Anatomy of large-volume neutrino telescopes

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17th Baksan school on particle astrophysics
April 3-11 2025, Terskol

Scope of these lectures

How the neutrino telesope actually works: main principles of event detection, data processing, reconstruction and analysis

Focus on Baikal-GVD with some insight into IceCube and KM3NeT projects

NOT in these lectures:
Potential astrophysical neutrino sources and their physics
Interpretations of experimental results

Lecture 1: Introduction, general principles of detection and analysis

Lecture 2: Detector response, readout, calibrations

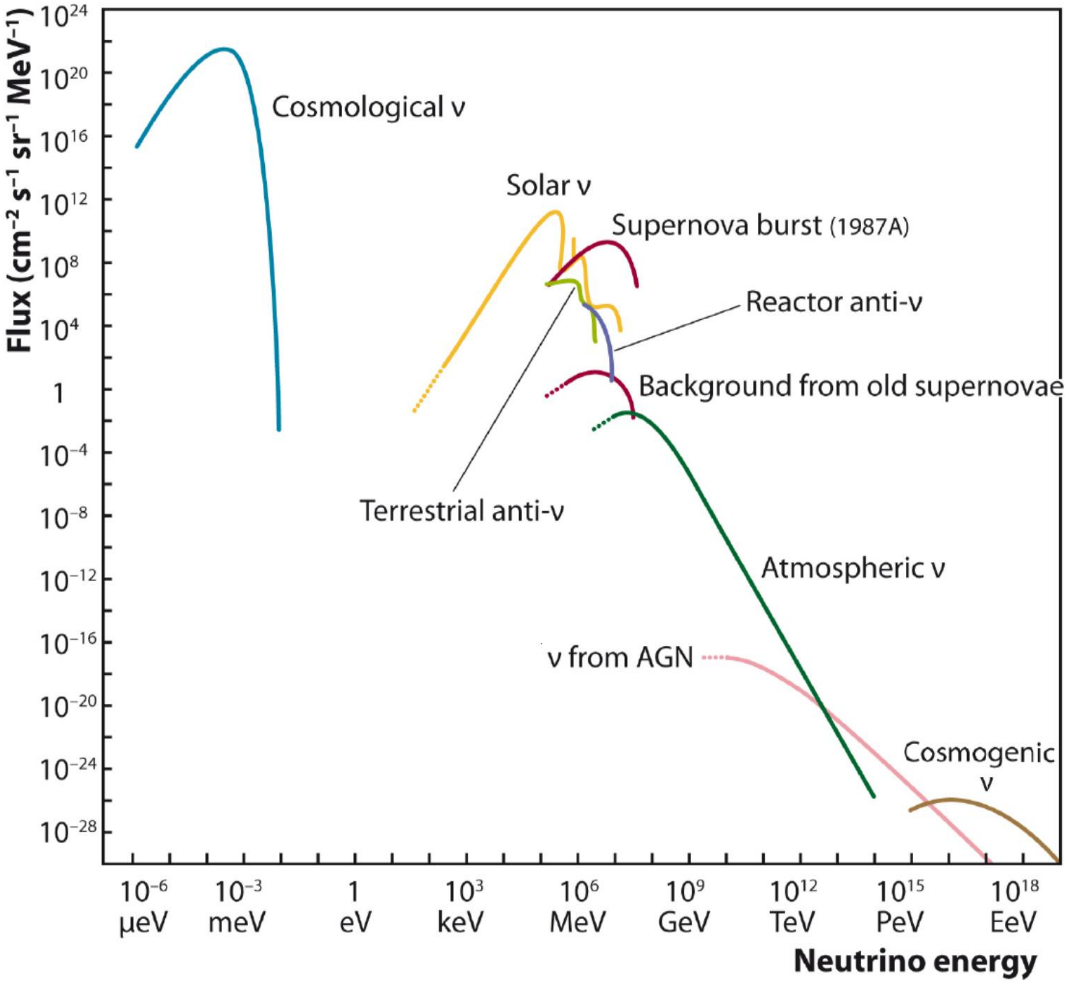
Lecture 3: Reconstruction, event selection, physics analysis

Lecture 4: Telescope development history, main experimental results to date, future projects

Lecture 1

- Motivation for large volume neutrino telescopes (LVNT)
- Neutrino detection principles
- LVNT projects taking physics data today
- Backgrounds to astrophysical neutrino
- Detector effective area
- Neutrino source search principles

Neutrino fluxes at the Earth



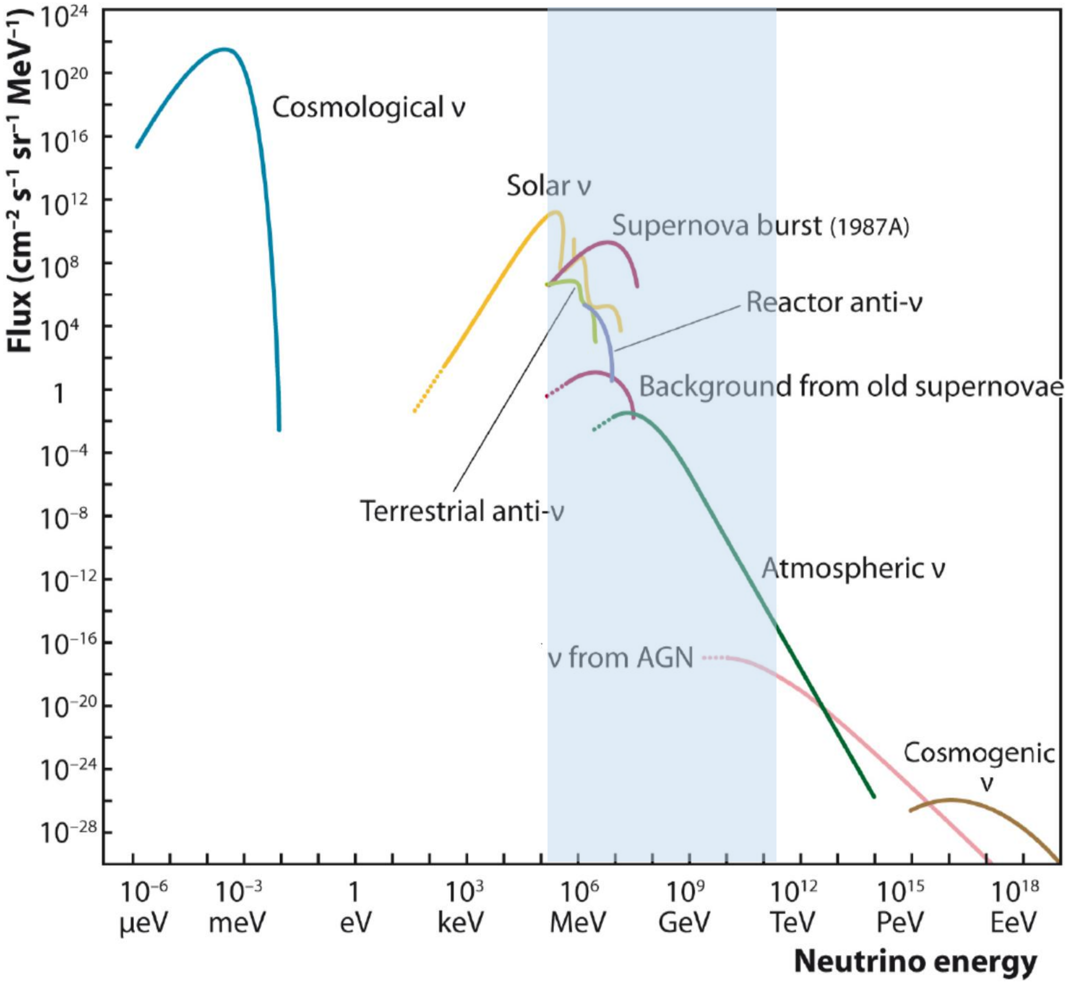
Extraterrestrial neutrino span the large energy range

Quickly falling flux with increasing energy

Variety of ingenious methods for neutrino detection across the spectrum

The smaller the target flux the larger the detector sensitive volume mass should be

Underground neutrino detectors



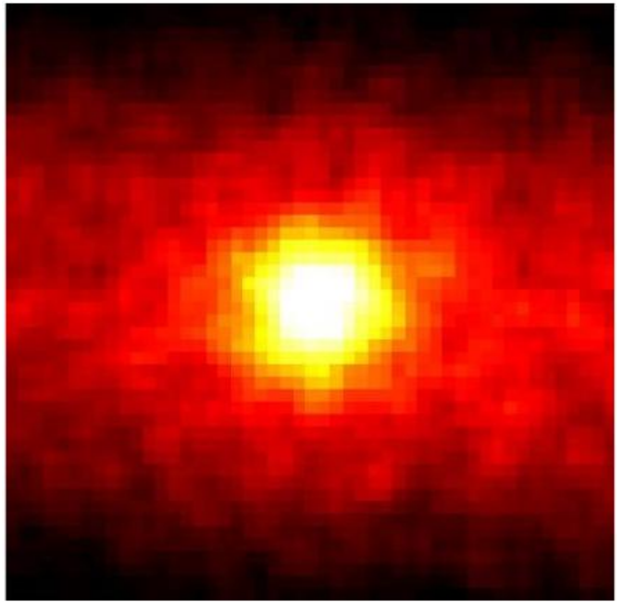
Energy range: sub-MeV - sub-TeV
Sensitive volume mass: 10’s tons -10’s kilotons

Great variety of exciting techniques and experiments

Here at Baksan valley: SaGe, BUST

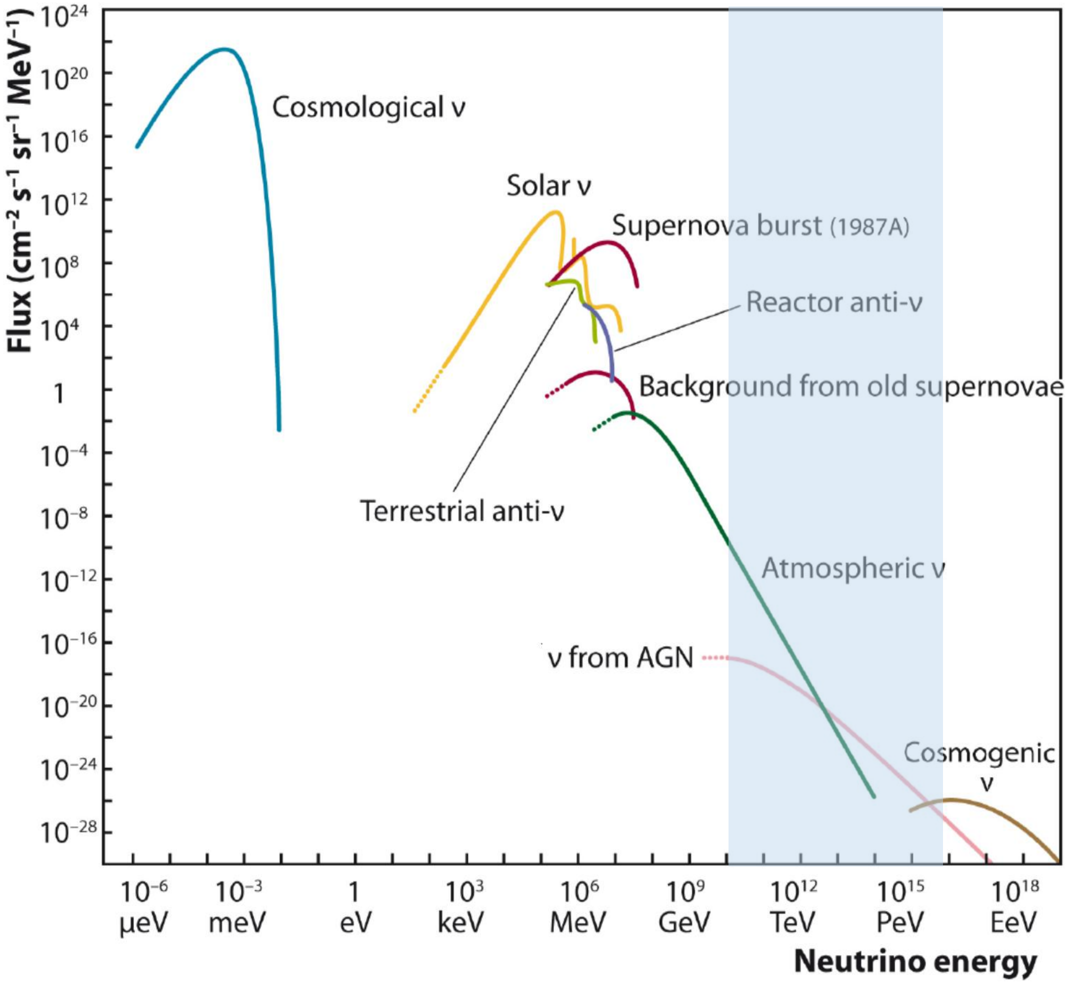
First steps of neutrino astrophysics
- Solar neutrios
- Supernova explosion SN 1987A

90°×90° in (RA, dec)



Unlocking neutrino astronomy: Super-Kamiokande, 1998
Sun in neutrinos

Large-volume neutrino telescopes



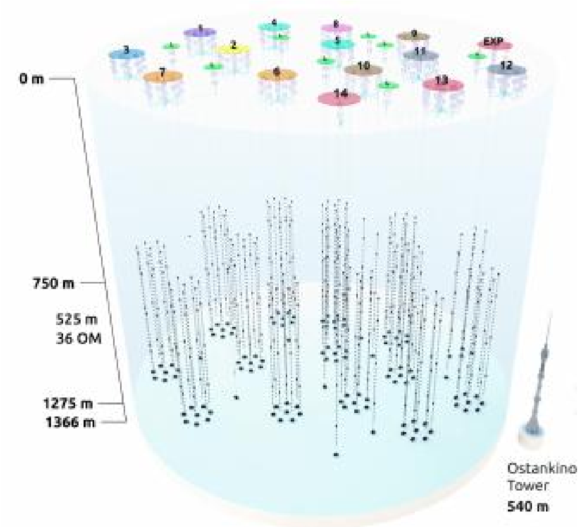
10's GeV - multi-PeV range

Large-volume neutrino telescopes (LVNT)

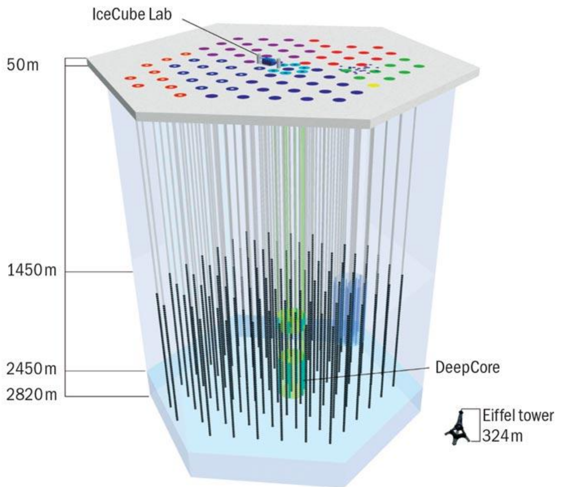
- Atmospheric neutrino
- Astrophysical neutrino (galactic, extragalactic)
- ~ cosmogenic neutrino

