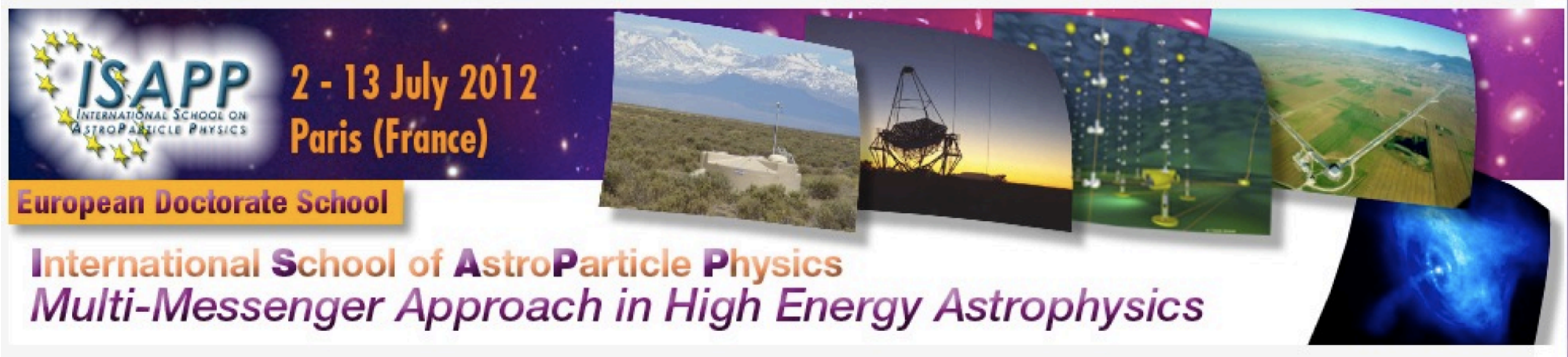


Neutrino Astronomy

Elisa Resconi, TU Munich

TECHNISCHE UNIVERSITÄT MÜNCHEN

Heisenberg-Programm
Deutsche Forschungsgemeinschaft

Content

FIRST PART

- Introduction
- Atmospheric muons and neutrinos:

  1) production of muons and neutrinos in the atmosphere

  2) muons and neutrinos in underground

  3) neutrino induced charged particles

  4) neutrino oscillation measurements / beyond: mass hierarchy?

Content

<u>SECOND PART</u>

- Astrophysical neutrinos:
  - connection with CR primary energies
  - High Energy neutrinos: reconstruction
- Neutrino telescopes: selected list of results
  - atmospheric neutrino oscillation
  - point source
  - GRB
  - high energy cascades: first extra-terrestrial neutrinos?

Introduction, few words

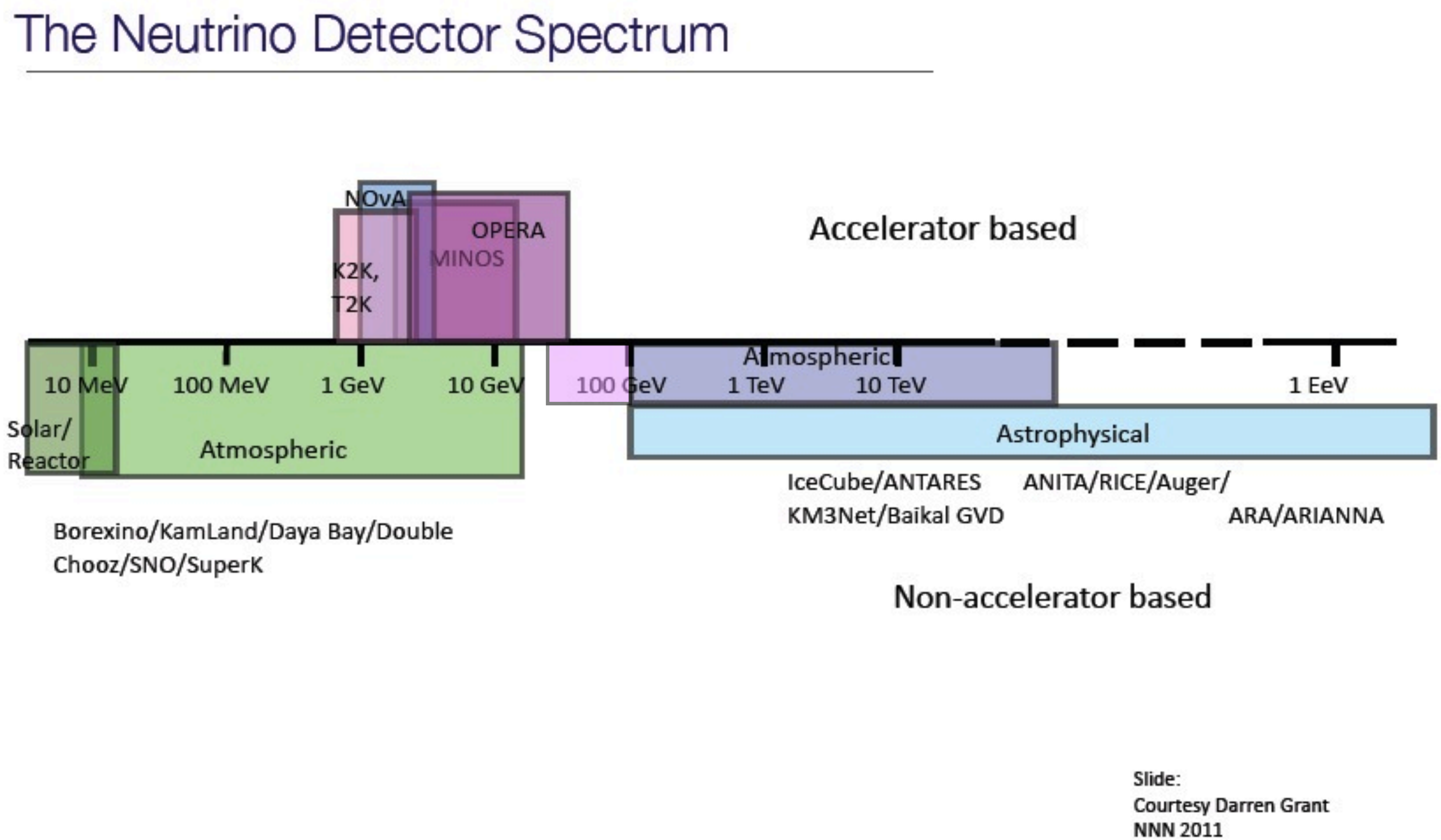
- Beginning in the 1970s, the dream of **high-energy neutrino astronomy** fascinated a small group of visionaries.
- The techniques were borrowed from **particle physics** and the potential sources were predicted from high-energy **astrophysics**.
- A true **new field of science** across different disciplines and communities got started… it was Hawaii time.
- Neutrinos interact only sporadically (weakly), hence the need for **huge detector volumes.**
- Natural medium (transparent, huge volume, inexpensive): **air, water** first choices. DUMAND, Baikal, Antares in water.

- Beginning in the 1970s, the dream of **high-energy neutrino astronomy** fascinated a small group of visionaries.
- 1990: AMANDA (**Antarctic Muon and Neutrino Detector Array)** collaboration formed.
- Very clear since the beginning the need of **km^3 scale neutrino telescope**
- **2000:** AMANDA completed at the South Pole, first demonstration of feasibility of a large neutrino telescope in the ice
- **May 30th, 2008**: Antares detector completed!
- 2002: IceCube project approved. The first km^3 scale neutrino telescope.
- 2004-2010 drilling of IceCube strings
- 18th of December 2010, IceCube neutrino telescope completed!

Warning!

In these two lectures, I will discuss the physics of neutrino telescopes in the most general way possible. Be aware, I am an IceCube member (and not an Antares one) so I will use IceCube as example in most of the cases.

Neutrino energy scales vs sources



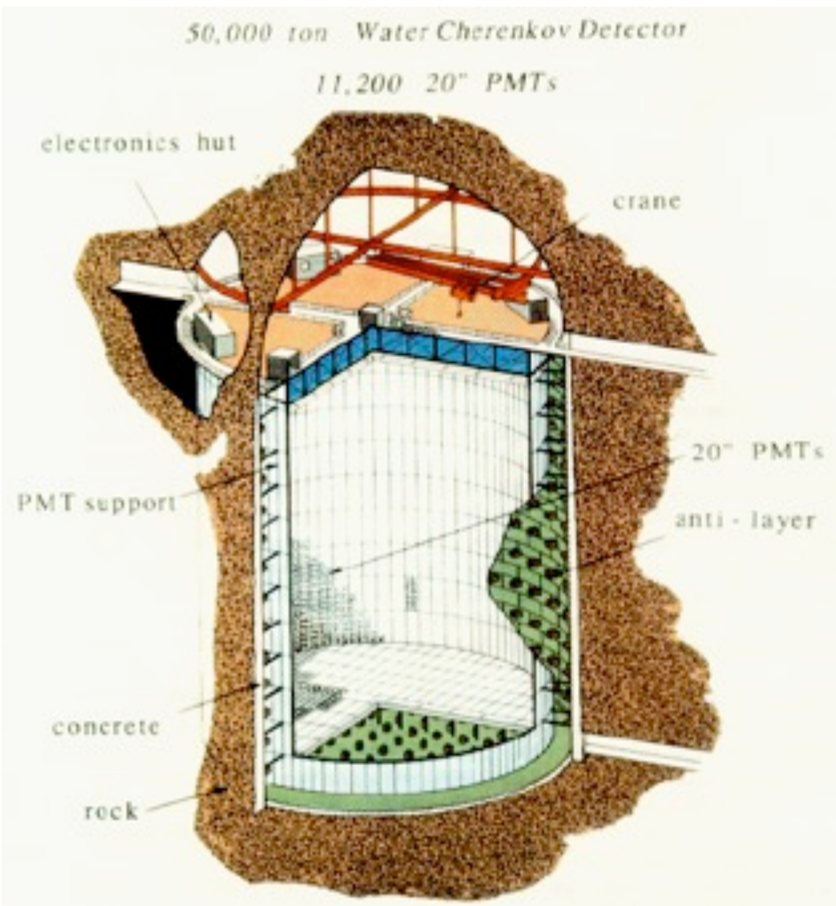
** boxes select primary detector physics energy regimes and are not absolute limits*

Introduction to neutrino experiments

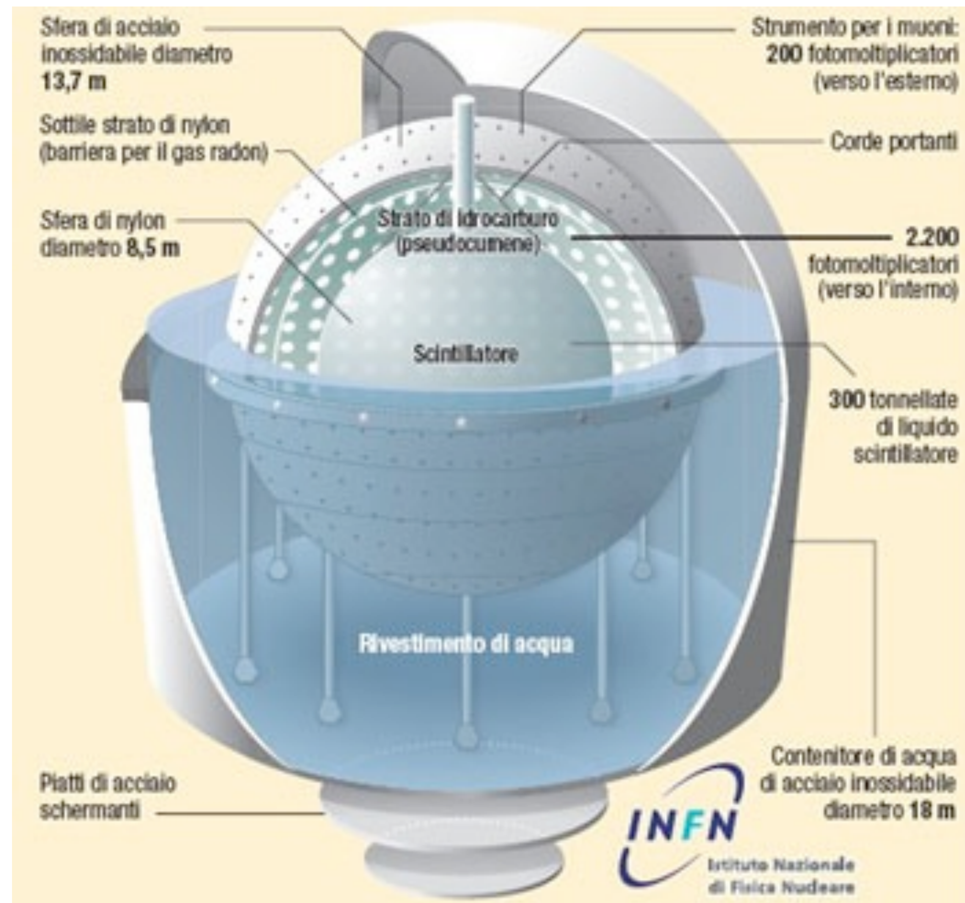
Low (**< 10 GeV**) Energy Experiments are installed in underground facilities:

- Neutrinos from SN Core Collapse

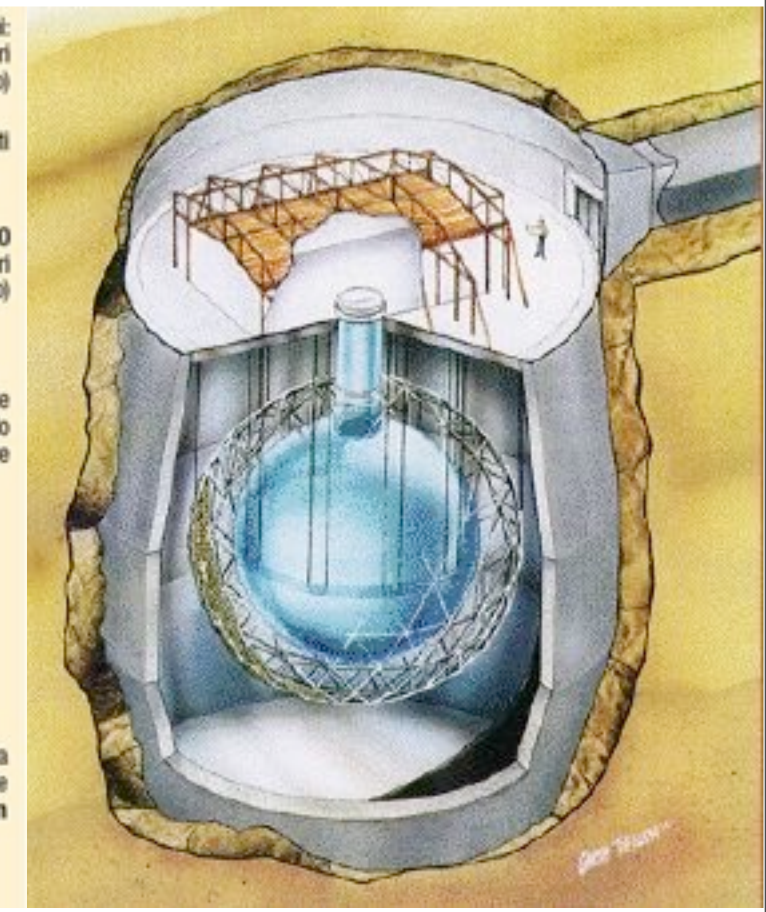
- Neutrinos from Sun



SuperKamiokande



Borexino

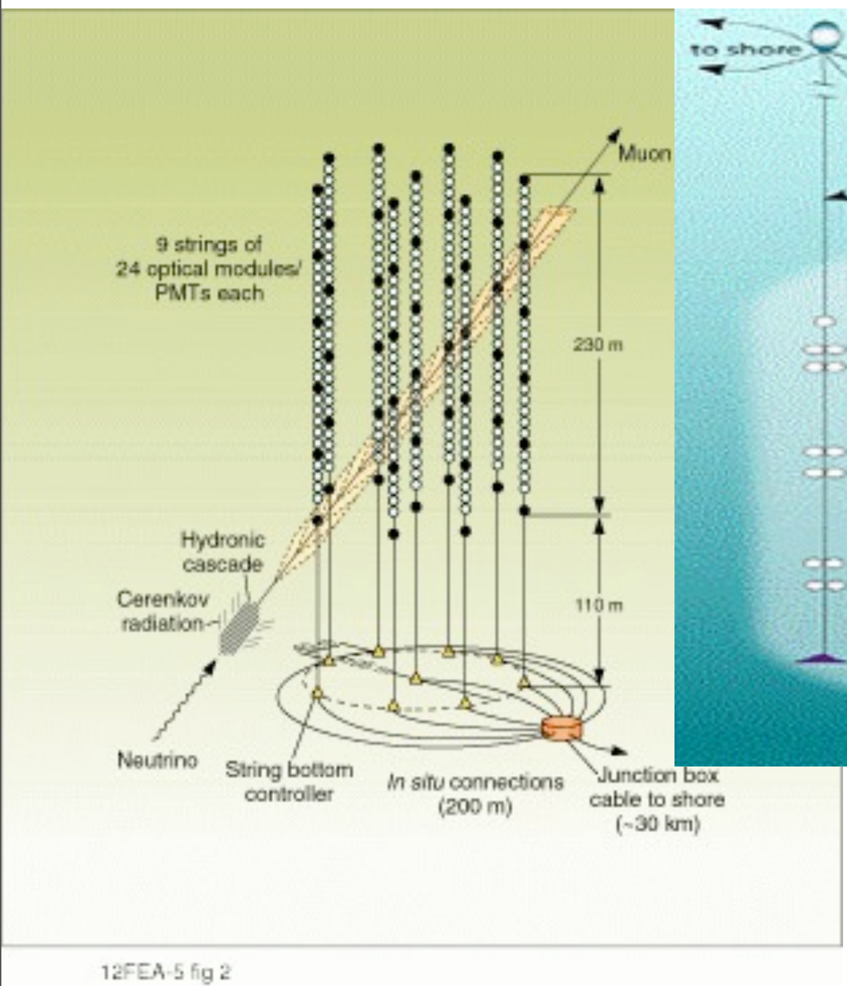


SNO

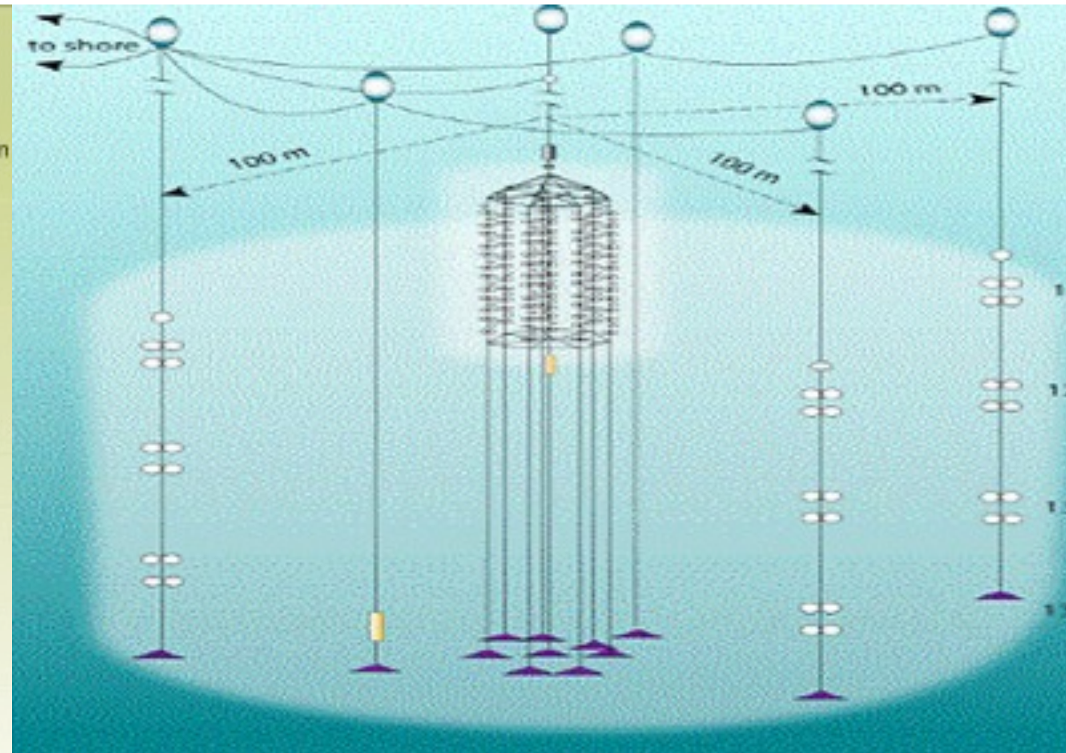
Discovery of neutrino oscillation, SN 1987A

Introduction to neutrino experiments

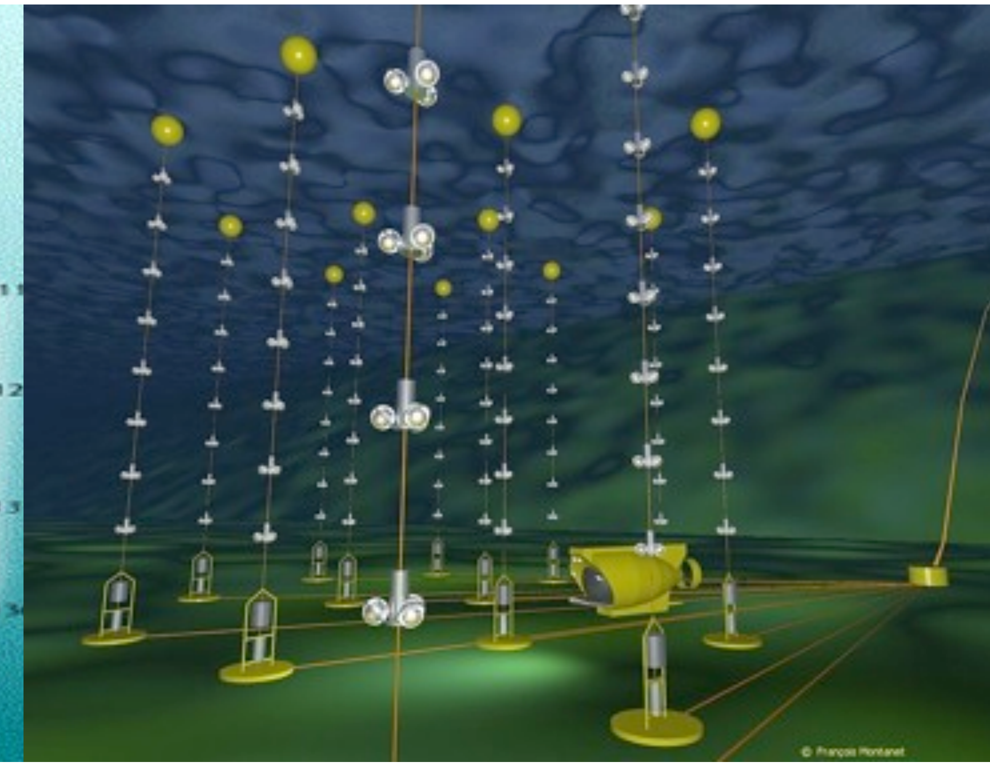
High (**>100 GeV**) Energy Experiments are installed in natural medium:
Option 1: WATER



DUMAND (never realized)



Baikal Neutrino Telescope



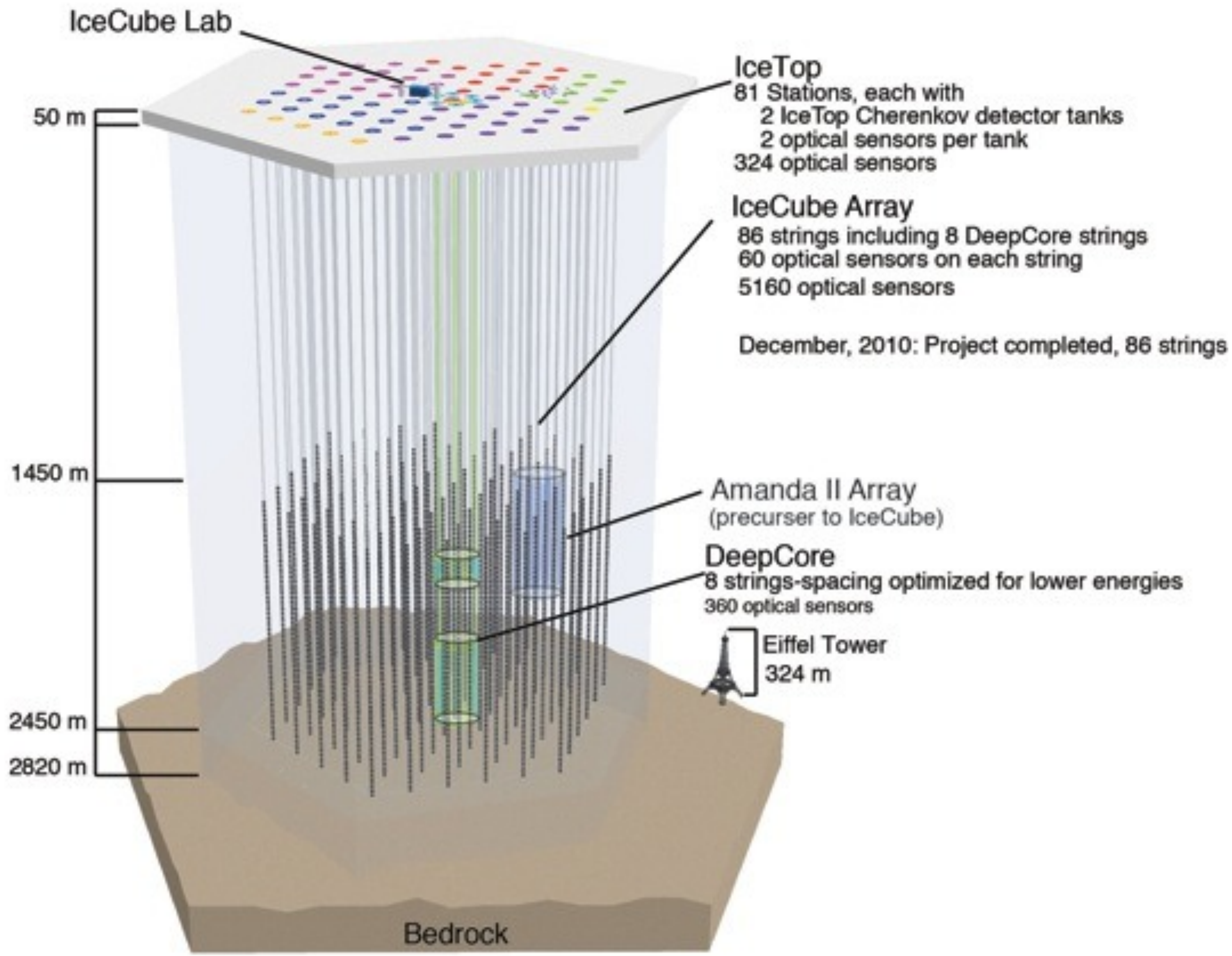
Antares

Introduction to neutrino experiments

High (**>100GeV**) Energy Experiments are installed in natural medium:
Option2: Ice @ South Pole

Extension at lower energies
(**~100 GeV - ~10 GeV**):
DeepCore

AMANDA (decommissioned),
IceCube (IceTop, "in-ice",
DeepCore)



Atmospheric muons and neutrinos

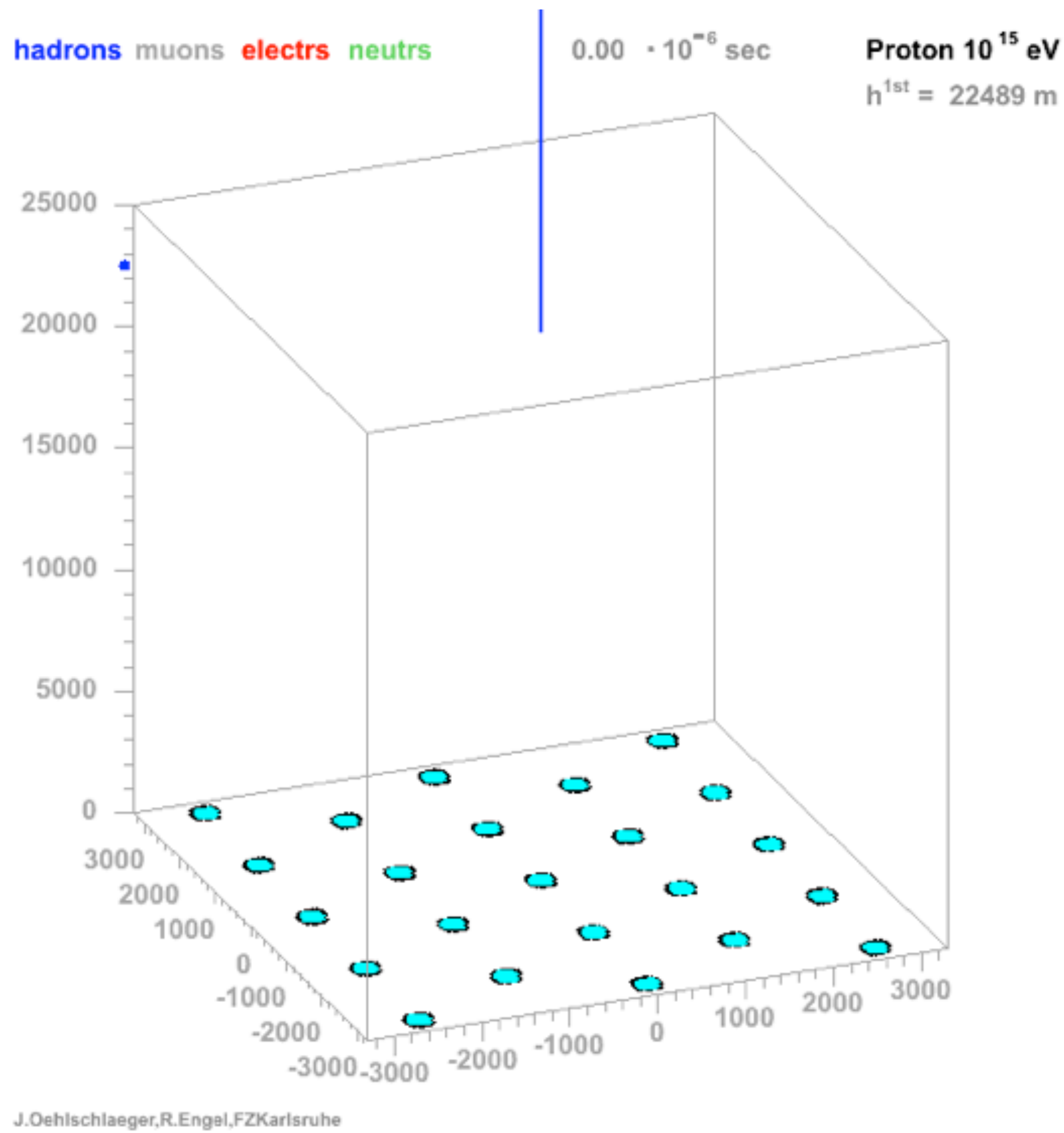
1) production of muons and neutrinos in the atmosphere

2) muons and neutrinos in underground

3) neutrino induced charged particles

1) production of muons and neutrinos in the atmosphere

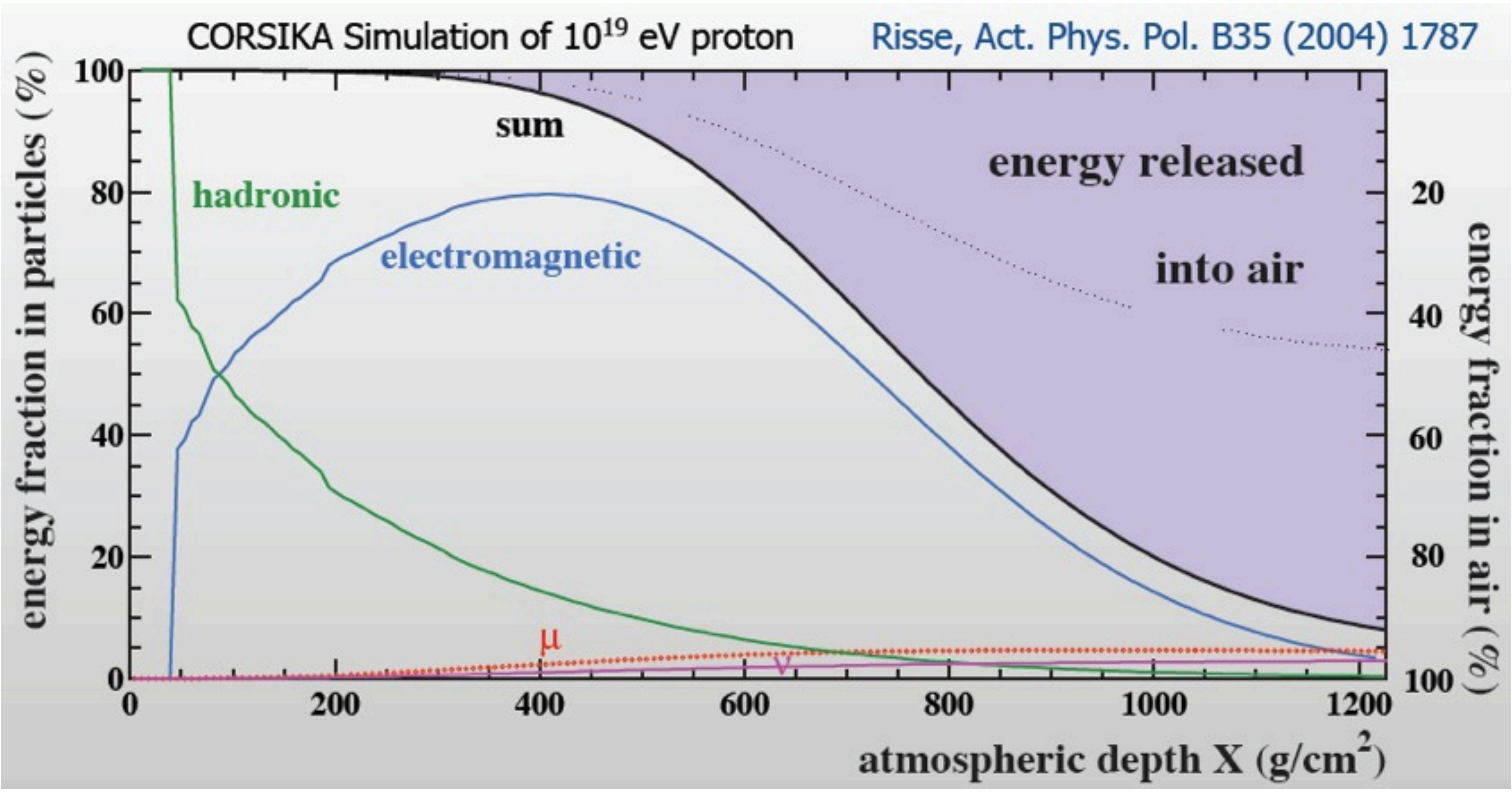
1) production of muons and neutrinos in the atmosphere



1) production of muons and neutrinos in the atmosphere

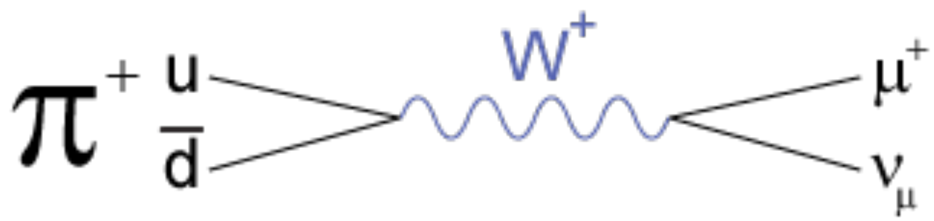
- Atmospheric muons and neutrinos are produced together
- Principle production channel: two body decays of charged pions and kaons
- Neutrinos also from the decay of muons but only important for low energies
- Neutrinos: the most abundant component of the cosmic radiation at ground
- Muons: the “penetrating component” of the cosmic radiation (abundant, nearly stable and small cross section)
- Muons are charged ⇒ easy to be detected ⇒ often used as calibration source for cosmic-ray detectors

1) production of muons and neutrinos in the atmosphere



1) production of muons and neutrinos in the atmosphere

$\pi^{\pm}$ mesons: mass = 139.6 MeV, mean lifetime= $2.6{\times}10^{-8}$ s.
Purely leptonic decay mode, ~100% branching ratio:



Electronic mode: suppressed with respect to the muonic one. Suppression factor given by the ratio of the half-widths of the pion–electron and the pion–muon decay reactions, experimentally measured:

$$R_\pi = (m_e/m_\mu)^2 \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.233 \times 10^{-4}$$

mu$^{\pm}$ decay important only at low energy (E < 2.5 GeV): muon decay length < production height (~ 15 km) above this energy, muons do not decay

1) production of muons and neutrinos in the atmosphere

mu$^{\pm}$ decay important only at low energy (E < 2.5 GeV): muon decay length < production height (~ 15 km)
above this energy, muons do not decay

At low energy: $\Phi_{\nu,\mu} \propto E^{-2.7}$ (same spectral index as primary spectrum)

Above critical energy $\Phi_{\nu} \propto E^{-3.7}$

Critical energy depends on zenith angle:
$E_{critical} = \boldsymbol{\varepsilon}_i / \cos\boldsymbol{\theta}$

"critical energy", i.e. the energy above which interactions dominate over decays.
Along the vertical (θ = 0°)

Table 1
Particle data summary.

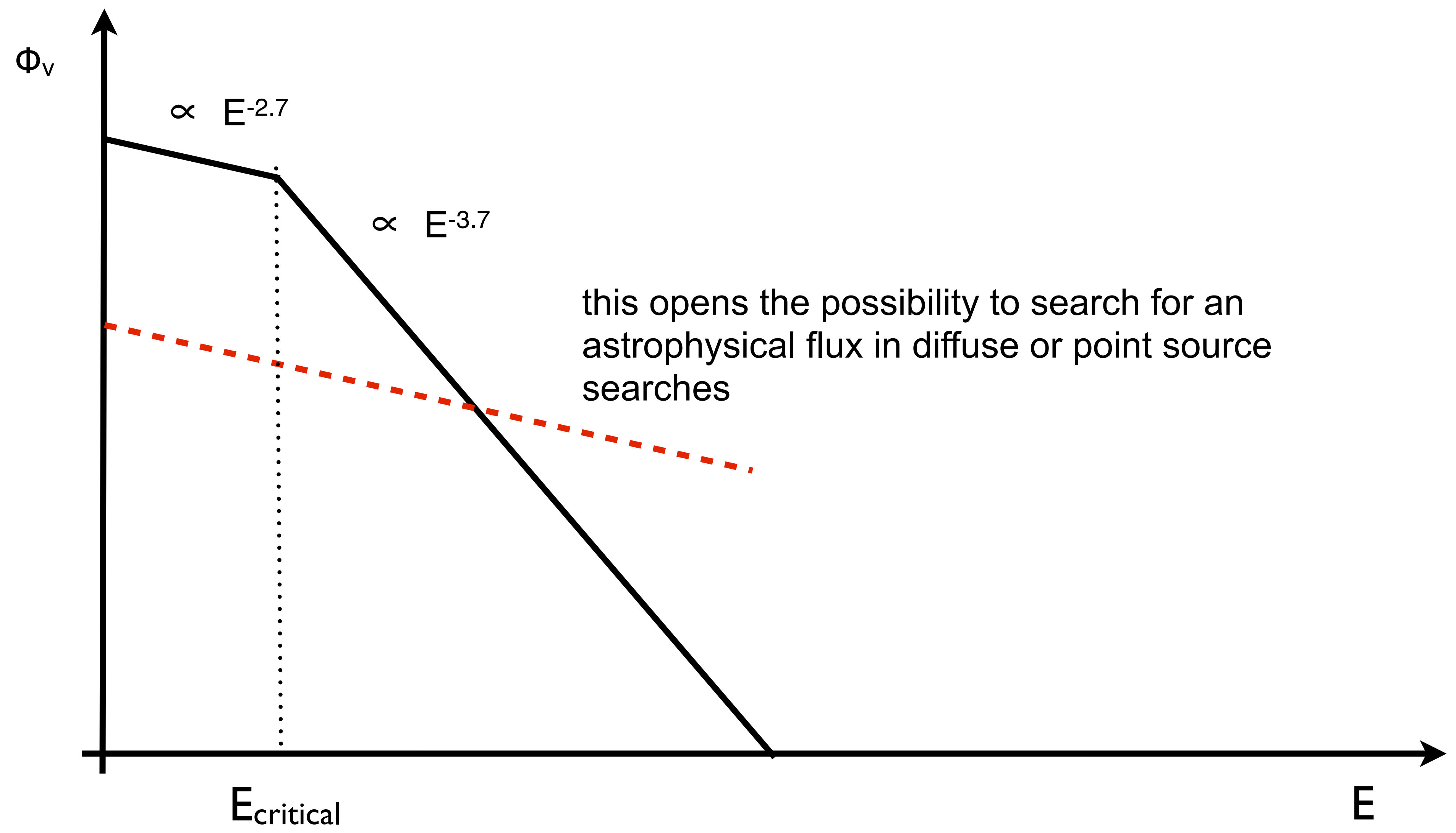
Particle	Elementary contents	mc^2 (MeV)	$c\tau$	ε_{critic} (1) (GeV)	Branching ratio B_i (2)
D^+, D^-	$c\bar{d}, \bar{c}d$	1870	317 μm	3.8×10^7	17.2 %
$D^o, \bar{D}^o$	$c\bar{u}, \bar{c}u$	1865	124 μm	9.6×10^7	6.8 %
D_s^+, D_s^-	$c\bar{s}, \bar{c}s$	1969	149 μm	8.5×10^7	5.2 %
Λ_c^+	udc	2285	62 μm	2.4×10^8	4.5 %
μ^+, μ^-	lepton	106	659 m	1.0	100 %
π^+, π^-	$u\bar{d}, \bar{u}d$	140	7.8 m	115	100 %
K^+, K^-	$u\bar{s}, \bar{u}s$	494	3.7 m	855	63.5 %
Λ^o	uds	1116	7.9 cm	9.0×10^4	0.1 %

(1) According to Eq. (1), with $h_o = 6.4$ km.
(2) For inclusive decays yielding leptons.

