Fluxes of atmospheric muons and neutrinos and their characteristics in the range of 100 GeV-10 PeV

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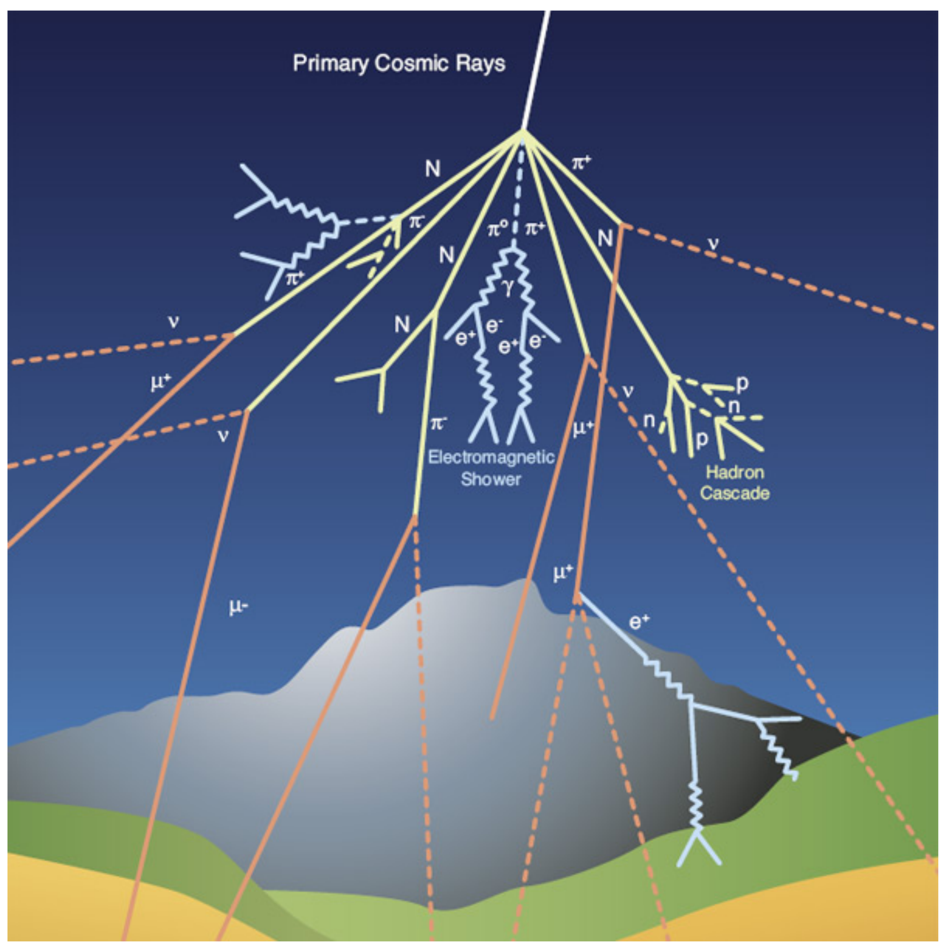
Neutrino and muon fluxes are generated in weak decays of mesons and baryons formed because of the interaction of cosmic rays with the Earth's atmosphere. The study of the mechanism of generation of high-energy leptons in an atmospheric cascade is of interest as an urgent theoretical problem in cosmic ray physics. Careful calculation of the energy spectra and zenith-angular distributions of atmospheric neutrinos that form an irremovable background is a necessary and urgent task of high-energy neutrino astrophysics and is of practical interest. Due to measurements of the spectra of muon neutrinos with an energy of up to ~650 TeV, electron neutrinos with an energy of up to ~20 TeV, and the spectrum of muons with an energy of up to ~1 PeV on the IceCube and ANTARES neutrino telescopes, it became possible to verify the correctness of calculations of the fluxes and characteristics of atmospheric muons (AM) and neutrinos (AH) in a single computational scheme.



