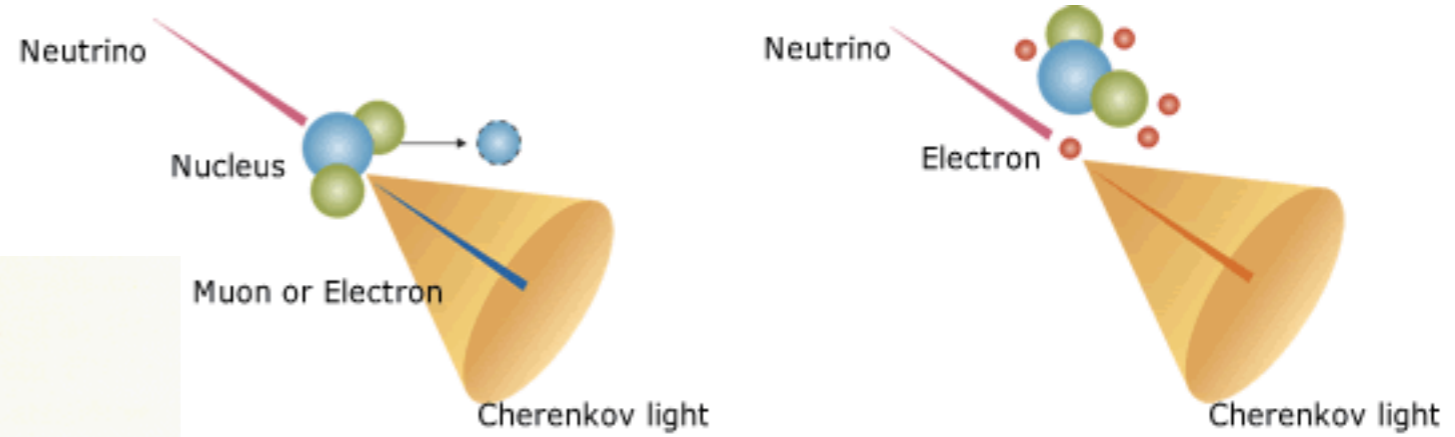
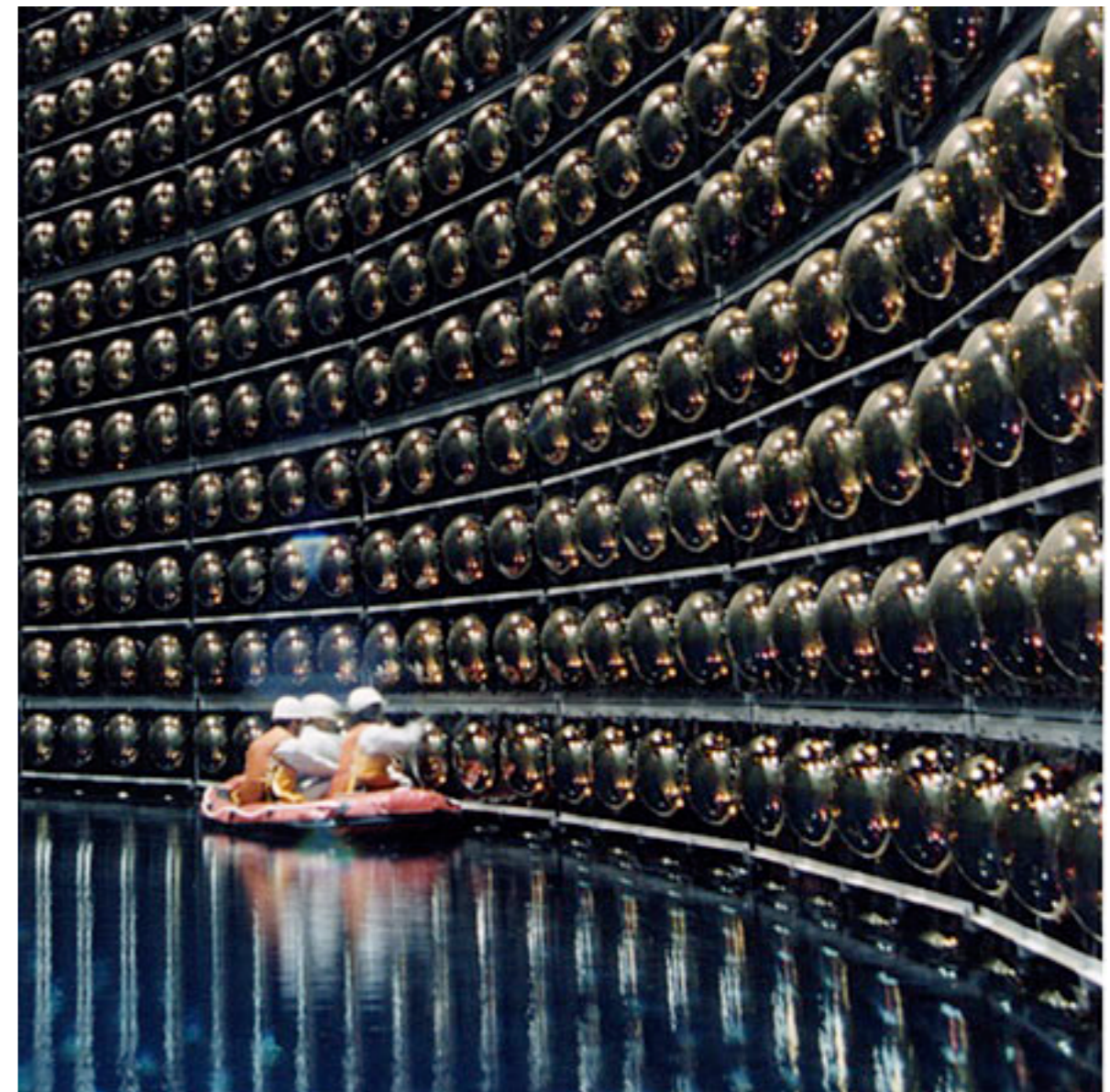
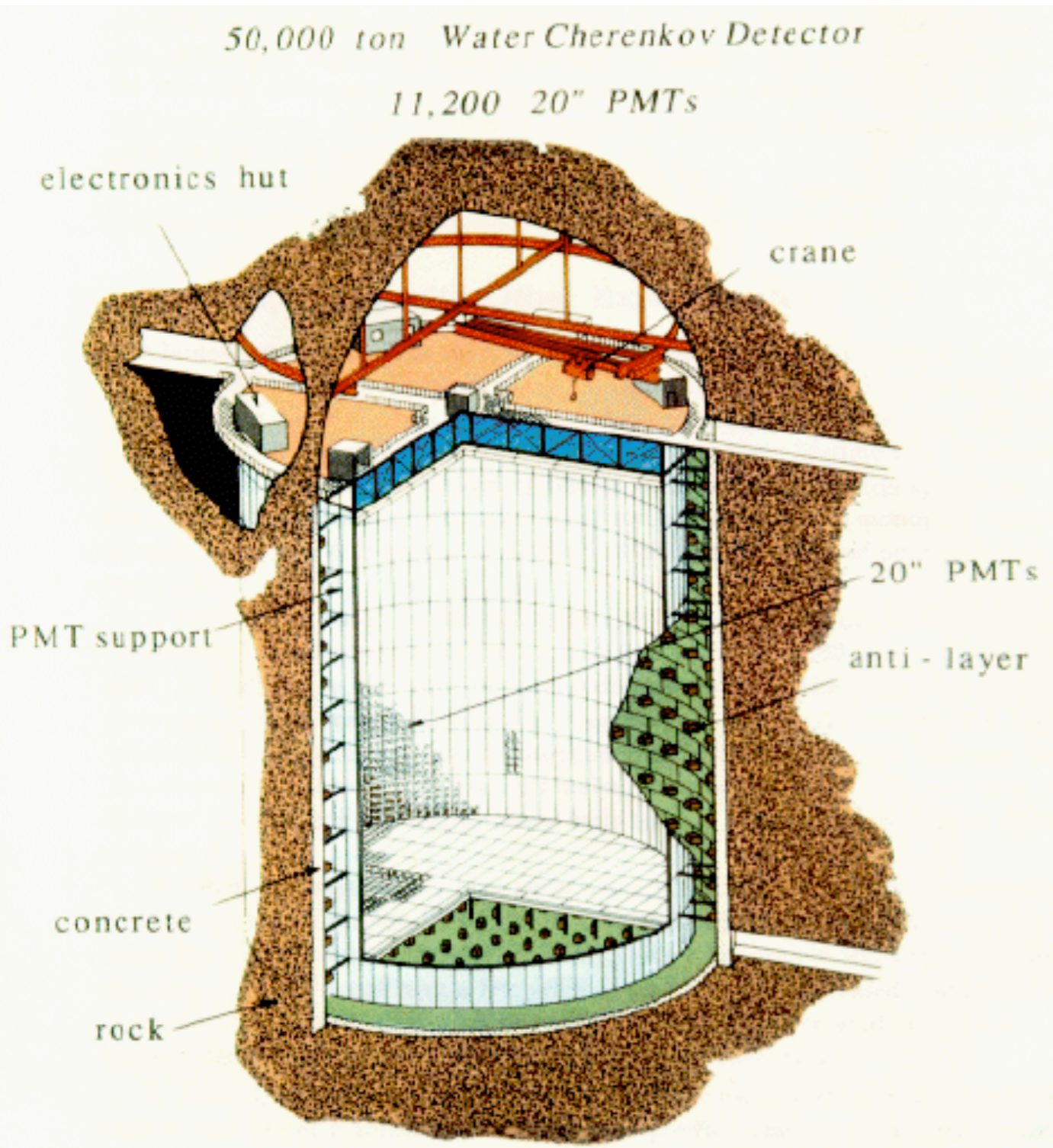


Cherenkov Detectors
for
MeV neutrino detection
supernovae/solar

Super-Kamiokande neutrino detector



The generated charged particle emits the Cherenkov light.



Neutrino scattering

neutrino scattering reaction $\nu_e + e^- \longrightarrow \nu_e + e^-$

scattered electron carries large fraction of neutrino energy and moves in direction close to initial direction of neutrino

cross section $9.3 \times 10^{-45} \text{ cm}^2 \times (E_\nu/\text{MeV})^2.$

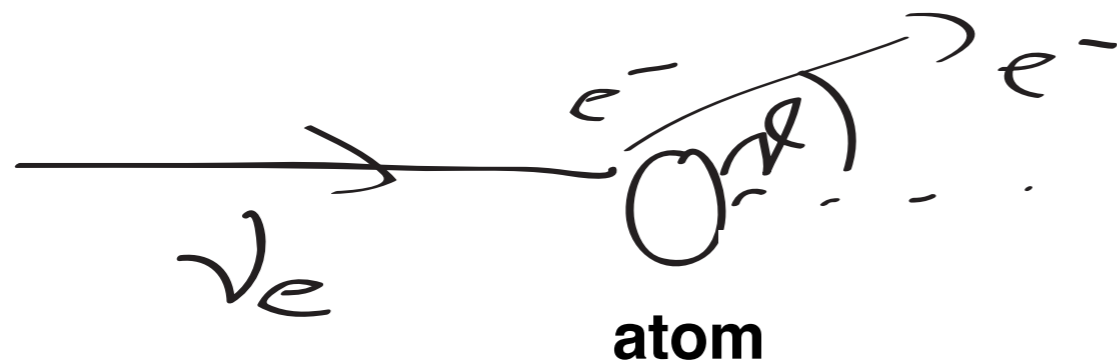
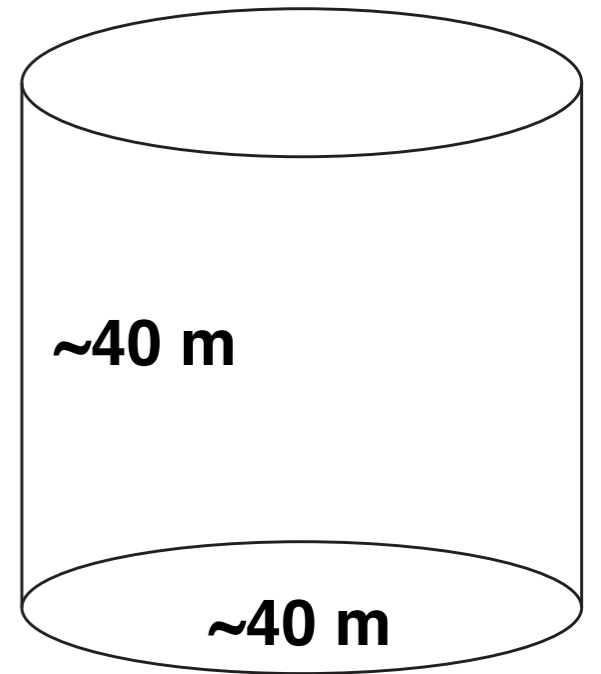
**Kamiokande experiment, Super-Kamiokande
threshold, originally 7.5 MeV, gradually lowered to 6.5 MeV**

—> ~13 neutrinos/day from Sun

~30 t typical size of a neutrino detector

**e.g. Super Kamiokande (50 000 t)
ultra-pure water (~30000 PMTs)**

method: neutrino-electron scattering



$$\sigma_{\nu e} \approx 10^{-43} \text{ cm}^2 \left(\frac{E_\nu}{10 \text{ MeV}} \right)$$

electrons are boosted in forward direction

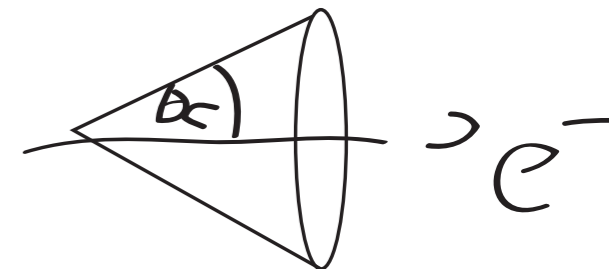
$$\cos \vartheta = \frac{1 + \frac{m_e}{E_\nu}}{\sqrt{1 + \frac{2m_e}{E'_e}}}$$

E_e' kinetic energy of recoil electron (Compton)

measurement of the electron via Cherenkov radiation in

water

$$\cos \Theta_c = \frac{1}{\beta n} \quad \text{H}_2\text{O} : n = 1.33 \Rightarrow \Theta_c = 42^\circ$$

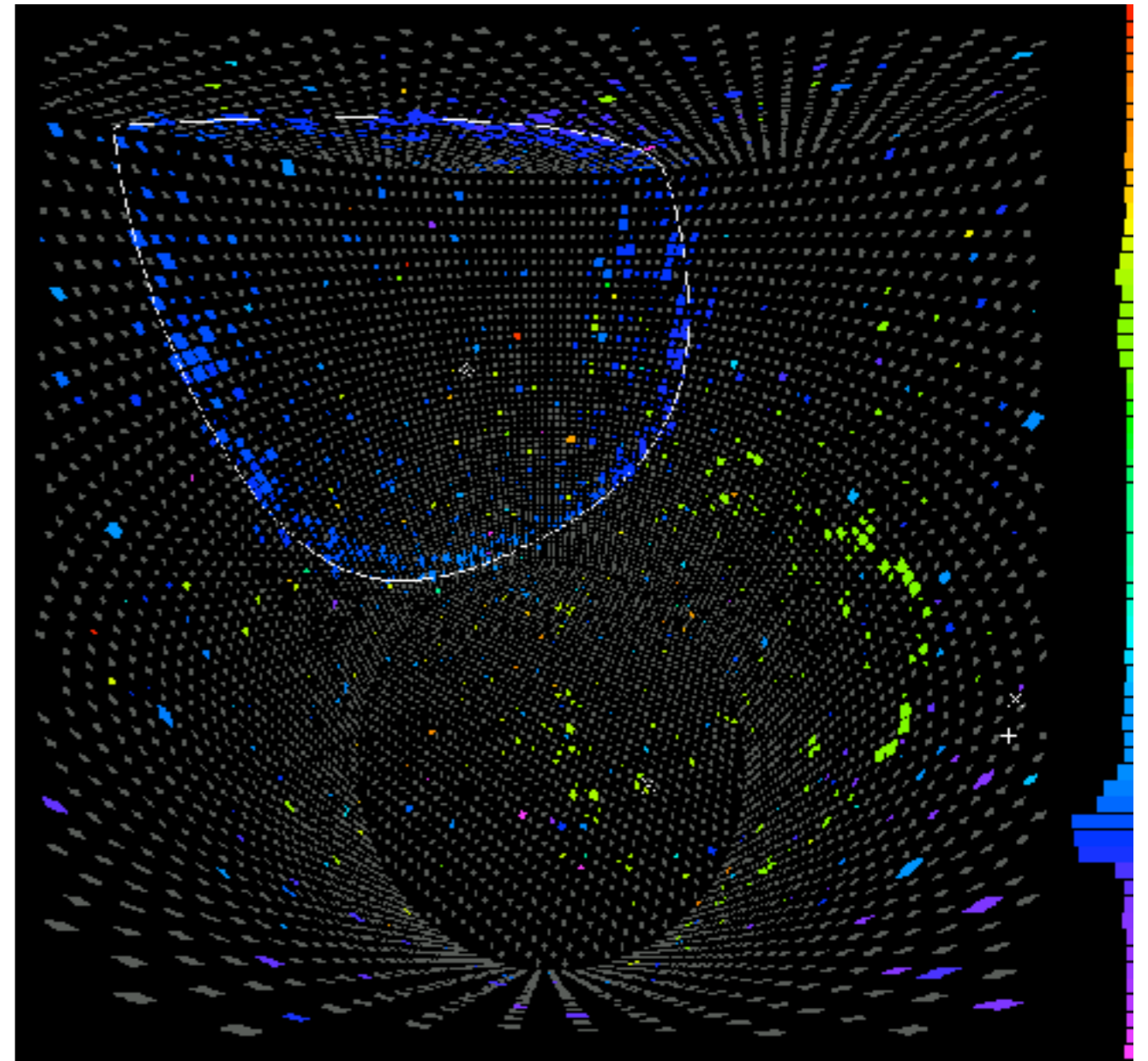
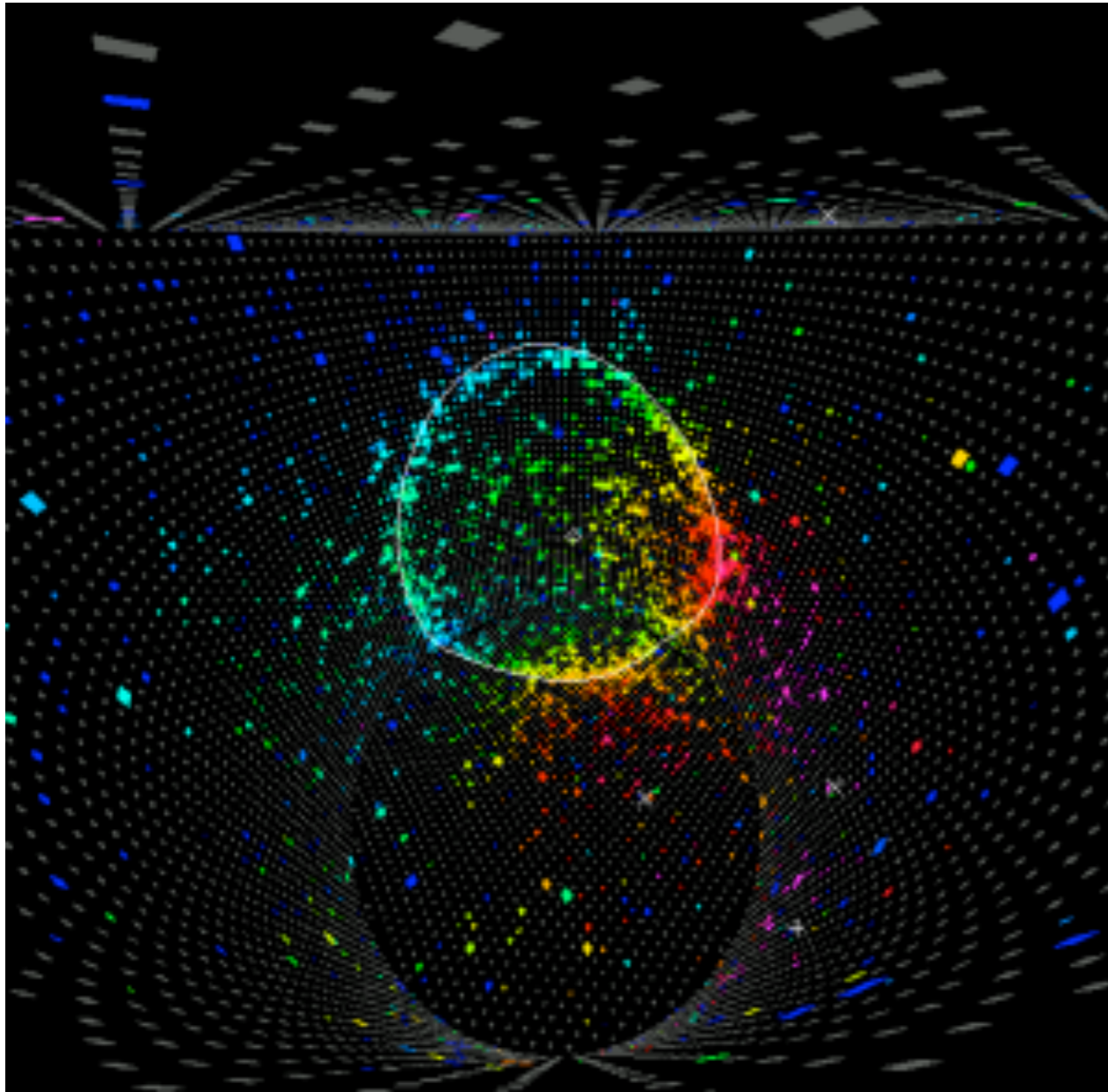


threshold $E_\nu > 7.5 \text{ MeV}$

Super Kamiokande

electron

muon



Super Kamiokande sun in neutrino „light“

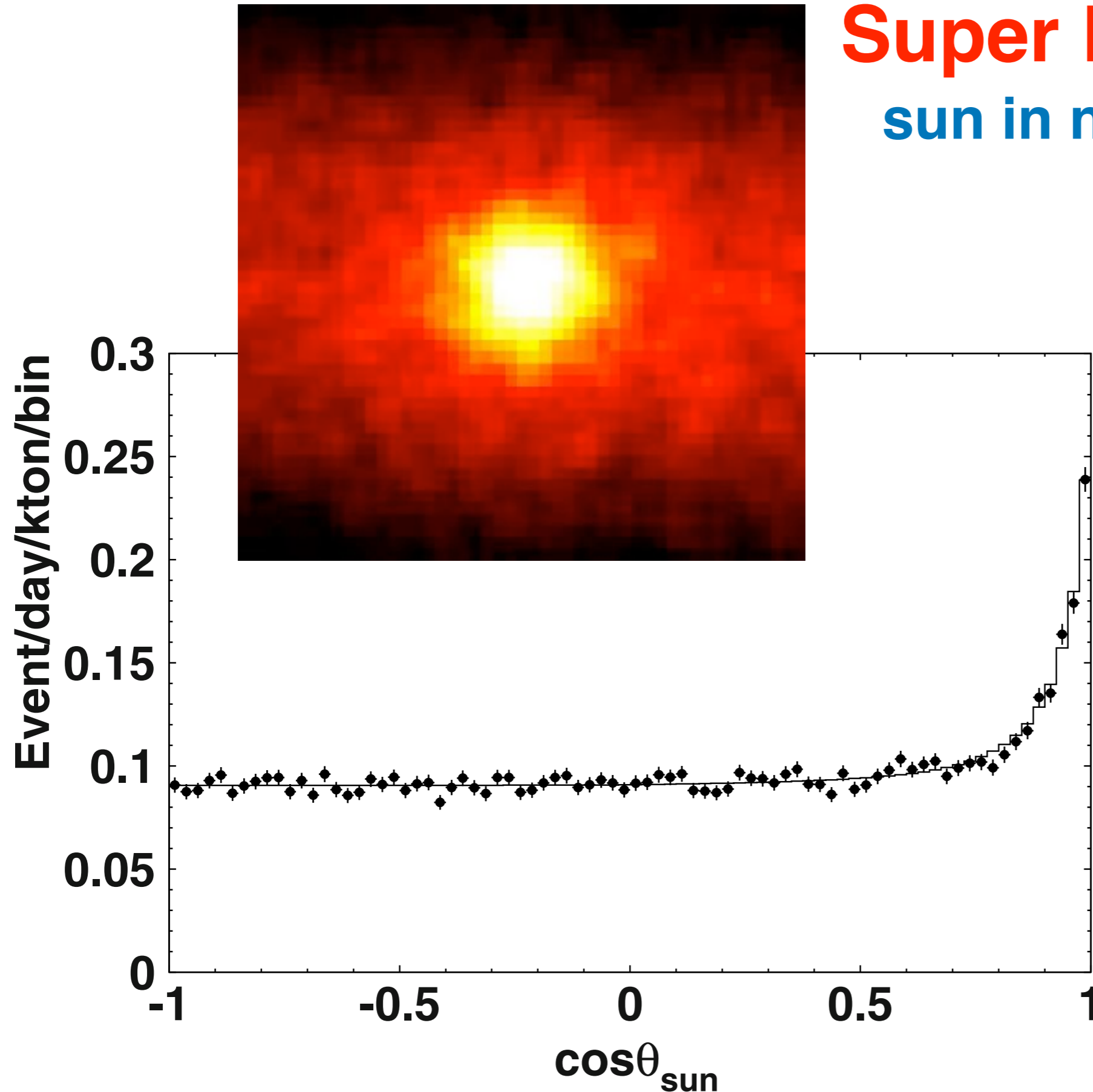
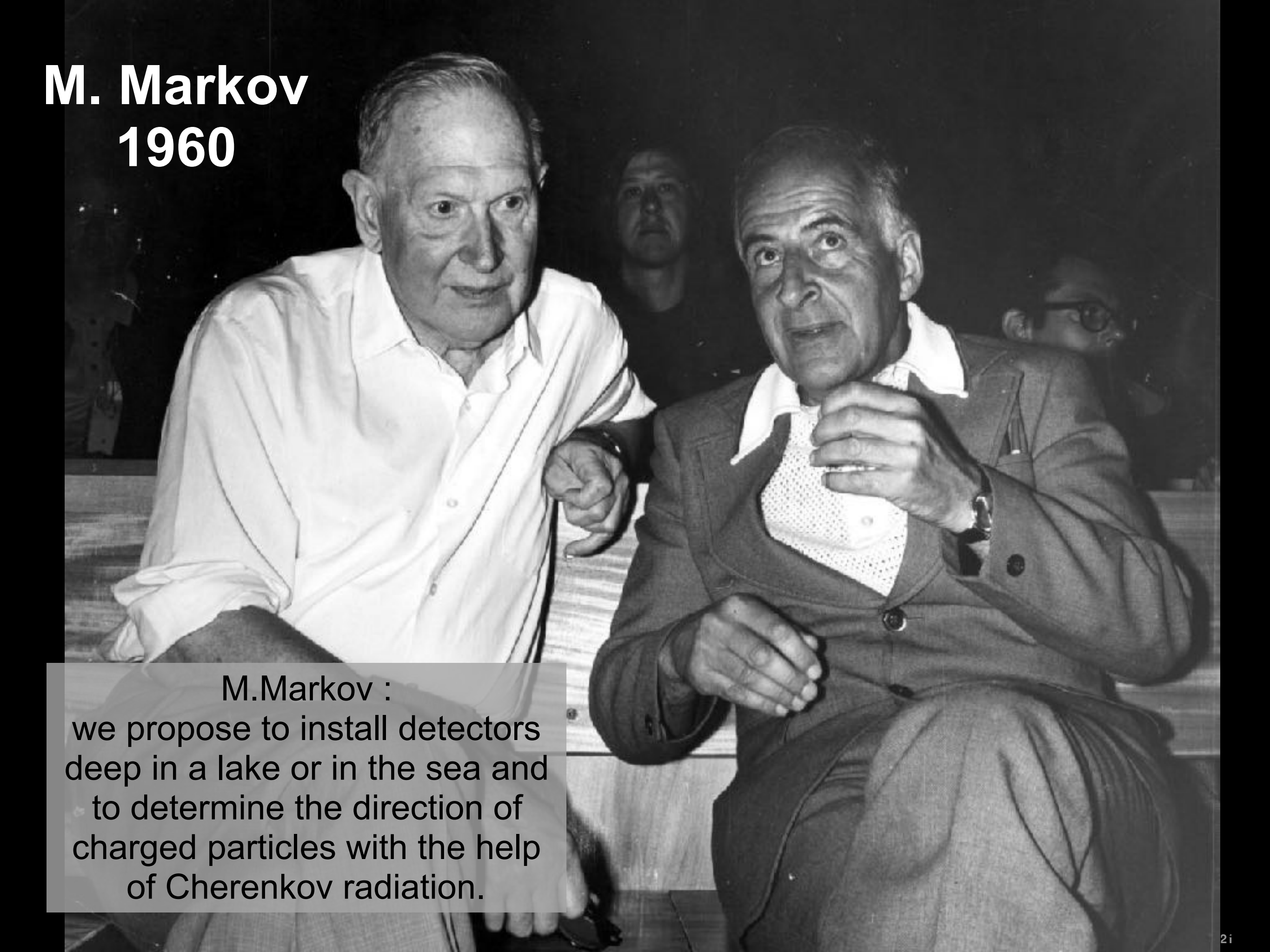


Fig. 3.1. Angular distribution of Super-Kamiokande neutrino events with respect to the direction of the Sun at the time of detection.

