Title: Particle/Astro Observations 2

Date: Jul 09, 2018 04:30 PM

URL: http://pirsa.org/18070023

Abstract:

multi-messenger identification of cosmic ray sources

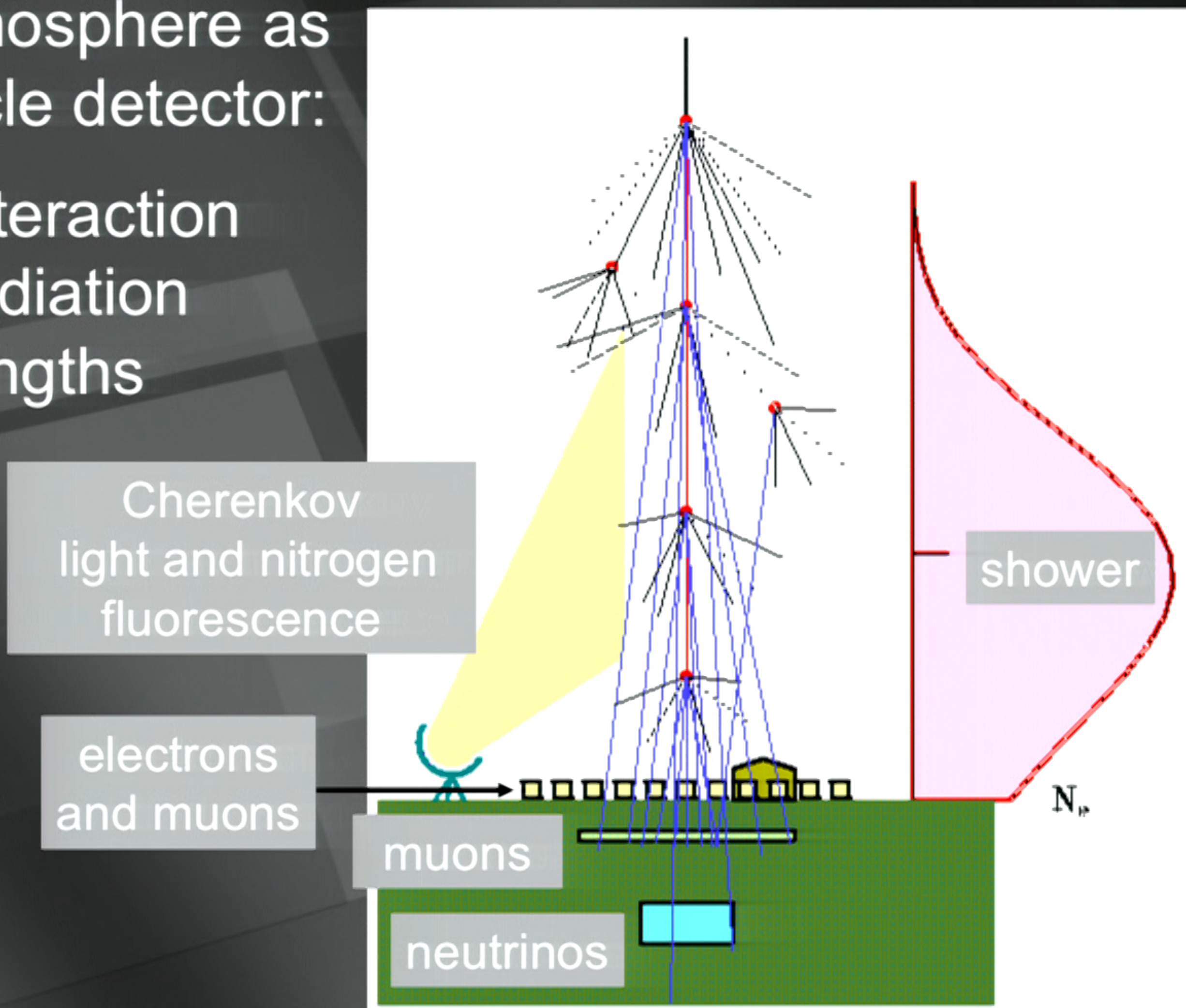
- **$\boxed{\text{cosmic rays}}$ with little magnetic deflection** *(flux very low near 10^{20} eV)*
- **associated pions produced in interactions close to the source and during propagation**

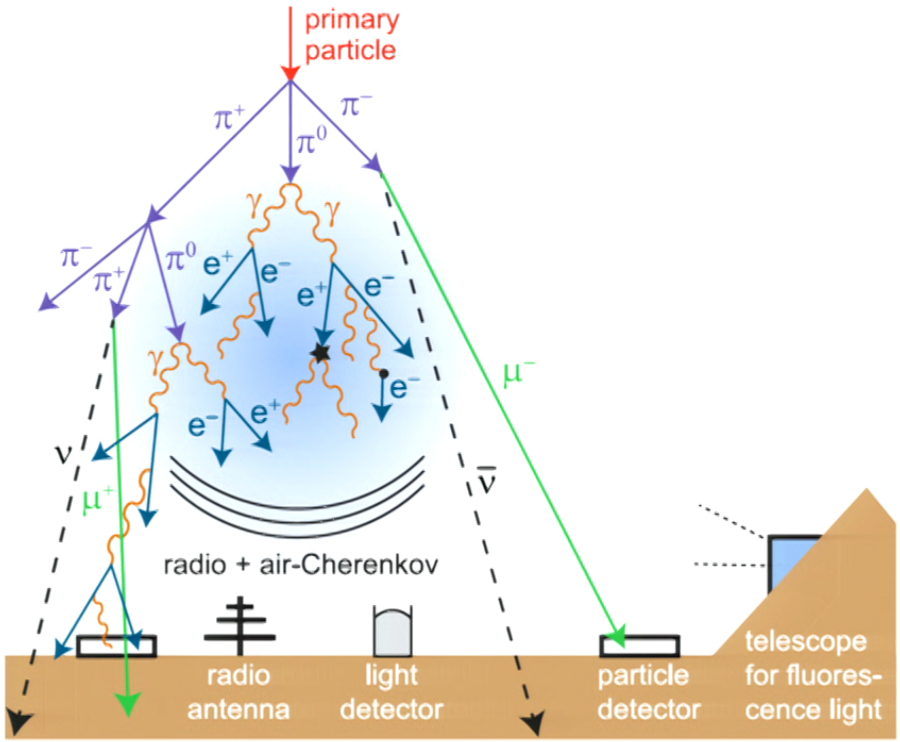
→ **$\boxed{\text{TeV photons:}}$** *difficult to disentangle from those produced by synchrotron radiation and inverse Compton scattering*

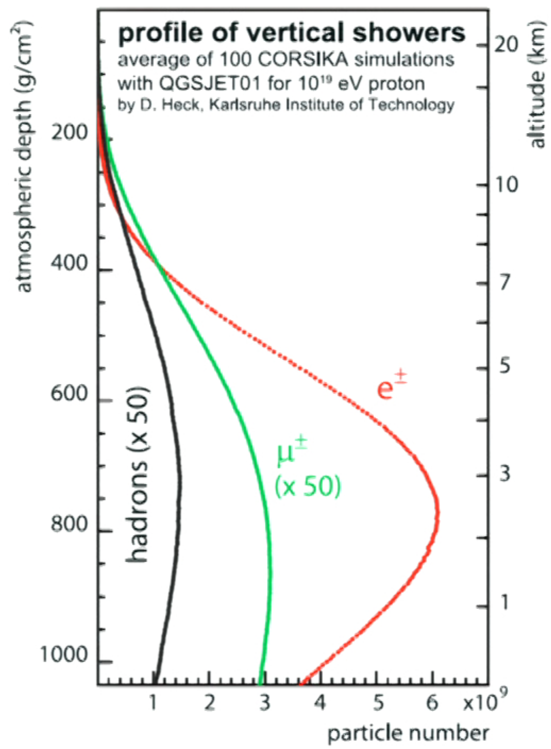
→ **$\boxed{\text{neutrinos:}}$** *difficult to detect (→ rationale for kilometer-scale detectors)*

the atmosphere as a particle detector:

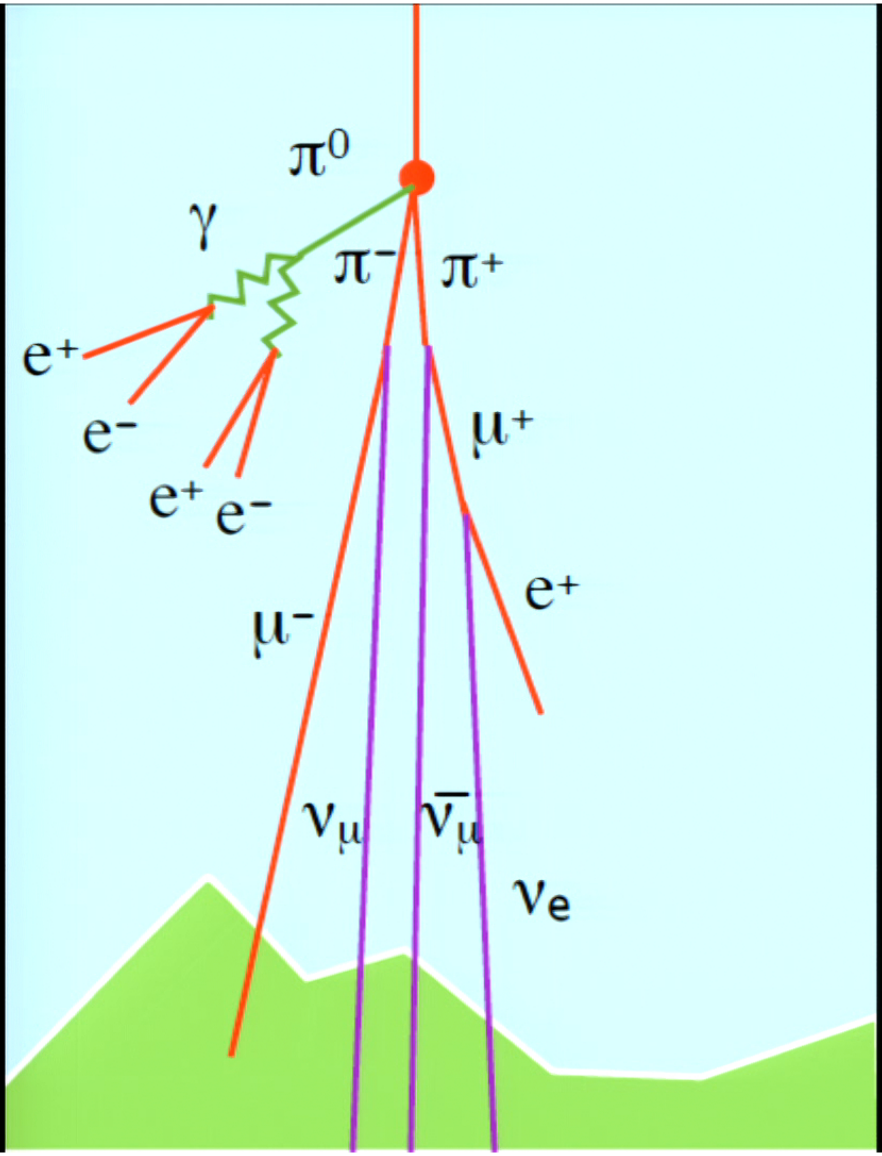
- 10 interaction
- 25 radiation lengths



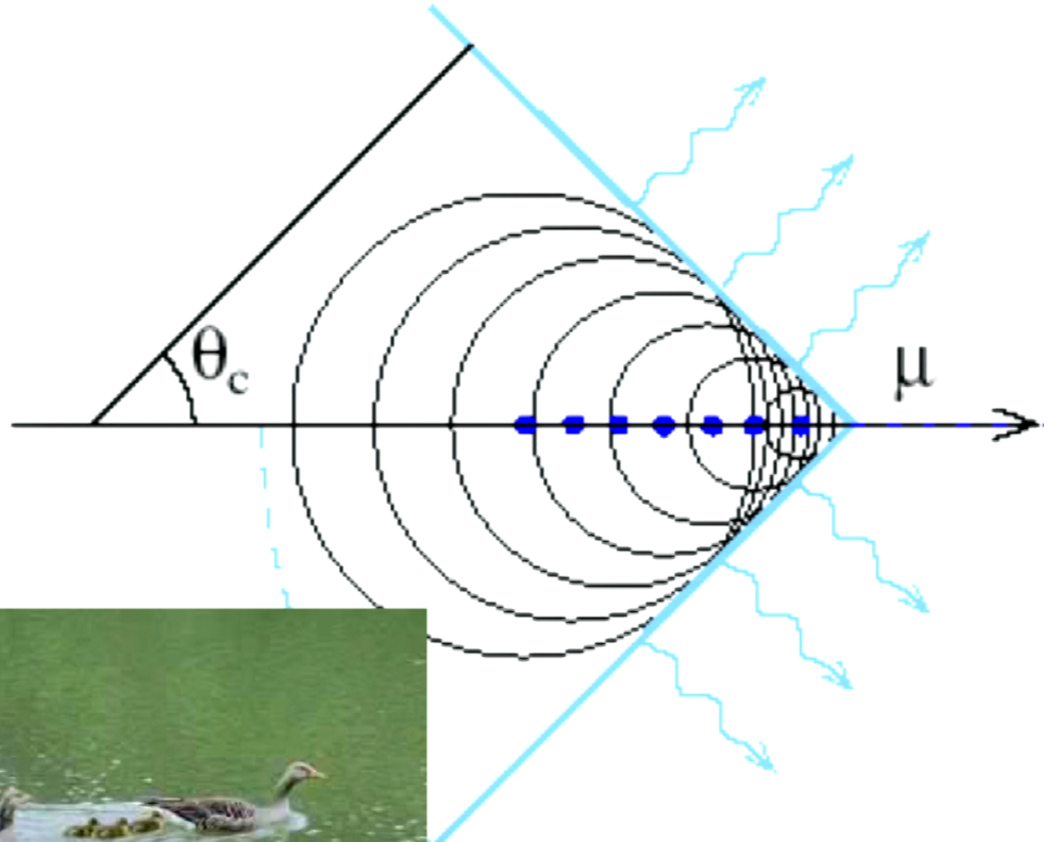

primary particle
π⁺
π⁰
π⁻
γ
e⁺
e⁻
μ⁻
μ⁺
ν
ν̄
radio + air-Cherenkov
radio antenna
light detector
particle detector
telescope for fluorescence light

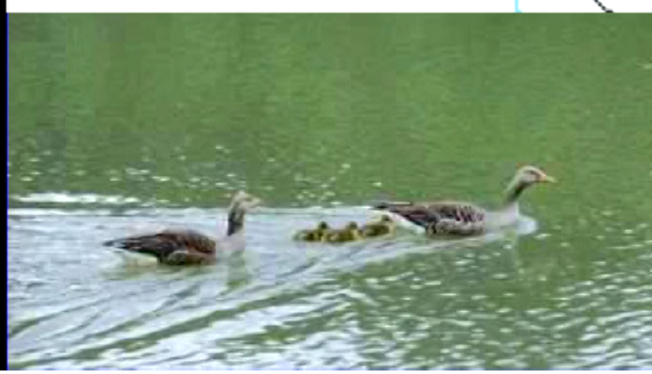

profile of vertical showers
average of 100 CORSIKA simulations with QGSJET01 for 10^19 eV proton
by D. Heck, Karlsruhe Institute of Technology
atmospheric depth (g/cm²)
altitude (km)
hadrons (x 50)
μ± (x 50)
e±
particle number
x10^9

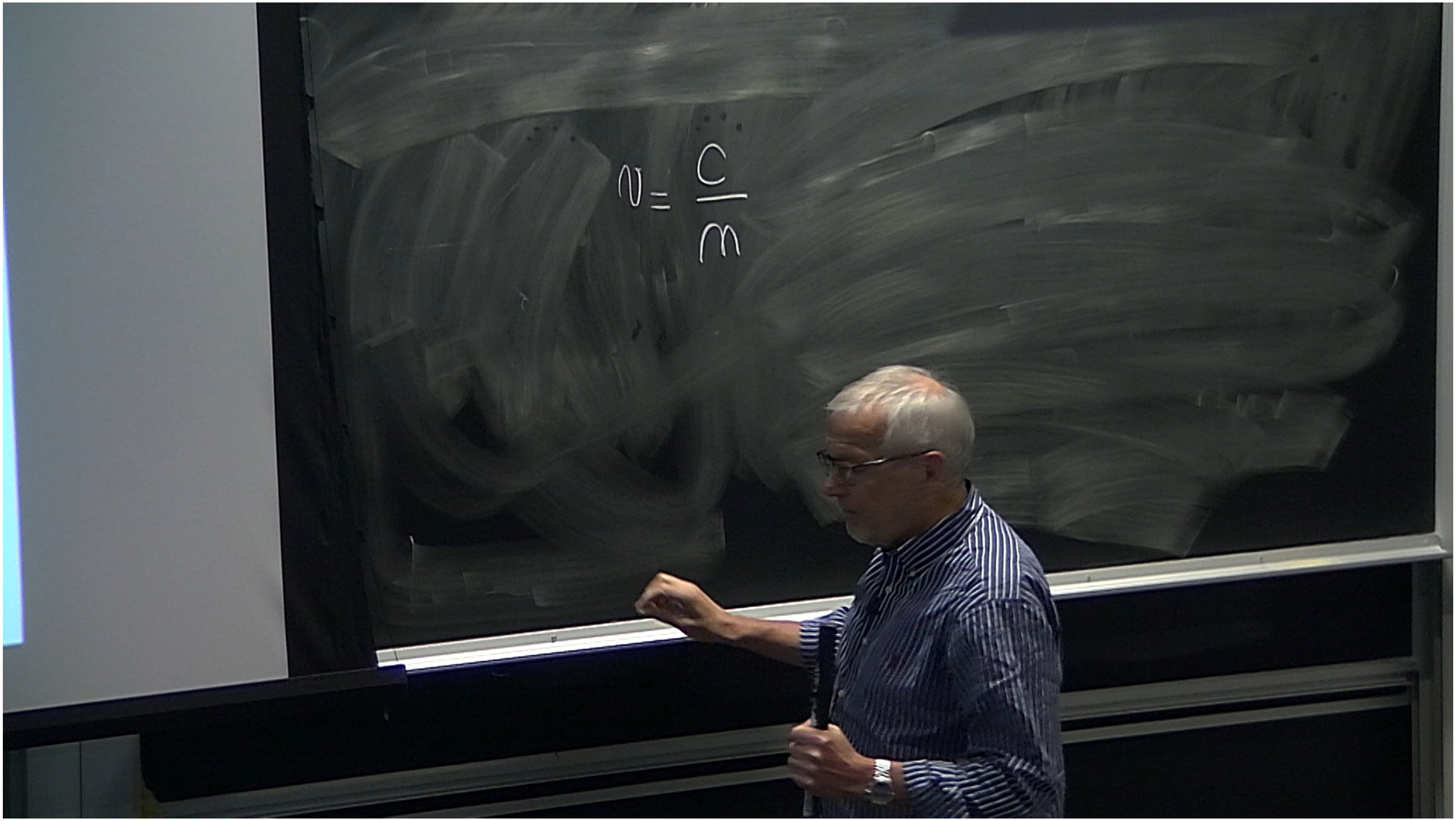
atmospheric muons
and
neutrinos



Cherenkov radiation: particle’s speed exceeds the speed of light






$v = \frac{c}{n}$

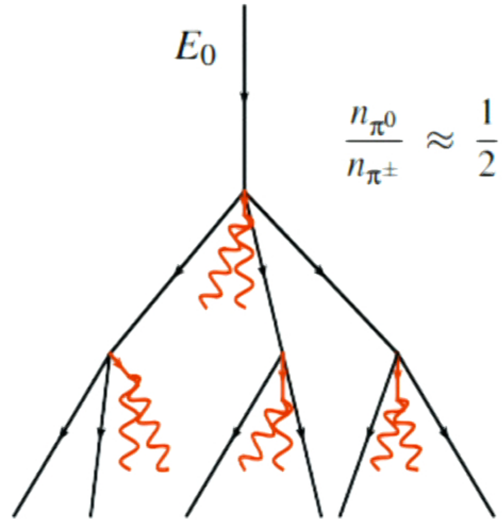
Hadronic energy

$$\frac{2}{3}E_0$$

$$\frac{2}{3}\left(\frac{2}{3}E_0\right)$$

$$\vdots$$

$$E_{\text{had}} = \left(\frac{2}{3}\right)^n E_0$$



$$\frac{n_{\pi^0}}{n_{\pi^\pm}} \approx \frac{1}{2}$$

Decay after n generations

$$E_{\pi^\pm} \sim 30\,\text{GeV}$$

$$n = 5, \quad E_{\text{had}} \sim 12\%$$
$$n = 6, \quad E_{\text{had}} \sim 8\%$$