Z(*E*,*h*)method

The method is based on an approach developed to solve the problem of neutrino transport in matter. Within the framework of this approach, the problem of transporting secondary nucleons in the atmosphere was solved without simplifying assumptions about the shape of the primary spectrum and the behavior of differential and total cross sections of hadron-nuclear interactions.

The main idea of the method is to reduce the integro-differential transfer equations to a nonlinear integral equation containing the Z-factor, a value directly related to the effective absorption ranges.

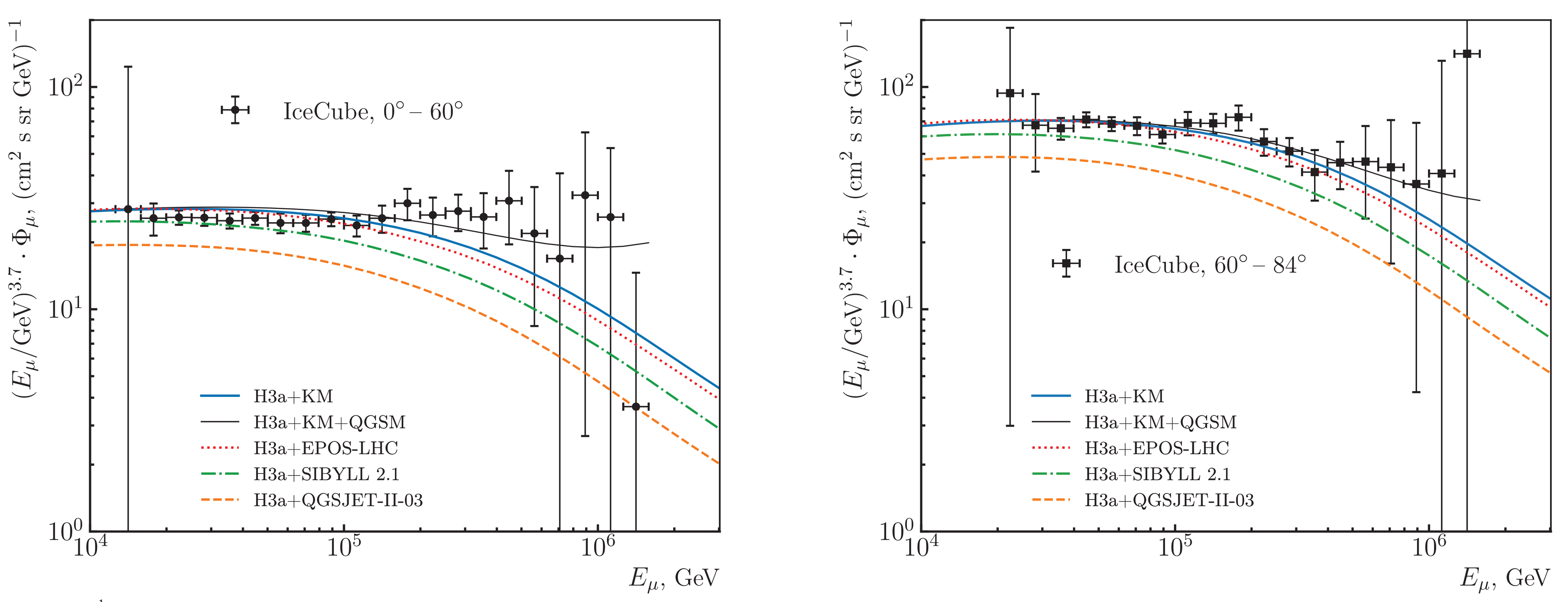
MCE$_Q$

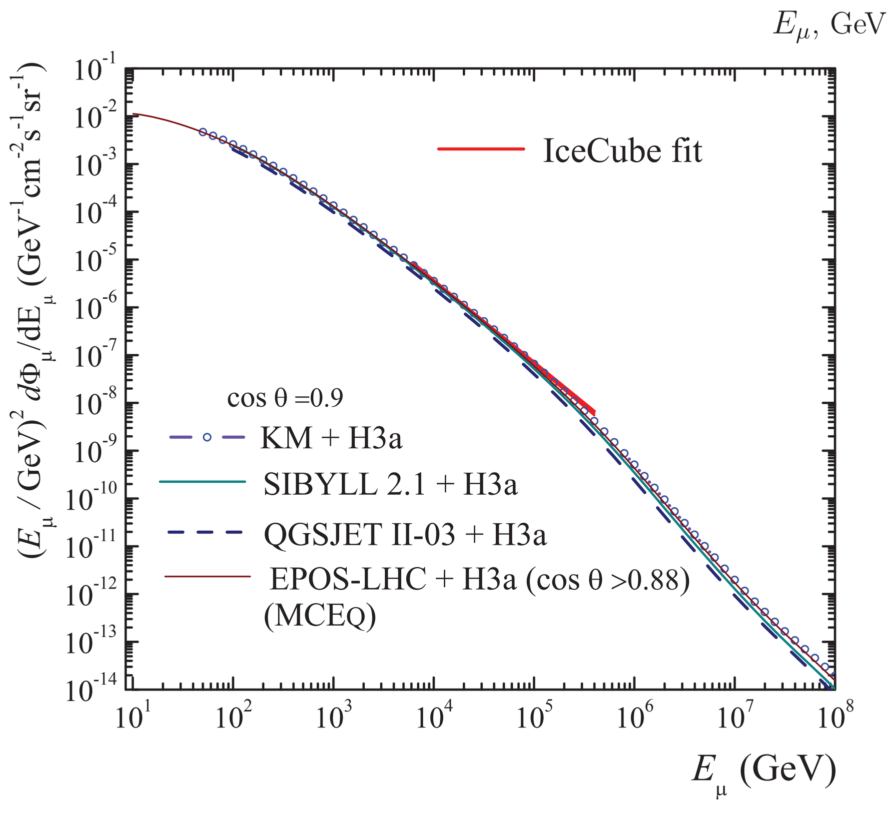
The Matrix Cascade Equation is used to calculate the fluxes of atmospheric leptons at high energies, including for inclusive fluxes of atmospheric muons and neutrinos. In the MCEQ method, instead of solving integro-differential equations, a system of discrete equations is numerically solved on a selected two–dimensional energy-depth grid in the atmosphere (*E*, *h*). At each step (Δ*E*, Δ*h*) , an event occurs either the particle decays or the particle interacts with the birth of a new particle and the original one, but with a different energy. The probabilities of these processes are determined by the inclusive cross sections of the particle's birth or the corresponding probability of