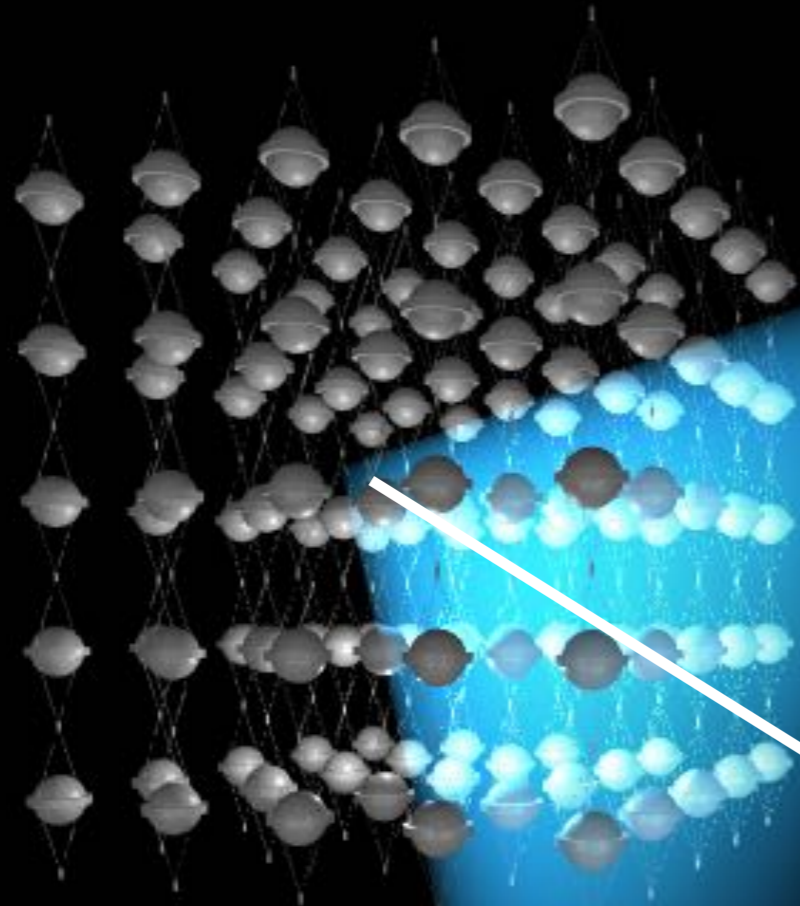
Cherenkov Detectors for Neutrino Astronomy

M. Markov 1960

A black and white photograph showing two men in the foreground. The man on the left is wearing a light-colored, long-sleeved button-down shirt and is looking towards the camera with a serious expression. The man on the right is wearing a dark suit jacket over a light-colored, patterned shirt and is looking off to the side with a thoughtful expression, his hand near his chin. In the background, other people are visible but out of focus. The overall setting appears to be an indoor event or meeting.

M. Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.

- speed of light in water $< c$
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



muon

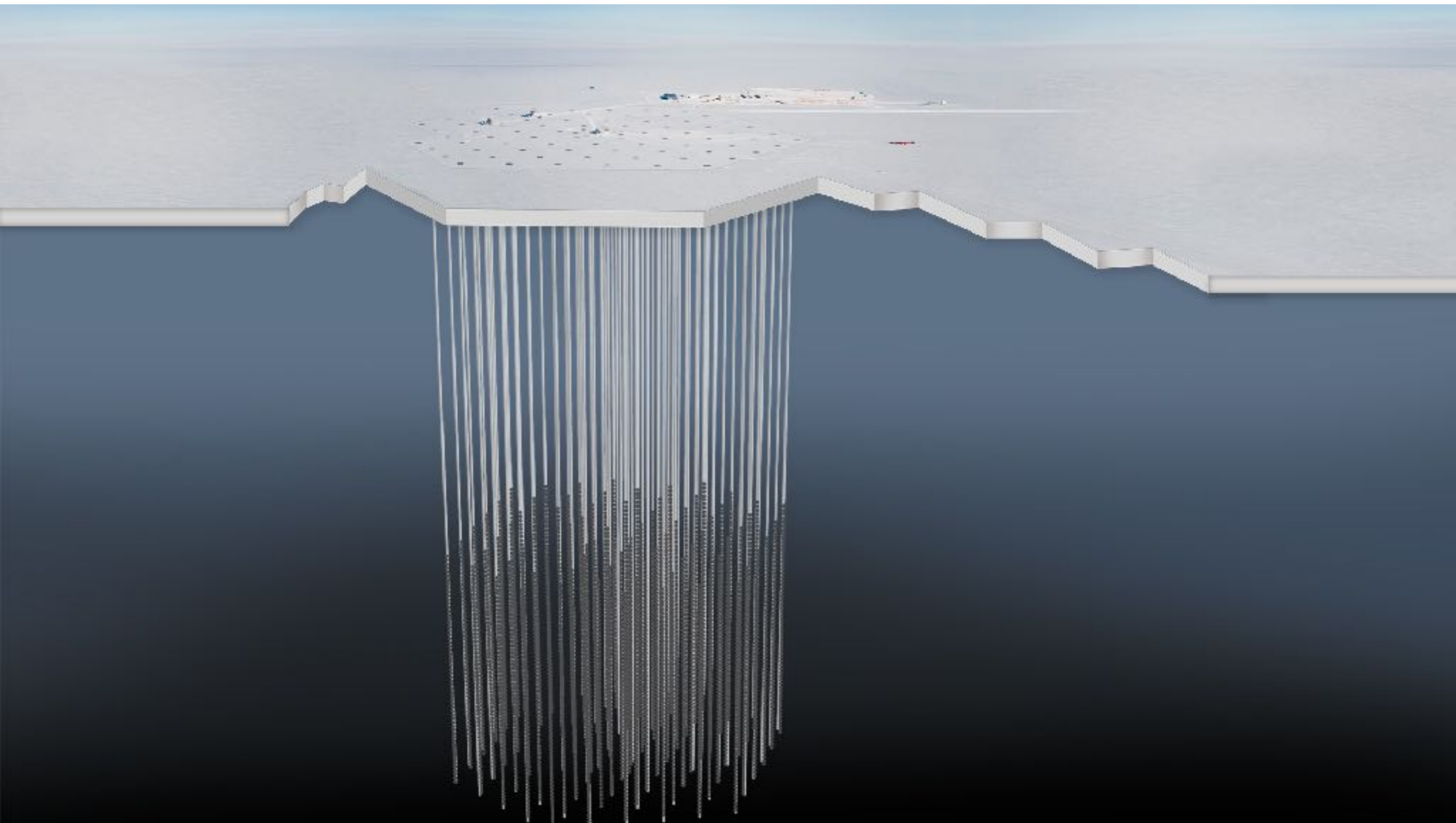
interaction

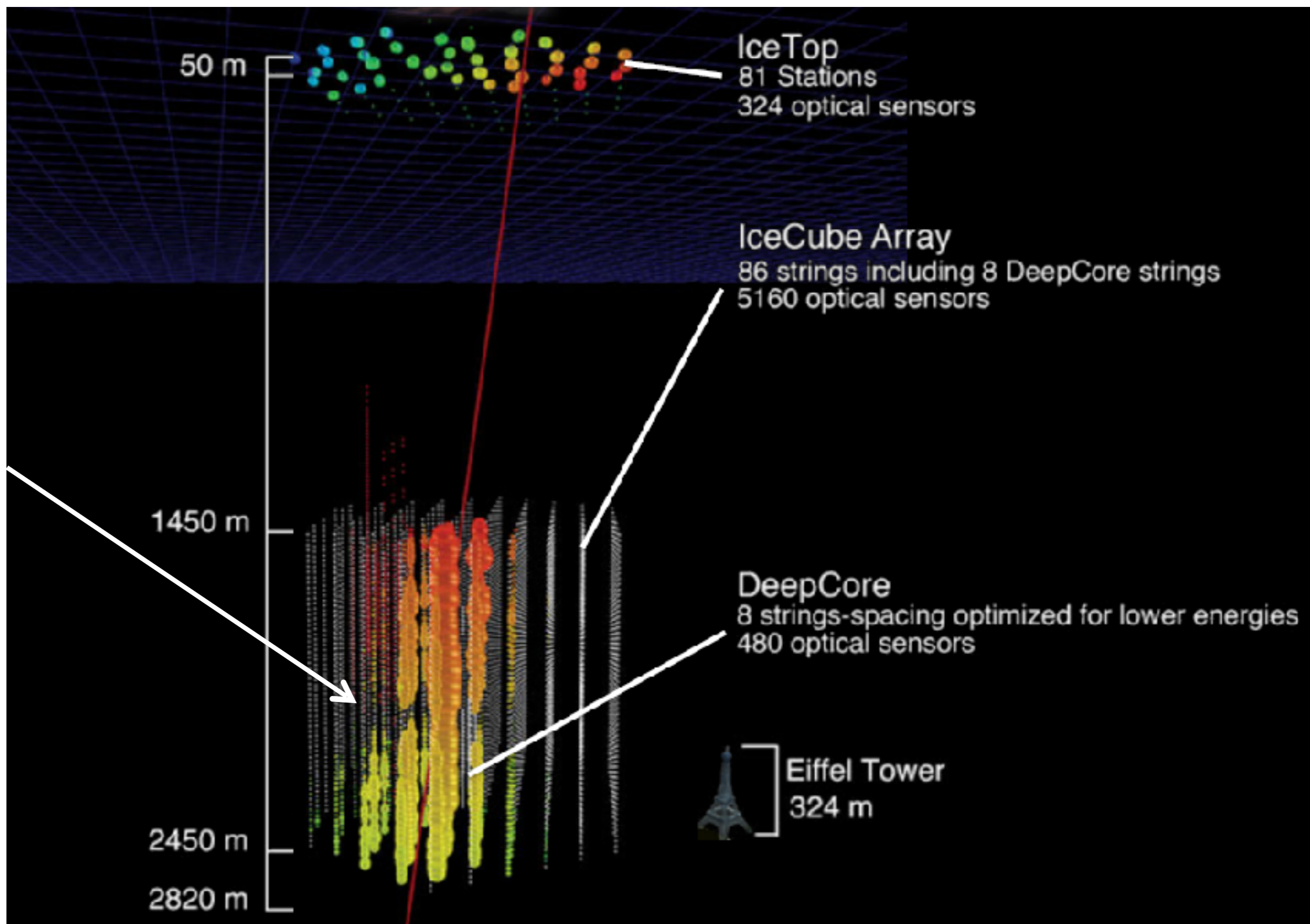
neutrino

- lattice of photomultipliers



ultra-transparent ice below 1.5 km



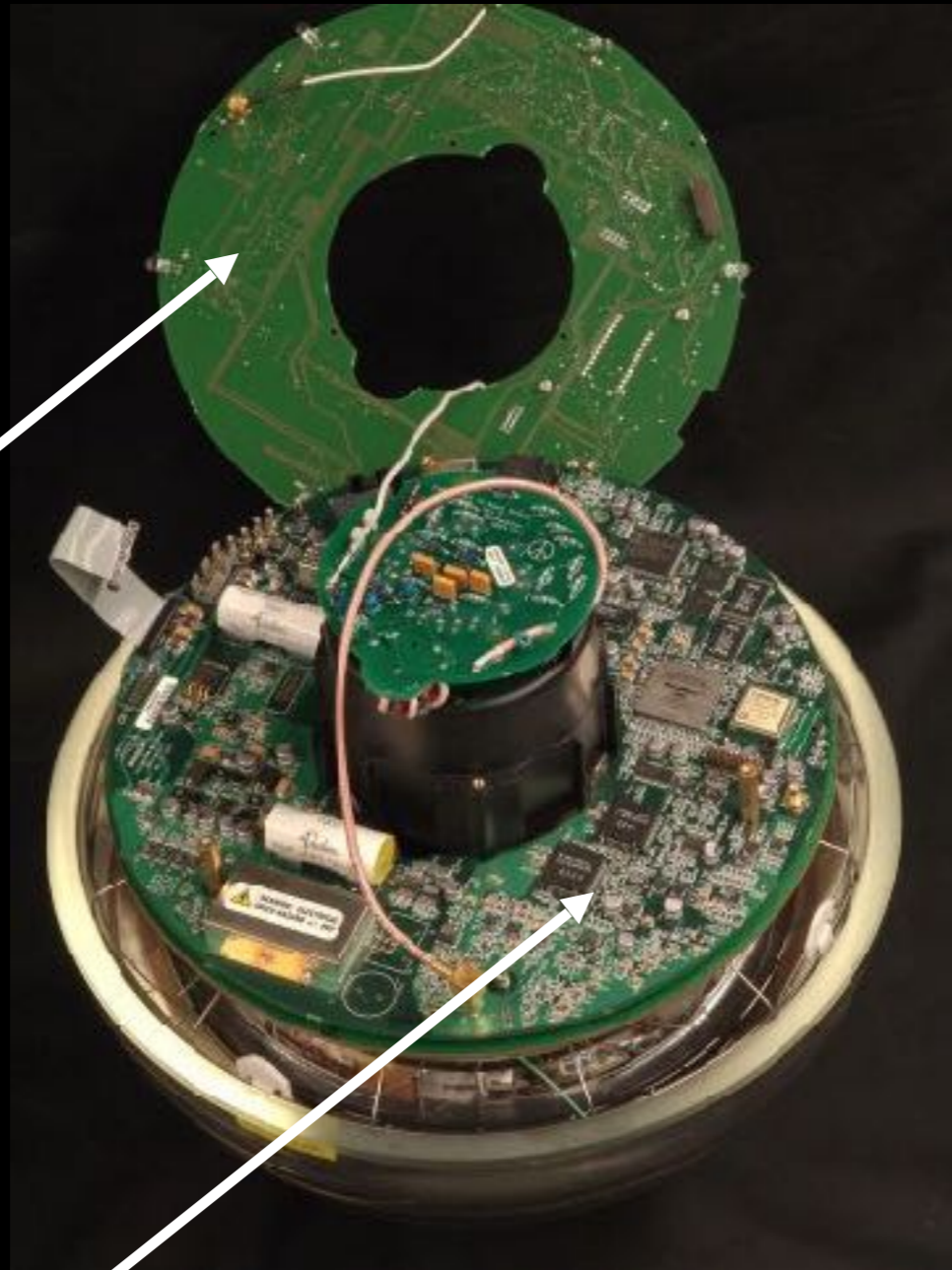


photomultiplier
tube -10 inch

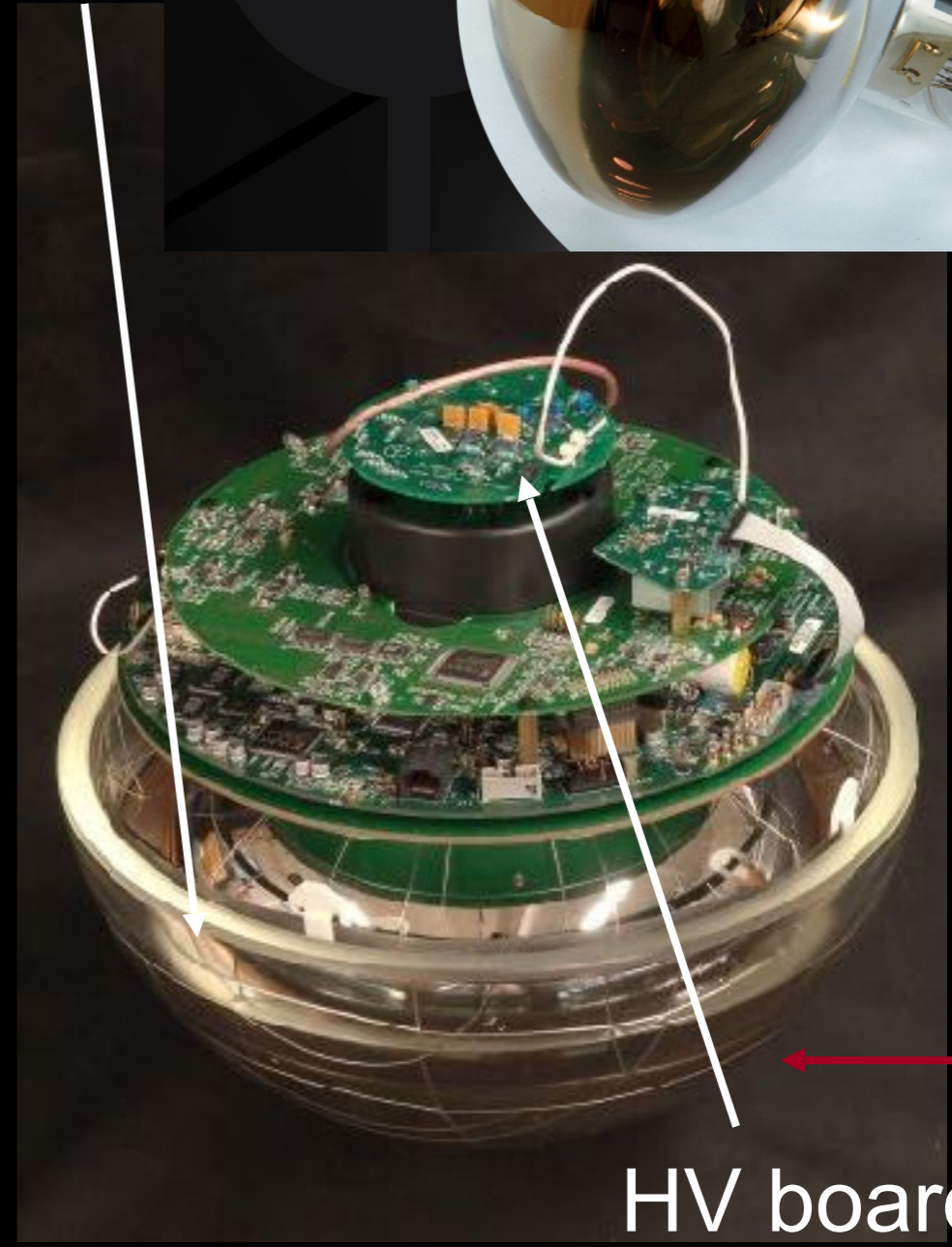


LED
flasher
board

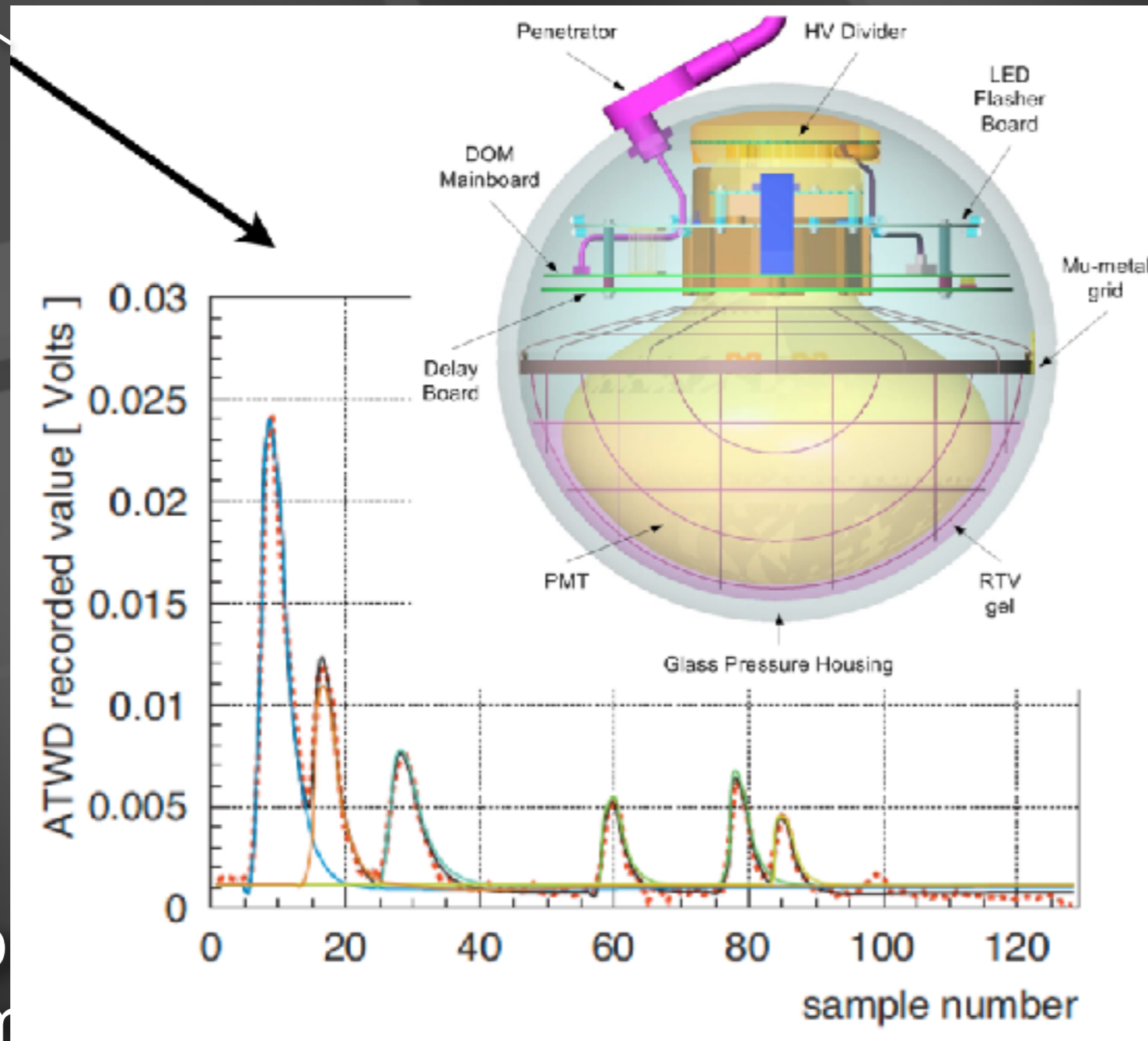
main
board



HV board

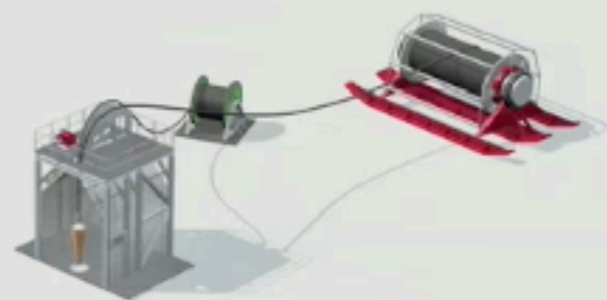


... each Digital Optical Module independently collects light signals like this, digitizes them,



...time stamp
sends them

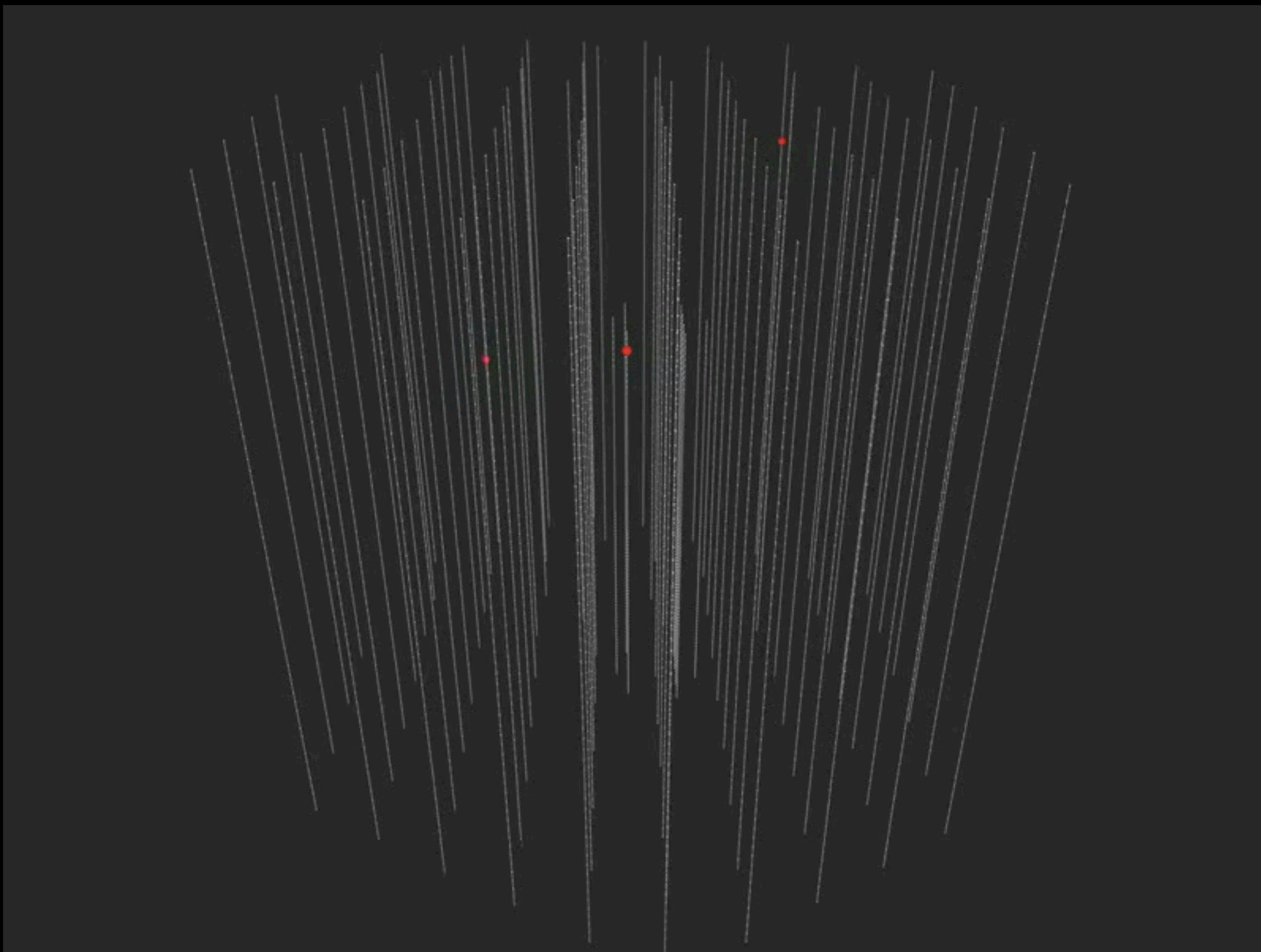
...ion, and
vents...



