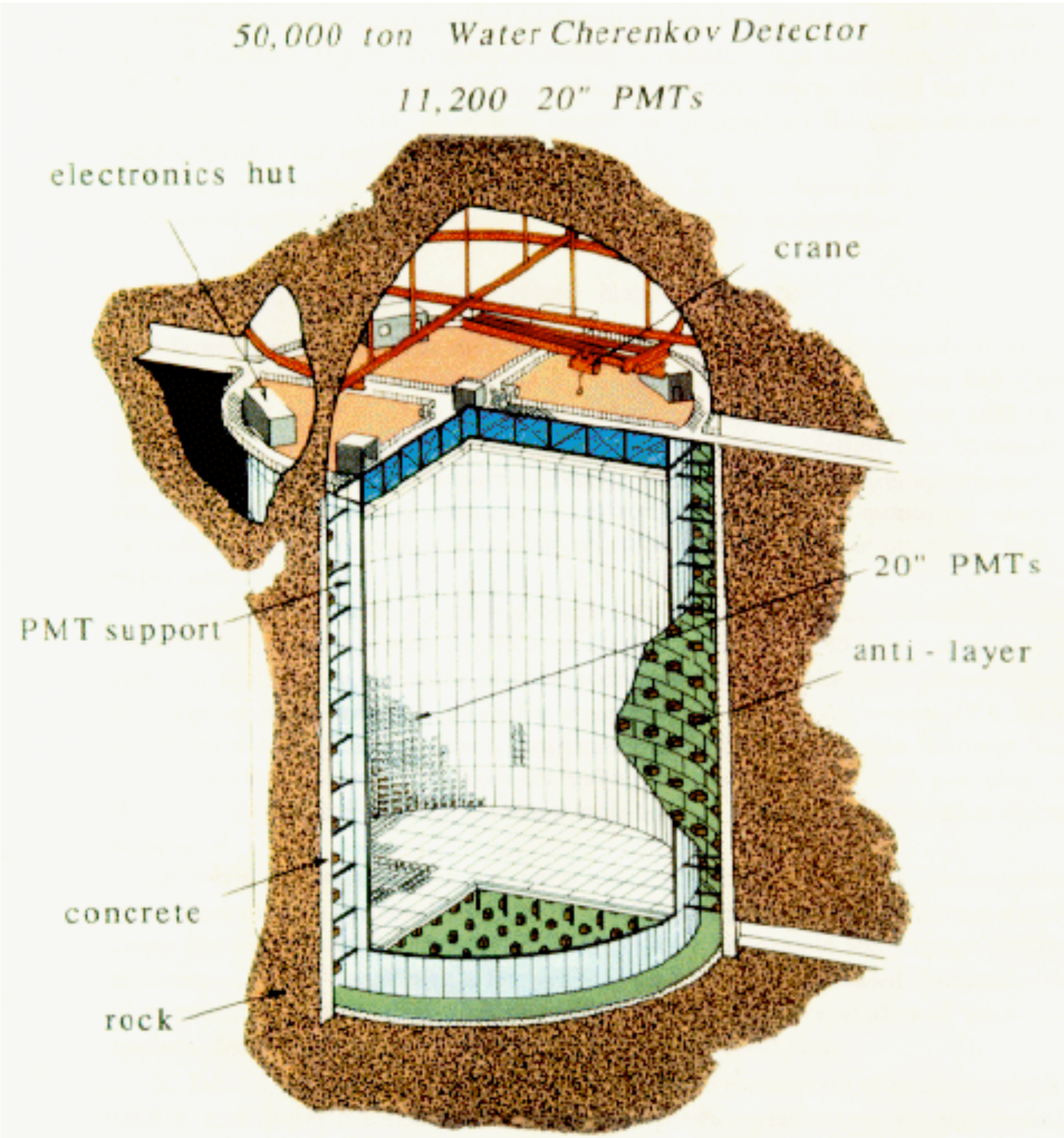
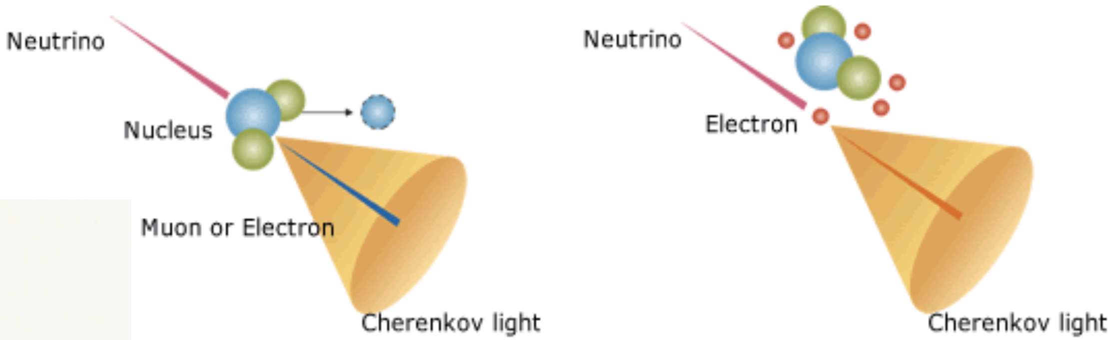
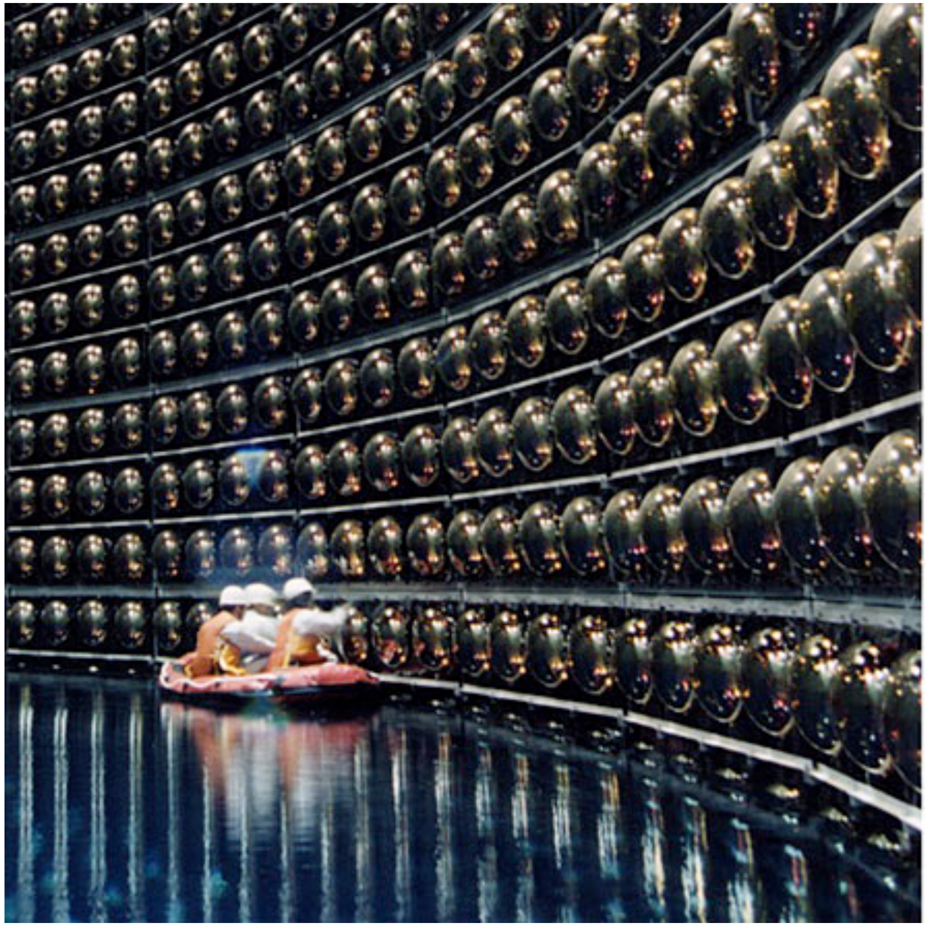
Cherenkov Detectors
for
MeV neutrino detection
supernovae/solar

Super-Kamiokande neutrino detector





The generated charged particle emits the Cherenkov light.



Neutrino scattering

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

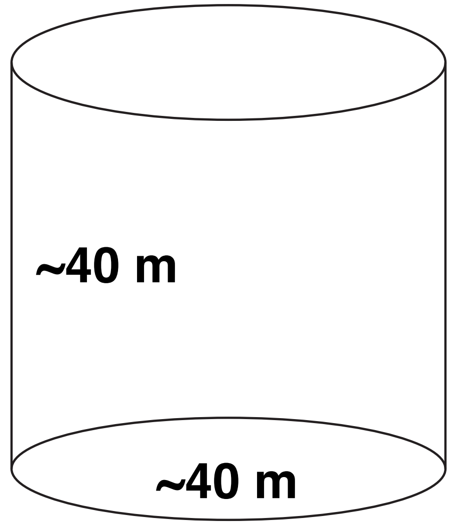
scattered electron carries large fraction of neutrino energy and moves in direction close to initial direction of neutrino

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

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

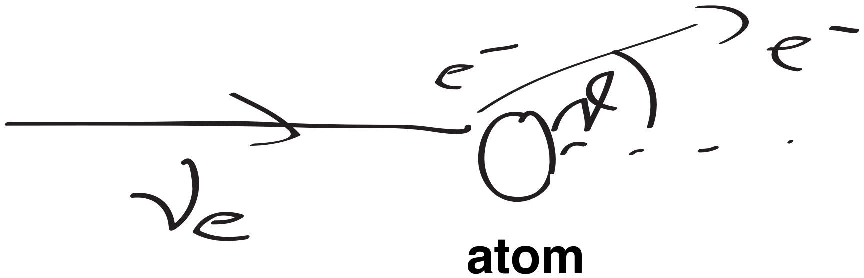
—> ~13 neutrinos/day from Sun

~30 t typical size of a neutrino detector



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

method: neutrino-electron scattering



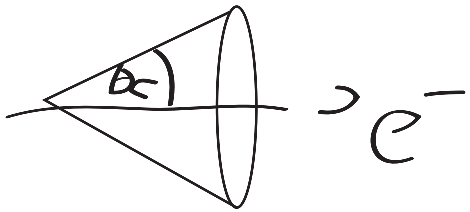
$$\sigma_{\nu e} \approx 10^{-43}\ \mathrm{cm}^2 \left(\frac{E_\nu}{10\ \mathrm{MeV}}\right)$$

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

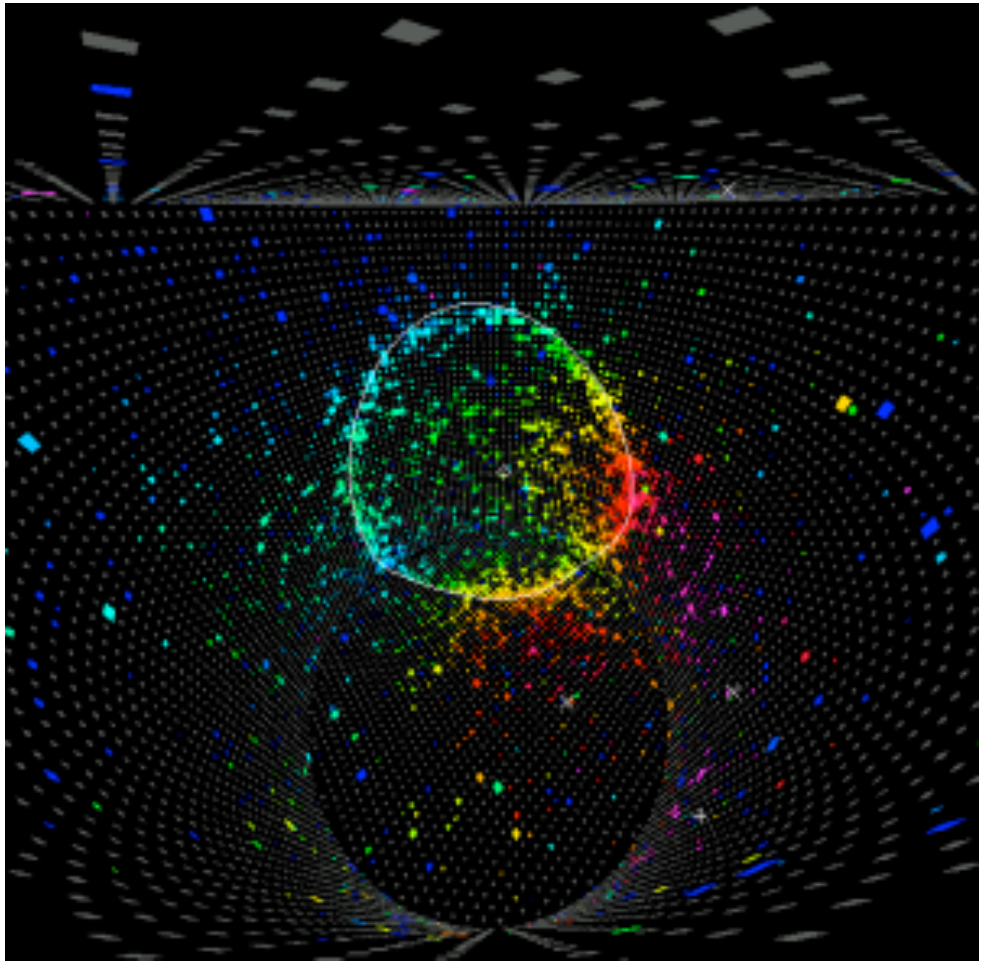
$$\cos\Theta_c = \frac{1}{\beta n} \quad \mathrm{H_2O} : n = 1.33 \Rightarrow \Theta_c = 42^\circ$$



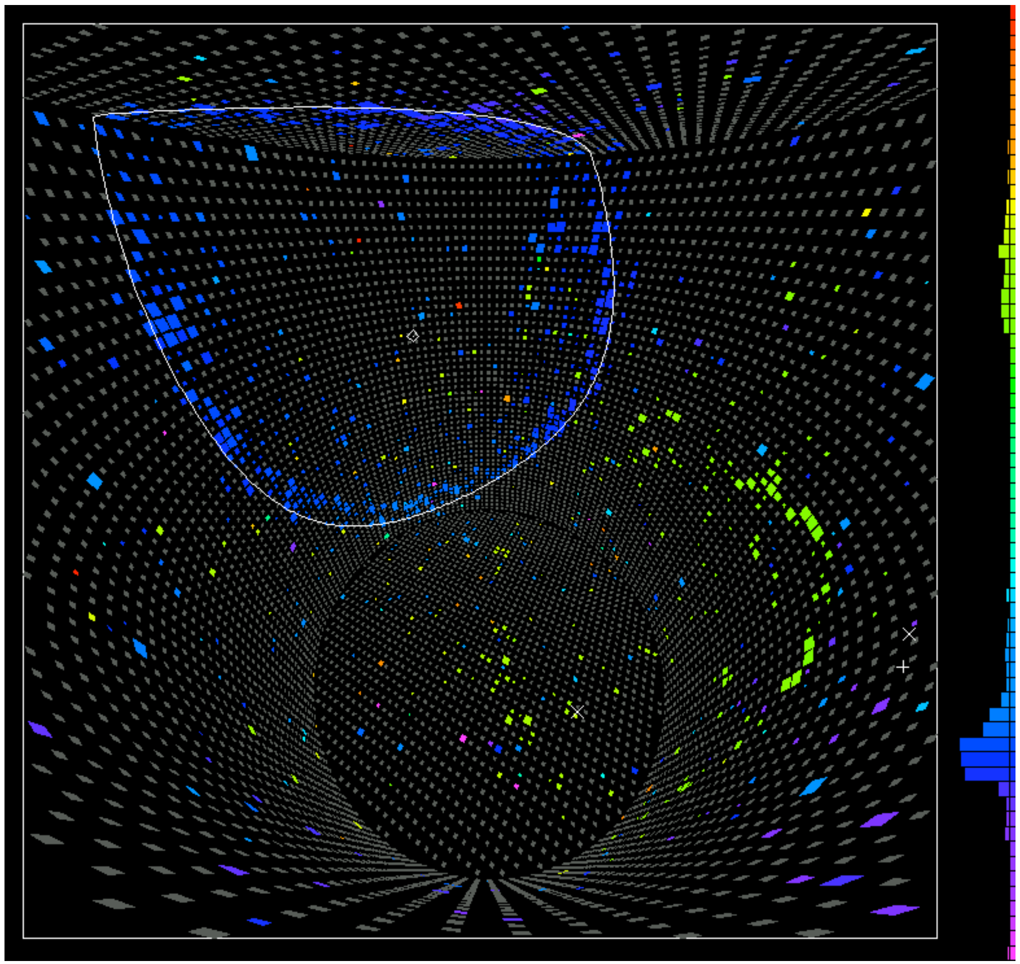
threshold $E_\nu > 7.5\ \mathrm{MeV}$

Super Kamiokande

electron



muon



Super Kamiokande

sun in neutrino „light“

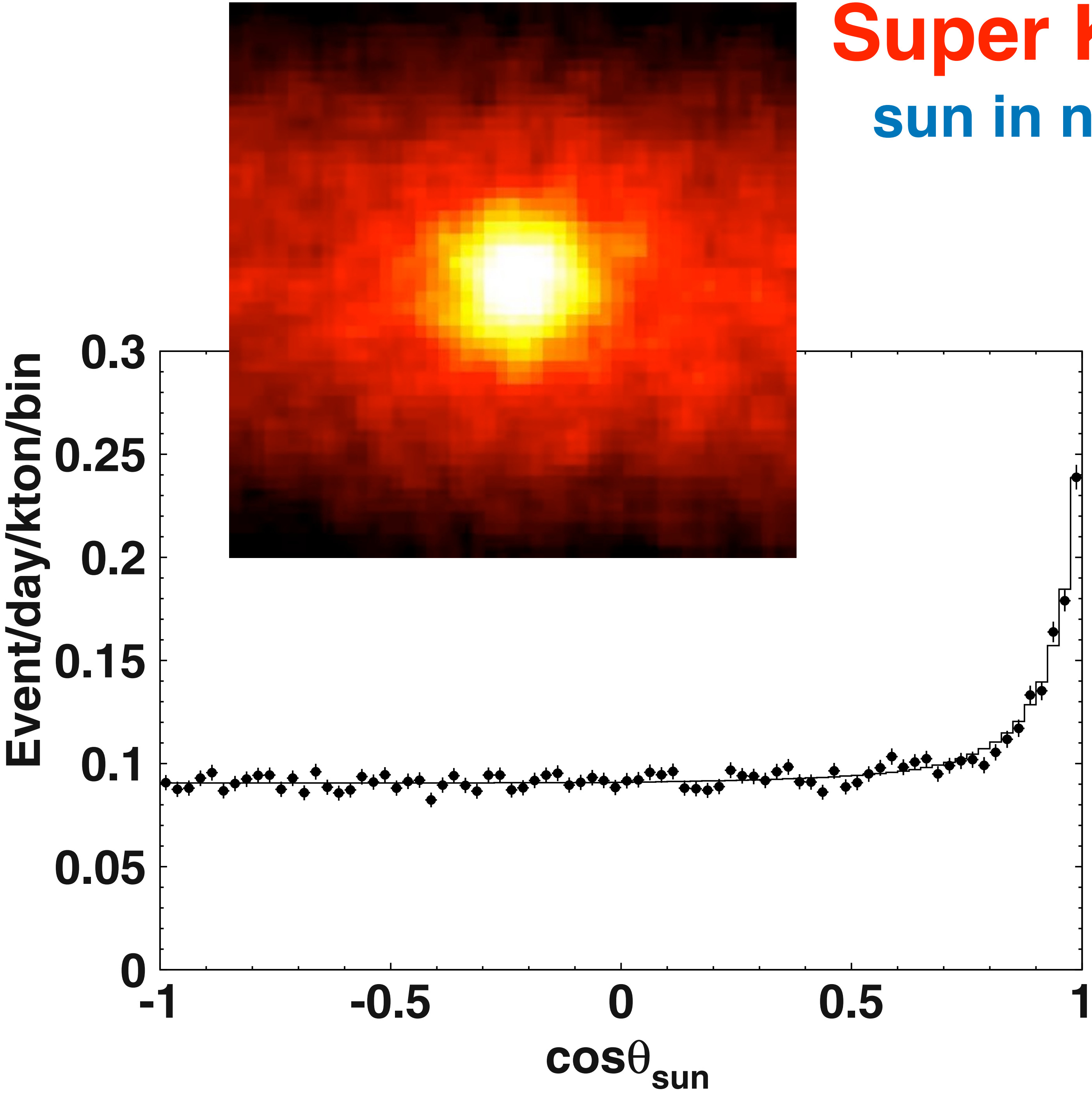
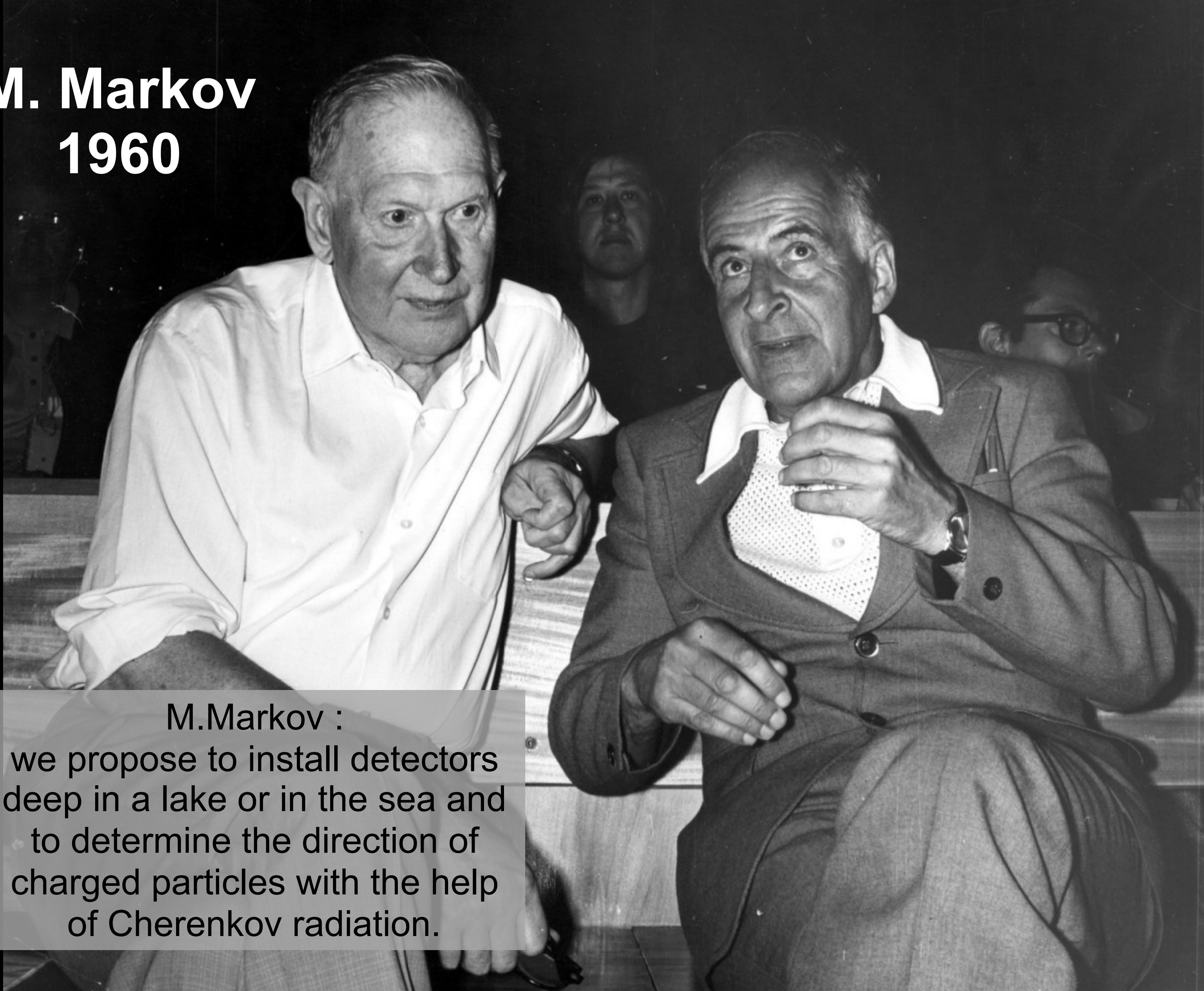


Fig. 3.1. Angular distribution of Super-Kamiokande neutrino events with respect to the direction of the Sun at the time of detection.