1) production of muons and neutrinos in the atmosphere

Critical energy depends also from matter density: in astrophysical environment density << atmospheric density.

Neutrino spectrum from astrophysical sites expected to be harder up to higher energies



1) production of muons and neutrinos in the atmosphere

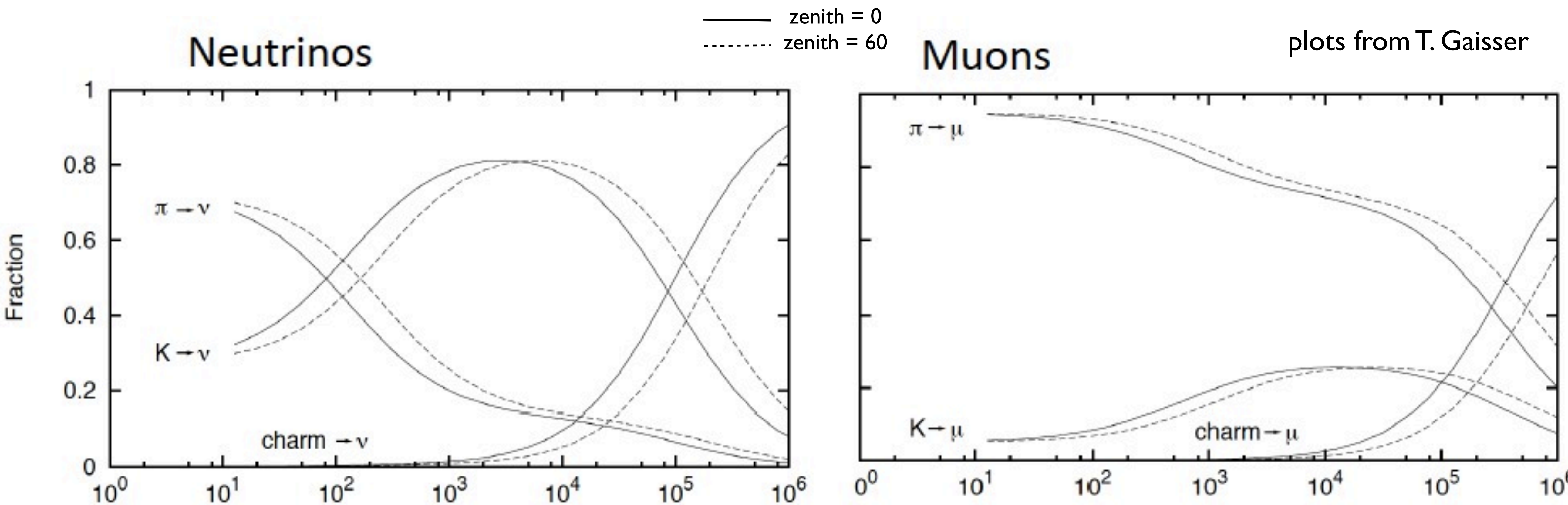
Atmospheric LEPTONS: different sources

➡ Prompt leptons (from charm)

http://cdsweb.cern.ch/record/295175/files/SCAN-9601255.tif

http://arxiv.org/pdf/hep-ph/0010306v3.pdf

plots from T. Gaisser



E_neutrino(GeV)   E_muon(GeV)

At higher energies atmospheric neutrinos from K mainly
Leptons produced by Charm (prompt) affected by large uncertainties
Hadroproduction of Charm hard to be calculated with pQCD, theoretical uncertainty very large

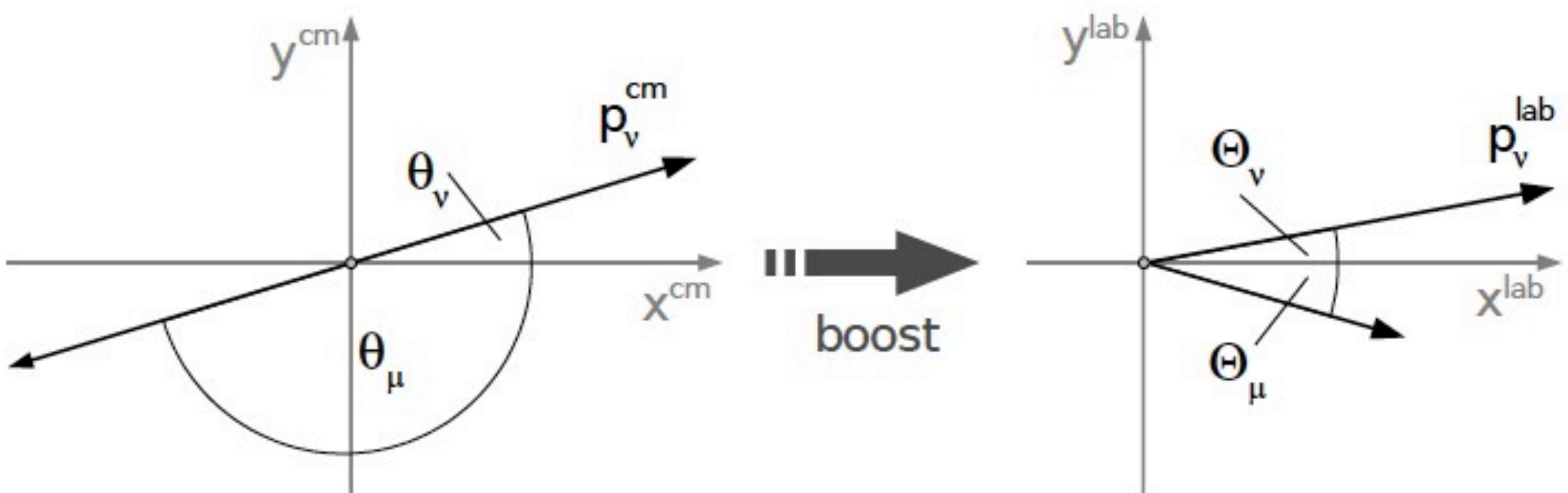
1) production of muons and neutrinos in the atmosphere

Atmospheric LEPTONS: Kinematic relation

MUONS:

- the most numerous energetic particles arriving at sea level
- flux of about 1 muon per square centimeter per second
- mean energy at sea level: ~ 4 GeV
- highly penetrating component, primary background for neutrino telescopes

MUONS and Neutrinos produced in the same meson decay:



Olaf Schulz, phD thesis

Figure 2.4: Two body decay of the parent meson into muon and neutrino. - The left figure displays the back-to-back kinematics in the meson center of mass (cm) frame. The right figure shows the momenta after Lorentz transformation into the laboratory frame.

The connection between muon and neutrino (and CR) is regularly used for physics.
Here now some practical cases.

1) production of muons and neutrinos in the atmosphere

Atmospheric LEPTONS: Kinematic relation

MUONS and Neutrinos produced in the same meson decay: let's take a high energy case and follow the muon and neutrino in their trajectory.

How much separated they arrive in underground?

Olaf Schulz, phD thesis

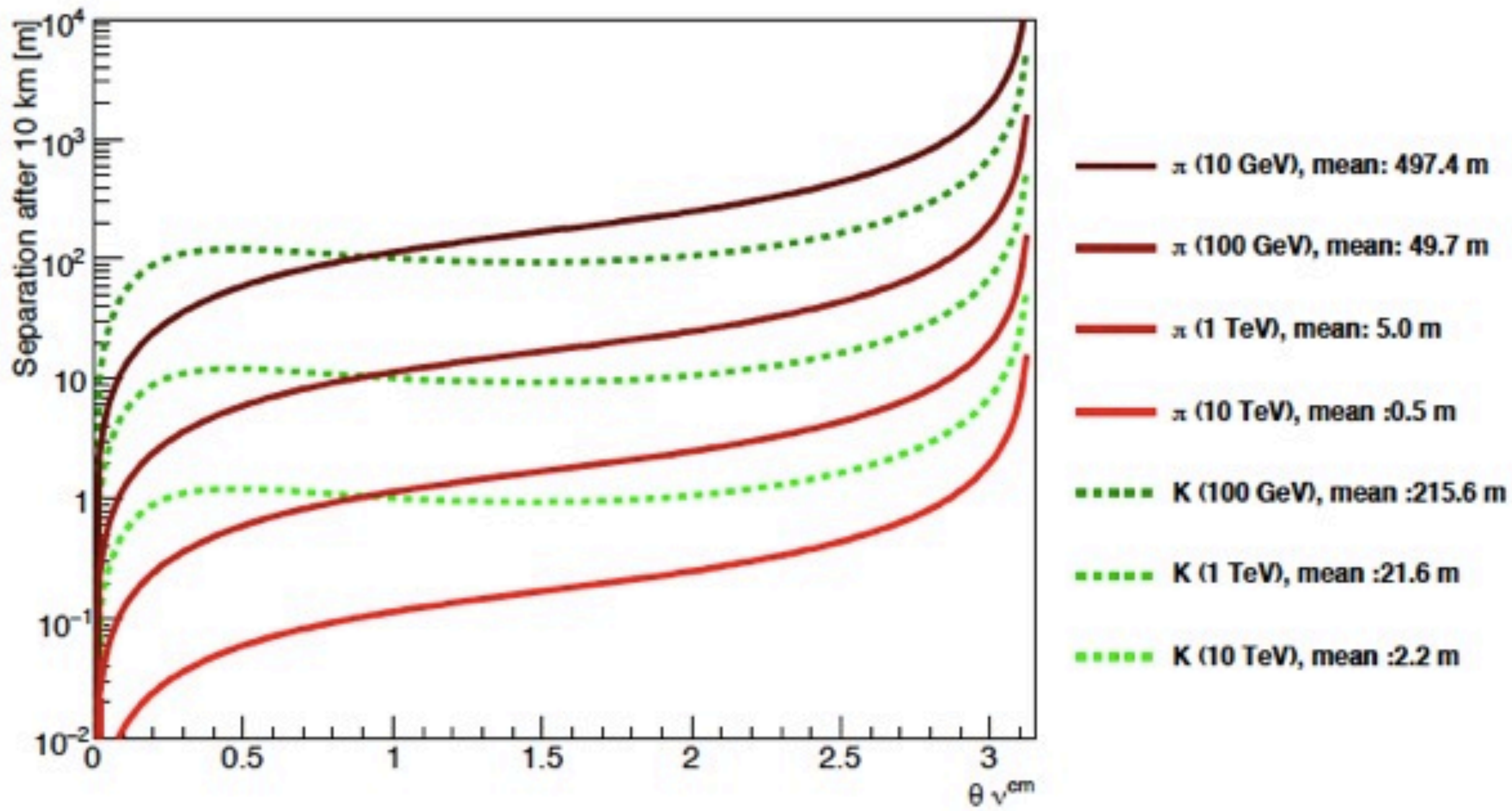


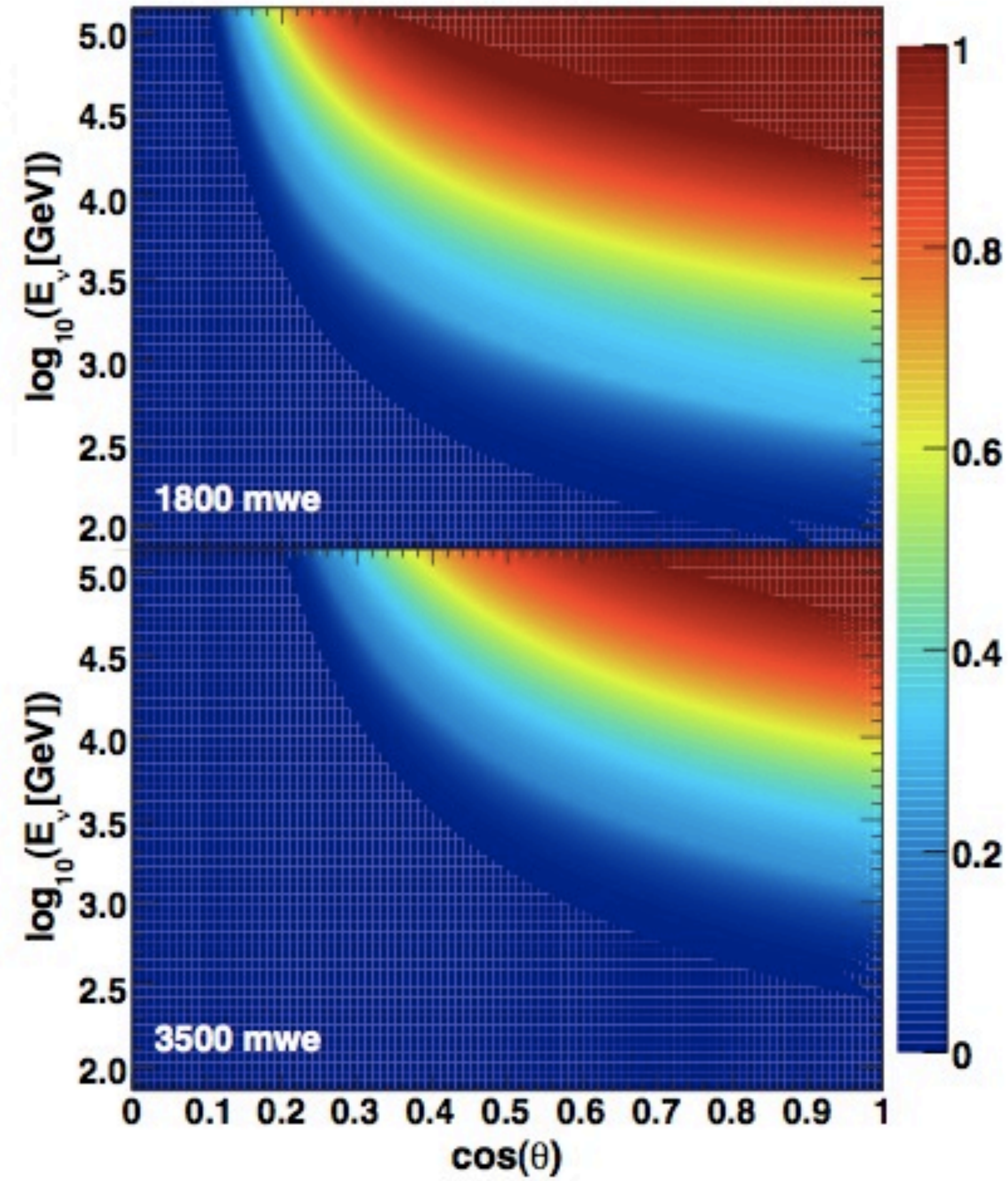
Figure 2.5: Distance of muon and neutrino 10 km after meson decay - The distance is shown in dependence of the neutrino angle w. r. t. the boost direction in the cms-frame θ_ν. The solid red curves represent the distances for decays of pions of 10 GeV to 10 TeV, the dashed green curves show the distances for kaon decays of 100 GeV to 10 TeV.

Atmospheric LEPTONS: Kinematic relation

MUONS and Neutrinos produced in the same meson decay: let's take a high energy case and follow the muon and neutrino in their trajectory.

How much separated they arrive in underground?

IF WE VETO ATMOSPHERIC MUONS AT HIGH ENERGY WE WILL VETO ALSO THE NEUTRINO!!!!



Vetoing atmospheric neutrinos in a high energy neutrino telescope.
Stefan Schonert , Thomas K. Gaisser , Elisa Resconi, Olaf Schulz
Published in **Phys.Rev. D79 (2009) 043009**
e-Print: **arXiv:0812.4308 [astro-ph]**

1) production of muons and neutrinos in the atmosphere

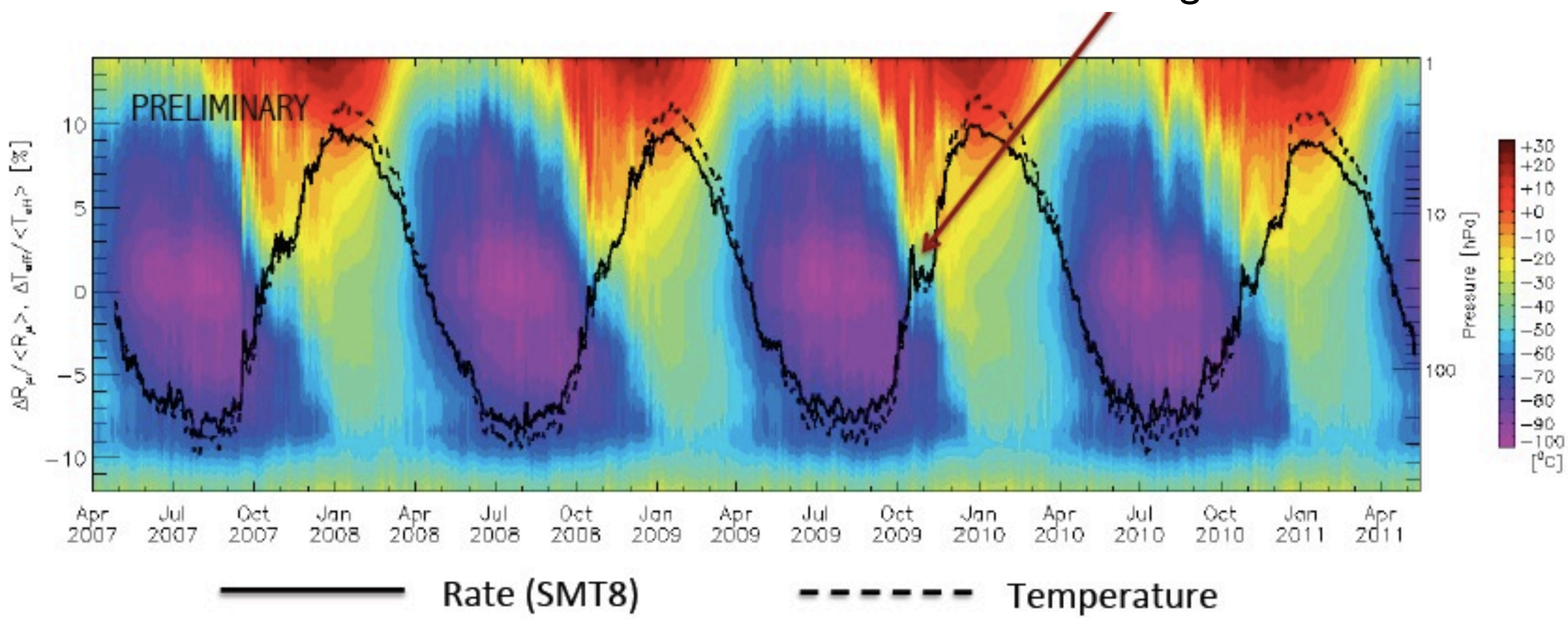
Seasonal variations of μ/ temperature dependence

arXiv:1111.2735

Studied by many experiments, with IceCube very high statistics
Correlation coefficient relates Rate and Temperature in the atmosphere

$$\frac{\Delta R_\mu}{\langle R_\mu \rangle} = \alpha_T^{exp} \frac{\Delta T_{eff}}{\langle T_{eff} \rangle}$$

IceCube underground muon data



1) production of muons and neutrinos in the atmosphere

MUONS and Neutrinos produced in the same meson decay: Spectra!

the two components carry the imprint from the same decays,

analytical calculations available from T. Gaisser book

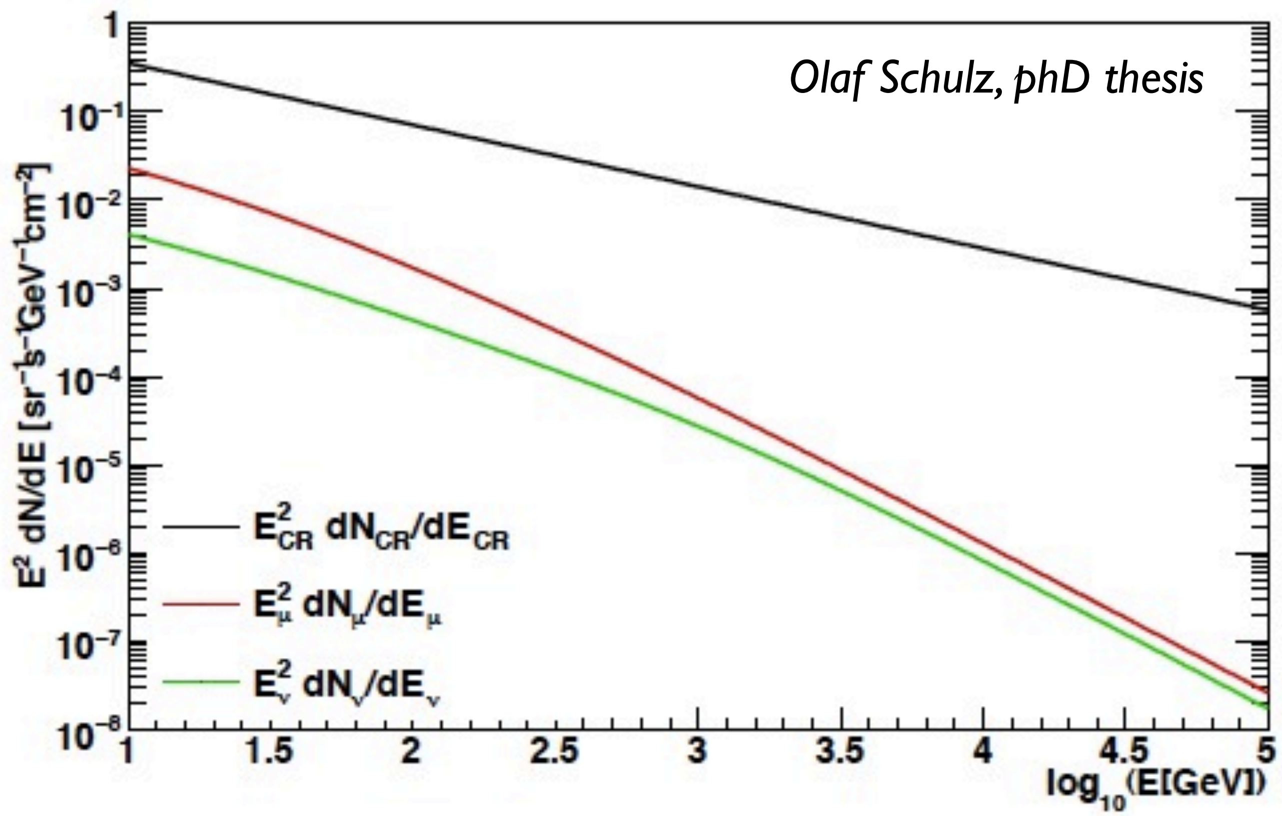


Figure 2.6: Cosmic ray (proton), muon and neutrino spectra - The analytically calculated spectra of muons (red) and neutrinos (green) from air-showers are shown together with the assumed initial cosmic ray spectrum (black) of the form $\frac{\mathrm{d}N(E)}{\mathrm{d}E} = E^{-2.7}$. This result was obtained from equations (2.37) and (2.38).

1) production of muons and neutrinos in the atmosphere

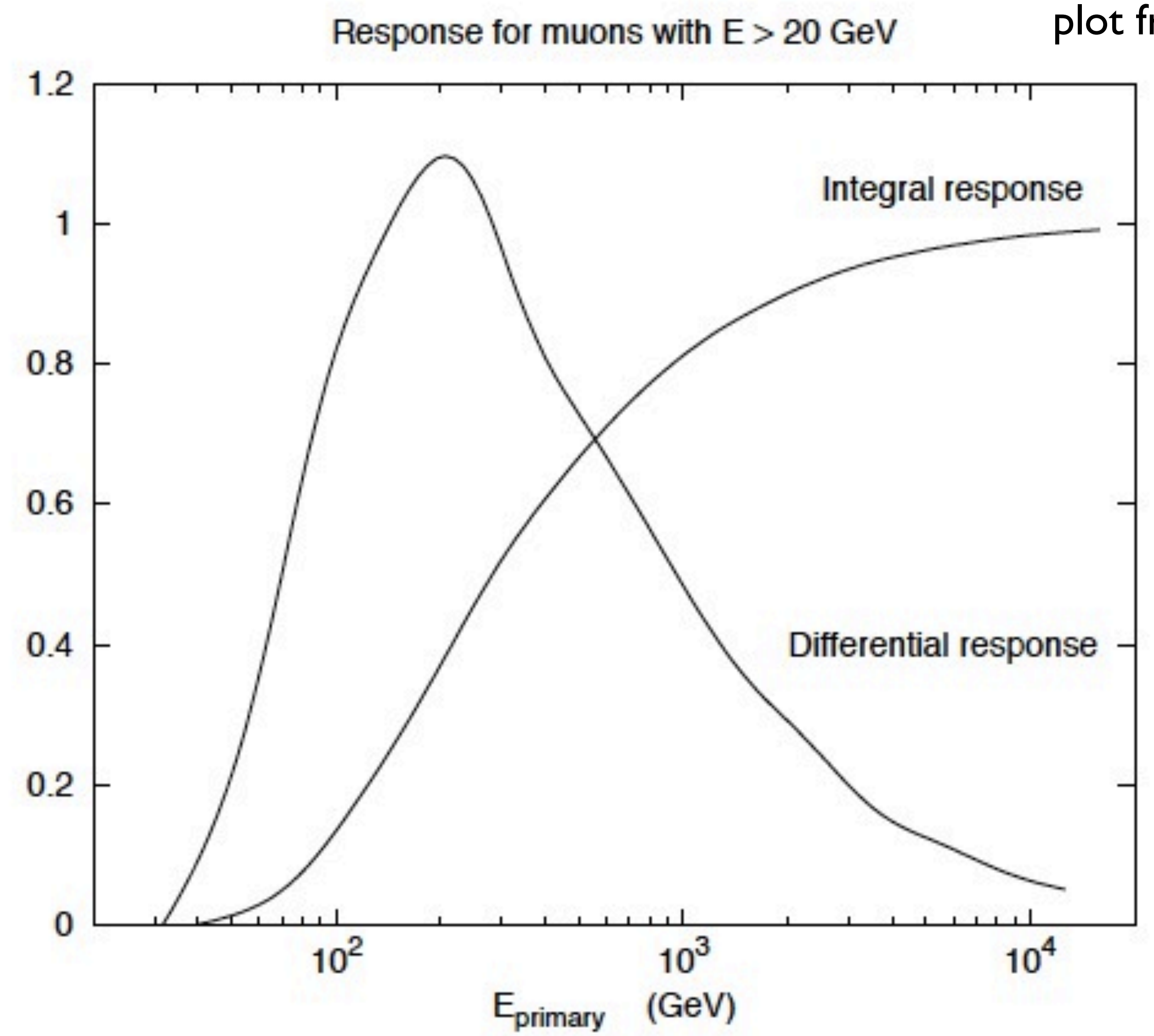
MUONS vs primary Cosmic Rays

The measure of the muon component carries information about the primary CR like:
- energy
- directionality

1) Energy

Muon response, as a function of primary energy **E**0 for **E**μ > 20 GeV.

plot from T. Gaisser



1) production of muons and neutrinos in the atmosphere

MUONS vs primary CR

The measure of the muon component carries information about the primary CR like:
- energy
- directionality

1) http://arxiv.org/pdf/0907.0498v2.pdf

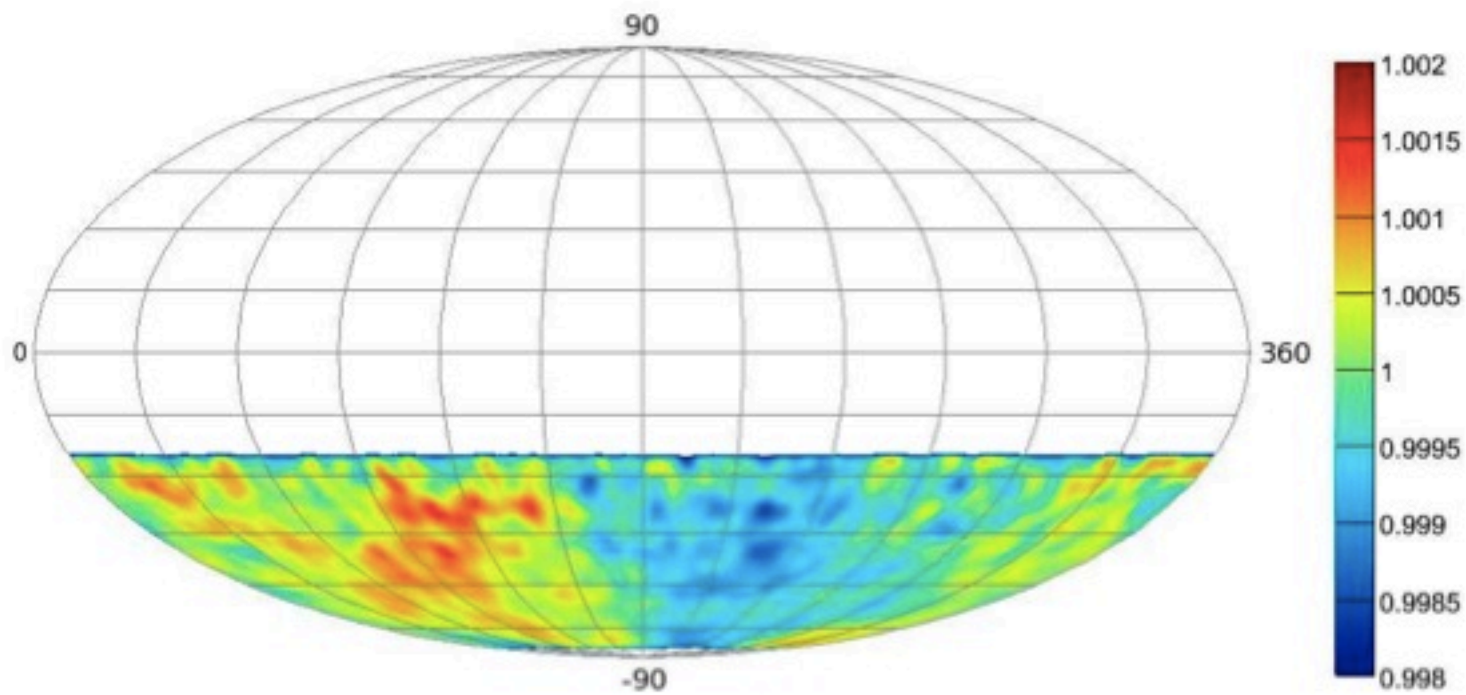


Fig. 3: The IceCube skymap in equatorial coordinates (Declination (Dec) vs. Right Ascension (RA)). The color scale is the relative intensity.

1) production of muons and neutrinos in the atmosphere

MUONS vs primary CR

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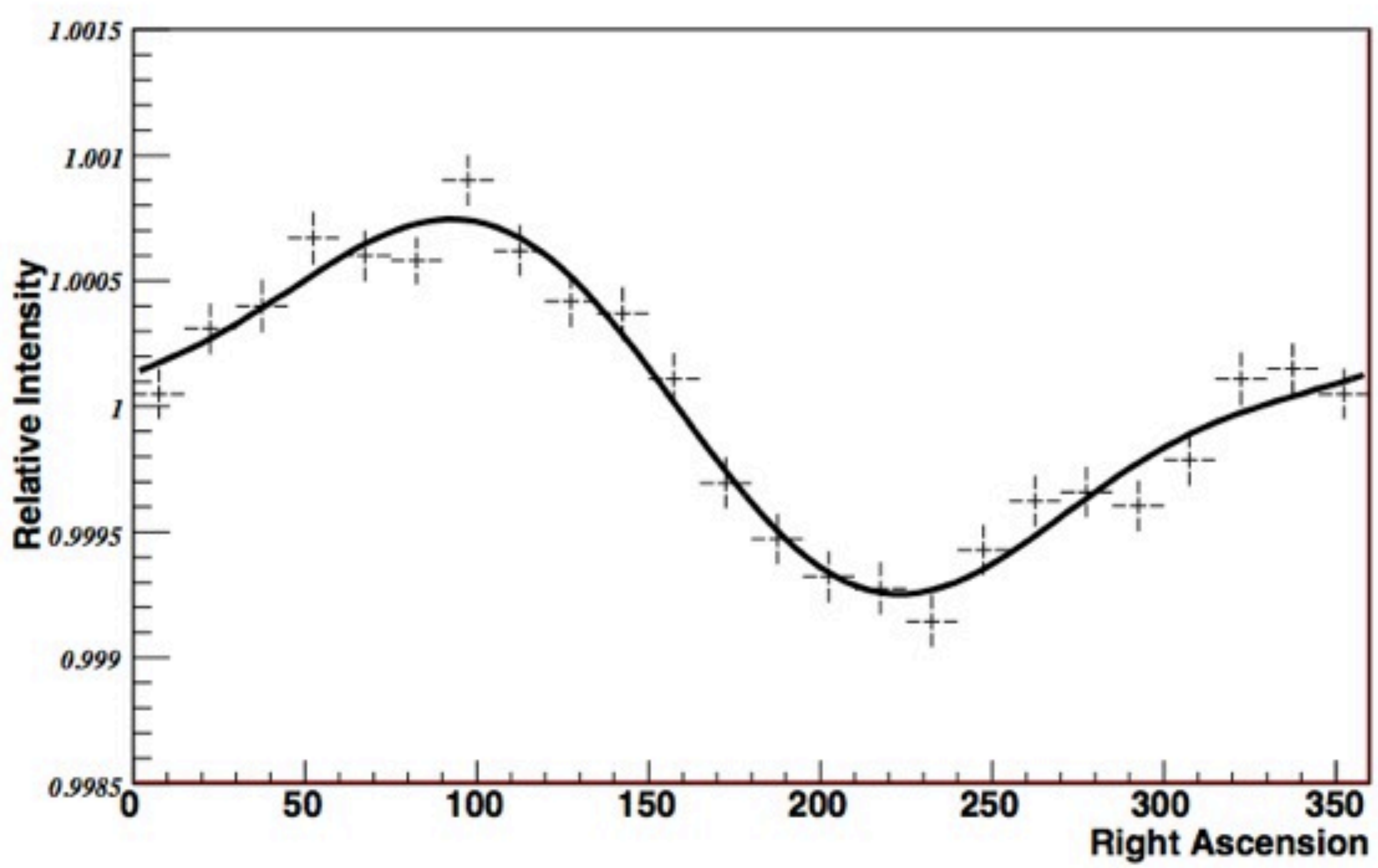

1) production of muons and neutrinos in the atmosphere

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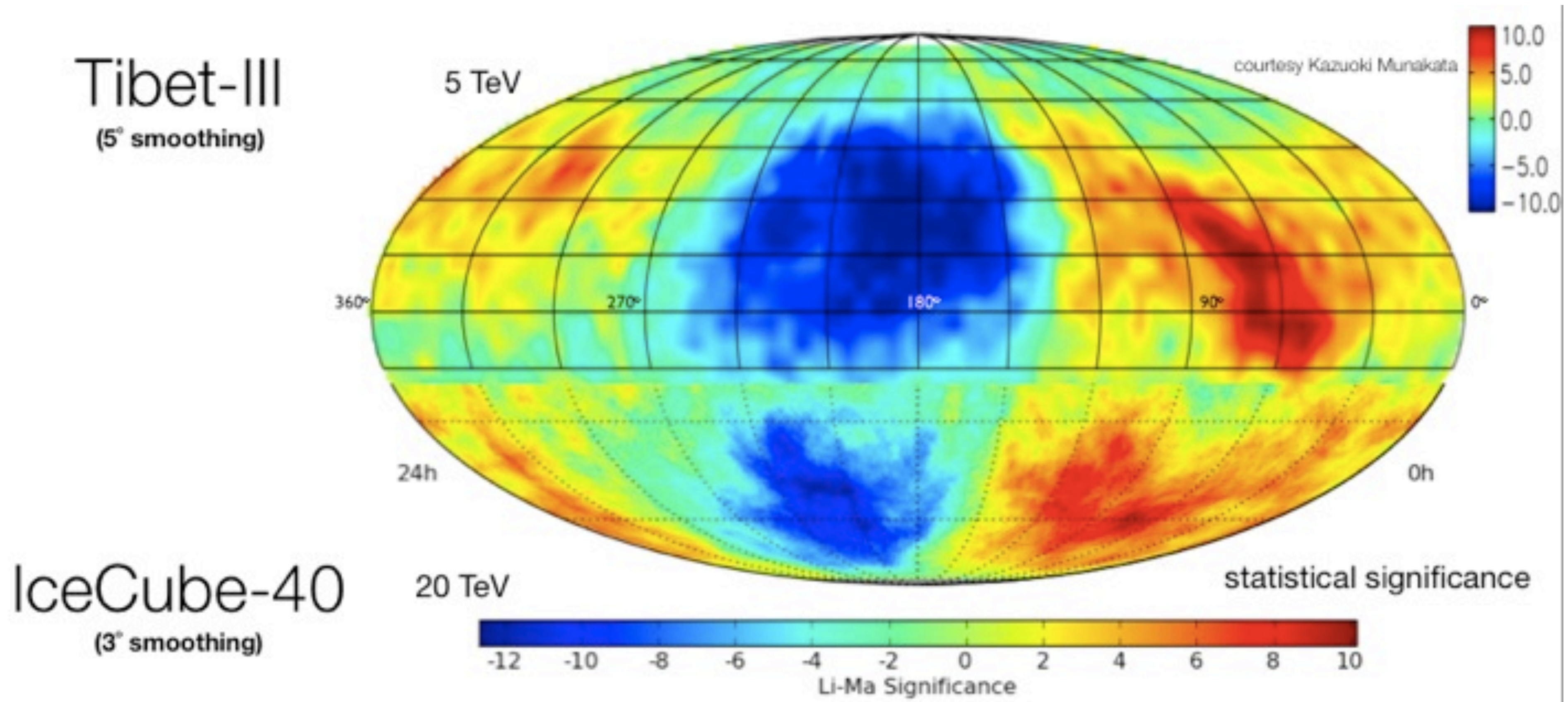

The reason of this anisotropy is not yet clear!

2) muons and neutrinos in underground

2) muons and neutrinos in underground

- Two contributions to the muon flux in underground:
  - penetrating atmospheric muons
  - neutrino-induced muons from all directions
- Muon energy loss mechanisms of fundamental importance for the measure of both components
- Depending on the physics contest one or another component could be signal or background in a neutrino telescope

2) muons through matter

Cherenkov light: energetic muons which cross a transparent medium will produce Cherenkov light. The Cherenkov light is emitted in a cone, which half opening angle θc

$$\cos(\theta_c) = \frac{1}{n\beta}$$

$\beta = v/c$ Lorentz factor of the particle

No emitted photons/ unit track x * wavelength interval is (Frank-Tamm formula):

$$\frac{d^2N}{dxd\lambda} = \frac{2\pi\alpha z^2}{\lambda^2} \cdot sin^2(\theta_c)$$

The muon propagates through the medium and loses energy by
- ionization of atoms
- stochastic radiative processes such as bremsstrahlung (suppressed respect the electron bremsstrahlung), pair production and photo-nuclear interaction

2) muons through matter

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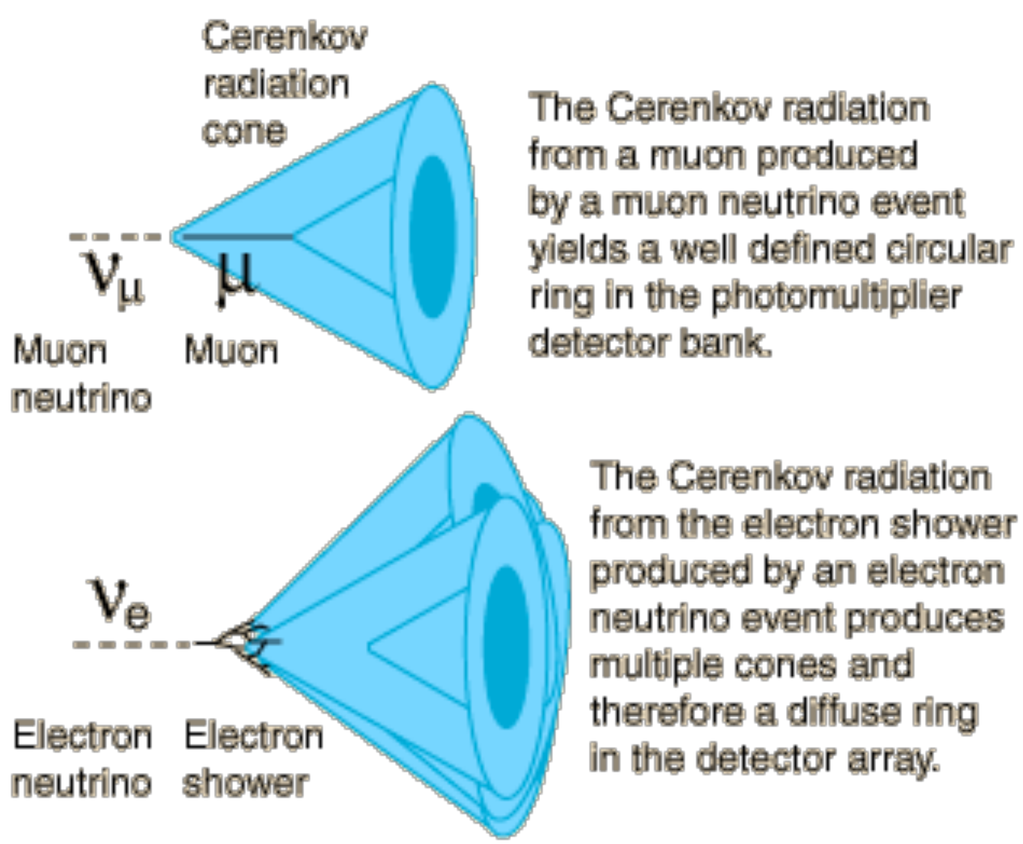
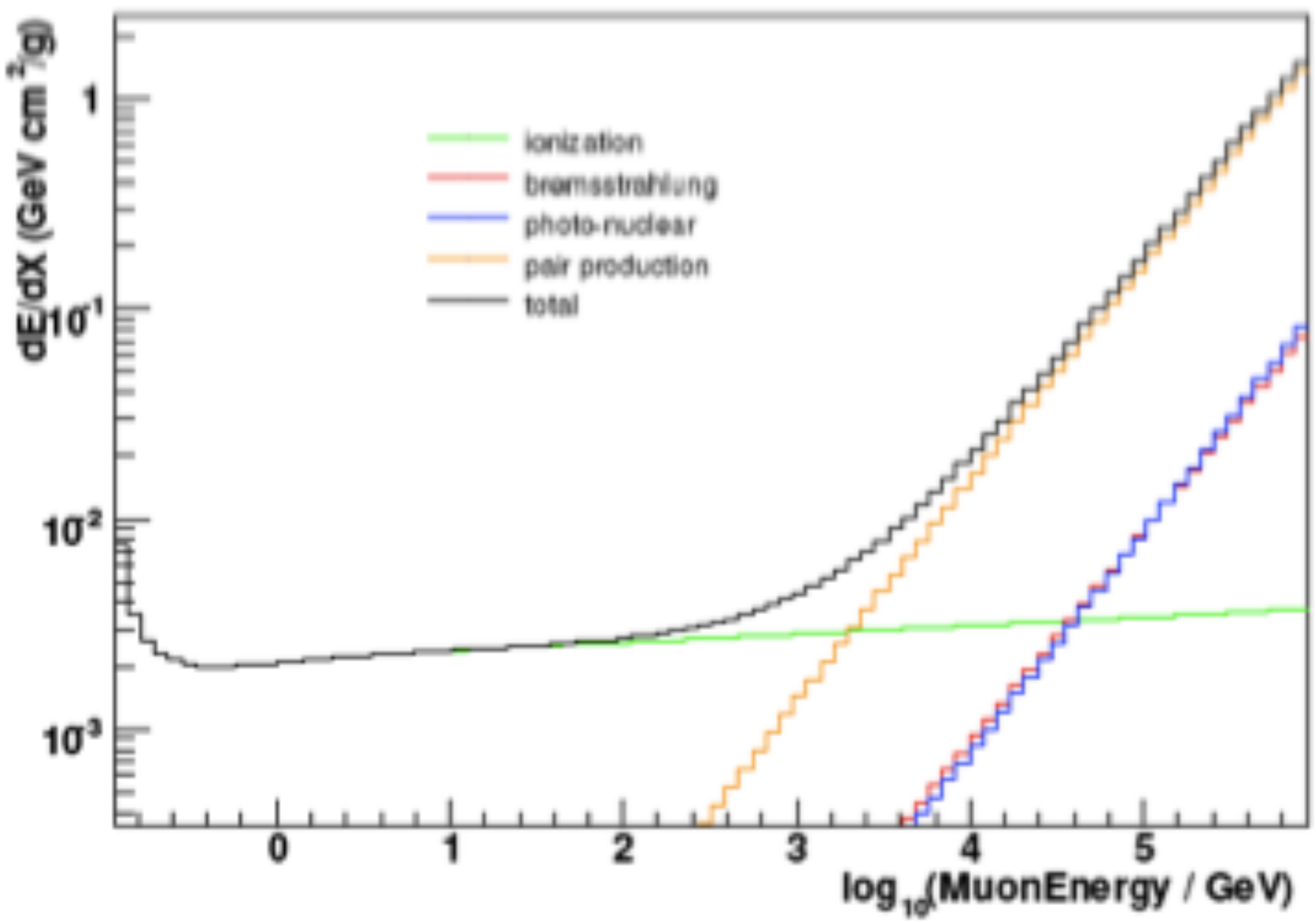


2) muons through matter

Energy loss: what is exactly emitting Cherenkov photons?



