Large Volume Neutrino Telescopes

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26th Baikal School on Particle Physics and Astrophysics
Juy 11-18, 2026, Bolshie Koty

Scope of these lectures

Lecture 1

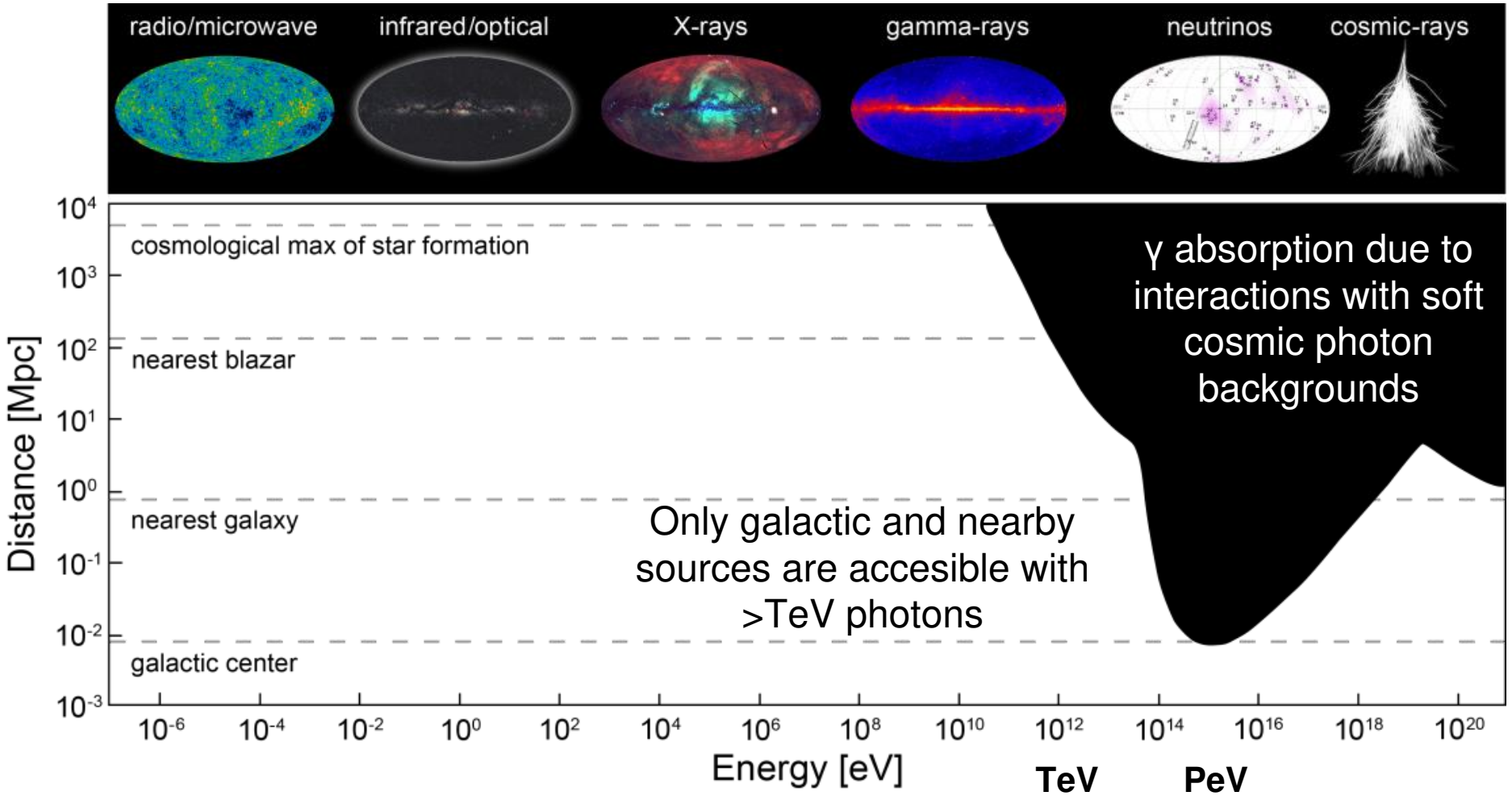
- Motivation for large-volume neutrino telescopes (LVNT)
- Astrophysical neutrino flux and its detection technique
- Response of LVNT to neutrino events

Lecture 2

- Data analysis principles
- LVNT development history
- Selected astrophysics results

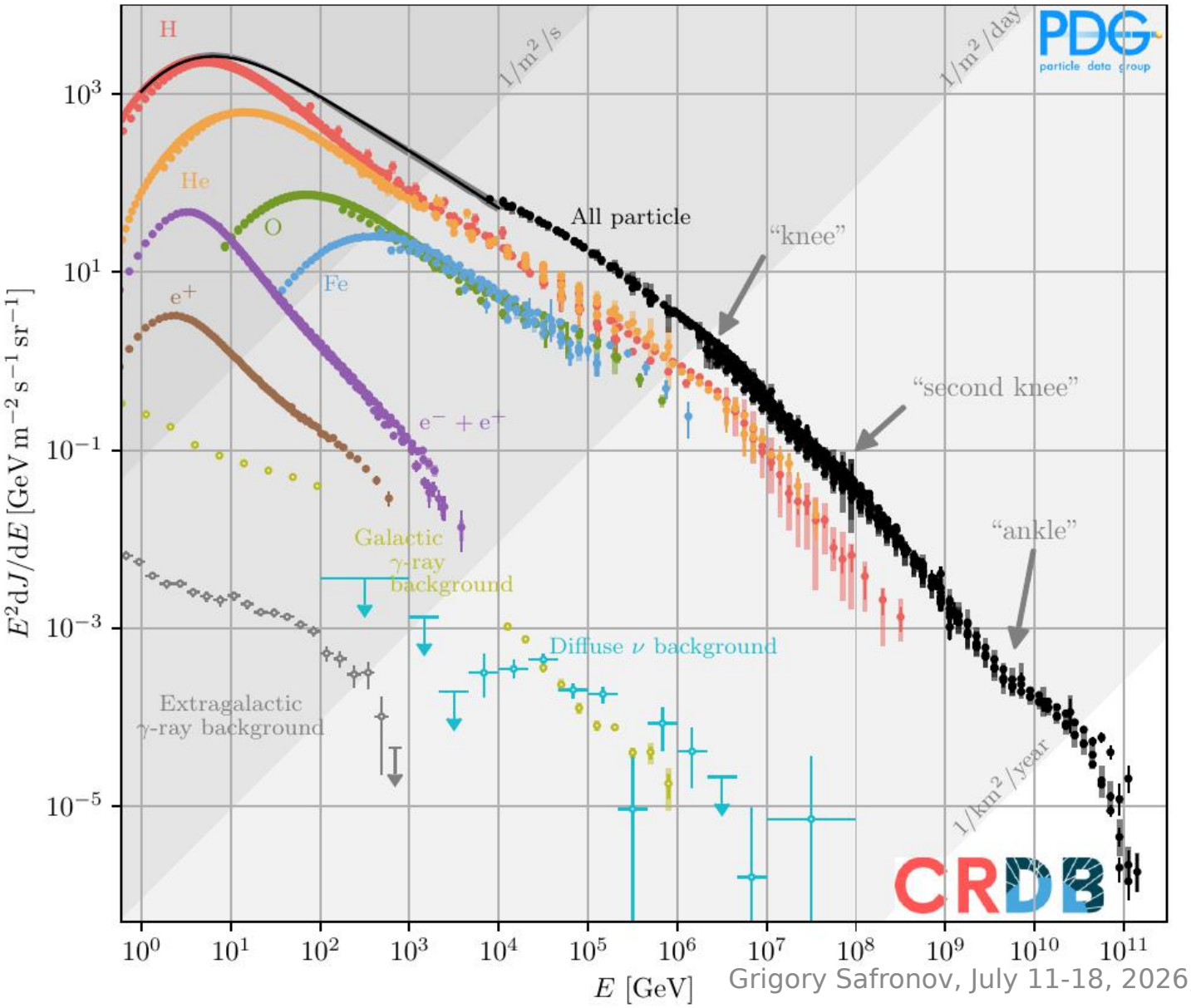
Physics motivation for LVNT

Vast majority of information about the Universe is obtained with EM spectrum



Universe is opaque for highest energy photons

Physics motivation for LVNT



From cosmic ray (CR) spectrum we know that extremely powerful particle accelerators exist in the universe

The range of observed charged cosmic ray (CR) particle energies extends up to 10^{11} GeV [10^{20} eV]

Experimental evidence for origin of such energetic particles remain vague

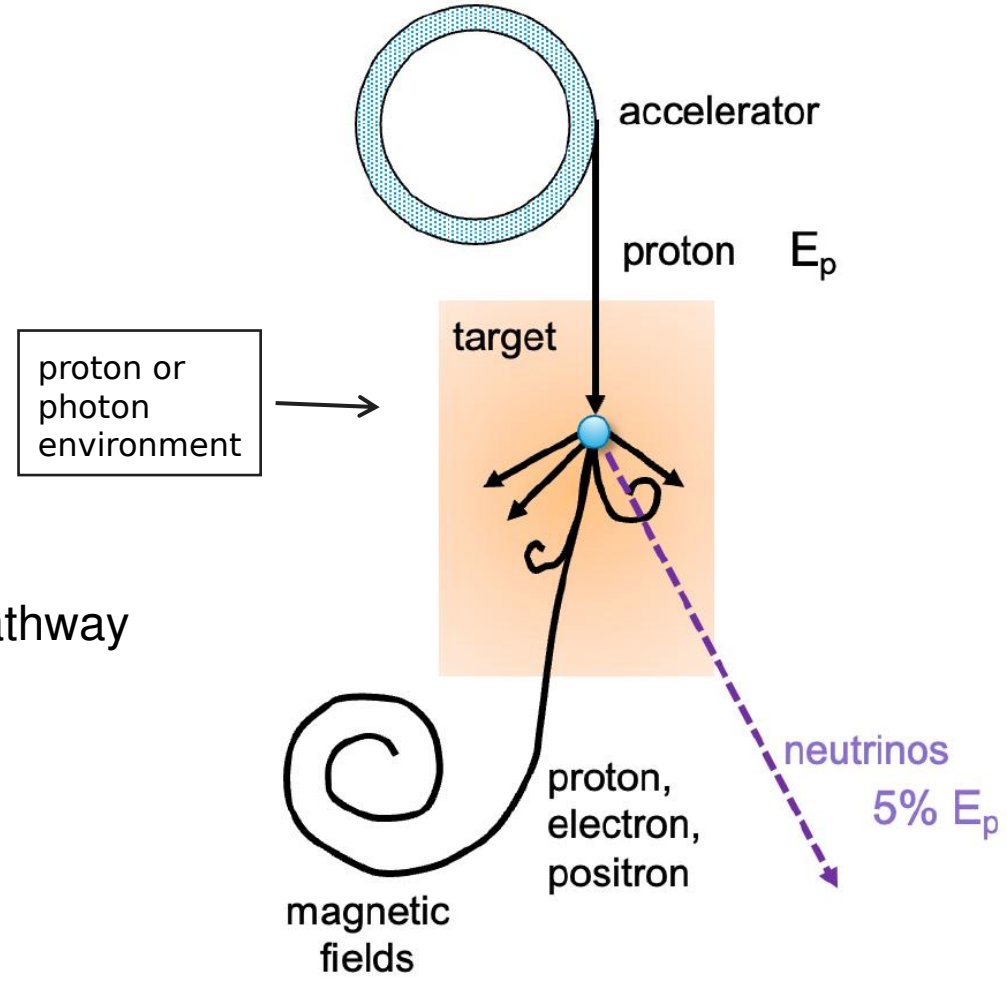
Neutrino properties suggest it as a good tool for unlocking this problem

High-energy neutrino production

Astrophysical neutrinos are produced
in interactions of energetic CR with cosmic environment

Production modes
photon-reach environment: $p\gamma \to \pi$
proton-reach environment: $pp \to \pi$

Neutrino energy: $E_\nu \sim E_p/20$



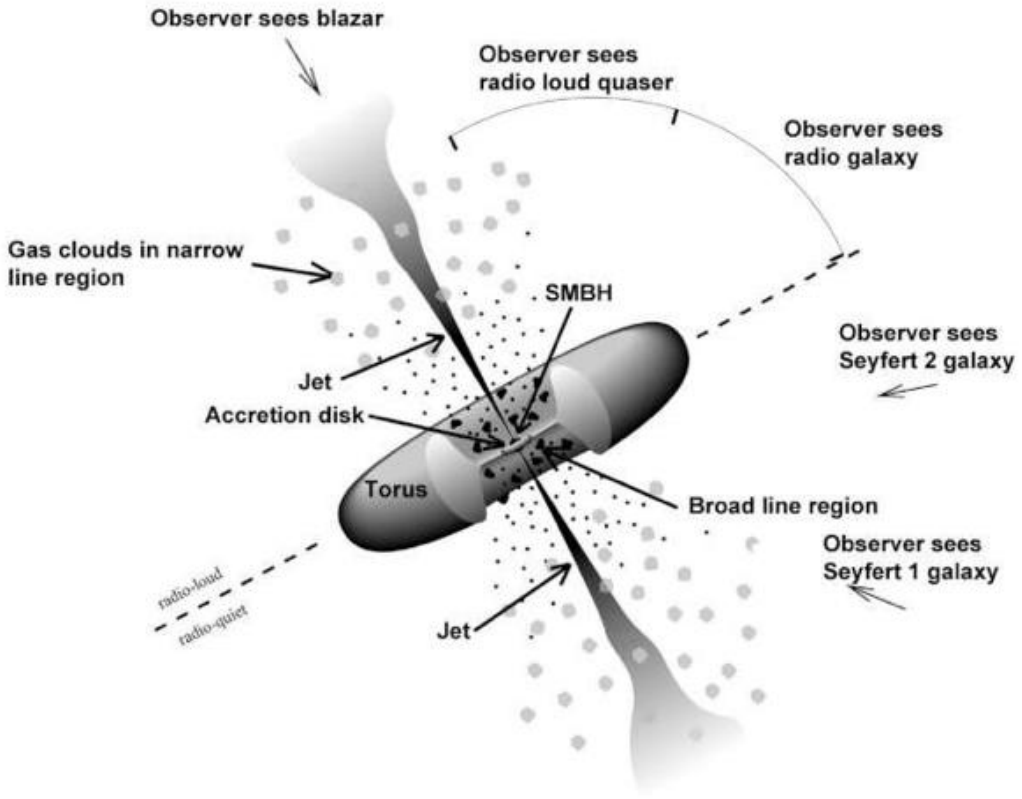
In general target environment can be anywhere on the CR pathway

- Near the high-energy CR source
- Dense environments on its pathway
- Soft photon backgrounds
- Earth atmosphere

Flavour ratio $\nu_e : \nu_\mu : \nu_\tau$

At the remote source: 1 : 2 : 0 at Earth 1 : 1 : 1

High-energy neutrino sources



AGN class depends on observer angle wrt the rotation axis

An example of pγ -dominated source

Active galactic nuclei (AGN)

Suggested ν production mechanism

- Protons are accelerated in shock-waves or black hole magnetosphere
- Interact with the EM radiation of the accretion disk

High-energy neutrino sources

An example of pp mechanism -dominated source:

Cosmic ray reservoirs, e.g.:

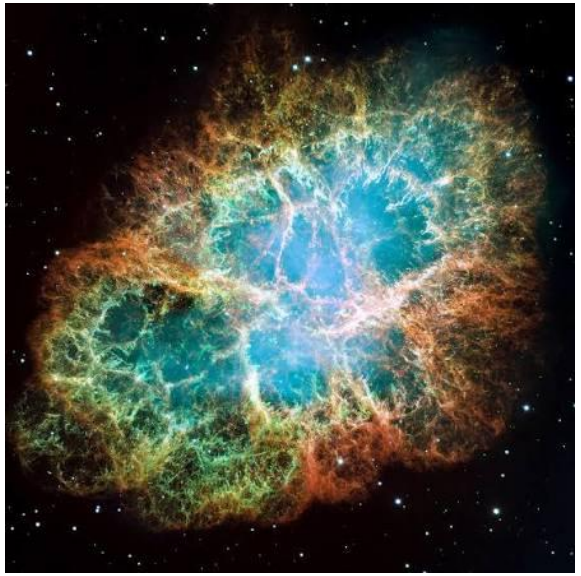
- Starburst galaxies
- Supernovae remnants (SNR)

High-energy protons are confined in the region

Accelerated in shockwaves

Interact with each other

Famous Crab SNR in our galaxy



Transient neutrino sources

Transient: lasting for only a short time; temporary [Cambridge Dictionary]

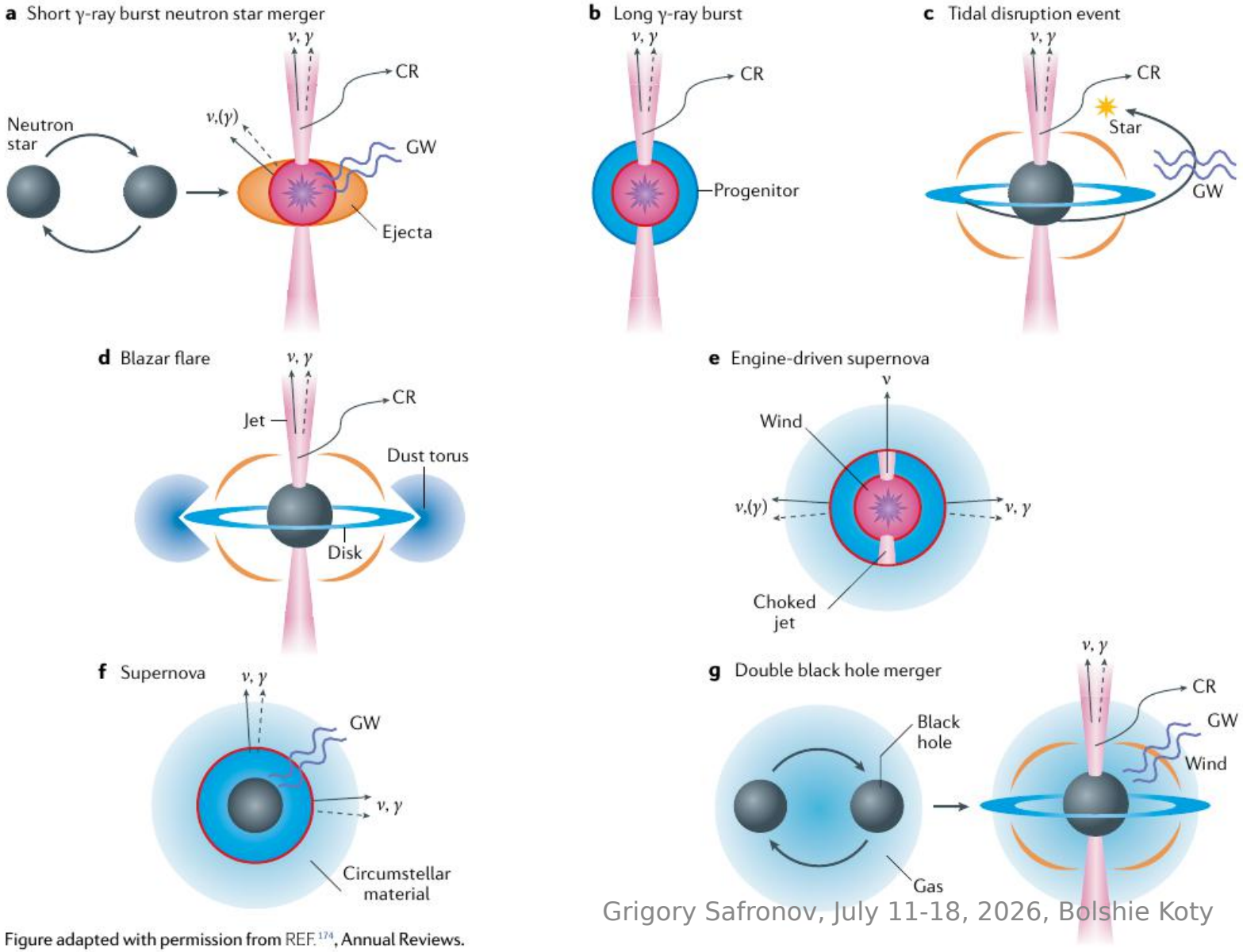


Figure adapted with permission from REF.[174], Annual Reviews.