Present generation: Gigaton mass scale

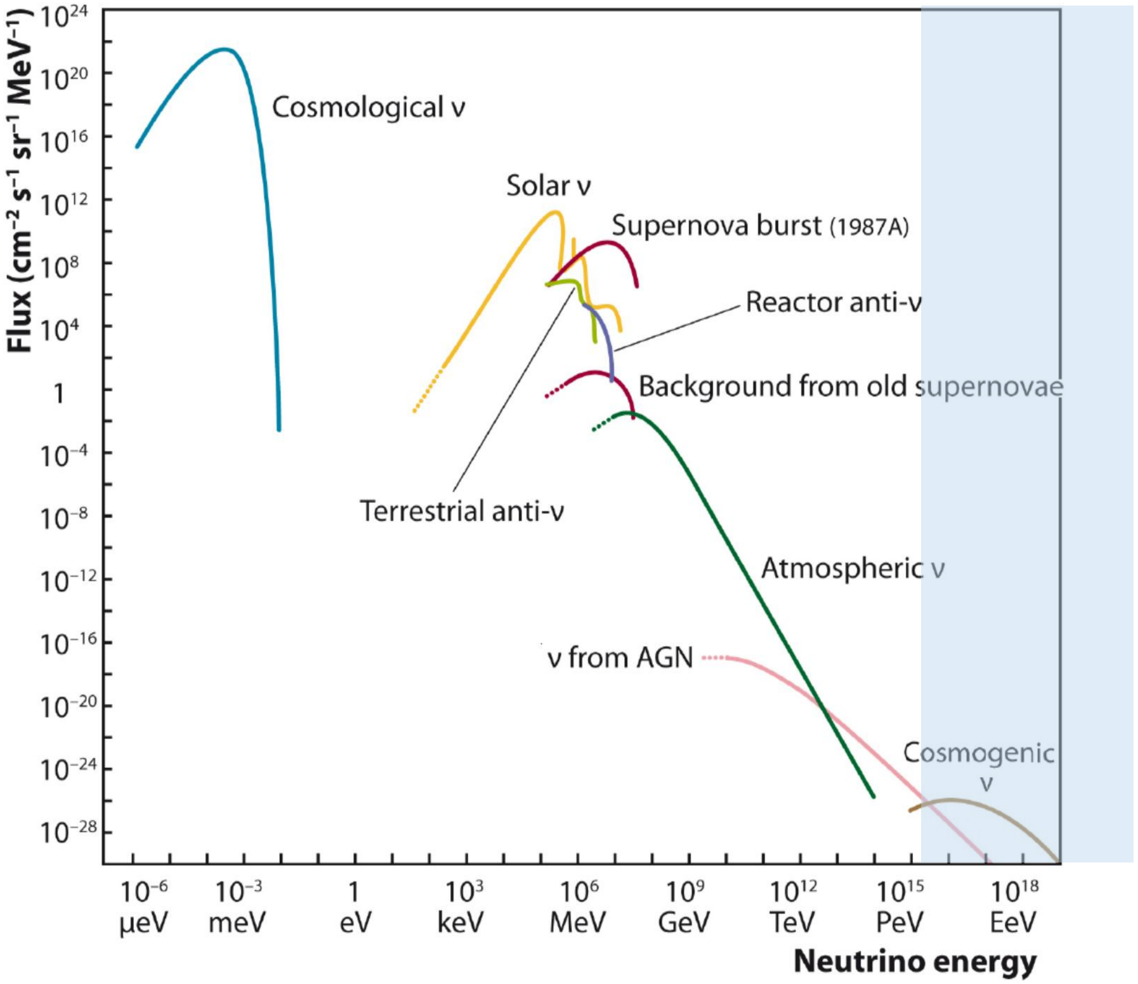
Baikal-GVD



IceCube



Ultra high-energy neutrino detectors



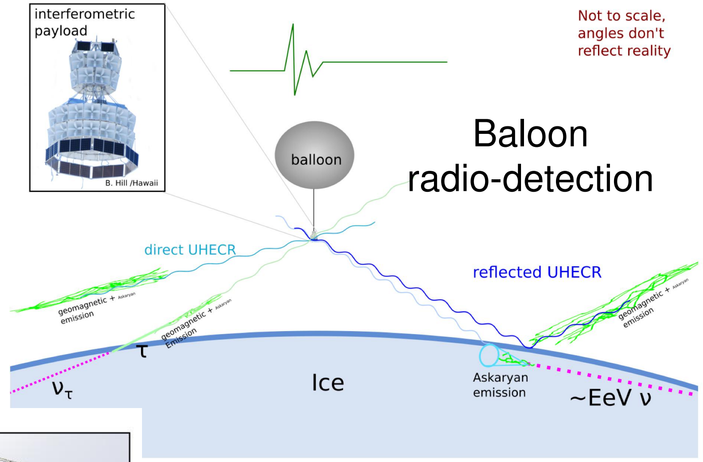
Multi-PeV and beyond

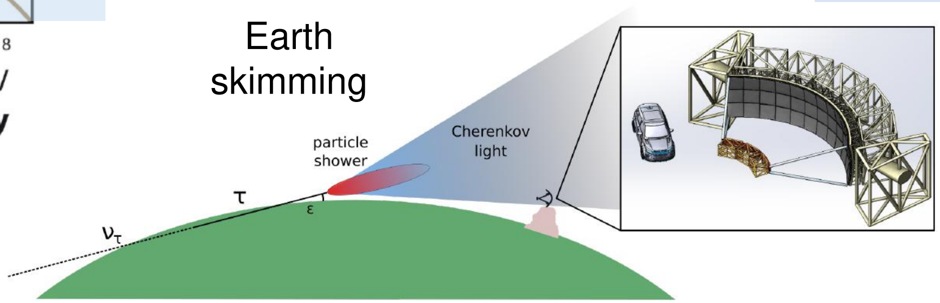
Cosmogenic (GZK) neutrino

Very sparse instrumentation, enormous sensitive volume mass

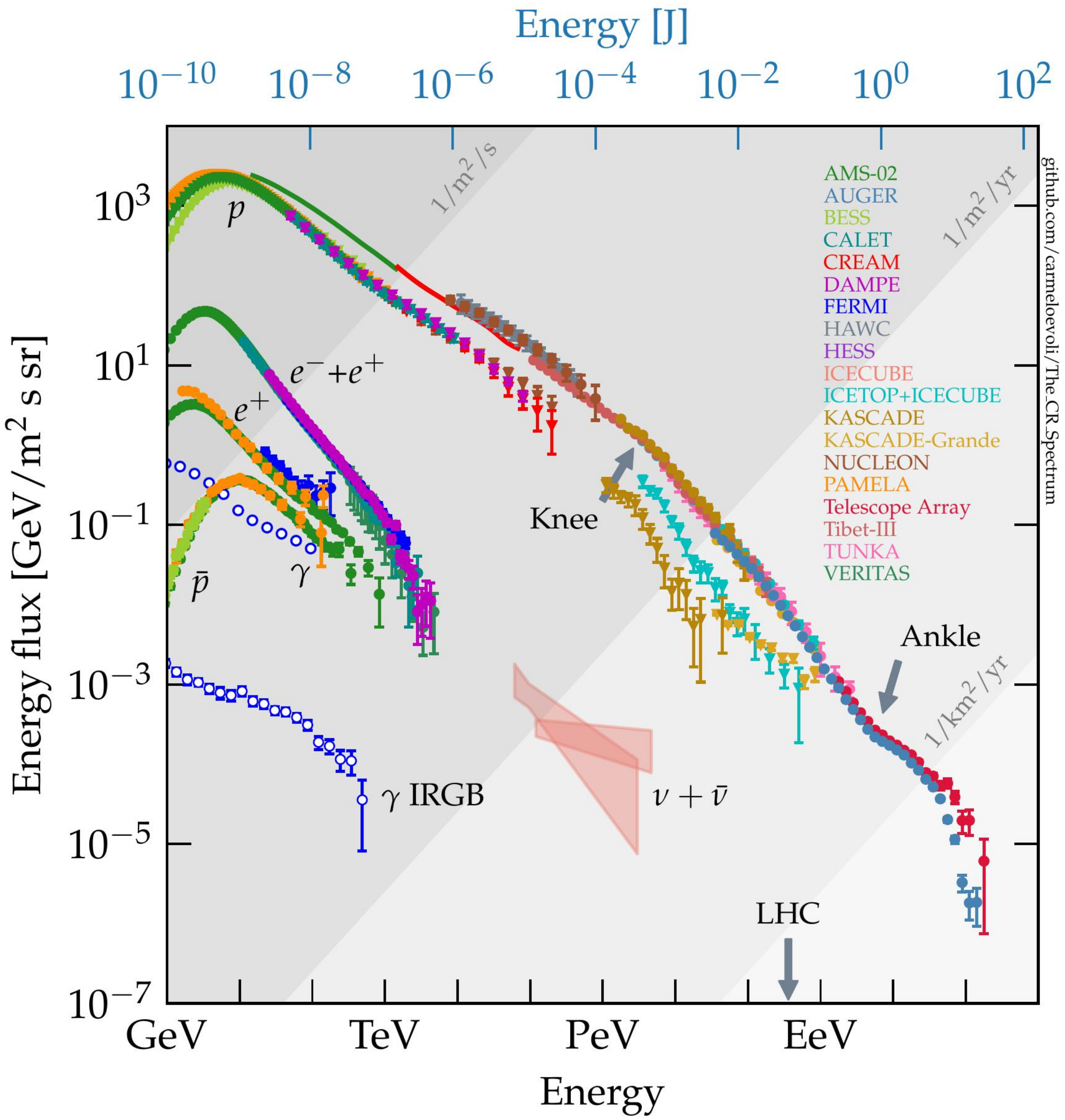
- Earth skimming
- Radio-detection
- Acoustic detection

Lots of impressive projects and concepts





Physics motivation for LVNT



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

That's an evidence for the existence of cosmic systems accelerating particles far beyond the LHC energy

Experimental evidence for origin of such particles remain vague

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

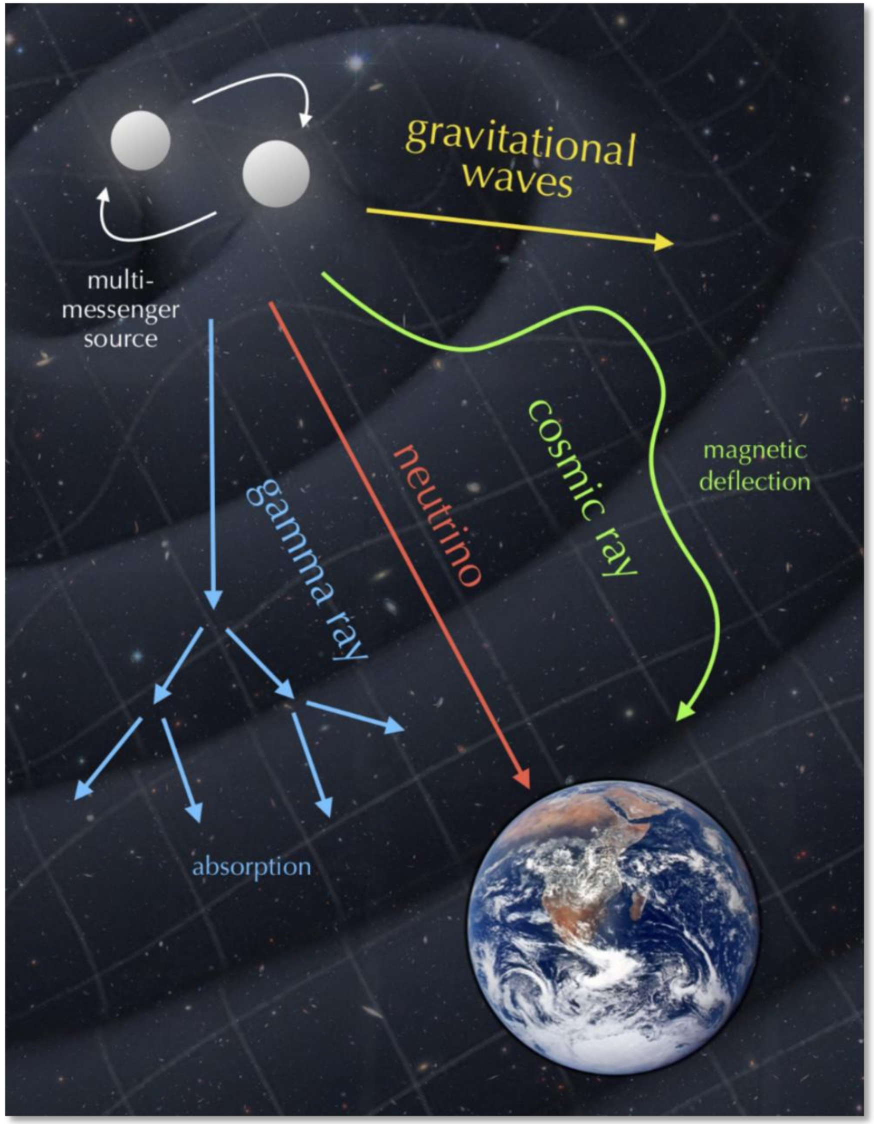
Physics motivation for LVNT

Neutrino interaction cross section is very low

- Can escape dense environments
- Penetrate dust and gas clouds
- Can propagate to cosmological distances with no absorption or scattering

Neutrino does not have electrical charge

- Is not deflected by cosmic magnetic fields → points directly at the source



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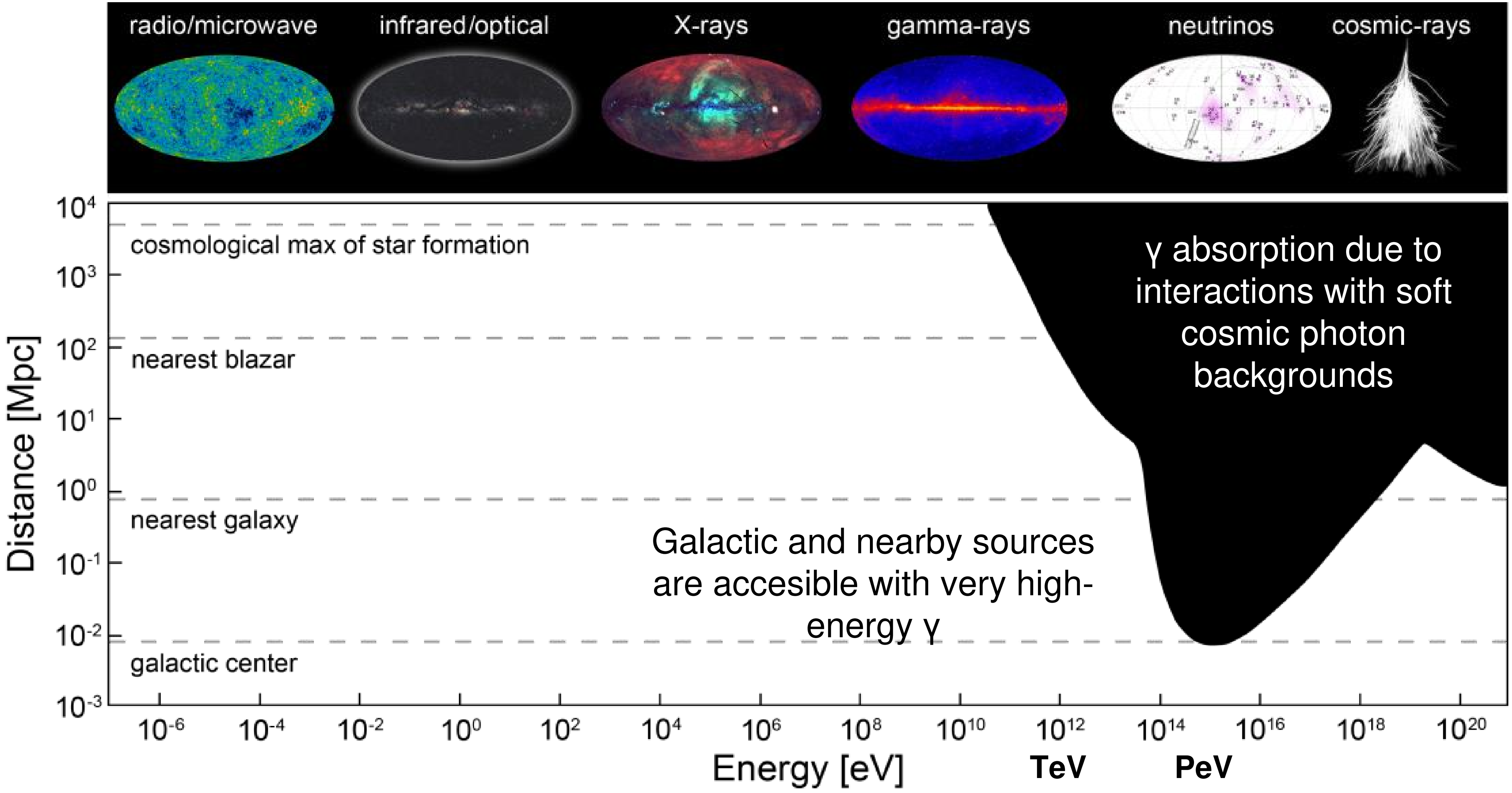


Neutrinos are the best messengers to probe sources at cosmological distances at TeV - PeV energies

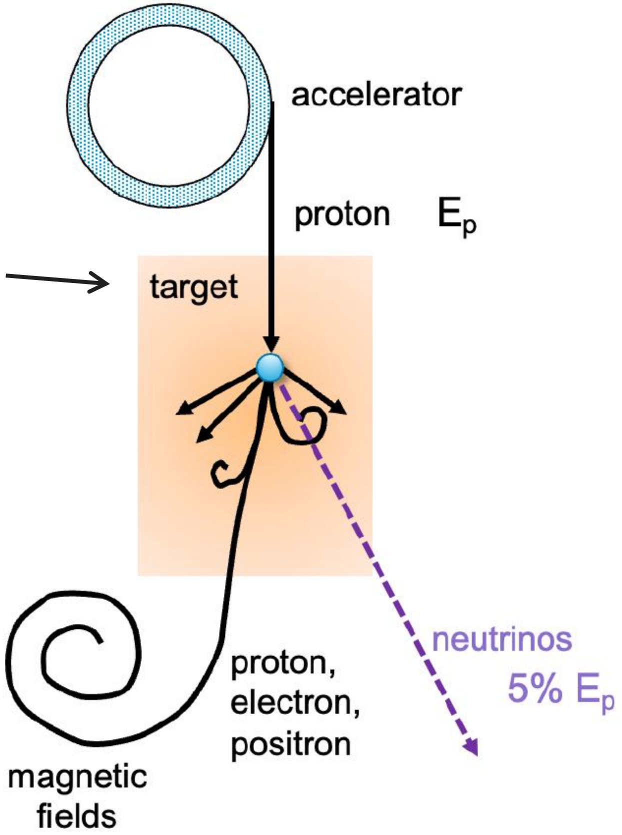
High-energy neutrino production

Astrophysical neutrinos are produced
in interactions of CR with cosmic environment

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

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

proton or photon environment



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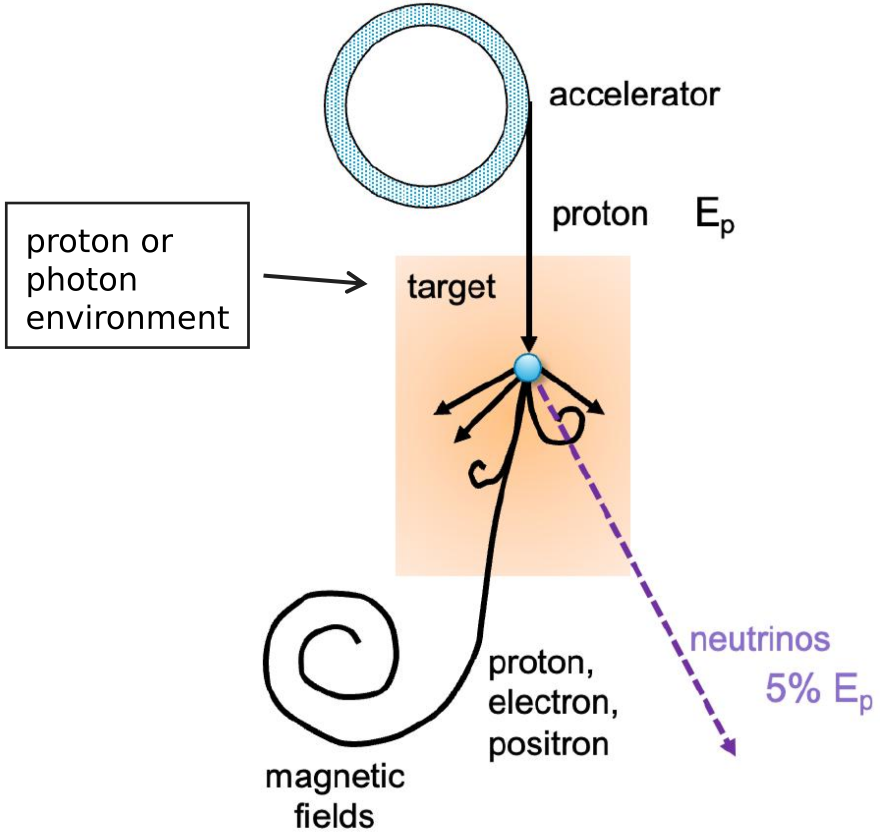
What if we could associate neutrino with some source?

- Neutrino is the marker of hadronic processes
- Direct probe of process energy scale near the source



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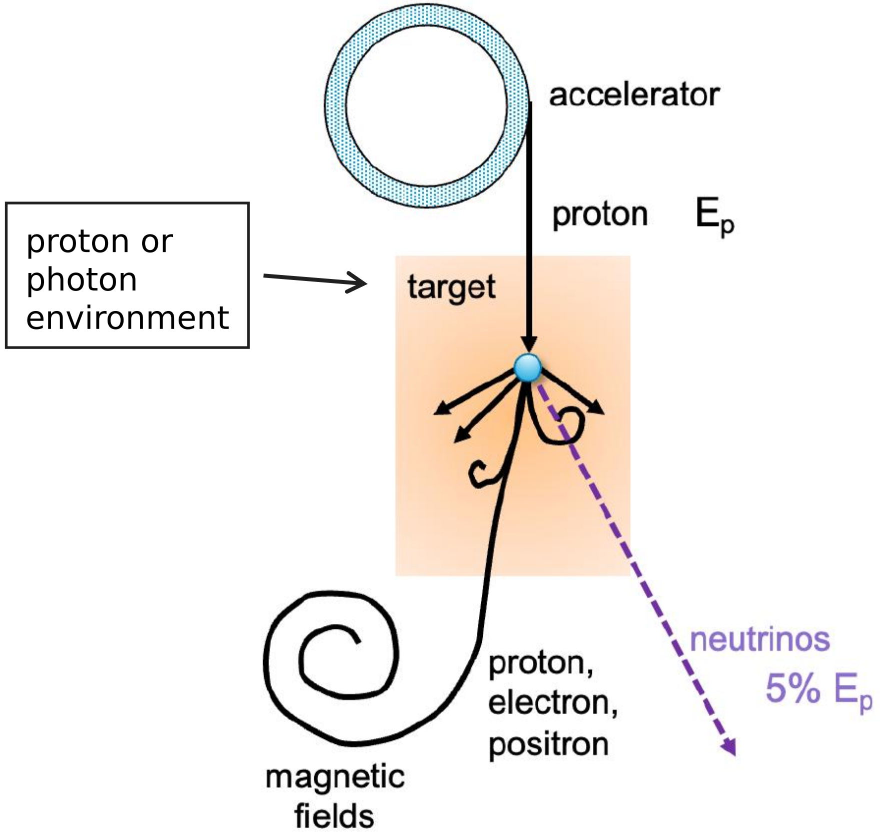