Sources of atmospheric muons and neutrinos

Частица (f)	Время жизни, c	Мода распада	Относительная ширина распада, %	Критическая энергия $\xi_f^{cr}(0°) = m_f c^2 H_0/c\tau_f$
$\mu^{\pm}_{e3}$	$2.19 \cdot 10^{-6}$	$e^{\pm} + \nu_e(\bar{\nu}_e) + \bar{\nu}_\mu(\nu_\mu)$	100	1.03 ГэВ
$\pi^{\pm}$	$2.60 \cdot 10^{-8}$	$\mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$	99.987	115 ГэВ
$K_L^0 : K^0_{Le3}$	$5.12 \cdot 10^{-8}$	$\pi^{\pm} + e^{\mp} + \bar{\nu}_e(\nu_e)$	40.55 ± 0.11	206 ГэВ
$K^0_{L\mu3}$		$\pi^{\pm} + \mu^{\mp} + \bar{\nu}_\mu(\nu_\mu)$	27.04 ± 0.07	
$K^{\pm}_{\mu2}$		$\mu^{+} + \nu_\mu(\bar{\nu}_\mu)$	63.55 ± 0.11	
$K^{\pm} : K^{\pm}_{e3}$	$1.24 \cdot 10^{-8}$	$\pi^0 + e^{\pm} + \nu_e(\bar{\nu}_e)$	5.07 ± 0.04	857 ГэВ
$K^{\pm}_{\mu3}$		$\pi^0 + \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$	3.35 ± 0.03	
$K_S^0 : K^0_{Se3}$	$0.90 \cdot 10^{-10}$	$\pi^{\pm} + e^{\mp} + \bar{\nu}_e(\nu_e)$	$(7.04 \pm 0.08) \cdot 10^{-2}$	120 ТэВ
$K^0_{S\mu3}$		$\pi^{\pm} + \mu^{\mp} + \bar{\nu}_\mu(\nu_\mu)$	$(4.69 \pm 0.05) \cdot 10^{-2}$	