2) muons through matter

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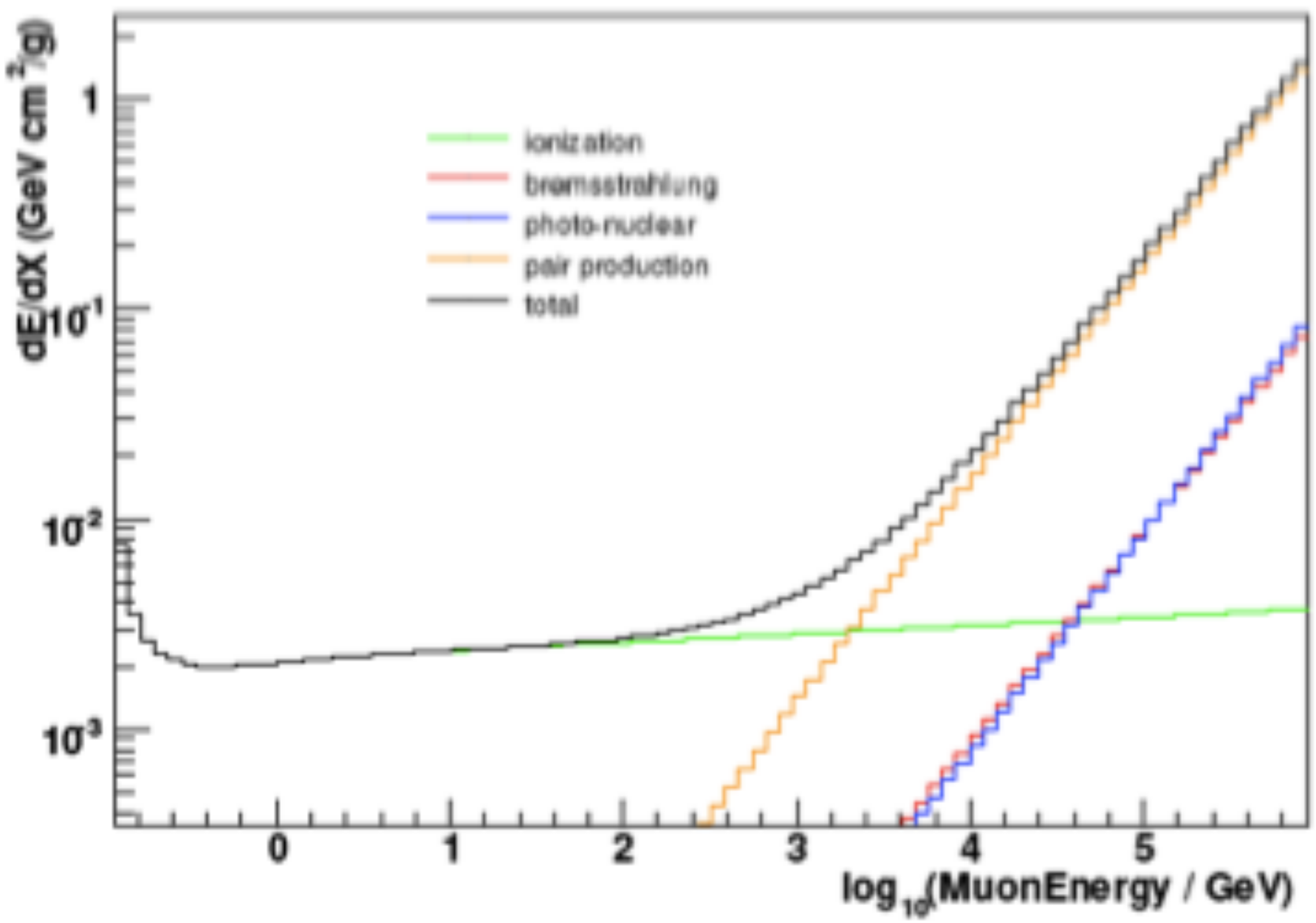
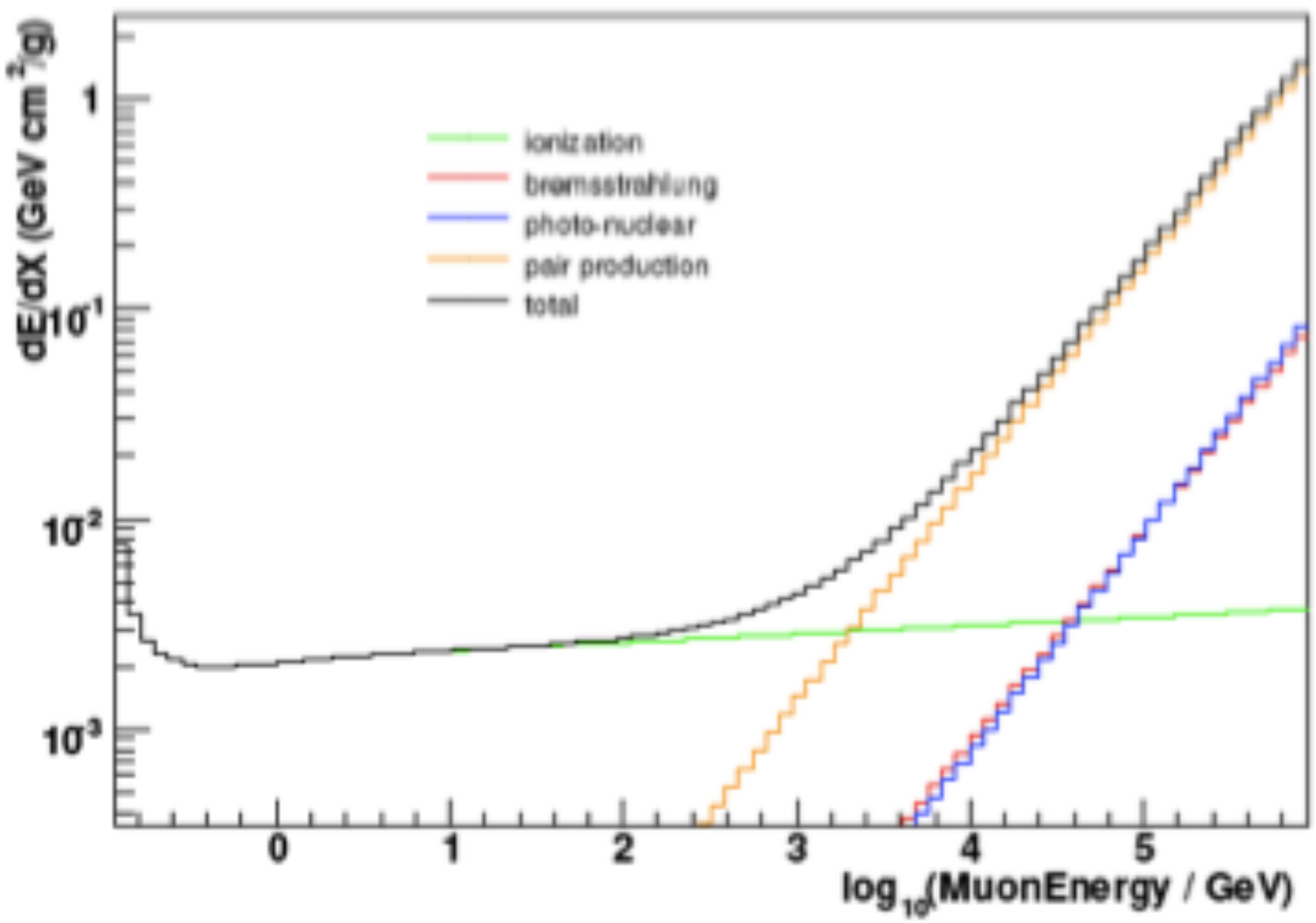


Eμ < 500 GeV ionization dominant (~ 2 MeV / cm)

2) muons through matter

Energy loss: what is exactly emitting Cherenkov photons?



Eμ < 500 GeV ionization dominant (~ 2 MeV / cm)

Eμ > 500 GeV stochastic energy loss dominant

2) muons through matter

Energy loss: Low energy regime (< 1 TeV)
Ionization loss rate nearly constant for relativistic muons:
- broad minimum for E_{muon} < 1 GeV,
- logarithmic rise at higher energies.

$$\frac{\mathrm{d}E}{\mathrm{d}X} \approx -[1.9 + 0.08 \ln(E_\mu/\mu)]$$

Approximate numerical formula for ionization loss of muons in rock valid for E_{muon} > 10 GeV. In this regime, the energy of the muon can be determined by the measure of the entire length of the muon. The partial measure of a track doesn't provide the energy information!

2) muons through matter

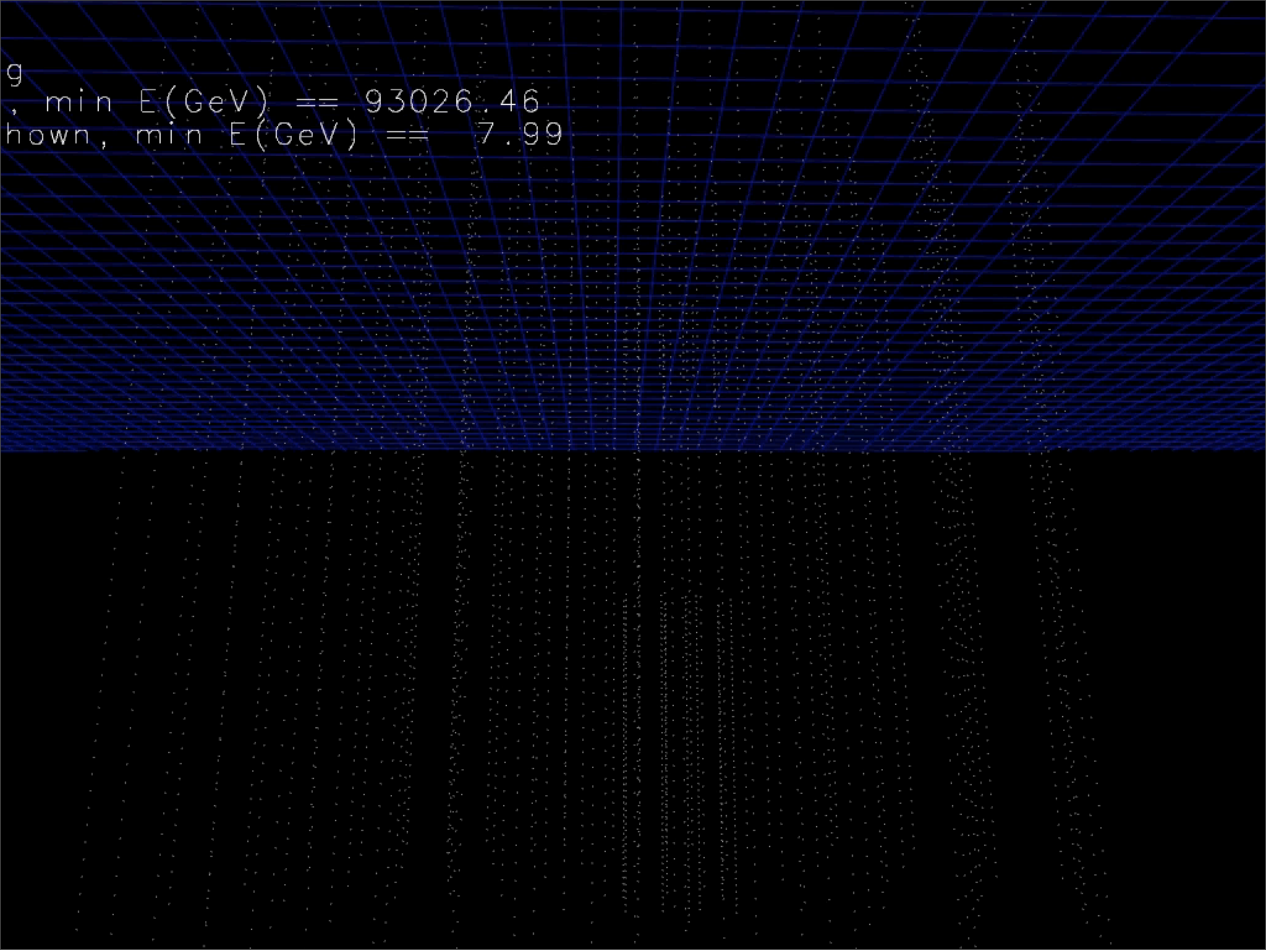
Energy loss: higher energy regime: the rate of **radiative loss** increases with energy. Radiative losses in the atmosphere can be neglected, they are important in underground (water / ice / rock). The mean energy of a beam of muons of initial energy $\mathbf{E_0}$ after penetrating a depth X of material is:

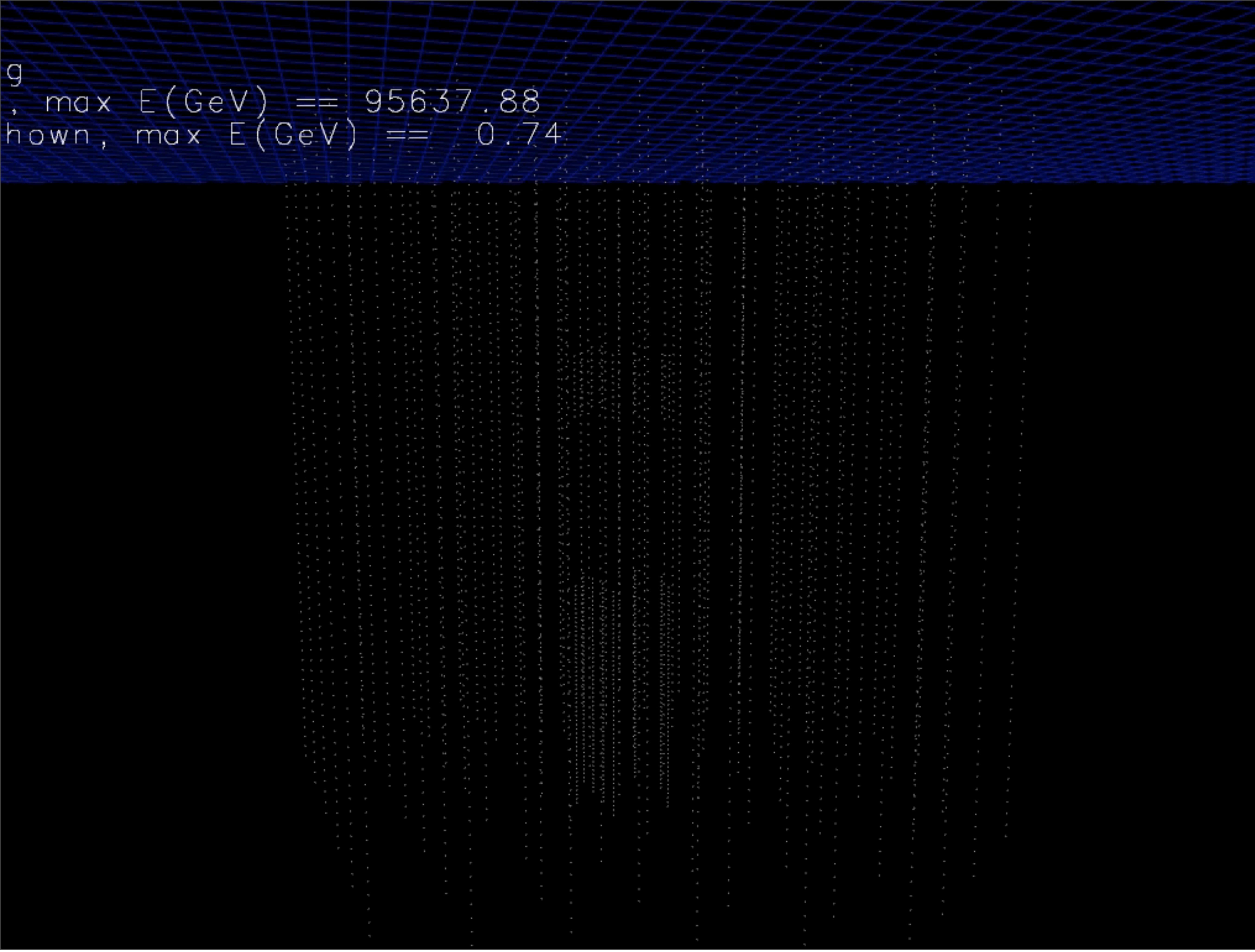
$$< E(X) >= (E_0 + \epsilon)e^{-X/\xi} - \epsilon.$$

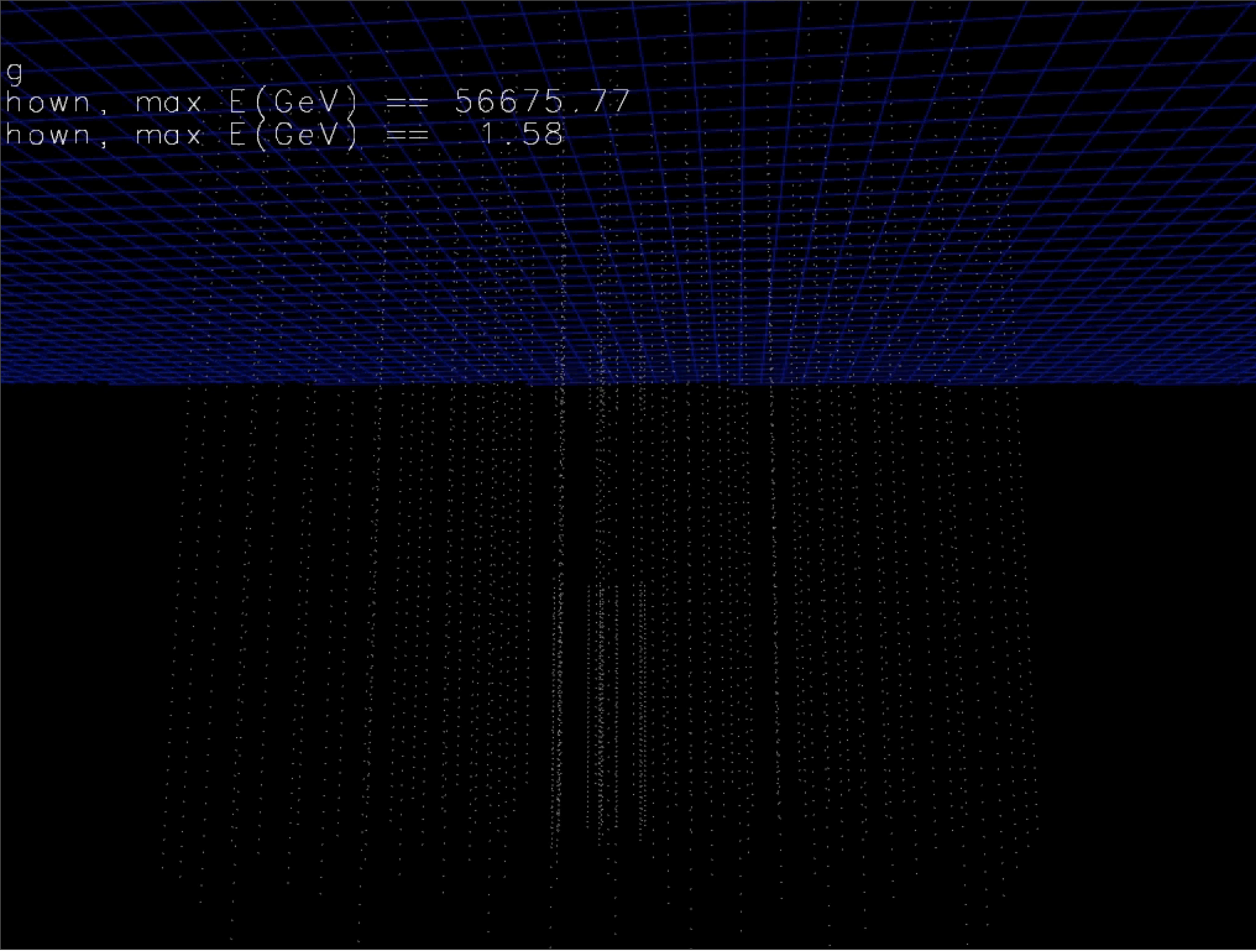
Above the critical energy, radiative losses dominated (TeV range). Since energy loss in radiative regime is proportional to the E_{muon}, the local measure of the stochastic energy loss allows an estimation of the energy of the muons.

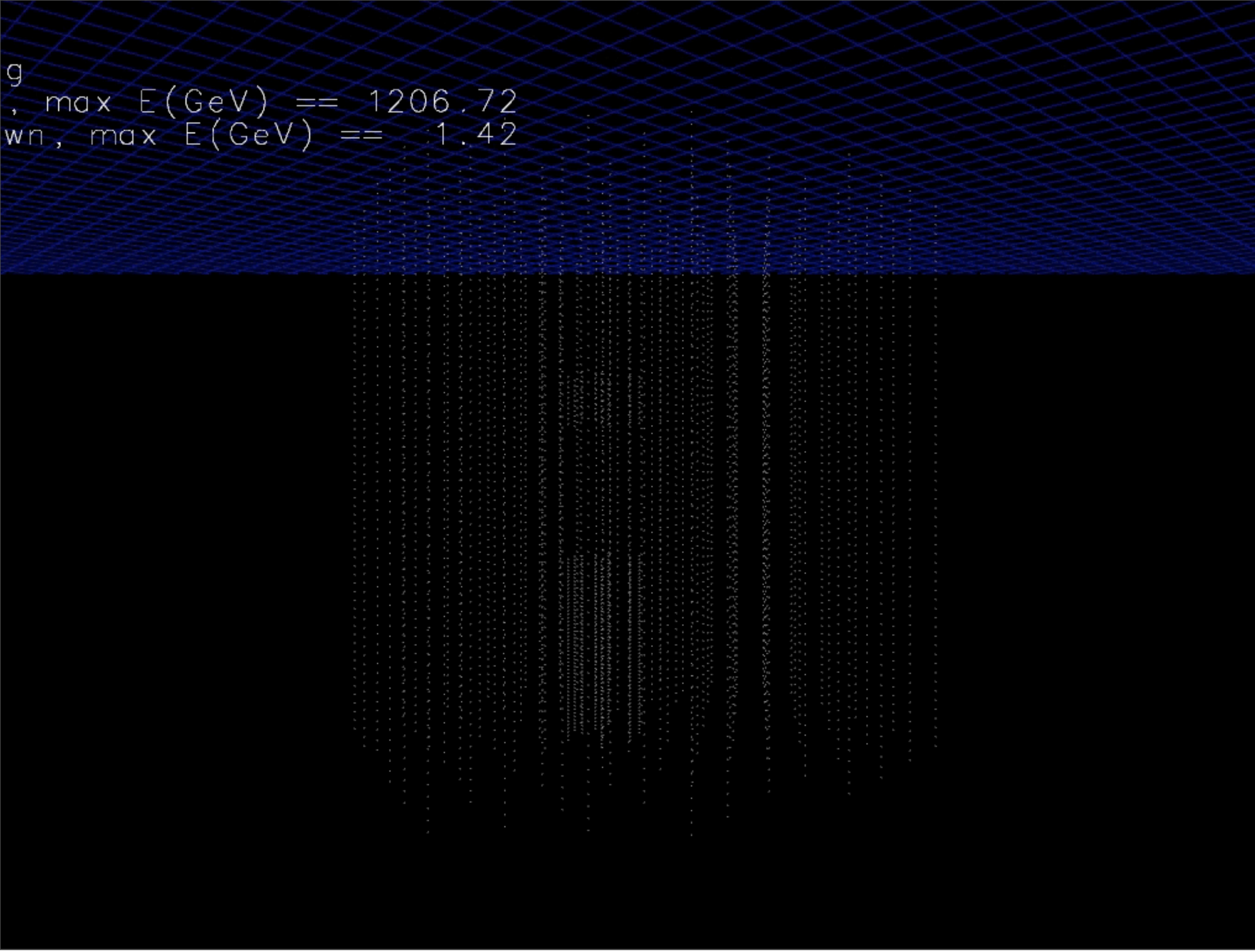
Note: charged secondary particles accompany the muon track. If their energy is above the Cherenkov threshold they will also emit Cherenkov light and contribute to the total light yield. This is the standard scenario in neutrino telescopes.

Simulation packages:
MMC: D. Chirkin, W. Rhode, Propagating leptons through matter with Muon Monte Carlo (MMC), Arxiv preprint hep-ph/0407075.
MUM: I. Sokalski, E. Bugaev, S. Klimushin, MUM: Flexible precise Monte Carlo algorithm for muon propagation through thick layers of matter, Physical Re- view D 64 (7) (2001) 074015.


g
, min E(GeV) == 93026.46
hown, min E(GeV) == 7.99


g
, max E(GeV) == 95637.88
hown, max E(GeV) == 0.74


g
hown, max E(GeV) == 56675.77
hown, max E(GeV) == 1.58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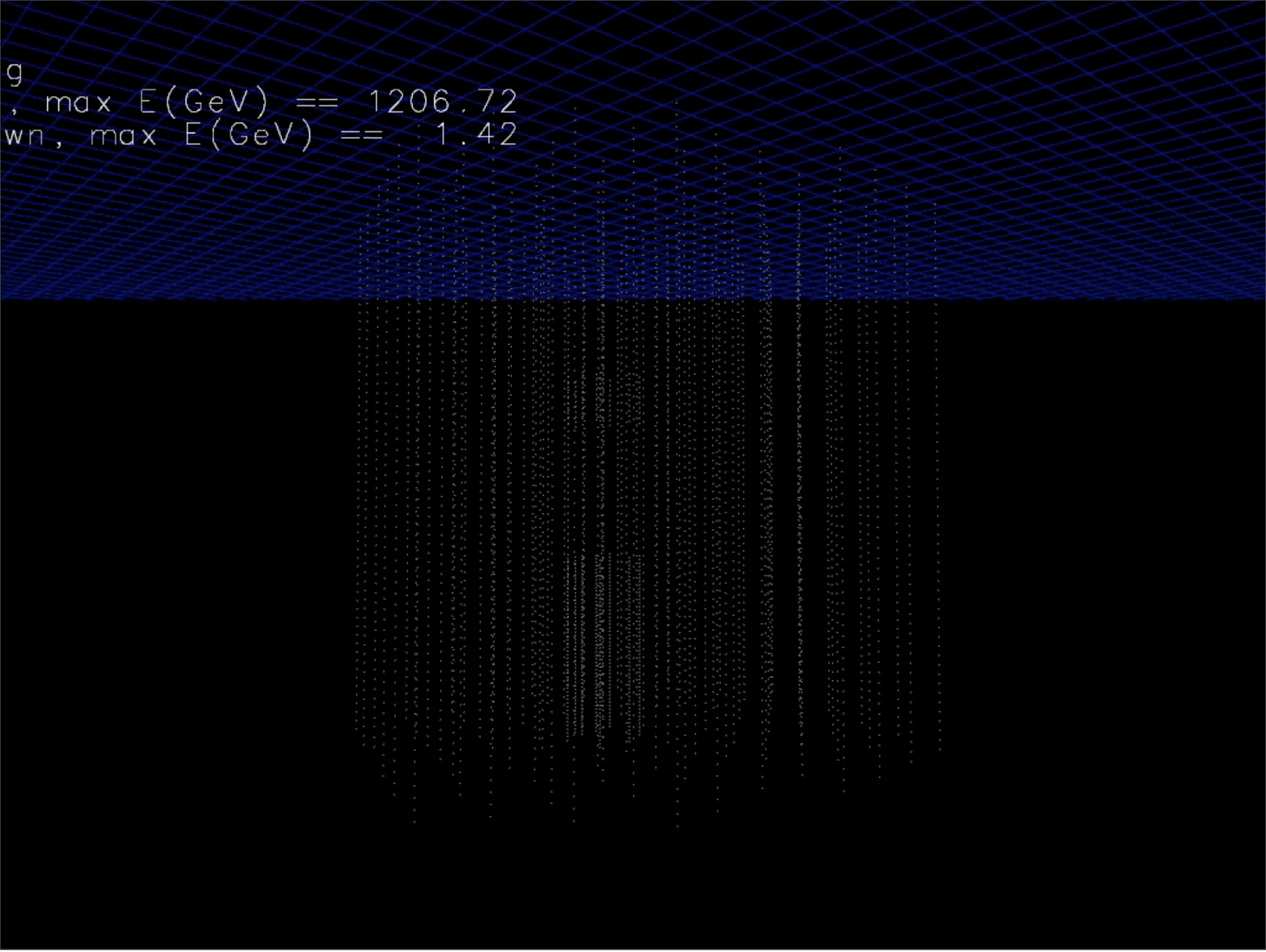
, max E(GeV) == 1206.72
wn, max E(GeV) == 1.42


g
, max E(GeV) == 1206.72
wn, max E(GeV) == 1.42

2) muons through matter

muon flux in underground: fluctuations in energy >> fluctuation in propagation. In-situ measurements available from underground laboratories and telescopes.

- SNOLab depth = 5890 m.w.e., deepest site

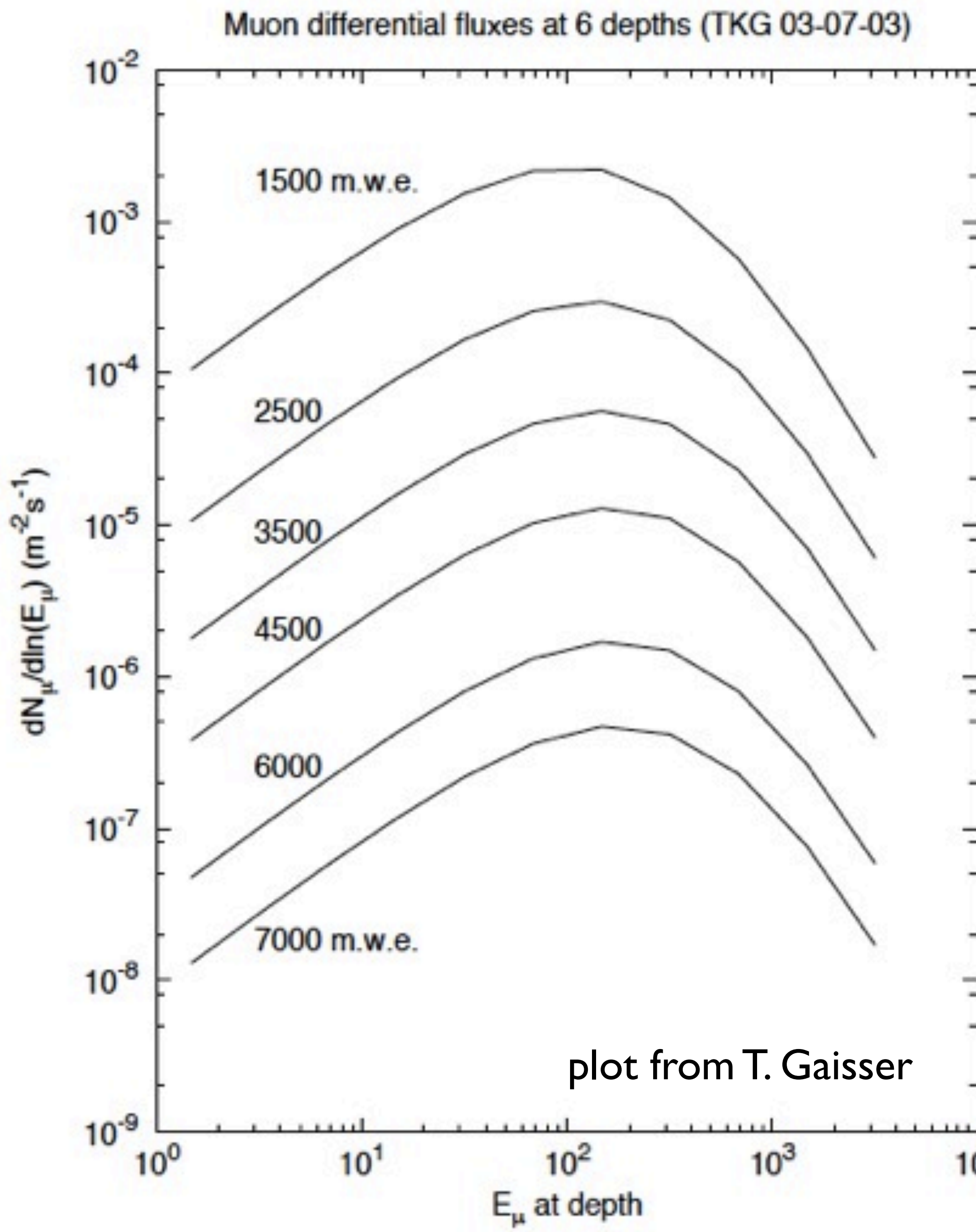


Figure 7.2 Local differential energy spectrum of muons underground, See G.L. Cassiday, J.W. Keuffel and J.A. Thompson, Phys. Rev. *D7*, 2022 (1973) for a plot that compares measurements over a larger range of depths.

2) muons through matter

ratio of stopping to through-going muons in a detector of thickness deltaX at a depth X >> deltaX

$$N_\mu(> E_0) \sim K E_0^{-\gamma_\mu},$$

at the surface

$$R(X) = \frac{\Delta N_\mu}{N_\mu} = \gamma_\mu \frac{\Delta E_0}{E_0} \approx \frac{\gamma_\mu \Delta E\, e^{X/\xi}}{(e^{X/\xi} - 1)\epsilon_\mu}.$$

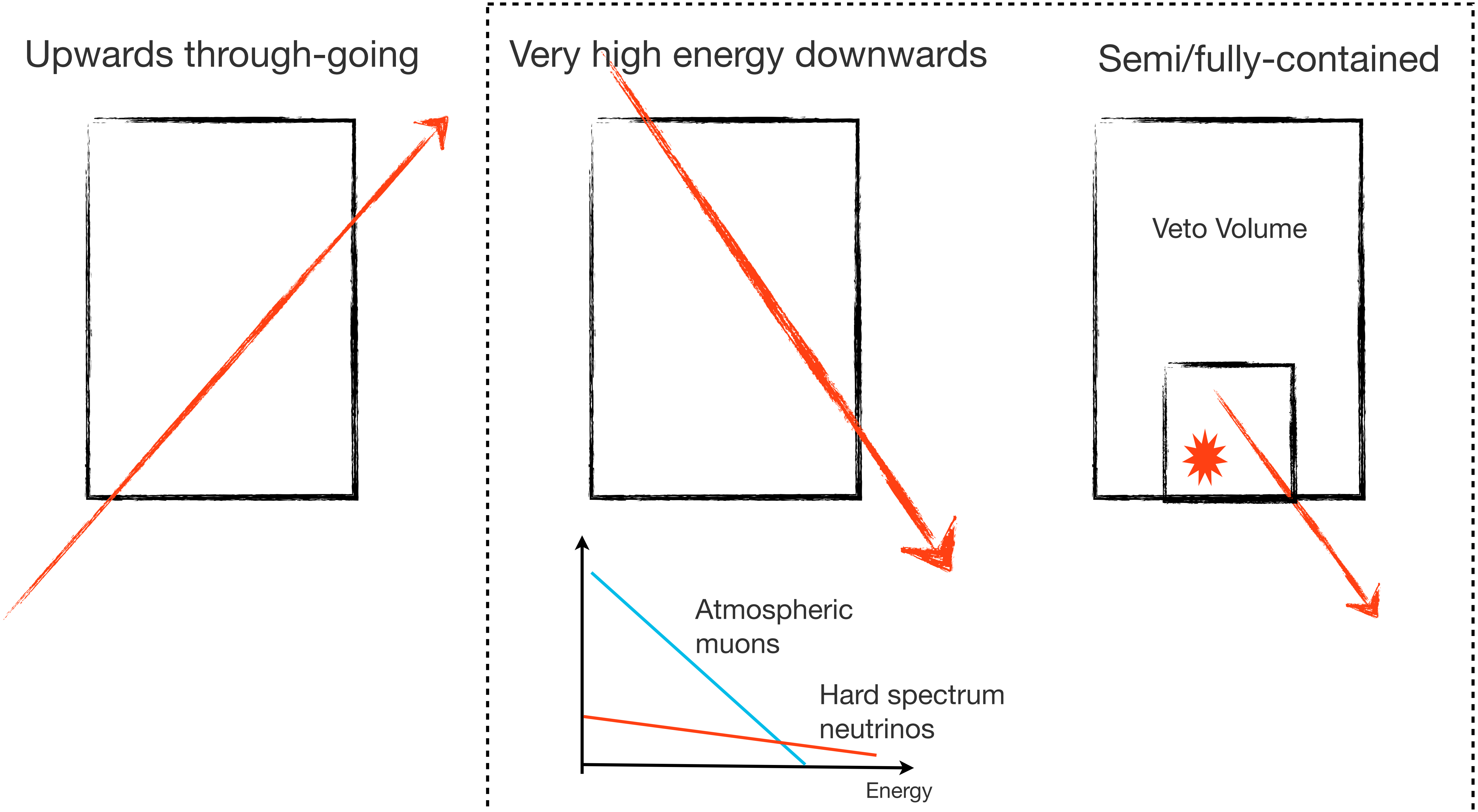
$$\Delta E \approx \alpha \Delta X$$

minimum energy needed to traverse the detector (typically several GeV)

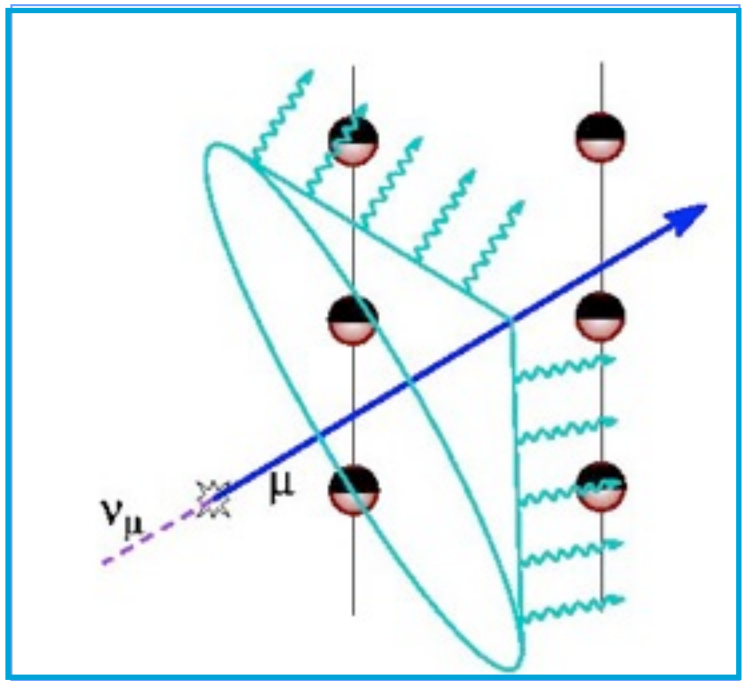
3) neutrino induced leptons

3) neutrino induced leptons

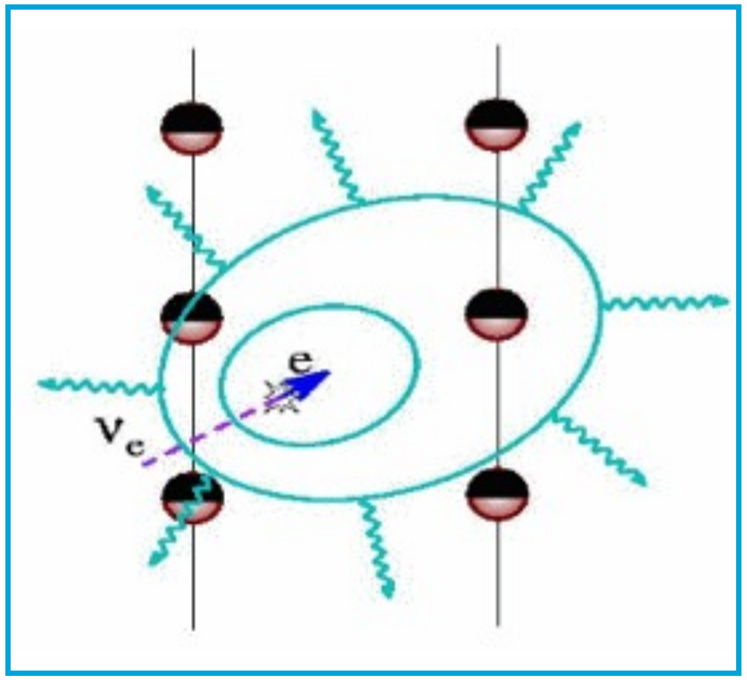
How are the neutrinos discriminated from muons?

