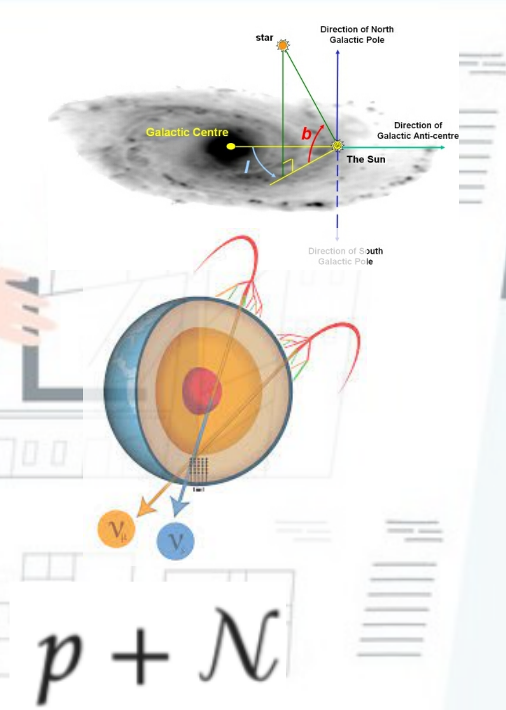
High Energy Neutrino Astronomy



Elisa Resconi

Experimental Physics with Cosmic Particles, TU Munich

@rdvvector

In these two lectures

The principles

- Grand Unified Neutrino Spectrum (GUNS)
- The neutrino cross sections
- Atmospheric muons and neutrinos
- The telescopes

The signals

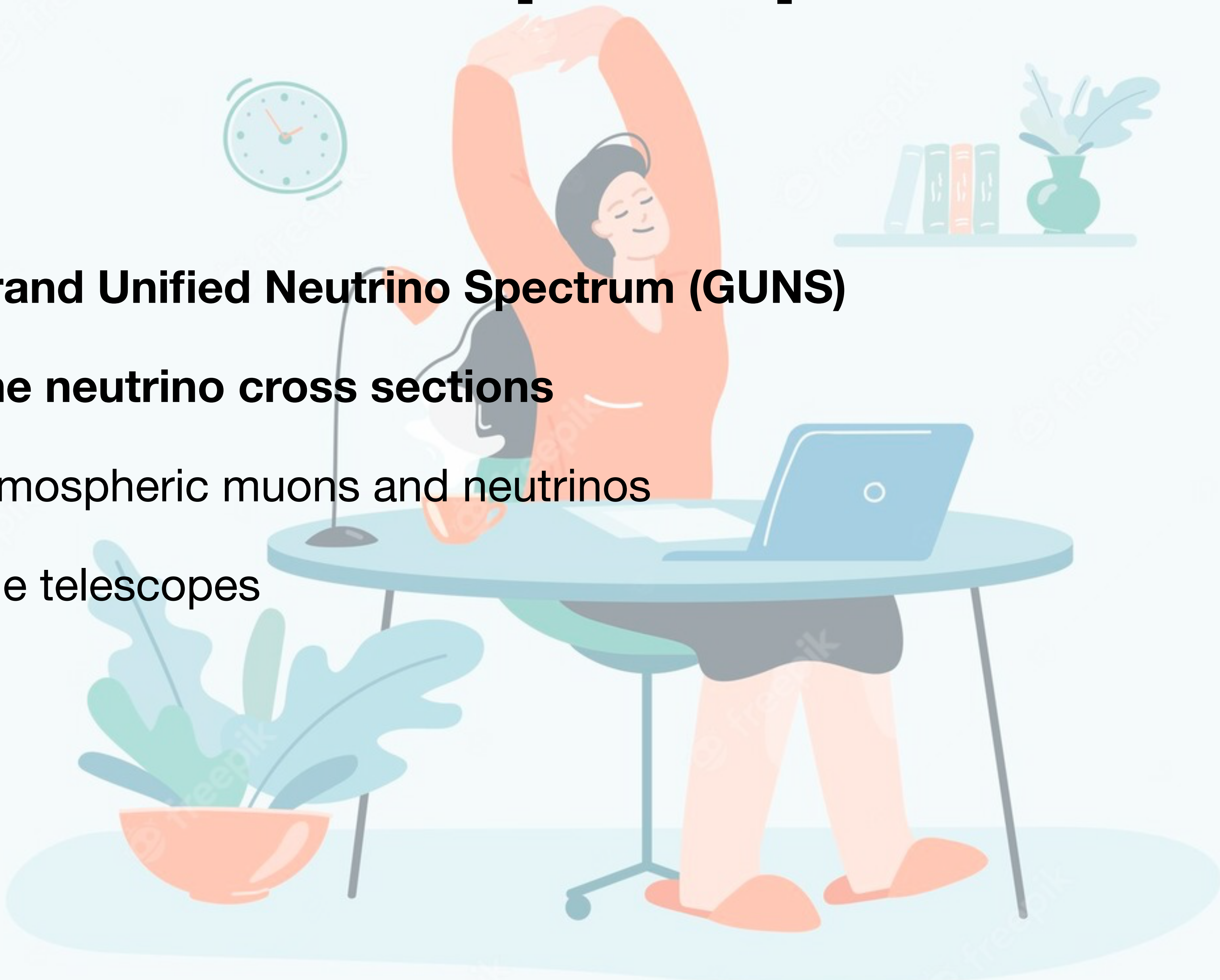
- The high energy neutrino background
- The first associations: AGN
- The Galactic plane

The future

- Next generation telescopes
- The PLEnuM effort

Central references highlighted in yellow

The principles

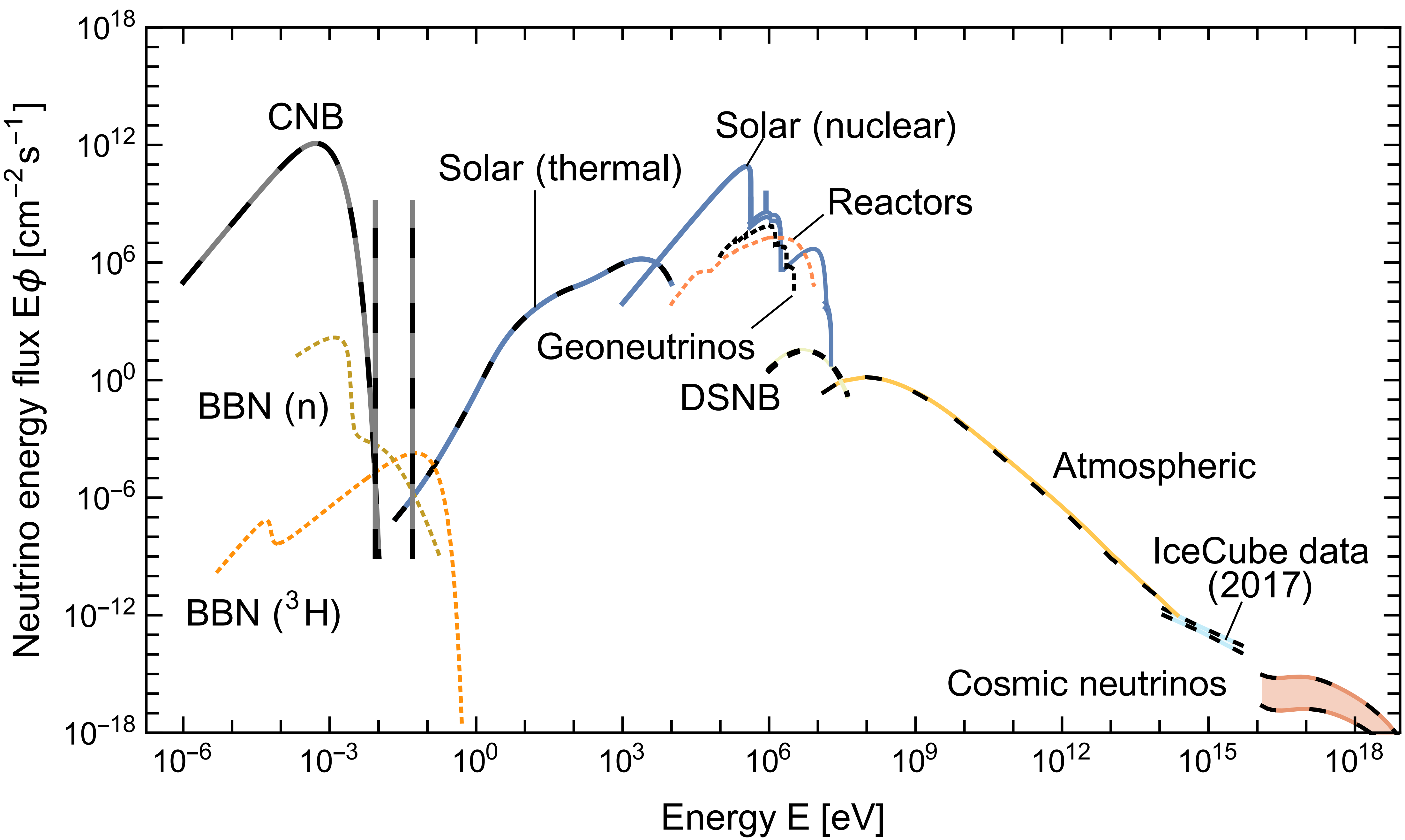


- **Grand Unified Neutrino Spectrum (GUNS)**
- **The neutrino cross sections**
- Atmospheric muons and neutrinos
- The telescopes

Vitagliano, Tamborra, Raffelt, Rev.Mod.Phys (2019), https://arxiv.org/pdf/1910.11878.pdf

NEUTRINOs from the Universe

Grand Unified Neutrino Spectrum (GUNS) at Earth integrated over directions and flavors



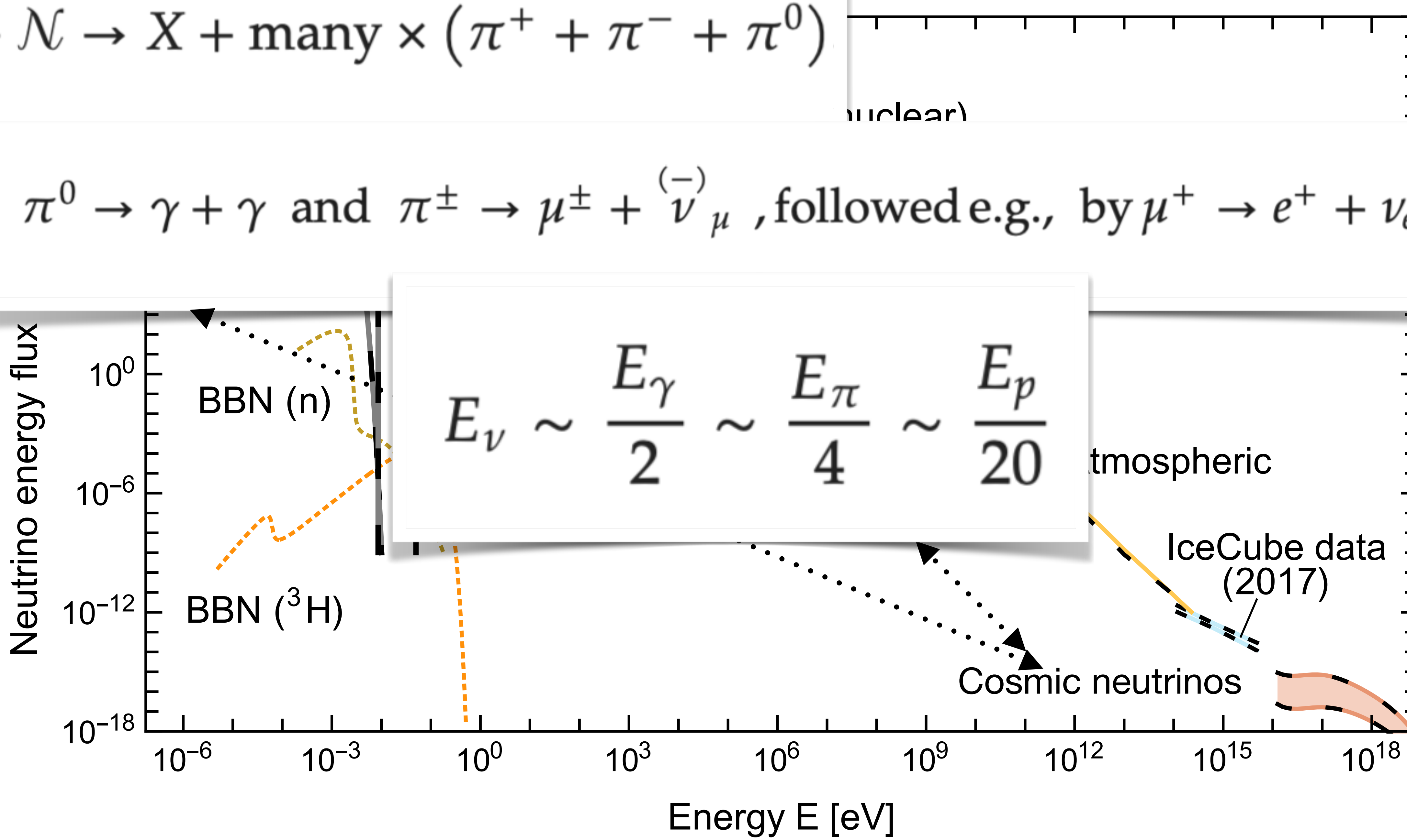
Palladino, Spurio, Vissani, https://www.mdpi.com/2218-1997/6/2/30

NEUTRINOs from the (HE) Universe

$$p + \mathcal{N} \rightarrow X + \text{many} \times (\pi^+ + \pi^- + \pi^0)$$

$$\pi^0 \rightarrow \gamma + \gamma \quad \text{and} \quad \pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu \text{, followed e.g., by } \mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu .$$

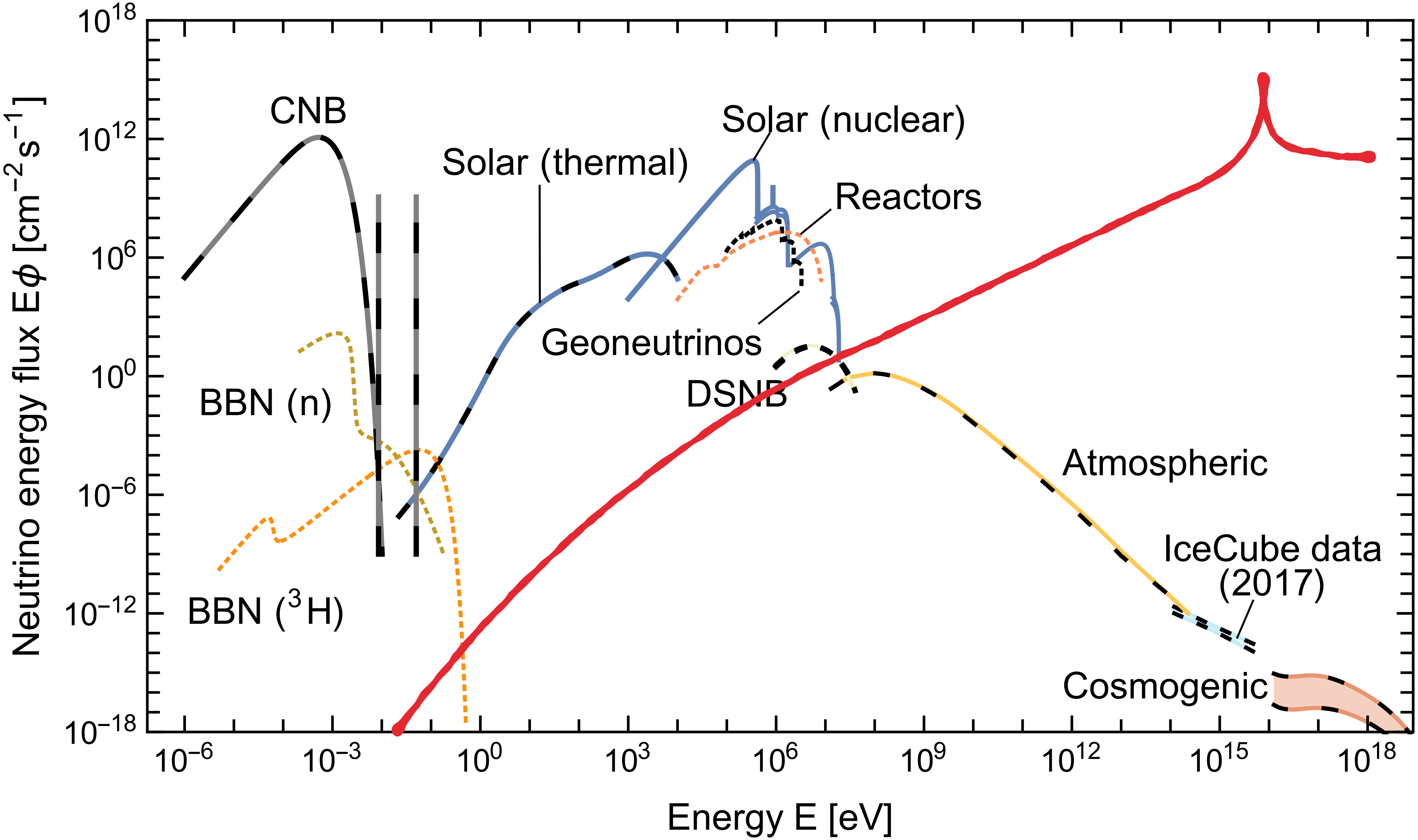
$$E_\nu \sim \frac{E_\gamma}{2} \sim \frac{E_\pi}{4} \sim \frac{E_p}{20}$$



