Recent Highlights from IceCube

Alexander Kappes

VLVnT 2013

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Outline

- The IceCube Neutrino Observatory and its performance
- Selected results from neutrino physics with IceCube
  - diffuse fluxes
  - point-like sources
  - WIMP from the Sun
- Selected results from cosmic-ray physics with IceCube and IceTop
  - cosmic-ray spectrum
  - cosmic-ray composition

The IceCube Collaboration

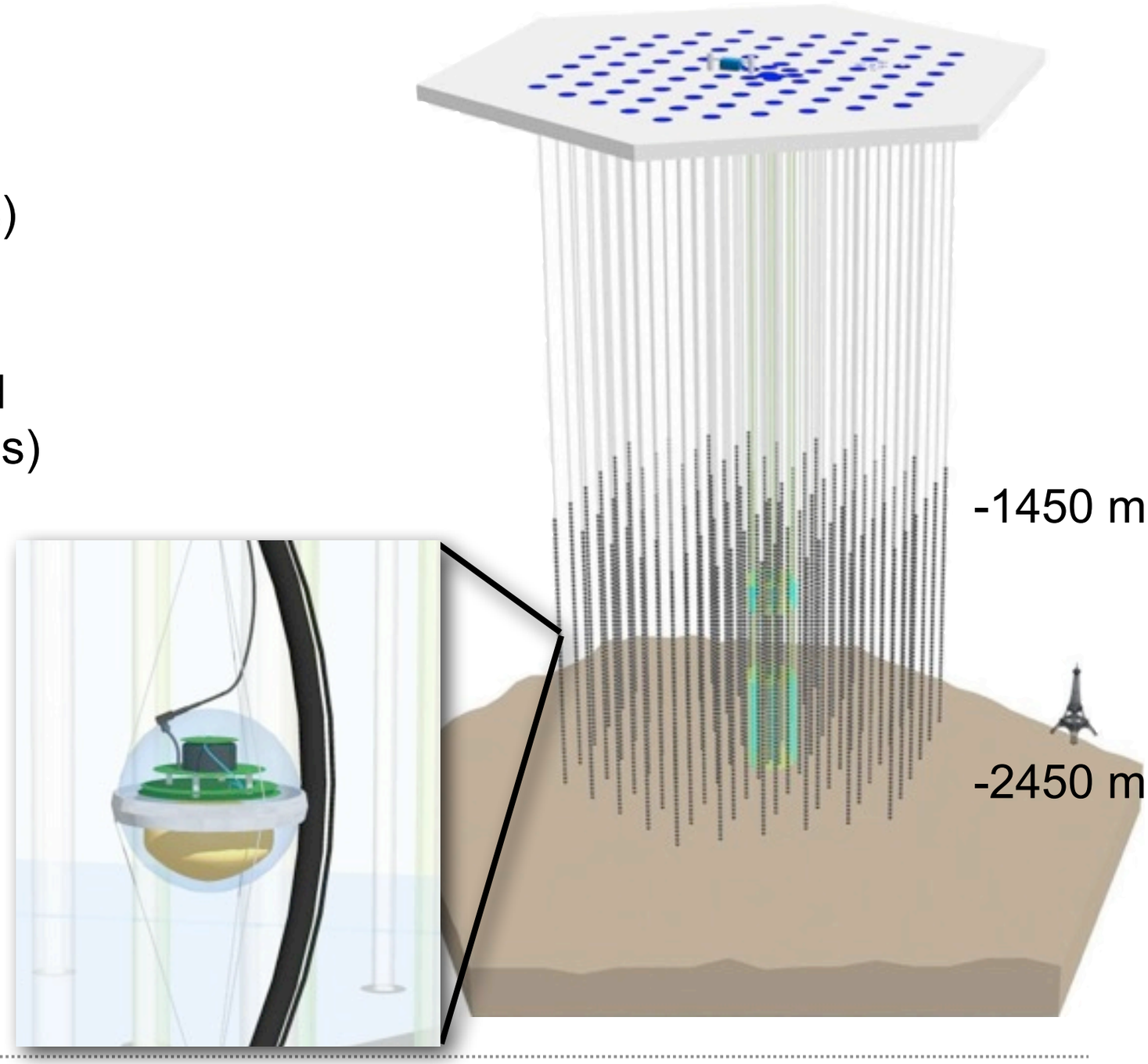
~280 authors from 40 institutes in 11 countries

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The IceCube Observatory

- IceTop: Air shower detector
  162 ice-filled tanks (324 PMTs)
- IceCube: 86 strings (5160 PMTs)
  Instrumented volume: 1 km^3
- DeepCore: densely instrumented central region (8 additional strings)
- Optical sensor
  10” photomultiplier (PMT)
  + in situ signal digitization
  in pressure glass sphere
- Completed since Dec. 2010
  (data taking since 2005)

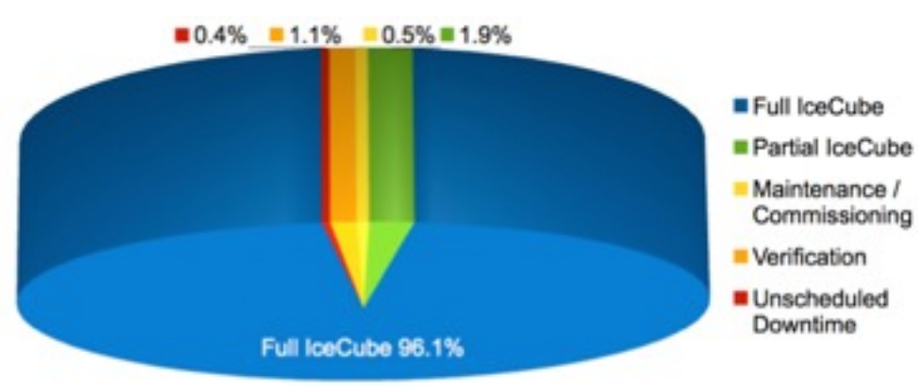


Detector history and status

IceCube DAQ systems
→ parallel talks J. Kelley, V. Baum

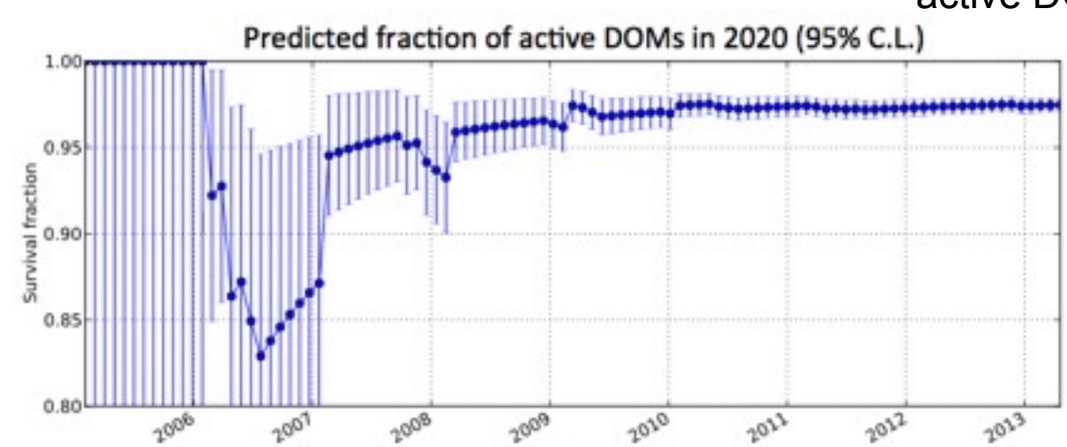
Strings	Year	Livetime	Trigger rate	HE ν rate	Detected ν (up-going)
AMANDA II (19)	2000–2006	3.8 years	100 Hz	5 / day	9000
IC40	2008/09	376 days	1100 Hz	35 / day	13000
IC59	2009/10	348 days	1900 Hz	118 / day	41000
IC79	2010/11	316 days	2250 Hz	152 / day	48000
IC86–I	2011/12	~ 340 days	2700 Hz	~ 160 / day	~ 54000
IC86–II	2012/13	~ 340 days	2700 Hz	~ 160 / day	~ 54000
IC86-III	current		2700 Hz	data taking/ processing	

High availability



High reliability

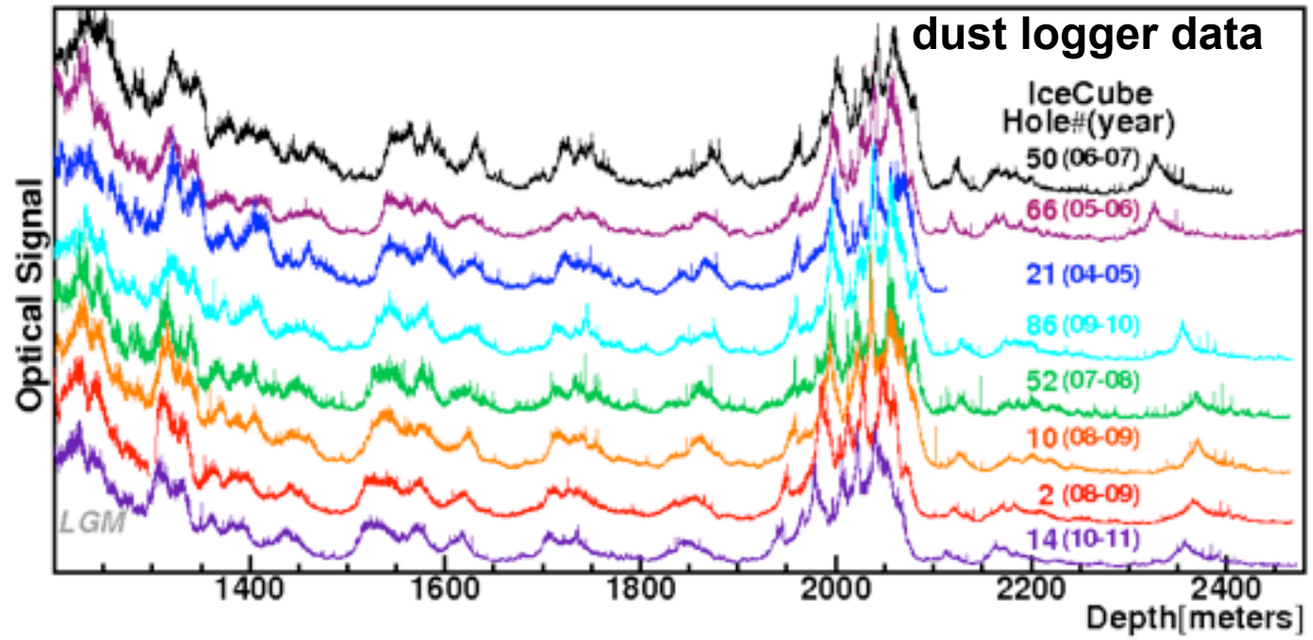
predicted fraction of active DOMs in 2020
↓
97.9%

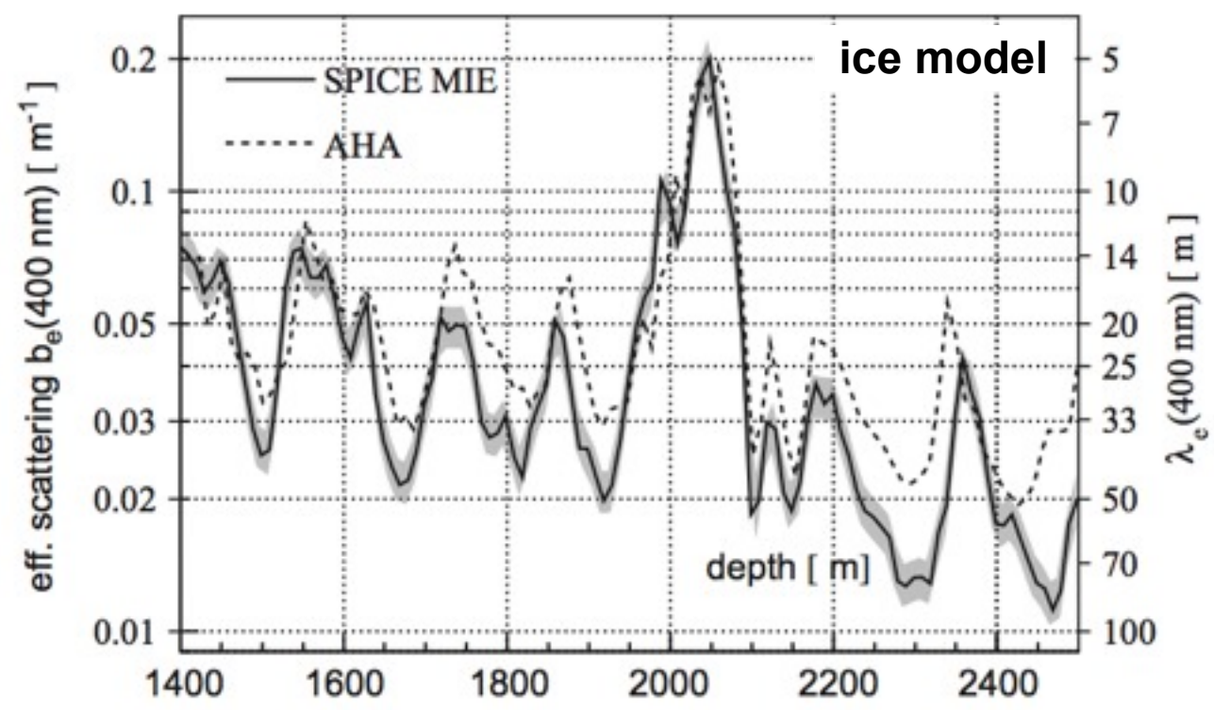


Optical ice properties

- Photon propagation dominated by scattering
  $\lambda_{eff.scat}$ 5 − 100 m
  λ_{abs} 20 − 250 m
- Ice below South Pole inhomogeneous (horizontal “dust layers”)
- Calibration devices
  - Dust logger (8 holes across detector)
  - LED flashers (12 on each DOM)
  - In-ice calibration laser (2)
- Uncertainty on ice properties ~10%

→ parallel talks D. Williams, P.O. Hulth, R. Shanidze

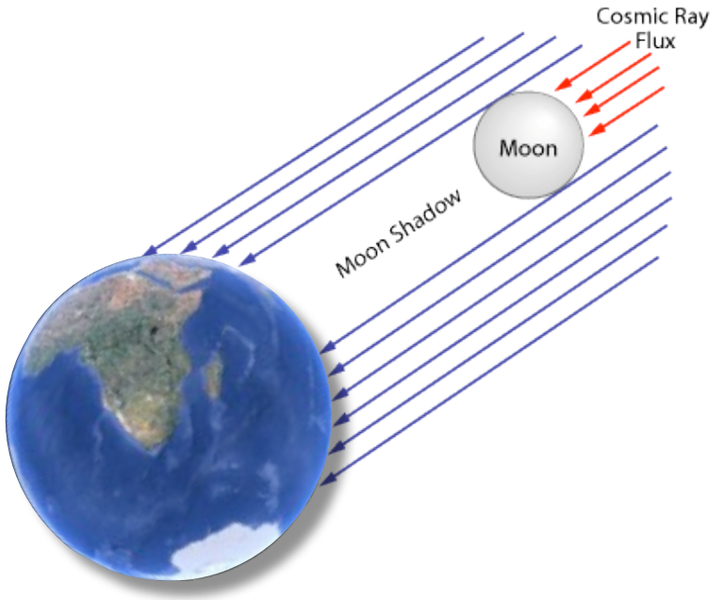




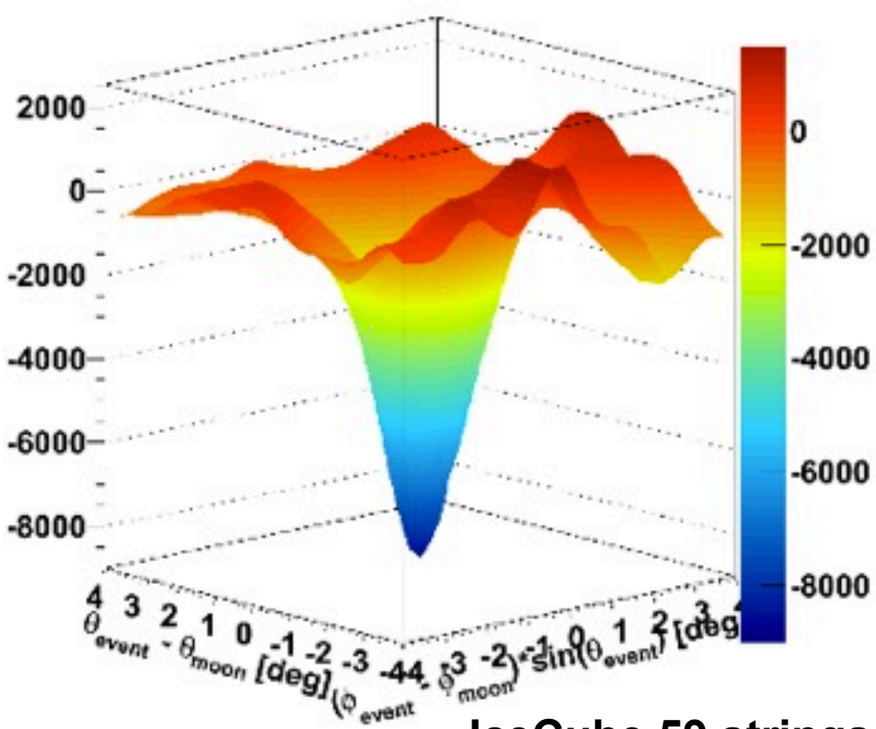
IceCube, NIM A711 (2013)

Pointing accuracy

- No neutrino reference point-source to validate absolute pointing
- Use lack of atmospheric muons from Moon direction (point-sink)
  - Moon diameter 0.5°
  - Angular muon resolution < 1°



- Measurement in IceCube
  (IceCube Coll., arXiv:1305.6811)
  - Observed in IC59 with > 12σ
  - Pointing accuracy < 0.2°
  - consistent with estimated angular resolution

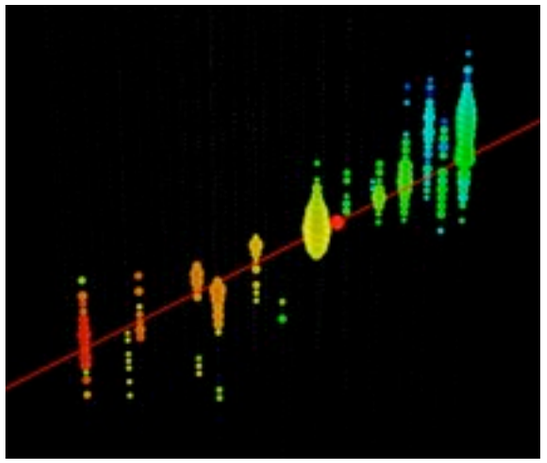


IceCube 59 strings

Event classes

Tracks:

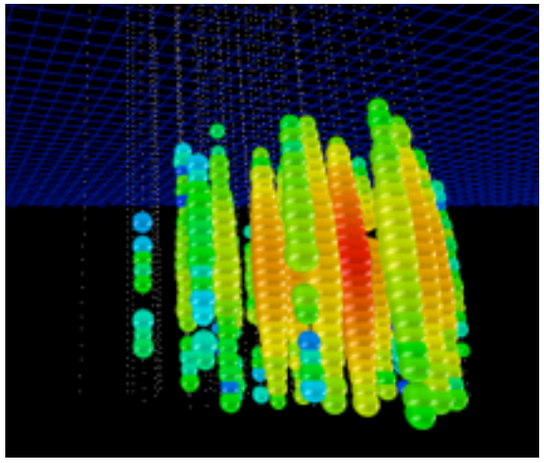
- Source: ν_μ CC interaction
- Good angular resolution (< 1°)
- Factor of 2 resolution in muon energy
- Sensitive volume ≫ instrumented volume



muon (IceCube data)

Cascades:

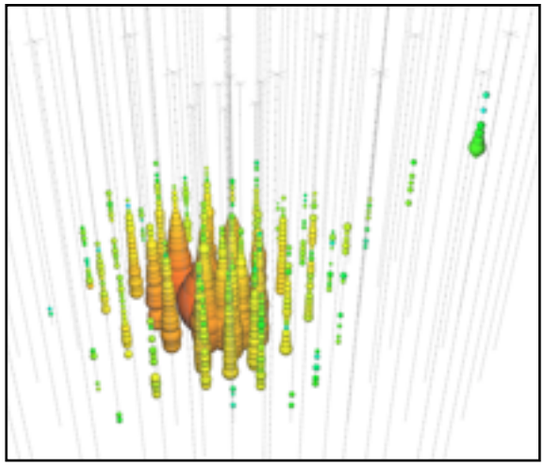
- Source: ν_e, ν_μ, ν_τ NC + ν_e CC interaction
- Good energy resolution (10−15% at high energies)
- Limited angular resolution (≳ 10°)
- Sensitive volume ≈ instrumented volume



cascade (IceCube data)

Composites:

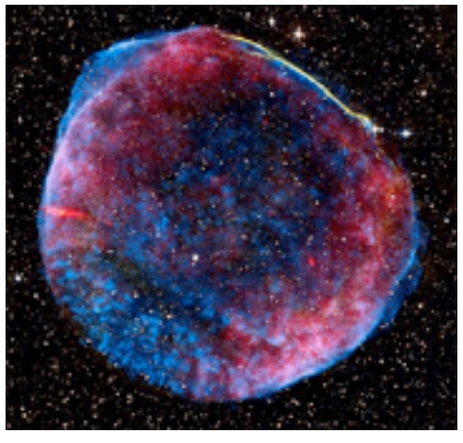
- Source: ν_μ CC (ν_τ CC) inside instrumented volume



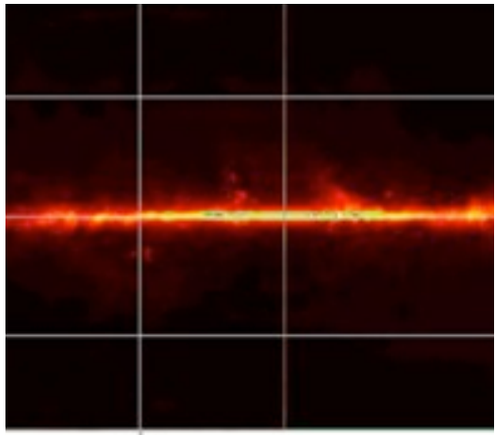
starting muon (IceCube data)

Physics with IceCube

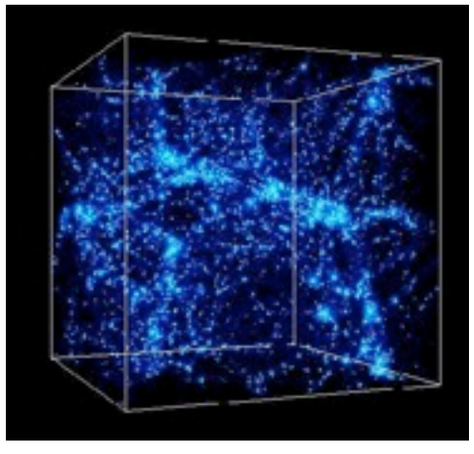
Cosmic accelerators



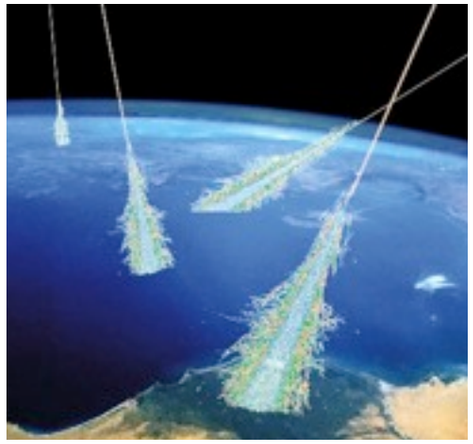
Diffuse fluxes



Dark Matter & Exotic Physics

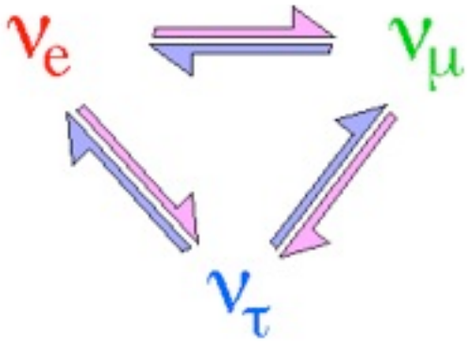


Cosmic rays



Supernovae

Neutrino Properties & Particle Physics



Physics with IceCube

Cosmic accelerators

- Point-like sources (SNRs, Binaries ...)
- Extended sources
- Transients (GRBs, AGN flares ...)

Diffuse fluxes

- All-sky fluxes (e.g. cosmogenic)
- Galactic plane
- Extended structures (e.g. Fermi-Bubbles)

Dark Matter & Exotic Physics

- Indirect DM search (Sun, Galactic halo)
- Magnetic monopoles, Q-balls
- Lorentz invariance violation

Cosmic rays

- Spectrum around "knee" (10^{15}–10^{17} eV)
- Composition
- Anisotropy

Supernovae

- Galactic/LMC SNe
- Phases
- Neutrino hierarchy

Neutrino Properties & Particle Physics

- Neutrino oscillations
- Charm in showers
- K/π ratio in showers
- Cross sections at very high energies

Physics with IceCube

Cosmic accelerators

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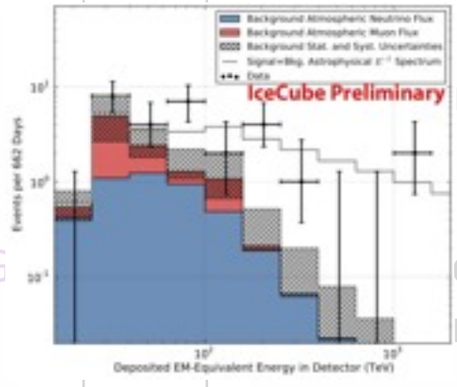

Diffuse fluxes

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mogenic)
plane
d structures
mi-Bubbles)

→ plenary talk N. Whitehorn

Dark Matter & Exotic Physics

- ☆ Indirect DM search (Sun, Galactic halo)
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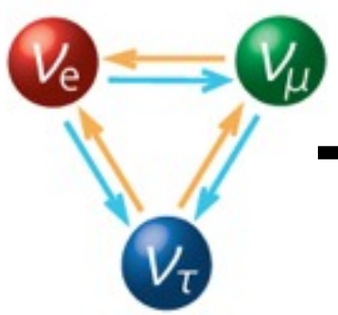
Cosmic rays



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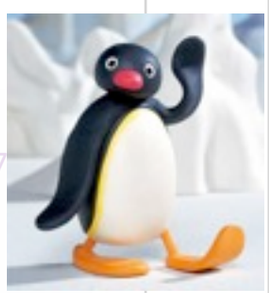

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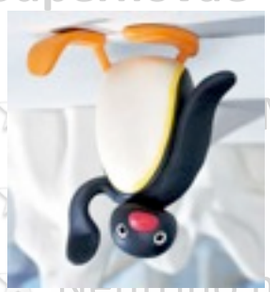
10^{17}

- ☆ Anisotropy

Supernovae



MC SNe
Neutrino hierarchy

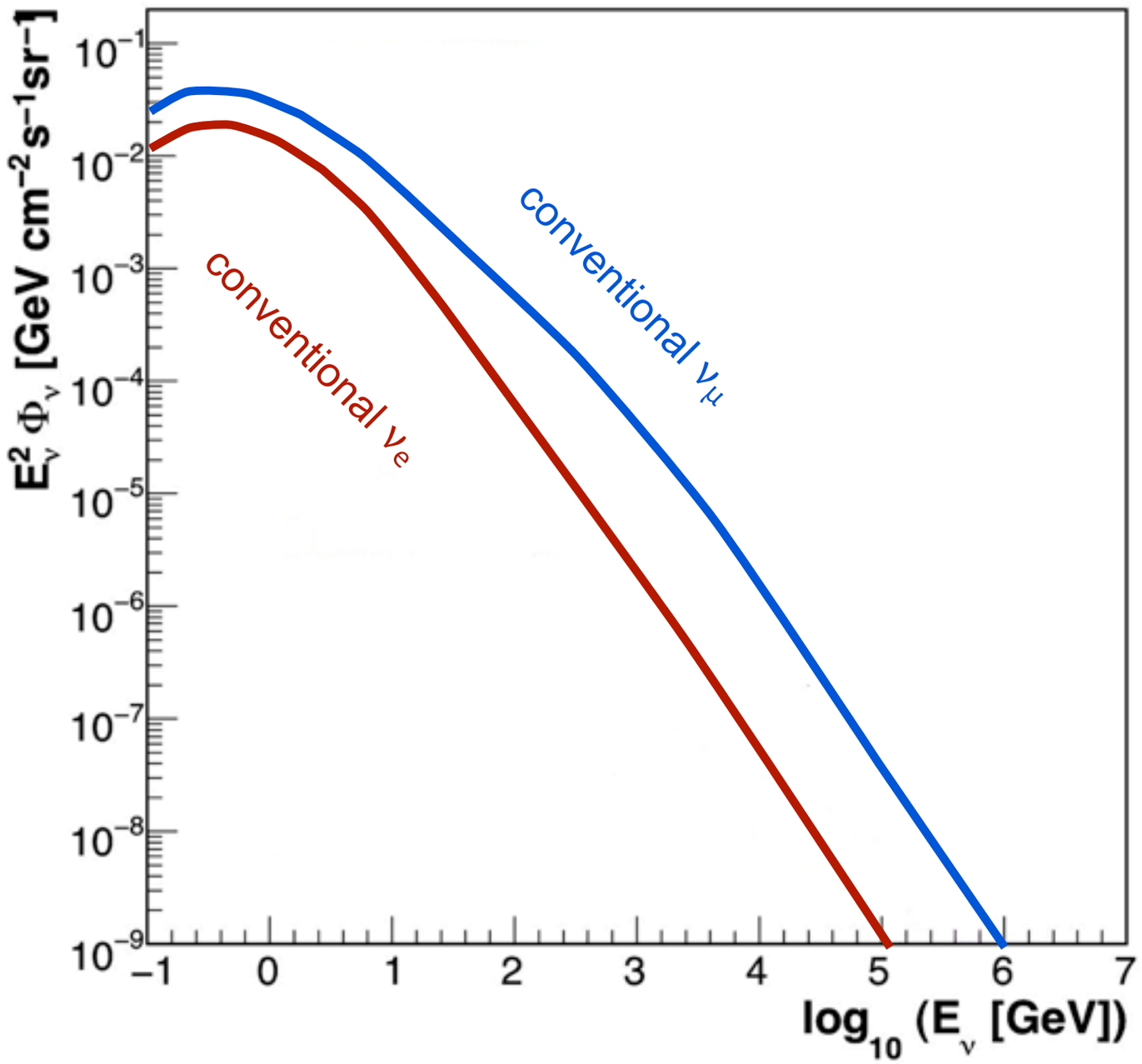
→ plenary talk T. DeYoung

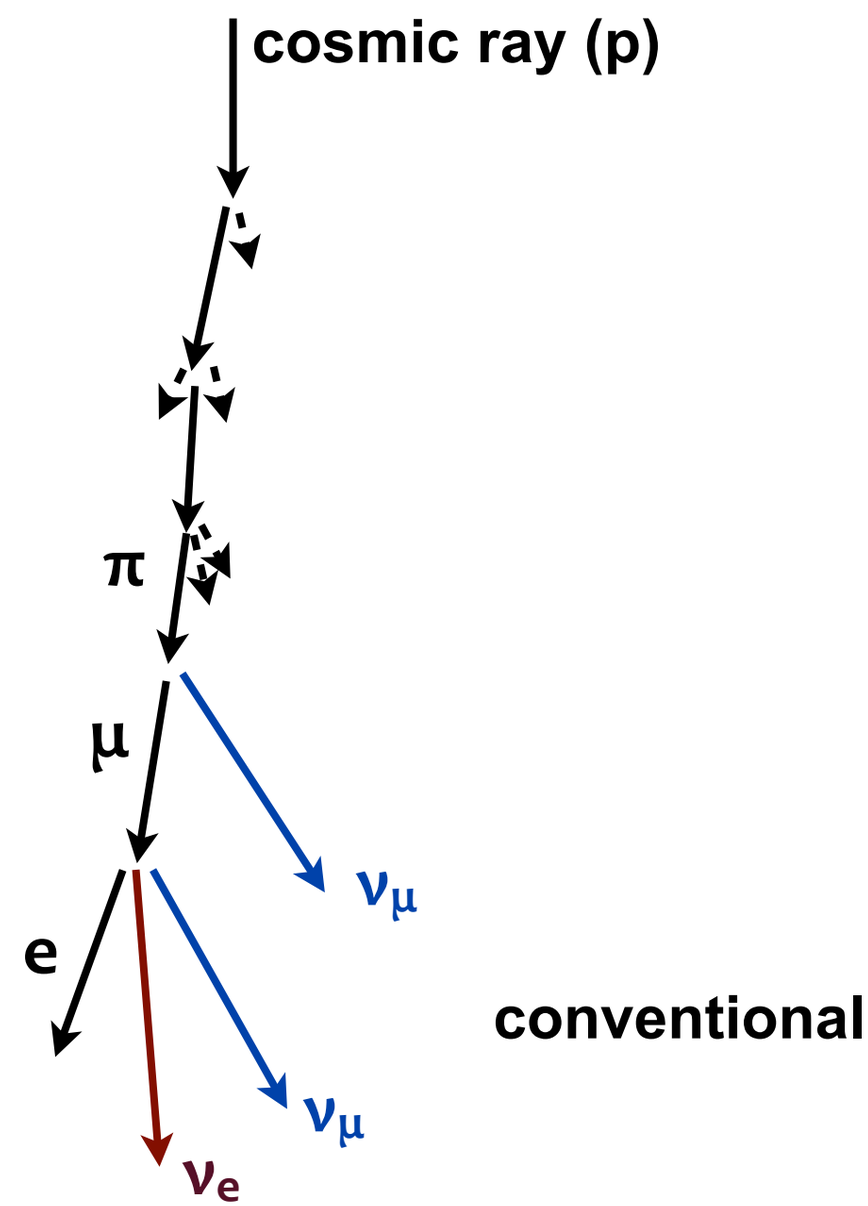
Neutrino Properties & Particle Physics

- ☆ Neutrino oscillations
- ☆ Charm in showers
- ☆ K/π ratio in showers
- ☆ Cross sections at very high energies

Neutrino physics with IceCube (selection)

Atmospheric neutrino spectra





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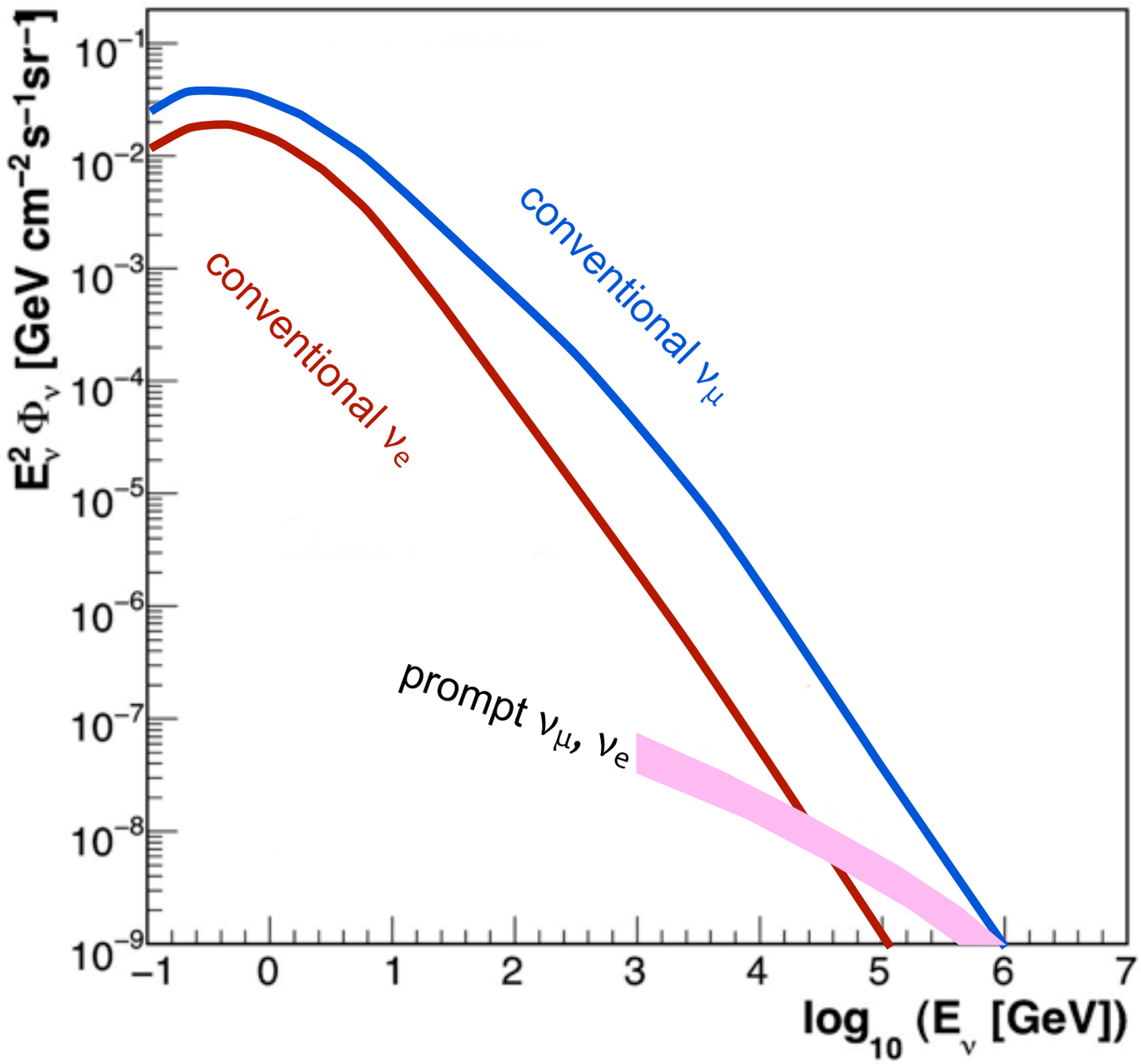

