What we know about atmospheric neutrino backgrounds…

NEUCOS Workshop

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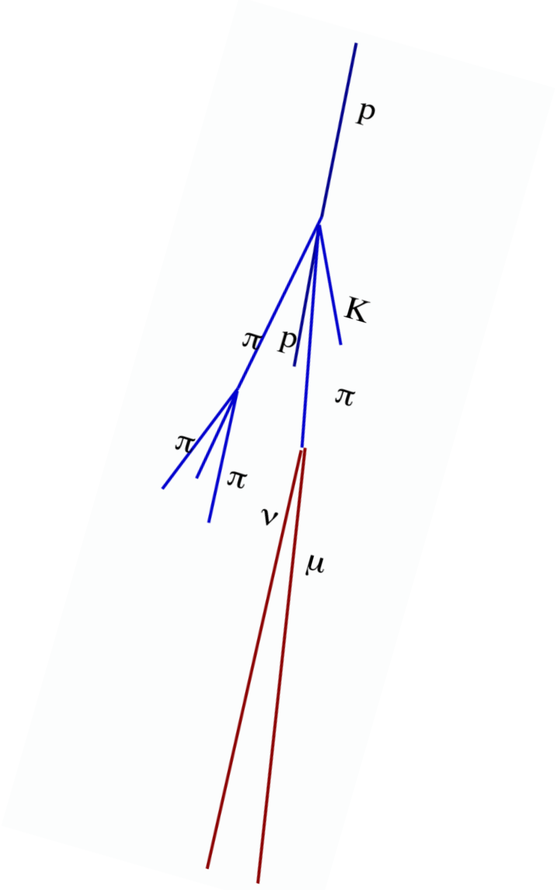
DESY Zeuthen



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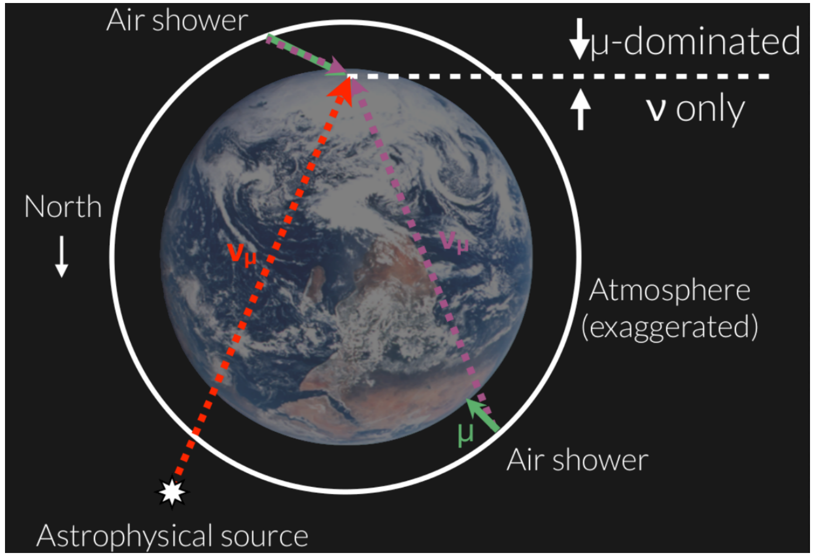
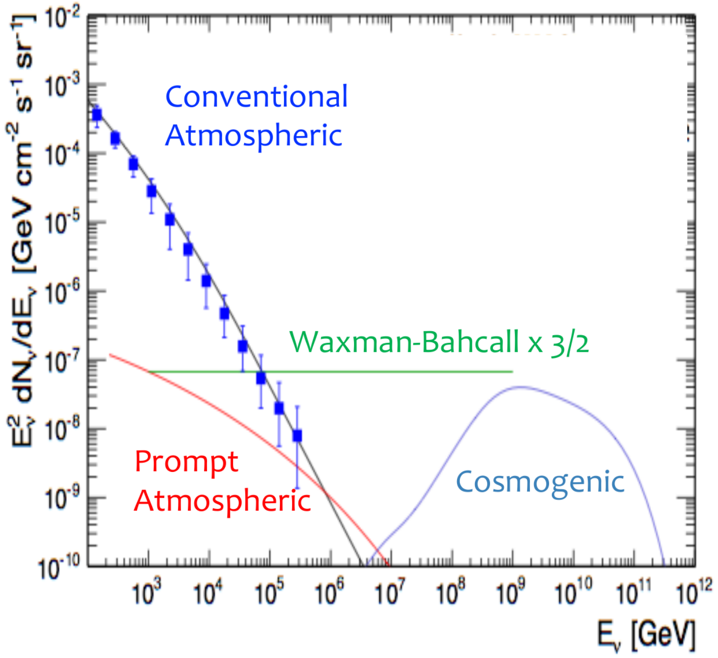
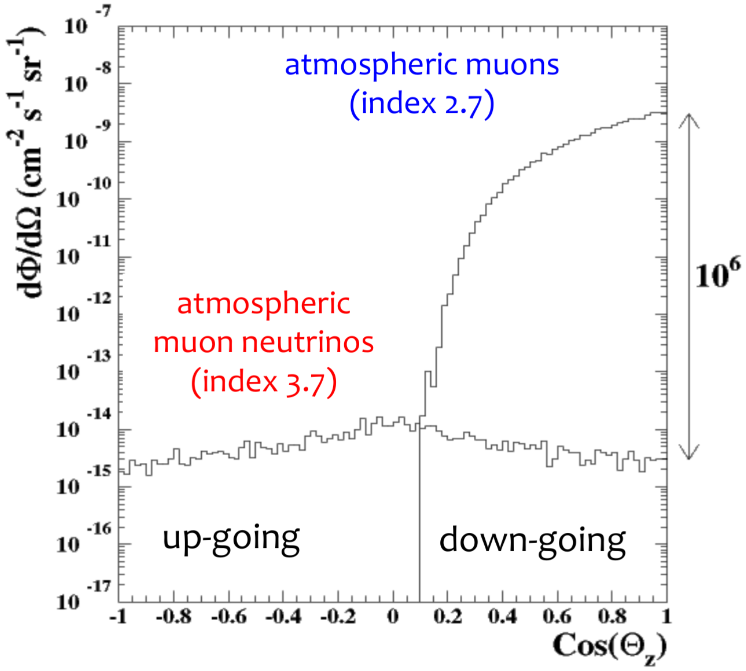
General features seen by a neutrino telescope

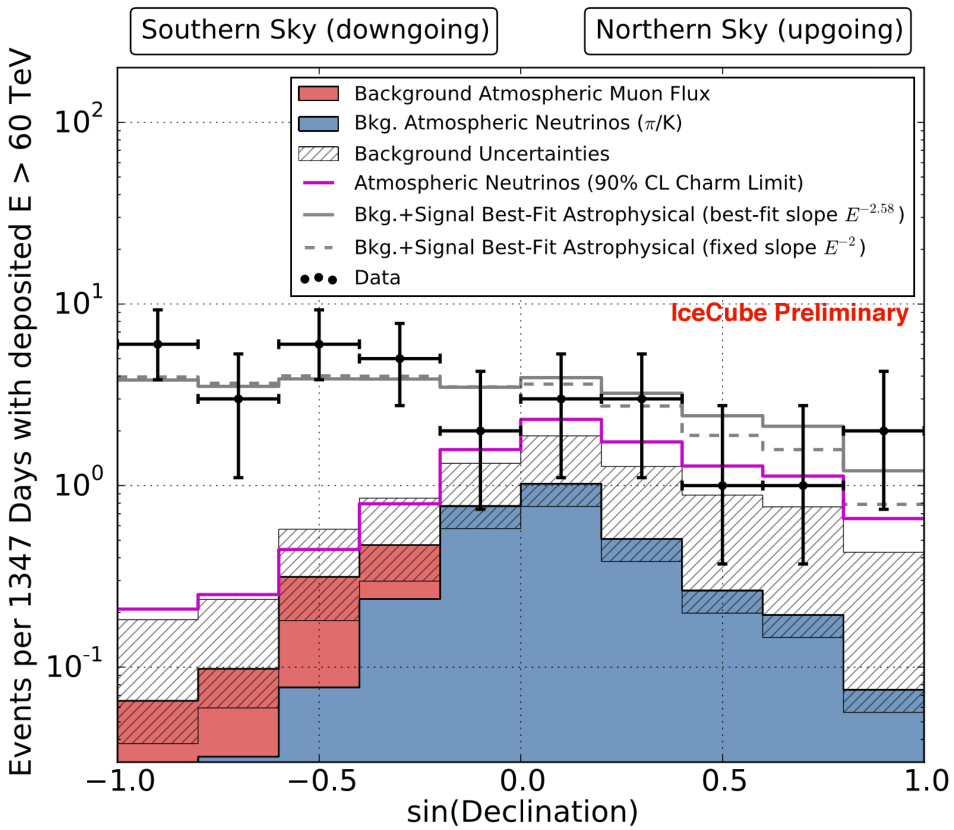
- Most of events detected by IceCube are background.
  - atmospheric μ ~$7x10^{10}$ /year ~ 3000 per second,
  - atmospheric ν_μ tracks > $8x10^4$ /year ~ 1 every 6 minutes
  - astrophysical* ν_μ tracks ~10/year < 1/month





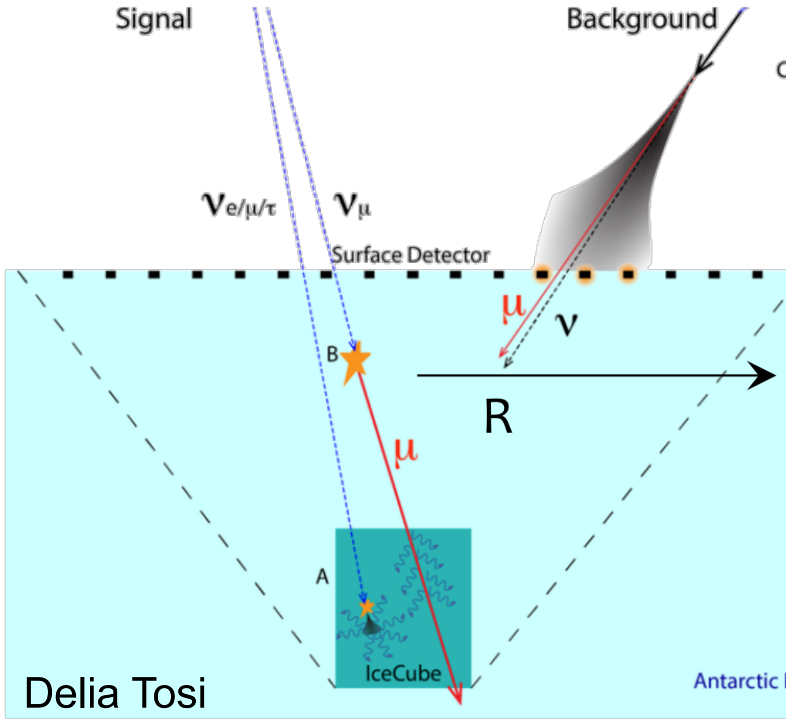


IceCube's southern sky: veto techniques are the key

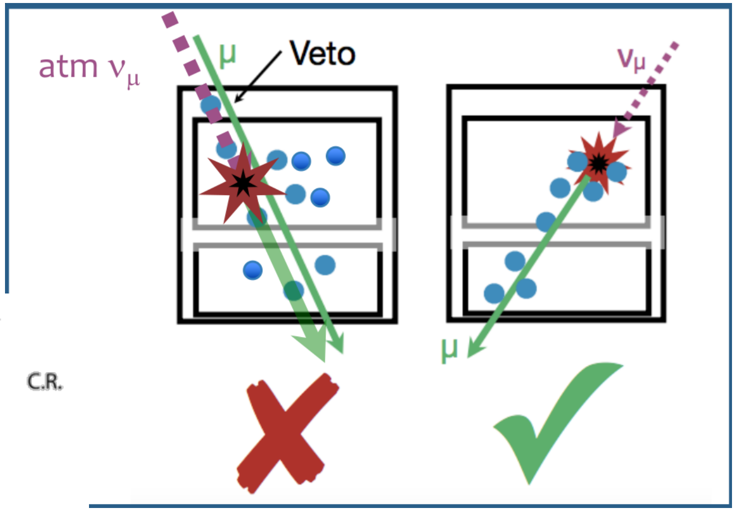


IceCube Collaboration, ICRC 2015

Surface veto



In-ice veto



Generalized veto probability

Lepton flux through convolution of response functions:

$$\phi_\ell(E_\ell,\theta) = \Sigma_A \int \mathrm{d}E\, R_\ell(A,E,E_\ell,\theta)$$