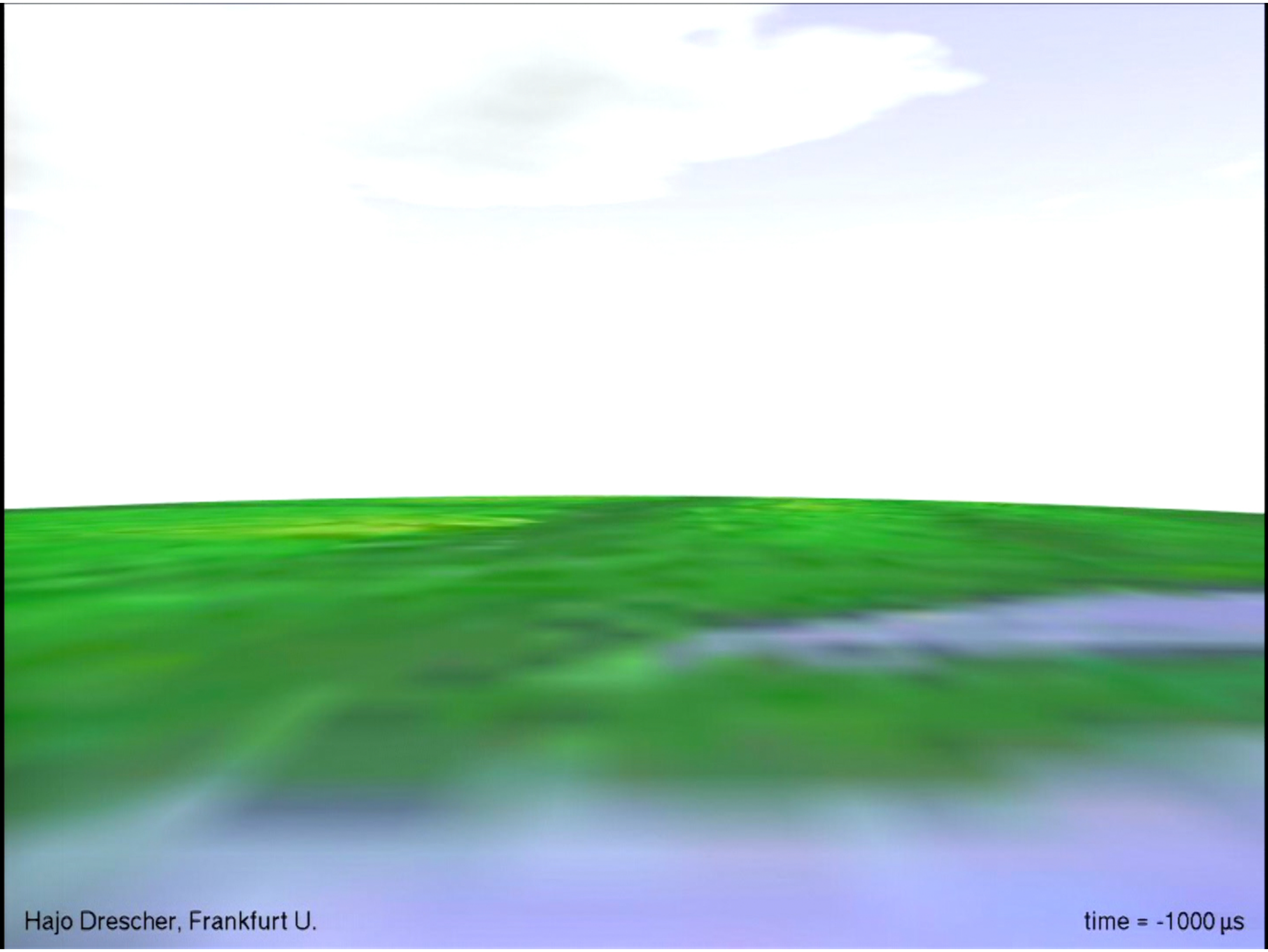
Electromagnetic energy

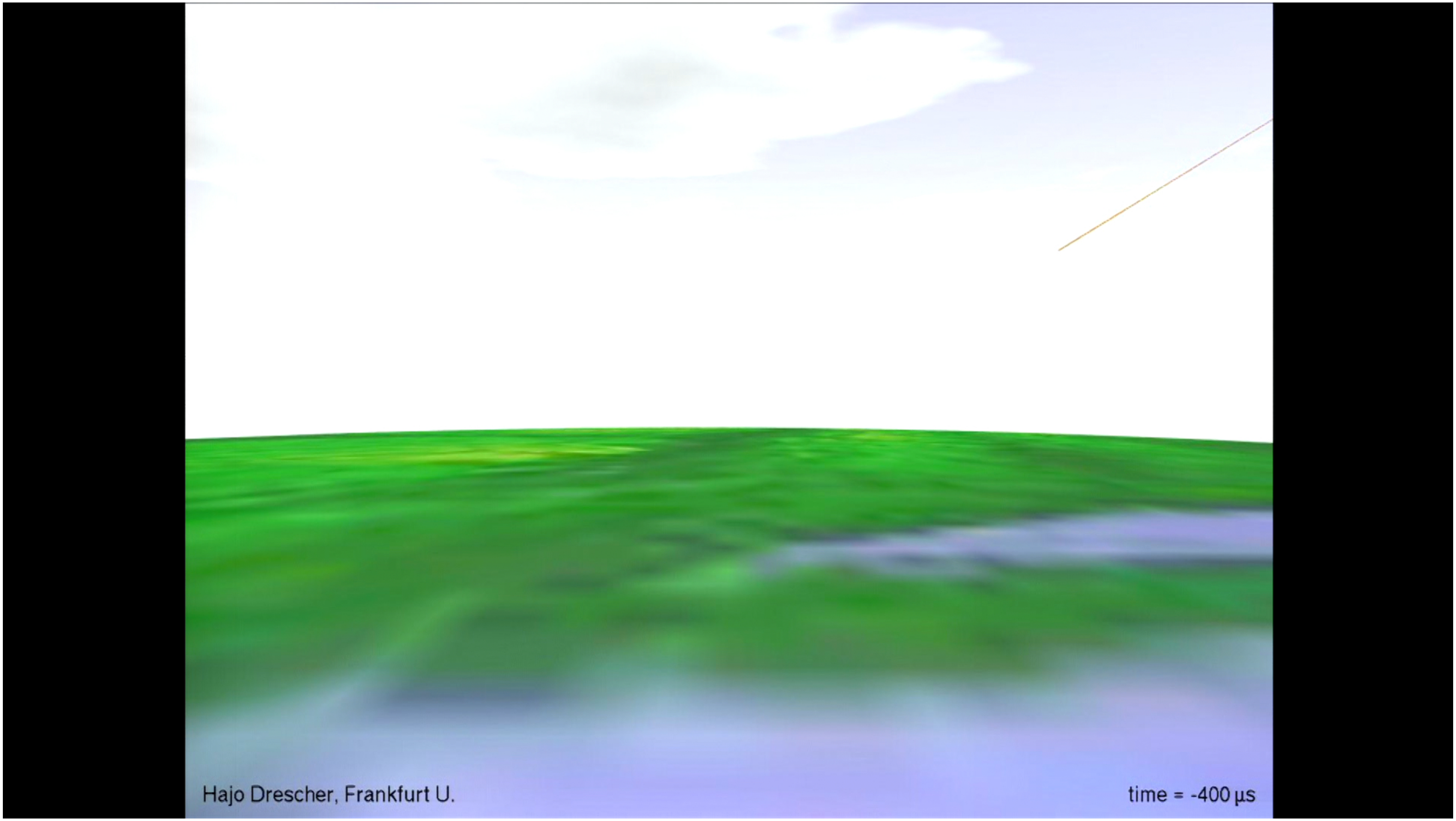
$$\frac{1}{3}E_0$$

$$\frac{1}{3}E_0 + \frac{1}{3}\left(\frac{2}{3}E_0\right)$$

$$\vdots$$

$$E_{\text{em}} = \left[1 - \left(\frac{2}{3}\right)^n\right] E_0$$


Hajo Drescher, Frankfurt U.
time = -1000 μs


Hajo Drescher, Frankfurt U.
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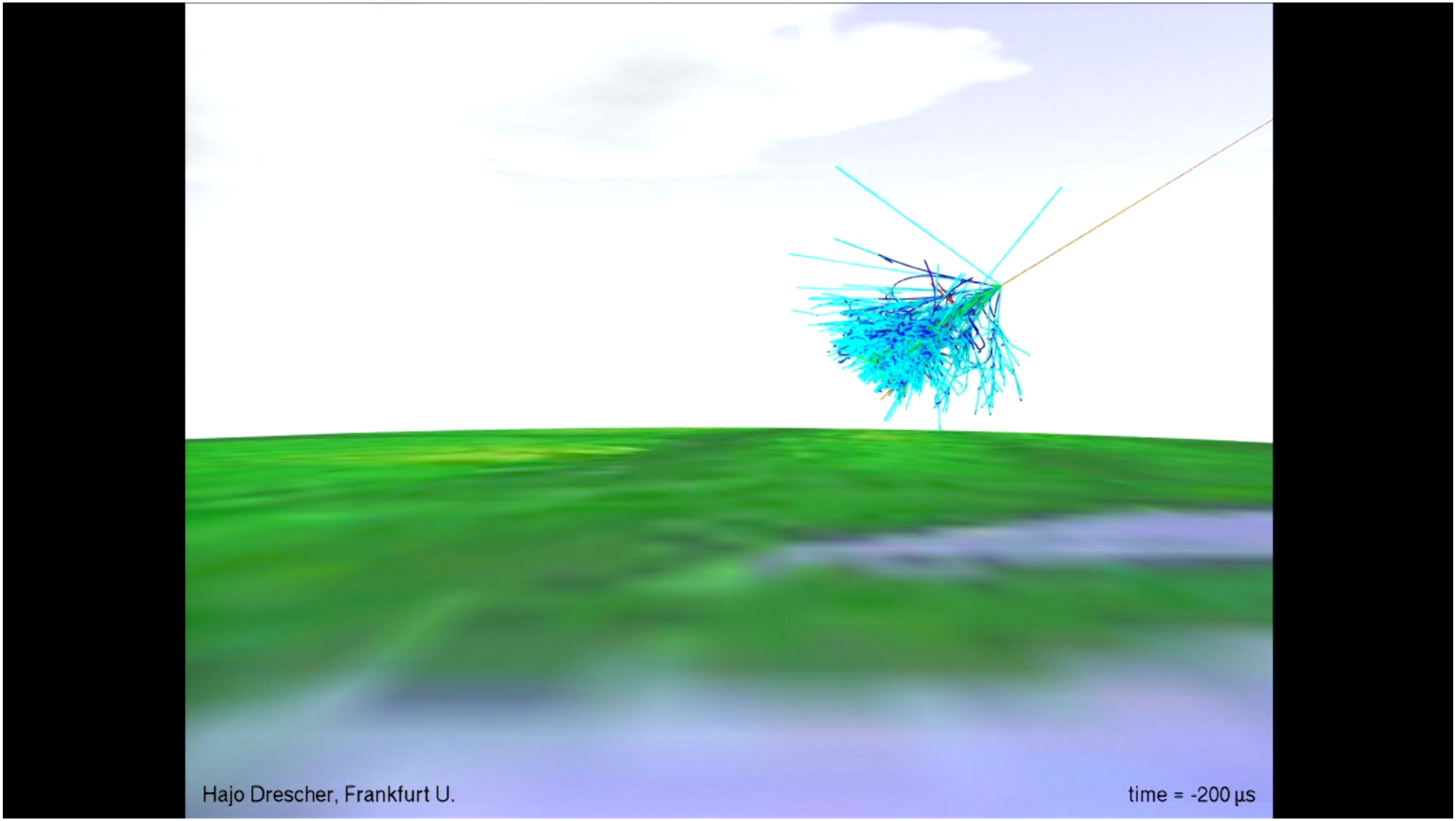
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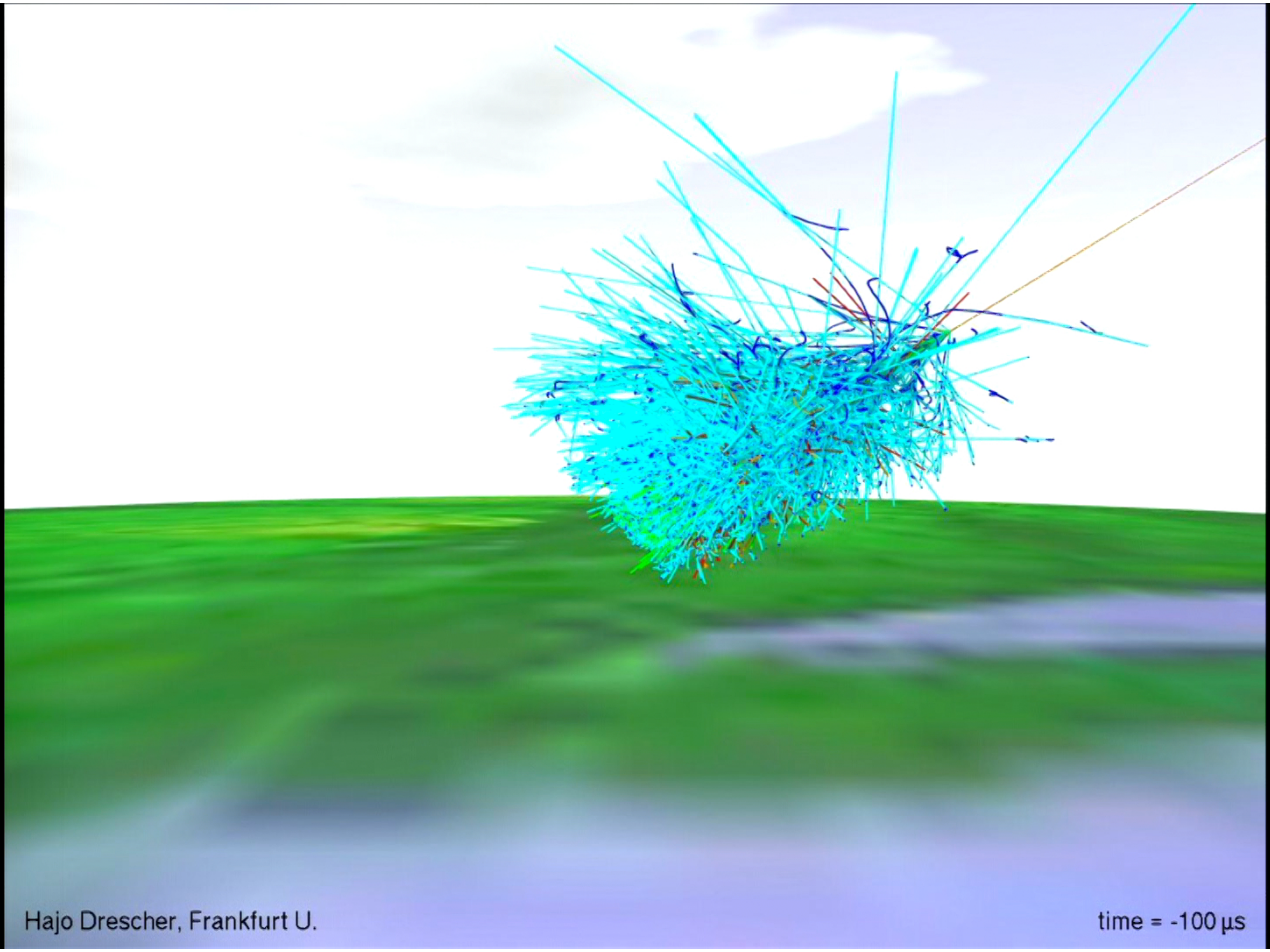
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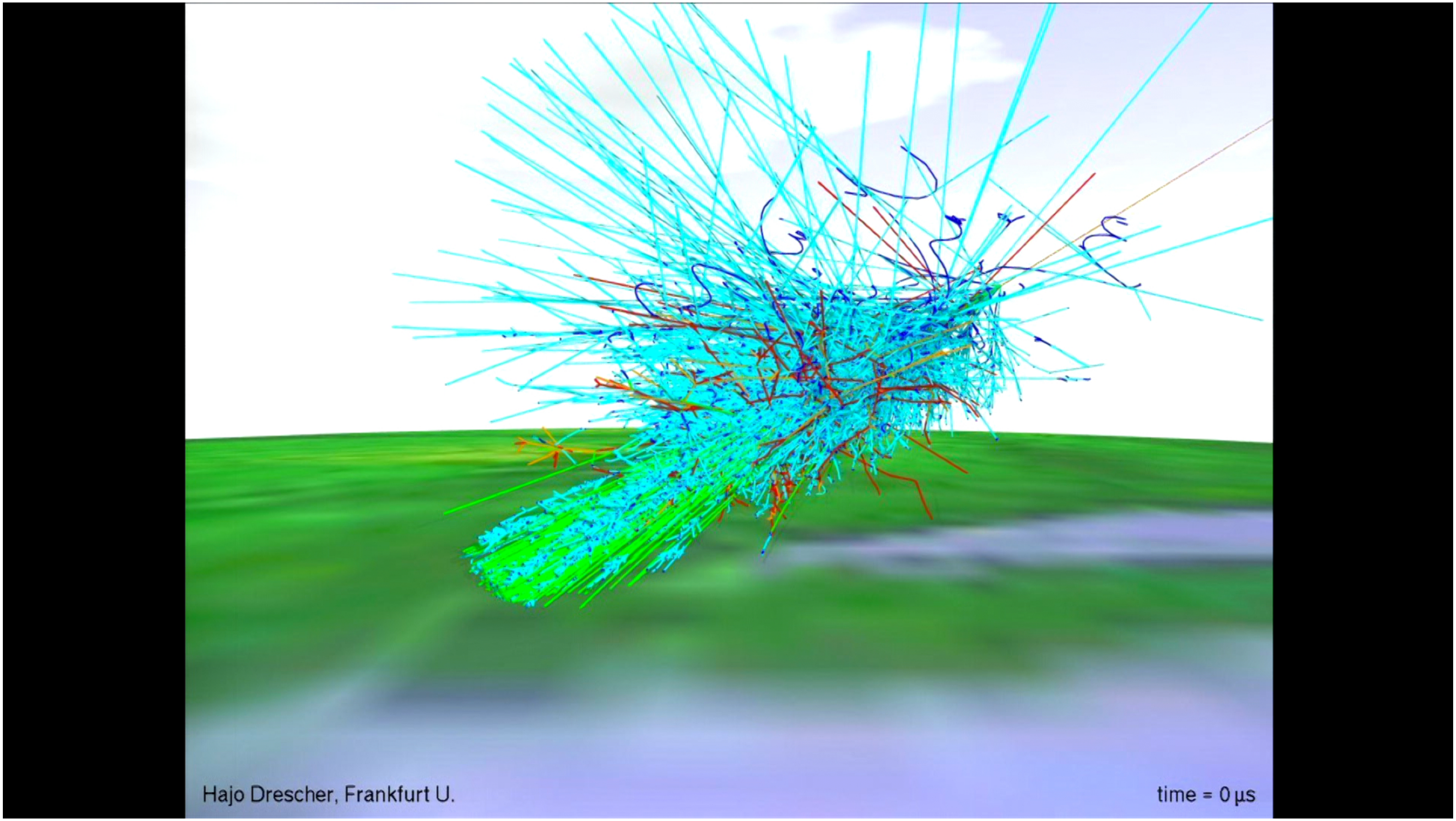
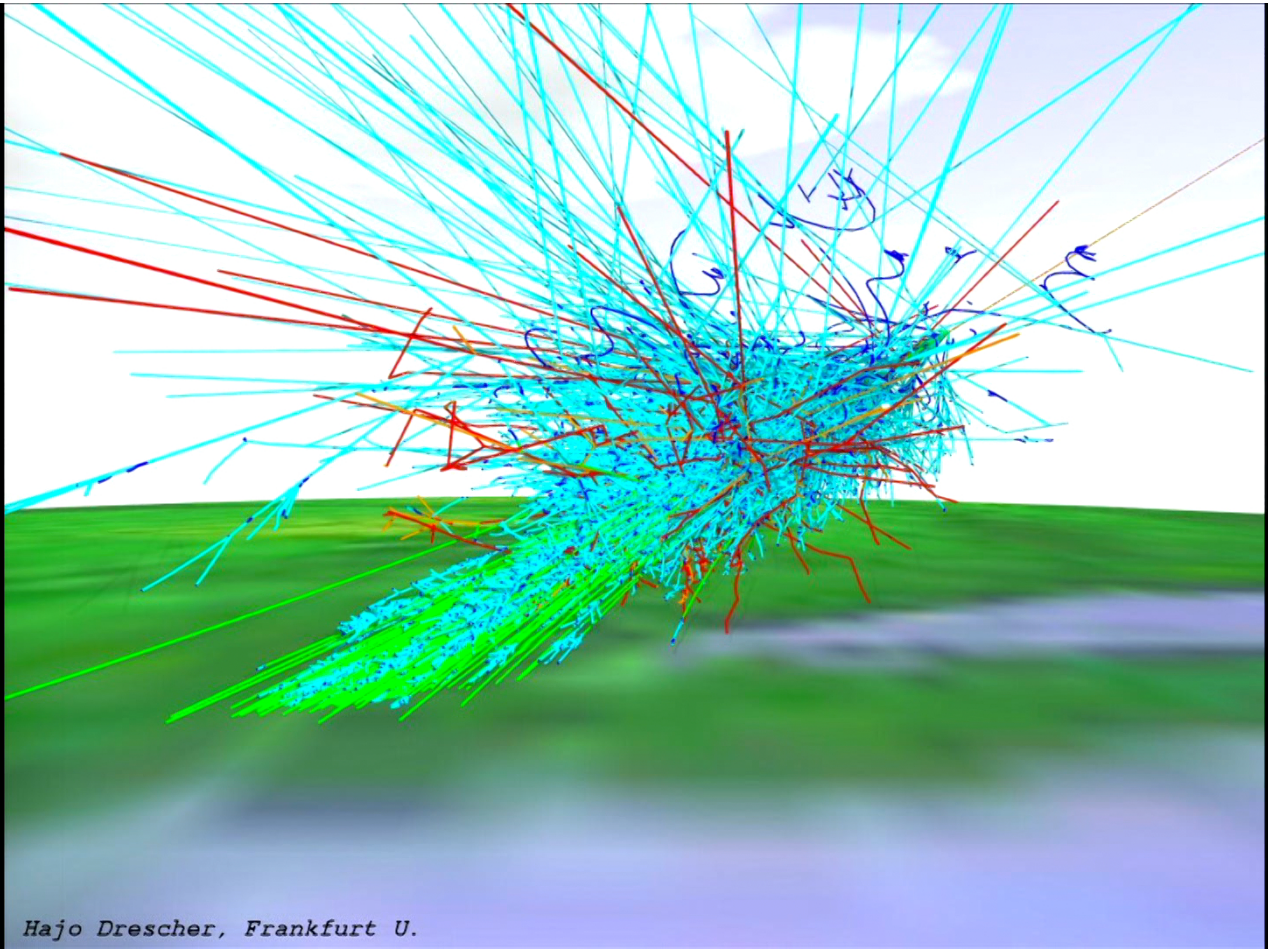
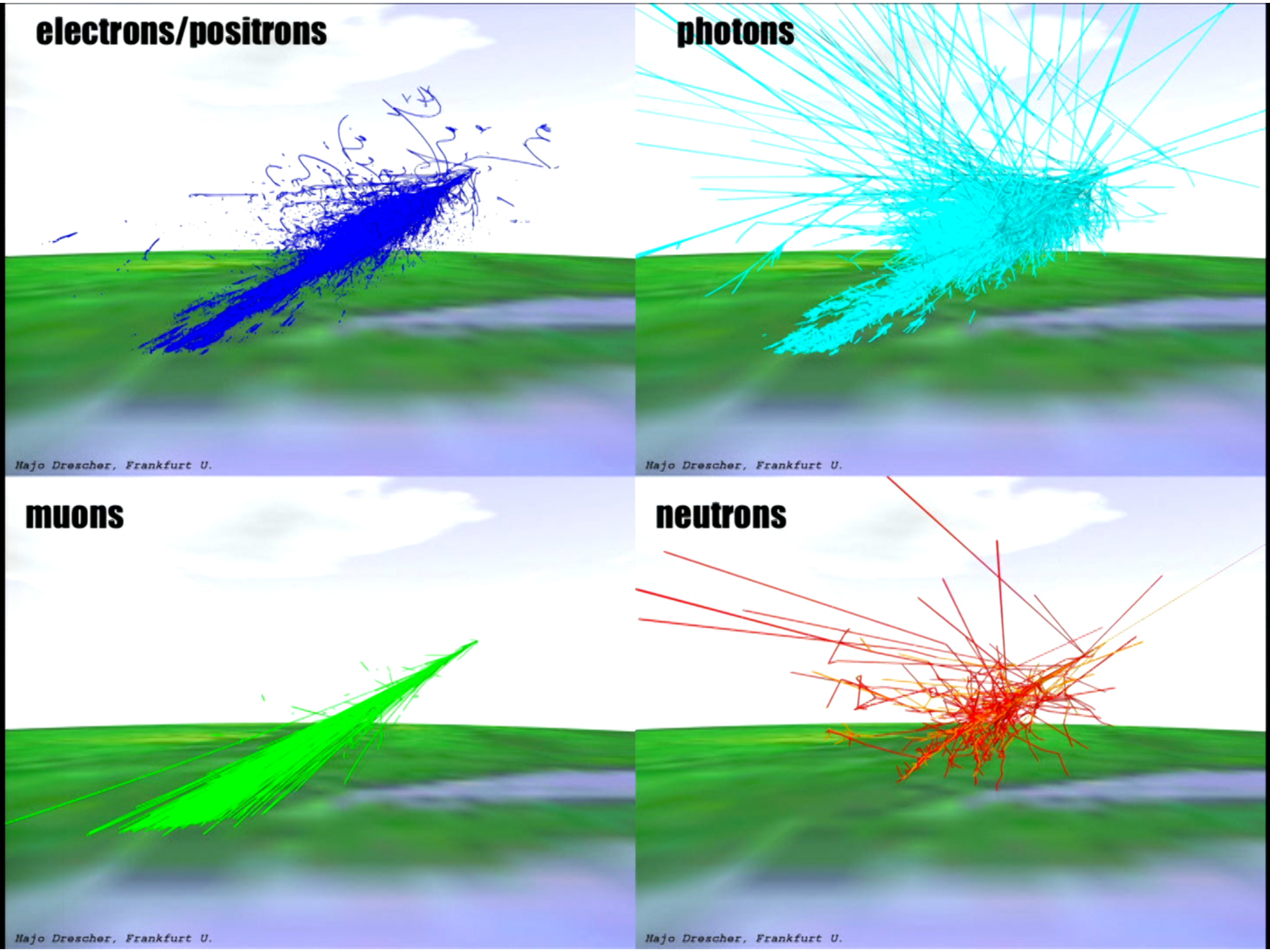
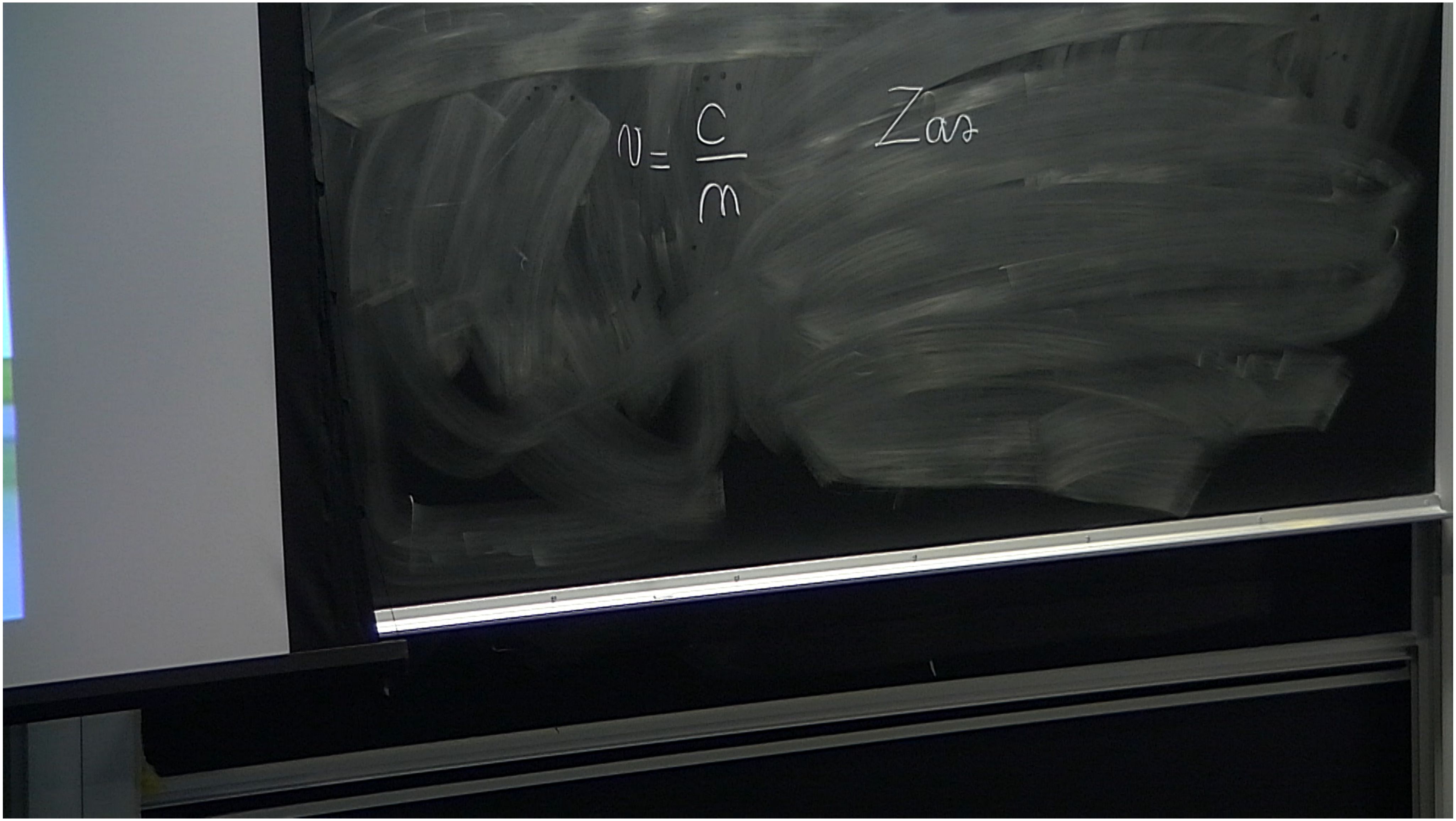

Hajo Drescher, Frankfurt U.
time = 0 μs


Hajo Drescher, Frankfurt U.


electrons/positrons
photons
muons
neutrons
Hajo Drescher, Frankfurt U.
Hajo Drescher, Frankfurt U.
Hajo Drescher, Frankfurt U.
Hajo Drescher, Frankfurt U.


$v = \frac{c}{m}$
Zaz

air showers

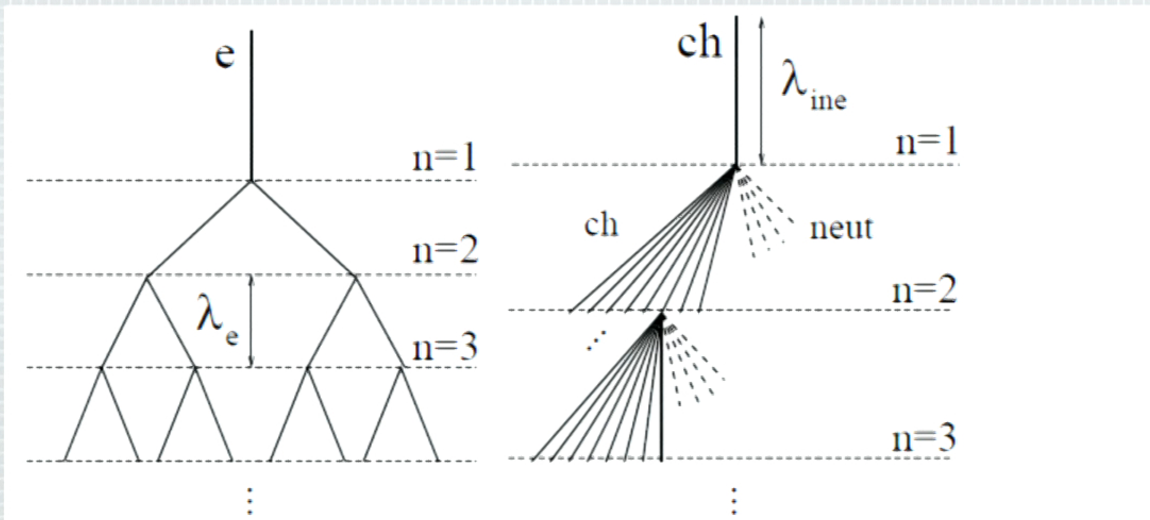
- the atmosphere is a detector with a total depth of 25 radiation length (λ_e) and 10 interaction length (λ_{ine}).

- an electromagnetic shower penetrates N radiation lengths until the particle energy is reduced to the critical energy of E_c~85 MeV at which the shower is absorbed in the atmosphere by e ionization. It is observed by the detection of electrons, positrons and (mostly) photons.

- a hadronic showers travels N' interaction lengths producing pions down to an energy ε_π where the pion interaction length is shorter than its decay length. At that point muon production stops.

electromagnetic showers

cross sections for γ + air → e^++e^- and e + air → γ+e are approximately equal



electromagnetic showers

$$number\ of\ \ particles\ n\ after\ N\ steps; \quad depth\ X = N\,\lambda_e$$

$$n\left(X\right) = 2^N = 2^{\frac{X}{\lambda_e}} \quad and \quad E\left(X\right) = \frac{E_i}{2^N} = \frac{E_i}{2^{\frac{X}{\lambda_e}}}$$

$$after\ complete\ development \quad N_{\max} = \lambda_e\, X_{\max}$$

$$E\left(X_{\max}\right) = E_c = \frac{E_i}{2^{\frac{X_{\max}}{\lambda_e}}} \quad \rightarrow \quad n_{\max} = 2^{N_{\max}} = 2^{\frac{X_{\max}}{\lambda_e}} = \frac{E_i}{E_c}$$

$$therefore$$

$$X_{\max} \approx \lambda_e \ln\frac{E_i}{E_c} \quad and \quad n_{\max} = \frac{E_i}{E_c}$$

hadronic showers

$$\lambda_e \quad \gamma \rightarrow e^+ + e^-$$

$$\lambda_{ine} \quad p \rightarrow n\left(\pi^0 + \pi^+ + \pi^-\right) \quad with \quad \pi^0 \rightarrow \gamma + \gamma \rightarrow em\,shower$$

$$\pi^{ch} \rightarrow \mu + \nu_\mu \rightarrow muons$$

$$E_{had} = \left(\frac{2}{3}\right)^N E_i \quad and \quad E_{em} = \left[1 - \left(\frac{2}{3}\right)^N\right] E_i$$

$$electromagnetic\ shower \rightarrow dictates\ total\ depth$$

$$X_{\max}^{em} = \lambda_{ine} + X_{\max}^{e} \approx \lambda_{ine} + \lambda_e \ln\left(\frac{E_i}{n E_c}\right)$$

$$hadronic\ shower: N\lambda_{ine}\ from\ E_i \rightarrow \varepsilon_\pi \approx 150\,GeV$$

$$\varepsilon_\pi = \frac{E_i}{n^N} \quad \rightarrow n_\mu = n_{ch}^N \equiv \left(\frac{E_i}{\varepsilon_\pi}\right)^\alpha \quad with\ \alpha = \frac{\ln n_{ch}}{\ln n} \approx 0.82 - 0.95$$

progress through instrumentation

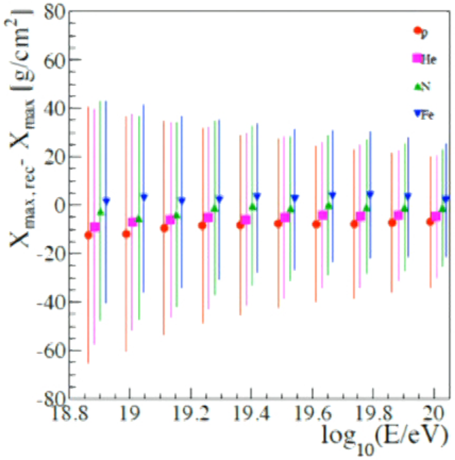
- Auger, Telescope Array …
- HESS, Magic, Veritas, Milagro, Tibet, Argo … HAWC
- IceCube, KM3NeT, GVD

Outlook: Upgrade of the Pierre Auger Observatory

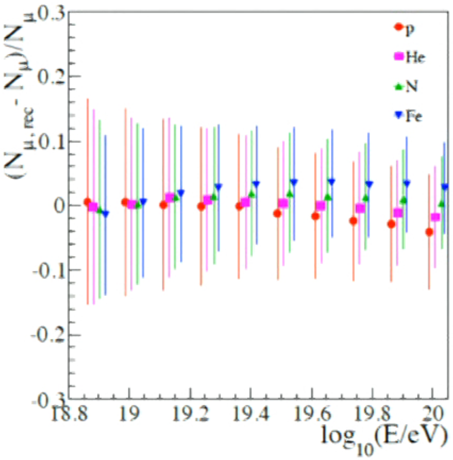
additional scintillators (4 m^2)

$\rightarrow$ event-by-event mass estimate, 100% duty cycle

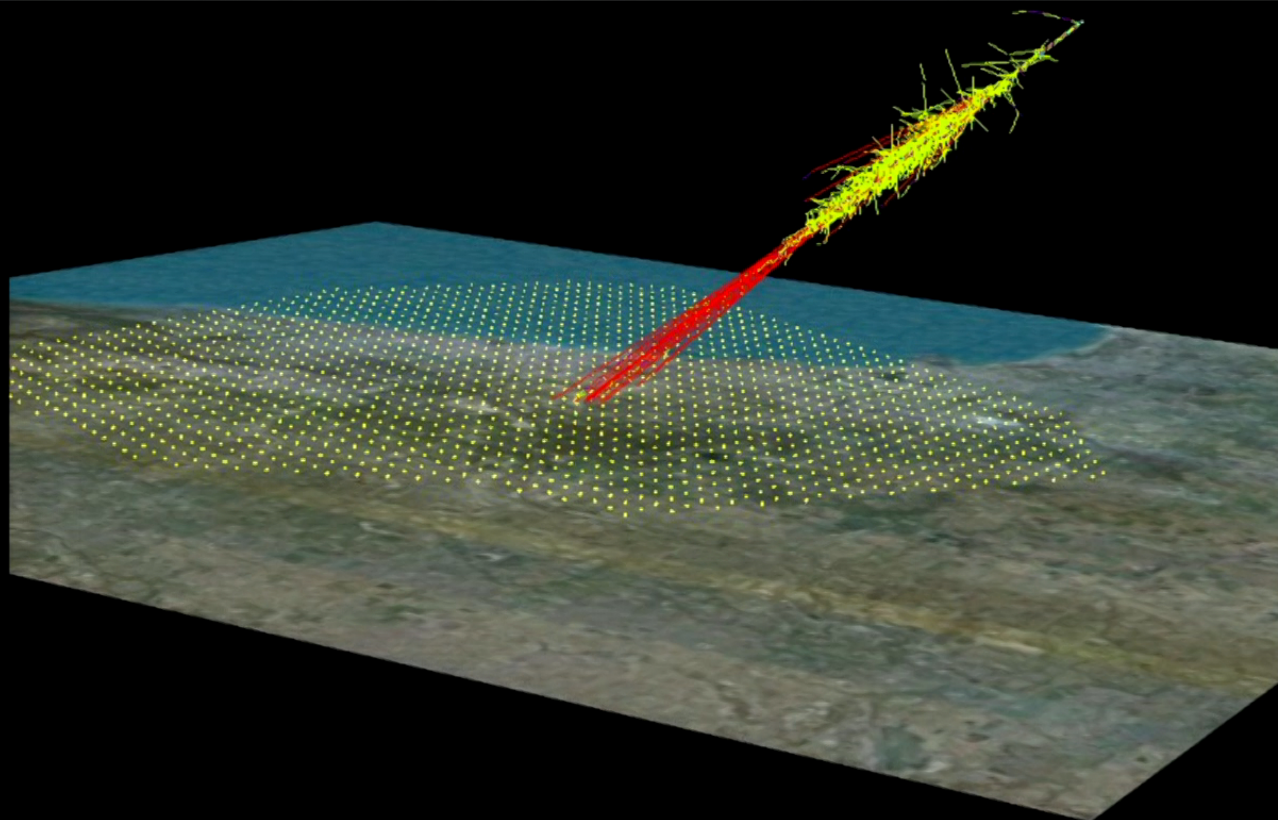
$X_{\max}$ determination:



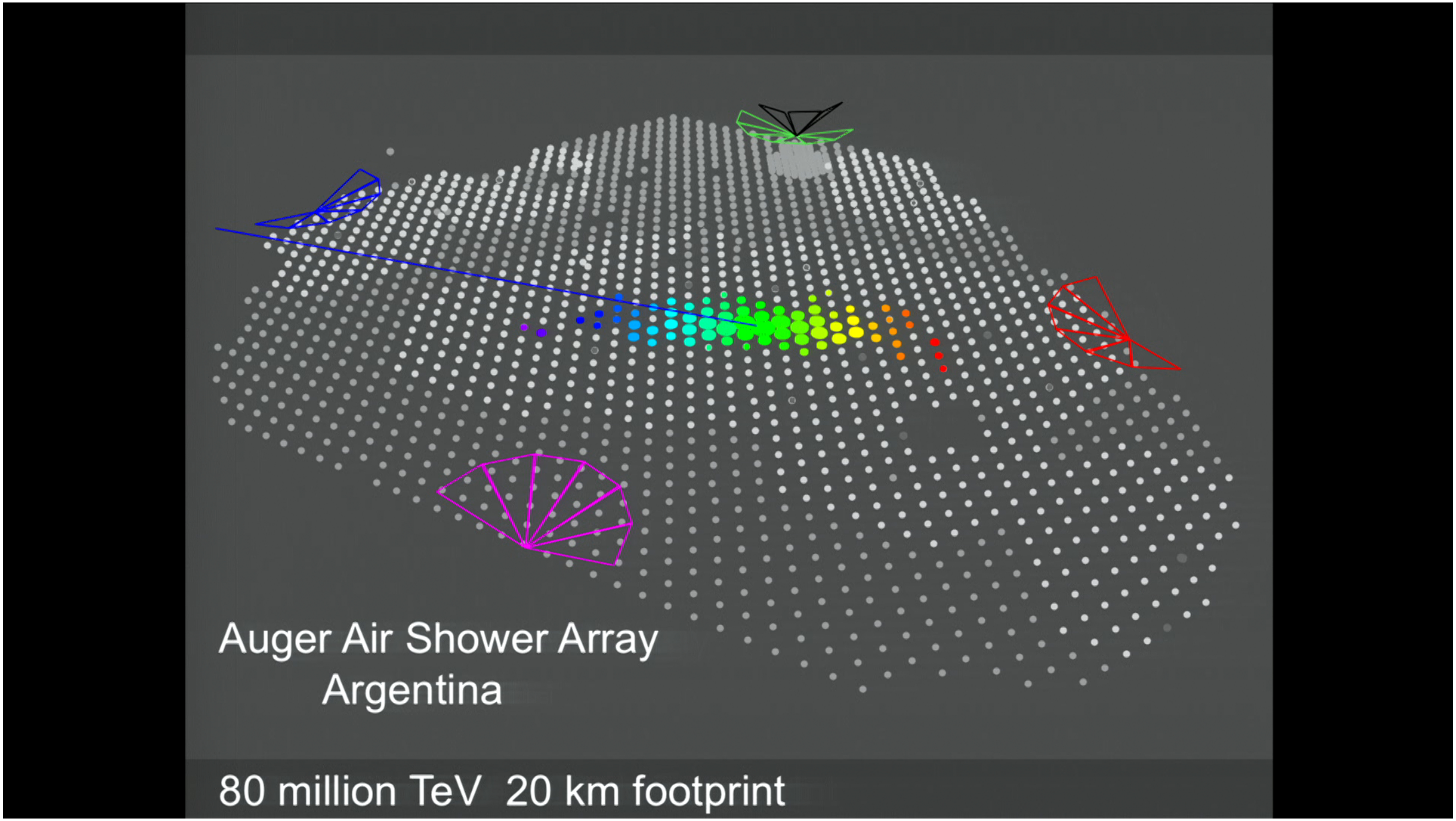
muon determination:



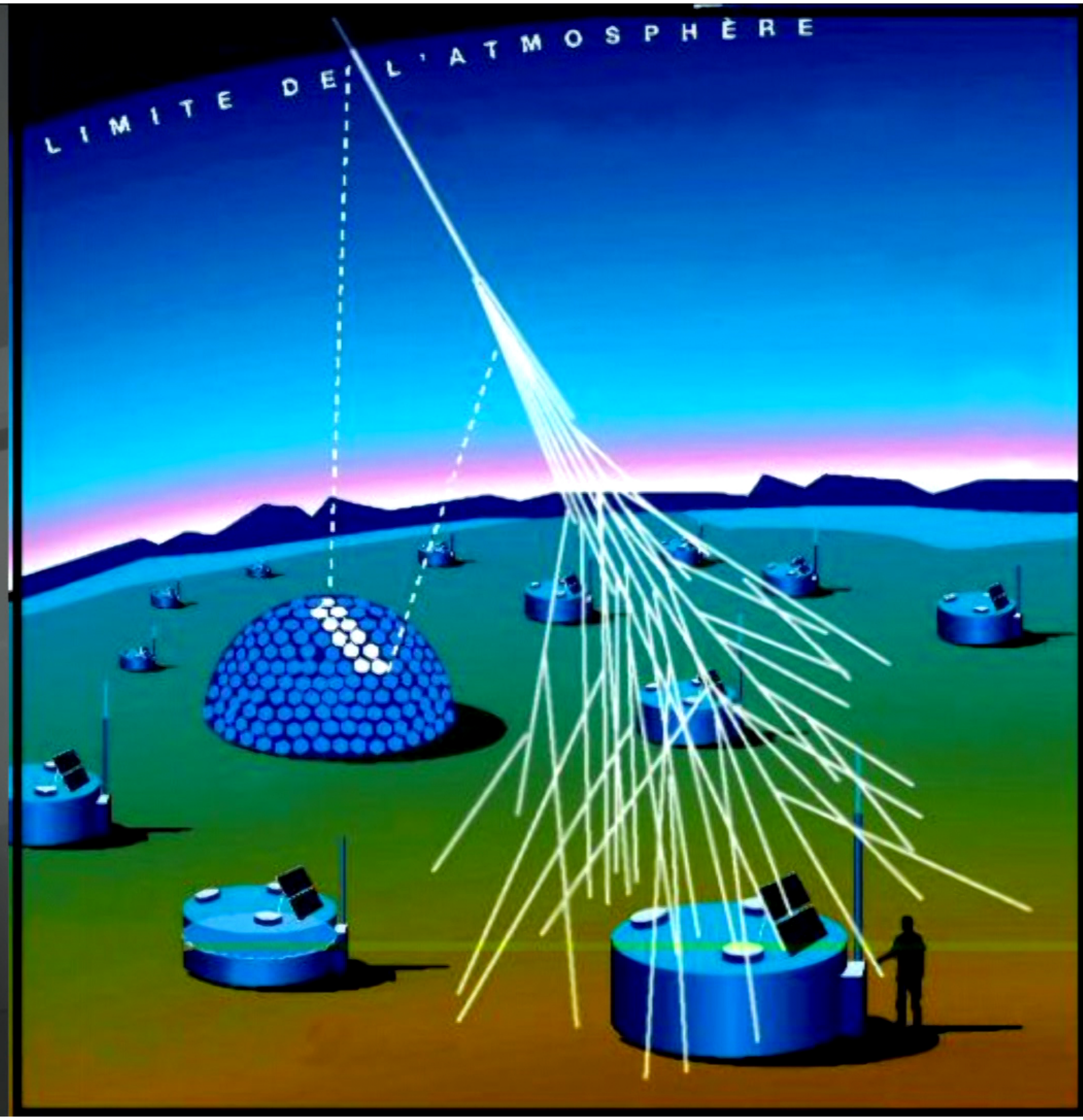
Pierre Auger Coll., arXiv:1604.03637

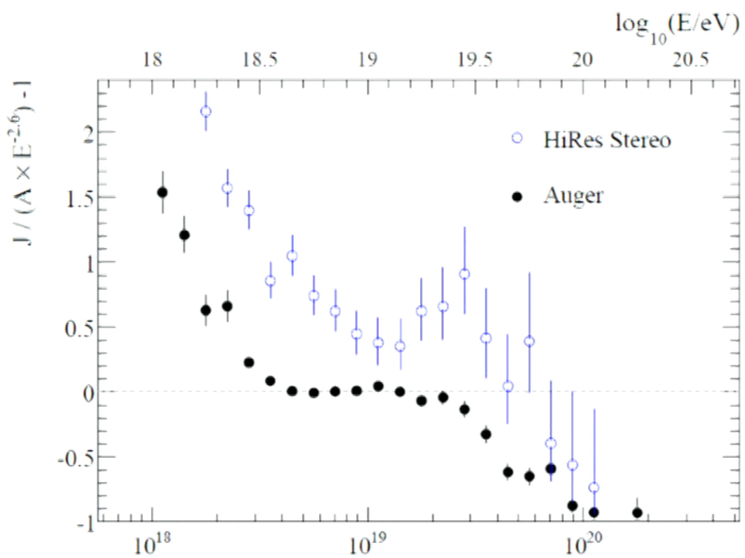


Auger ~ 3000 km^2 air shower array


Auger Air Shower Array
Argentina
80 million TeV 20 km footprint

Auger array

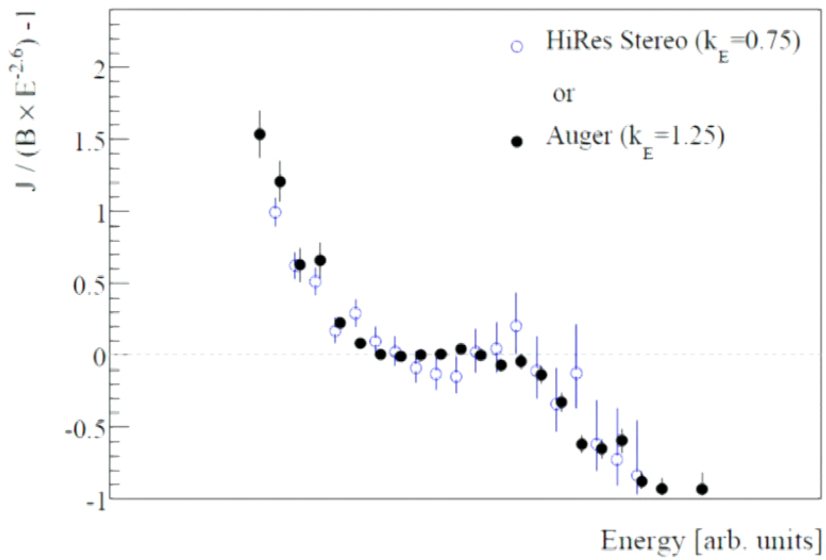




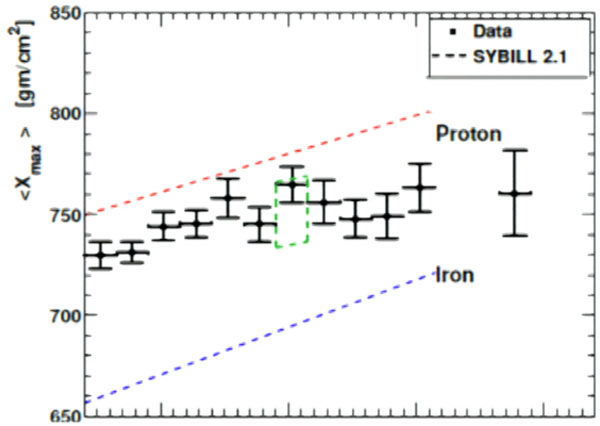
(Auger PRL **101** (2008) 61101; PLB (2010); HiRes APP **32** (2009) 53)

consistent with HiRes and confirmed by Telescope Array

GZK absorption feature appears at the expected energy



Comparison to Telescope Array

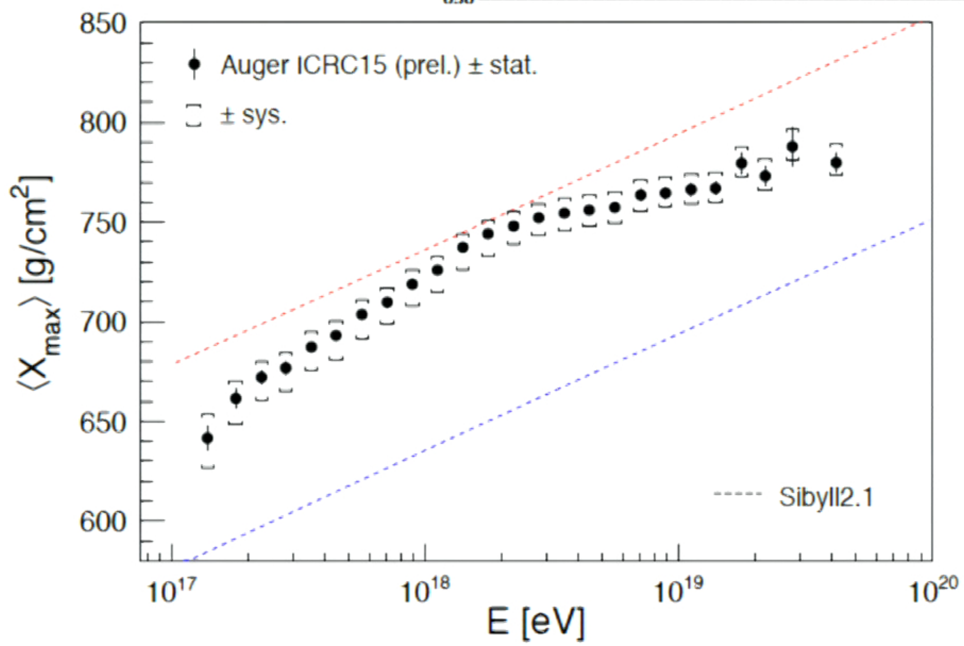


TA: $\langle X_{\max} \rangle$ biased by acceptance

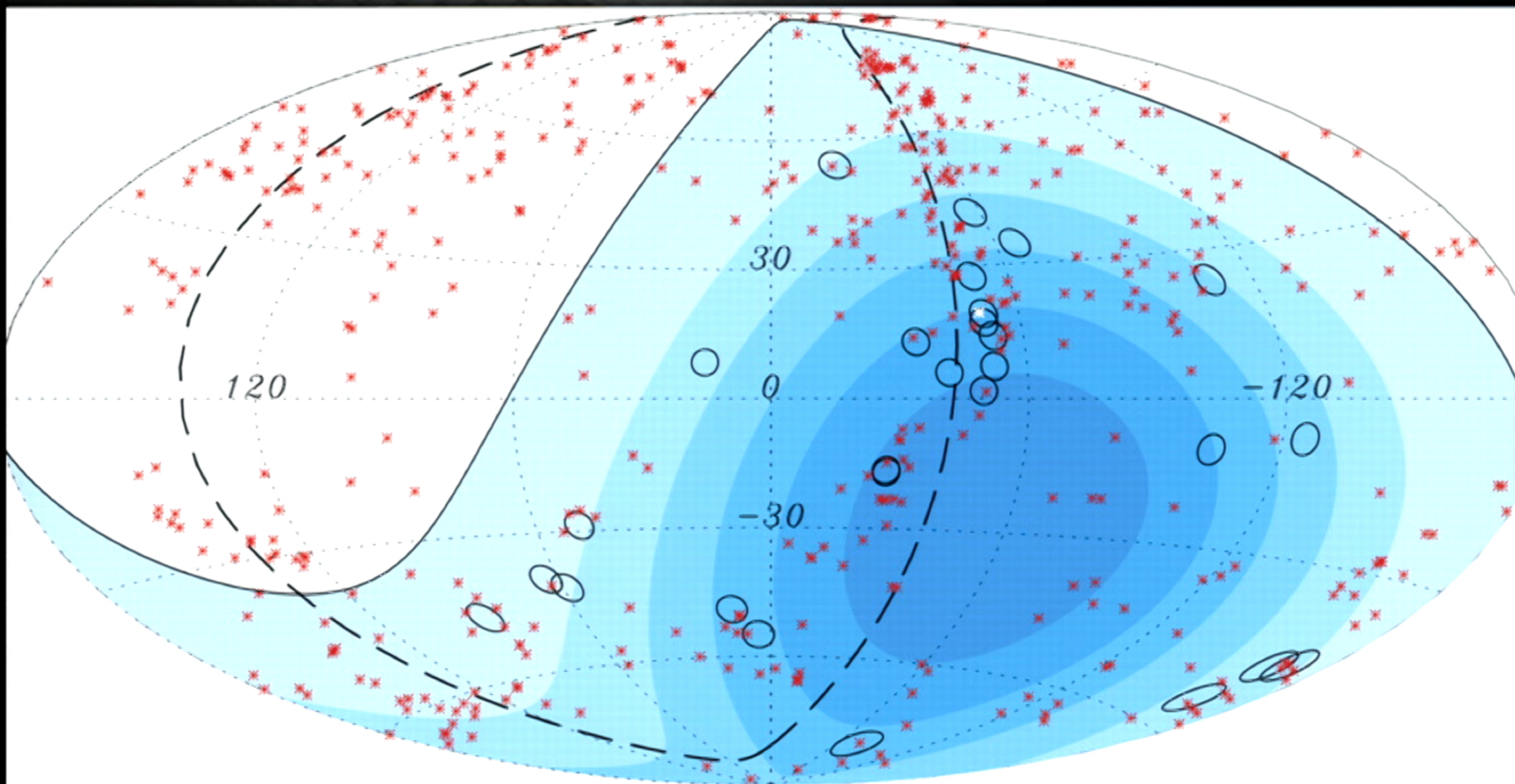
TA Coll., APP **64** (2014) 49

Auger: unbiased $\langle X_{\max} \rangle$

PRD **90** (2014) 122005 & ICRC15 prel.