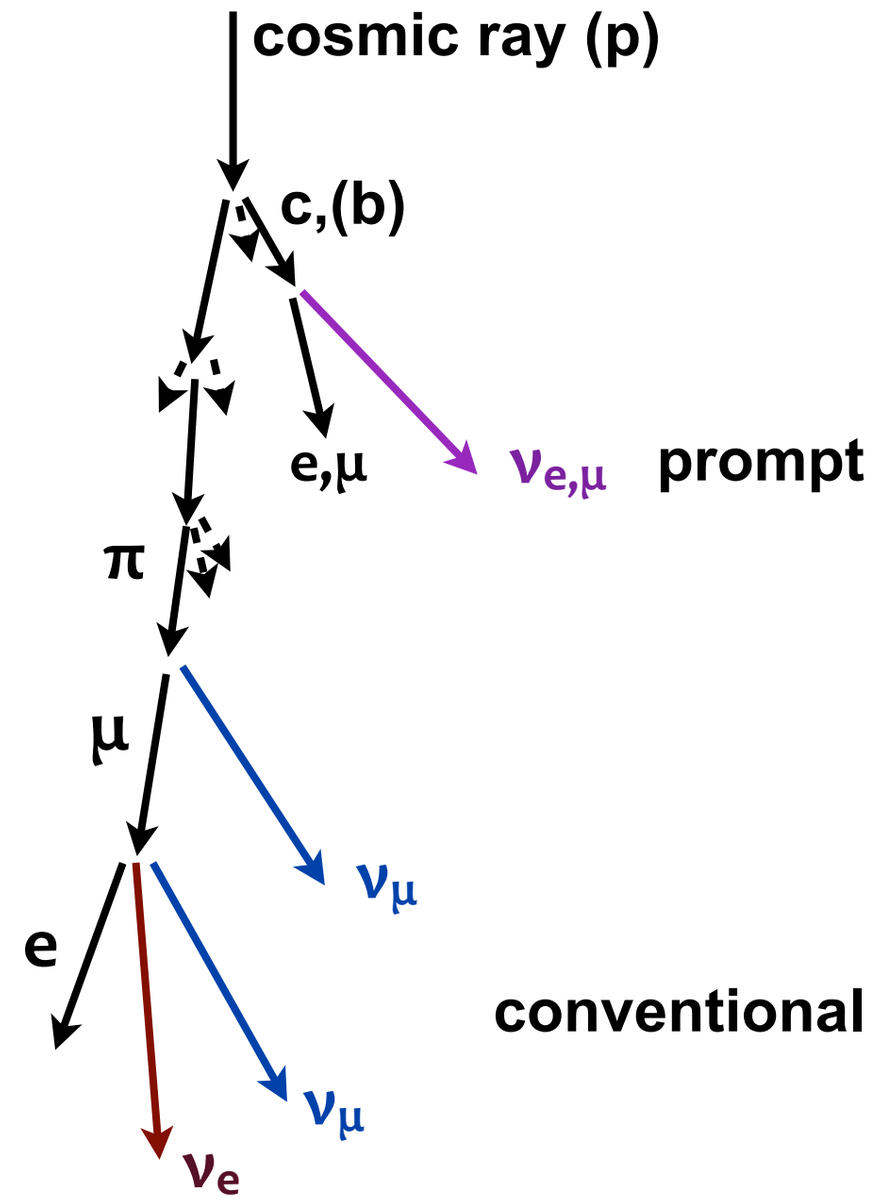

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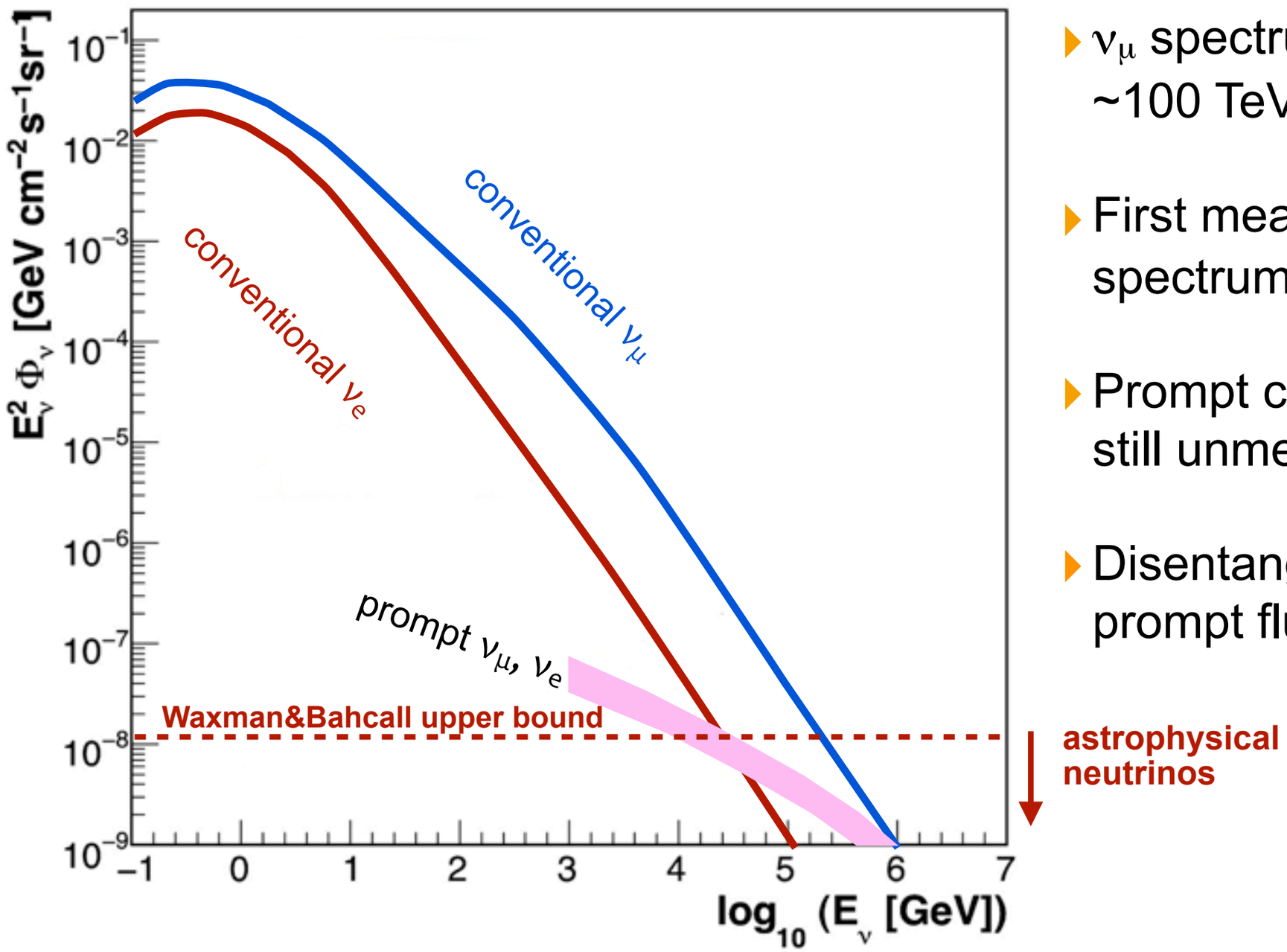
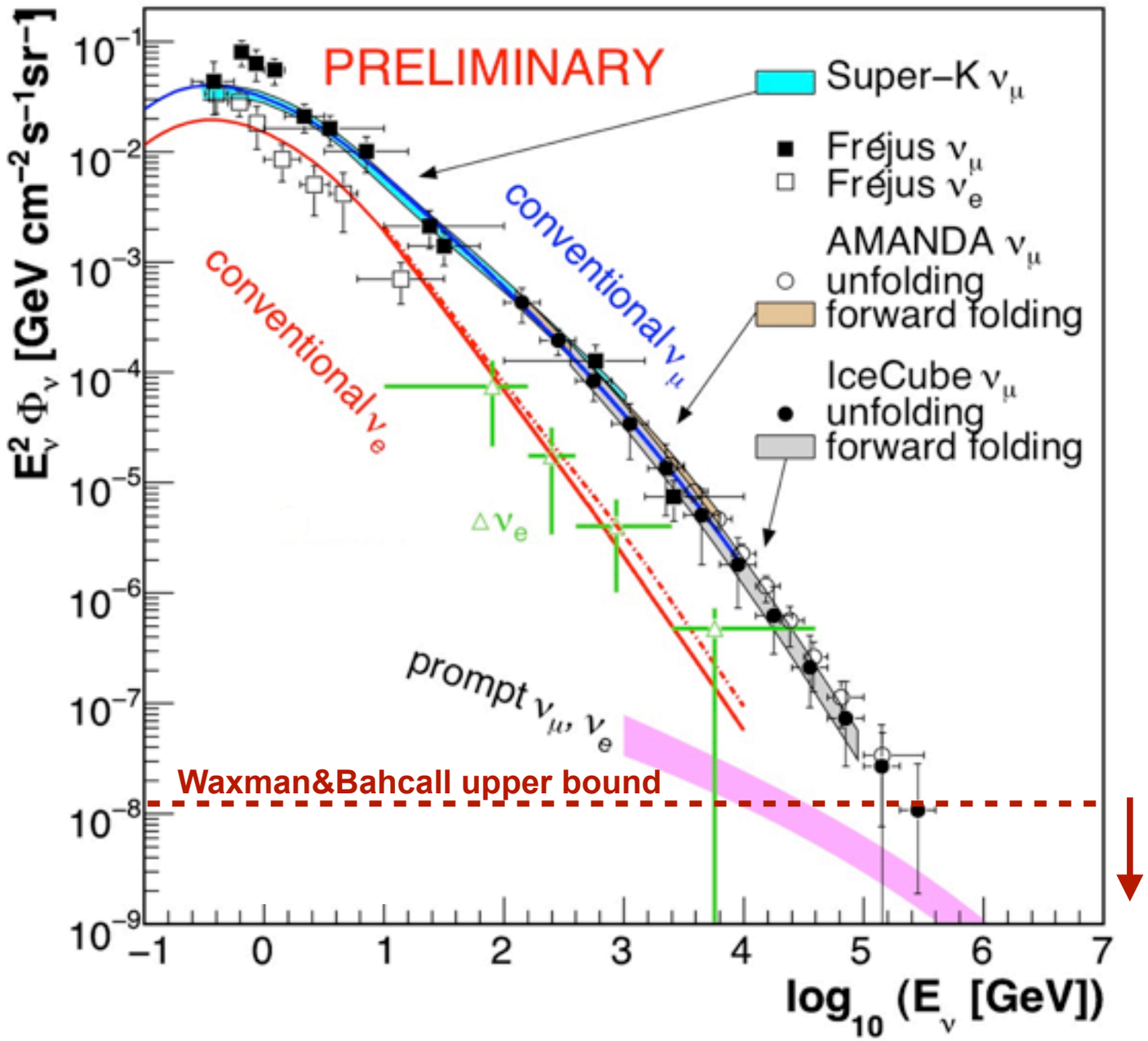


- ν_μ spectrum measured to ~100 TeV with high accuracy
- First measurement of ν_e spectrum at TeV energies
- Prompt components still unmeasured
- Disentangling cosmic and prompt fluxes challenging

astrophysical neutrinos

Atmospheric neutrino spectra



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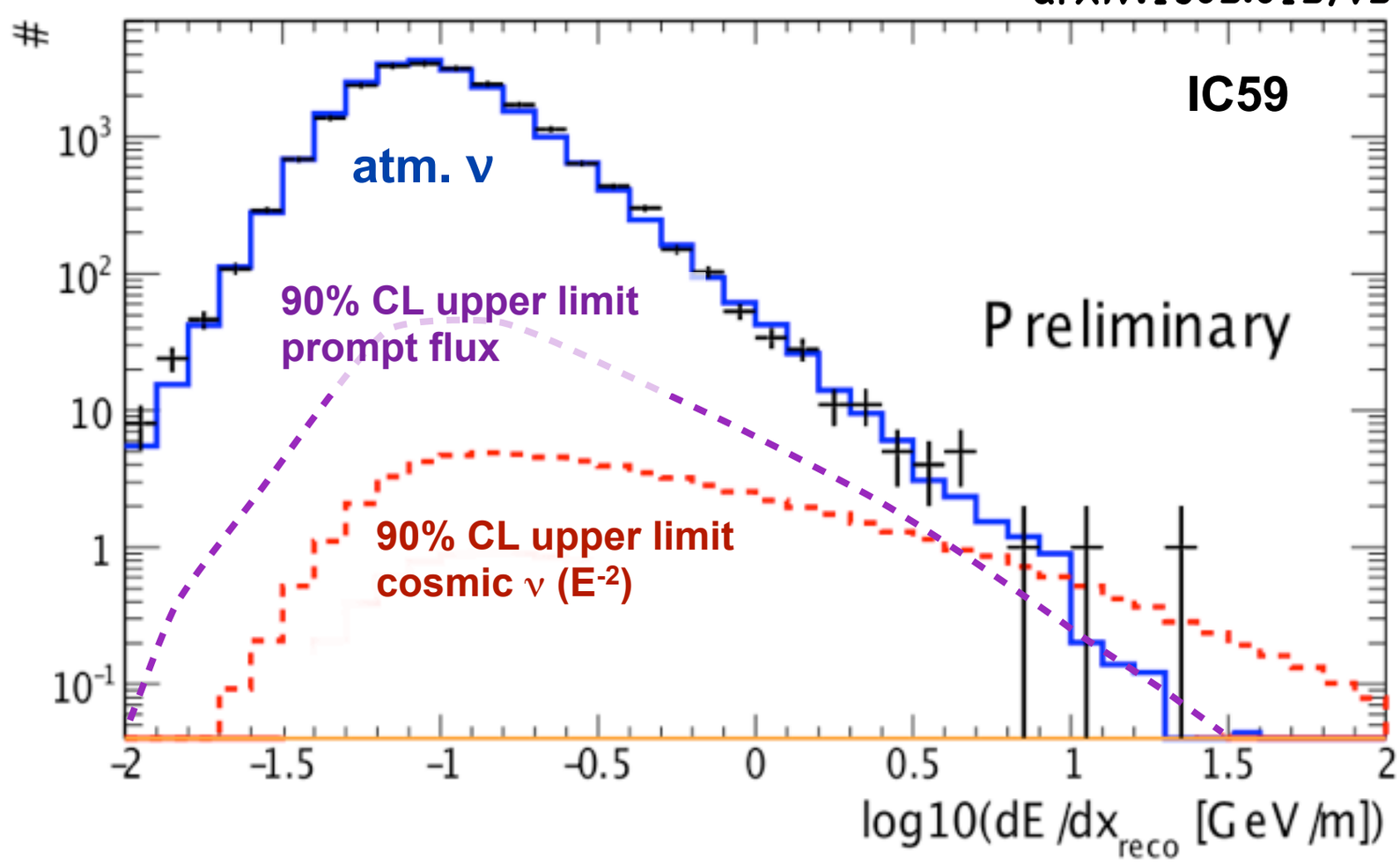
astrophysical neutrinos

Prompt and cosmic neutrinos with muons in IC59

- Spectrum of up-going muons in dE/dx_{reco}
- Non-significant excess (1.8σ) above conventional atm. neutrinos at high energies
  → upper limits (90% CL)
  - prompt: 3.8 × Enberg et al., PRD (2008)
  - $E^2\ \Phi < 1.4\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

arXiv:1302.0127v2



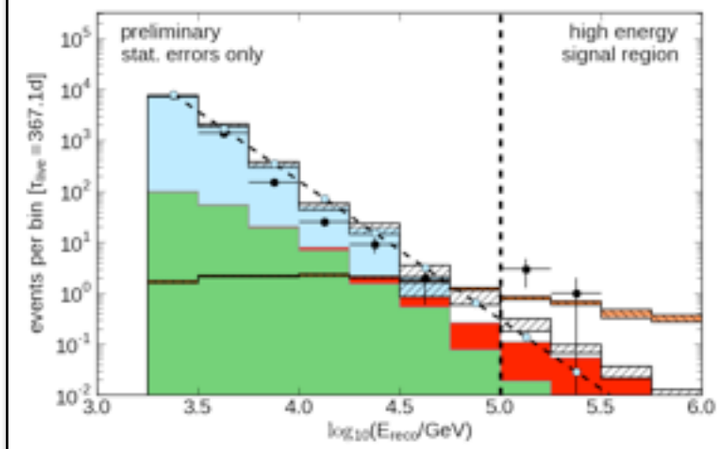
Prompt and cosmic neutrinos with cascades in IC59

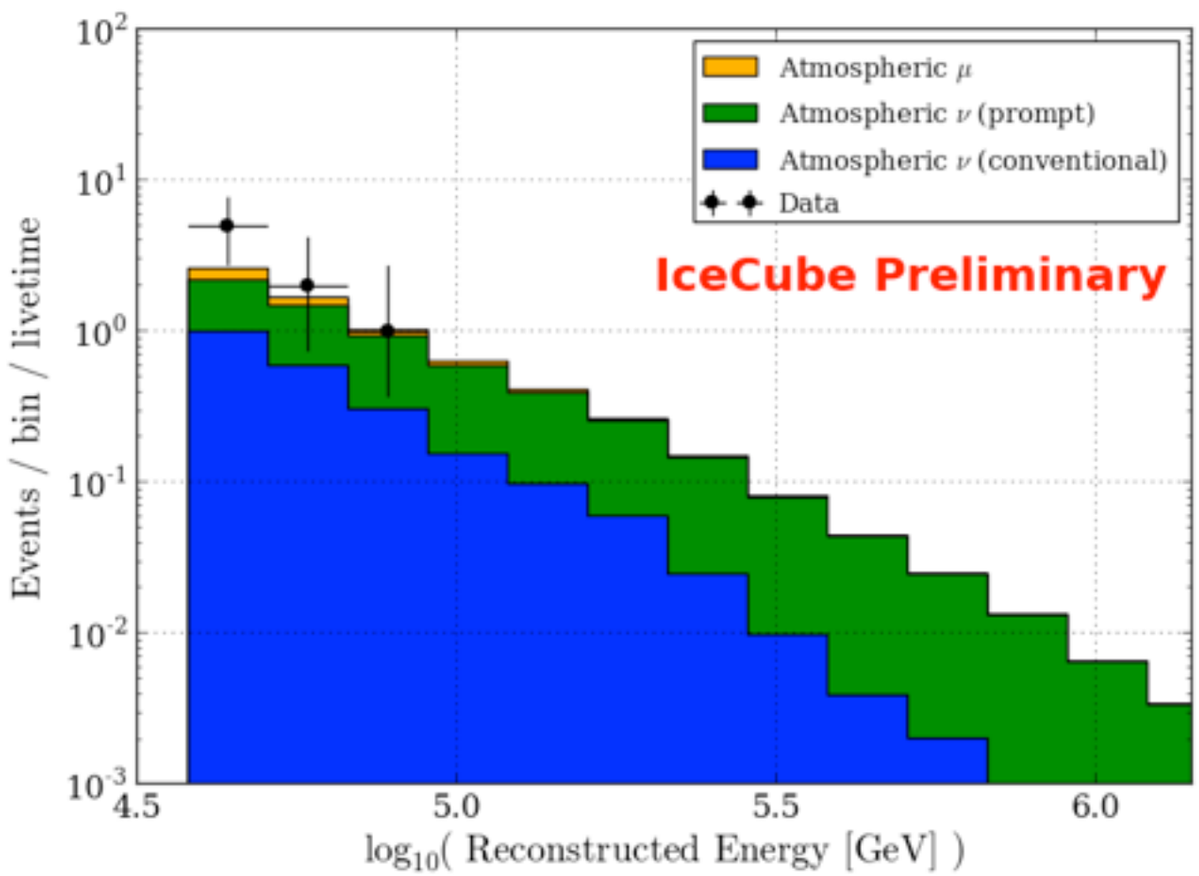
- Search for contained showers (8 found with 4 expected)
- Data compatible with conventional atmospheric neutrinos

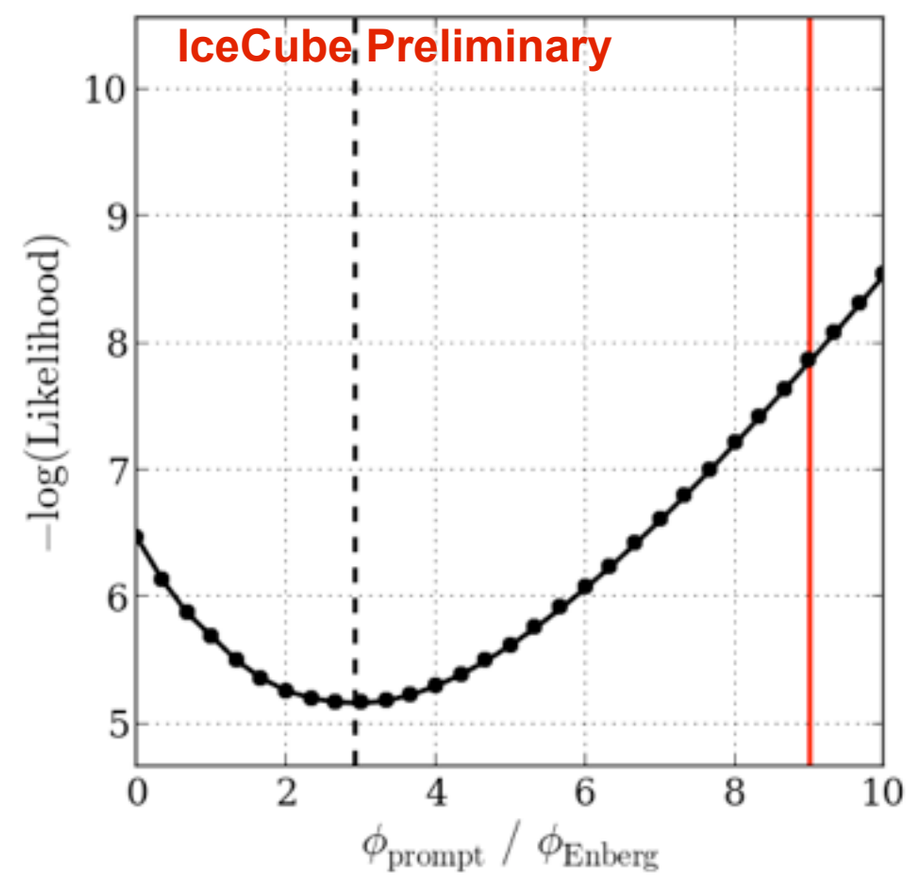
  → upper limits (90%) on prompt and cosmic (E^{-2}) fluxes:

  - prompt: 9 × Enberg et al. (best fit 2.3 × Enberg et al.)
  - $E^2\,\Phi < 1.8\times10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1} (43 TeV – 6.3 PeV)

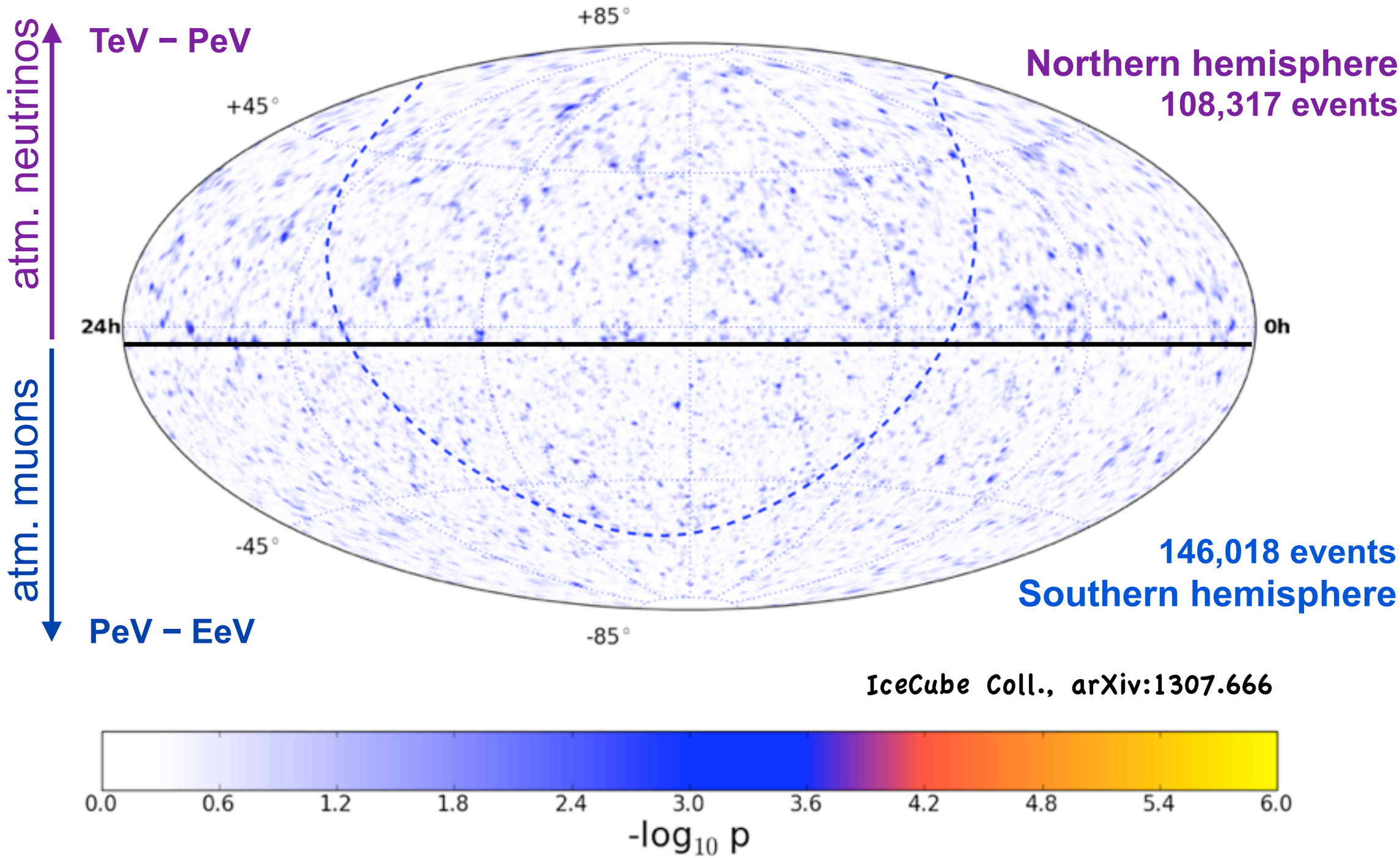
Retrospect IC40: 2.4σ excess







Point sources: Significance skymap (IC40+59+79)



IceCube Coll., arXiv:1307.666

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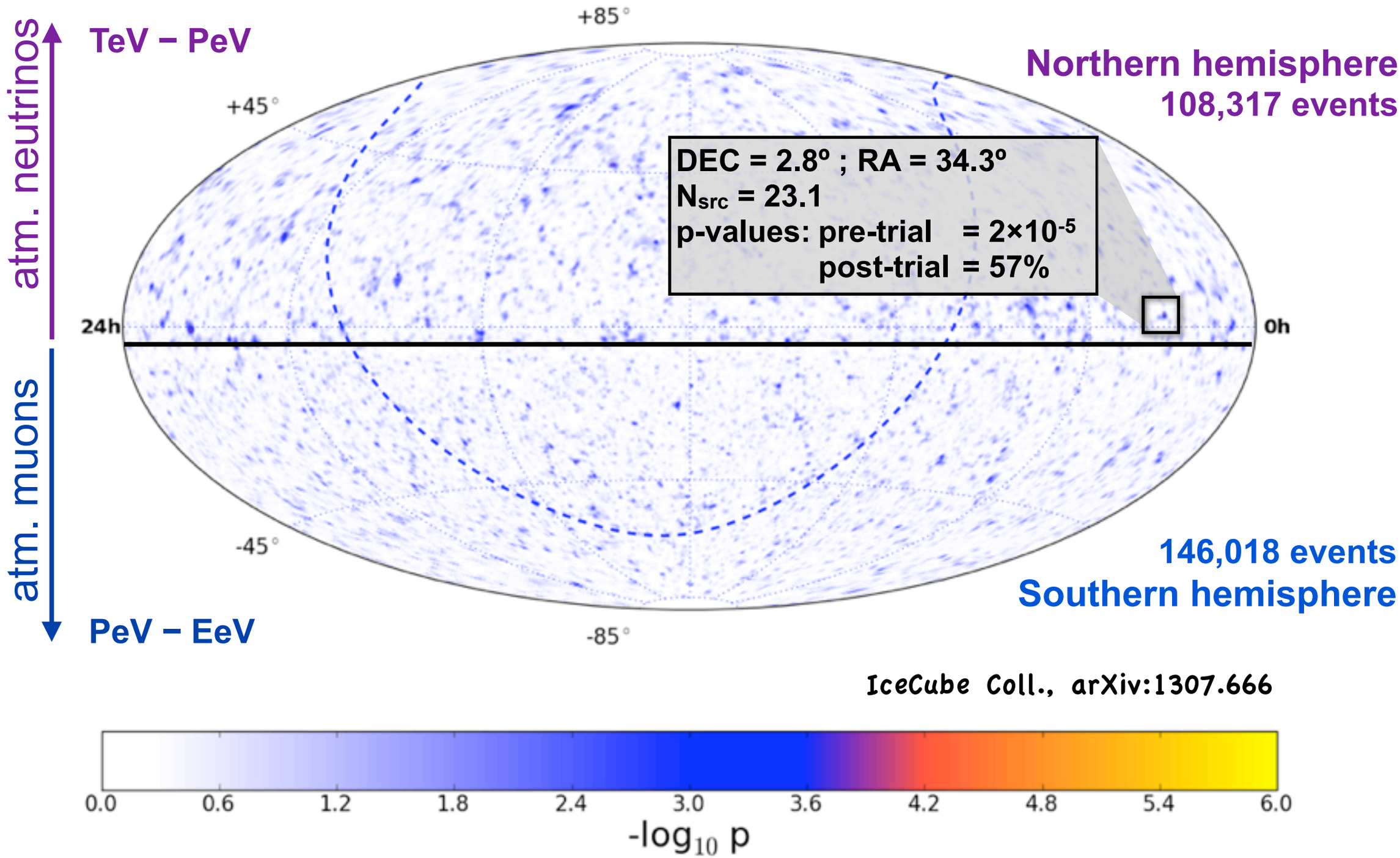

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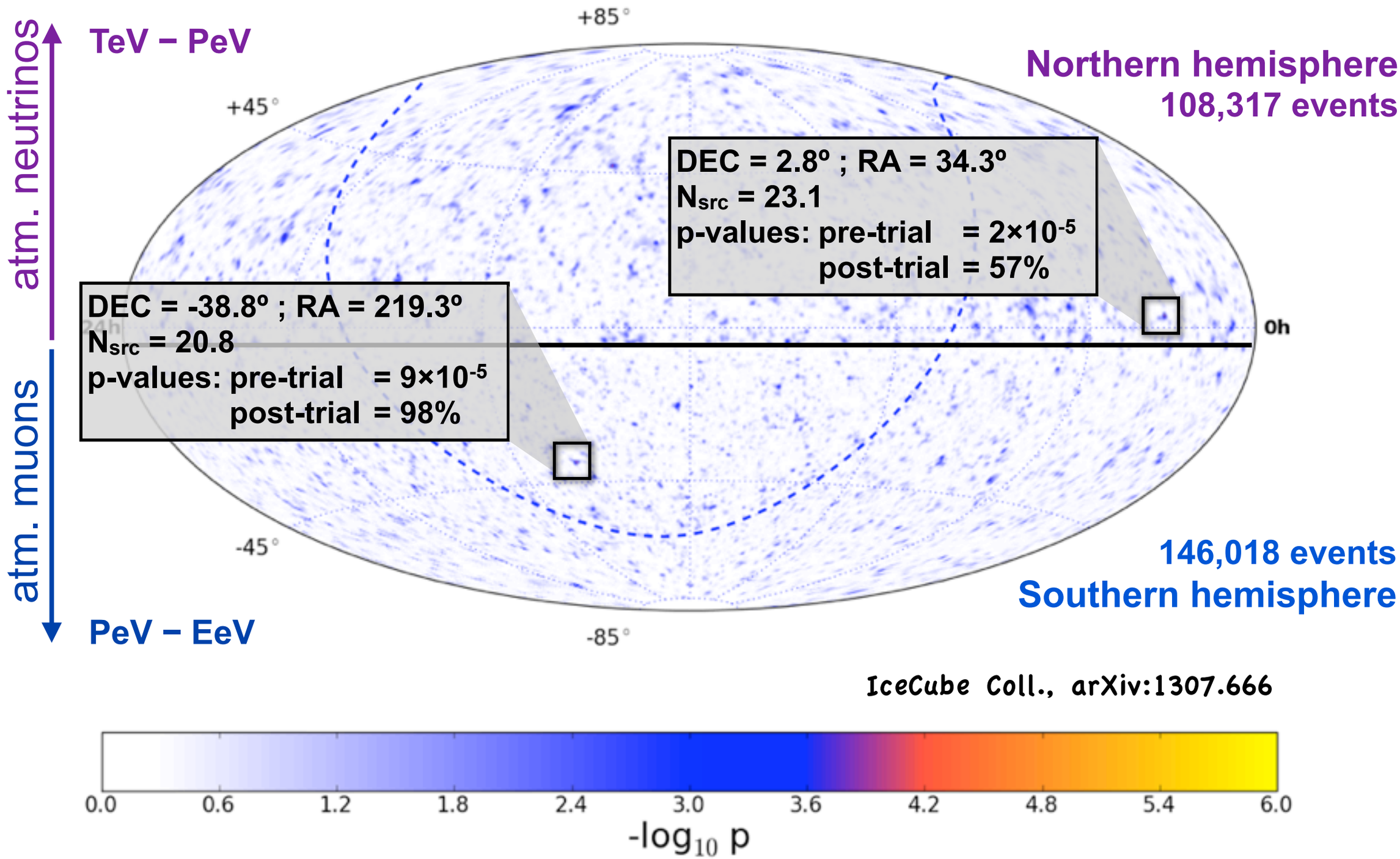

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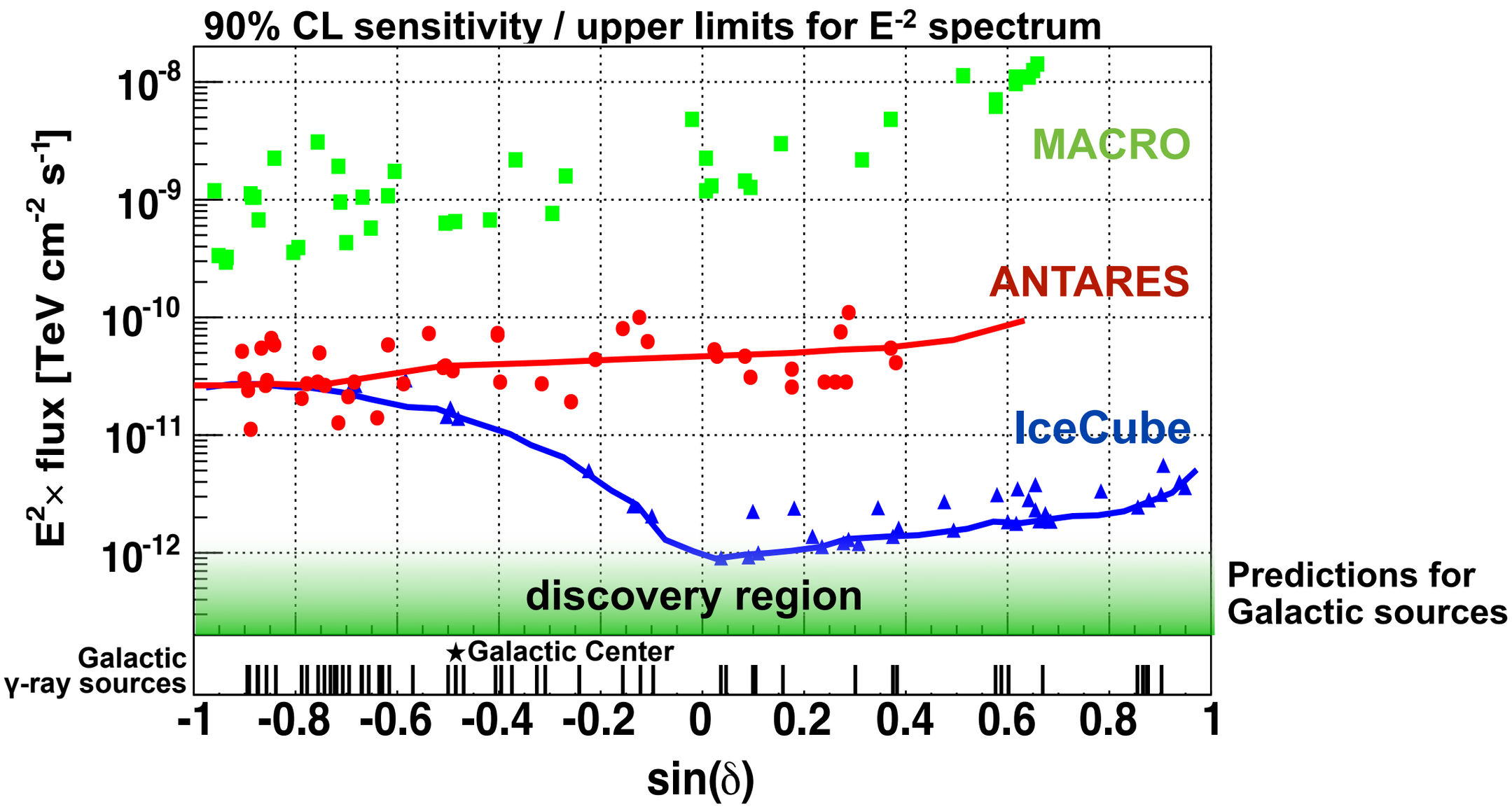
Point sources: Sensitivities & upper limits (IC40+59+79)



- Accumulation of data + improved reconstruction
  → further significant sensitivity improvement in next years

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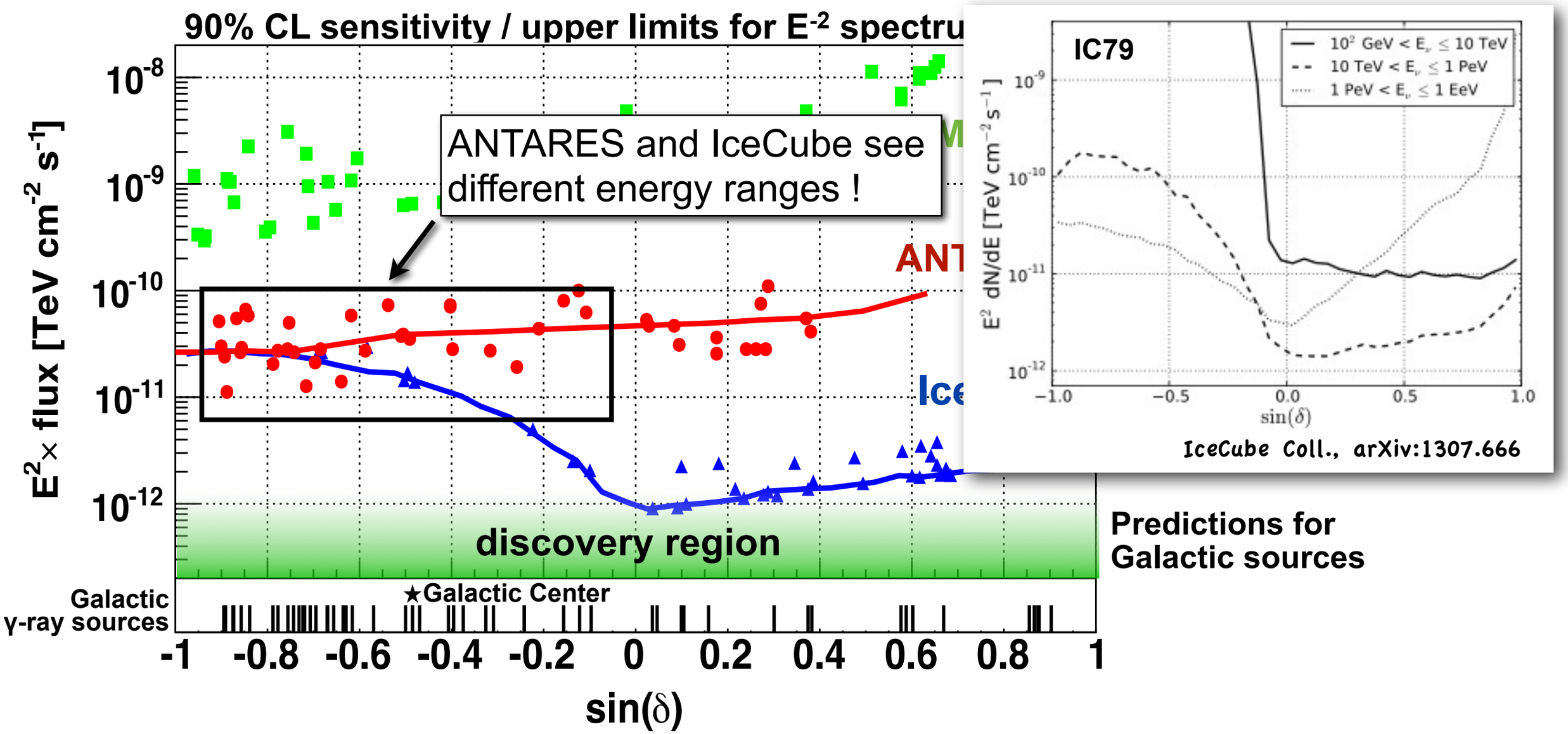

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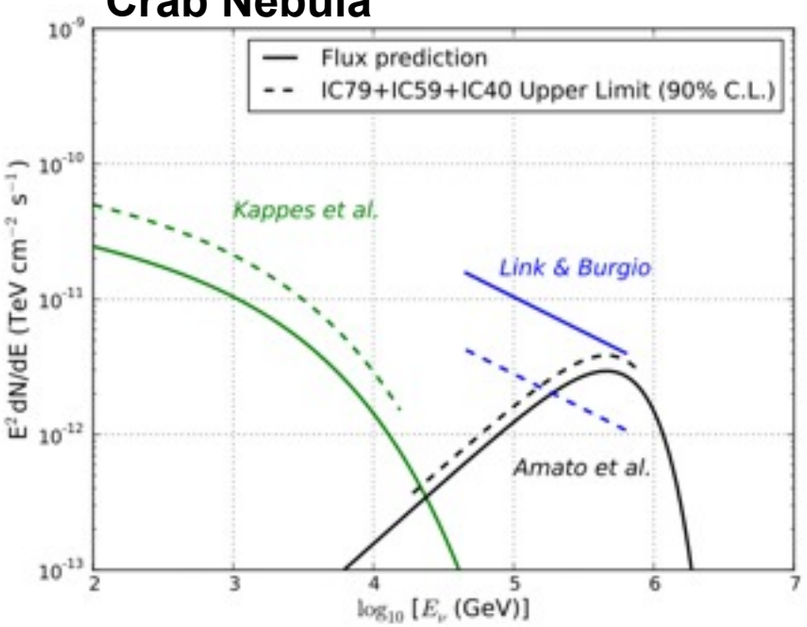
Selected point sources (classes)