Response function

$$R_\ell(A,E,E_\ell,\theta) = \phi_N(A,E) \times \frac{\mathrm{d}N_l(>E_l,A,E,\theta)}{\mathrm{d}E_l}$$

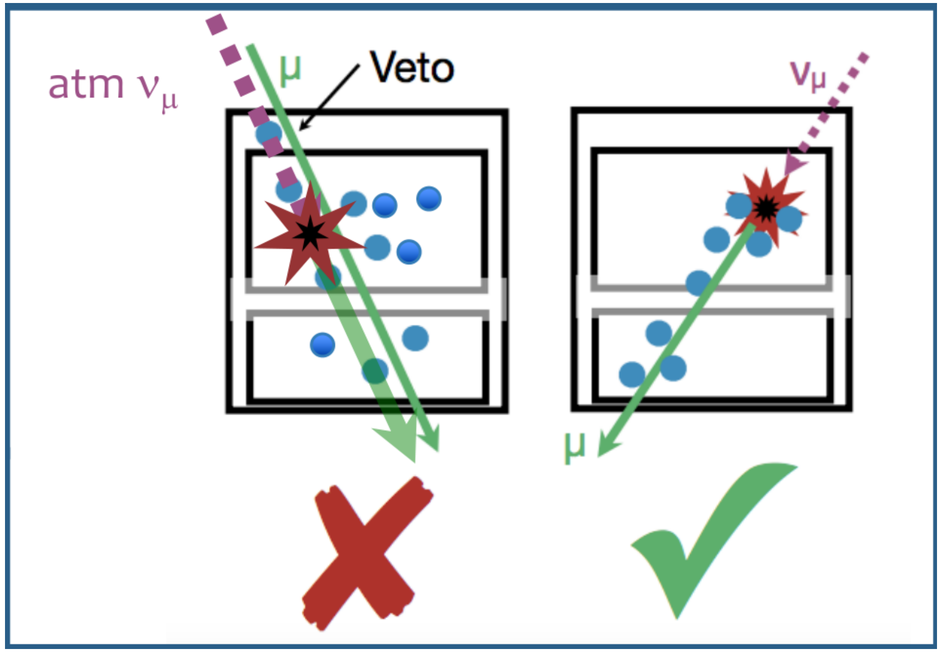
Parameterization for the response function (Elbert-Formula)

$$N_l(>E_l,A,E,\theta) = \mathrm{K}_l \frac{A}{E_l \cos^*\theta} x^{-p_1}\left(1-x^{p_3}\right)^{p_2}$$

Leptons are uncorrelated from different sub-showers

$$P(N_\mu = 0|E,E_{\mu,\min},\theta) = e^{-N_\mu(A,E,\tilde{E}_{\mu,\min}(\theta),\theta)}$$

Principle of the atmospheric veto



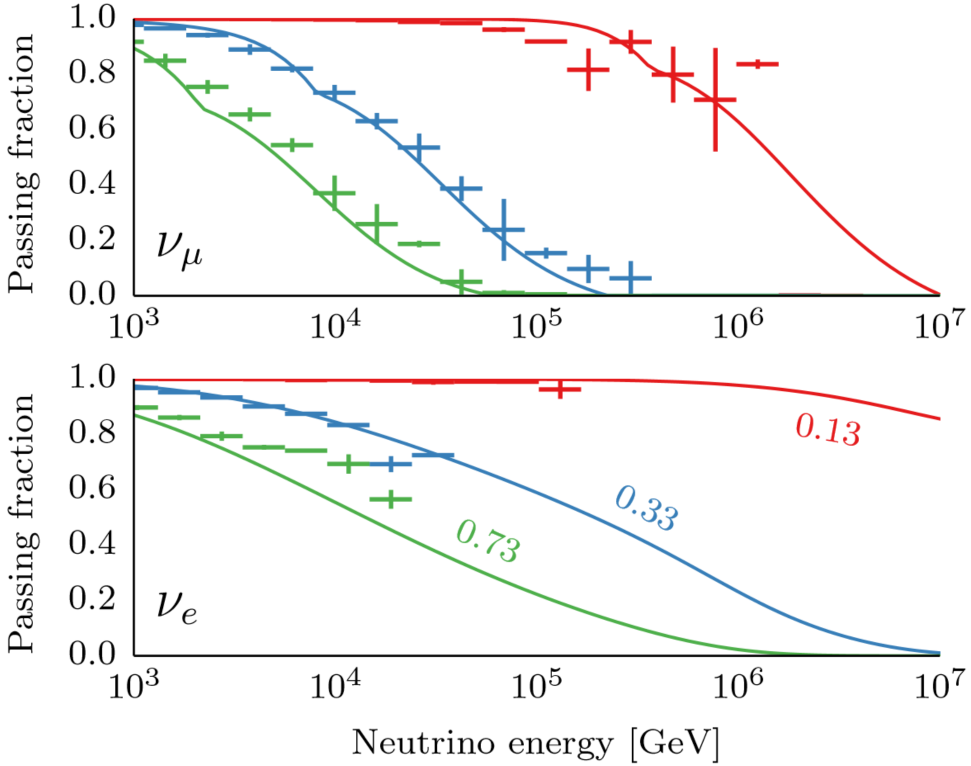
Passing rate (background suppression)

$$P_\nu(E_\nu,\theta) = \frac{\Sigma_A \int \mathrm{d}E\, R_\nu P(N_\mu = 0)}{\Sigma_A \int \mathrm{d}E\, R_\nu}$$

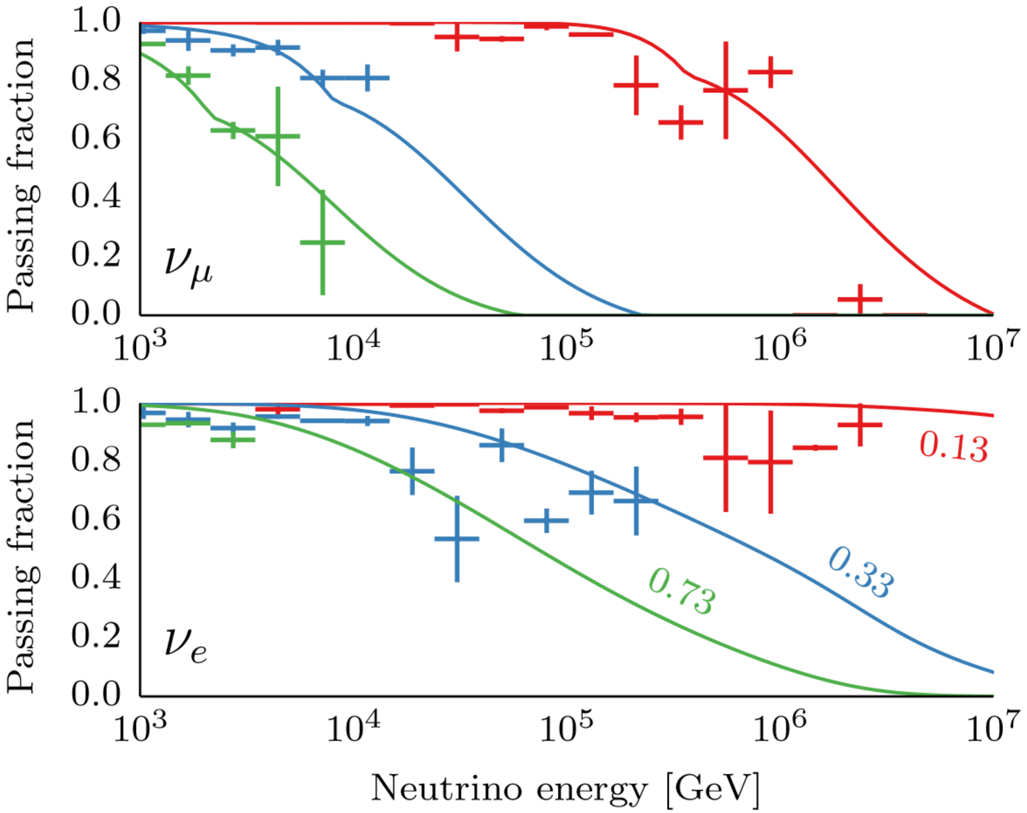
Gaisser, Jero, Karle and van Santen, PRD 90, 023009 (2014)

Agreement with Monte Carlo

Conventional (pi/K) neturinos

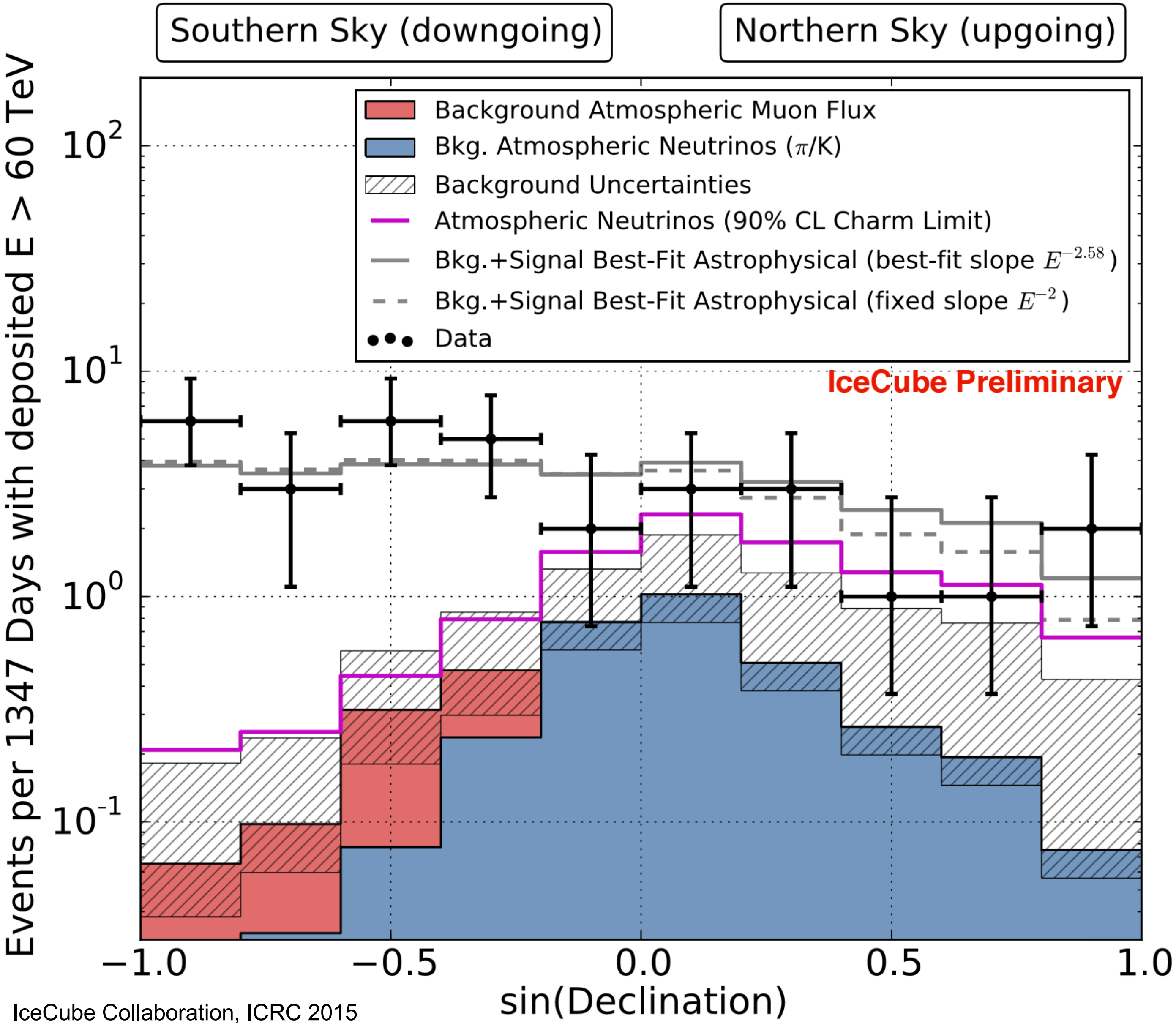


Prompt (charm) neturinos



Gaisser, Jero, Karle and van Santen, PRD 90, 023009 (2014)