[Nature Reviews Physics volume 1, pages 585–599 (2019)]

Many more possible sources

P. Meszaros

arXiv:1708.03577 (2017)

More useful reading:

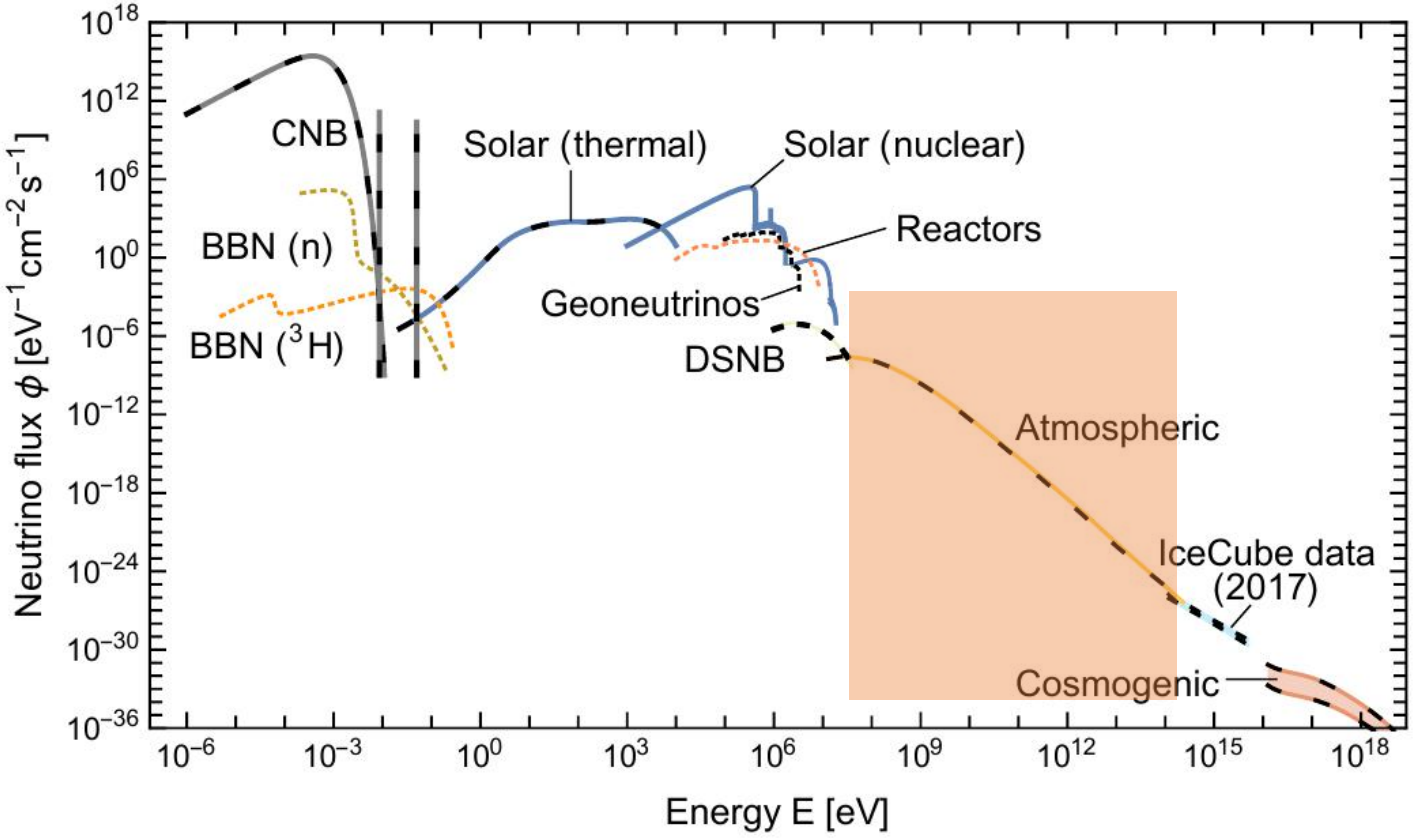
S. Troitsky

arXiv:2311.00281 (2024)

High-energy neutrino fluxes

Flux of neutrino at Earth spans over large energy range

Full-sky neutrino flux at Earth differential in energy

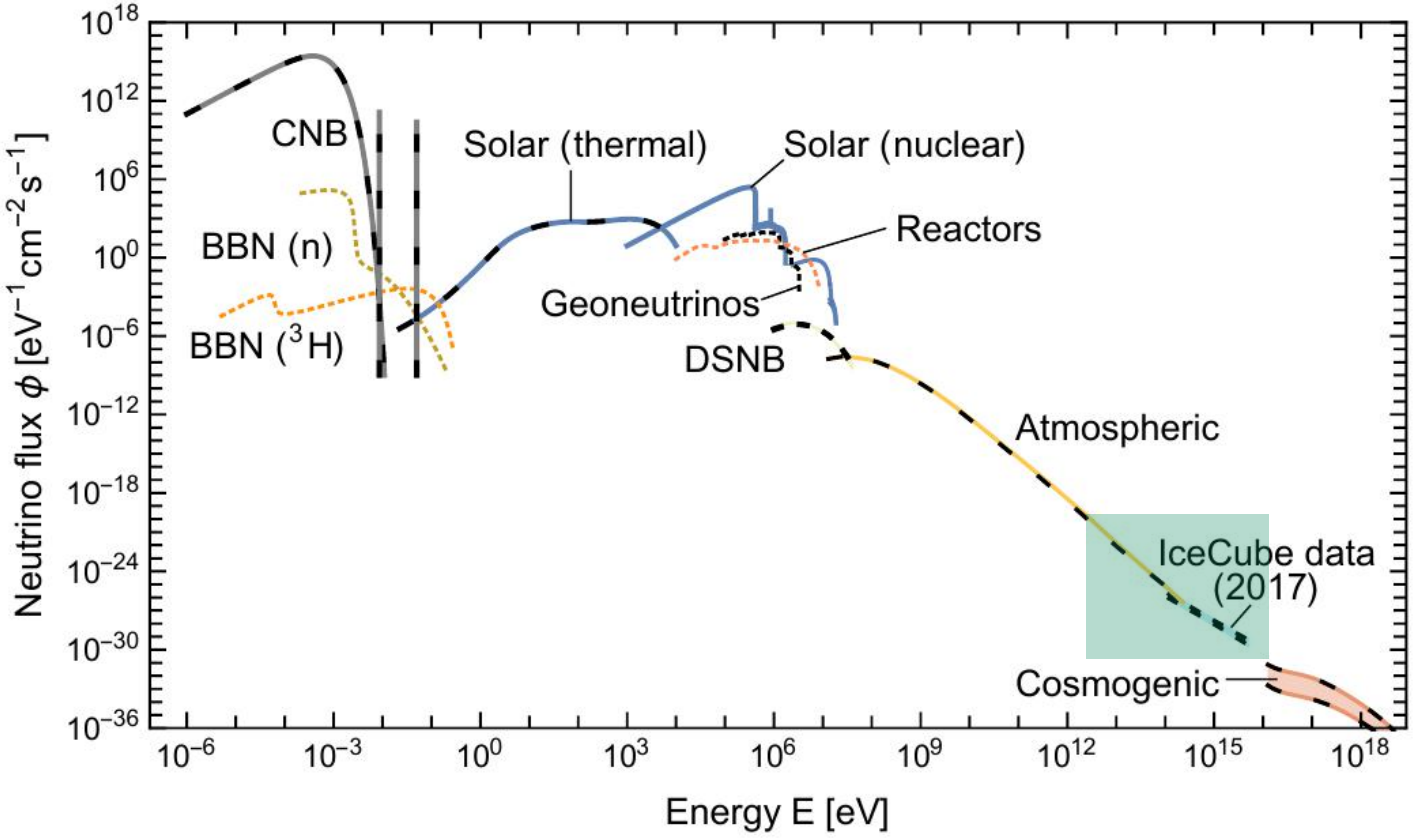


Atmospheric neutrino flux from CR hitting the atmosphere

High-energy neutrino fluxes

Flux of neutrino at Earth spans over large energy range

Full-sky neutrino flux at Earth differential in energy



At TeV-PeV eneries
astrophysical neutrino flux starts to
contribute

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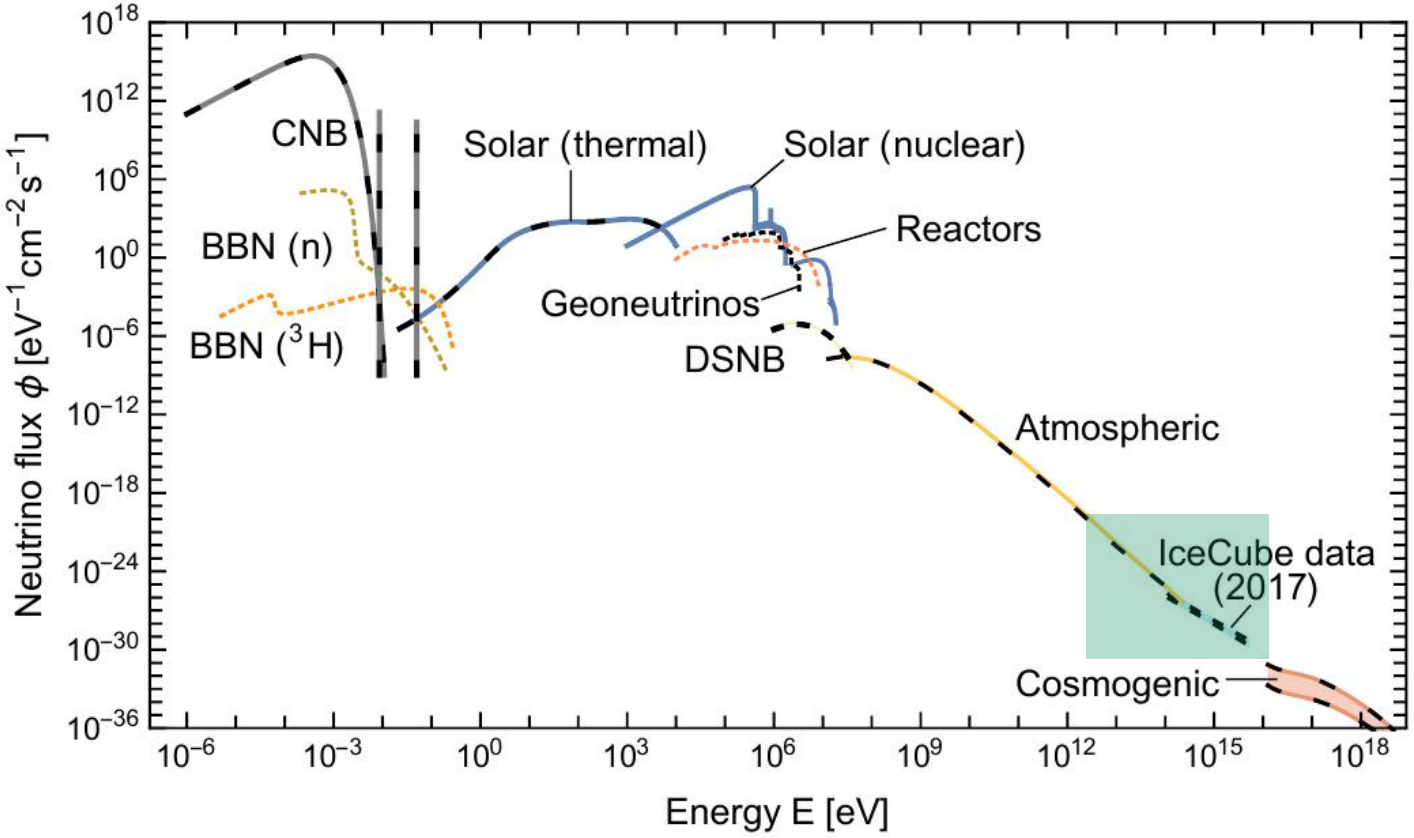


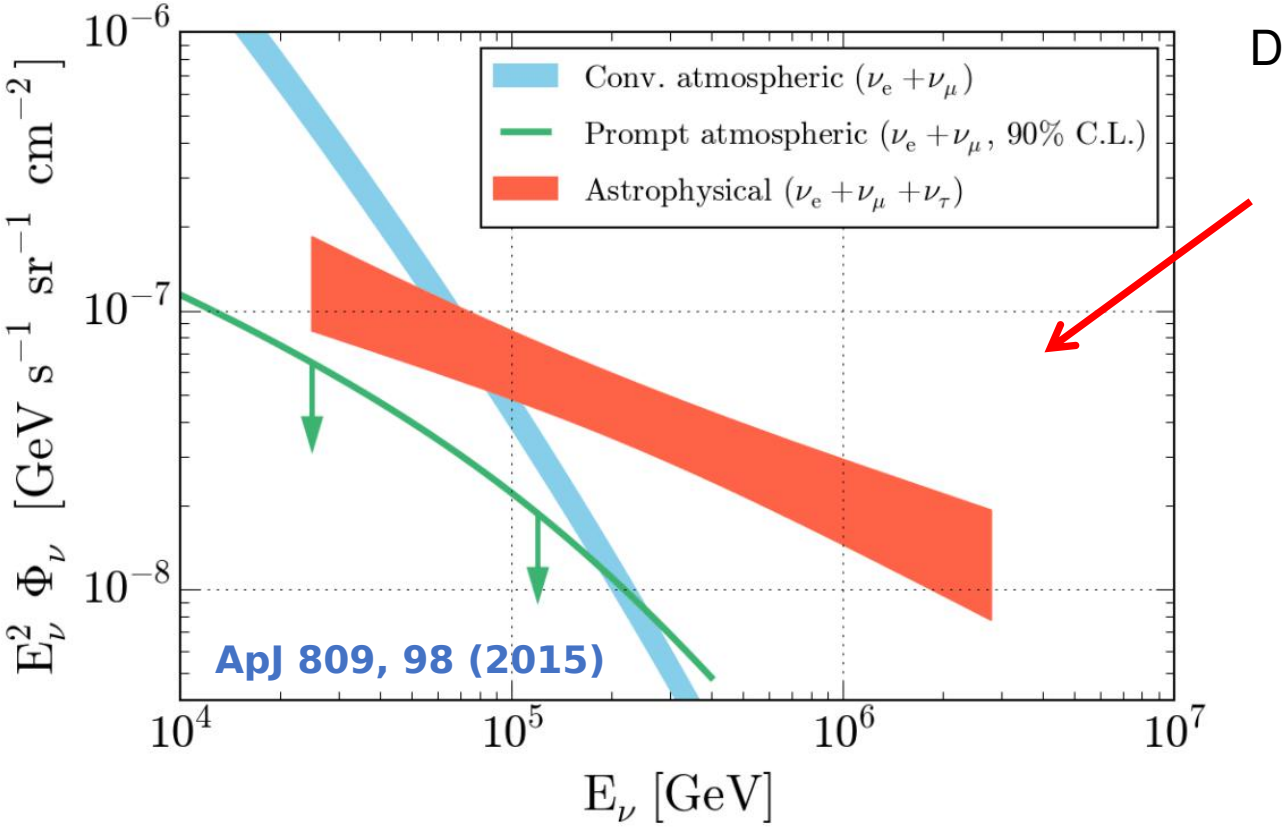
At TeV-PeV eneries astrophysical neutrino flux starts to contribute

Let's zoom into our region of interest

High-energy neutrino fluxes

Overall astrophysical neutrino flux overcome atmospheric neutrino background around 50-100 TeV

Flux per solid angle differential in energy



Diffuse all-flavour astrophysical flux: overall flux from the sky disregarding potential sources

High-energy neutrino fluxes

Overall astrophysical neutrino flux overcome atmospheric neutrino background around 50-100 TeV

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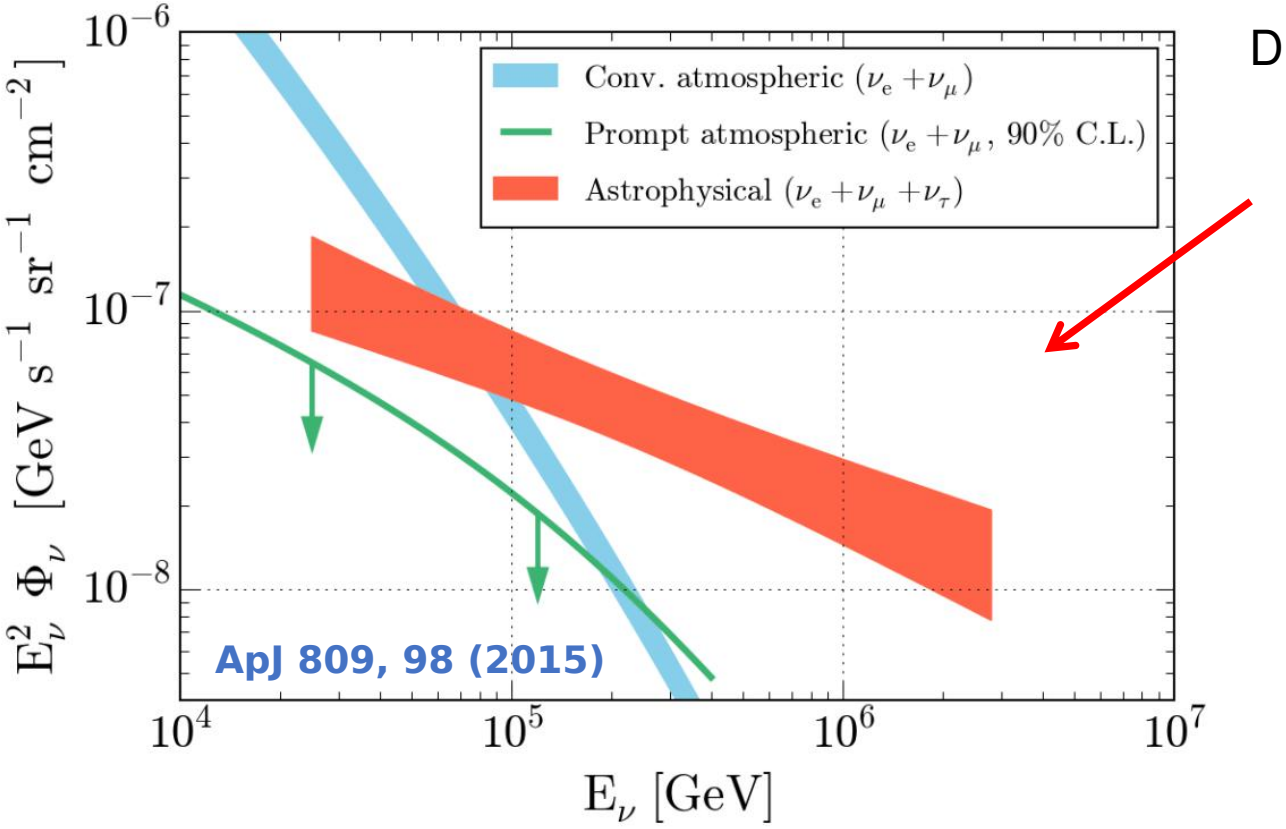


Diffuse all-flavour astrophysical flux: overall flux from the sky disregarding potential sources

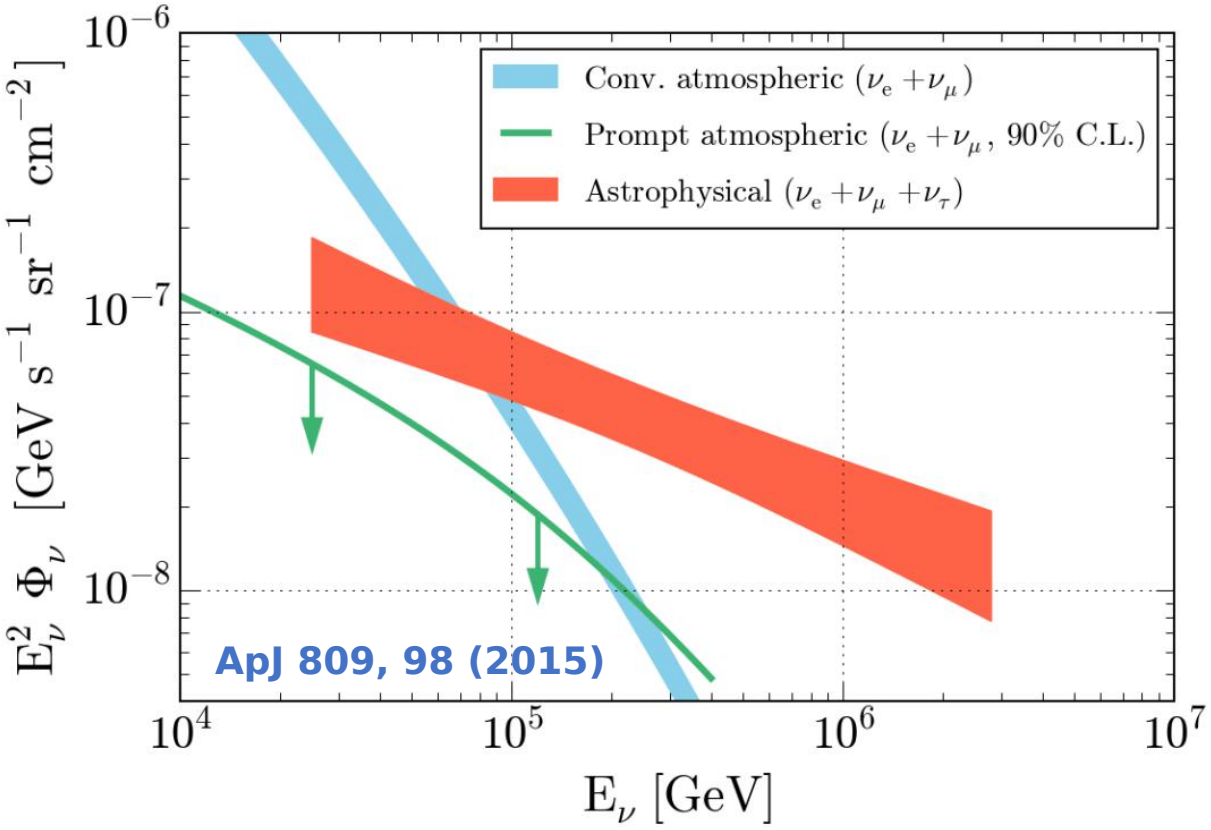
High-energy neutrino fluxes are often discussed as a single power-law with spectral index γ and normalisation φ_0

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu) = \phi_0 E_\nu^{-\gamma}$$

Atmospheric neutrino, “soft” spectrum: $\gamma \sim 3.7$
Astrophysical neutrino, “hard” spectrum: $\gamma \sim 2.5$

High-energy neutrino fluxes

Flux per solid angle differential in energy



Usual normalisation point: 100 Tev

$$\frac{d\Phi_\nu}{dE_\nu}(E_\nu) = \phi_0 \left(\frac{E_\nu}{100\mathrm{TeV}} \right)^{-\gamma}$$

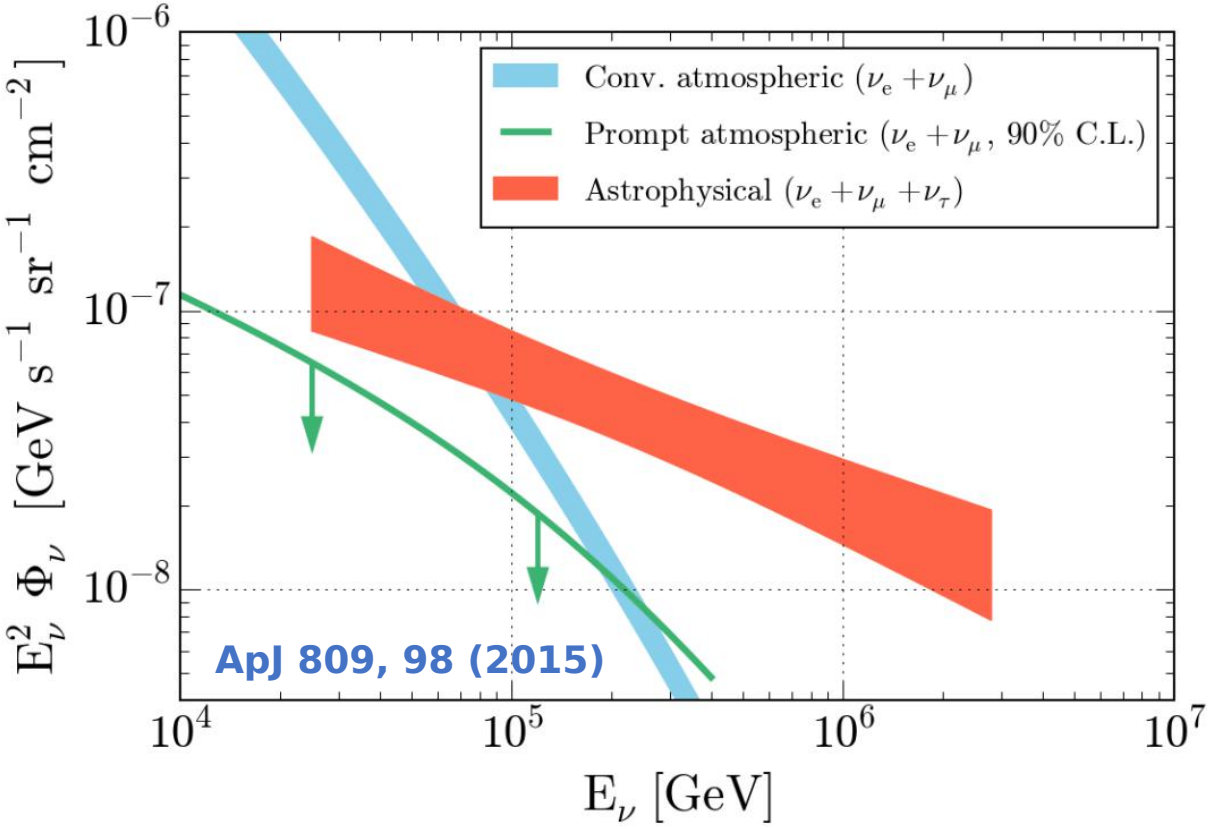
IceCube 9.5 yr. track spectrum fit

$\varphi_0 = 1.44 \cdot 10^{-18}$ (GeV^{-1} cm^{-2} s^{-1} sr^{-1}), $\gamma = 2.37$

R. Abbasi et al 2022 ApJ 928 50

High-energy neutrino fluxes

Flux per solid angle differential in energy



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R. Abbasi et al 2022 ApJ 928 50

With this spectrum the integrated flux of particles with E > 10 TeV is: ~ 13 per m^2 per year

How do we detect such a low neutrino flux?