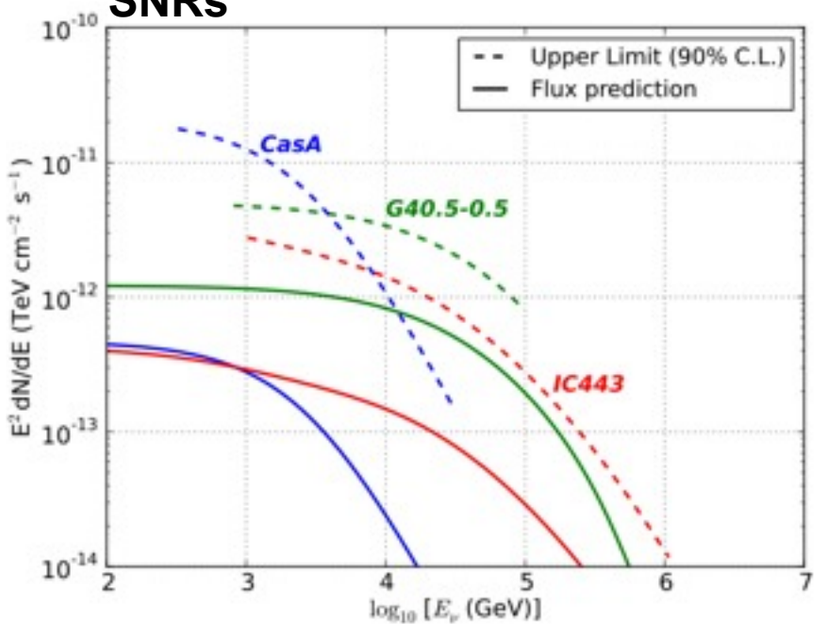
- Investigation of 14 Galactic and 28 extra-galactic pre-selected sources
  - lowest Galactic p-value 5.8% (HESS J0632+057)
  - lowest extra-galactic p-value 23% (PKS 1454-354)

  (p-values pre-trial)
- Crab nebula:
  - limit only factor 2 above (purely hadronic) flux prediction
  - exclusion of other neutrino production models ≳ 90% level (optimistic assumptions)
- SNRs & 6 stacked Milagro sources: start to approach (purely hadronic) predictions

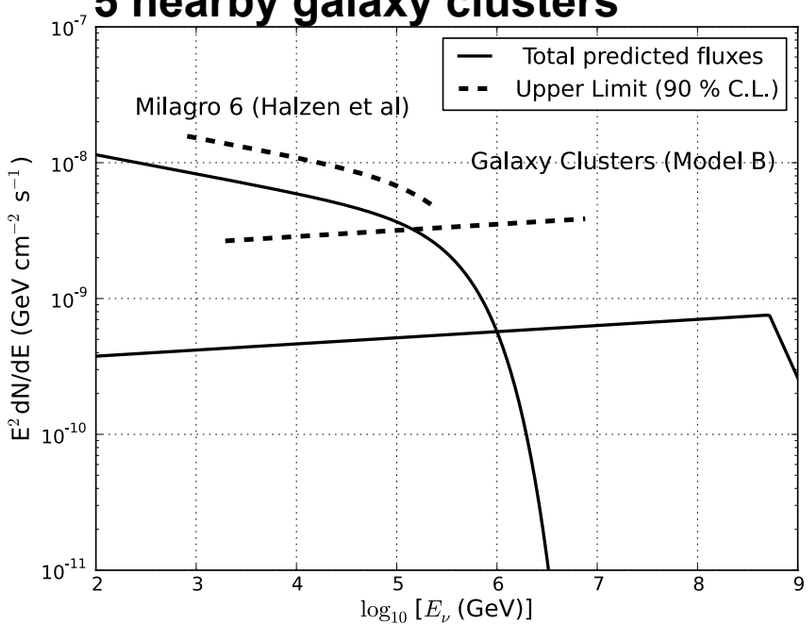
Crab Nebula



SNRs



6 Milagro sources & 5 nearby galaxy clusters



IceCube Coll., arXiv:1307.666

Selected point sources (classes)

small-scale anisotropies
→ parallel talk A. Bernhard

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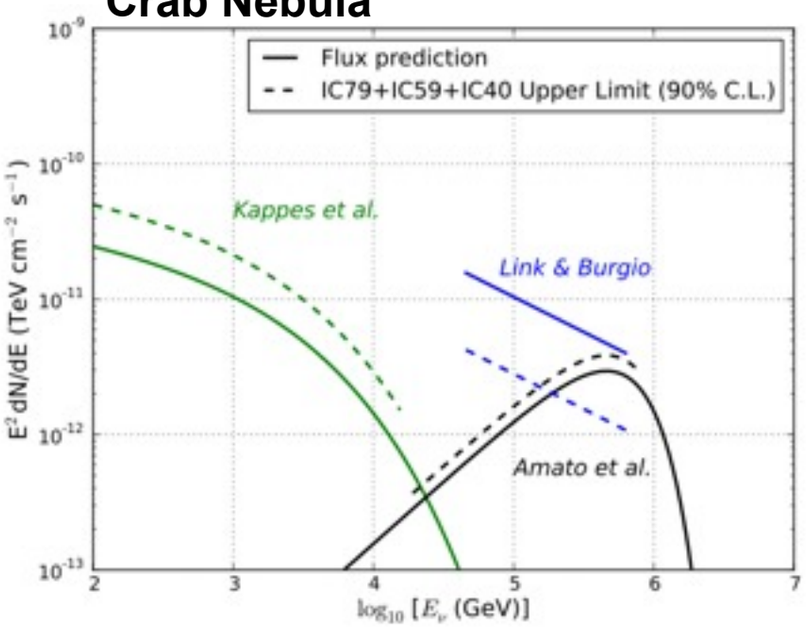
Crab Nebula



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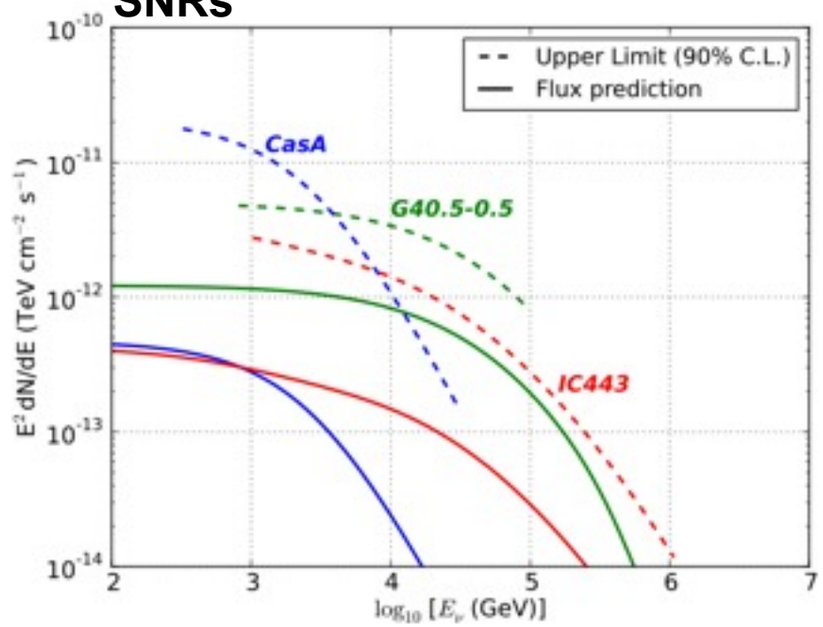

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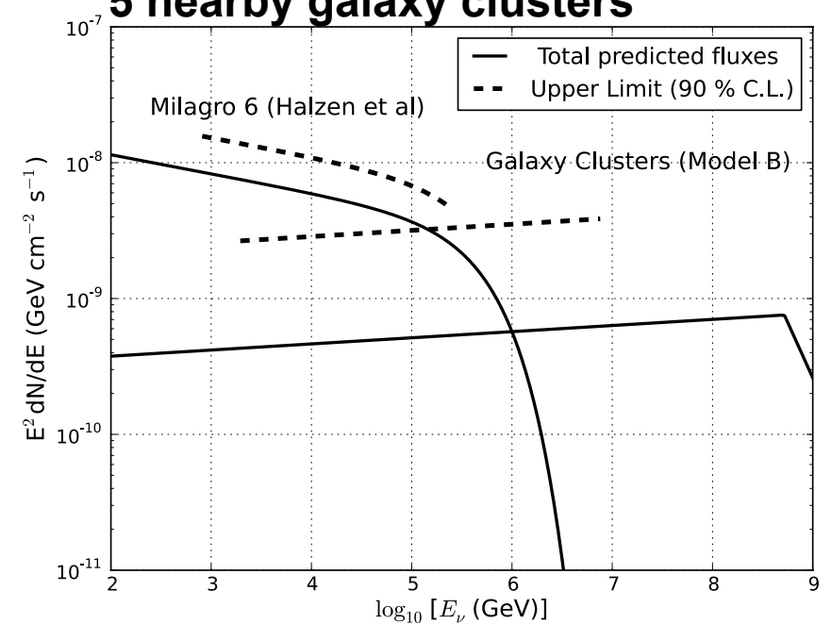

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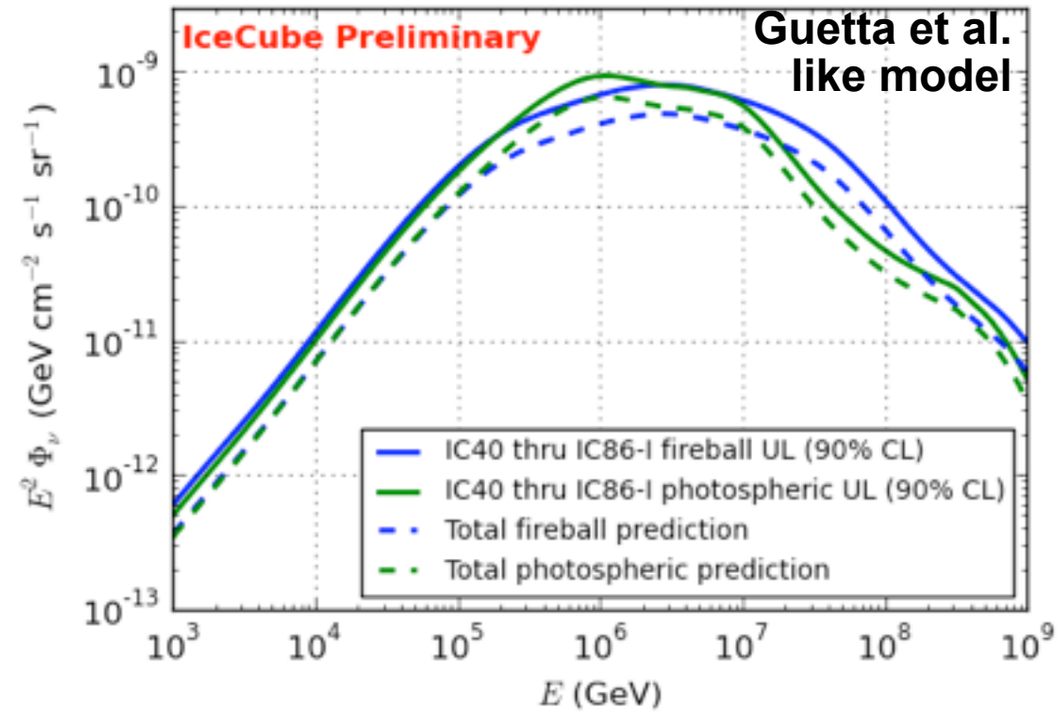
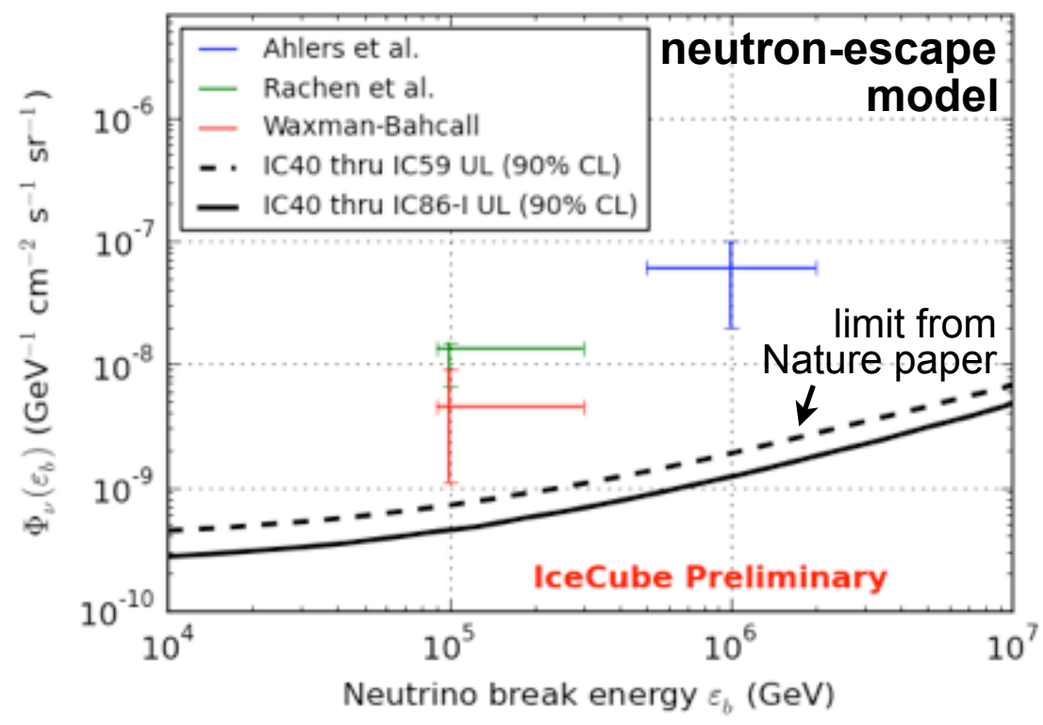
Update on search for neutrinos from GRBs

- Nature publication in 2012 on non-observation of neutrinos from GRBs: factor two below predictions
  → theoretical follow-up calculations:
  Guetta et al. approximations too optimistic

- Guetta et al. like model
  (no normalization to observed cosmic rays)
  - now includes full particle physics
    [following Hümmer et al., PRL 108 (2012)]
  - another two years of data (IC40+59+79+86-I)
    → total ~500 bursts
  - 90% CL exclusion limits reach now also reduced flux predictions

- Neutron escape models
  - normalized to observed cosmic rays
    → less parameter dependent
  - further increase of exclusion power

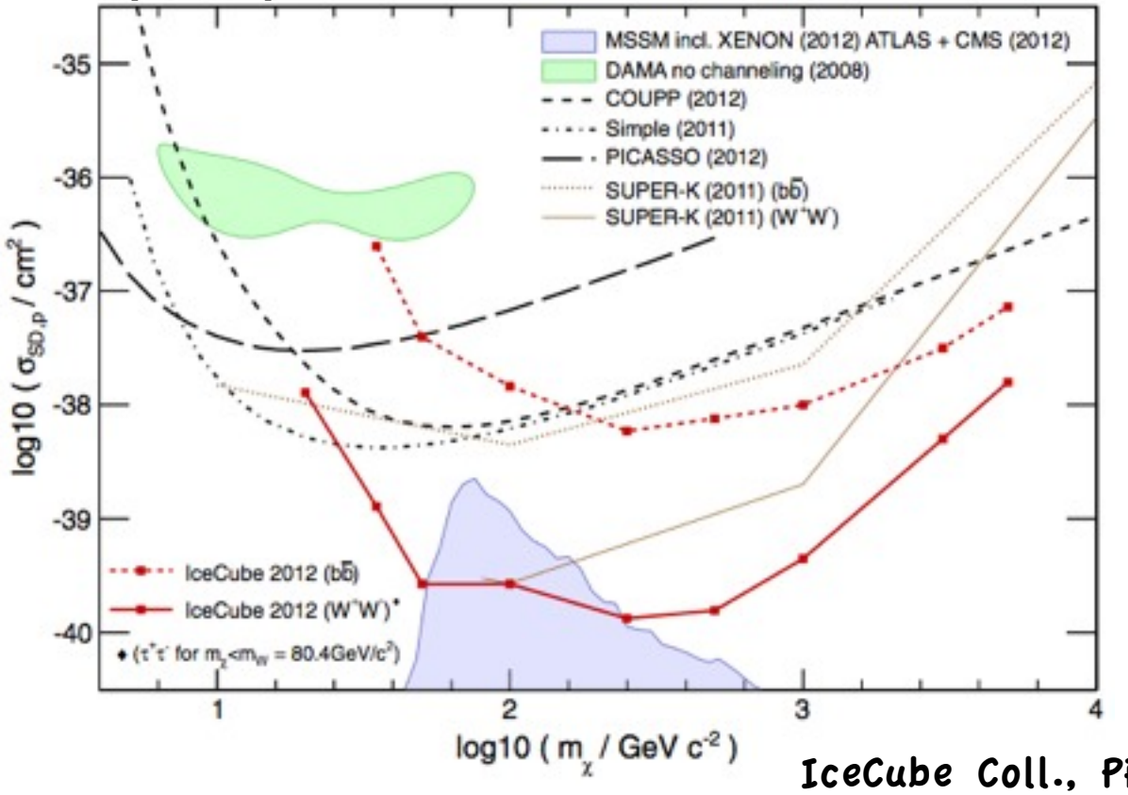




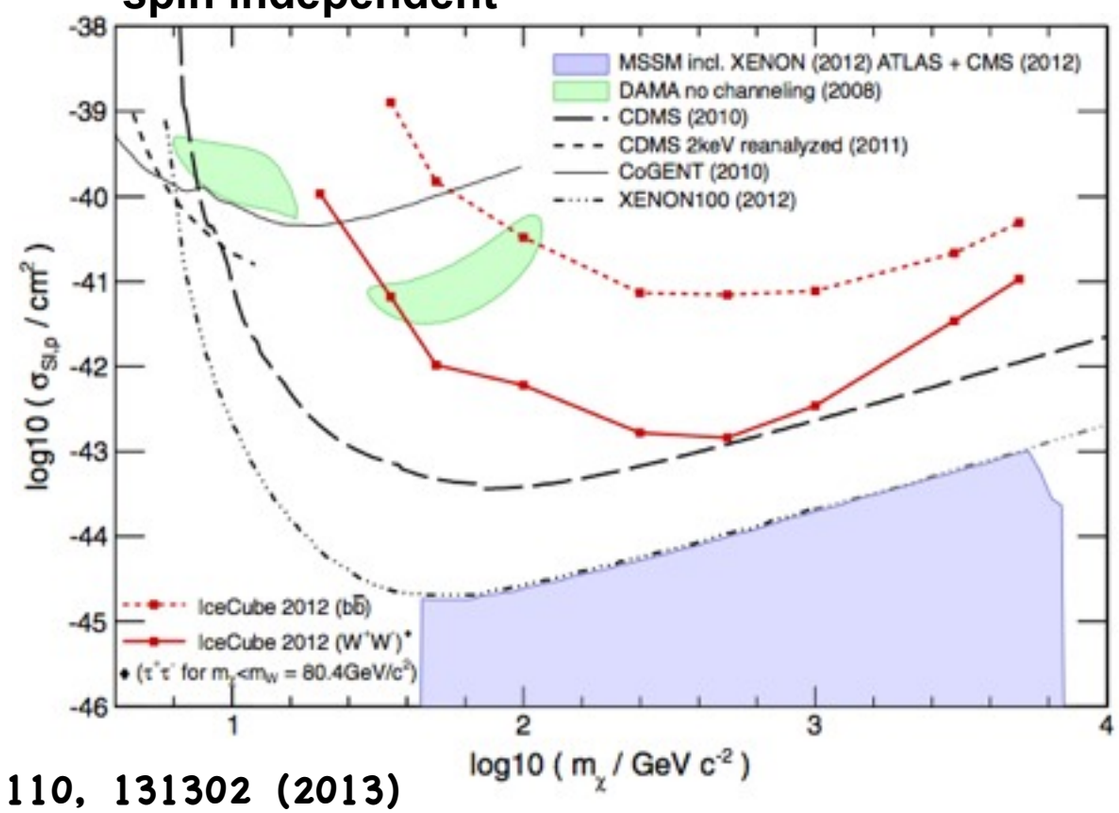
Search for Dark Matter accumulation in the Sun

