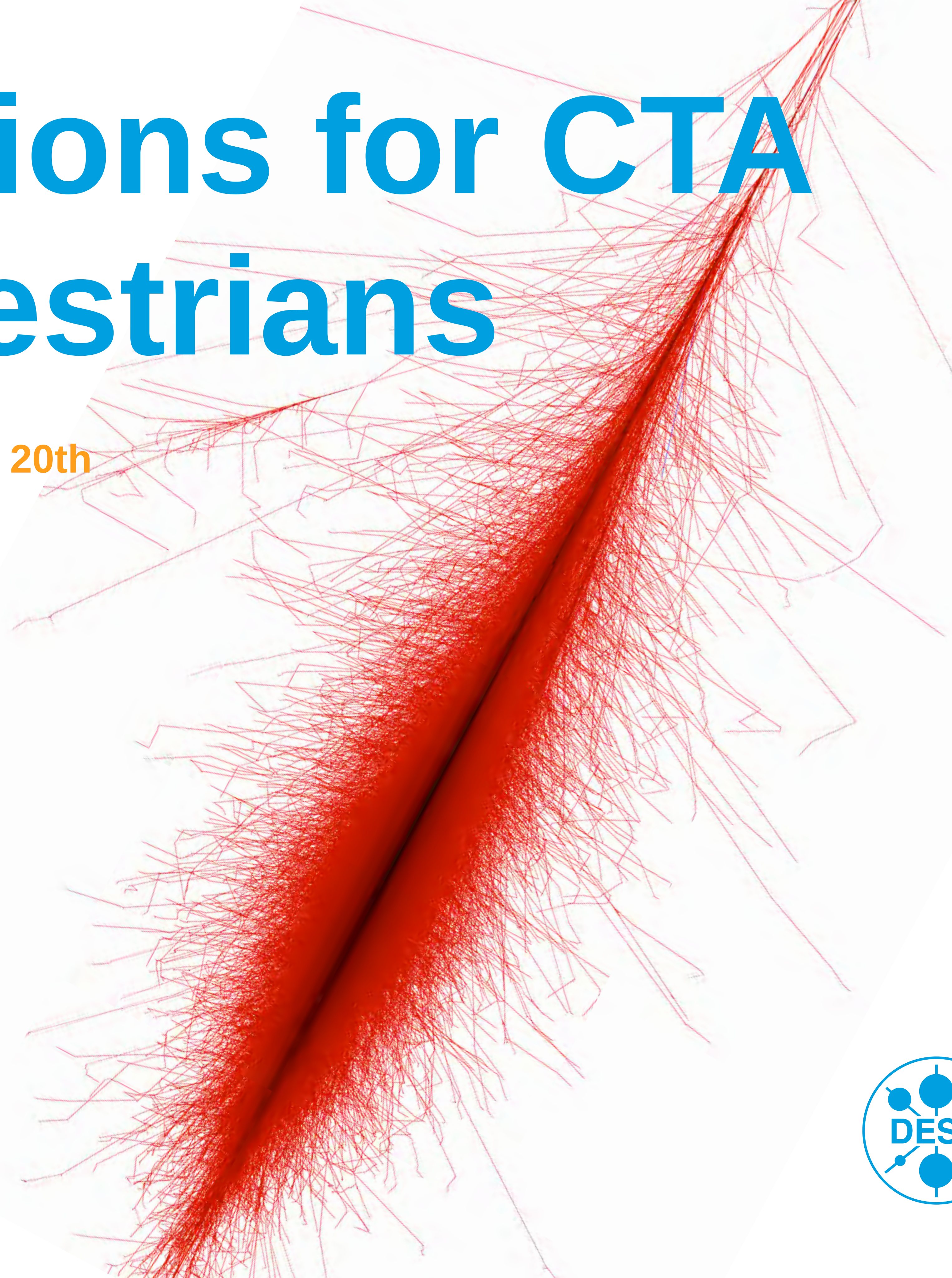
Simulations for CTA for Pedestrians

DESY Seminar - 2018, June 20th

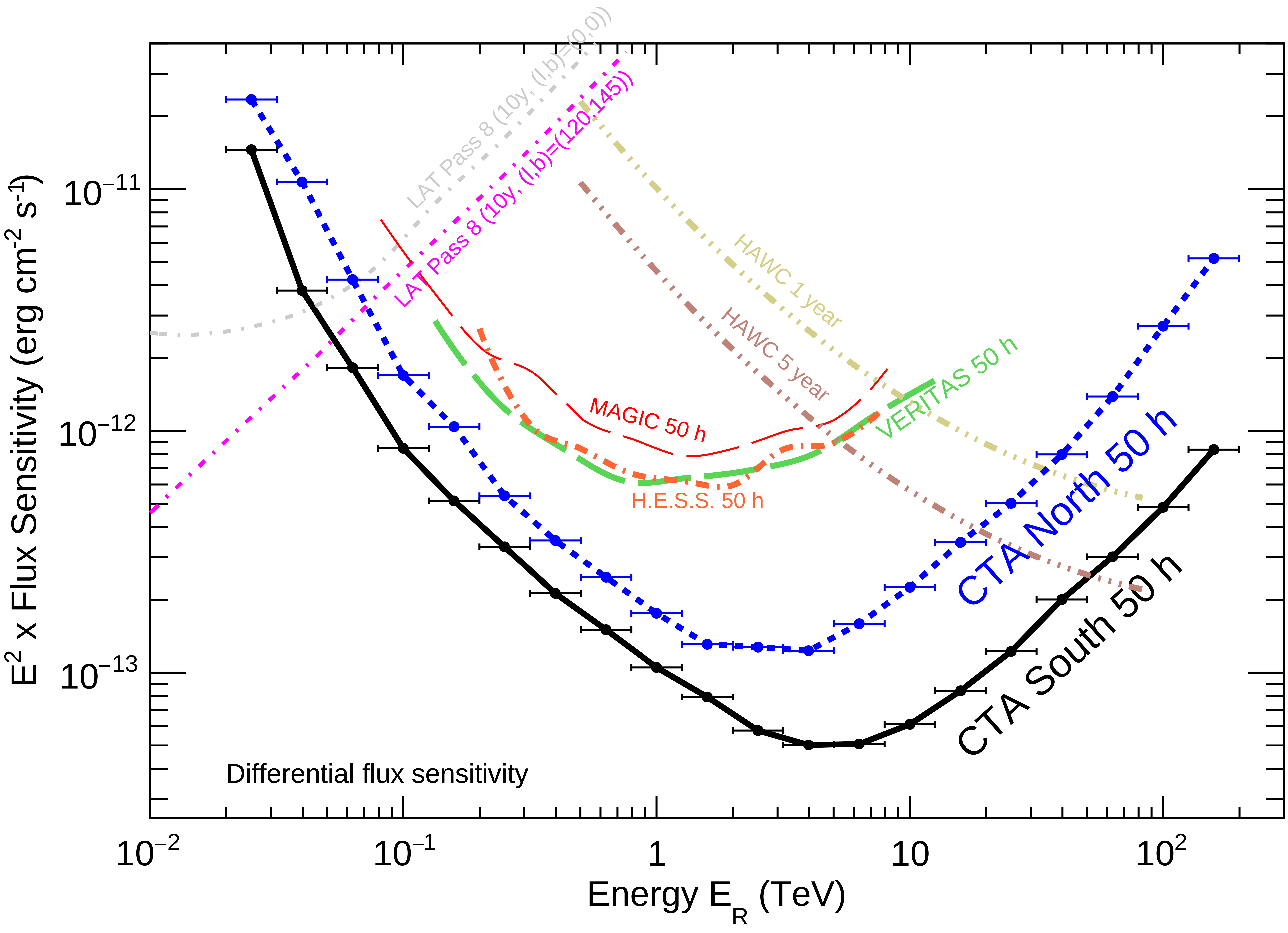


Gernot Maier

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

Simulations for CTA for Pedestrians



LAT Pass 8 (10y, (l,b)=(0,0))
LAT Pass 8 (10y, (l,b)=(120,45))
HAWC 1 year
HAWC 5 year
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
CTA North 50 h
CTA South 50 h
Differential flux sensitivity
E^2 x Flux Sensitivity (erg cm^{-2} s^{-1})
10^{-11}
10^{-12}
10^{-13}
10^{-2}
10^{-1}
1
10
10^2
Energy E_R (TeV)

Overview

- **Air Shower Simulations**
- **Atmosphere**
- **Telescope & Camera Simulations**
- **Gamma-ray like proton events**
- **Conclusions**

Why do we need simulations for CTA?

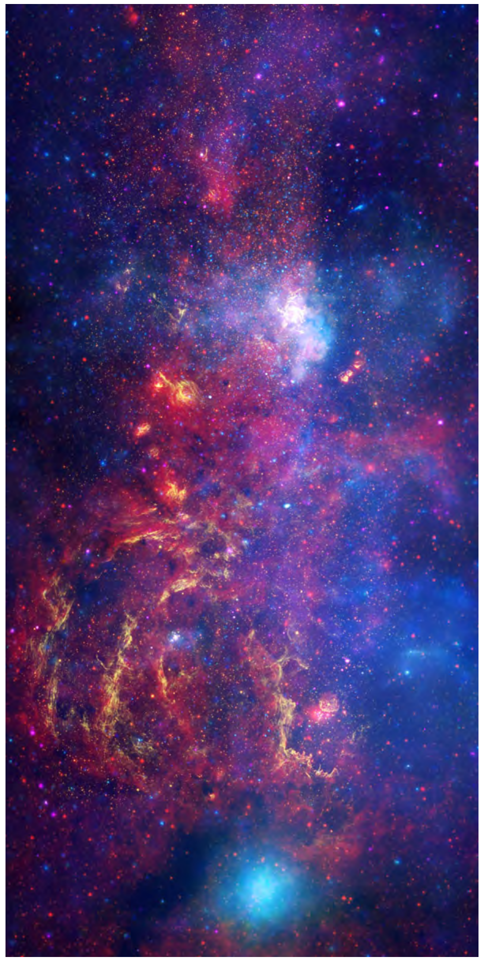
- **during preparation phase:**
  - site selection
  - array layout optimisation
  - design optimisation

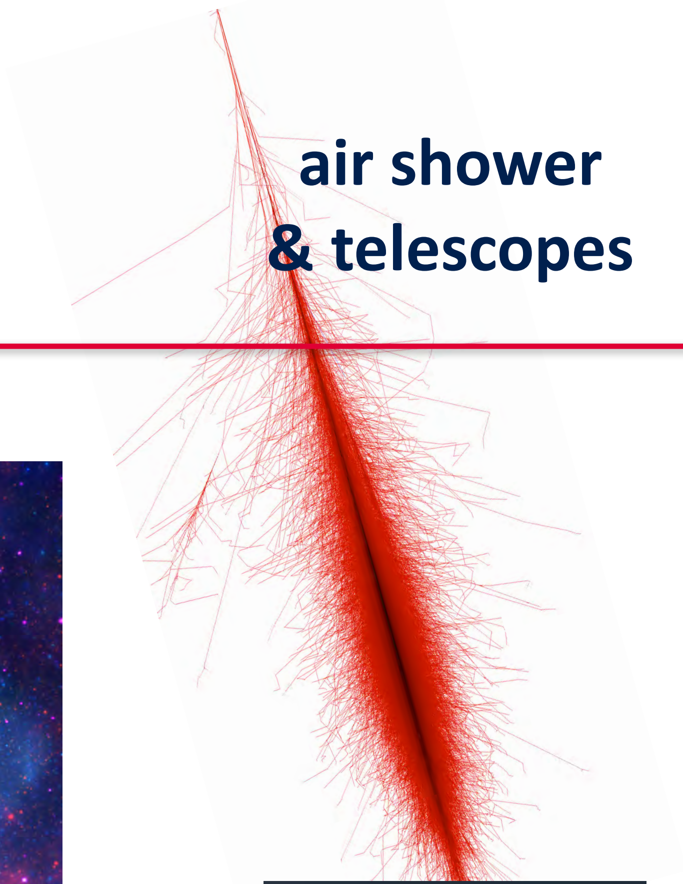
- **during pre-construction design phase**
  - verification of requirements

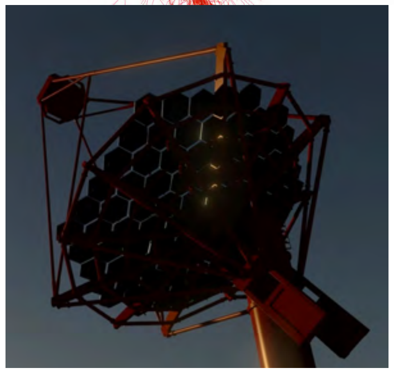
- **during operation phase**
  - calculation of instrument response functions

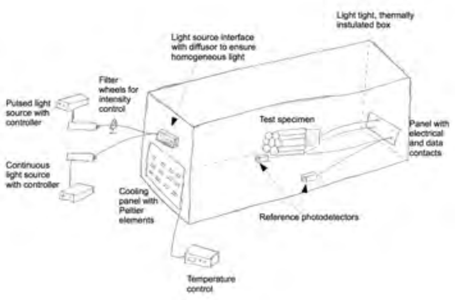
Simulations / Measurements / Analysis

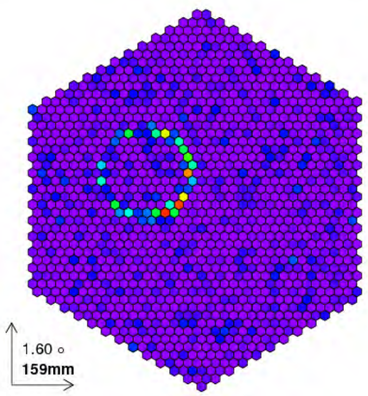
gamma-ray emitter | air shower & telescopes | calibration | reconstruction | science analysis

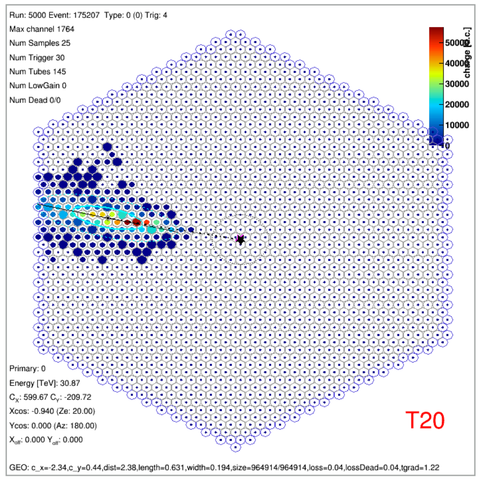


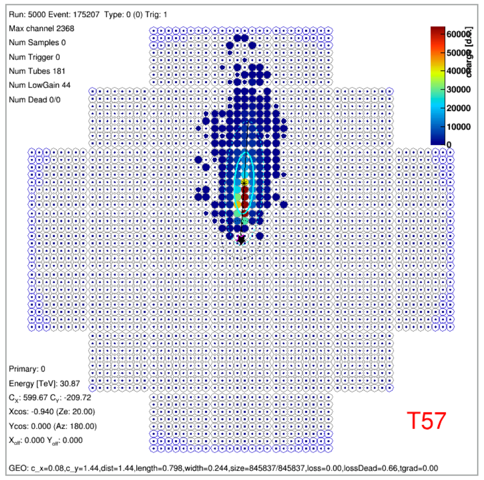


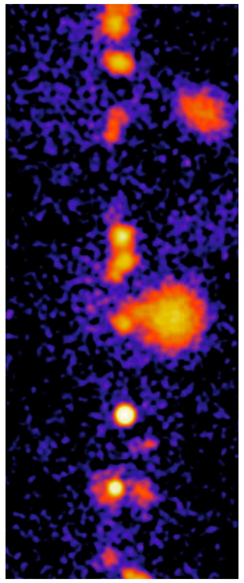


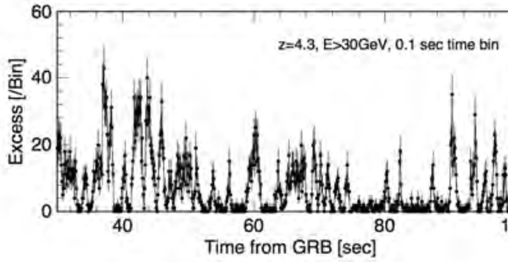


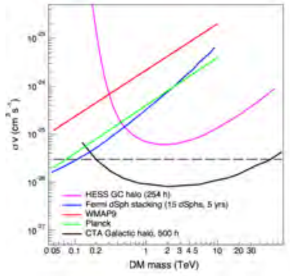




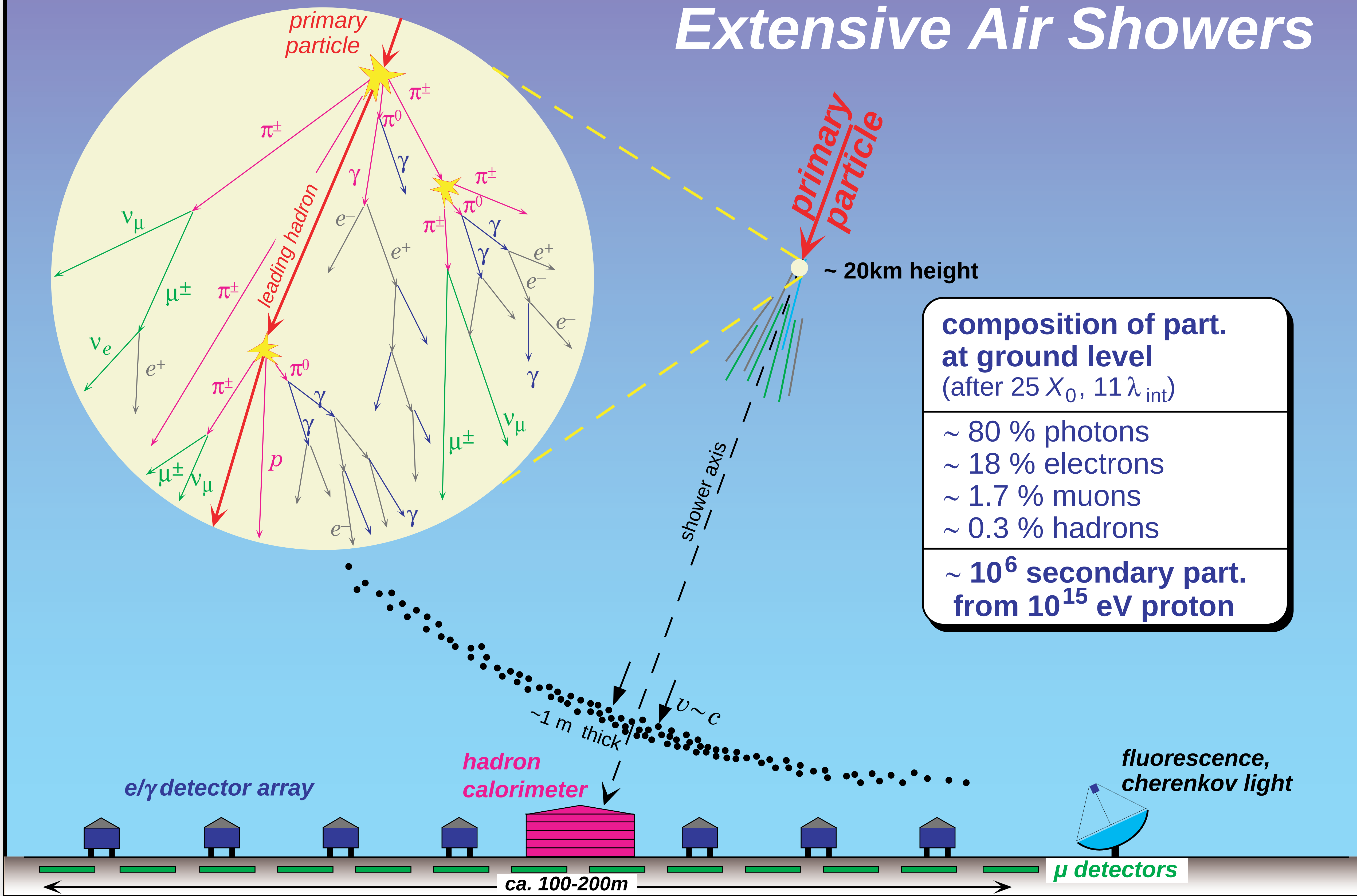








Extensive Air Showers

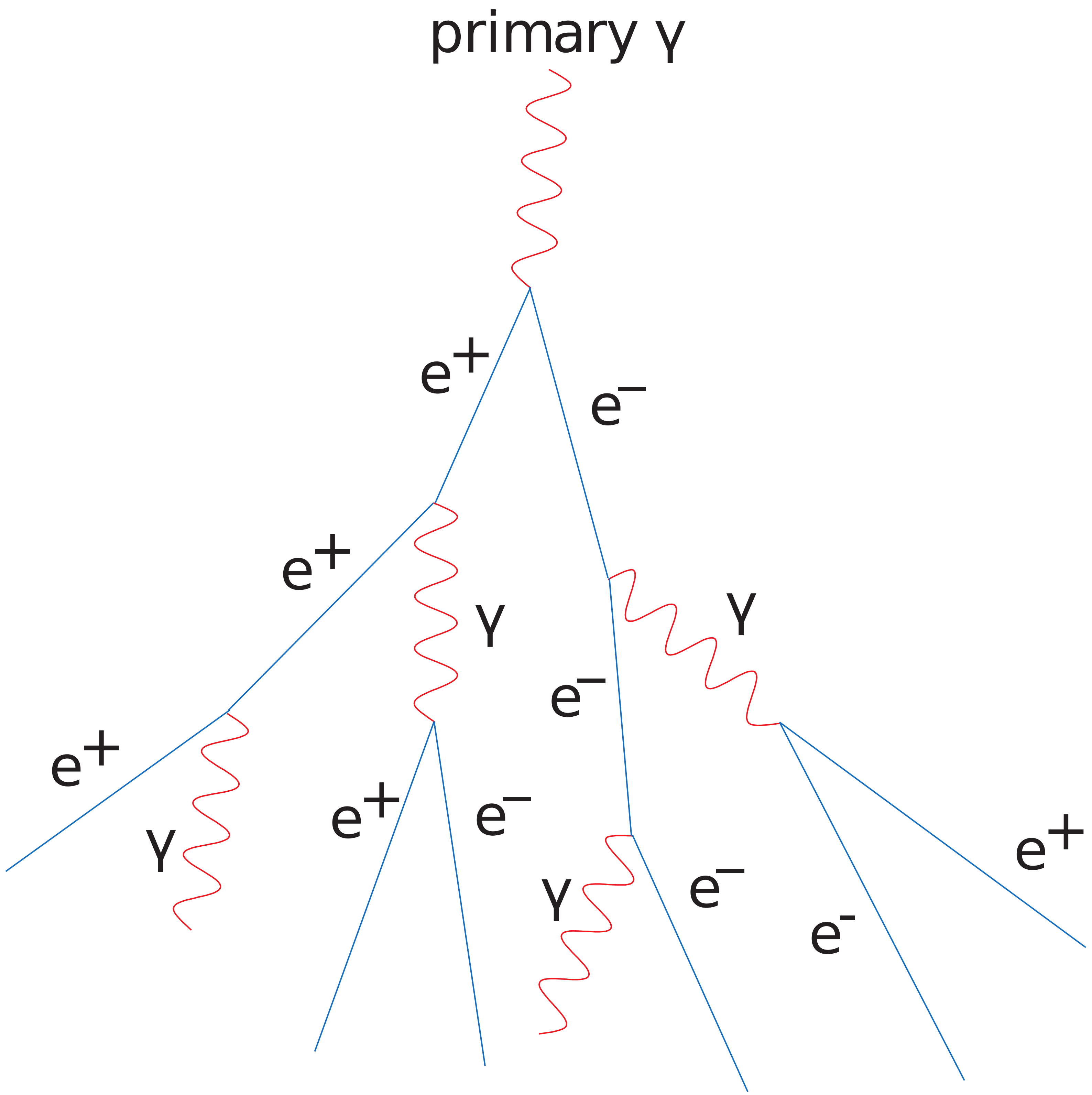


composition of part. at ground level
(after 25 X_0, 11 λ_{int})

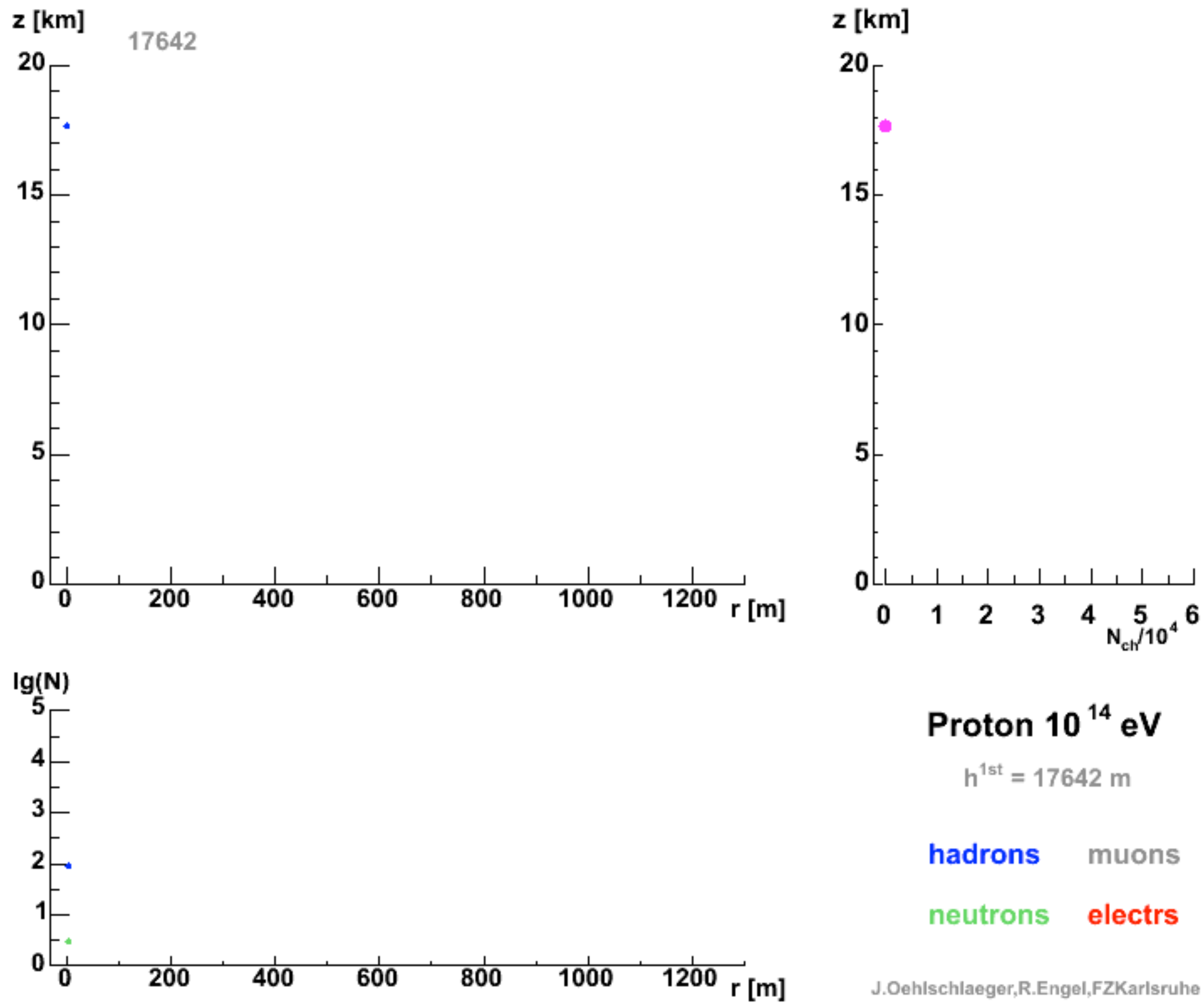
~ 80 % photons
~ 18 % electrons
~ 1.7 % muons
~ 0.3 % hadrons

~ 10^6 secondary part. from 10^{15} eV proton

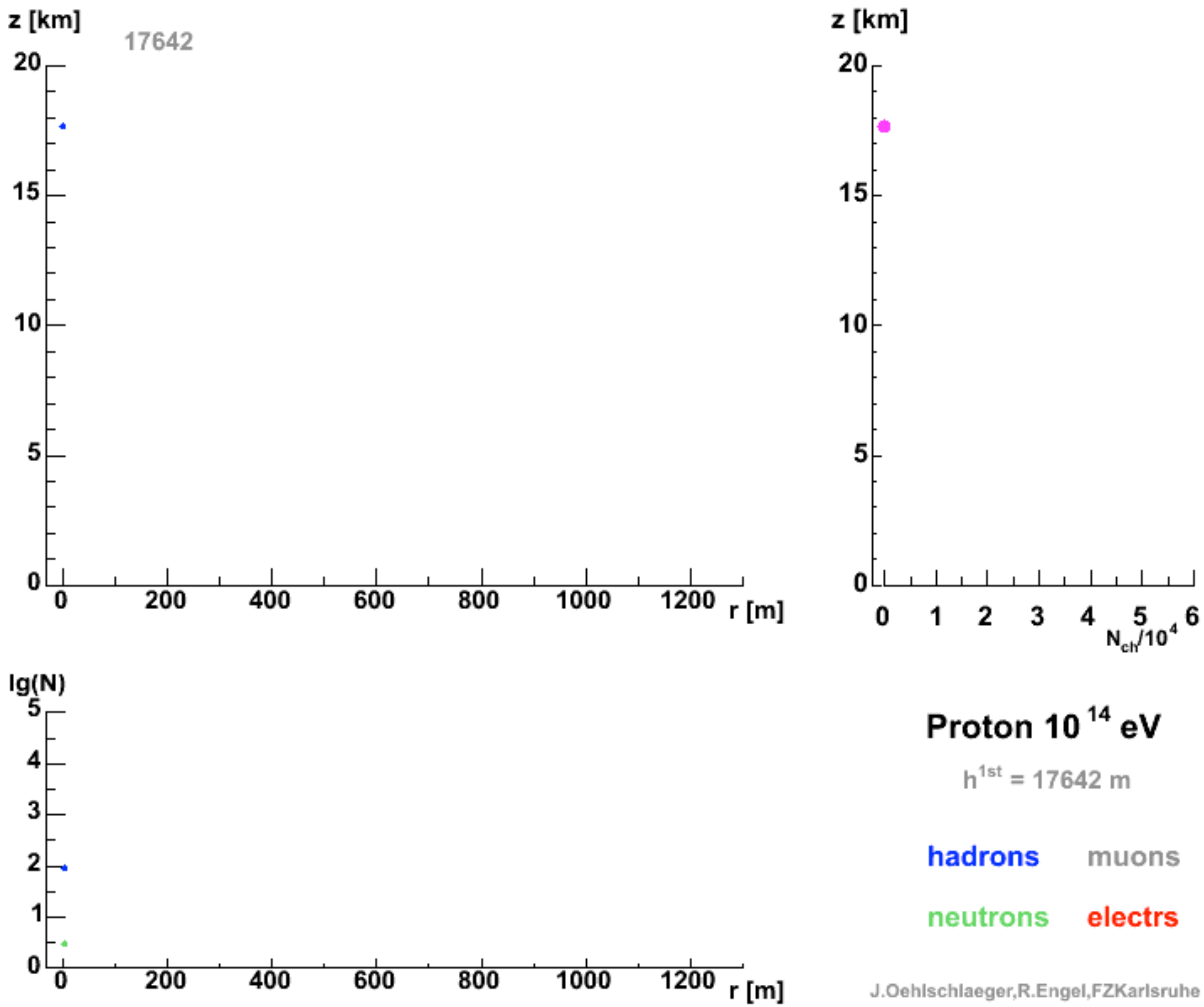
Extensive Air Showers



Extensive Air Showers



Extensive Air Showers



Cherenkov Emission

emitted when velocity *v* of charged particle exceeds local speed of light:

