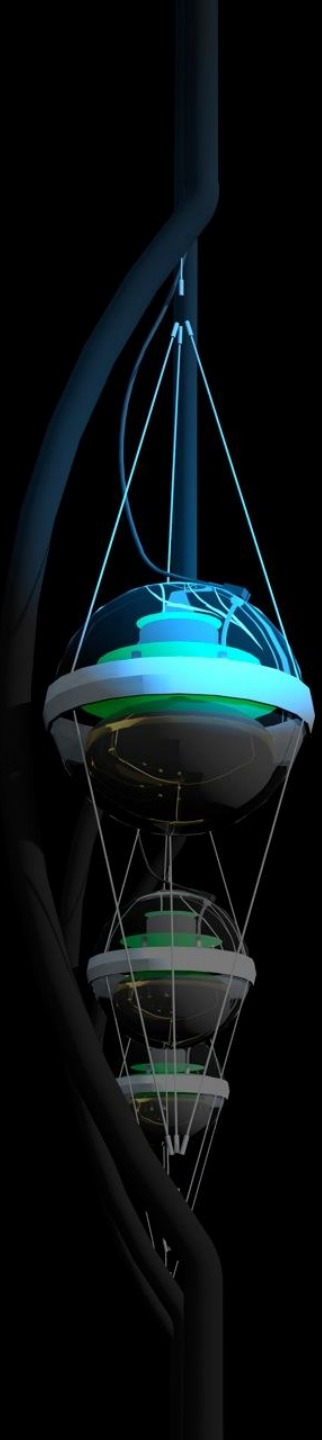
High-Energy Neutrino Astronomy (1)

Christian Spiering

Summer School
UNDERSTANDING NEUTRINOS
Prague, Sept 2012

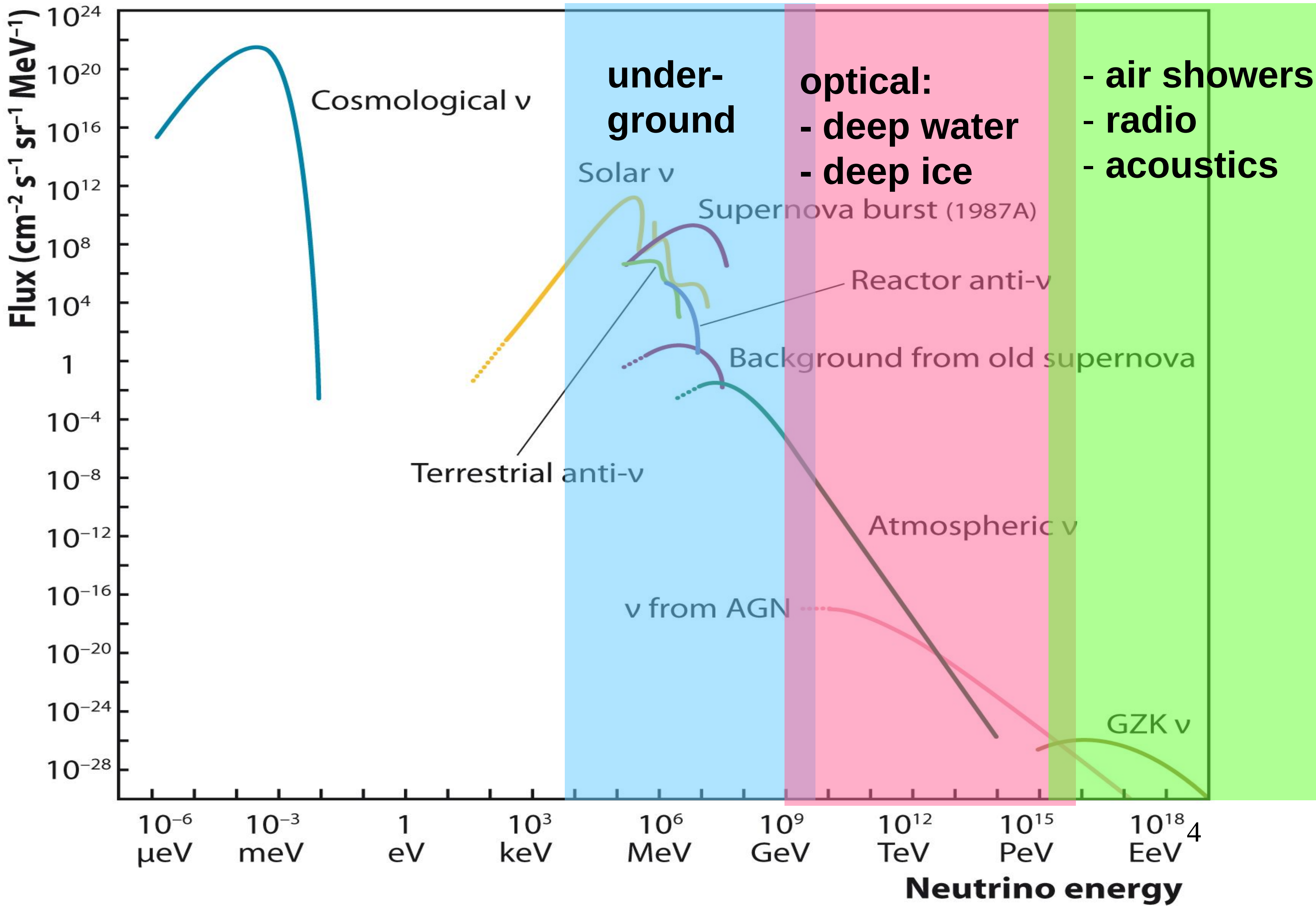
Content

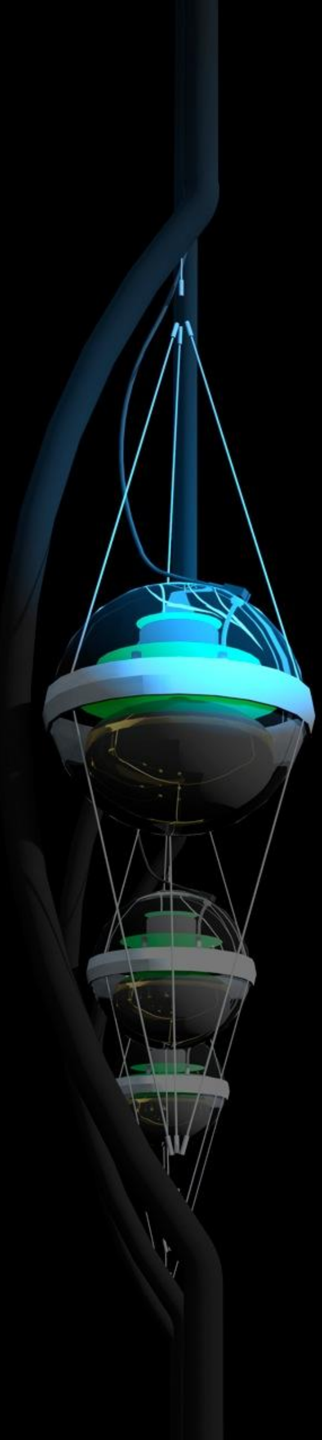
- Lesson 1: Basics
  - Neutrinos in the Universe: a synoptic view
  - Cosmic rays and the high energy-universe
  - Cosmic Particle Acceleration
  - Generation of neutrinos and gamma rays in cosmic sources
  - Propagation of cosmic rays and gamma rays
  - Detection of high energy neutrinos
  - The devices: From Baikal to IceCube
- Lesson 2: Results



Neutrinos in the Universe:
A synoptic view

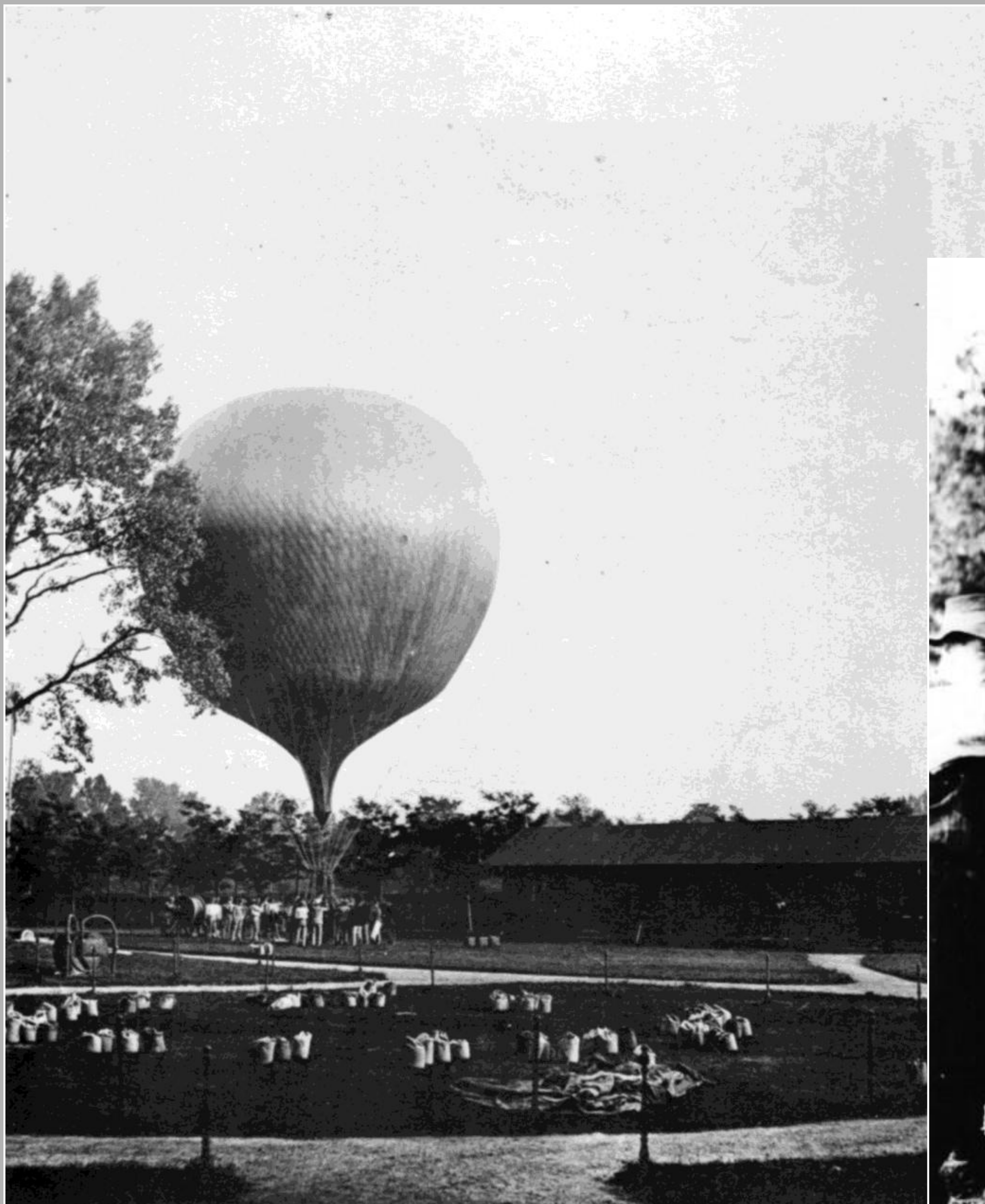
Fluxes of cosmic neutrinos





Cosmic Rays and the high-energy universe

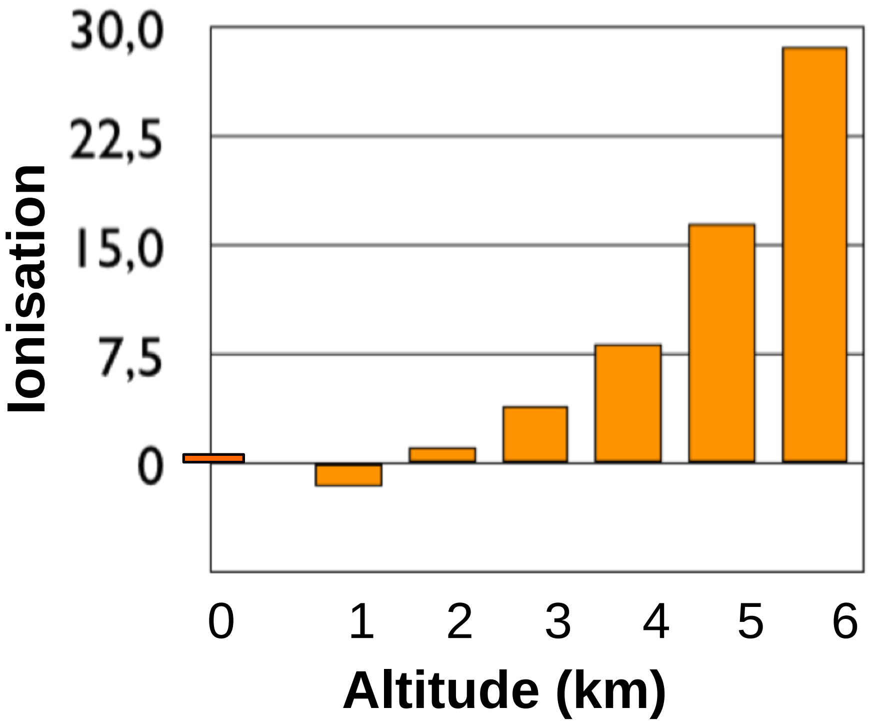
Victor Hess
August 7, 1912

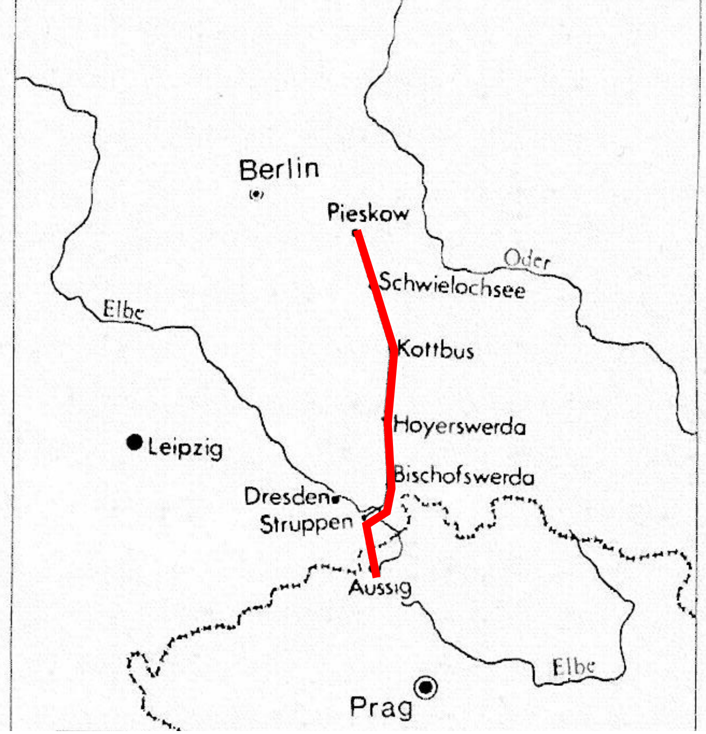


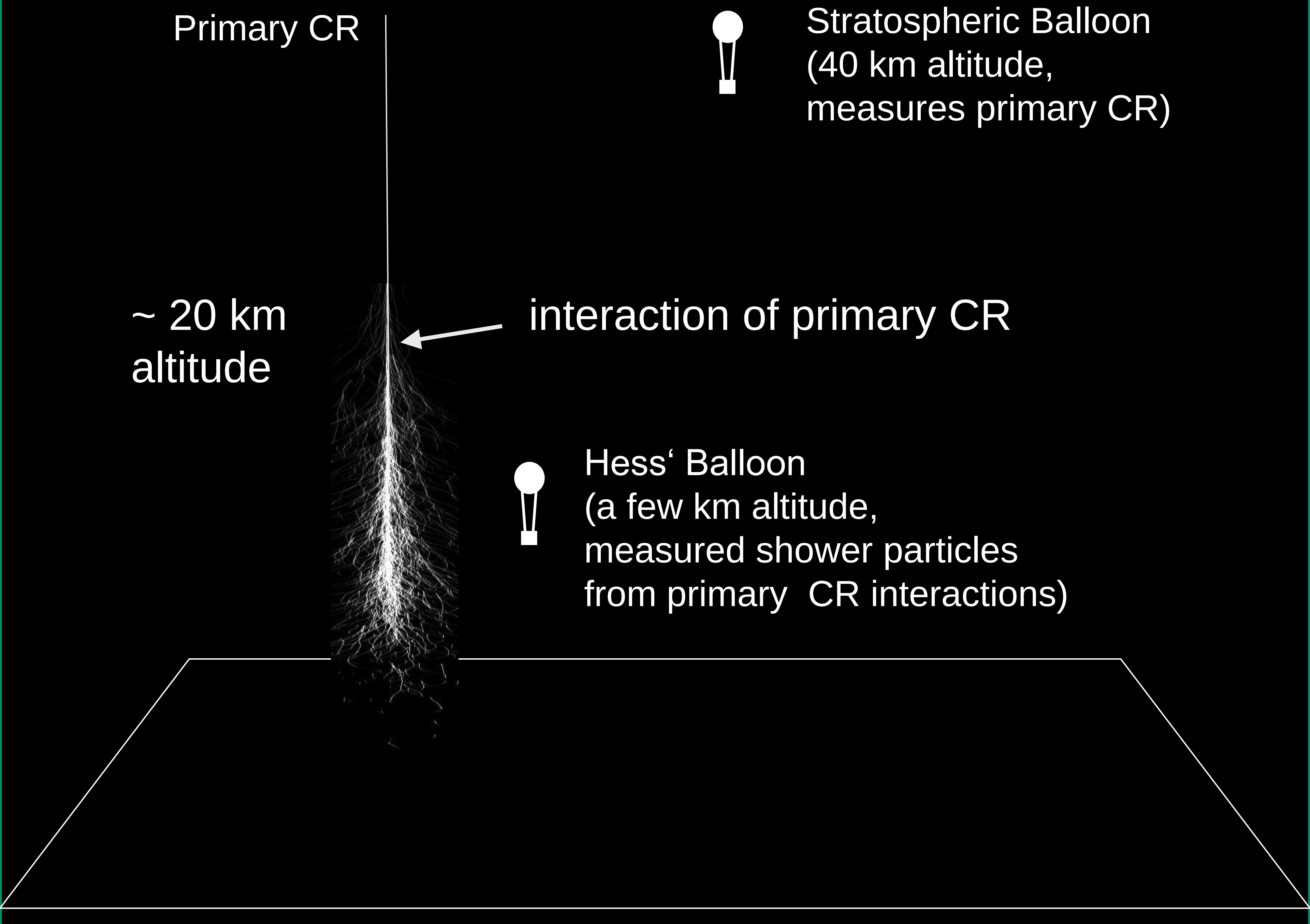
The discovery of cosmic rays

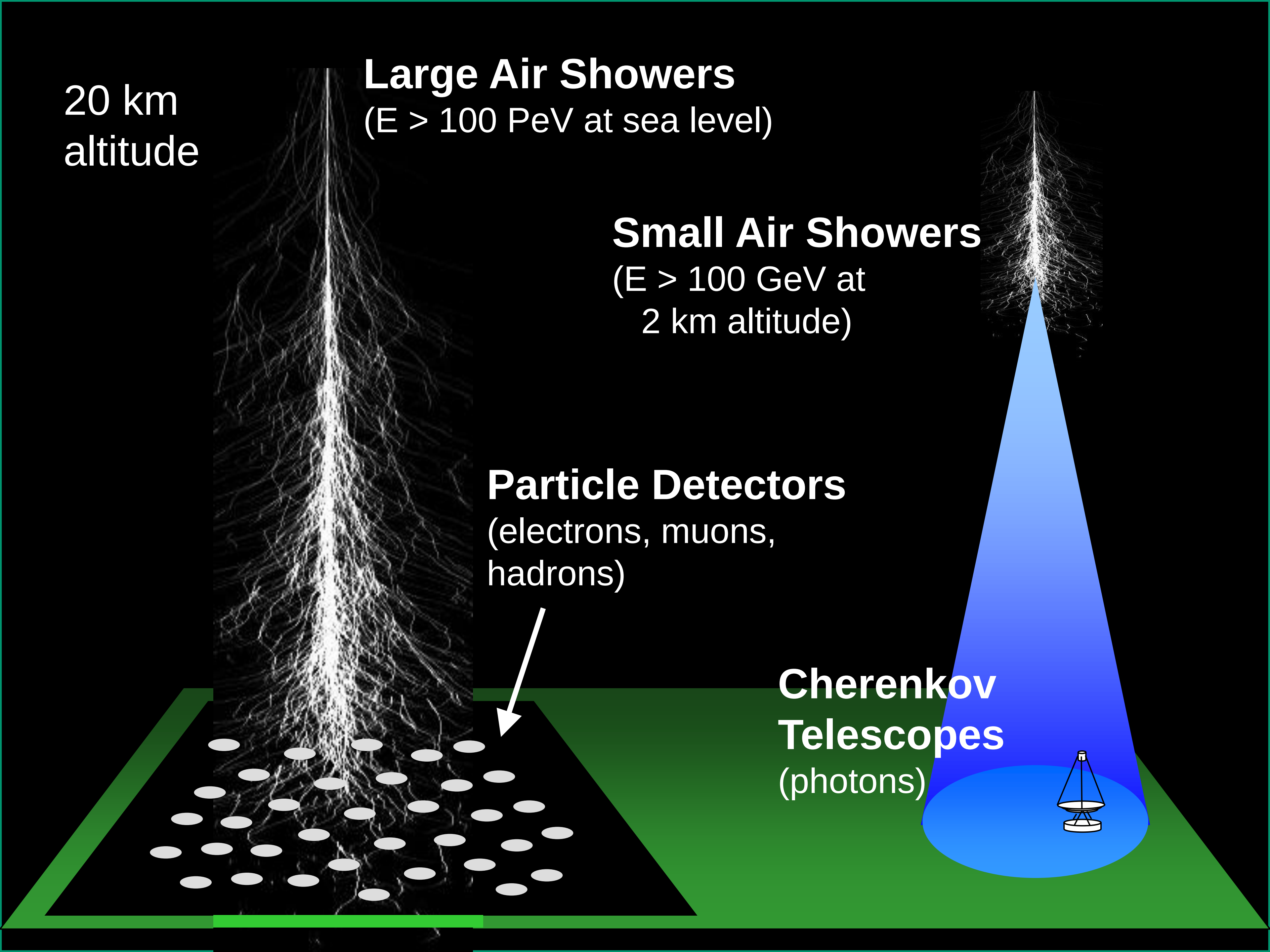
„Die Annahme, dass der Ursprung dieser durchdringenden Strahlung nicht in den bekannten radioaktiven Stoffen der Erde oder der Atmosphäre zu suchen ist, gewinnt dadurch bedeutend an Wahrscheinlichkeit.“ (Phys. Zeitschr. XIV (1913) 1153)

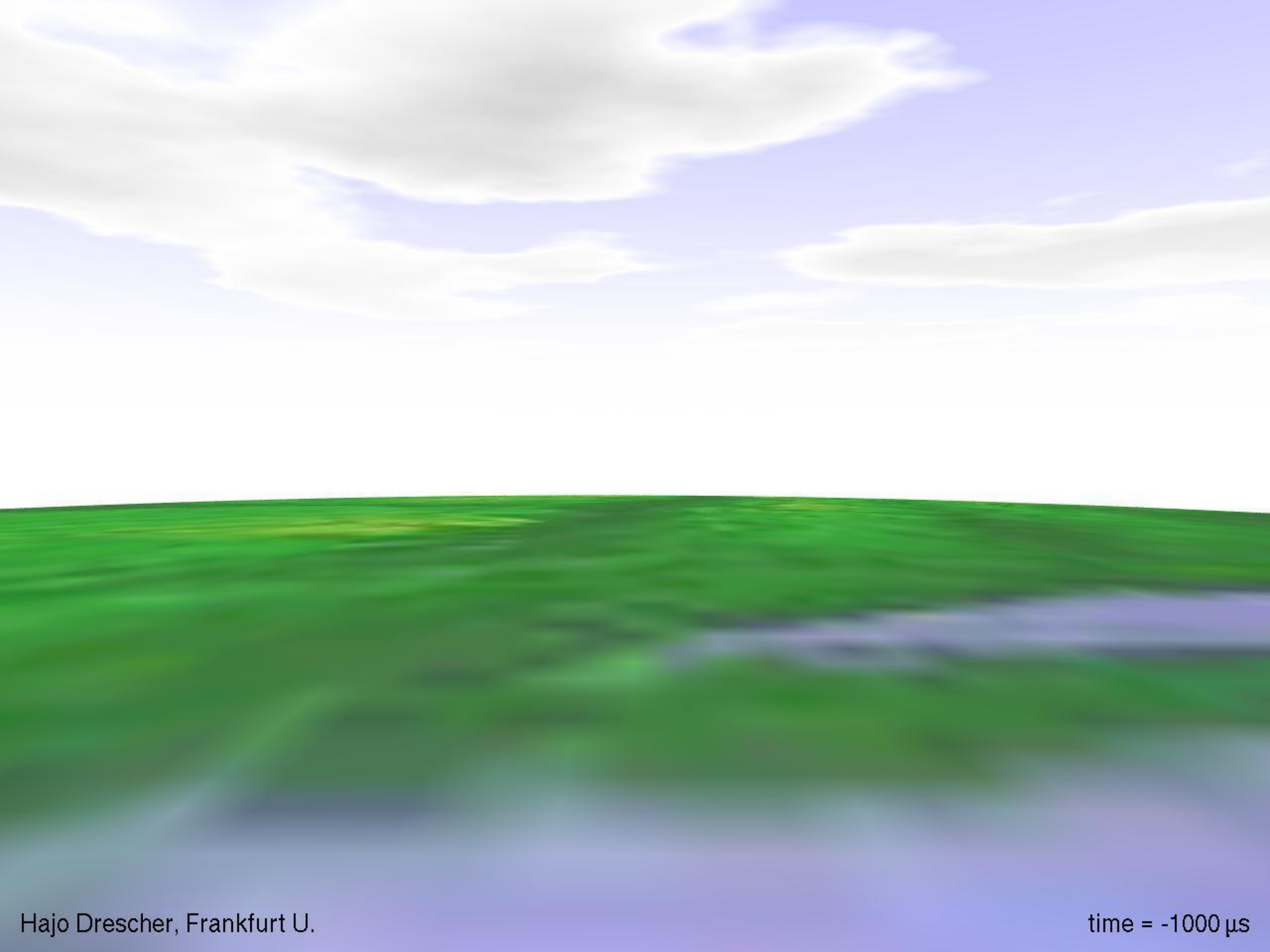
Nobel Prize 1936

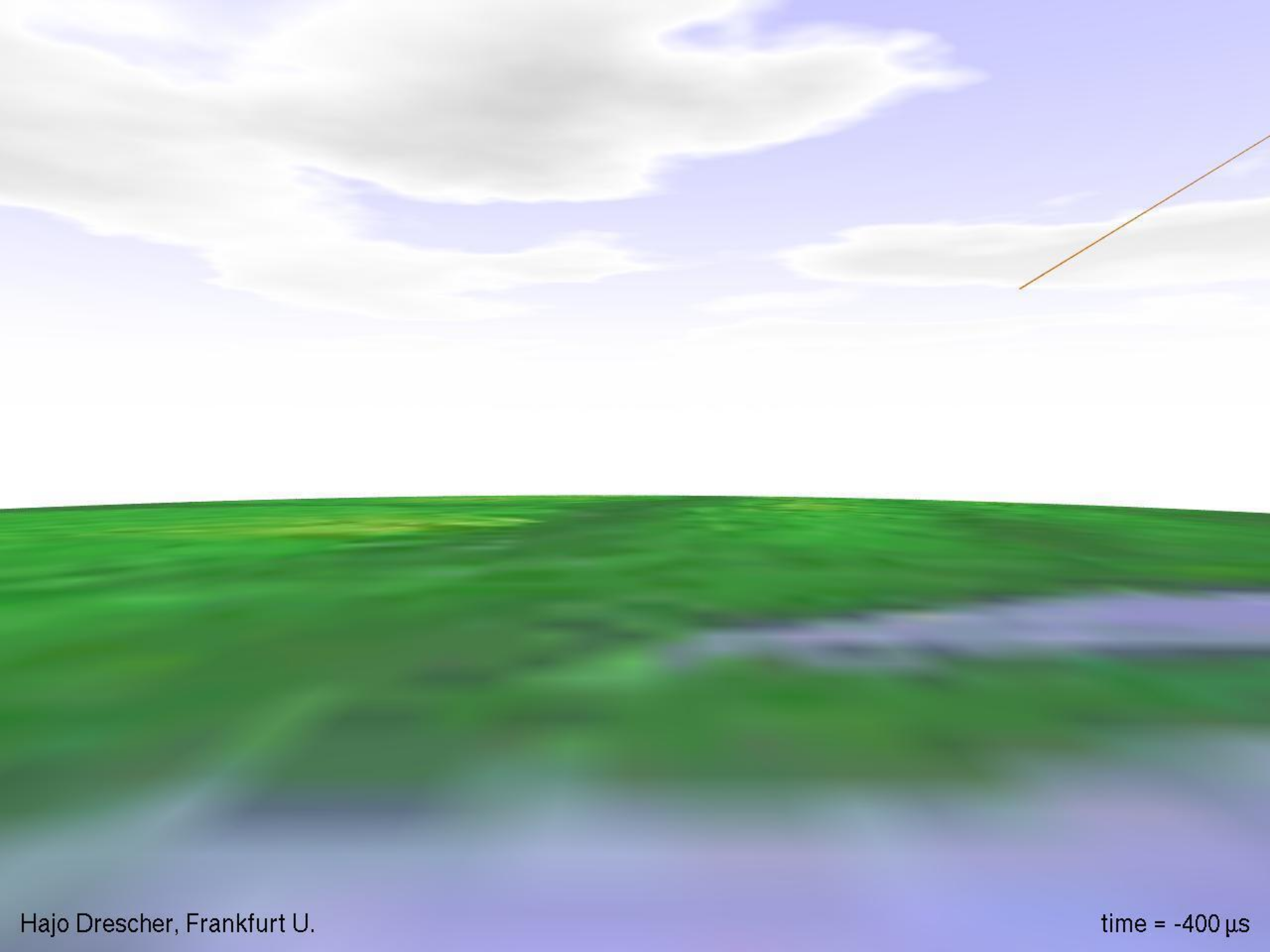





Primary CR
Stratospheric Balloon
(40 km altitude,
measures primary CR)
~ 20 km
altitude
interaction of primary CR
Hess‘ Balloon
(a few km altitude,
measured shower particles
from primary CR interactions)


20 km
altitude
Large Air Showers
(E > 100 PeV at sea level)
Small Air Showers
(E > 100 GeV at
2 km altitude)
Particle Detectors
(electrons, muons,
hadrons)
Cherenkov
Telescopes
(photons)