Auger : the sources revealed ?



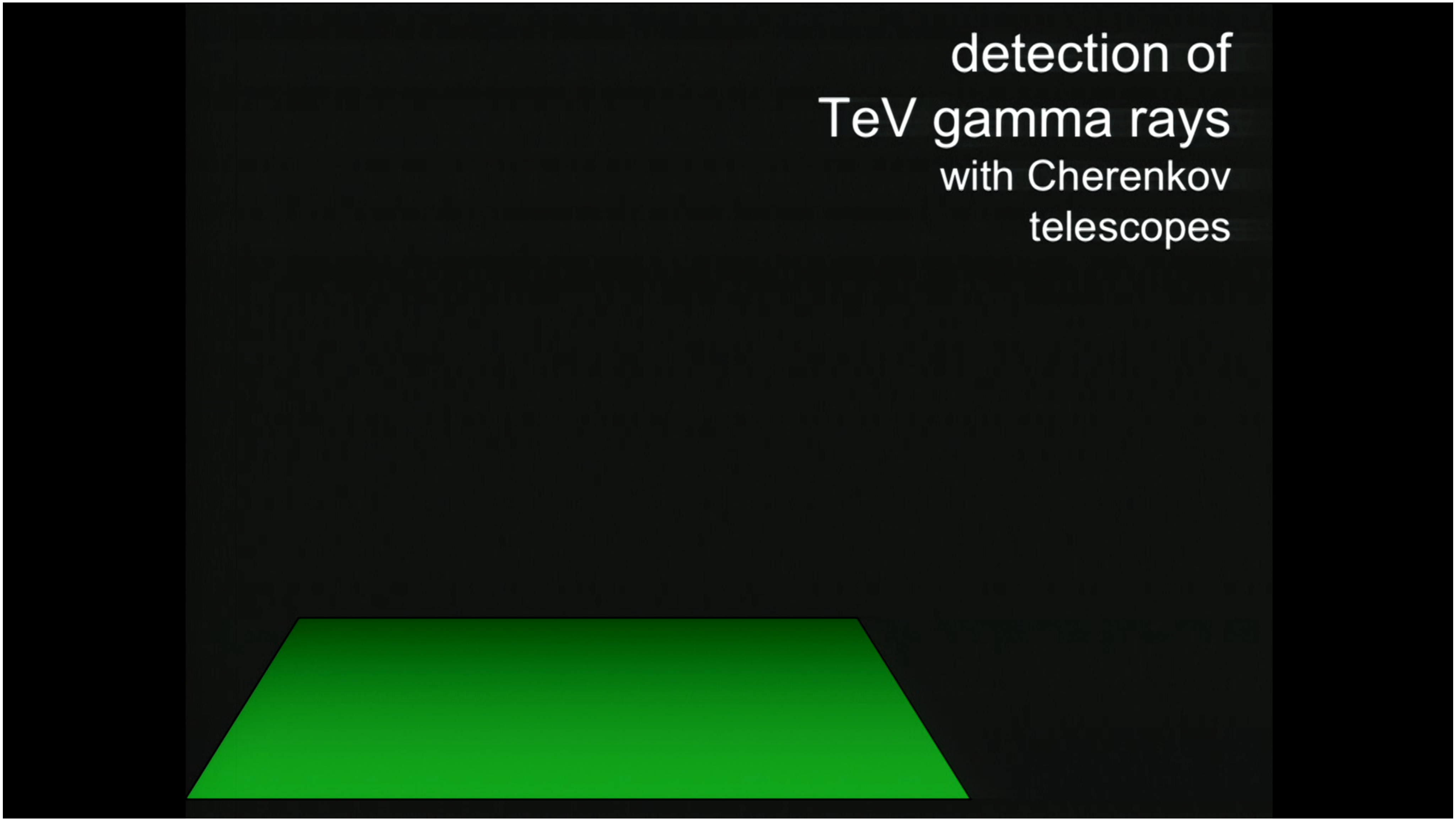
proton astronomy ?

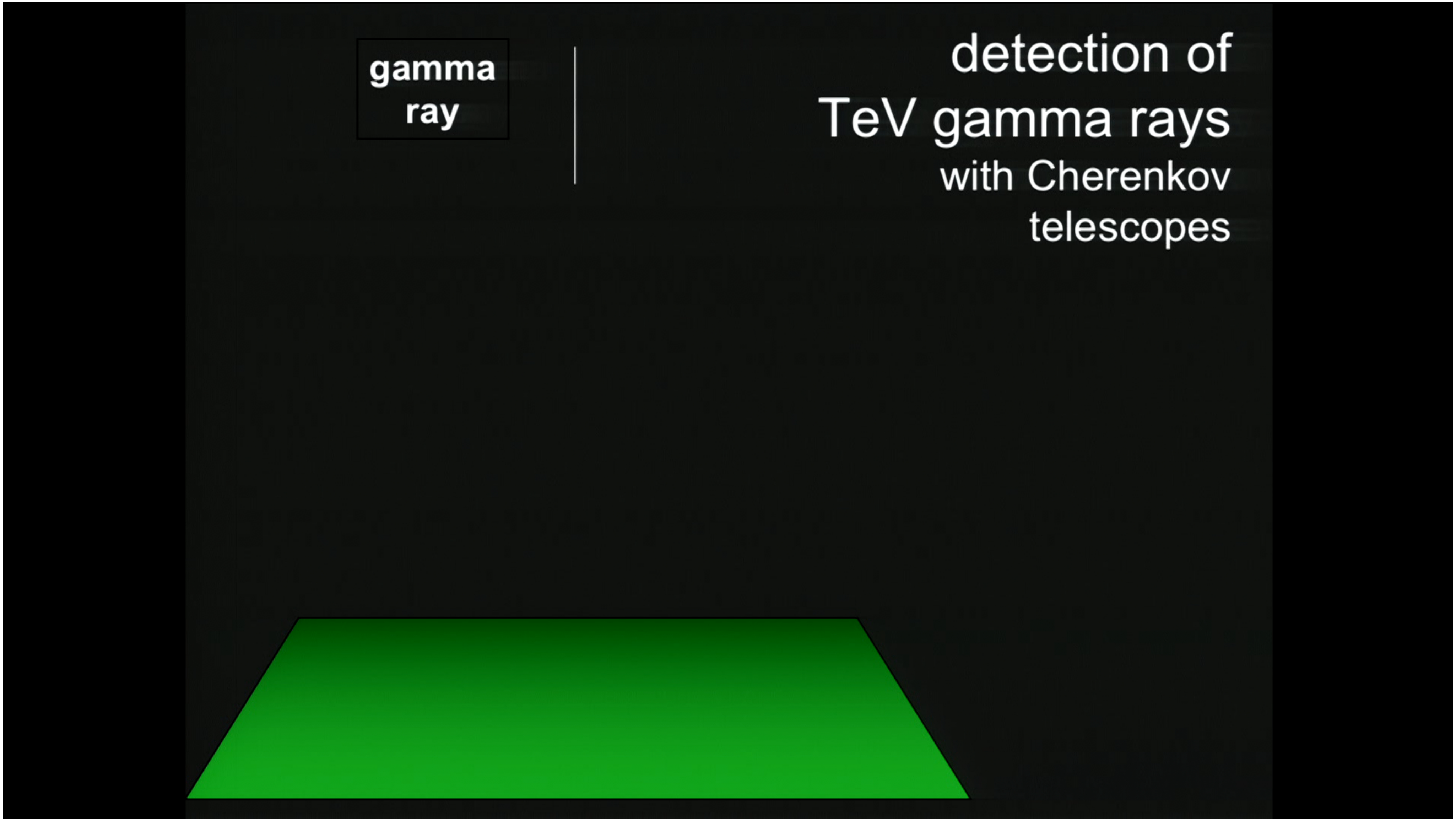
pointing of cosmic rays :

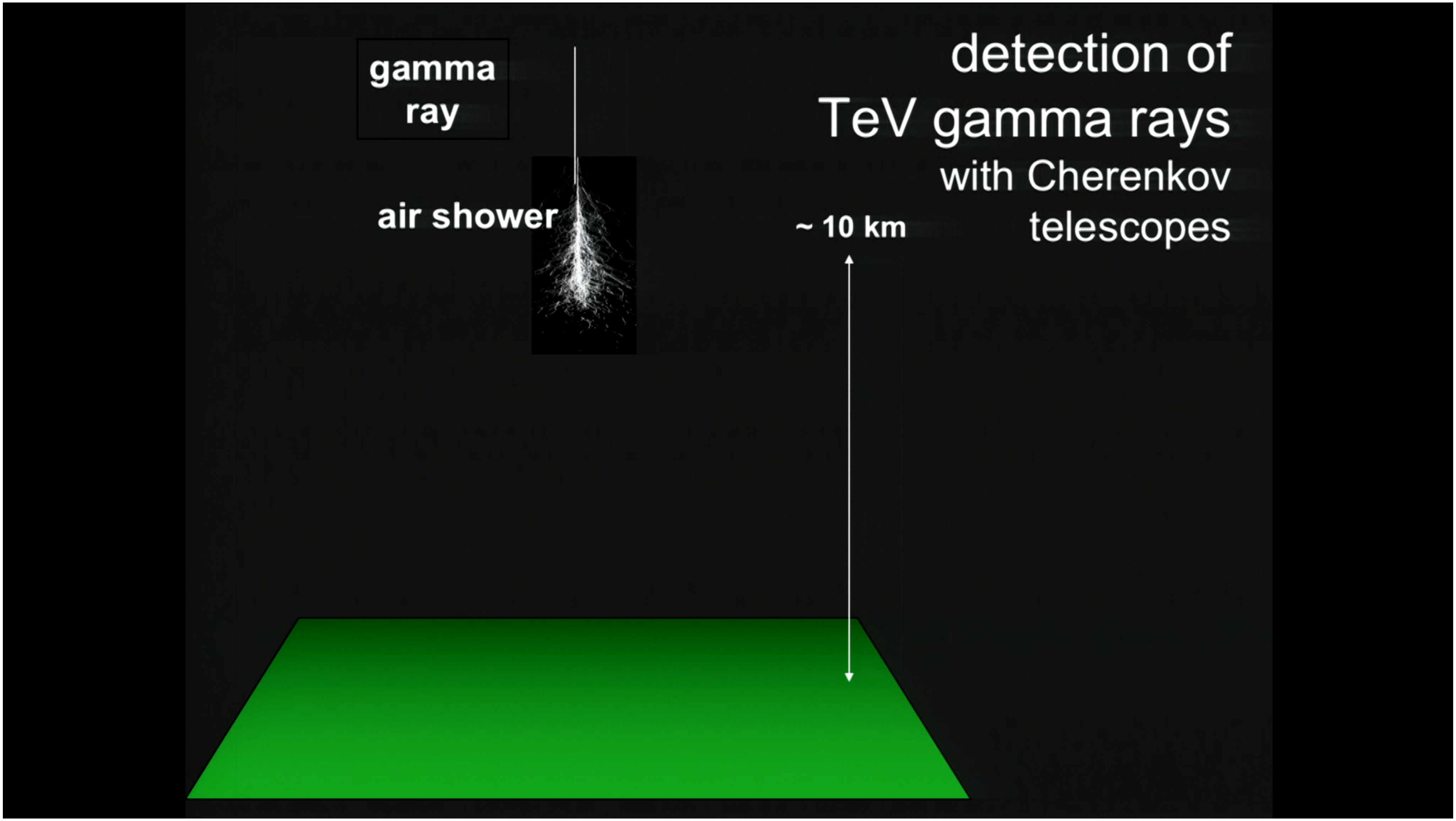
$$\theta \cong \frac{d}{R_{gyro}} = \frac{dB}{E}$$

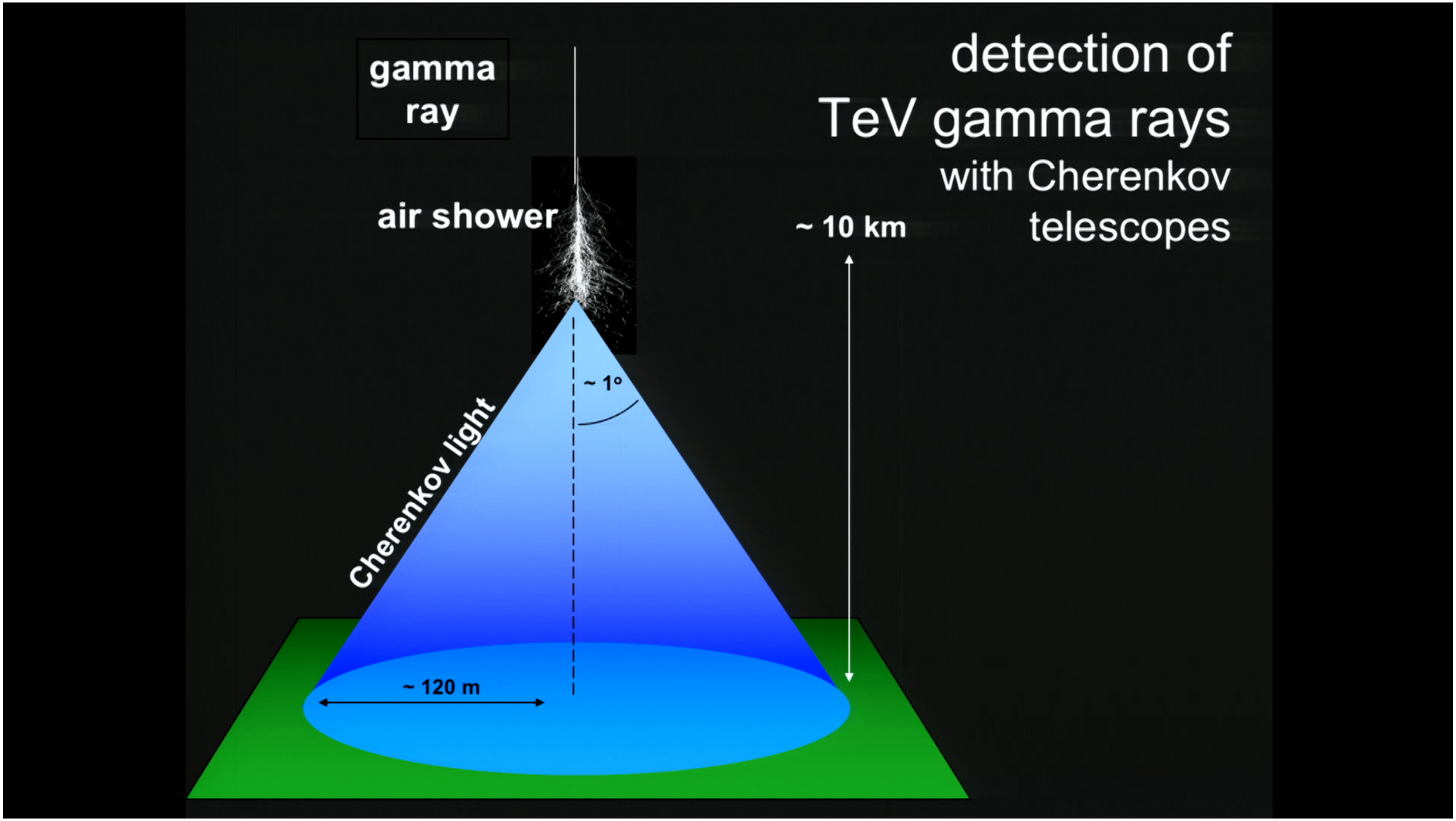
$$\frac{\vartheta}{0.1^\circ} \cong \frac{\left(\frac{d}{1\,Mpc}\right)\left(\frac{B}{10^{-9}\,Gauss}\right)}{\frac{E}{3\times10^{20}\,eV}}$$

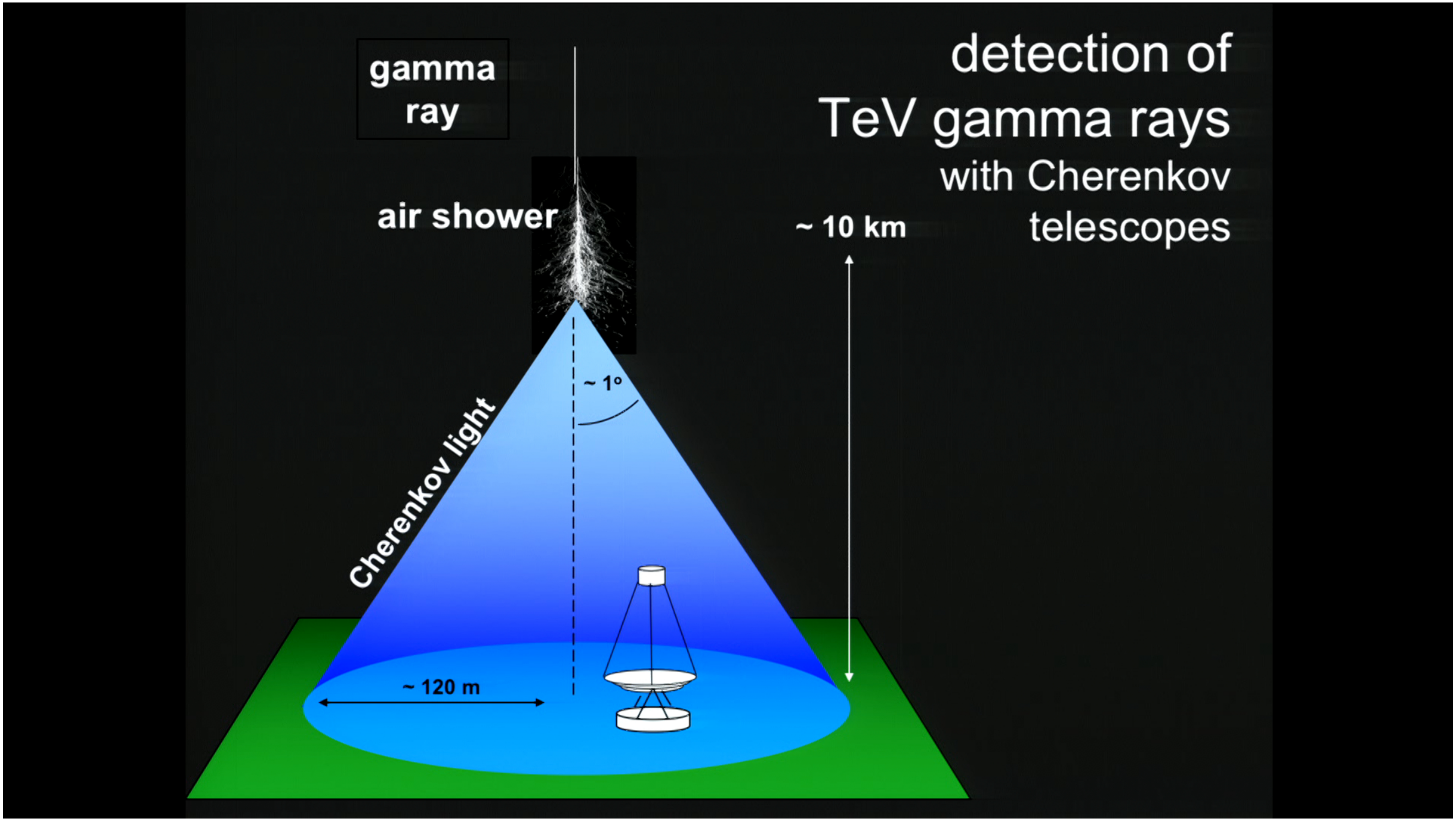
TeV gamma ray astronomy

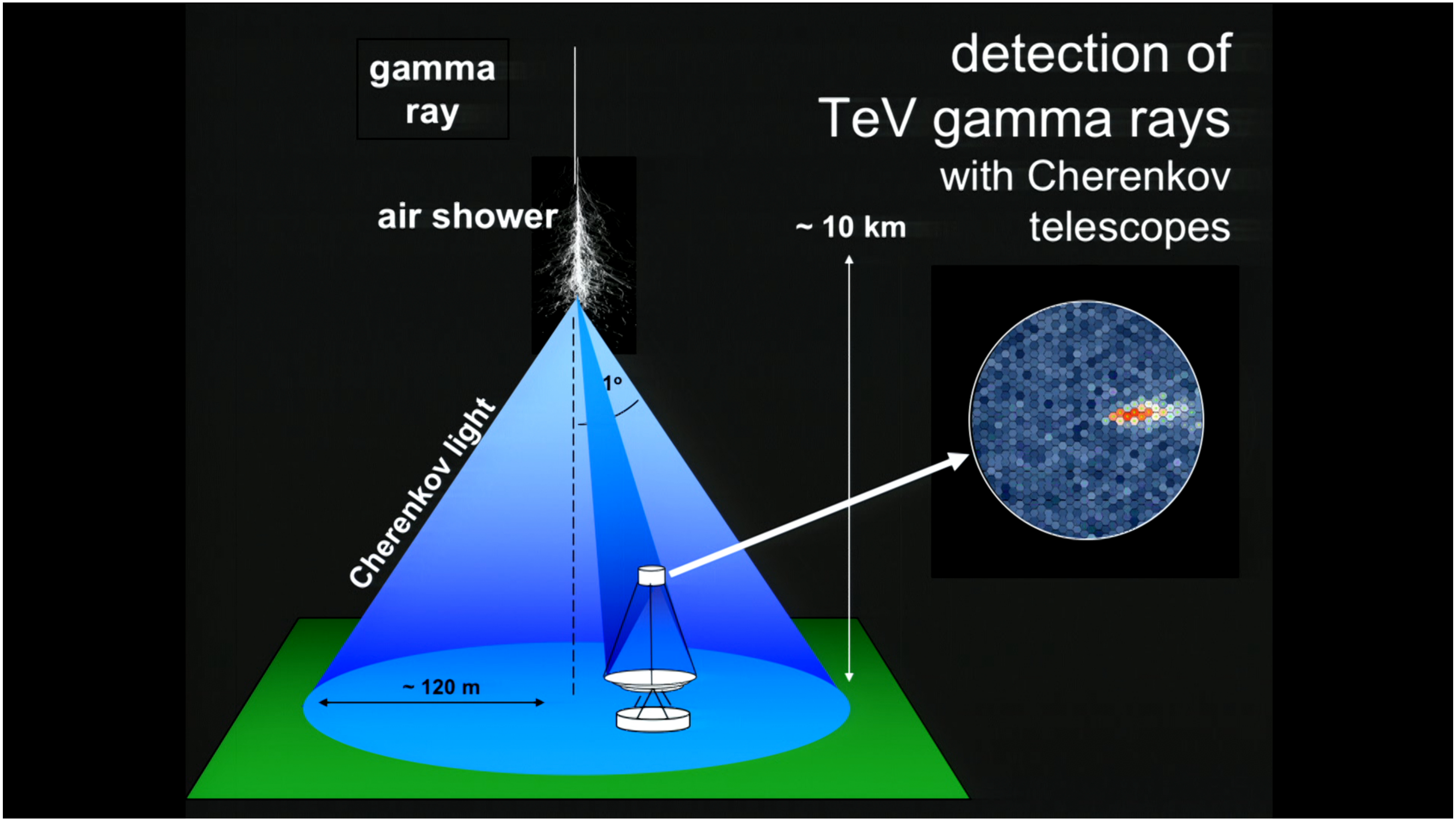

detection of
TeV gamma rays
with Cherenkov
telescopes


gamma ray
detection of
TeV gamma rays
with Cherenkov
telescopes

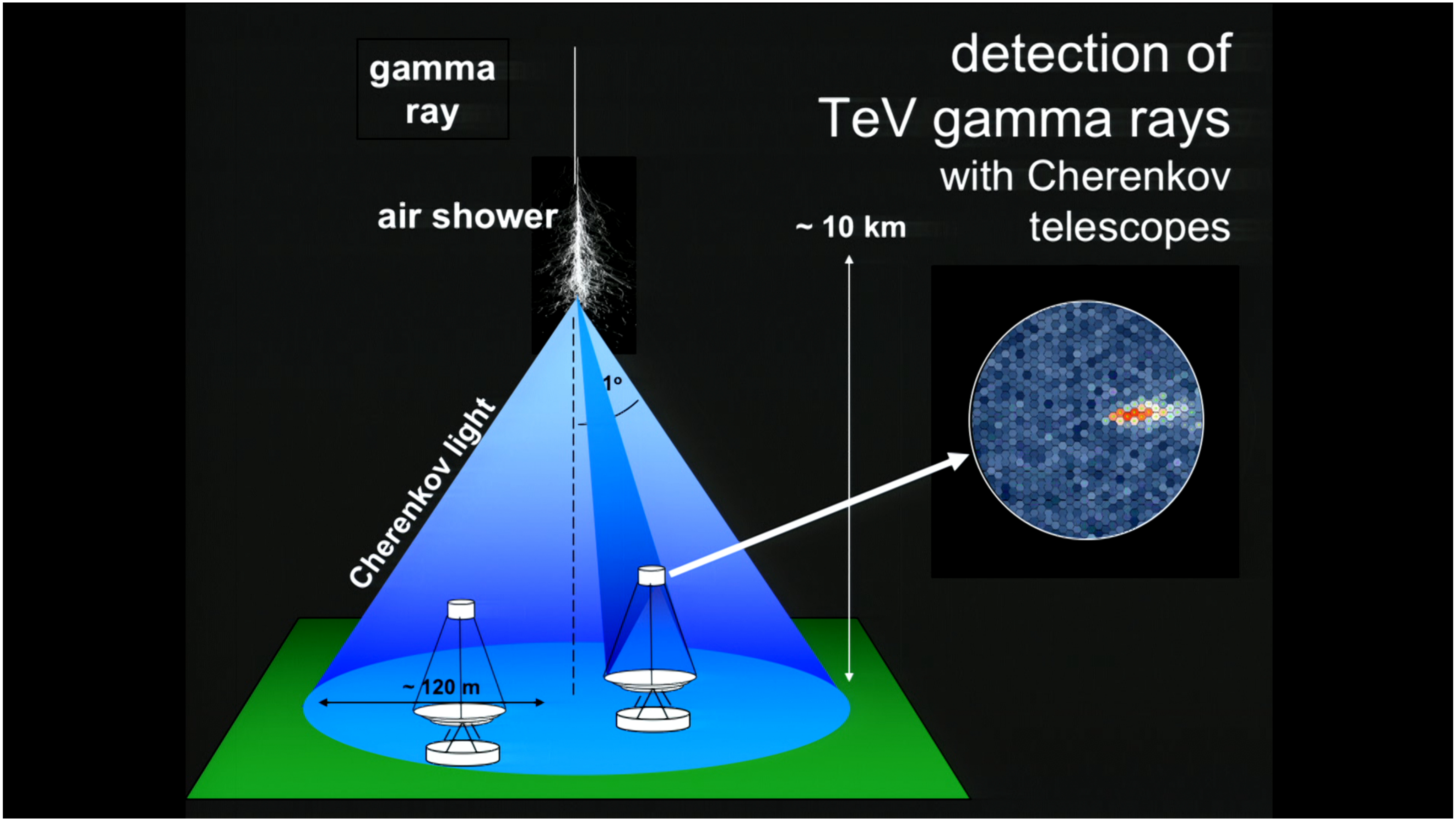

gamma
ray
air shower
detection of
TeV gamma rays
with Cherenkov
telescopes
~ 10 km

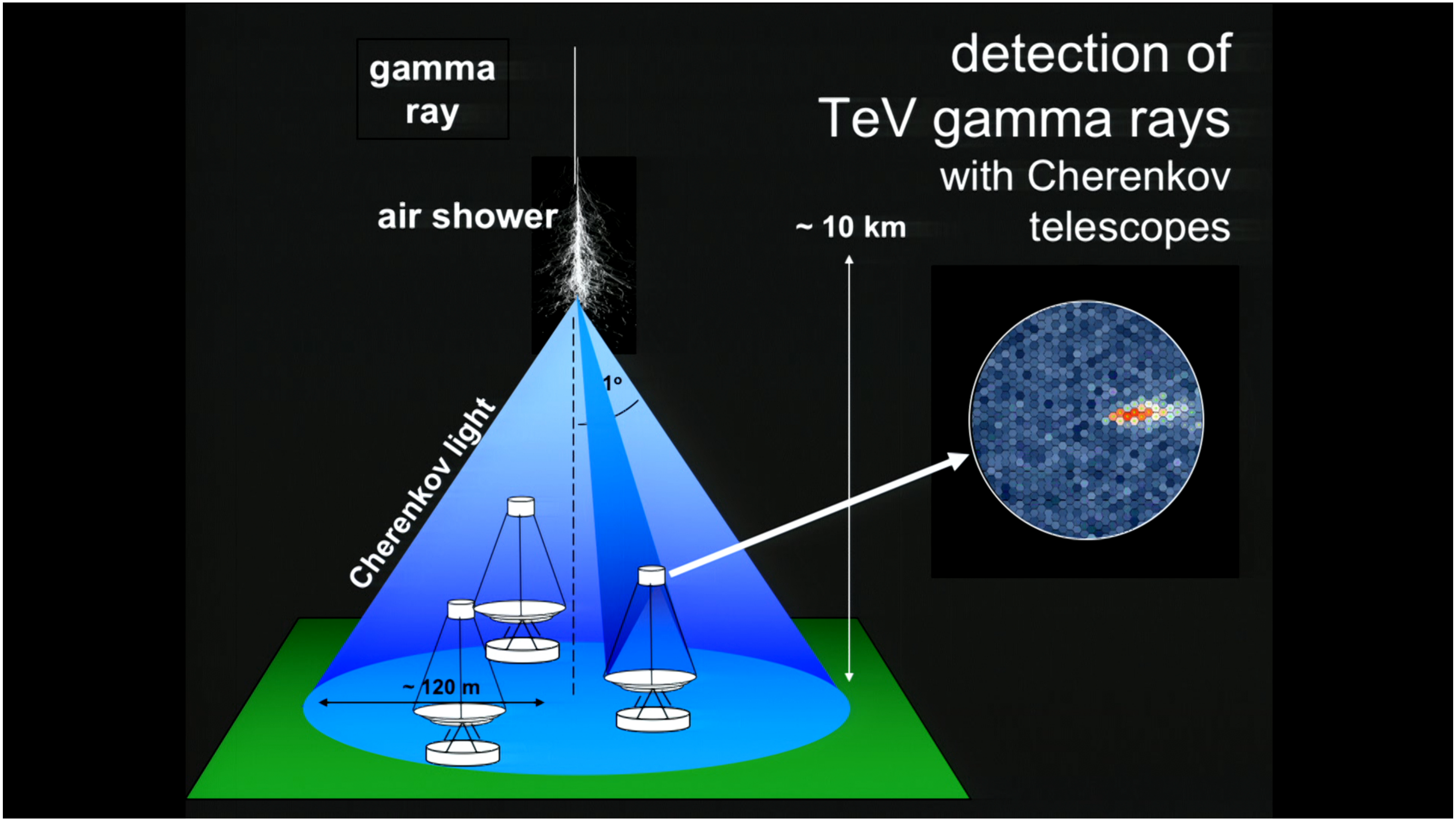

detection of
TeV gamma rays
with Cherenkov
telescopes
gamma
ray
air shower
~ 10 km
~ 1°
Cherenkov light
~ 120 m


detection of
TeV gamma rays
with Cherenkov
telescopes
gamma
ray
air shower
~ 10 km
~ 1°
Cherenkov light
~ 120 m

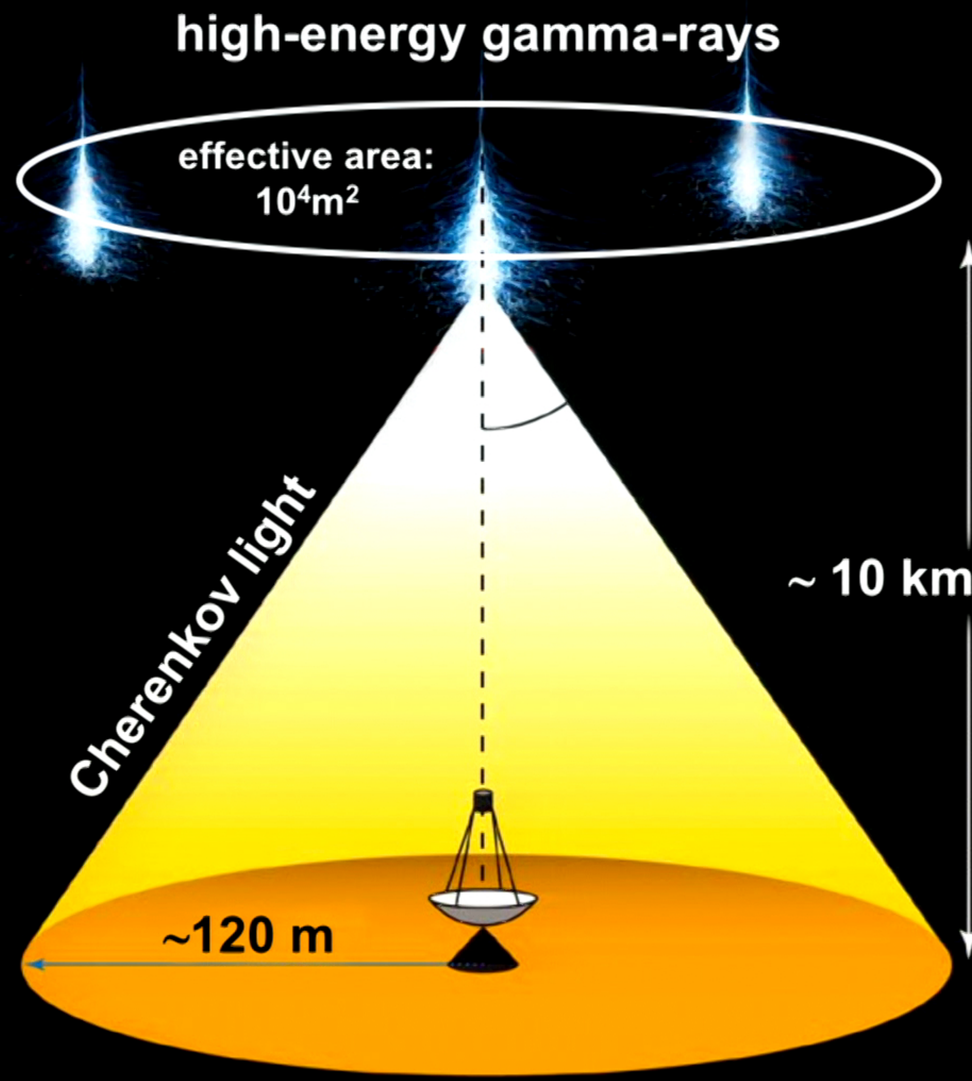


detection of
TeV gamma rays
with Cherenkov
telescopes
gamma
ray
air shower
~ 10 km
1°
Cherenkov light
~ 120 m


gamma
ray
air shower
detection of
TeV gamma rays
with Cherenkov
telescopes
~ 10 km
1°
Cherenkov light
~ 120 m


gamma
ray
air shower
detection of
TeV gamma rays
with Cherenkov
telescopes
~ 10 km
1°
Cherenkov light
~ 120 m