Cherenkov Detectors
for
Neutrino Astronomy

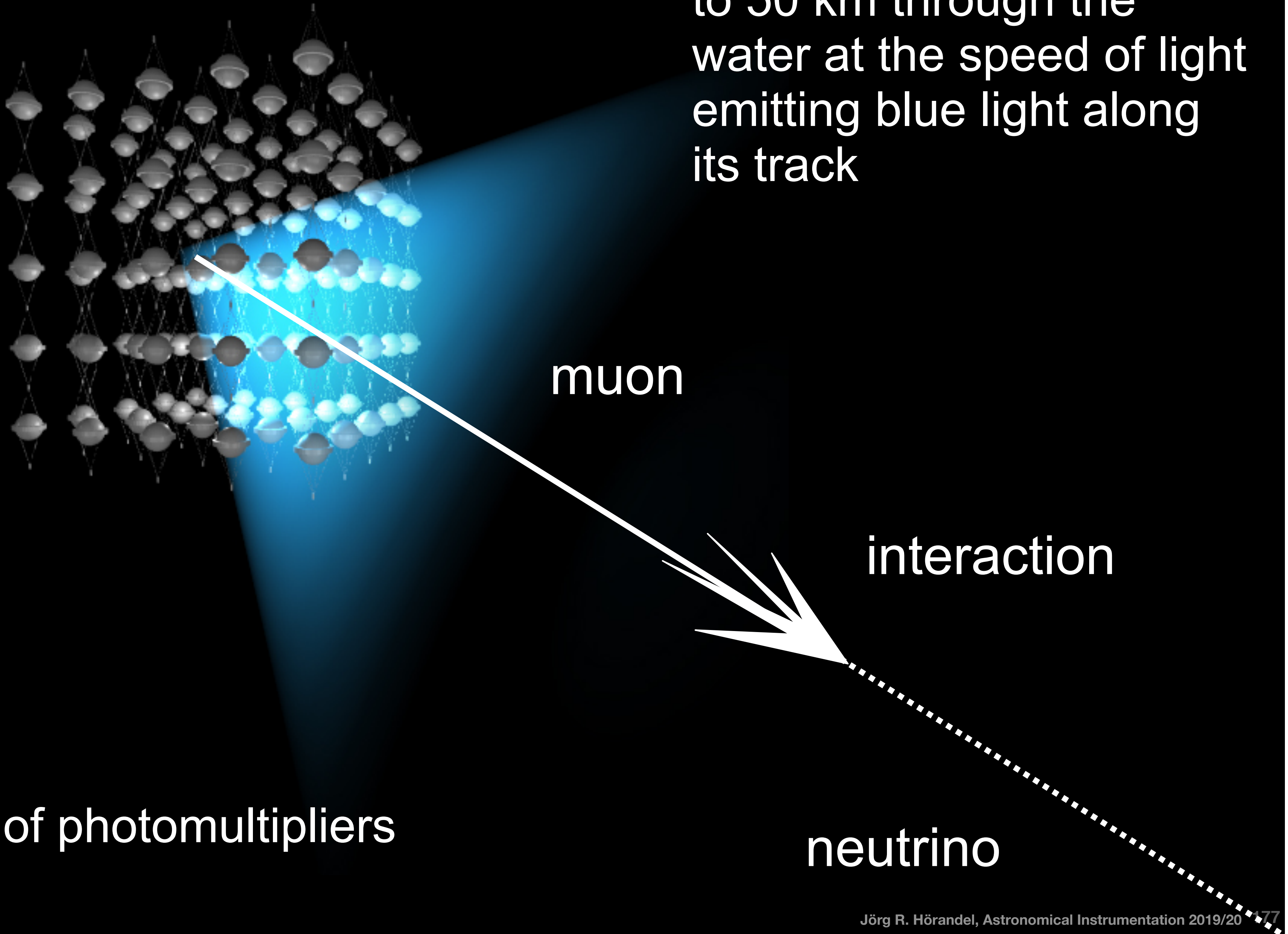
following a lecture from Francis Halzen

M. Markov
1960



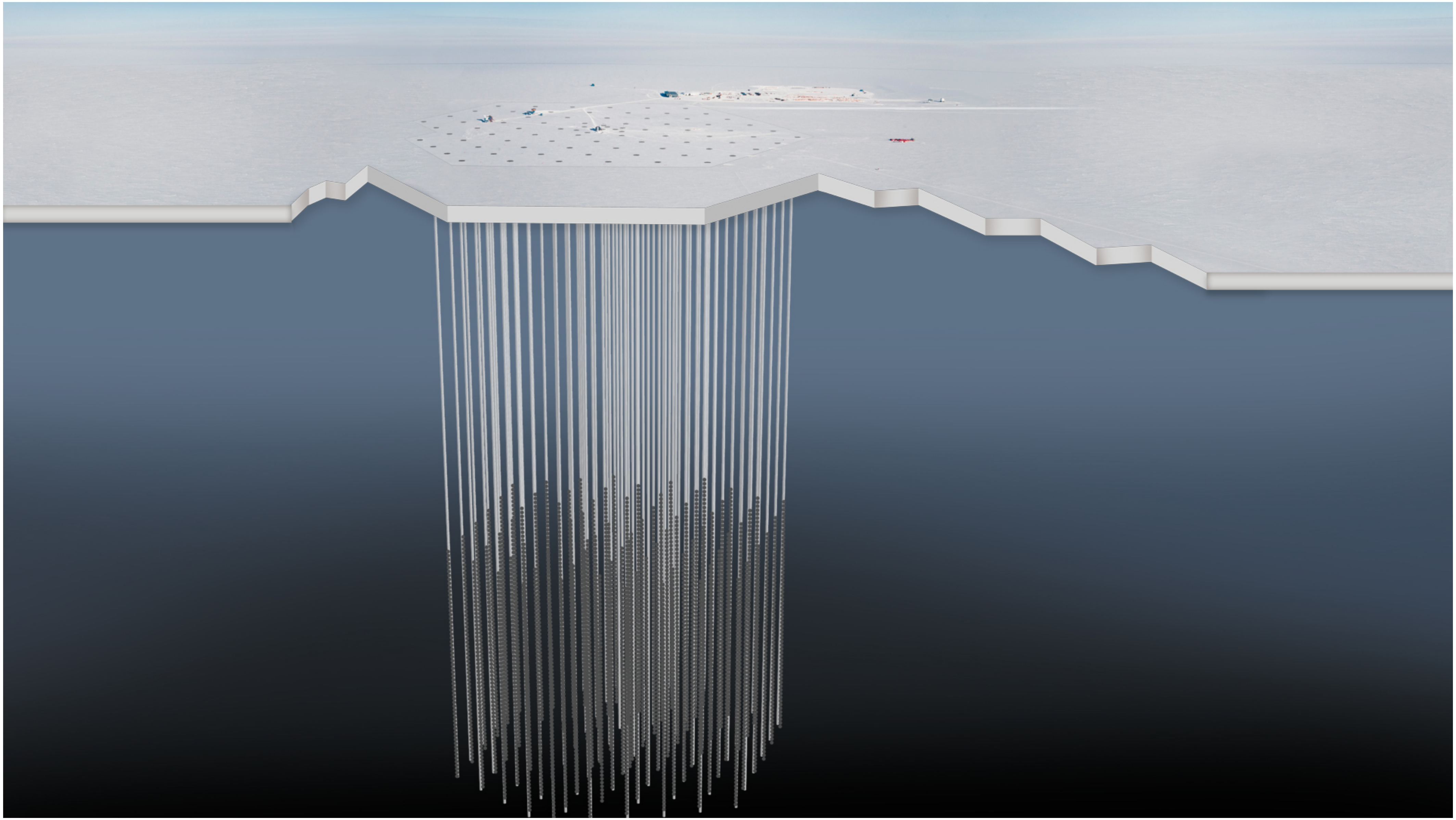
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

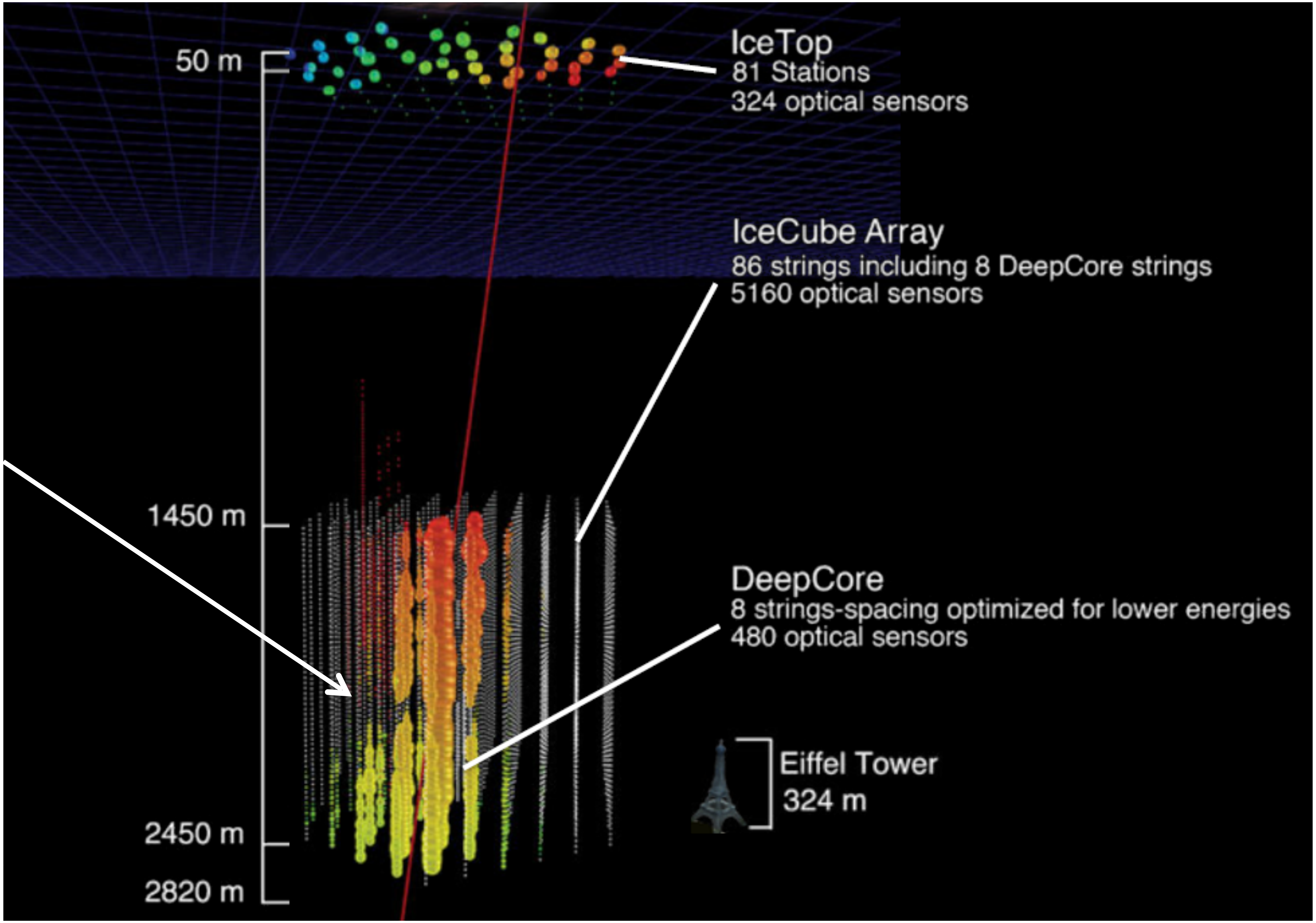
- speed of light in water < c
- muon travels from 50 m to 50 km through the water at the speed of light emitting blue light along its track



- lattice of photomultipliers

ultra-transparent ice below 1.5 km

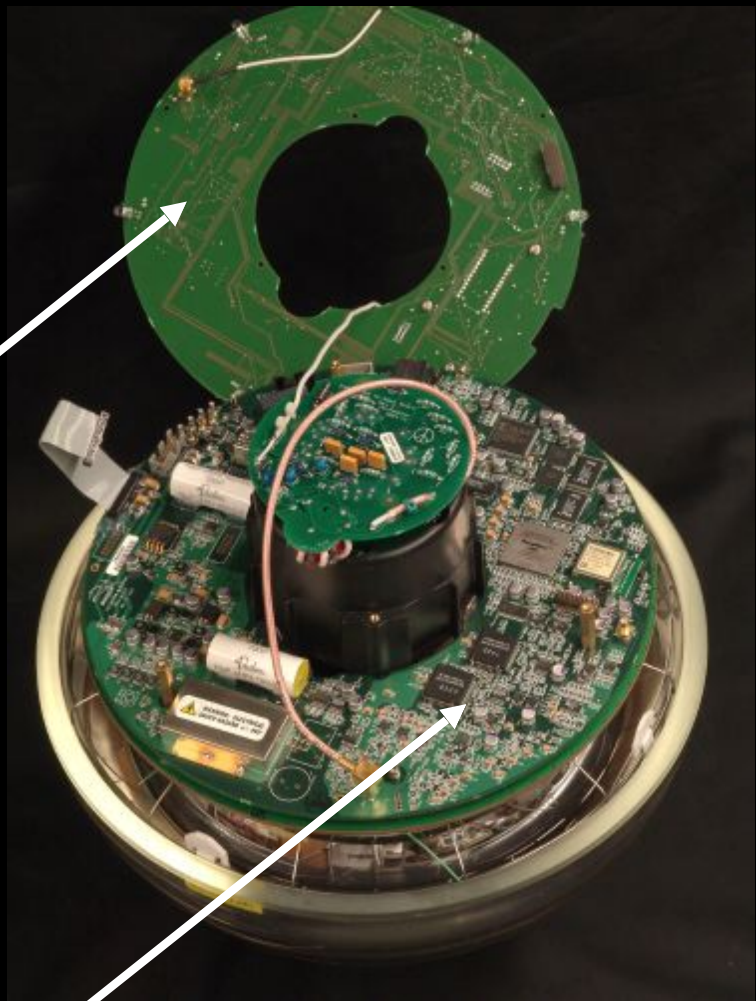




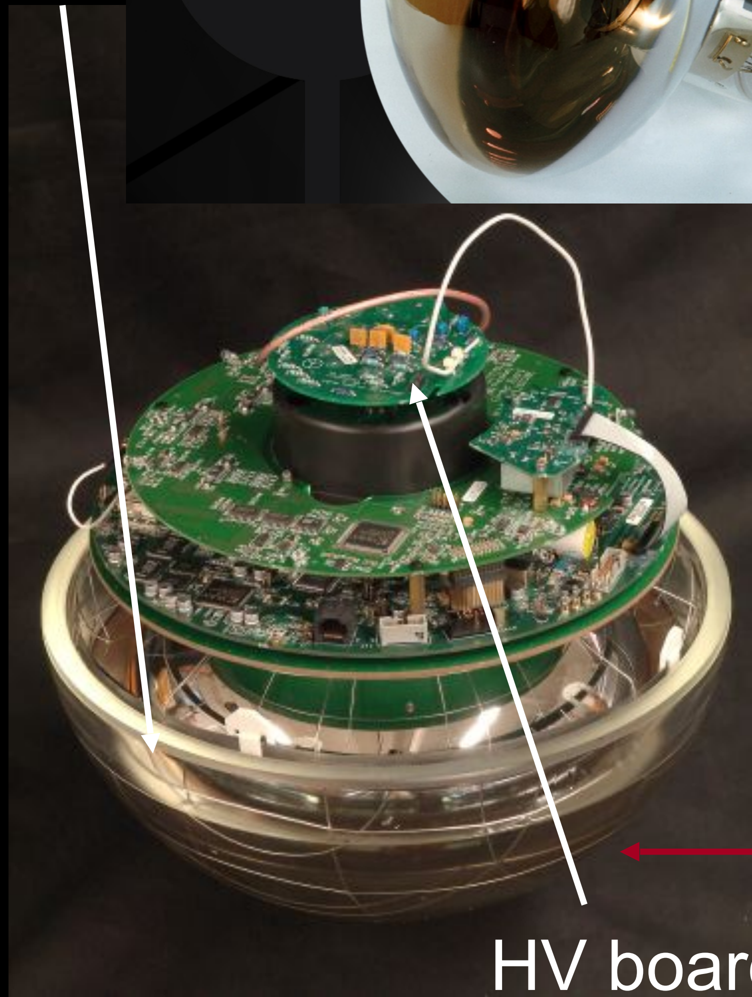
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m

