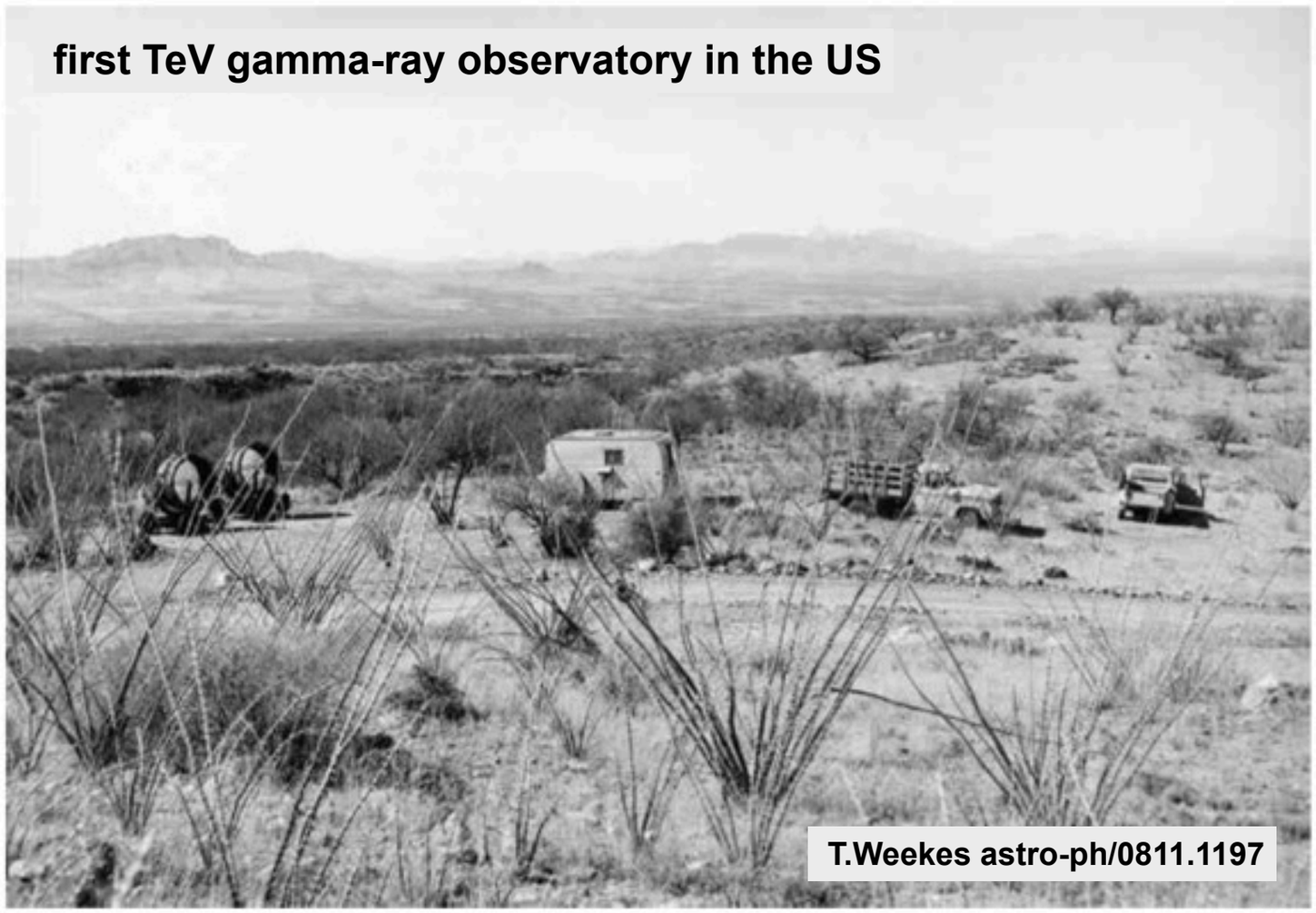
Detectors in Astroparticle Physics

Graduiertenkolleg “Masse, Spektrum, Symmetrie” (Autumn 2011)

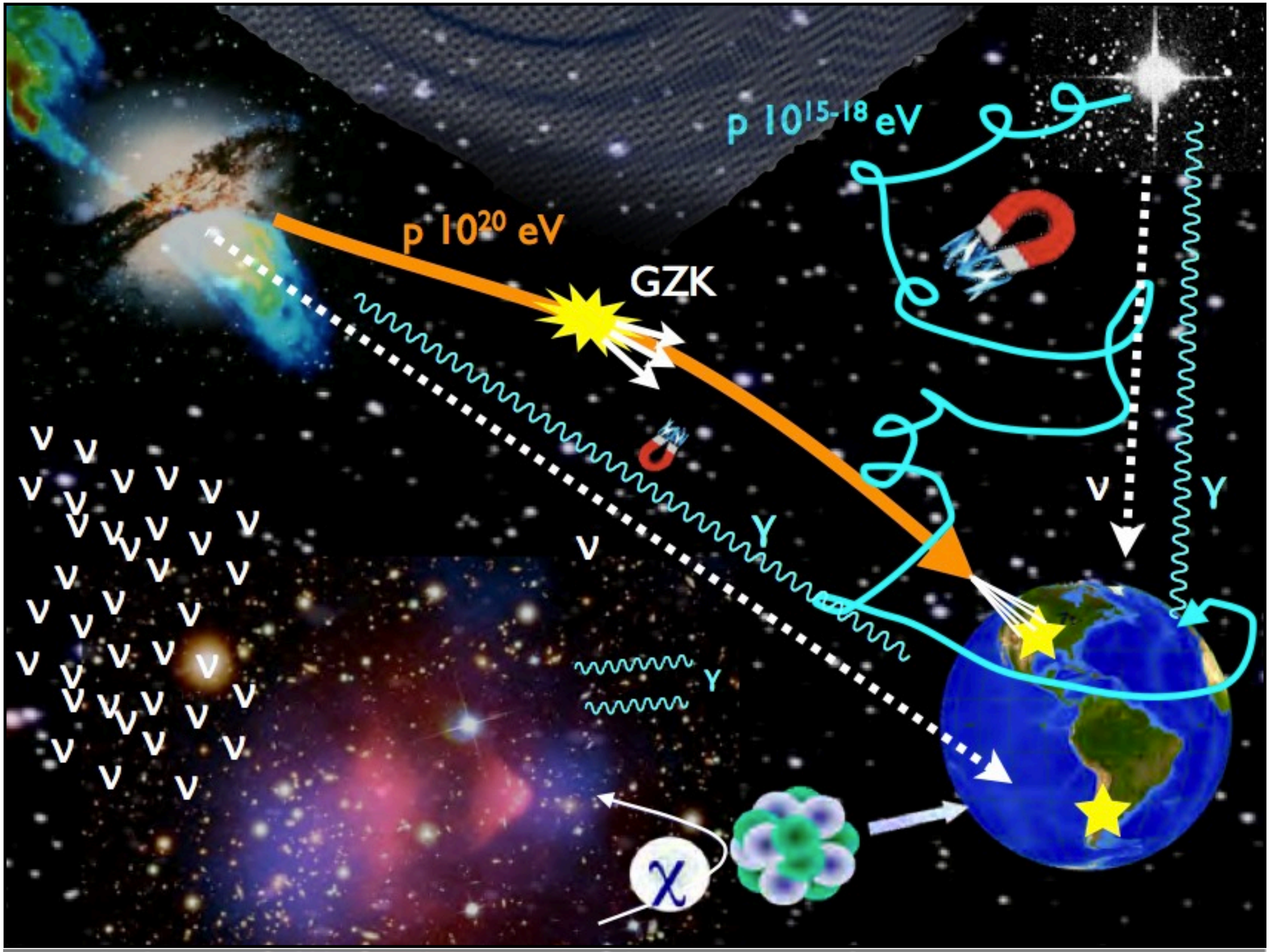


Gernot Maier

HUMBOLDT-UNIVERSITÄT ZU BERLIN

DESY

HELMHOLTZ ASSOCIATION


p 10^15-18 eV
p 10^20 eV
GZK
ν
γ
χ

Charged particles

Cosmic Rays (protons, ..., iron nuclei), electrons

10^3 eV — 10^{15} eV — 10^{20} eV

Neutrons, Neutrinos

(Gravitational waves)

Charged particles

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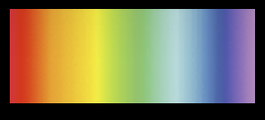
10^3 eV — 10^{15} eV — 10^{20} eV

Neutrons, Neutrinos

(Gravitational waves)

Photons



Radio — Infrared — Ultraviolet — Gamma-rays

Microwaves — Visible — X-rays

1 m - 1 km	1 cm	1 µm - 1 mm	400-700 nm	10 - 400 nm	0.01 - 10 nm	< 0.01 nm
	1 K	100 K	10,000 K		10^8 K	10^{10} K
			eV		keV	MeV GeV TeV

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			eV		keV	MeV GeV TeV

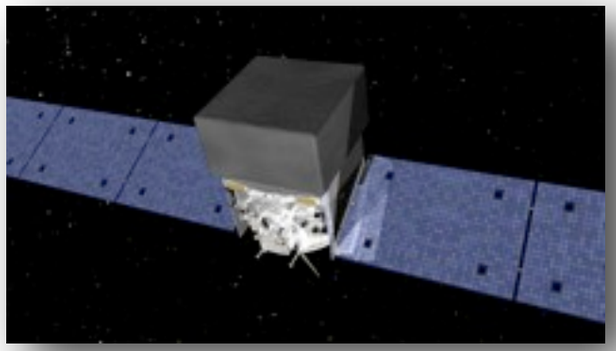
Particles beyond the Standard Model

(Constituents of Dark Matter)

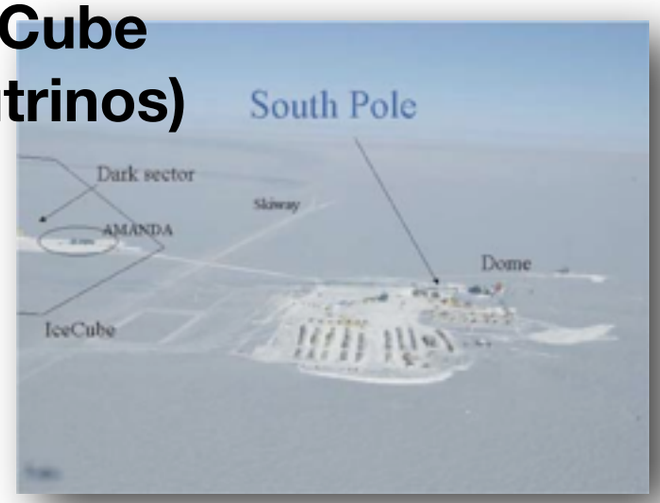
Experiments (1)

Note: smooth transition from Astroparticle Physics to Astronomy

Fermi (Gamma-rays)



IceCube (Neutrinos)

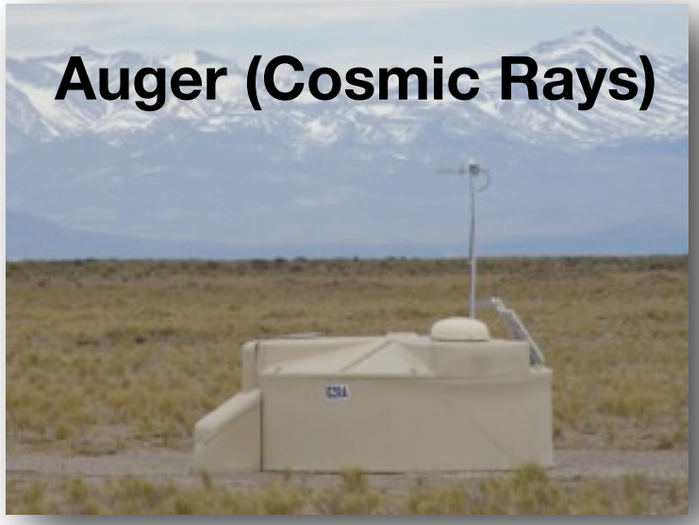


LIGO (Gravitational waves)

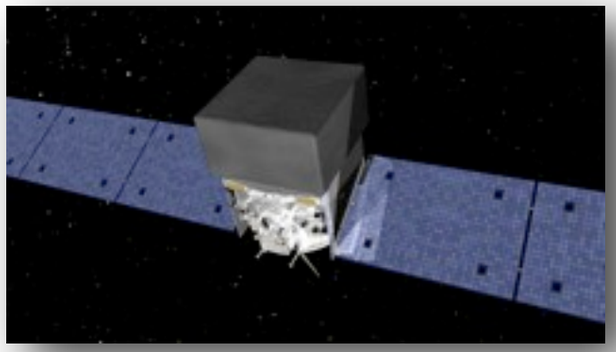
Experiments (1)

Note: smooth transition from Astroparticle Physics to Astronomy

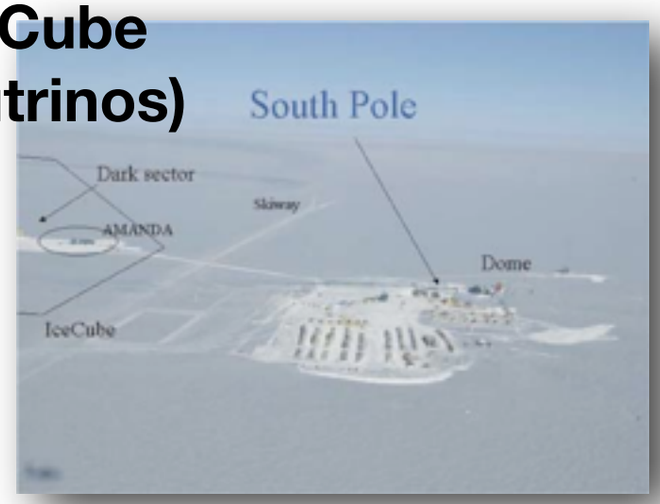
Auger (Cosmic Rays)



Fermi (Gamma-rays)



IceCube (Neutrinos)



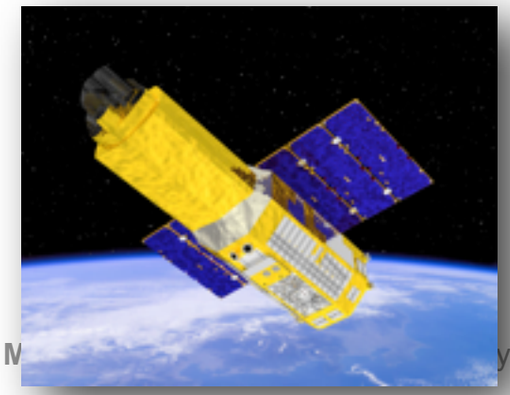
VLT (Optical)

VERITAS (Gamma-rays)

Arecibo (Radio)

LIGO (Gravitational waves)

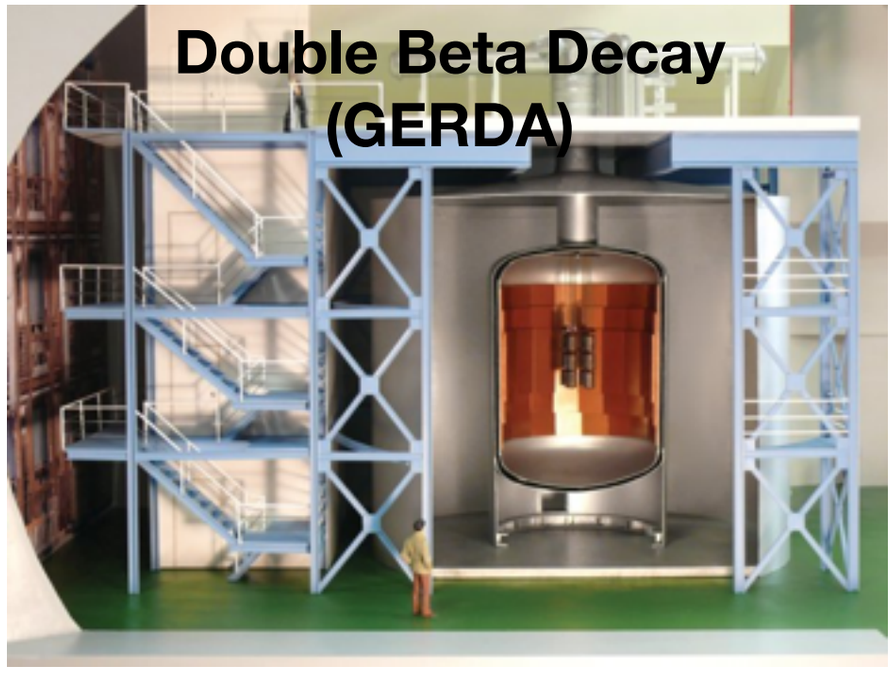
Suzaku (X-rays)

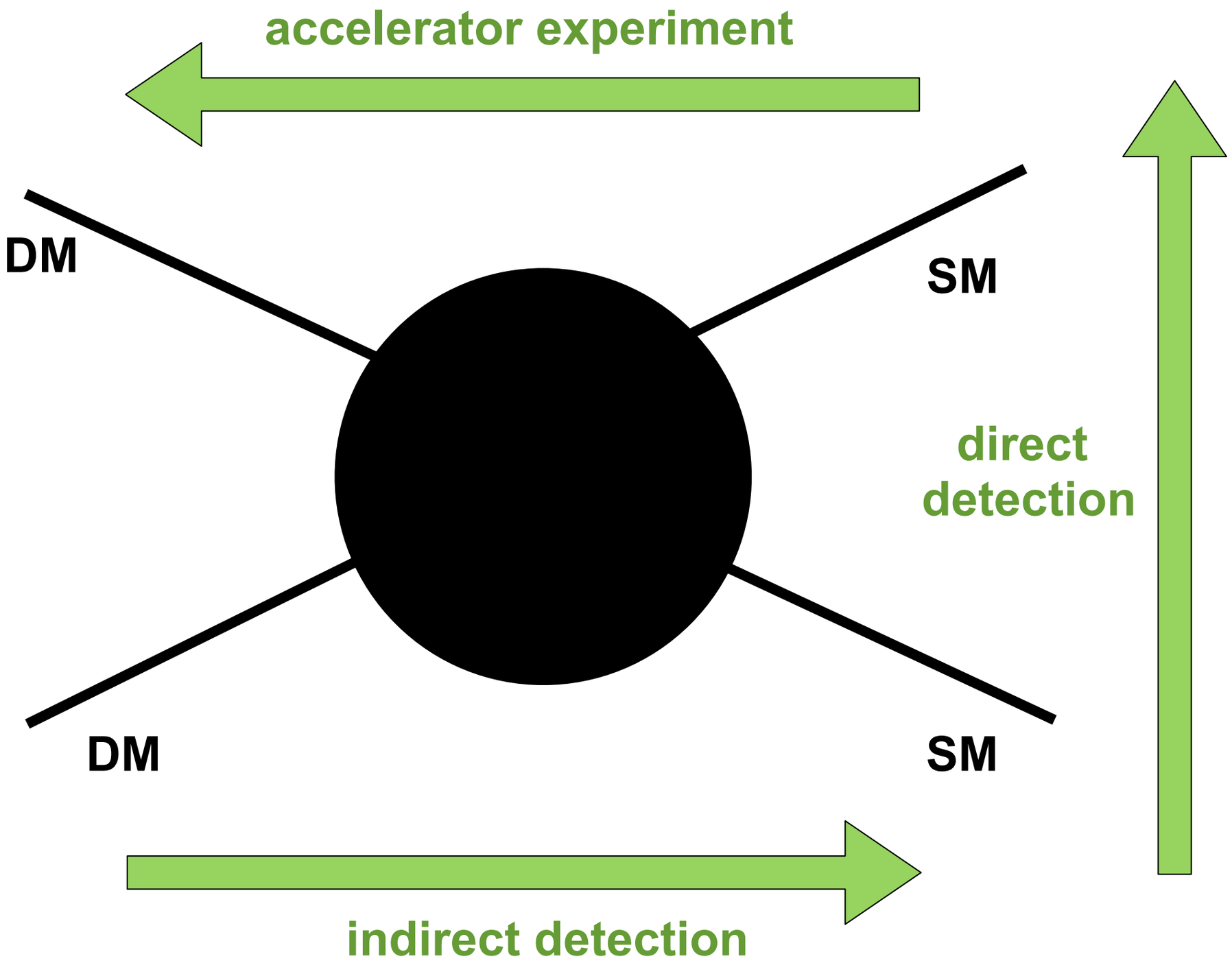


Spitzer (IR)

Experiments (2)

Note: smooth transition from Astroparticle Physics to Particle Physics



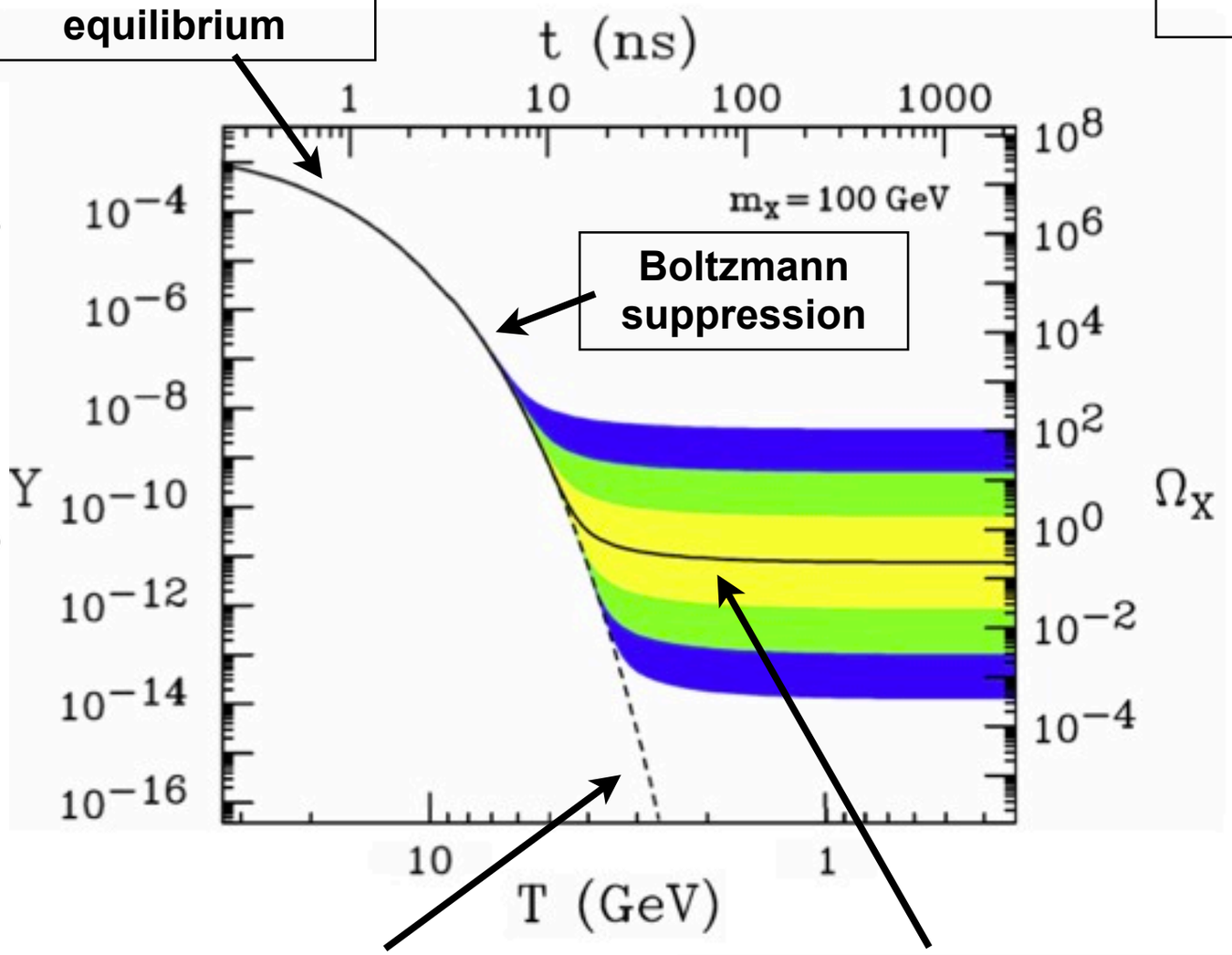

accelerator experiment
DM
SM
direct
detection
DM
SM
indirect detection

The WIMP miracle

Evolution of a thermal relic's number density

XX ↔ SM SM

all particles in thermal equilibrium

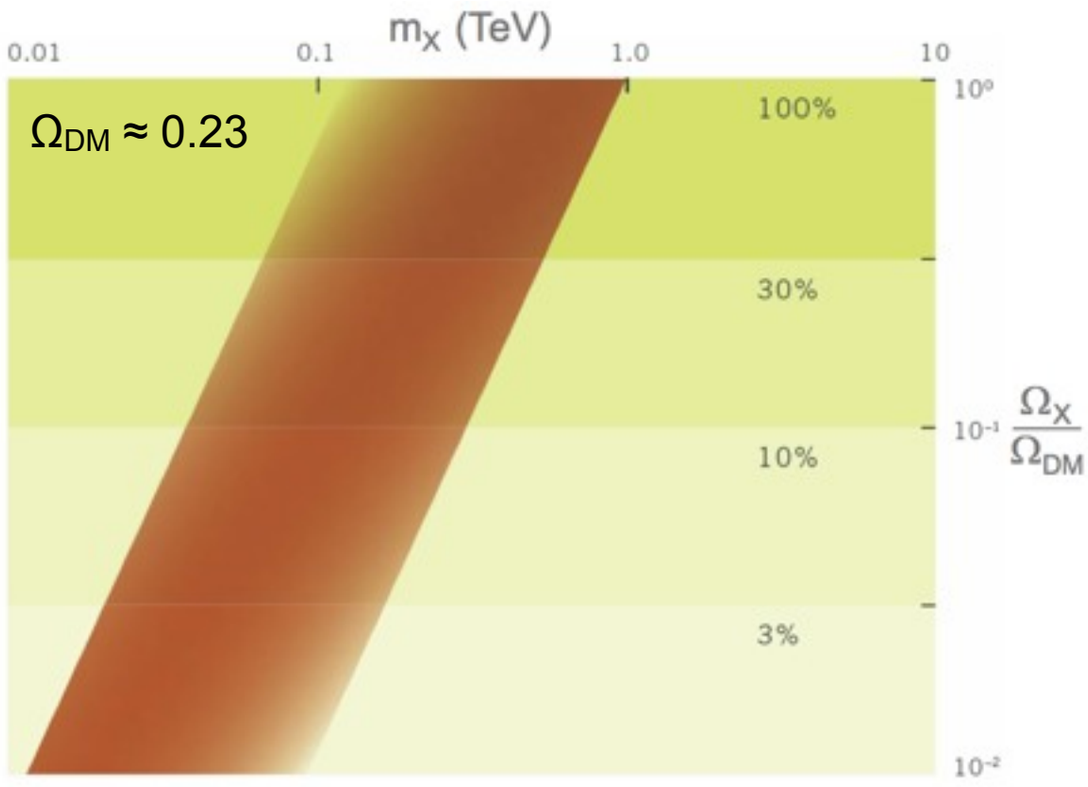


without expansion: number of DM particles would drop to zero

expansion of the Universe: particles cannot find each other to annihilate: freeze out

number densities can be calculated by solving the Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_A v \rangle \left(n^2 - n_{\mathrm{eq}}^2 \right)$$



weak-scale particles make excellent dark matter particles

natural mass range is 10 GeV to a few TeV

Indirect Dark Matter Search

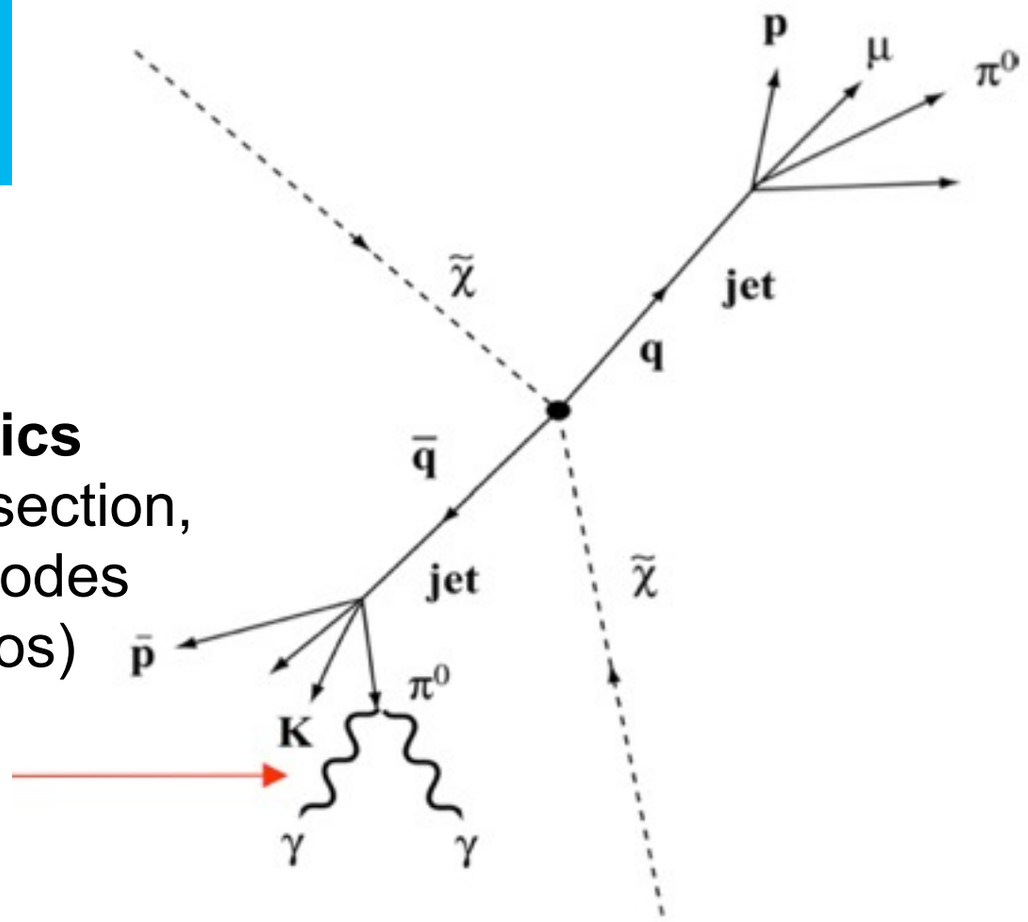
gamma-ray flux from DM annihilation

$$\frac{d\Phi}{dE} = J(\psi) \cdot \frac{d\Phi^{PP}}{dE}$$

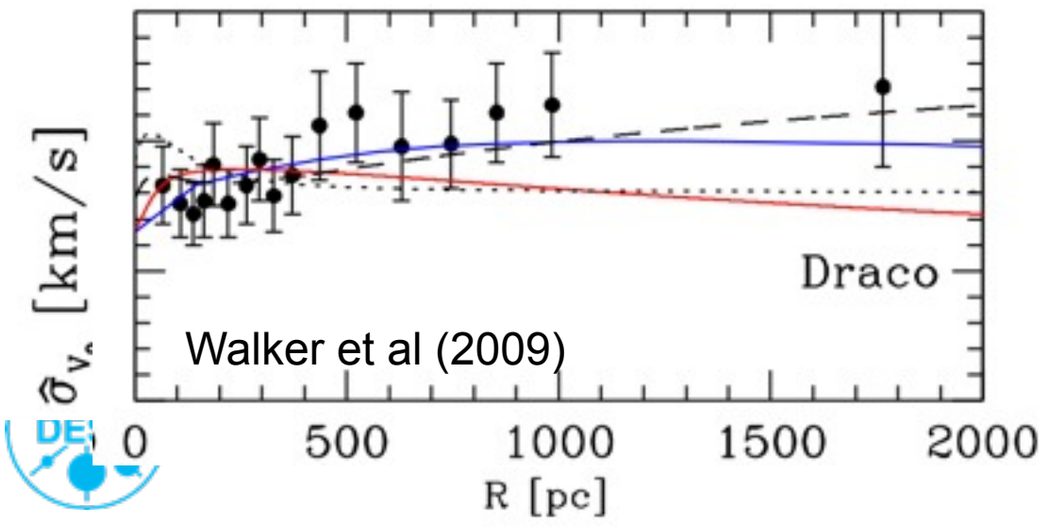
particle physics
(mass, cross section, annihilation modes branching ratios)

