Astroparticle Physics 2919/20

Lectures:

04.02.2020 1. Historical introduction, basic properties of cosmic rays
06.02.2020 2. Hadronic interactions and accelerator data
11.02.2020 3. Cascade equations
13.02.2020 4. Electromagnetic cascades
18.02.2020 5. Extensive air showers
20.02.2020 6. Detectors for extensive air showers
27.02.2020 7. High energy cosmic rays and the knee in the energy spectrum of cosmic rays
03.03.2020 8. Radio detection of extensive air showers
05.03.2020 9. Acceleration, astrophysical accelerators and beam dumps
10.03.2020 10. Extragalactic propagation of cosmic rays
12.03.2020 11. Ultra high energy cosmic rays
17.03.2020 12. Astrophysical gamma rays and neutrinos
14.04.2020 13. Neutrino astronomy
12.05.2020 14. Gamma-ray astronomy

http://particle.astro.ru.nl/goto.html?astropart1920

lecture 13
Neutrino astronomy
Gaisser chapter 18

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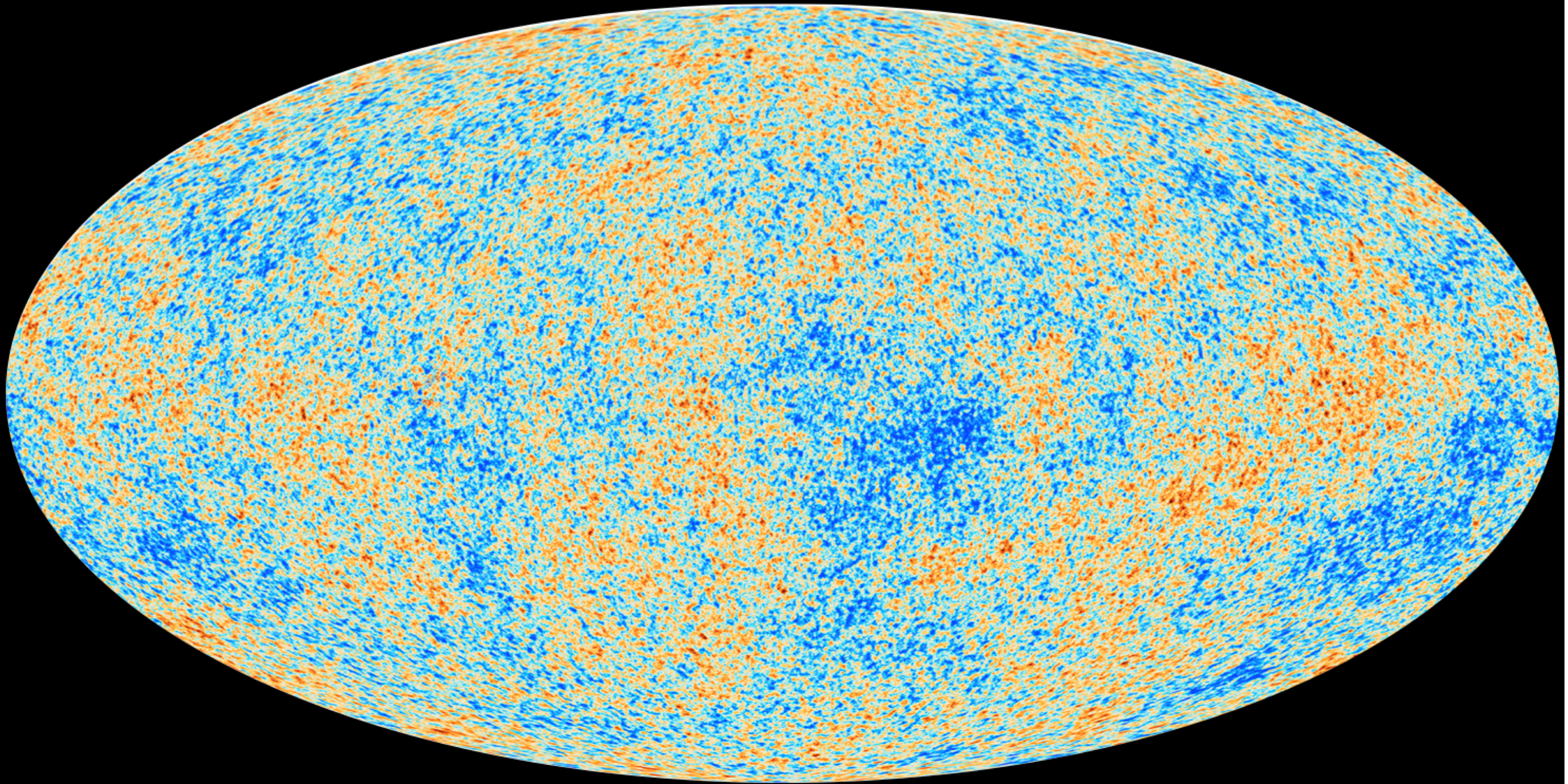
IceCube:
Building a New Window on the Universe

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
  → muon neutrinos through the Earth
  → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

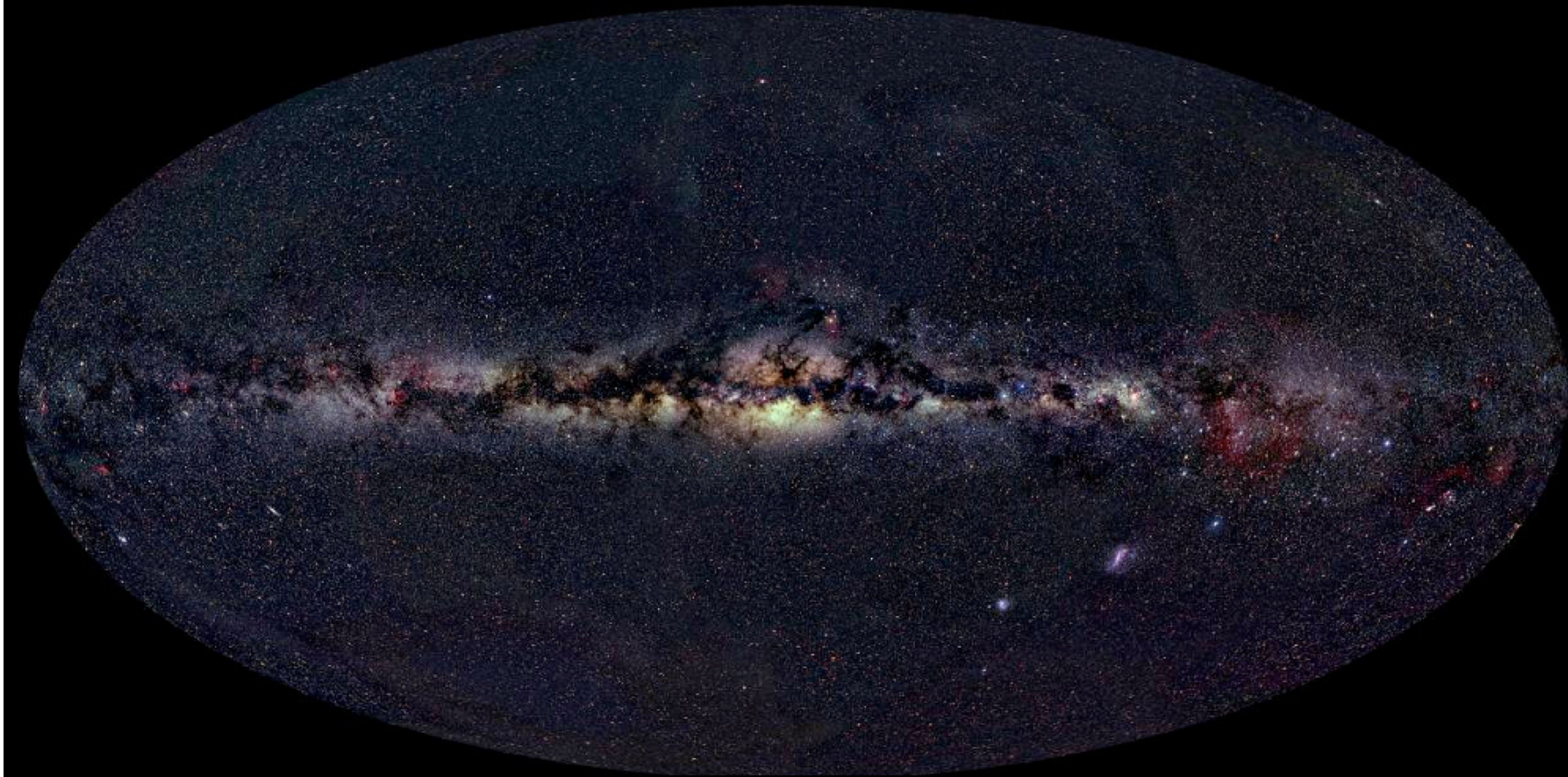
icecube.wisc.edu

Cosmic Horizons – Microwave Radiation
380.000 years after the Big Bang



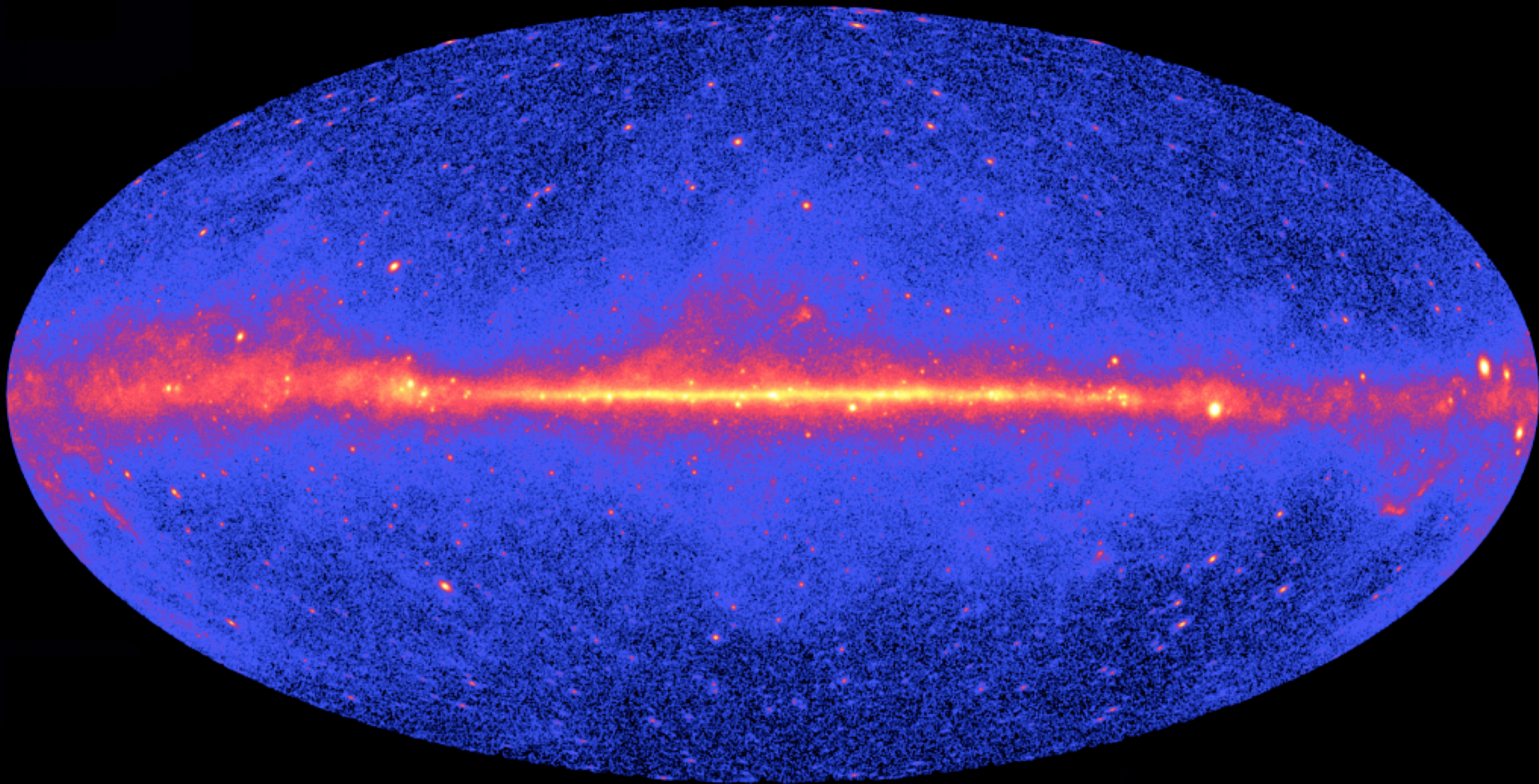
wavelength = 10^{-3} m ⟺ energy = 10^{-4} eV

Cosmic Horizons – Optical Sky



wavelength = 10^{-6} m $\Leftrightarrow$ energy = 1 eV

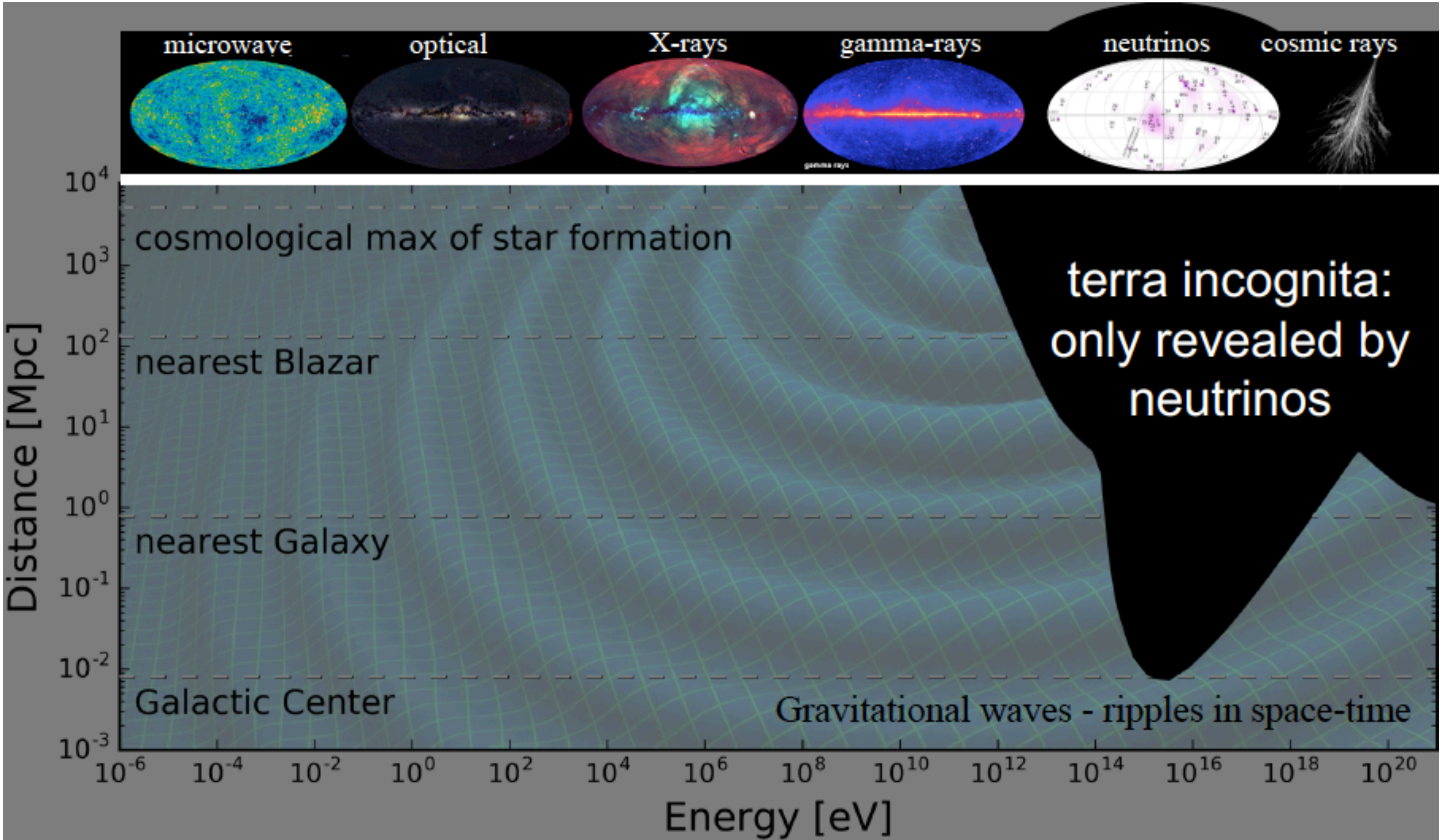
Cosmic Horizons – Gamma Radiation



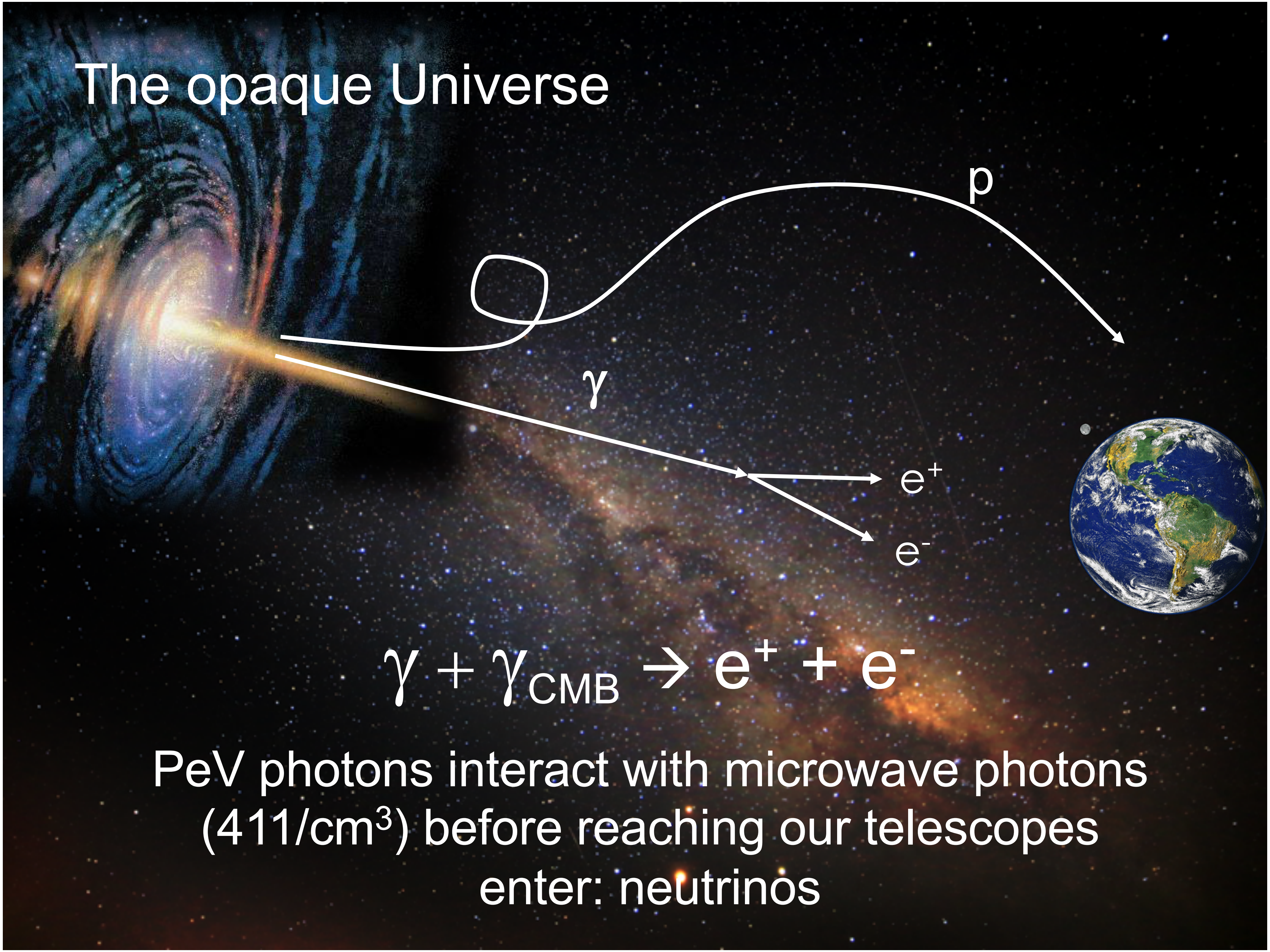
wavelength = 10^{-15} m ⇔ energy = 1 GeV

Cosmic Horizons – Gamma Radiation

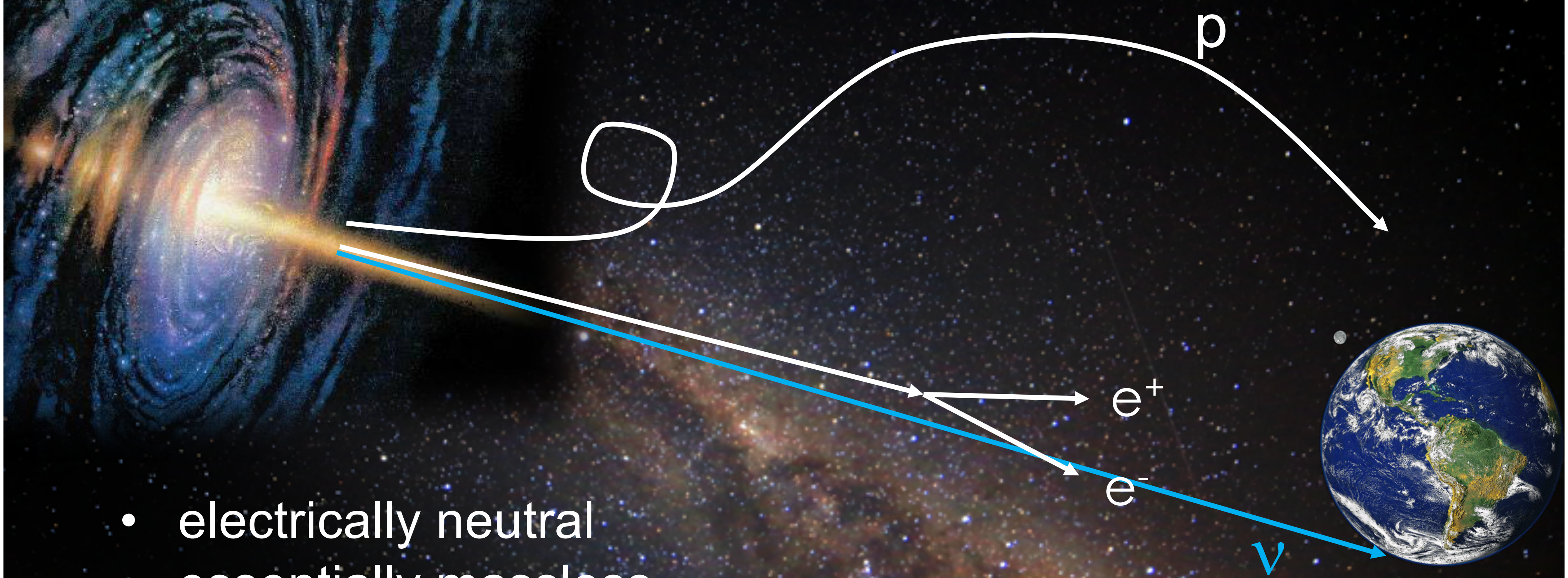
wavelength = 10^{-21} m ⟺ energy = 10^{3} TeV



- 20% of the Universe is opaque to the EM spectrum
- non-thermal Universe powered by cosmic accelerators
- probed by gravity waves, neutrinos and cosmic rays

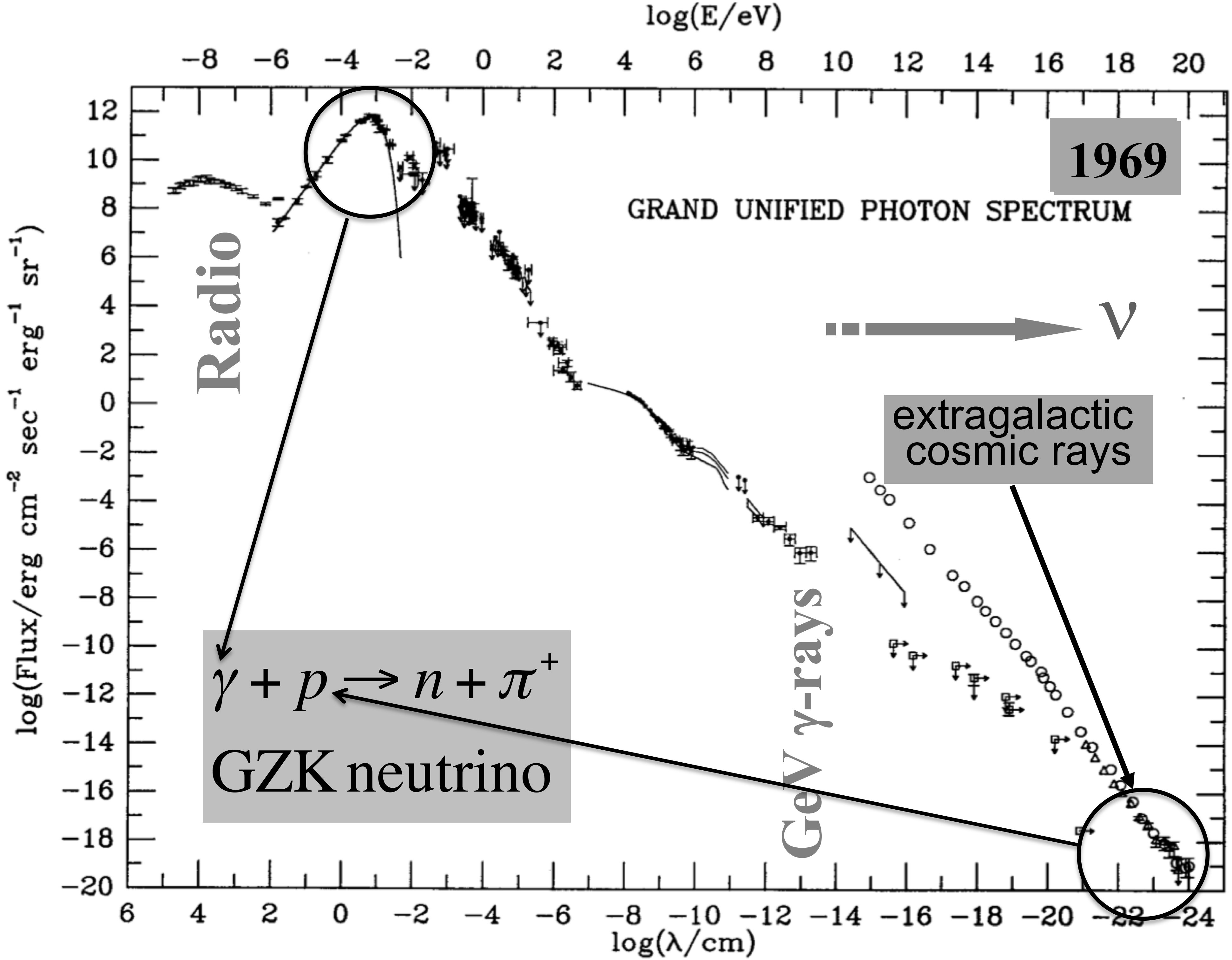

The opaque Universe
p
γ
e+
e-
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
PeV photons interact with microwave photons
(411/cm^3) before reaching our telescopes
enter: neutrinos

