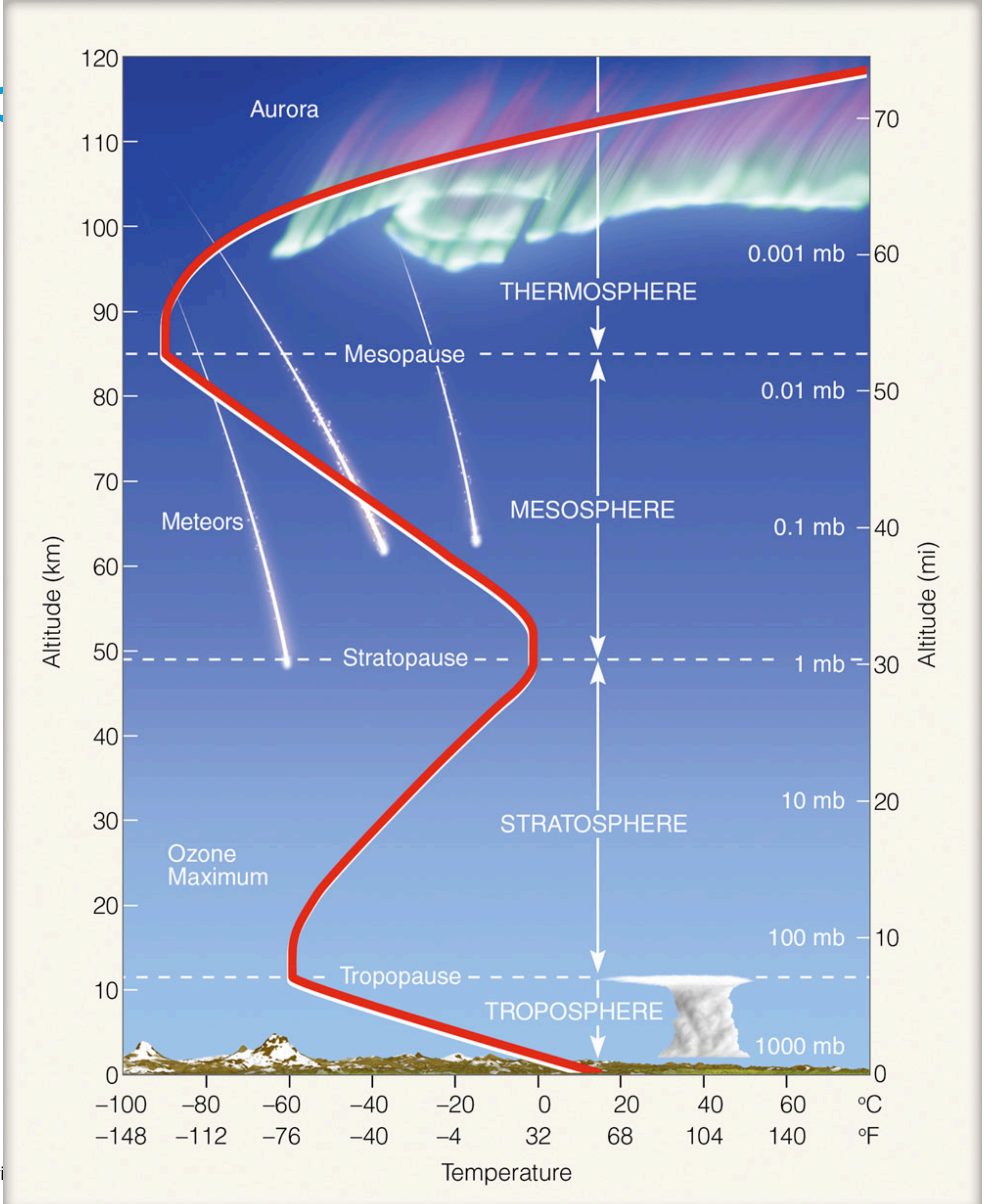
Atmosp

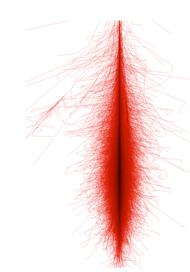
https://ghsearth.weebly.com/atmosphere.html



Atmosp

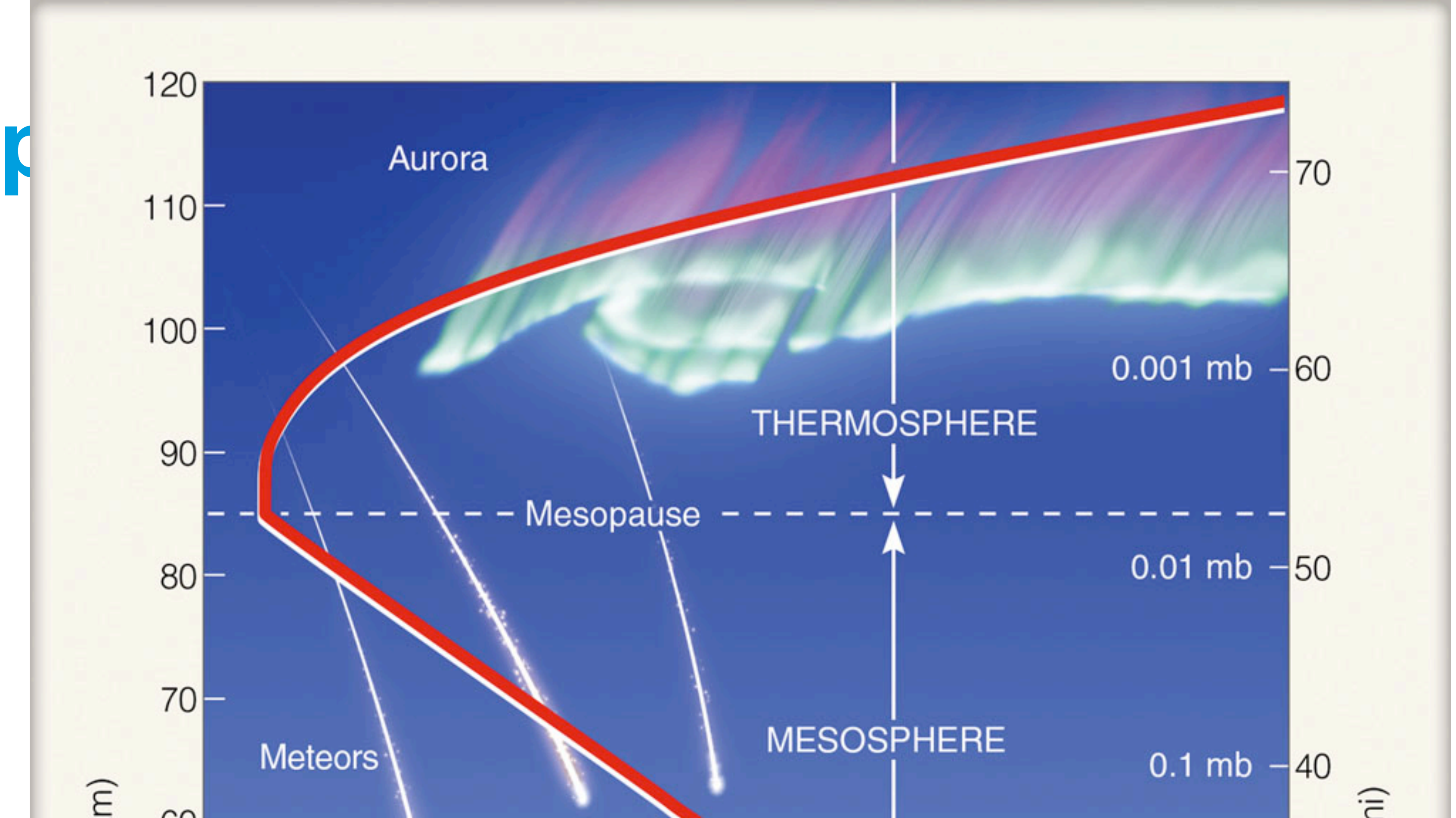
https://ghsearth.weebly.com/atmosphere.html

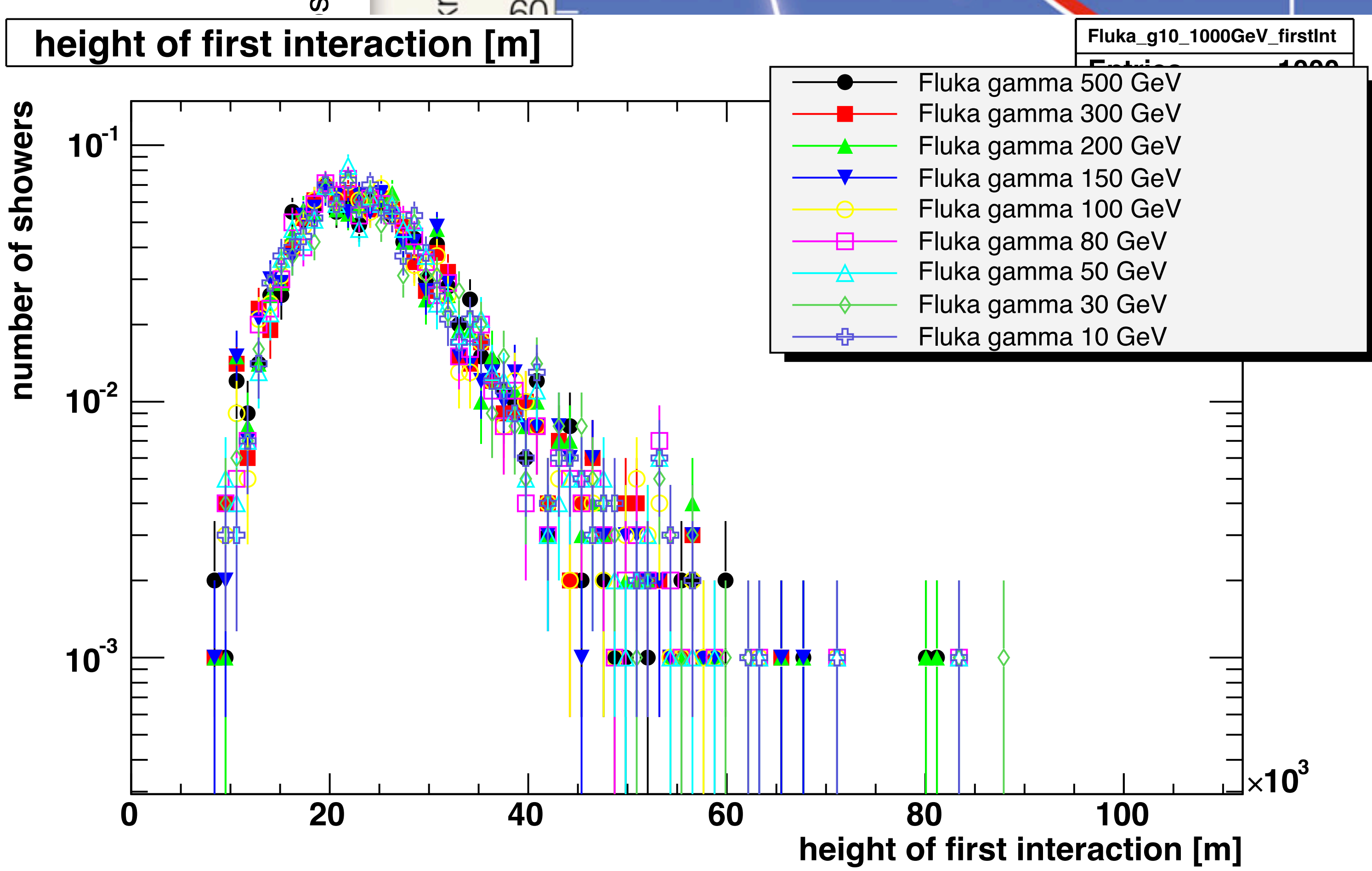


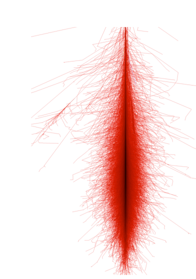


Atmosp

sphere.html

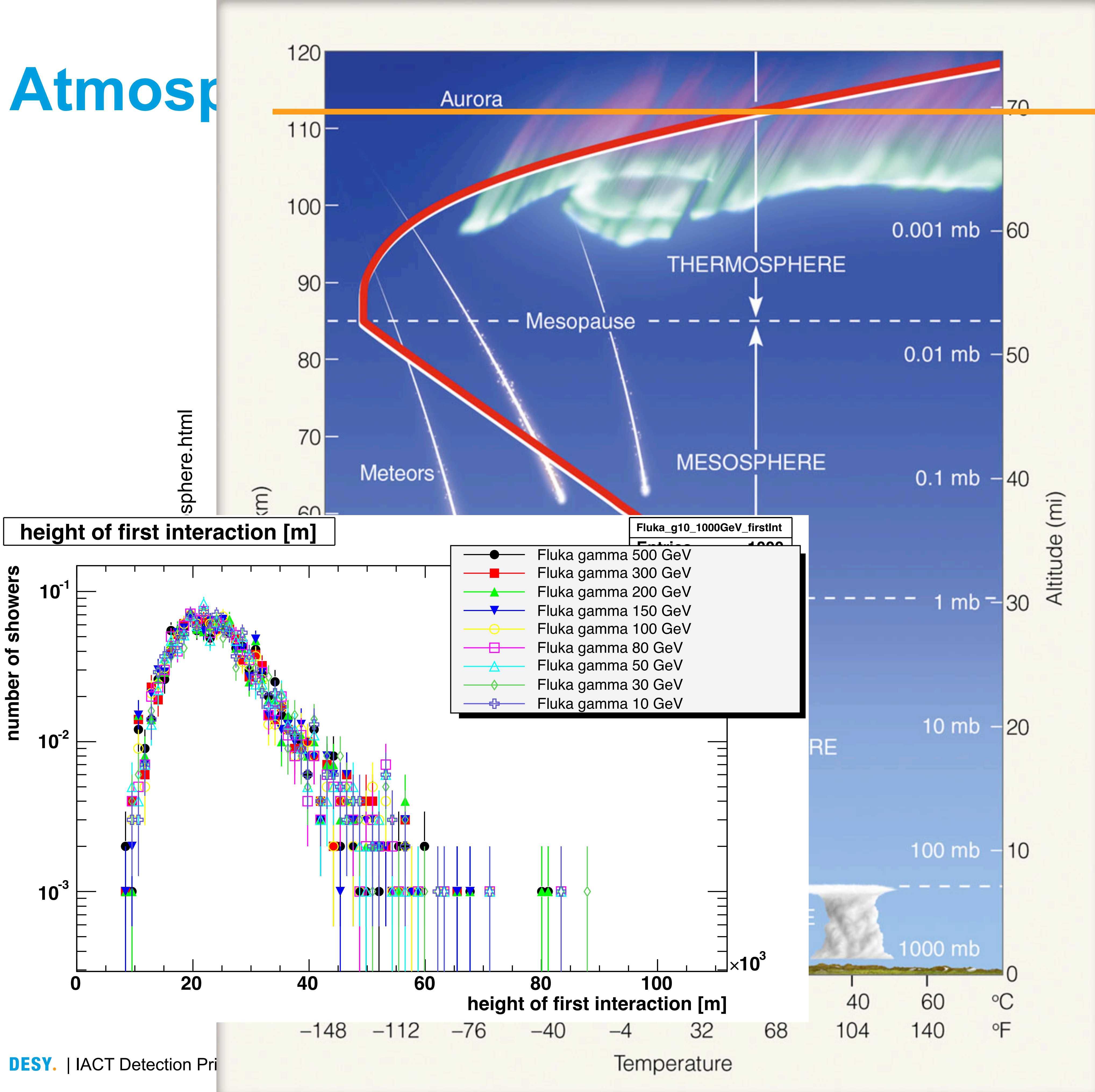






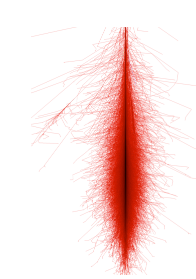
Atmosp

sphere.html



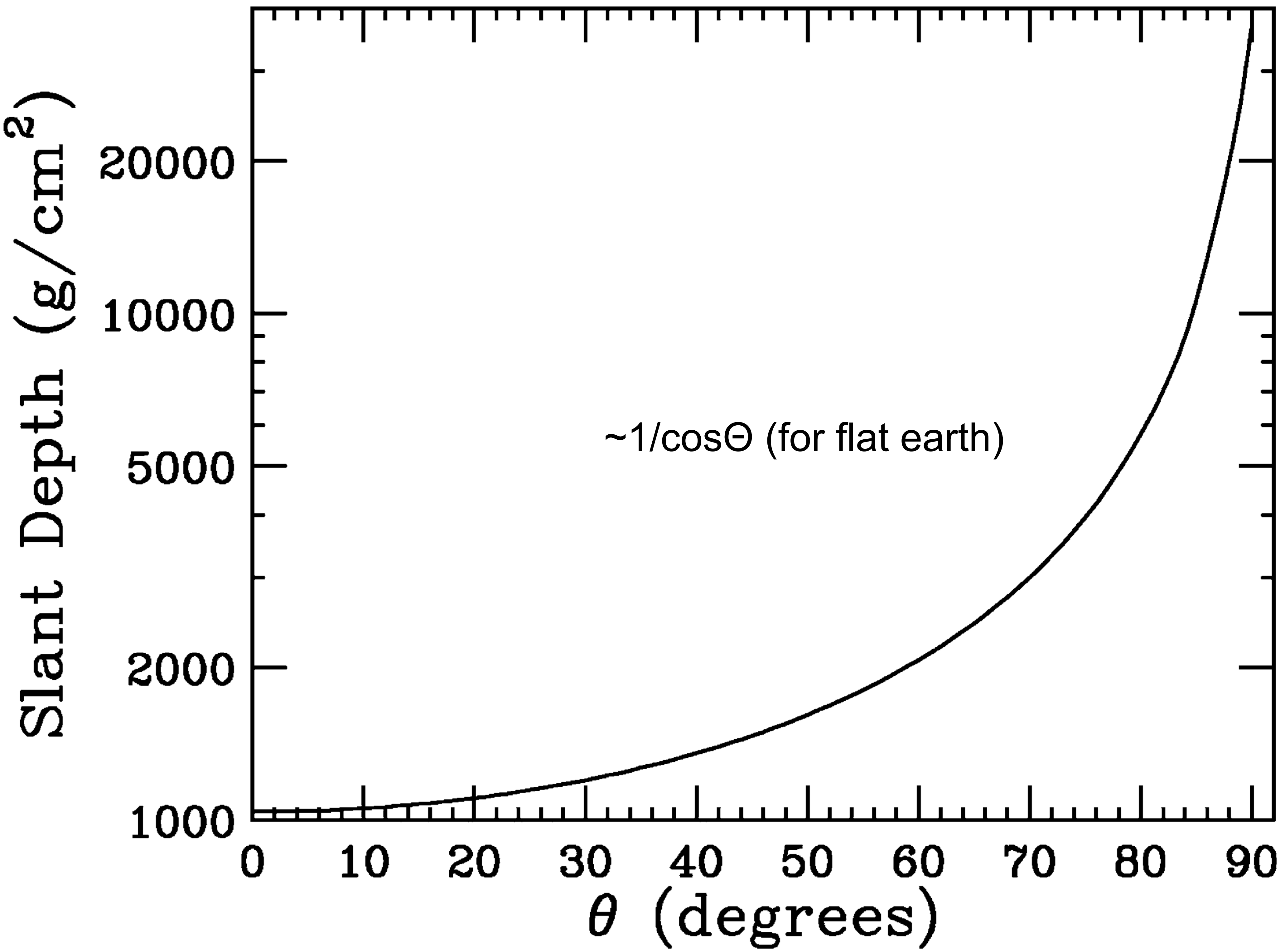
Shower simulations
(CORSIKA)

Top of atmosphere
112.8 km



Thickness vs zenith angle.

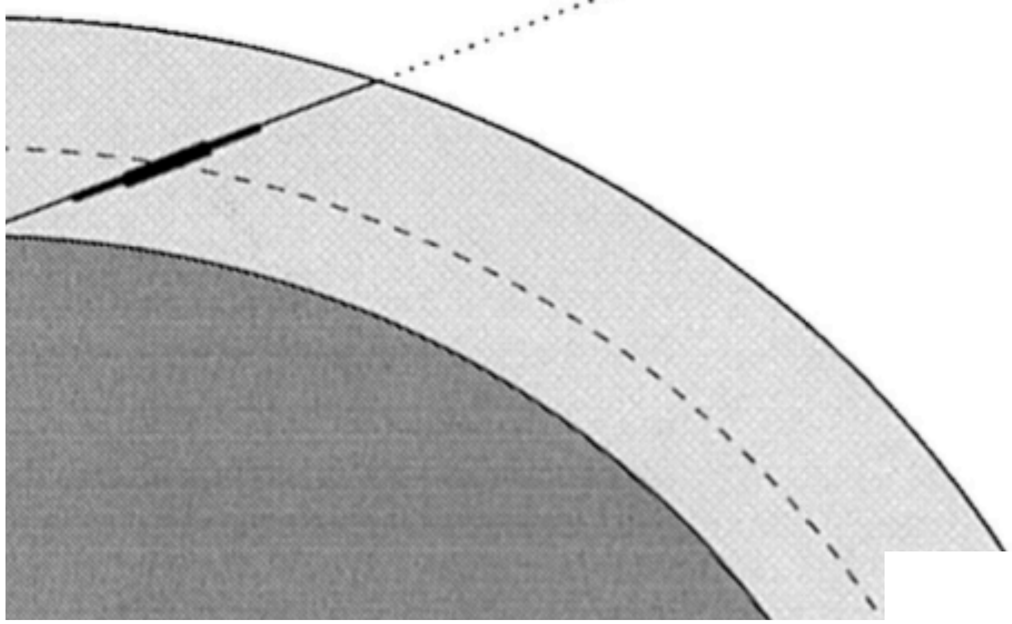
Anchordoqui et al. 2004

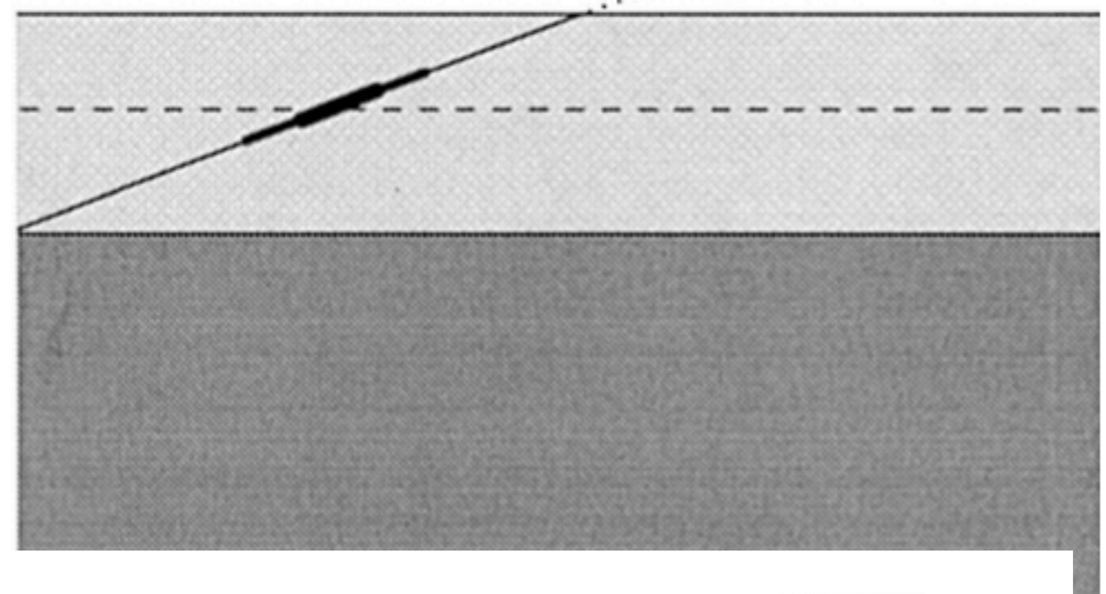


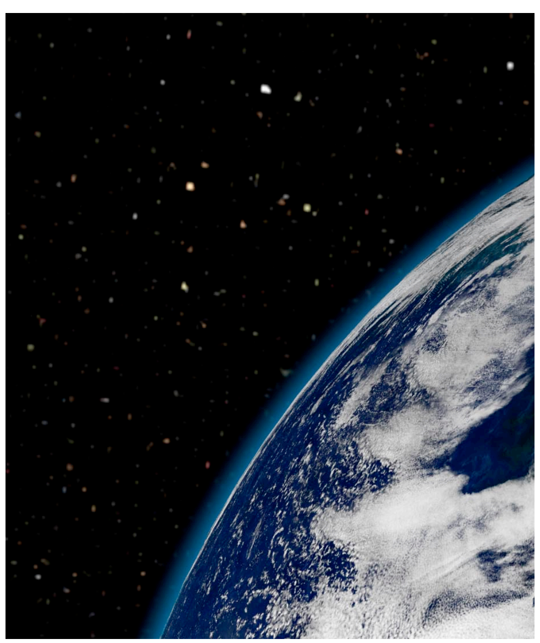
Flat earth.

Bernlöhr 2000

~4% difference in thickness at 80 deg for curved atmosphere







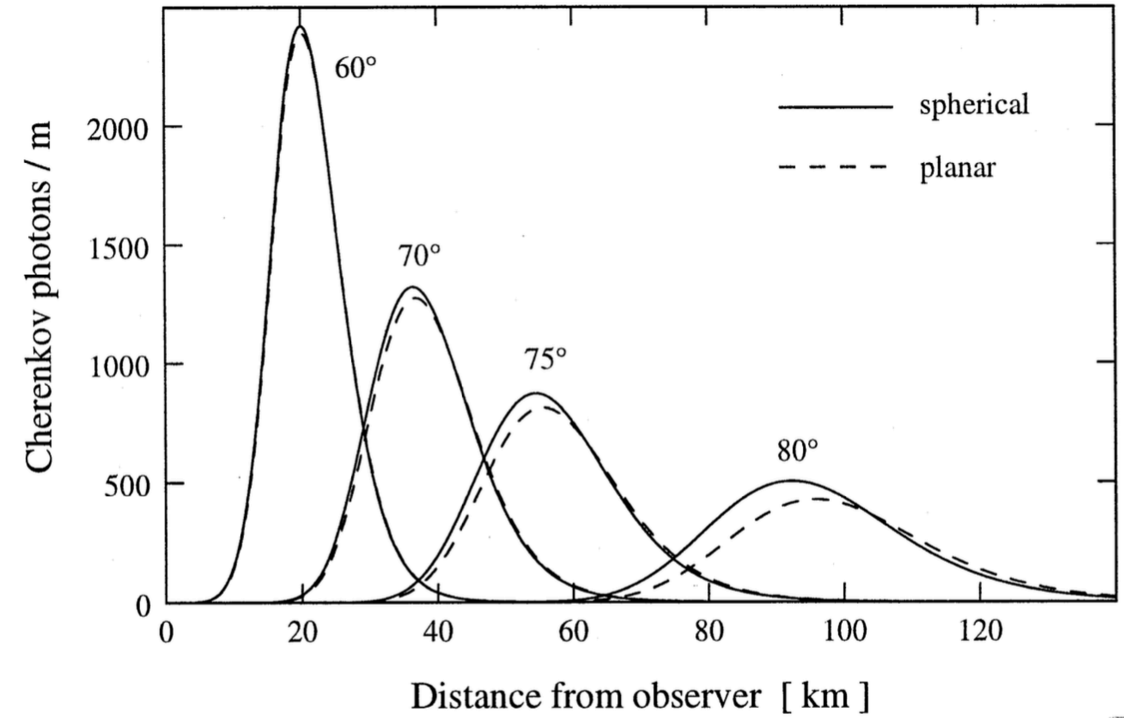
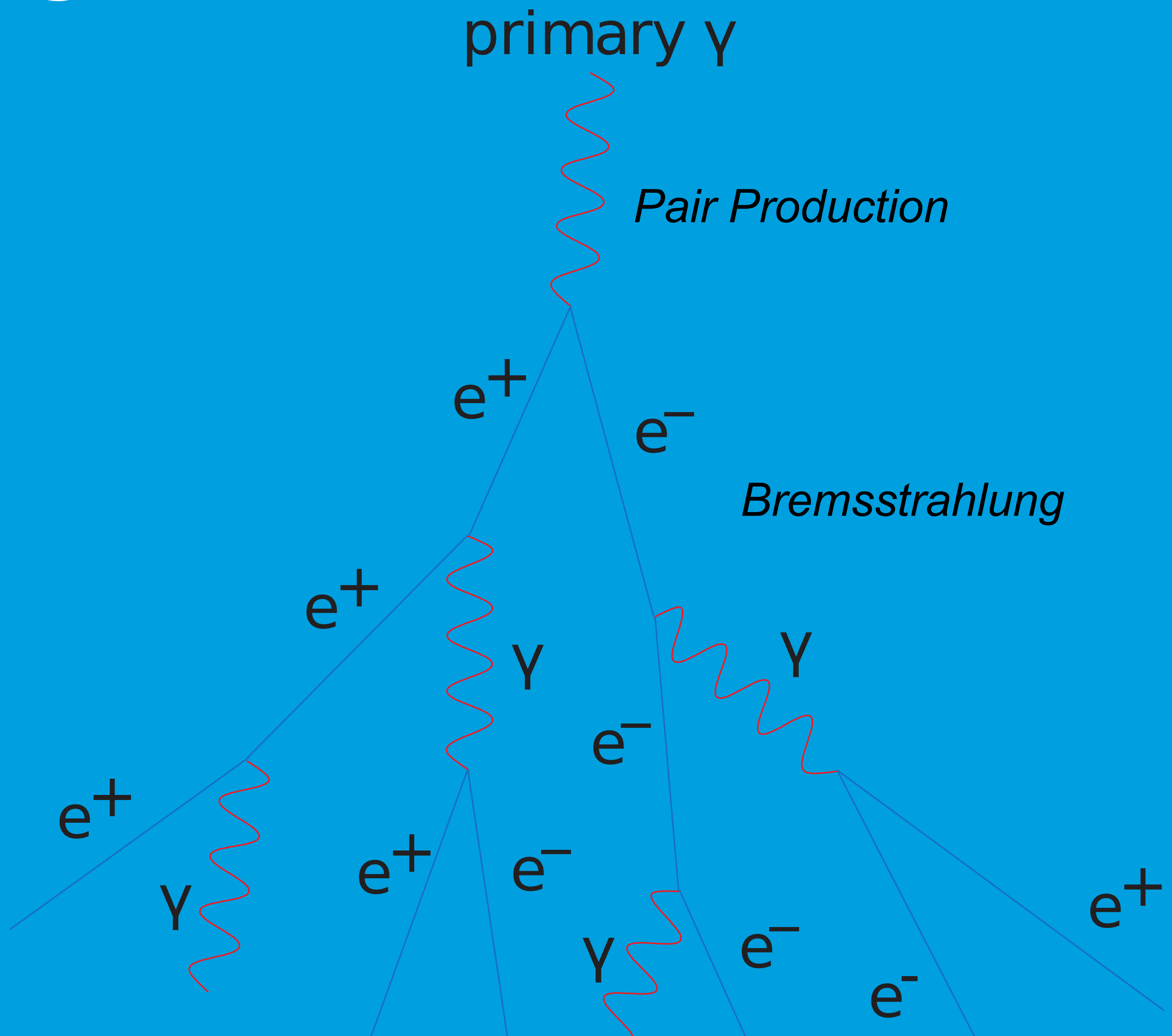


Fig. 14. The average longitudinal Cherenkov emission profile as a function of distance from the observer (Cherenkov photons emitted in the wavelength range 300–600 nm per meter along the

Air showers.
Primary Gamma.

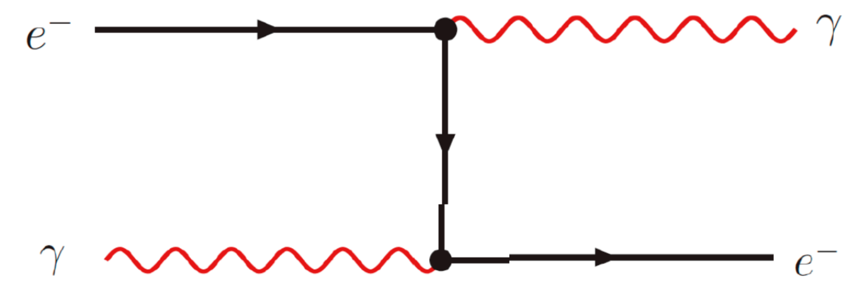


Z=atomic number

Bremsstrahlung.

$$e + Z \rightarrow e + \gamma + Z$$

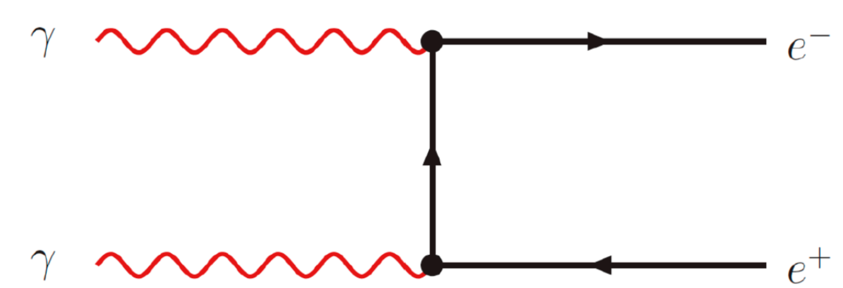
$$e + \gamma_{\mathrm{virtual}} \rightarrow e + \gamma$$



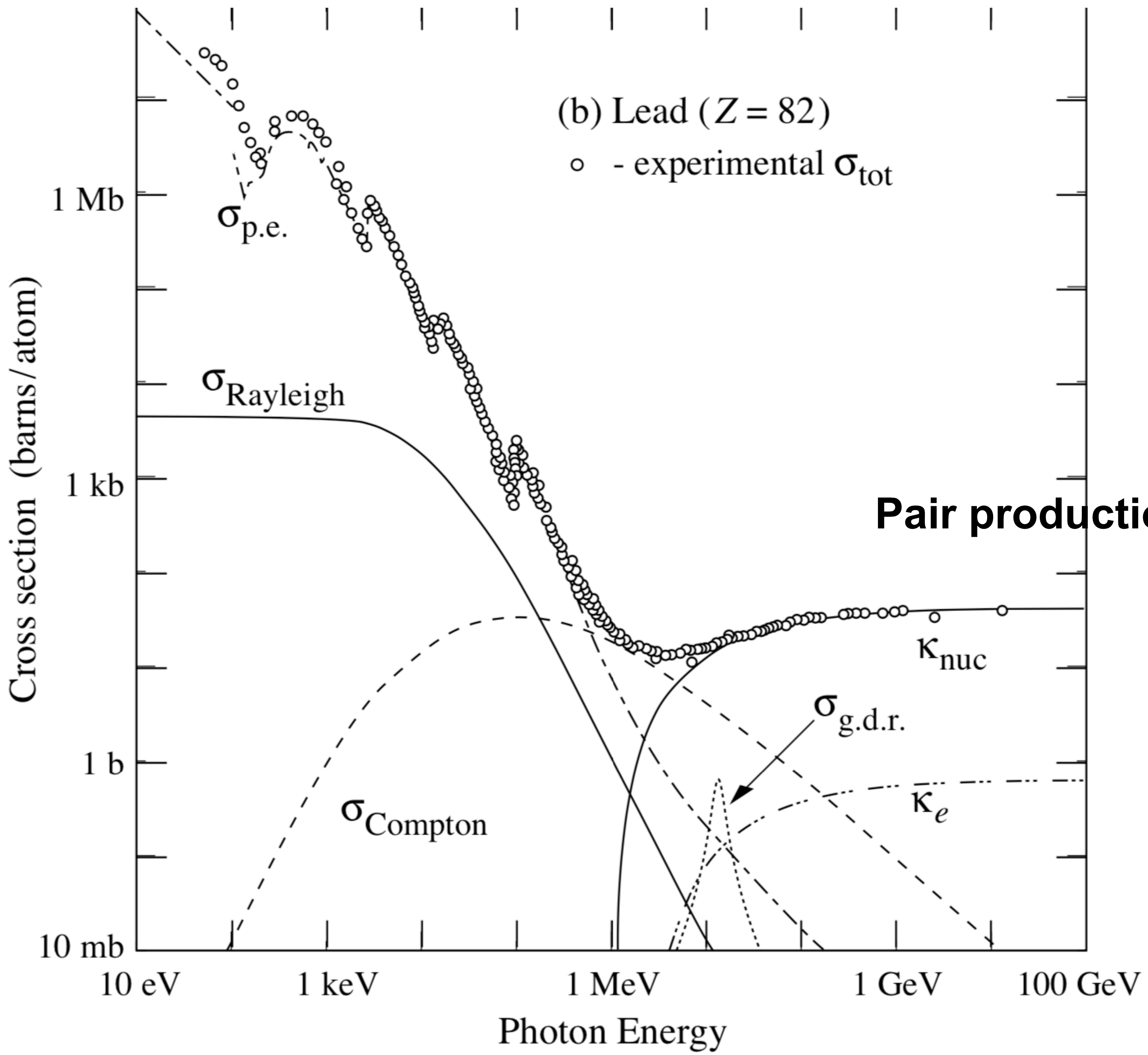
Pair production.

$$\gamma + Z \rightarrow e^+ + e^- + Z$$

$$\gamma + \gamma_{\mathrm{virtual}} \rightarrow e^+ + e^-$$



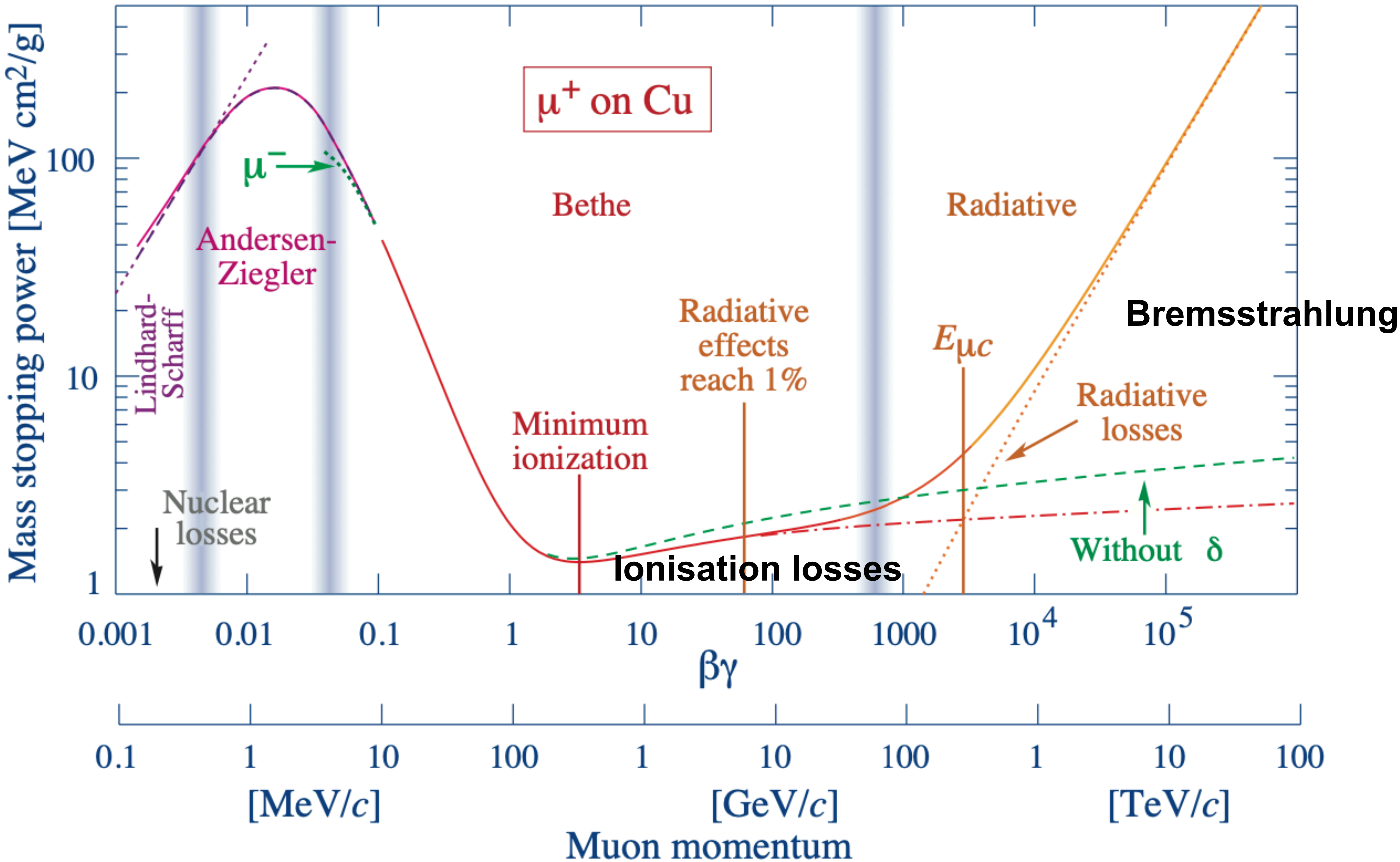
Photon interaction.



Pair production

Particle Physics Review

Energy losses electrons / muons.



Particle Physics Review

Radiation length.

characteristic amount of matter traversed by
electrons/positrons or photons

mean distances over which a high-energy electron reduces its energy by a factor 1/e	7/9th of the mean free path for pair production for a high-energy photon

From fit to data (Dahl):

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

mixtures:

$$1/X_0 = \sum w_j/X_j$$

w_j: fraction by weight

$$\text{Air: } X_0 \approx 37\,\text{g/cm}^2$$

Scale variable frequently used:

$$t = x/X_0,$$

Radiation length vs "Pair length"

Physical Meaning of the "Radiation Length"

$$\langle E_e(X) \rangle = E_e(0)\; e^{-X/\lambda_{\rm rad}}$$

Physical Meaning of the "Pair Length"

$$N_\gamma(X) = N(0)\; e^{-X/\lambda_{\rm pair}}$$

$$\lambda_{\rm rad}^{\rm air} \simeq 37\;\frac{\rm g}{\rm cm^2}$$

$$\lambda_{\rm pair} \simeq \frac{9}{7}\;\lambda_{\rm rad}$$

(Slide from Lipari 2018)

Radiation vs ionization losses - Critical energy.

$$dE/dX = -\alpha(E) - E/X_0$$

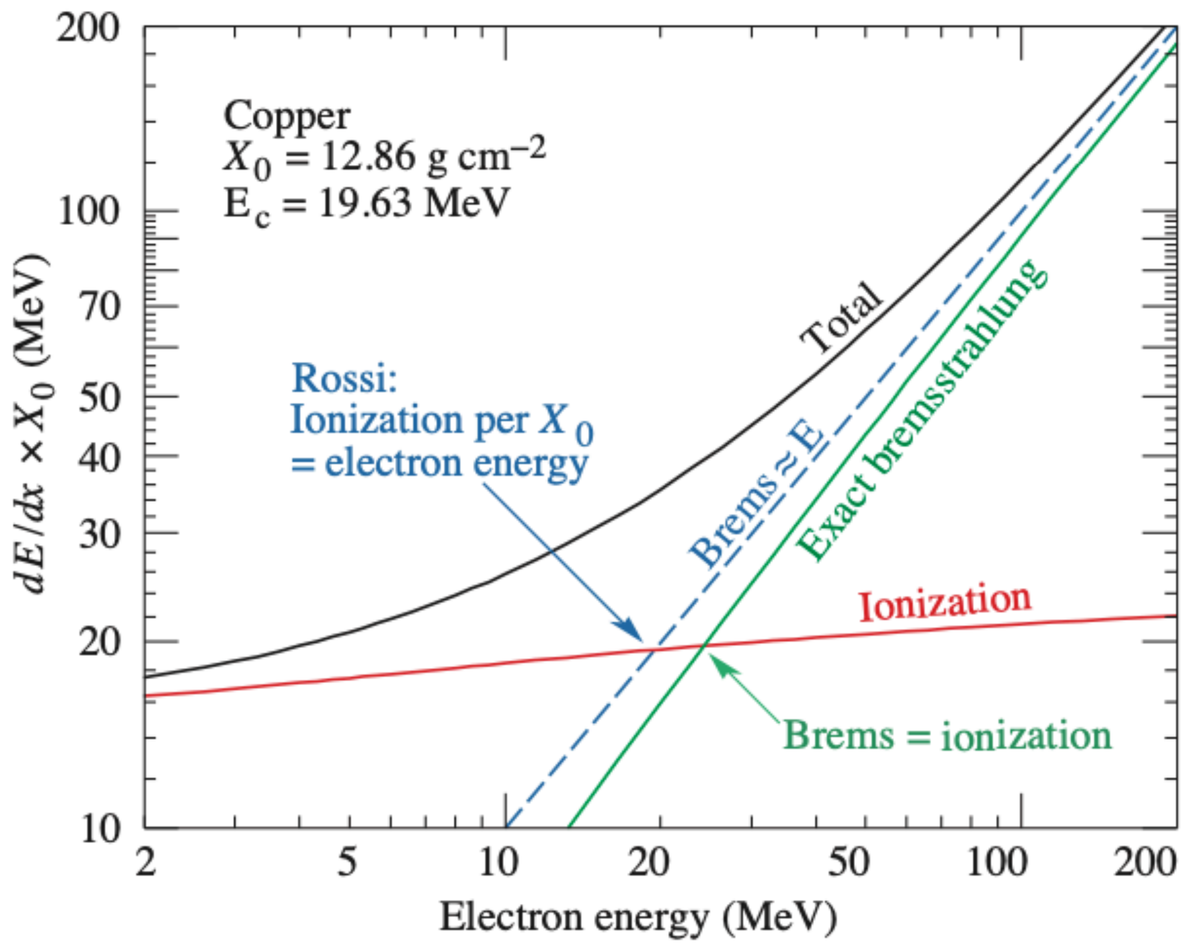


Figure 34.13: Two definitions of the critical energy E_c.

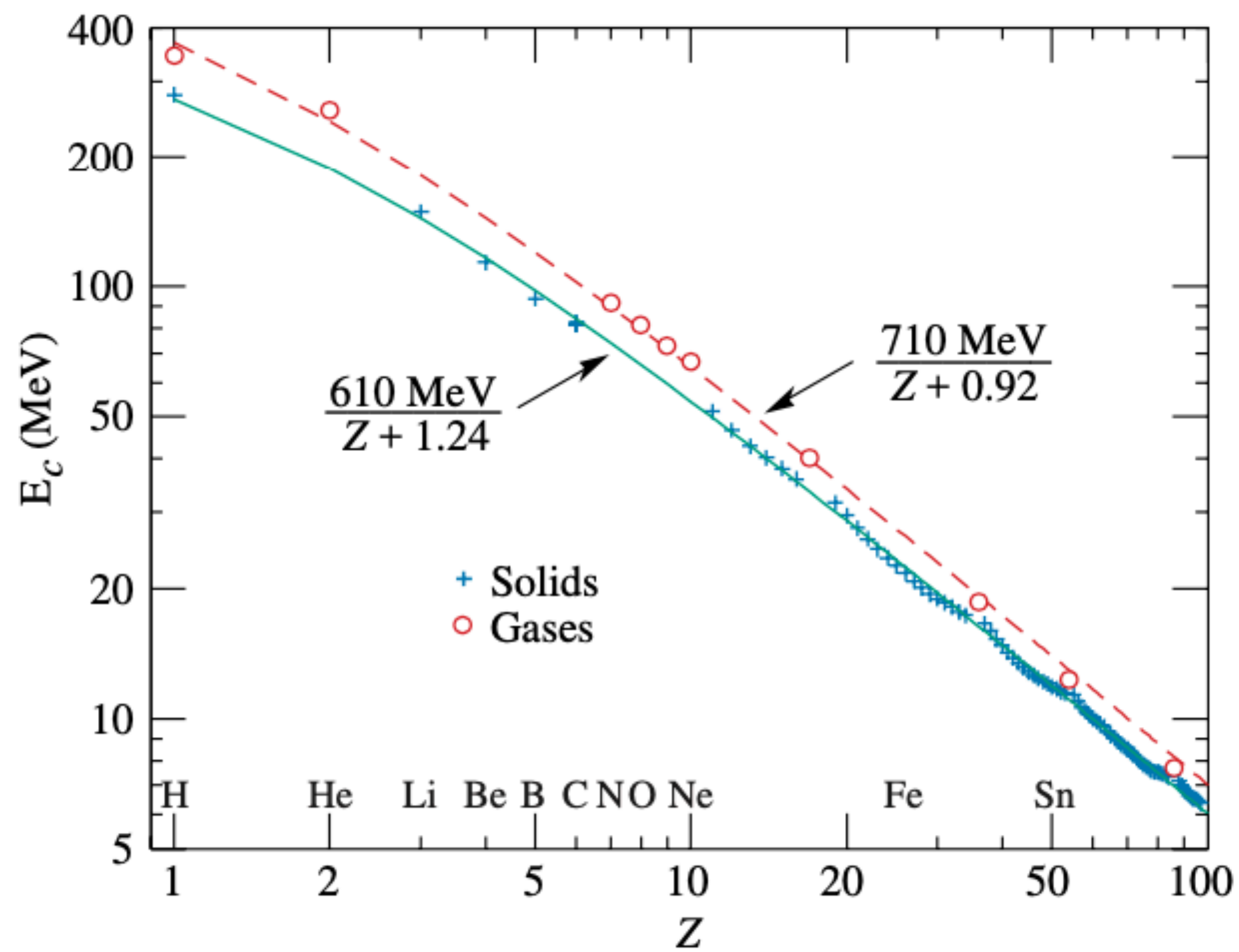
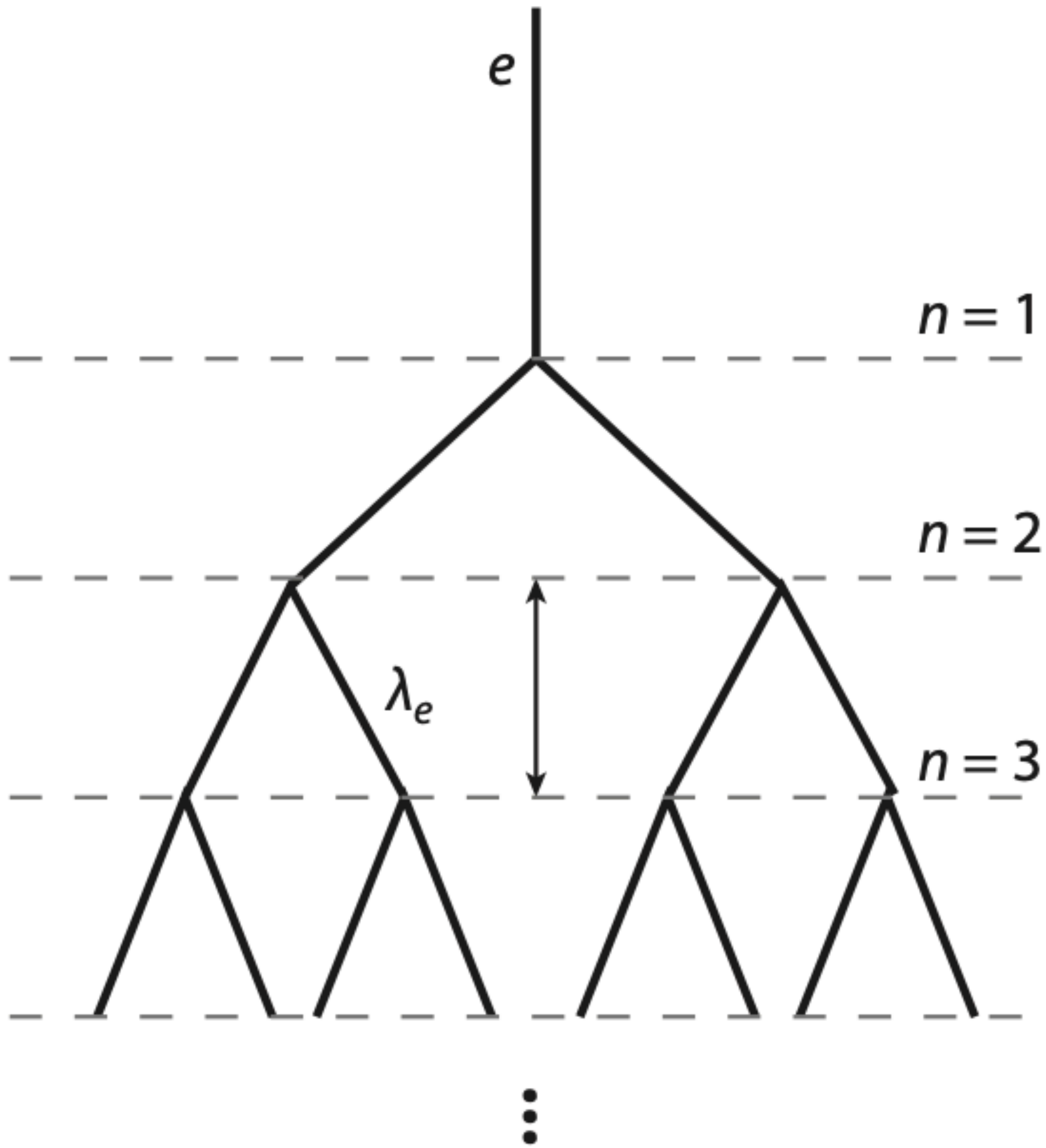


Figure 34.14: Electron critical energy for the chemical elements, using Rossi's definition [2]. The fits shown are for solids and liquids (solid line) and gases (dashed line). The rms deviation is 2.2% for the solids and 4.0% for the gases.

Air: $E_c \approx 85\,\mathrm{MeV}$

Heitler model.

(introduced by Carlson & Oppenheimer 1937)



Simplification:

- one "electron-photon" particle
- initial energy E
- any interaction leads to two new particles of energy E/2
- characteristic splitting length X_0
- critical energy E_C

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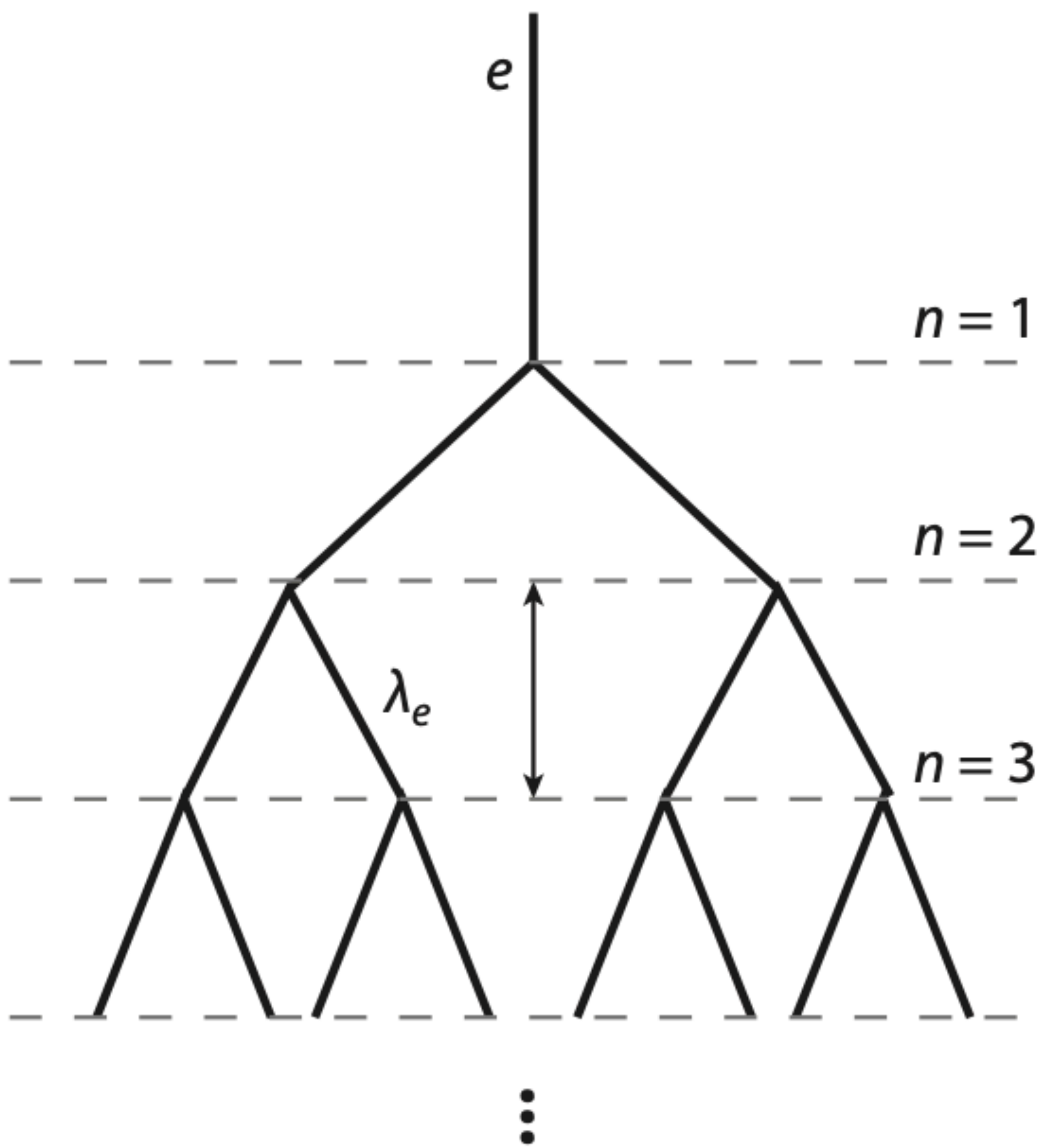
(introduced by Carlson & Oppenheimer 1937)



Shower development stops at

$$\frac{E}{2^n} = E_c$$

Maximum number of particles

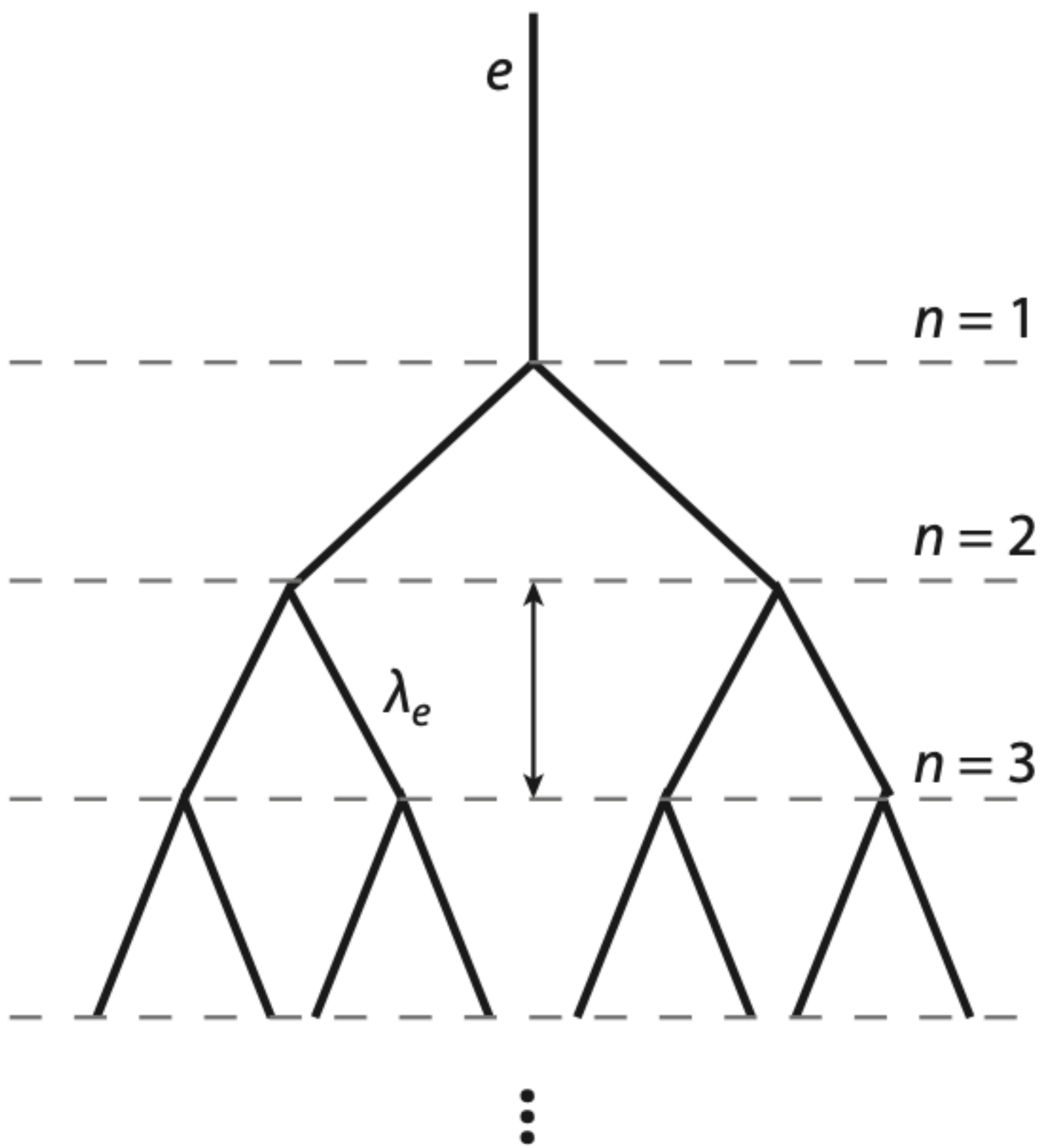
$$N_{max} = 2^n$$
$$= 2^{\log_2 E/E_c}$$
$$= E/E_c$$

Shower maximum at

$$X_{max} \propto X_0 \log \frac{E}{E_C}$$

Heitler model.