photomultiplier tube -10 inch

LED flasher board

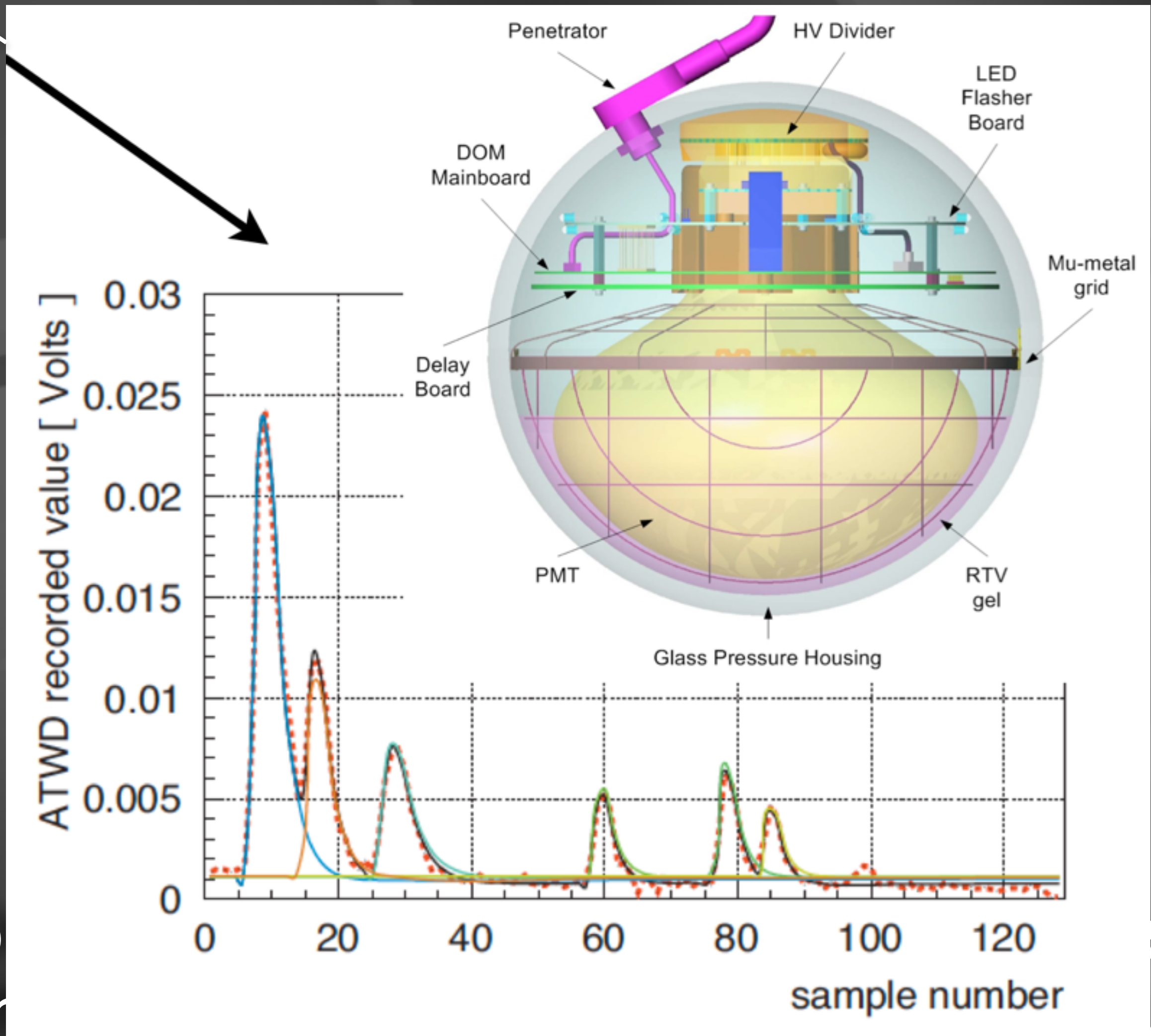


main board

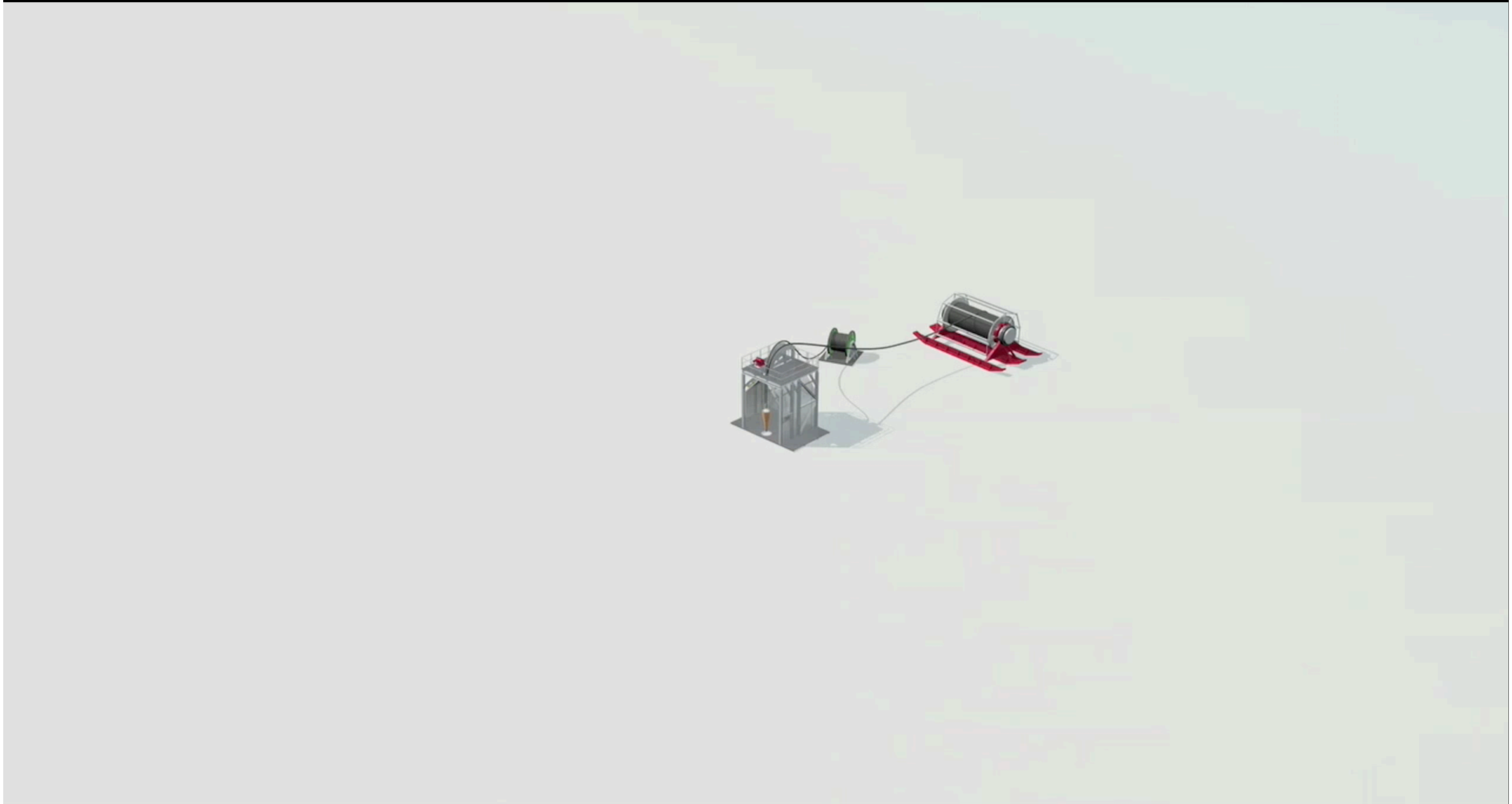


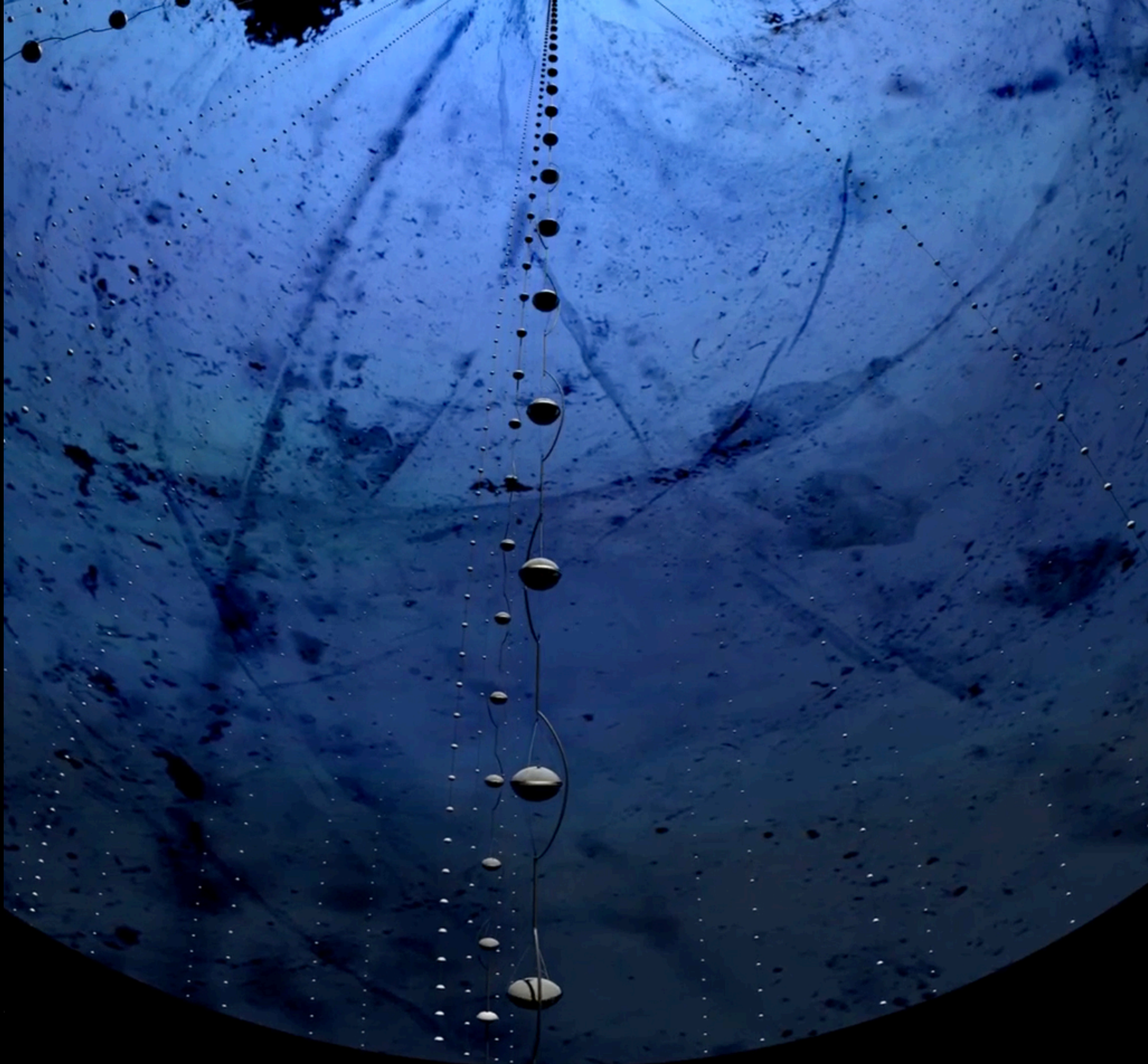
HV board

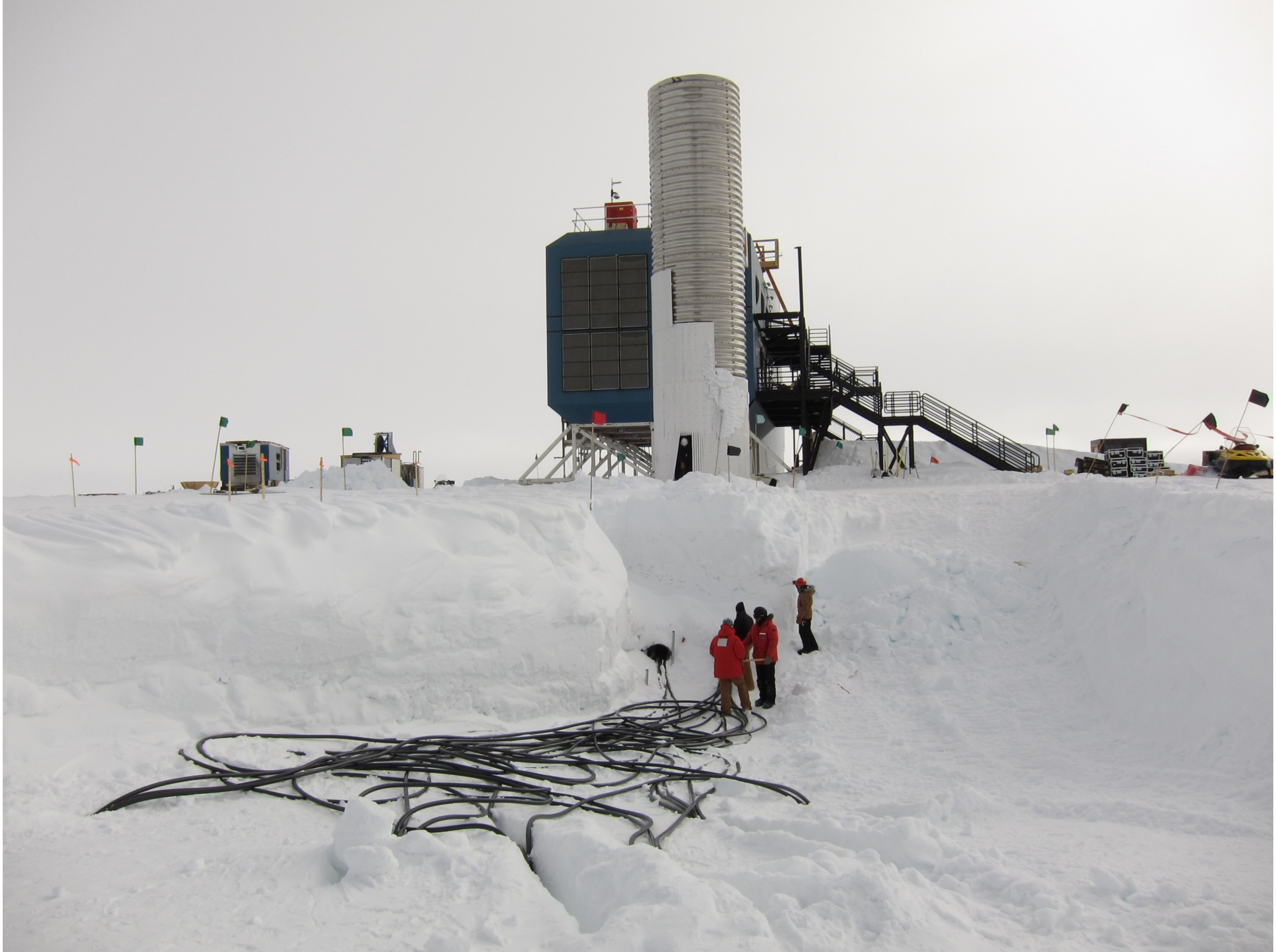
… each Digital Optical Module independently collects light signals like this, digitizes them,

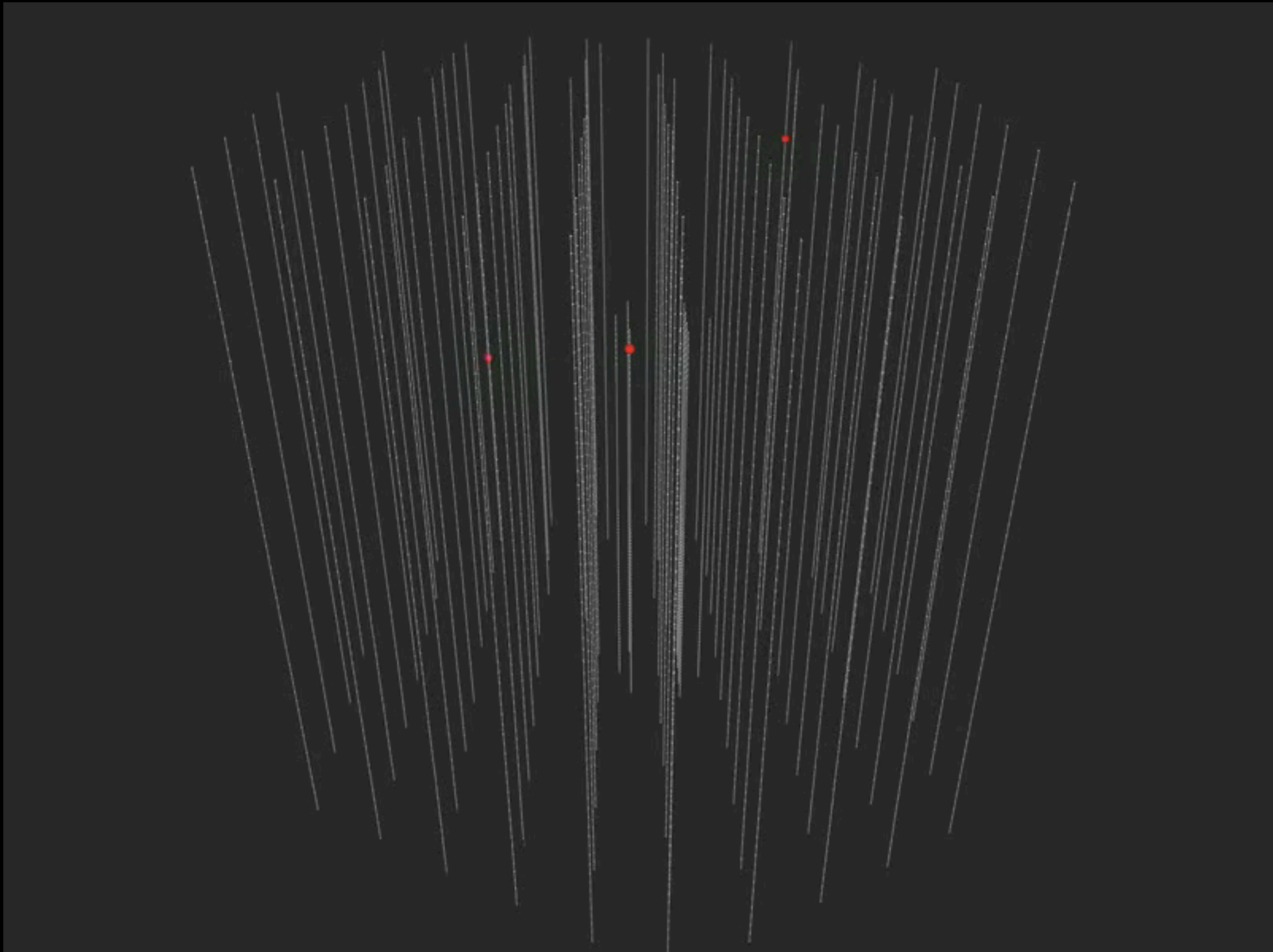


…time stamp … sion, and sends them … vents…

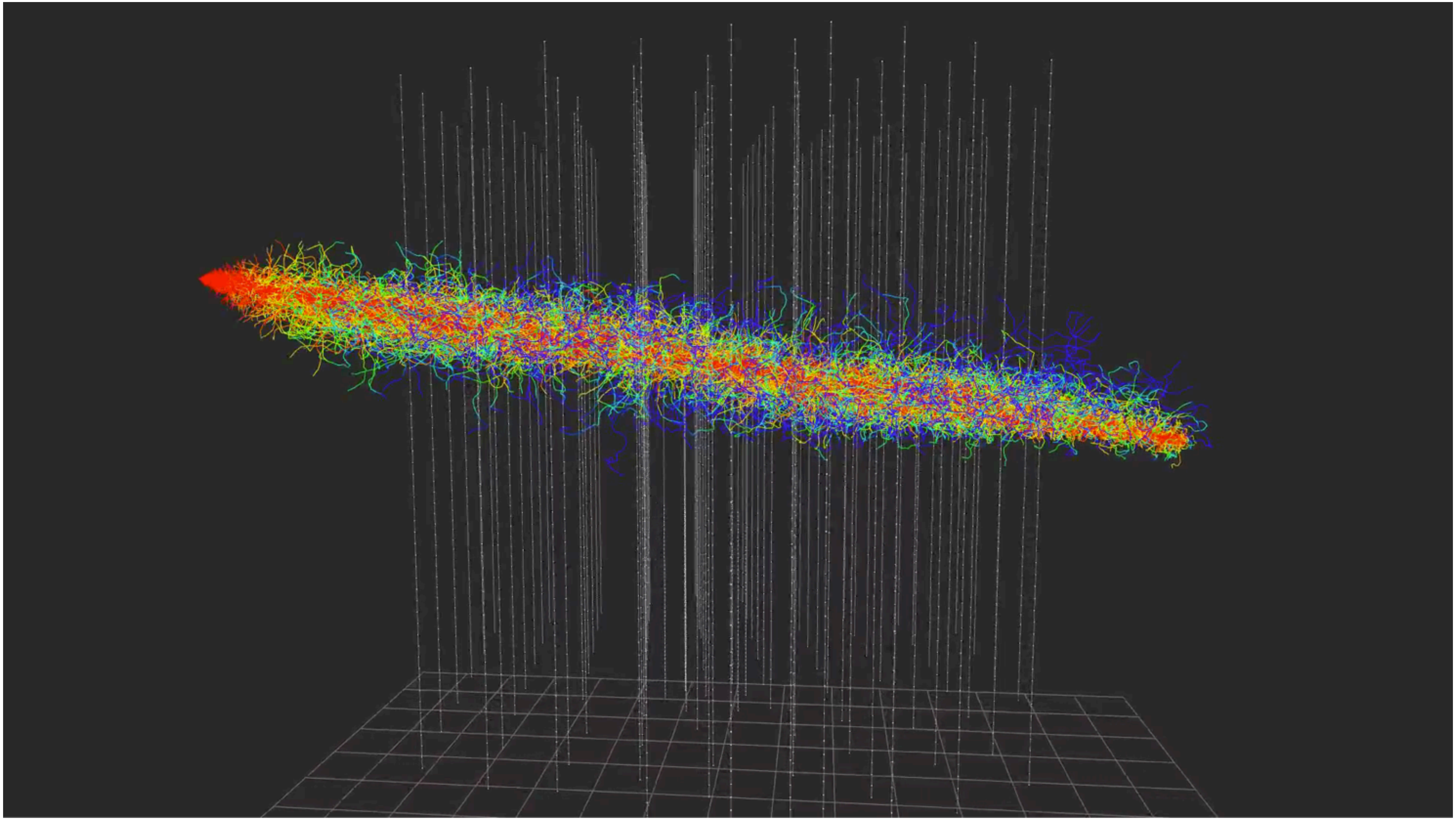


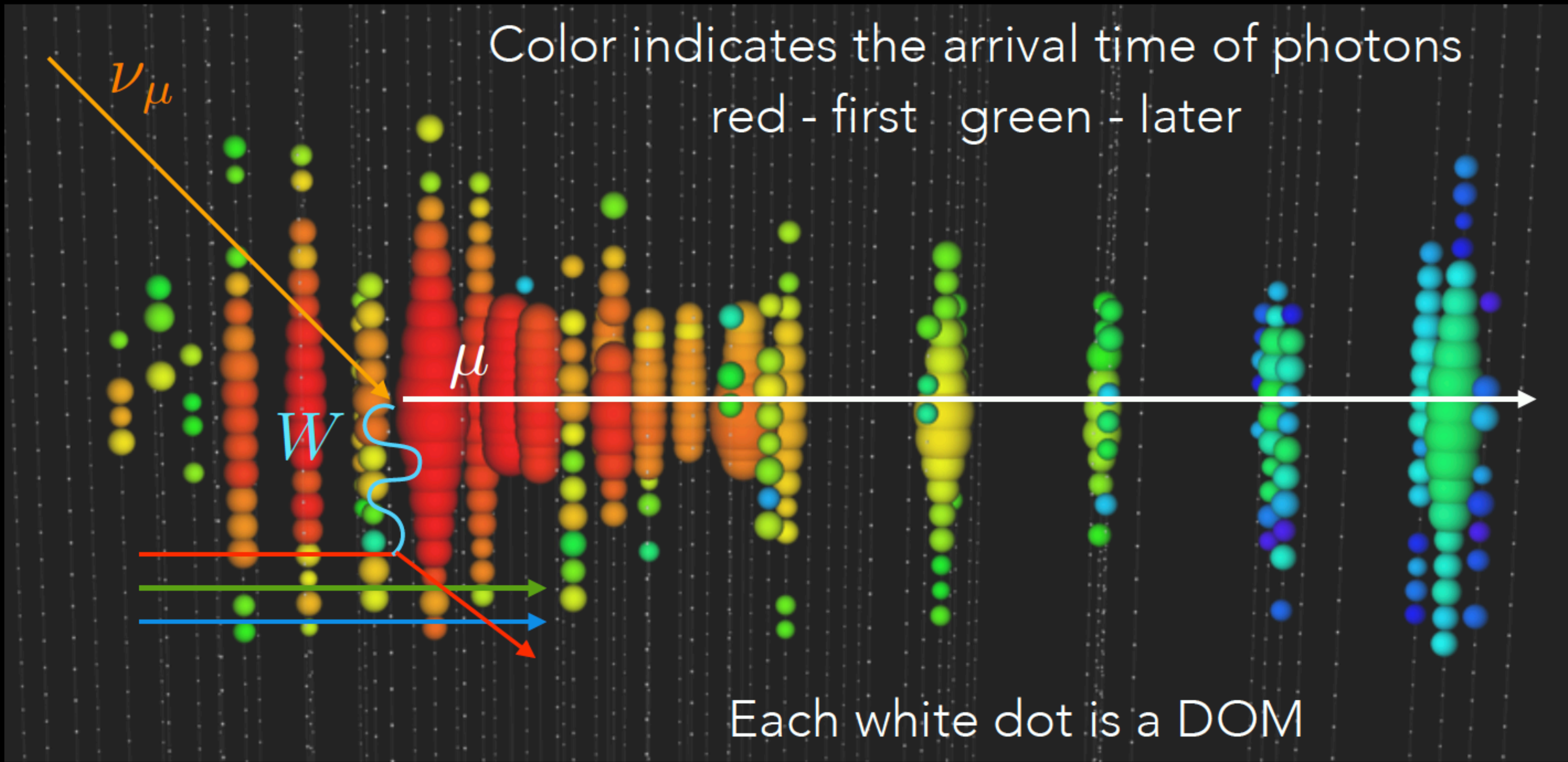






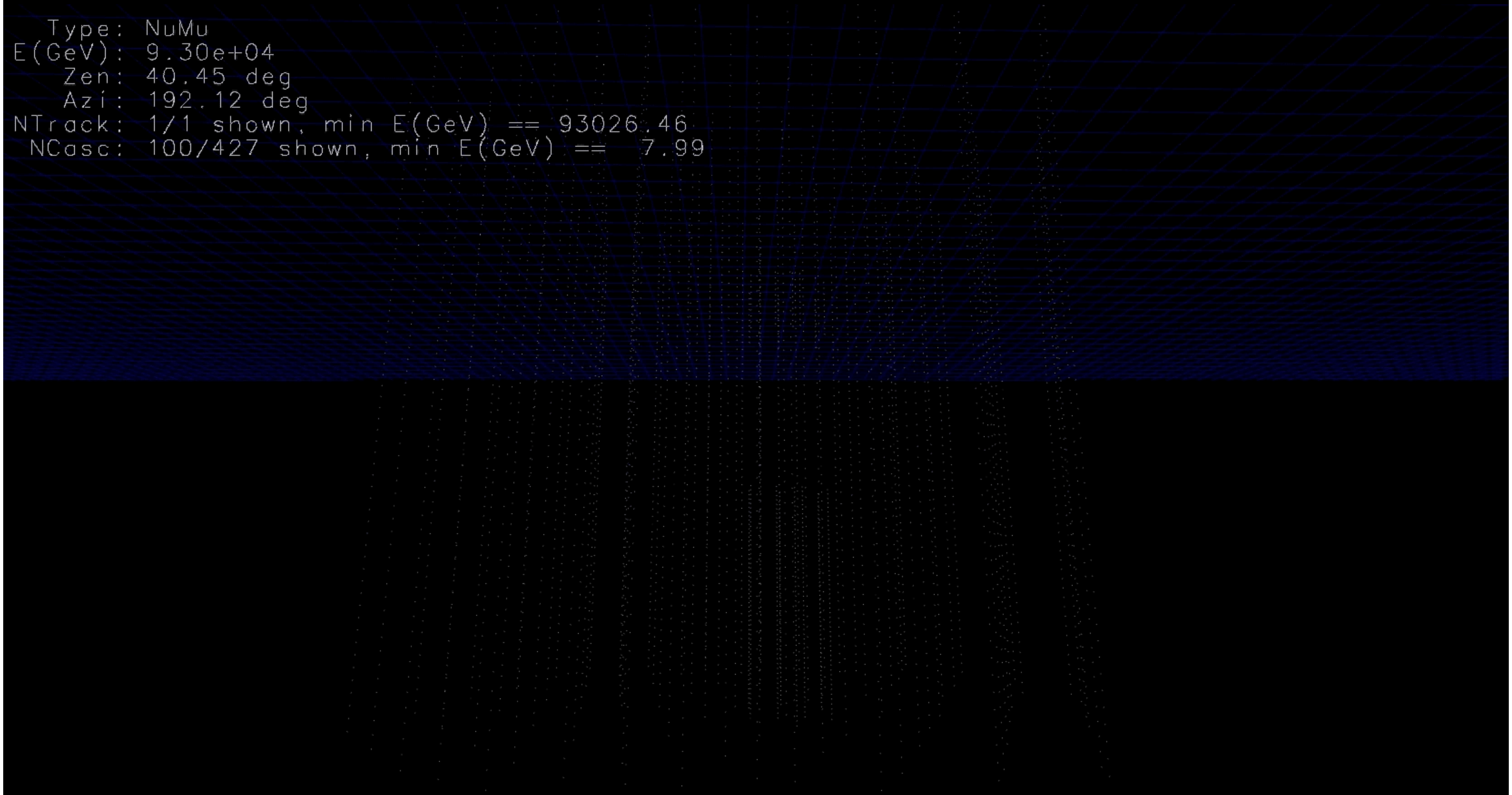
muon track: color is time; number of photons is energy