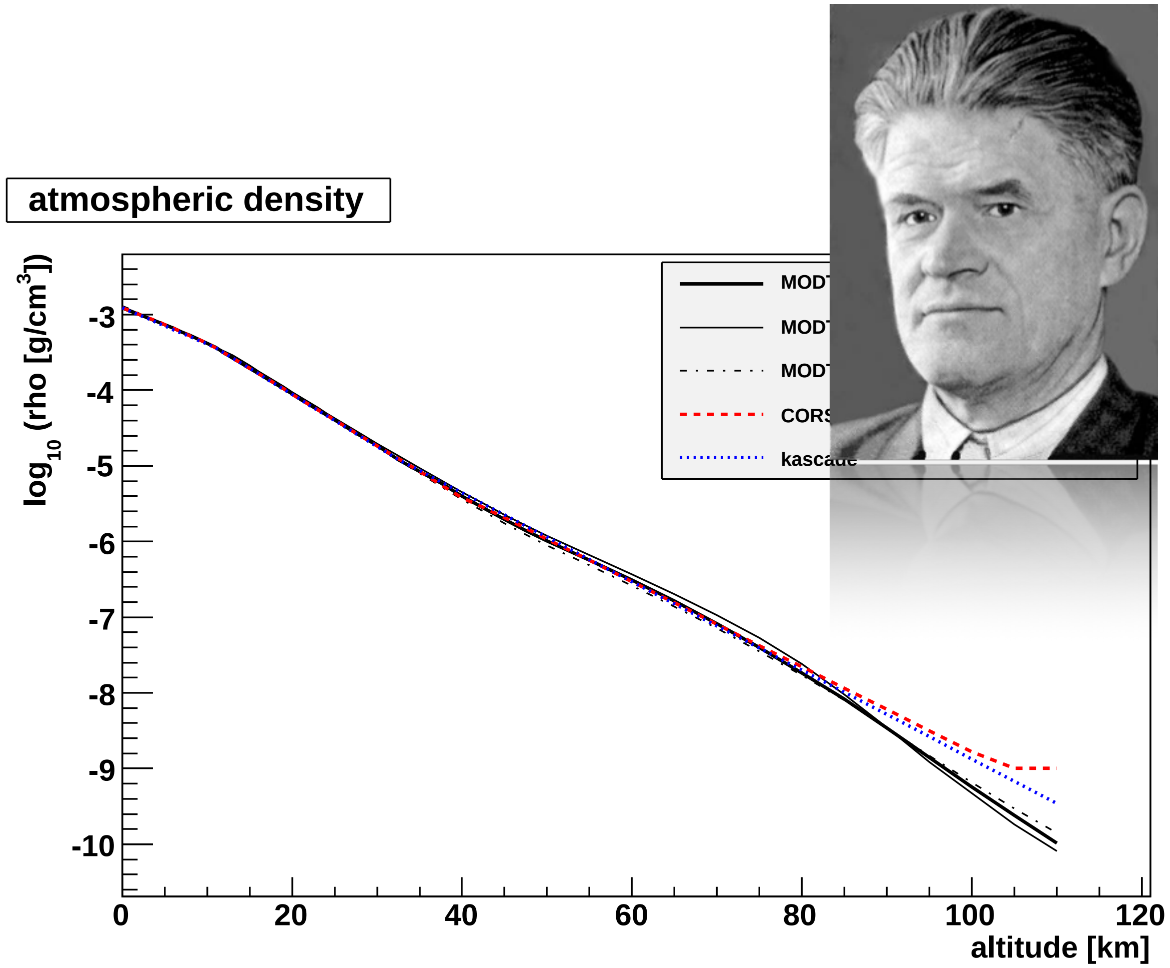
$$nv/c = n\beta > 1$$

light is emitted along a cone with half opening angle θ

$$\cos\Theta = 1/(\beta n)$$

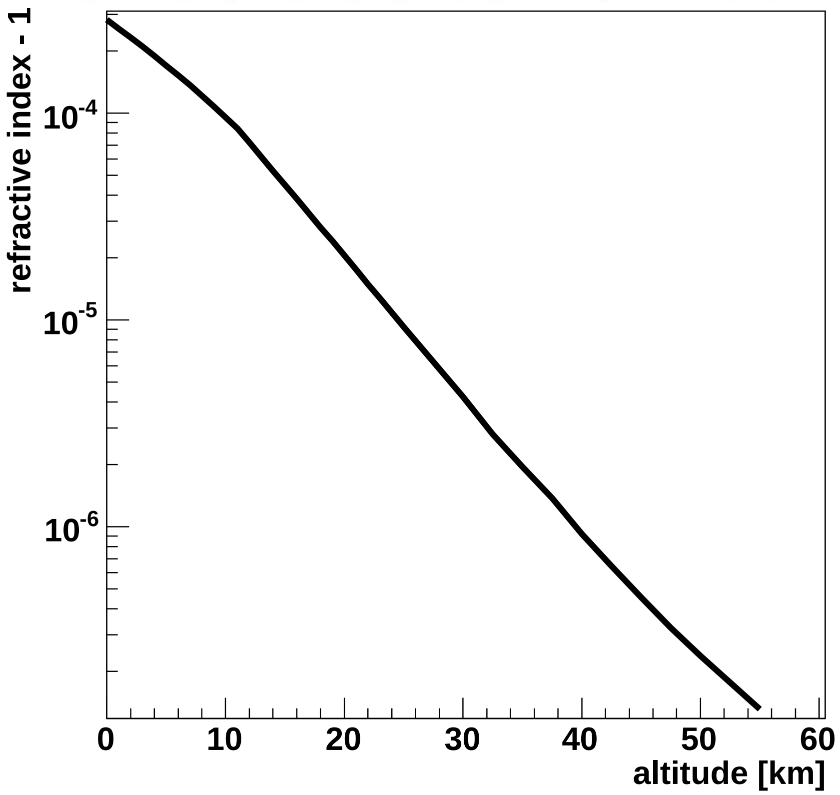
number of Cherenkov photons per path length x:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