(introduced by Carlson & Oppenheimer 1937)



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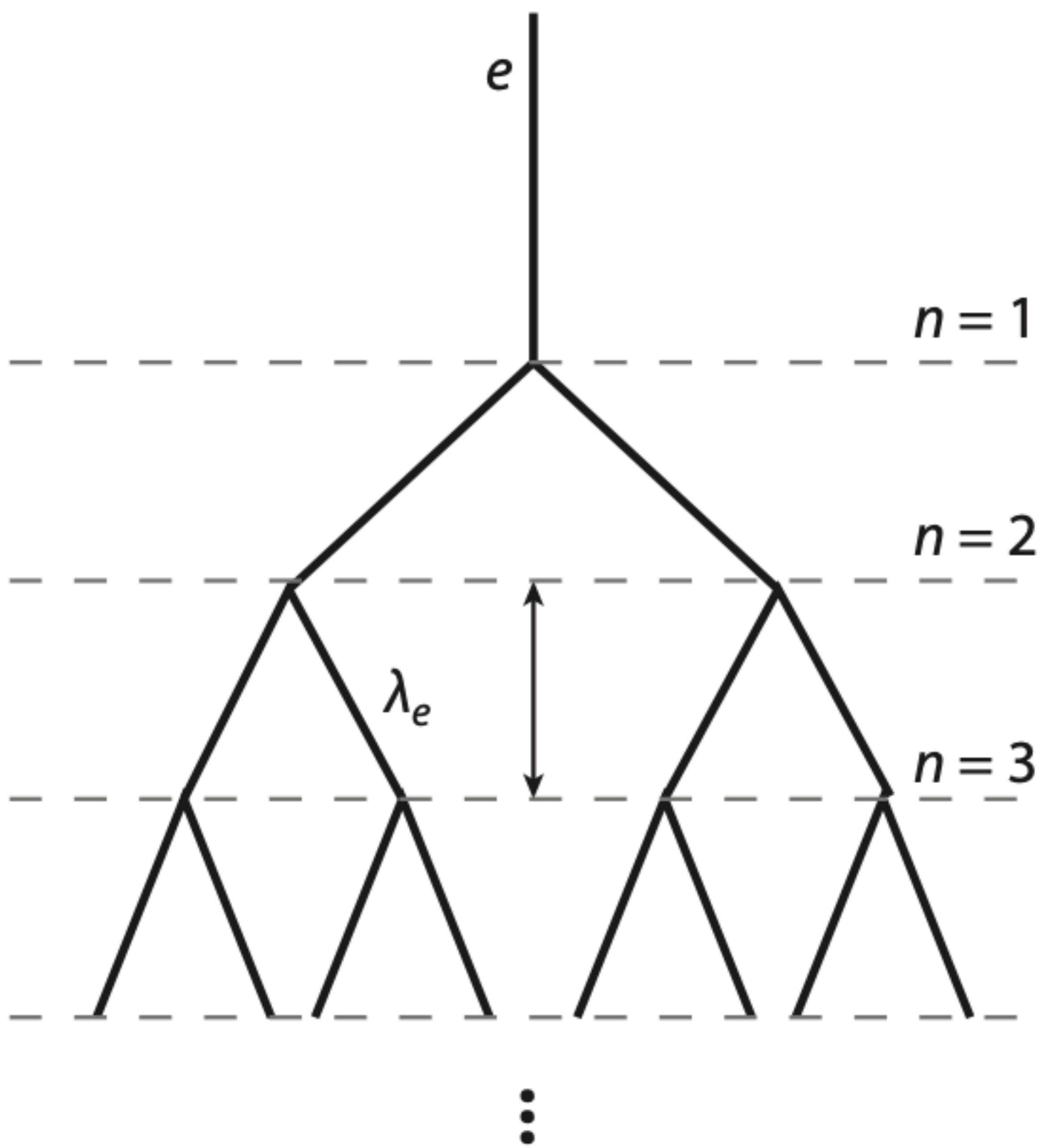


Simplification:

- one "electron-photon" particle
- initial energy E
- any interaction leads to two new particles of energy E/2
- characteristic splitting length X_0
- critical energy E_C

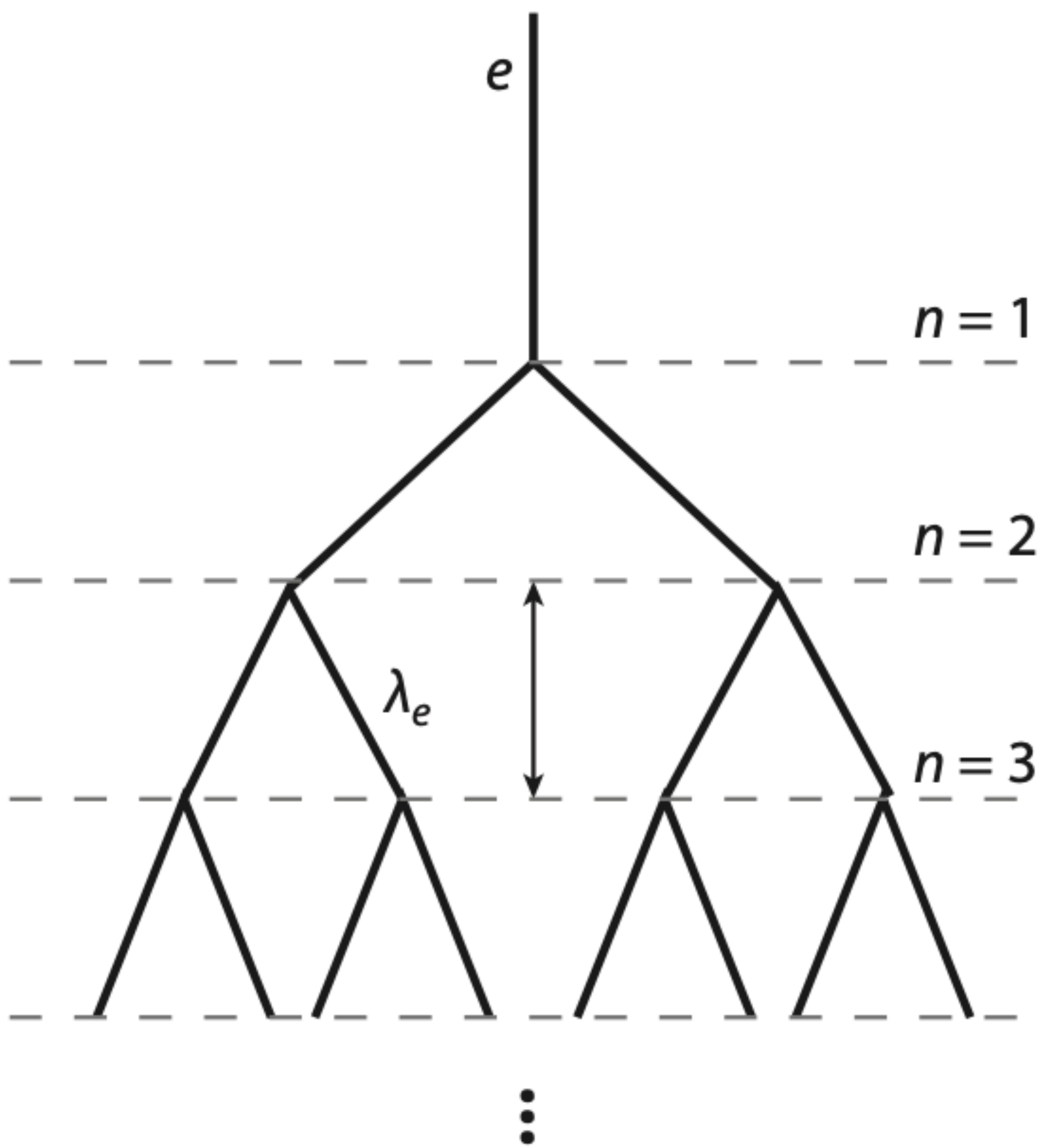
Surprisingly good:

- X_{max} predictions quite good
- e/ɣ assumed to be 2, in reality closer to 1/6

Why is it a simplification?

Heitler model.

(introduced by Carlson & Oppenheimer 1937)



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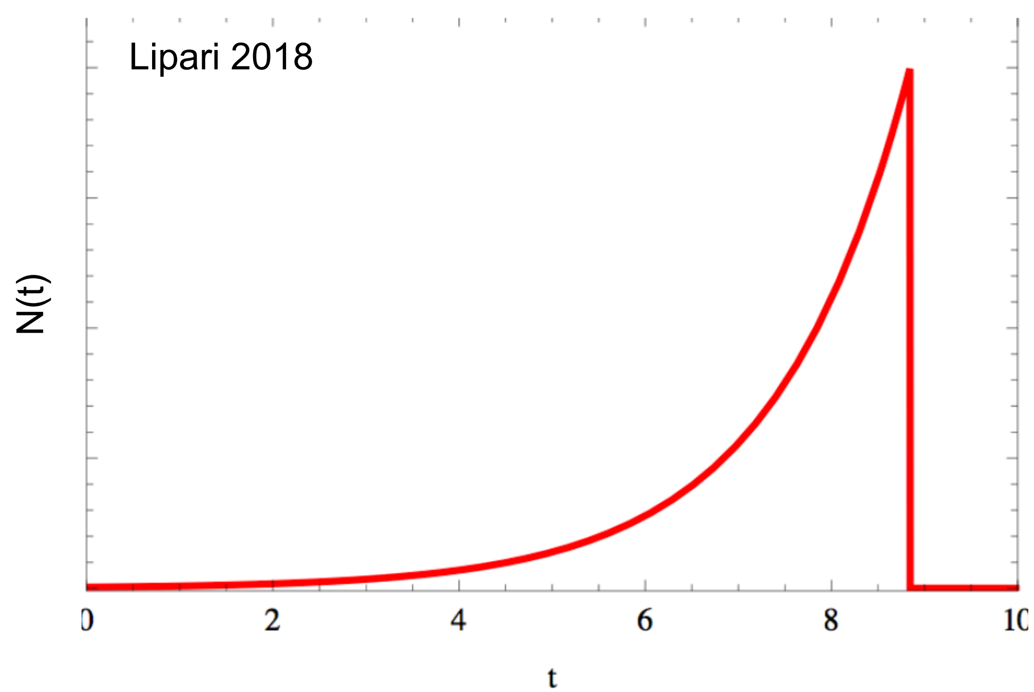
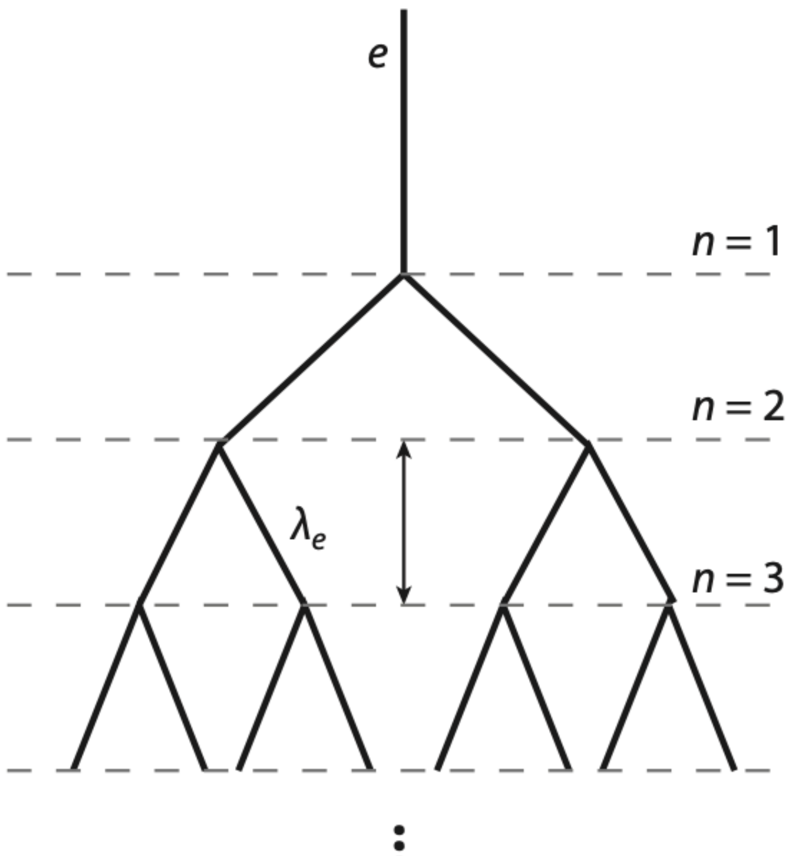


Heitler model. Simplifications.

- particle interactions are stochastic processes
- atmosphere is complicated (e.g., density profile)
- analytical solutions insufficient -> Monte Carlo Methods



Simplification (what is wrong):

- ✗ one "electron-photon" particle
- ✓ initial energy E
- ✗ any interaction leads to two new particles of energy E/2
- ✗ characteristic splitting length X_0
- ✗ critical energy E_C

Any interaction leads to two new particles with E/2?

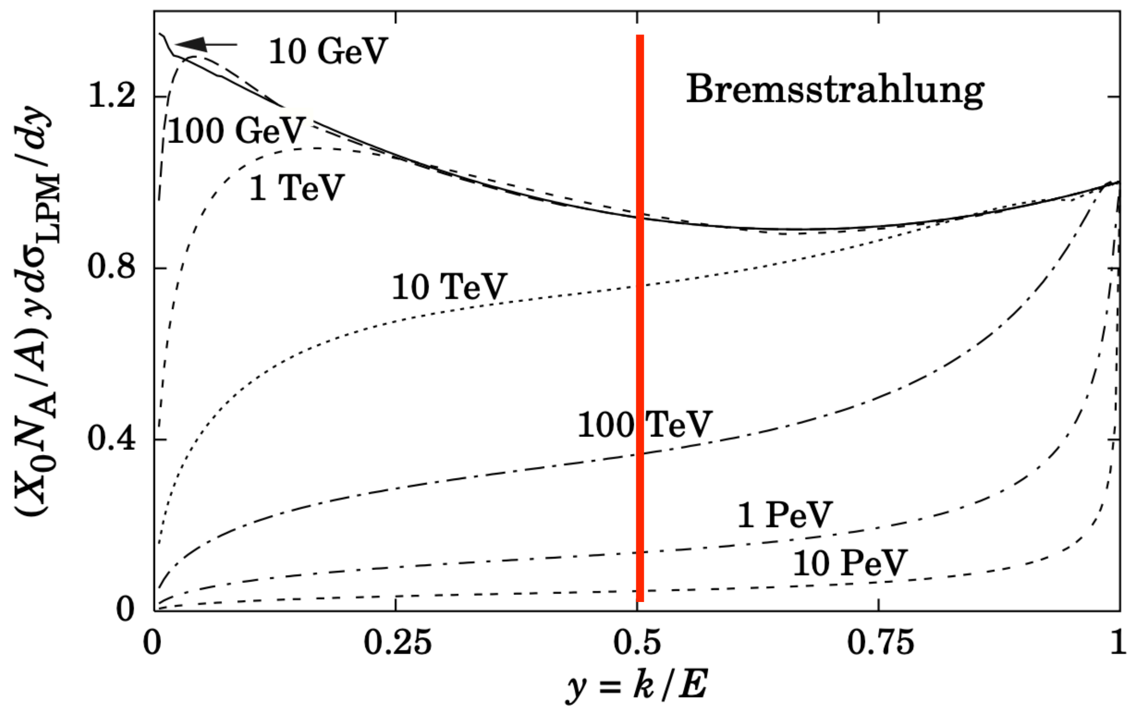


Figure 34.12: The normalized bremsstrahlung cross section $k\, d\sigma_{LPM}/dk$ in lead versus the fractional photon energy $y = k/E$. The vertical axis has units of photons per radiation length.

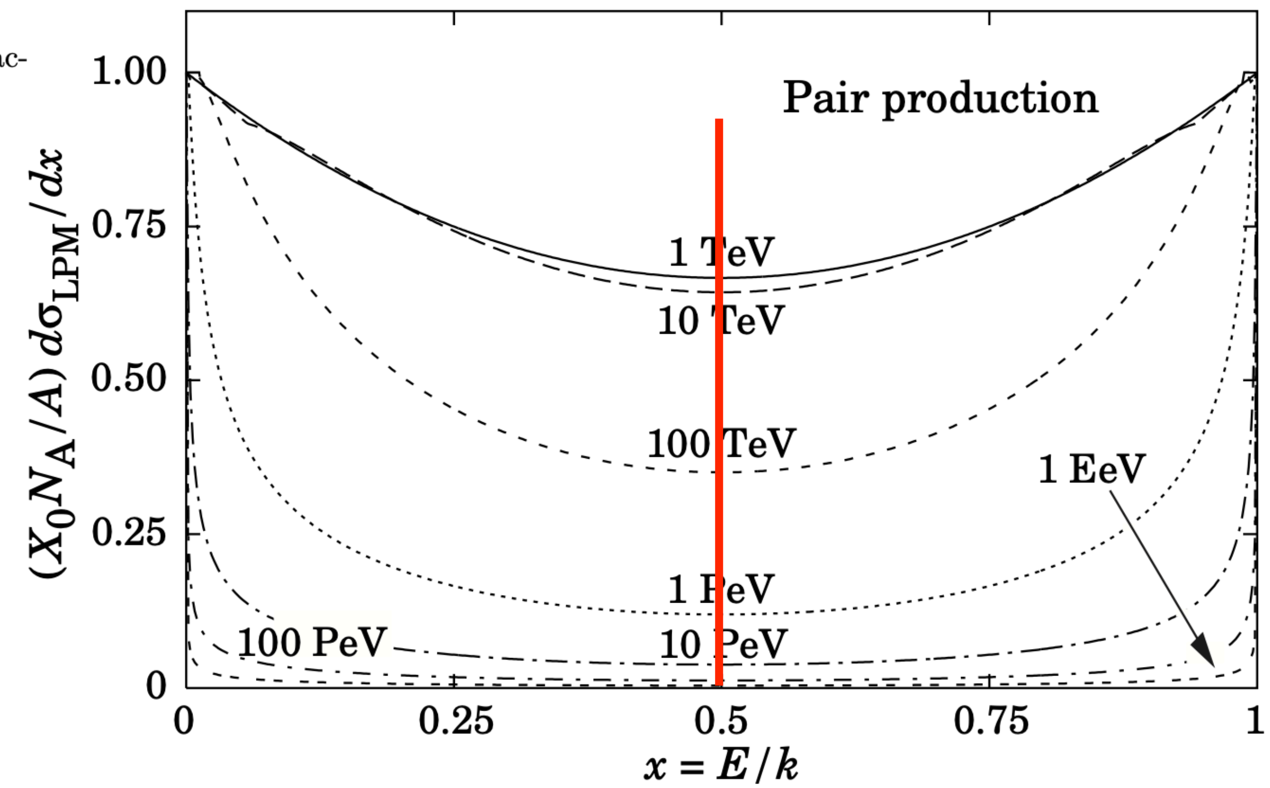
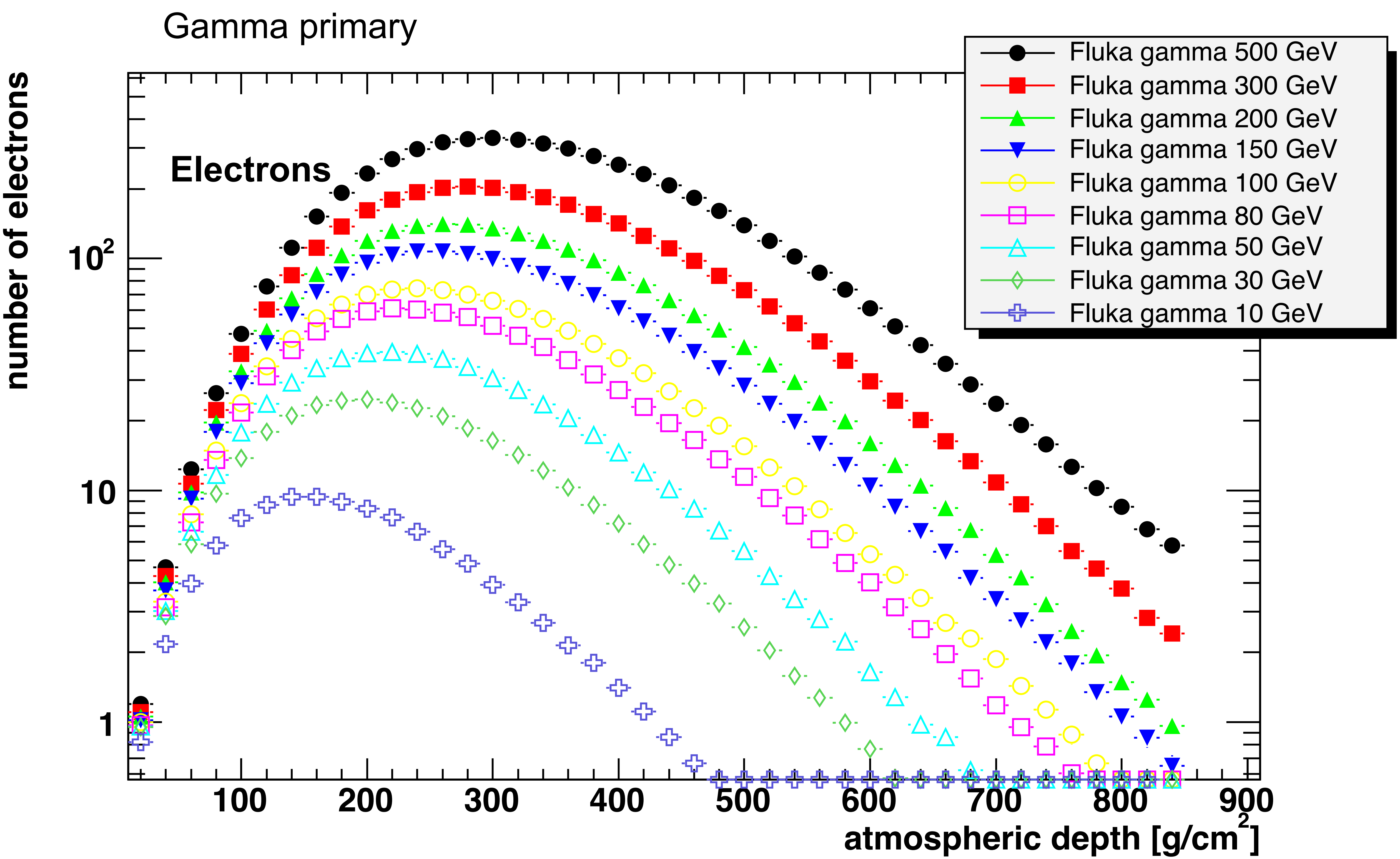
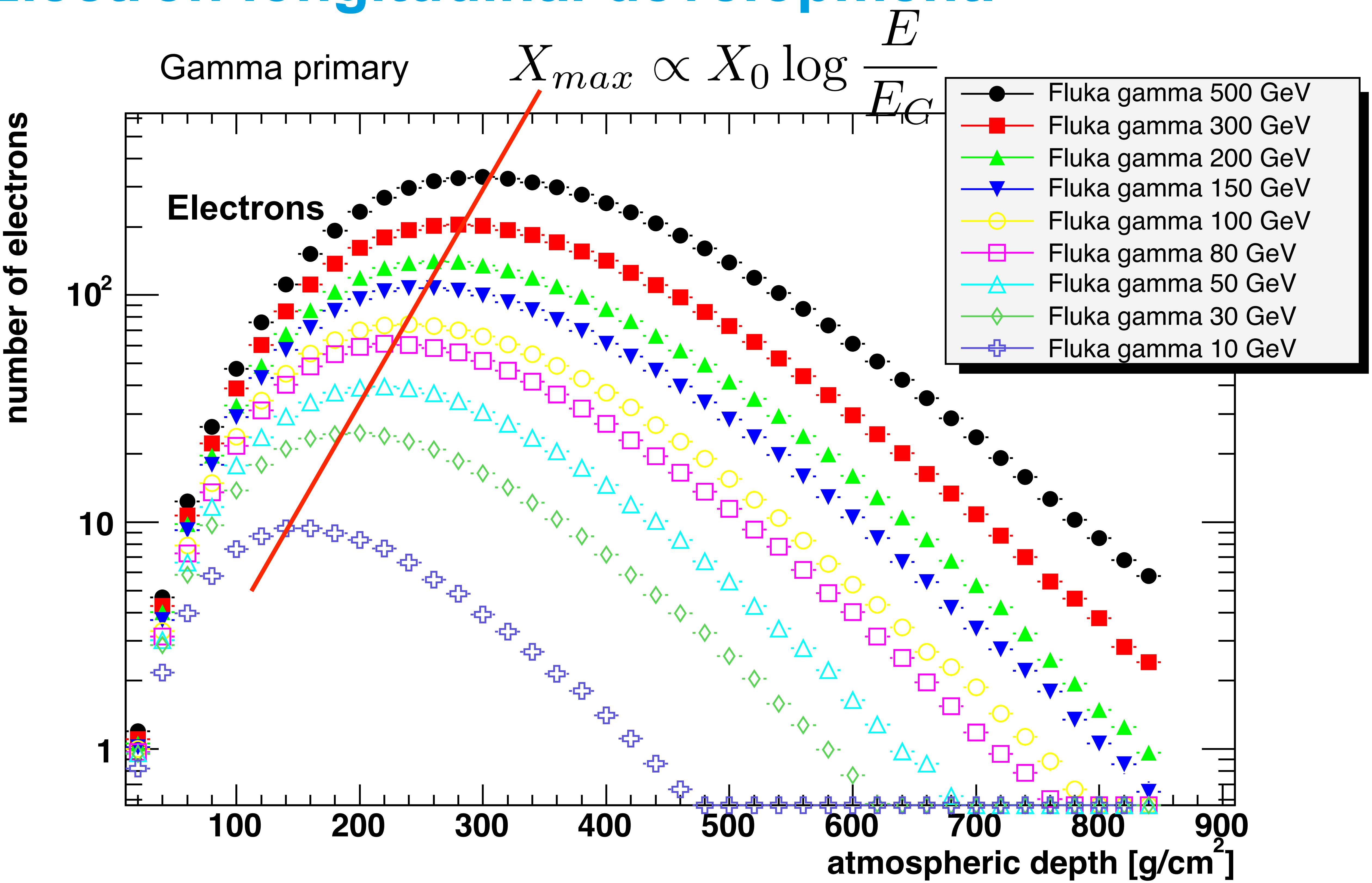


Figure 34.18: The normalized pair production cross section $d\sigma_{LPM}/dx$, versus fractional electron energy $x = E/k$.

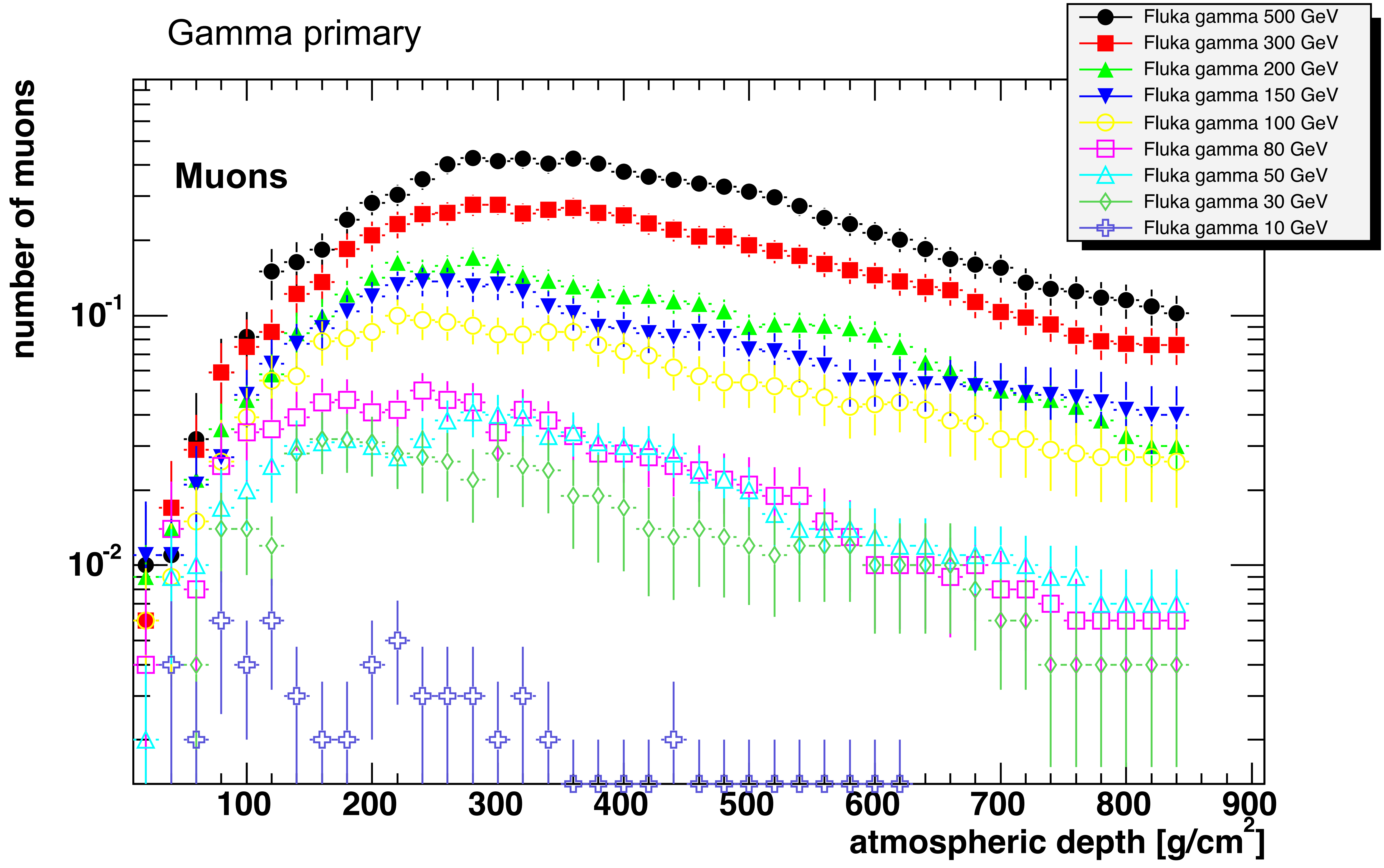
Electron longitudinal development.



Electron longitudinal development.



Non-EM particles in gamma-ray showers.



Pair production cross section with $1/m^2$ term.

Air showers.
Primary Hadrons.

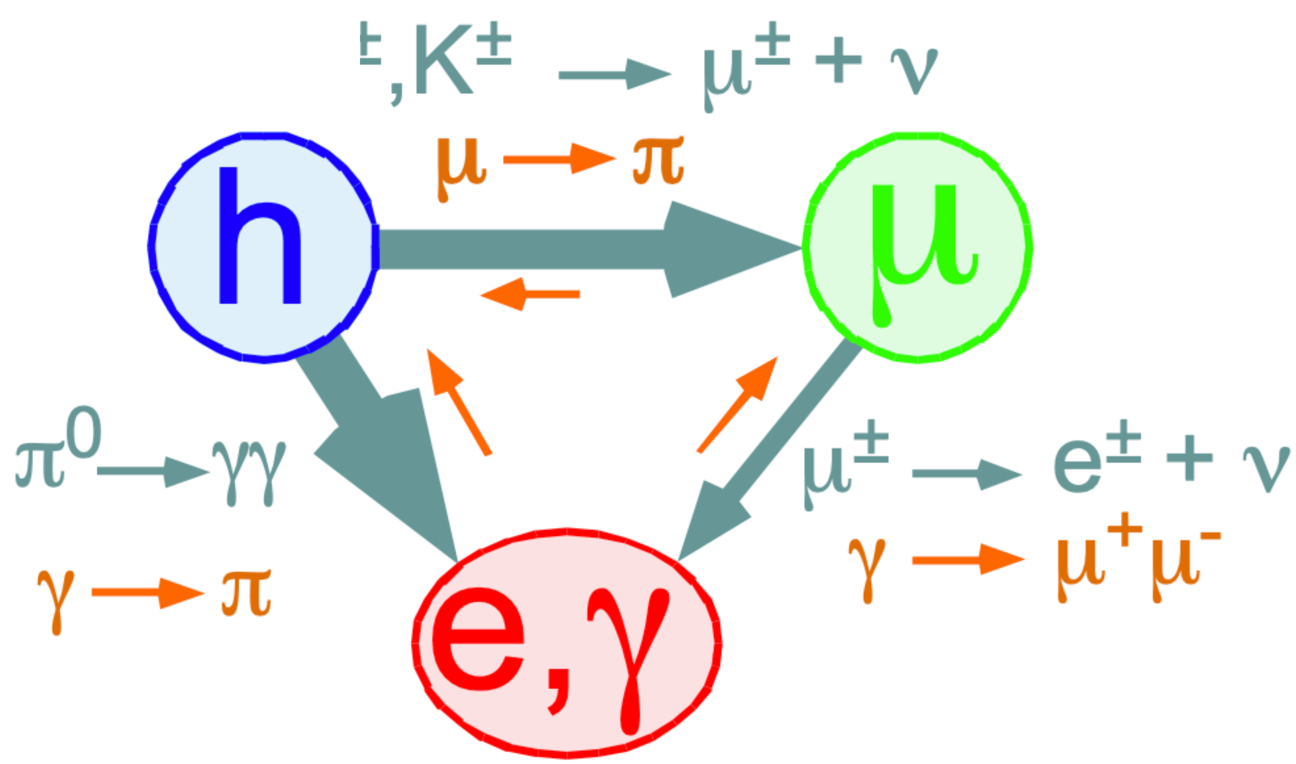
Why do we care?

Hadronic showers.

- different secondaries, transverse momentum, resonances, QCD color flows, string fragmentation, jet production, pomerons, parton densities, … this is complicated...
  - absolute necessity of good models (LHC!).
  - QGSJet, Epos, Sibyl, FLUKA, URQMD, ...
- basic picture from simplified model:
  - produce pions, muons, e^-/e^+, γ's

Energy flow.

J.Knapp 2017

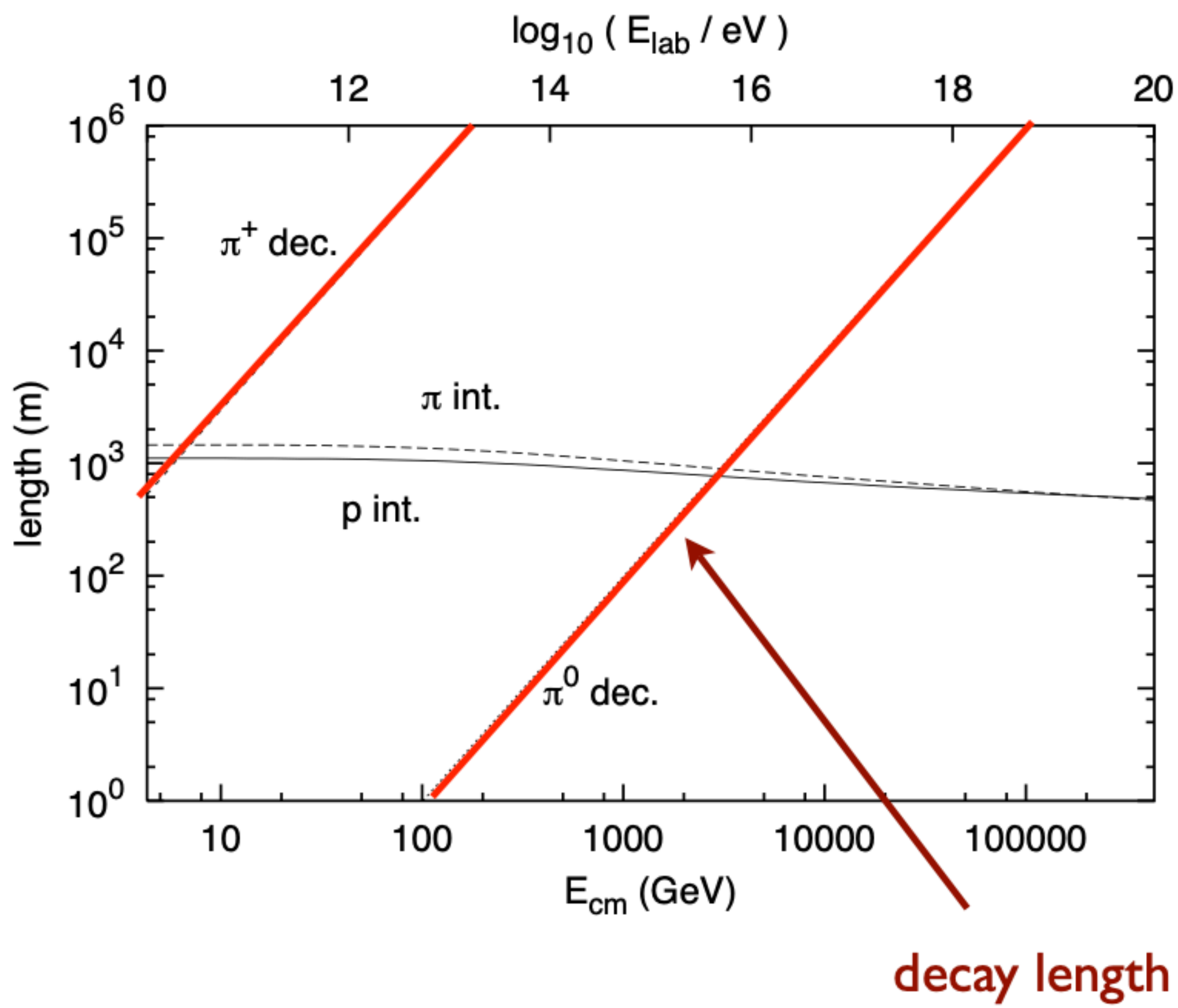


Pions - decay vs interaction.

Slide from Ralph Engel (2008)

Comparison at sea level

$$\lambda_{\rm int} = \frac{\langle m \rangle}{\sigma_{\rm ine}}$$



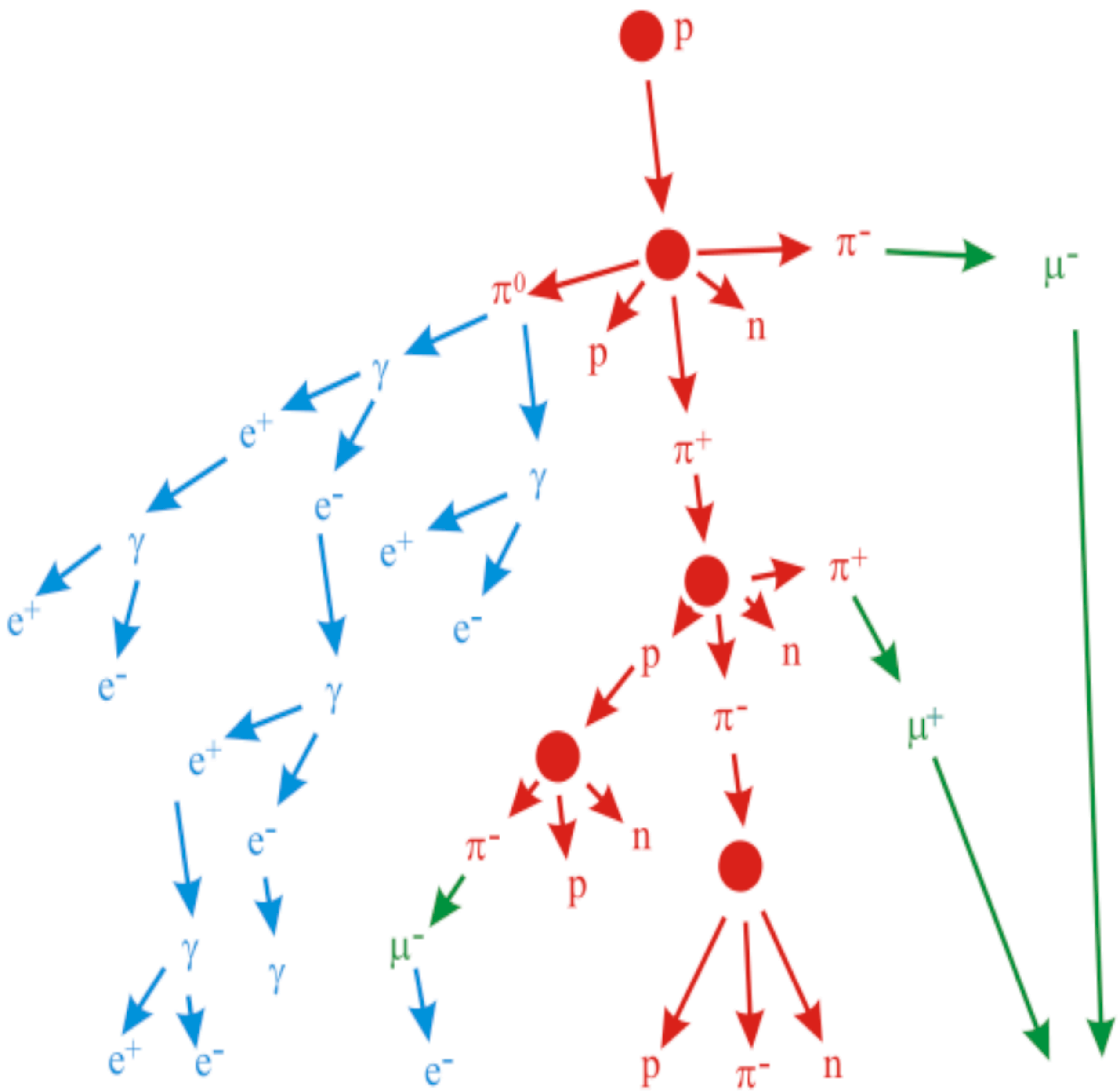
$$c\tau_{\pi^\pm} = 7.8\,\mathrm{m}$$

$$c\tau_{\pi^0} = 25.1\,\mathrm{nm}$$

$$\pi^+ \longrightarrow \mu^+ \nu_\mu \longrightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

$$\pi^0 \longrightarrow \gamma\gamma$$

Heitler Matthews Model.



from Cazon 2018

Simplification:

- neutral pions decay immediately (initiate electromagnetic shower)
- charged pions interact and initiate secondary cascade
- cascade stops of E = E_{decay}
- each charged pions produces one muon during decays
- muons don't interact

Can get some basic predictions, e.g.

$$N_\mu = \left(\frac{E_\circ}{\xi_c^\pi}\right)^\beta \approx 10^4 \left(\frac{E_\circ}{1\ \mathrm{PeV}}\right)^{0.85}$$

$$\frac{E_{em}}{E_\circ} = \frac{E_\circ - N_\mu \xi_c^\pi}{E_\circ} = 1 - \left(\frac{E_\circ}{\xi_c^\pi}\right)^{\beta-1}$$

~ 70% (at energies relevant for CTA)

Superposition model.

Proton-induced shower

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

$$X_{\max} \sim \lambda_{\text{eff}} \ln(E_0)$$

$$N_\mu = \left(\frac{E_0}{E_{\text{dec}}}\right)^\alpha \qquad \alpha \approx 0.9$$

Assumption: nucleus of mass *A* and energy E_0 corresponds to *A* nucleons (protons) of energy $E_n = E_0/A$

$$N^A_{\max} = A\left(\frac{E_0}{AE_c}\right) = N_{\max}$$

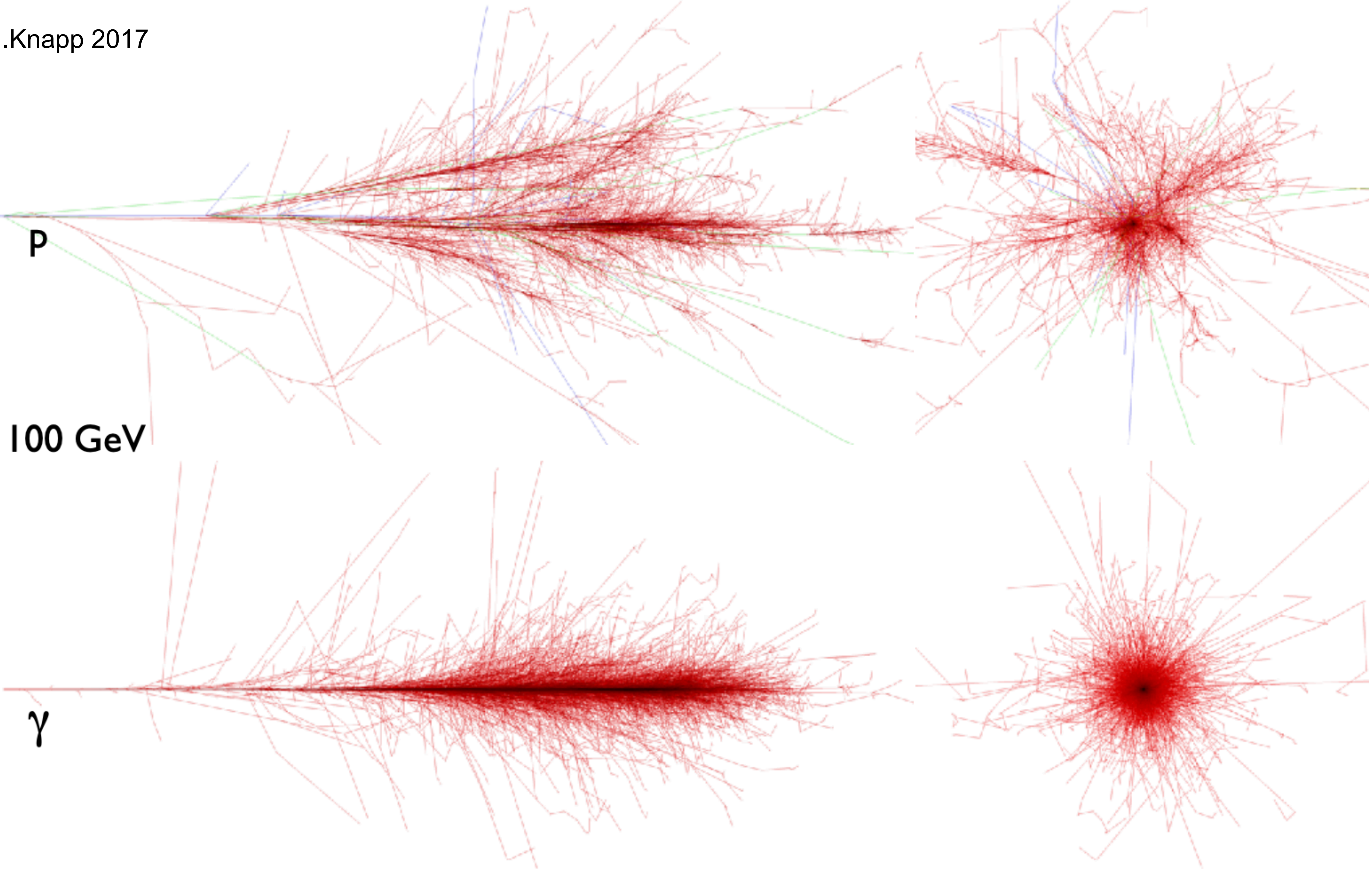
$$X^A_{\max} \sim \lambda_{\text{eff}} \ln(E_0/A)$$

$$N^A_\mu = A\left(\frac{E_0}{AE_{\text{dec}}}\right)^\alpha = A^{1-\alpha} N_\mu$$

Many more muons compared to protons: He: 3.5x; Fe 37x

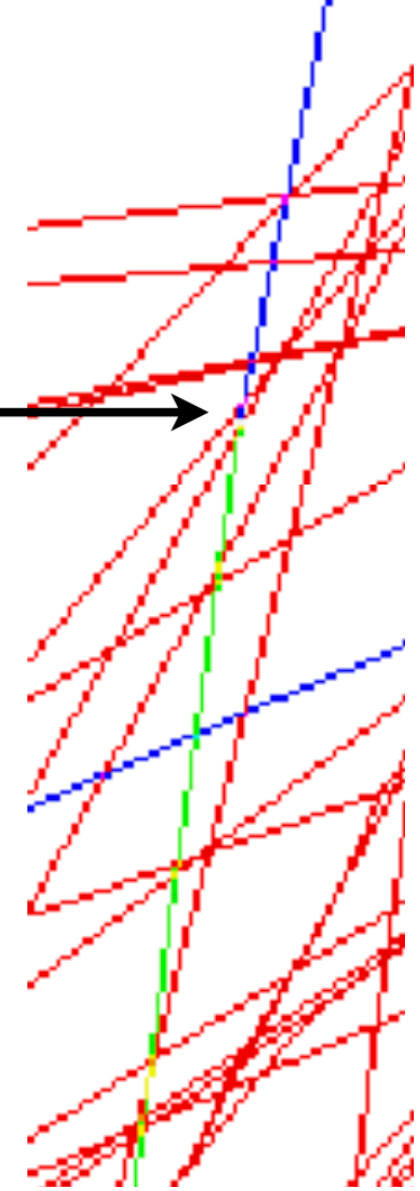
Gamma vs protons.

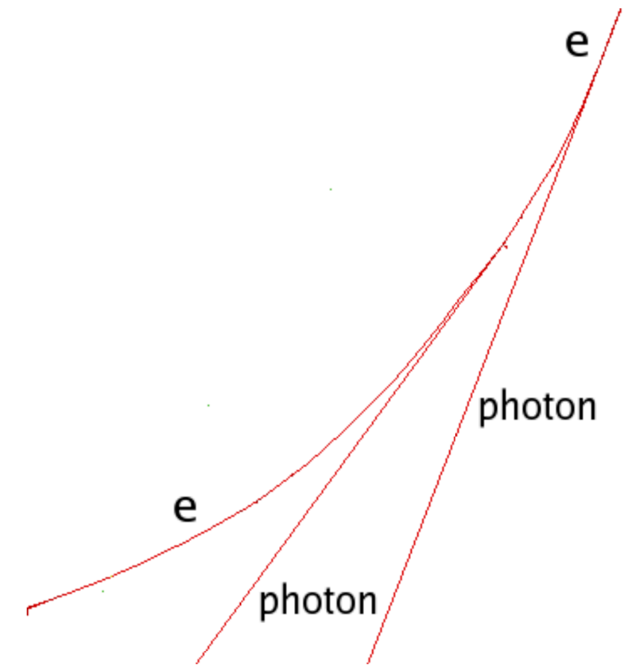
J.Knapp 2017

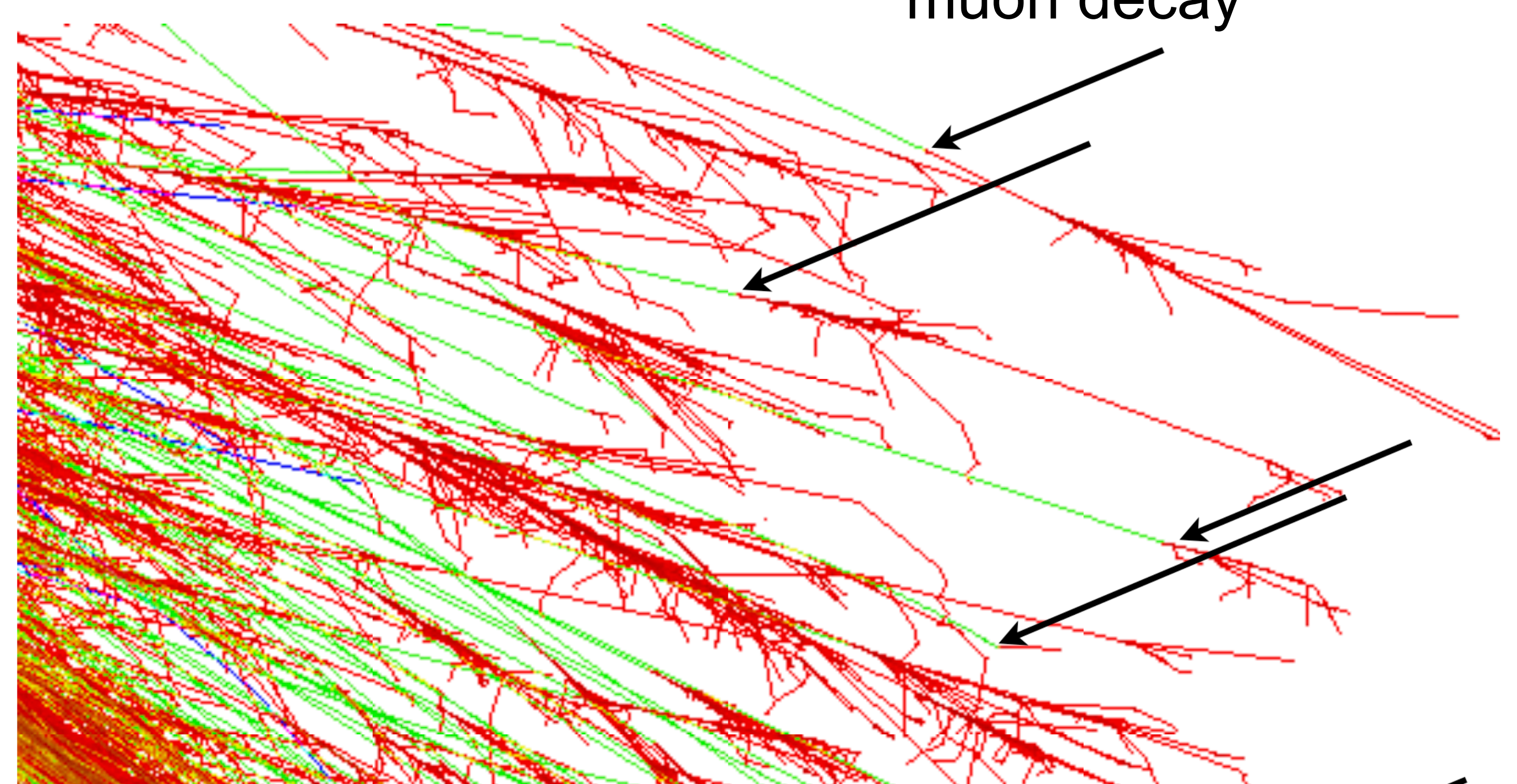


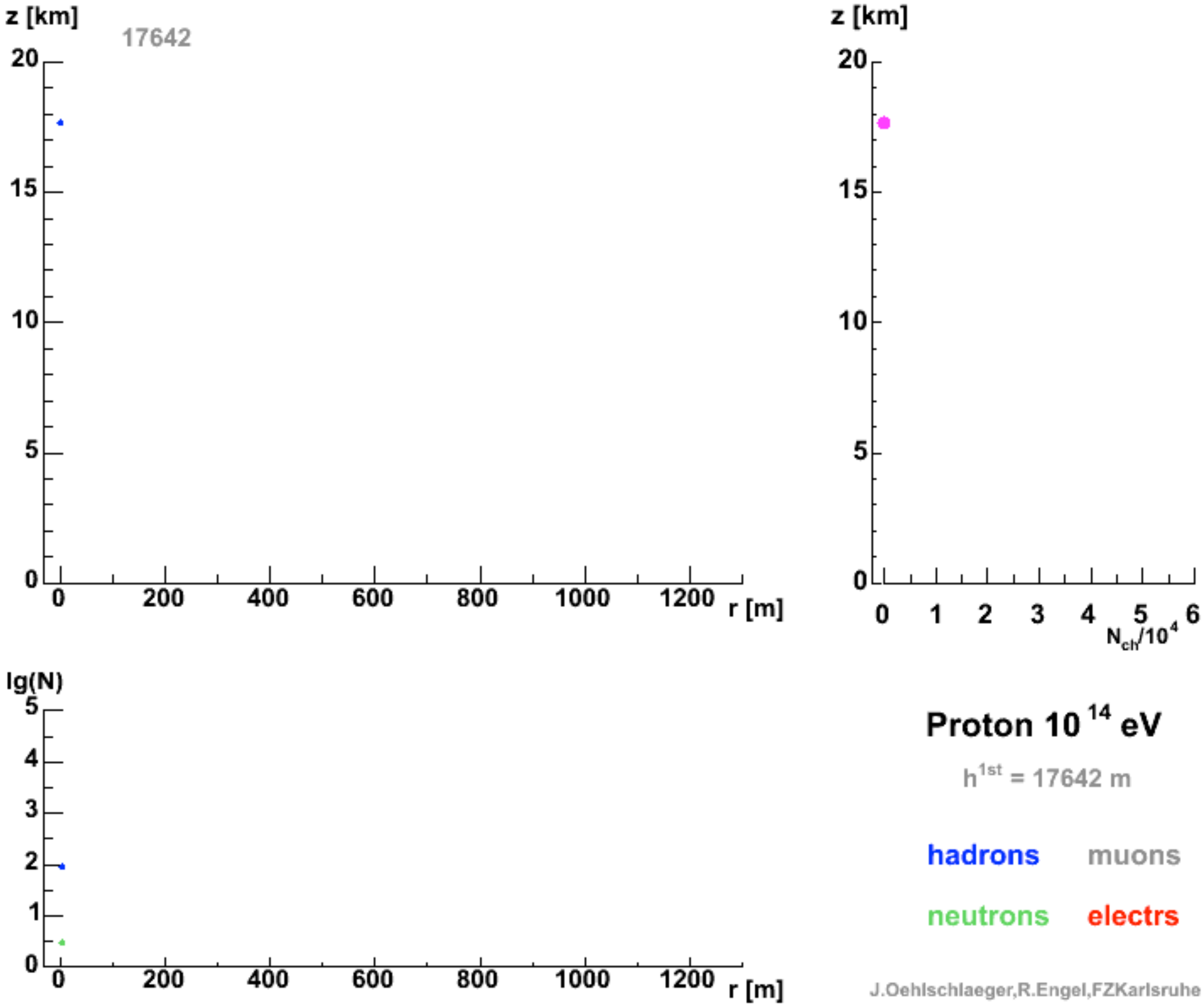
Proton shower.