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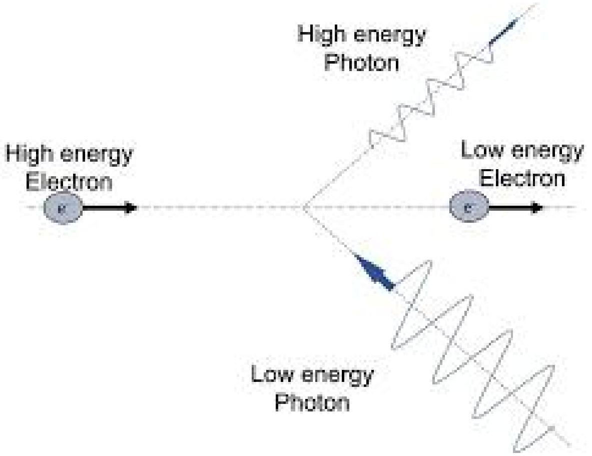
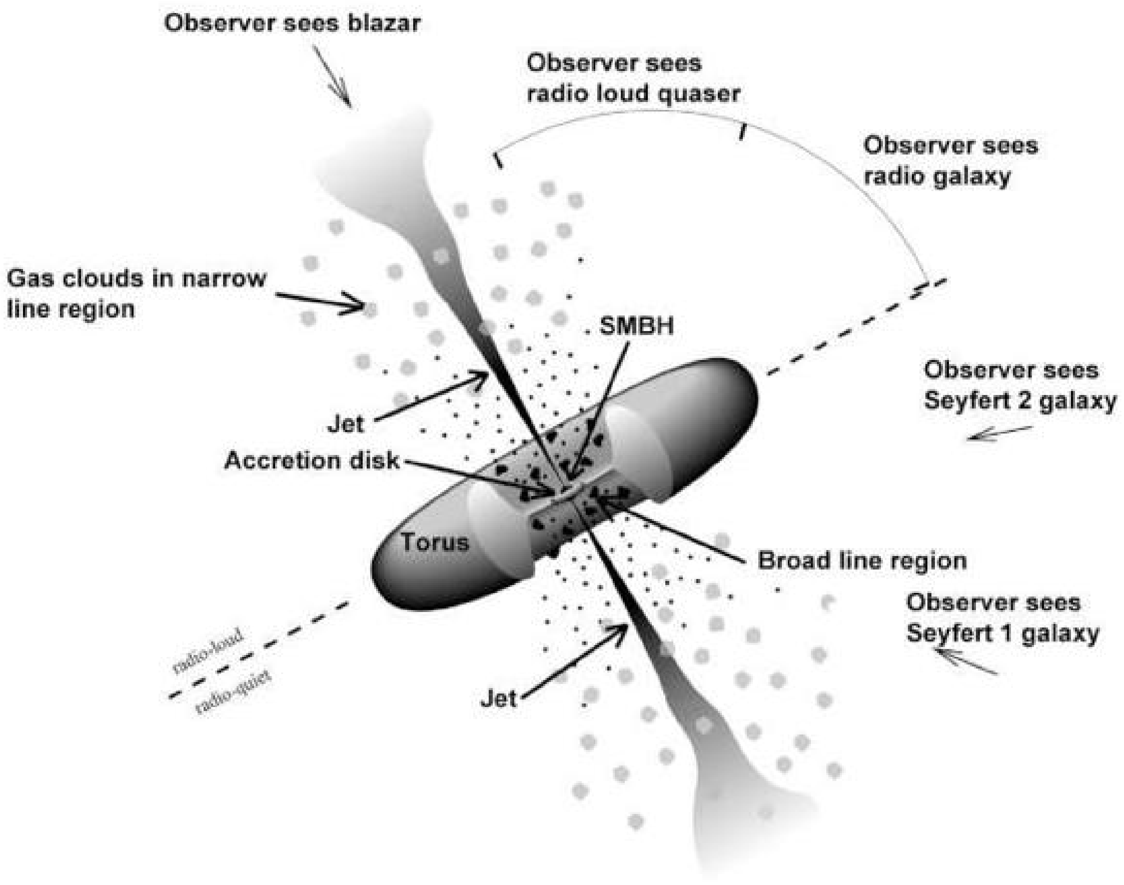
Constraint on inverse
compton scattering
in high-energy γ sources



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

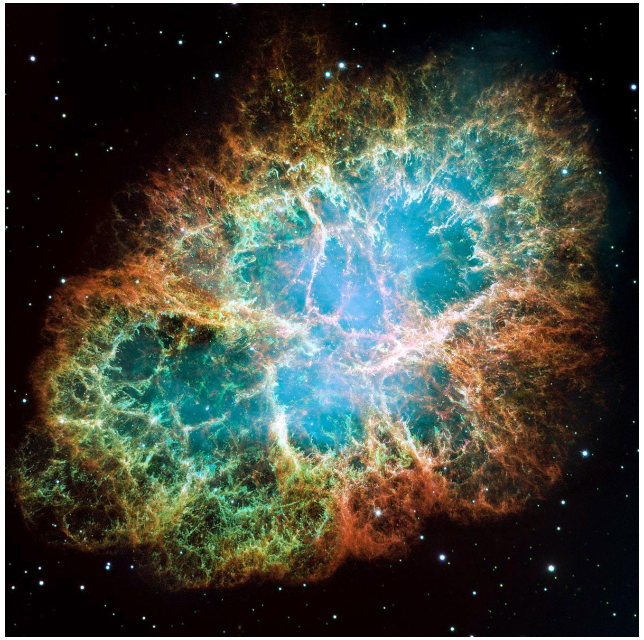
An example of pp mechanism -dominated source:

Supernova remnants (SNR)

"CR reservoirs"

- High-energy protons are confined in SNR
- Accelerated in supernovae shockwave
- Interact with each other

Textbook SNR:
Crab nebula



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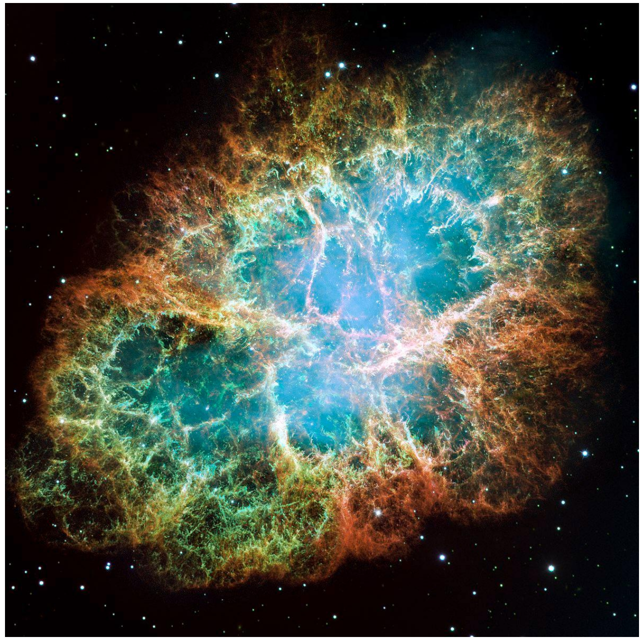


Suggested reading on HE neutrino sources:

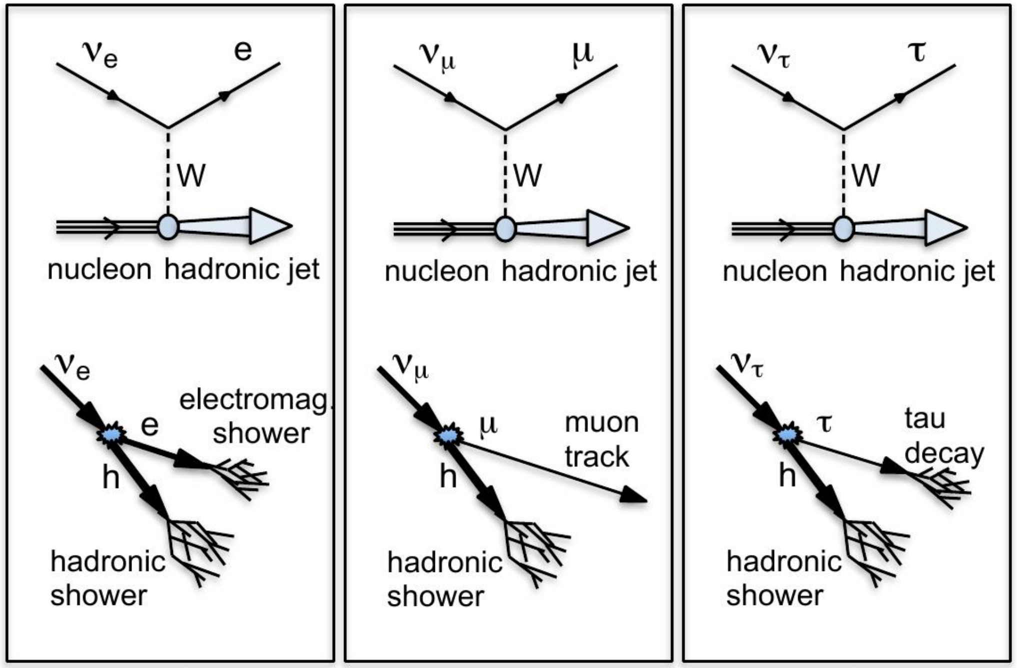
P. Meszaros arXiv:1708.03577 (2017)
S. Troitsky arXiv:2311.00281 (2024)

High-energy neutrino detection

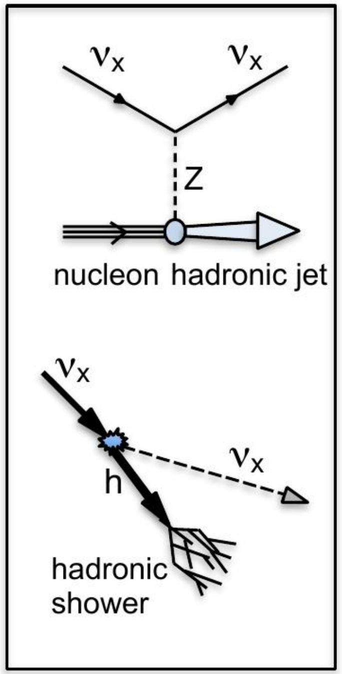
High-energy neutrino interaction signatures

Above E_v ~ 1 GeV - deep inelastic scattering (DIS)

Charged current interactions (CC)



Neutral current interactions (NC)



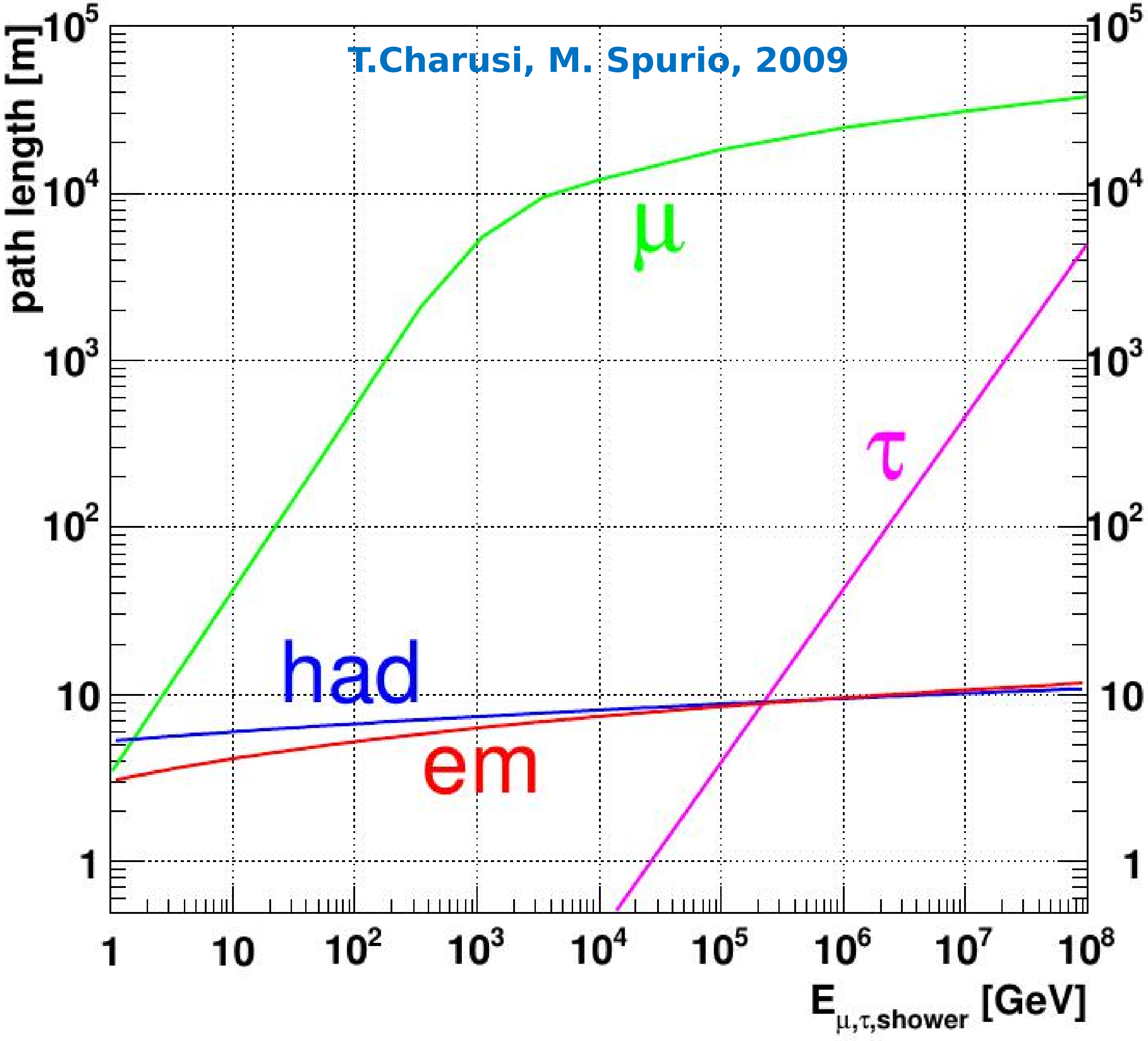
Muon and partially -neutrino in CC: muon with kilometers track length

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

High-energy neutrino interaction with matter

TeV muons have path length of order of 10 km

Hadronic or electromagnetic cascades
extend to 5-10 meters



Detection principle

Suggestion by M.A. Markov at ICHEP 1960:

- Sparse array of photodetectors enclosed in hermetic containers in natural water reservoir
- Cerenkov light from charged particle produced in neutrino interaction is detected

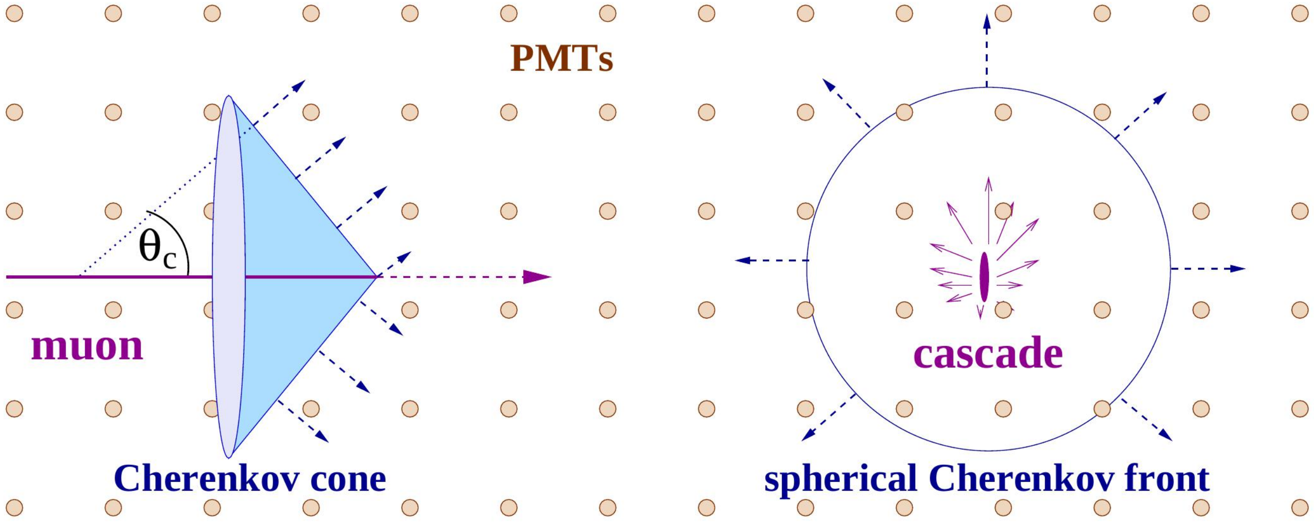
Basic detection channels:

Tracks (CC, ν_μ ν_τ):

- Good angular resolution: ~0.3° - 0.5°
- Poor energy resolution: 200-300%
- Thet best for point source searches
- Increased sensitive volume due to muon propagation range

Cascades (CC ν_e ν_τ, NC):

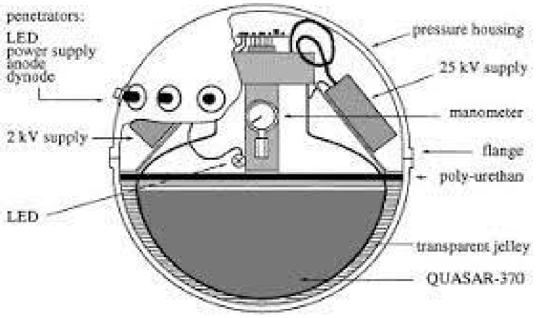
- Moderate angular resolution 3°-10°
- Good energy resolution: 5-30%
- The best for energy spectrum measurement
- Detect interactions inside or very close to the detector

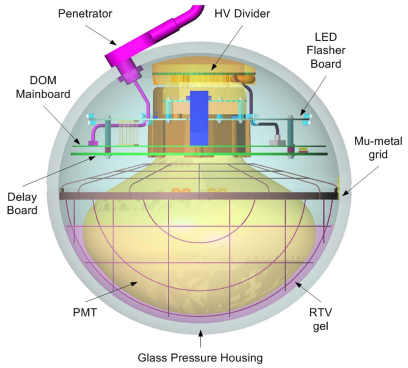


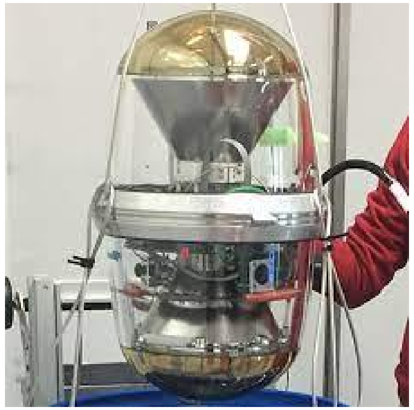
3d optical sensor structure
>10m sensor spacing

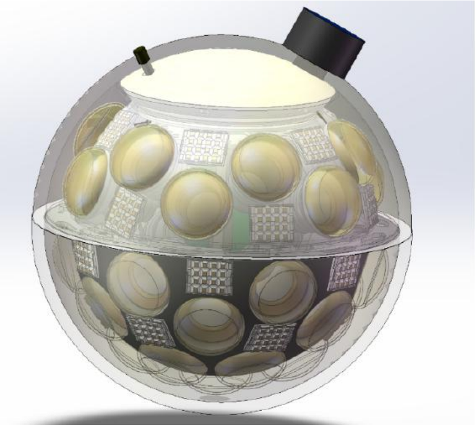
Optical modules (OM)

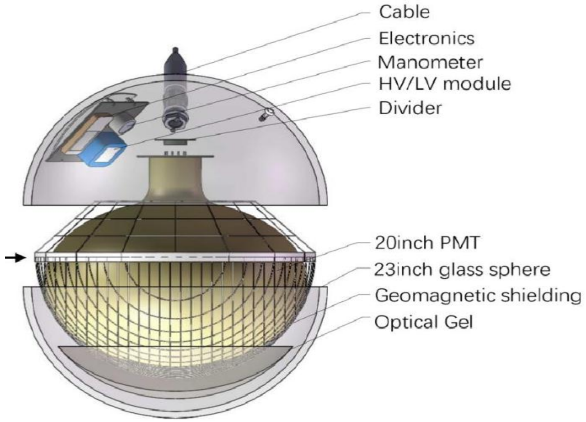
Hermetic transparent container with enclosed PMTs
Also contains power distribution, readout electronics and various sensors