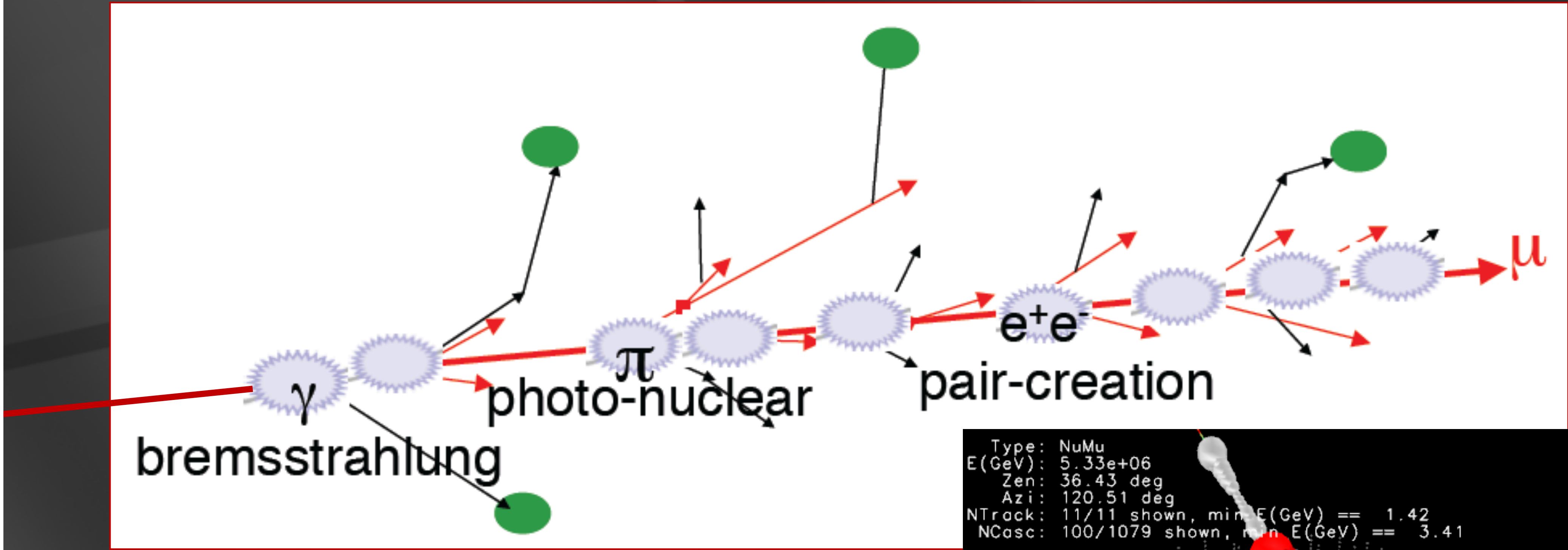


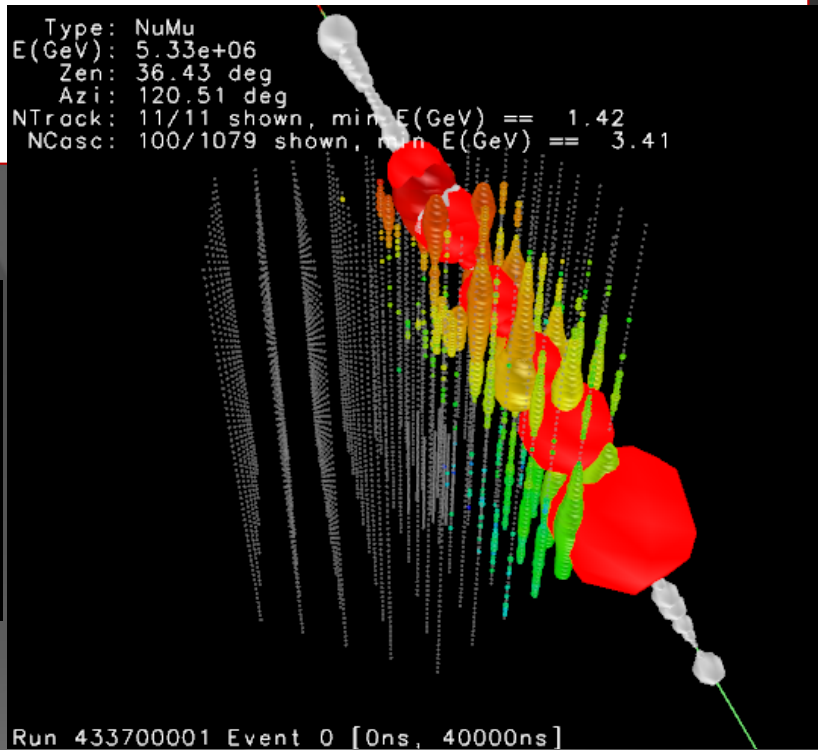


Nov.12.2010, duration: 3,800 nanosecond, energy: 71.4TeV

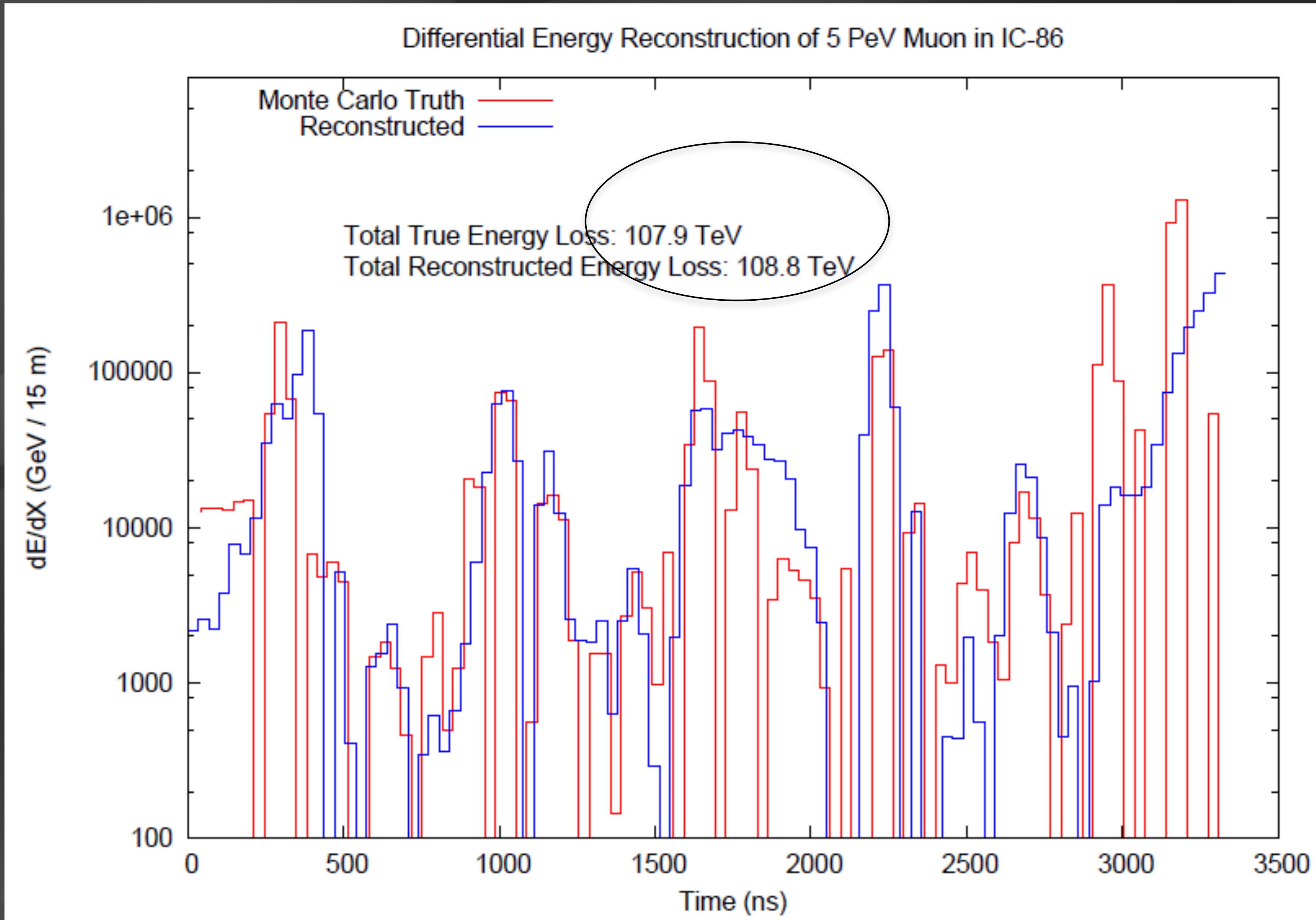
93 TeV muon: light ~ energy







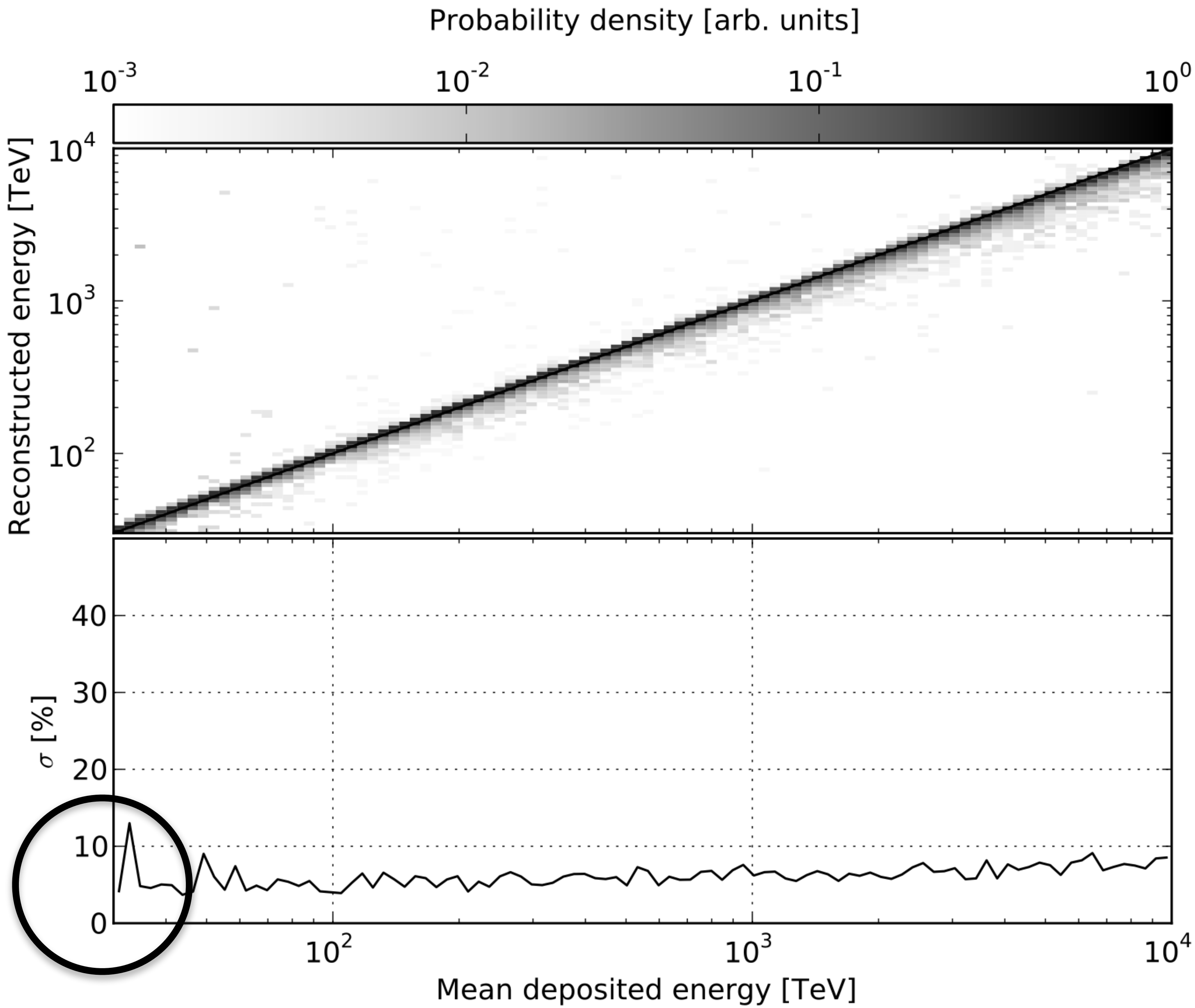
convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

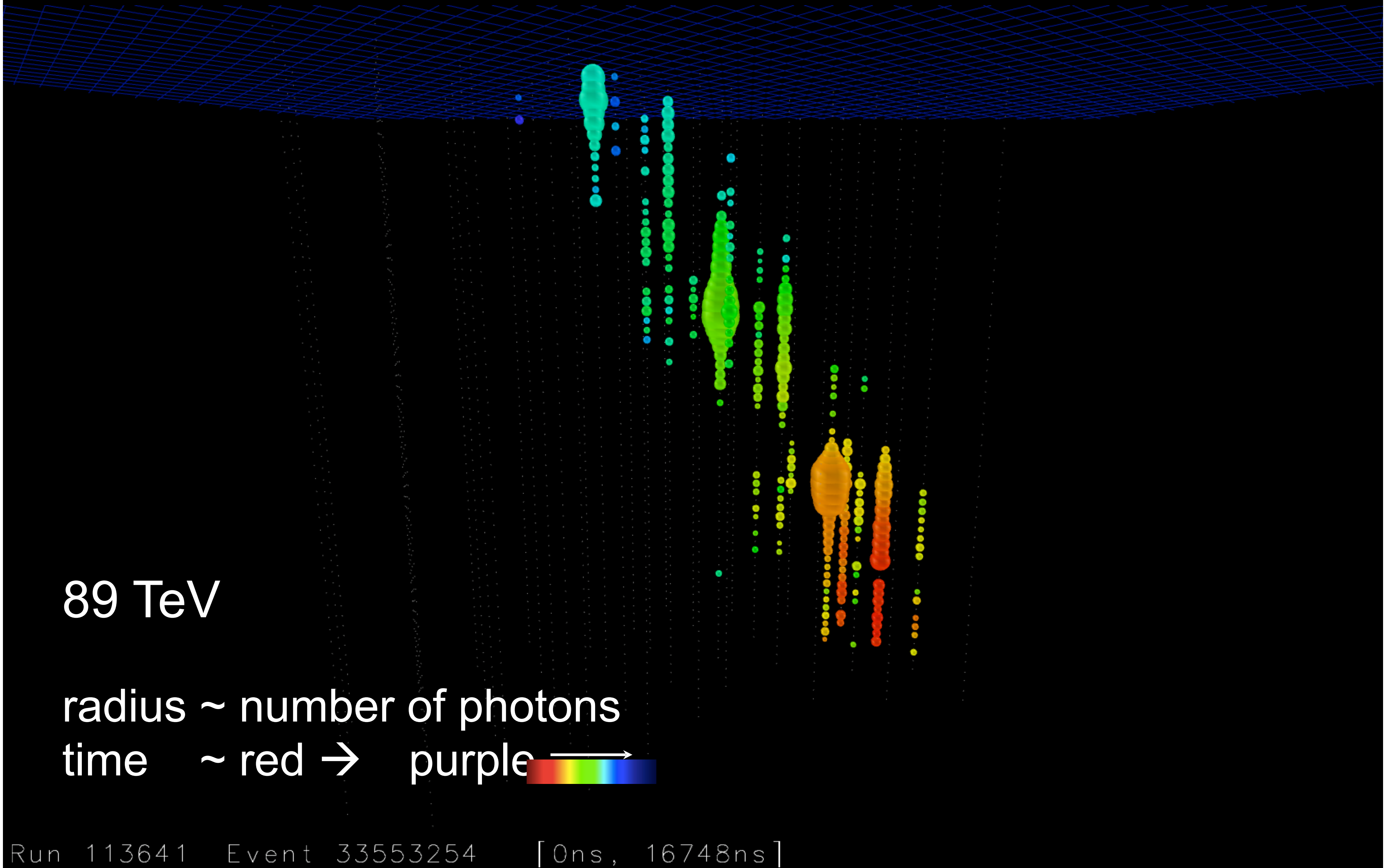


1.1 km

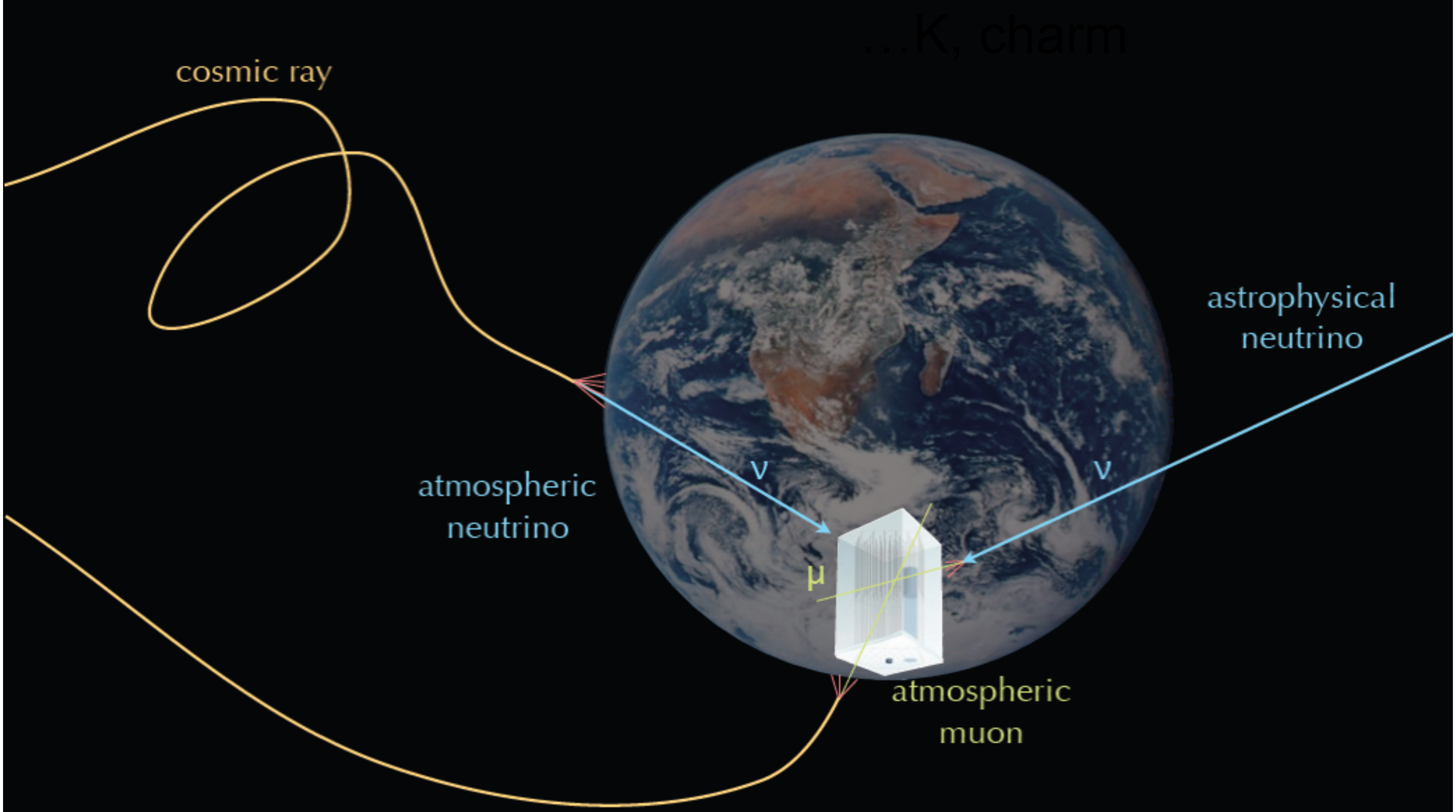
limited angular and energy resolution: computing → ice properties

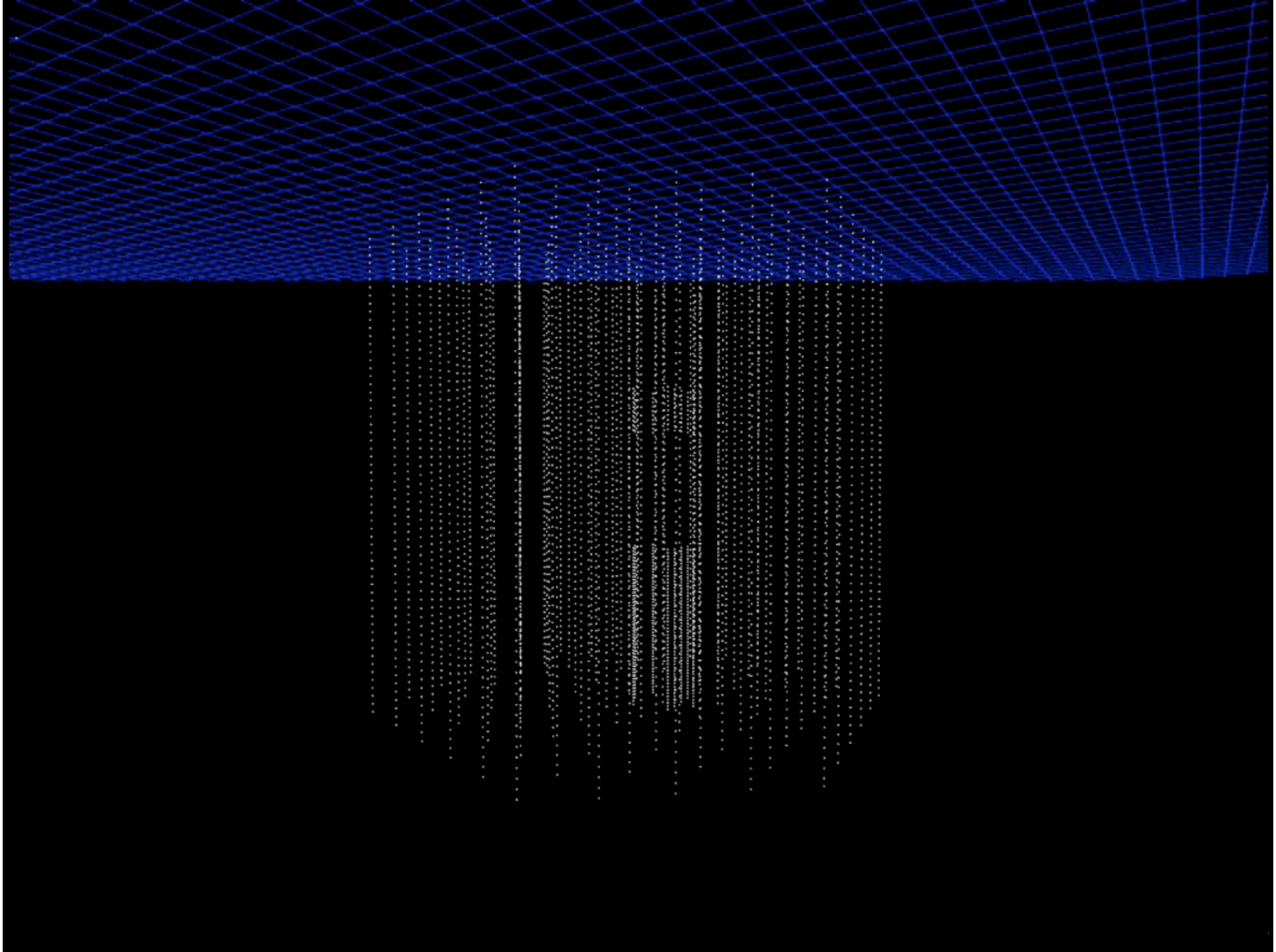
energy reconstruction of electromagnetic showers




89 TeV
radius ~ number of photons
time ~ red → purple
Run 113641 Event 33553254 [0ns, 16748ns]

Signals and Backgrounds





… you looked at 10msec of data !