Formaggio, Zeller, Rev. Mod. Phys. 2012, arXiv:1305.7513

The cross sections

Neutrino-electron scattering as example

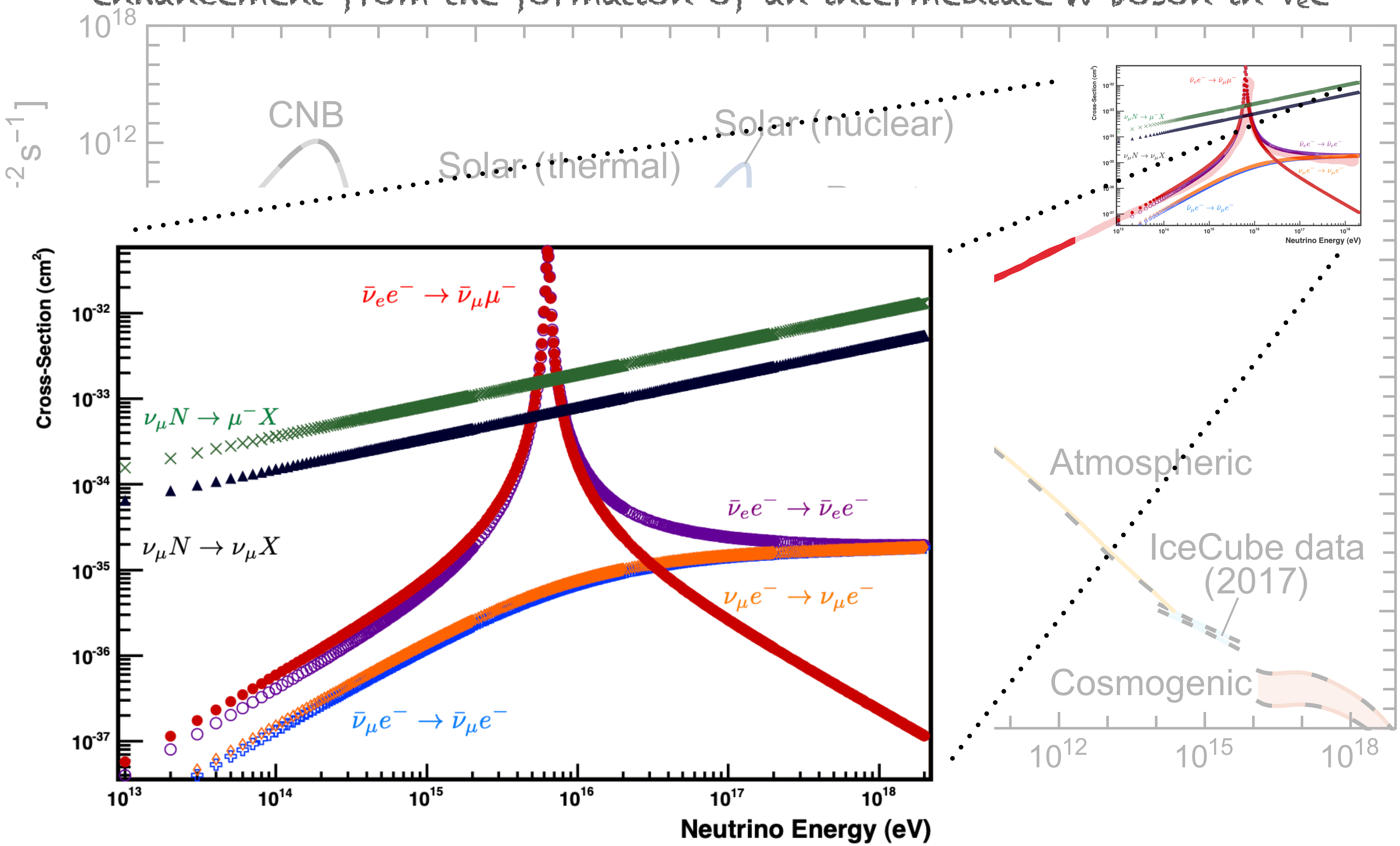


FUTURE '80-PRESENT PRESENT-FUTURE

Formaggio, Zeller, Rev. Mod. Phys. 2012, arXiv:1305.7513

The cross section in the high energy regime

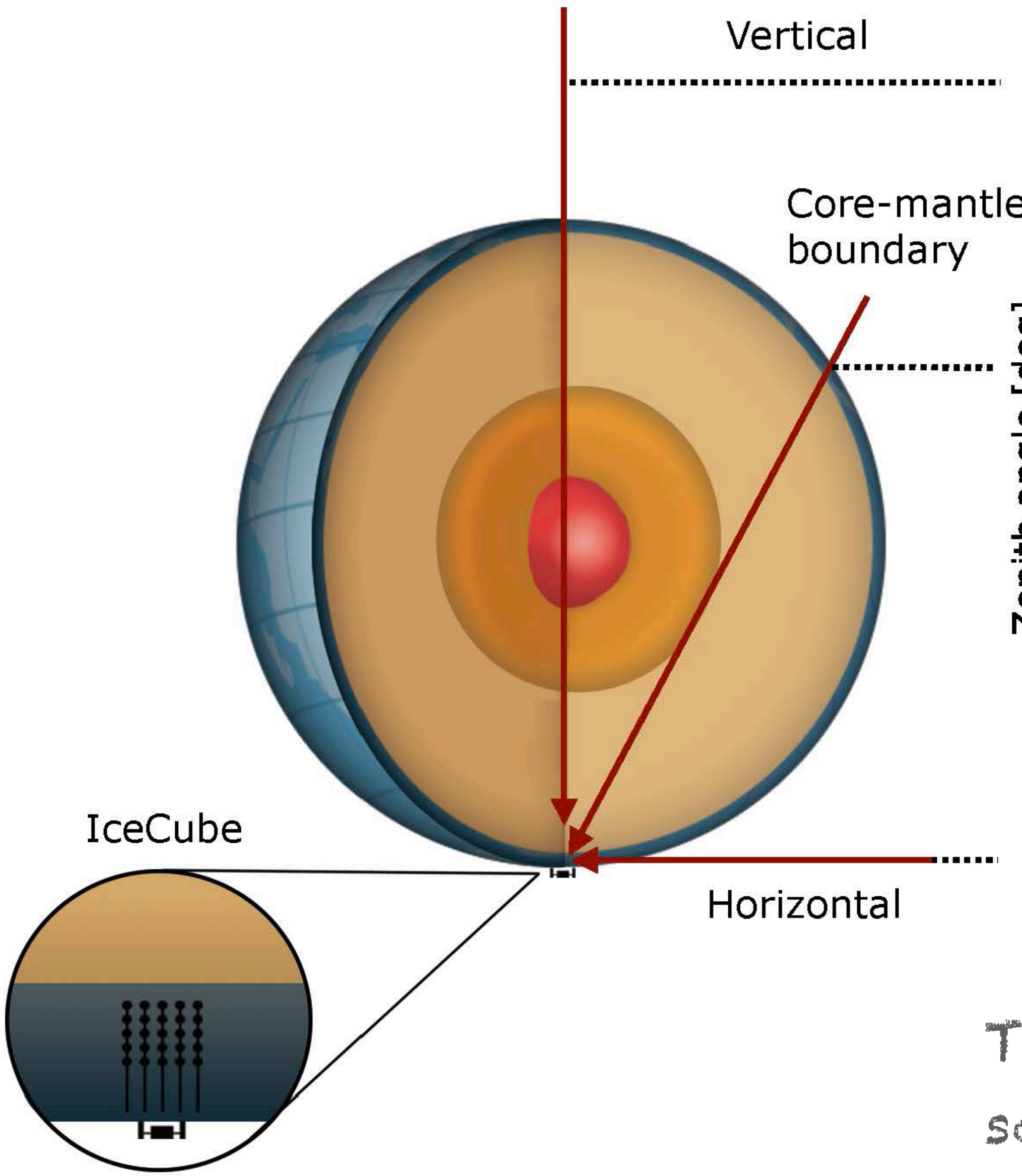
Neutrino-electron scattering sub-dominant to neutrino-nucleus interaction (small target mass). One exception: Glashow resonance resonant enhancement from the formation of an intermediate W-boson in $\bar{\nu}_e e^-$

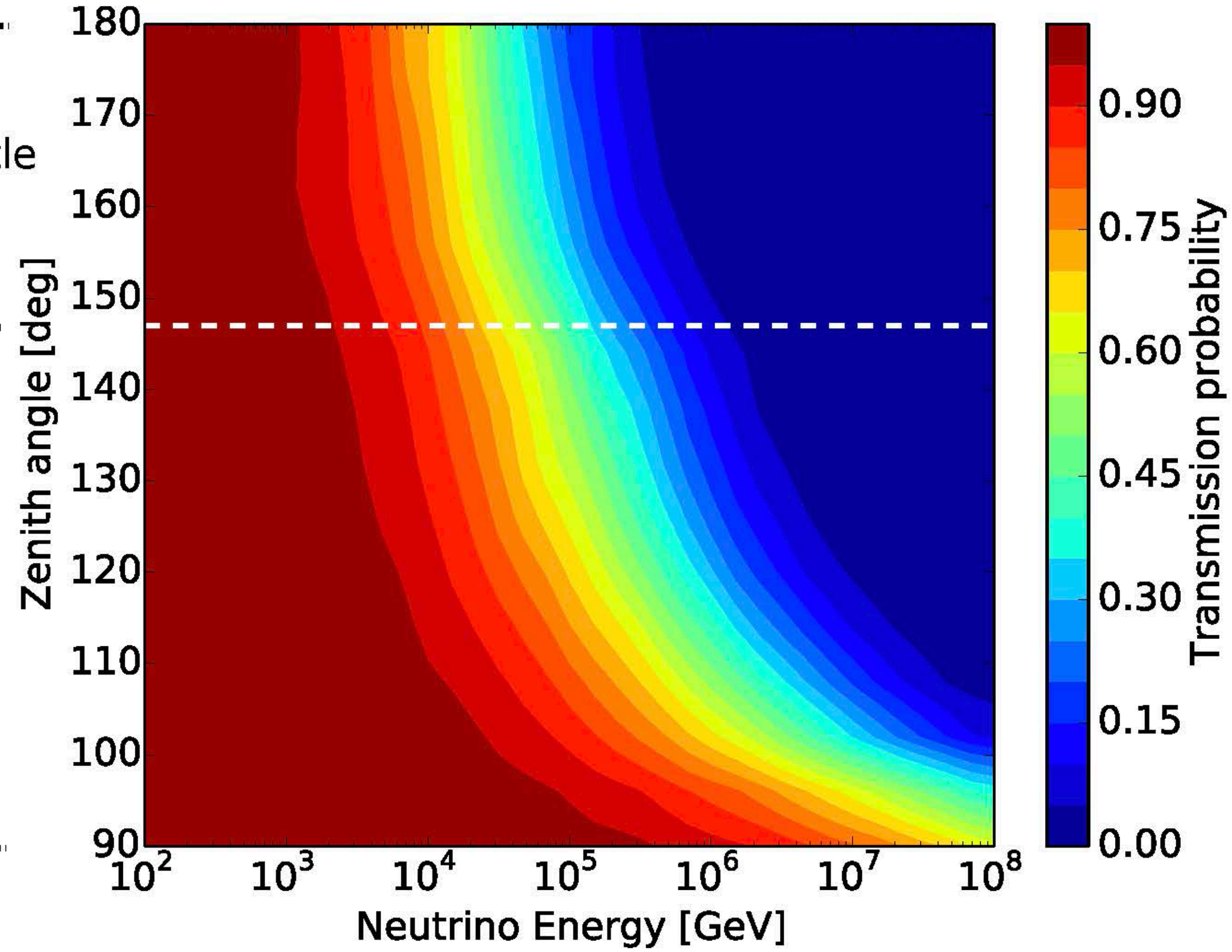


IceCube Collaboration, "Measurement of the multi-TeV neutrino cross section with IceCube using Earth absorption," Nature 551 (2017) 596-600.

The cross section in the high energy regime

At high energy the Earth is NOT transparent to neutrinos





The field of view of NTs gets squeezed around the telescope's horizon (at higher E)

The horizontal sky areas covered

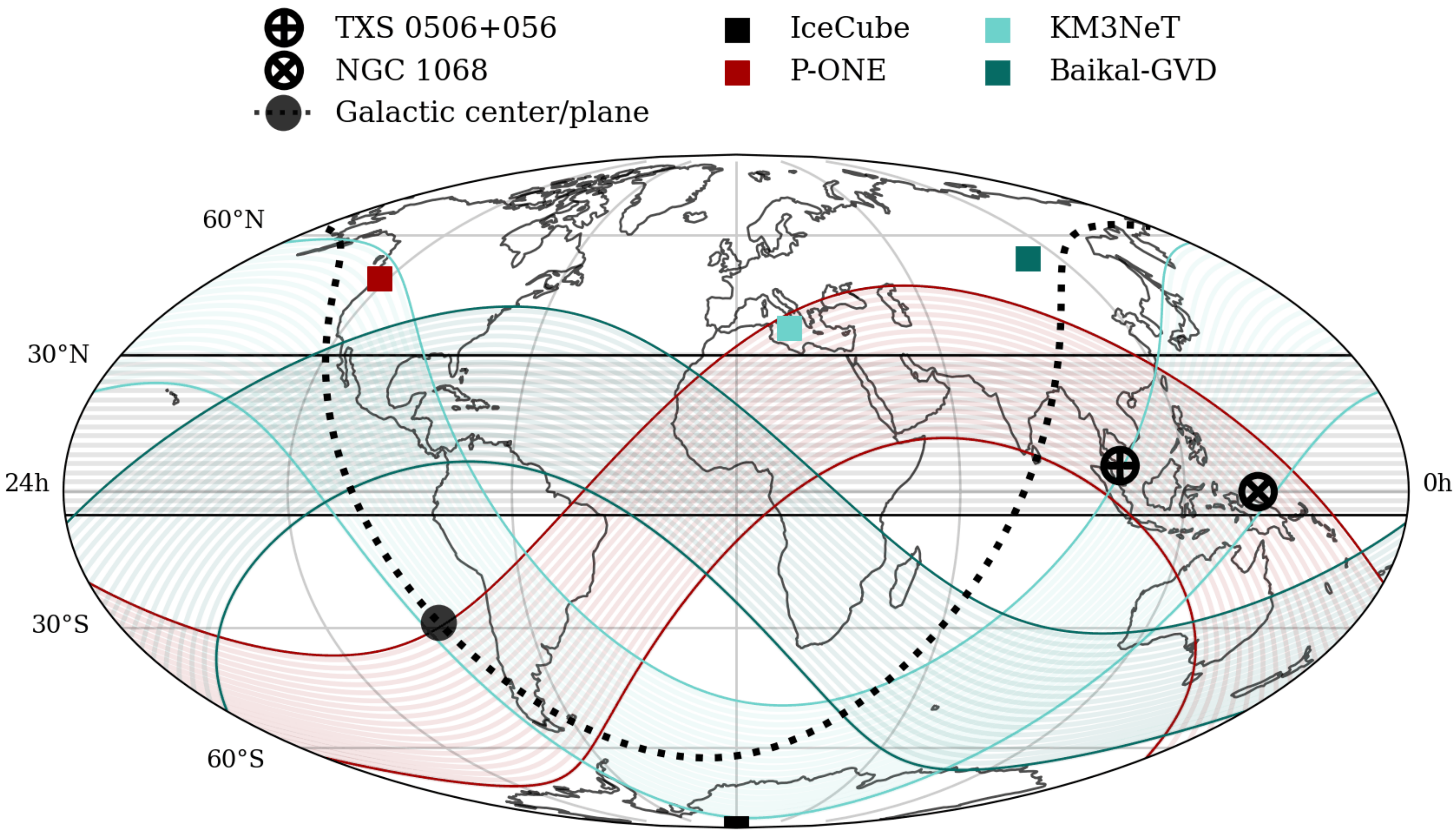
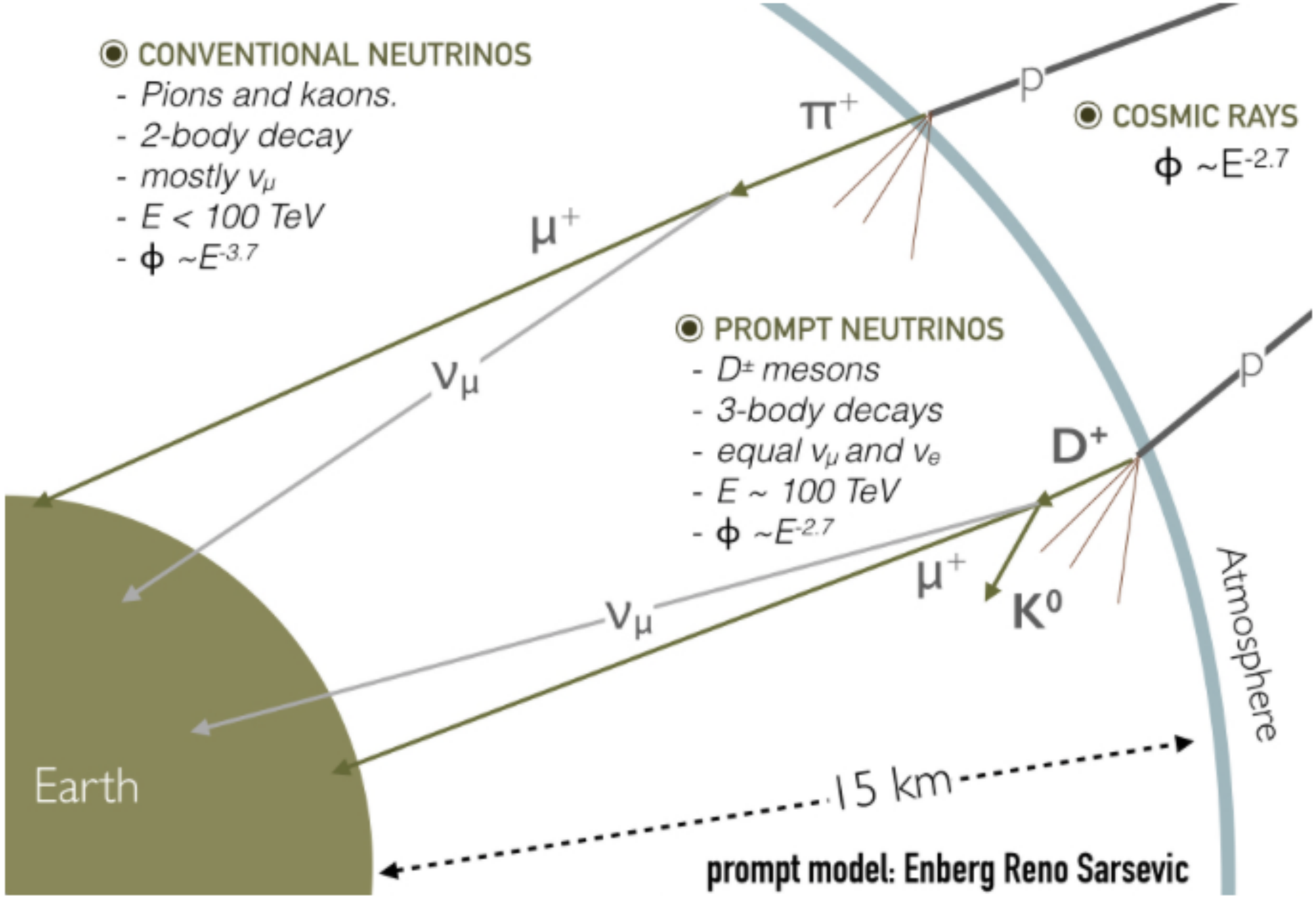


image from M. Huber (TUM), L. Schumacher (ECAP)

The principles

- Grand Unified Neutrino Spectrum (GUNS)
- The neutrino cross sections
- **Atmospheric muons and neutrinos**
- The telescopes

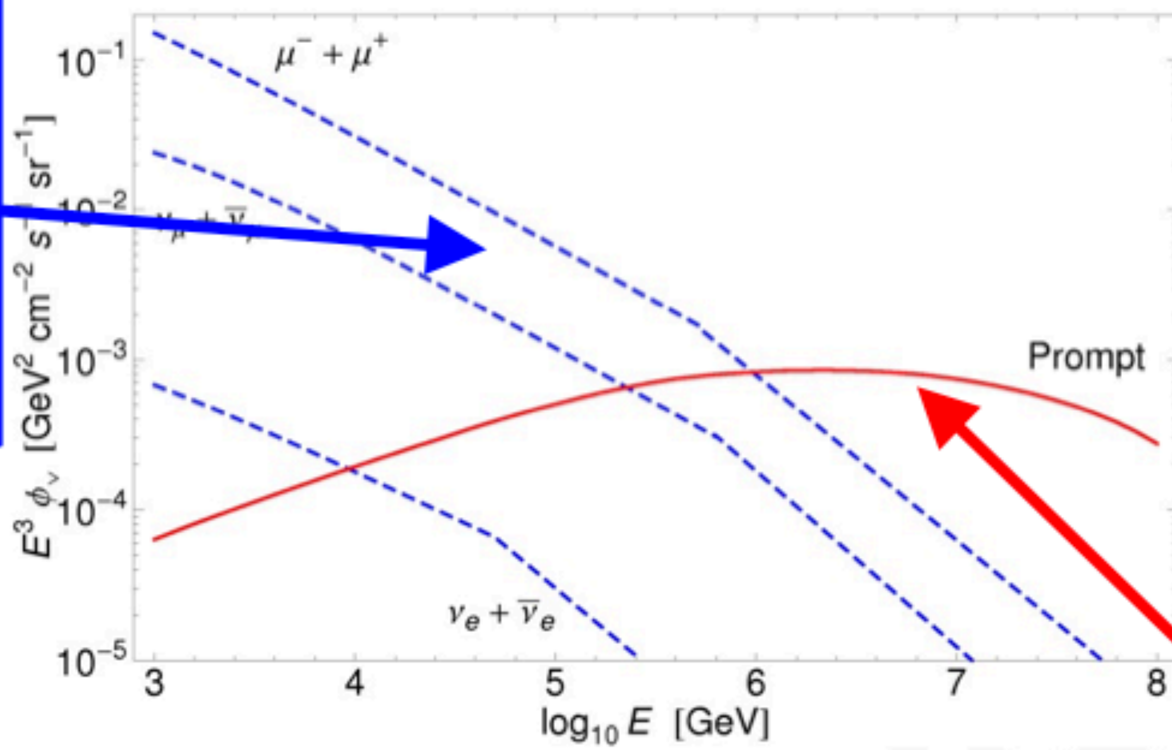
Atmospheric Neutrinos



Atmospheric Neutrinos

Many channels: two families - two spectral indexes

Pions: long-lived
⇒ lose energy
⇒ conventional flux



Charm: short-lived
⇒ don't lose energy
⇒ prompt flux

Pions (and kaons) are produced in more or less every inelastic collision;

$\pi^\pm$, $K^\pm$ are long-lived;

⇒ lose energy through collisions before decay;

⇒ neutrino energies are degraded.