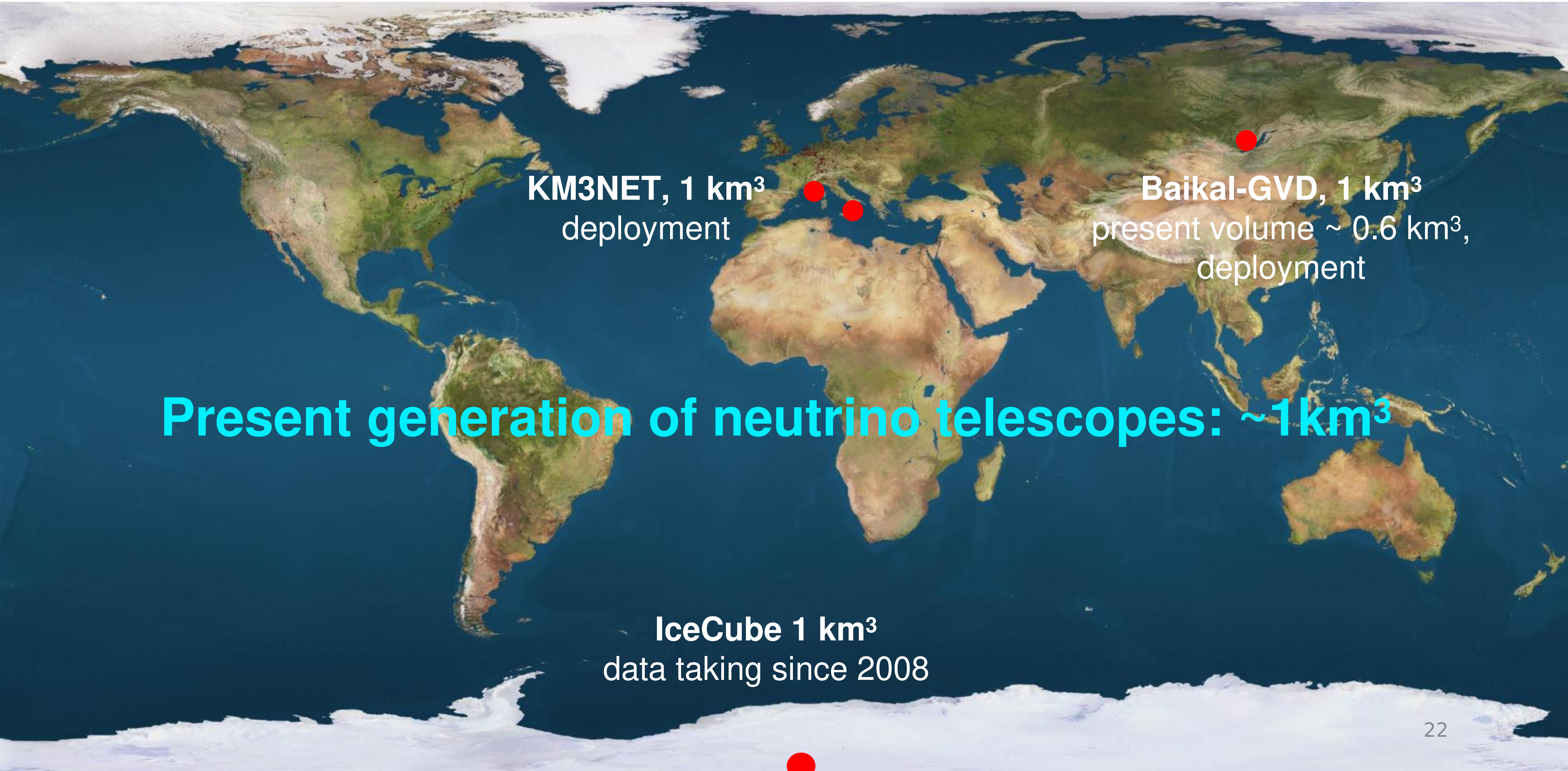






OM design is a key component of LV neutrino telesope

Operating large-volume neutrino telescopes



Baikal-GVD neutrino telescope

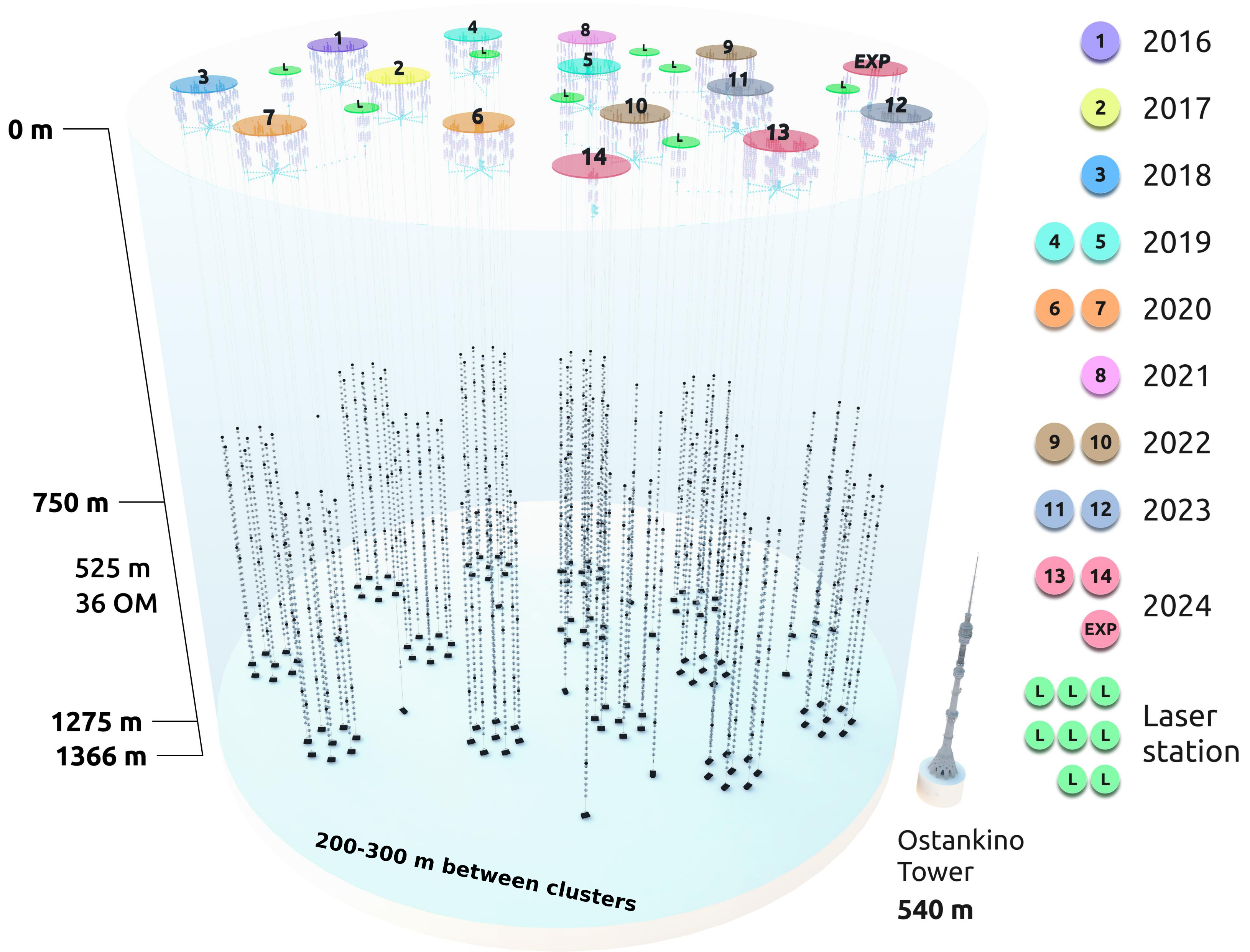
Presently detector consists of 117 strings arranged into 14 independent detectors - **clusters**

- 4212 OMs in total

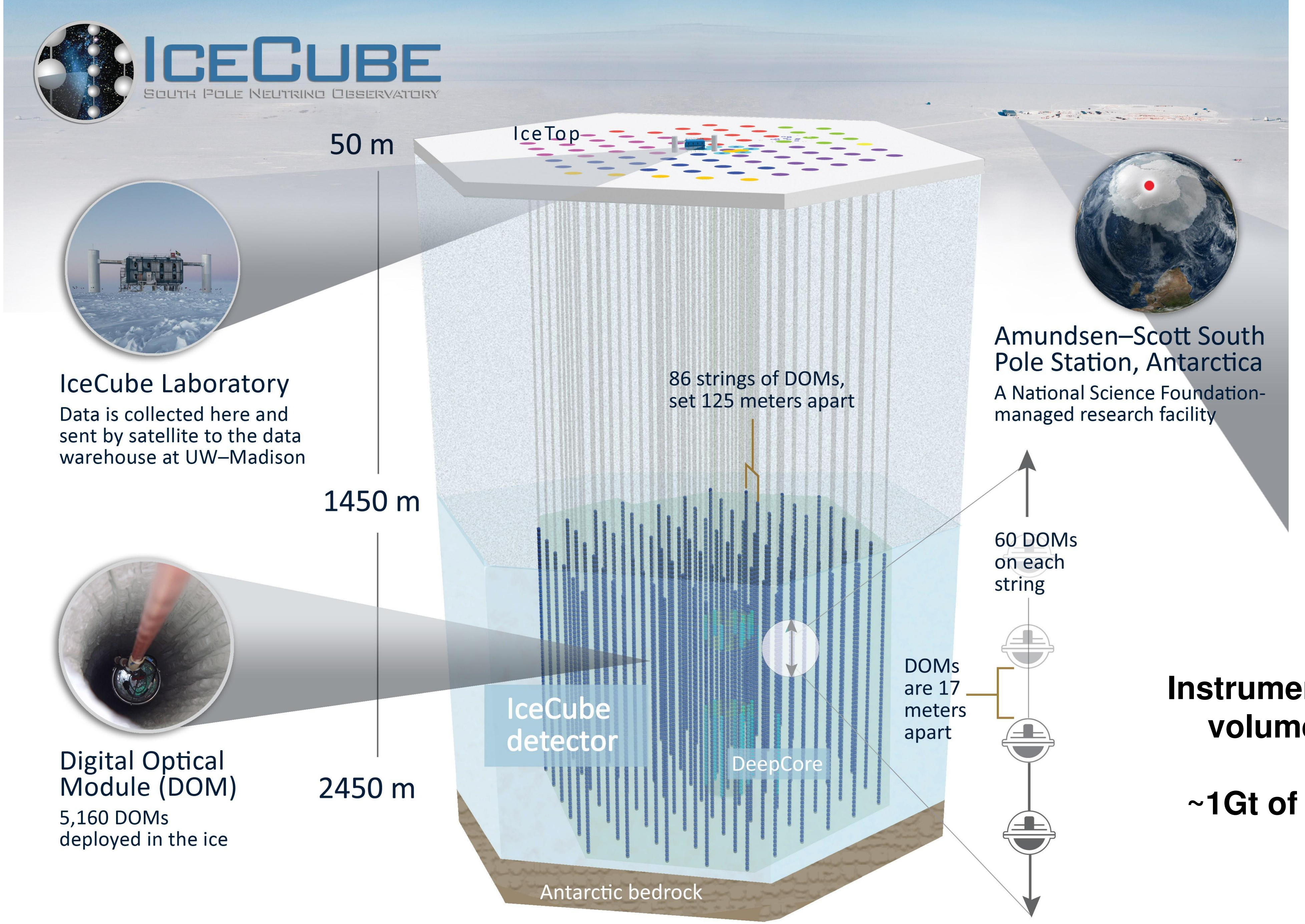
Baikal-GVD cluster:

- 8 regular strings, 525 m is instrumented with optical modules (OM), 15m step between OM
- 60m radius
- Inter-cluster string carrying lasers, some instrumented with OMs

Detection volume: ~0.6 Gt



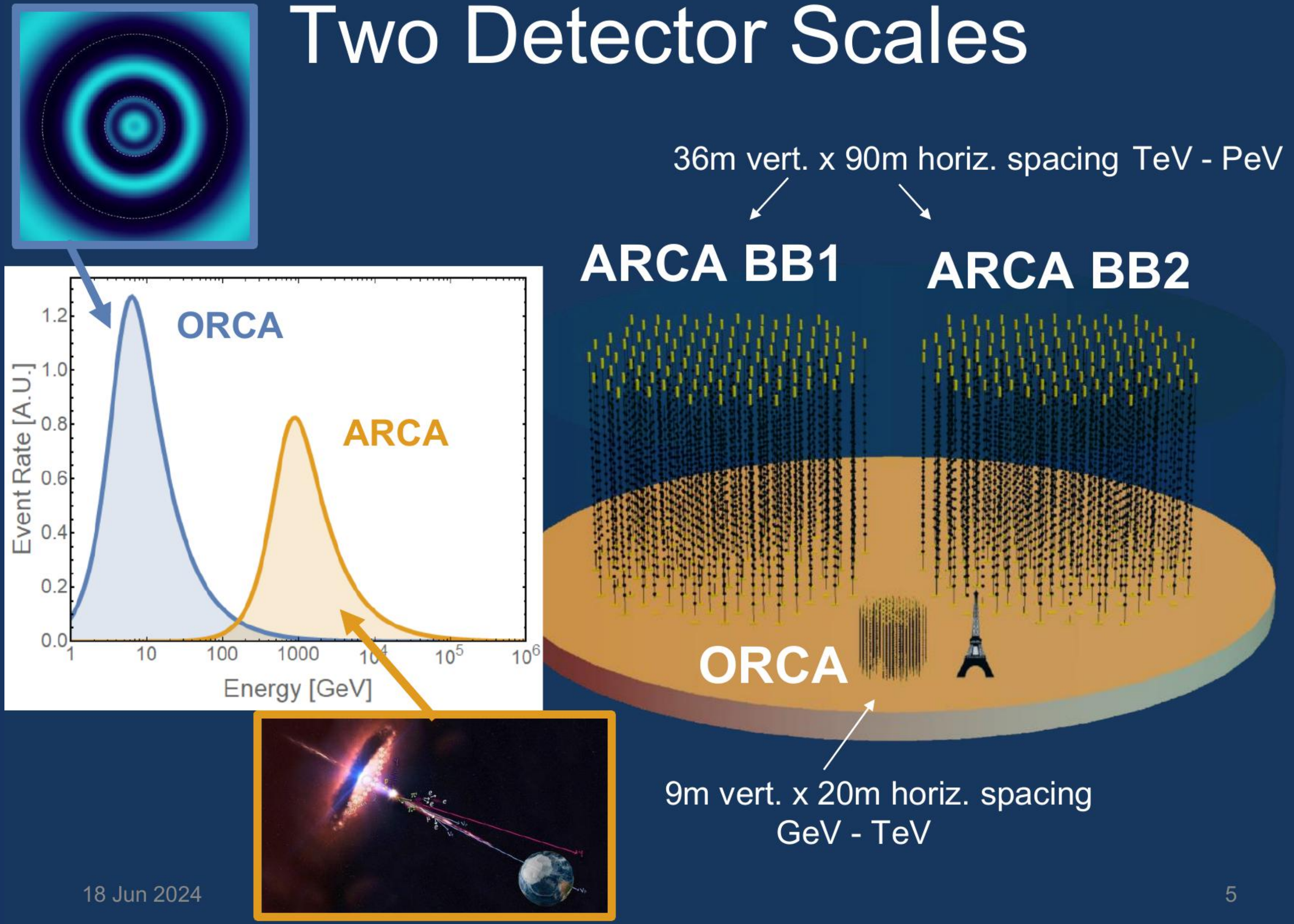
https://icecube.wisc.edu/science/icecube/



Instrumented volume:

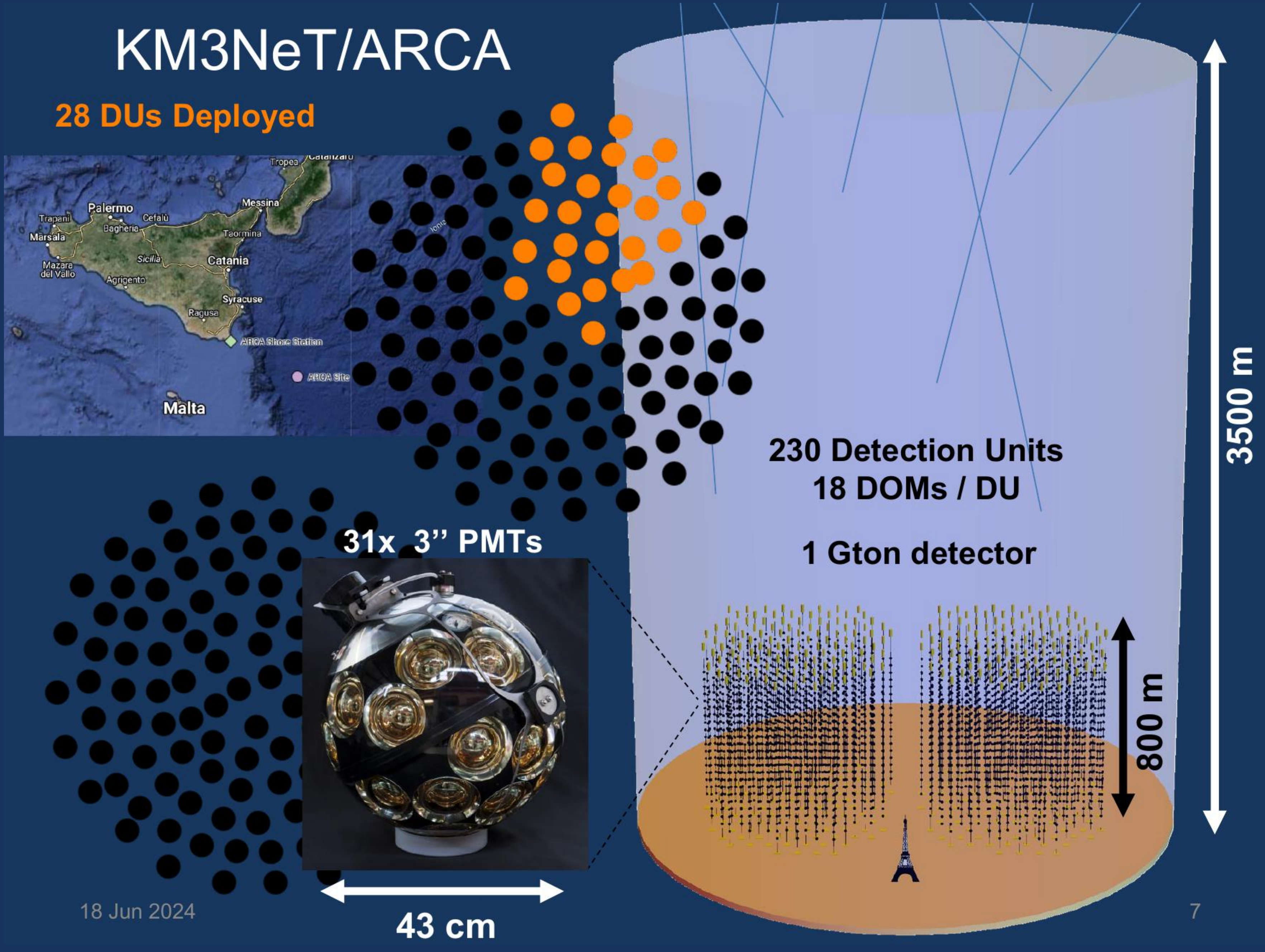
~1Gt of Ice

KM3NeT


Two Detector Scales
36m vert. x 90m horiz. spacing TeV - PeV
ARCA BB1
ARCA BB2
ORCA
ARCA
Event Rate [A.U.]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
10
100
1000
10^4
10^5
10^6
Energy [GeV]
ORCA
9m vert. x 20m horiz. spacing
GeV - TeV
18 Jun 2024
5

5 additional DUs deployed in October 2024

KM3NeT



15% of the detector deployed

Joao Coelho, "Latest Results from KM3NeT", Neutrino 2024, June 18, 2024

Backgrounds

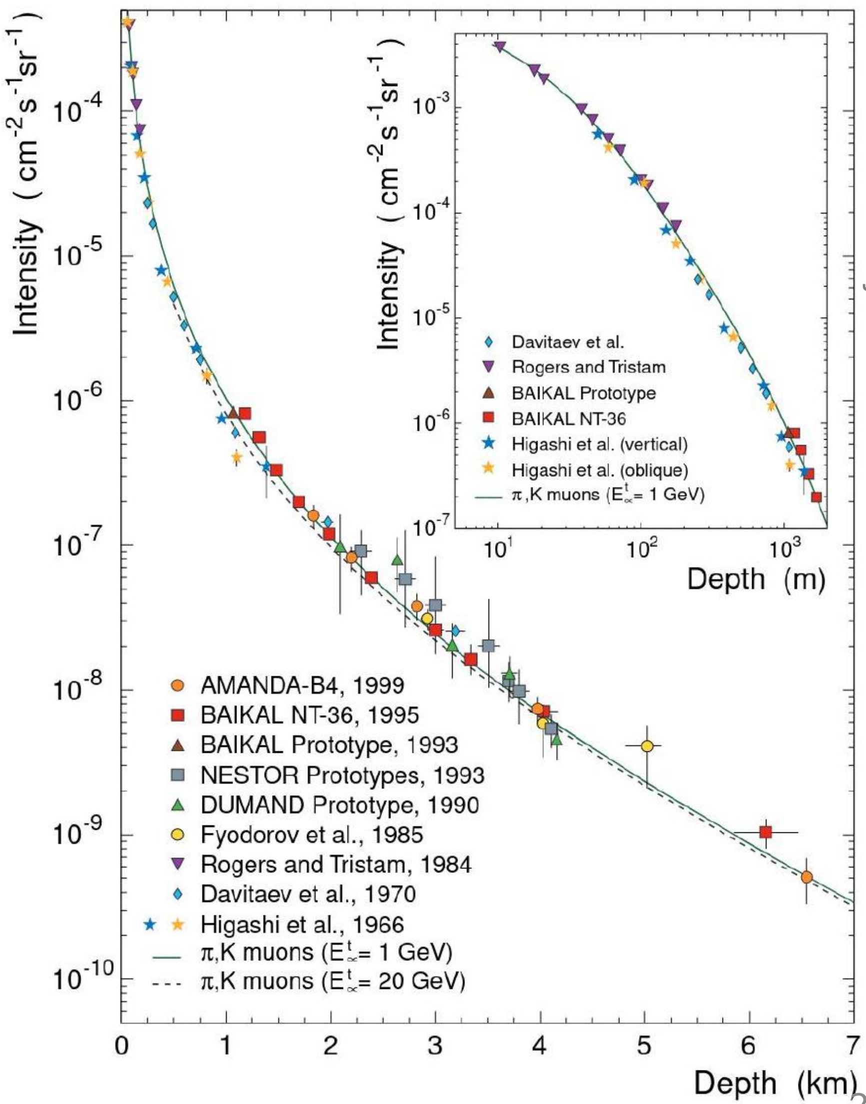
Large backgrounds are involved with any LVNT telesope project