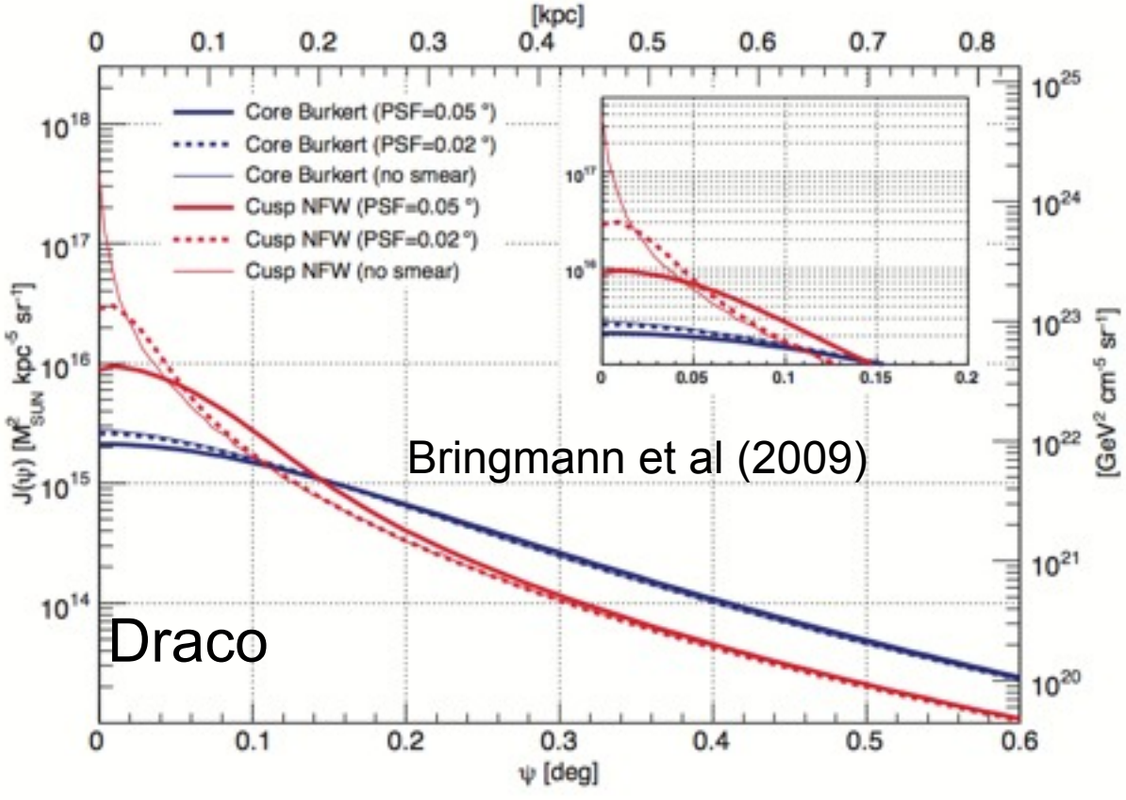
astrophysical factor
(DM morphology at emission region)

$$J(\psi) = \frac{1}{4\pi} \int d\Omega \int d\lambda \left[\rho^2(r(\lambda,\psi)) \cdot B_{\vartheta_r}(\theta)\right]$$



major uncertainty due to unknown core profiles

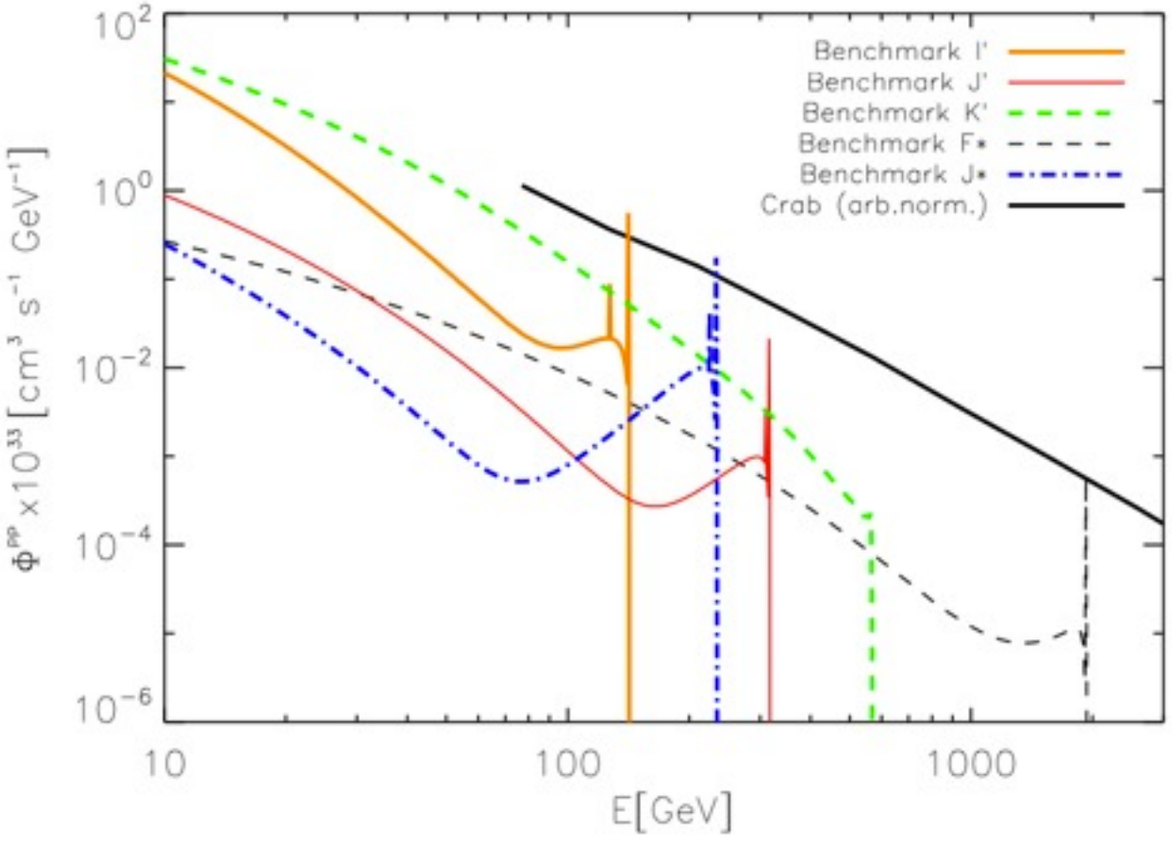


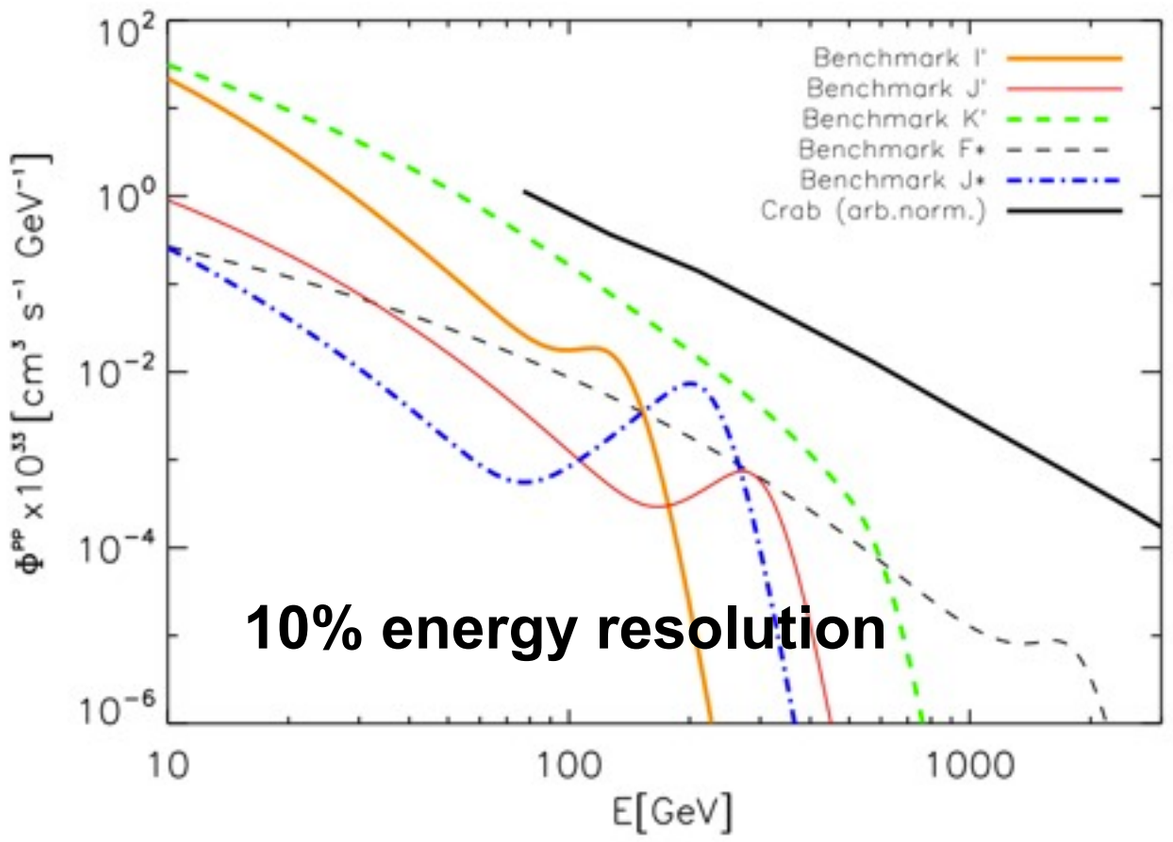


Particle Physics Factor

$$\frac{d\Phi^{PP}}{dE} = \frac{\sigma v}{2m_\chi^2} \cdot \sum_i B^i \int dE' \frac{dN_\gamma^i(E')}{dE'} R_\epsilon(E - E')$$

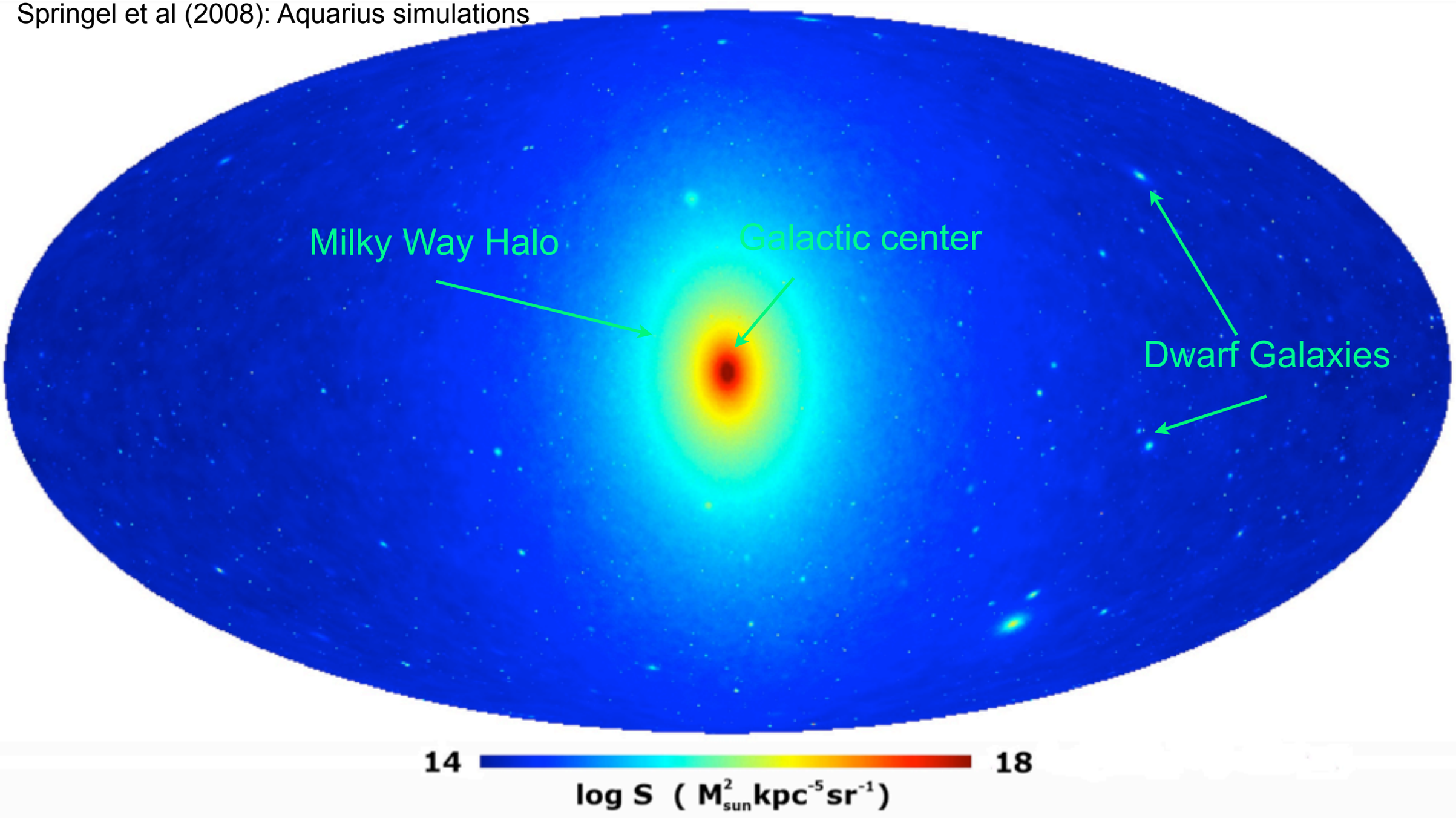
Bringmann et al (2009)

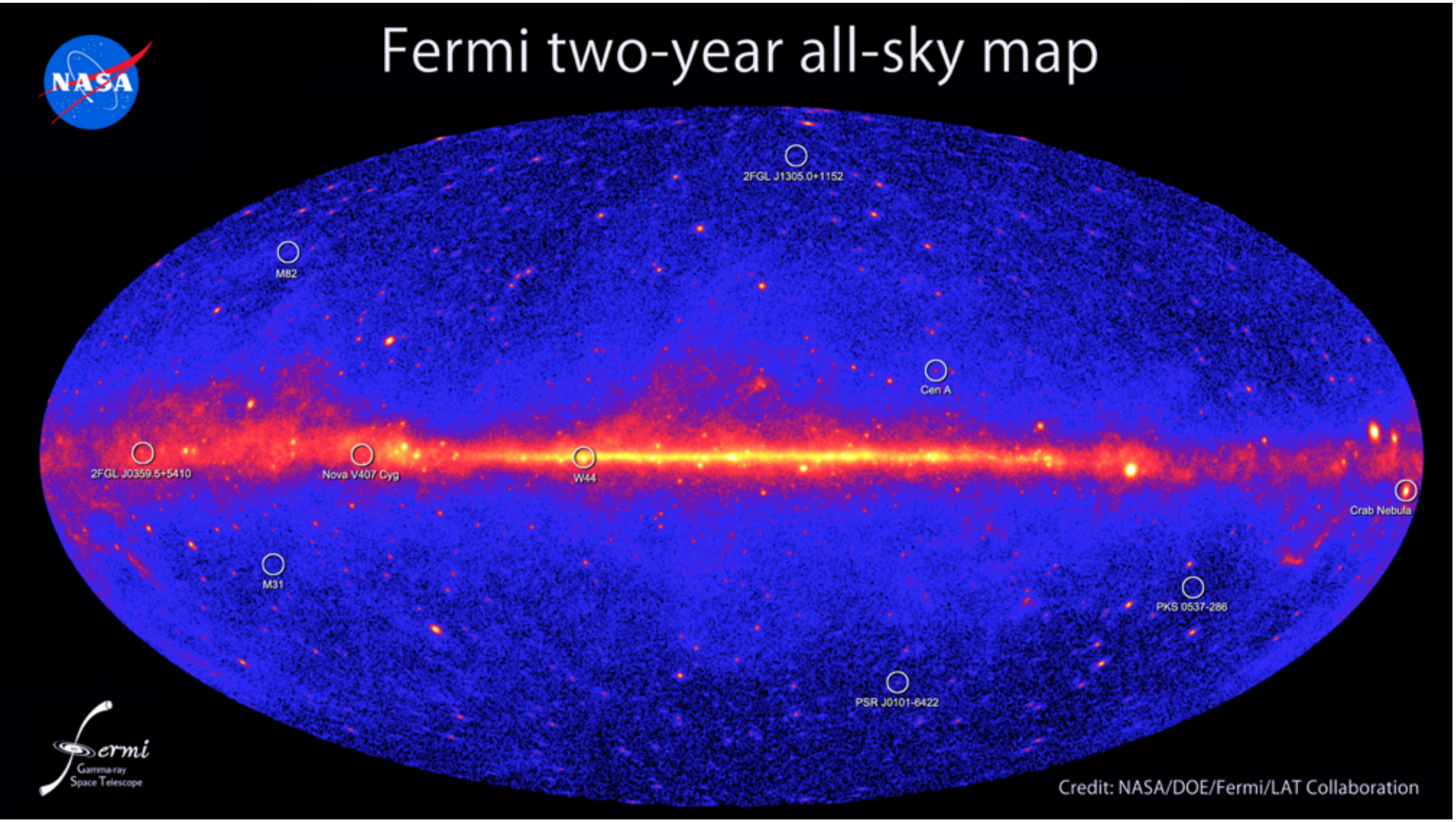




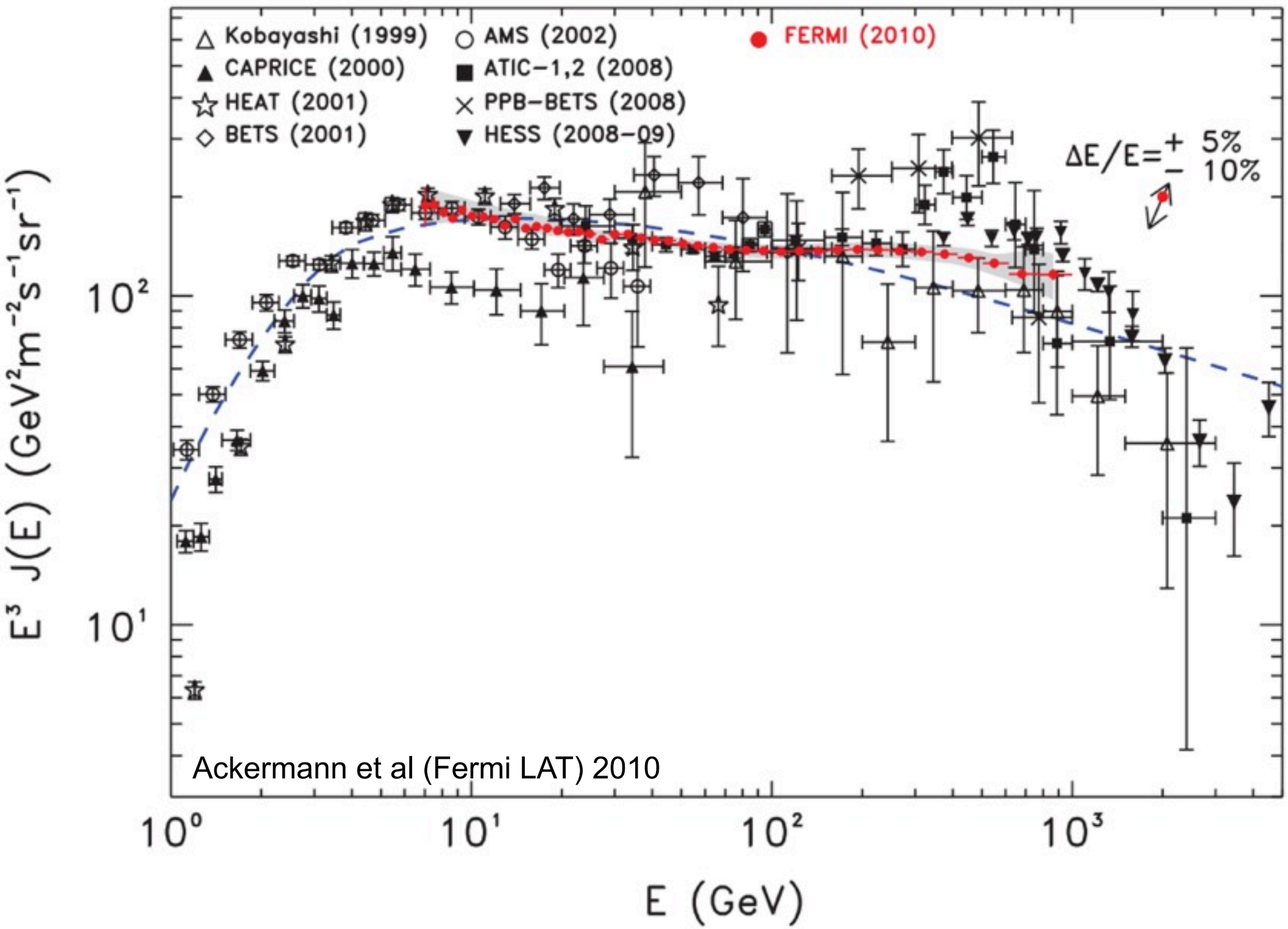
DM density

Springel et al (2008): Aquarius simulations



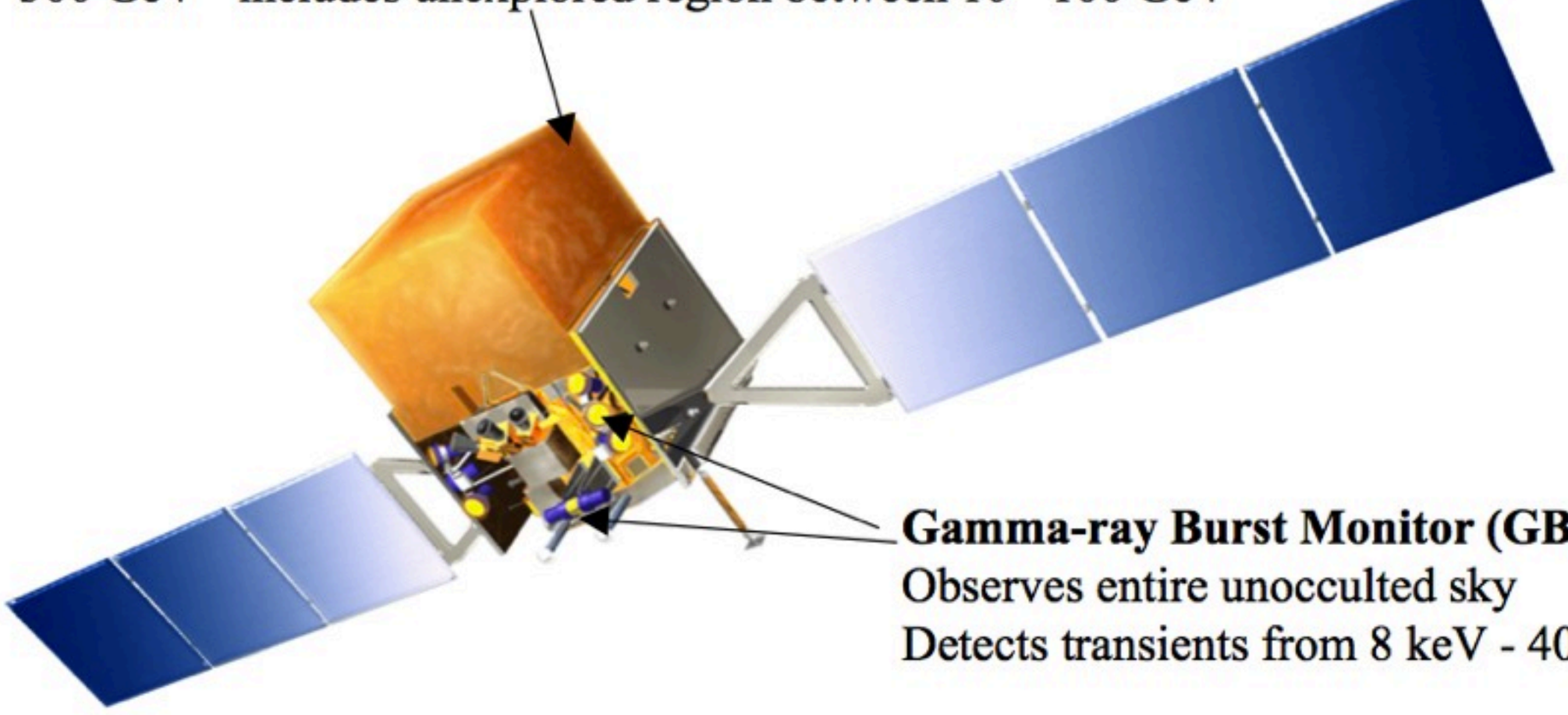

Fermi two-year all-sky map
2FGL J1305.0+1152
M82
Cen A
2FGL J0359.5+5410
Nova V407 Cyg
W44
Crab Nebula
M31
PKS 0537-286
PSR J0101-6422
Fermi
Gamma-ray
Space Telescope
Credit: NASA/DOE/Fermi/LAT Collaboration

Electron Spectrum



The Fermi Observatory

Large Area Telescope (LAT)
Observes 20% of the sky at any instant, views entire sky every 3 hrs
20 MeV - 300 GeV - includes unexplored region between 10 - 100 GeV



Gamma-ray Burst Monitor (GBM)
Observes entire unocculted sky
Detects transients from 8 keV - 40 MeV

Compared to EGRET: increased effective area, improved angular resolution, broader energy range

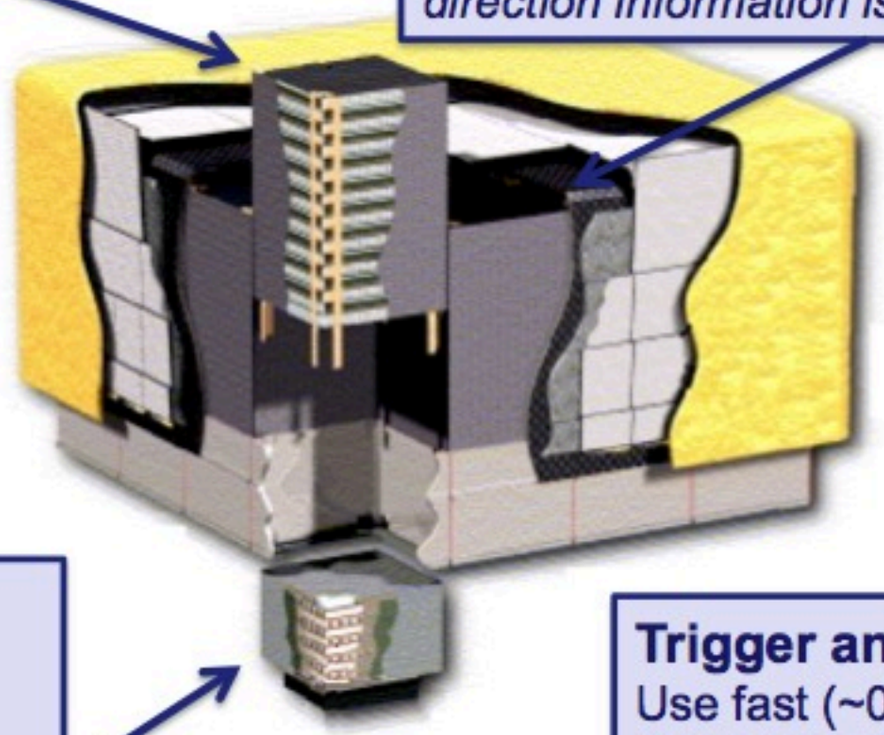
Large Area Telescope (LAT)

Tracker (TKR):
18 Si bi-layers
Front- 12 layers (~60% X_o)
Back- 6 layers (~80% X_o)

Angular resolution ~2x better for front
Many EM showers start in TKR

Anti-Coincidence Detector (ACD):

ε = 0.9997 for MIPs
Segmented: less self-veto *when good direction information is available*



Calorimeter (CAL):
8 layers (8.6 X_o on axis)

ΔE/E ~ 5-20%
Hodoscopic, shower profile and *direction* reconstruction above ~200 MeV

Trigger and Filter
Use fast (~0.1 μs) signals to trigger readout and reject cosmic ray (CR) backgrounds
Ground analysis uses slower (~10μs) shaped signals

LAT Hardware Components

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TRK (Si/Tungsten)
18 bi-layers
point resolution ~70 µm
direction reconstruction
main trigger

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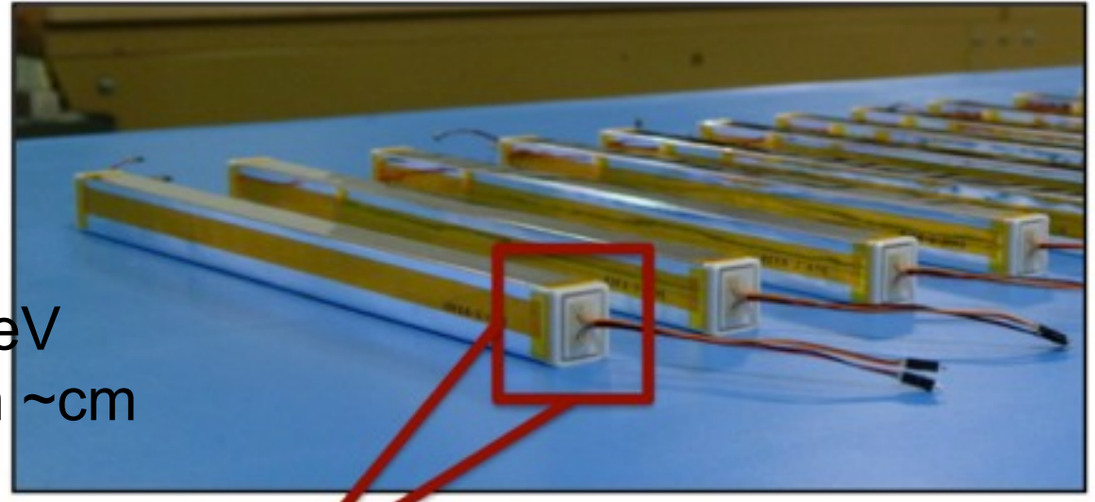
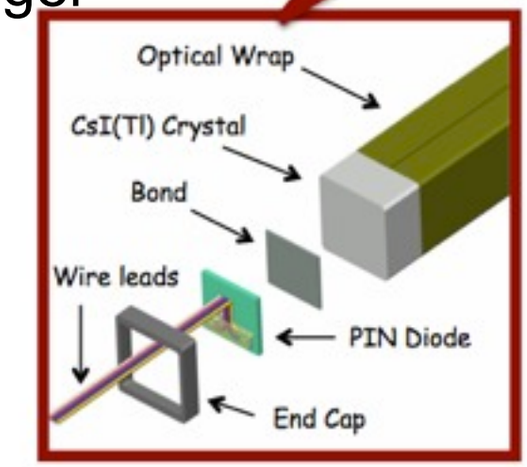
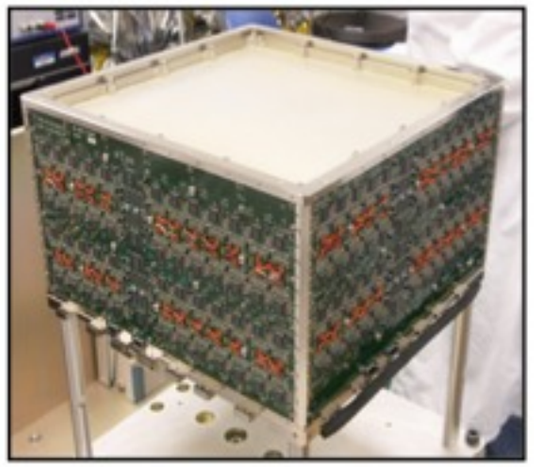
18 bi-layers
point resolution ~70 µm
direction reconstruction
main trigger

CsI CAL
2 MeV - 100 GeV
position resolution ~cm
12*8*16 logs
energy/event trigger



