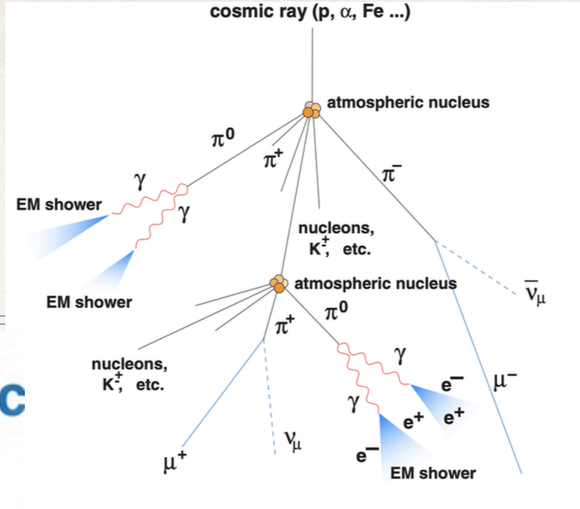
Detector simulations for IACTs

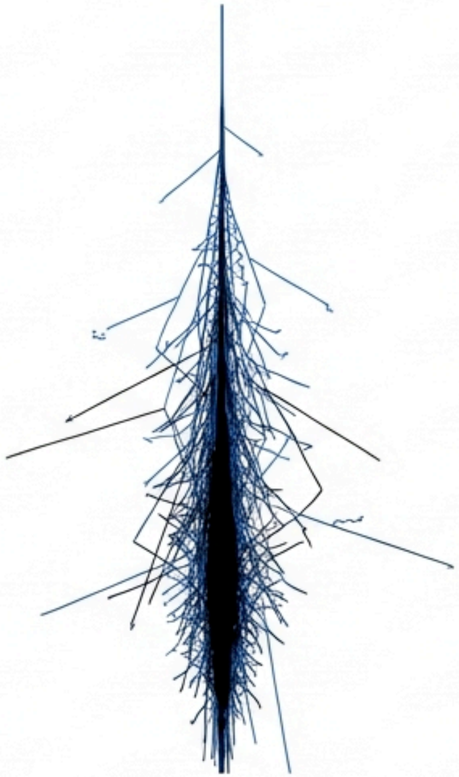
Atreyee Sinha, TIFR

Heavily borrowed from lectures at previous CTAO schools by Gernot Maier

Brief recap



Gamma Ray (EM)

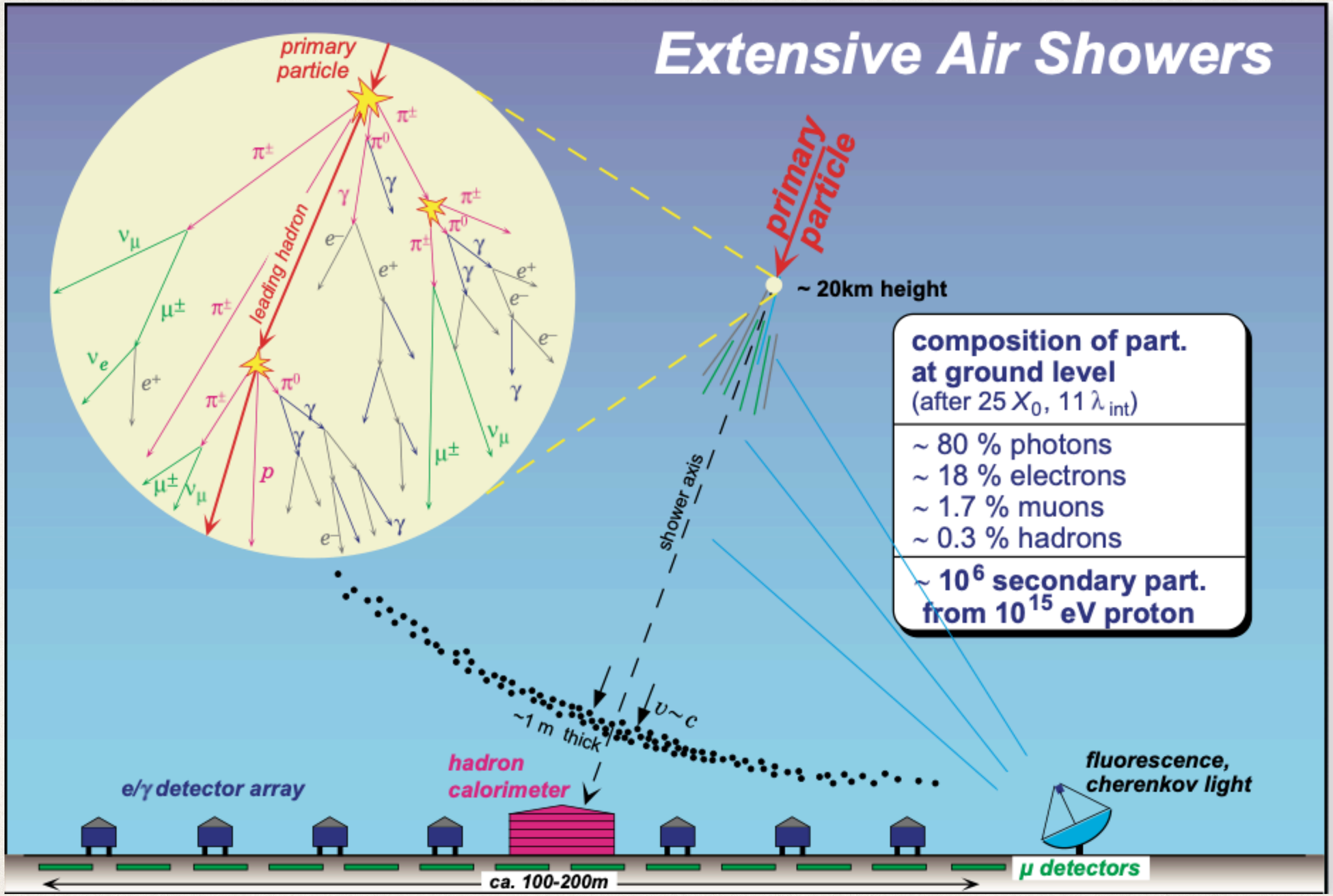


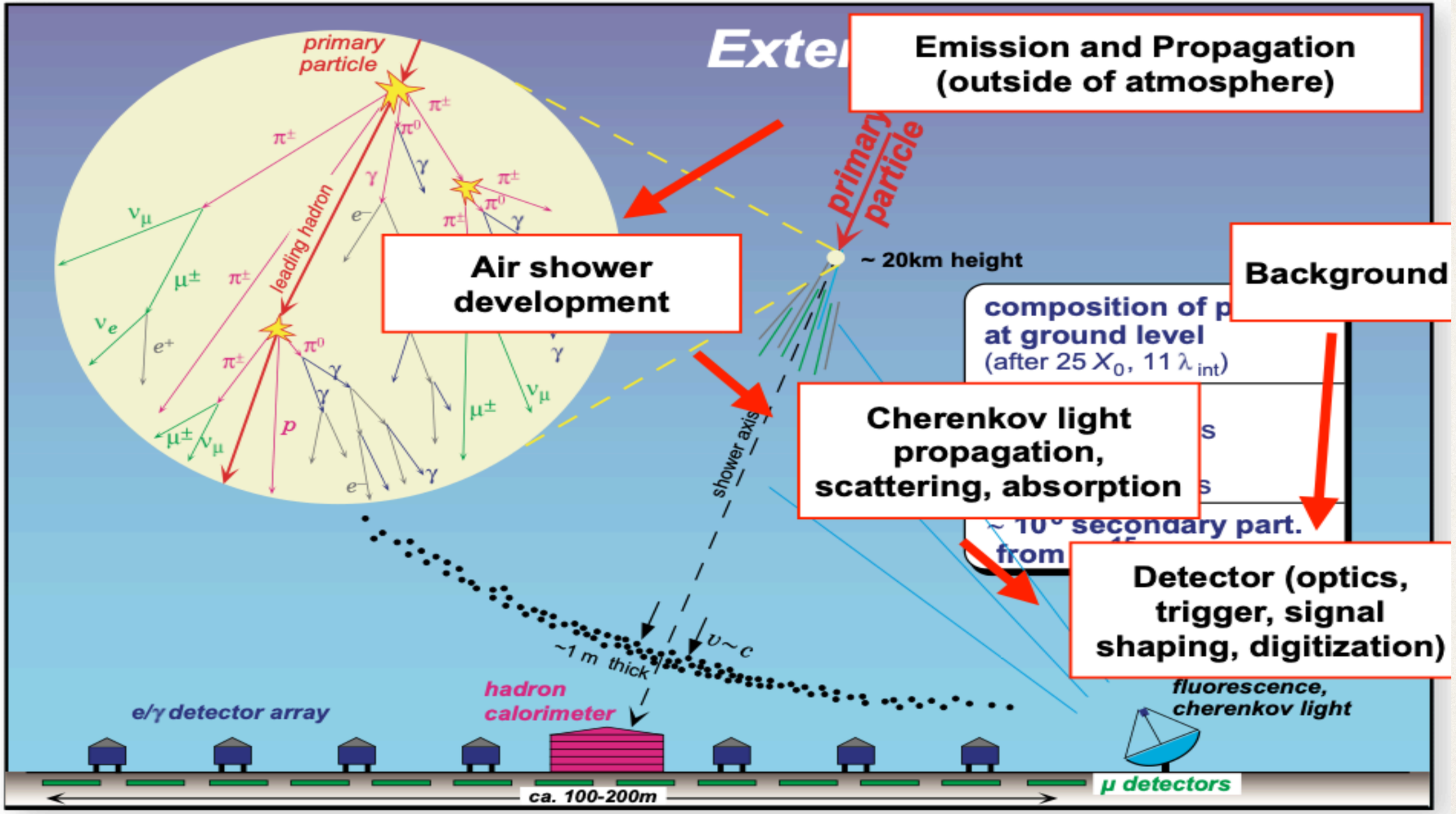
Muon-poor

- **Sub-shower Feeding**: $\pi^0 \to \gamma\gamma$ feeds EM component.
- **Decay**: $\pi^\pm \to \mu^\pm \nu$ generates Muon signature.
- **Fluctuations**: Protons vary significantly in depth of first interaction ($\lambda_I \approx 90\ \mathrm{g/cm^2}$).

Proton (Hadronic

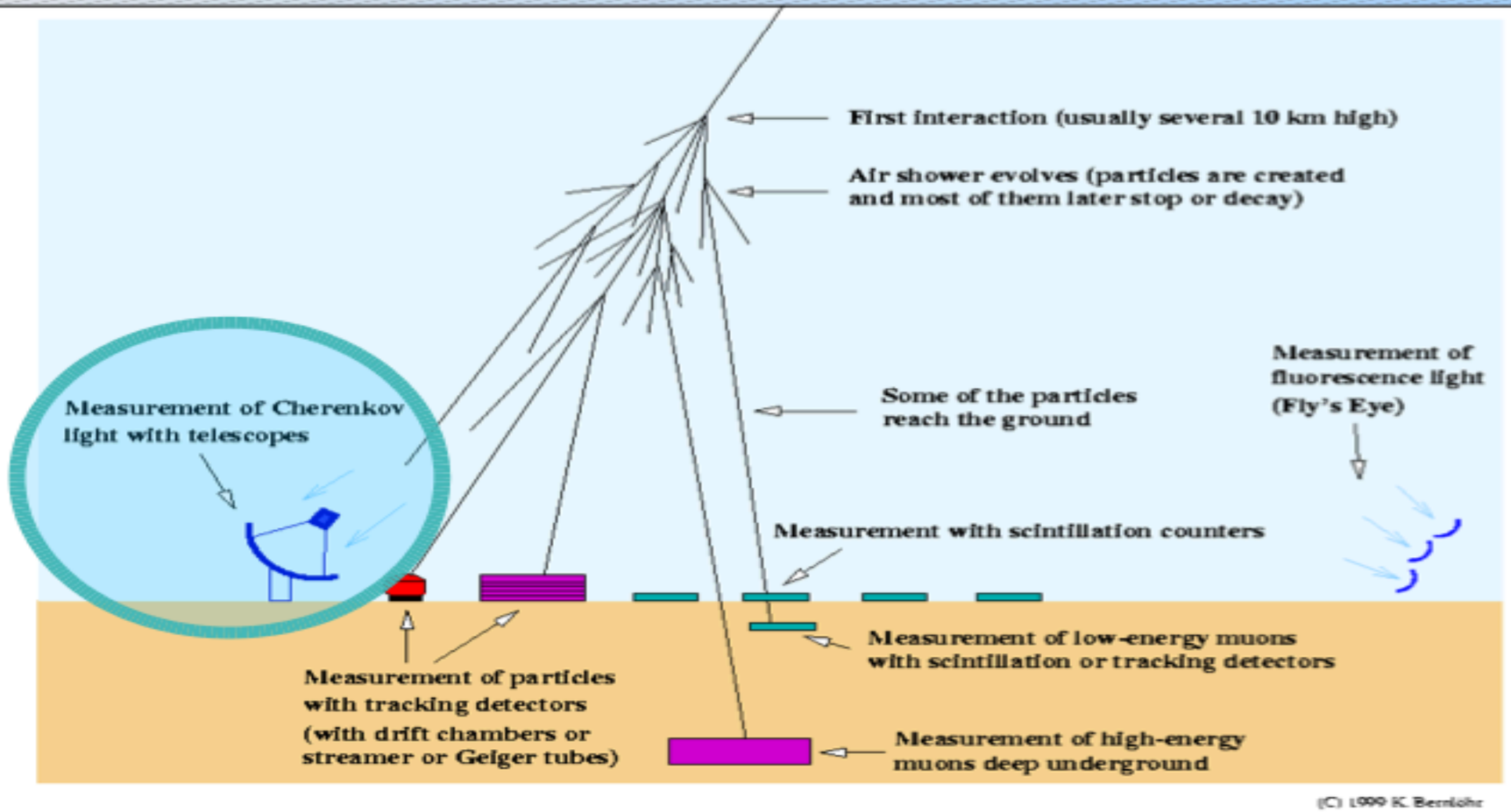
Muon-rich


Extensive Air Showers
primary particle
leading hadron
~ 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
~1 m thick
$v \sim c$
e/γ detector array
hadron calorimeter
fluorescence, cherenkov light
μ detectors
ca. 100-200m



Air showers are complicated: use Monte Carlo simulations.