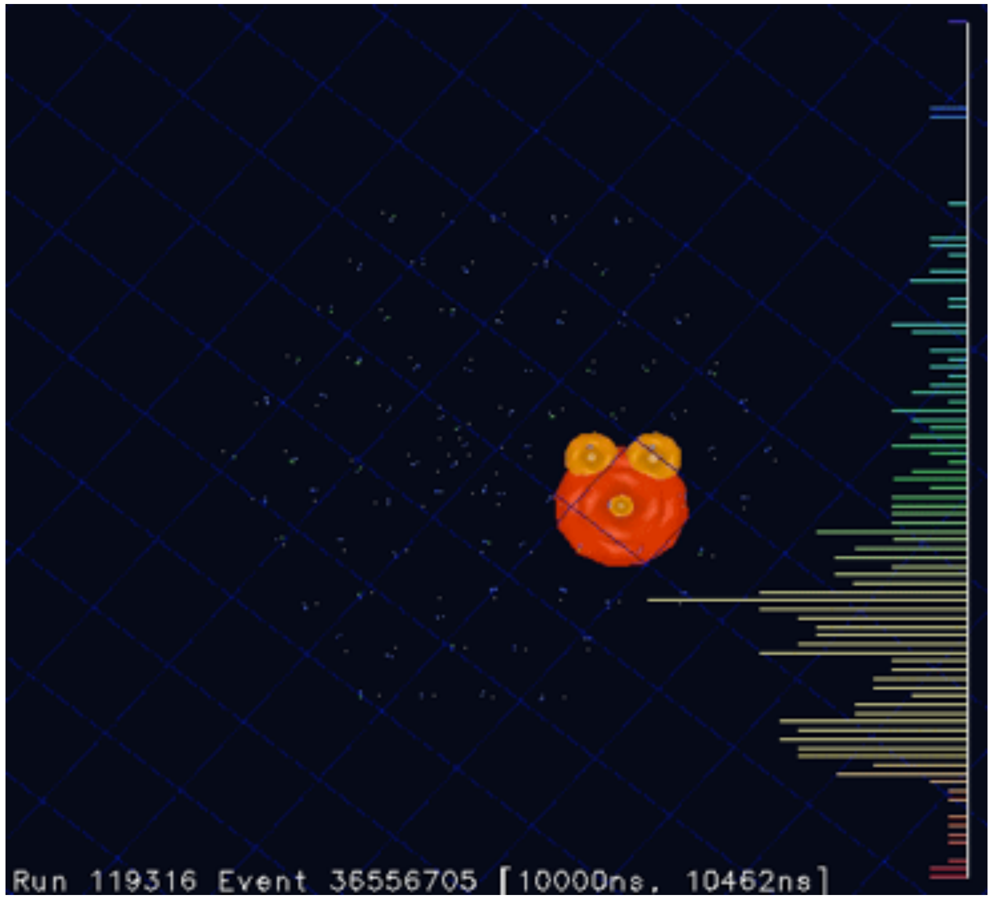


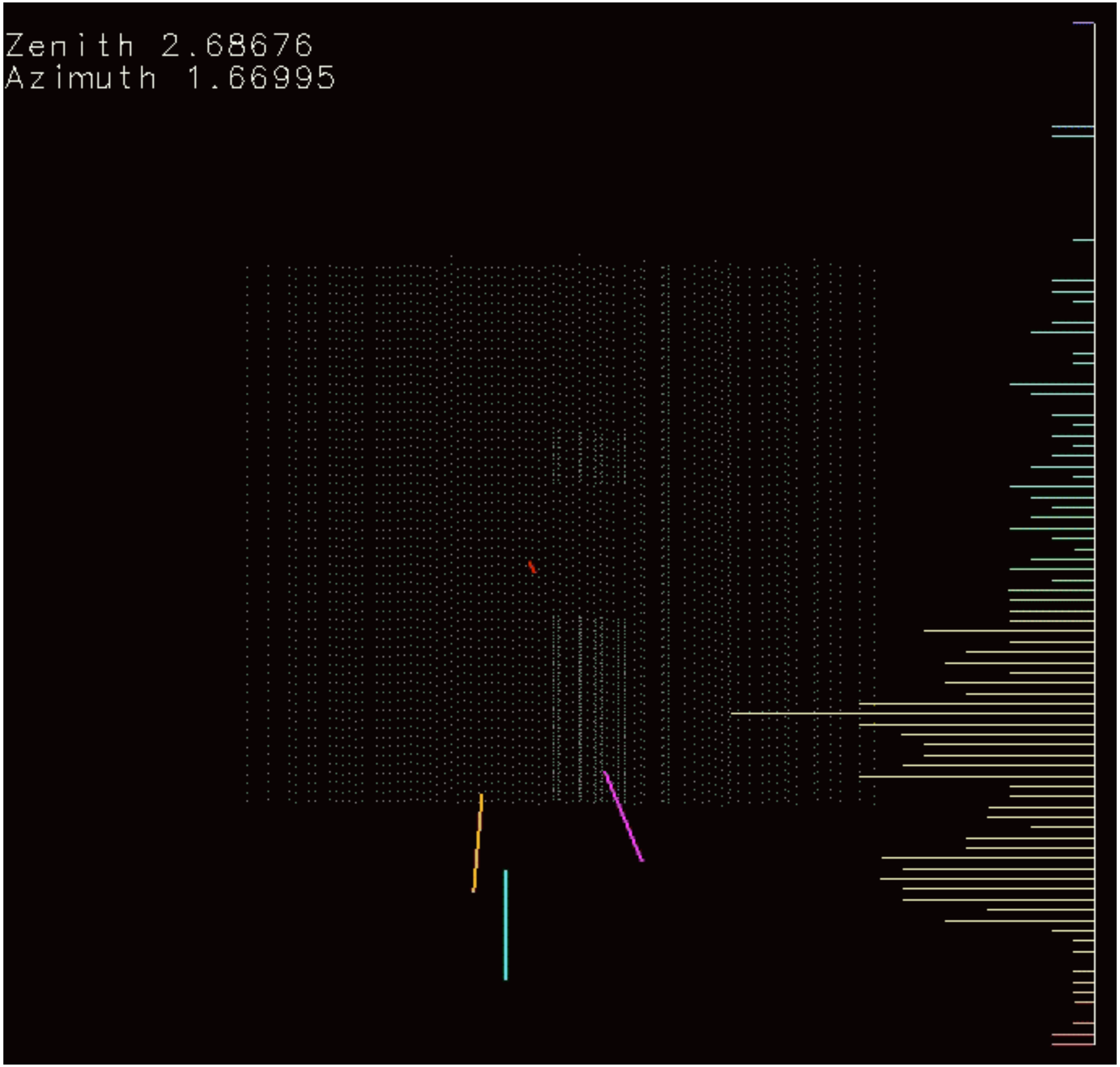
Track-like



cascades-like

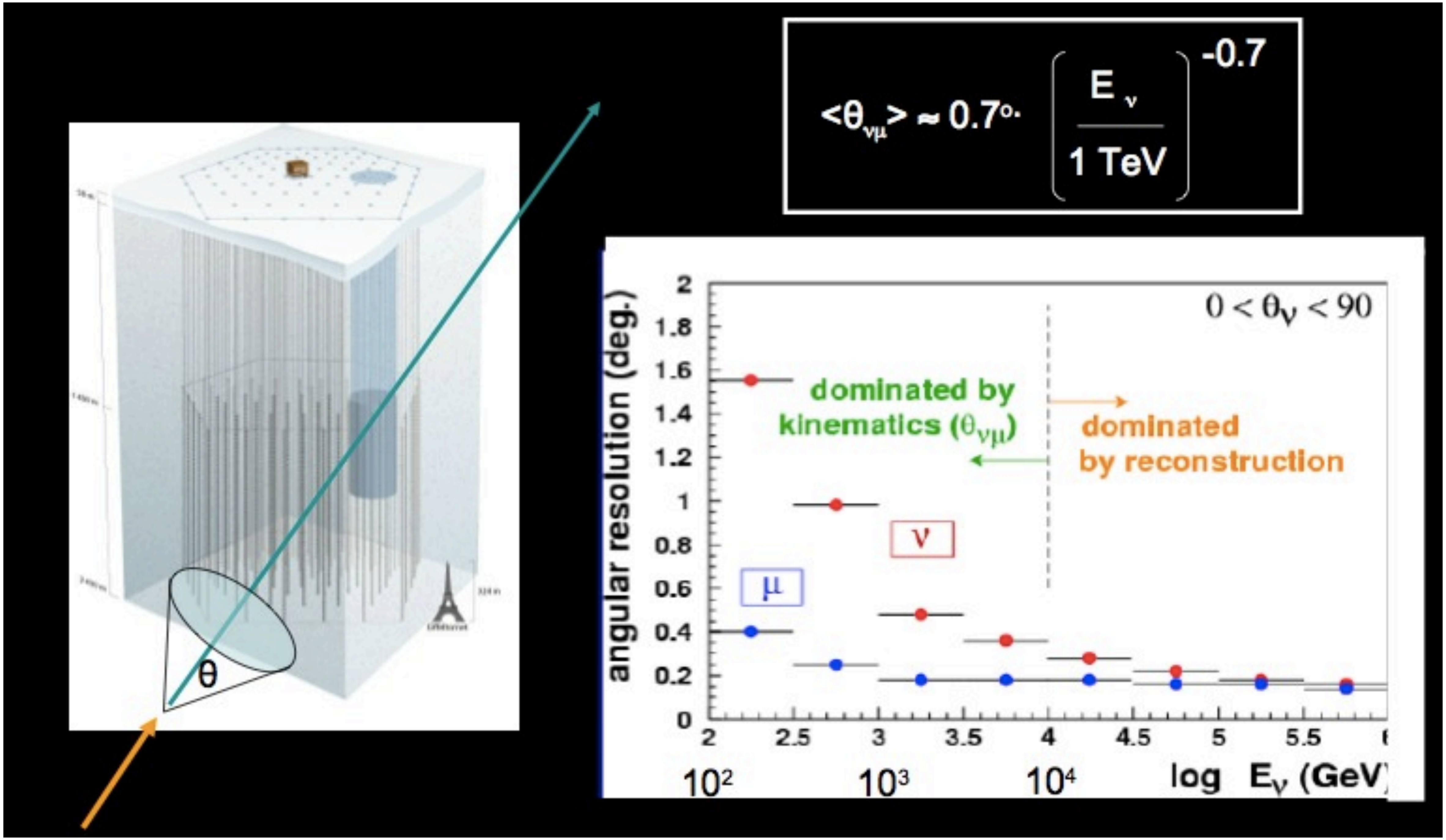





Zenith 2.68676
Azimuth 1.66995

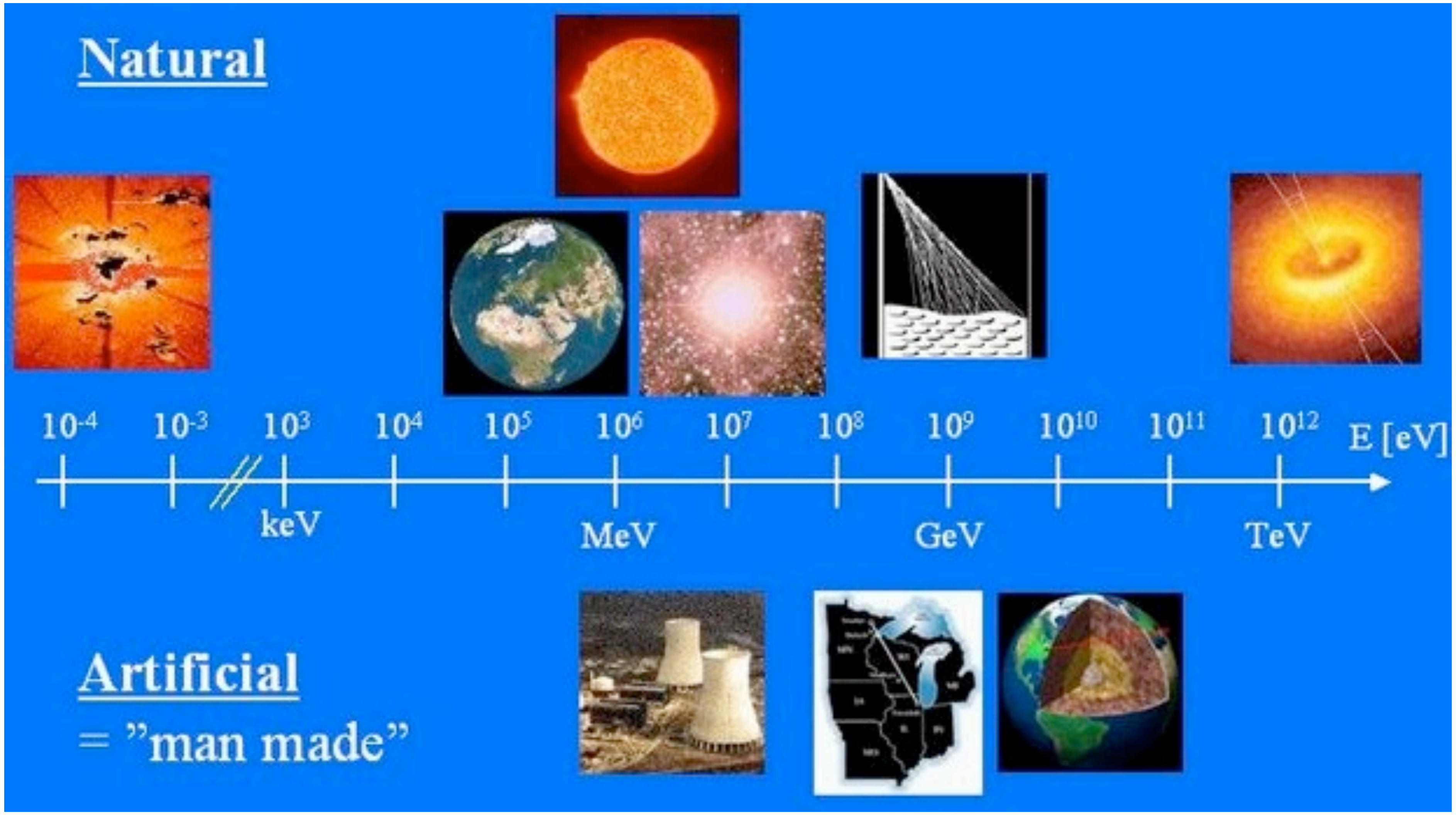
3) neutrino induced leptons

Kinematical angle



3) neutrino induced leptons

Cross sections, effective area calculations



shell model

impulse approximation (Fermi gas etc)

quark parton model (DIS)

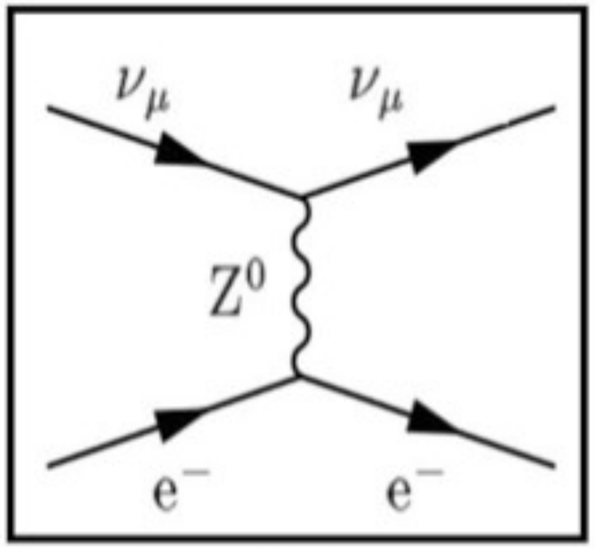
3) neutrino induced leptons

Cross sections, effective area calculations

Case 1: neutrino-electron scattering. Purely leptonic process, cross section determined

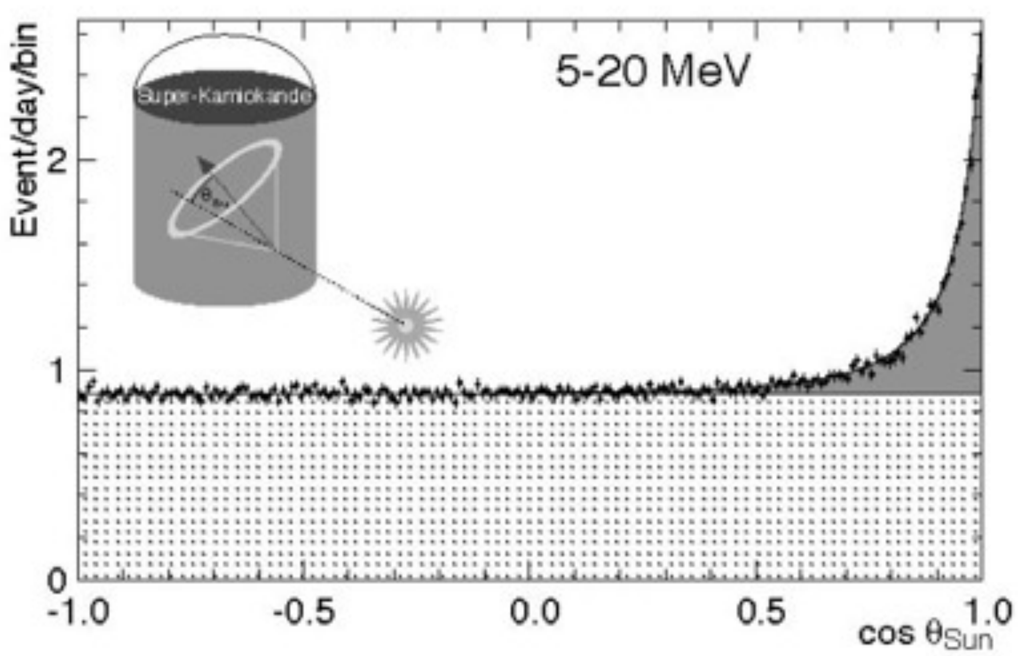
$\nu + e^- \rightarrow \nu + e^-$

$$\sigma = \frac{2G_F^2 m_e}{\pi}\left[\left(g_L^2 + \frac{g_R^2}{3}\right)E_\nu - g_L g_R \frac{m_e}{2}\right] \qquad g_L = \sin^2\theta_W \overset{e}{\underset{\mu,\tau}{\pm}} \frac{1}{2} \qquad g_R = \sin^2\theta_W$$



Both CC and NC are present for ν_e but not for ν_μ and ν_τ

- Cross section liner with neutrino E
- Cross section small! about 4 order or magnitude less then scattering on nucleons
- Electron recoil preserves knowledge of incident neutrino direction (directionality)
- Channel used for solar and SN core collapse neutrinos. For example SuperKamiokande

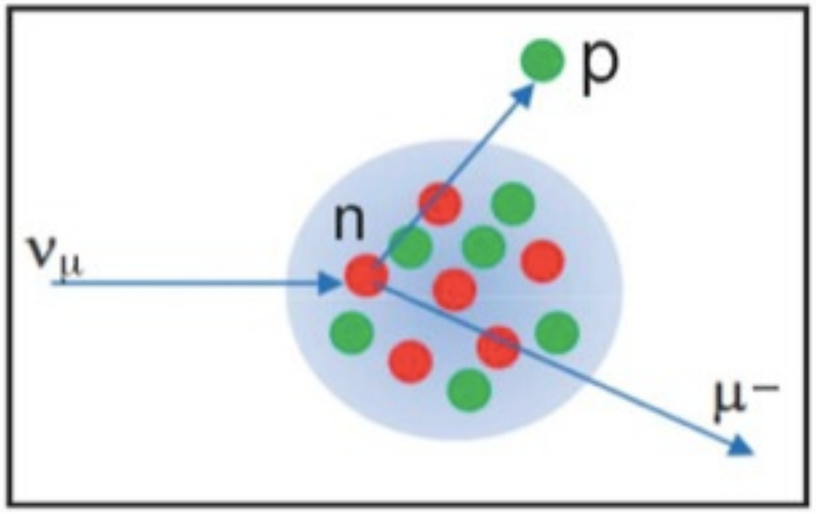


3) neutrino induced leptons

Cross sections, effective area calculations

Case 2: neutrino-nucleon interaction
Quasielastic charged-current reactions

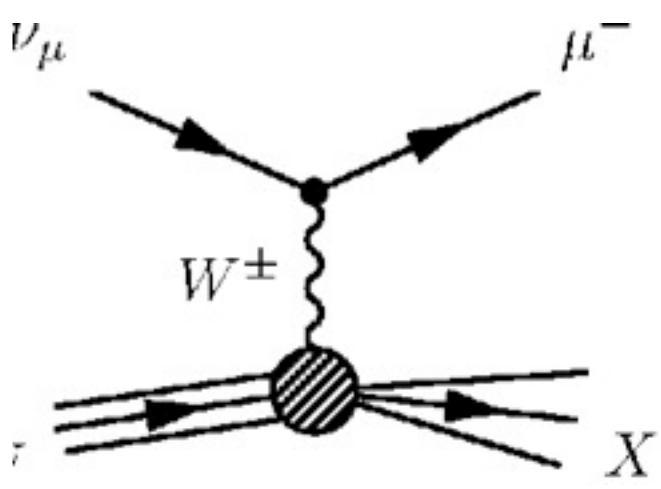
figure taken from P. Vogel



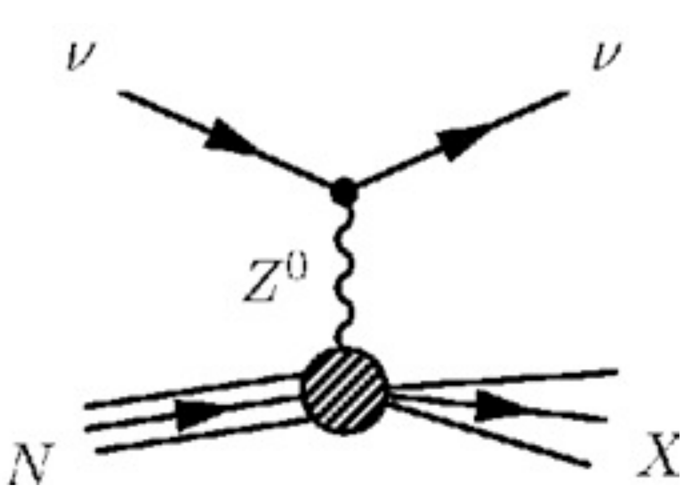
- The CC and NC neutrino interaction terms in the SM Lagrangian are exactly calculable.

- At **high interaction energies** (> 10 GeV) when the quarks are asymptotically free, the scattering off bare quarks is calculable.

- At **lower energies** (< 10 GeV) where the neutrinos interact with bound nucleons or the nucleus as a whole, strong interactions prevent the hadronic current from being exactly calculable



charge-current interaction



neutral-current interaction

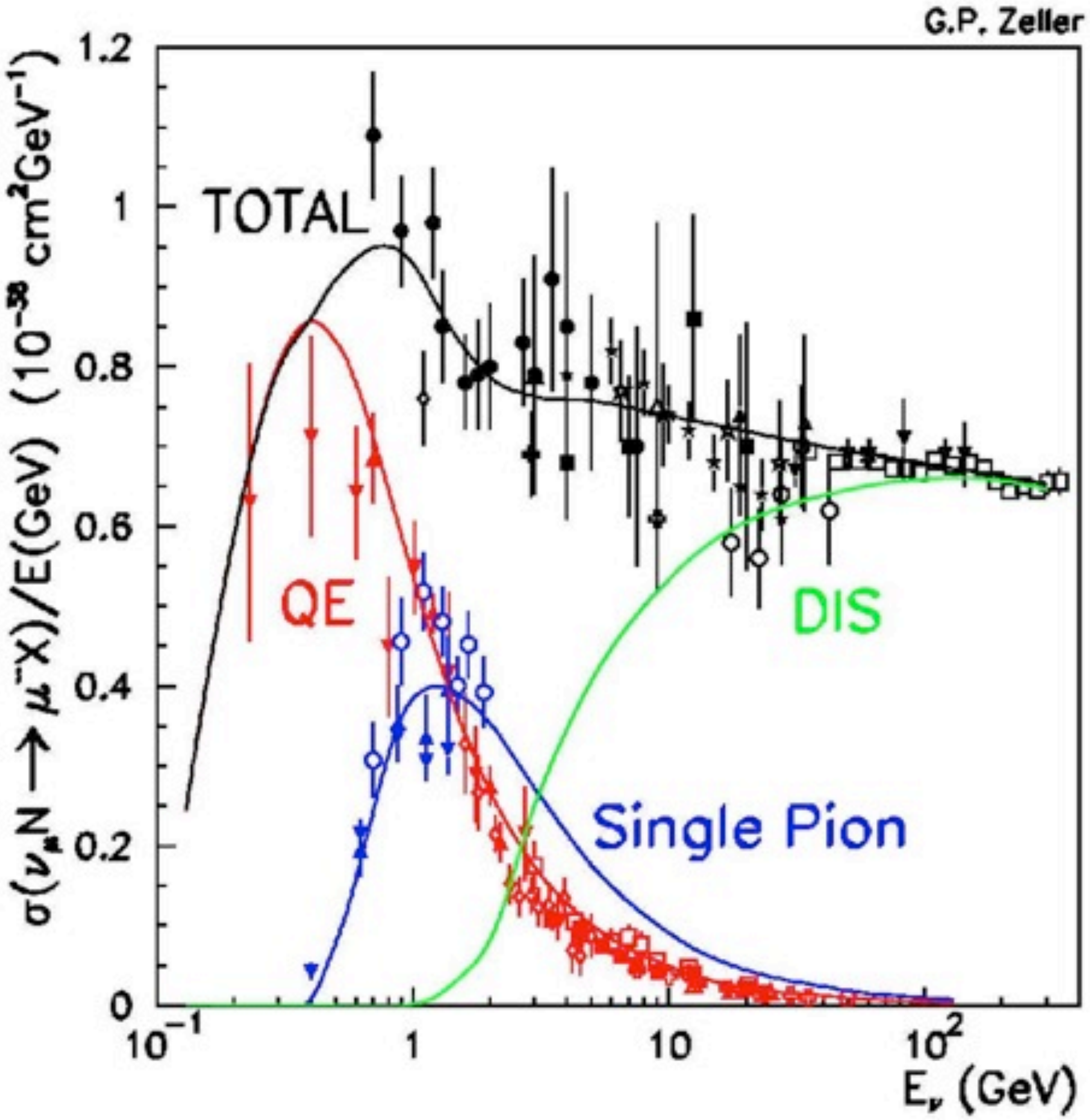
3) neutrino induced leptons

Cross sections, effective area calculations

Interactions of high-energy neutrinos, $E_{neutrinos}$ > 10 GeV, are dominated by **deep inelastic scattering (DIS)**.

At lower energies various competing effects influence the cross sections: DIS, single pion production, and quasi-elastic scattering.

At energies above 100 GeV the measurements are extremely precise.



The few-GeV energy range is the challenging boundary between the non-perturbative and perturbative regimes. For this reason, dedicated MonteCarlo studies are performed.

3) neutrino induced leptons

GENIE Neutrino Monte Carlo Generator C.Andreopoulos et al. http://arxiv.org/pdf/0905.2517v2.pdf

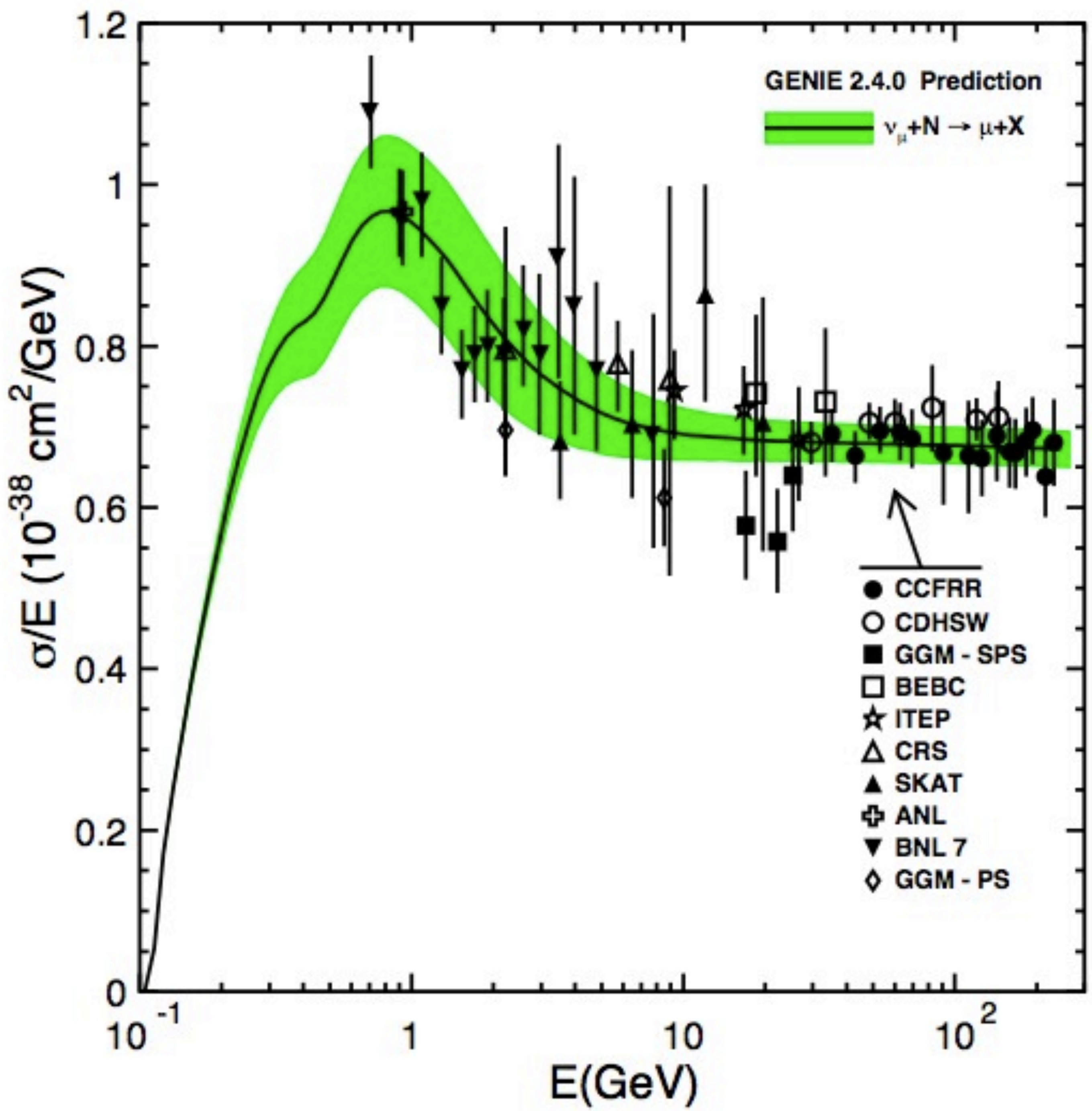


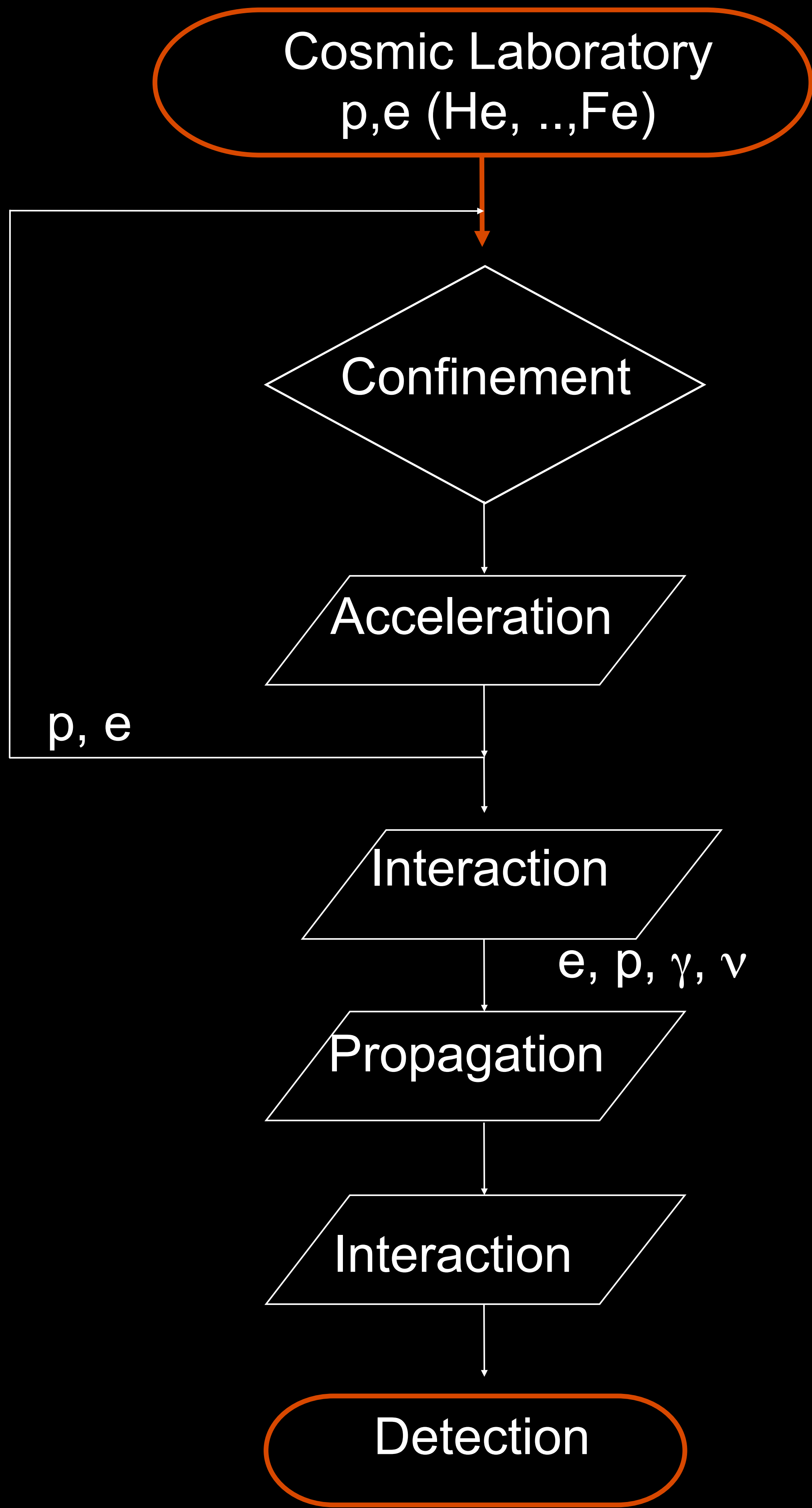
Figure 5: GENIE default cross section for $\nu\mu$ charged current scattering from an isoscalar target. The shaded band indicates the estimated uncertainty on the free nucleon cross section. Data are from [62] (CCFRR), [63] (CDHSW), [64] (GGM-SPS), [65, 66] (BEBC), [67] (ITEP), [68] (CRS, SKAT), [69] (ANL), [70] (BNL) and [71] (GGM-PS)

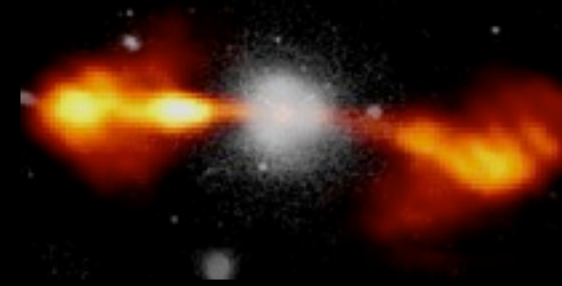
Content

<u>SECOND PART</u>

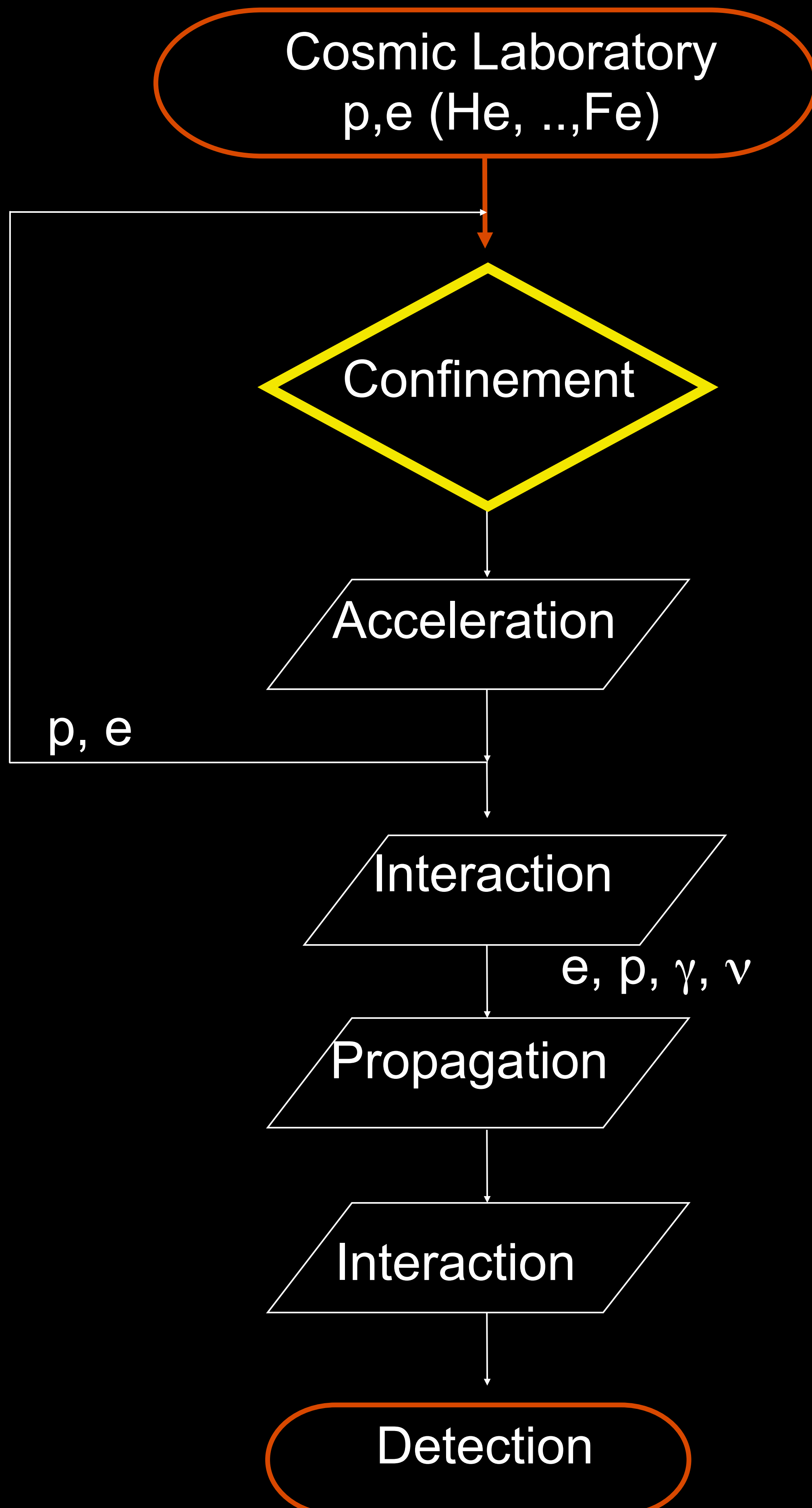
- Astrophysical neutrinos:
    - connection with CR primary energies
- Neutrino telescopes: selected list of results
    - SuperNovae neutrinos
    - Atmospheric neutrino oscillation
    - Neutrinos from GRBs
    - High energy cascades: first extra-terrestrial neutrinos?
- One possible future: PINGU