Atmospheric flux: main background for up-going neutrino analyses



IceCube Collaboration, ICRC 2015

- Grey hatched are the uncertainties
- Not only related to the flux, neutrino propagation, flavors and interactions included
- Dominant uncertainties of calculations:
  - **Hadronic interactions**
  - **Cosmic ray flux**

Transport equations (hadronic cascade equations)

System of non-linear PDE for each particle species *h* (~62 x #E-bins) *:*

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

cosmic ray physics

Interactions with air

Decays

atmospheric physics

Energy losses (radiative)

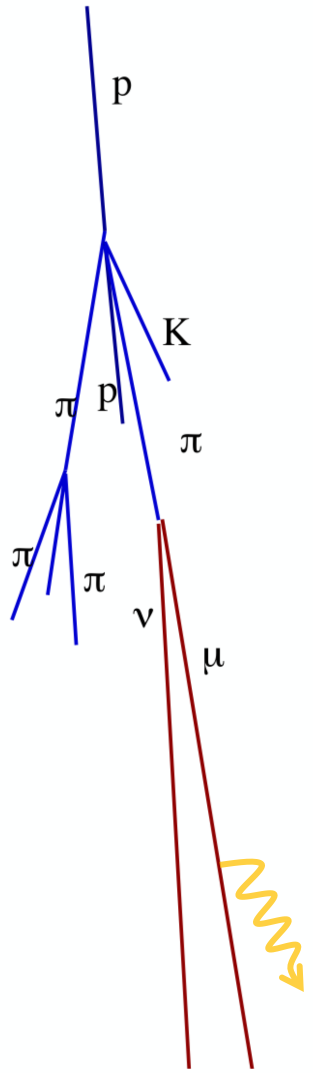
Re-injection from interactions

Re-injection from decays

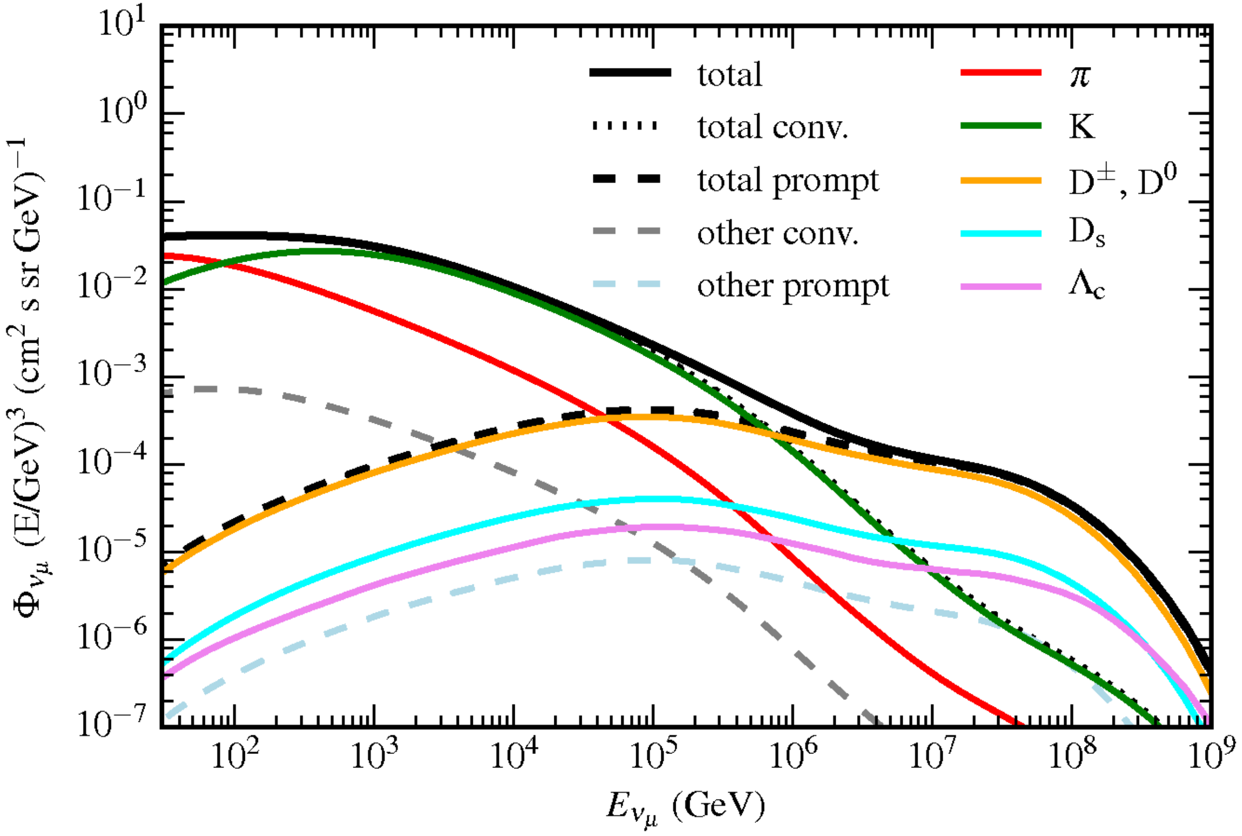
Hadronic high-energy physics

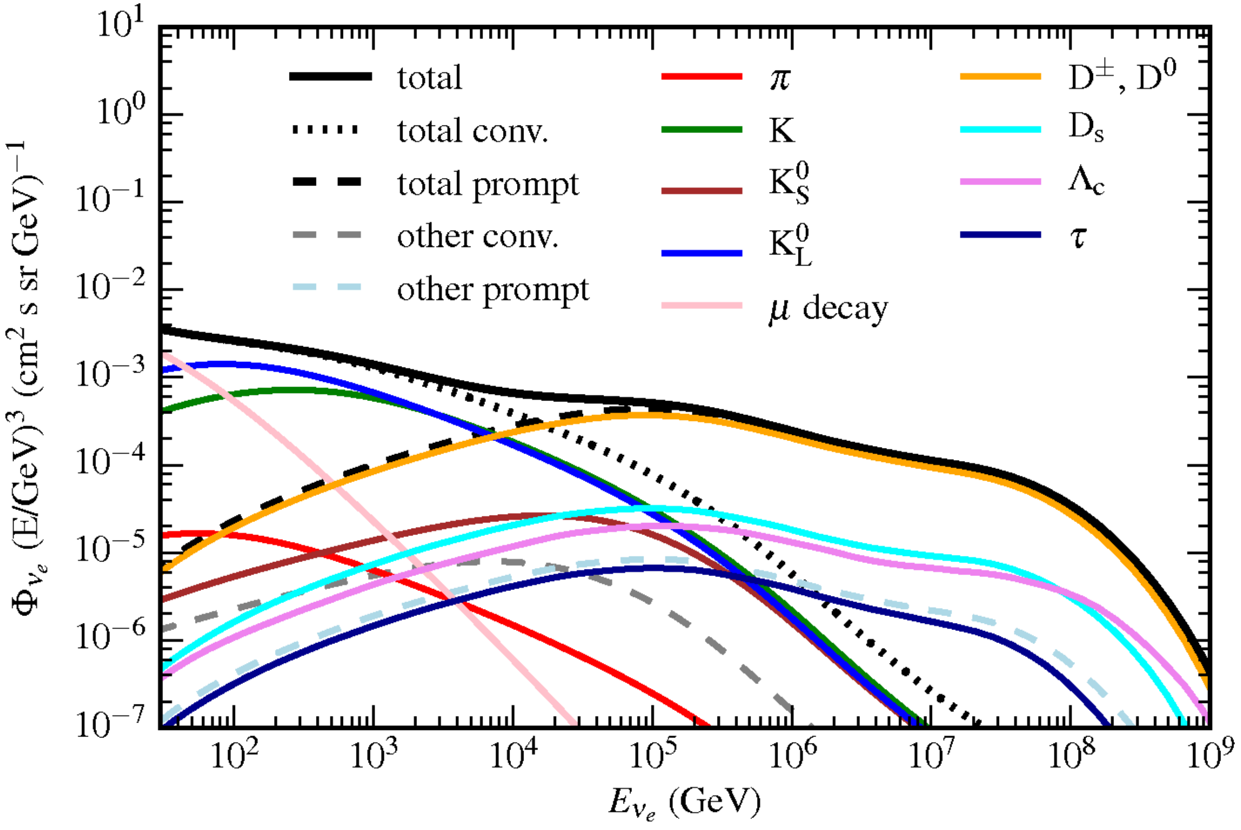
Depth

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



Relevant particles for lepton production