Air shower measurement methods



What is different about IACT simulations?

- We are using the earth's atmosphere as a calorimeter
  - ~ 10s km of vertical atmosphere
  - Very low density medium
  - ~ millions of secondary particles
- Large (~billions) of Cherenkov photons

Geant4 <u>can</u> do this! BUT

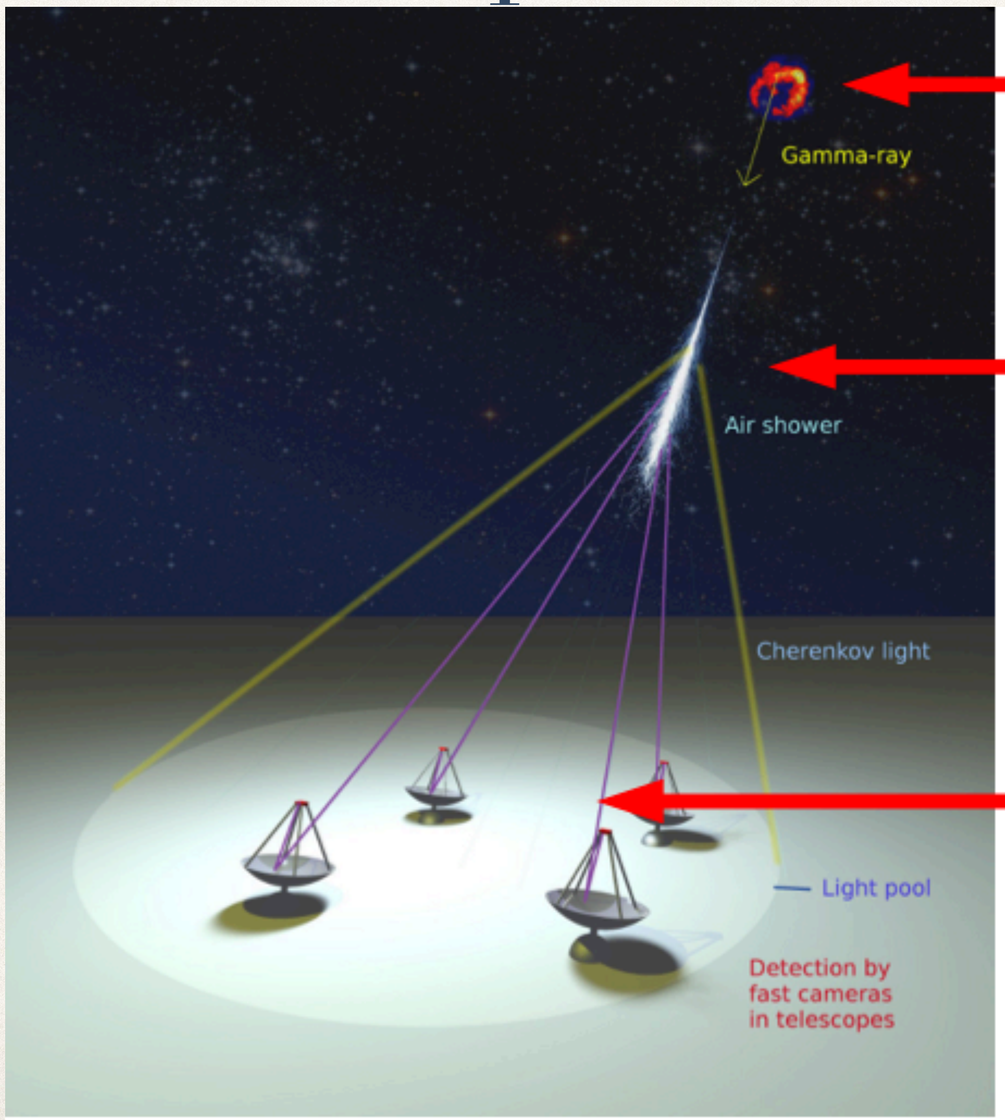
Memory heavy and inefficient!

And often unnecessary!

IACT simulations

- Expensive to do simulations for different sources etc
- Monte Carlo simulations done to obtain Instrument Response Functions, which are then used during analysis
  - Simulate shower propagation in the atmosphere to obtain Cherenkov photons on ground level
    - CORSIKA
  - Simulate the Cherenkov photons trajectory in your Telescope Optics and through your camera to obtain output of camera
    - simtel_array
  - Use simulated output for training your event identification, getting instrument response
    - Subject of tomorrow's talk

Simulation steps



Emission and propagation to Earth: Astrophysics (not dealt with here).

Particle cascade ("air shower") is normally simulated with CORSIKA, up to light propagation to positions of individual telescopes.

Shower simulation

Cherenkov light atm. transmission, optical properties of telescopes, photon detection, nightsky background, electronic signals, trigger decisions, digitization of signals, ...

Telescope simulation

Simulating the atmosphere

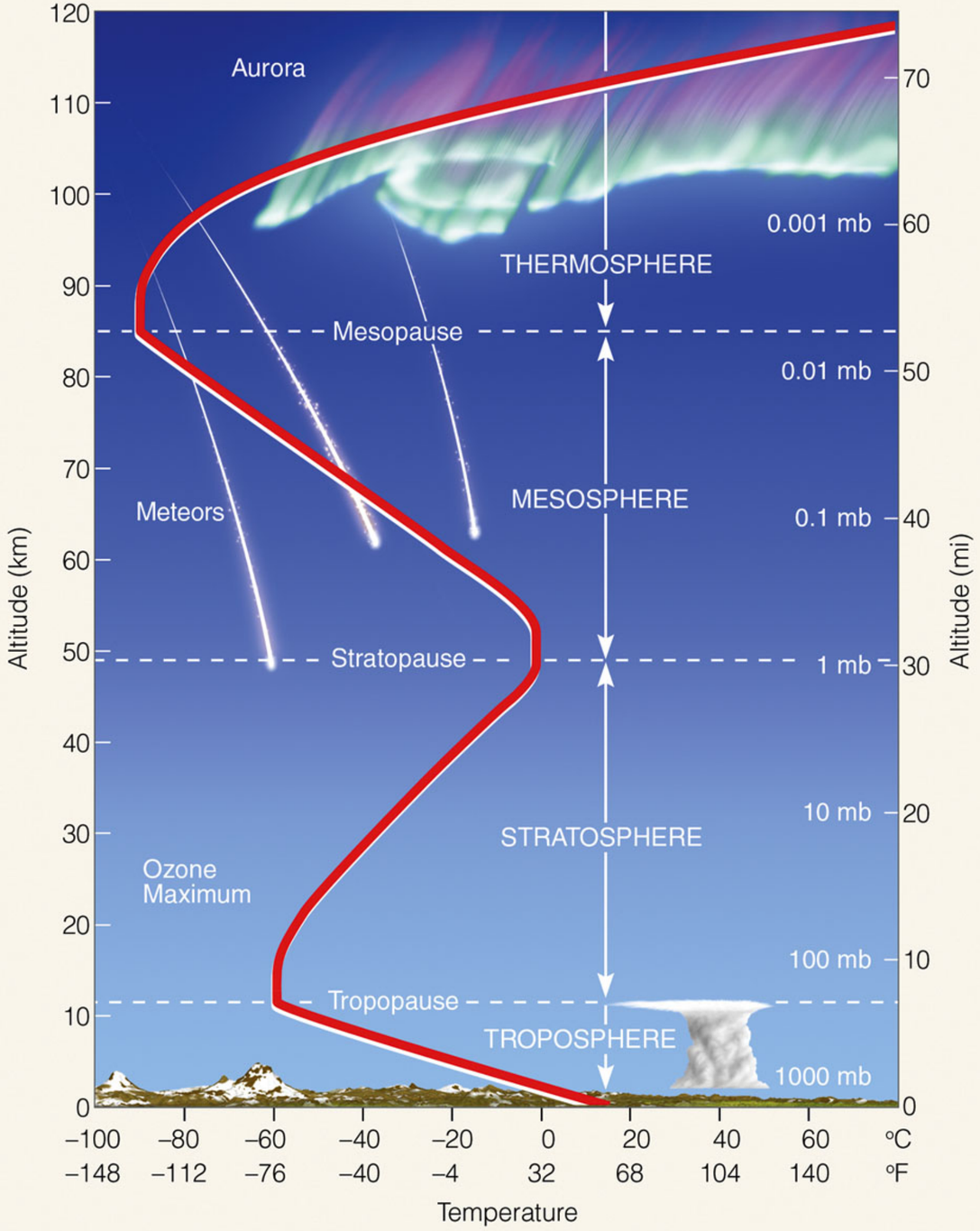
- Composition: 78% N_2, 21% O_2, 0.9% Ar.
- Density (isothermal approximation):
  - For air shower simulations: need to be better than isothermal approximation

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

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

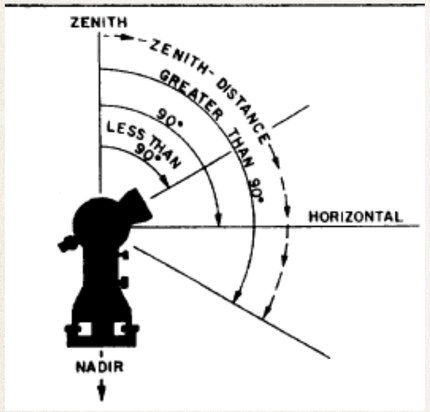
- Actual matter traversed by air shower: slant depth / thickness

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


Aurora
THERMOSPHERE
Mesopause
MESOSPHERE
Meteors
Stratopause
STRATOSPHERE
Ozone
Maximum
Tropopause
TROPOSPHERE
0.001 mb
0.01 mb
0.1 mb
1 mb
10 mb
100 mb
1000 mb
Altitude (km)
Altitude (mi)
Temperature
°C
°F
120
110
100
90
80
70
60
50
40
30
20
10
0
70
60
50
40
30
20
10
0
−100
−80
−60
−40
−20
0
20
40
60
−148
−112
−76
−40
−4
32
68
104
140