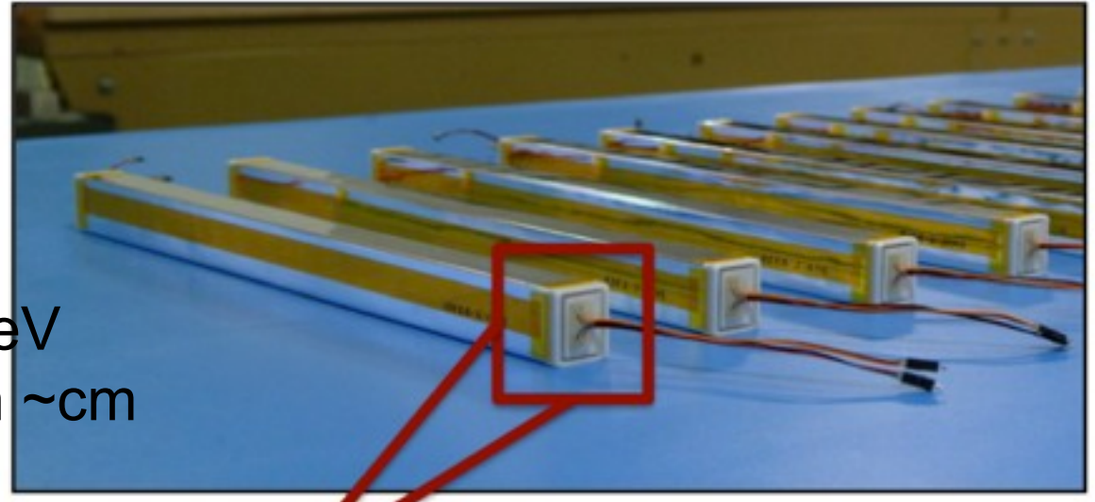


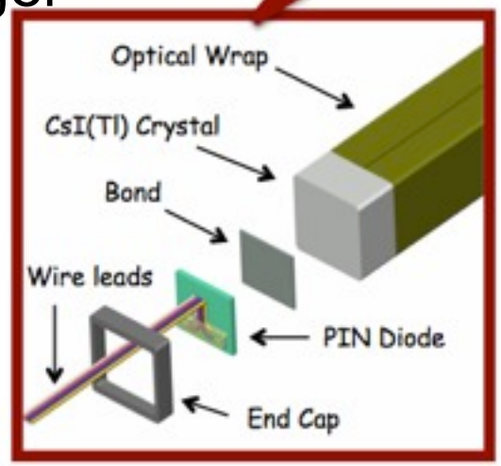


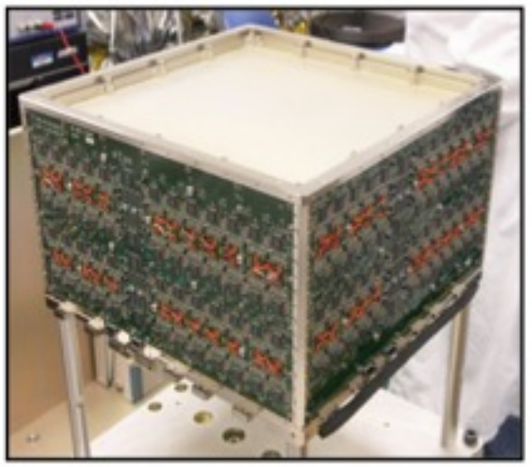
LAT Hardware Components

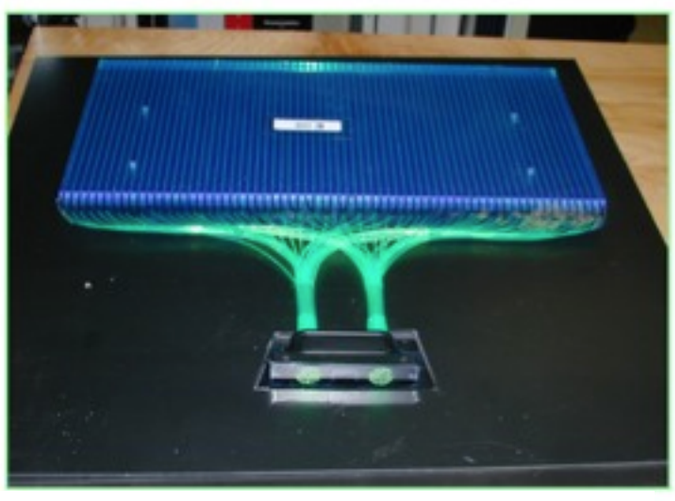
TRK (Si/Tungsten)
18 bi-layers
point resolution ~70 μm
direction reconstruction
main trigger

CsI CAL
2 MeV - 100 GeV
position resolution ~cm
12*8*16 logs
energy/event trigger



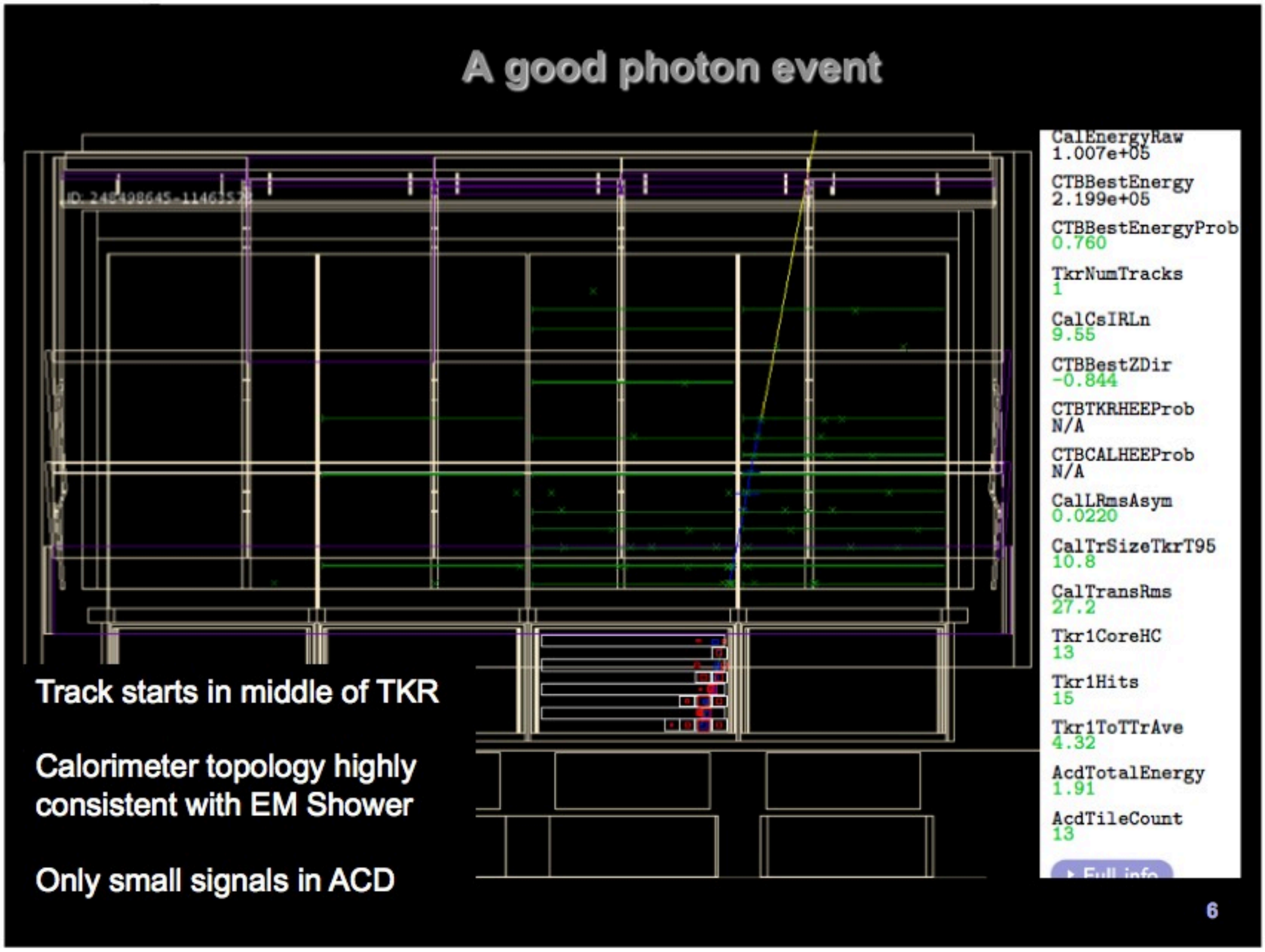






ACD
89 tiles, 8 ribbons
2 PMT/tile/ribbon
onboard filter veto
background rejection

A good photon event



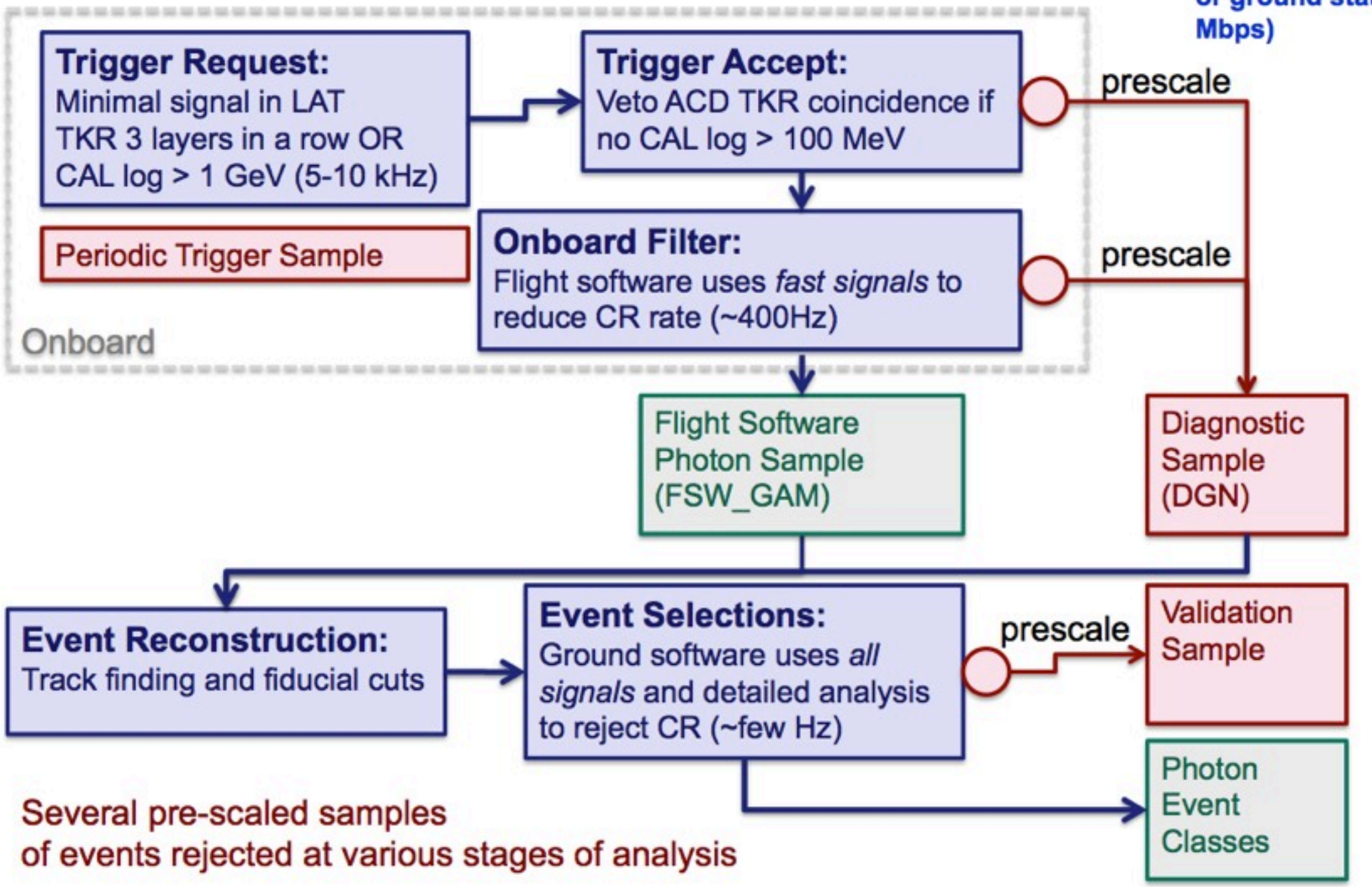
Track starts in middle of TKR

Calorimeter topology highly consistent with EM Shower

Only small signals in ACD

LAT - Photon Selection

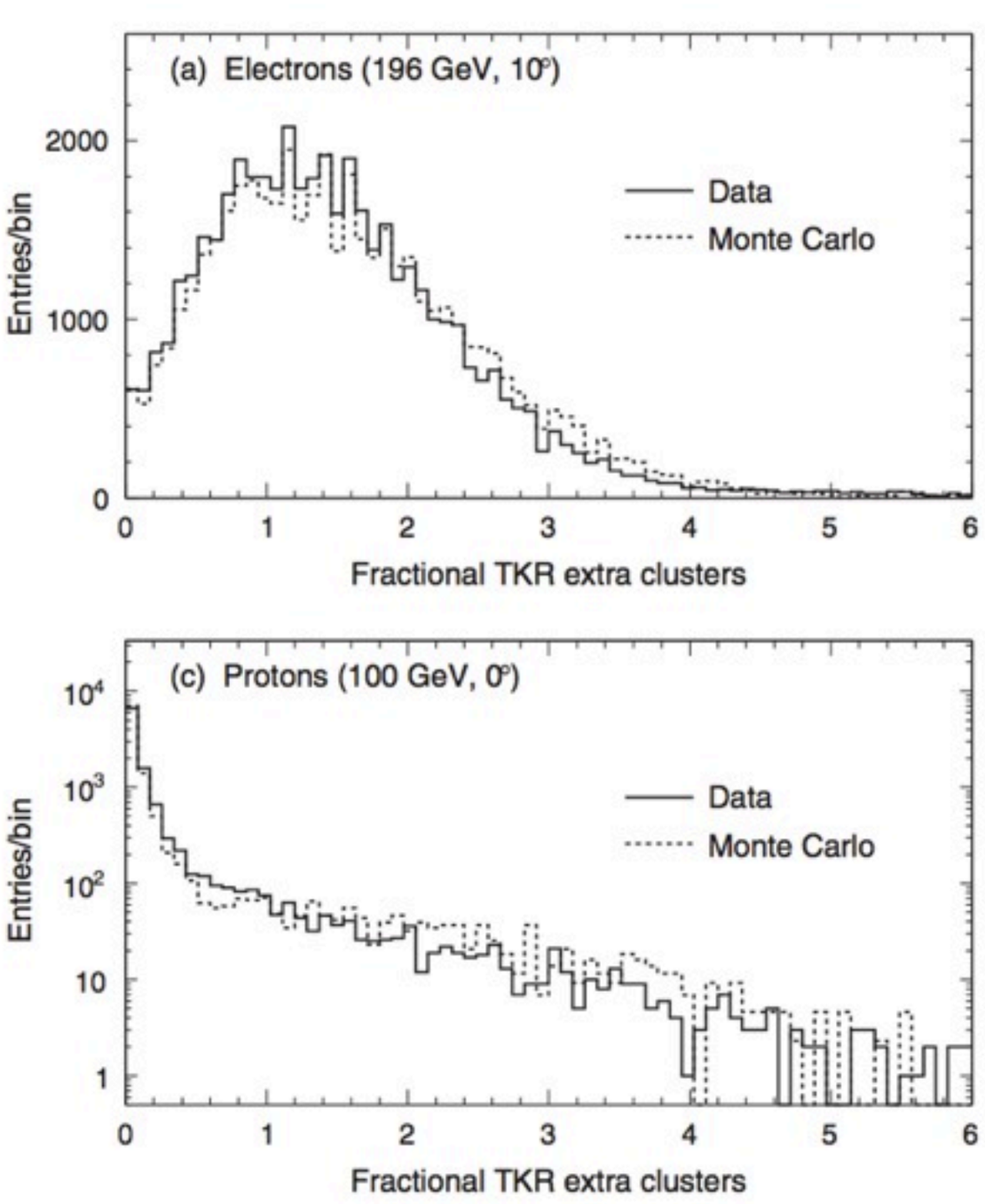
- **Communications:**
  - **Science data link via TDRSS Ku-band (40 Mbps, 8-10, 10 min contacts per day)**
  - **S-band via TDRSS (8kbps) or ground stations (1.26 Mbps)**



(E.Charles, Fermi School Delaware 2011)

LAT - Beam tests

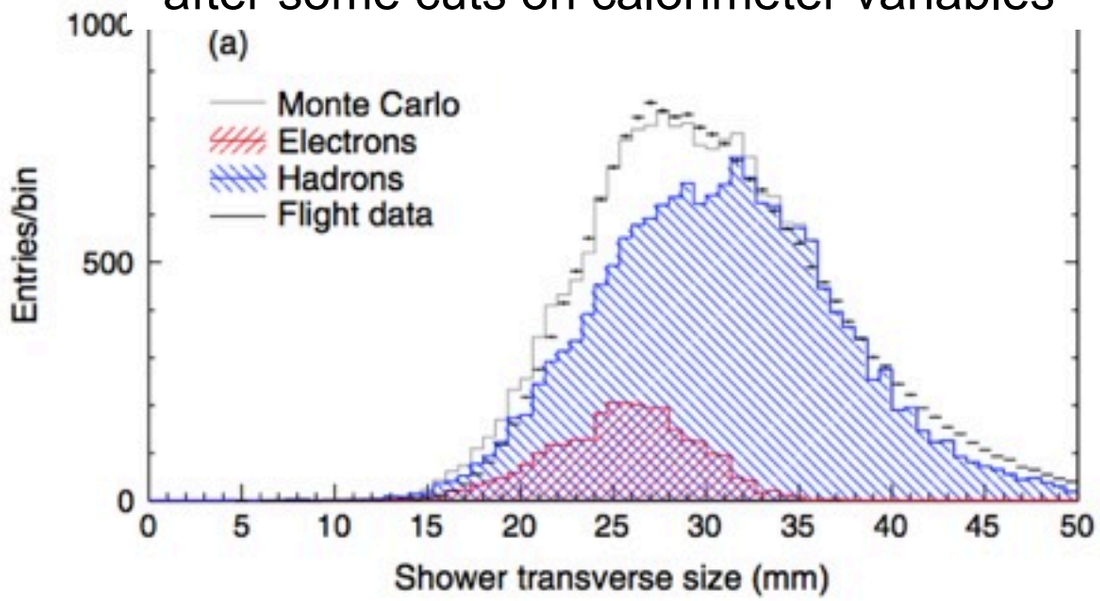
photon/electron/proton/π/C/Xe at CERN and GSI



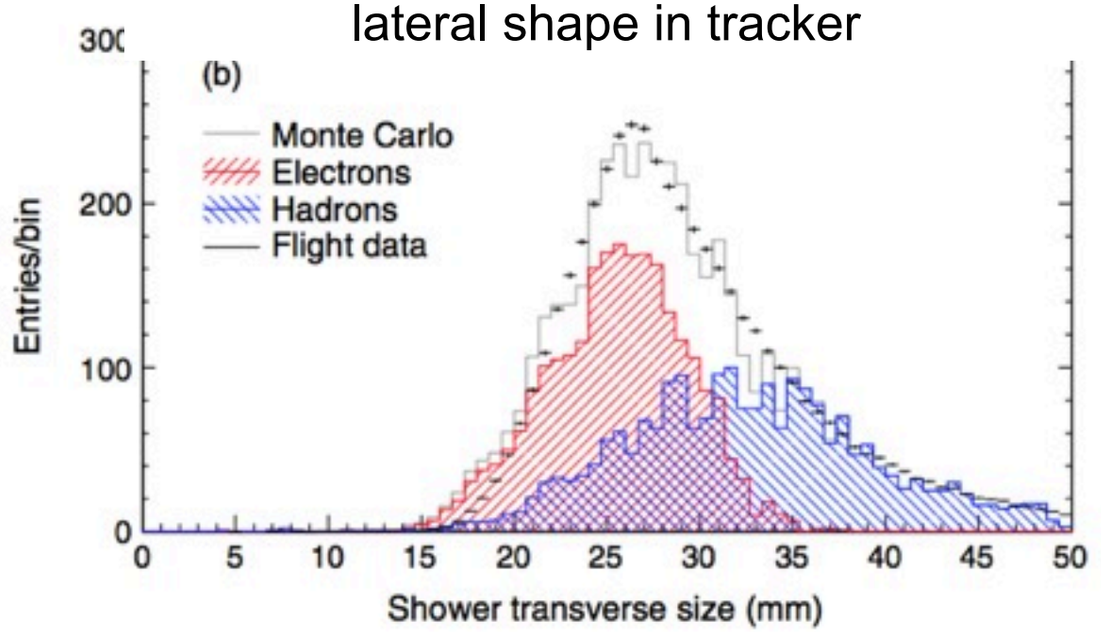
Electron Identification

use lateral/longitudinal shower shape to distinguish between electrons and hadrons

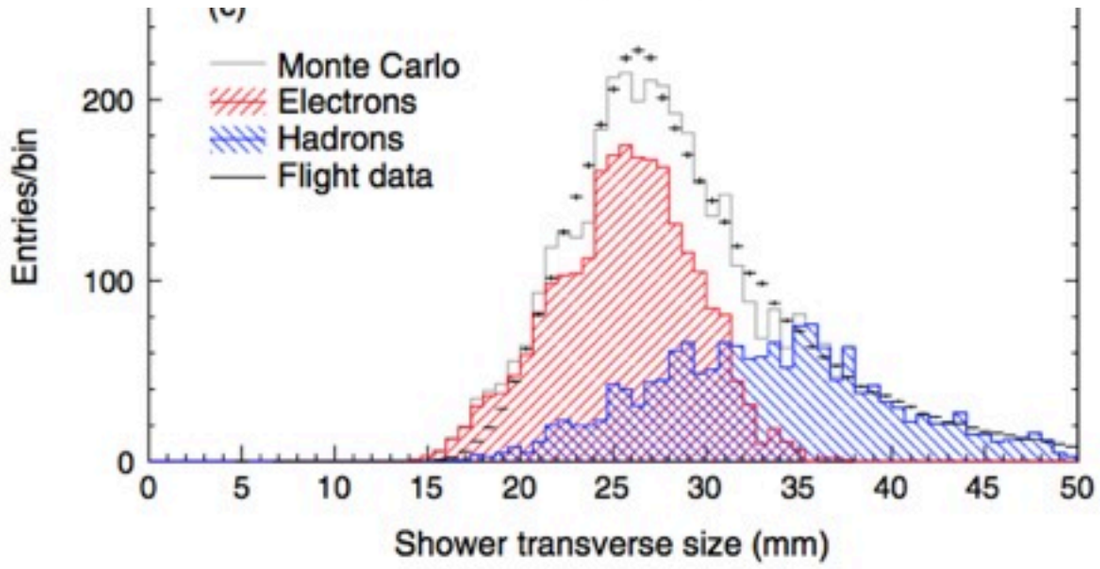
after some cuts on calorimeter variables



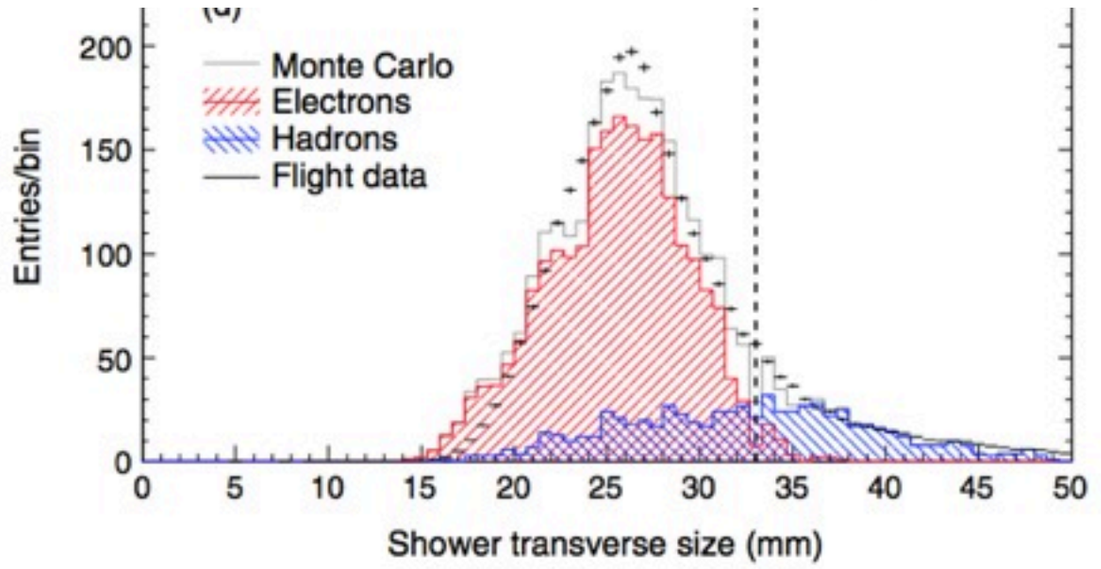
lateral shape in tracker



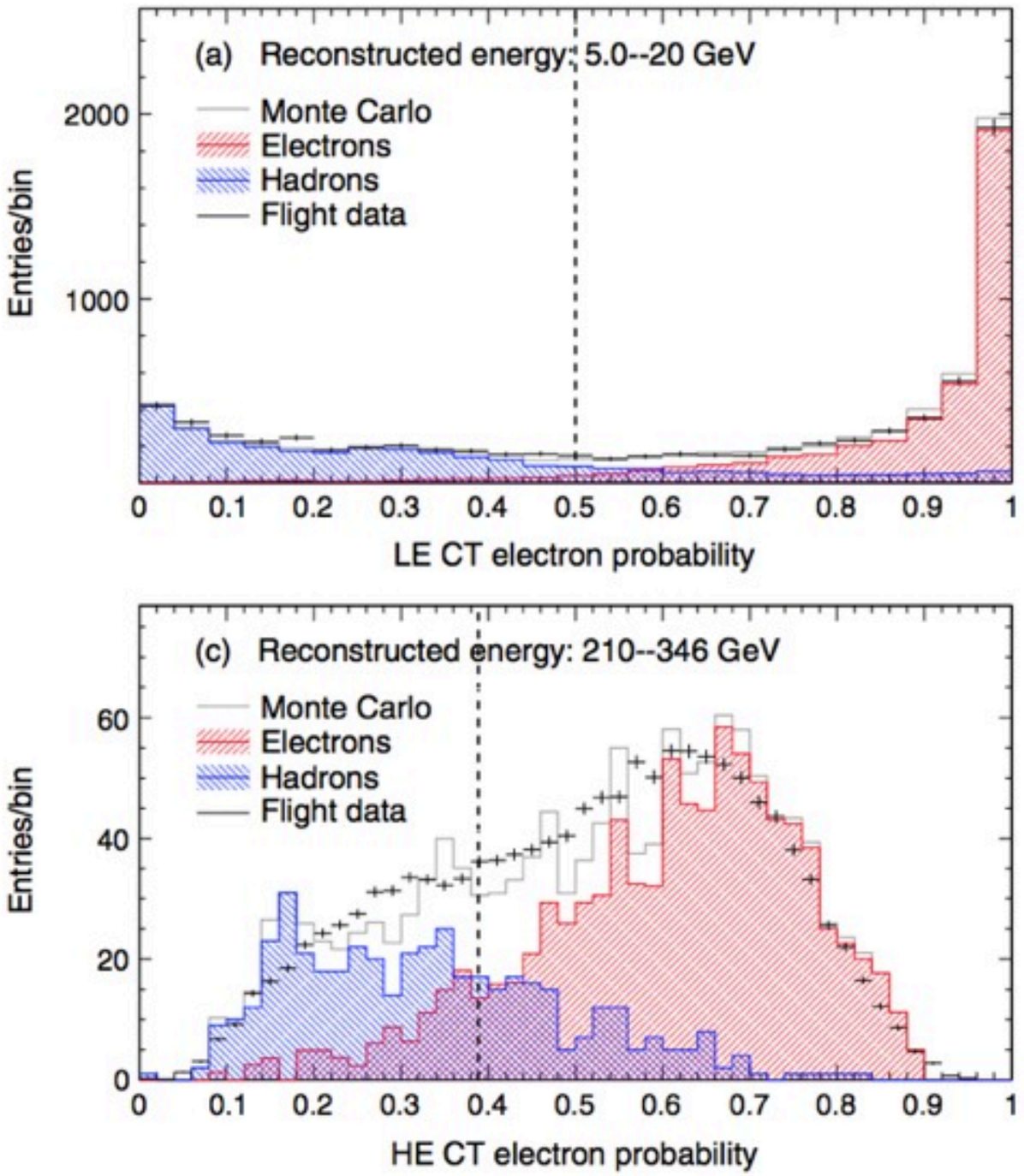
ACD (energy deposition)