Neutrinos? Perfect Messenger



- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays

- … but difficult to detect: how large a detector?



log(E/eV)
1969
GRAND UNIFIED PHOTON SPECTRUM
Radio
ν
extragalactic cosmic rays
$\gamma + p \longrightarrow n + \pi^+$
GZK neutrino
GeV γ-rays
log(Flux/erg cm⁻² sec⁻¹ erg⁻¹ sr⁻¹)
log(λ/cm)

cosmic rays interact with the microwave background

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

cosmic rays disappear, neutrinos with EeV (10^6 TeV) energy appear

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

1 event per cubic kilometer per year

...but it points at its source!

nonthermal universe: cosmic accelerators

- accelerator must contain the particles

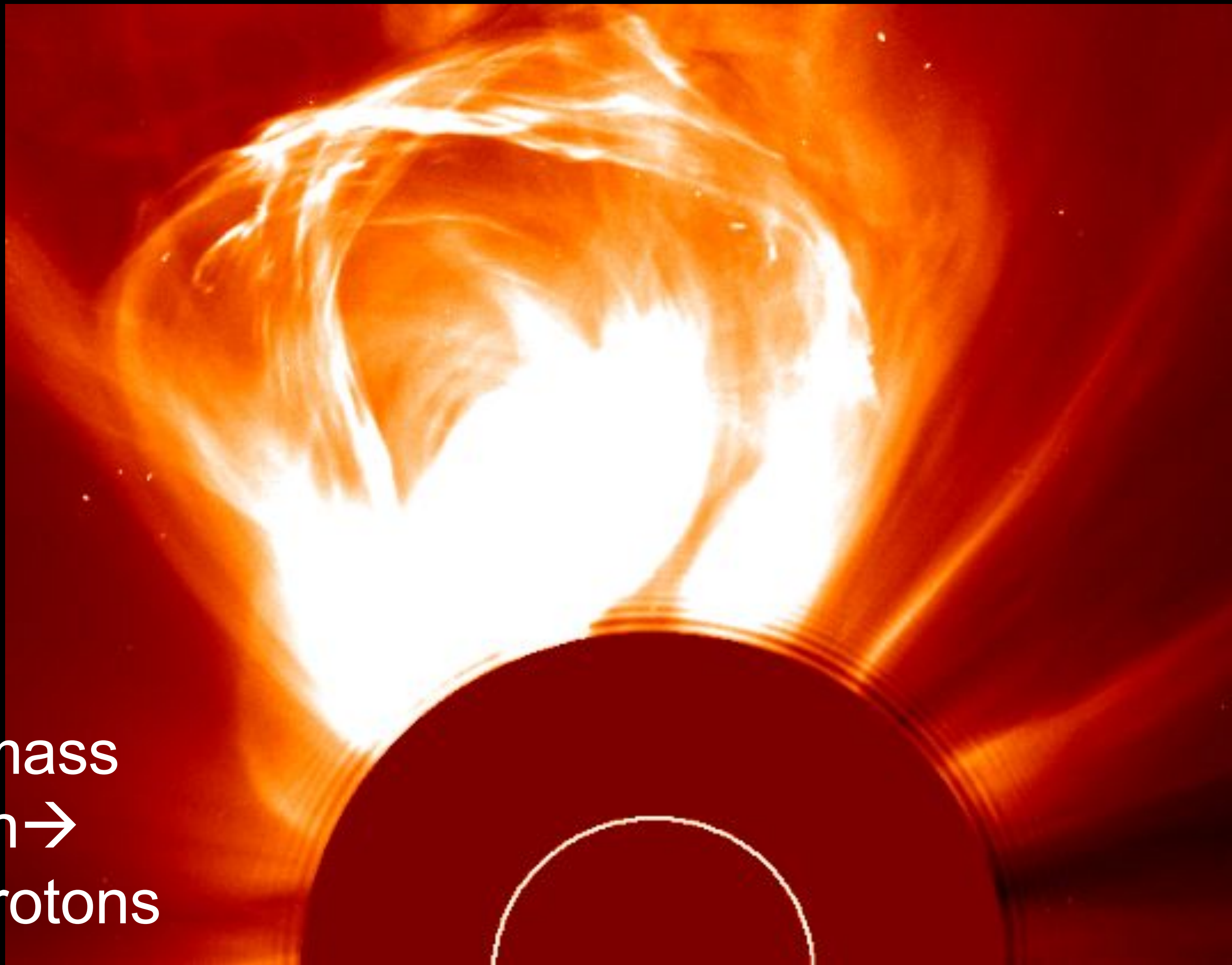
$$R_{gyro} \left(= \frac{E}{\mathrm{v} q B}\right) \leq R$$

$$E \leq \mathrm{v}\, qBR$$

challenges of cosmic ray astrophysics:

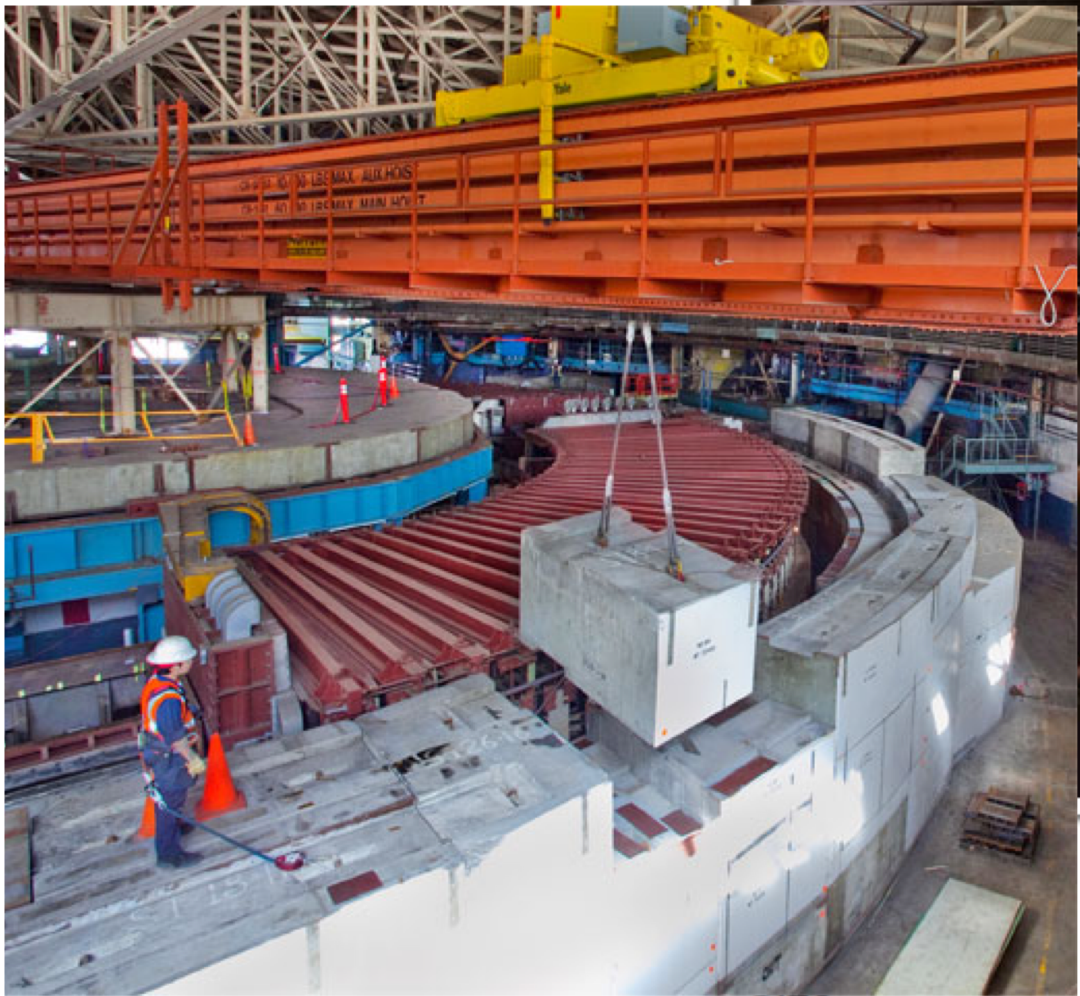
- dimensional analysis, difficult to satisfy
- accelerator luminosity is high as well

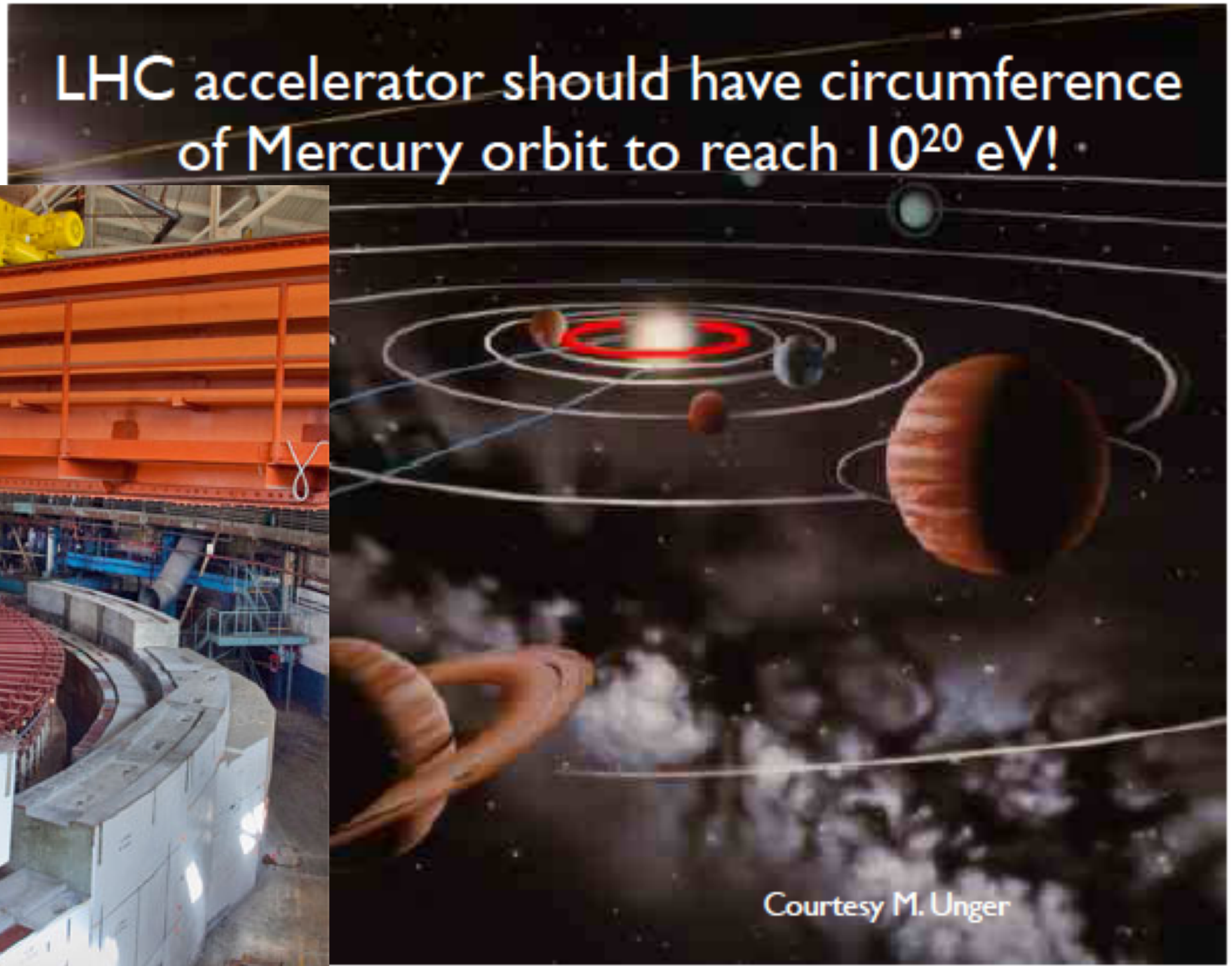
the sun constructs an accelerator

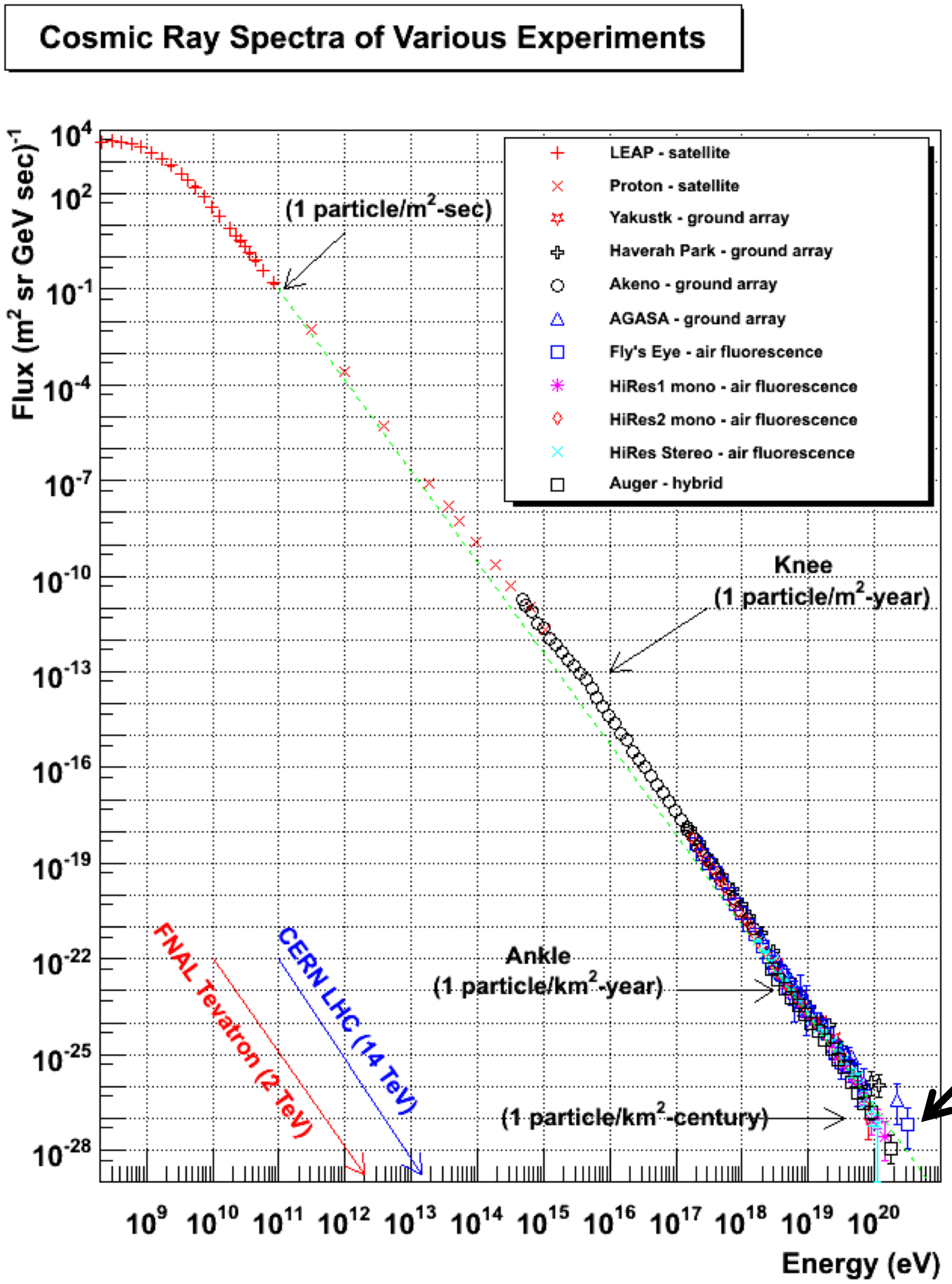


coronal mass ejection→ 10 GeV protons

accomodating energy and luminosity are challenging



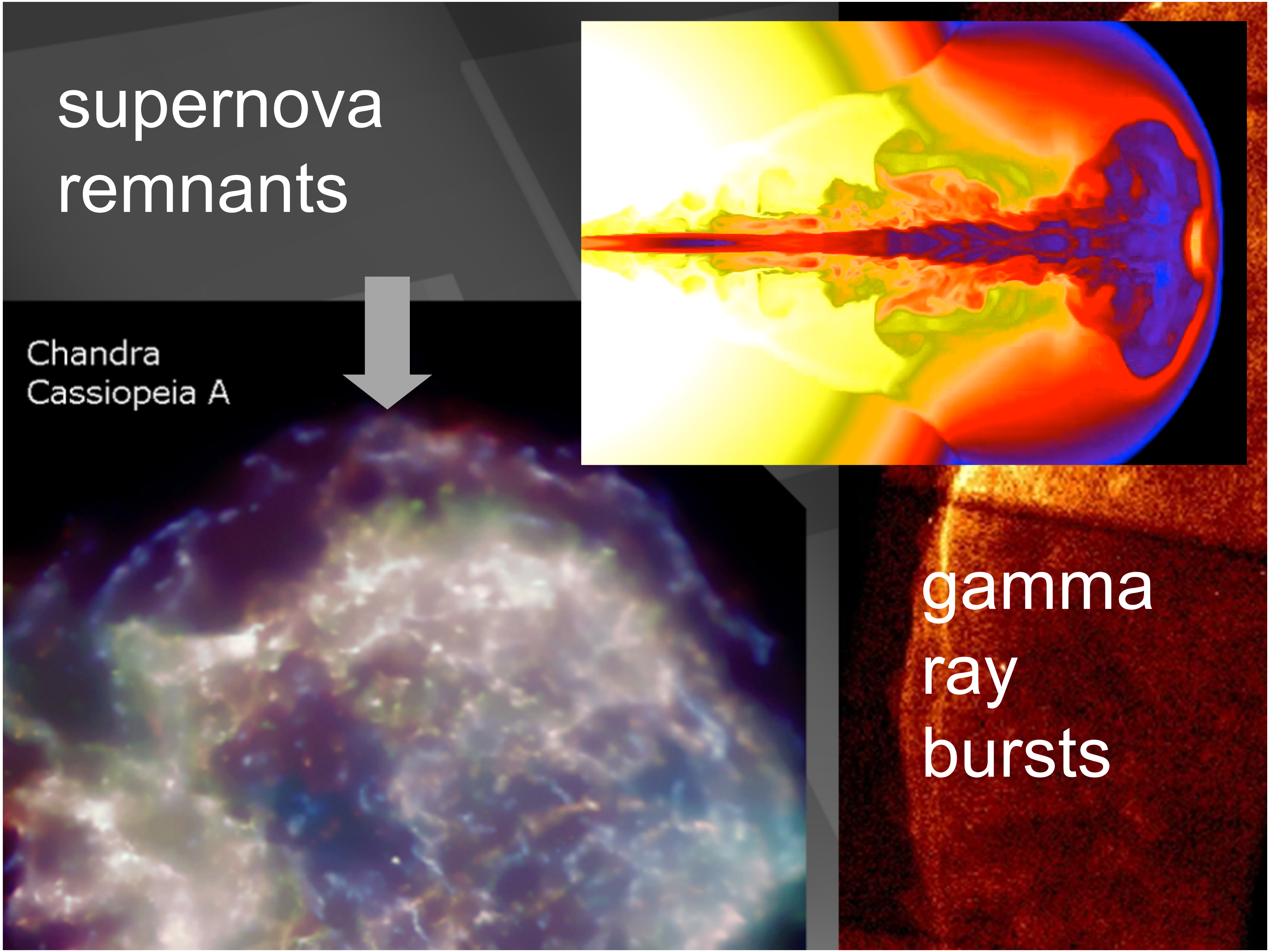


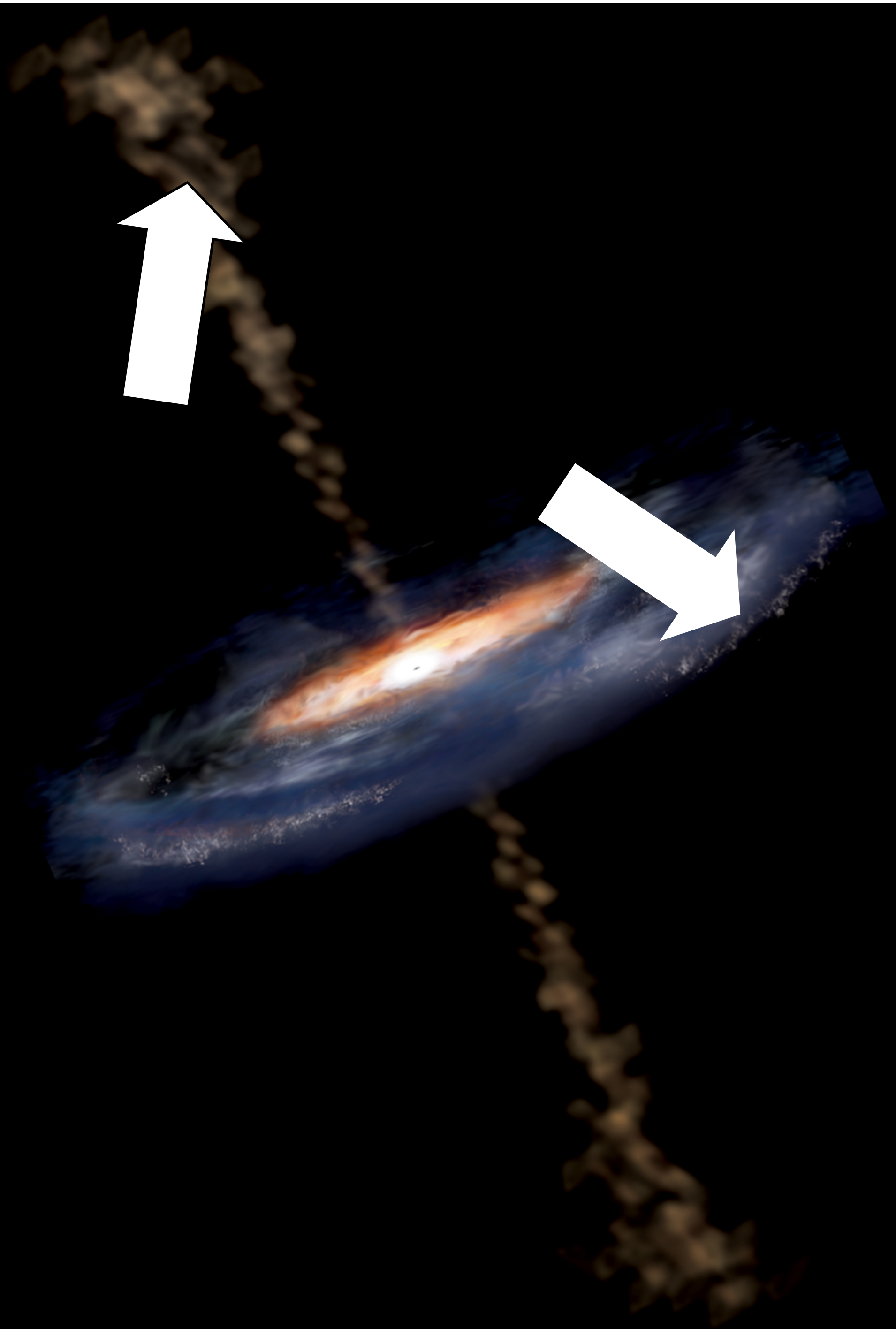


cosmic ray accelerators:
where, how?