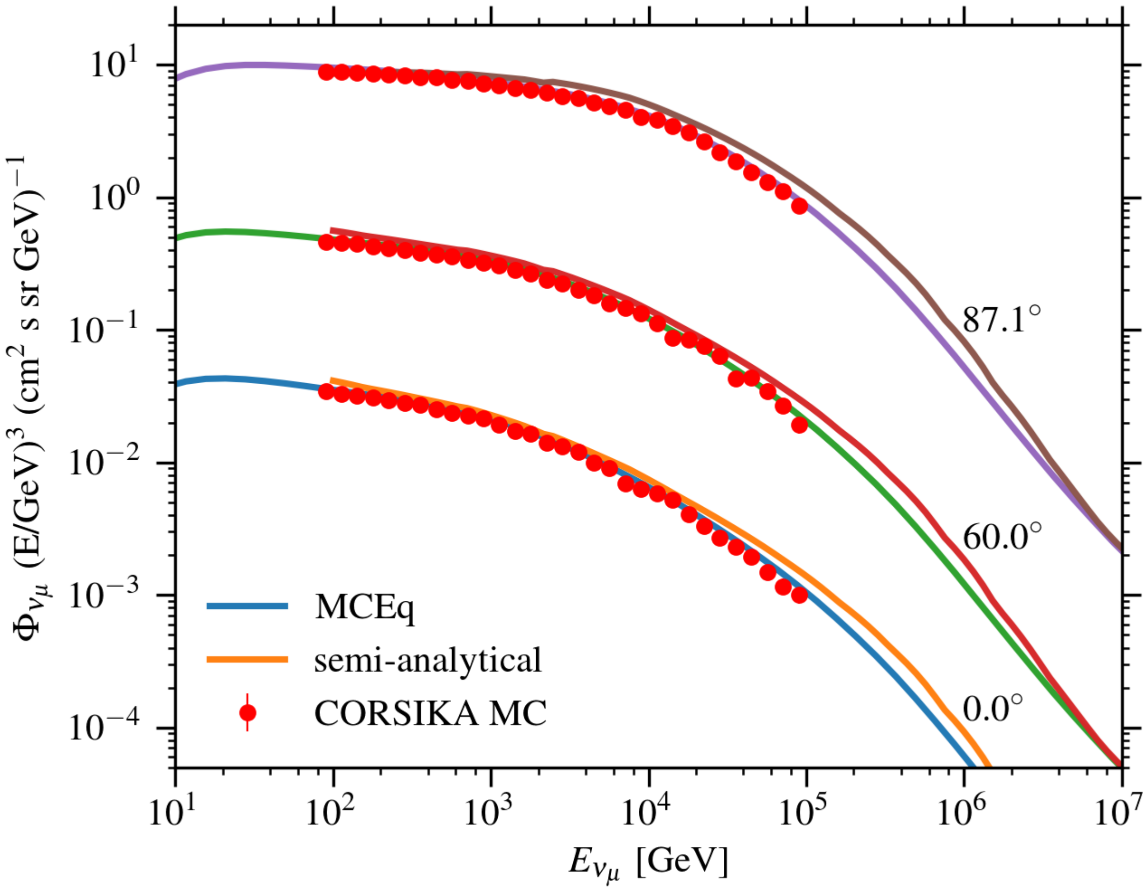

Muon neutrinos


Electron neutrinos

pion decay kaon decay charm decay

muon decay kaon decay charm decay

MCEq: open-source Python code

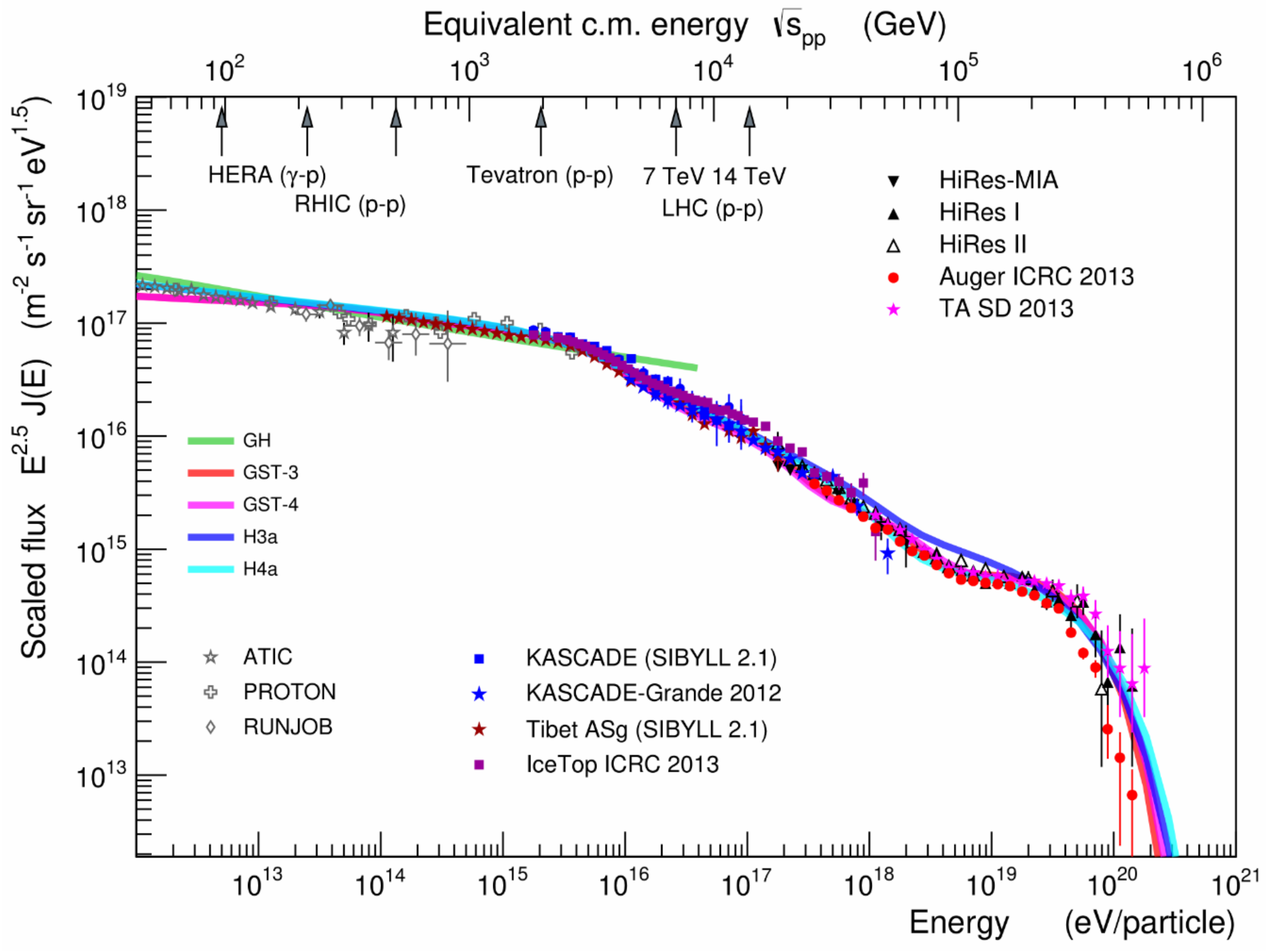


- Simultaneous solution of ~8000 kinetic equations
- Energy range > 1 GeV – 10^{11} GeV
- All models included
- High optimization: GPU, multi-core,… (BLAS, MKL, CUDA) (~**milli-seconds** to seconds)
- MIT licensed @ https://github.com/afedynitch/MCEq

More info on method tomorrow.

CORSIKA: A. Fedynitch, J. Becker Tjus and P. Desiati, PRD 2012
MCEq: A. Fedynitch, R. Engel, T. K. Gaisser, F. Riehn and S. Todor. PoS ICRC 2015, 1129

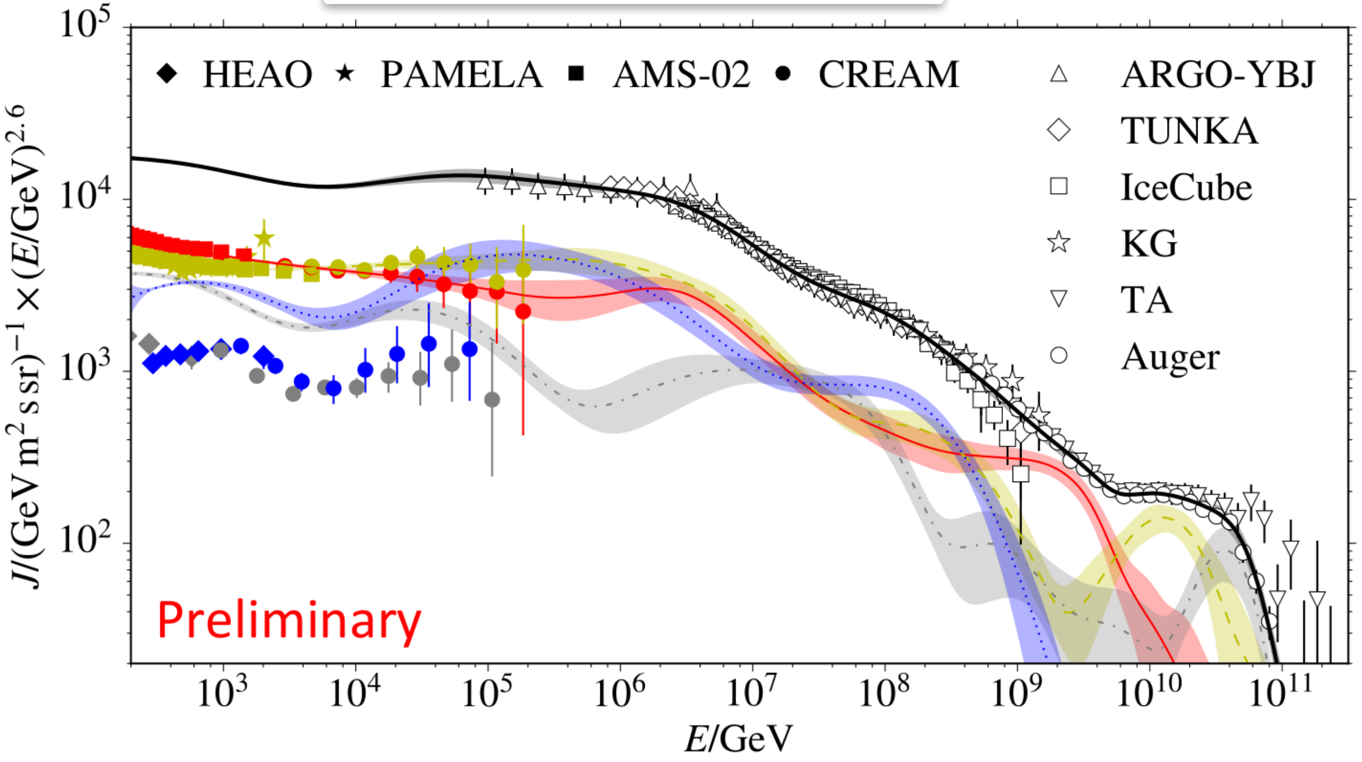
Comic ray spectrum at the top of the atmosphere



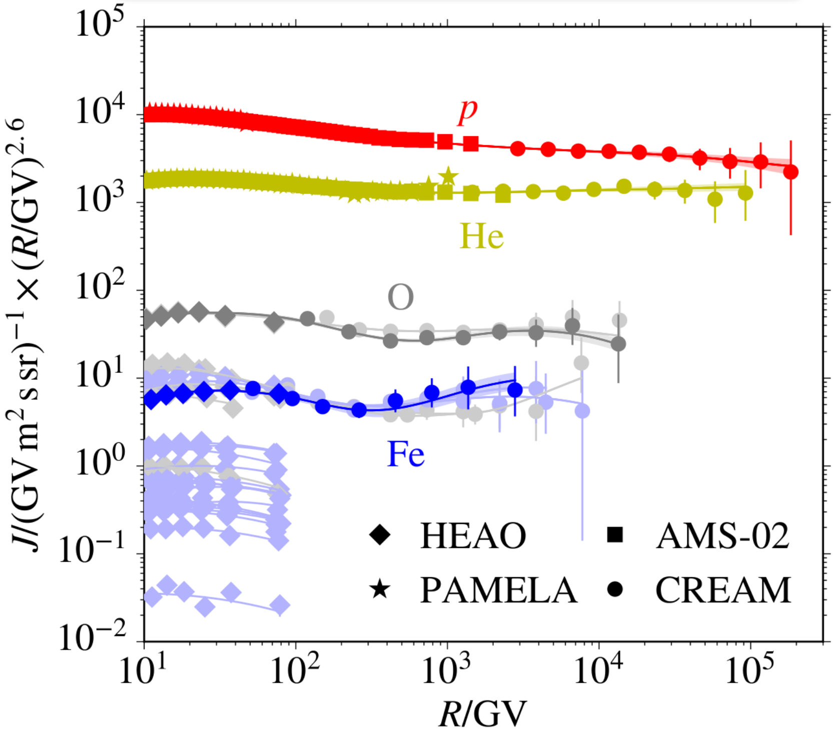
- None of the shown models is a real fit (with covariance matrix)
- GST-X and HXa are quite extreme assumptions for UHECR
- No error estimates!