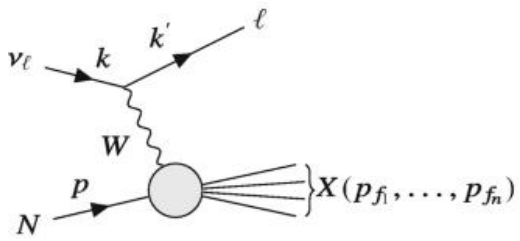
Neutrino interaction cross-section

Interaction cross-section: $\sigma(\mathrm{cm}^2) = \mathrm{rate}(\mathrm{s}^{-1})/\mathrm{flux}(\mathrm{cm}^{-2}\mathrm{s}^{-1})$

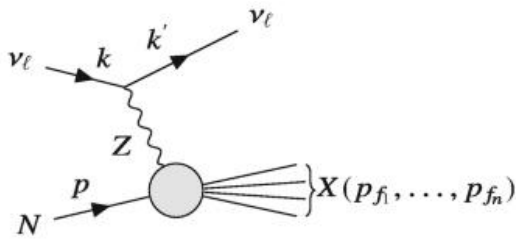
Neutrinos interact with nucleons of the target detector volume

Above E_ν ~ 1 GeV νN interaction goes via Deep Inelastic Scattering (DIS)

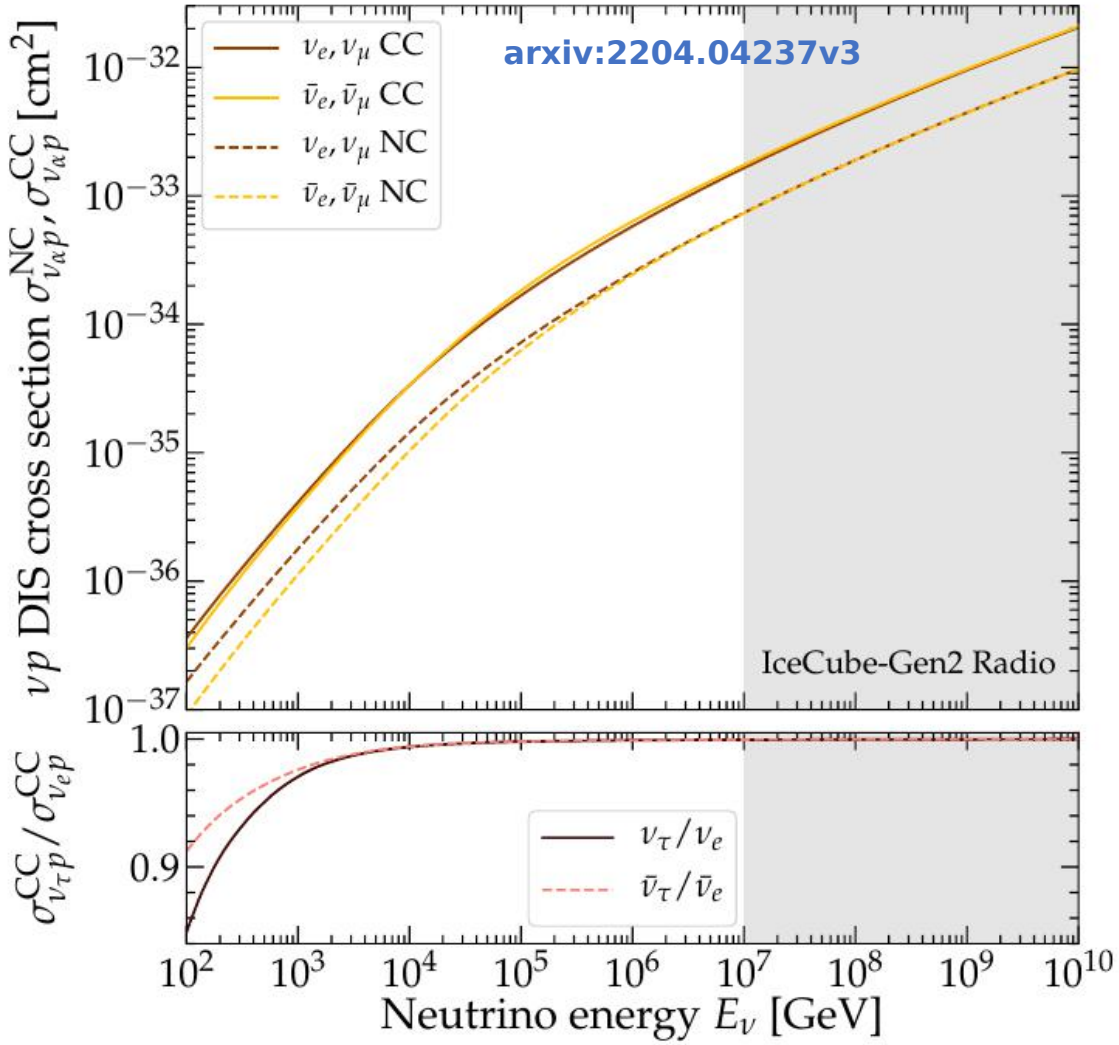
Charged Current (CC) interaction (W± bosons)



Neutral current (NC) interaction (Z boson)

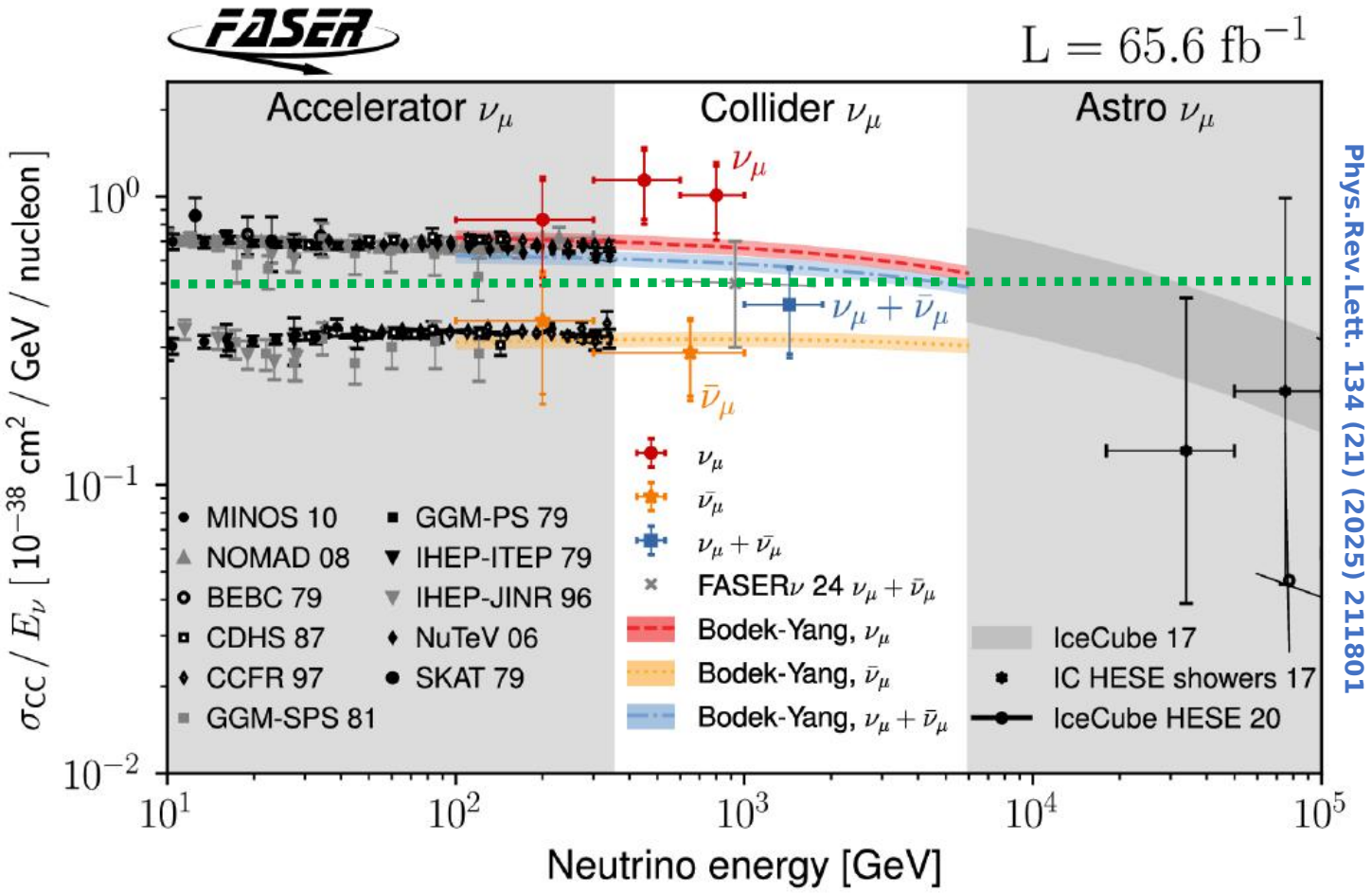


NC cross-section is ~ 3 times smaller than CC



Neutrino interaction cross-section

Neutrino cross-section measurements



Neutrino interaction cross-section scales as ~E_ν for TeV energies

Assume $\nu + \bar{\nu}$ CC cross-section:

$$\sigma_{\nu+\bar{\nu}} = E_\nu(\mathrm{GeV}) \times 5 \times 10^{-39}(\mathrm{cm}^2/\mathrm{GeV})$$

Neutrino interaction rate

To calculate number of interactions per some volume one has to integrate the total flux with the cross-section

full-sky flux convoluted with
cross-section - rate of interactions per nucleon

Rate of events per s in volume *V*:

$$R = \frac{\rho V}{\mu} N_A I$$

where:

$$I = \sum_{\nu} \int_{E_{min}}^{E_{max}} \frac{d\Phi}{dE_\nu}(E_\nu)\sigma_{\nu+\bar{\nu}}(E_\nu)dE_\nu$$

number of nucleons per *V*

sum over ν flavours

full-sky flux

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full-sky flux

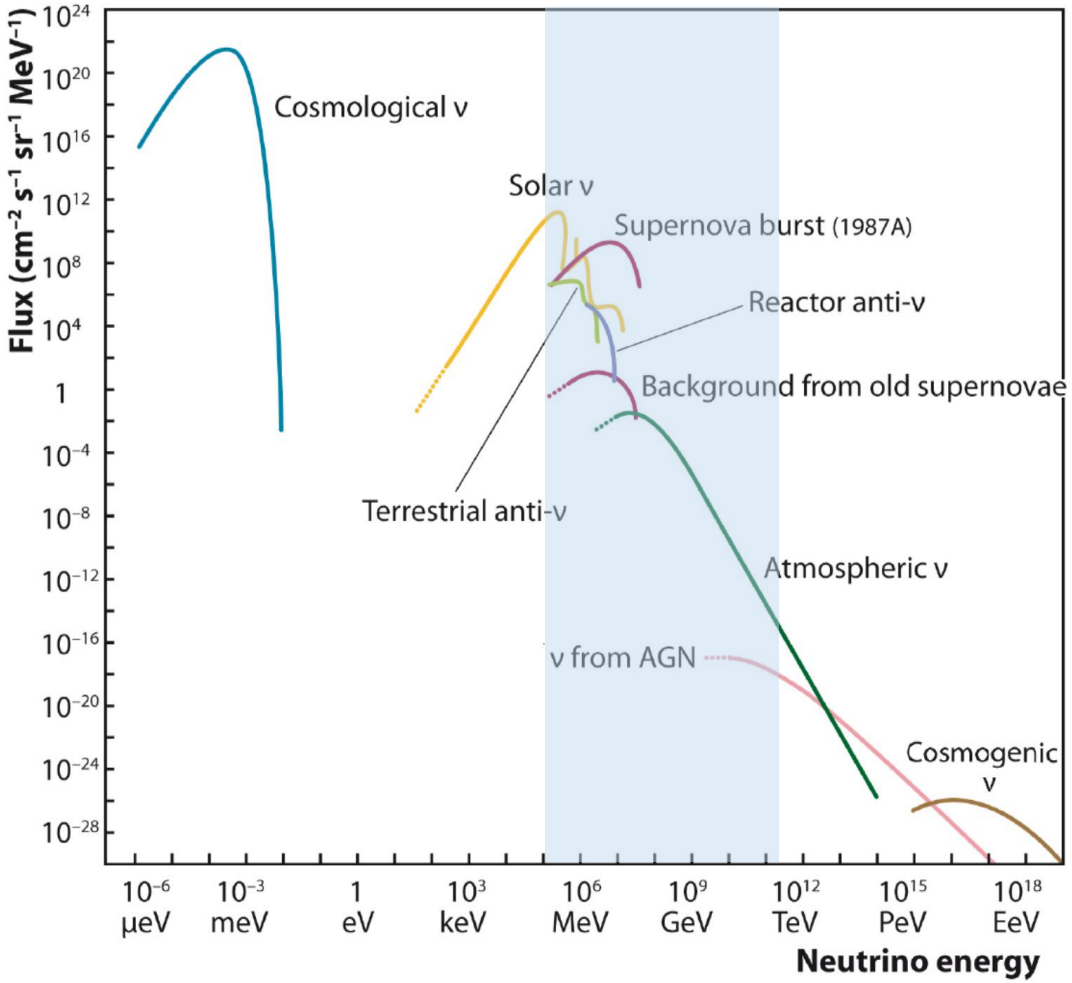
Let's calculate rate of all-flavour CC interactions within 1 m^3 or 1 tonne of water for $E_\nu > 10$ TeV

Let's take the IceCube track flux: $\varphi_0 = 1.44*10^{-18}$ ($GeV^{-1}cm^{-2}s^{-1}sr^{-1}$), $\gamma = 2.37$

We get: ~$3.2*10^{-7}$ per tonne **per year**

Underground neutrino detectors

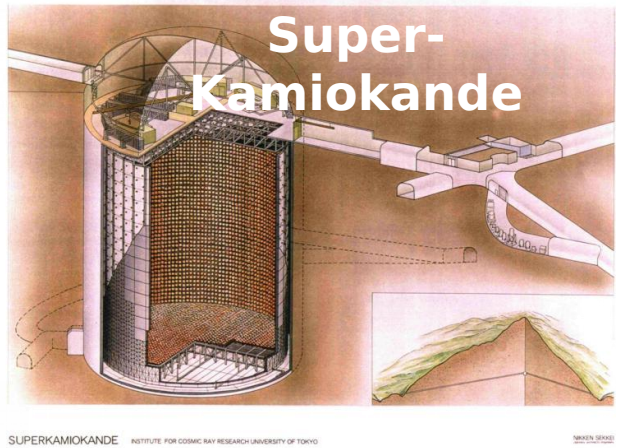
Solar neutrino, neutrino physics, see lectures by prof. Langjan Wen

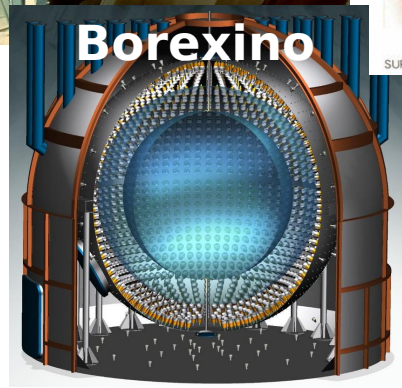


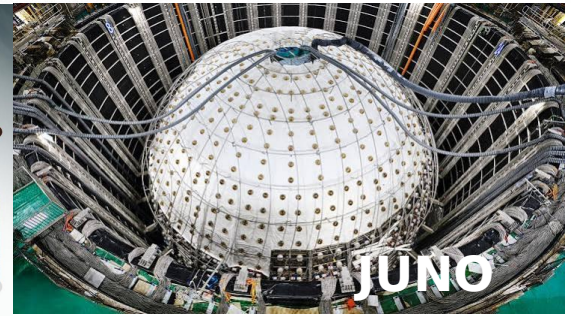
Great variety of exciting experimental techniques

Sensitive volume mass: **10's tons -10's kilotons**









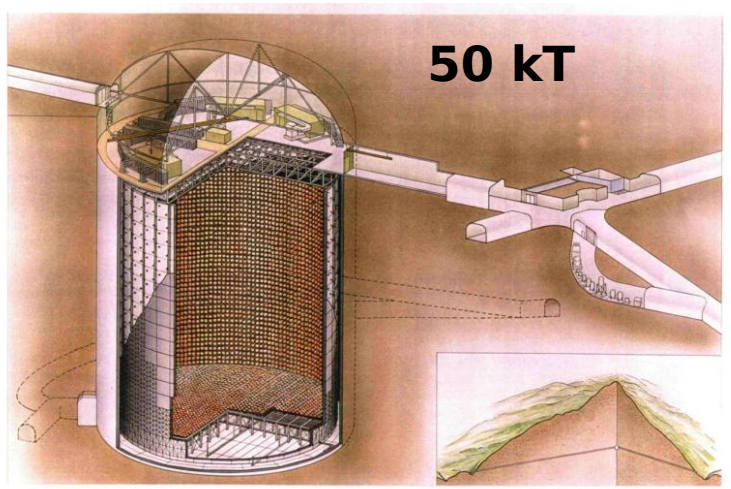
and many-many others

Underground neutrino detectors

Largest underground neutrino experiments: water-tank detectors

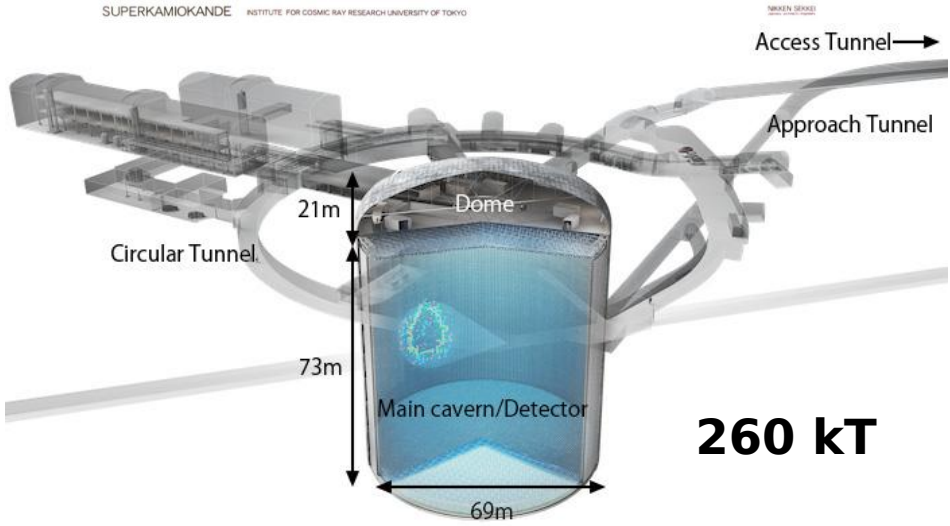
Super-Kamiokande detector

50 kT of water → would undergo just **~0.016** interactions per year for astro. ν with $E_\nu > 10$ TeV