- a cosmic photon initiates an electromagnetic shower high in the atmosphere
- the shower particles emit Cherenkov radiation
- this radiation is captured by mirrors read out by a cluster of photomultipliers



TeV gamma ray

MAGIC atmposheric Cherenkov telescope

TeV γ survey instruments ~ 2-3 π

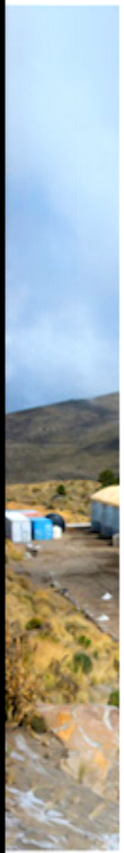
gamma rays are muon-poor air showers

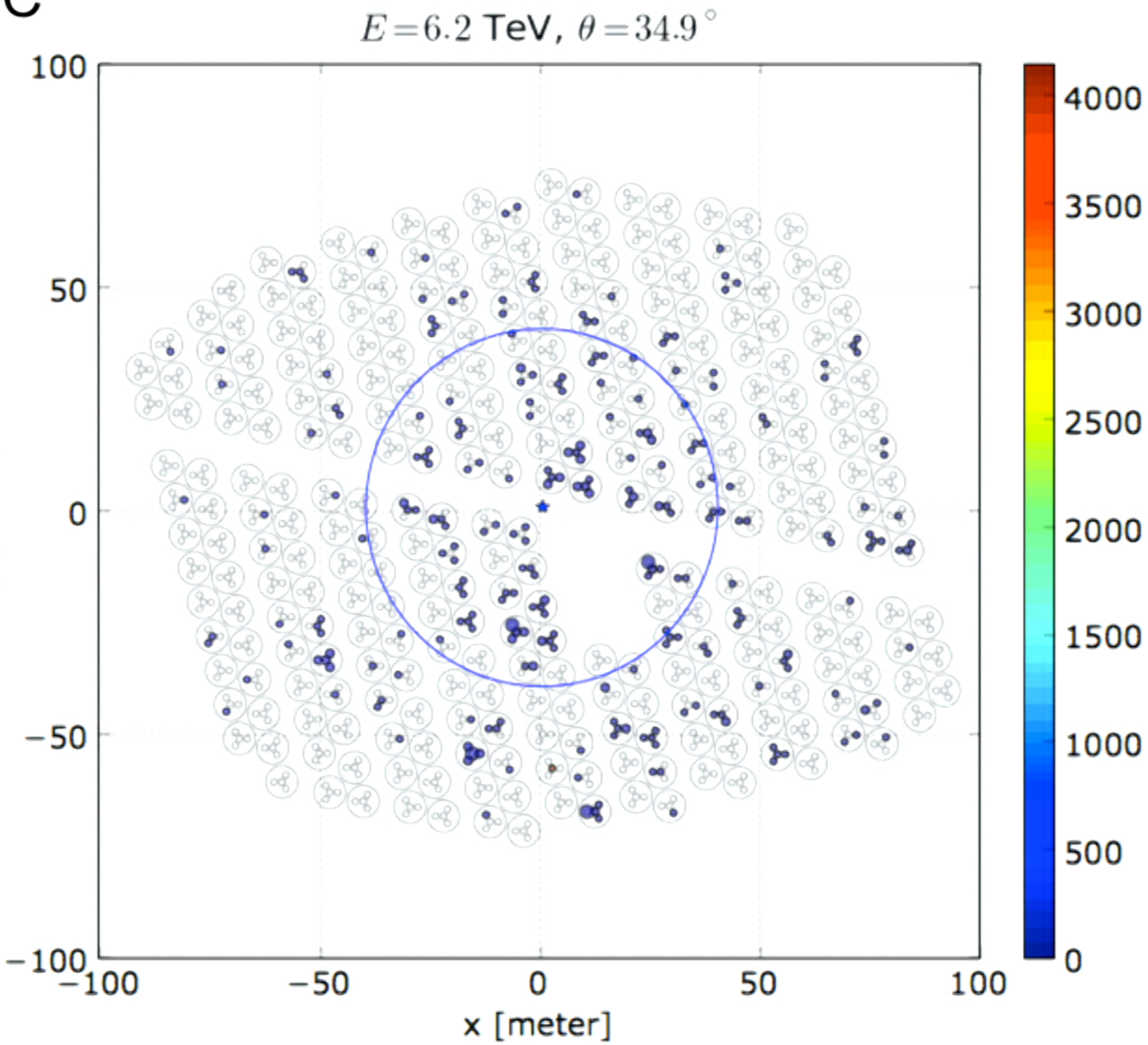
Tibet array and ARGO

Milagro

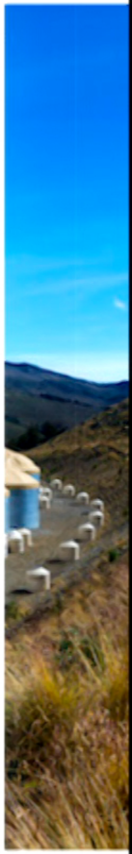
HAWC

HAWC

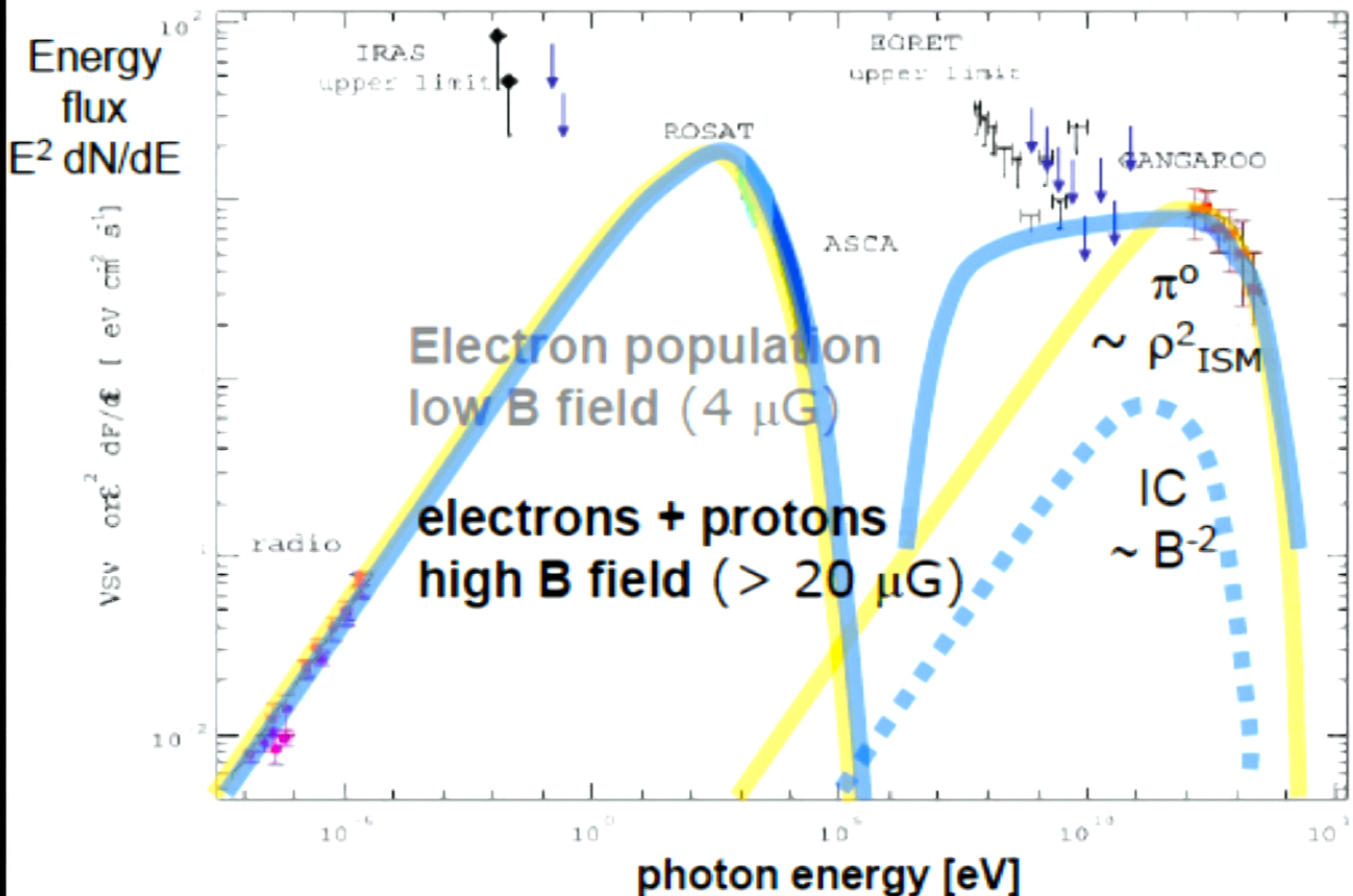




$E = 6.2$ TeV, $\theta = 34.9^\circ$
100
50
0
−50
−100
y [meter]
−100
−50
0
50
100
x [meter]
4000
3500
3000
2500
2000
1500
1000
500
0
hit times [ns]



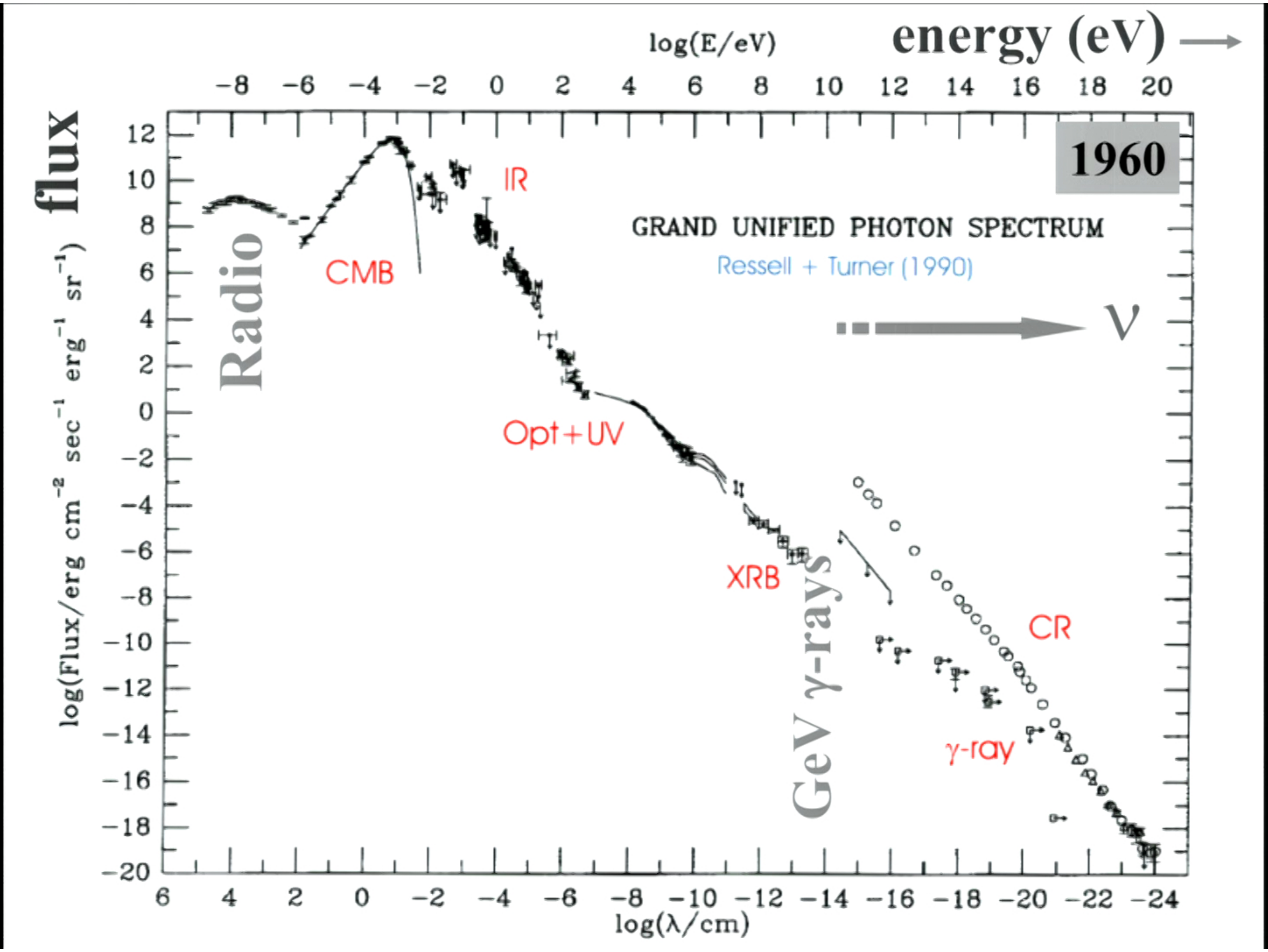
electromagnetic vs hadronic



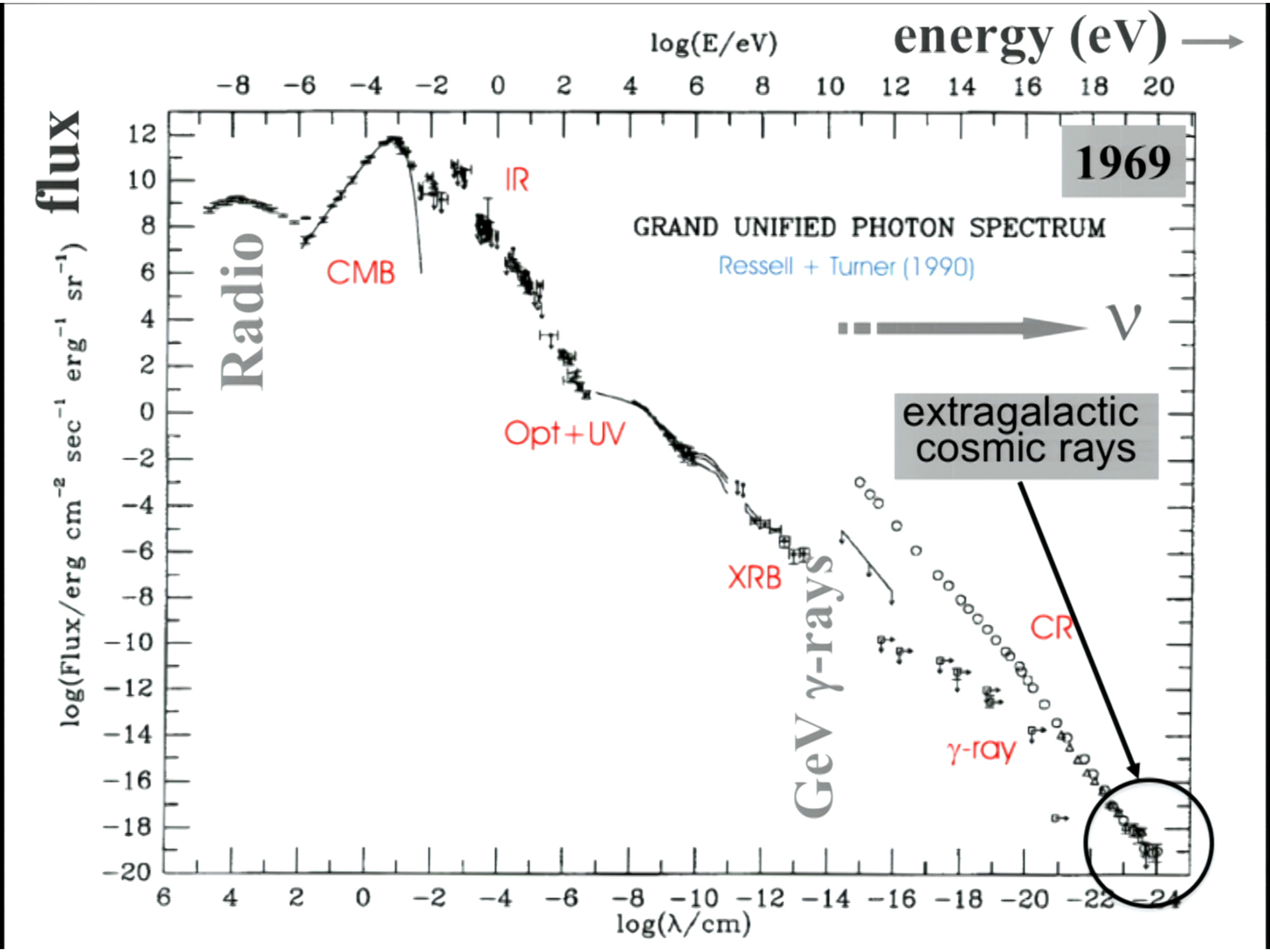
high energy neutrino astronomy

neutrino astronomy

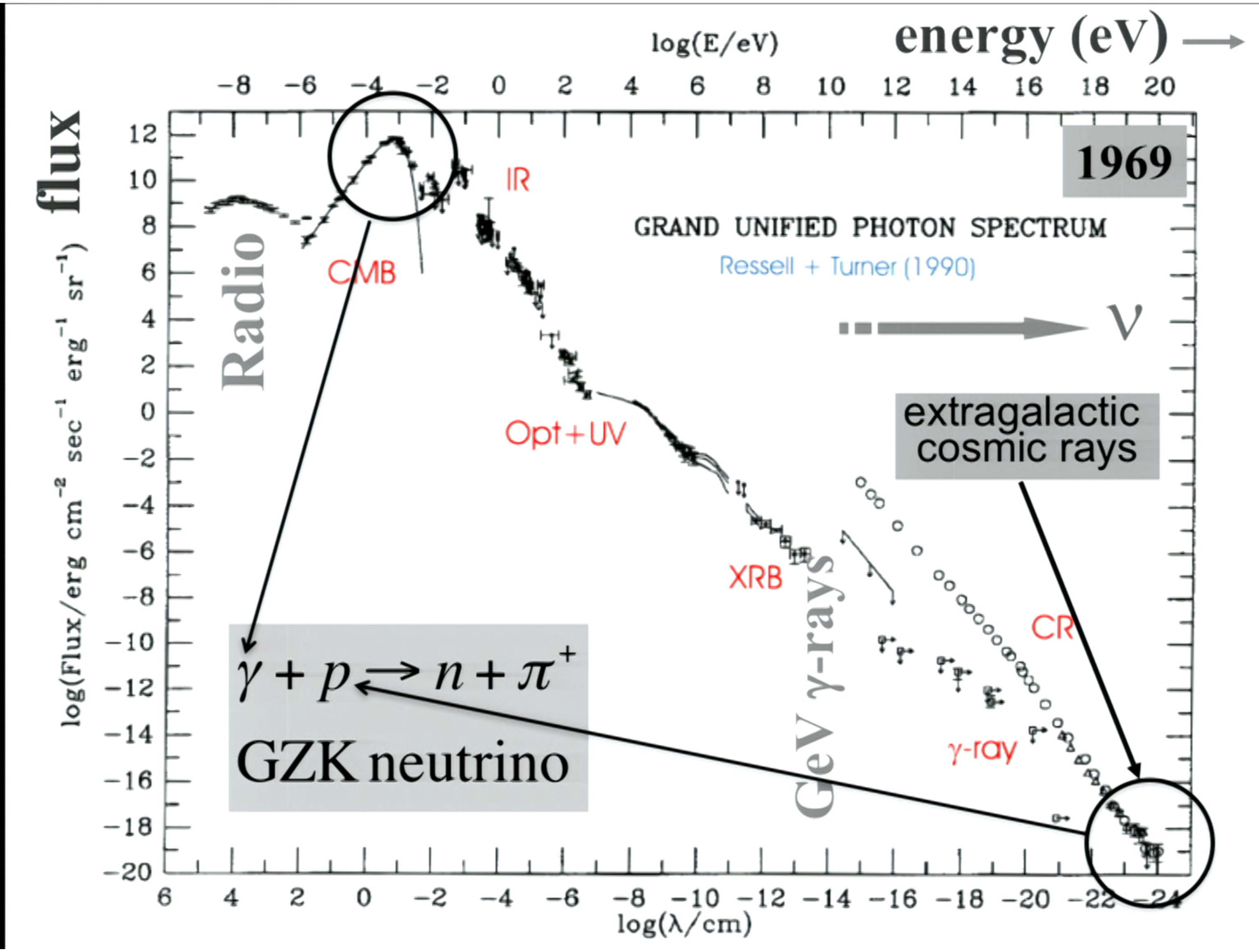
kilometer-scale detectors have the capability of detecting astrophysical neutrinos from cosmic sources with an energy density in neutrinos comparable to their energy density in the observed cosmic rays and TeV gamma rays



energy (eV)
log(E/eV)
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
1960
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
CR
γ-ray
ν
log(λ/cm)



log(E/eV)
energy (eV)
1969
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
Radio
CMB
IR
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
ν
Opt+UV
extragalactic cosmic rays
XRB
GeV γ-rays
CR
γ-ray
log(λ/cm)



log(E/eV)
energy (eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Ressell + Turner (1990)
flux
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
Radio
CMB
IR
Opt+UV
XRB
GeV γ-rays
γ-ray
CR
ν
extragalactic cosmic rays
$\gamma + p \Rightarrow n + \pi^+$
GZK neutrino
log(λ/cm)

cosmic rays interact with the microwave background

$$p + \gamma \rightarrow n + \pi^{+}$$

$400\ cm^{-3}$

$10^{-28}\ cm^{2}$

$$\lambda_{\rm int} = \{n_{cmb}\sigma_{\gamma + p}\}^{-1} \sim 10\ Mpc$$

$$E_{p} \geq 5 \times 10^{7}\ TeV$$

cosmic rays interact with the microwave background

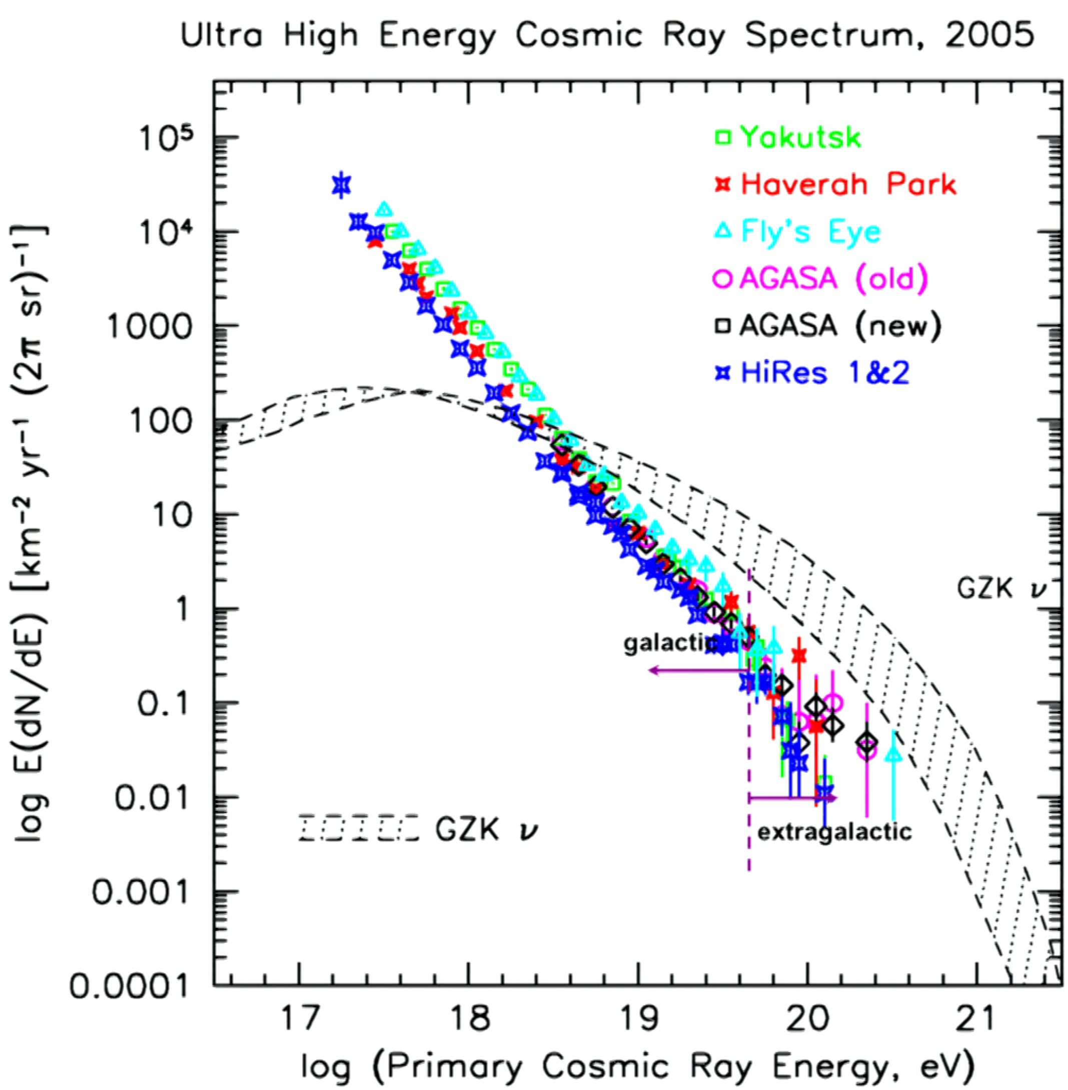
$$p + \gamma \rightarrow n + \pi^{+} \ and \ p + \pi^{0}$$

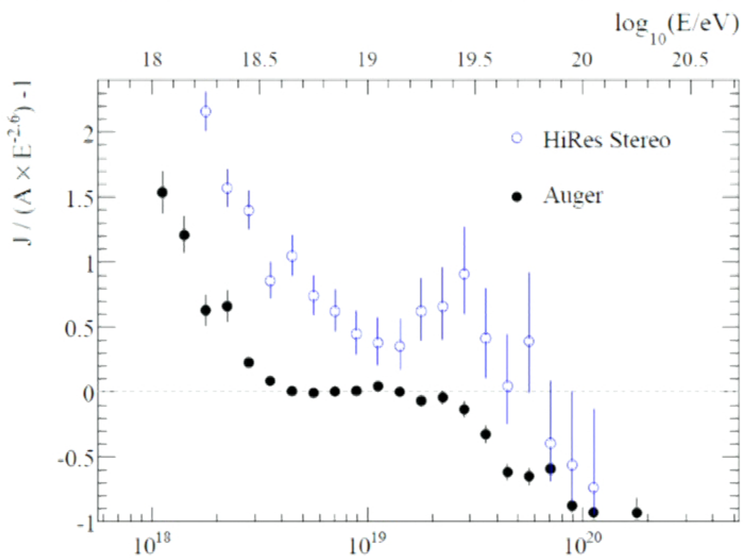
cosmic rays disappear, neutrinos with EeV (10^{18} eV) energy appear

$$\pi \rightarrow \mu + \upsilon_{\mu} \rightarrow \{e + \upsilon_{\mu} + \upsilon_{e}\} + \upsilon_{\mu}$$

1 event per cubic kilometer per year
...but it points at its source!

neutrinos from GZK interactions

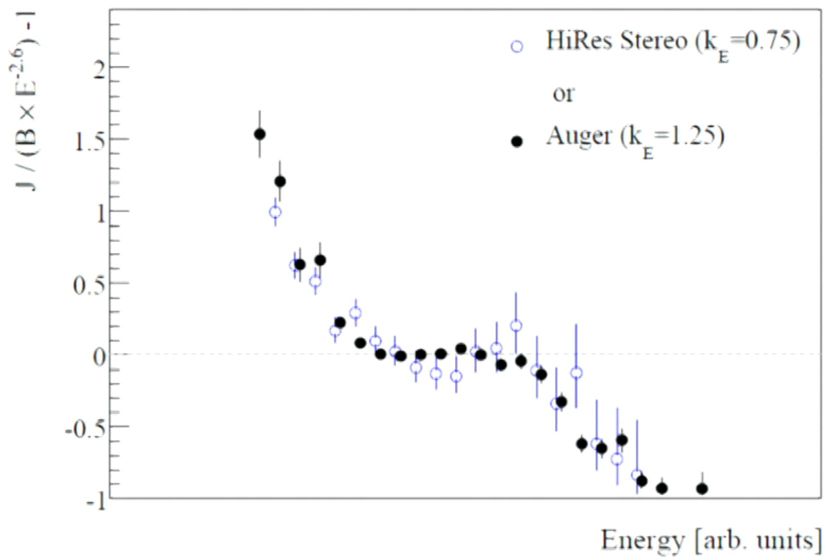


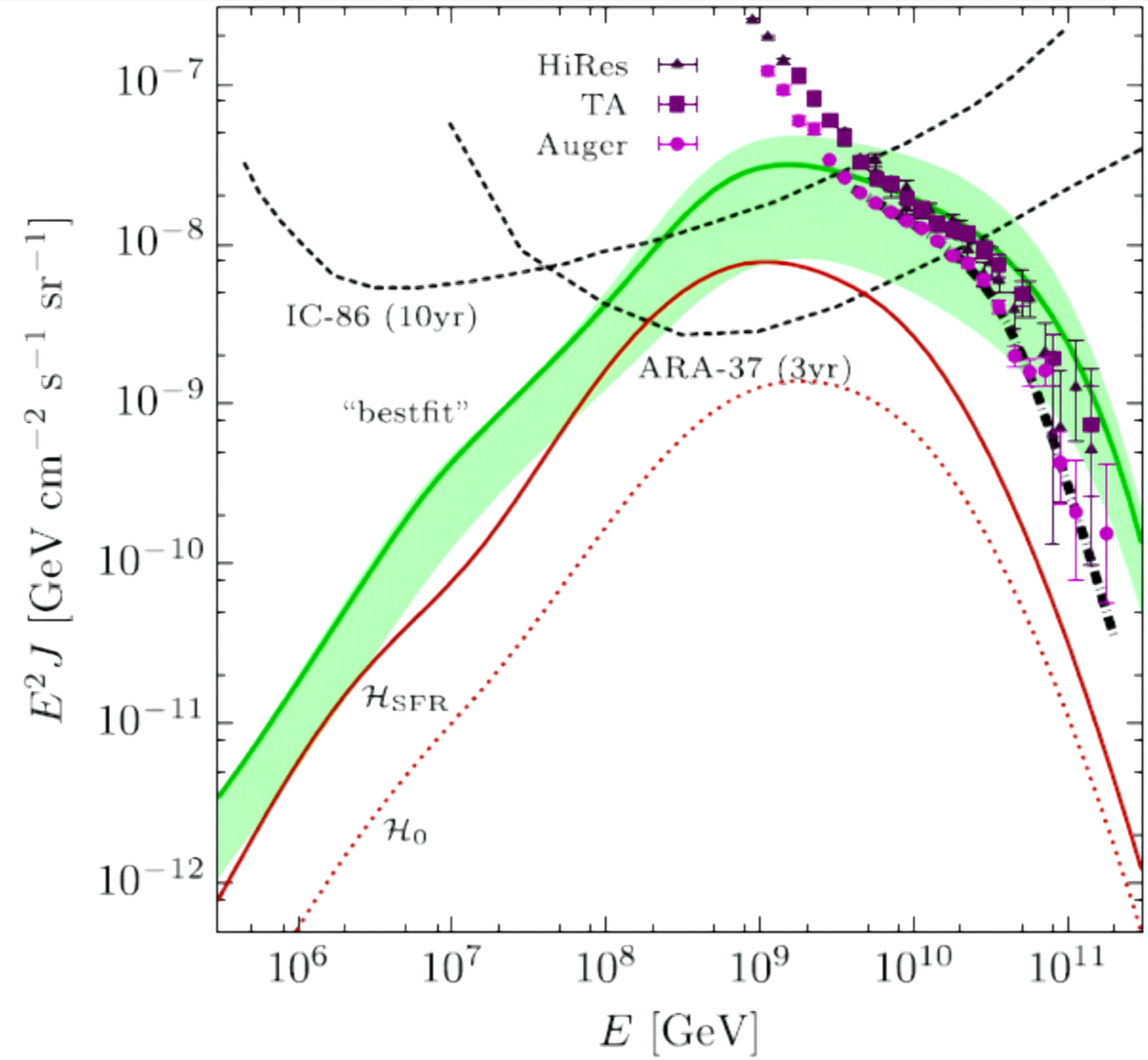


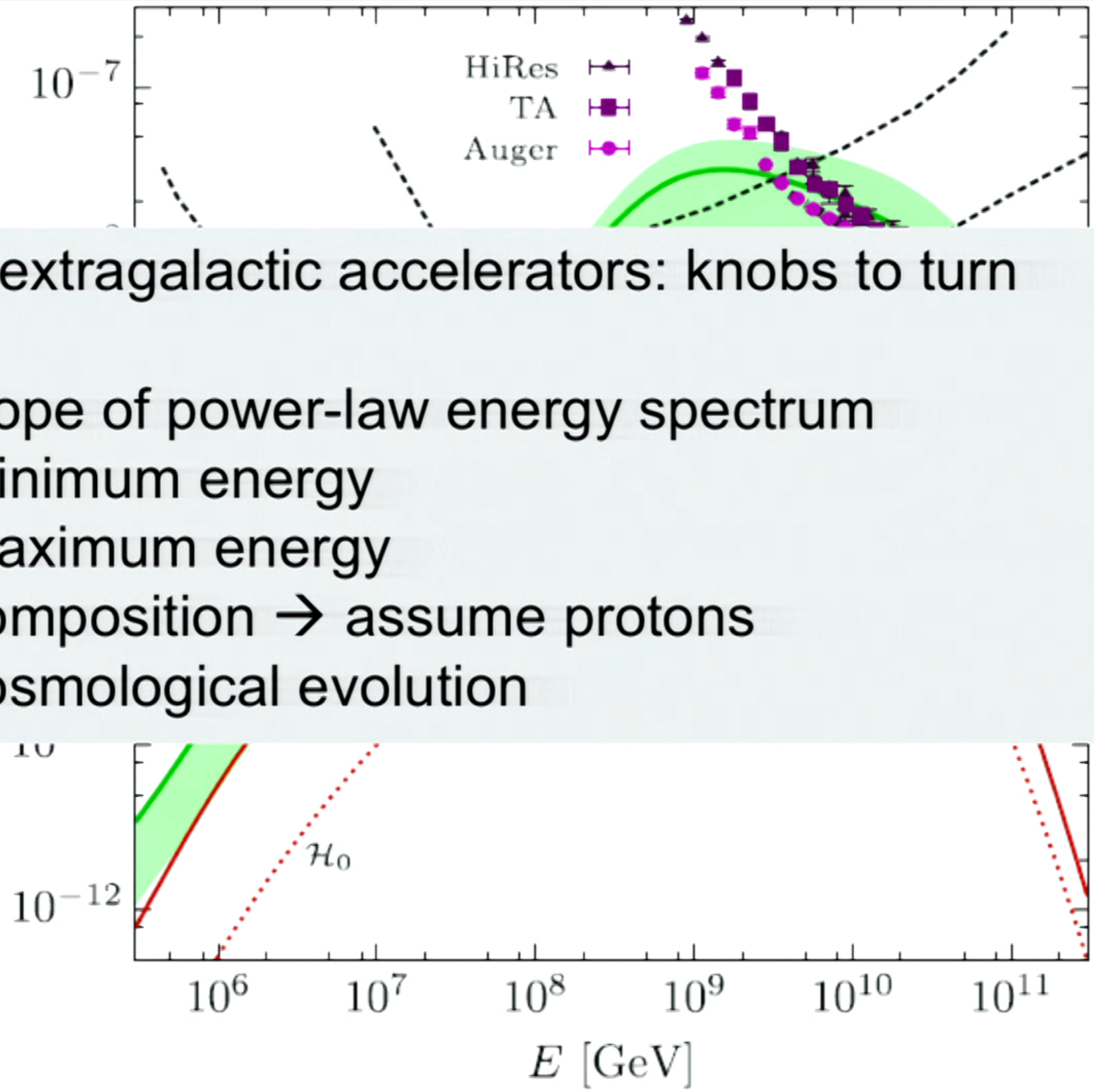
(Auger PRL **101** (2008) 61101, PLB (2010); HiRes APP **32** (2009) 53)

confirmed by Telescope Array

GZK absorption feature appears at the expected energy

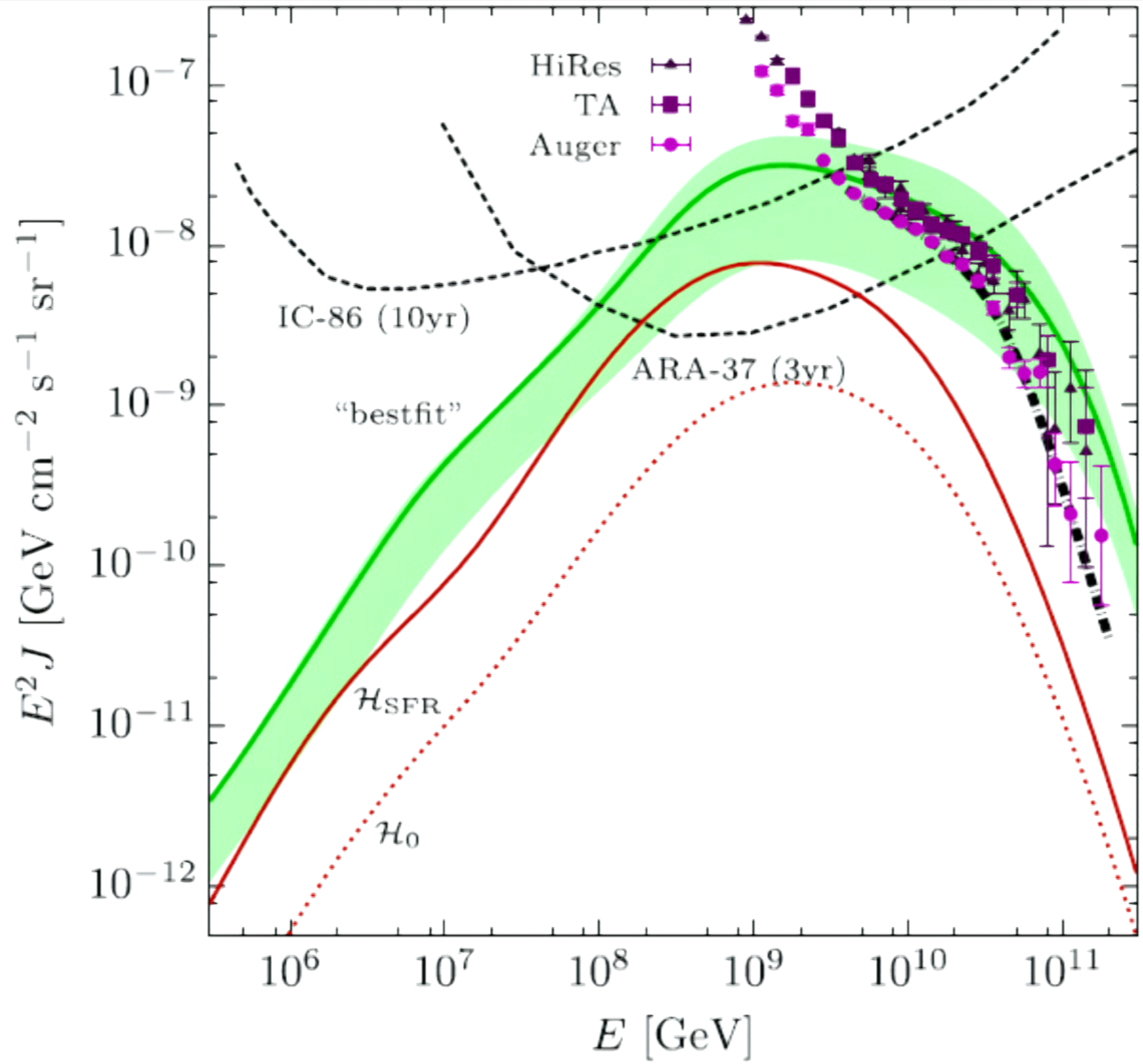



HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\mathrm{SFR}}$
$\mathcal{H}_0$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^6
10^7
10^8
10^9
10^{10}
10^{11}