Hajo Drescher, Frankfurt U.
time = -1000 µs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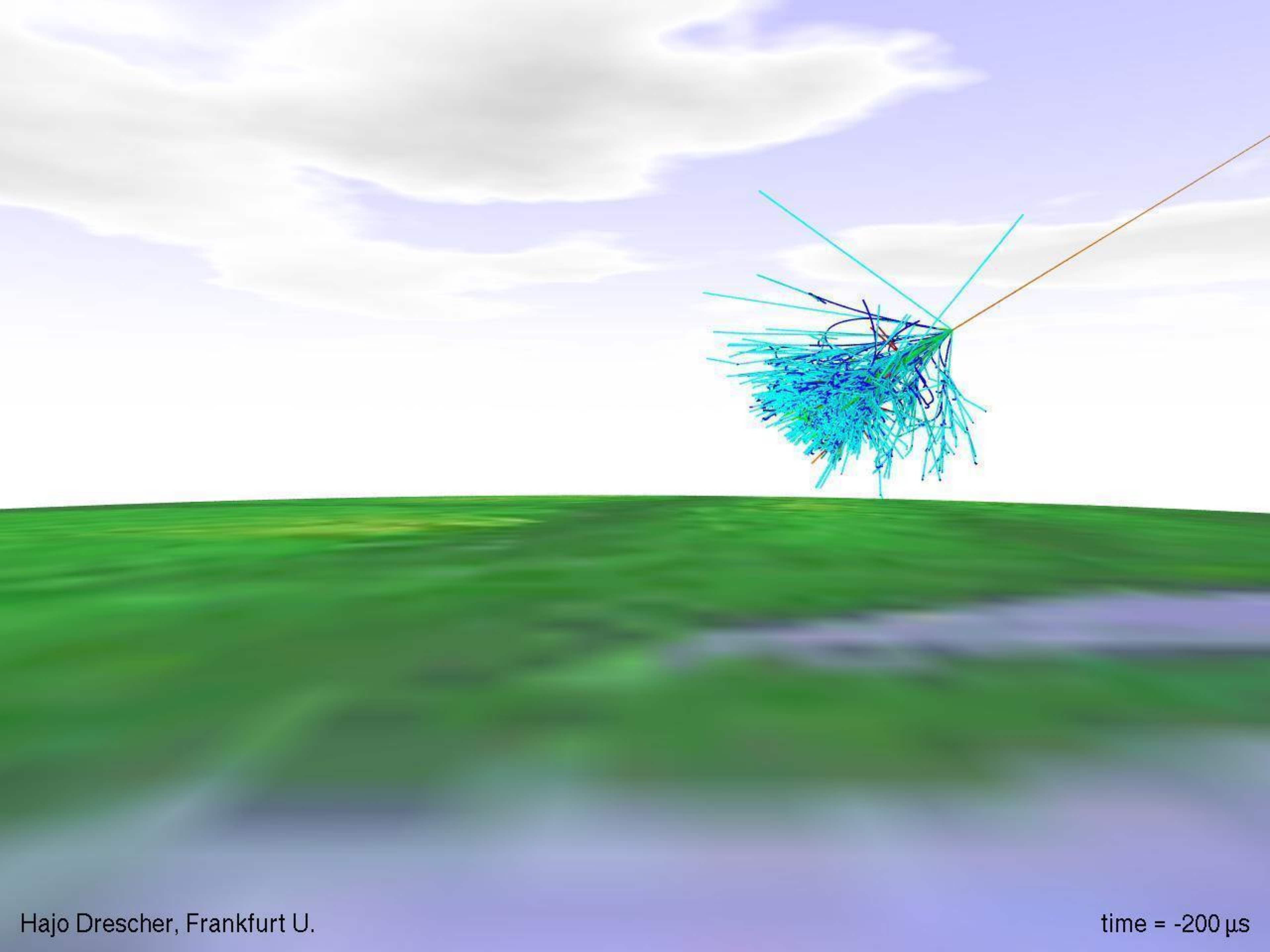
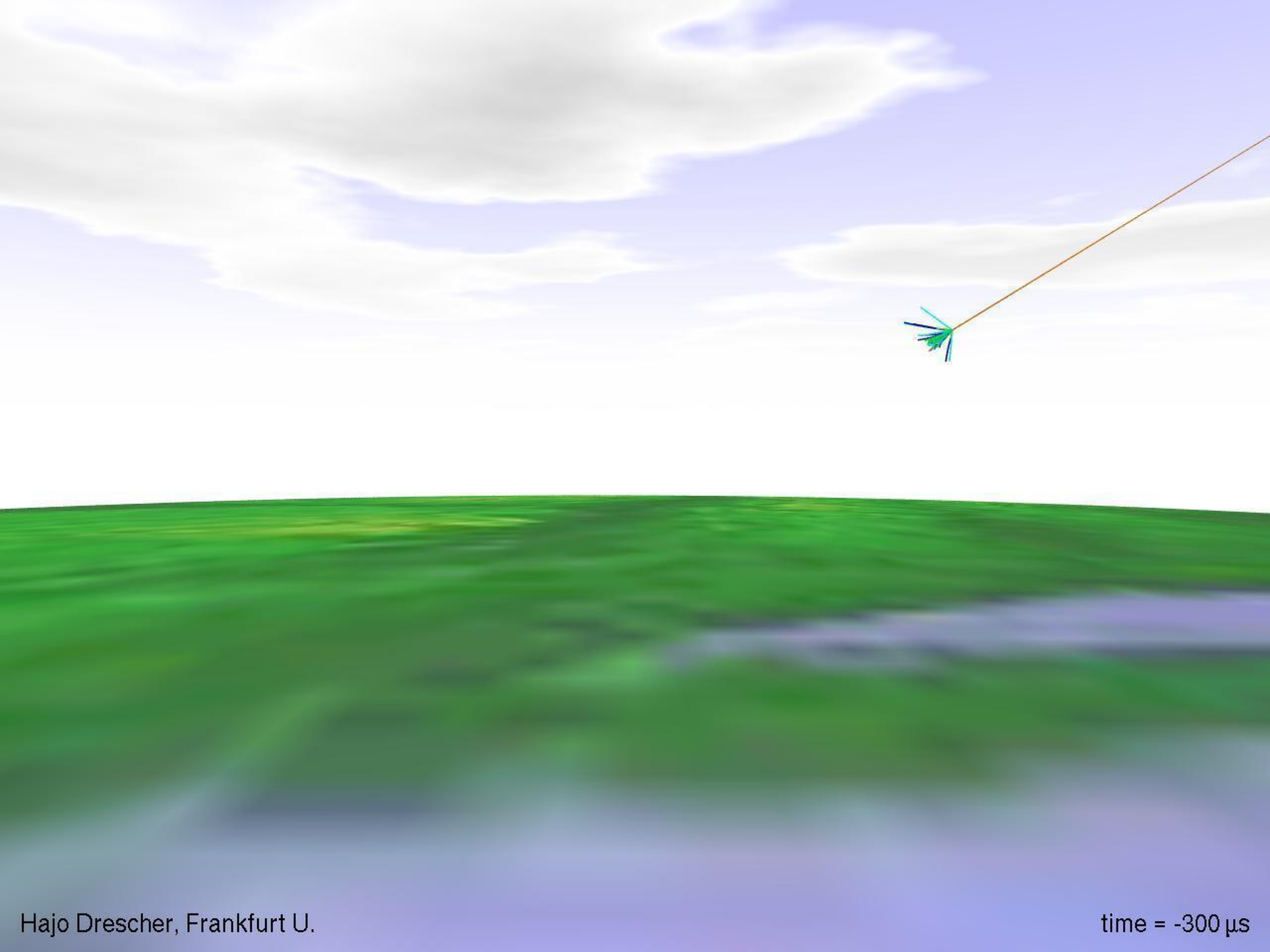
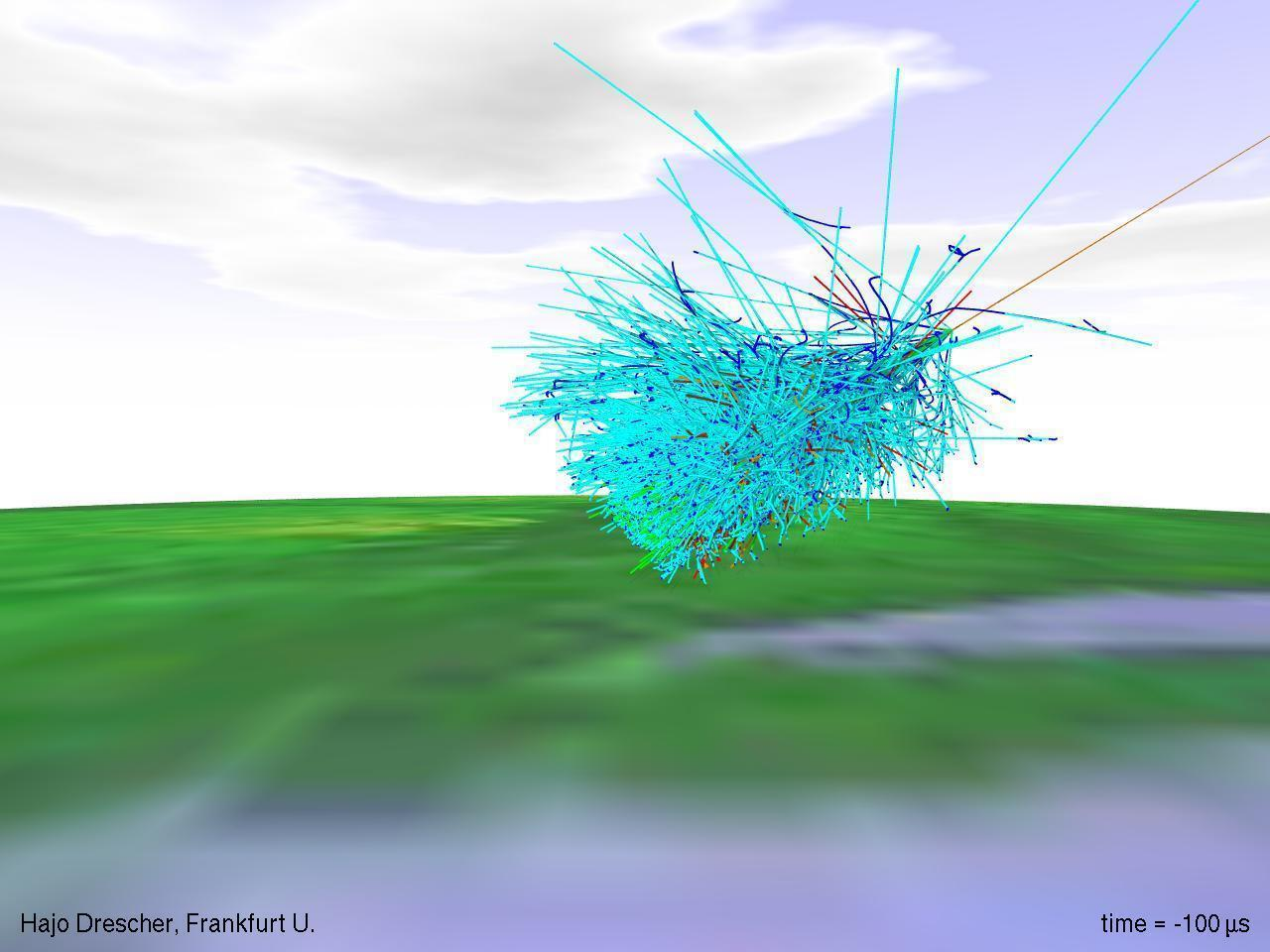

Hajo Drescher, Frankfurt U.
time = -200 µs


Hajo Drescher, Frankfurt U.
time = -300 µs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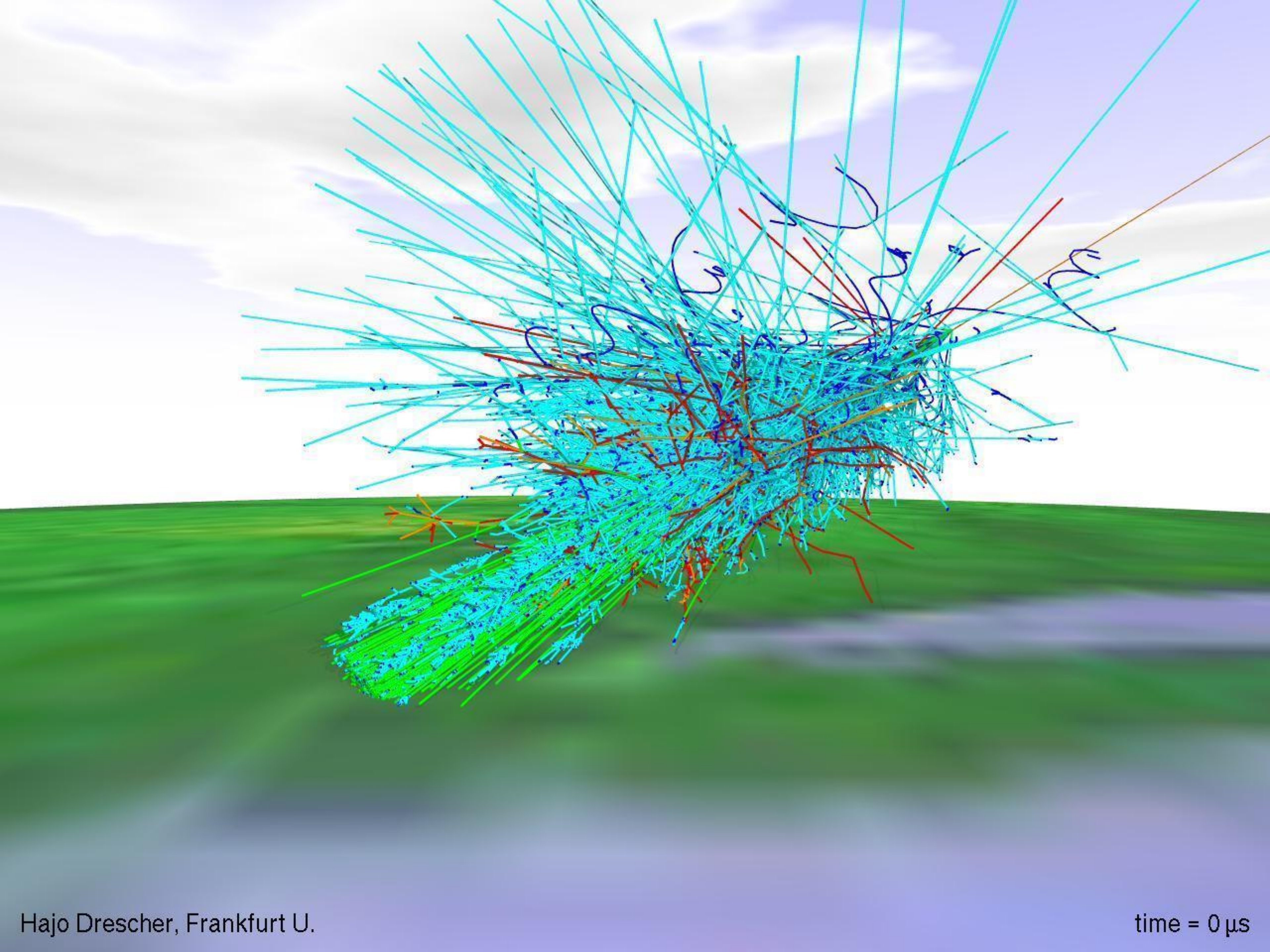
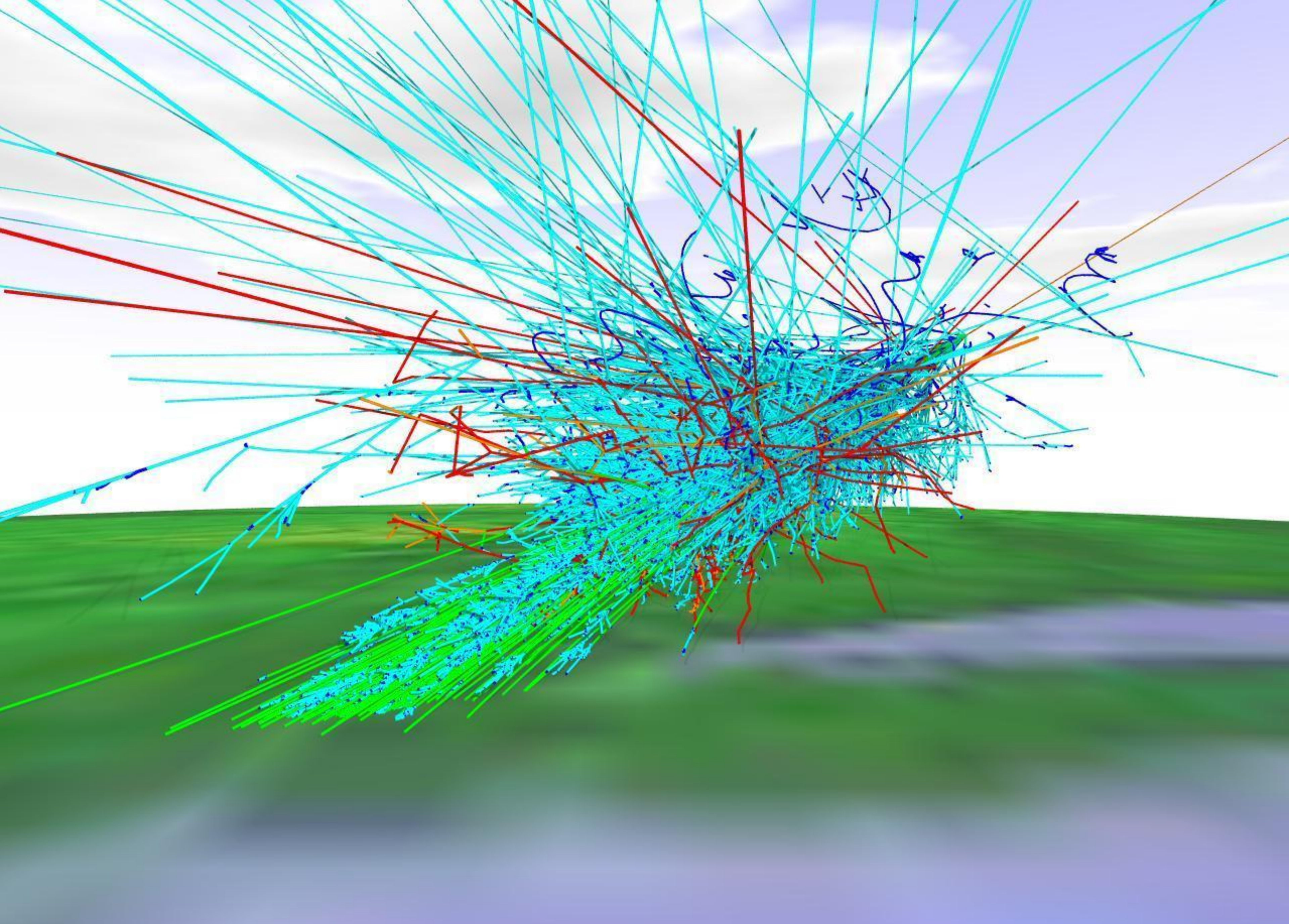
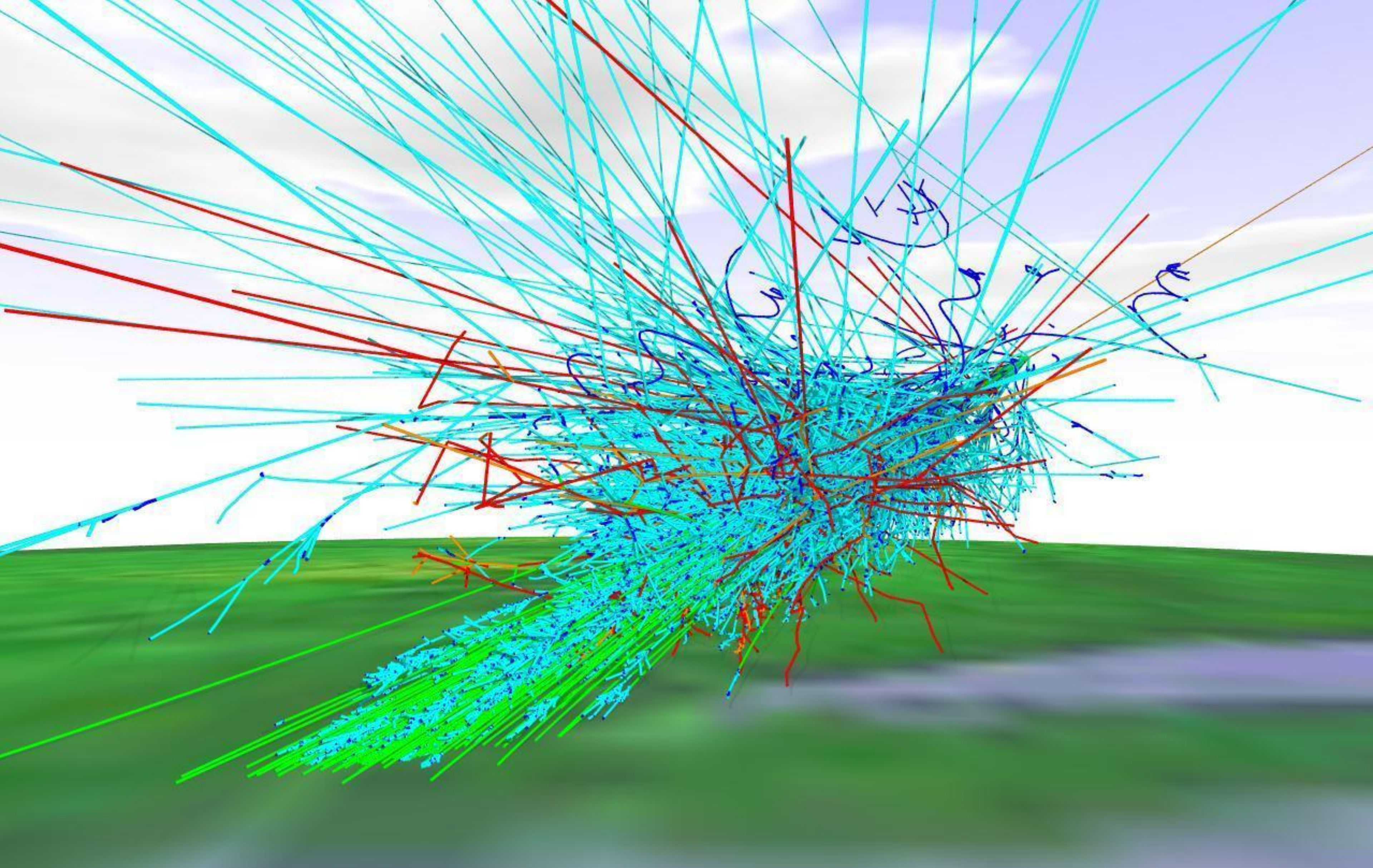
time = -100 µs


Hajo Drescher, Frankfurt U.
time = 0 µs

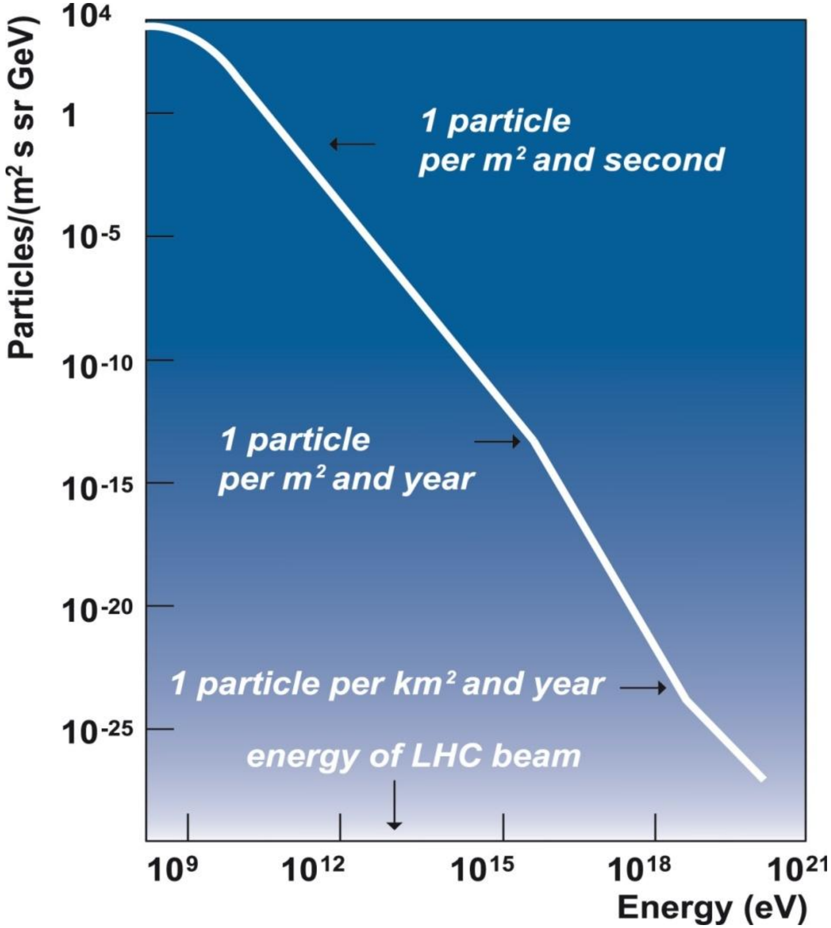

Hajo Drescher, Frankfurt U.

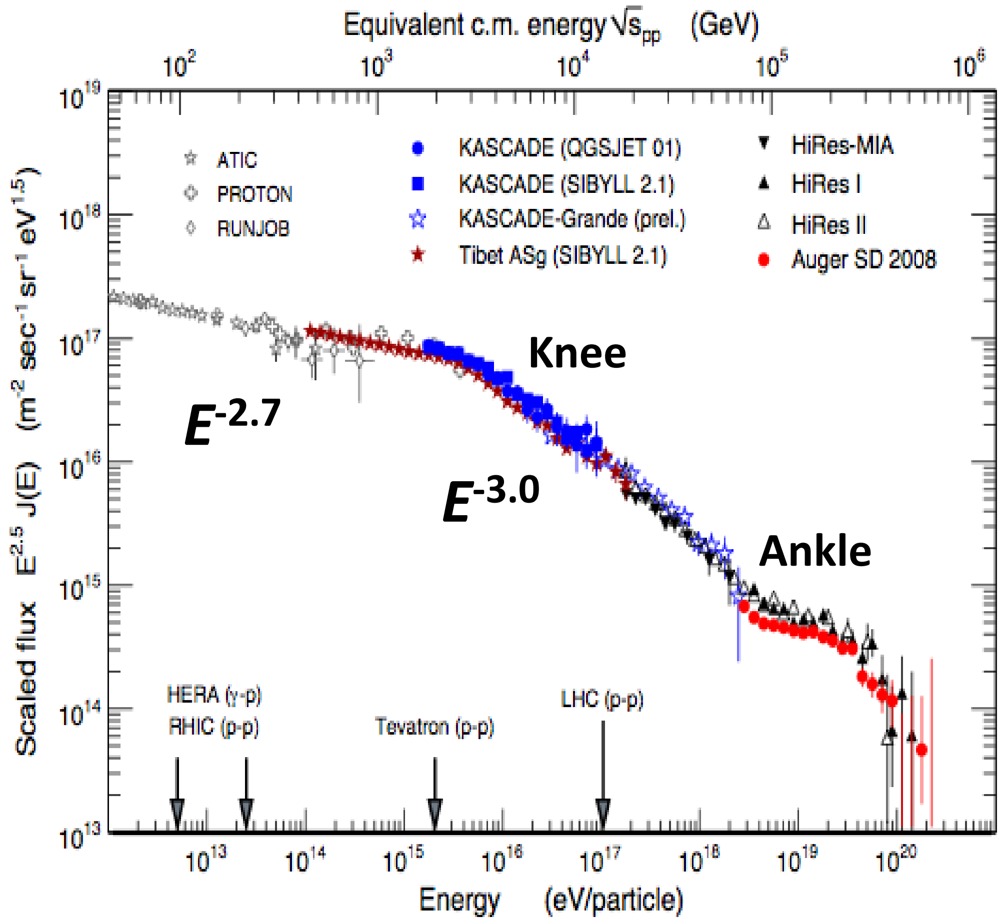


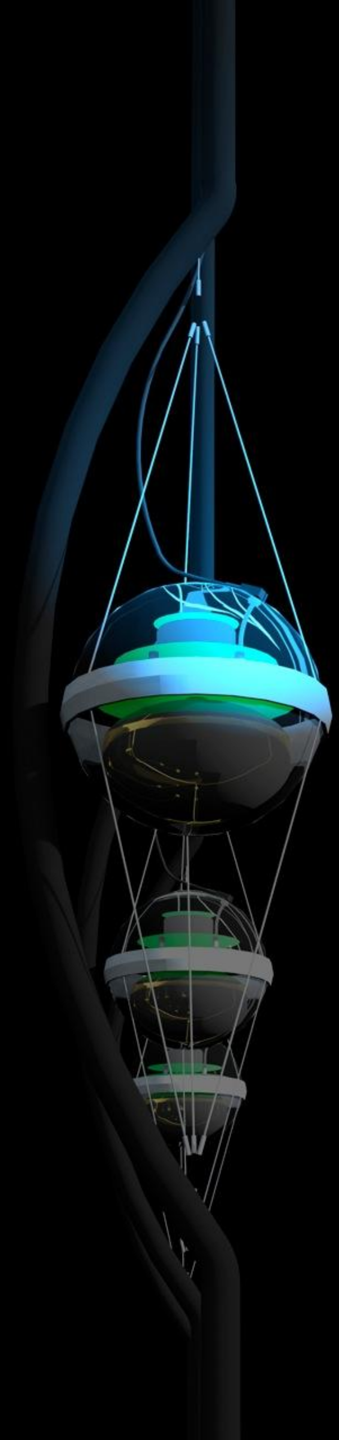
Energy: LHC × 10 000 000

Hajo Drescher, Frankfurt U.

The spectrum of cosmic rays



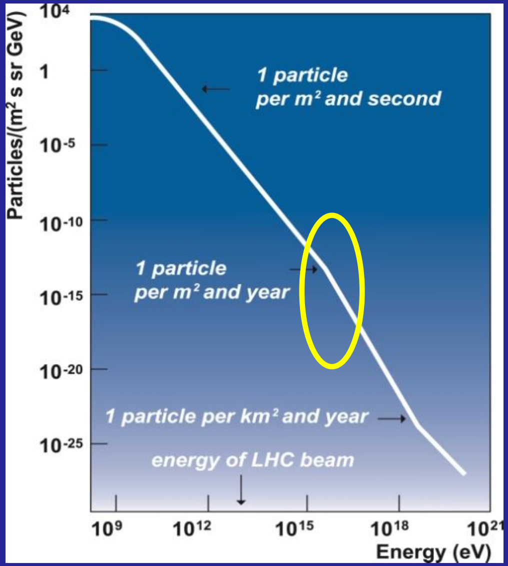




Cosmic Particle Acceleration

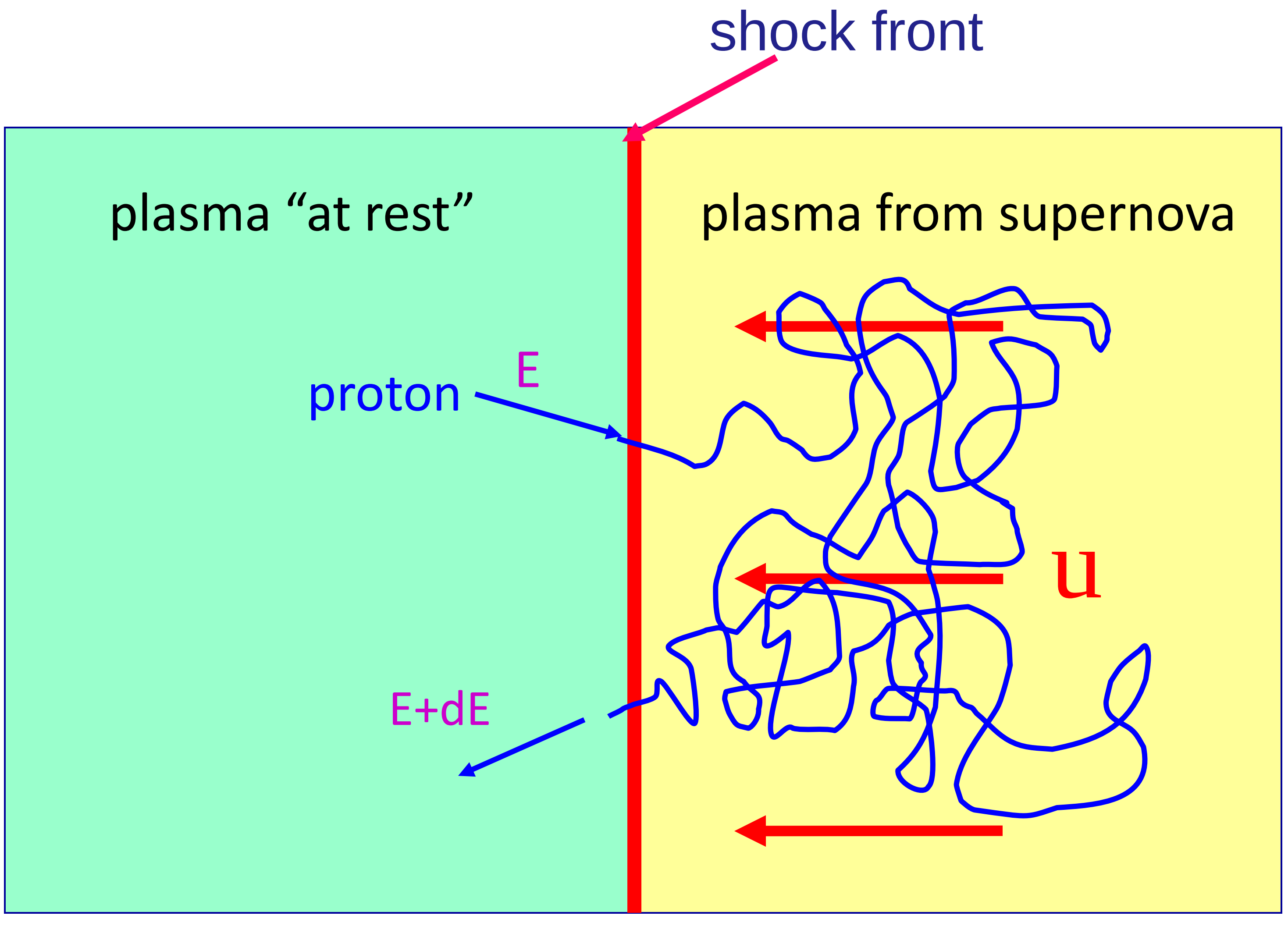
Supernovae:
Shock Waves into interstellar medium

up to 10^{16} eV

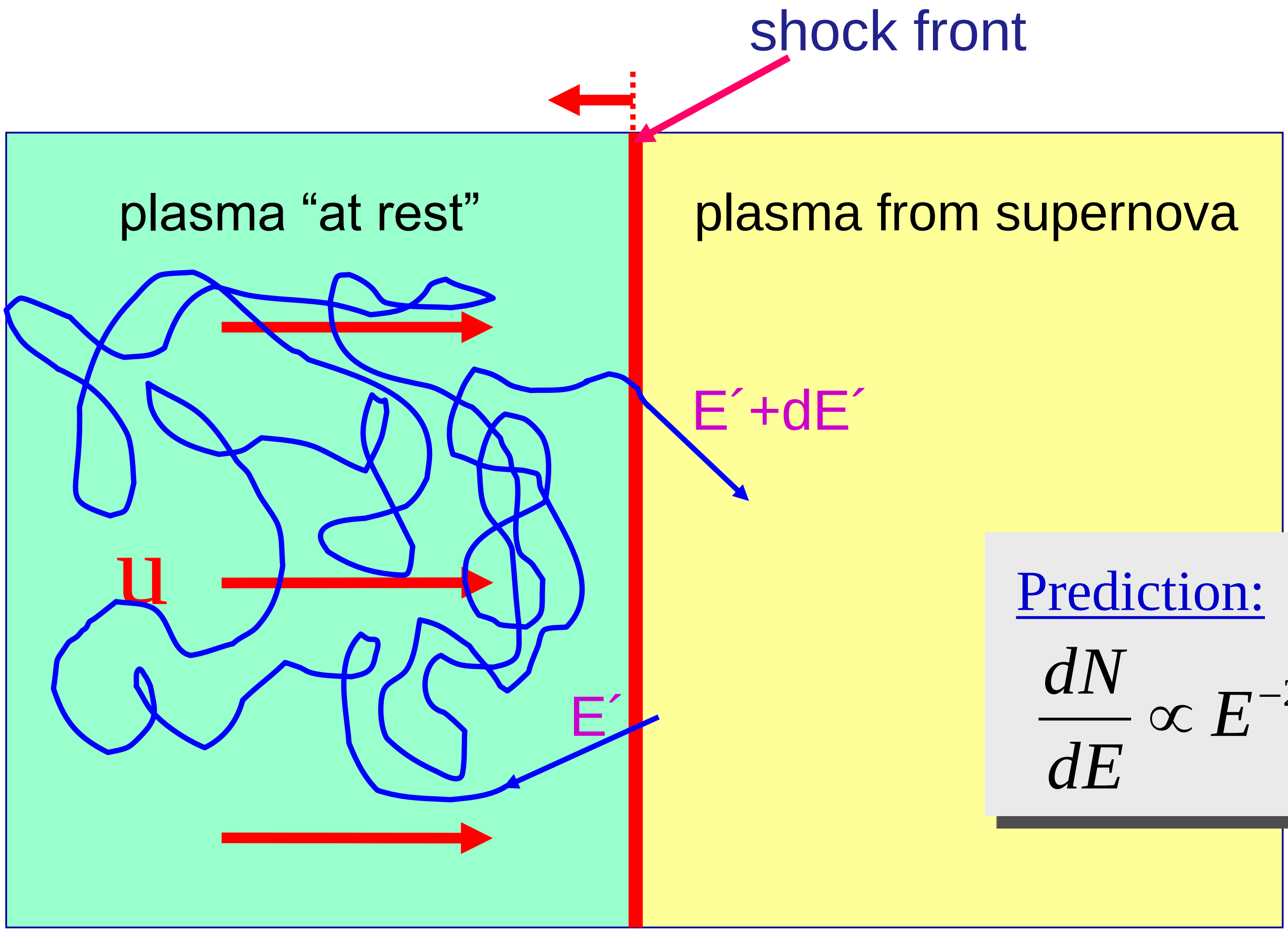


Also: binary systems, micro-quasars neutron-star pole caps

Shockwave Acceleration (Enrico Fermi)



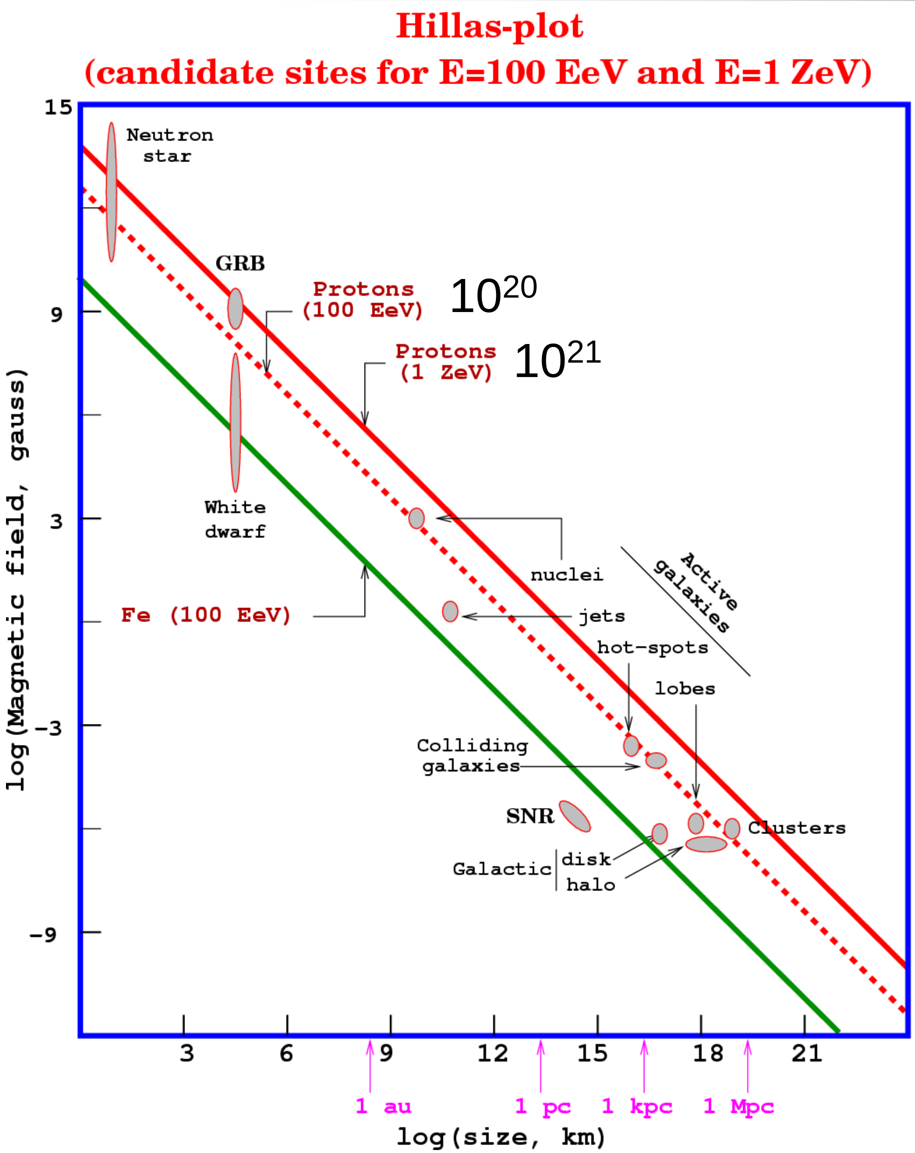
Shockwave Acceleration (Enrico Fermi)