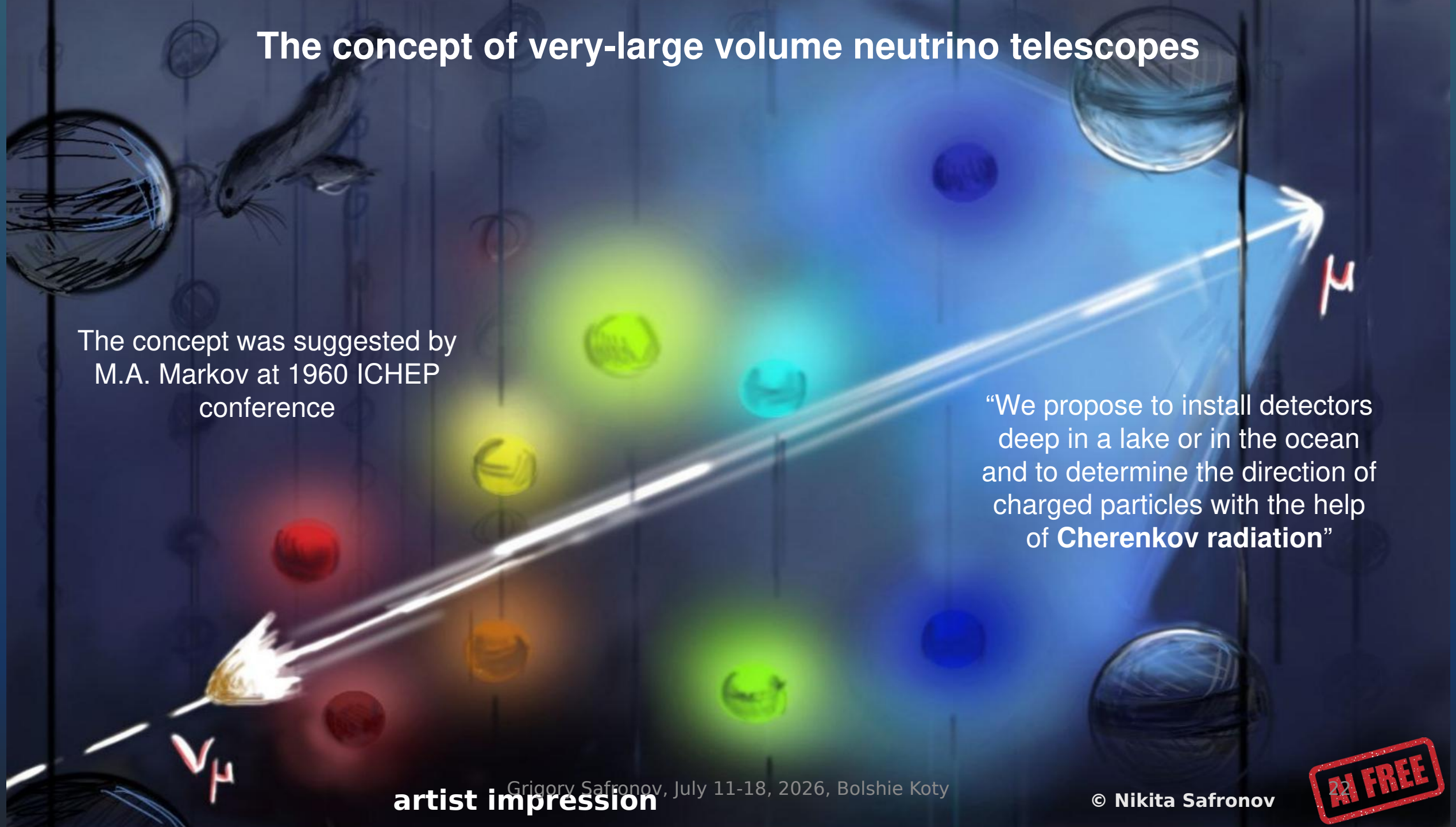
Hyper-Kamiokande, to be launched soon

260 kT of water → would undergo **~0.083** such interactions per year



For the studies of astro neutrino flux we need different detection techniques

The concept of very-large volume neutrino telescopes



The concept was suggested by M.A. Markov at 1960 ICHEP conference

"We propose to install detectors deep in a lake or in the ocean and to determine the direction of charged particles with the help of **Cherenkov radiation**"

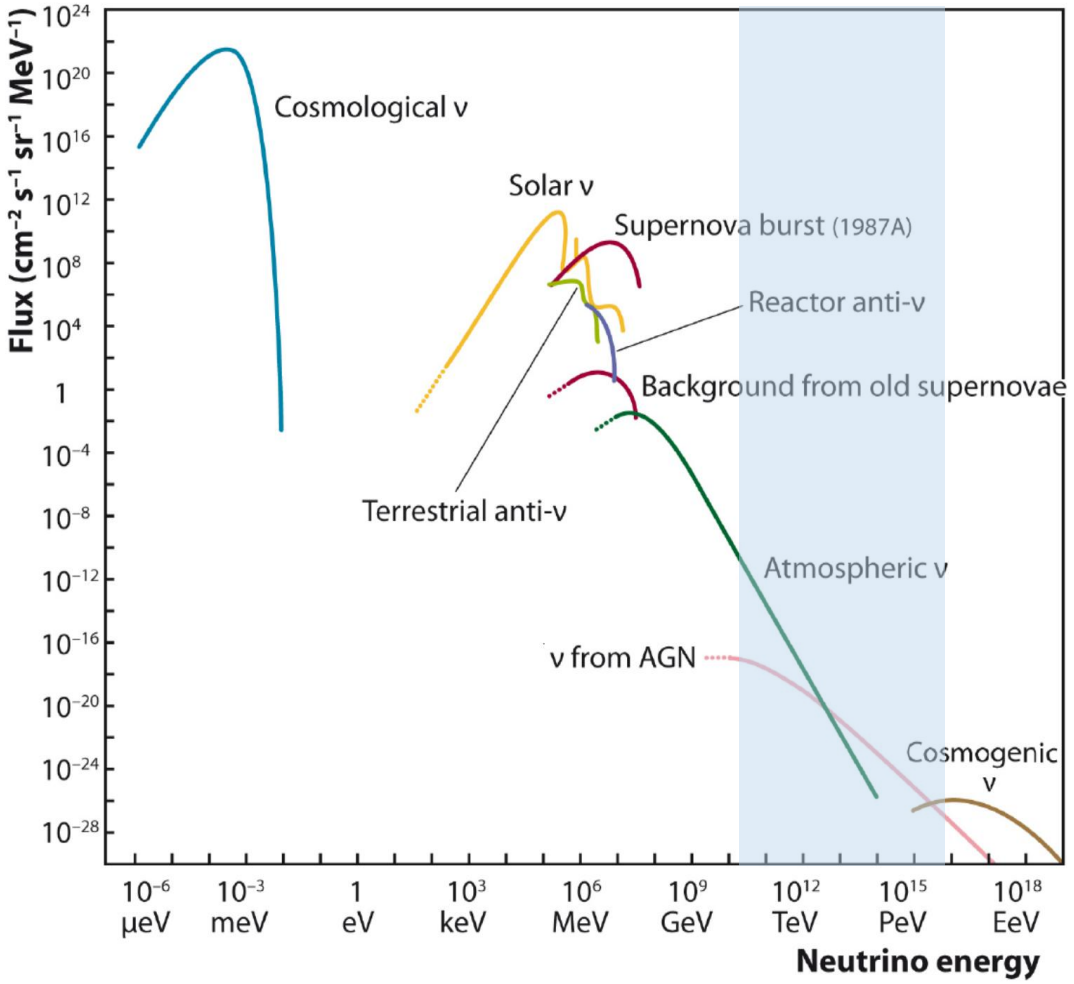
artist impression

© Nikita Safronov

AI FREE

Large-volume neutrino telescopes

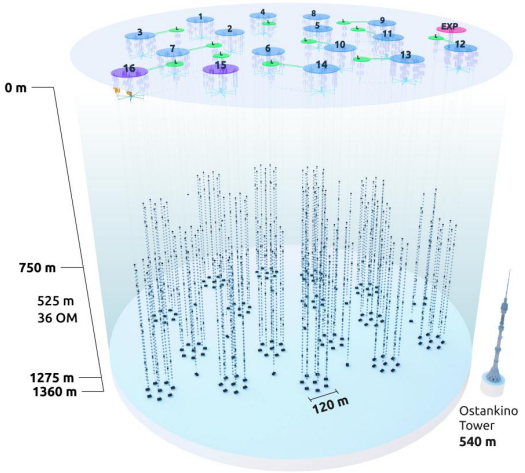
Present generation: **Gigaton mass scale**



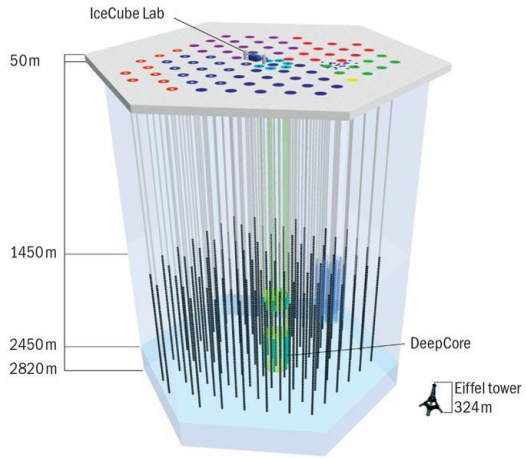
Energy range: 10's GeV - multi-PeV range

- Atmospheric neutrino
- Astrophysical neutrino (galactic, extragalactic)
- ~ cosmogenic neutrino

Baikal-GVD



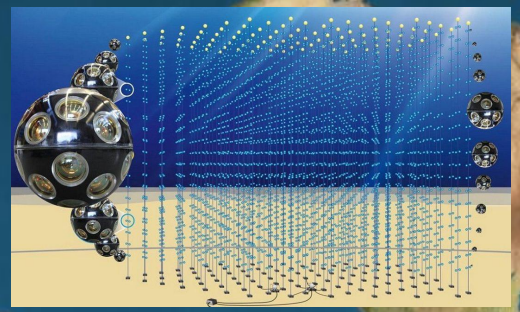
IceCube

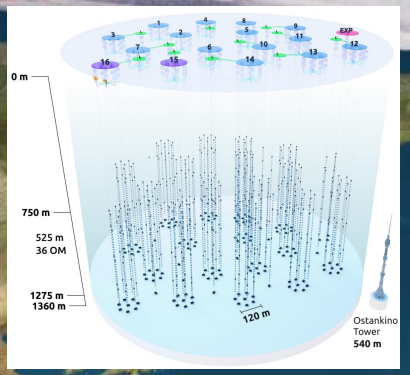


320 events per year for 1Gt of water for E_ν > 10 TeV

Operating large-volume neutrino telescopes

KM3NeT, 1 km³
deployment

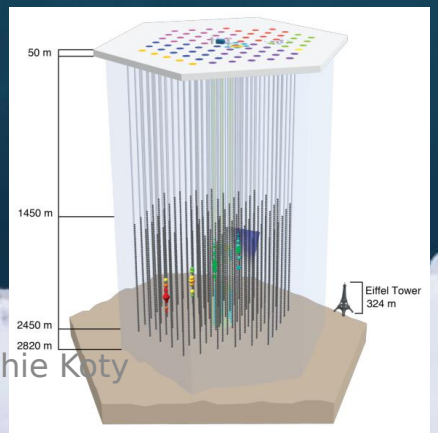




Baikal-GVD, 1 km³
present volume ~ 0.8 km³,
deployment

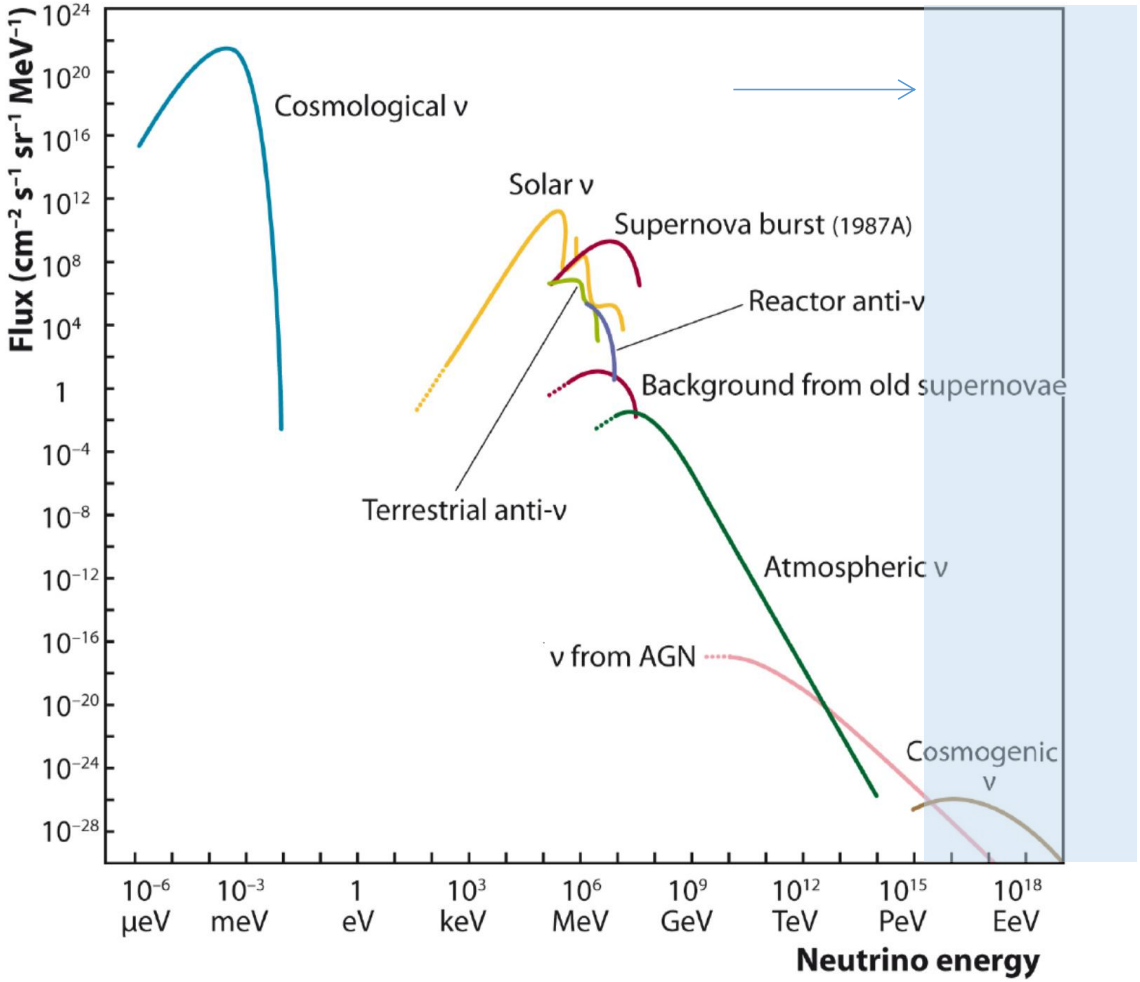
Present generation of neutrino telescopes: ~1km³

IceCube 1 km³
completed in 2010



Ultra high-energy neutrino detectors

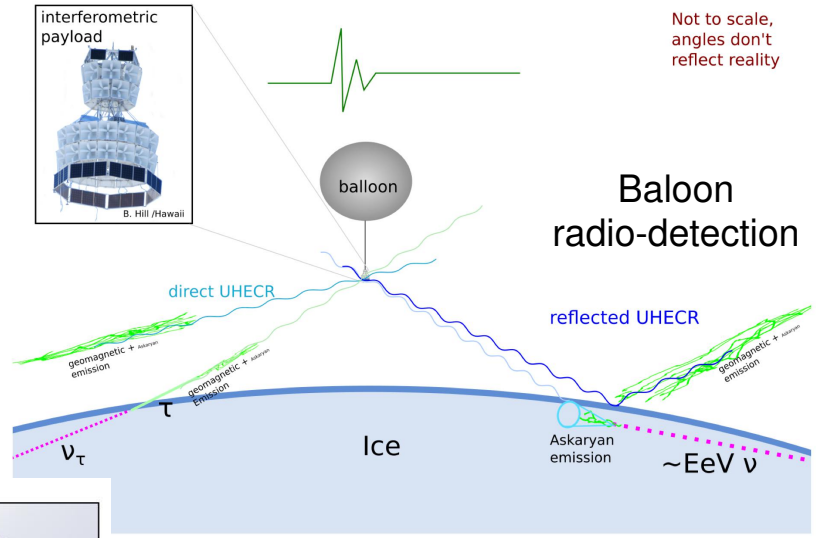
Very sparse instrumentation, **enormous sensitive volume: O(100km³) and more**



Multi-PeV neutrinos and beyond

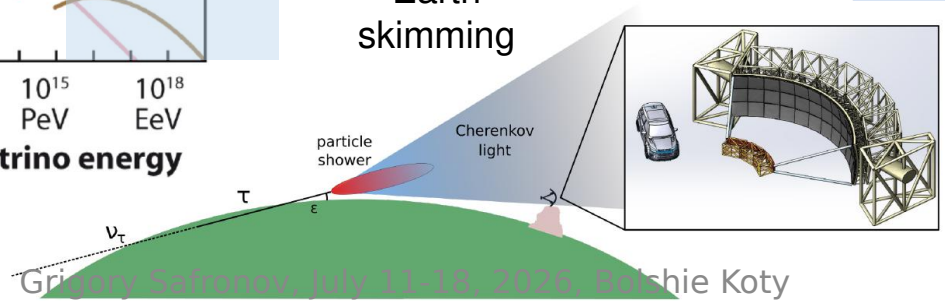
- Earth skimming
- Radio-detection
- Acoustic detection

Lots of impressive projects and concepts



Baloon radio-detection

Earth skimming



Not in this lecture :(

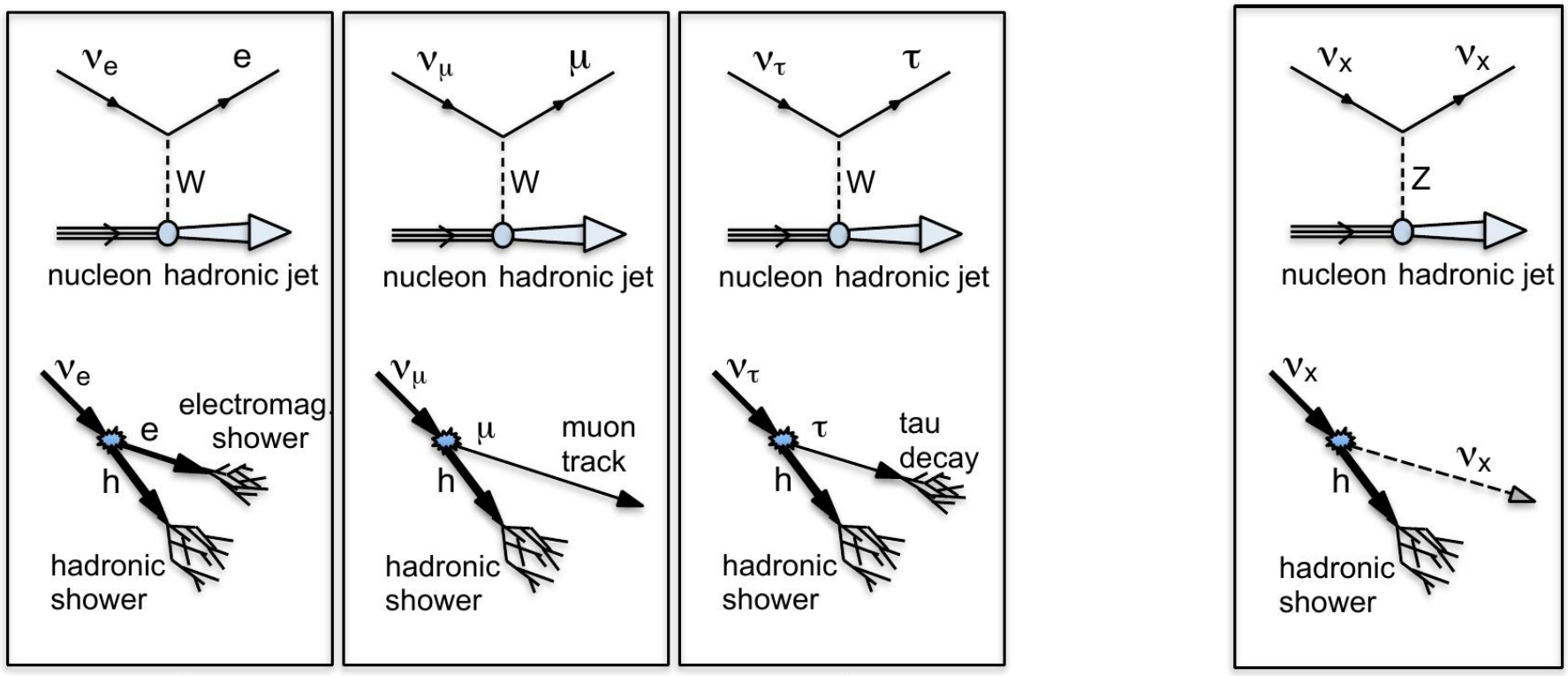
Detection of events

High-energy neutrino interaction signatures

Deep Inelastic Scattering topologies

Charged current interactions (CC)

Neutral current interactions (NC)



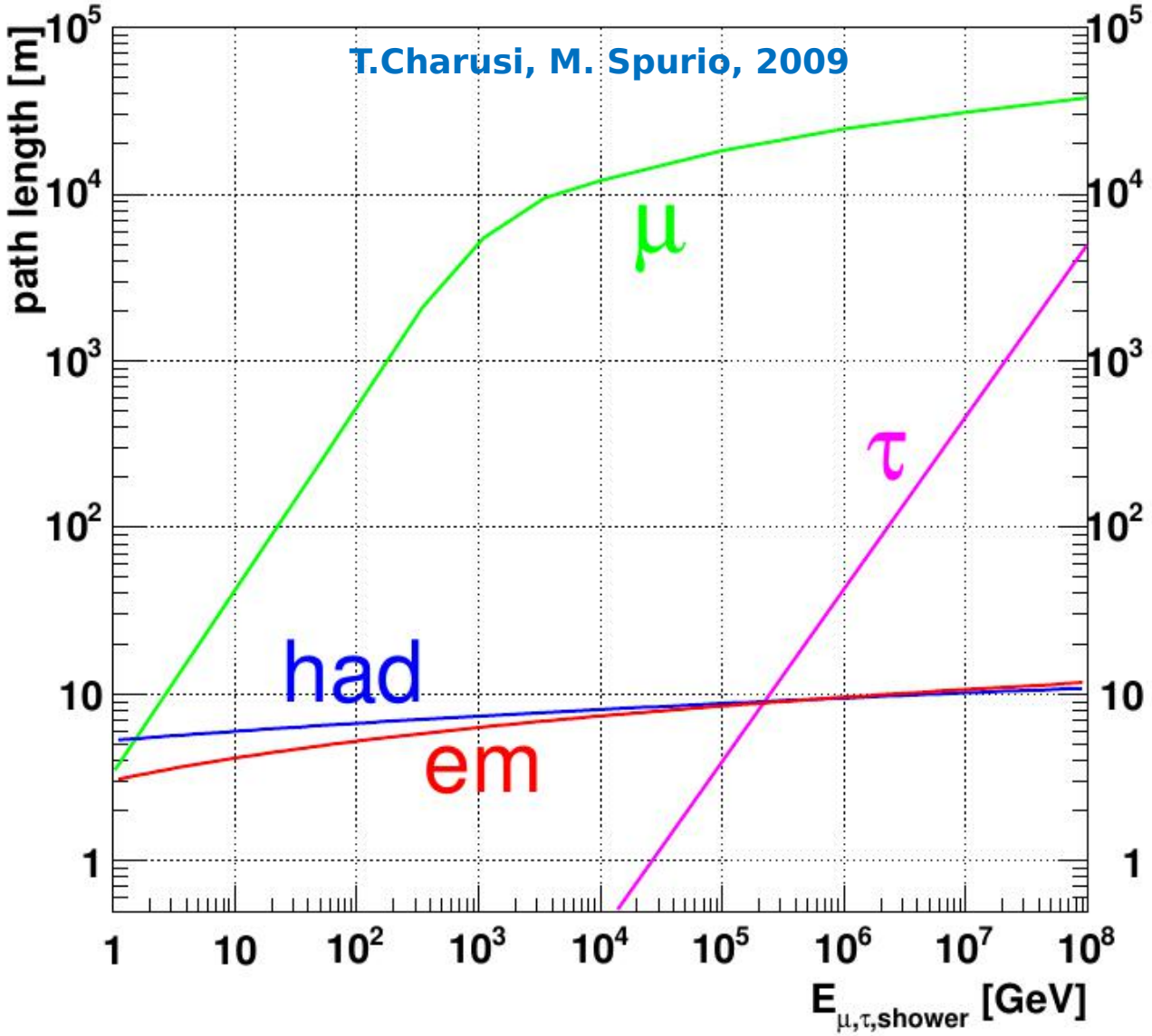
Muon and partially -neutrino in CC: muon with kilometers track length