Background PMT pulses
- PMT dark current
- Natural glow of detection environment

More in Lecture 2

Atmospheric muons
- Downgoing bundles of muons produced in CR interactions with atmosphere
- Background quickly falls with the detector depth
- Muon rate is suppressed by the factor of 10^4 at 1km depth

Atmospheric muon flux vs. depth in water (ice)



DOI:10.1103/PhysRevD.58.054001

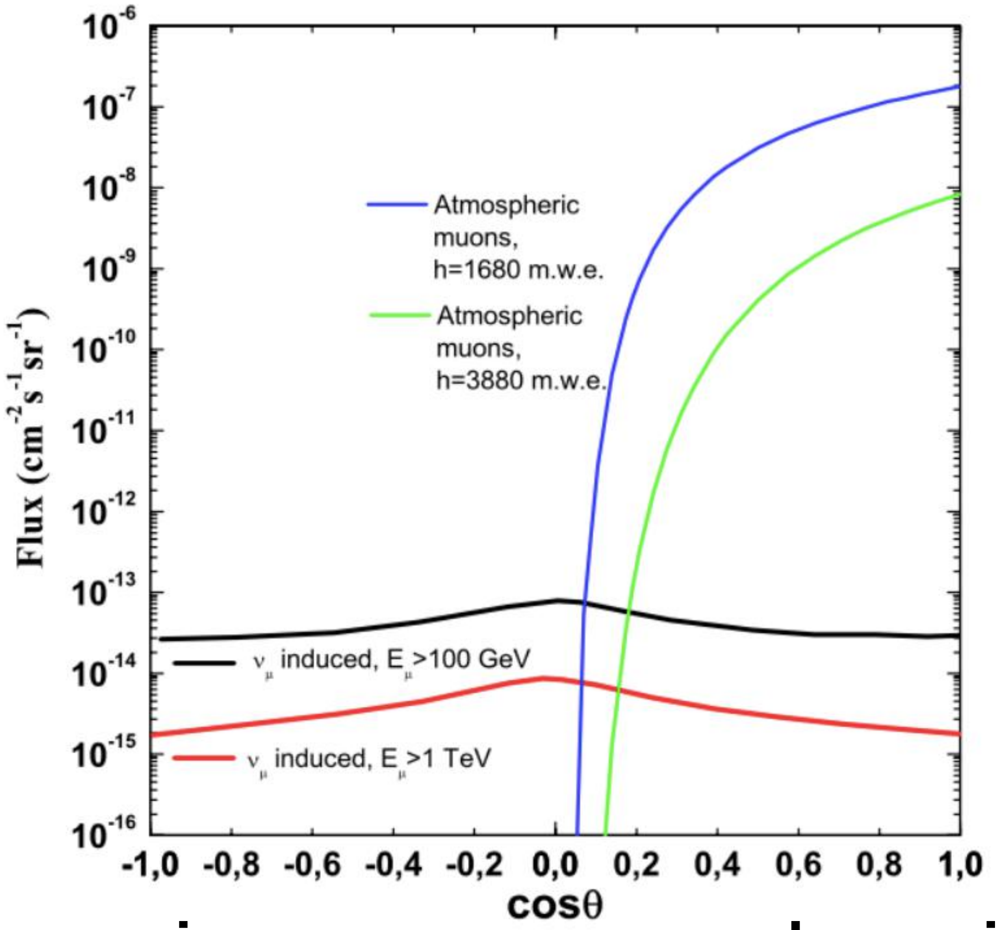
Backgrounds

Atmospheric muon background is many orders of magnitude larger than neutrino-induced event rate

Muon background can be minimized with a cut on zenith angle, by looking at "upgoing events"

One of reasons PMTs are oriented downwards - maximise the sensitivity to upgoing events

True zenith angle distribution



upgoing downgoing

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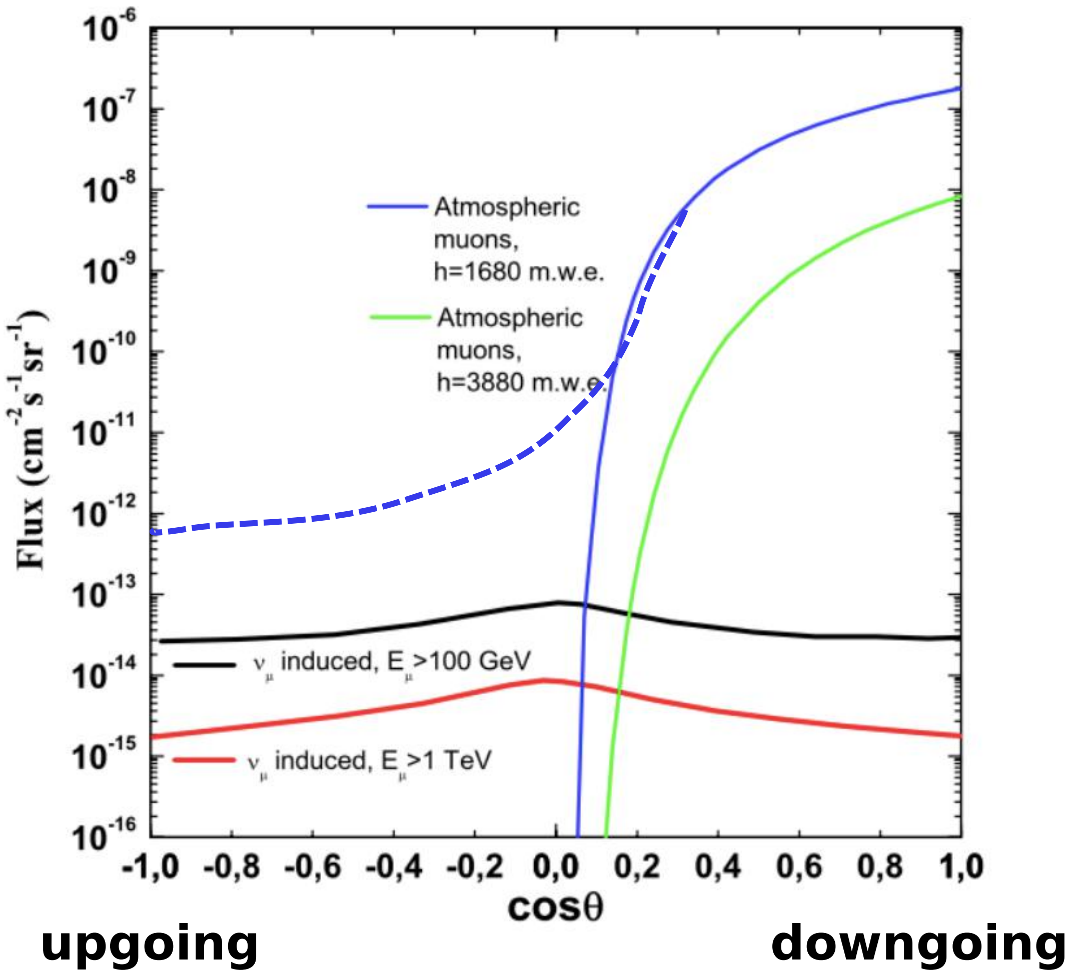
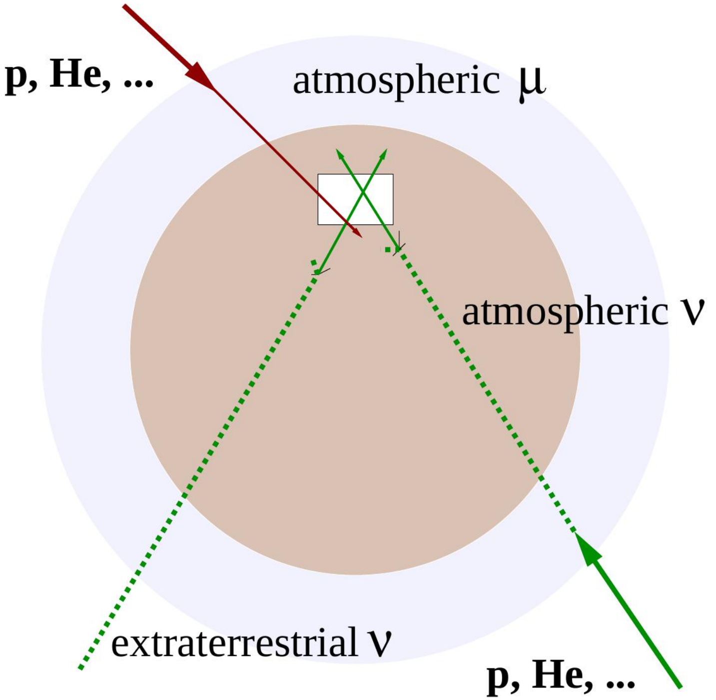


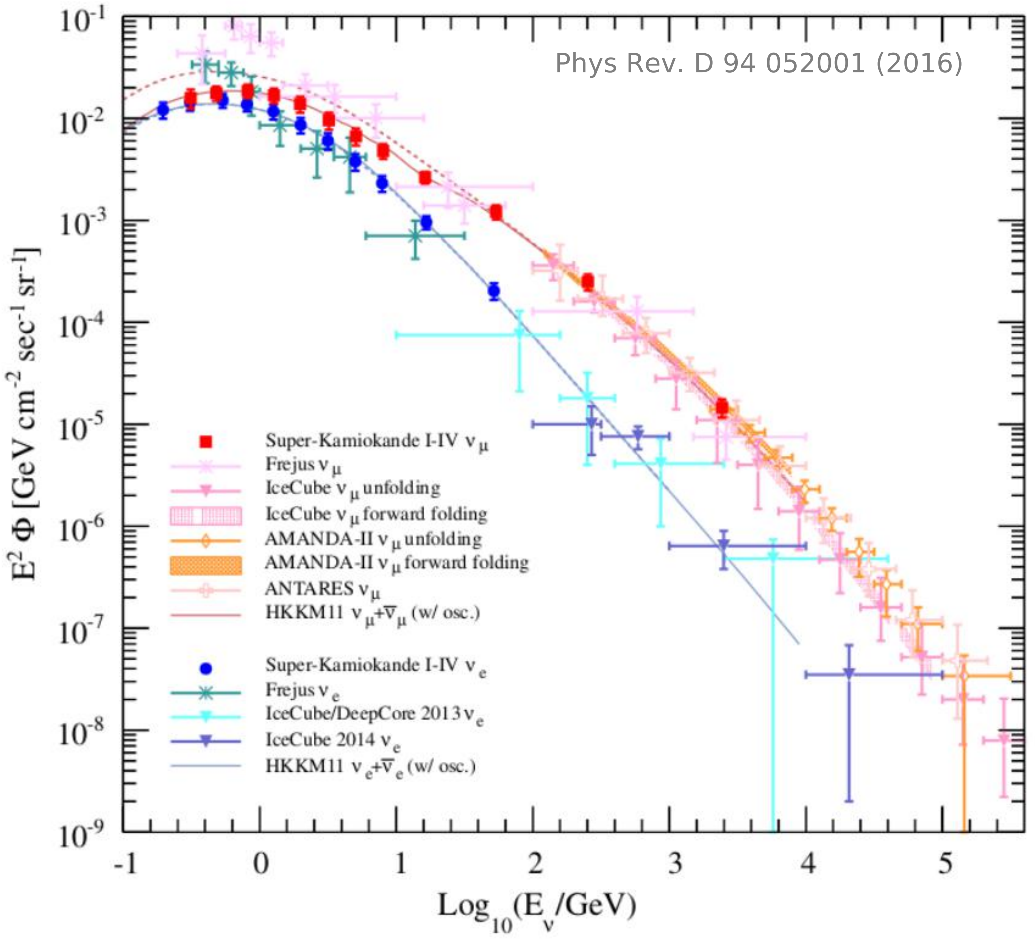
Reconstructed muon events contribute to the background in upgoing region due to angular resolution and misreconstructed events (more in Lecture 3)

Backgrounds



Atmospheric neutrino:

Irreducible background to astrophysics searches



Muon neutrino dominate in atmospheric neutrino flux

- By more than factor 10 at > TeV energies
- Thus atmospheric background is larger for track channel

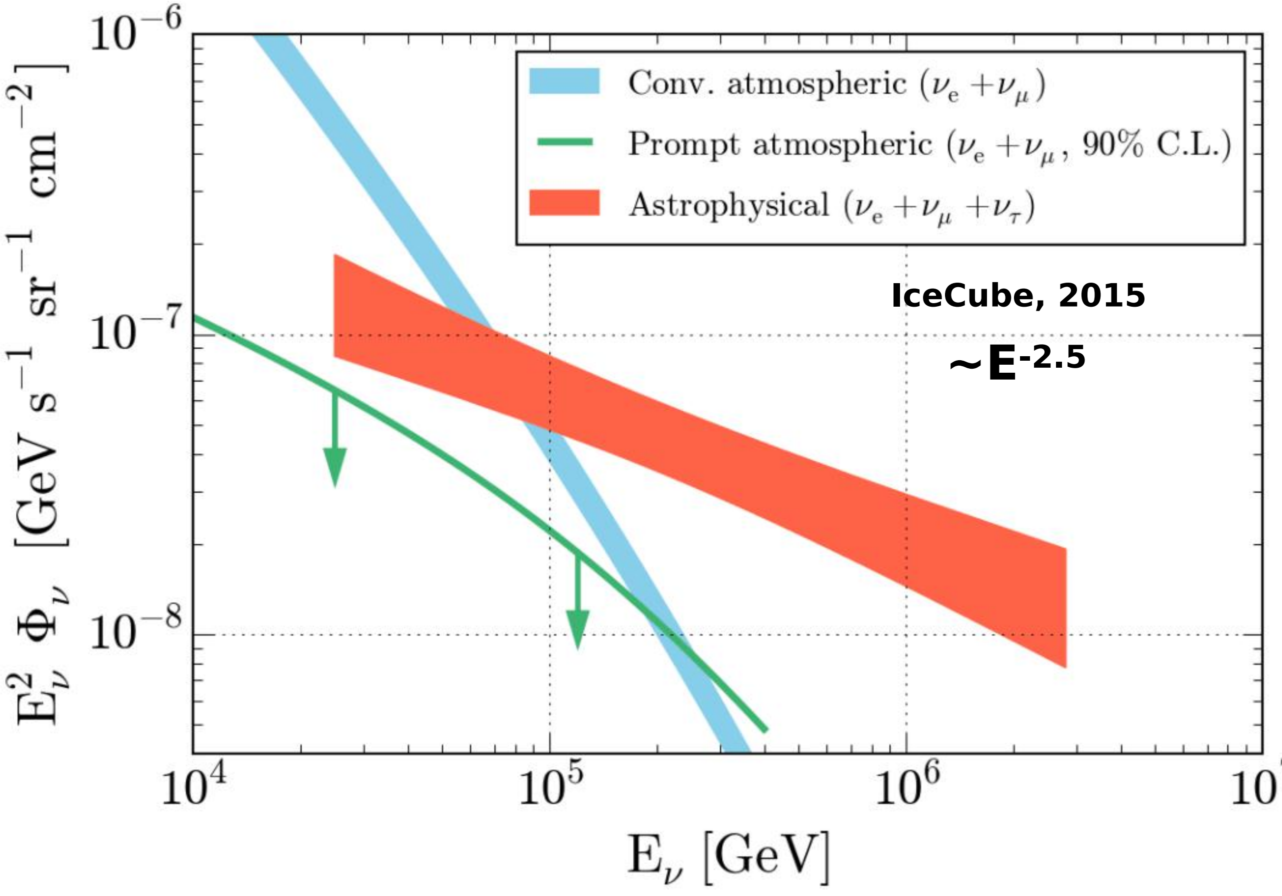
Backgrounds

Atmospheric neutrino - “standard candle” for neutrino telescope

- Atmospheric neutrino flux measurement is one of the first measurement performed at LVNT
- Detector performance and Monte-Carlo validation

Spectrum slope of atmospheric neutrino ~$E^{-3.7}$ while that of astrophysical neutrino ~$E^{-2.5}$

- **Background can be reduced by a cut on event energy**



ApJ 809, 98 (2015)

Detector effective area

LVNT effective area defines the neutrino event rate: key to telescope sensitivity

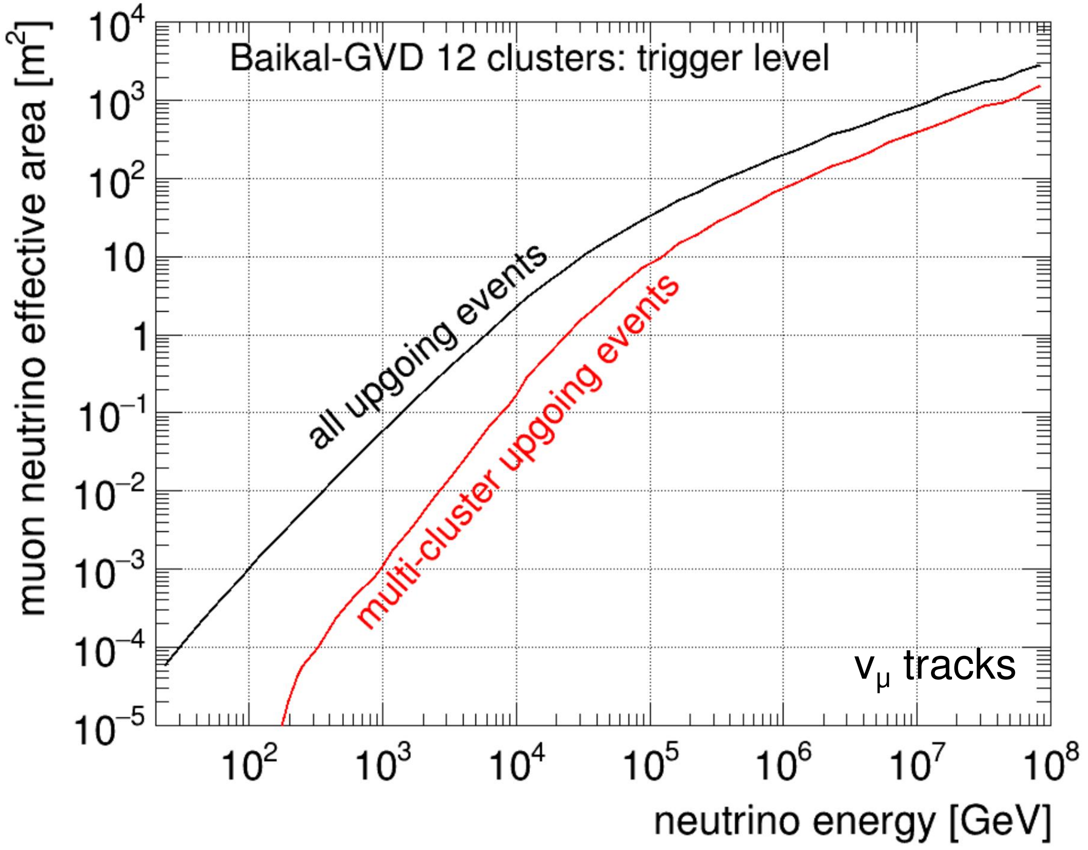
Effective area: an equvalent area of the telescope which detects 100% of incoming particle flux