J.Knapp 2017





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17642
20
15
10
5
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200
400
600
800
1000
1200
r [m]
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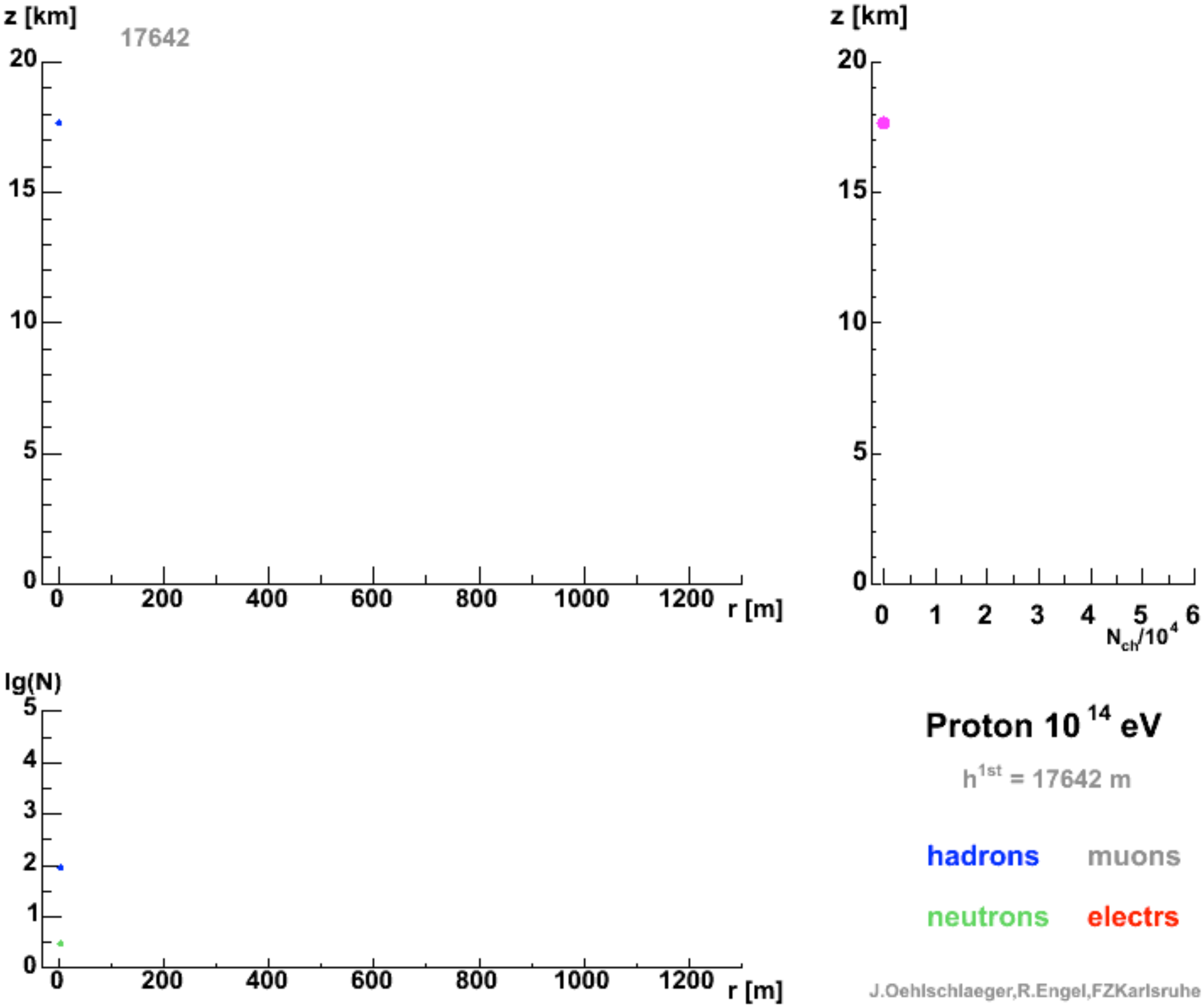
20
15
10
5
0
0
1
2
3
4
5
6
N_ch/10^4
lg(N)
5
4
3
2
1
0
0
200
400
600
800
1000
1200
r [m]
Proton 10^14 eV
h^1st = 17642 m
hadrons
muons
neutrons
electrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe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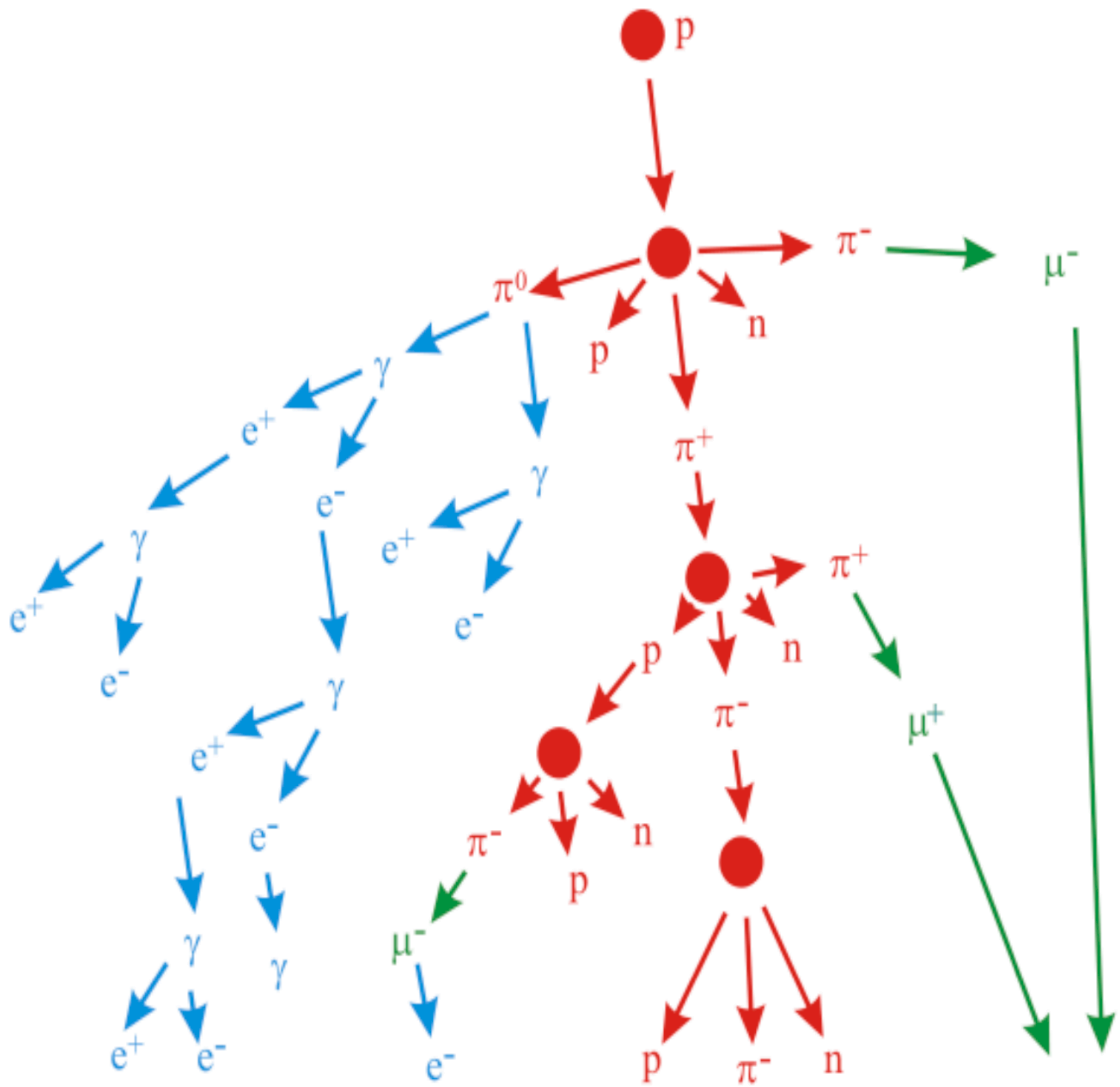
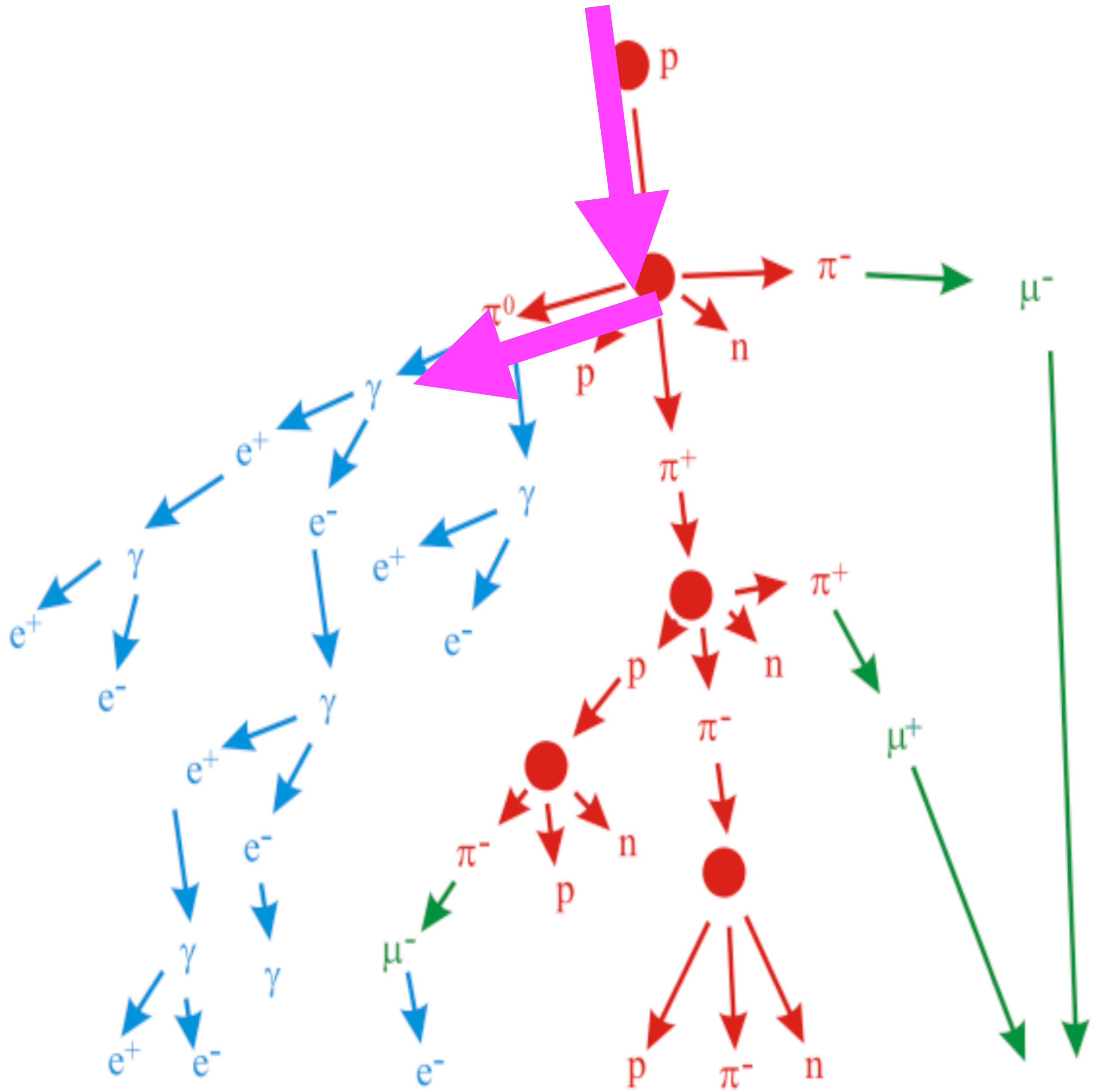
15
10
5
0
0
200
400
600
800
1000
1200
r [m]
z [km]
20
15
10
5
0
0
1
2
3
4
5
6
$N_{ch}/10^4$
lg(N)
5
4
3
2
1
0
0
200
400
600
800
1000
1200
r [m]
Proton 10^{14} eV
h^{1st} = 17642 m
hadrons
muons
neutrons
electrs
J.Oehlschlaeger,R.Engel,FZKarlsruhe

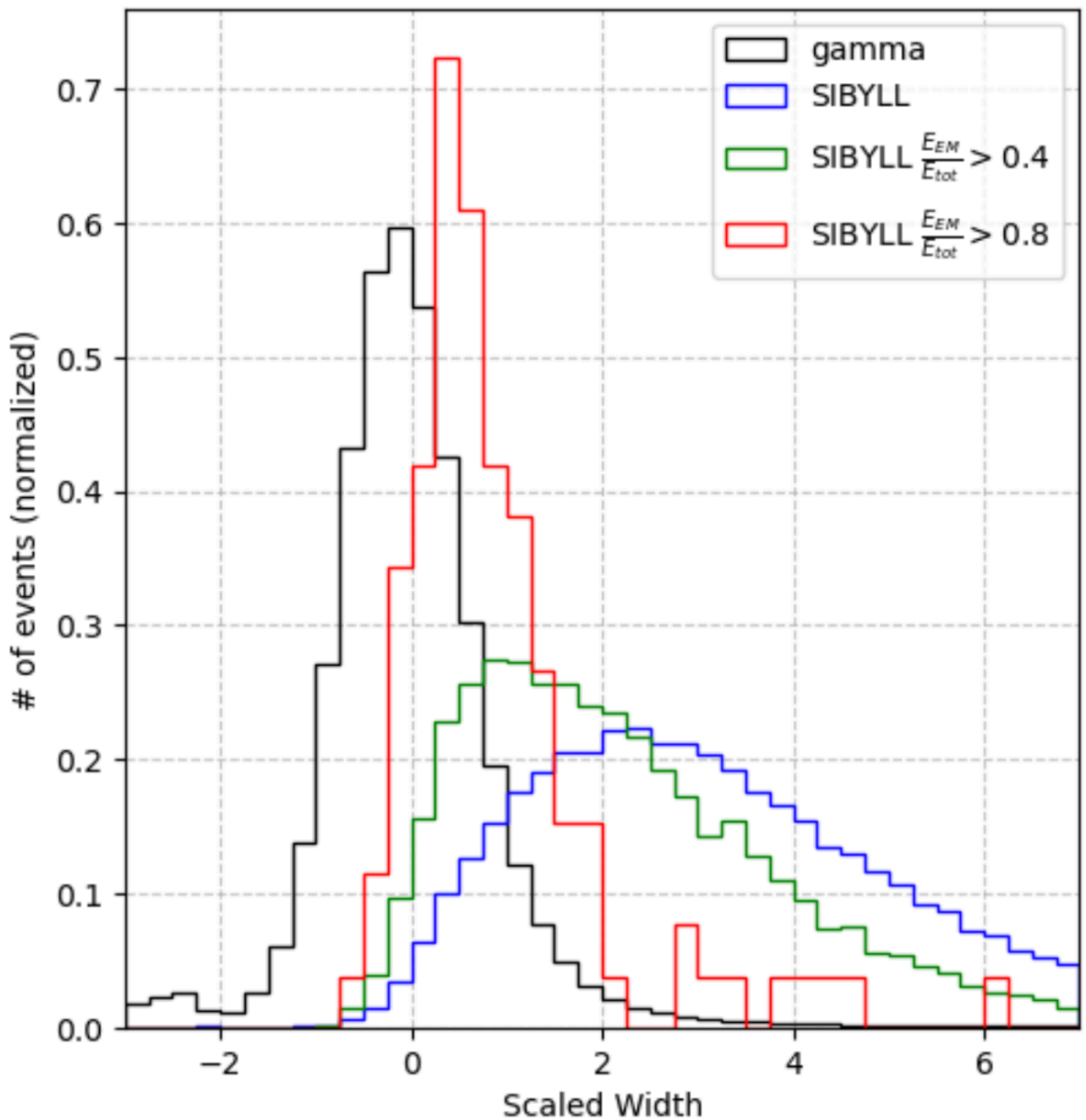
Irreducible background from hadronic showers?



Irreducible background from hadronic showers?

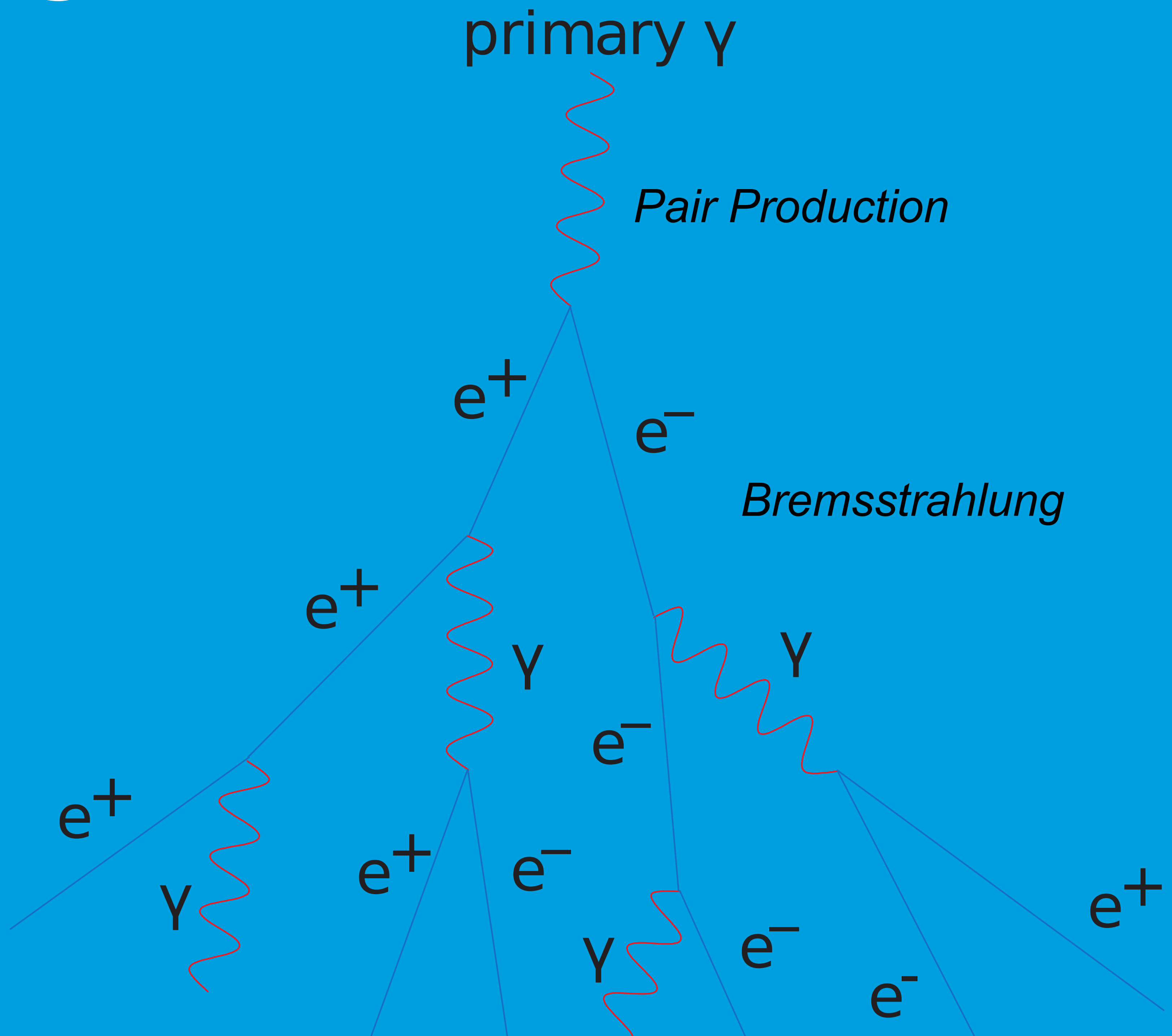


Single Pion Dominated Events.



Dan Parsons
(see also Maier & Knapp 2007)

Air showers.
Primary Electrons.



Air showers.
Lateral extension.

Lateral extension of electromagnetic showers.

determined by multiple Coulomb scattering
(and not opening angle of pair production / Bremsstrahlung)

Scatter angle distribution not Gaussian (as expected by central limit theorem)
single scattering important, as cross section falls off too slowly with $1/\theta^4$

$$\frac{d\sigma}{d\Omega}_{|\,Rutherford} = z^2 Z^2 \alpha^2 \hbar^2 \frac{1}{\beta^2 p^2} \frac{1}{4 \sin^4 \frac{\theta}{2}}$$

Molière's Theory for multiple scatter.
For air showers: Kamata & Nishimura (1959) and Greisen (1956)
Implementation in air shower codes non-trivial (check EGS manual on multiple scatter)

Note: different lateral distributions for each particle type (electrons, photons, ...)

Multiple Scattering

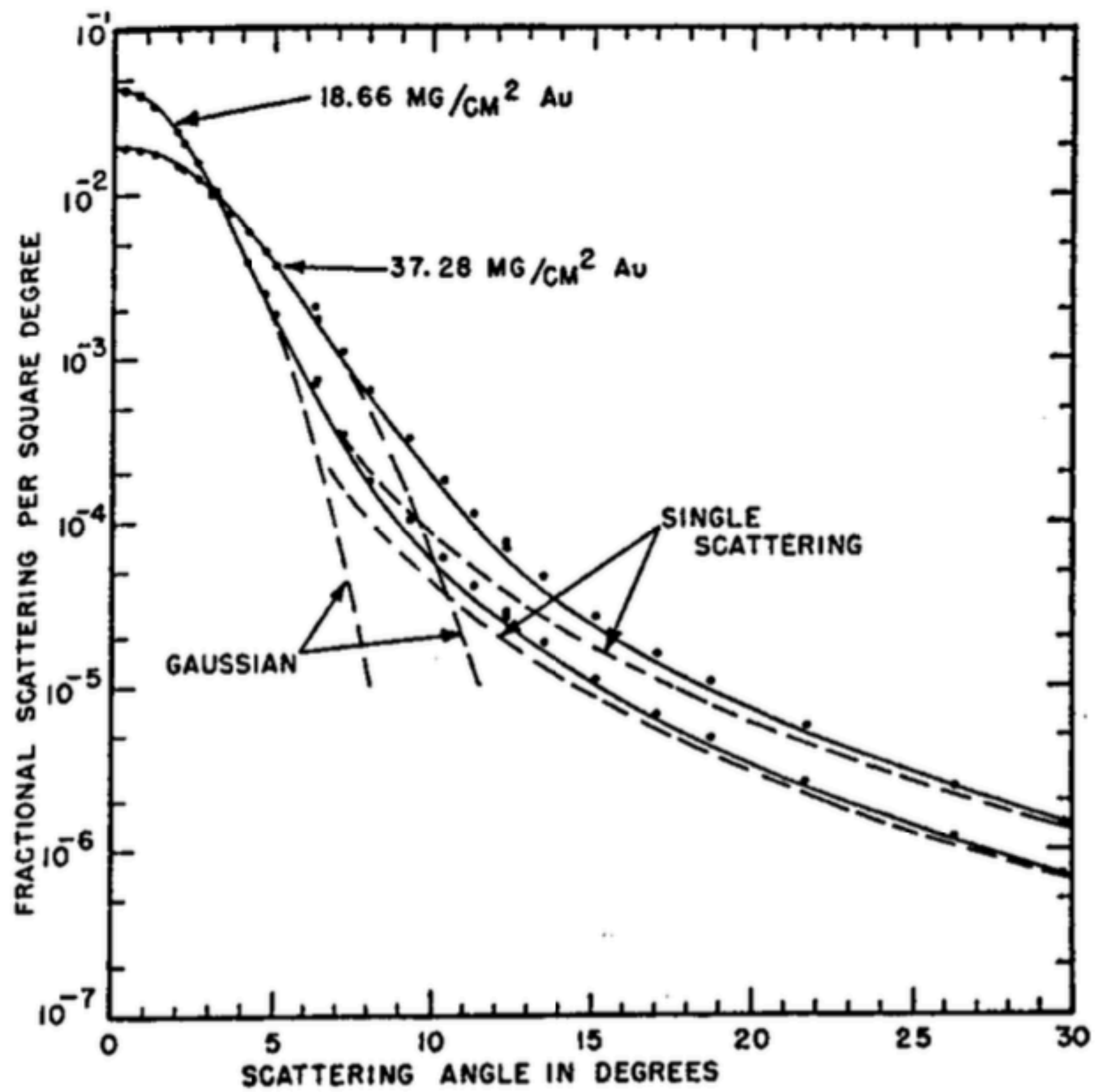


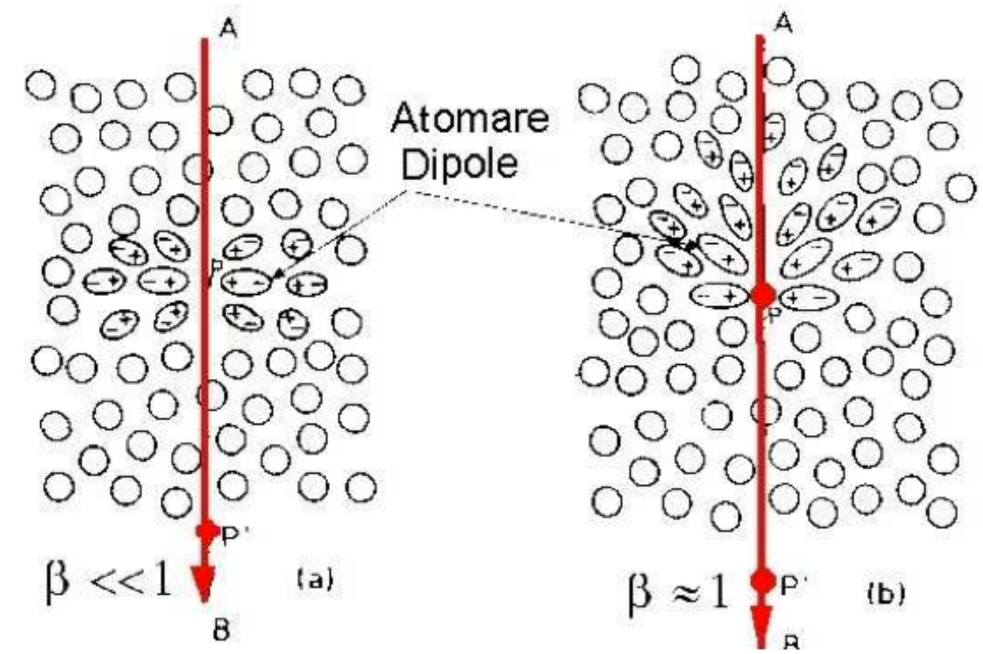
FIG. 3. Angular distribution of electrons from thick and thin gold foils from 0° to 30°. The solid line represents the theory of Molière extrapolated through the region where his small and large angle approximations give different values. The dotted lines at small angles represent the continuation of the gaussians of Fig. 1. At larger angles, the dotted line represents the single scattering contribution.

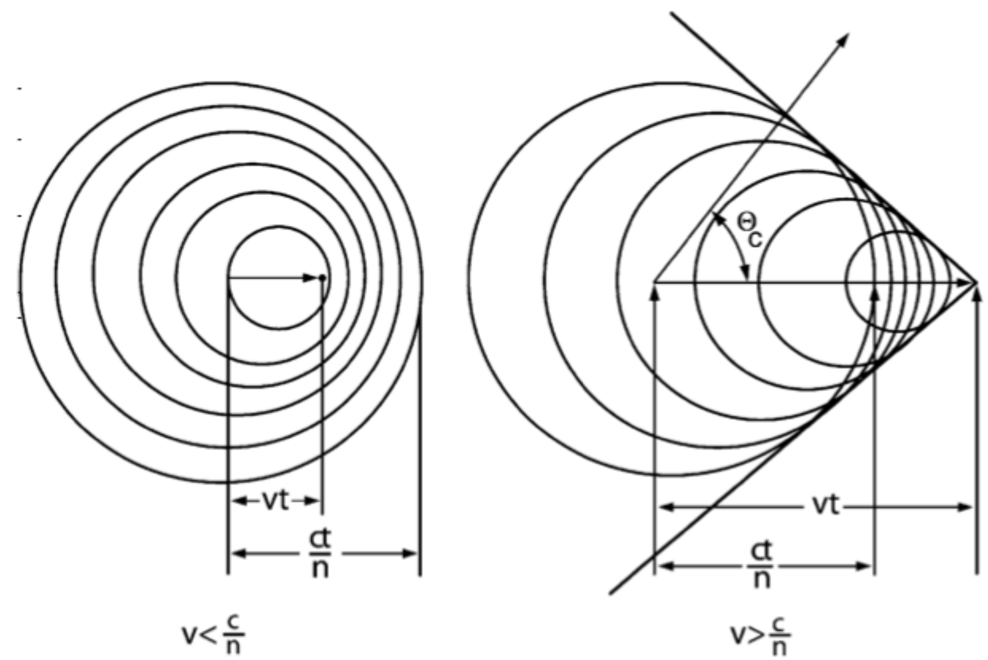
Hanson et al 1951

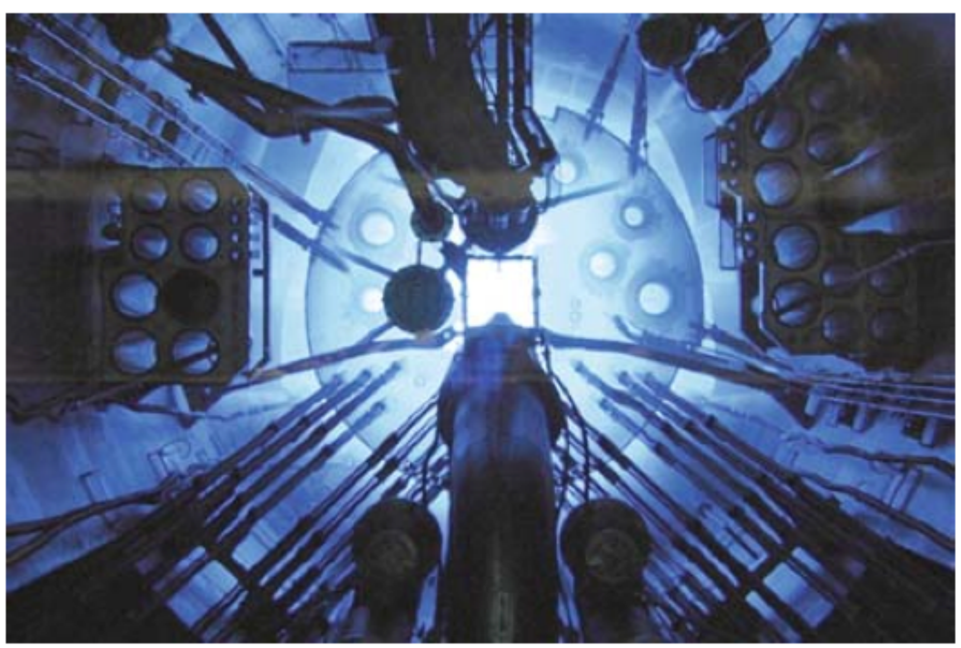
Cherenkov light.

Cherenkov Light.

- polarization of dielectric medium by charged particle
- constructive interference when particle is faster than the emitted radiation (c/n)
- emission in a cone with respect to the particle direction







Cherenkov condition: $n\beta > 1$

Cherenkov.

You can get a Nobel prize
for your PhD...

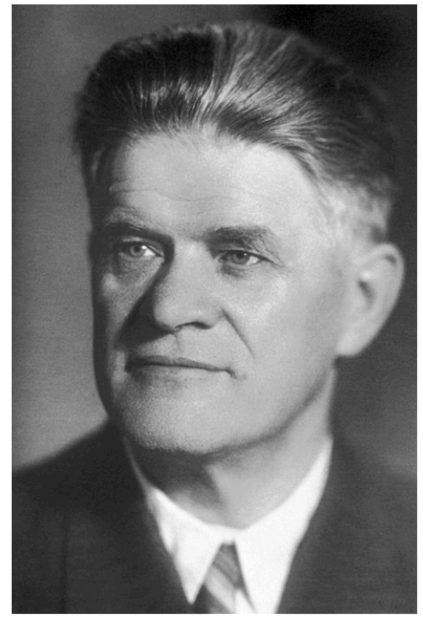


Photo from the Nobel Foundation archive.

Pavel Alekseyevich Cherenkov
The Nobel Prize in Physics 1958

Born: 28 July 1904, Novaya Chigla, Russia

Died: 6 January 1990, USSR (now Russia)

Affiliation at the time of the award: P.N. Lebedev Physical Institute, Moscow, USSR (now Russia)

Prize motivation: “for the discovery and the interpretation of the Cherenkov effect”

Prize share: 1/3

arXiv > physics > arXiv:1101.4535

Physics > History and Philosophy of Phy

[Submitted on 24 Jan 2011]

The Discovery of Cherenkov Radiation and its use in the detection of extensive air showers

A A Watson

Cascades of charged p
atmosphere: these 'ex
arrival direction distrib

the intensity of radiation found using a technique, called 'quenching', in which the dark-adapted eye was used with a graded wedge to provide calibration of the light intensity. These were difficult and delicate experiments requiring high levels of both patience and experimental skill. Cherenkov discovered that light was emitted even when the vessel contained only sulphuric acid, the solvent for the uranyl salt. He went on to demonstrate that the light was observed in a range of different solvents. In a moving obituary [4], which mentions only briefly Cherenkov's considerable post-war contributions to accelerator physics, Chudakov writes "The phenomenon was not and probably could not have been discovered earlier by someone more experienced in physics than Cherenkov was in the 1930s. To determine the nature of the faint blue light produced in different liquids by gamma rays from a radioactive source seemed to require a young fellow from a rural area, inexperienced but with immense patience and vigour".

Observation of polarization was an important clue to the eventual interpretation but the critical breakthrough was Cherenkov's discovery in 1936 that the radiation was emitted asymmetrically only in the forward direction with respect to the direction of the incoming γ-ray beam [5], at an angle

Cherenkov emission.

What you absolutely need to know.

Cherenkov condition: $n\beta > 1$

light is emitted along a cone with half opening angle θ: $\cos\Theta = \frac{1}{n\beta}$

good approximation: $\Theta_c \approx \sqrt{2(n-1)}$ radians

number of Cherenkov photons per path length x:

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2\beta^2}\right) \frac{d\lambda}{\lambda^2} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \sin^2\Theta \frac{d\lambda}{\lambda^2}$$

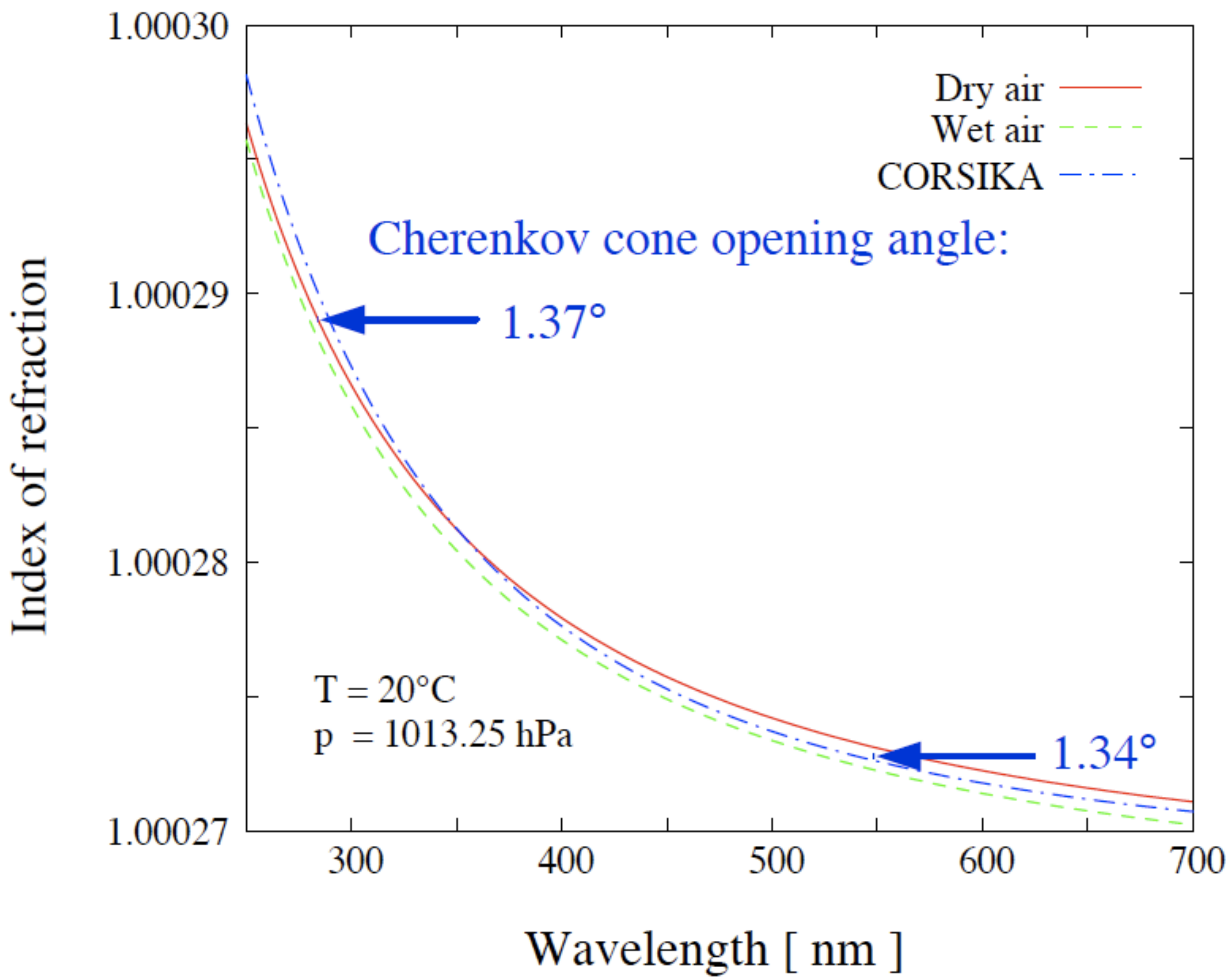
$\beta = v/c$ n = refractive index z = charge

ƛ= wavelength $\alpha = 1/137$

Index of refraction.

refractive index in air scales with density: $n = 1 + 0.000283\ \rho(h)/\rho(0)$

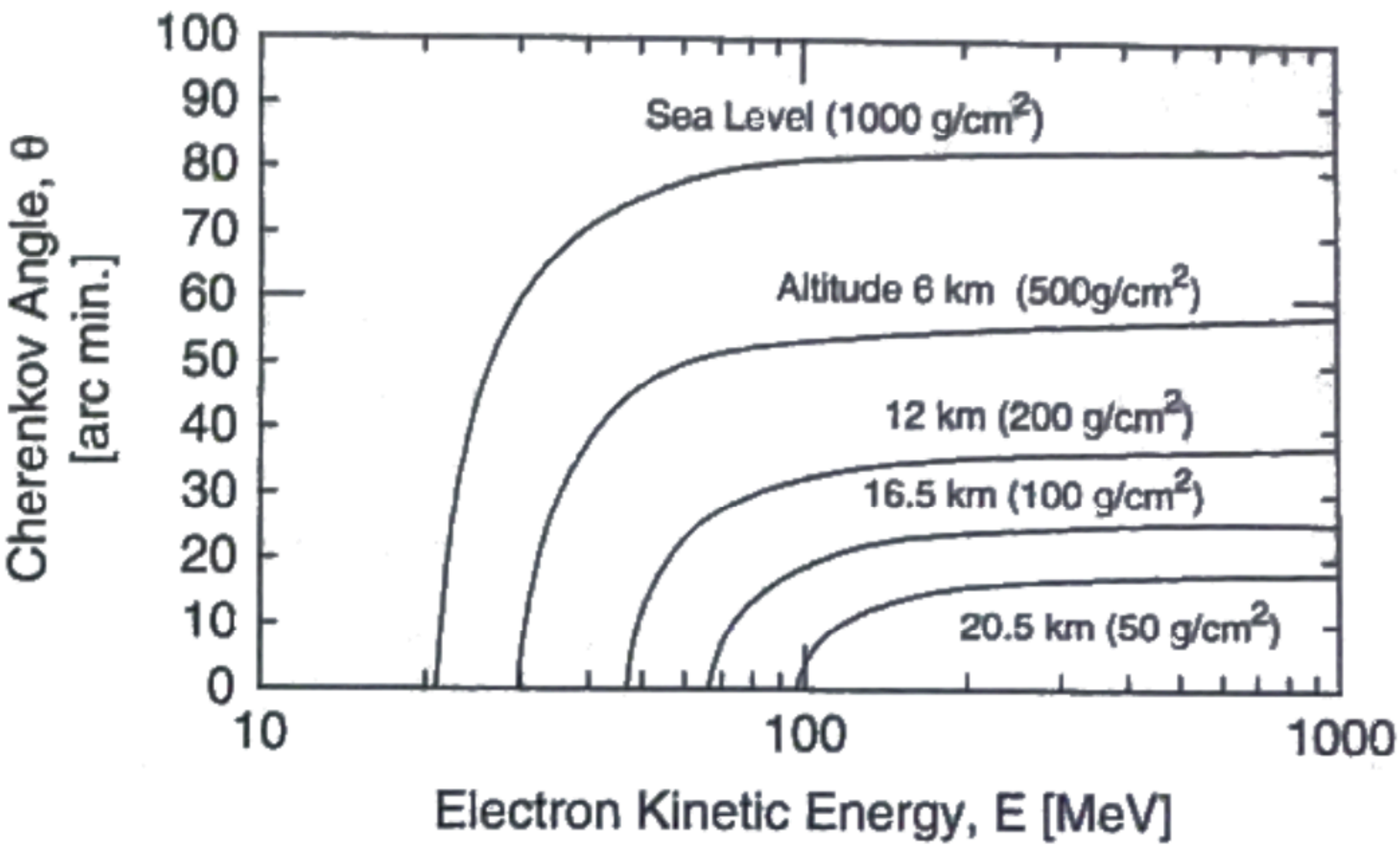
(additional dependency on pressure, temperature, water vapor content)



Current simulations use n(450 nm).

Cherenkov angle vs electron energy

Thresholds for Cherenkov emission:
Electrons: 20 MeV at sea level / 35 MeV at 10 km
Muons: 4.5 GeV at sea level / 8 GeV at 10 km

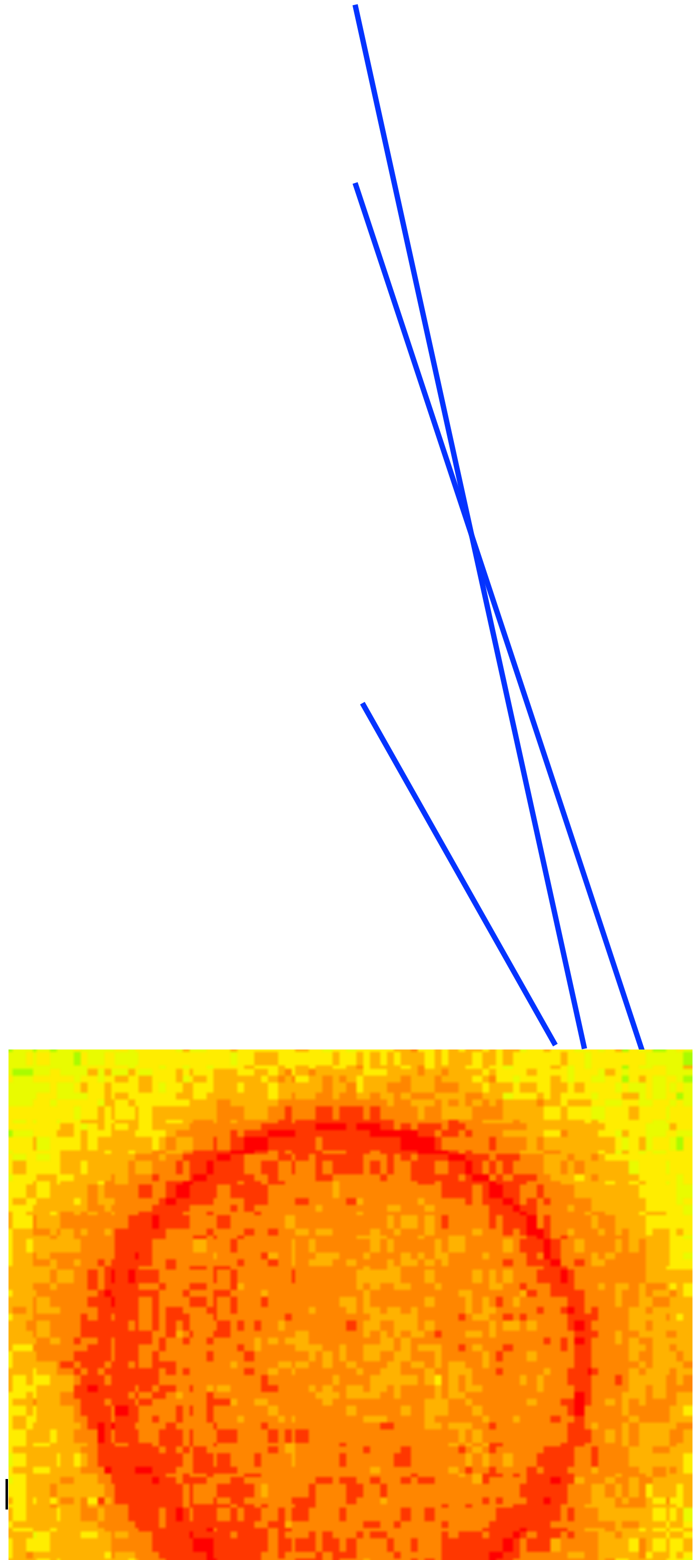


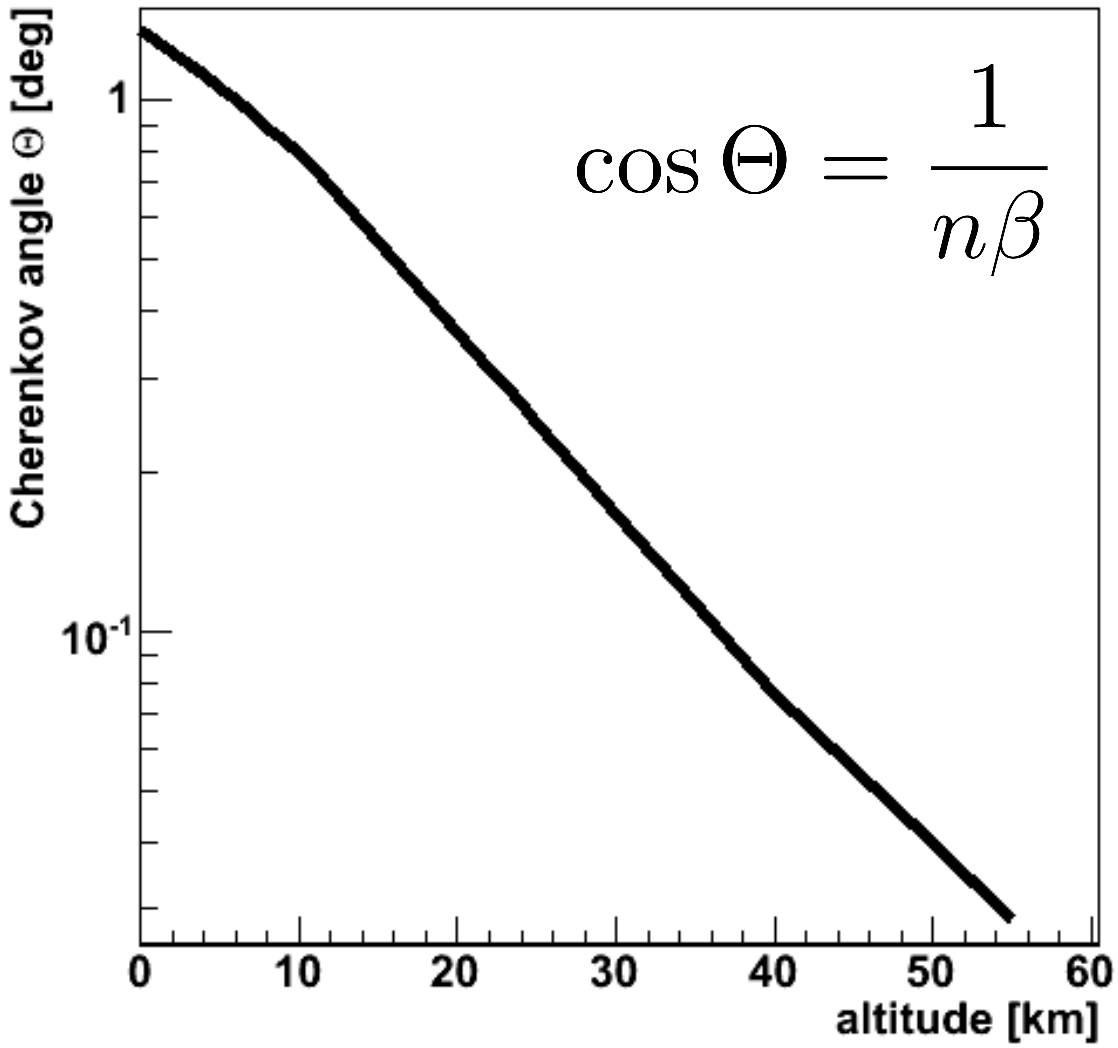
Grieder 2010.

Cherenkov emission in the Atmosphere

refractive index in air scales with density

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

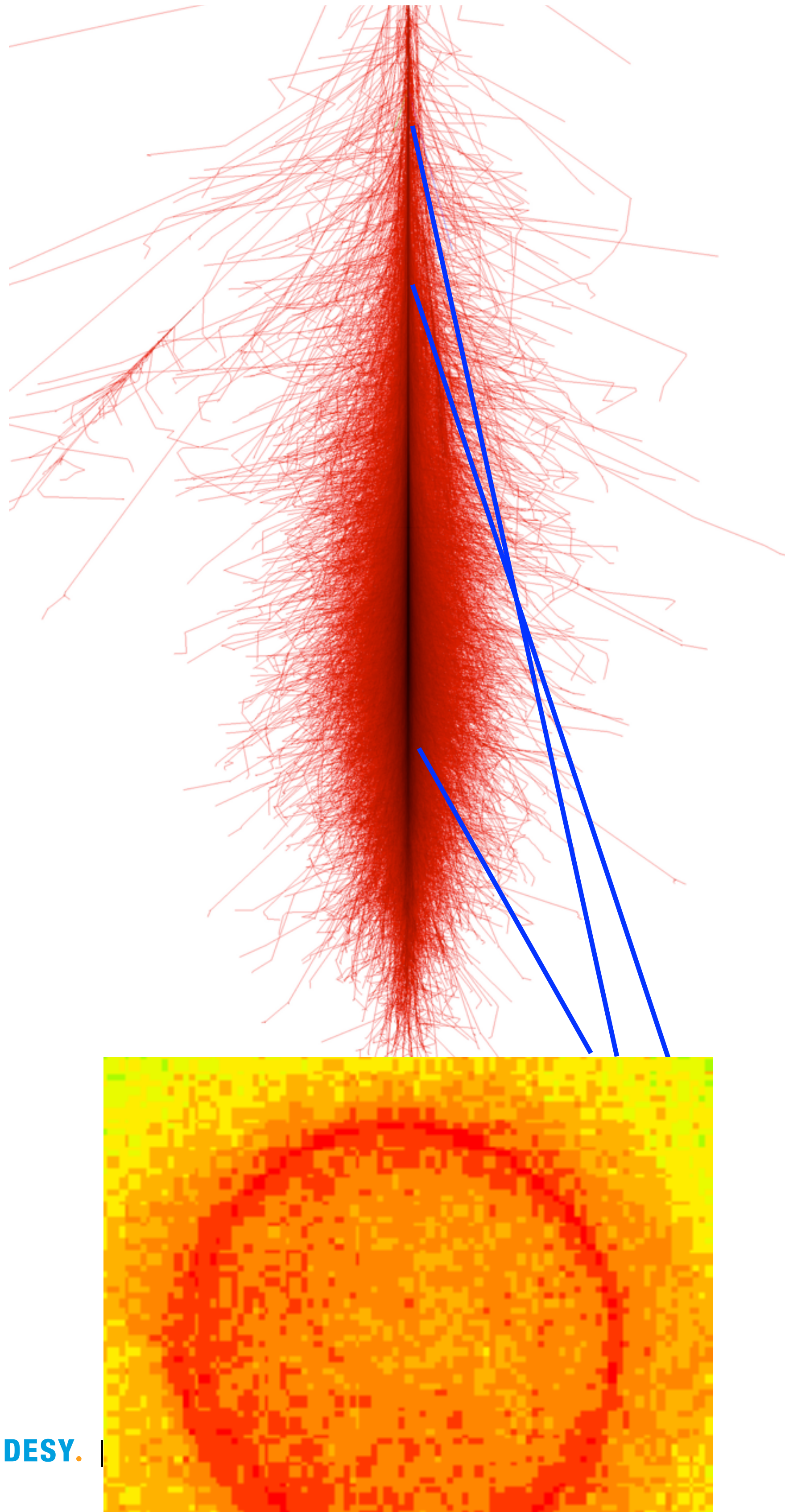




$$\cos\Theta = \frac{1}{n\beta}$$

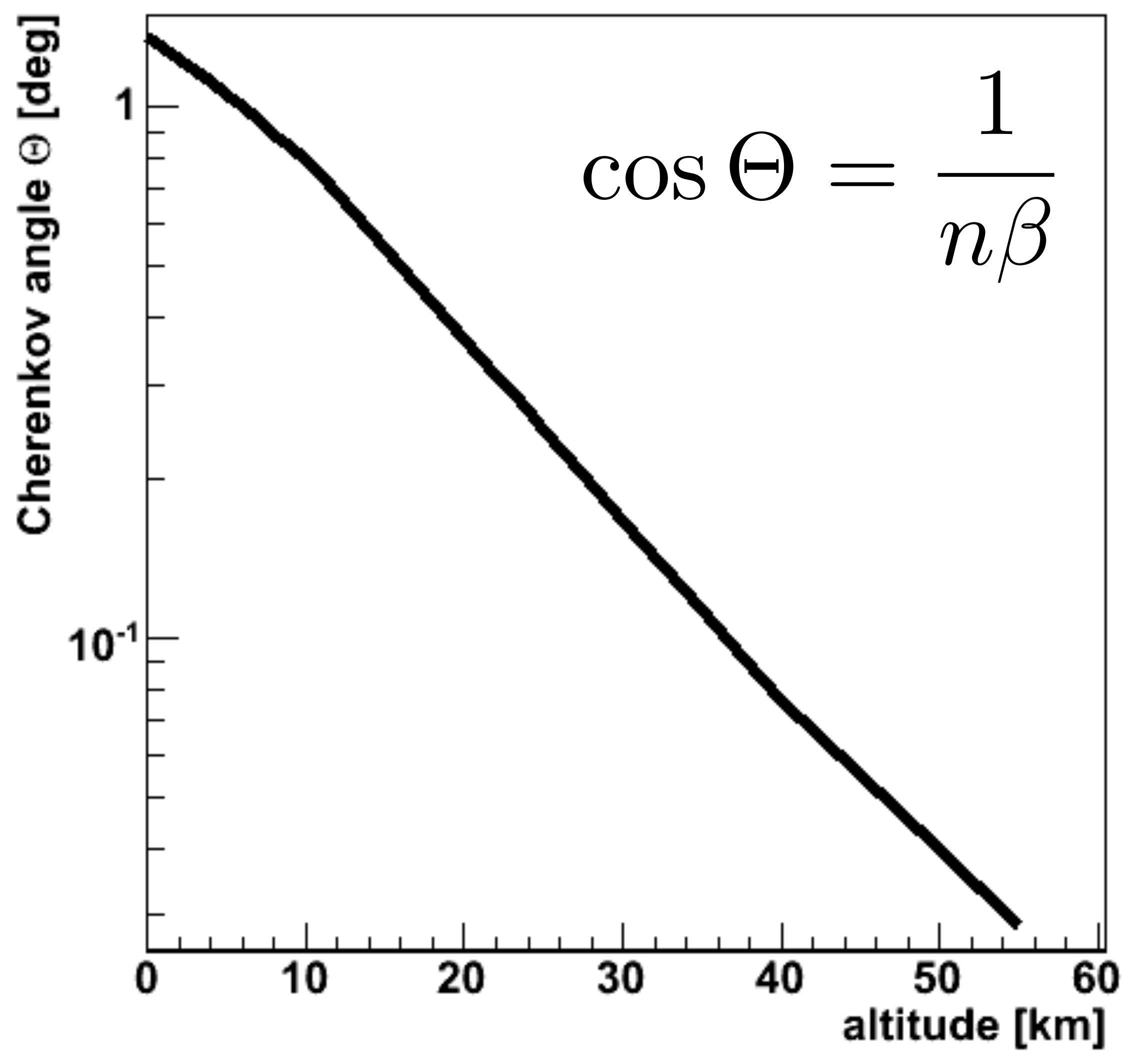
~1.3 deg at sea level

Cherenkov emission in the Atmosphere



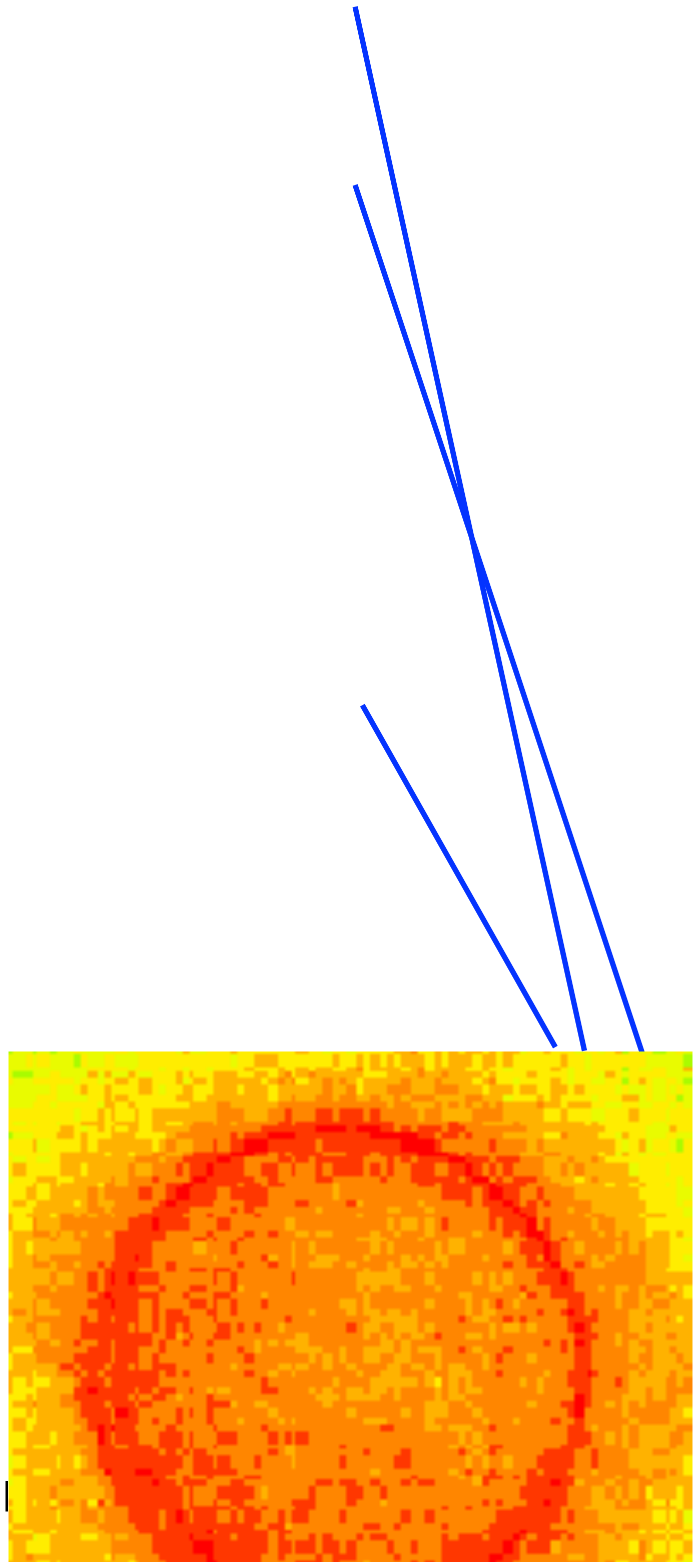
refractive index in air scales with density

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



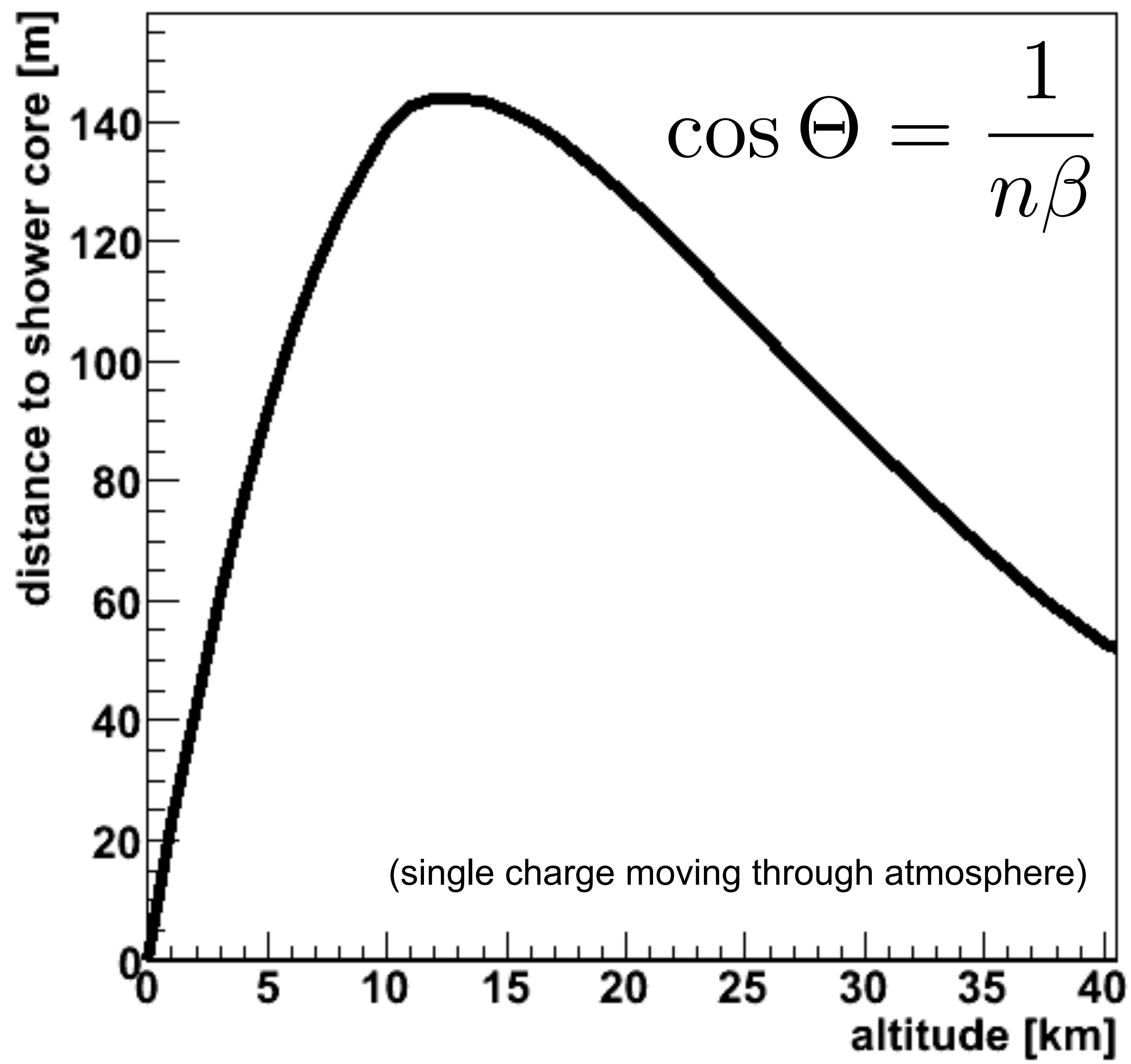
~1.3 deg at sea level

Cherenkov emission in the Atmosphere

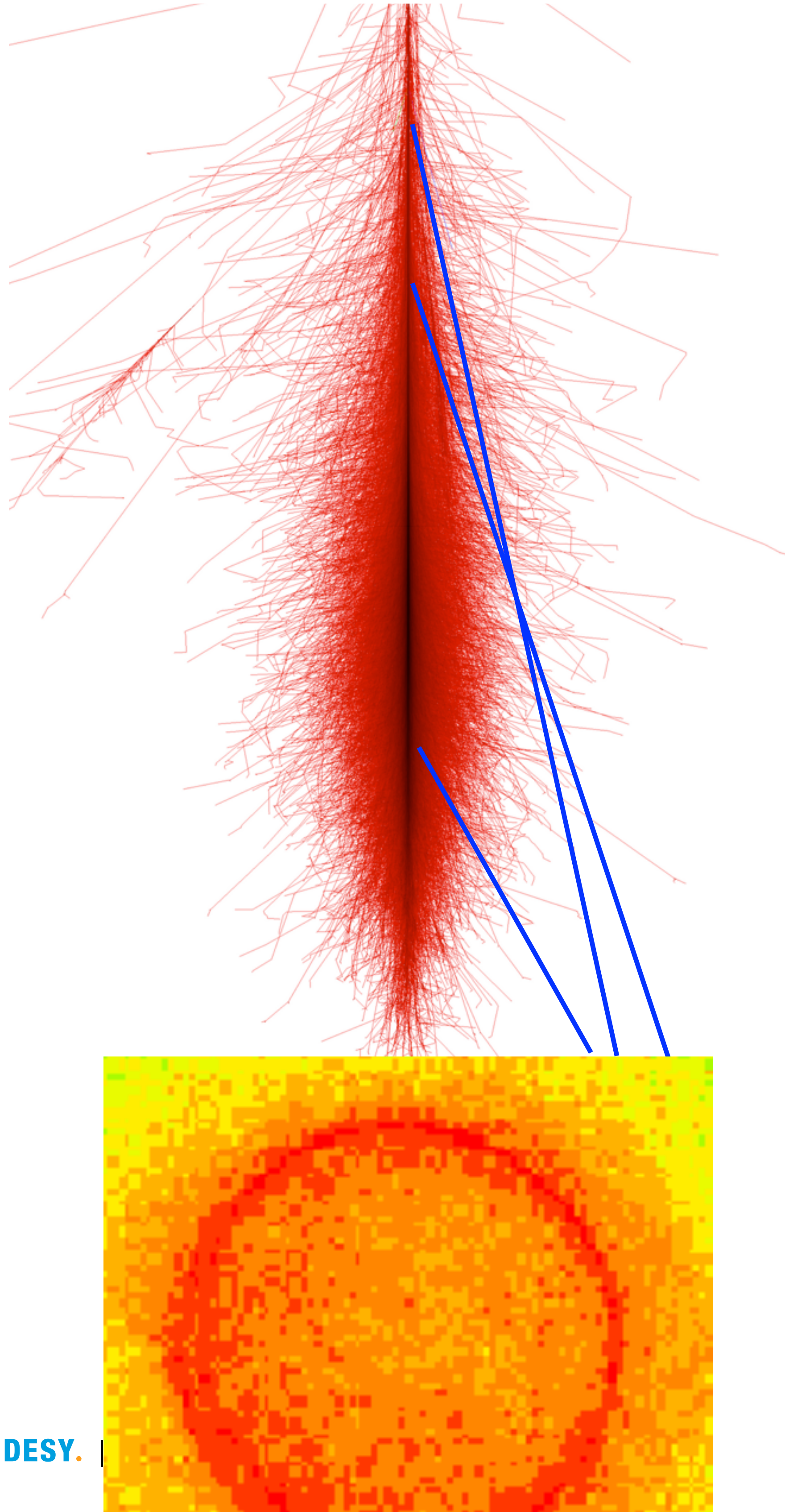


refractive index in air scales with density

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

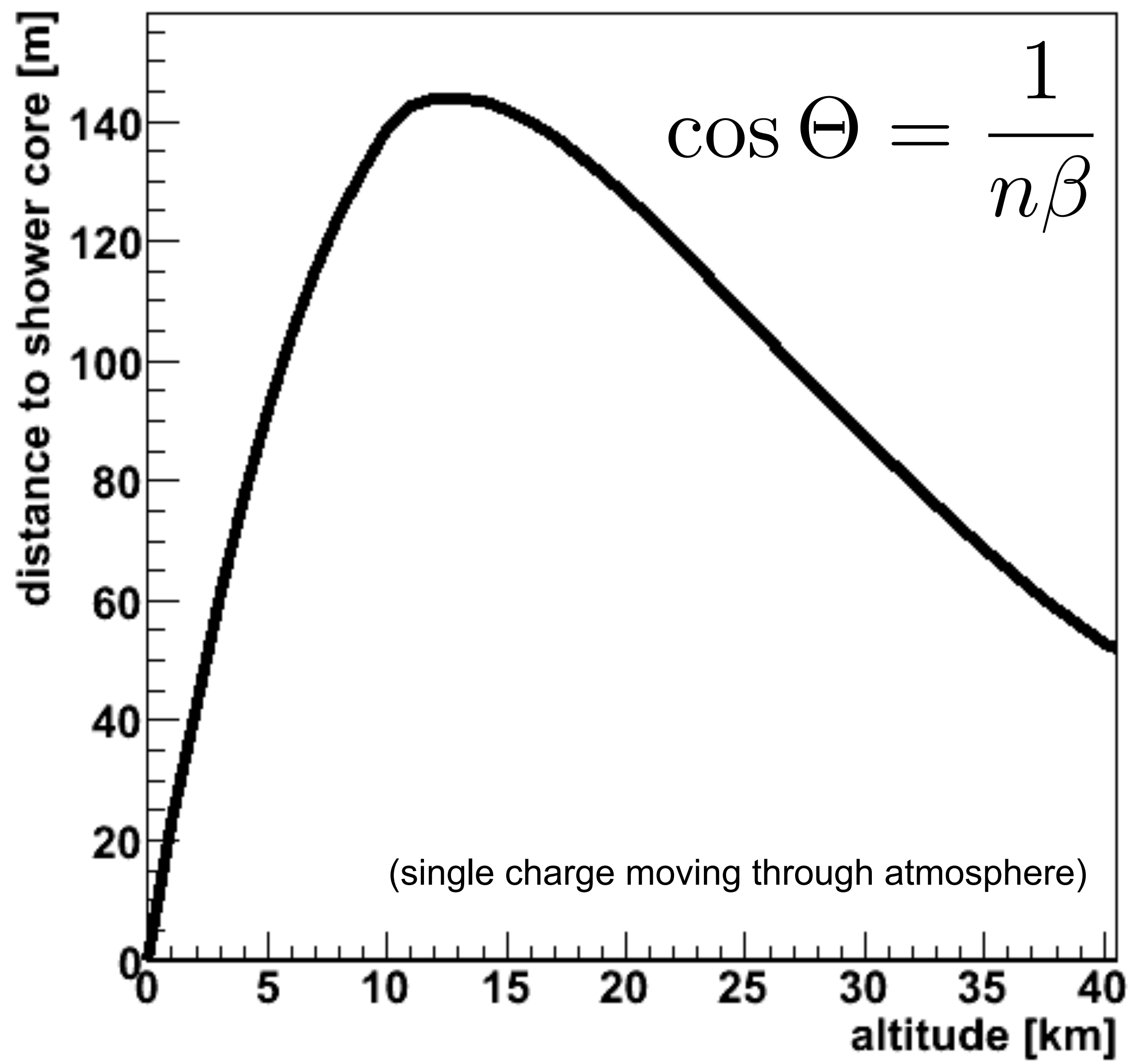


Cherenkov emission in the Atmosphere

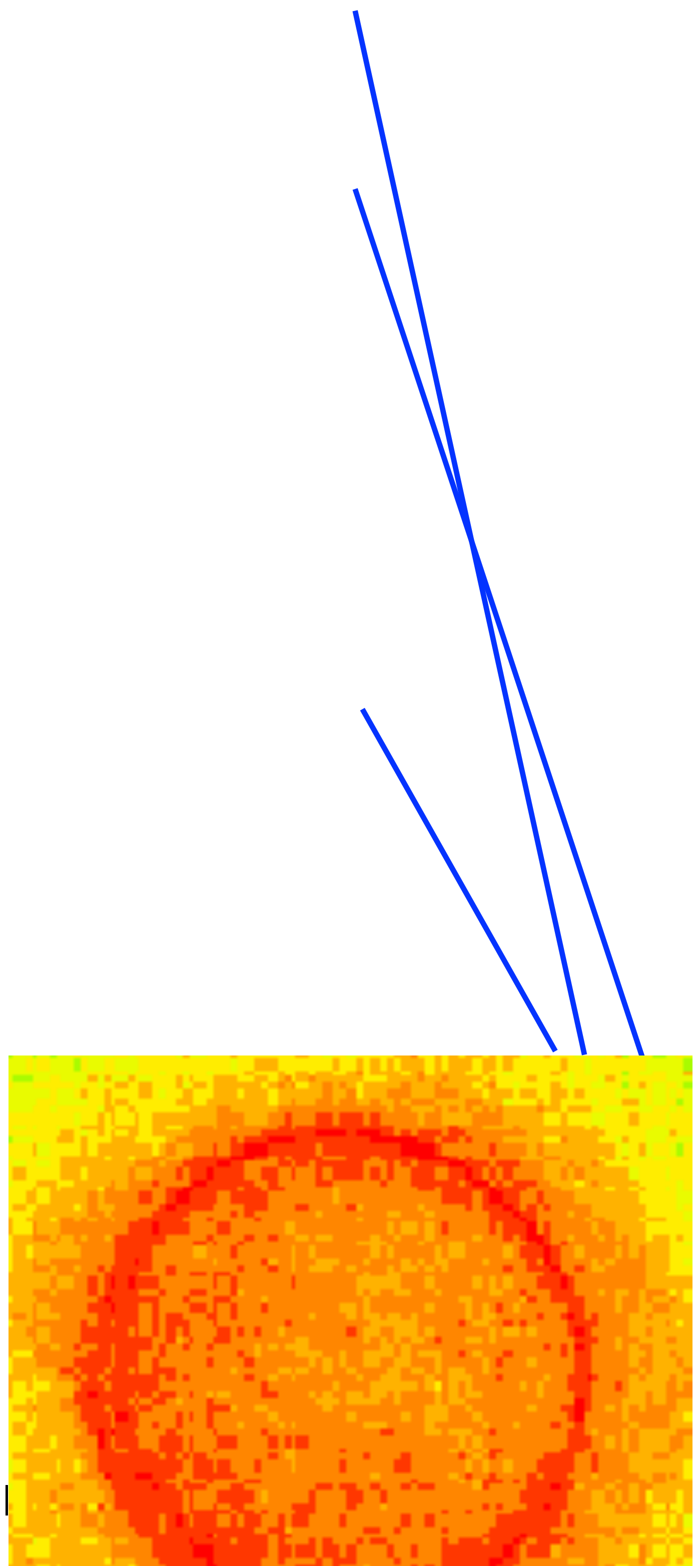


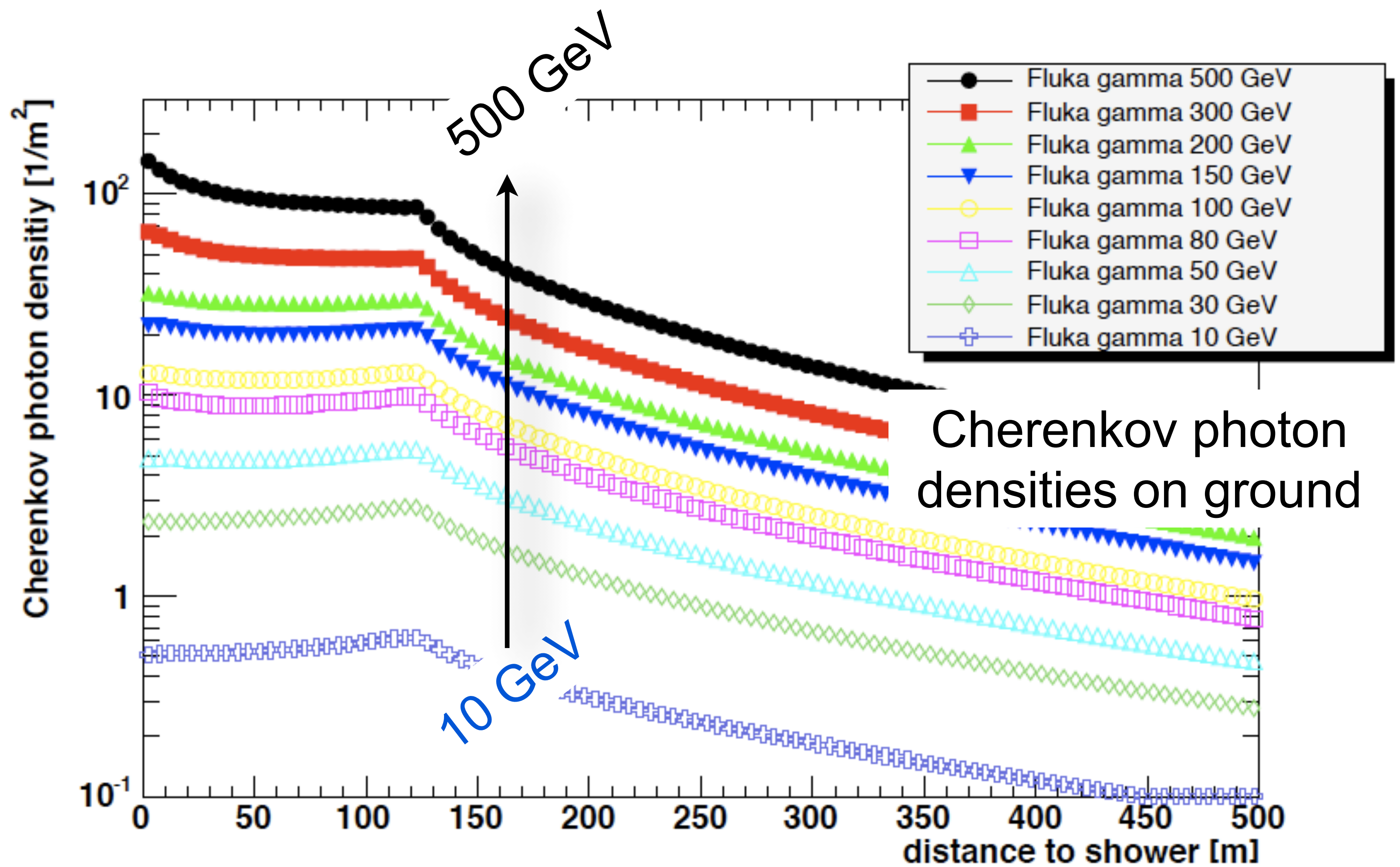
refractive index in air scales with density