In other cases: local energy deposition in the form of cascade

Particle propagation range

TeV muons have path length of order of >10 km

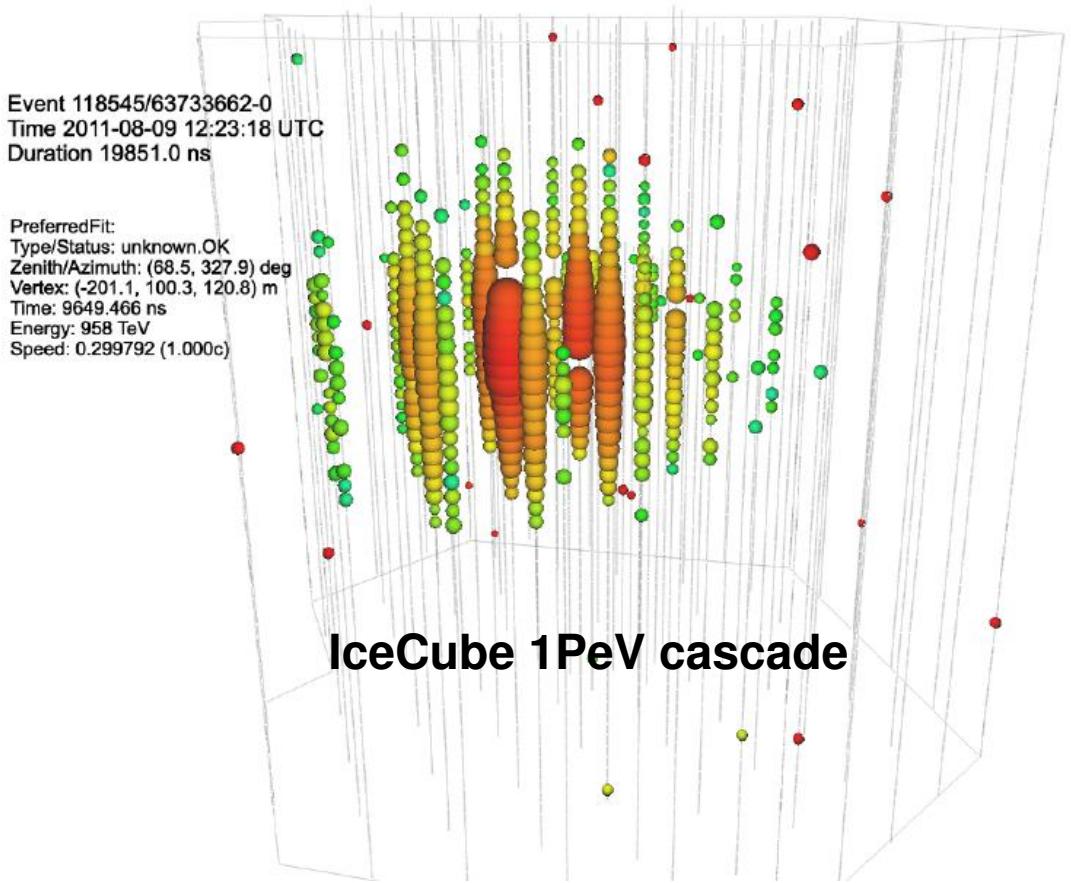
Hadronic or electromagnetic cascades extend to 5-10 meters



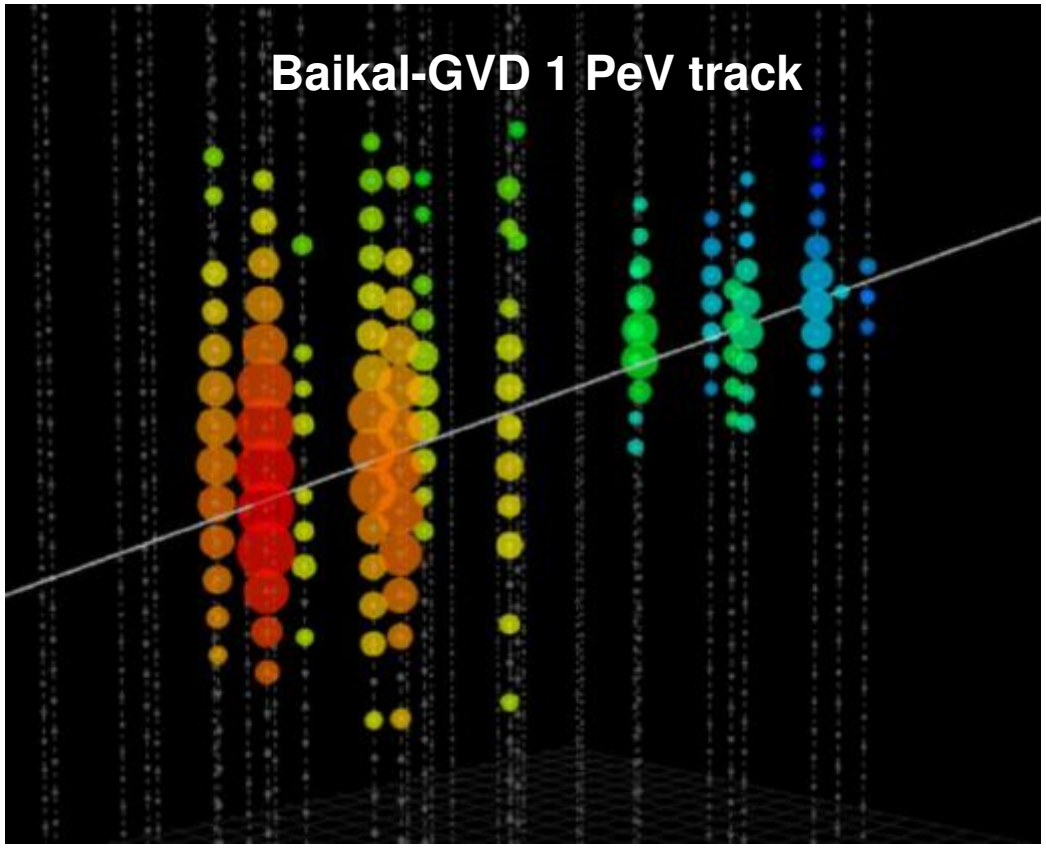
Event examples

late

early



IceCube 1PeV cascade



Let’s follow how the 10 TeV muon signal is generated in conditions of the Baikal-GVD detector

Generation of photons

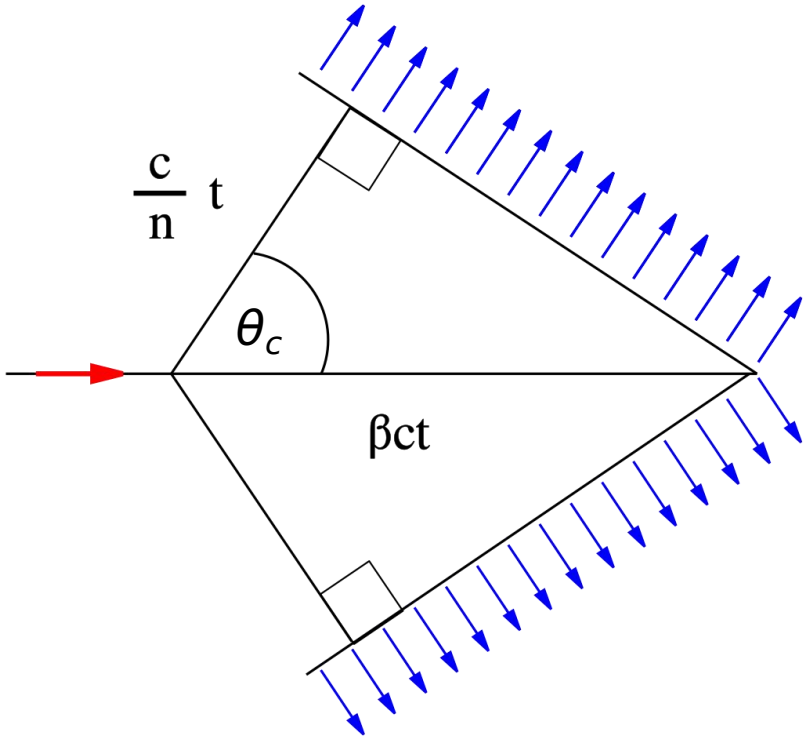
Photodetection

Cerenkov radiation

Charged particles moving with velocity above the speed of light in medium emit the Cerenkov radiation

Radiation intensity (Frank-Tamm):

$$\frac{dN^2}{dxd\lambda} = \frac{2\pi\alpha}{\lambda^2}(1 - \frac{1}{\beta^2 n^2})$$



Threshold energy

Particles above that energy emit the radiation

$$E > E_{th} = m(1 - \frac{1}{n^2})^{-1/2}$$

In water:

- electron: 775 keV
- muon: 159 MeV

Cerenkov angle (ultrarelativistic case)

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

for water: ~42°

Cerenkov radiation

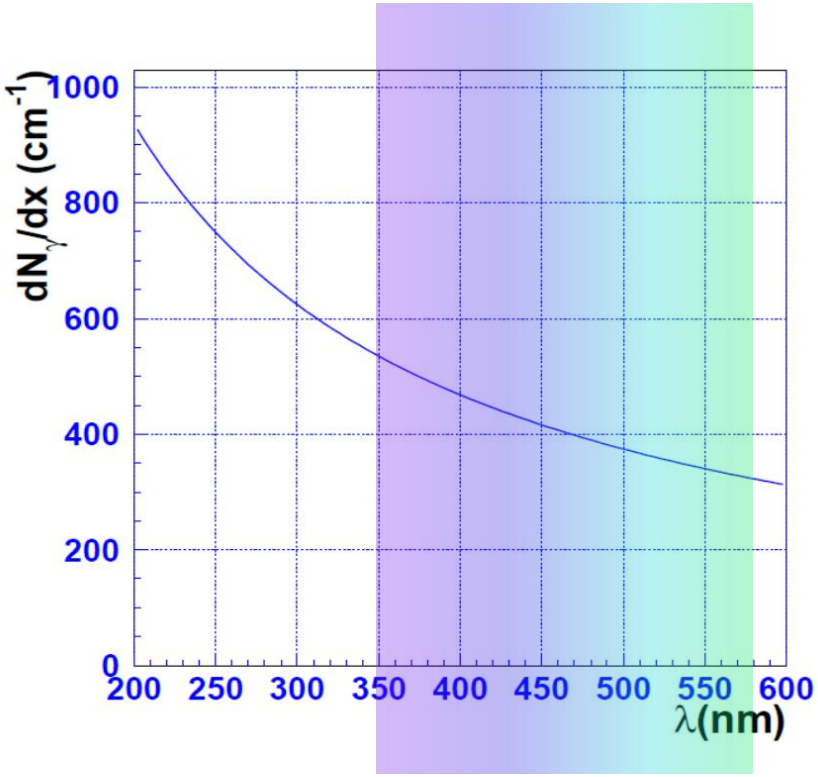
Photomultipliers commonly used in LVNT are sensitive to ~blue region of visible spectrum

Number of photons emitted by muon or electron with β~1 per unit length in some wavelength band:

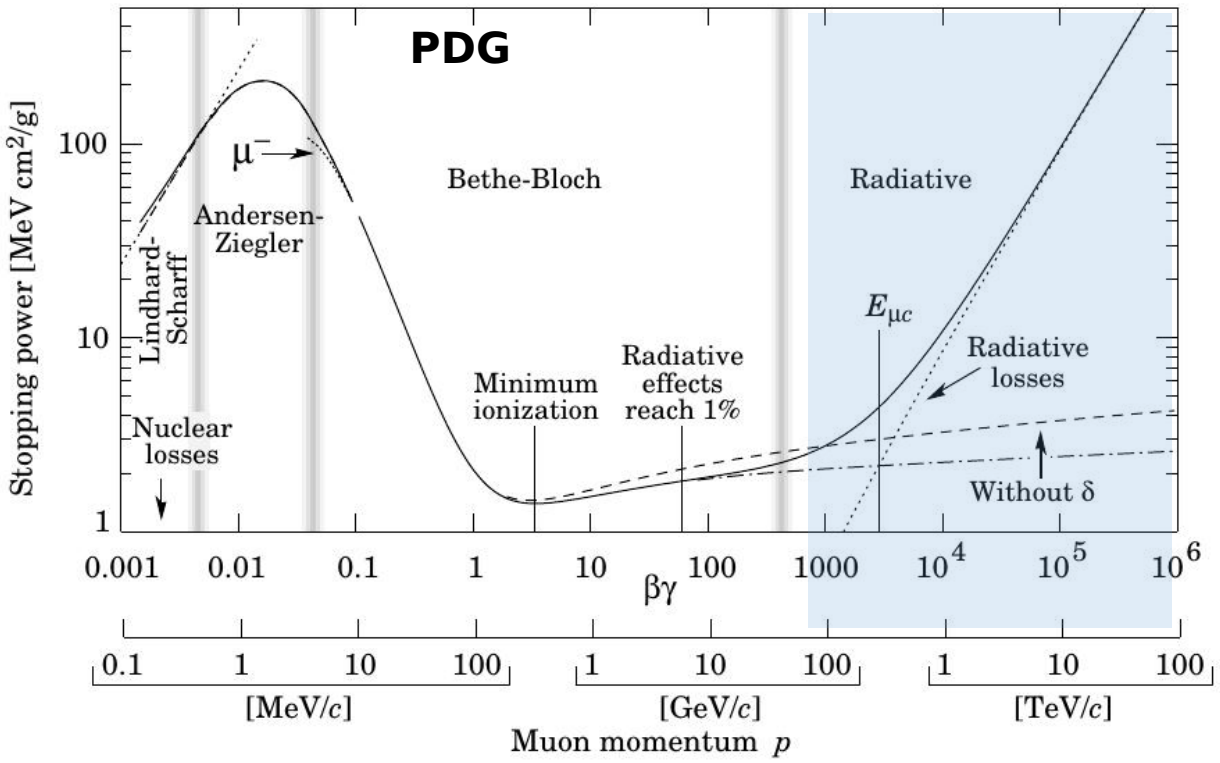
$$\frac{dN_\gamma}{dx} = 2\pi\alpha \sin^2(\theta_C)\left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right)$$

Number of photons emitted in **350-580nm** band by β~1 charged particle per 1m: **~22500**

approximate photodetection band



High-energy muon energy losses



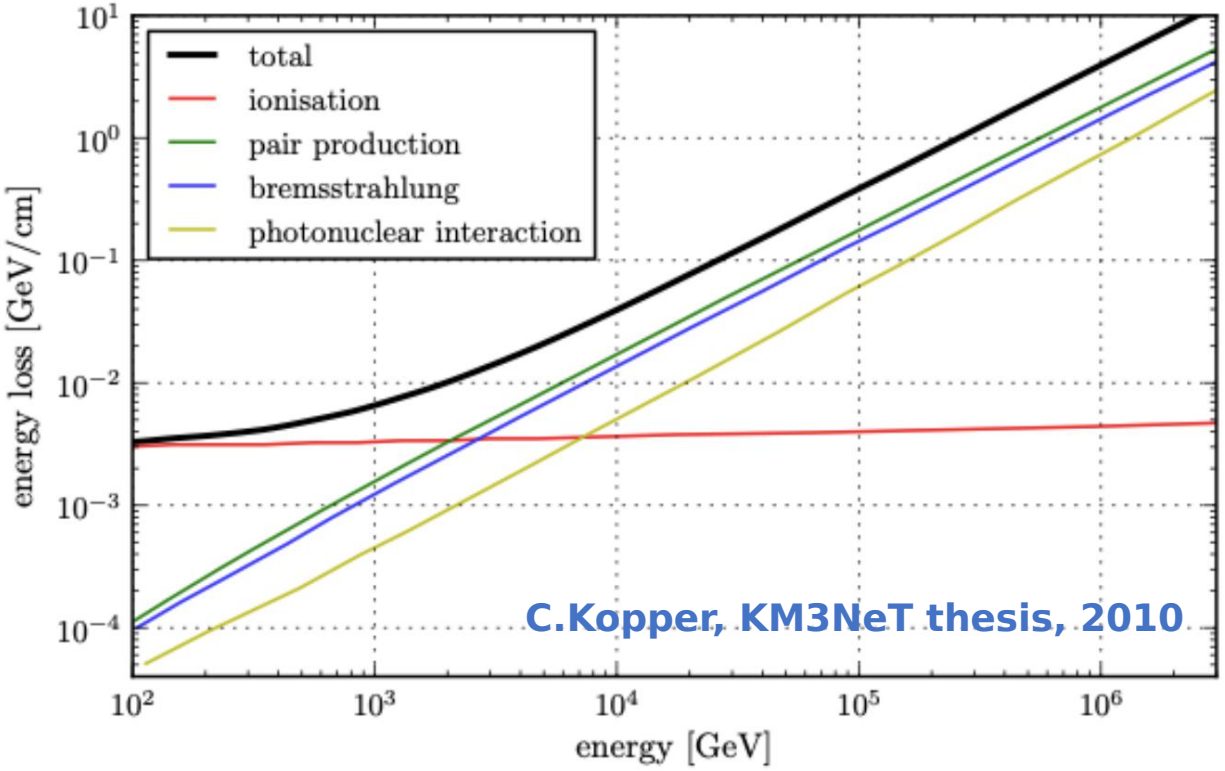
At E_μ < ~100 GeV muon loose energy just through ionisation

~2 MeV energy loss per cm

Starting from ~ 1TeV
stochastic energy losses
due to hard radiative processes
start to dominate

High-energy muon energy losses

High-energy muon energy loss in water



Linear growth of energy loss for E > 1 TeV

$$-\frac{\mathrm{d}E_\mu}{\mathrm{d}x} = a + b \cdot E_\mu$$

Losses manifest themselves as showers along the muon track

Main contribution from electromagnetic showers

- **e^+e^- pair production**
- **bremsstrahlung**

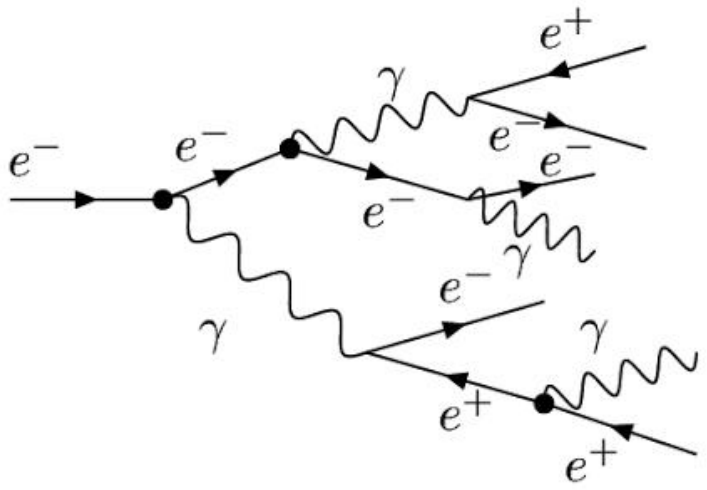
Hadronic showers are less important

- **photonuclear interactions**

Let's consider 10 TeV muon, energy loss ~ 0.05 GeV/cm or **5 GeV/m**

Light yield due to EM energy losses

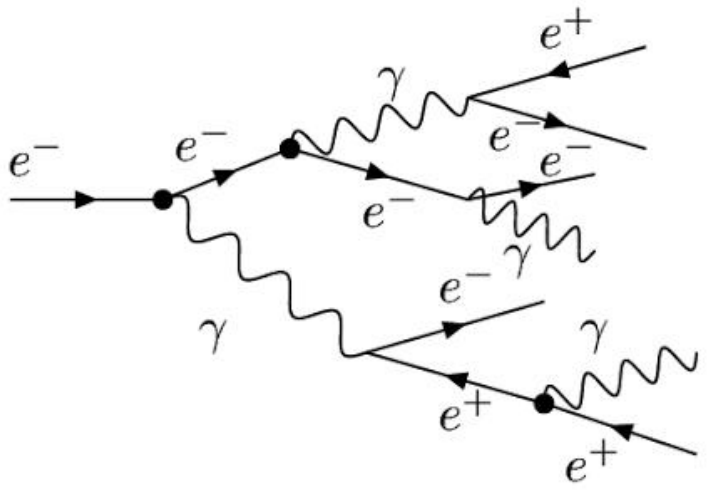
Charged particles in accompanying EM cascades emit Cherenkov light



Such cascades effectively increase Cherenkov-emitting tracks length due to multiple charged particles

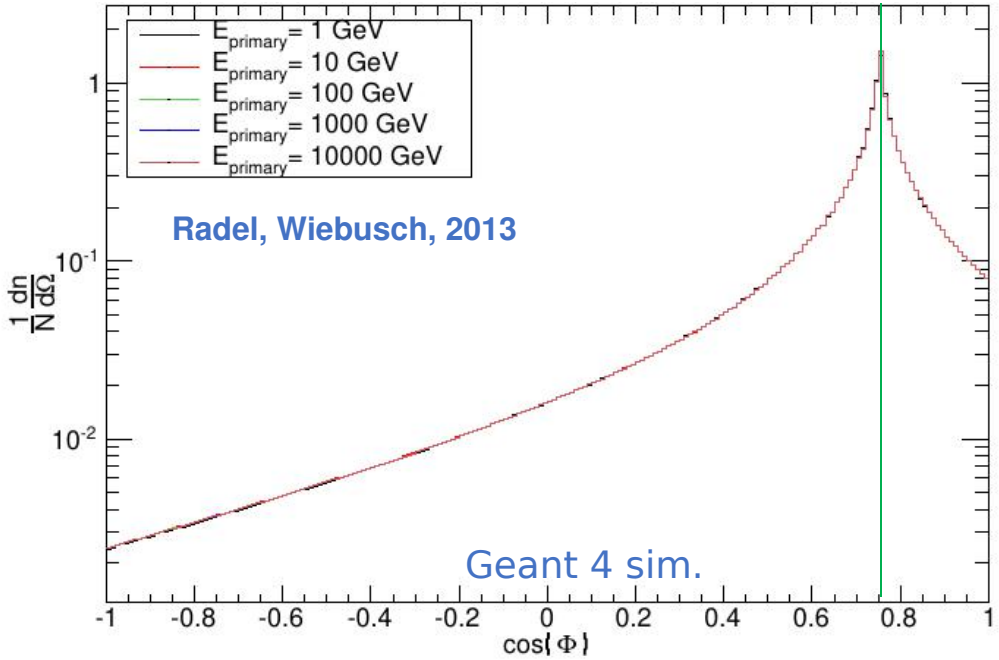
Light yield due to EM energy losses

Charged particles in accompanying EM cascades emit Cherenkov light



Such cascades effectively increase Cherenkov-emitting tracks length due to multiple charged particles