High energy hadronic collisions

QGSJET S. Ostapchenko https://arxiv.org/pdf/2208.05889.pdf
EPOS LHC T. Pierog et al., https://arxiv.org/pdf/1306.0121.pdf
SYBILL F. Riehn et al., https://arxiv.org/pdf/1912.03300.pdf

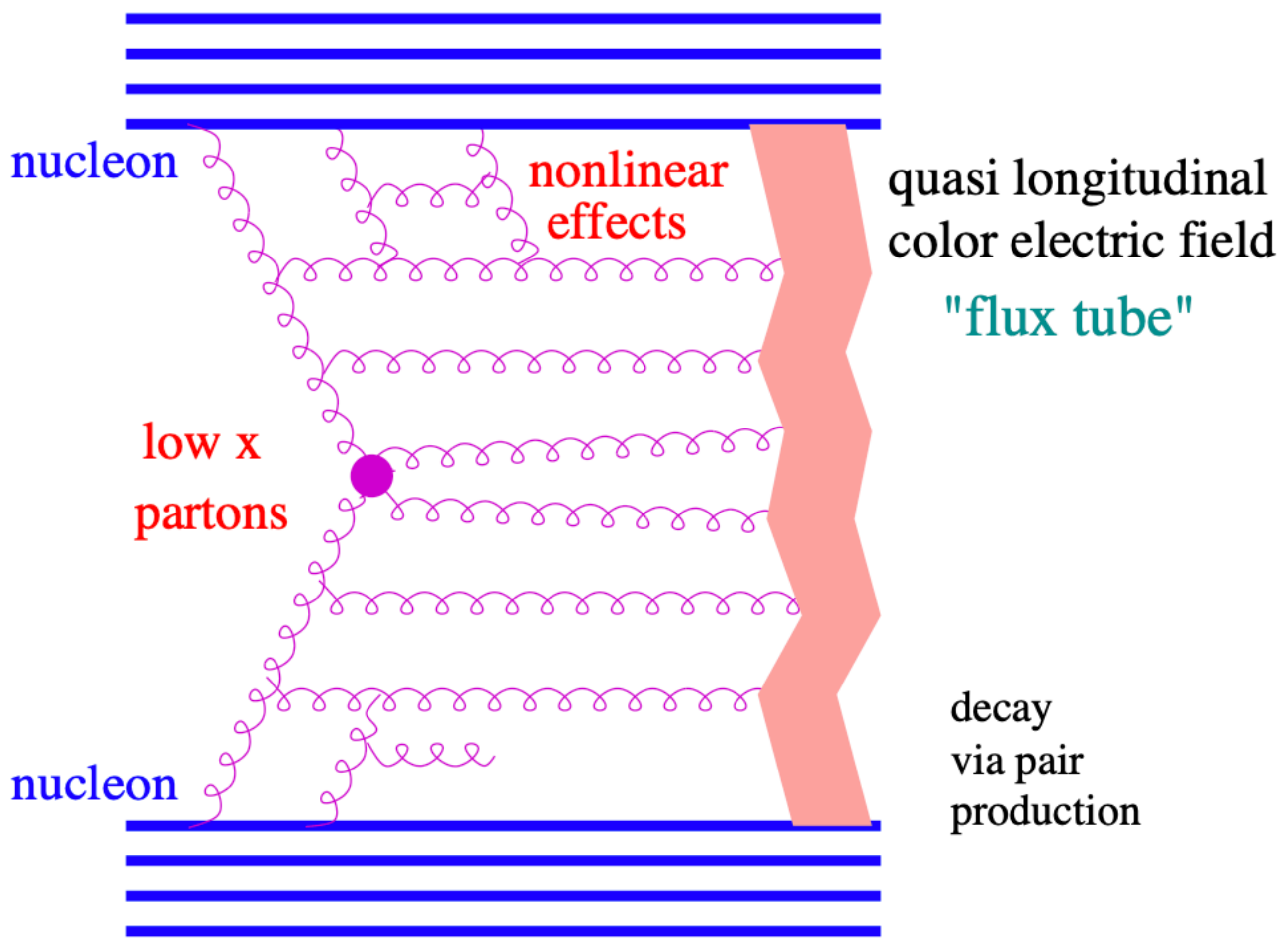
Treatment of hadron-hadron interactions based on QCD.

Monte Carlo approach; generators of high energy hadronic interactions for inelastic collisions with air nuclei of

1) the primary CR particles and
2) secondary hadrons produced in the course of EAS development.

Three main ingredients:

1) phenomenological approaches;
2) calibration of CR interaction models, based on accelerator data (LHC);
3) self-consistency.



High energy hadronic collisions

What do these models calculate? example:

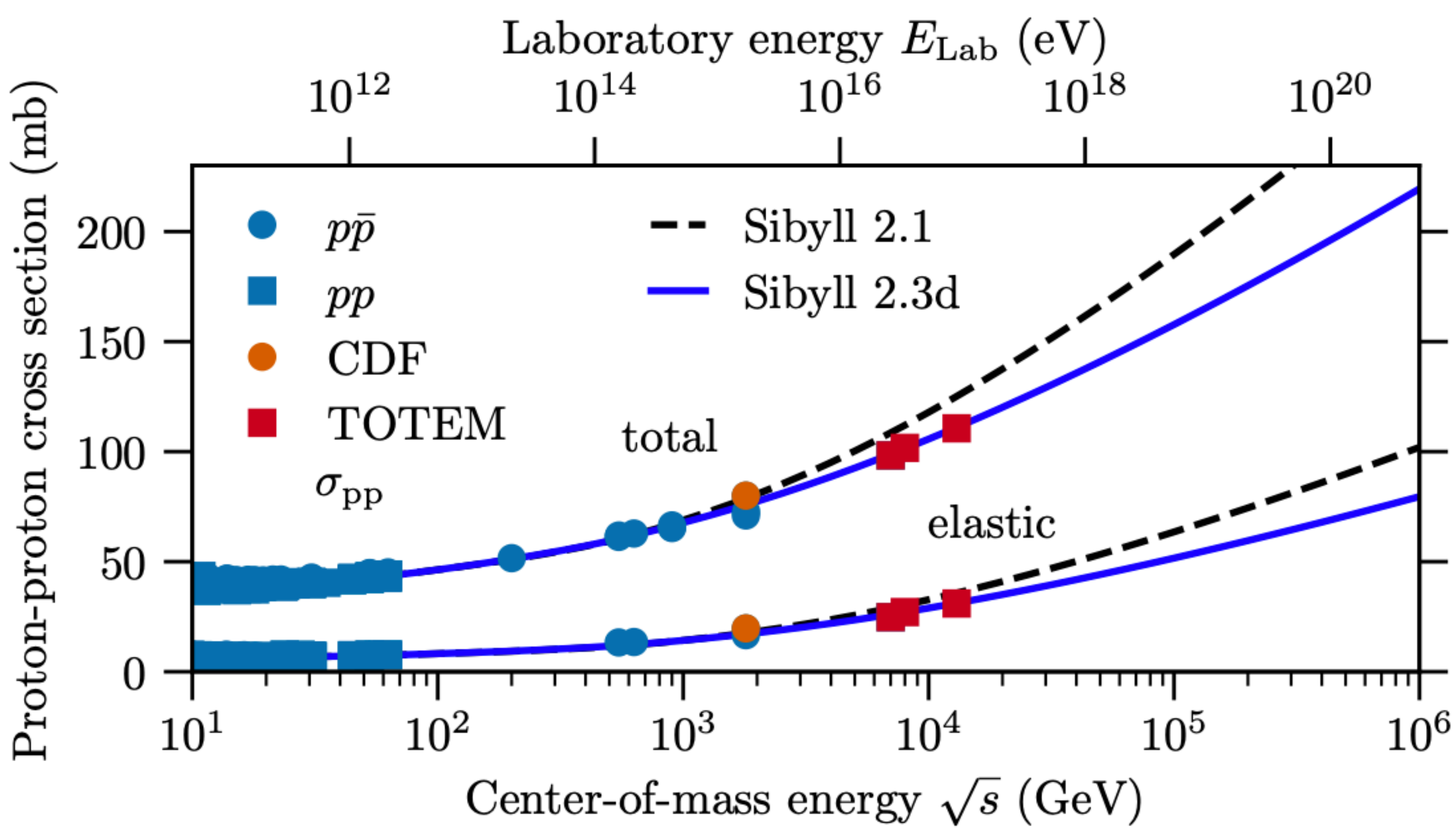


FIG. 5. Total and elastic proton–proton cross section. SIBYLL 2.1 is tuned to the 1.8 TeV CDF value at the Tevatron [60, 64]. The narrower hard interaction profile reduces the inelastic cross section (see Figure 6) in SIBYLL 2.3d such that total and elastic cross sections coincide with the TOTEM measurements at the LHC [65, 66].

High energy hadronic collisions

What do these models calculate? example:

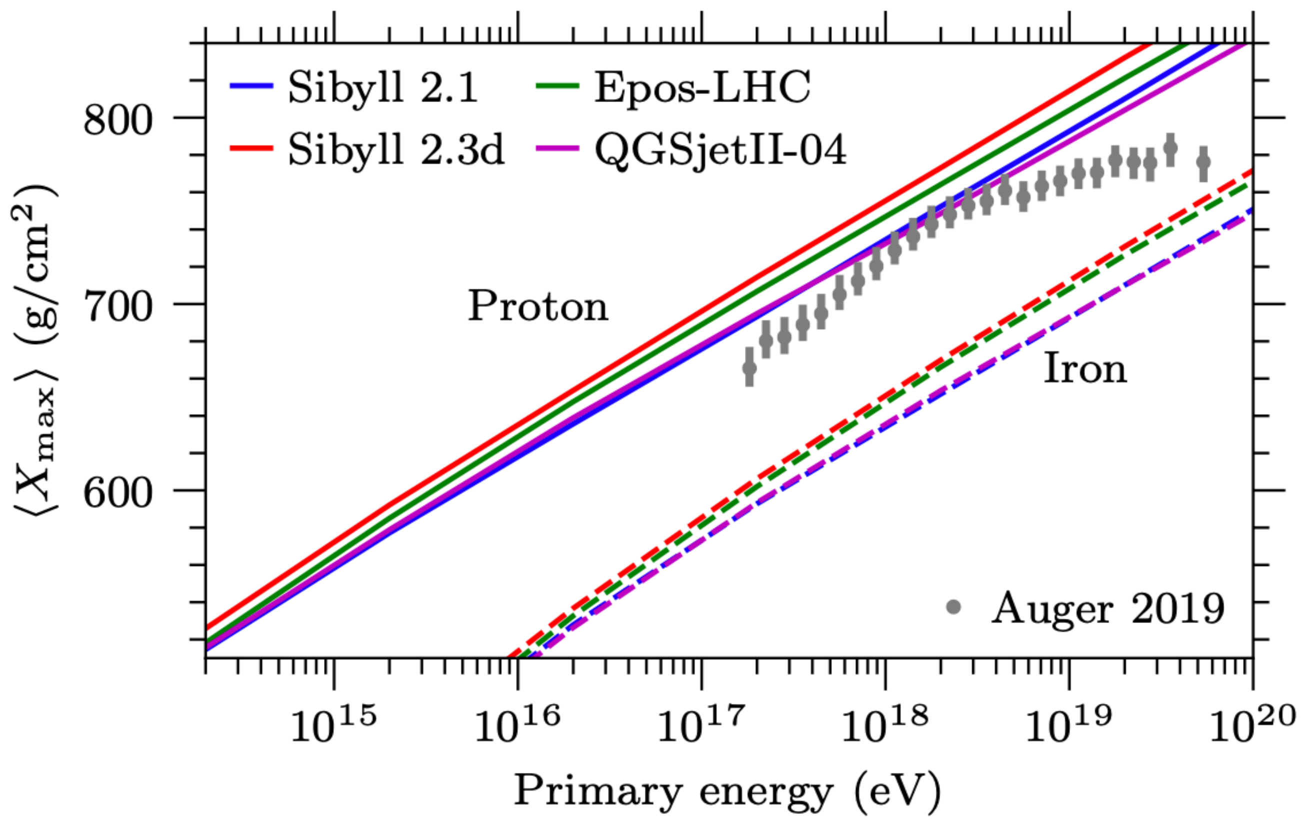


FIG. 26. Average depth of air-shower maxima $\langle X_{\mathrm{max}} \rangle$ for different models compared to recent data from the Pierre Auger Observatory [128, 129] obtained with the fluorescence detectors. The model lines represent the expectations for a pure proton and iron composition, respectively. The deviation of the data from the pure composition indicates a change toward a mixed composition, i.e. cosmic-ray consist of a combination of light and heavier nuclei. The modifications in SIBYLL 2.3d drive the interpretation toward heavier nuclei since the $\langle X_{\mathrm{max}} \rangle$ becomes deeper.

High energy hadronic collisions

What do these models calculate? example:

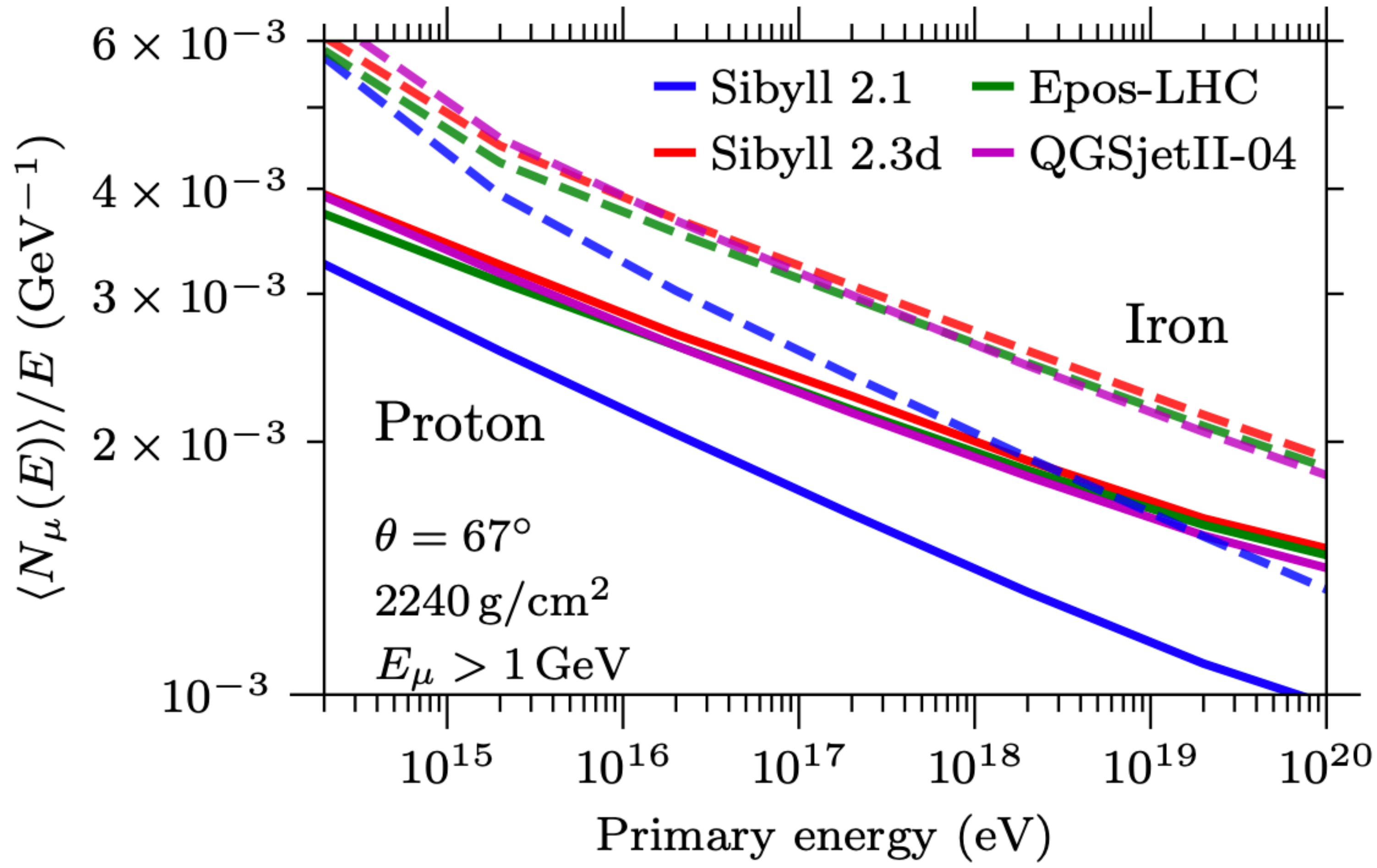


FIG. 33. Average number of muons at ground in proton and iron showers in air for $E_\mu > 1\,\text{GeV}$. It is remarkable that at 10^{17} eV, the expectation from SIBYLL 2.3d for protons overtakes iron in SIBYLL 2.1.