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



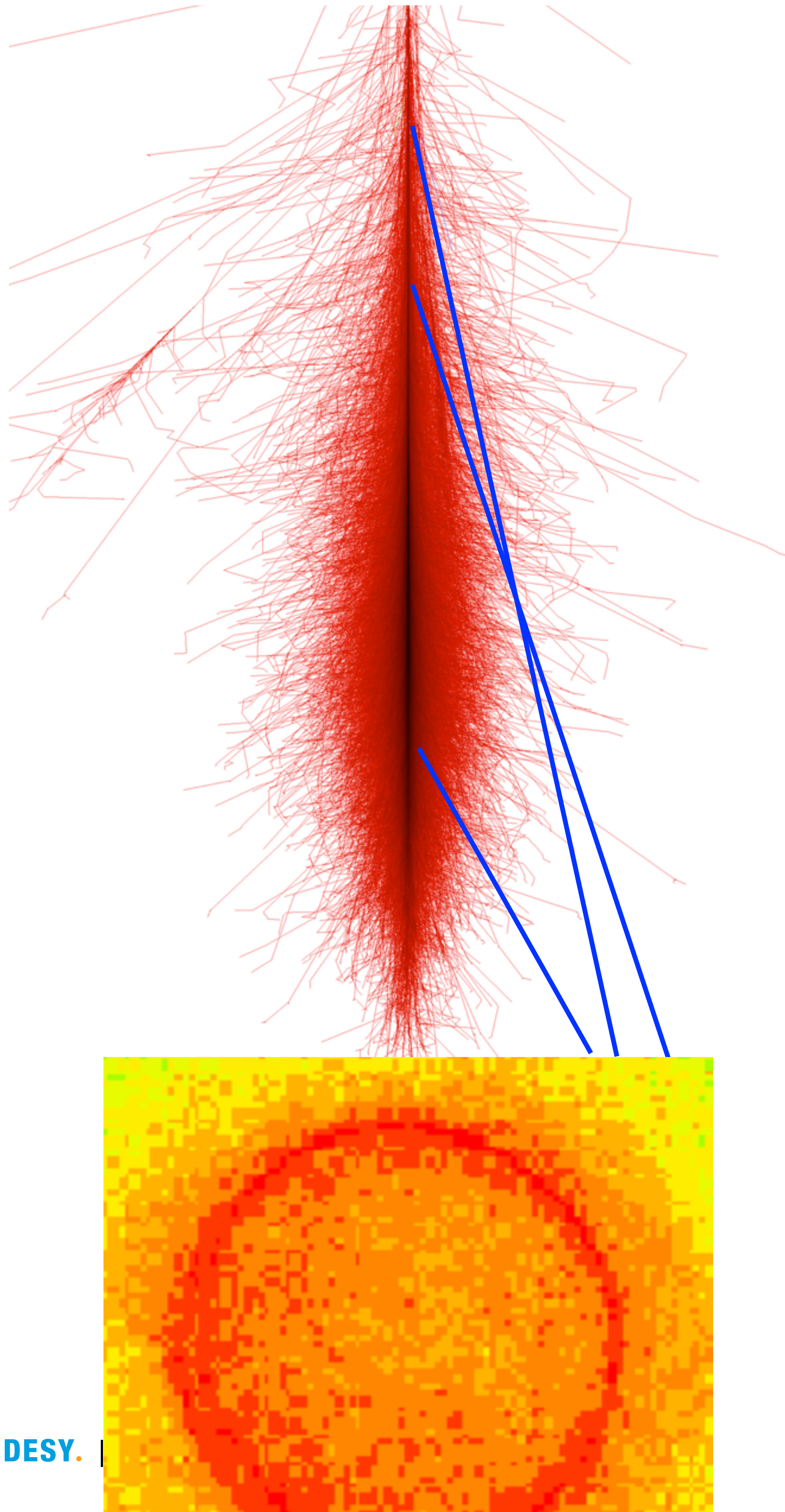
Lateral distributions.

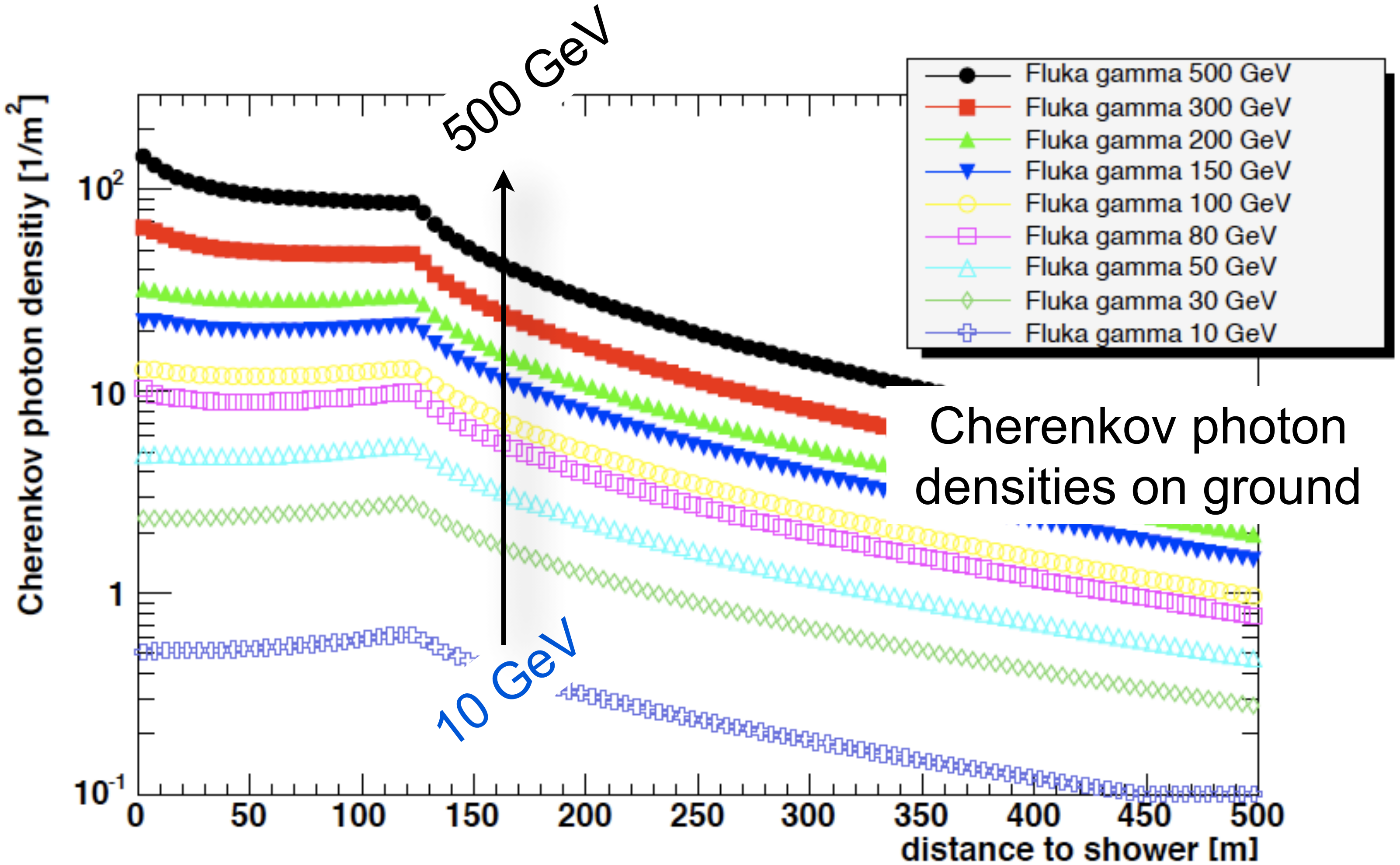




Cherenkov light from air showers:
weak (~10 ph/m²), short (~ns),
blue (300-550nm) flash of light

Lateral distributions.

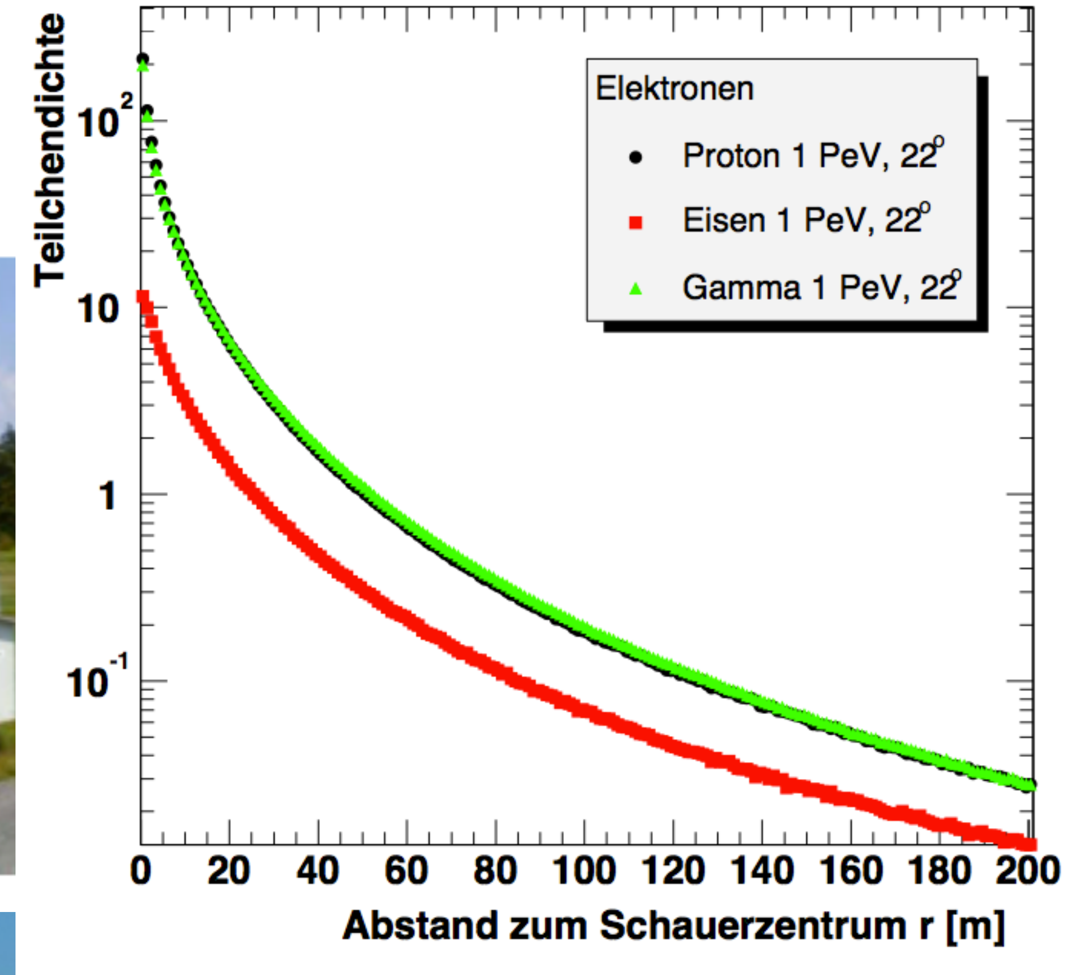


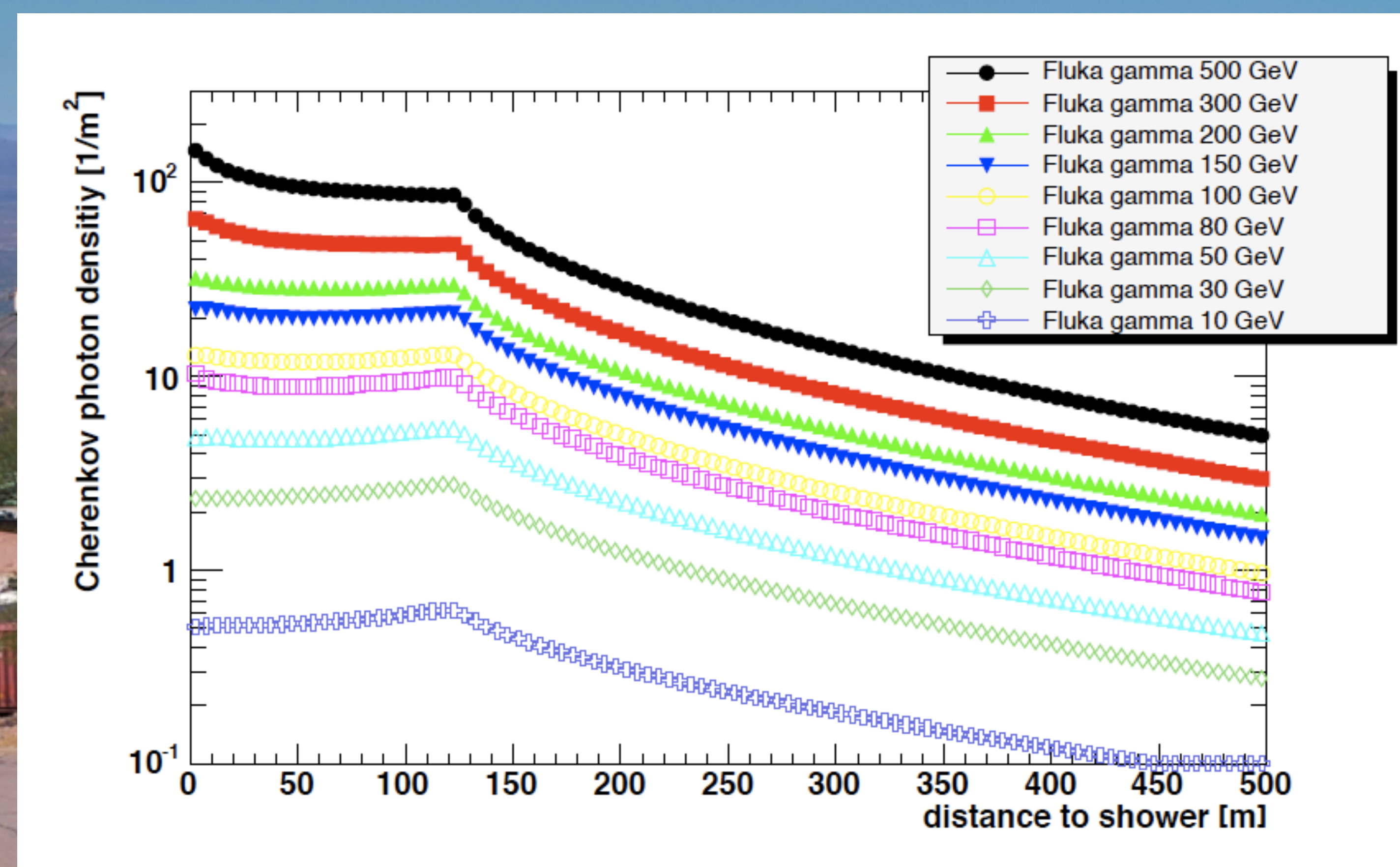


Cherenkov light from air showers:
weak (~10 ph/m²), short (~ns),
blue (300-550nm) flash of light

Lateral distributions

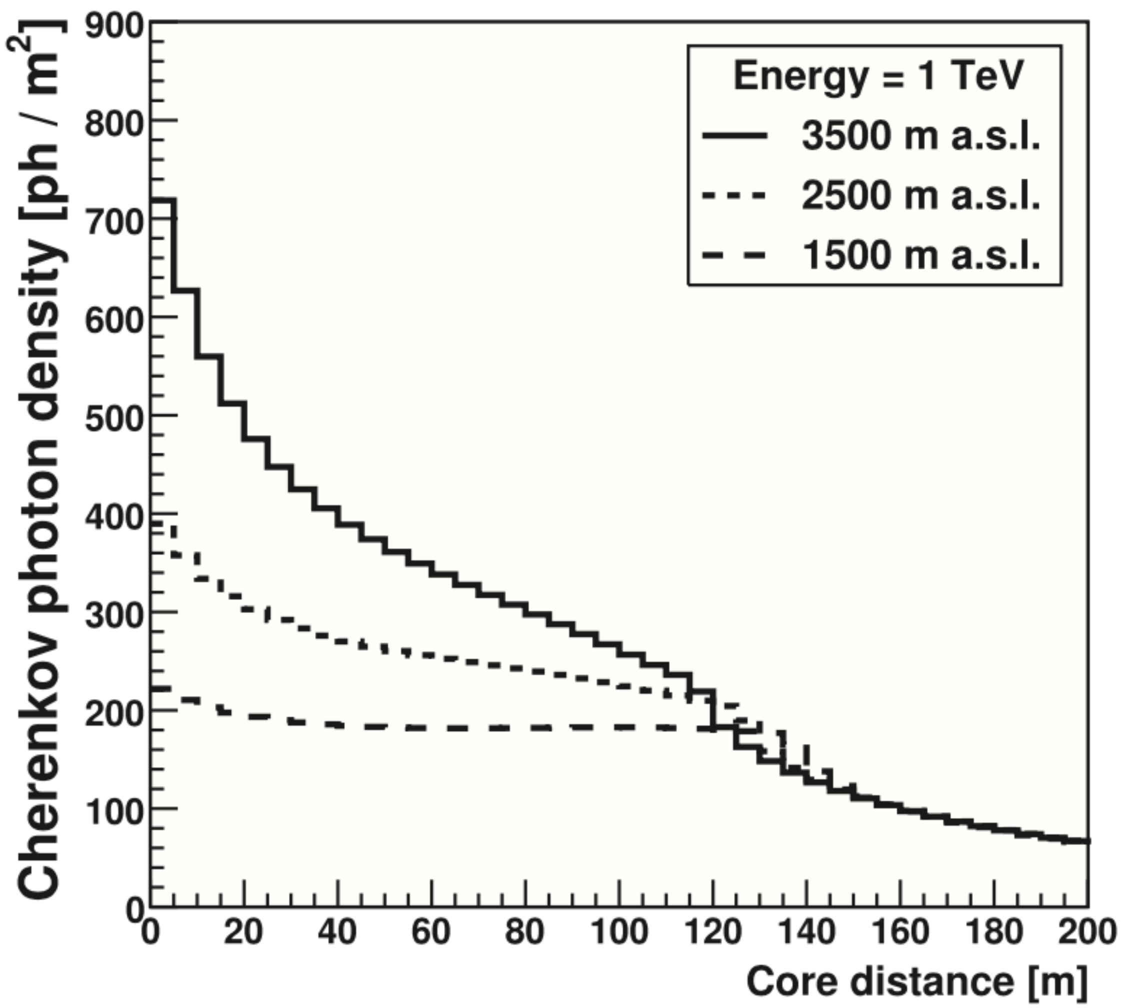
Lateral distributions

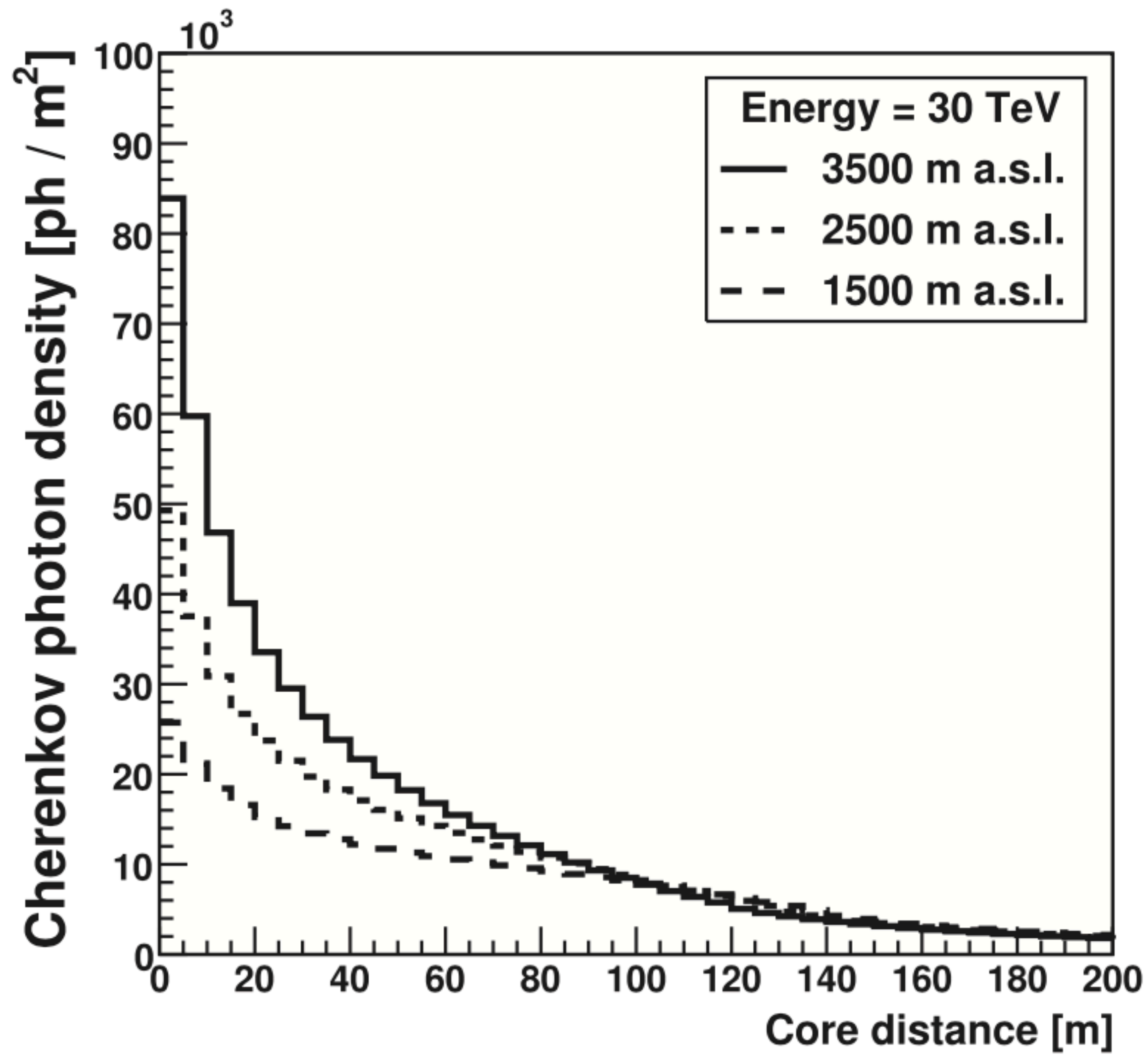


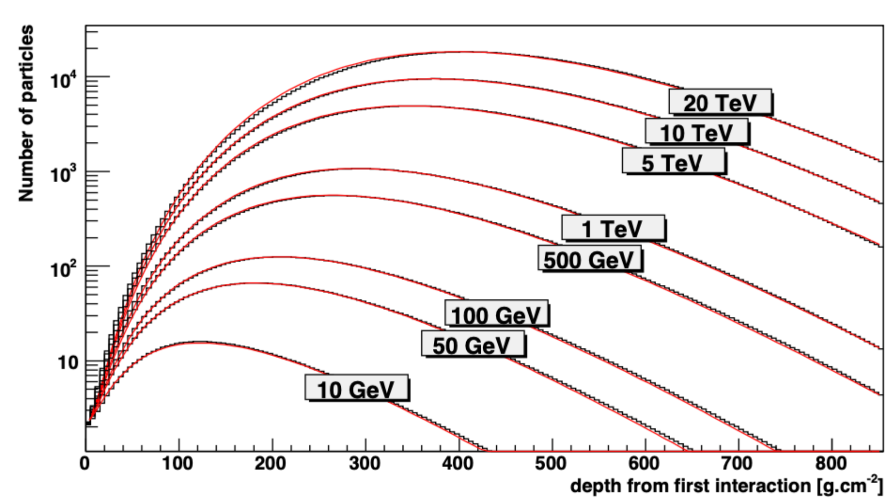


Lateral distributions vs shower development.

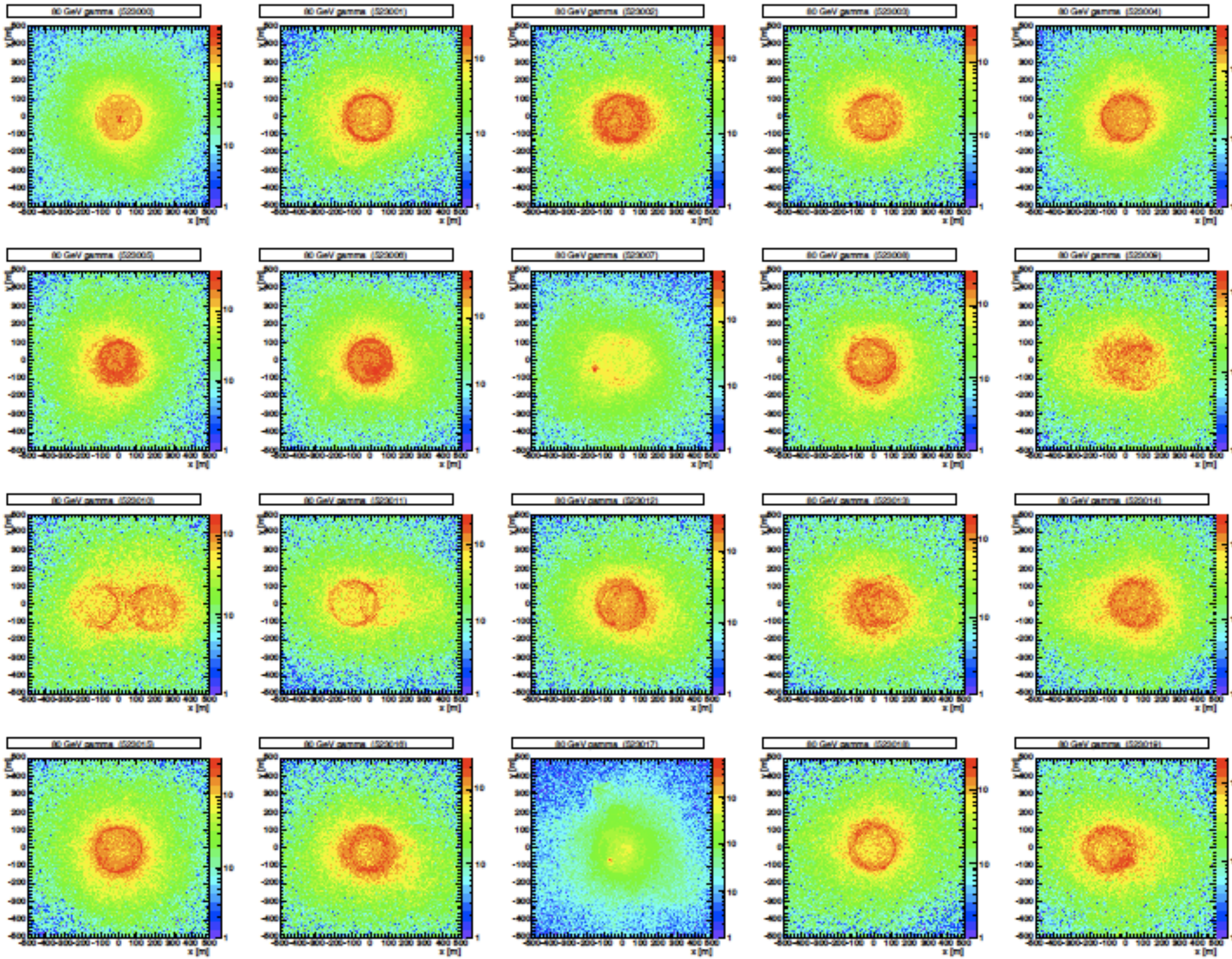
T. Hassan et al./Astroparticle Physics 93 (2017) 76–85



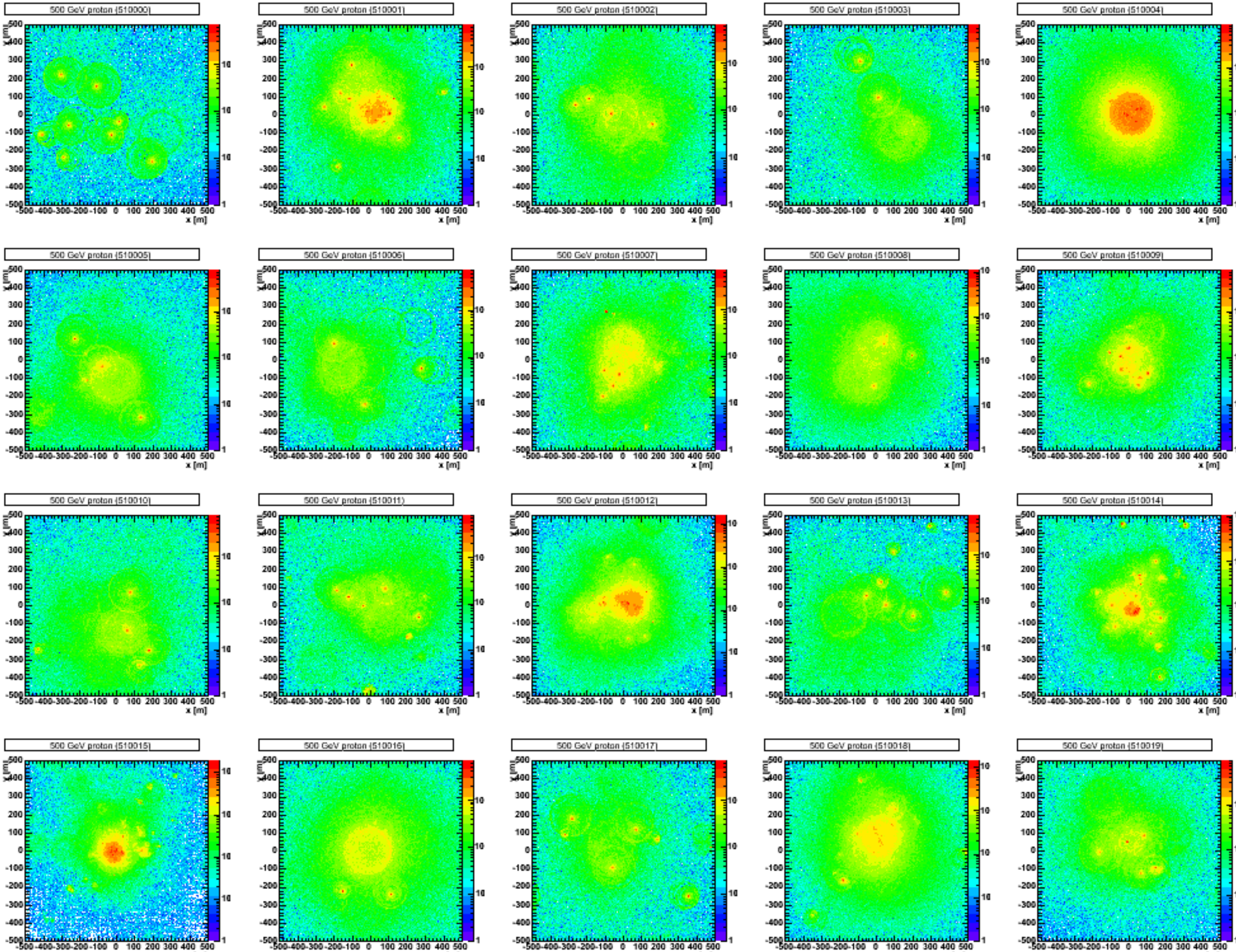




de Naurois 2009

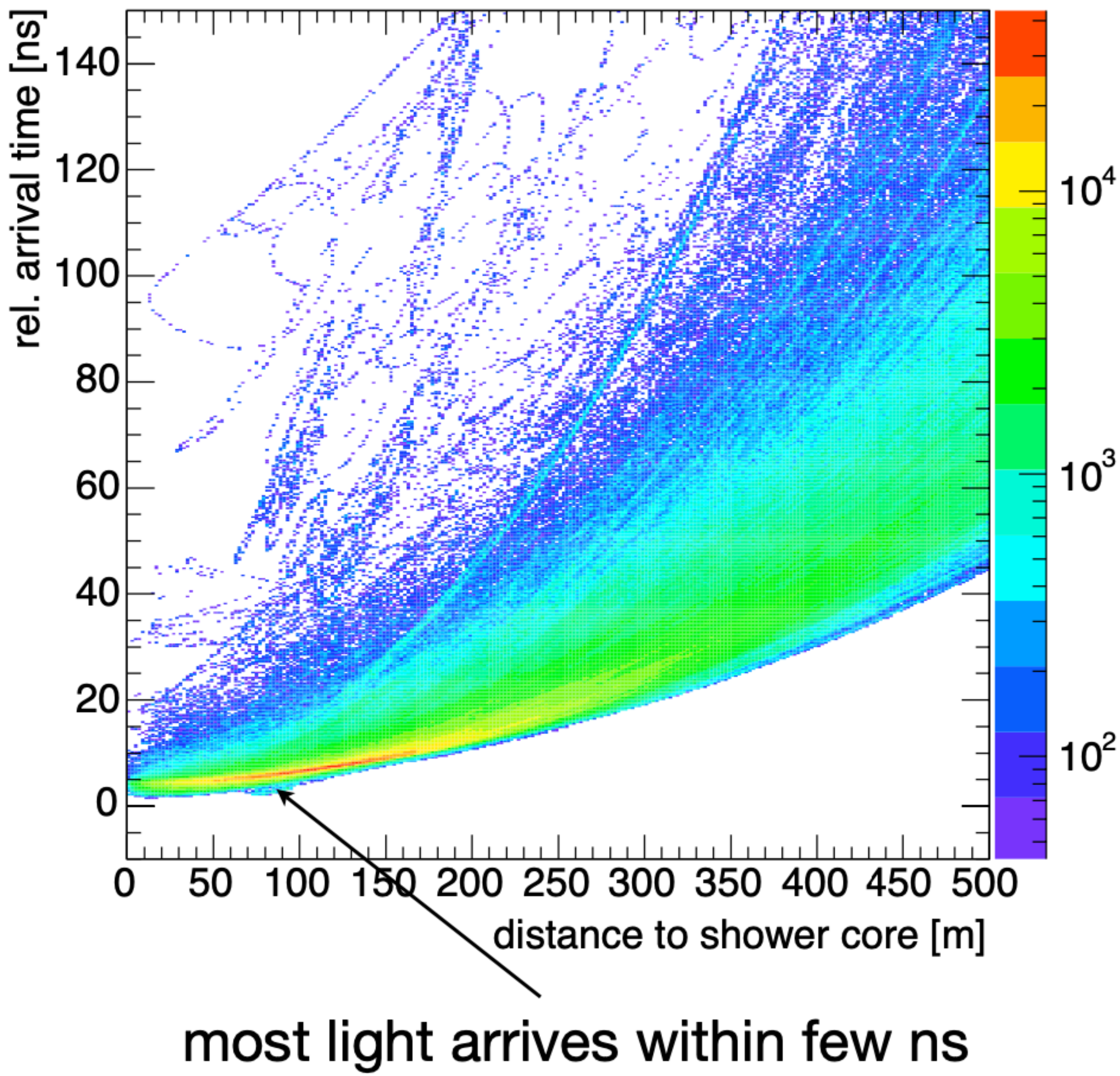


randomly selected showers with 80 GeV primary photon energy



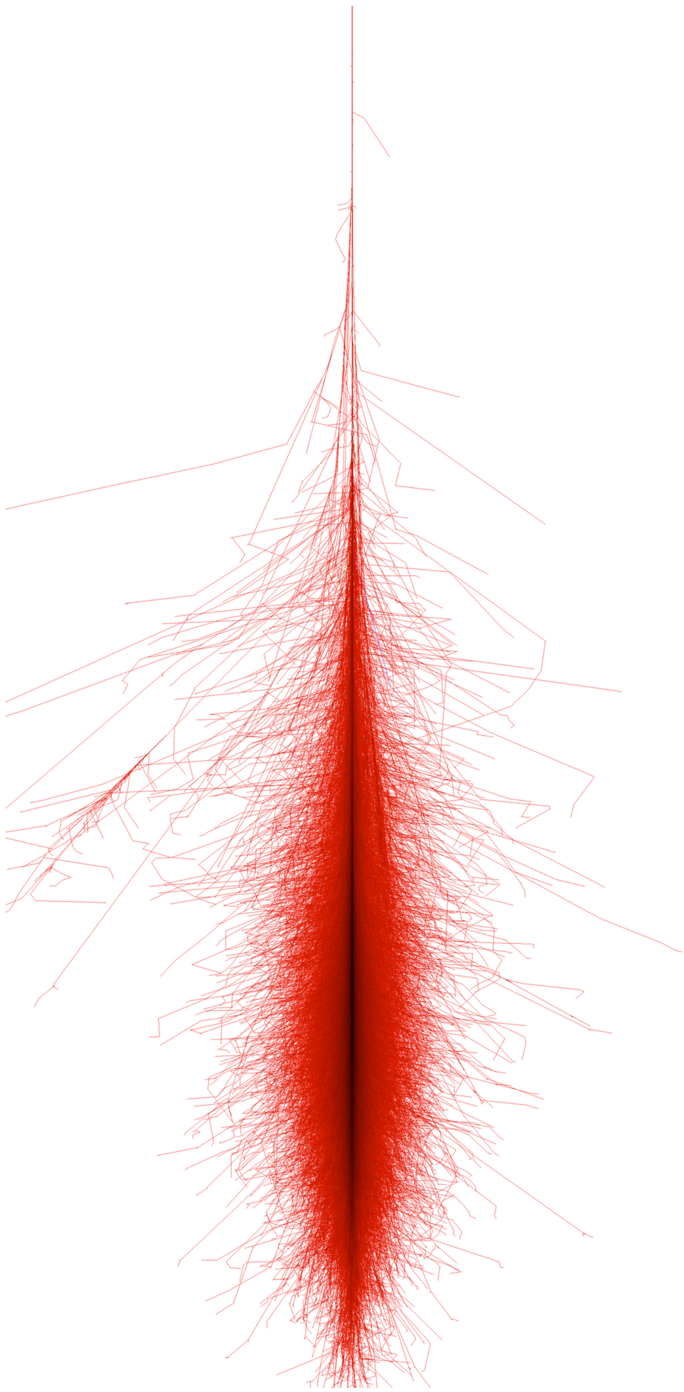
randomly selected showers with 500 GeV primary proton energy

Cherenkov photon arrival time.

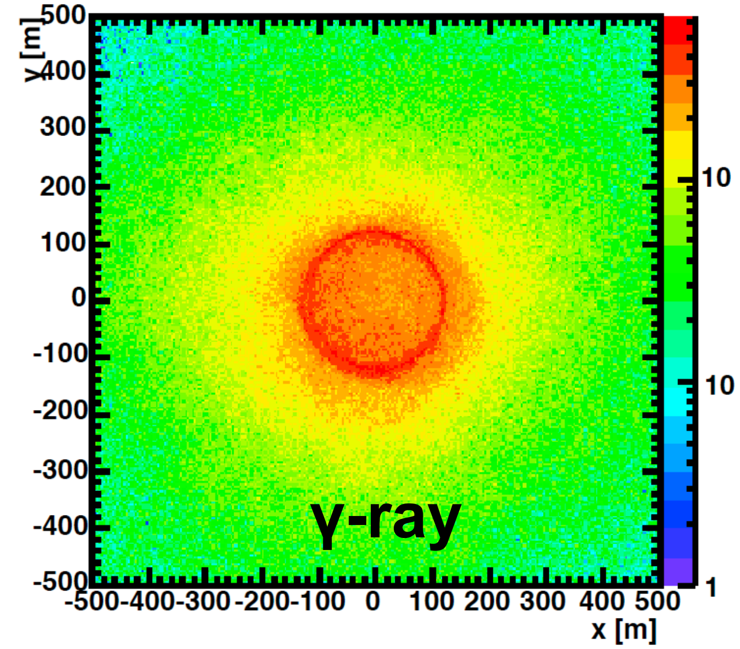


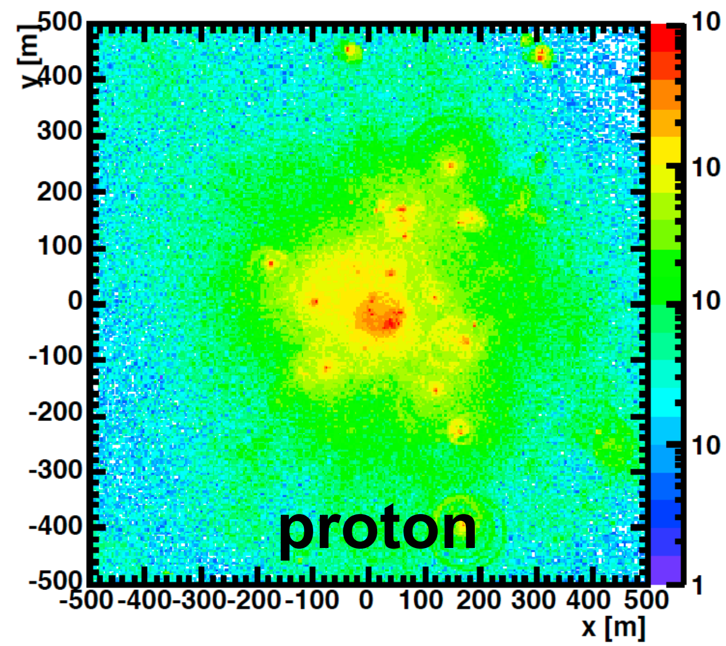
Proton vs Gamma-ray showers

γ-ray

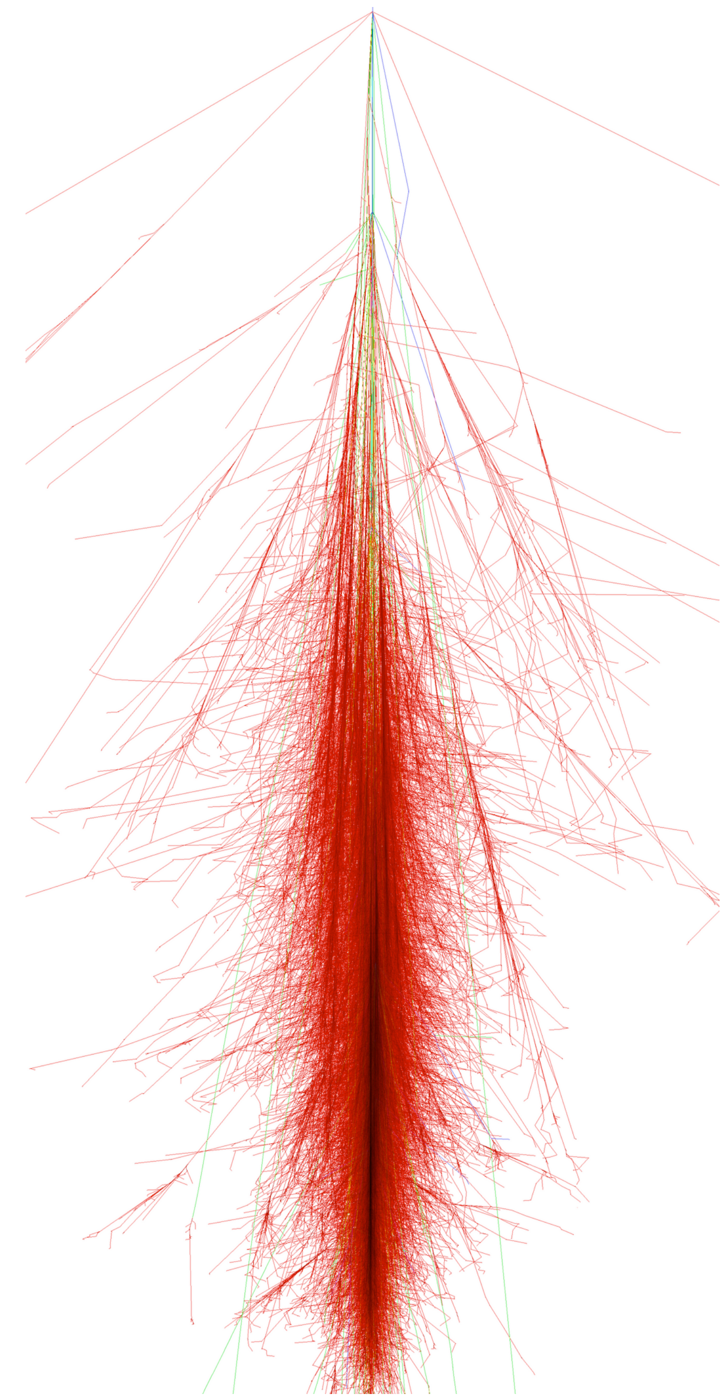


Cherenkov photons on ground

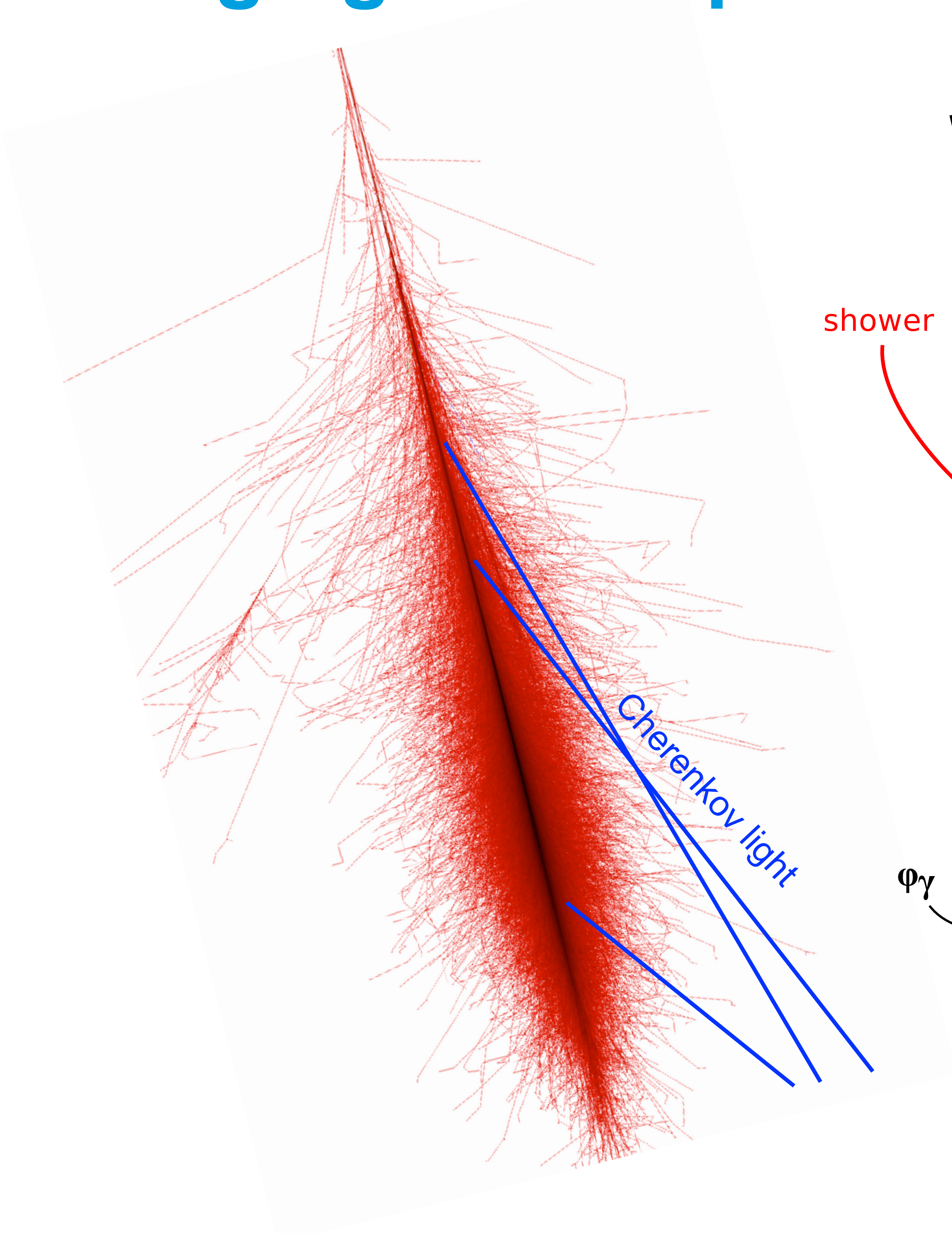


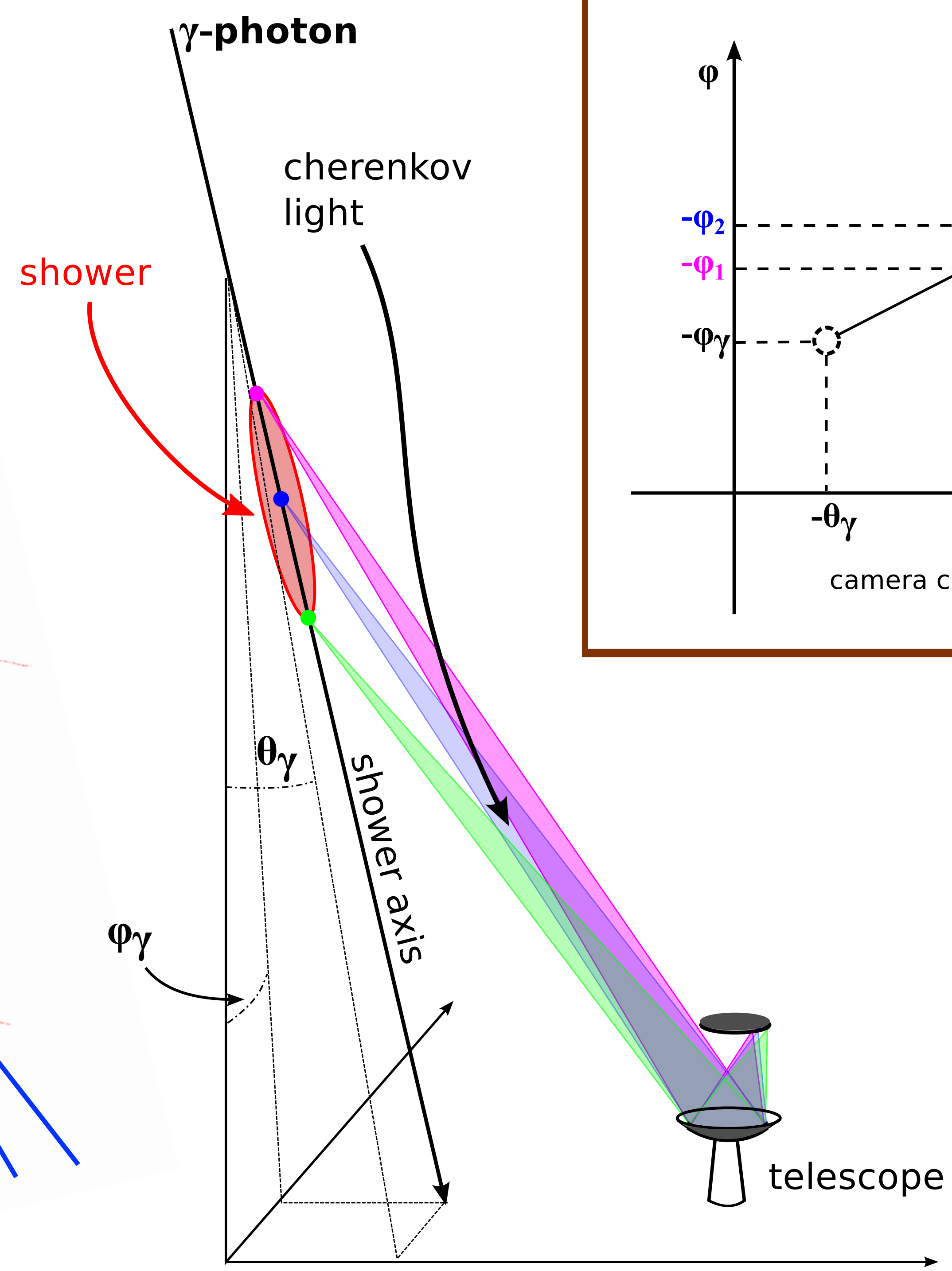


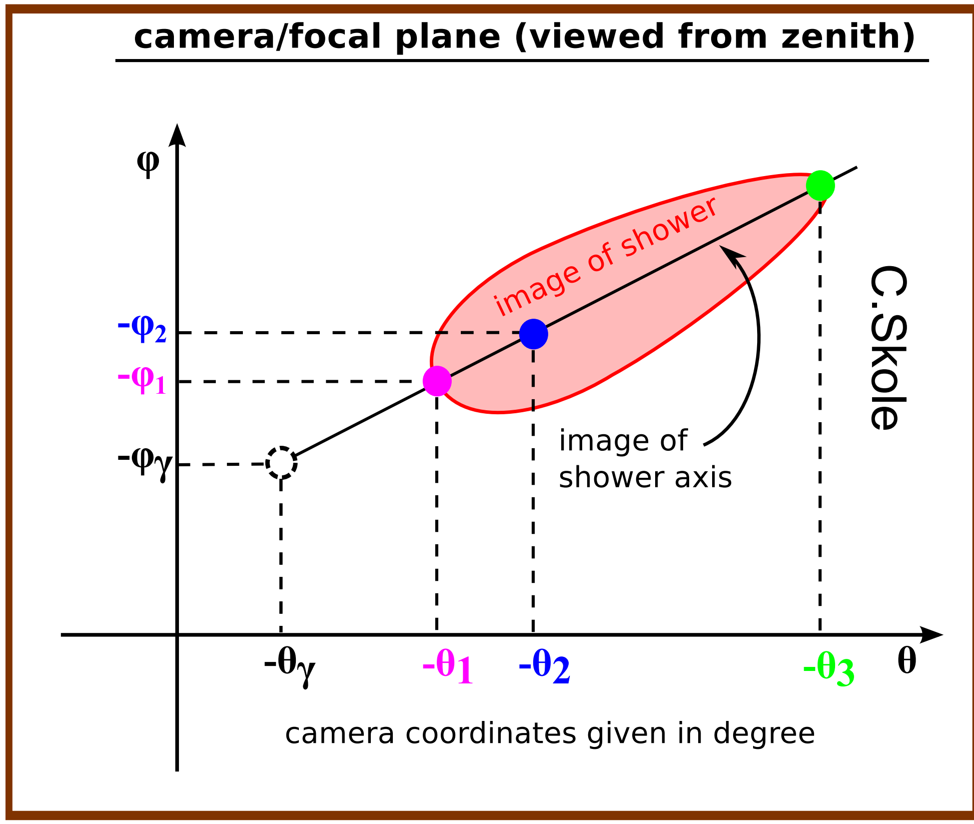
proton



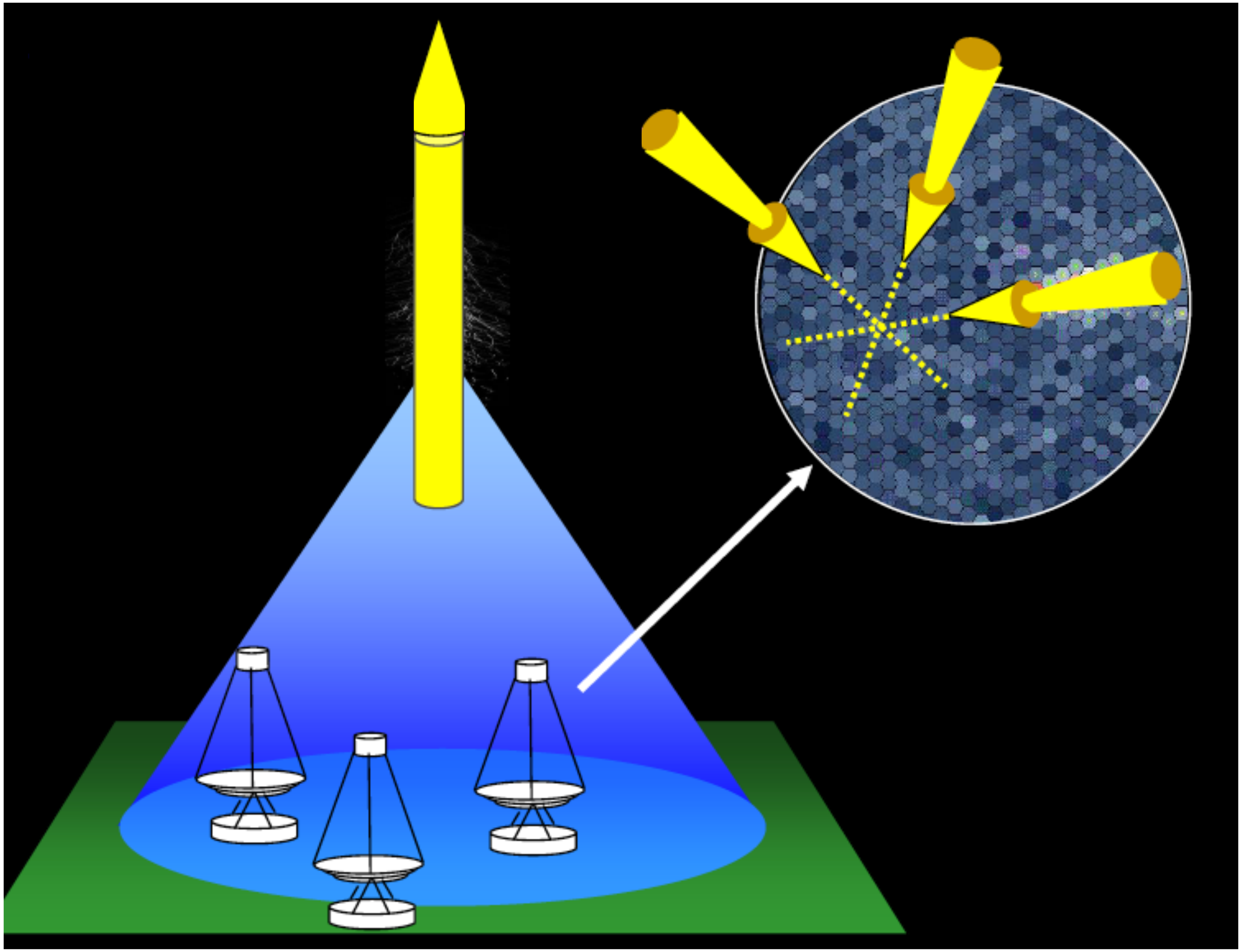
Imaging Technique - Air Showers





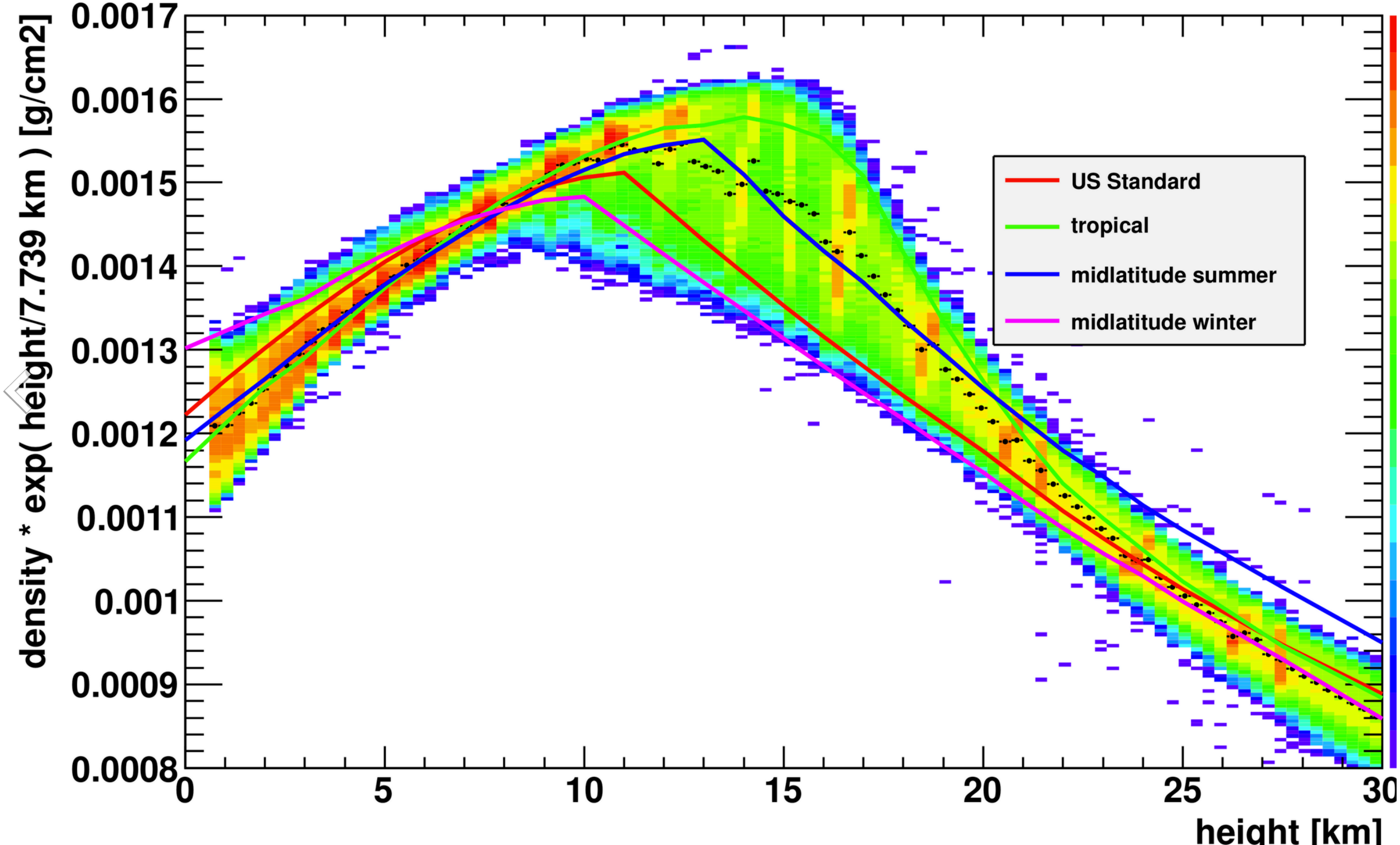


Stereoscopy.