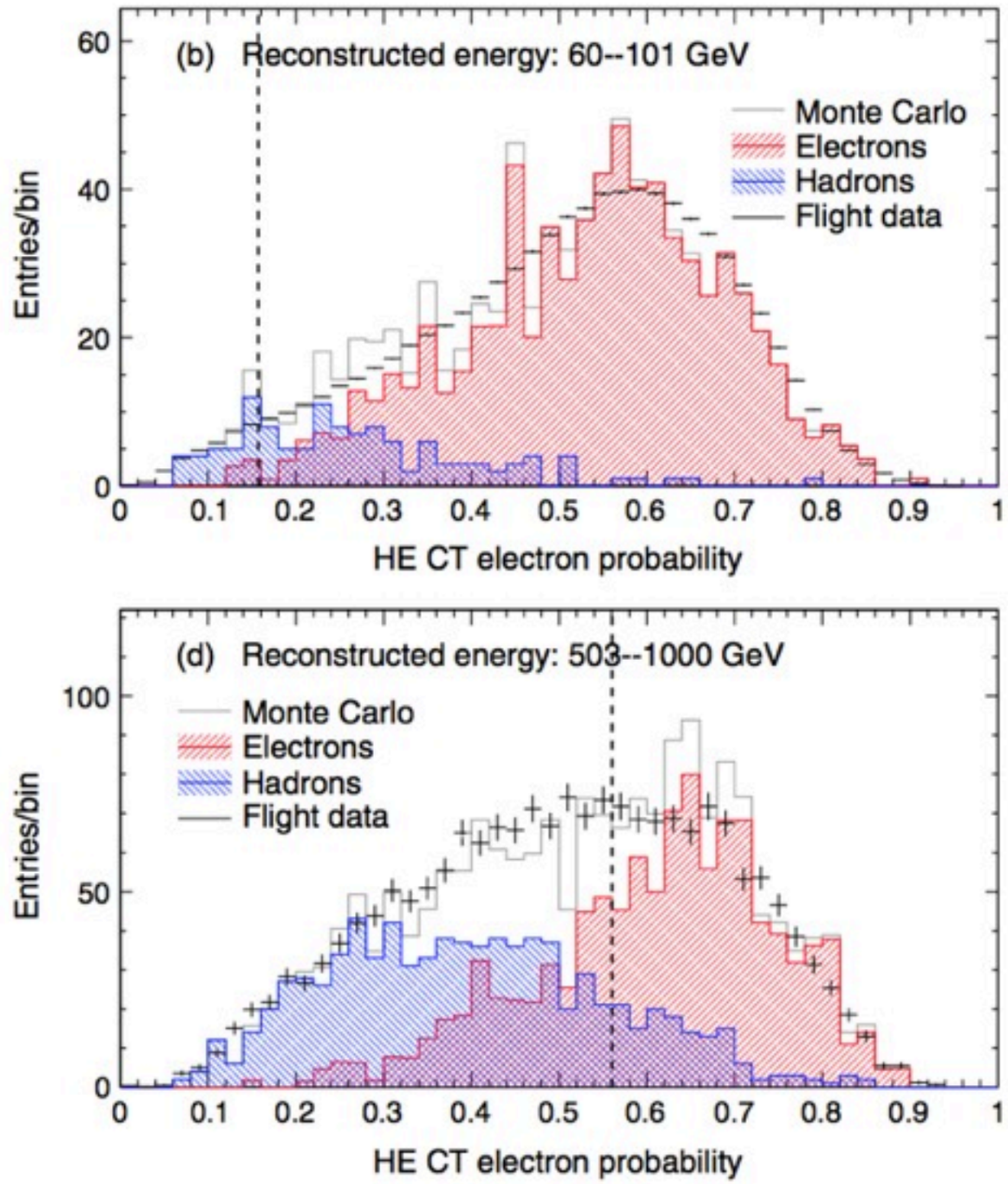


after classification tree analysis

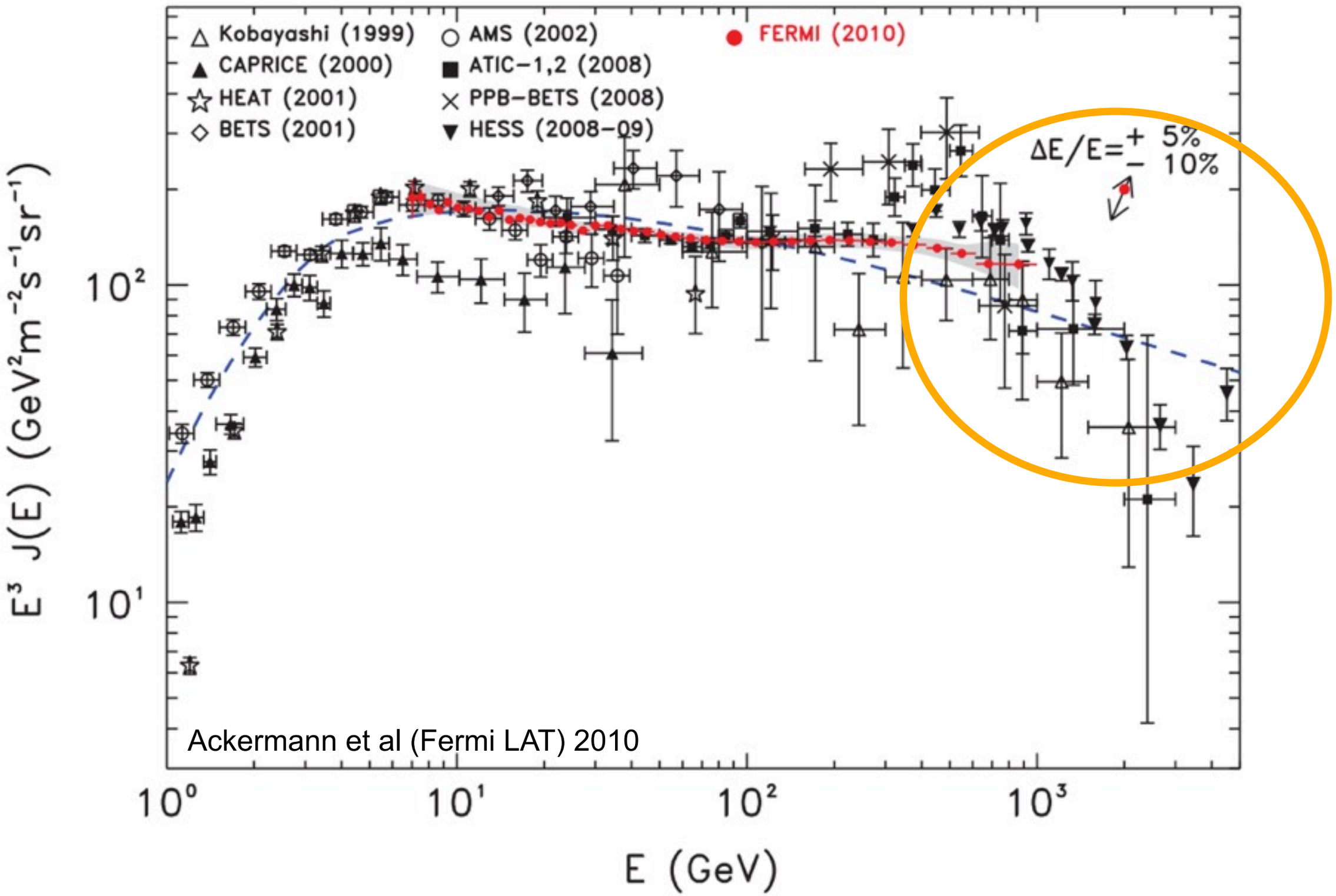


Residual Contamination

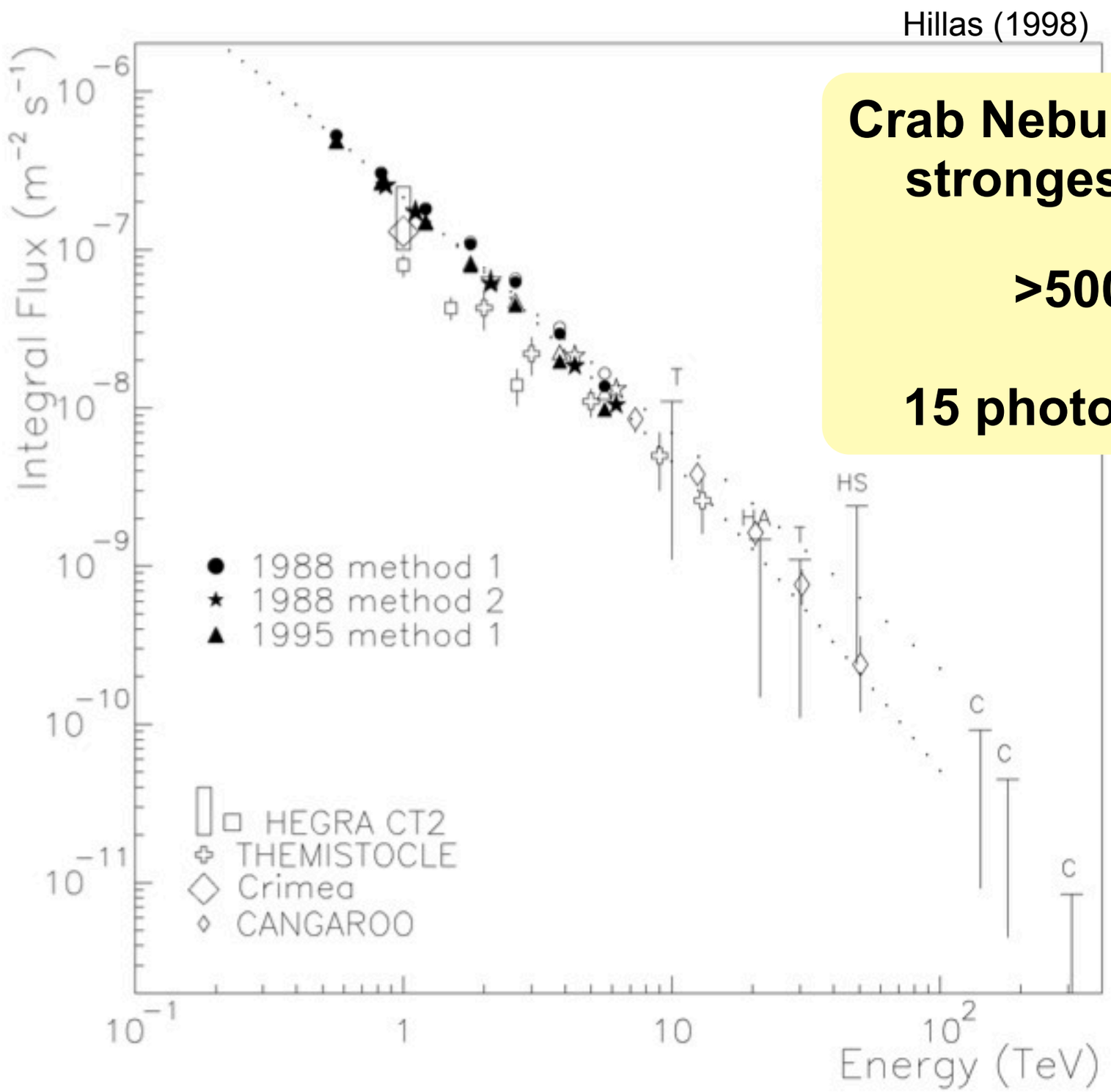




Electron Spectrum



The Crab Nebula



Crab Nebula among the strongest sources:

>500 GeV:

15 photon/m²/100 y

VHE astronomy:

energy, direction, particle type

Gamma-Photon

Particle shower

Cherenkov Light

Cherenkov light from air showers: weak, short (~ns), blue flash of light

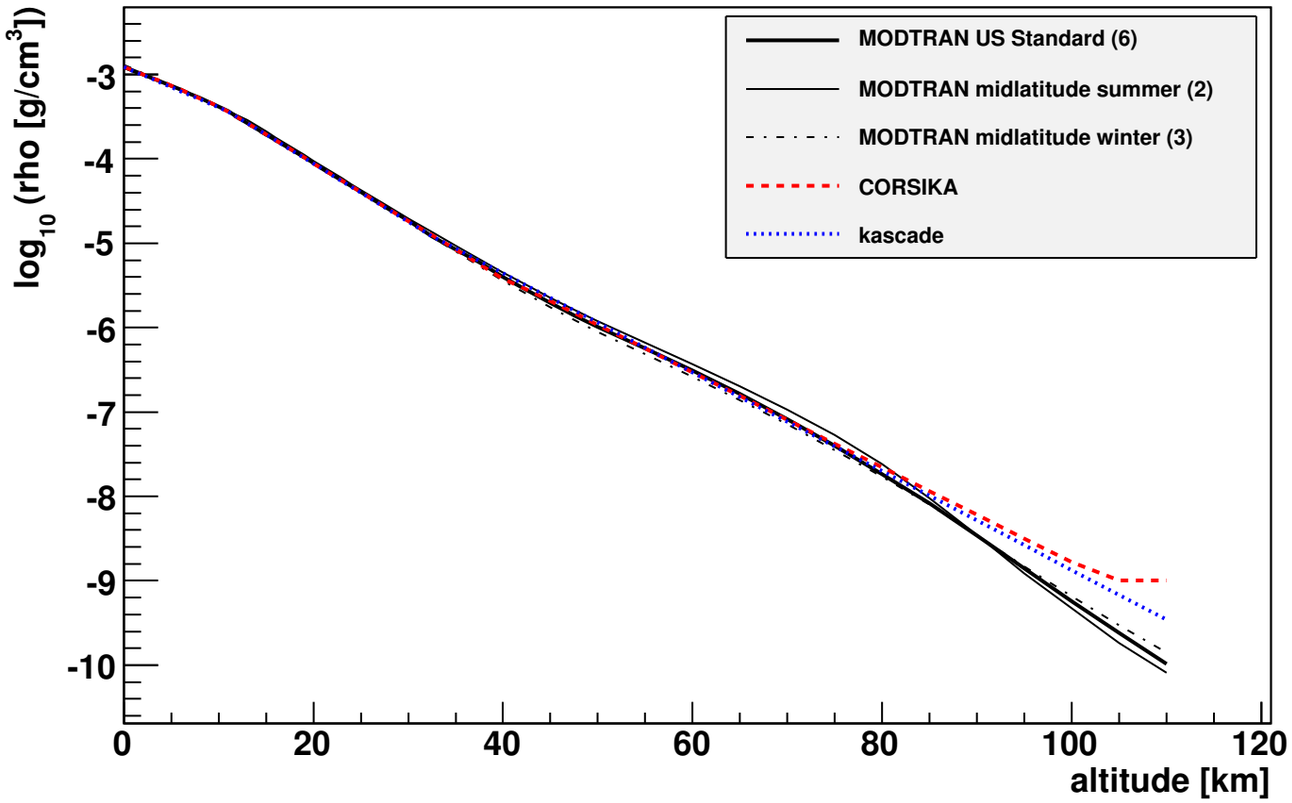
Atmosphere

Earth

Cherenkov Light

Pavel Alekseyevich Cherenkov (Nobel price1958)

atmospheric density



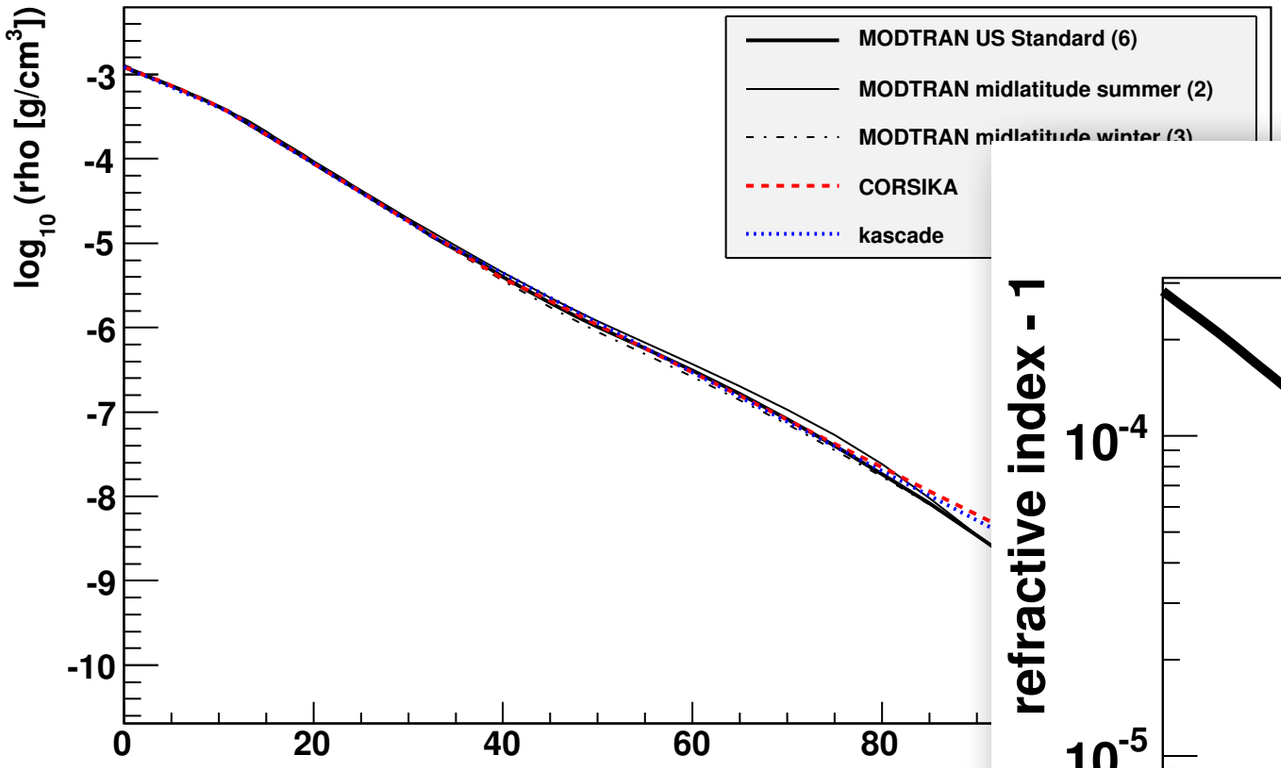
$$\cos\theta = 1 / (\beta n)$$

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

Cherenkov Light

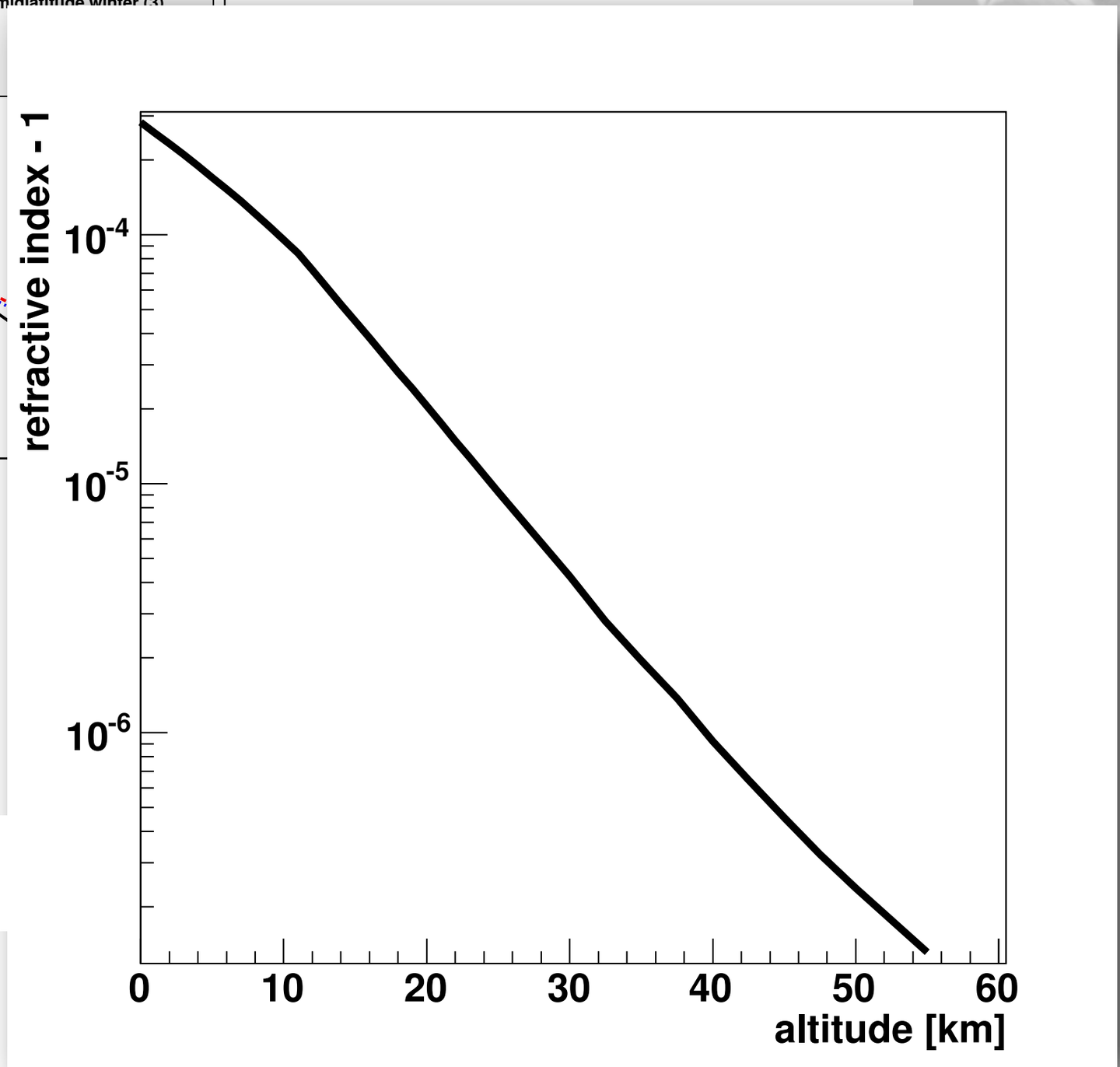
Pavel Alekseyevich Cherenkov (Nobel price1958)

atmospheric density



refractive index in air scales with density

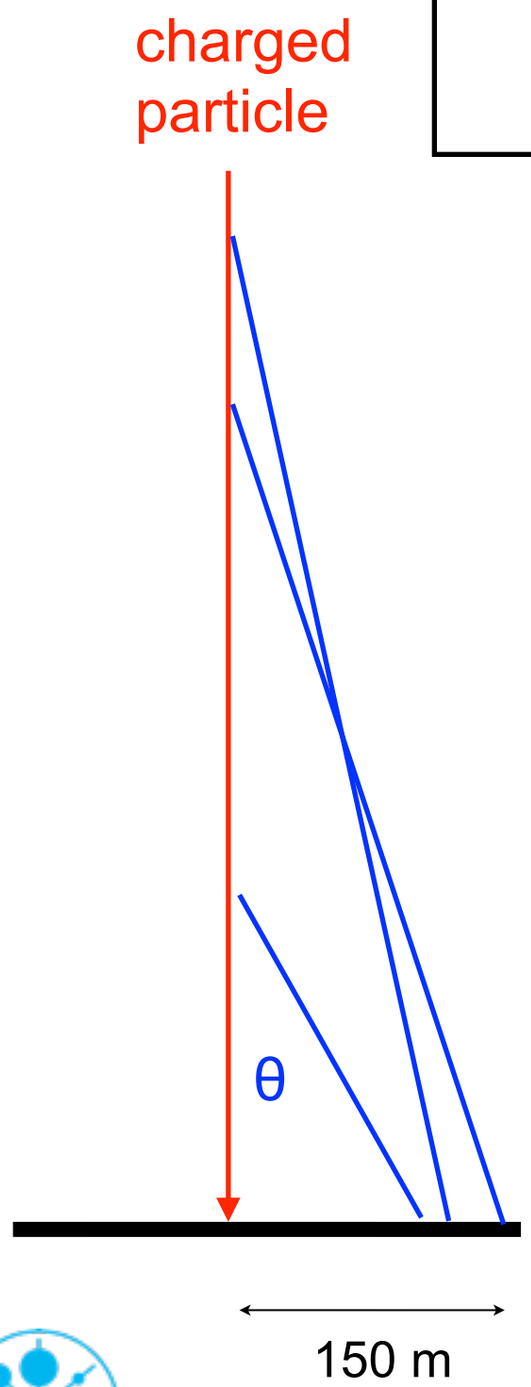
$$n = 1 + 0.000283\ \rho(h)/\rho(0)$$

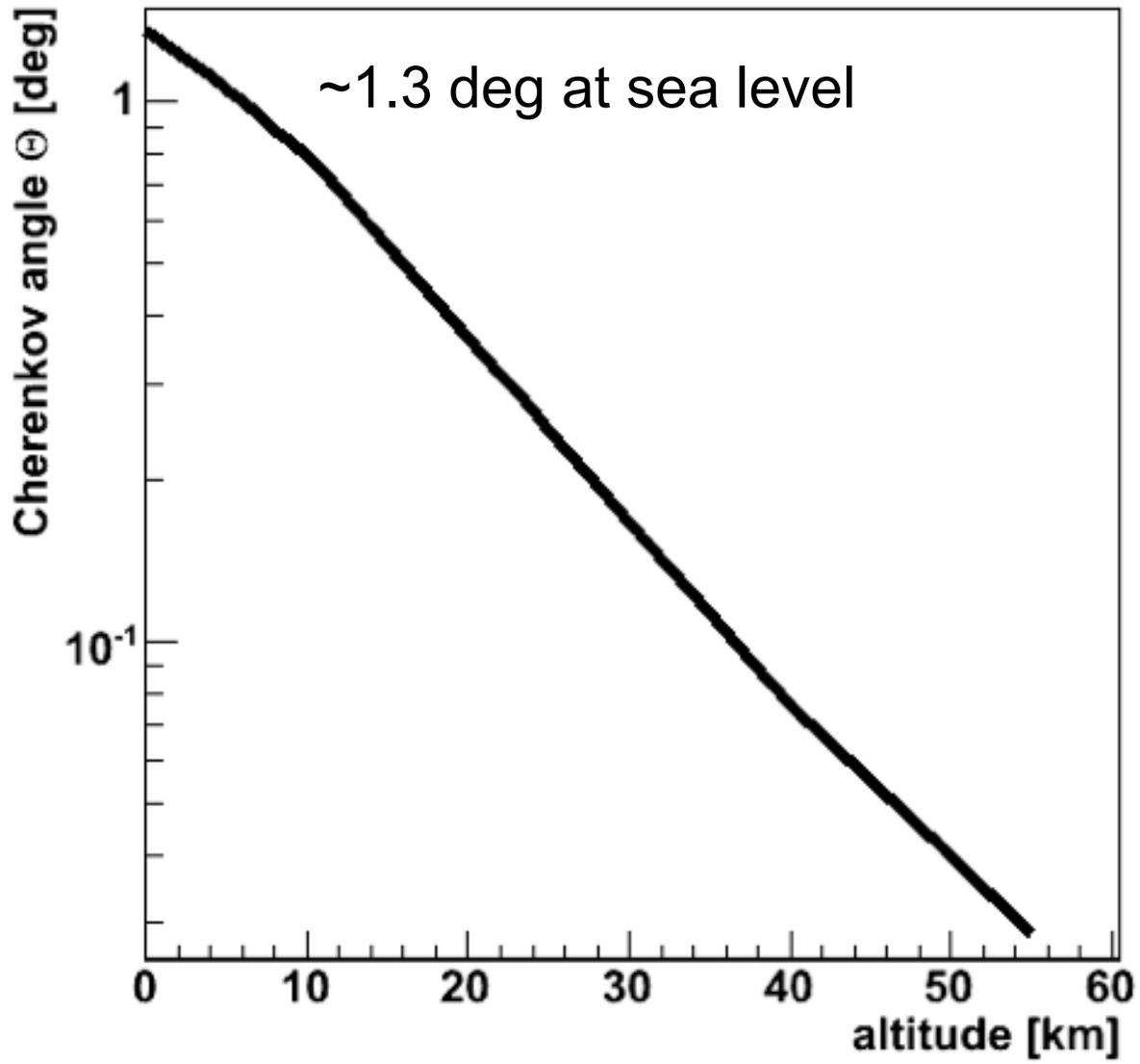


Cherenkov radiation: emission angle

light is emitted along a cone with half opening angle θ:

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

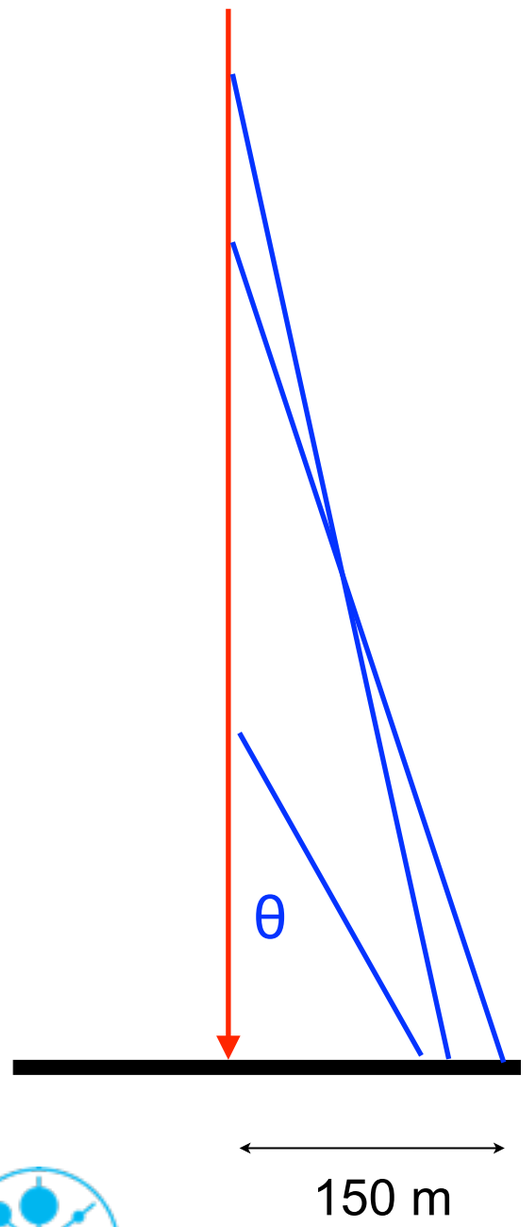


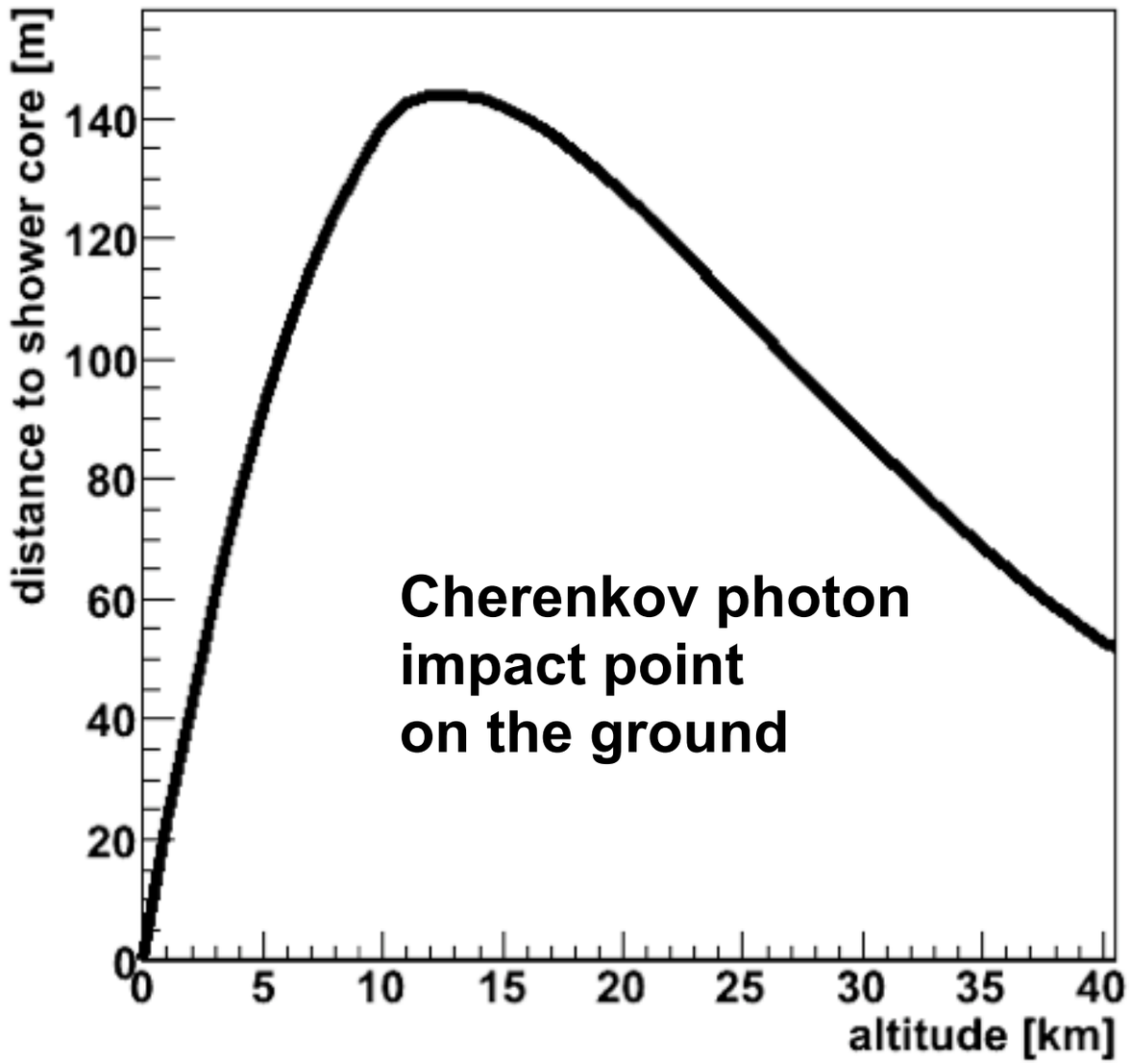


Cherenkov radiation: emission angle

light is emitted along a cone with half opening angle θ:

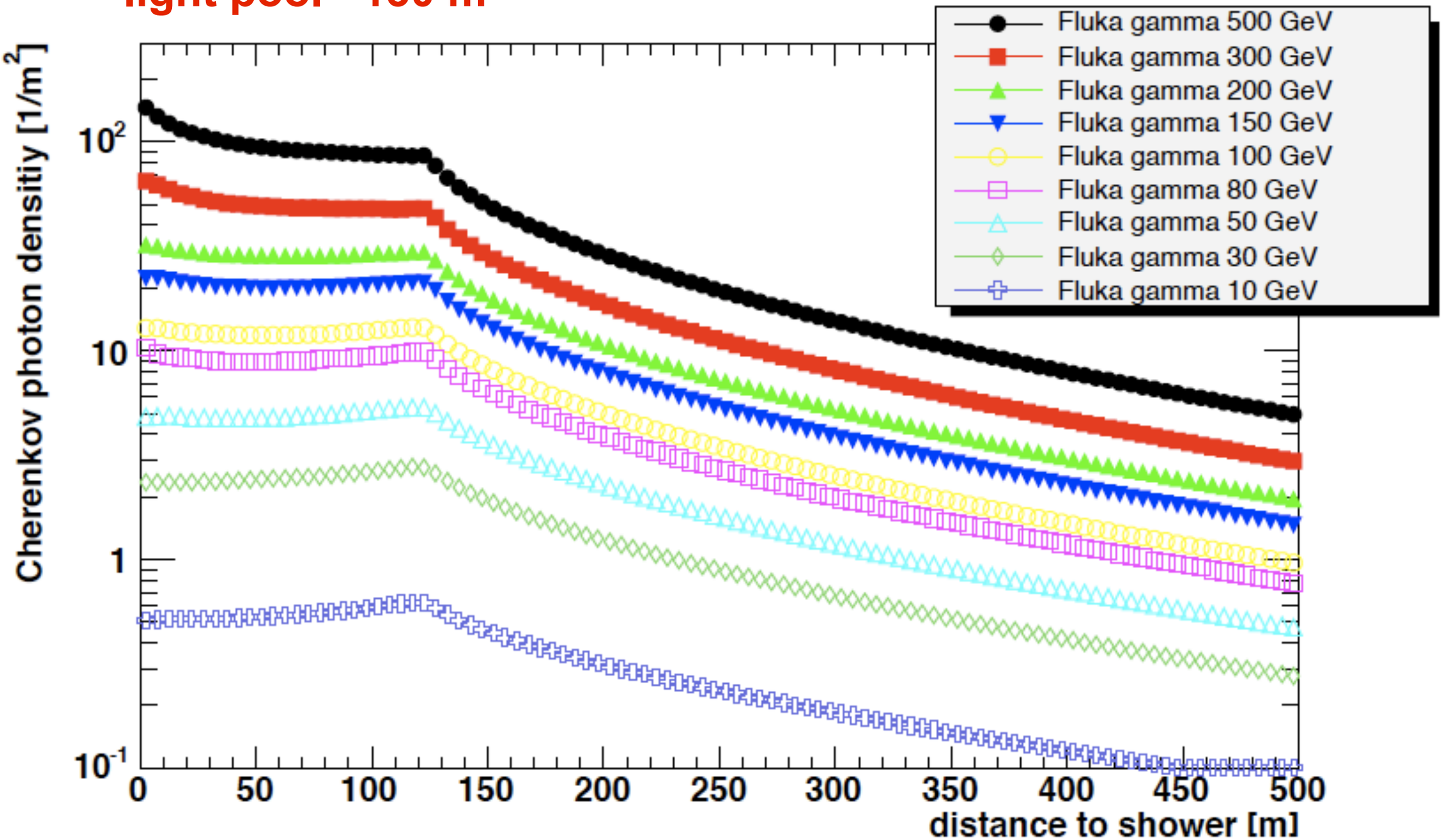
$$\cos\theta = 1 / (\beta n)$$





Lateral distribution of Cherenkov photons on the ground

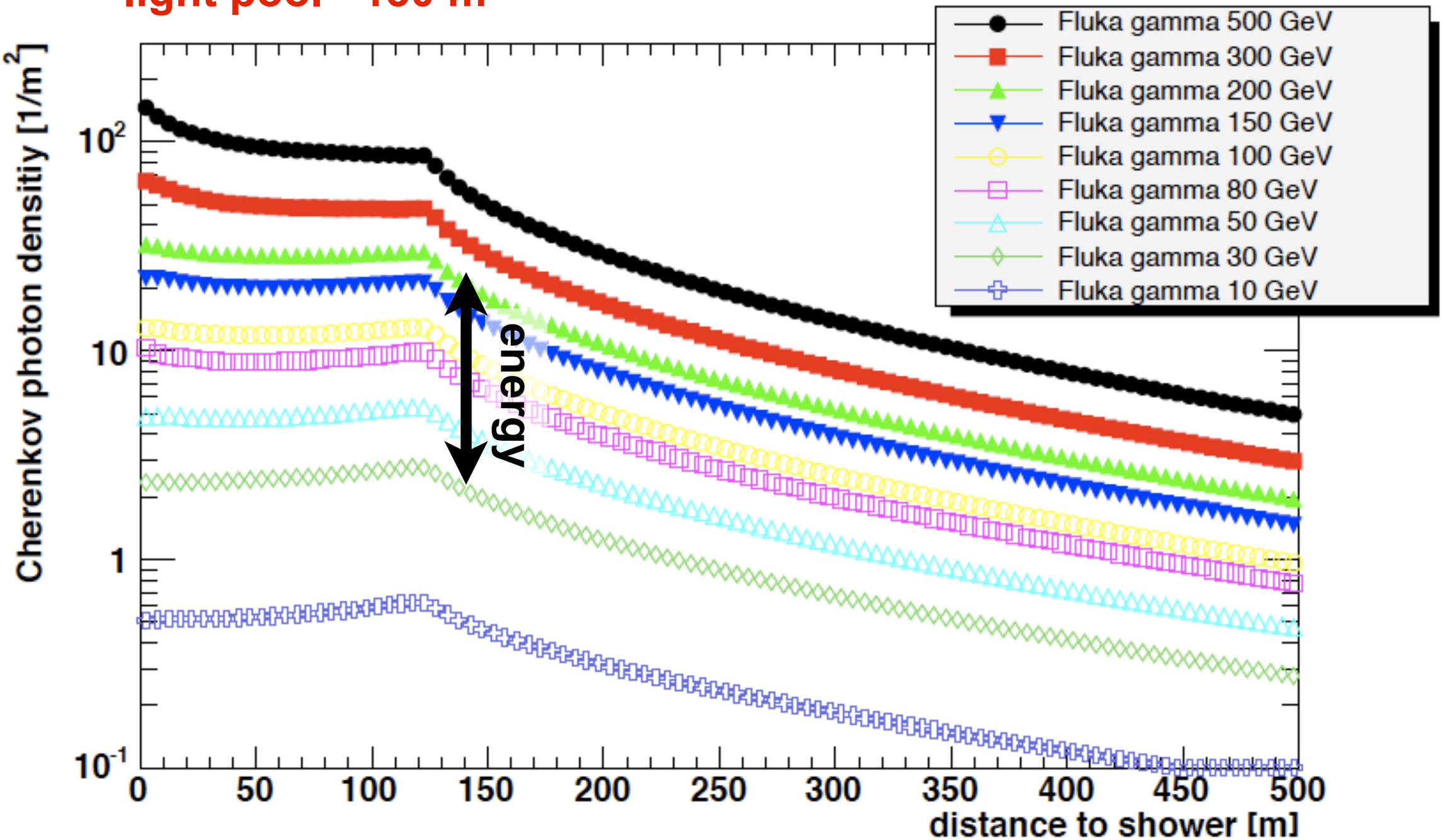
light pool ~130 m



typical mirror area: 100 m²

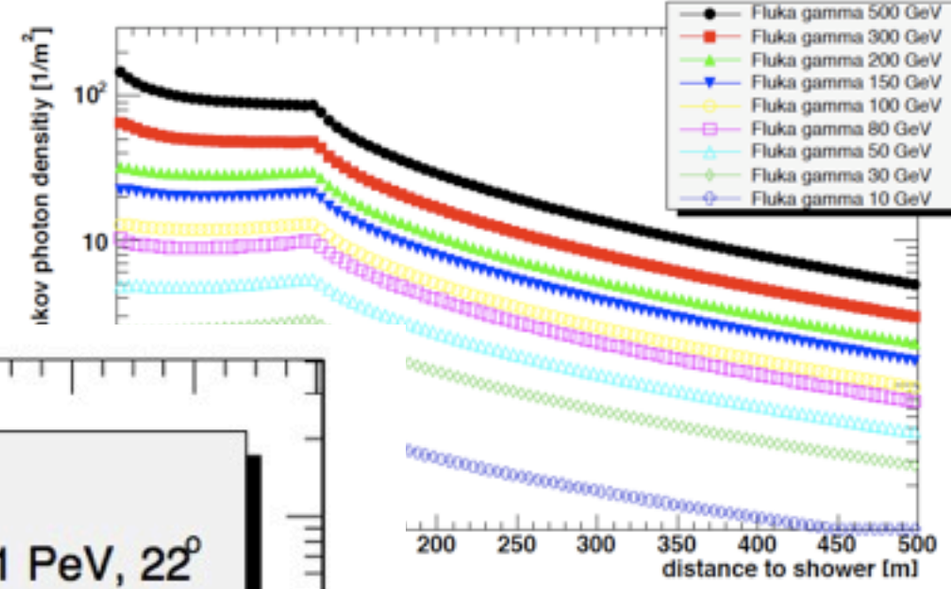
Lateral distribution of Cherenkov photons on the ground