Production of secondary particles (leptons)

The cascade equation

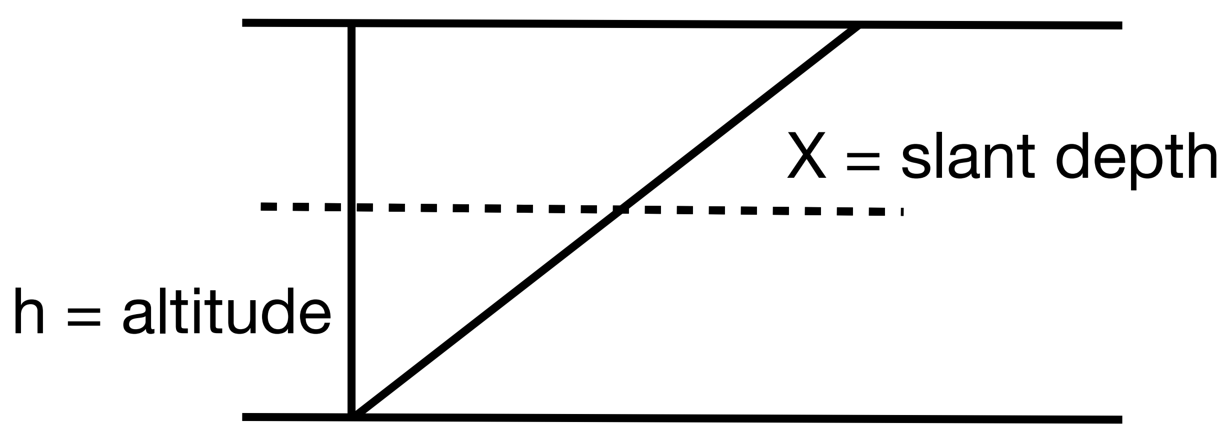
One-dimensional cascade equation

$$\frac{dN(E,X)}{dX} = -\frac{N(E,X)}{\lambda_N(E)} + \int_E^\infty \frac{N(E',X)}{\lambda_N(E')} F_{NN}(E,E') \frac{dE'}{E}$$

where:

- N(E,X)dE = flux of nucleons (n,p) at depth X in the atmosphere with energy interval E, E+dE

- X [g/cm^2]= slant depth = distance from the top of the atmosphere downward along the direction of the incident



Production of secondary particles (leptons)

https://indico.scc.kit.edu/event/667/contributions/7176/attachments/3515/5146/200625_CKA8_WS_Anatoli.pdf

Matrix Cascade Equations (MCEq)
Open source numerical iterative cascade equation solver

System of coupled non-linear PDE for each particle species *h* :

$$\frac{\mathrm{d}\Phi_h(E,X)}{\mathrm{d}X} = -\frac{\Phi_h(E,X)}{\lambda_{\mathrm{int},h}(E)} - \frac{\Phi_h(E,X)}{\lambda_{\mathrm{dec},h}(E,X)} - \frac{\partial}{\partial E}(\mu(E)\Phi_h(E,X)) + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{int},k}(E_k)} + \sum_k \int_E^\infty \mathrm{d}E_k \frac{\mathrm{d}N^{\mathrm{dec}}_{k(E_k)\to h(E)}}{\mathrm{d}E}\frac{\Phi_k(E_k,X)}{\lambda_{\mathrm{dec},k}(E_k,X}$$

cosmic ray physics

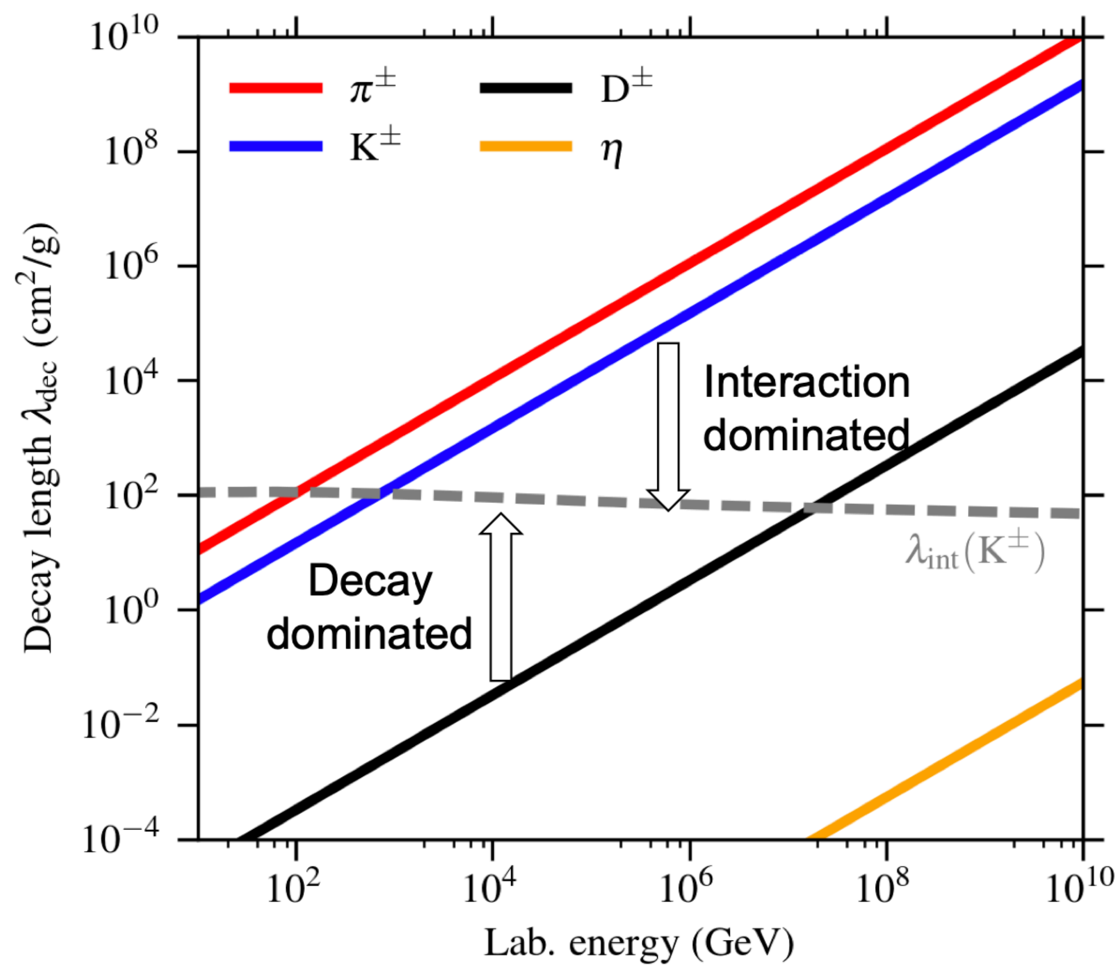
Interactions with air

Decays

atmospheric physics

Continuous losses

particle physics



$$X(h_0) = \int_0^{h_0} \mathrm{d}\ell\ \rho_{\mathrm{air}}(\ell)$$

https://github.com/mceq-project/MCEq

Production of secondary particles (leptons)

https://indico.scc.kit.edu/event/667/contributions/7176/attachments/3515/5146/200625_CKA8_WS_Anatoli.pdf

Matrix Cascade Equations (MCEq)
Open source numerical iterative cascade equation solver, very flexible, allows to compare different interaction models (theoretical systematic uncertainties)

INPUT

Hadronic interaction models are:

- SIBYLL-2.3c (=d: will be fixed in next release)
- SIBYLL-2.3c01
- SIBYLL-2.3
- SIBYLL-2.1
- EPOS-LHC
- QGSJet-II-04
- QGSJet-II-03
- QGSJet-01c
- DPMJET-III-3.0.6
- DPMJET-III-19.1
- SIBYLL-2.3c_pp (for proton-proton collisions)

Atmosphere models from

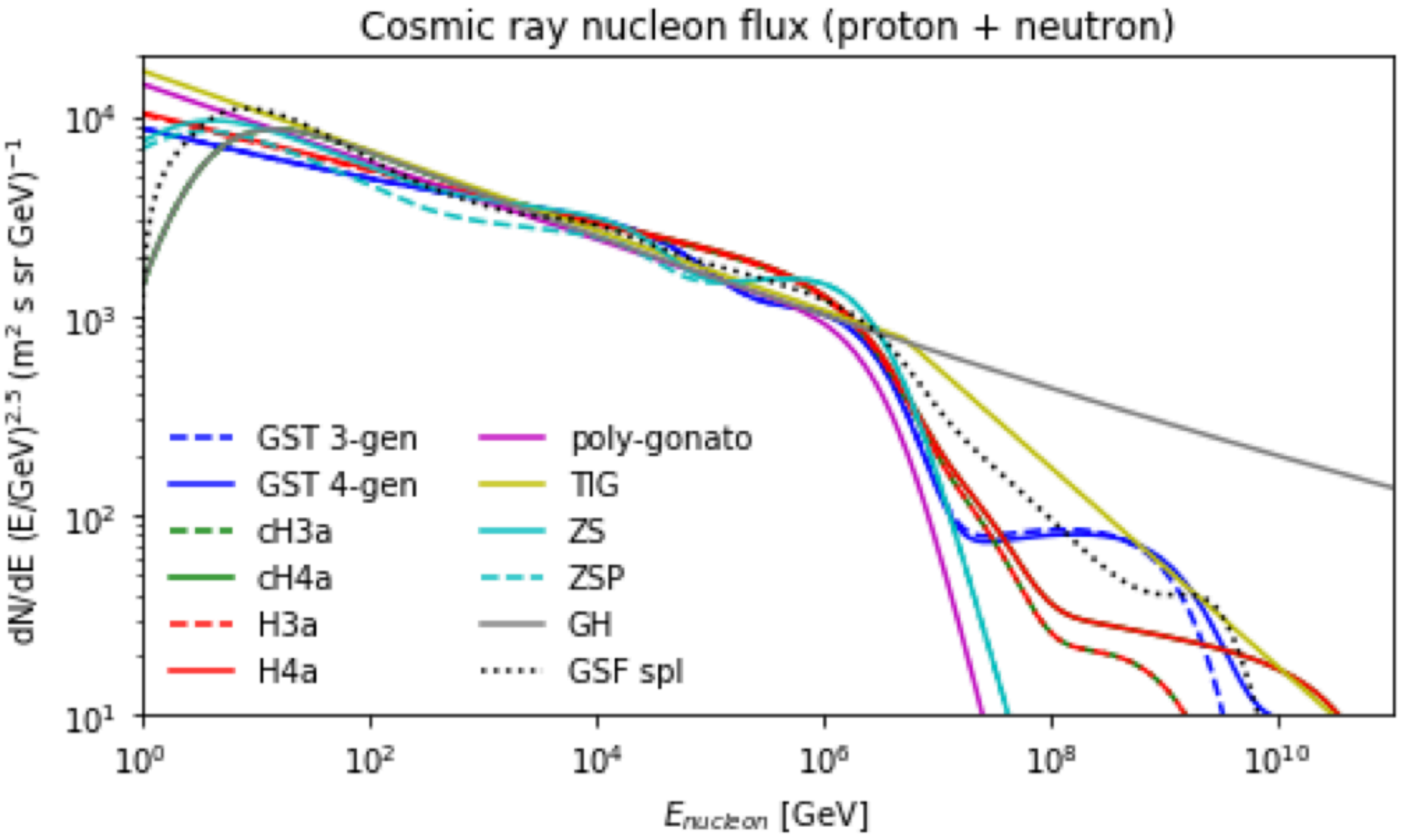
- CORSIKA7 (multiple locations)
- NRLMSISE-00 (global, “static”)
- Some special cases and interface to tabulated atm.

Production of secondary particles (leptons)

https://indico.scc.kit.edu/event/667/contributions/7176/attachments/3515/5146/200625_CKA8_WS_Anatoli.pdf

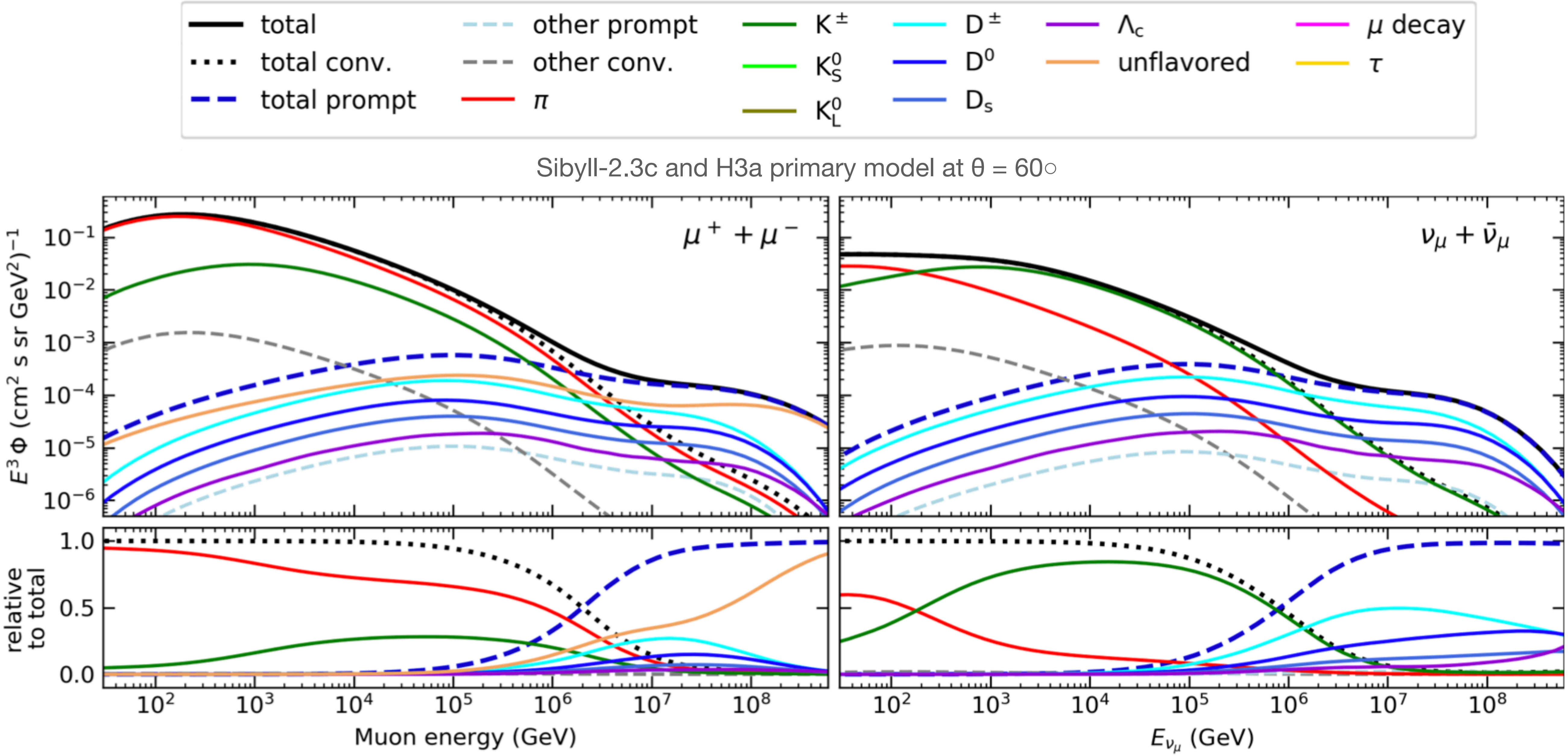
Cosmic ray flux models are in the independent crflux module.

INPUT



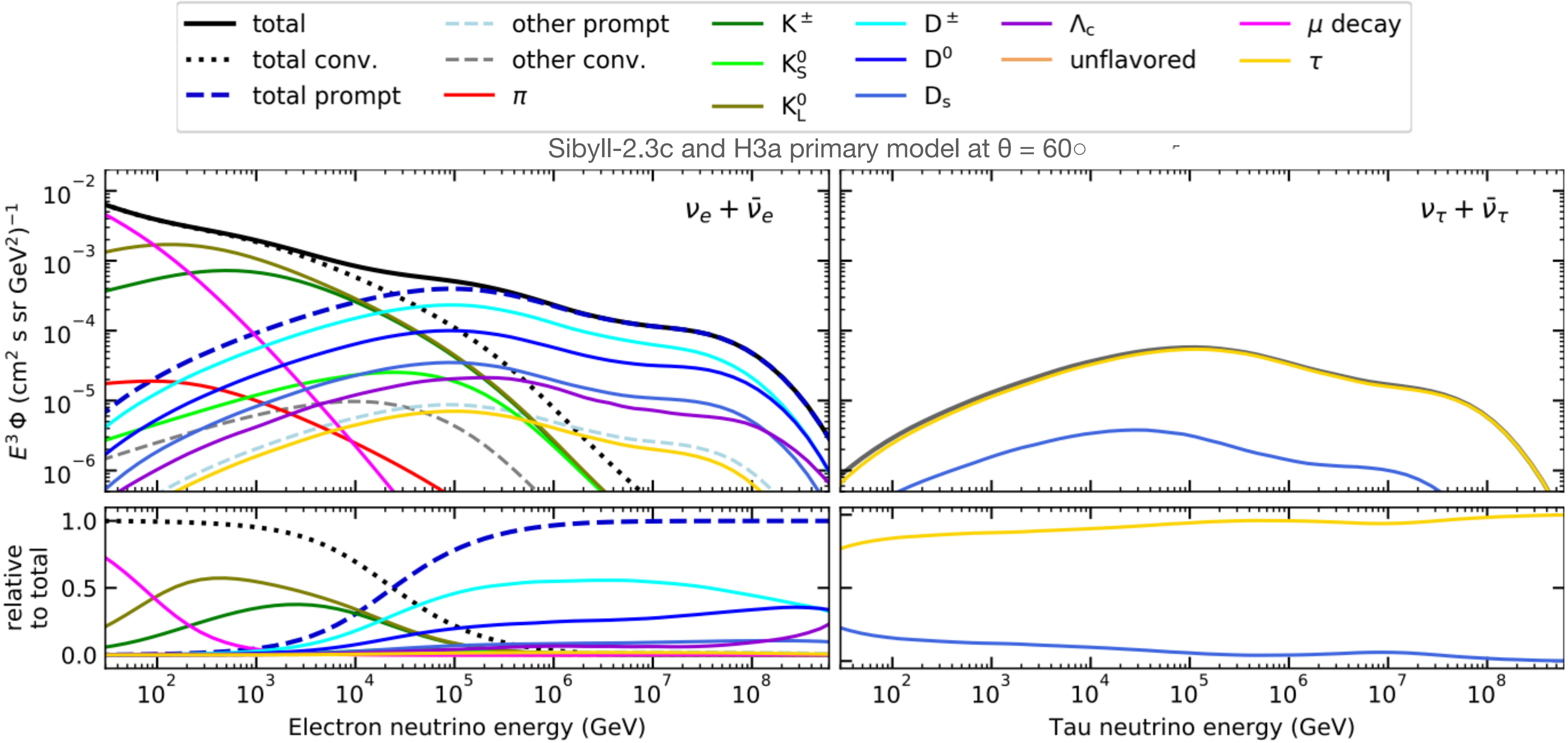
Production of secondary particles (leptons)

https://arxiv.org/pdf/1806.04140.pdf



Production of secondary particles (leptons)

https://arxiv.org/pdf/1806.04140.pdf



Production of secondary particles (leptons)

https://arxiv.org/pdf/1806.04140.pdf

Matrix Cascade Equations (MCEq)

Charmed hadrons play an important role for the prompt flux of high energy leptons in the atmosphere.