Neutrino
event counting rate: $R(s^{-1}sr^{-1}) = \Phi_\nu A_{eff}$

neutrino flux **effective area**

Effective area depends on
- Instrumented volume of the telescope
- OM sensitivity
- Water transparency
- Density of optical modules
- Detection channel
- Reconstruction algorithms
- Event selection requirements

ν_μ trigger-level effective area of Baikal-GVD



Detector effective area

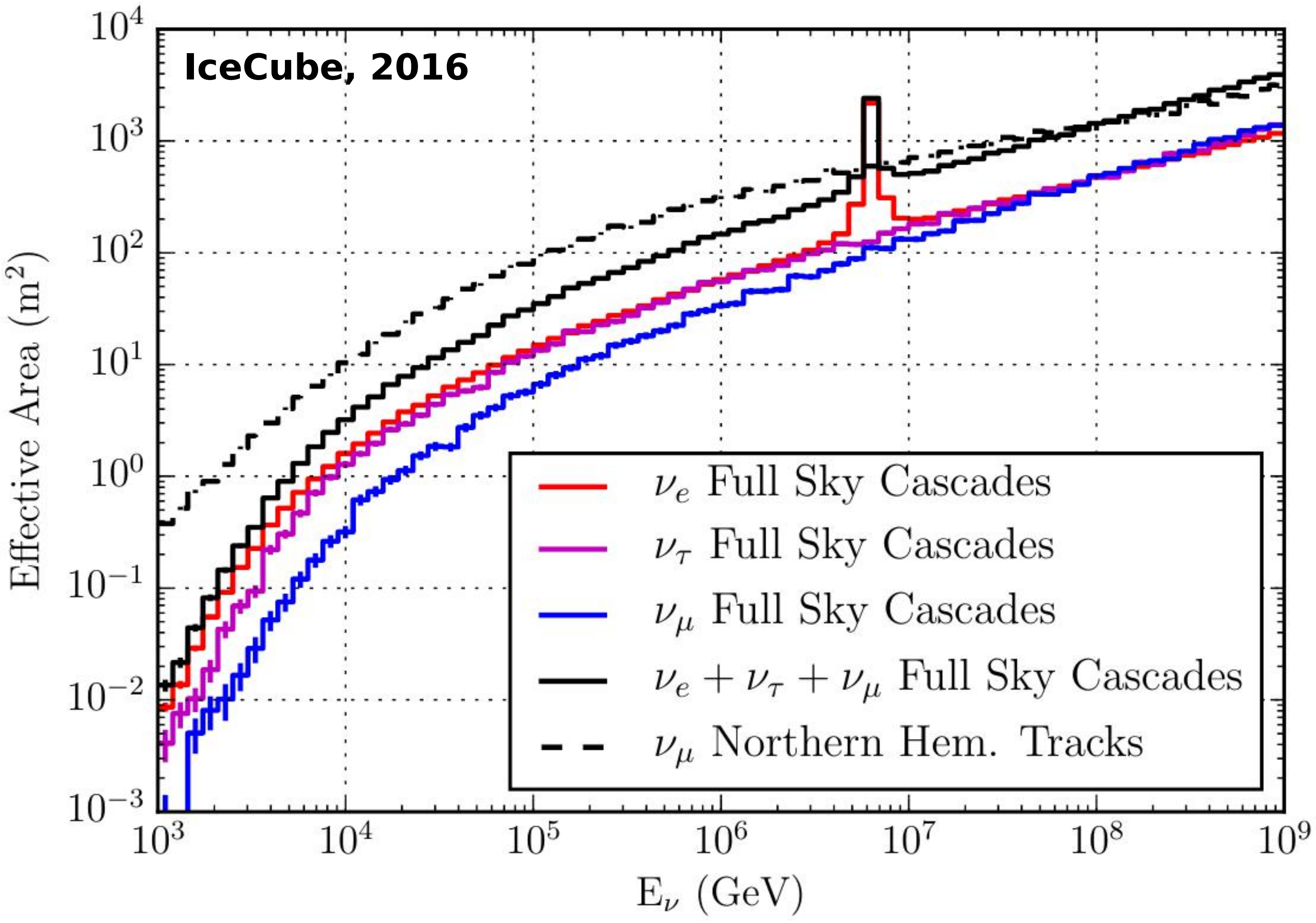
Muon neutrino effective area is larger due to muon propagation range

- Problematic detection of downgoing events due to muon background

Full sky can be observed in cascades as starting events inside the detector

- Veto on through-going downgoing muons

IceCube effective area for various event types



Detector effective area

To minimize backgrounds experiments develop so-called "event selections" defined by
- Detection channel
- Reconstruction algorithms
- Selection algorithms and cuts

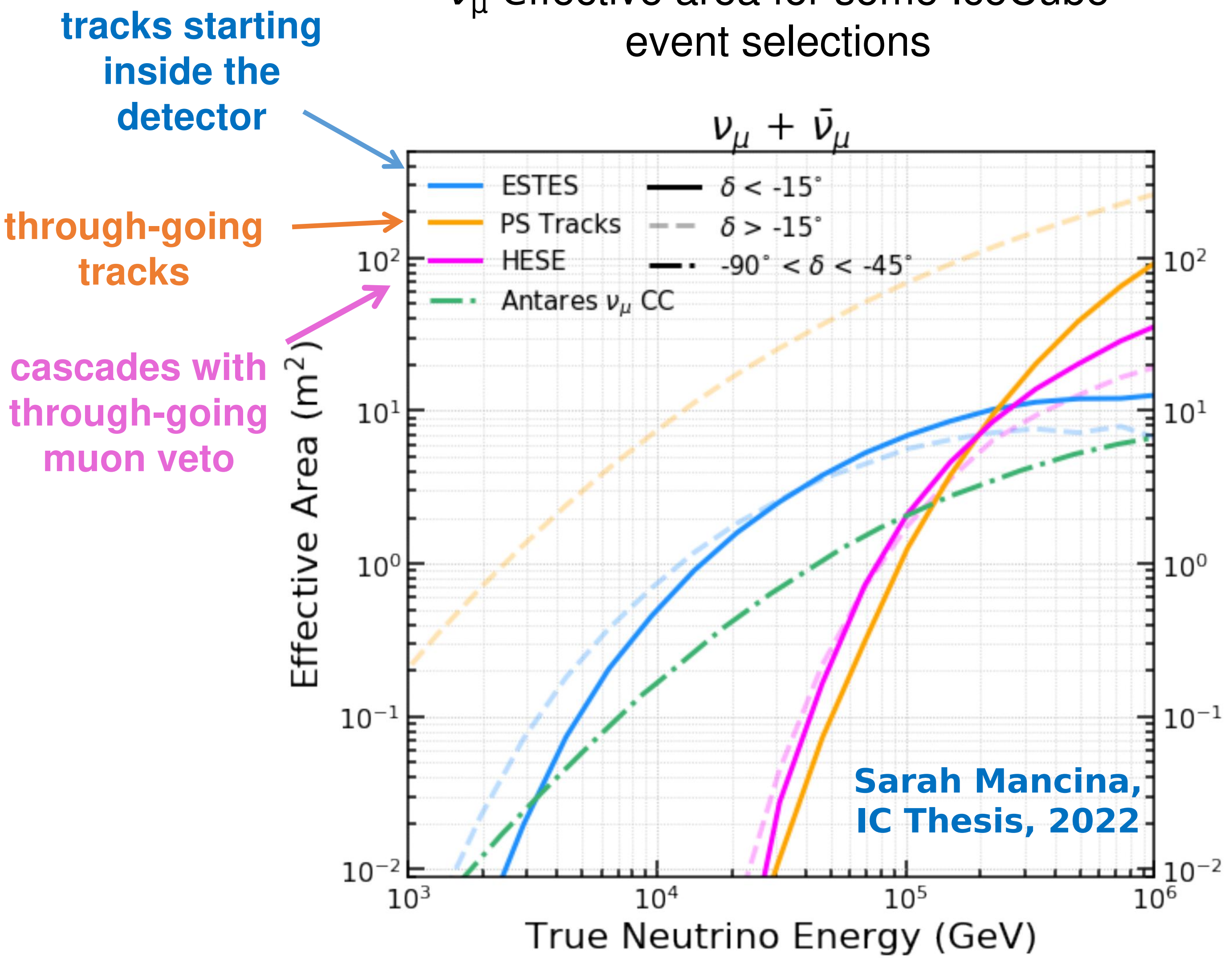
Each step in applied data reduction algorithms reduce the effective area

Each event selection is characterised by its own effective area

Further analysis can further reduce the effective area

One needs to be very careful when developinng event selection and analysis to keep effective area as high as possible

ν_μ effective area for some IceCube event selections

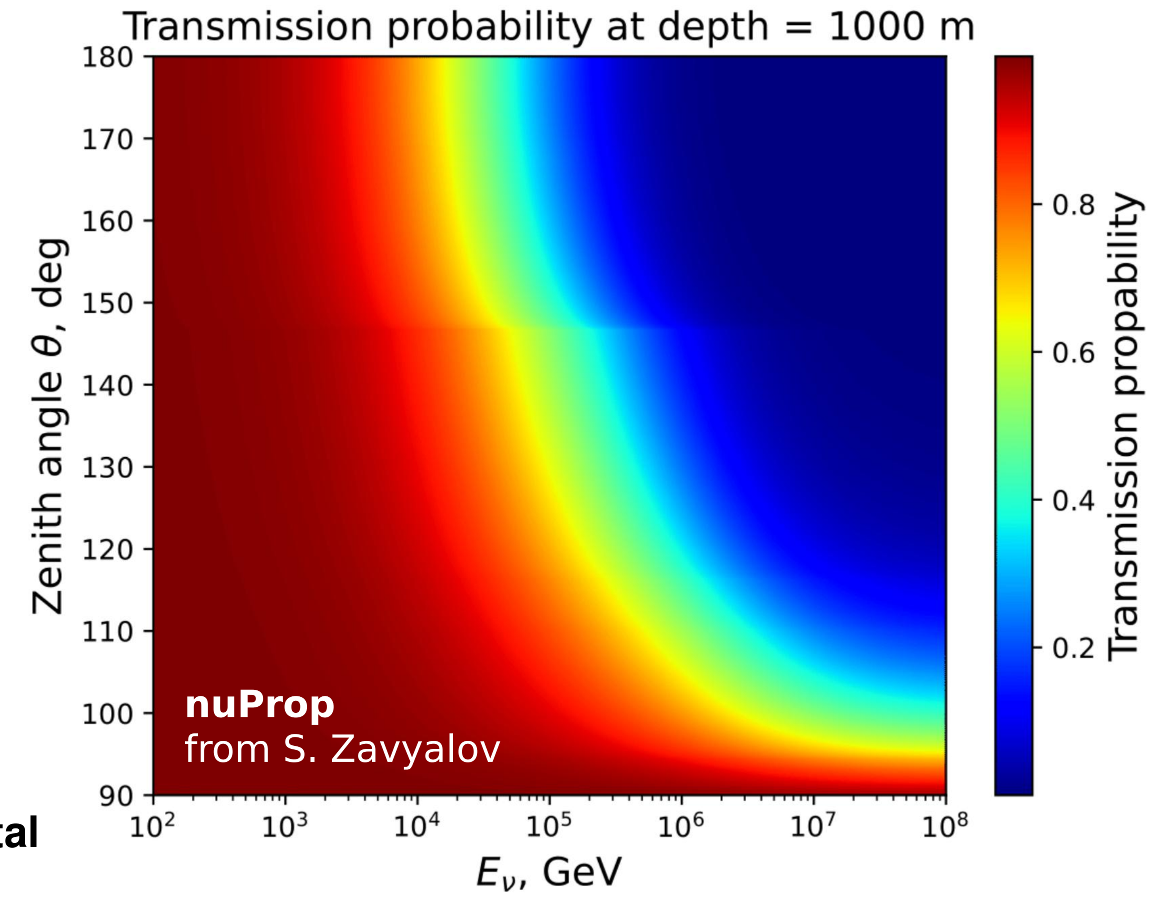


Neutrino propagation through Earth

Earth is not fully transparent
for high-energy neutrino

E > 100's TeV neutrino are downgoing or
nearly-horizontal

upgoing
vertical

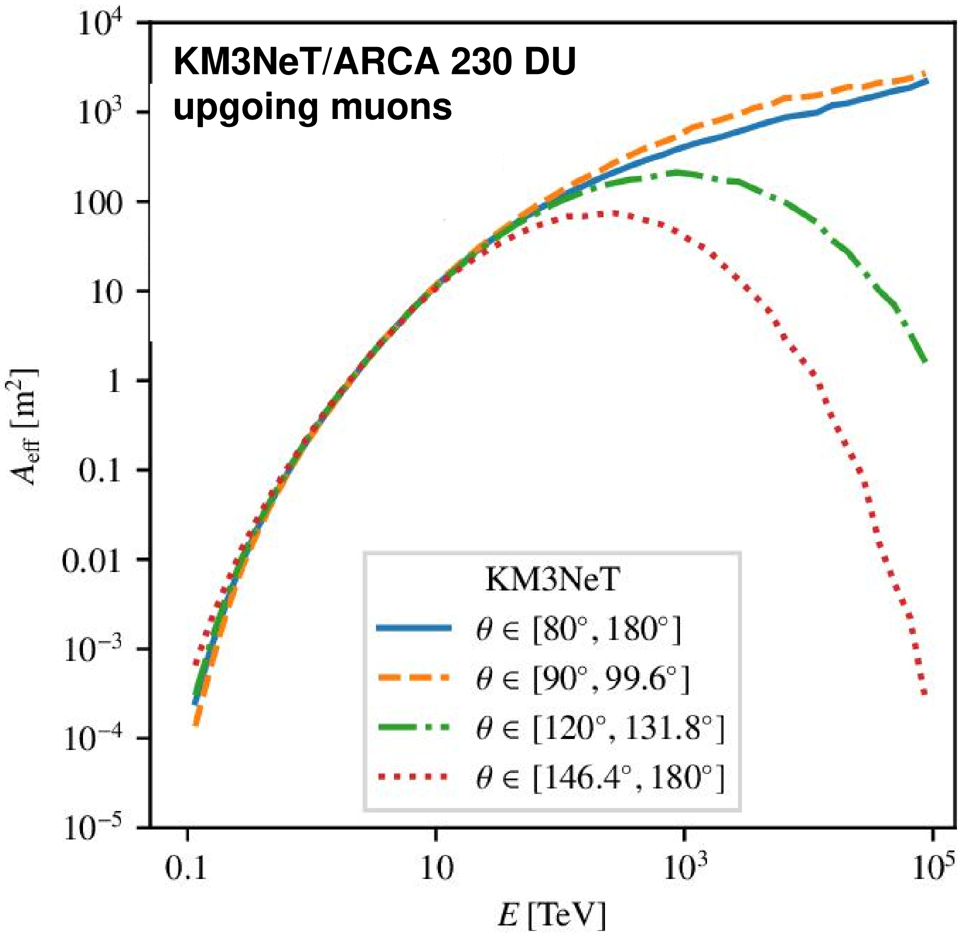


horizontal

Earth as a part of the neutrino telescope

Absorption in Earth should be taken into account for realistic effective area estimation

Impact on effective area at highest energies

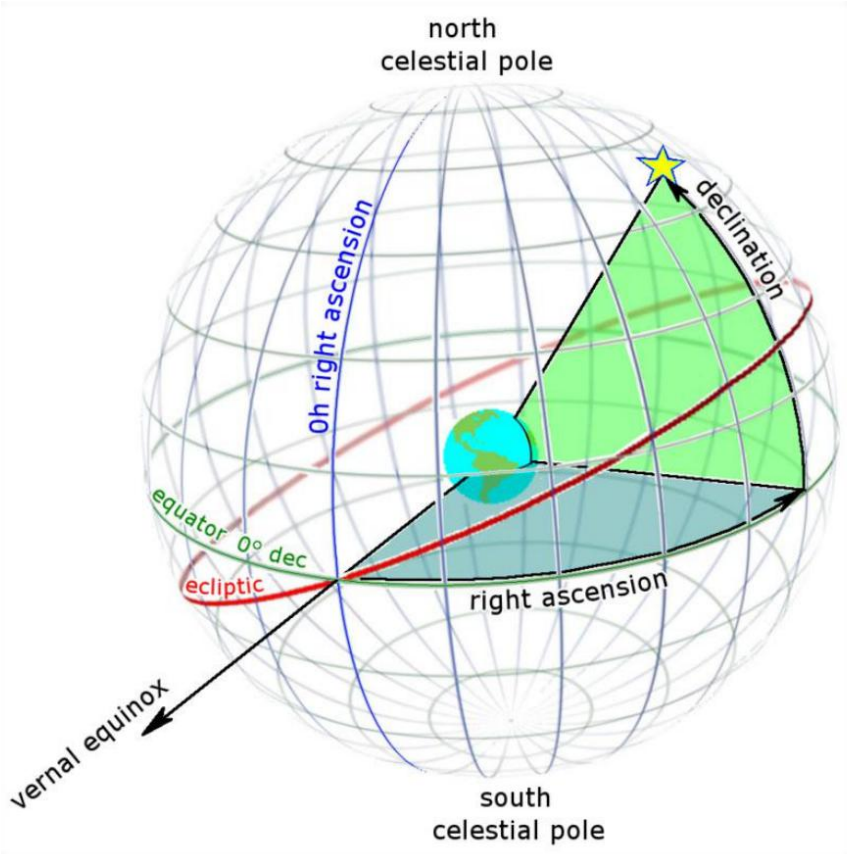


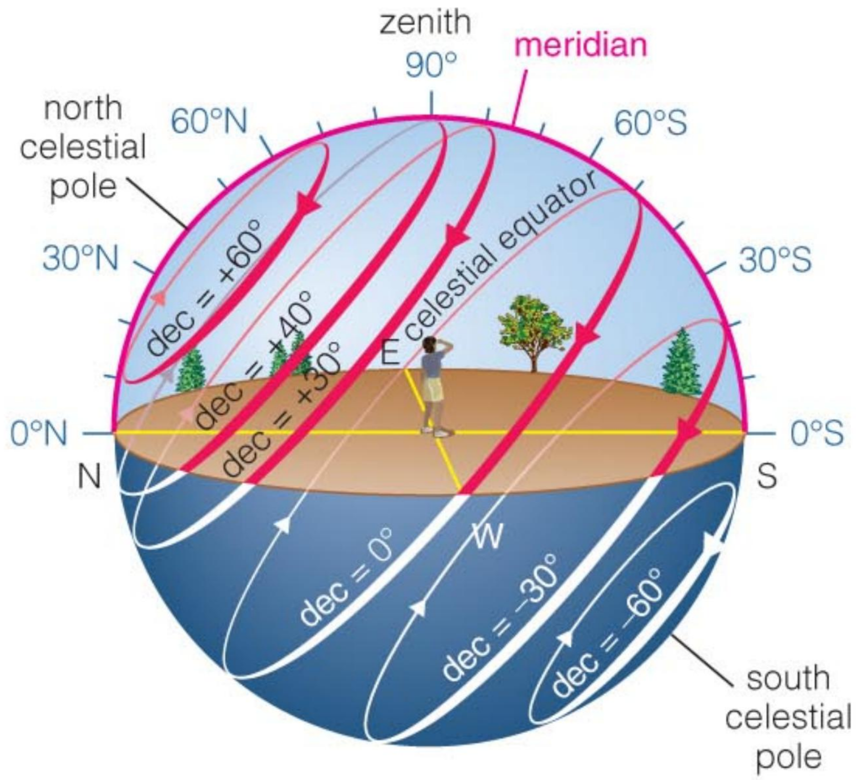
EPJC 84, 112 (2024)

Best 100's TeV - PeV muon detection: nearly-horizontal tracks

Equatorial coordinate system

Right Ascension (RA) and declination (dec) are defined wrt. the Earth equator plane