Thickness vs zenith angle

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



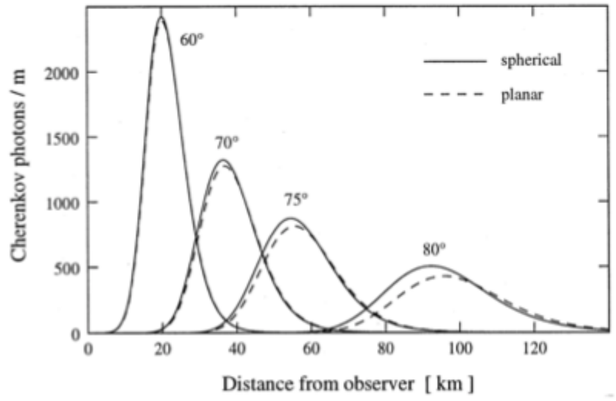
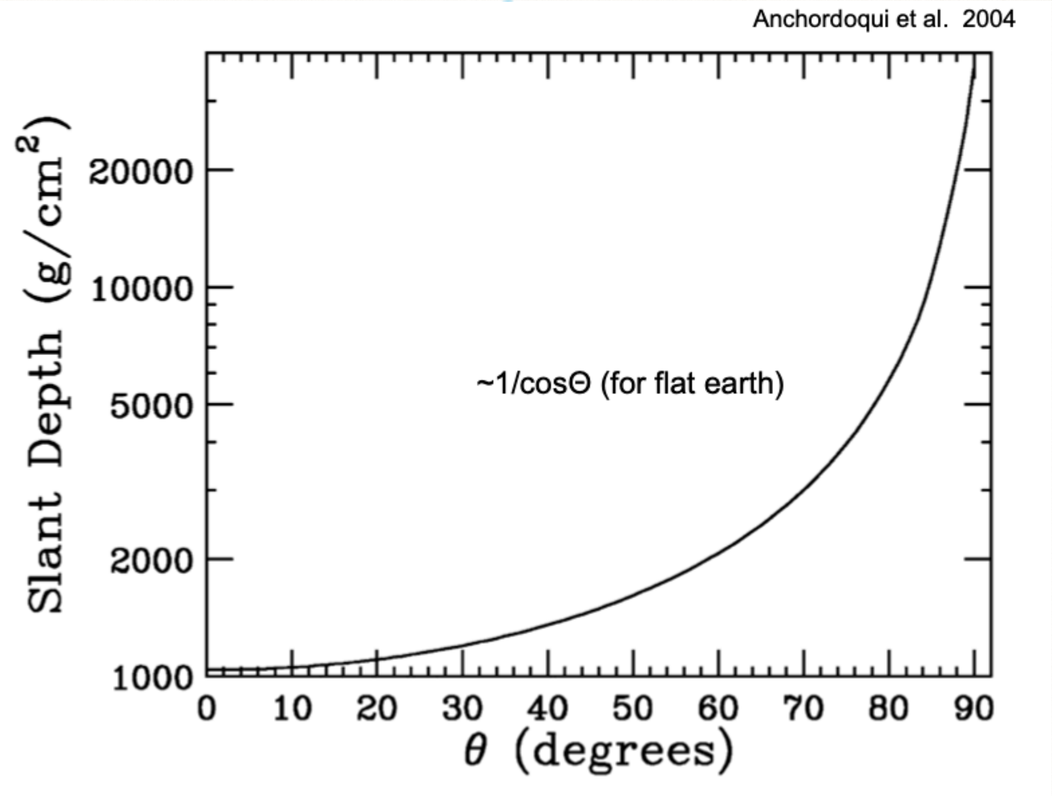
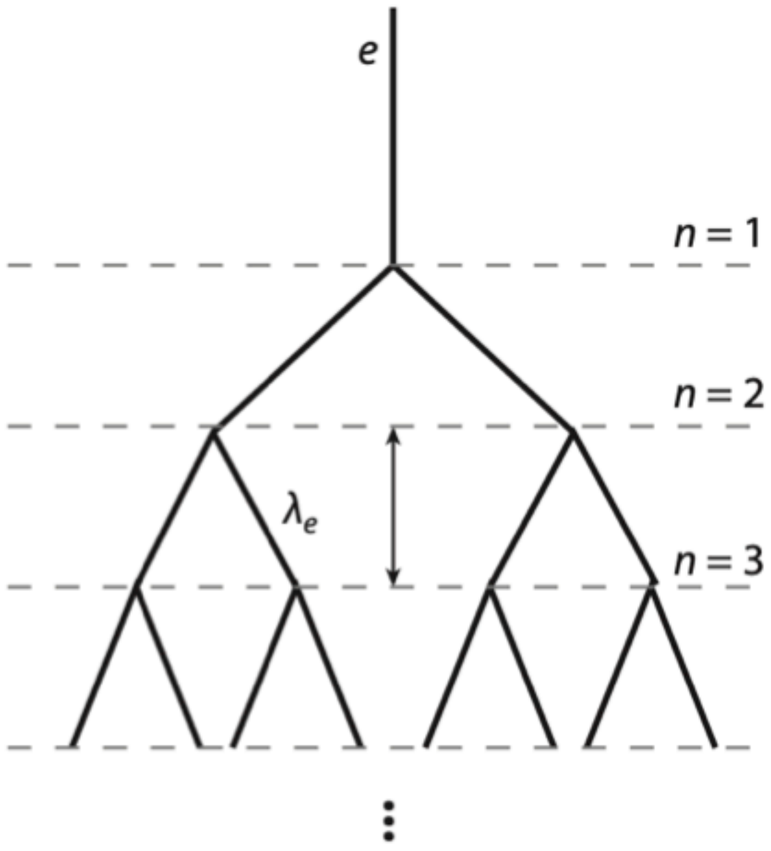


Fig. 14. The average longitudinal Cherenkov emission profile as a function of distance from the observer (Cherenkov photons emitted in the wavelength range 300–600 nm per meter along the



Air shower in the atmosphere

(introduced by Carlson & Oppenheimer 1937)

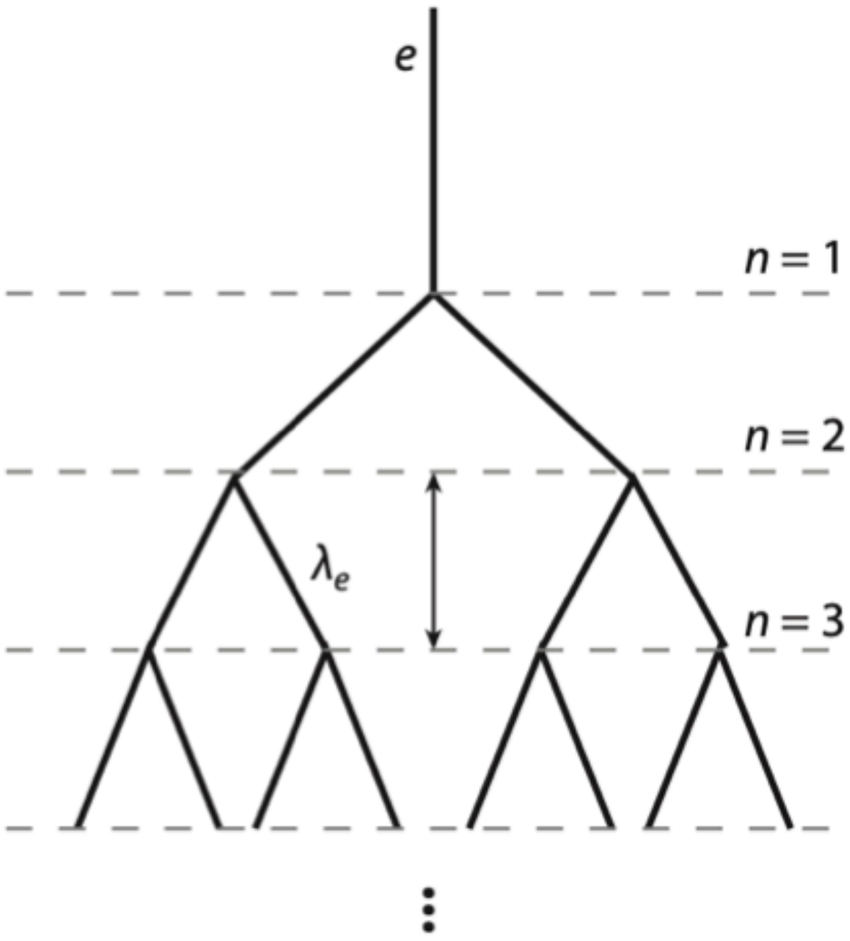


Simplification:

- 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

Heitler model.

(introduced by Carlson & Oppenheimer 1937)