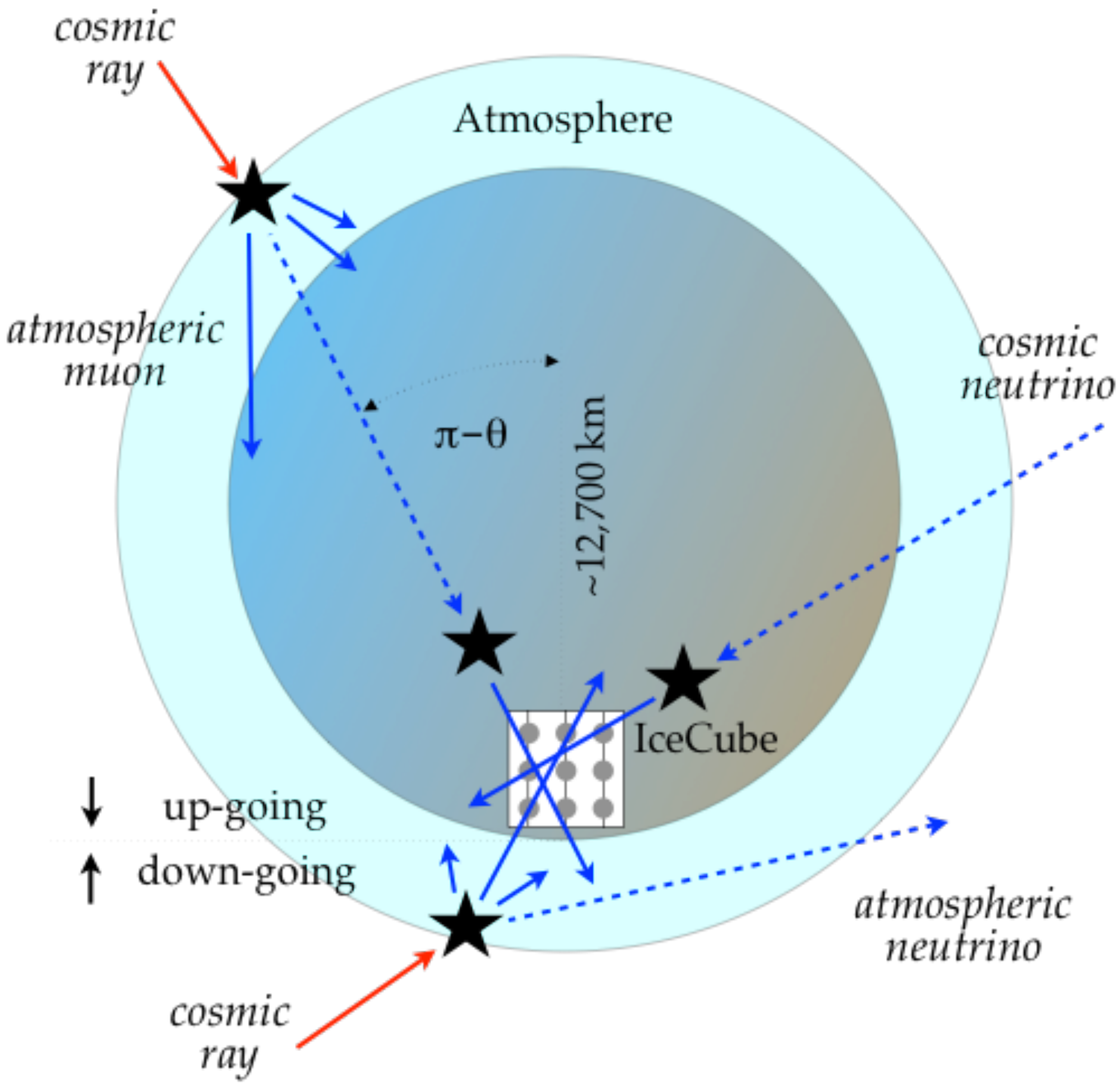
muons detected per year:

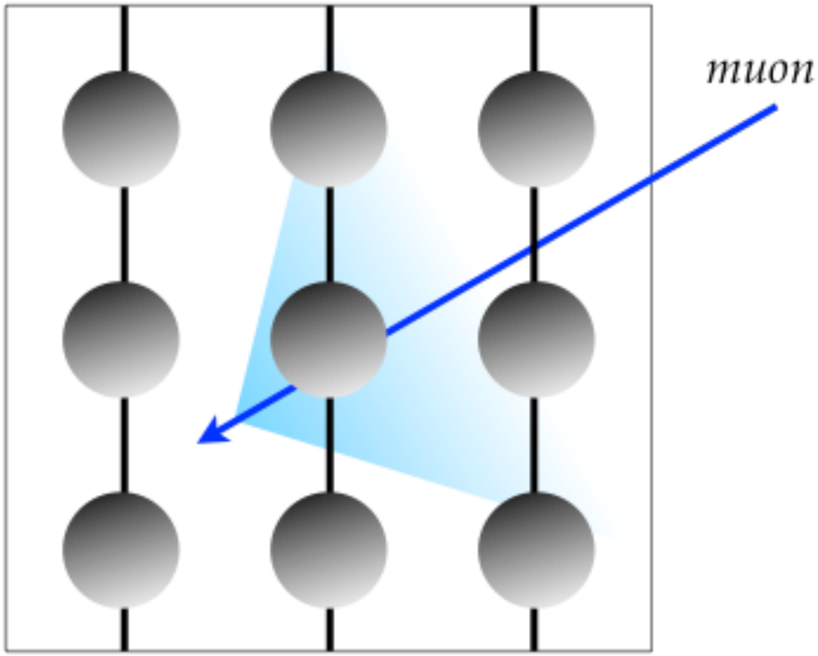
- atmospheric* μ ~ 10^{11}
- atmospheric** $\nu \rightarrow \mu$ ~ 10^{5}
- cosmic $\nu \rightarrow \mu$ ~ 10

* 3000 per second

** 1 every 6 minutes

- rejecting atmospheric muons

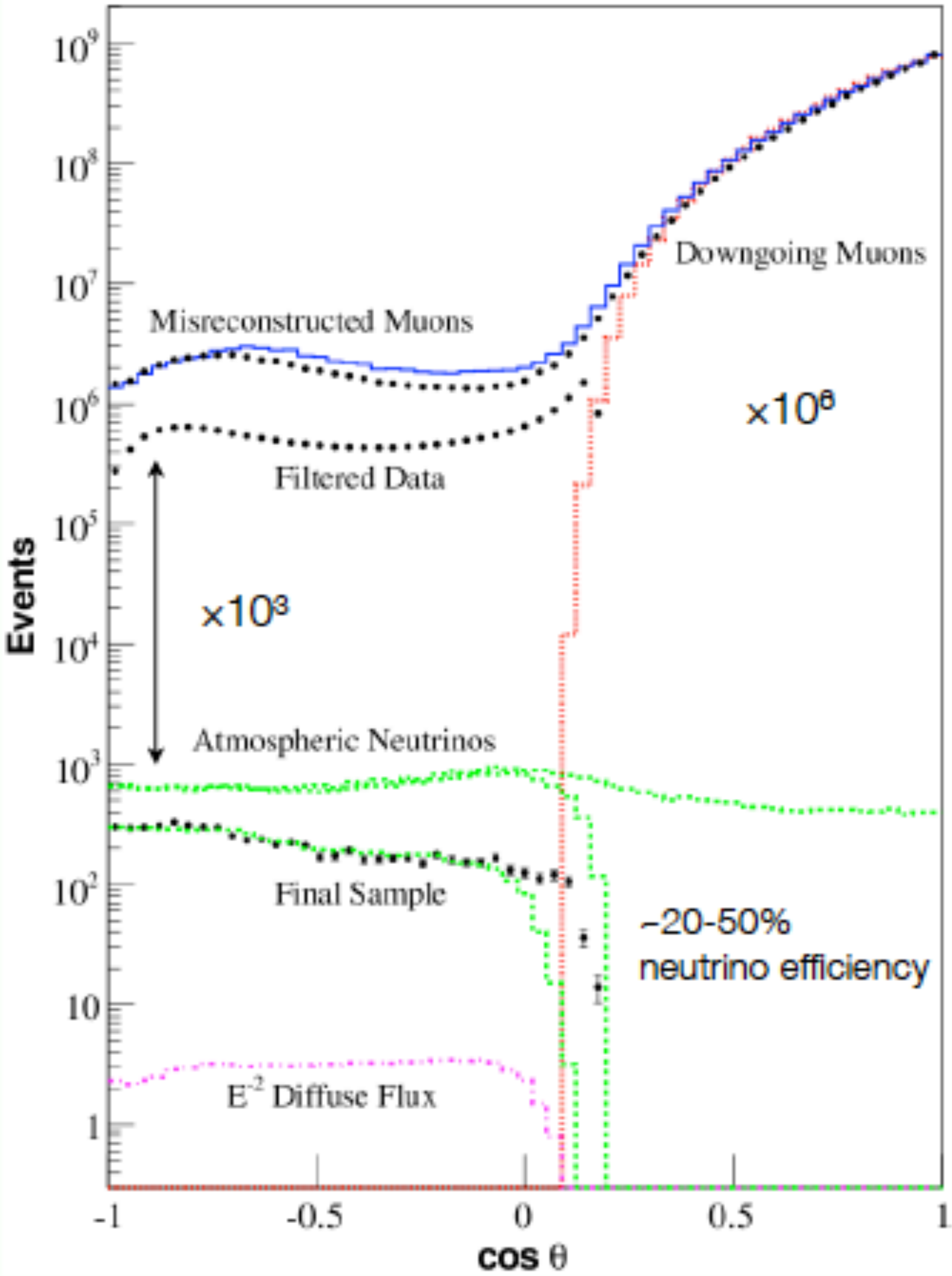


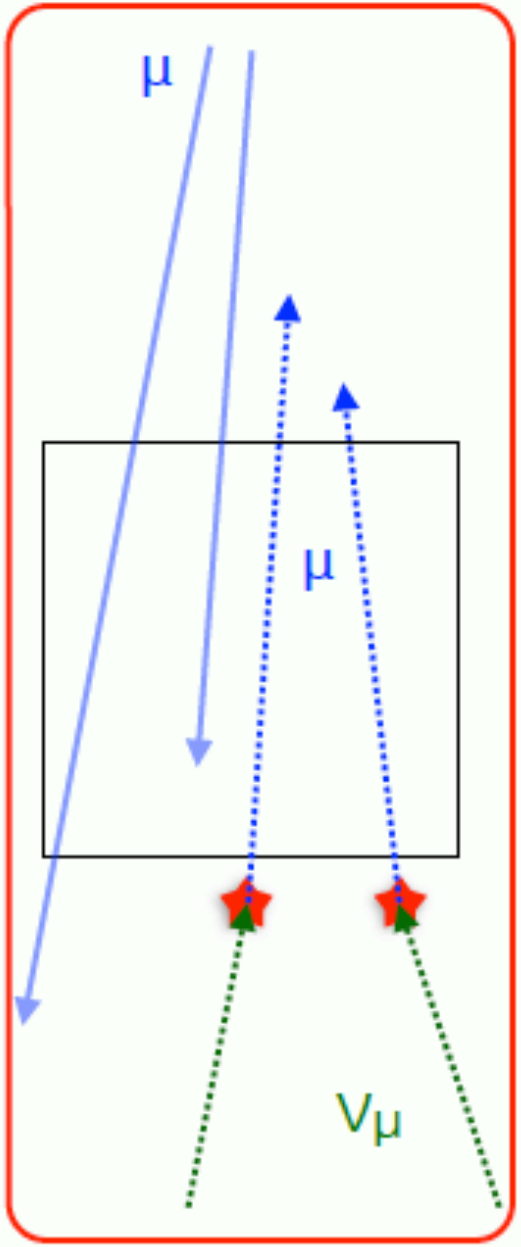


Cherenkov light detection
in optical modules

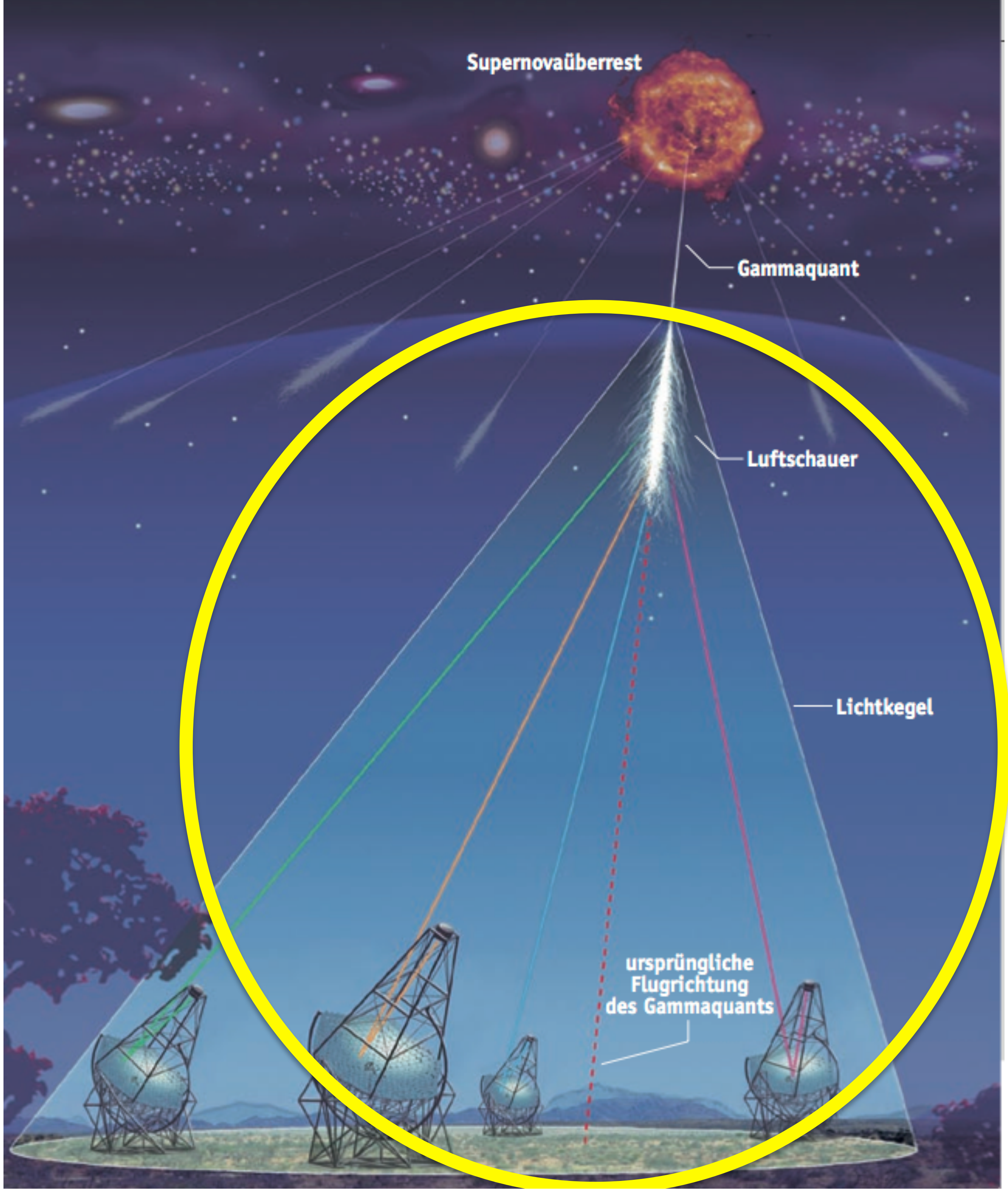
- rejecting atmospheric neutrinos

through-going (tracks)



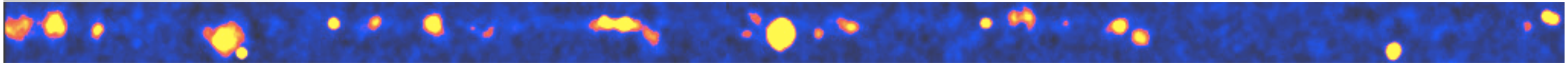


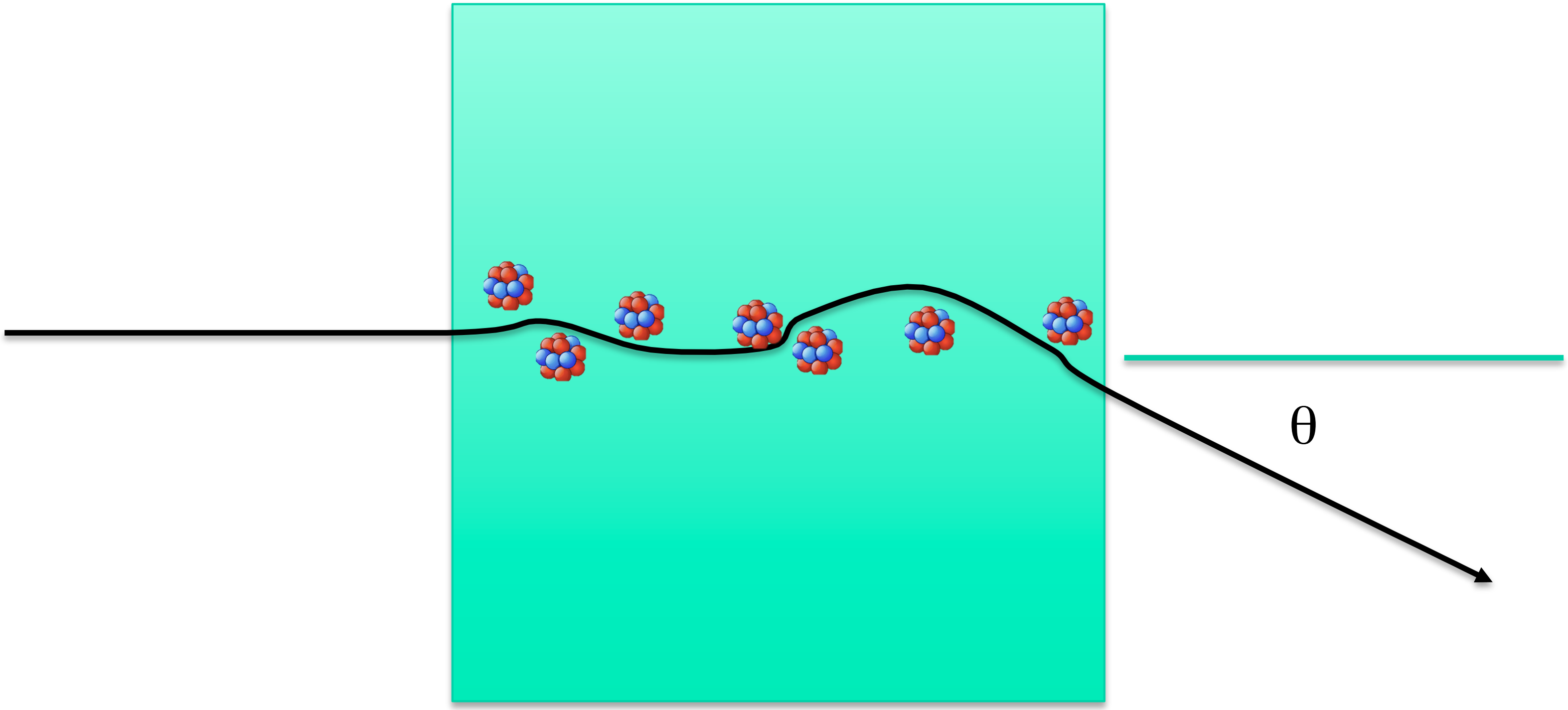
Cherenkov Detectors
for
Gamma-ray Astronomy



Werner Hofmann

Need to know: Multiple Coulomb scattering



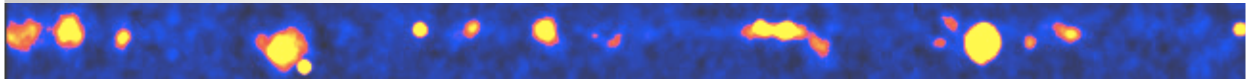


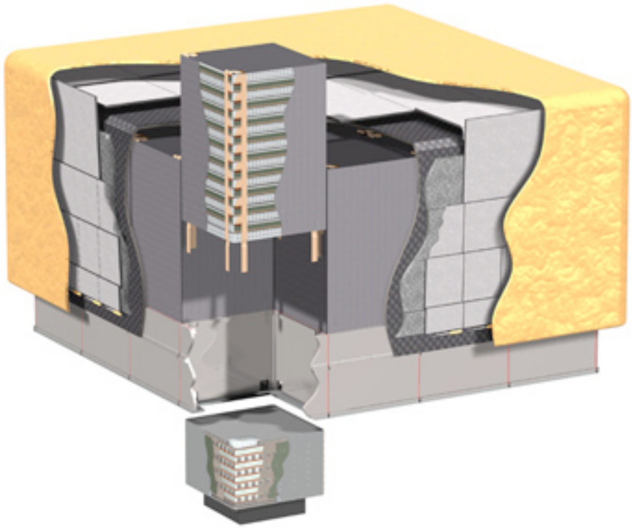
$$\theta_{rms} \approx \frac{14\ \mathrm{MeV/c}}{p}\sqrt{\frac{x}{X_0}}$$

$$\approx 1^0 \quad \text{for 1 GeV particle over 1 RL}$$

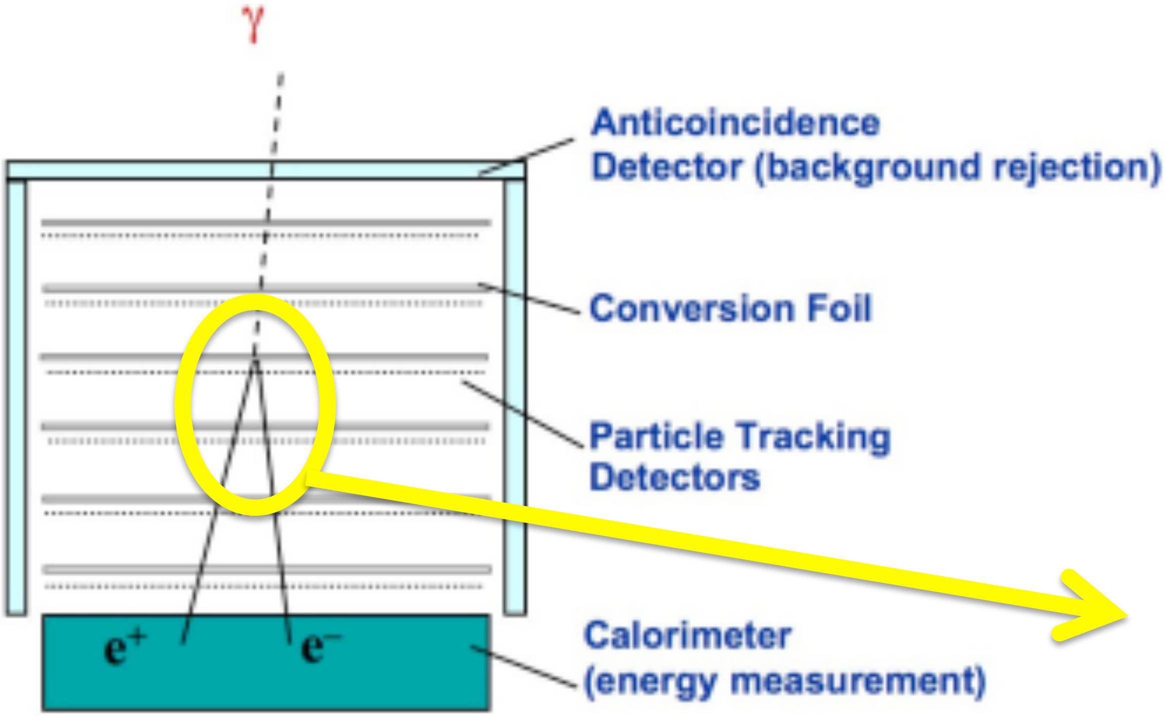
$$\approx 10^0 \quad \text{for 100 MeV particle over 1 RL}$$