gravitational energy from collapsing star converted into particle acceleration

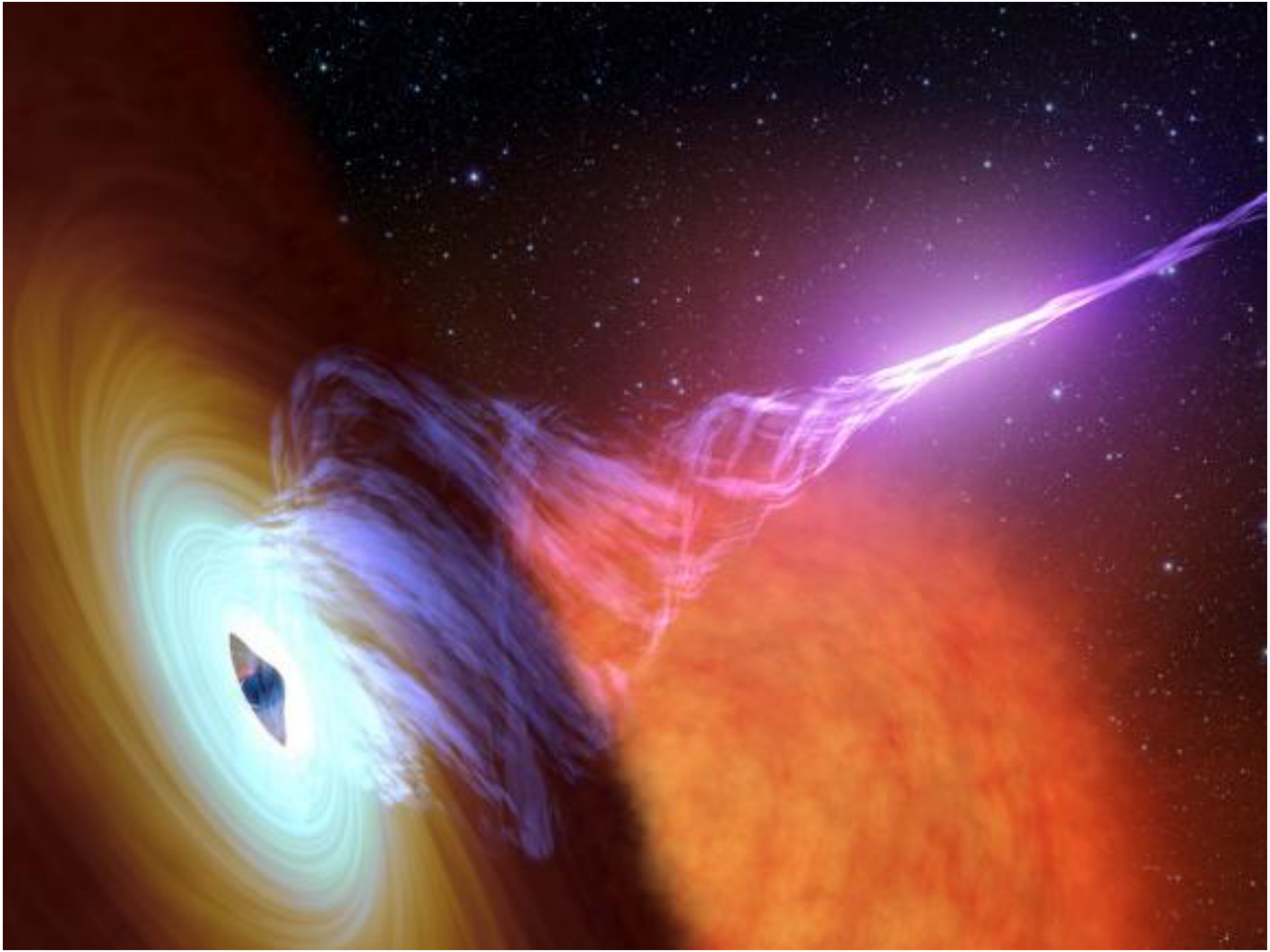
LHC filling the orbit of Mercury

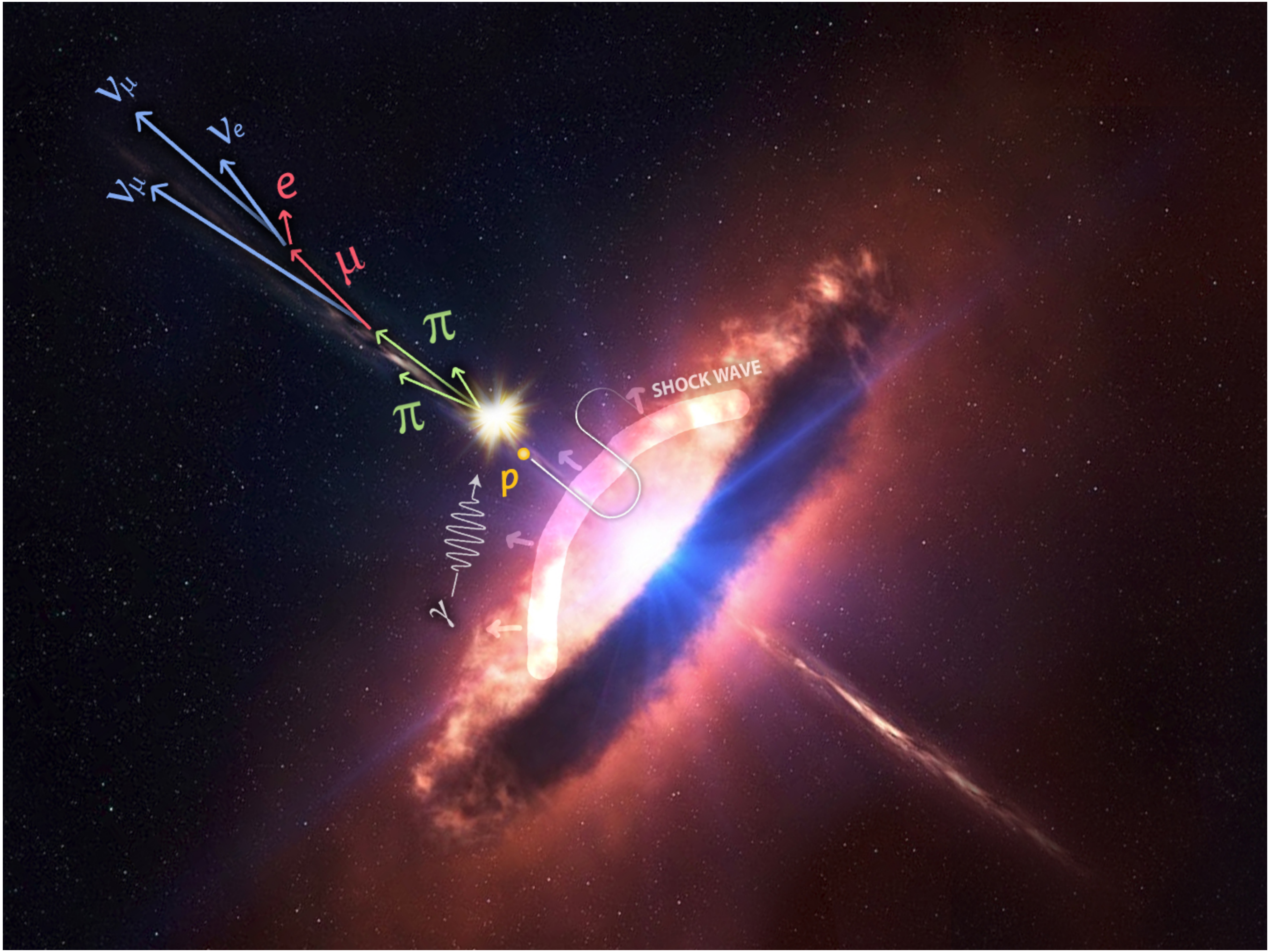

supernova
remnants
Chandra
Cassiopeia A
gamma
ray
bursts



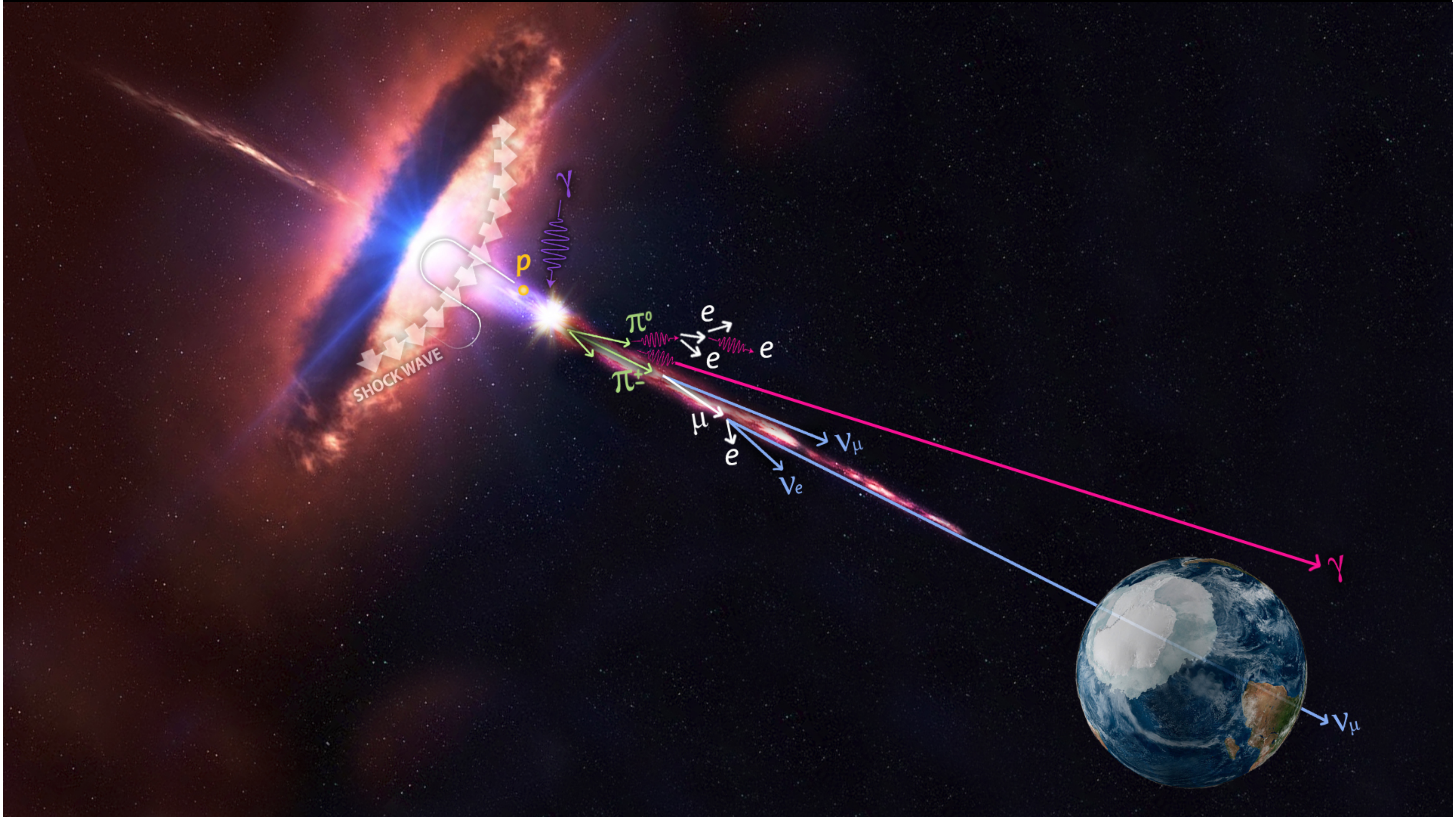
active galaxy

particle flows near
supermassive
black hole



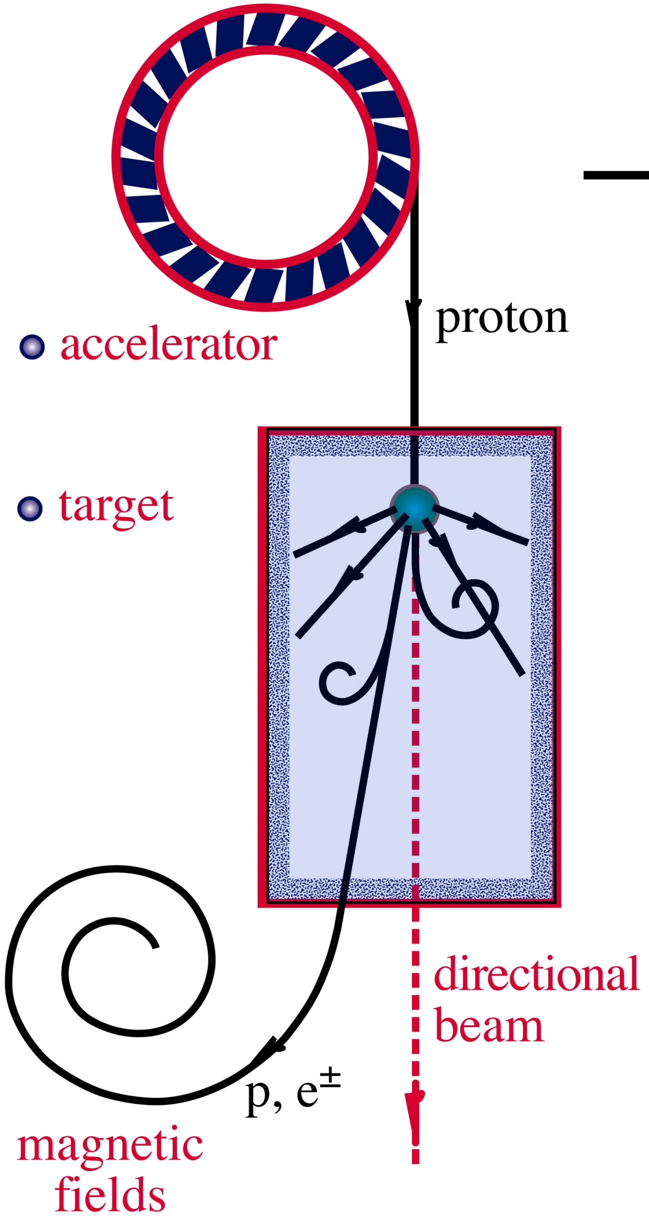


νμ
νe
e
νμ
μ
π
π
SHOCK WAVE
p
γ



blazar geometry

ν and γ beams : heaven and earth



accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

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

~ cosmic ray + neutrino

$$\rightarrow p + \pi^0$$

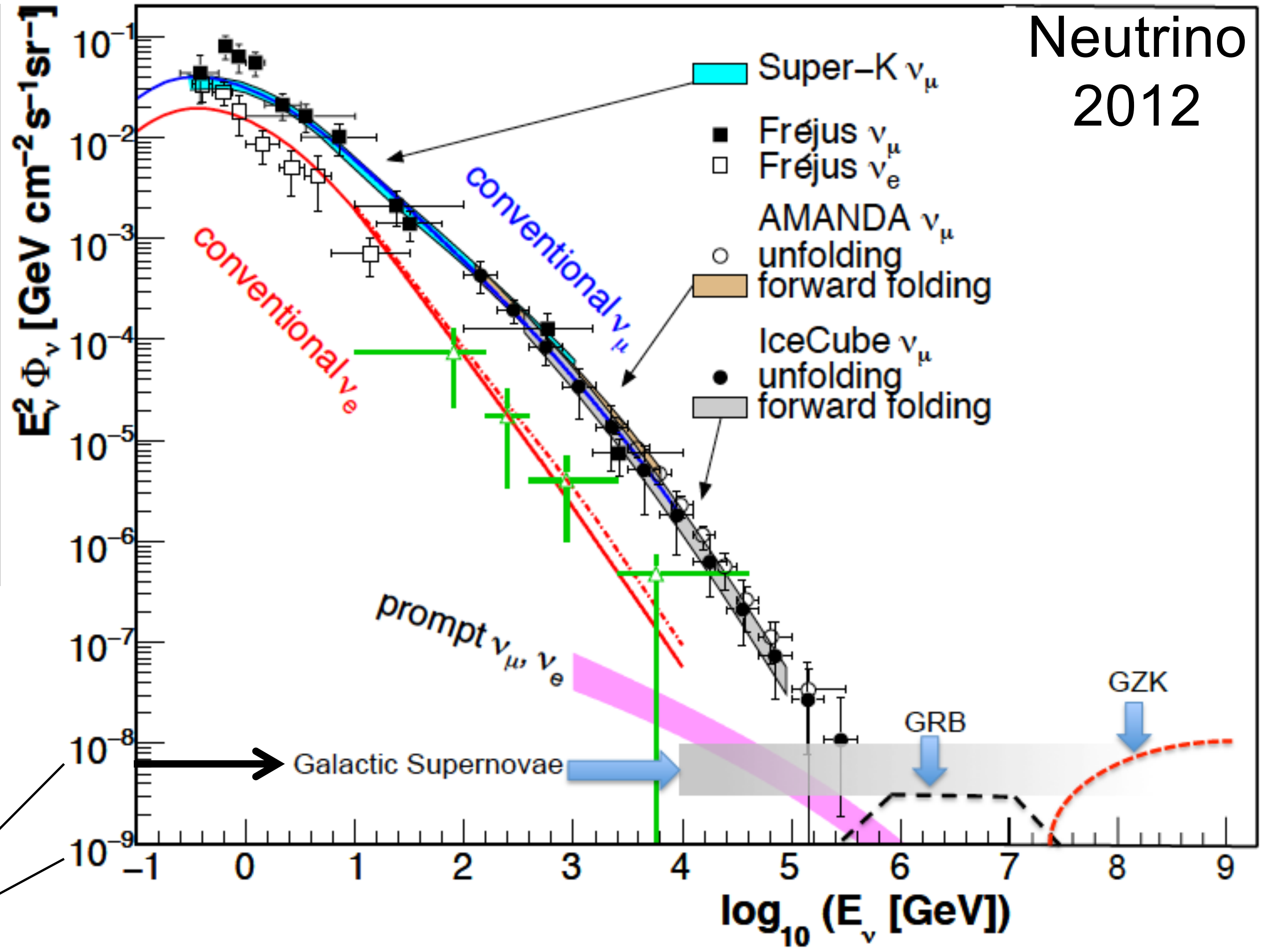
~ cosmic ray + gamma

above 100 TeV

- cosmic neutrinos
- atmospheric background disappears

$dN/dE \sim E^{-2}$

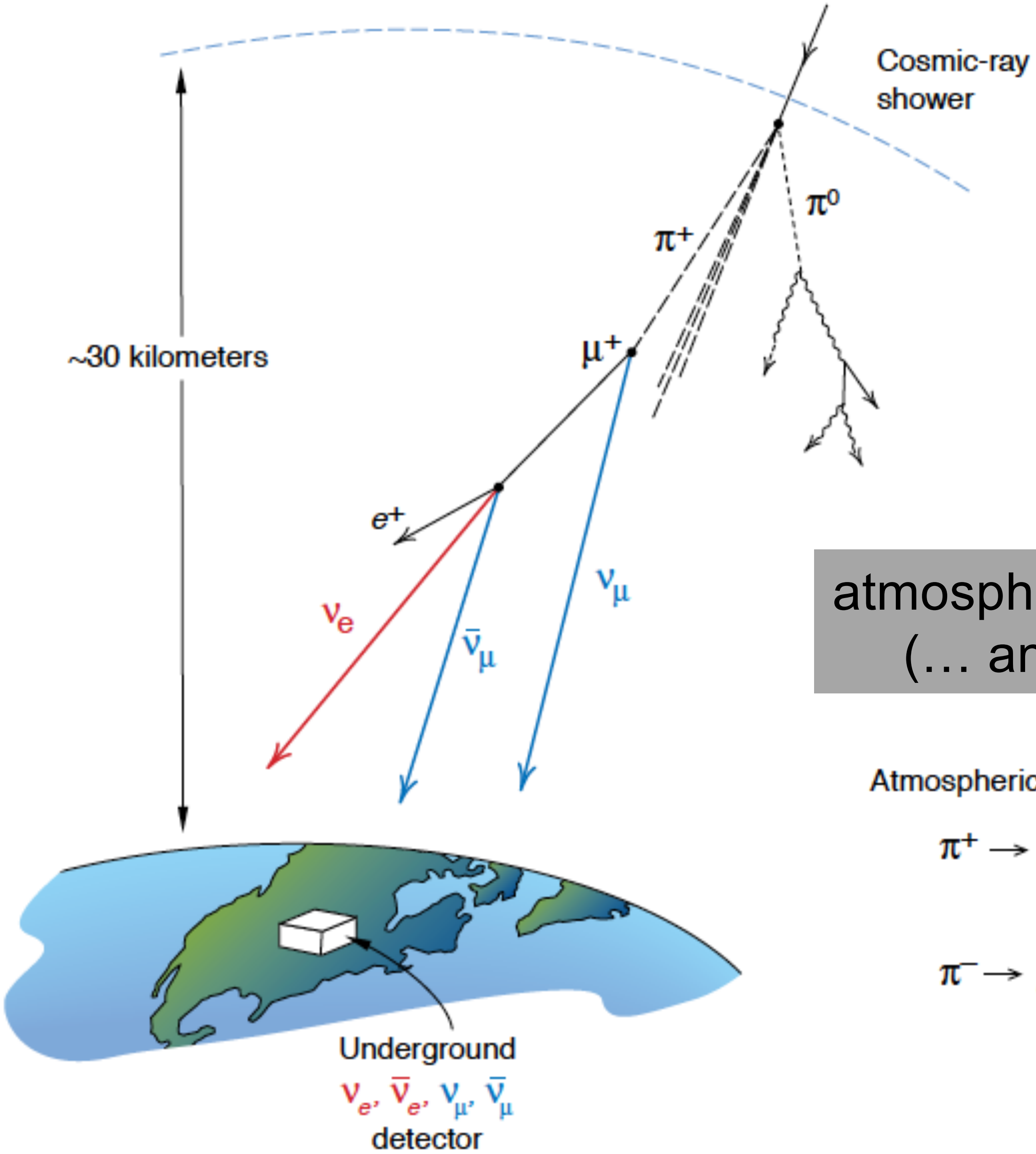
10—100 events per year for fully efficient detector



atmospheric

cosmic

100 TeV

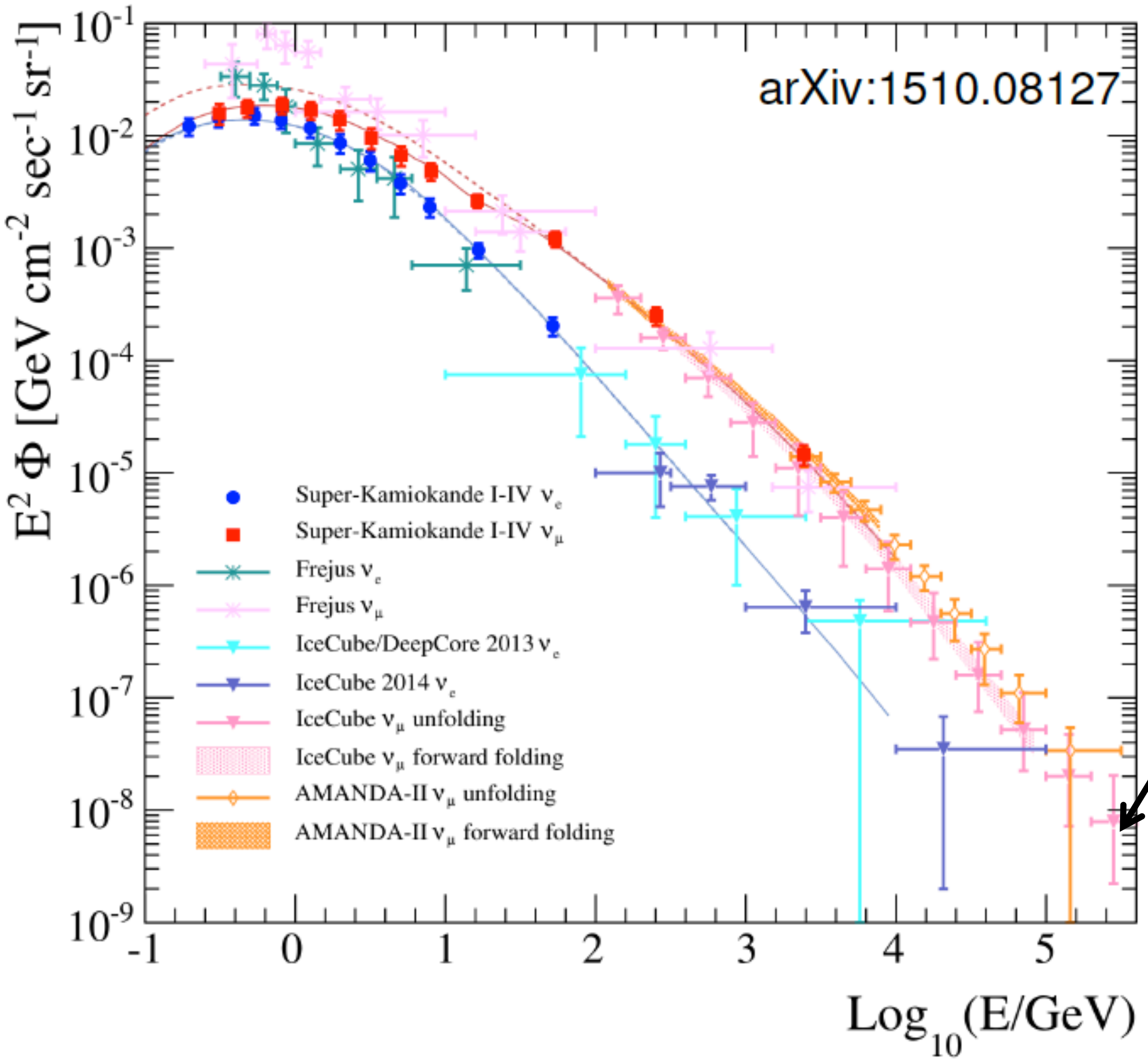


atmospheric neutrinos (… and muons!)