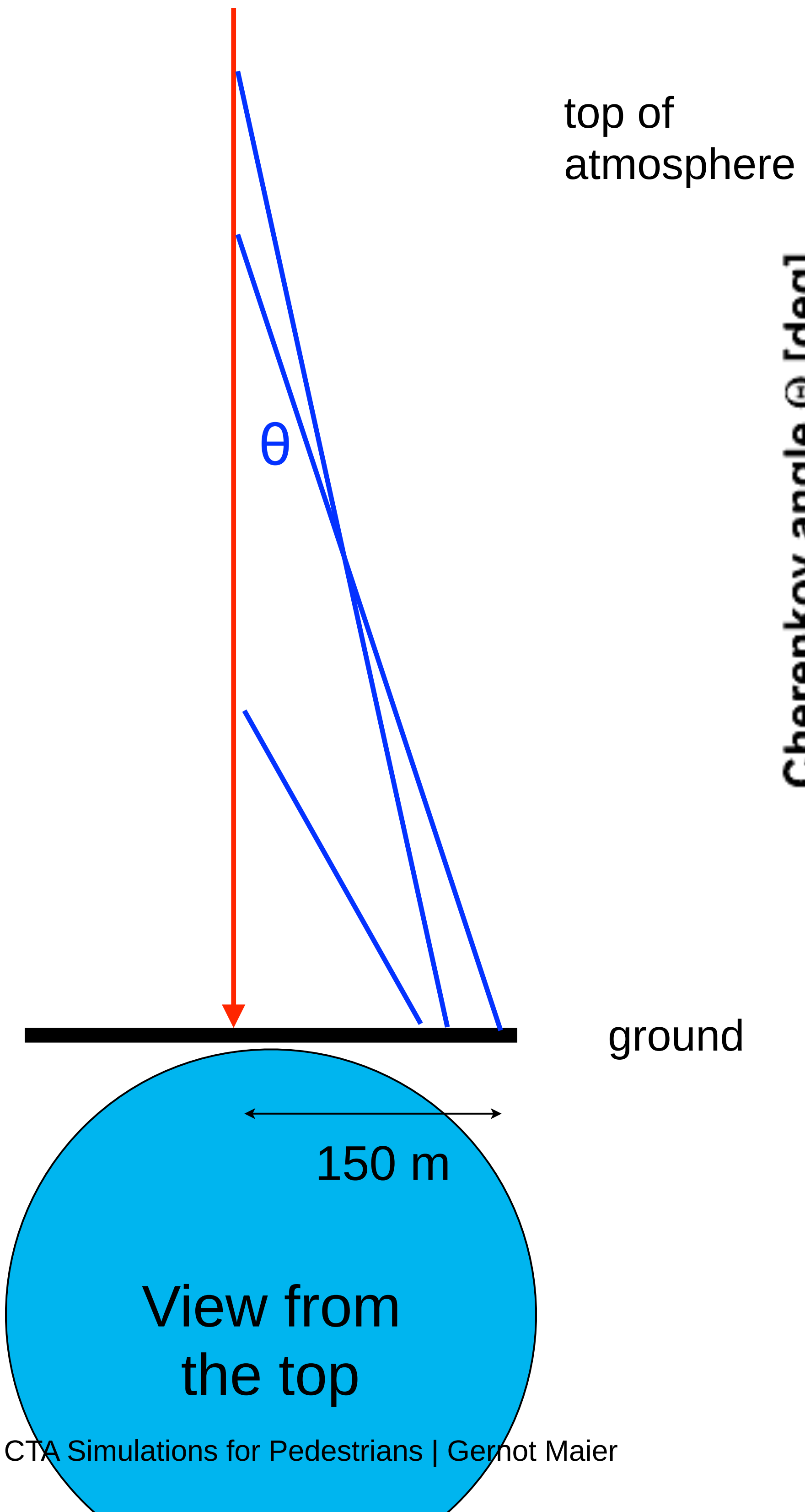


refractive index in air scales with density

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

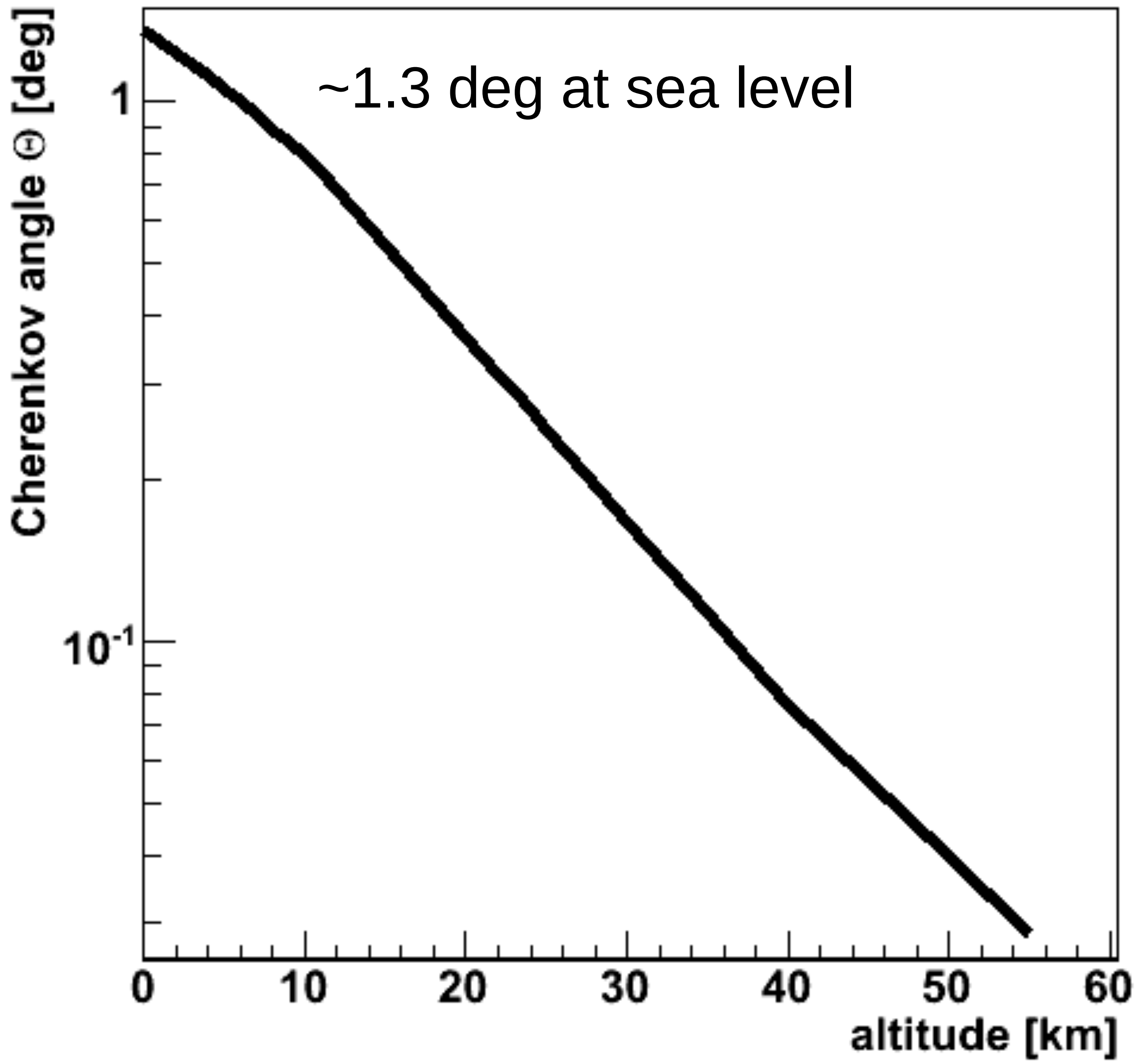


Cherenkov radiation: emission angle

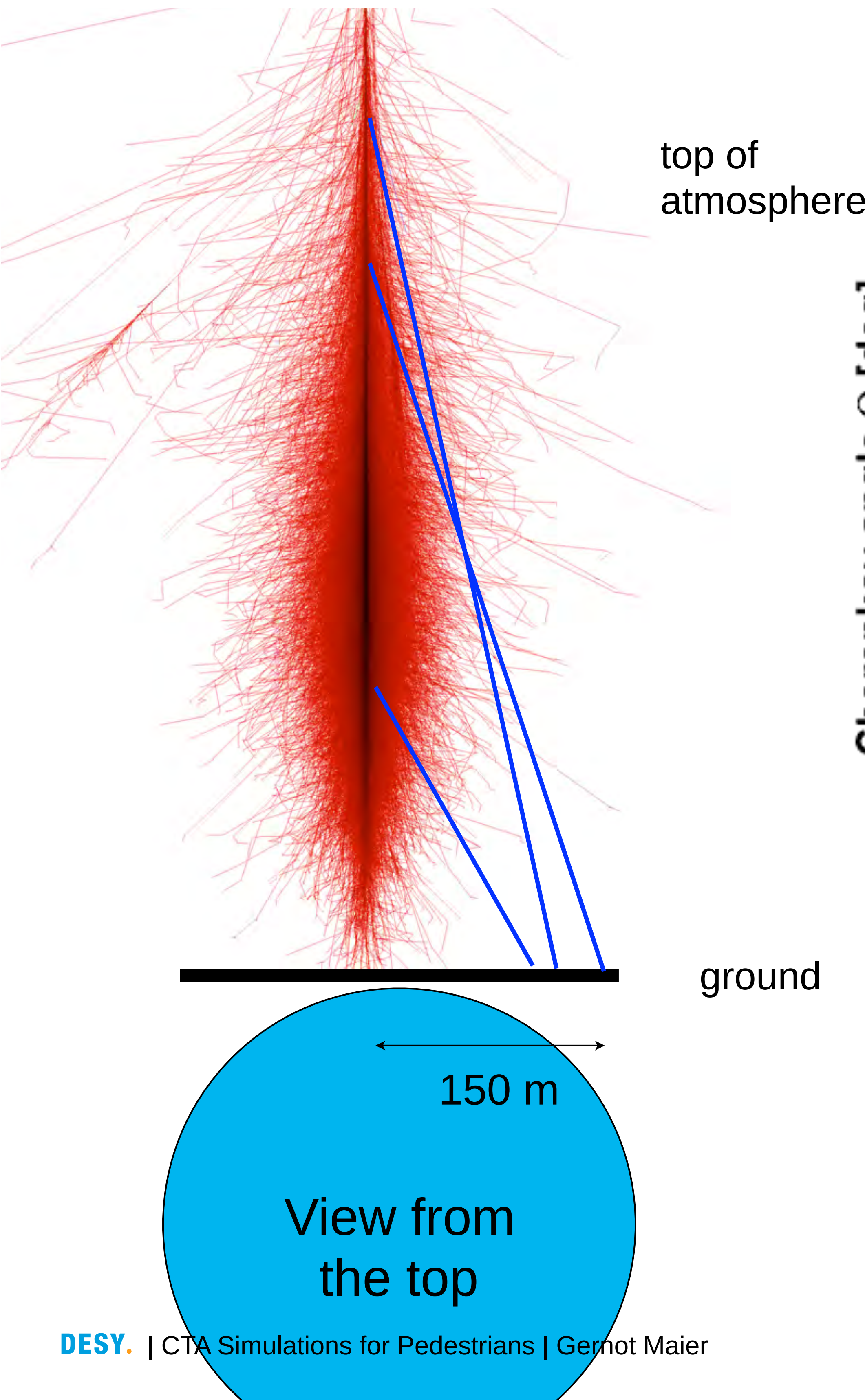


light is emitted along a cone with half opening angle θ

$$\cos \Theta = 1/(\beta n)$$

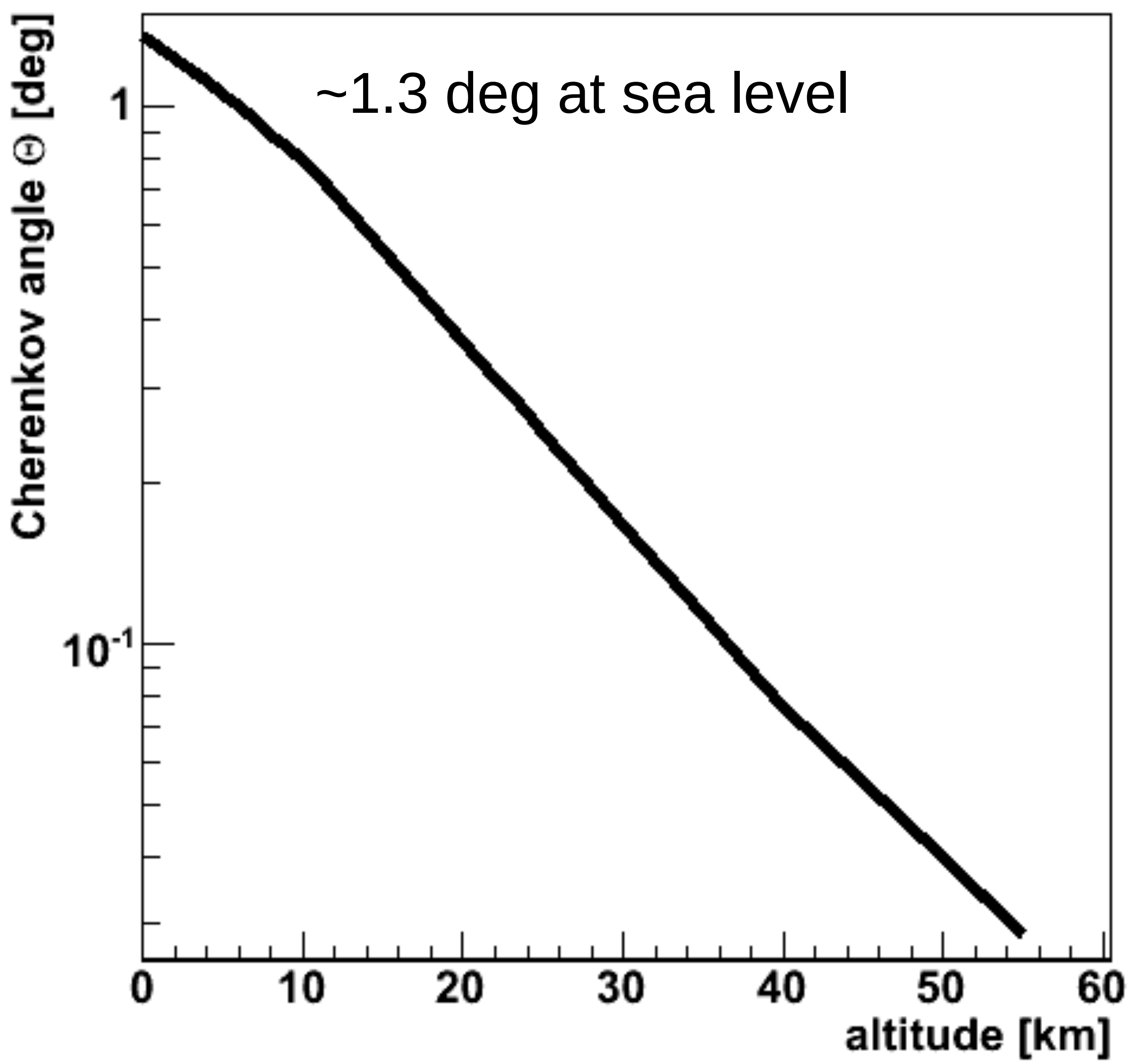


Cherenkov radiation: emission angle

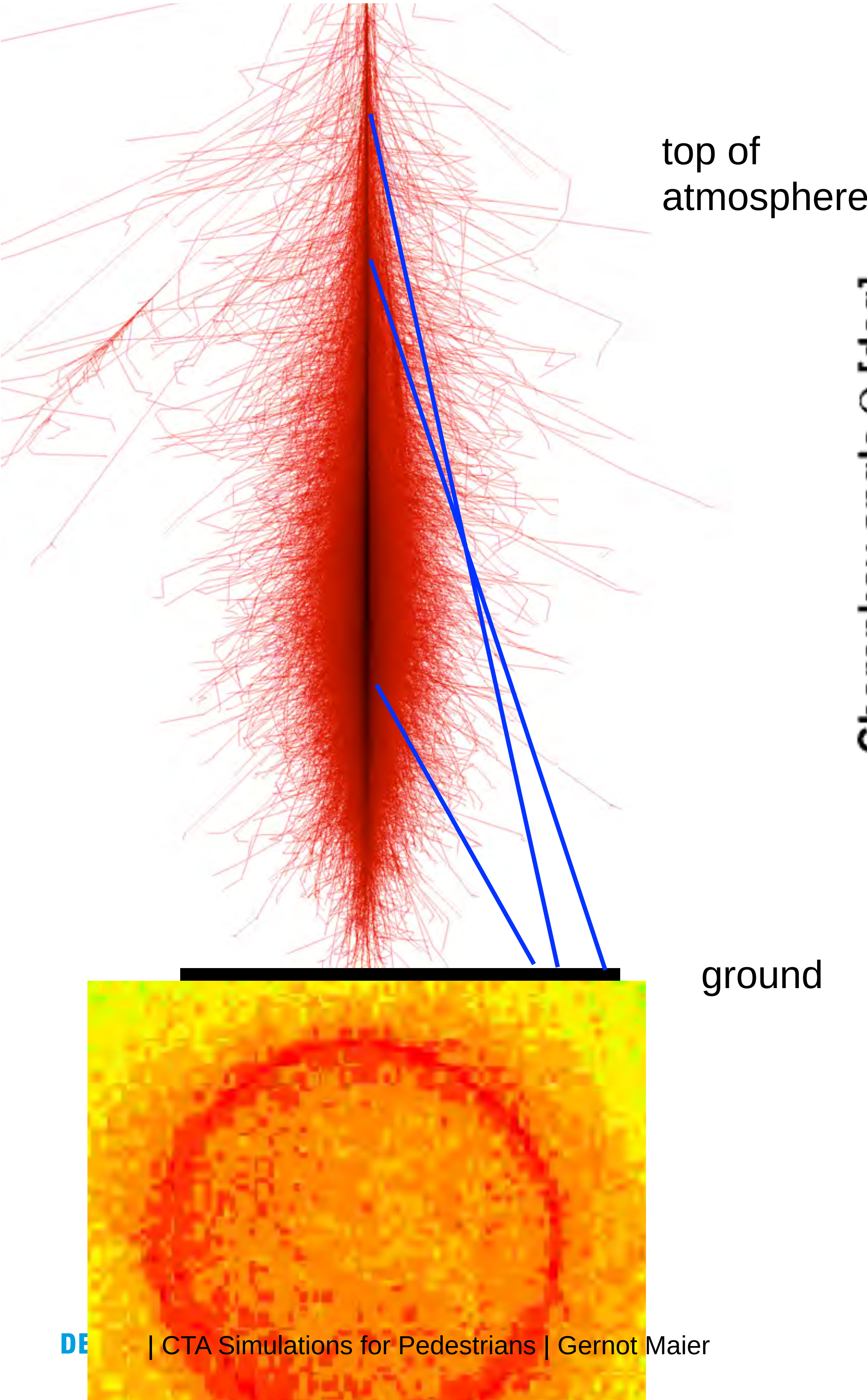


light is emitted along a cone with
half opening angle θ

$$\cos\Theta = 1/(\beta n)$$

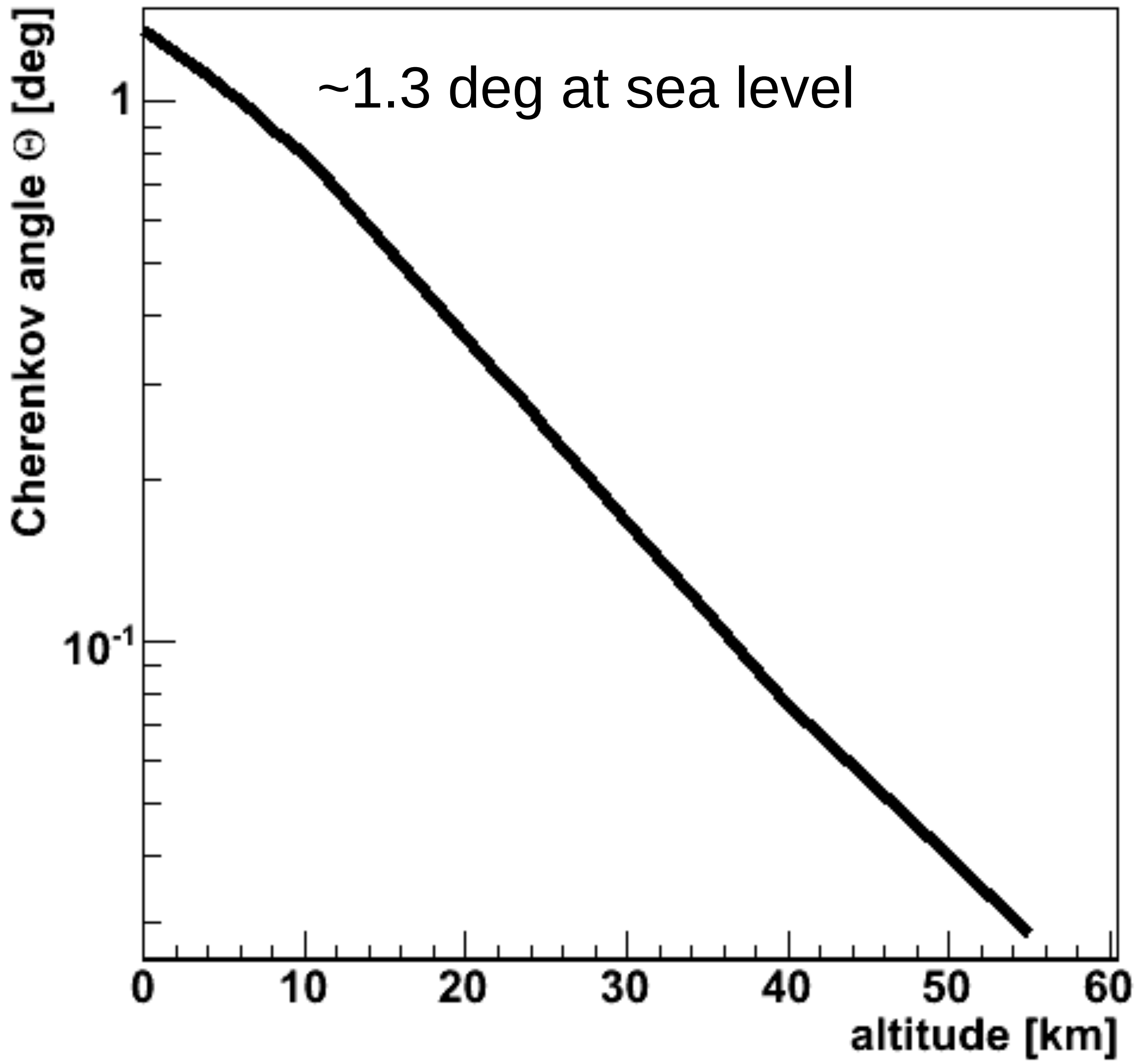


Cherenkov radiation: emission angle

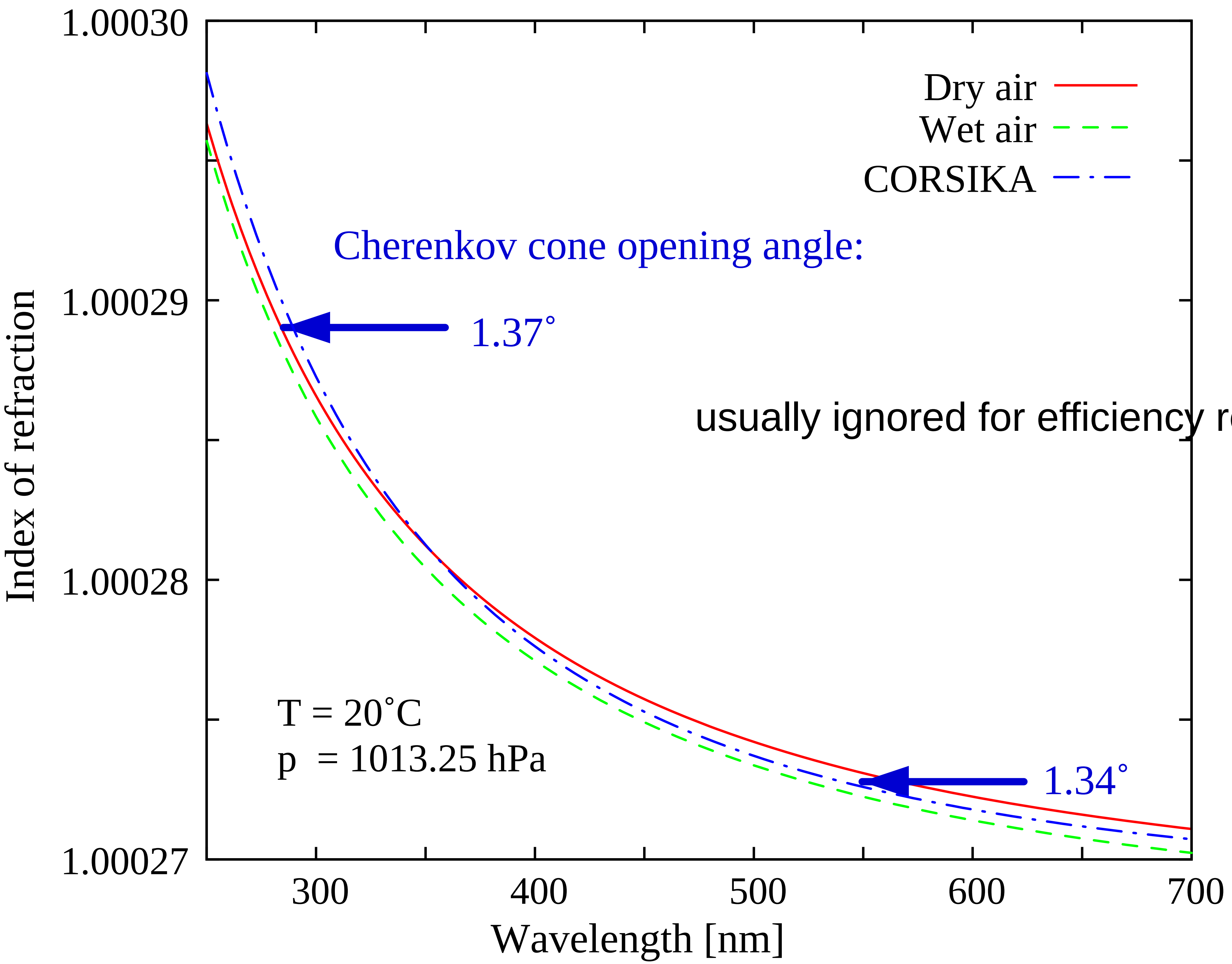


light is emitted along a cone with half opening angle θ

$$\cos\Theta = 1/(\beta n)$$

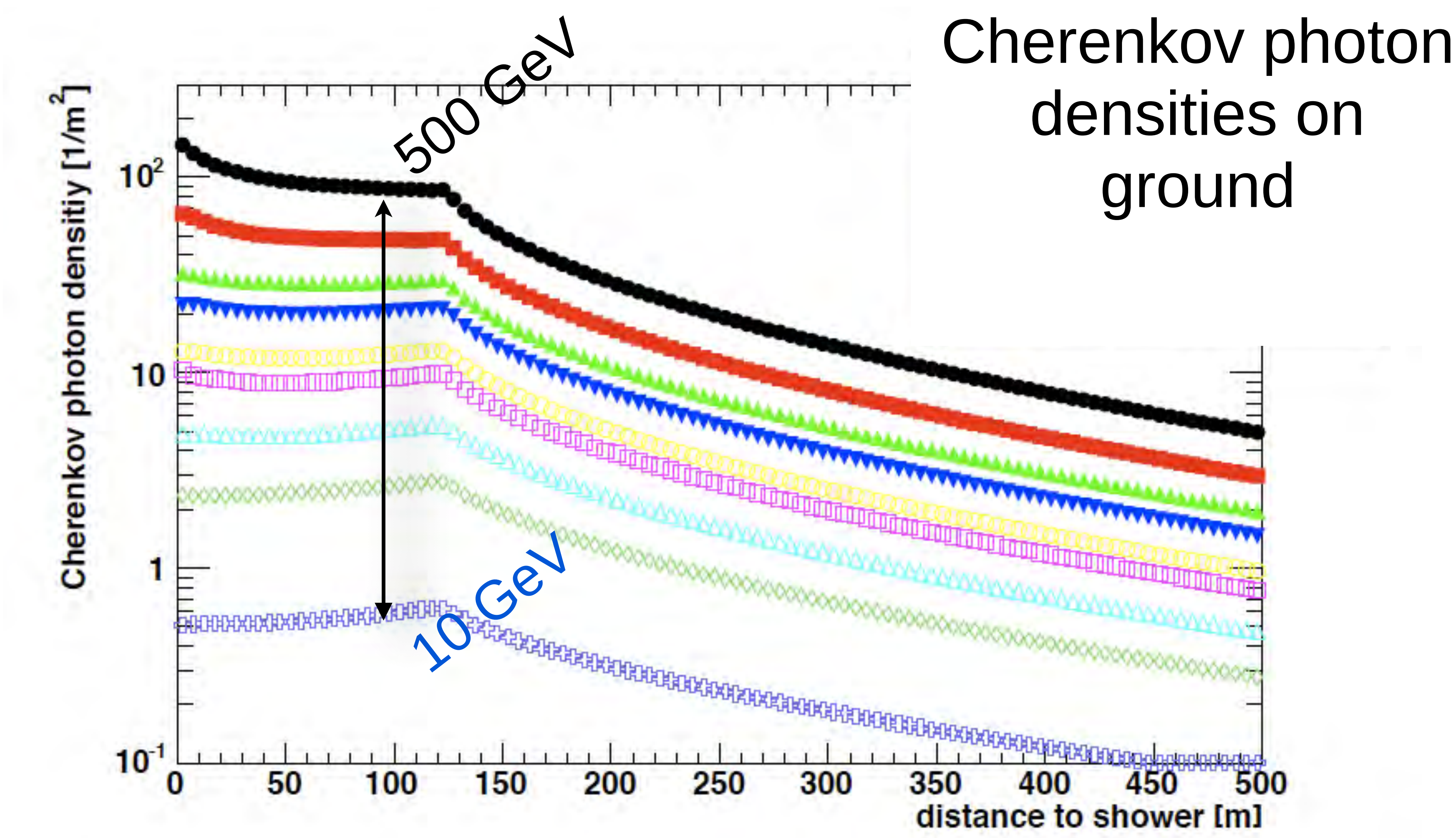


Index of refraction



usually ignored for efficiency reasons

Imaging Technique - Air Showers

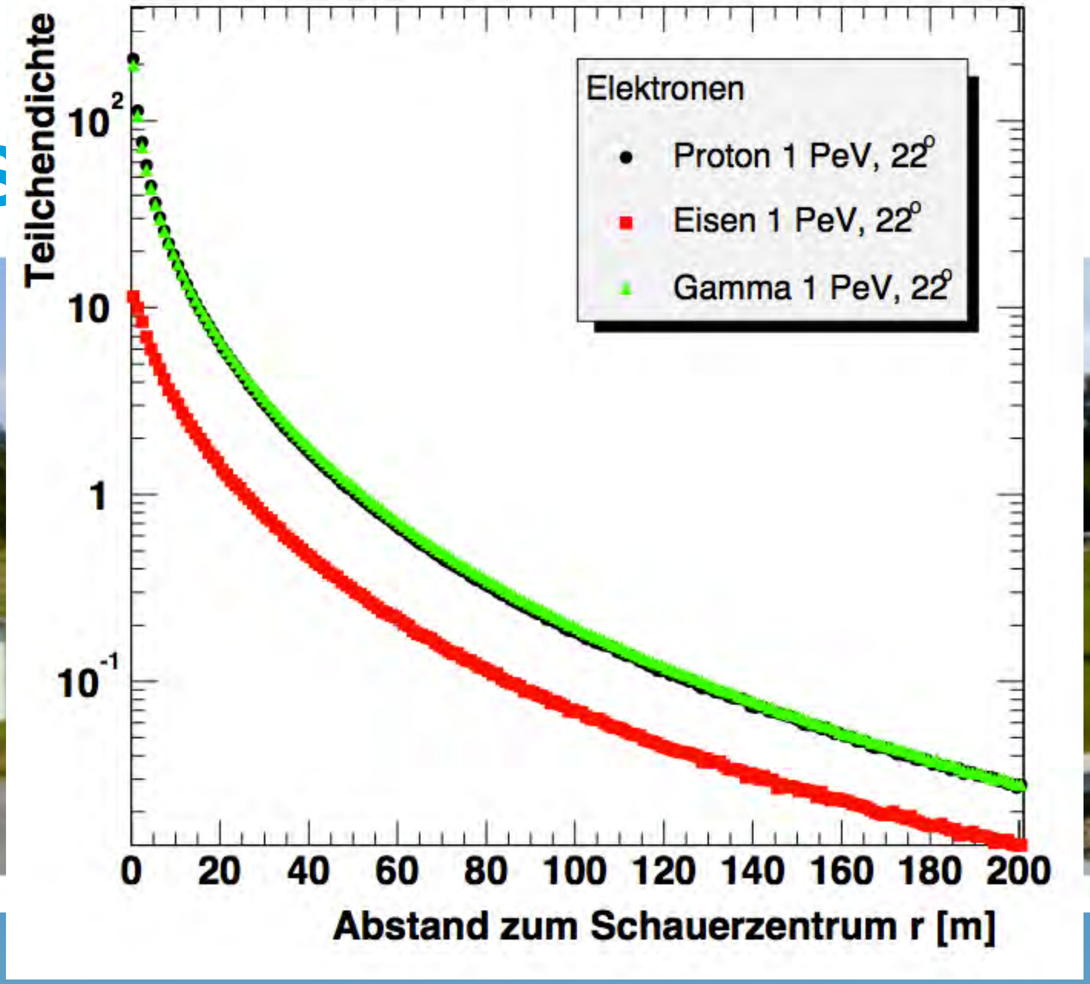


Lateral distribution comparison

Lateral distribution comparis

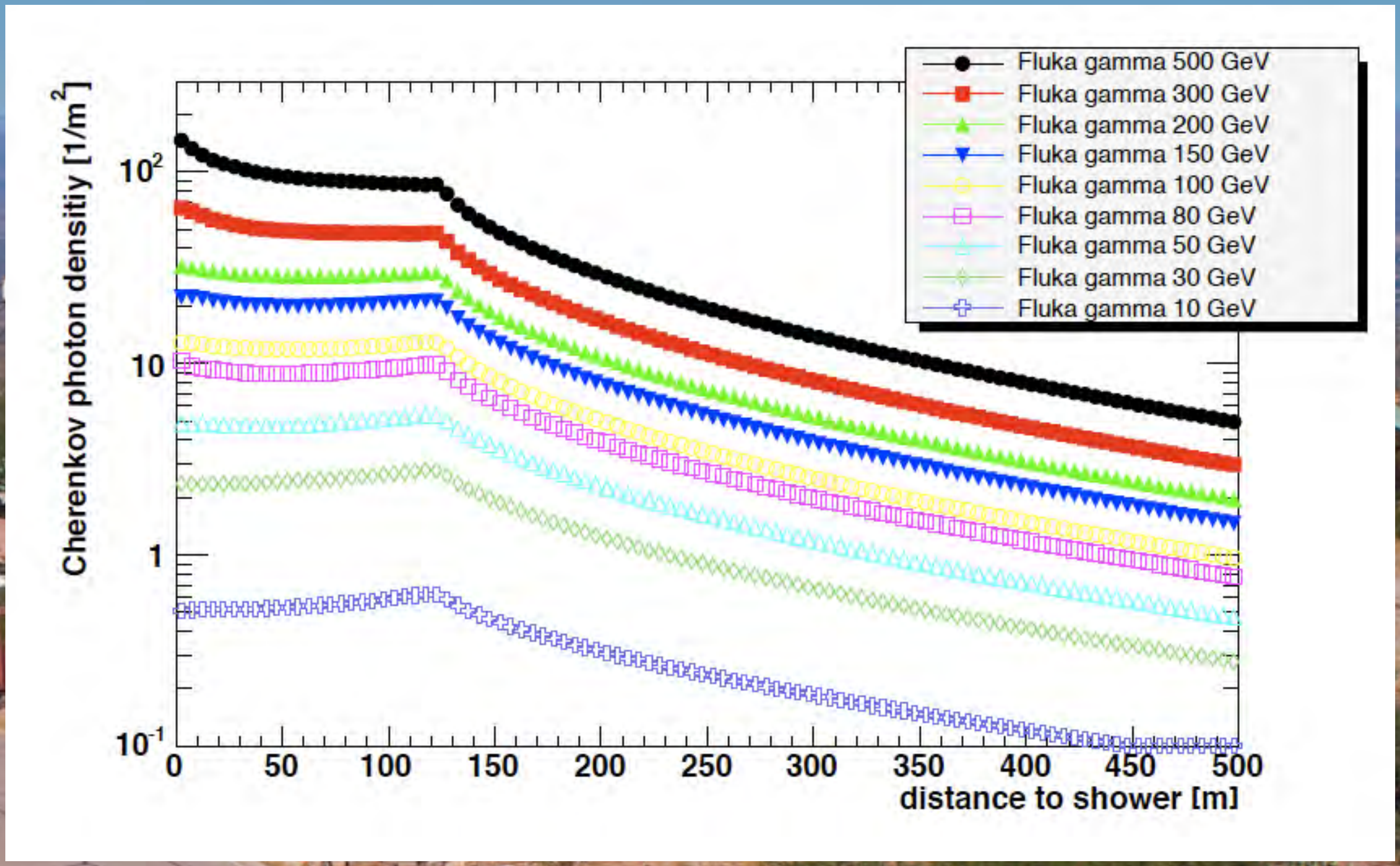
KASCADE air shower array

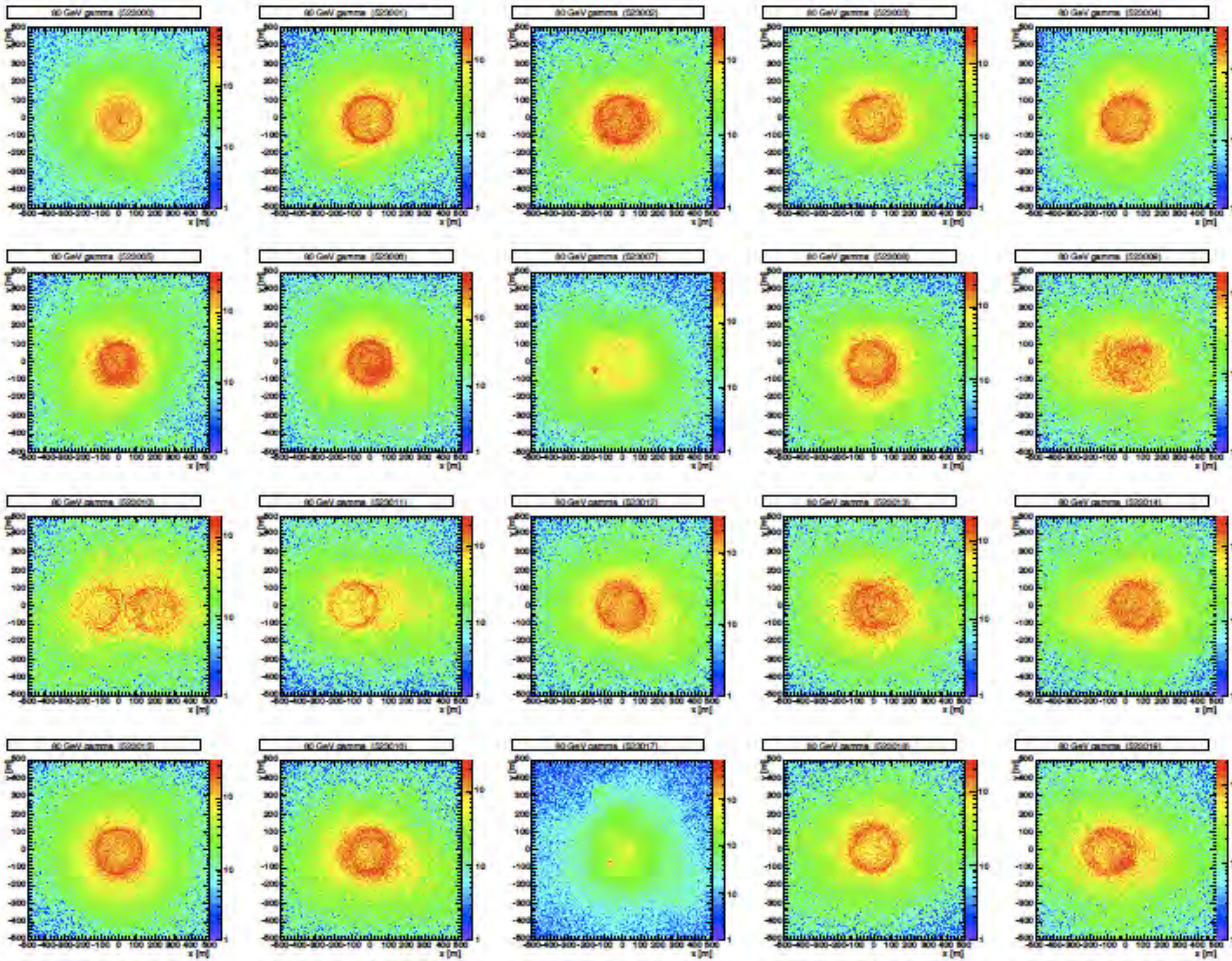
13 m distance



VERITAS

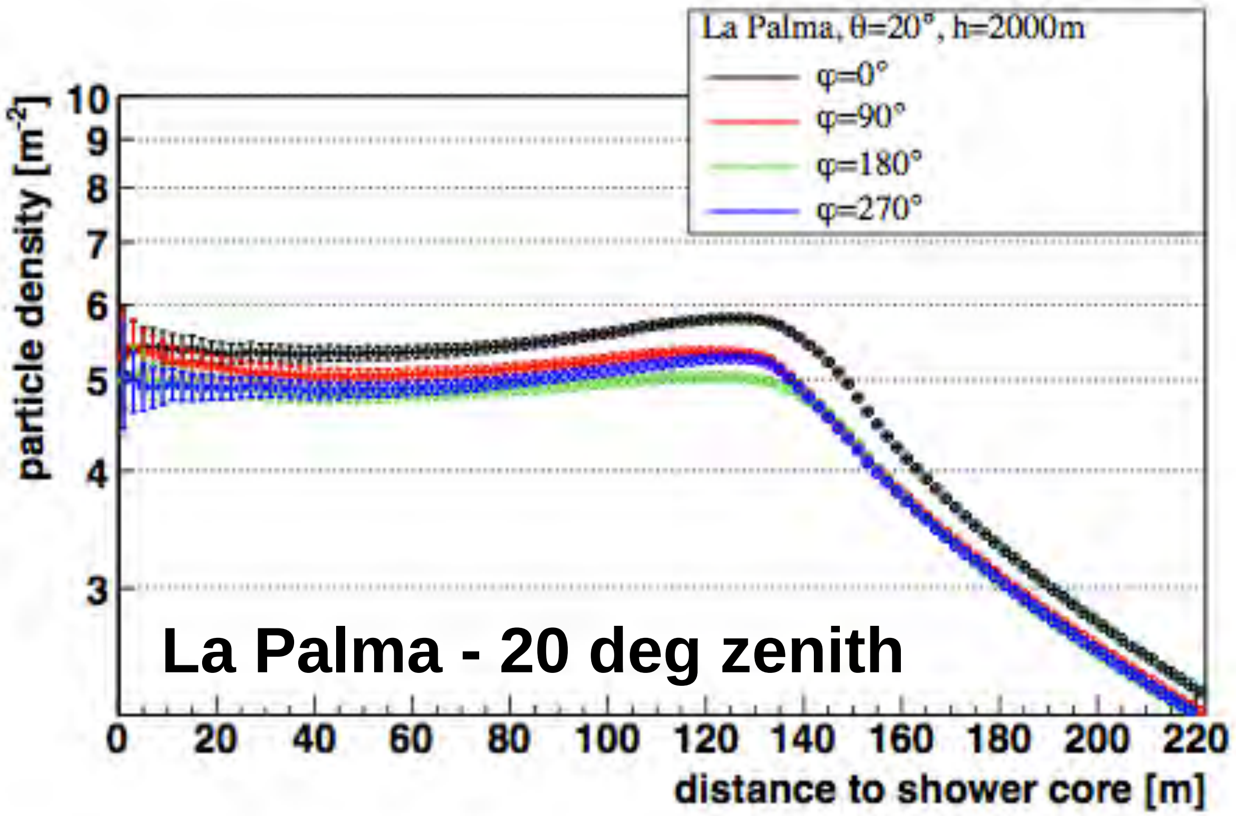
100 m distance

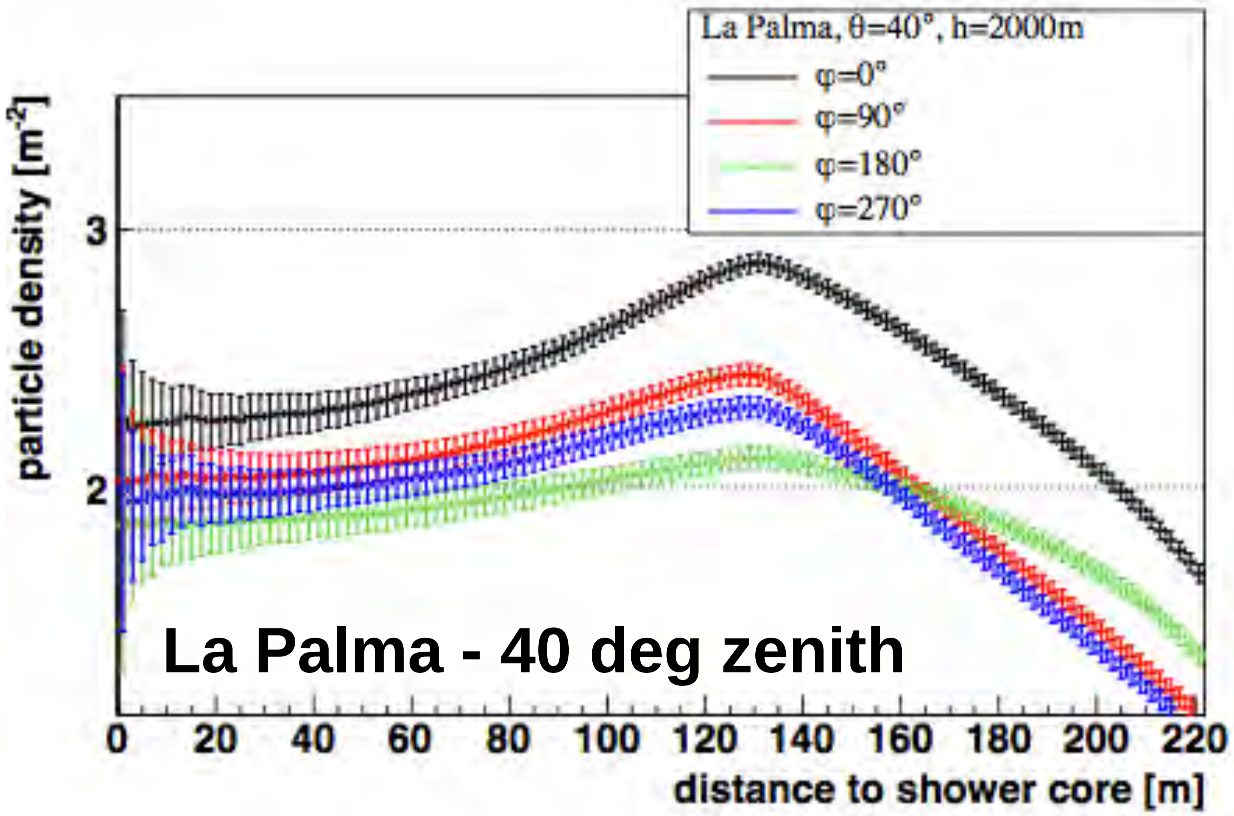




randomly selected showers with 80 GeV primary photon energy

Geomagnetic Field

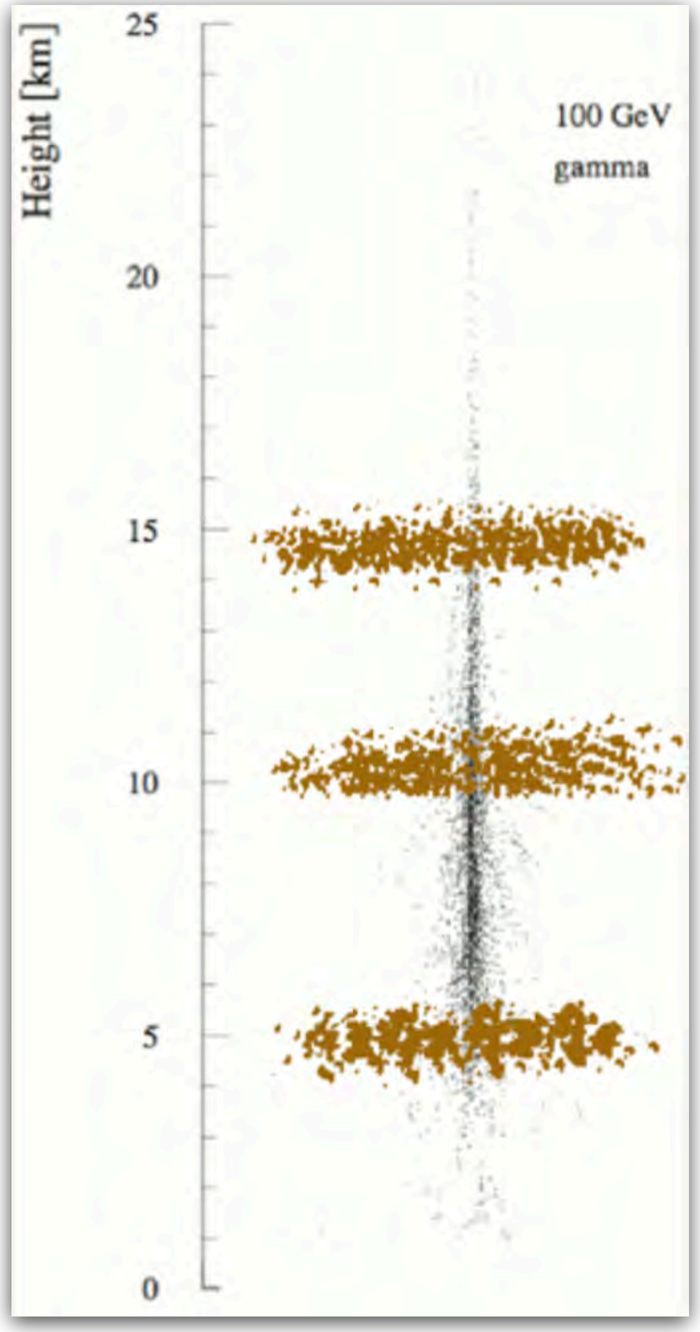




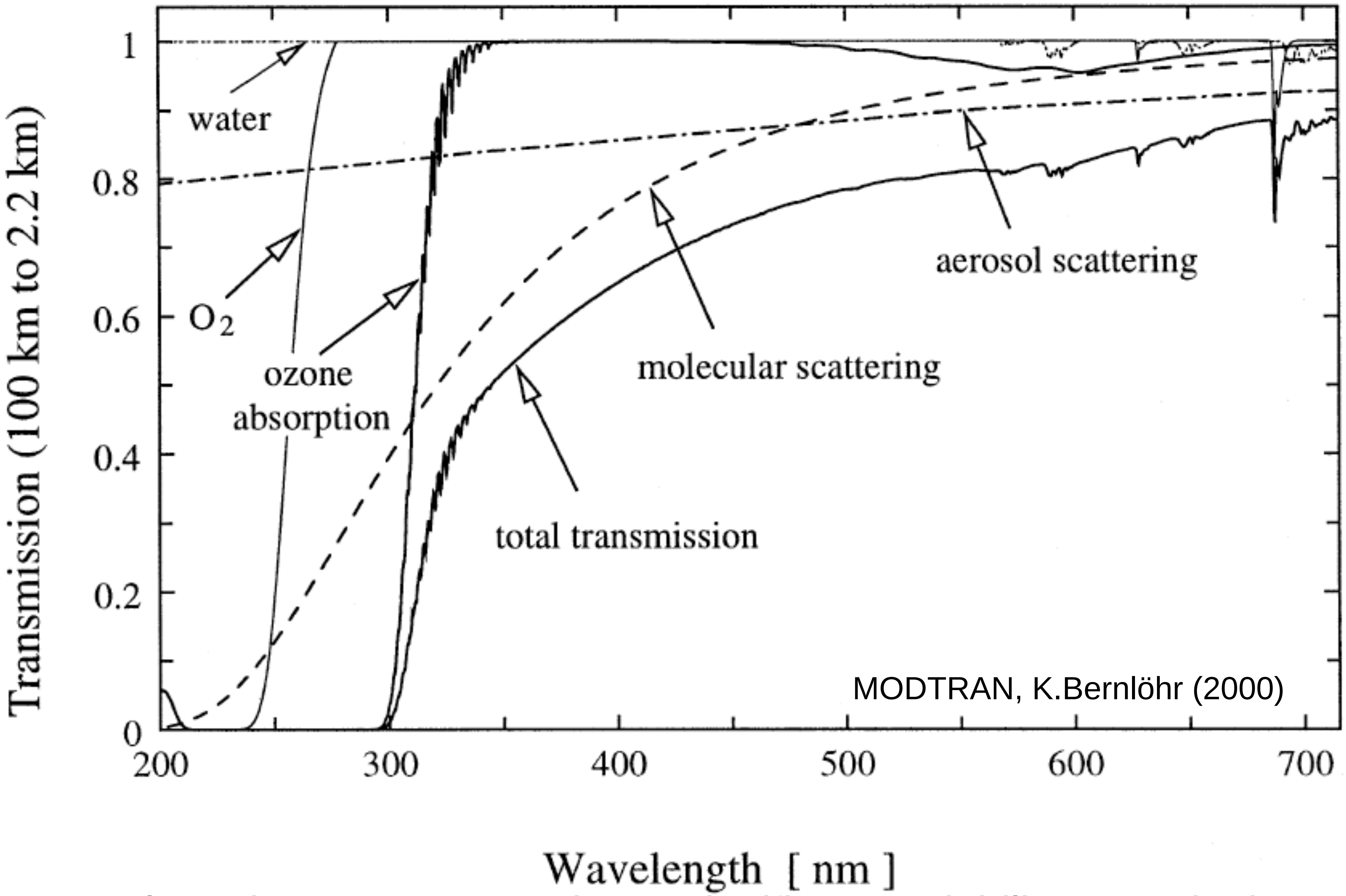
Krause 2011

Atmosphere

- aerosol layers
- molecular profile
- clouds
- different levels of ozone
- star field and/or night-sky background levels



