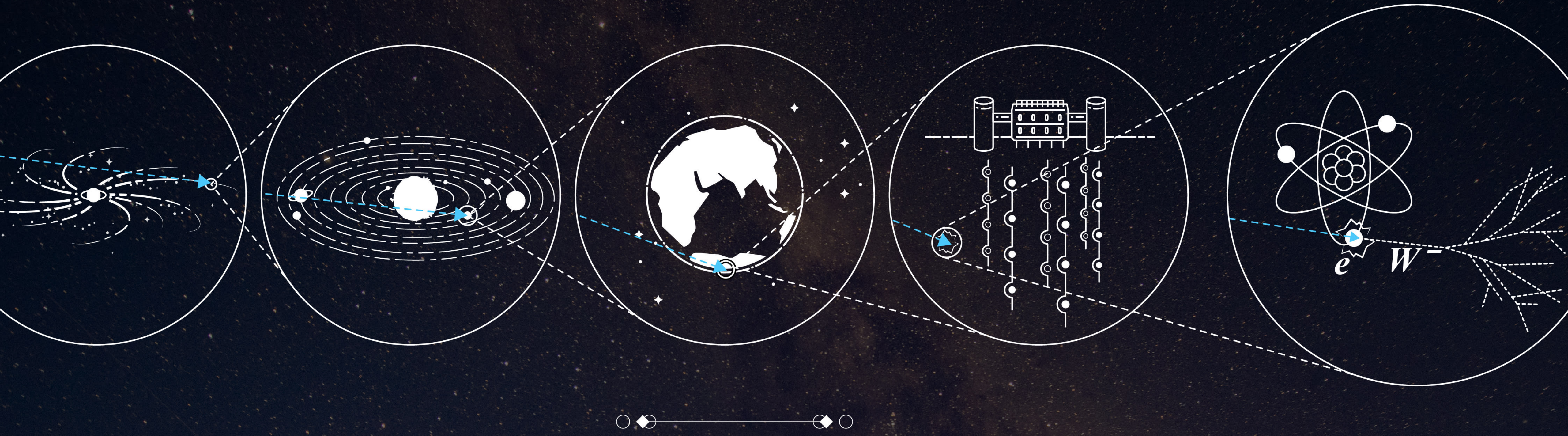
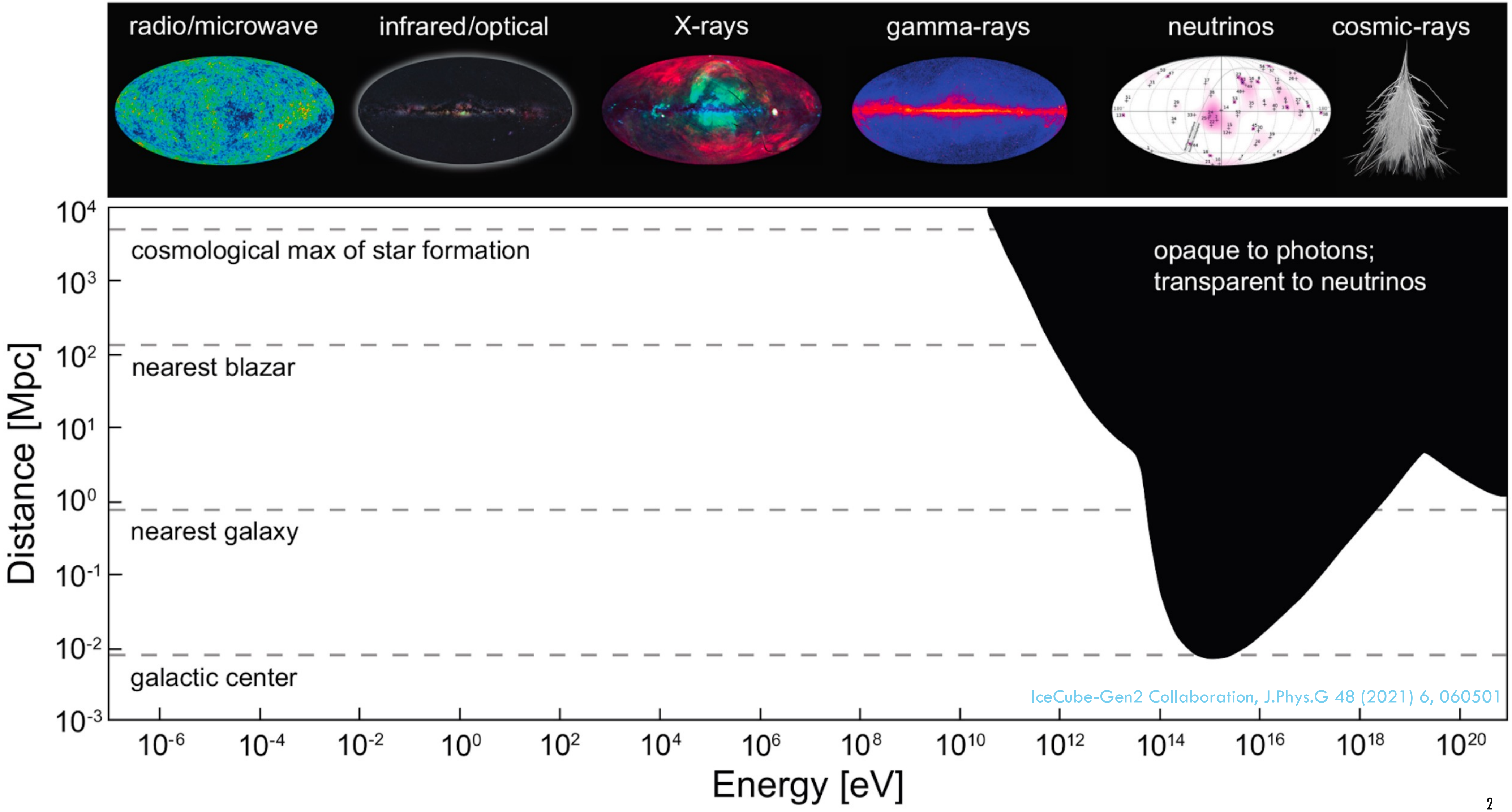
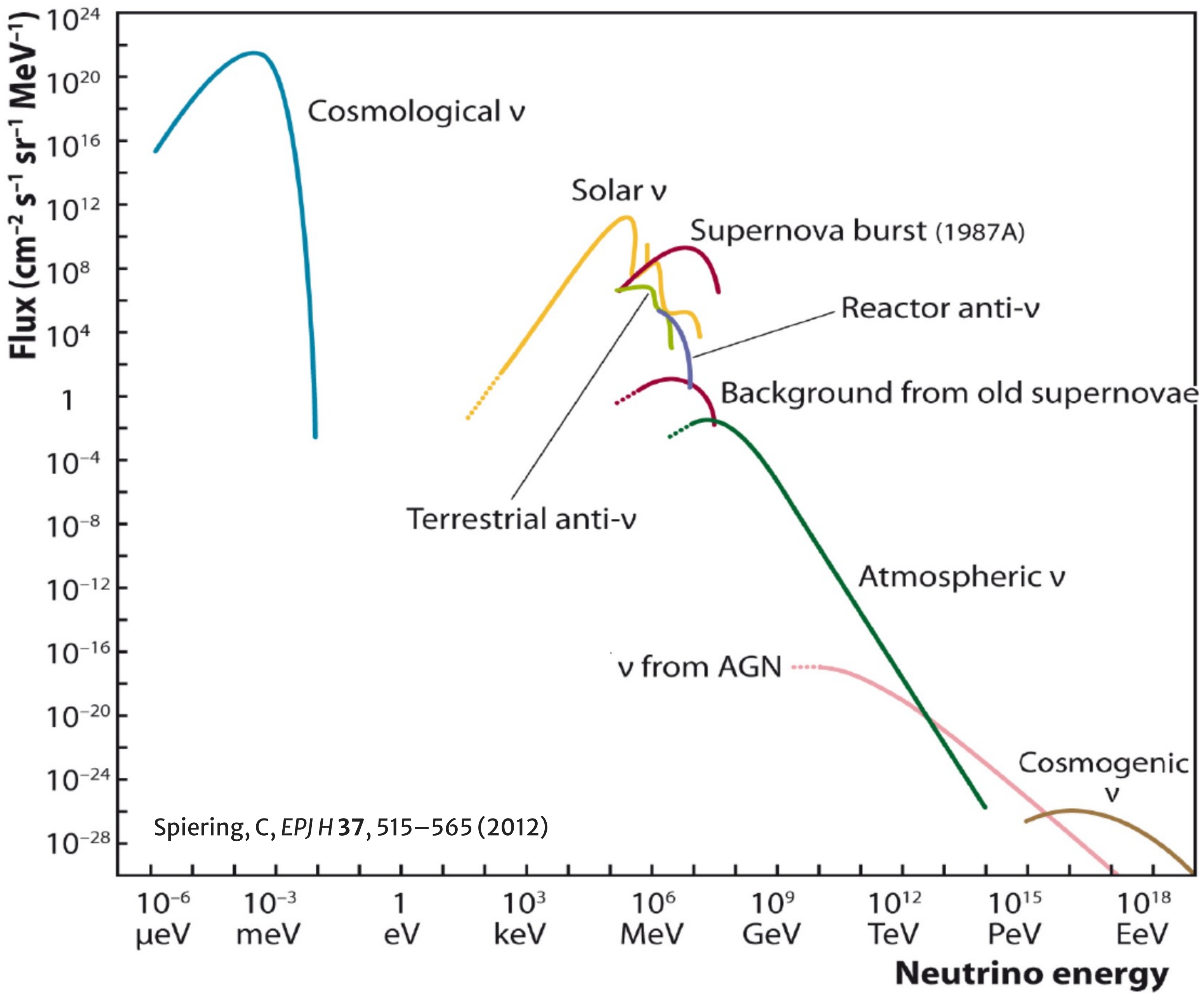


FORWARD CHARM WITH ICECUBE

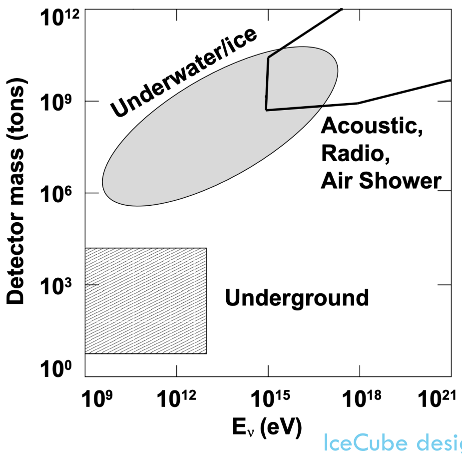
Lu Lu
University of Wisconsin-Madison

NEUTRINOS: THE WINDOW TO THE EXTREME UNIVERSE

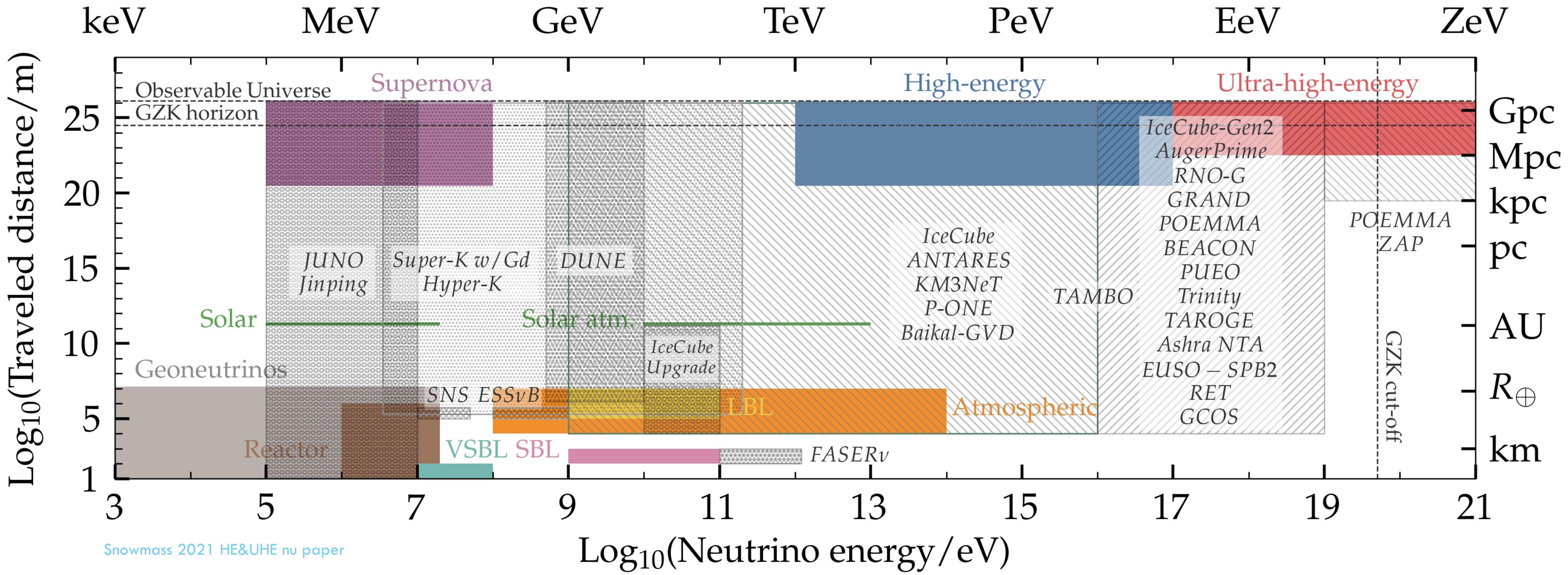



Flux (cm⁻² s⁻¹ sr⁻¹ MeV⁻¹)
Cosmological ν
Solar ν
Supernova burst (1987A)
Reactor anti-ν
Background from old supernovae
Terrestrial anti-ν
Atmospheric ν
ν from AGN
Cosmogenic ν
Neutrino energy
Spiering, C, EPJ H 37, 515–565 (2012)