4) Astrophysical Neutrinos





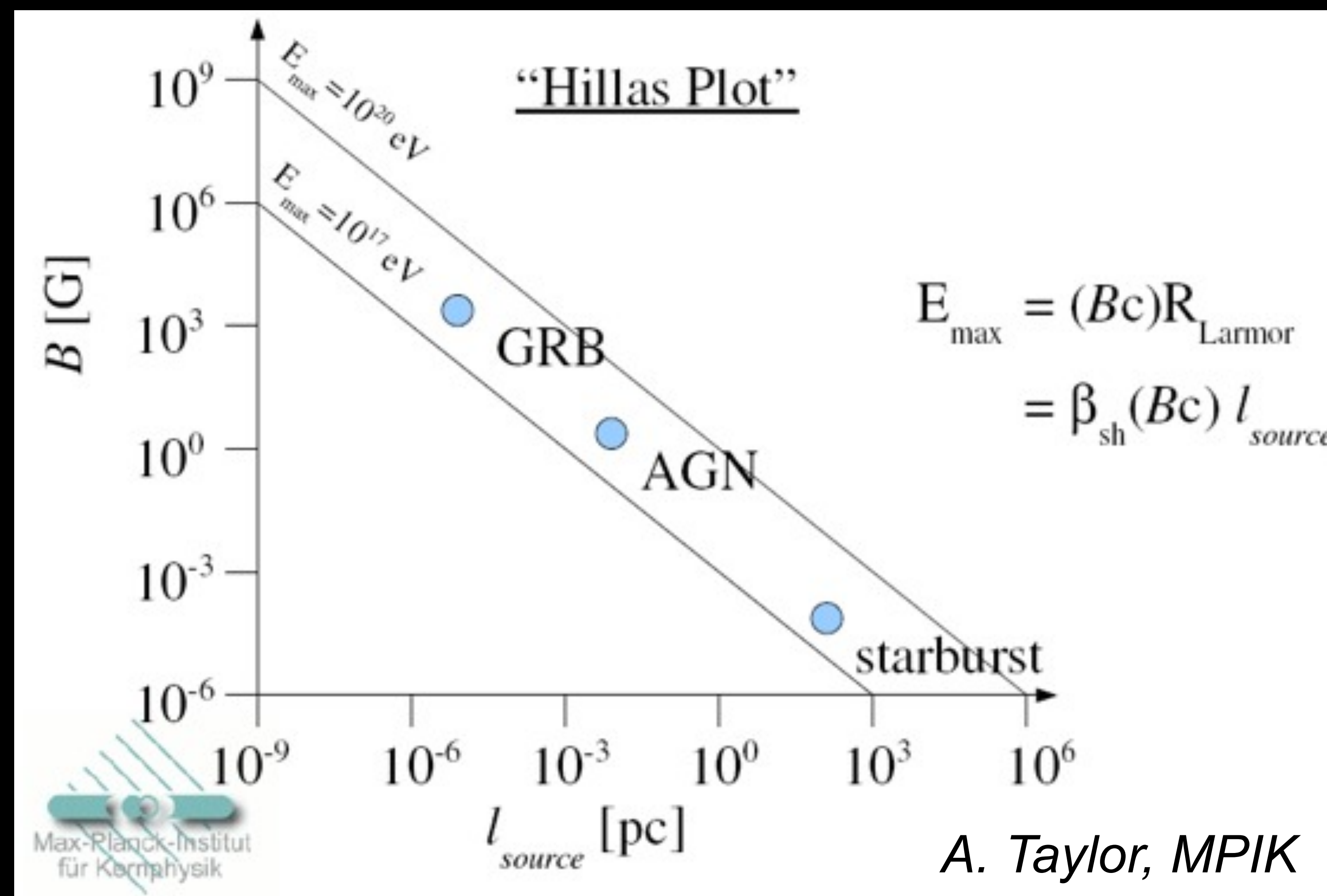
Cosmic particles flowchart



Cosmic particles flowchart

Source size, Magnetic Field

A. M. Hillas,
Ann. Rev. Astron. Astrophys. **22**, 425 (1984)



Cosmic particles flowchart

Cosmic Laboratory
p,e (He, ..,Fe)

Confinement

Acceleration

p, e

Interaction

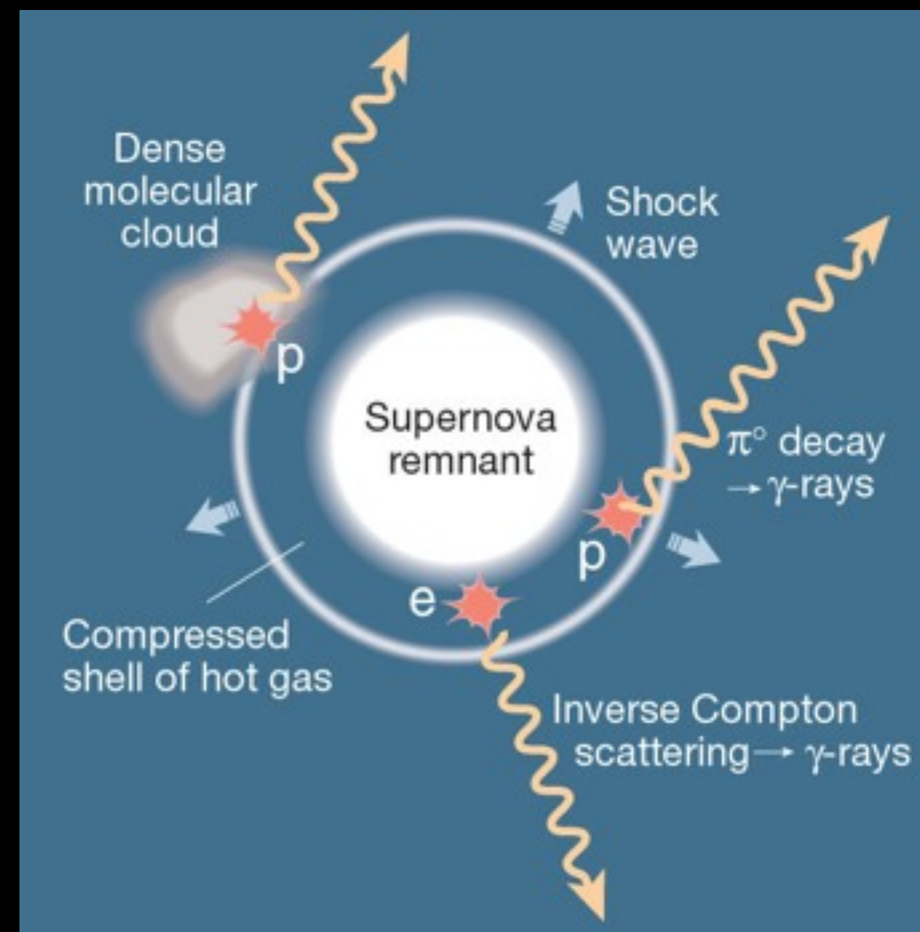
e, p, γ, ν

Propagation

Interaction

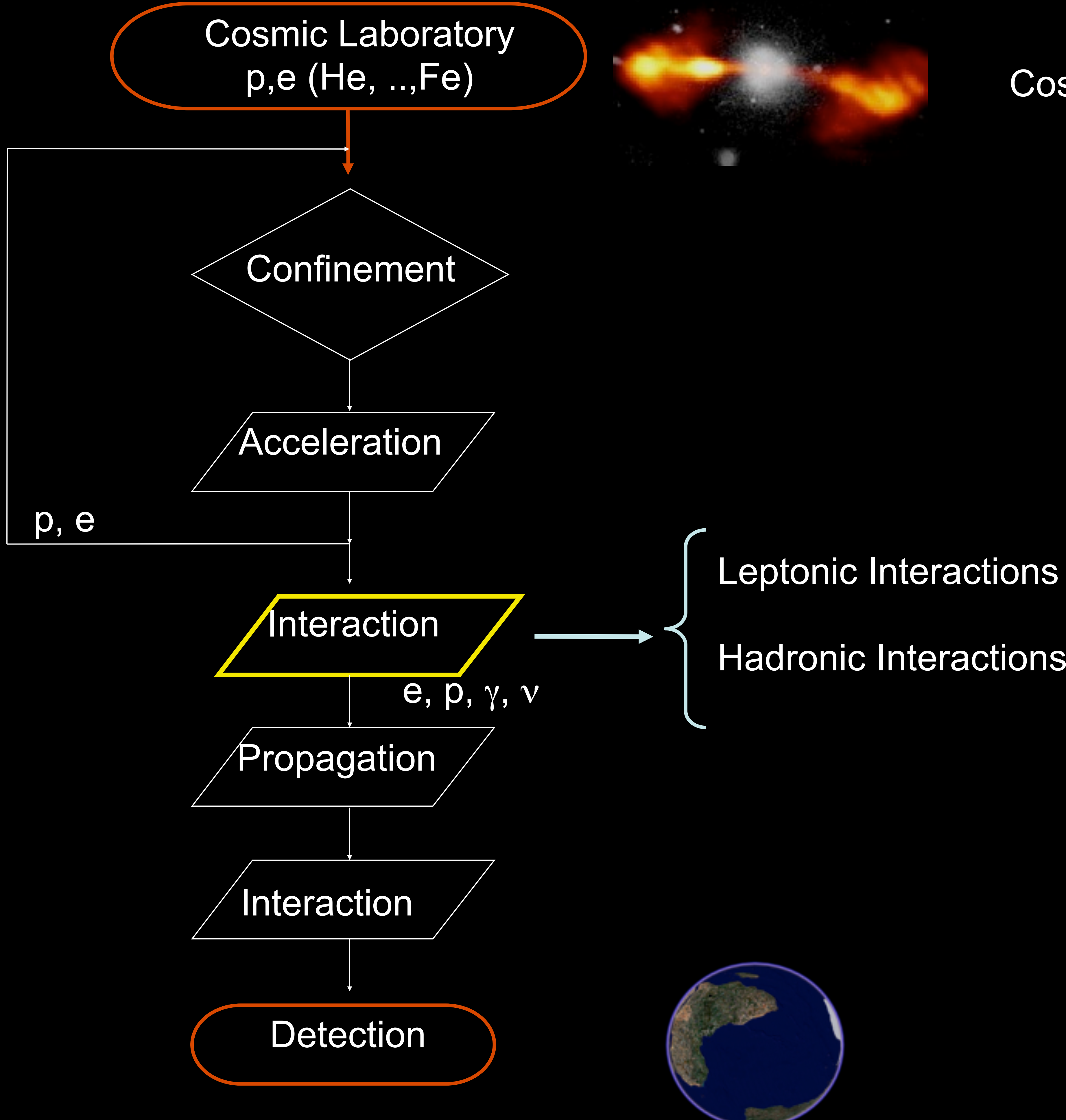
Detection

Various ideas:
Diffusive shock acceleration
More in L2

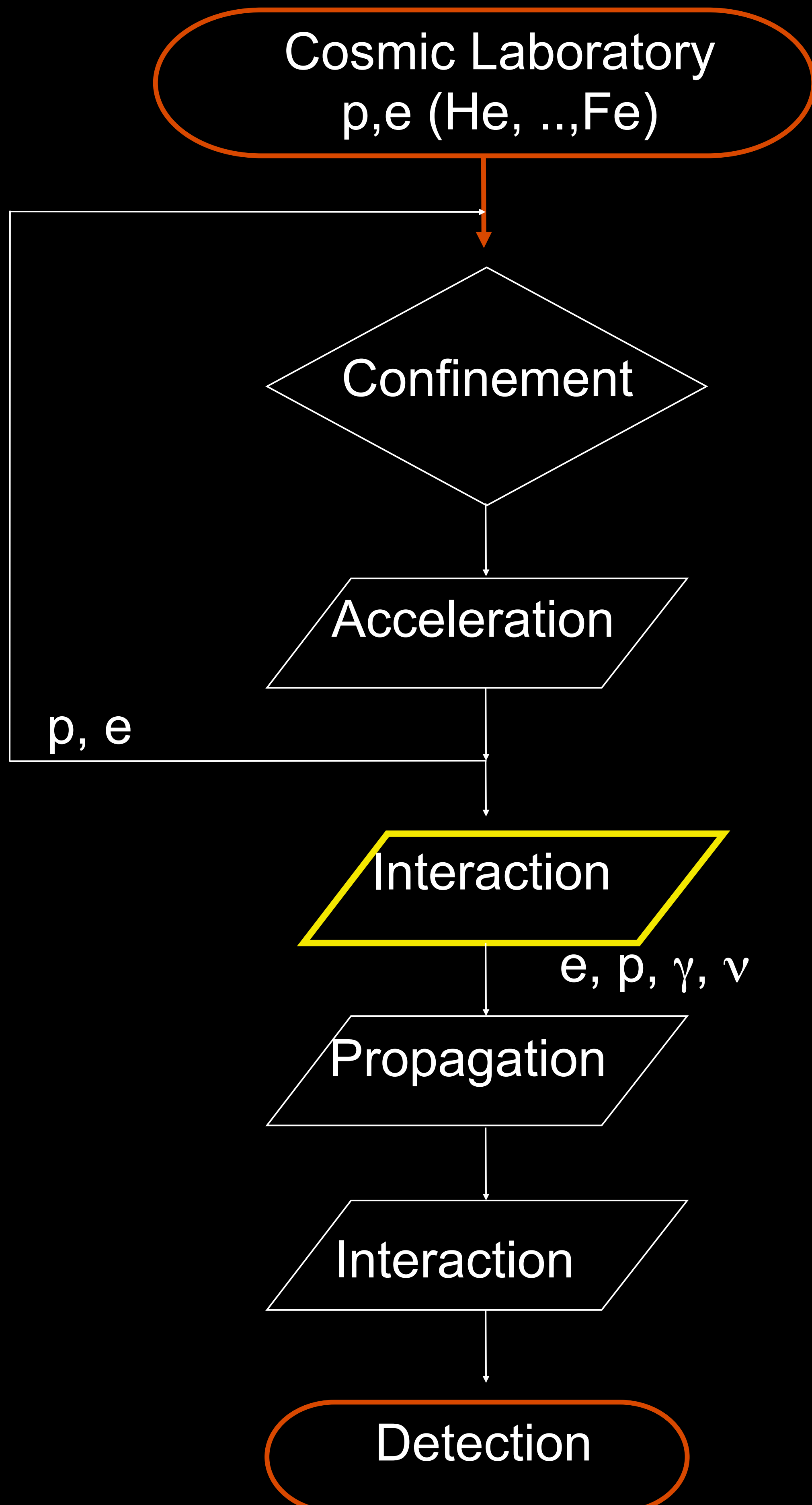


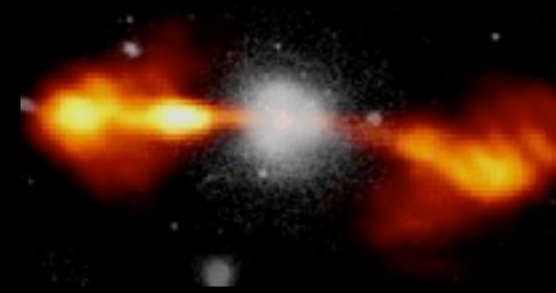
Felix Aharonian, Nature ***416****, 797-798,2002*

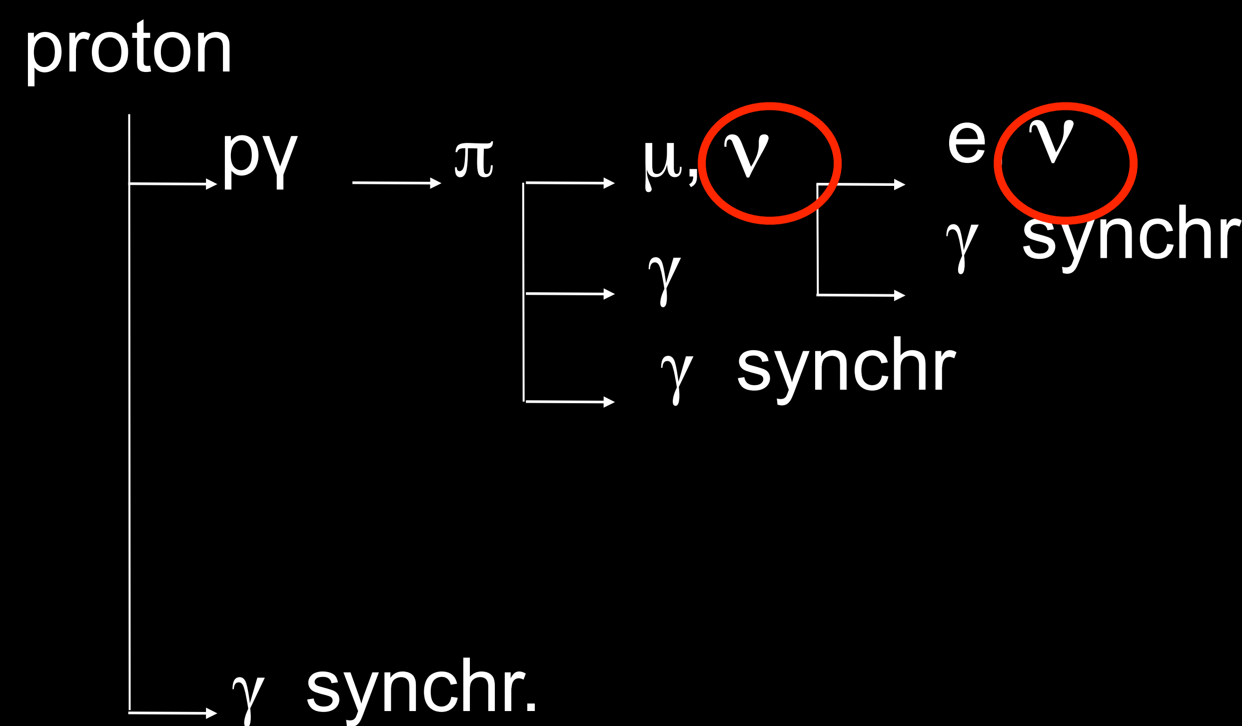
Cosmic particles flowchart



Cosmic particles flowchart

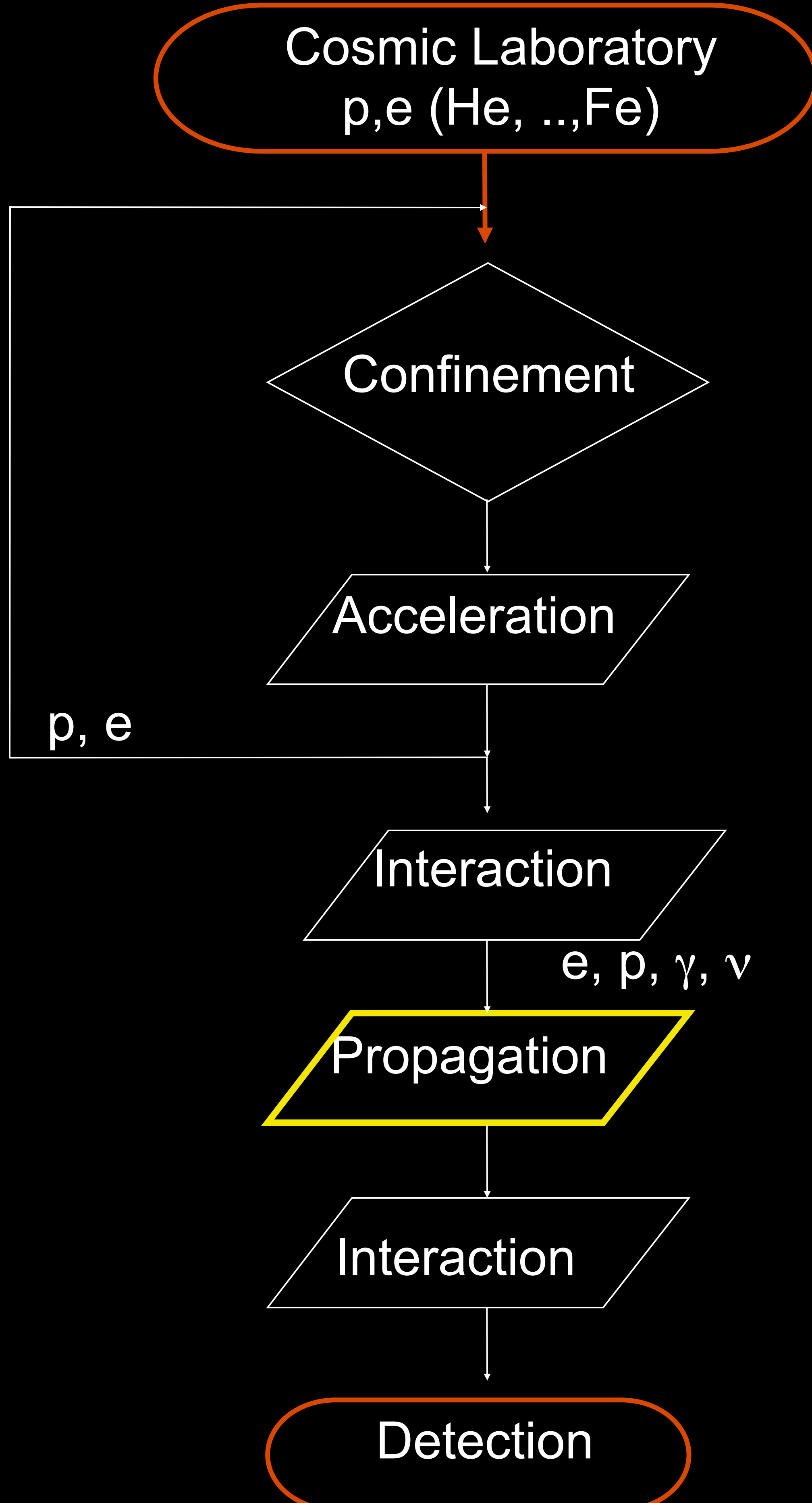






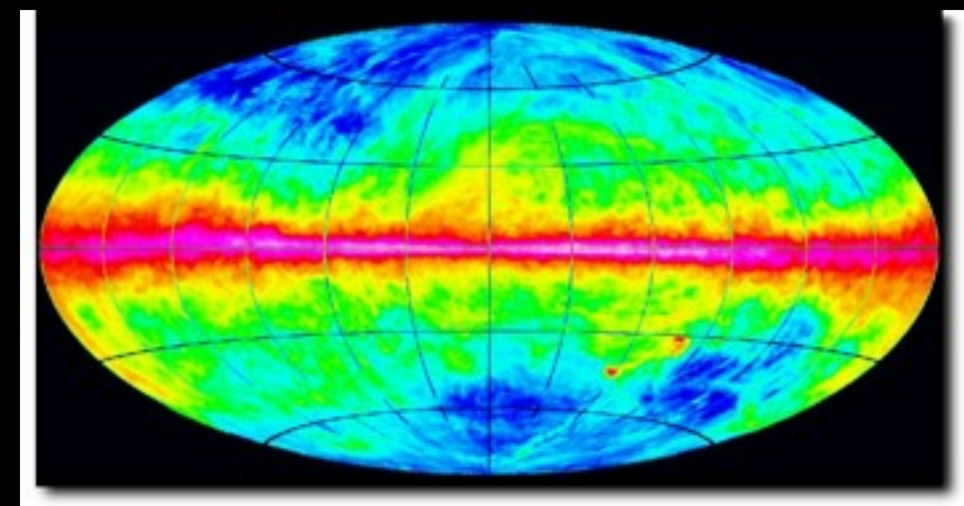
Three Messengers:

Charged Particles, Gamma-rays and Neutrinos



Cosmic particles flowchart

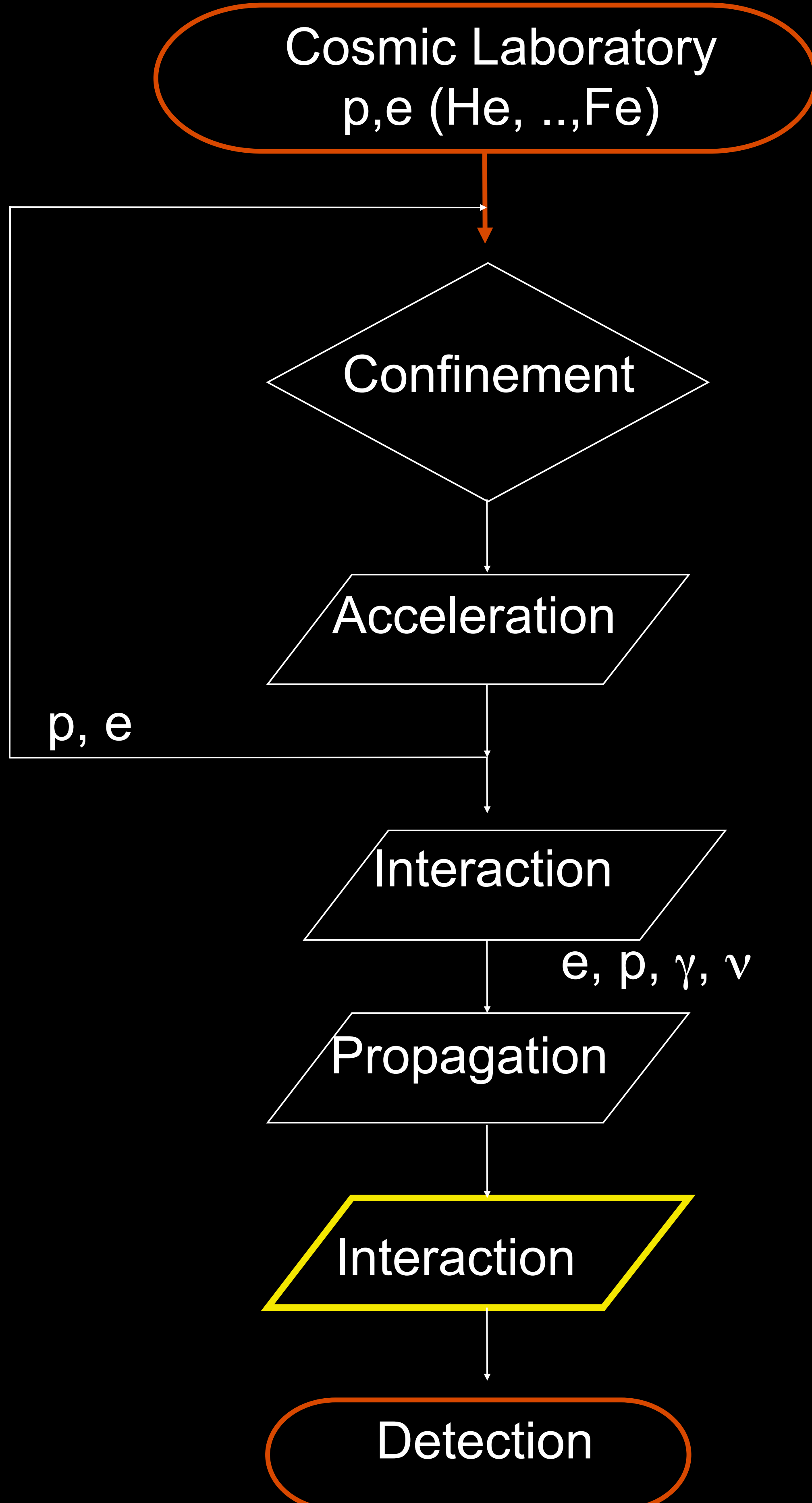
The Leiden/Argentine/Bonn (LAB)
Survey of Galactic HI



H2, NANTEN

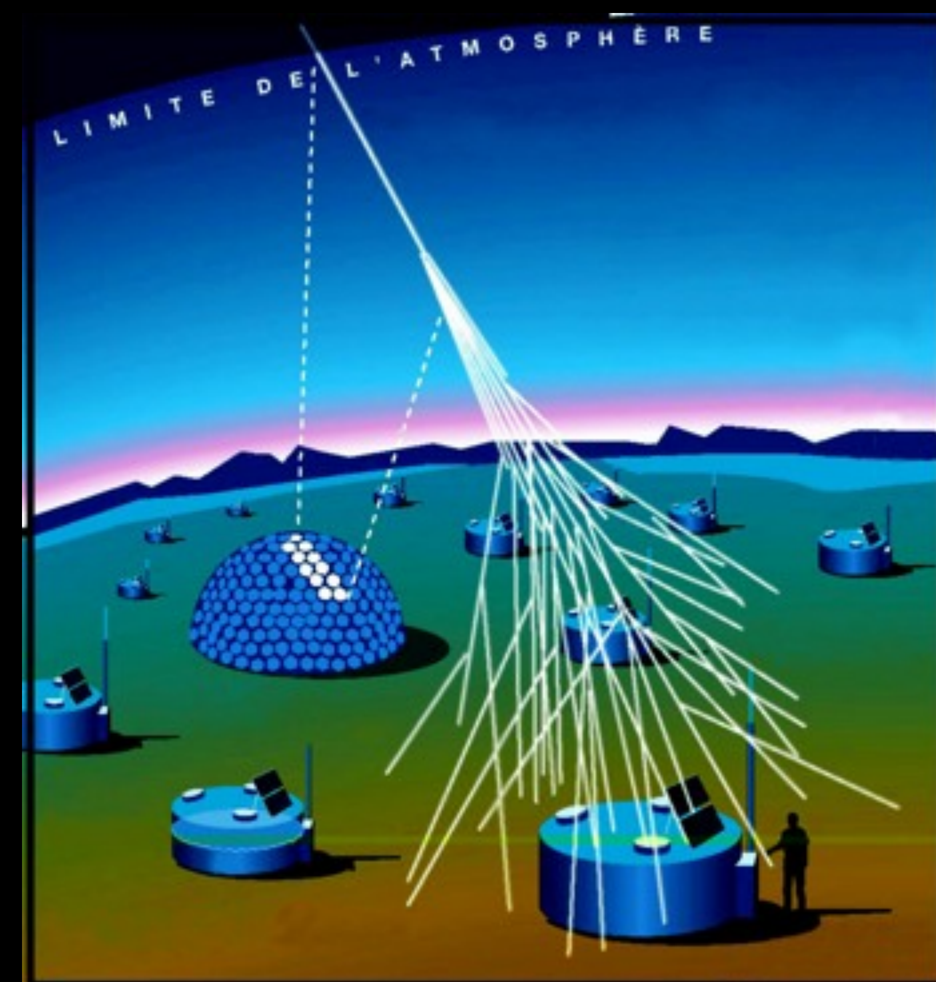
Lorentz Invariance Violation?

- p: magnetic field deviation
- γ: absorption
- ν: no interaction, point back to the source

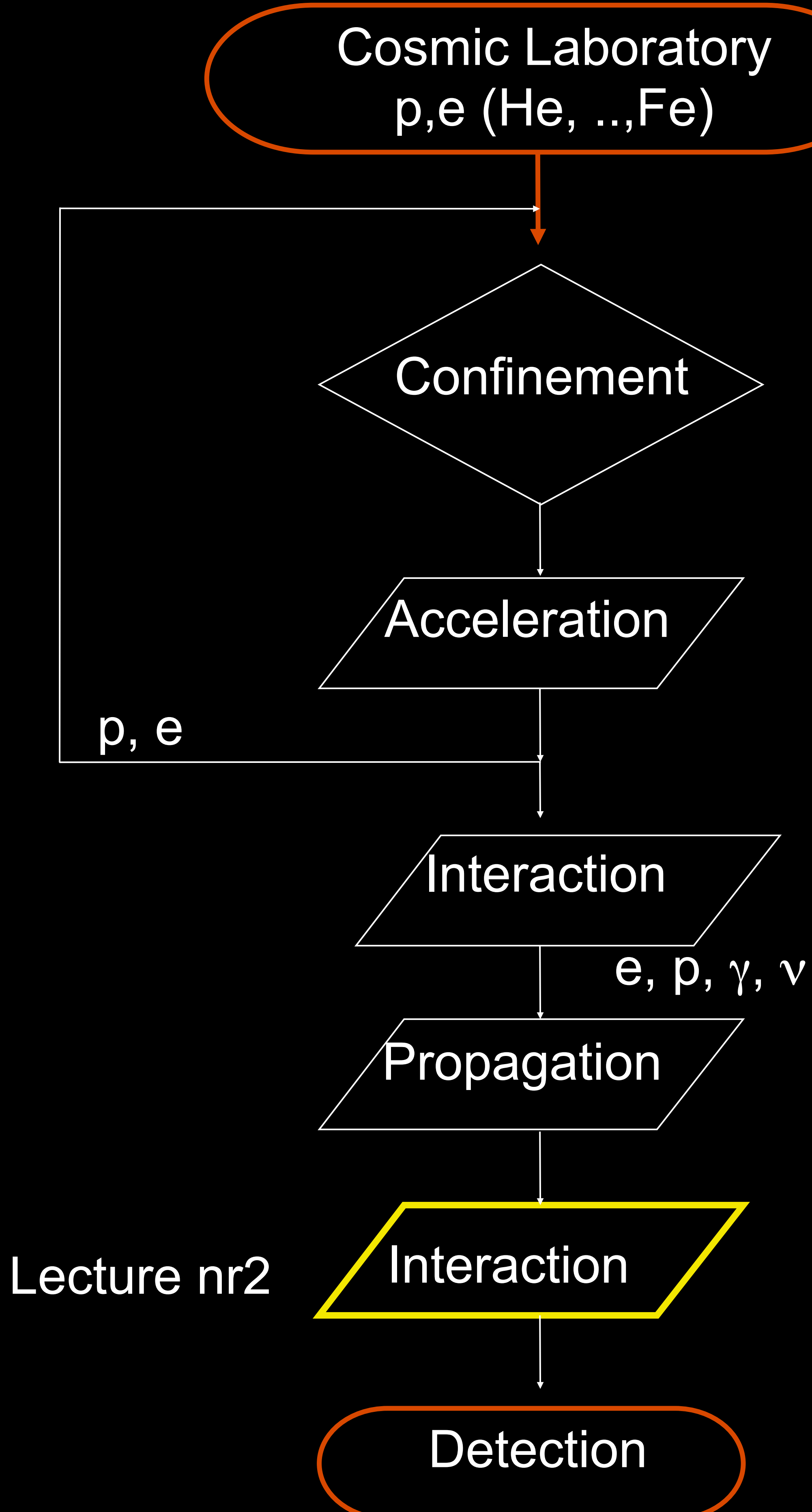


Cosmic particles flowchart

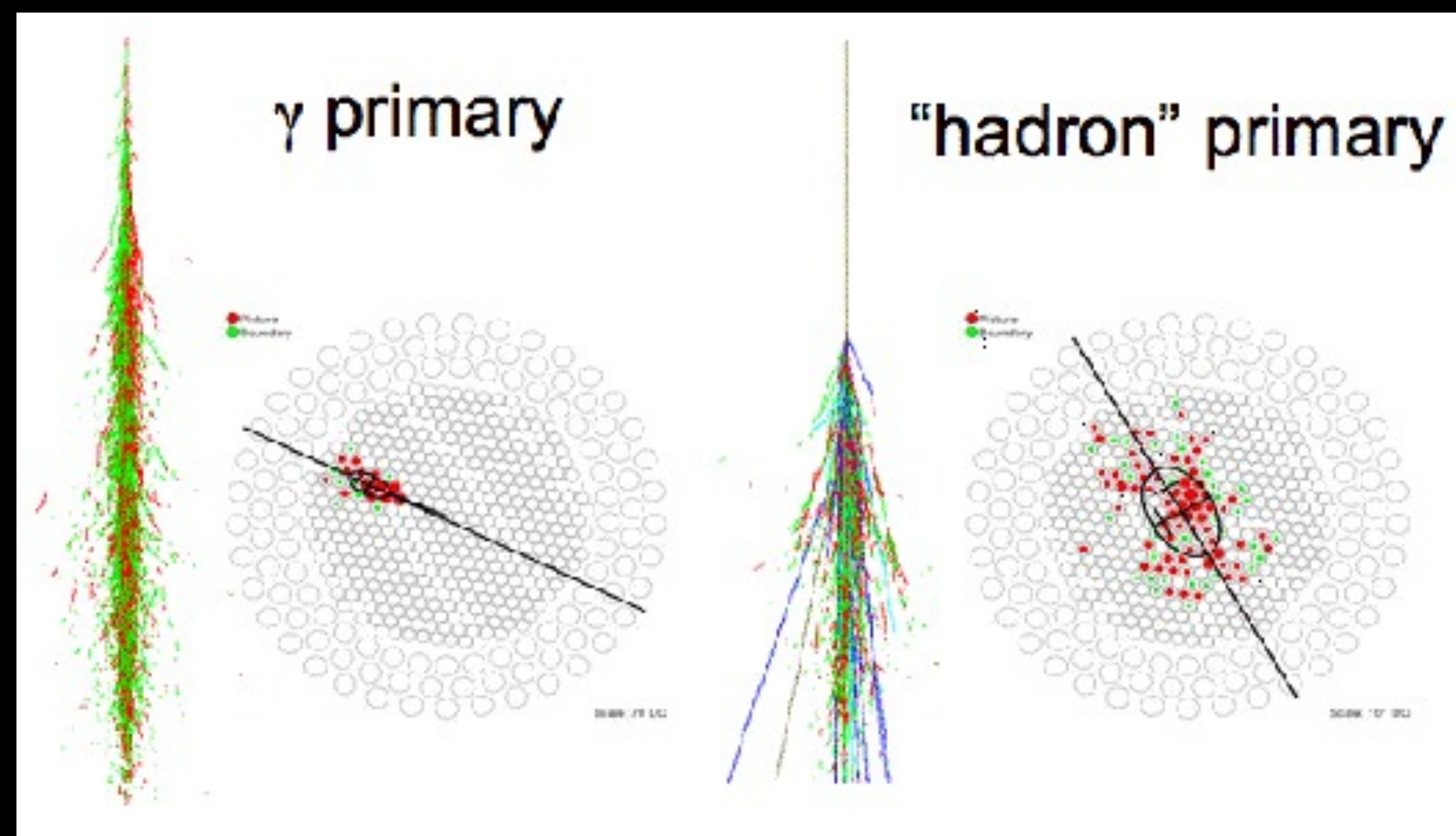
Proton interaction in Earth atmosphere
Air showers



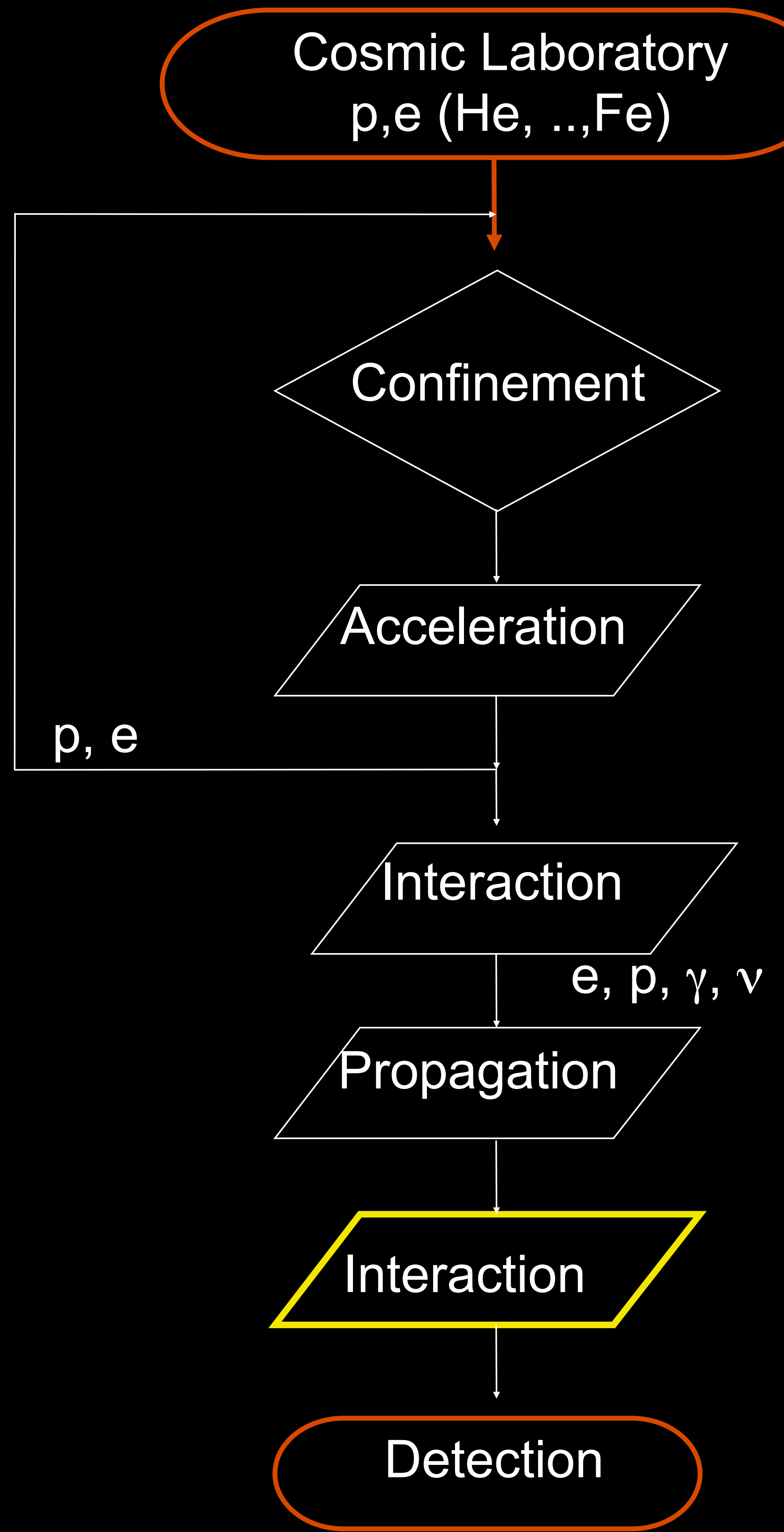
Cosmic particles flowchart

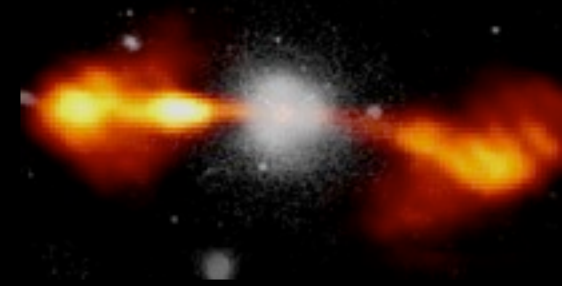


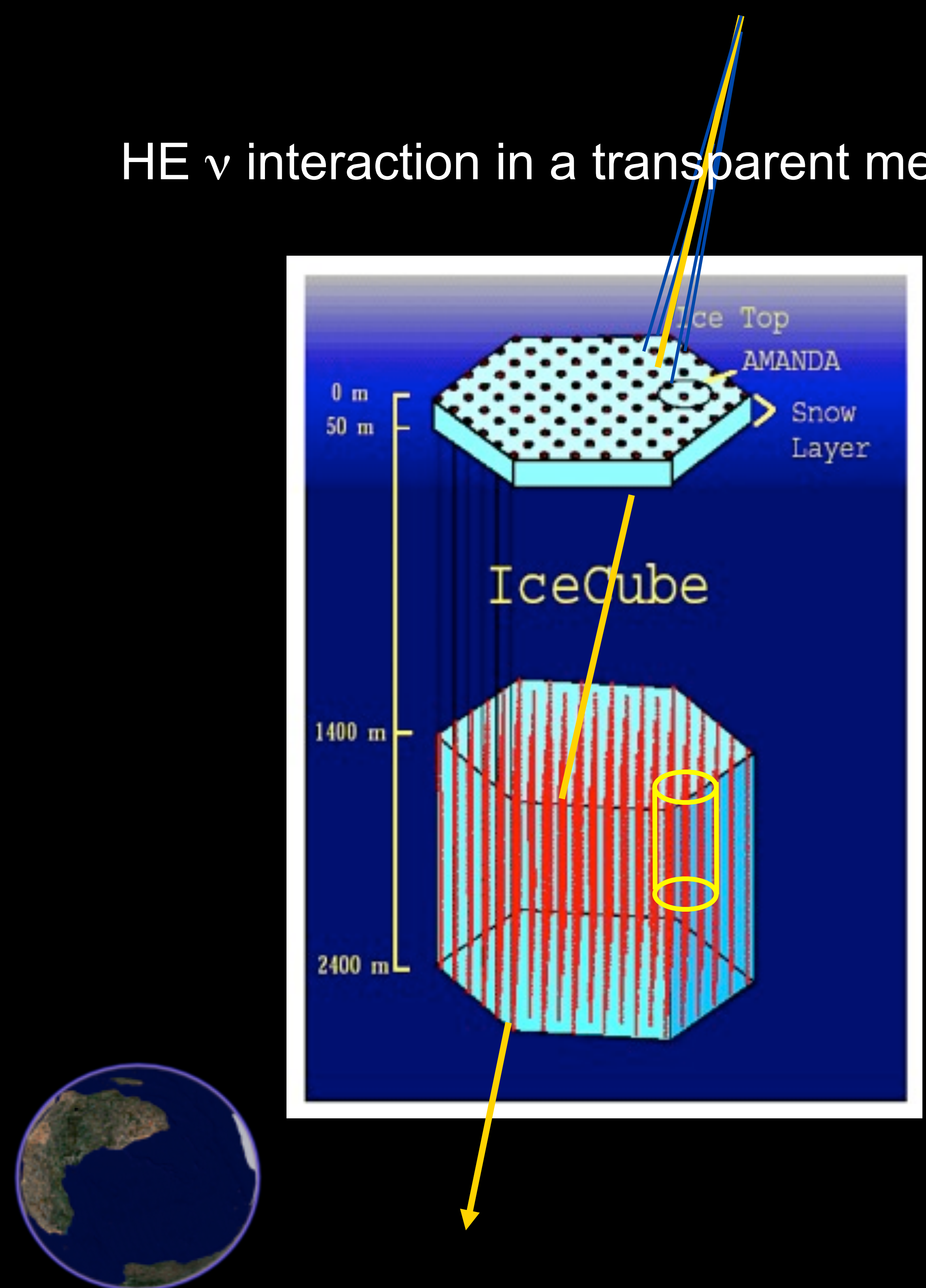
Proton and γ-rays interaction in Earth atmosphere
Air showers