Shower development stops at

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

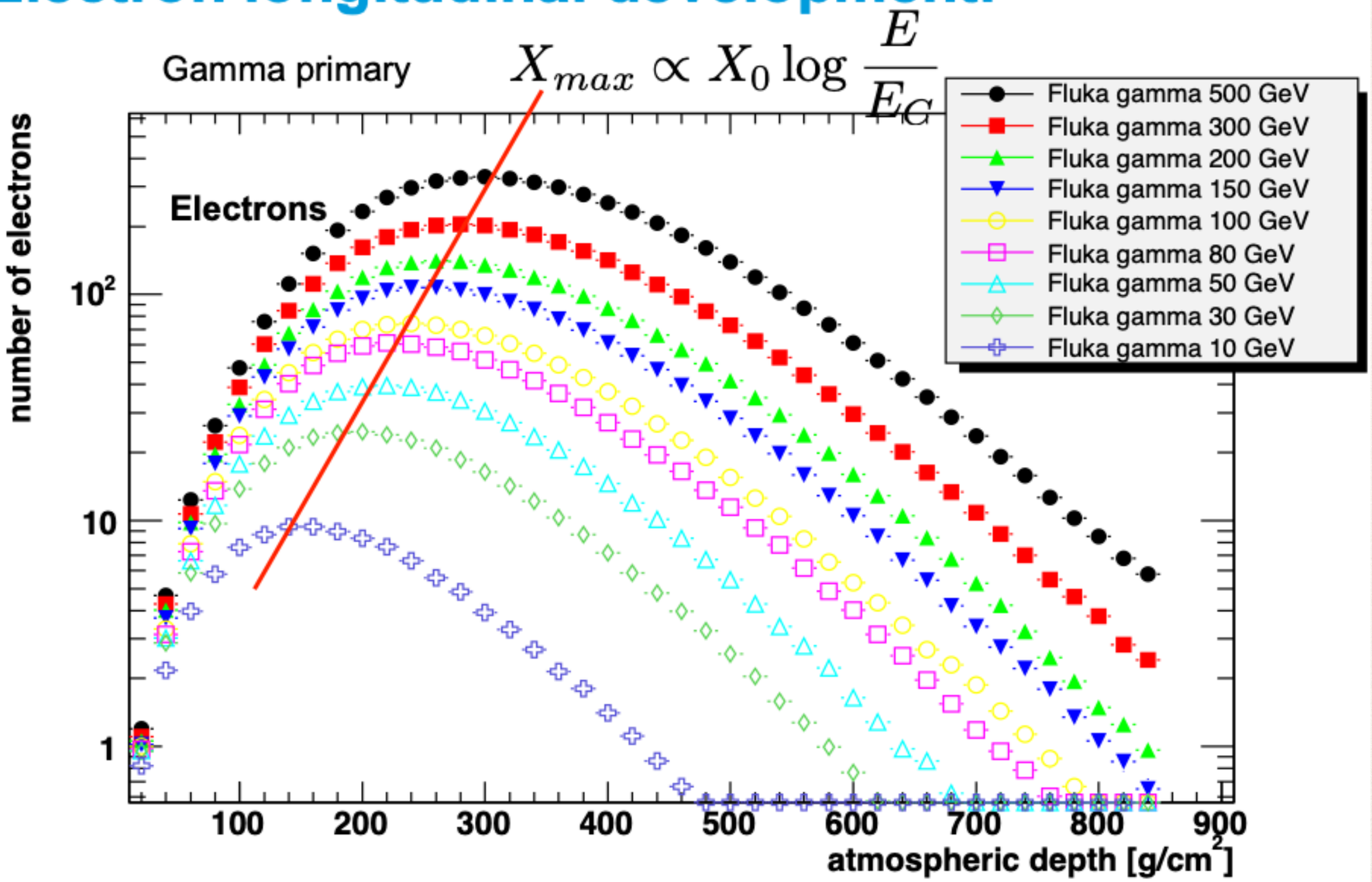
Maximum number of particles

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

Shower maximum at

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

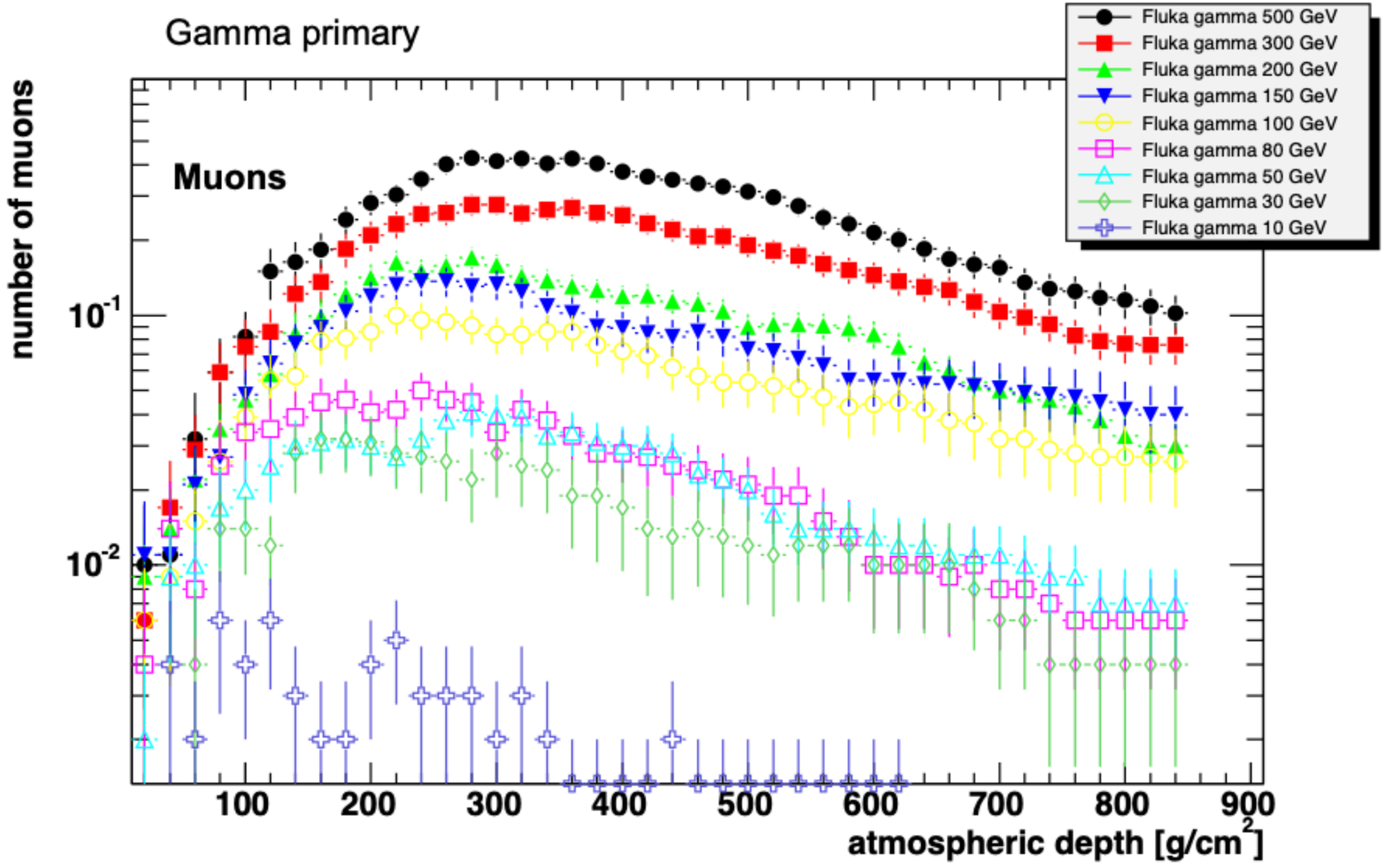
Electron longitudinal development.



Heitler Model

- X_max predictions surprisingly good
- Electron to gamma ratio assumed to be ~ 2, does not match!
  - Why?

Non-EM particles in gamma-ray showers.



Pair production cross section with 1/m² term.

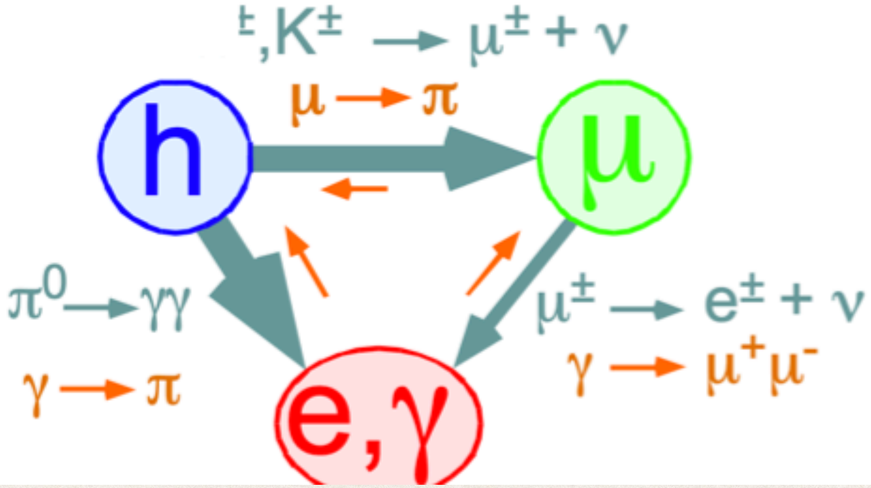
Air shower are 99% hadronic!

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

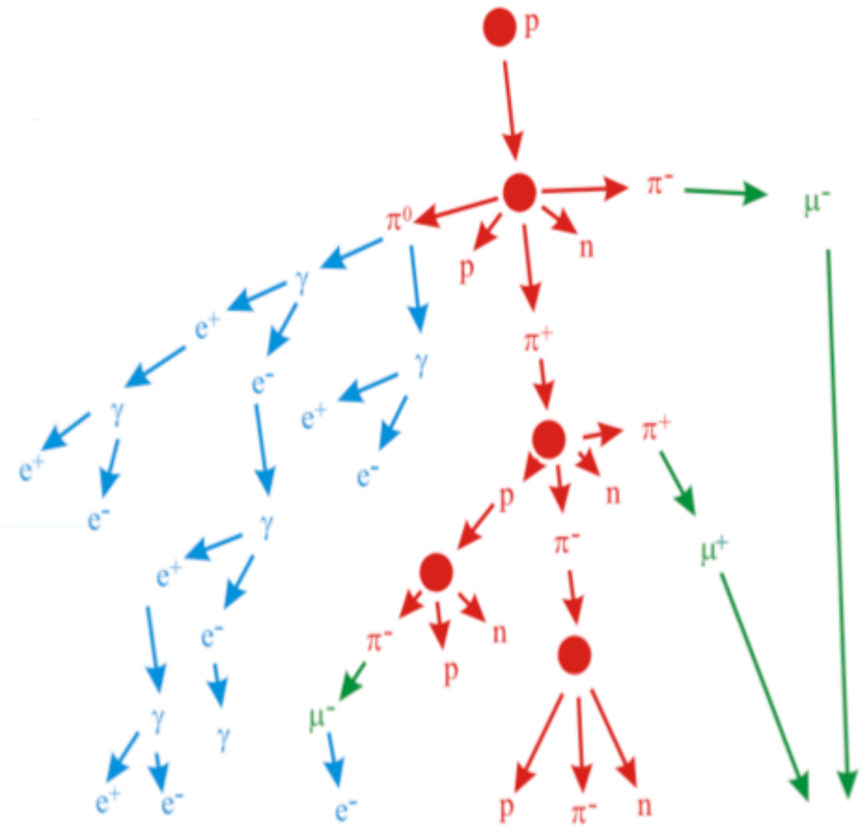
Energy flow.

J.Knapp 2017



Matthews 2005

Heitler Matthews Model.



om 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.

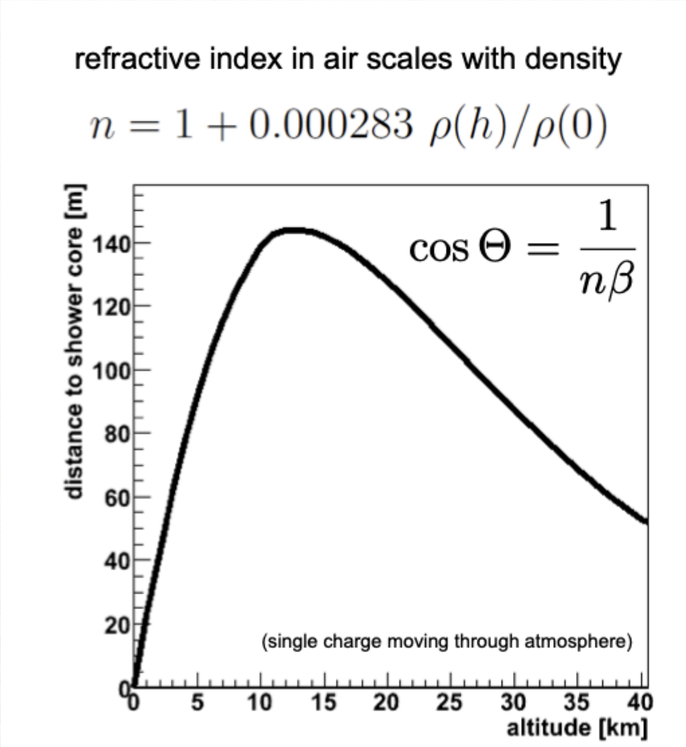
$$N_\mu = \left(\frac{E_\circ}{\xi_c^\pi}\right)^\beta \approx 10^4 \left(\frac{E_\circ}{1\ \mathrm{PeV}}\right)^{0.85}$$

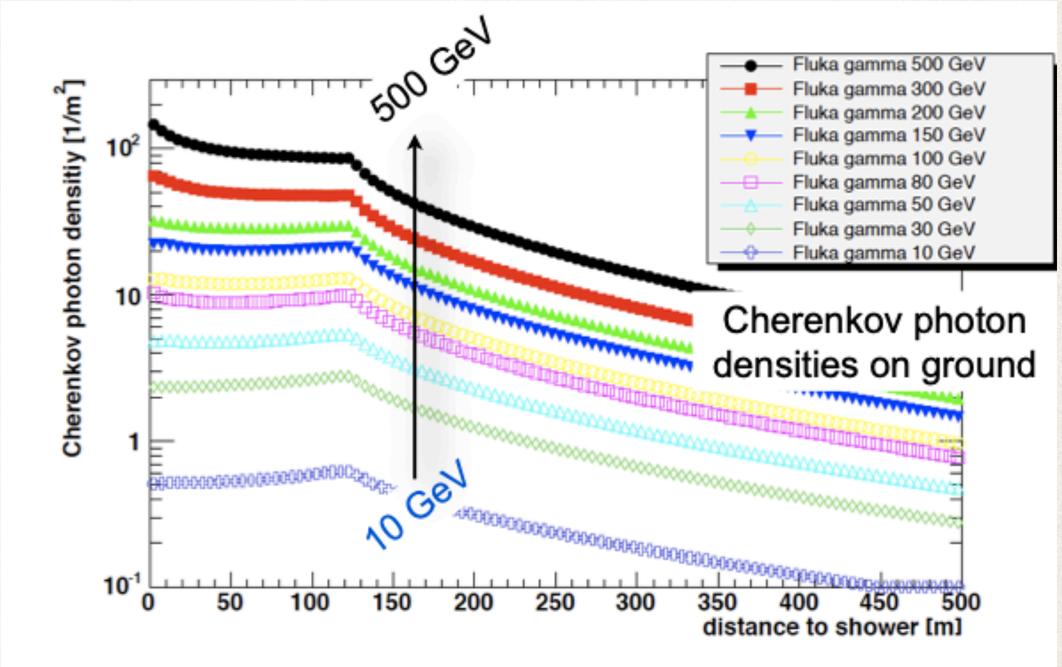
$$\frac{E_{em}}{E_\circ} = \frac{E_\circ - N_\mu \xi_c^\pi}{E_\circ} = 1 - \left(\frac{E_\circ}{\xi_c^\pi}\right)^{\beta-1}$$

~ 70% (at energies relevant for CTA)