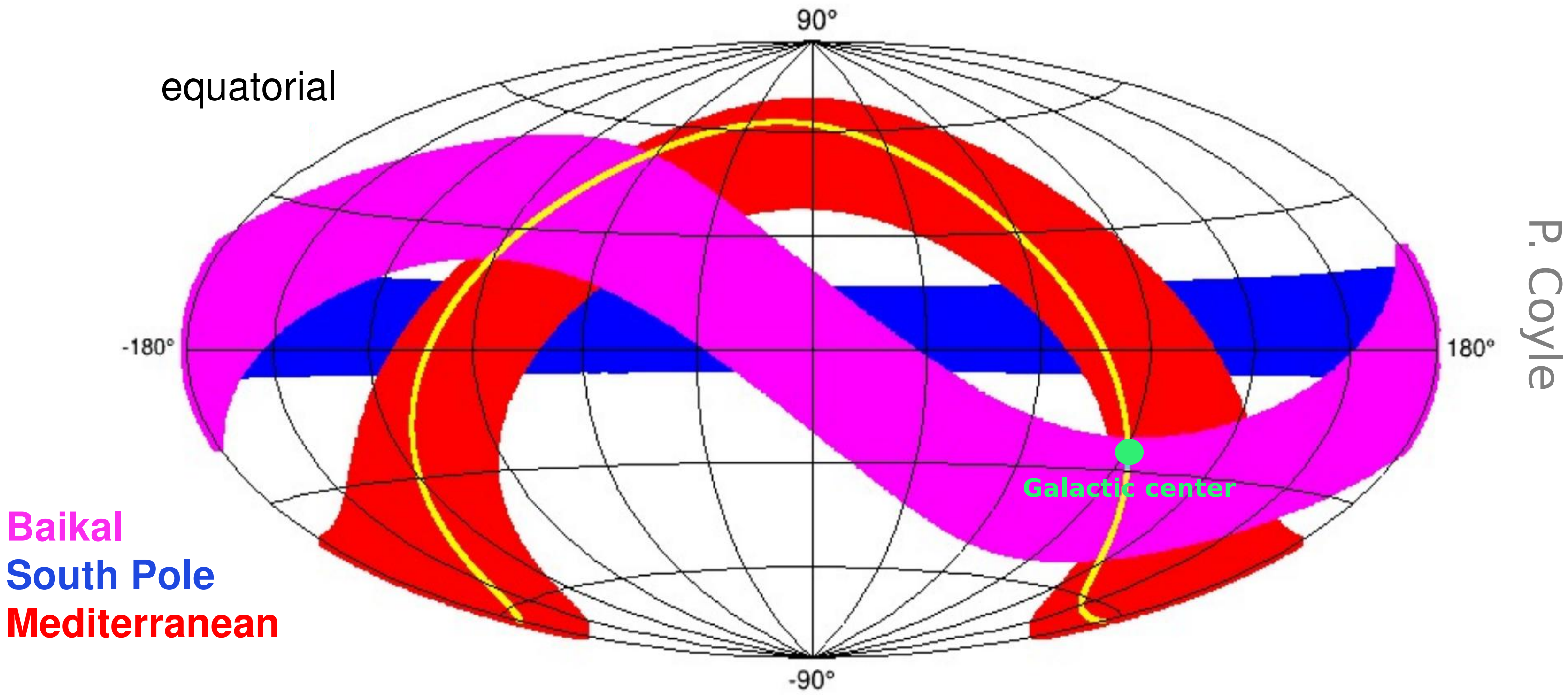
- **RA:** angle wrt the vernal equinox direction in equatorial plane (0-24h)
- **dec:** angle between equatorial plane and direction to the star

Stars revolve daily around celestial poles
Daily trajectory in zenith angle is defined by declination

Neutrino telescope sensitivity areas

Best sensitivity areas of different telescopes compliment each other

Instantaneous best sensitivity area in nearly-horizontal tracks:



Bands rotates with the Earth’s rotation (excepth for the South Pole)

Point source search

Actual number of events detected by the telescope is a function of energy, angle and livetime

$$N_\nu = \int dt \int d\Omega \int_0^\infty dE \, A_{\text{eff}}(E,\Omega)\, \phi_\nu(E_\nu, \Omega, t)$$

livetime of analysis

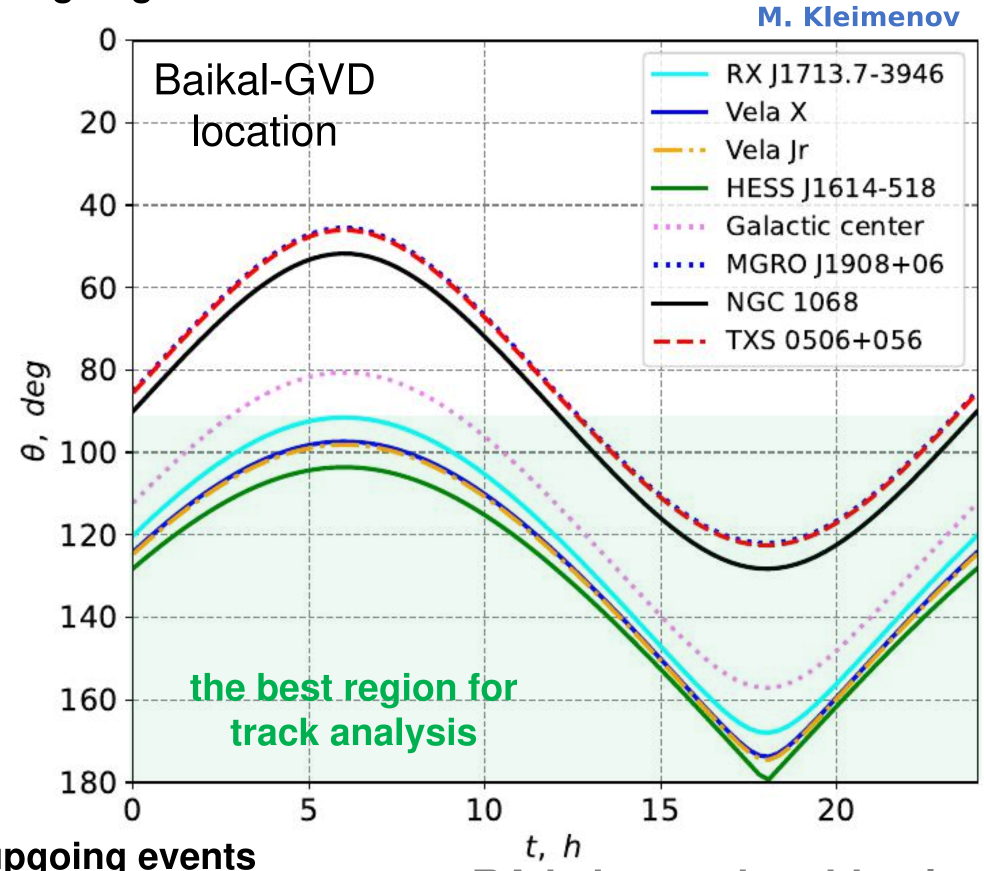
area of assumed source daily movement band

source or background flux

Detector effective area depends on zenith angle

The more time source spends in a region with large effective area the more signal events are expected

downgoing events



upgoing events

RA is ignored at this plot

Point source search

Widely used point source unbinned likelihood search approach **[J. Braun et. al.,2008]**

Fix potential source direction in equatorial coordinates: $\vec{x}_s$

Assume the symmetric detector angular resolution σ

Choose some (RA,dec) region around the source, e.g. 4 σ

Suppose we have a data sample and N events have entered the (RA,dec) region

Evaluate the likelihood function over all data events

$$\mathcal{L}(\vec{x}_s, n_s, \gamma) = \prod_N \left(\frac{n_s}{N}\mathcal{S}_i + (1 - \frac{n_s}{N})\mathcal{B}_i \right)$$

Where S_i and B_i are the signal and background probability density functions (PDF)
n_s is the number of signal events, free parameter

Point source search

PDF for signal: $$\mathcal{S}_i(\vec{x}_i, \vec{x}_s, E_i, \gamma) = \frac{1}{2\pi\sigma^2} e^{-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma^2}} P(E_i|\gamma)$$

data event coordinates

spatial term

spectral term
E_i data event energy estimate, **γ is the source spectrum power**

PDF for background: $$\mathcal{B}_i = P(\vec{x}_i, E_i | \phi_{atm} + \phi_{mu} + \phi_{diffuse})$$

Likelihood is maximised with free n_s and γ

- Depending on analysis γ can also be fixed to some value or set of values

The test statistic of the form $$\lambda = -2 \cdot sign(\hat{n}_s) \cdot log\left[\frac{\mathcal{L}(\vec{x}_s, 0)}{\mathcal{L}(\vec{x}_s, \hat{n}_s, \hat{\gamma})}\right]$$ is used for hypothesis testing

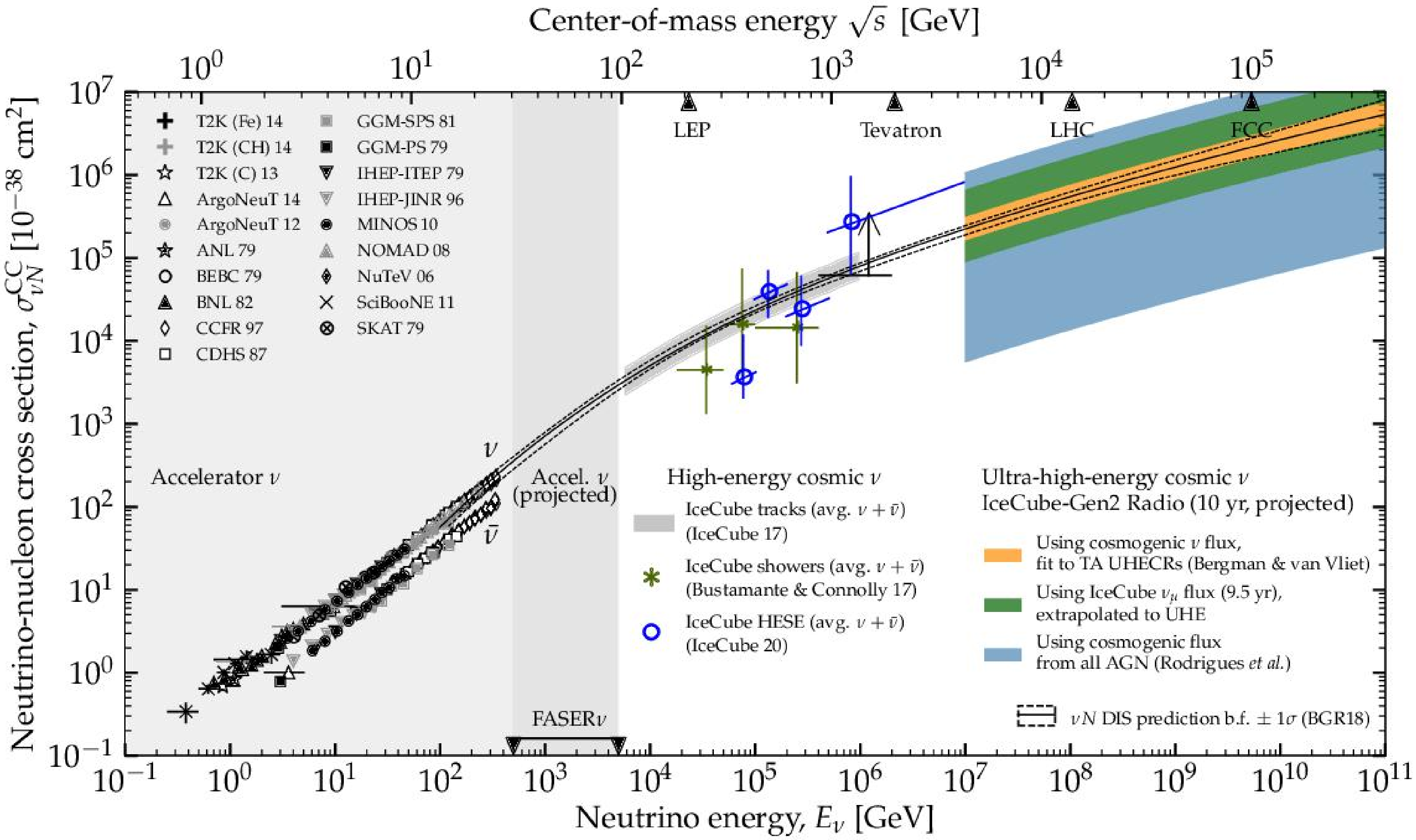
The power of good angular resolution

- The better the angular resolution - the smaller is the (RA, dec) region, the less background enters N
- The test statistic gains larger value for optimal parameters, thus better discovery potential

Next lecture

- Passage of charged particles through the detector
- Photodetector response
- Detection medium backgrounds
- Detector readout and triggering
- Detector positioning and calibrations

BACKUP



Center-of-mass energy $\sqrt{s}$ [GeV]
10^0 10^1 10^2 10^3 10^4 10^5
LEP
Tevatron
LHC
FCC
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Accelerator ν
Accel. ν (projected)
FASERν
ν
$\bar{\nu}$
High-energy cosmic ν
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (Bustamante & Connolly 17)
IceCube HESE (avg. $\nu + \bar{\nu}$) (IceCube 20)
Ultra-high-energy cosmic ν
IceCube-Gen2 Radio (10 yr, projected)
Using cosmogenic ν flux, fit to TA UHECRs (Bergman & van Vliet)
Using IceCube ν_μ flux (9.5 yr), extrapolated to UHE
Using cosmogenic flux from all AGN (Rodrigues *et al.*)
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
Neutrino-nucleon cross section, $\sigma^{CC}_{\nu N}$ [10^{-38} cm^2]
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
Neutrino energy, E_ν [GeV]

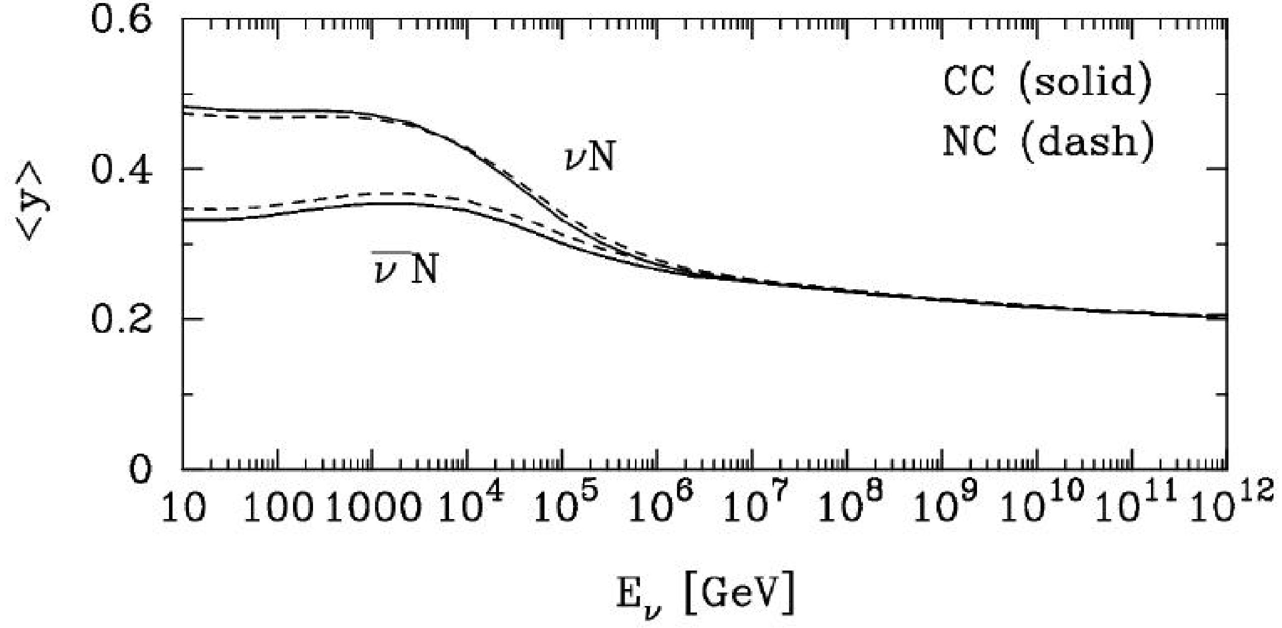
High-energy neutrino interaction with matter