Atmospheric neutrino source

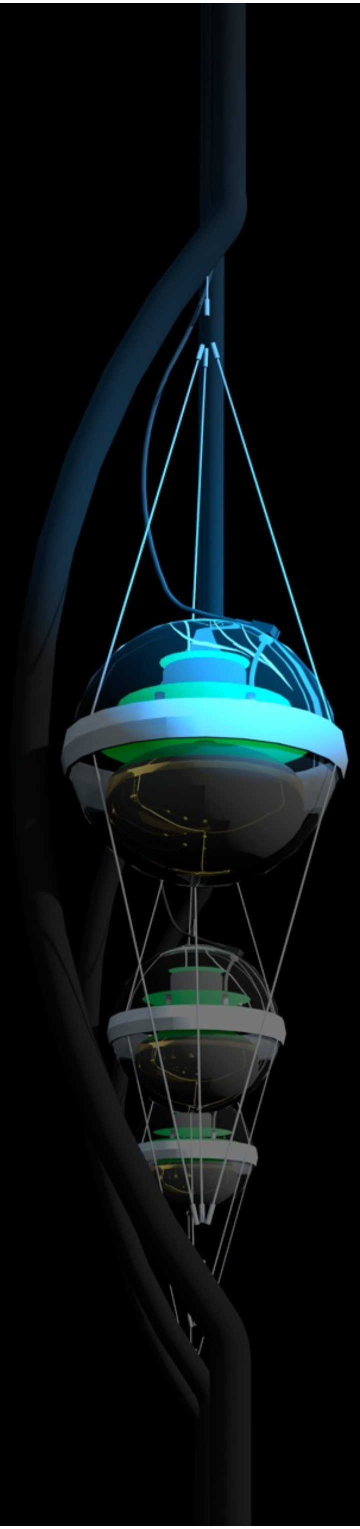
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$
$$\hookrightarrow e^- + \bar{\nu}_e + \nu_\mu$$



< 1 atmospheric neutrino event per cubic kilometer per year

atmospheric neutrino spectrum (energy measurement) well understood



IceCube

francis halzen

- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
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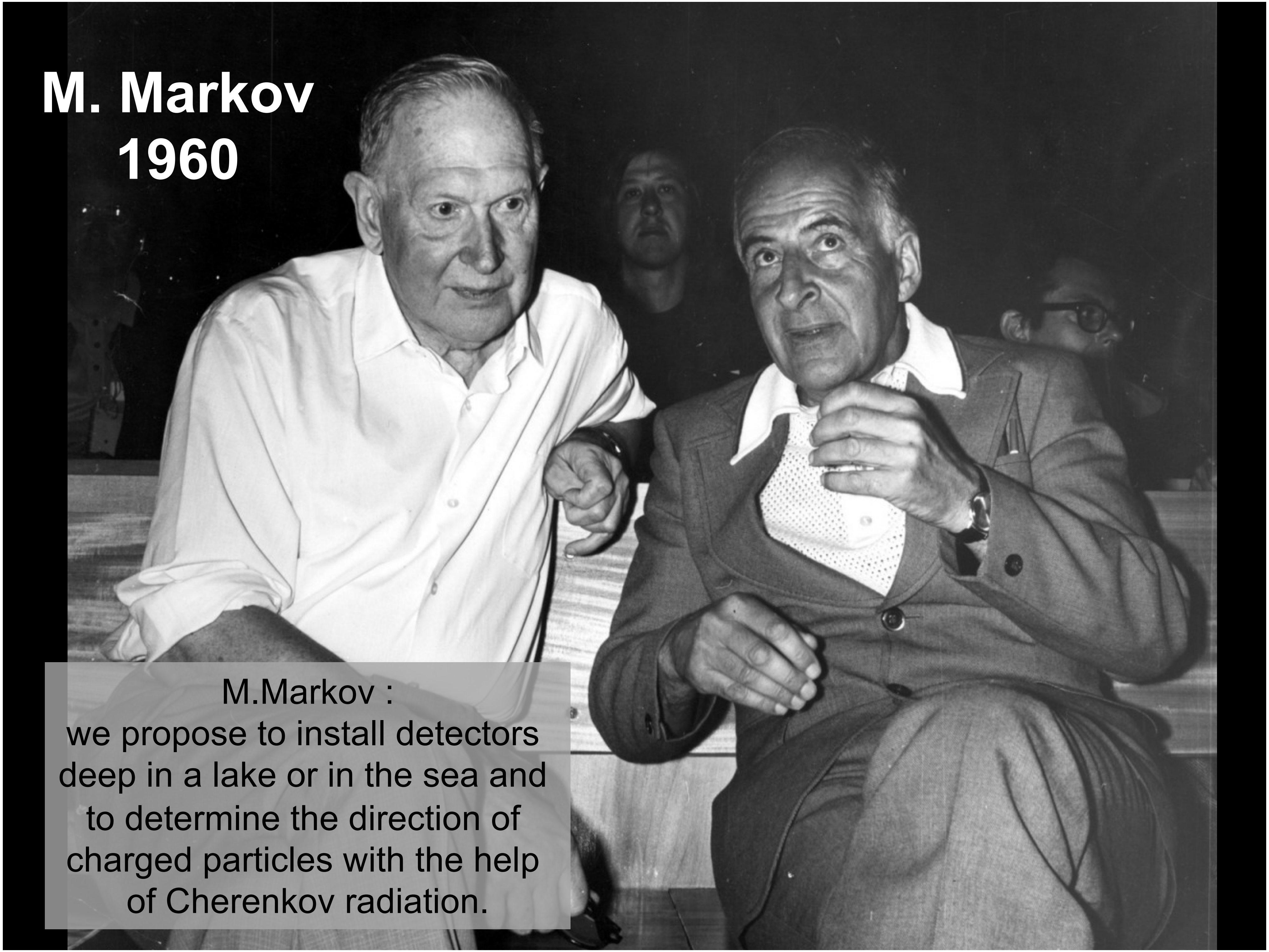
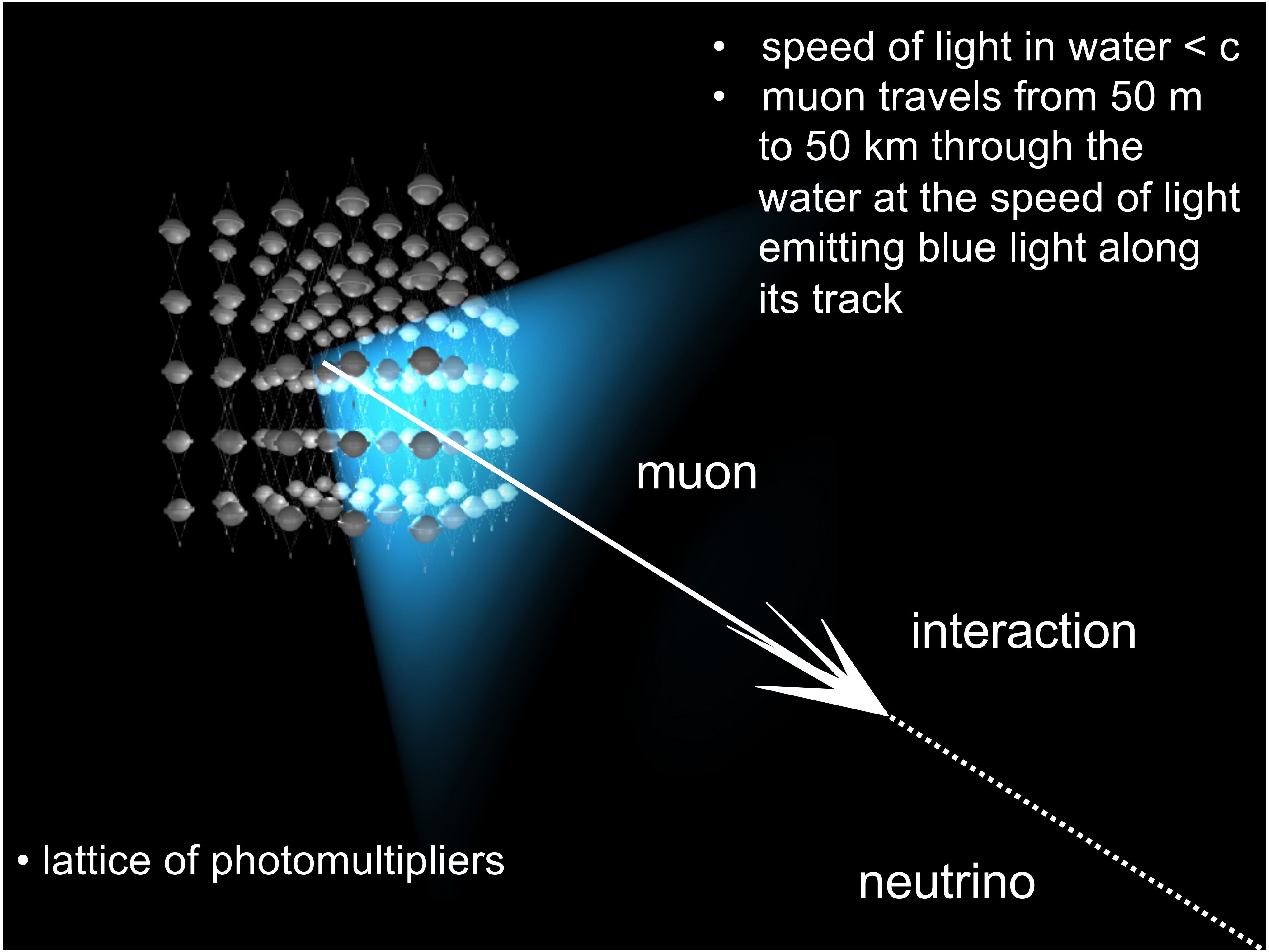
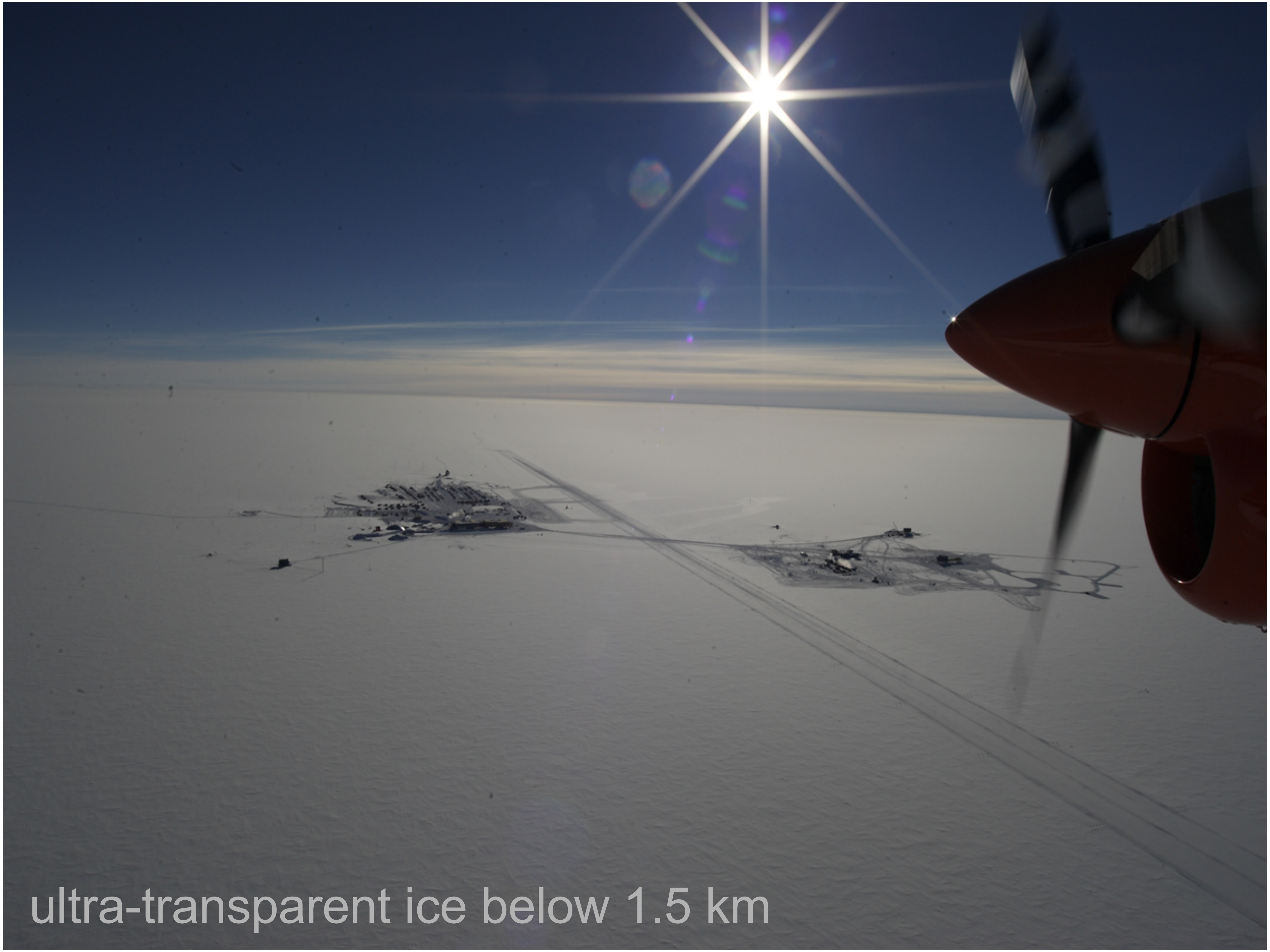
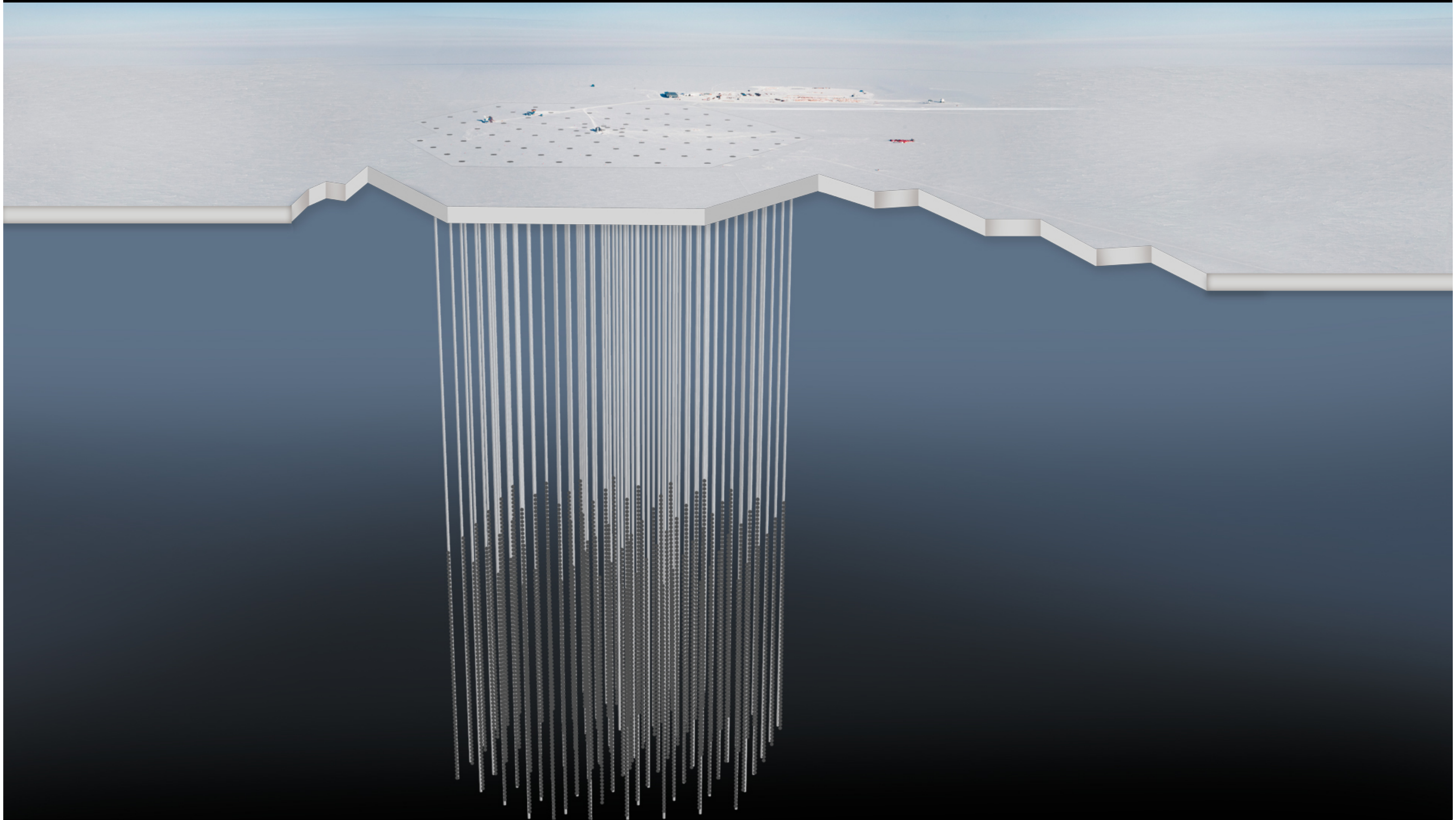
iceCube.wisc.edu

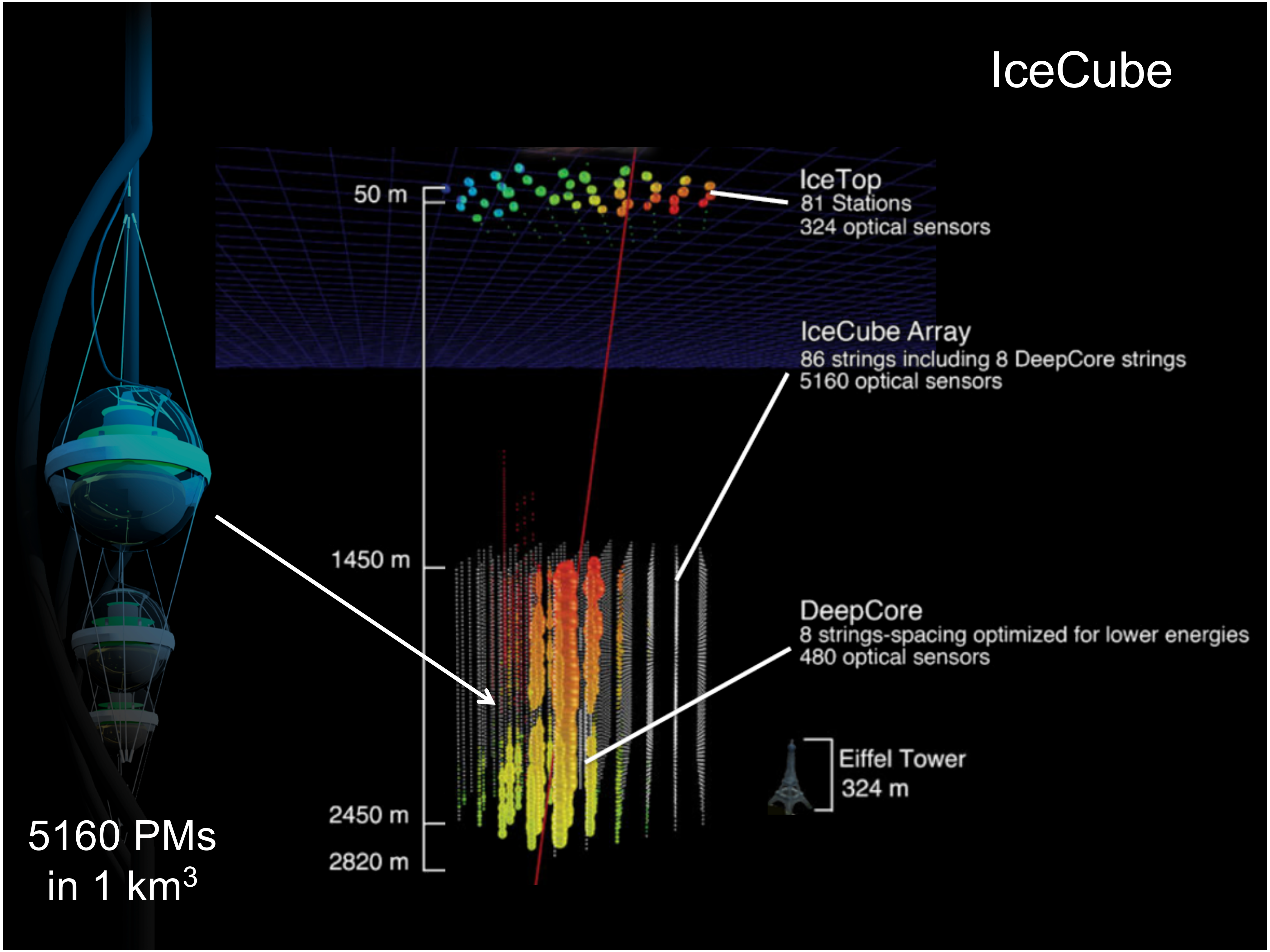

M. Markov
1960
M.Markov :
we propose to install detectors
deep in a lake or in the sea and
to determine the direction of
charged particles with the help
of Cherenkov radiation.


• 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
muon
interaction
neutrino
• lattice of photomultipliers


ultra-transparent ice below 1.5 km

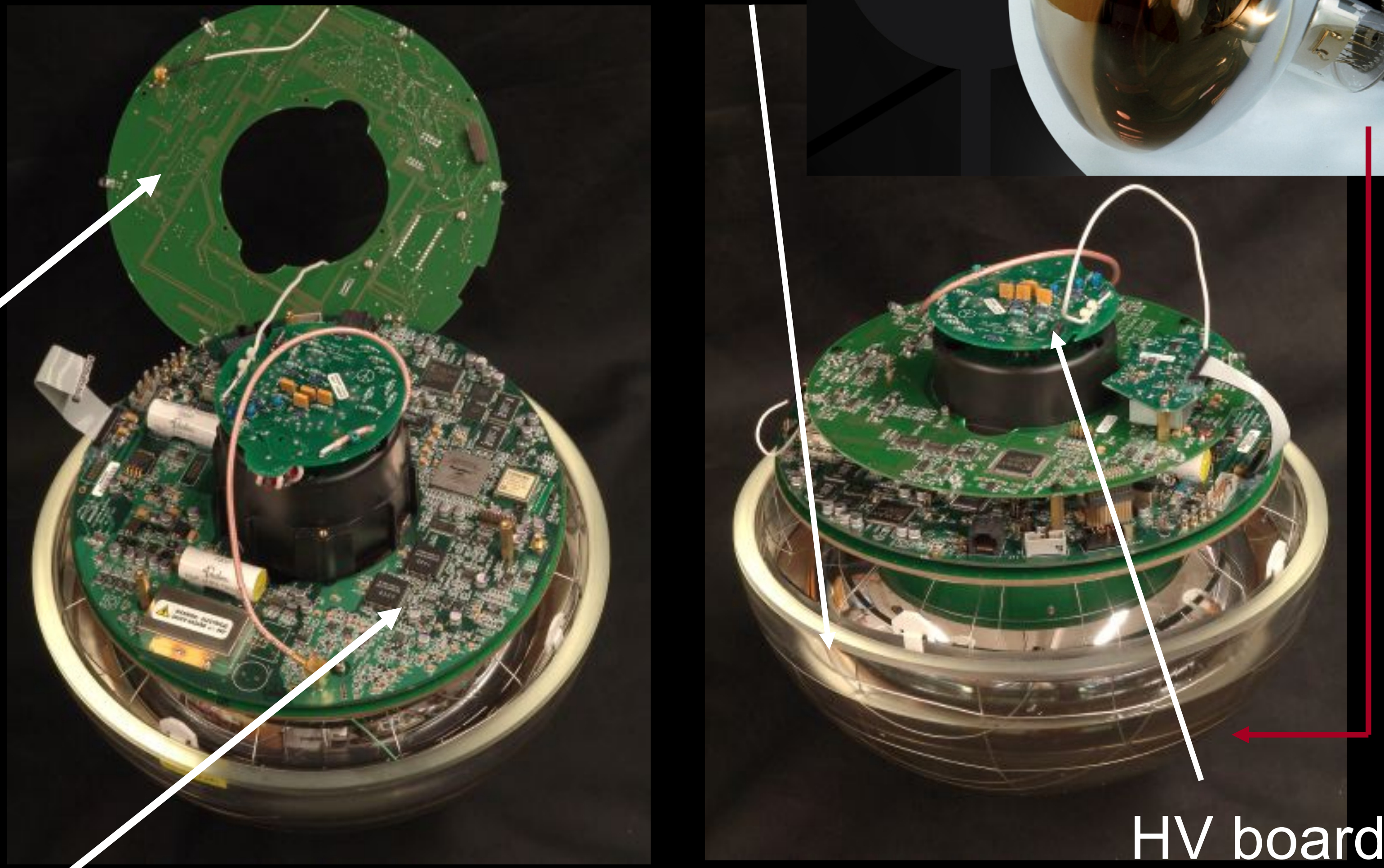
instrument 1 cubic kilometer of natural ice below 1.45 km