Not yet experimentally detected!

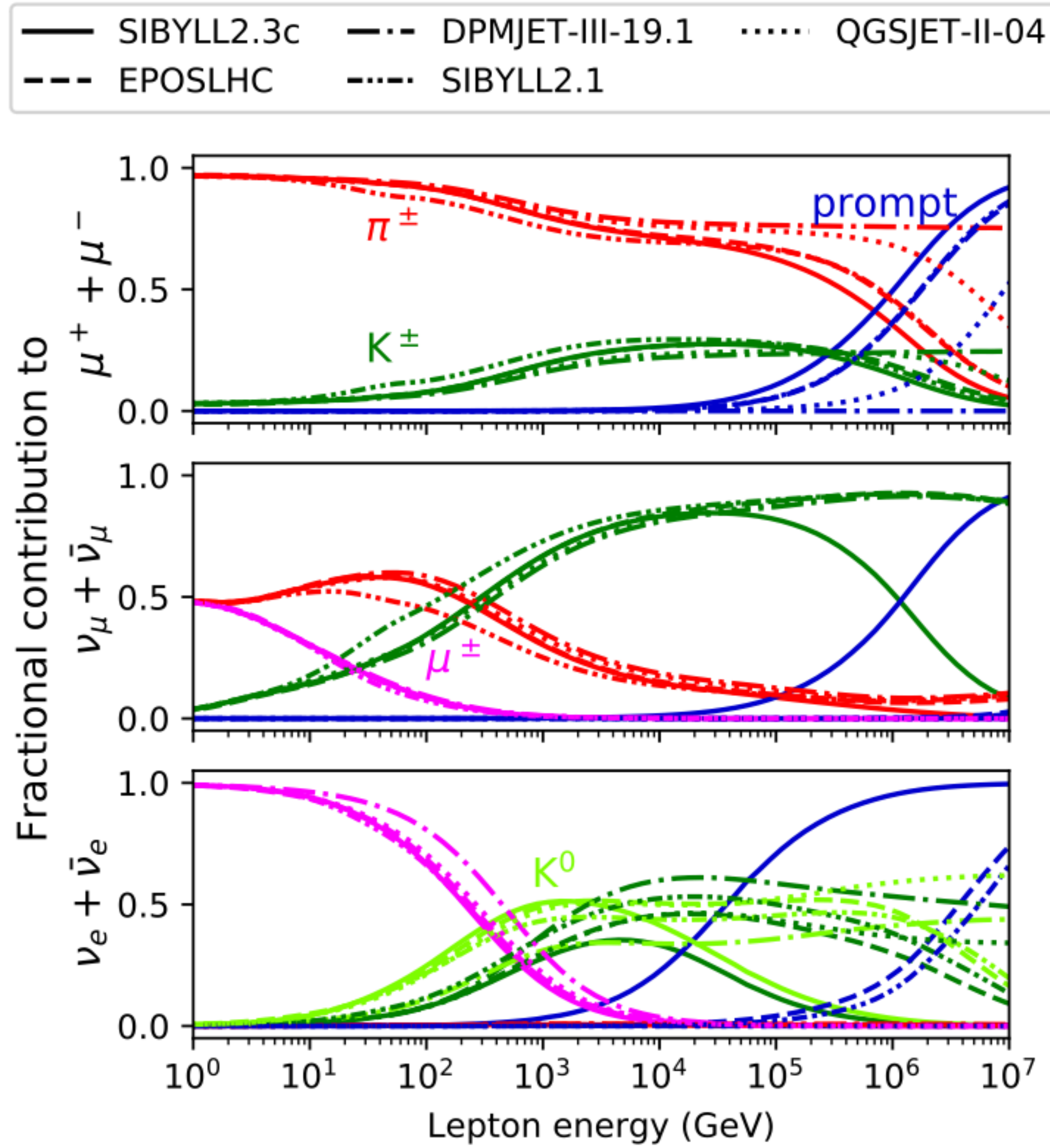


FIG. 6.1. Fractions of hadrons decaying into atmospheric leptons. The muon flux (upper panel) is calculated with the indicated interaction models for $\theta = 0^\circ$. The neutrino fluxes (lower panels) show the results for zenith averaged fluxes.

Production of secondary particles (leptons)

https://arxiv.org/pdf/1806.04140.pdf

Matrix Cascade Equations (MCEq)

Very large systematic uncertainties still dominate the understanding of the spectrum;

Within uncertainties all the models are compatible;

We need more and better measurements in neutrino telescopes.

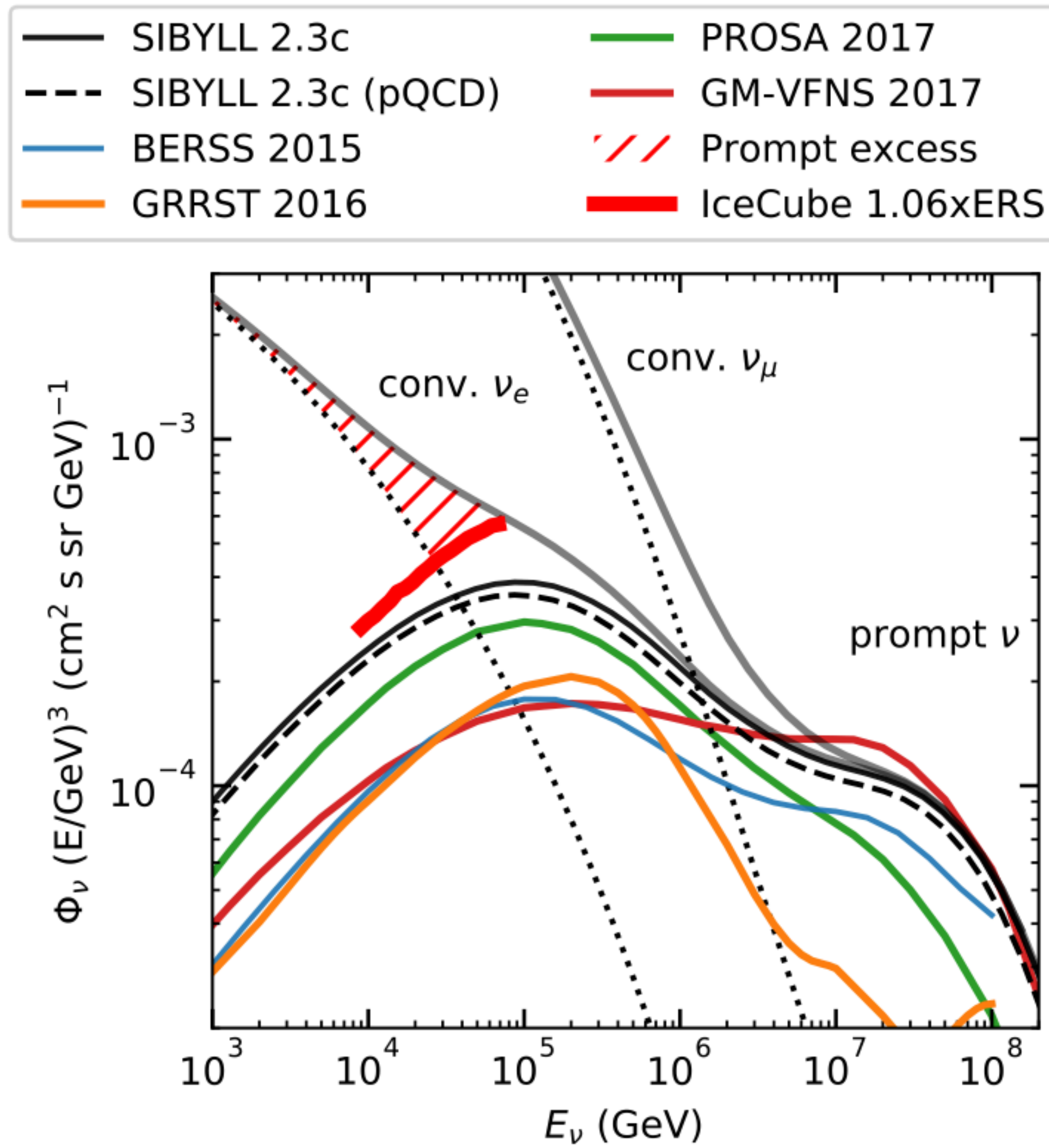


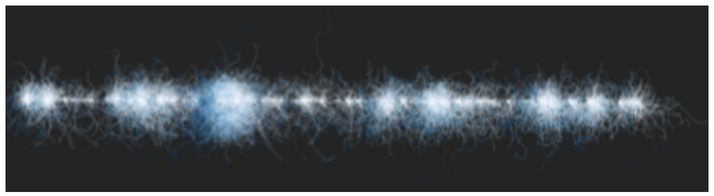
FIG. 6.4. Prompt atmospheric muon and electron neutrino fluxes averaged over zenith angles. All fluxes are computed for the H3a cosmic ray flux model and the most differences arise from the charm cross section calculations. SIBYLL-2.3C

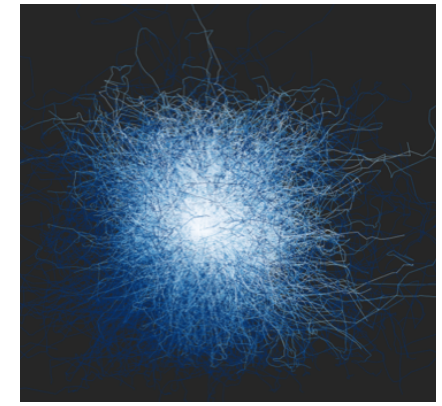
The principles

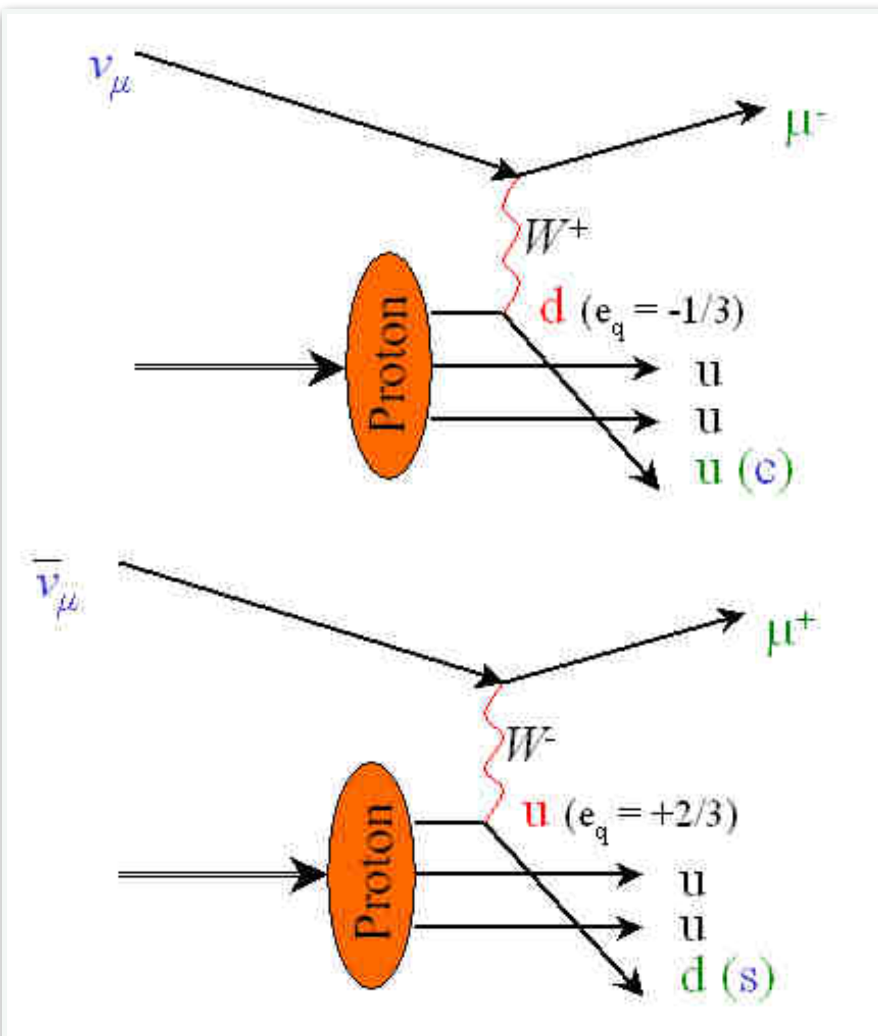
- Grand Unified Neutrino Spectrum (GUNS)
- The neutrino cross sections
- Atmospheric muons and neutrinos
- **The telescopes**

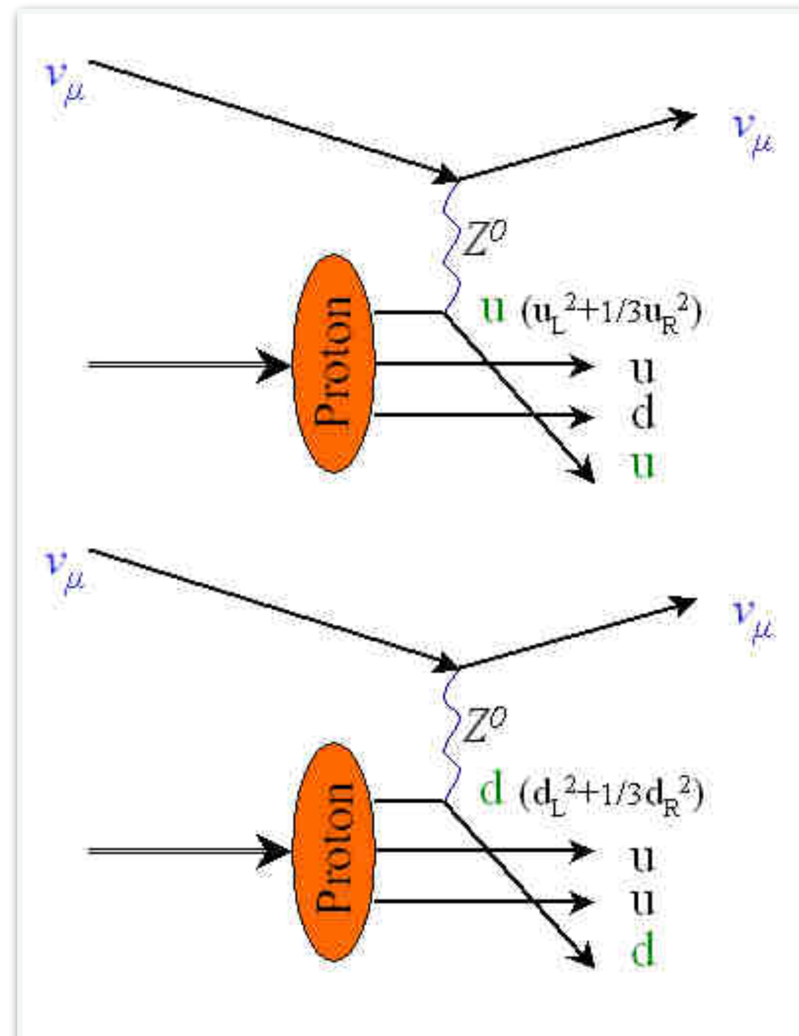
(HE) Neutrino Detection in Telescopes

Two detection channels









Few more topologies: starting, thoroughgoing, semi-contained …

Current & future Cherenkov neutrino telescopes

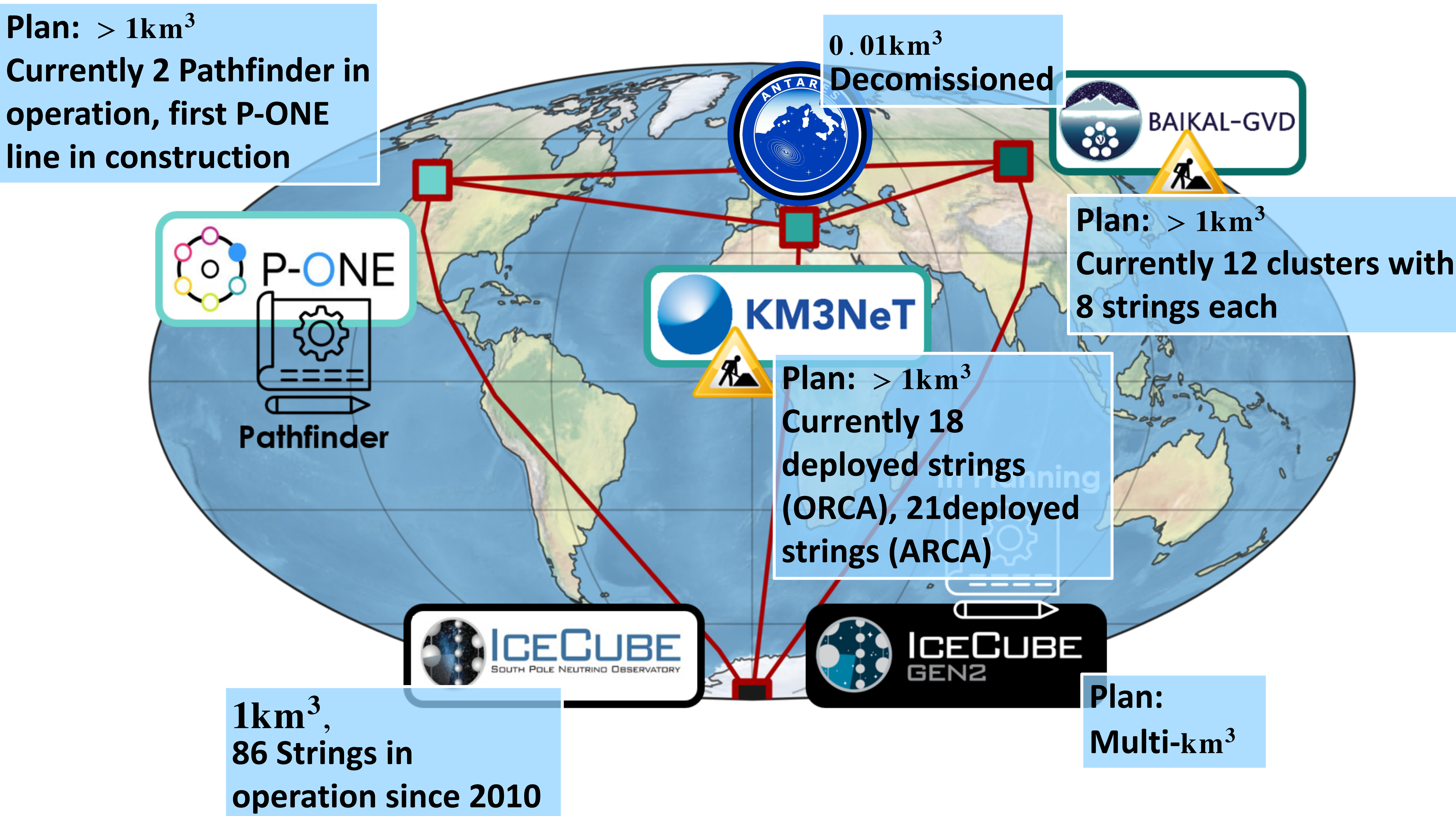


image modified from Lisa Schumacher (ECAP)