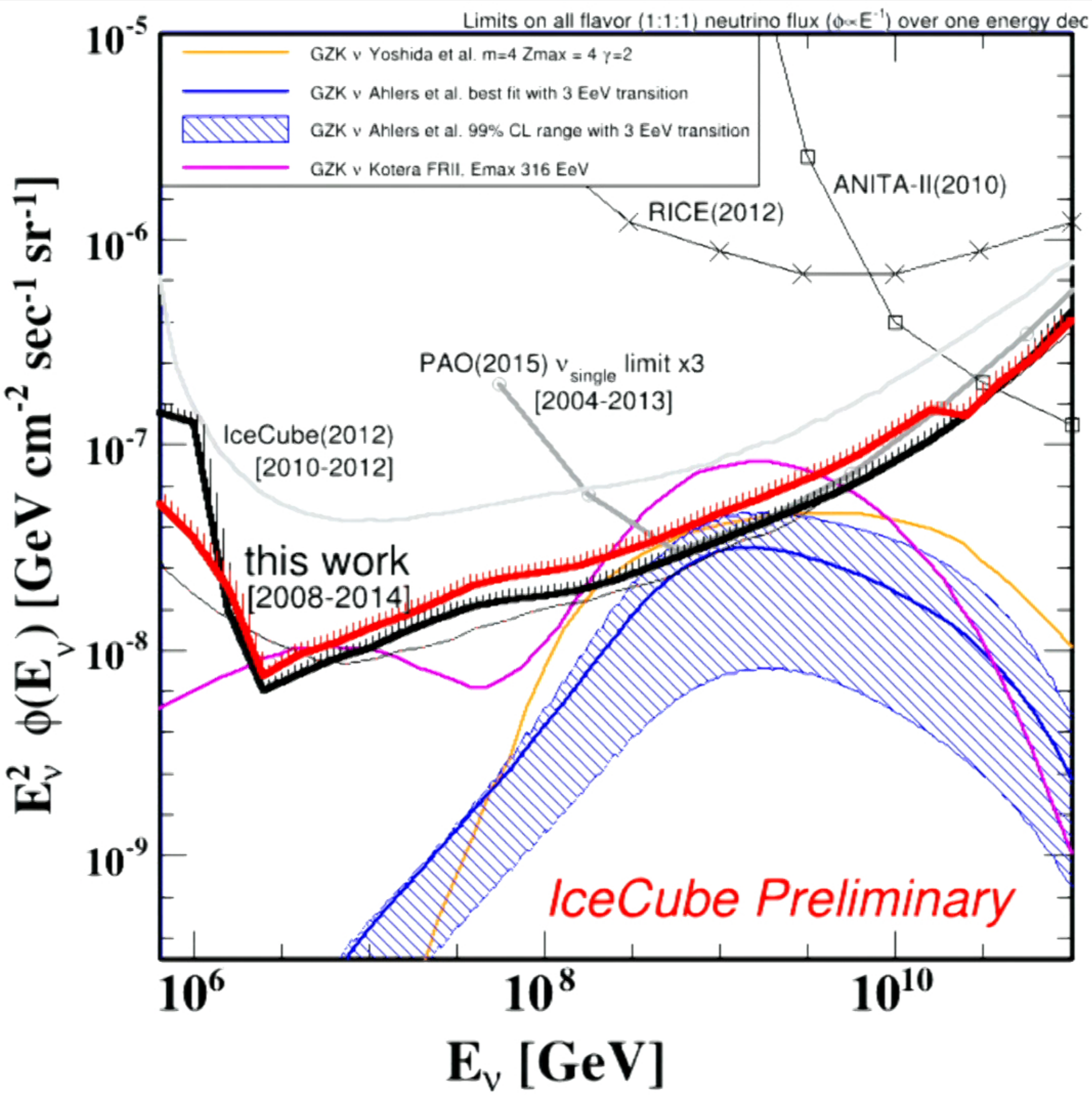


the extragalactic accelerators: knobs to turn

- slope of power-law energy spectrum
- minimum energy
- maximum energy
- composition → assume protons
- cosmological evolution

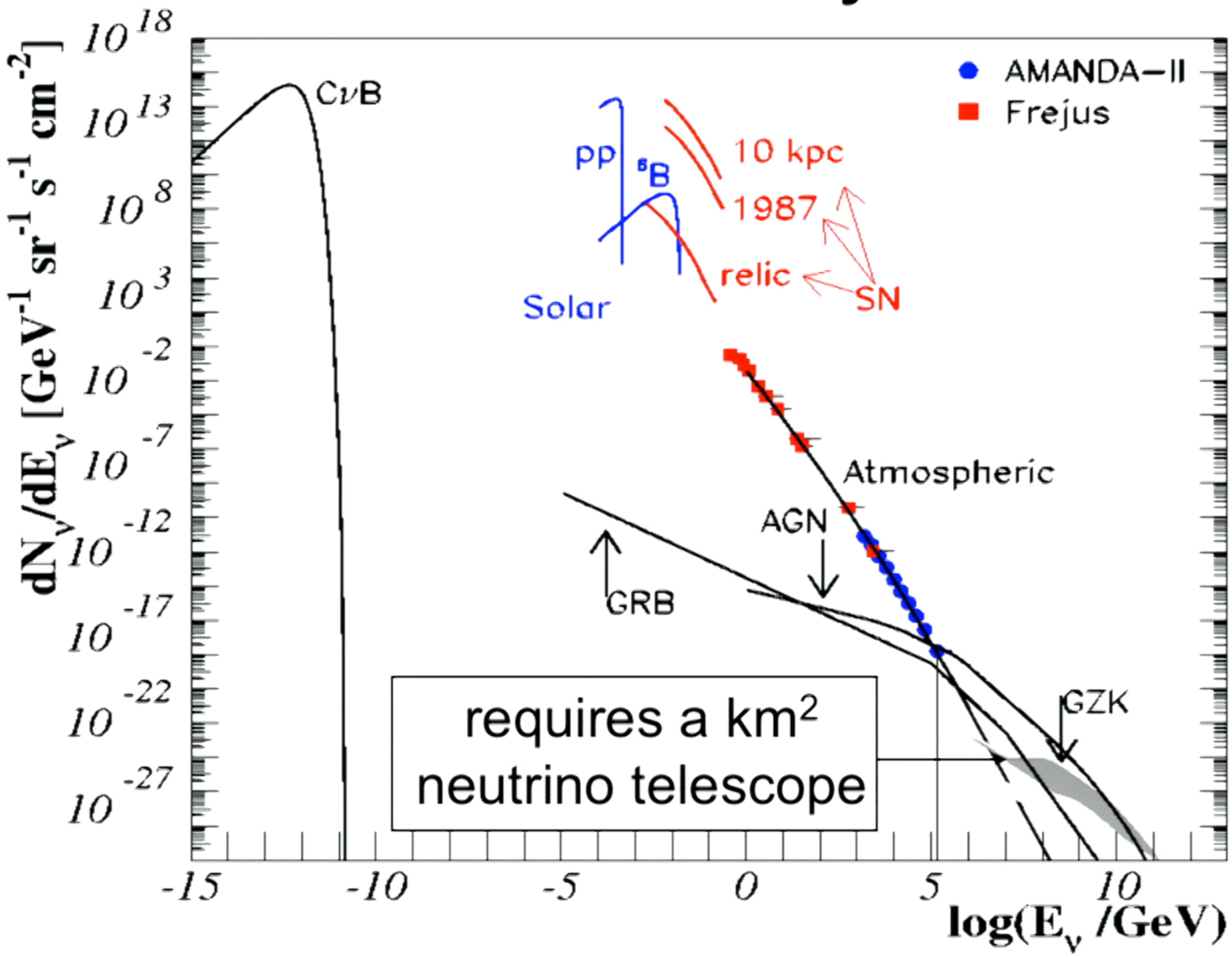


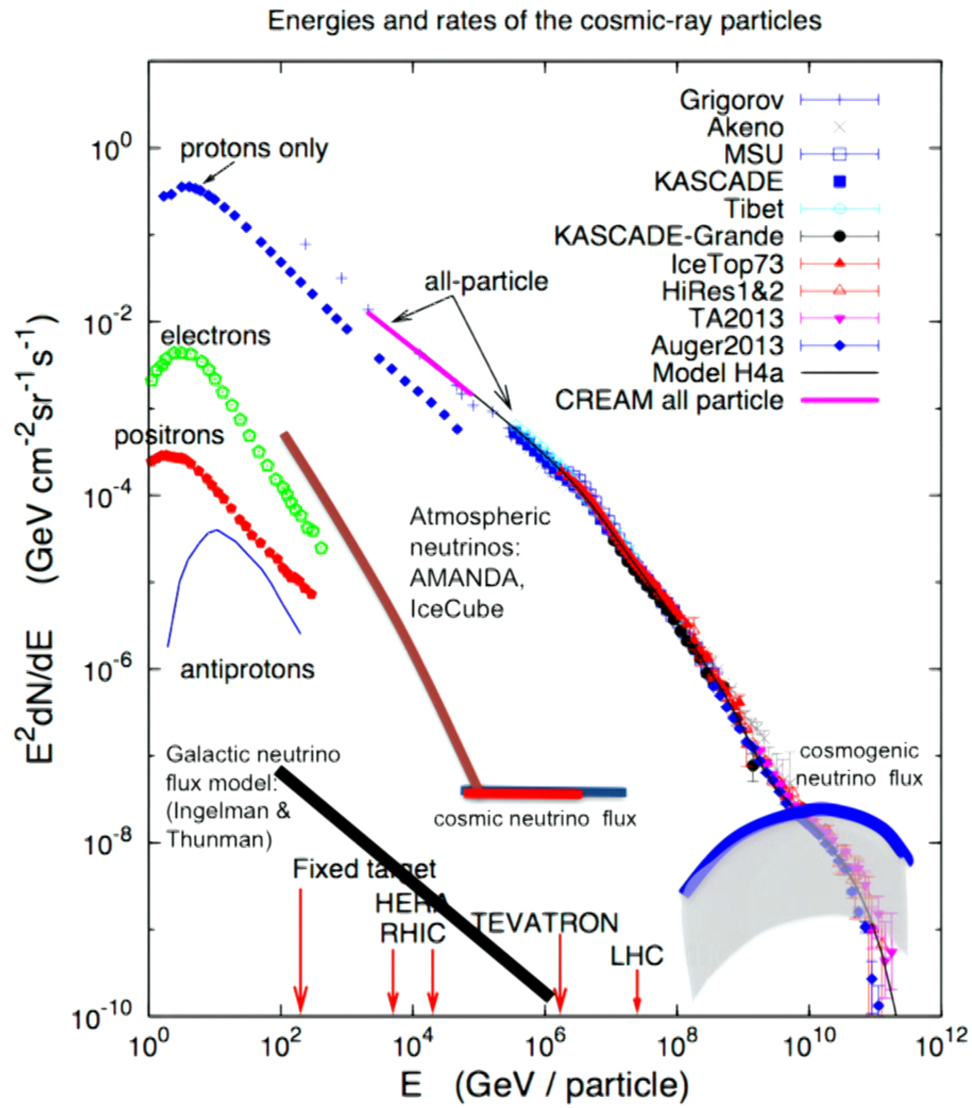
HiRes
TA
Auger
IC-86 (10yr)
ARA-37 (3yr)
"bestfit"
$\mathcal{H}_{\rm SFR}$
$\mathcal{H}_0$
$E^2 J$ [GeV cm^{-2} s^{-1} sr^{-1}]
E [GeV]



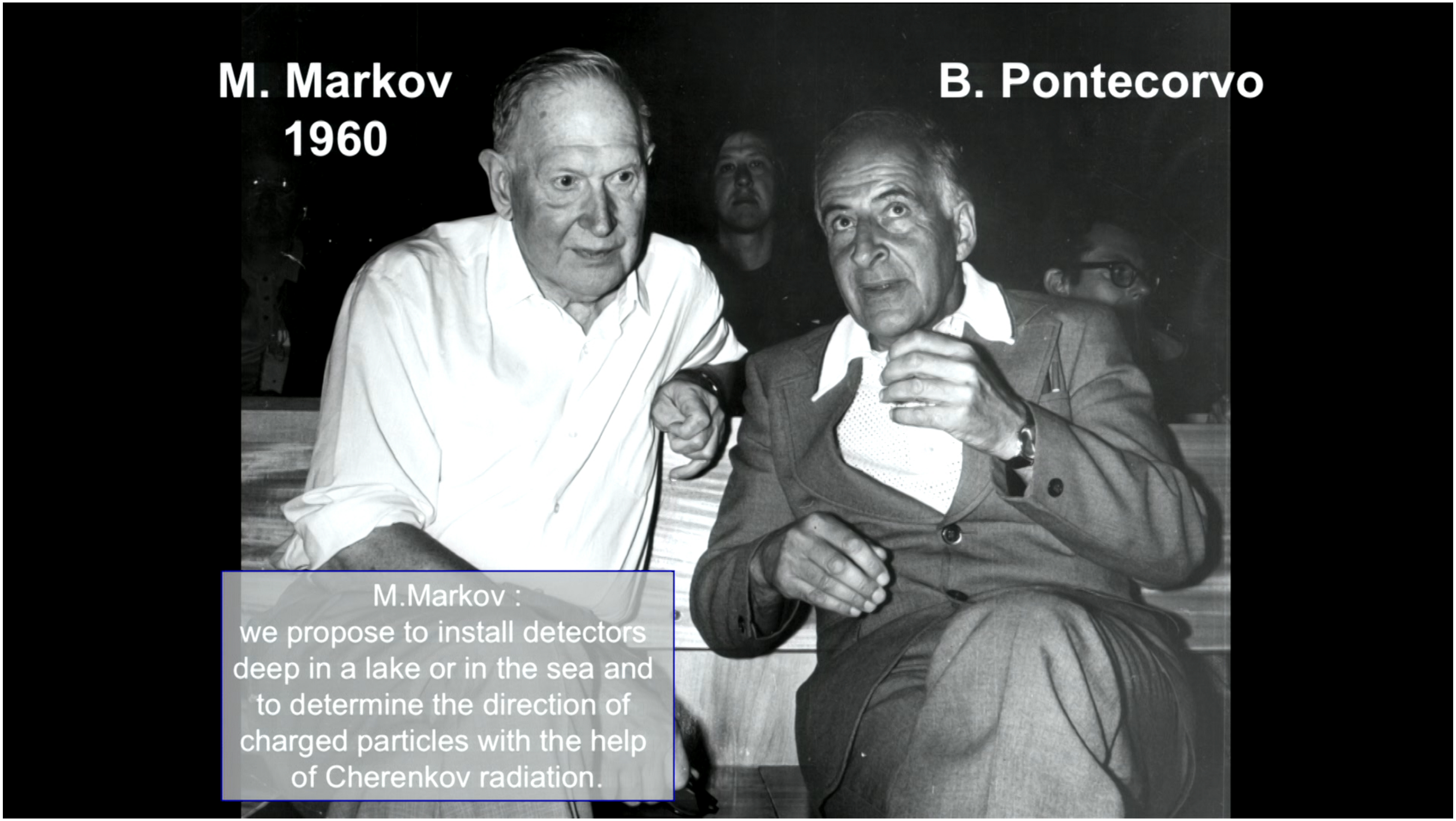
Limits on all flavor (1:1:1) neutrino flux (φ∝E⁻¹) over one energy dec
GZK ν Yoshida et al. m=4 Zmax = 4 γ=2
GZK ν Ahlers et al. best fit with 3 EeV transition
GZK ν Ahlers et al. 99% CL range with 3 EeV transition
GZK ν Kotera FRII, Emax 316 EeV
ANITA-II(2010)
RICE(2012)
PAO(2015) ν_single limit x3
[2004-2013]
IceCube(2012)
[2010-2012]
this work
[2008-2014]
IceCube Preliminary
$E_\nu^2\ \phi(E_\nu)$ [GeV cm^{-2} sec^{-1} sr^{-1}]
E_ν [GeV]

neutrino sky

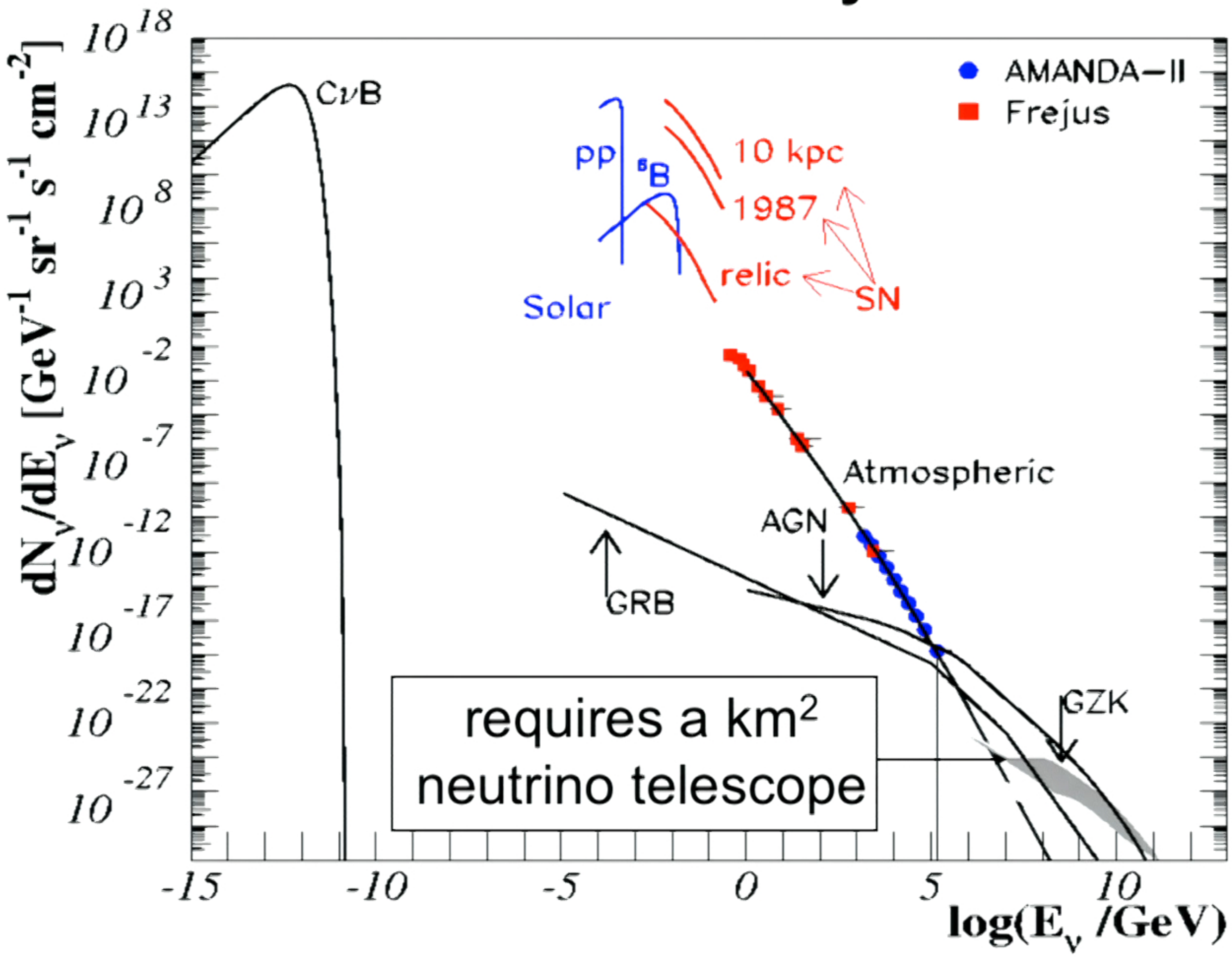


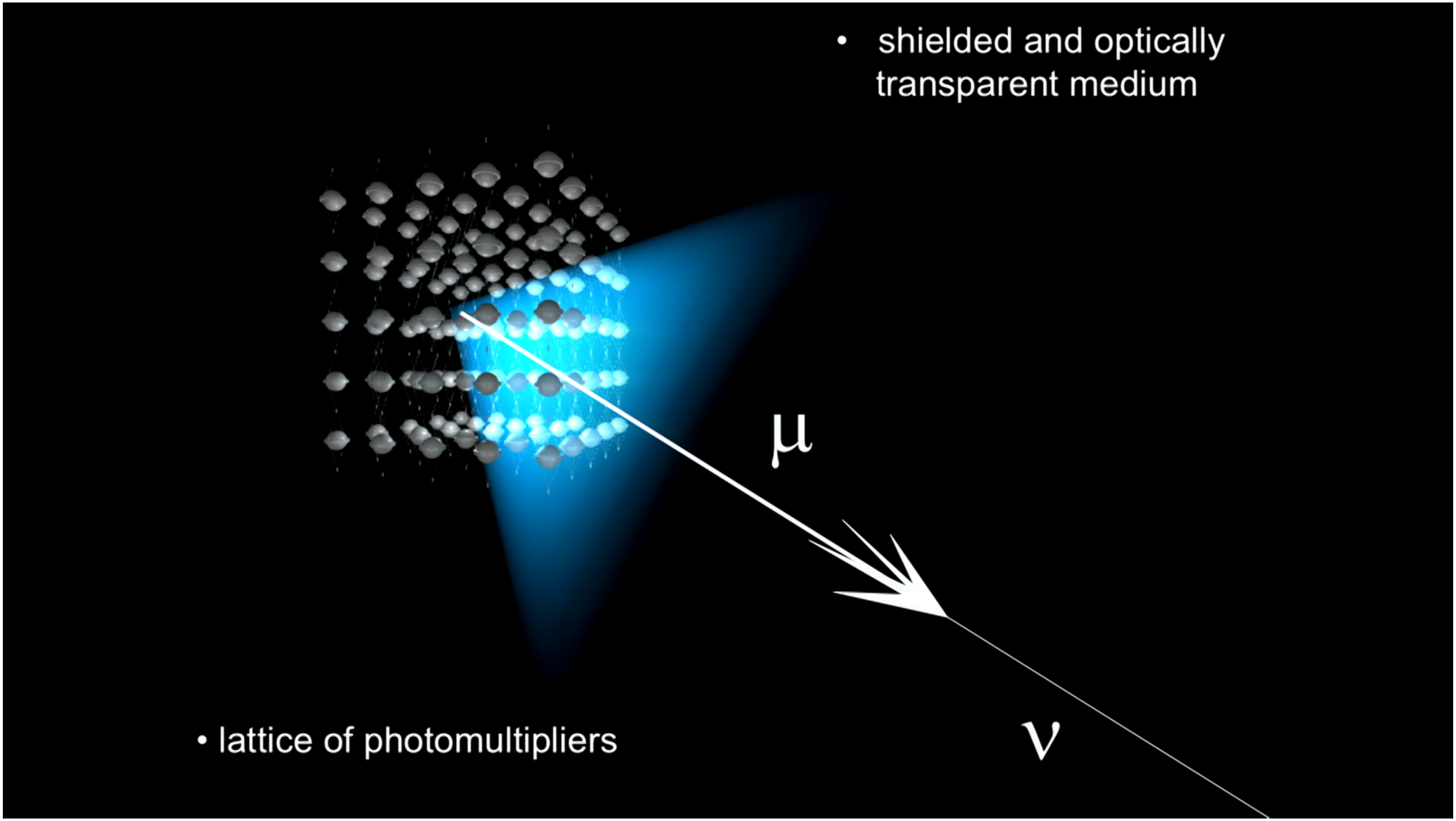


Energies and rates of the cosmic-ray particles
protons only
electrons
positrons
antiprotons
all-particle
Atmospheric neutrinos: AMANDA, IceCube
Galactic neutrino flux model: (Ingelman & Thunman)
cosmic neutrino flux
cosmogenic neutrino flux
Fixed target
HERA
RHIC
TEVATRON
LHC
Grigorov
Akeno
MSU
KASCADE
Tibet
KASCADE-Grande
IceTop73
HiRes1&2
TA2013
Auger2013
Model H4a
CREAM all particle
$E^2 dN/dE$ (GeV cm^{-2}sr^{-1}s^{-1})
E (GeV / particle)

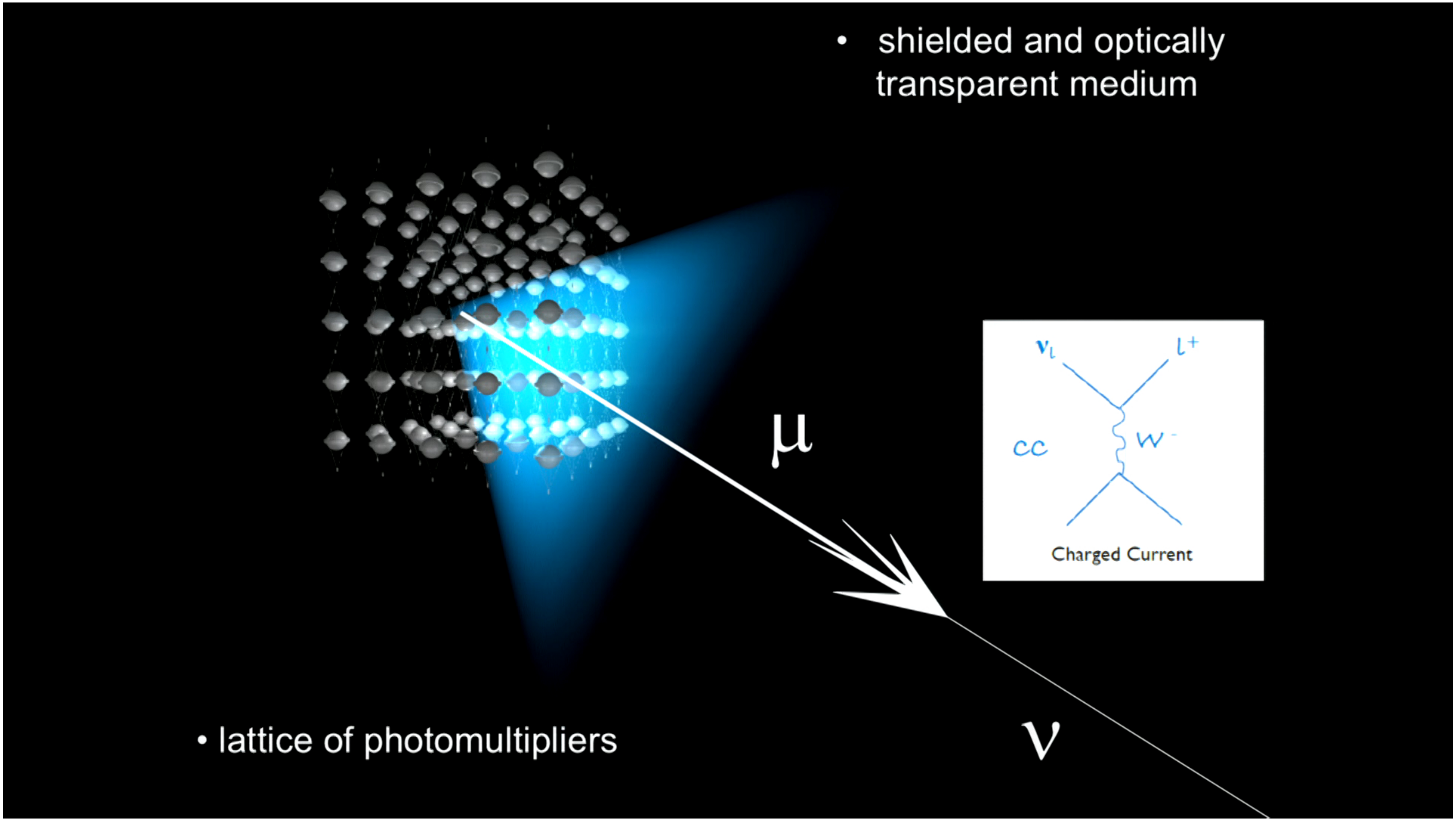

M. Markov
1960
B. Pontecorvo
M.Markov :
we propose to install detectors deep in a lake or in the sea and to determine the direction of charged particles with the help of Cherenkov radiation.

neutrino sky

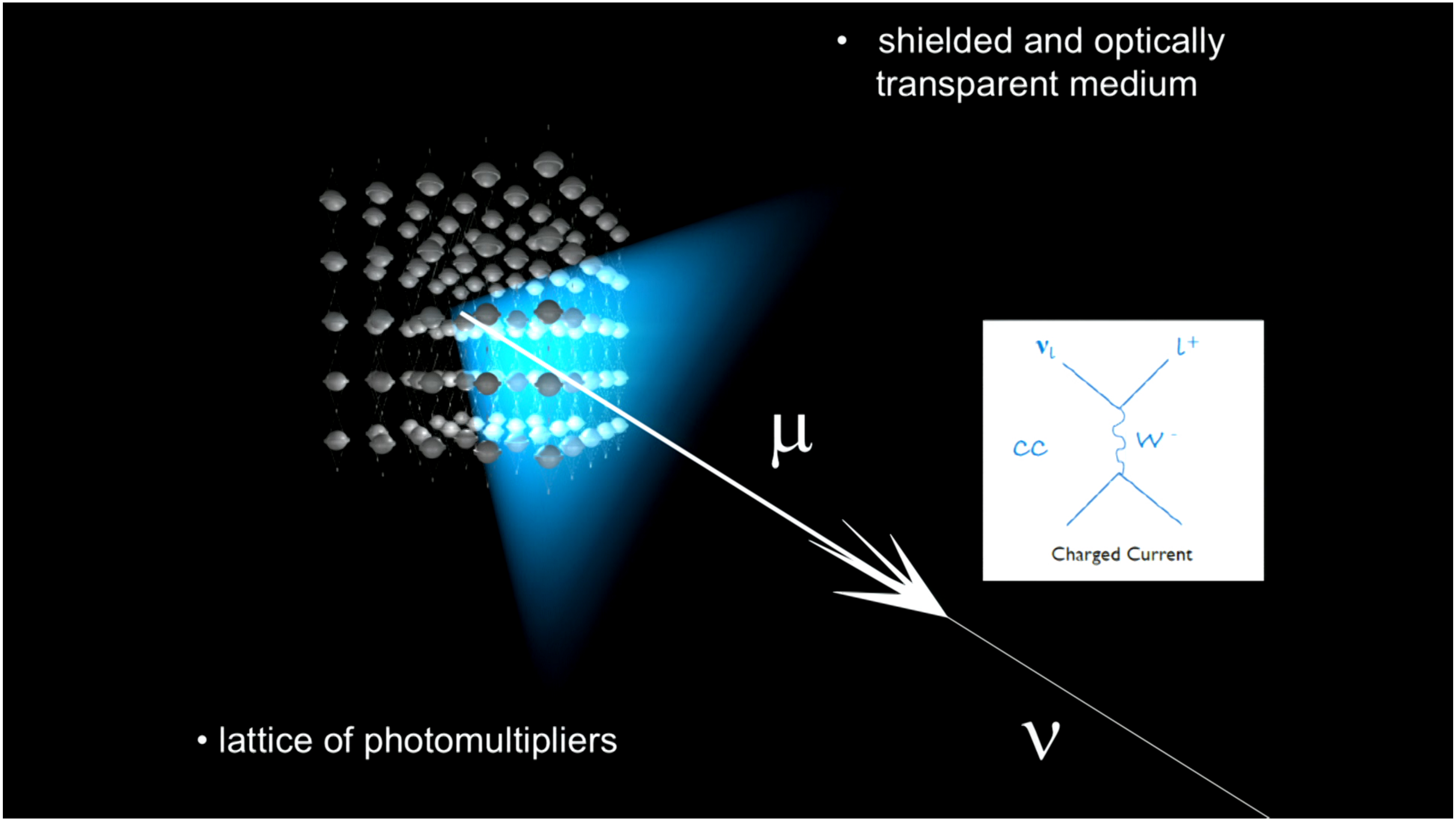




• shielded and optically transparent medium
μ
• lattice of photomultipliers
ν



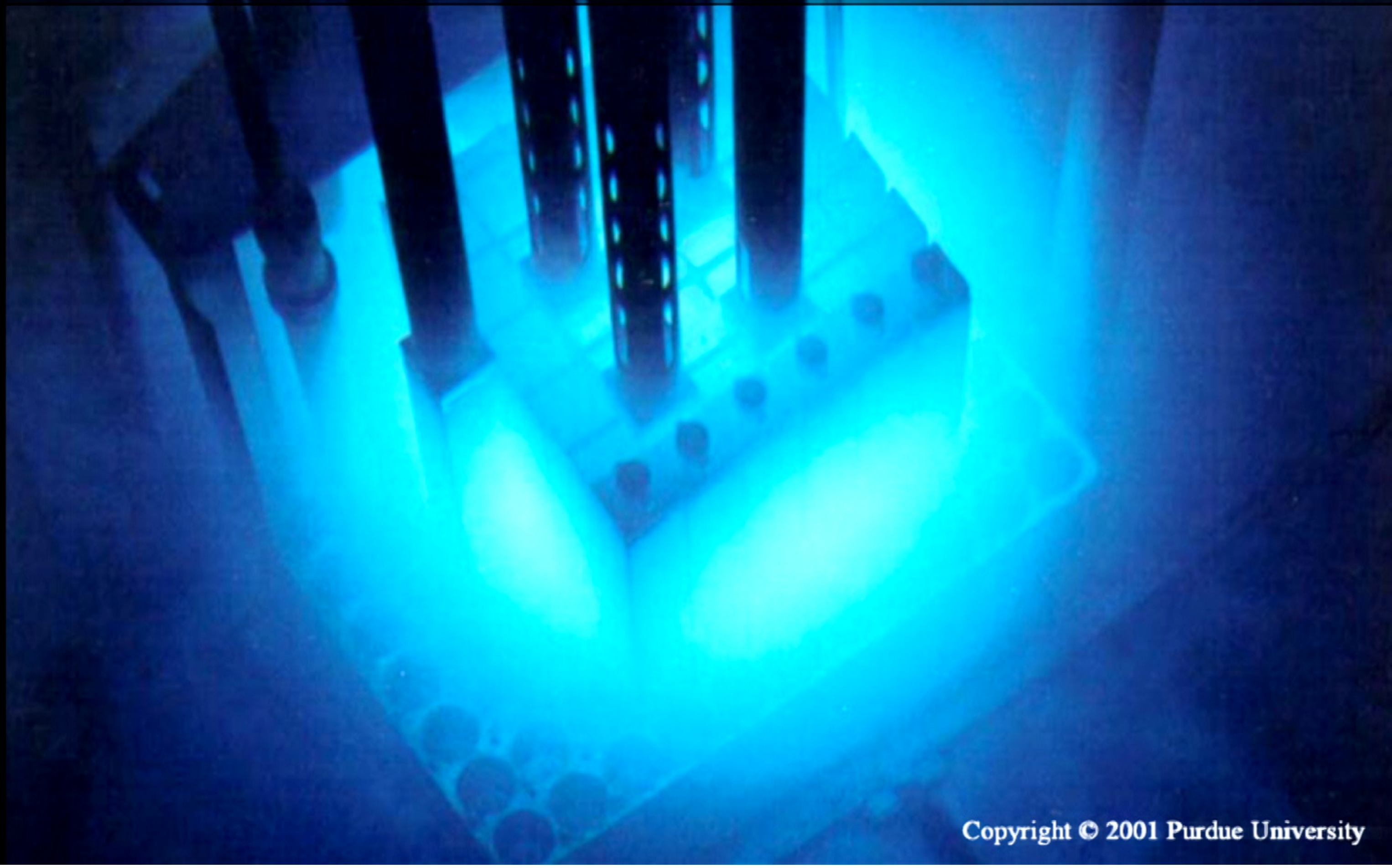
• shielded and optically transparent medium
μ
ν
ν_l
l^+
cc
W^-
Charged Current
• lattice of photomultipliers