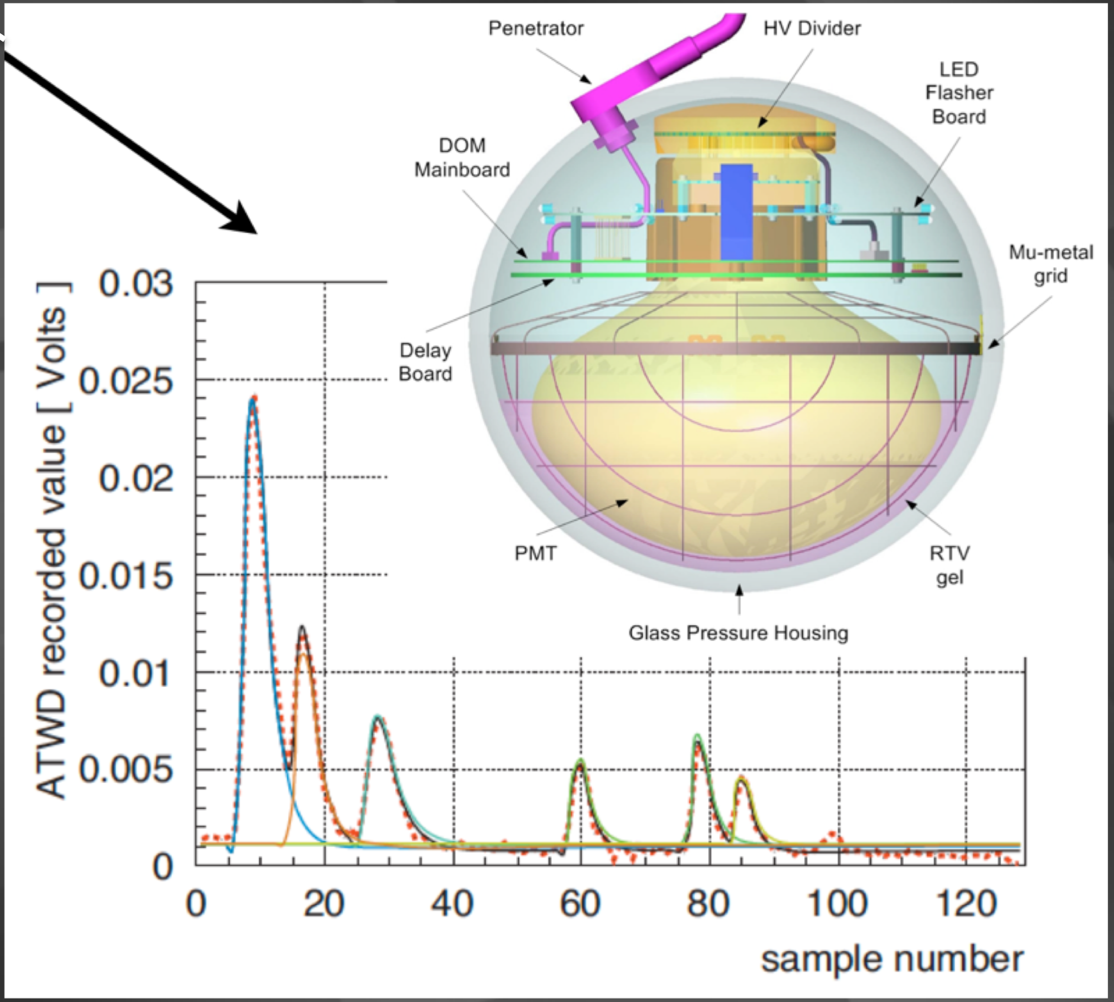

IceCube
IceTop
81 Stations
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
5160 PMs
in 1 km³

photomultiplier tube -10 inch

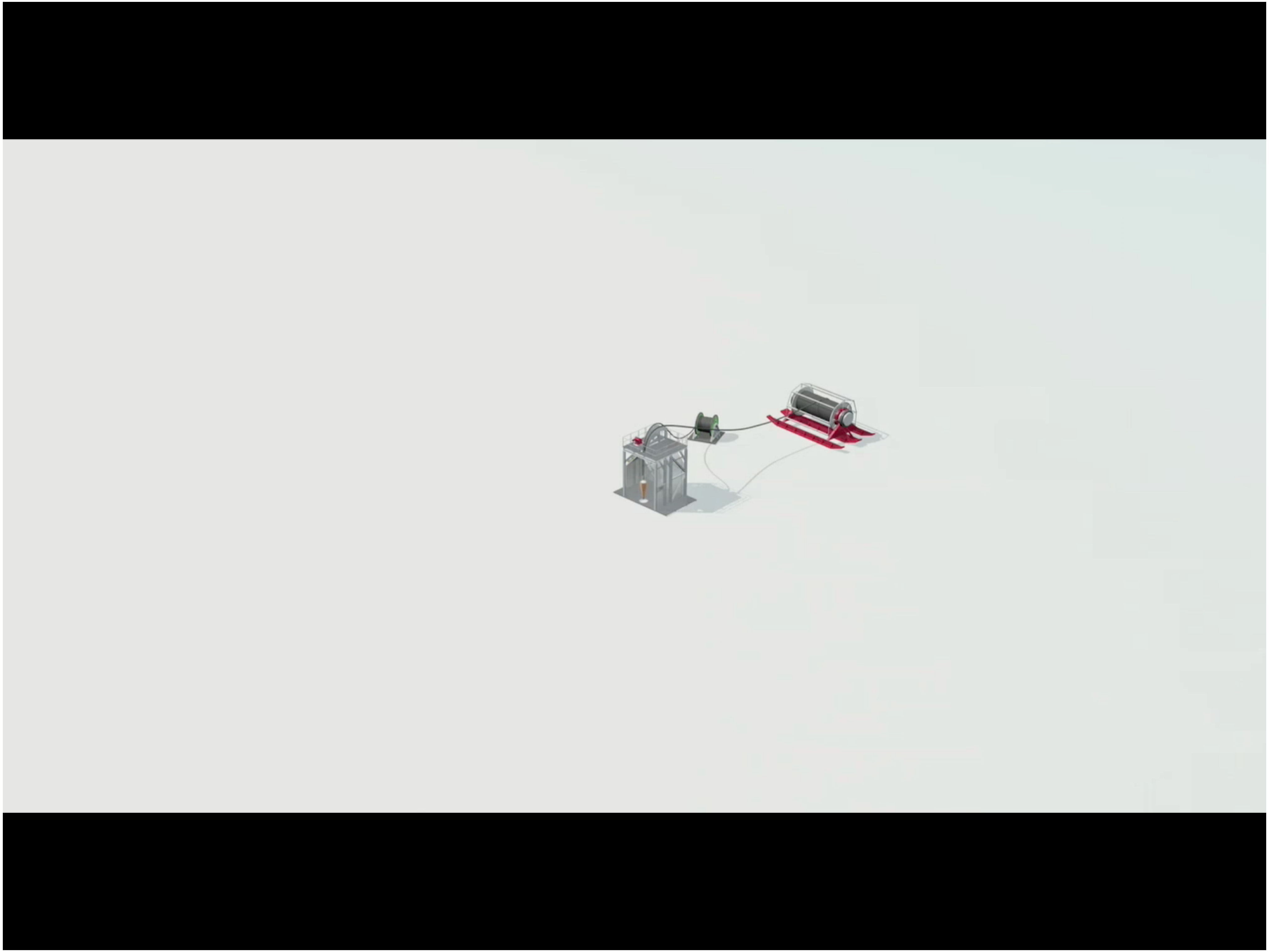
architecture of independent DOMs

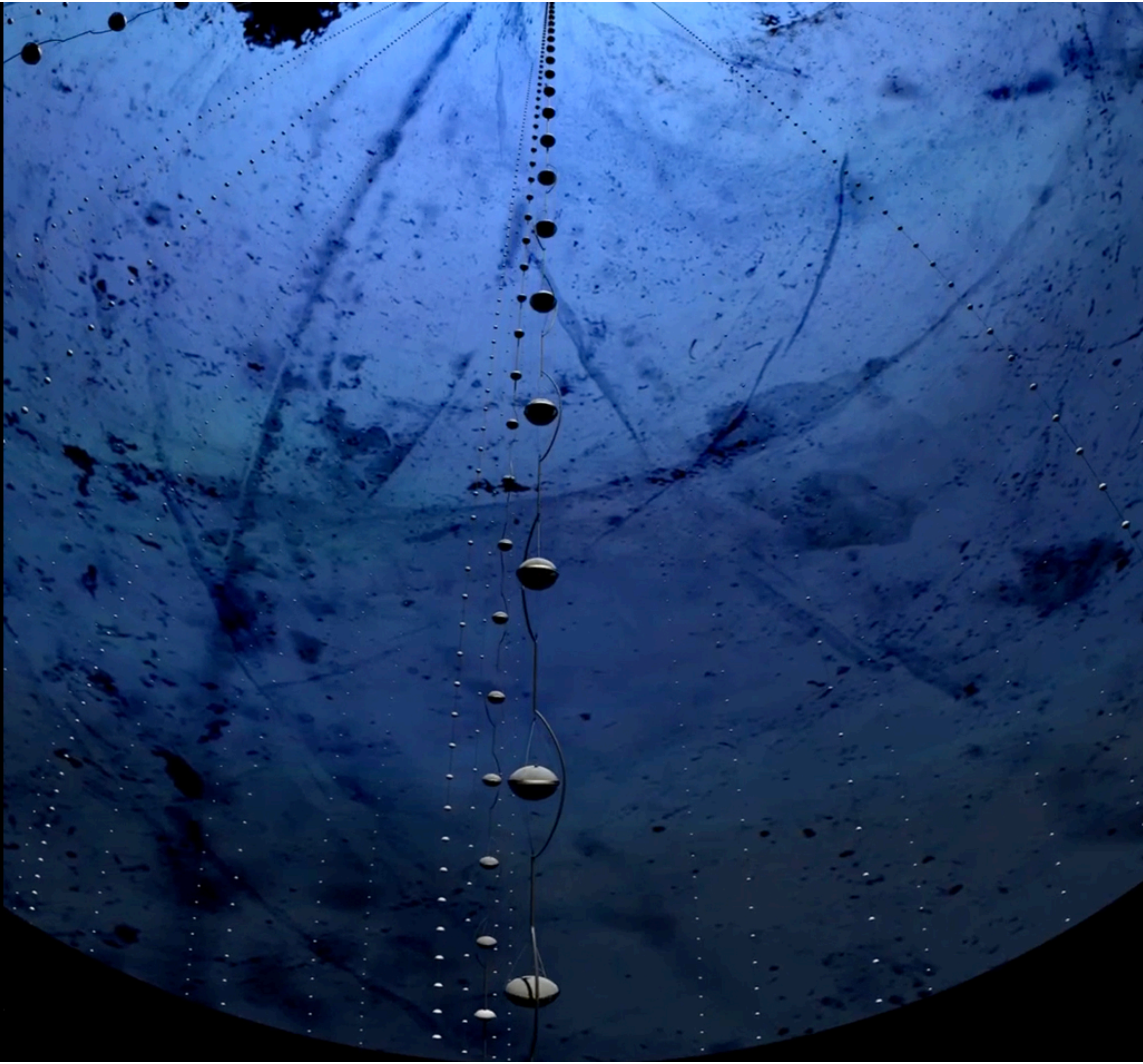


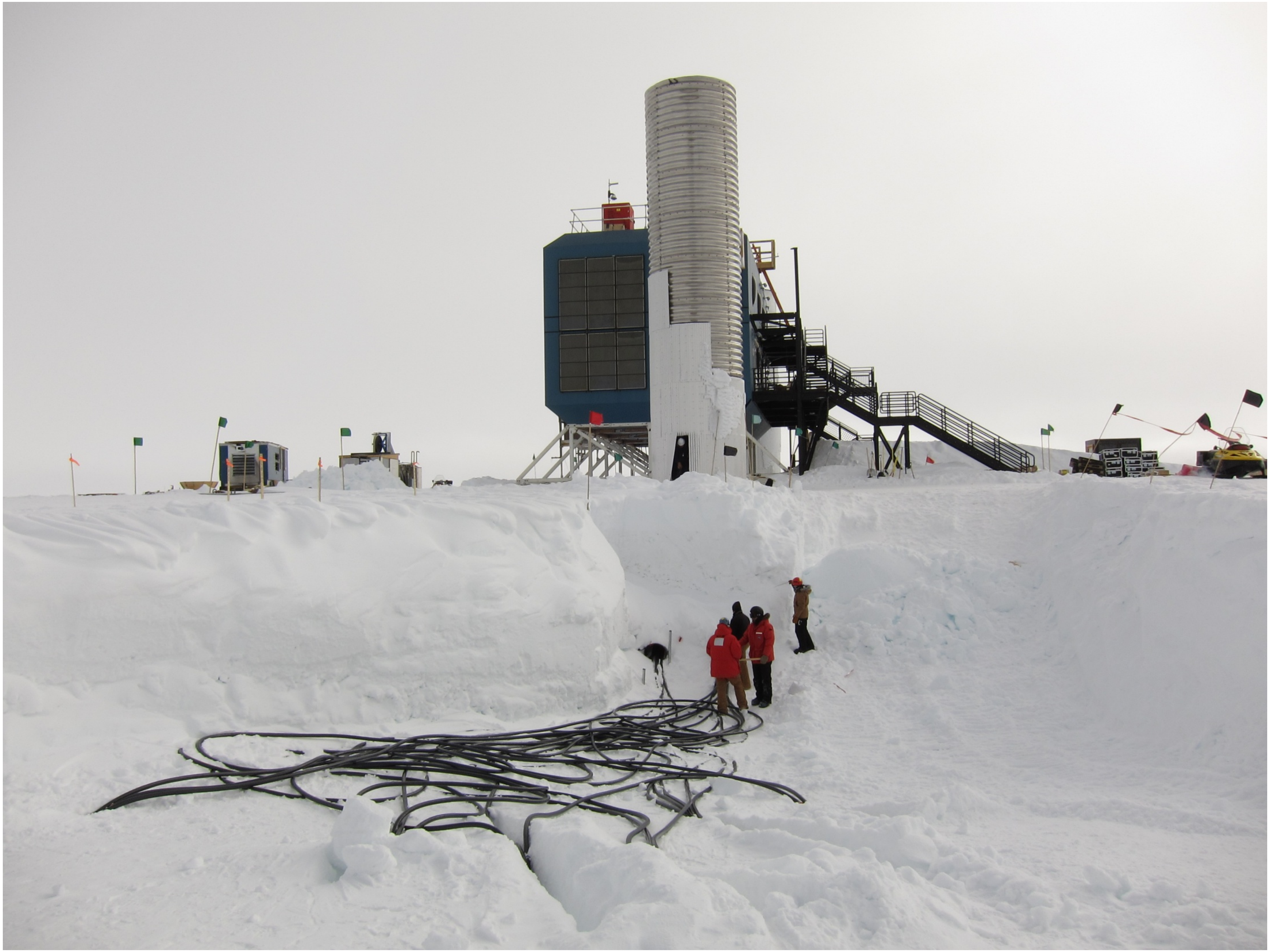
… each Digital Optical Module independently collects light signals like this, digitizes them,

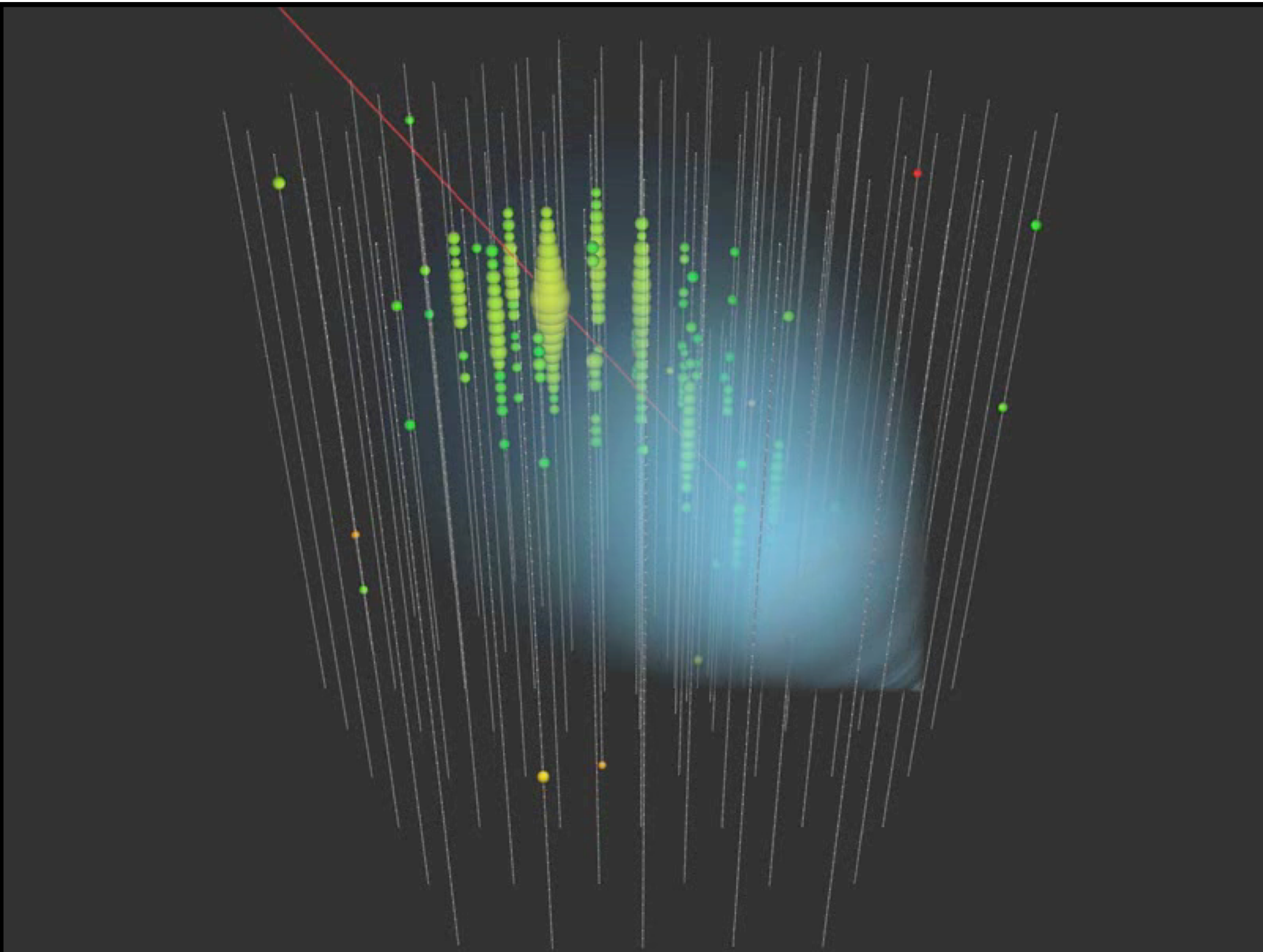


…time stamps them with 2 nanoseconds precision, and sends them to a computer that sorts them events…

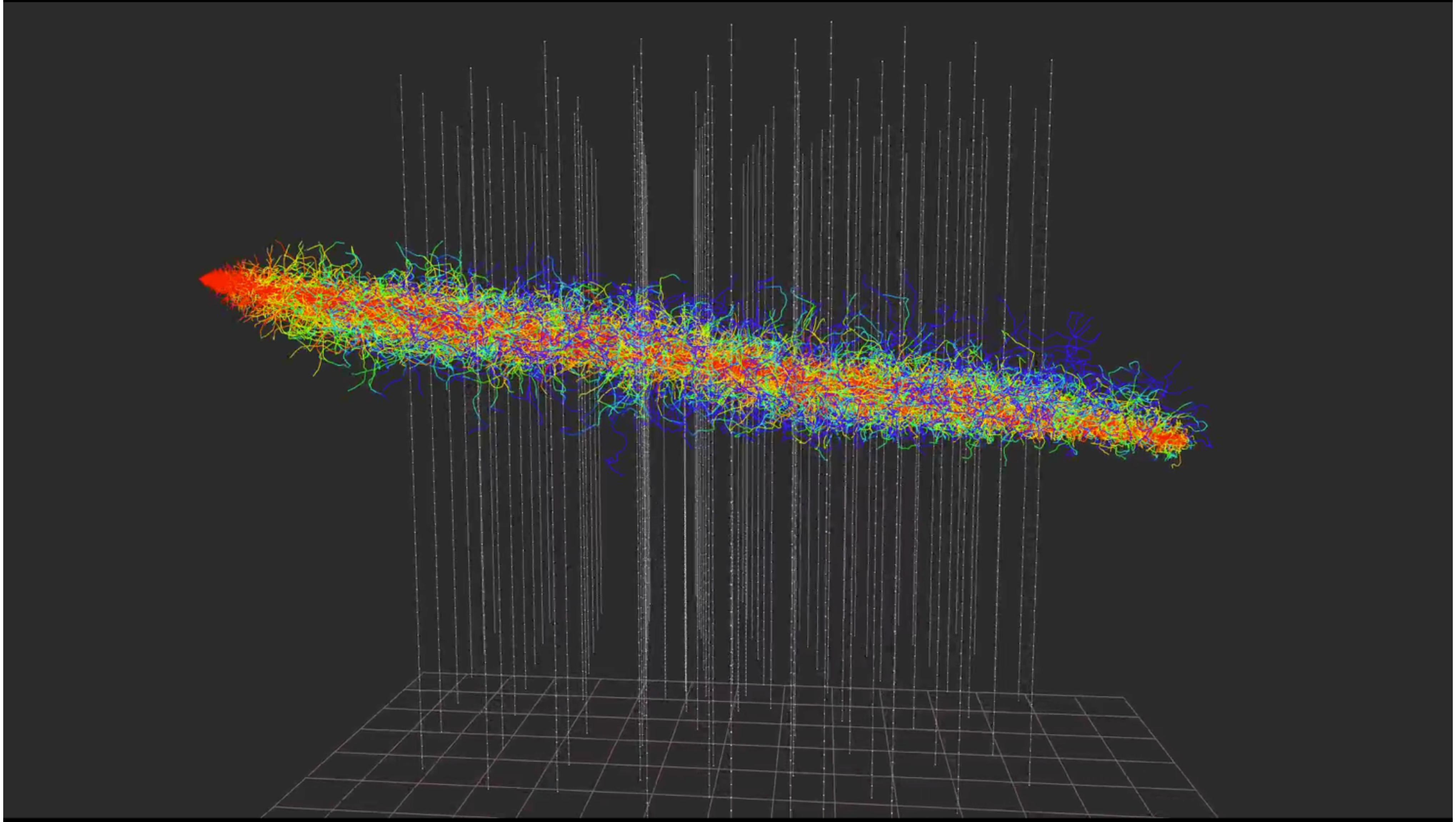


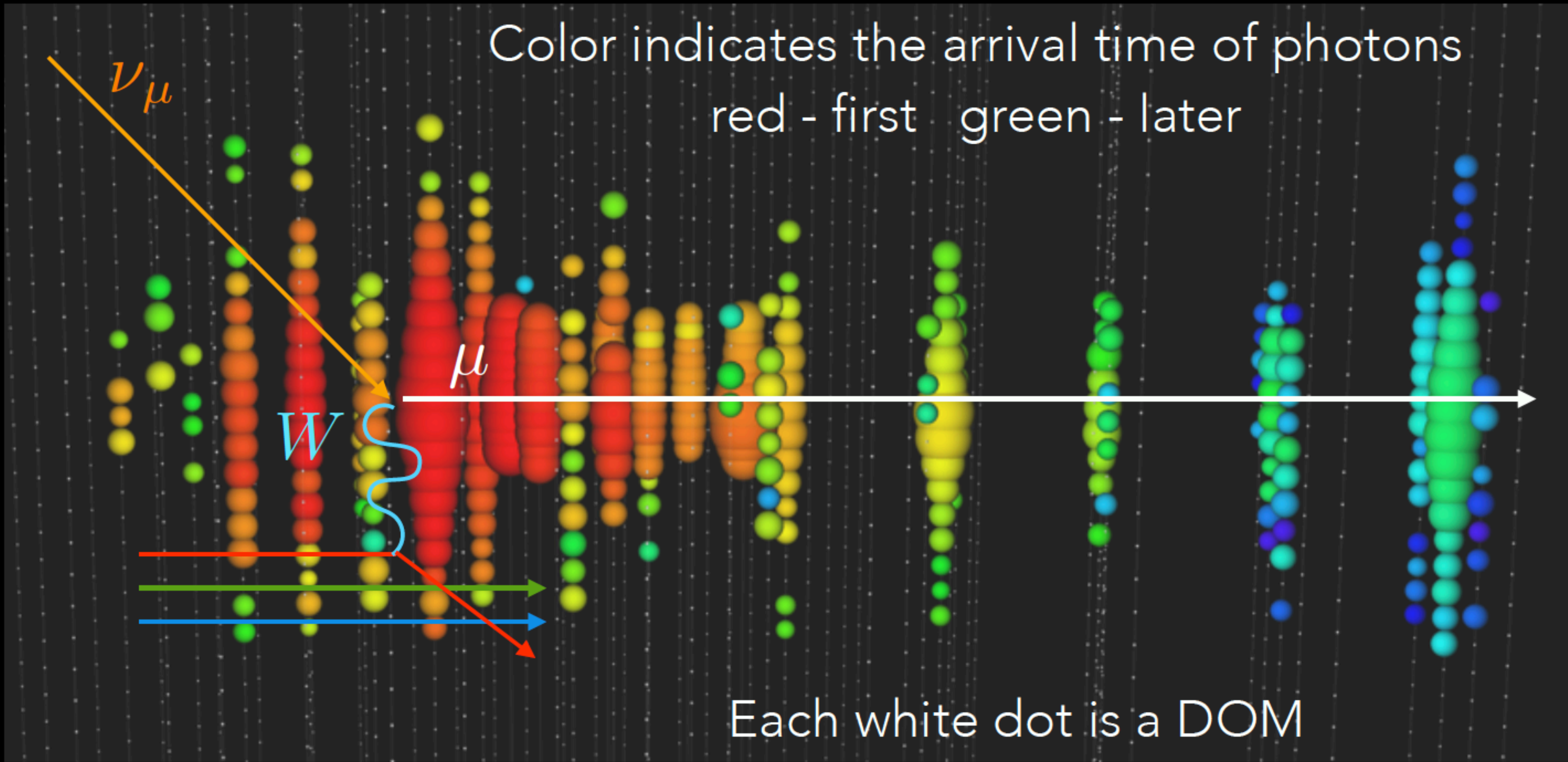






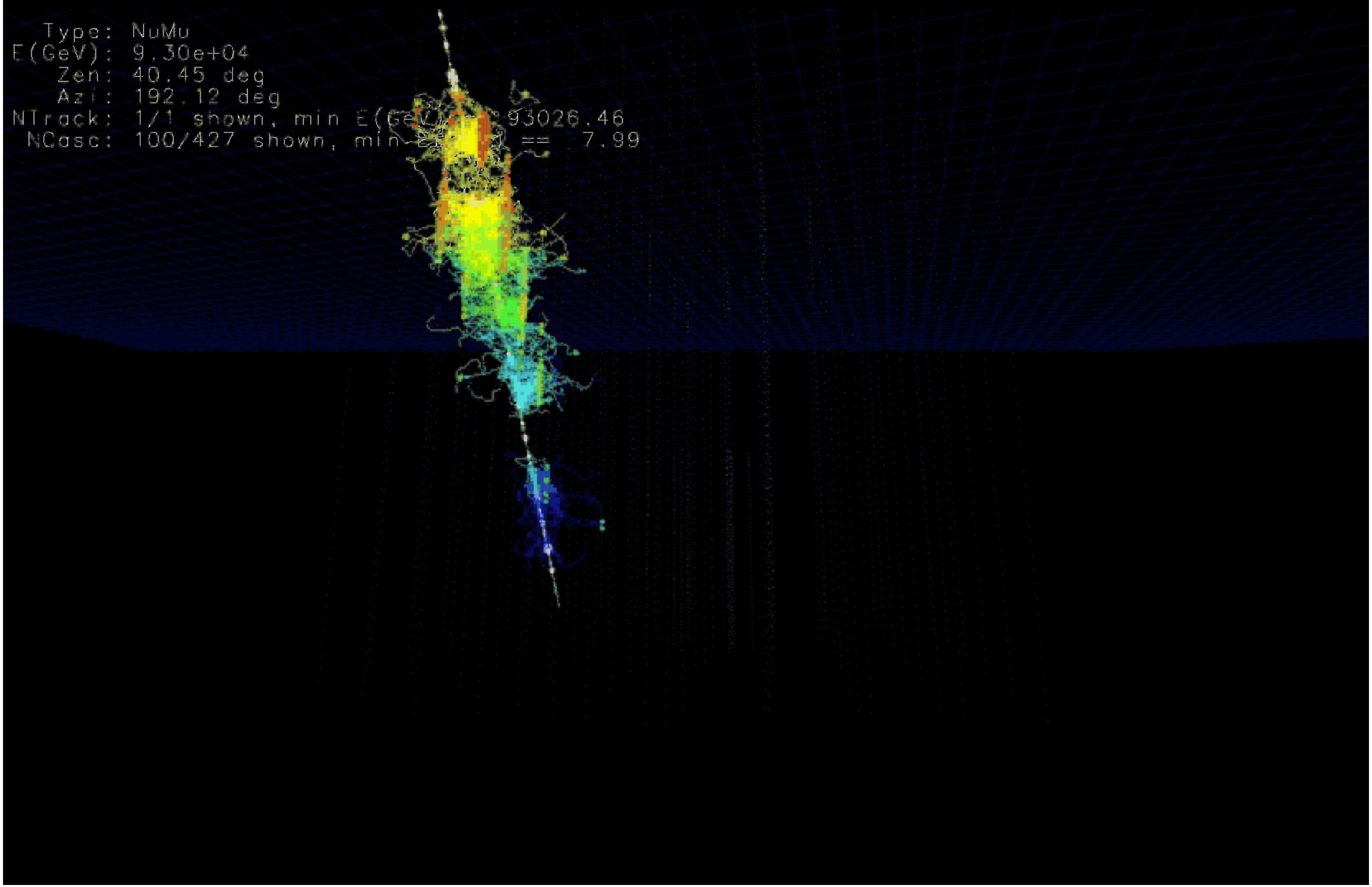
muon track: color is time; number of photons is energy neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