Cherenkov emission in the atmosphere

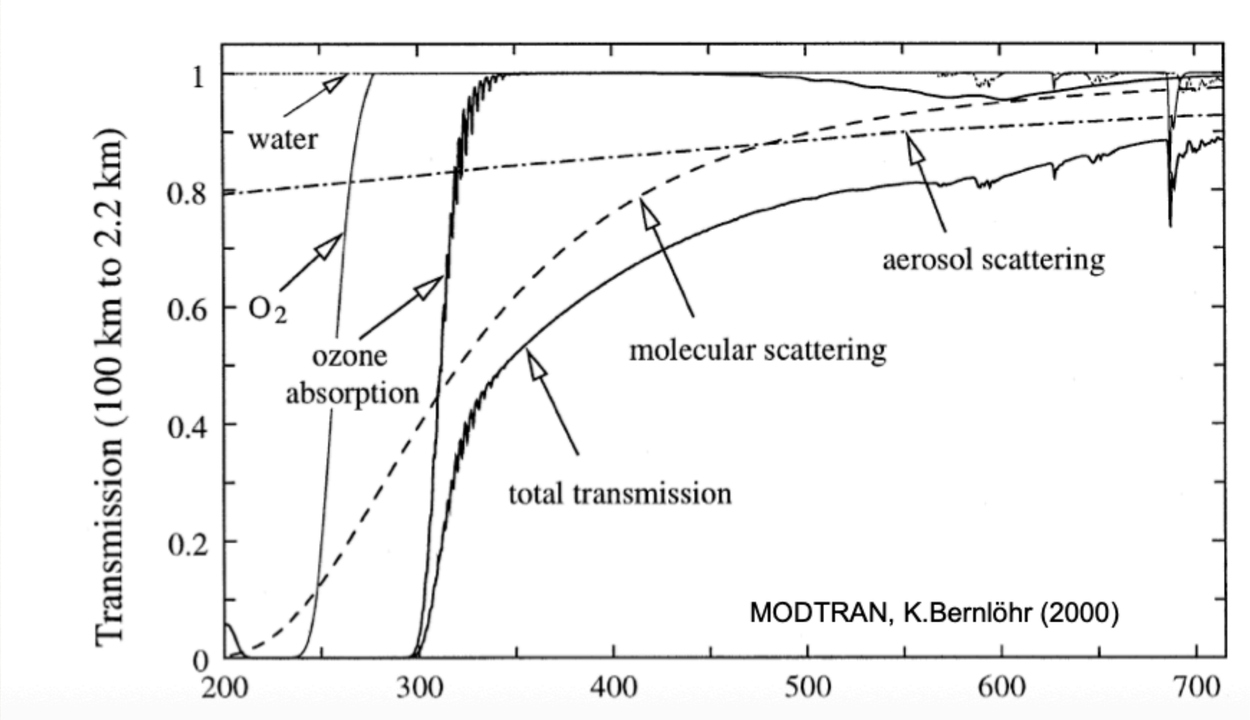
- Weak ~ 10 - 100ph/m2
- Short ~ ns
- Blue ~ 300-600 nm



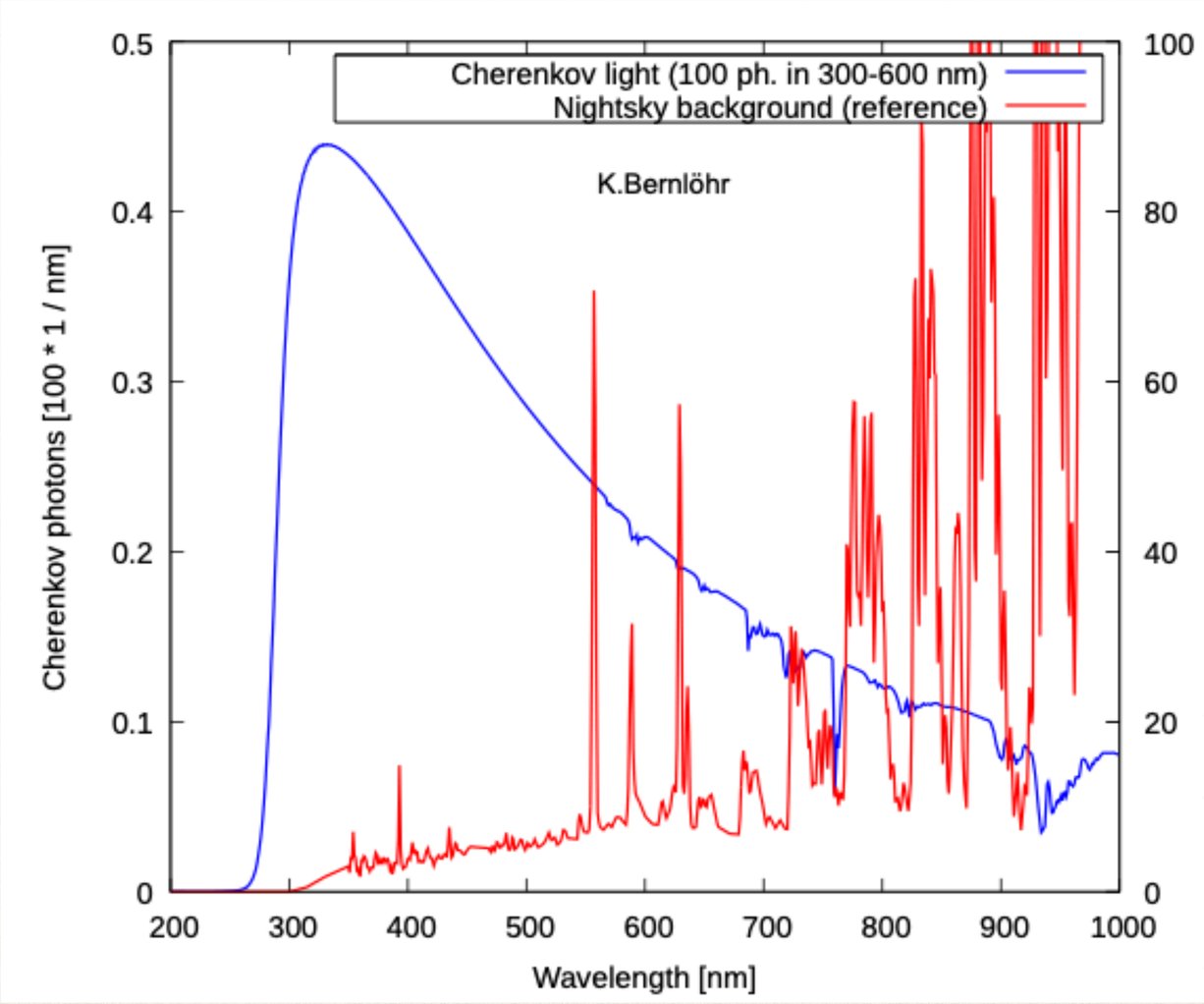


Propagation of Cherenkov light

- Molecular absorption bands
- Rayleigh scattering
- Aerosol scattering
- Clouds…



Cherenkov photons after extinction

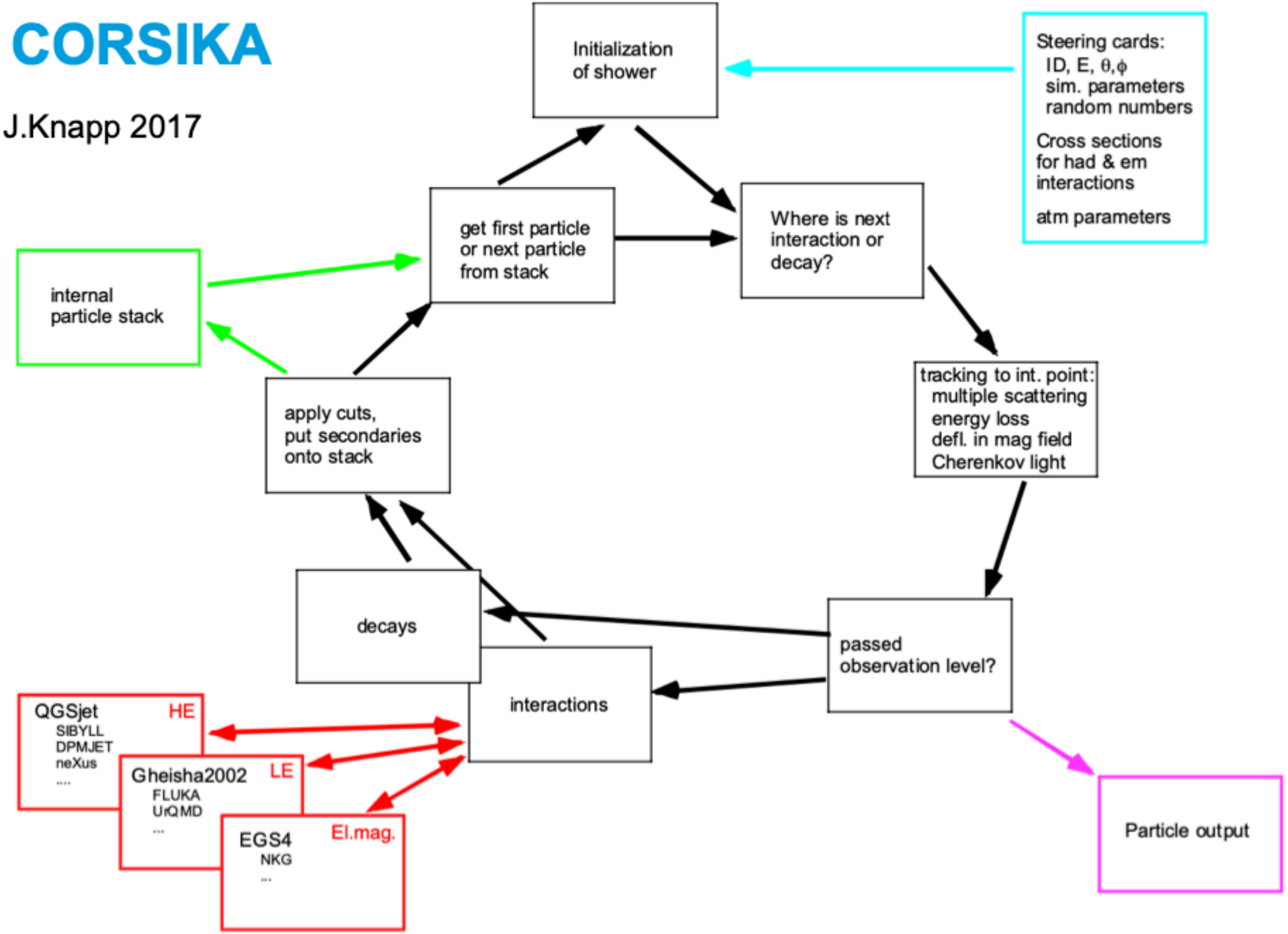


CORSIKA package

- CORSIKA (COsmic Ray SImulations for KAscade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles.
  - Protons, light nuclei up to iron, photons, and many other particles may be treated as primaries.
    - Energies ~ 100 EeV
  - Full simulations without toy model assumptions
  - Geo-magnetic field
  - Allows different atmospheric density profiles
  - Different hadronic interaction models
- https://www.iap.kit.edu/corsika/

CORSIKA

J.Knapp 2017



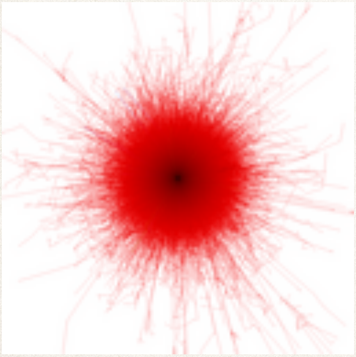
A CORSIKA input card

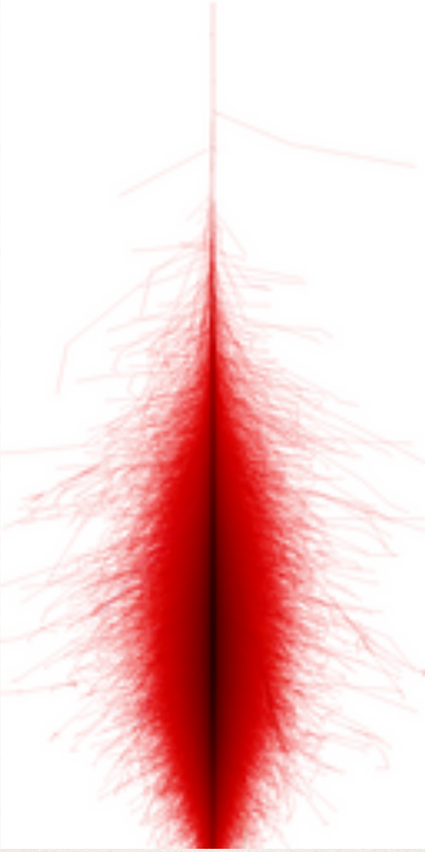
```
RUNNR   1001                          number of run
EVTNR   1                             number of first shower event
NSHOW   10                            number of showers to generate
DATBAS  yes                           write a file with parameters used
*
* [ Random number generator: 4 sequences used in IACT mode ]
*
SEED    58485   430   0               seed for 1st random number sequence
SEED    63432   435   0               seed for 2nd random number sequence
SEED    20103   481   0               seed for 3rd random number sequence
SEED    59475   490   0               seed for 4th random number sequence
*
* [ Primary particle options ]
*
PRMPAR  1                             particle type of prim. particle
```