Seasonal changes - density vs height.

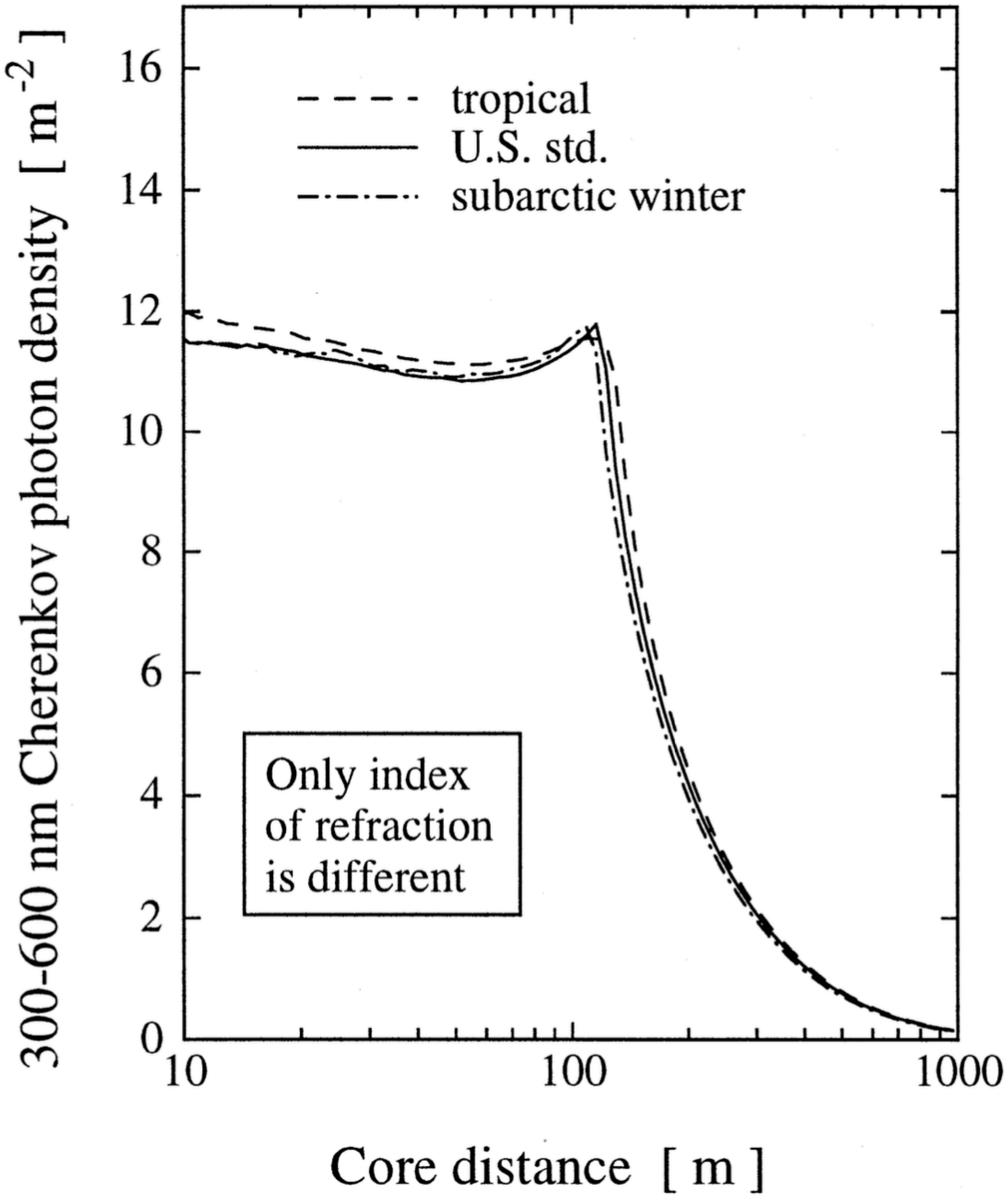
Example from Tucson, Arizona (1995-2010)

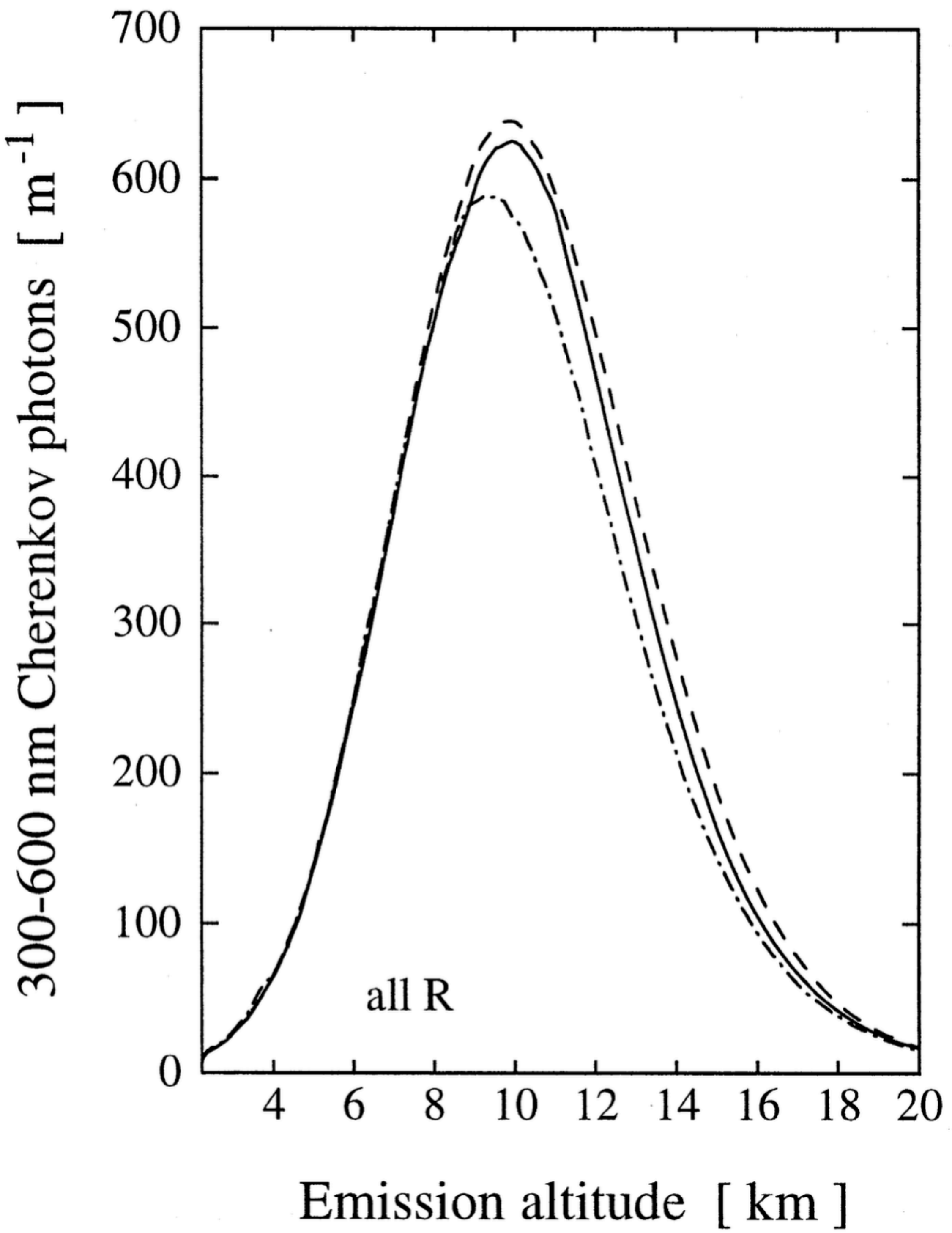


Changes shower development and refractive index.

Refractive index only (same density profile).

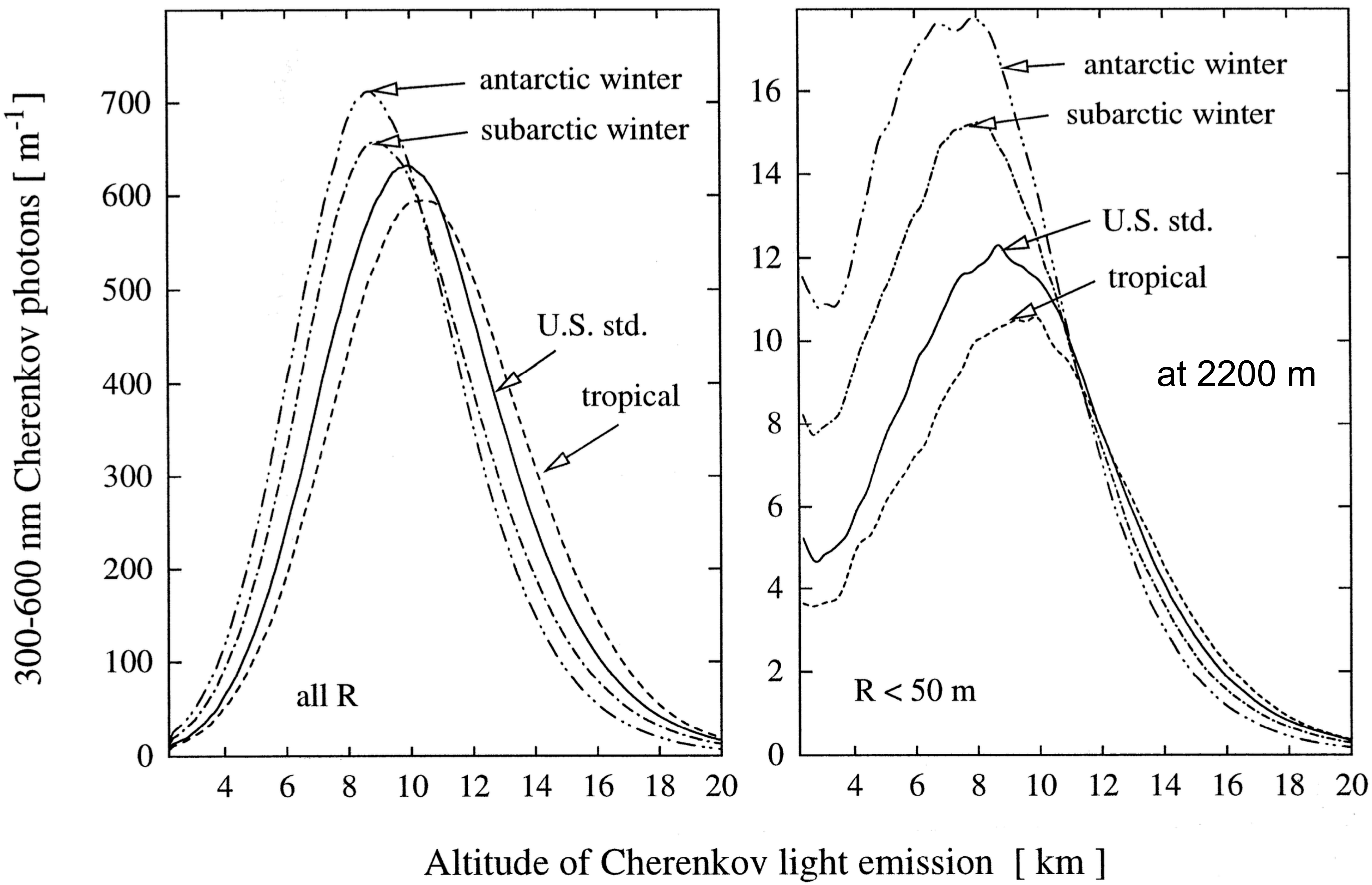
K. Bernlöhr / Astroparticle Physics 12 (2000) 255–268





Different atmospheric profiles.

K. Bernlöhr / Astroparticle Physics 12 (2000) 255–268

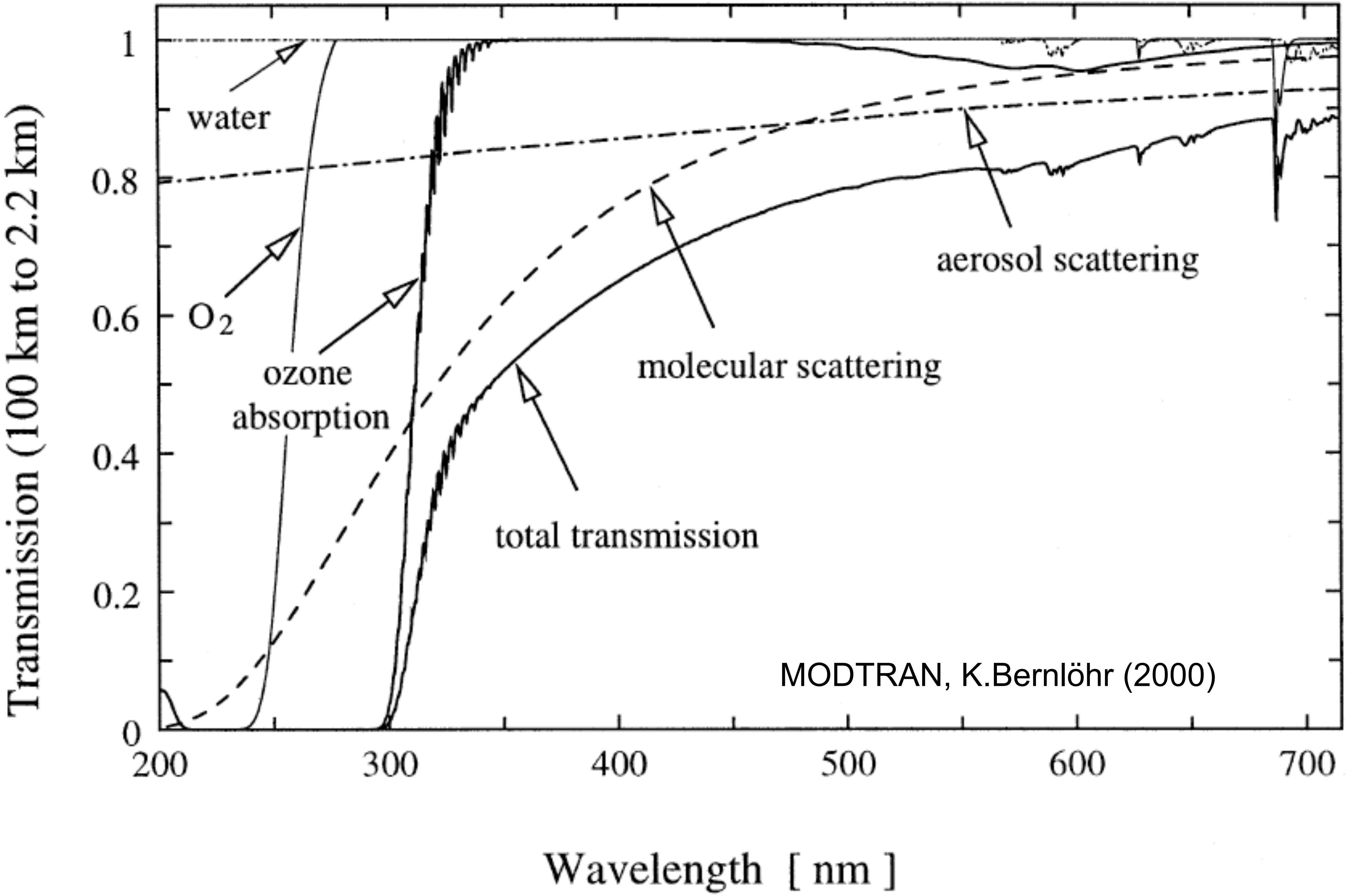


No absorption applied.

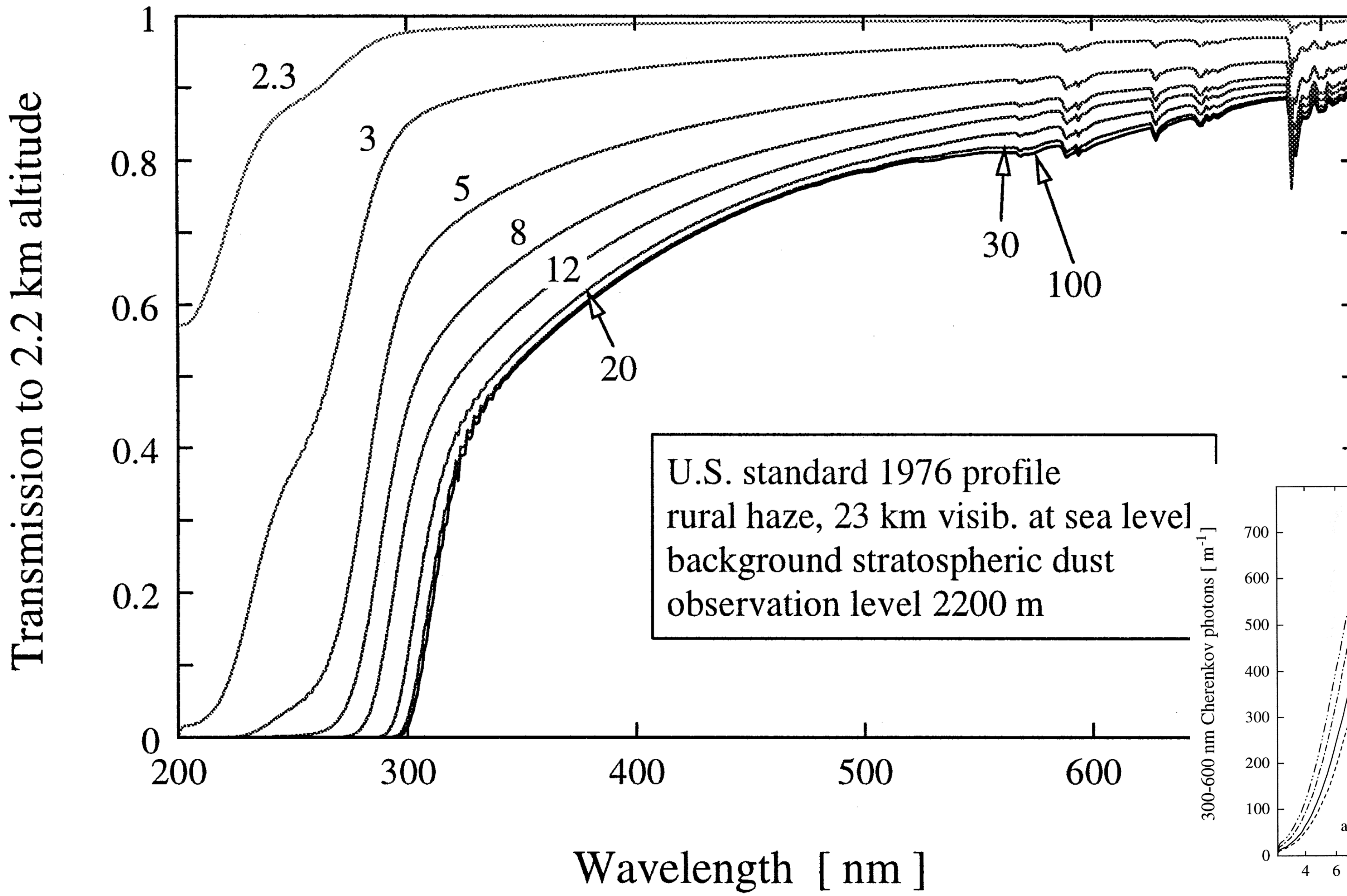
Propagation of Cherenkov light.

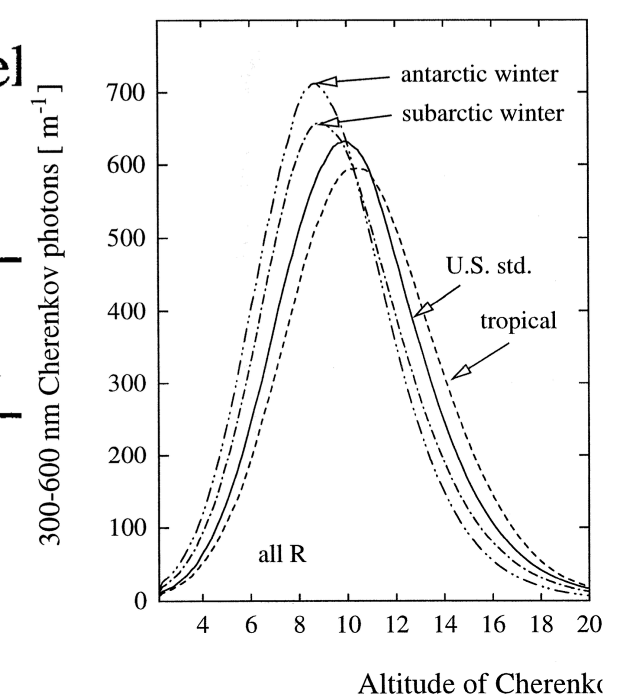
- molecular absorption bands
- molecular (Rayleigh) scattering
- aerosol (Mie) scattering & absorption
- current simulations: scattered == absorbed
- clouds not covered here.

Atmospheric extinction.

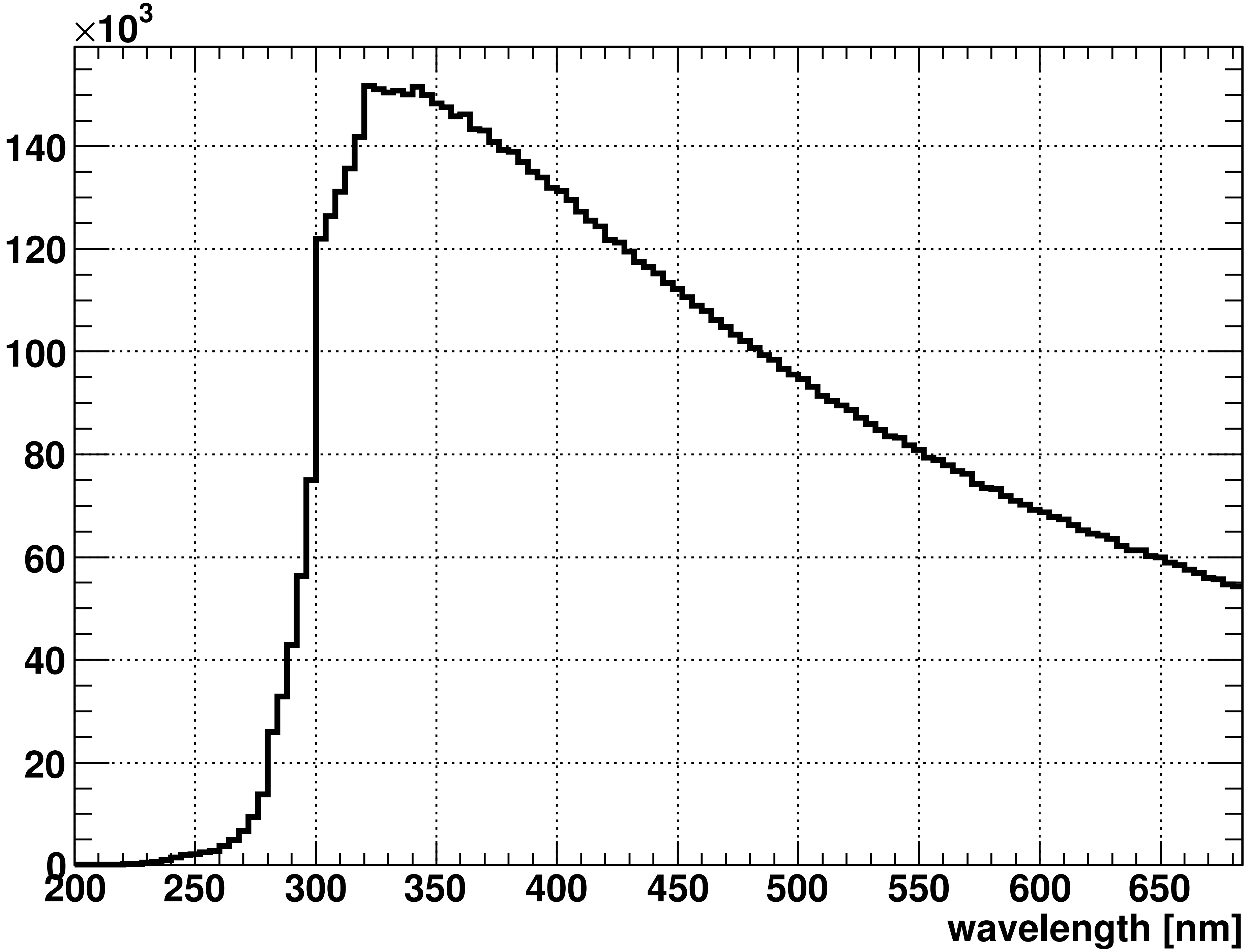


Atmospheric Extinction.



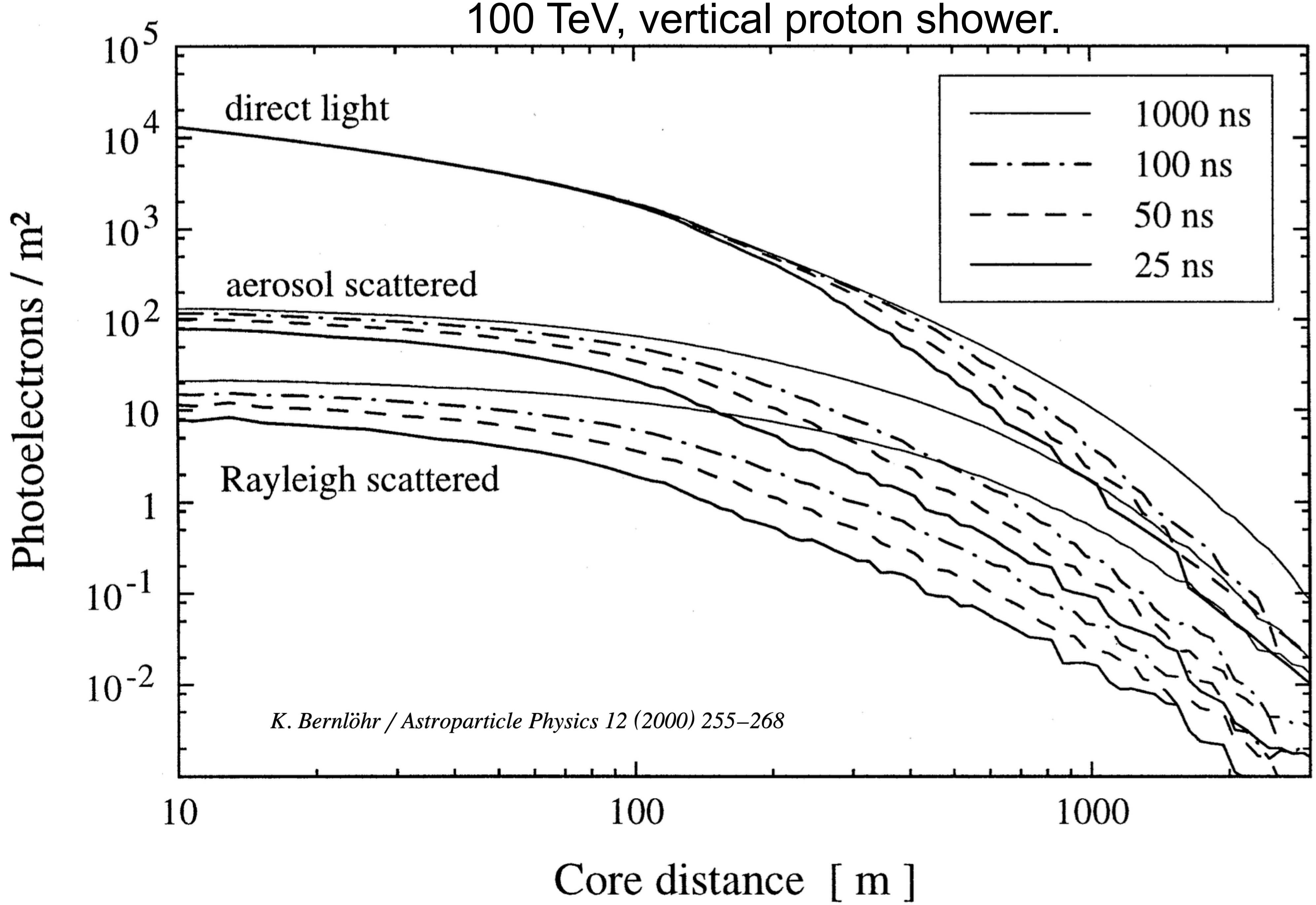


Cherenkov spectrum after extinction.



Scattered == absorbed?

100 TeV, vertical proton shower.

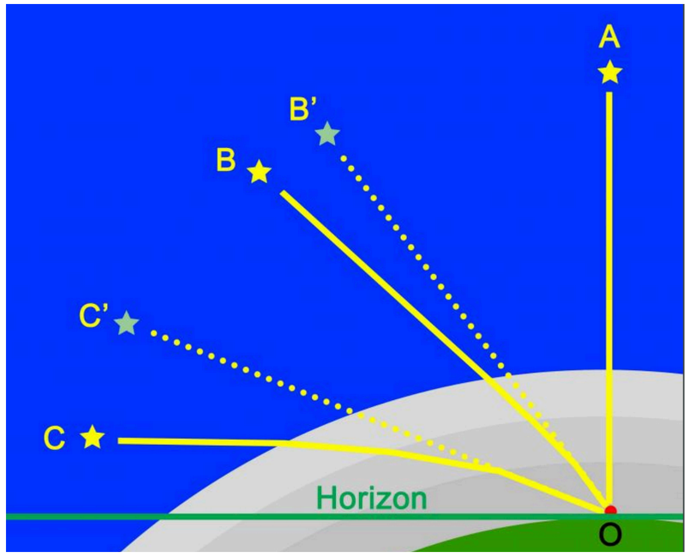


Refraction.

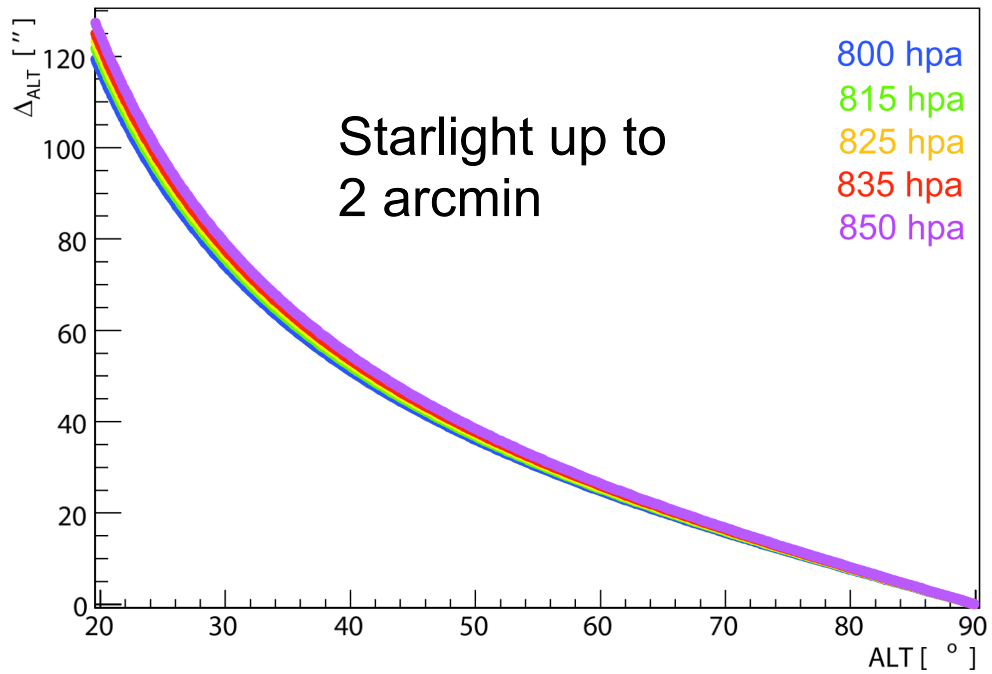
https://britastro.org/2019/atmospheric-refraction

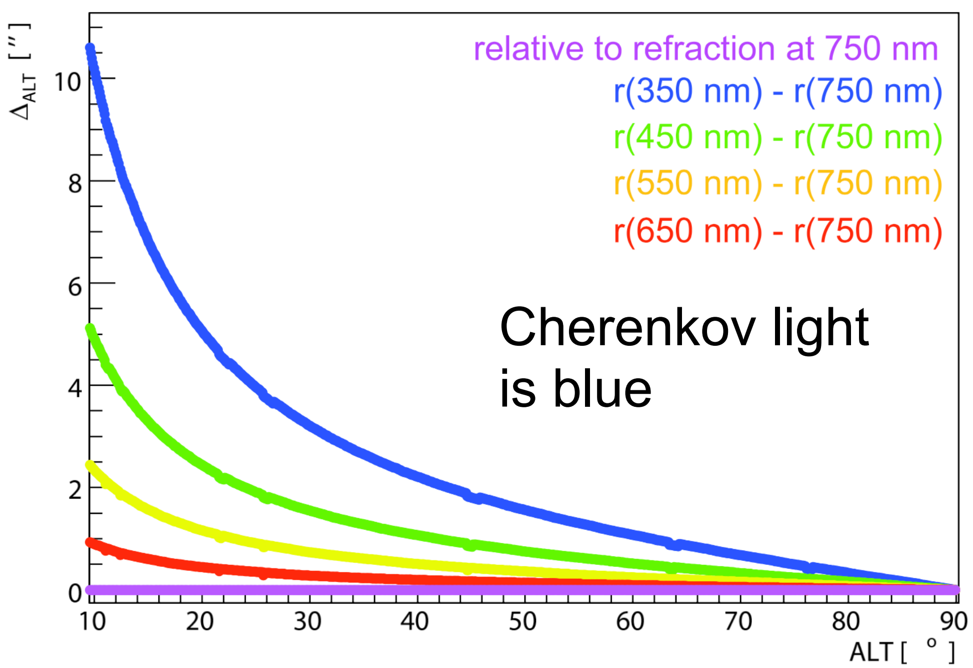
Snell's law:

$$\sin(\theta_2) = \frac{n_1}{n_2} \cdot \sin(\theta_1)$$

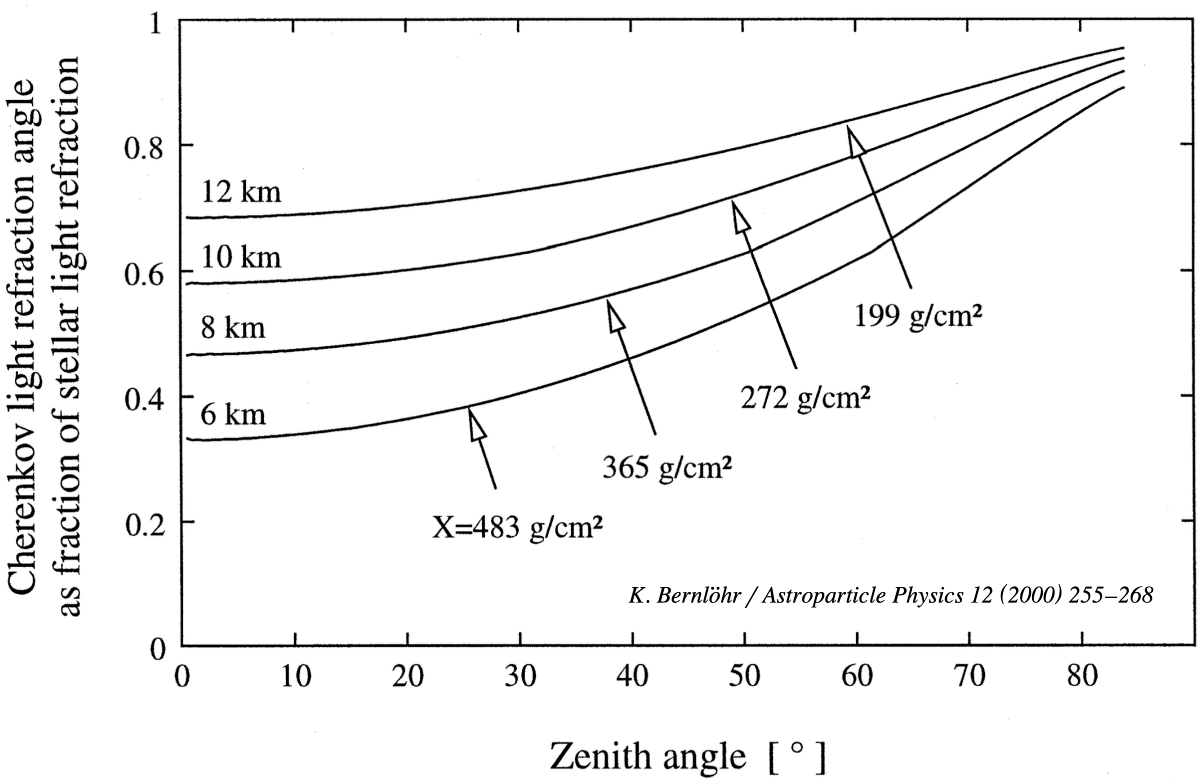


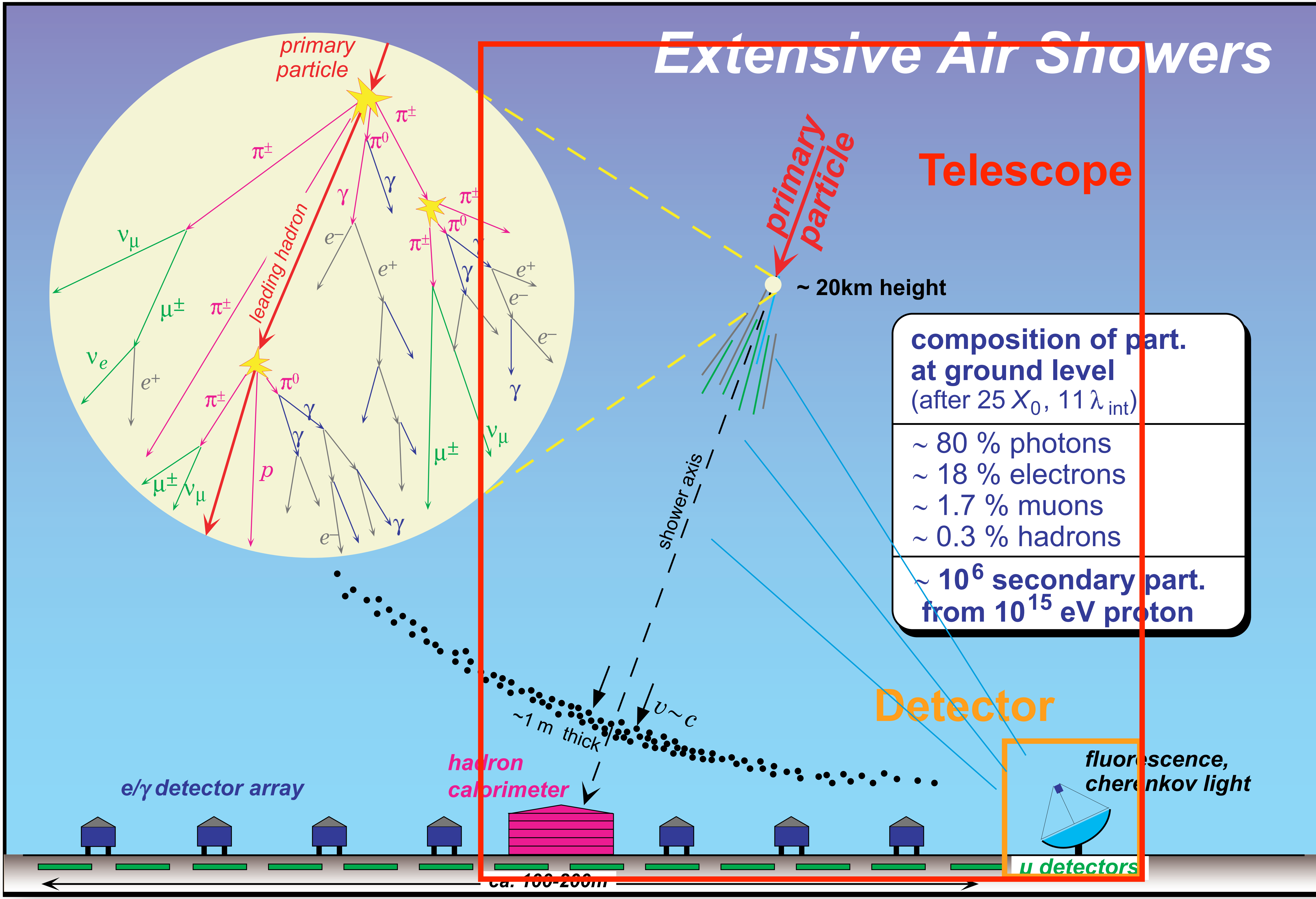
Thesis I. Braun (2007)



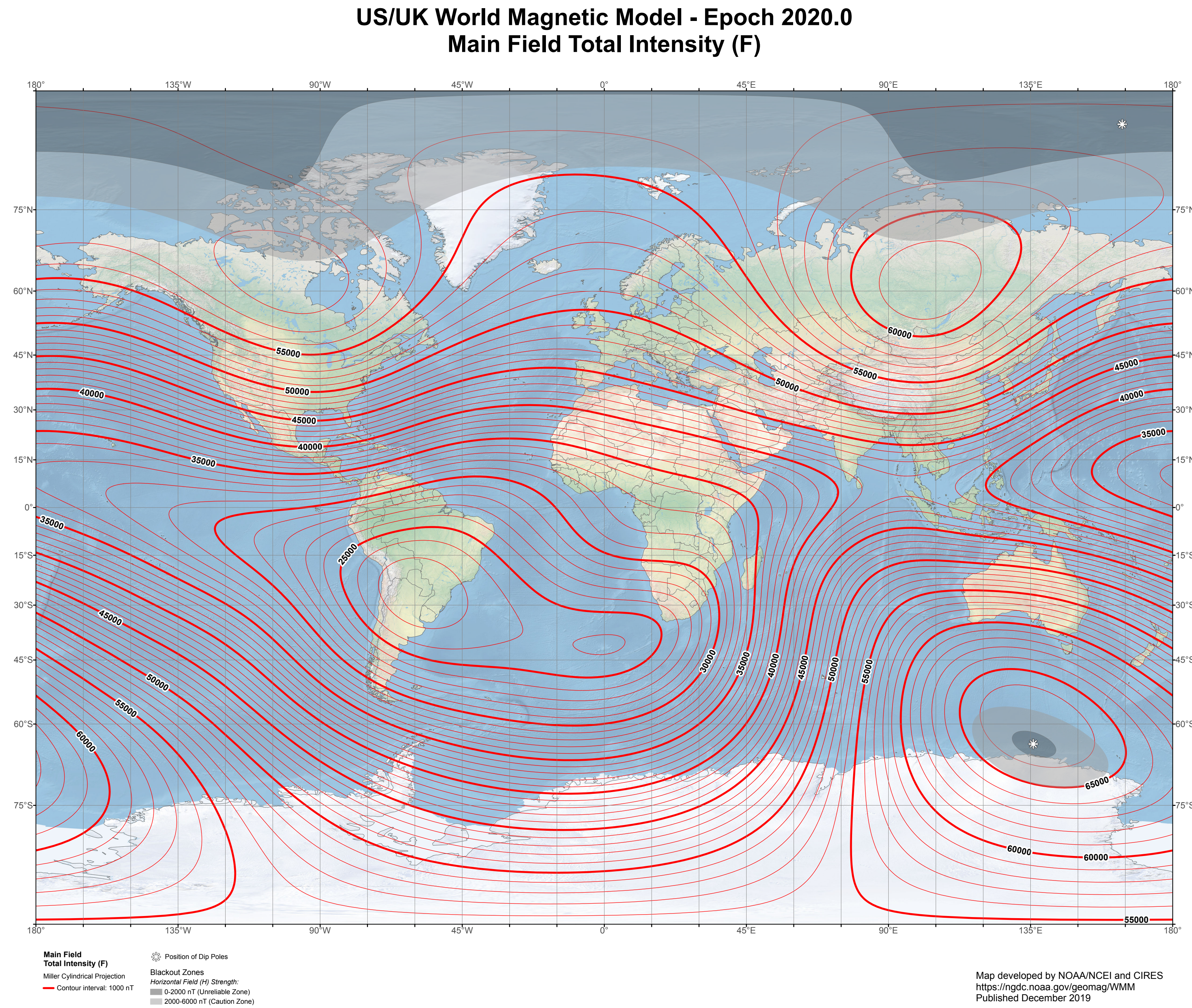


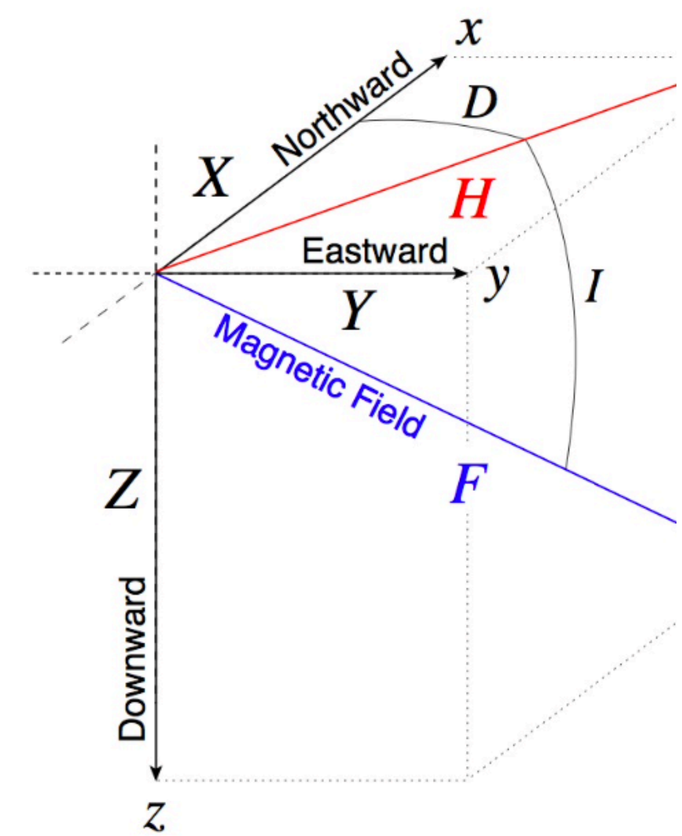
Cherenkov light is emitted in the atmosphere




Extensive Air Showers
primary particle
π±
π0
γ
e−
e+
νμ
μ±
νe
leading hadron
p
primary particle
Telescope
~ 20km height
composition of part. at ground level
(after 25 X0, 11 λ int)
~ 80 % photons
~ 18 % electrons
~ 1.7 % muons
~ 0.3 % hadrons
~ 10^6 secondary part. from 10^15 eV proton
shower axis
~1 m thick
υ~c
Detector
hadron calorimeter
e/γ detector array
fluorescence, cherenkov light
μ detectors
ca. 100-200m

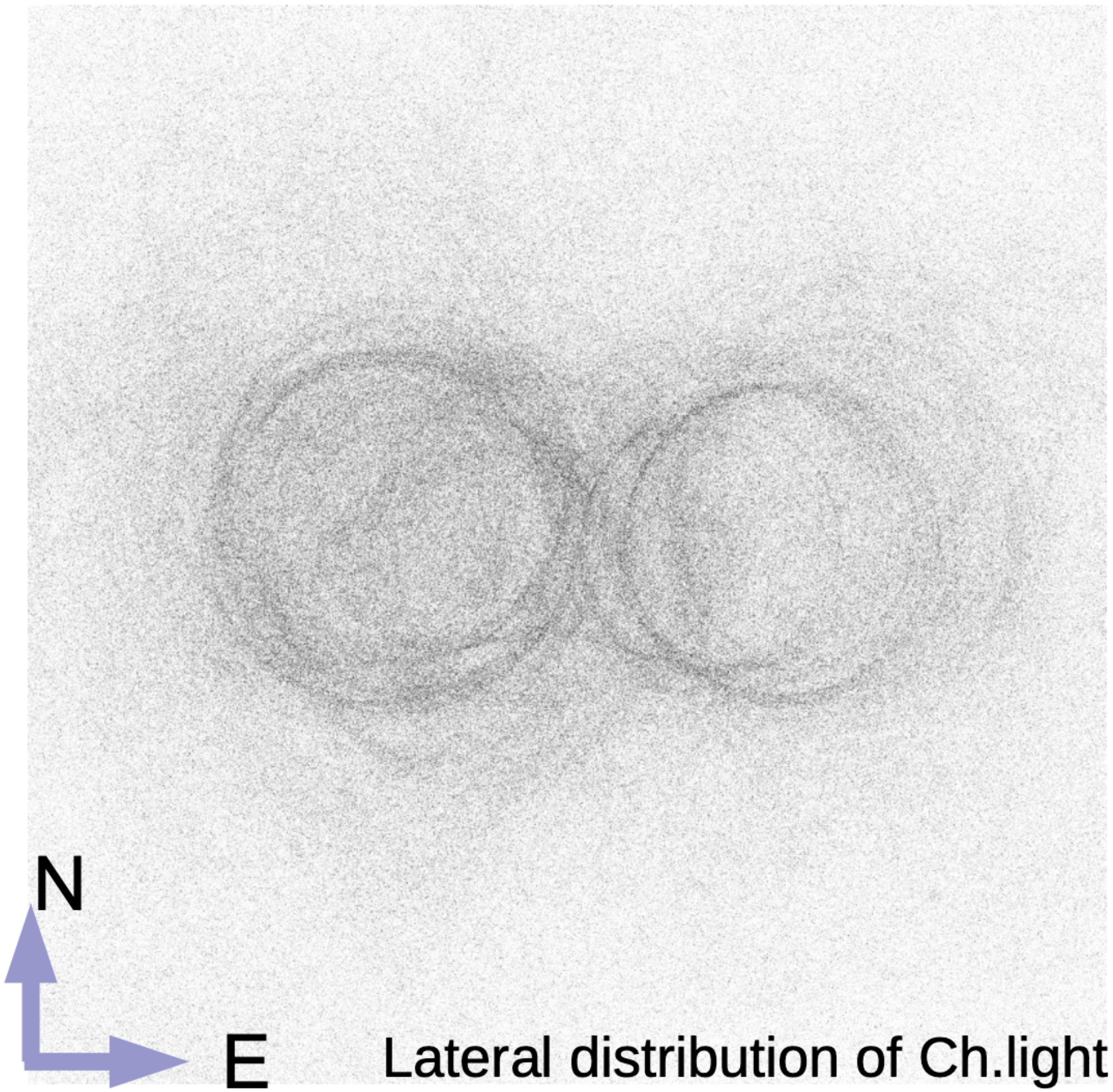
Geomagnetic field.



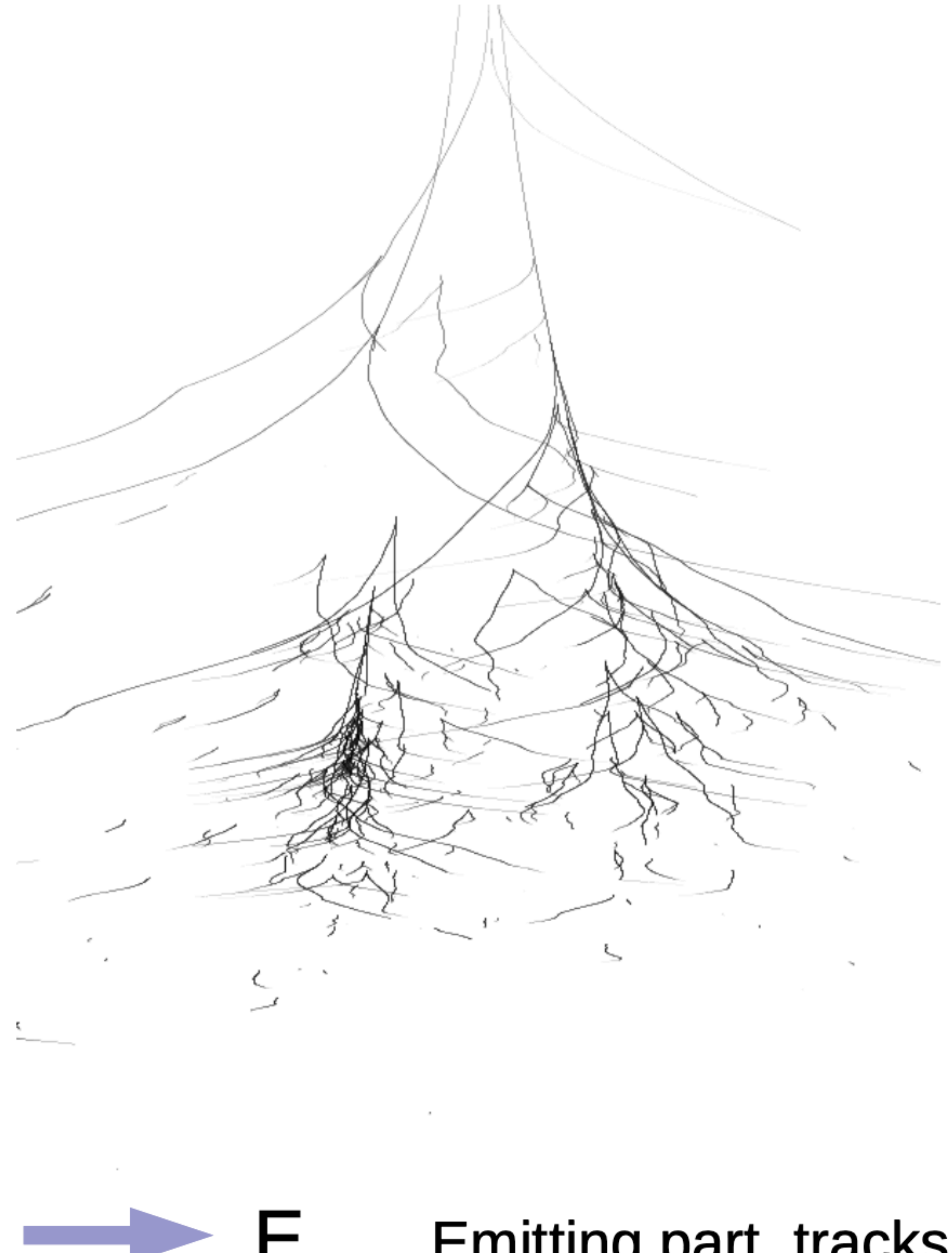


Field intensity (F)
Horizontal component (H)
Vertical component (Z)
Declination (D)
Inclination (H)

Geomagnetic field.