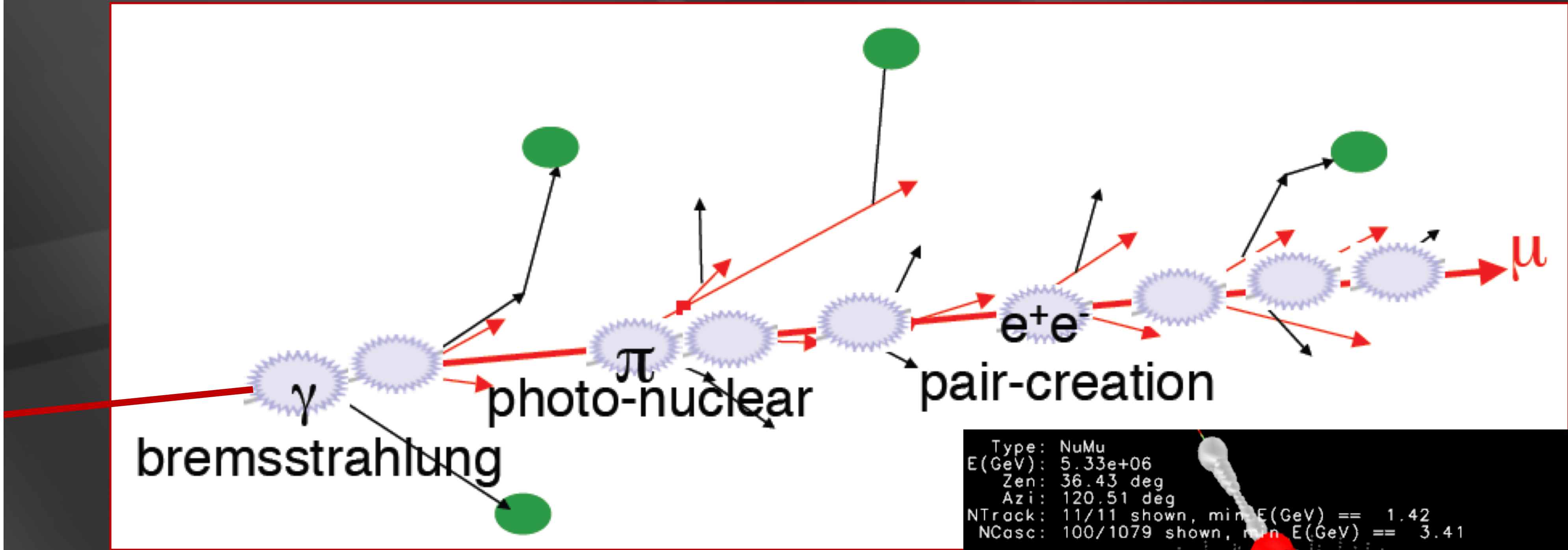


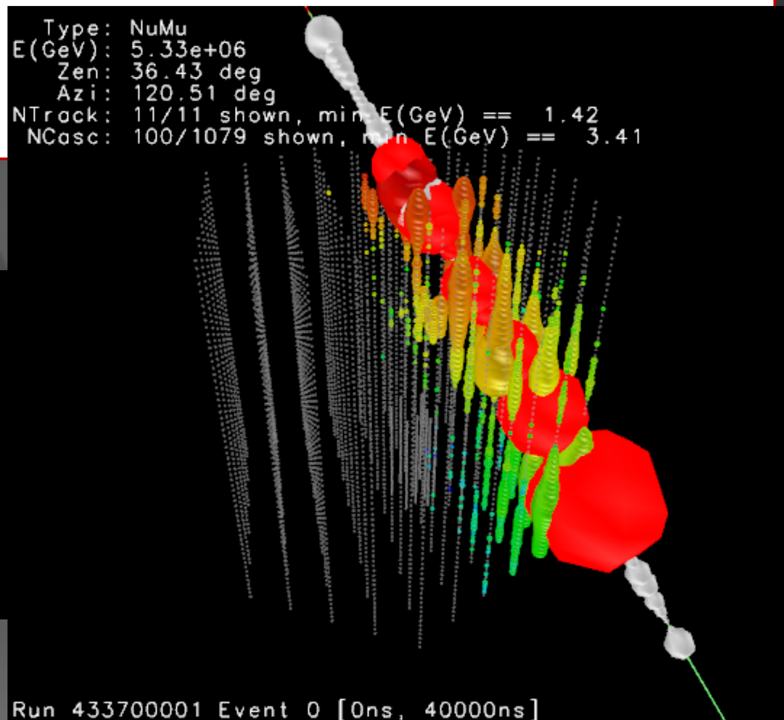
Nov.12.2010,   duration: 3,800 nanosecond,   energy: 71.4TeV

93 TeV muon: light ~ energy

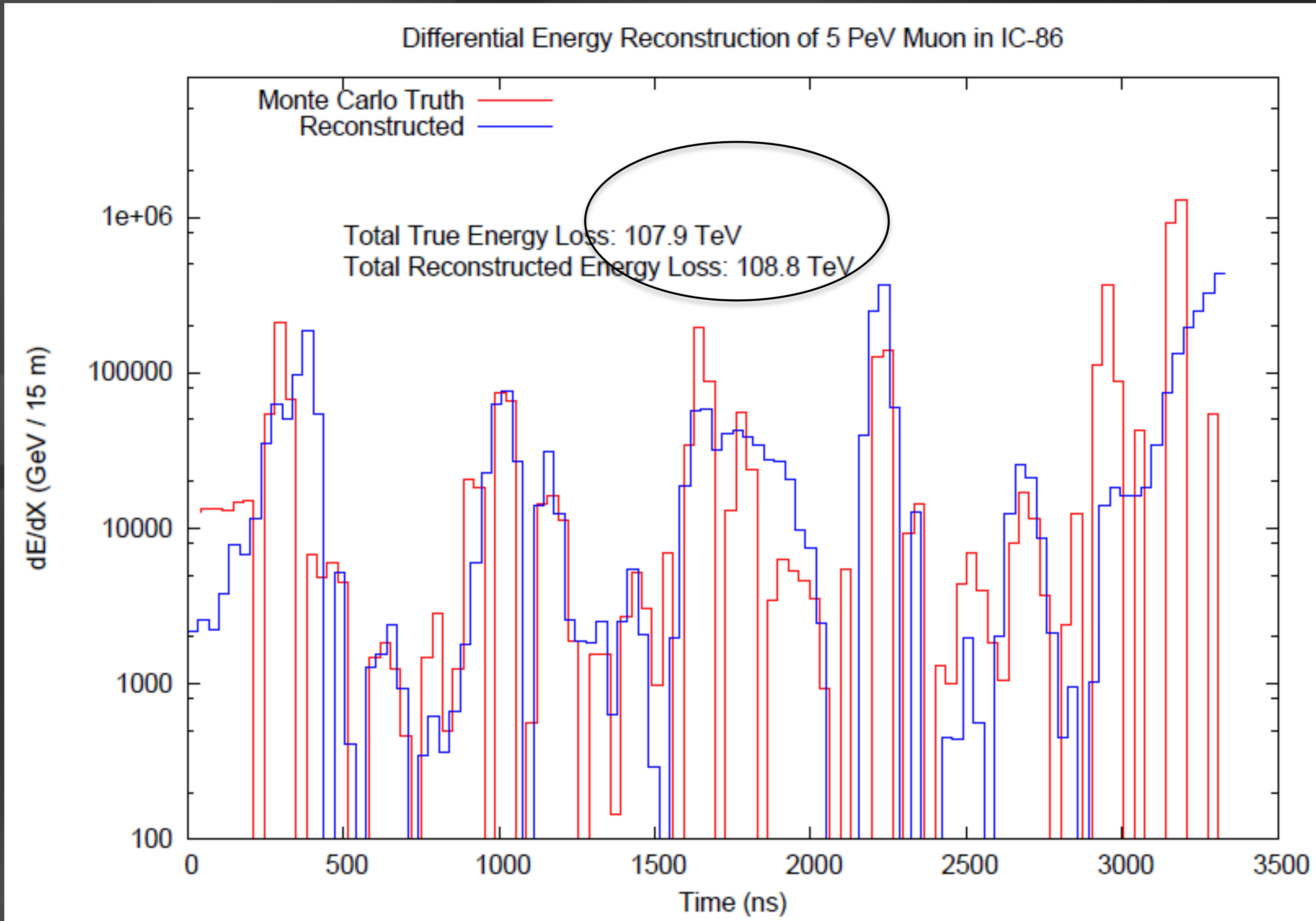


energy measurement (> 1 TeV)





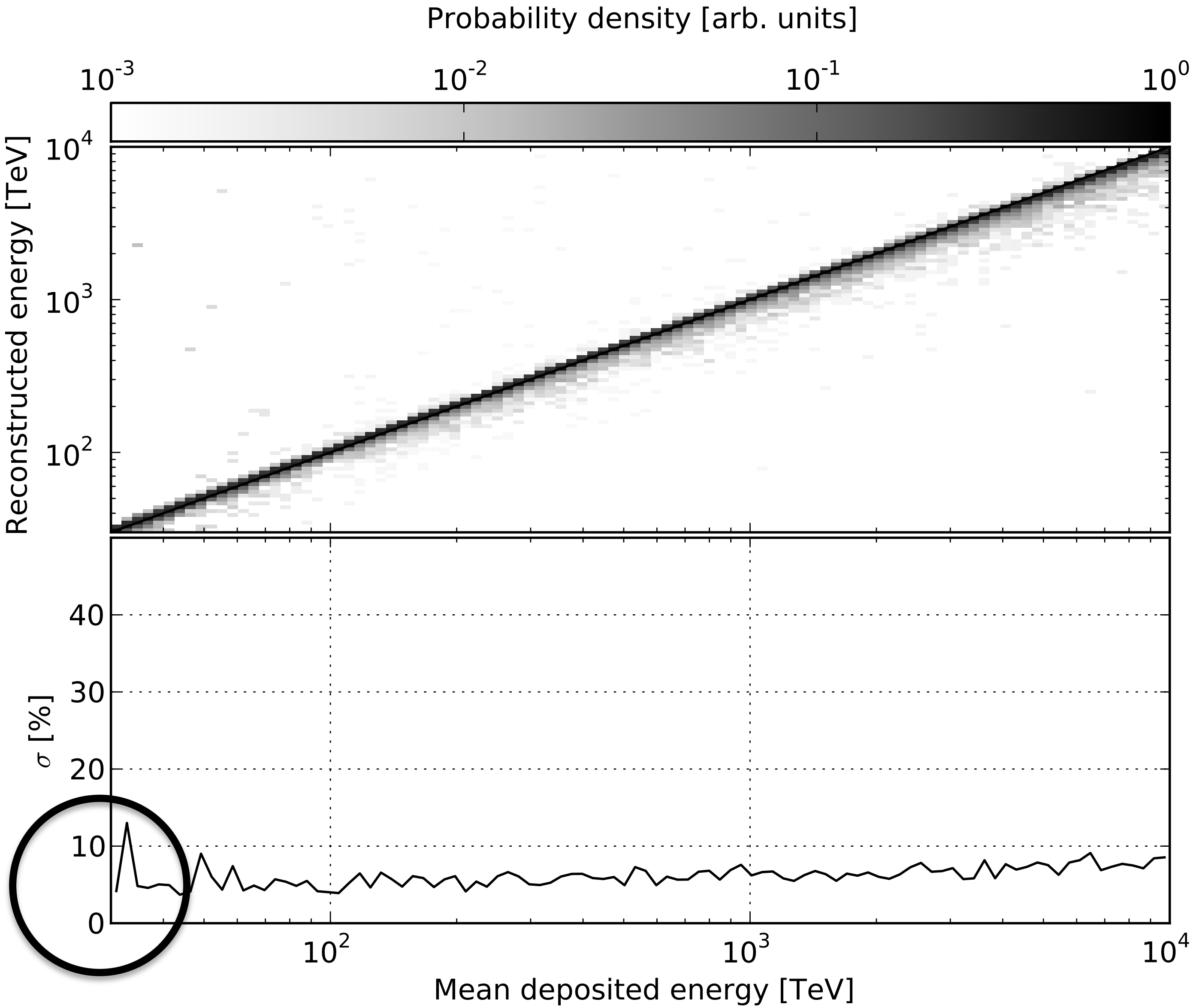
convert the amount of light emitted to a measurement of the muon energy (number of optical modules, number of photons, dE/dx, …)

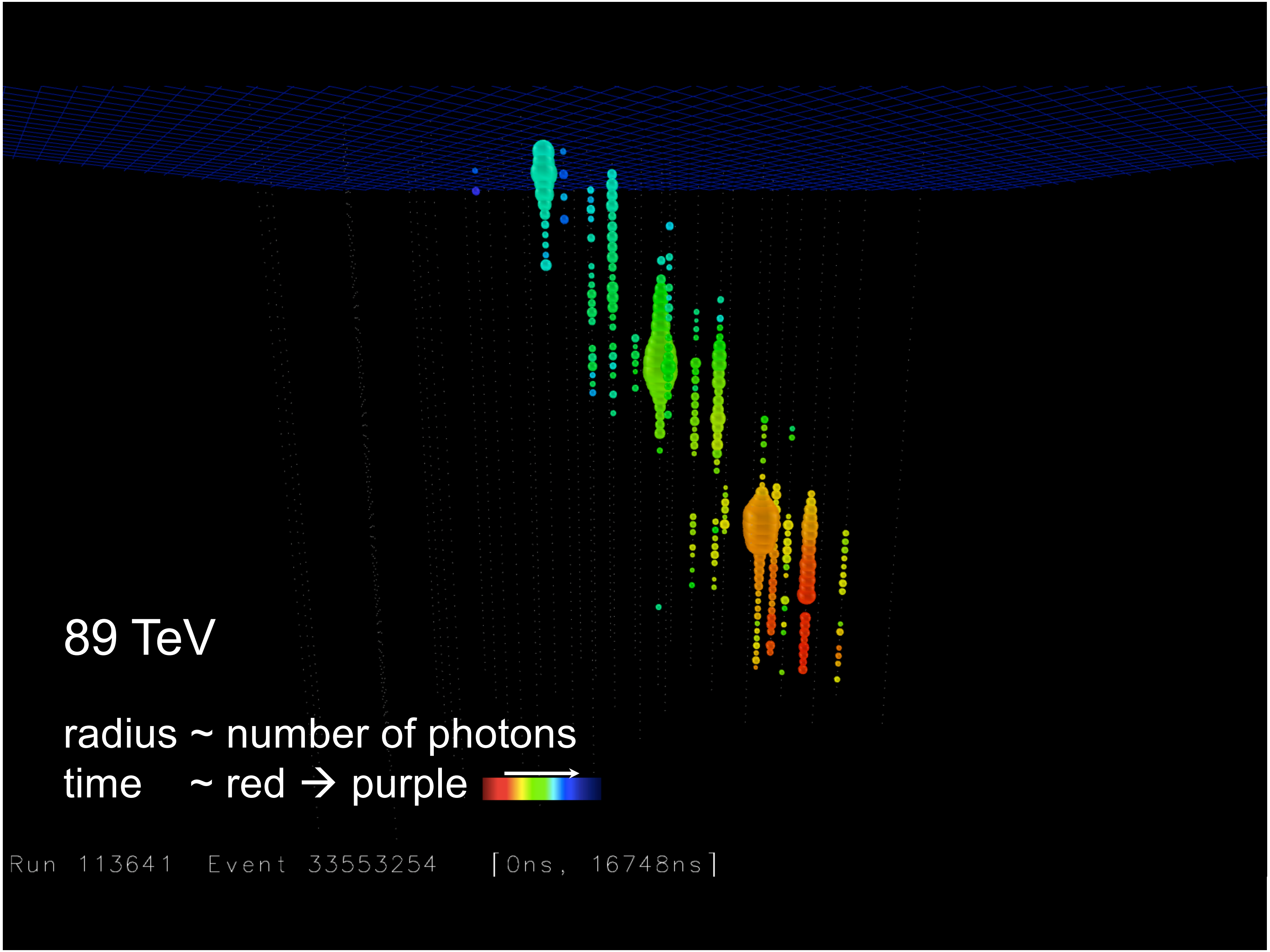


1.1 km

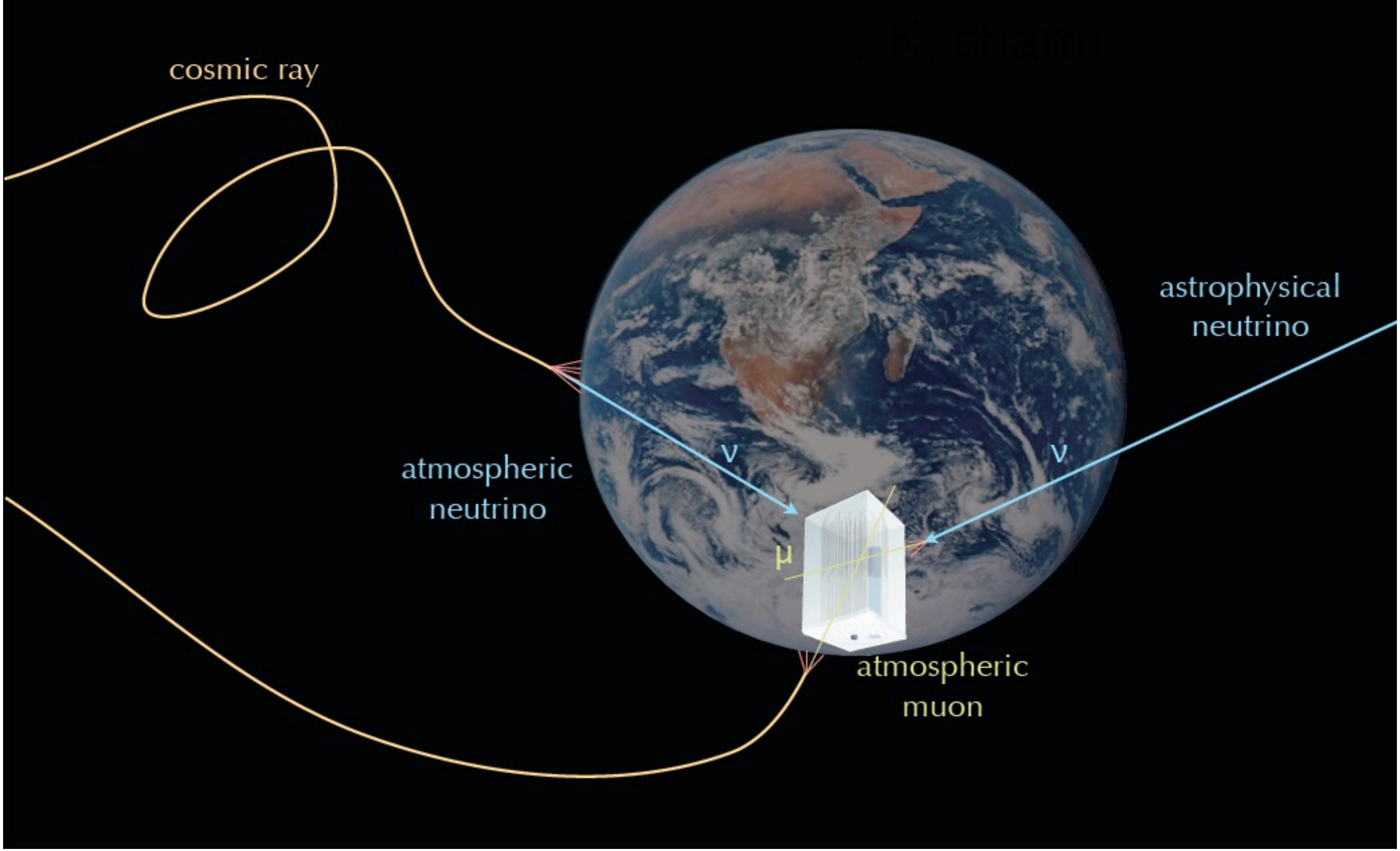
limited angular and energy resolution: computing → ice properties

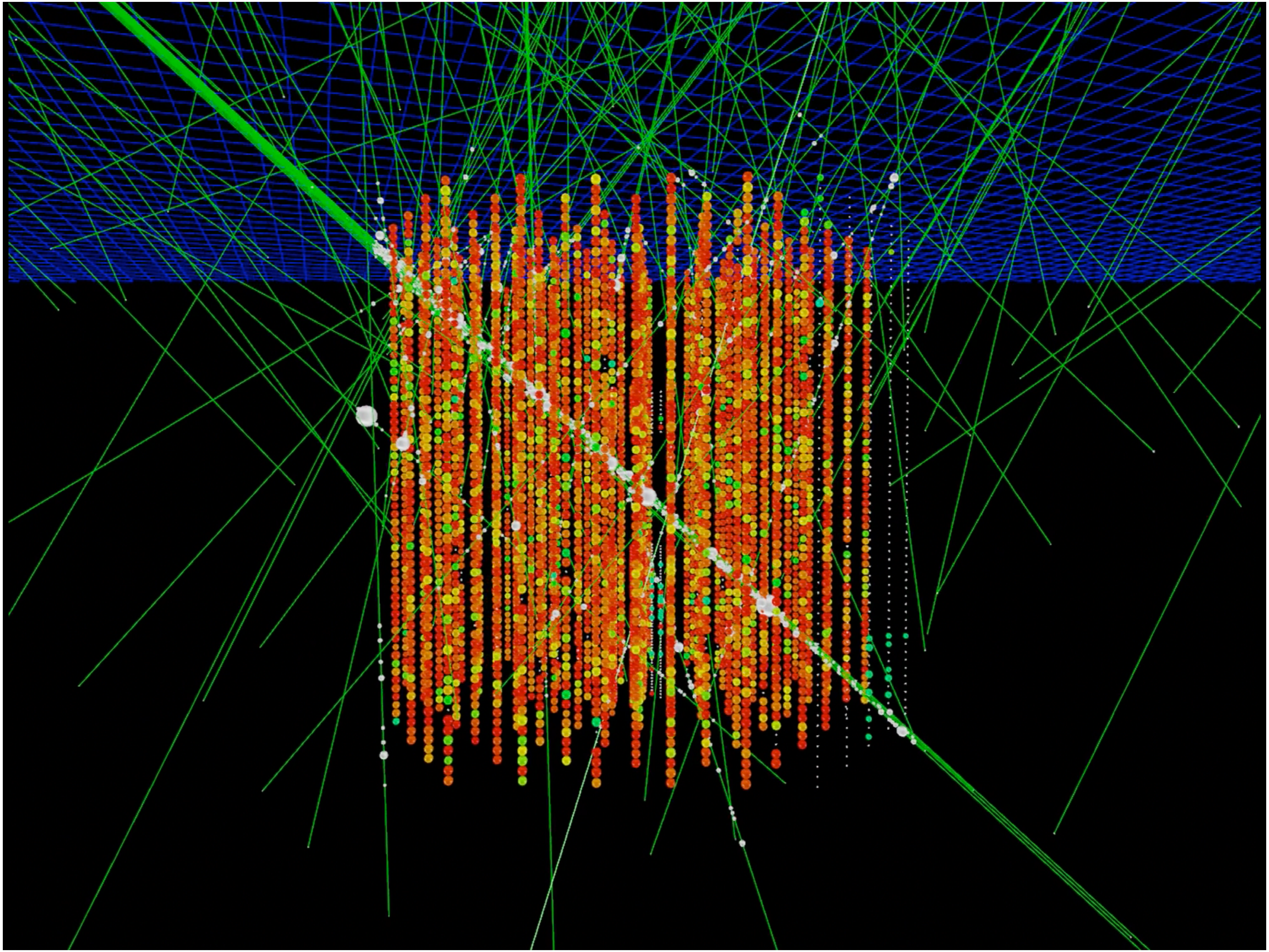
energy reconstruction of electromagnetic showers




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

Signals and Backgrounds





… you looked at 10msec of data !