NEUTRINO DETECTIONS



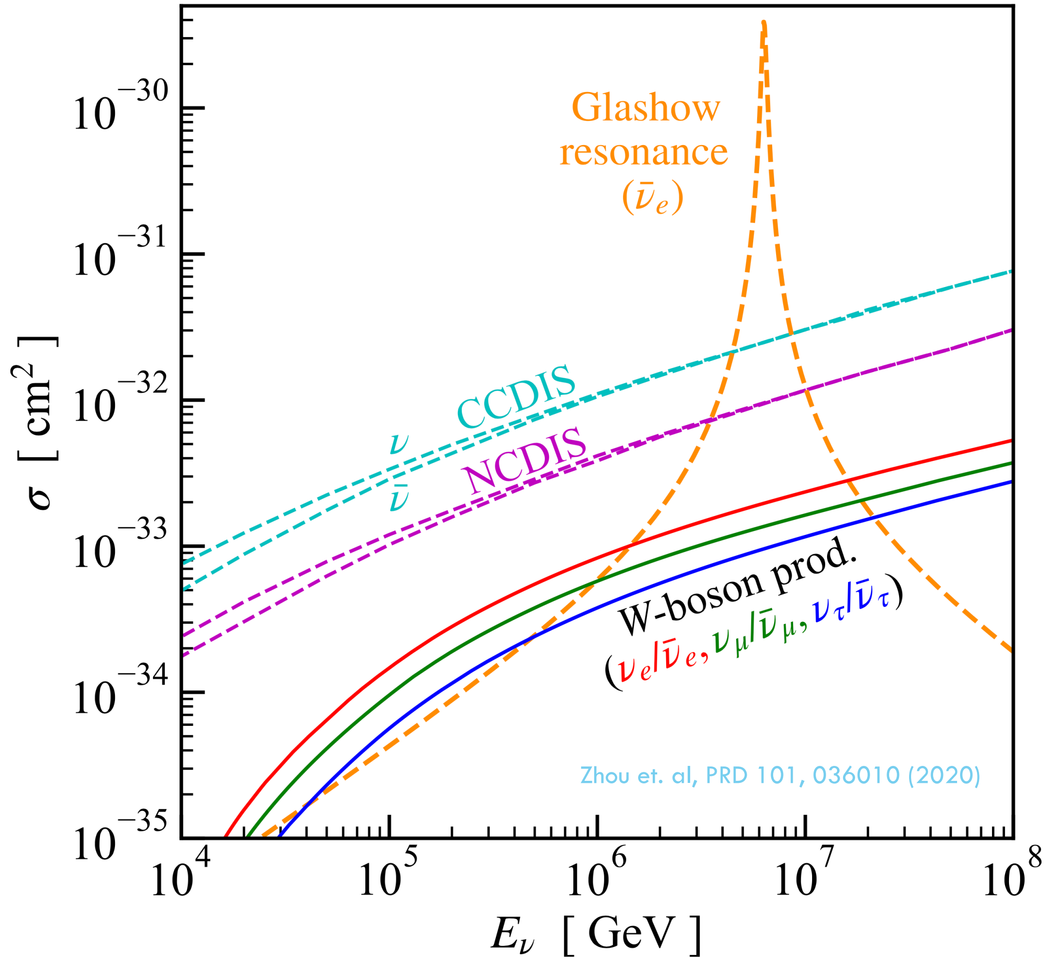
IceCube design report

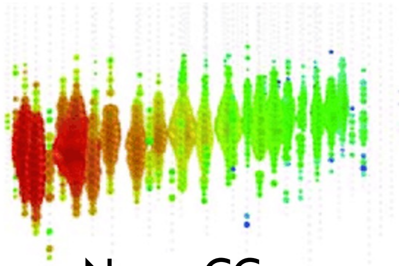


Snowmass 2021 HE&UHE nu paper

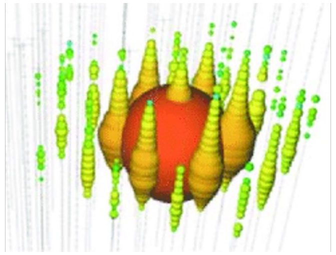
NEUTRINO INTERACTIONS

Detect Cherenkov radiation from secondary charged particles

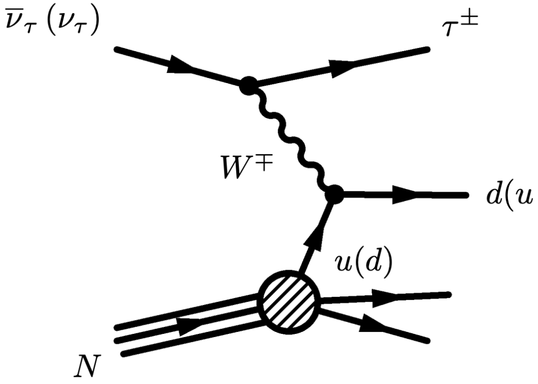


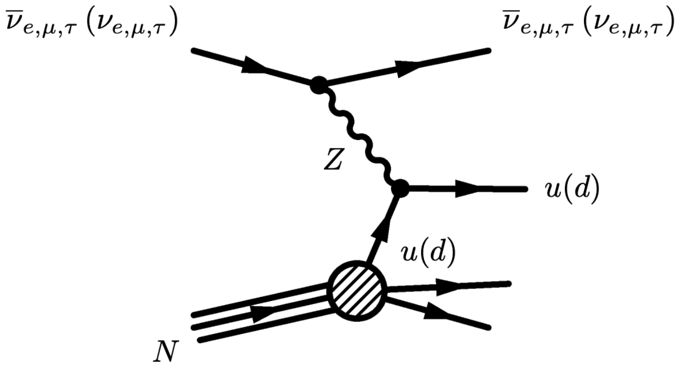


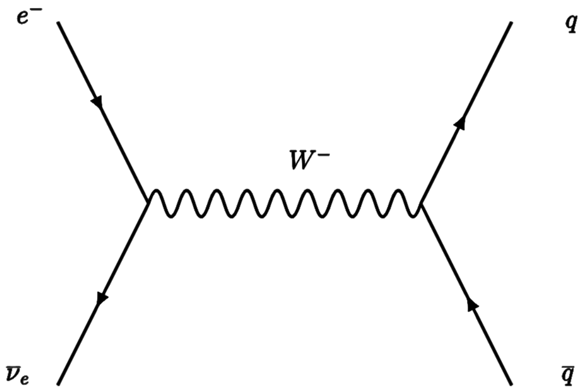
Numu CC

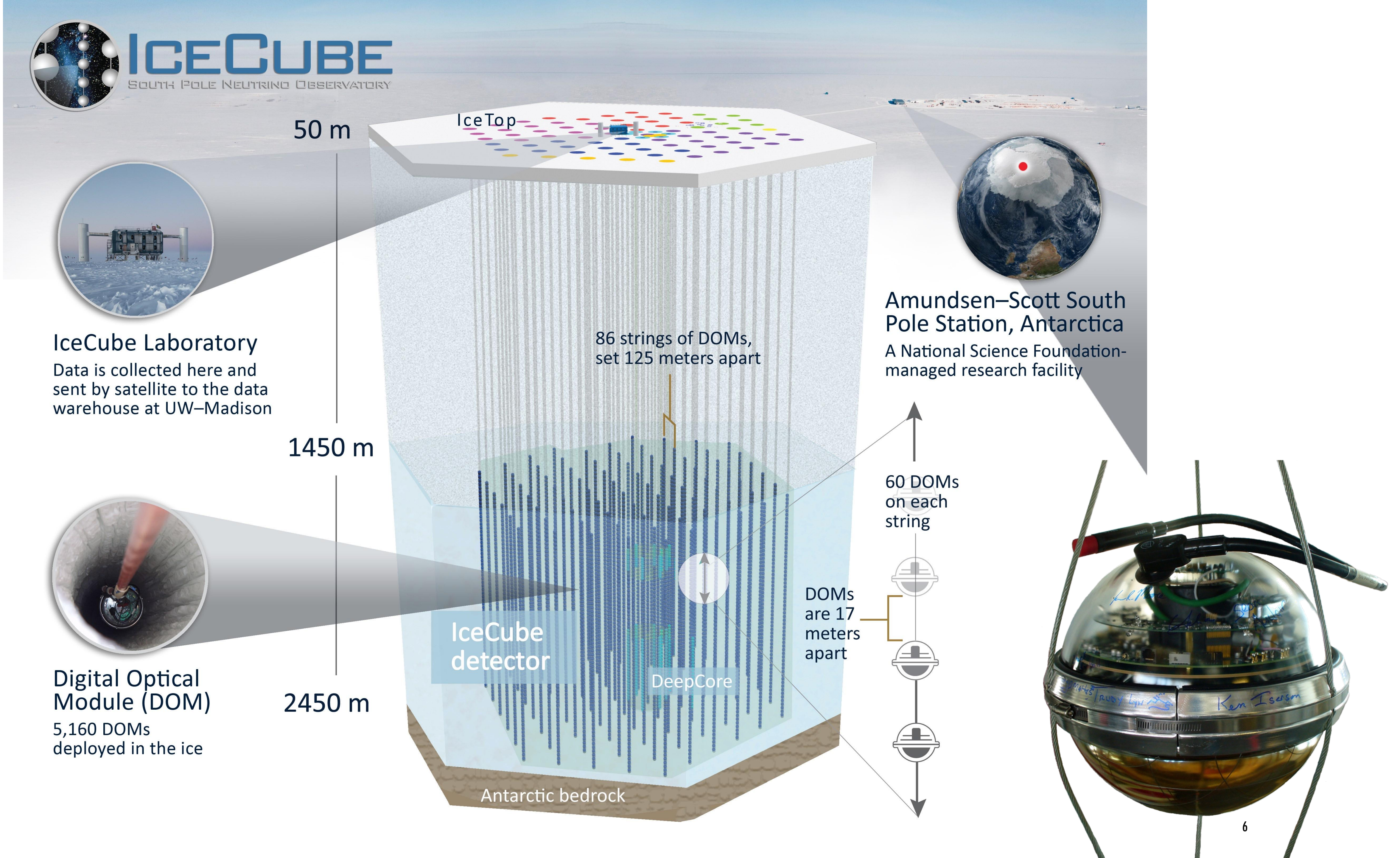


Nue CC, all NC







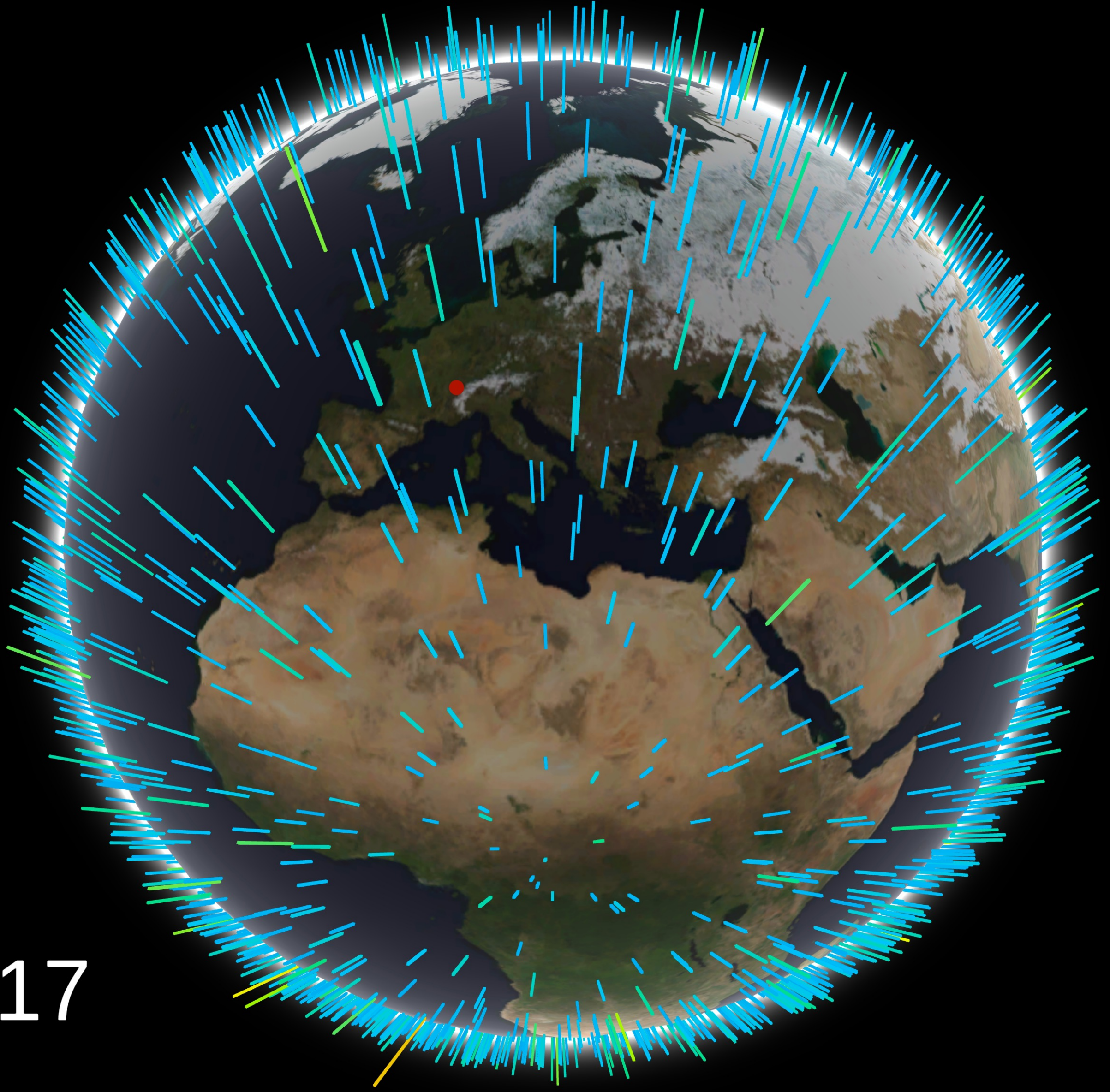

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and
sent by satellite to the data
warehouse at UW–Madison
86 strings of DOMs,
set 125 meters apart
Amundsen–Scott South
Pole Station, Antarctica
A National Science Foundation-
managed research facility
60 DOMs
on each
string
DOMs
are 17
meters
apart
IceCube
detector
DeepCore
Digital Optical
Module (DOM)
5,160 DOMs
deployed in the ice
Antarctic bedrock

Origins of icecube neutrinos?

>1Tev >10Tev >100Tev

FPS:60

NGC1068



Geneva, Switzerland

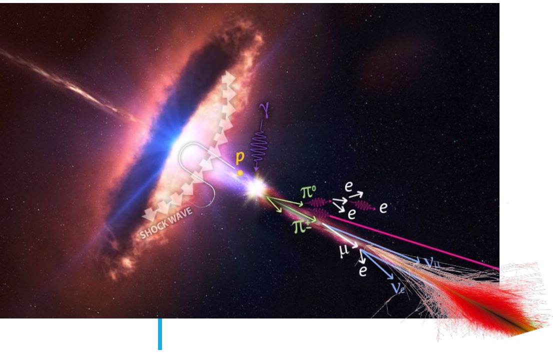
https://user-web.icecube.wisc.edu/~lulu/globe_AR/webcity/ngc1068/

46.4771 6.2017

By: Lu Lu, Yugov Seva

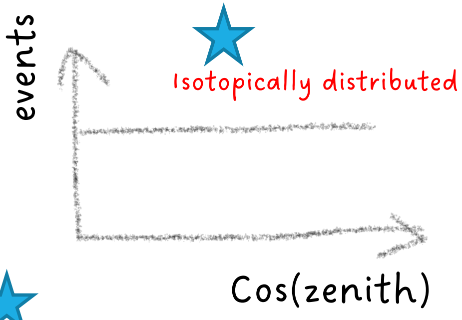
Extragalactic

ASTROPHYSICAL



- Hadronic interactions proton-proton or proton-gamma at source
- Super massive blackhole accelerator beam many light years of baseline
- Energy ranges from TeV to EeV

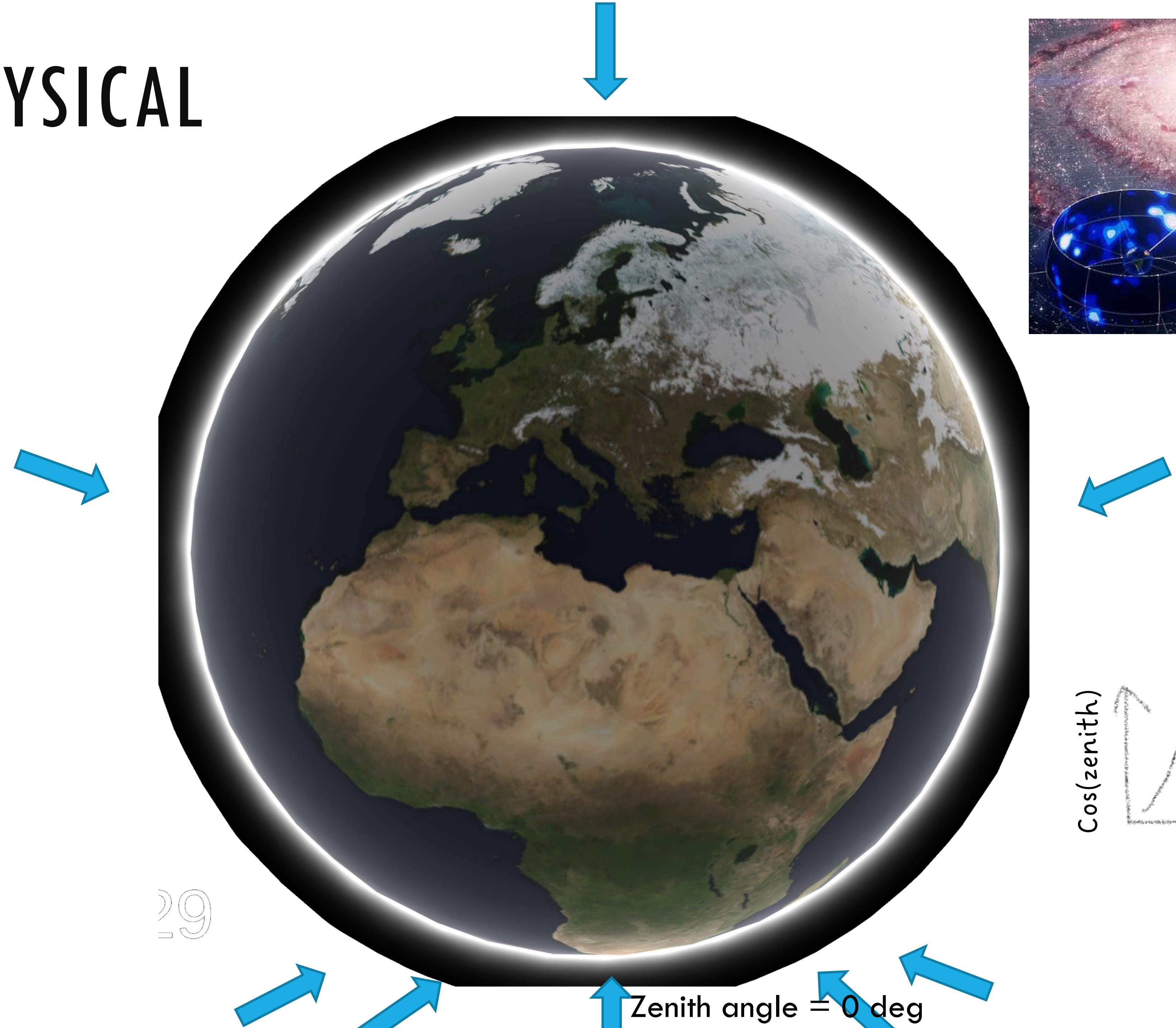
Zenith angle = 0 deg

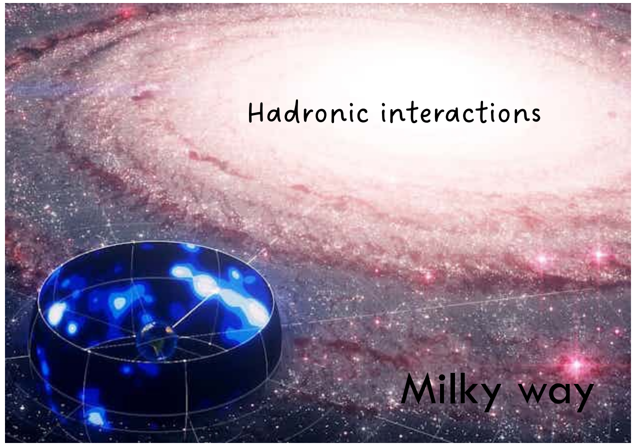


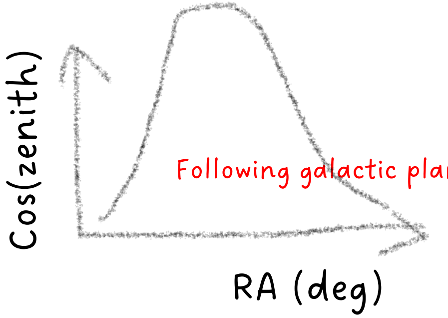
Galactic

ASTROPHYSICAL

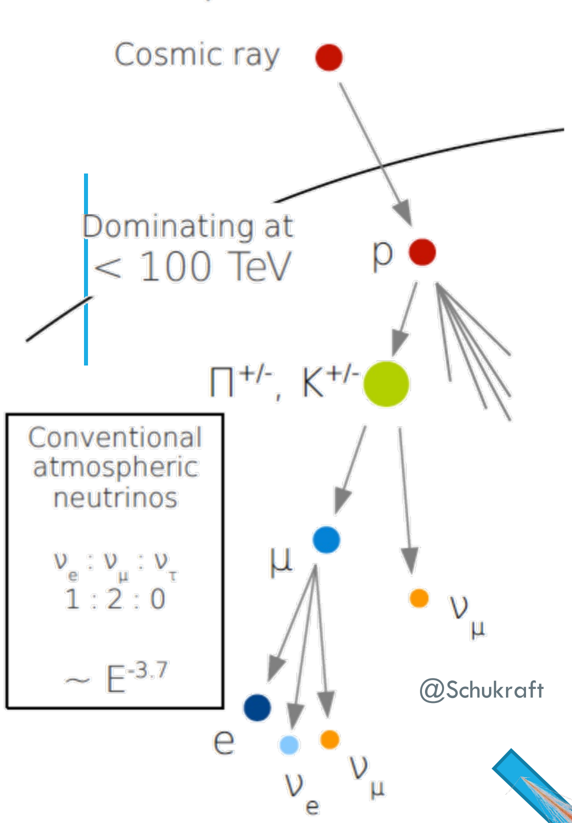
- Hadronic interactions proton-proton or proton-gamma at galactic plane
- ~10% diffuse astrophysical flux
- Zenith angle follows galactic plane distribution, not isotropic