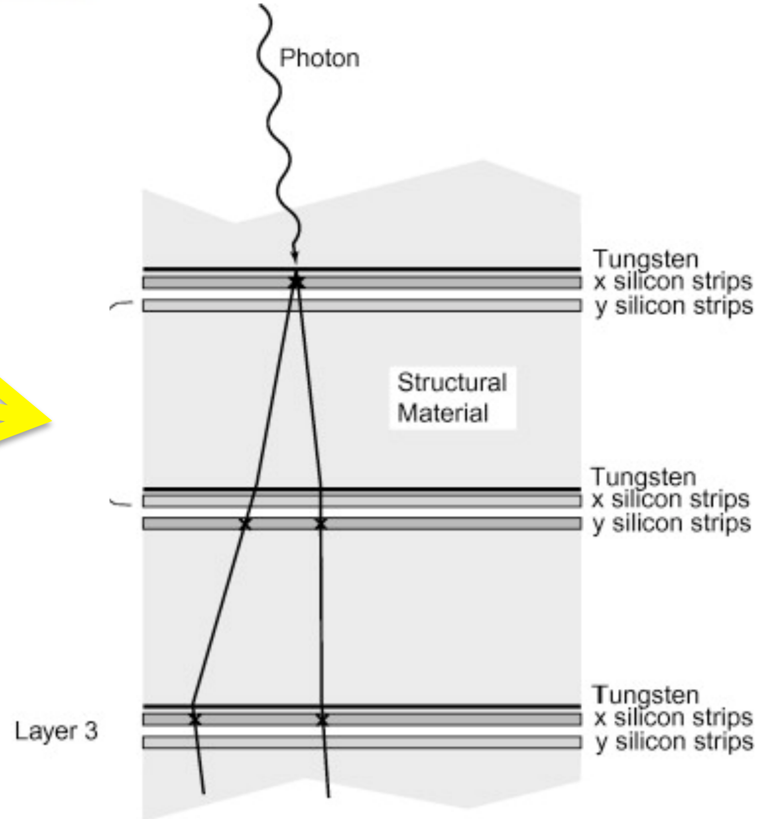
Fermi LAT





Pair conversion tracker and calorimeter

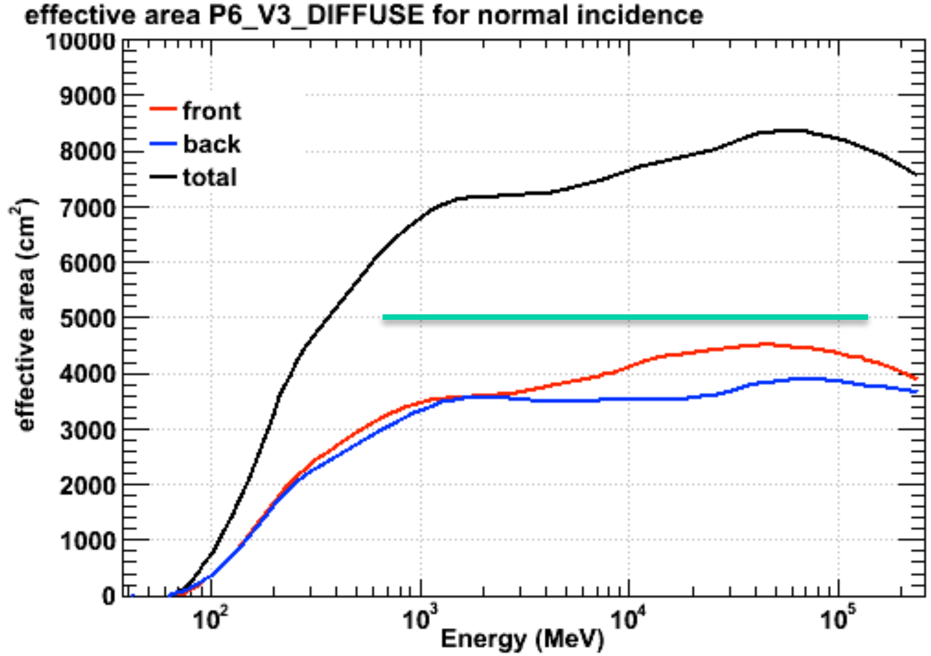


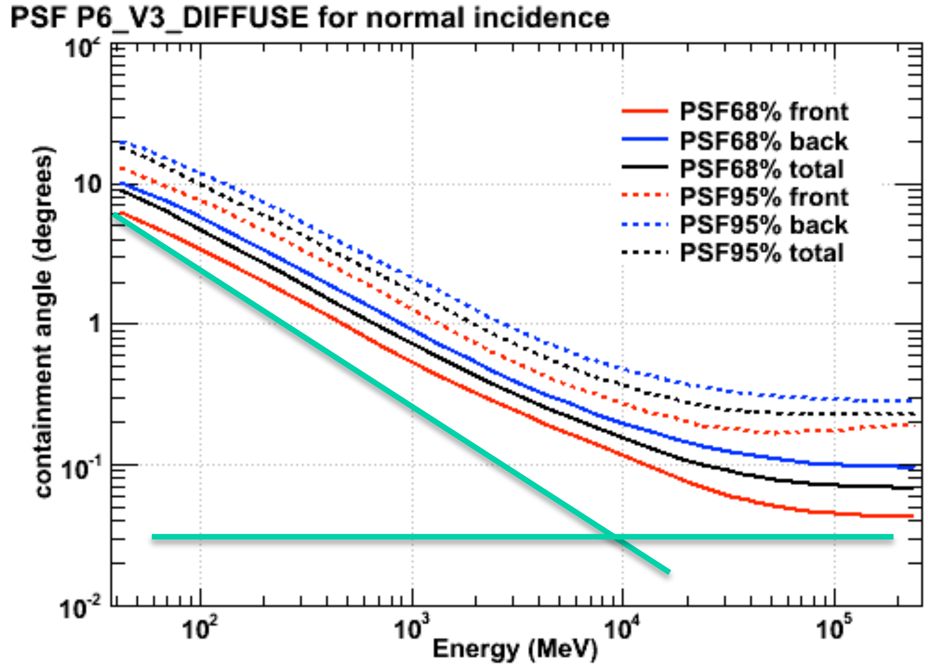


12 planes with 3% RL
4 last planes with 18% RL

Conversion prob. after 10 layers
(30% RL): (7/9) x 30%

Effective detection area:
1.4 m x 1.4 m x 23% = 0.5 m²

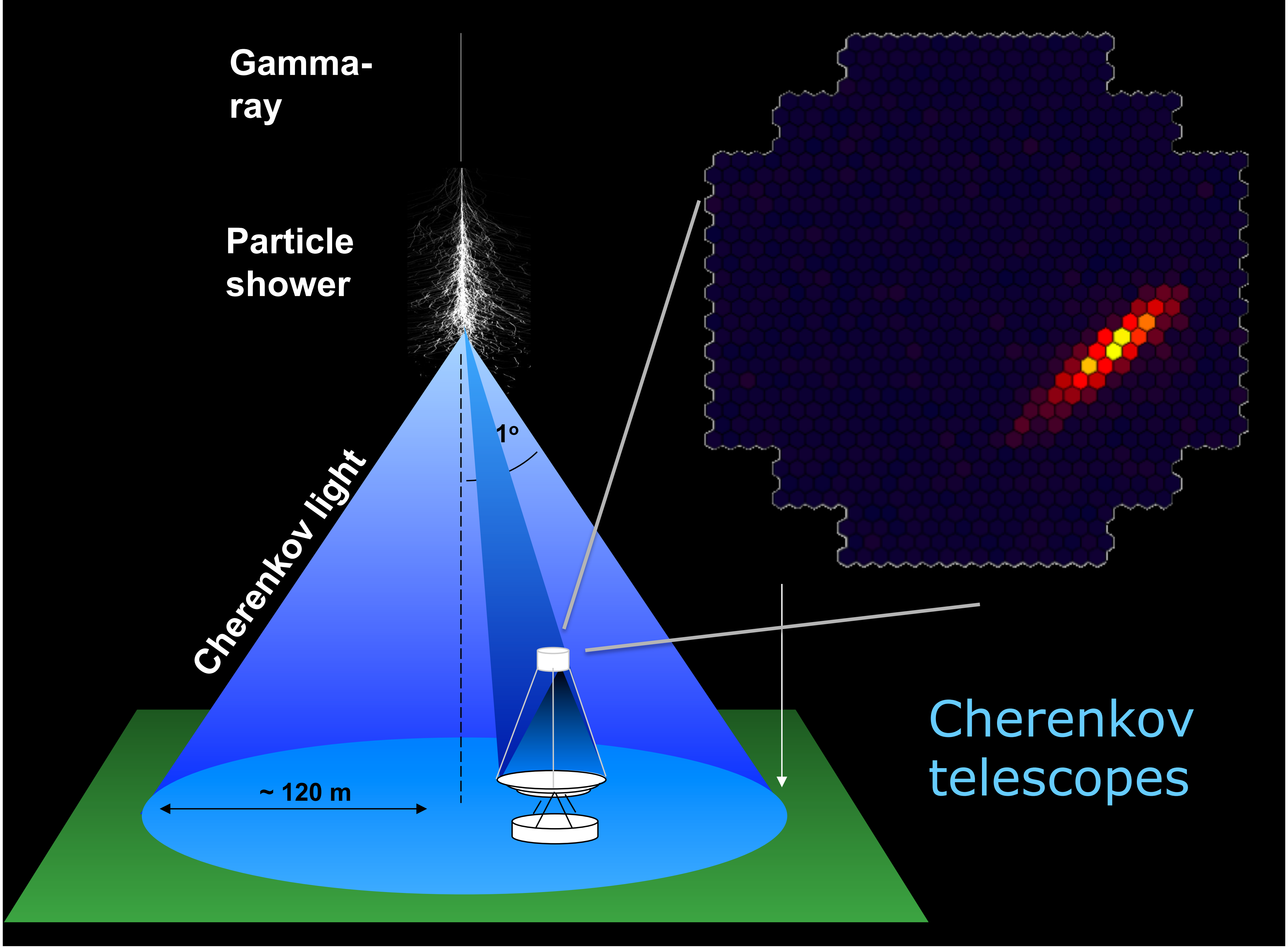




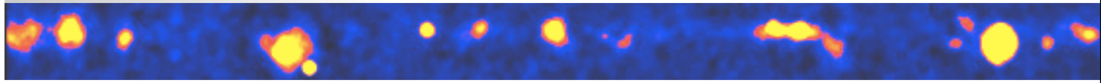
Angular resolution:
track over 3 layers = 10% RL

$$\theta_{rms} \approx \frac{14 \text{ MeV/c}}{p}\sqrt{\frac{x}{X_0}} \approx \frac{0.3^0}{E_{GeV}}$$

Strip resolution
50 μm/10 cm = 0.03°


Gamma-
ray
Particle
shower
Cherenkov light
1°
~ 120 m
Cherenkov
telescopes

Shower development

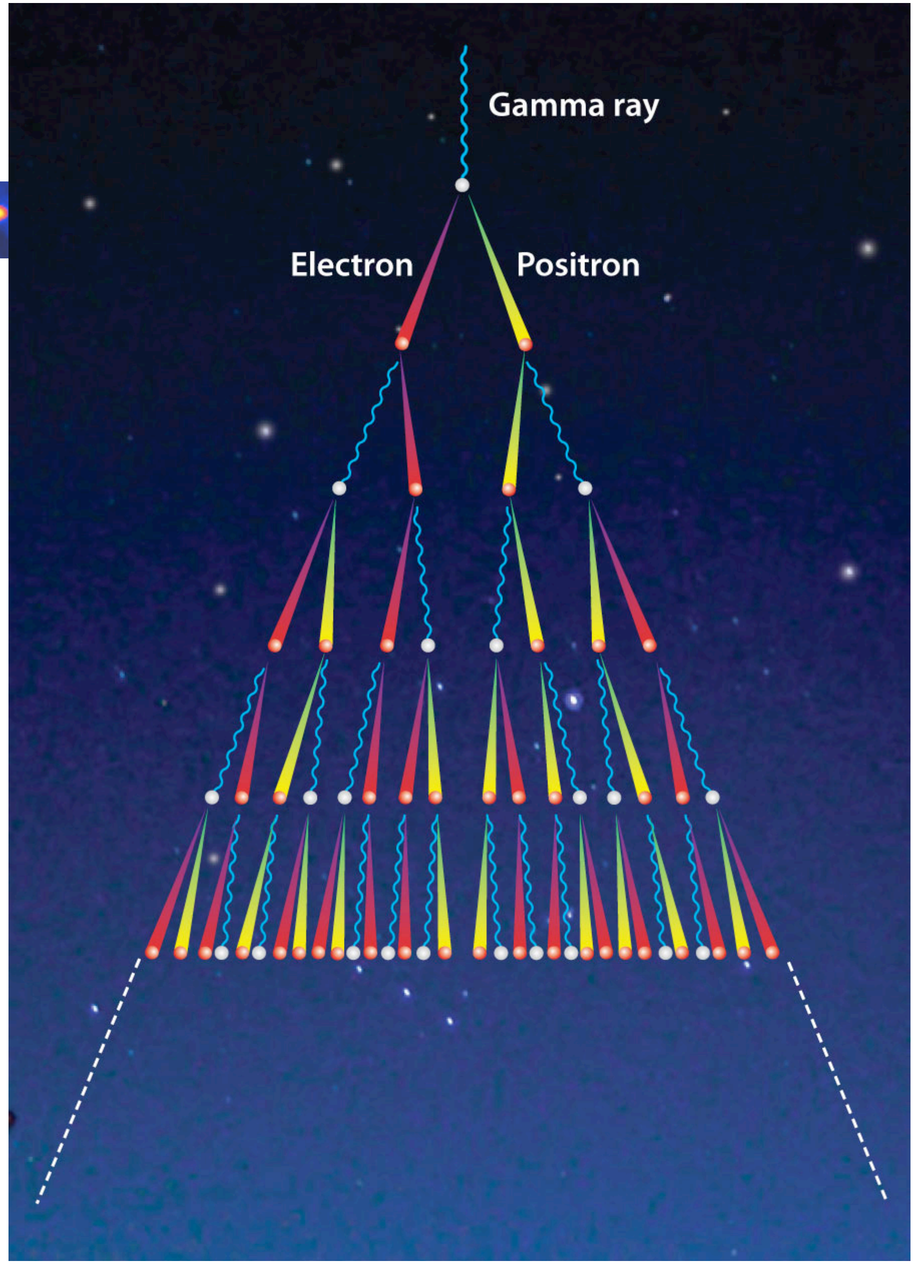


Particle number doubles after ~each radiation length until ionization losses dominate ("critical energy" ~85 MeV)

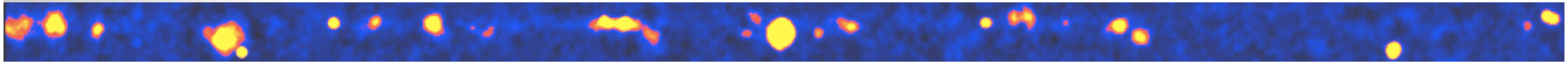
$$t_{max} \approx \frac{\ln(E_0 / E_c)}{\ln 2} \approx 14 \text{ RL at 1 TeV}$$

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

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

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

Cherenkov angle

$$\theta = \arccos(\beta n) \underset{\cos\theta \approx 1 - \frac{\theta^2}{2}}{\approx} \sqrt{2\left(1 - \frac{1}{\beta n}\right)} \underset{\beta=1}{\approx} \sqrt{2\varepsilon} \approx 0.8^0 \quad \text{at shower max.}$$

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

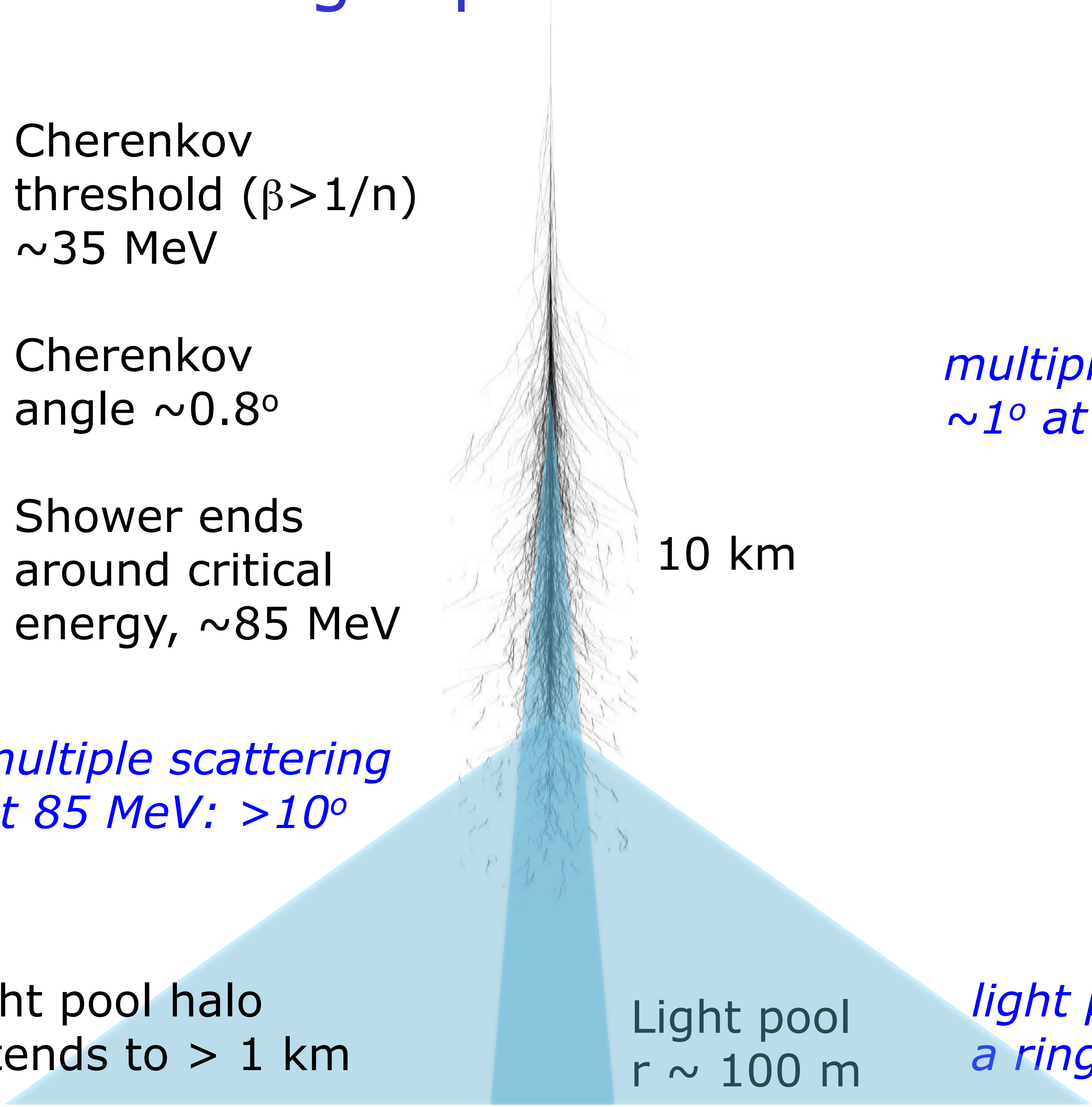
Cherenkov threshold ($\beta > 1/n$) ~35 MeV

Cherenkov angle ~0.8^{o}

Shower ends around critical energy, ~85 MeV

multiple scattering at 85 MeV: >10^{o}

multiple scattering: ~1^{o} at 1 GeV



Light pool halo extends to > 1 km

light pool not a ring, but filled

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. lenght (1000 m @ shower max):

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

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

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

Considering only the higher-energy shower particles

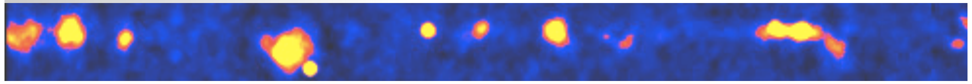
2RL higher up higher up:

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

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

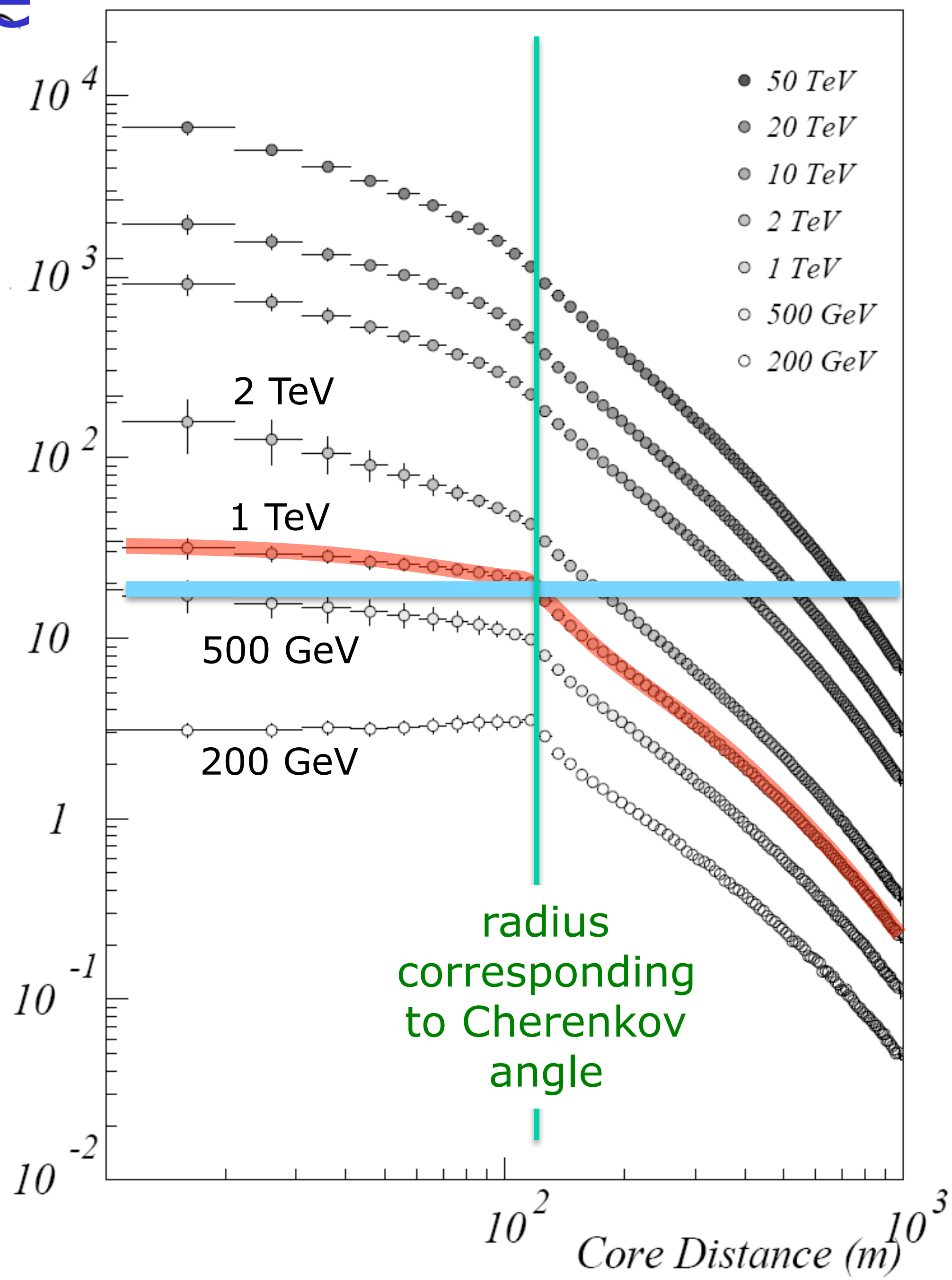
$\Rightarrow$ over 110 m radius light pool: ~300 ph./m^2