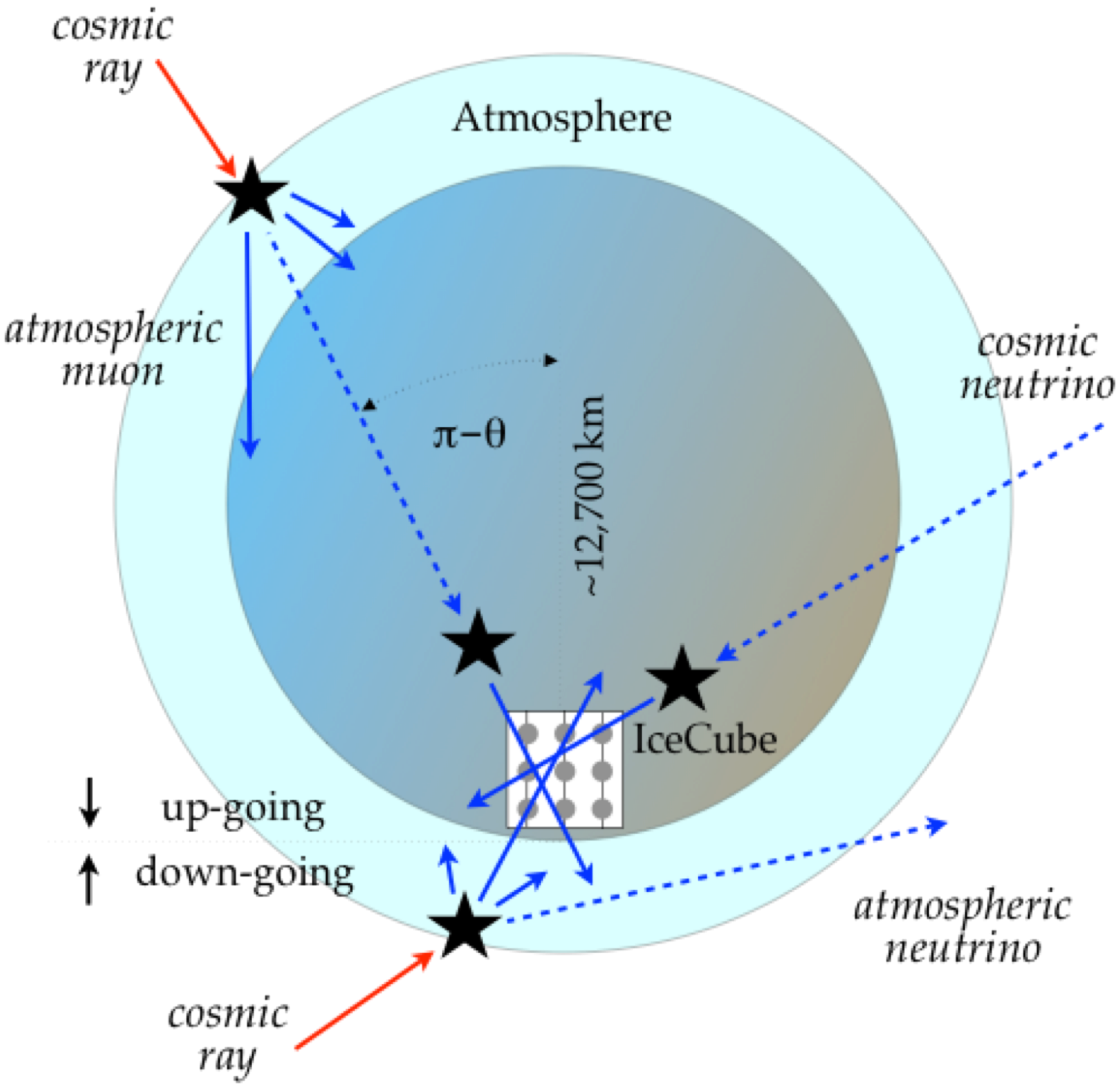
muons detected per year:

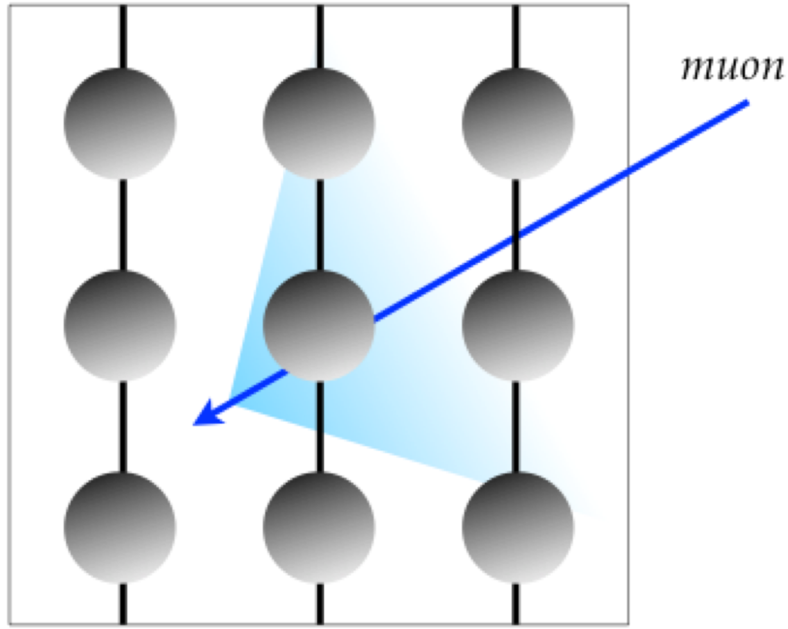
• atmospheric*	μ	$\sim 10^{11}$
• atmospheric**	$\nu \rightarrow \mu$	$\sim 10^{5}$
• cosmic	$\nu \rightarrow \mu$	~ 10

* 3000 per second

** 1 every 6 minutes

- rejecting atmospheric muons

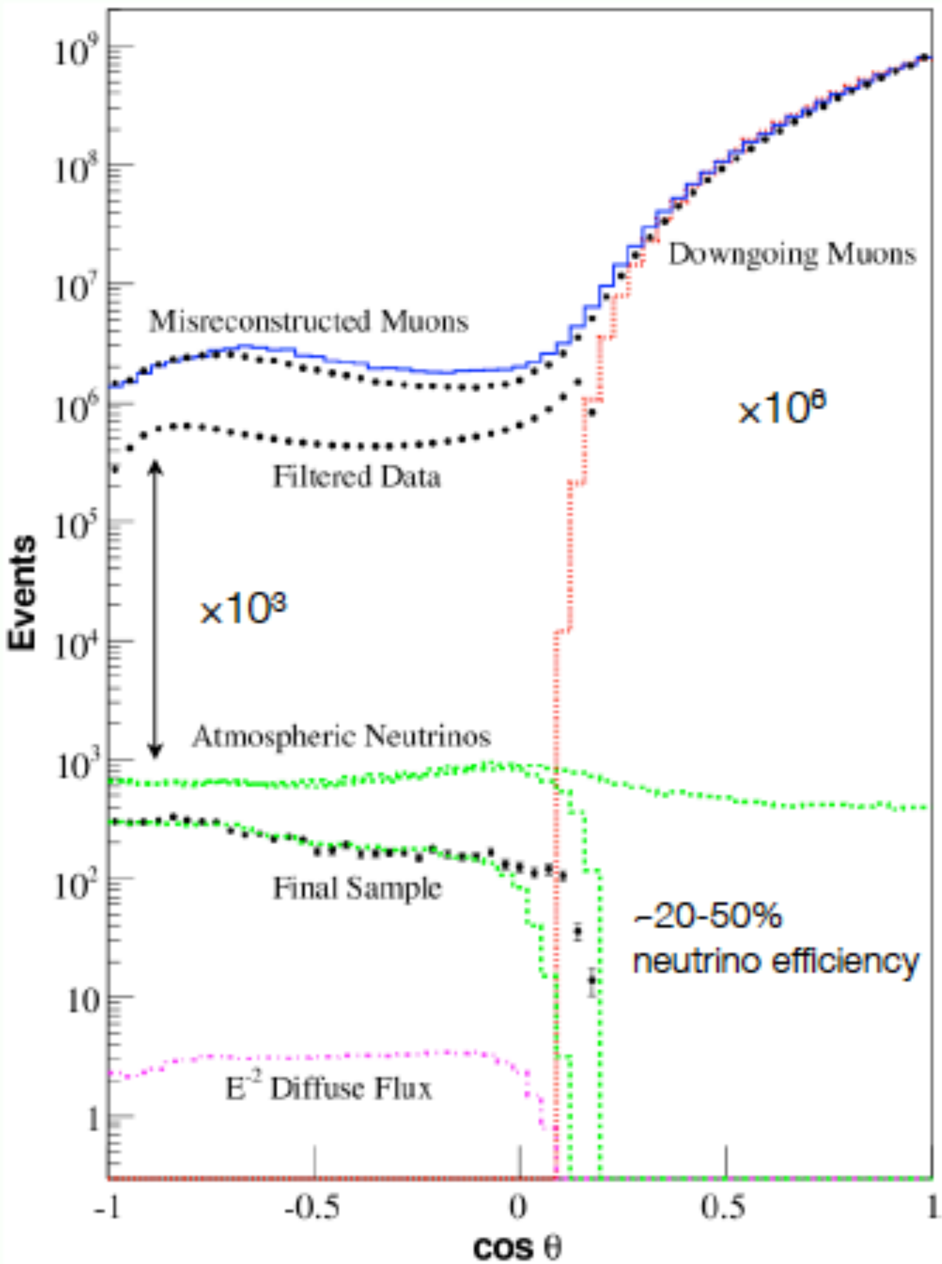


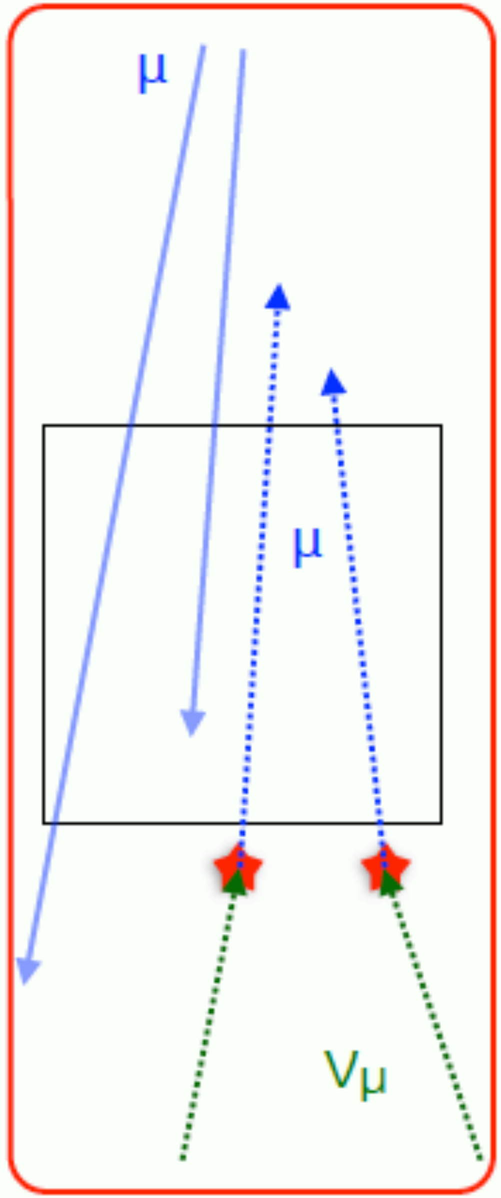


Cherenkov light detection
in optical modules

- rejecting atmospheric neutrinos

through-going (tracks)

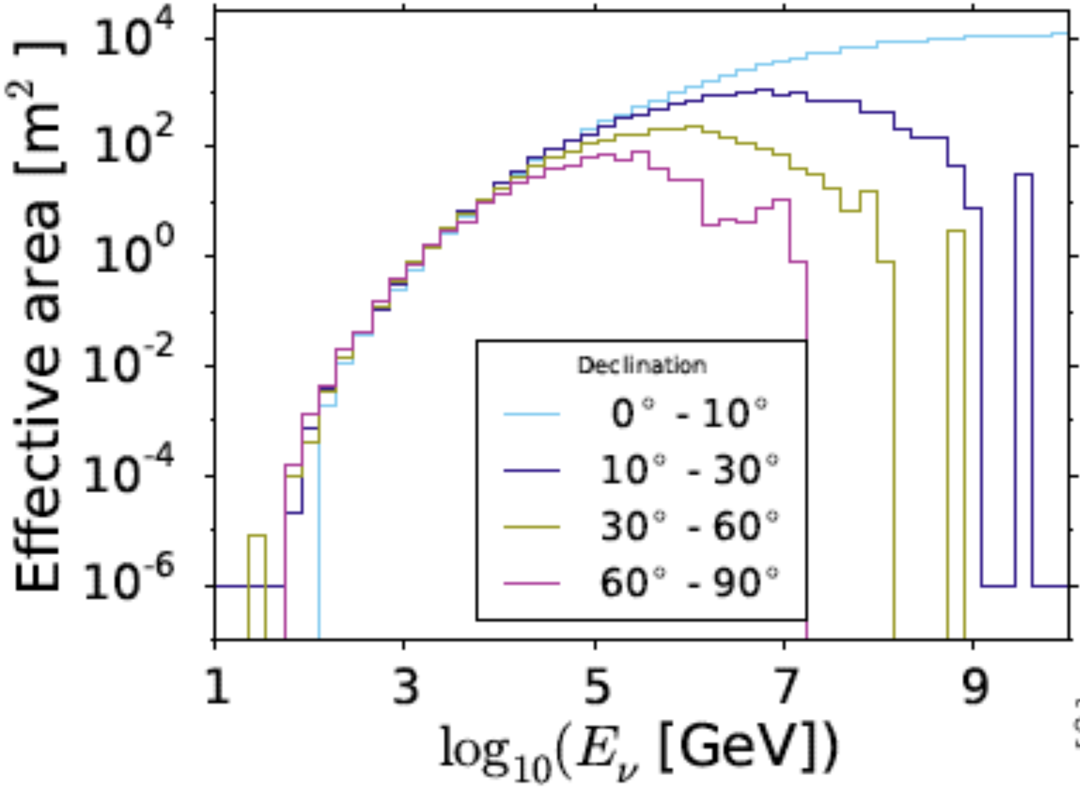




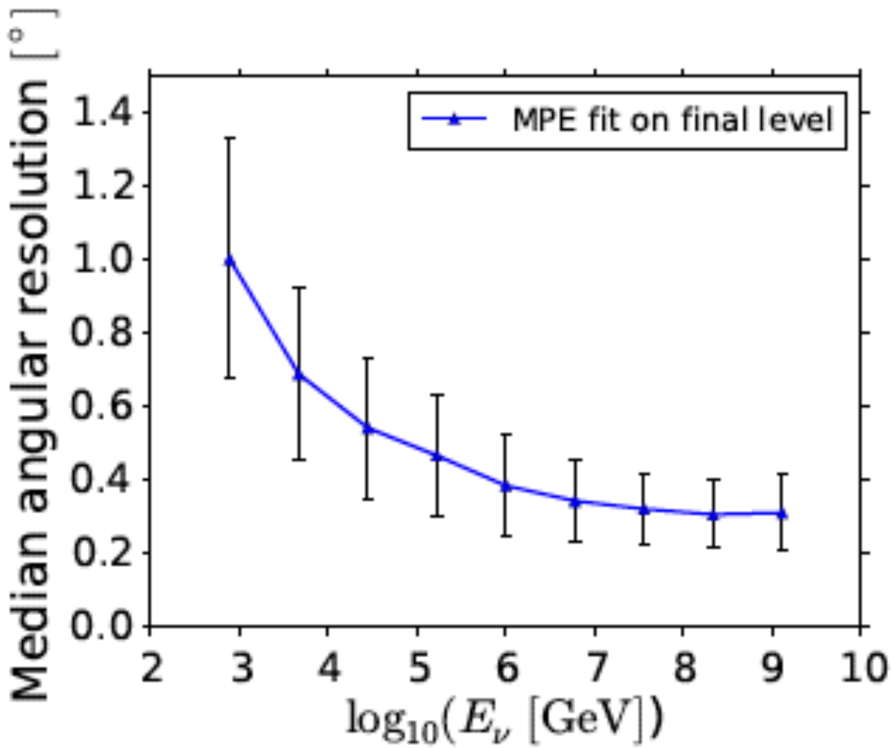
selection cuts for on-line numu extraction

Cut Level	Selection criterion	Atms. μ (mHz)	Data (mHz)	Atms. ν_μ (mHz)	Astro. $\times 10^{-3}$ (mHz)
0	$\cos\theta_{\mathrm{MPE}} \leq 0$	1010.5	1523.81	7.166	6.23
1	$\mathrm{SLogL}(3.5) \leq 8$	282.49	504.44	5.826	5.62
2	$N_{\mathrm{Dir}} \geq 9$	8.839	22.01	3.076	4.06
3	$((\cos\theta_{\mathrm{MPE}} > -0.2)$ AND $(L_{\mathrm{Dir}} \geq 300$ m) OR $(\cos\theta_{\mathrm{MPE}} \leq -0.2)$ AND $(L_{\mathrm{Dir}} \geq 200$ m))	1.124	4.30	2.313	3.69
4	$\Delta_{\mathrm{Split/MPE}} < 0.5$	0.100	2.15	1.899	3.26
5	$((\cos\theta_{\mathrm{MPE}} \leq -0.07)$ OR $((\cos\theta_{\mathrm{MPE}} > -0.07)$ AND $(\Delta_{\mathrm{SPE/Bayesian}} \geq 35)))$	0.080	2.08	1.880	3.25
6	$((\cos\theta_{\mathrm{MPE}} \leq -0.04)$ OR $((\cos\theta_{\mathrm{MPE}} > -0.04)$ AND $(\Delta_{\mathrm{SPE/Bayesian}} \geq 40)))$	0.075	2.06	1.875	3.24

Table 2. IceCube neutrino selection cuts and corresponding passing event rate for the IC-2012 season. At an final selection an event has to fulfill all cut criteria to pass the selection (i.e. a logical AND condition between the cut levels is applied). The atmospheric-neutrino flux is based on the prediction by Honda [71], but atmospheric-muon rate is calculated from CORSIKA simulations. The event rate for IceCube data stream corresponds to the total livetime of 332.36 days. The astrophysical neutrino flux is estimated assuming $dN/dE = 1 \cdot 10^{-8}\ \mathrm{GeV cm^{-2} s^{-1}} (\frac{E}{\mathrm{GeV}})^{-2}$. (Atms. = atmospheric, Astro. = astrophysical)



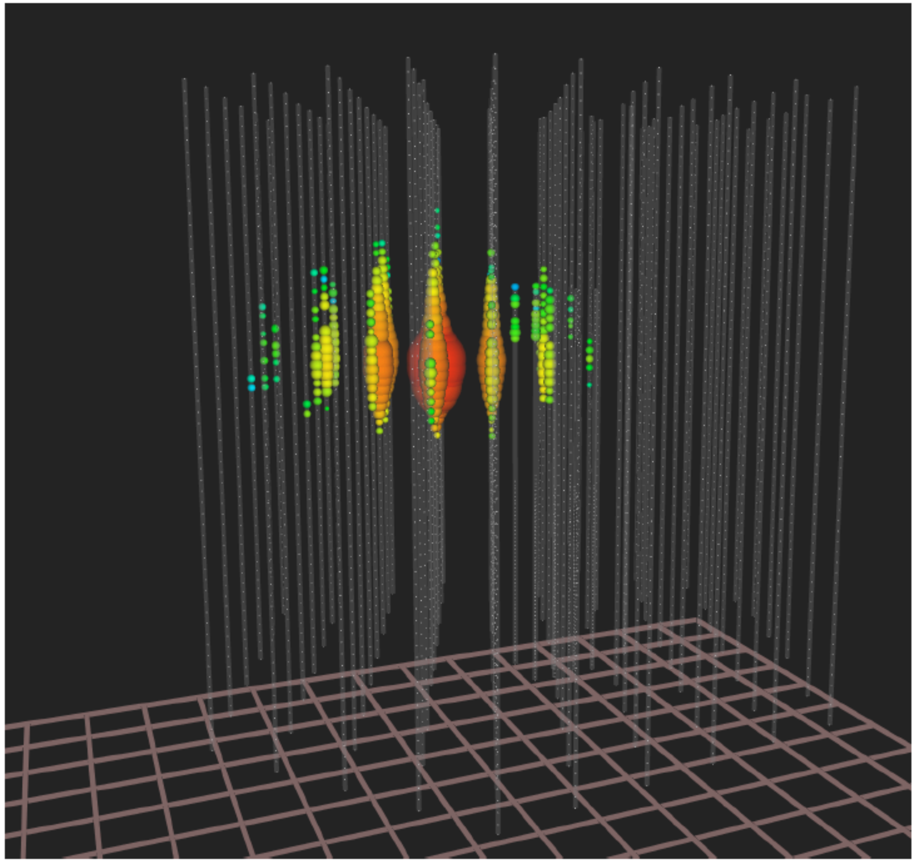
Effective area [m^2]
Declination
0° - 10°
10° - 30°
30° - 60°
60° - 90°
10^4
10^2
10^0
10^{-2}
10^{-4}
10^{-6}
1
3
5
7
9
$\log_{10}(E_\nu$ [GeV])

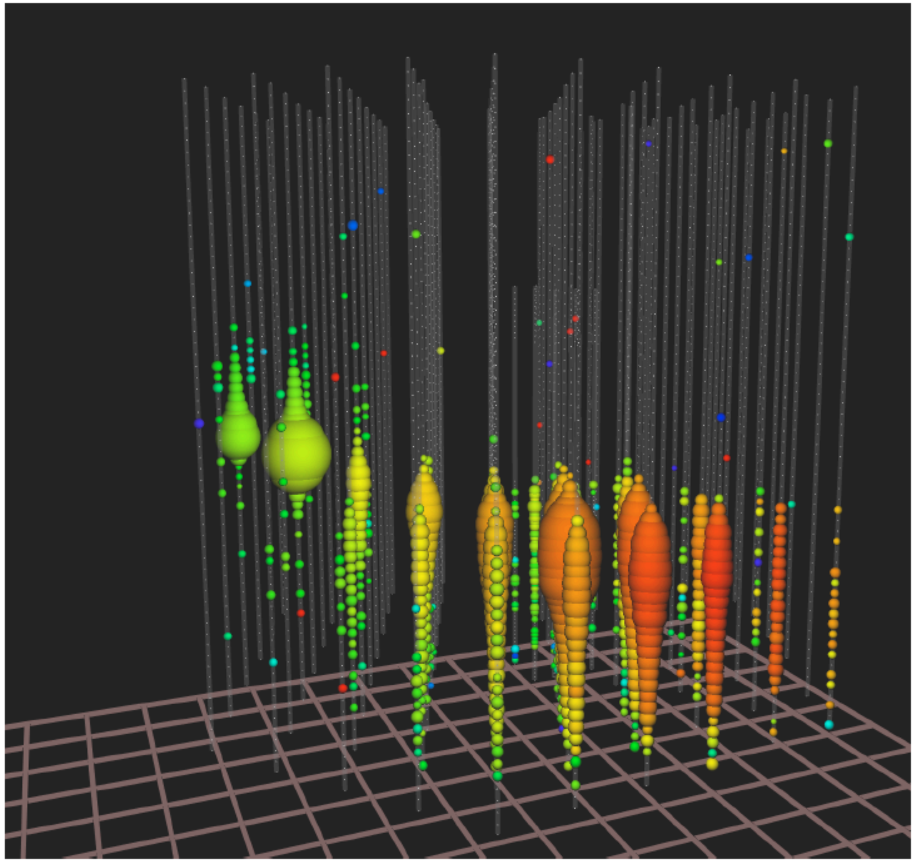


Median angular resolution [°]
MPE fit on final level
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
2
3
4
5
6
7
8
9
10
$\log_{10}(E_\nu$ [GeV])

isolated neutrinos interacting *inside* the detector (HESE)

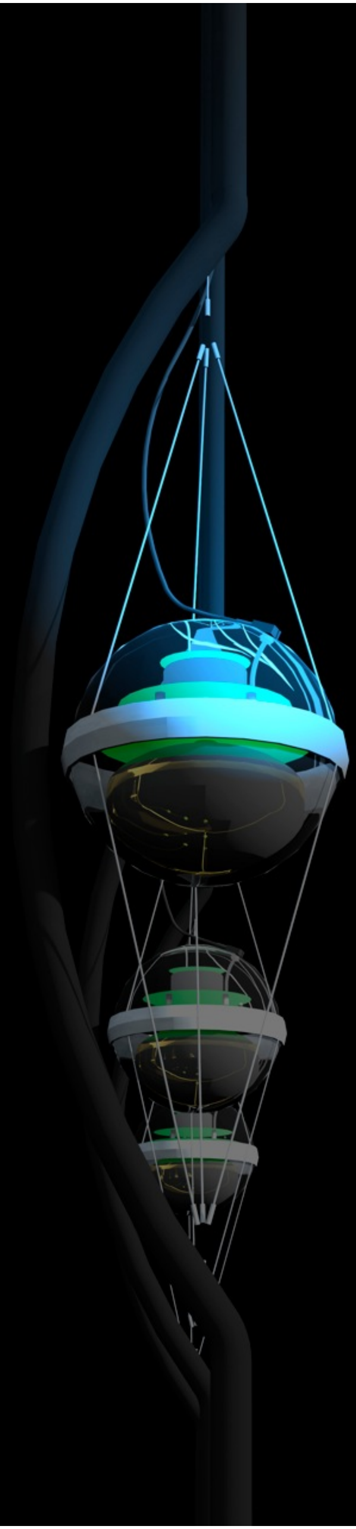
up-going muon tracks (UPMU)





total energy measurement all flavors, all sky

astronomy: angular resolution superior (<0.5°)