Prediction:

$$\frac{dN}{dE} \propto E^{-2}$$

The spectrum of cosmic rays



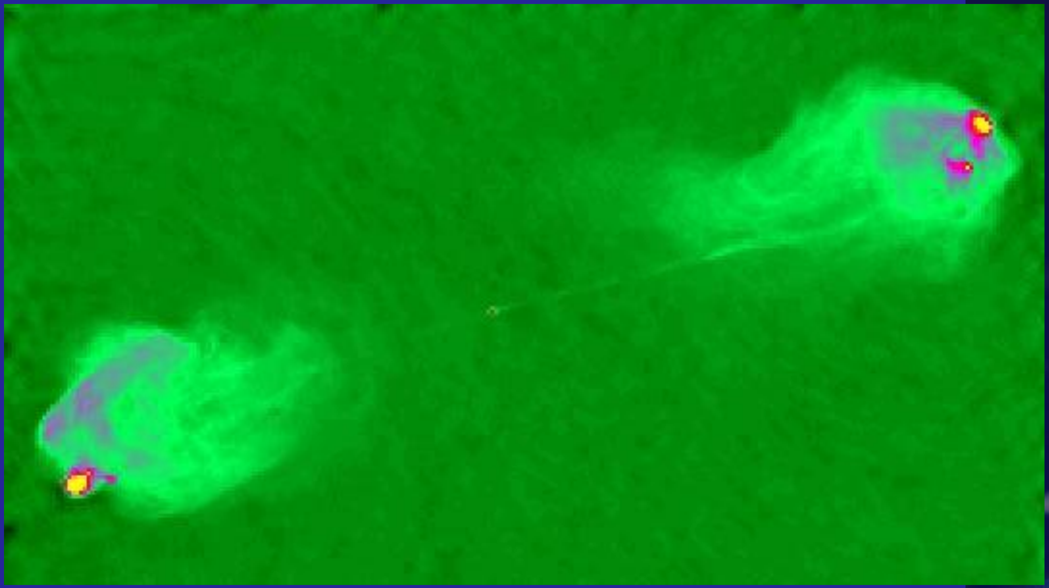
$$E_{max} \sim Z \cdot \beta \cdot B \cdot L$$

Maximal energy controlled by

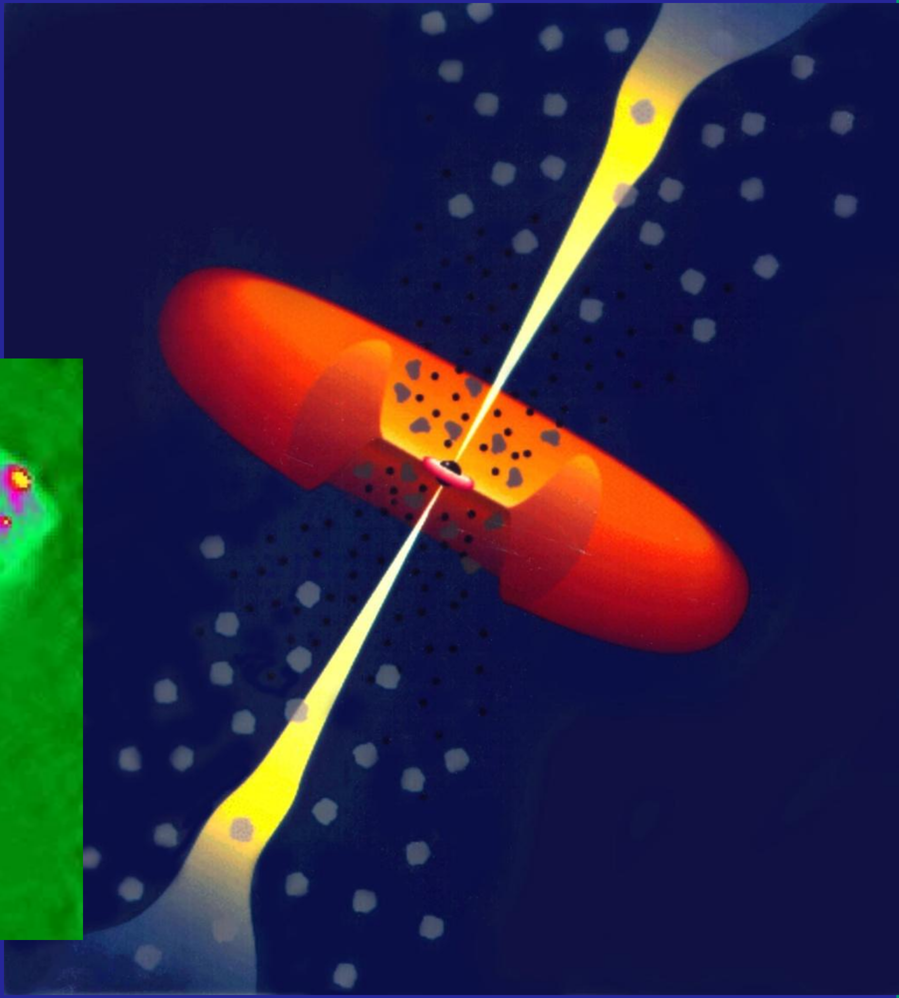
- Speed of shock wave β
- Magnetic field ***B***
- Size of cosmic accelerator ***L***
- Particle charge ***Z***

Active Galaxies: Accretion Disks and Jets

up to 10^{20} eV

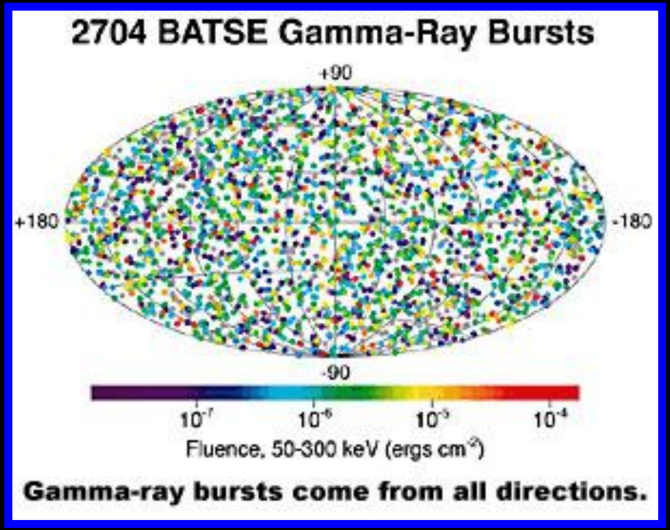


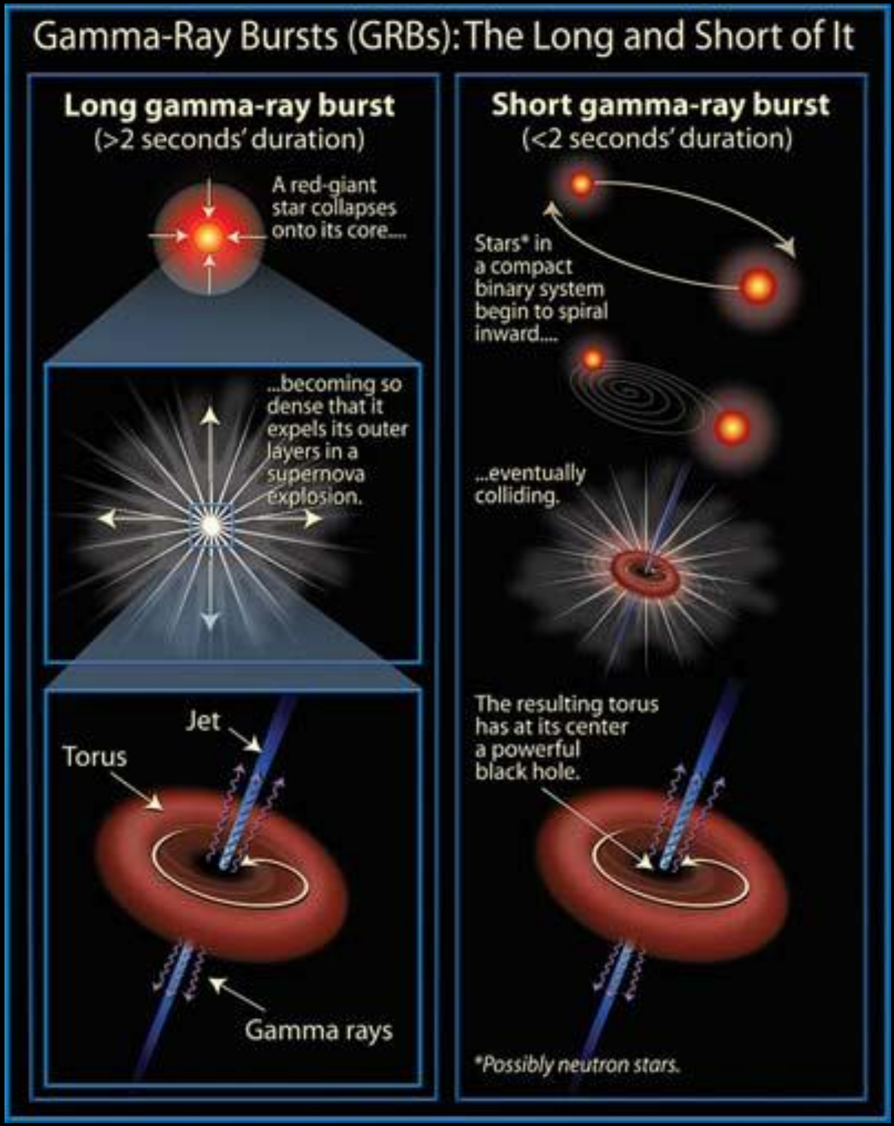
VLA image of Cygnus A



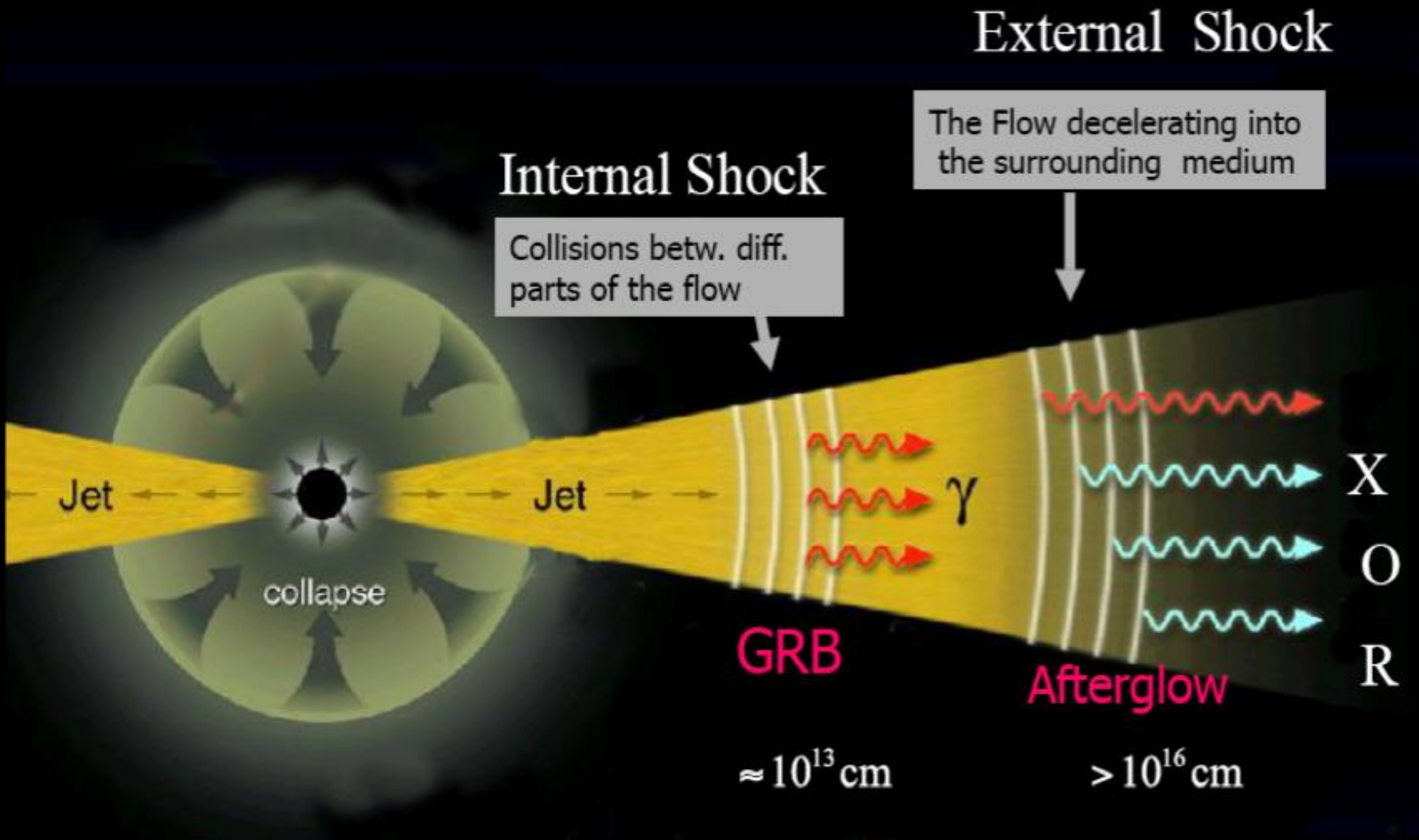
Gamma Ray Bursts

- 1969: Vela Satellite: signals from USSR or from cosmos?
- 2002: BATSE detector at GRO: 2704 bursts



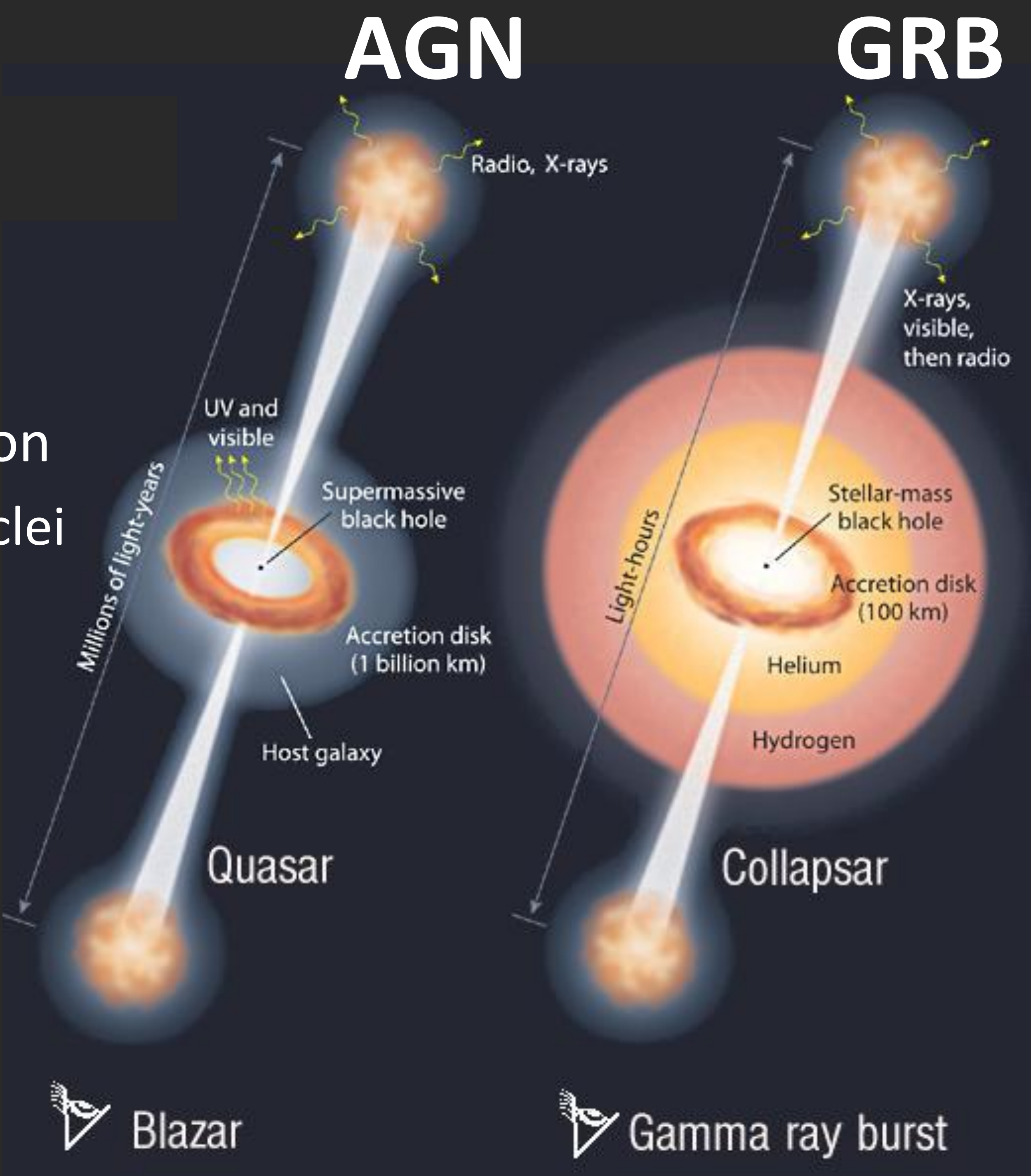


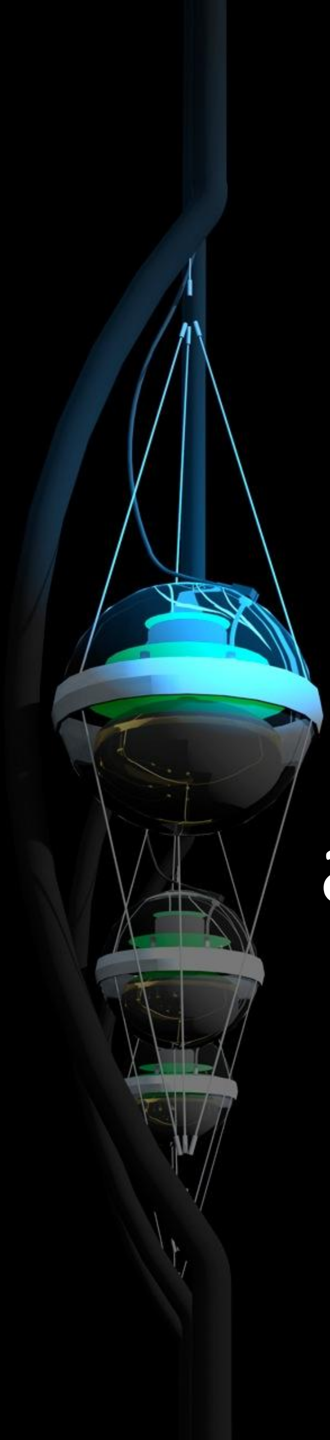
Gamma Ray Bursts: shock acceleration



up to 10^{21} eV

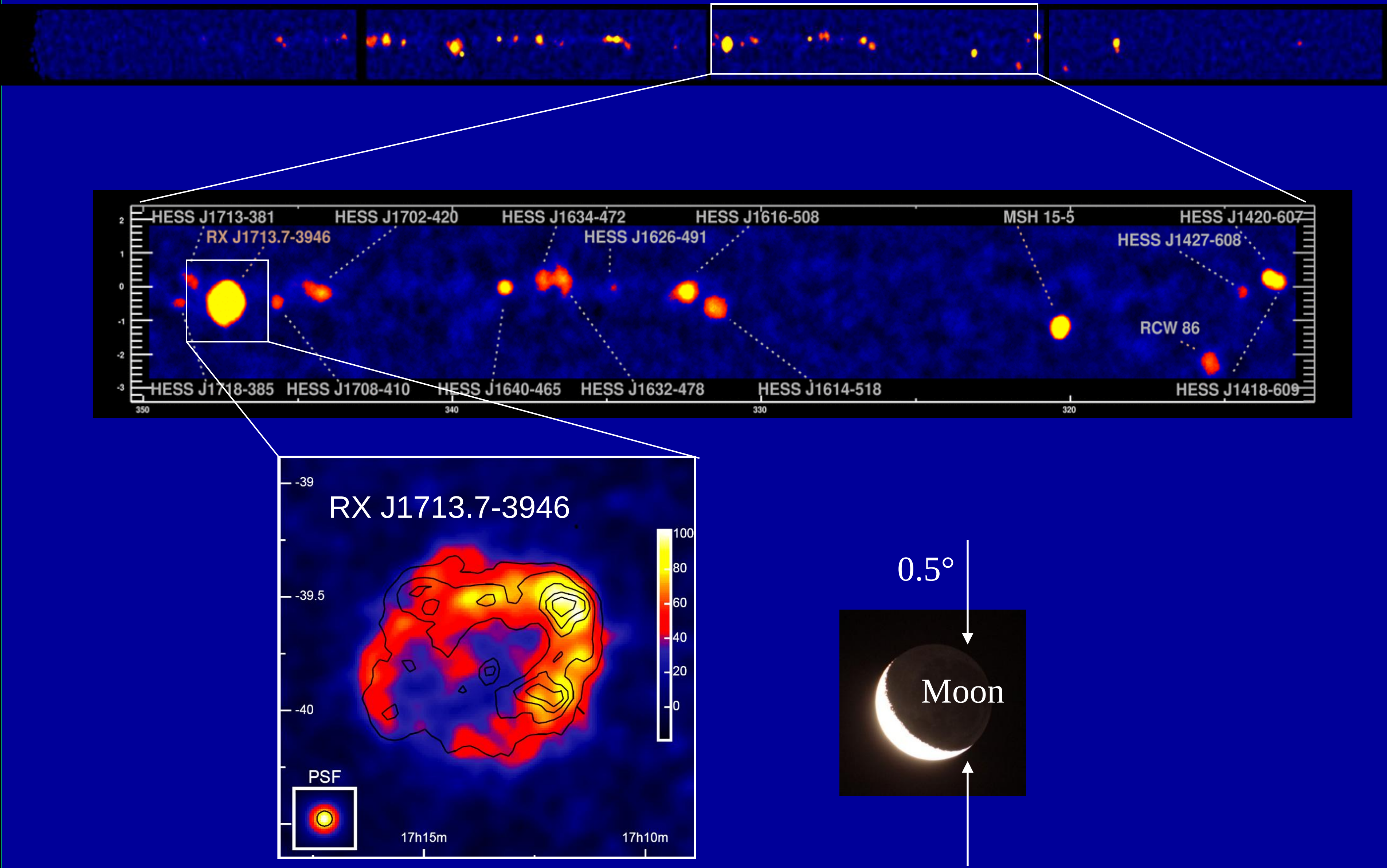
- Gamma Ray Bursts
  - $100 < \Gamma < 1000$
  - $E_{max} \sim 10^{21}$ eV
  - $L \sim 10^{51}$ erg/s
  - ~10 sec duration
- Active Galactic Nuclei
  - $\Gamma \sim 3\text{-}10$
  - $E_{max} \sim 10^{21}$ eV
  - $L \sim 10^{46}$ erg/s



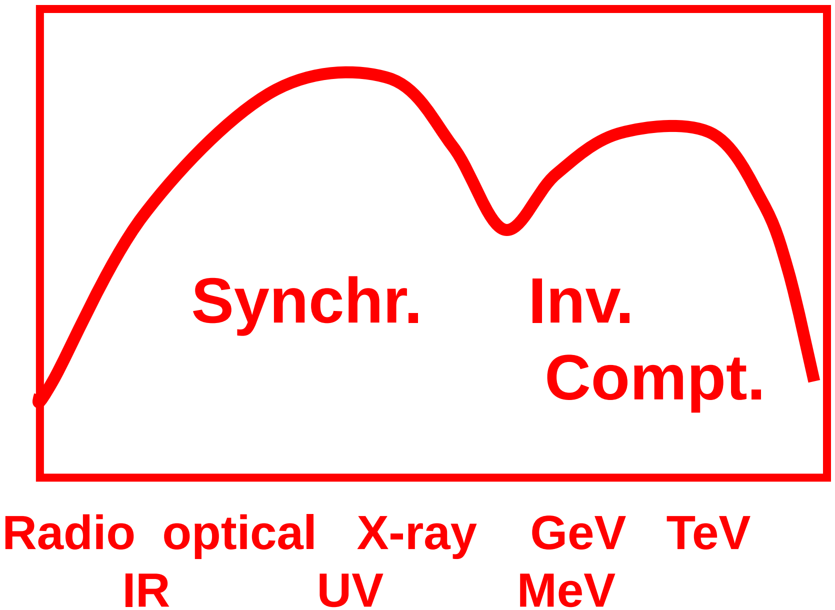


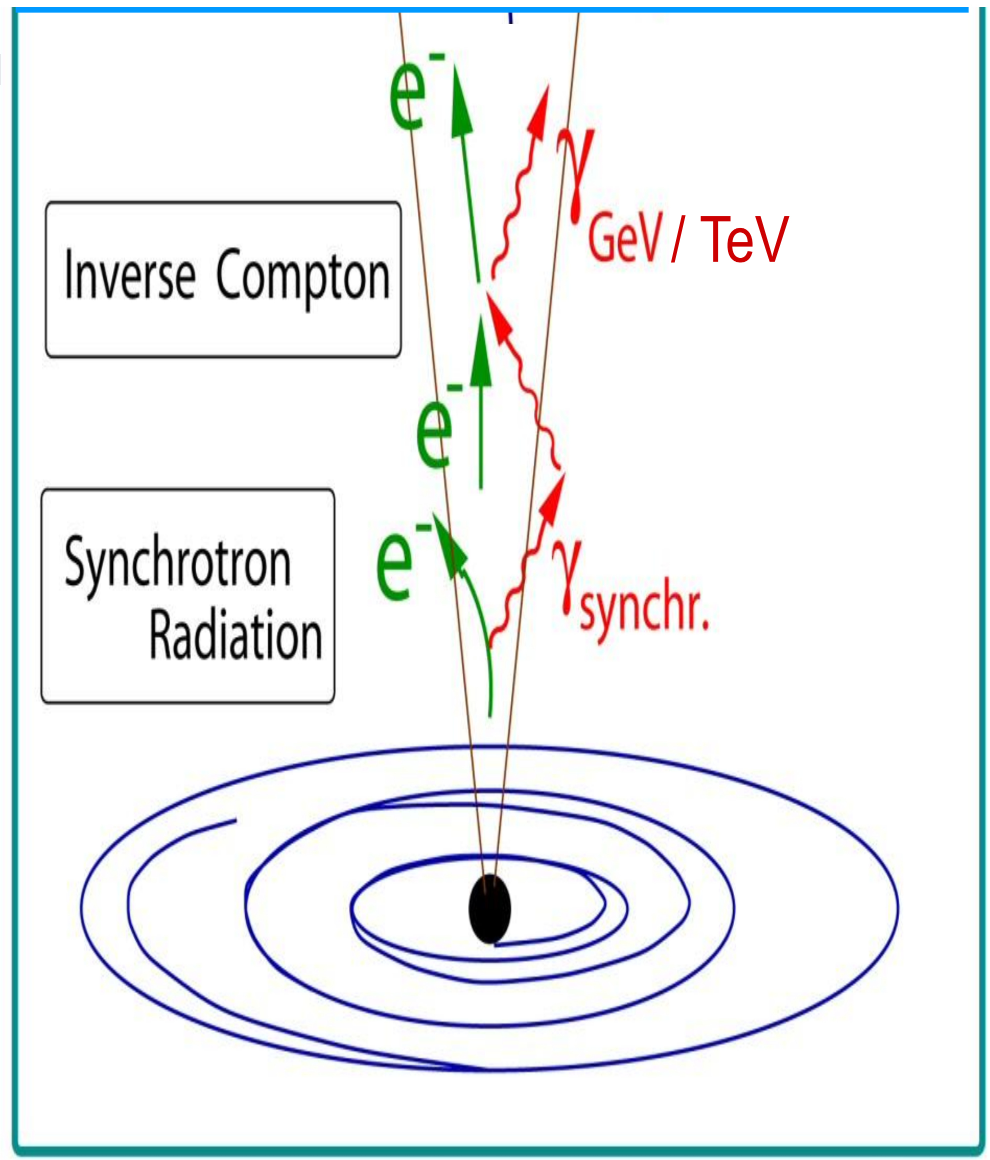
Generation of gamma rays and neutrinos in cosmic sources

H.E.S.S. scan of the galactic plane



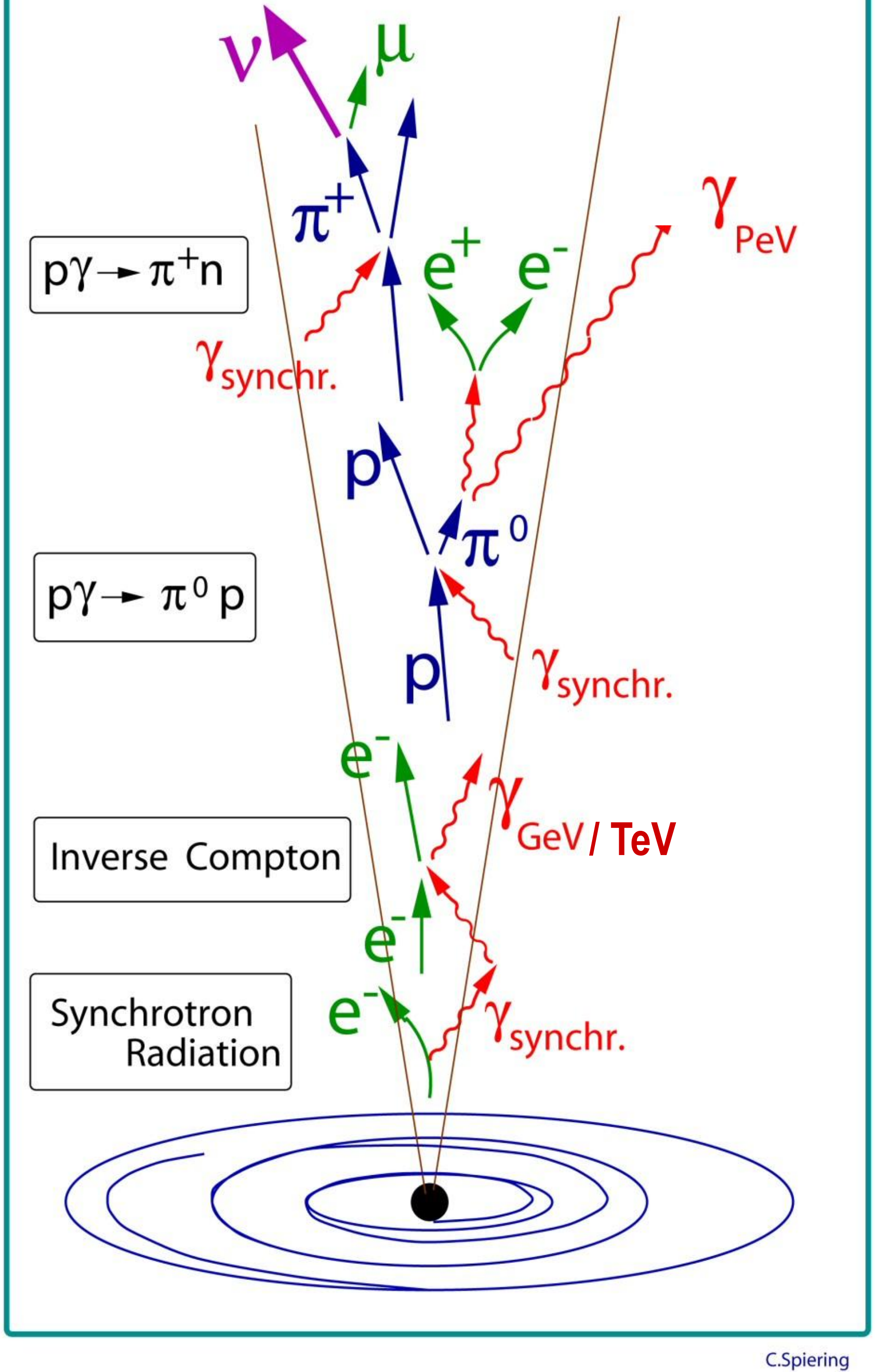
The electromagnetic spectrum of the TeV Gamma-sources known until now