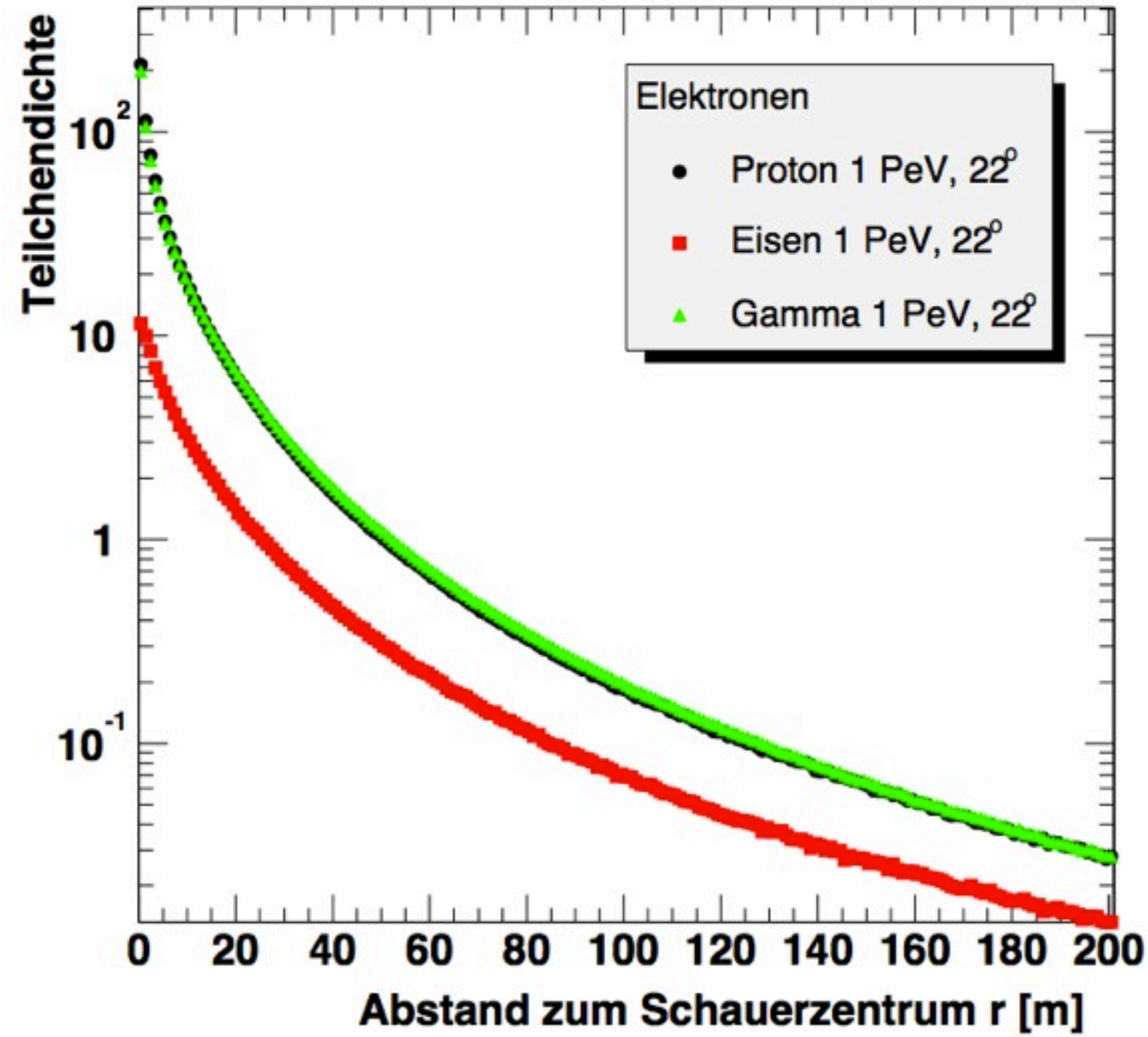
light pool ~130 m



typical mirror area: 100 m²

Particle lateral distributions



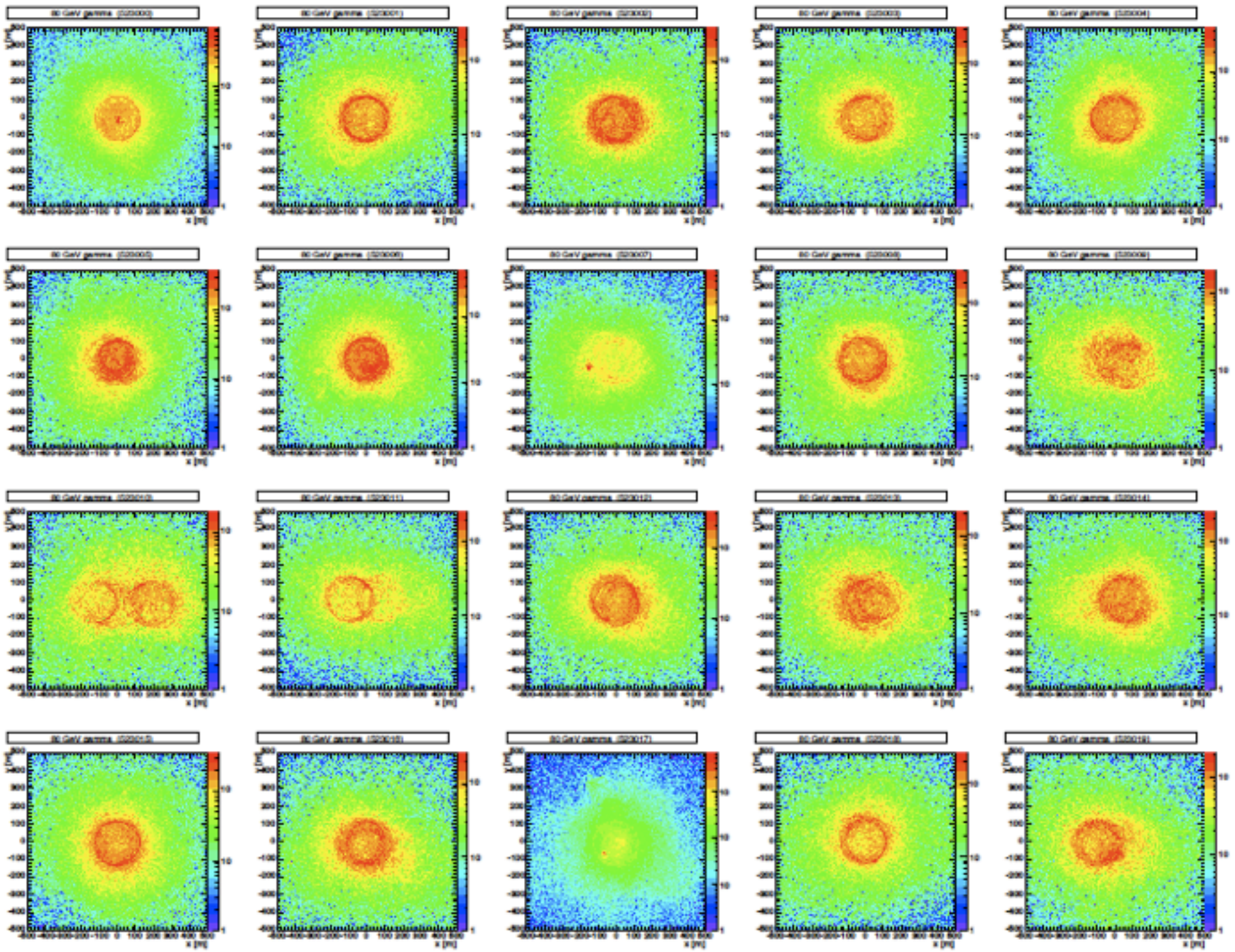


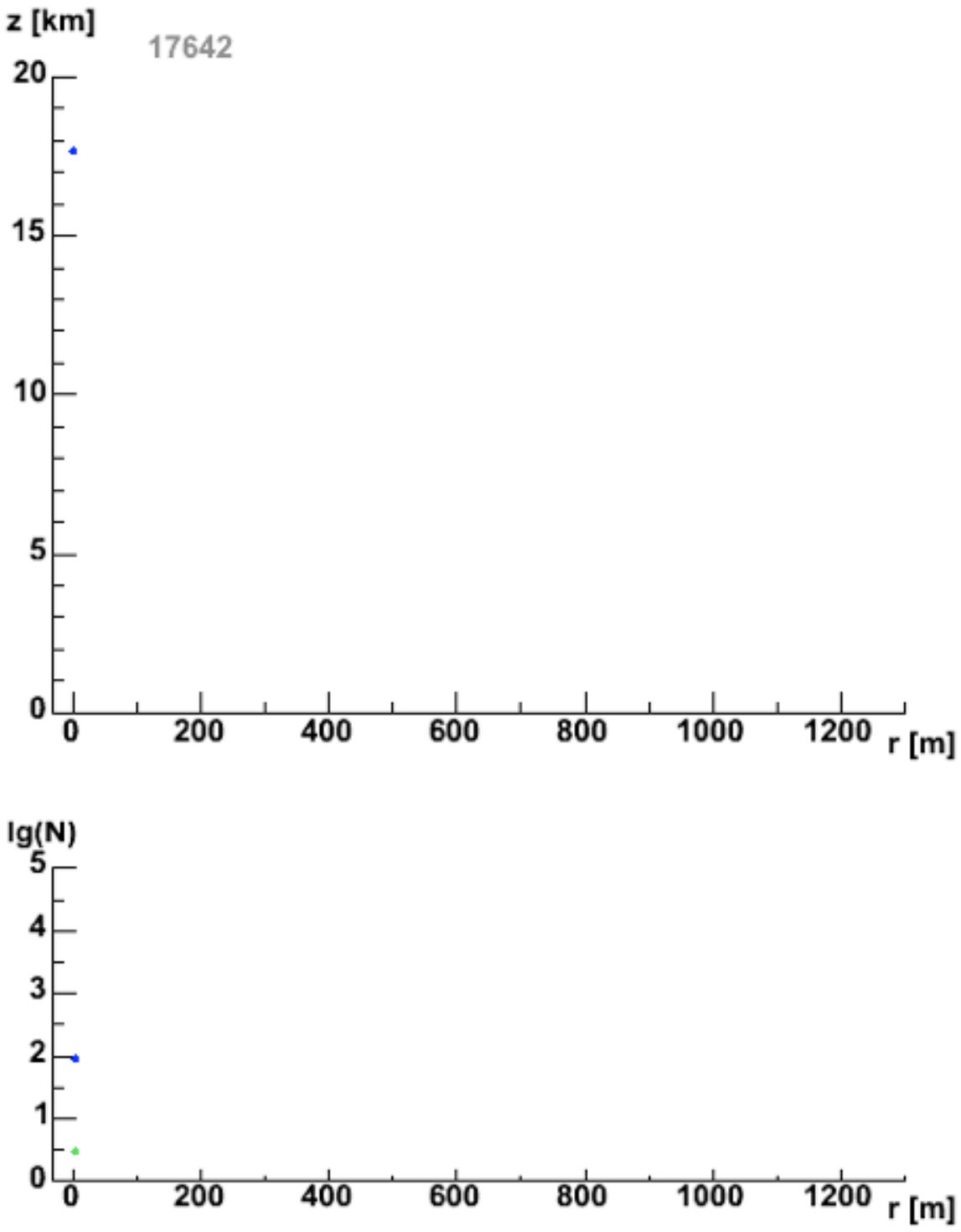
KASCADE air shower array

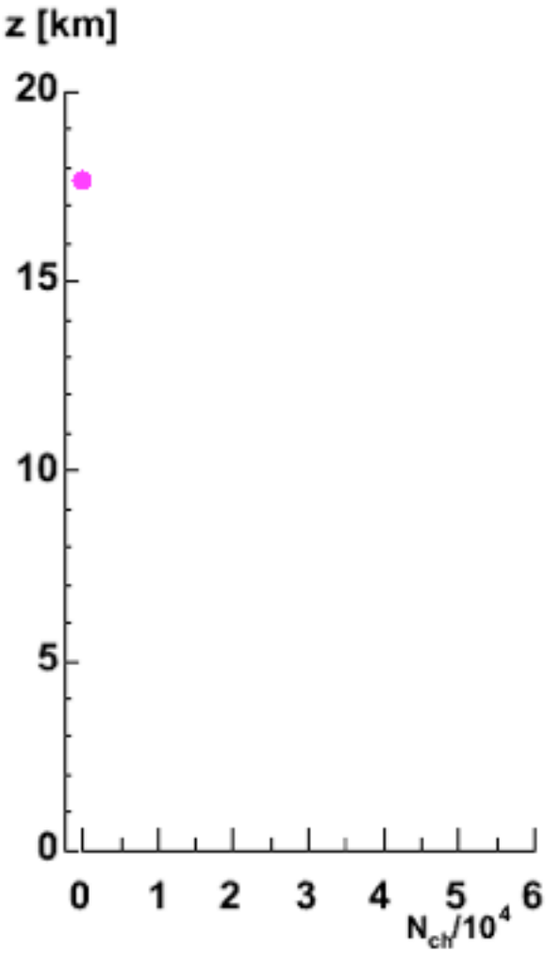
VERITAS

Shower fluctuations

randomly selected showers with 80 GeV primary photon energy







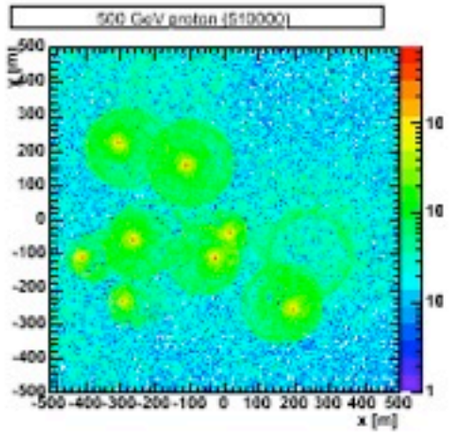
Proton 10^{14} eV

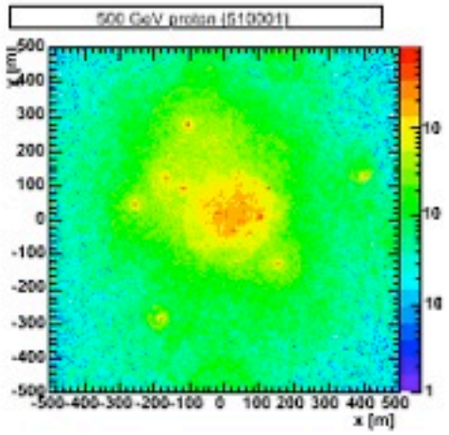
h^{1st} = 17642 m

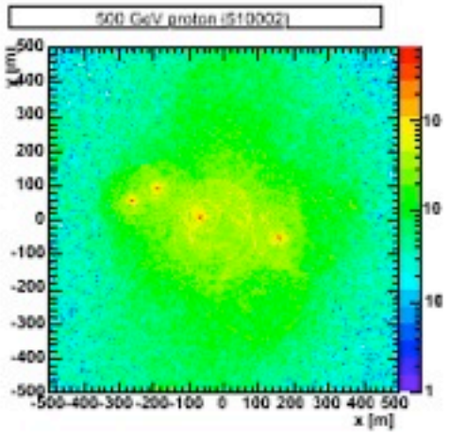
hadrons muons

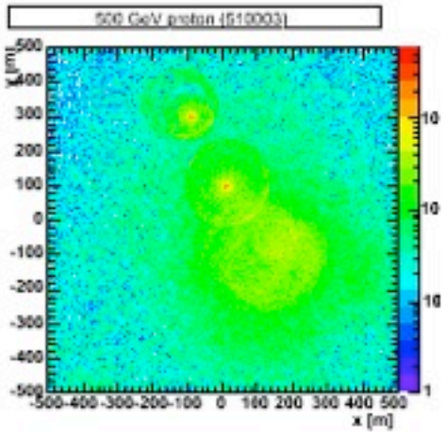
neutrons electrs

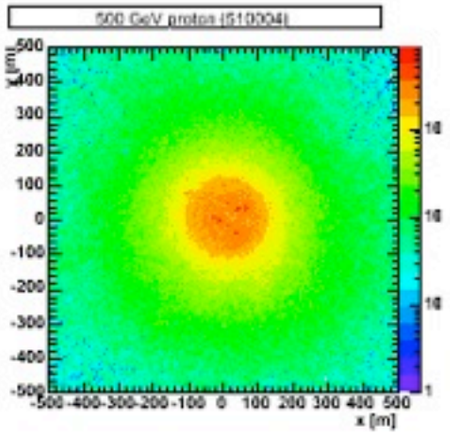
J.Oehlschlaeger,R.Engel,FZKarlsruhe

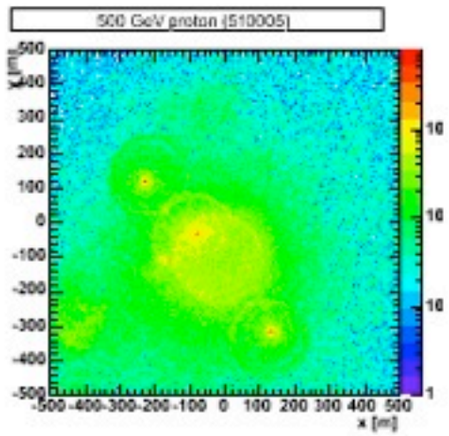

500 GeV proton (510000)
y [m]
x [m]

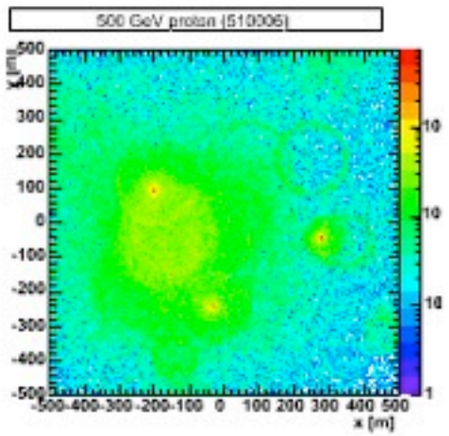

500 GeV proton (510001)
y [m]
x [m]

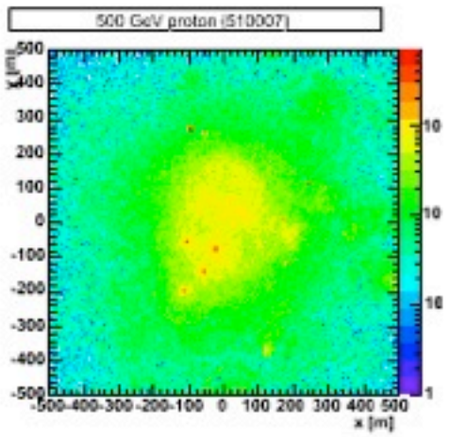

500 GeV proton (510002)
y [m]
x [m]

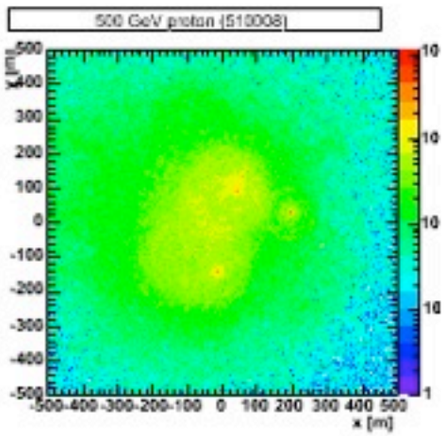

500 GeV proton (510003)
y [m]
x [m]

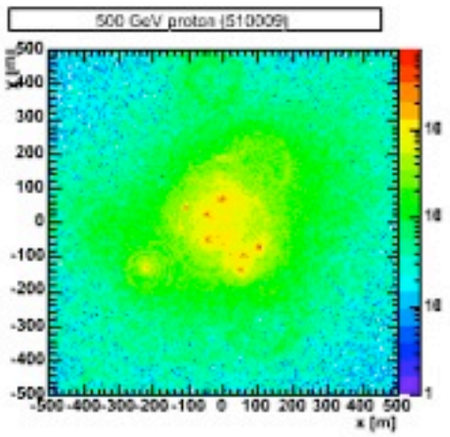

500 GeV proton (510004)
y [m]
x [m]

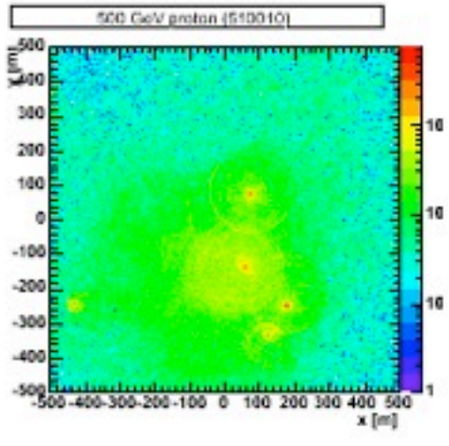

500 GeV proton (510005)
y [m]
x [m]

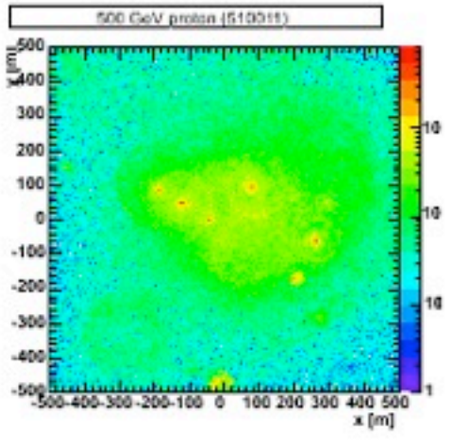

500 GeV proton (510006)
y [m]
x [m]

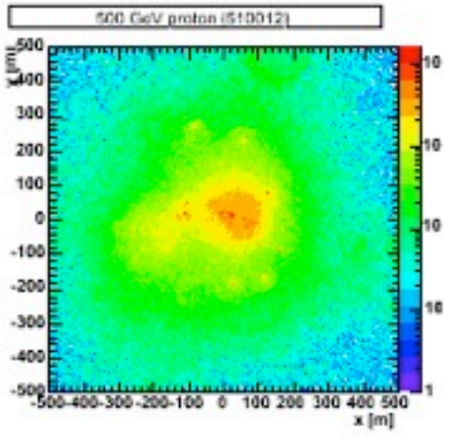

500 GeV proton (510007)
y [m]
x [m]

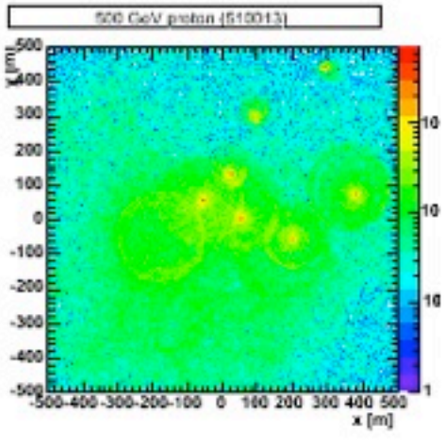

500 GeV proton (510008)
y [m]
x [m]

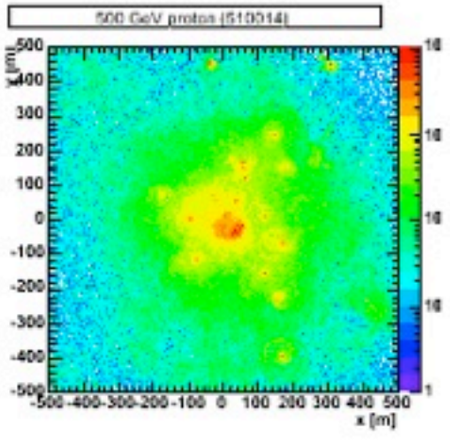

500 GeV proton (510009)
y [m]
x [m]

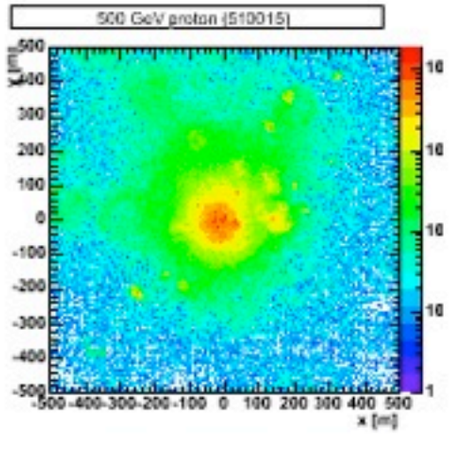

500 GeV proton (510010)
y [m]
x [m]

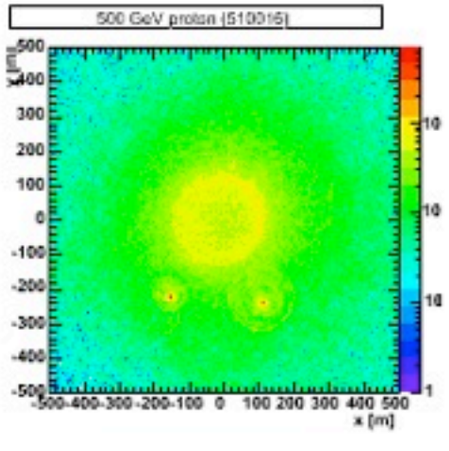

500 GeV proton (510011)
y [m]
x [m]

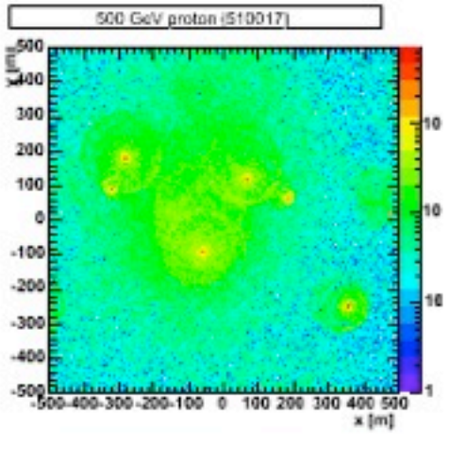

500 GeV proton (510012)
y [m]
x [m]

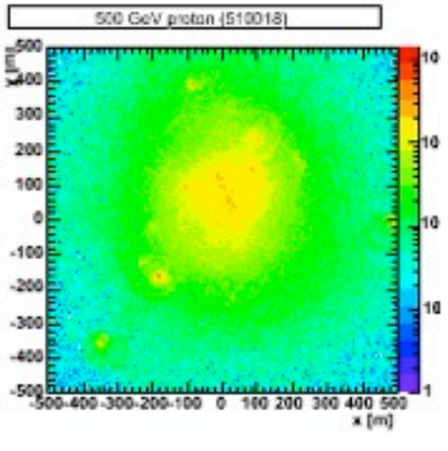

500 GeV proton (510013)
y [m]
x [m]

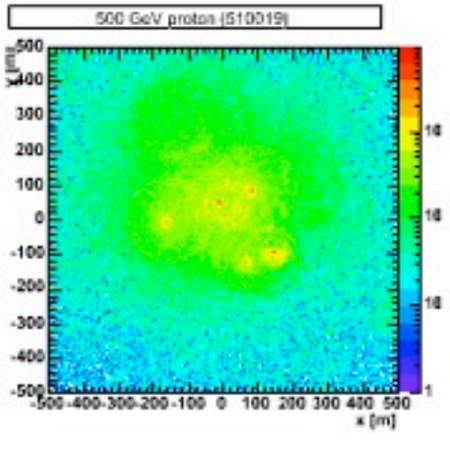

500 GeV proton (510014)
y [m]
x [m]


500 GeV proton (510015)
y [m]
x [m]


500 GeV proton (510016)
y [m]
x [m]

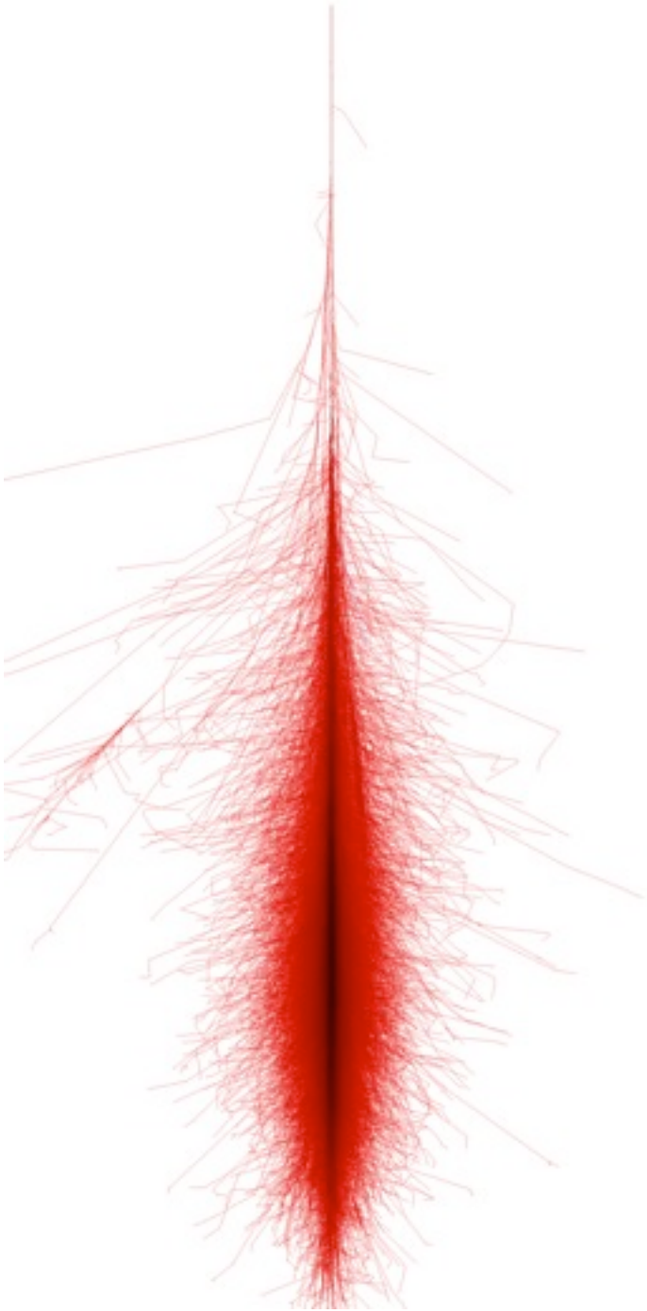

500 GeV proton (510017)
y [m]
x [m]


500 GeV proton (510018)
y [m]
x [m]

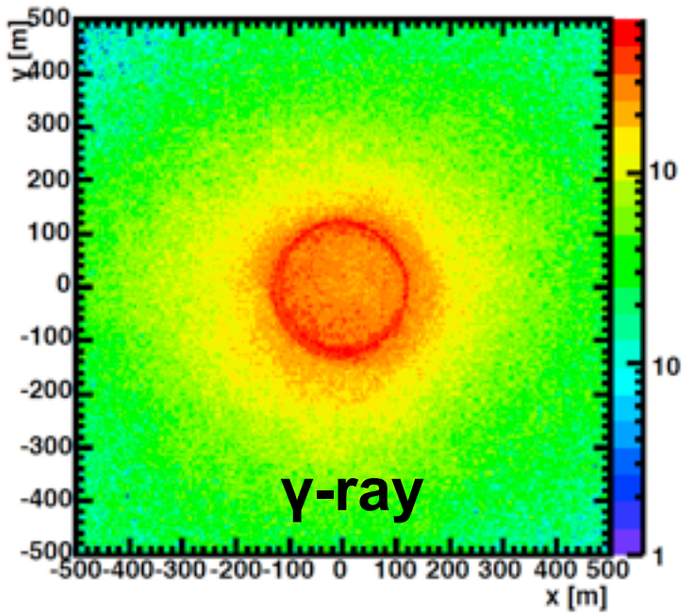

500 GeV proton (510019)
y [m]
x [m]

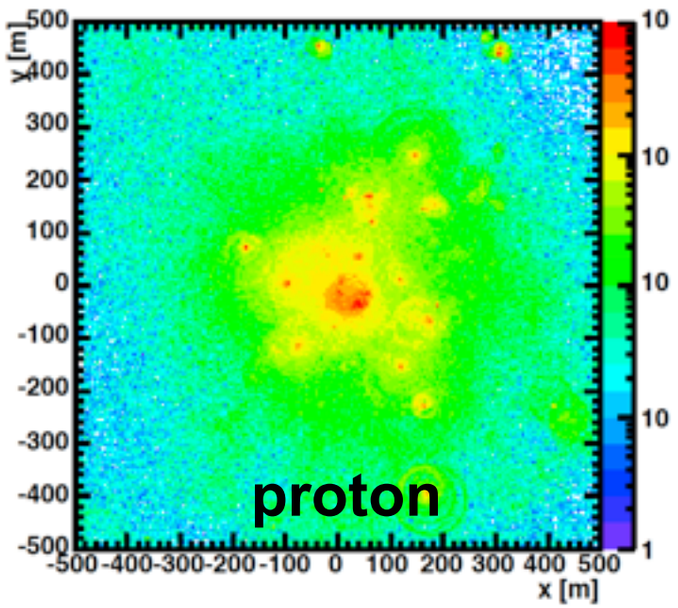
Proton vs Gamma-ray showers

γ-ray

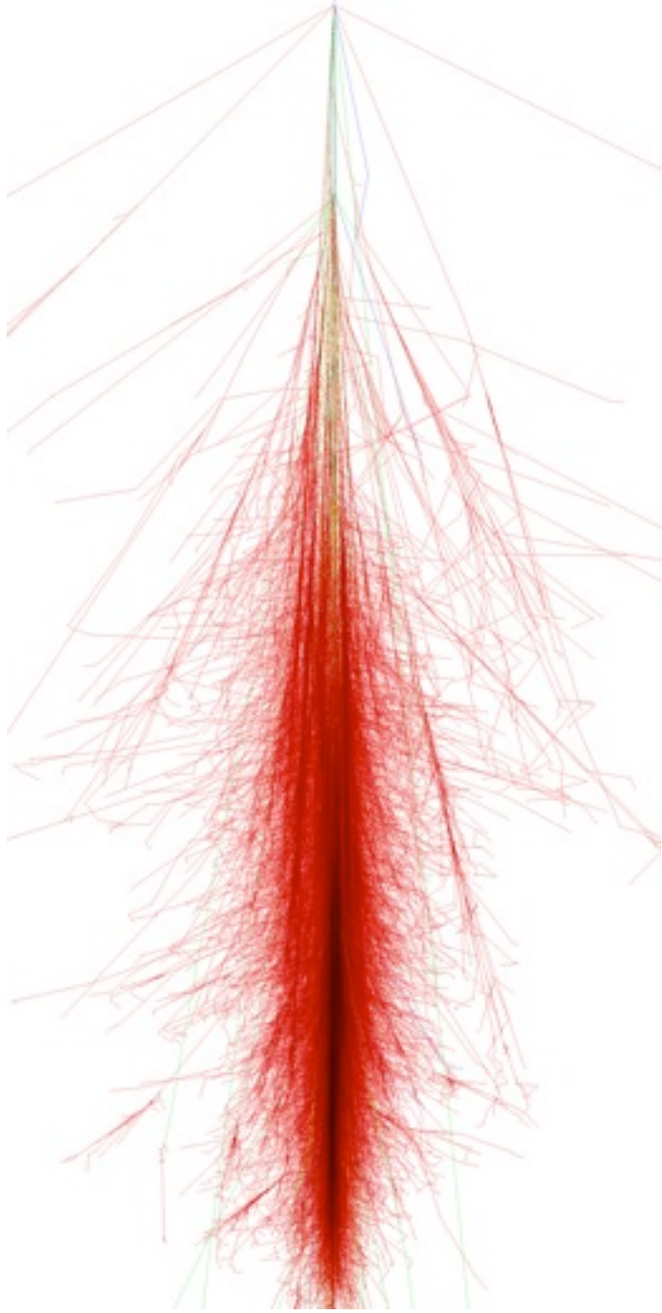


Cherenkov photons on ground

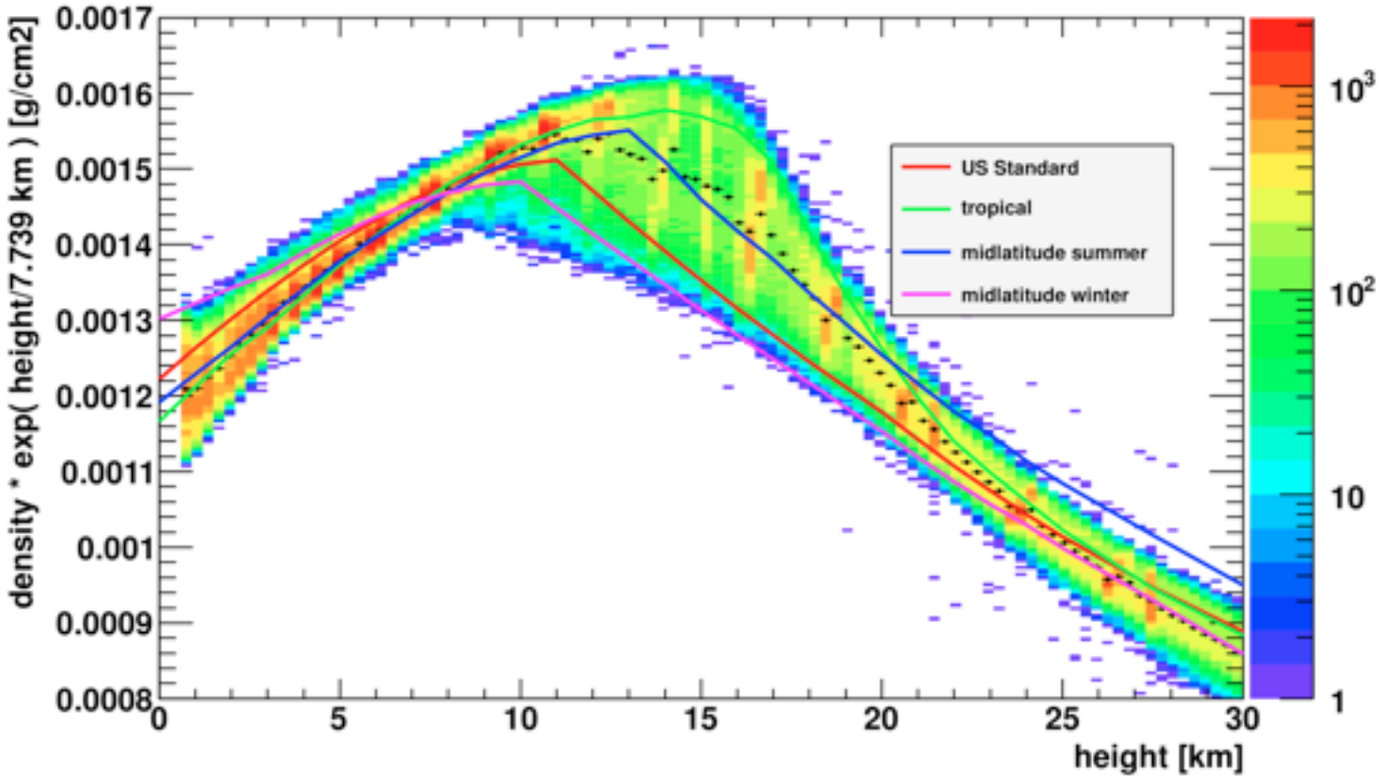


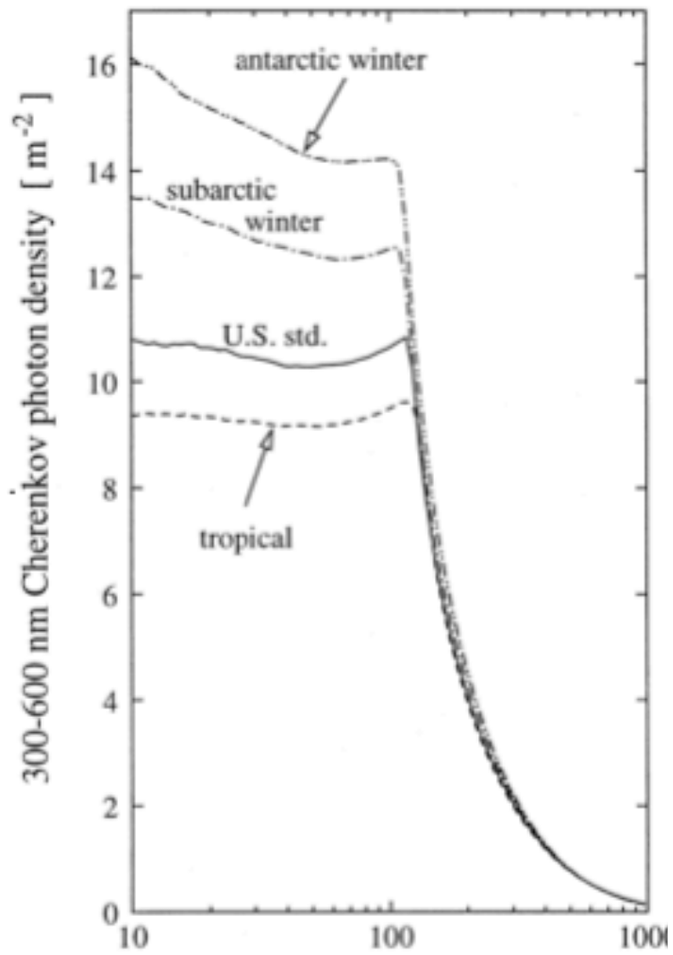


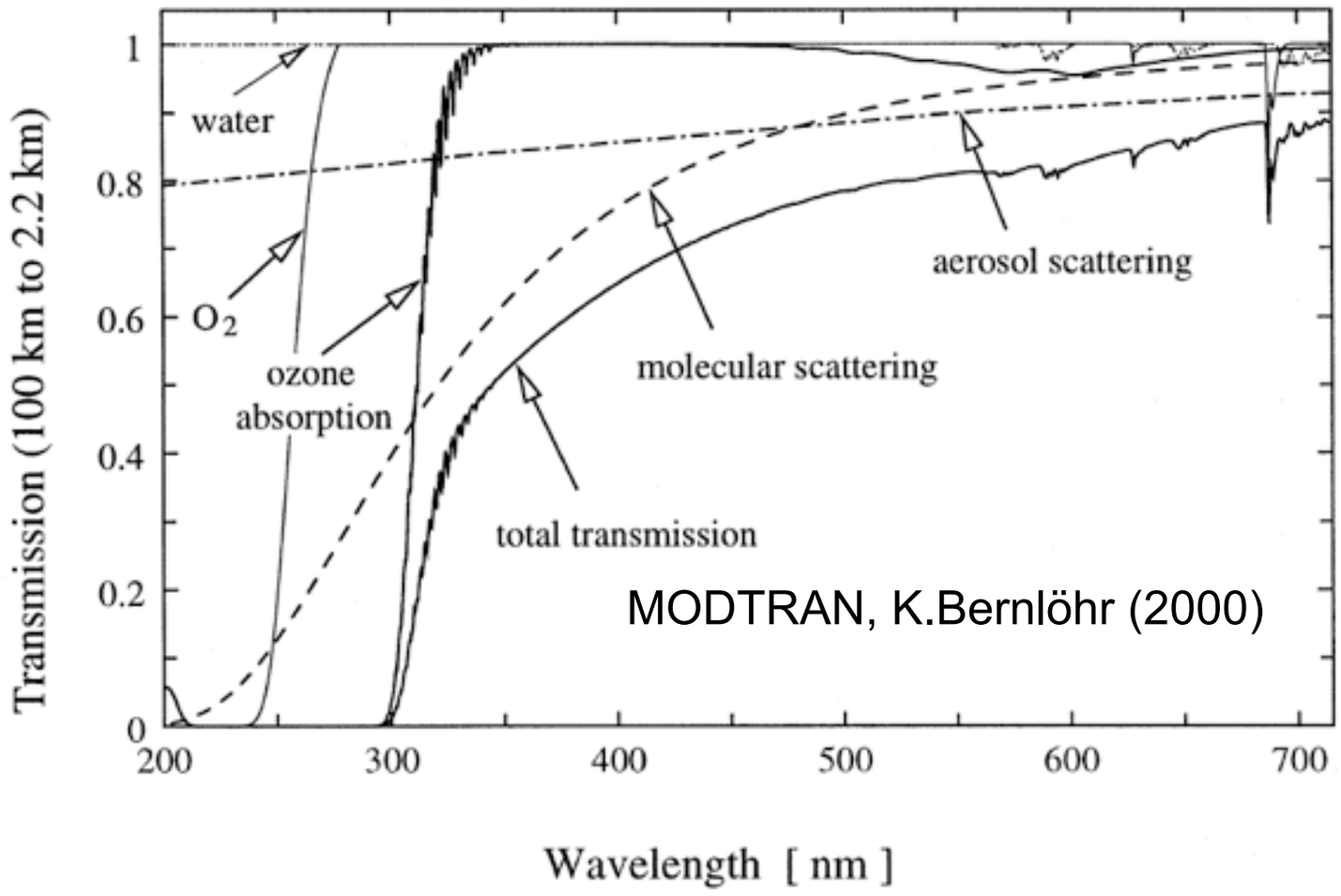
proton



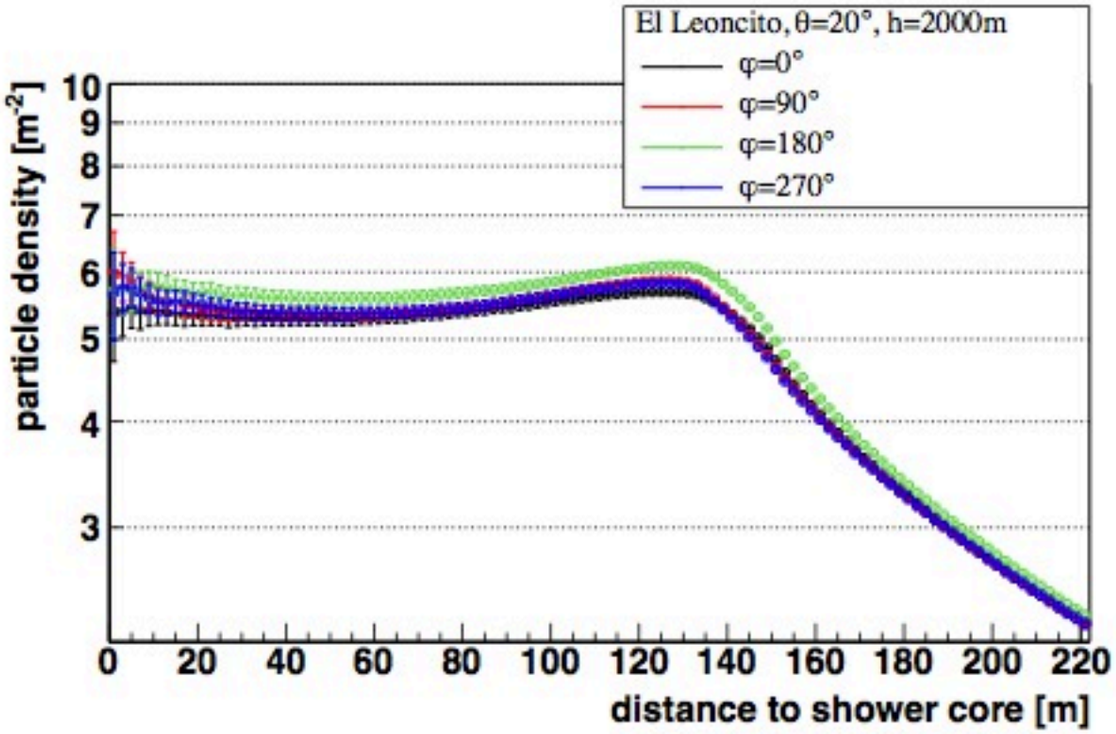
Atmosphere

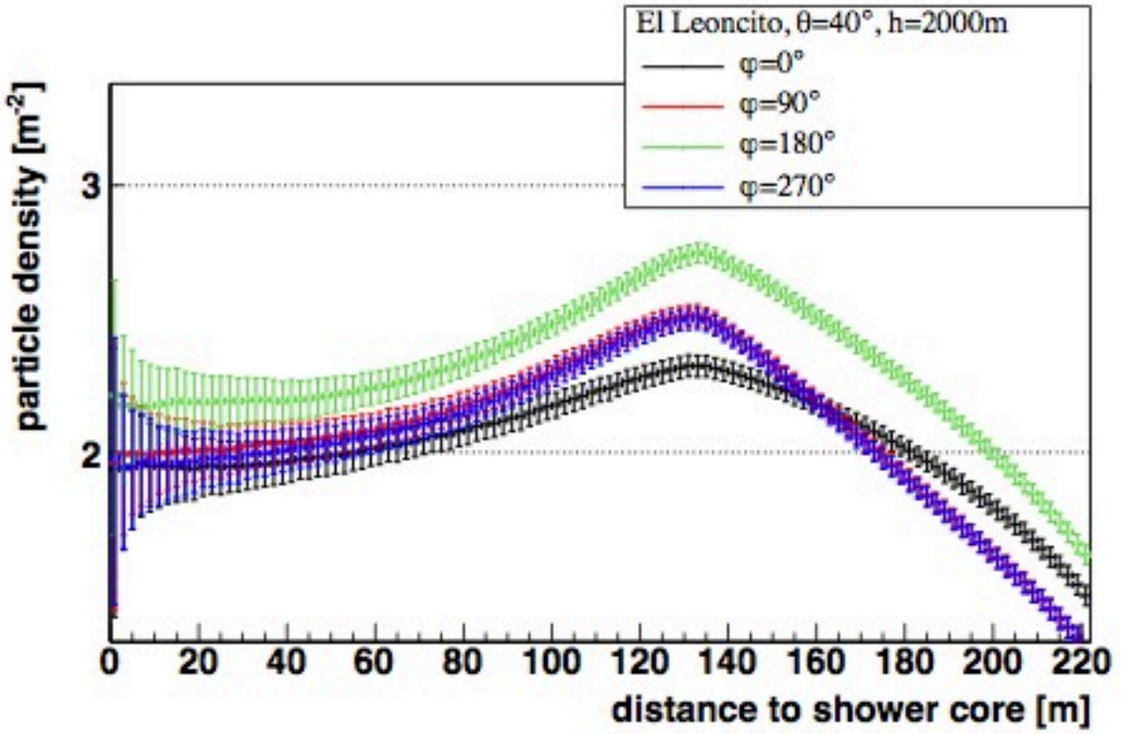

density * exp(height/7.739 km) [g/cm2]
height [km]
US Standard
tropical
midlatitude summer
midlatitude winter

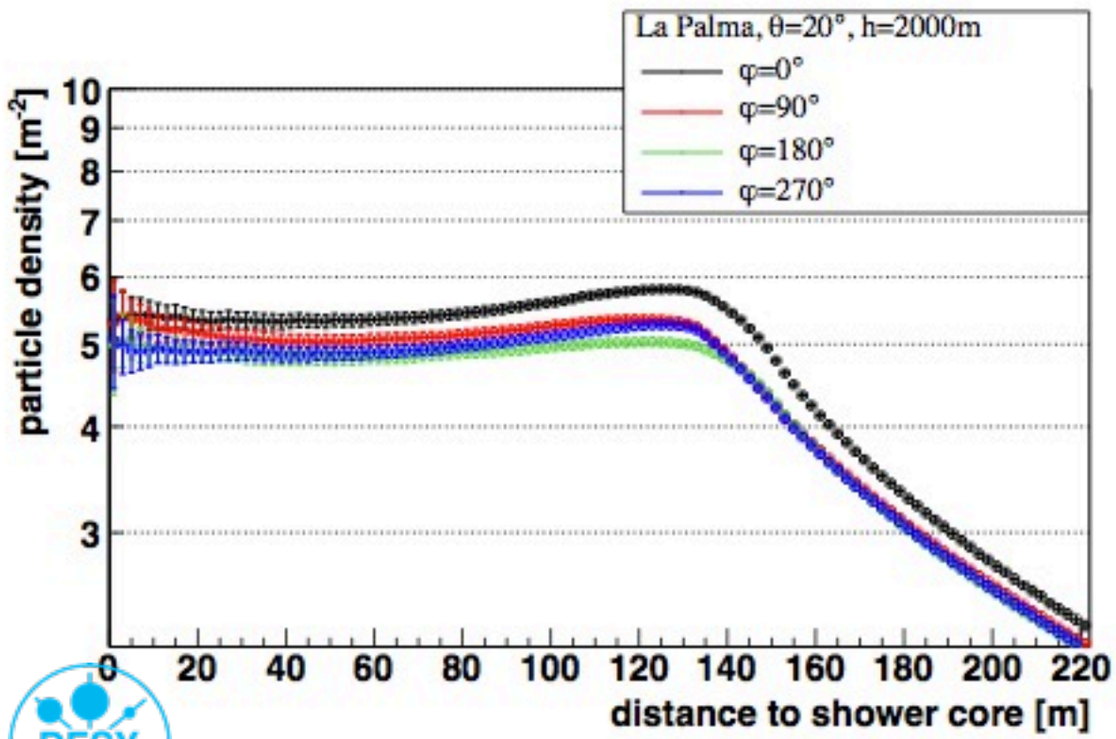

300-600 nm Cherenkov photon density [m^{-2}]
antarctic winter
subarctic winter
U.S. std.
tropical

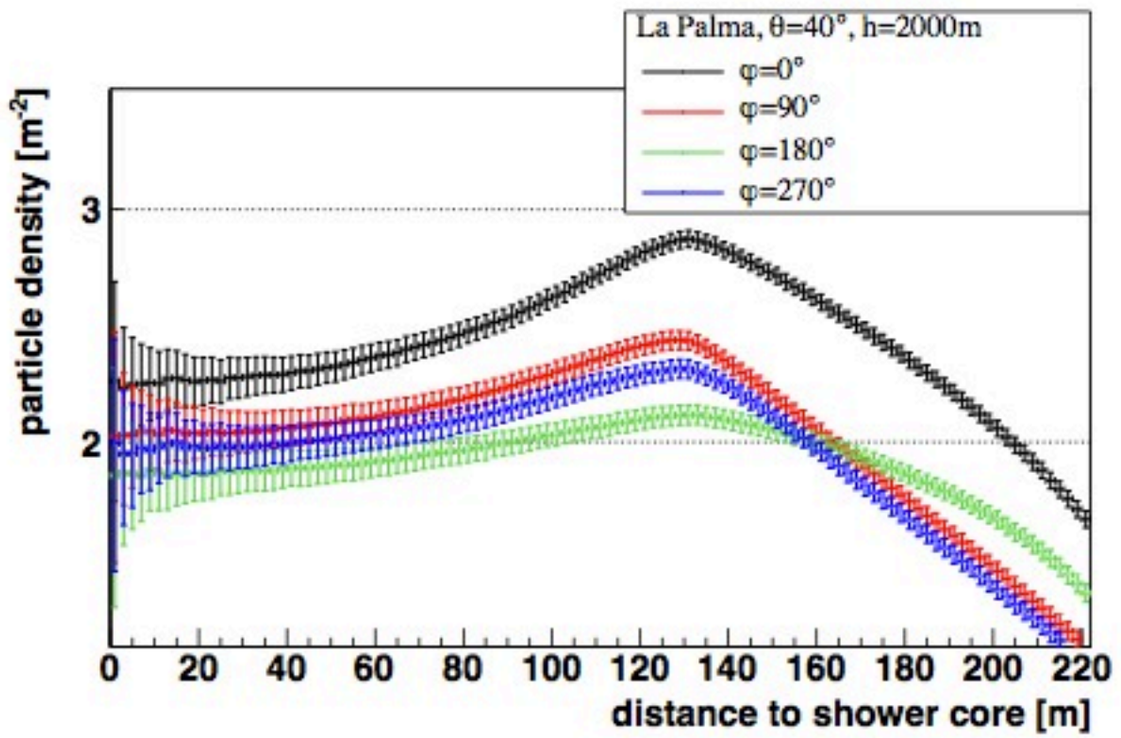

Transmission (100 km to 2.2 km)
Wavelength [nm]
water
O_2
ozone absorption
aerosol scattering
molecular scattering
total transmission
MODTRAN, K.Bernlöhr (2000)

Geomagnetic Field









Whipple Observatory

completed in 1968
upgrade with imaging camera proposed 1977
first detection (Crab Nebula) 1986

MAGIC

TACTIC

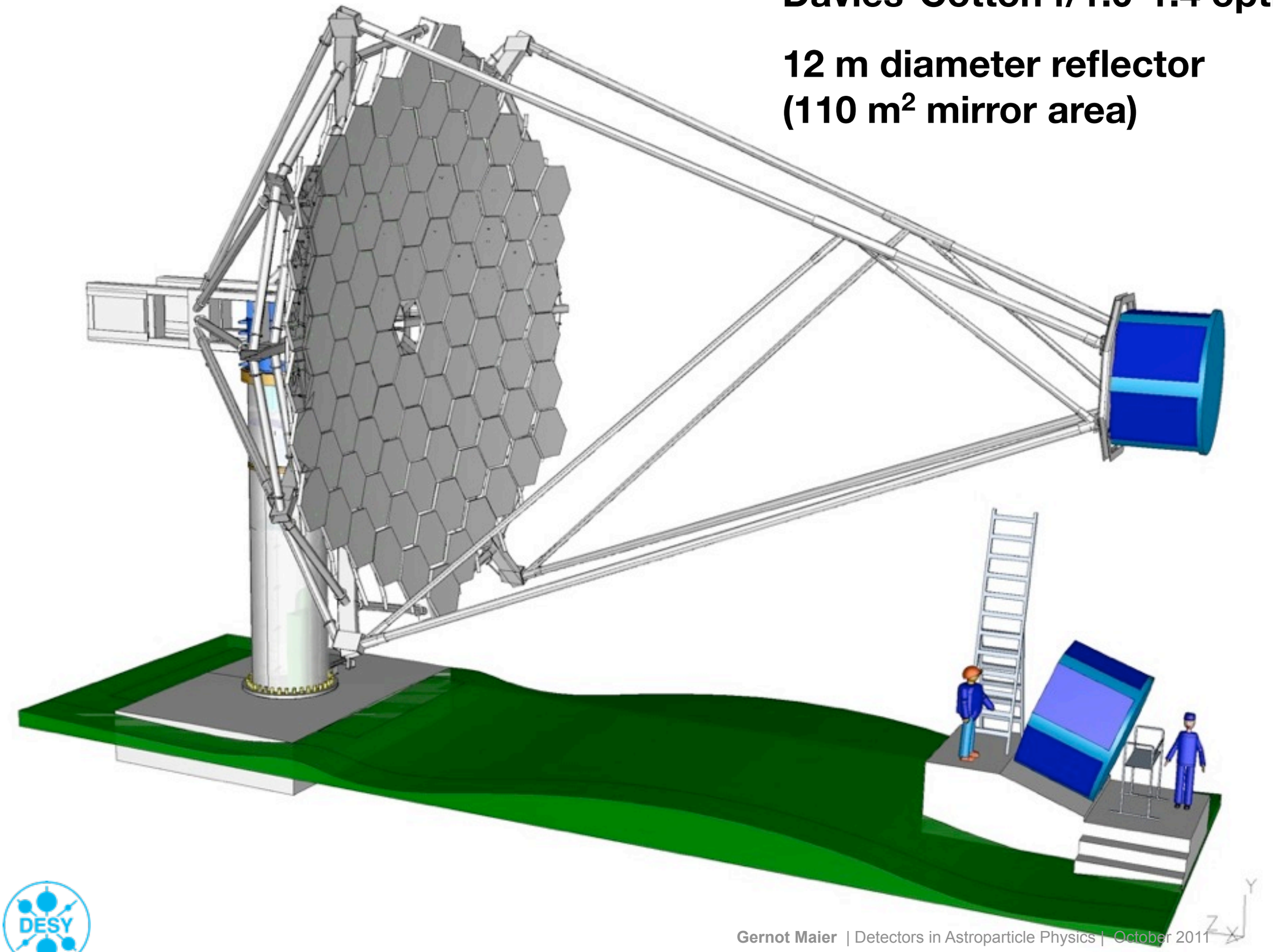
VERITAS

H.E.S.S.