Lateral distribution of Ch.light

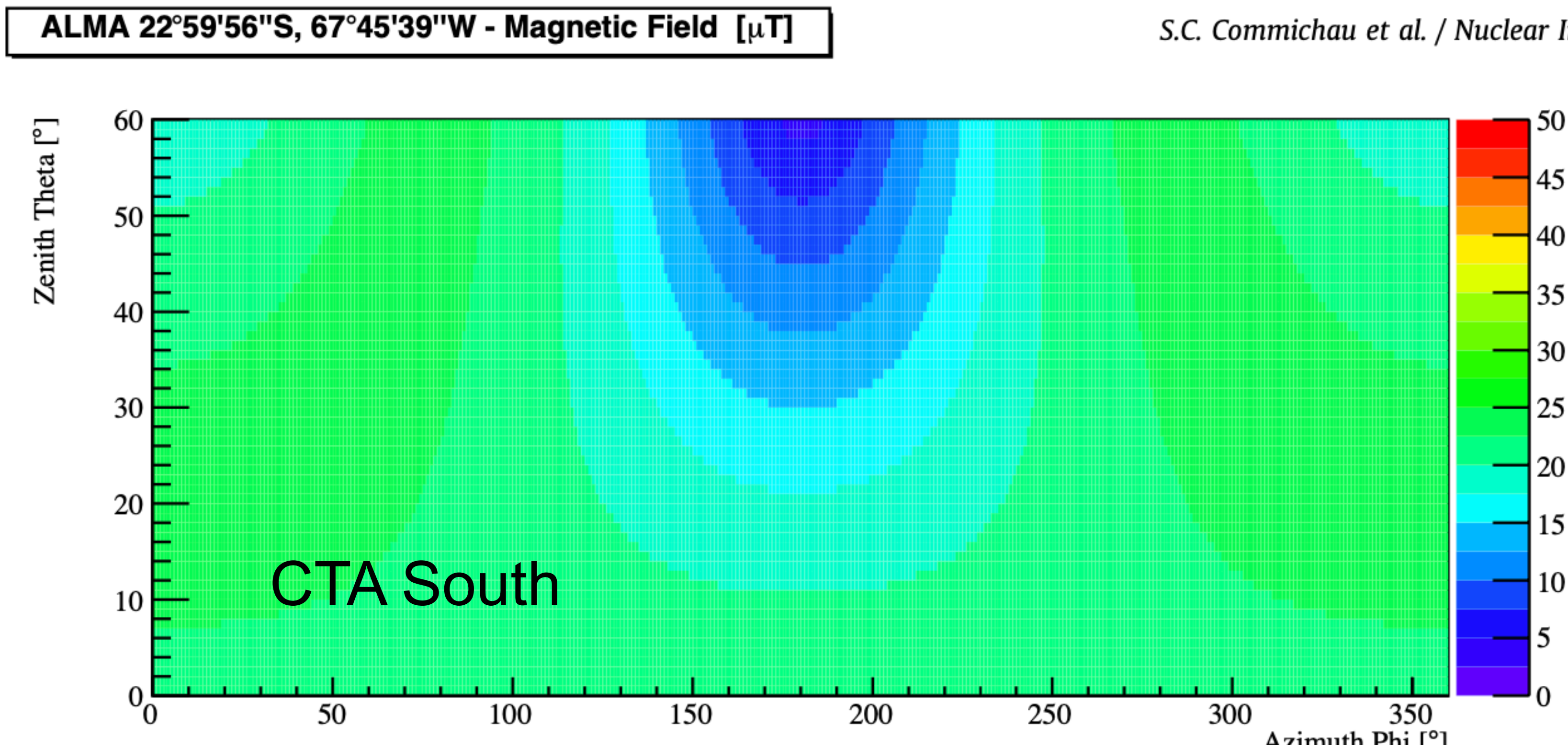


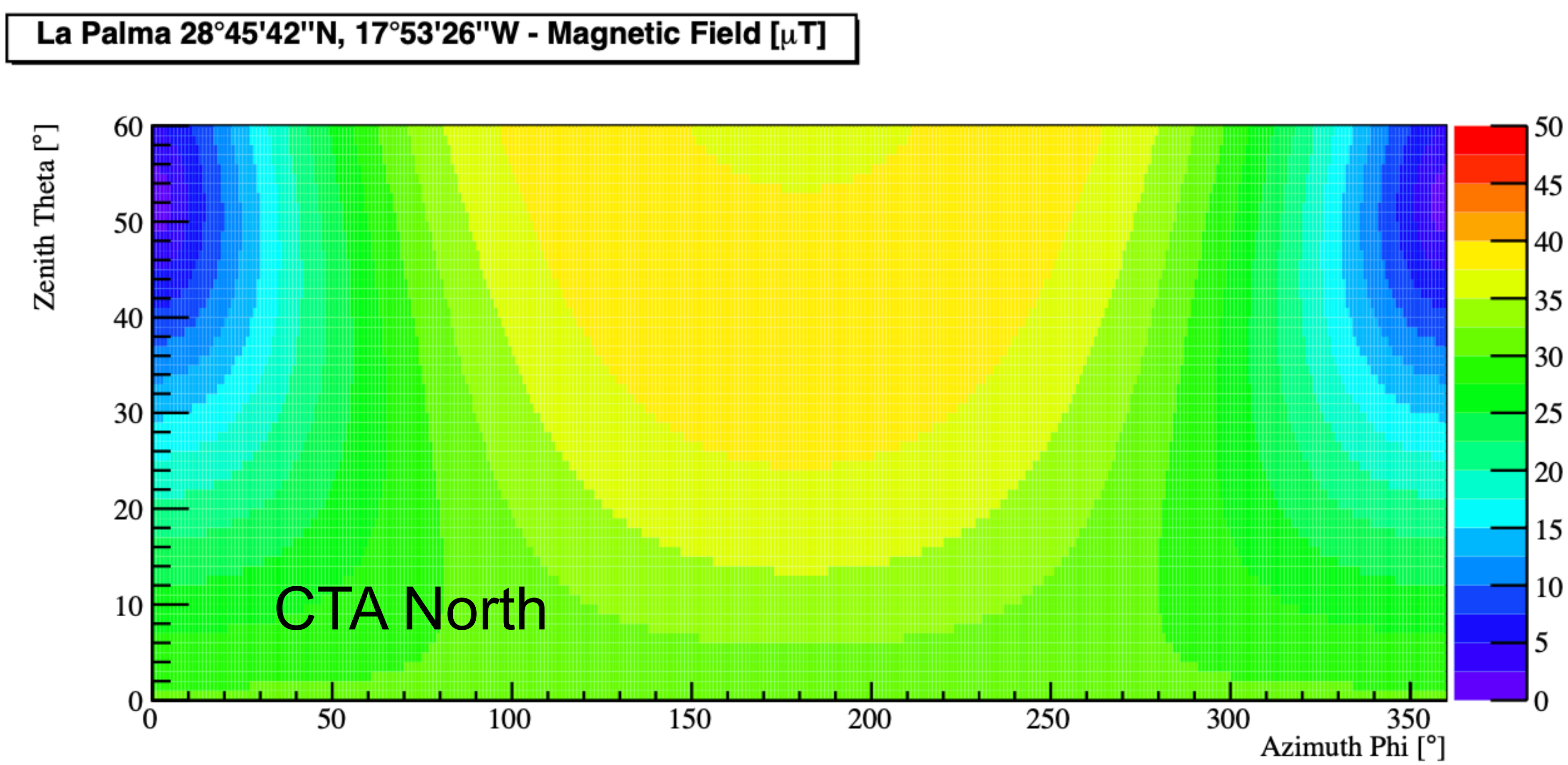
Emitting part. tracks

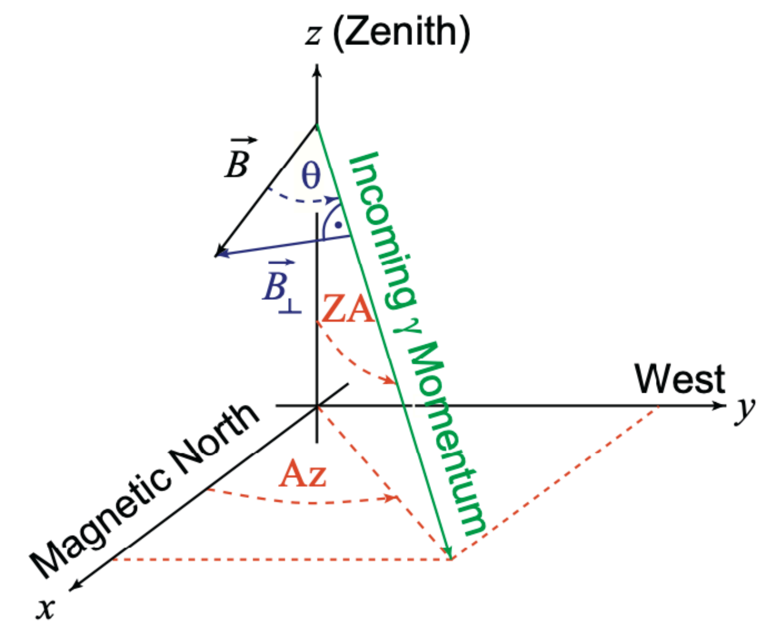
from K.Bernlöhr

Magnetic field normal to shower direction.

S.C. Commichau et al. / Nuclear Instruments and Methods in Physics Research A 595 (2008) 572–586

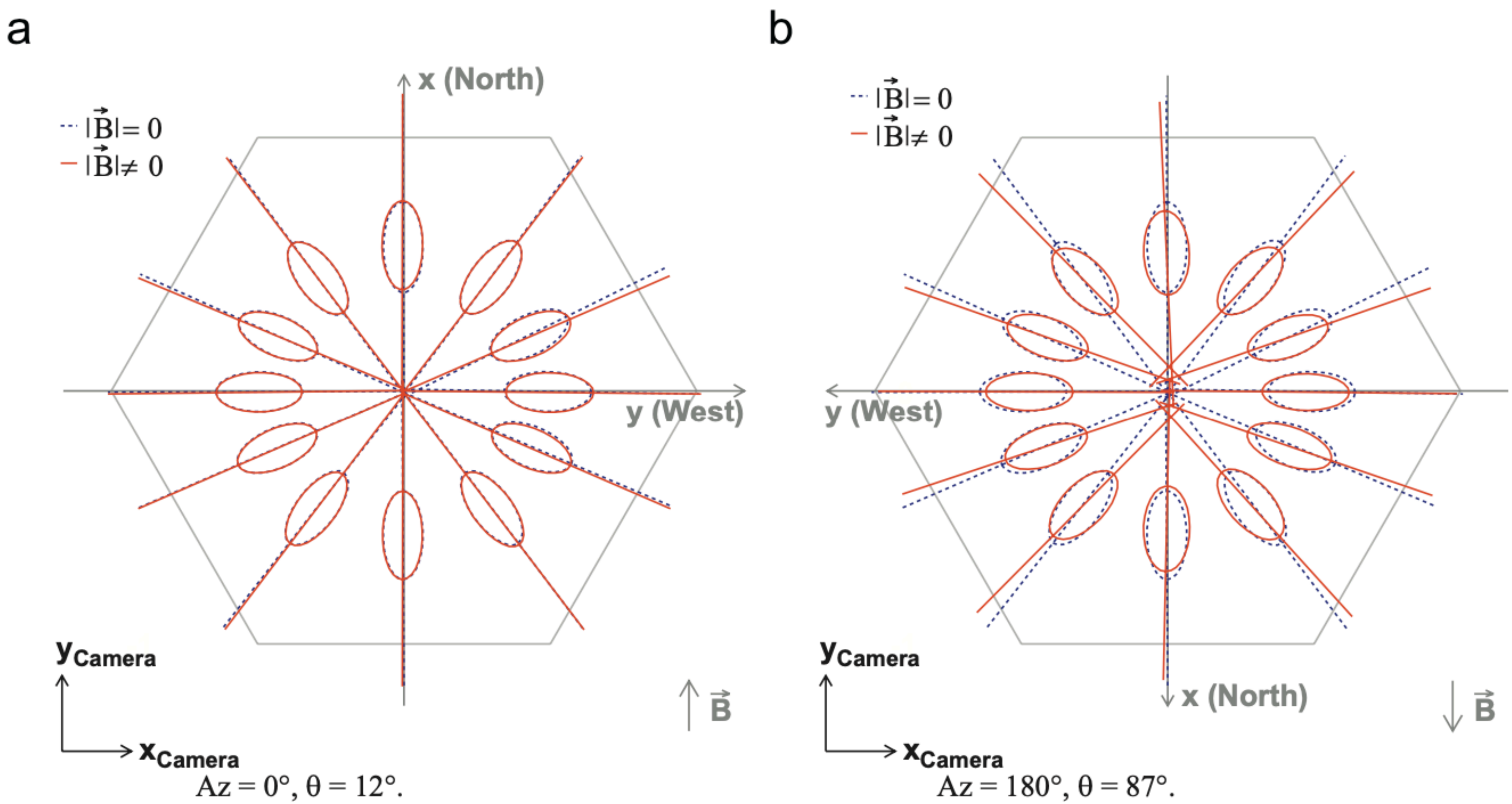






Thesis M.Krause

Geomagnetic field - impact on image reconstruction.

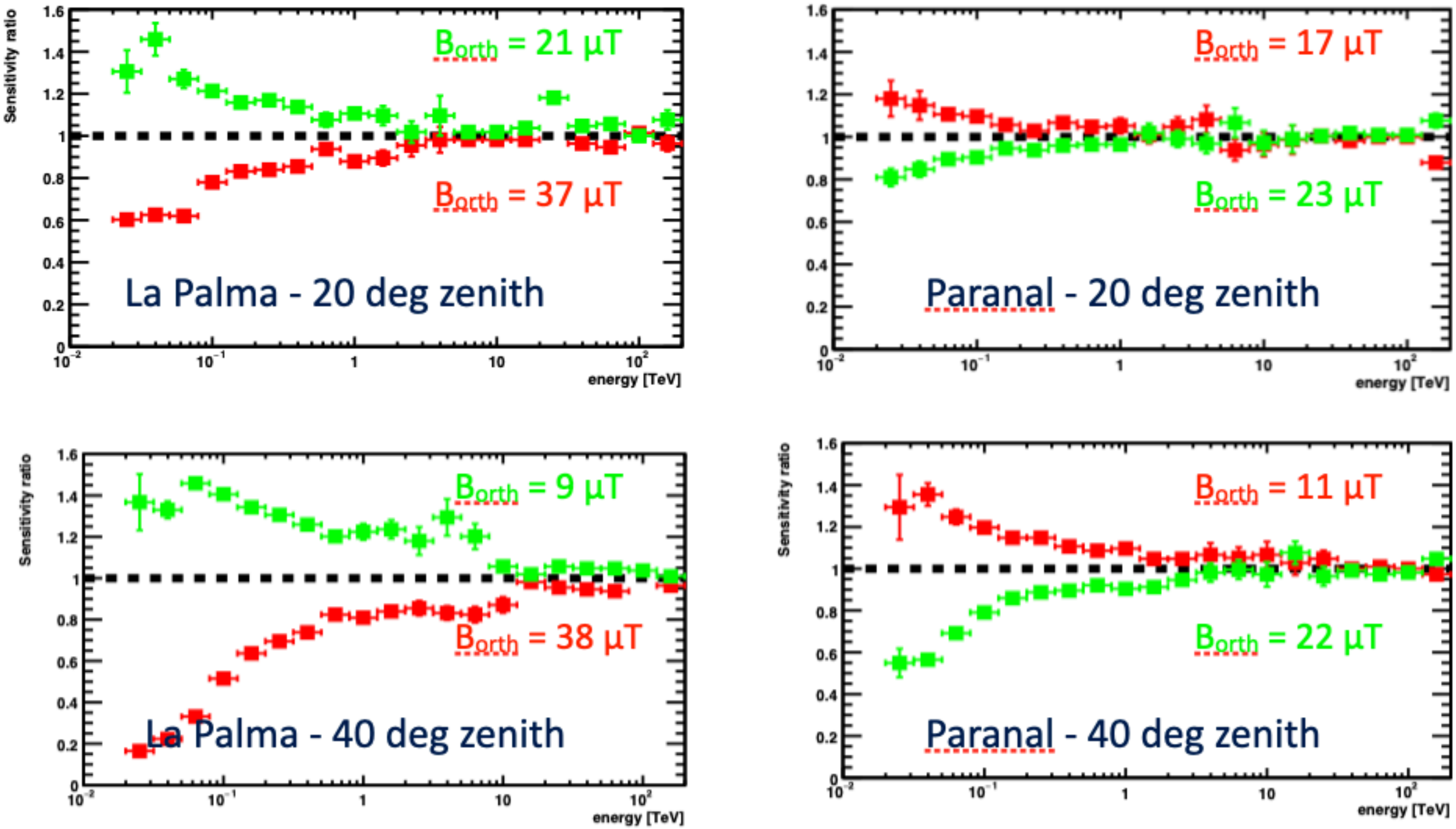


450 GeV γ-rays, 100 m impact parameter, ZA = 40°, Az = 0° and 180°,

S.C. Commichau et al. / Nuclear Instruments and Methods in Physics Research A 595 (2008) 572–586

Geomagnetic field - impact on sensitivity.

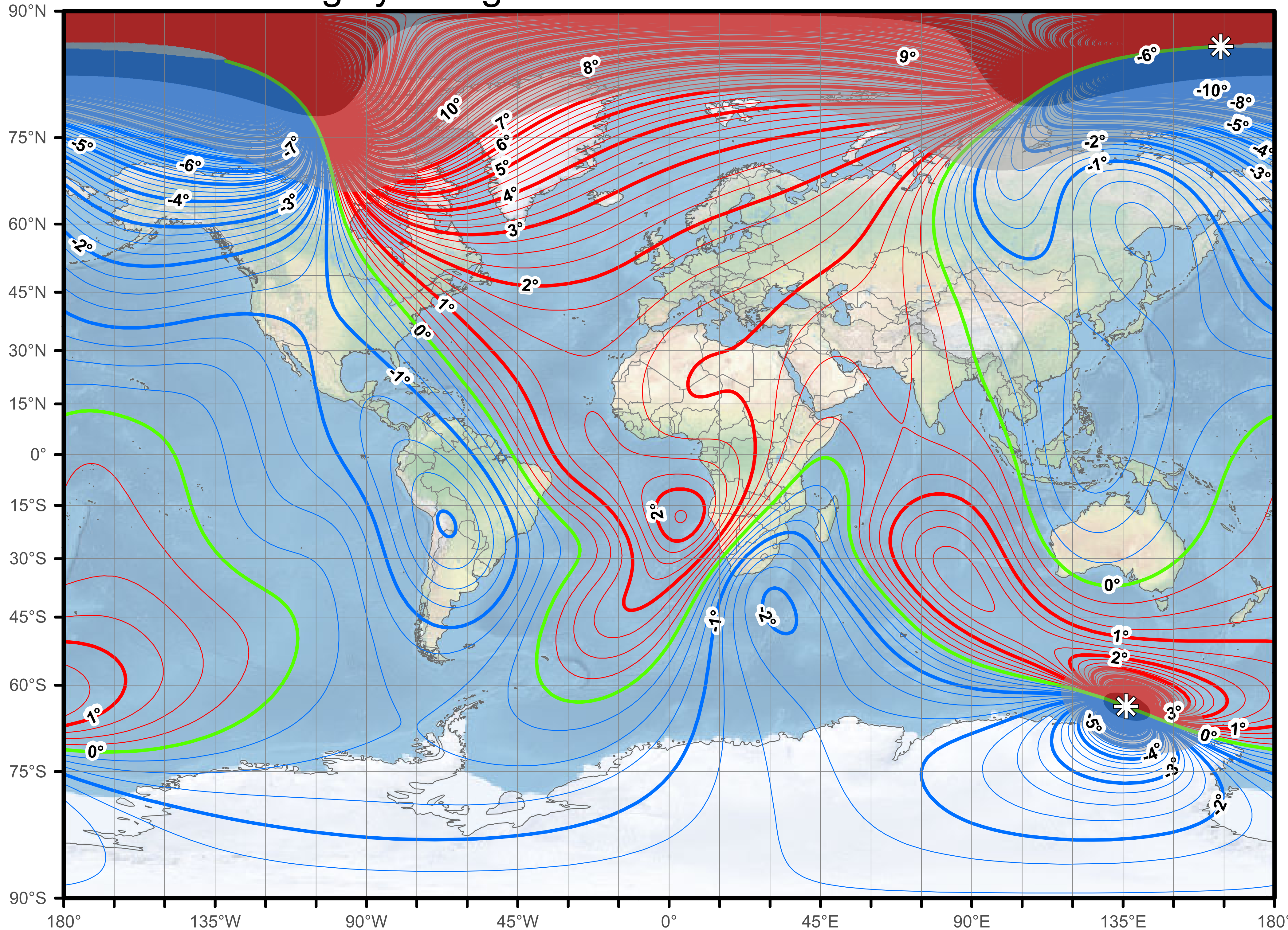
Looking North - Looking South



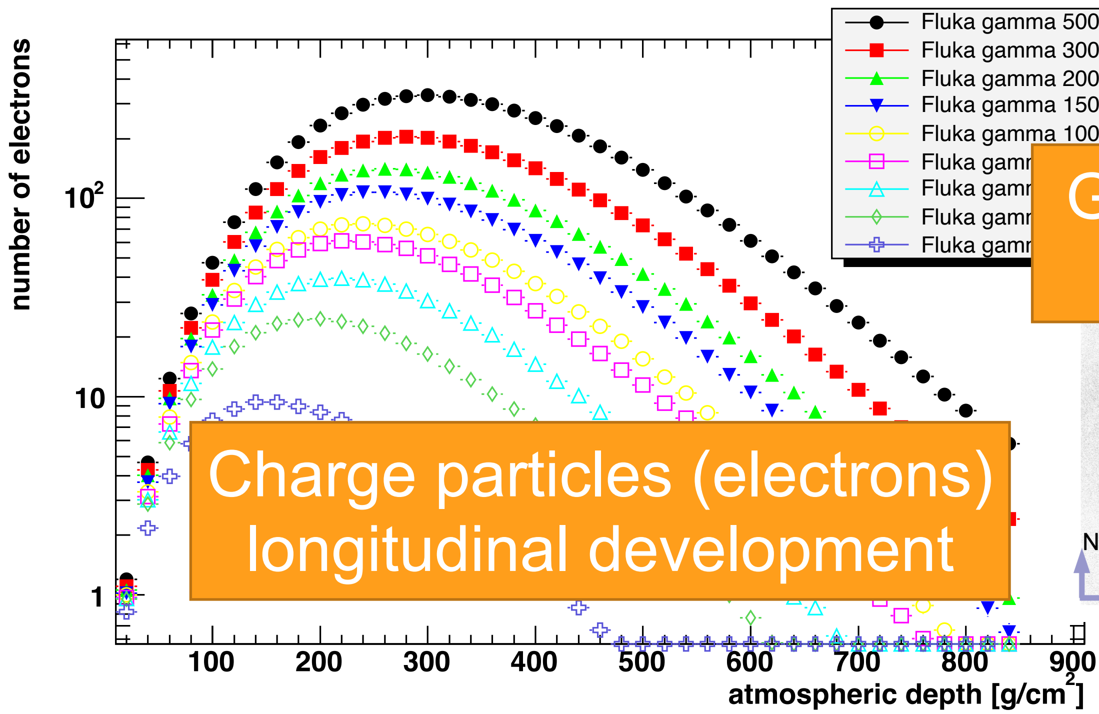
(using analysis techniques ignoring the impact of the geomag. field on the shower development)

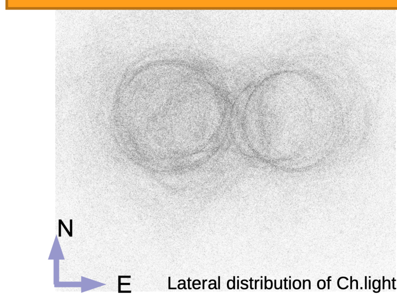
Geomagnetic field - 10 y change in declination.

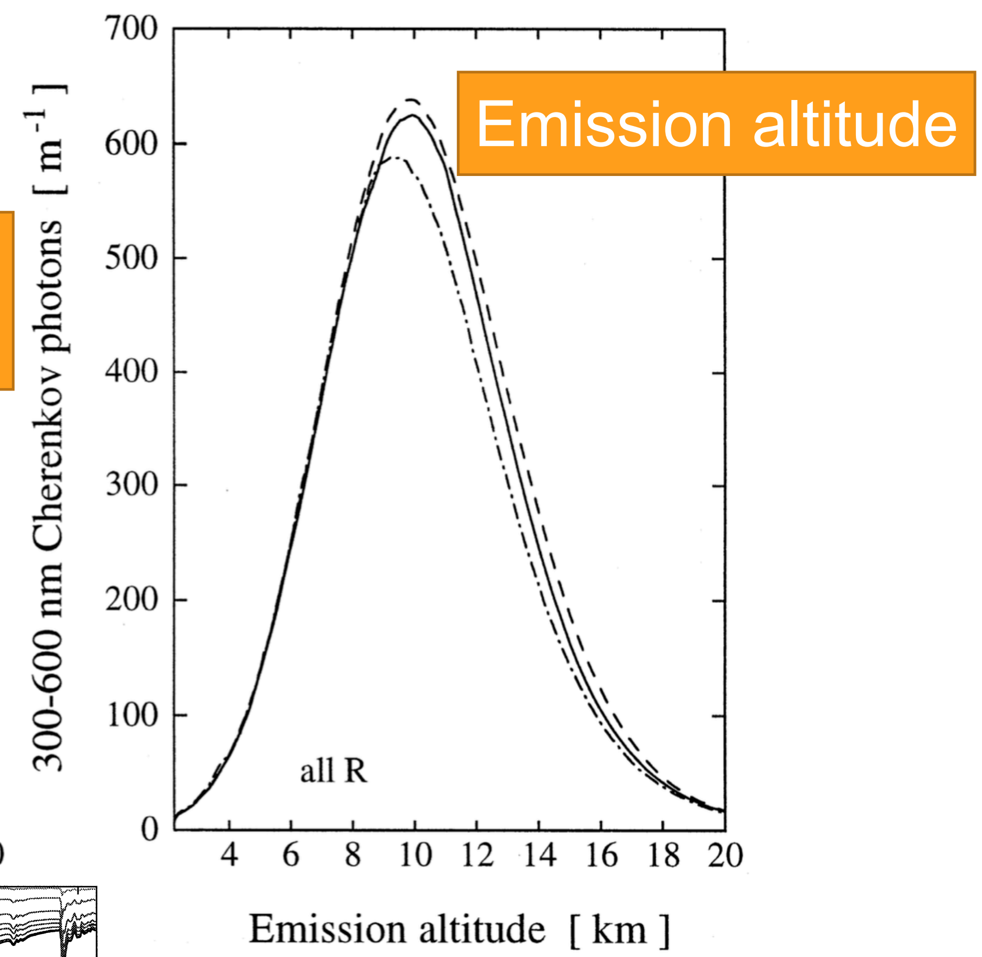
Roughly 2 deg / decade at La Palma

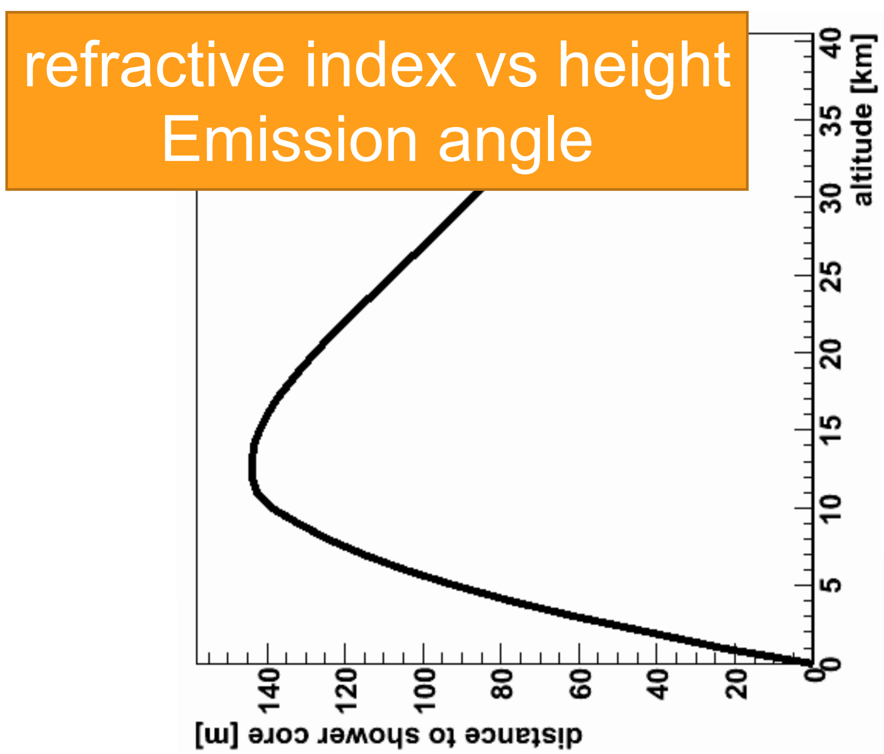


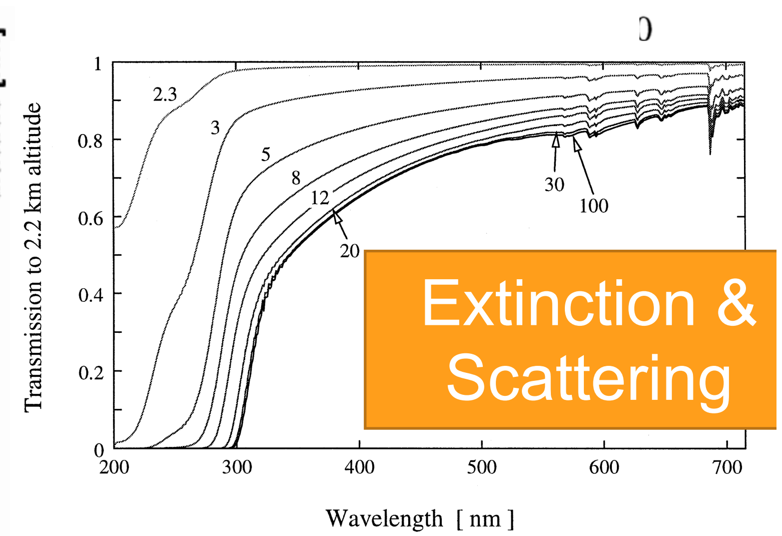
Summary - Cherenkov photons on the ground.

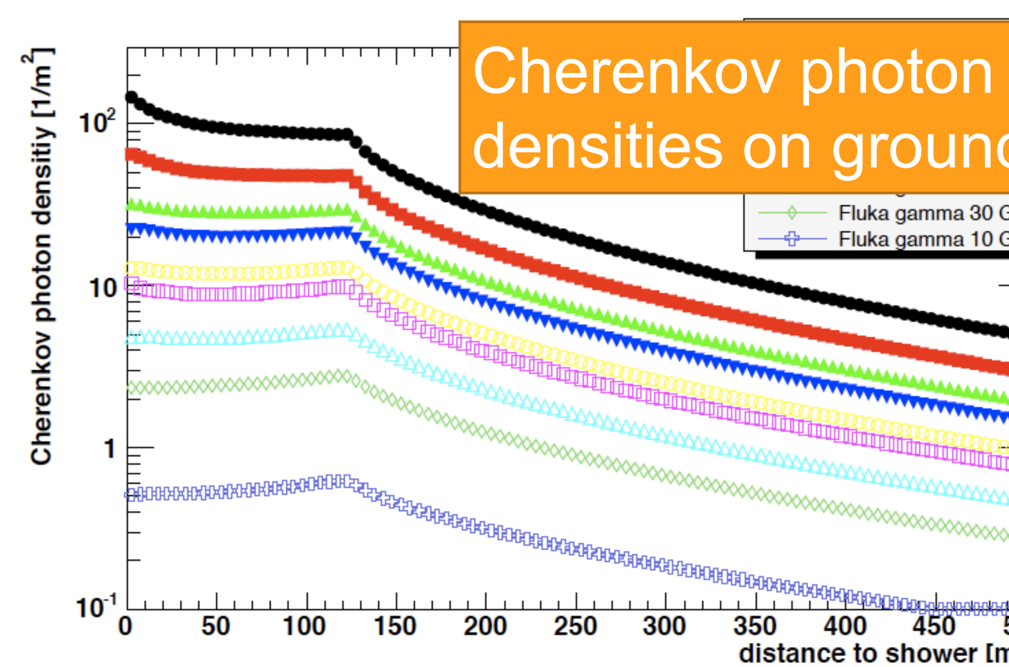










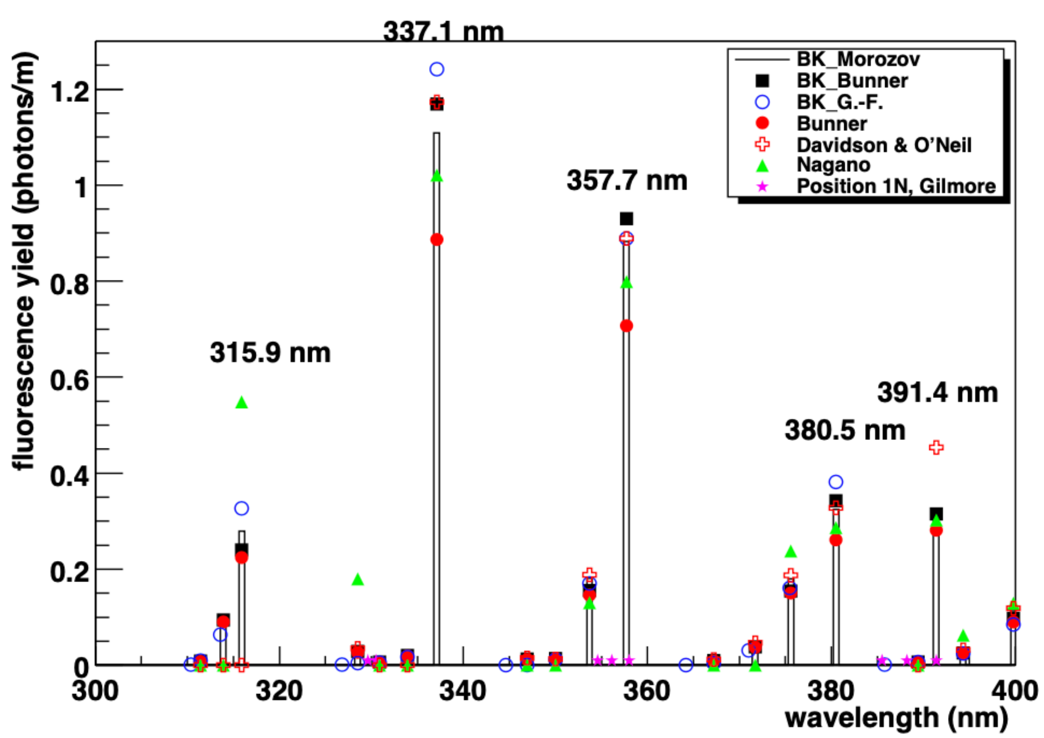


First detectors

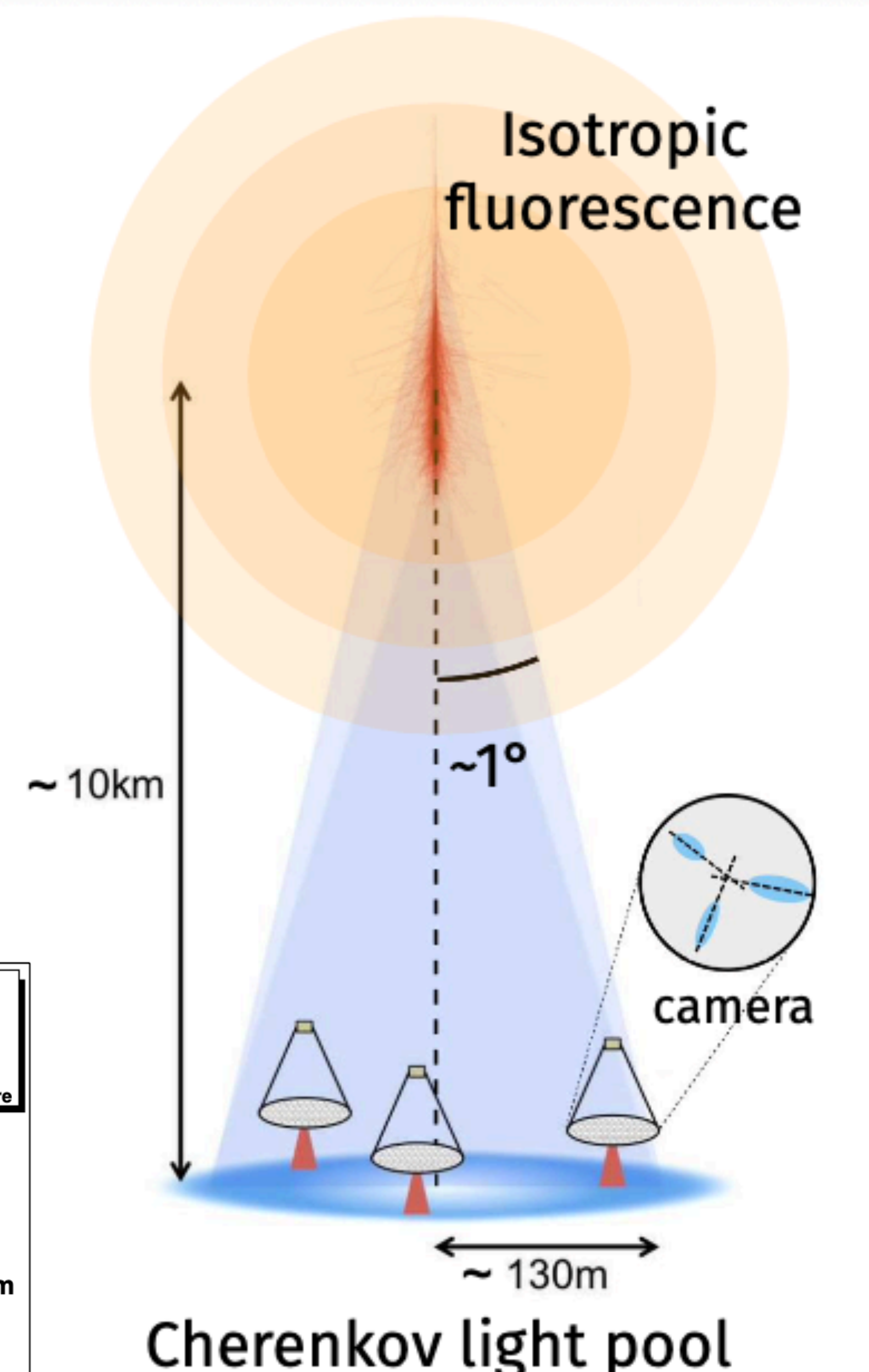
Backgrounds.

Fluorescence.

- fluorescence emission from de-excitation of N_2 states (290-430 nm)
- less efficient light emission
  for 1 GeV electron near ground: 30 photons from Cherenkov light vs 4 photons from fluorescence light (per m track length)
- longer time profile: microseconds vs 10s of nanoseconds

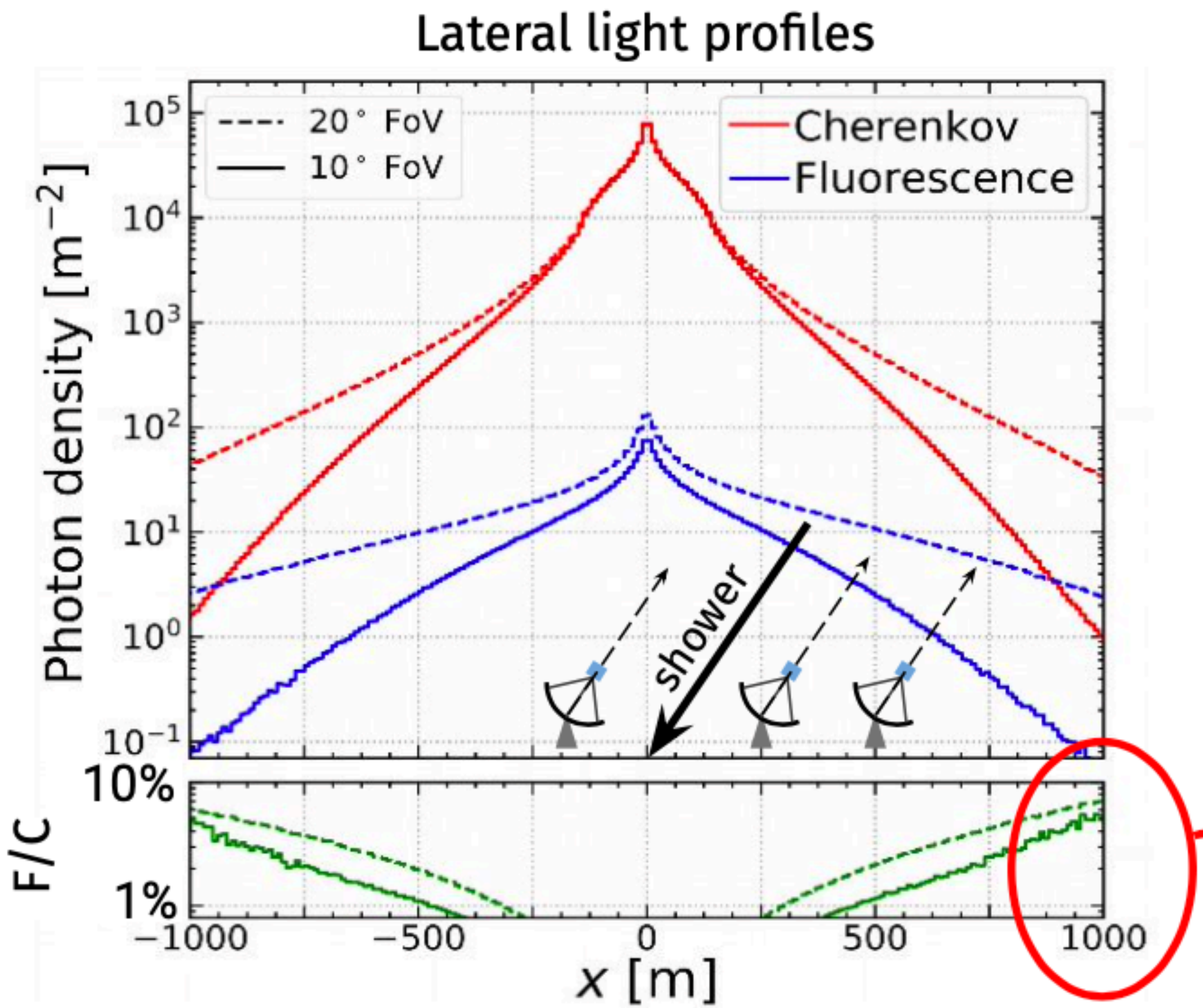


Keilhauer et al 2005



Morcuende et al 2005

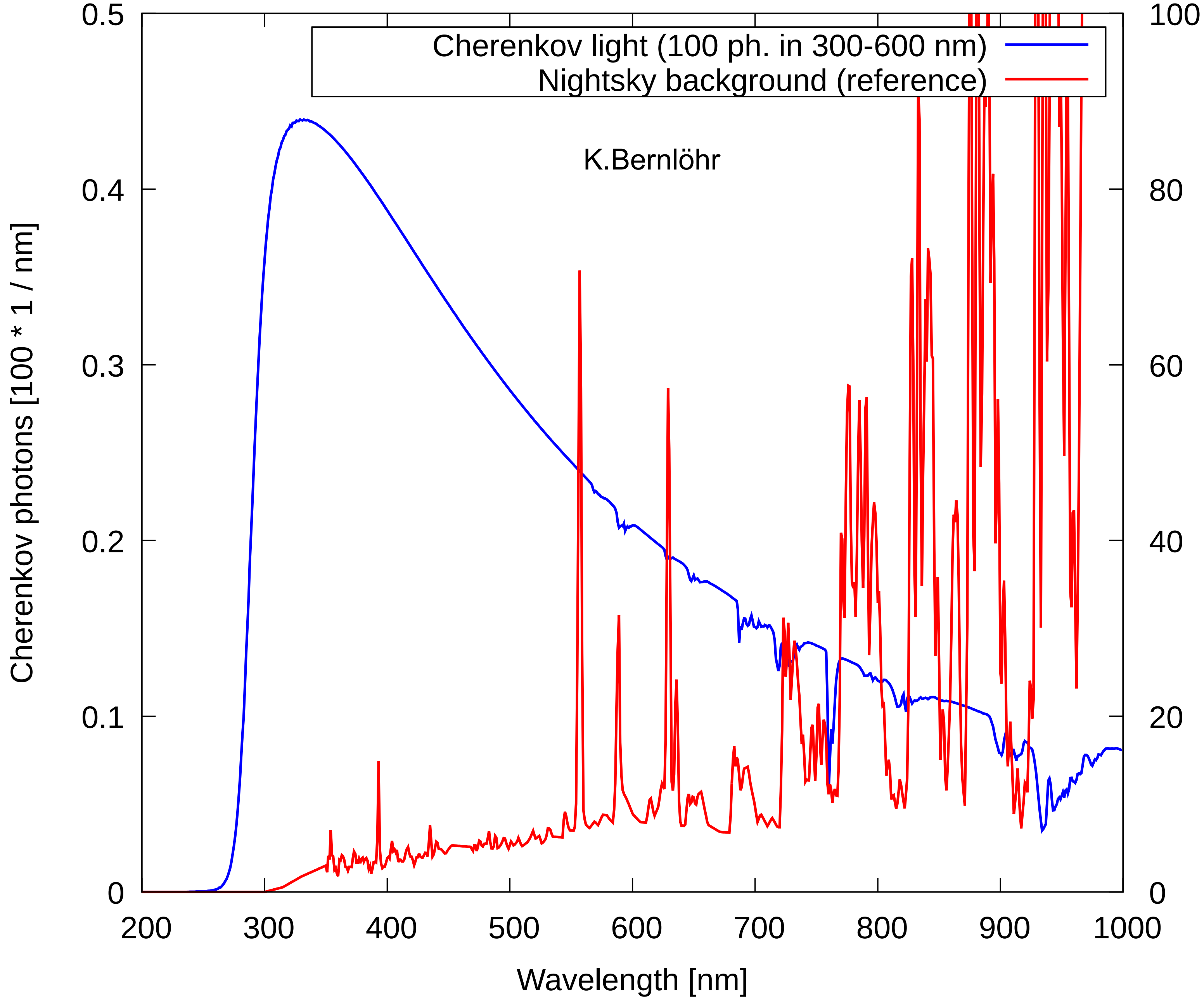
Fluorescence.



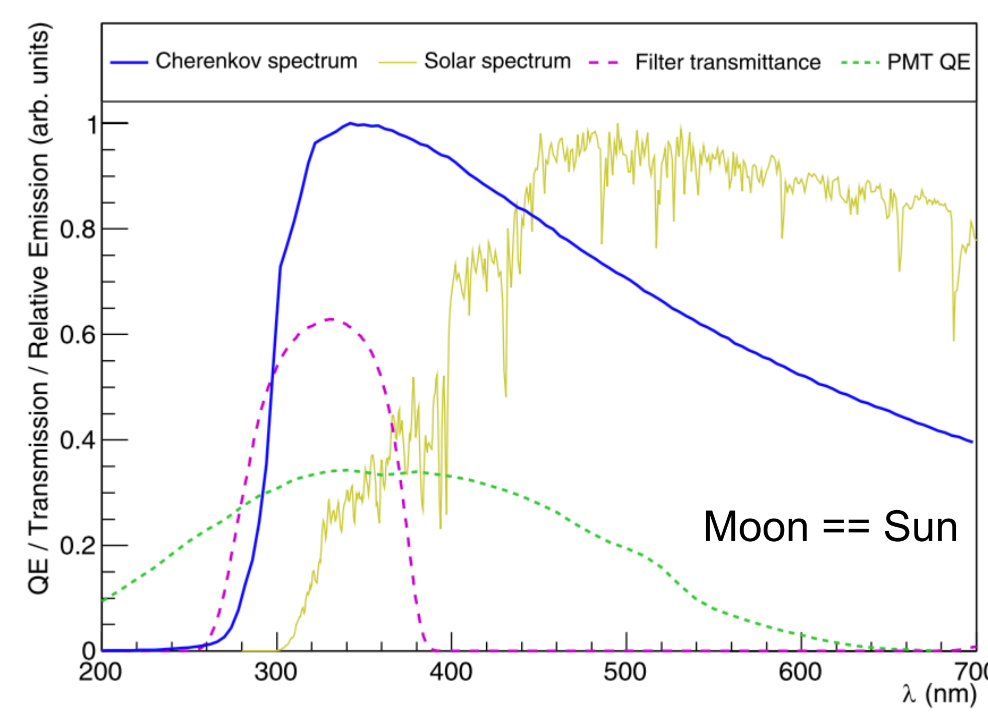
Max 5% of recorded signal

Morcuende et al 2005

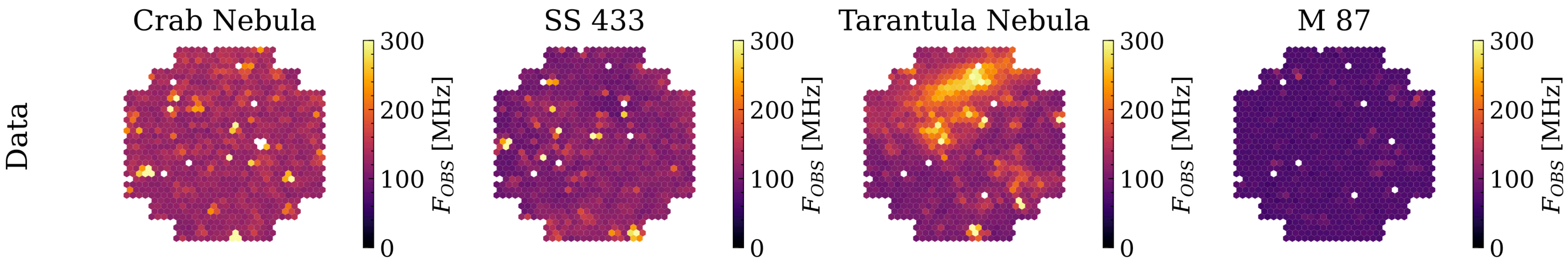
Night sky background.



S. Archambault et al. / Astroparticle Physics 91 (2017) 34–43

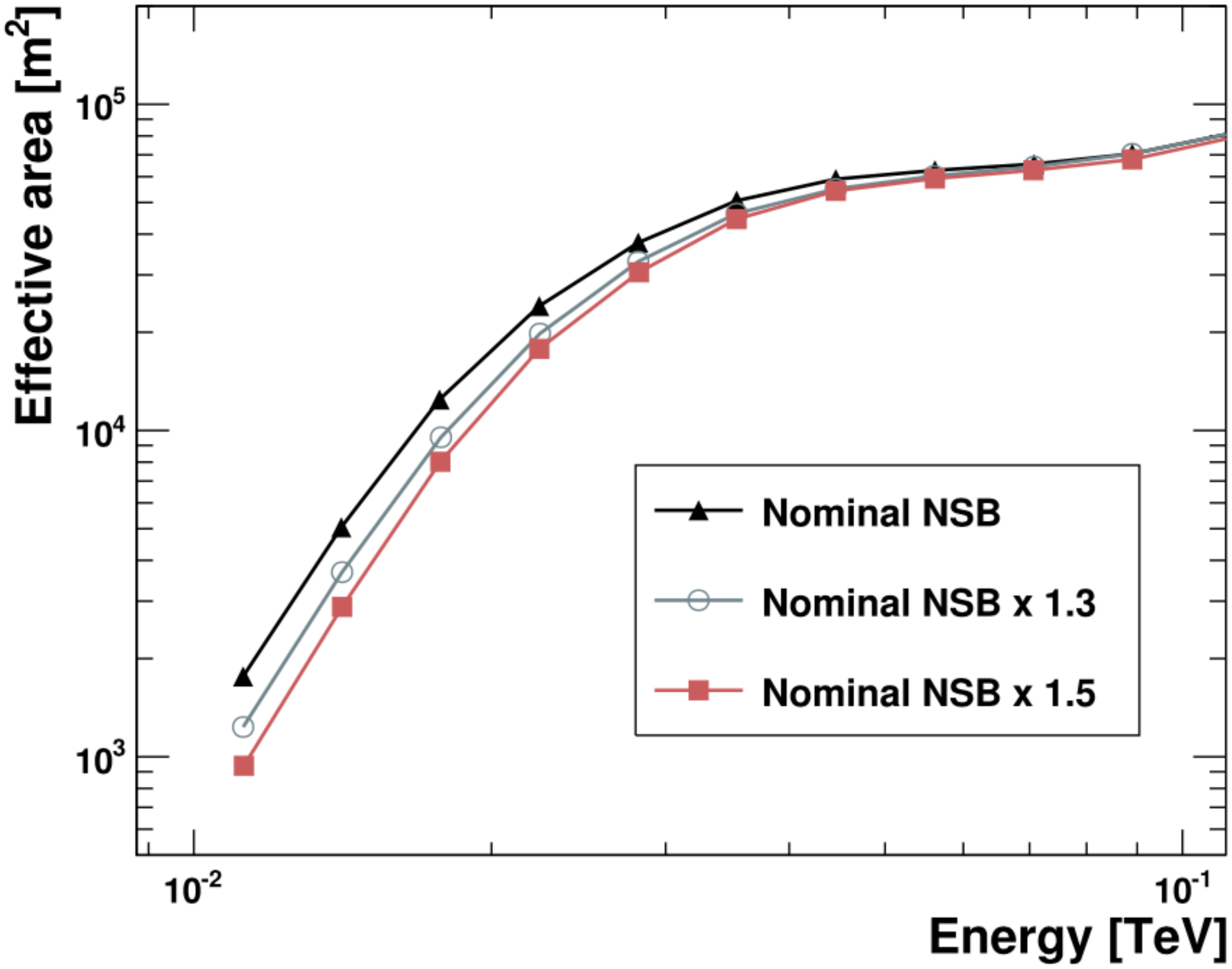


Night-sky background - stars



Roellinghoff et al 2025

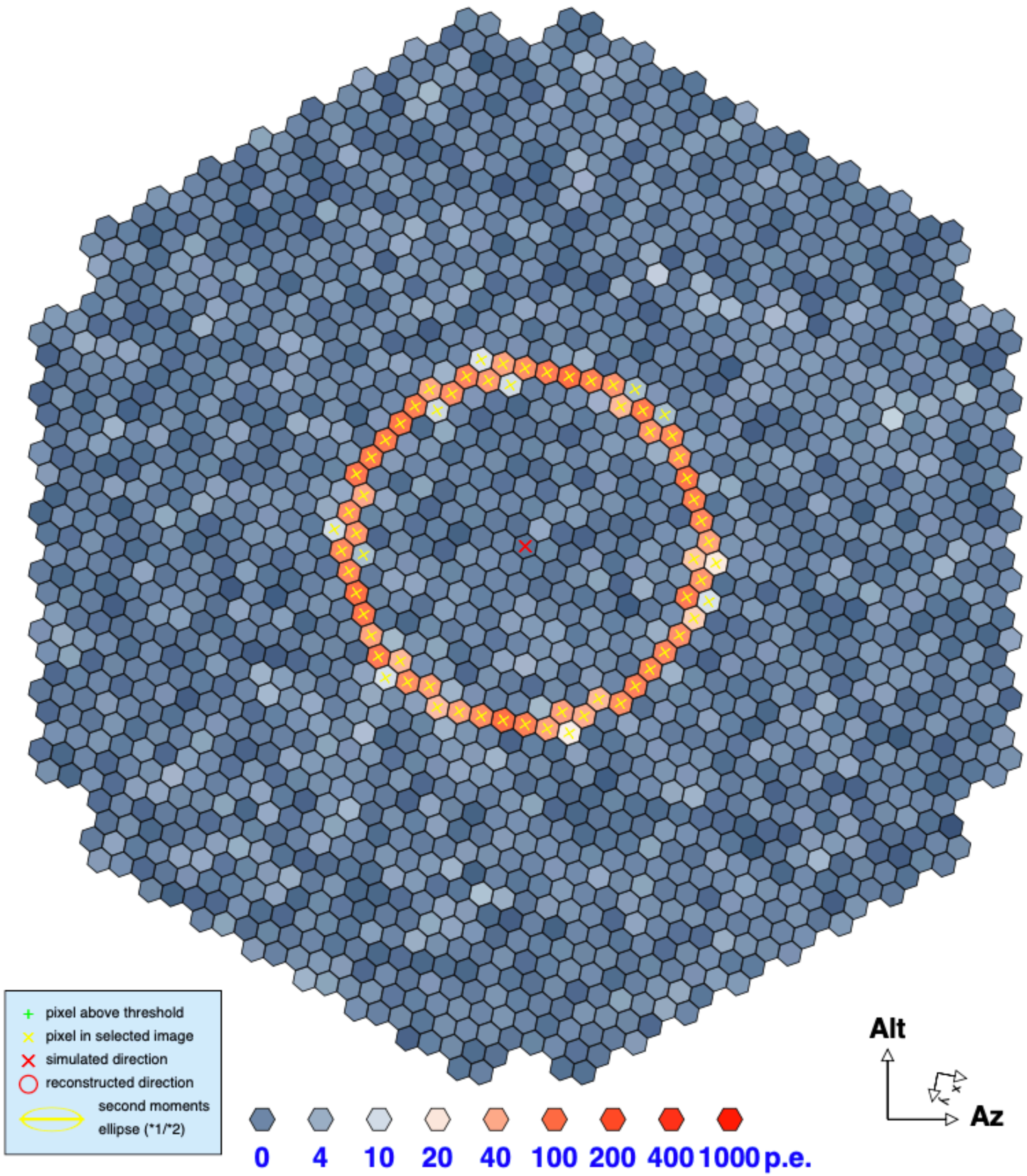
Impact of high night-sky-background light levels.



T. Hassan et al./Astroparticle Physics 93 (2017) 76–85

Muons.

K.Bernlöhr



Muons

arXiv > astro-ph > arXiv:1907.04375

Astrophysics > Instrumentation and Methods for Astrophysics

[Submitted on 9 Jul 2019]

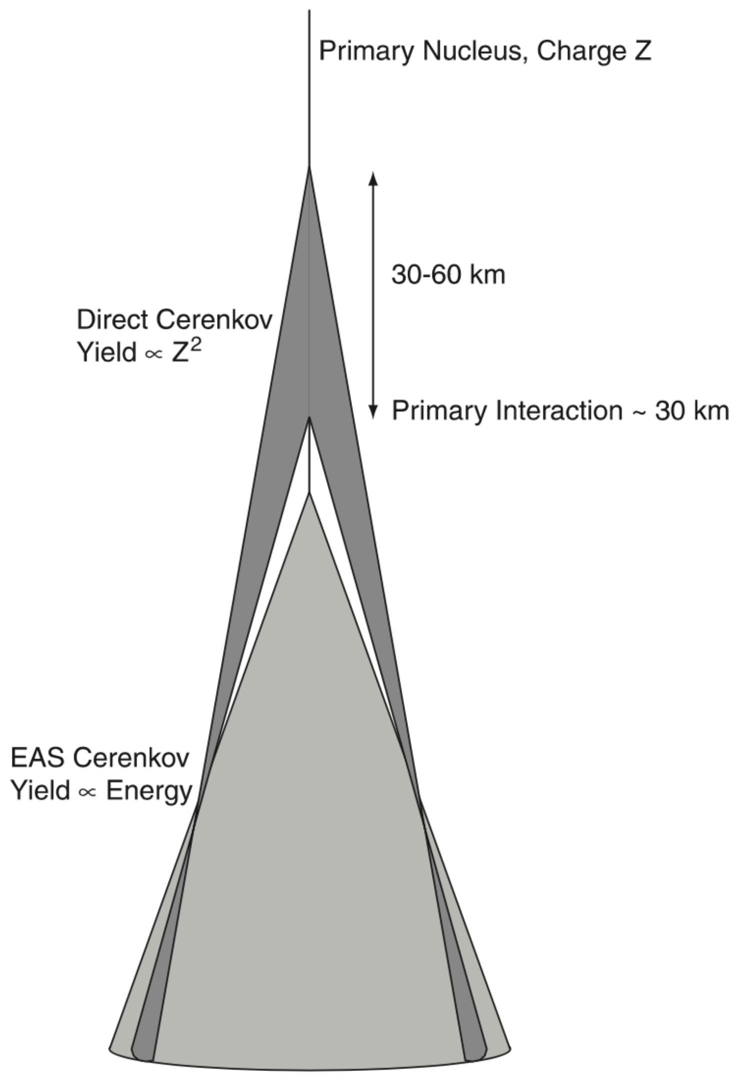
Using Muon Rings for the Calibration of the Cherenkov Telescope Array: A Systematic Review of the Method and its Potential Accuracy

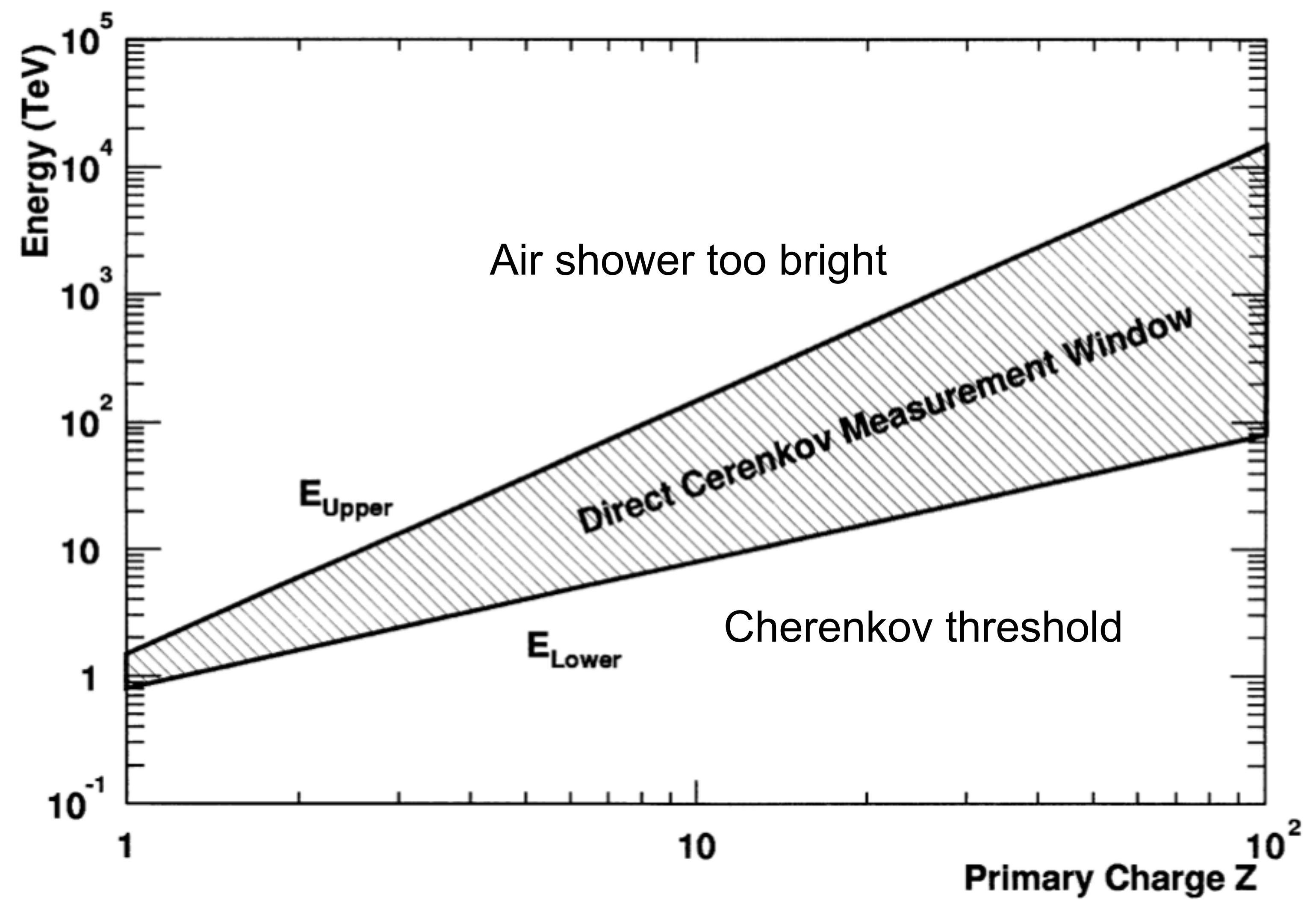
Markus Gaug, Steven Fegan, Alison Mitchell, Maria-Concetta Maccarone, Teresa Mineo, Akira Okumura

The analysis of ring images produced by muons in an Imaging Atmospheric Cherenkov Telescope (IACT) provides a powerful and precise method to calibrate the IACT optical throughput and monitor its optical point-spread function (PSF). First propos
collaboration in the early 90's, this method has been refined by the so-called second generation of IACT experiments: H.E.S.S., MAGIC and VERITAS. We review here the progress made with these instruments and investigate the applicability of the met
throughput calibration method for the different telescope types forming the future Cherenkov Telescope Array (CTA). We find several additional systematic effects not yet taken into account by previous authors and propose several new analytical meth
the analysis. Slight modifications in hardware and analysis need to be made to ensure that such a calibration works as accurately as required for the CTA. We derive analytic estimates for the expected muon data rates for optical throughput calibration
fielding and monitoring of the optical PSF. The achievable statistical and systematic uncertainties of the method are also assessed.