ATMOSPHERE Conventional



$$\pi^{\pm}\ K^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\overline{\nu}_{\mu})$$ (63.5% for K)

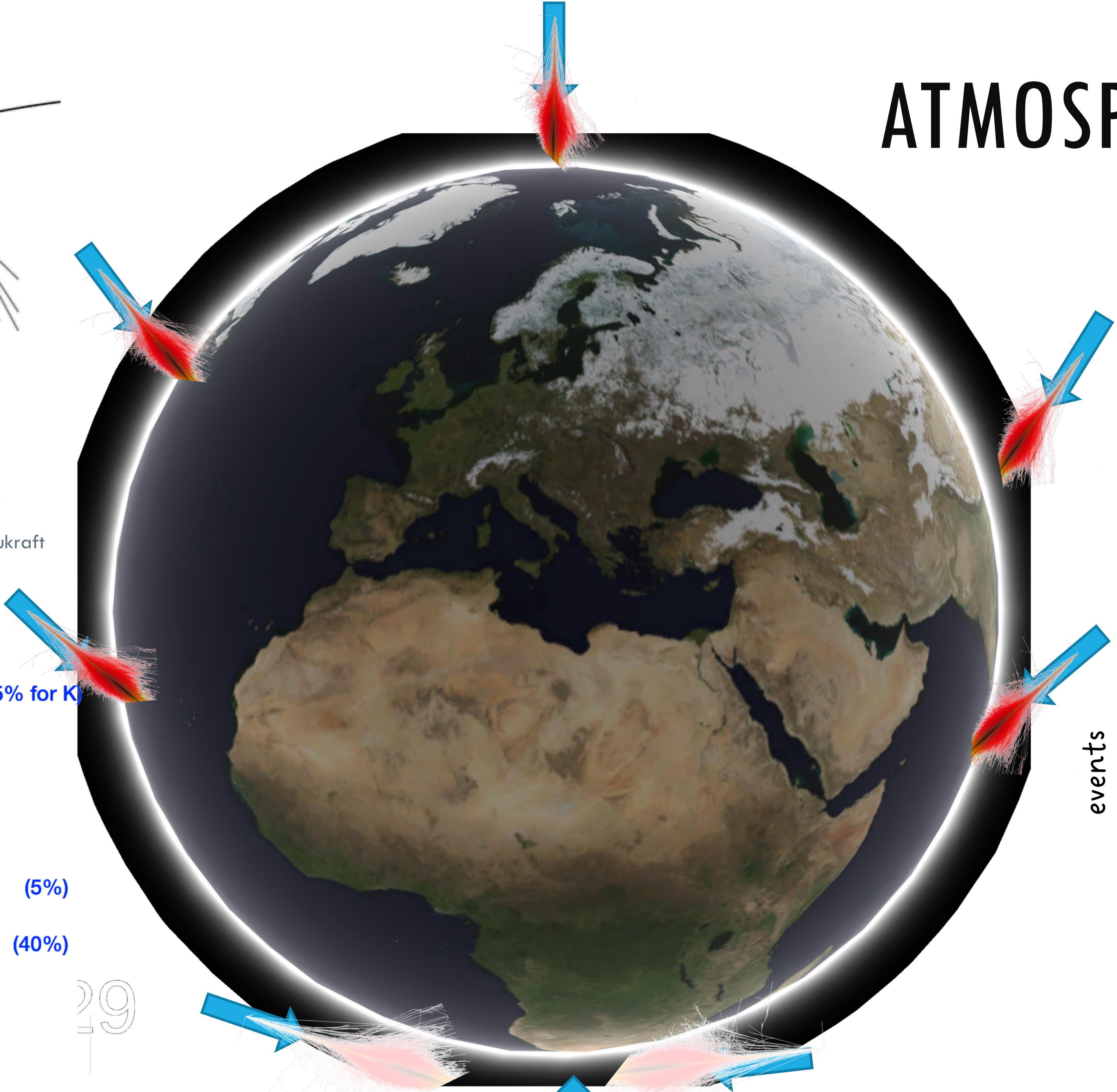
$$\hookrightarrow e^{\pm} + \nu_{e}(\overline{\nu}_{e}) + \overline{\nu}_{\mu}(\nu_{\mu})$$

→ E_ν ~ 100/cosθ GeV

$$K^{\pm} \rightarrow \pi^{0} e \nu_{e}$$ (5%)

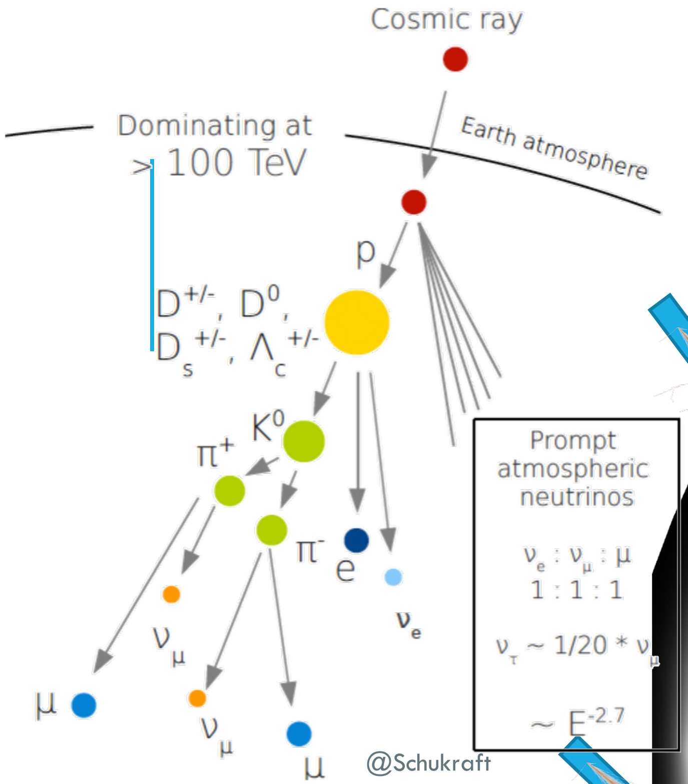
$$K^{0}_{L} \rightarrow \pi e \nu_{e}$$ (40%)

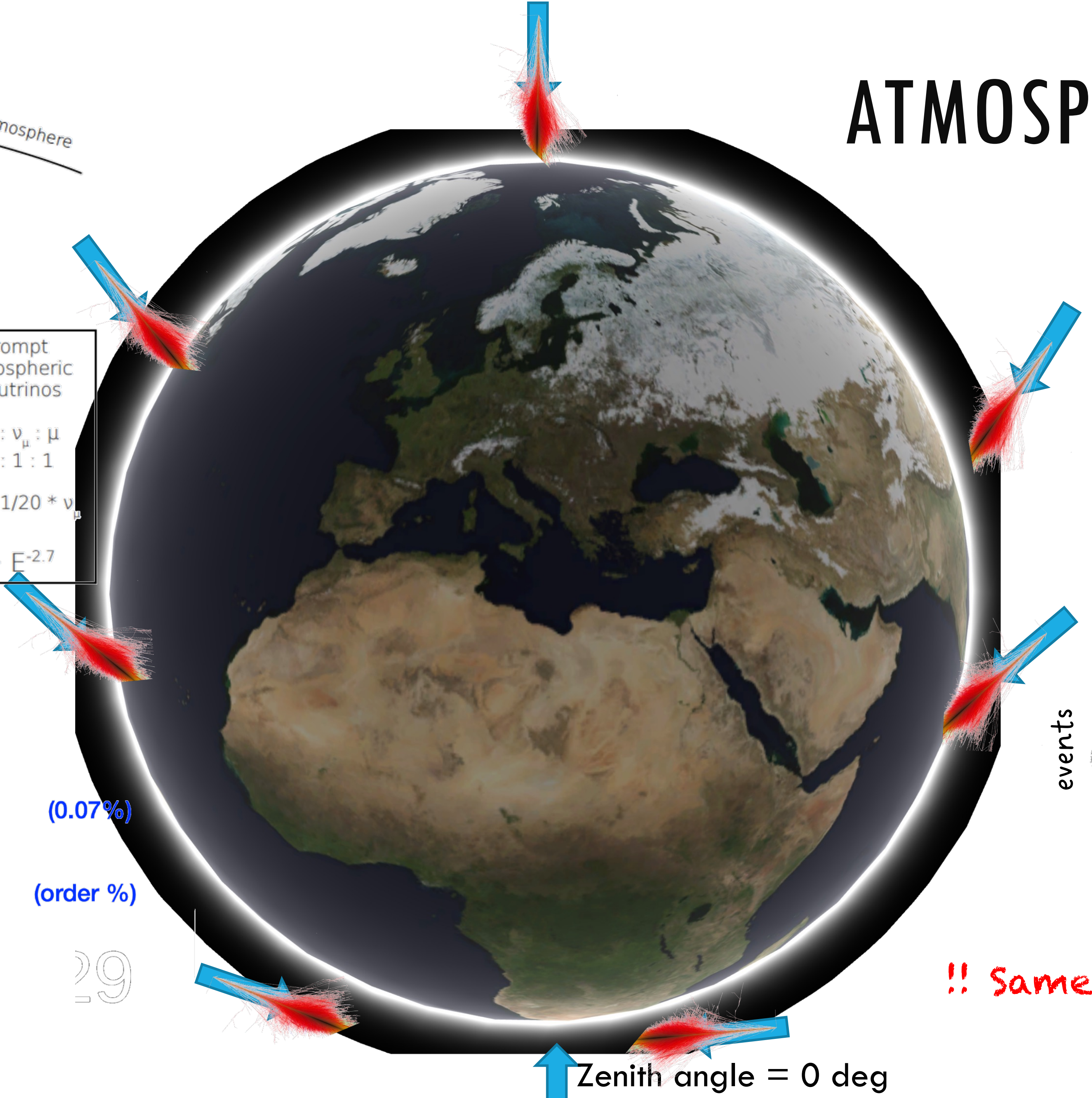
→ E_ν ~ 100/cosθ TeV

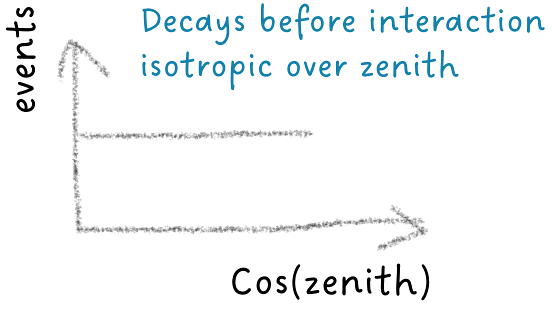


Zenith angle = 0 deg

ATMOSPHERE Prompt







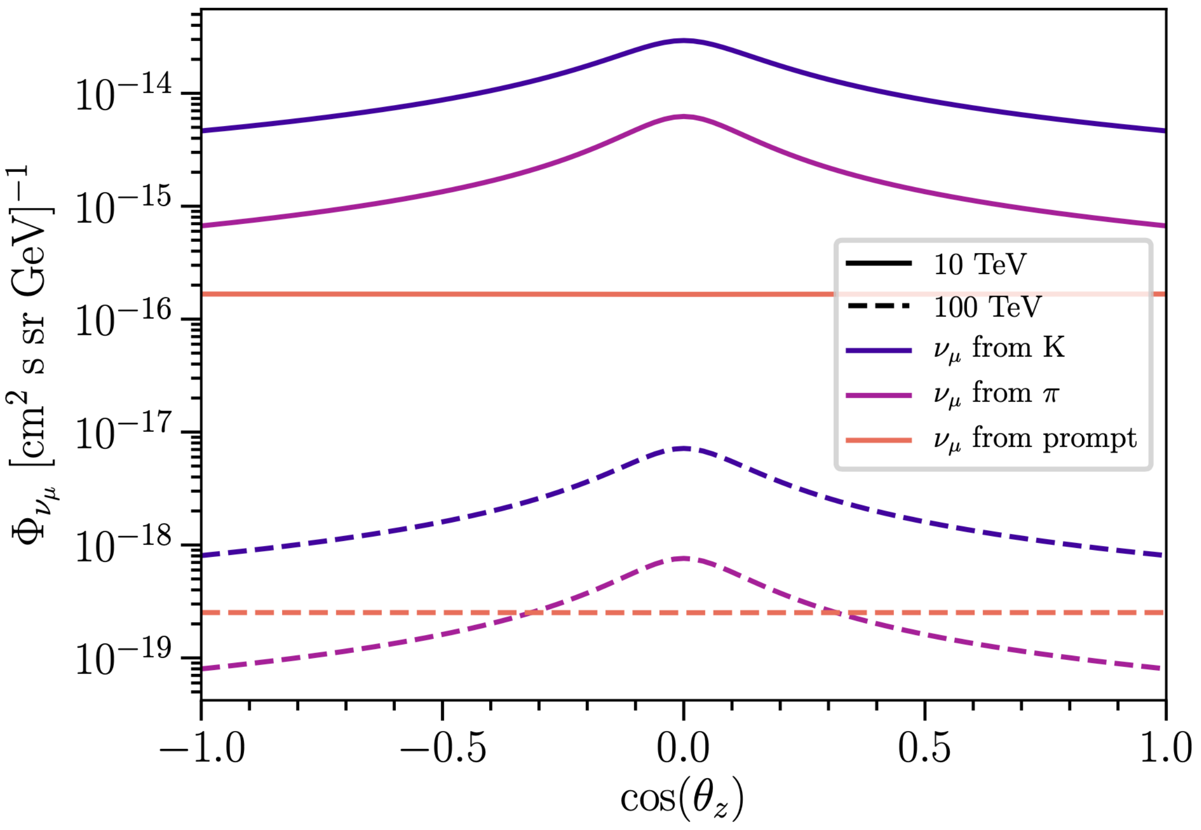
$K_S^0 \rightarrow \pi e \nu_e$ (Gaisser & Klein 2014) (0.07%)

$D, \Lambda_c \rightarrow \ell + \nu_\ell + \ldots$ (order %)