- WIMPs (χ^0) captured by elastic scattering off nuclei in Sun
- Accumulation in center → annihilation to neutrinos
  (R parity conservation assumed)
- After some time: equilibrium between capture and annihilation
  → annihilation rate depends on WIMP scattering cross section
- Sun mainly protons → IceCube mostly sensitive to spin-dependent cross section

spin dependent



spin independent



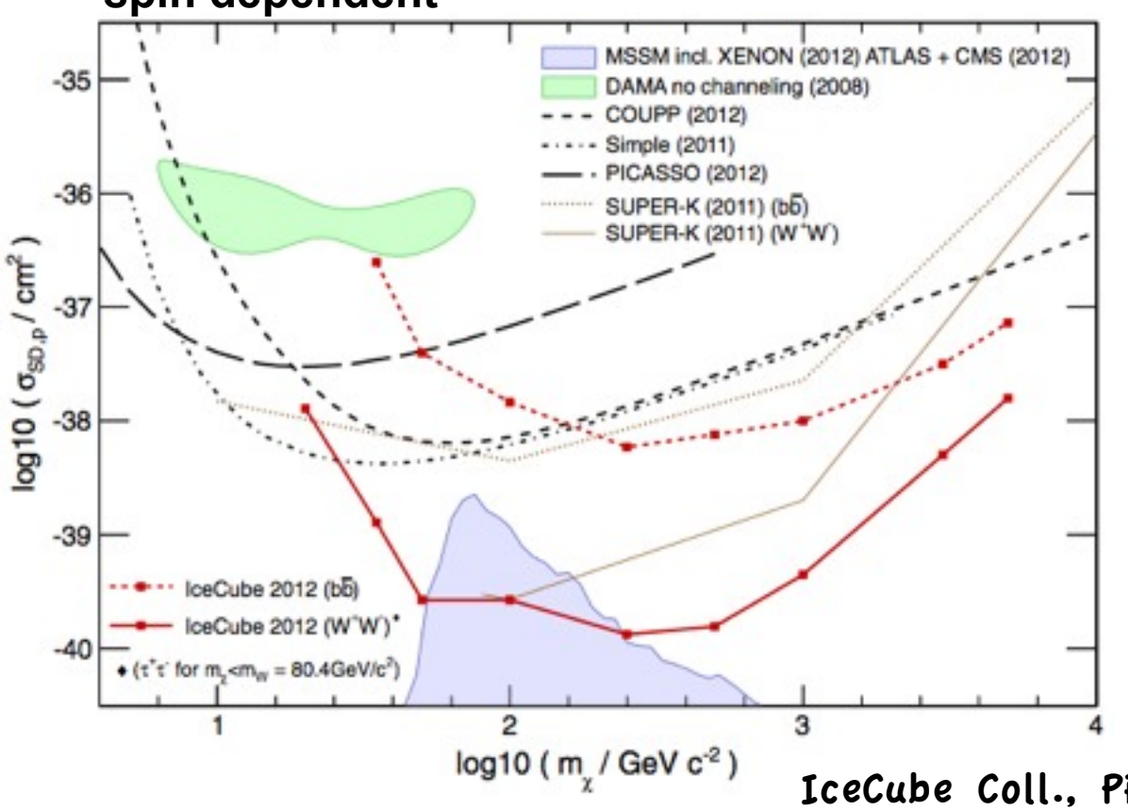
IceCube Coll., PRL 110, 131302 (2013)

Search for Dark Matter accumulation in the Sun

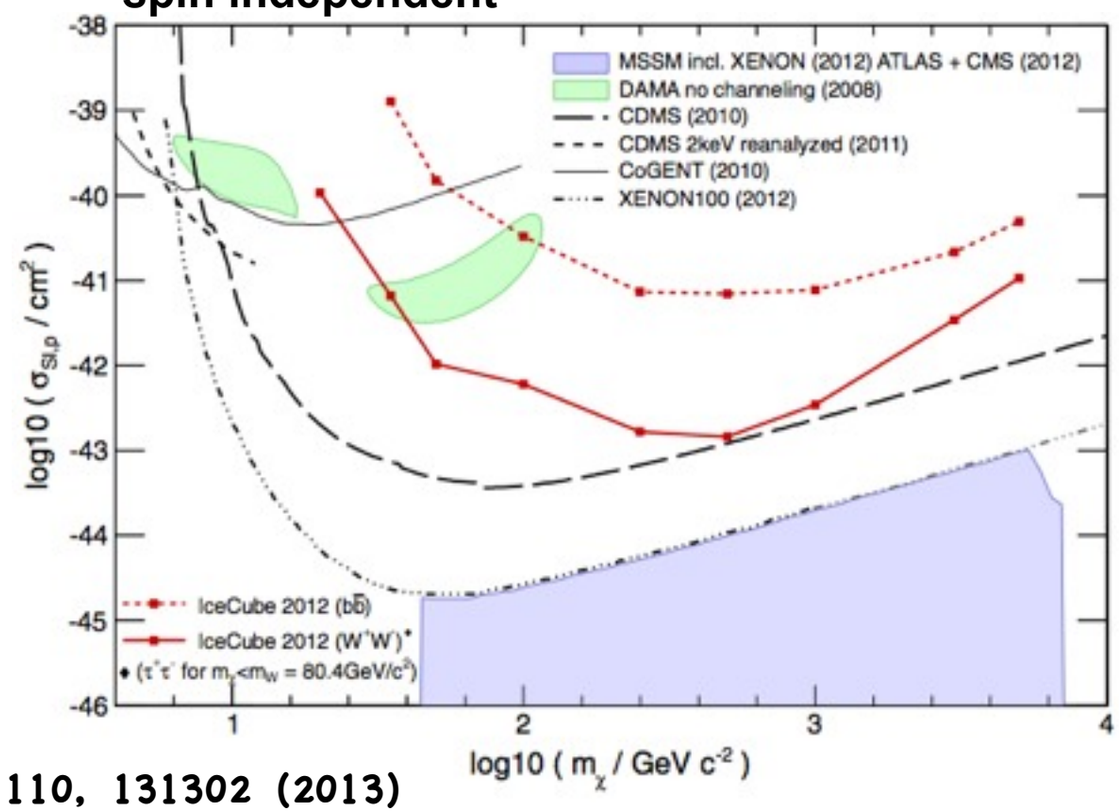
- WIMPs (χ^0) captured by elastic scattering off nuclei in Sun
- Accumulation in center → annihilation to neutrinos (R parity conservation assumed)
- After some time: equilibrium between capture and annihilation → annihilation rate depends on WIMP scattering cross section
- Sun mainly protons → IceCube mostly sensitive to spin-dependent cross section

Galactic Center search → parallel talk S. Flis

spin dependent



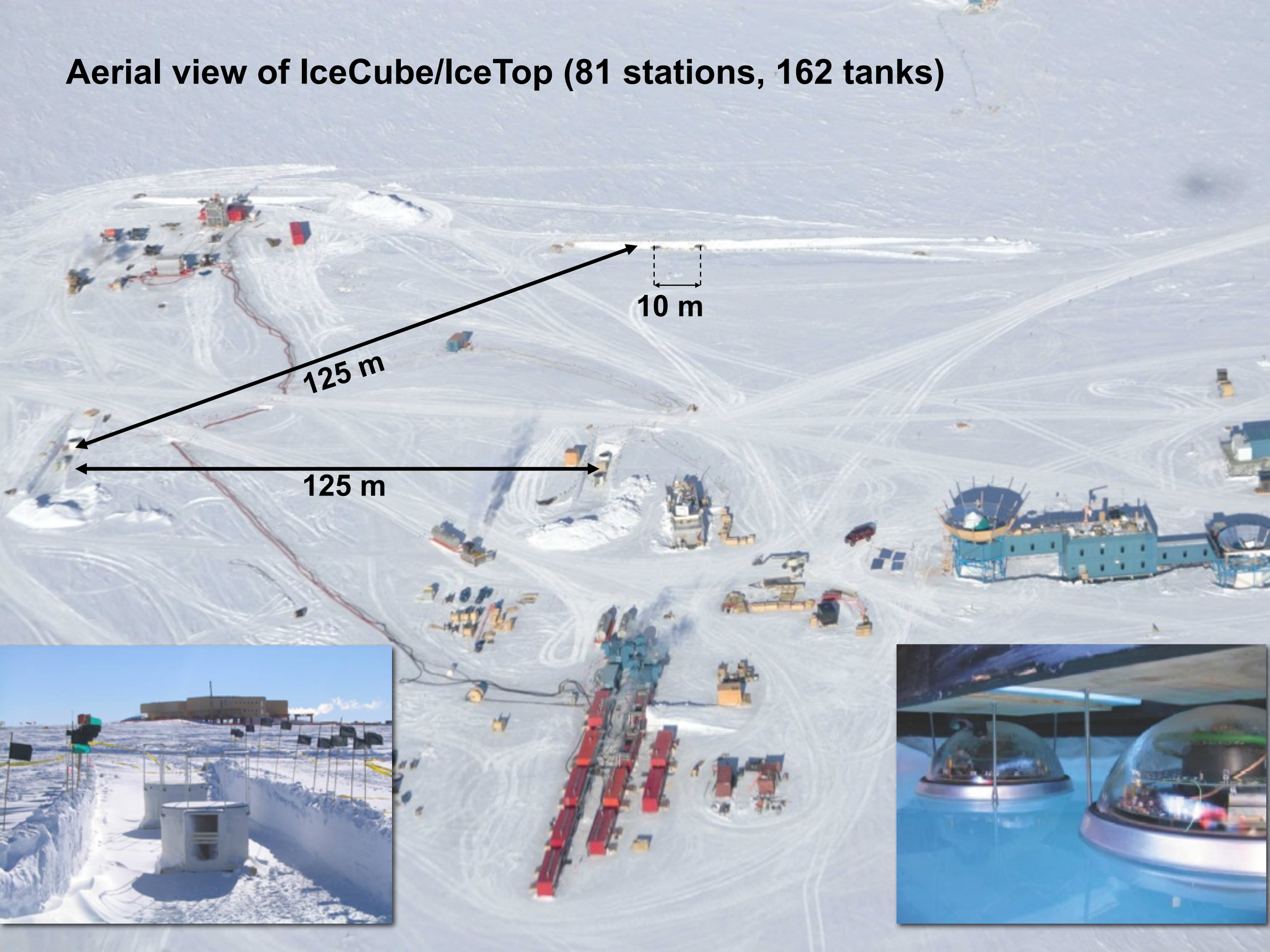
spin independent



IceCube Coll., PRL 110, 131302 (2013)

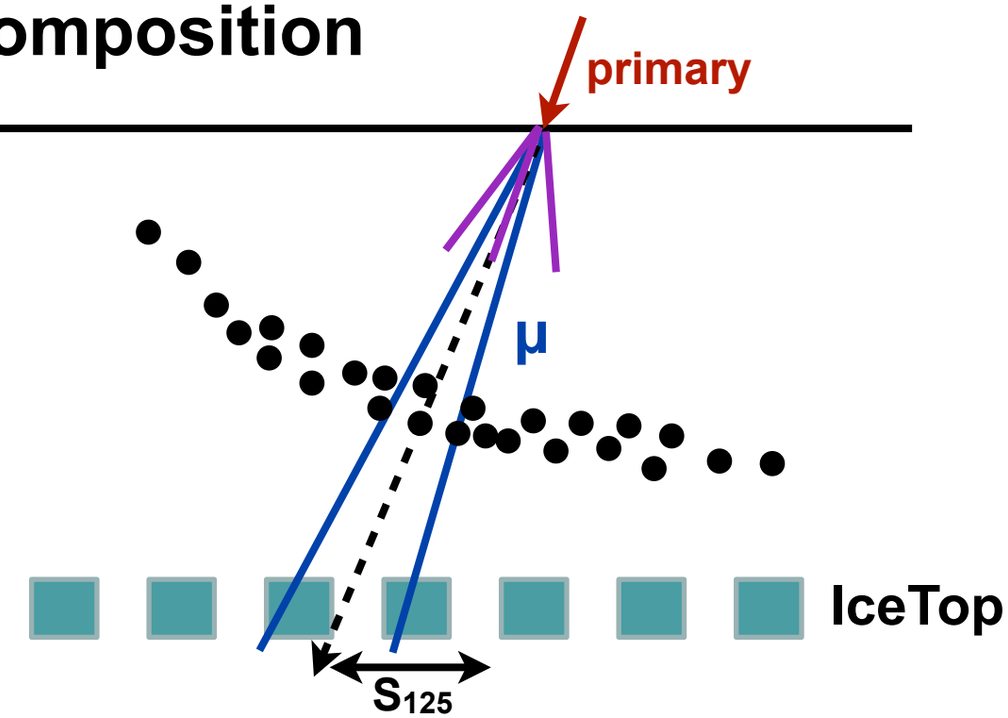
Cosmic-ray physics with IceCube & IceTop (selection)

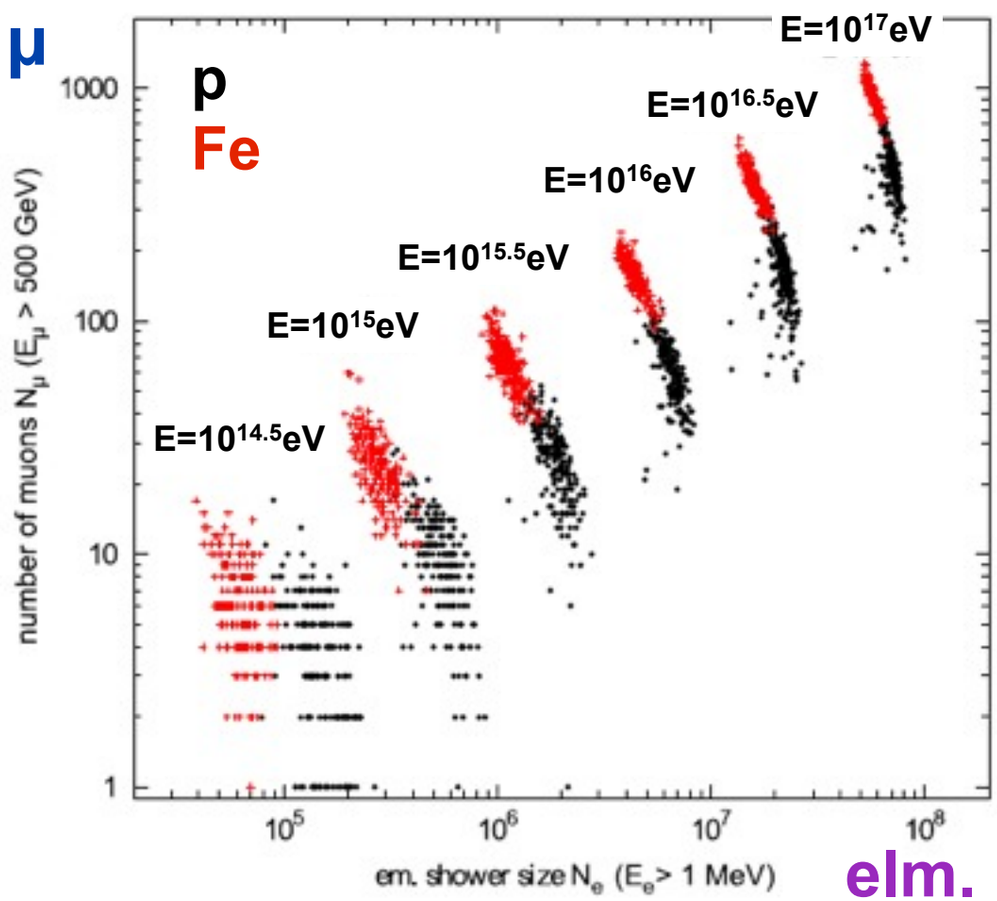
Aerial view of IceCube/IceTop (81 stations, 162 tanks)

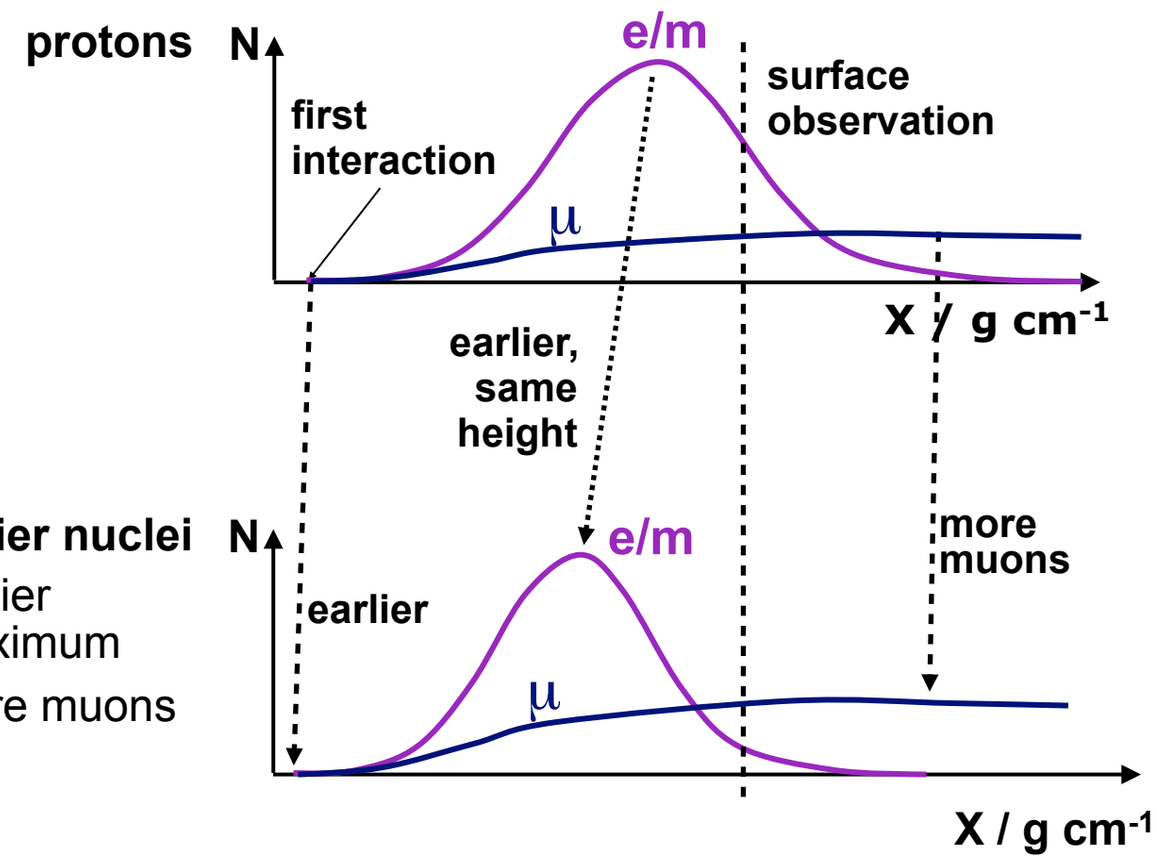


IceTop and cosmic rays - Spectrum and composition

- IceTop 2835 m above sea-level (692 g cm^{-2} atmosphere) → close to shower maximum
- Shower energy measured from signal 125 m from shower core (S_{125})
- Measured spectrum depends on assumed composition