Current & future Cherenkov neutrino telescopes

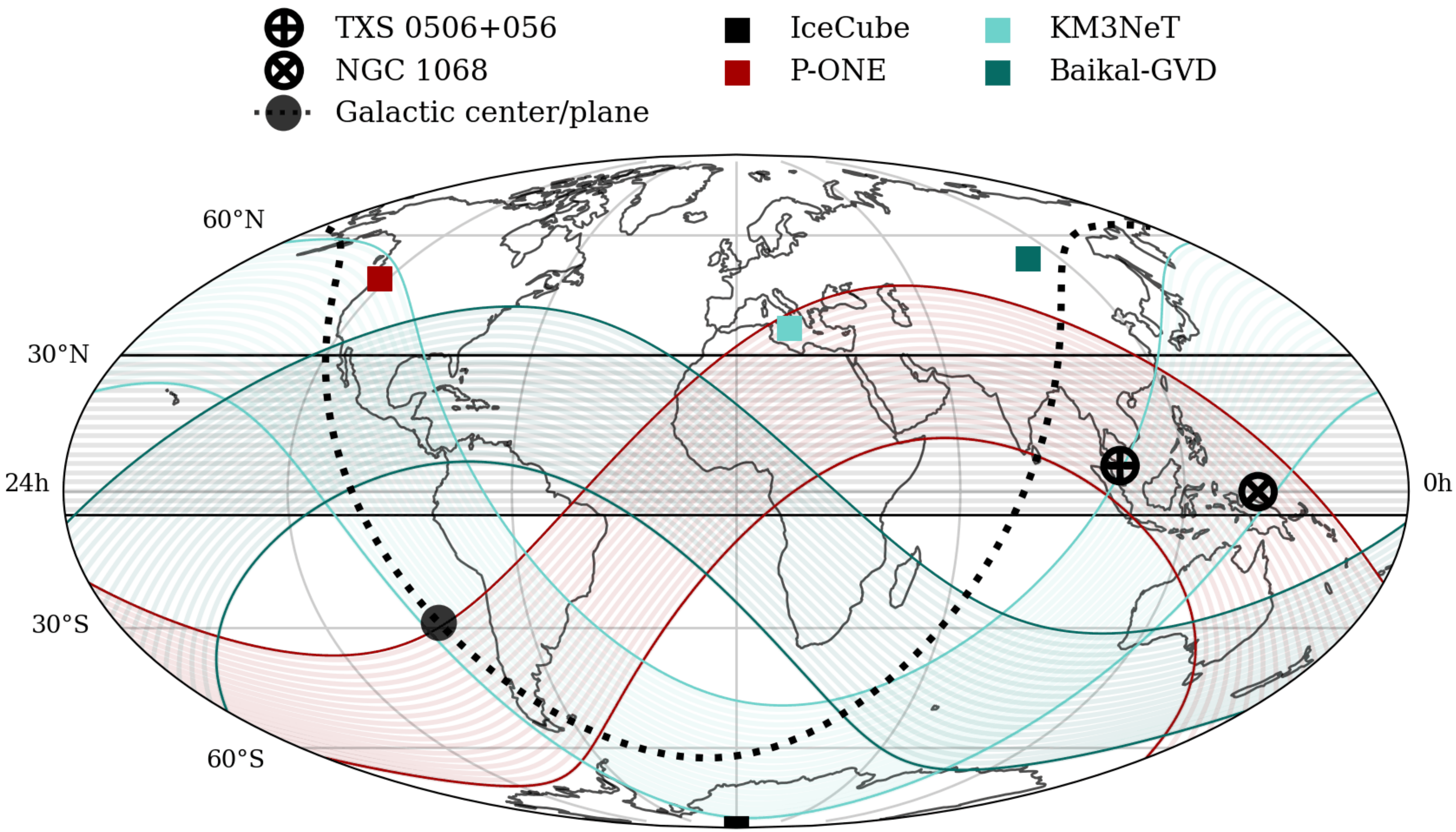
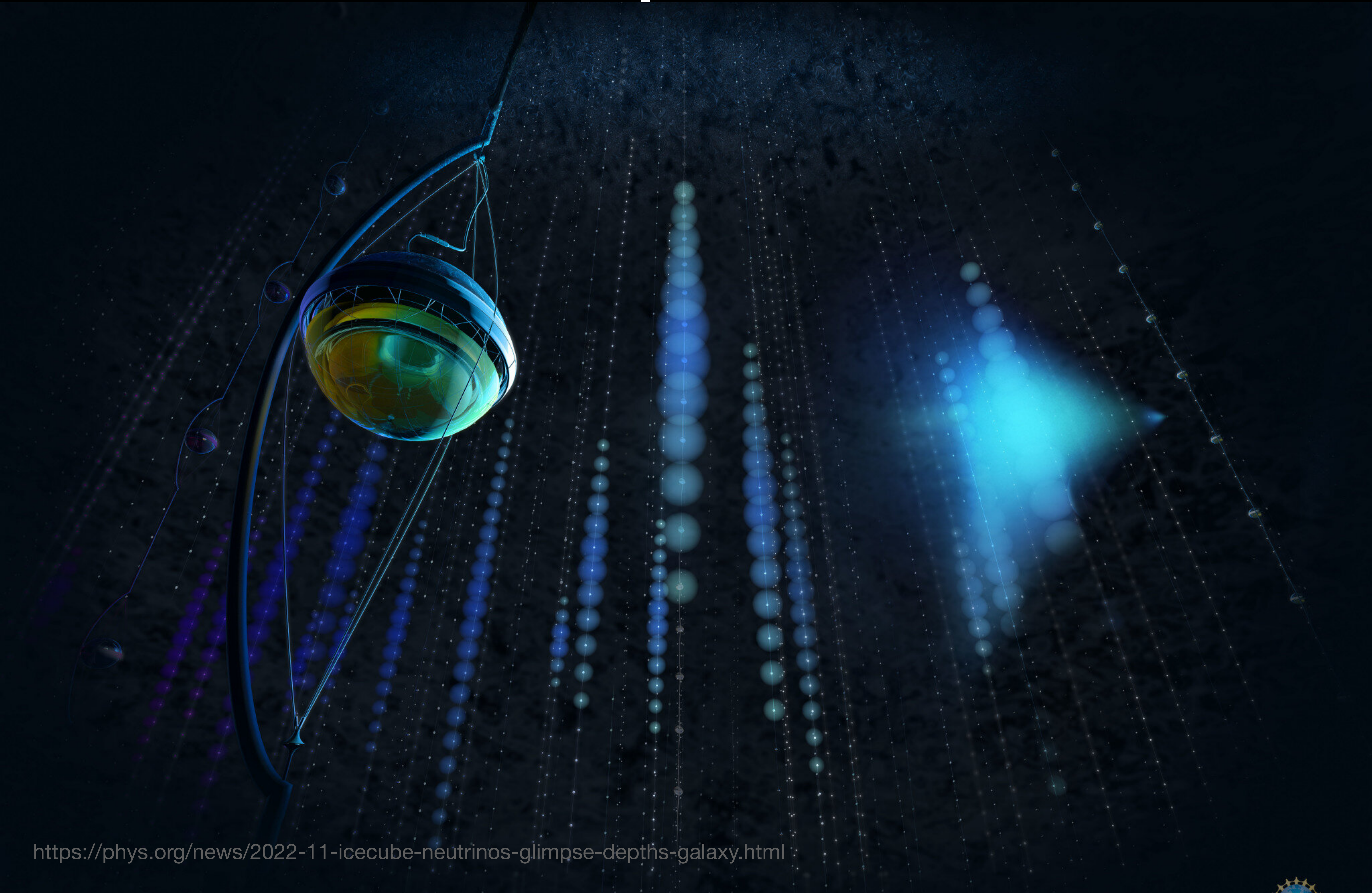


image from M. Huber (TUM), L. Schumacher (ECAP)

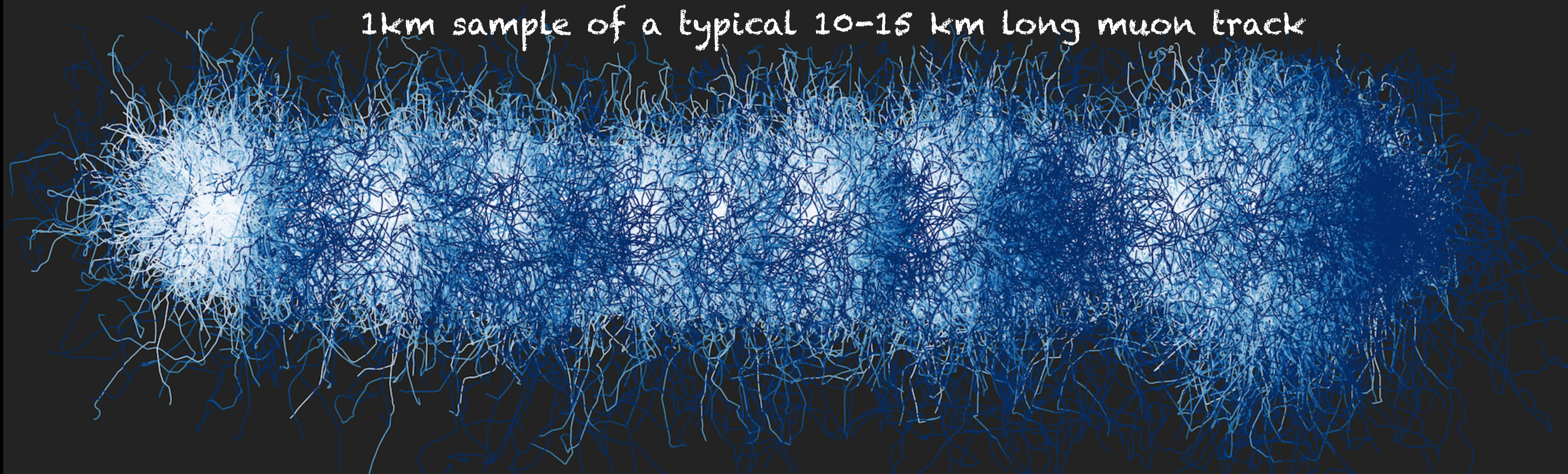
Neutrino Telescopes



https://phys.org/news/2022-11-icecube-neutrinos-glimpse-depths-galaxy.html

1 PeV horizontal muon

medium: IceCube ice



medium: seawater

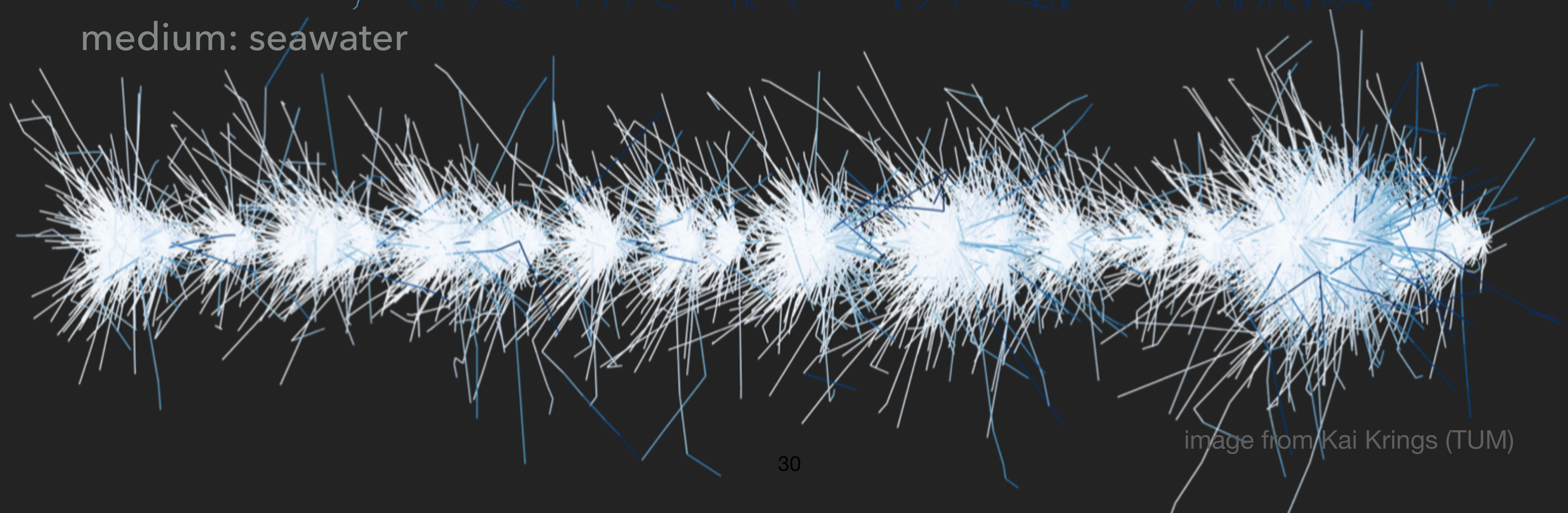
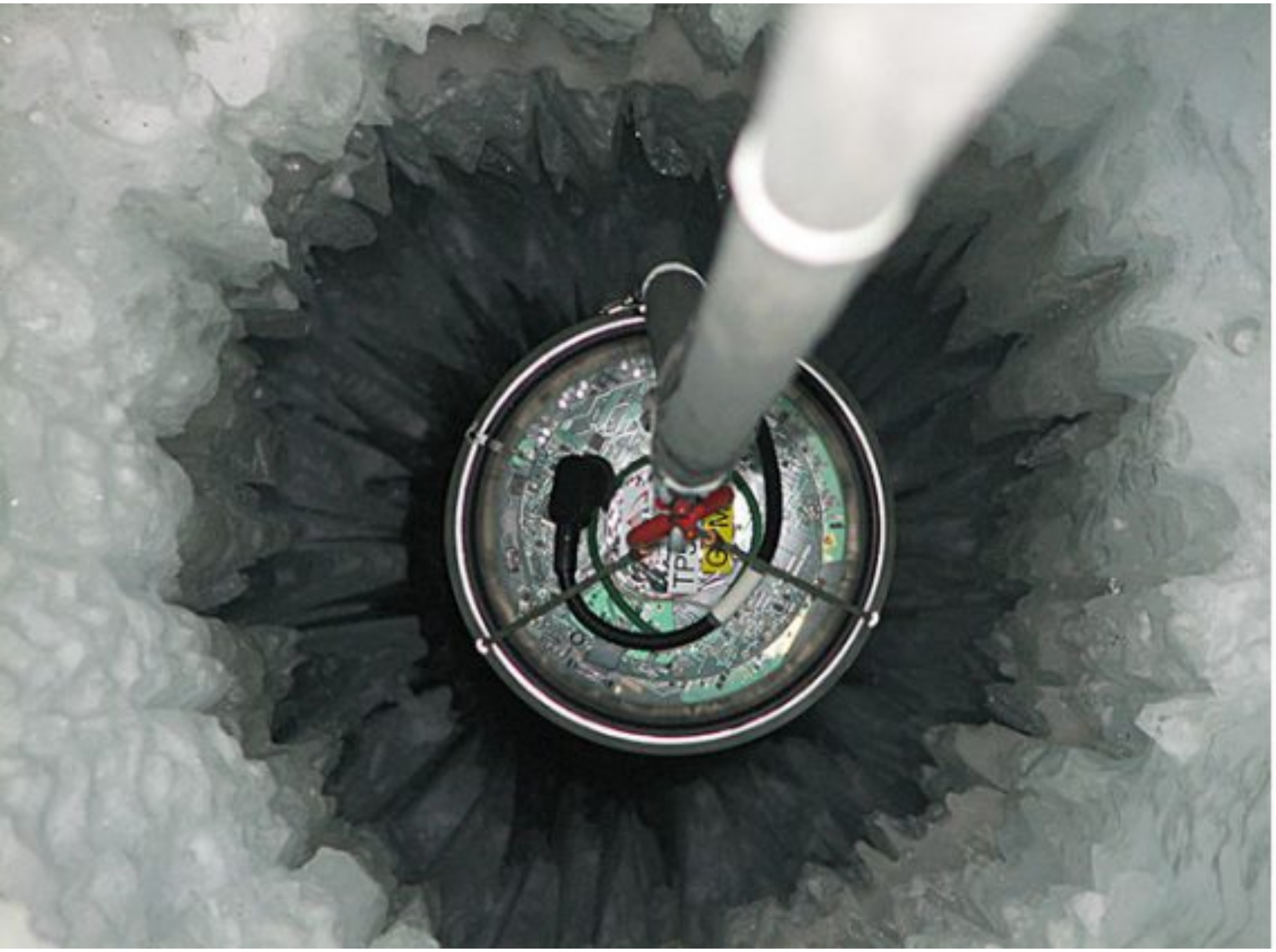