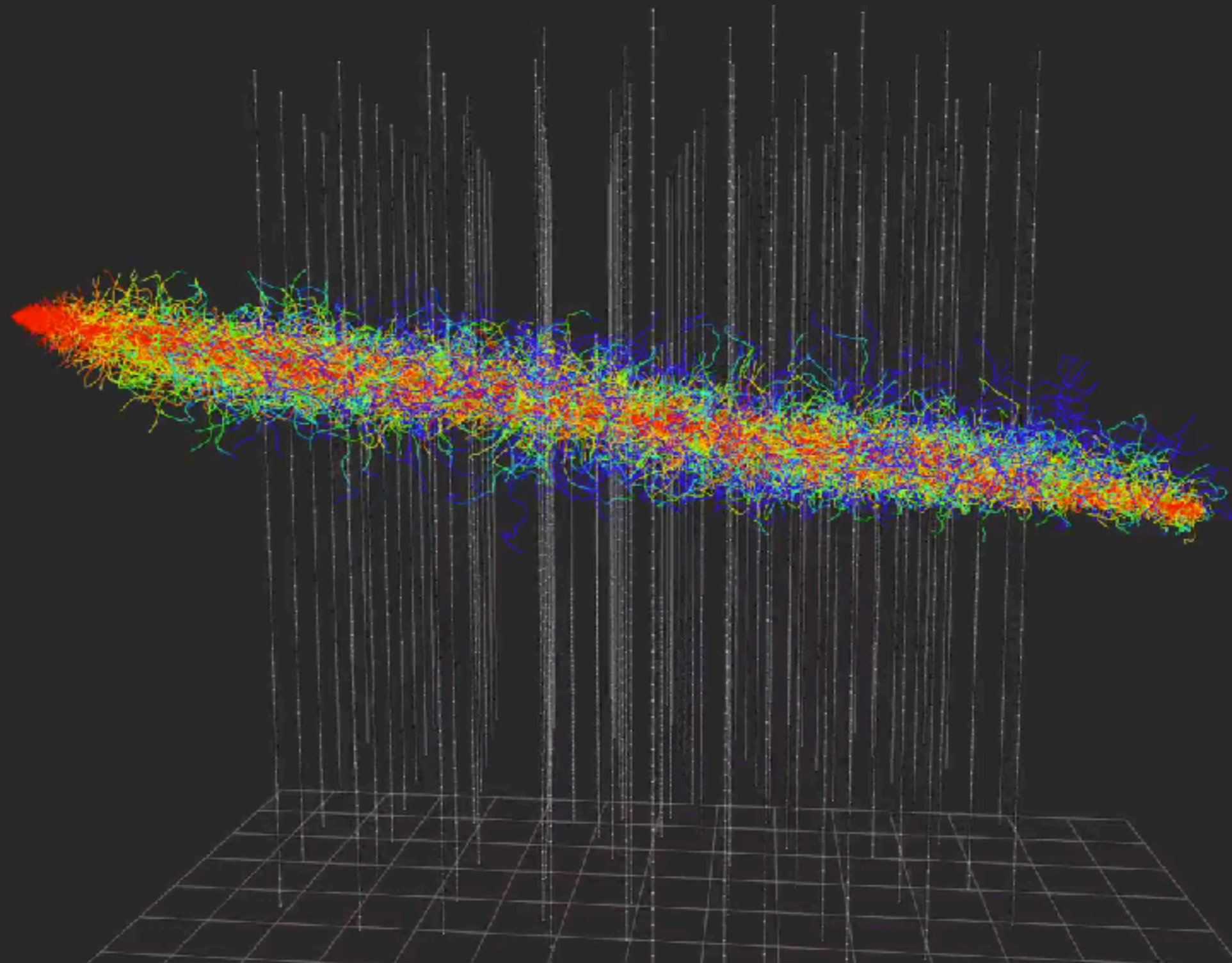


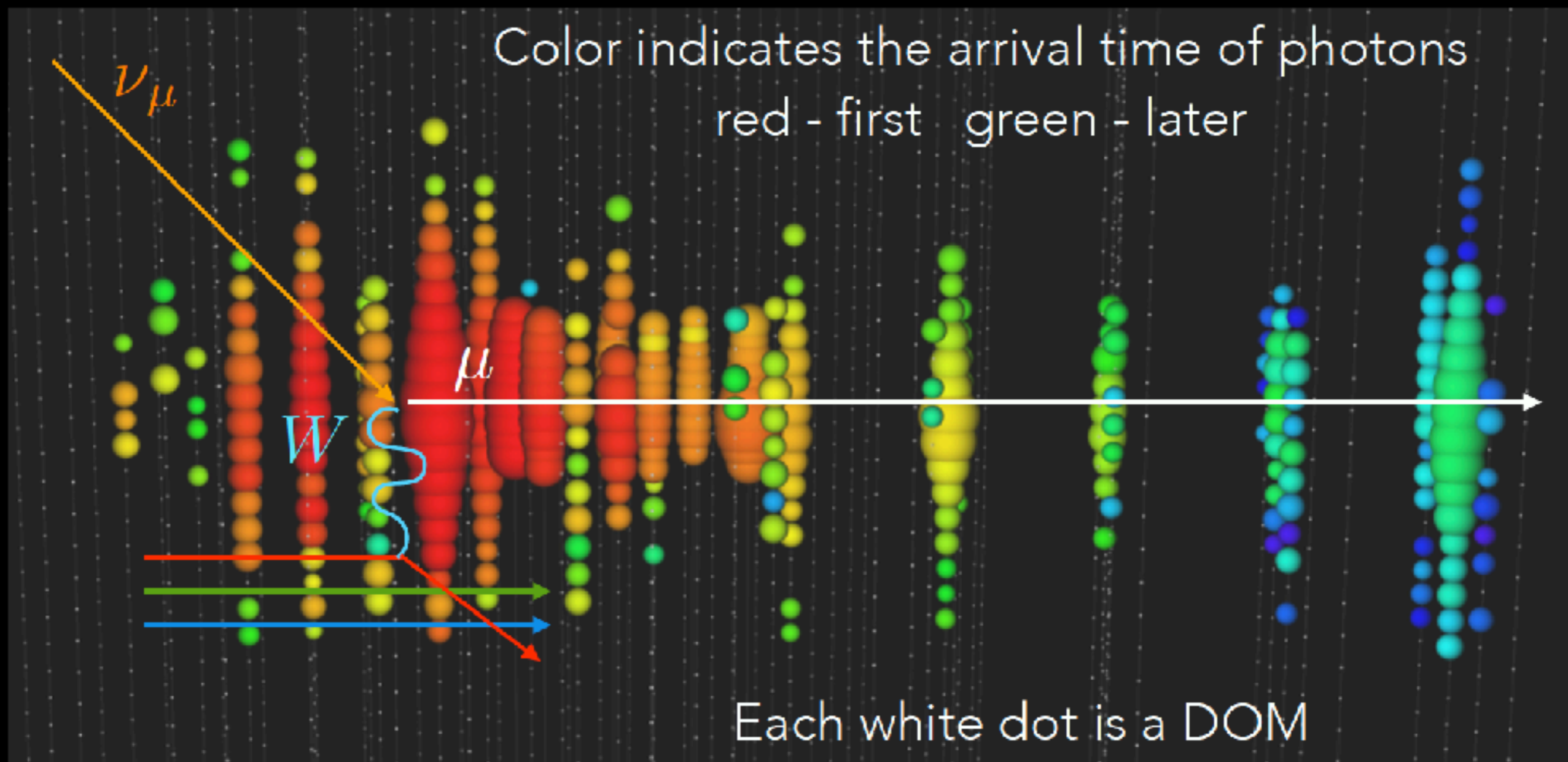






muon track: color is time; number of photons is energy

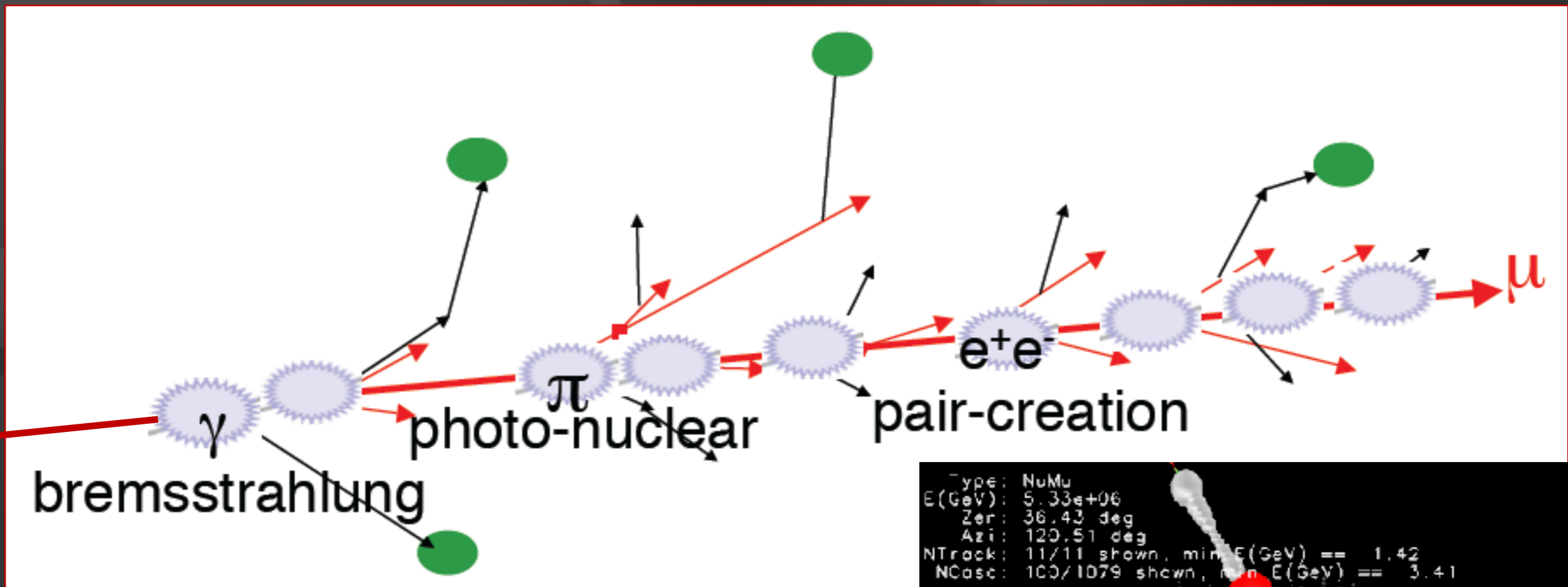




Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

93 TeV muon: light ~ energy

```
Type: NuVc  
E(GeV): 9.30e104  
Zen: 40.45 deg  
Azi: 192.12 deg  
NTrack: 1/1 shown, min E(GeV) == 93025.46  
NCas: 100/127 shown, min E(GeV) == 7.89
```

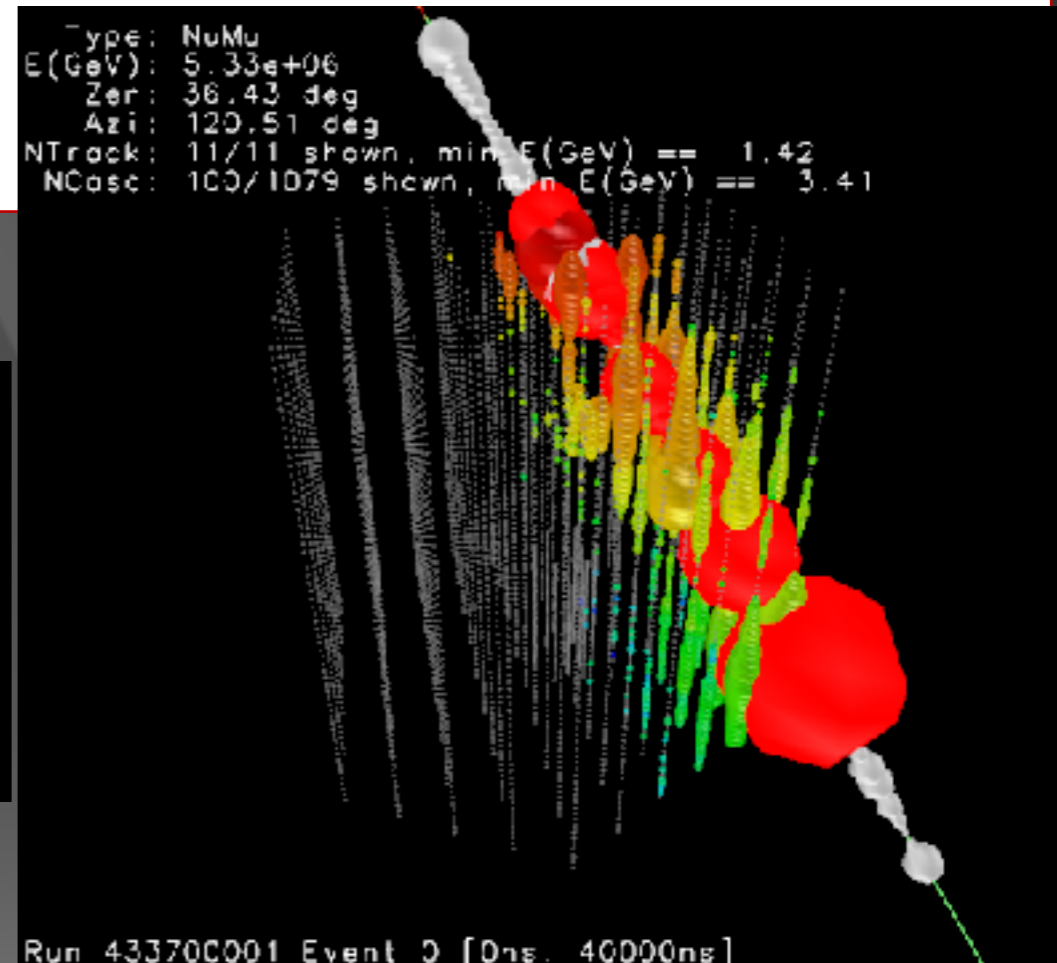


convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx , ...)

```

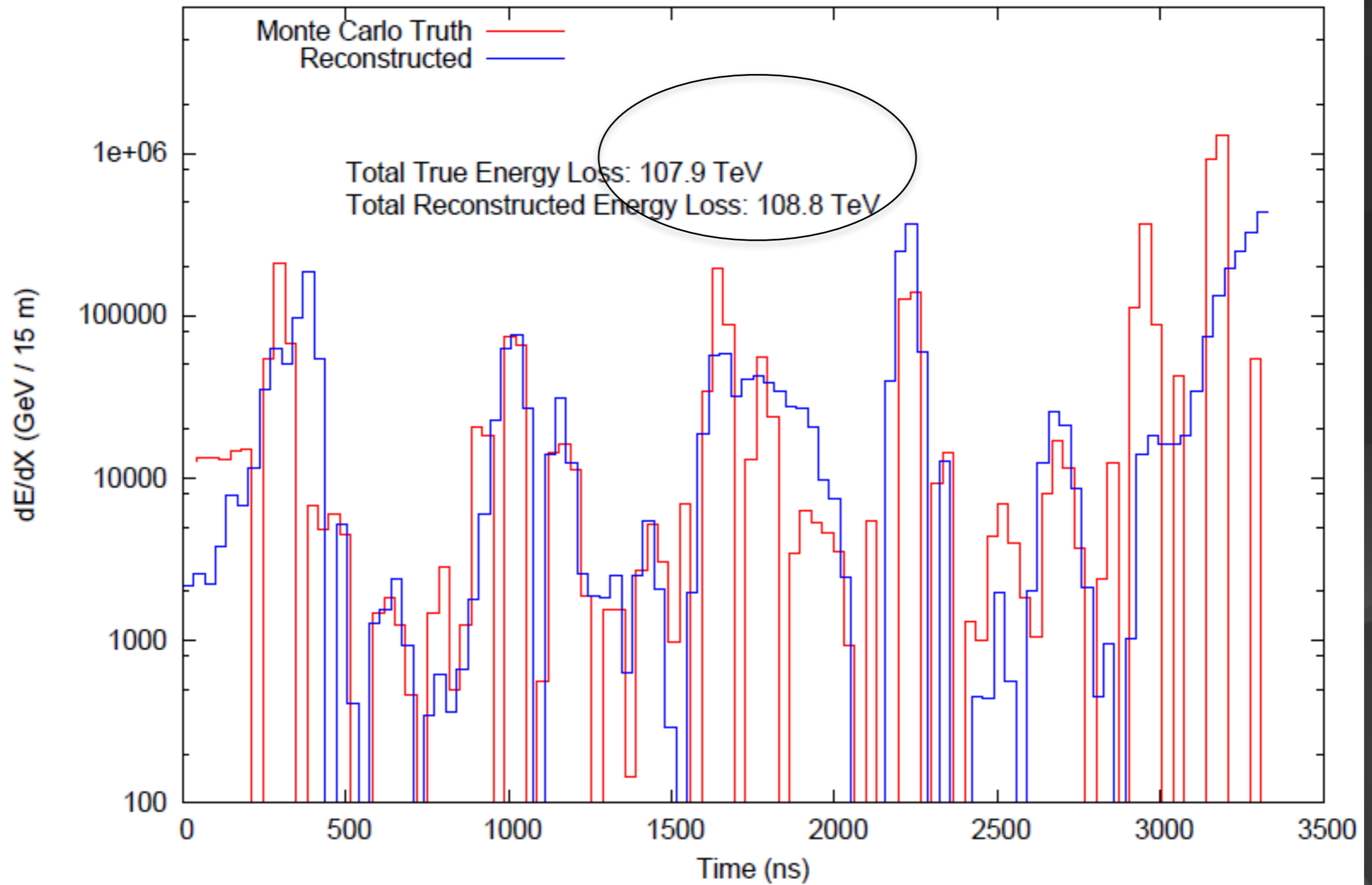
Type: NuMu
E(GeV): 5.33e+06
Zer: 36.43 deg
Azi: 120.51 deg
NTrack: 11/11 shown, min E(GeV) == 1.42
NCasc: 100/1079 shown, min E(GeV) == 3.41

```



Run 43370C001 Event 0 [015. 4000ns]