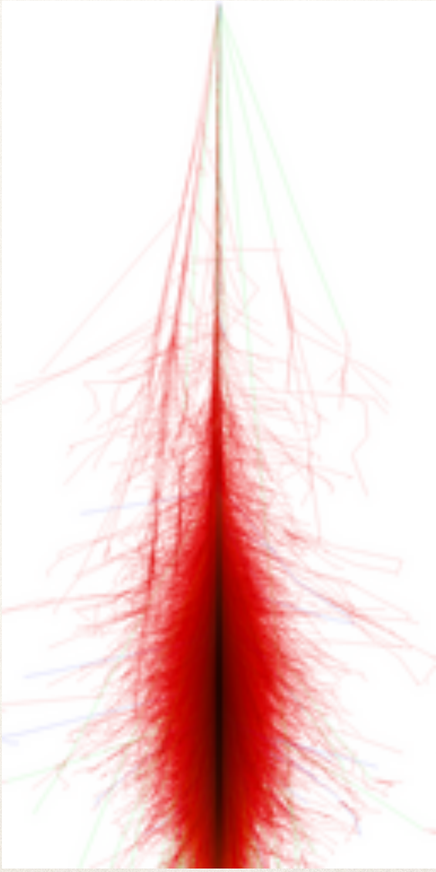
```
ESLOPE  -2.0                          slope of primary energy spectrum
ERANGE  100 10E3                      energy range of primary particle (in GeV)
THETAP  30.  30.                      range of zenith angle (degree)
PHIP    -14. -14.                     range of azimuth angle (degree):
*                                        from South if PHIP=ARRANG
VIEWCONE 0. 0.                        can be a cone around fixed THETAP/PHIP
*
* [ Site specific options ]
*
OBSLEV  1800.E2                       observation level (in cm)
ATMOSPHERE 10 N                       table of atmospheric profile
*                                       (10 N: Windhoek average, no refr.)
* ATMOSPHERE 1 N                      table of atmospheric profile
*                                       (1 N: tropical, no refr.)
MAGNET  12.5  -25.9                   magnetic field Gamsberg [H, Z] (muT)
ARRANG  -14.                          rotation of array to north [D] (degree)
*
```

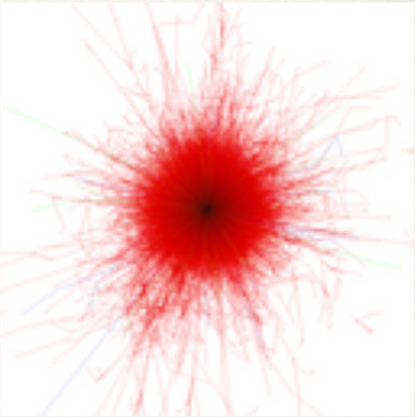
```
* [ Cherenkov emission parameters ]
*
CERSIZ  10.                           bunch size Cherenkov photons
CERFIL  F                             Cherenkov output to extra file
CWAVLG  200.  700.                    Cherenkov wavelength band
*
* [ H.E.S.S. telescopes ] (x -> North, y -> West)
*
*            X     Y    Z    R        (all in cm)
TELESCOPE     0 -8485    0  750       Tel. 1
TELESCOPE  8485     0    0  750       Tel. 2
TELESCOPE     0  8485    0  750       Tel. 3
TELESCOPE -8485     0    0  750       Tel. 4
*
CSCAT   10  500e2  0.                 use shower several times
*
* [Interaction flags]
*
FIXHEI  0.  0                         first interaction height & target
FIXCHI  0.                            starting altitude (g/cm**2)
ELMFLG  T   T                         em. interaction flags (NKG,EGS)
RADNKG  200.E2                        outer radius for NKG lat.dens.determ.
HADFLG  0  0  0  0  0  0              flags for hadr. interaction
ECUTS   0.3  0.1  0.020  0.020        energy cuts for particles
MUADDI  F                             additional info for muons
MUMULT  T                             muon multiple scattering angle
LONGI   F  20.  F  F                  longit.distr. & step size & fit
MAXPRT  0                             max. number of printed events
ECTMAP  1.E6                          cut on gamma factor for printout
STEPFC  1.0                           mult. scattering step length fact.
*
* [ Debugging and output options ]
*
DEBUG   F  6  F  1000000              debug flag and logical unit for output
DIRECT  /dev/null                     /dev/null means no normal CORSIKA data
```

Simulated showers (10 TeV)





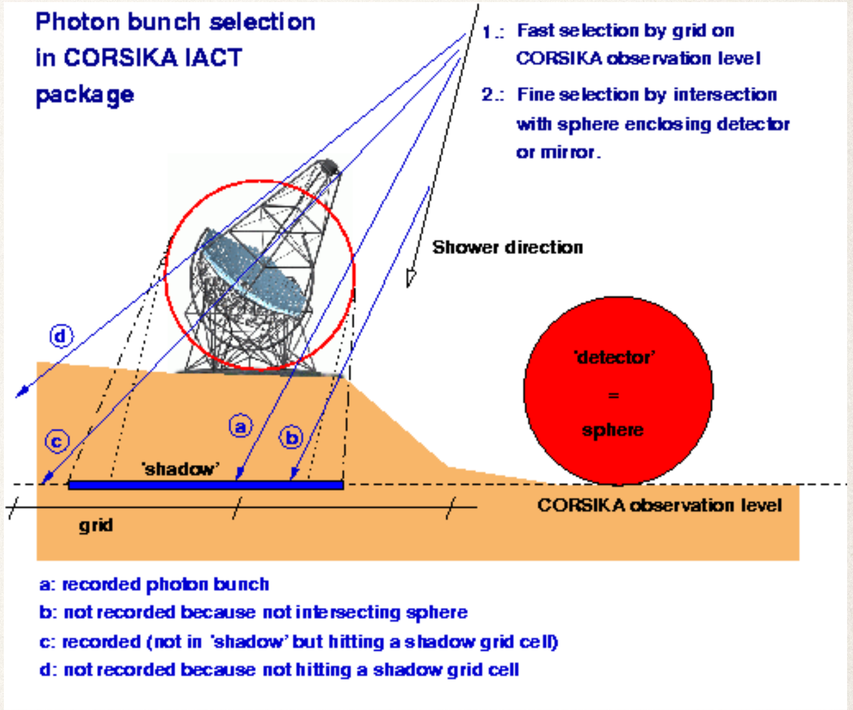




Simulating your telescope

Dedicated package

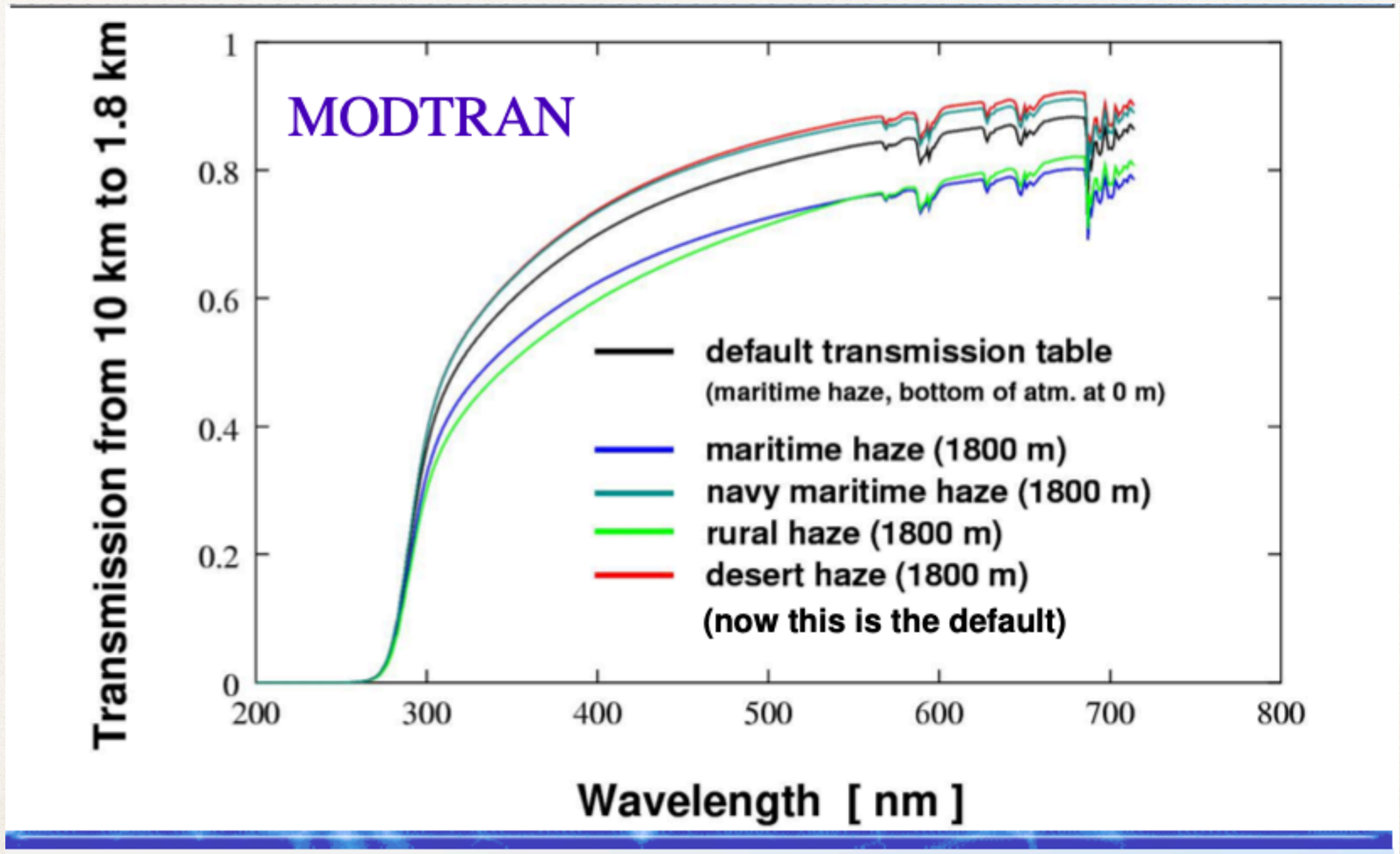
- Simtel array: developed by Konrad Bernlöhr
- Originally developed for HEGRA telescopes (~ 1990s)
- Adapted then to H.E.S.S.
  - Tested extensively on H.E.S.S.
- Telescopes and cameras are fully configurable.
- Main production tool for most IACT simulations today



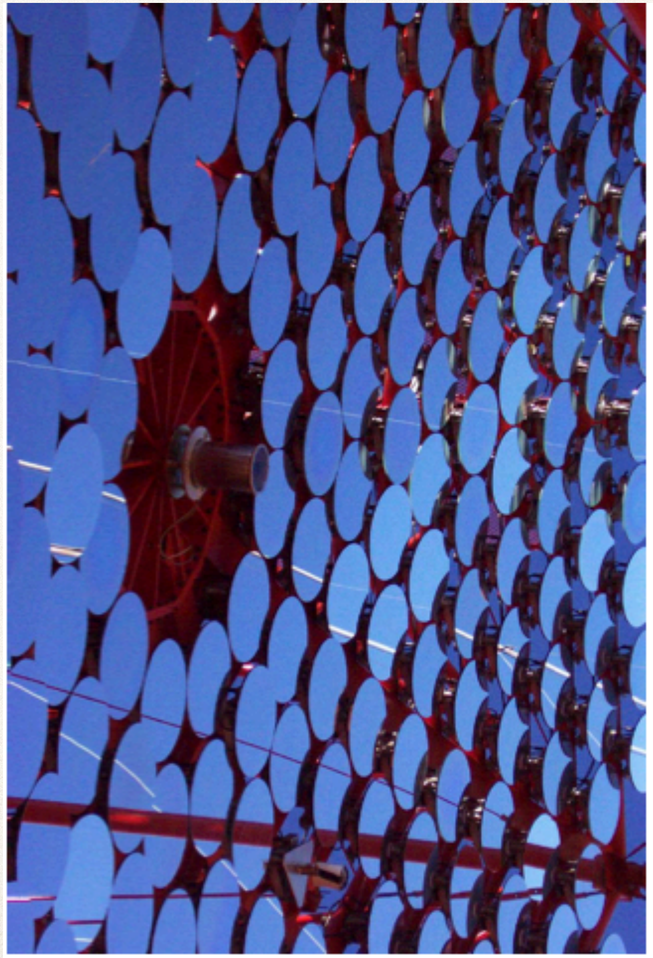
1. Optics

- Atmospheric transmission
- Ray tracing and reflection on segmented mirrors
- Shadowing by camera support
- Light travel in light concentrators
- Mirror reflectivity, funnel efficiency, PMT quantum efficiency