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



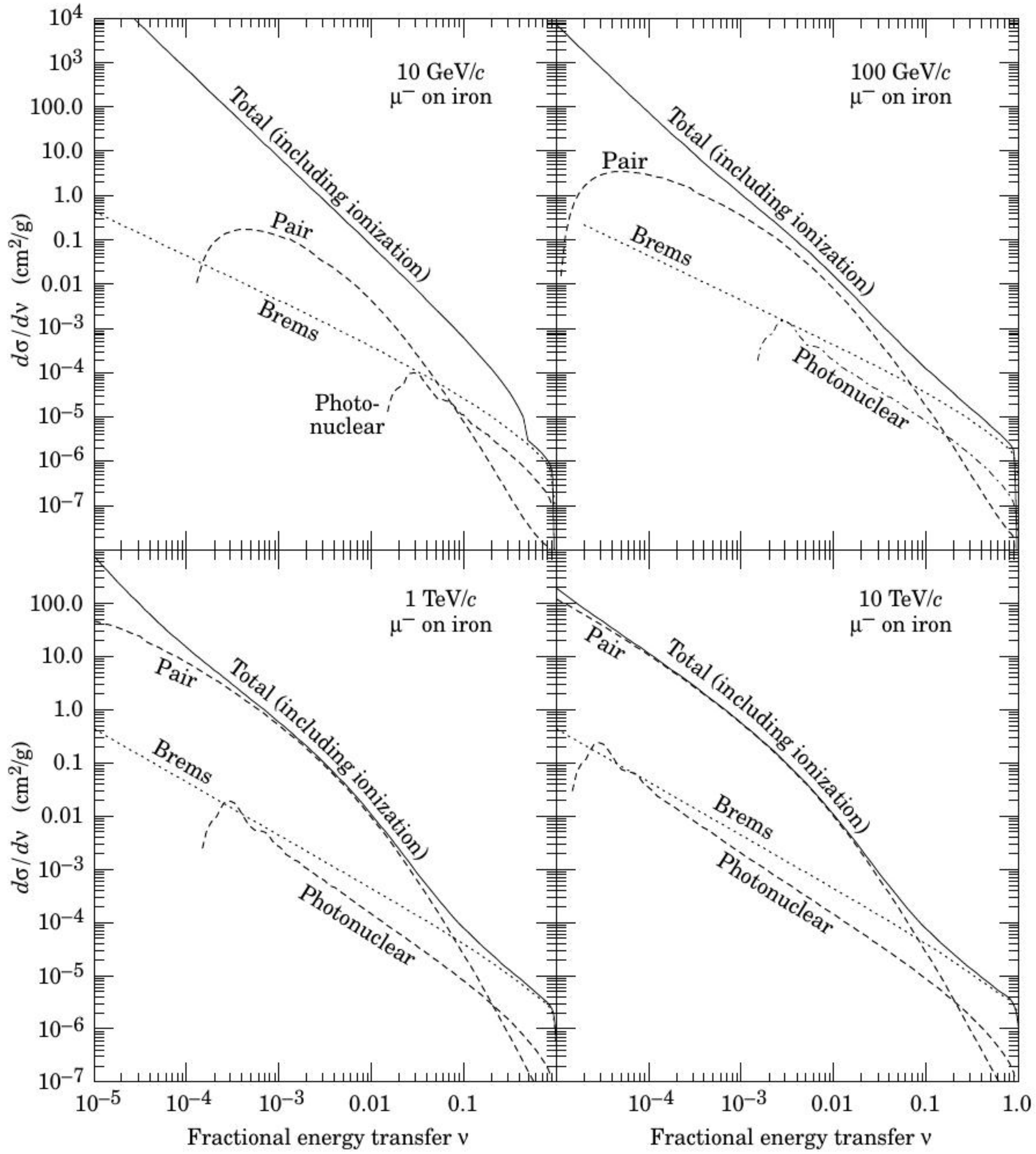
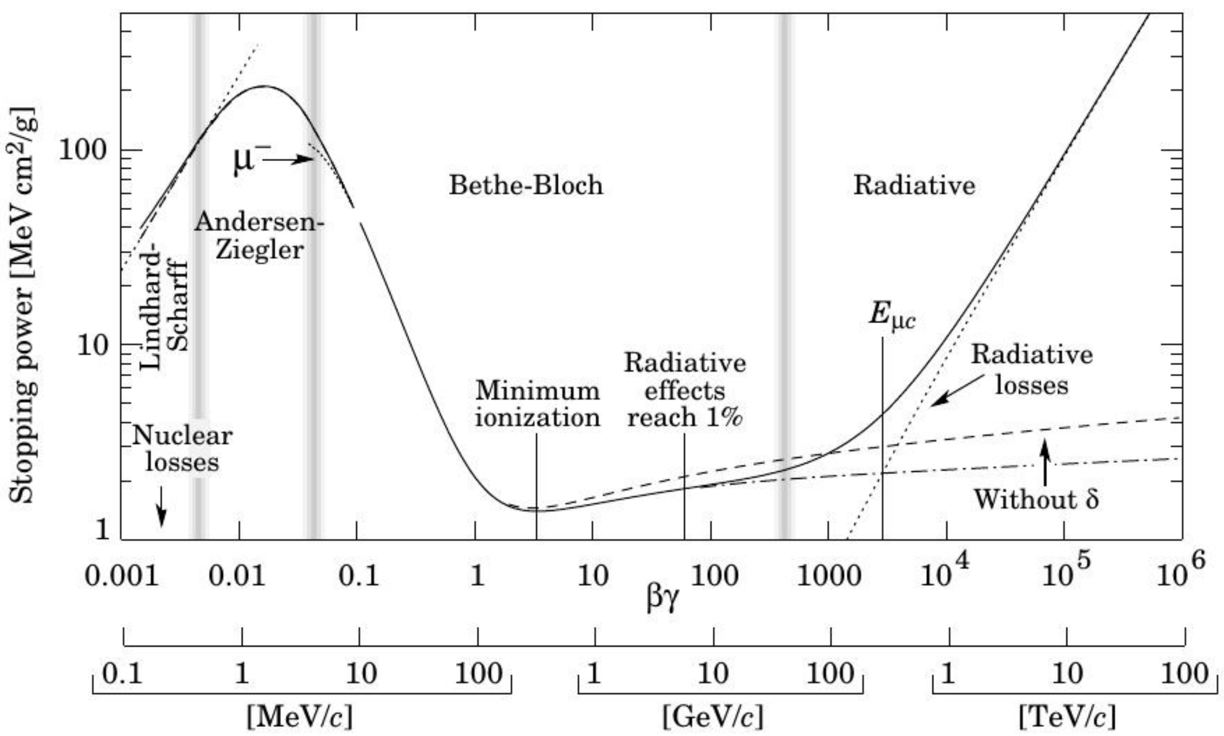
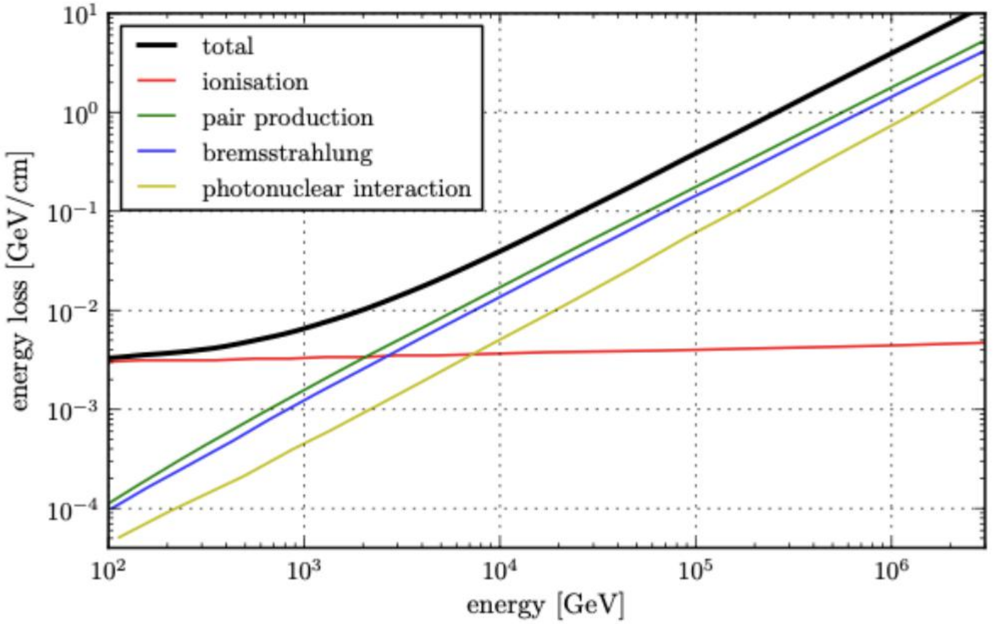


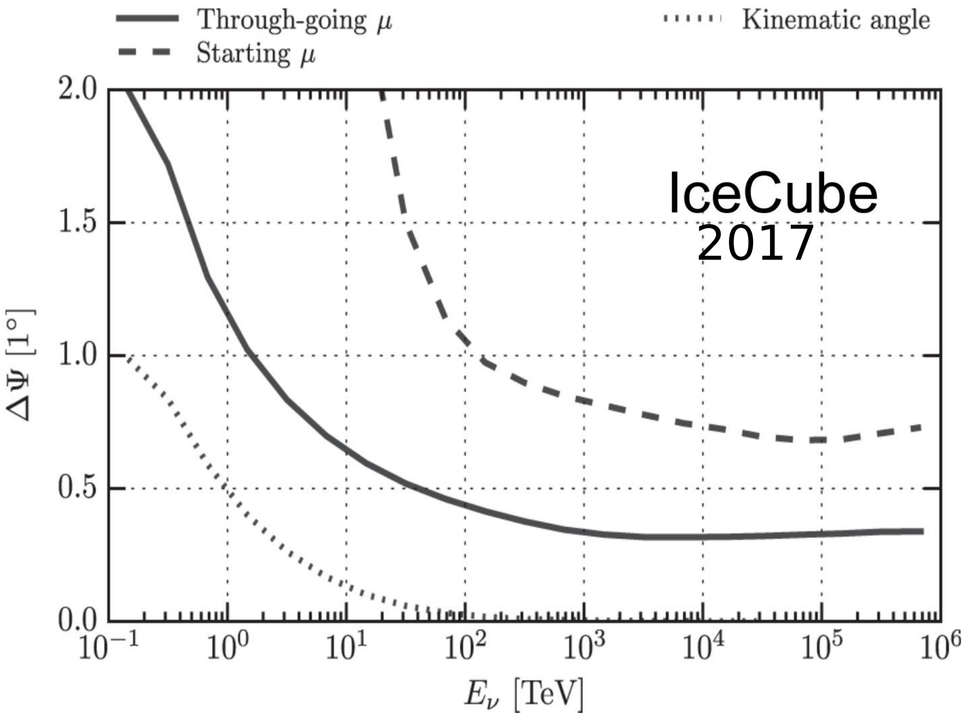
Figure 4: Differential cross section for total and radiative processes as a function of the fractional energy transfer for muons on iron.

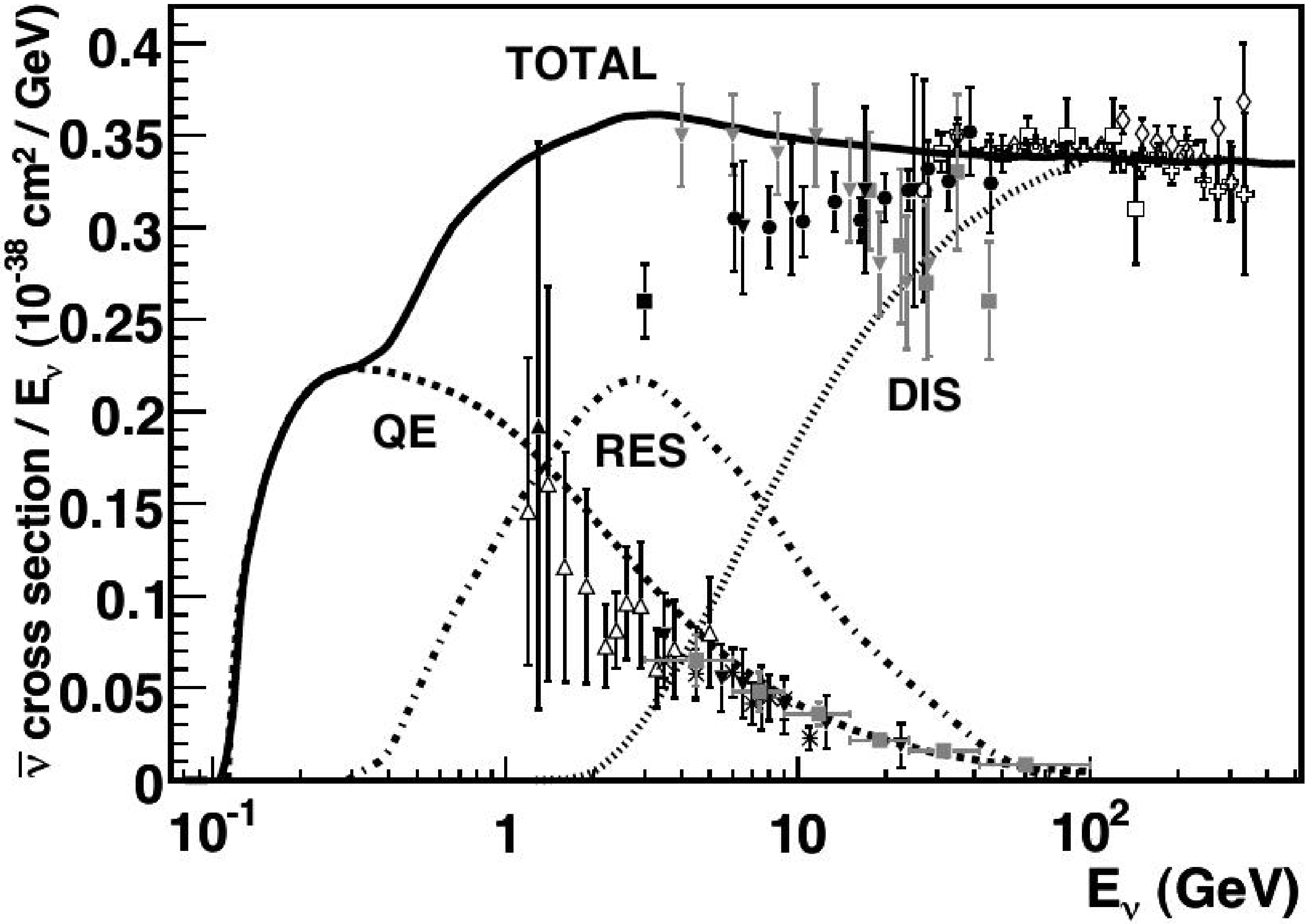




Angular resolution

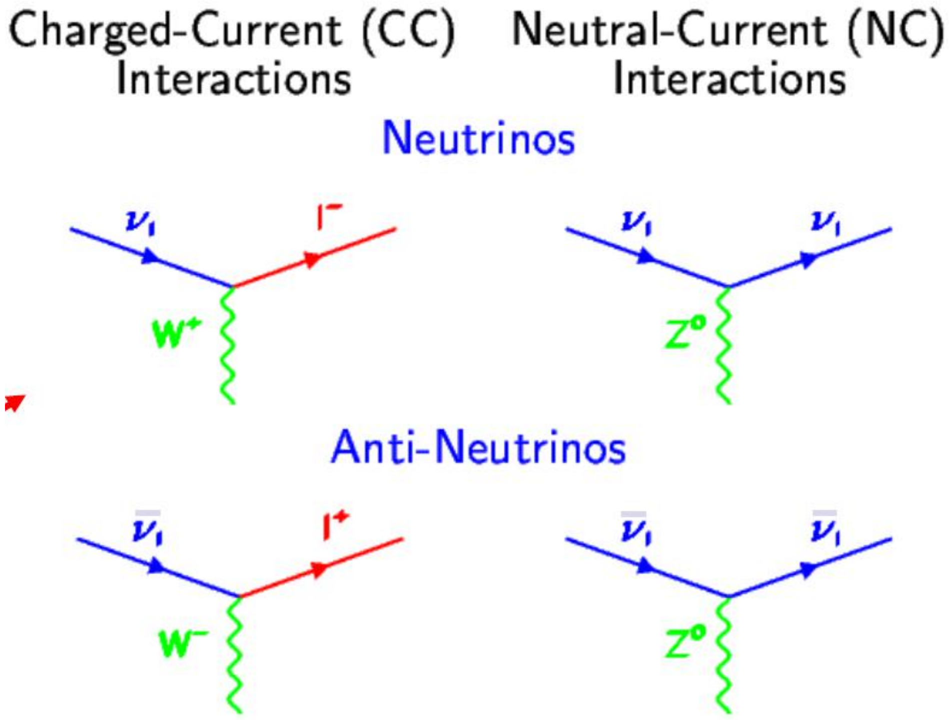
$$\sqrt{\langle\theta^2\rangle} \approx \frac{1.5^\circ}{\sqrt{E_\nu\,[\mathrm{TeV}]}}$$



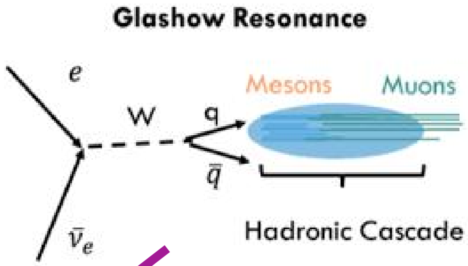


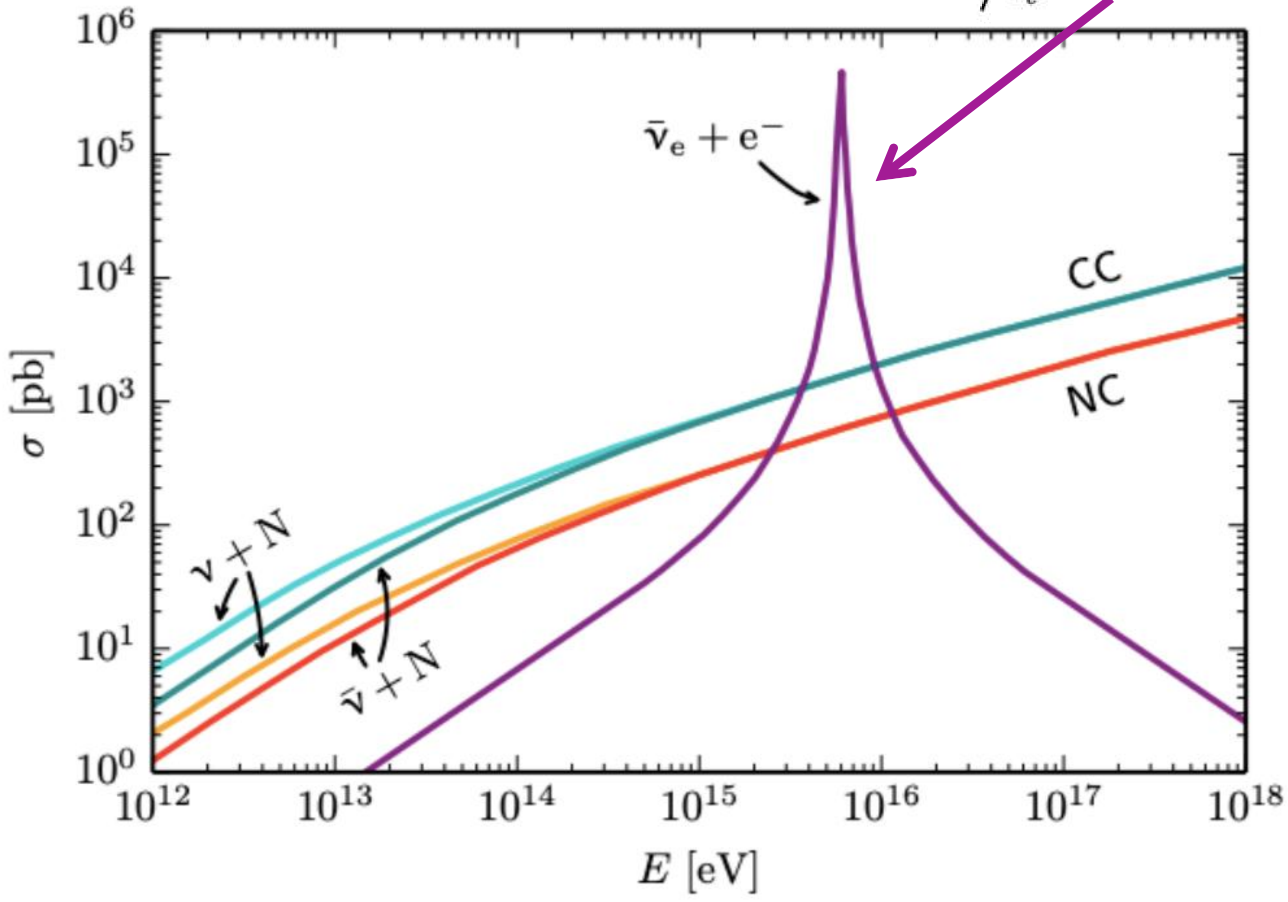
$\bar{\nu}$ cross section / E_ν (10^{-38} cm^2 / GeV)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
TOTAL
QE
RES
DIS
10^{-1}
1
10
10^2
E_ν (GeV)

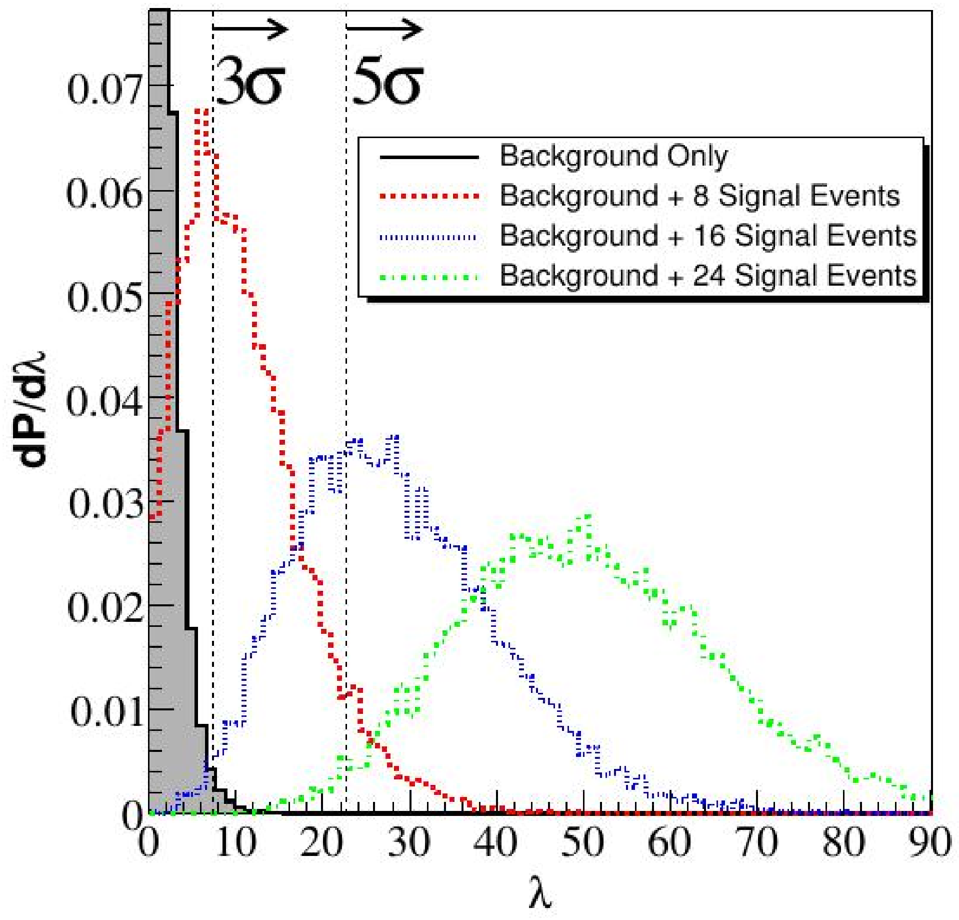
High-energy neutrino interaction with matter



Glashow resonance







3σ
5σ
Background Only
Background + 8 Signal Events
Background + 16 Signal Events
Background + 24 Signal Events
dP/dλ
λ
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
10
20
30
40
50
60
70
80
90