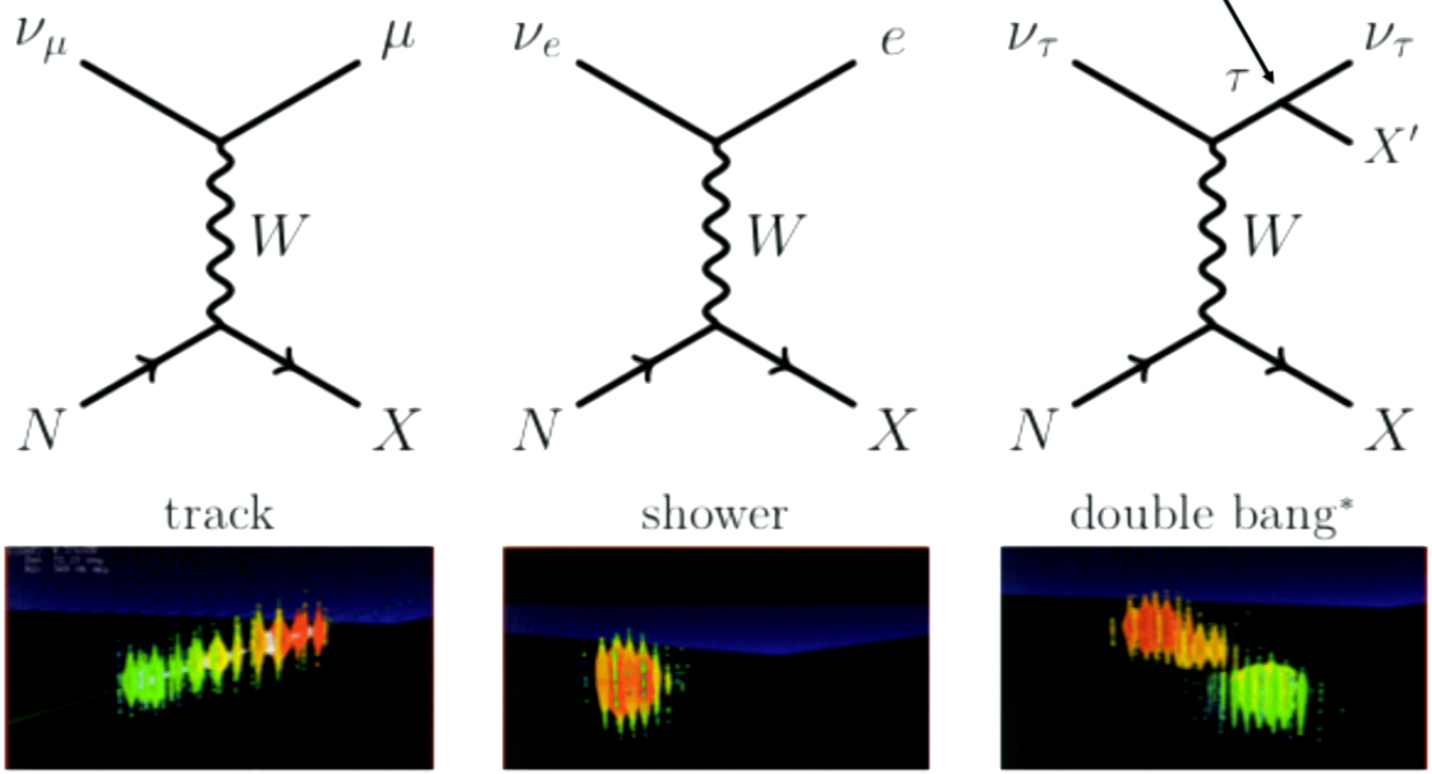
• shielded and optically transparent medium
• lattice of photomultipliers
μ
ν
ν_l
l+
CC
W-
Charged Current

photomultiplier tube -10 inch

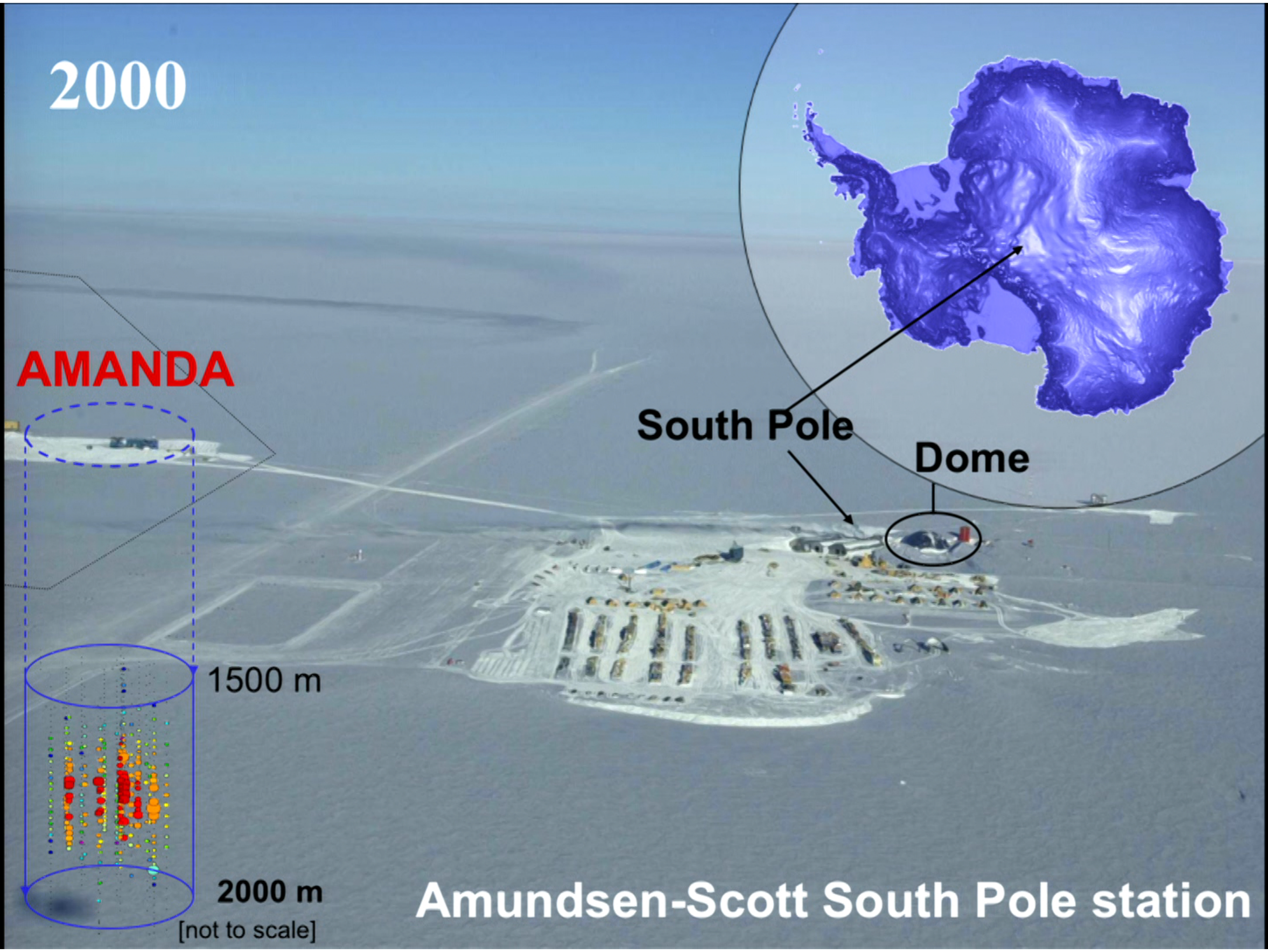
particles produced in a nuclear reactions produce blue light in water



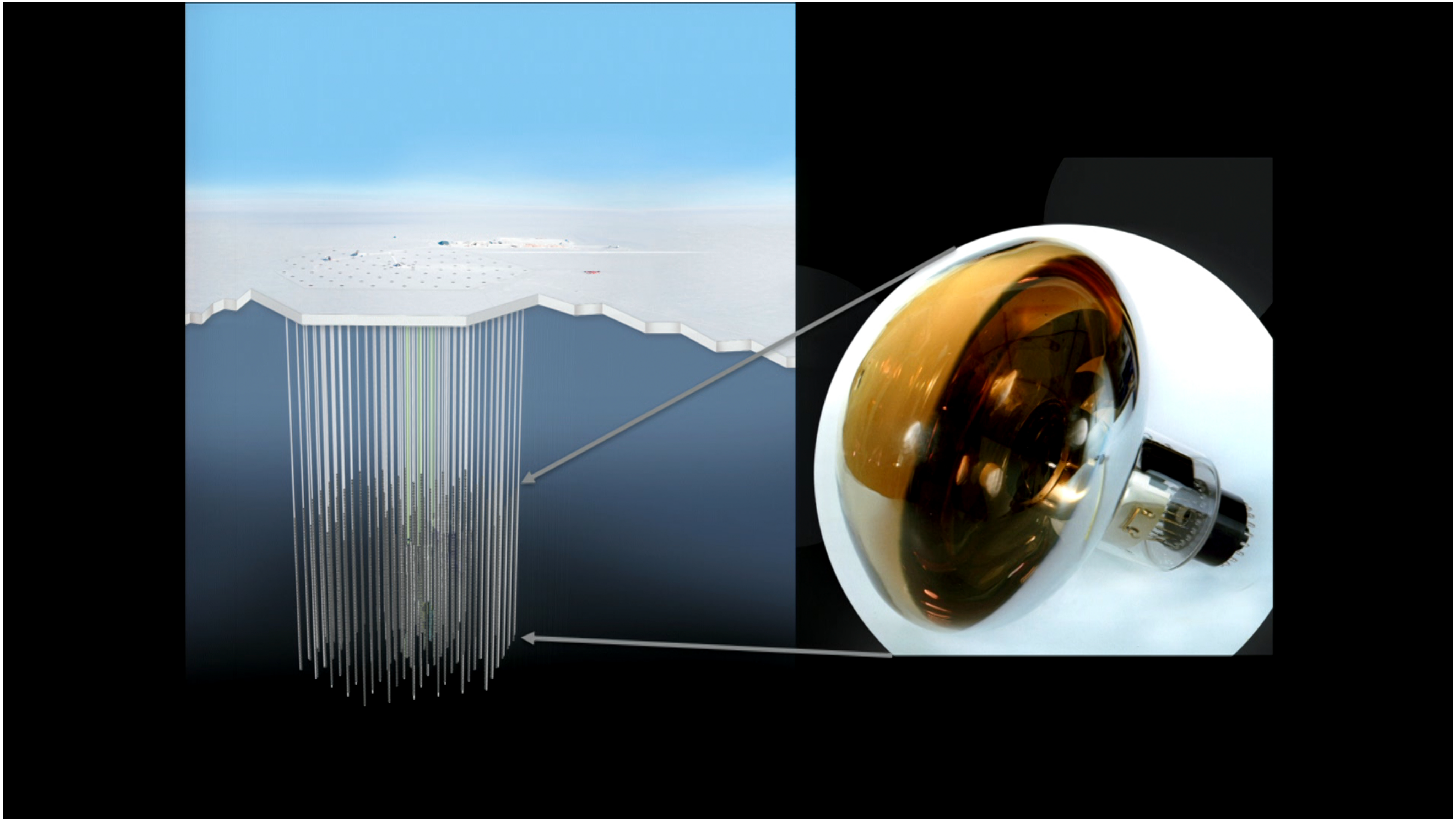
tau decay length:
50m per PeV

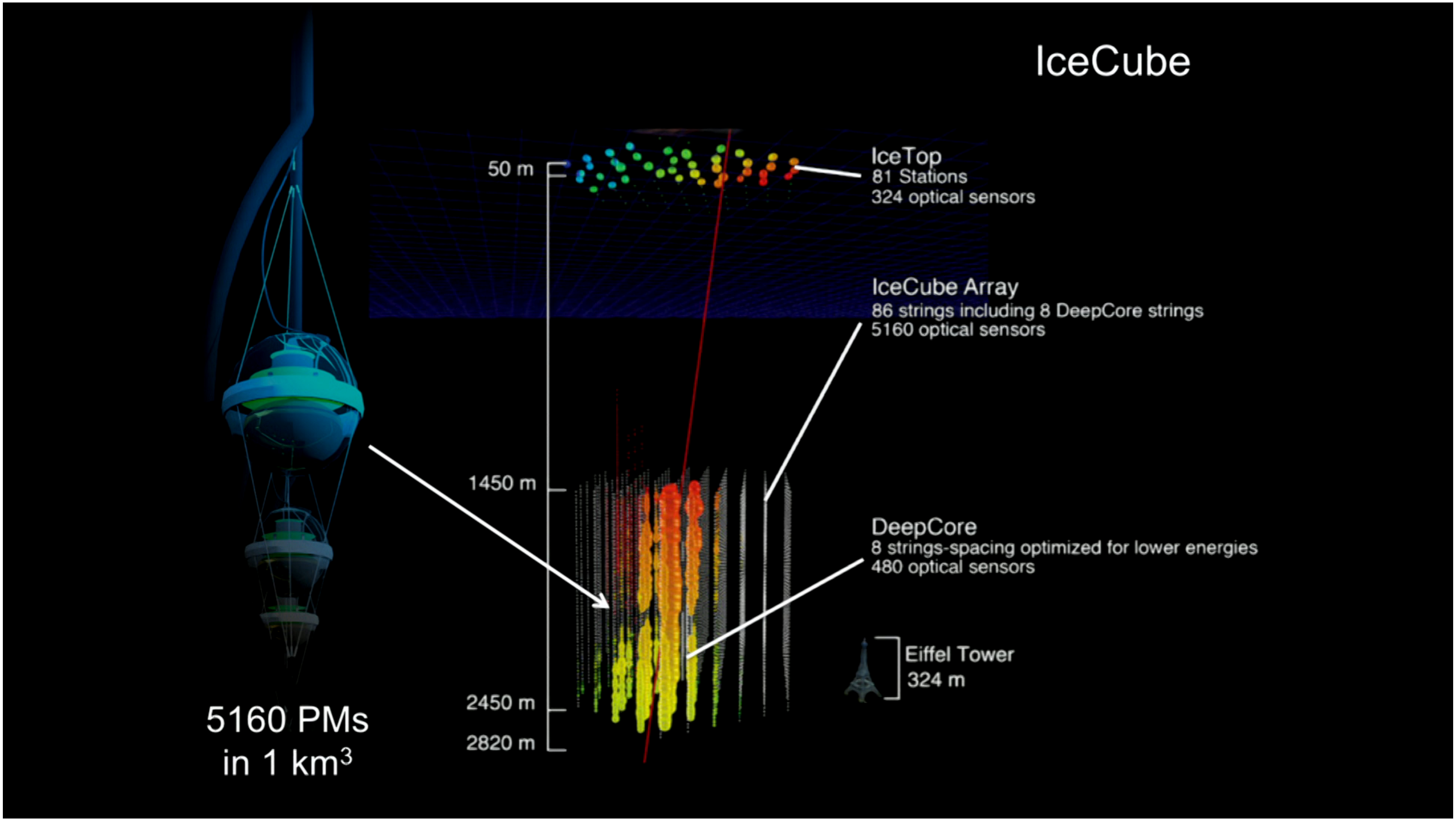



ultra-transparent ice below 1.5 km



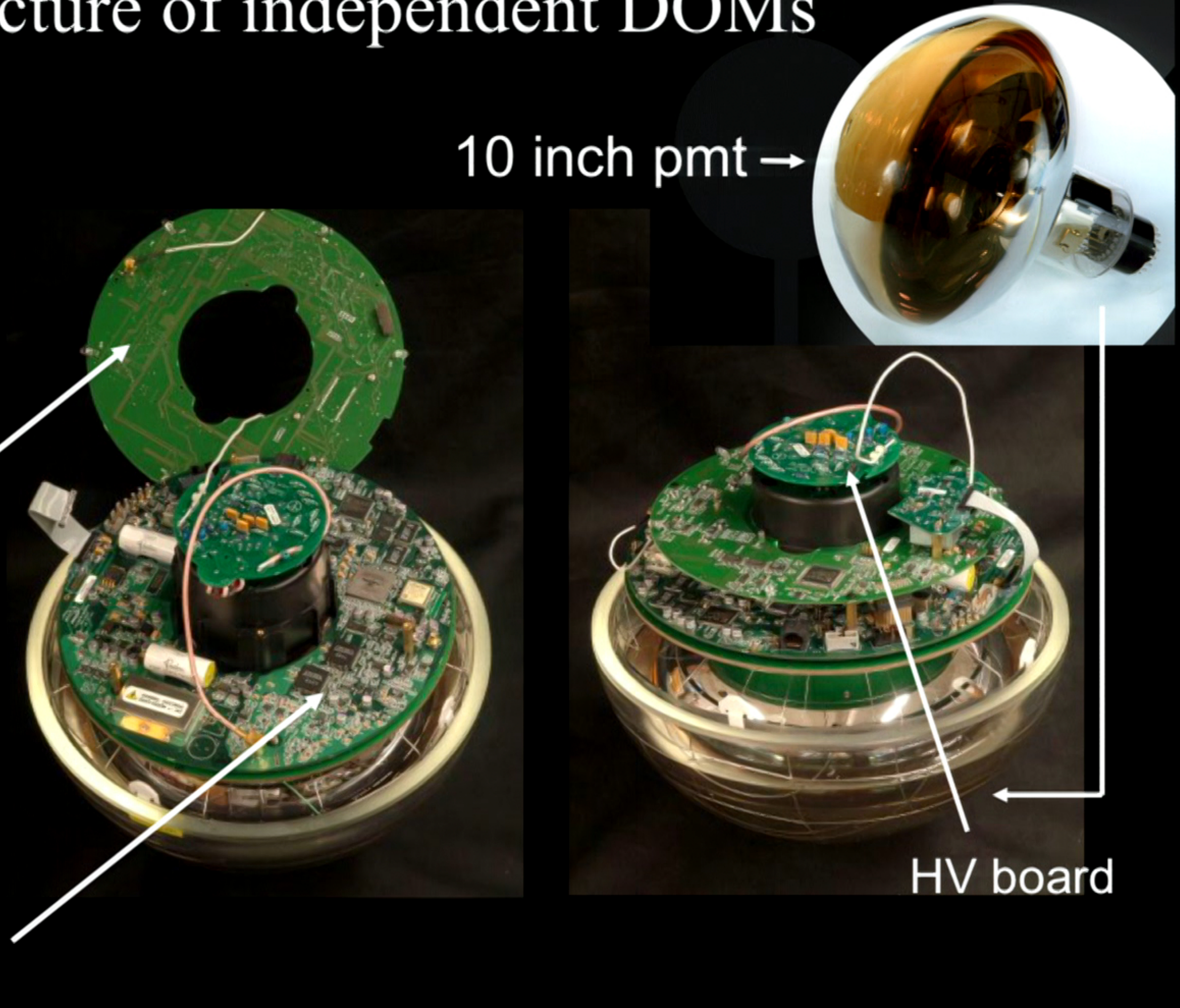
2000
AMANDA
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station



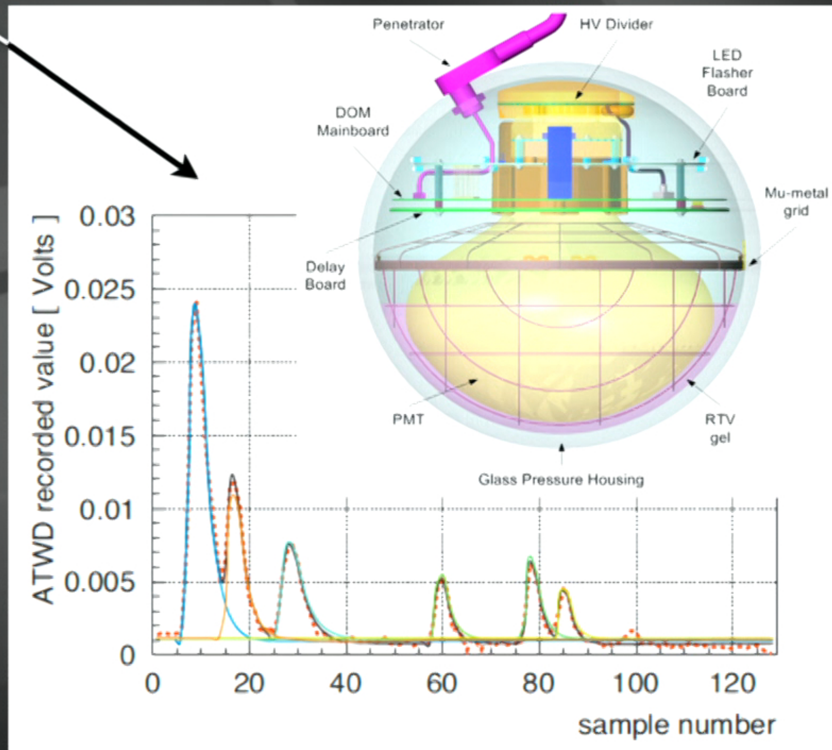


IceCube
50 m
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
5160 PMs
in 1 km3

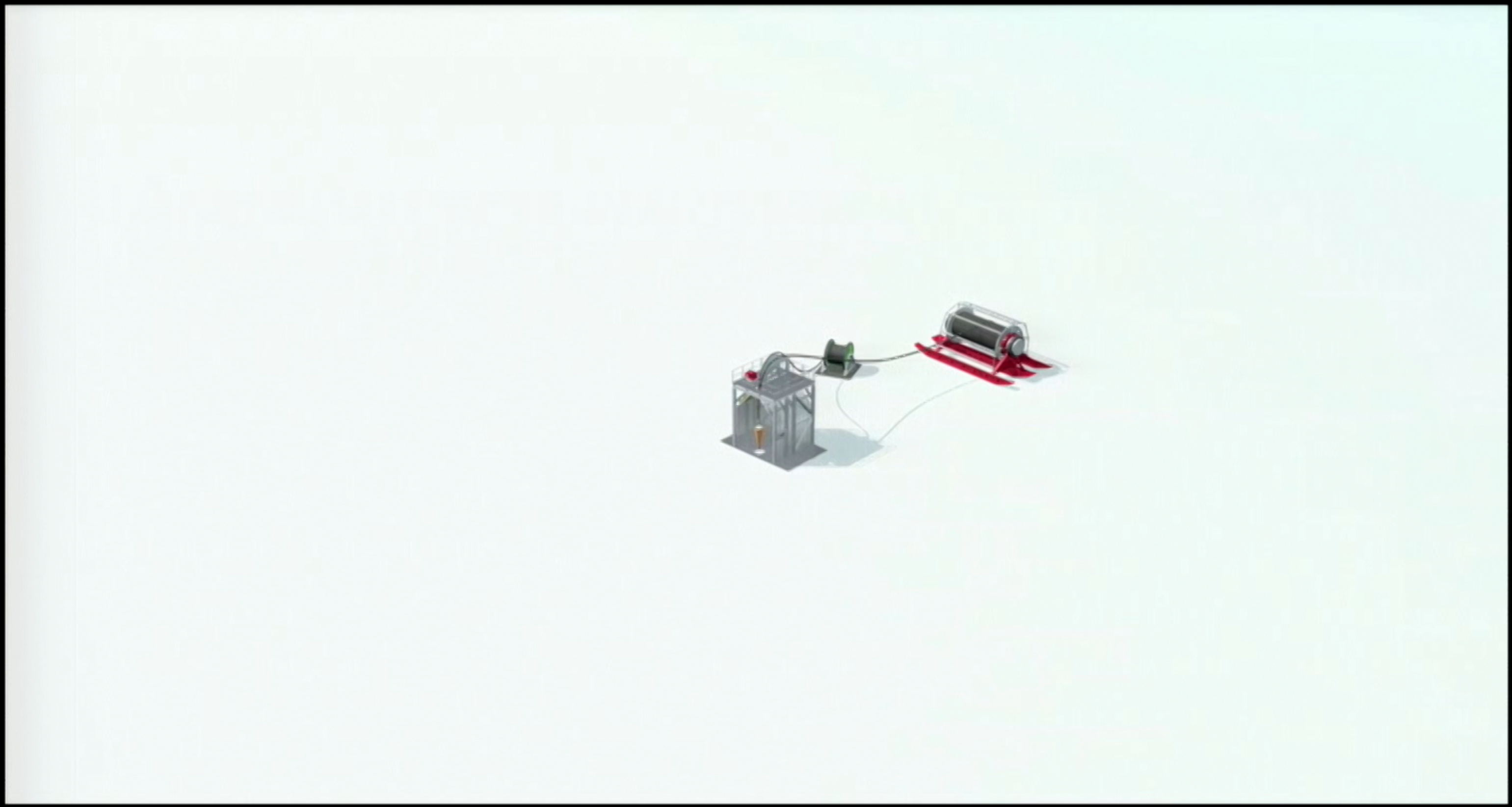
architecture of independent DOMs

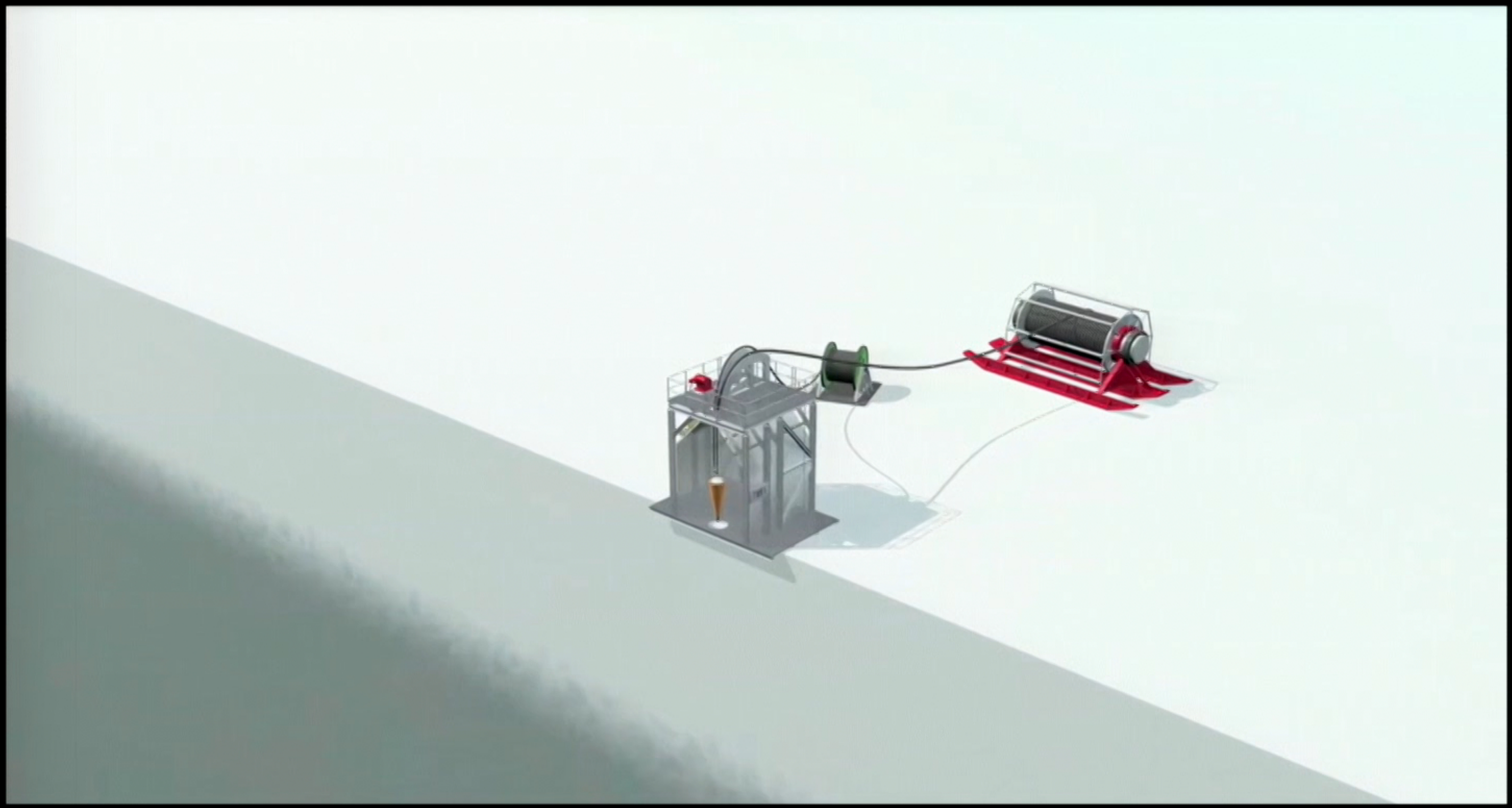


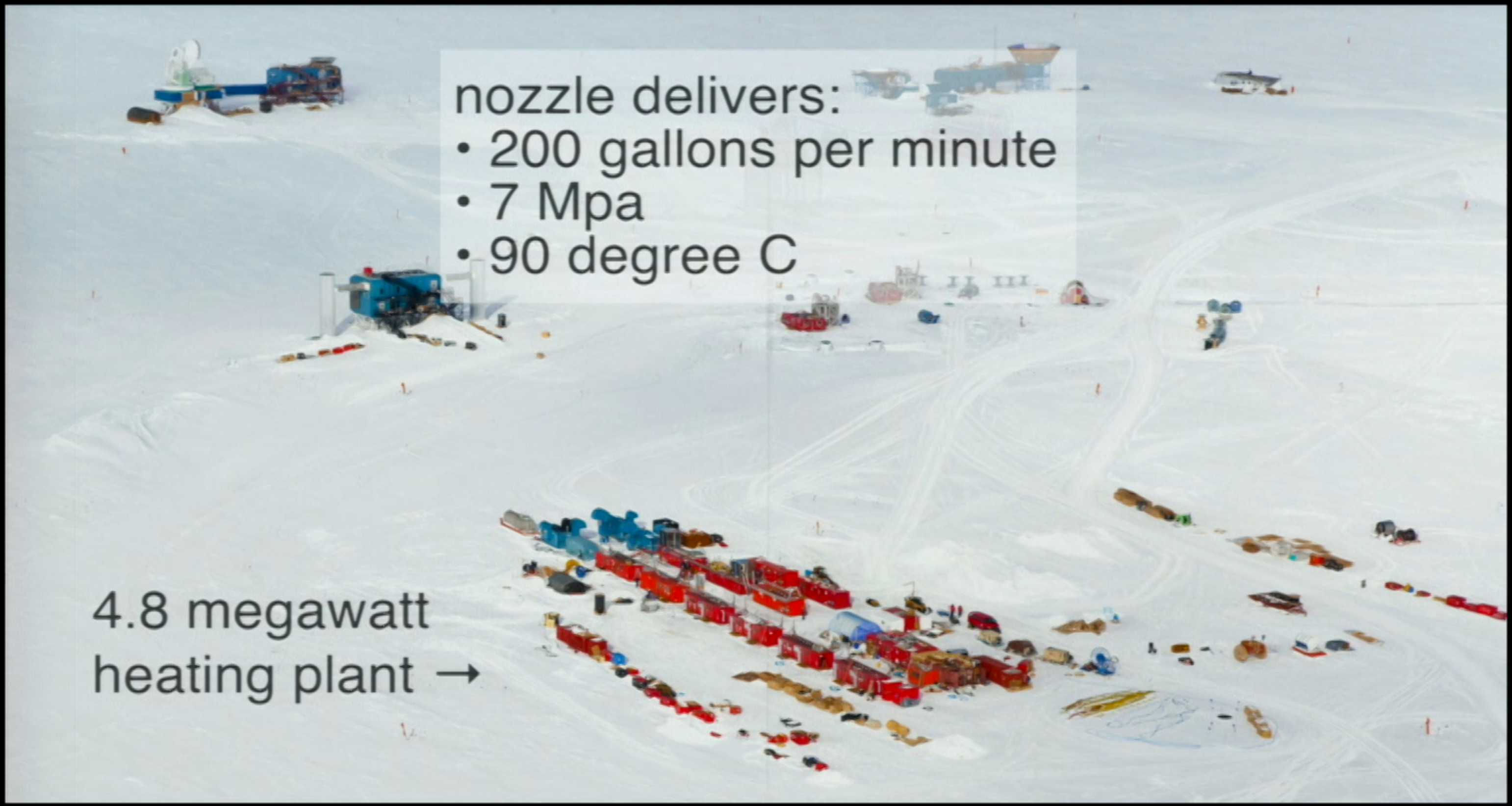
… each Digital Optical Module independently collects light signals like this, digitizes them,

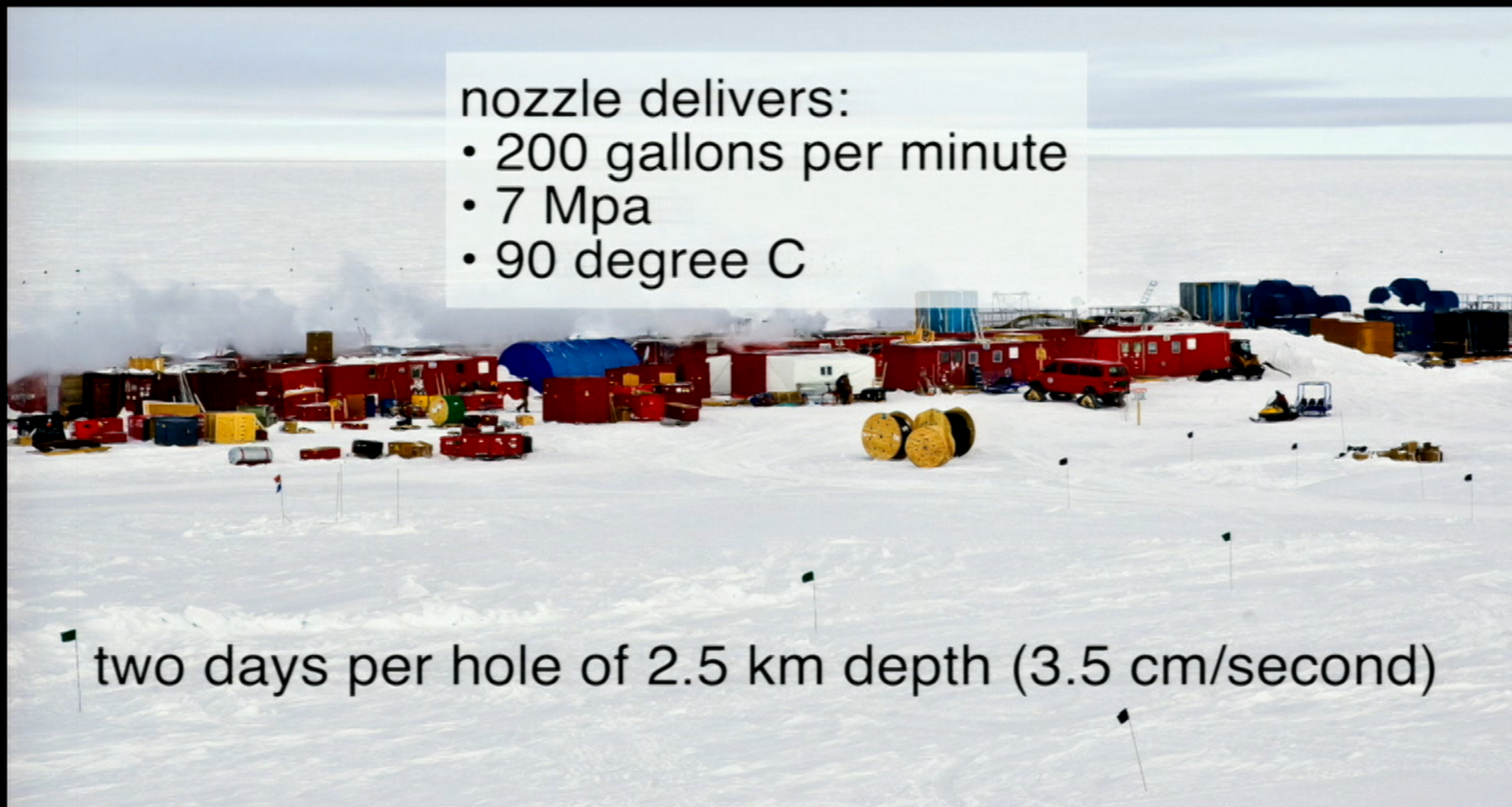


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…






nozzle delivers:
• 200 gallons per minute
• 7 Mpa
• 90 degree C
4.8 megawatt
heating plant →