C.Spiering

An electron-hadron accelerator



Neutrino-Production

by proton interaction with matter or with a photon field

$$p + p \rightarrow \pi + ...$$

$$\hookrightarrow \mu + \nu_\mu$$

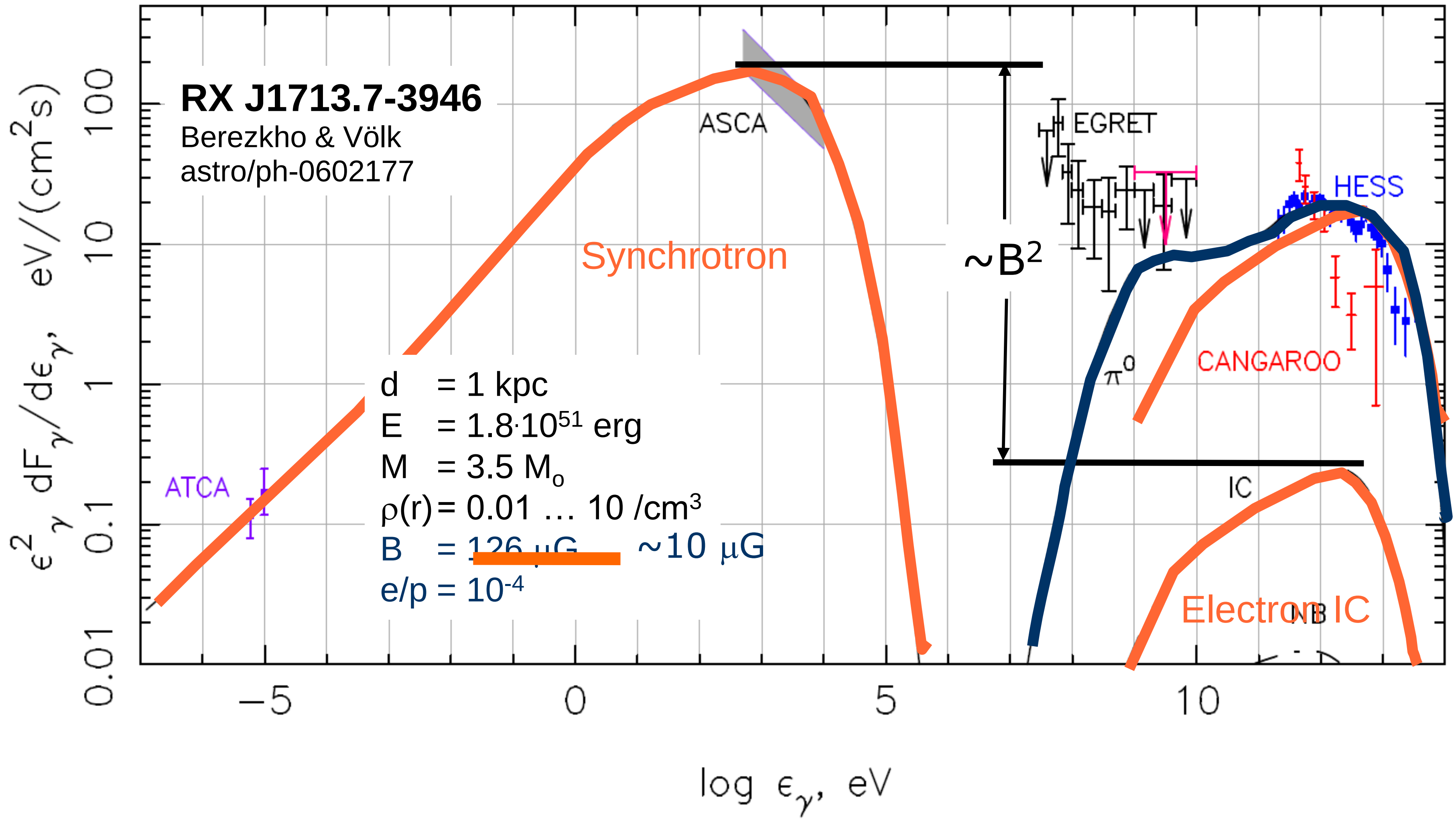
$$\hookrightarrow e + \nu_e + \nu_\mu$$

$$p + \gamma \rightarrow n + \pi^+$$ **or** $$\rightarrow p + \pi^0$$

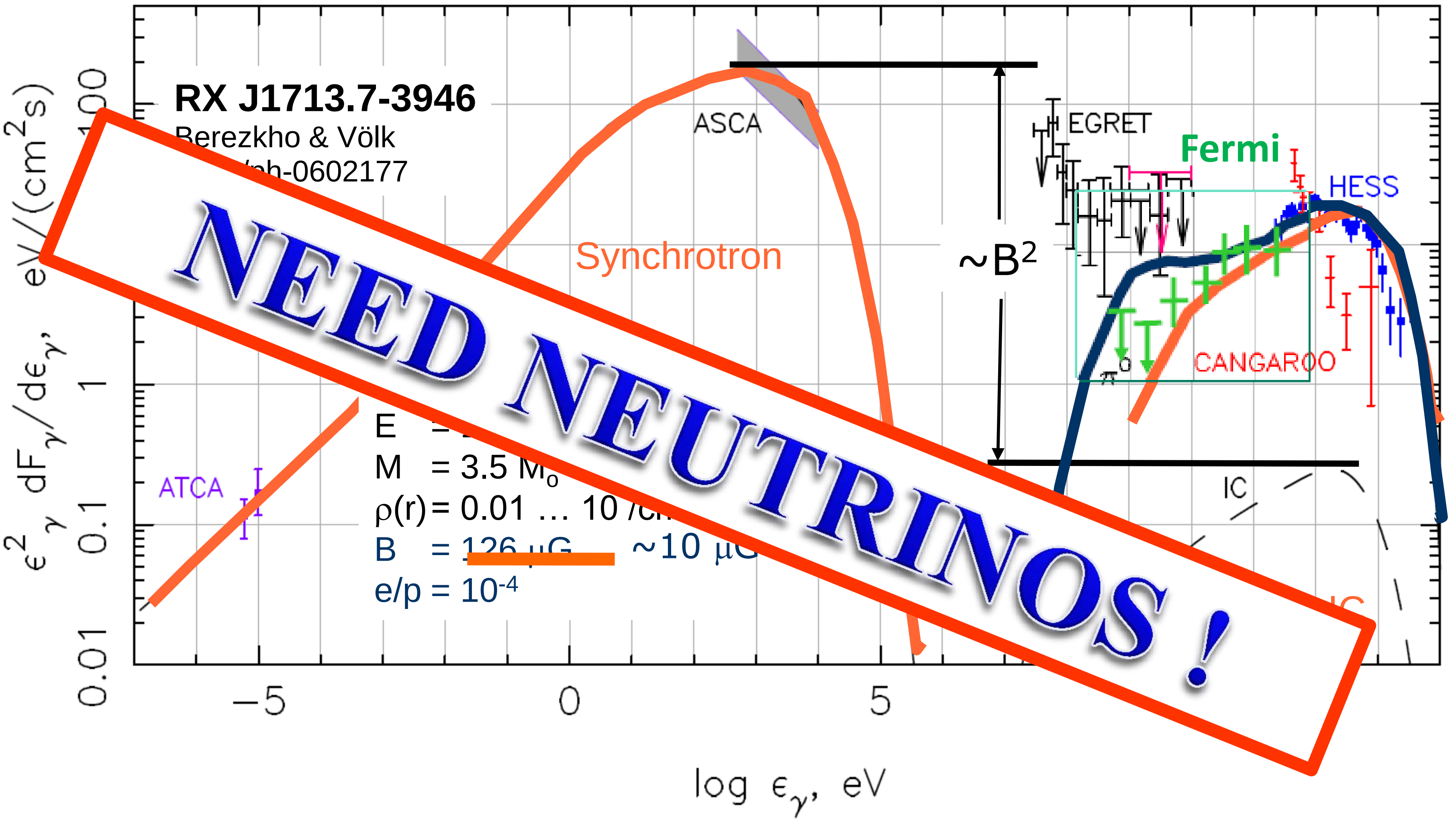
$$\hookrightarrow \mu + \nu \qquad\qquad \hookrightarrow \gamma + \gamma$$

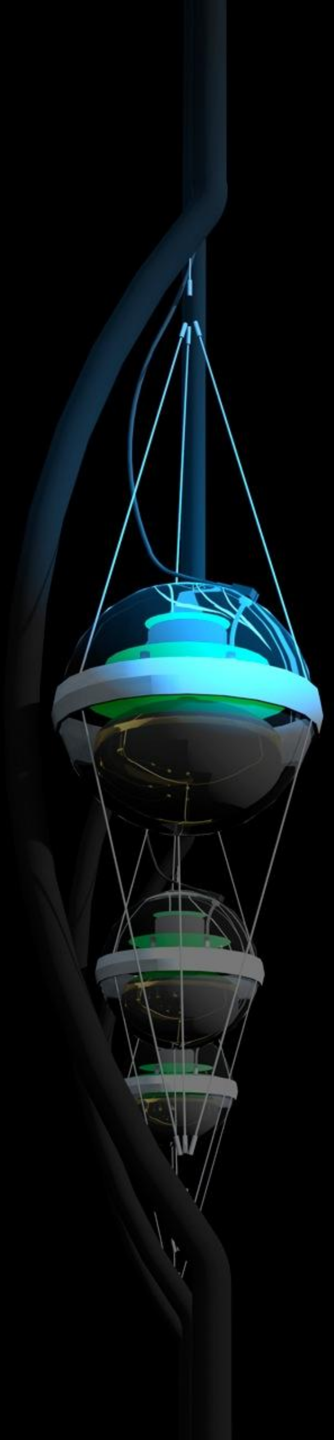
i.e. $\nu_e : \nu_\mu : \nu_\tau \sim$ 1:2:0 (→ 1:1:1 at Earth)

Spectral Energy distribution of RX J1713.7-3946



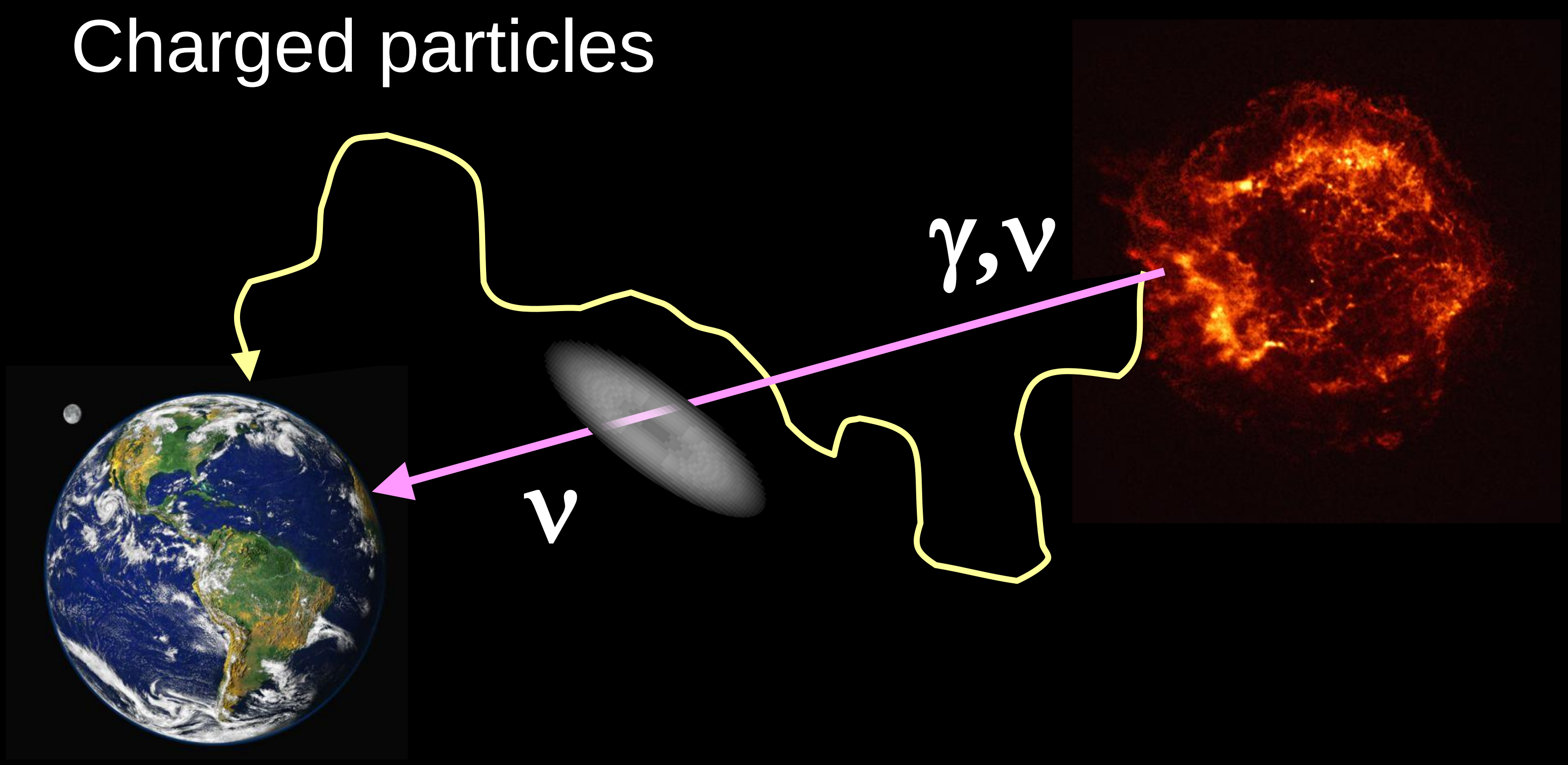
Spectral Energy distribution of RX J1713.7-3946



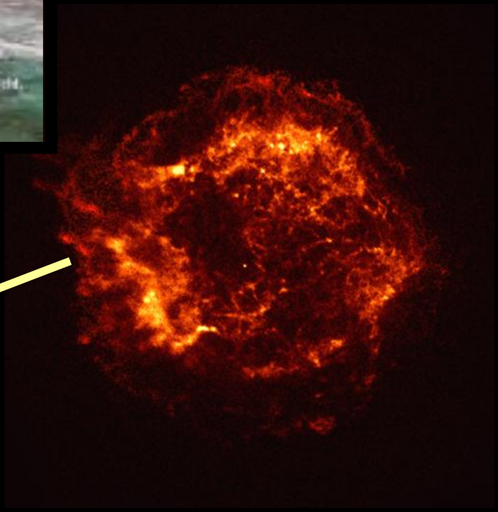


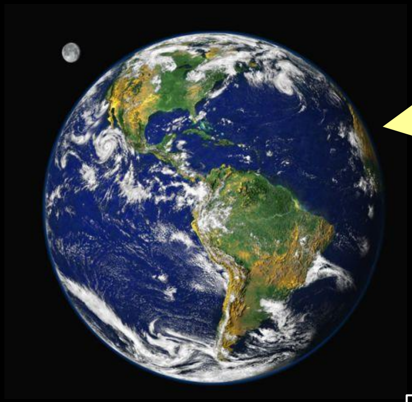
Propagation of gamma rays and cosmic rays

Charged cosmic rays vs. gamma rays and neutrinos



Pierre Auger Observatory

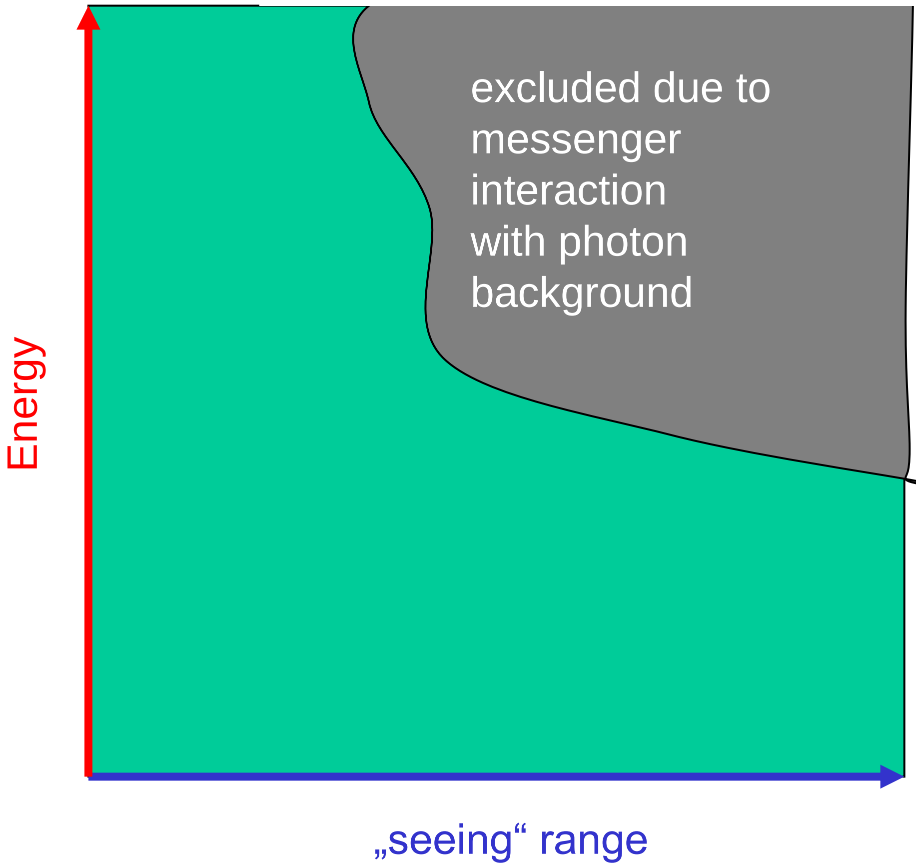




Charged particles at highest energies

No point sources identified yet

Transparency of the Universe



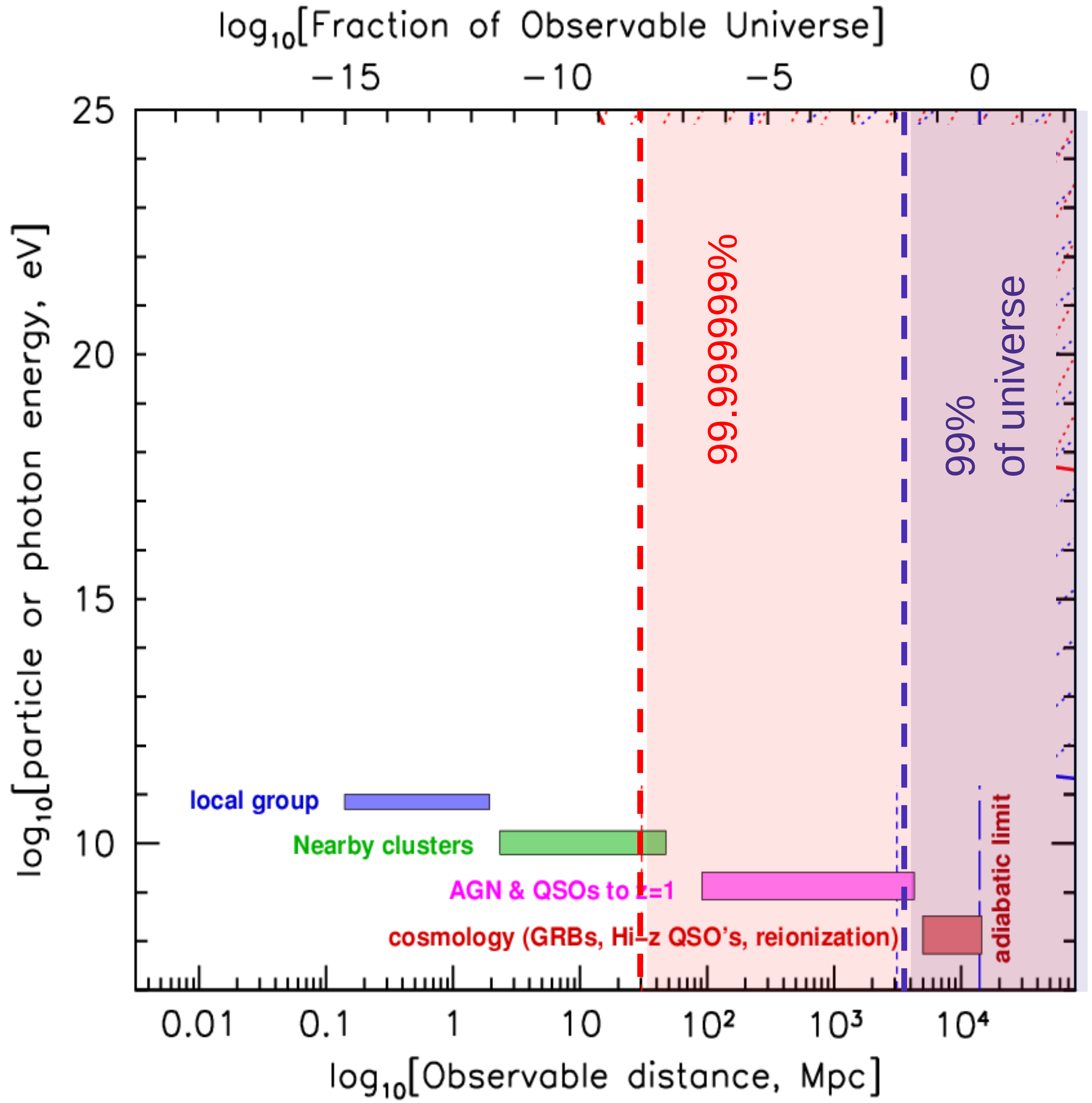
photons of all energies in universe (3K $\rightarrow$ visible)

interactions with p and γ:

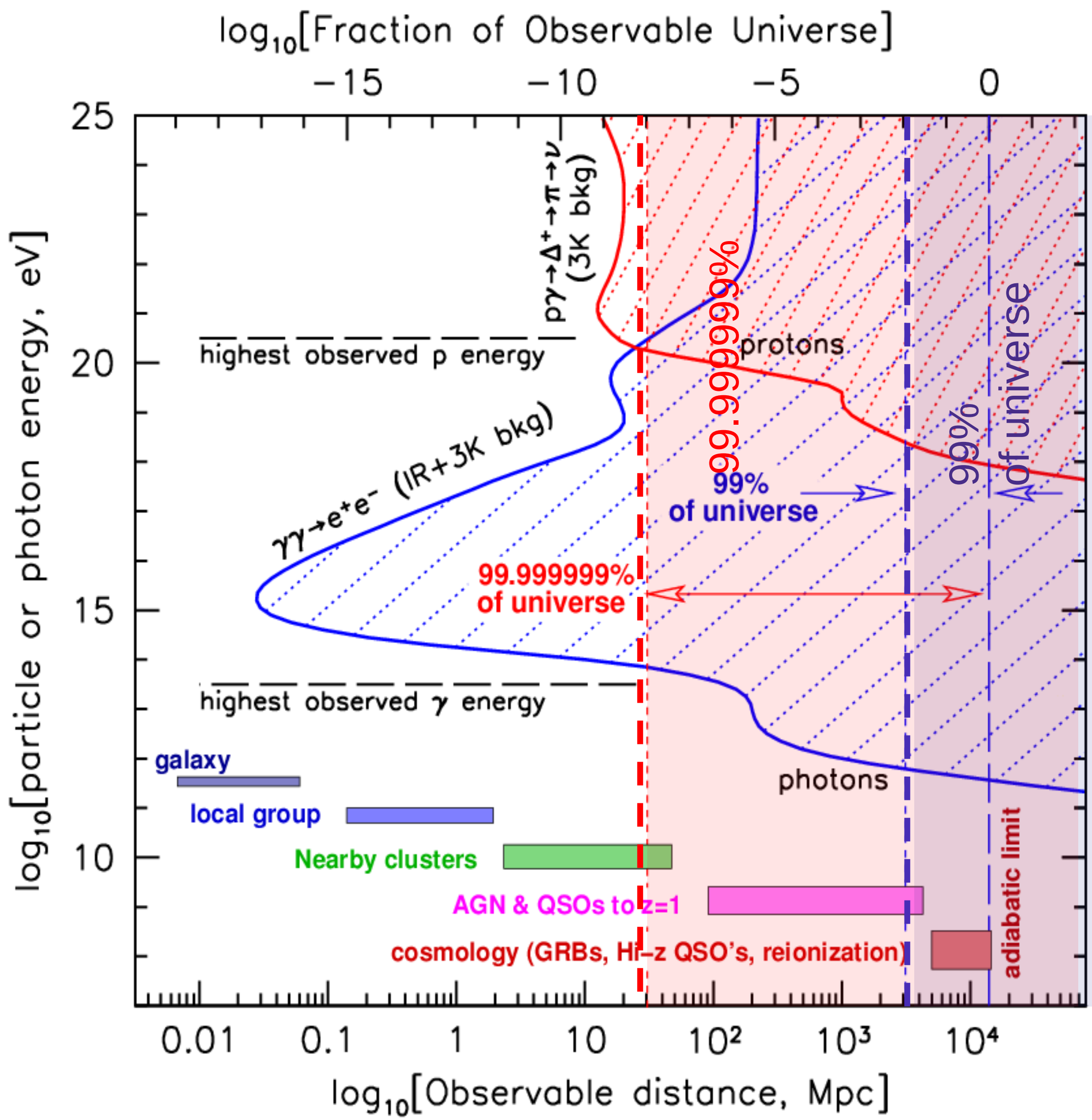
$$p + \gamma_{3K} \rightarrow \Delta^{+}(1232) \rightarrow p + \pi$$