Intensity vs distance



detected photons per m²

detection threshold



I. de la Calle Perez, S. D. Biller

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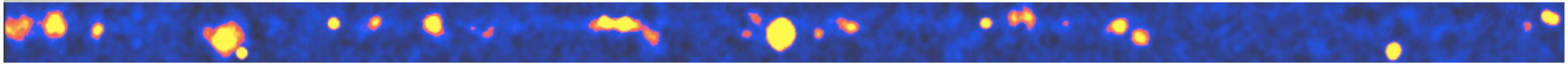
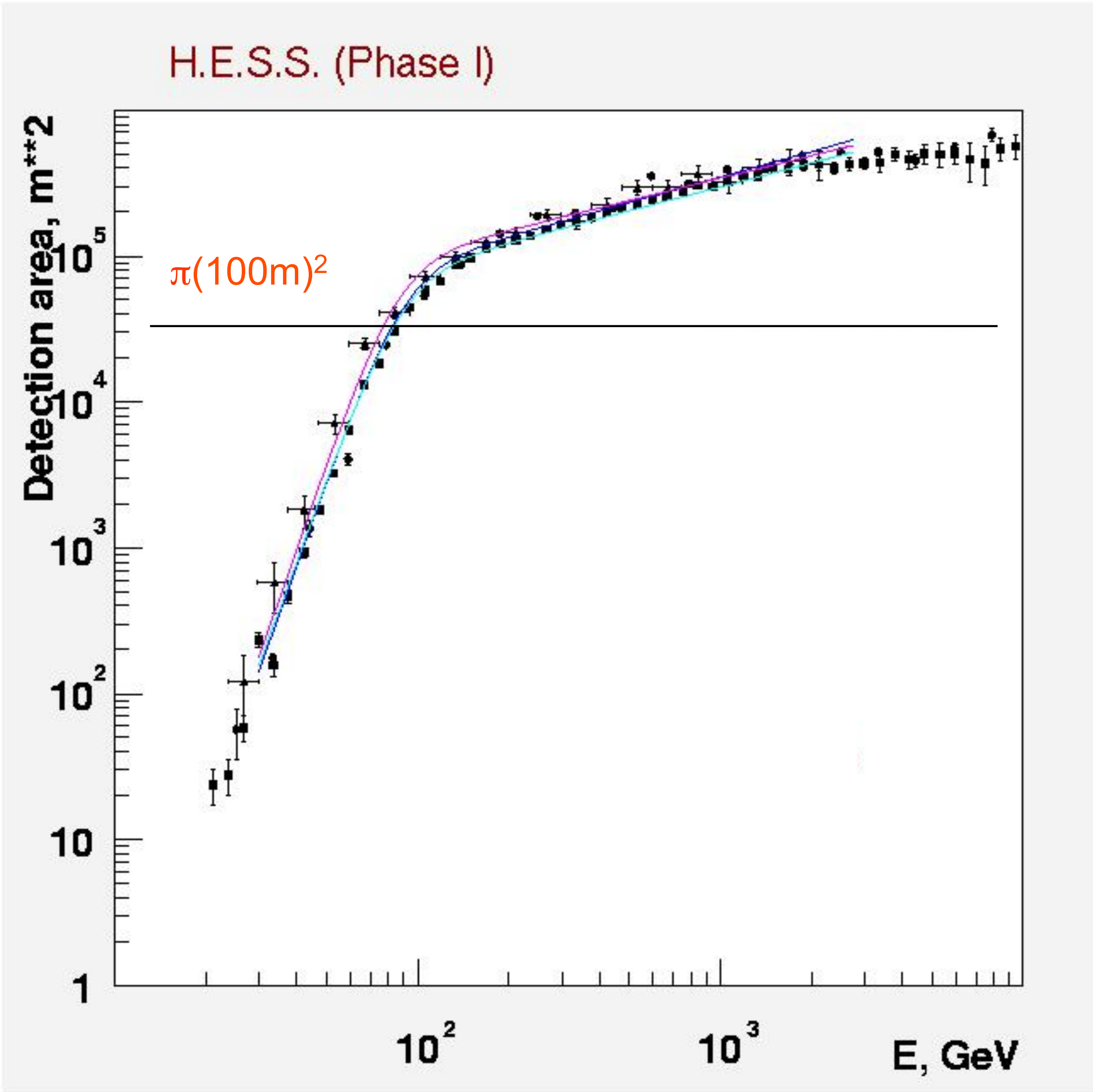
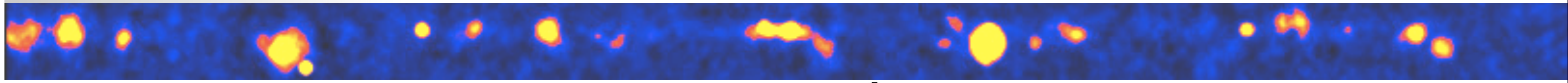
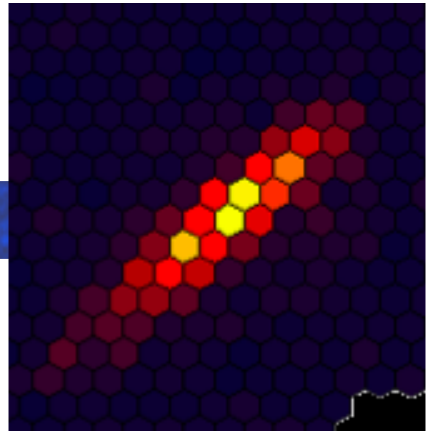
Energy threshold & detection area

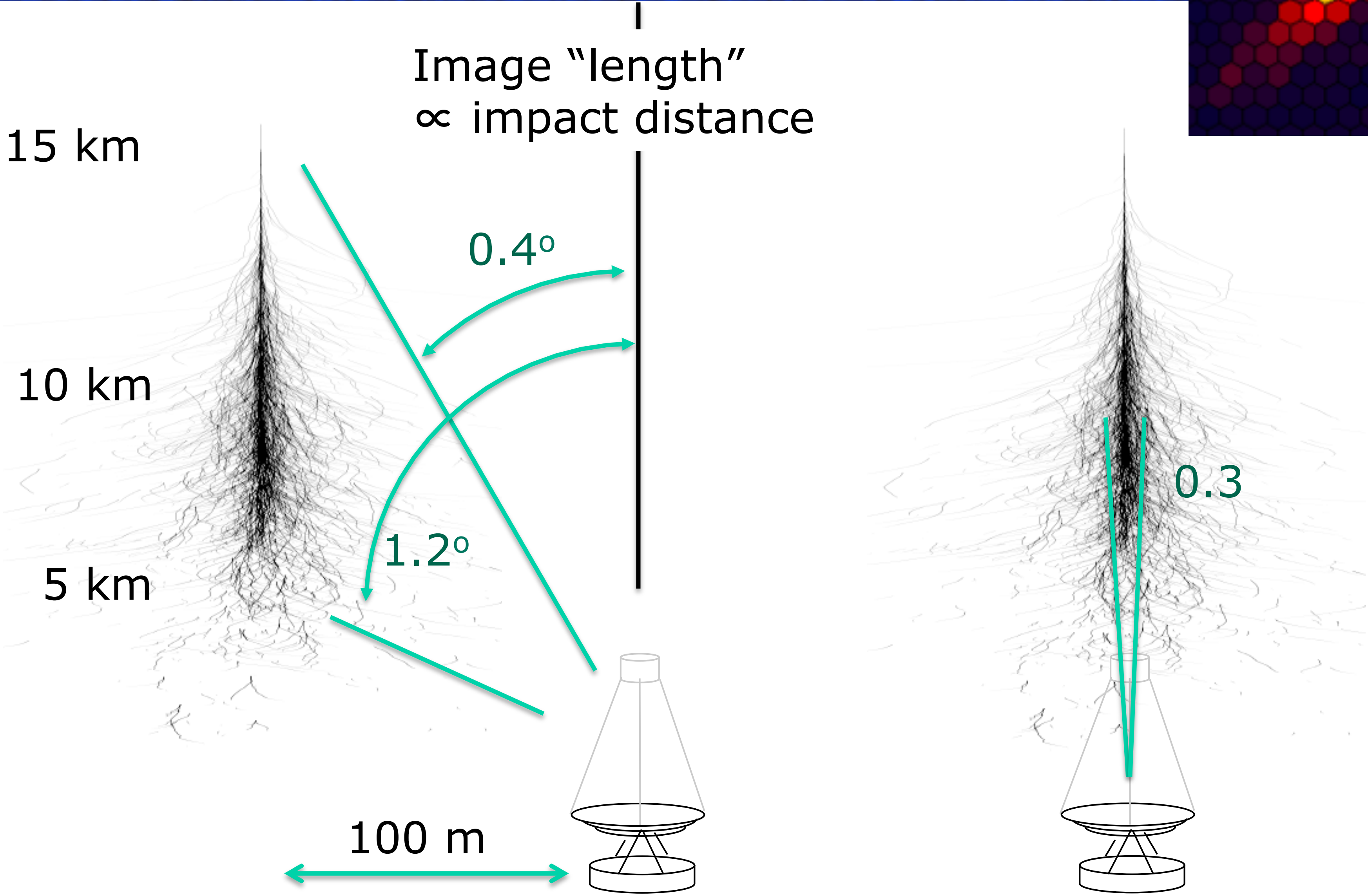




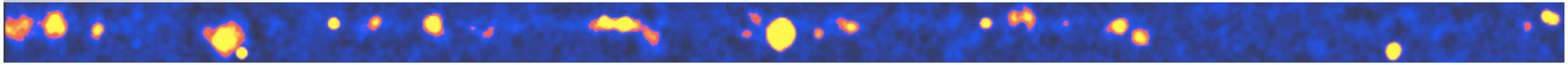
Typical image







Angular resolution



governed by

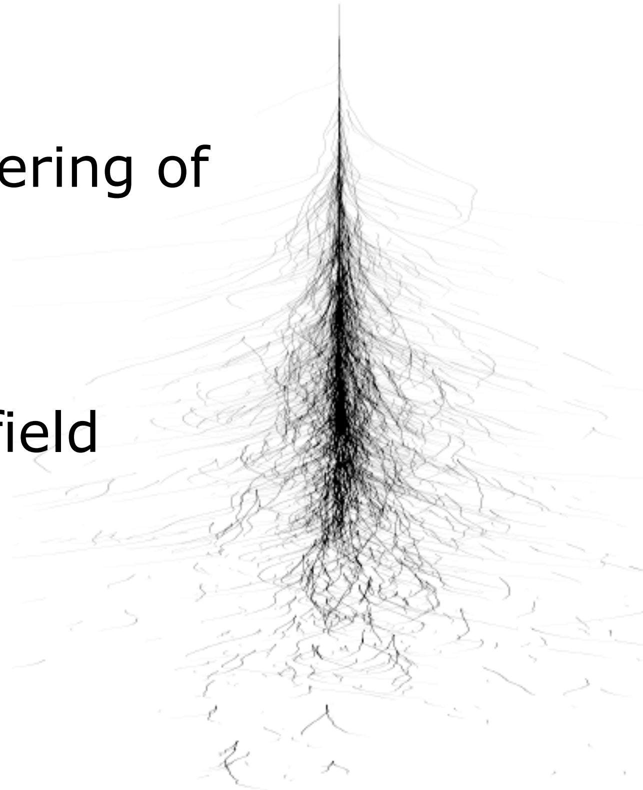
shower fluctuations and multiple scattering of shower particles
(typically 1000 particles @ 1 TeV)

deflection of particles in Earth magn. field

photon statistics in image
(typically 100 photons)

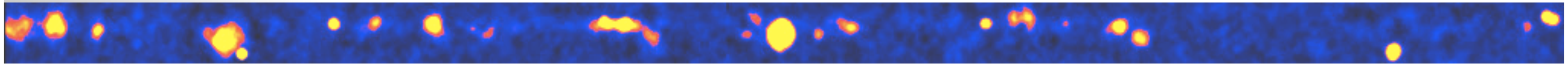
reconstruction algorithm

…



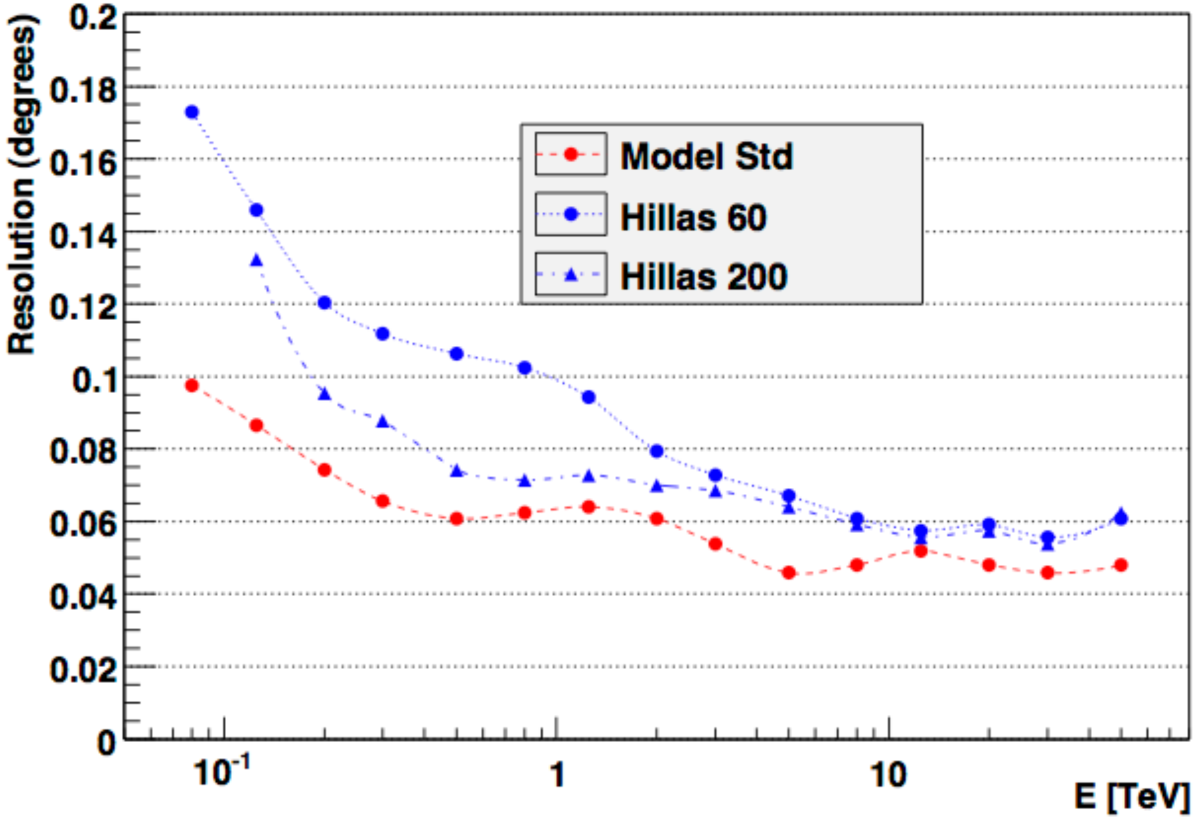
Angular resolution

...somewhat oversimplified...



Photons within the central 110 m pool scatter within $\sim 1^0$ from shower axis

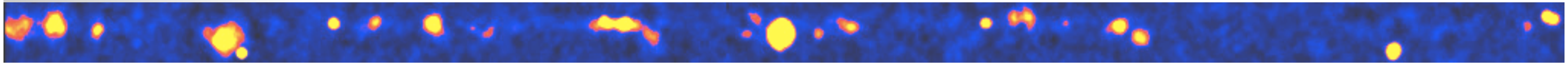
Measure shower direction with precision $\sim \frac{1^0}{\sqrt{n_{ph}}} \approx 0.1^0$



H.E.S.S.

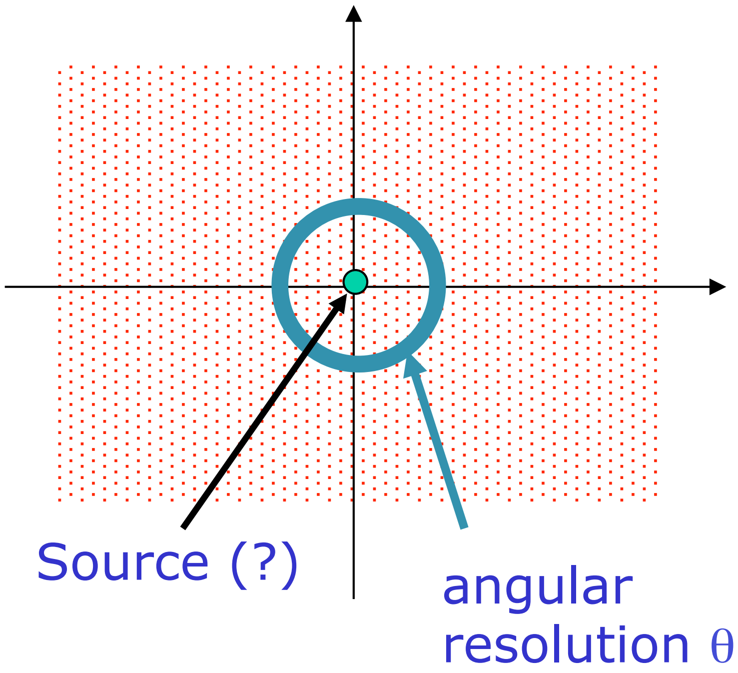
note:
no. of detected photons does not increase linearly with energy, since showers eff. area increases!

Sensitivity in a toy model



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

reconstructed shower directions



# of background events:

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

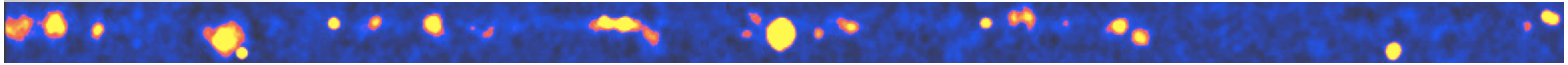
# of signal events:

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

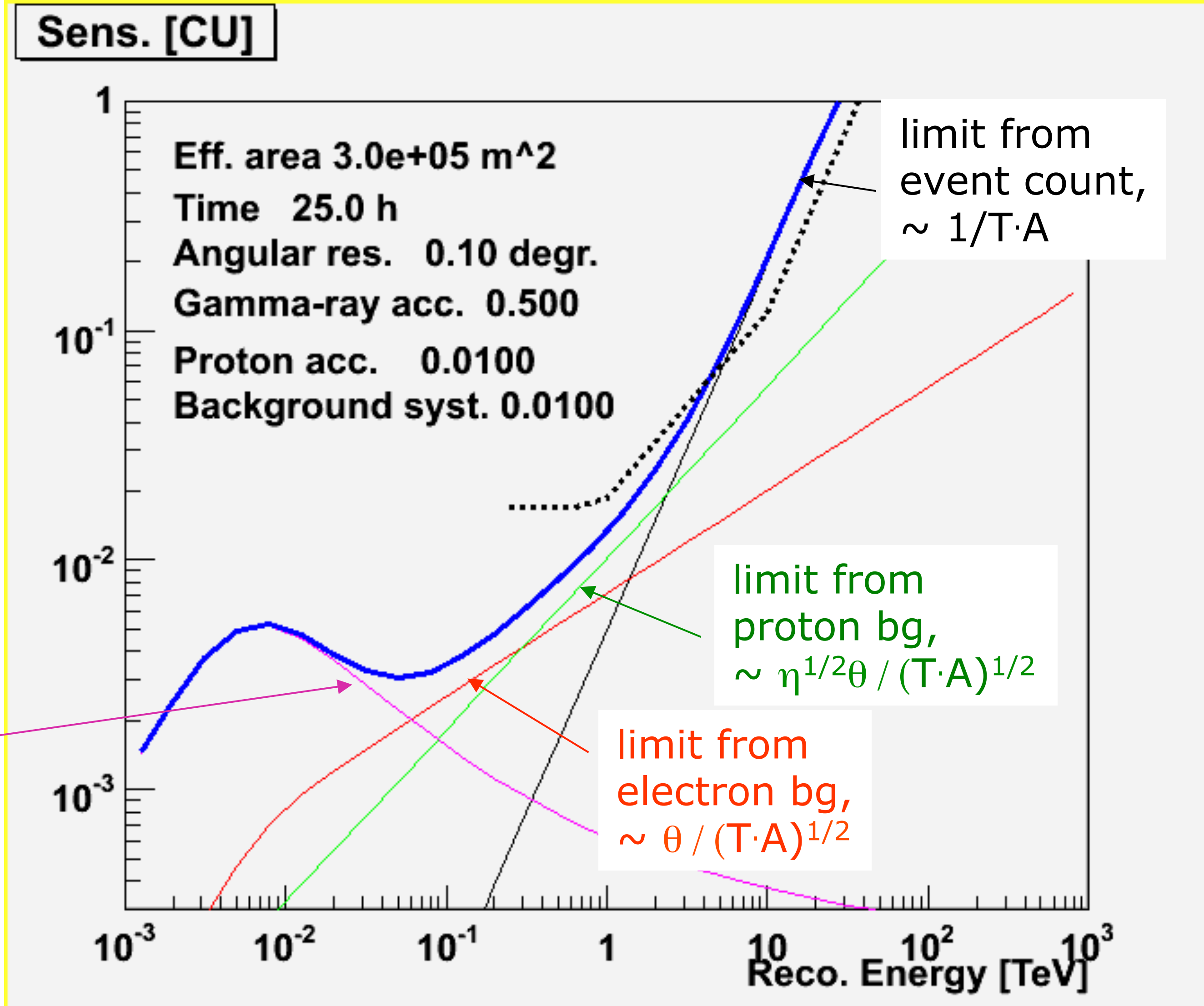
Significance ≅ #Signal/#Background$^{1/2}$:

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

Sensitivity in a toy model



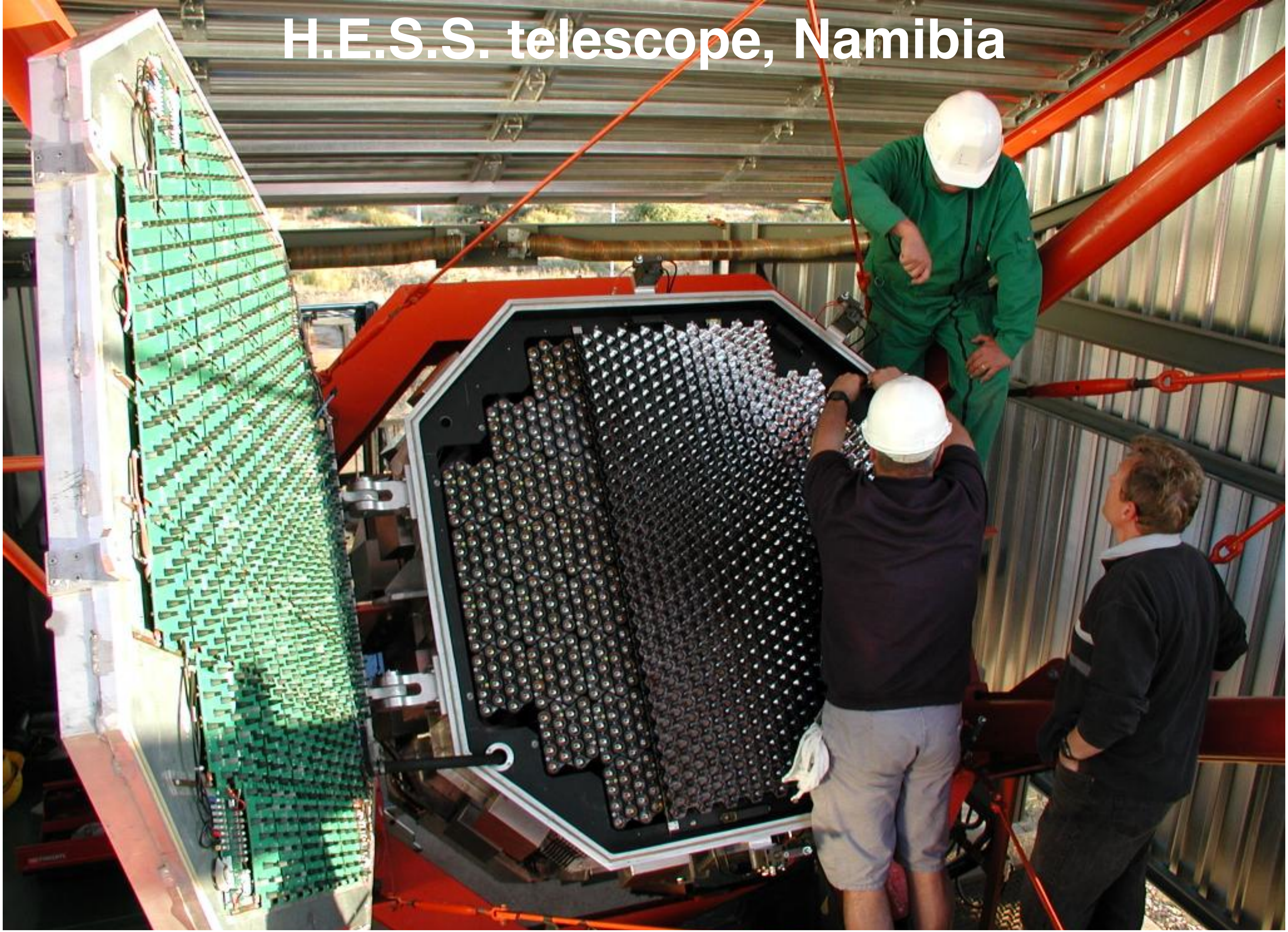
Minimal detectable flux per band $\Delta\log_{10}E=0.2$, relative to a power-law Crab spectrum