Differential Energy Reconstruction of 5 PeV Muon in IC-86

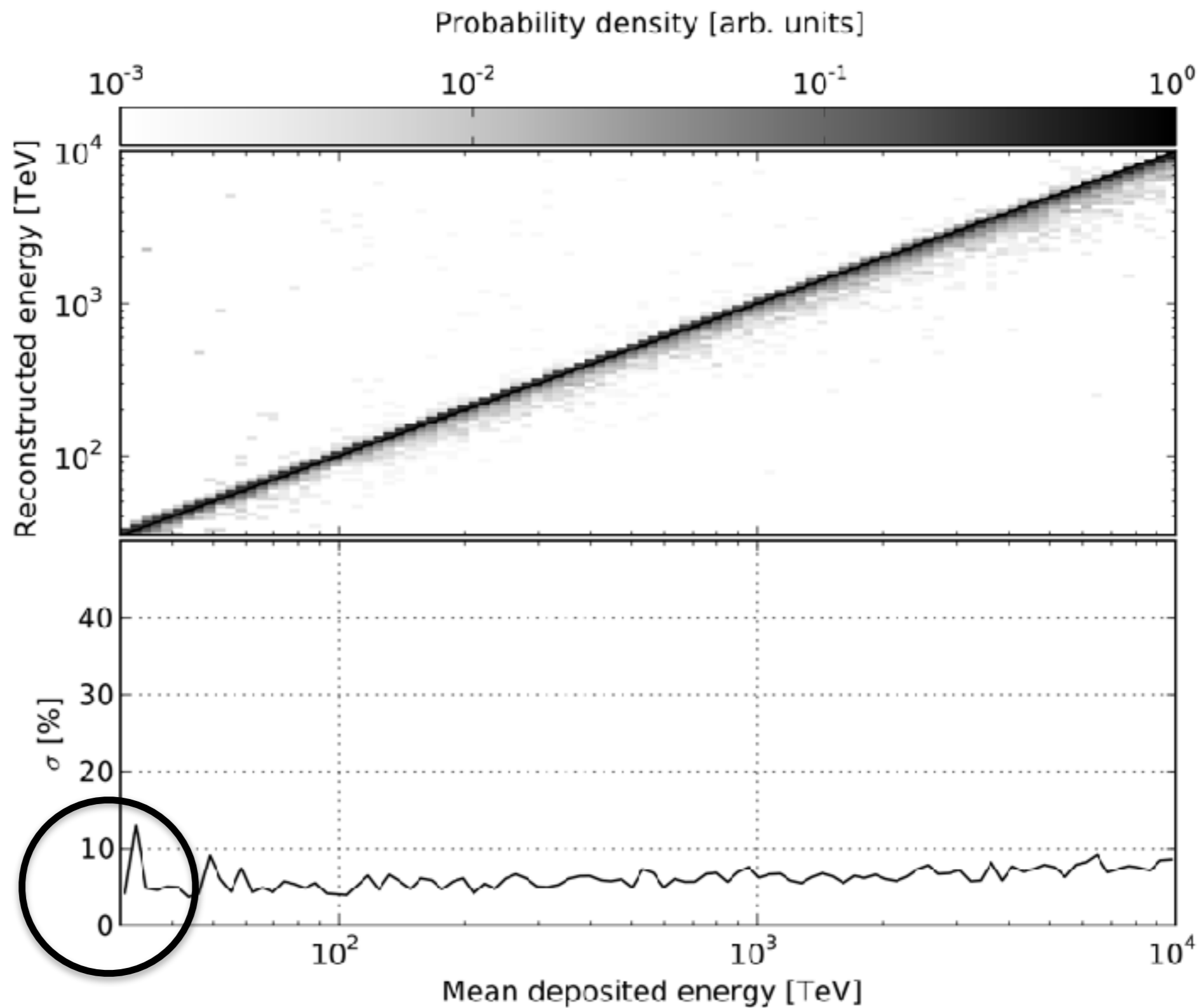


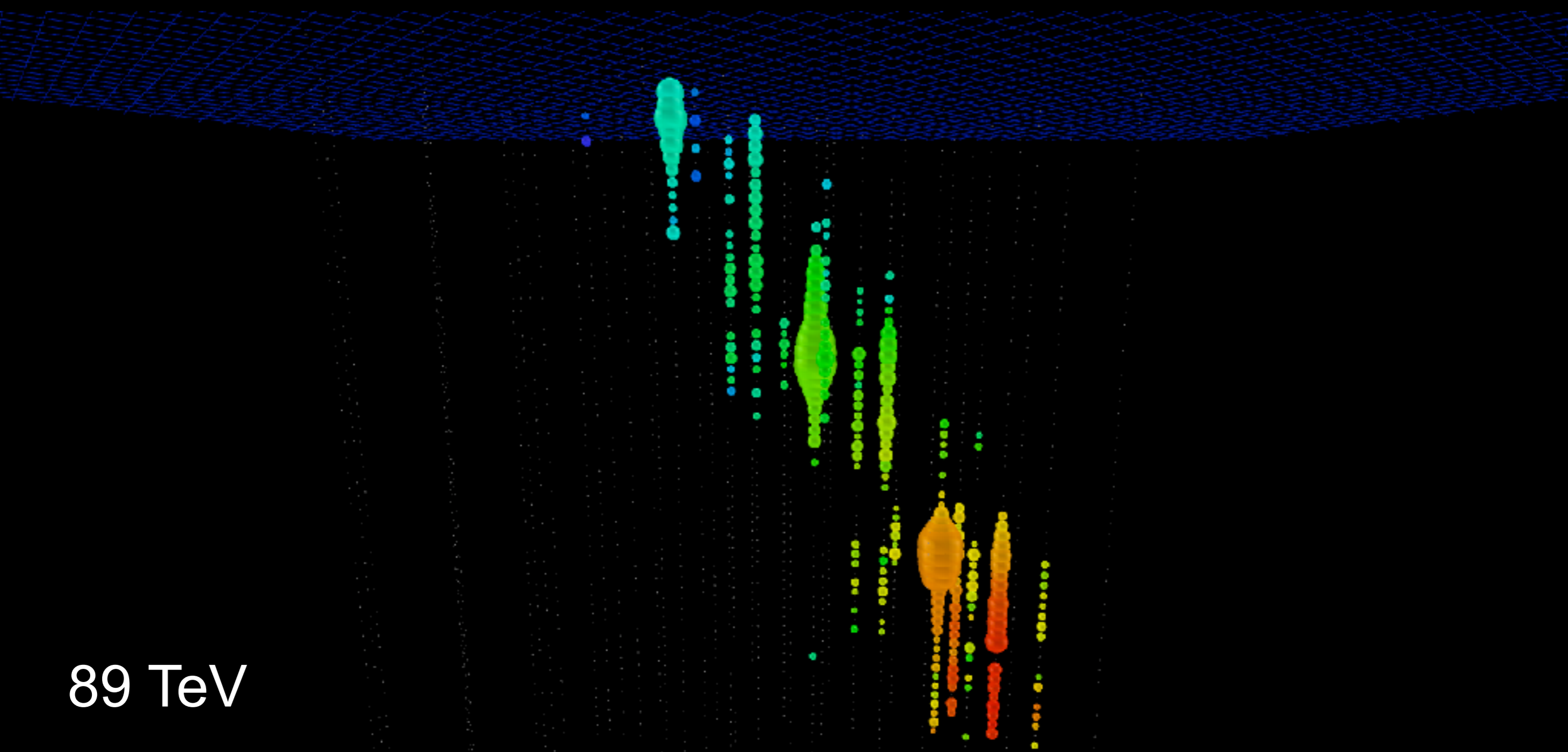
1.1 km



limited angular and energy resolution: computing \rightarrow ice properties


energy reconstruction of electromagnetic showers





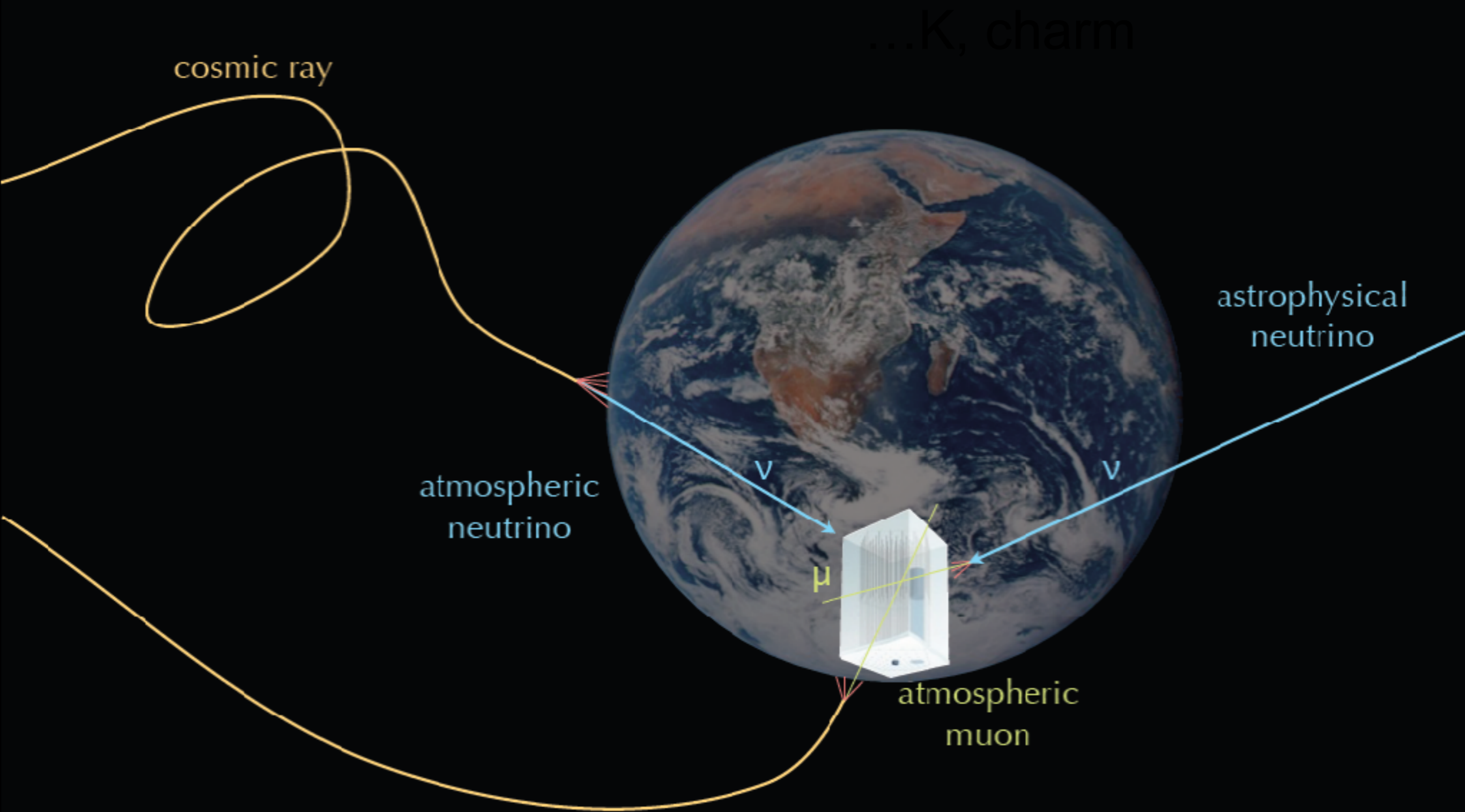
89 TeV

radius ~ number of photons

time ~ red → purple 

Run 13641 Event 33553254 [0ns, 16748ns]

Signals and Backgrounds



... you looked at 10msec of data !

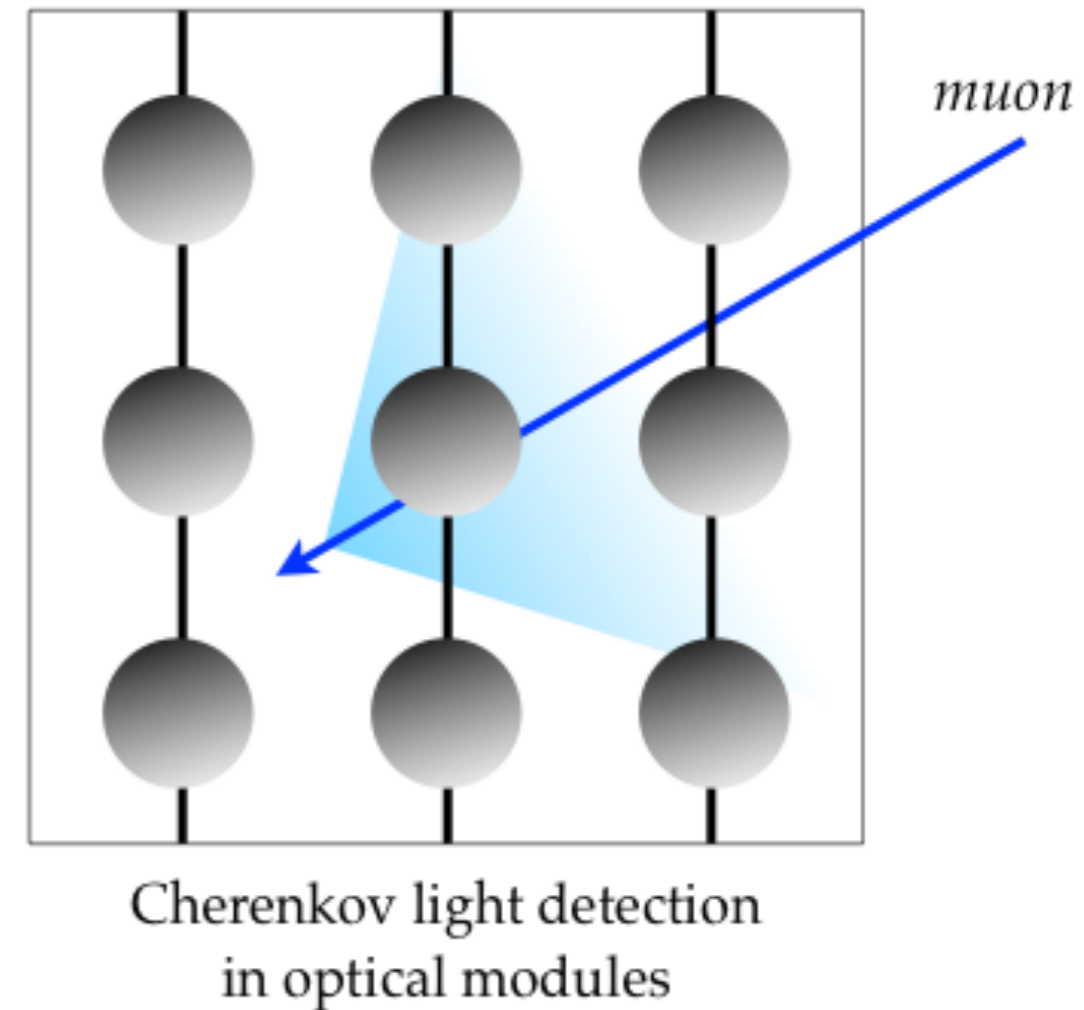
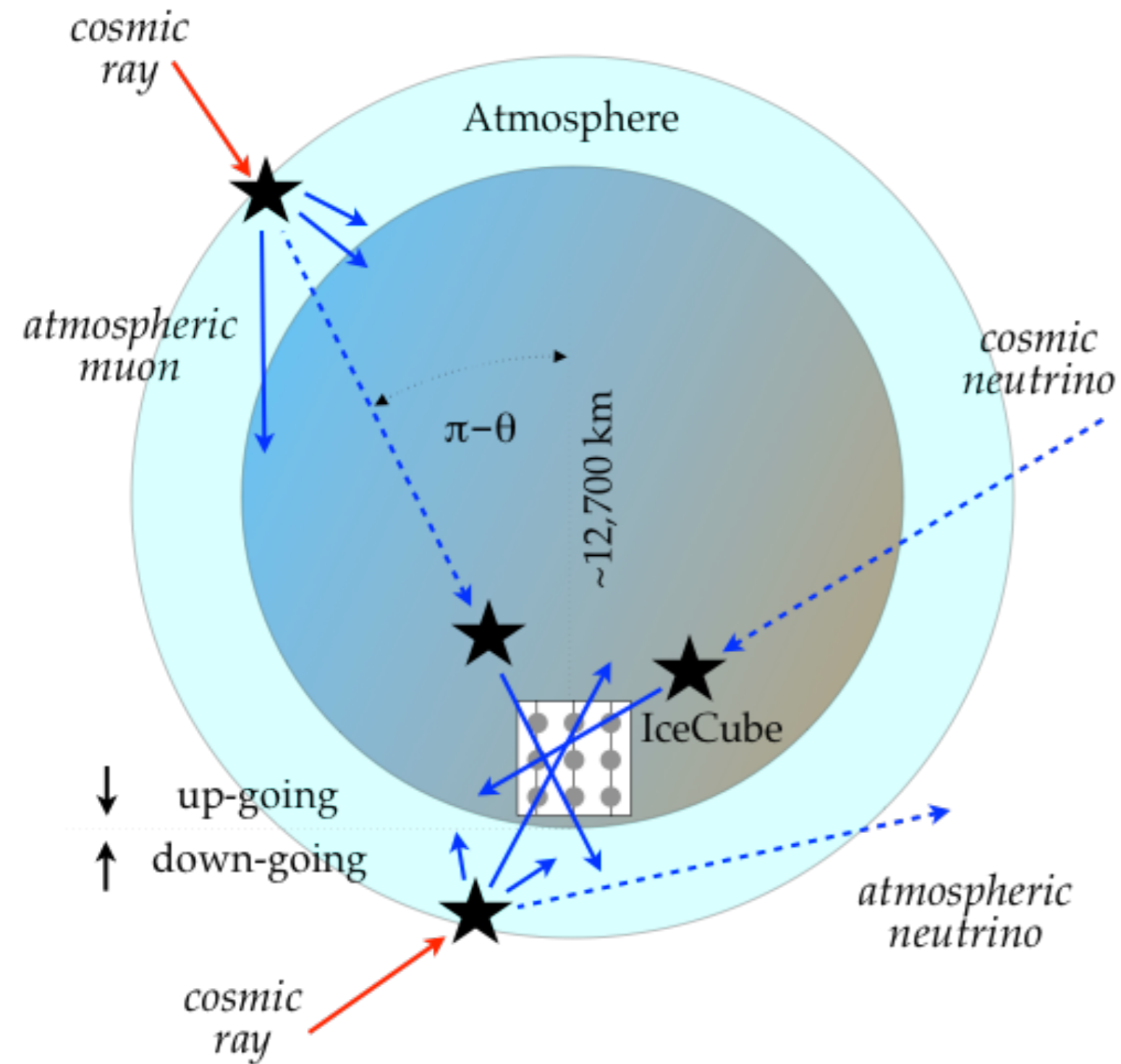
muons detected per year:

- atmospheric* μ $\sim 10^{11}$
- atmospheric** $\nu \rightarrow \mu$ $\sim 10^5$
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

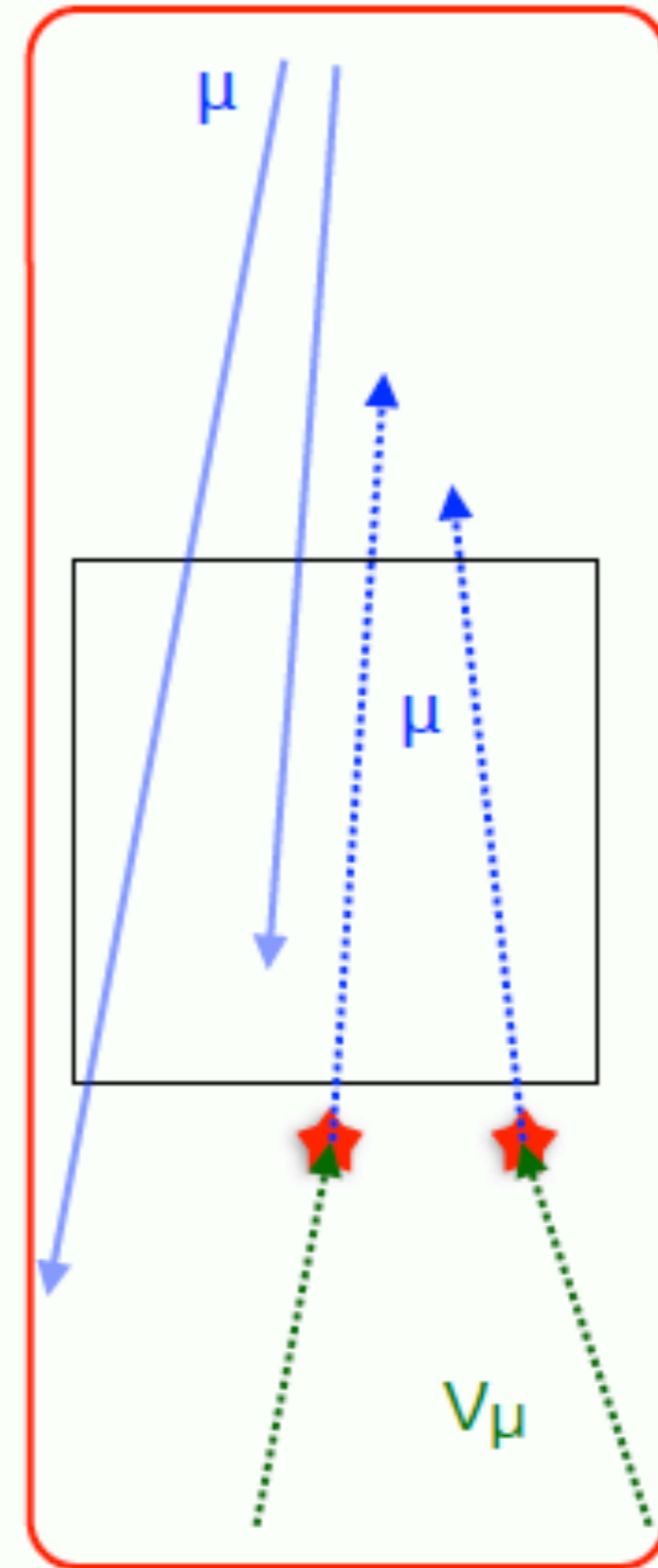
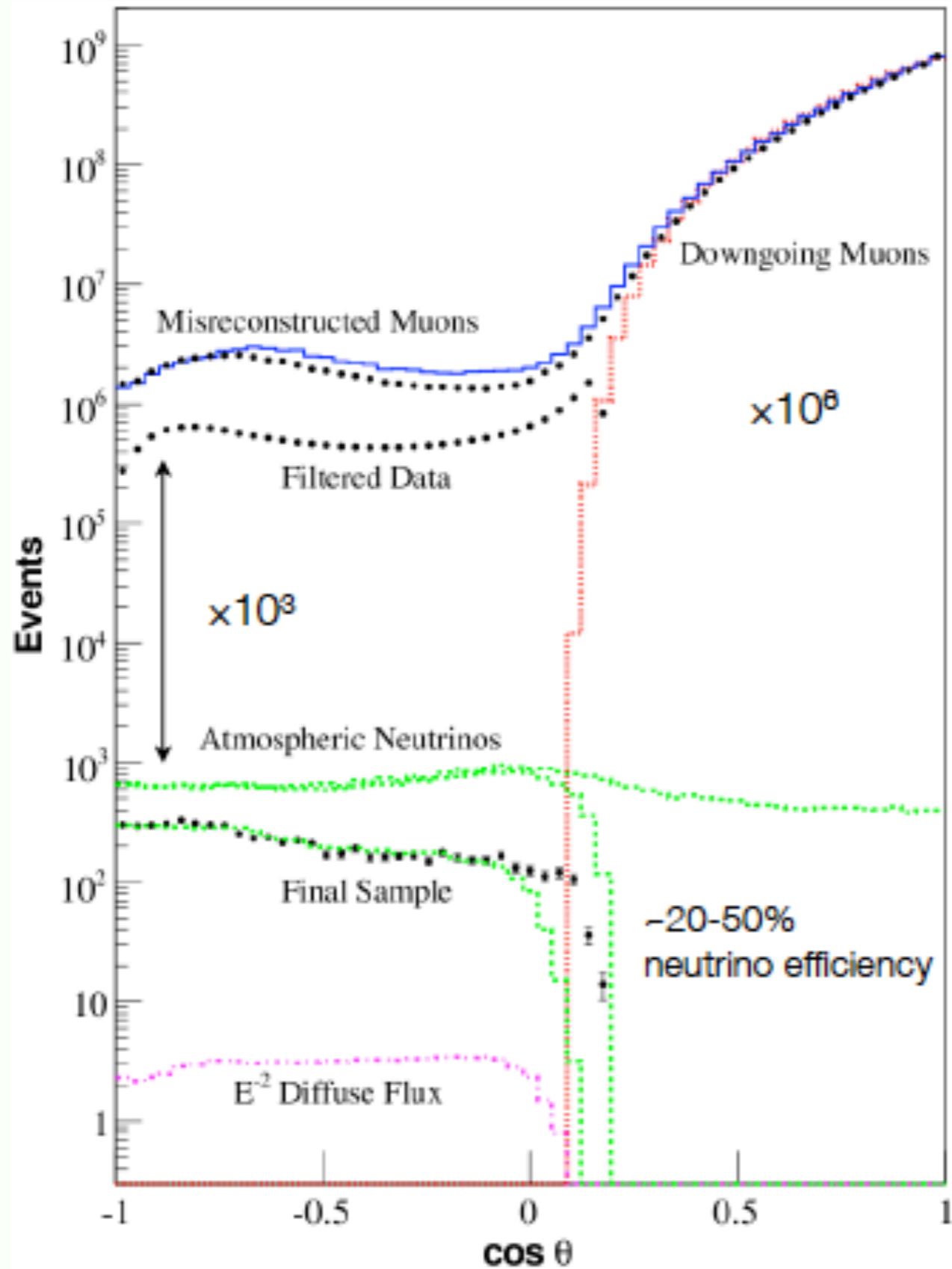
** 1 every 6 minutes

- rejecting atmospheric muons



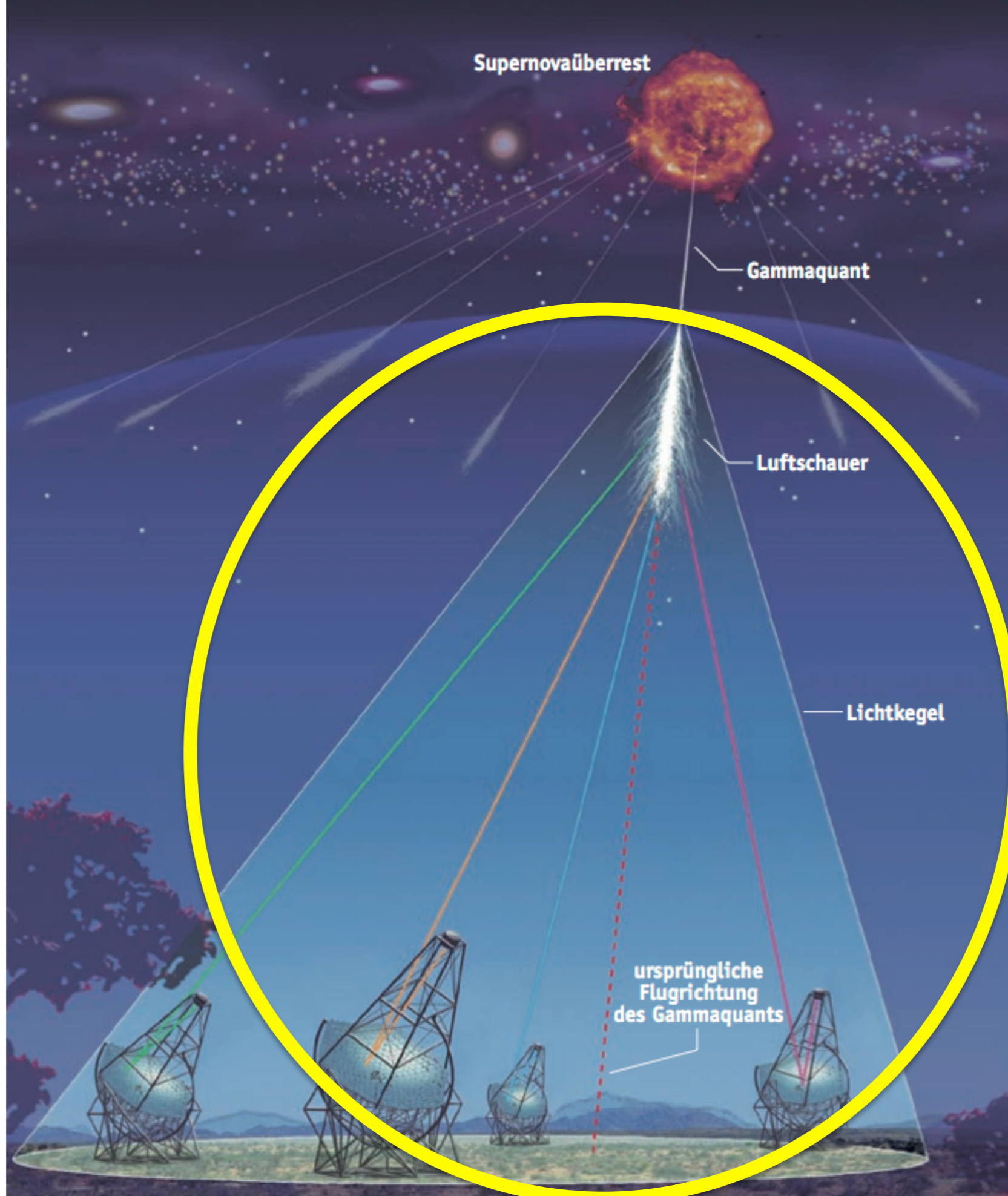
- rejecting atmospheric neutrinos

through-going
(tracks)

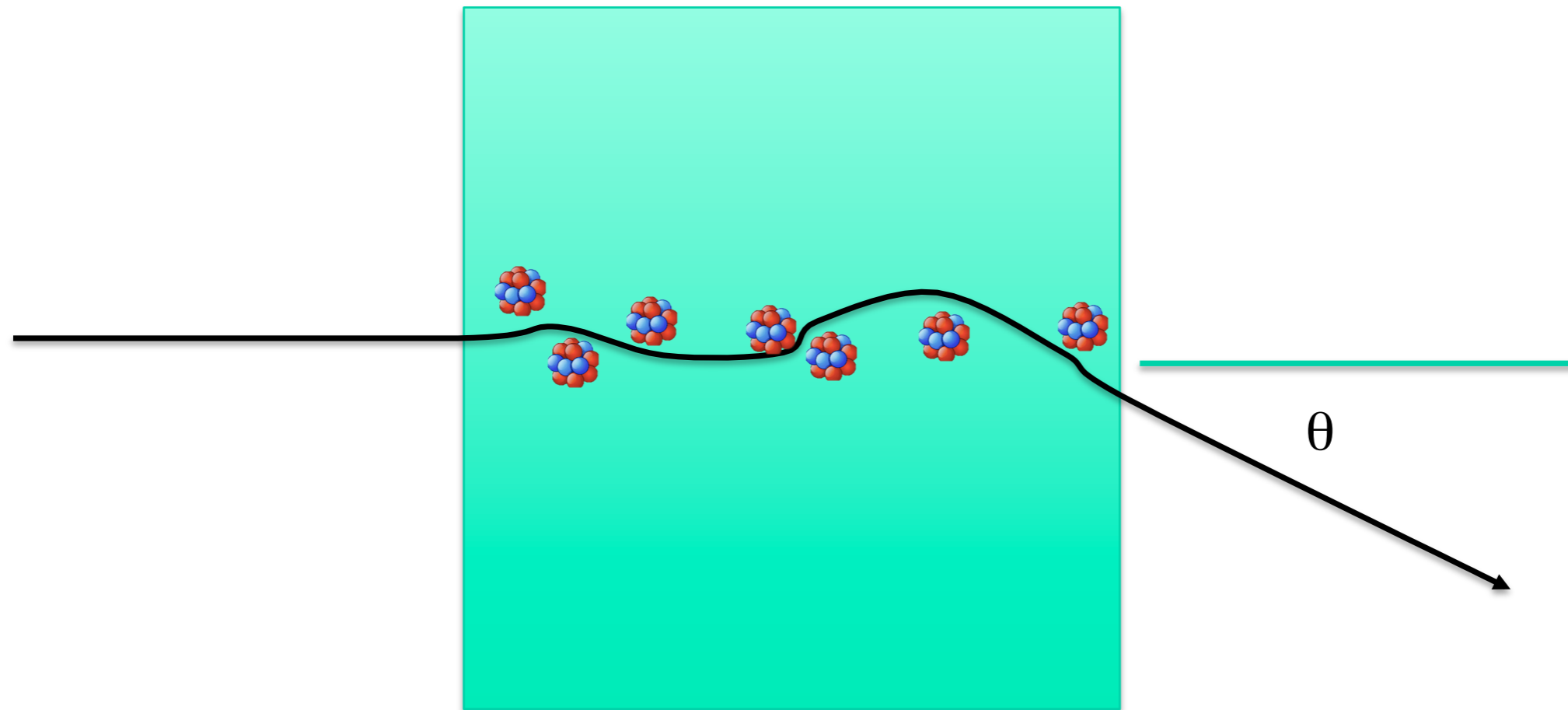
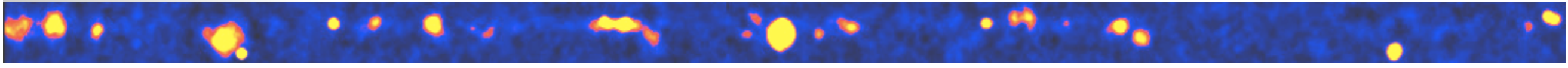