GSF: Global Spline Fit

All-particle flux



Description of low-energy data

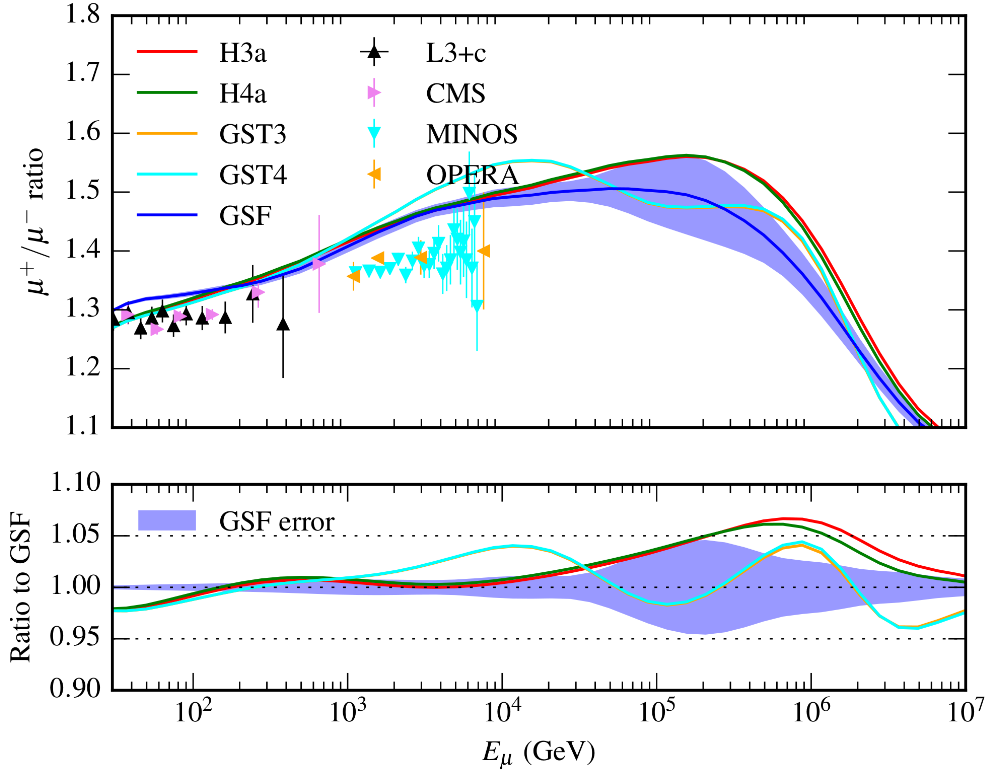


- Data-driven representation of the cosmic ray flux
- Based on B-splines, full covariance matrix
- Errors under control

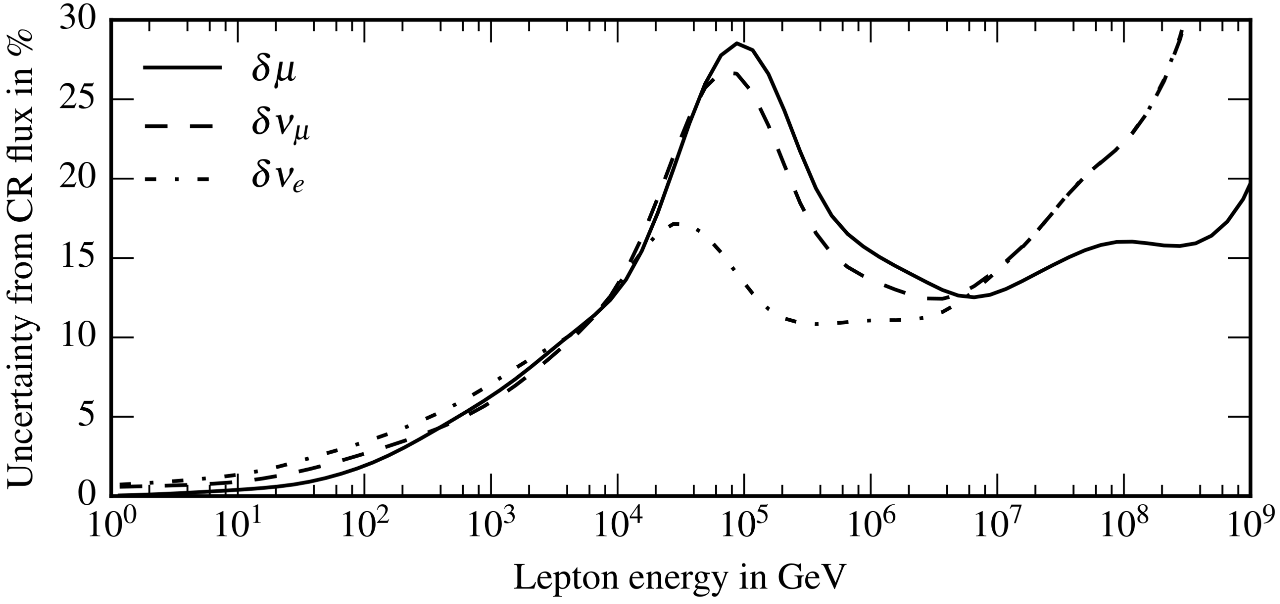
H. Dembinski, AF, R. Engel, T. K. Gaisser, F. Riehn, T. Stanev, in prep.

CR flux errors propagated into leptons

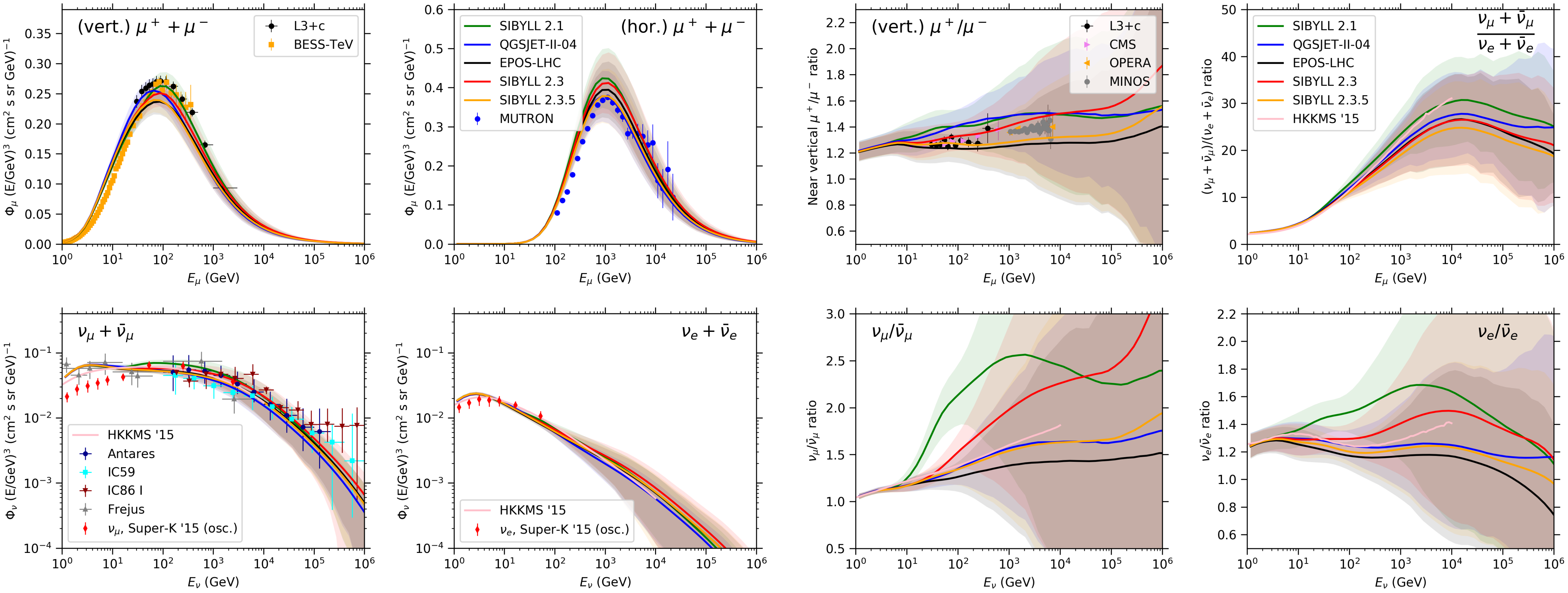
Total CR uncertainty charge ratio



Total CR uncertainty on lepton flux

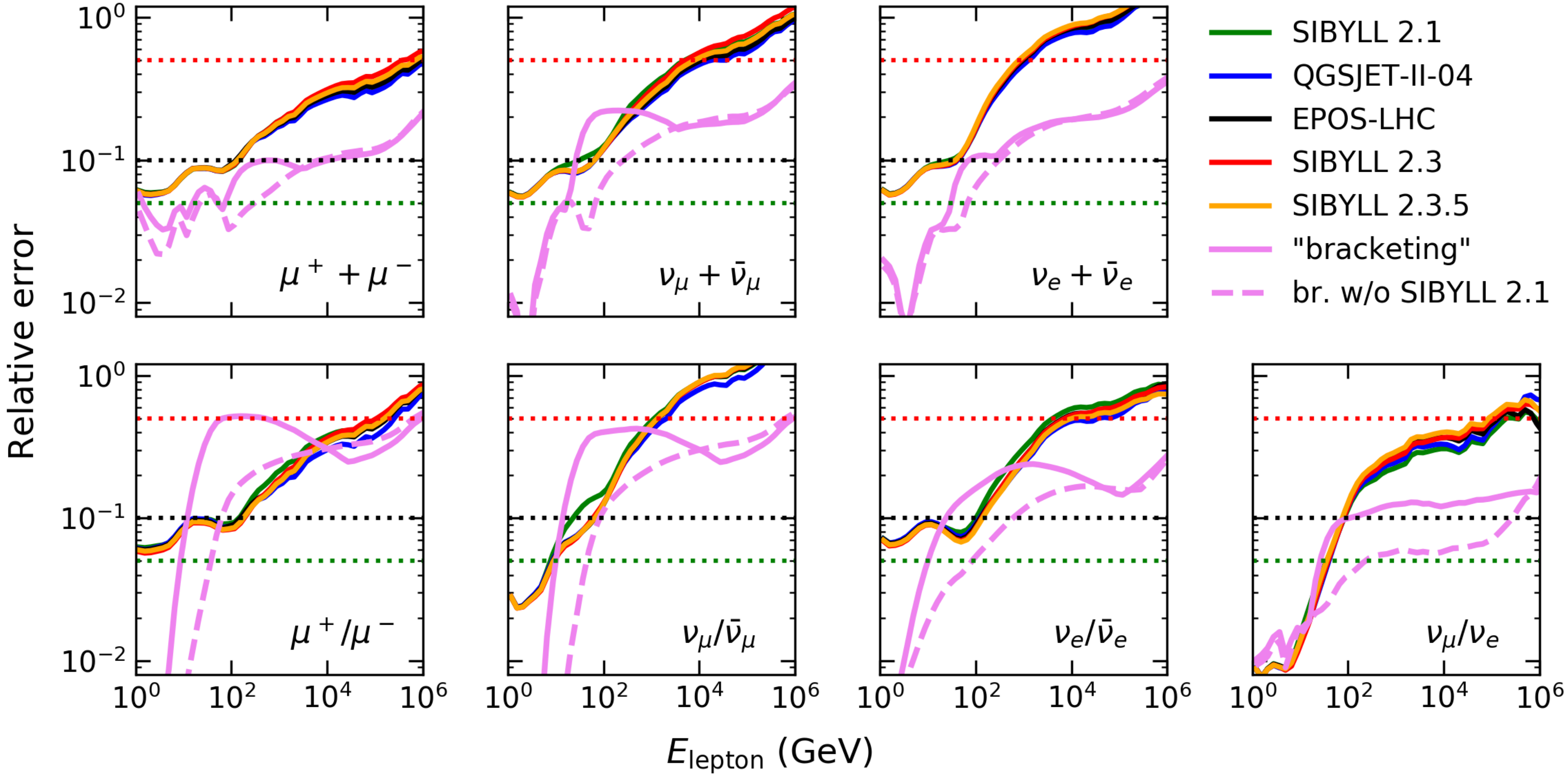


Hadronic uncertainties



Atmospheric leptons are able to constrain hadronic physics

Hadronic uncertainties



Atmospheric leptons are able to constrain hadronic physics

Why constraints on particle production at high energy are weak

Kinematic variables

$$\theta = \arctan \frac{p_T}{p_z}$$

$$\eta = -\ln\left(\tan \frac{\theta}{2}\right)$$

$$x_{\text{lab}} = \frac{E_{\text{secondary}}}{E_{\text{primary}}} \approx \frac{p_{z,\text{secondary}}}{E_{\text{primary}}}$$