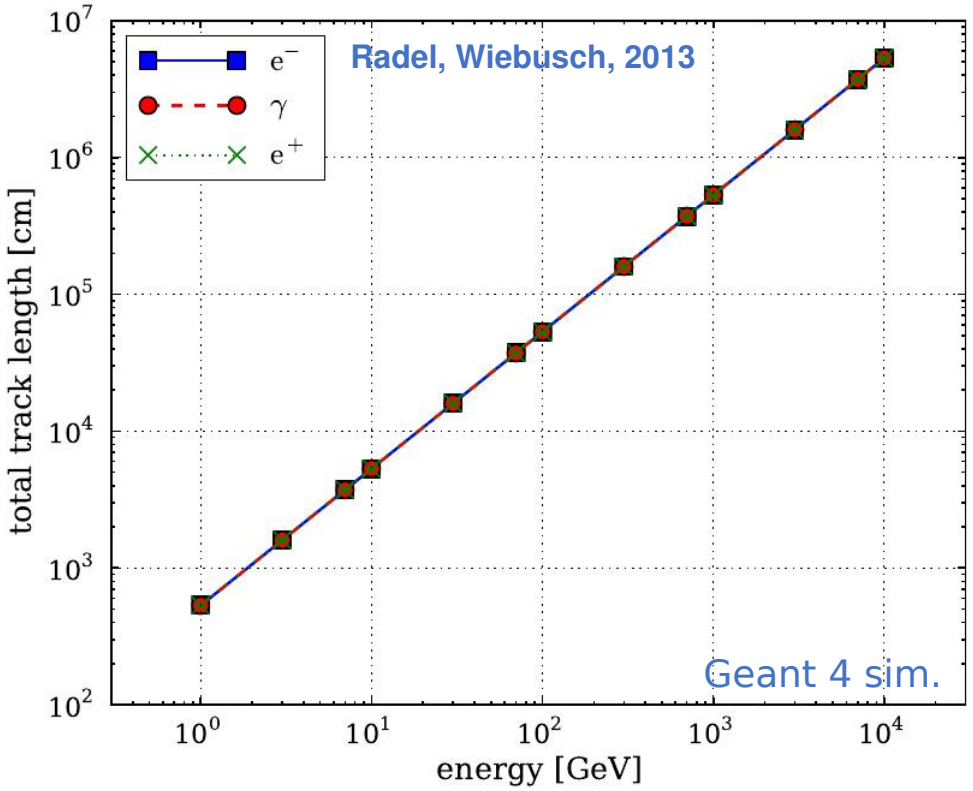
Light emission angle via cascade deviates from Cherenkov angle but peaks at it



Cerenkov angle wrt. muon

Light yield due to EM energy losses

Total Cerenkov-radiating
track length vs cascade energy



Light yield due to EM energy losses

Total Cerenkov-radiating
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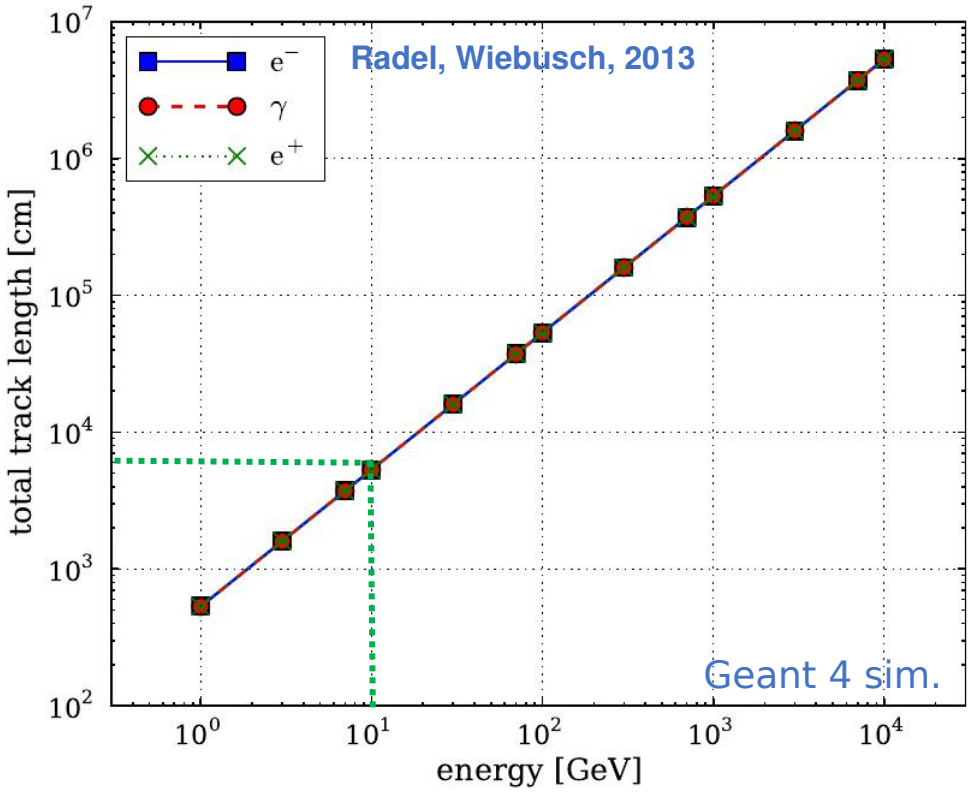
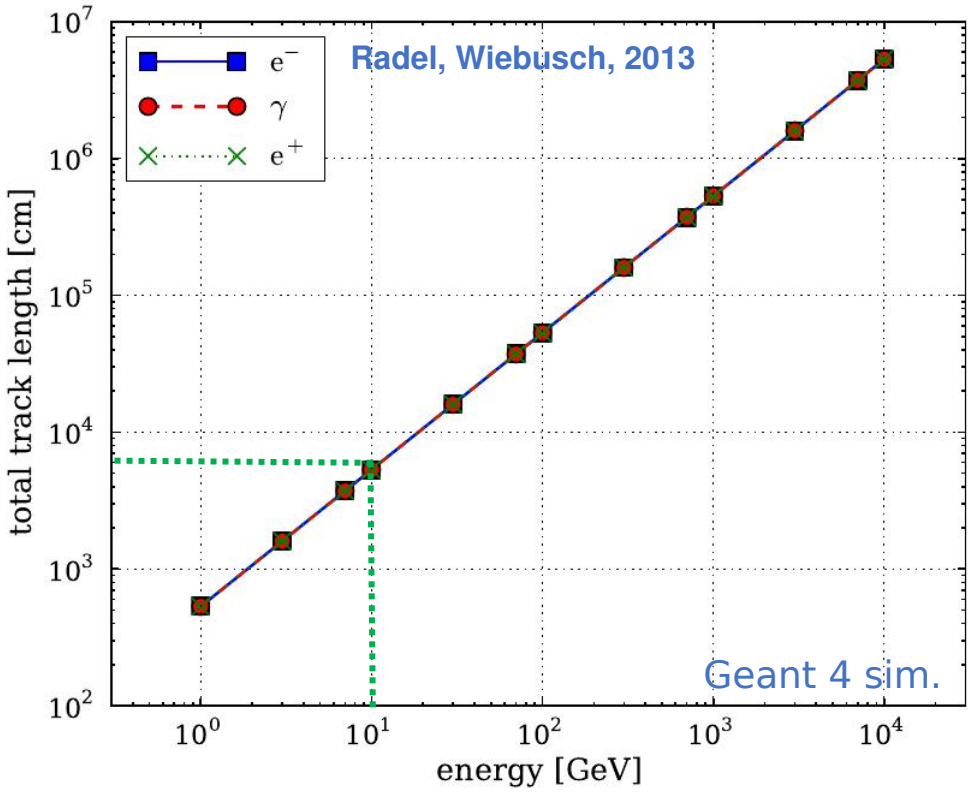


Assume our 10 TeV muon loose energy in one 5 GeV EM shower
It adds ~30 m of Cerenkov-emitting track length!

~7×10⁵ photons per m in total

Light yield due to EM energy losses

Total Cerenkov-radiating
track length vs cascade energy



Assume our 10 TeV muon loose energy in one 5 GeV EM shower
It adds ~30 m of Cerenkov-emitting track length!

~7×10⁵ photons per m in total

Let's propagate these photons to the photodetector

Light absorption

Light absorption is the main factor affecting amount of light seen by photodetectors along the track

Light intensity as a function of distance, *x*

$$I(x,\lambda) = I_0(\lambda)e^{-x/L(\lambda)}$$

L(λ) - absorption length

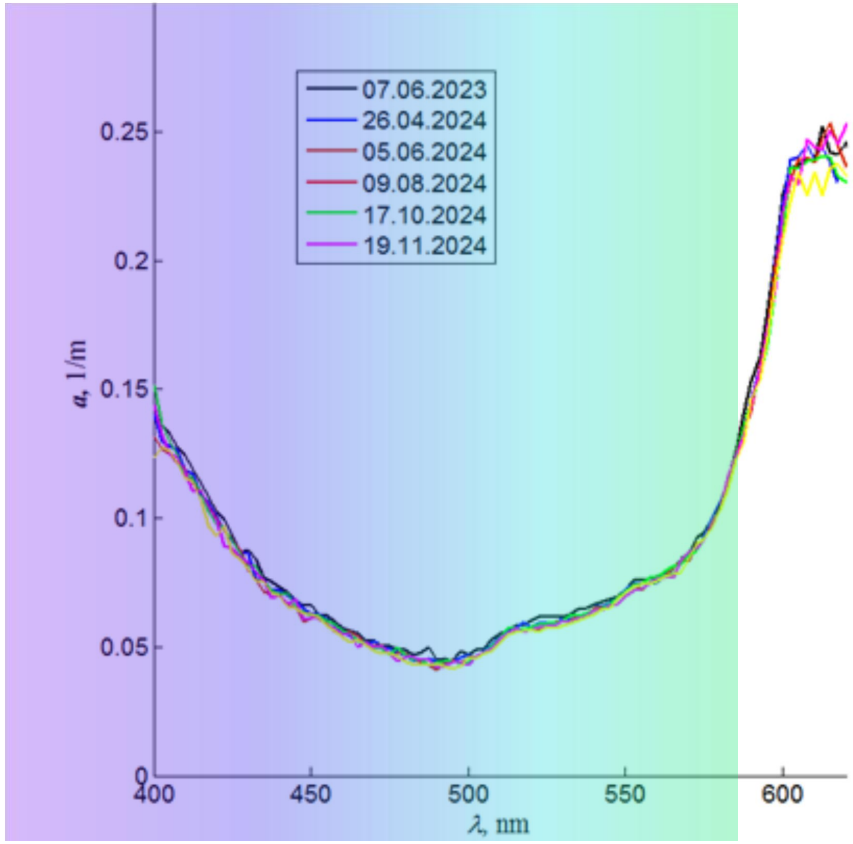
Estimate the light field for 10 TeV muon at few radii

$$\frac{dN}{dS} \sim \frac{1}{2\pi R}\frac{dN}{dx}\exp(-\frac{R}{L\sin(\theta_c)})$$

Assume 13m average absorption length

10 m : ~0. 35 γ/cm²
22 m : ~0.019 γ/cm²
30 m : ~0.012 γ/cm²

1/*L*(λ) for Baikal-GVD site



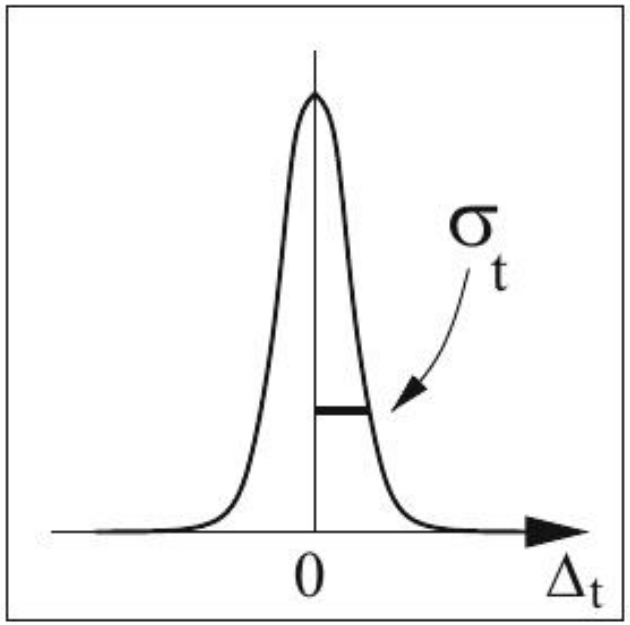
Light scattering

Light scattering causes delay of photon arrival wrt. track or cascade model

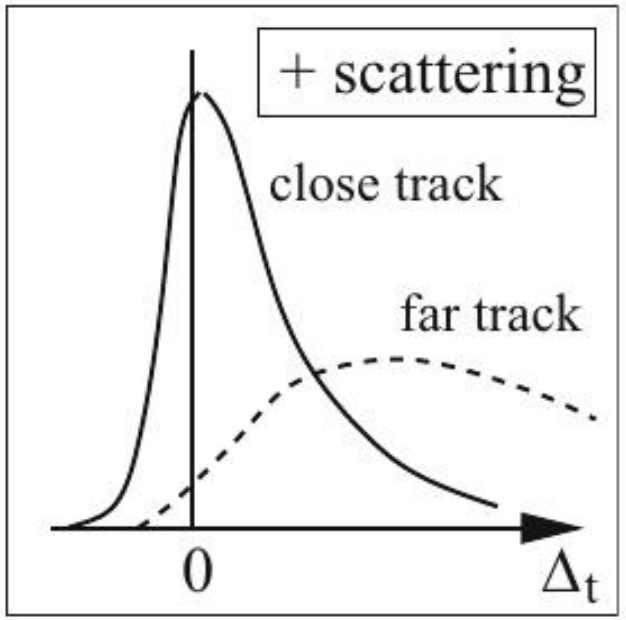
Short scattering length wrt. the absorption length causes lots of difficulties in reconstruction and analysis

Leads to usage of complex likelihood functions in reconstruction

Deviation of time of arrival at PMT wrt. hypothesis of direct Cerenkov light from the MIP muon



Distortion introduced by light scattering



Detection medium at different telescope sites

location	peak abs. length (m)	eff. scat. length (m)
Baikal	22	few 100s
Mediterannean	60	few 100s
South Pole	> 100	avg. 20 - 40
Pacific, Vancouver	28	few 100s
South China Sea	27	few 100s

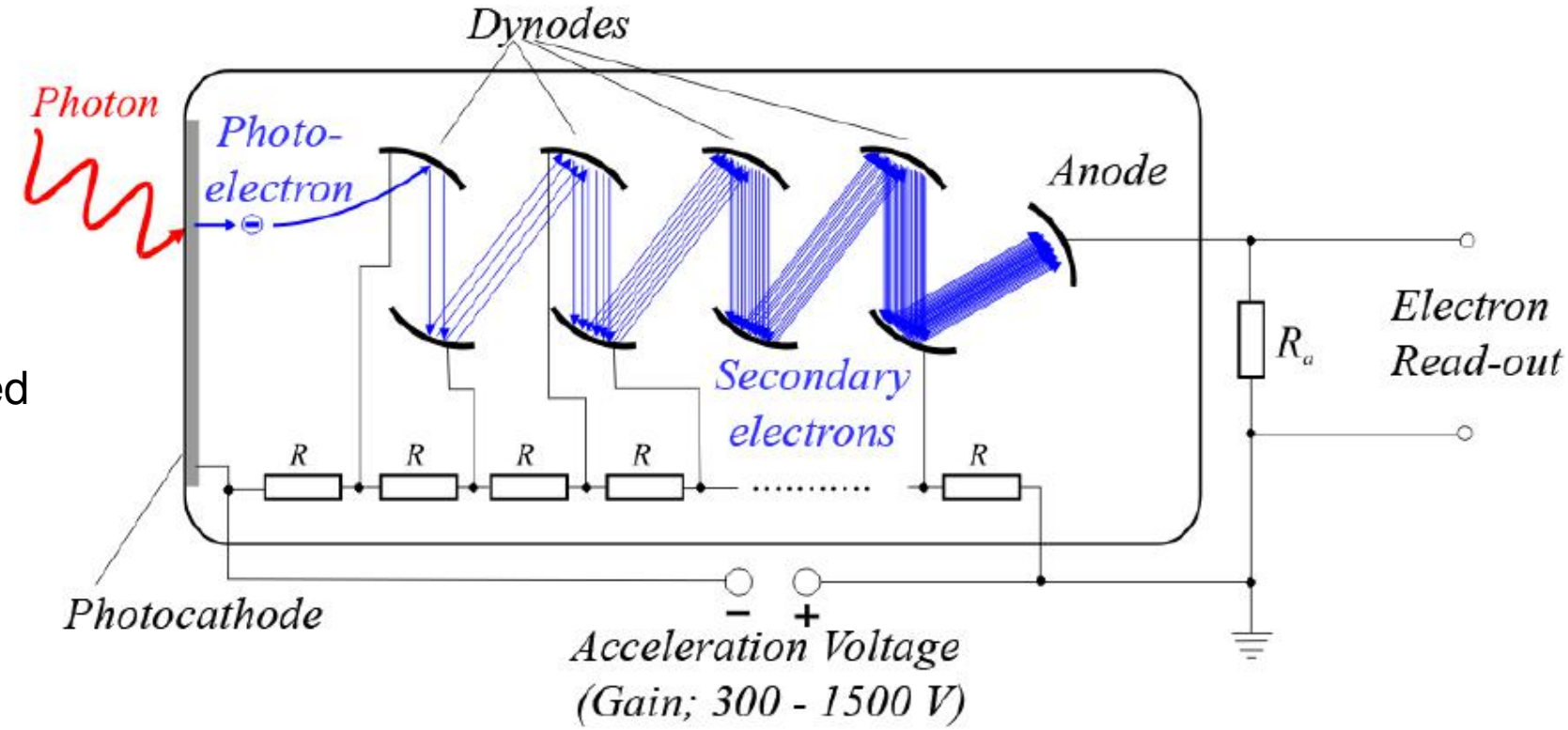
Light propagation properties in water-based telescopes
are very different from ice

Photodetection: photomultiplier tubes

PMT properties crucial for LVNT

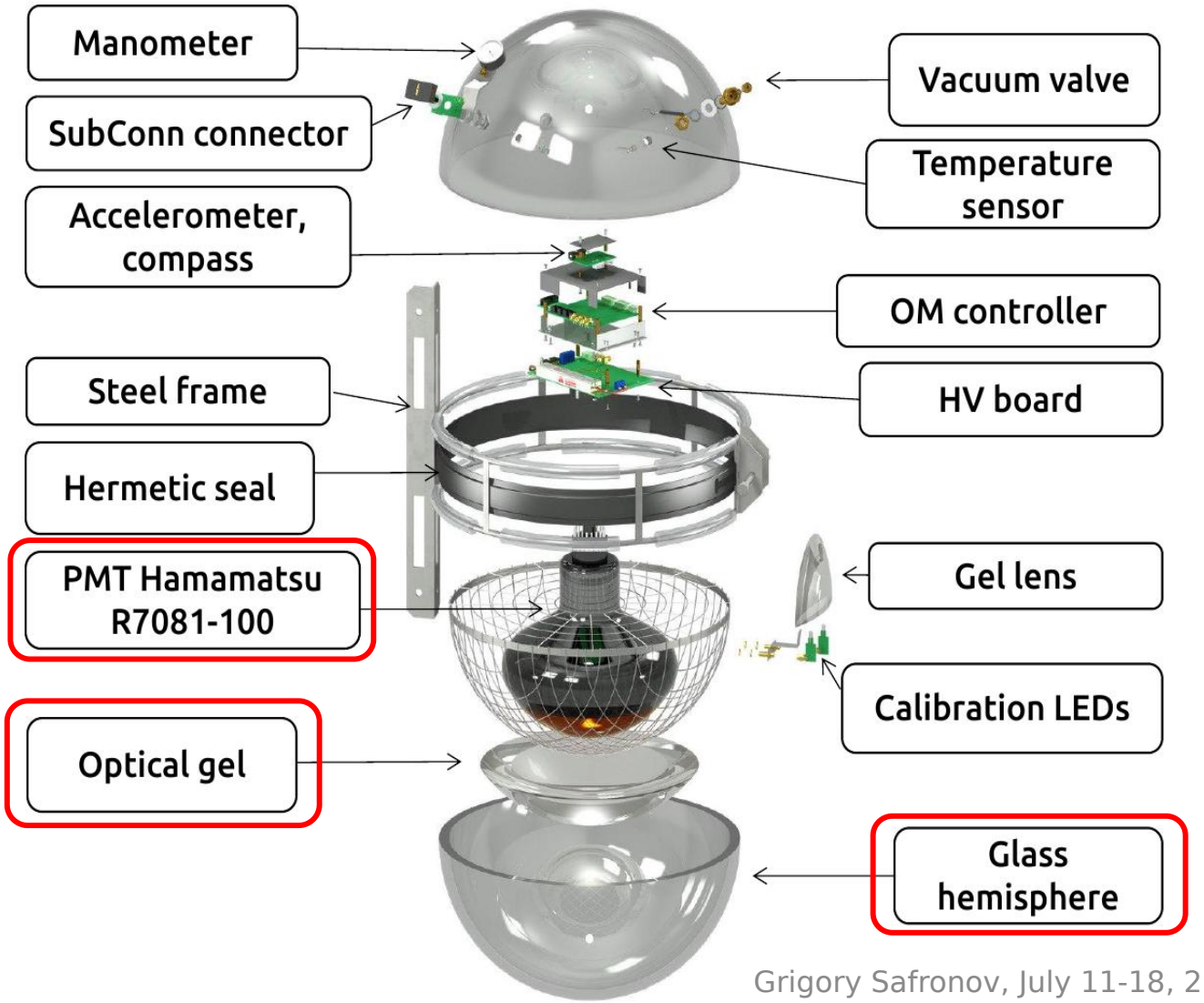
- Photocathode area
- Photocathode quantum efficiency (probability for photon to be coverted to the electron)
- Time measurement precision