Cherenkov Detectors **for** **Gamma-ray Astronomy**



Need to know: Multiple Coulomb scattering

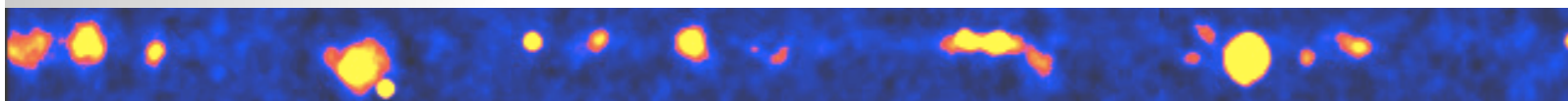


$$\theta_{rms} \approx \frac{14 \text{ MeV}/c}{p} \sqrt{\frac{x}{X_0}}$$

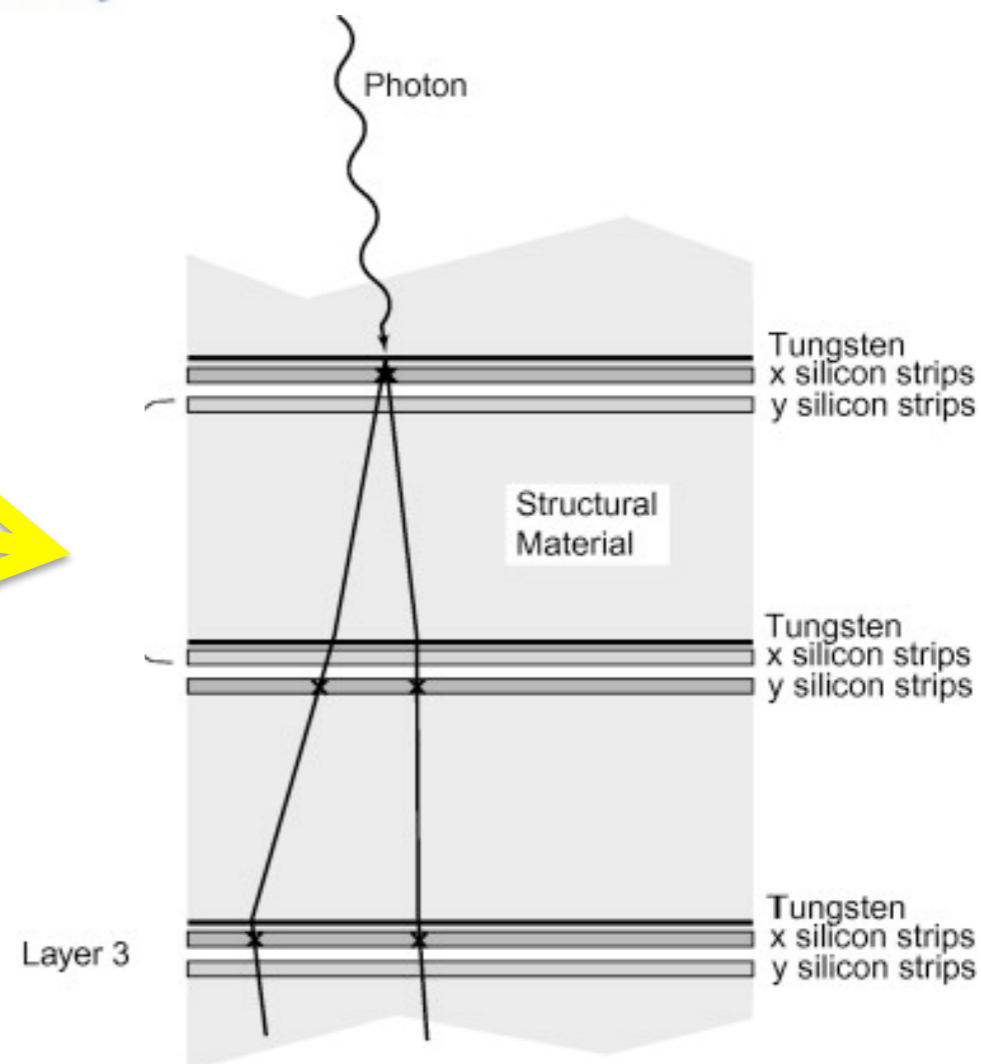
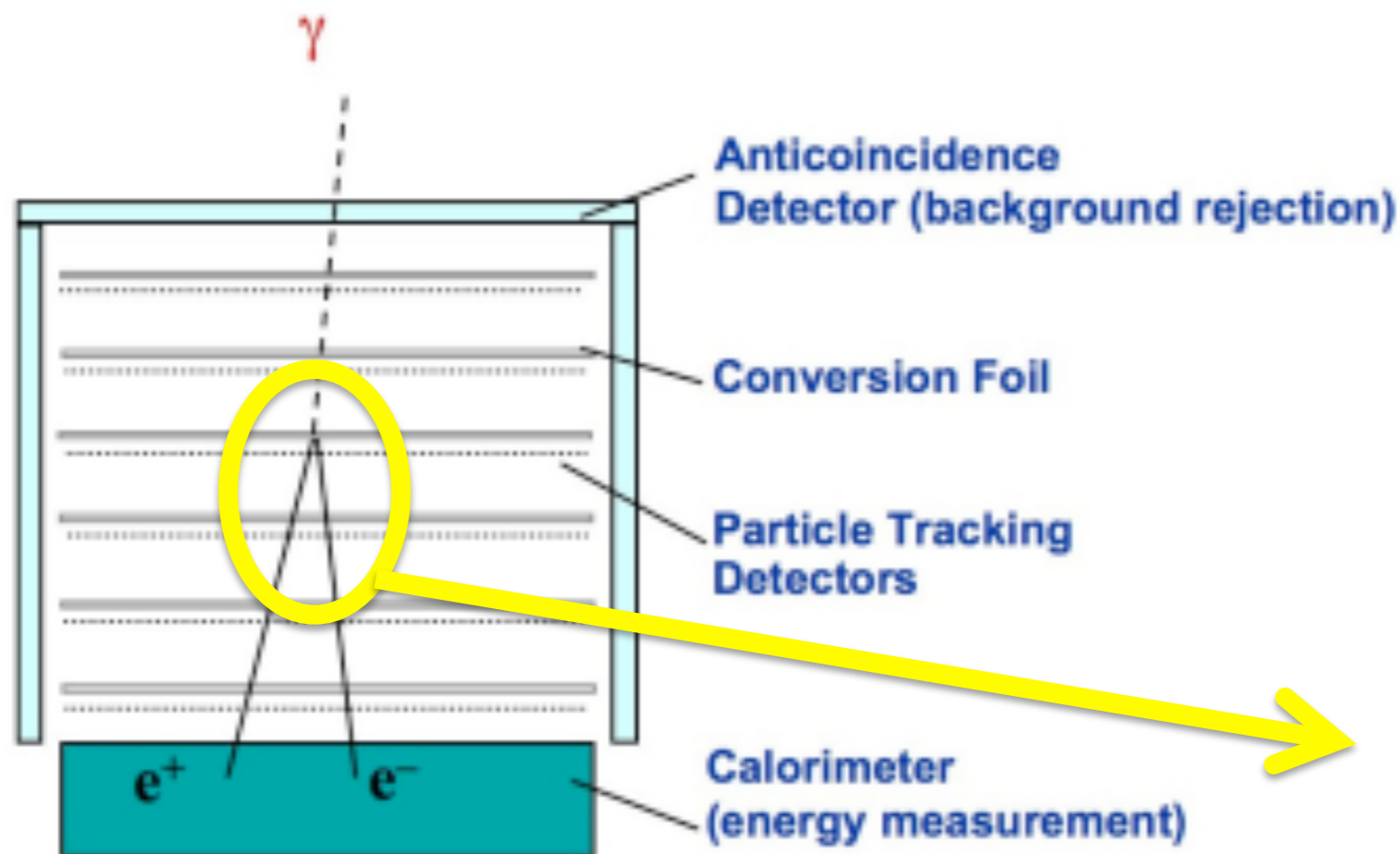
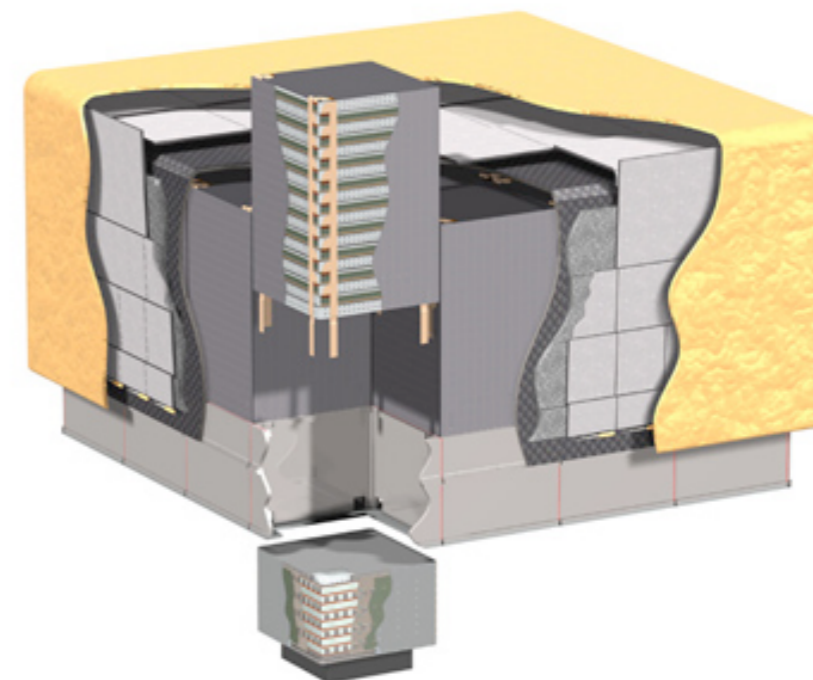
$\approx 1^\circ$ for 1 GeV particle over 1 RL

$\approx 10^\circ$ for 100 MeV particle over 1 RL

Fermi LAT



Pair conversion tracker and calorimeter



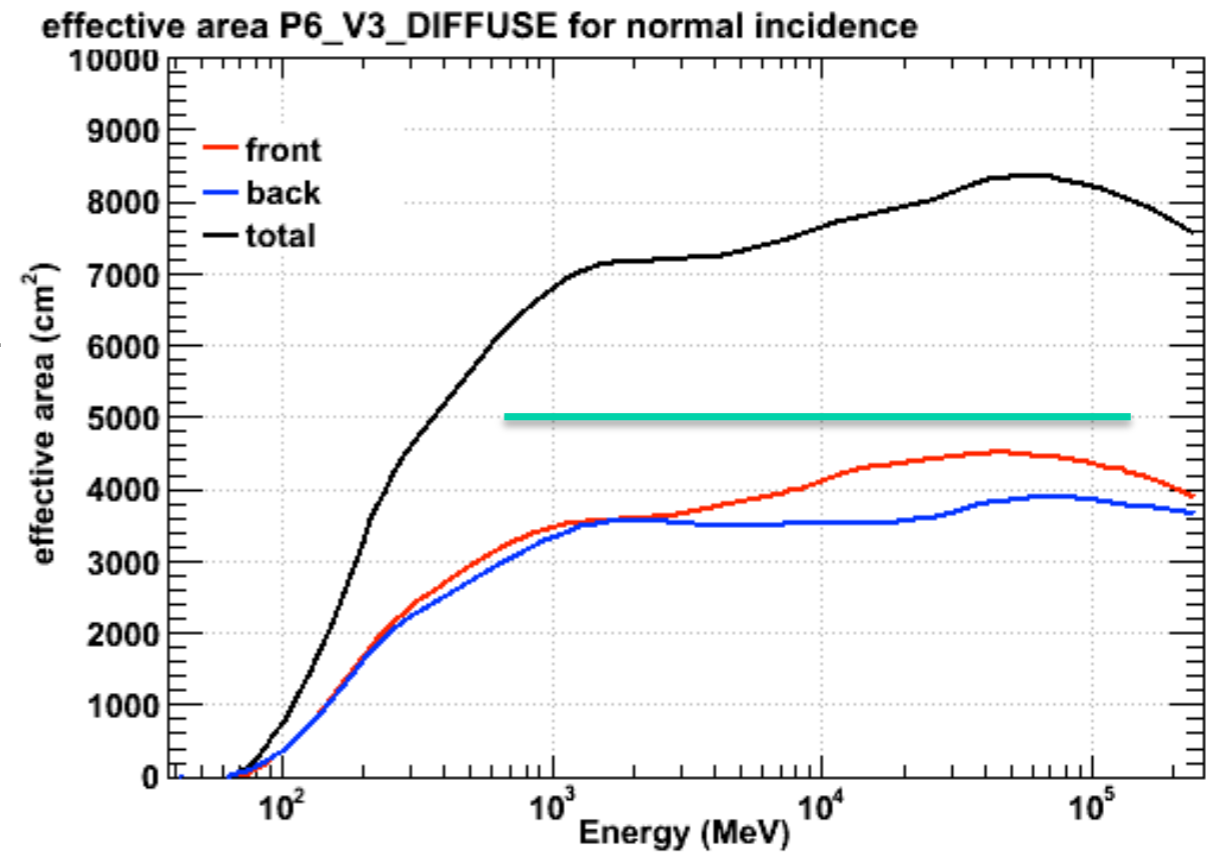
12 planes with 3% RL
4 last planes with 18% RL

Conversion prob. after 10 layers

(30% RL): $(7/9) \times 30\%$

Effective detection area:

$1.4 \text{ m} \times 1.4 \text{ m} \times 23\% = 0.5 \text{ m}^2$



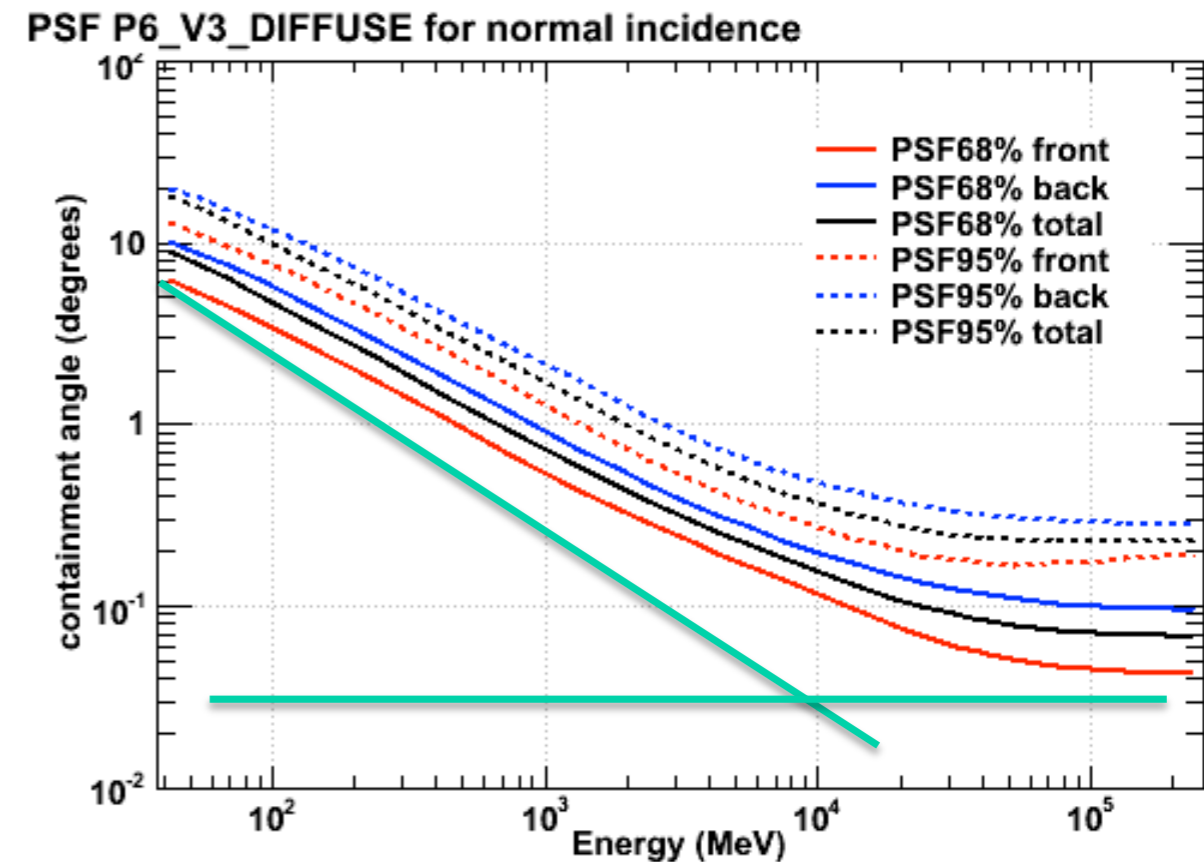
Angular resolution:

track over 3 layers = 10% RL

$$\theta_{rms} \approx \frac{14 \text{ MeV}/c}{p} \sqrt{\frac{x}{X_0}} \approx \frac{0.3^\circ}{E_{GeV}}$$

Strip resolution

$50 \mu\text{m}/10 \text{ cm} = 0.03^\circ$



Gamma-ray

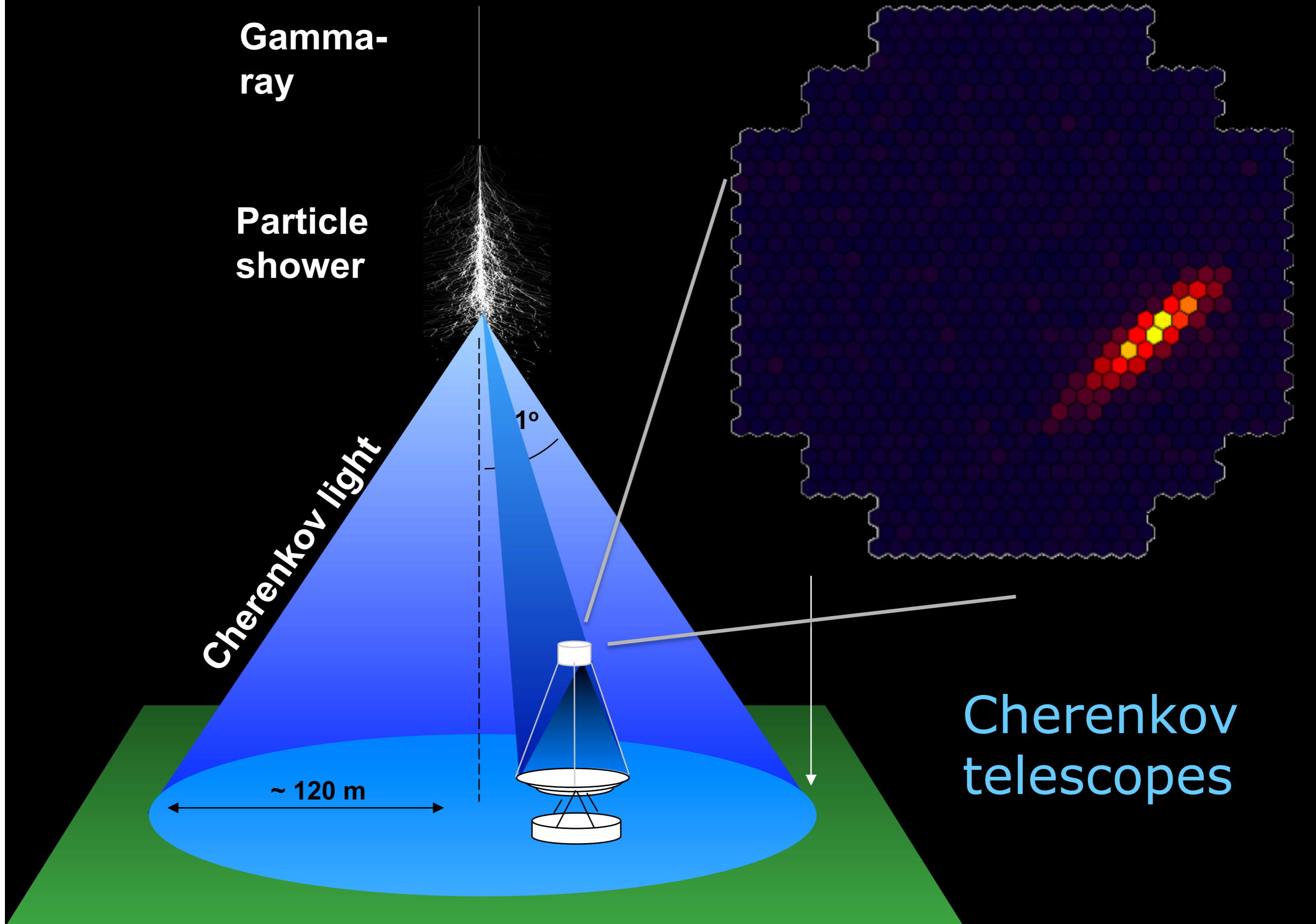
Particle shower

Cherenkov light

1°

~ 120 m

Cherenkov telescopes



Shower development

Particle number doubles after ~each radiation length until ionization losses dominate

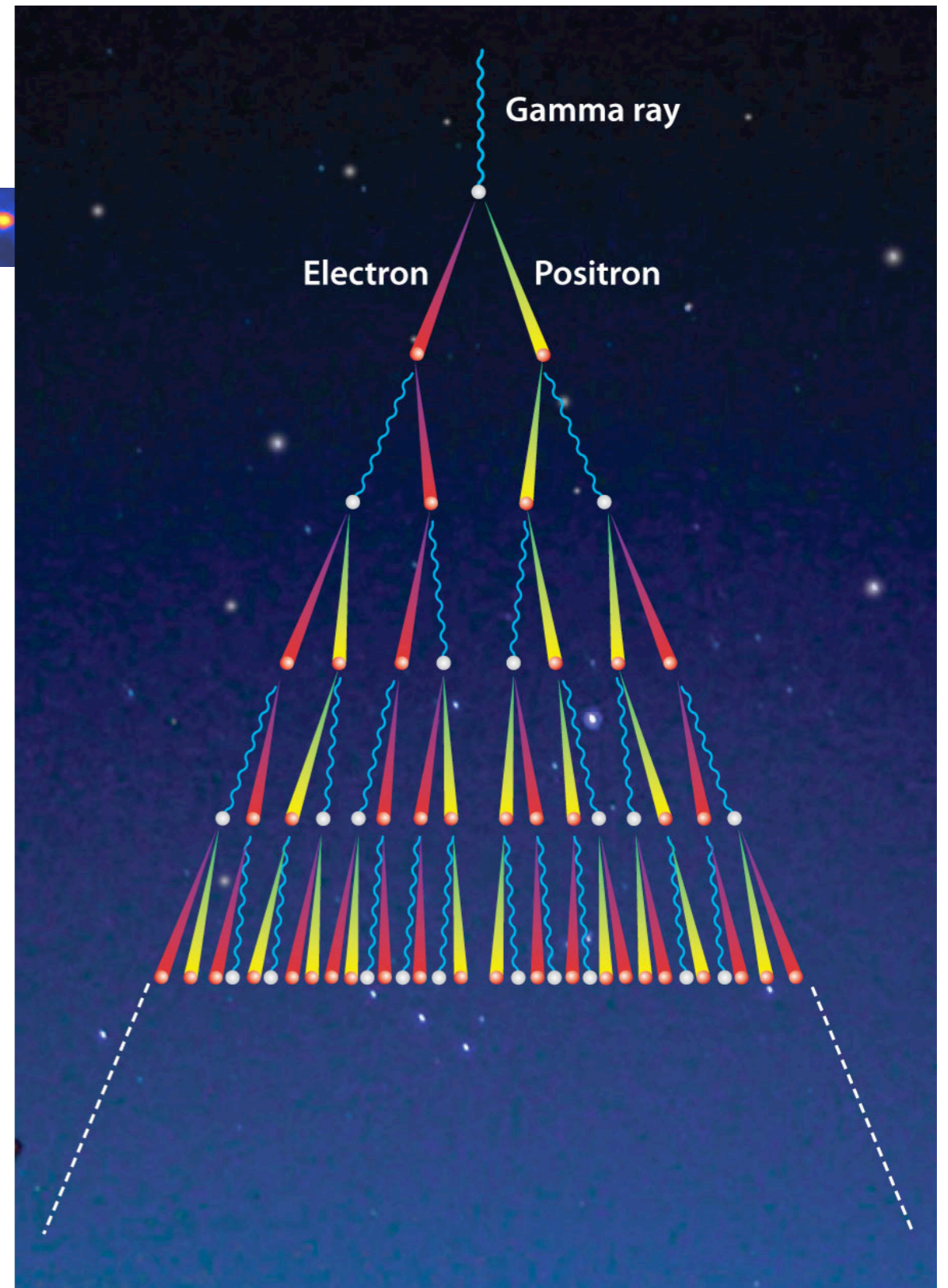
losses dominate

("critical energy" ~ 85 MeV)

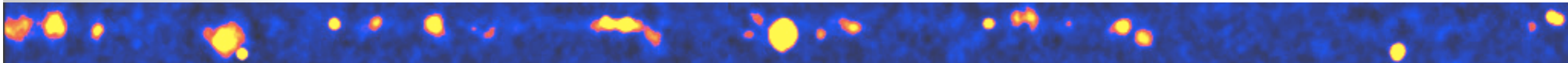
$$t_{\max} \approx \frac{\ln(E_0 / E_c)}{\ln 2} \approx 14 \text{ RL at 1 TeV}$$