Propagation of Cherenkov Photons in the Atmosphere

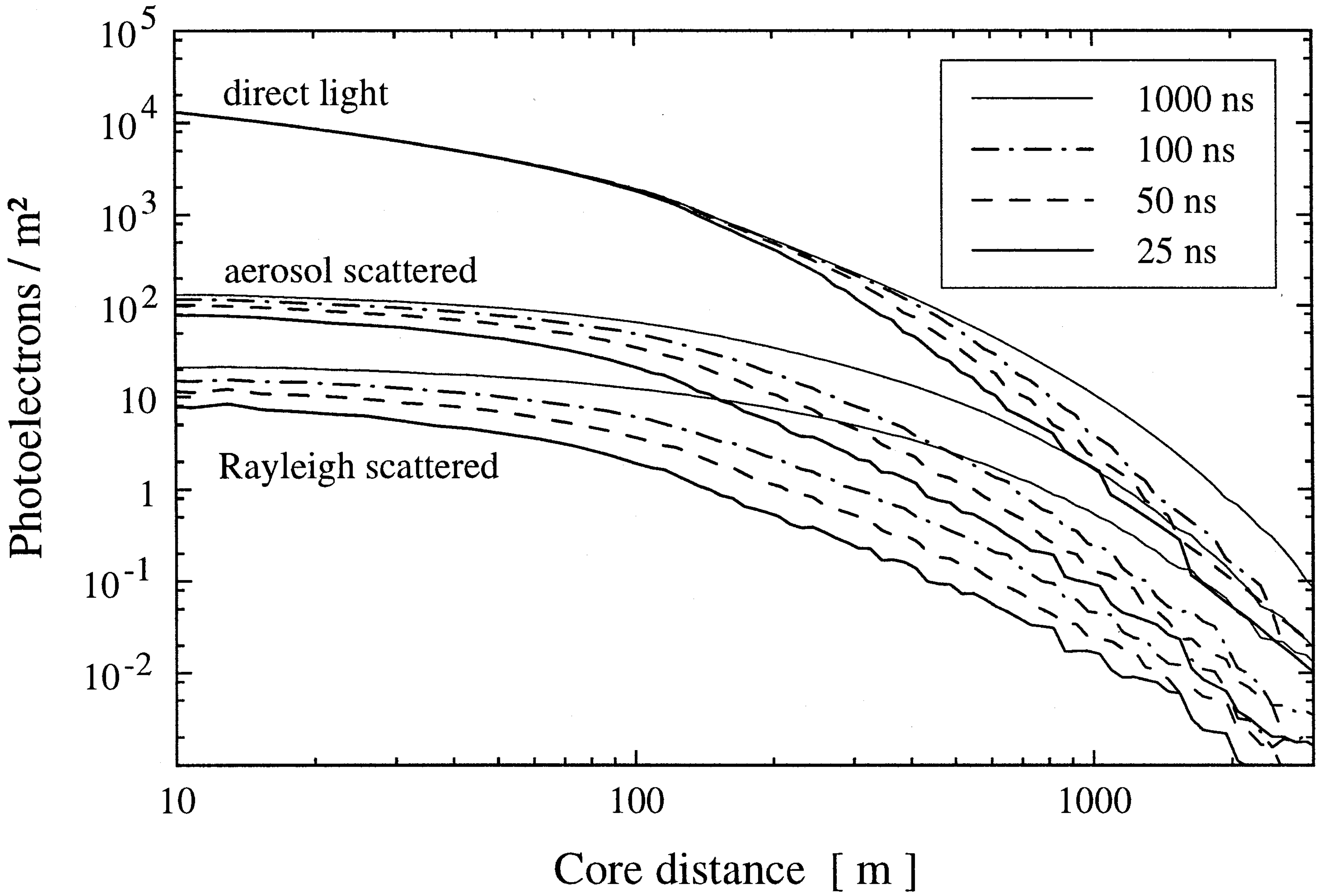


Aerosols and ozone content shows significant variability at each site

Deep tropospheric ozone intrusions might be an issue for CTA S

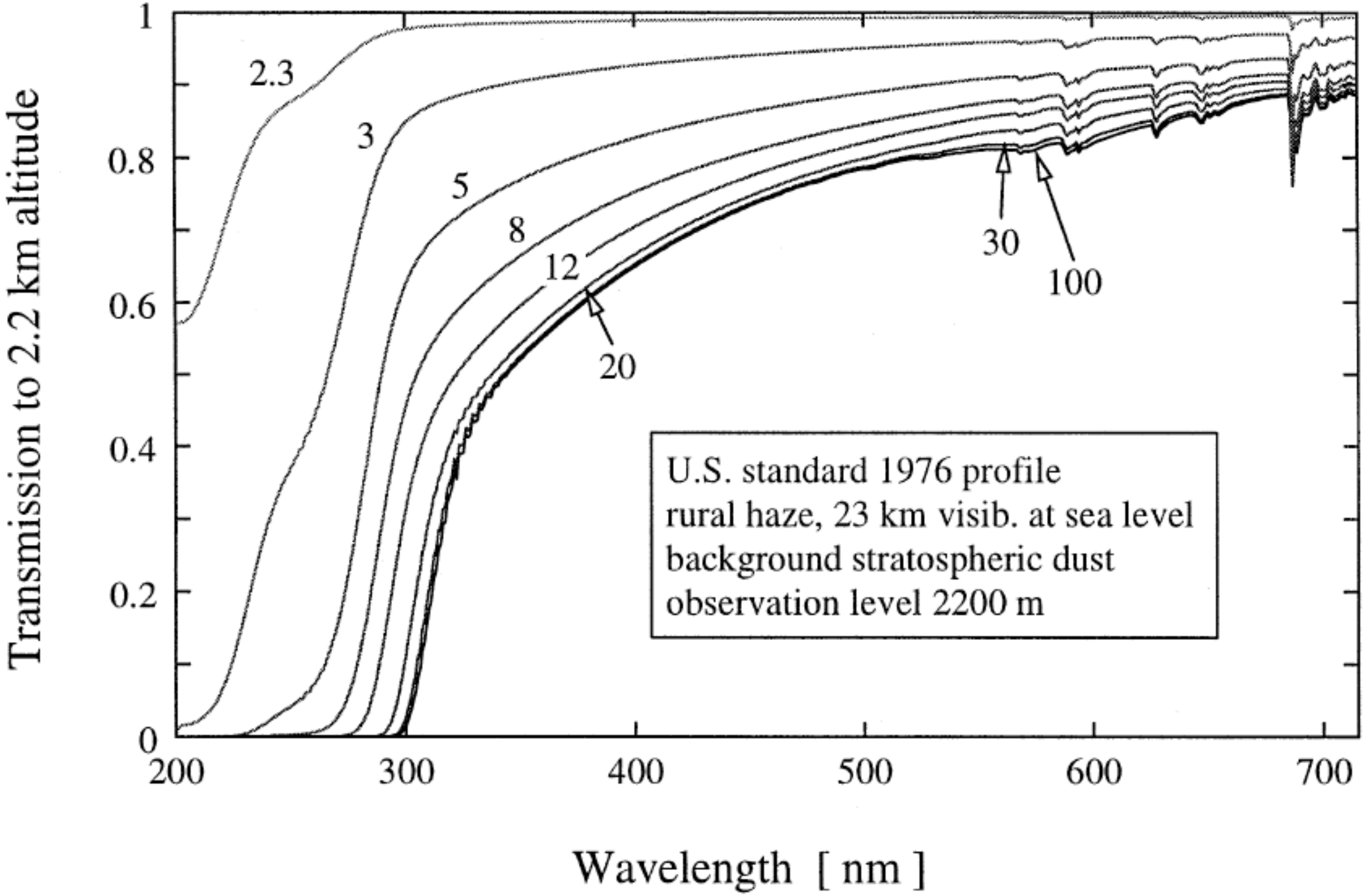
Multiple Scattering of Photons

Currently ignored - treated as lost photons

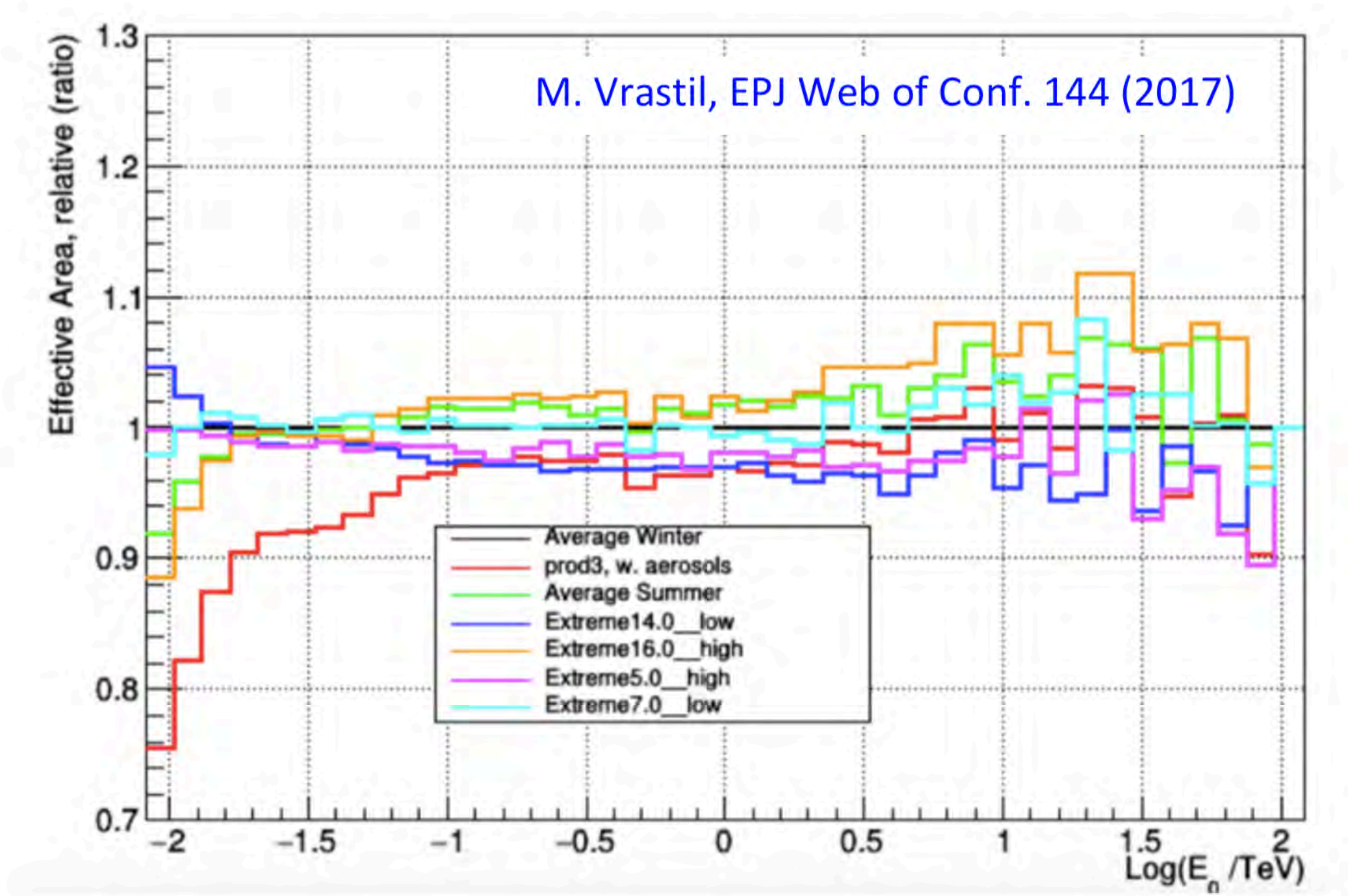


Propagation of Cherenkov Photons in the Atmosphere

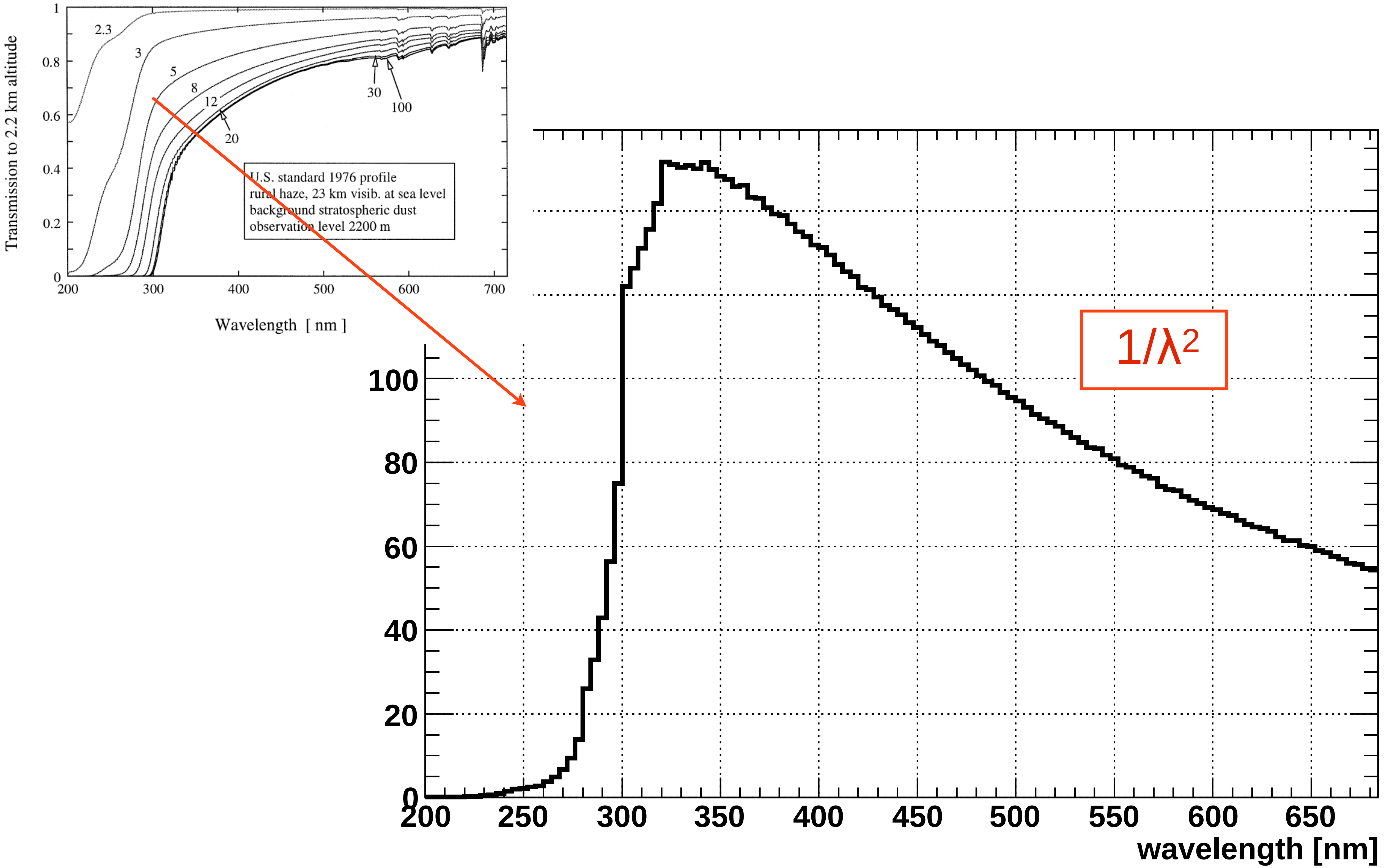
MODTRAN & K.Bernlöhr (2000)



Molecular profiles

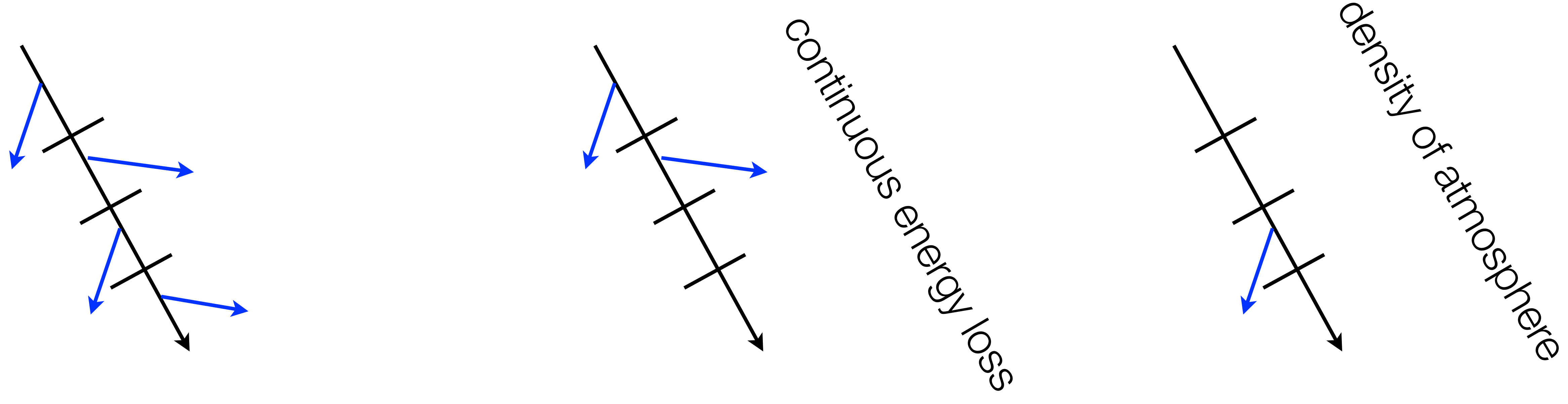


Cherenkov radiation: wavelength distribution



Cherenkov light production

- a single singly-charged vertical particle could emit up to half a million photons
- gamma shower of 100 TeV may result in more than 100 billion photons
- **challenge to simulate!**
- ignore wavelength dependency of index of refraction
- photons are emitted in bunches (typically 5 photons per bunch)

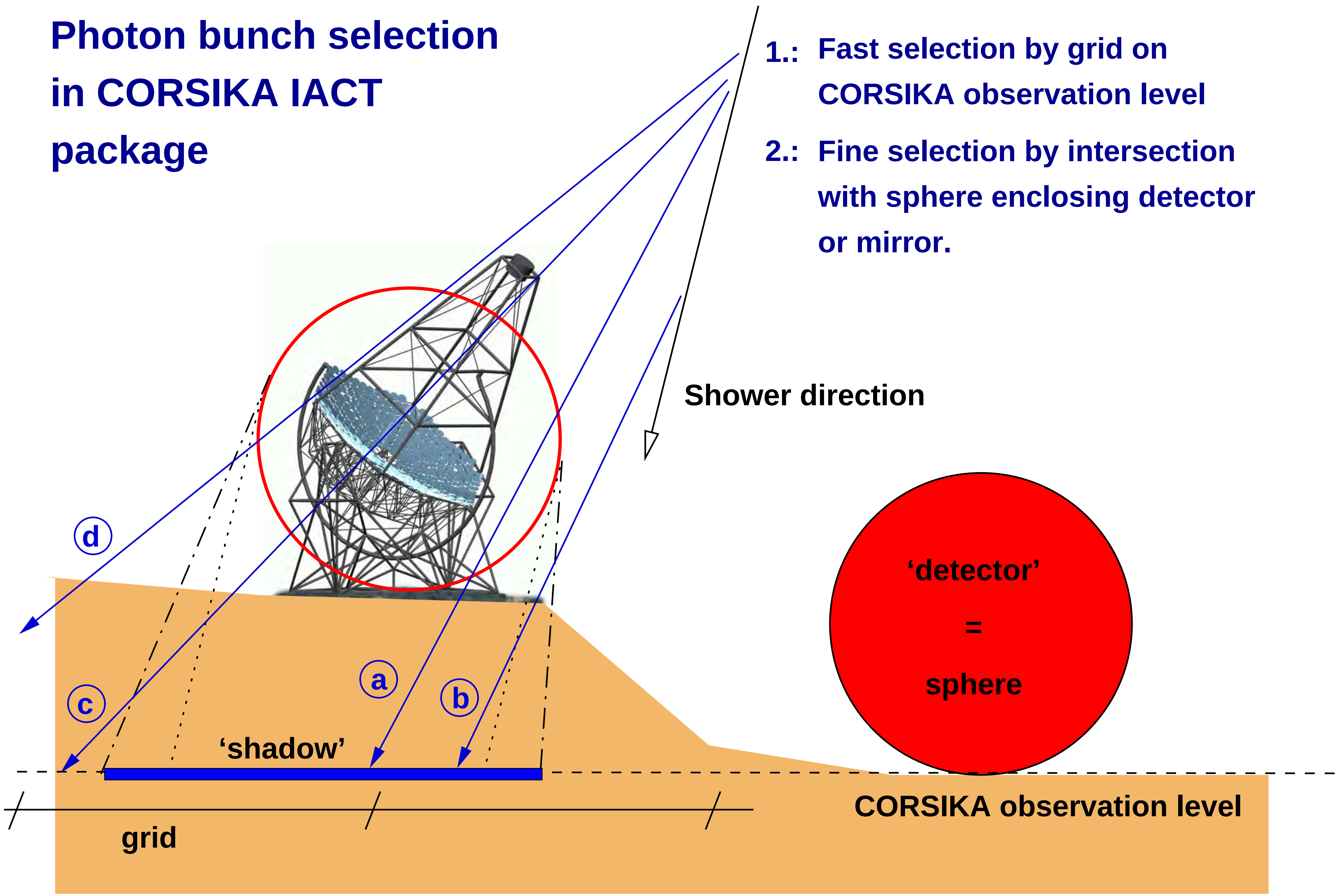


Step size needs to be small enough (e.g. bending in geomagnetic field)

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.



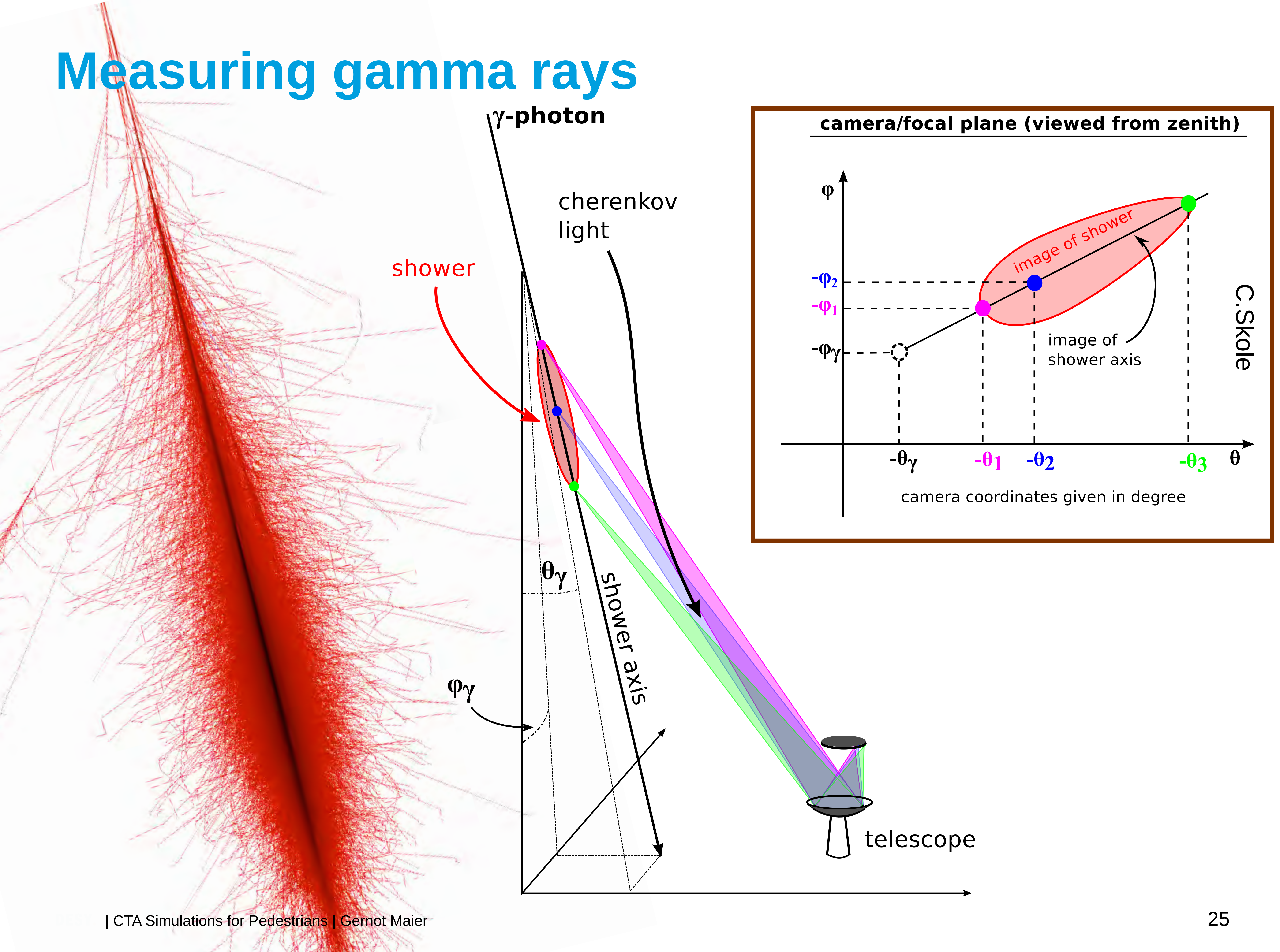
a: recorded photon bunch

b: not recorded because not intersecting sphere

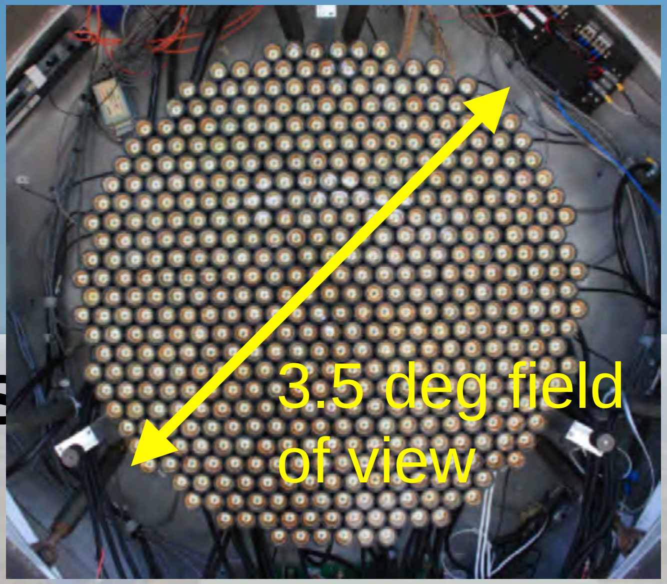
c: recorded (not in 'shadow' but hitting a shadow grid cell)

d: not recorded because not hitting a shadow grid cell

Measuring gamma rays



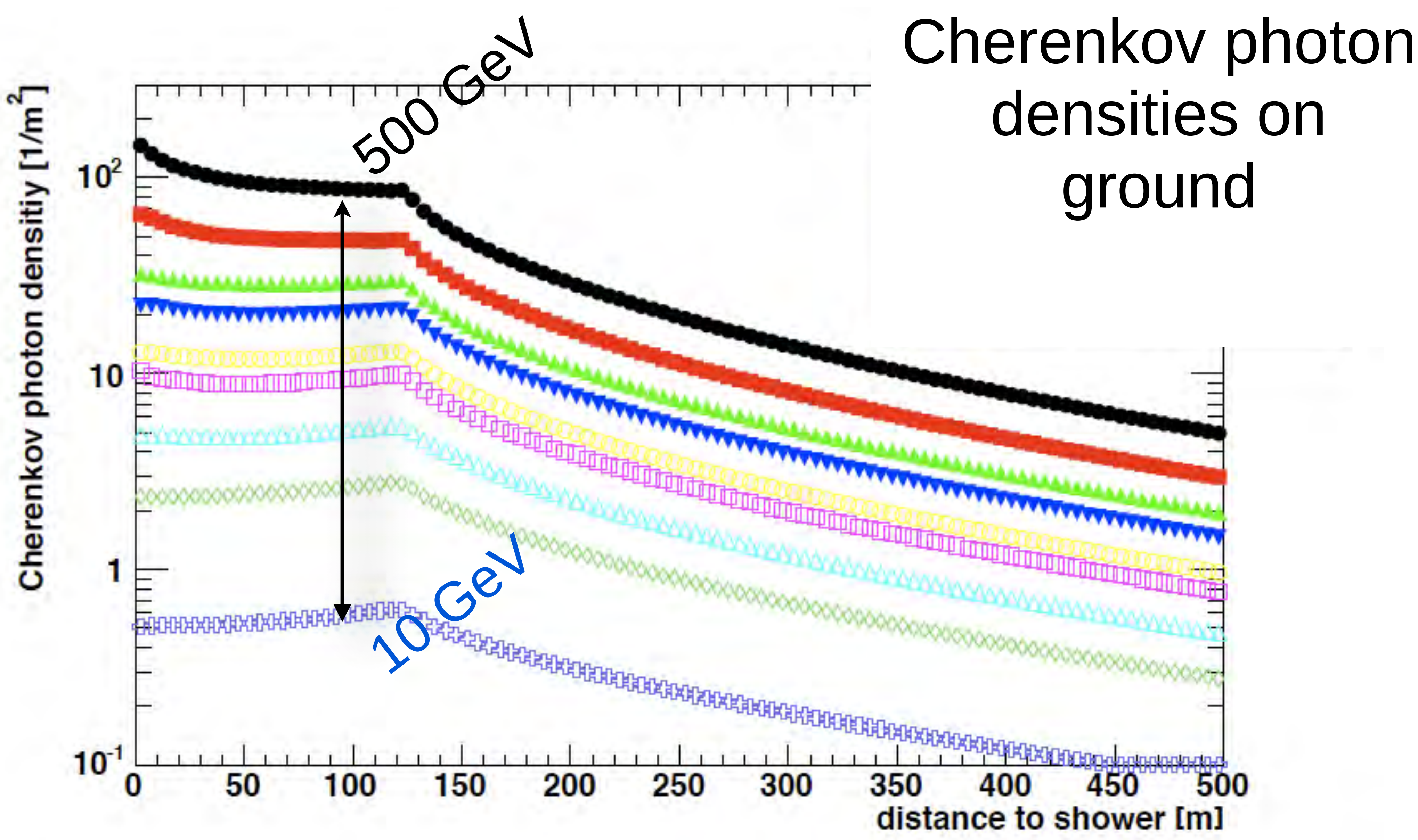
VERITAS



- 4 x 12 m diameter telescopes
- 4 x 500 pixel PMT cameras
- 500 MHz FADC readout
- Sensitivity <1% in 25 h
- Energy range 100 GeV to 30 TeV
- typically per year:
  - 850 h dark operation
  - 200 h moonlight operation
  - 250 h very bright moonlight conditions
- in operation since >10 years:
  - >12 000 h observations

CTA Telescopes

Sm
4-5
>5
larg
larg

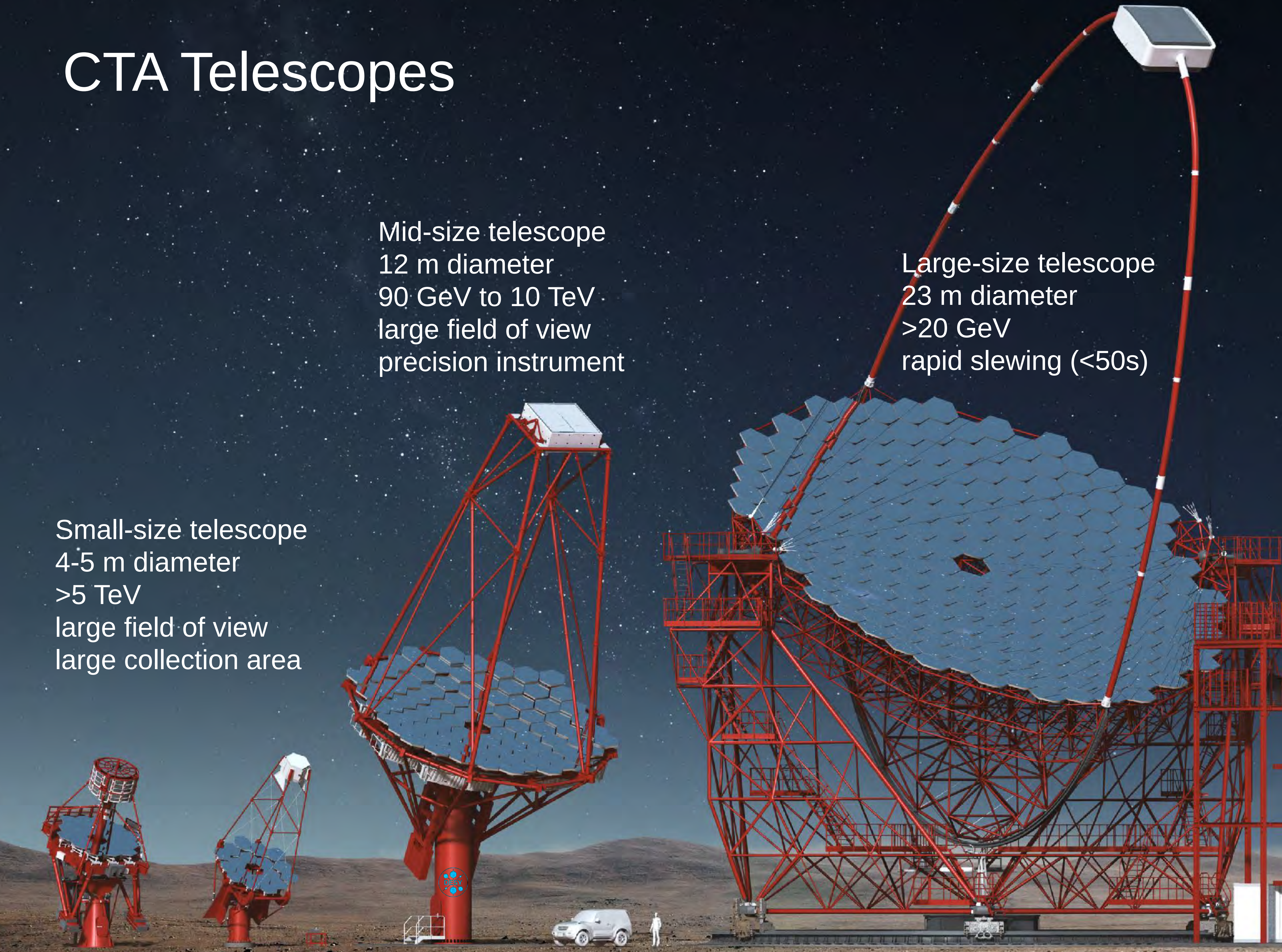


CTA Telescopes

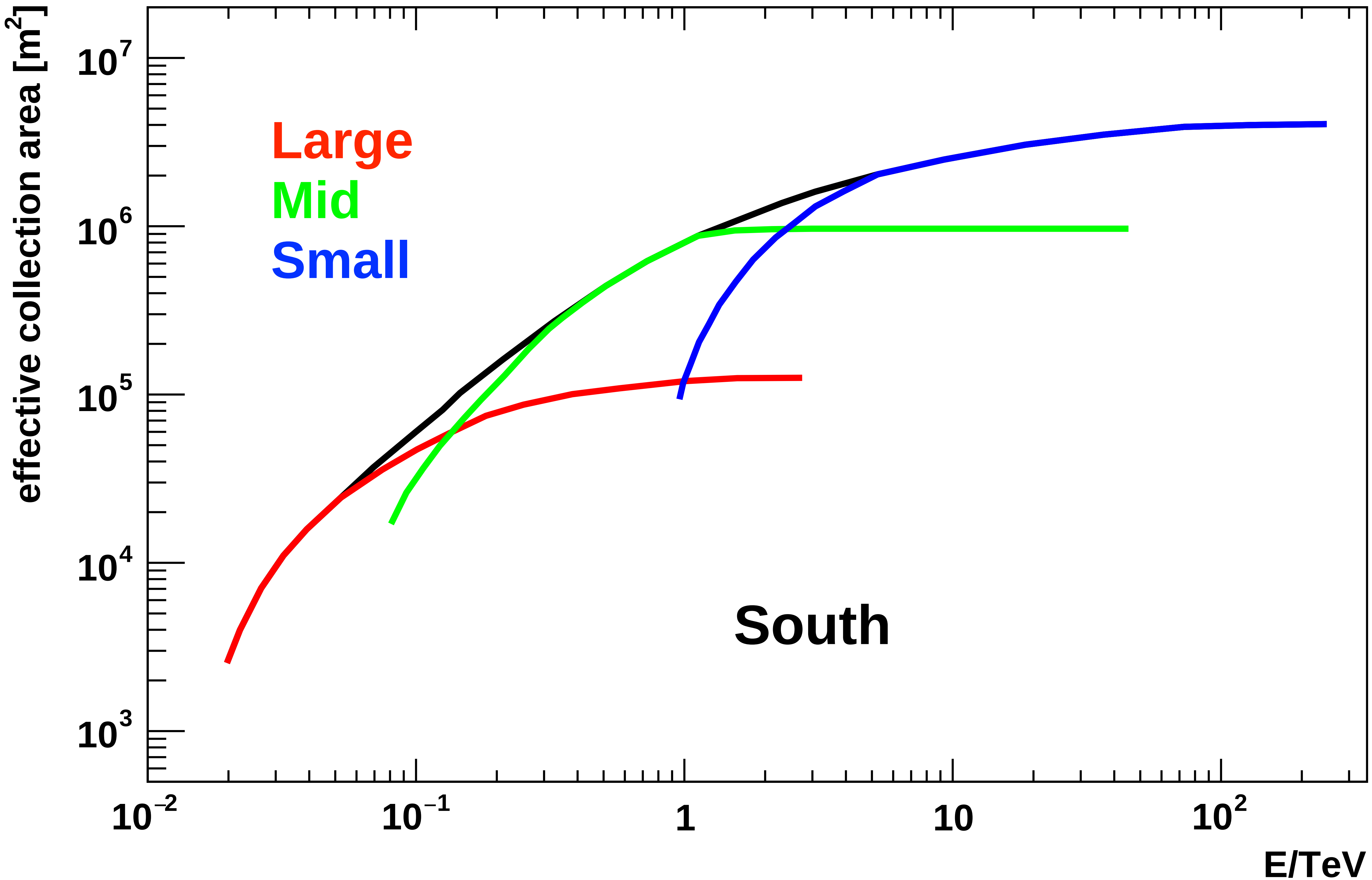
Mid-size telescope
12 m diameter
90 GeV to 10 TeV
large field of view
precision instrument

Large-size telescope
23 m diameter
>20 GeV
rapid slewing (<50s)