Cosmic particles flowchart

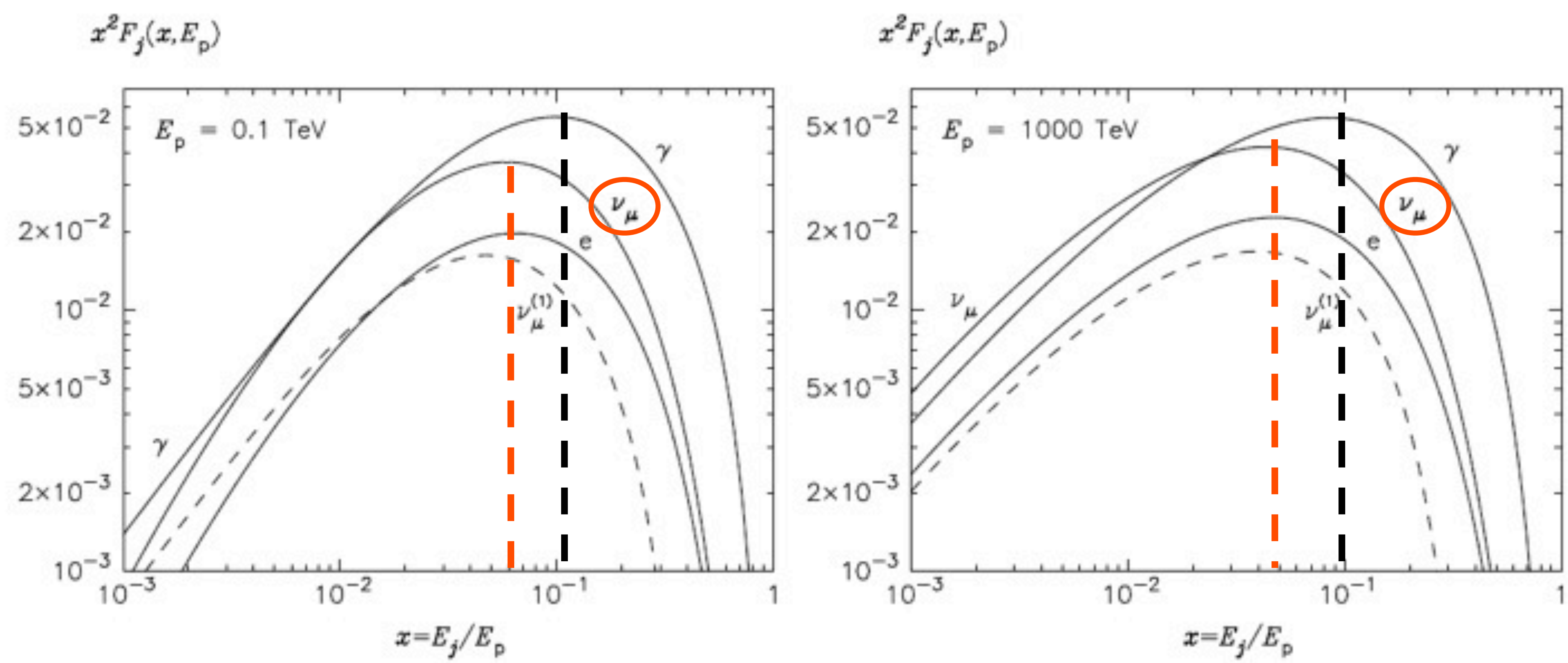






4) Astrophysical Neutrinos : Cosmic Rays

Ep:Eγ:Eν = 1: 0.1: 0.05



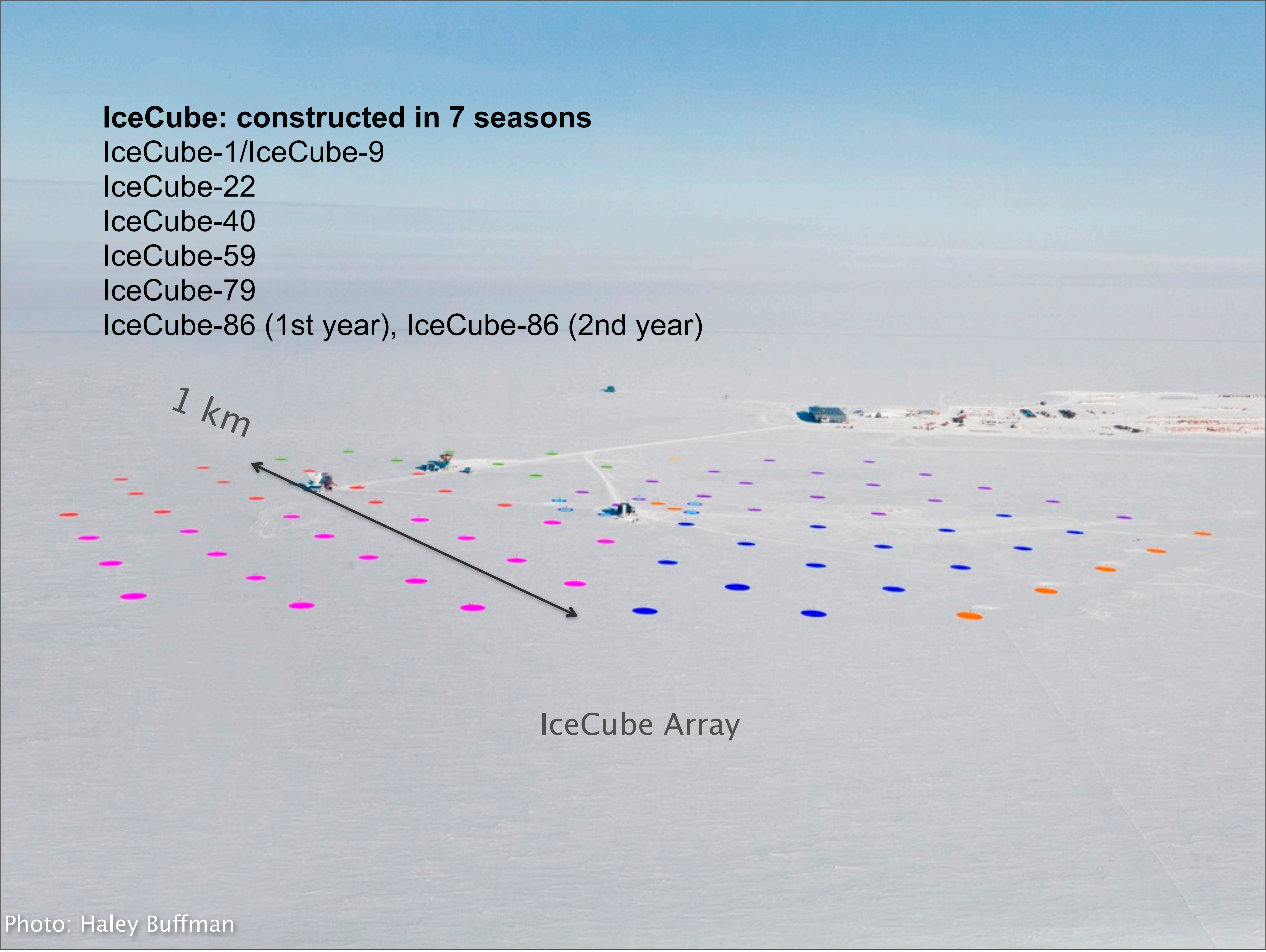
- Reference:
- pp Interaction (S.R. Kelner, F. A. Aharonian,V.V. Bugayov, Phys.Rev.D74:034018,2006)
- pγ Interaction (S.R. Kelner, F.A. Aharonian, Phys.Rev.D78:034013,2008)
- A. Reimer et al., SOPHIA MonteCarlo, http://ebl.stanford.edu/

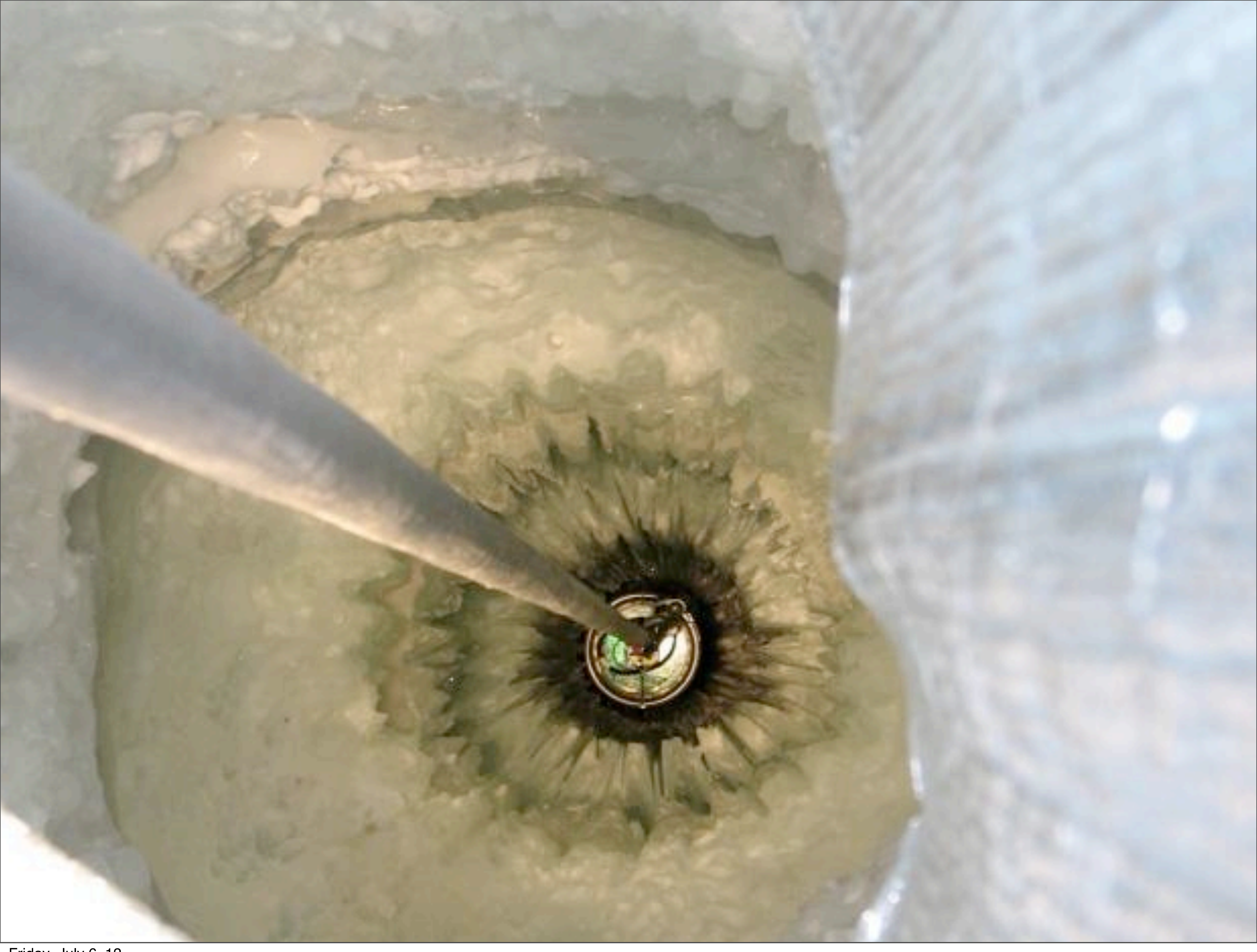
5) Neutrino telescopes: selected list of results

- list of physics topics in a neutrino telescope
- SN core collapse
- atmospheric neutrino oscillation
- point source
- GRB
- high energy cascades: first extra-terrestrial neutrinos?

IceCube: constructed in 7 seasons

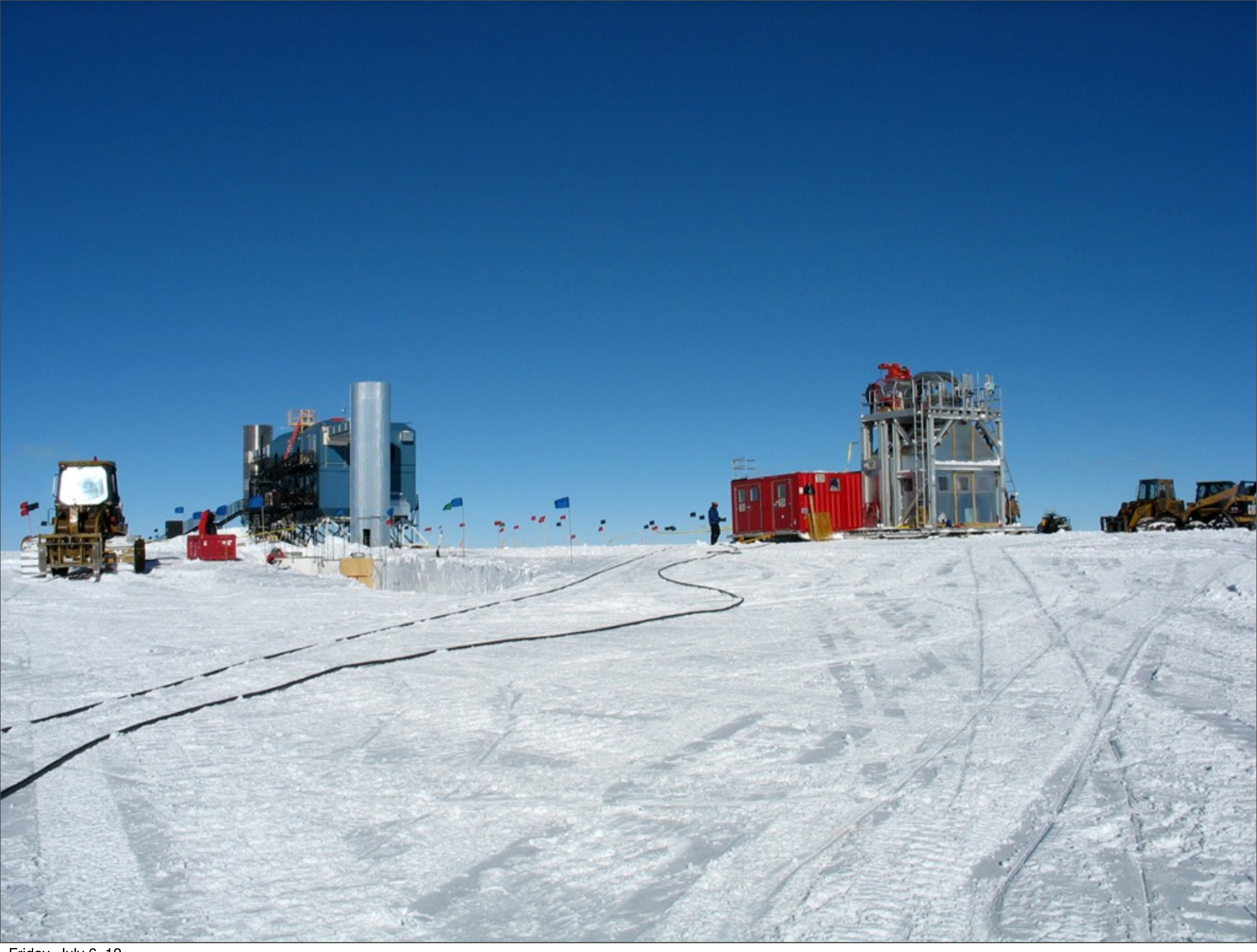
IceCube-1/IceCube-9
IceCube-22
IceCube-40
IceCube-59
IceCube-79
IceCube-86 (1st year), IceCube-86 (2nd year)





The drill of 3 km holes in the ice ??

we have a better system ....







after 7 years:

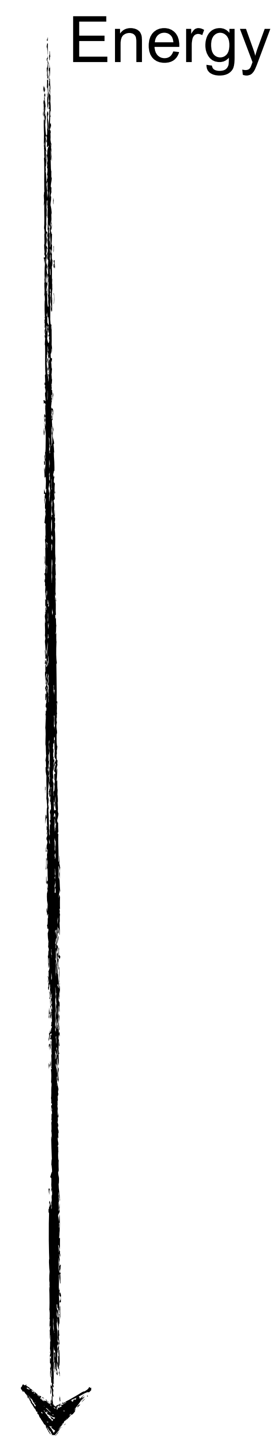
December 2010

The IceCube Collaboration

Friday, July 6, 12

5) Neutrino telescopes: physics topics

- Core collapse SuperNovae
- Atmospheric neutrino oscillation (including non standard)
- Indirect Dark Matter Search
- Anisotropies in CR
- Astrophysical neutrinos (point source, diffuse flux)
- Neutrino from GRBs
- UHE/EHE neutrinos (cosmogenic neutrinos)
- Cascades induced events



5) Neutrino telescopes: core collapse SN

Supernovae = progenitors of galactic accelerators

➔ What is a Supernovae explosion?
is the final stage of a massive star (initial mass > 8$M_\odot$)
(see M.S.Longair vol. 2, “HIgh Energy Astrophysics”, ch 15)

close to final stage of nuclear fusion (end of stellar evolution)
the core of the star runs out of nuclear fuel
➔ gravitational collapse
➔ huge explosion with liberation of huge amount of energy, envelope is ejected at high velocity
➔ possible left over: neutron star, black hole

➔ SN observed by “eye” in our Galaxy during the last 1000 years
➔ 1006, 1054 (Crab Nebula), 1572 (Tyco), 1604 (Kepler)
➔ SN1987A
Others could have been obscured by dust (for example. Cassiopaeia A)

SuperNovae: classification and core-collapse

S. Perlmutter (Nobel 2011) http://supernova.lbl.gov/PDFs/PhysicsTodayArticle.pdf

Supenovae are used as **standard candles** in order to study cosmology
As early as 1938, Walter Baade, working closely with Fritz Zwicky, pointed out that supernovae were extremely promising candidates for measuring the cosmic expansion.
Most important steps for the use of SN as standard candles: classification!

The uniformity of the type Ia supernovae became even more striking when their spectra were studied in detail as they brightened and then faded.
Then, as the exploding ball of gas expands, the outermost layers thin out and become transparent, letting us see the spectral signatures of conditions further inside. Eventually, if we watch the entire time series of spectra, we get to see indicators that probe almost the entire explosive event. It is impressive that the type Ia supernovae exhibit so much uniformity down to this level of detail.

In short (cosmology is not the topic here): the classification and observation of SN at cosmological distances brought to the evidence of an accelerating universe, existence of cosmological constant etc.

(for entertainment you can read “The extravagant Universe” R.P. Kirshner)

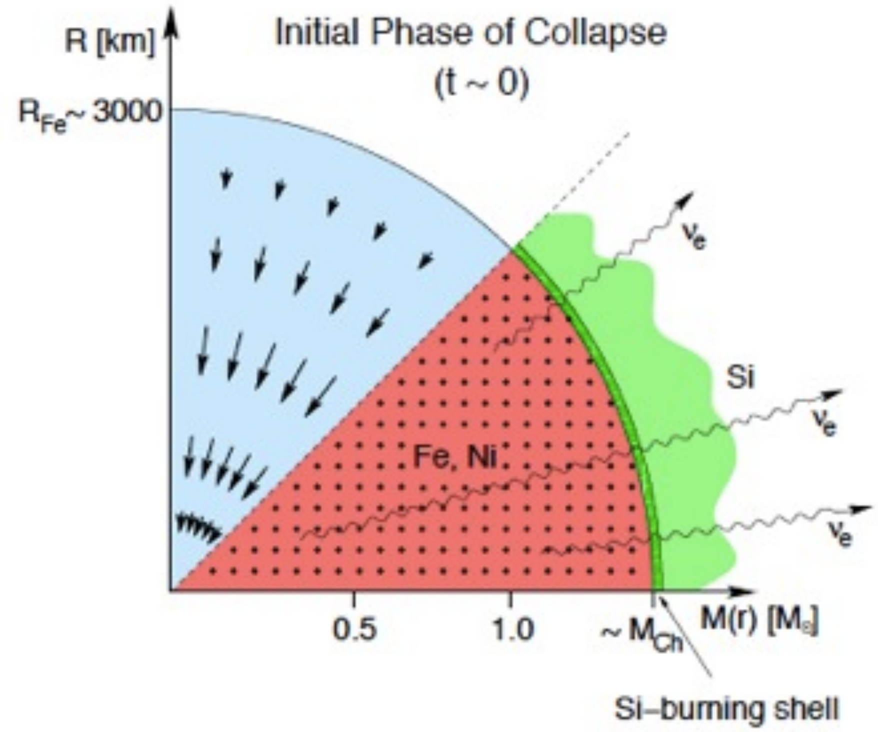
SuperNovae: classification and core-collapse

Core-collapse supernovae and related (MeV) neutrino emission

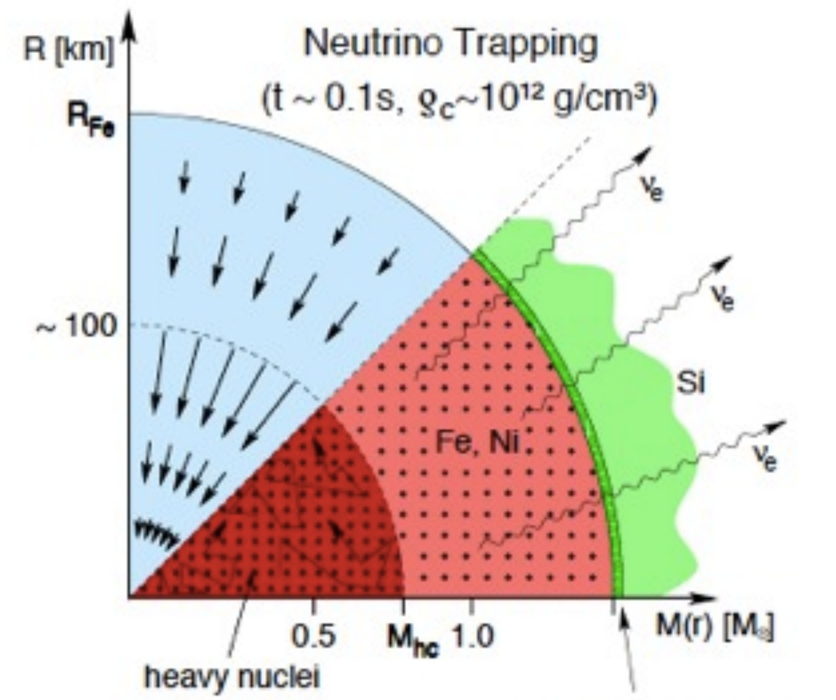
ref (theory): H.-Th. Janka et al, astro-ph :0612072

Various subsequent nuclear fusion stages take place in the progenitor star of a core-collapse supernova

- Initial Phase of Collapse, t=0:
during the collapse of the iron core, protons undergo electron capture. In this reaction, electron neutrinos are produced. At this early stage, the neutrinos can stream away freely from the core. The electron density of the core is reduced and the collapse accelerated.



- Neutrino Trapping, t ~ 0.1 sec:
as soon as the core density increases, neutrinos undergo coherent scattering with nuclei and get trapped in the core. A "neutrinosphere" is formed in which the mean free path of the neutrinos is smaller than the core radius.

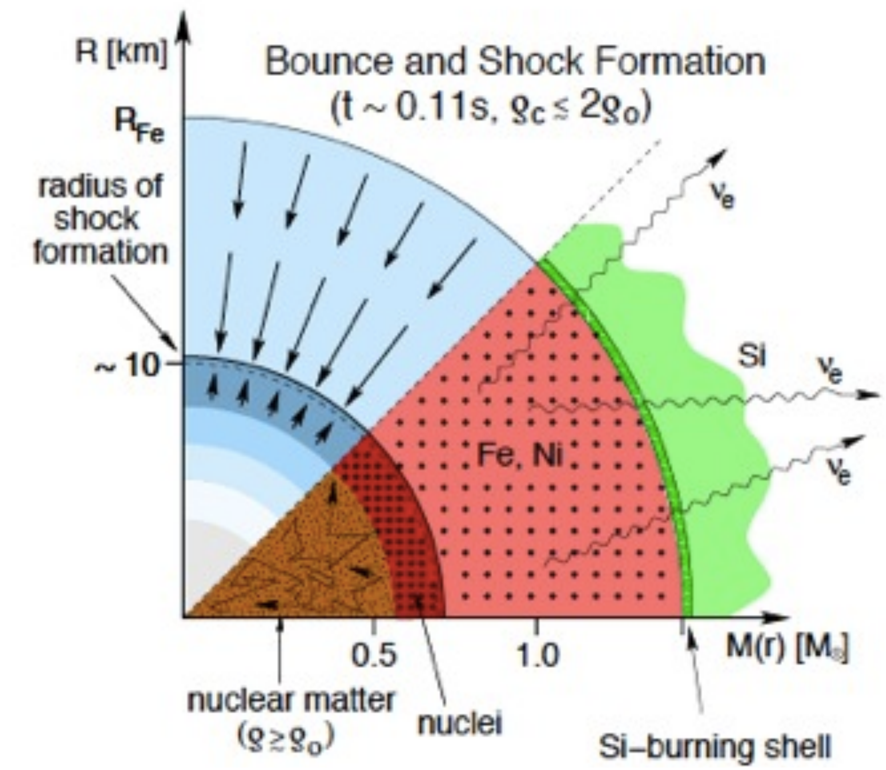


SuperNovae: classification and core-collapse

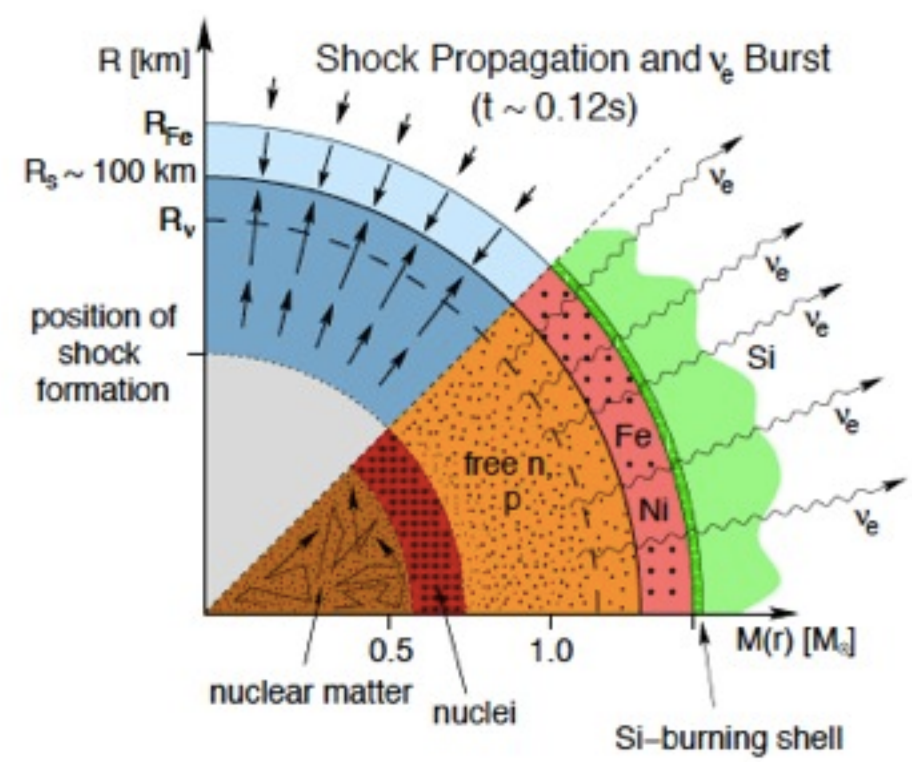
Core-collapse supernovae and related (**MeV**) neutrino emission

ref (theory): H.-Th. Janka et al, astro-ph :0612072

- Bounce and Shock Formation, t~0.11 sec:
as soon as nuclear density is reached, neutrinos don’t scatter any more with nuclei but directly with free nucleons. Nuclear matter is characterized by a much lower compressibility, hence the core decelerate and bounces back generating a shock wave into the outer core. This bounce will trigger ultimately the supernovae explosion.
How this happen in details, is not yet completely clarified.



- Shock Propagation and ν_e Burst, t ~ 0.12 sec:
In the most simple case, when the shock wave succeeds to blow away the outer shells of the star then we speak about ‘prompt mechanism’. But if the shock is not strong enough, as it seams from modern simulation, then dissociation of heavy nuclei into nucleons continues and neutrinos scatters primarily with nucleons. We remind here that the coherent scattering cross section is proportional to the square of the mass number ($\sigma_{coh} \propto A^2$). Then, neutrinos succeed again to escape from the core and they produce the so-called neutronization burst or neutrino burst at shock break-out.
The total neutrino energy emitted in such a burst is of the order of 10^{53}~erg.

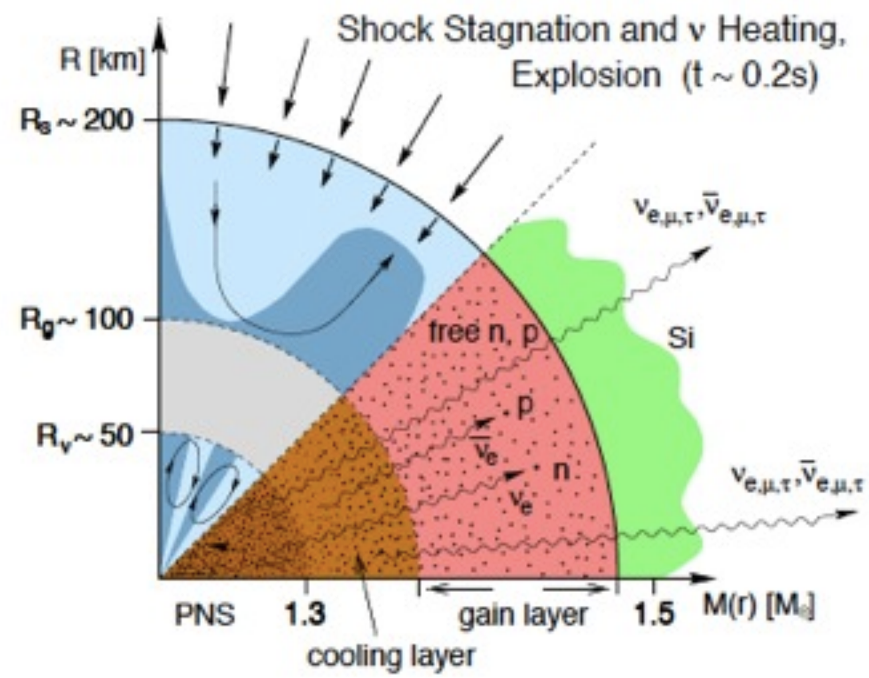


SuperNovae: classification and core-collapse

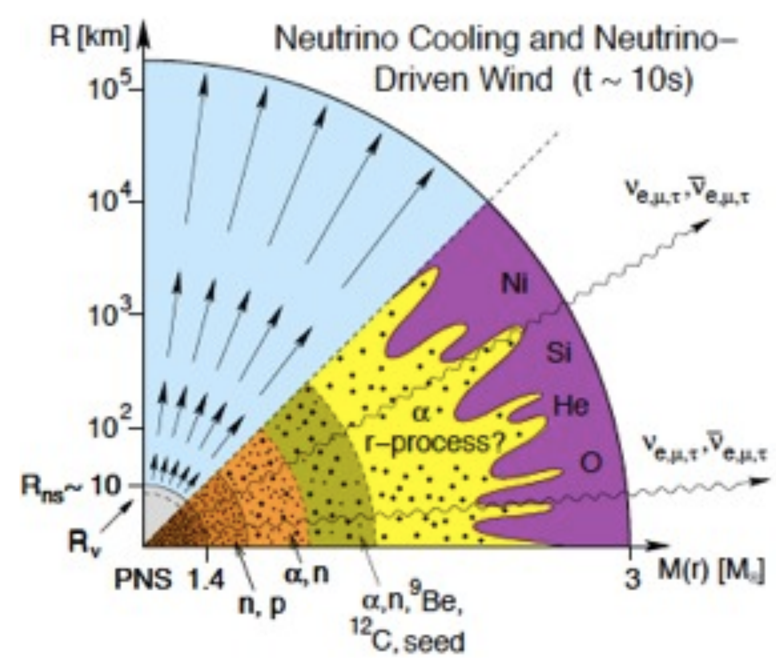
Core-collapse supernovae and related (**MeV**) neutrino emission

ref (theory): H.-Th. Janka et al, astro-ph :0612072

- Shock Stagnation and Neutrino Heating, t ~ 0.2 sec: the energy loss due to escaping neutrinos weakened the shock that transform in accretion. At this stage a proto-neutron star that will evolve in the remnant of the explosion. During this accretion phase, neutrinos of all flavor as well as anti-electron neutrinos are produced.



- Neutrino Cooling and Neutrino Driven Wind, t ~ 10 sec: Finally, the proto-neutron star cools and form a neutron star. In this last process, neutrinos of all flavors are emitted with a timescale of tens of seconds and their luminosity drops fast.



SuperNovae: classification and core-collapse

Core-collapse supernovae and related (**MeV**) neutrino emission

ref (theory): H.-Th. Janka et al, astro-ph :0612072

about 99% of the energy of a Supernovae (SN) is released in energetic (MeV) neutrinos

A lot of questions are still open: (from the ref)

- Do we understand the neutrino physics sufficiently well?
- Are our models correct in predicting the luminosities and mean energies of the radiated neutrinos?
- How important is rotation in the collapsing core?
- Do magnetohydrodynamic effects play a crucial role, tapping a large reservoir of free energy of rotation?

The measurement of neutrino signals and gravitational waves will be able to yield such information, but that will require a galactic supernova to happen !! fingers crossed!!

The neutrino light curve will be of major importance.

IceCube can perform the most precise measure of the time profile of the neutrino burst (2 msec resolution). More in the Lecture on IceCube.

SuperNovae: classification and core-collapse

Core-collapse supernovae and related (**MeV**) neutrino emission

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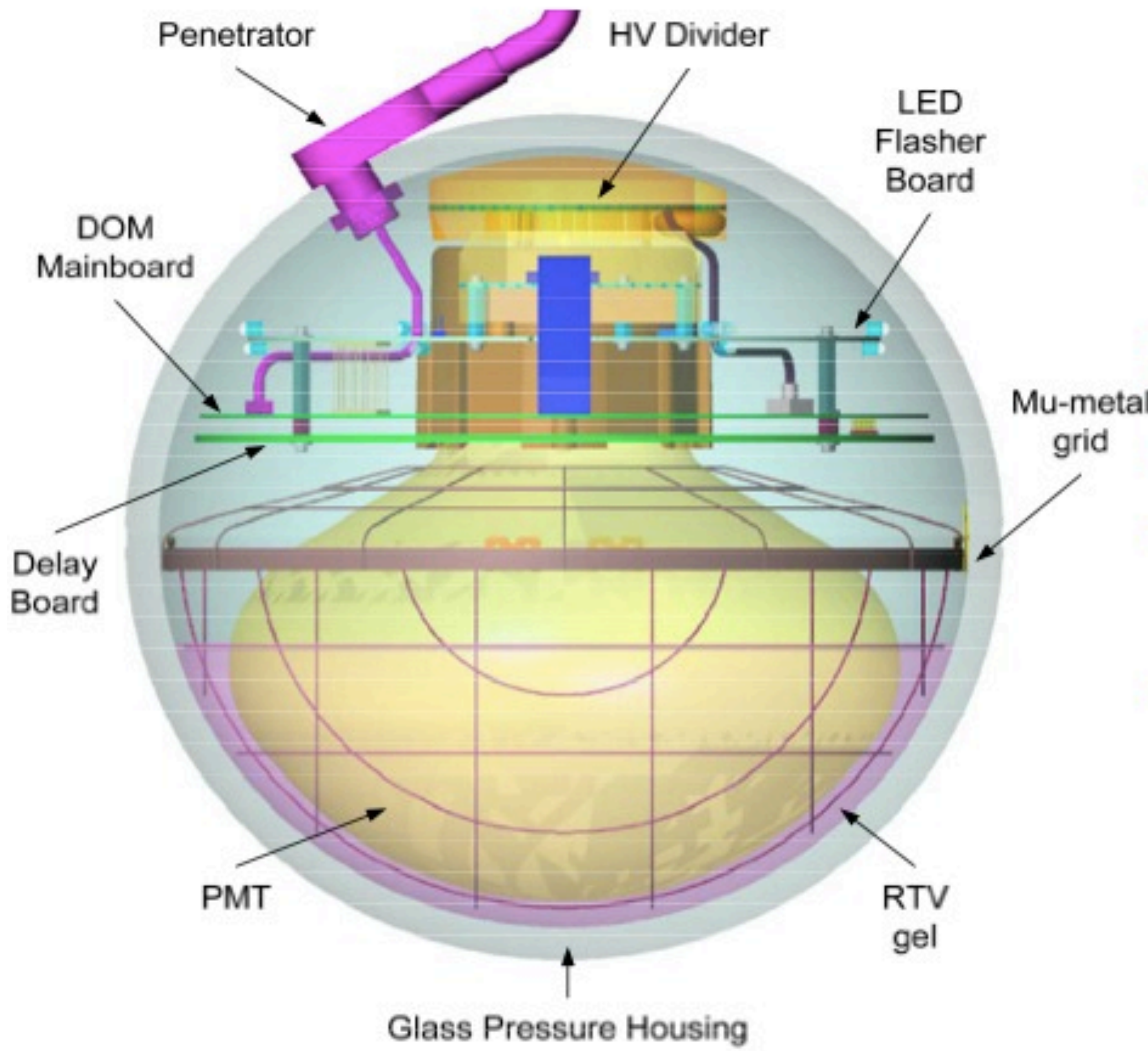
5) Neutrino telescopes: core collapse SN

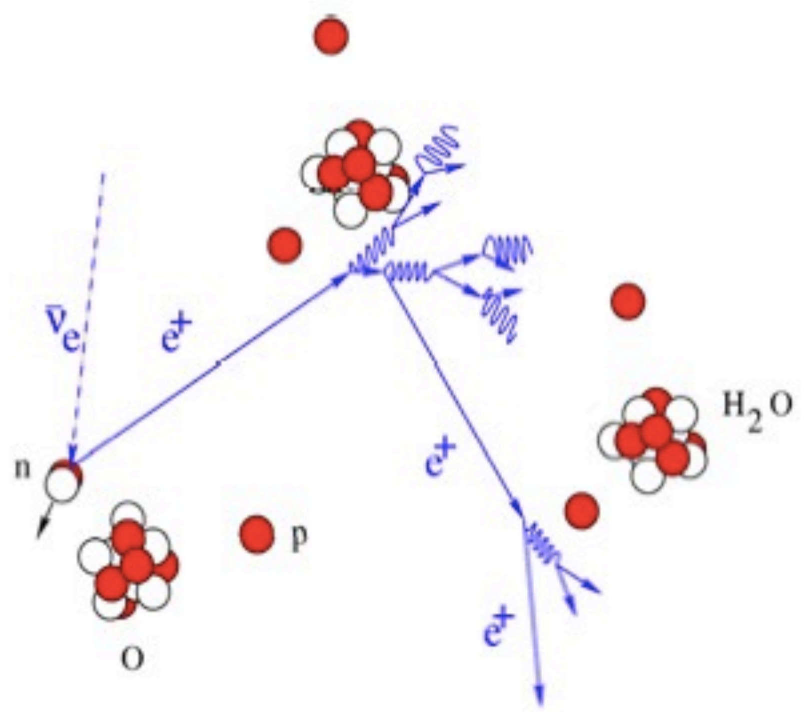
How does it work (*first proposed by Halzen, Jacobsen & Zas, astro-ph/9512080)*

IceCube DOM

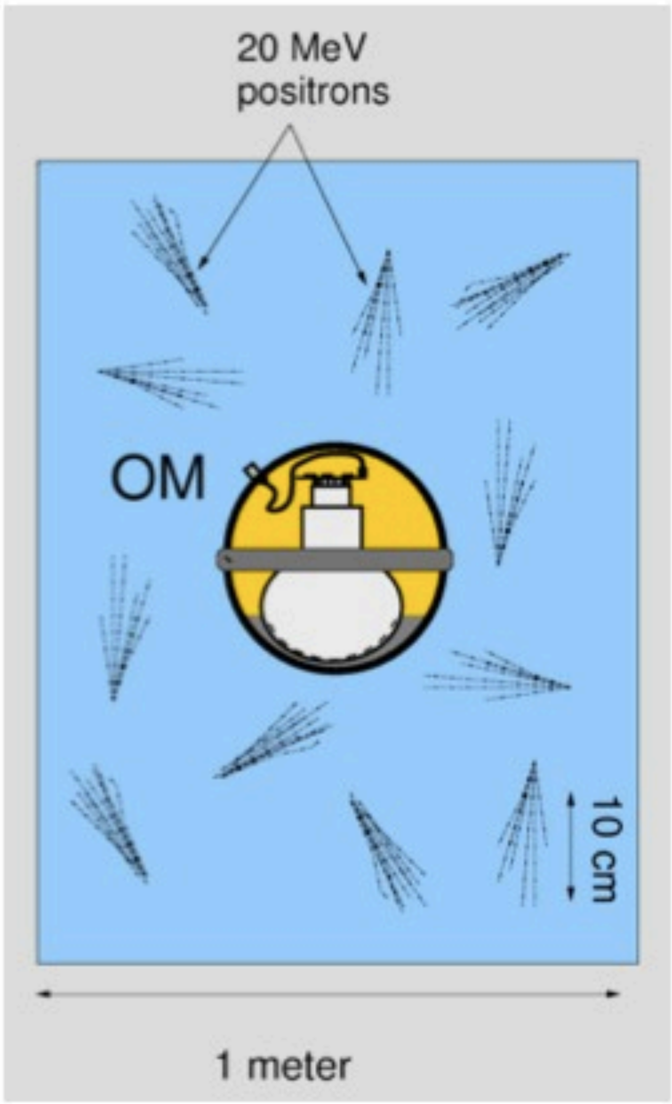


- On board HV, digitization, and rate measurement (**1.6ms** bins)
- Low power: 3.75 W
- **Low noise: ~ 260 Hz**
- Fast timing: resolution between DOMs: $\Delta t < 5$ ns
- Large dynamic range:
  - 1000 pe / 10 ns
  - 10,000 pe / 1 μs

5) Neutrino telescopes: core collapse SN



- ice uniformly illuminated
- detect correlated rate increase on top of PMT noise



IceCube can also detect large numbers of MeV neutrinos by observing a collective rise in all photomultiplier rates on top of the dark noise. With **2 ms timing resolution**, IceCube can track subtle features in the temporal development of the supernova neutrino burst. For a supernova at the galactic center, its sensitivity matches that of a background-free megaton-scale supernova search experiment. The sensitivity decreases to 20 standard deviations at the galactic edge (30 kpc) and 6 standard deviations at the Large Magellanic Cloud (50 kpc).