More exact (PDG):

$$t_{\max} \approx \ln(E_0 / E_c) + 0.5 \\ \approx 10 \text{ RL at 1 TeV}$$



Cherenkov light pool size & intensity



Refractive index of air

$$n = 1 + \varepsilon \quad ; \quad \varepsilon \approx 3 \cdot 10^{-4} e^{-h/8km} \approx 10^{-4} \quad \text{at shower maximum}$$

Cherenkov threshold

$$\text{Cherenkov threshold } \beta > \frac{1}{n} \quad ; \quad \beta = \frac{\sqrt{E^2 - m^2}}{E} \approx 1 - \frac{m^2}{2E^2} > \frac{1}{n} \approx 1 - \varepsilon$$

$$\frac{m^2}{2E^2} < \varepsilon \quad \Rightarrow \quad E > \frac{m}{\sqrt{2\varepsilon}} = 35 \text{ MeV (at shower maximum); } < E_{crit} !$$

Cherenkov angle

$$\theta = \arccos(\beta n) \underset{\cos \theta \approx 1 - \frac{\theta^2}{2}}{\approx} \sqrt{2 \left(1 - \frac{1}{\beta n} \right)} \underset{\beta=1}{\approx} \sqrt{2\varepsilon} \approx 0.8^\circ \quad \text{at shower max.}$$

Light yield

$$\text{Yield} \sim 500 \sin^2 \theta \frac{\text{ph.}}{\text{cm}} \approx 1000 \varepsilon \frac{\text{ph.}}{\text{cm}} \approx 0.1 \frac{\text{ph.}}{\text{cm}} \approx 10^4 / \text{RL} (\sim 1 \text{ km})$$

Cherenkov light pool size & intensity

Cherenkov
threshold ($\beta > 1/n$)
 ~ 35 MeV

Cherenkov
angle $\sim 0.8^\circ$

Shower ends
around critical
energy, ~ 85 MeV

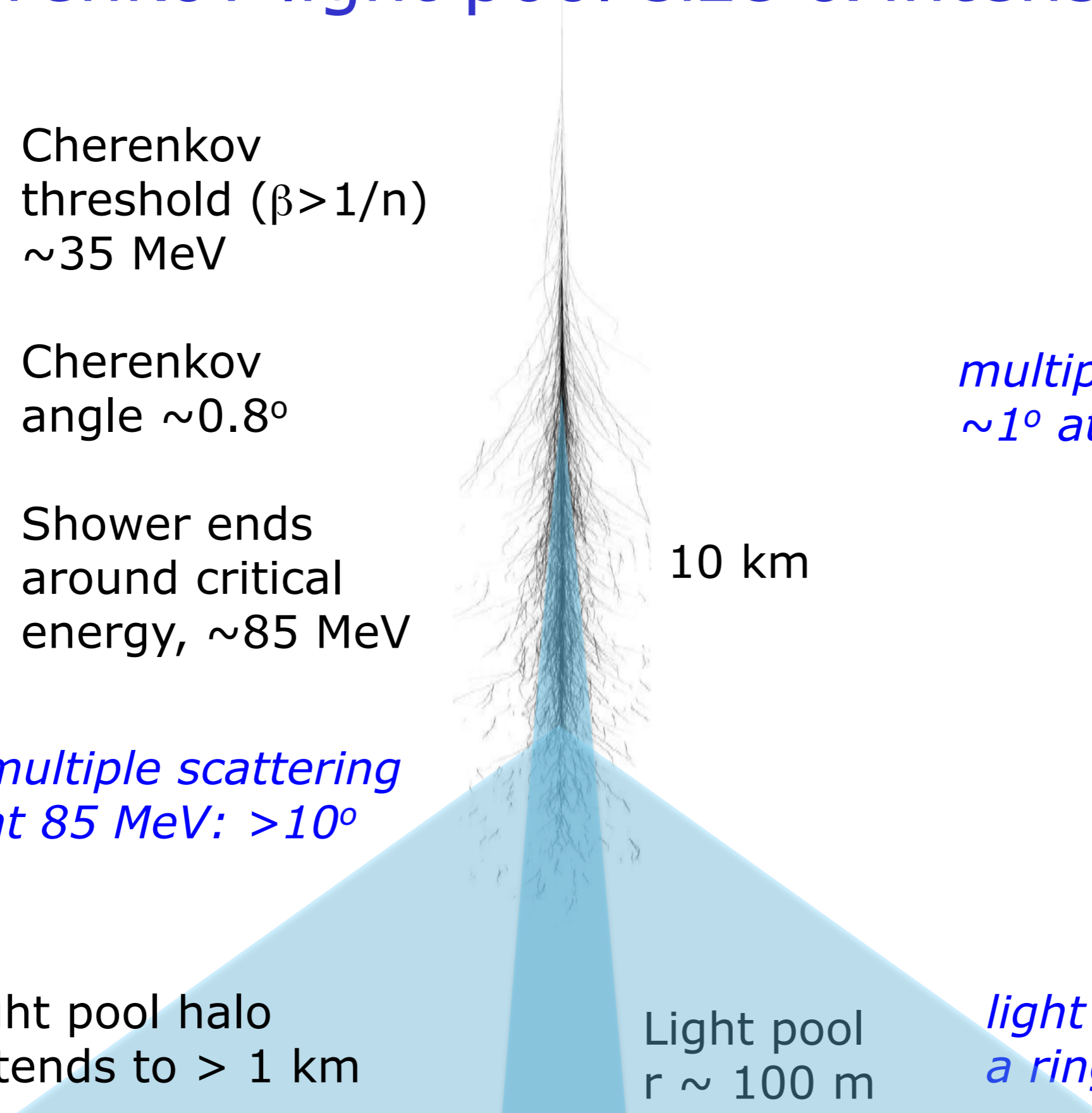
*multiple scattering
at 85 MeV: $> 10^\circ$*

Light pool halo
extends to > 1 km

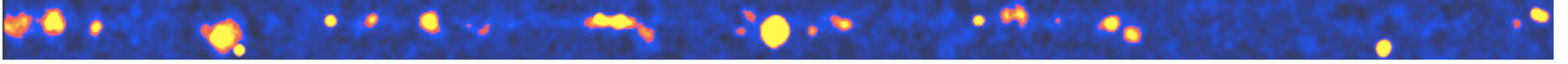
Light pool
 $r \sim 100$ m

*light pool not
a ring, but filled*

*multiple scattering:
 $\sim 1^\circ$ at 1 GeV*



Cherenkov light pool size & intensity



Cherenkov light from full shower

A TeV shower contains $E_0 / E_c \approx 10^4$ particles

Over 1 rad. length (1000 m @ shower max):

$$\Rightarrow 10^4 \text{ part.} \times 1000 \text{ m} \times 0.1 \text{ ph./cm} \approx 10^8 \text{ ph./TeV}$$

With mult. scatt. angle at E_{crit} : $\sim 10^0$

$$\Rightarrow \text{Radius of light pool } \sim 1\text{-}2 \text{ km}; \text{ photon density } \sim \text{few } 10 \text{ ph./m}^2$$

Considering only the higher-energy shower particles

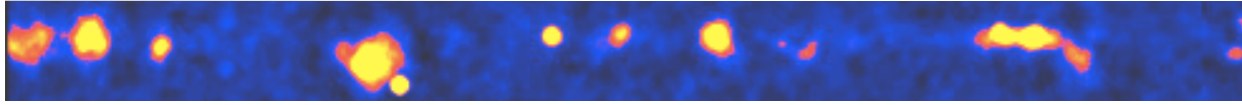
2RL higher up higher up:

For $\theta_{ms} \approx \theta_{Ch.}$: $E \approx 1 \text{ GeV}$; shower contains ~ 1000 particles

$$\Rightarrow 1000 \text{ part.} \times 1000 \text{ m} \times 0.1 \text{ ph./cm} \approx 10^7 \text{ ph./TeV}$$

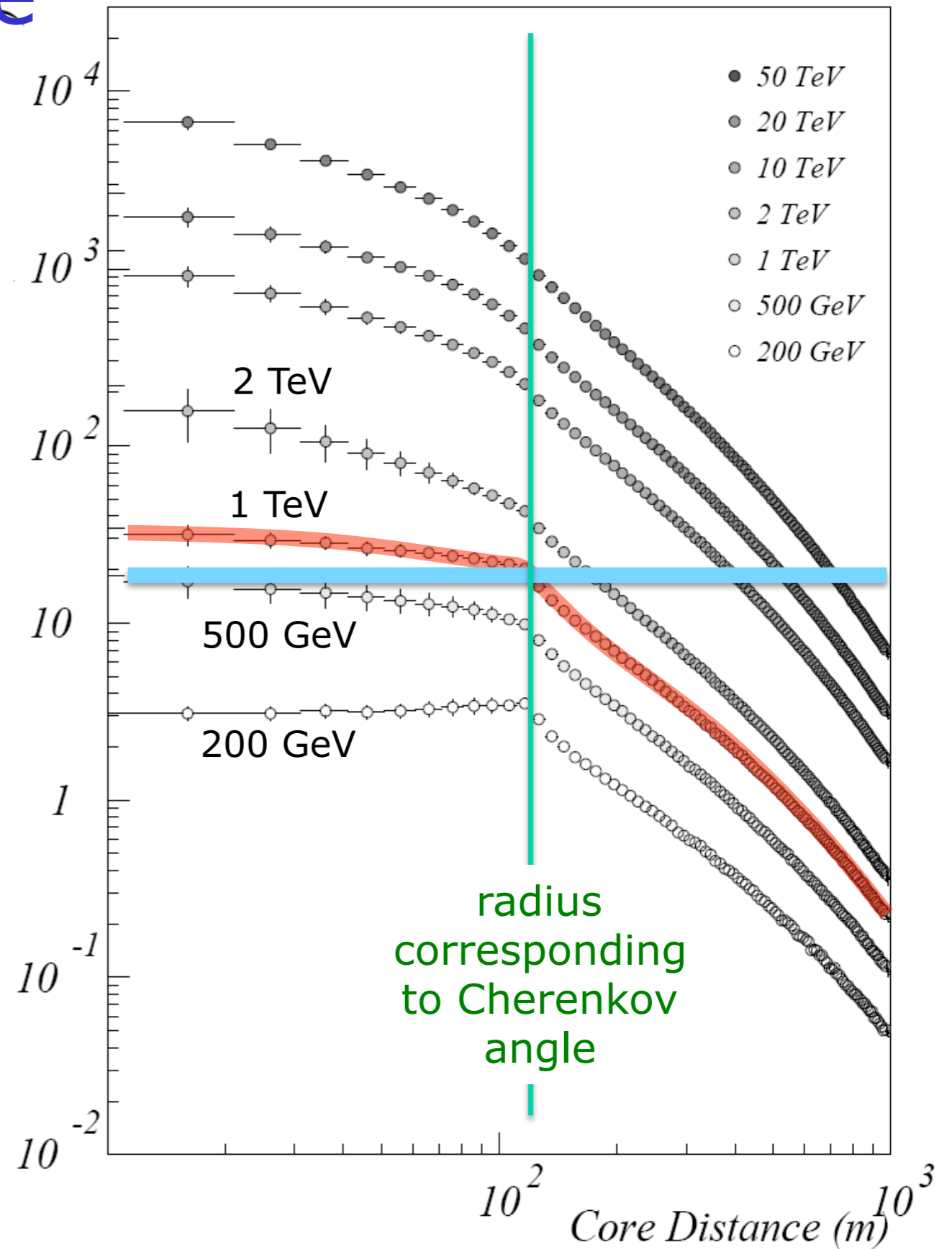
$$\Rightarrow \text{over } 110 \text{ m radius light pool: } \sim 300 \text{ ph./m}^2$$

Intensity vs distance



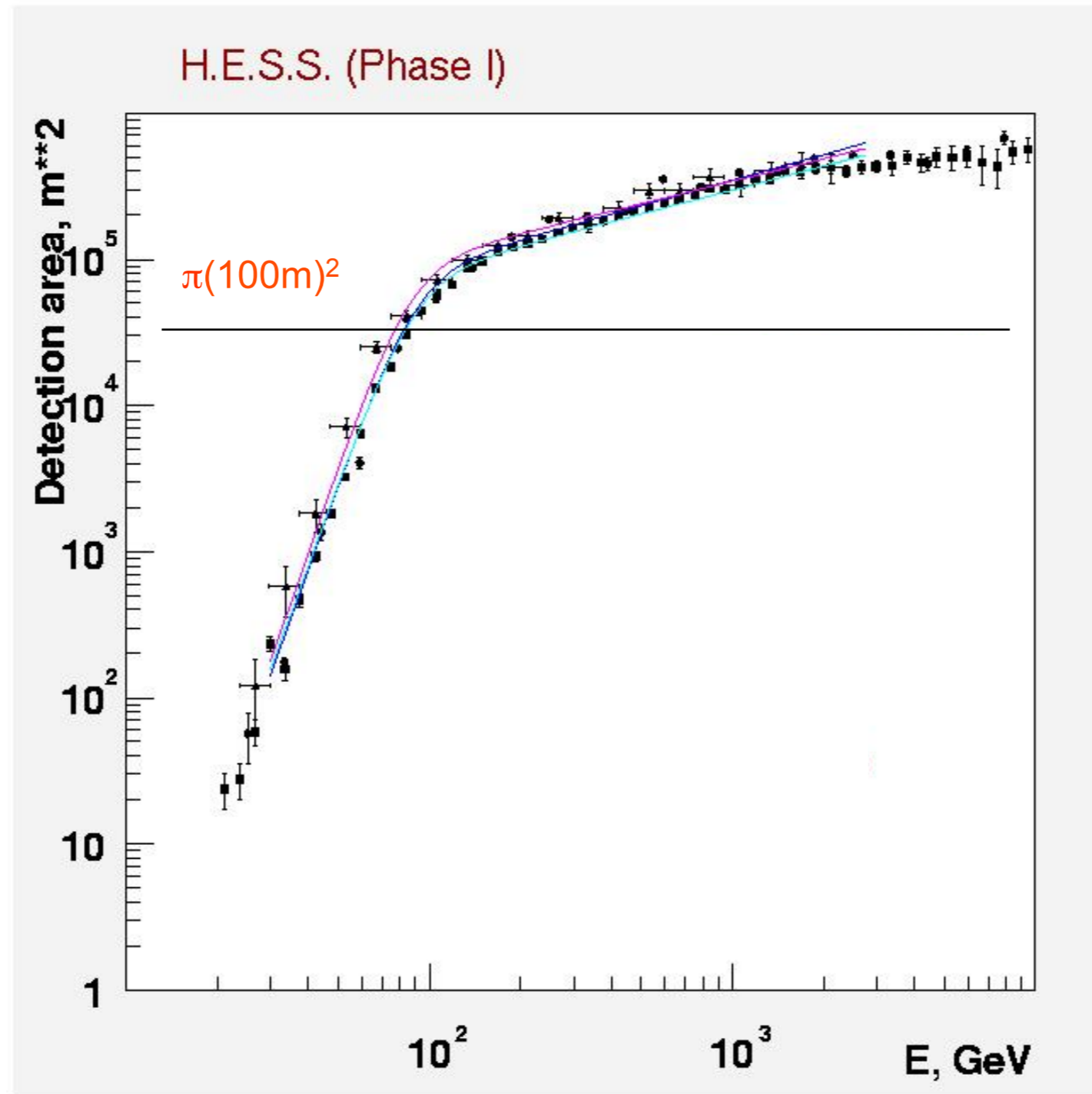
detected photons per m^2

detection threshold



I. de la Calle Perez, S. D. Biller
APP 26 (2006) 69

Energy threshold & detection area



Typical image

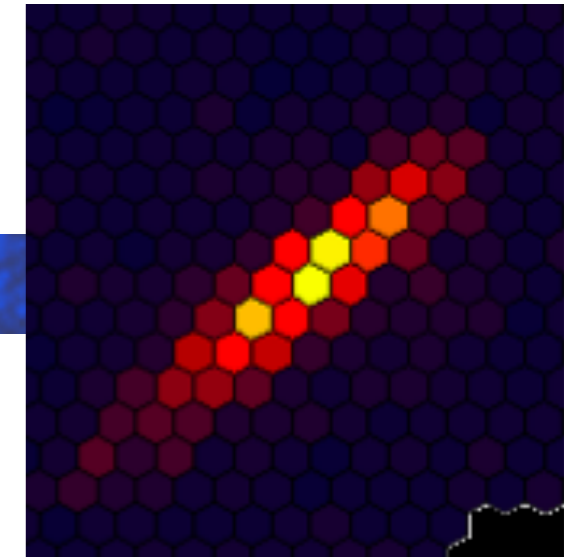
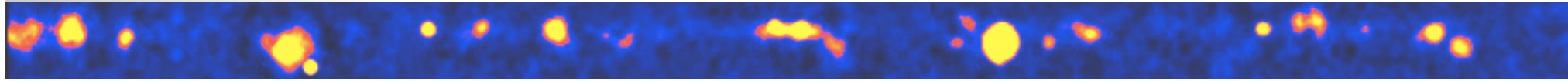


Image "length"
 \propto impact distance

15 km

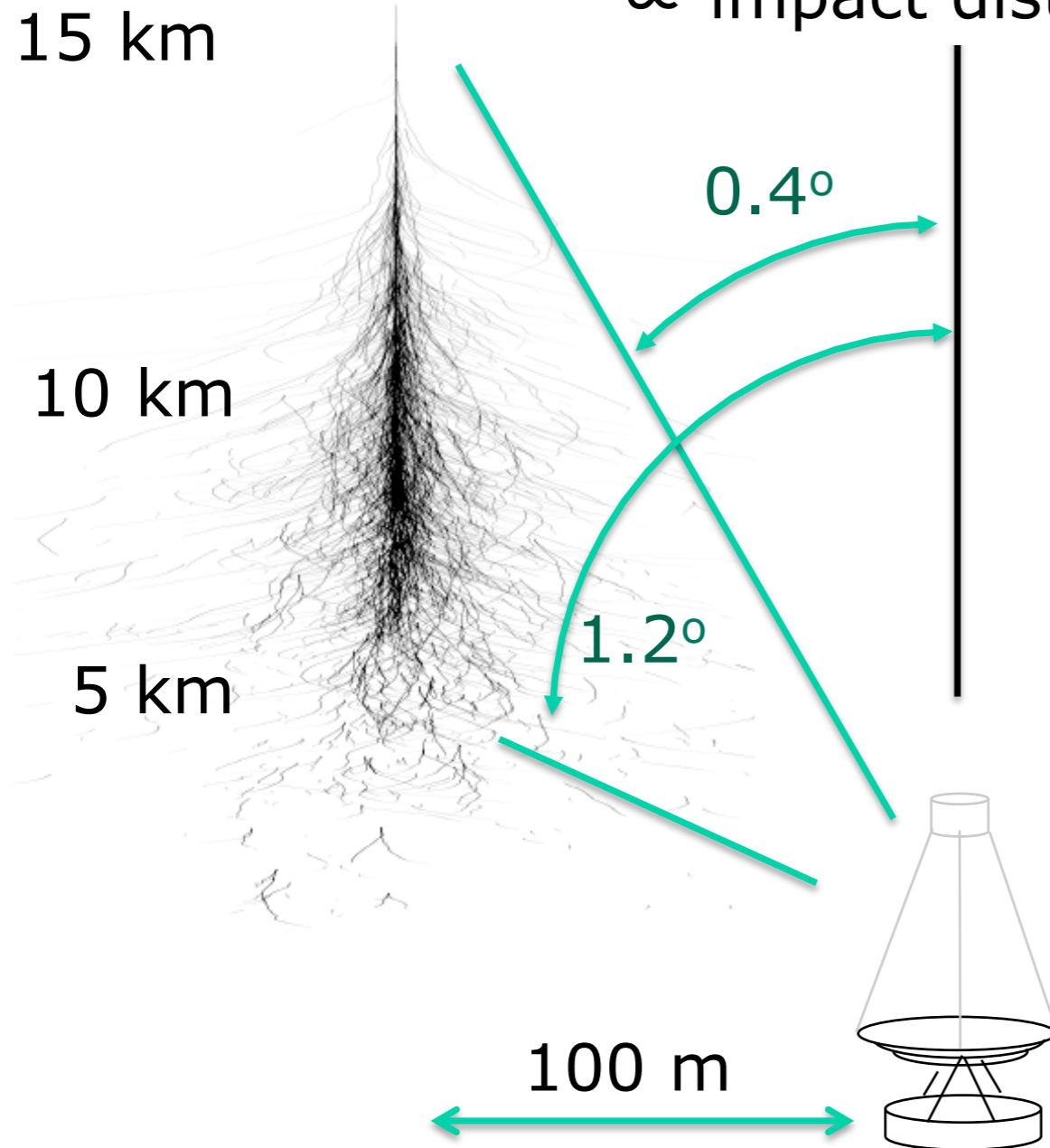
10 km

5 km

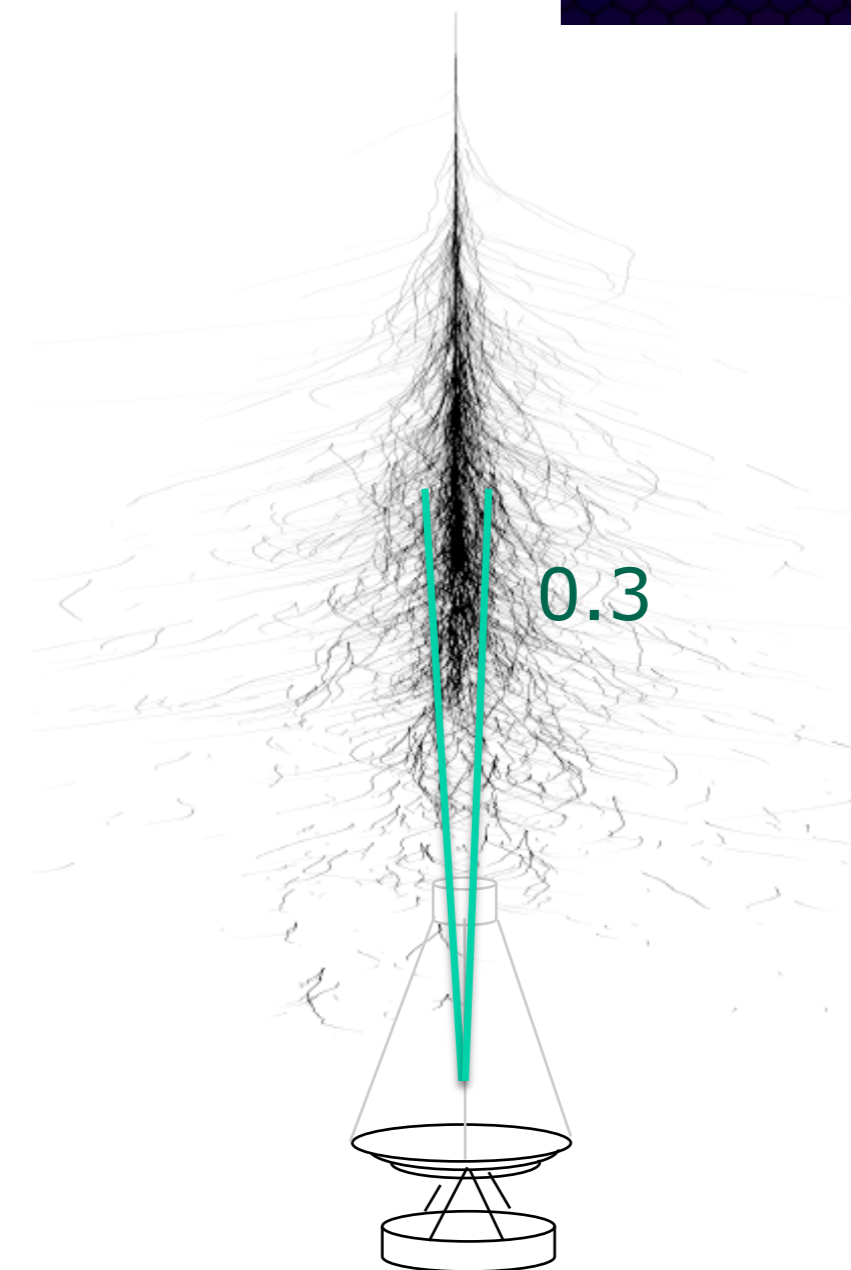
0.4°

1.2°

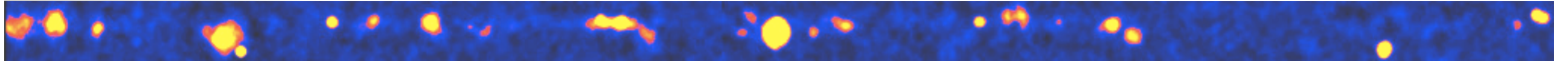
100 m



0.3



Angular resolution



governed by

shower fluctuations and multiple scattering of shower particles

(typically 1000 particles @ 1 TeV)

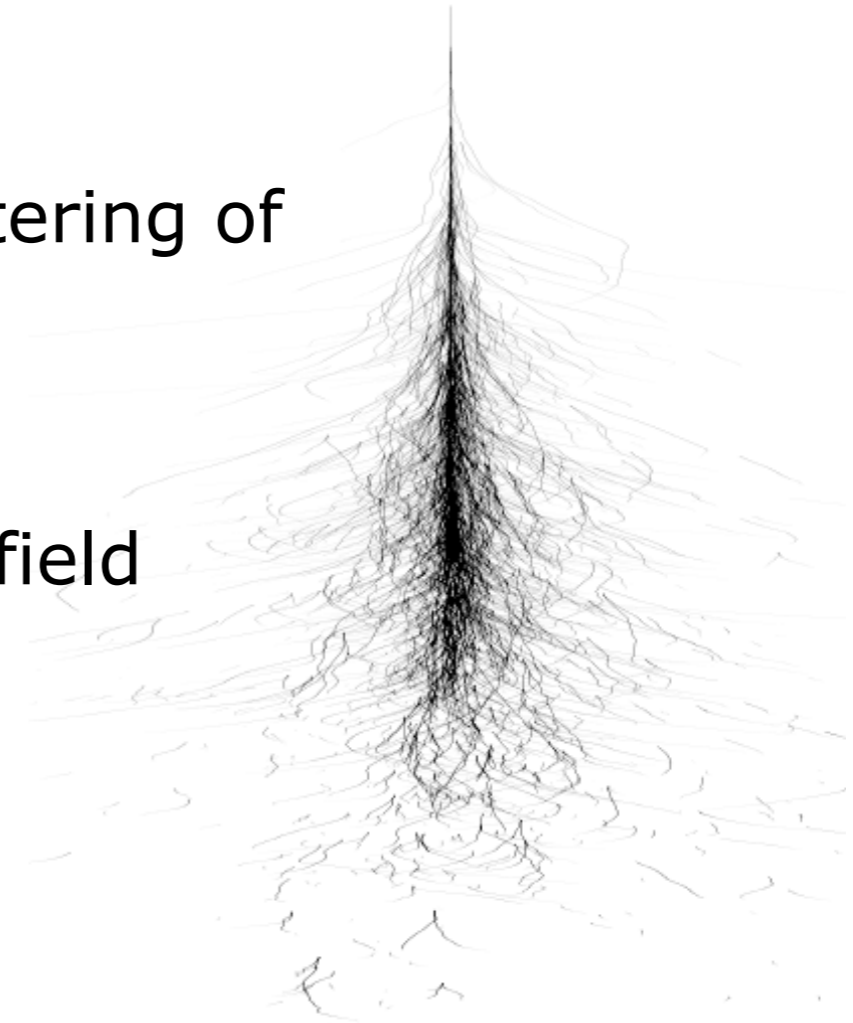
deflection of particles in Earth magn. field

photon statistics in image

(typically 100 photons)

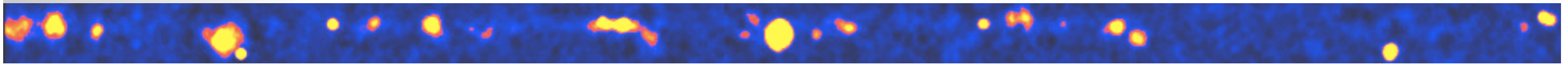
reconstruction algorithm

...