$$\gamma_{H.E.} + \gamma_{IR/3K} \rightarrow e^{+}\, e^{-}$$

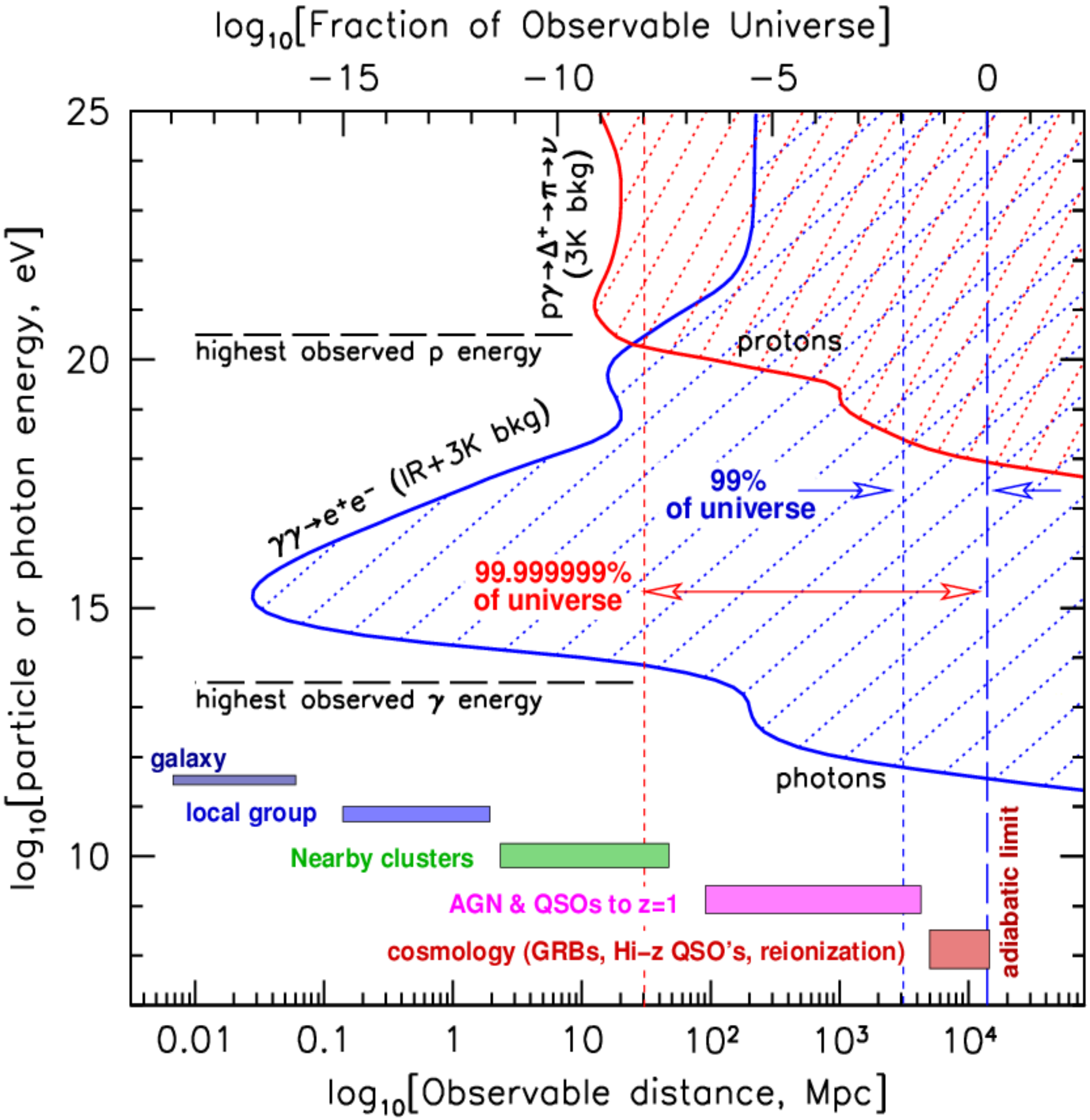
Transparency of the Universe

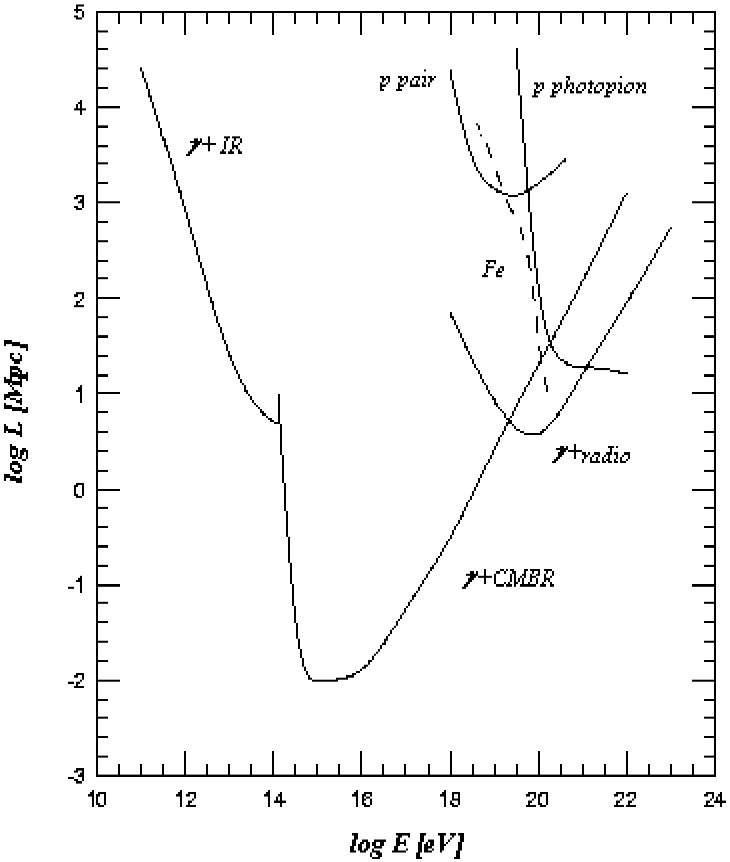


Transparency of the Universe

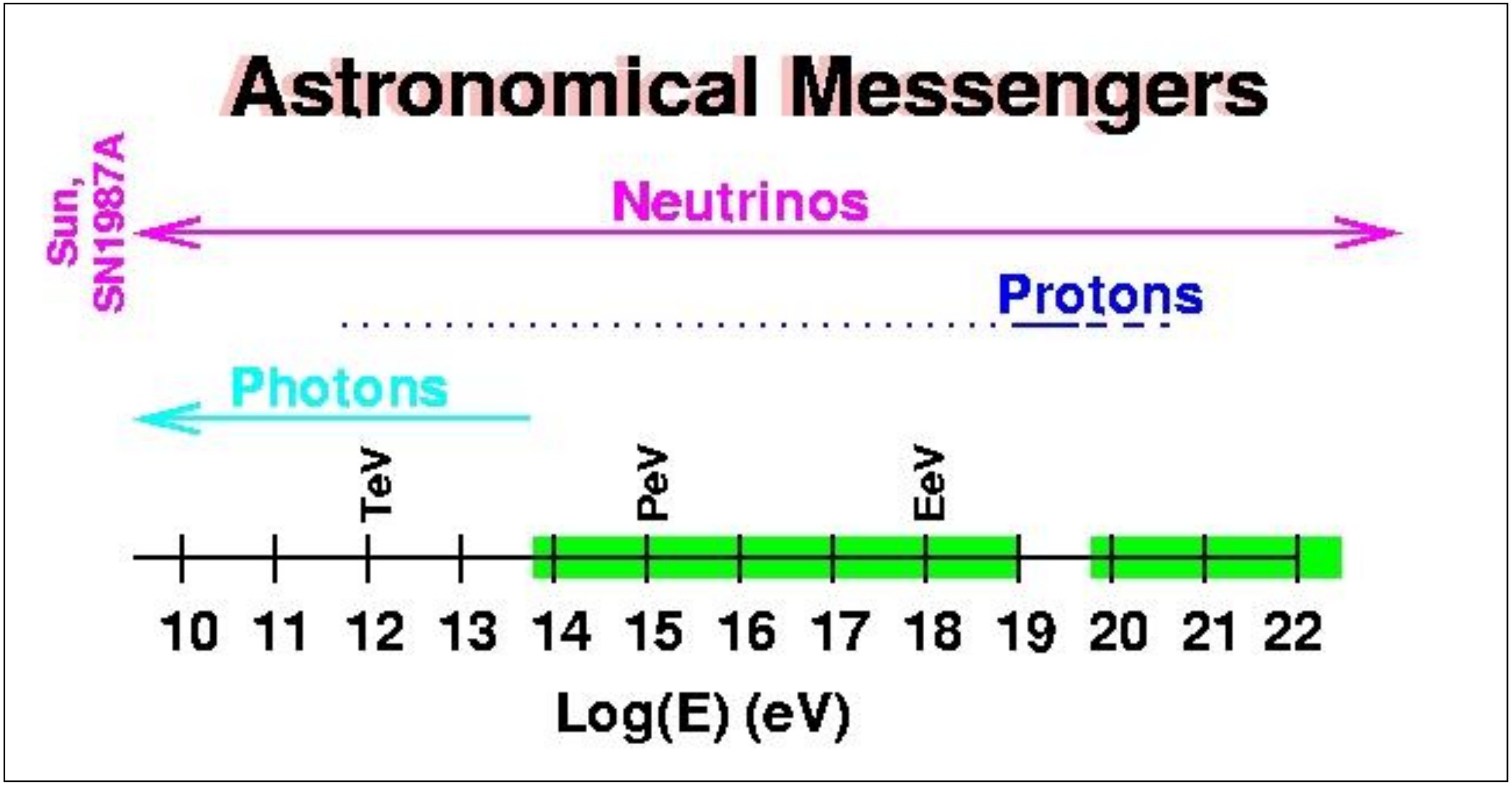


Transparency of the Universe

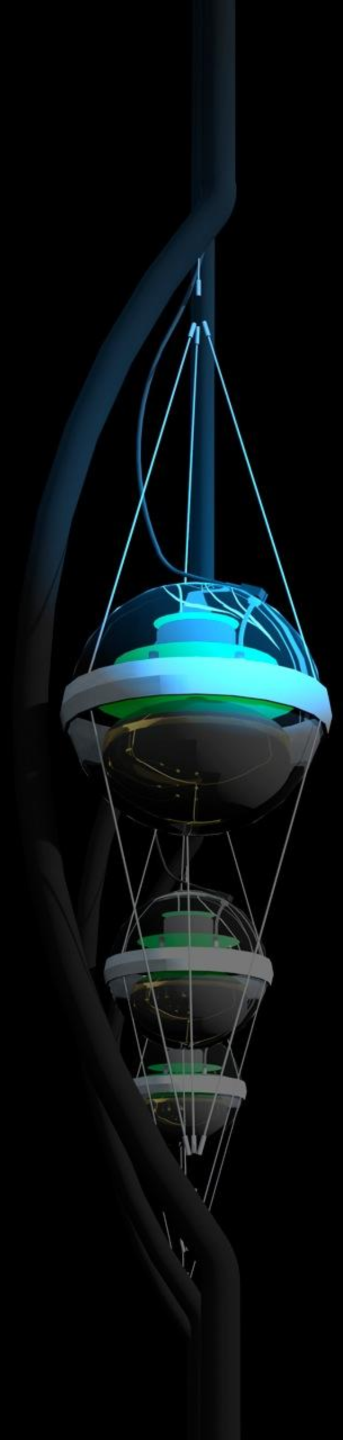




Accessible energy regions

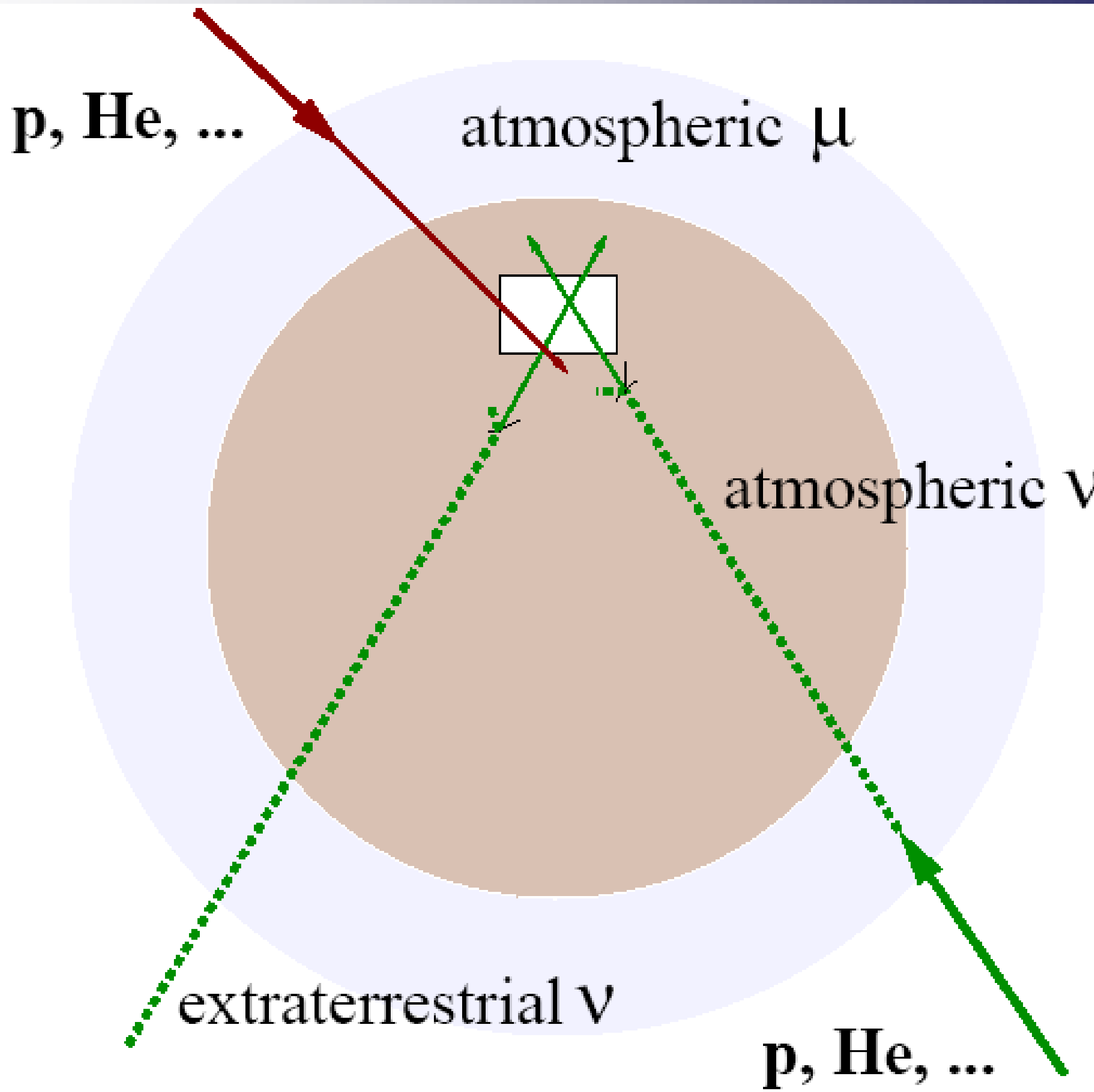


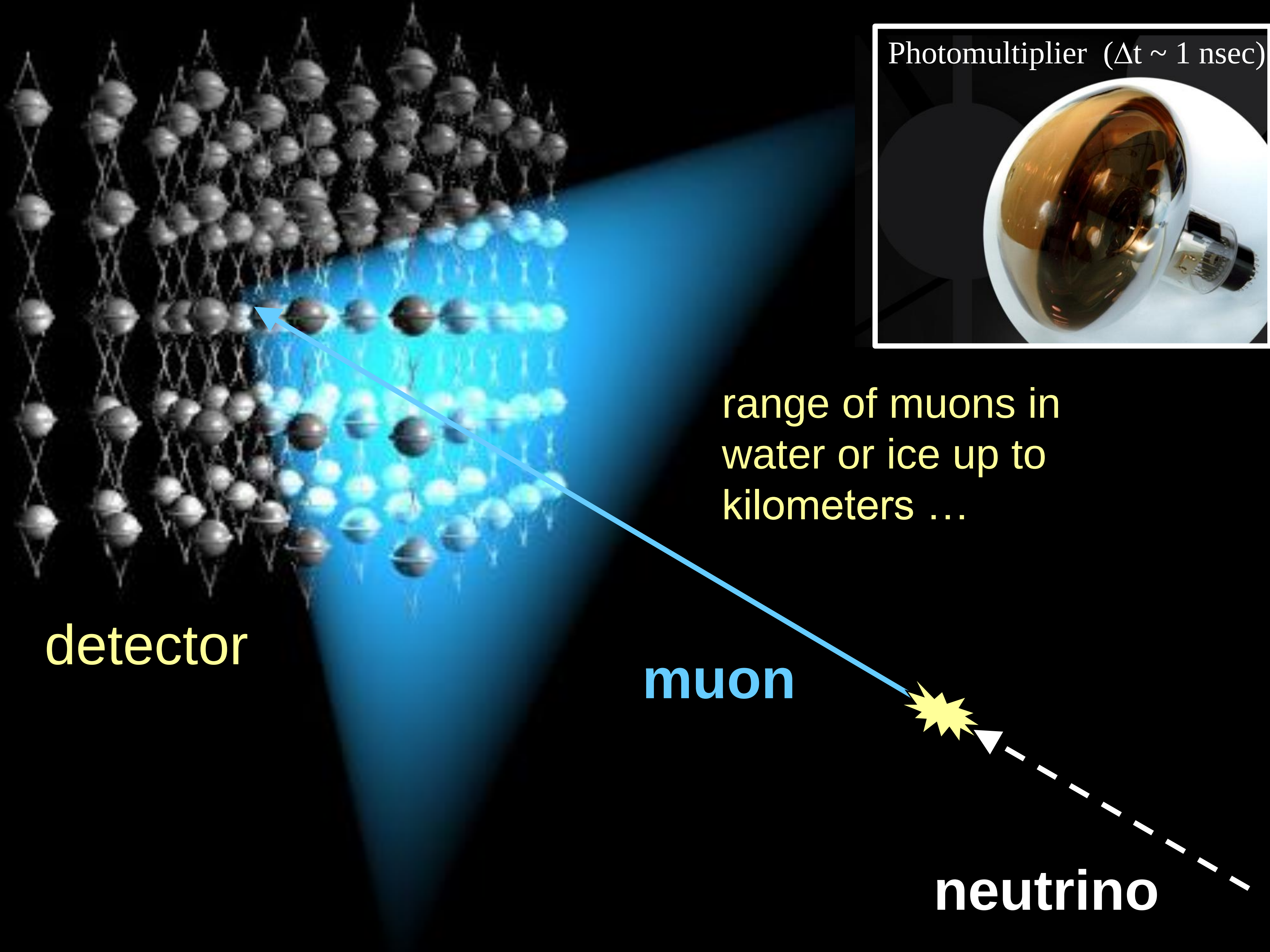
In green: no chance with gamma rays and charged cosmic rays to see and point extragalactic sources



Detection of high-energy neutrinos

High energy particles deep underground/water



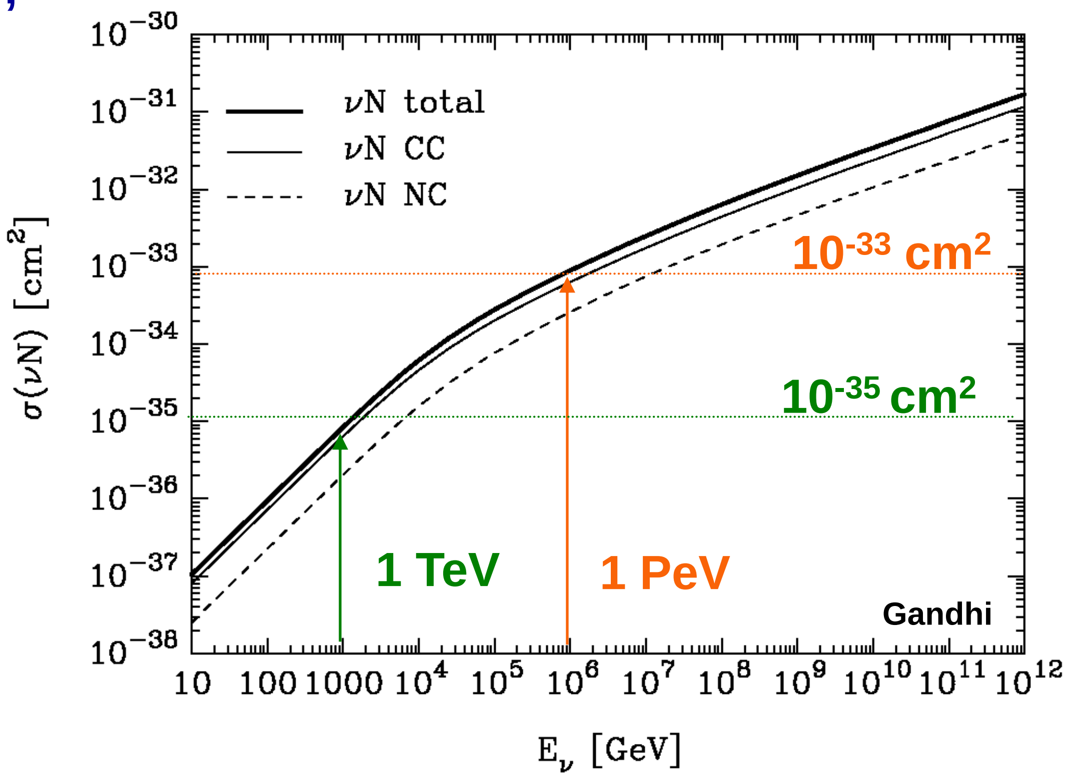

Photomultiplier (Δt ~ 1 nsec)
range of muons in water or ice up to kilometers …
detector
muon
neutrino

Neutrino cross sections

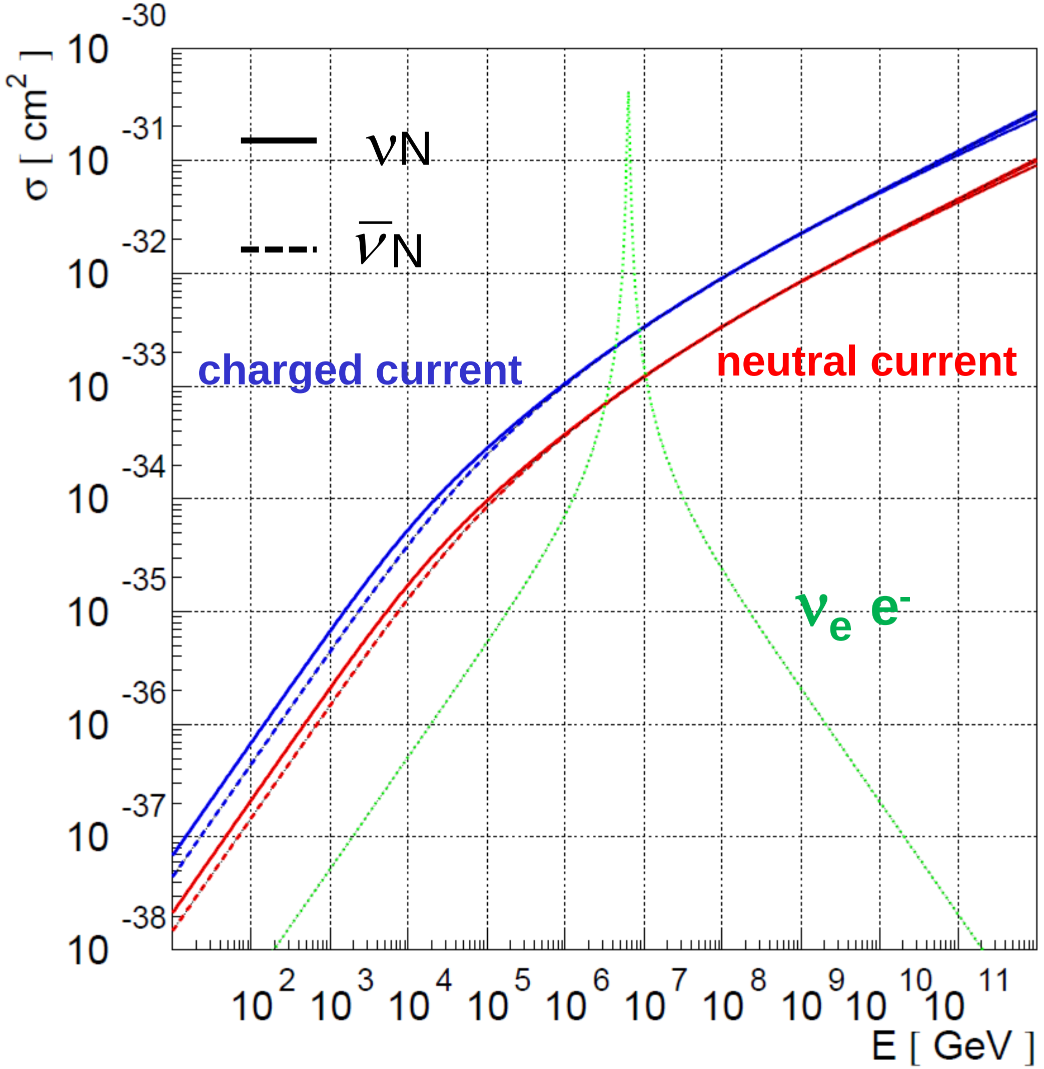
Neutrinos are detected indirectly, following an interaction on a target nucleus N:

$$\nu_\ell + N \rightarrow \ell^- + X$$

$$\sigma_{\nu N} \begin{cases} \propto E_\nu & E_\nu \leq 5\text{TeV} \\ \propto E_\nu^{0.4} & E_\nu > 5\text{TeV} \end{cases}$$

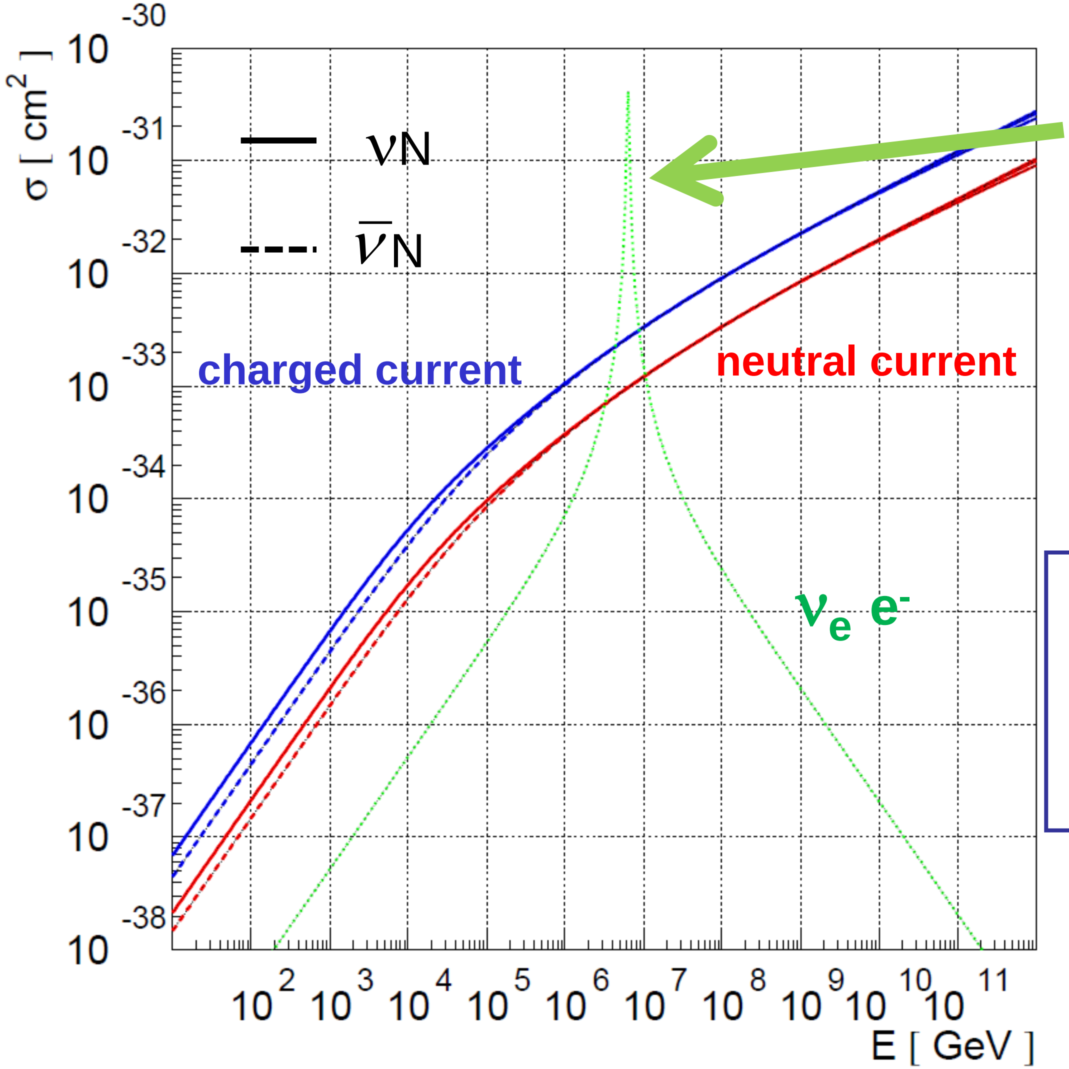


Neutrino cross sections



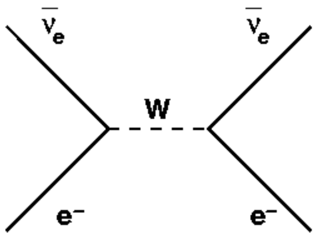
laboratory energies

Neutrino cross sections



laboratory energies

resonant production of real W^- from hitting ambient electrons:



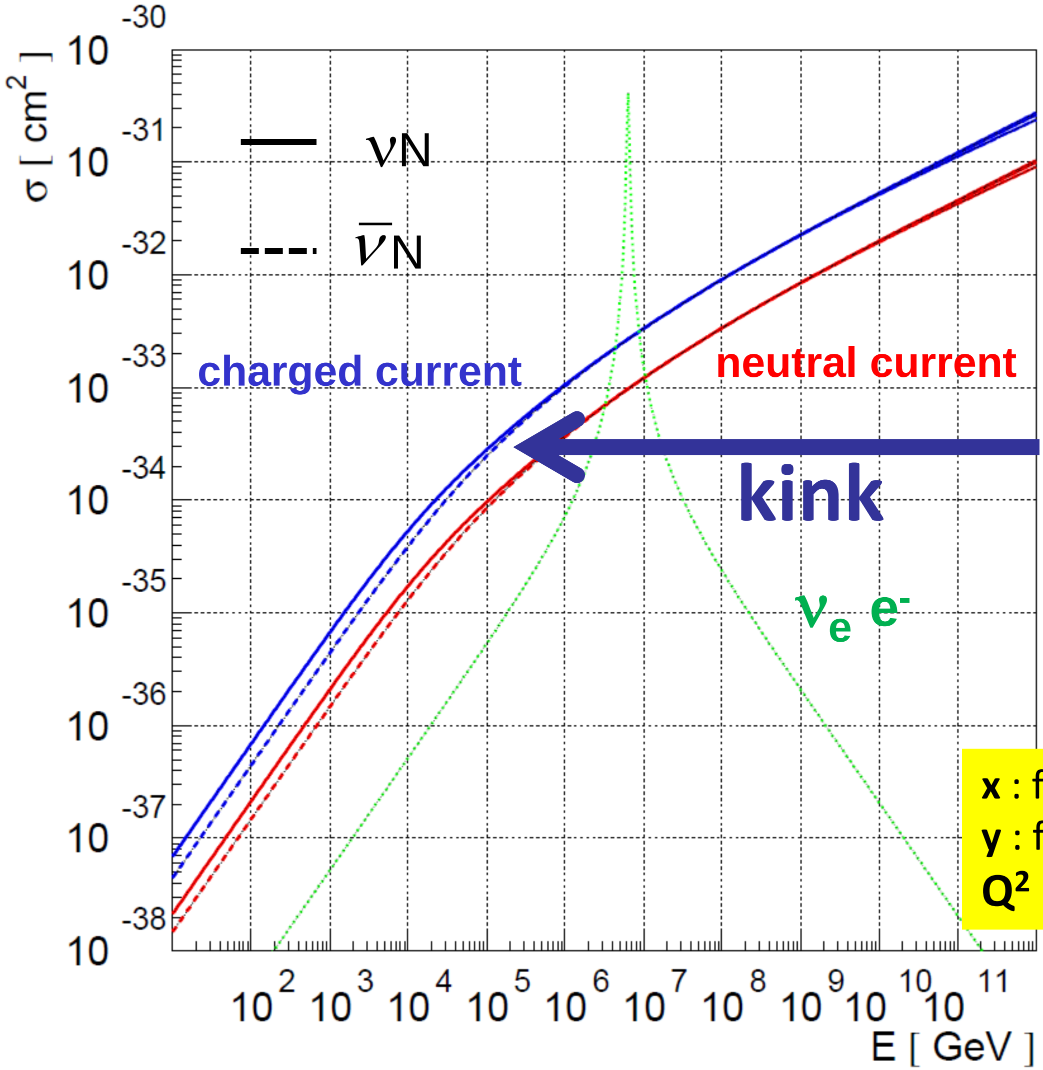
neutrino laboratory energy: 6.3 PeV = 6.3 x 10^{15} eV

resonance width: ±130 TeV

peak cross section: 5 x 10^{-31} cm^2

„Glashow resonance“

Neutrino cross sections



laboratory energies

The propagator effect:

kink at the point were the maximum Q^2 (which grows with E_ν) comes close to the W mass squared.

$$\frac{d\sigma^2}{dxdy} = \frac{2\ G_F{}^2 E_\nu}{\pi} \cdot \left(\frac{M_W{}^2}{Q^2 + M_W{}^2}\right) \cdot$$

$$\cdot\ (xq(x, Q^2) + x\bar{q}\ (x, Q^2)(1-y)^2\ )$$

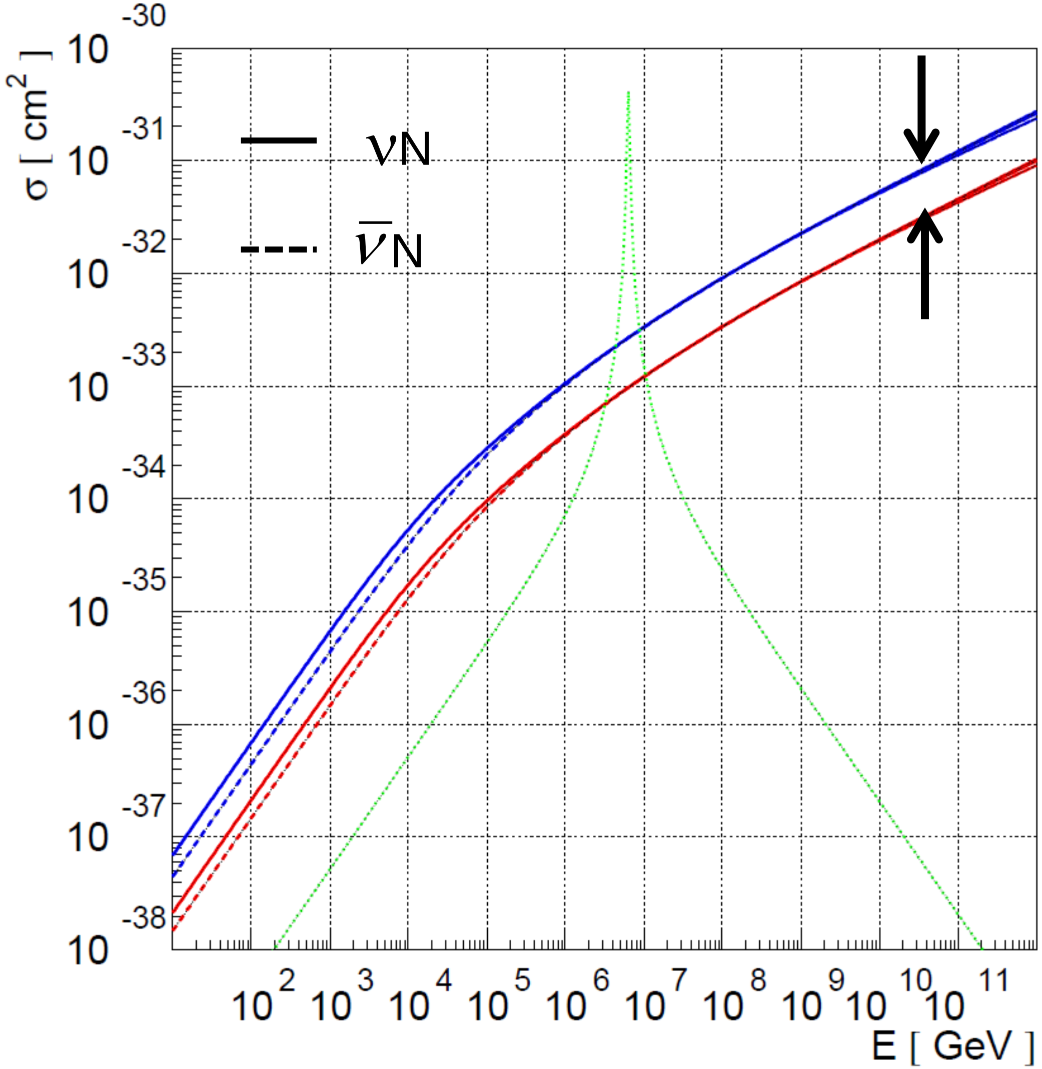
G_F = Fermi constant = 1.17 x 10^{-5} GeV^{-2}

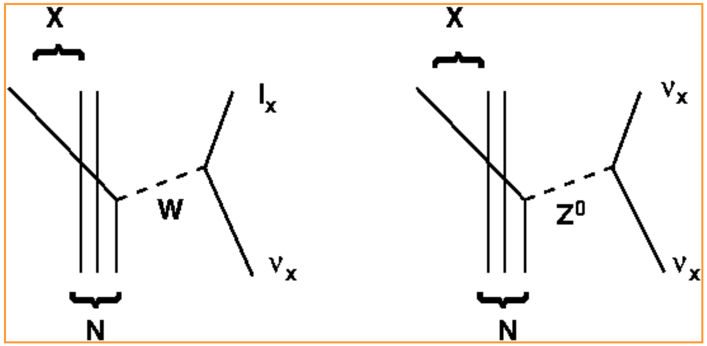
x : fraction of nucleon momentum carried by quark
y : fraction of neutrino momentum transferred to N
Q^2 = xys = -(4-momentum of W/Z)^2

xq(x) = momentum distribution of quarks

$x\bar{q}(x)$ = momentum distribution anti-quarks

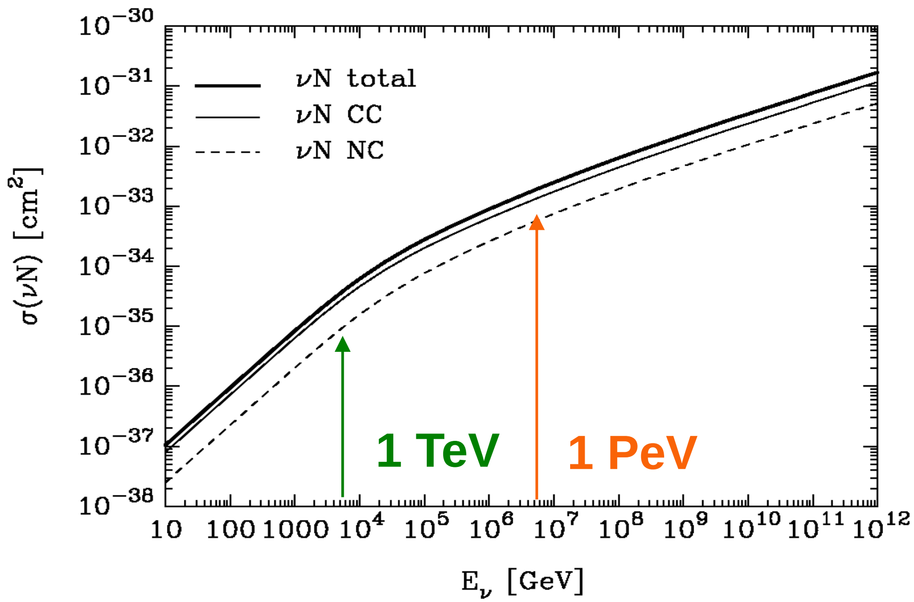
Neutrino cross sections

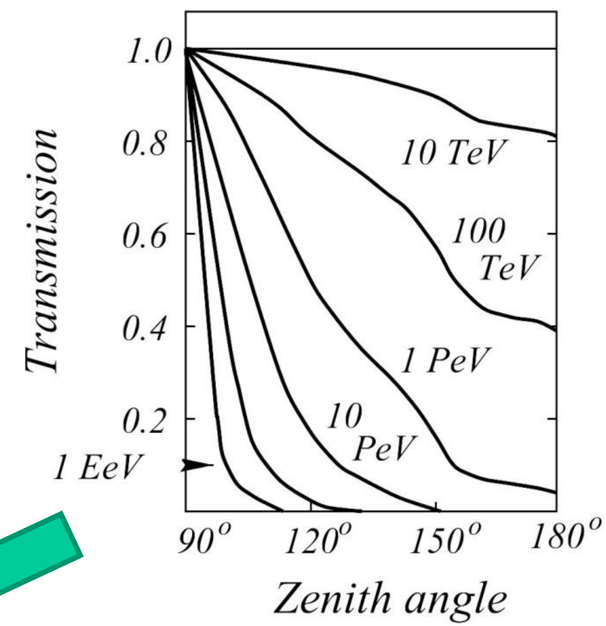


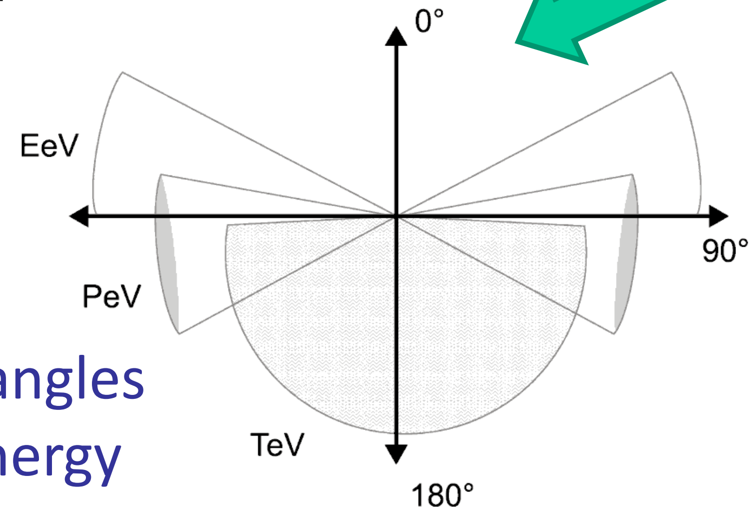


- W-exchange is pure V-A current (only left handed coupling)
- Z has also right handed coupling
- Z slightly heavier than w
- NC/CC ~ 0.31 (0.38) for ν (anti-ν)

Neutrino transmission through the Earth



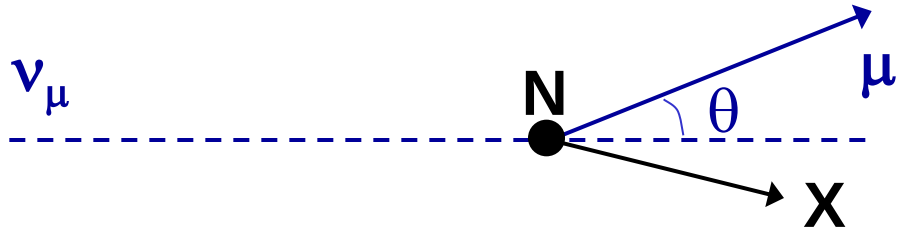




Optimium zenith angles
as a function of energy

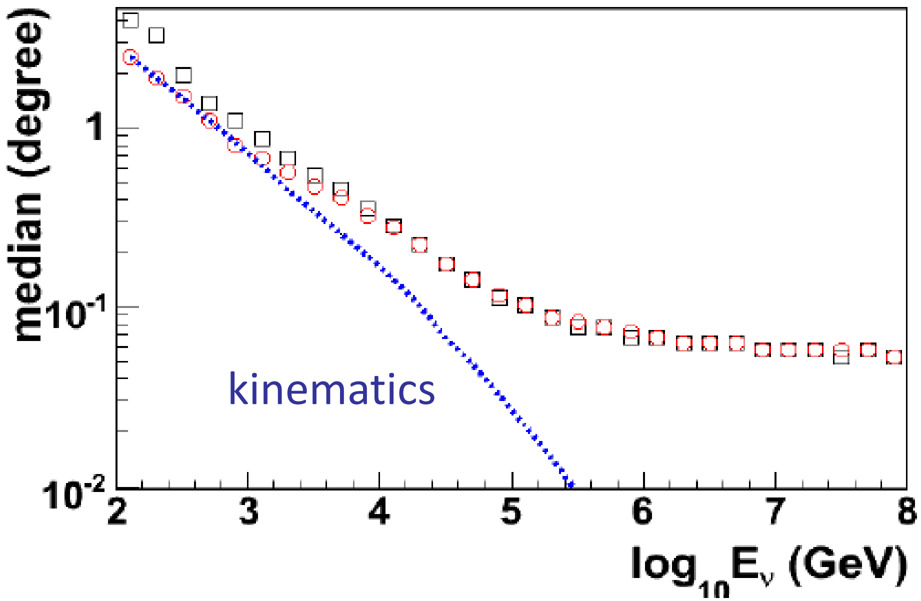
Pointing accuracy

At >TeV energies the muon and the neutrino are co-linear



$$\langle\theta\rangle \approx \frac{1.5^\circ}{\sqrt{E_\nu\,[\mathrm{TeV}]}}$$

Reconstruction of the μ trajectory allows the identification of the ν direction



Calculated median of the angular error in KM3NeT

Muon energy loss

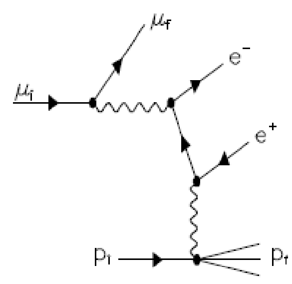
$$-\frac{dE}{dx} \propto a + b \cdot E$$

$$a = 0.2\left[\frac{GeVcm^2}{g}\right]$$ → ionization

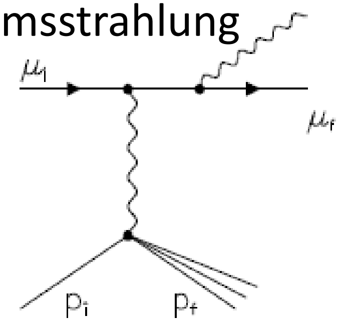
$$b = 4 \cdot 10^{-4}\left[\frac{cm^2}{g}\right]$$

$$R_\mu = \frac{1}{b}\ln\left[a + bE_\mu\right]$$

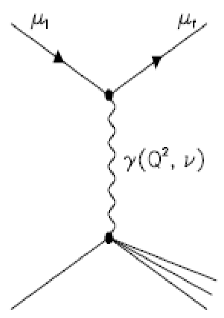
Pair creation

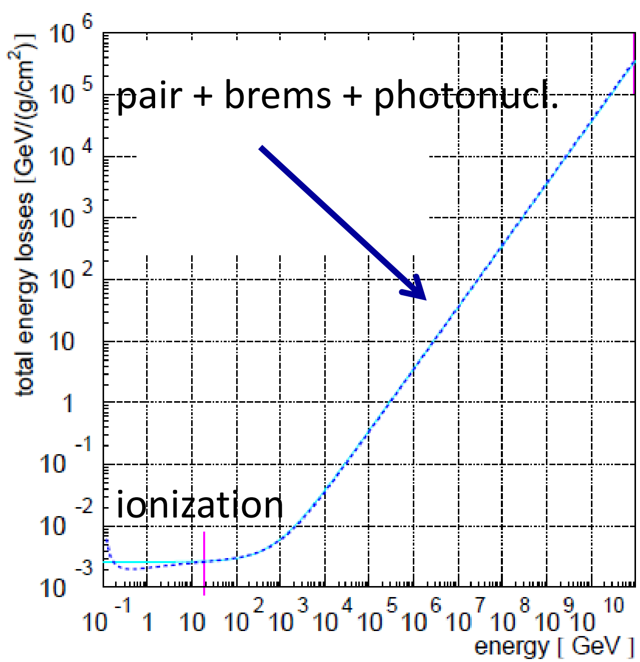


bremsstrahlung



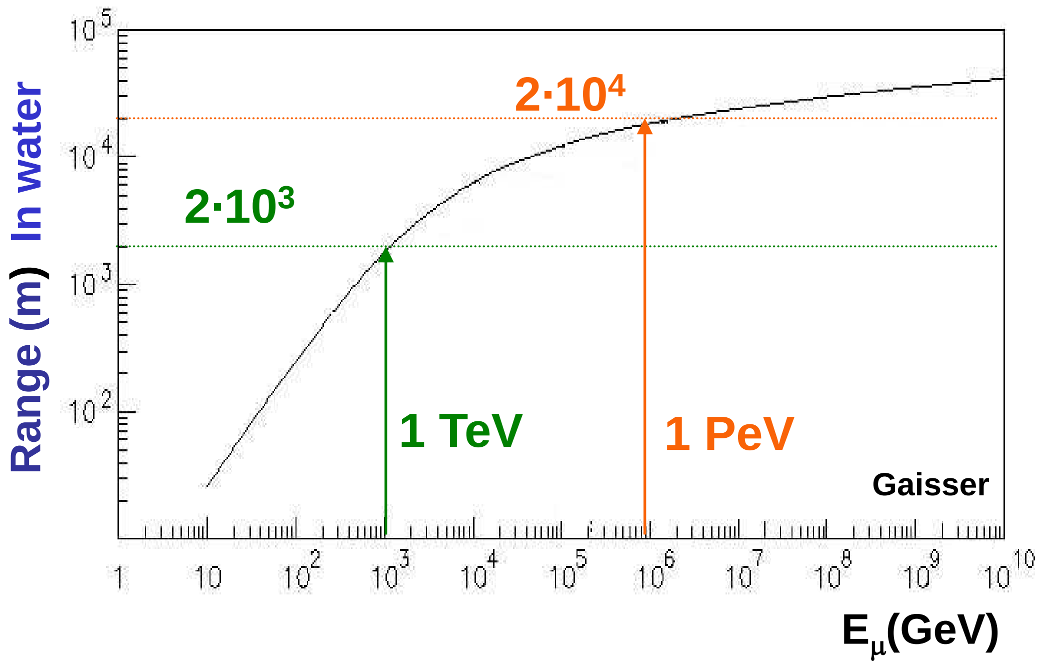
photonuclear reaction

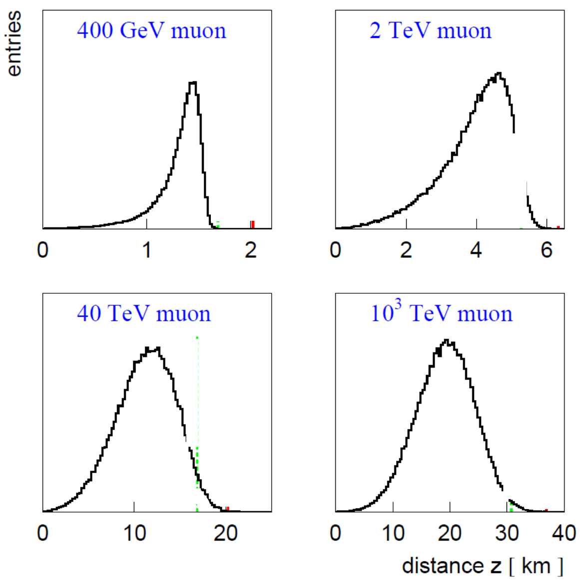




Pair creation: often, with small dE
Bremsstrahlung: rare, with larger dE
Photonuclear: very rare, very large dE