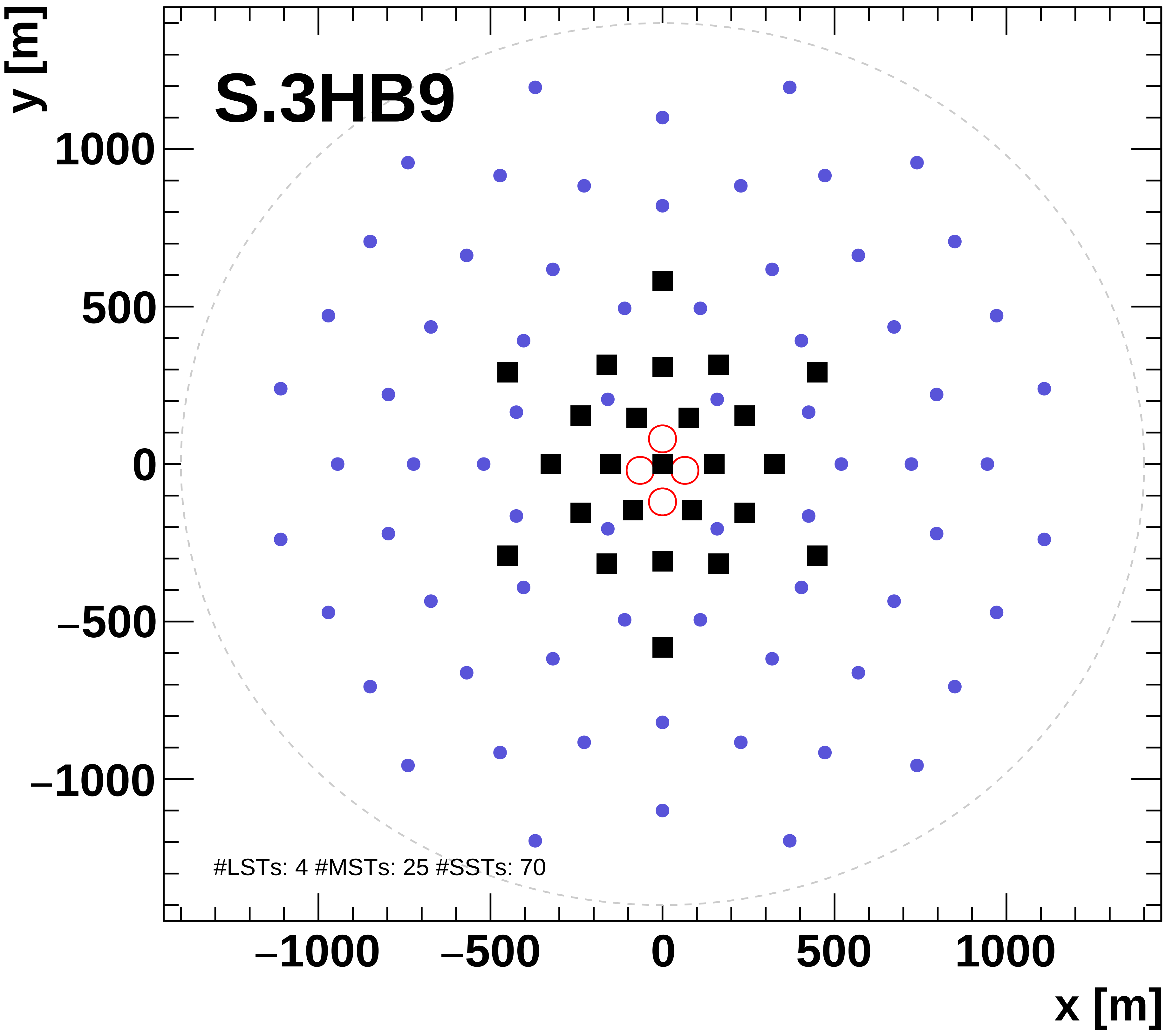
Small-size telescope
4-5 m diameter
>5 TeV
large field of view
large collection area



Gamma-ray effective area



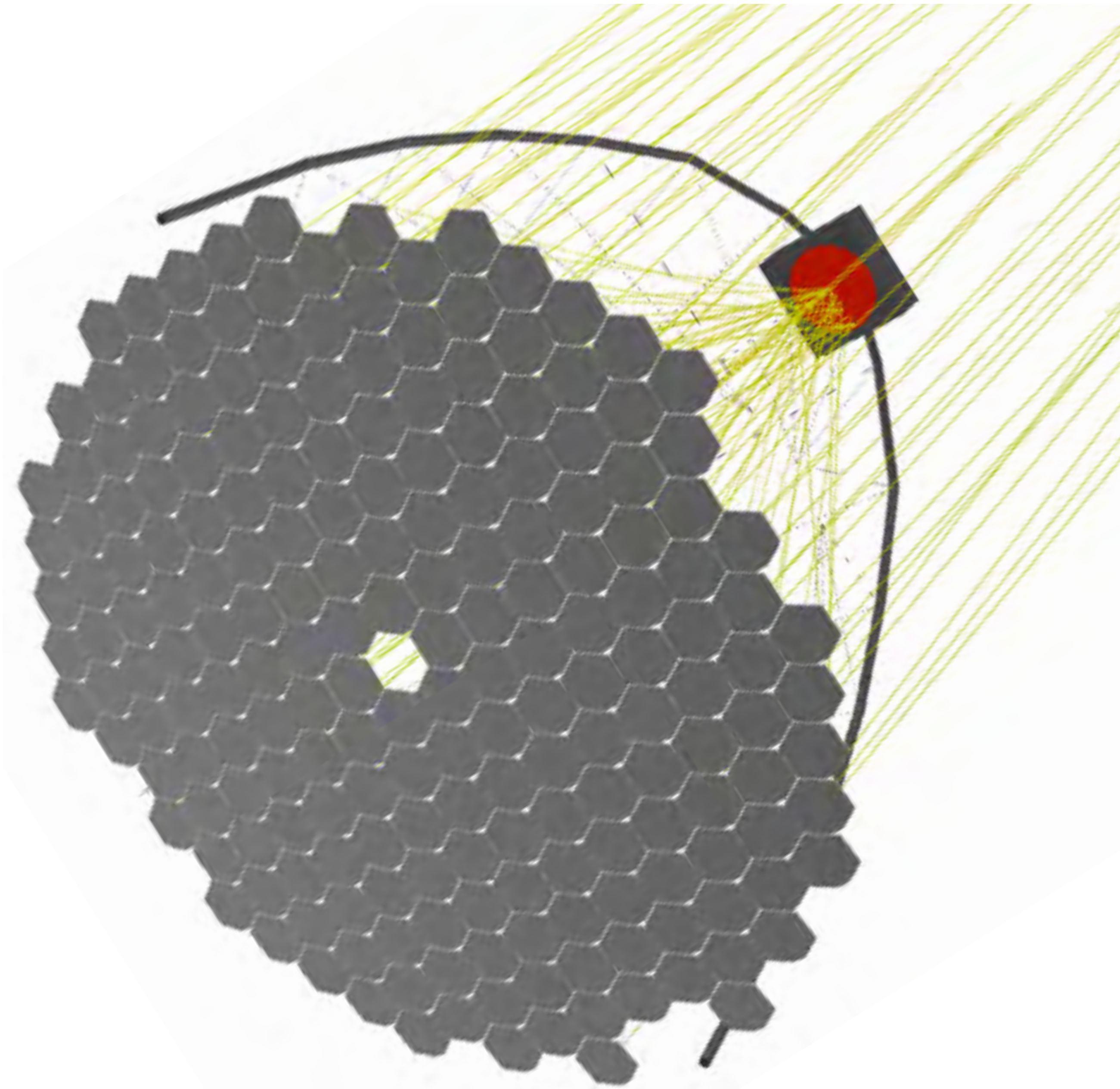
CTA Layout

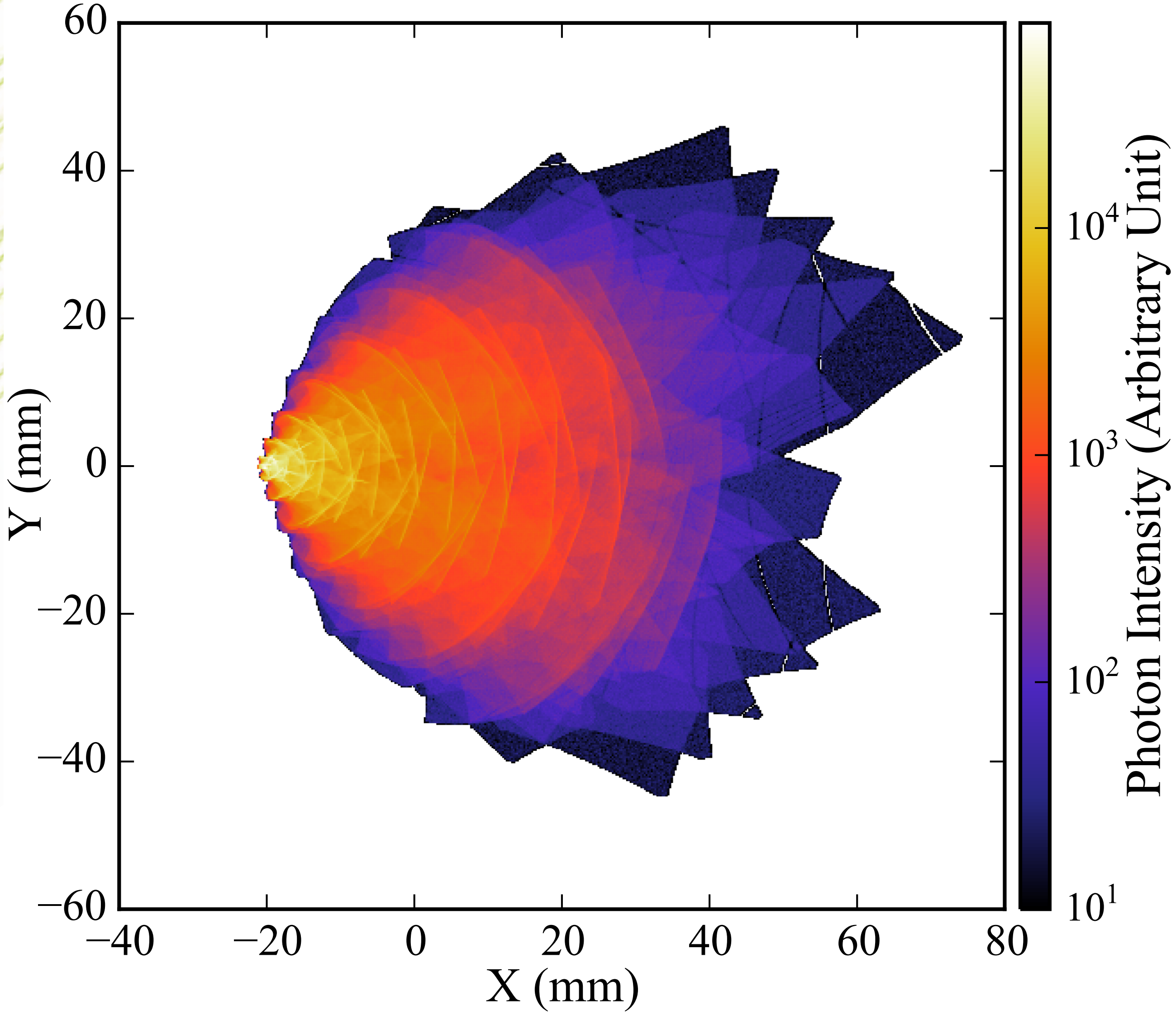

S.3HB9
y [m]
1000
500
0
–500
–1000
–1000
–500
0
500
1000
x [m]
#LSTs: 4 #MSTs: 25 #SSTs: 70

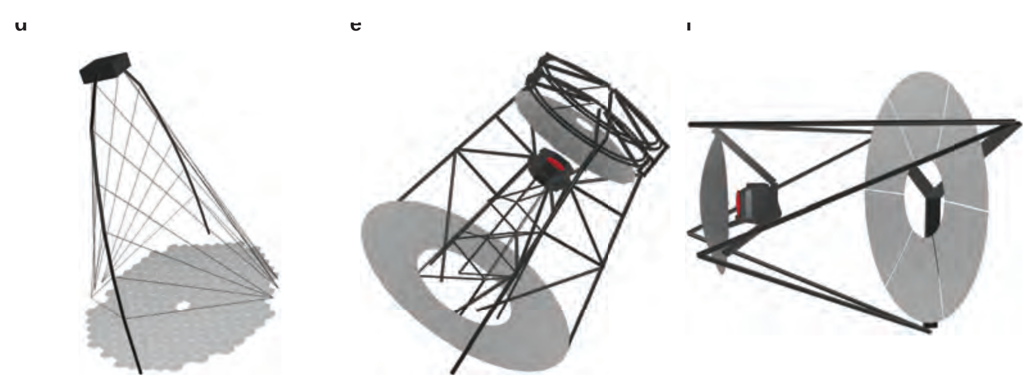
Telescope Simulations

Optical Ray-tracing

By Koji Noda







Digitisation, Trigger, Readout

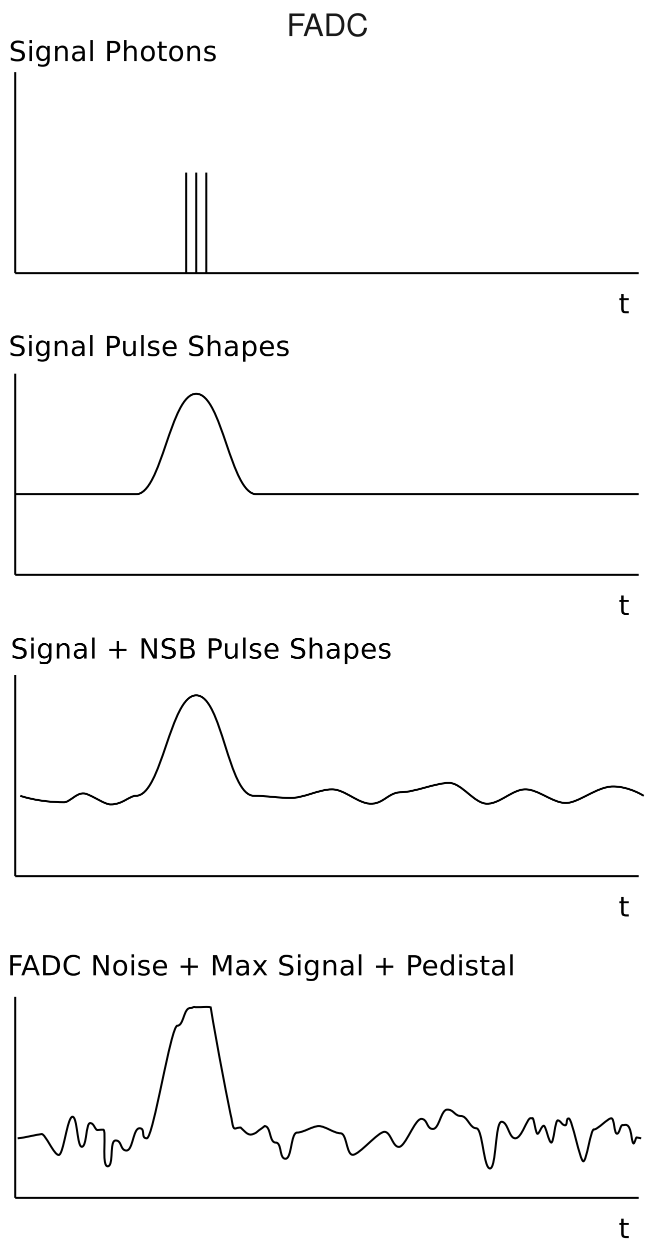
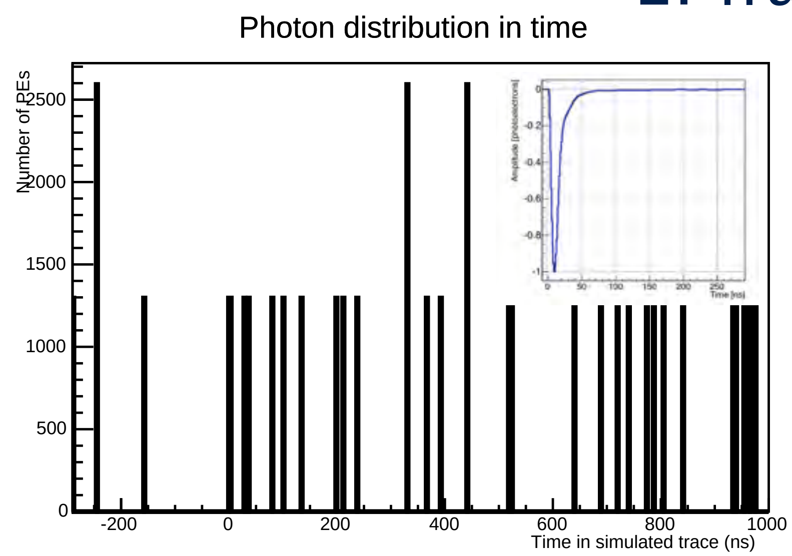
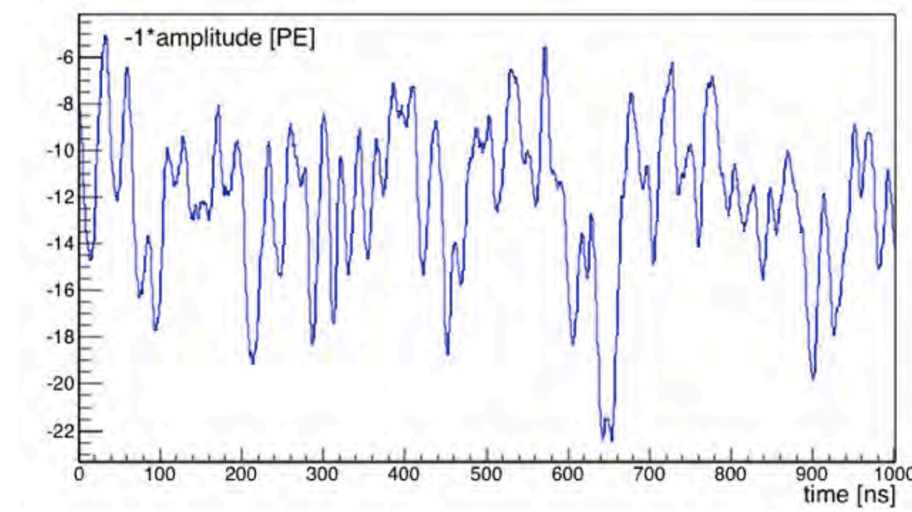


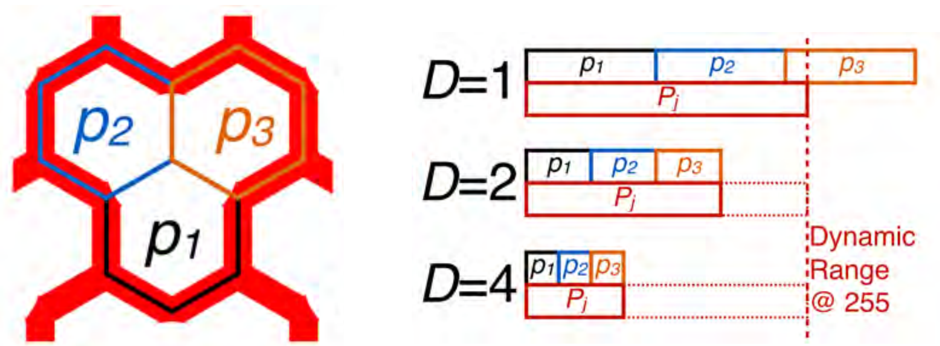
Figure 2 – Very simple illustration of the FADC signal creation.