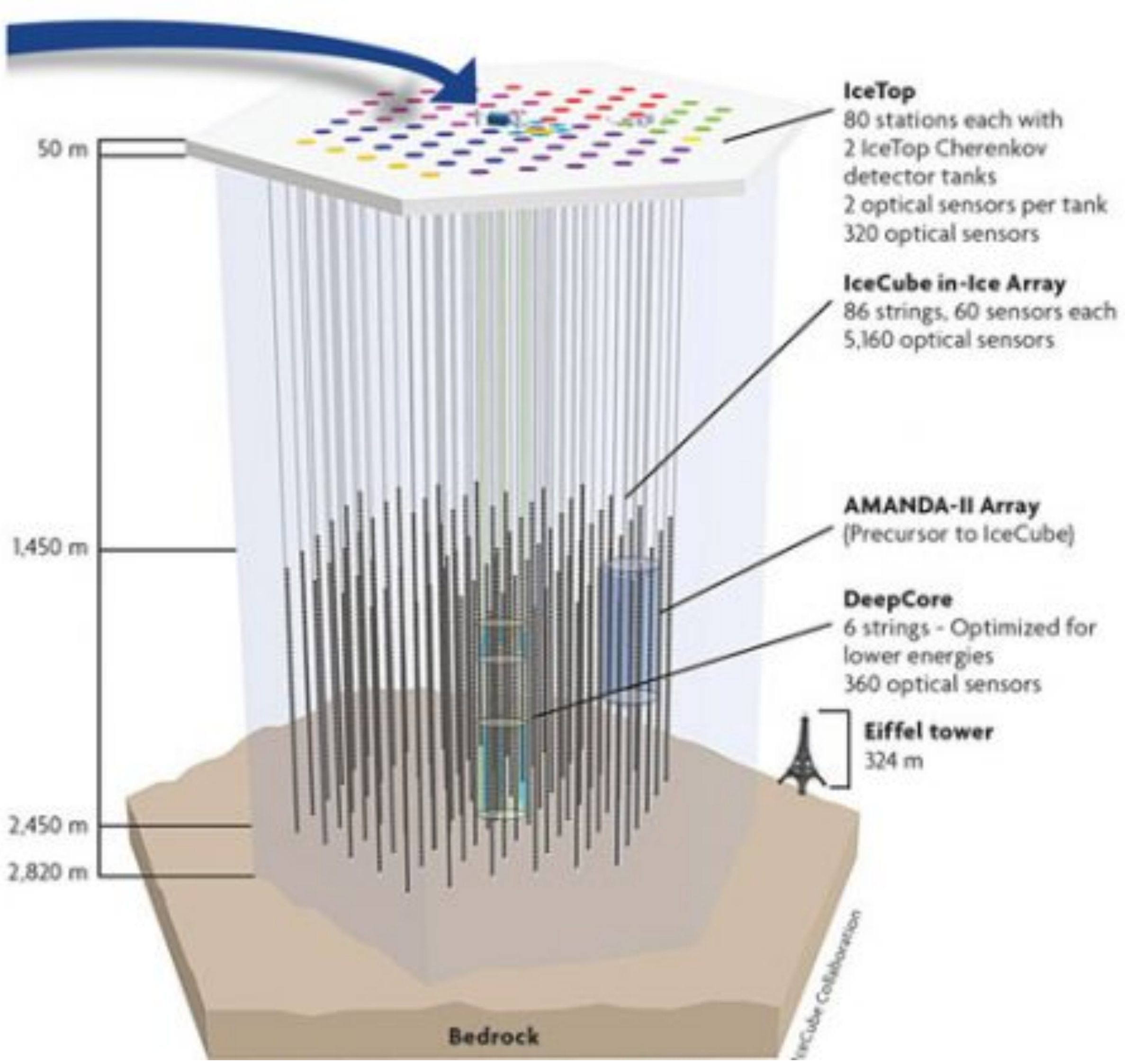
image from Kai Krings (TUM)

Neutrino Detectors and Telescopes

Detection Methods:
driven by the target material & volume required

Water & ice: similar structure, main elements: PMTs, readout electronics, power/data transfer cables, data acquisition, data filtering and statistical data analysis



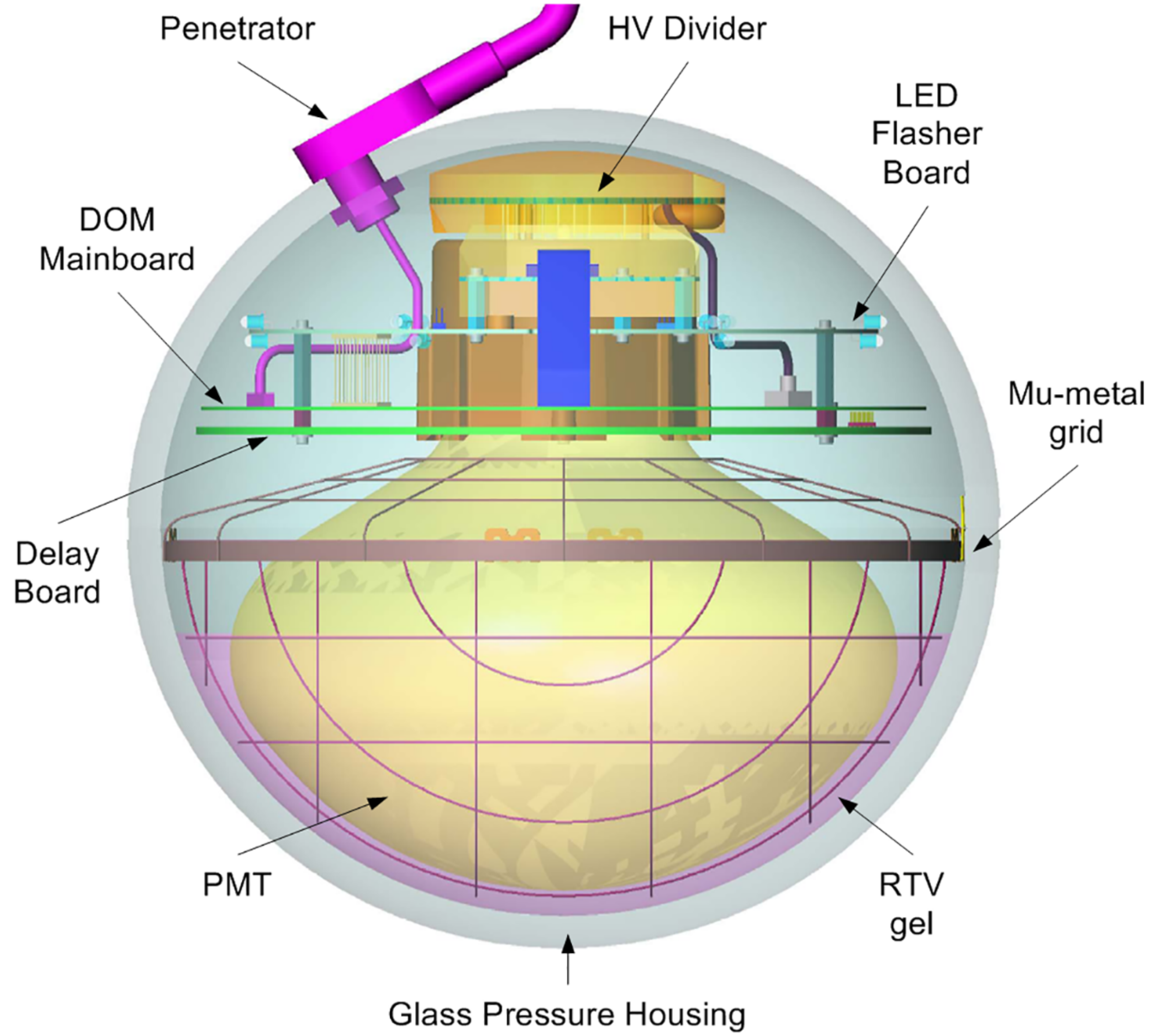


Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

IceCube

- 13 mm thick glass sphere (from Benthosphere) is able to withstand pressures exceeding 500 bar.
- PMT:
  - HAMAMATSU R7081-02 25-cm diameter photomultiplier tube with a spherical photocathode and 10 dynodes.
  - gain of 10^7 @ Voltage: 1200 - 1400 volts.
- Silicone gel: optical coupling to the glass pressure sphere and mechanical support for the PMT.
- A mu-metal wire cage provides magnetic shielding.
- Electronics: supported by the neck of the PMT. Four printed circuit boards.
  - From top to bottom:
    - a passive base for distributing high voltage to the PMT anode and dynodes;
    - a "flasher board" with twelve LEDs (405 nm) arranged in six pairs;
    - the PMT HV is generated on a daughter board situated on the flasher board;
    - the mainboard, which contains most of the functionality in the DOM; and a 75 ns delay line, which is fabricated on a PCB of the same size as the mainboard.
- Communication with the surface is via 0.9 mm copper wire, which penetrates the pressure sphere in a molded assembly.



Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

IceCube

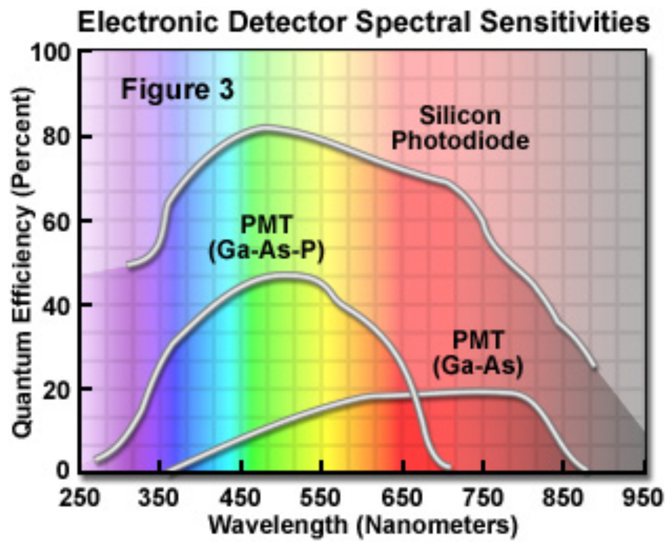
- PMTs

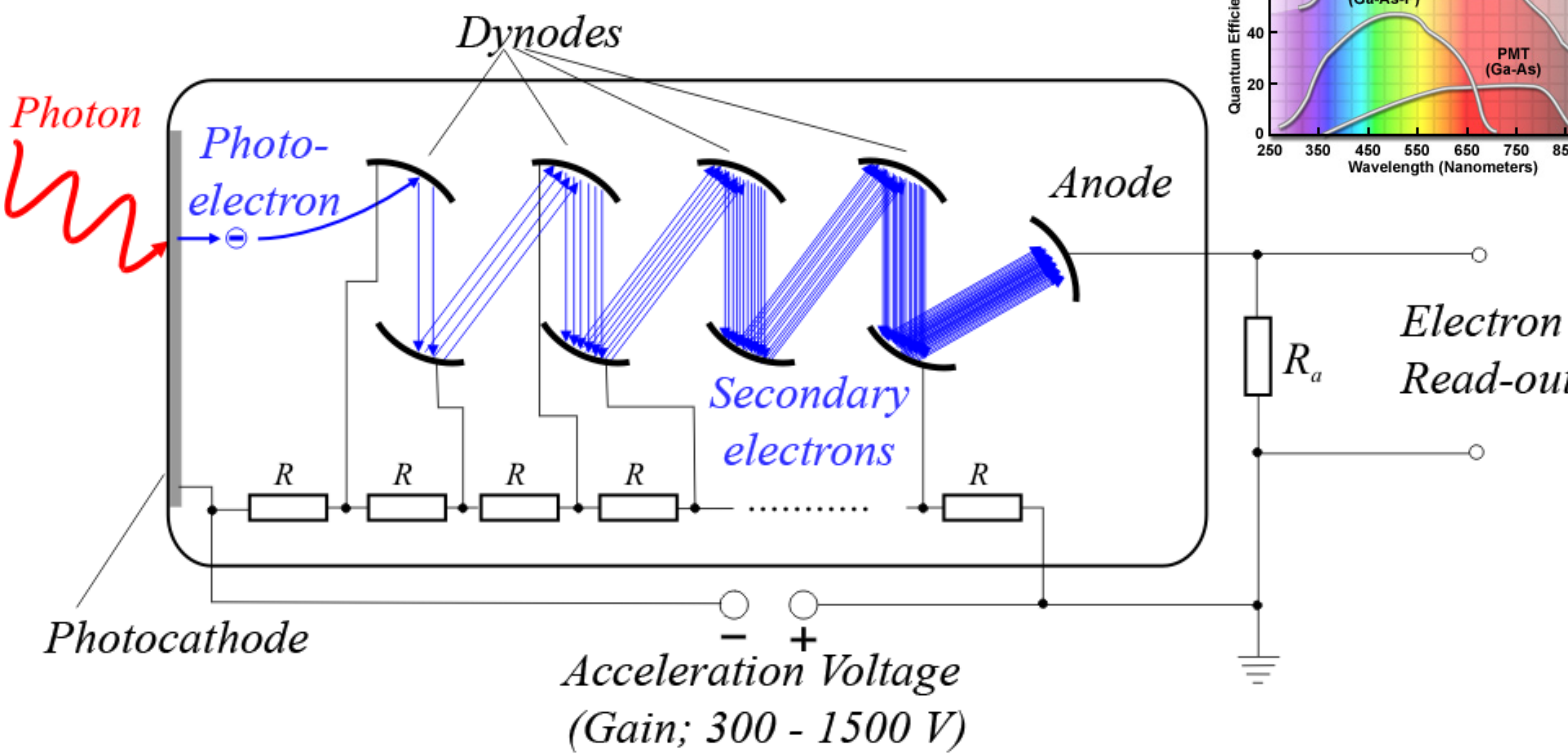
Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

IceCube

- PMTs





Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

- Signal read-out

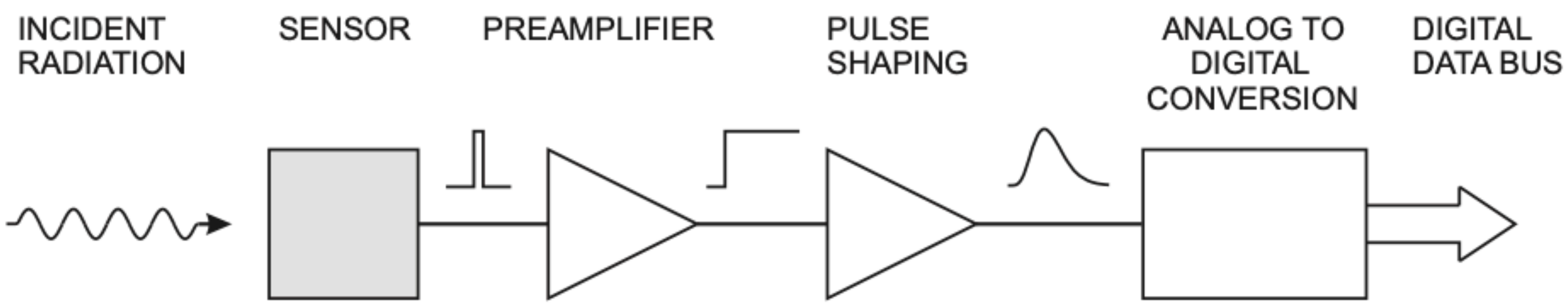


Figure 1: Basic detector functions: Radiation is absorbed in the sensor and converted into an electrical signal. This low-level signal is integrated in a preamplifier, fed to a pulse shaper, and then digitized for subsequent storage and analysis.

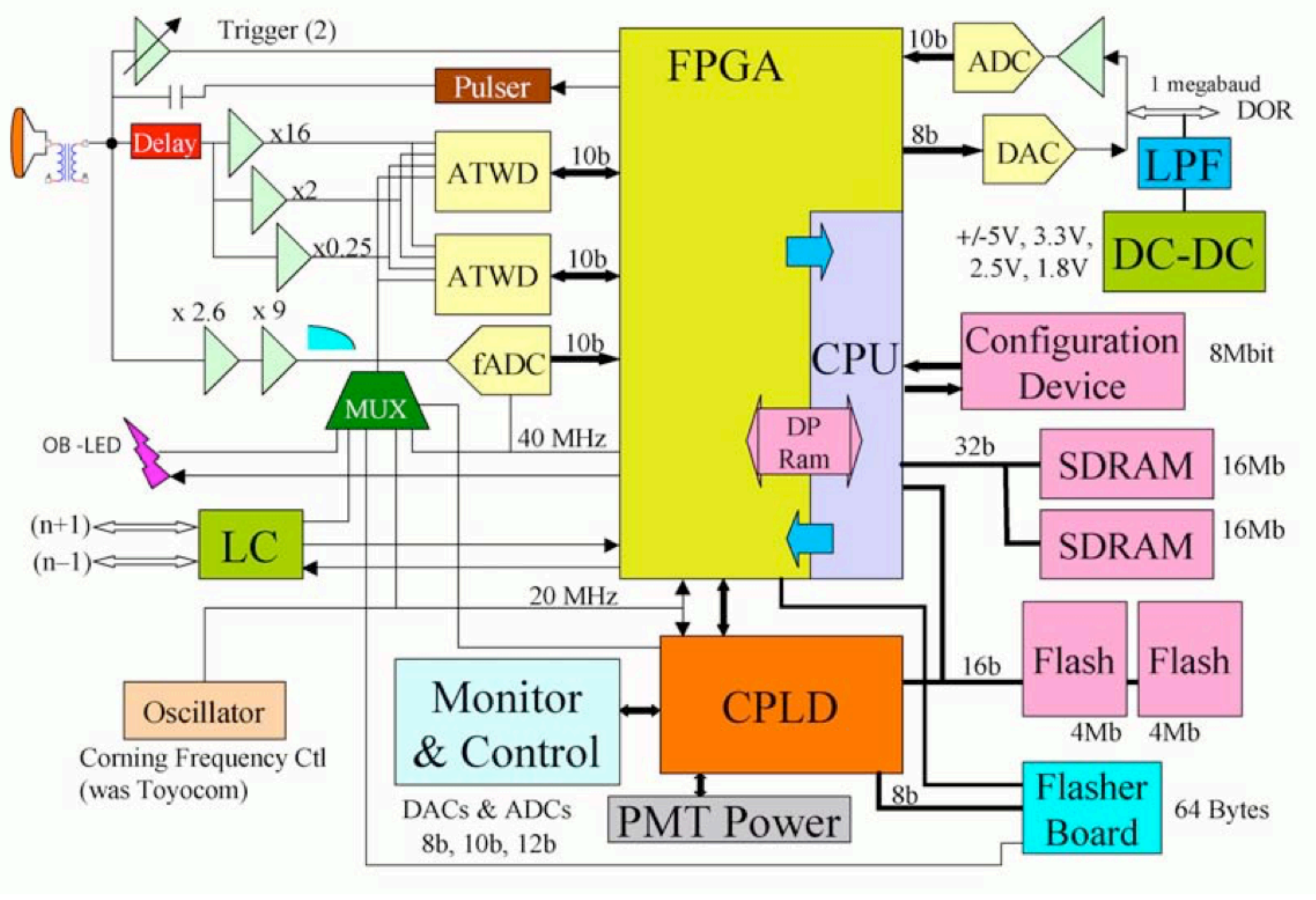
https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/spieler.pdf

Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

IceCube

- Mainboard block diagram.