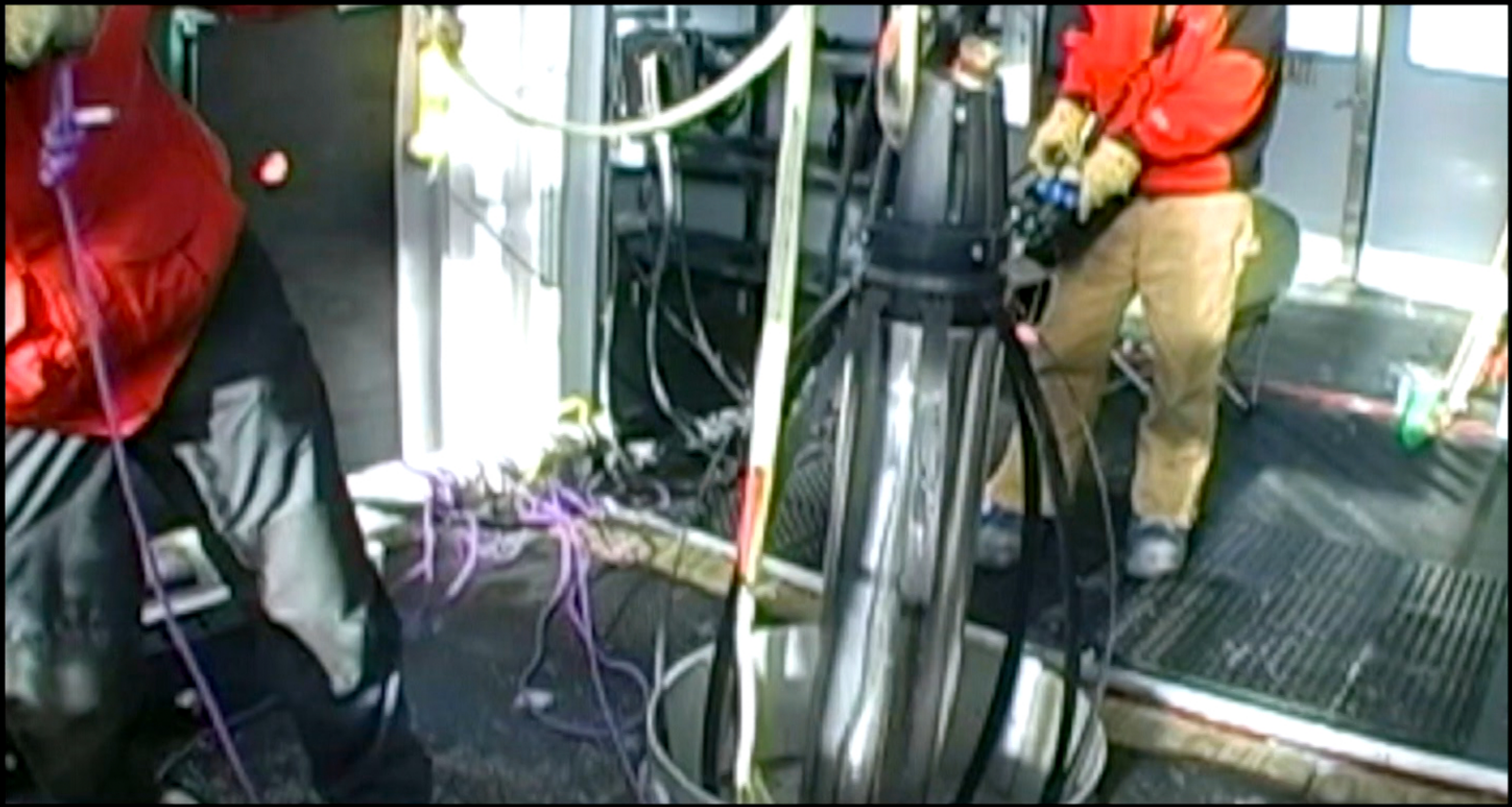

nozzle delivers:
• 200 gallons per minute
• 7 Mpa
• 90 degree C
two days per hole of 2.5 km depth (3.5 cm/second)

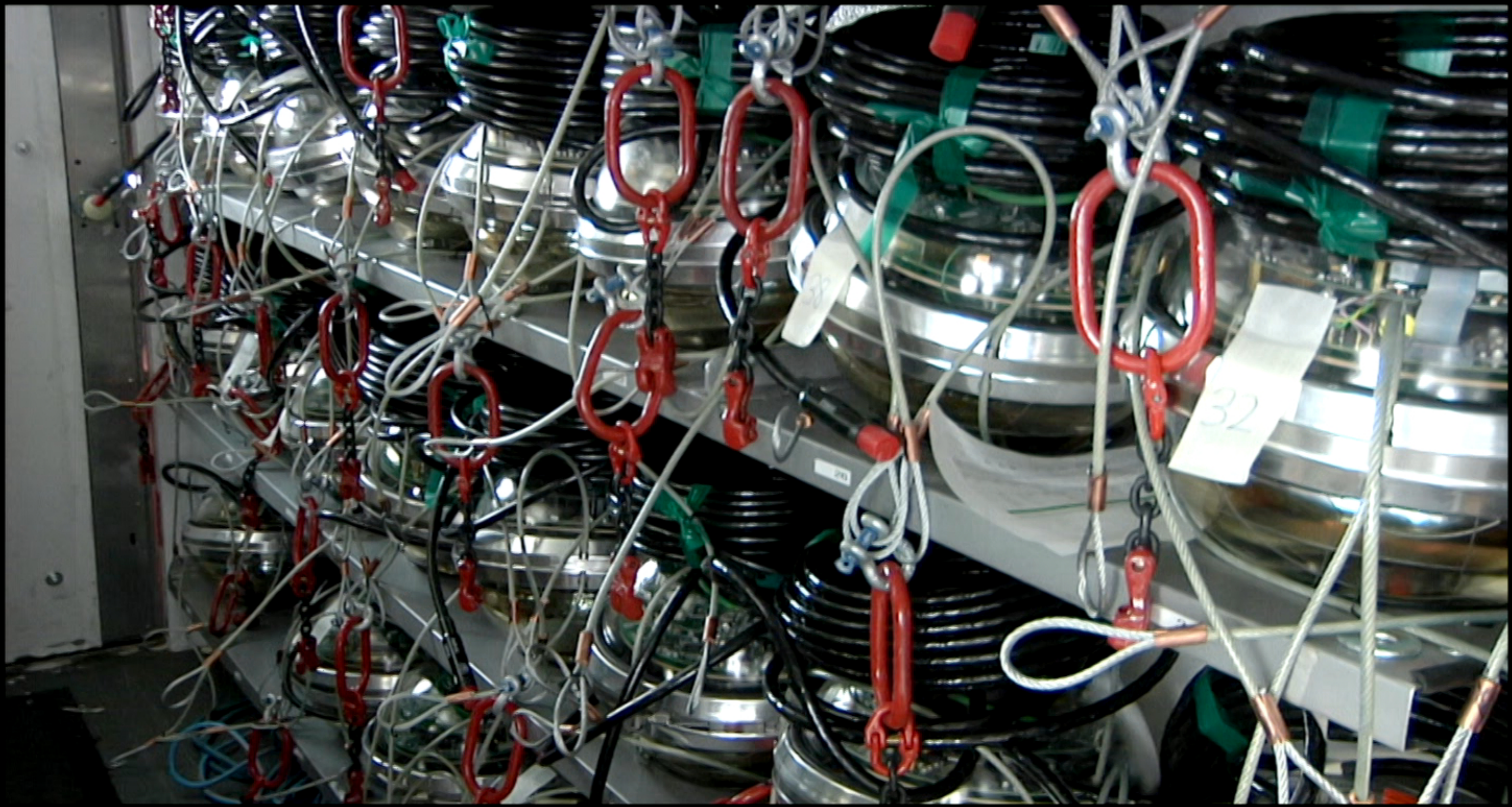

S2RH

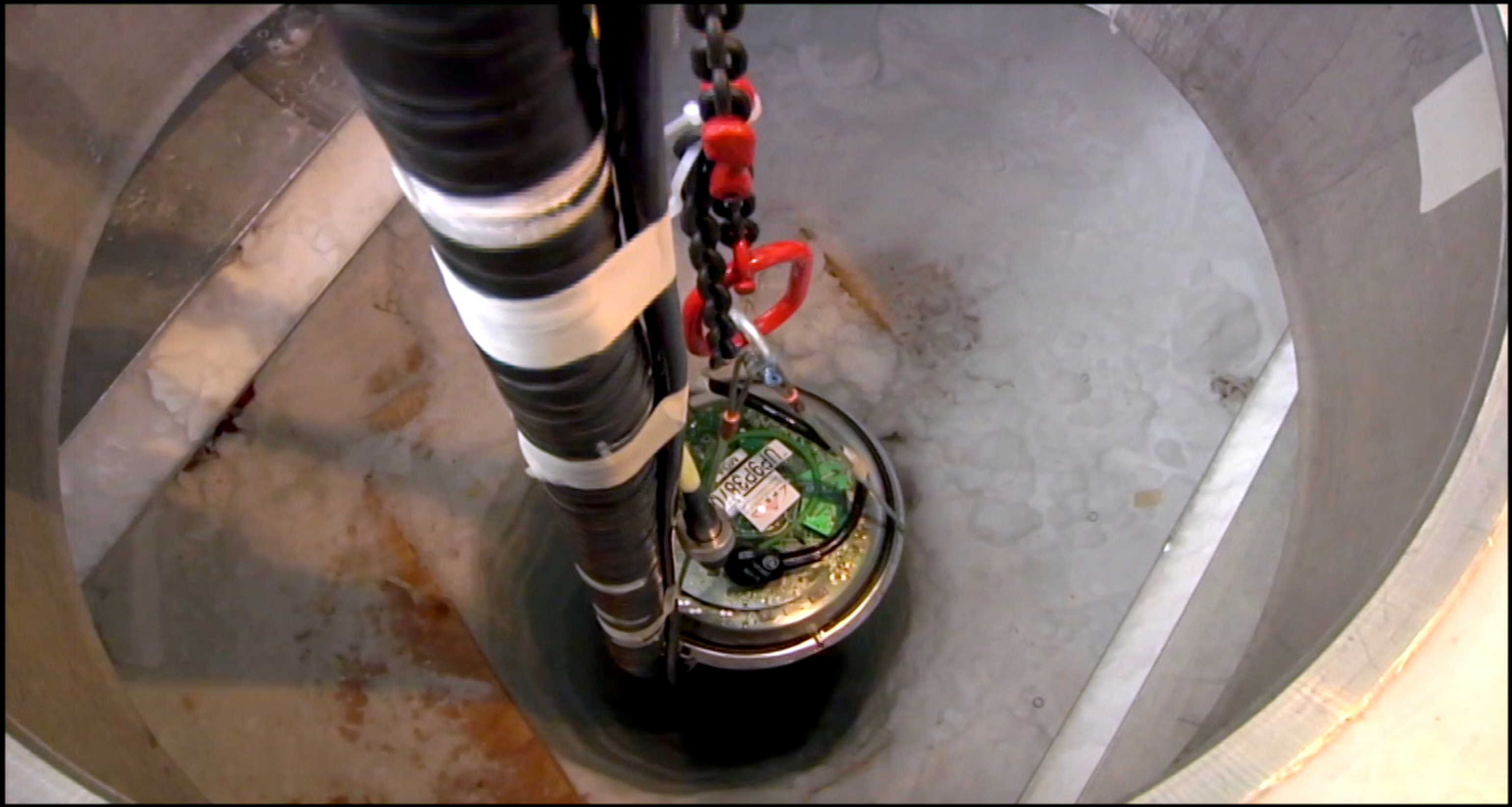

AN8
AN8

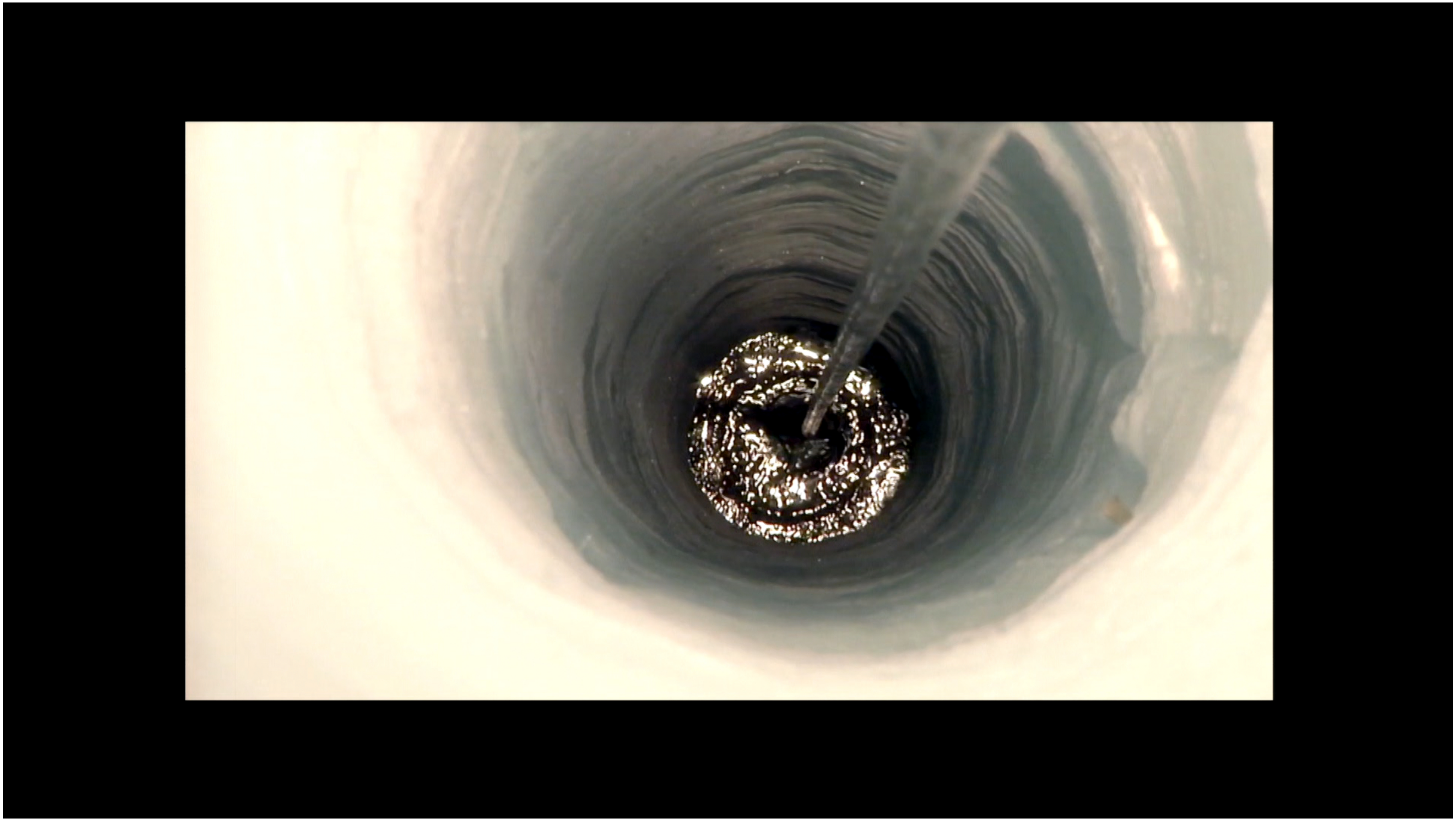

RETURN FROM MHP1

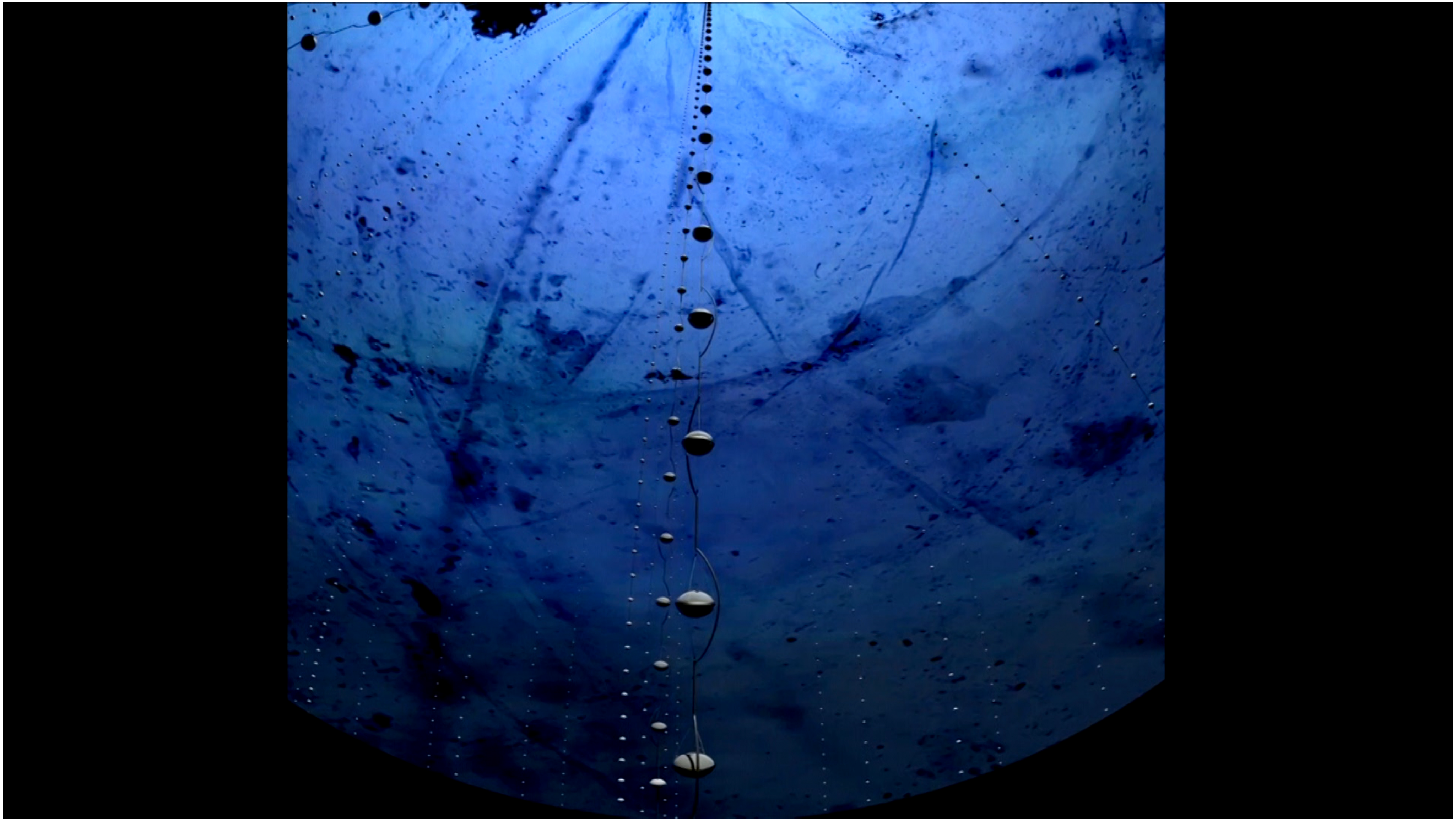

RETURN FROM MHP1

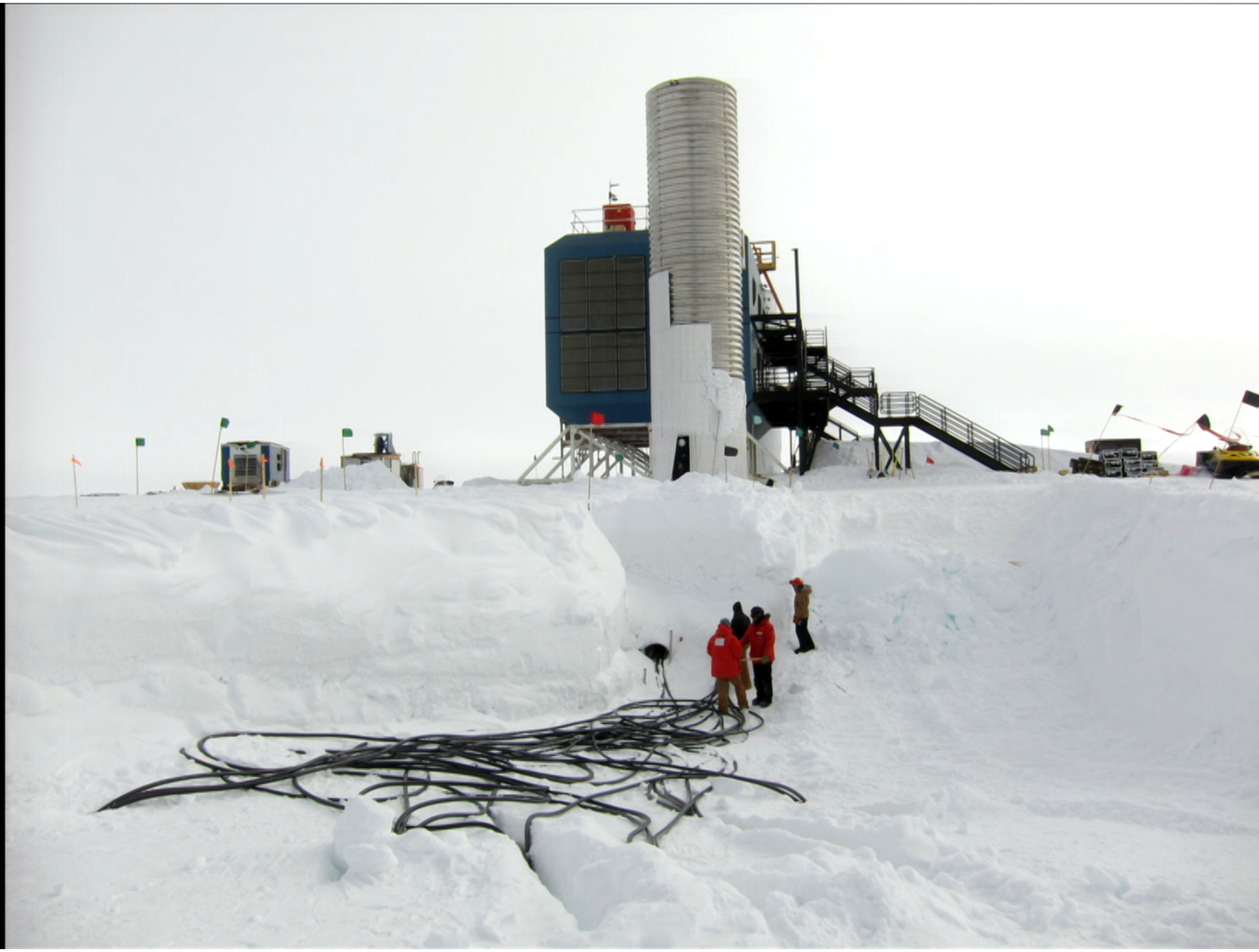


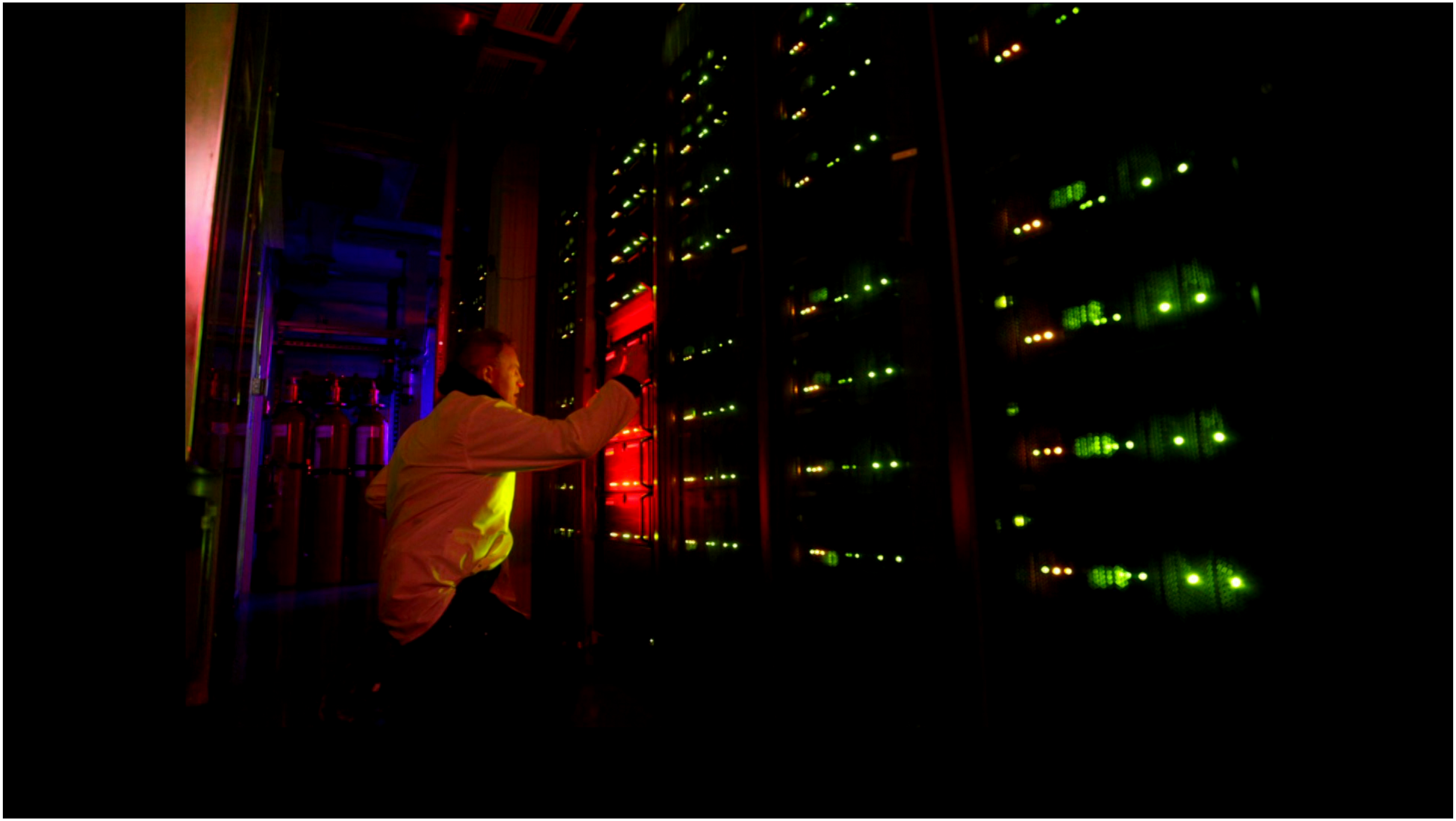


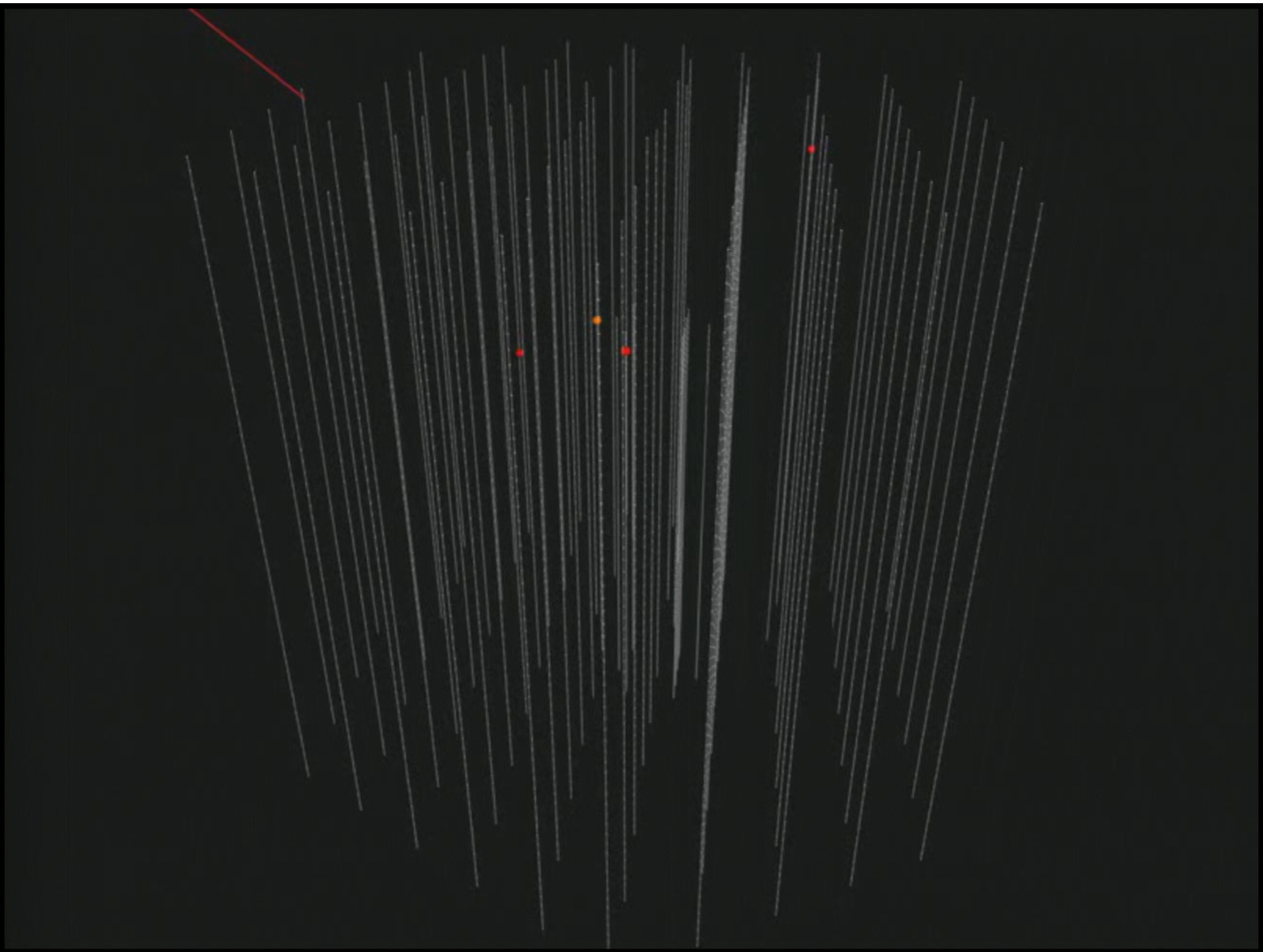




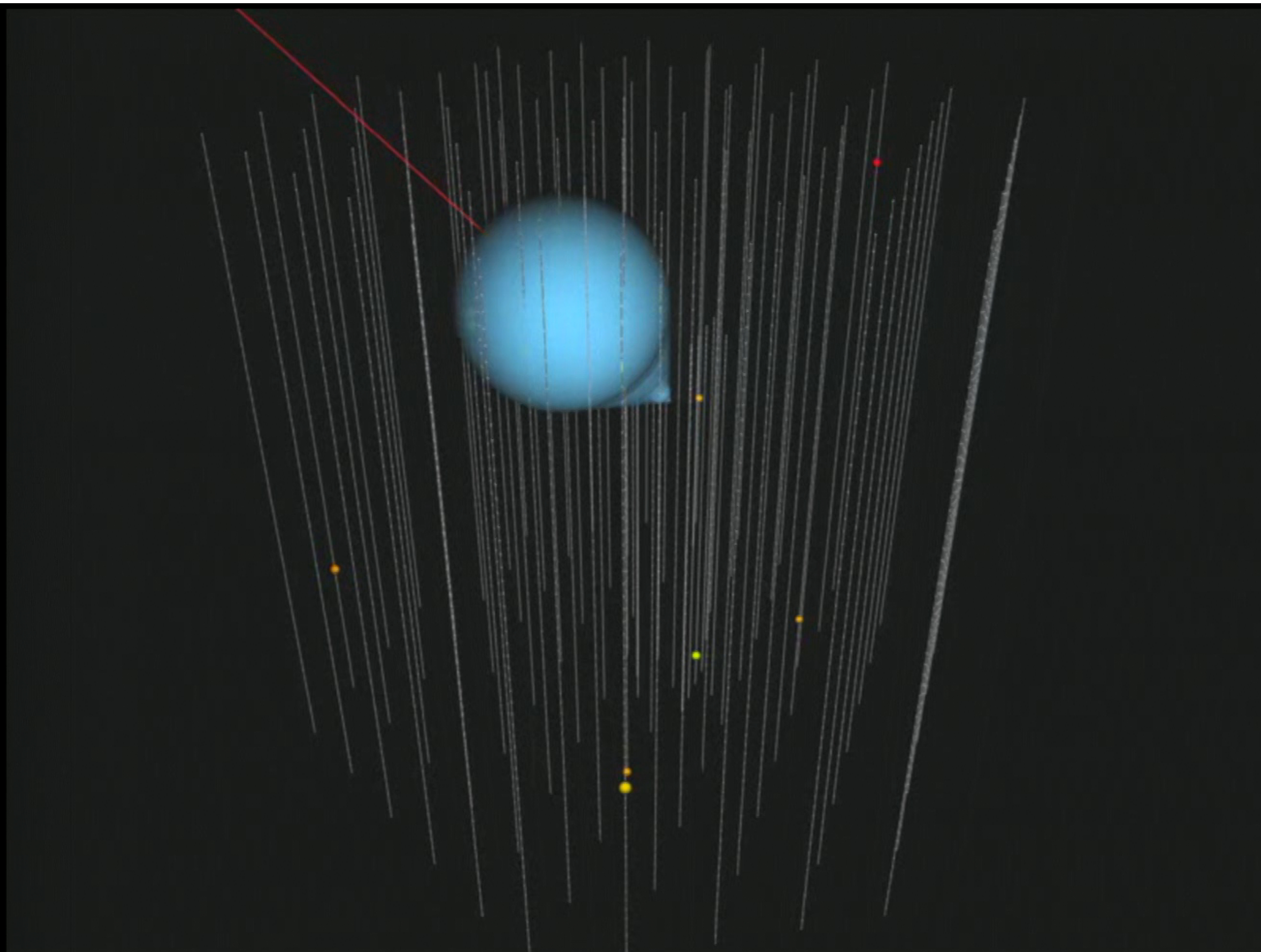




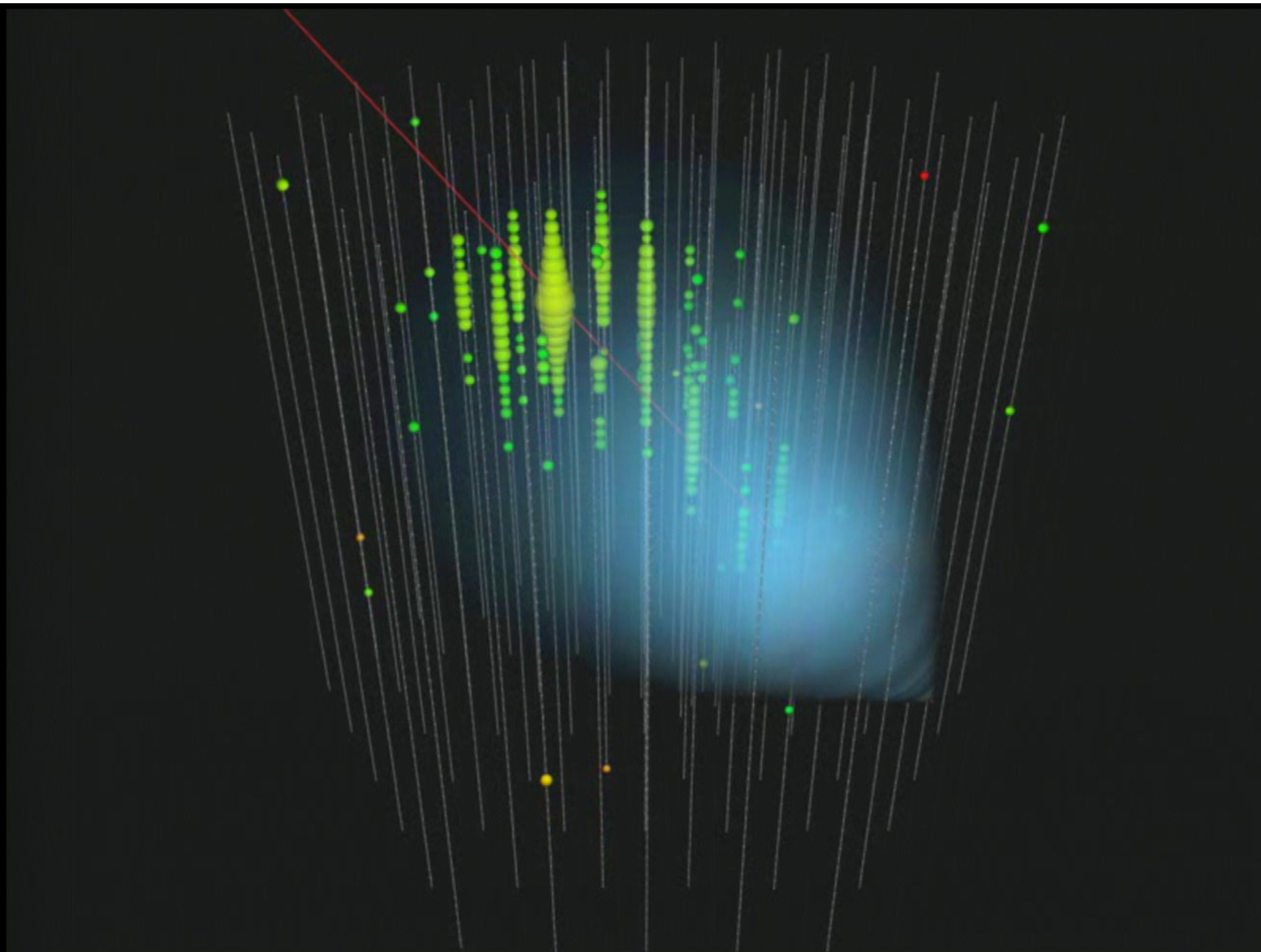




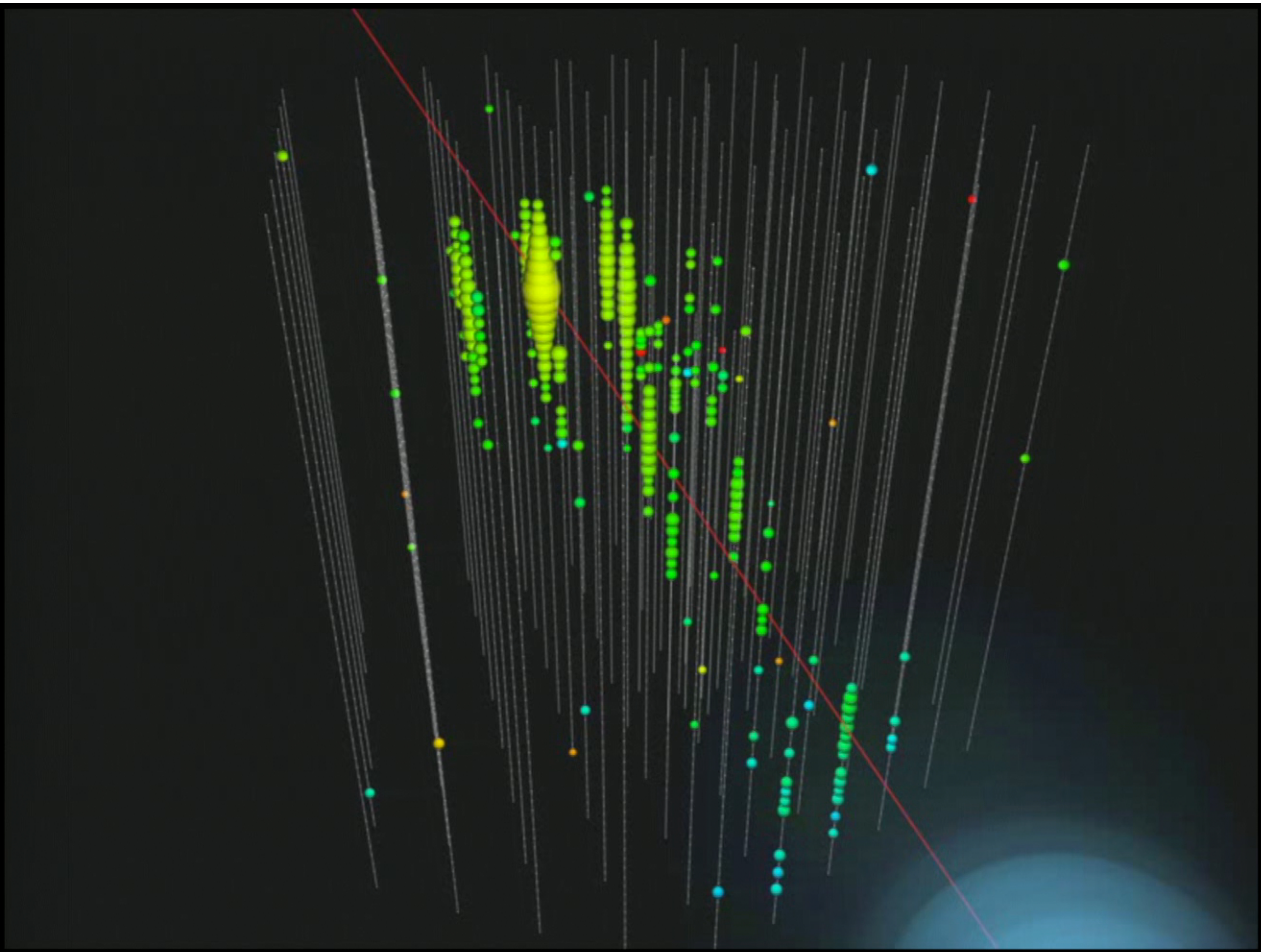
muon track: color is time; number of photons is energy