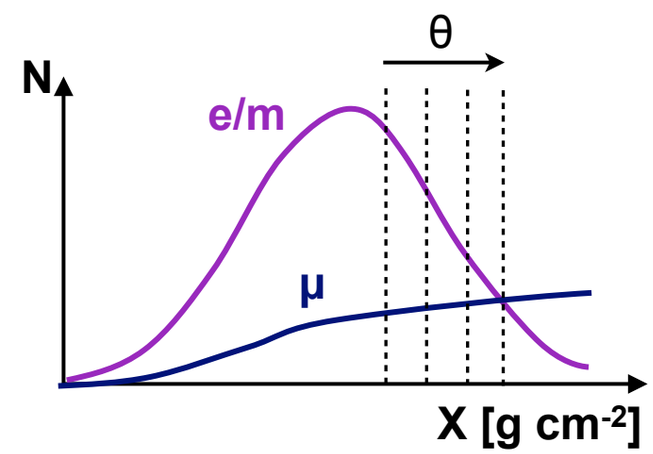




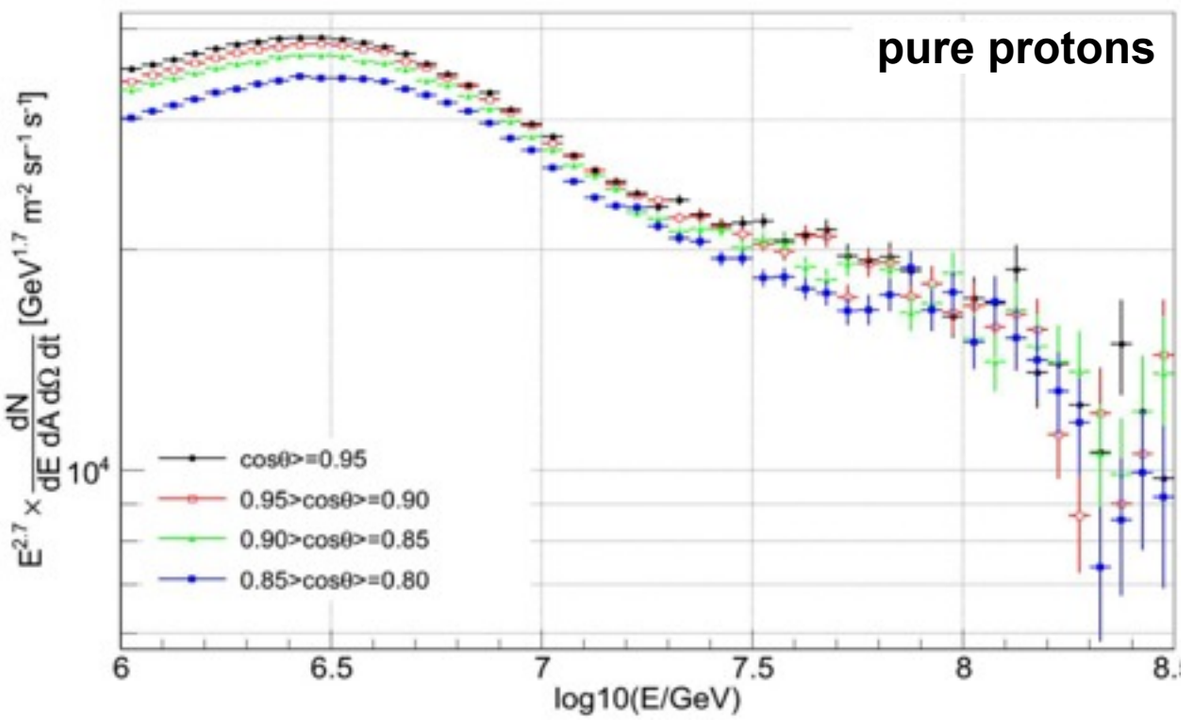


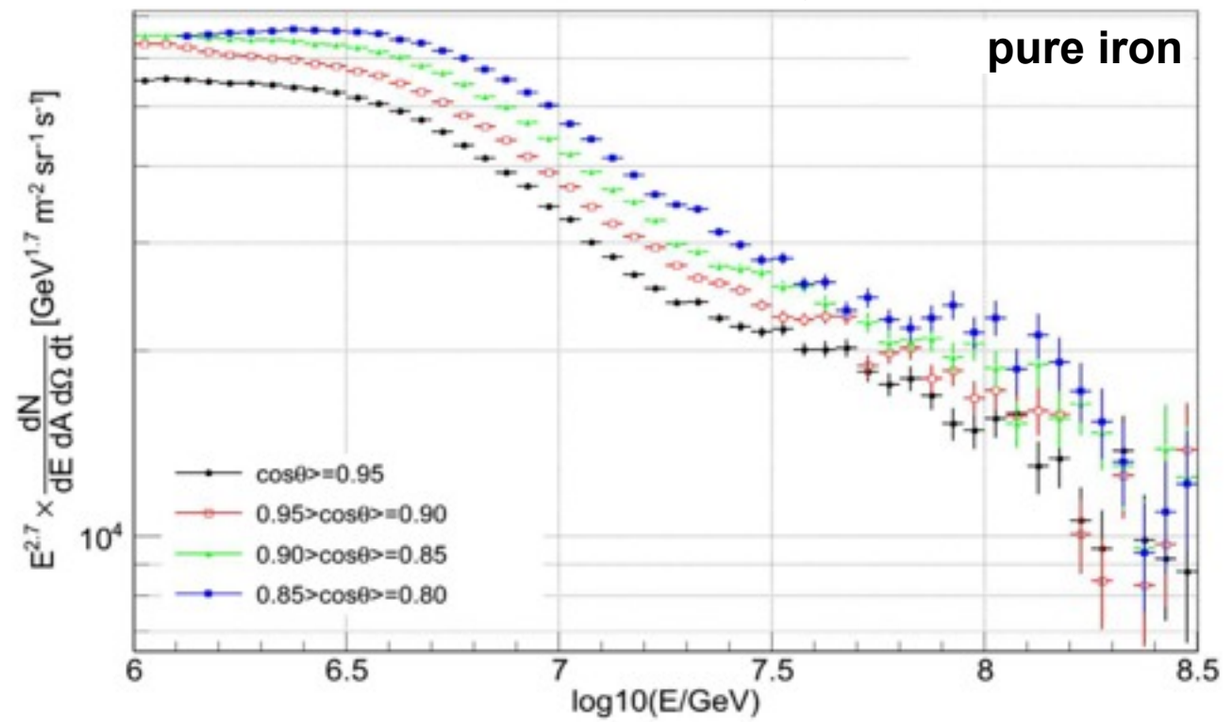
IceTop and cosmic rays - Spectrum and composition

- Atmosphere (slant) depth depends on zenith angle
  $X(\theta) = X(0) / \cos(\theta)$
- Flux not isotropic for pure proton or iron assumption
  → mixed composition needed
  → composition sensitivity with IceTop only



IceCube Coll., arXiv:1307.3795





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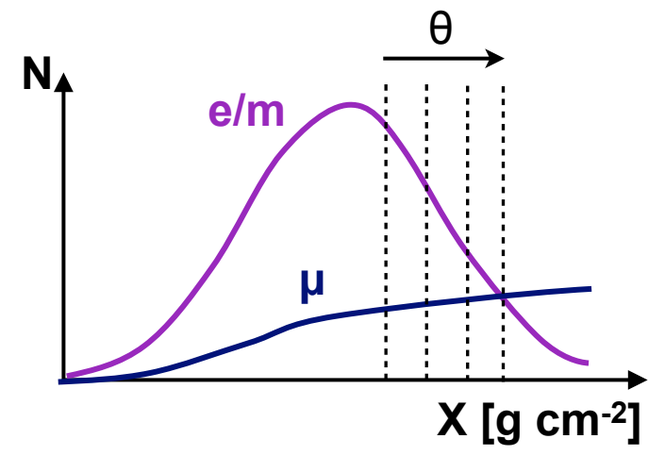
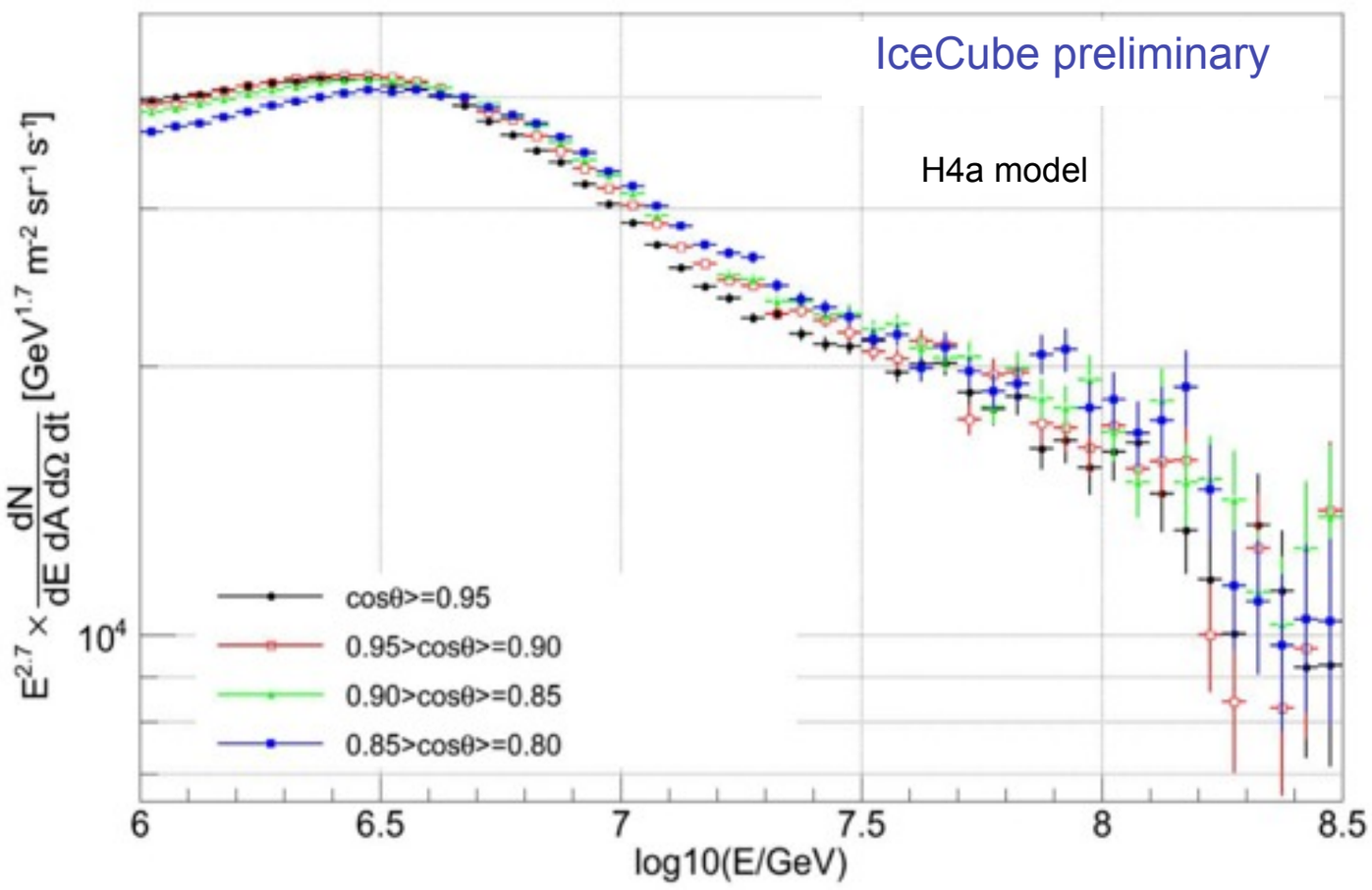
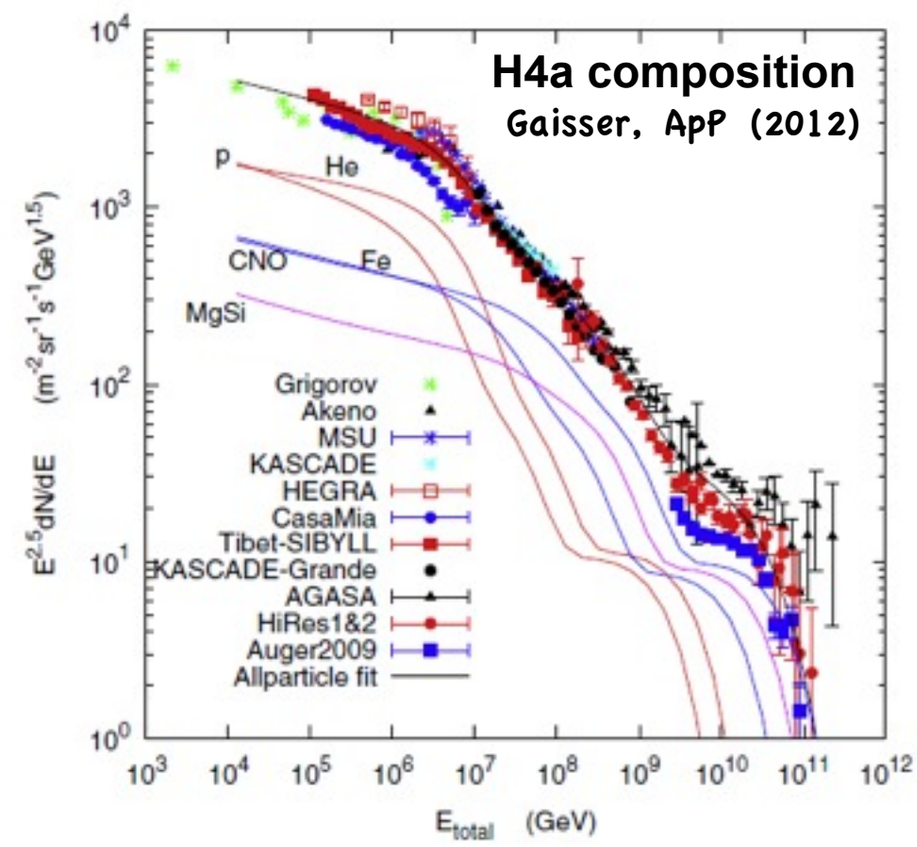
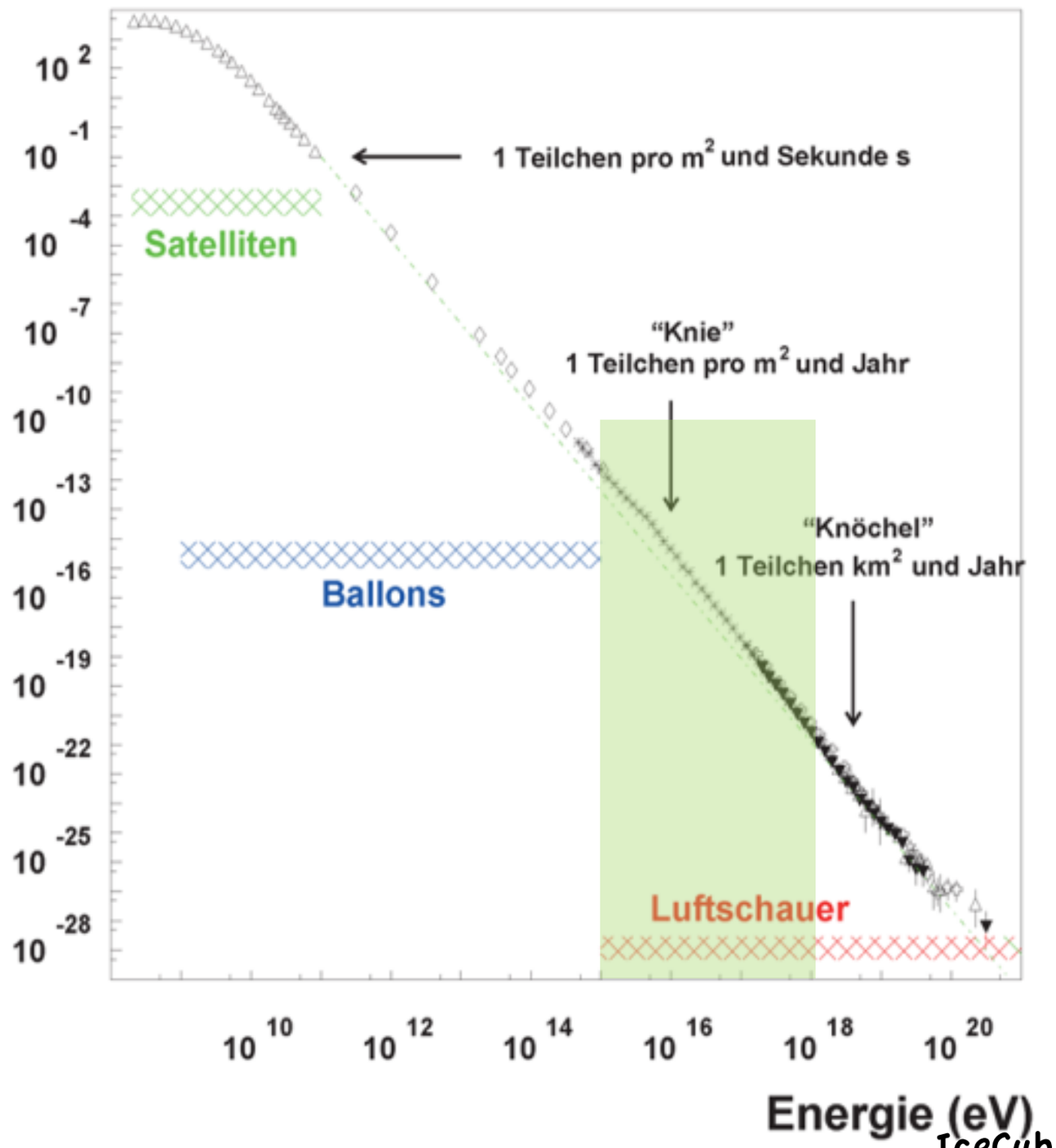






IceTop and cosmic rays - The fine-structure of the spectrum



IceCube Coll., arXiv:1307.3795

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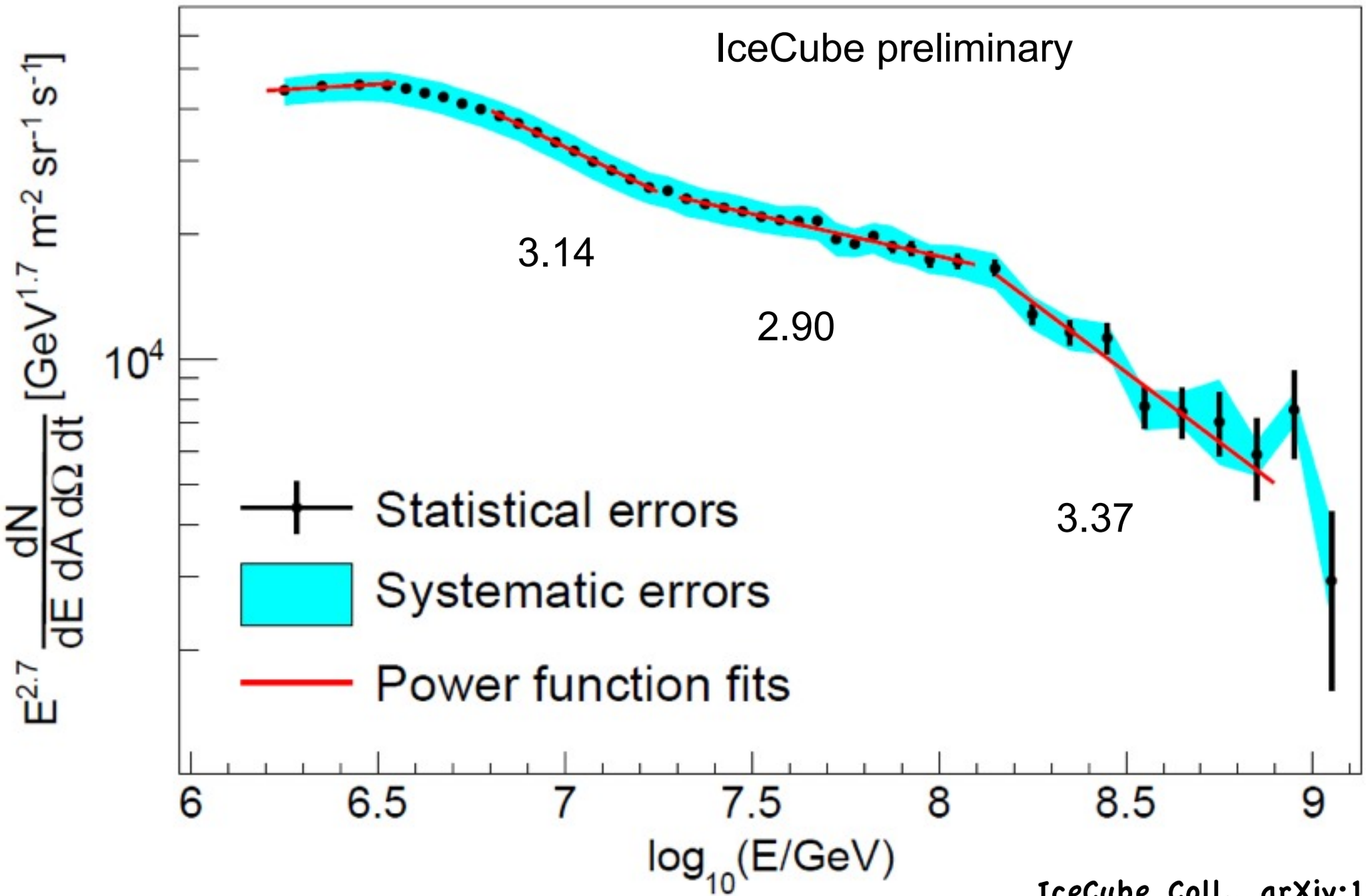