$\eta, \eta' \rightarrow \mu^+ \mu^-$

!! Same with Astrophysical

ATMOSPHERIC NEUTRINO FLUX DEPEND ON ZENITH ANGLE

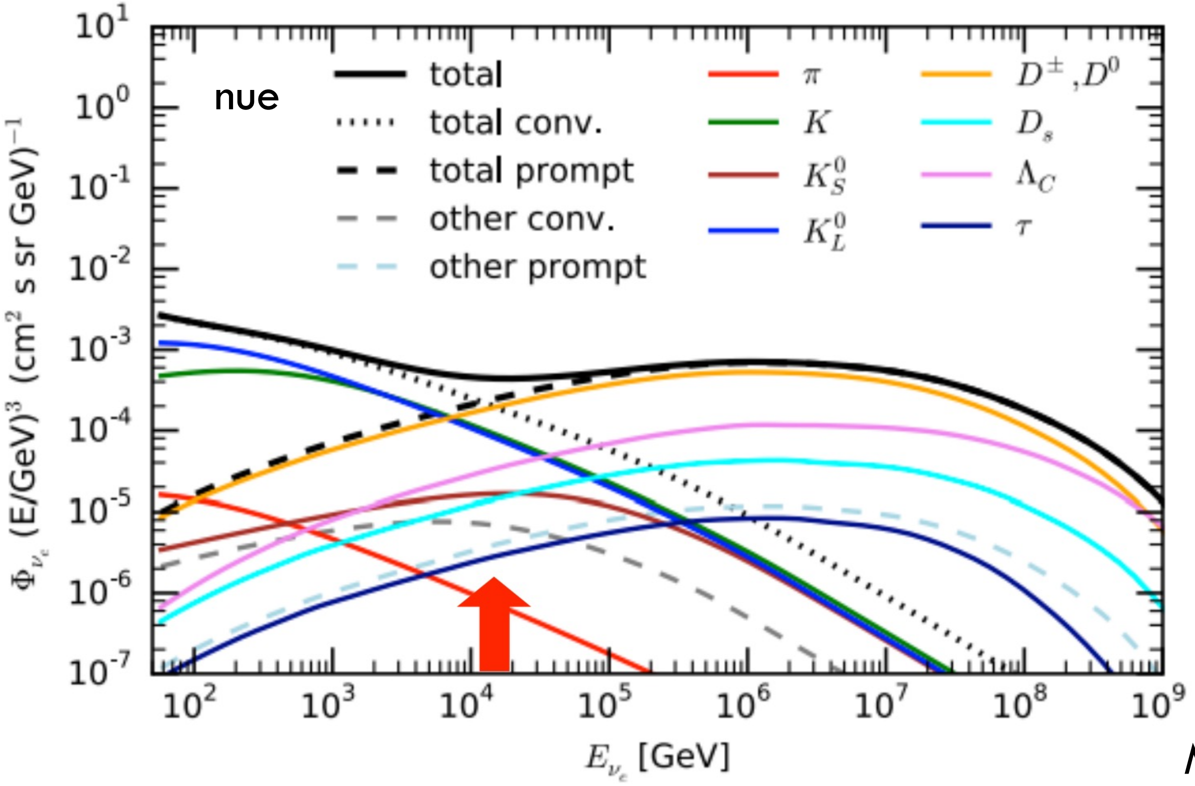


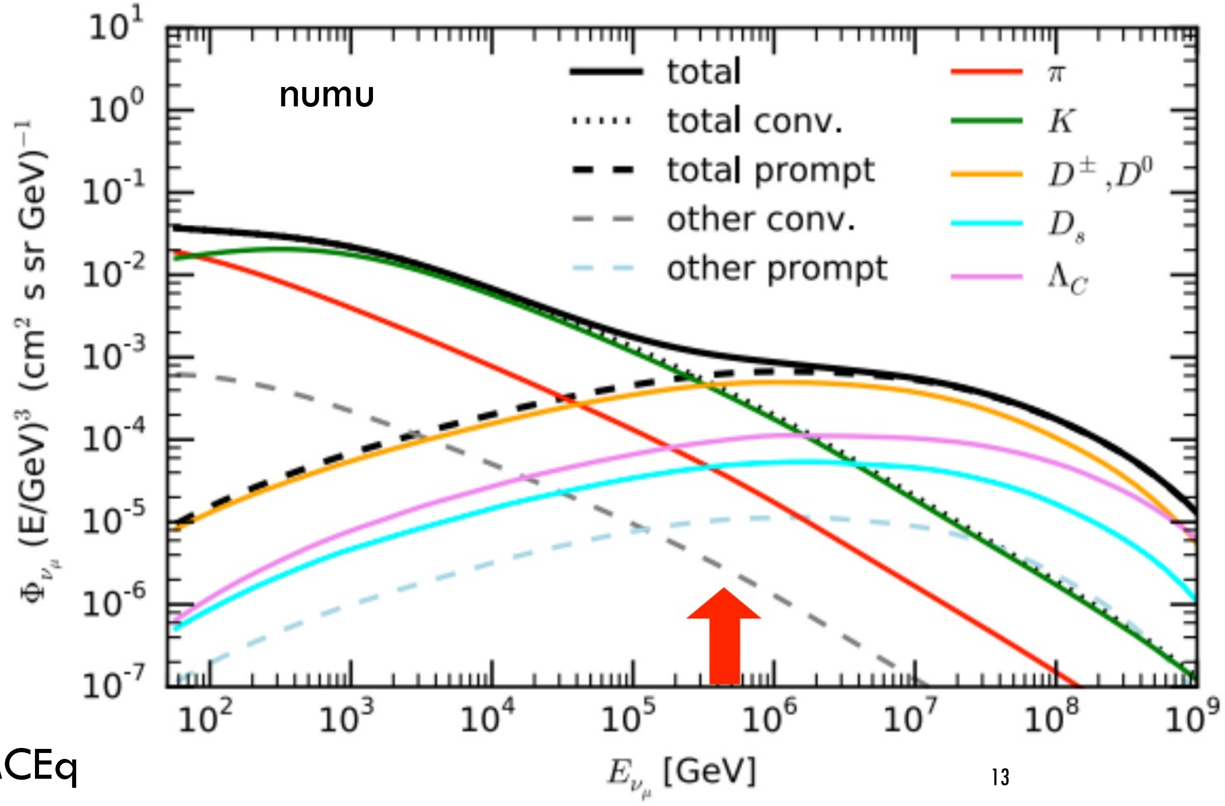
- prompt is isotropic over zenith
  - degenerate from extragalactic diffuse flux (signal)
- conventional peaks at horizon
  - νμ production dominated by kaon decay

ATMOSPHERIC NEUTRINO FLUX DEPEND ON ENERGY AND FLAVOUR

Nue: prompt overtakes conventional at ~20 TeV

Numu: prompt overtakes conventional at ~200 TeV



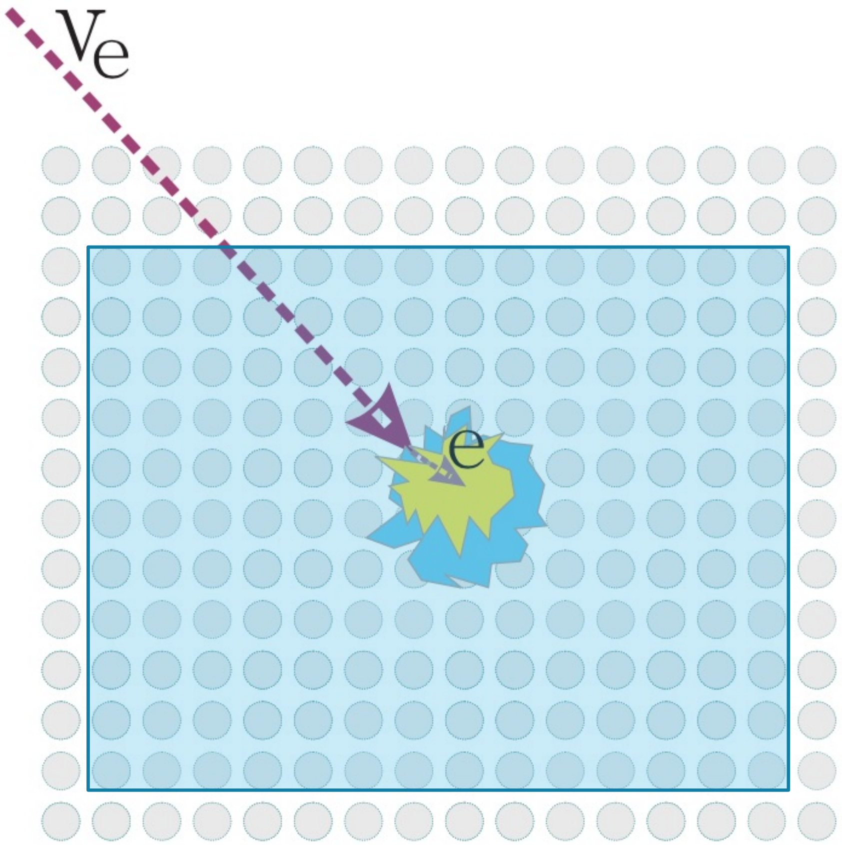


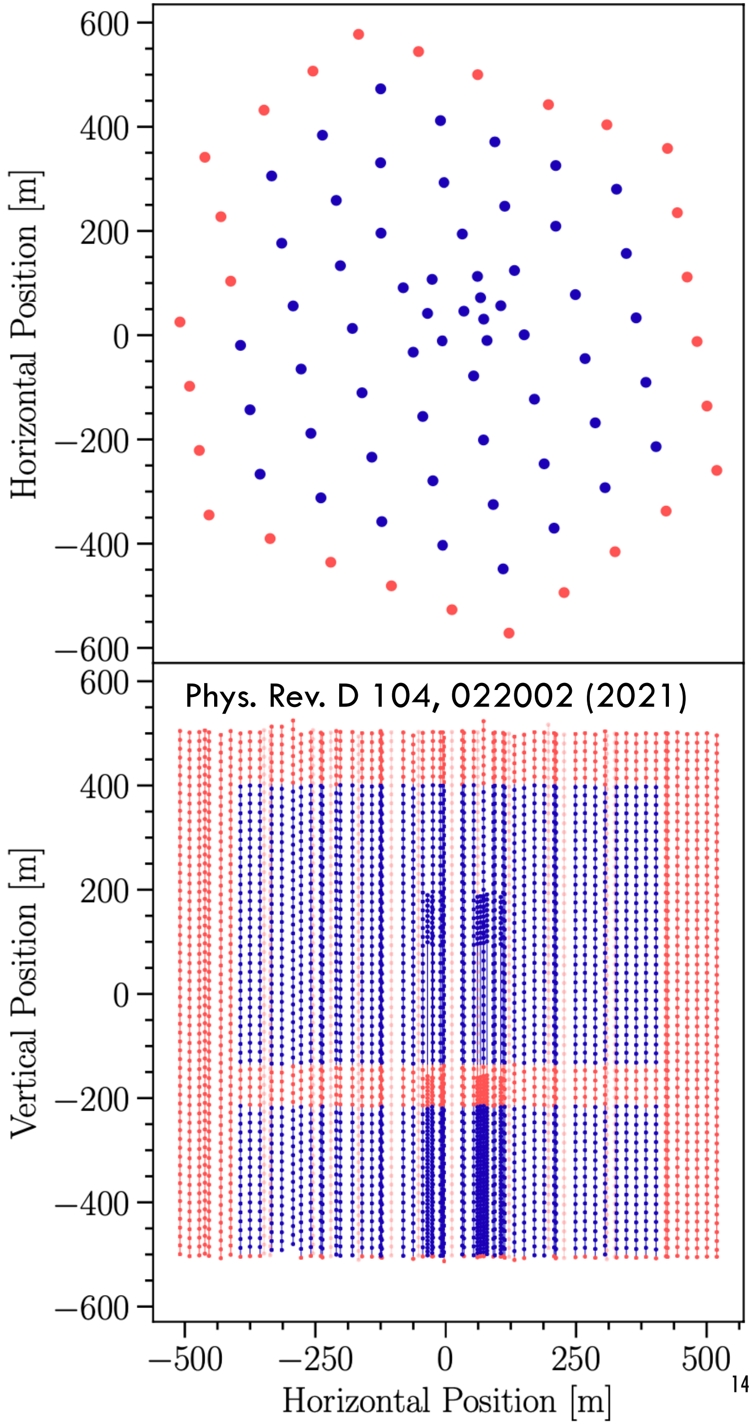
MCEq

Analysis 1

HIGH ENERGY STARTING EVENTS (HESE)

Veto layer to select pure neutrino events



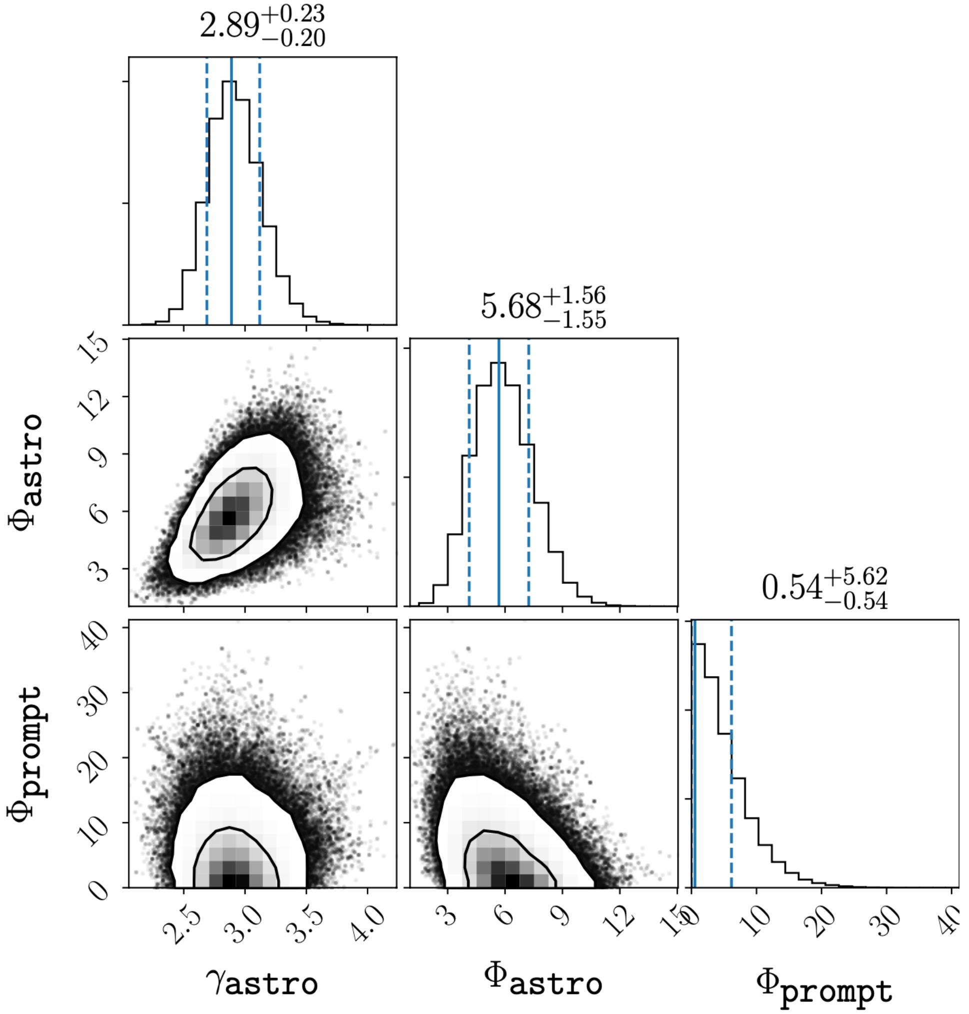


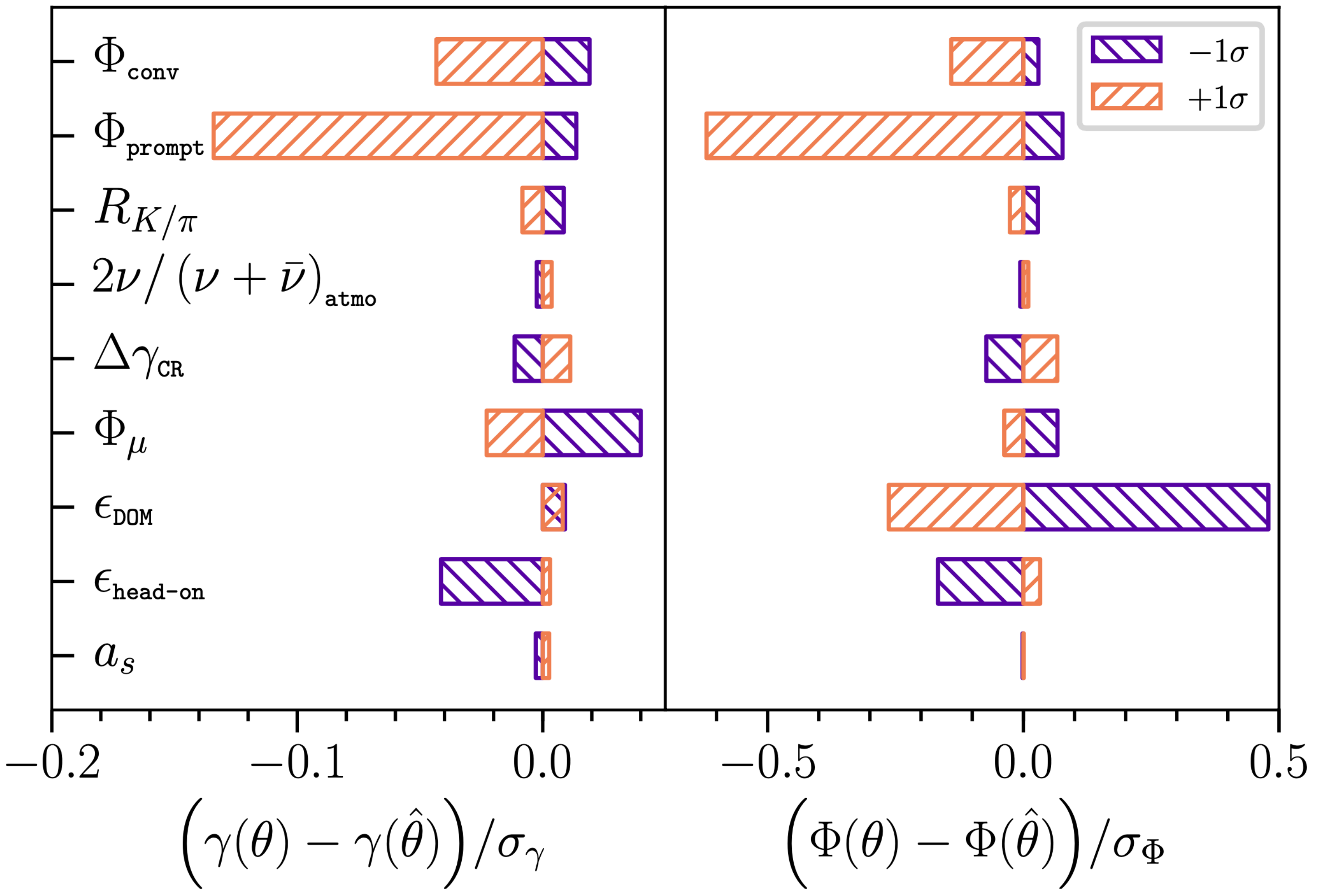
Phys. Rev. D 104, 022002 (2021)