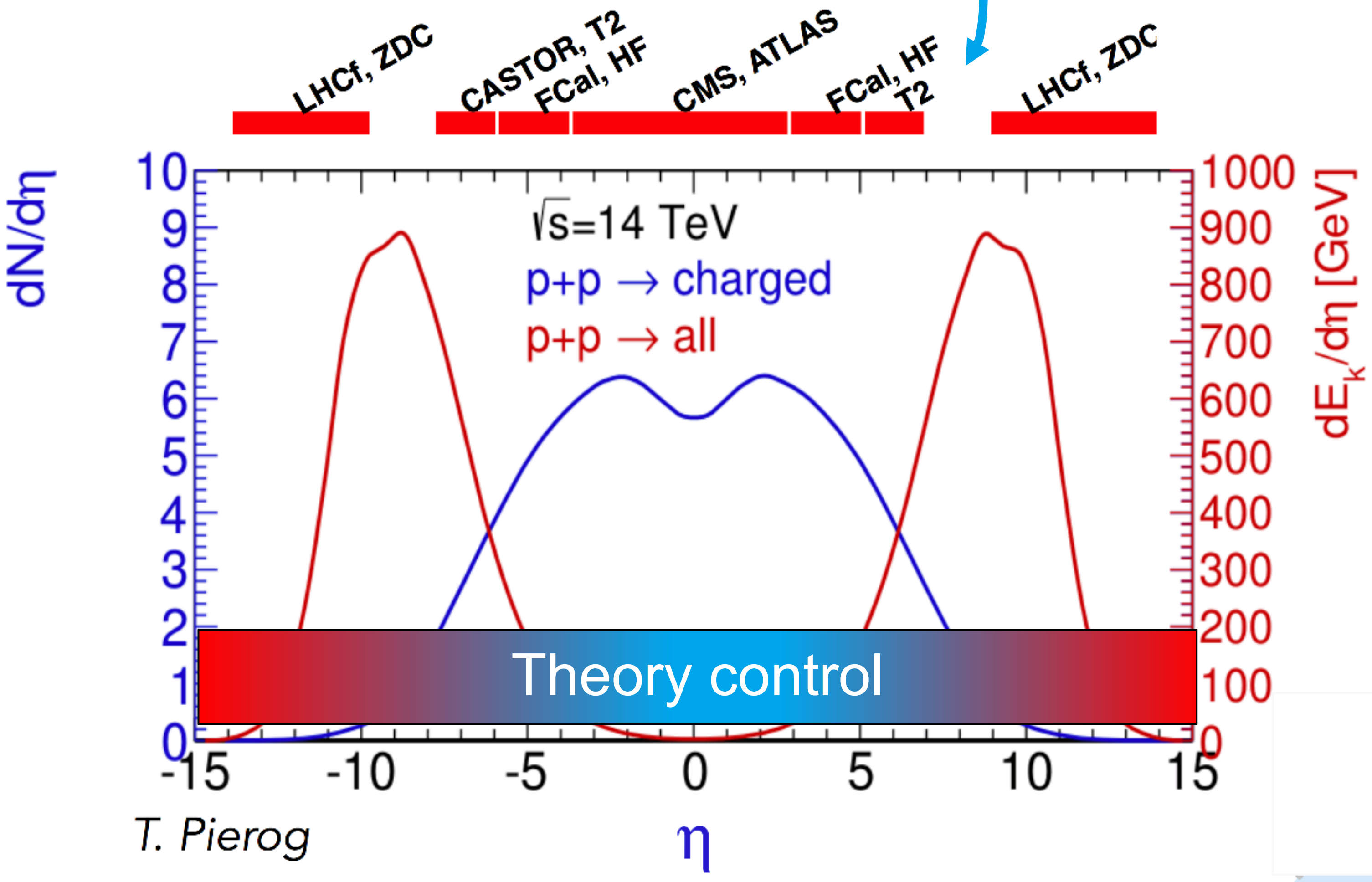
For atmospheric leptons

$$p_z \sim \text{TeV} - \text{PeV}$$

$$p_T \sim \text{few GeV}$$

$$\theta \sim \mu\text{rad}$$

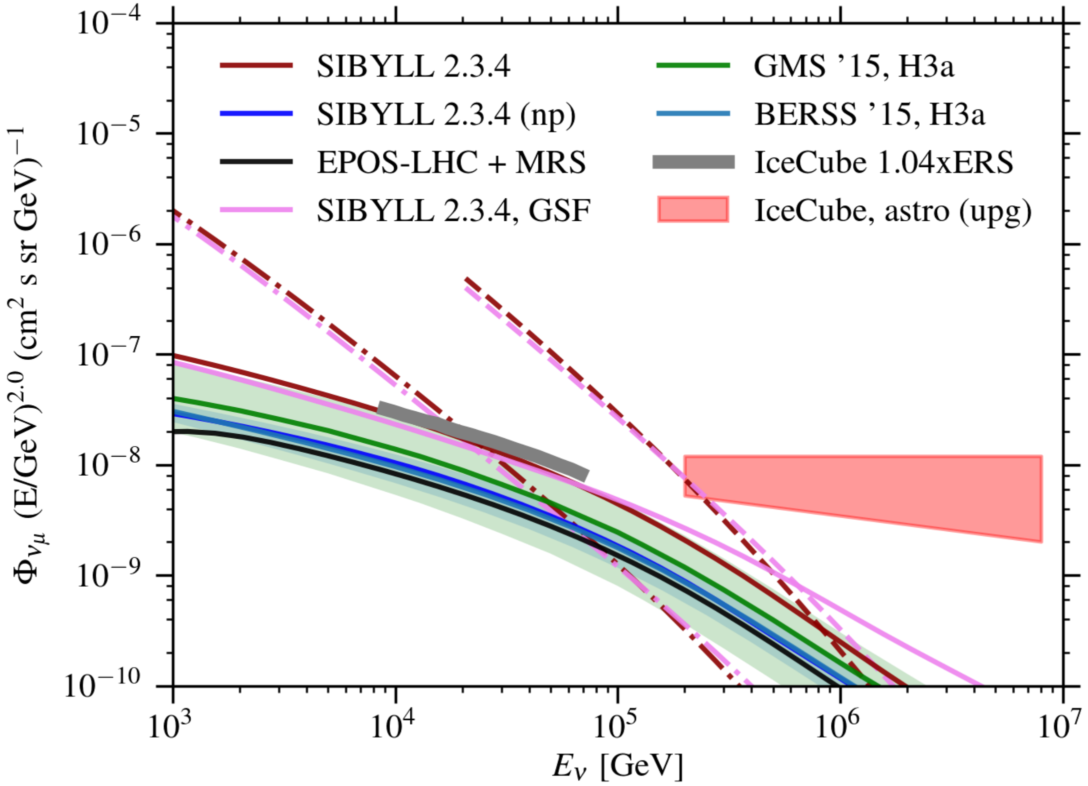
$$\boxed{x_{\text{lab}} > 0.1, \quad \eta \to \infty}$$



T. Pierog

Beam pipe!

Prompt muon neutrinos from charm



- SIBYLL 2.3(.4) is the only MC model
- The perturbative (central) component is at the level of state-of-the-art NLL/NLO calculations
- Compatible with LHC data and IceCube limit
- New CR flux model (GSF) changes situation a bit
- Uncertainties from QCD very large and calculations are compatible

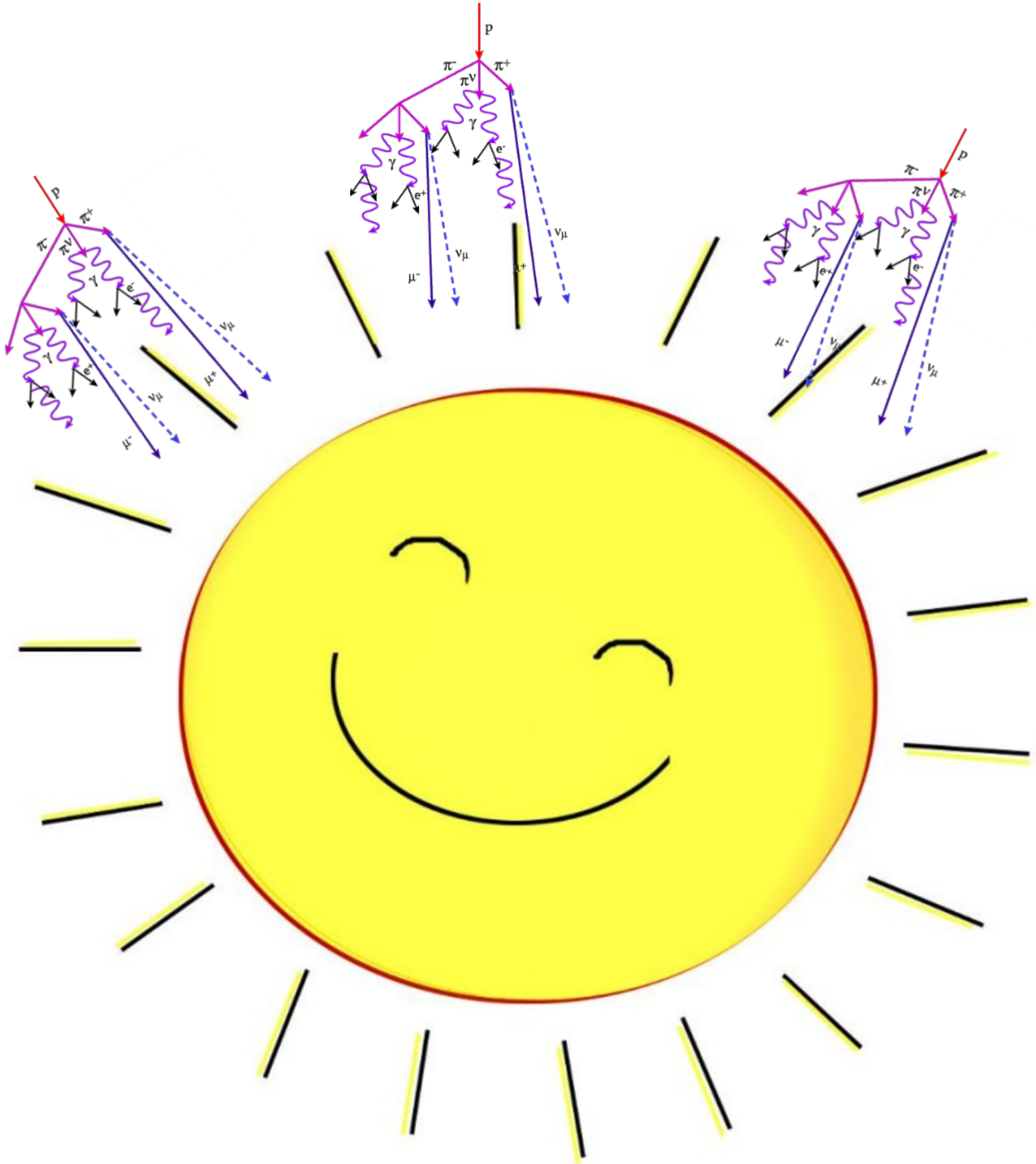
IceCube: Astrophys.J. 833 (2016)
GMS: Garzelli et al., JHEP 1510 (2015) 115
BERSS: Bhattacharya et al. JHEP 2015: 110

Solar **Atmospheric Neutrinos** and the Sensitivity Floor for Solar Dark Matter Annihilation Searches

Carlos Argüelles, Gwen de Wasseige, AF and Ben Jones
arXiv: 1703.07798

Some slides are borrowed from Carlos!