Muon energy loss





Muons have long tracks in water $R_\mu\left(E_\mu = 300\text{GeV}\right) \approx 1\ \text{km}$

Due to the long muon range the target volume is much bigger than the detector instrumented volume

The number of muon events in units of detection area A and observation time T is:

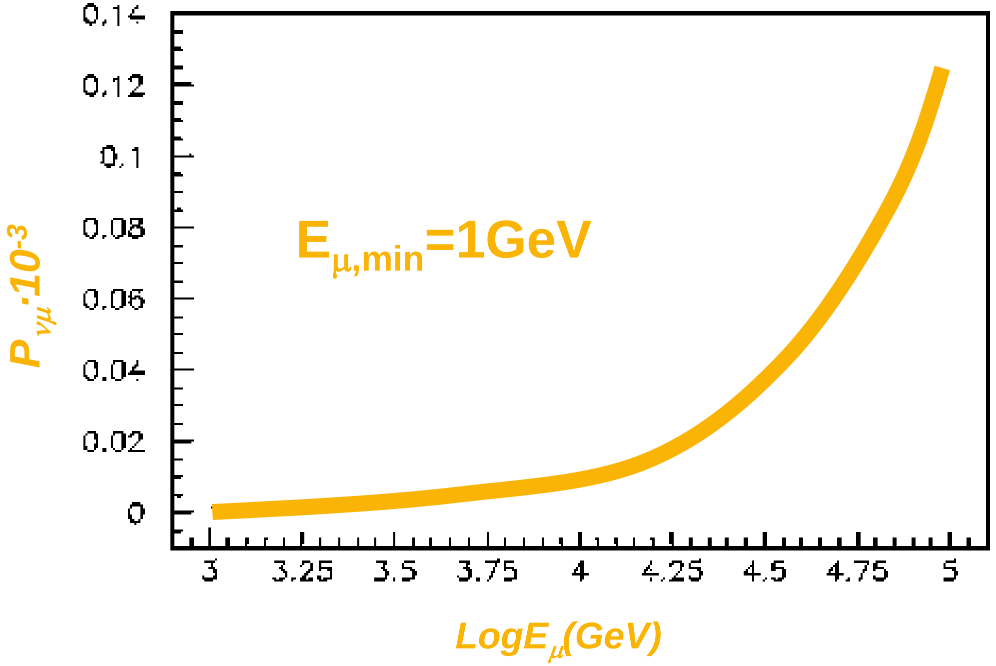
$$\frac{N_\mu\left(E_{\mu,min},\vartheta\right)}{AT}=\int_{E_{\mu,min}}^{E_\nu} dE_\nu\,\Phi_\nu\left(E_\nu,\vartheta\right)\cdot P_{\nu\mu}\left(E_\nu,E_{\mu,min}\right)\cdot e^{-\sigma_{tot}\left(E_\nu\right)N_A Z(\vartheta)}$$

- **Neutrino flux spectrum**

The number of muon events in units of detection area A and observation time T is:

$$\frac{N_\mu\left(E_{\mu,min},\vartheta\right)}{AT} = \int_{E_{\mu,min}}^{E_\nu} dE_\nu \, \Phi_\nu\left(E_\nu,\vartheta\right) \cdot P_{\nu\mu}\left(E_\nu,E_{\mu,min}\right) \cdot e^{-\sigma_{tot}(E_\nu)N_A Z(\vartheta)}$$

- Neutrino flux spectrum
- Probability to produce a detectable ($E_\mu > E_{min}$) muon



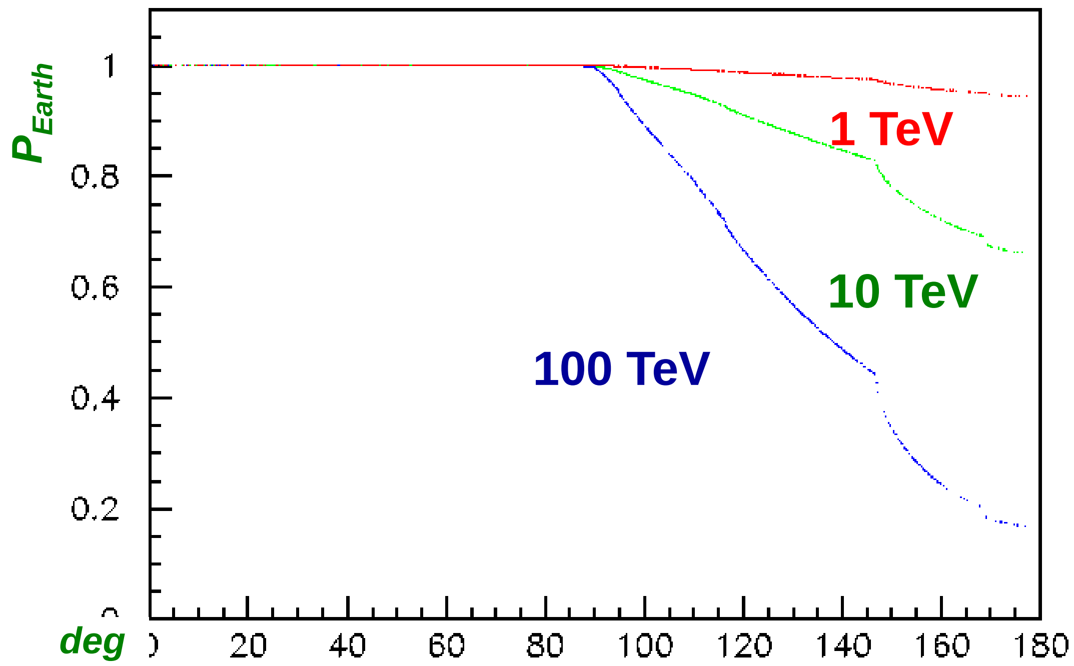
10^{-6} @ 1 TeV

The number of muon events in units of detection area A and observation time T is:

$$\frac{N_\mu\left(E_{\mu,min},\vartheta\right)}{AT} = \int_{E_{\mu,min}}^{E_\nu} dE_\nu \, \Phi_\nu\left(E_\nu,\vartheta\right) \cdot P_{\nu\mu}\left(E_\nu,E_{\mu,min}\right) \cdot e^{-\sigma_{tot}(E_\nu)N_A Z(\vartheta)}$$

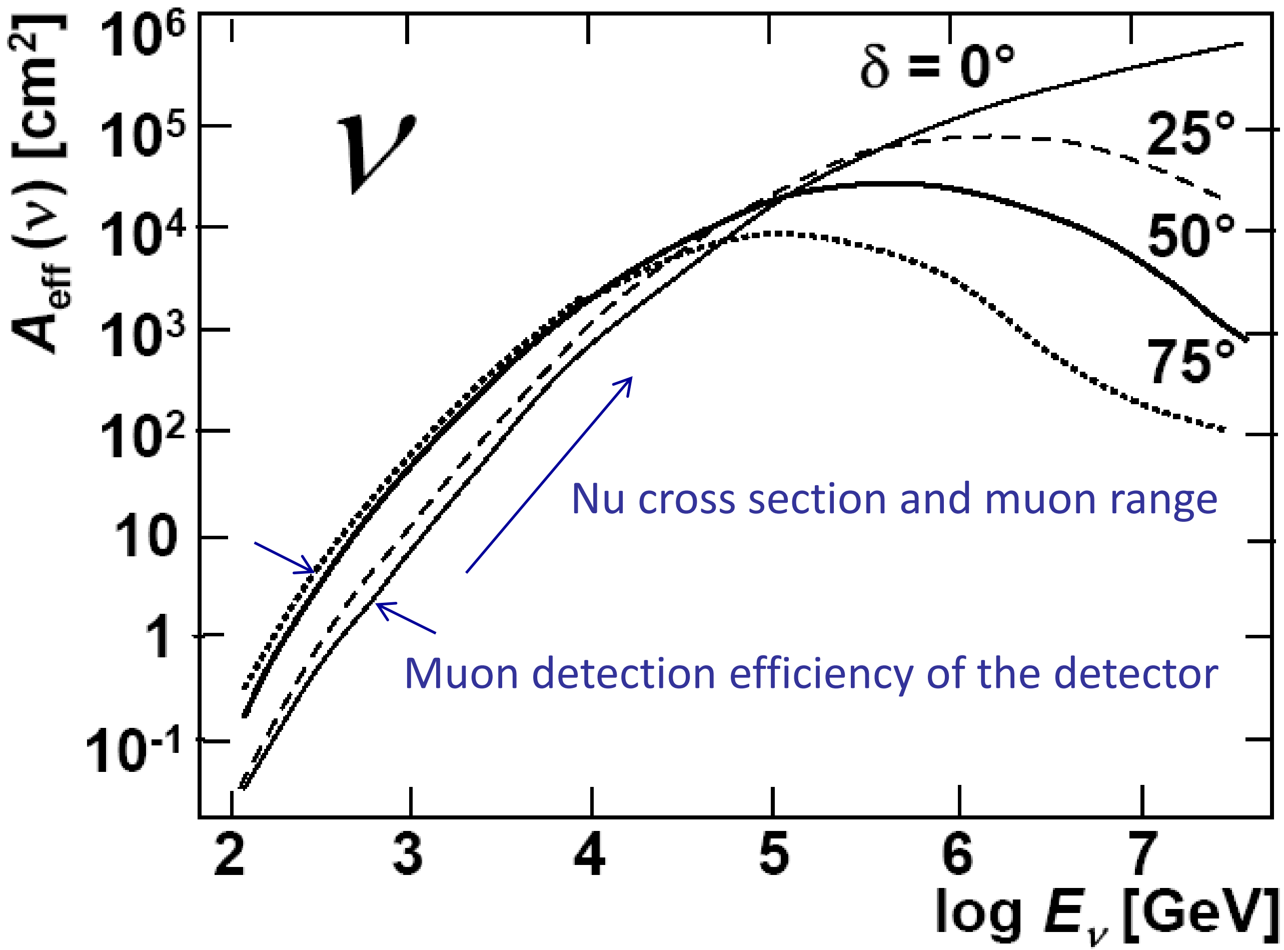
- **Neutrino flux spectrum**
- **Probability to produce a detectable ($E_\mu > E_{min}$) muon**
- **Earth transparency to HE neutrinos**

→ >PeV neutrinos search for "horizontal" tracks



Effective area

IceCube effective area as function of neutrino energy and zenith angle

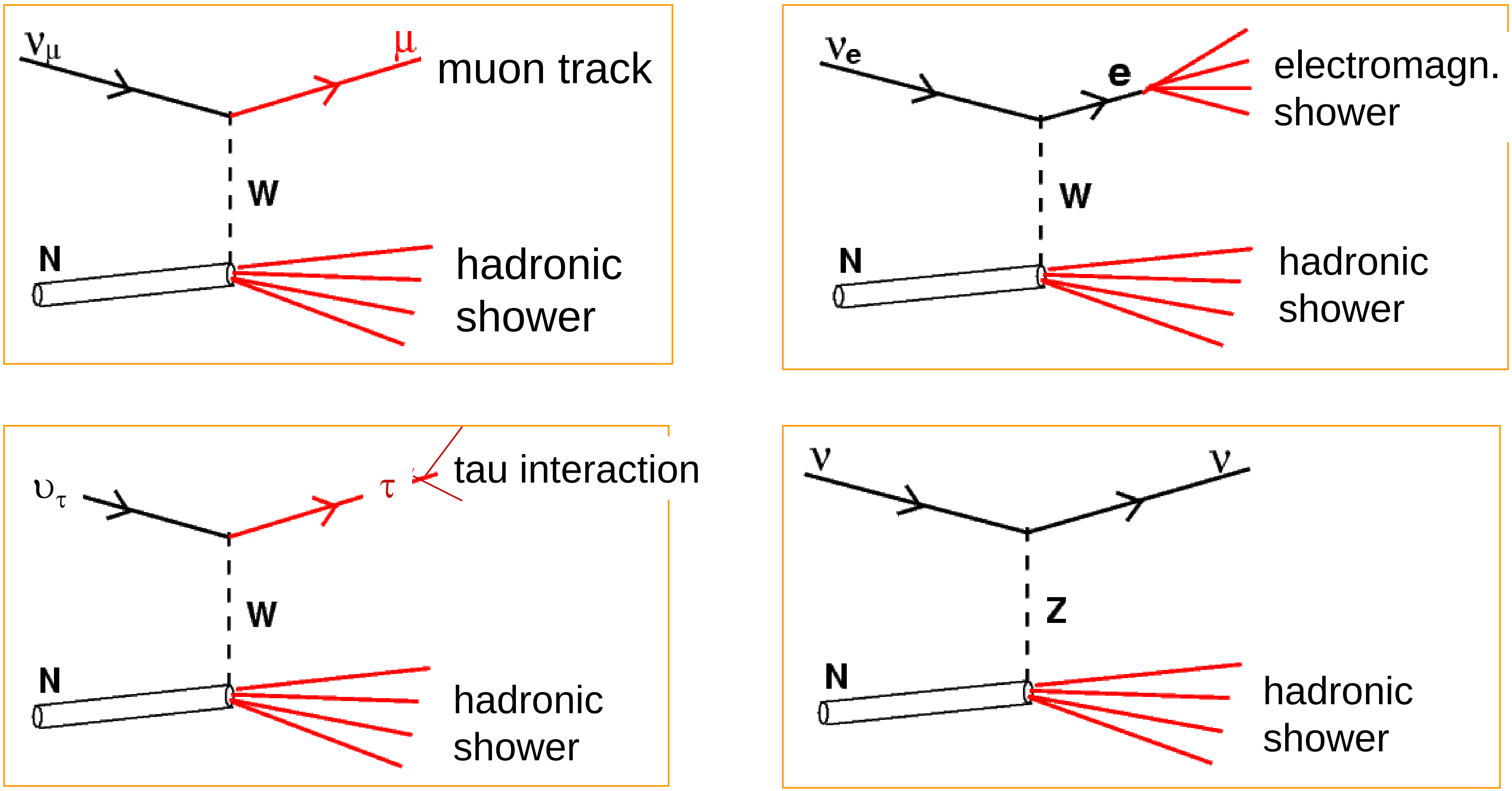


Earth shadowing

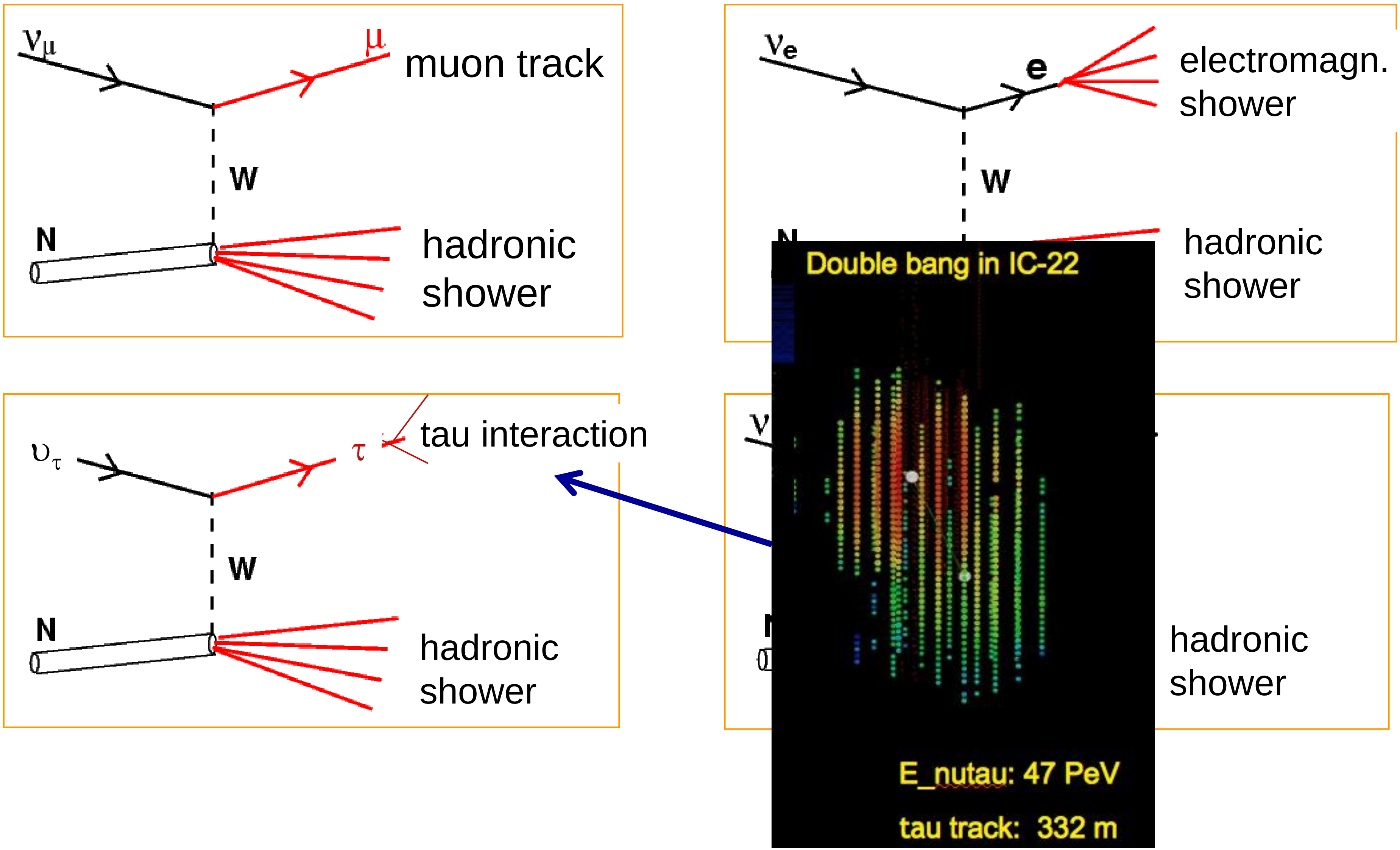
Compare to air shower gamma telescope:

$A_{eff}(\gamma) \sim 10^{10}$ cm²

Muon tracks and cascades

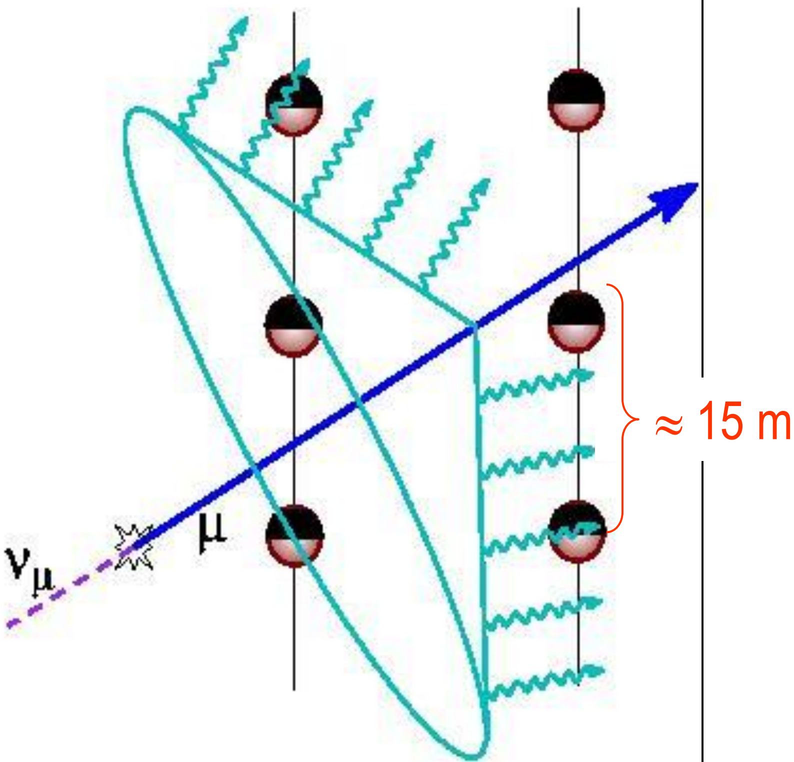


Muon tracks and cascades



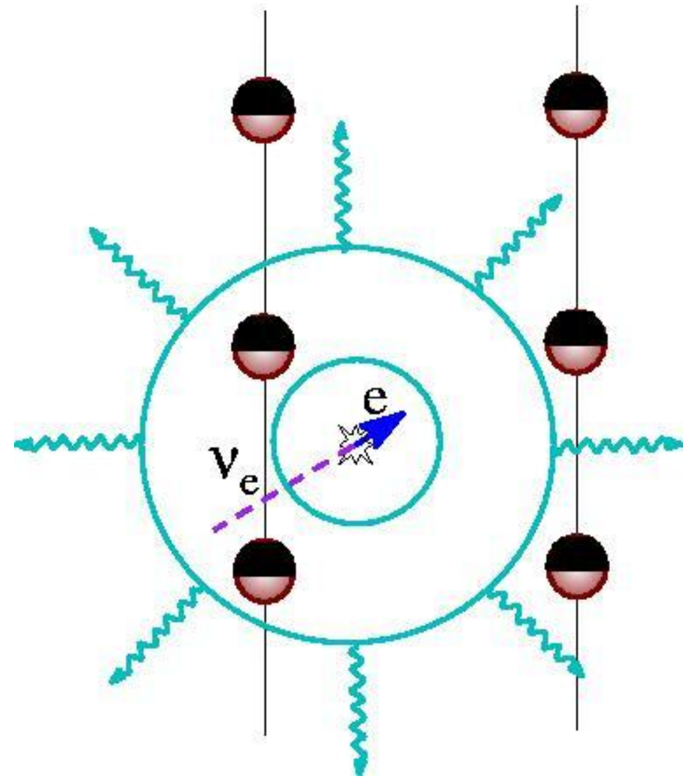
Muon tracks and cascades

O(km) long muon tracks



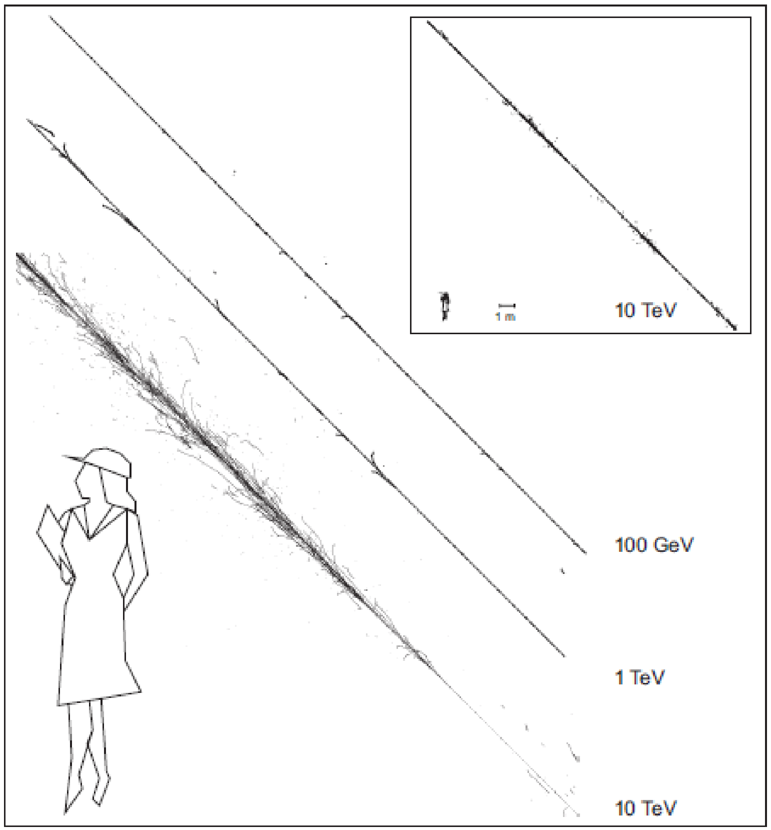
direction determination
by Cherenkov light timing
Cherenkov angle in water ~ 42°

O(10m) Cascades, ν_e ,ν_τ , Neutral Current

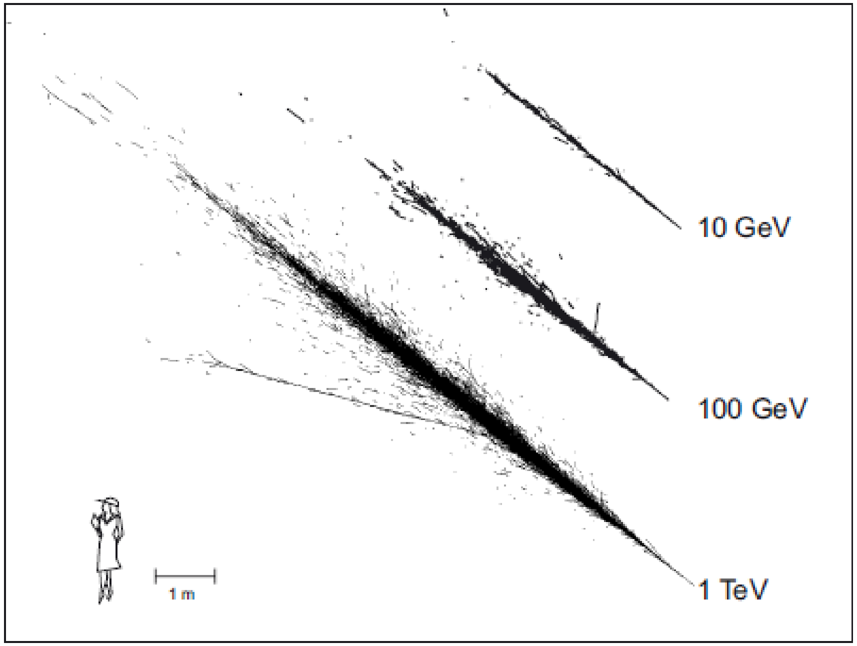


Muon tracks and cascades

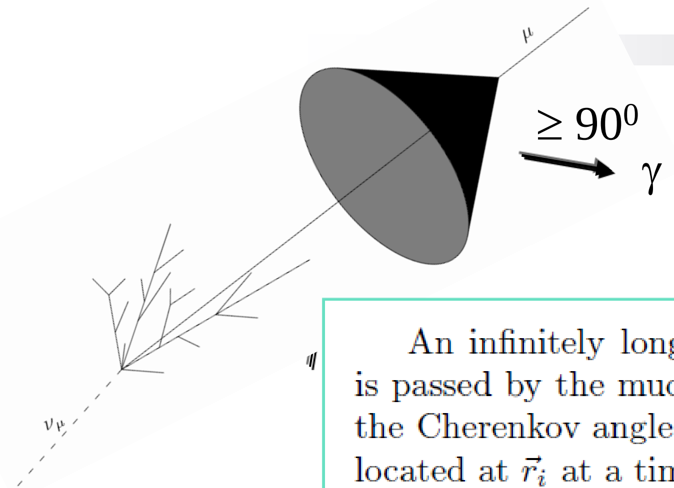
muons: dE/dx



cascades: E (contained events)



Muon track reconstruction



Number of Cherenkov photons from a minimum ionizing particle

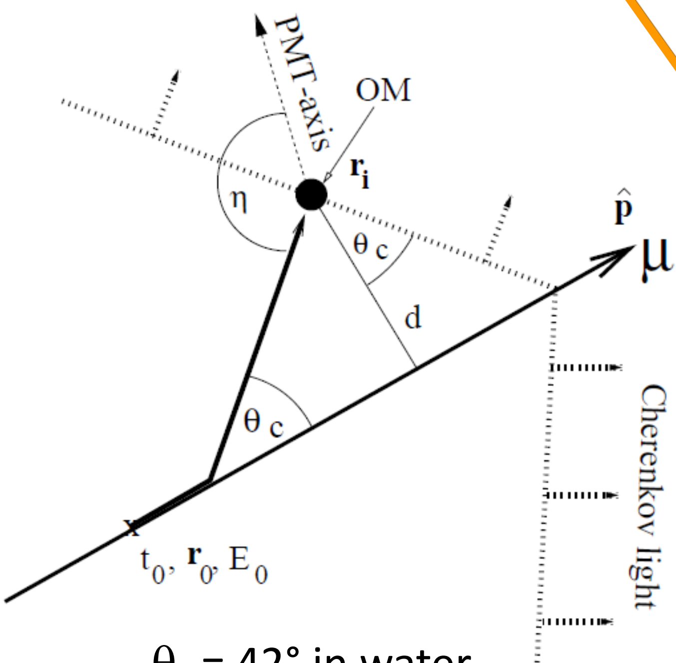
$$\frac{dN_\gamma}{d\lambda dx} = \frac{2\pi\alpha^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n_p^{\ 2}}\right) \int_{300nm}^{600nm} \approx 335/\text{cm}$$

An infinitely long muon track can be described by an arbitrary point $\vec{r}_0$ on the track which is passed by the muon at time t_0, with a direction $\vec{p}$ and energy E_0. Photons propagating under the Cherenkov angle θ_c and on a straight path ("direct photons") are expected to arrive at PM i located at $\vec{r}_i$ at a time

$$t_{geo} = t_0 + \frac{\vec{p} \cdot (\vec{r}_i - \vec{r}_0) + d \cdot \tan\theta_c}{c}$$