Comparing atmospheric muon's fluxes with data of IceCube



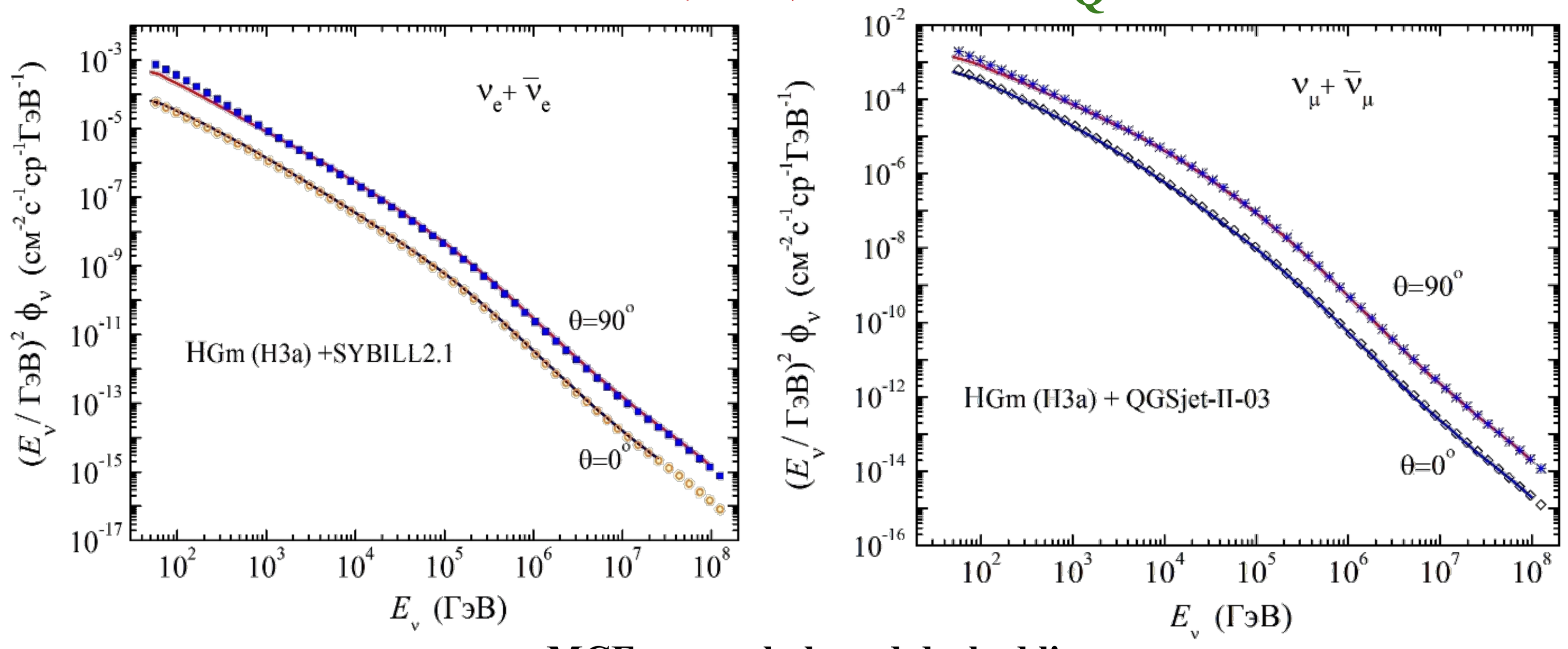


Vertical AM flux **IceCube fit**