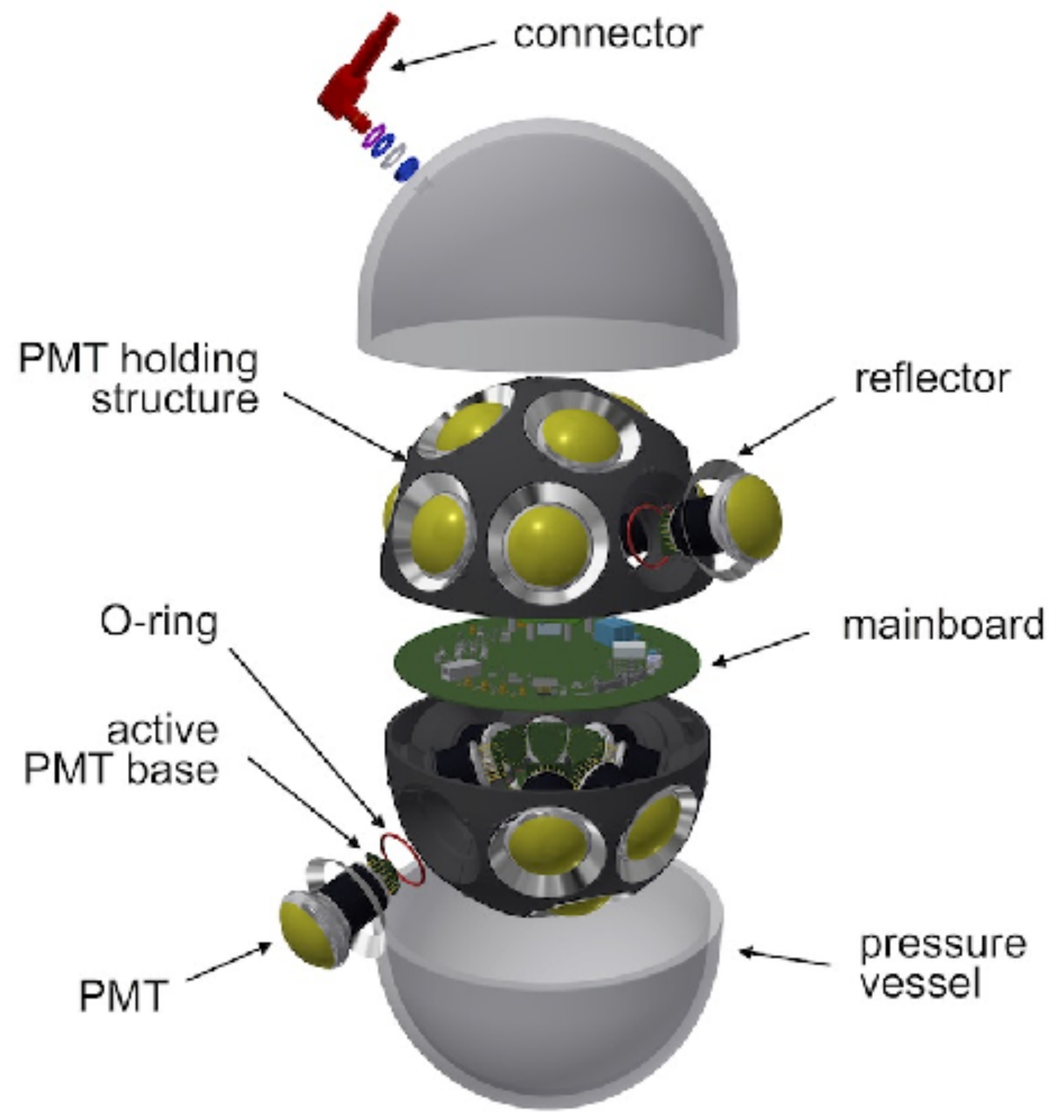


https://cds.cern.ch/record/920022/files/p20.pdf

Neutrino Detectors and Telescopes

Detection Methods: multi-PMTs Digital Optical Modules

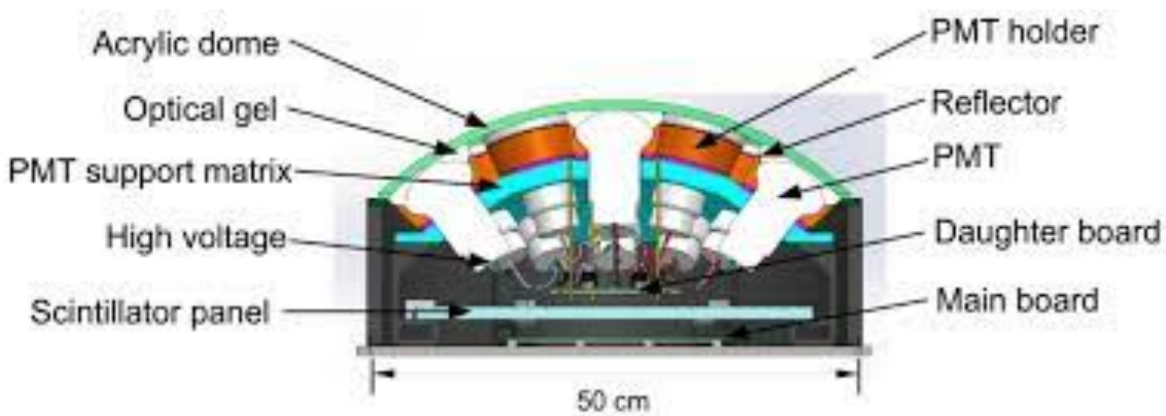
KM3NeT, HyperKamiokande, IceCube-Upgrade, P-ONE



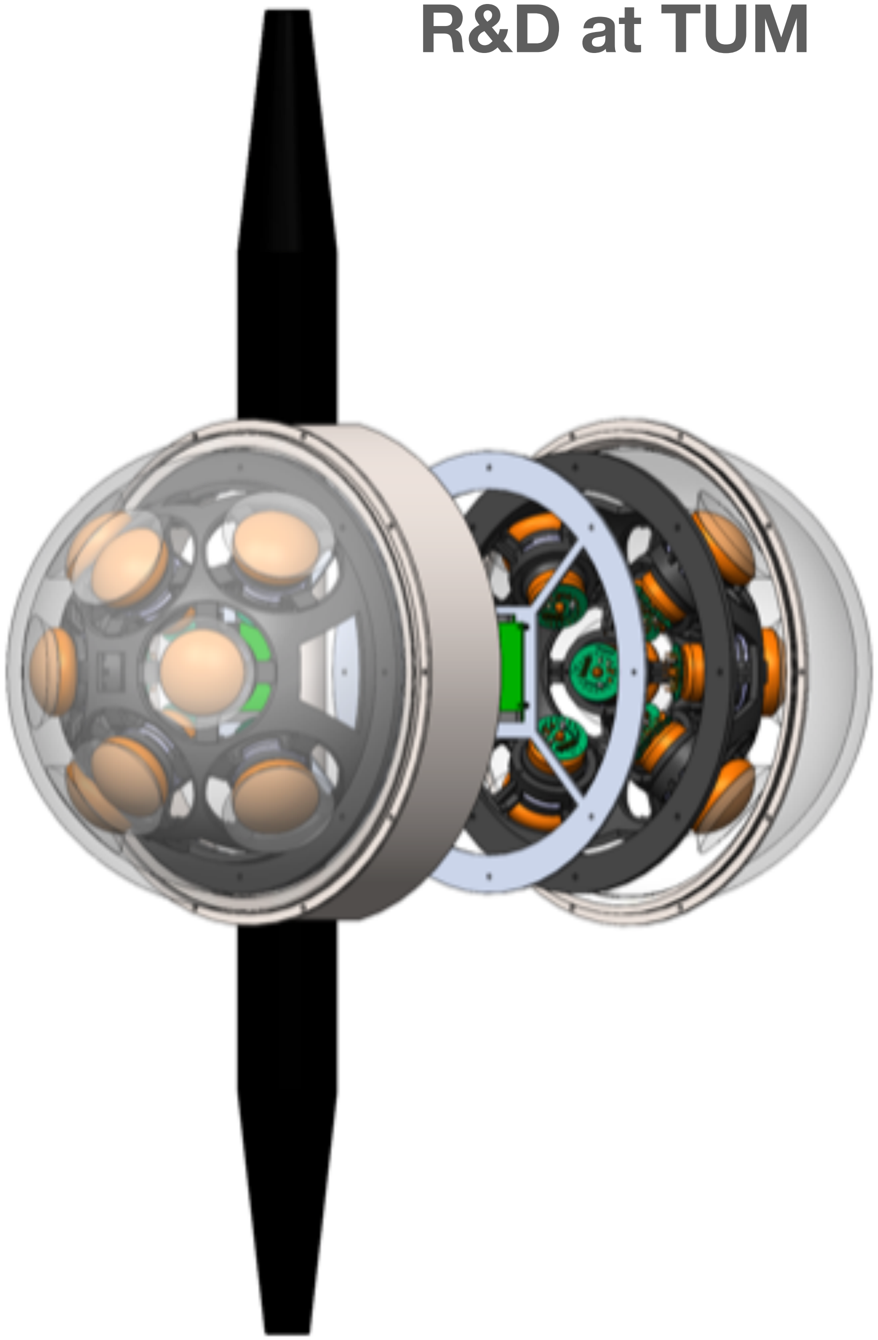
Neutrino Detectors and Telescopes

Detection Methods: multi-PMTs Digital Optical Modules

KM3NeT, HyperKamiokande, IceCube-Upgrade, P-ONE



P-ONE
R&D at TUM

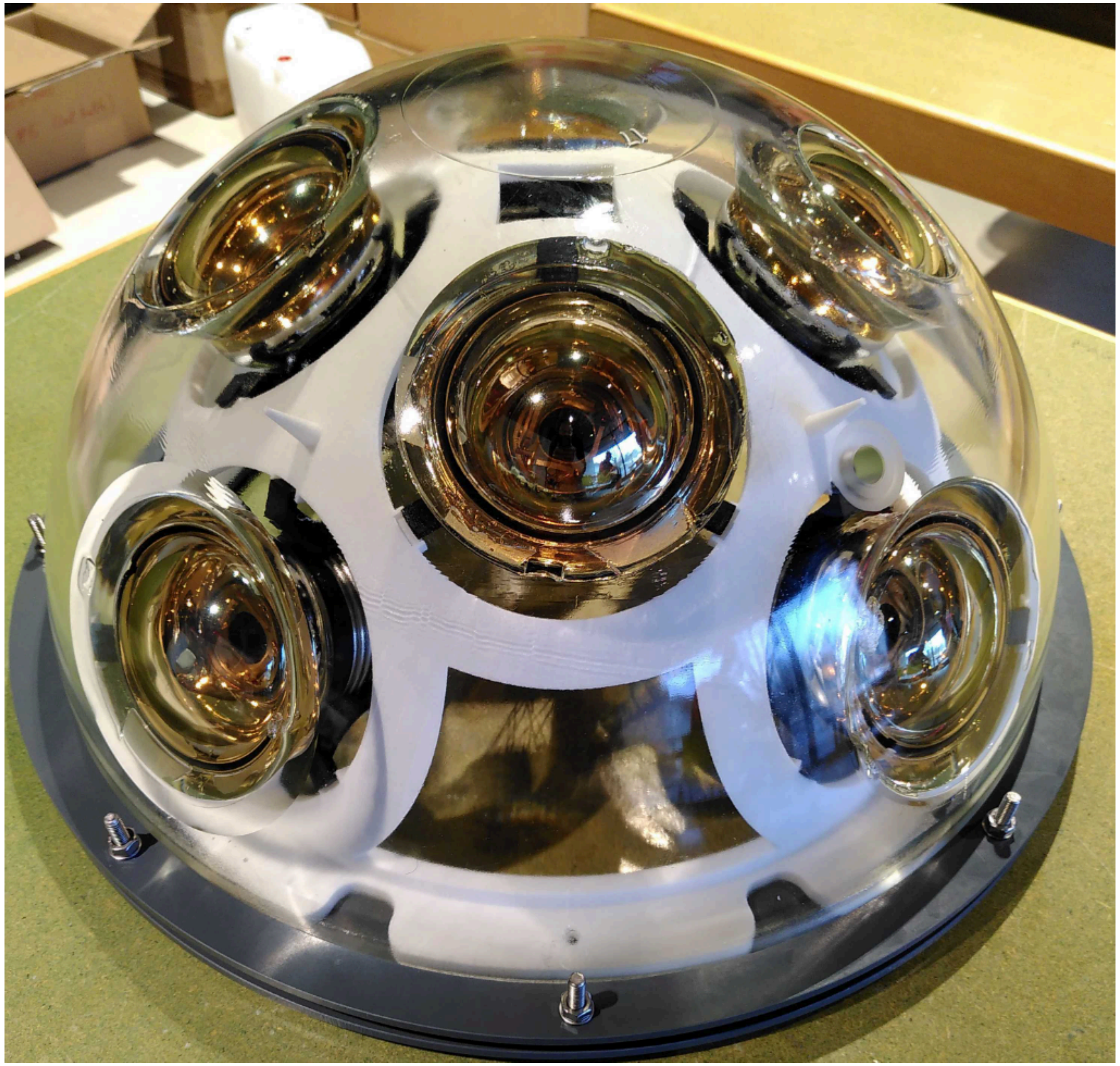


Neutrino Detectors and Telescopes

Detection Methods: multi-PMTs Digital Optical Modules

P-ONE: R&D at TUM

First half module mounted on the 23.12.22

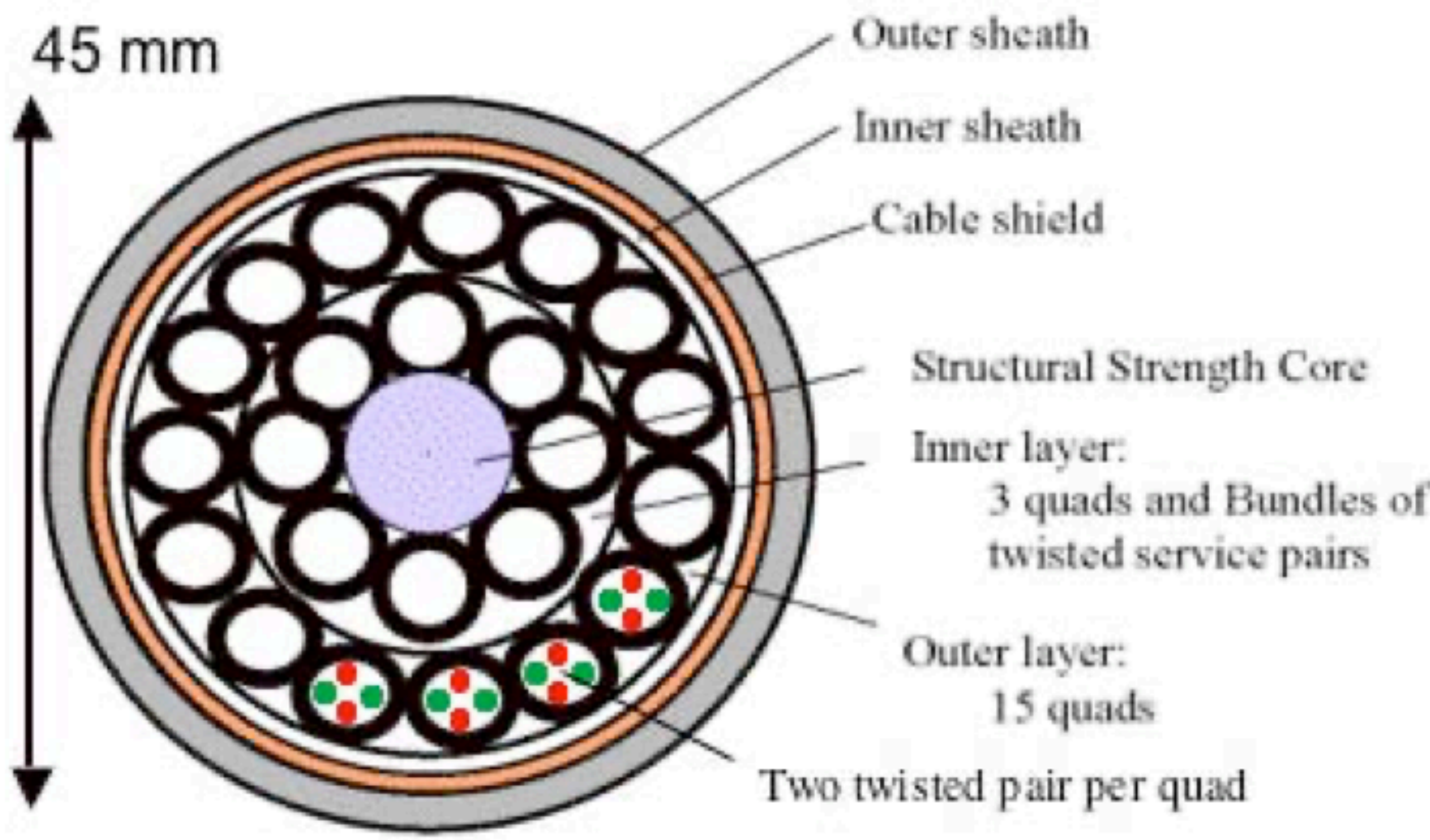


Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

IceCube

- The cable

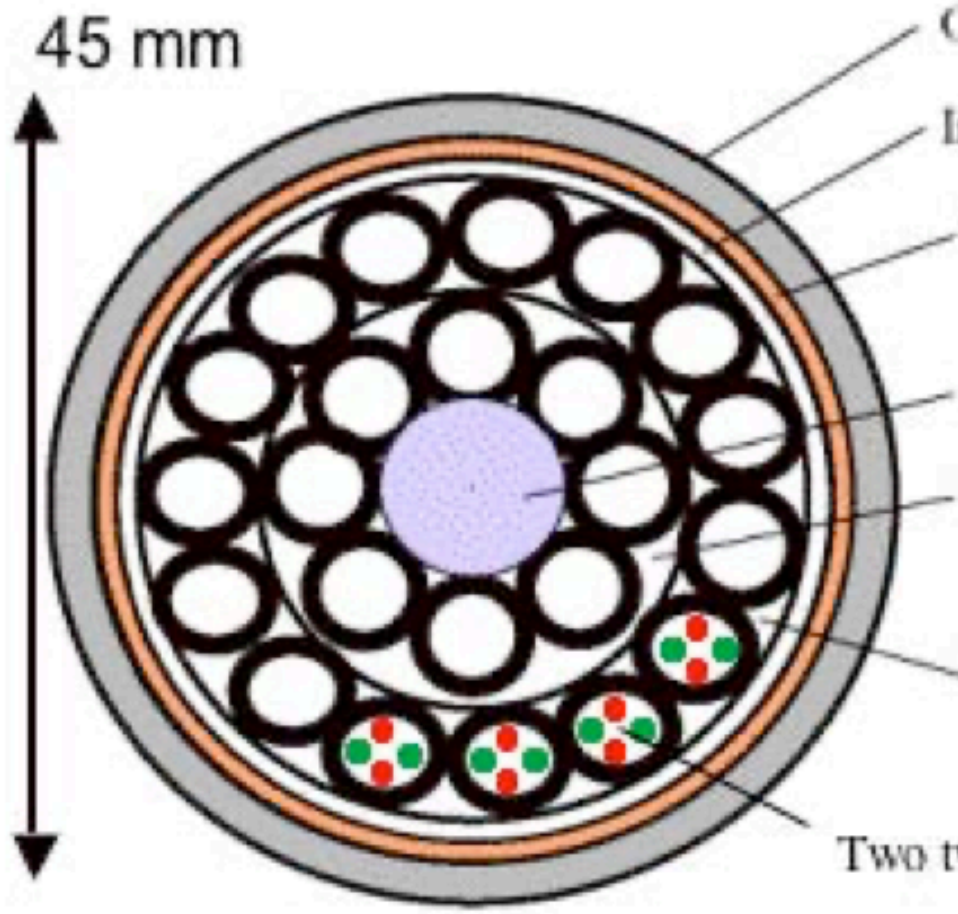


Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

IceCube

- The cable



Neutrino Detectors and Telescopes

Detection Methods: Digital Optical Modules

P-ONE, first cable in production