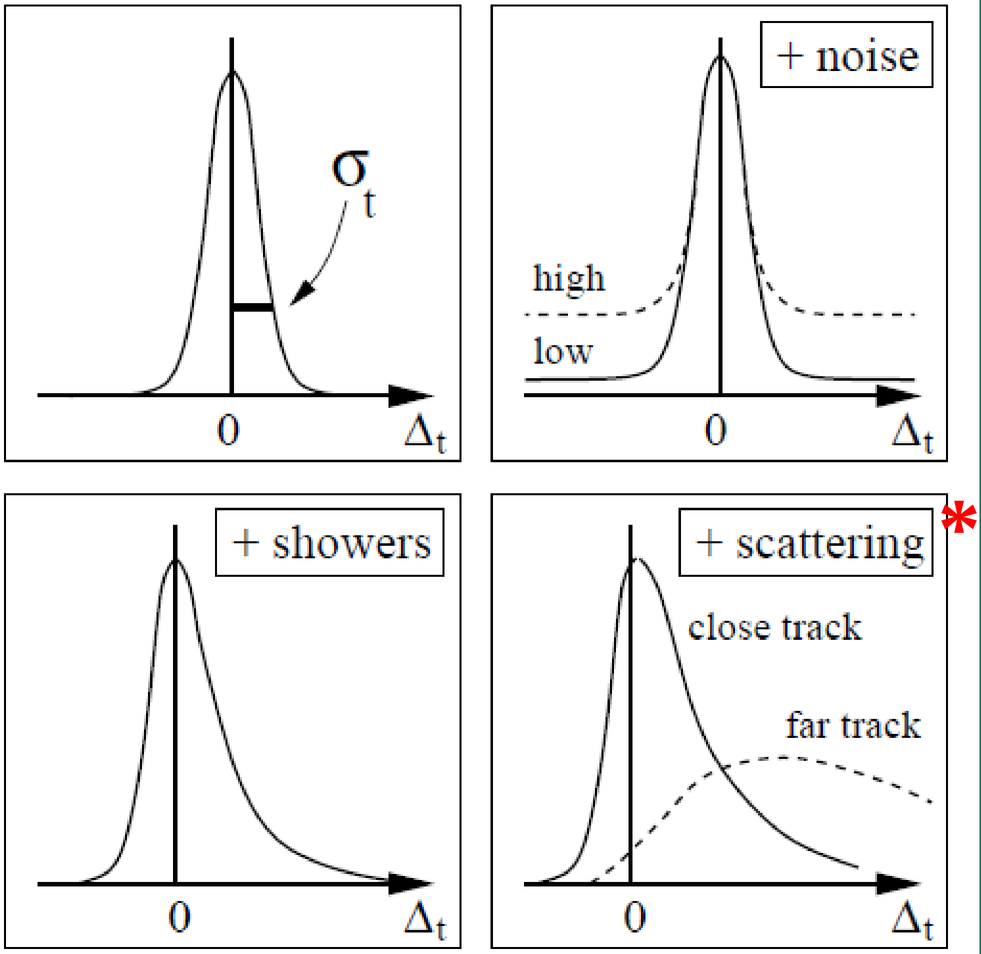
Then minimize:

$$t_{res} = t_{hit} - t_{geo}.$$



θ_c = 42° in water

Reconstruction: t_{res} distributions



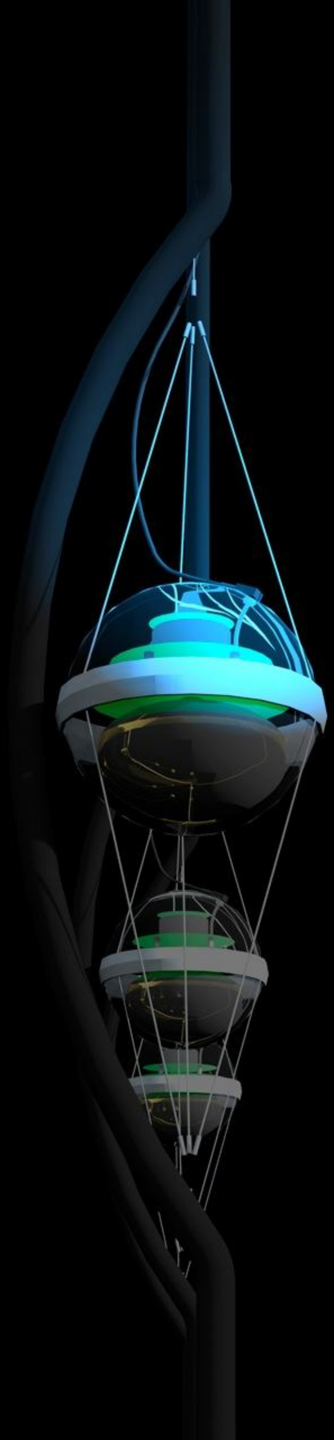
- Time residuals not Gaussian distributed
- Have to cut away noise hits
- Need special propability density fuction which describe the delayed arrive due to light emission of showers (compated to muons) and of light scattering (small in water, strong in ice)

$$\chi^2 = \sum_{i=1}^{N} \frac{(t_i - t_{i0})^2}{\sigma_i^2}$$

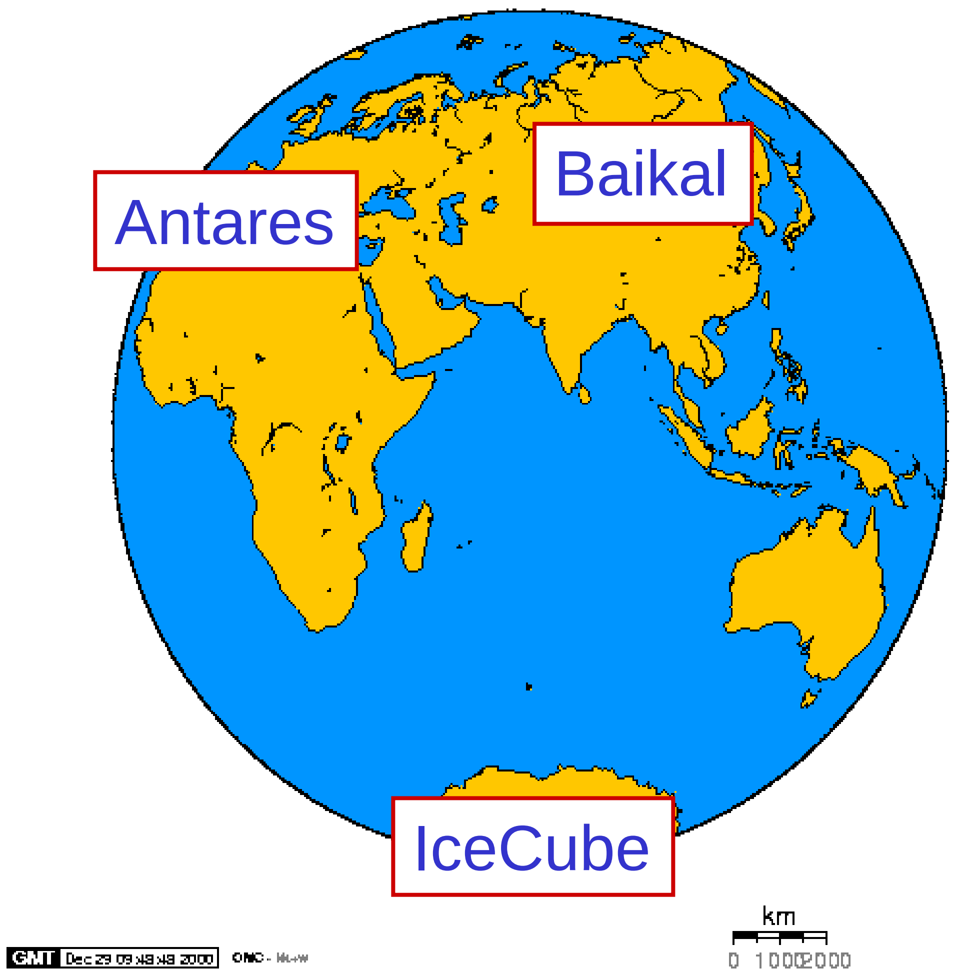
⇓

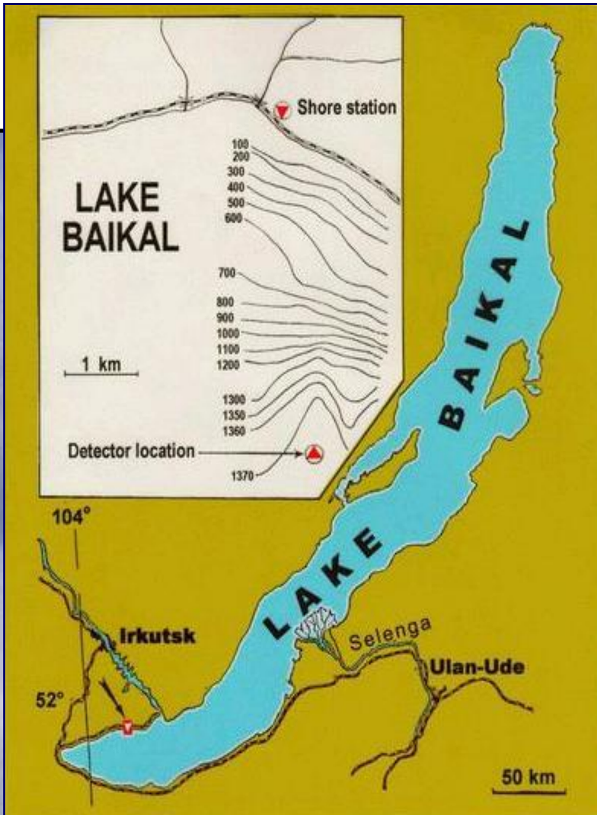
$$L = f(t_i, t_{i0}, \sigma_i, dist, \lambda_{abs}, \lambda_{scatt})$$

*light scattering is strong in ice!



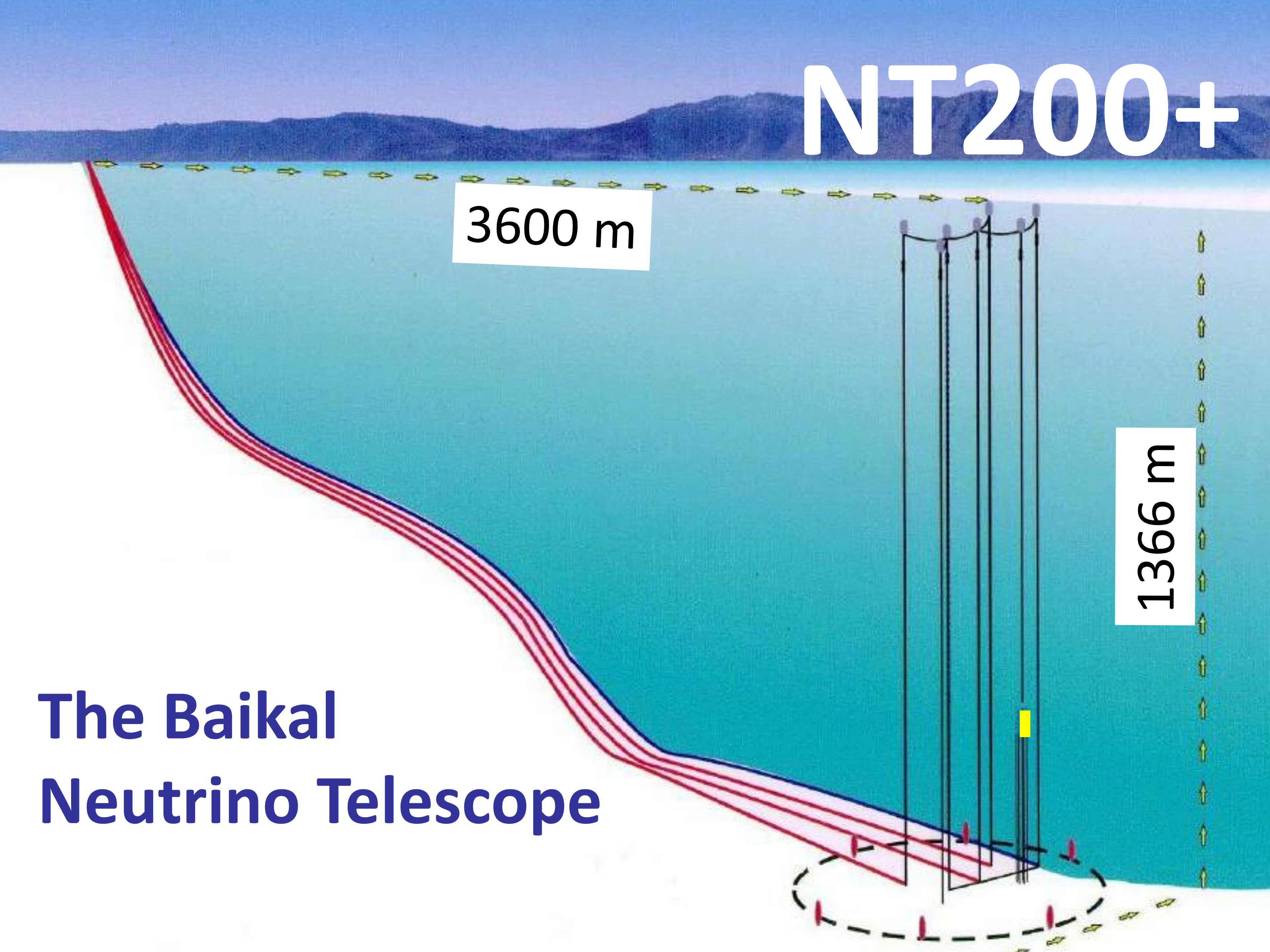
The devices:
From Baikal to IceCube

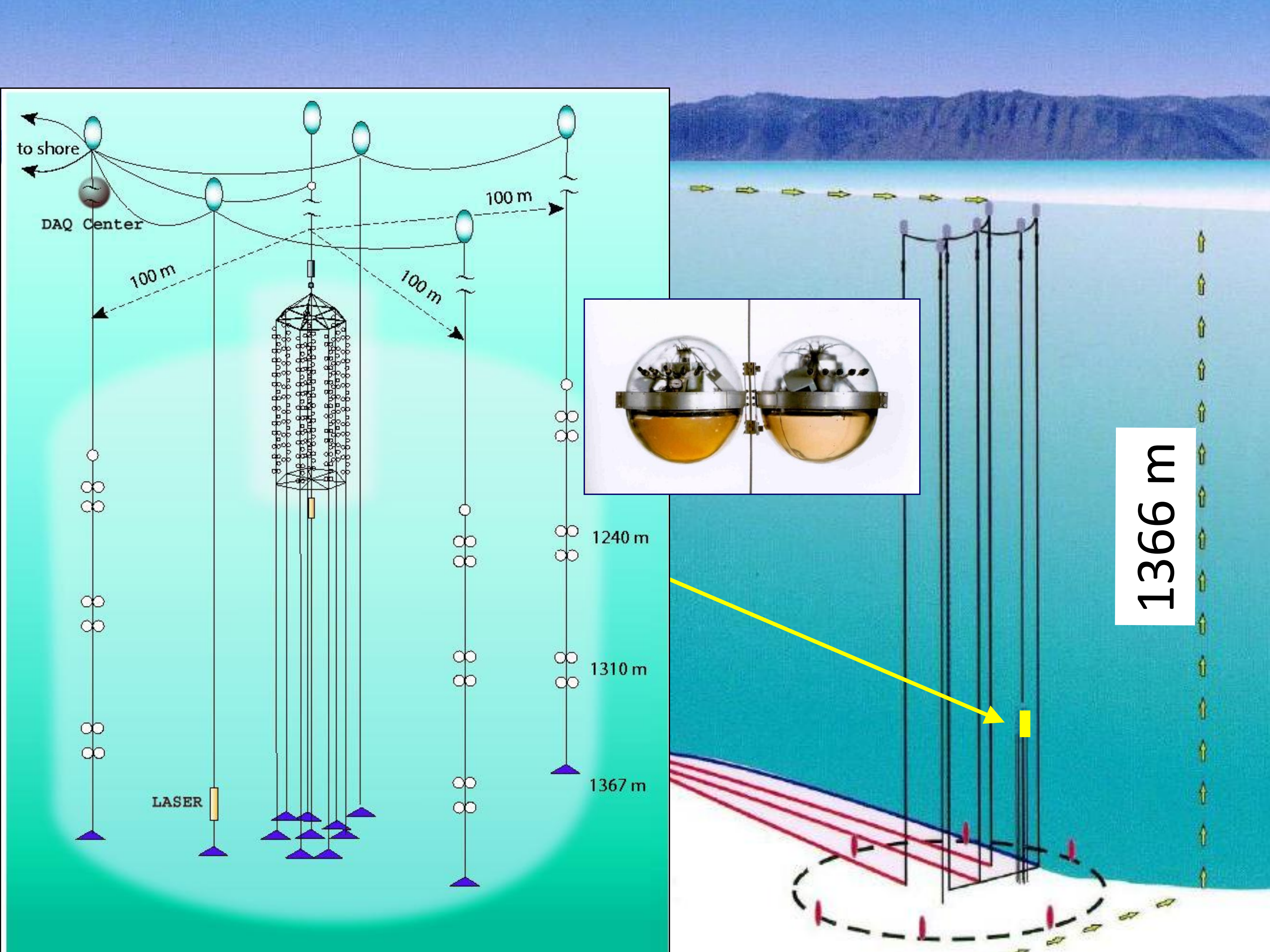

Antares
Baikal
IceCube
km
0 1000 2000

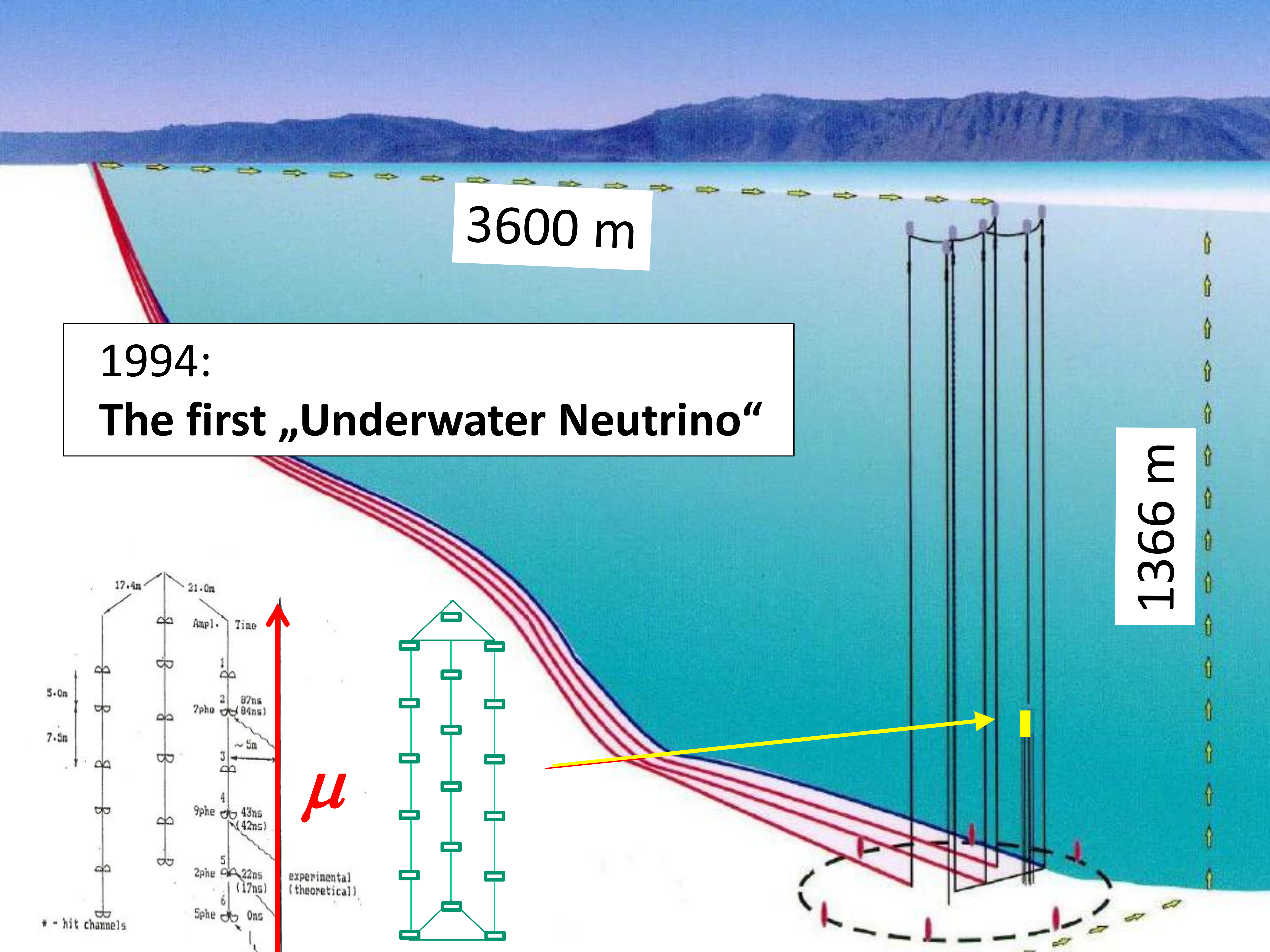


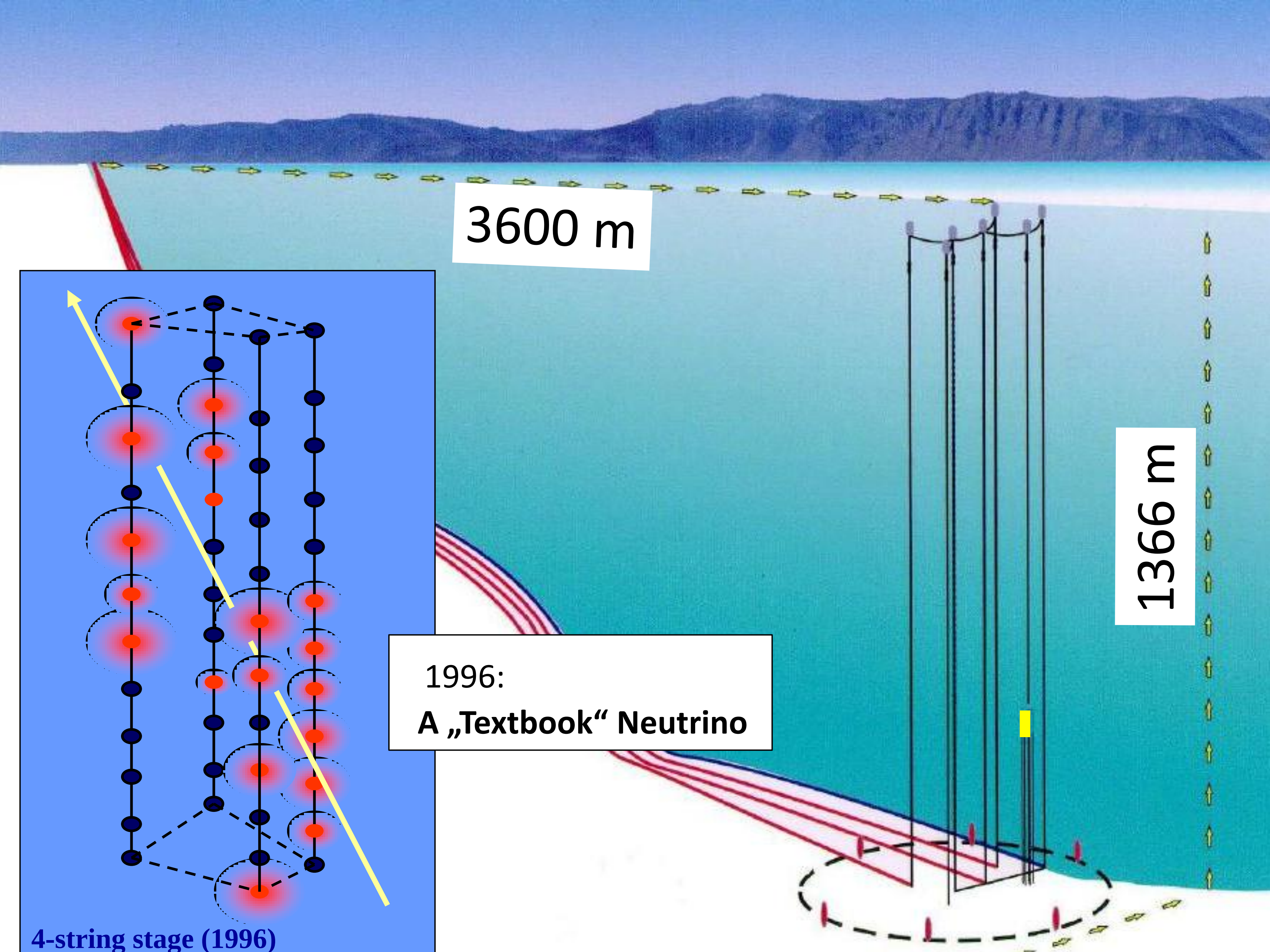
The Baikal Neutrino Telescope

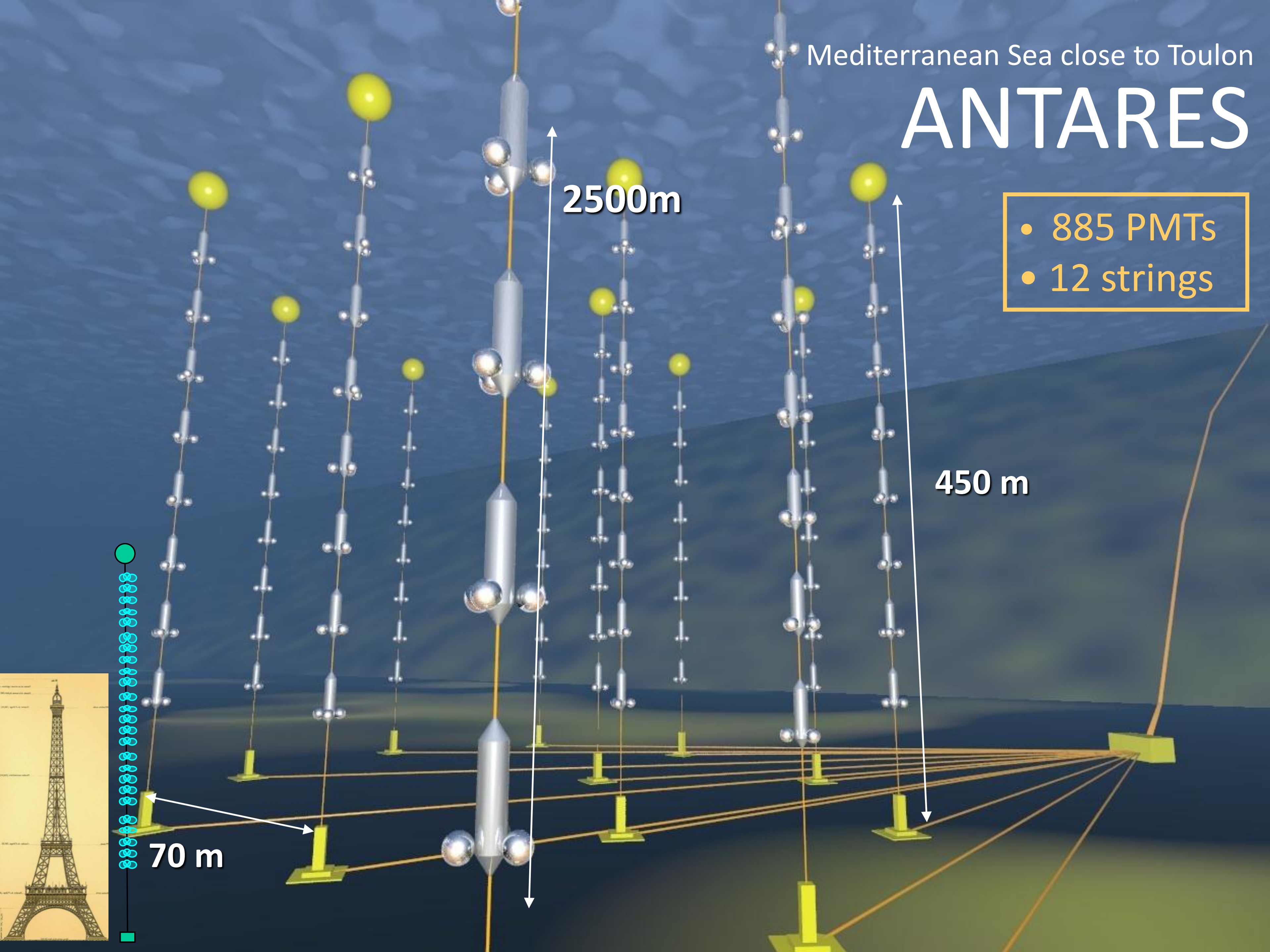
(start of the project 1981)


NT200+
3600 m
1366 m
The Baikal
Neutrino Telescope

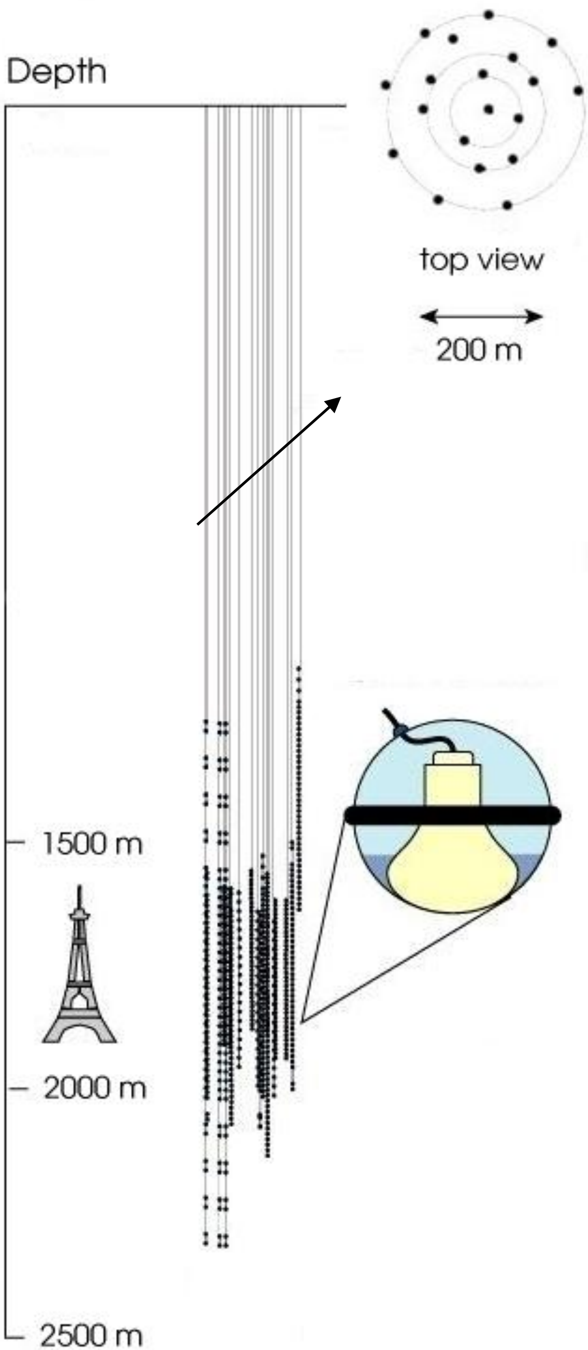

to shore
DAQ Center
100 m
100 m
100 m
LASER
1240 m
1310 m
1367 m
1366 m


3600 m
1994:
The first „Underwater Neutrino“
1366 m
17.4m
21.0m
Ampl.
Time
5.0m
7.5m
7phe
87ns
(84ns)
~5m
9phe
43ns
(42ns)
2phe
22ns
(17ns)
5phe
0ns
experimental
(theoretical)
* - hit channels
μ

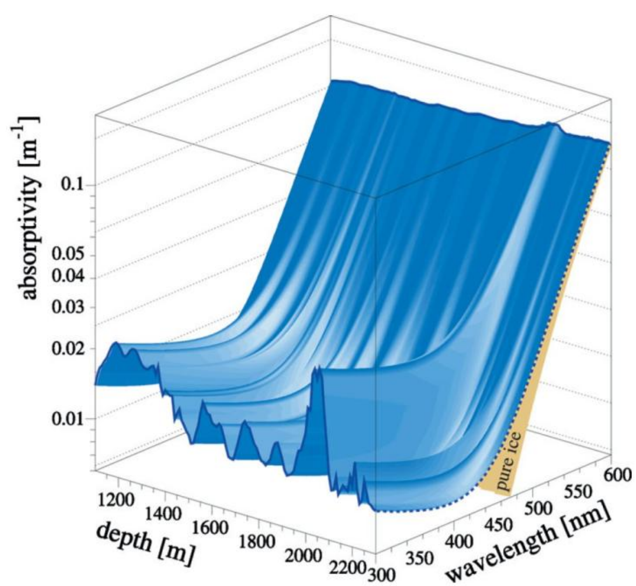

3600 m
1366 m
4-string stage (1996)
1996:
A „Textbook“ Neutrino

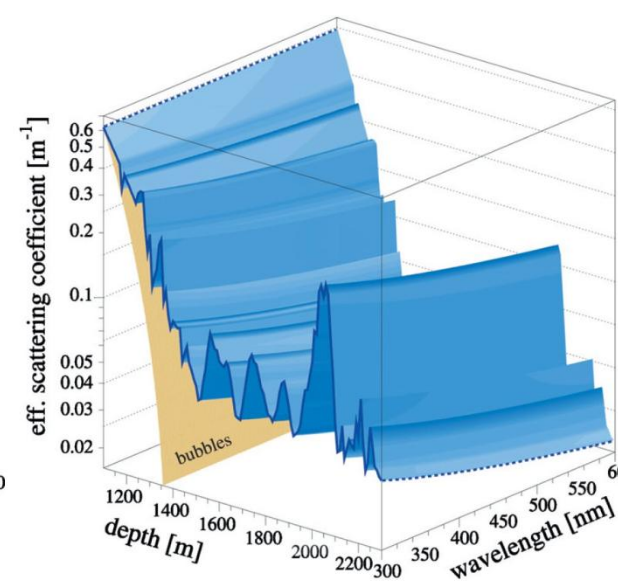

Mediterranean Sea close to Toulon
ANTARES
• 885 PMTs
• 12 strings
2500m
450 m
70 m

AMANDA-II

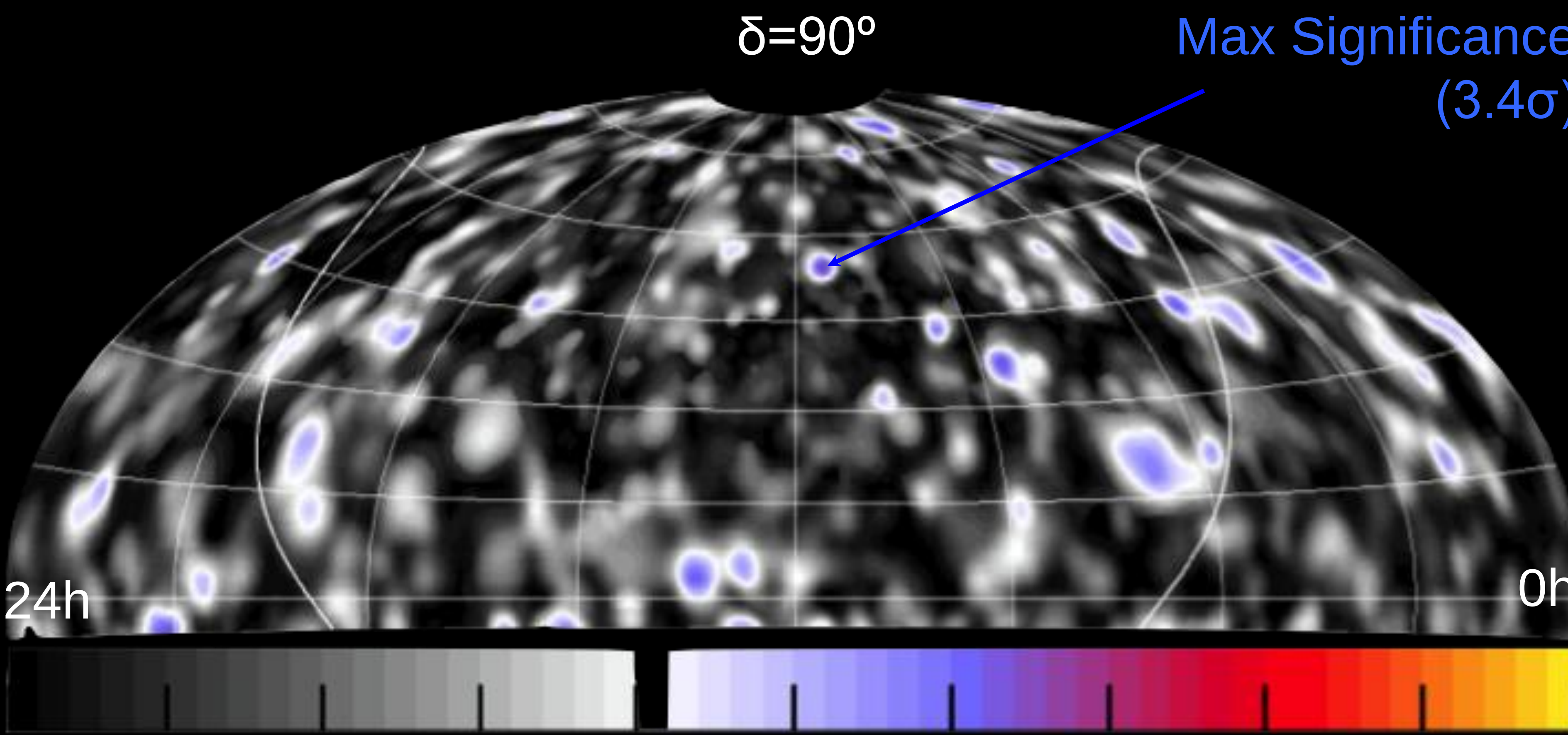


- 19 strings
- 677 optical modules with 8´´ PMTs
- Construction January 1996 – January 2000
- Operated until April 2009