1. Trace Generation

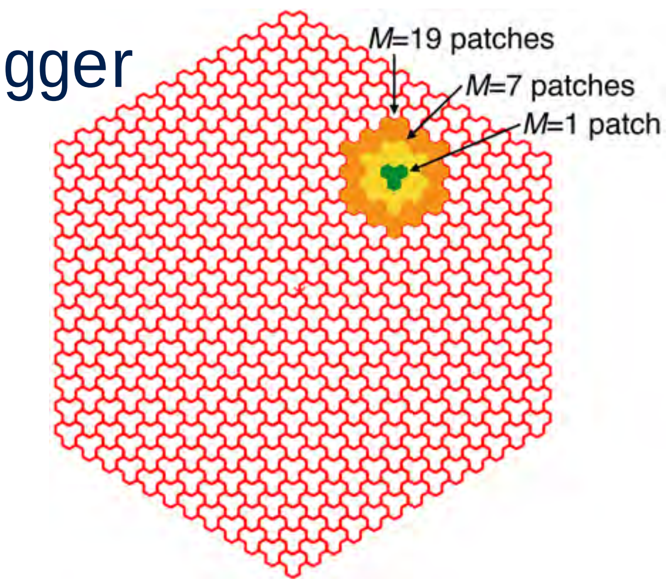




2. Digitization

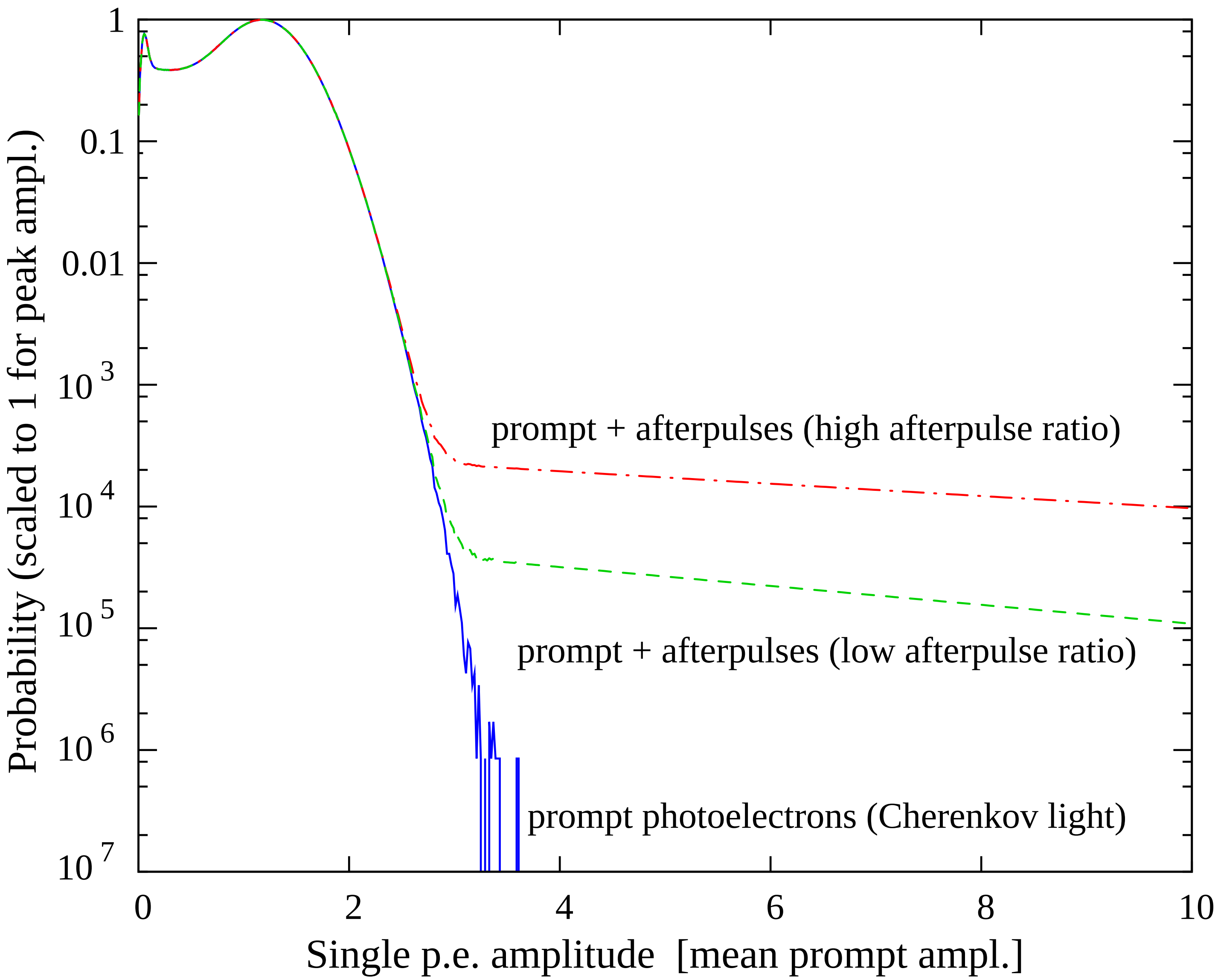


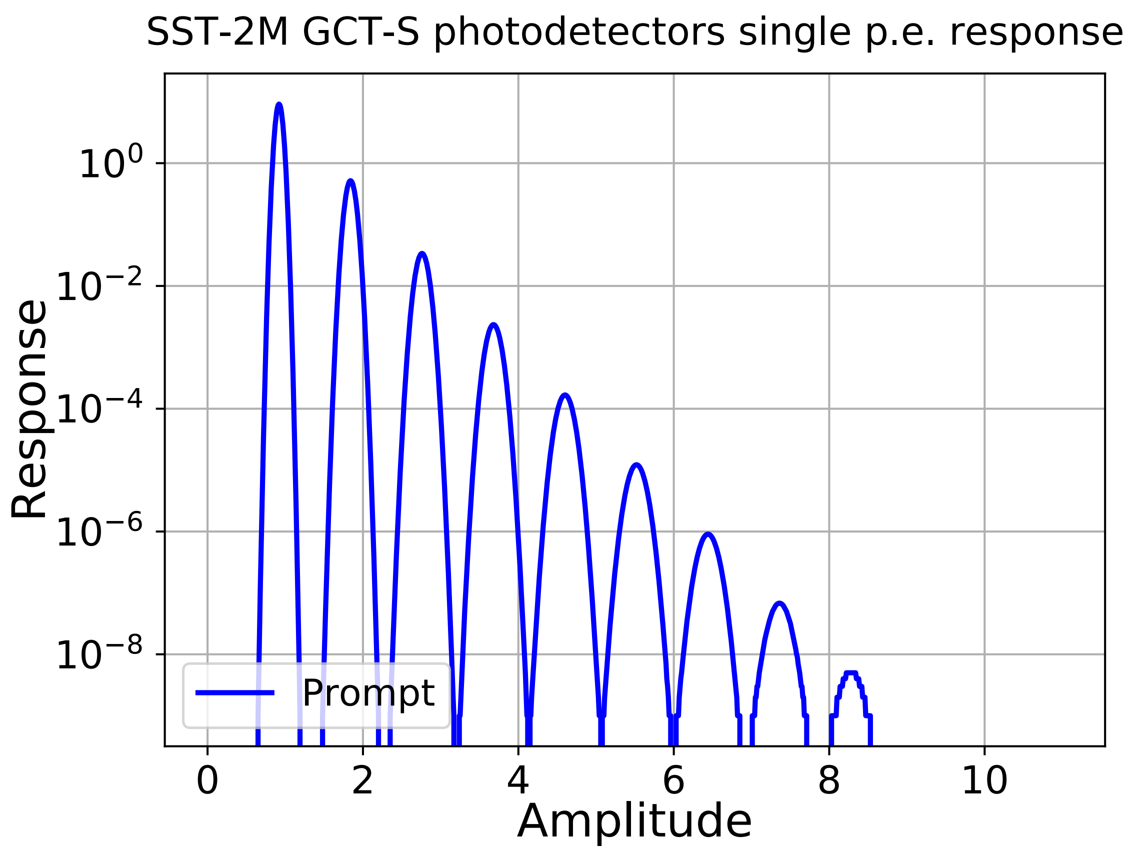
3. Trigger



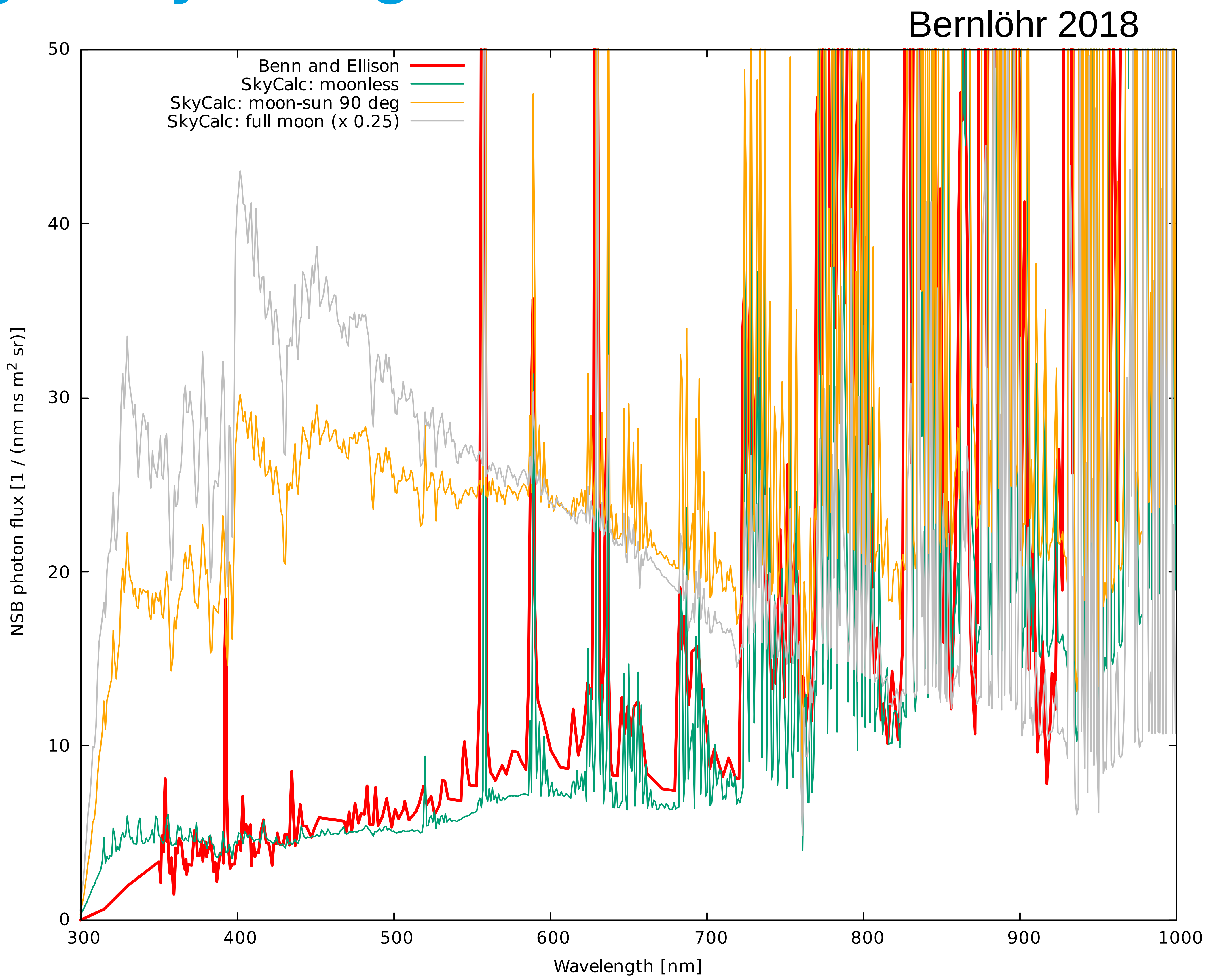
Al Samari 2015

Amplitude distributions

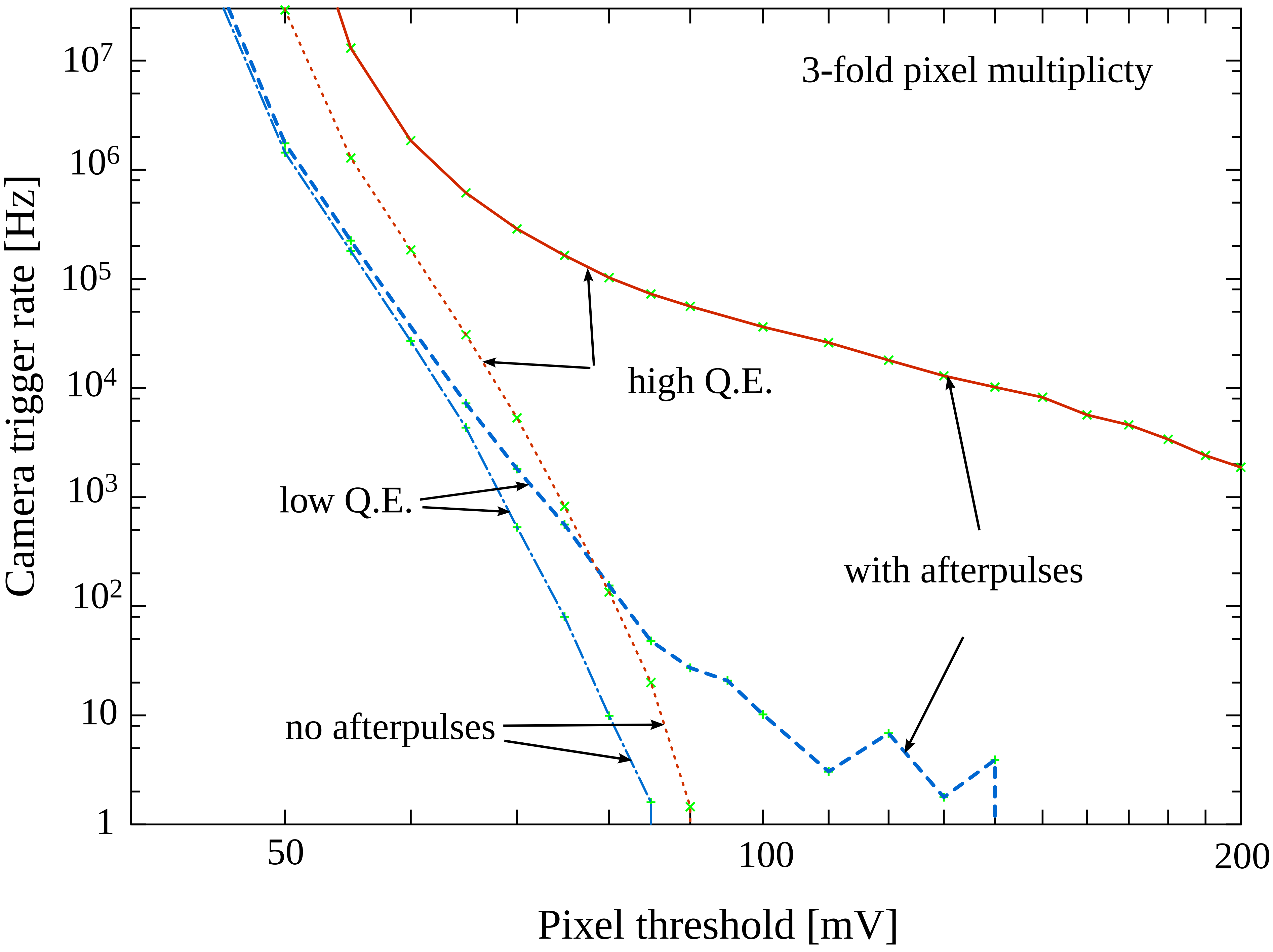




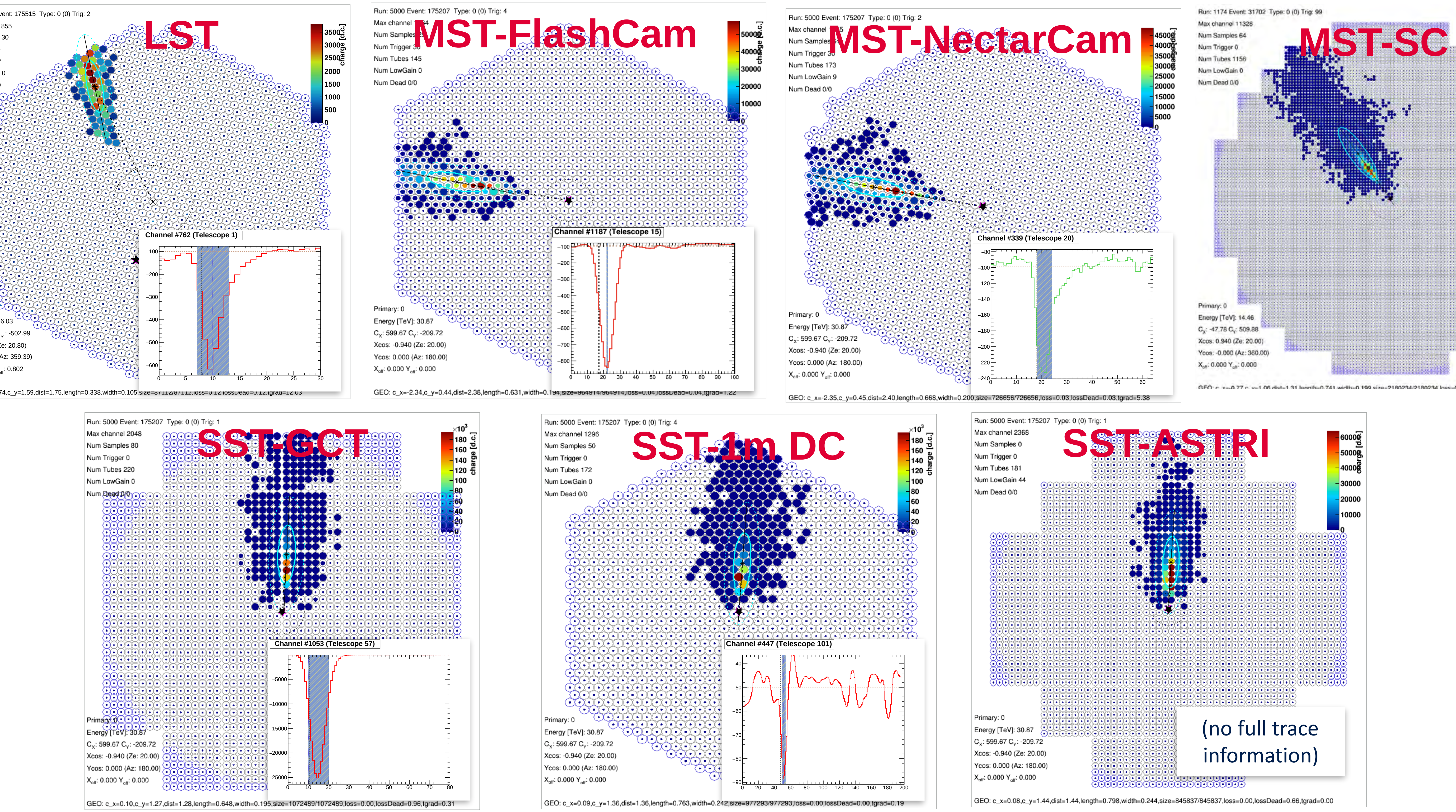
Night-sky background



Camera trigger rates



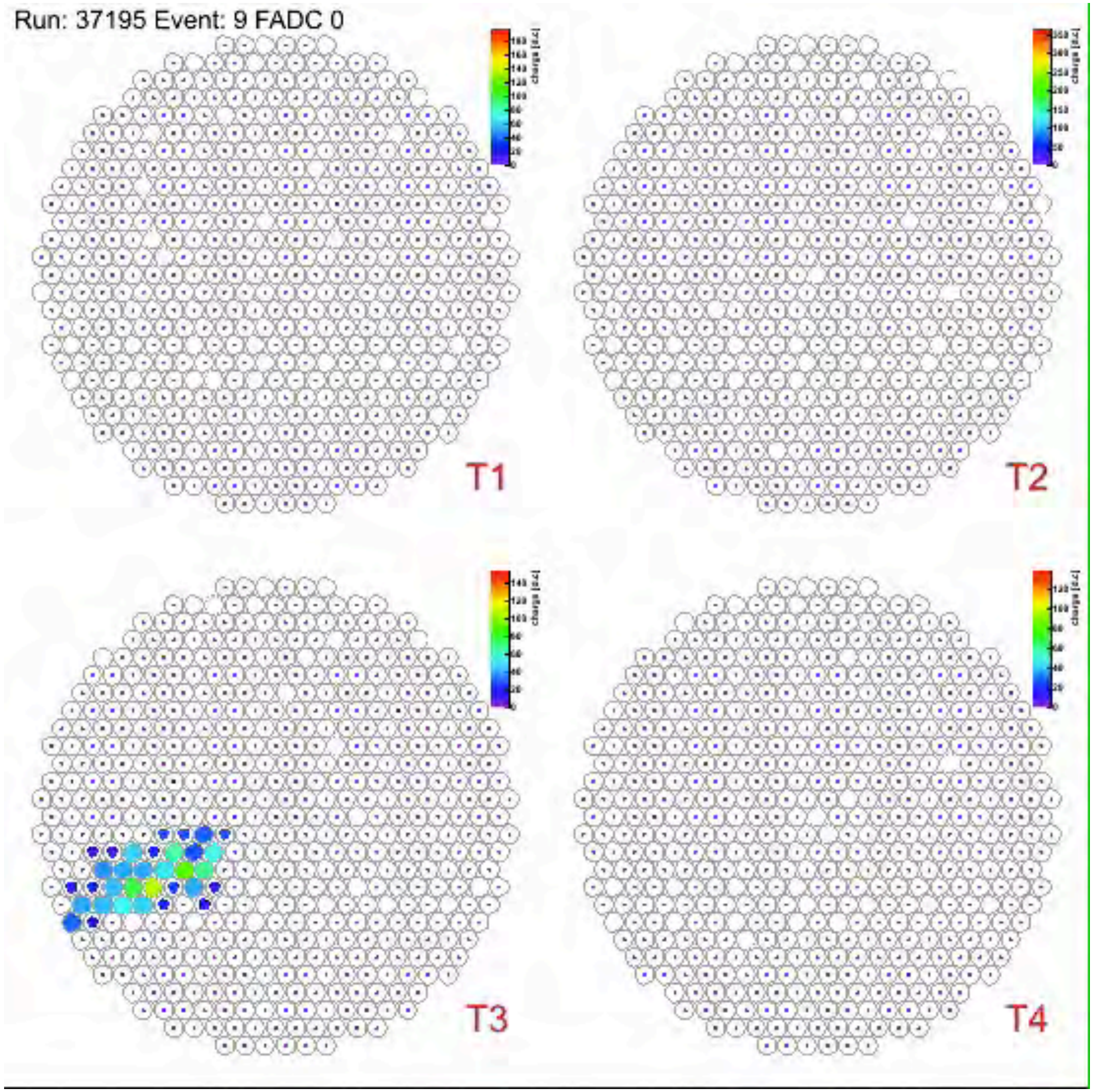
CTA Zoo of Cameras



Typical Events

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

event display VERITAS



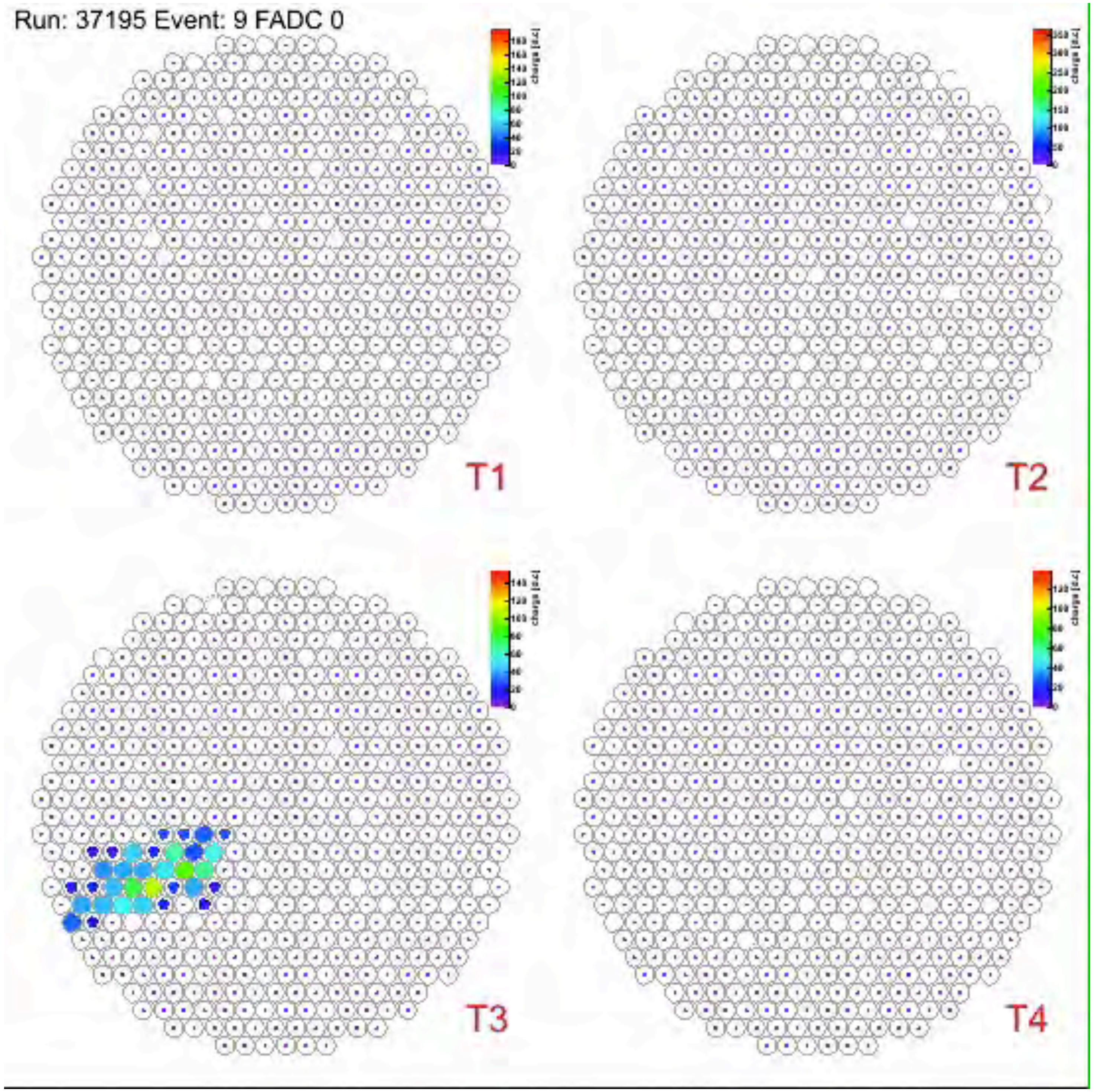
about every 100th event is a γ-ray

(each frame 2 ns long)

Typical Events

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

event display VERITAS

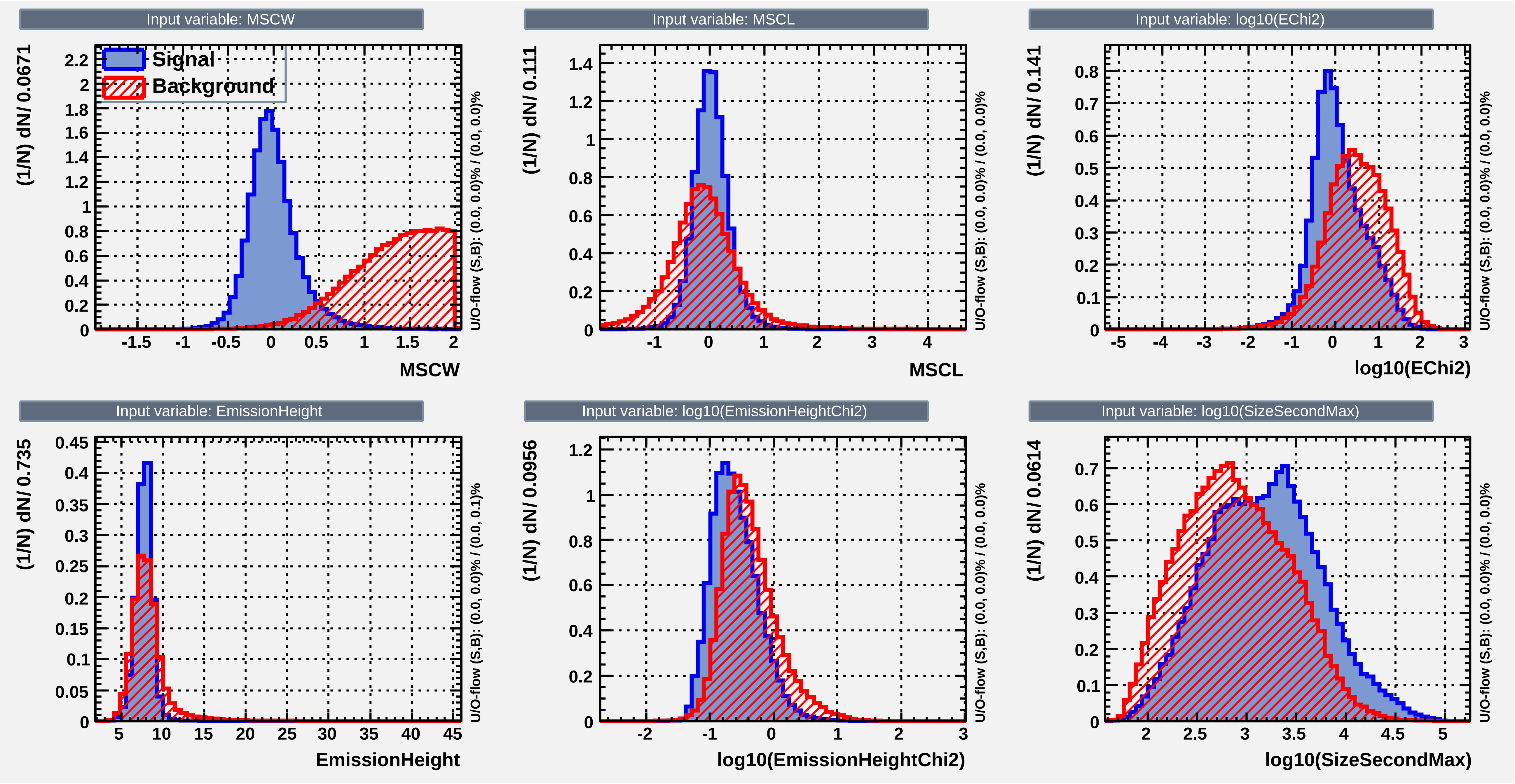


about every 100th event is a γ-ray

(each frame 2 ns long)

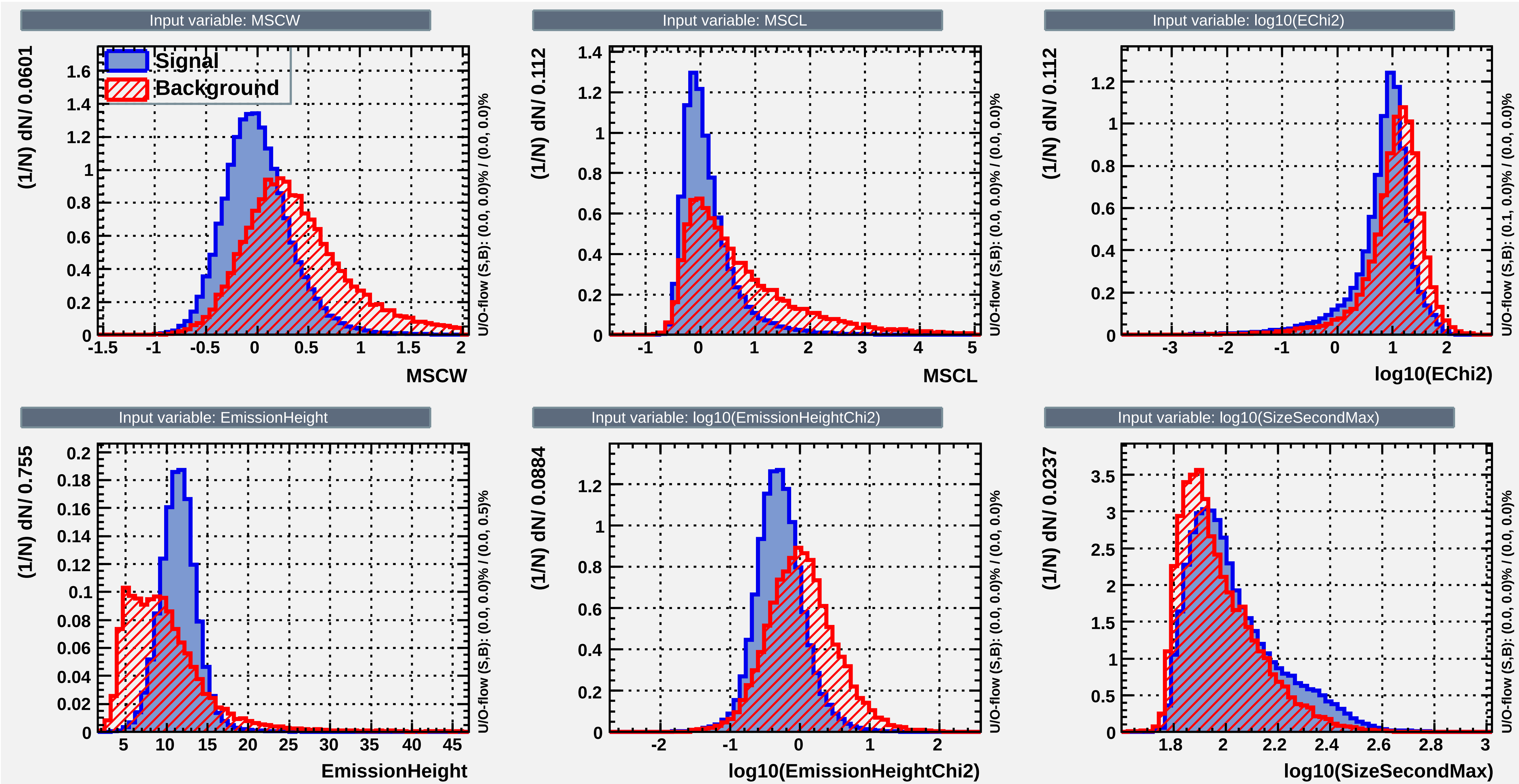
Gamma-hadron separation

reconstructed energies roughly 10 TeV



Gamma-hadron separation

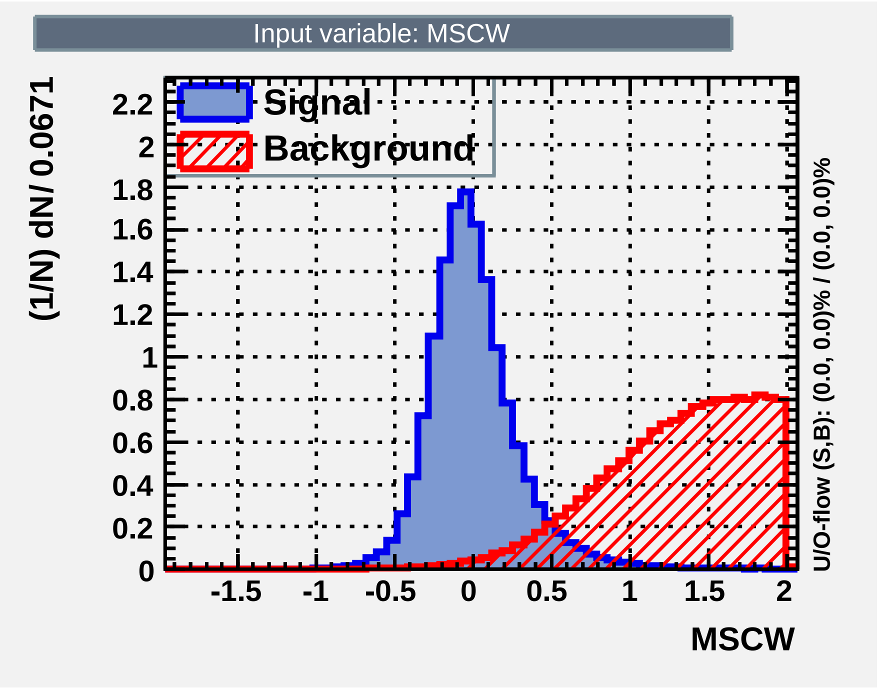
reconstructed energies roughly 60 GeV



Background Suppression

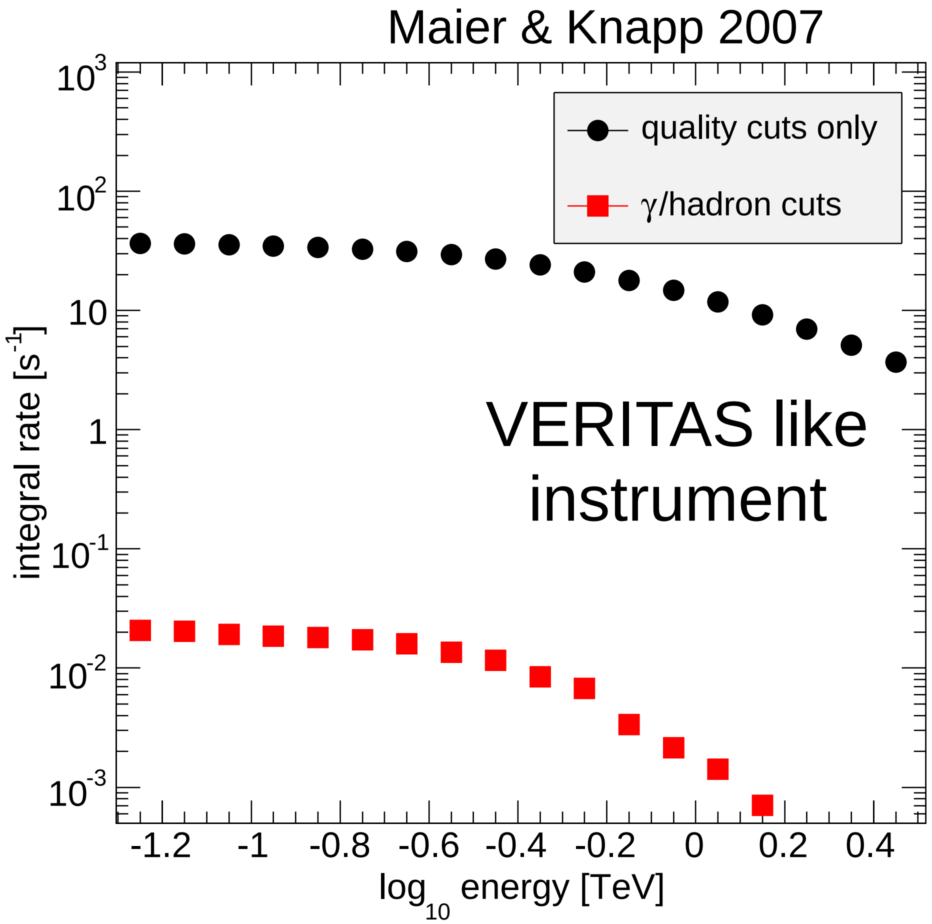
- **Imaging atmospheric Cherenkov telescope are extremely powerful in suppressing background hadronic events**

Triggered : Reconstructed : After Cuts =   400 Hz : 350 Hz : <1 Hz

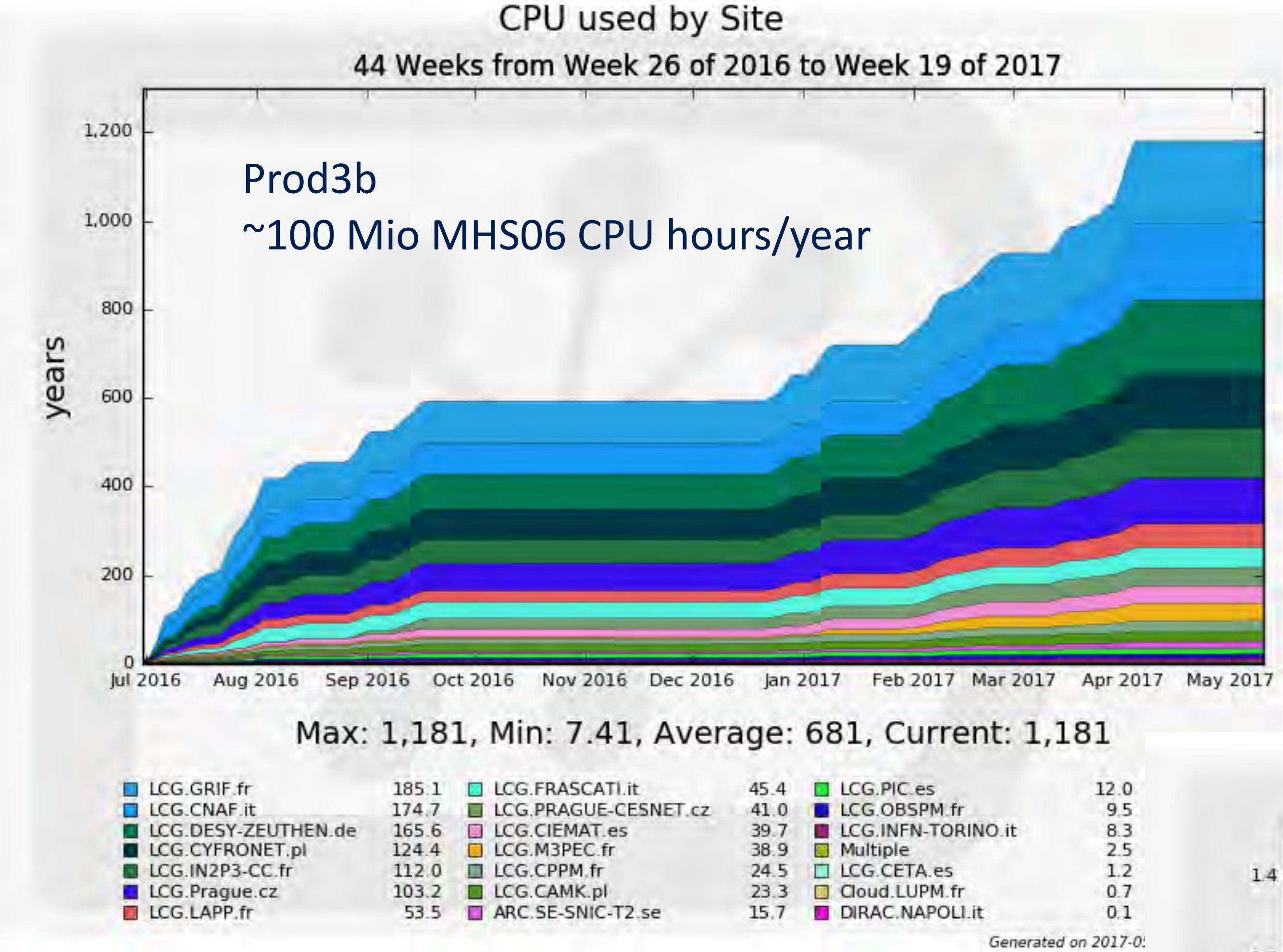


- **large MC productions required for instrument design optimisation:** e.g. for CTA:
  - ~100 billion proton events 4 GeV - 600 TeV
  - 0.5-1 Petabyte of detector simulation output

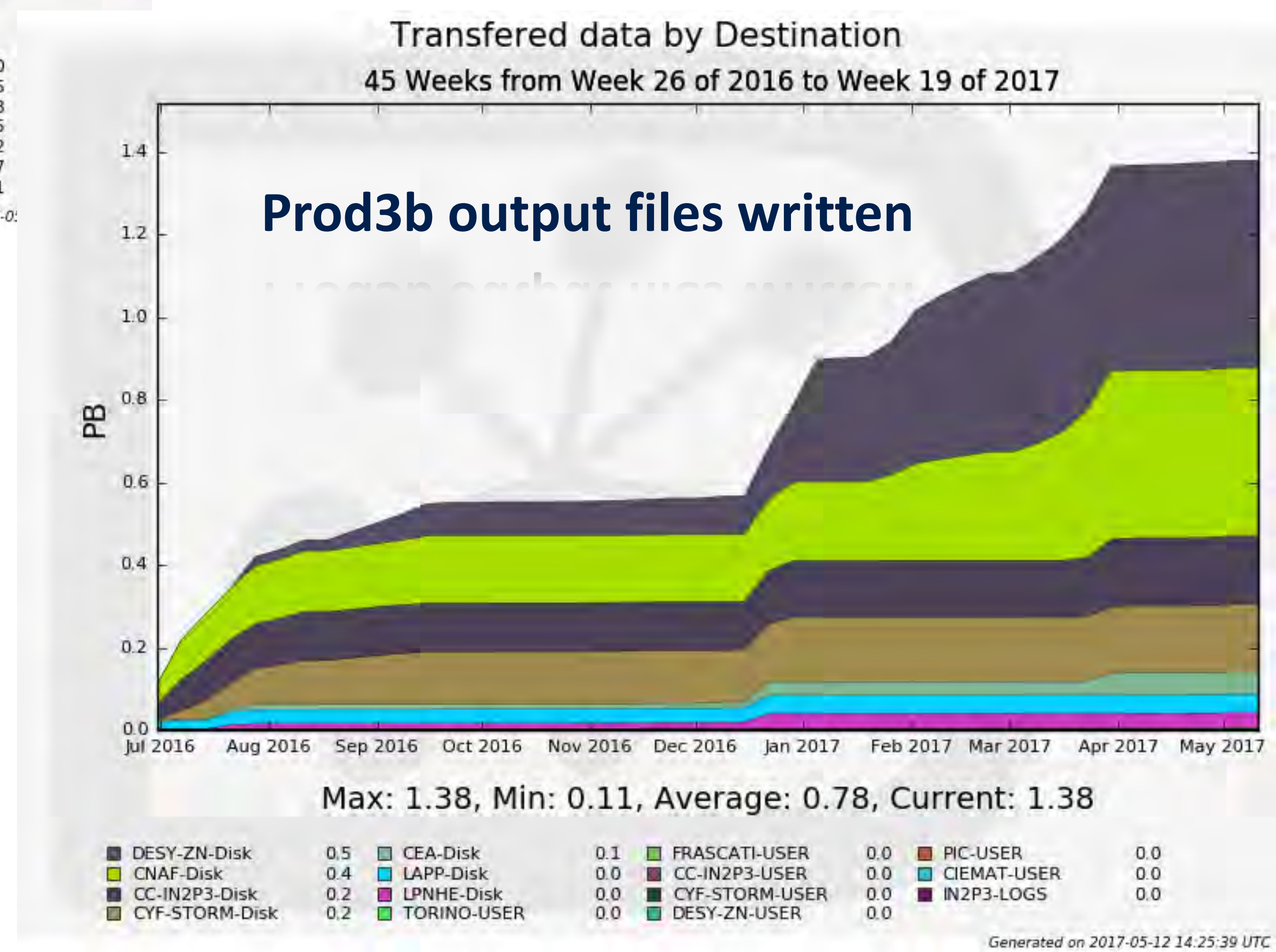
Remaining background: gamma-ray like proton events