Basic PMT structure



Photodetection: optical module

Baikal-GVD optical module



Hamamatsu R7081-100 PMT

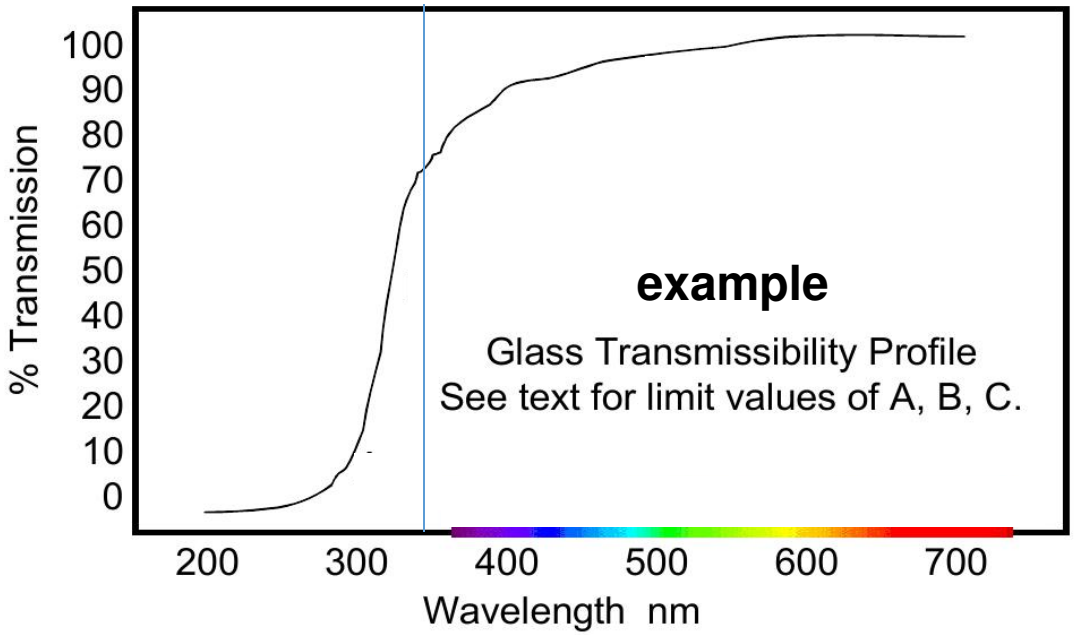
high-quantum-efficiency
10-inch photocathode



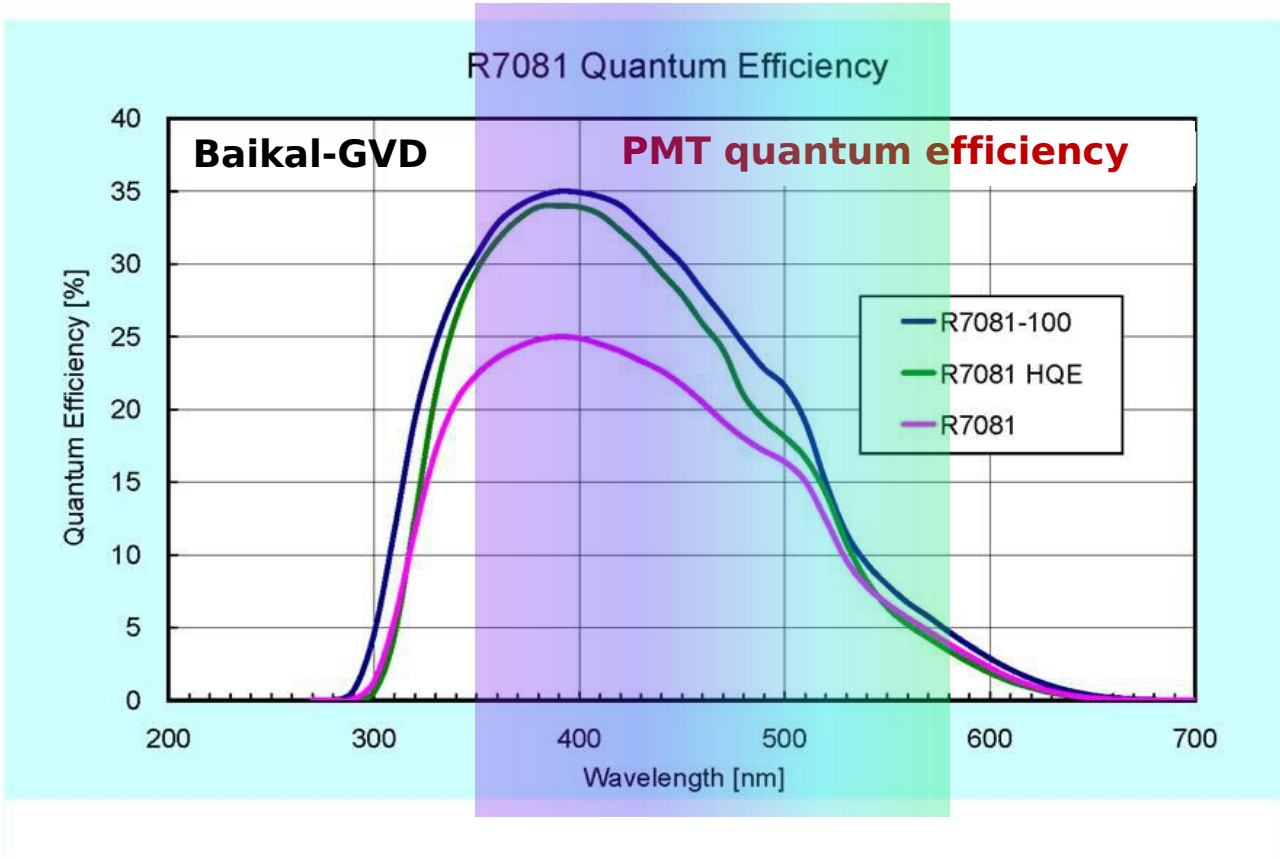
Optical contact of PMT to glass sphere is provided by optical gel lens

Photodetection efficiency

Important elements for sensitivity to incoming photons:
Glass sphere and optical gel transparency



Consider glass + gel
transparent starting ~350 nm



Quantum efficiency - probability for the photon to be converted into photoelectron

We defined optimal detection band as 350 - 580 nm

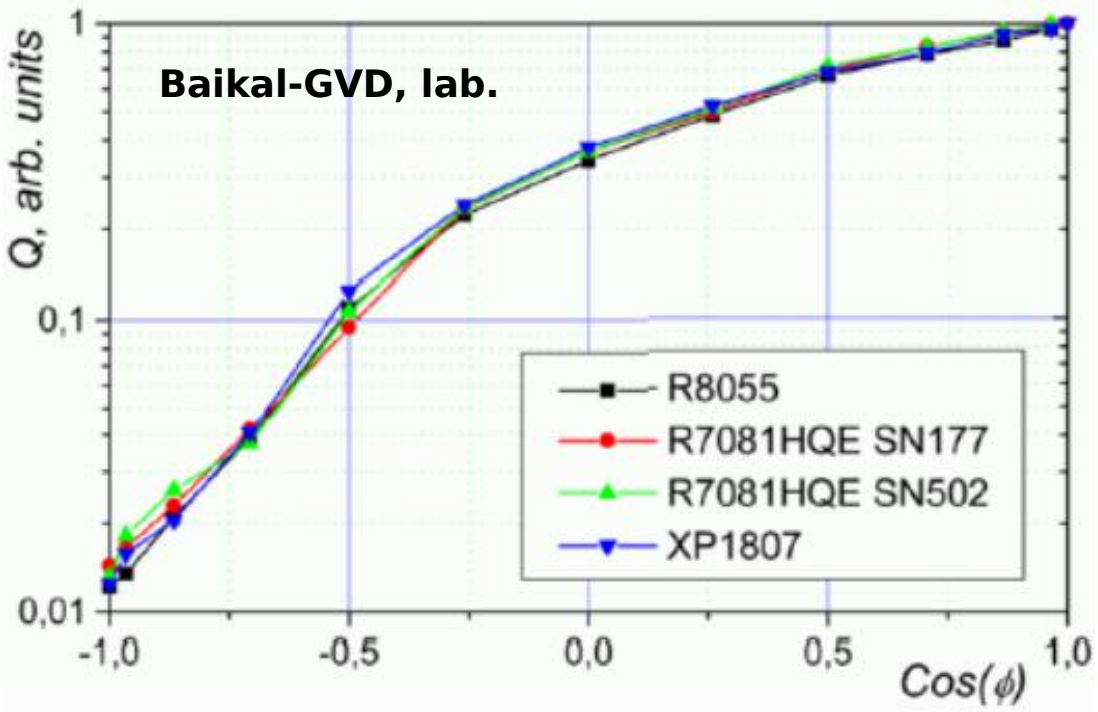
Photodetection angular sensitivity

Optical module assembly have non-uniform sensitivity depending on angle and point of entry

Usually characterized by total relative sensitivity and angular sensitivity, measured in-situ

PMTs are directed towards the lake bottom maximizing sensitivity to upgoing events

rear **head-on**



Photoelectron yield

Calculate number of photoelectrons produced at photocathode by 10 TeV muon

Consider

- Photocathode area: $\pi R^2 \sim 506.7$
- Average quantum efficiency as 0.2
- Angular sensitivity correction as 0.8

distance (m)	light field (γ/cm²)	photoelectron yield	non-zero p.e. prob. (%)
10	0.35	28.3	~100
22	0.019	1.54	78.5
30	0.012	0.97	62.1

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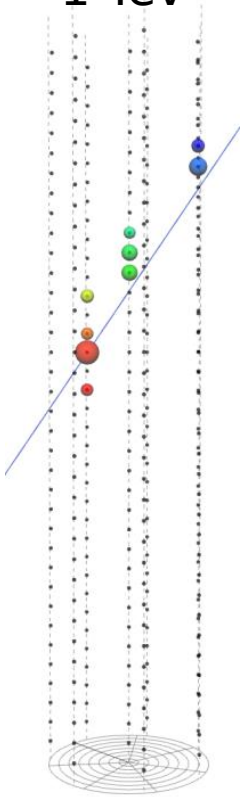
For the reliable direction reconstruction we need at least 7 - 8 hits at 3 strings

The lower the energy the smaller the probability to obtain needed number of hits

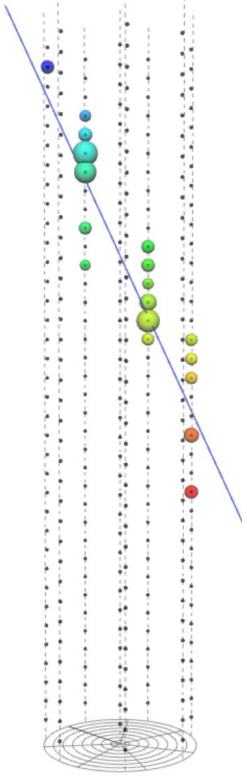
Photoelectron yield

Baikal-GVD response to different energies

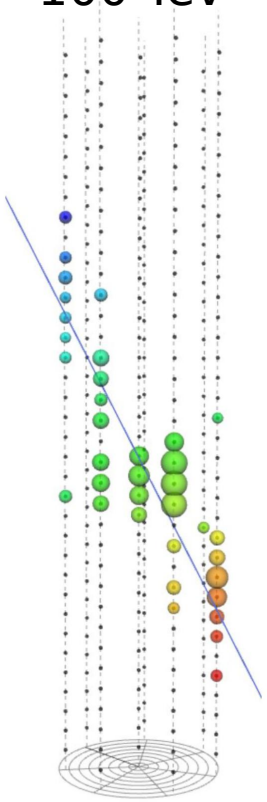
1 Tev



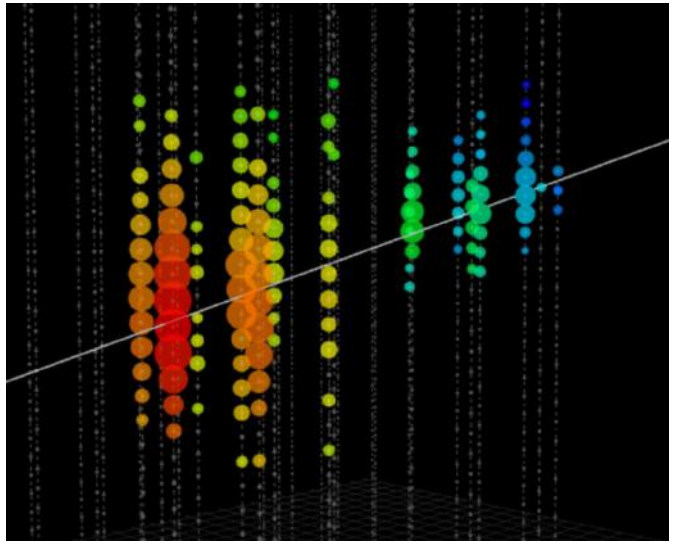
10 Tev



100 Tev



1 PeV

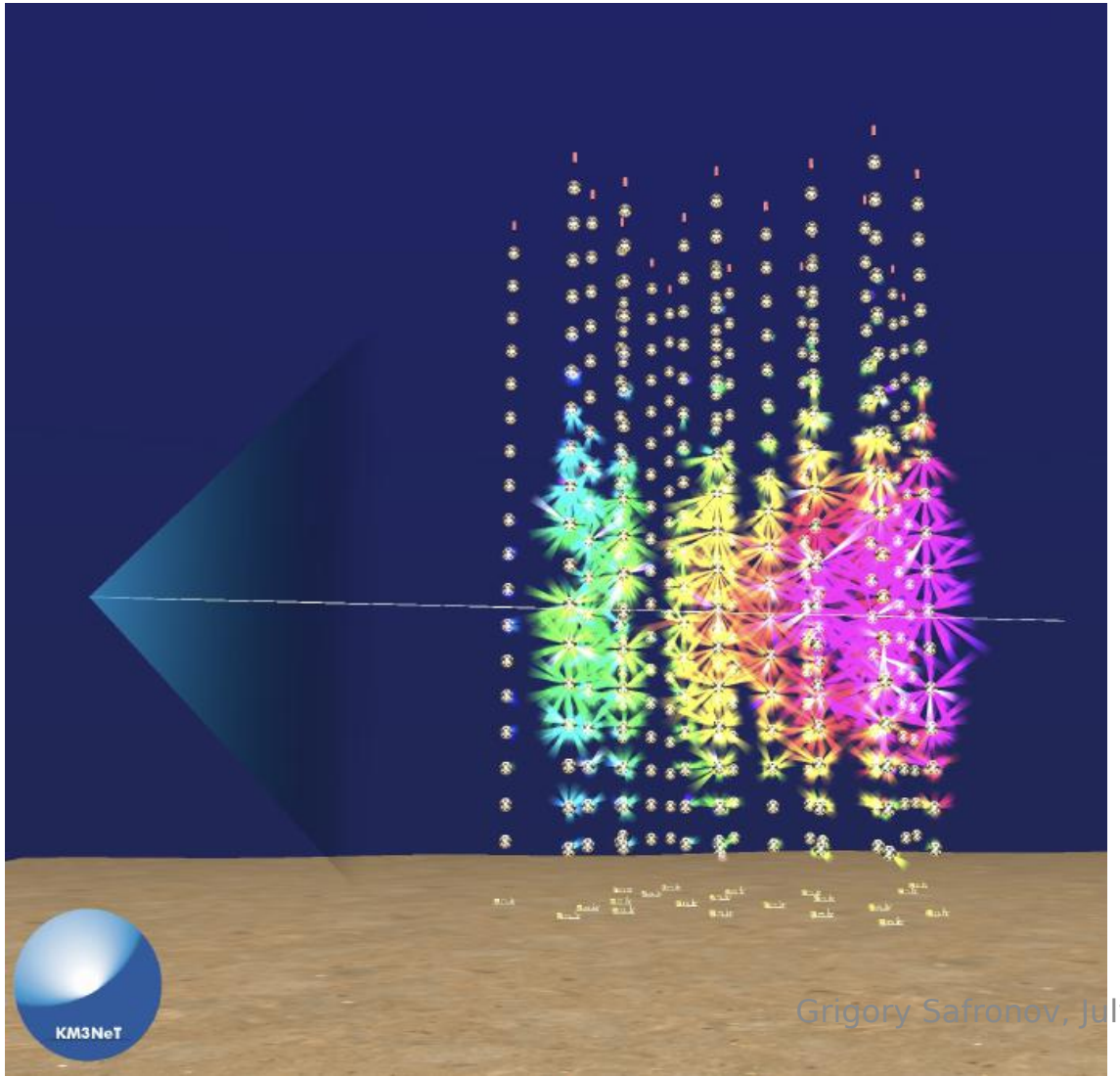


Response at lower energies is sparse, low-charge and fluctuating: hard to reconstruct
High energies: easier to reconstruct

Photoelectron yield: 120 PeV KM3NeT muon event

Enormous KM3NeT event detected in Feb. 23

Nature volume 638, pages 376–382 (2025)

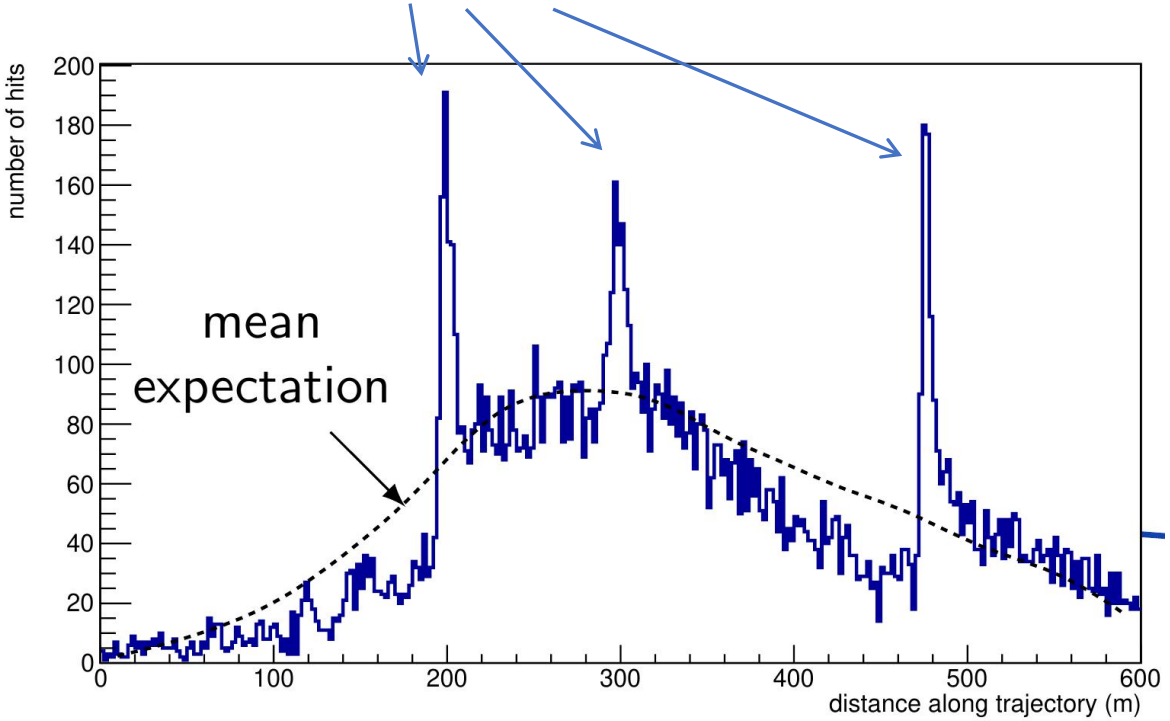


KM3NeT OM: 31 PMTs

3672 fired PMTs



Large showers along the muon trajectory



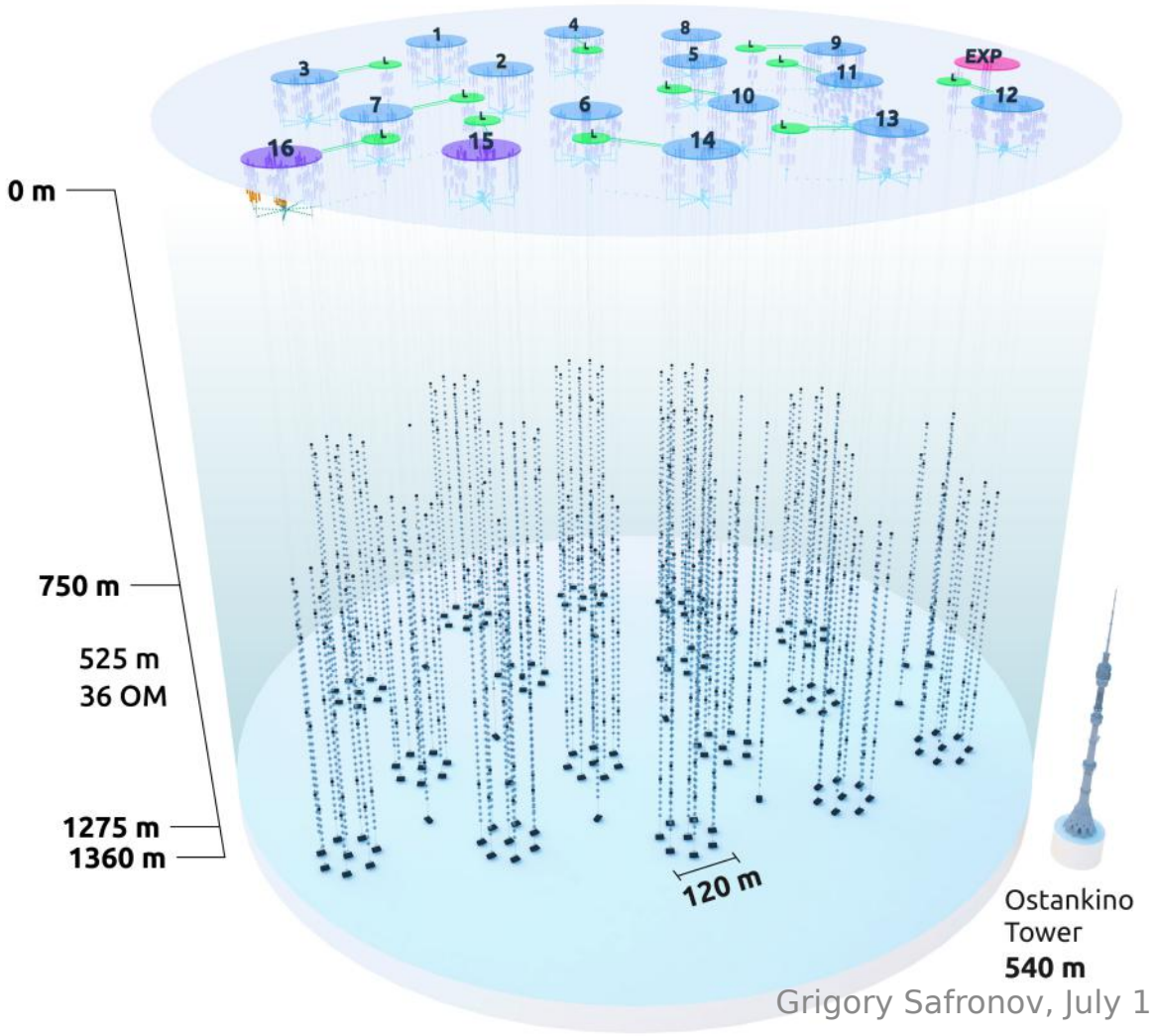
Summary

With Gigaton -scale detectors we can study the astrophysical neutrino flux

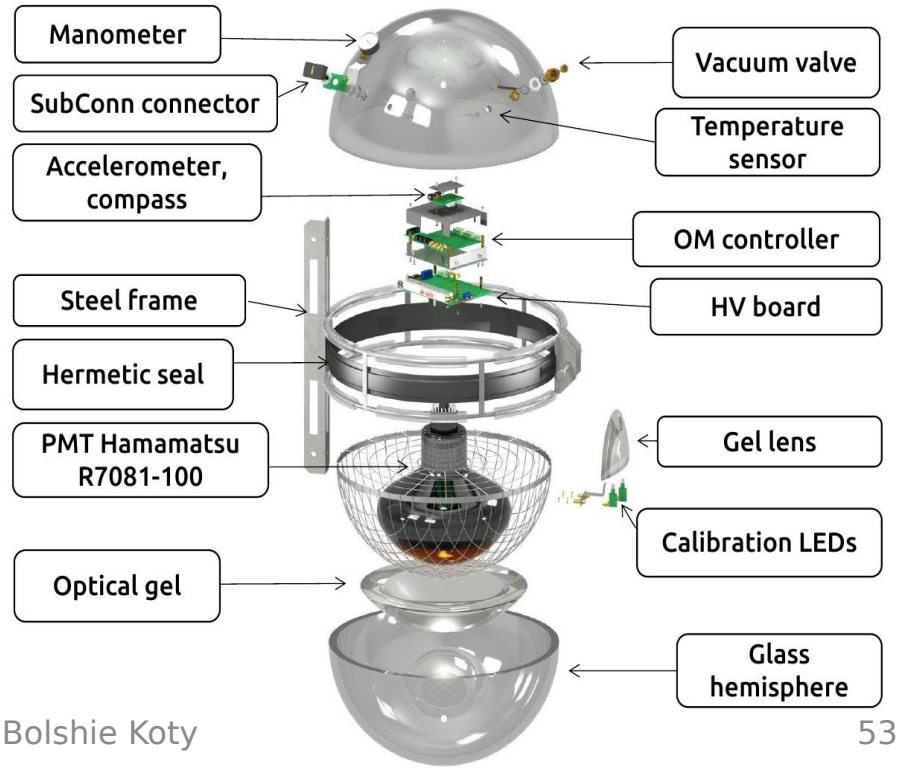
Detector response is defined by
- Particle energy
- Detection medium transparency
- PMT characteristics