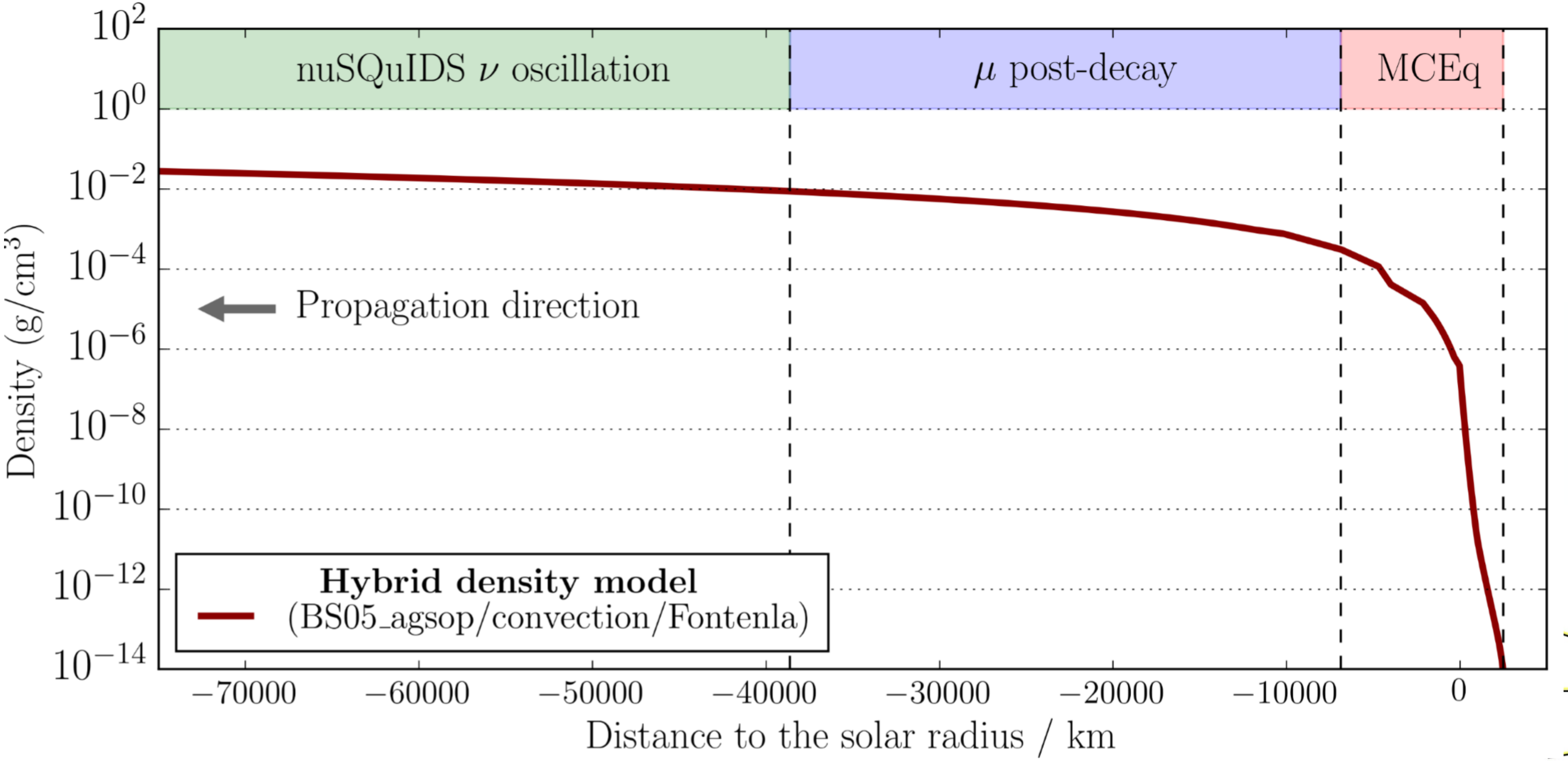
The setup

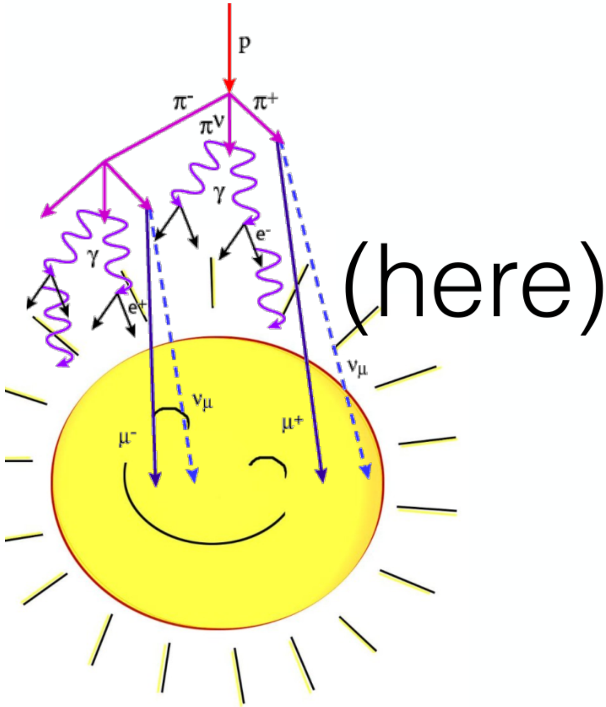


- The Sun receives the same CR spectrum as the earth
- It has an atmosphere

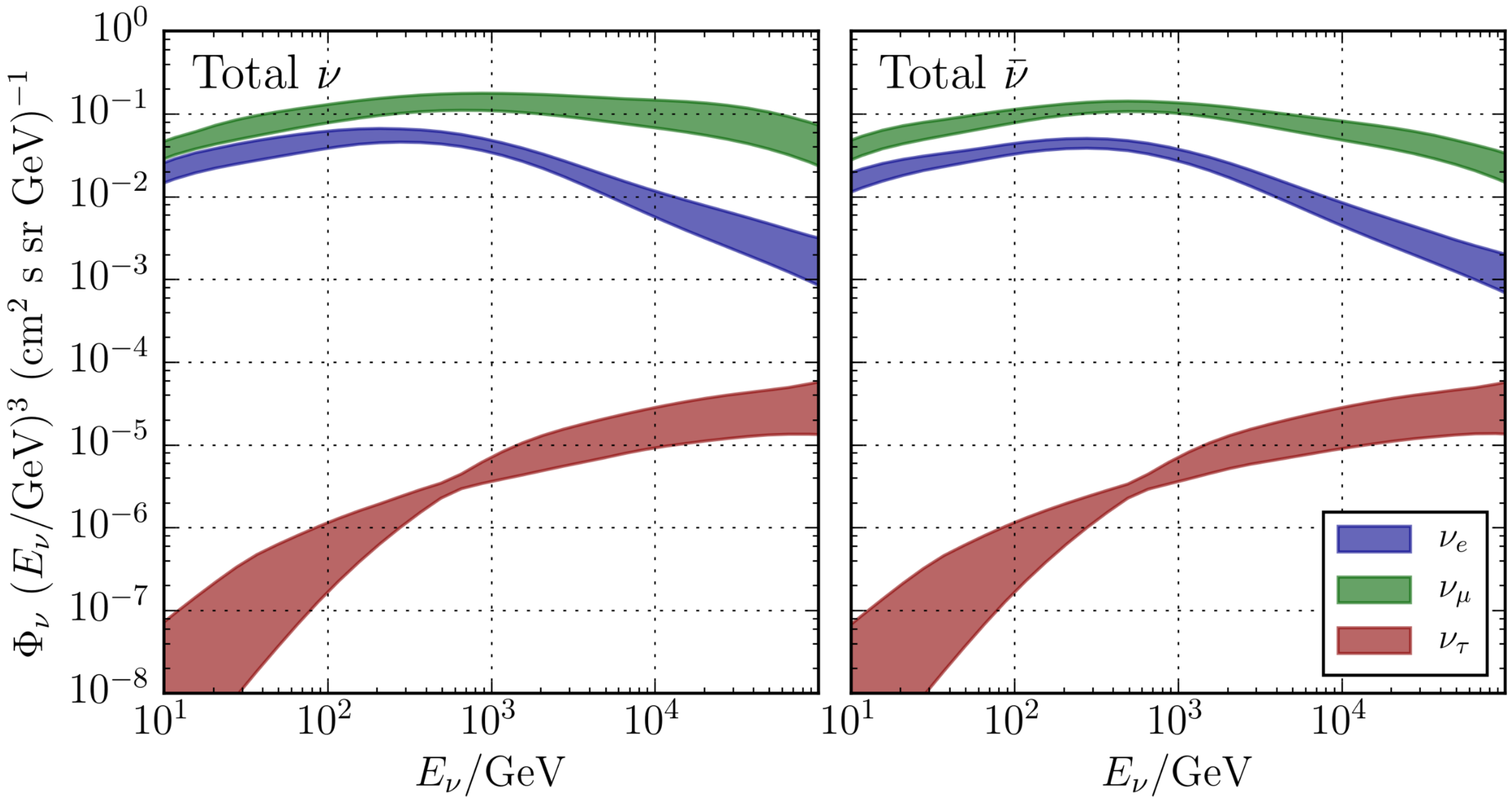
There are air-showers and atmospheric leptons are produced!

Calculation scheme





Fluxes at the sun



- Uncertainty bands include
  - Hadronic
  - Cosmic ray
  - Atmospheric model
- Such a level of detailed was never achieved in the past
- … and not by our competitors
  - Ng et al. (1703.10280)
  - Edsjö et al. (1704.02892) (use MCEq, too!)

For neutrino propagation we use the nuSQuIDS package

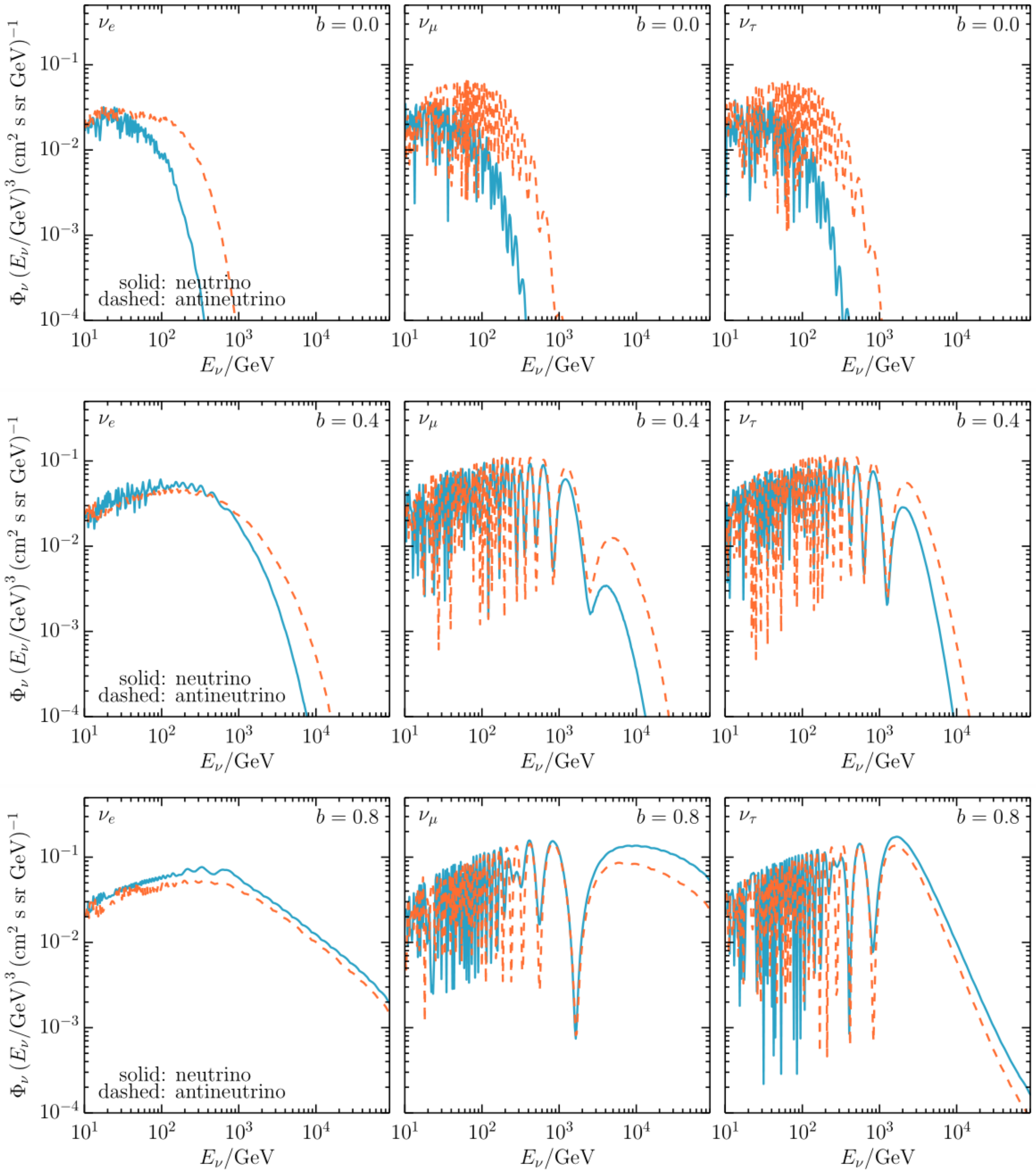
$$\frac{\partial \rho(E,x)}{\partial x} = -i[H_1(E,x),\rho(E,x)] - \{\Gamma(E,x),\rho(E,x)\} + F[\rho,\bar{\rho};E,x]$$