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

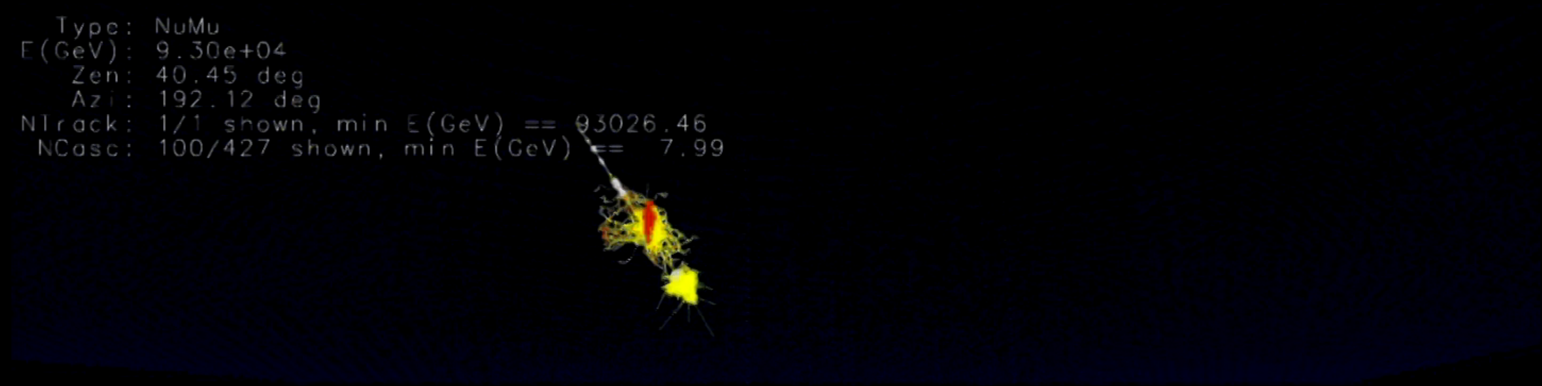


muon track: color is time; number of photons is energy

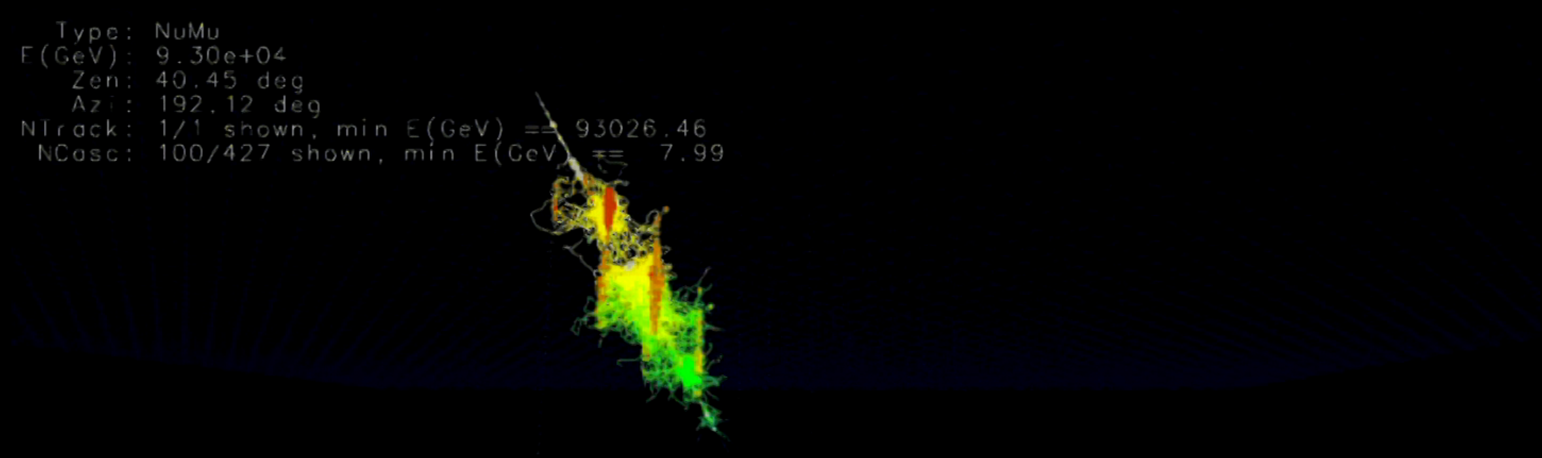


muon track: color is time; number of photons is energy

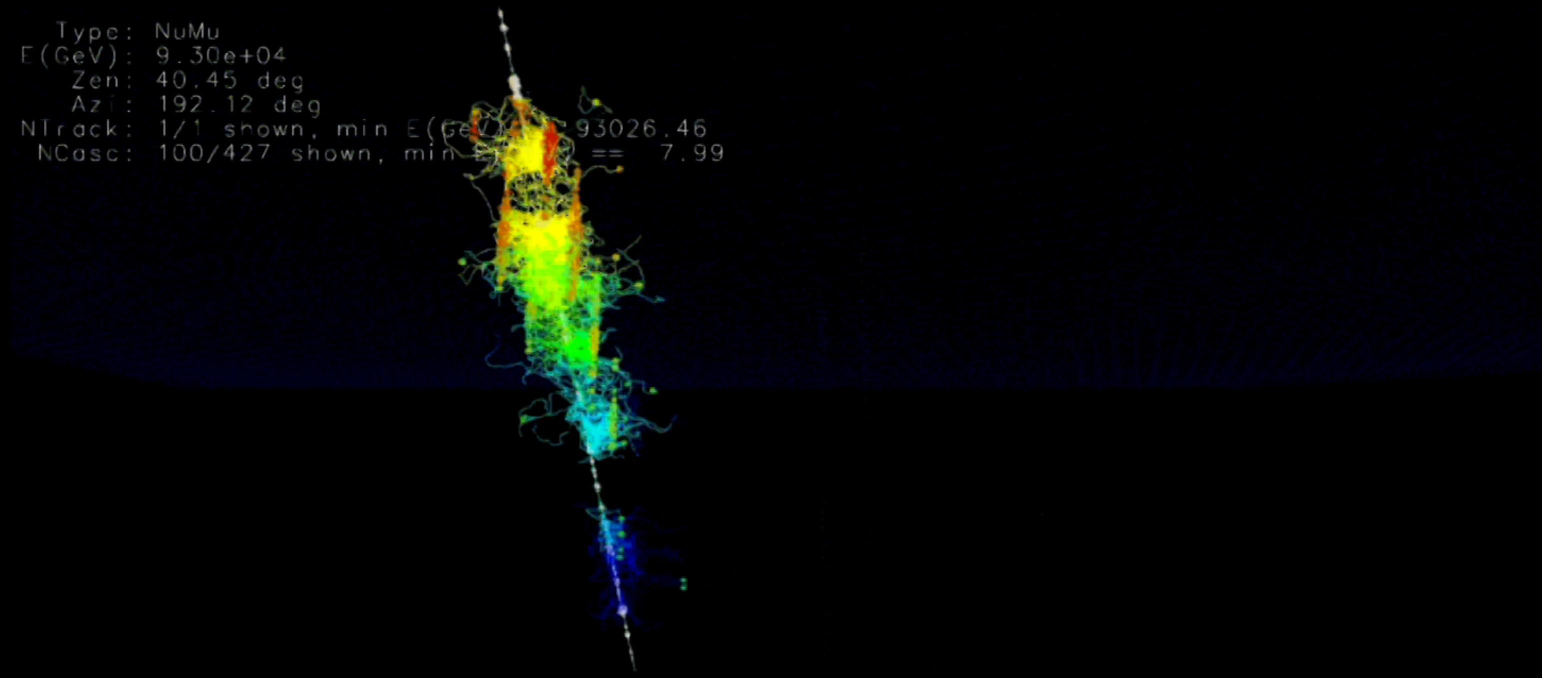
93 TeV muon: # photons ~ energy



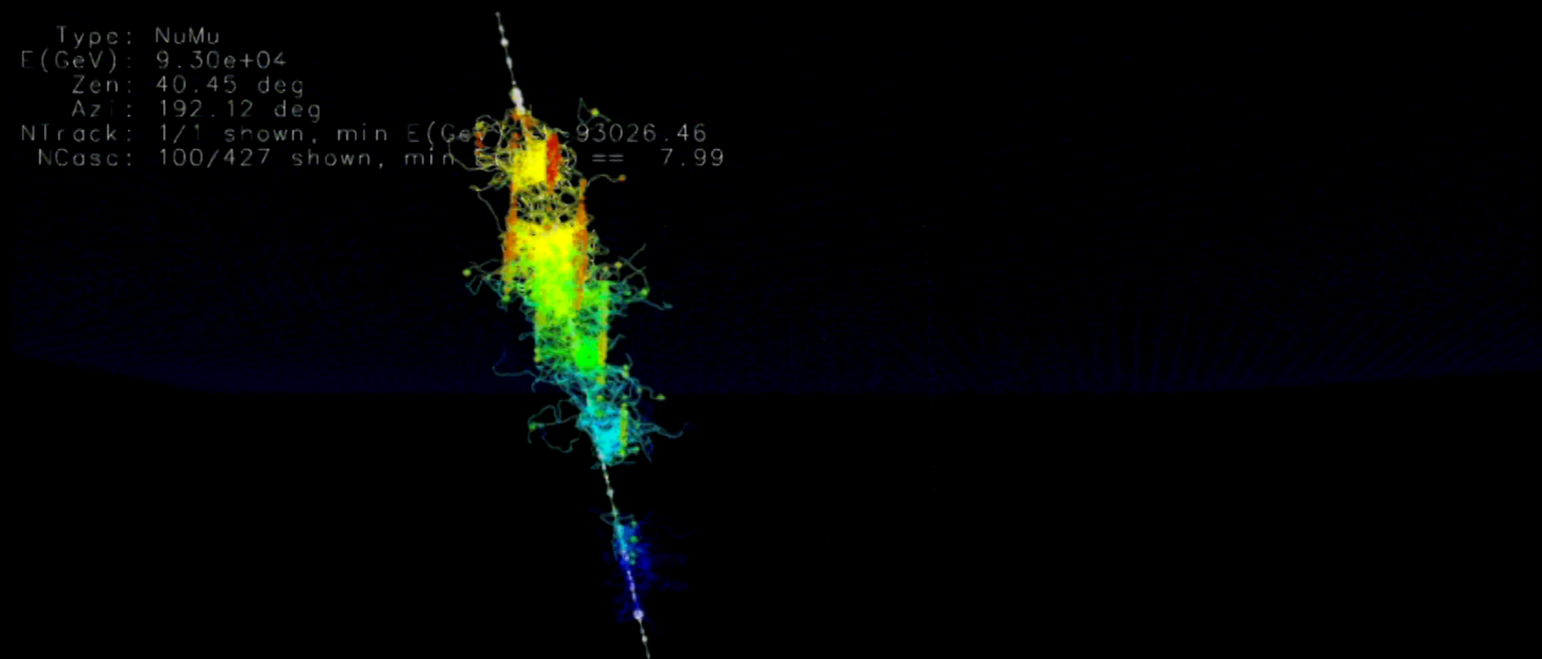
93 TeV muon: # photons ~ energy



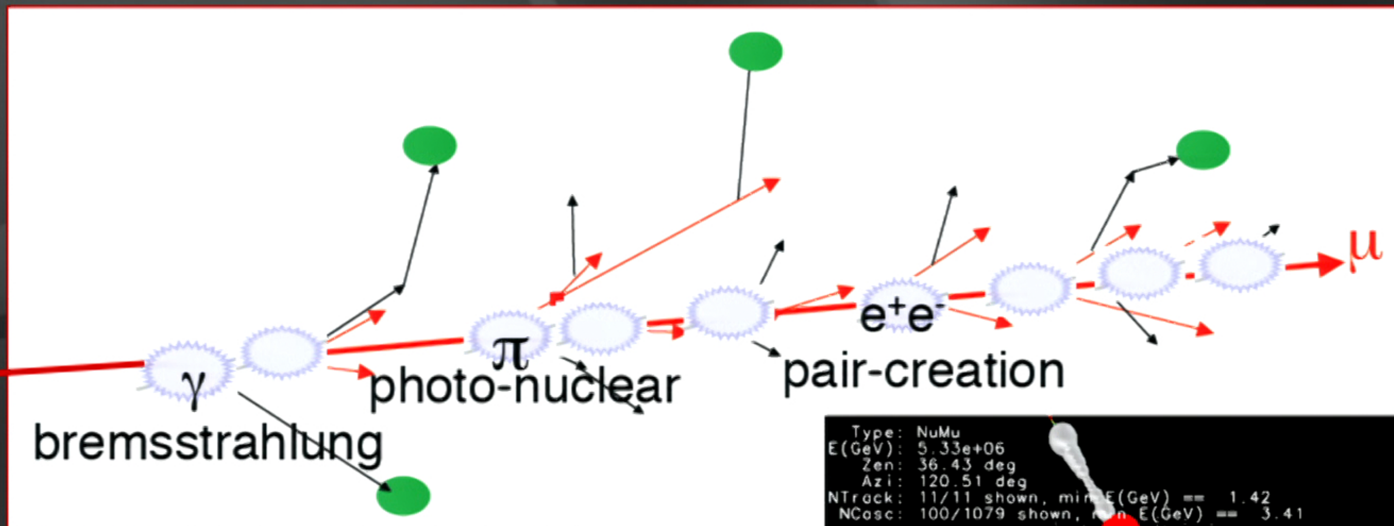
93 TeV muon: # photons ~ energy

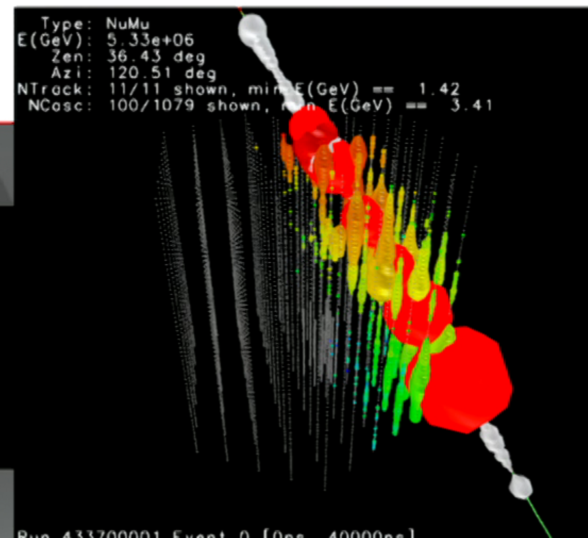


93 TeV muon: # photons ~ energy

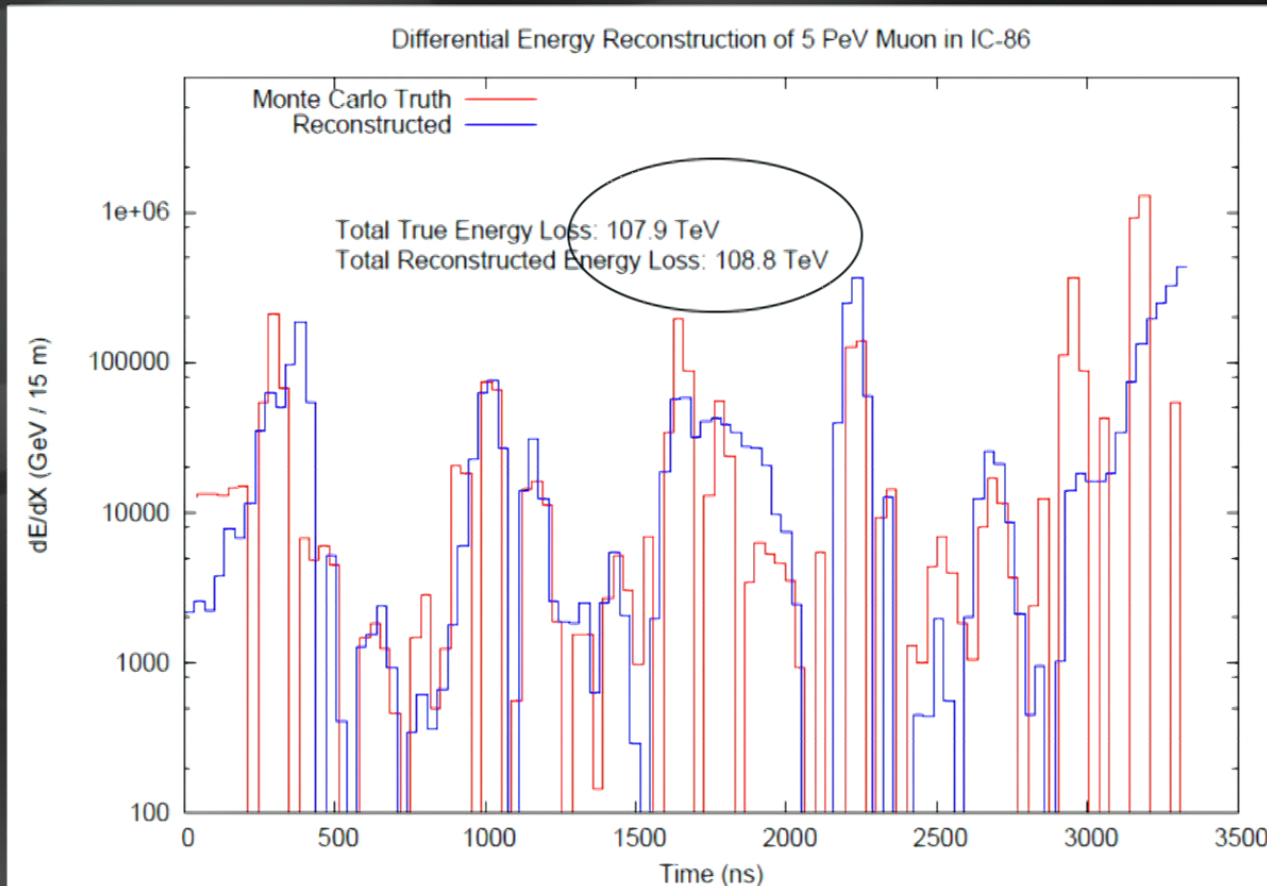


energy measurement (> 1 TeV)





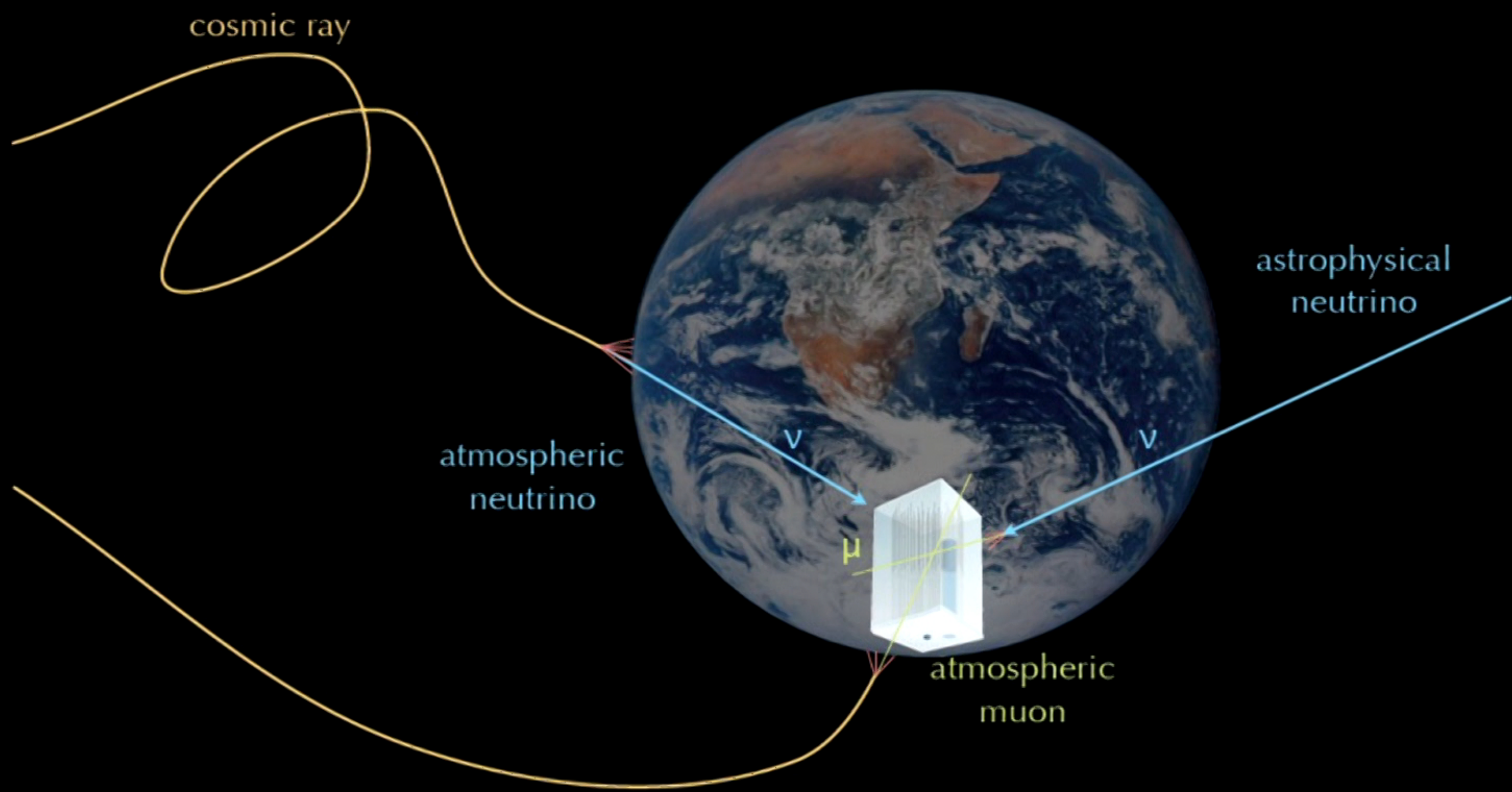
convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

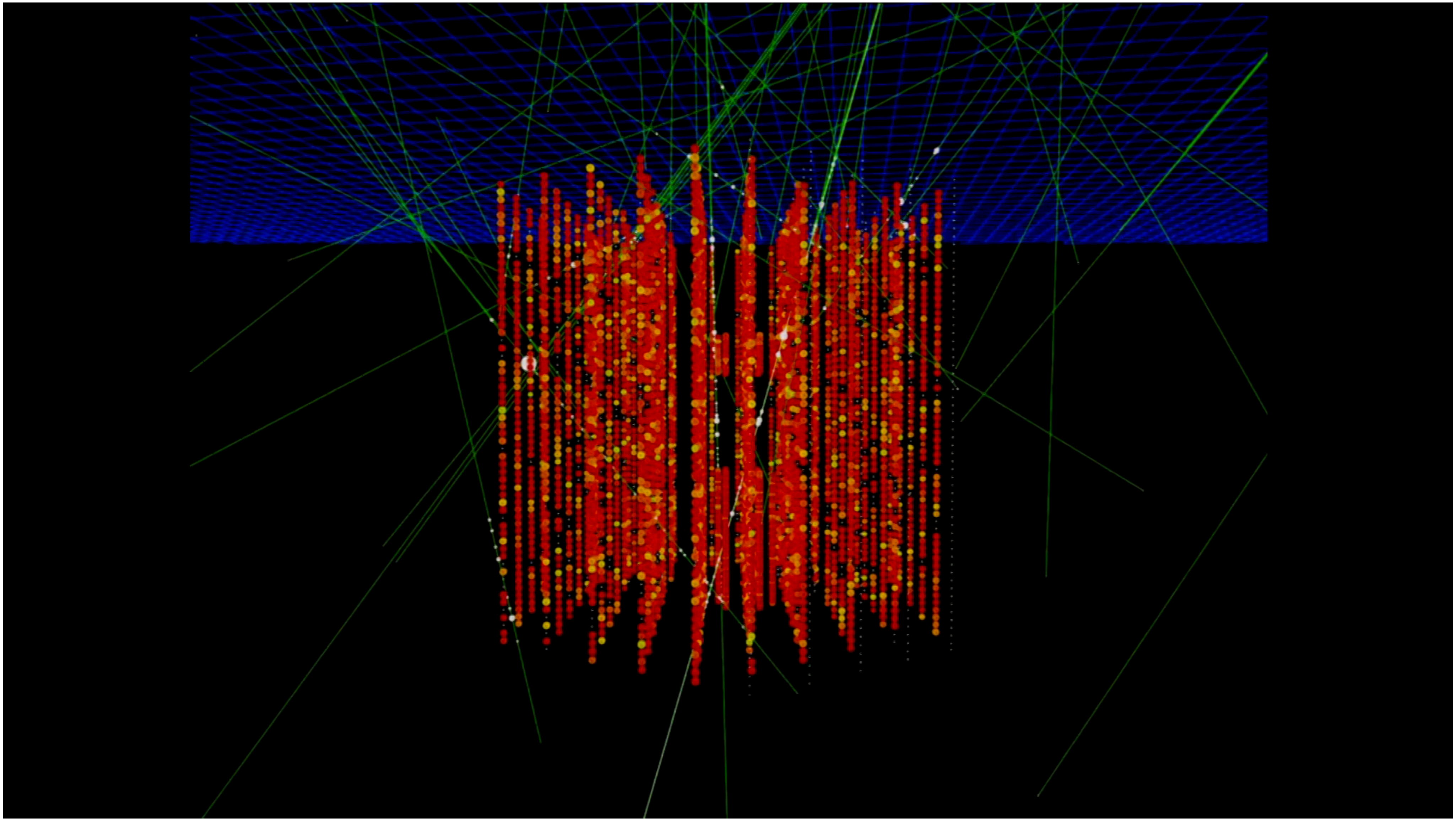


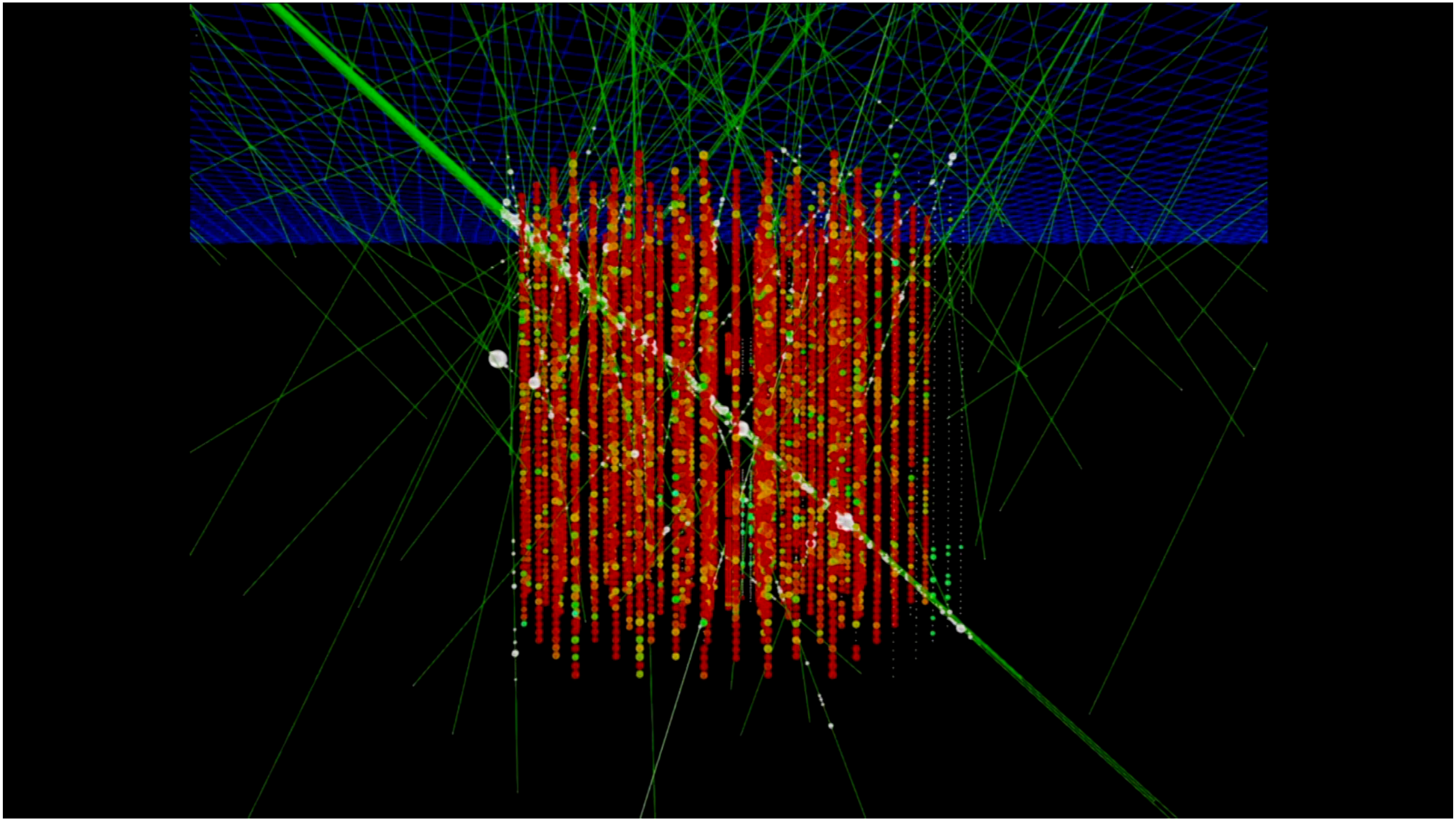
1.1 km

improving angular and energy resolution

Signals and Backgrounds





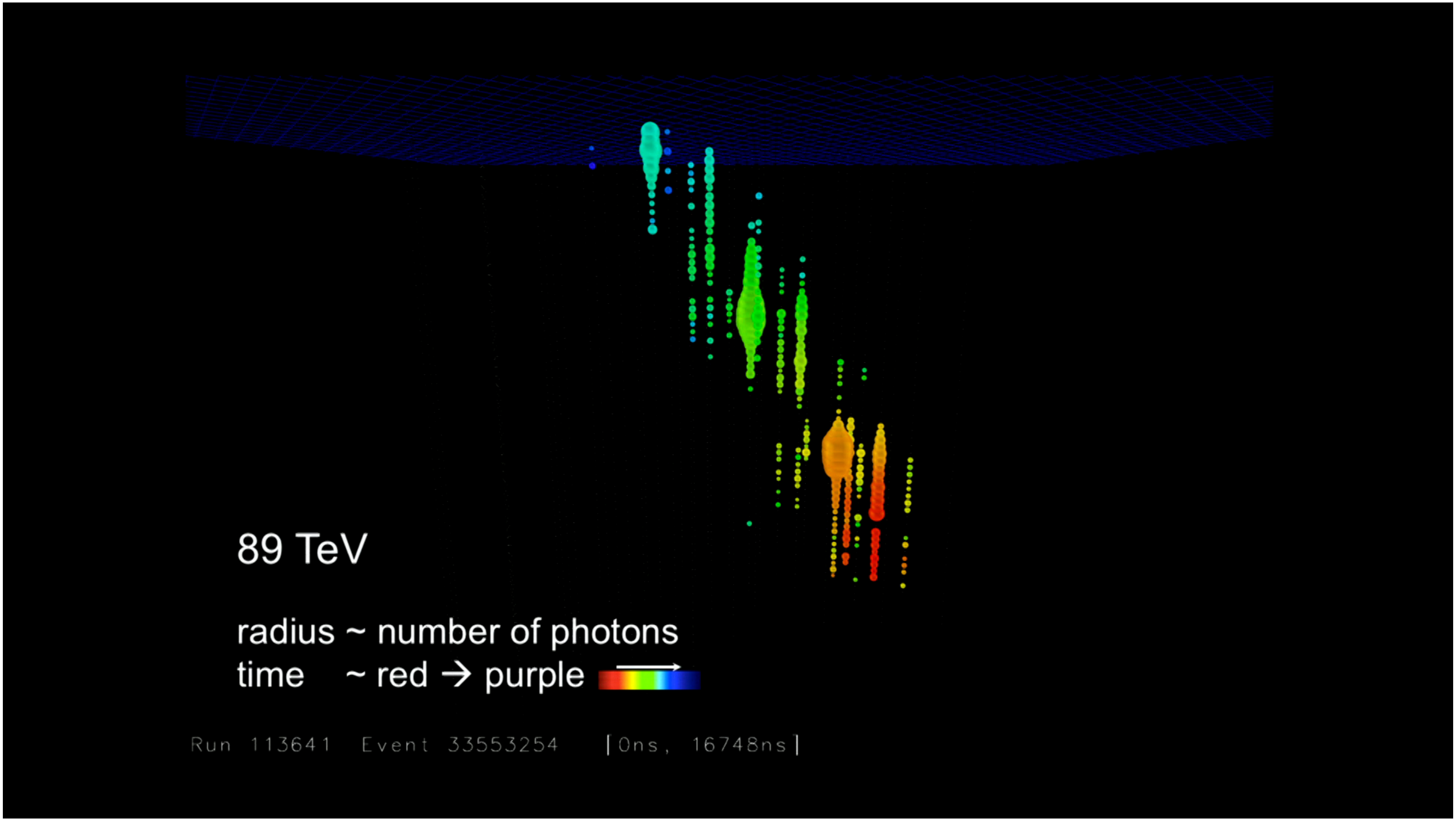


… you looked at 10msec of data !

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


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