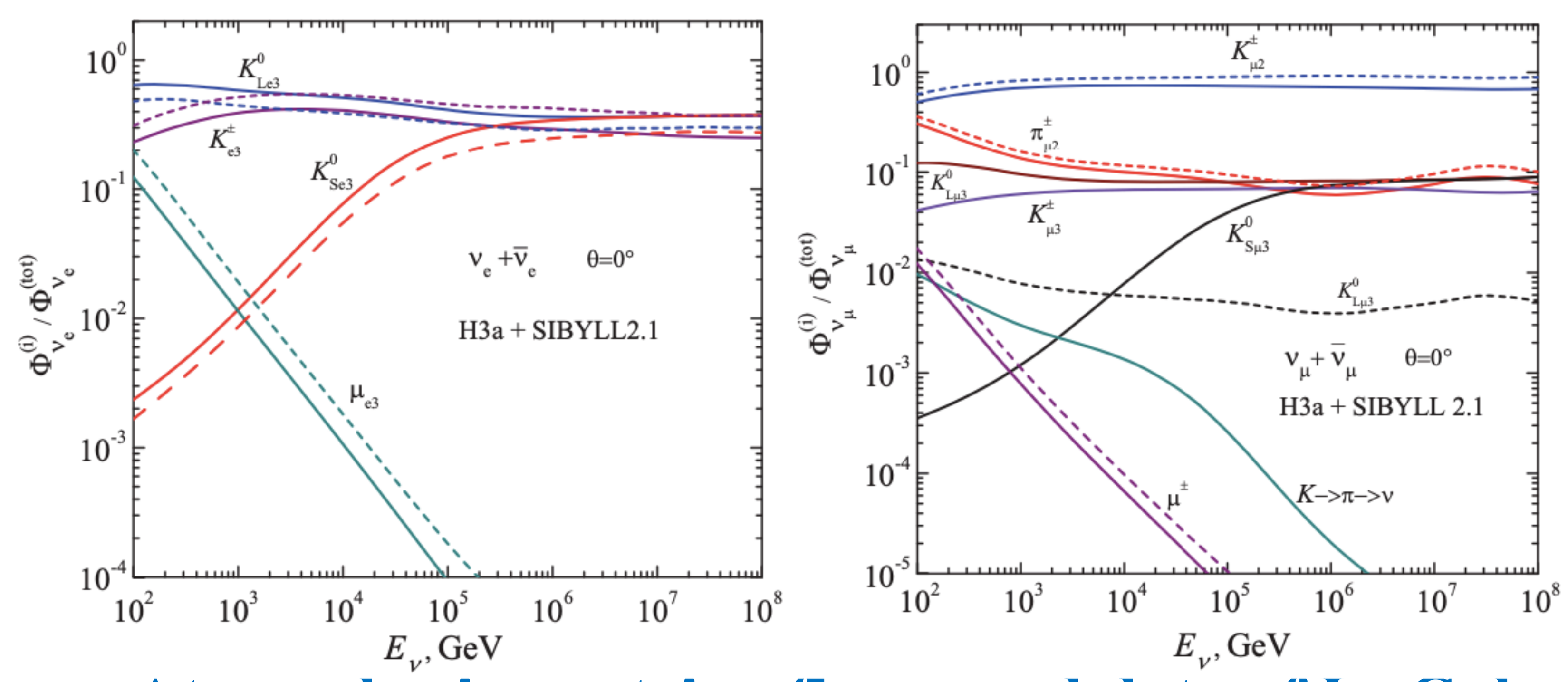
$$\frac{d\Phi_\mu}{dE_\mu} = (9.0 \pm 0.3) \cdot 10^{-17} \left(\frac{E_\mu}{50\ TeV}\right)^{-3.74 \pm 0.03}$$