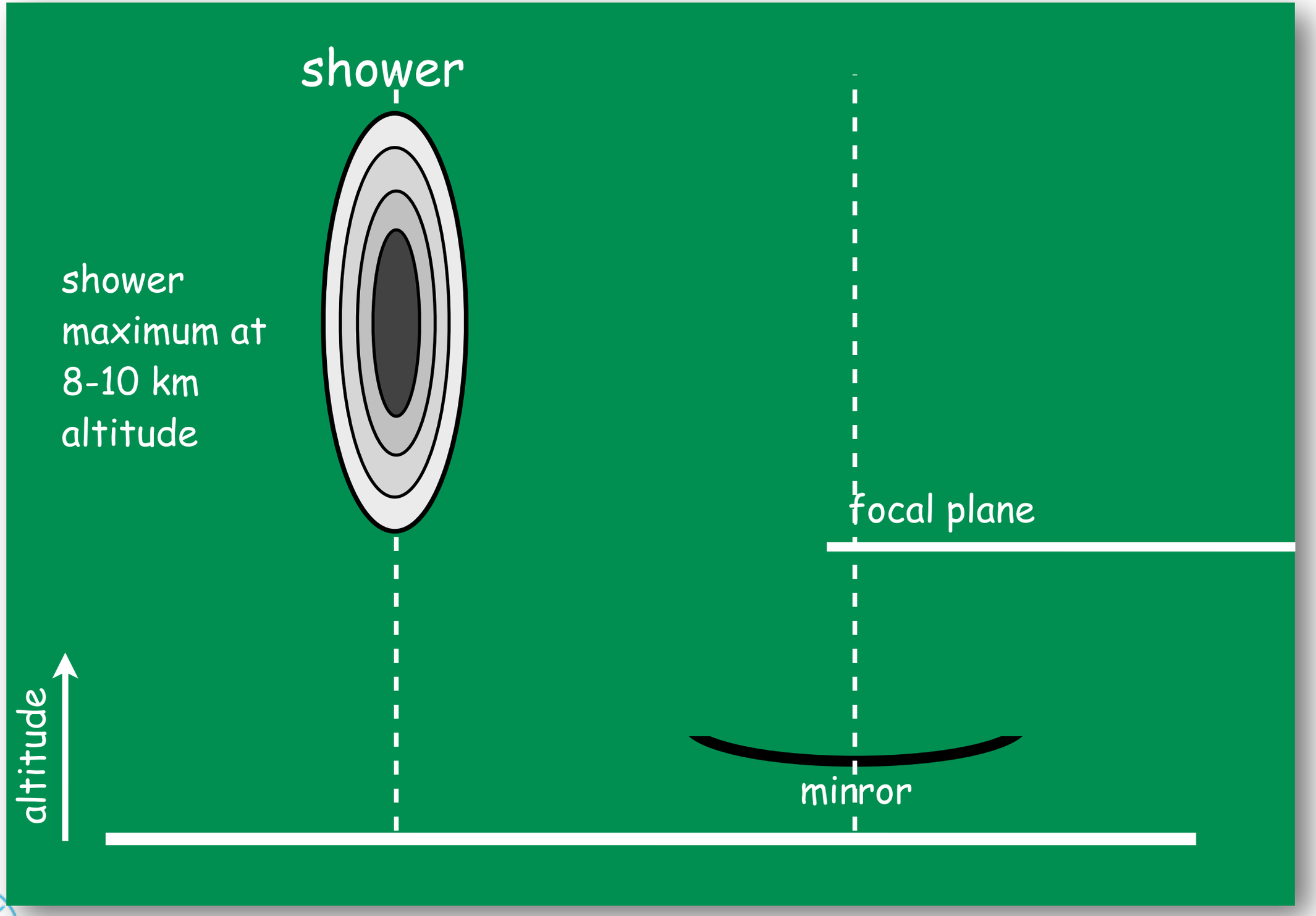
Observatory	Elevation (km)	Telescopes #	Mirror Area (m^2)	FoV (degrees)	First Light	Threshold (GeV)	Sensitivity (%Crab)
H.E.S.S.	1.8	4	428	5	2003	100	0.7
VERITAS	1.3	4	424	3.5	2007	100	1
MAGIC	2.2	1	236	3.5	2005	50	1.6
HAGAR	4.3	7	31	3	2008	60	9
Whipple	2.3	1	75	2.2	1985	400	10
CANGAROO III	0.1	3(4)	172 (230)	4	2006	400	10
PACT	1.1	24	107	3	2001	750	11
TACTIC	1.3	1	10	2.8	2001	1500	70
SHALON	3.3	1	11.2	8	1996	1000?	?

Davies-Cotton f/1.0-1.4 optics

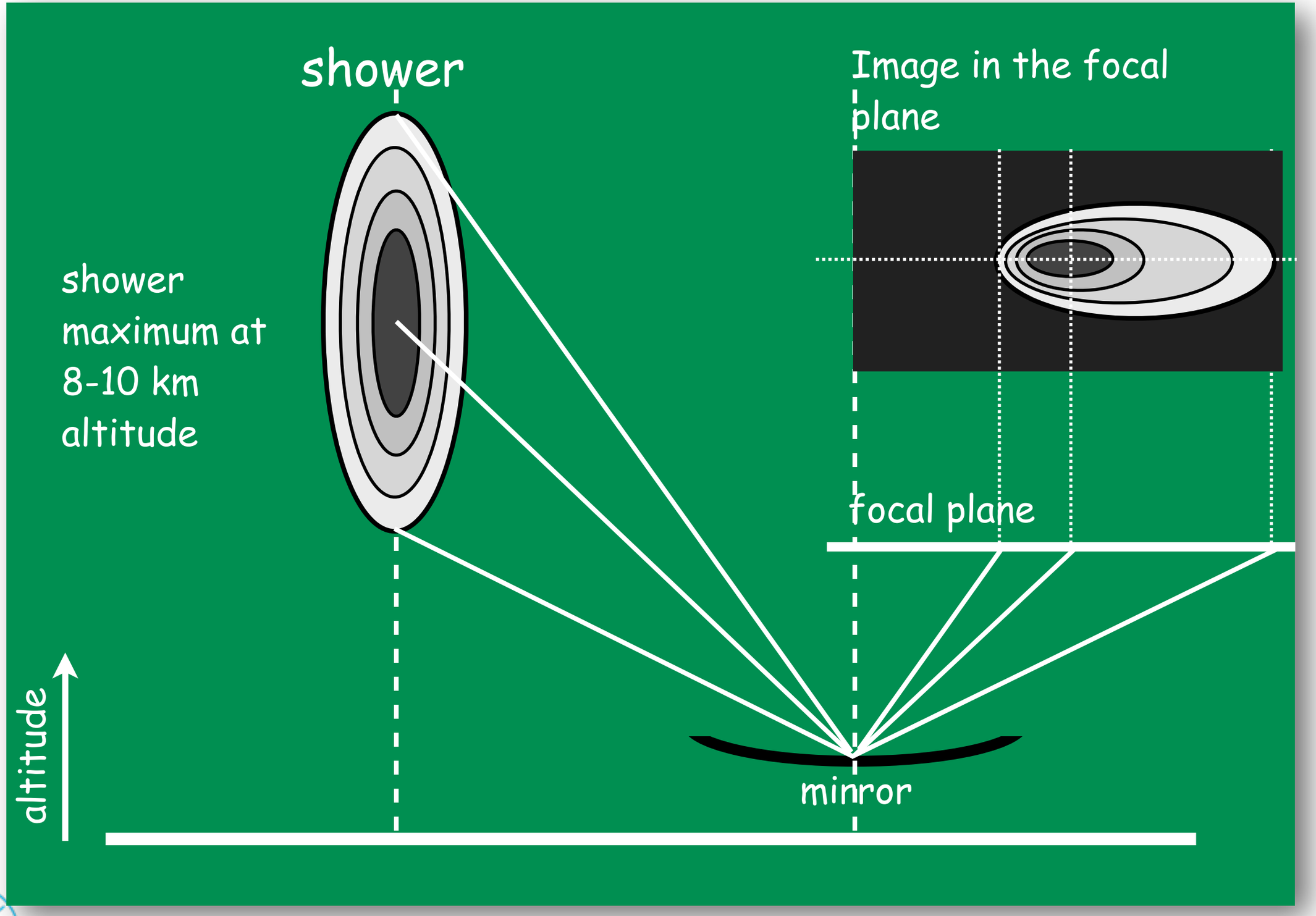
12 m diameter reflector
(110 m^2 mirror area)



Imaging Atmospheric Cherenkov Telescopes

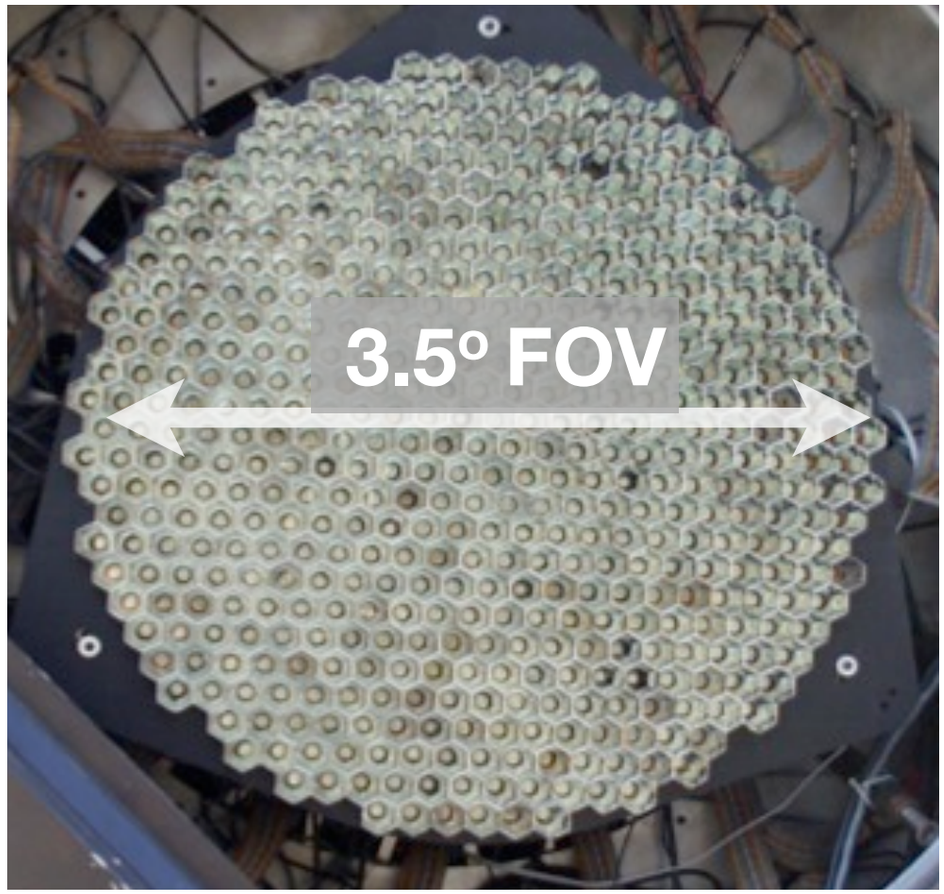


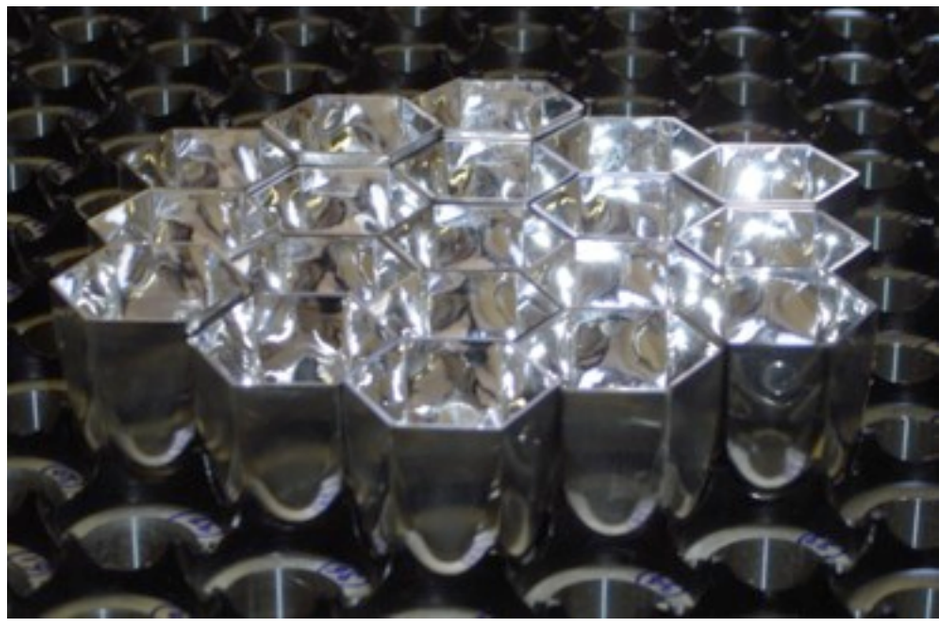
Imaging Atmospheric Cherenkov Telescopes

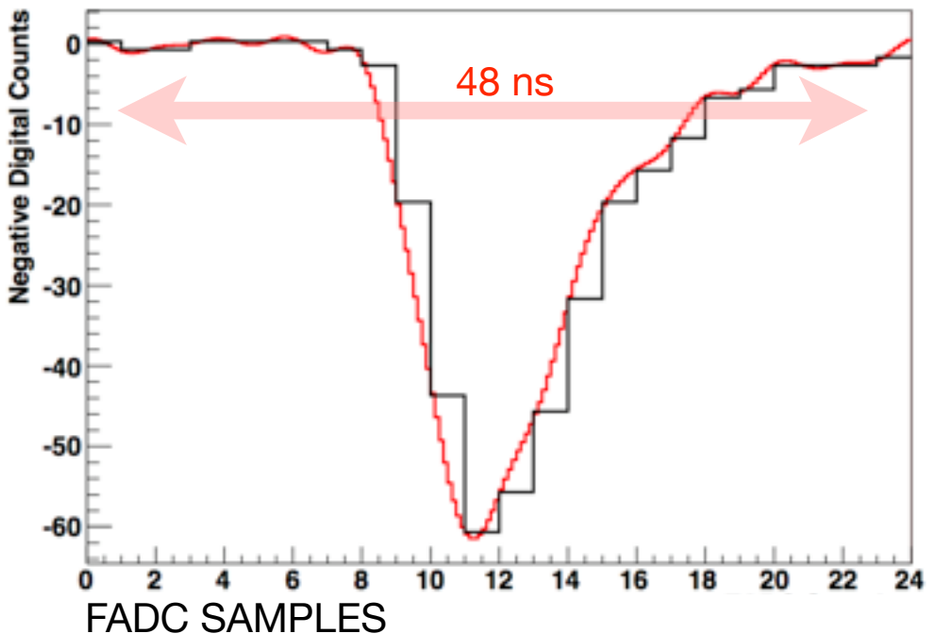


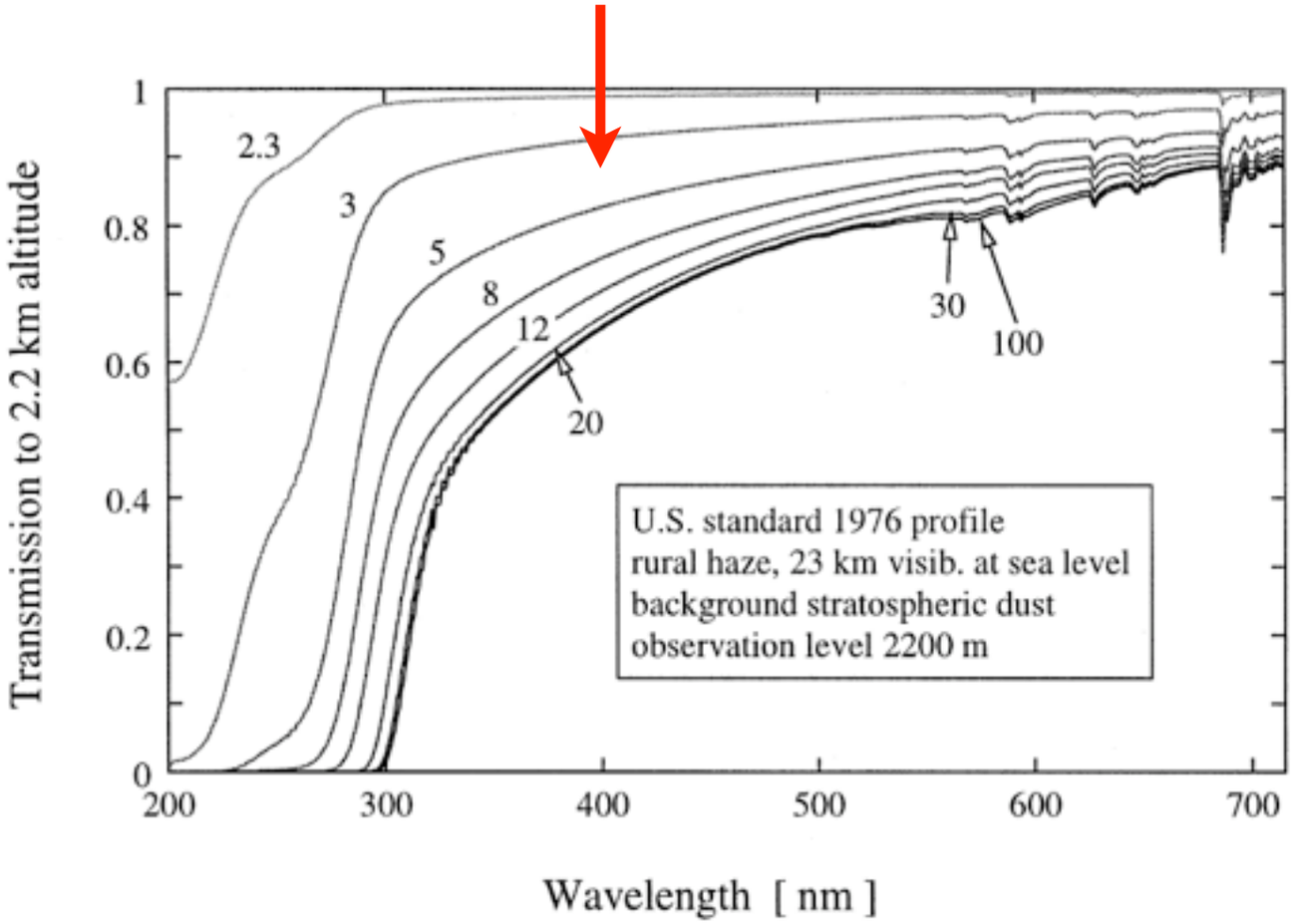
VERITAS: Camera, electronics and data acquisition

- 499 PMTs (Photonis XP 2970/02)
- 0.15º pixel separation, 3.5º field of view
- light concentrator
- 500 MSample/s flash ADC (2 ns)
- 8 bit dynamic range (dual range)
- typical data rate 6 Mbyte/s per telescope
- dead time for typical array rate of 300 Hz is 8-10%