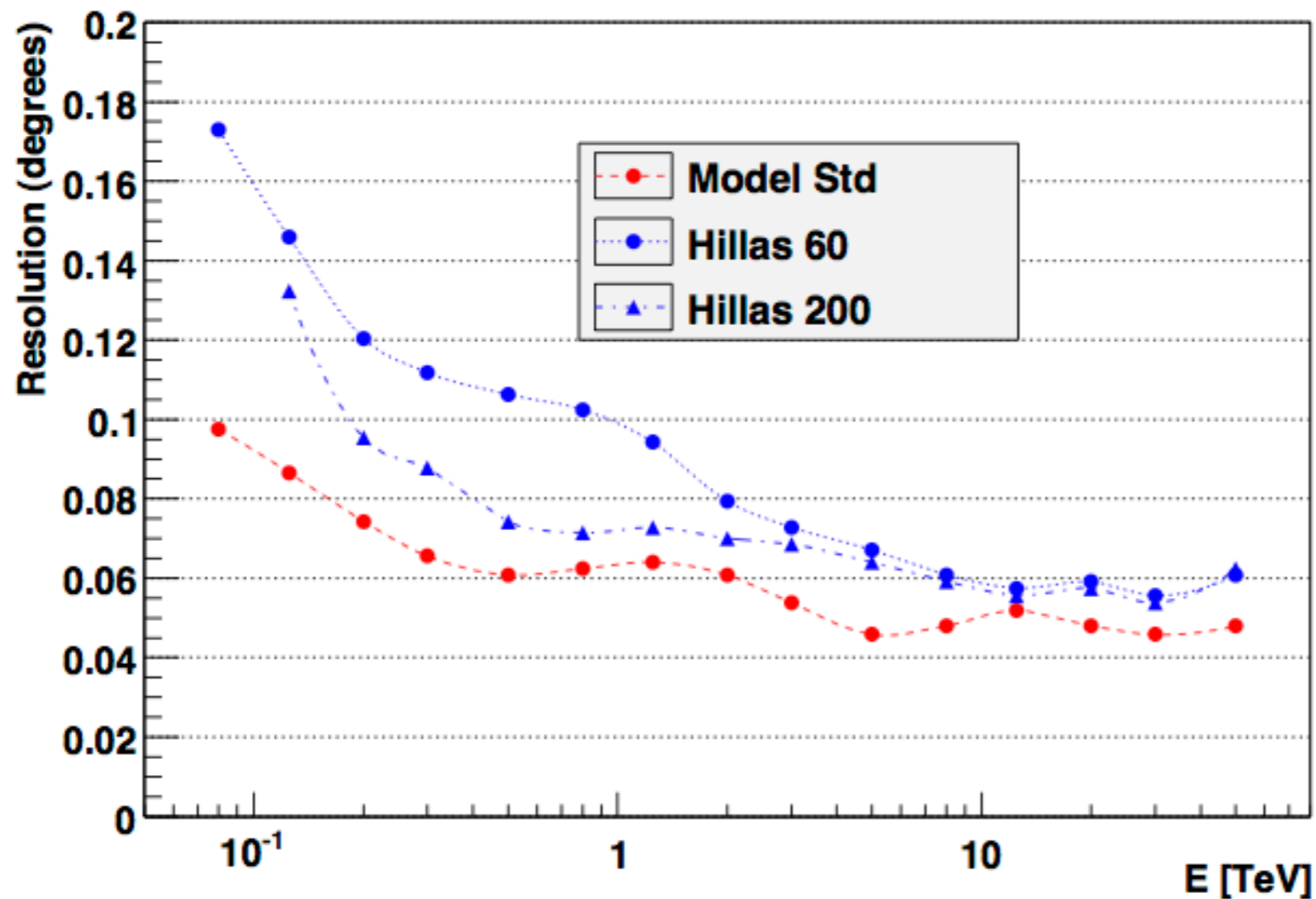
Angular resolution

...somewhat oversimplified...



Photons within the central 110 m pool scatter within $\sim 1^\circ$ from shower axis

Measure shower direction with precision $\sim \frac{1^\circ}{\sqrt{n_{ph}}} \approx 0.1^\circ$



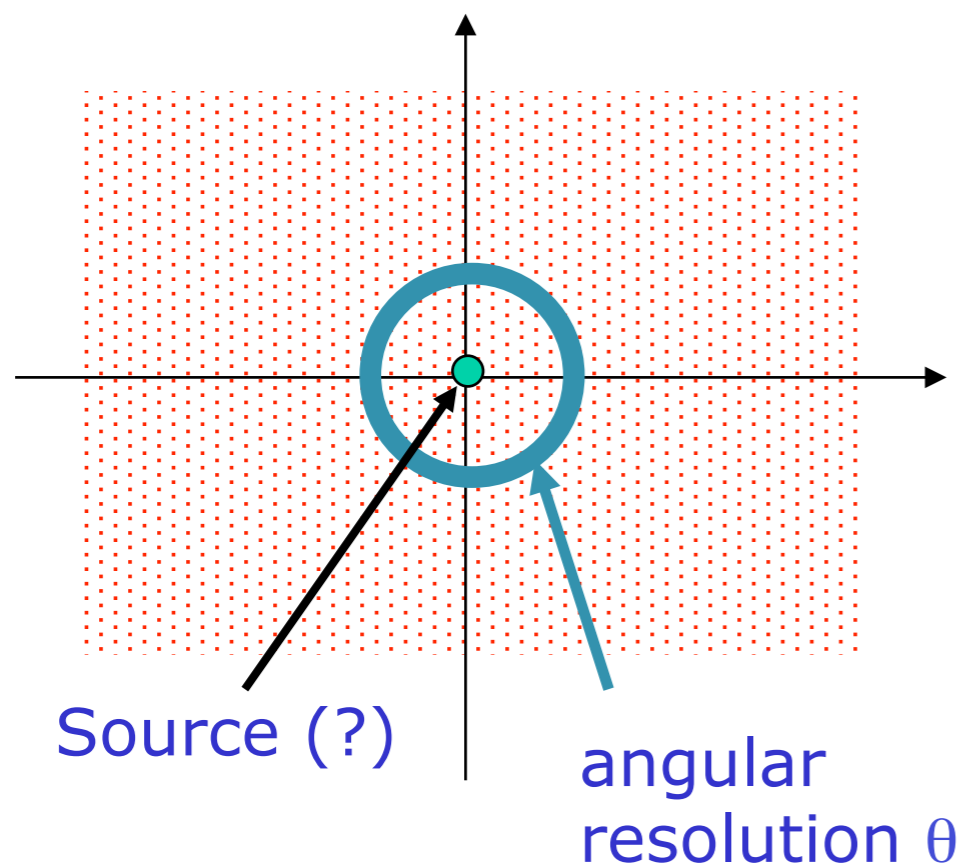
H.E.S.S.

note:
no. of detected
photons does
not increase linearly
with energy, since
showers eff. area
increases!

Sensitivity in a toy model

Ignore threshold; assume some (fixed) detection area A and observation time T

reconstructed
shower directions



of background events:

$$(dN/d\Omega dA dT)_{BG} \eta_{BG} \pi\theta^2 T A$$

of signal events:

$$(dN/dA dT)_{Sig} \eta_{Sig} T A$$

Significance \cong

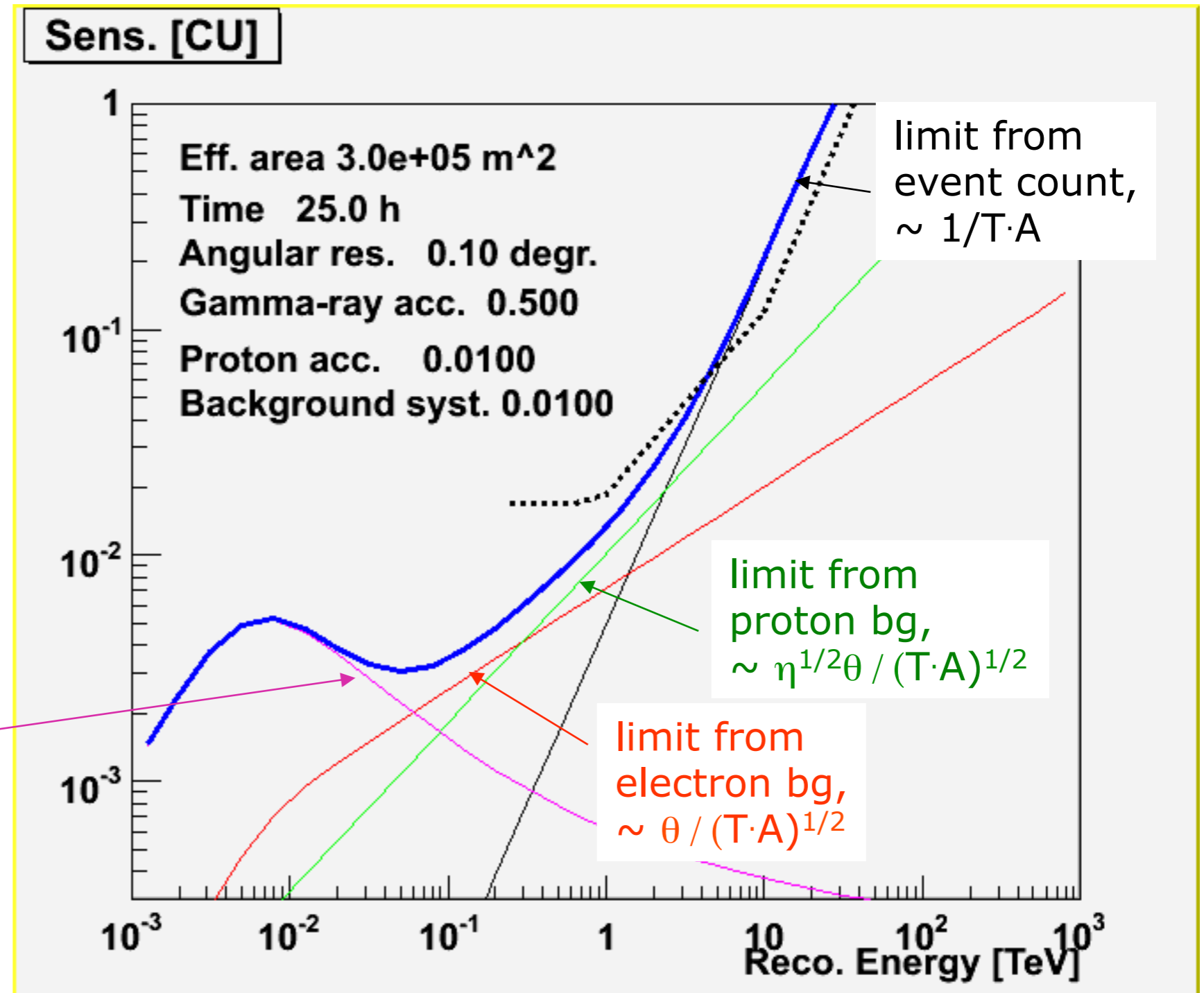
#Signal/#Background^{1/2}:

$$\sim (T A)^{1/2} \eta_{BG}^{-1/2} \theta^{-1}$$

Sensitivity in a toy model

Minimal detectable flux per band
 $\Delta \log_{10} E = 0.2$,
 relative to a power-law
 Crab spectrum

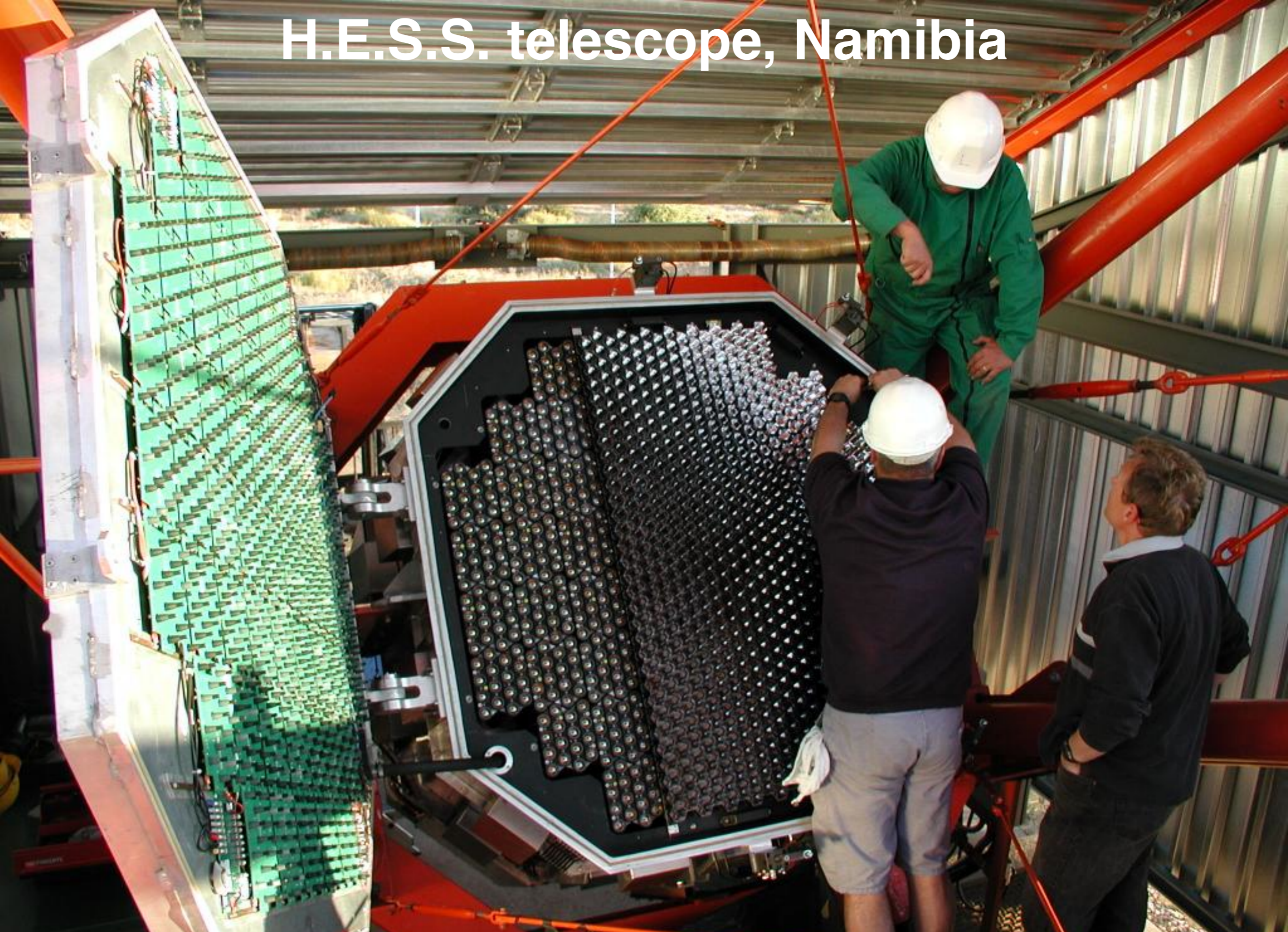
limit from
 syst. error
 on background,
 indep. of T,A;
 $\sim \theta^2$



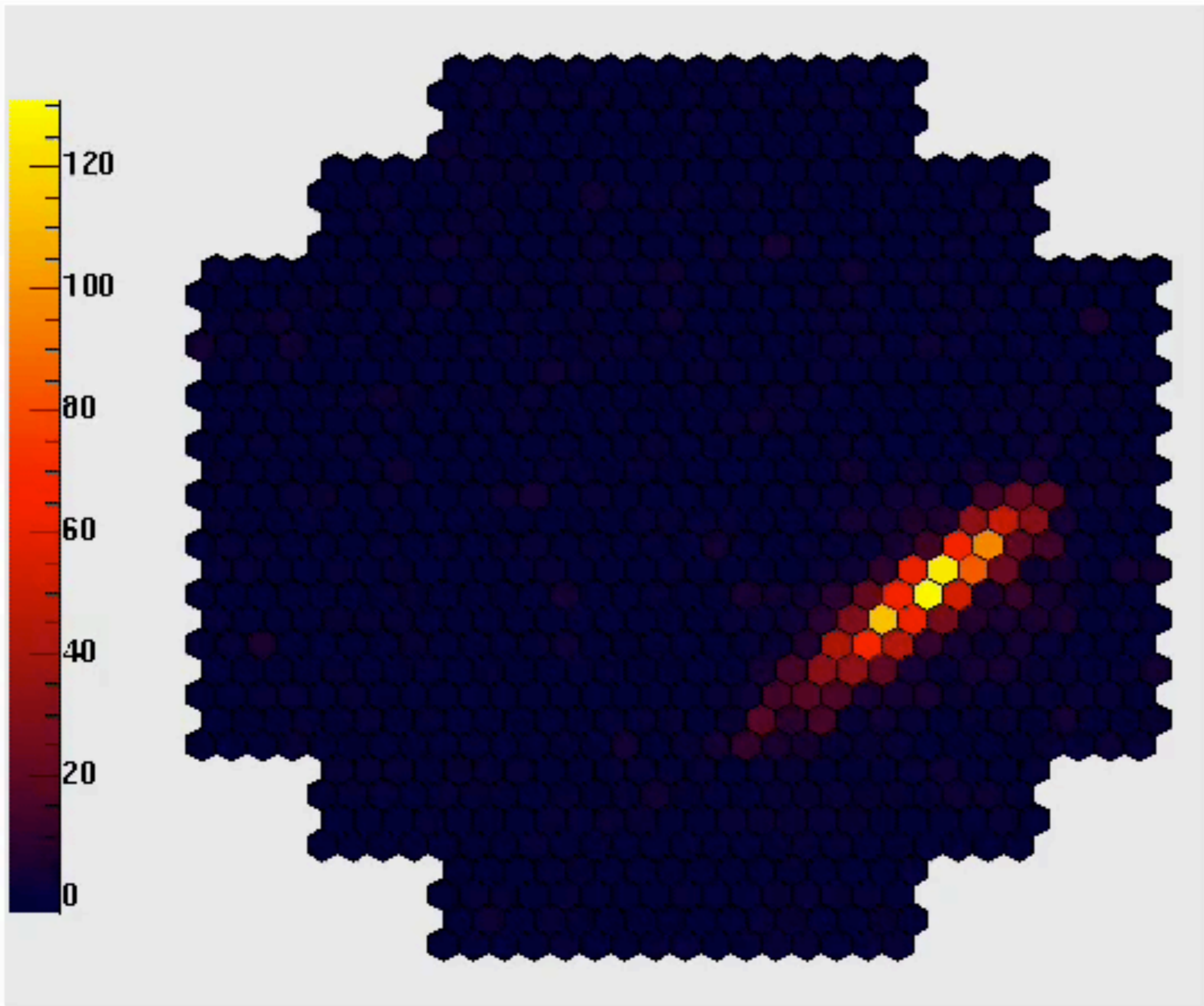
H.E.S.S. telescope, Namibia



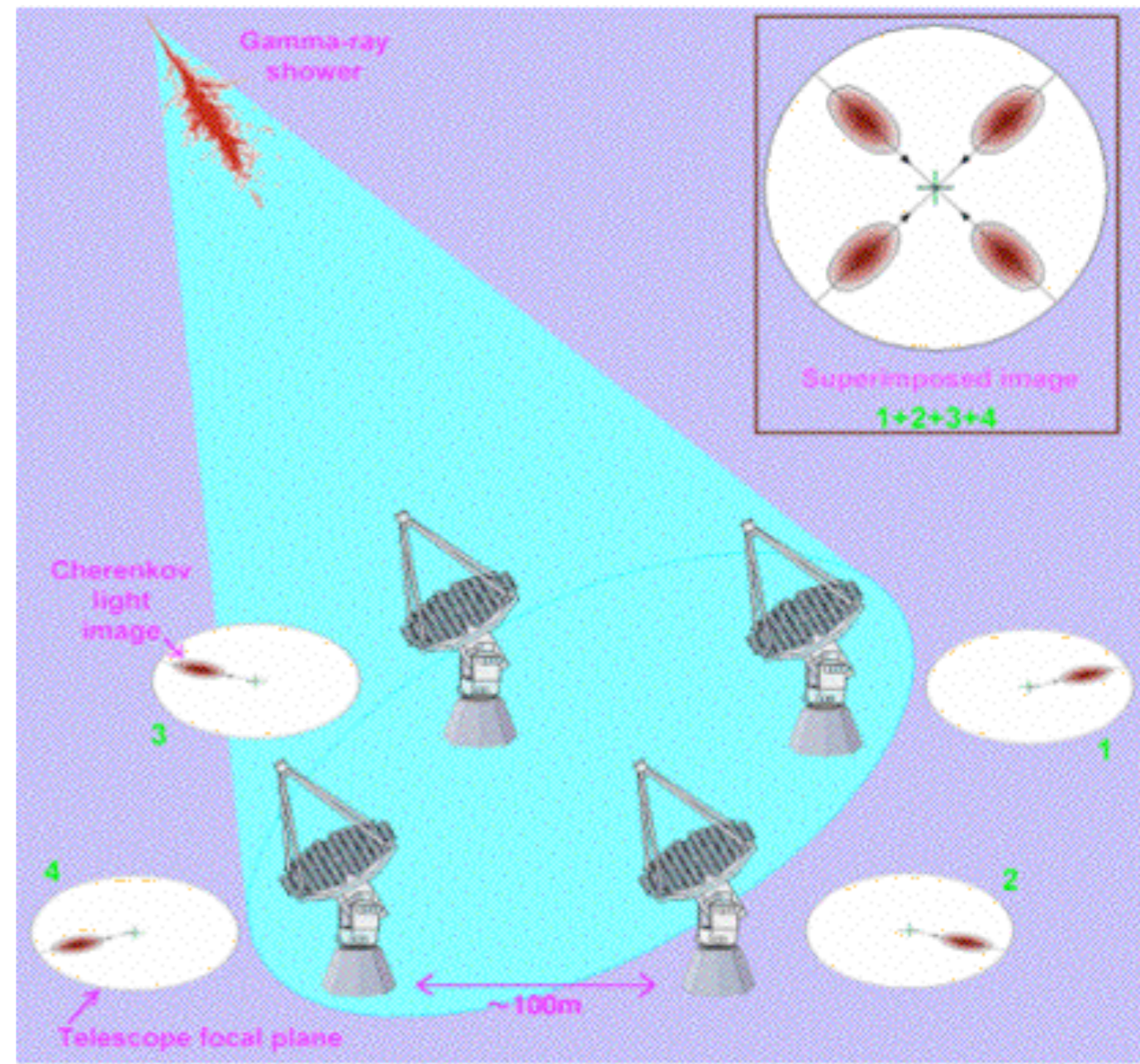
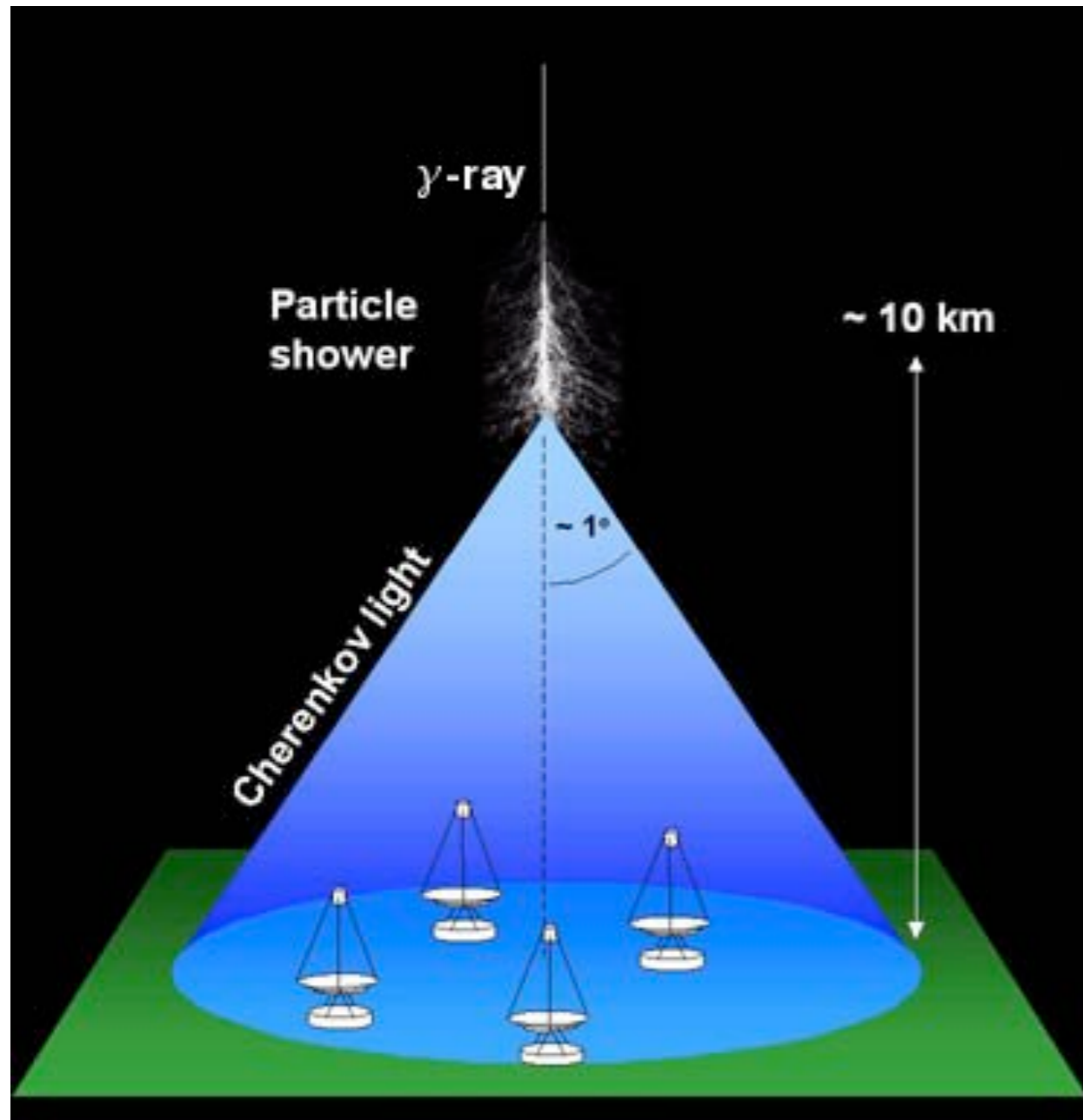
H.E.S.S. telescope, Namibia