Analysis 1

HESE: PROMPT FLUX

$$\phi_\nu^{\rm atm} = \Phi_{\rm conv}\left(\phi_\nu^\pi + R_{K/\pi}\phi_\nu^K\right)\left(\frac{E_\nu}{E_0^c}\right)^{-\Delta\gamma_{CR}} + \Phi_{\rm prompt}\phi_\nu^p\left(\frac{E_\nu}{E_0^p}\right)^{-\Delta\gamma_{CR}}$$





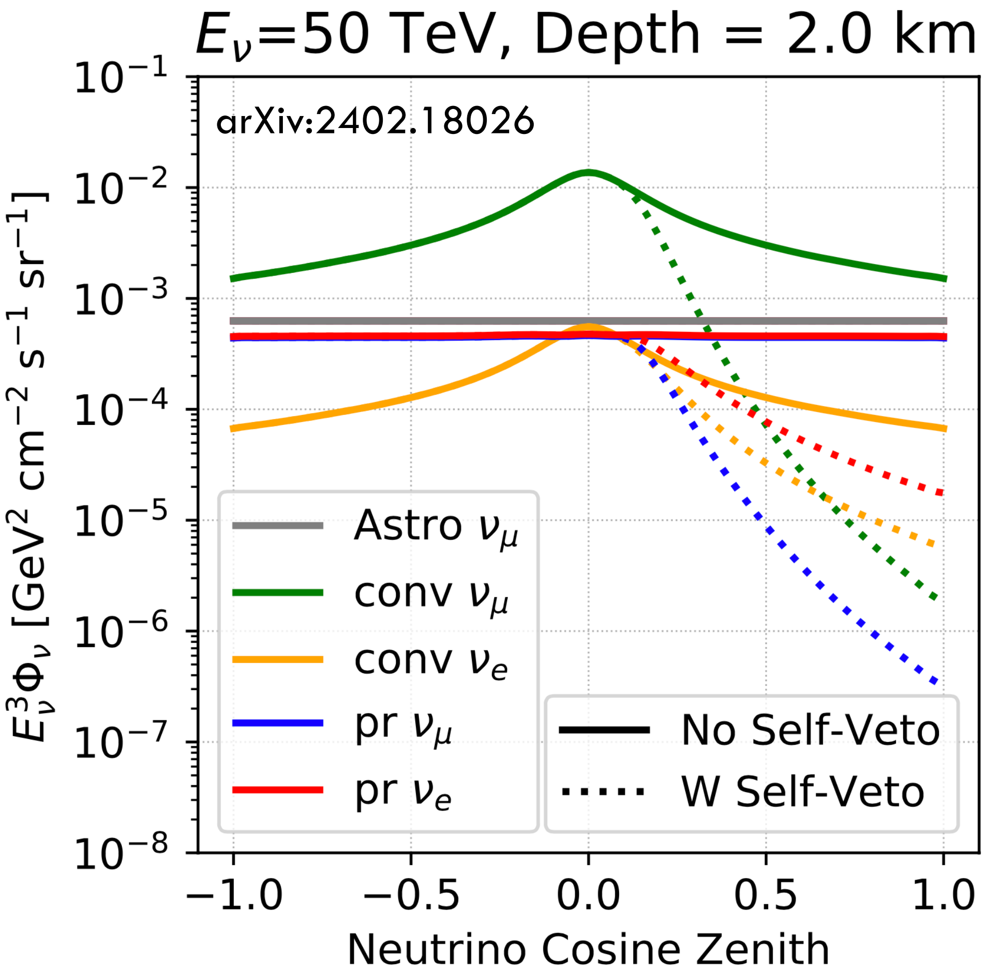
Phys. Rev. D 104, 022002 (2021)

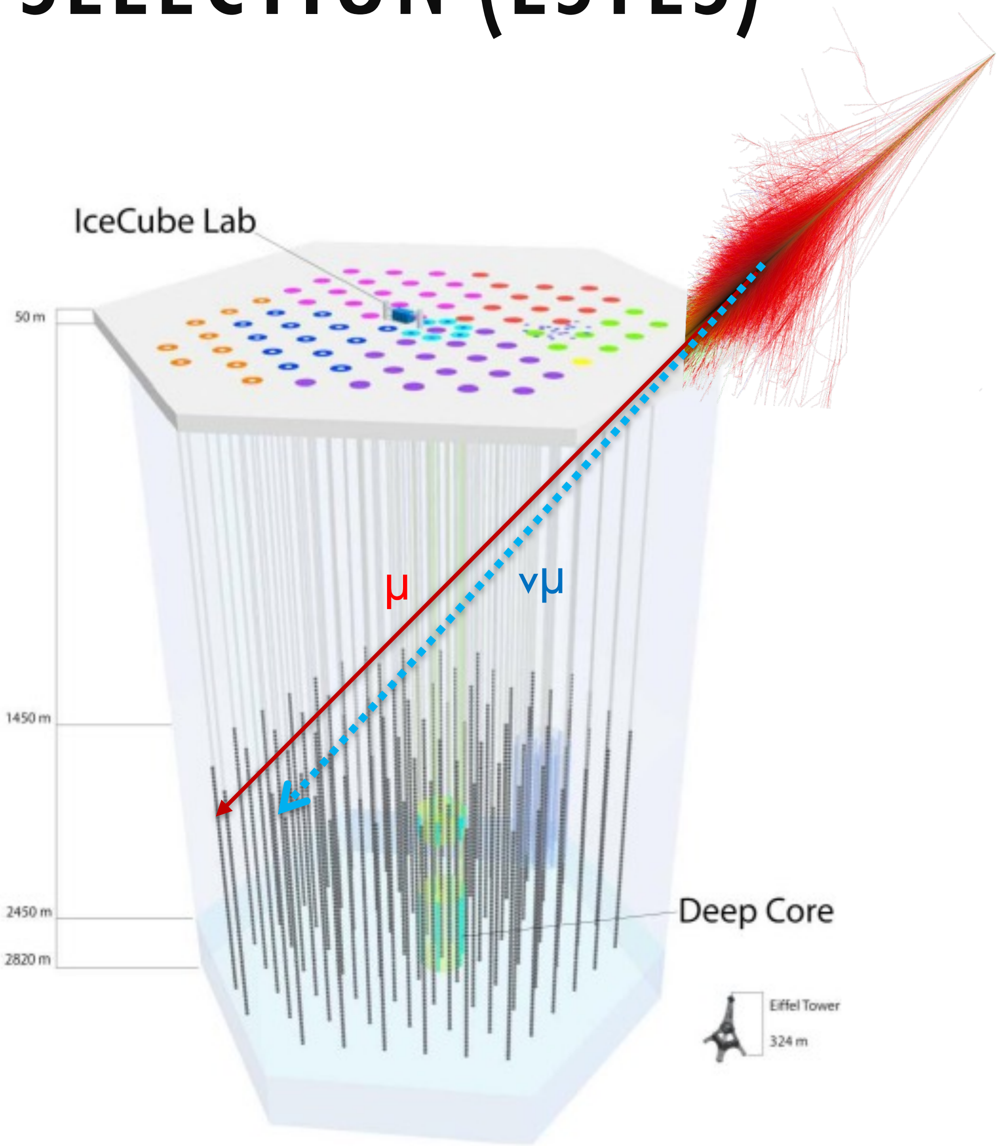
Prompt is bounded at 0

Analysis 2

ENHANCED STARTING TRACK SELECTION (ESTES)

Breaking degeneracy of prompt: self-veto

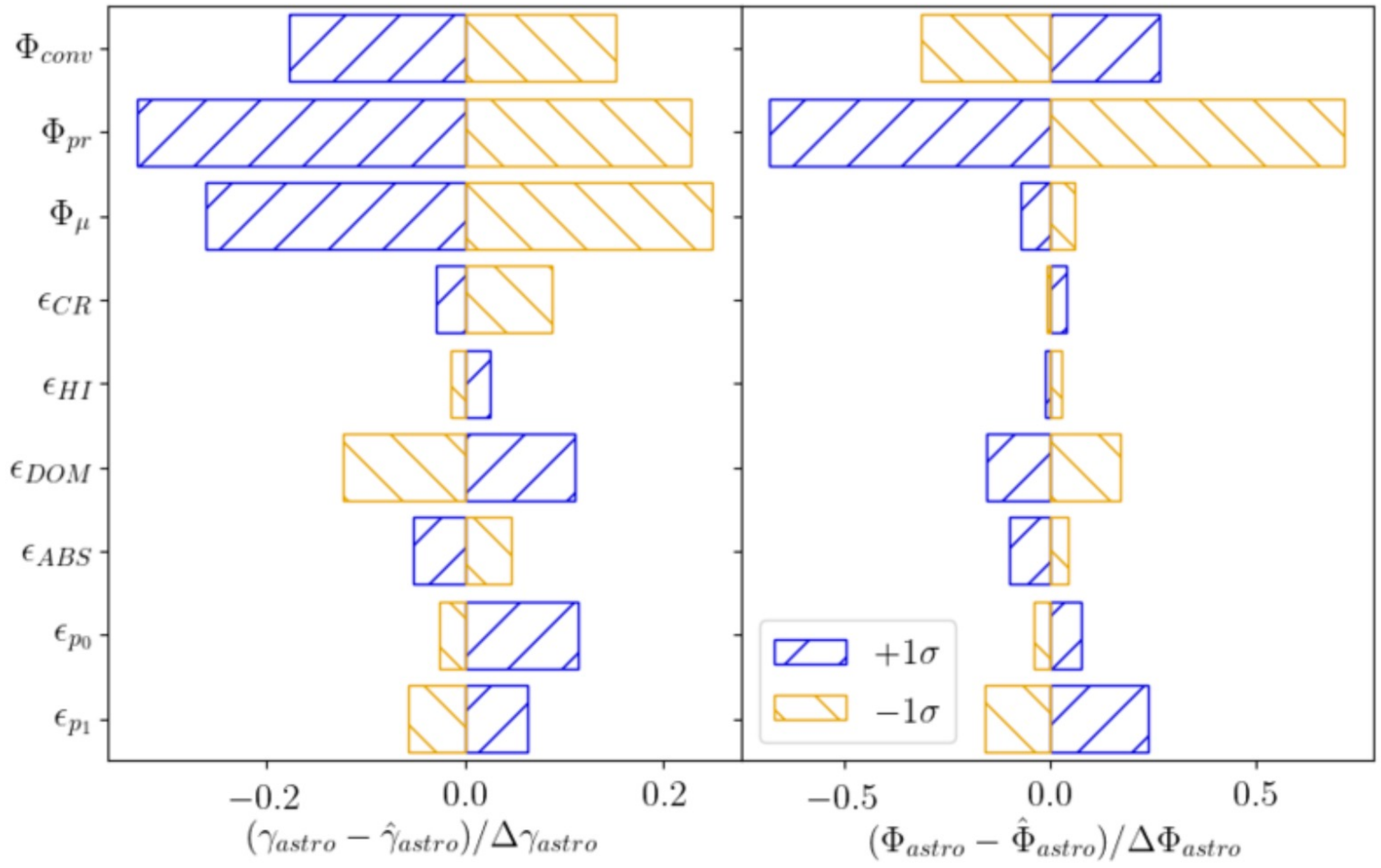




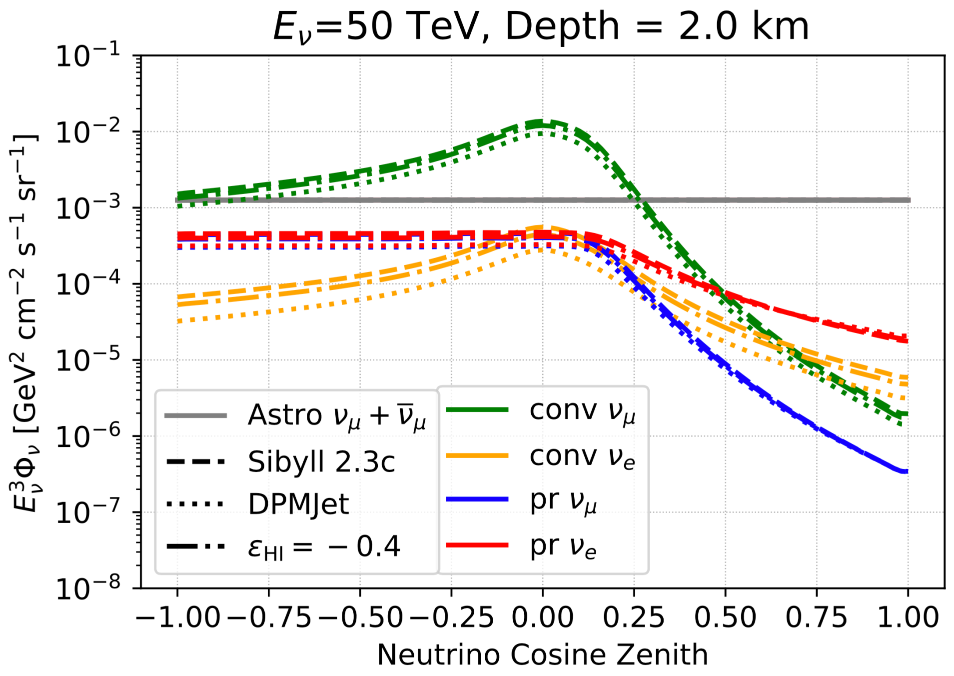
Phys. Rev. D 90, 023009 (2014), JCAP07(2018)047