Tenholt F. et al (IceCube Collaboration). High-energy atmospheric muons in IceCube and IceTop // 35th ICRC, Bexco, Busan, Korea. PoS (ICRC2017). – 2017. – Vol. 317 – P. 1710.01194

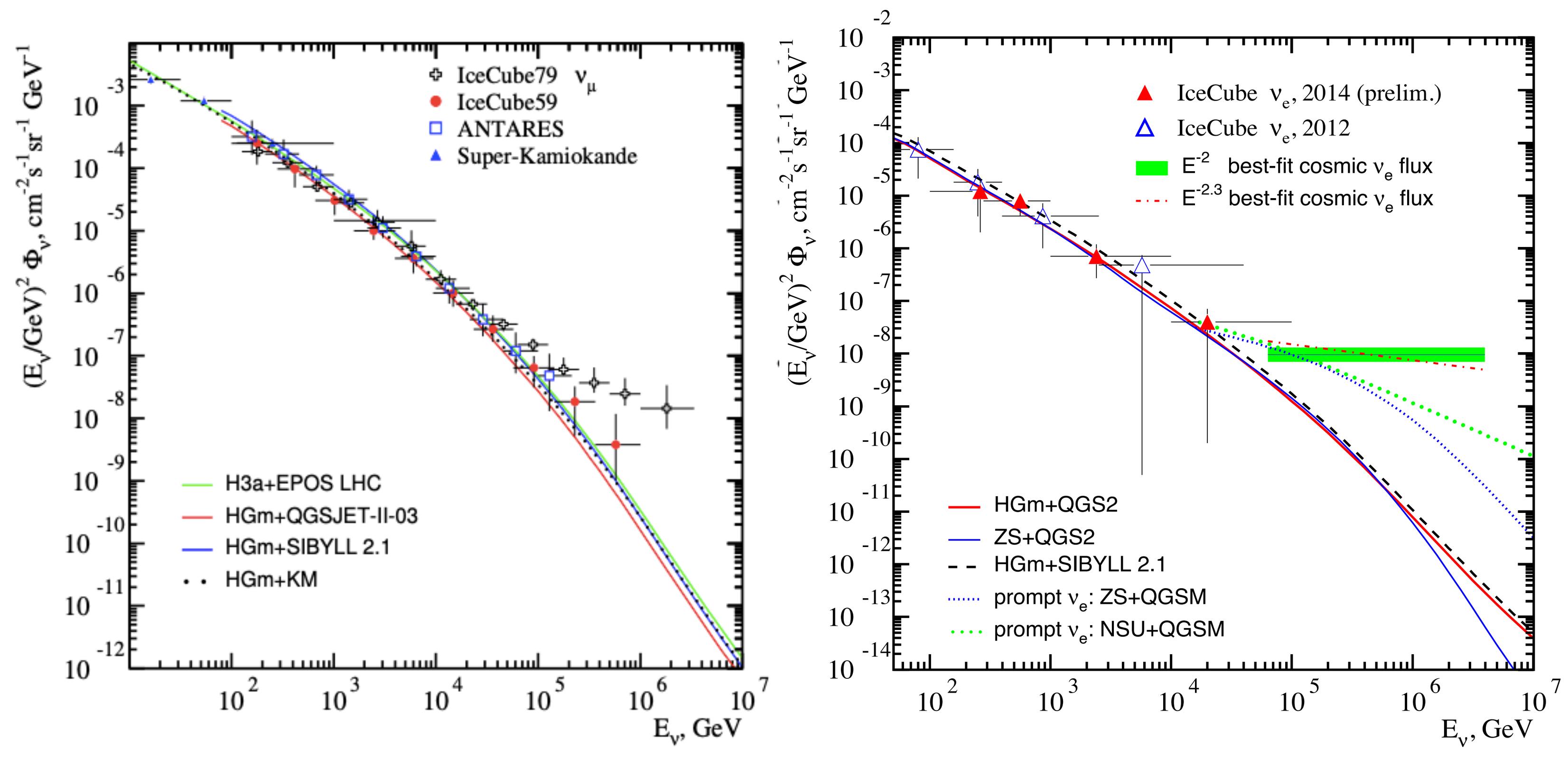
Z(E,h) vs MCE$_Q$