H.E.S.S. telescope, Namibia



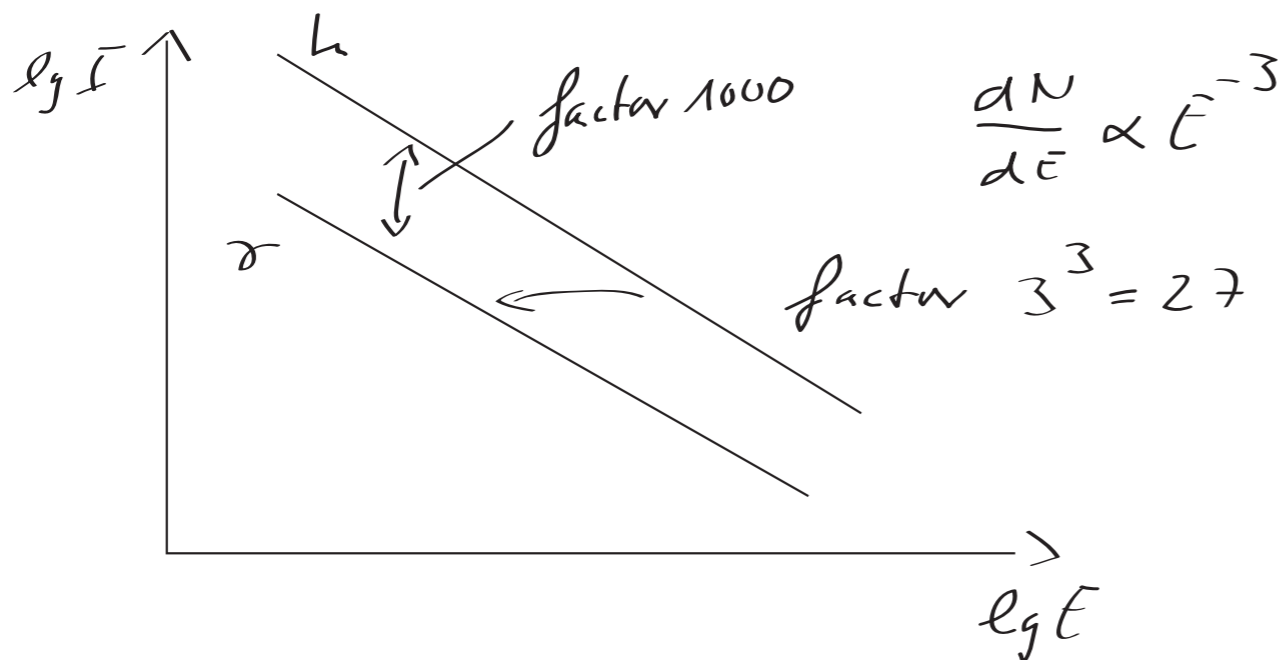
stereo observation



high background of hadronic particles

reduction through two effects:

- 1) hadronic particles produce only 1/3 Cherenkov light as photons of the same energy



hadronic particles at same number of Cherenkov photons are only $\frac{1000}{27} \approx 37$ times more abundant

- 2) pattern recognition in Cherenkov image

e/m cascades produce „smoother“ images

hadronic interaction length

vs

radiation length

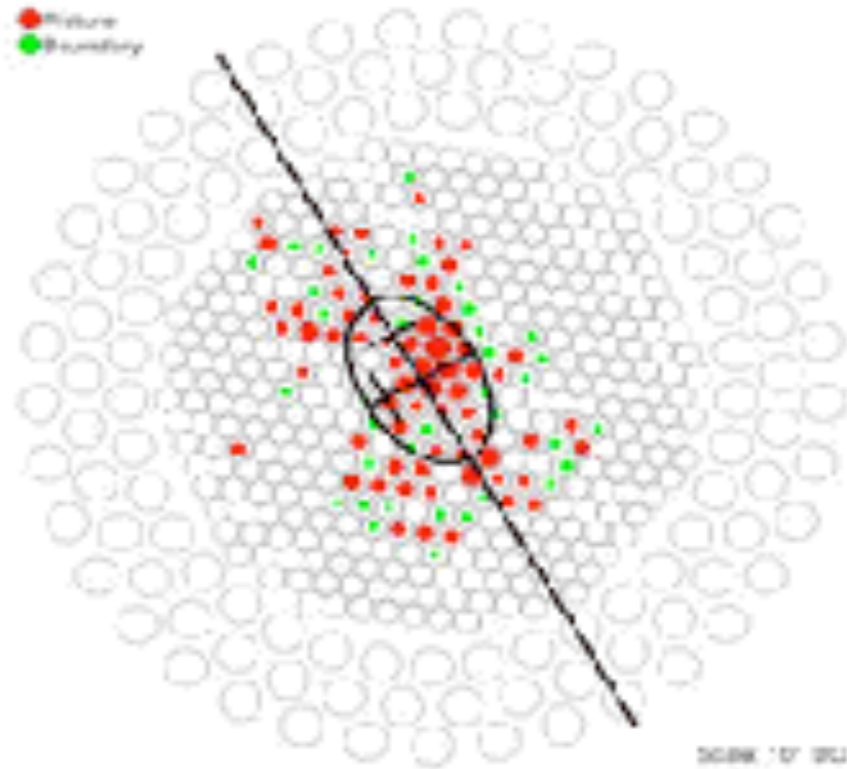
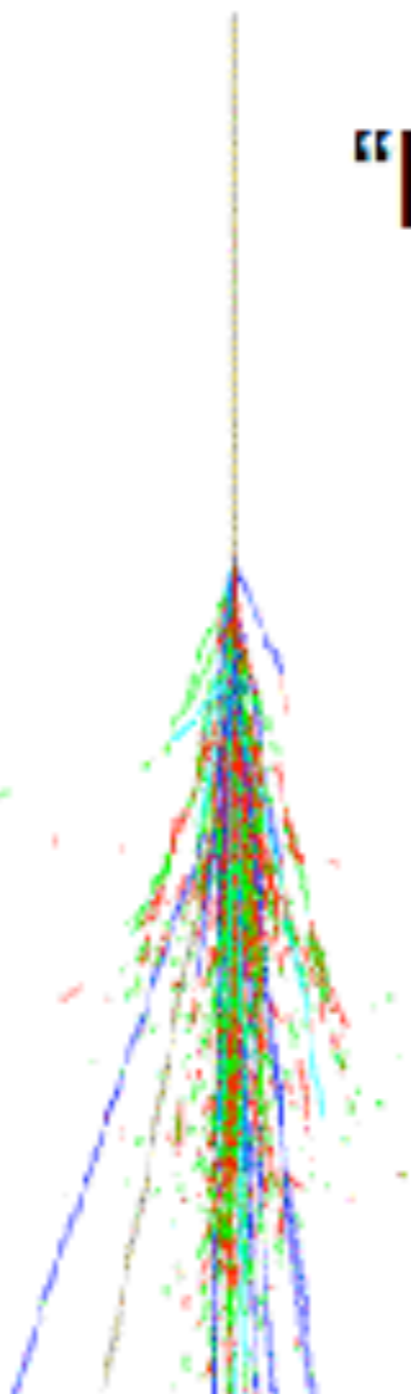
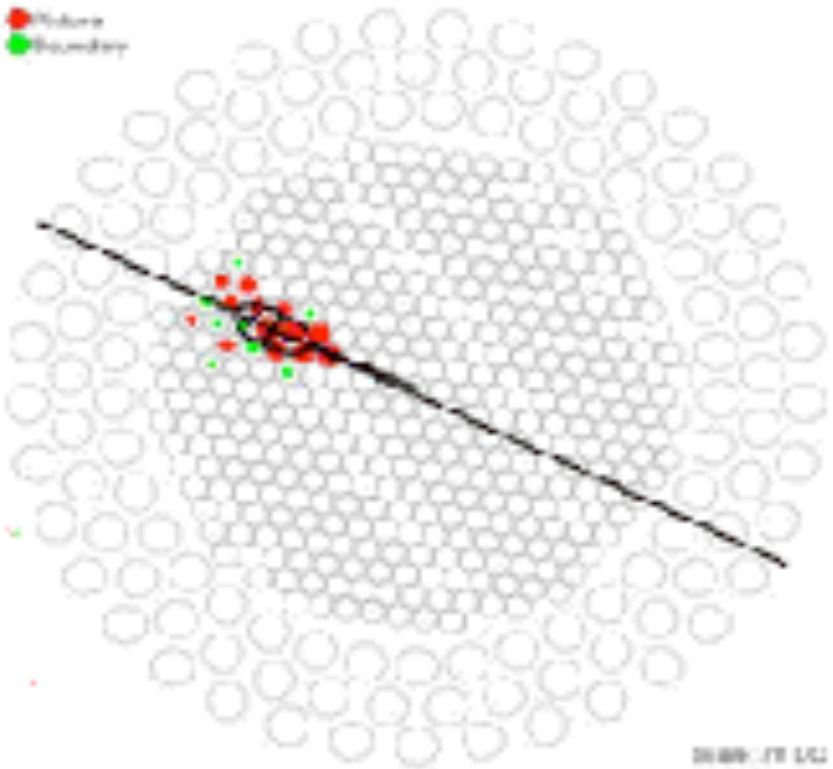
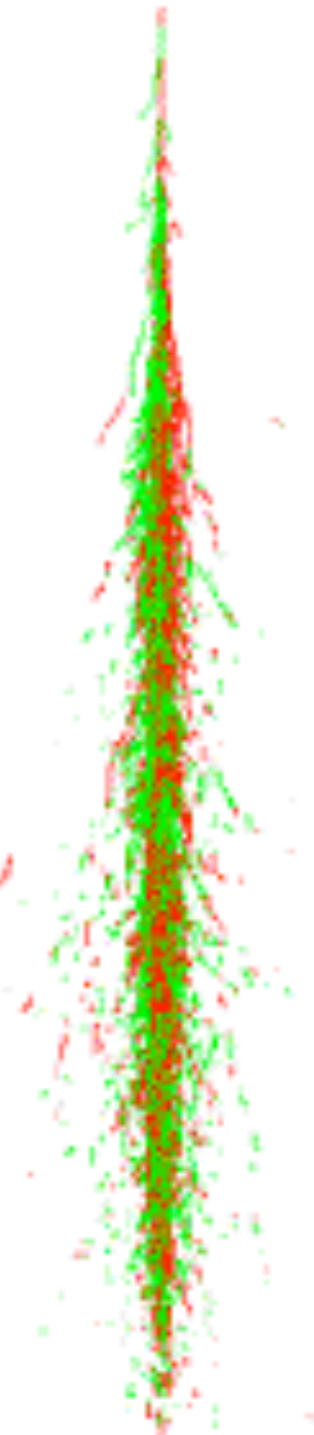
$$\lambda_I = 90 \frac{\text{g}}{\text{cm}^2}$$

$$X_0 = 36 \frac{\text{g}}{\text{cm}^2}$$

gamma-hadron separation

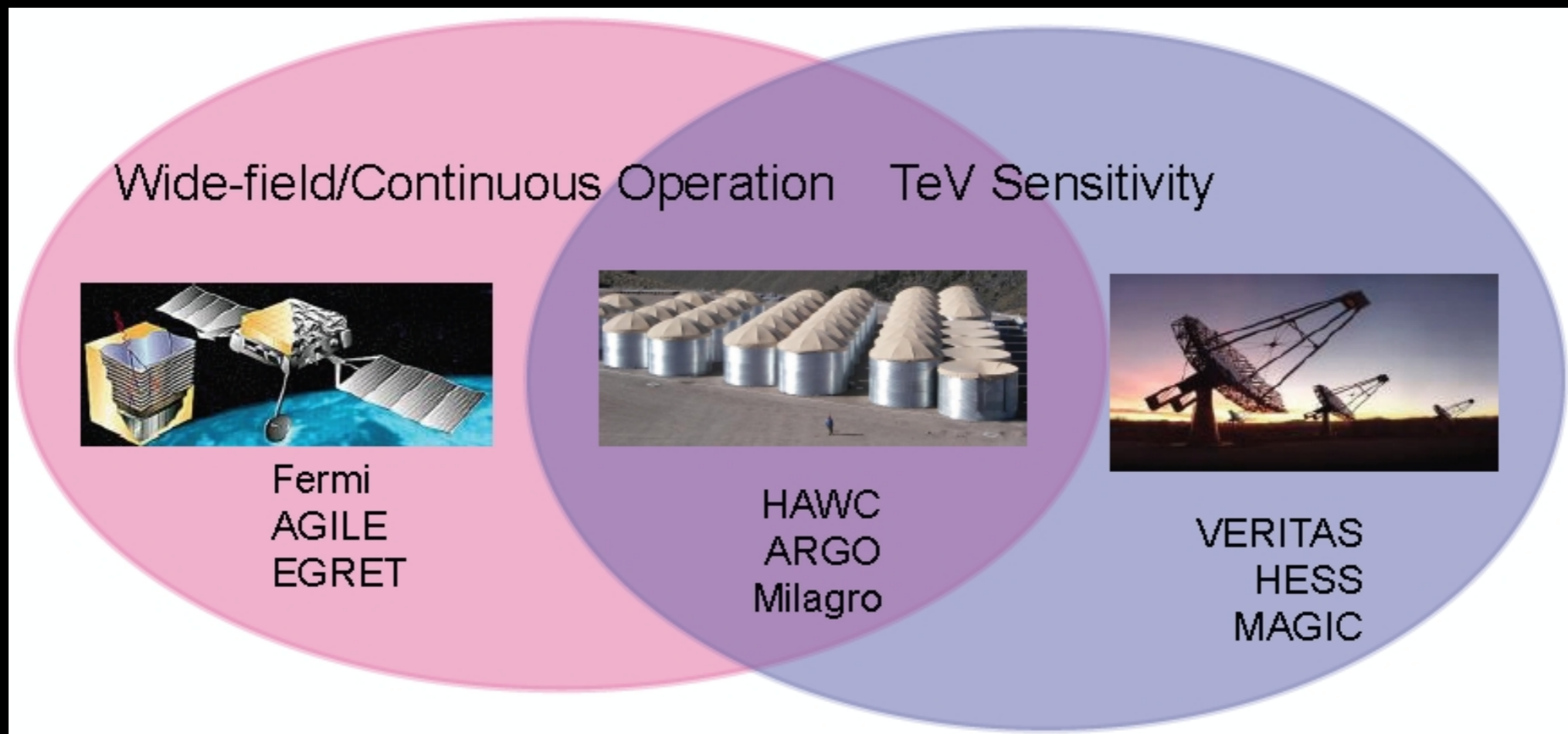
γ primary

“hadron” primary

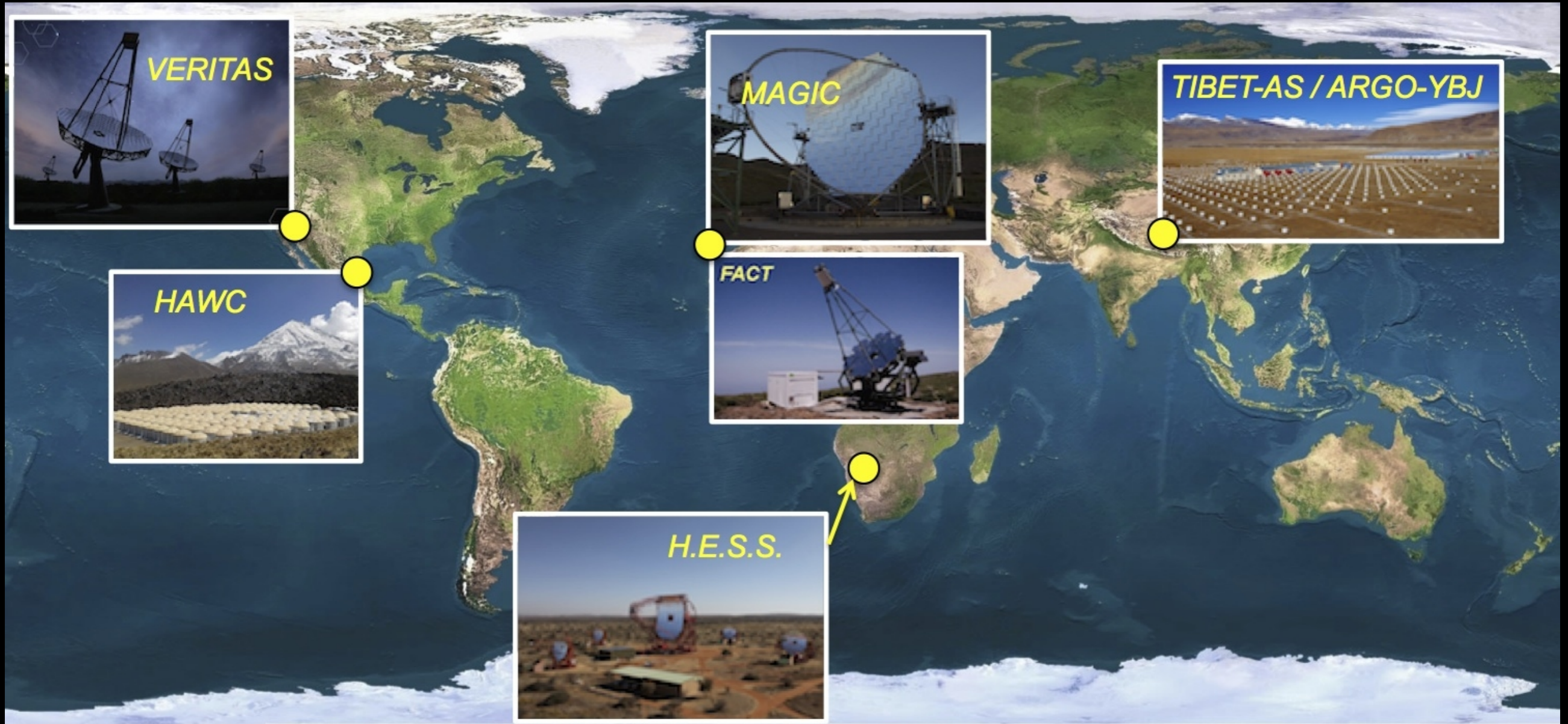


Complementarity of gamma-ray instruments

- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
 - Current Imaging Atmospheric Cherenkov Telescopes (IACTs) have excellent energy and angle resolution, but FoV of 0.003 sr and duty cycle of 10%
 - Particle detectors have an aperture > 2 sr and duty cycle of 90% but angular resolution of $\sim 0.6^\circ$ (@ 1 TeV)



INSTRUMENTS



Status of H.E.S.S. II

HESS is an array of four 12m IACTs + one 28m telescope (CT5, FoV $\sim 3.5^\circ$)

CT5 is operational since 2012

Energy range from 30 GeV to 100 TeV

Focus system of CT5 under study \Rightarrow Focusing close to the altitude of shower maximum maximizes the γ -ray acceptance close to the energy threshold

Major upgrade of HESS I camera from 2015-2016: reducing the dead time of the cameras, improving the overall performance of the array and reducing the system failure rate related to aging

62, 98, 107, 108, 1011, 1046



The Cherenkov Telescope Array (CTA)

46, 47, 58, 61, 62, 63, 65, 78, 83, 202, 204, 209, 210, 236, 249, 252, 264, 265, 274, 276, 294, 305, 318, 329, 370, 372, 395, 424, 465, 469, 506, 556, 603, 605, 610, 629, 665, 673, 674, 684, 699, 723, 736, 773, 824, 862, 882, 900, 954, 965, 1052, 1057, 1058, 1101, 1179, 1319, 1324, 1397

> 1200 members

194 Institutes from 31 countries

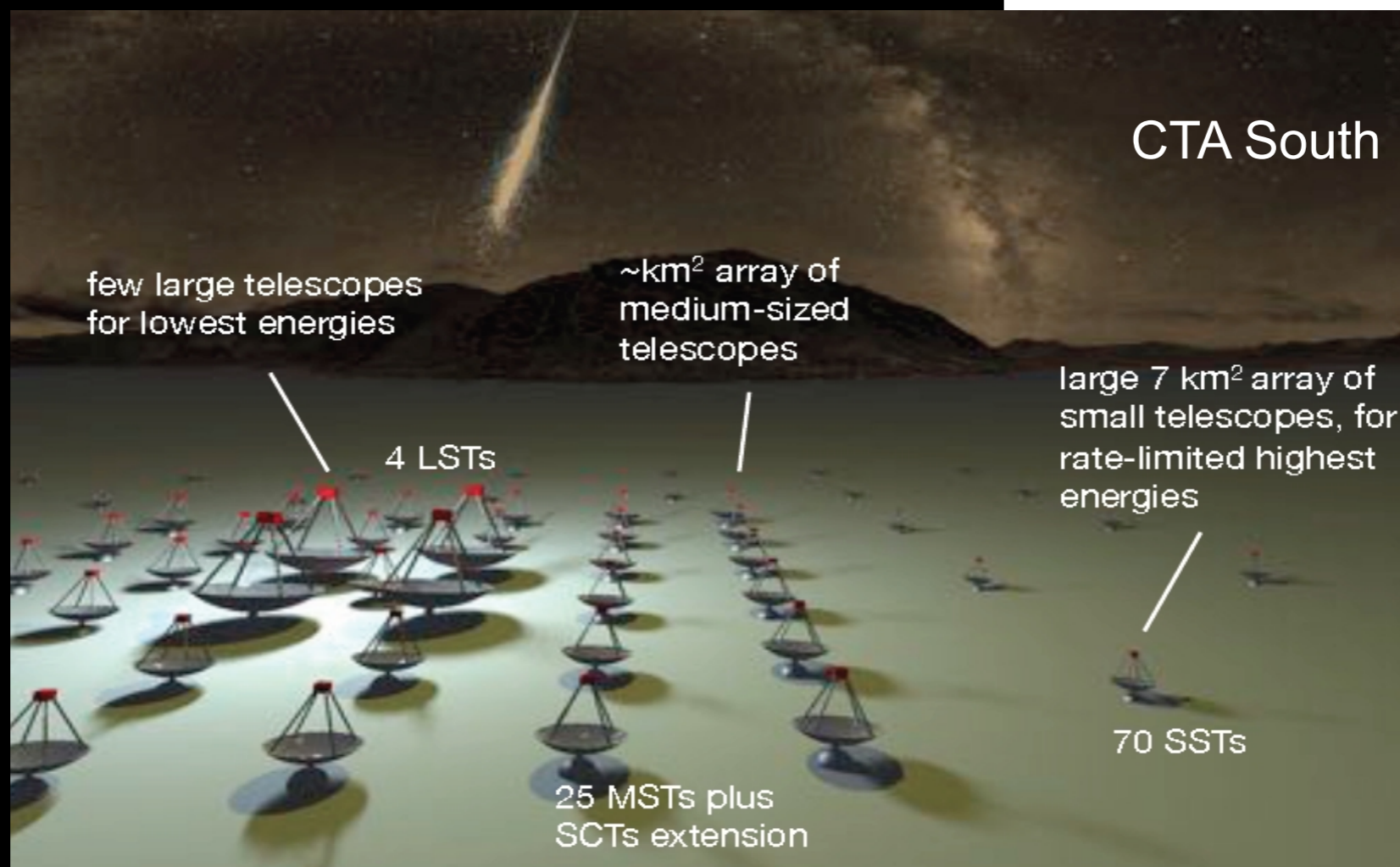
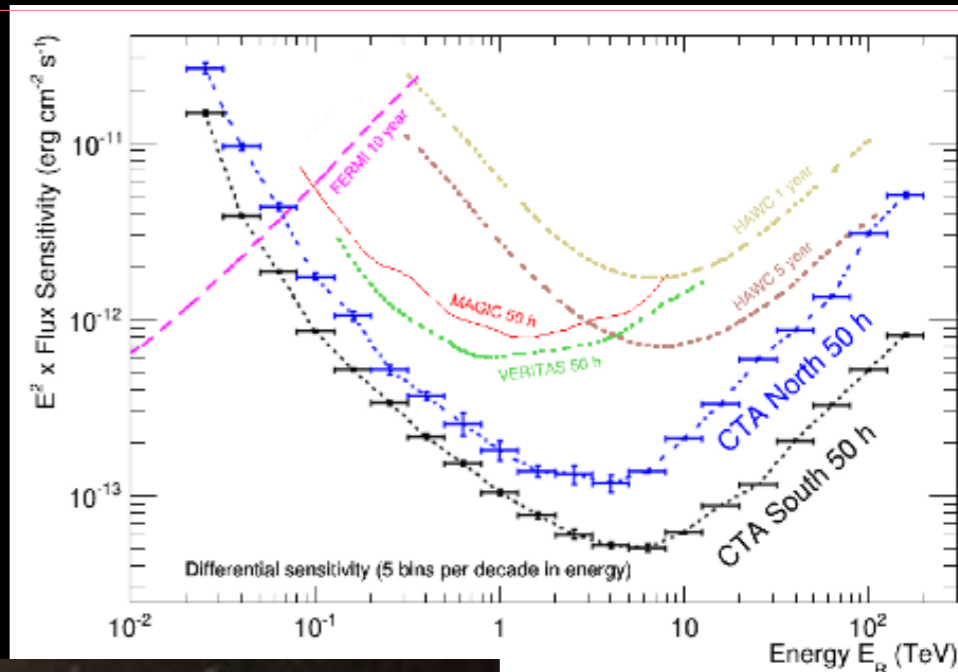
2 sites selected:

North (La Palma, Spain)

South (Paranal, Chile)

Initial construction could start in 2016

Early science: towards the end of the decade



CTA South

few large telescopes
for lowest energies

~km² array of
medium-sized
telescopes

4 LSTs

large 7 km² array of
small telescopes, for
rate-limited highest
energies

70 SSTs

25 MSTs plus
SCTs extension