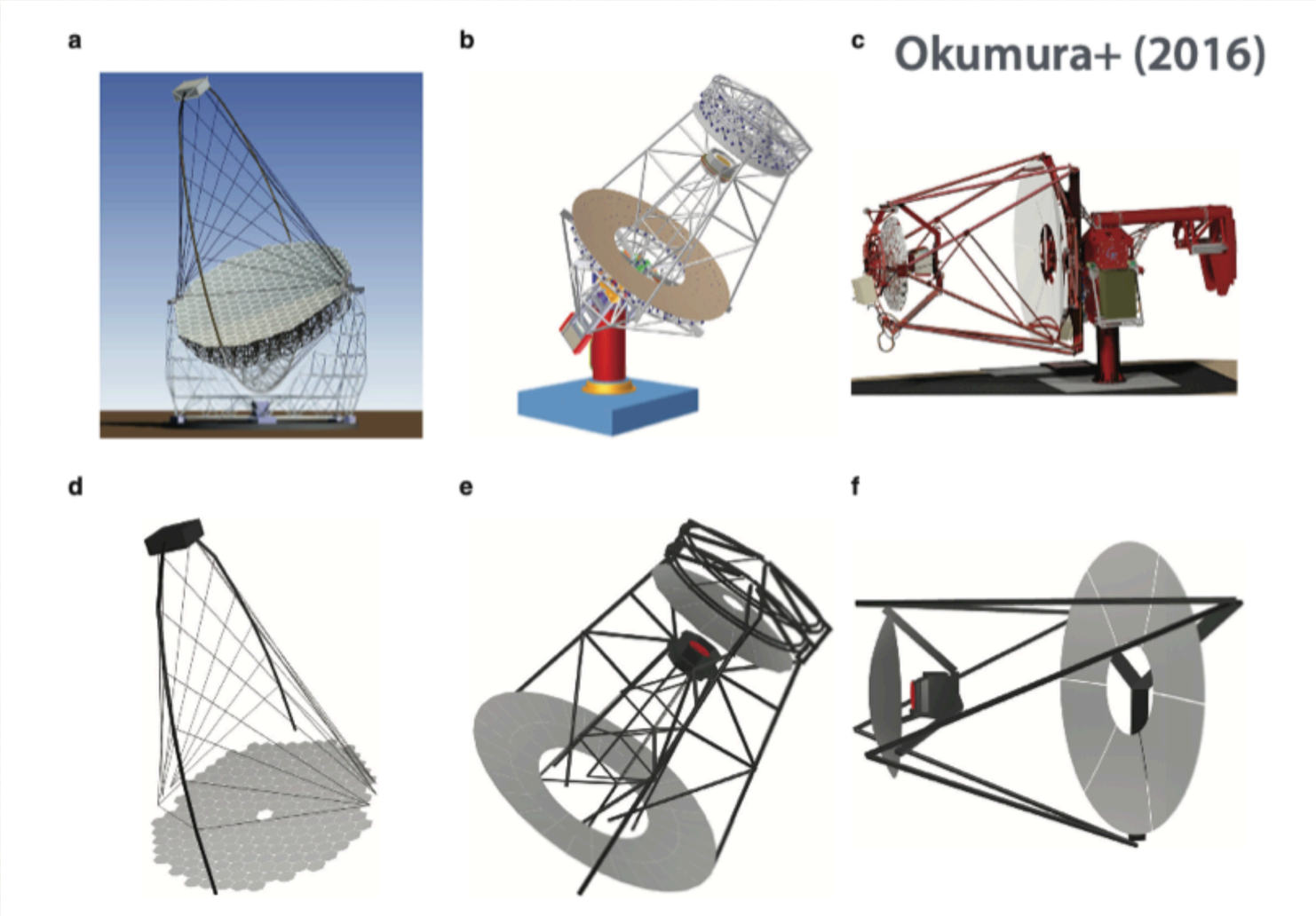
Atmospheric transmission (close to earth)



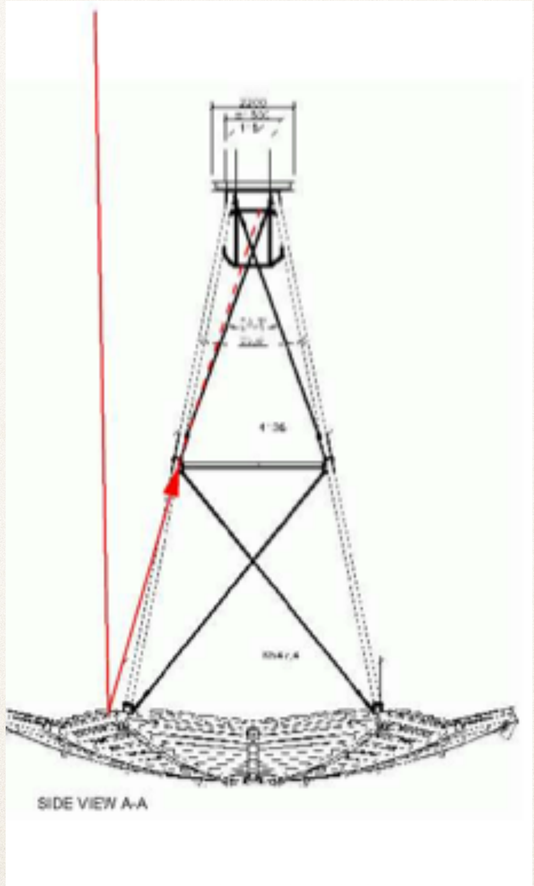
Ray tracing

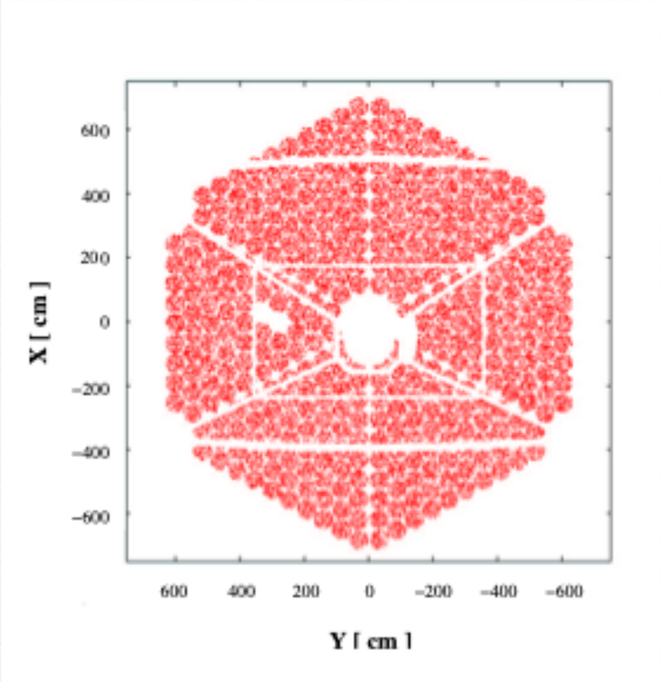


- Photons are fully ray-traced on non-perfect mirror facets with random misalignments.
- Acceptance in camera depending on angle of incidence.


a
b
c
Okumura+ (2016)
d
e
f

Shadowing by masts/camera



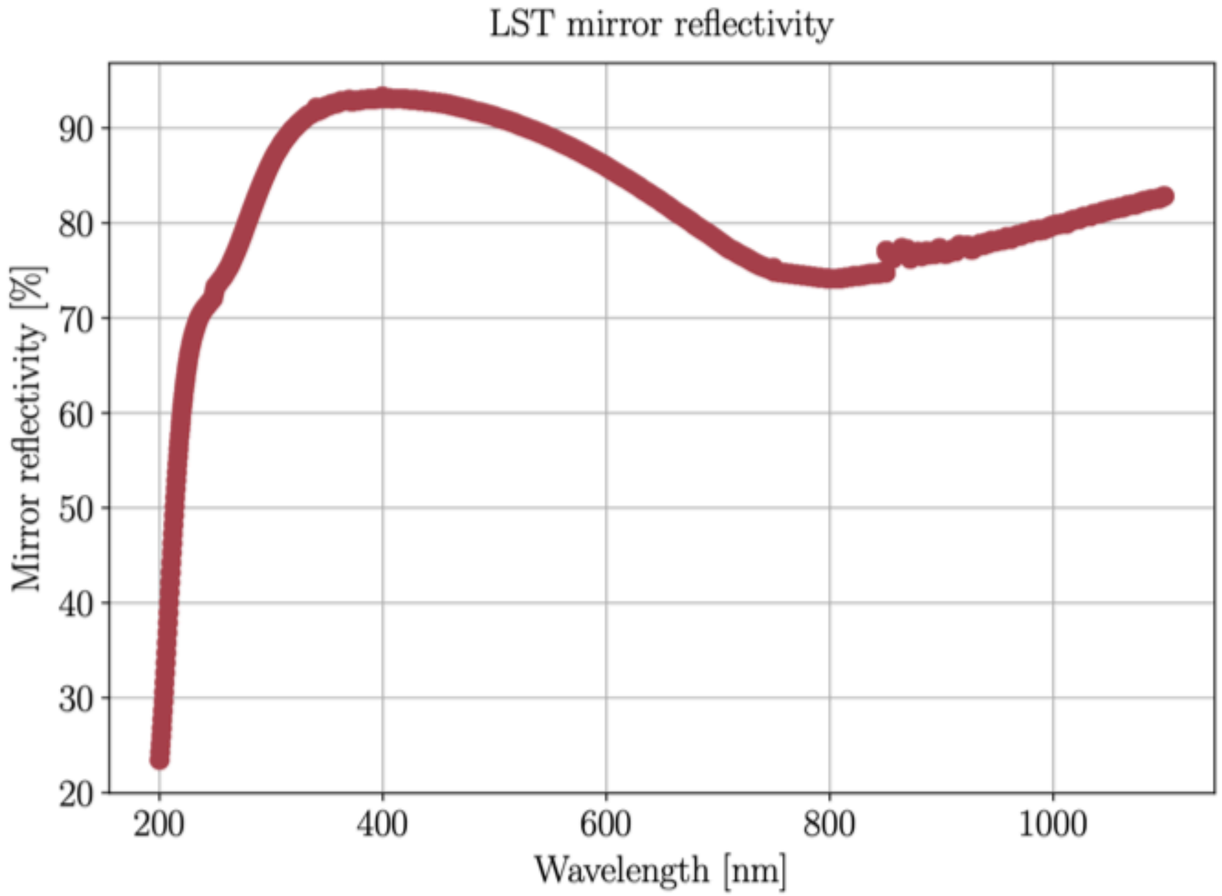


Shadowing in HESS

Optical PSF

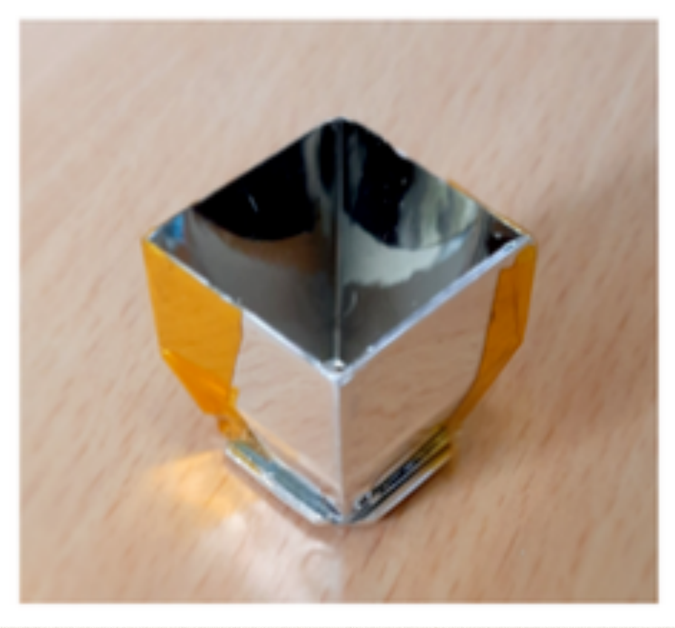
- Measurement of star light imaged on the closed camera lid by a dedicated CCD camera mounted at the dish centre.
- Reproduced by mirror quality + mounting + accuracy

Mirror reflectivity.