MCE$_Q$ – symbols and dashed lines



Atmospheric neutrino fluxes and data of IceCube

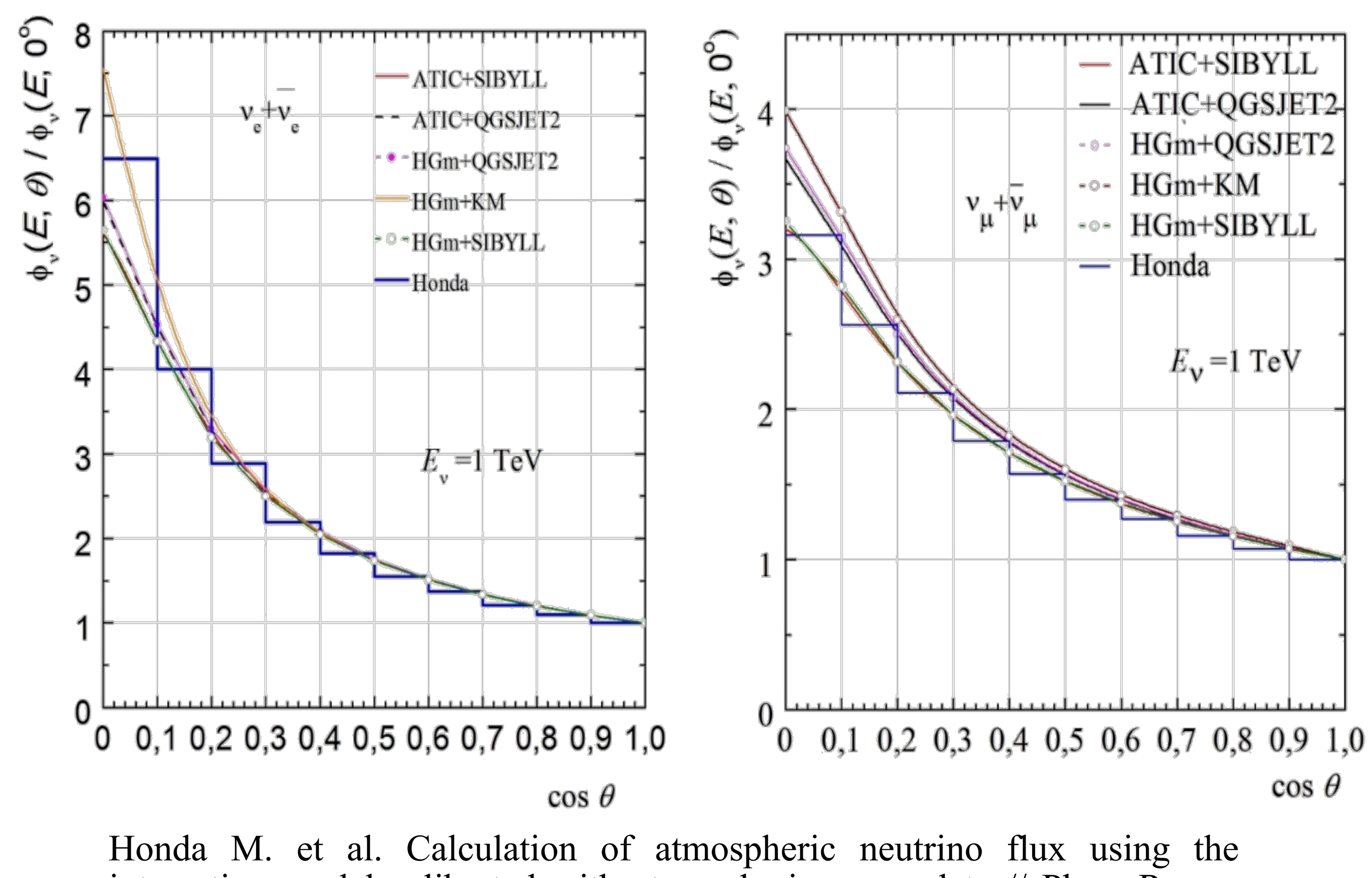


$$E_\nu^2 \cdot \phi_\nu = (2.06^{+0.35}_{-0.26}) \cdot 10^{-8} \left(\frac{E_\nu}{10^5\ GeV}\right)^{-(0.46 \pm 0.12)}$$