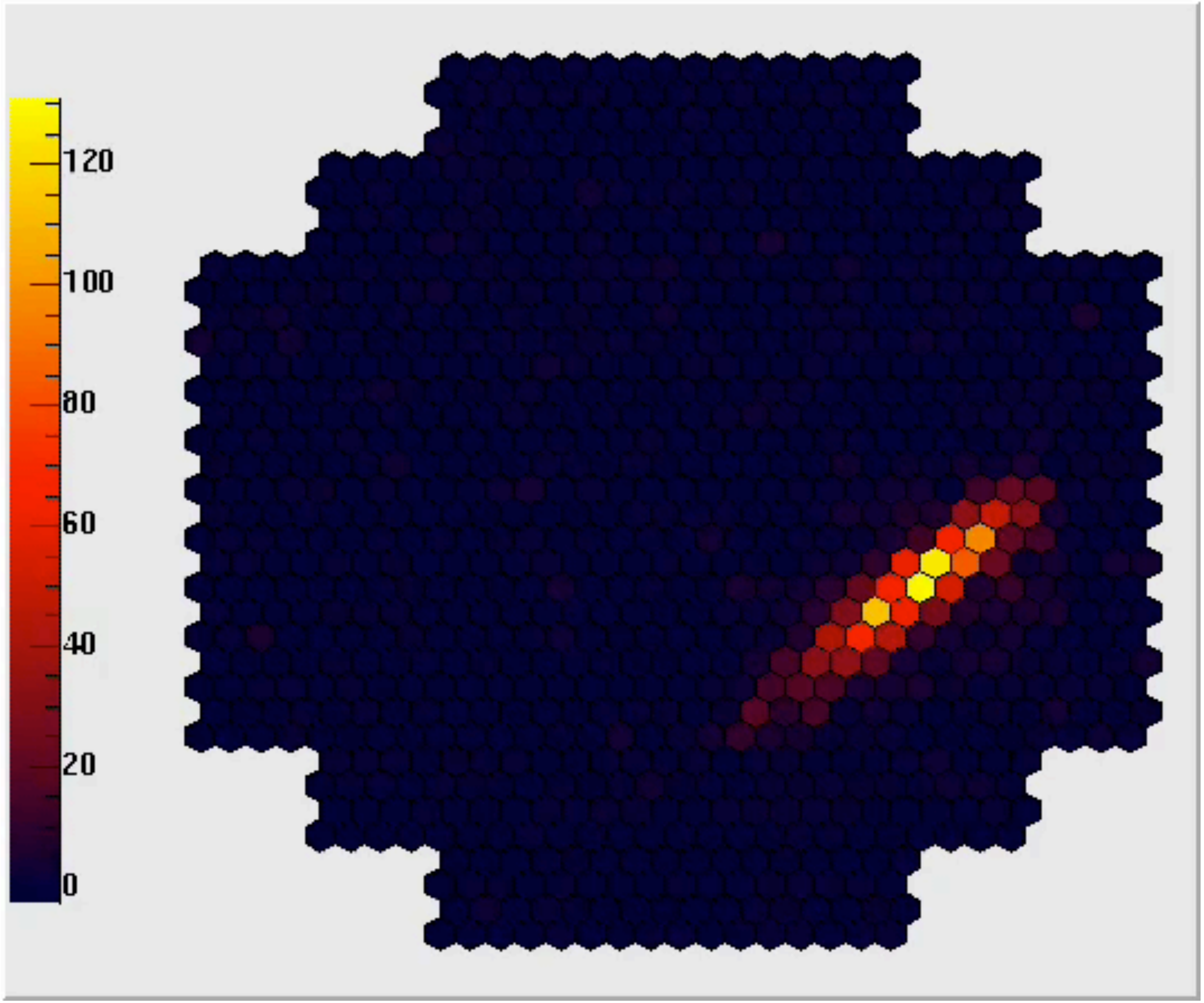
limit from syst. error on background, indep. of T,A; $\sim\theta^2$

H.E.S.S. telescope, Namibia

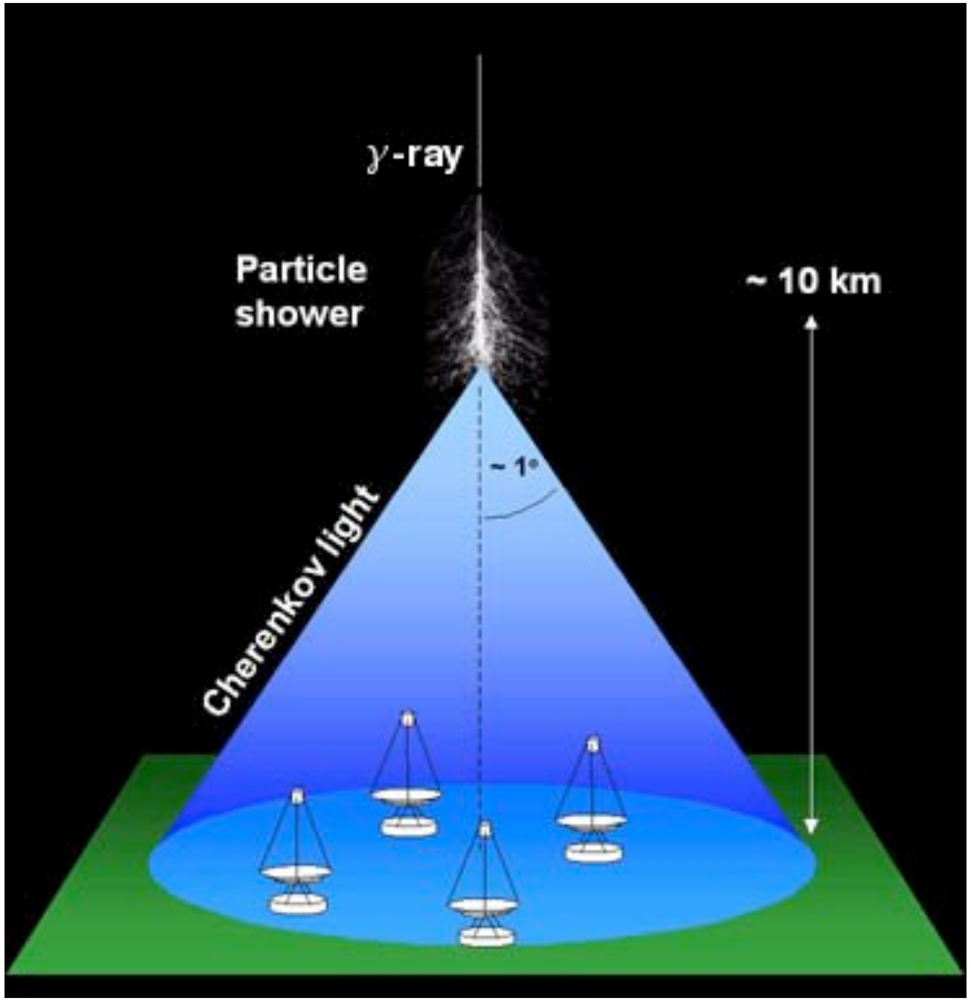
H.E.S.S. telescope, Namibia

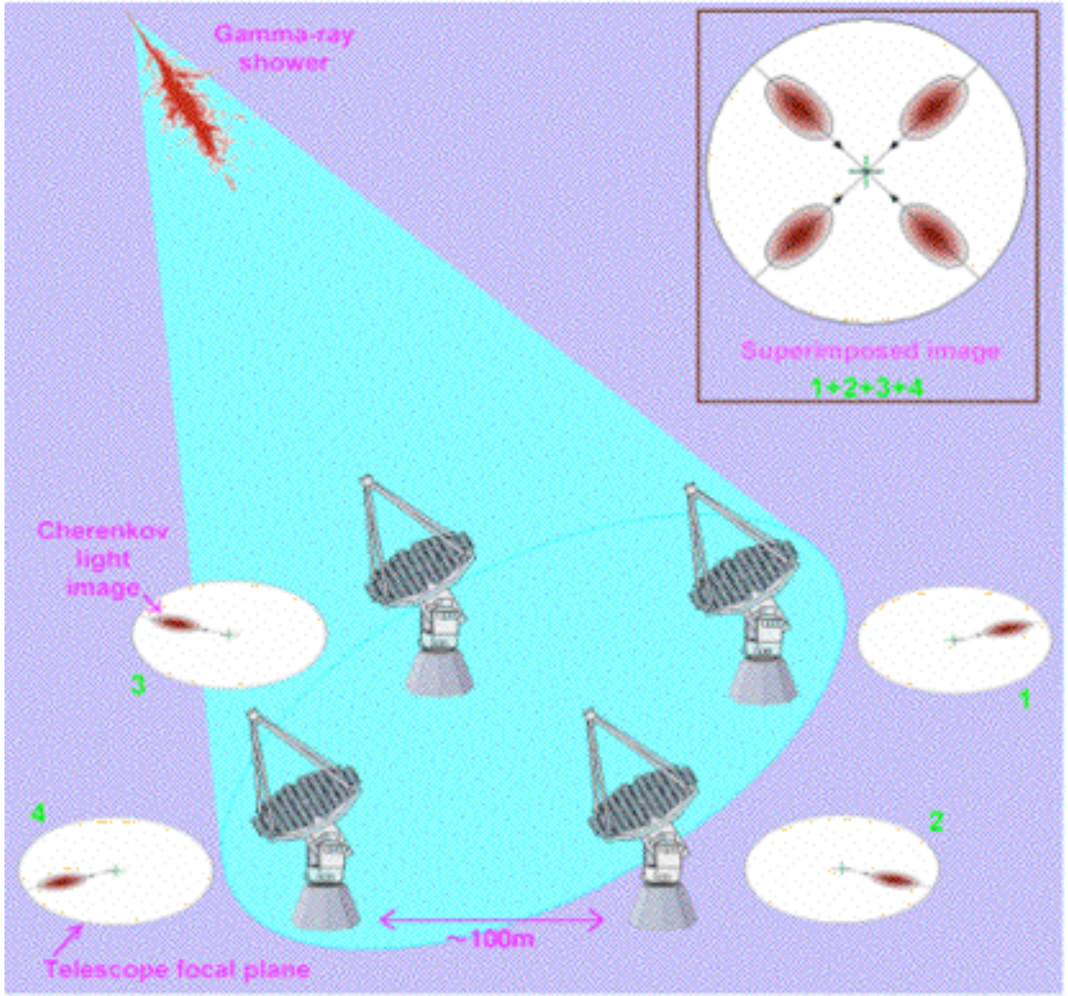


H.E.S.S. telescope, Namibia



stereo observation

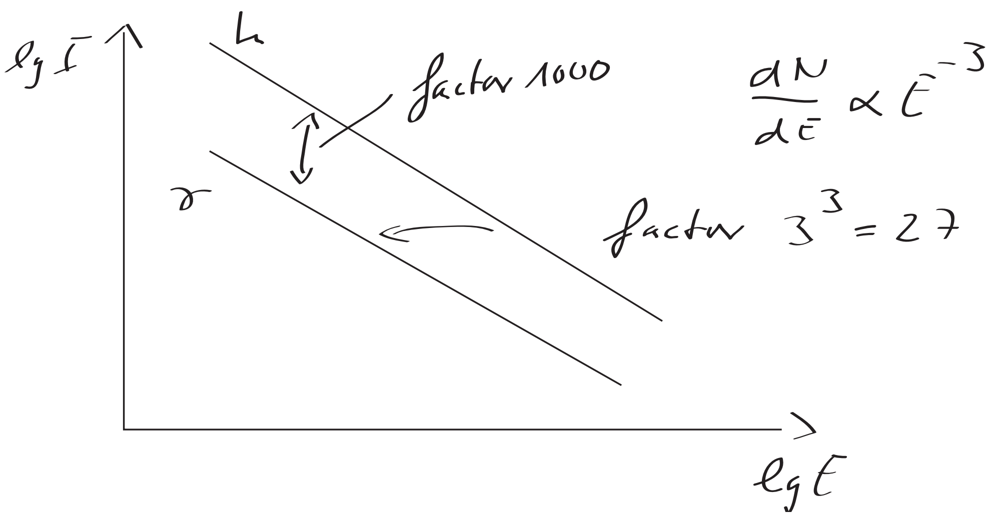




high background of hadronic particles

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

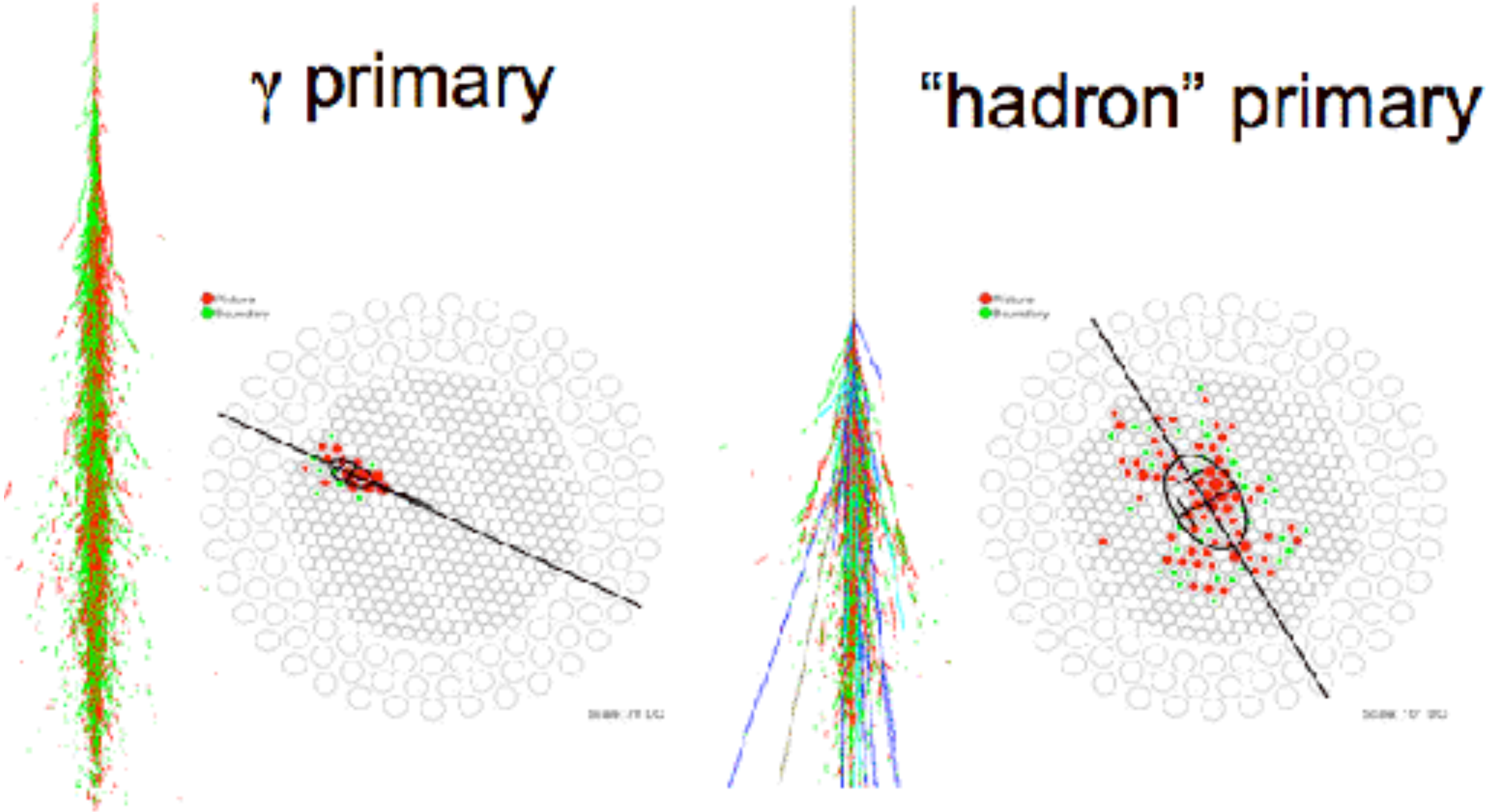
vs

radiation length

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

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

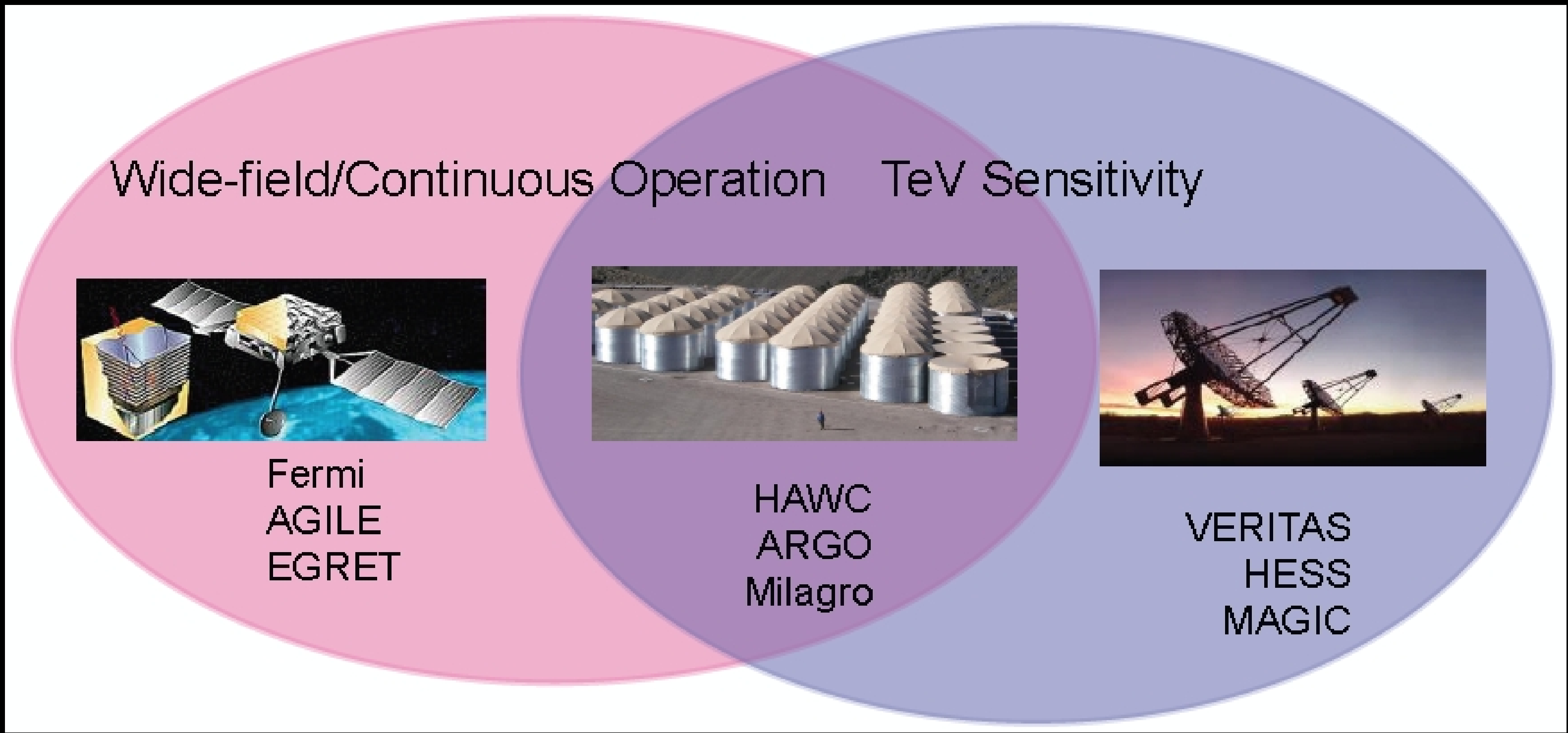
gamma-hadron separation



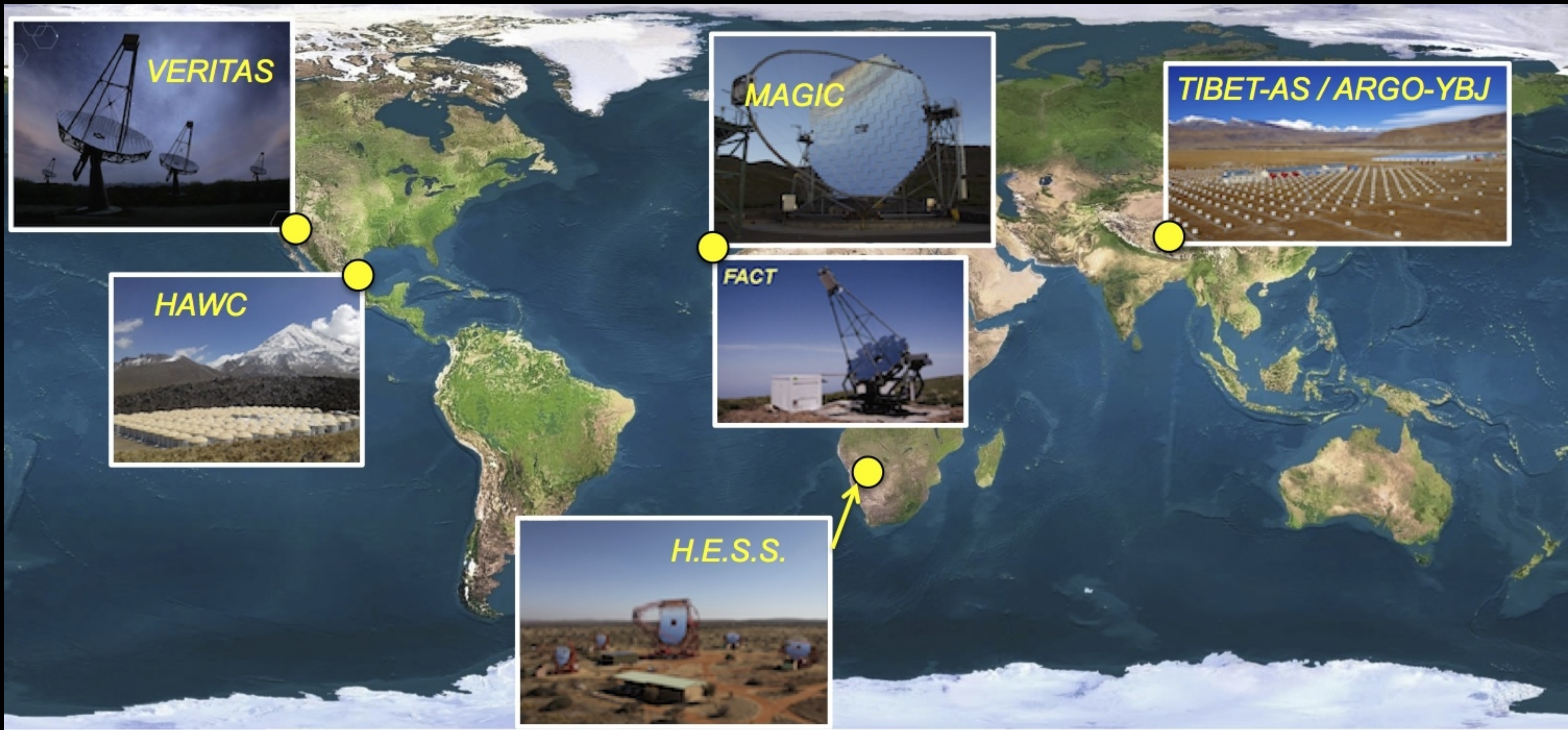
Complementarity of gamma-ray instruments

- 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 ~0.6° (@ 1 TeV)



INSTRUMENTS



Status of H.E.S.S. II

HESS is an array of four 12m IACTs + one 28m telescope (CT5, FoV ~ 3.5°)

CT5 is operationnal since 2012
Energy range from 30 GeV to 100 TeV
Focus system of CT5 under study => 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