Analysis 2

ESTES: PROMPT IMPACT ACCORDING TO ASIMOV TEST



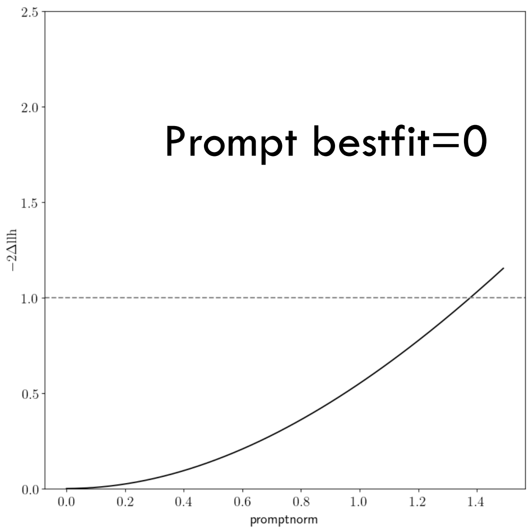
PhD thesis, Manuel Silva



https://github.com/tianluyuan/nuVeto

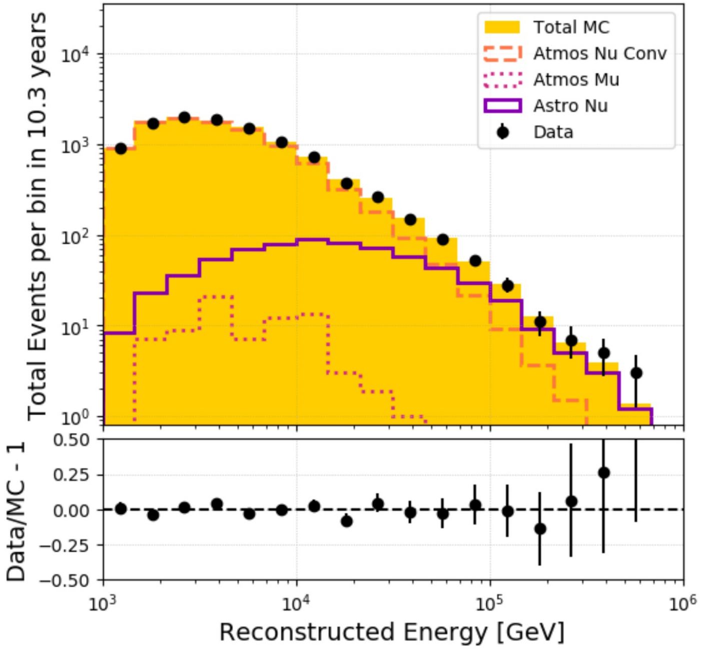
Analysis 2

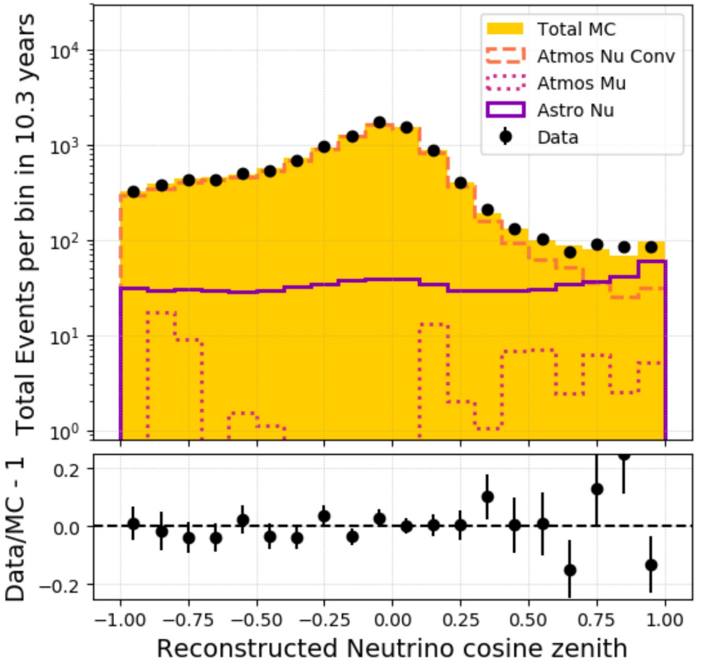
ESTES: DATA RESULTS

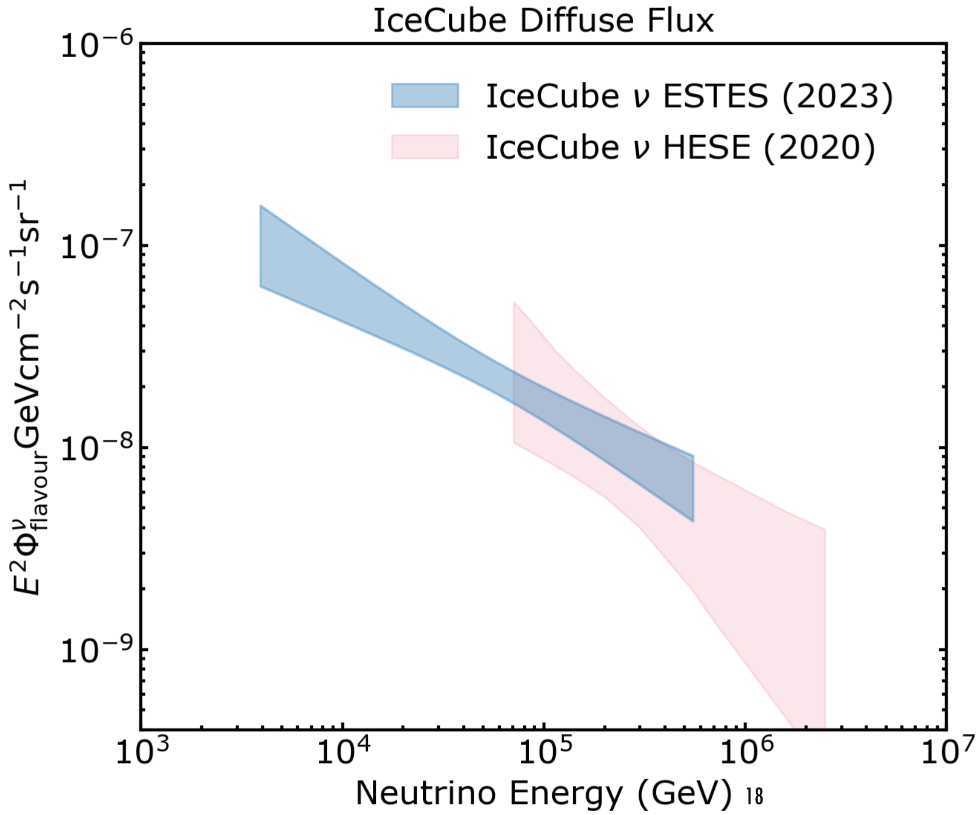


Extended the original HESE measurement to lower energies

Data prefers 0 prompt

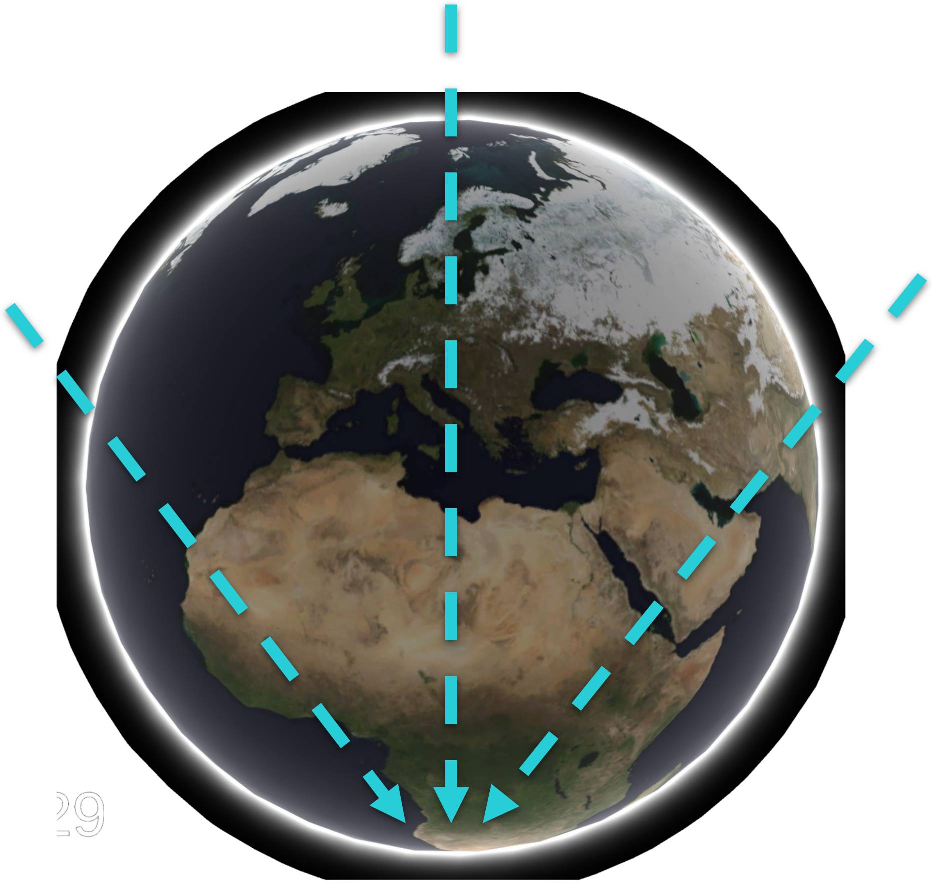


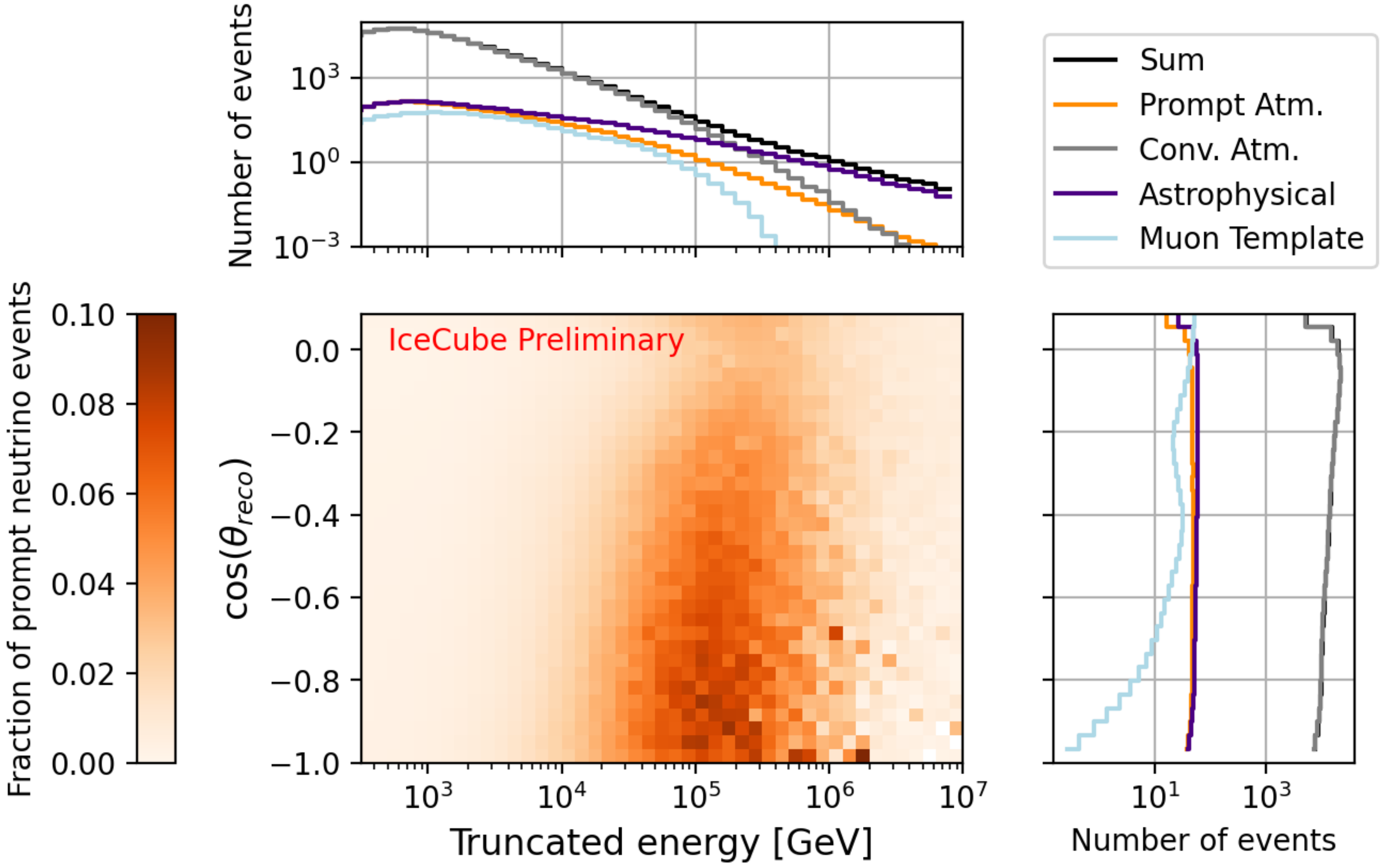




NORTHERN TRACKS

Use Earth as a shield

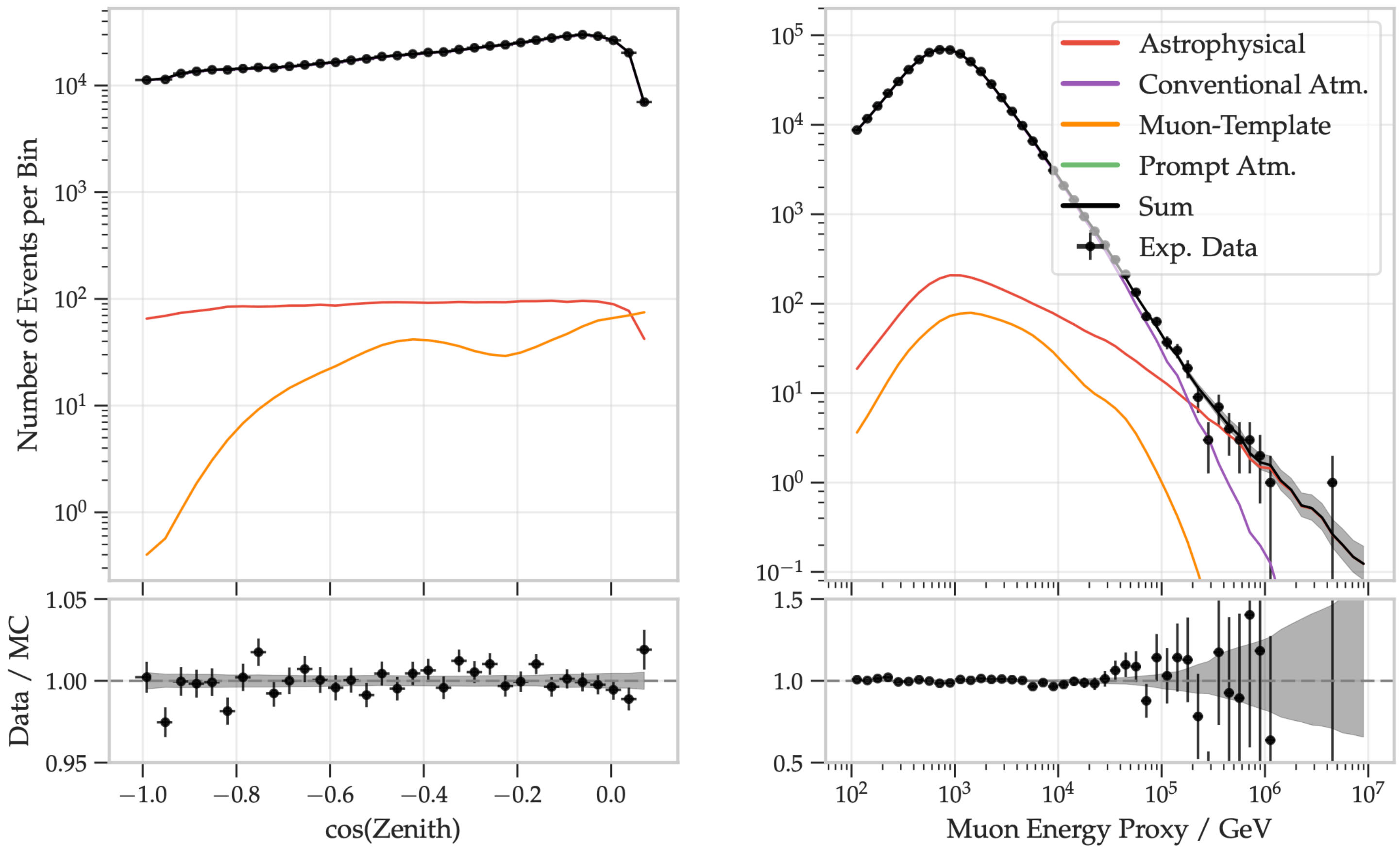


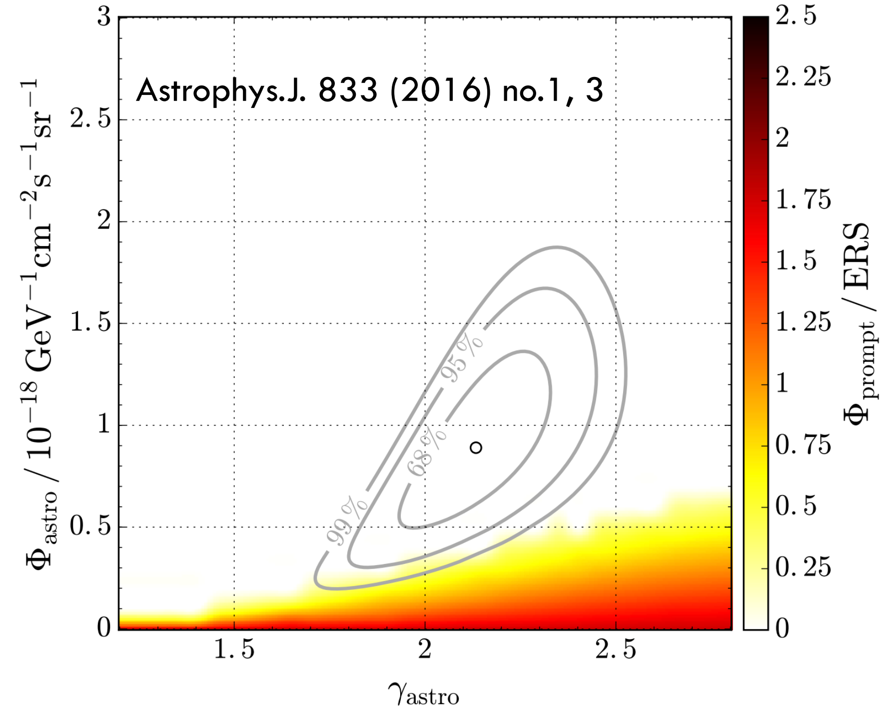


NORTHERN TRACKS

- Hadronic interaction model switched to Barr parameters
- Atmospheric predictions now produced with MCEq

$$\Phi_{\text{astro.}}^{\nu_\mu+\bar{\nu}_\mu}(E_\nu) = \phi_{\text{astro.}} \times \left(\frac{E_\nu}{100\,\text{TeV}}\right)^{-\gamma_{\text{SPL}}}$$