$$\begin{aligned}
\bar{F}[\rho,\bar{\rho};E,x] = {} & \sum_\alpha \bar{\Pi}_\alpha(E,x) \int_E^\infty \mathrm{Tr}\left[\bar{\Pi}_\alpha(E_{\bar{\nu}_\alpha},x)\bar{\rho}(E_{\bar{\nu}_\alpha},x)\right] \frac{1}{\bar{\lambda}^\alpha_{\mathrm{NC}}(E_{\bar{\nu}_\alpha},x)} \frac{\partial \bar{N}^\alpha_{\mathrm{NC}}(E_{\bar{\nu}_\alpha},E)}{\partial E} dE_{\bar{\nu}_\alpha} \\
& +\bar{\Pi}_\tau(E,x) \int_E^\infty \int_{E_\tau}^\infty \mathrm{Tr}\left[\bar{\Pi}_\tau(E_{\bar{\nu}_\tau},x)\bar{\rho}(E_{\bar{\nu}_\tau},x)\right] \\
& \qquad \times \frac{1}{\bar{\lambda}^\tau_{\mathrm{CC}}(E_{\nu_\tau},x)} \frac{\partial \bar{N}^\tau_{\mathrm{CC}}(E_{\bar{\nu}_\tau},E_\tau)}{\partial E_\tau} \frac{\partial \bar{N}^{\mathrm{all}}_{\mathrm{dec}}(E_\tau,E)}{\partial E} dE_{\bar{\nu}_\tau} dE_\tau \\
& \left(\mathrm{Br}_e\bar{\Pi}_e(E,x) + \mathrm{Br}_\mu\bar{\Pi}_\mu(E,x)\right) \int_E^\infty \int_{E_\tau}^\infty \mathrm{Tr}\left[\Pi_\tau(E_{\nu_\tau},x)\rho(E_{\nu_\tau},x)\right] \\
& \qquad \times \frac{1}{\lambda^\tau_{\mathrm{CC}}(E_{\nu_\tau},x)} \frac{\partial N^\tau_{\mathrm{CC}}(E_{\nu_\tau},E_\tau)}{\partial E_\tau} \frac{\partial N^{\mathrm{lep}}_{\mathrm{dec}}(E_\tau,E)}{\partial E} dE_{\nu_\tau} dE_\tau \qquad (10\mathrm{b}) \\
& + \left(\sum_\alpha \bar{\Pi}_\alpha(E,x)\right) \int_E^\infty \mathrm{Tr}\left[\bar{\Pi}(E_{\bar{\nu}_e},x)\bar{\rho}(E_{\bar{\nu}_e},x)\right] \frac{1}{\bar{\lambda}_{\mathrm{GR}}(E_{\bar{\nu}_e},x)} \frac{\partial \bar{N}^e_{\mathrm{GR}}(E_{\bar{\nu}_e},E)}{\partial E} dE_{\bar{\nu}_e}
\end{aligned}$$

- Accounts for CC, NC, oscillations, tau regeneration.
- Fast: 15-30 minutes
- Open-source!

https://github.com/arguelles/nuSQuIDS

Propagation and geometry



Aggregated flux pointing towards Earth

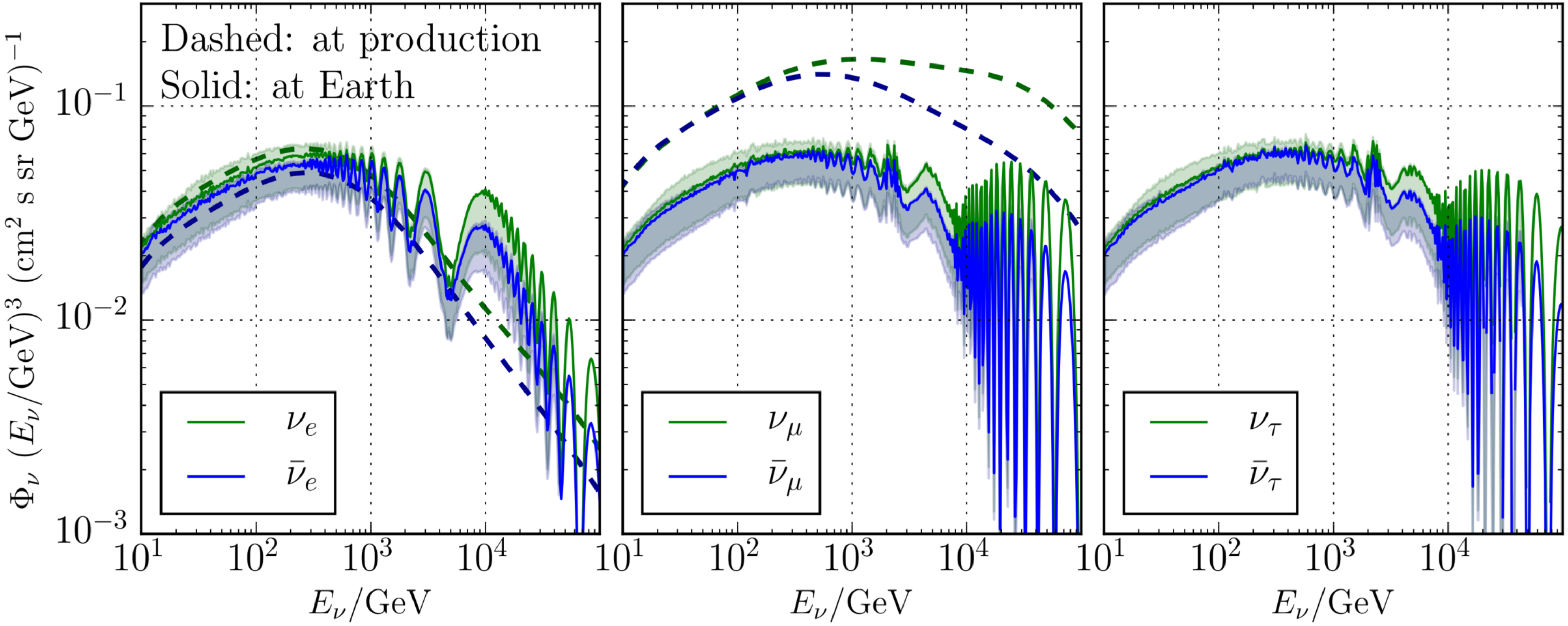
$$\Phi(E_\nu)_\alpha = 2\int db\ b\Phi_{b,\alpha}(E_\nu)\Omega_\odot$$

b = impact parameter

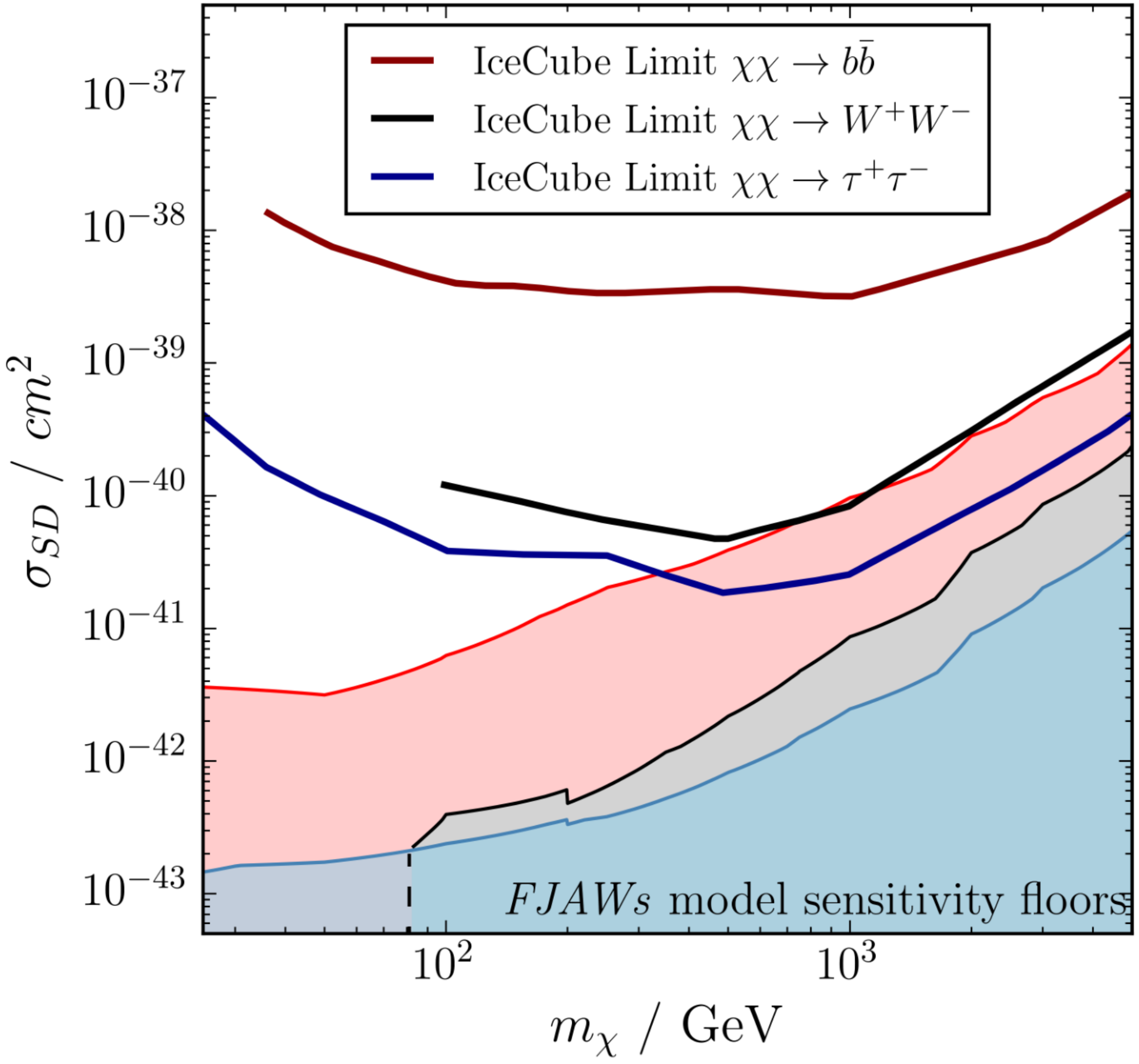
Propagated fluxes are averaged across one orbit

$$\bar{\Phi}_\alpha(E_\nu) = \frac{1}{2\pi}\sum_\beta \int_0^{2\pi} d\theta\ P_{osc}^{\beta,\alpha}(r(\theta), E_\nu)\Phi_{b,\beta}(E_\nu)$$

Fluxes at Earth



Will we be able to see dark matter from the sun?



- IceCube can reach the solar limits soon
- … or find Dark Matter
- … or see atmospheric neutrinos from the Sun

Conclusions

- Most aspects of atmospheric neutrino production are understood
- Hadronic uncertainties are huge, since accelerator-based experiments are not sensitive to the relevant phase-space for secondary particle production
- Ongoing effort to use atmospheric lepton data for constraining hadronic uncertainties; sensitivity to non-perturbative QCD effects
- Atmospheric neutrino production in the sun are described to very high detail and it will be possible to observe them soon. Good agreement between different studies!
- Solar atmospheric fluxes available @ https://dspace.mit.edu/handle/1721.1/108394