BACKUP

Baikal-GVD detector







Light scattering

Photons propagating in media experience scattering such that a photon on average scatters at angle $\langle \cos(\theta) \rangle$ at a distance $L_s(\lambda)$

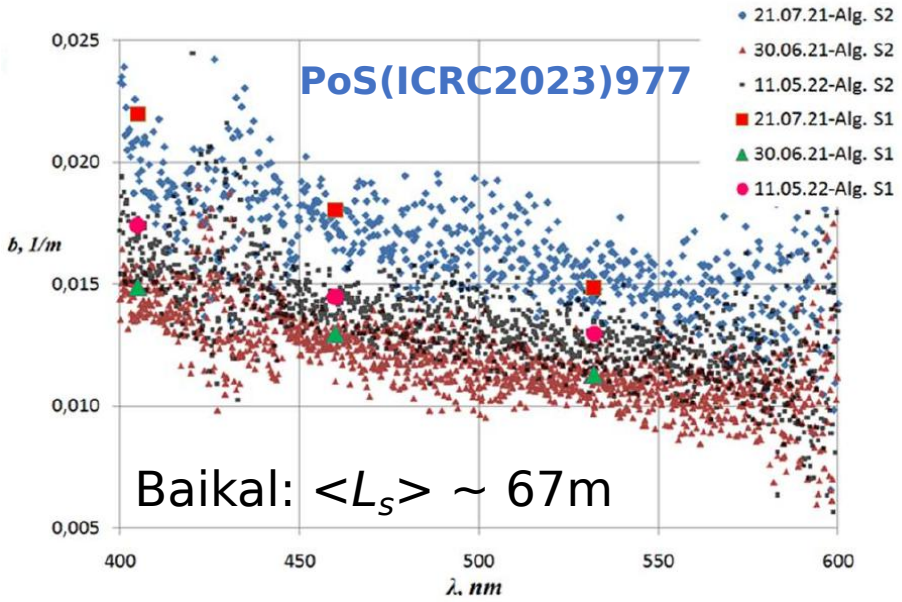
Effective scattering length takes into account scattering angle:

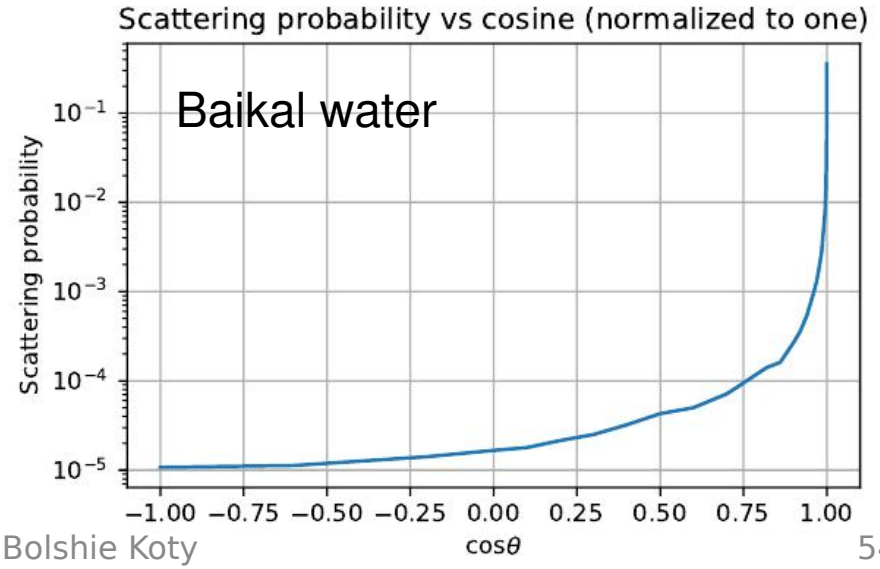
$$L_s^{\text{eff}}(\lambda) \simeq \frac{L_s(\lambda)}{1 - \langle \cos\theta \rangle}$$

For Baikal or Mediterranean water average scattering angle is close to 0°

Effective scattering length reaches hundreds of meters

добавить про длину ослабления





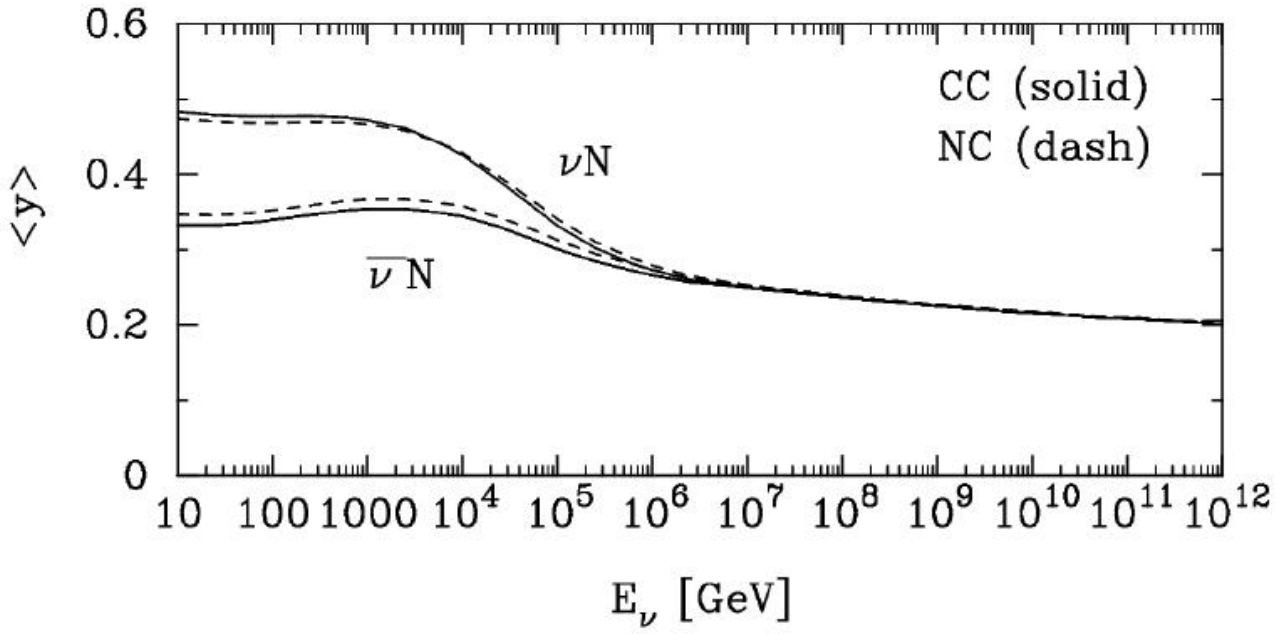
High-energy neutrino interaction with matter

An outging lepton or cascade carries information about neutrino

Angular deviation of lepton in CC interactions:

$$\sqrt{\langle\theta^2\rangle} \approx \frac{1.5^\circ}{\sqrt{E_\nu\,[\mathrm{TeV}]}}$$

Fraction of neutrino energy passed to proton remnants



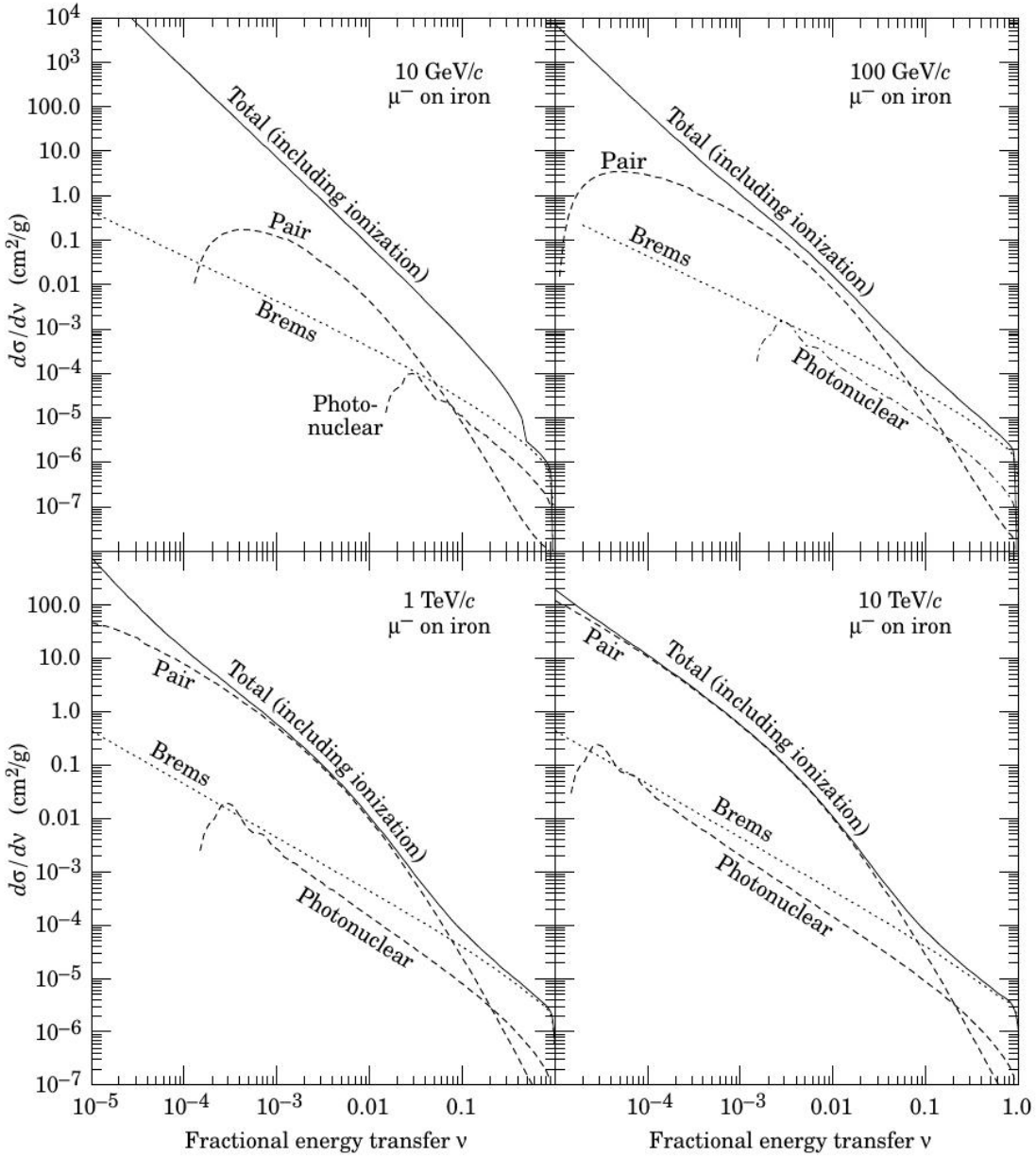
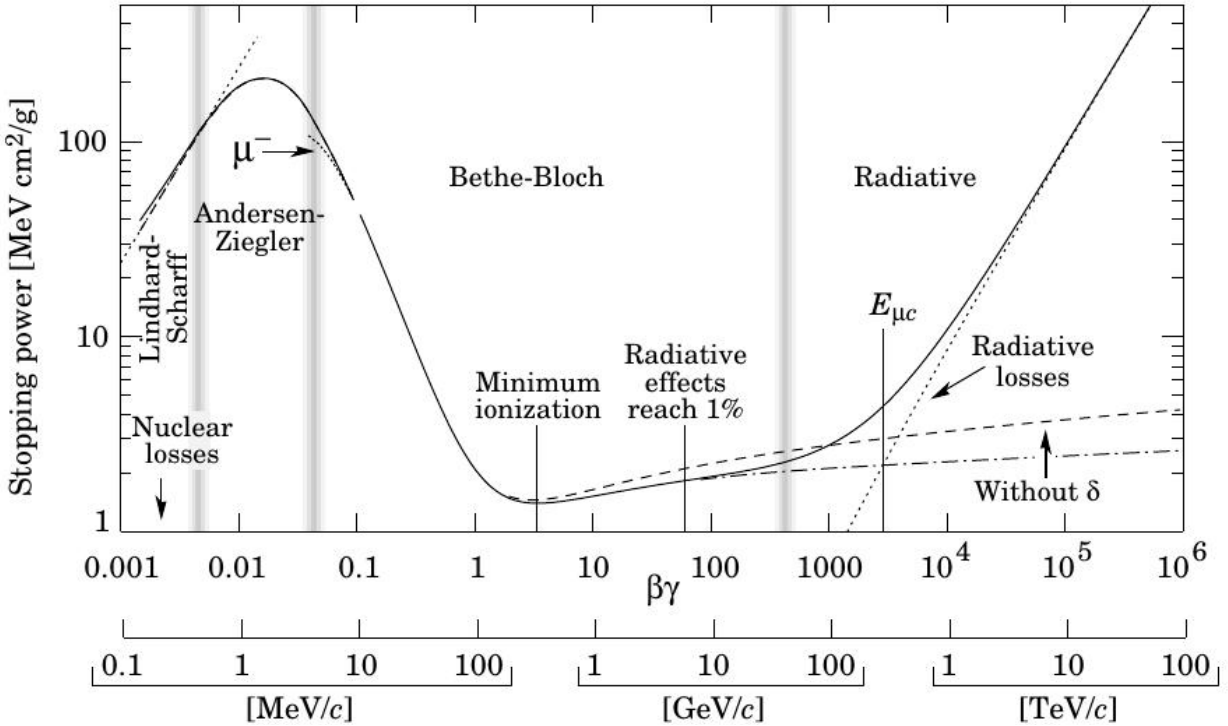
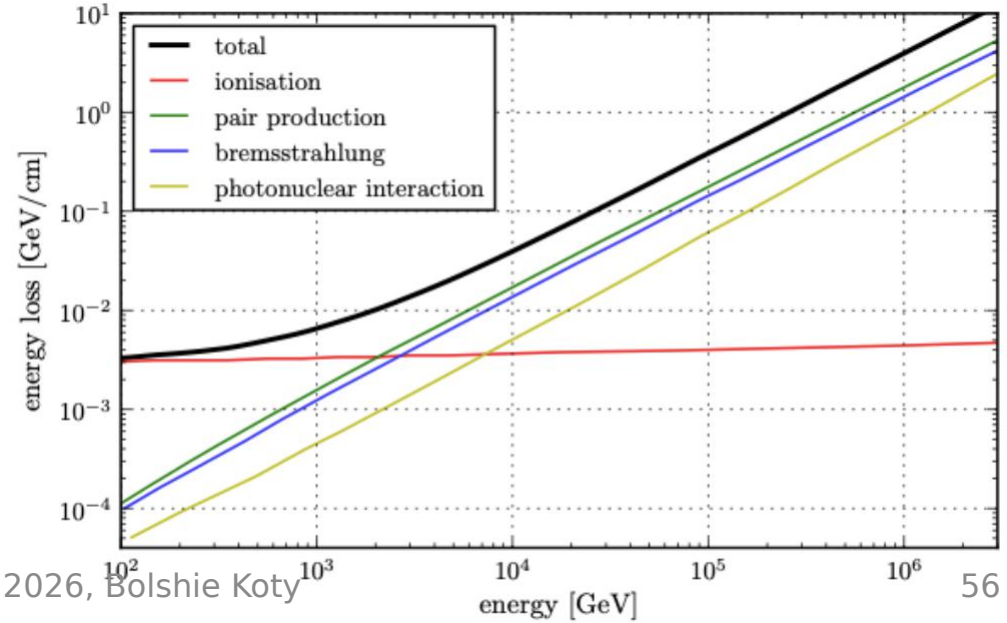
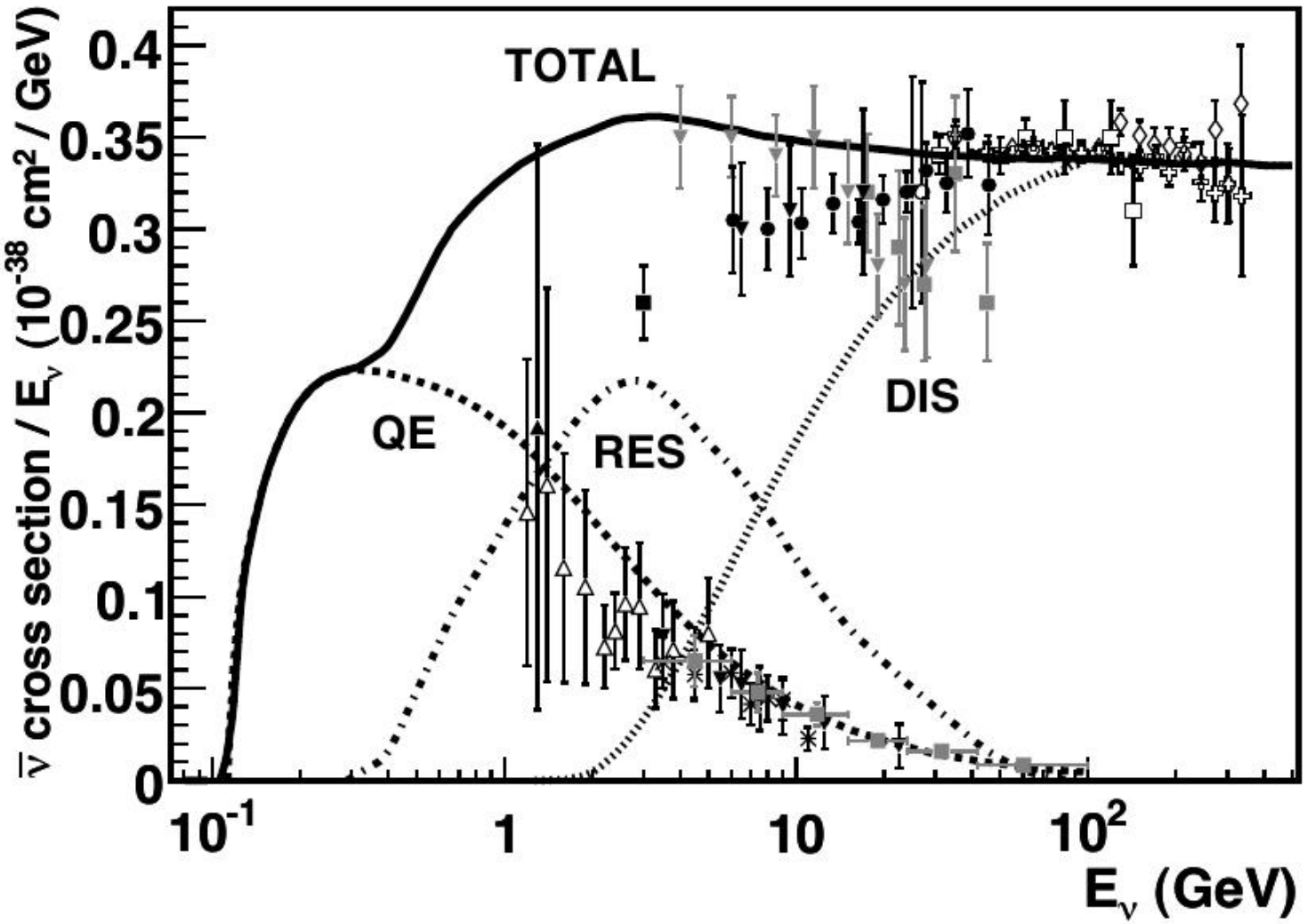


Figure 4: Differential cross section for total and radiative processes as a function of the fractional energy transfer for muons on iron.






TOTAL
QE
RES
DIS
$\bar{\nu}$ cross section / E_ν (10^{-38} cm^2 / GeV)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
10^{-1}
1
10
10^2
E_ν (GeV)