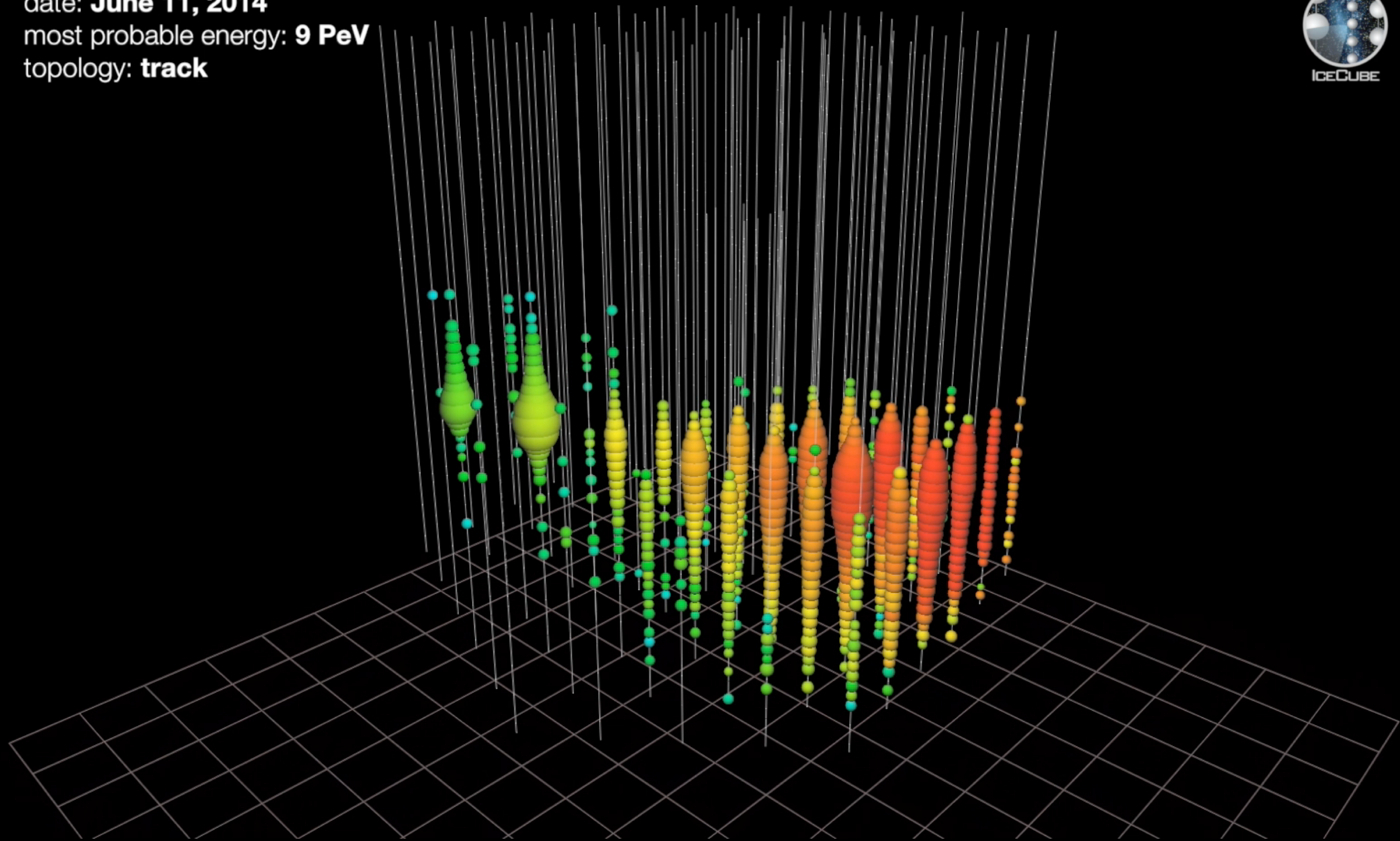
IceCube

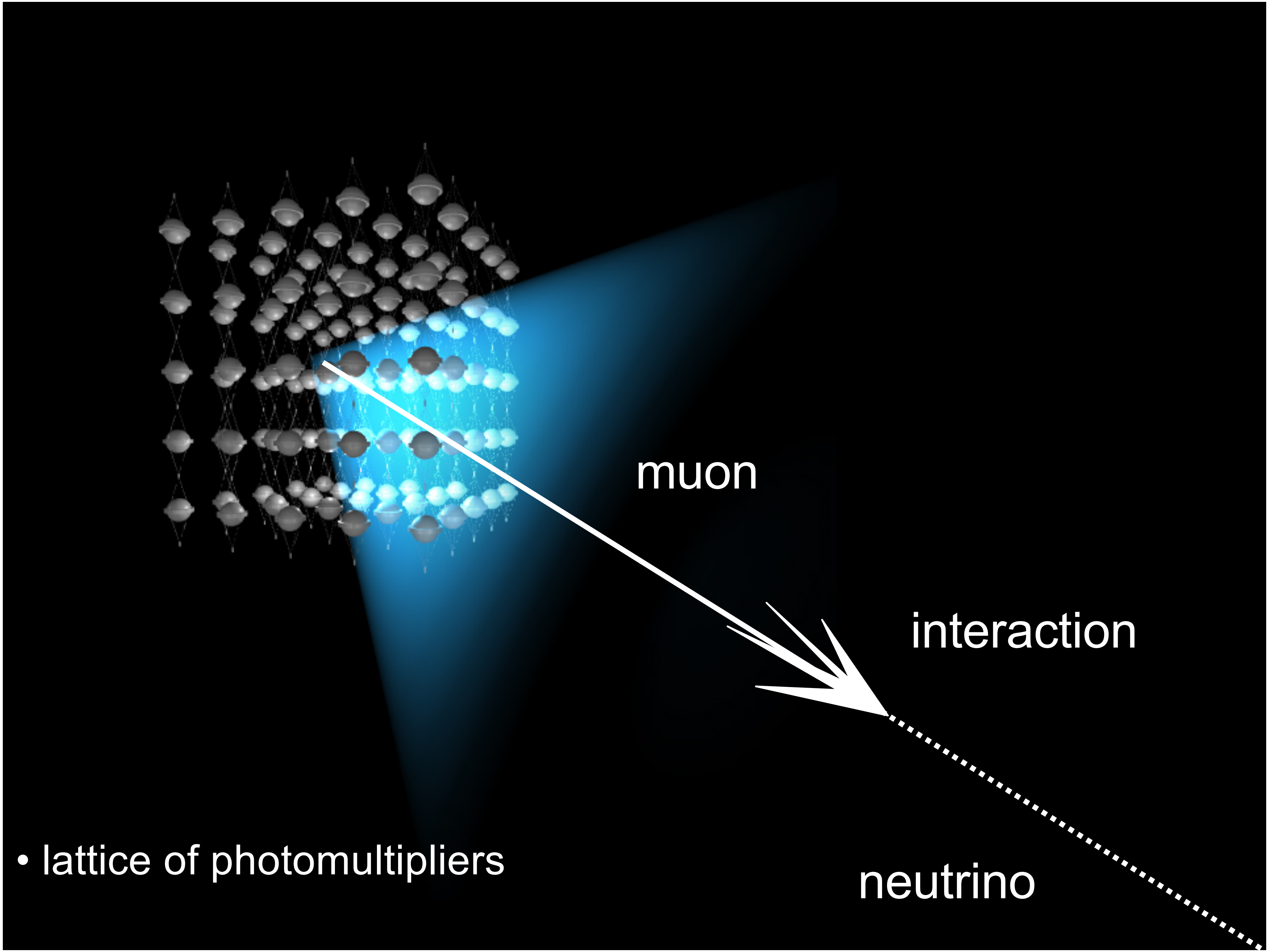
francis halzen

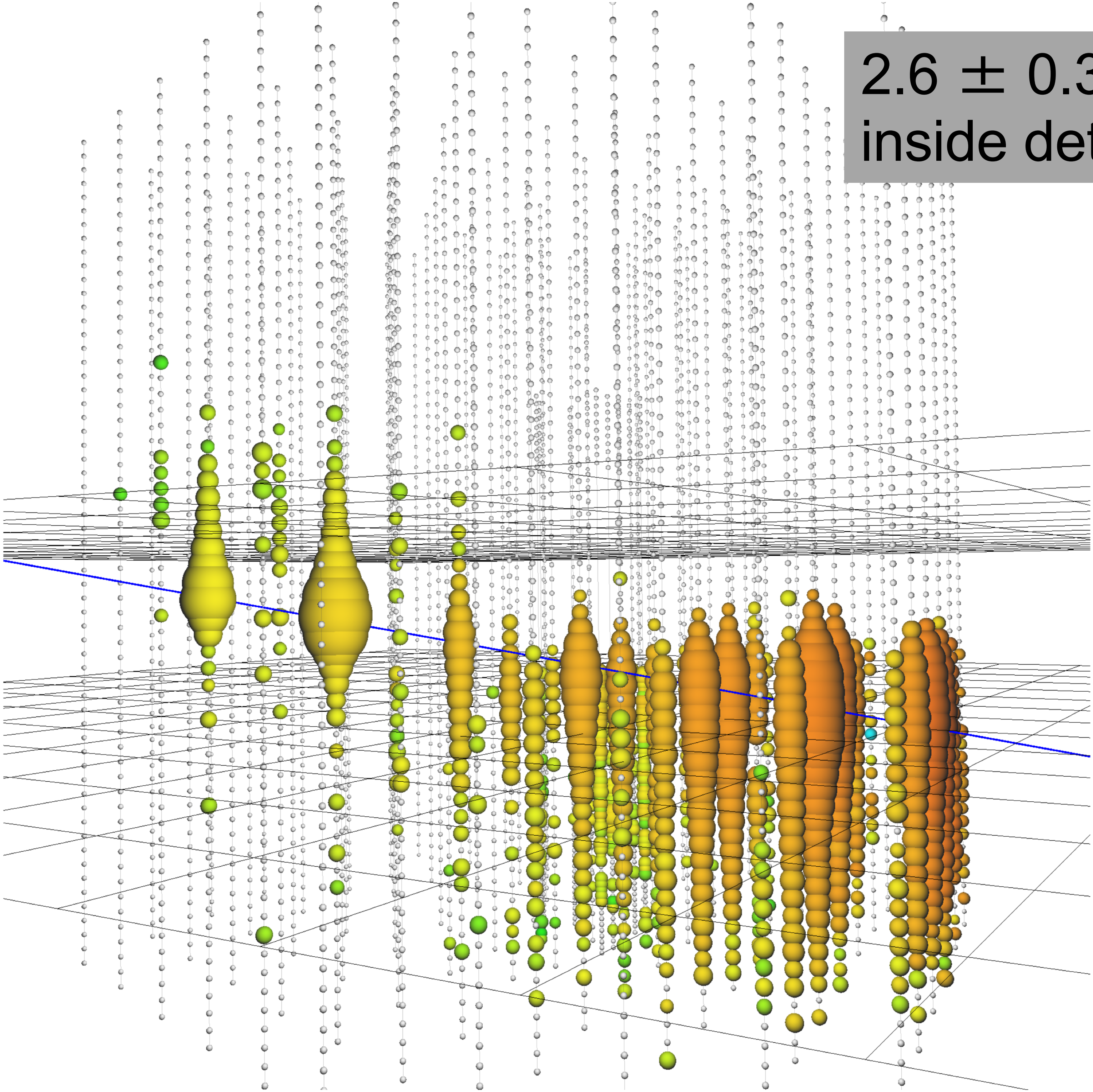
- IceCube
- cosmic neutrinos: two independent observations
  - → muon neutrinos through the Earth
  - → starting neutrinos: all flavors
- where do they come from?
- Fermi photons and IceCube neutrinos
- the first high-energy cosmic ray accelerator
- what next?

IceCube.wisc.edu

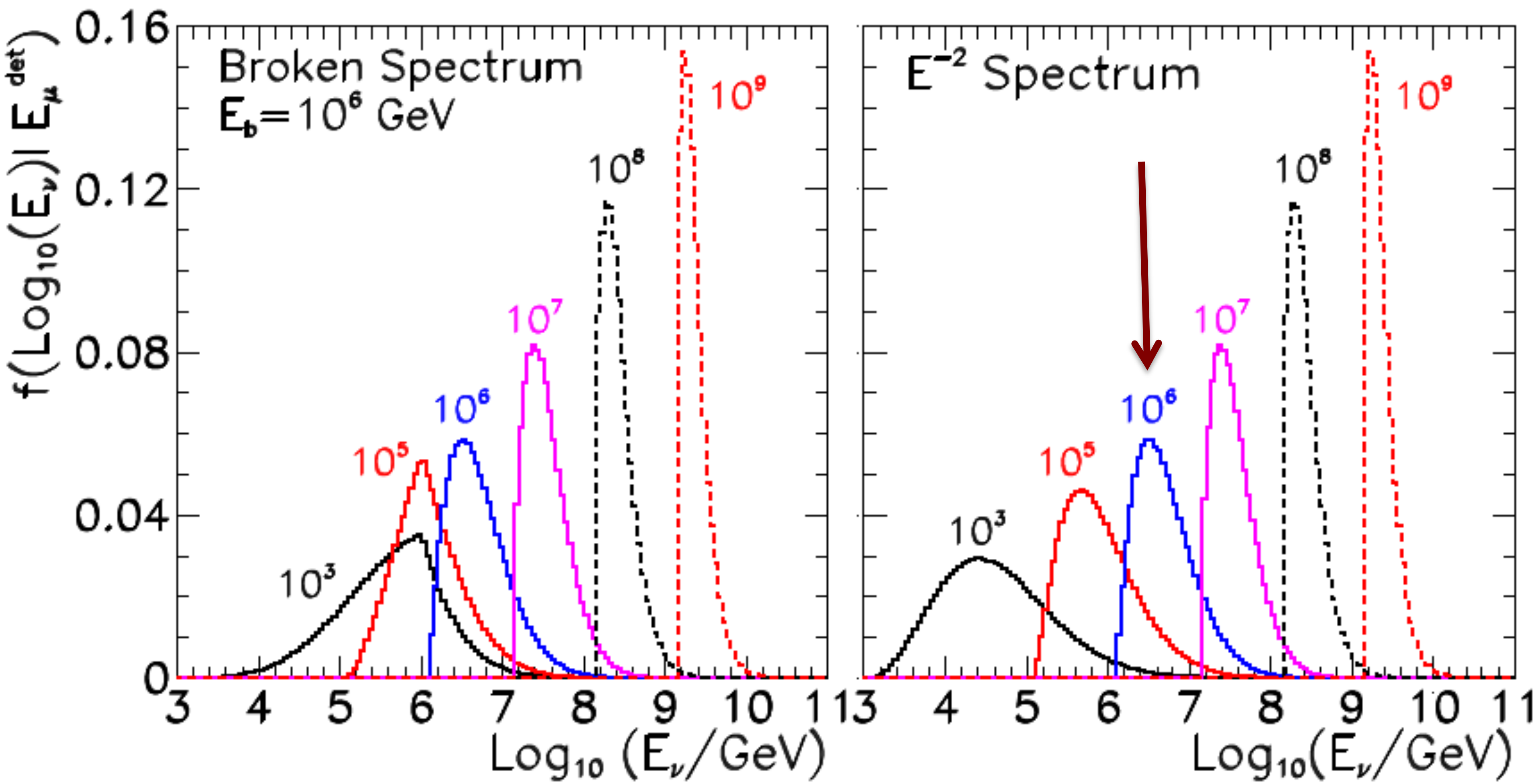
date: **June 11, 2014**
most probable energy: **9 PeV**
topology: **track**




muon
interaction
neutrino
• lattice of photomultipliers

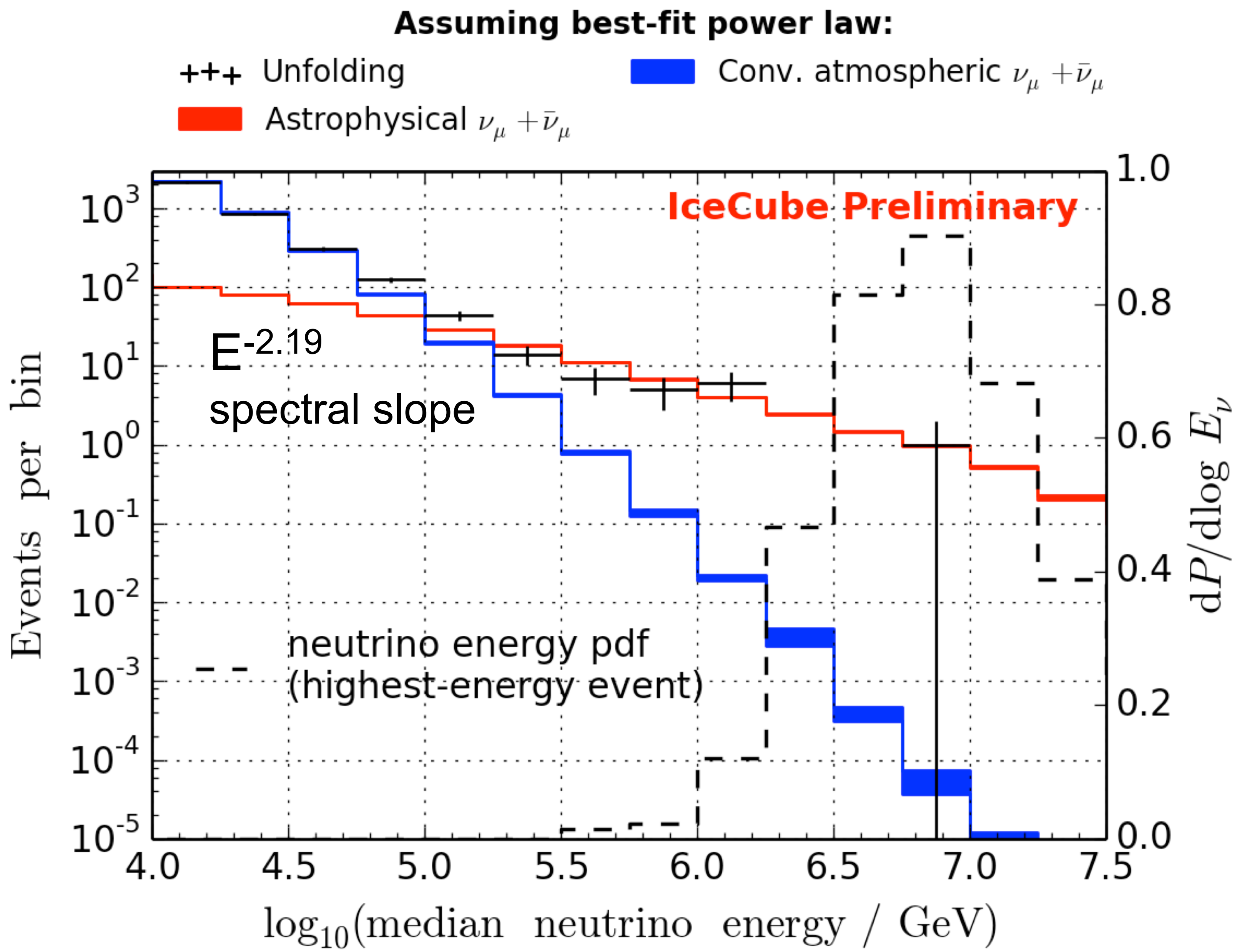

2.6 ± 0.3 PeV
inside detector

distribution of the parent neutrino energy corresponding to the energy deposited by the secondary muon inside IceCube

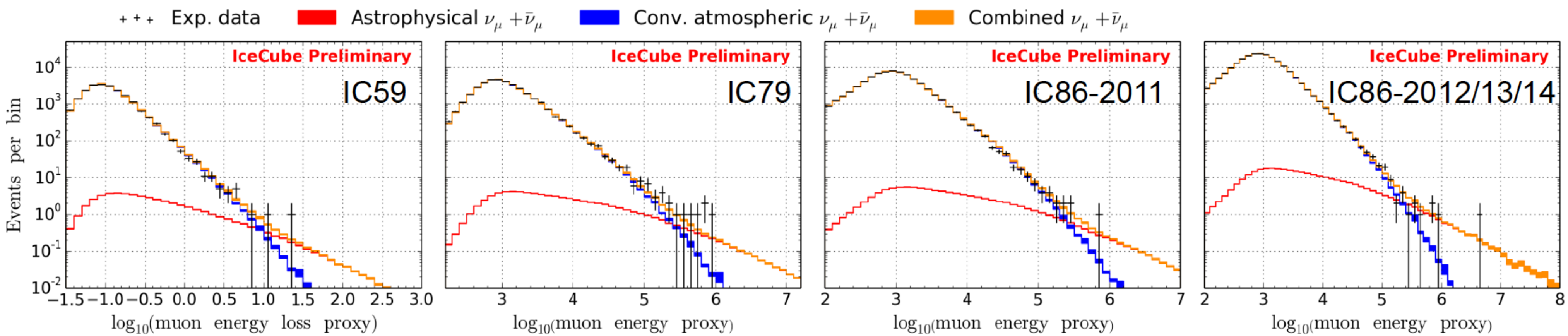


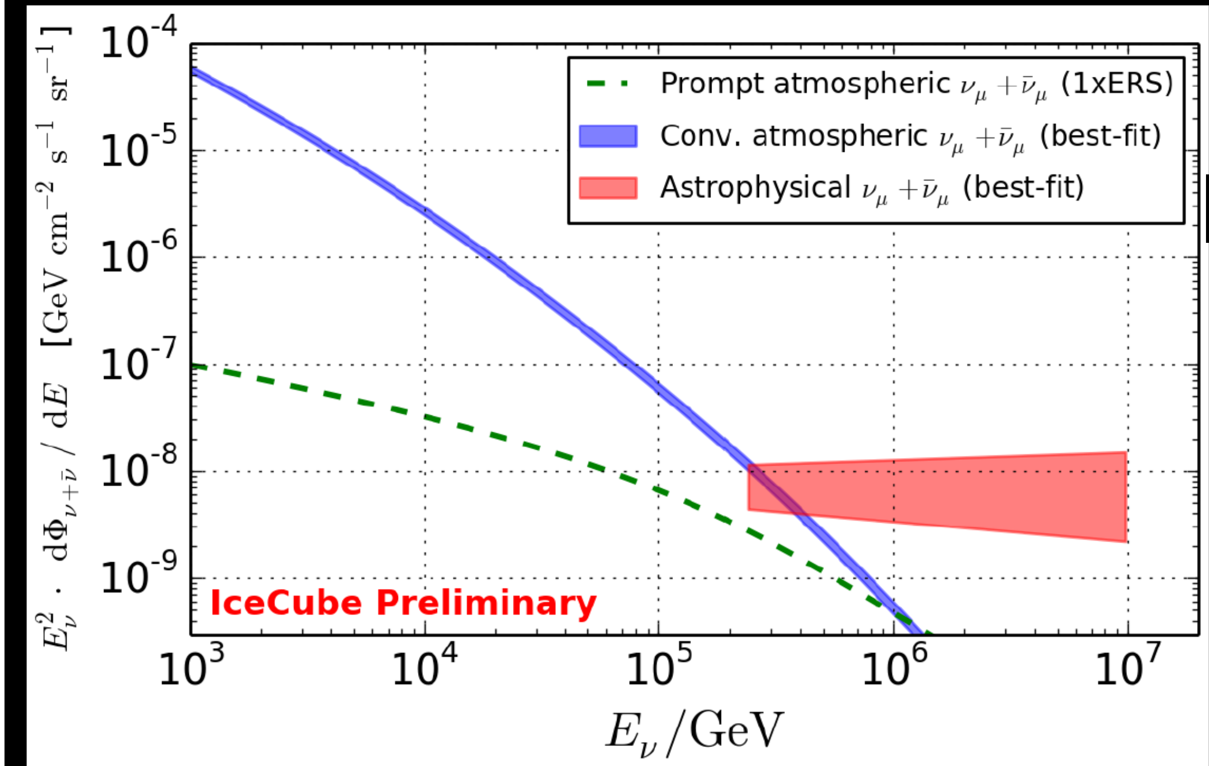
~ 550 cosmic neutrinos in a background of ~340,000 atmospheric

atmospheric background: less than one event/deg^2/year



after 7 years → 6.4 sigma   120 cosmic neutrinos/year/flavor





- Best-fit astrophysical normalization:

  0.97+.27-.25 $\times 10^{-18}\ \mathrm{GeV^{-1} cm^{-2} s^{-1} sr^{-1}}$

- Best-fit spectral index:

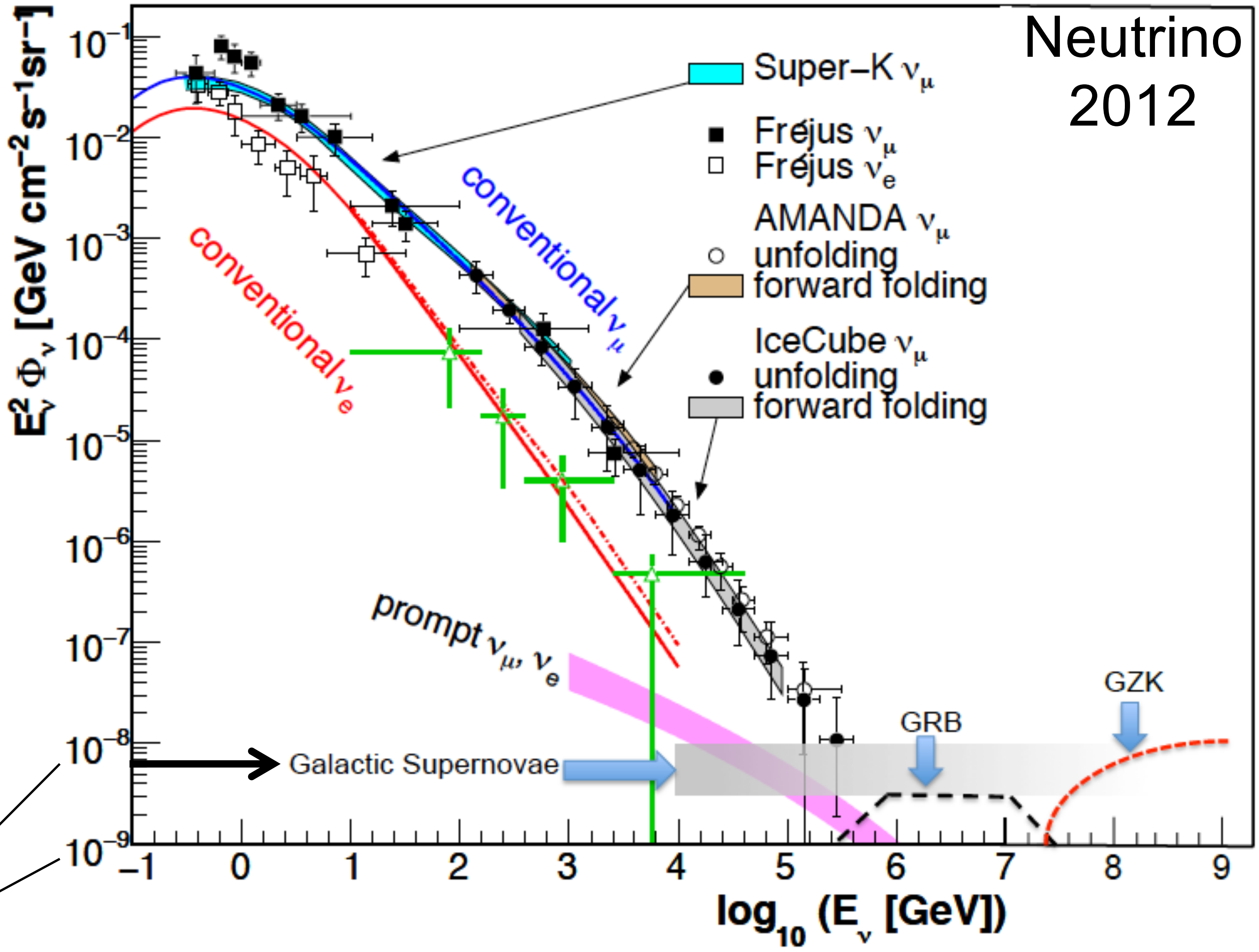
  γ_{astro} = 2.16 ± 0.11

- Energy ranges:

  240 TeV – 10 PeV

- Atmospheric-only hypothesis excluded by 6.0σ above 100 TeV

- cosmic neutrinos
- atmospheric background disappears



$$dN/dE \sim E^{-2}$$

10—100 events per year for fully efficient detector

atmospheric

cosmic

100 TeV

430 TeV inside detector

PeV ν_μ

no air shower

all cosmic neutrinos are isolated by self-veto