Computing

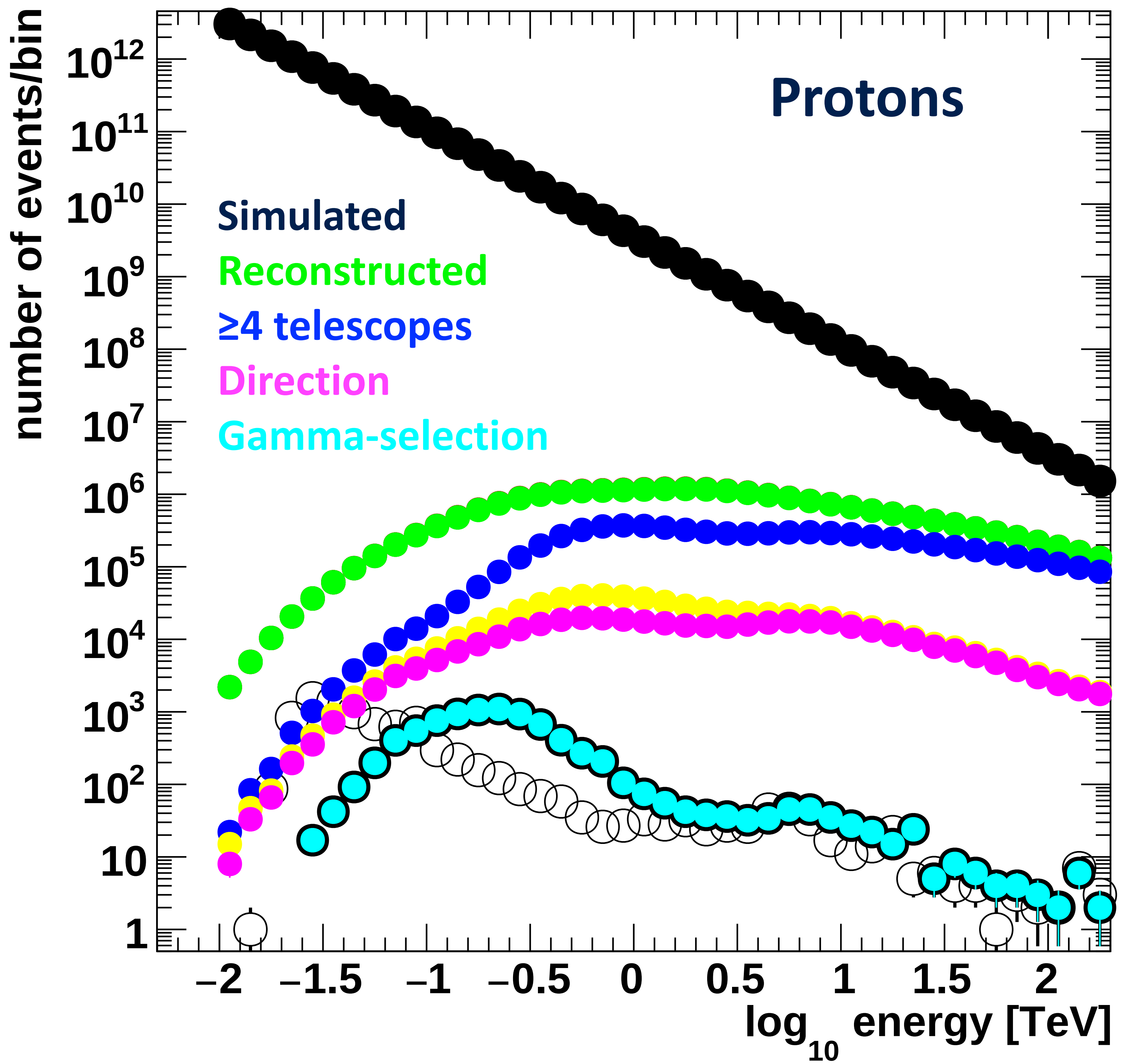


CPU used by Site
44 Weeks from Week 26 of 2016 to Week 19 of 2017
Prod3b
~100 Mio MHS06 CPU hours/year
years
0
200
400
600
800
1,000
1,200
Jul 2016
Aug 2016
Sep 2016
Oct 2016
Nov 2016
Dec 2016
Jan 2017
Feb 2017
Mar 2017
Apr 2017
May 2017
Max: 1,181, Min: 7.41, Average: 681, Current: 1,181
LCG.GRIF.fr 185.1
LCG.CNAF.it 174.7
LCG.DESY-ZEUTHEN.de 165.6
LCG.CYFRONET.pl 124.4
LCG.IN2P3-CC.fr 112.0
LCG.Prague.cz 103.2
LCG.LAPP.fr 53.5
LCG.FRASCATI.it 45.4
LCG.PRAGUE-CESNET.cz 41.0
LCG.CIEMAT.es 39.7
LCG.M3PEC.fr 38.9
LCG.CPPM.fr 24.5
LCG.CAMK.pl 23.3
ARC.SE-SNIC-T2.se 15.7
LCG.PIC.es 12.0
LCG.OBSPM.fr 9.5
LCG.INFN-TORINO.it 8.3
Multiple 2.5
LCG.CETA.es 1.2
Cloud.LUPM.fr 0.7
DIRAC.NAPOLI.it 0.1

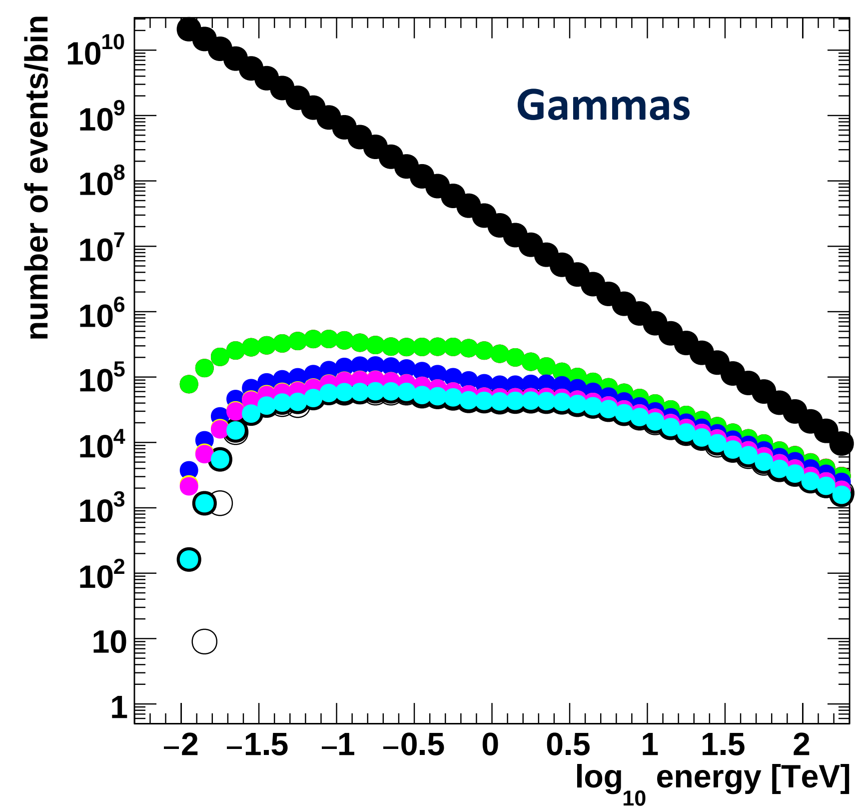


Transfered data by Destination
45 Weeks from Week 26 of 2016 to Week 19 of 2017
Prod3b output files written
PB
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Jul 2016
Aug 2016
Sep 2016
Oct 2016
Nov 2016
Dec 2016
Jan 2017
Feb 2017
Mar 2017
Apr 2017
May 2017
Max: 1.38, Min: 0.11, Average: 0.78, Current: 1.38
DESY-ZN-Disk 0.5
CNAF-Disk 0.4
CC-IN2P3-Disk 0.2
CYF-STORM-Disk 0.2
CEA-Disk 0.1
LAPP-Disk 0.0
LPNHE-Disk 0.0
TORINO-USER 0.0
FRASCATI-USER 0.0
CC-IN2P3-USER 0.0
CYF-STORM-USER 0.0
DESY-ZN-USER 0.0
PIC-USER 0.0
CIEMAT-USER 0.0
IN2P3-LOGS 0.0
Generated on 2017-05-12 14:25:39 UTC

Background suppression

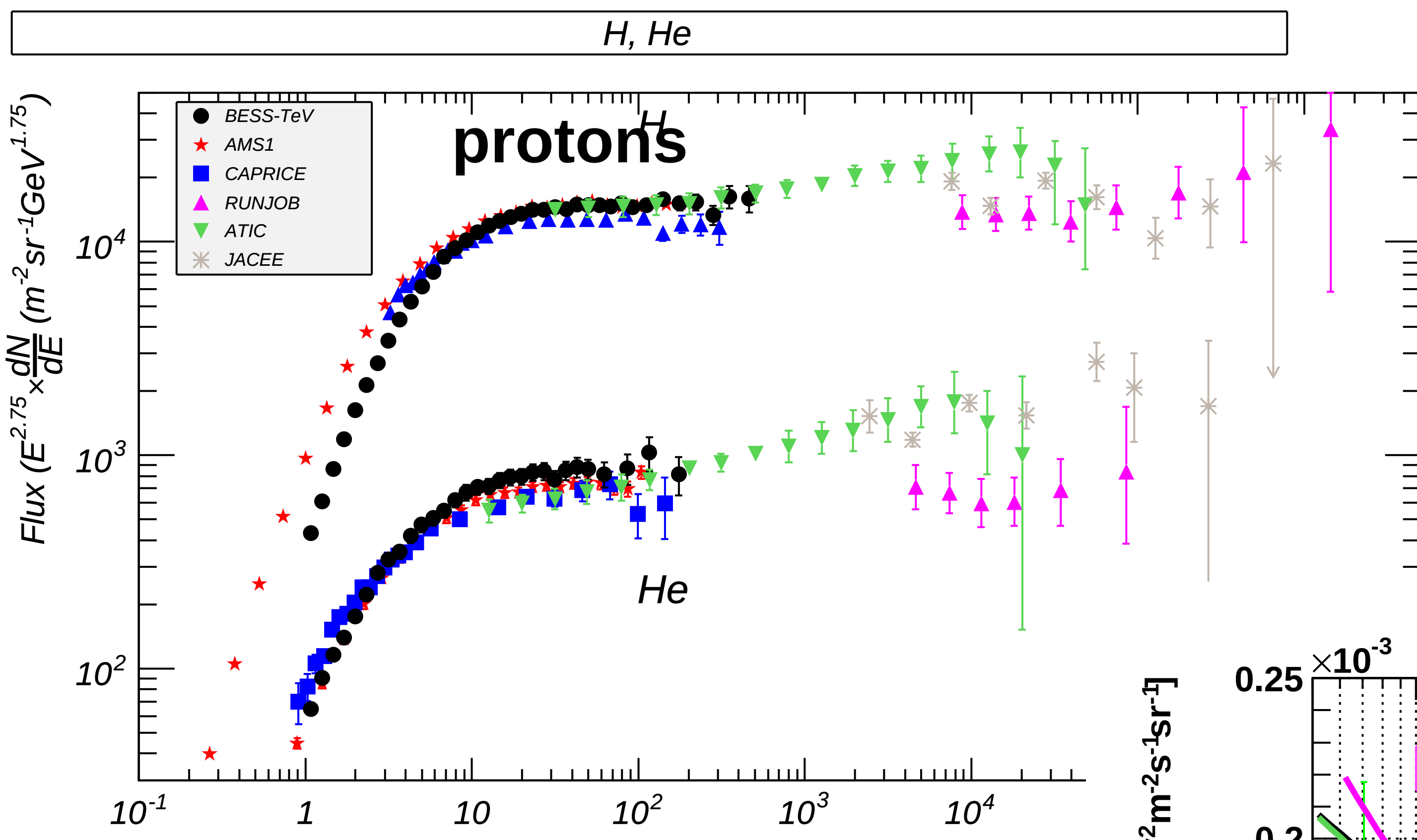


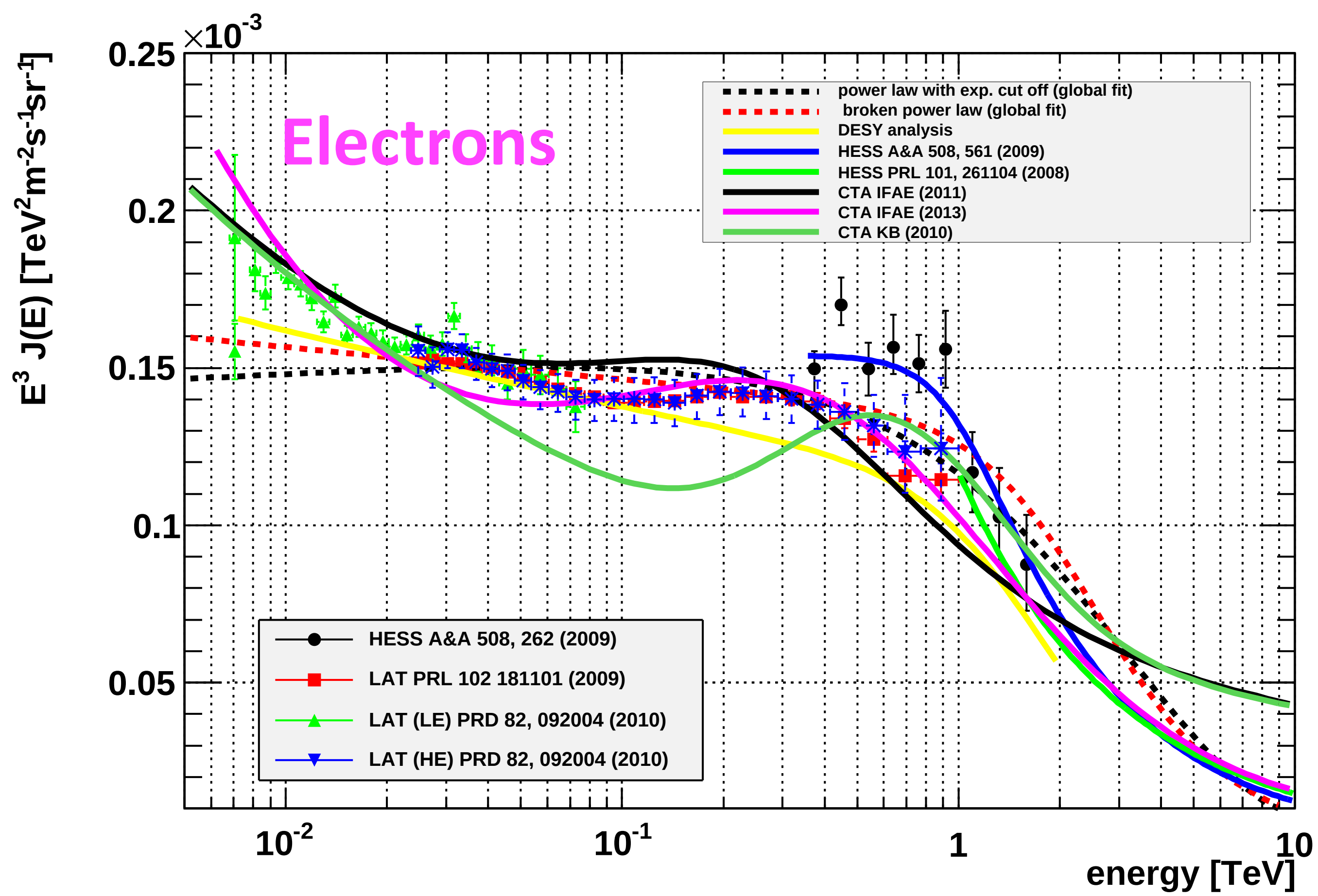
Less than 10,000 proton events left after all cuts…
(and each MC shower has been used 10 times)



(note that plots depend heavily on scatter area for the core numbers)