IceCube Coll., arXiv:1307.3795

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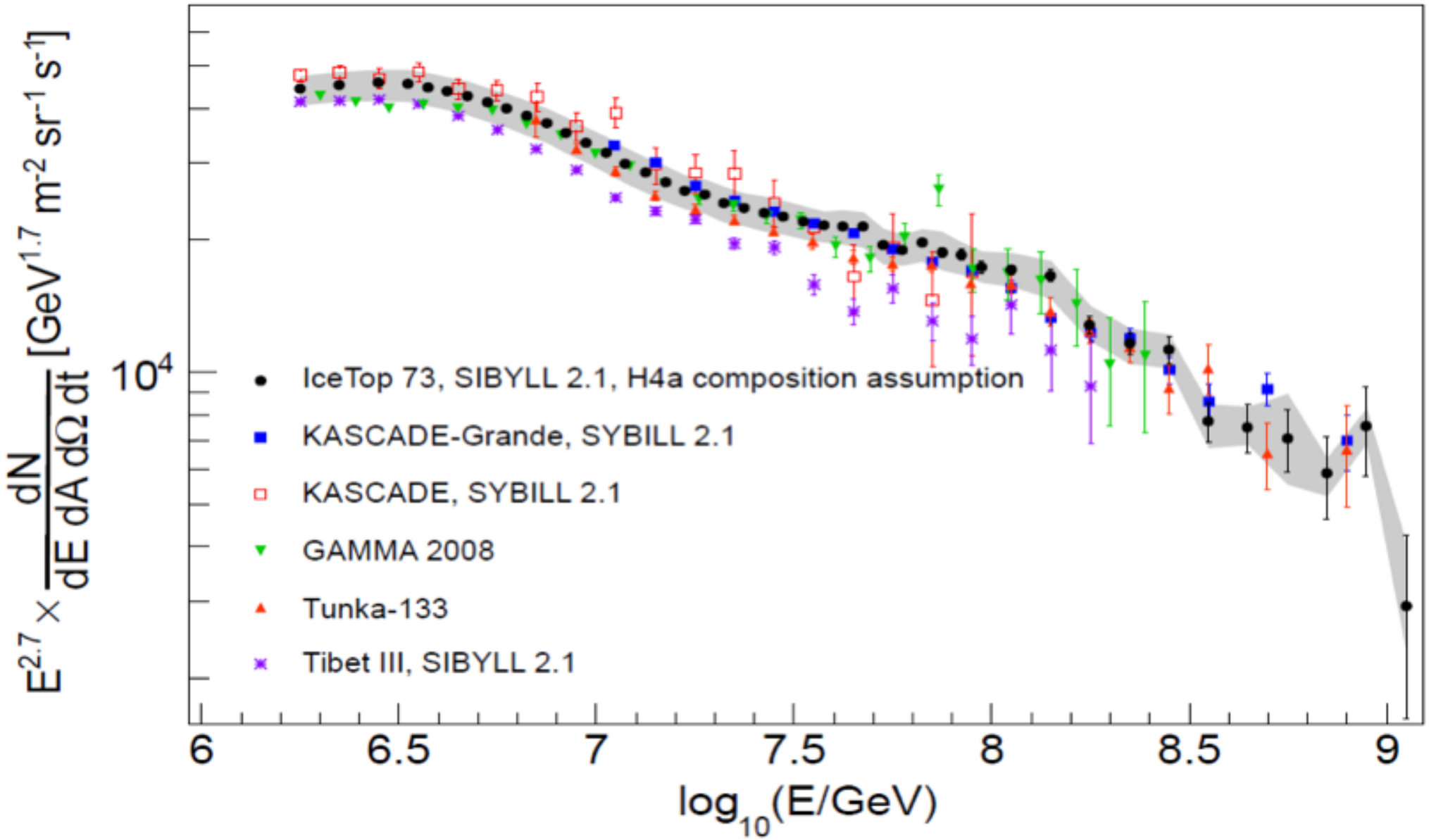
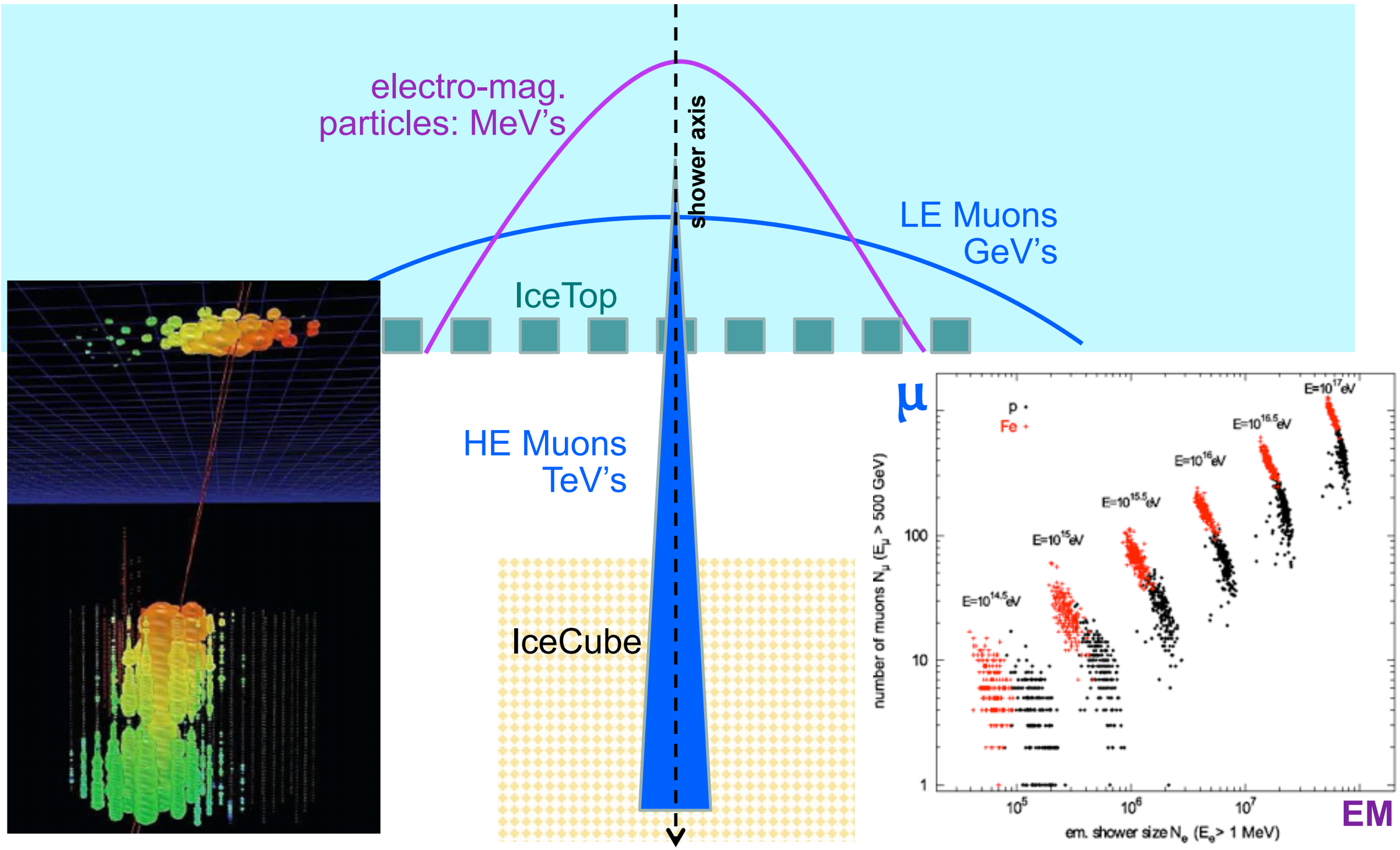
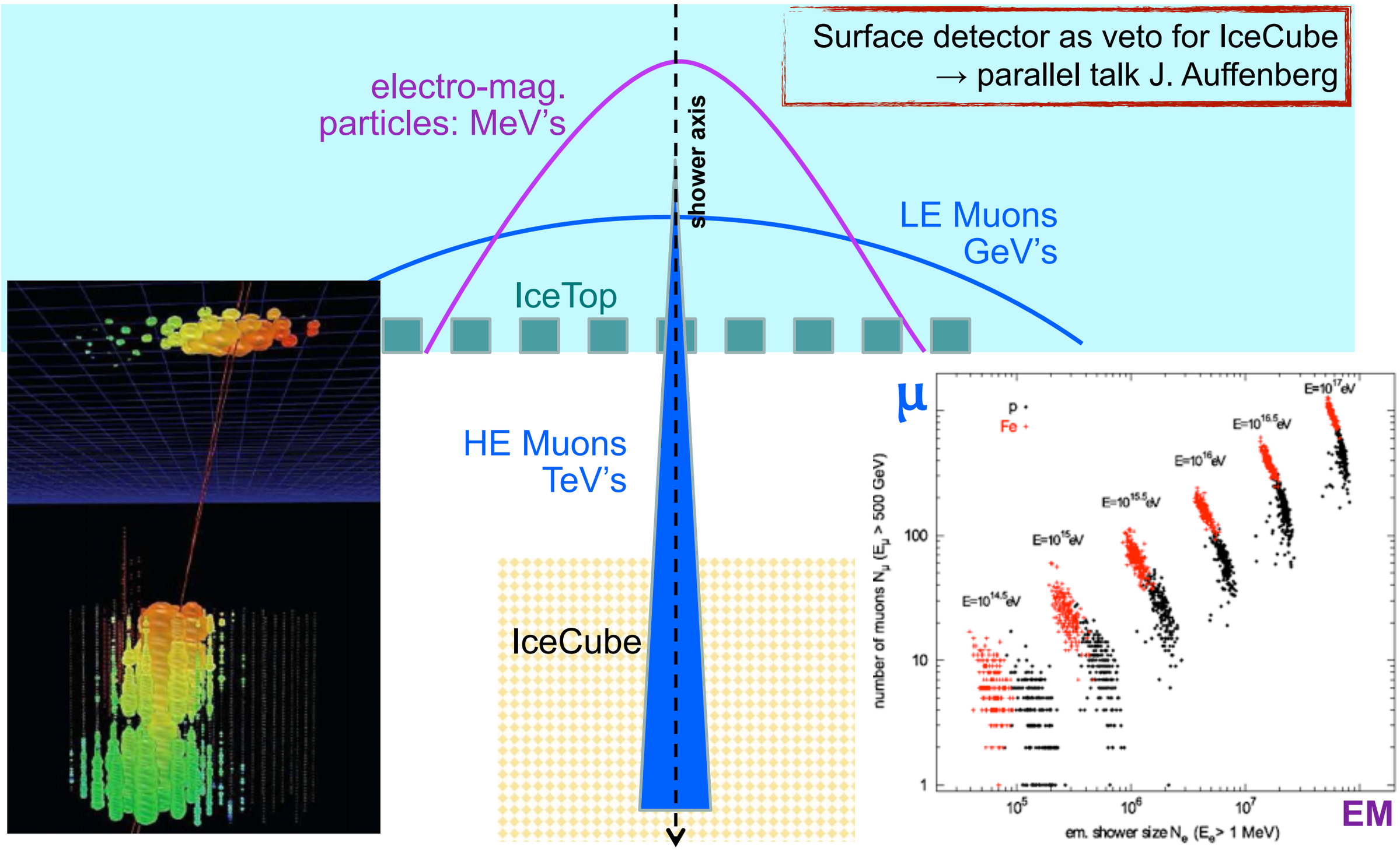


IceCube Coll., arXiv:1307.3795

Cosmic rays composition - Combing IceCube and IceTop

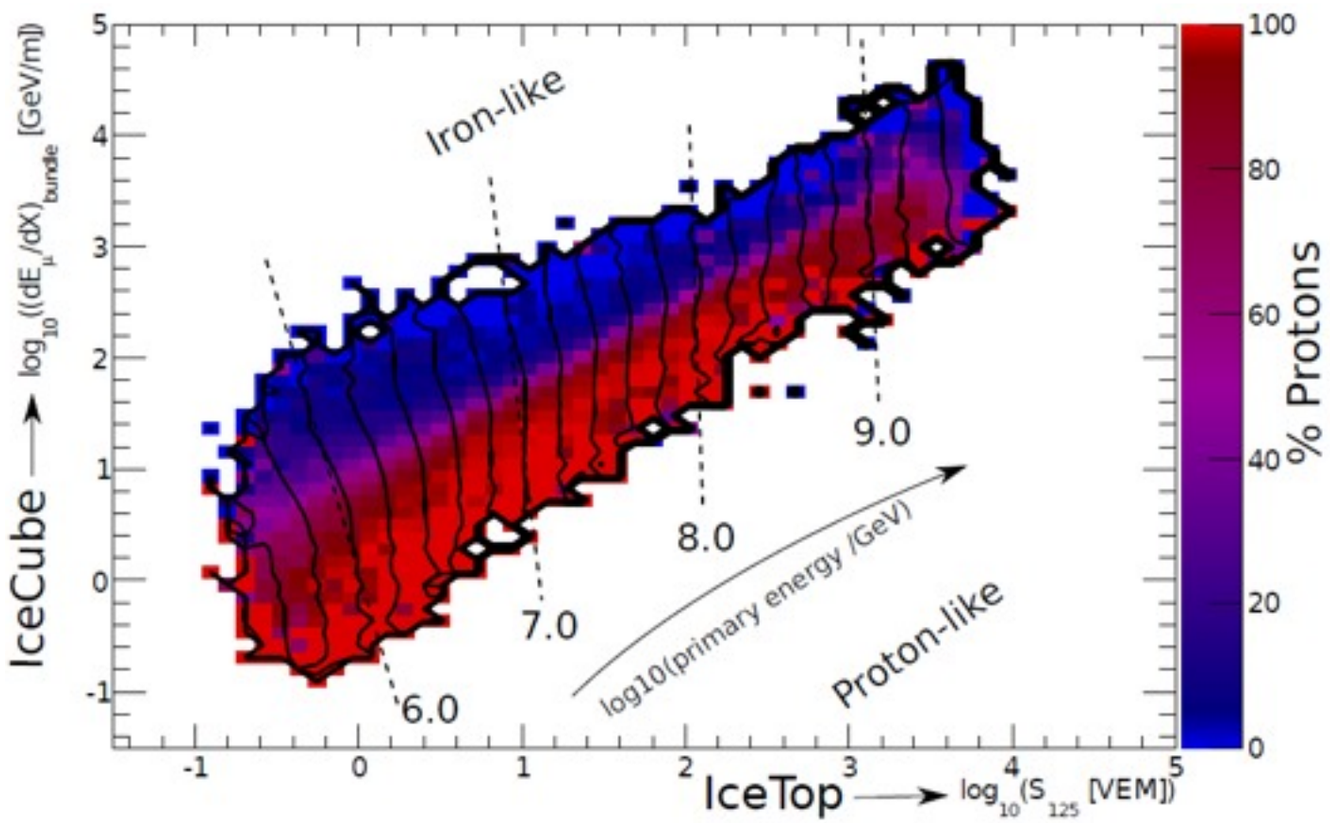


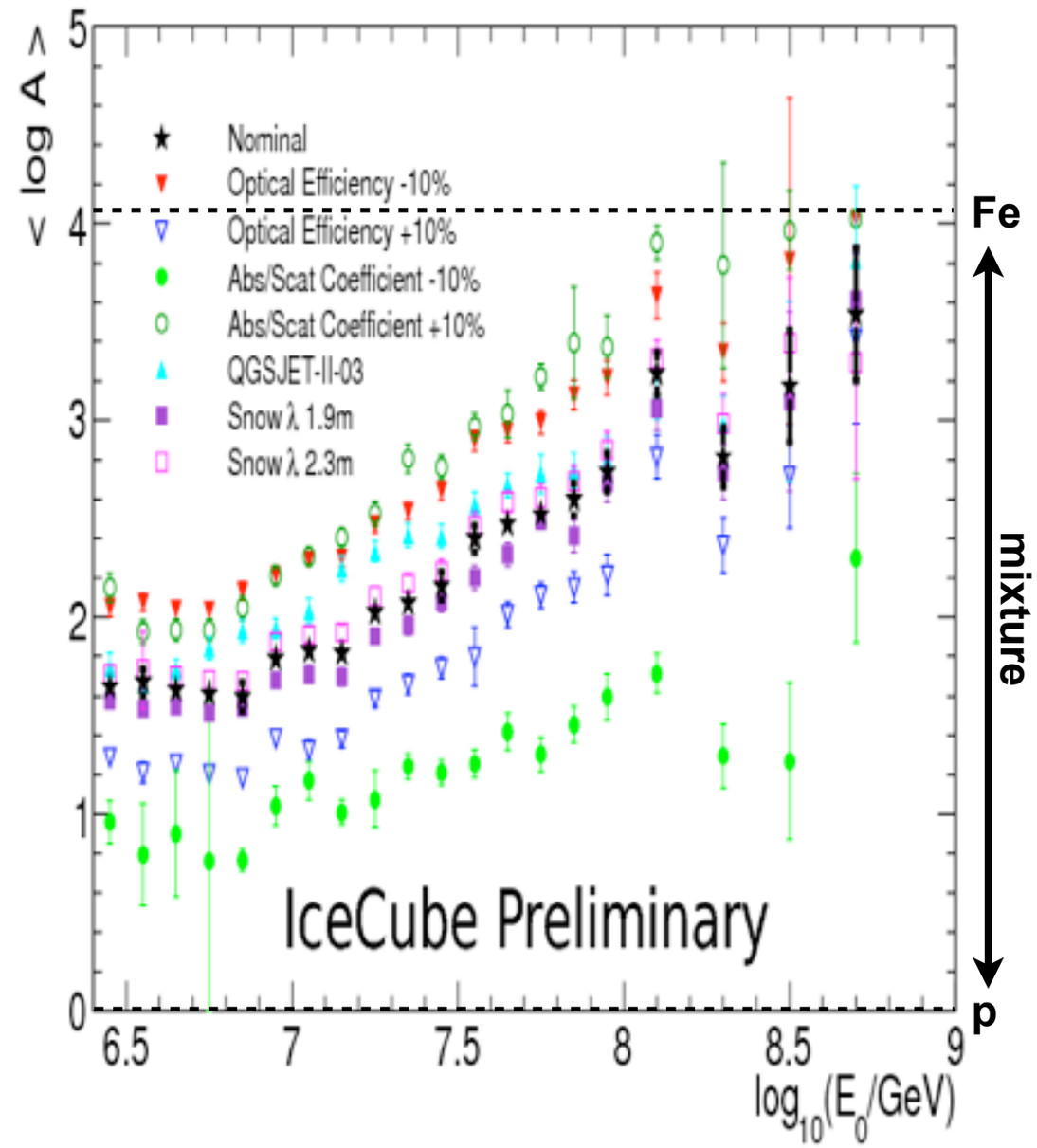
Cosmic rays composition - Combing IceCube and IceTop



Cosmic ray composition - Combing IceCube and IceTop

- Ratio of high-energy muons (IceCube, dE/dx) to air shower energy (IceTop, S_{125}) depends on composition (+ zenith angle)
- Observe increasing “heaviness” of composition with increasing energy





Summary

- The IceCube Observatory has proven to be a detector of high reliability and availability
- Up to now, about ~4 km^3 yr of accumulated high-quality data
- IceCube allows to cover a wide variety of physics topics both in astroparticle and particle physics (→ see talk T. DeYoung)
- IceCube has set several best limits on astrophysical neutrino fluxes (and probably more → see talk N. Whitehorn) with growing impact on astrophysics
- IceTop (+IceCube) develops into a very powerful tool to investigate the cosmic ray-spectrum and its composition around the knee

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