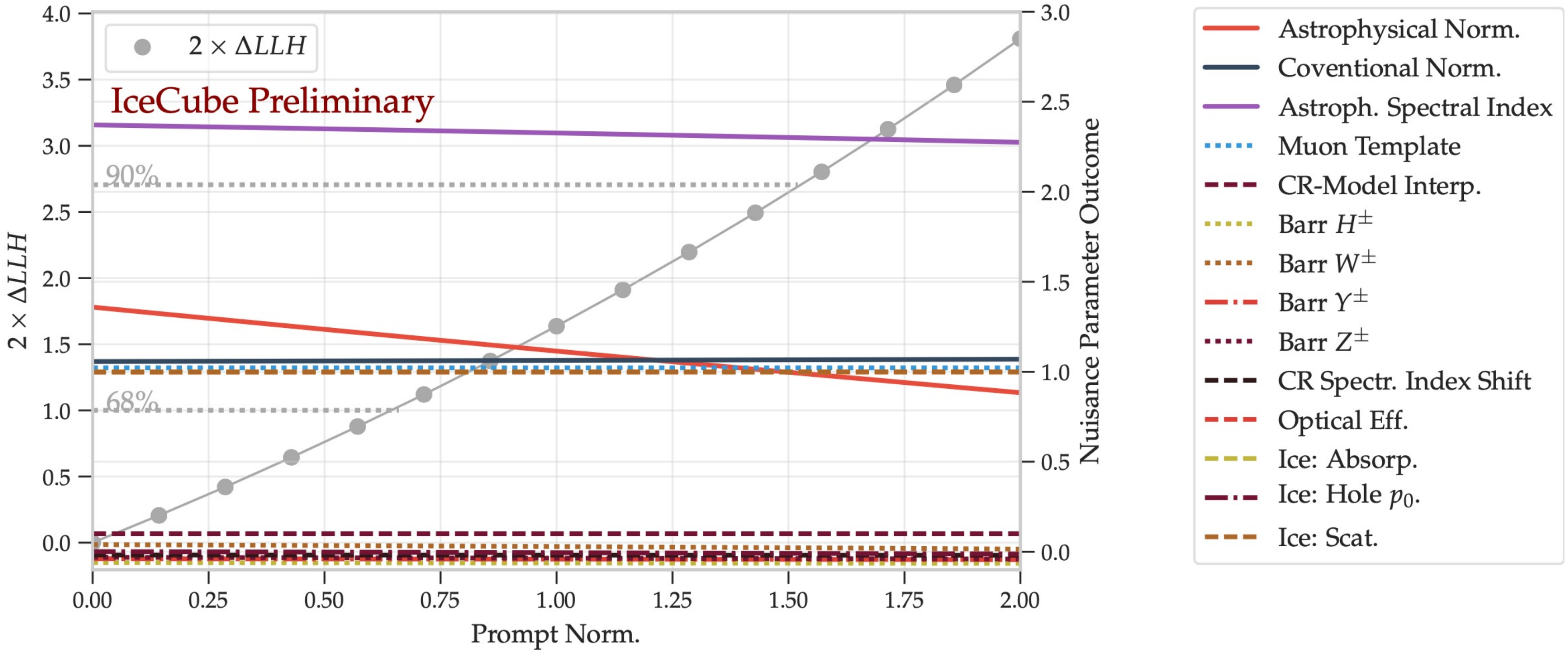
Astrophys. J. 928 (2022) 50

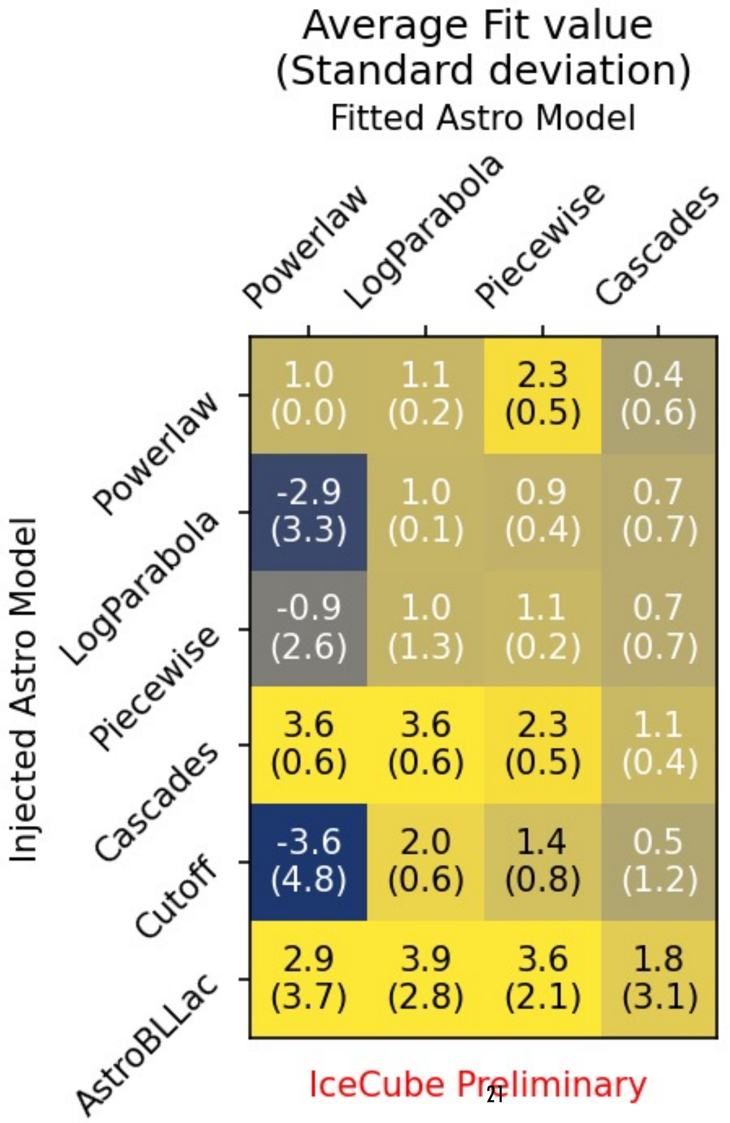
Analysis 3

NORTHERN TRACK: DATA FIT PROMPT=0

Mis-modelling of astrophysical spectrum leads to bias in prompt

i.e., structures beyond single power law

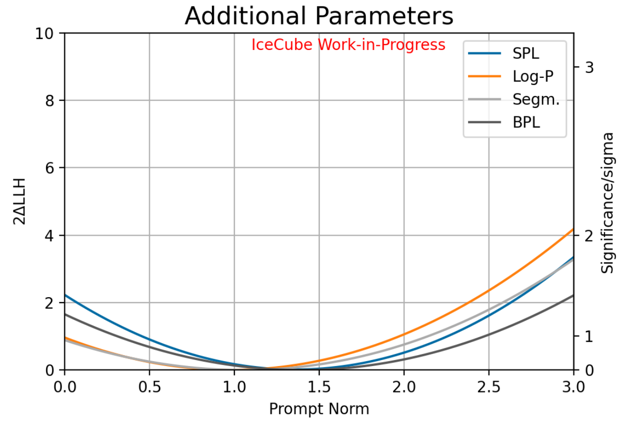


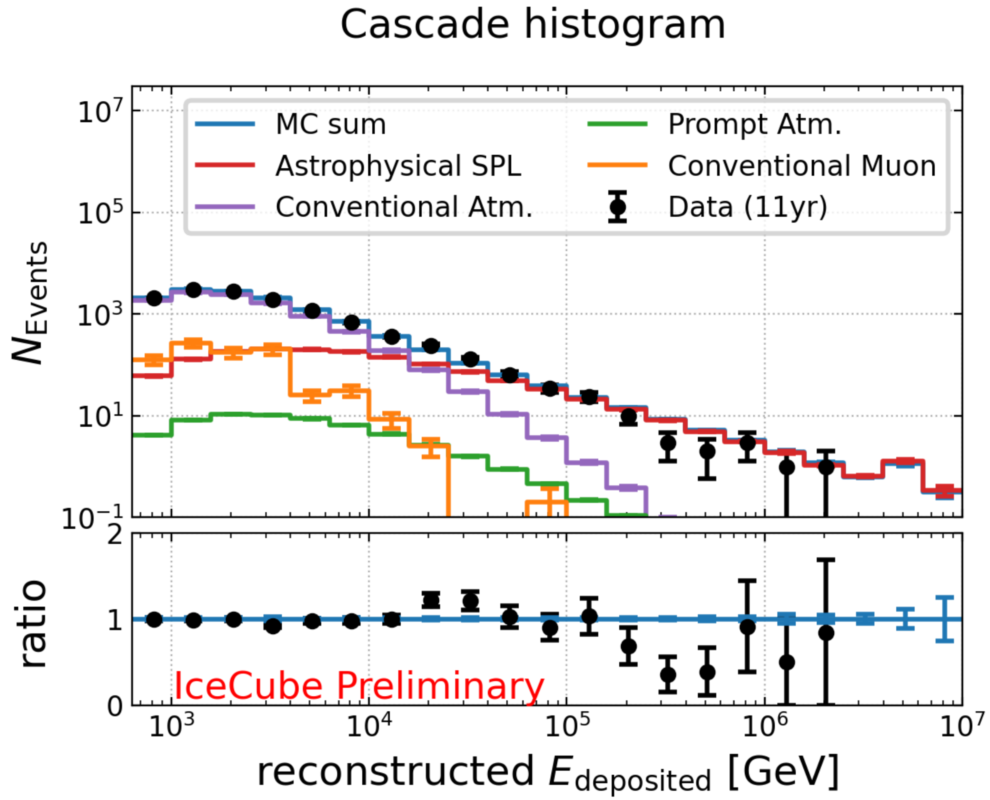


PhD thesis, Joeran Stettner

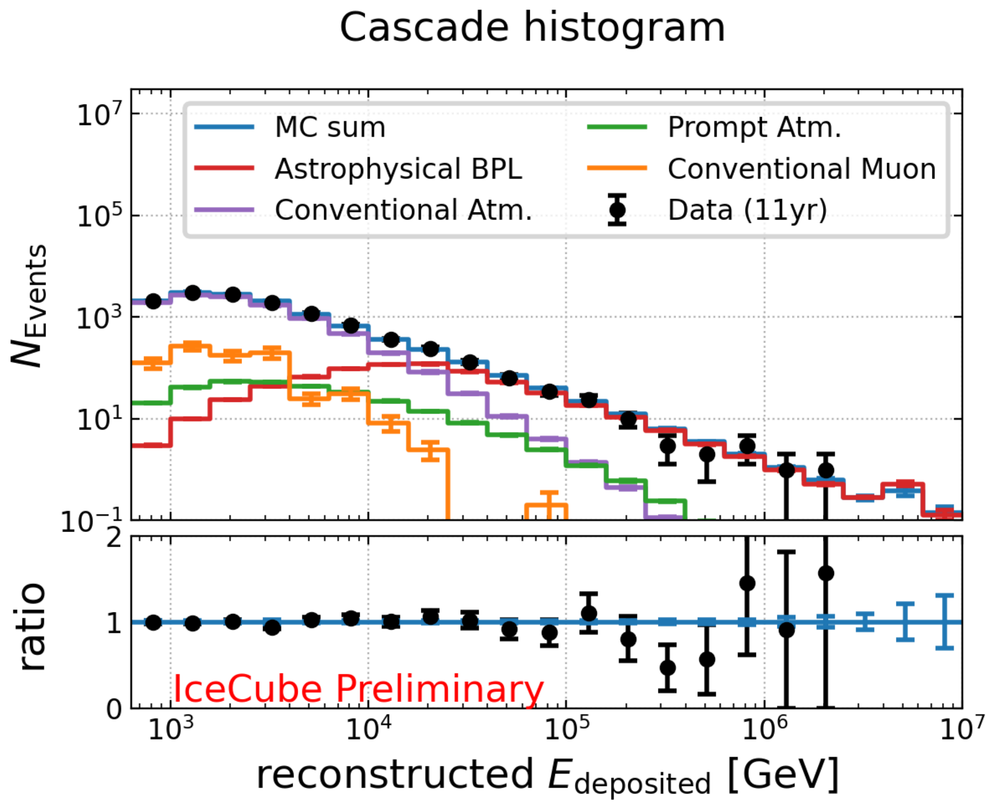
COMBINED FIT: TRACKS AND CASCADES

* high statistics of tracks to constrain conv., self-veto from cascades for prompt
* single power law no longer describes data & prompt bestfit non zero