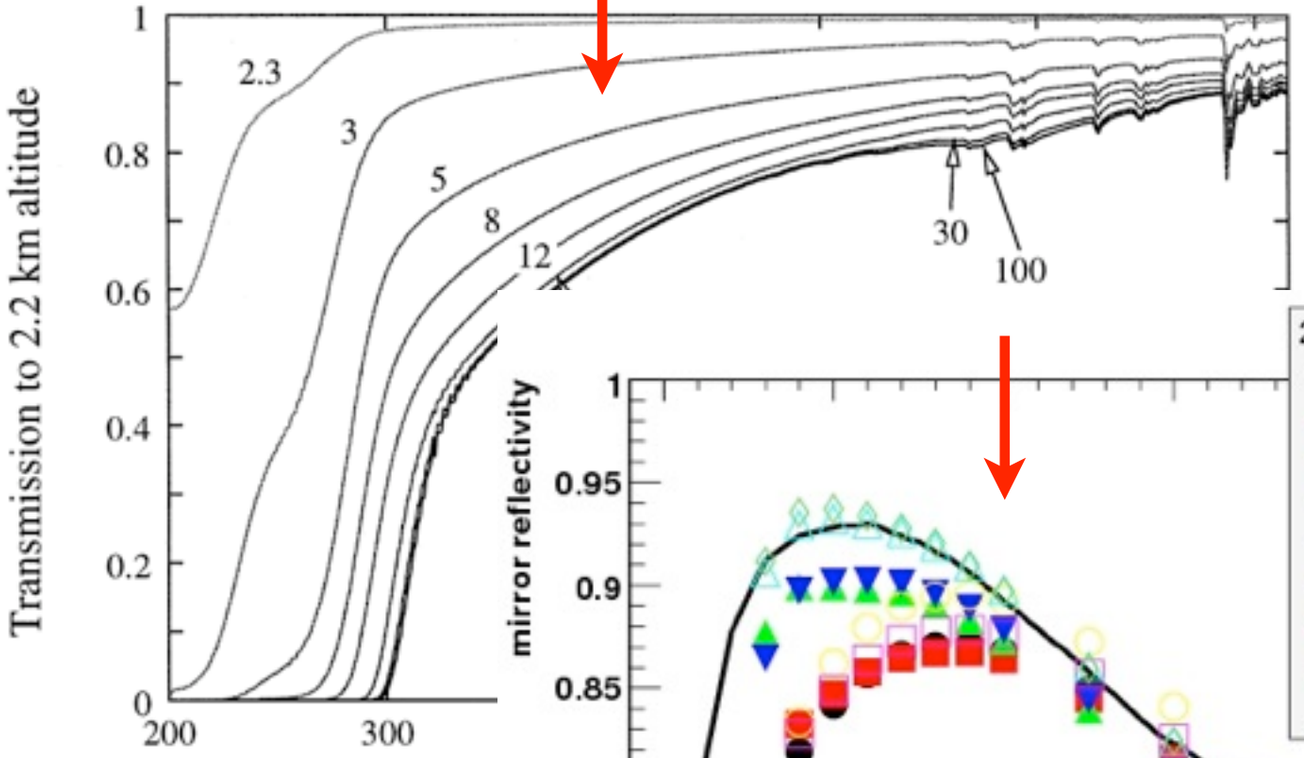




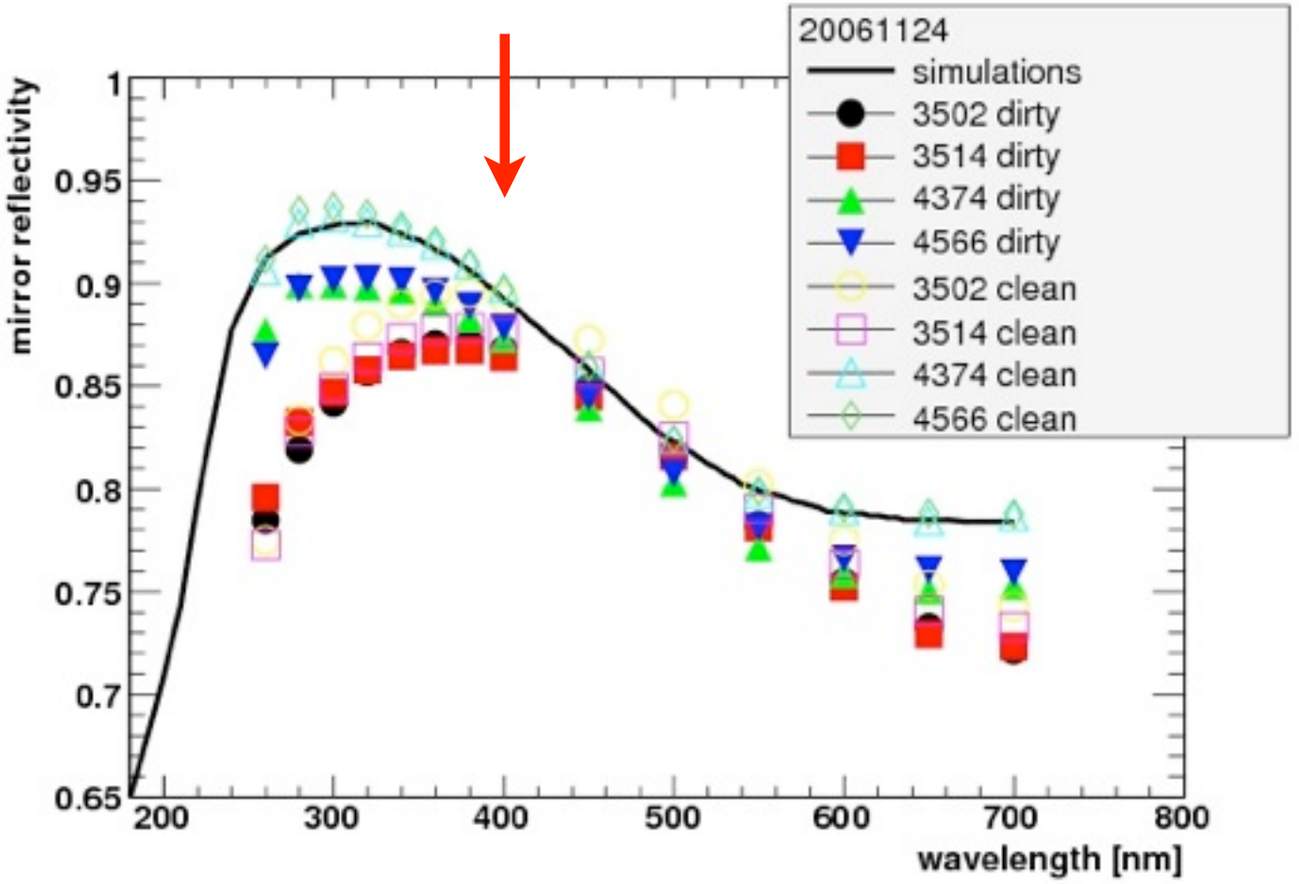




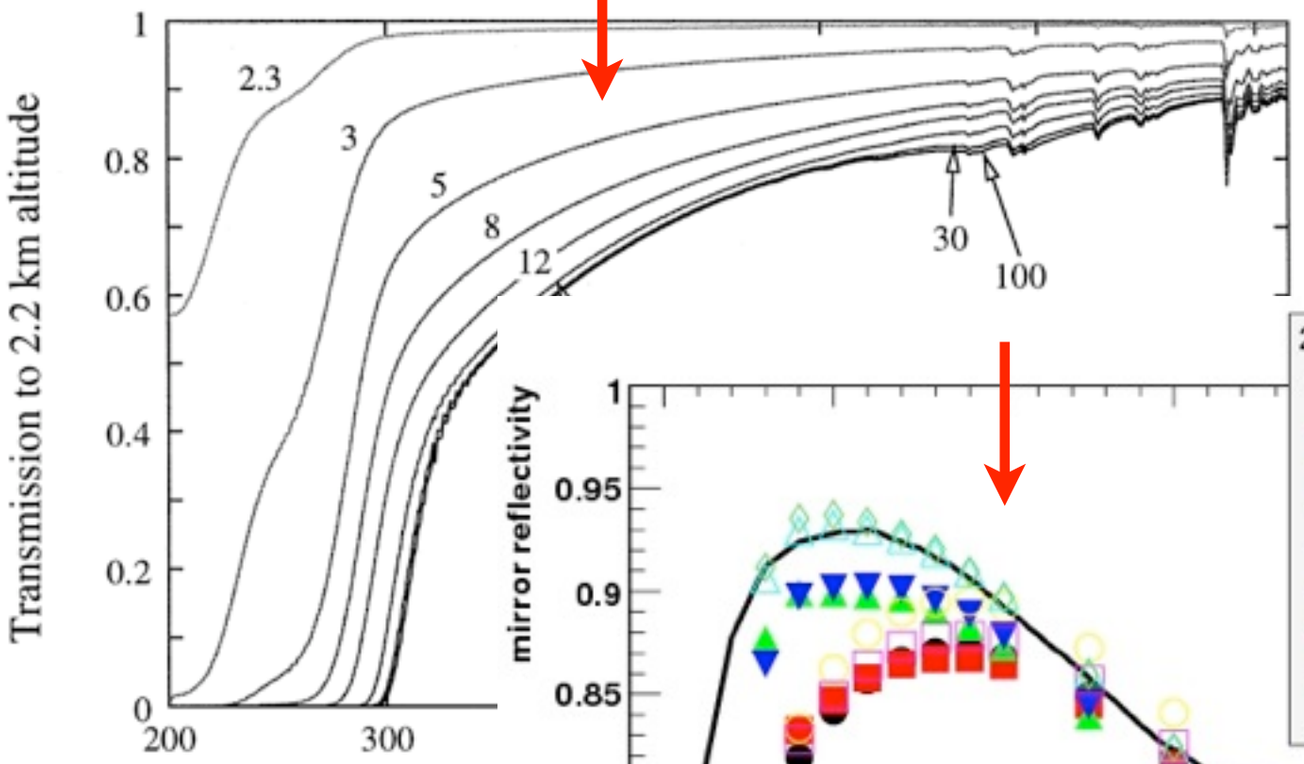
atmospheric extinction



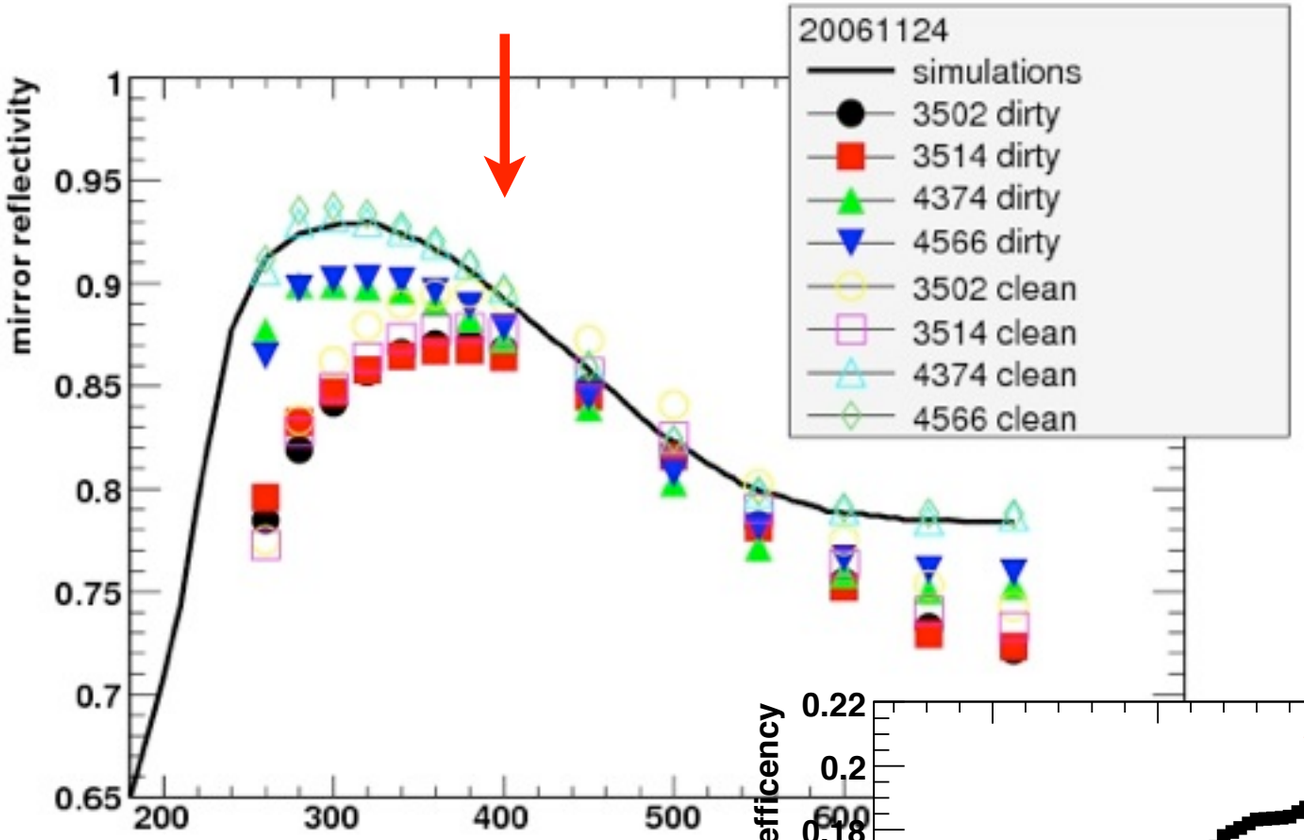
atmospheric extinction



mirror reflectivity

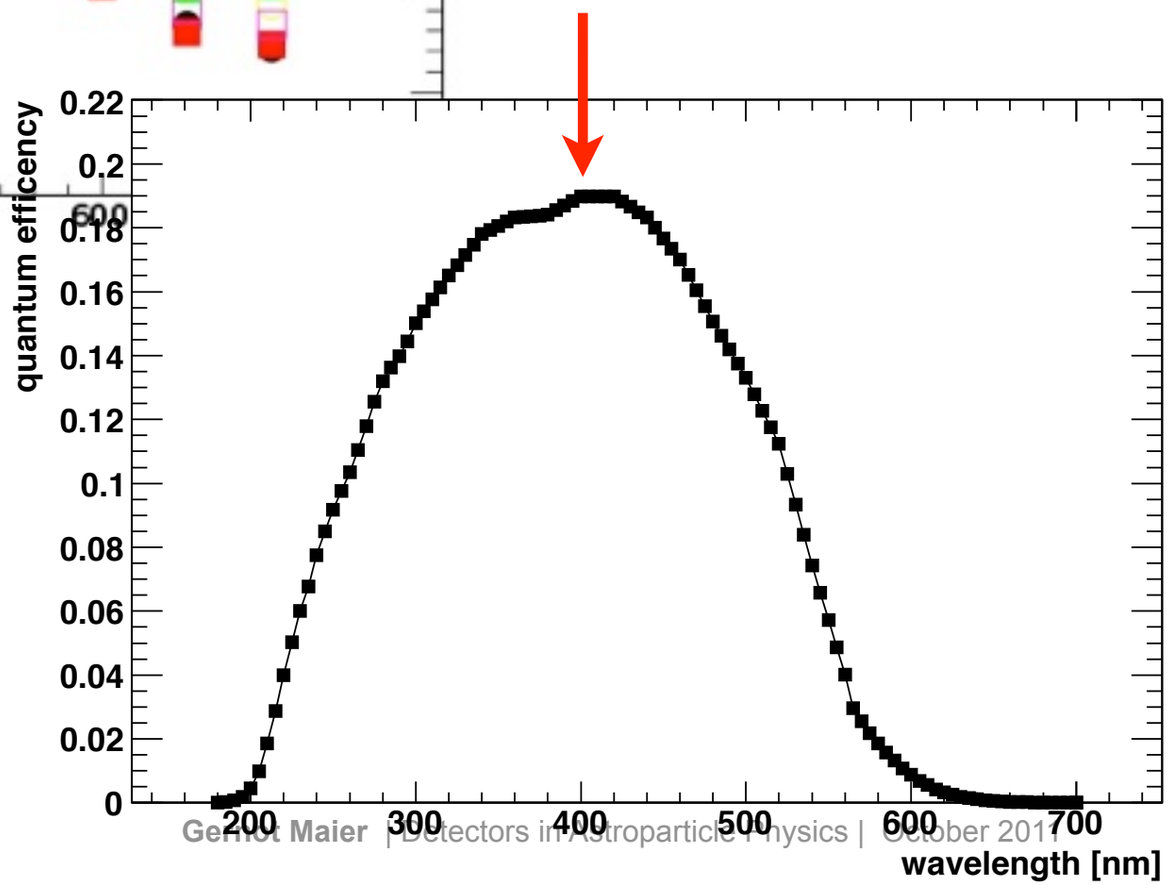


atmospheric extinction

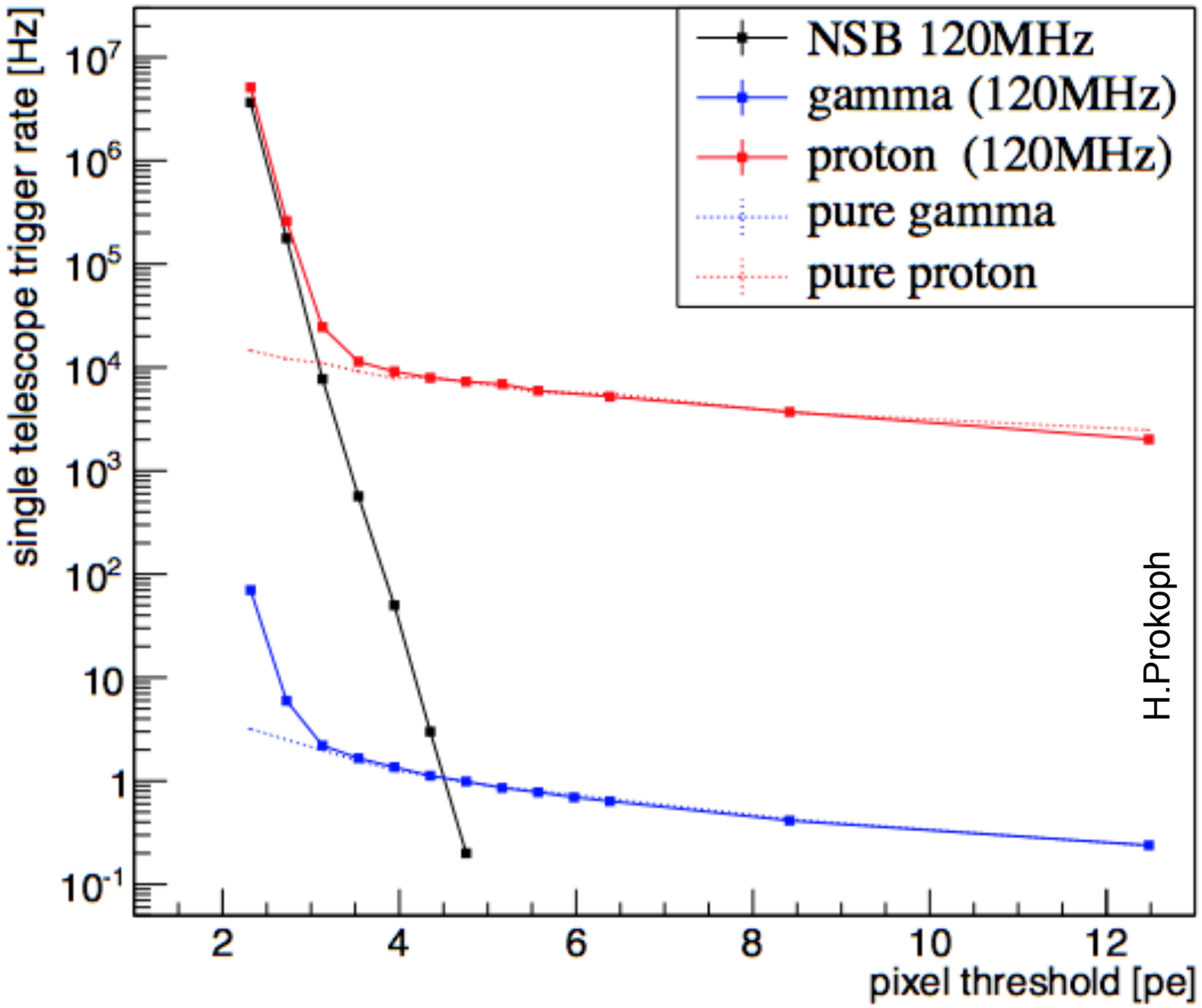


mirror reflectivity

quantum efficiency



Background....



(for a mid-size CTA telescope)

Level 1 (Pixel) Trigger:

Constant fraction discriminators with rate feedback
(typical threshold at 50 mV or ~4-5 photoelectrons)

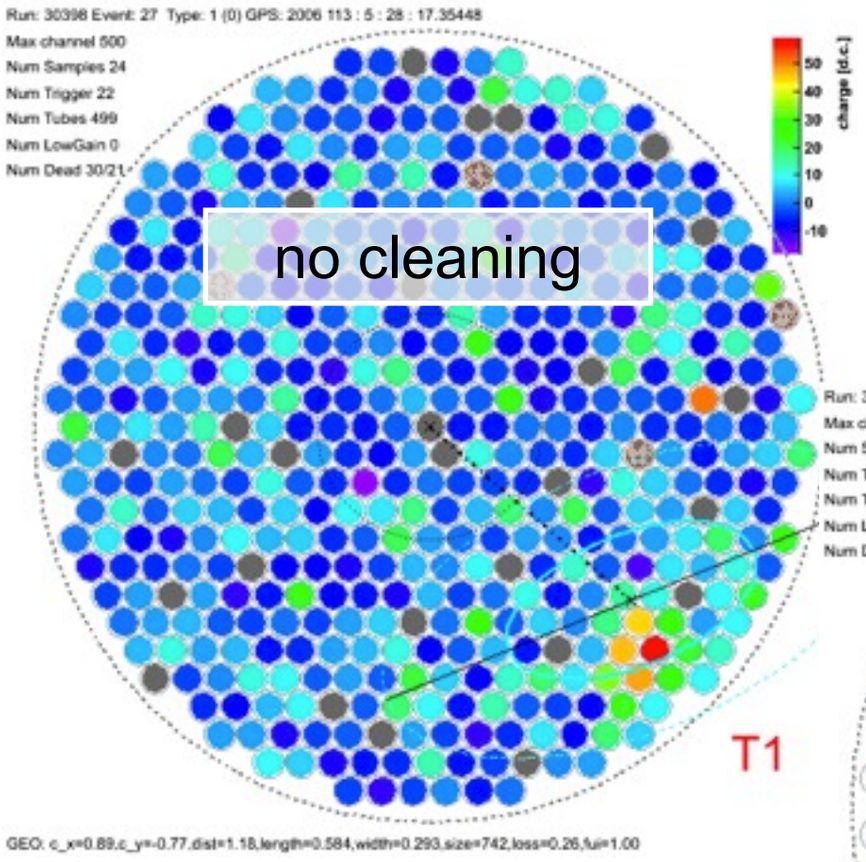
Level 2 (Pattern) Trigger:

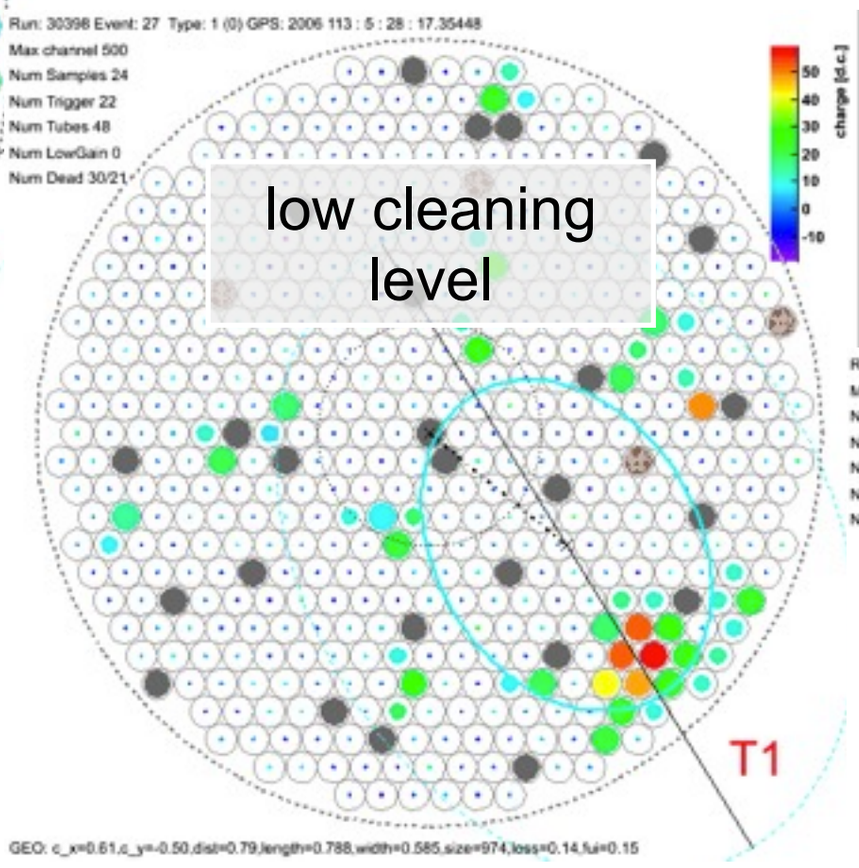
Recognize patterns of trigger pixel in the camera
(default is three adjacent pixels in a time window of 6 ns)

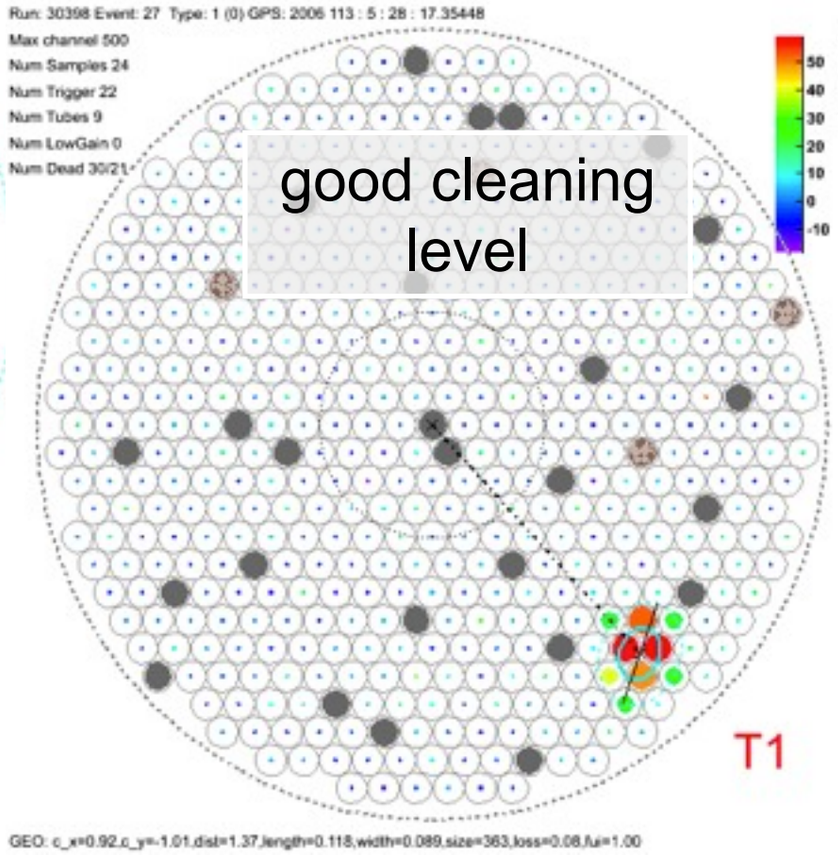
Level 3 (Array) Trigger:

Telescope coincidence trigger
(i.e. in a time window of ~100 ns)

Image Cleaning

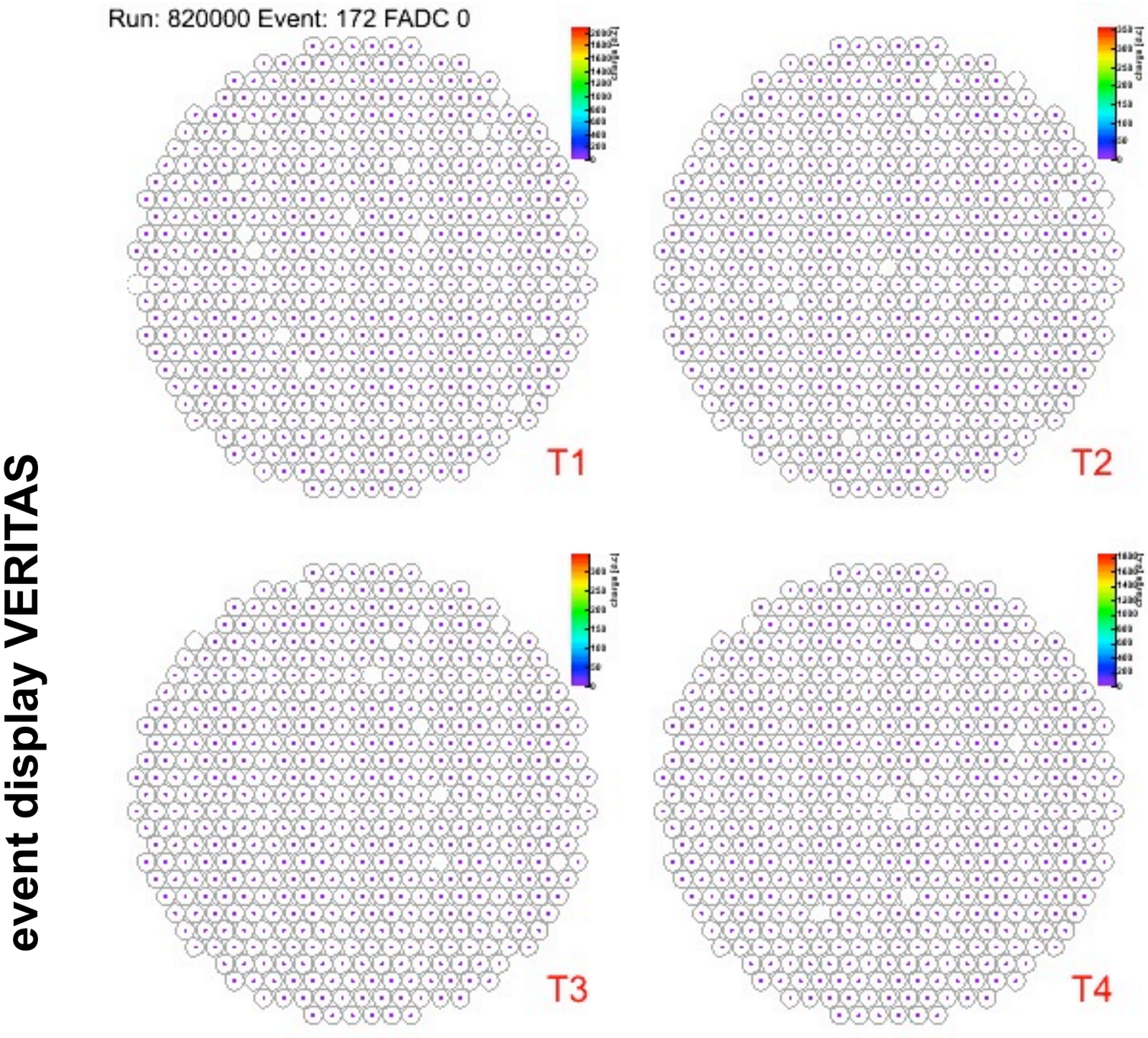






remove pixel with low signal/noise ratios (taking into account expected noise and time evolution of signal)

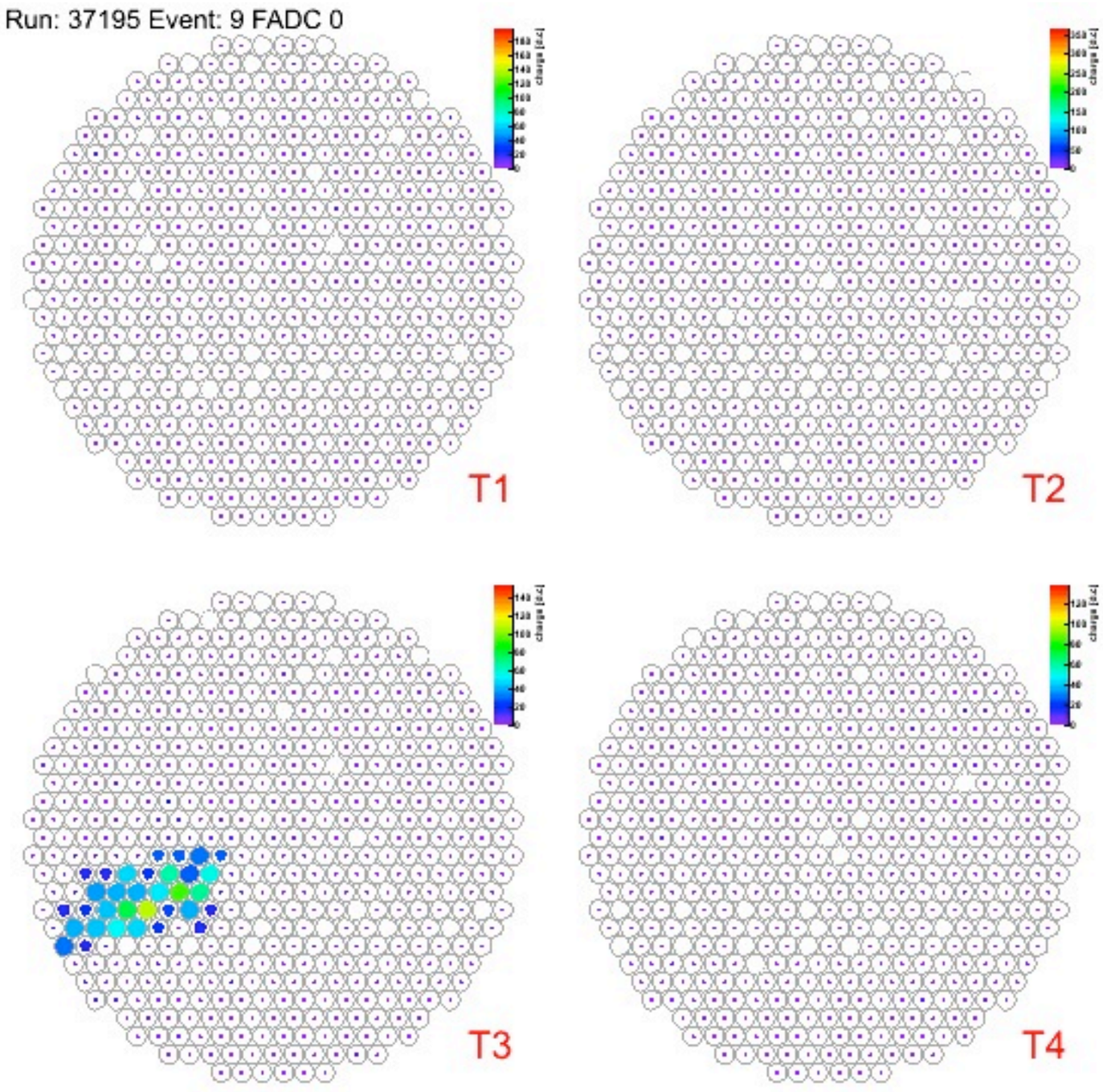
Gamma-ray Events - Monte Carlo Simulations



event display VERITAS

(each frame 2 ns long)

Observations

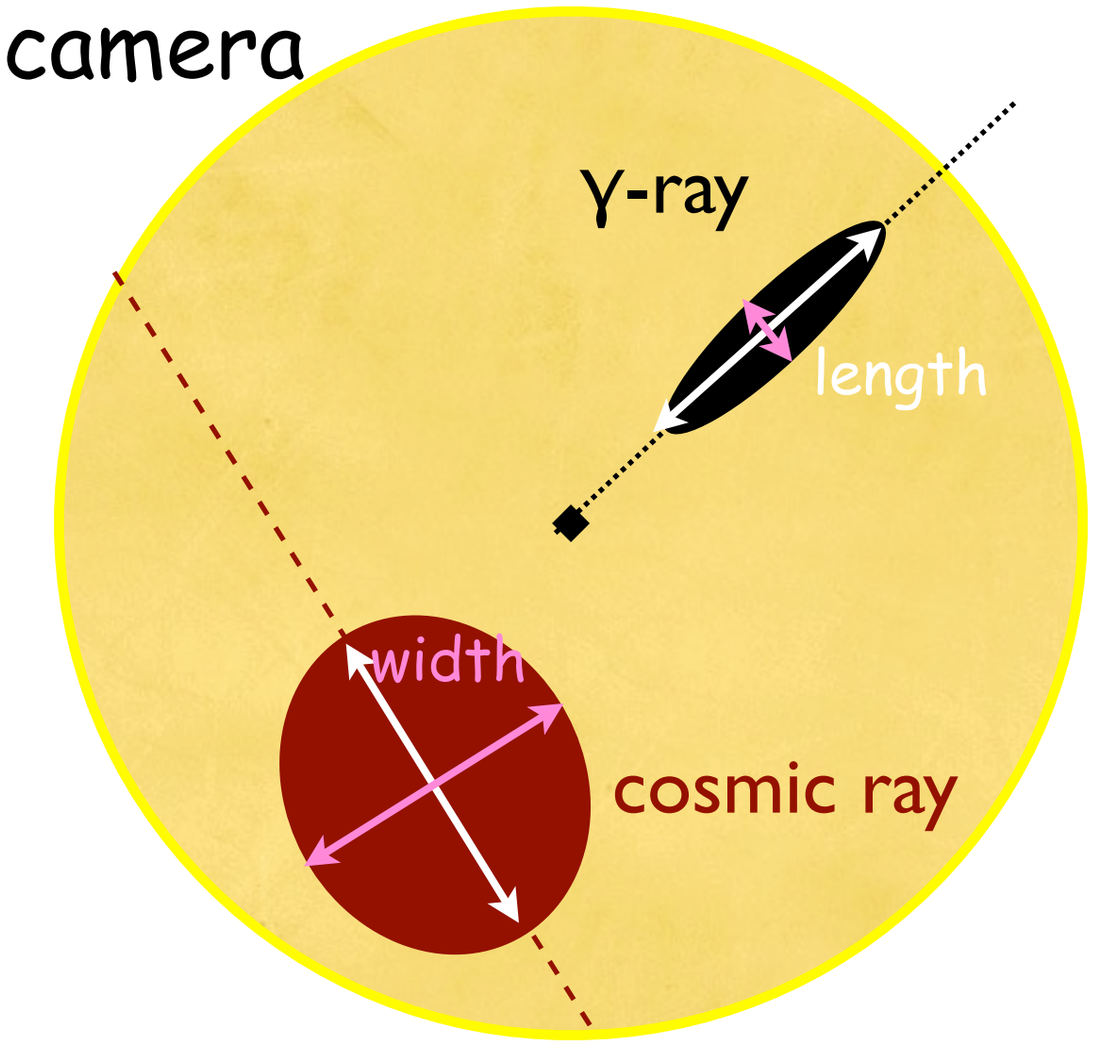


event display VERITAS

about every 1000th event is a γ-ray

(each frame 2 ns long)

gamma/hadron separation



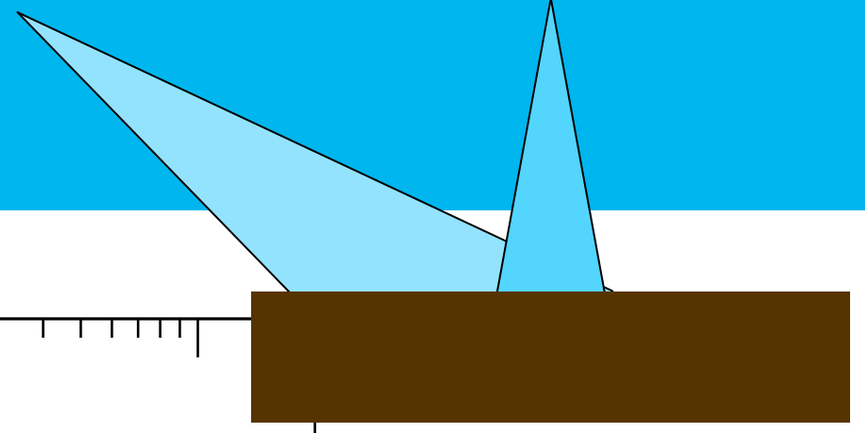
(based on Image/Hillas parameters)

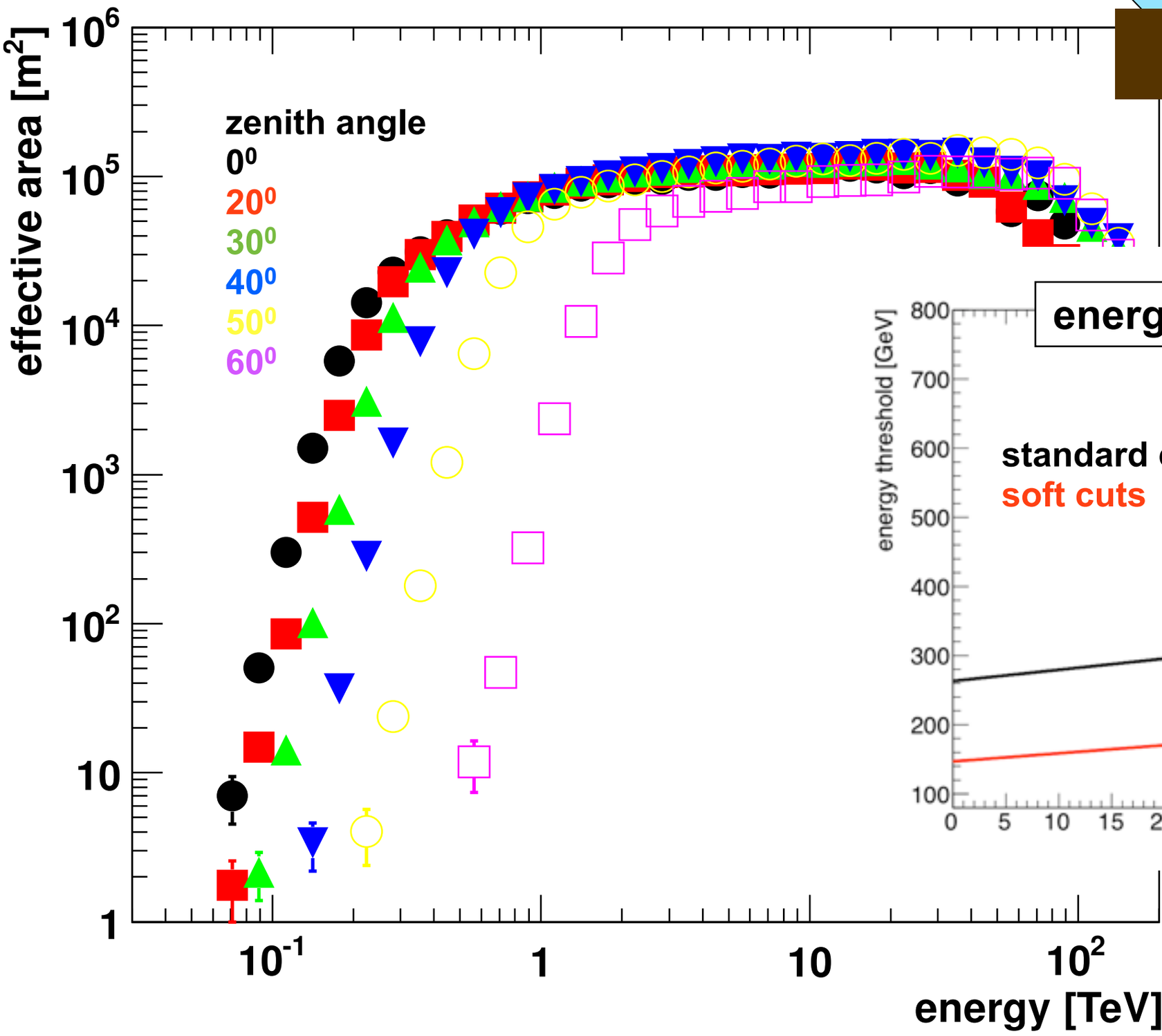
mean scaled width

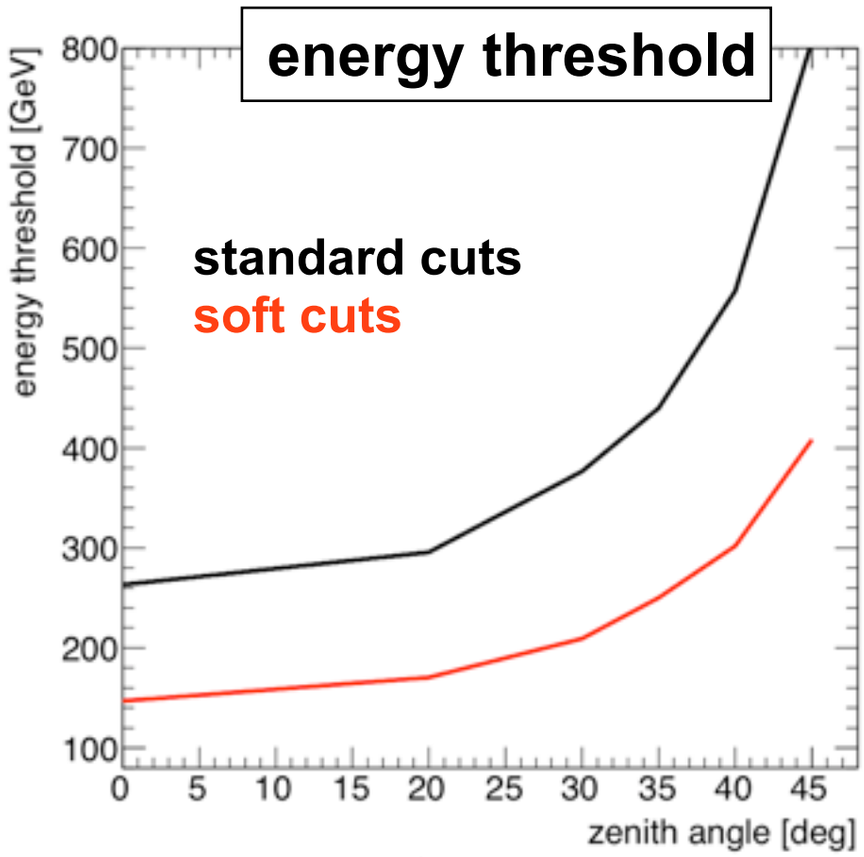
$$mscw = \frac{1}{N_{\text{images}}} \left[\sum_{i}^{N_{\text{images}}} \frac{\text{width}_i - w_{\text{MC}}(R, s, \Theta)}{\sigma_{\text{width, MC}}(R, s, \Theta)} \right]$$

(same for length)

Effective Areas







The Cherenkov Telescope Array