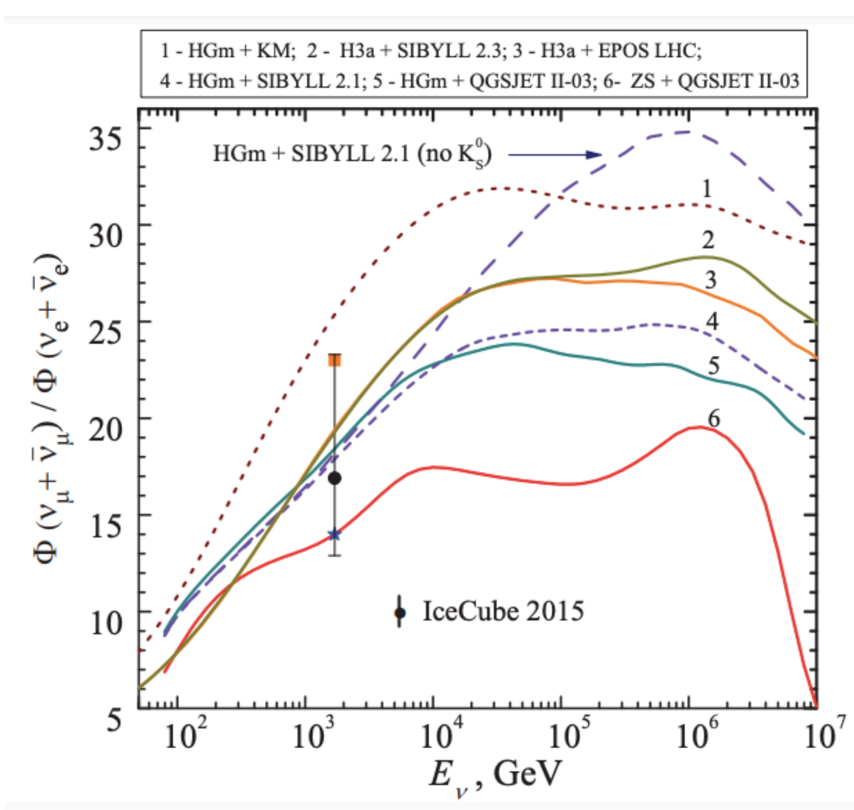
Aarsten M. G. et al. (IceCube Collaboration) Atmospheric and astrophysical neutrinos above 1 TeV interacting in IceCube // Phys. Rev. – 2015. – Vol. D91. –P. 022001.

Characteristics of atmospheric neutrino fluxes

Zenith-angular distribution



Honda M. et al. Calculation of atmospheric neutrino flux using the interaction model calibrated with atmospheric muon data // Phys. Rev. – 2007. – Vol. D 75. – P. 043006. Histogram and



Flavor ratio $R_{\nu_\mu/\nu_e}(E_\nu) = \dfrac{\left\langle \phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu} \right\rangle_\theta}{\left\langle \phi_{\nu_e} + \phi_{\bar{\nu}_e} \right\rangle_\theta}$

- **Symbol of IceCube flavor ratio:**

$$R_{\nu_\mu/\nu_e} = 16.9\ at\ E_\nu = 1.7\ TeV$$

Bartol

Aartsen M.G. et al. (IceCube Collaboration). Measurement of the atmospheric νe spectrum with IceCube // Phys. Rev. – 2015. – Vol. D91. – P. 122004.