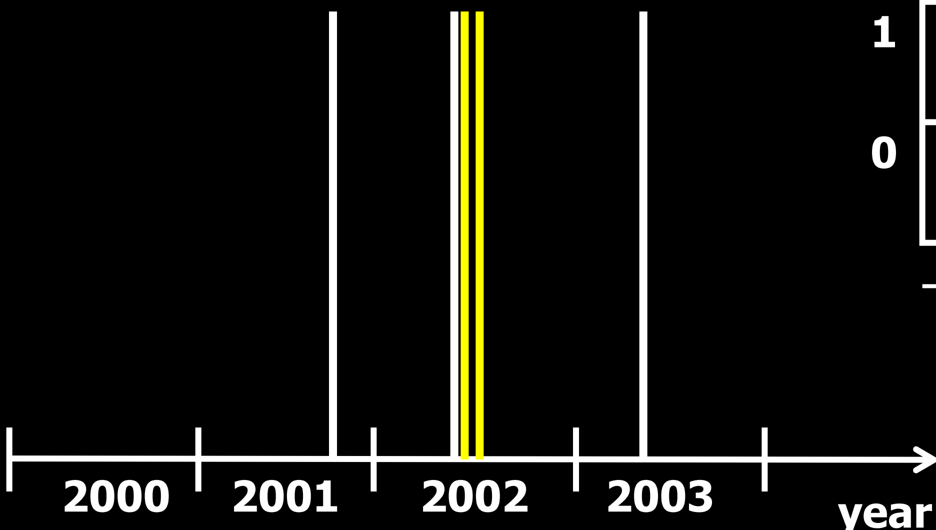
Neutrino Skymap of AMANDA



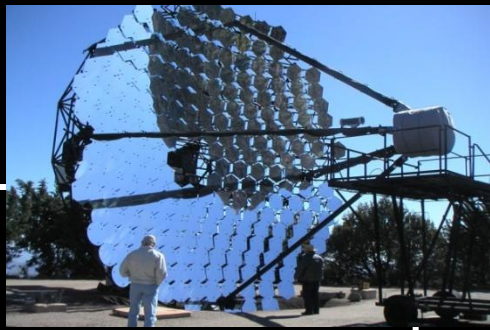
AMANDA, 7 Years, 6595 Neutrinos

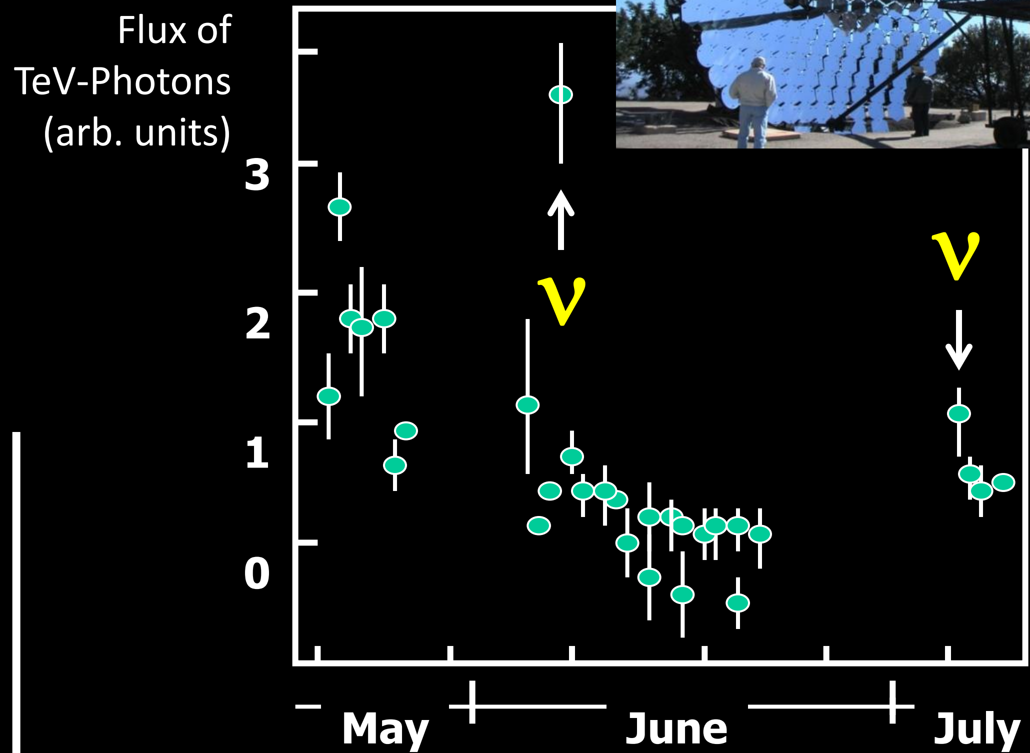
An intriguing event

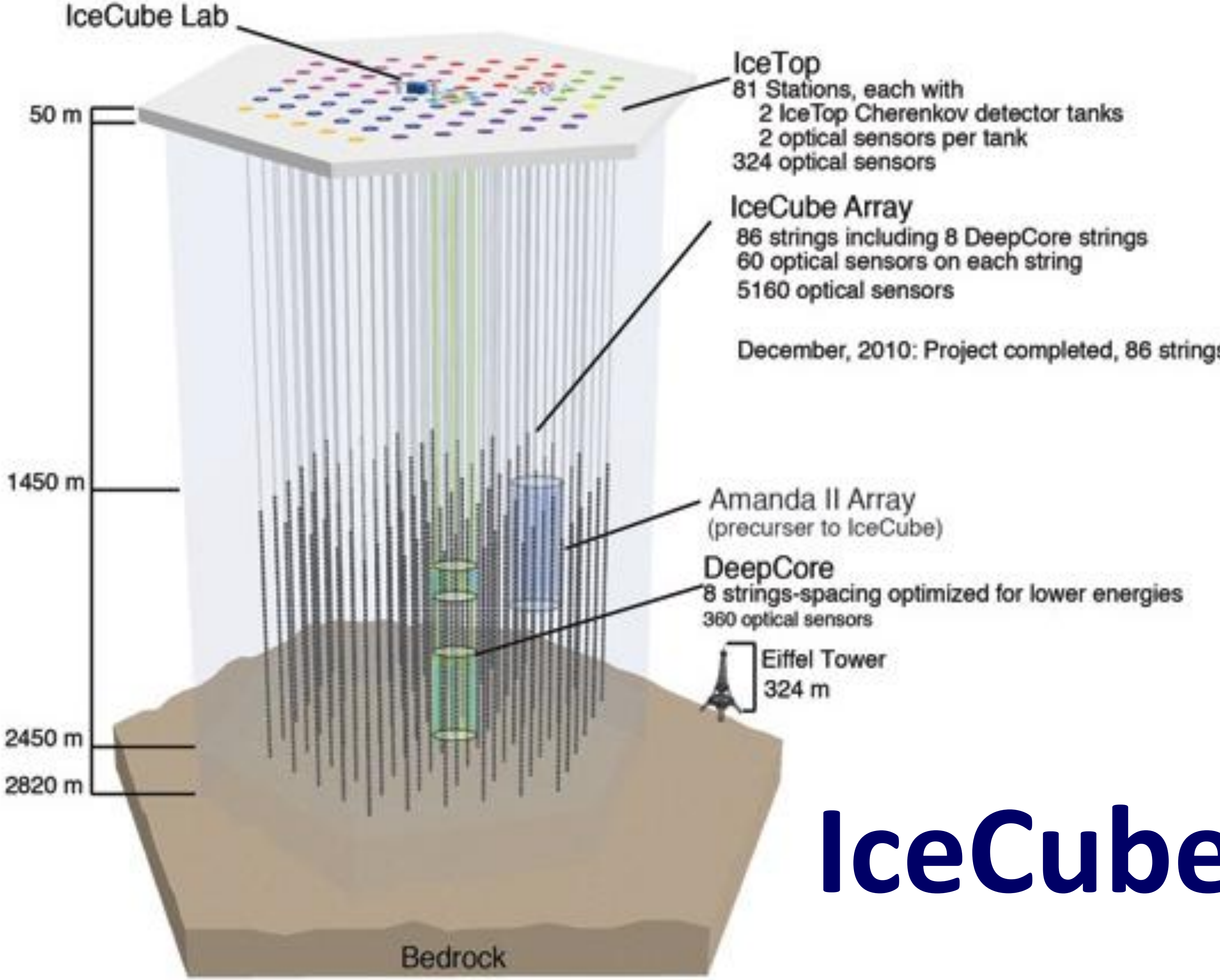
Arrival time of neutrinos from the direction of the AGN 1ES1959+650



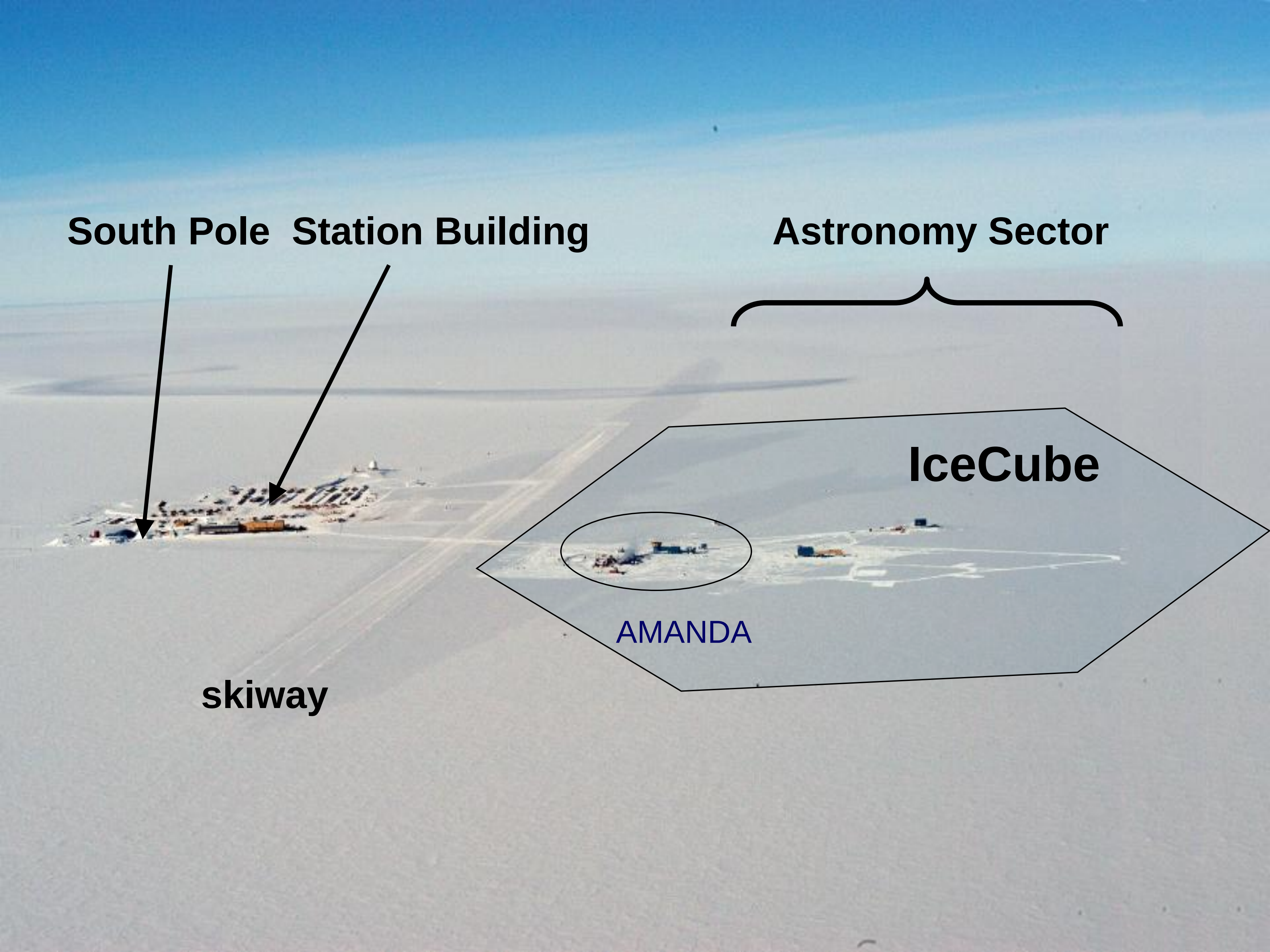
WHIPPLE



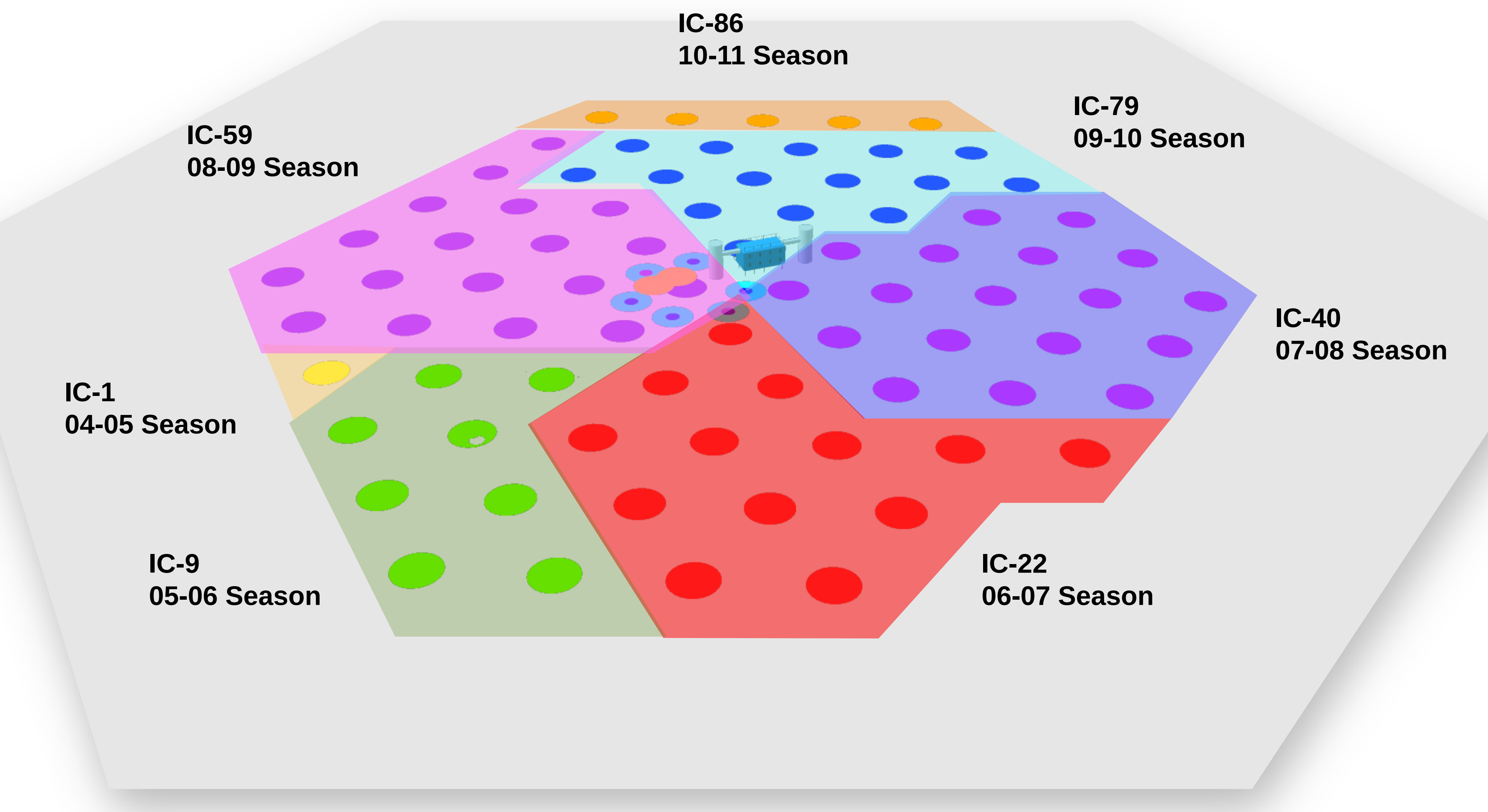



IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
Amanda II Array
(precurser to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
360 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

IceCube


South Pole
Station Building
Astronomy Sector
IceCube
AMANDA
skiway

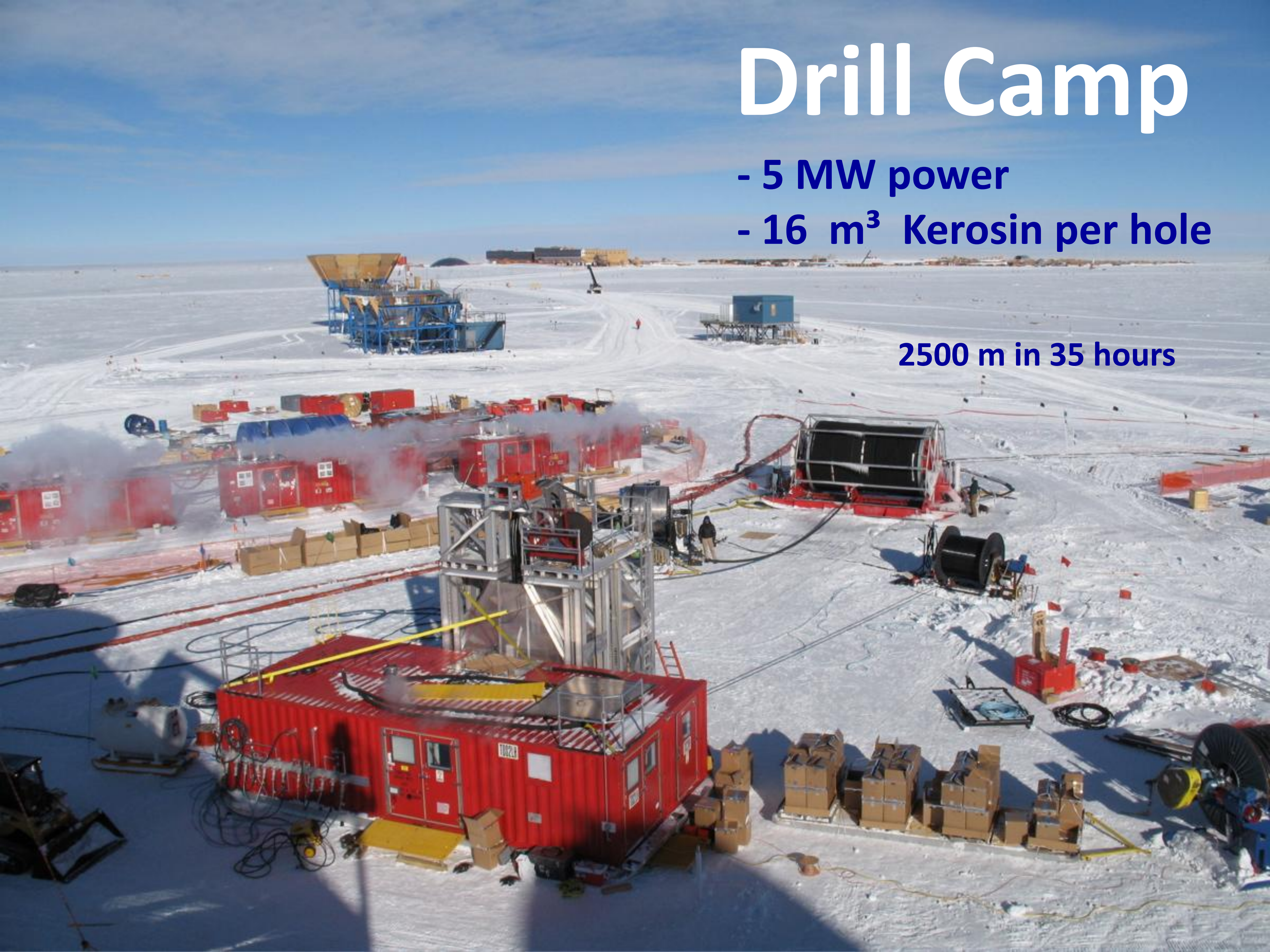
Completed December 18, 2010

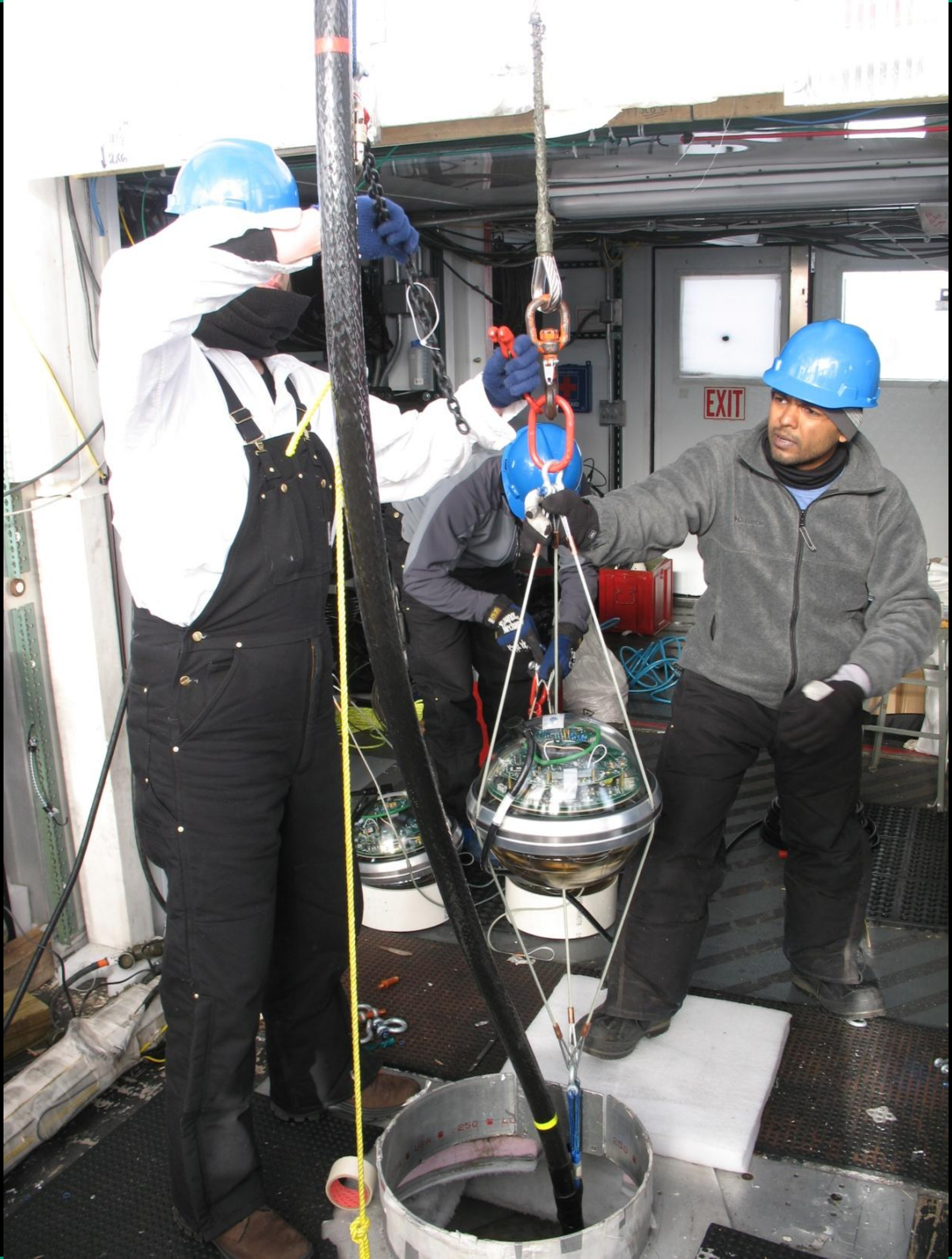


Drill Camp

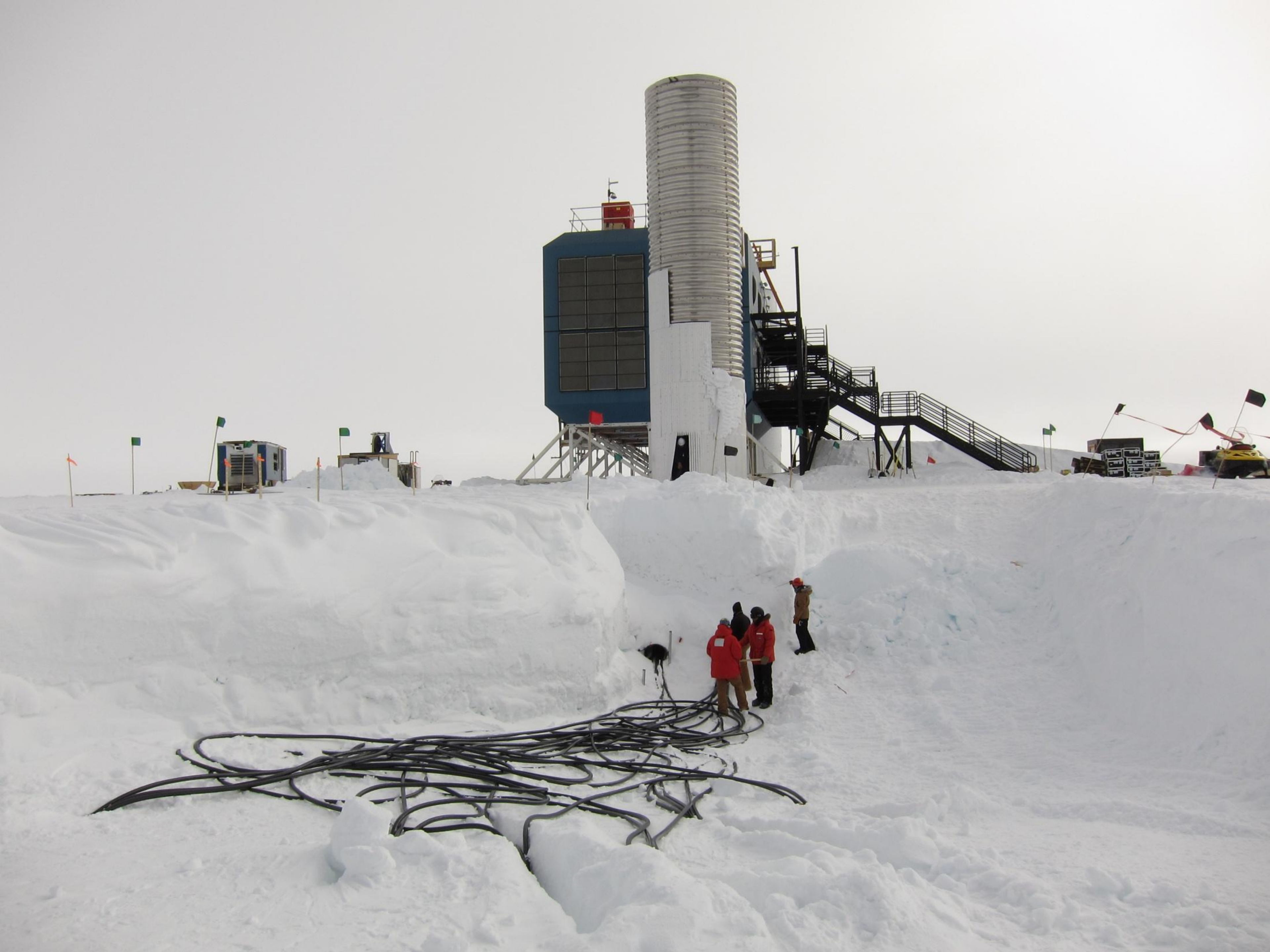
- 5 MW power
- 16 m^3 Kerosin per hole

2500 m in 35 hours

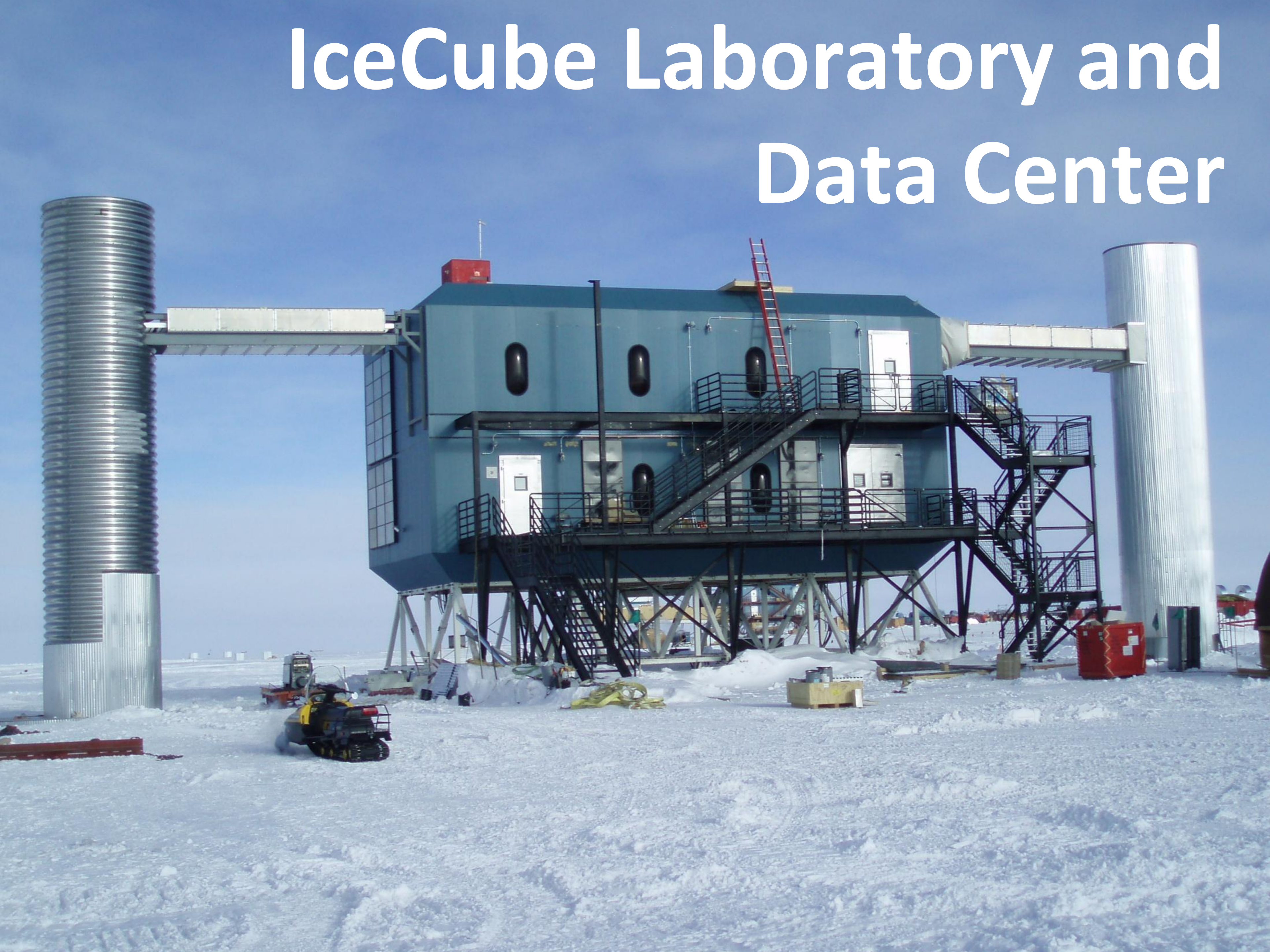



EXIT

The last (86th) string

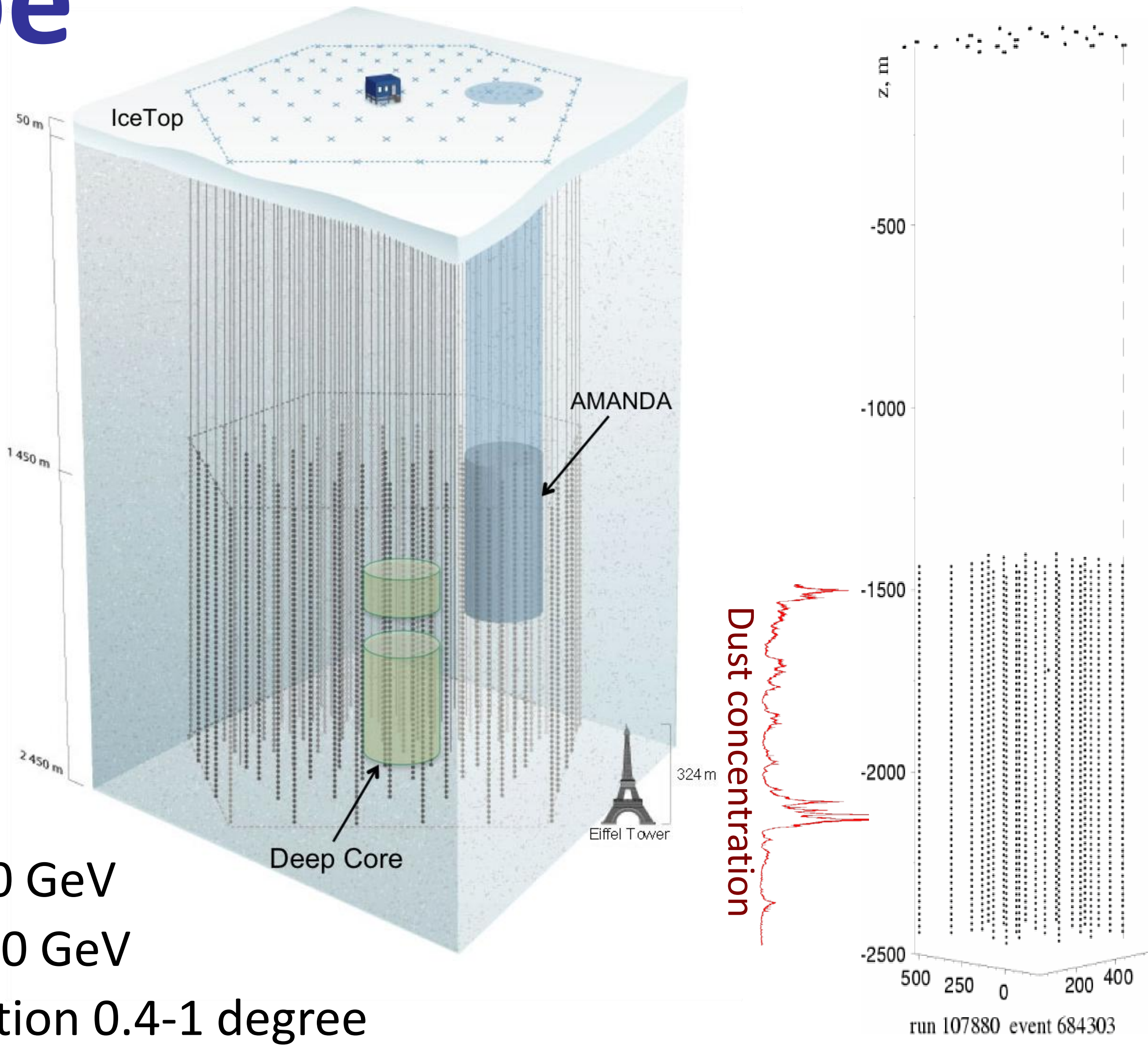


IceCube Laboratory and Data Center




17 racks of computers
Power: 60 kW total for full IceCube
Filtered data sent by satellite

IceCube



- ~220 ν/day
- 1.7×10^8 μ/day
- Threshold:
  - IceCube ~ 100 GeV
  - DeepCore ~ 10 GeV
- Angular resolution 0.4-1 degree

END OF LECTURE 1