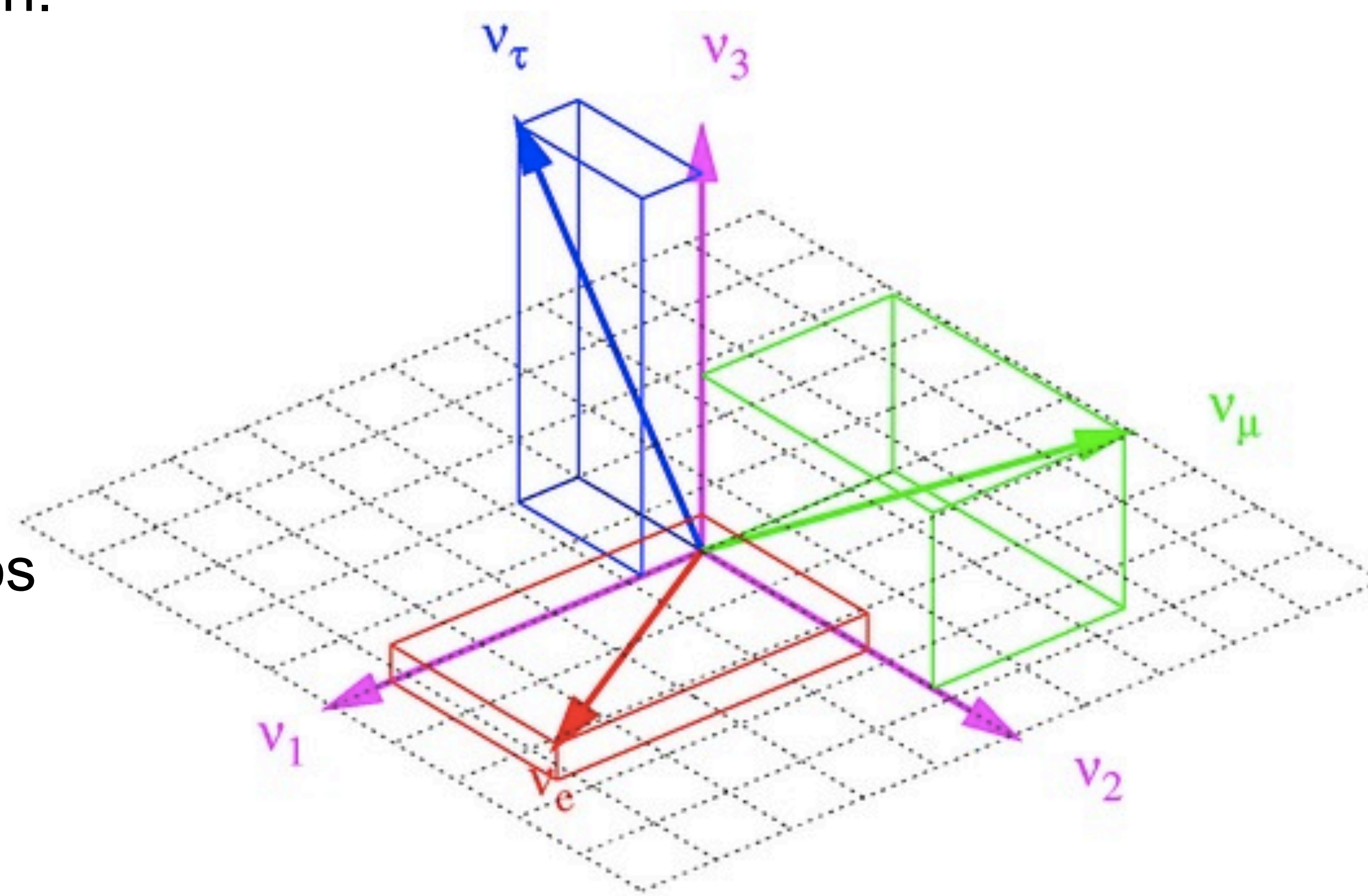
http://arxiv.org/pdf/1106.6225v1.pdf

5) Neutrino telescopes: core collapse SN

No SN core collapse observed yet!

5) Neutrino telescopes: atmospheric neutrinos

- Neutrinos have a **non vanishing mass**. Absolute value not (yet) known.
- What is measured: $(m_i\text{-}m_j)^2$ and mixing angles
- Discovered in oscillation measurements (SK, SNO)
- Oscillation of atmospheric neutrinos measured up to few GeV



Graphical representation of the neutrino mixing angles. Here, θ_{12} = 32.5°, θ_{23} = 25°, and, arbitrarily, θ_{13} = 5°. http://nu.phys.laurentian.ca/~fleurot/oscillations/

Standard Atmospheric Neutrino Oscillation in 2D (oscillogram)

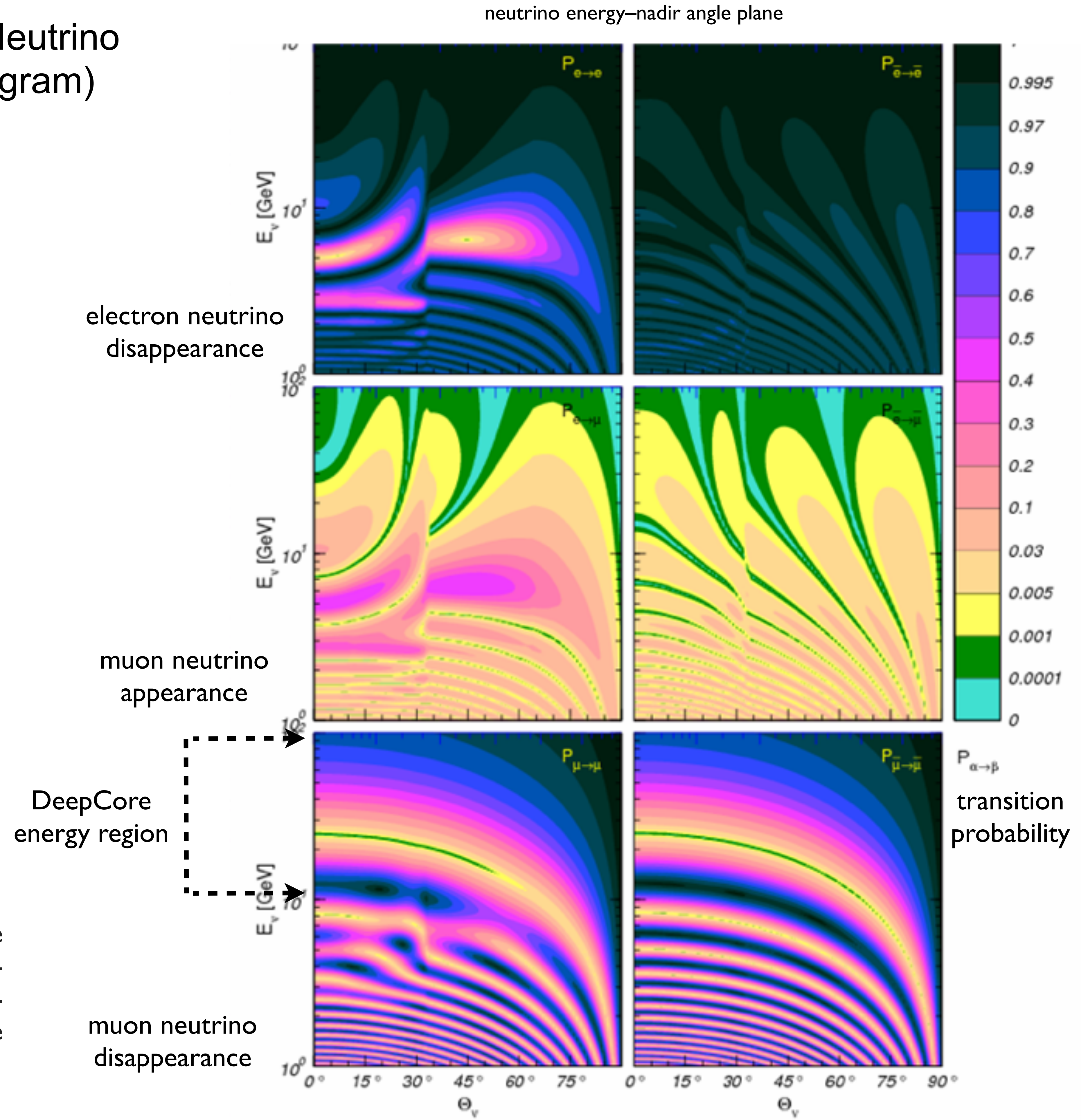


Fig. 3: Neutrino oscillogram of the Earth from Akhmedov-Maltoni-Smirnov modified from arXiv:hep-ph/0612285v2 (private communication).

Data Analysis Strategy

Channel: muon neutrino disappearance.
Observable: Zenith distribution, up-going track-like events.
Analysis based on the combined use of 2 neutrino samples (see Fig. 1):

1) Oscillation sample: Low-energy sample [10-100 GeV], DeepCore events, energy region covering oscillation large minima. Sample realized via few but severe straight cuts and a veto strategy for good reconstruction quality and high purity. Cosmic ray atmospheric background < 8%.

2) Reference sample: High-energy sample [100GeV-50 TeV], IceCube events, sample outside the oscillation region. Sample realized on the base of straight cuts.

Note: for this very first test we have used fixed mixing parameters taken from:
G.L. Fogli et al, "Observables sensitive to absolute neutrino masses. II", Phys.Rev. D78 (2008) 033010, arXiv.org (0805.2517)

Data Analysis Strategy for Standard Atmospheric Neutrino Oscillation

Data: IceCube 79-strings, life time 317.9 days

Statistical Measure:

Low-energy sample:
- observed: 719
- expected (standard oscillation, fixed mixing param.): 789 ± 28 (stat)
- expected (no oscillation): 1015 ± 32 (stat)

High-energy sample:
- observed: 39639
- expected (standard oscillation, fixed mixing param.): 33719 ± 770 (stat)
- expected (no oscillation): 33810 ± 770 (stat)

Systematic errors budget:
factorized in normalization, correlated and uncorrelated factors between the two neutrino samples.
Note: all the systematic effects are treated as multi-normal distributions with widths obtained from MonteCarlo simulation.

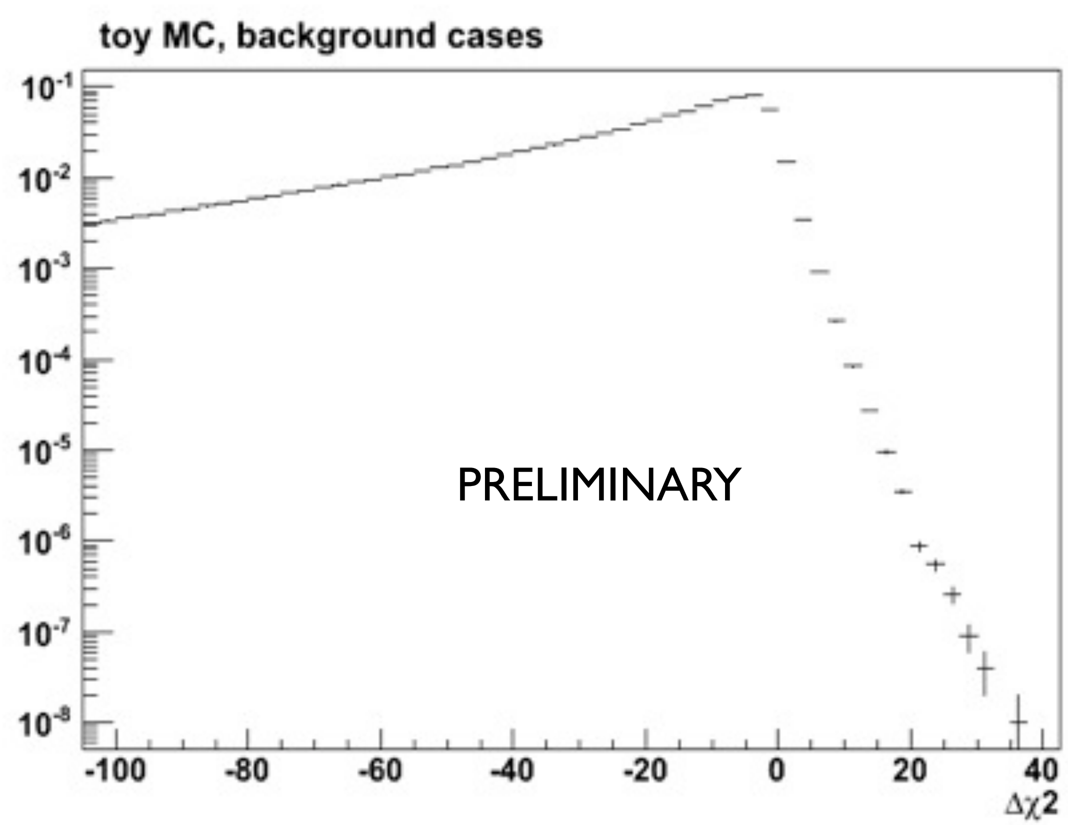
Systematic errors

	Norm. Low-energy	Norm. High-energy	Correlated	Un-correlated
Cosmic Rays, norm	25%	25%	25%	0%
Cosmic Rays, index	3%	7%	0%	10%
Atmospheric Neutrino model	5%	7%	5%	2%
Optical properties of Antarctic ice	20%	5%	5%	15%
Optical Module efficiency	10%	15%	10%	5%
Total	35%	30%	28%	20%

Statistical Test

Frequentist two point hypotheses test where
H0 = non oscillation hypothesis
H1 = oscillation hypothesis with mixing parameters fixed at global best fit values.
H1 is used only in order to define the test statistic.

Significance test: chi-square of *both* low- and high-energy zenith distributions.
Systematic errors included following covariance matrix method (for reference see for example L. Lyons "Statistics for Nuclear and Particle Physicists").
Final significance (p-value) estimated via pseudo-experiments (the delta-chi square expected for two given hypotheses is not a chi-square distribution)



Note: no fit of the mixing parameters performed, no fit of nuisance parameters performed.

Results on IceCube 79 data: the zenith distribution

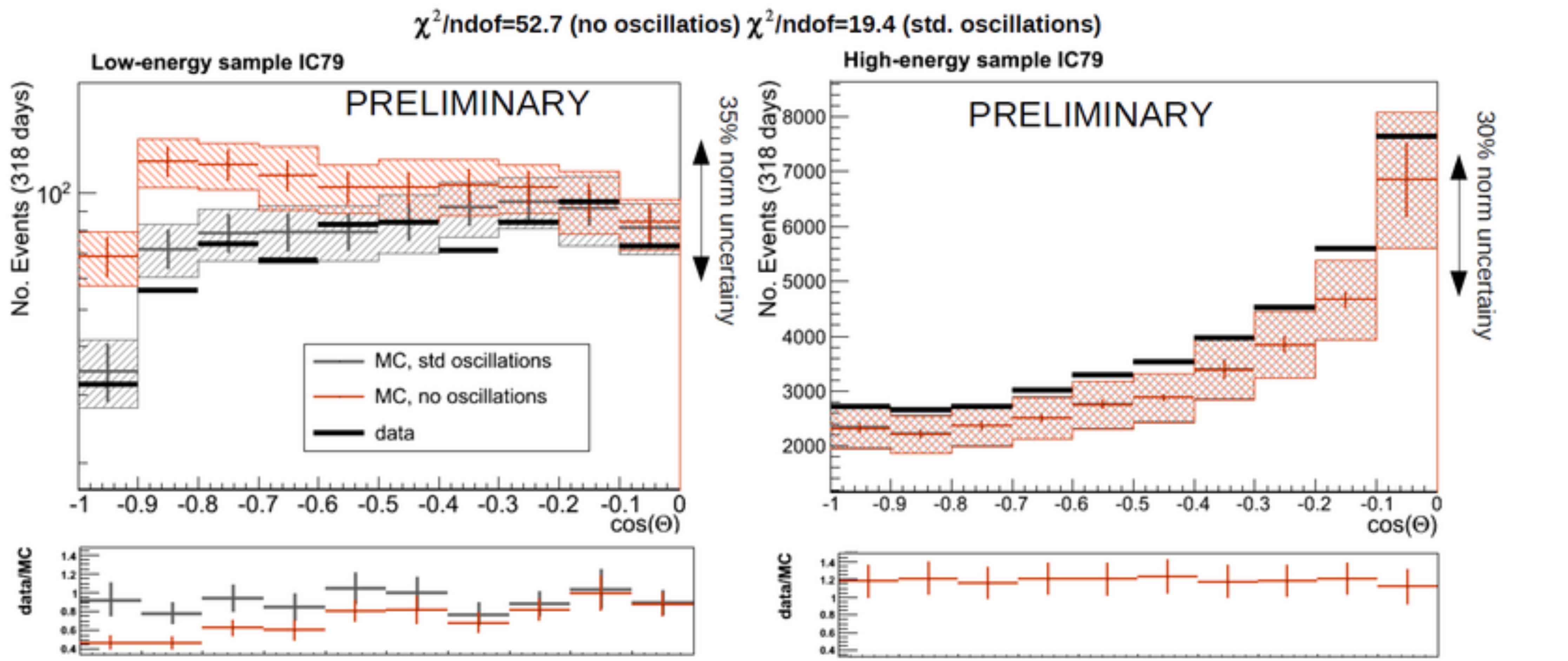


Fig. 4: Reconstructed zenith distribution of the low-energy sample (left) and the high-energy sample (right). The range of observations allowed by MC simulations including statistic and shape-dependent systematic fluctuations is indicated by the boxes, while the error bars indicate only statistical fluctuations. In addition to the shape-dependent systematic errors, there is a normalization uncertainty of each plot (35% for low-energy and 30% high energy). These normalizations of low-energy and high-energy are highly correlated, the uncorrelated normalization uncertainty of each plot is 20%.

delta chi-square = 33.3, p-value = 1 x 10^{-8}

Results: the energy-proxy distribution of the low-energy neutrino sample

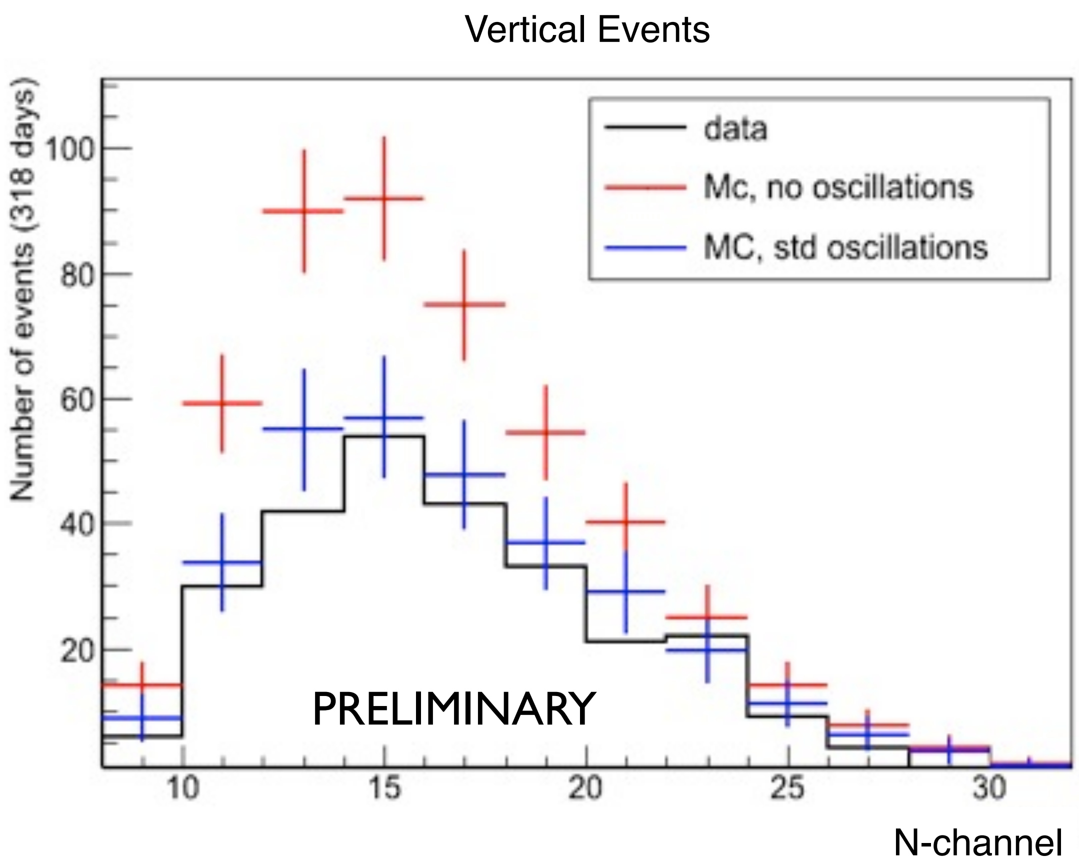


Fig. 5: distribution of the number of hit DOMs for vertical events (cos(theta)<-0.55) of the low-energy event selection. Errors are statistical only.

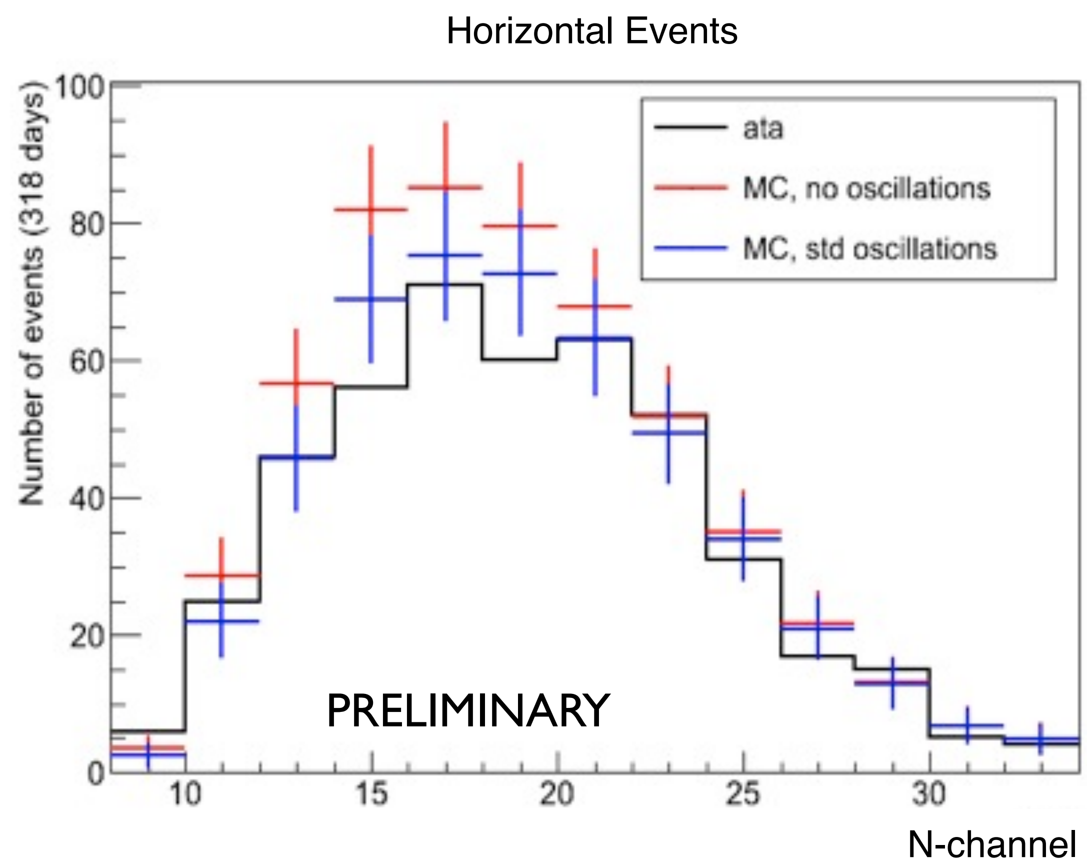


Fig. 6: distribution of the number of hit DOMs for horizontal events (cos(theta)> - 0.55) of the low-energy event selection. Errors are statistical only.

Oscillations

IceCube, instrumented with the compact core DeepCore, has explored for the first time the energy region where standard neutrino oscillation are expected to manifest. Through the analysis of the data collected in 79-strings configuration, the non-oscillation hypothesis is rejected with high statistical significance. Data are in good agreement with standard oscillation expected from global best fit mixing parameters available from the literature.

Systematic effects have been investigated and factorized in normalization, correlated and uncorrelated terms.

As a next step, we plan to investigate the oscillation parameters and test non standard oscillation scenarios (like sterile neutrinos). More sophisticated reconstruction methods and an improved knowledge of the optical properties of the Antarctic deep ice will provide a reduction of the overall systematic uncertainty.

The observation of atmospheric neutrino oscillation provide as well a starting point for the feasibility study of a next infill phase, PINGU. With 20 additional strings and a set of new calibration instruments, PINGU will target precise measurements in the atmospheric neutrino sector. The challenging goal is the measurement of the mass hierarchy in the MegaTon PINGU.

Antares has also recently reported a disappearance of events attributed to neutrino oscillation.

5) Neutrino telescopes: GRBs

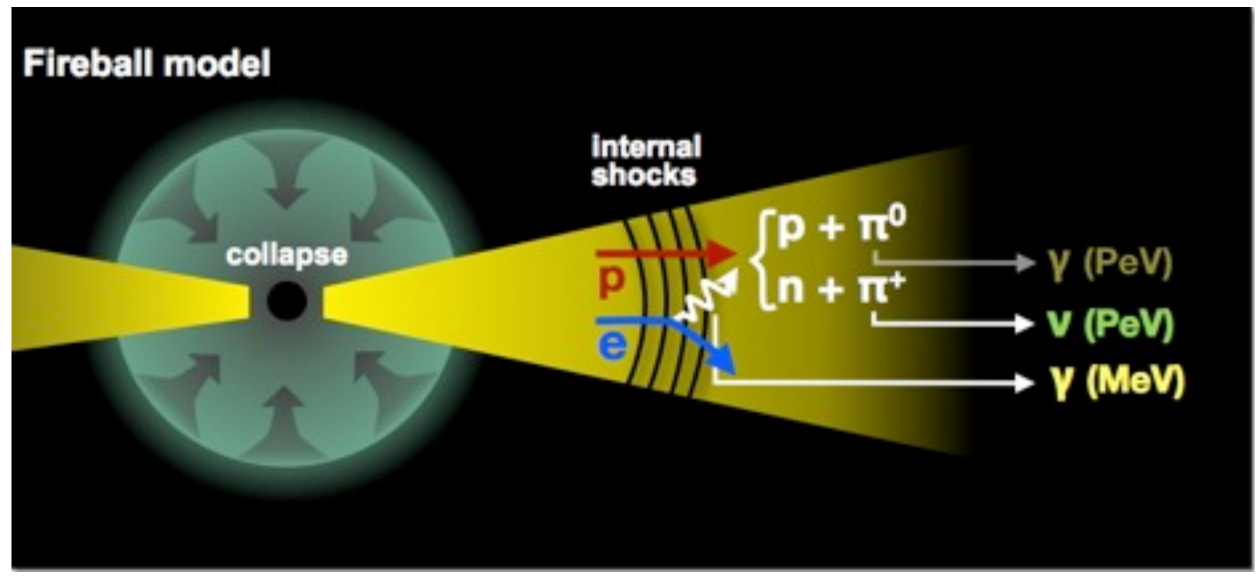
Fireball Model:

• Internal shocks as fireball expands, accelerate particles via Fermi mechanism

• High energy protons and photons in the expanding fireball interact

• Photo-pion production leads to neutrinos via pion decay, muon decay

If GRBs responsible for UHECR, then models predict neutrino fluxes above 100 TeV that are well within reach of km^3 neutrino detector



$$
\begin{aligned}
p + \gamma \;&\rightarrow\; \pi^0 + p \\
&\quad\hookrightarrow\; \gamma + \gamma + p \\
&\rightarrow\; \pi^+ + n \\
&\quad\hookrightarrow\; \mu^+ + \nu_\mu + n \\
&\quad\hookrightarrow\; e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n
\end{aligned}
$$

TeV Gammas ($\gamma + \gamma$)

Cosmic Rays? (n)

TeV Neutrinos (ν_μ; $\nu_{\bar{\mu}} + \nu_e$)

5) Neutrino telescopes: GRBs

GRB search catalog assembled from GCNs alerts.
Most detections by Fermi GBM but also SWIFT and Interplanetary Network.

Two partial configurations:

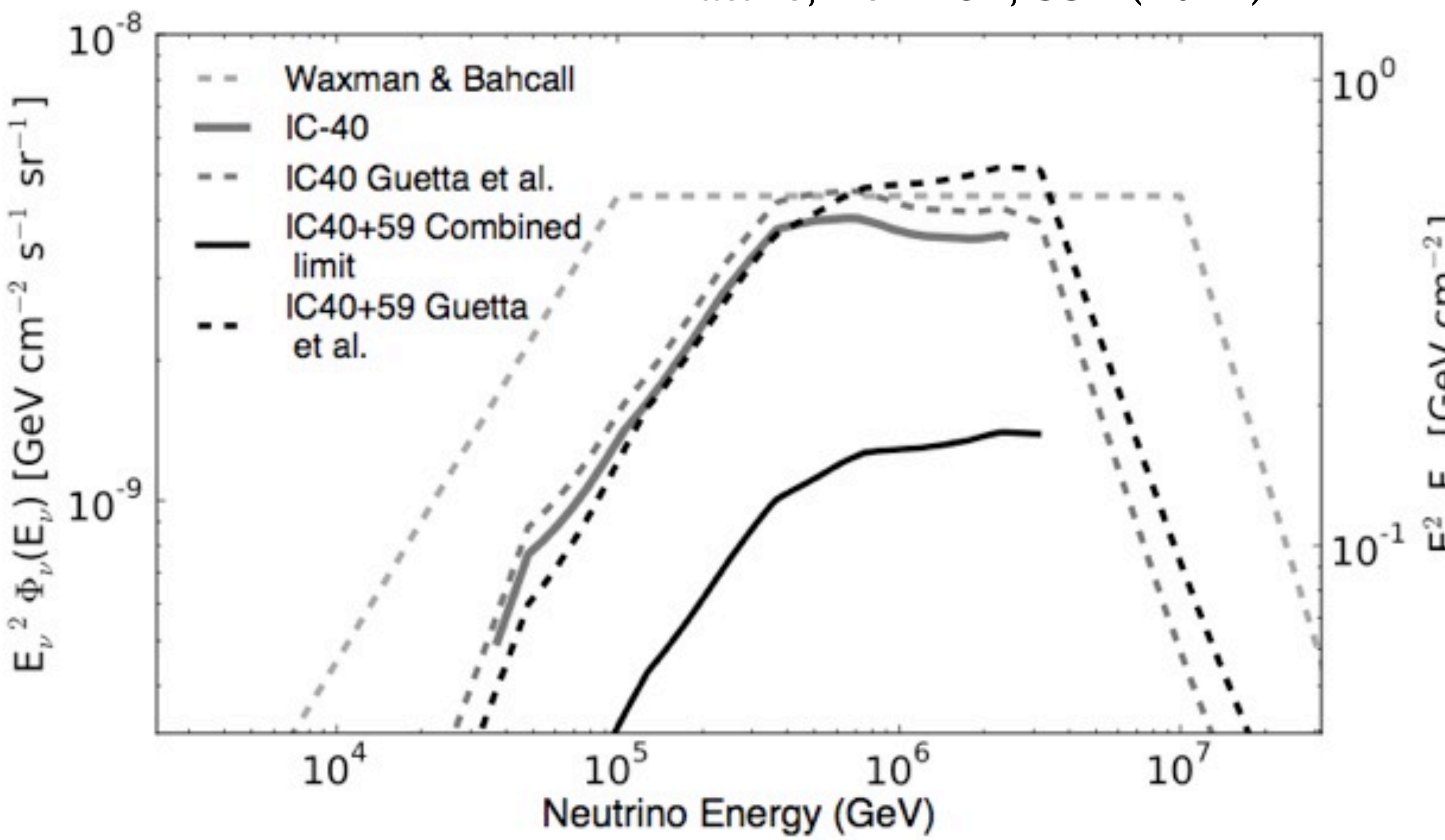
2008-9 (40-string) data:
117 GRBs in northern sky

2009-10 (59-string) data:
98 GRBs in northern sky
another 85 GRBs in southern sky also analyzed

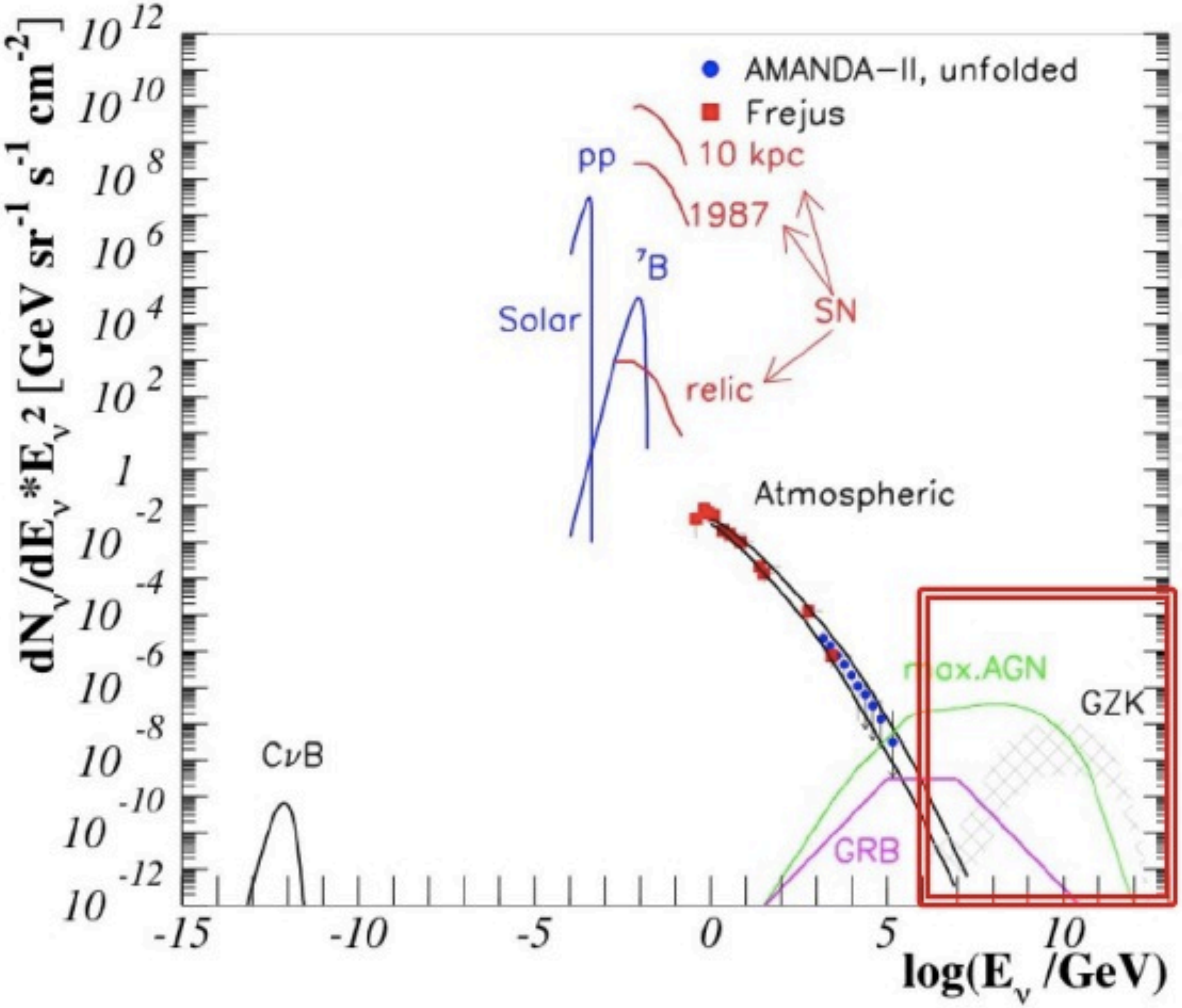
Because of short duration, searches are very low-background.

<u>One event can be significant.</u>

Nature, Vol. 484, 351 (2012)

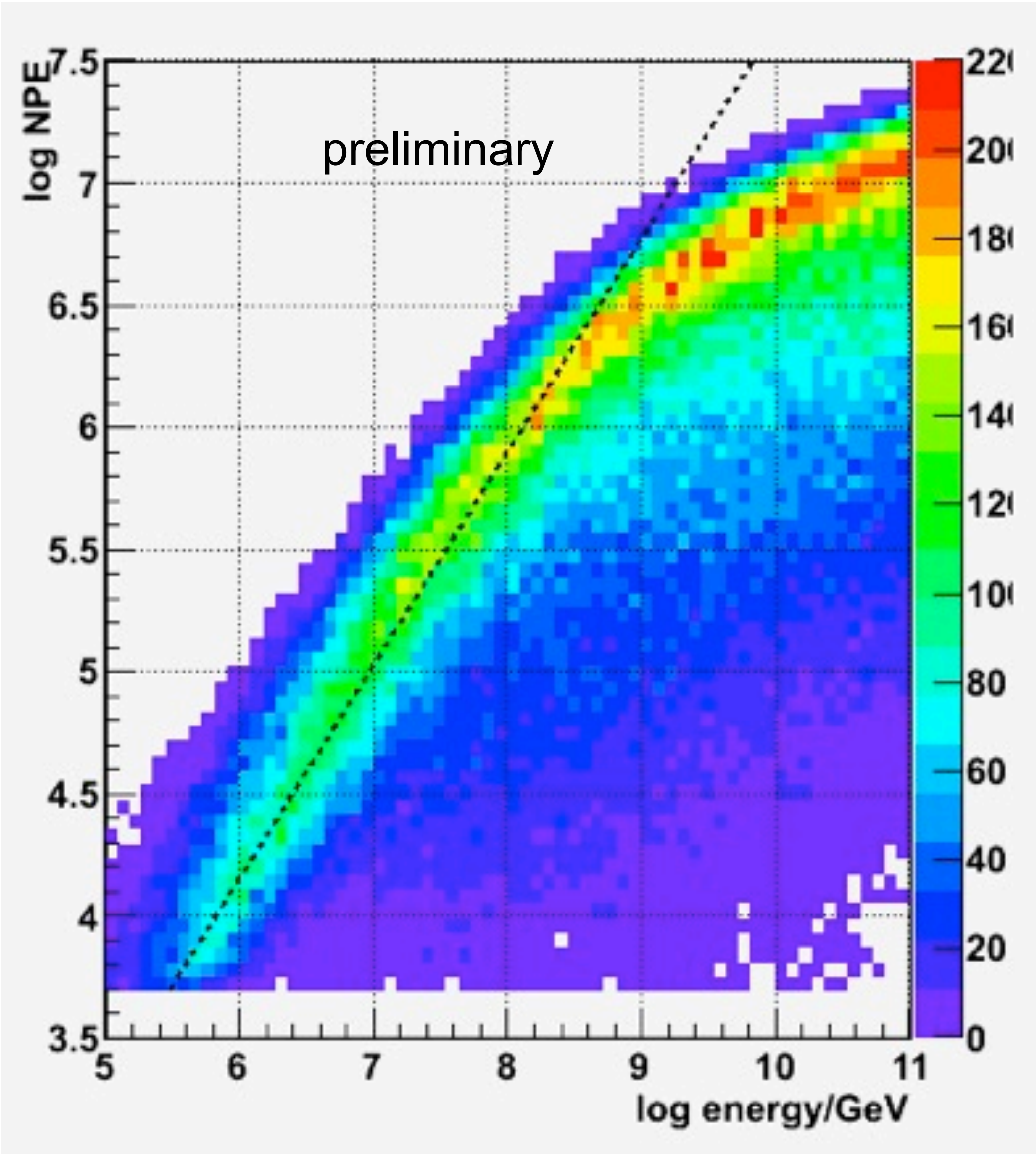


5) Neutrino telescopes: UHE cascades



5) Neutrino telescopes: UHE cascades

Verification of the energy estimator for ultra-high-energy events:



Count all the number of pulses (NPE) extracted from the ADCs on the main board of the DOMs.