Direct Cherenkov Light (not a background).

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2\beta^2}\right) \frac{d\lambda}{\lambda^2} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \sin^2\Theta \frac{d\lambda}{\lambda^2}$$

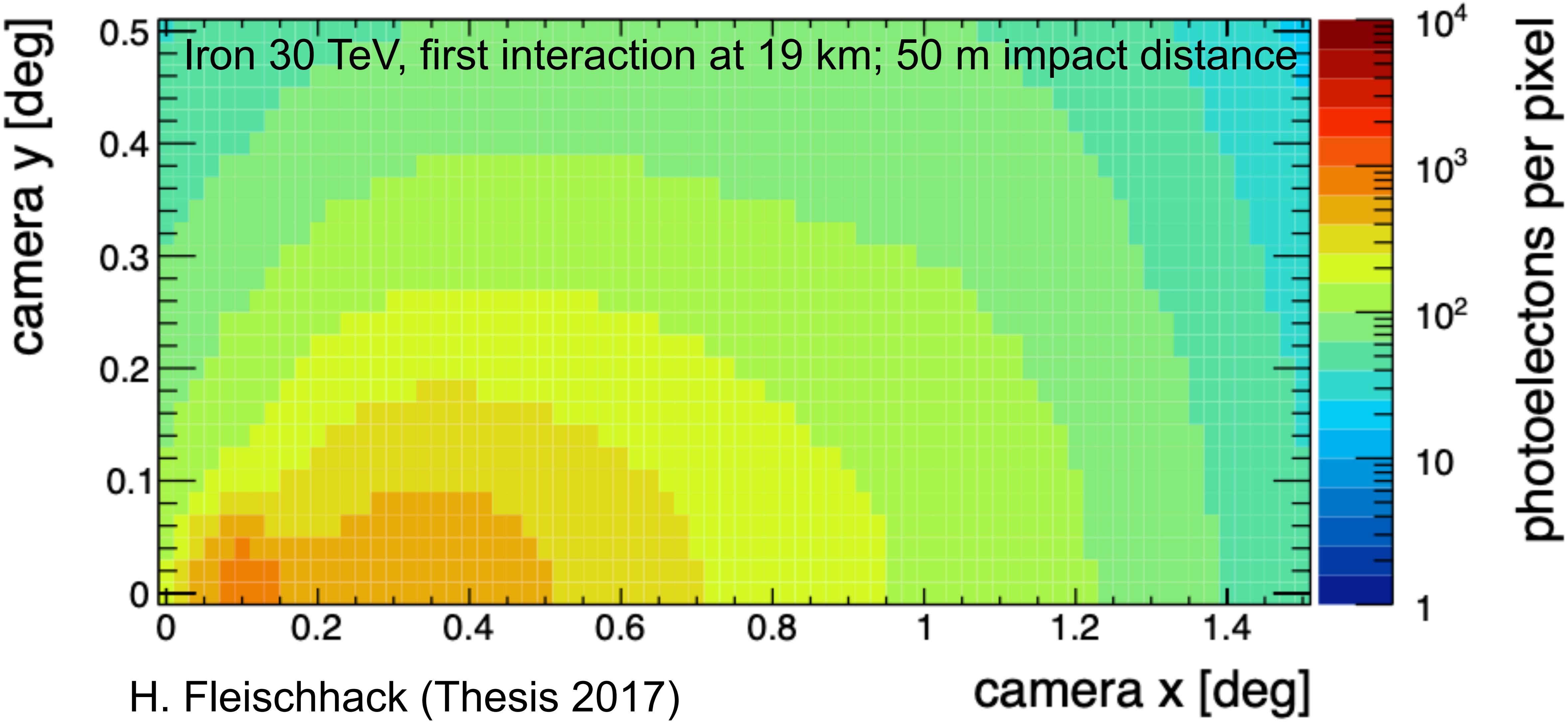




D.B. Kieda et al. / Astroparticle Physics 15 (2001) 287–303

Direct Cherenkov Light (not a background).

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(1 - \frac{1}{n^2\beta^2}\right) \frac{d\lambda}{\lambda^2} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \sin^2\Theta \frac{d\lambda}{\lambda^2}$$



H. Fleischhack (Thesis 2017)

D.B. Kieda et al. / Astroparticle Physics 15 (2001) 287–303

Simulations.

CORSIKA.
sim_telarray.

(others packages exist)

CORSIKA

ICRC 1990.

HE 7.3–3

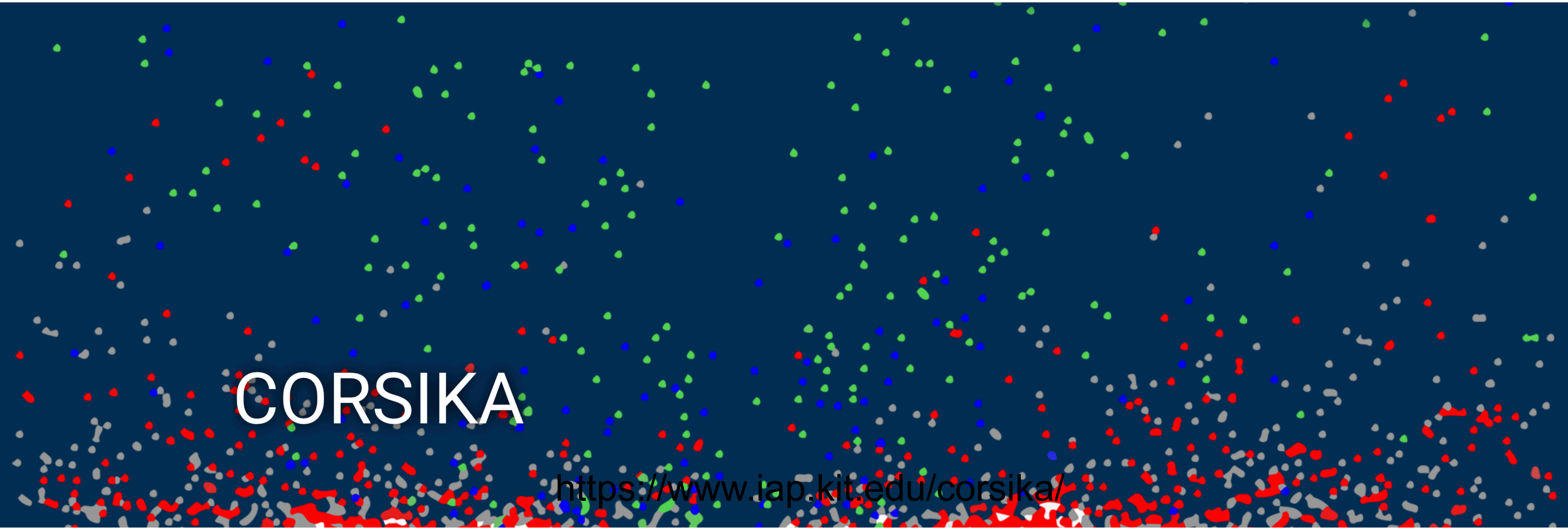
AIR SHOWER SIMULATIONS FOR KASCADE

J.N.Capdevielle[1], P.Gabriel, H.J.Gils, P.K.F.Grieder[2], D.Heck, N.Heide, J.Knapp, H.J.Mayer, J.Oehlschläger, H.Rebel, G.Schatz, and T.Thouw

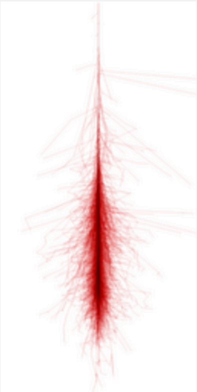
Kernforschungszentrum und Universität Karlsruhe,
D-7500 Karlsruhe, Federal Republic of Germany
[1]Laboratoire de Physique Théorique, Université de Bordeaux,
F-33170 Gradignan, France
[2]Physikalisches Institut der Universität Bern,
CH-3012 Bern, Switzerland

Abstract

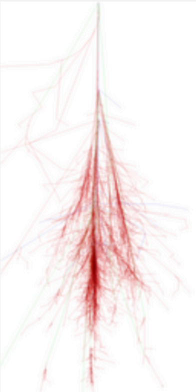
A detailed simulation program for extensive air showers and first results are presented. The mass composition of cosmic rays with $E_0 \geq 10^{15}$eV can be determined by measuring electrons, muons and hadrons simultaneously with the KASCADE detector.



CORSIKA 7

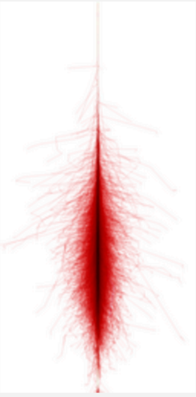


Photon shower



Proton shower

Iron shower

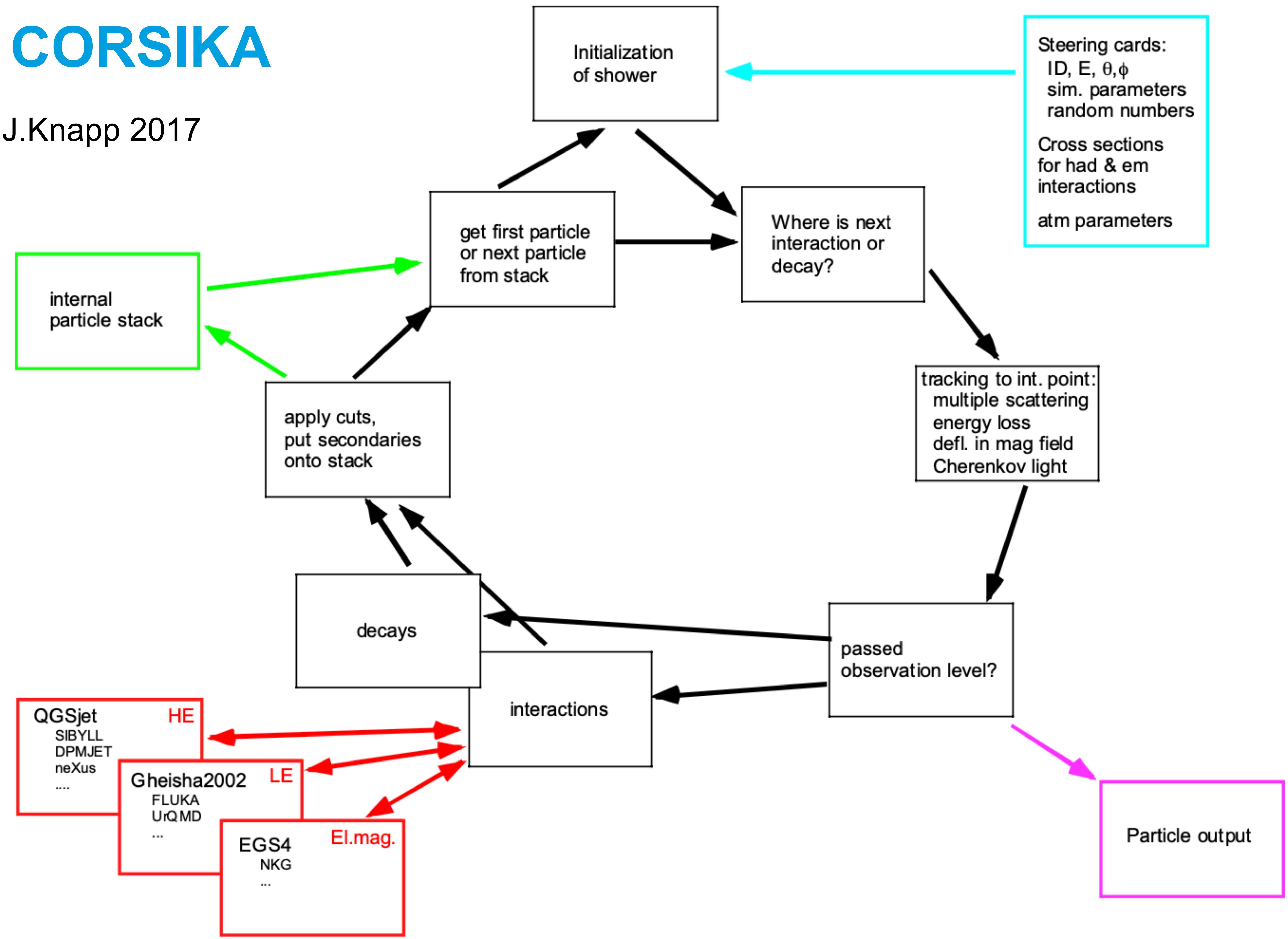


Muon shower

(Compiled by Fabian Schmidt, University of Leeds, UK)

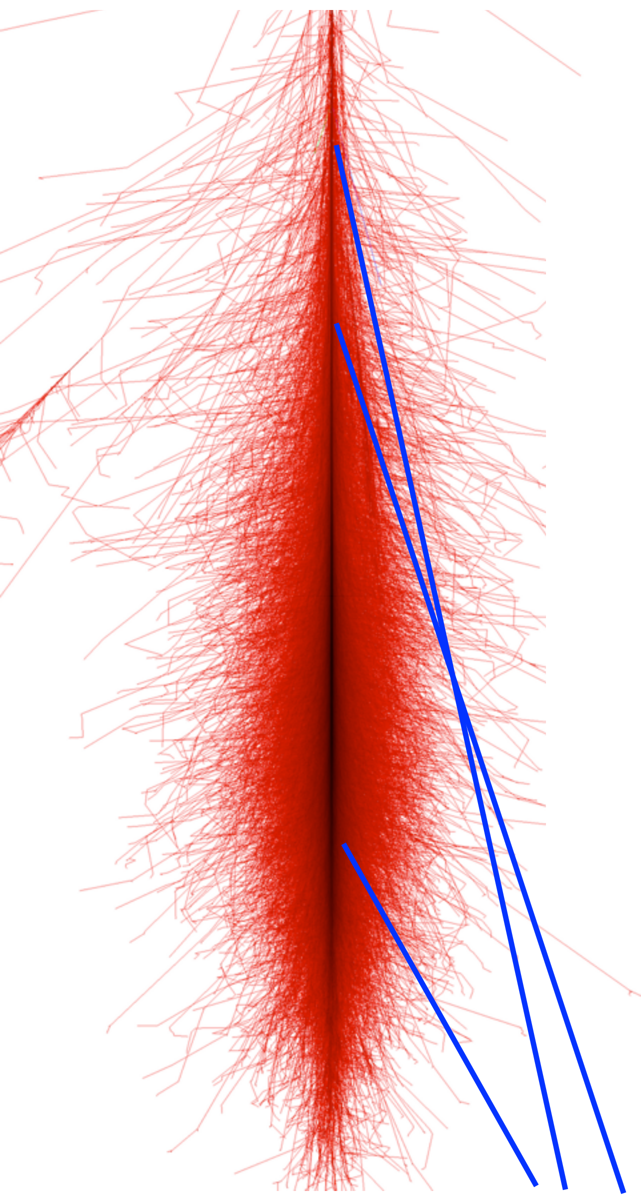
CORSIKA

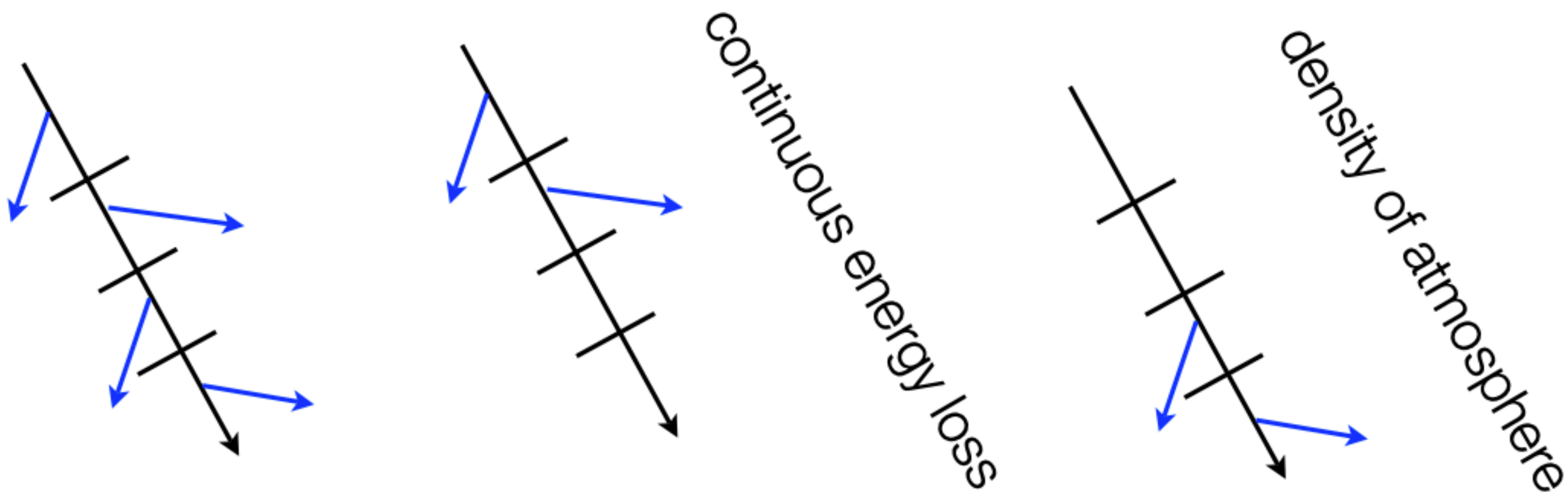
J.Knapp 2017



Cherenkov emission in the simulations.

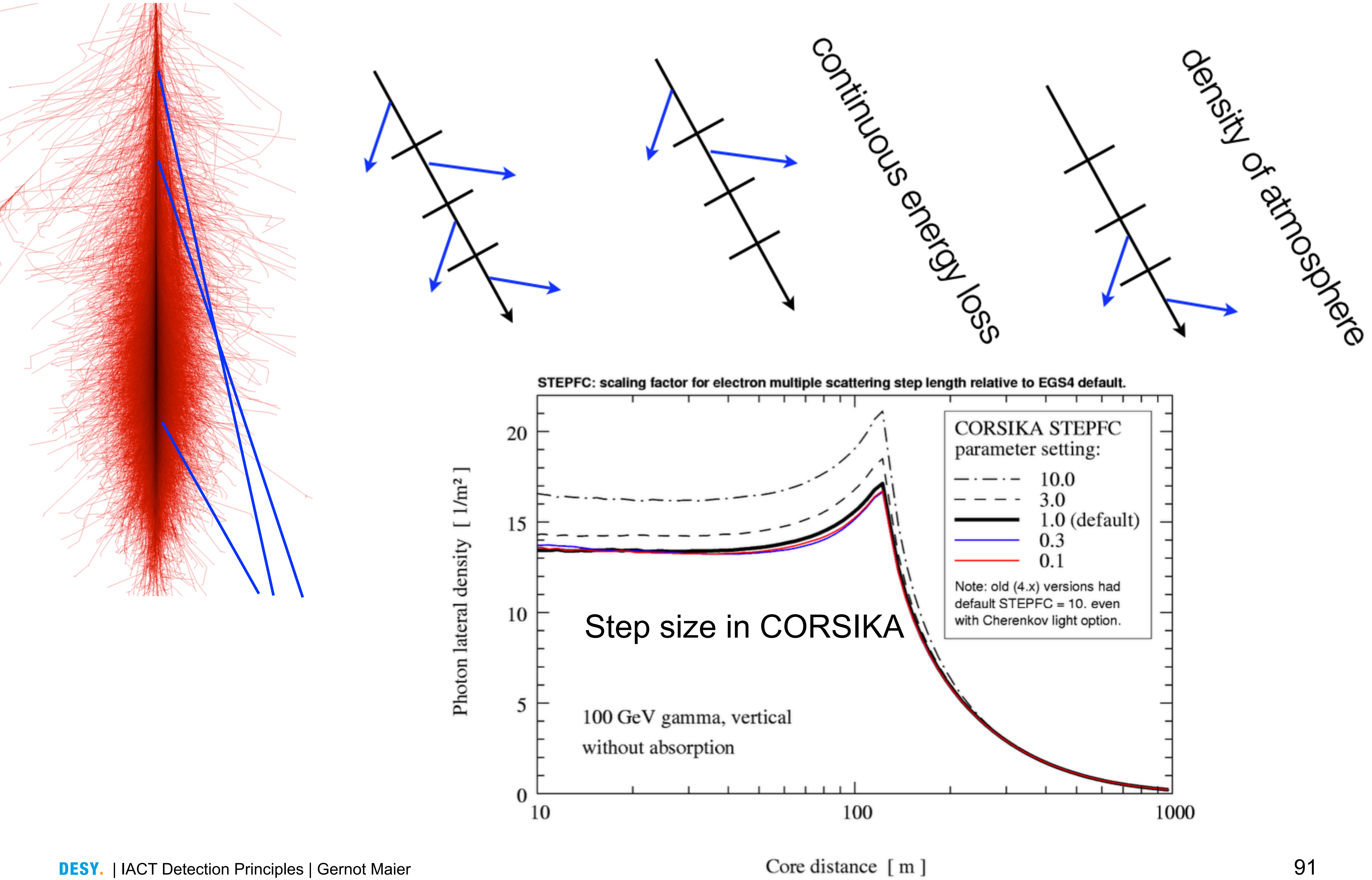
Large number of Cherenkov photons emitted.
(100 TeV shower with typically 100 billion photons.



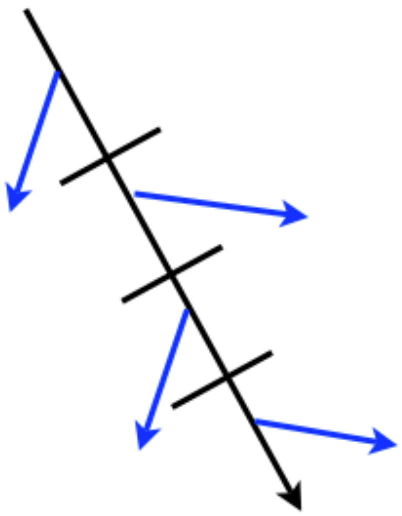


(ignoring generally wavelength dependence of refractive index)

Cherenkov emission in the simulations.



Bunches.



Not all emitted Cherenkov photons will lead to a detection.
Emit in **bunches**
(non integer)

K.Bernlöhr

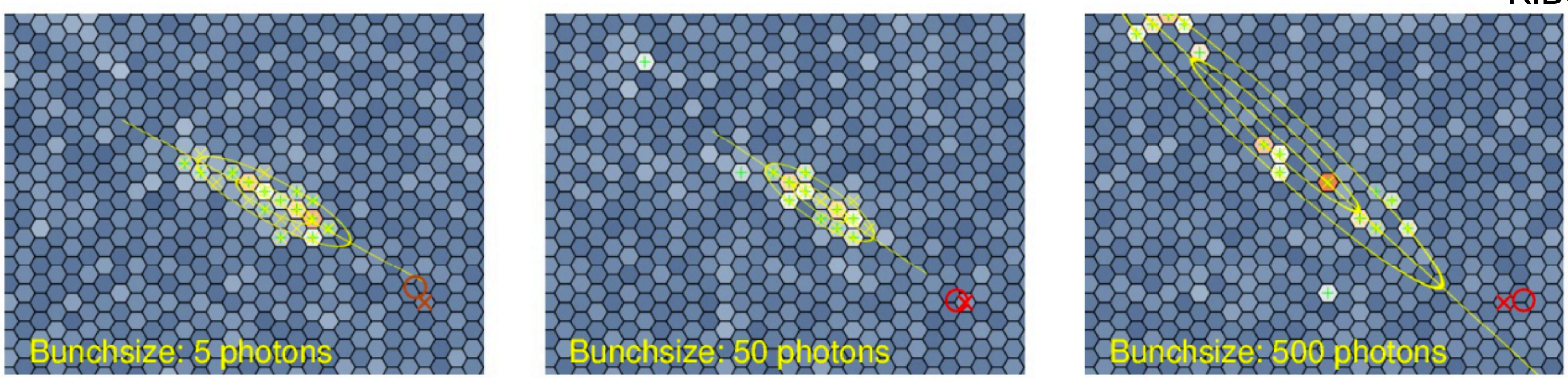


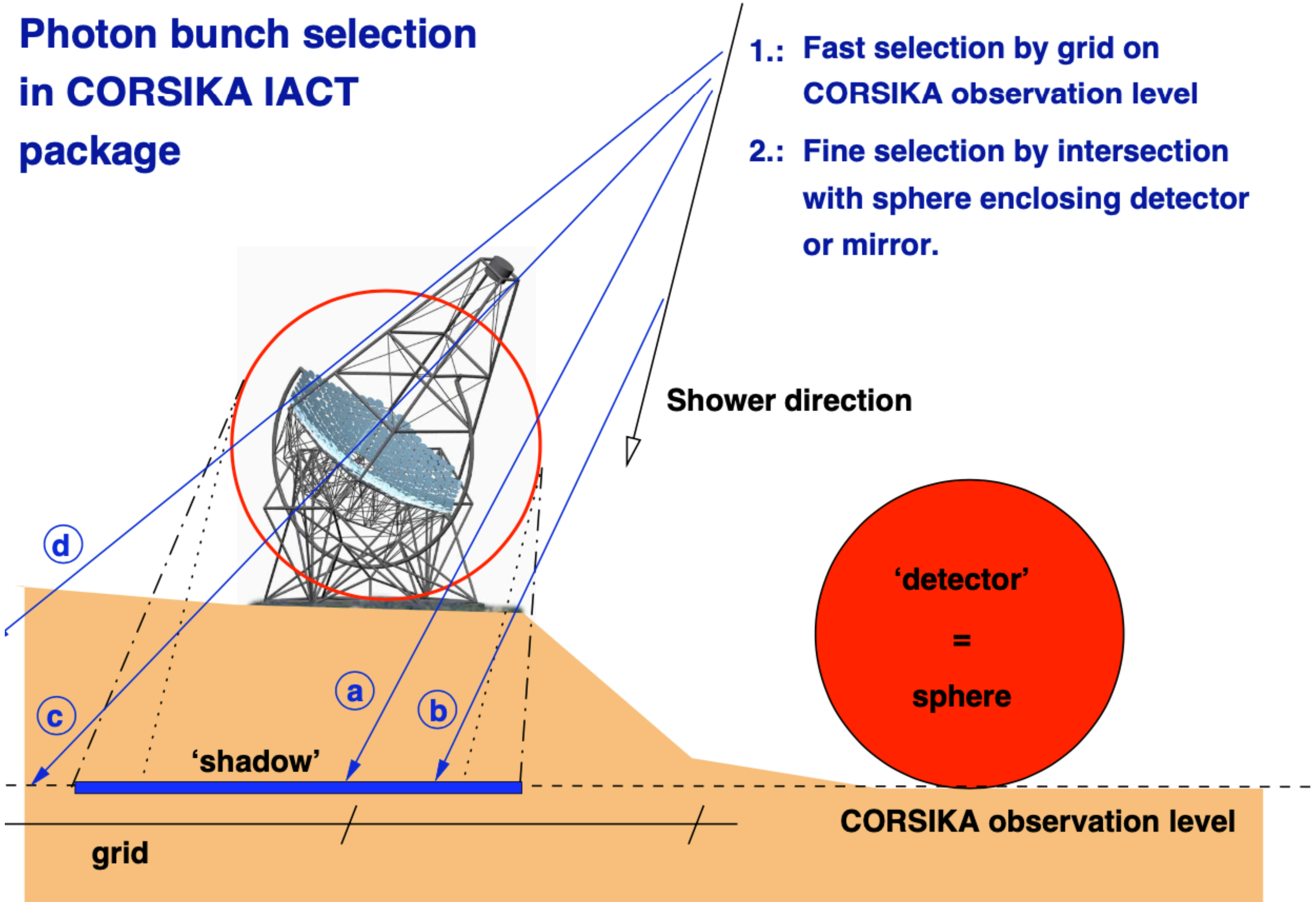
Image quality: good | poor | unusable

Detector level.

Photon bunch selection in CORSIKA IACT package

1.: Fast selection by grid on CORSIKA observation level

2.: Fine selection by intersection with sphere enclosing detector or mirror.



a: recorded photon bunch

b: not recorded because not intersecting sphere

c: recorded (not in 'shadow' but hitting a shadow grid cell)

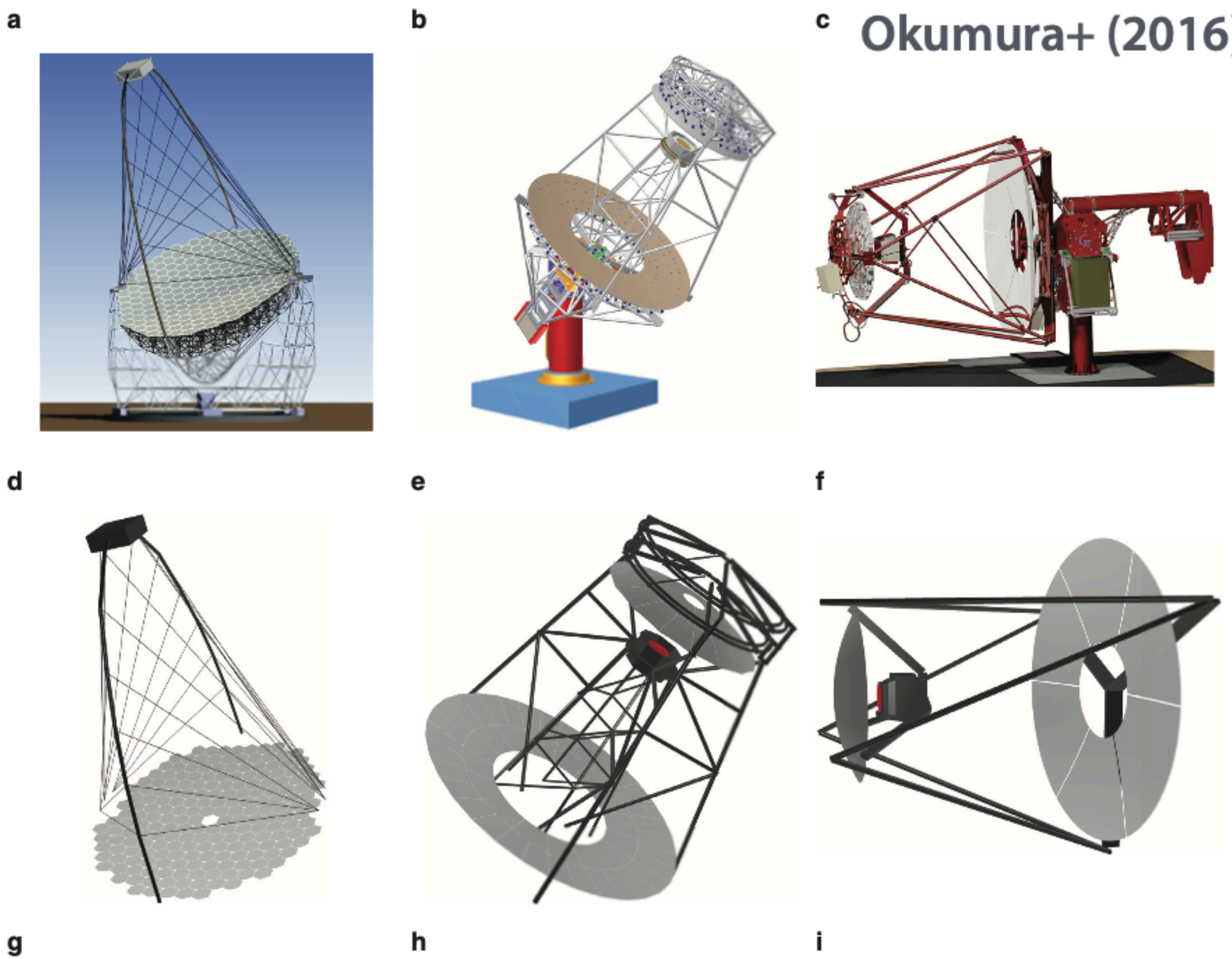
d: not recorded because not hitting a shadow grid cell

TELESCOPE X Y Z R
...

Telescopes.

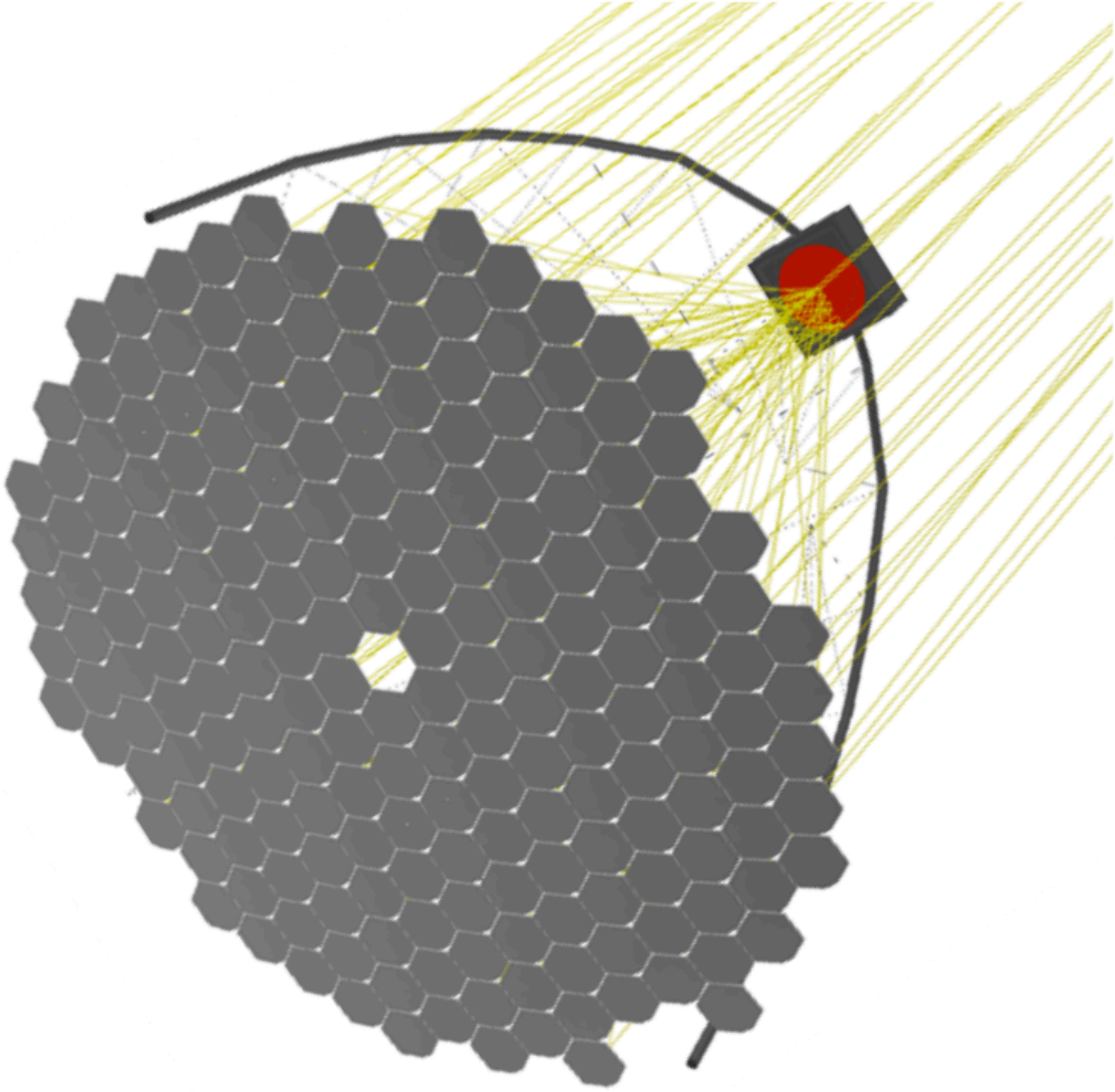
Telescope Optics.

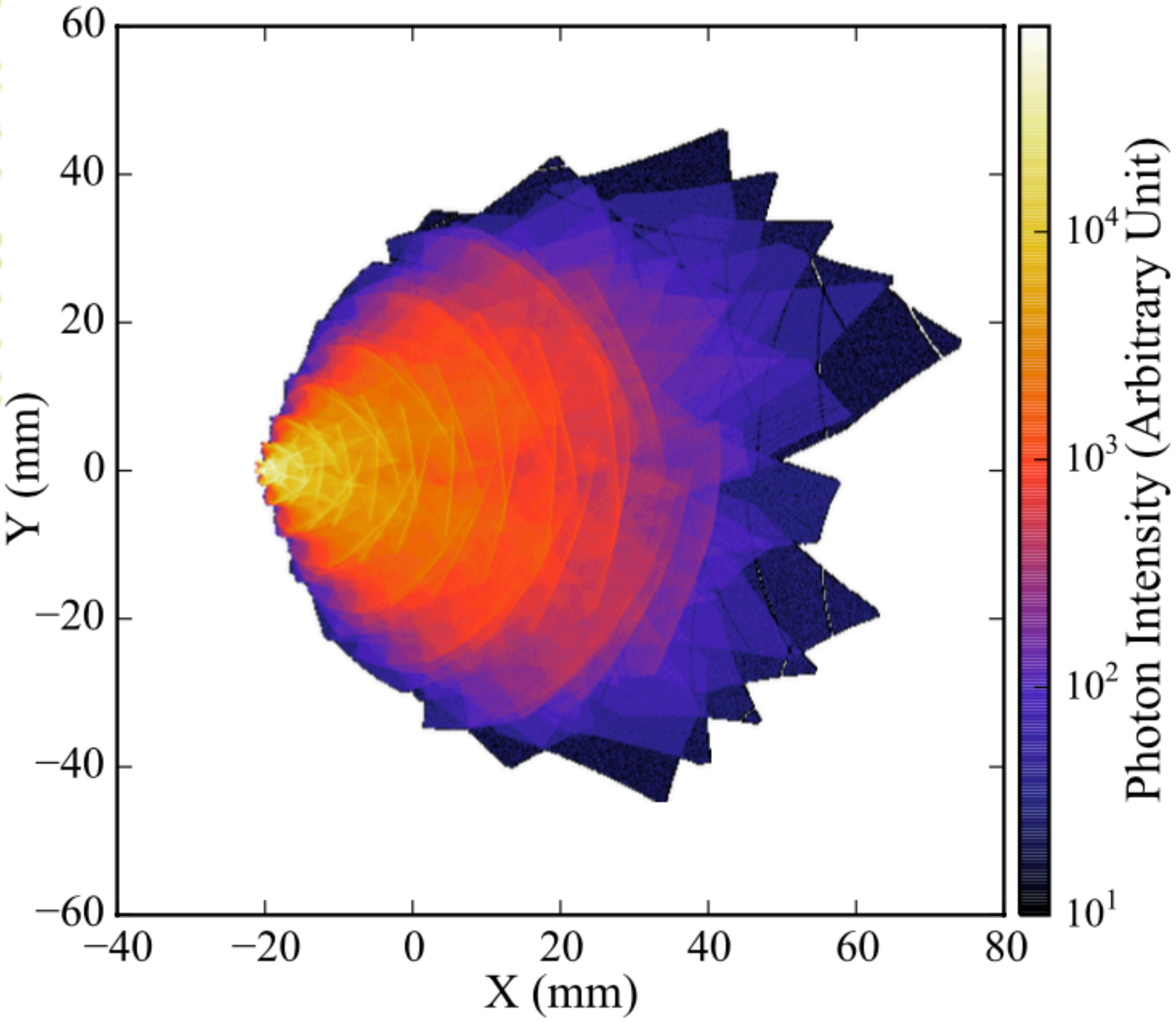
- imaging quality - optical point-spread function
- (non)isochronism
- costs



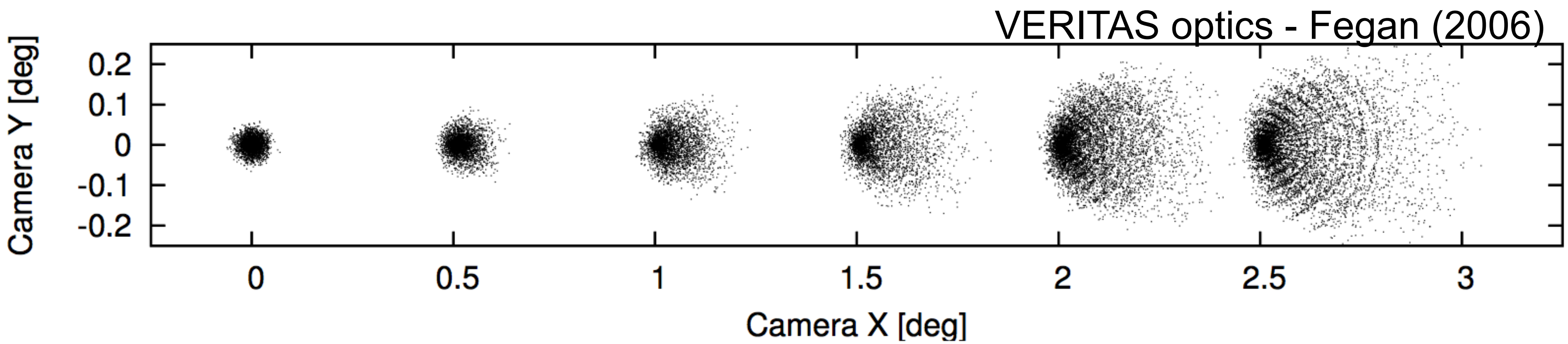
Ray tracing and optical PSF.

By Koji Noda

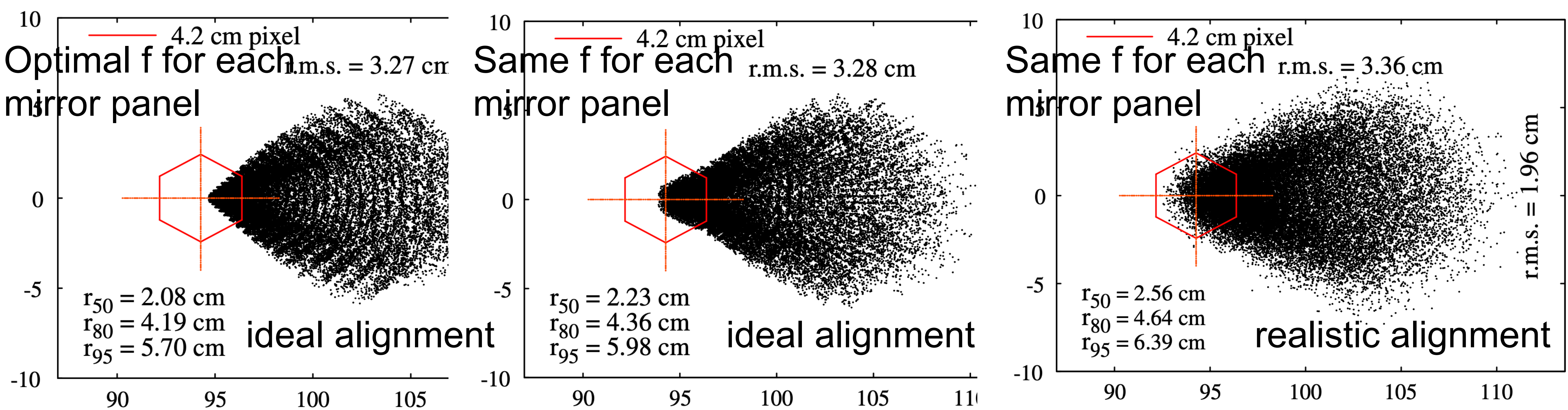




Optical point-spread function.

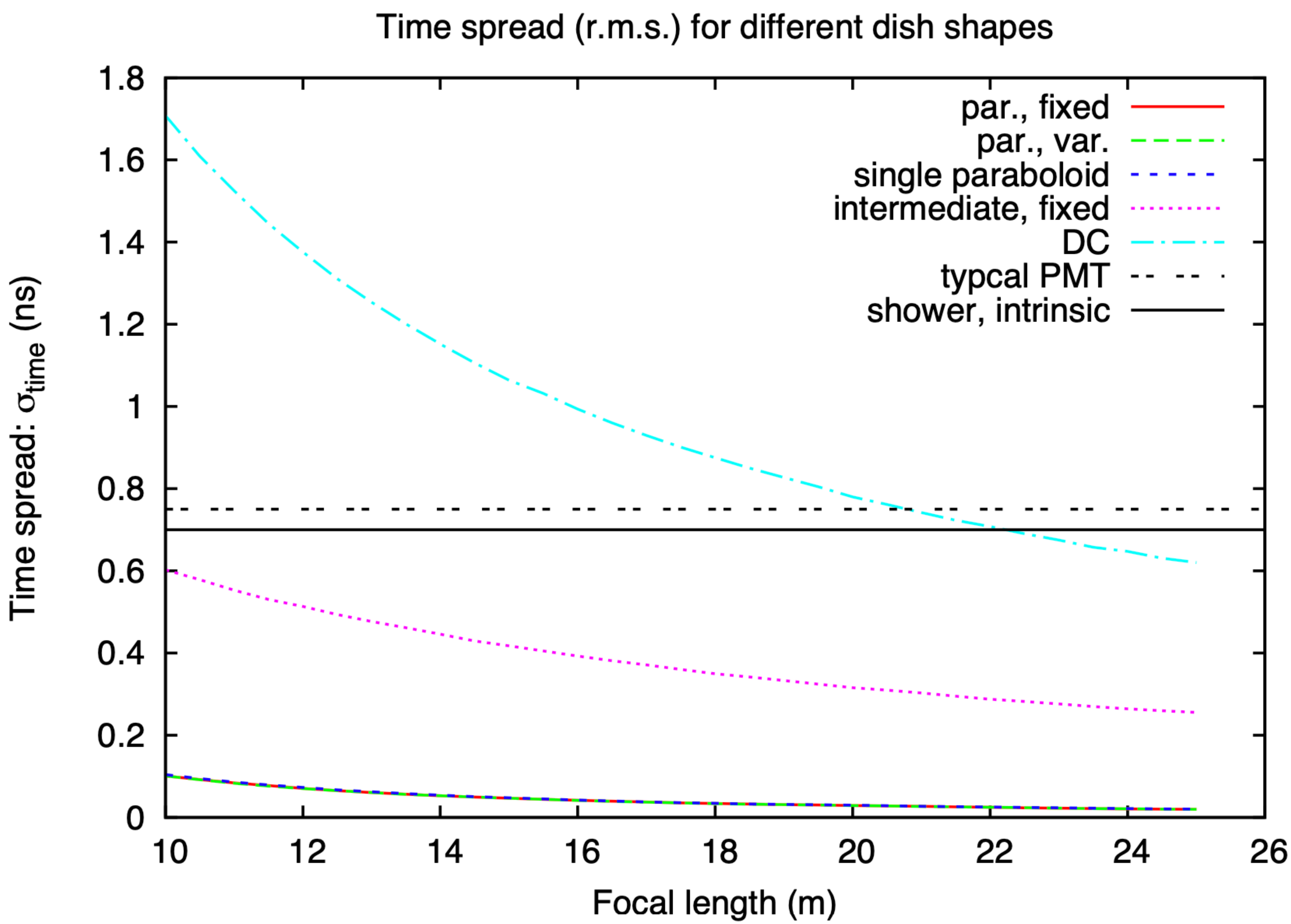


HESS 2 (K. Bernlöhr 2006)



Time spread - mirror design

K.Bernlöhr
(internal note 2009)

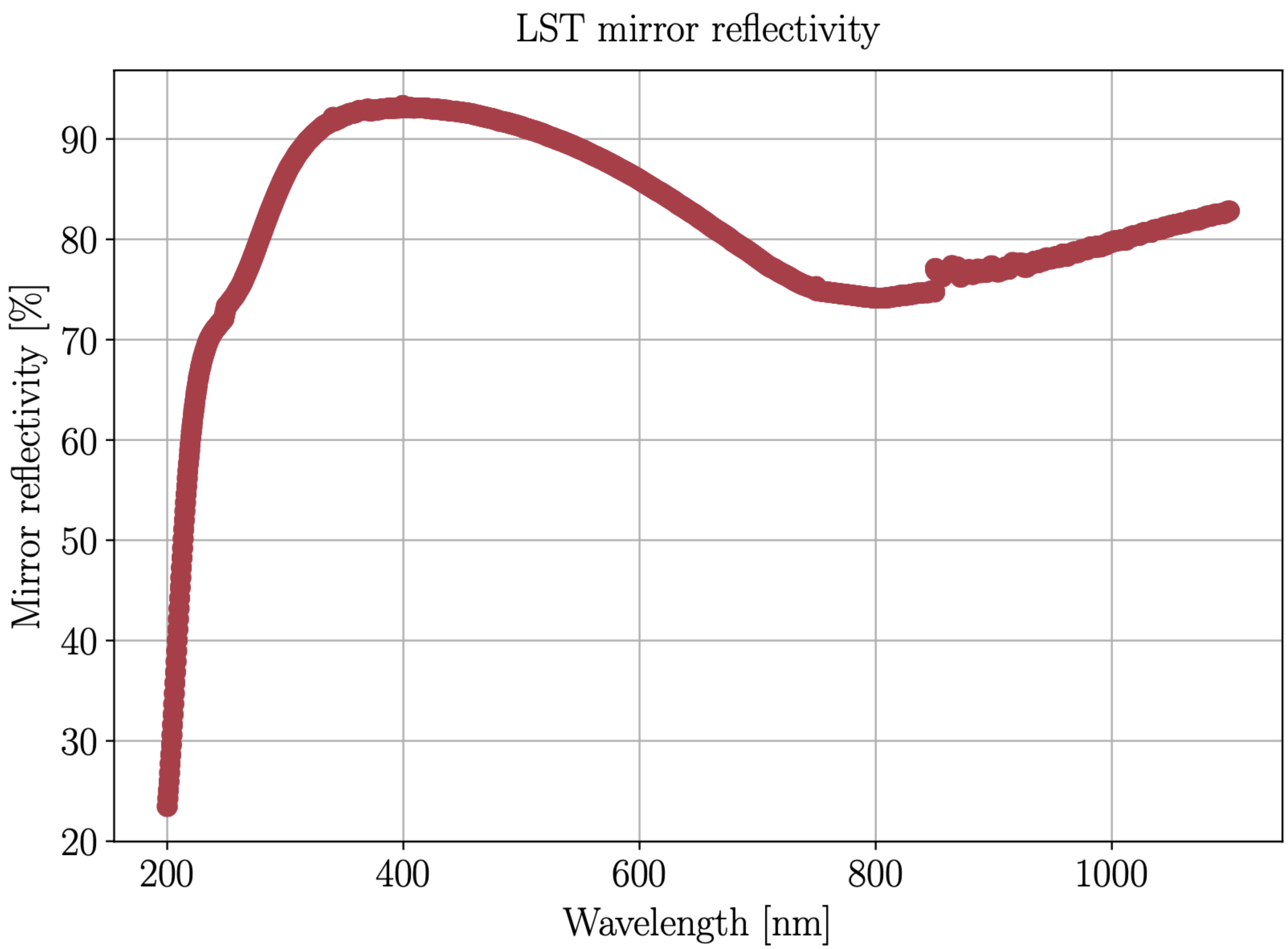


Parabolic vs Davis Cotton vs Intermediate design

- optical point-spread function:
  - Davis-Cotton with smaller radial PSF than parabolic (especially with increased off-axis angles)
  - transverse direction PSF very similar
- timing
  - parabolic mirror essentially isochronous
  - 12-m Davis Cotton: top-hat time distribution of 3.6 ns (1.05 ns rms)

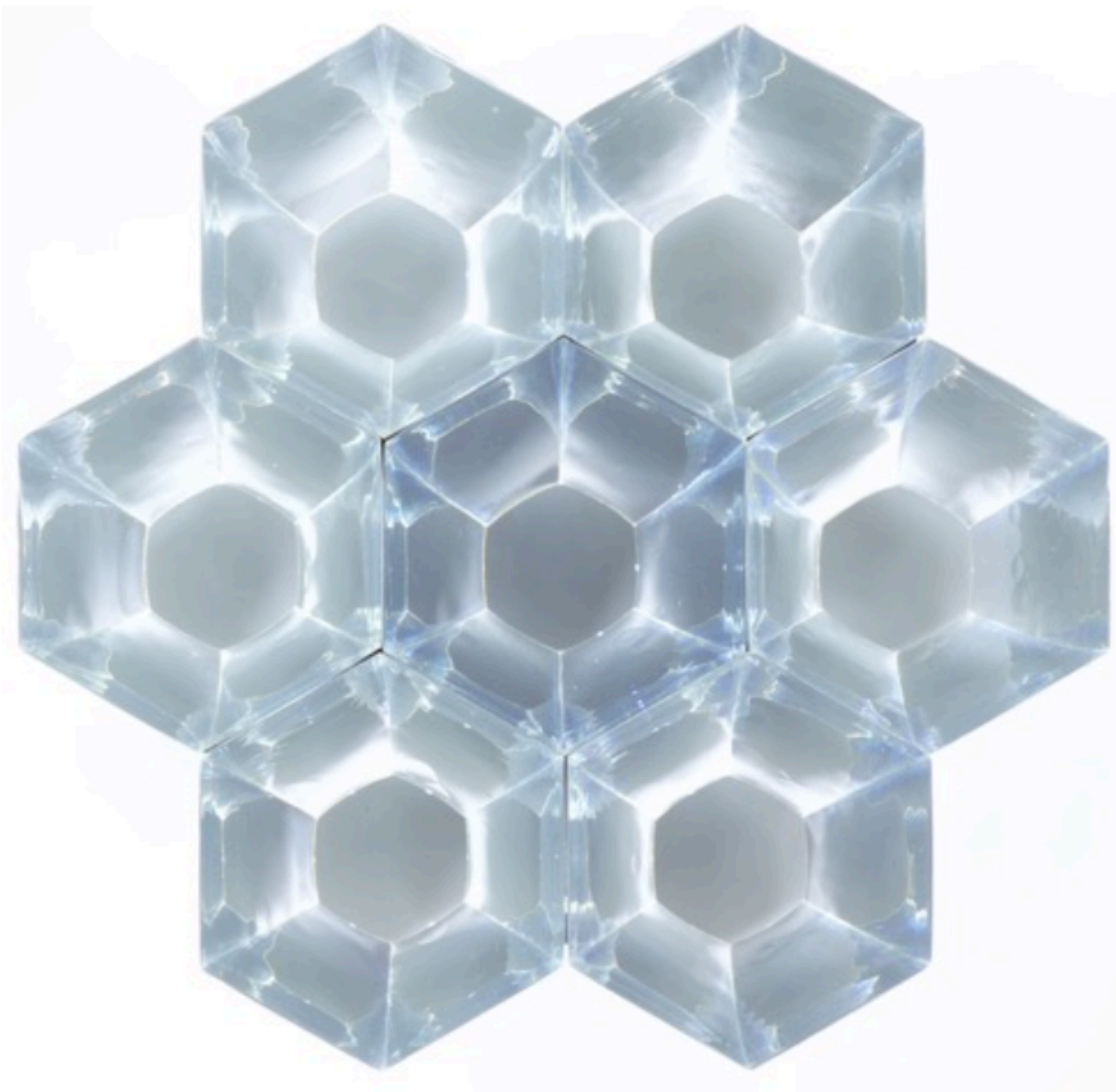
- CTA MSTs are following an intermediate design using a dish between Davis-Cotton and parabolic
  - almost DC-like PSF with a time spread of 0.41 ns rms

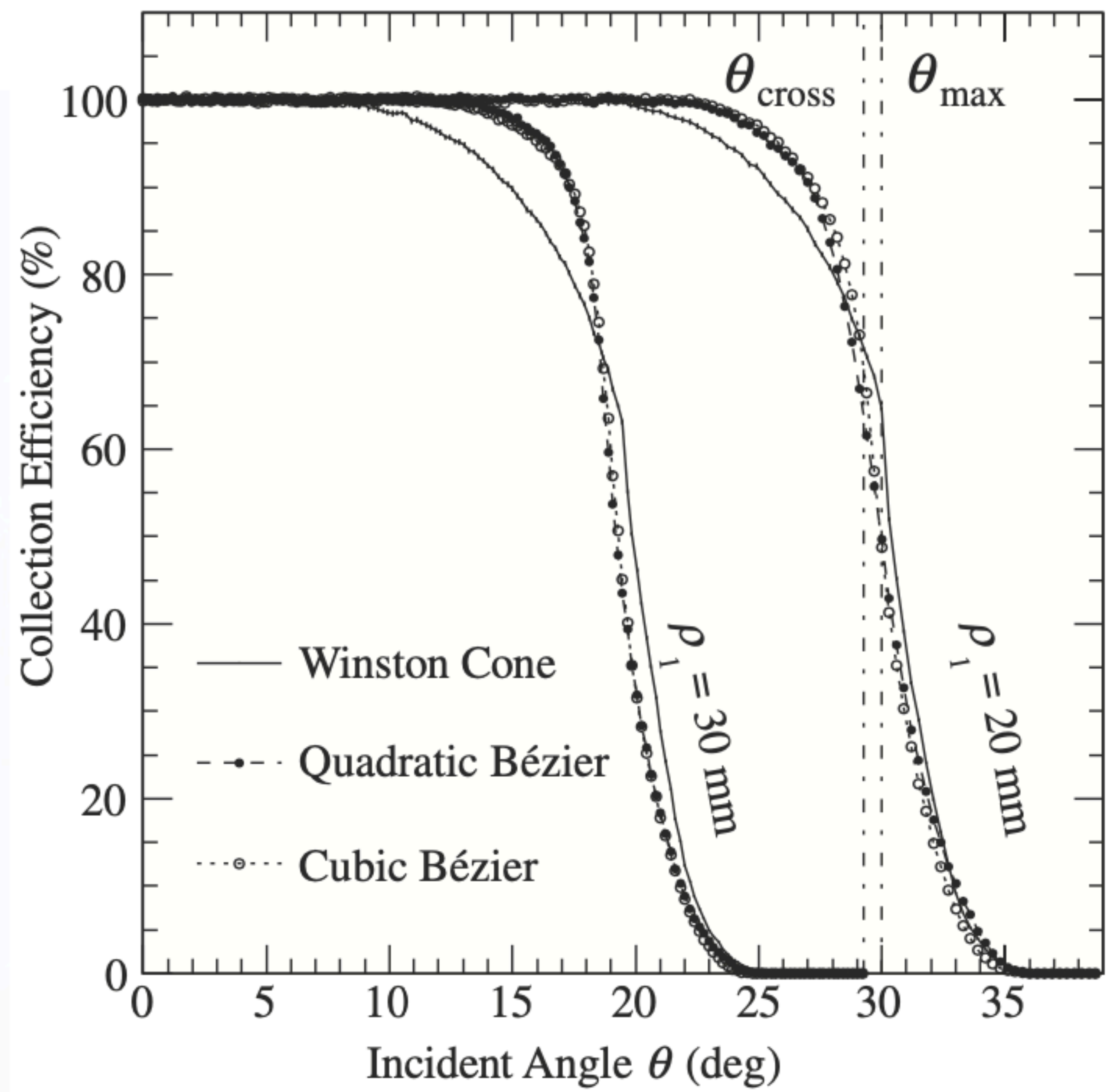
Mirror reflectivity.



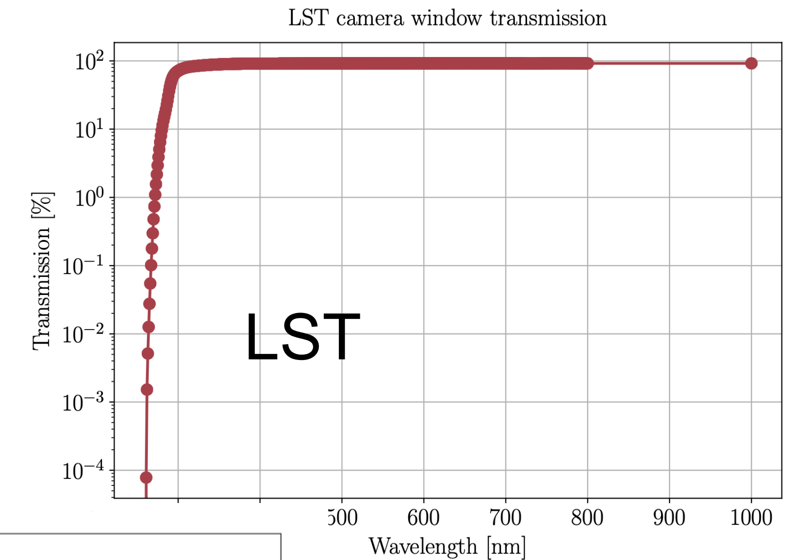
Light concentrators.

Okumura (2012)





Camera Window.