Light concentrators

- Funnels used to fill the empty space between PMTs/SiPM



Camera window

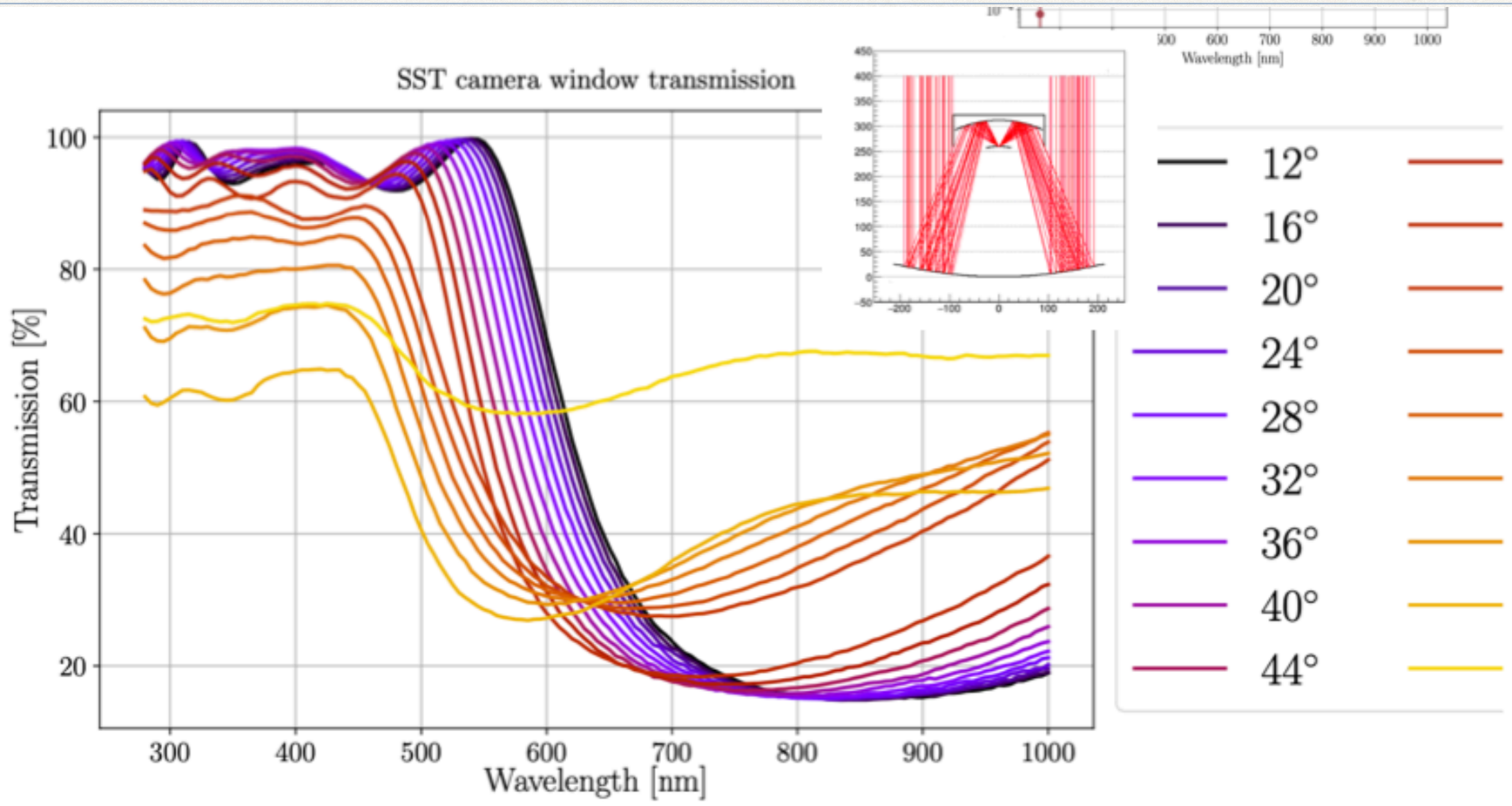
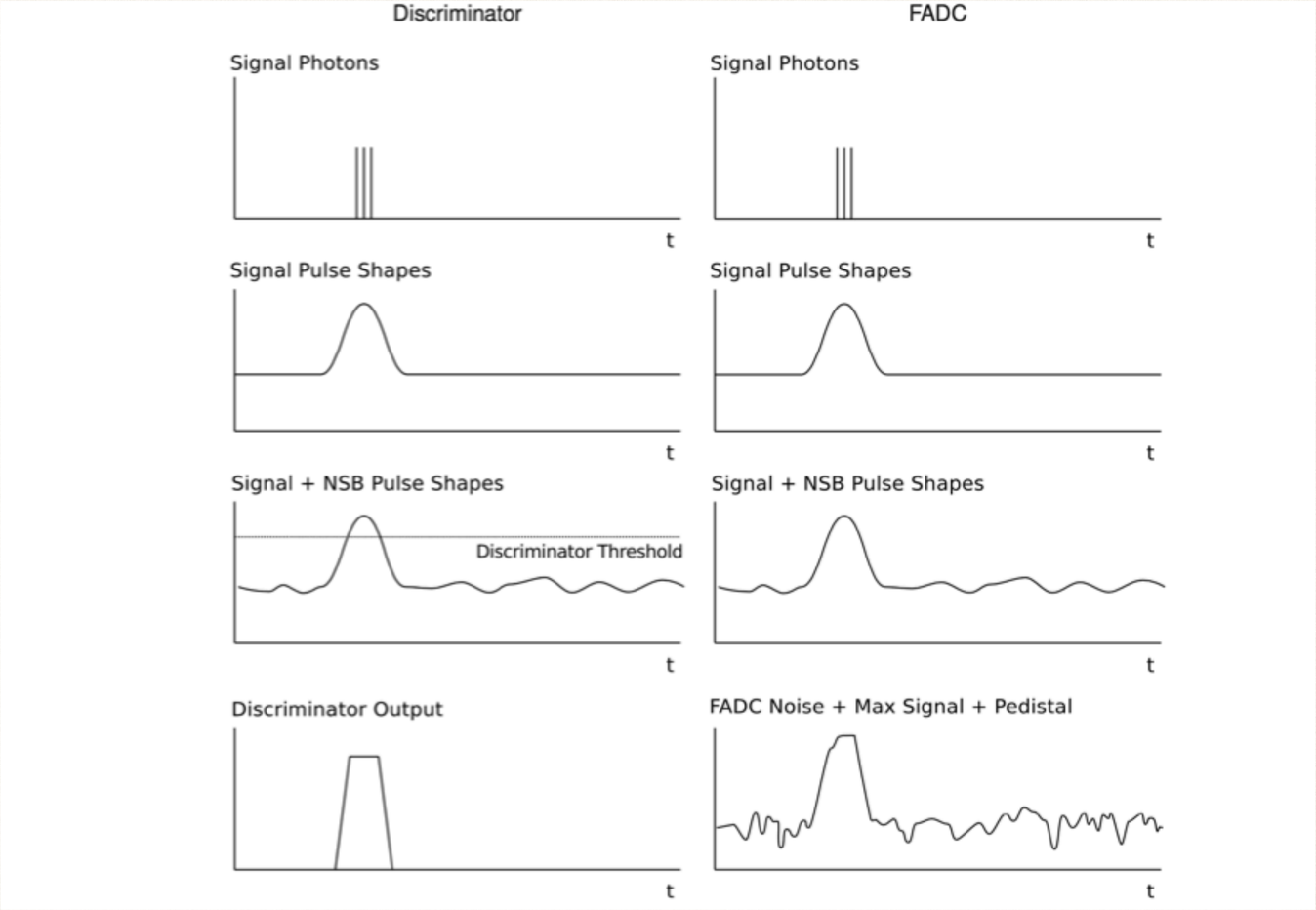


Figure 5 – Camera window transmission as a function of wavelength and incident angle for the SST camera.

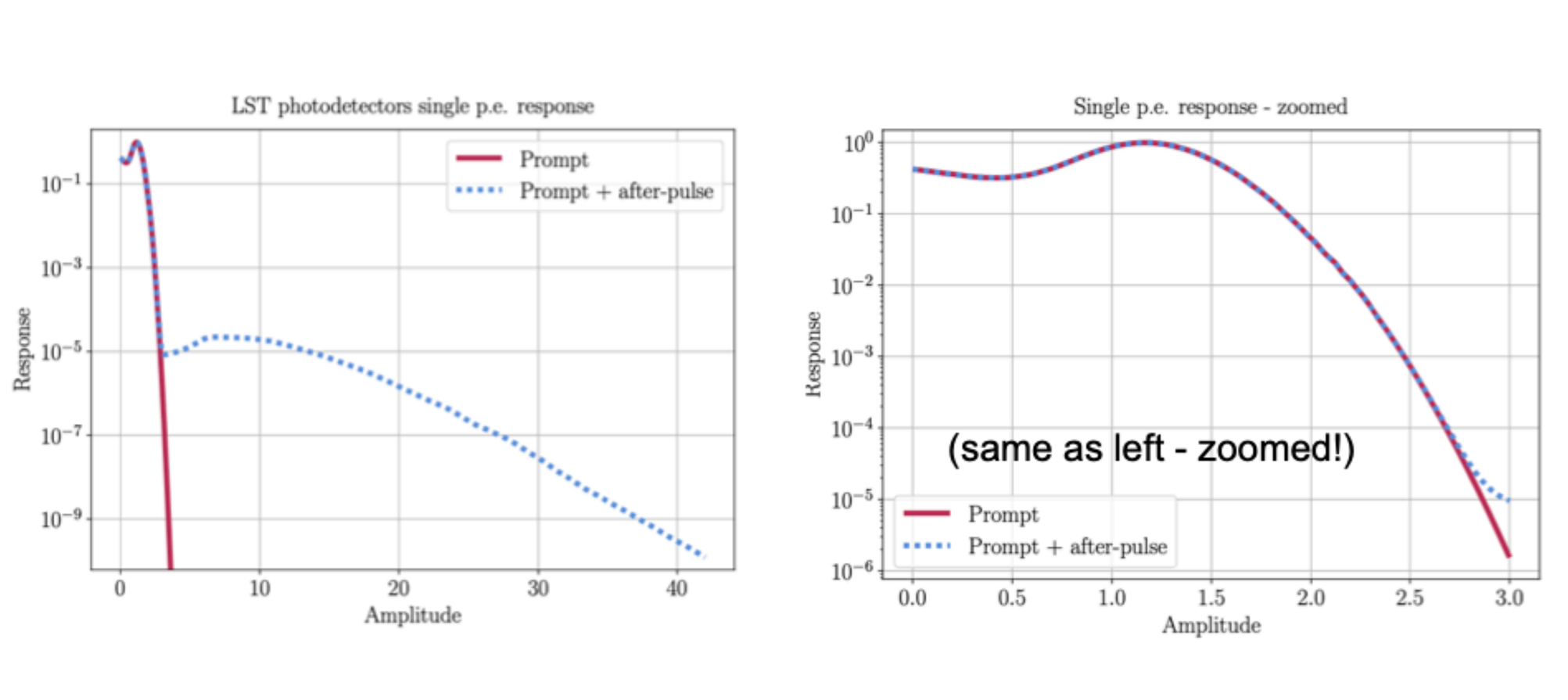
Simulating camera

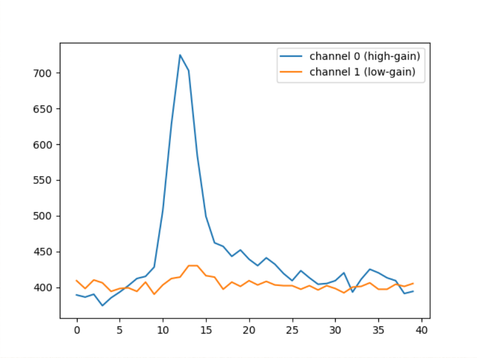
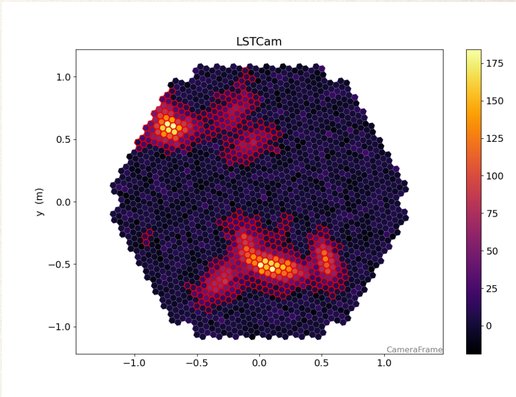
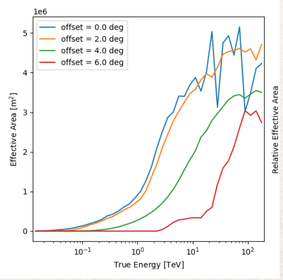
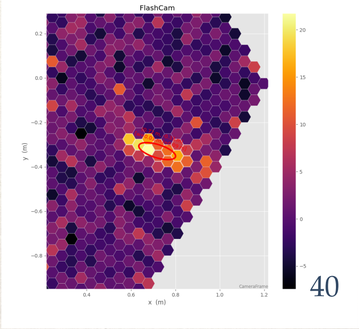
- Optics result: # photons hitting your camera pixels
- Need to convert it to number of photon electrons at each pixel
  - Gain of each channel
  - Single photon response of photo detector
  - Trigger condition
  - NSB
  - FADC pulse shape

Trigger and response - toy sketch



Single photo electron response



End stage of simulations

- Full signal output from each pixel (multiple channel) of camera
- This output is then analysed to understand the telescope performance
  - Image cleaning + reconstruction
  - More on this tomorrow!