Study the linearity regime

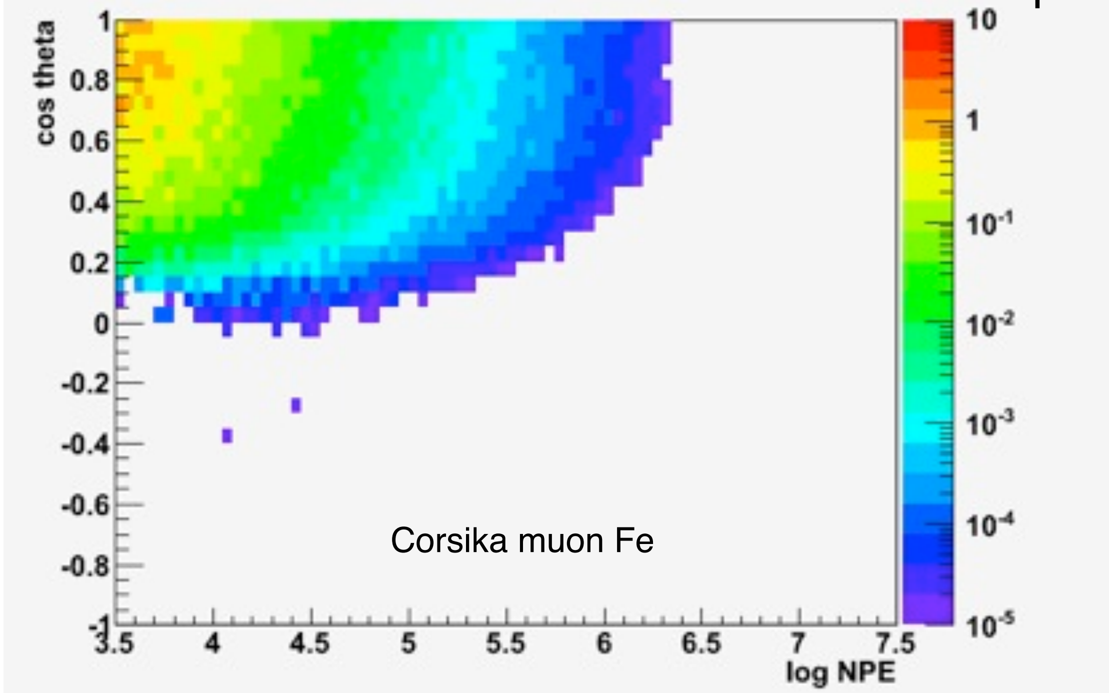
Study the various components of the background
and signal region

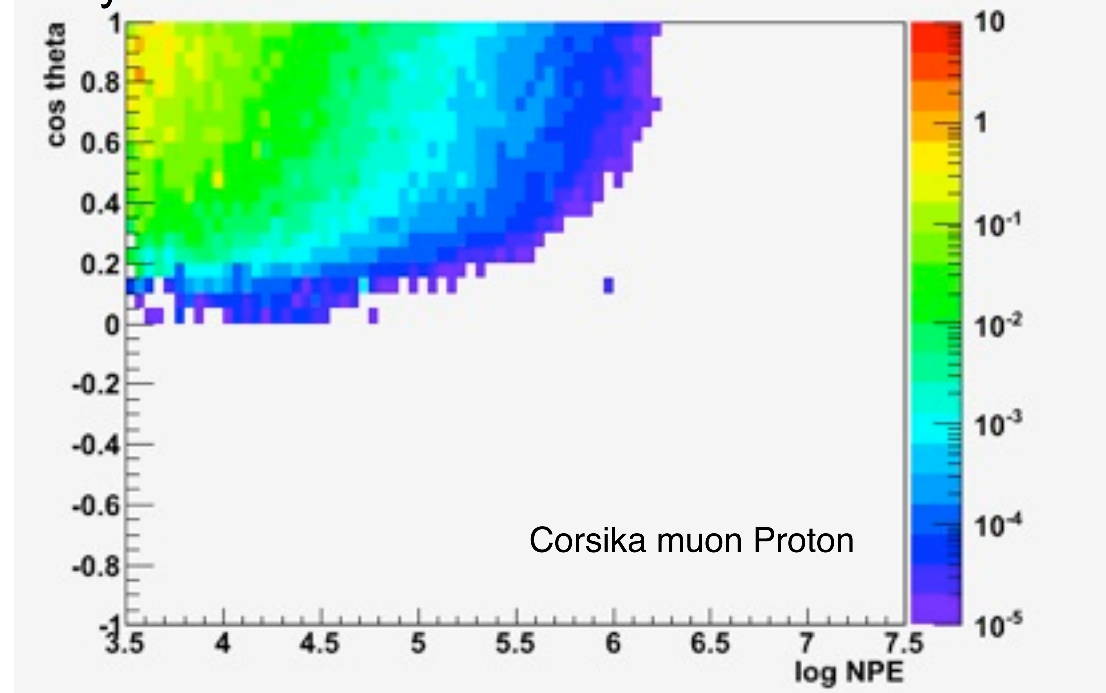
Study the distribution of Use this energy estimator for basic cuts

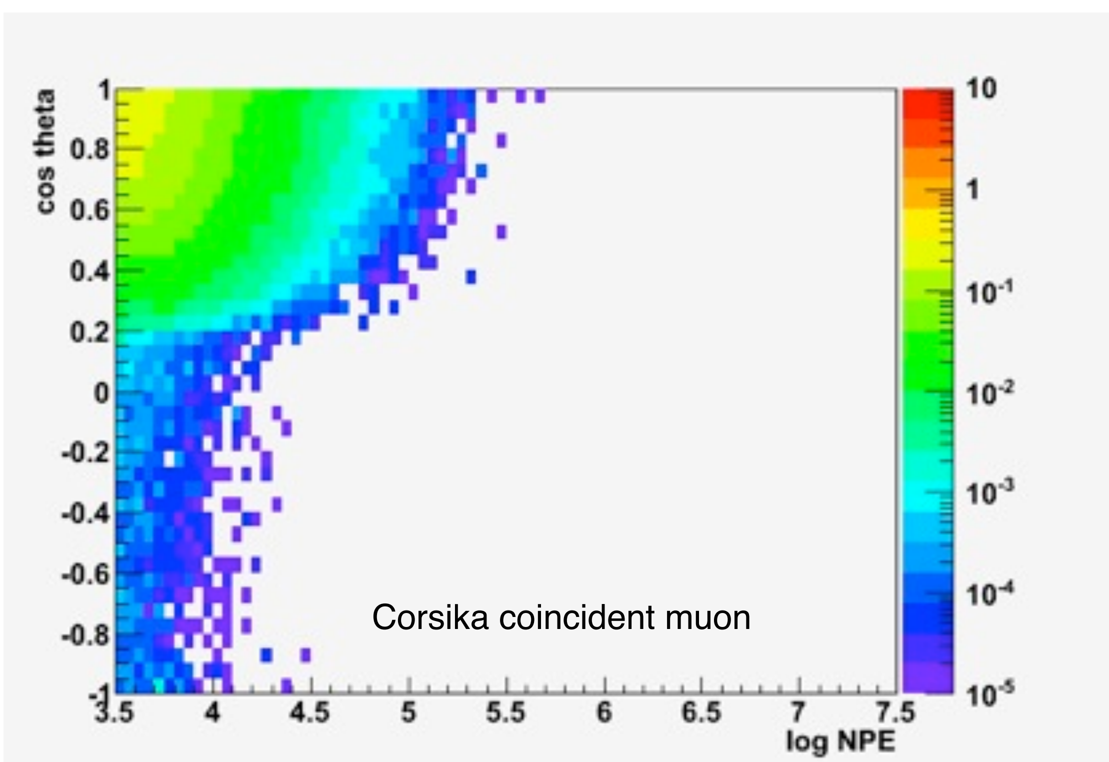
5) Neutrino telescopes: UHE cascades

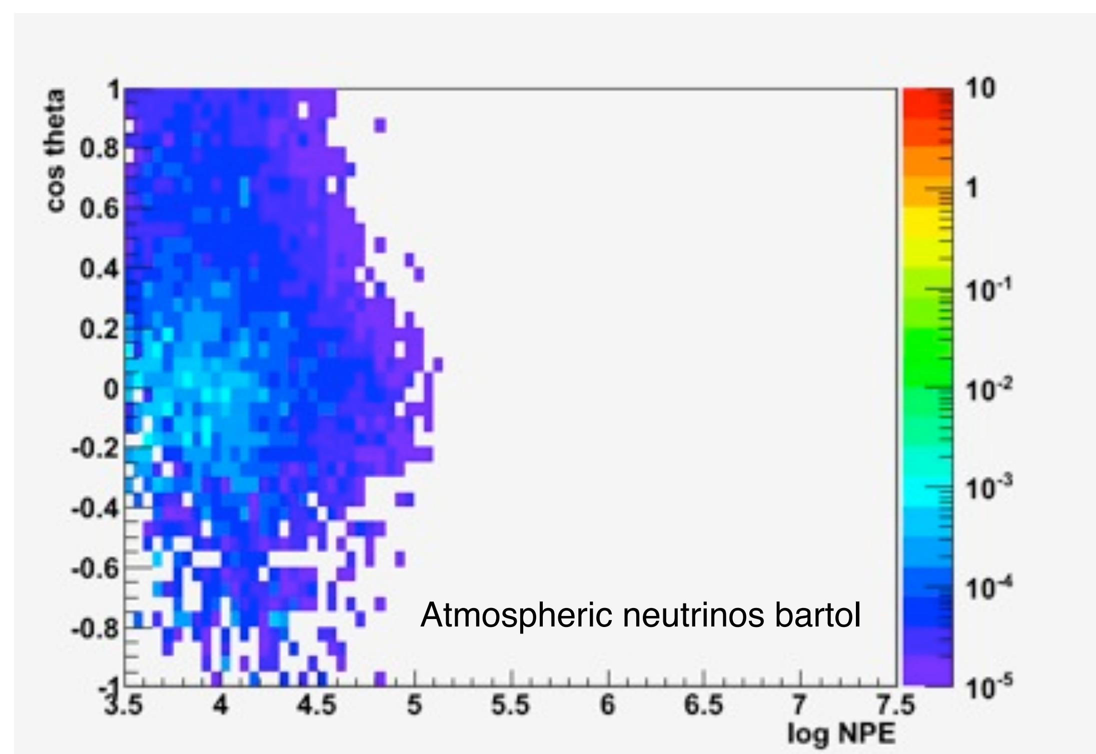
Build 2D distribution (energy - direction): background components

preliminary



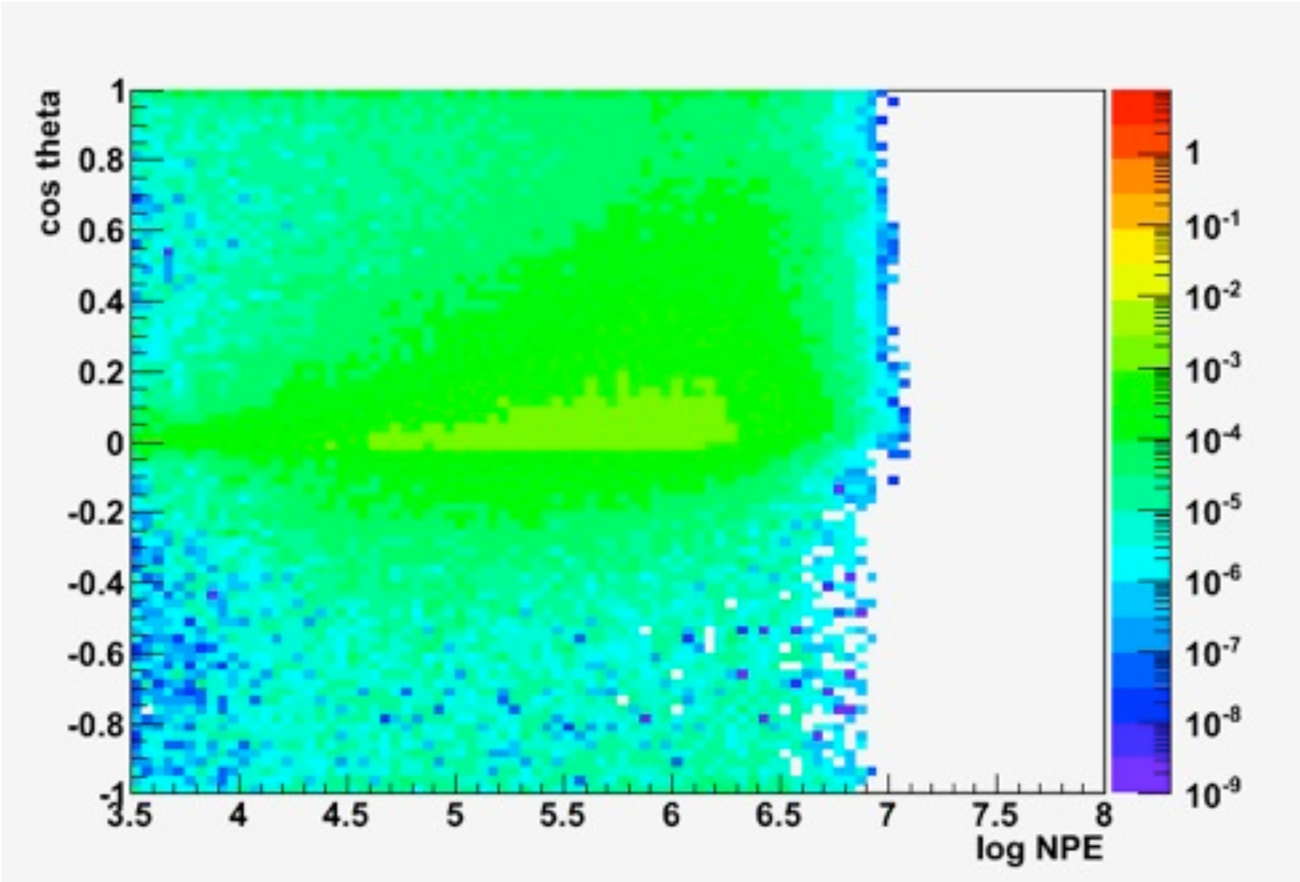


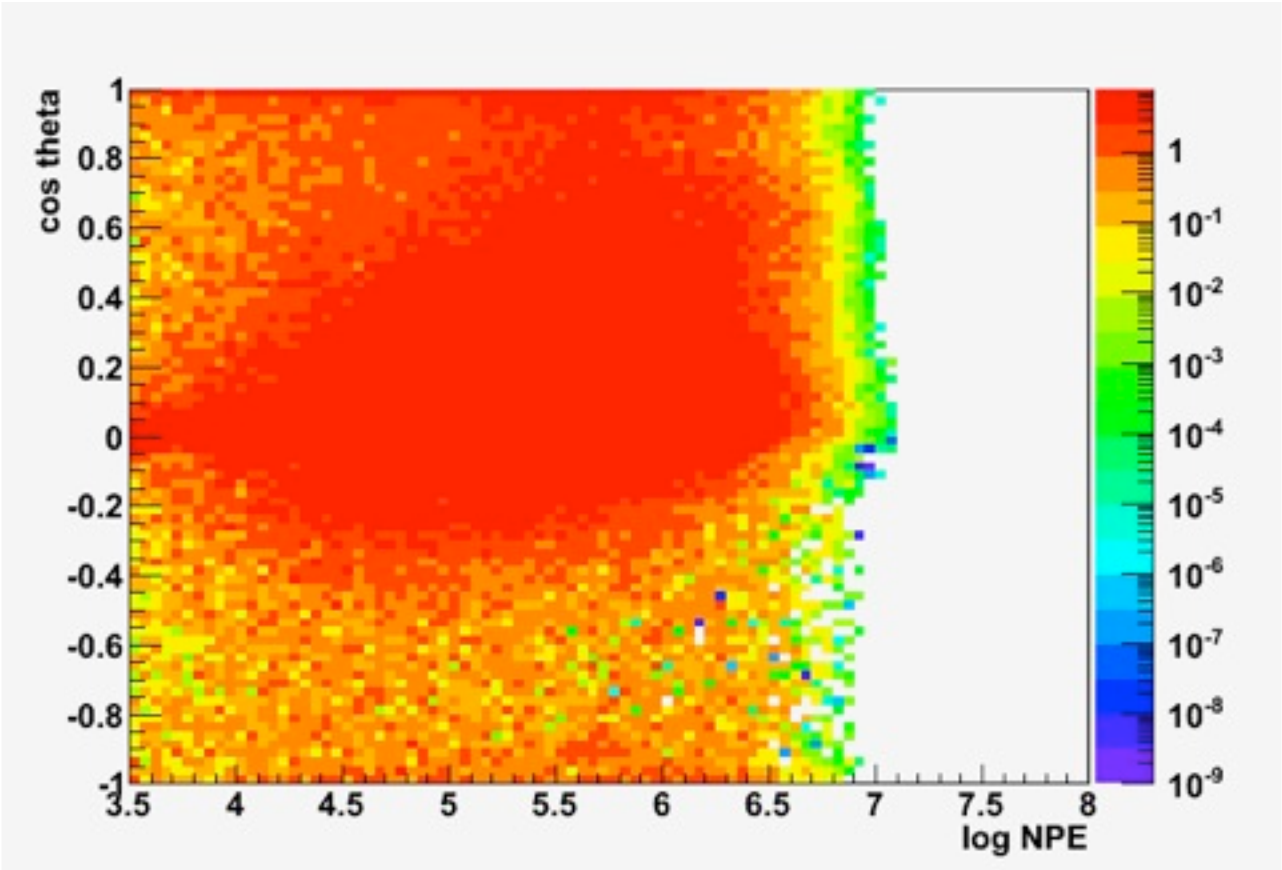




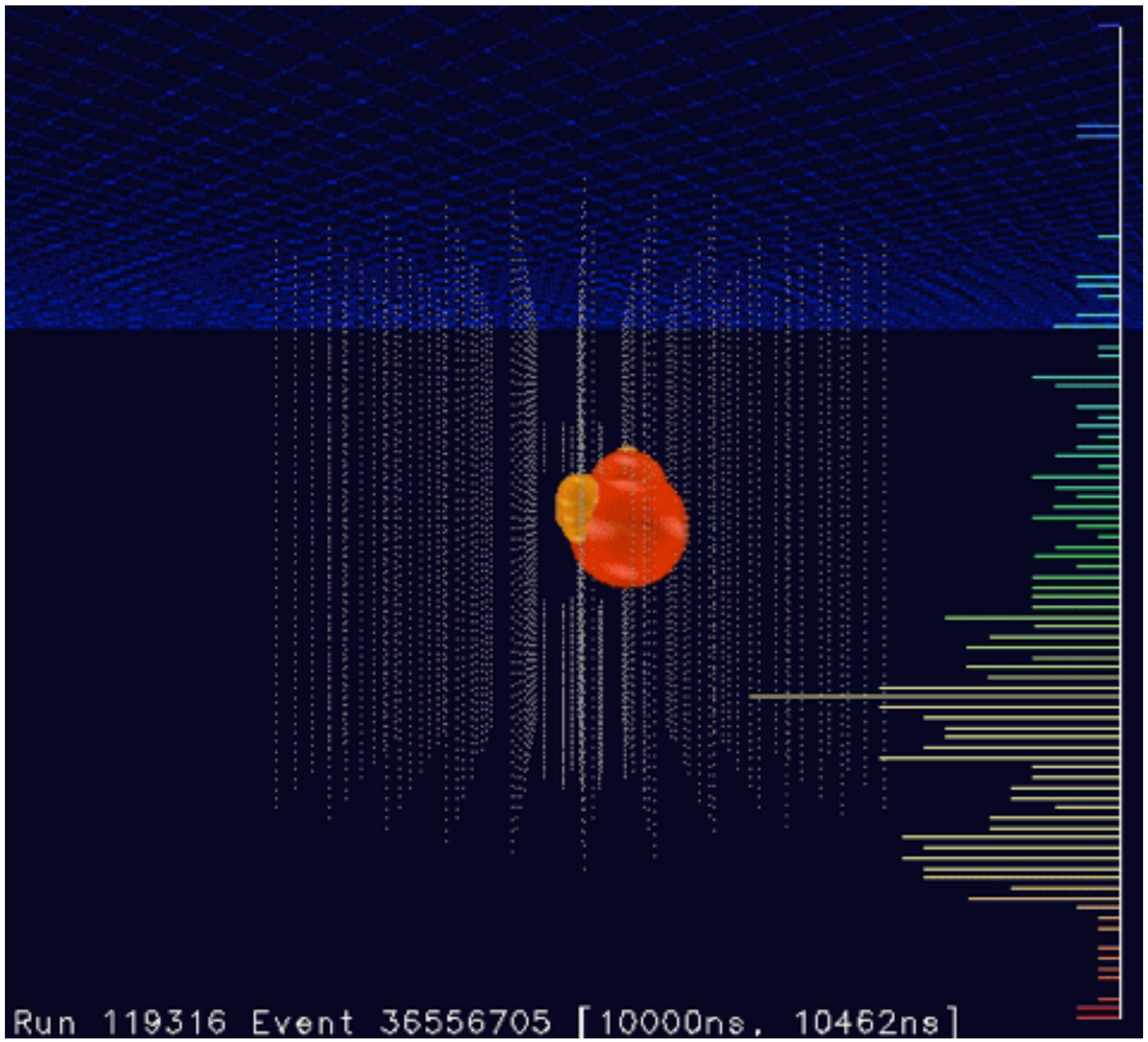
5) Neutrino telescopes: UHE cascades

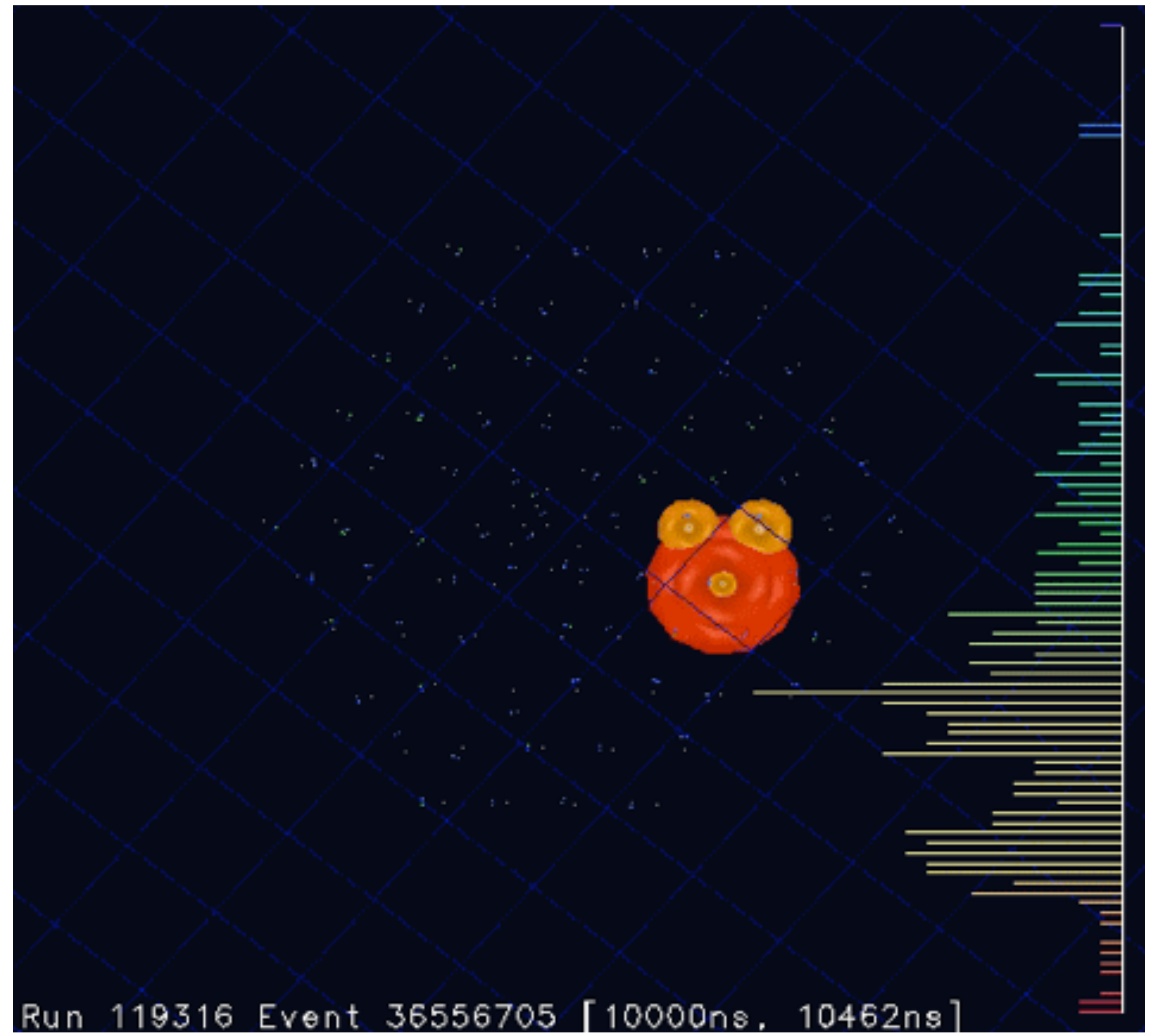
Build 2D distribution (energy - direction): possible signal for cosmogenic
realize a 2D cut just by comparison
no optimization done for the moment
very simple analysis to allow aggressive schedule for IC86





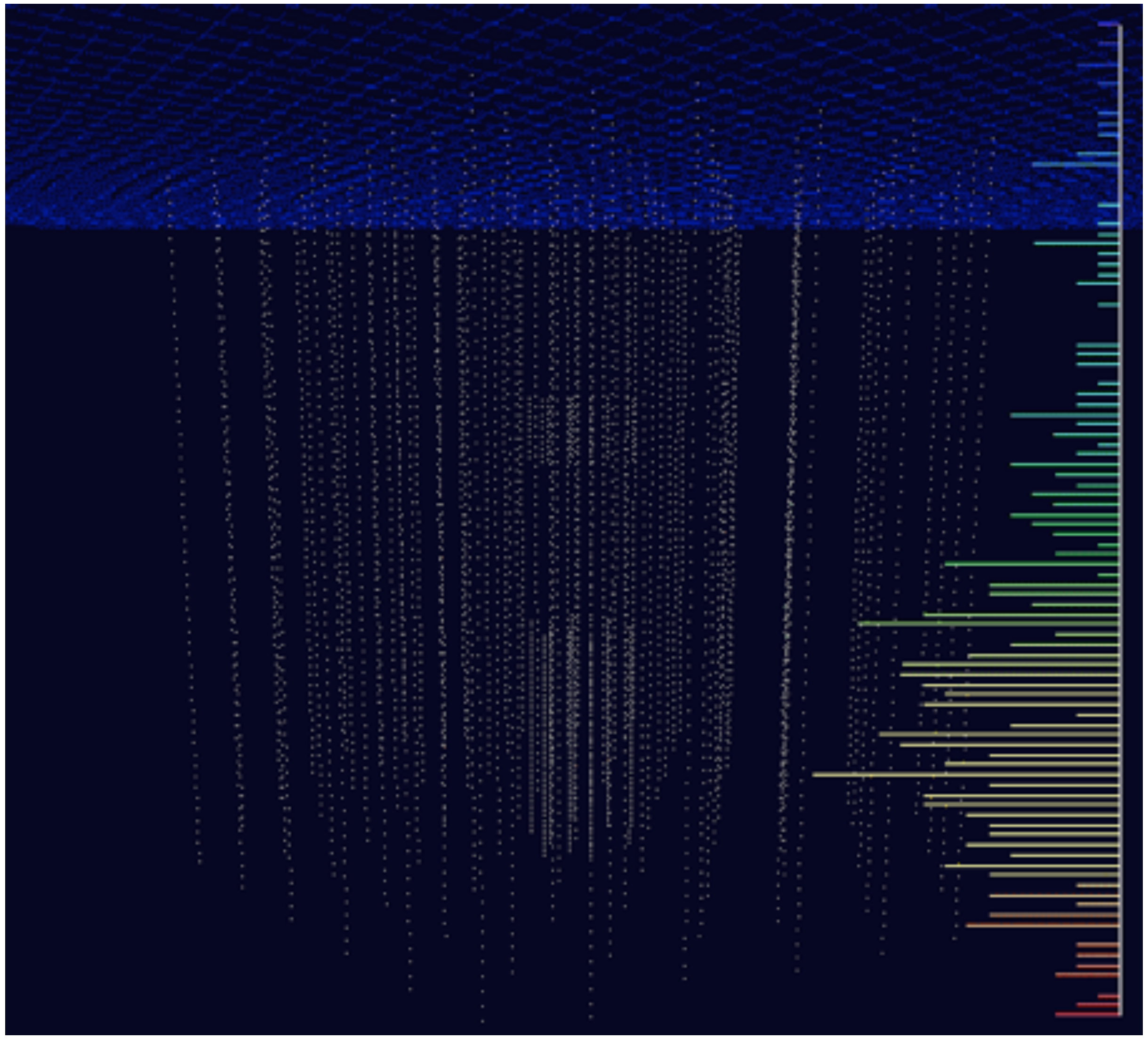
5) Neutrino telescopes: UHE cascades

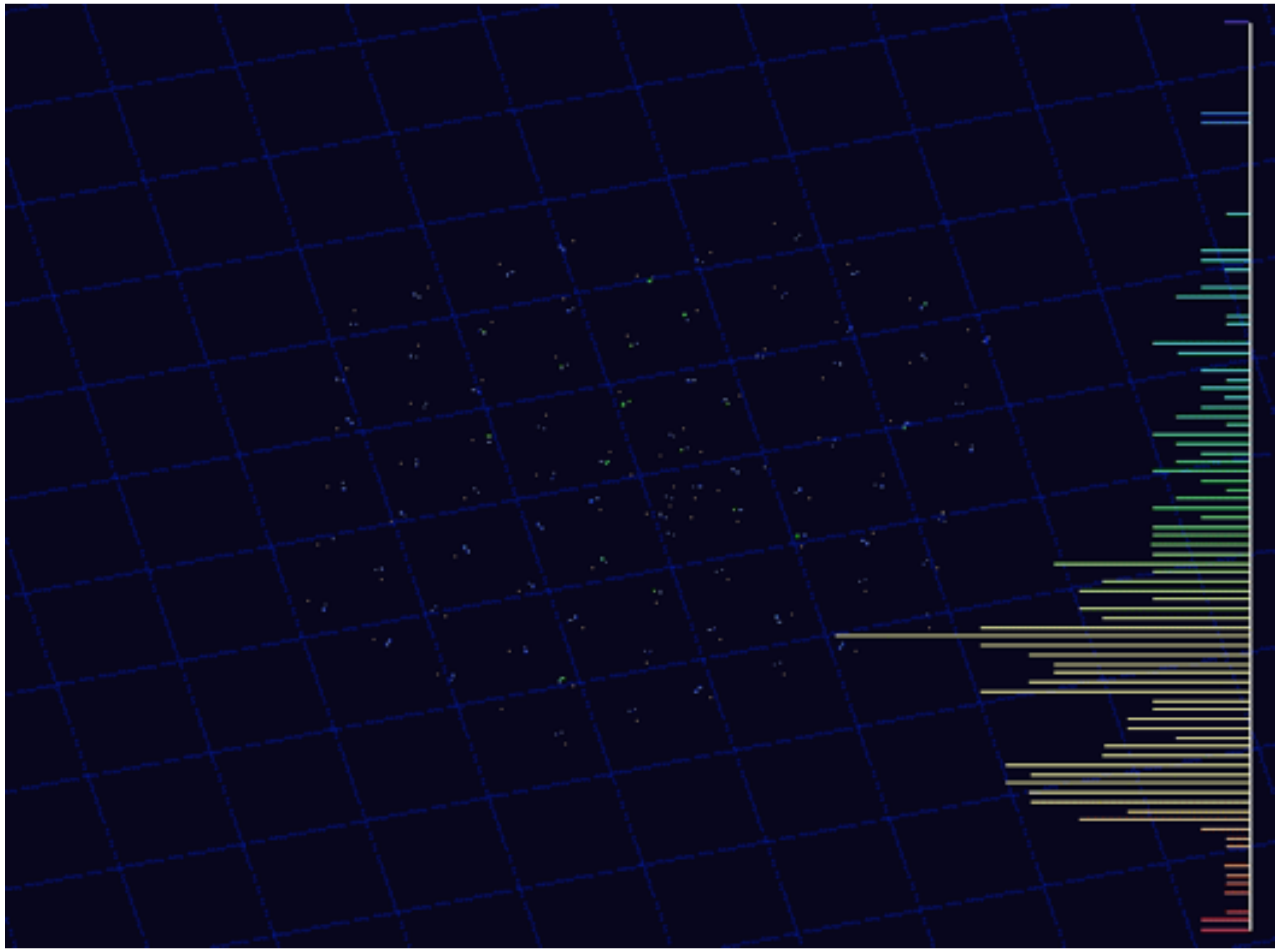




Event 1:
Time: 2011-08-09
Energy estimated: ~ 1 PeV (still under study!)
Downward direction (still under study!)
No sign left in IceTop

5) Neutrino telescopes: UHE cascades

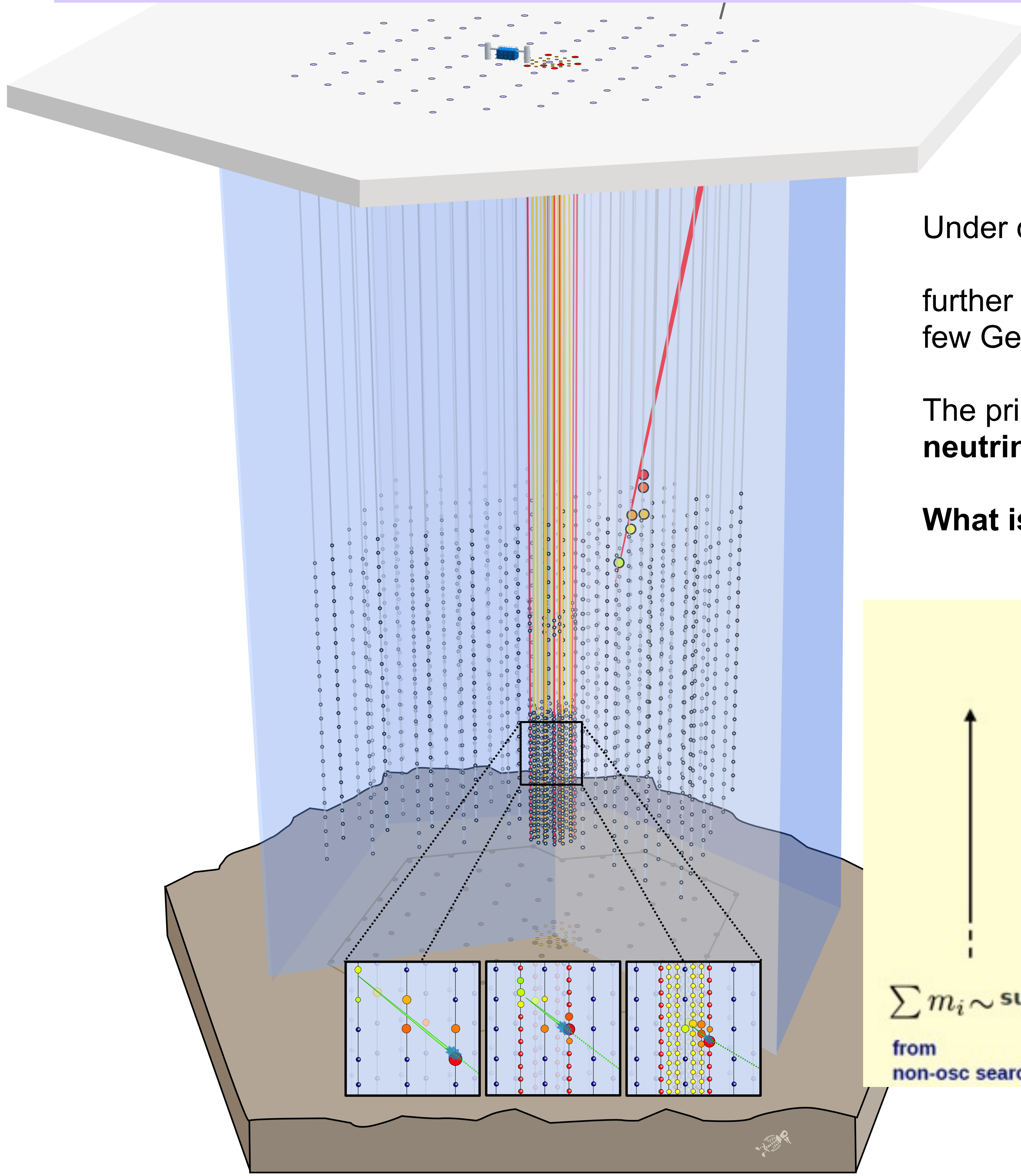




Event 2:
Time: 2012-01-03
Energy estimated: ~ 1 PeV (still under study!)
Downward direction (still under study!)
No sign left in IceTop

two words about the future

PINGU (Precision IceCube Next Generation Upgrade)

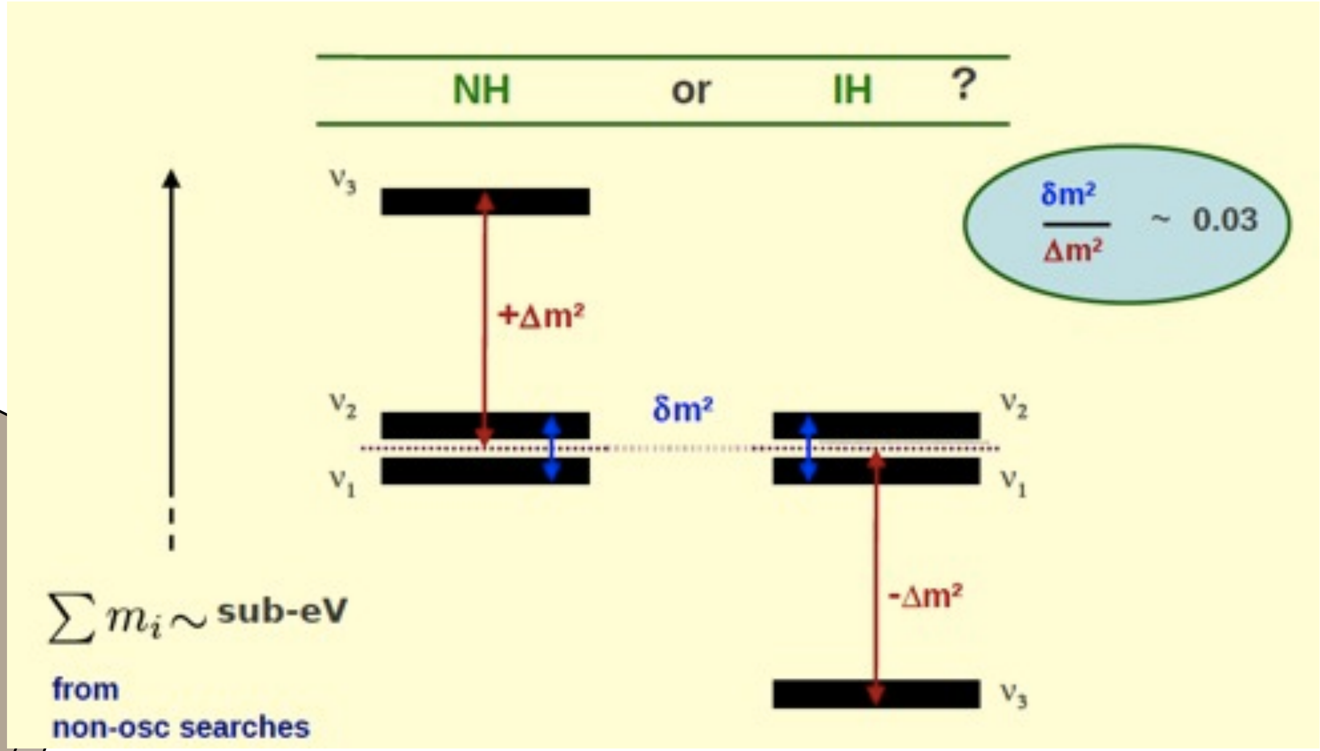


Under discussion:

further extension of IceCube for the energy region from few GeV to 50 GeV

The primary physics goal of PINGU is the study of the **neutrino mass hierarchy**

What is "mass hierarchy":



Conclusive remarks

Neutrino astronomy is strongly interconnected with primary CR, gamma-ray astronomy, the multi-wavelength community and particle physics.

Neutrino astronomy is at a tipping point.

The next 2-5 years of fundamental importance for the future of the field.

We are ready to welcome surprises!

We are constantly at the hunt of interested new collaborators, if interested contact me!

How does it work a data analysis in IceCube?

STEP 1:

- Collect data @ South Pole (monitor, calibrate, correct ...)
- Reconstruct data (clever algorithm ...)
- Filter data on-line (don't lose your signal there ...)
- Transmit them through the satellite (hope the satellites work ...)

How does it work a data analysis in IceCube?

STEP 2:

- Filter them again and again
- Realize simulated data (the model)
- Check experimental data vs simulated data and

don't panic !!!

How does it work a data analysis in IceCube?

STEP 3:

- Optimize the search for well reconstructed neutrinos
- Optimize the search for best efficiency
- Develop a good search algorithm
- Make your statistics right
- Discuss / defend your work
- with the Collaboration and ...