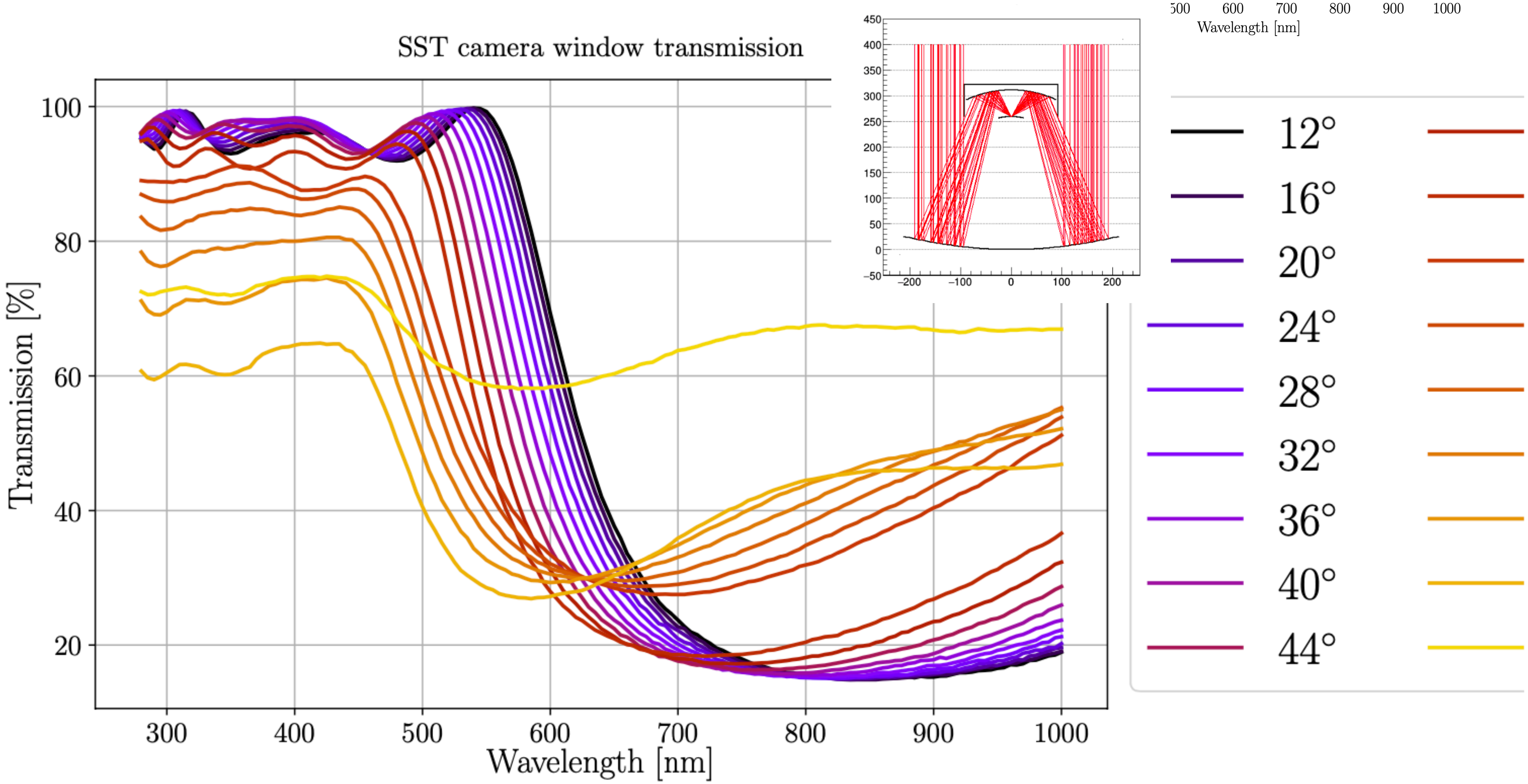
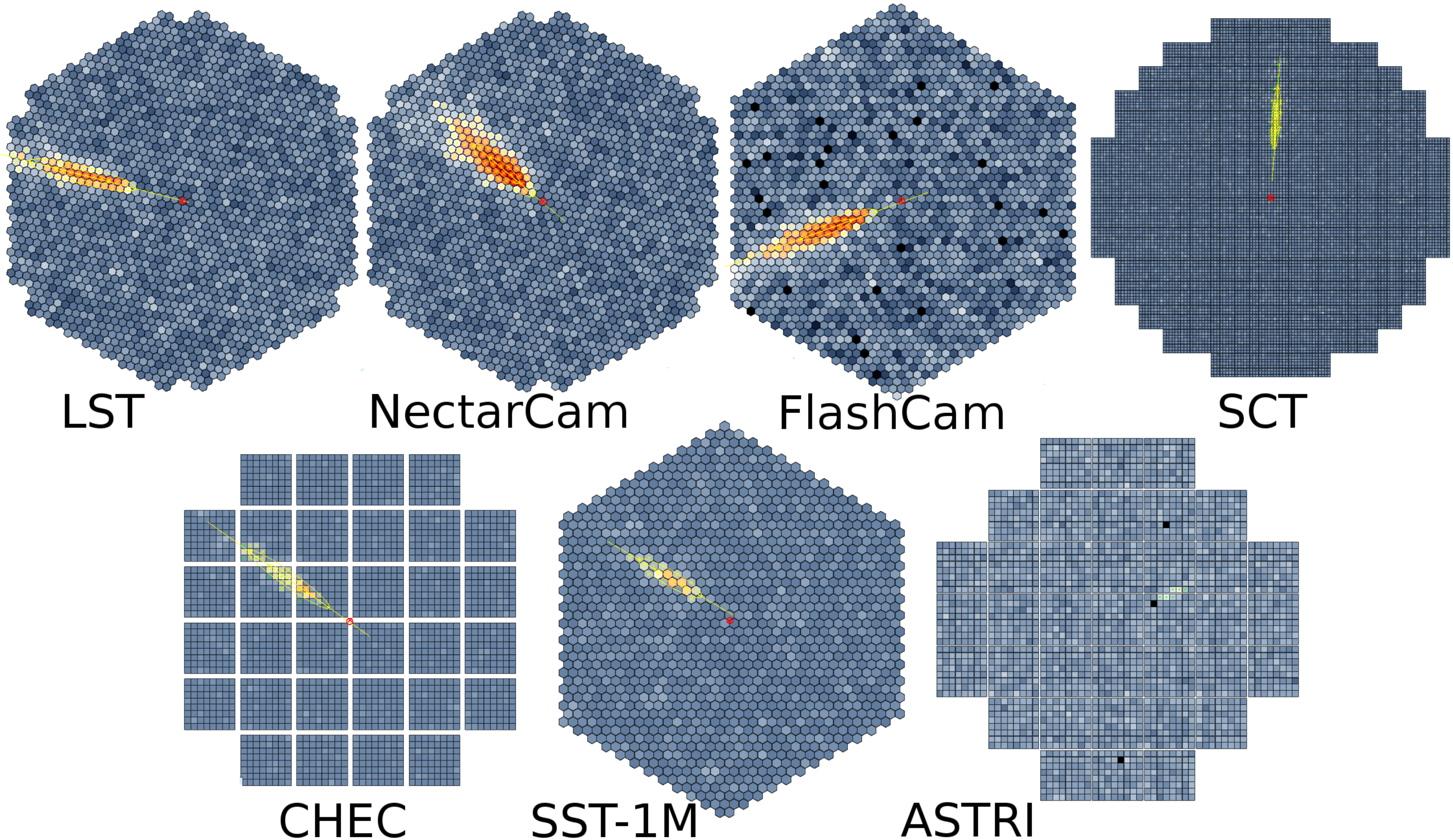


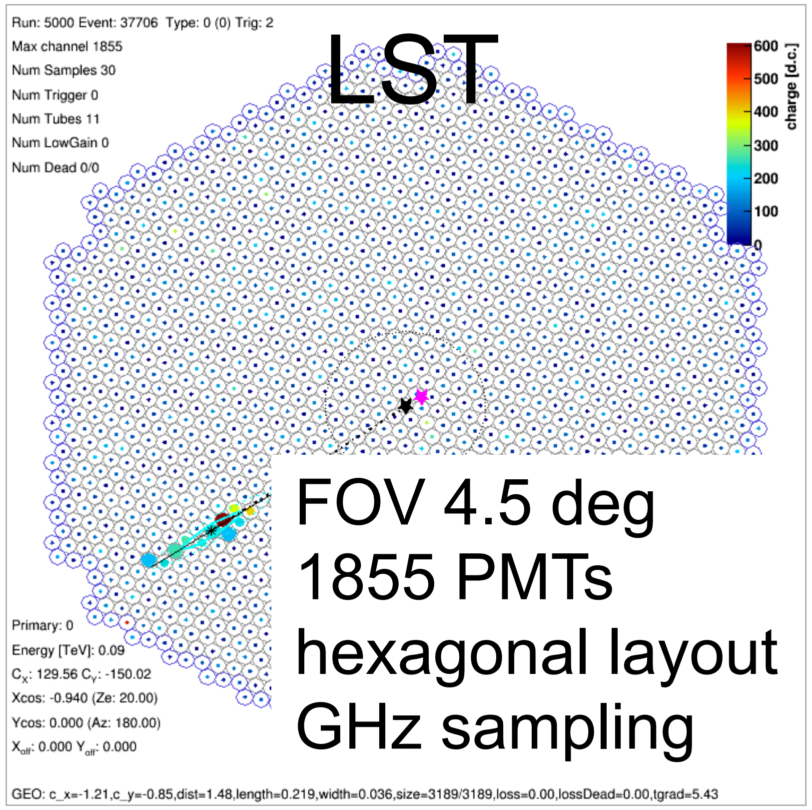
Figure 5 – Camera window transmission as a function of wavelength and incident angle for the SST camera.

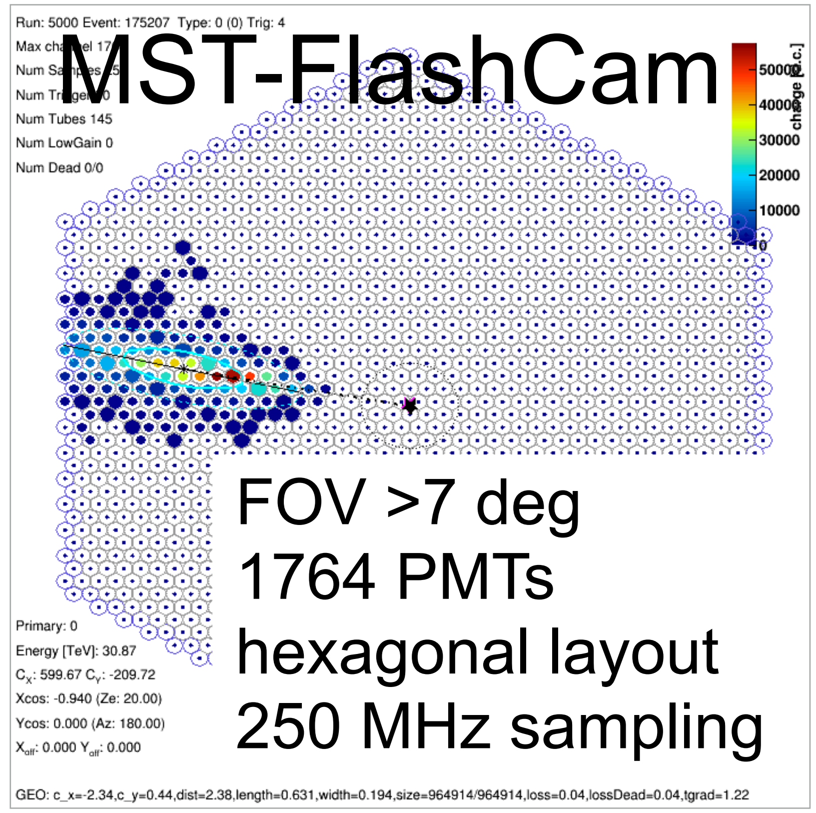
Cameras.

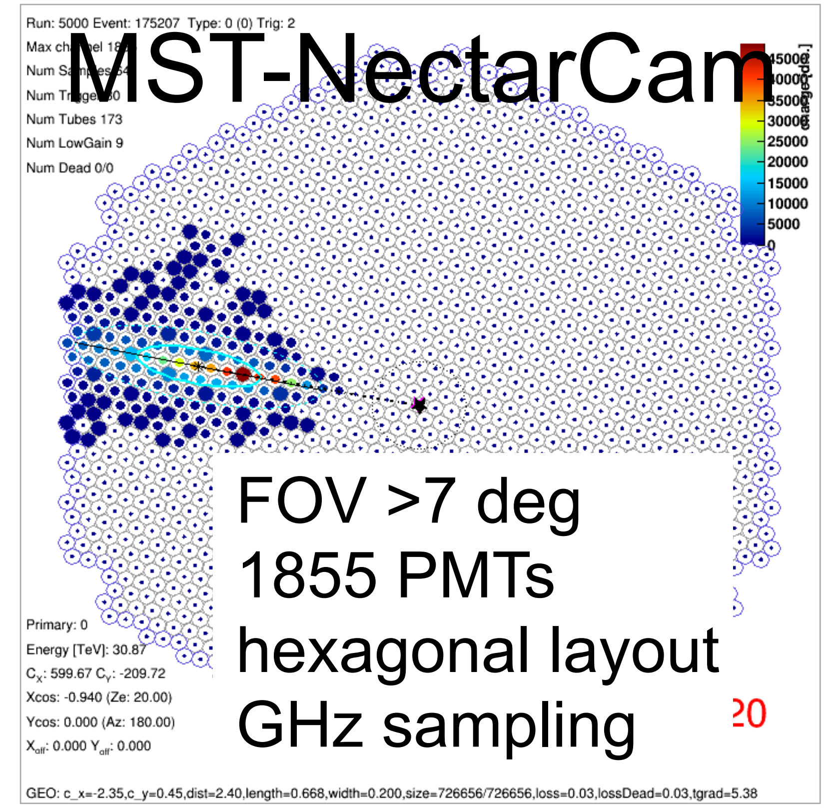
K.Bernlöhr

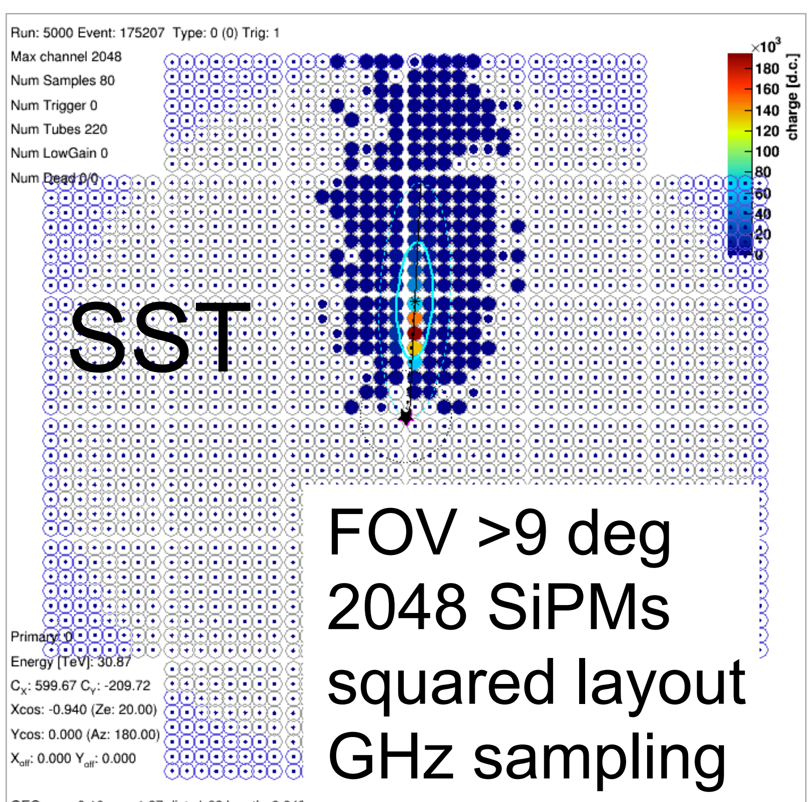


Telescopes and Camera types



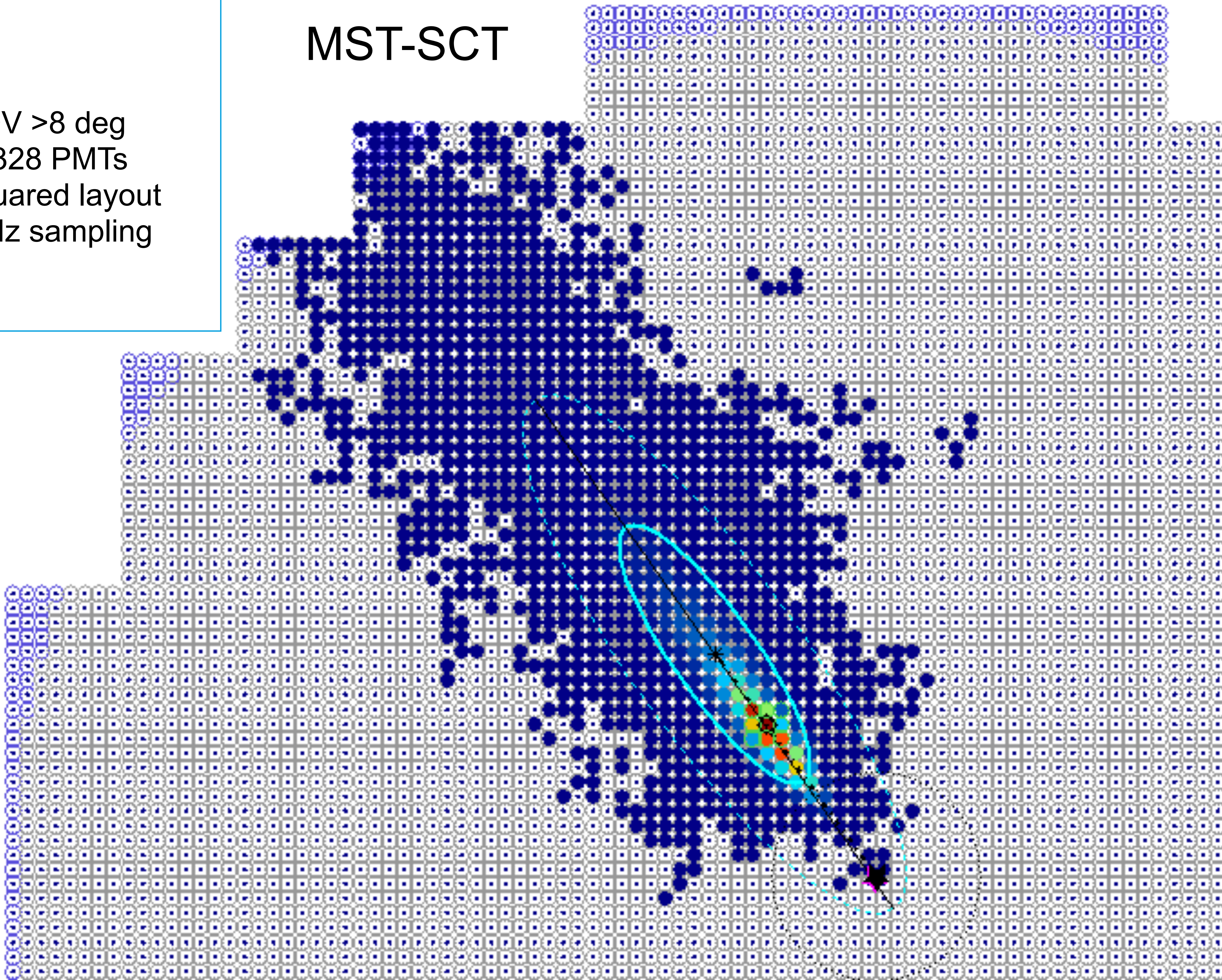




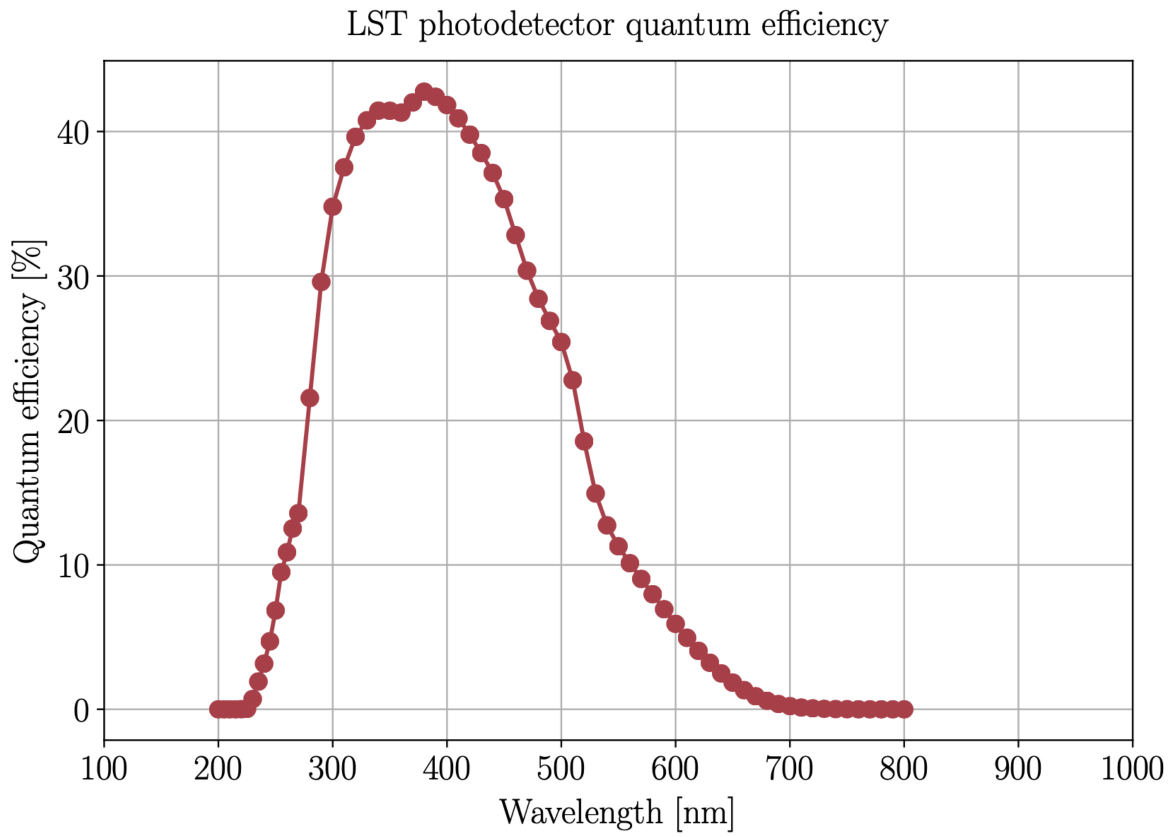


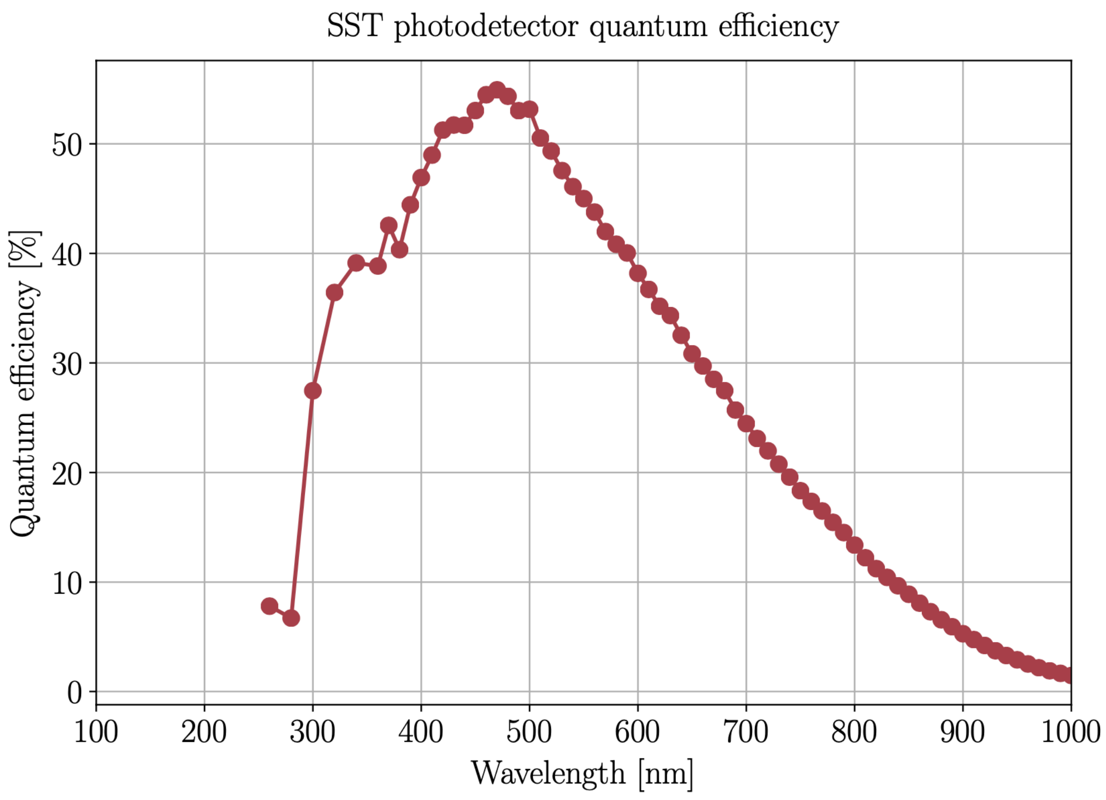
MST-SCT

FOV >8 deg
11328 PMTs
squared layout
GHz sampling

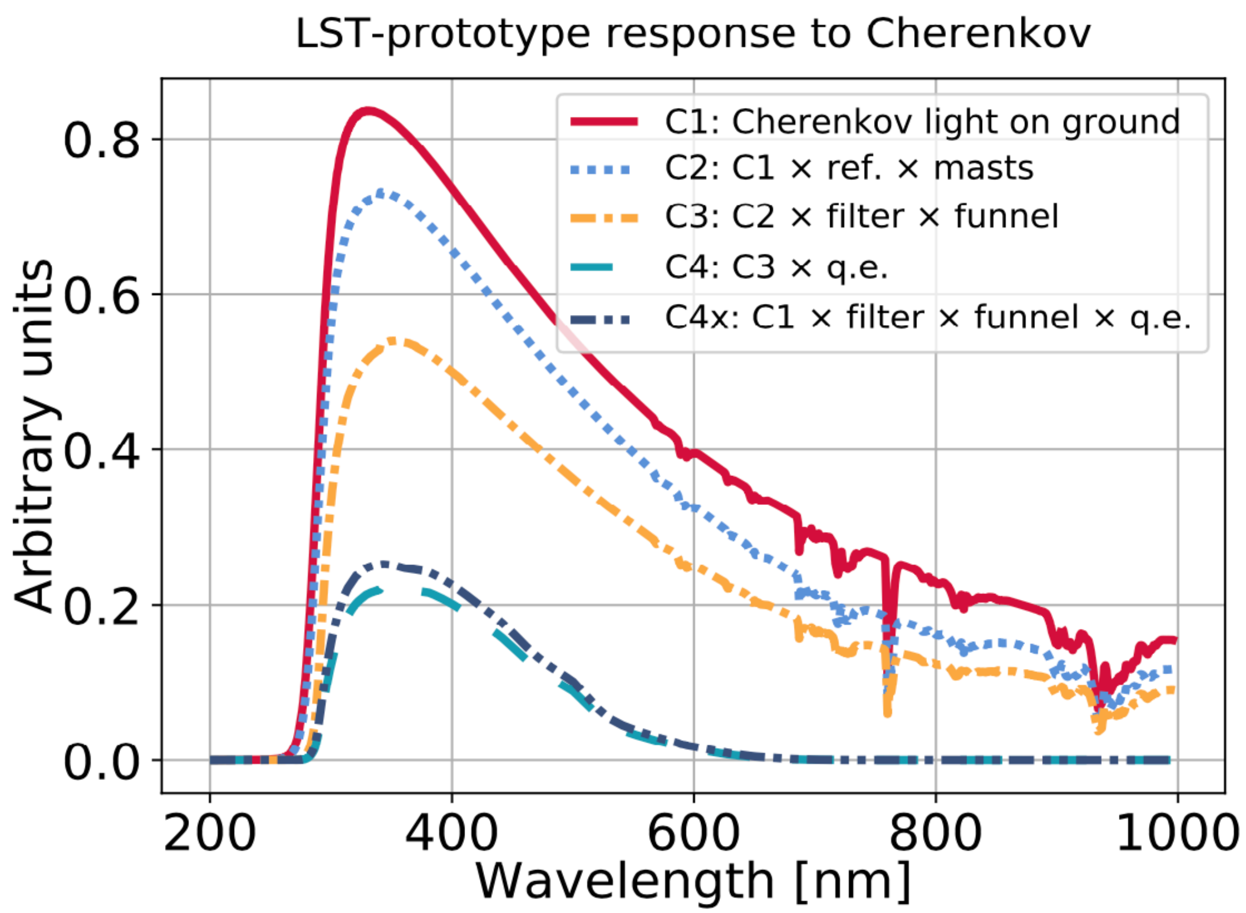


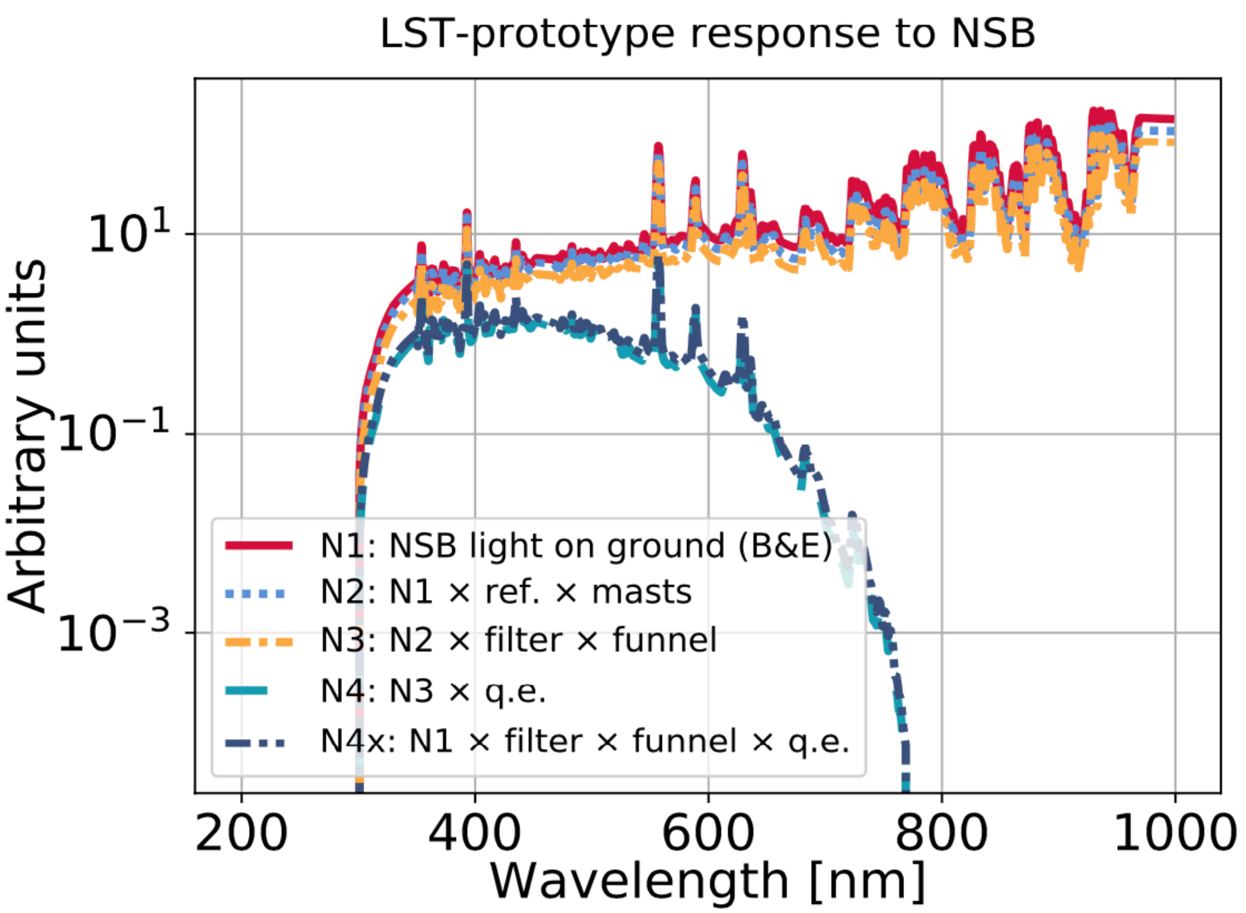
Quantum and photodetector efficiencies.



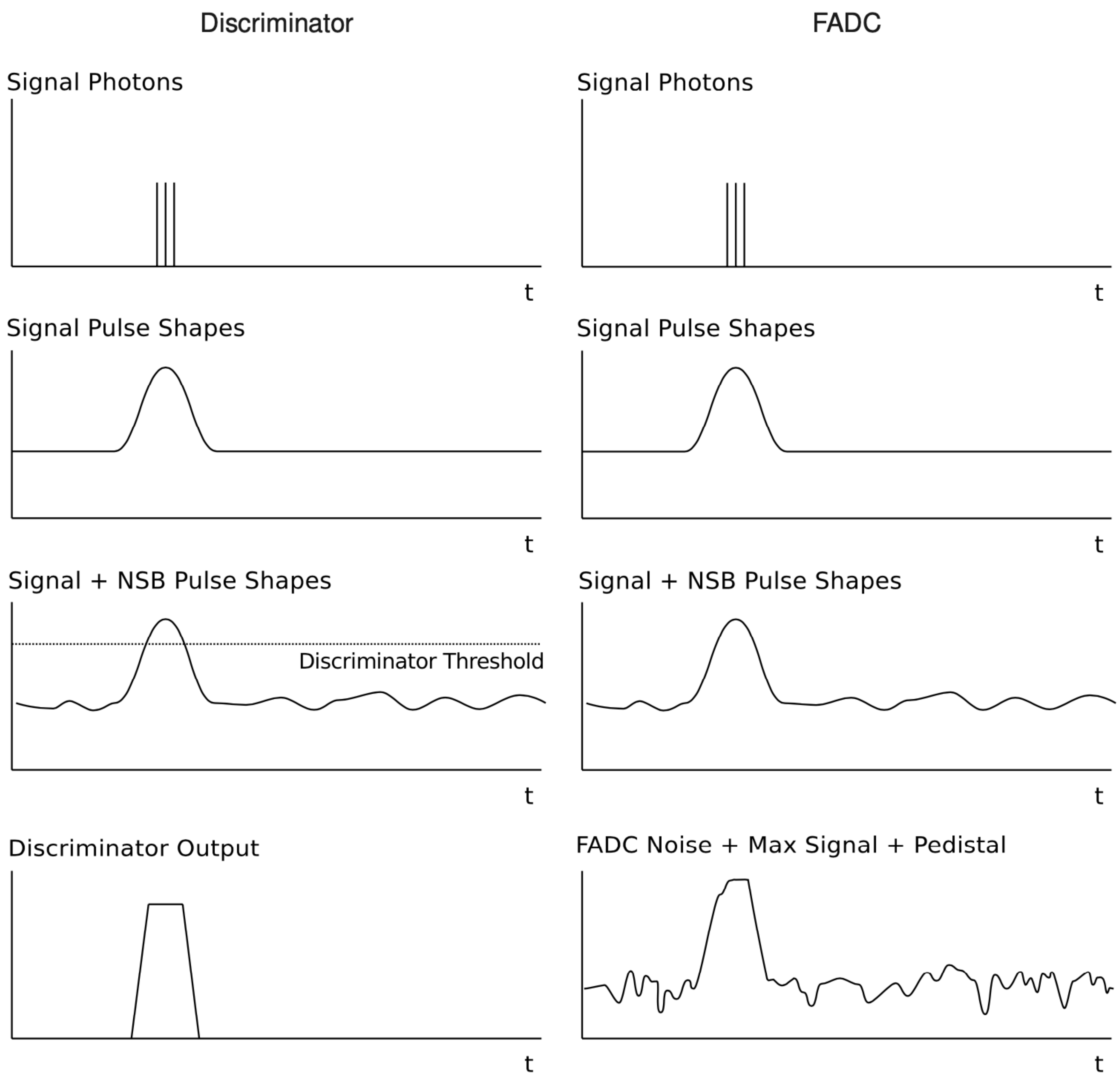


Efficiencies.

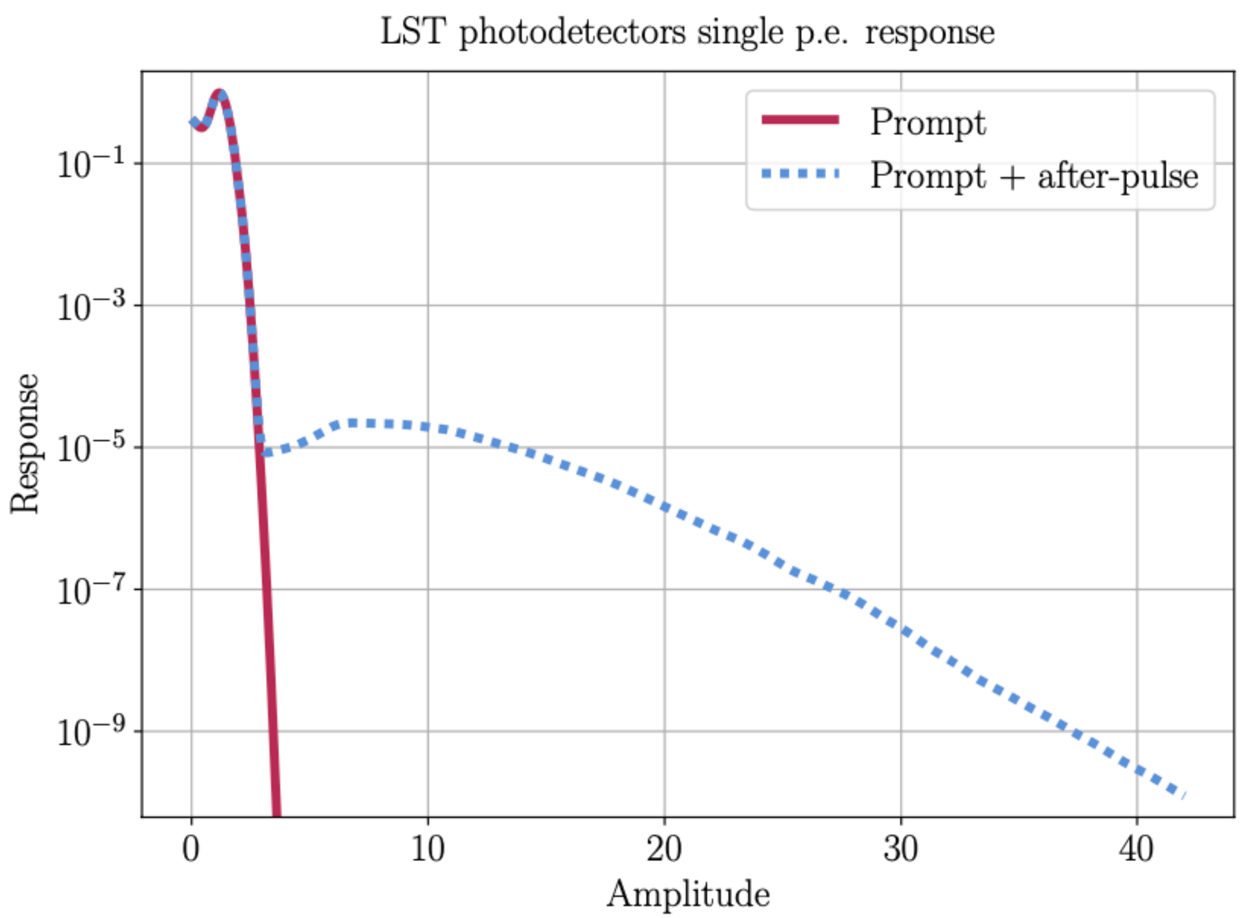


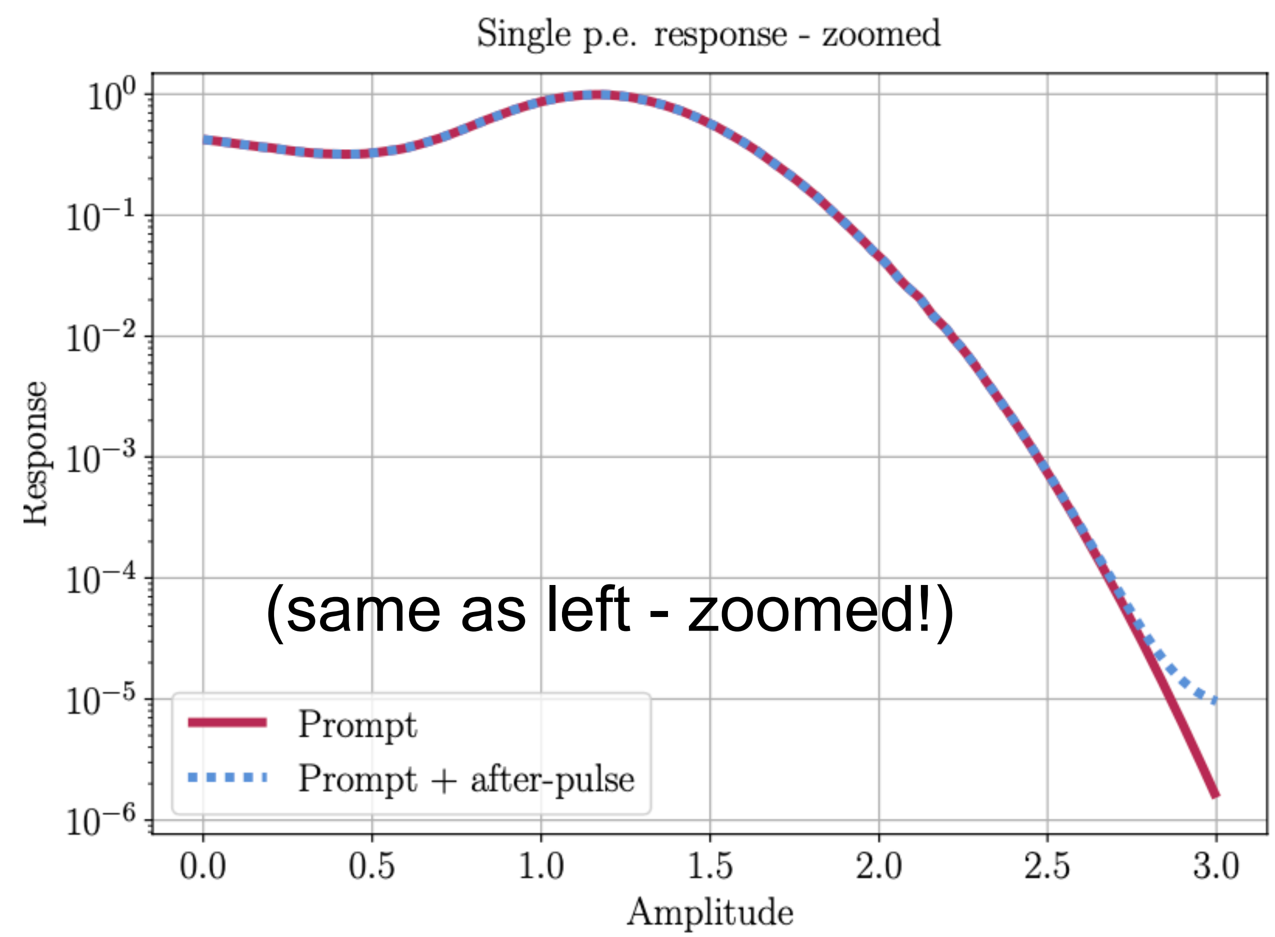


Trigger and readout - oversimplified.

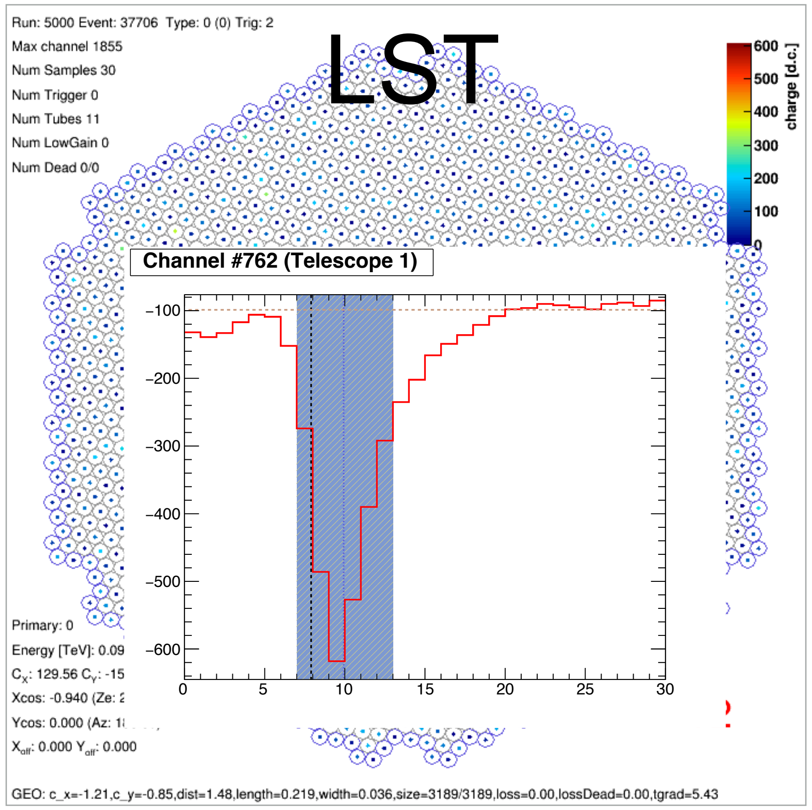


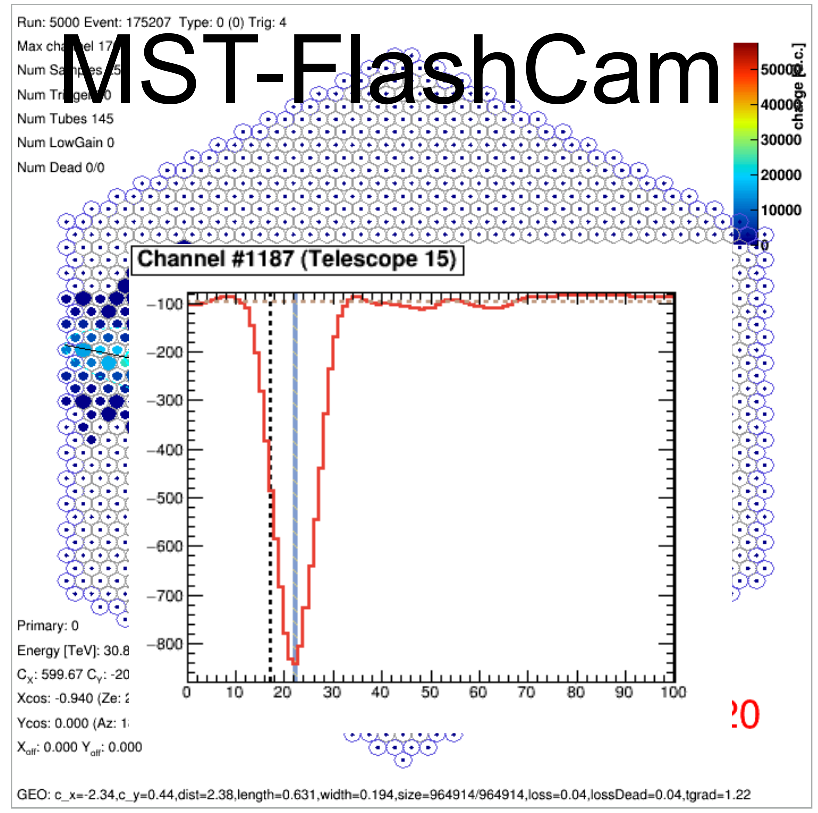
Single photo electron response.

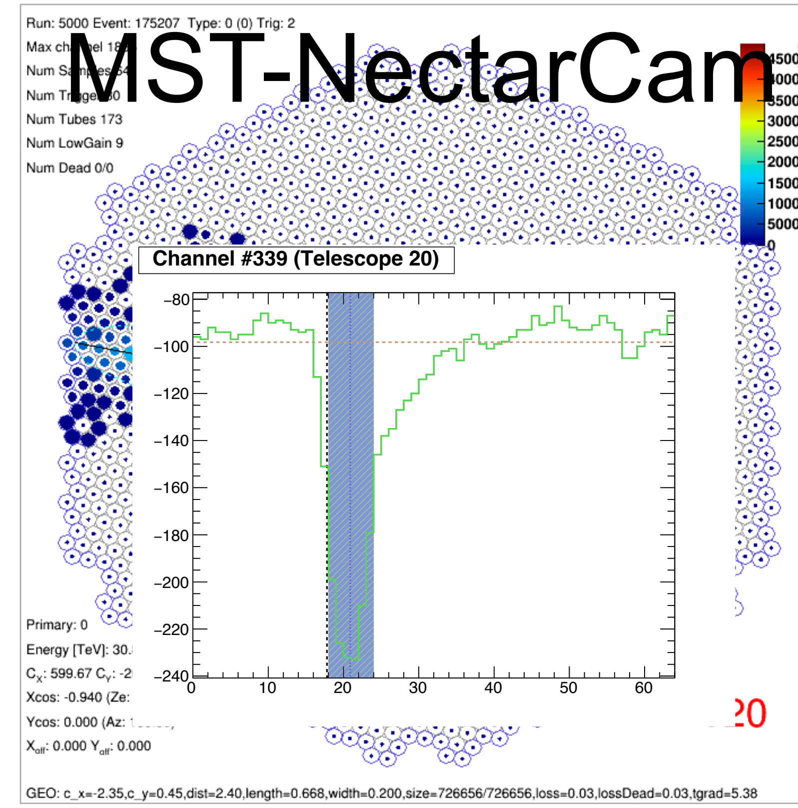


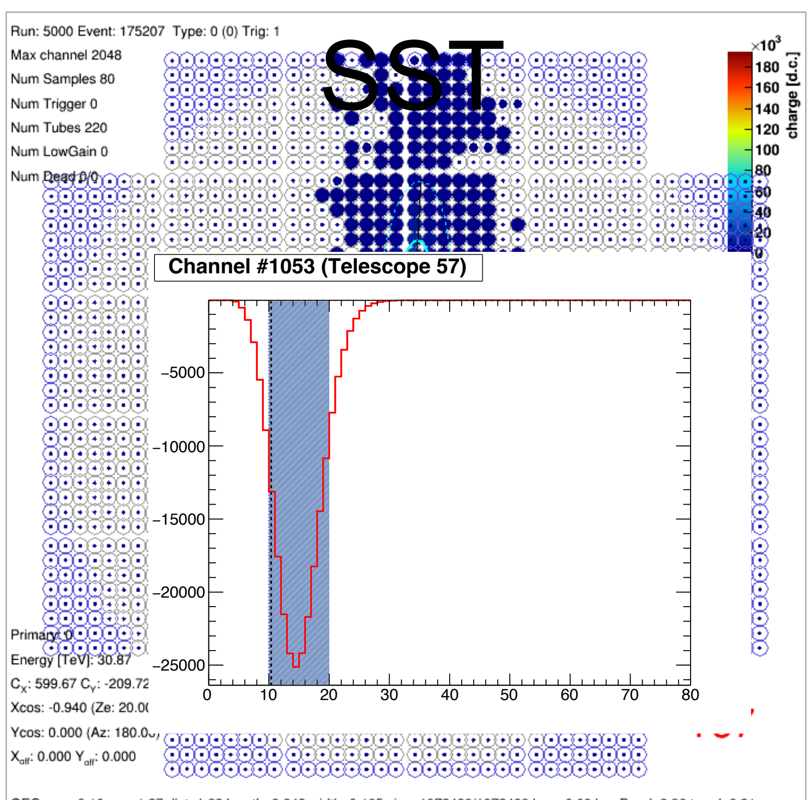


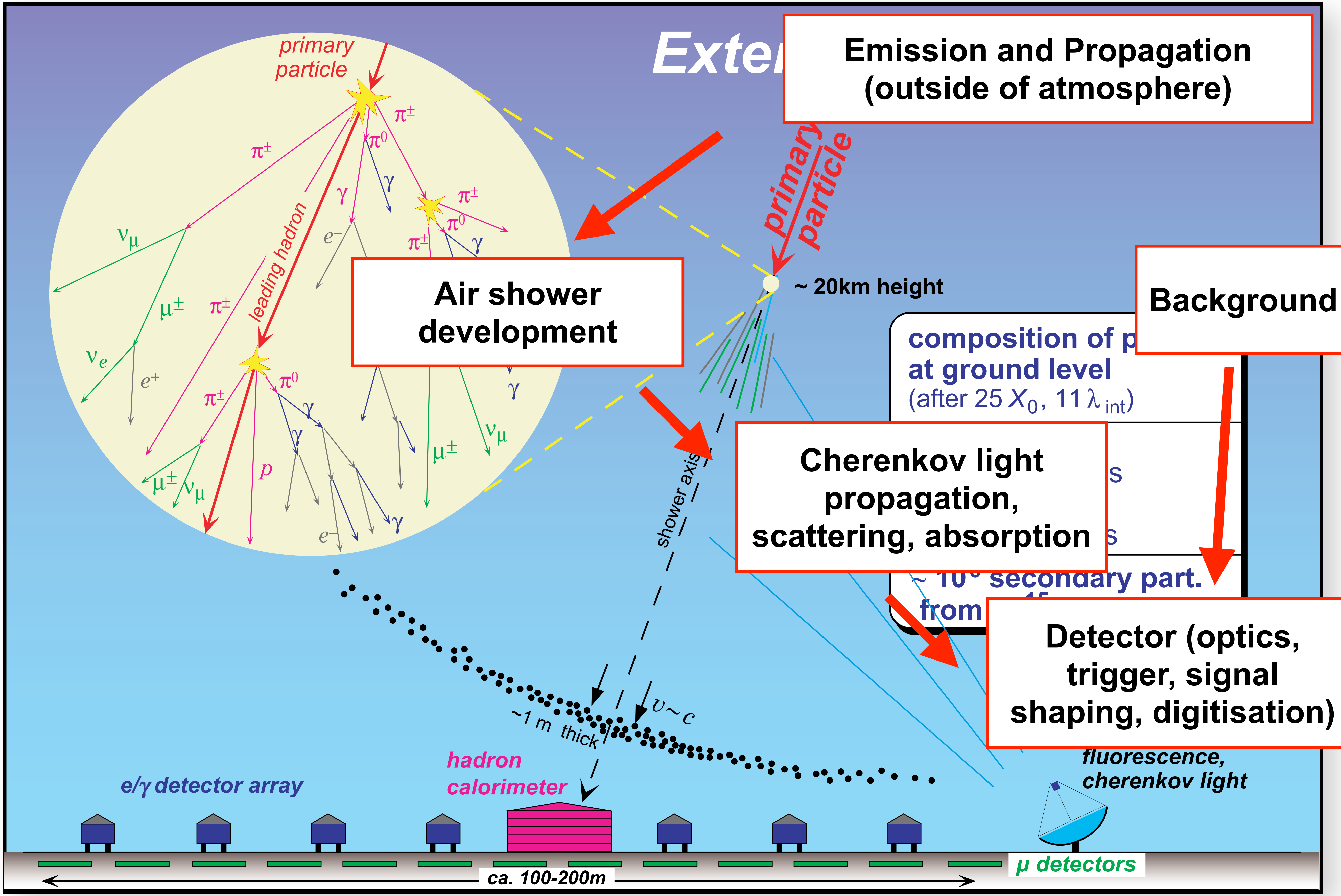
Telescopes and Camera types









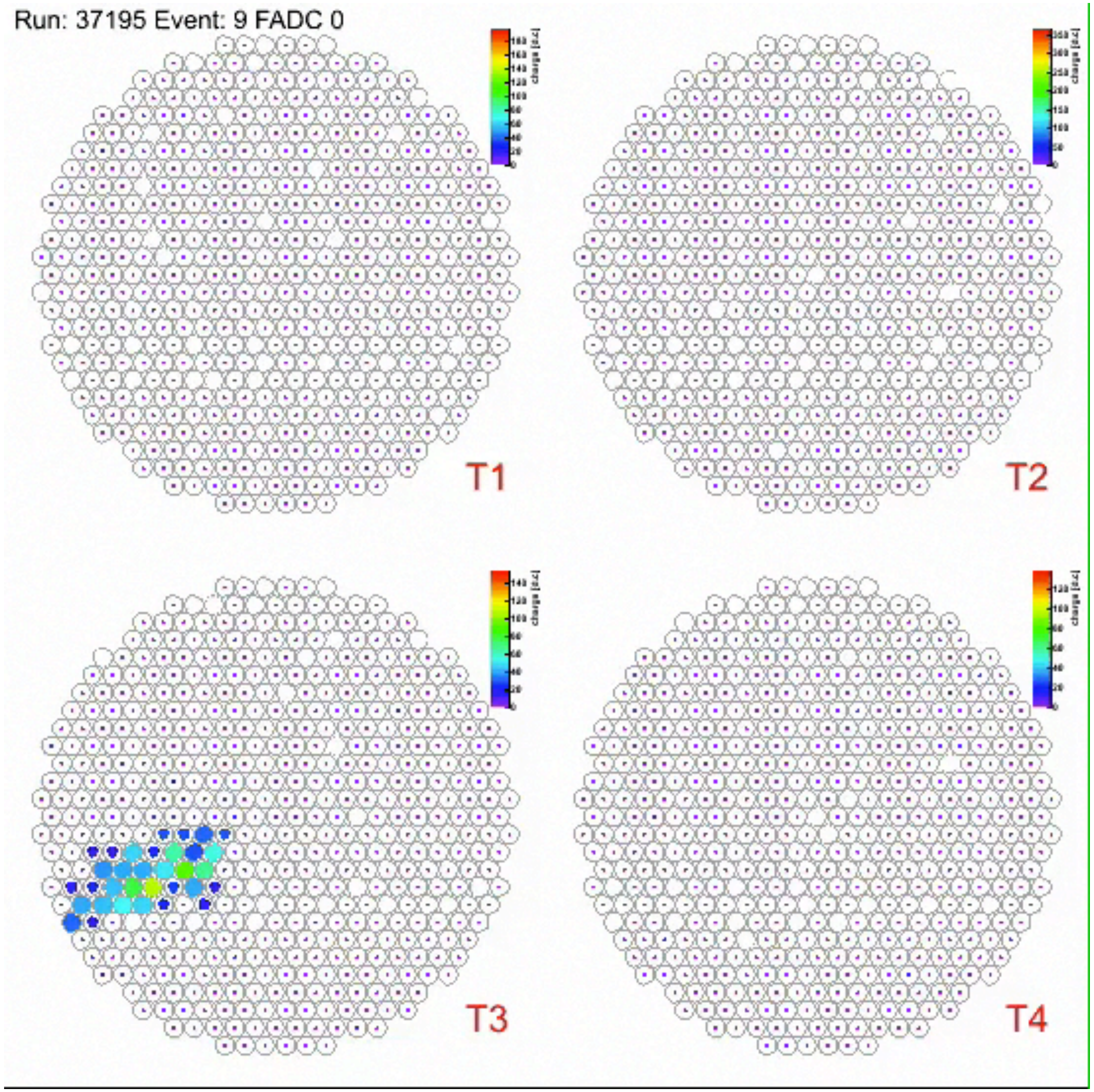


Air showers are complicated: use Monte Carlo simulations.

VERITAS Events

Typical readout rate: 350 Hz
Signal rate from a strong source 0.3 Hz

event display VERITAS



about every 100th event is a γ-ray

(each frame 2 ns long)

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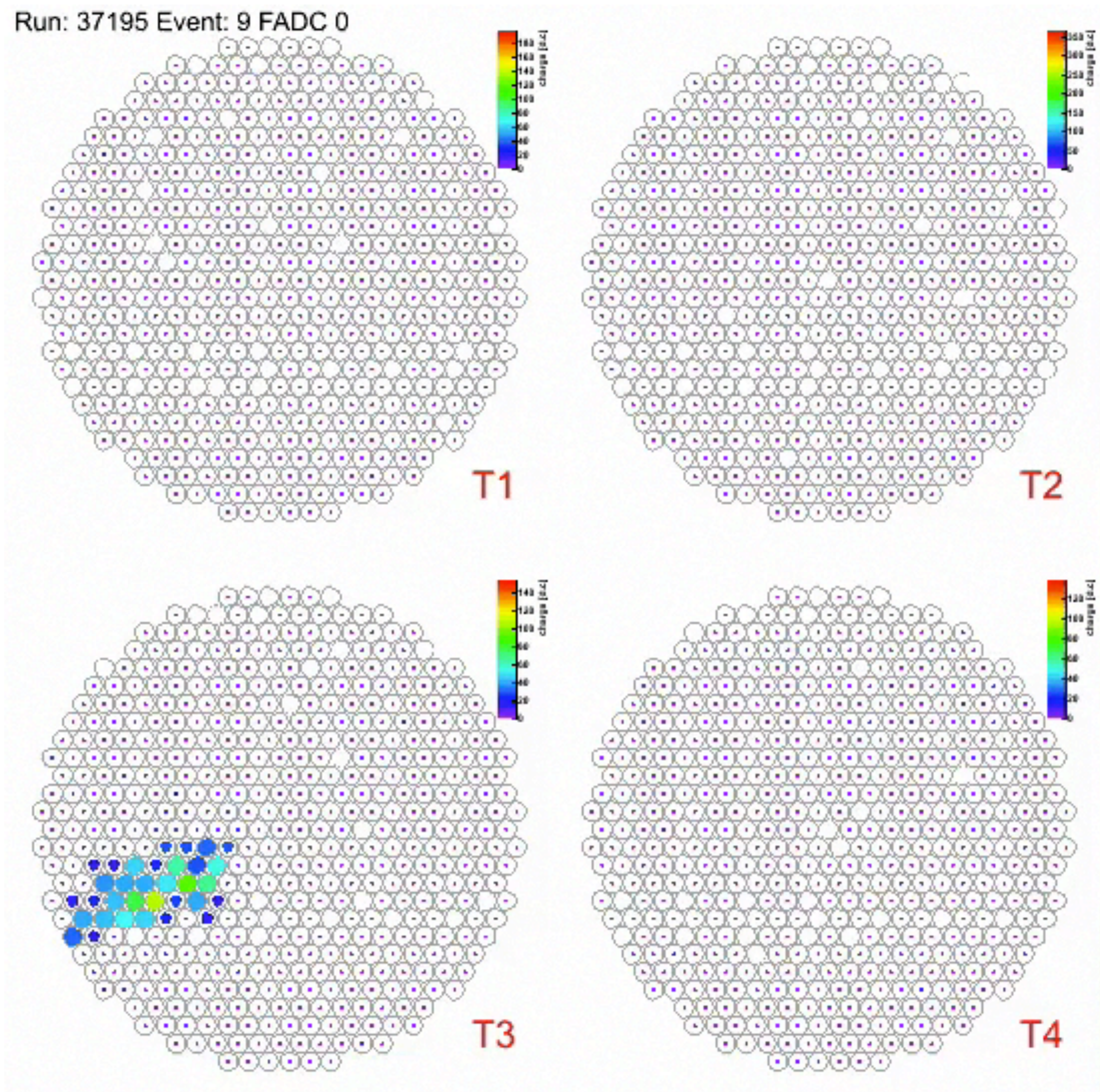

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