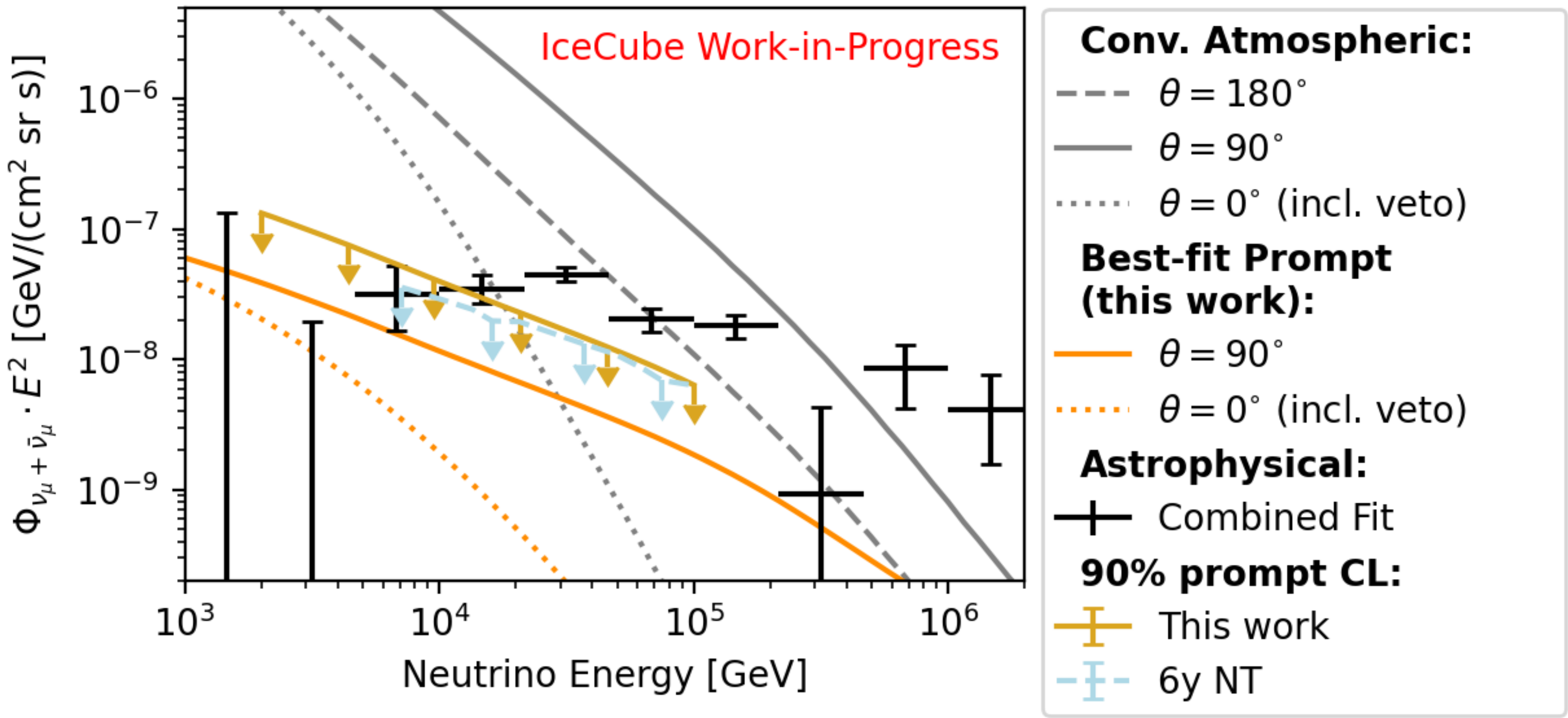
Single power law



Broken power law

TRACK+CASCADE FIT

State of art

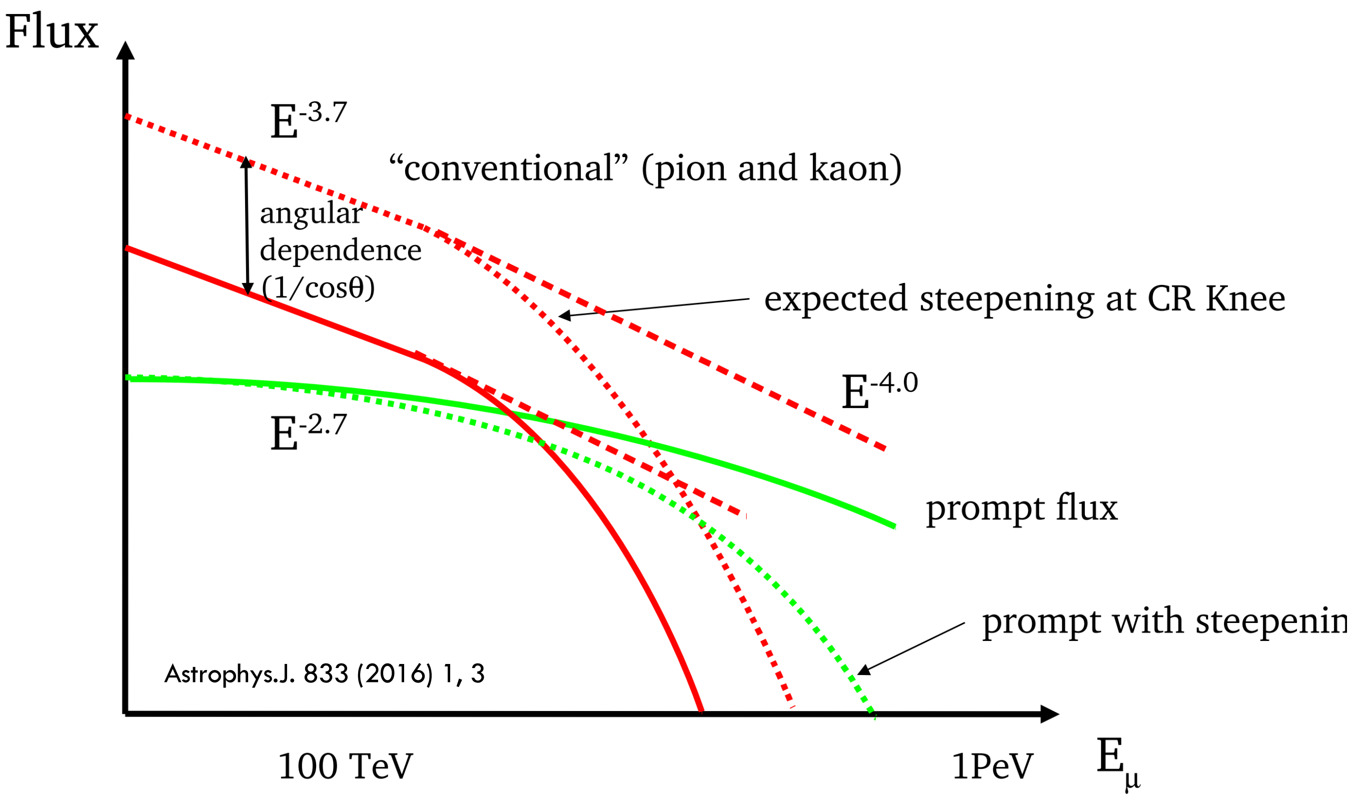


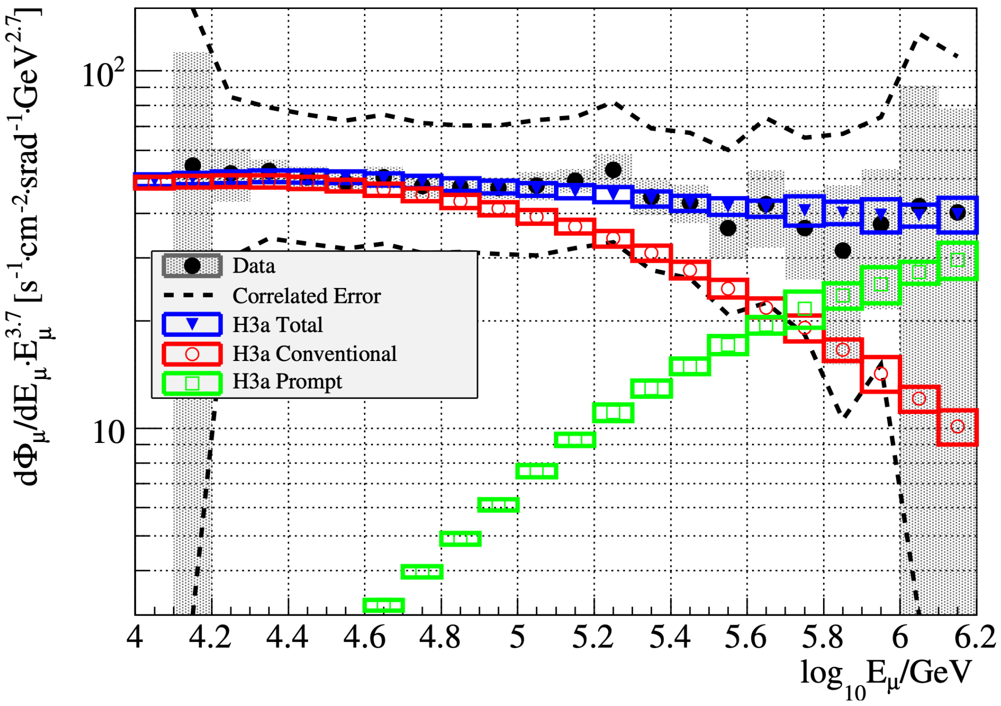
** could do study how would precise knowledge (narrow prior) of prompt impact on astrophysical spectrum. Currently no prior

Work-in-progress

ATMOSPHERIC MUON AND NEUTRINO FLUX

Neutrinos and muons share same hadronic origin from the Atmospheric air showers





CR Model	Best Fit (ERS)	χ^2/dof	1σ Interval (90% CL)
GST-Global Fit [13]	2.14	7.96/9	1.27 - 3.35 (0.77 - 4.30)
H3a [13]	4.75	9.09/9	3.17 - 7.16 (2.33 - 9.34)
Zats.-Sok. [35]	6.23	13.98/9	4.55 - 8.70 (3.59 - 10.68)
PG Constant $\Delta\gamma$ [33]	0.94	9.07/9	0.36 - 1.63 (< 2.15)
PG Rigidity [33]	6.97	5.86/9	4.73 - 10.61 (3.53 - 13.83)

muon deficit due to prompt component from charm production and unflavored η mesons

-> important for rare event identifications

Work-in-progress

CHARM FROM DEEP INELASTIC SCATTERING

$D^0, D^{+/-}, D_s^{+/-}, \Lambda_C^{+/-}$

Charm: higher inelasticity from DIS & may decay semileptonically
-> modelled as inelasticity uncertainty

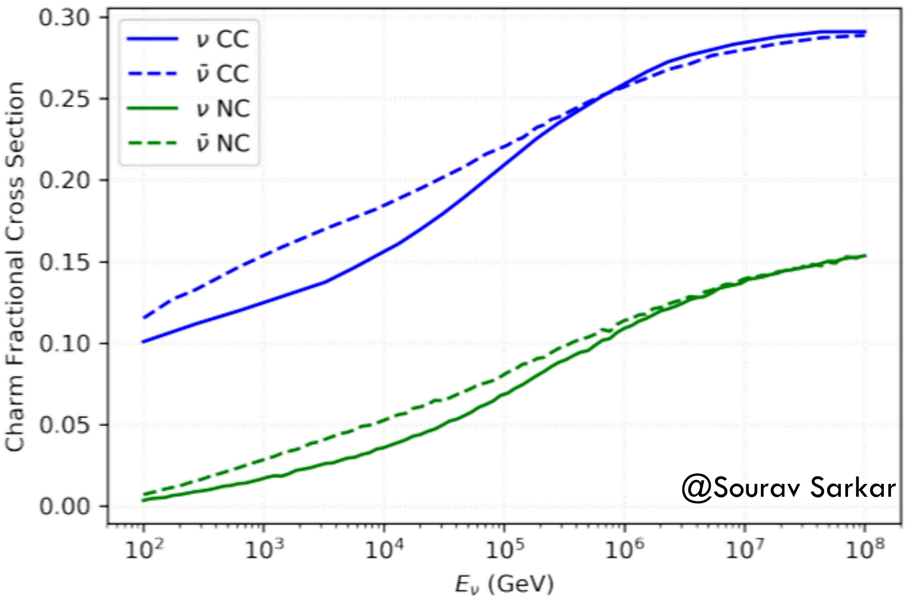
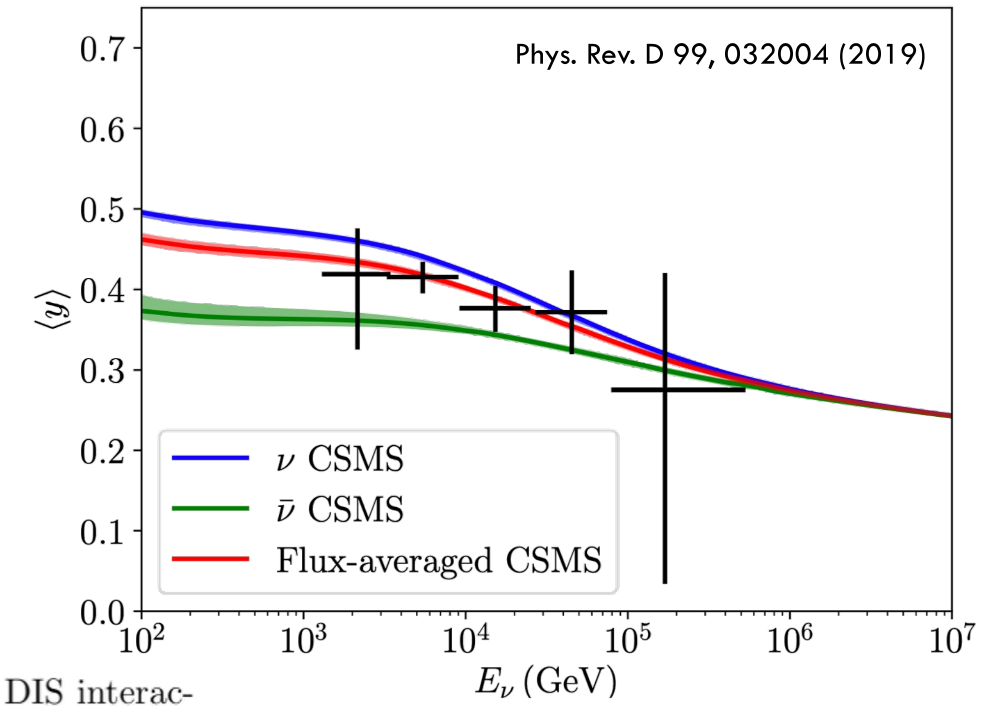


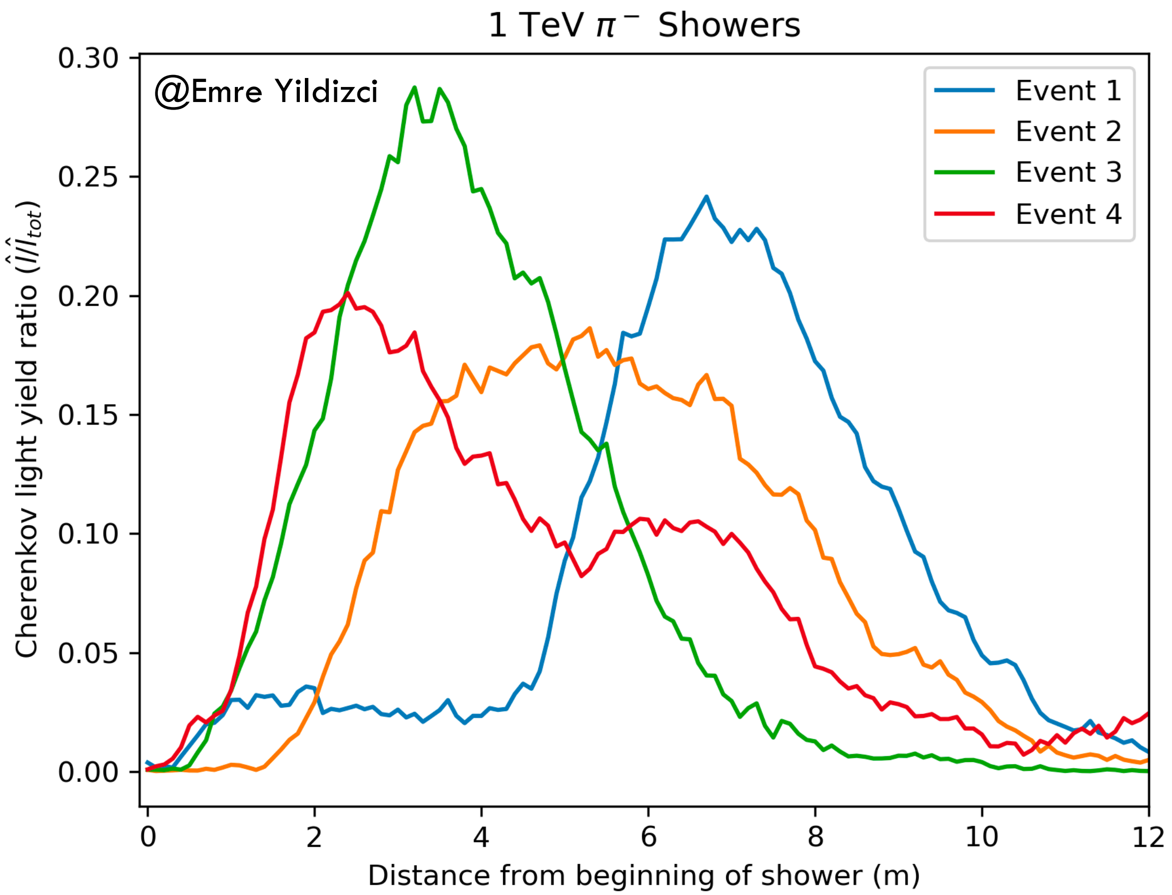
Figure 2.11: Charm production fraction computed from PYTHIA neutrino CC and NC DIS interactions using CT14nlo.



Background for nutau searches sensitive at tau length~10m (D0 interaction/decay length ~3.3m at 50 TeV)

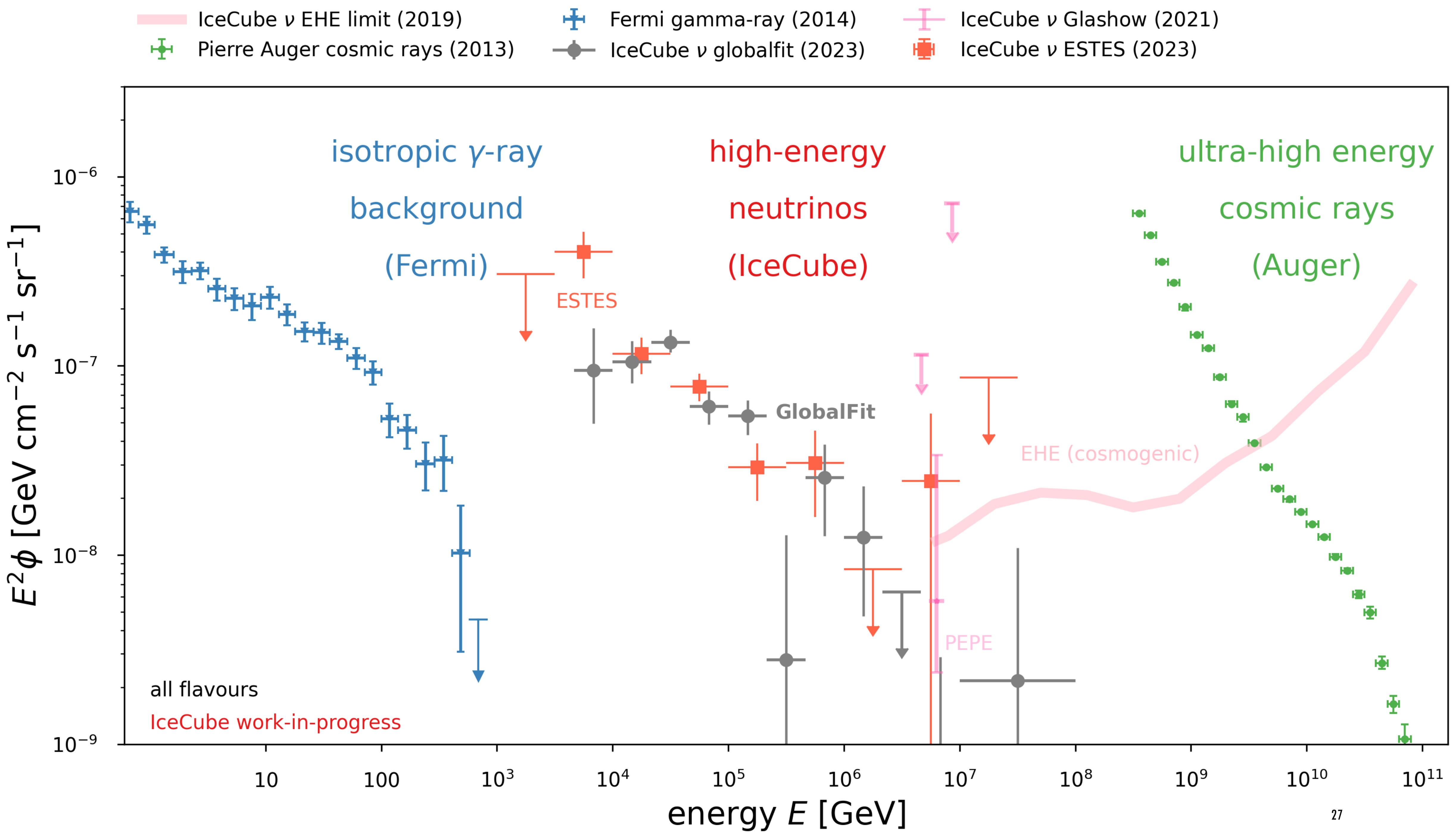
Work-in-progress

CHARM FROM HADRONIC SHOWER IN ICE



charm produced in hadronic showers are not currently considered in nutau and flavour analyses

Shower profile fluctuations introduce additional systematics


IceCube ν EHE limit (2019)
Pierre Auger cosmic rays (2013)
Fermi gamma-ray (2014)
IceCube ν globalfit (2023)
IceCube ν Glashow (2021)
IceCube ν ESTES (2023)
isotropic γ-ray background (Fermi)
high-energy neutrinos (IceCube)
ultra-high energy cosmic rays (Auger)
ESTES
GlobalFit
EHE (cosmogenic)
PEPE
all flavours
IceCube work-in-progress
$E^2\phi$ [GeV cm^{-2} s^{-1} sr^{-1}]
energy E [GeV]

CONCLUSION

* IceCube diffuse analysis has come a long way –modernizing treatments of atmospheric neutrino flux uncertainties + hadronic interaction models -> now in transition to DAEMON flux (see Anatoli's talk)

* Self-veto breaks degeneracy of atmospheric prompt flux -> precise modeling of self-veto is a priority for diffuse analysis in the era of high statistics when features are becoming significant in the flux spectrum

* Prompt flux remains dominate systematic uncertainty for astrophysical parameters: followup studies possible to provide quantitative statement

* Unsolved: unify uncertainties in atmospheric muons and neutrinos

* Did not mention – nu seasonal variation, muons from IceTop (i.e., muon puzzle), cross section measurements, Sterile neutrino search, di-muon search, leptoquark search …

Many plots taken from PhD thesis of : Joeran Stettner, Sebastian Schoenen, Manuel Silva, Austin Schneider

And curtsies to support from: Jakob Böttcher, Philipp Fürst, Erik Ganster, Richard Naab, Tianlu Yuan.