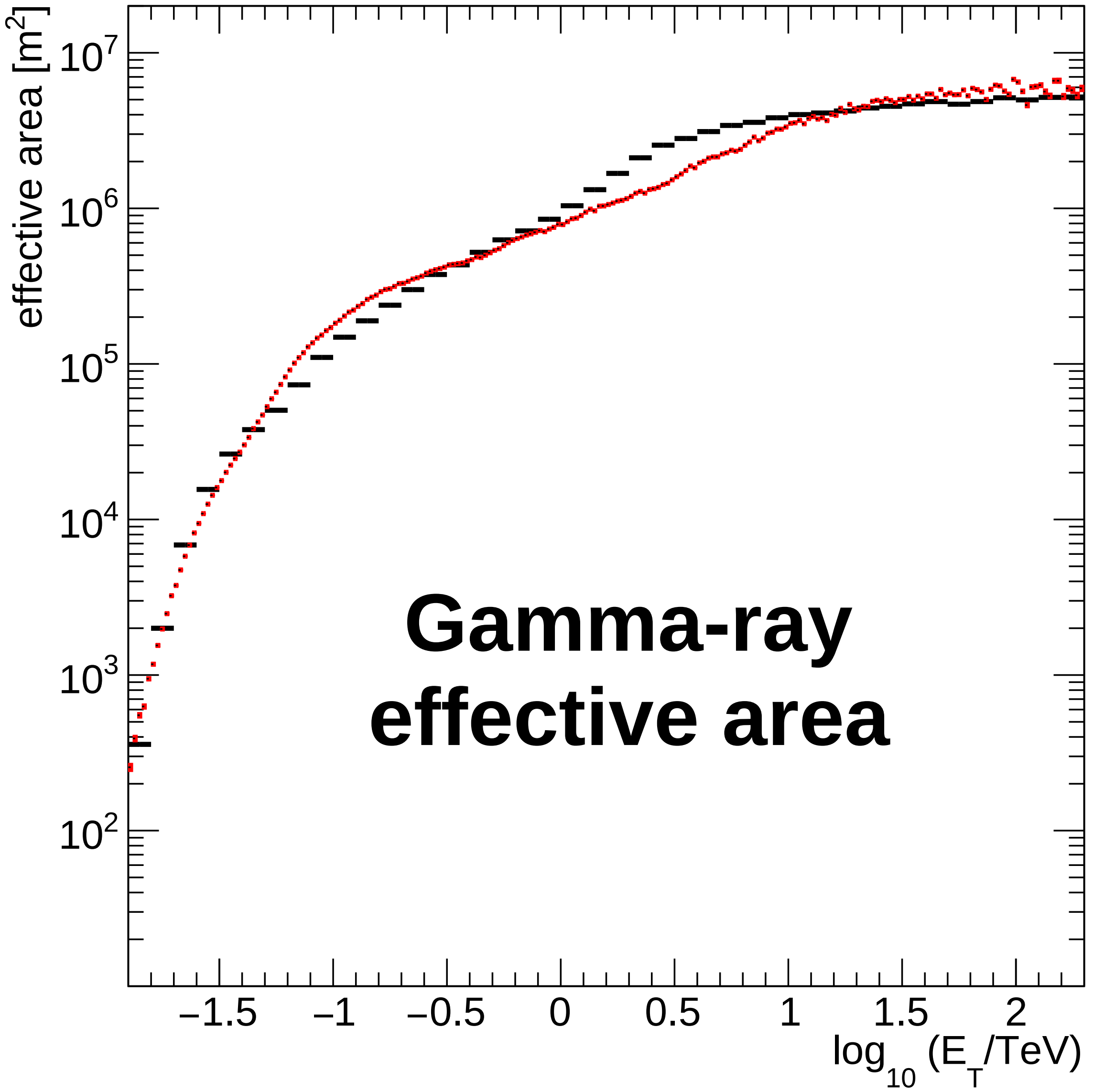
Cosmic ray background



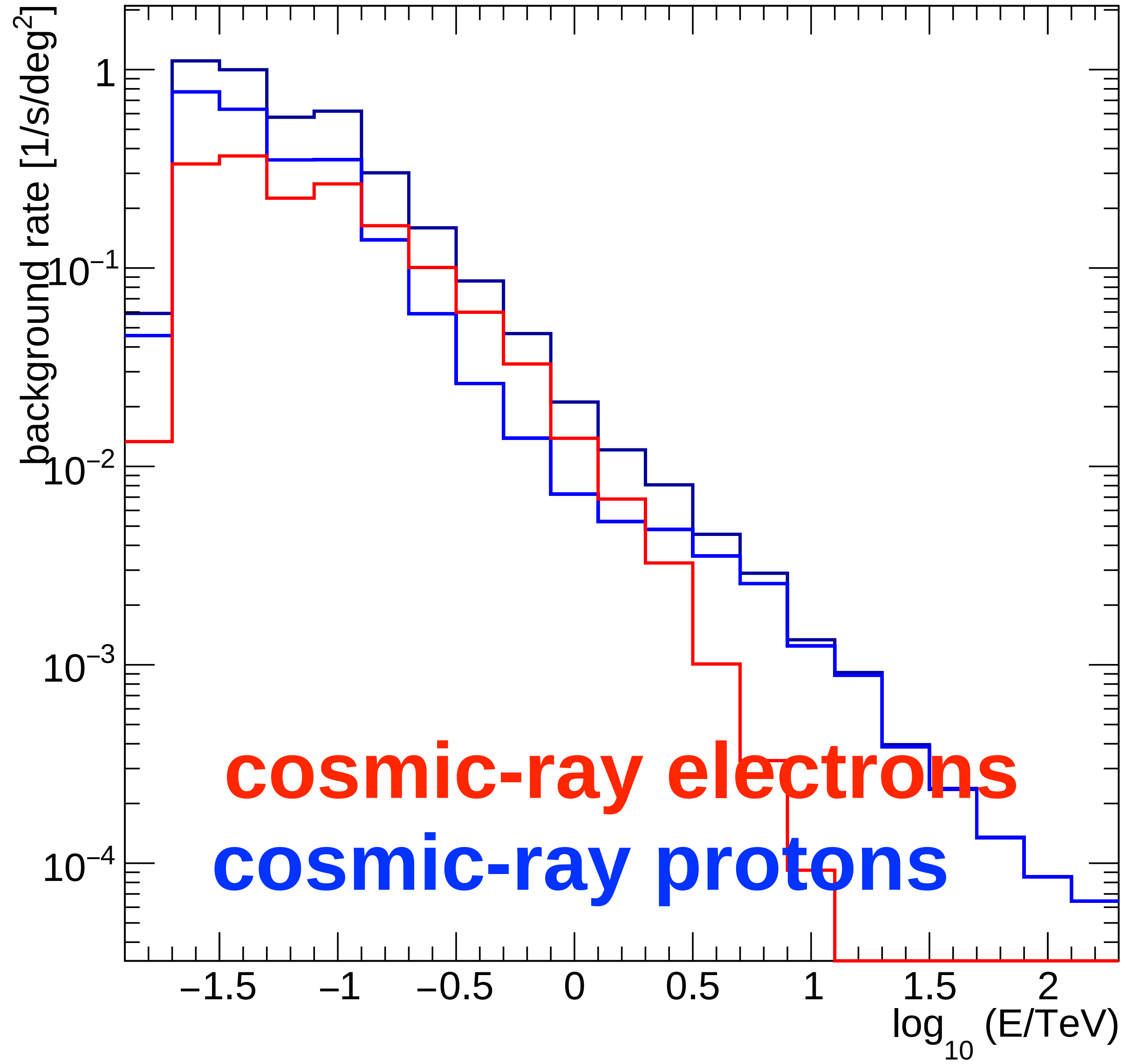


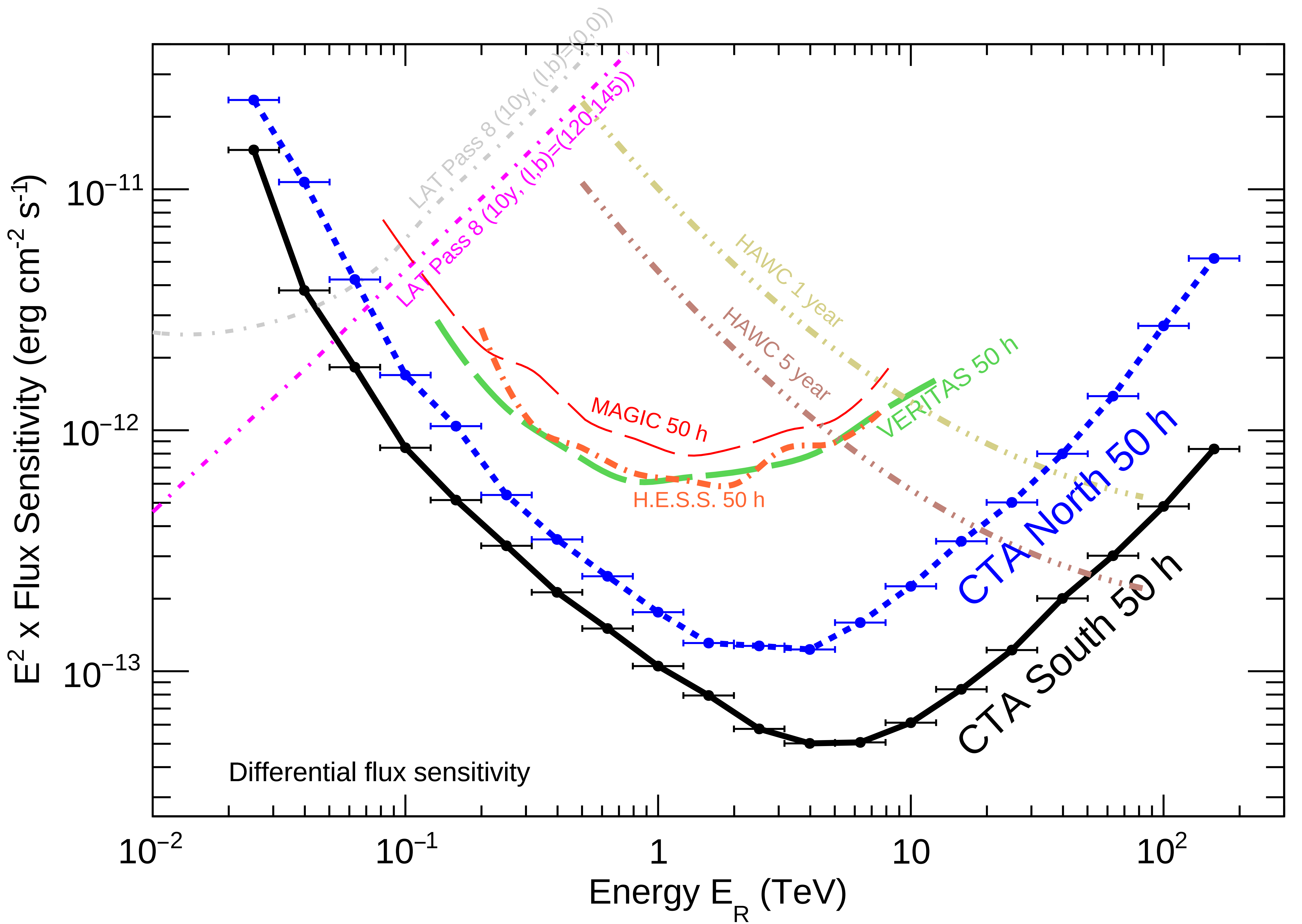
CTA Sensitivity

Signal



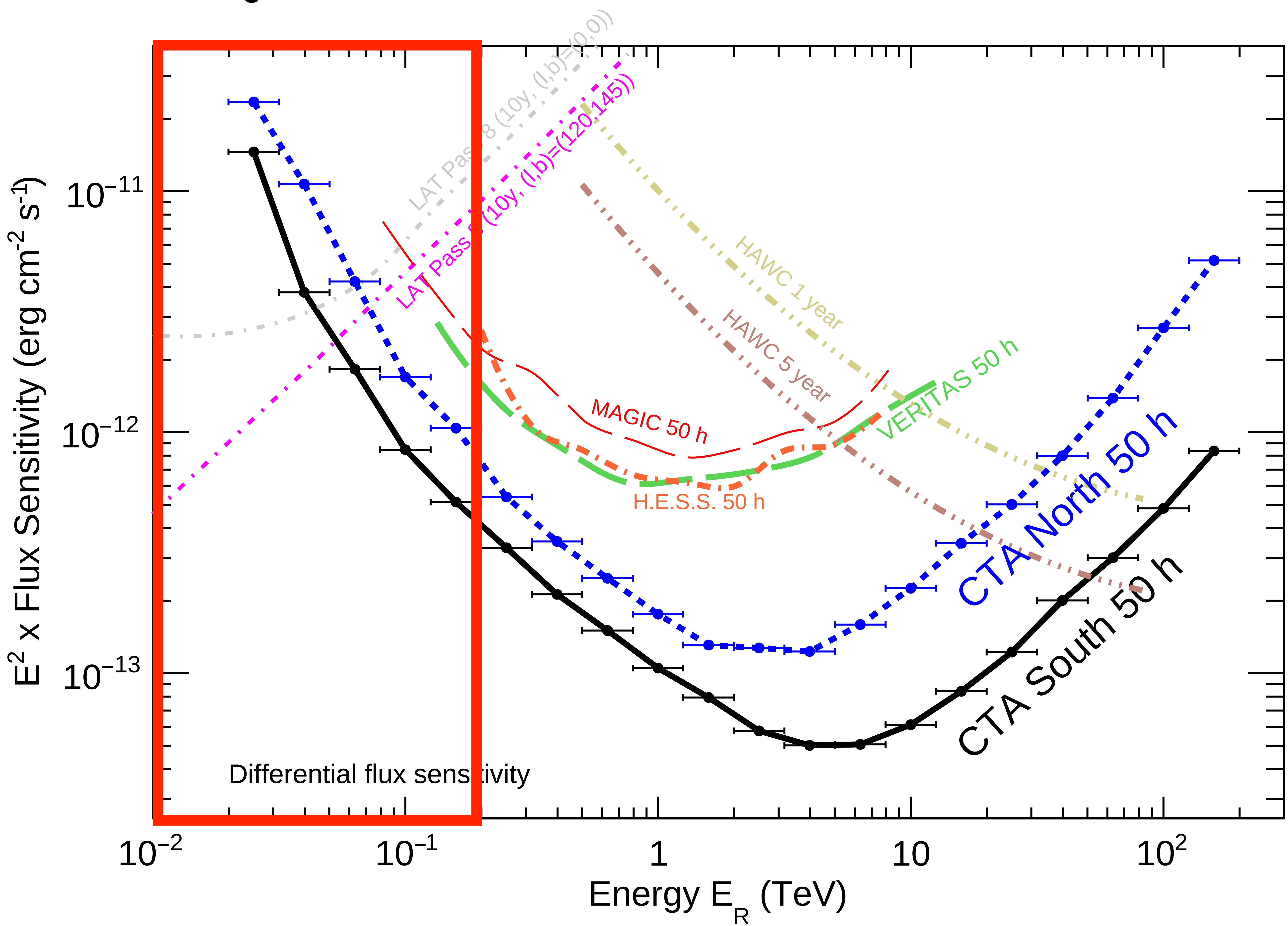
Background

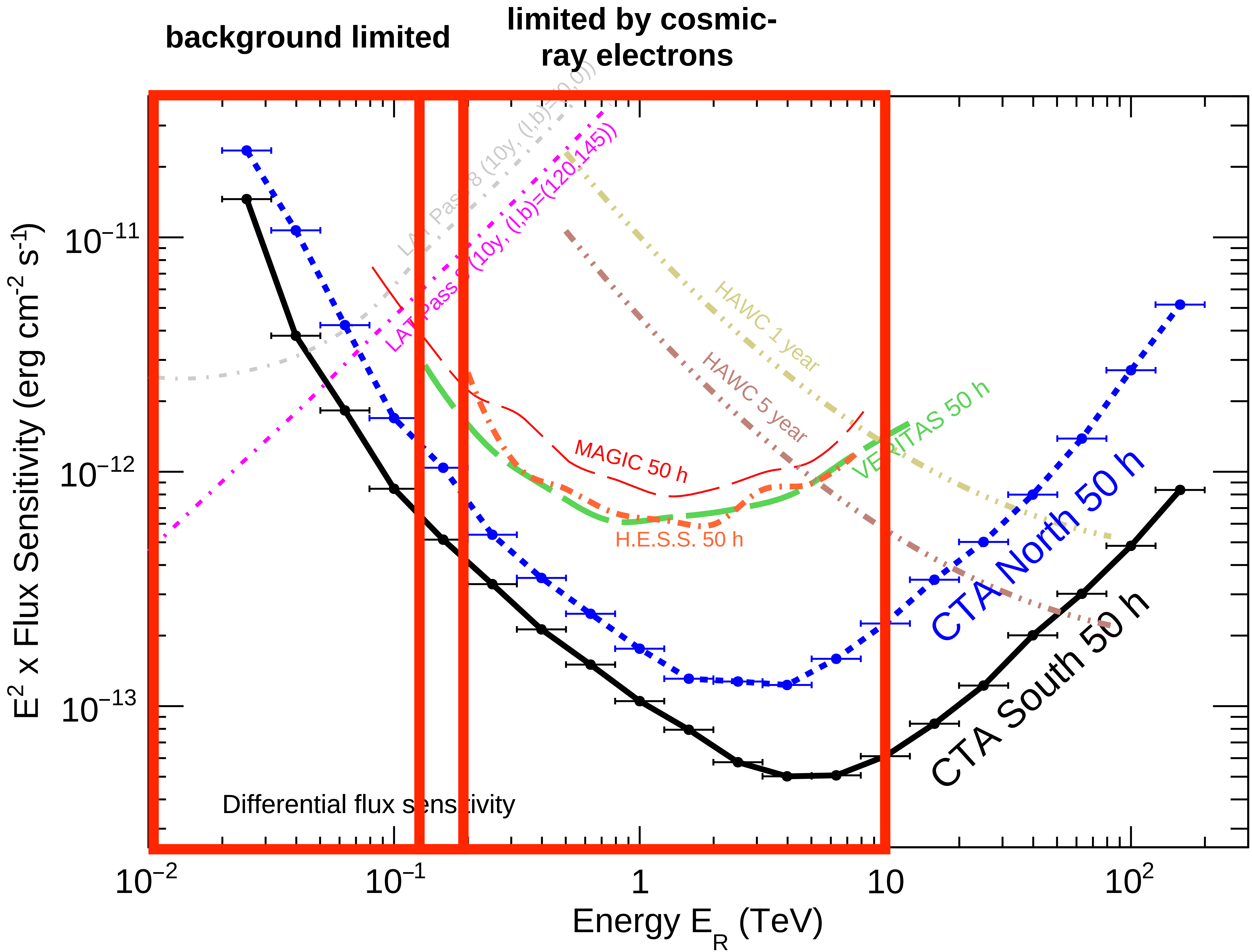


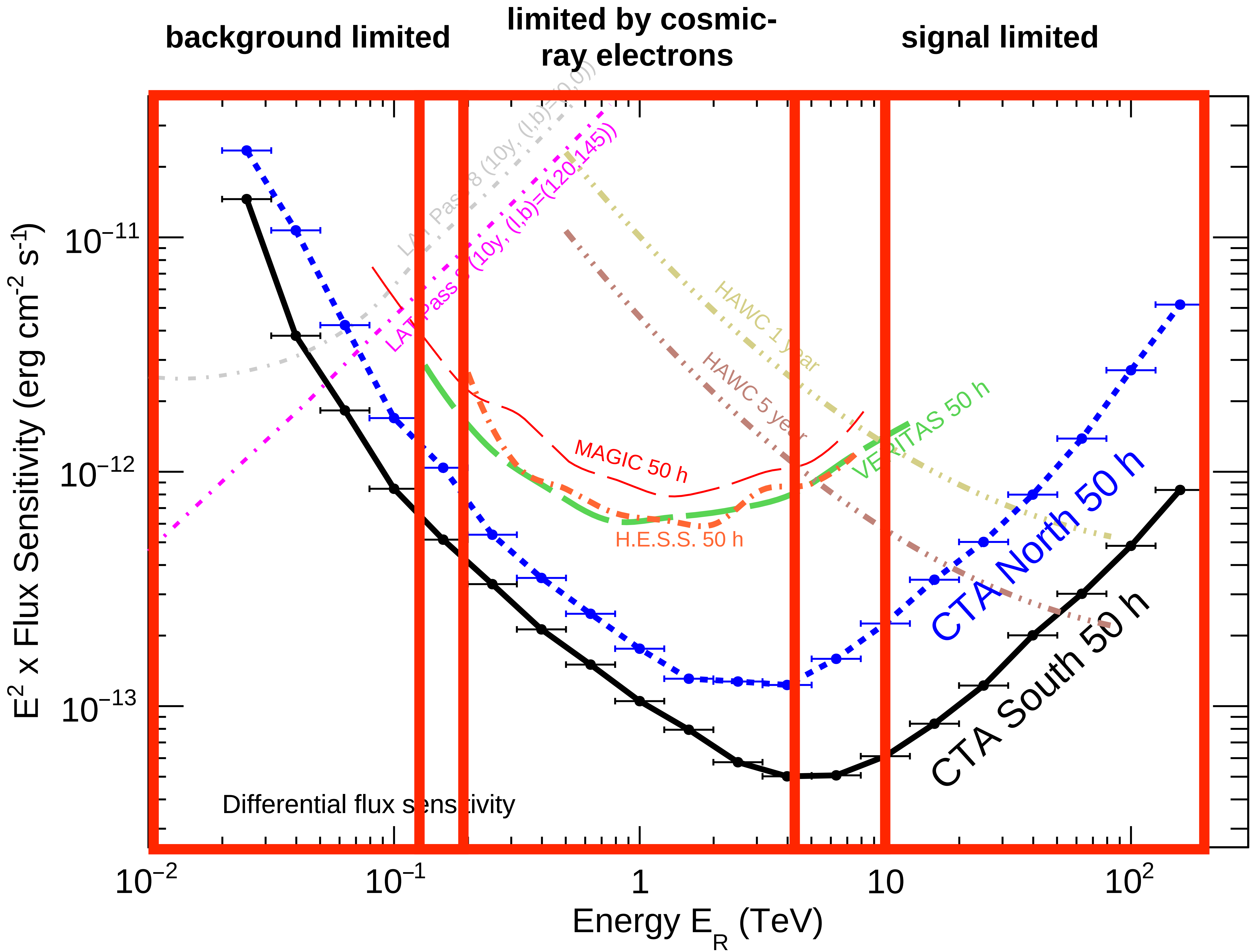


E² x Flux Sensitivity (erg cm⁻² s⁻¹)
Energy E_R (TeV)
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻²
10⁻¹
1
10
10²
LAT Pass 8 (10y, (l,b)=(0,0))
LAT Pass 8 (10y, (l,b)=(120,45))
HAWC 1 year
HAWC 5 year
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
CTA North 50 h
CTA South 50 h
Differential flux sensitivity

background limited

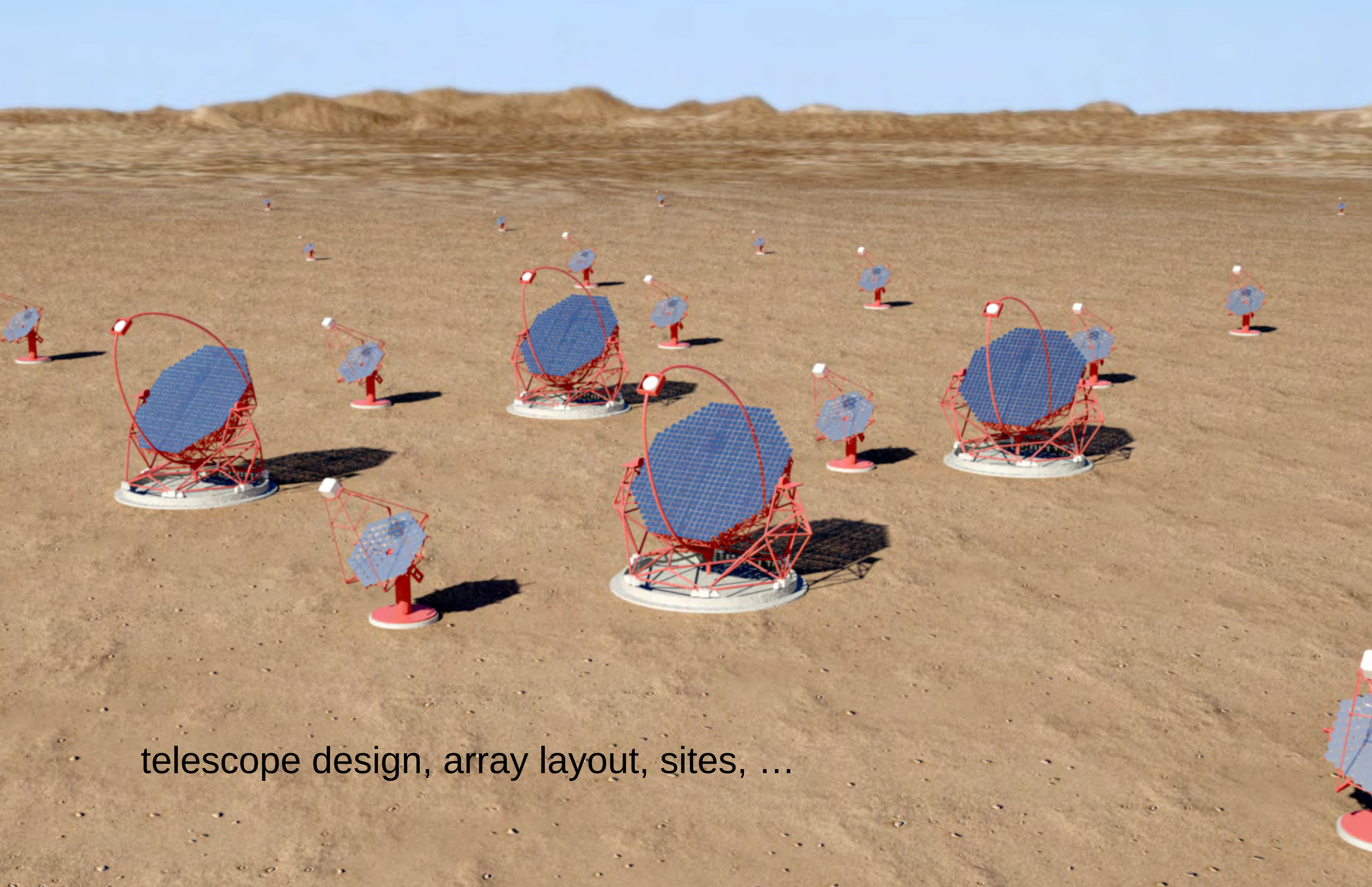



background limited
limited by cosmic-ray electrons
E^2 x Flux Sensitivity (erg cm^-2 s^-1)
10^-11
10^-12
10^-13
Energy E_R (TeV)
10^-2
10^-1
1
10
10^2
LAT Pass 8 (10y, (l,b)=(0,0))
LAT Pass 8 (10y, (l,b)=(120,45))
HAWC 1 year
HAWC 5 year
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
CTA North 50 h
CTA South 50 h
Differential flux sensitivity



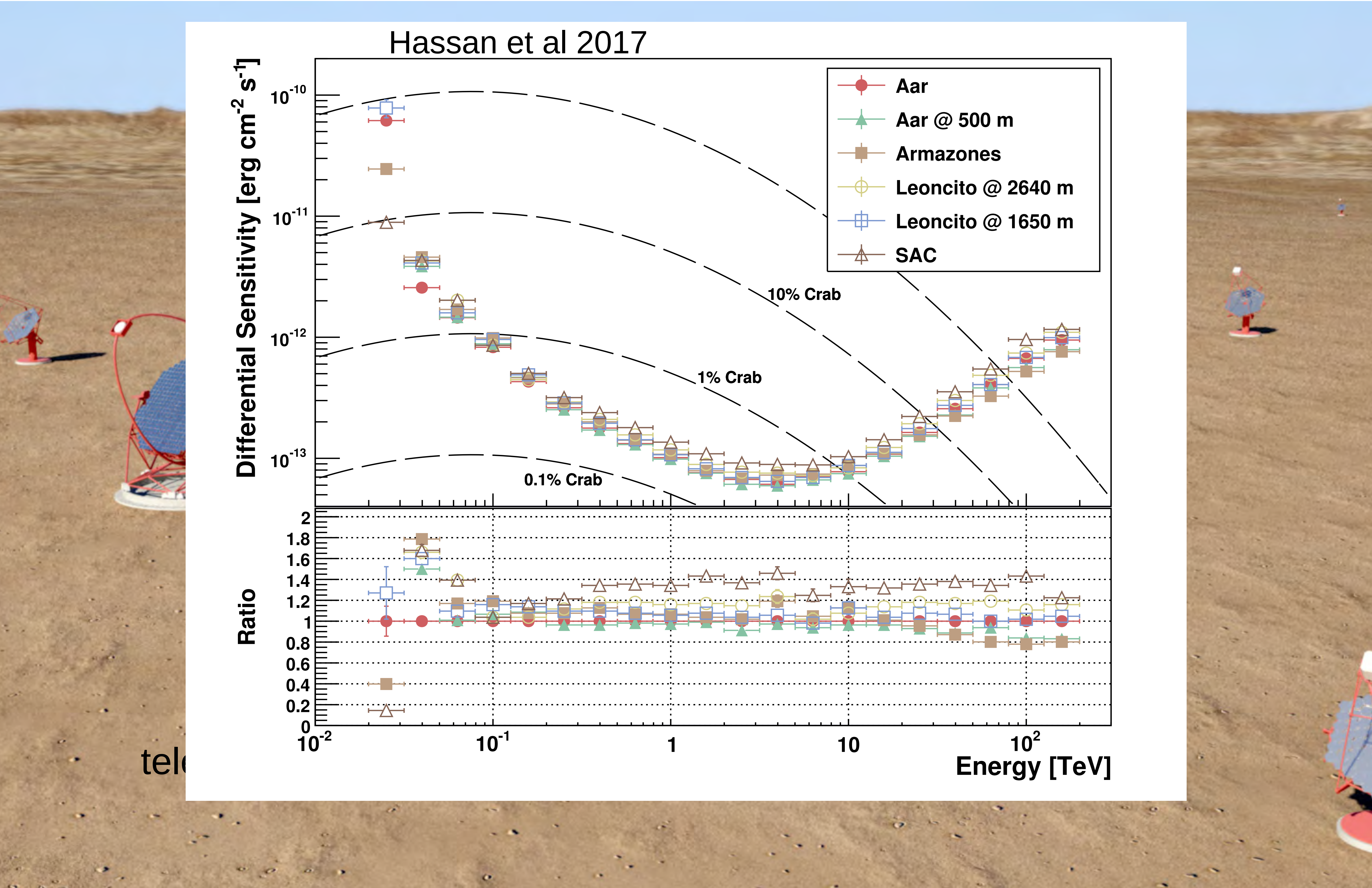
background limited
limited by cosmic-ray electrons
signal limited
E^2 x Flux Sensitivity (erg cm^-2 s^-1)
10^-11
10^-12
10^-13
10^-2
10^-1
1
10
10^2
Energy E_R (TeV)
MAGIC 50 h
H.E.S.S. 50 h
VERITAS 50 h
HAWC 1 year
HAWC 5 year
CTA North 50 h
CTA South 50 h
Differential flux sensitivity

Instrument Design and Optimisation



telescope design, array layout, sites, …

Instrument Design and Optimisation

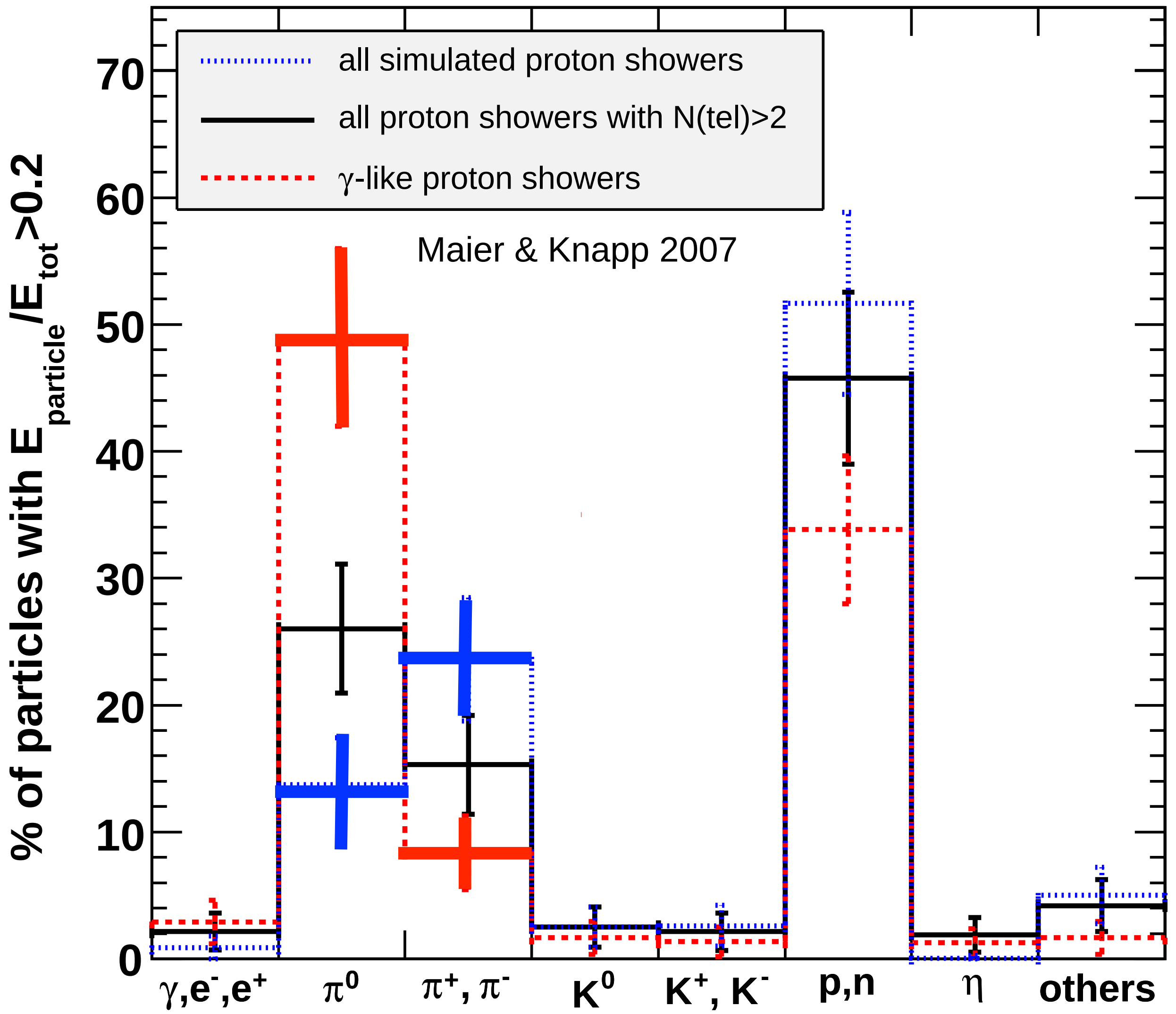


tele

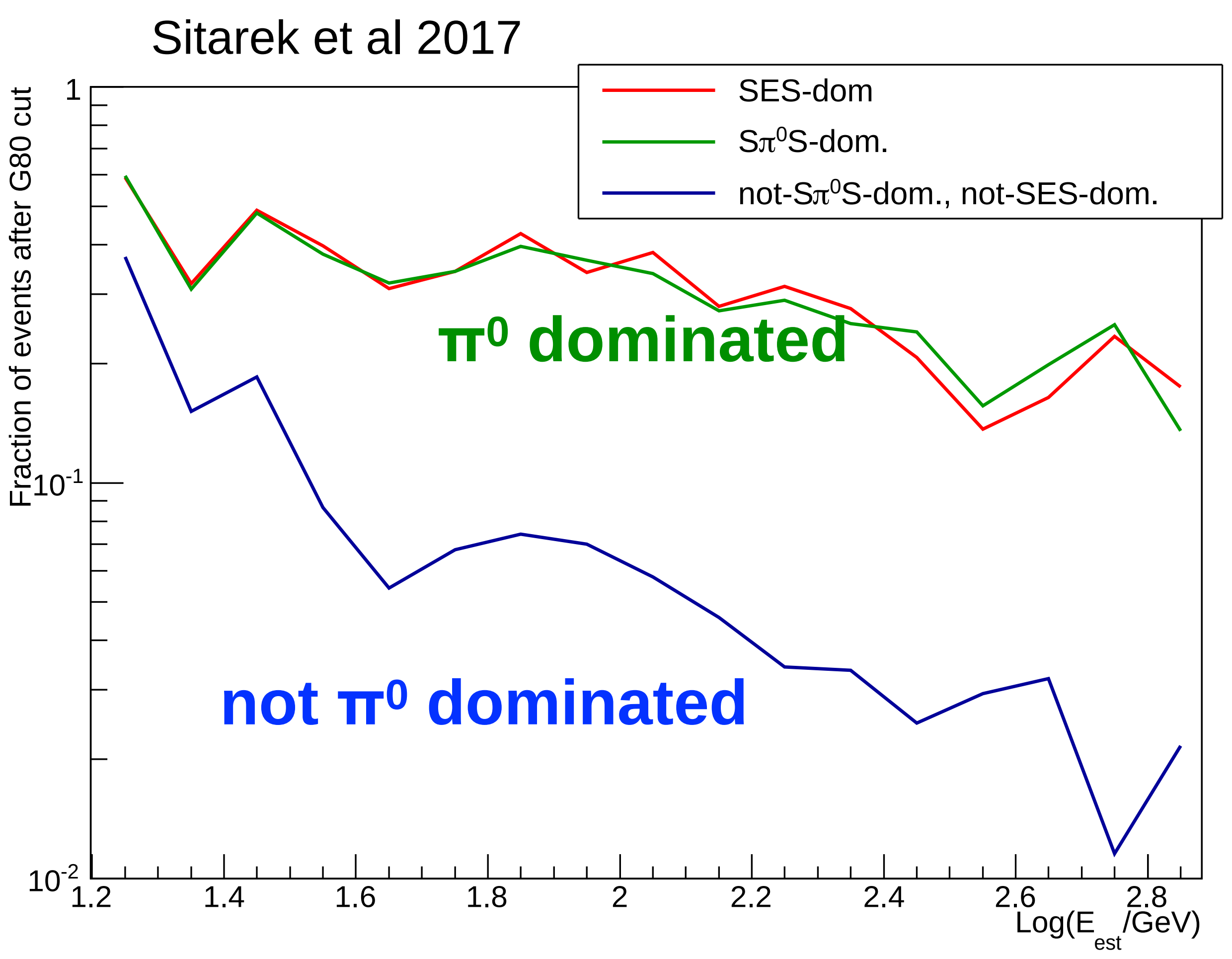
Gamma-ray like proton events

Gamma-ray like proton events

particle distribution after first interactions



fraction of events after gamma/ hadron separation cuts

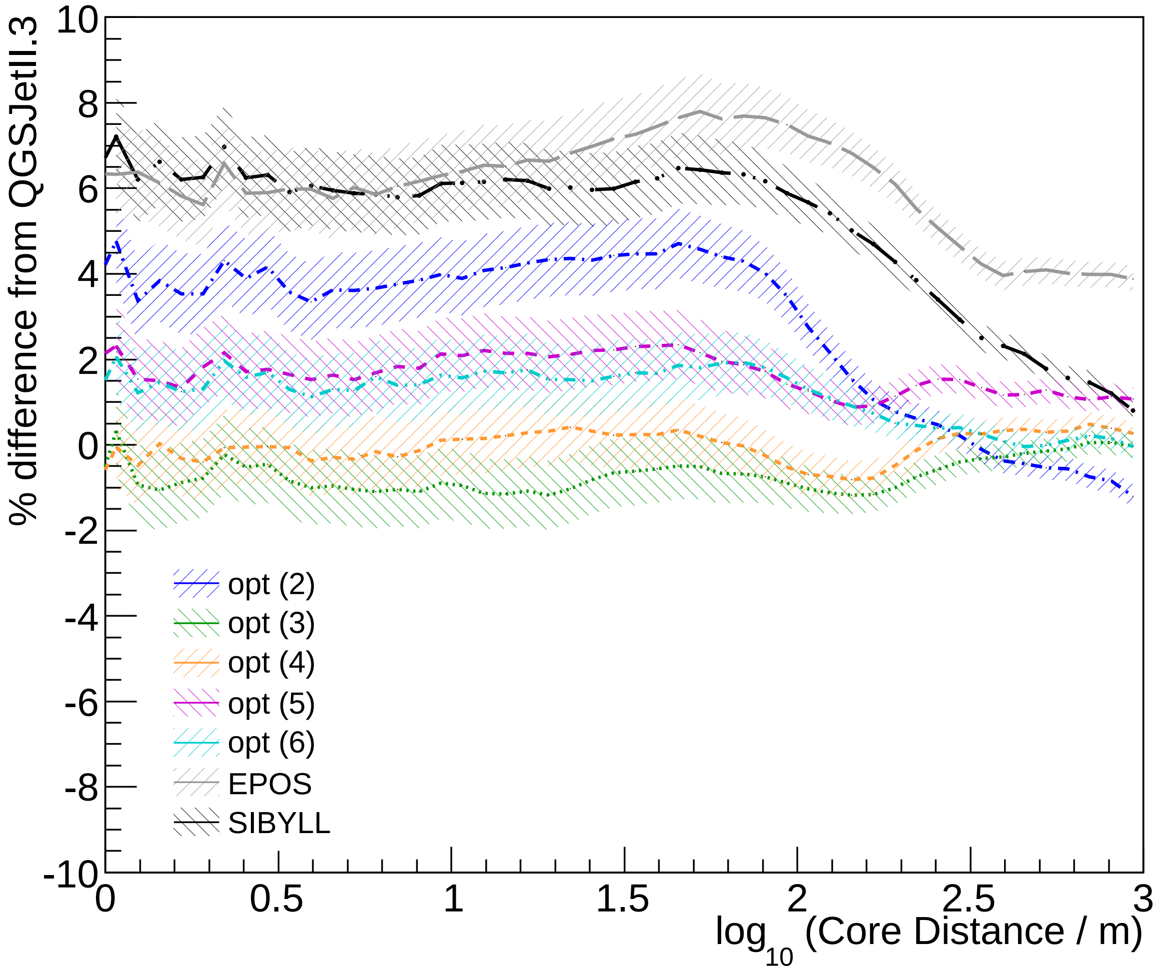


before / **after** gamma/hadron separation

Impact of Hadronic Interaction Models

Surprisingly little in literature…

Parson et al 2011

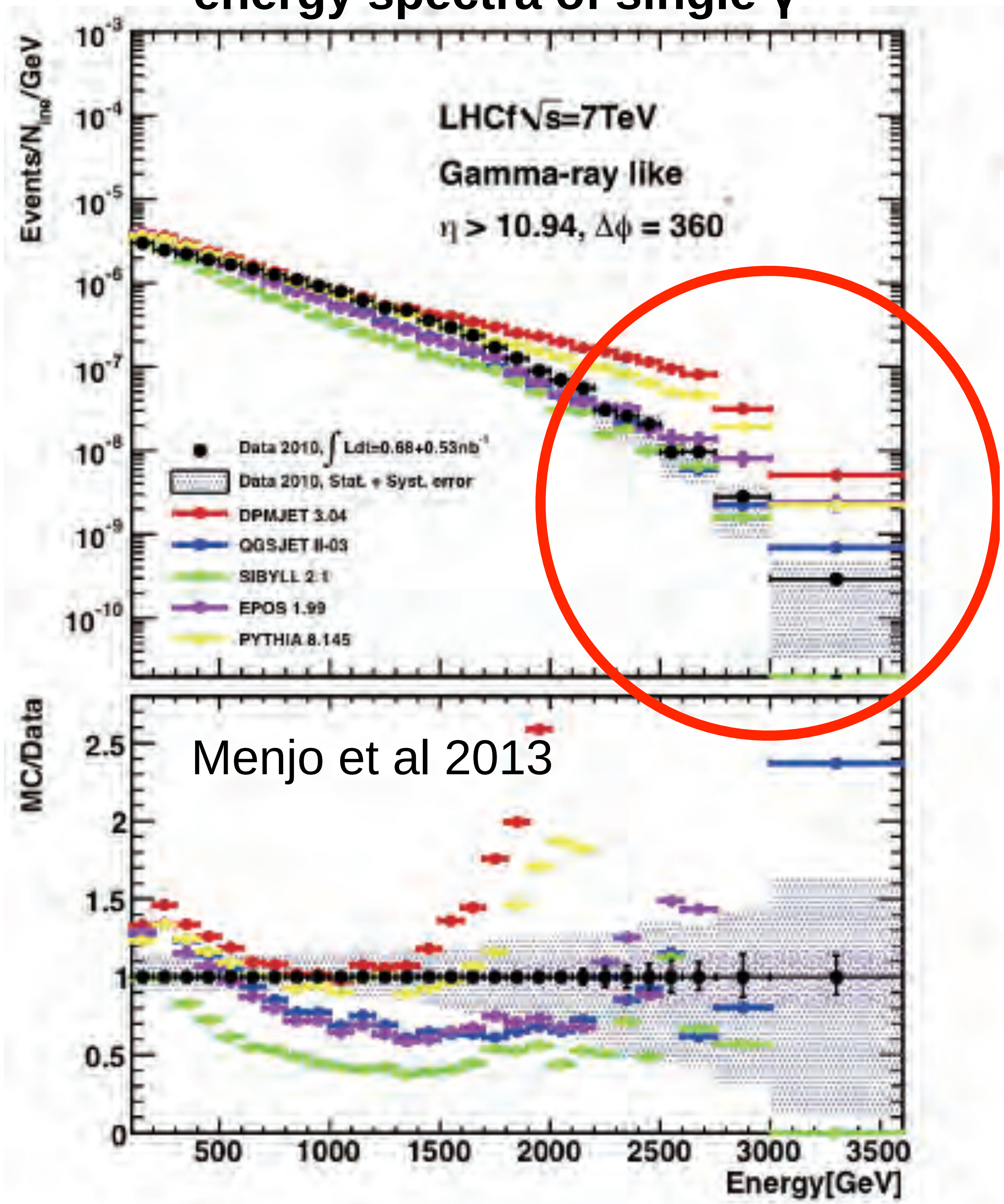


Cherenkov Photon Density
Relative to QGSJet-II

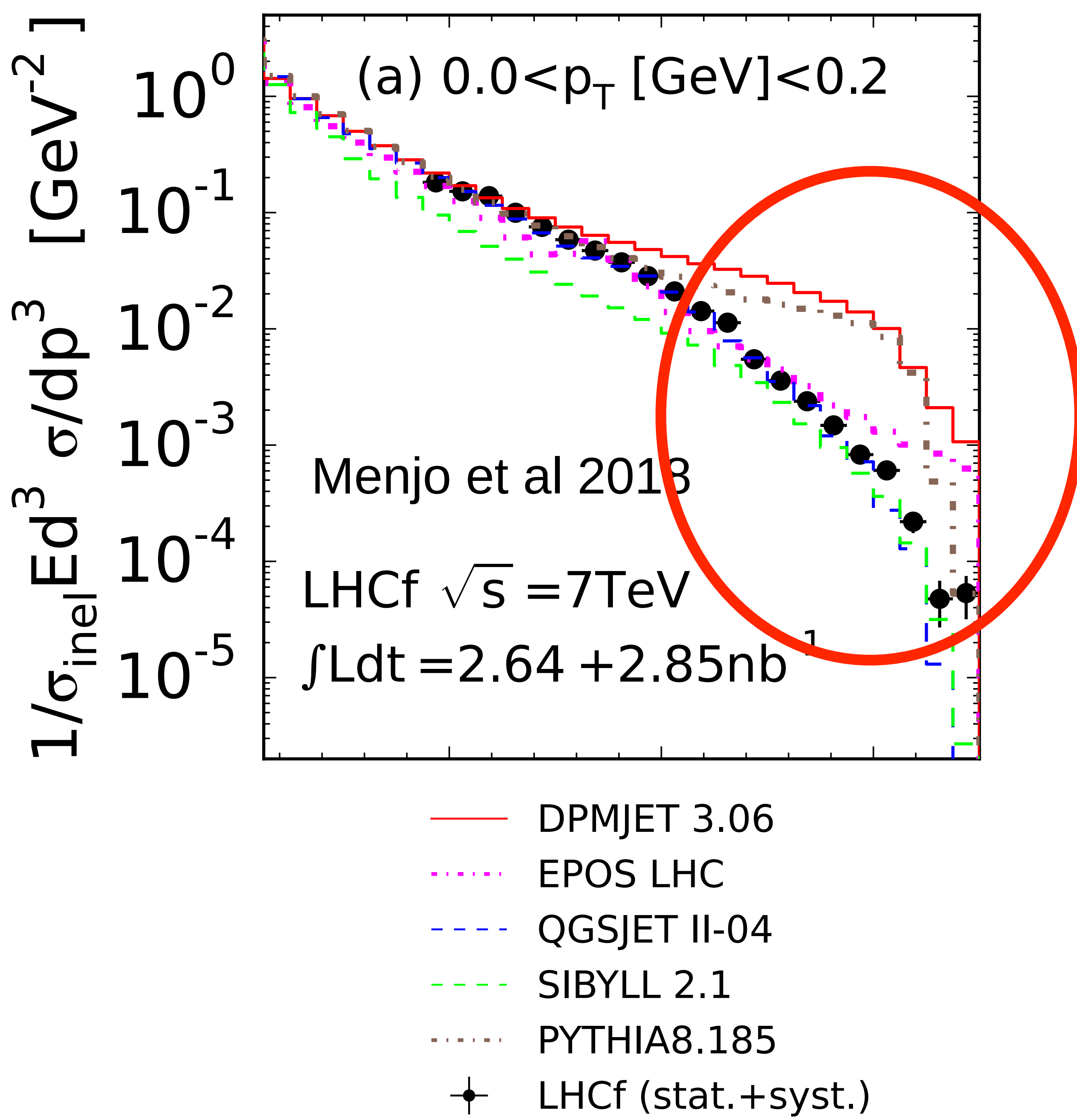
Unpublished internal CTA studies show differences up to a factor of two in remaining number of background events

LHCf: energy spectra of single γ

energy spectra of single γ



longitudinal momentum spectra of π^0



Conclusions

- CTA Monte Carlo contributed to all major design decisions
  - telescope sizes and number of telescopes
  - site selections
  - layout
- Next big step is the verification of the actual instrument design
- And of course the fun starts with actual data ….