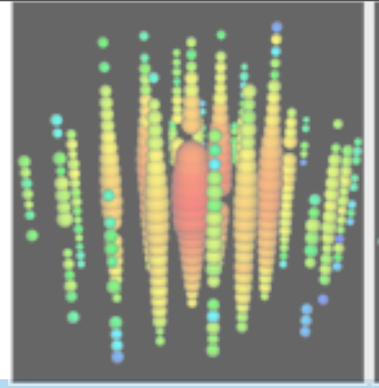
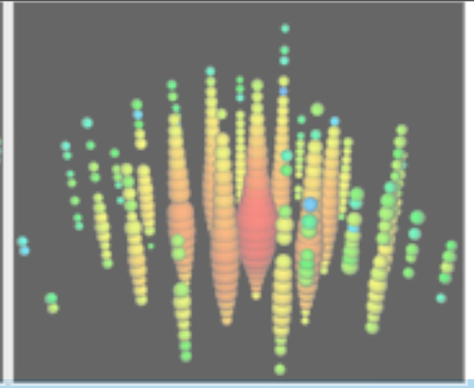
WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER





ALMA MATER STUDIORUM UNIVERSITÀ DI BOLOGNA A.D. 1088

L'Osservatorio IceCube al Polo Sud

tra astrofisica di neutrini e fisica delle particelle

Paolo Desiati

desiati@wipac.wisc.edu

Wisconsin IceCube Particle Astrophysics Center
Department of Astronomy

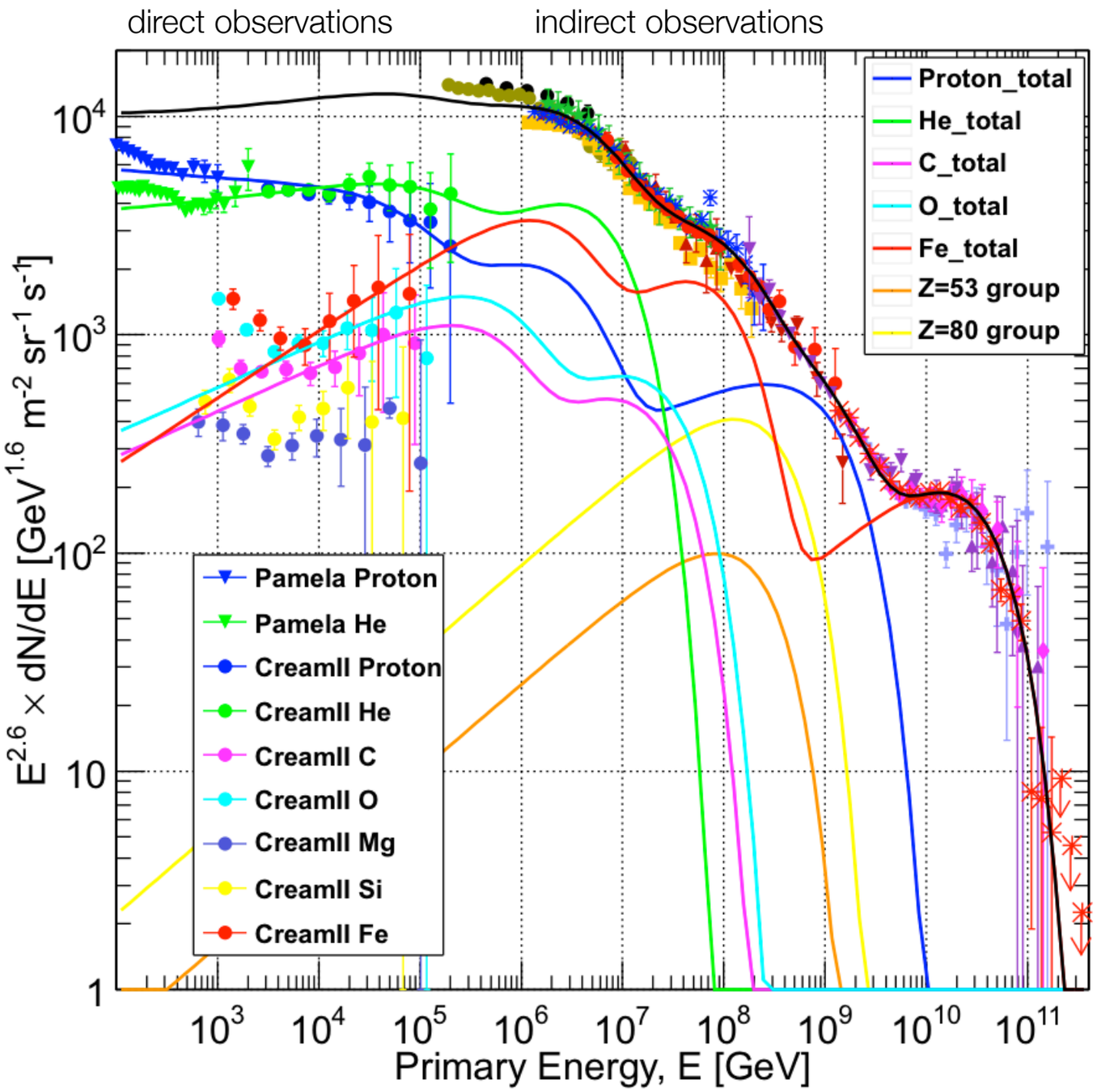
University of Wisconsin - Madison

Università degli Studi di Bologna
11 Novembre 2013

cosmic rays
spectrum

- cosmic rays produced in the **Galaxy** below 10^8-10^9 GeV
- **spectral features** from acceleration mechanisms & propagation effects
- **source distribution** in Galaxy and our neighborhood
- **magnetic field** configurations in local interstellar medium
- **anisotropy**

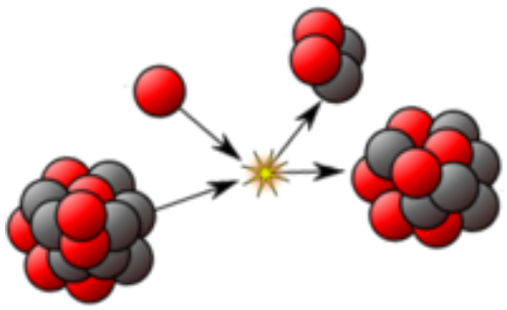
Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565



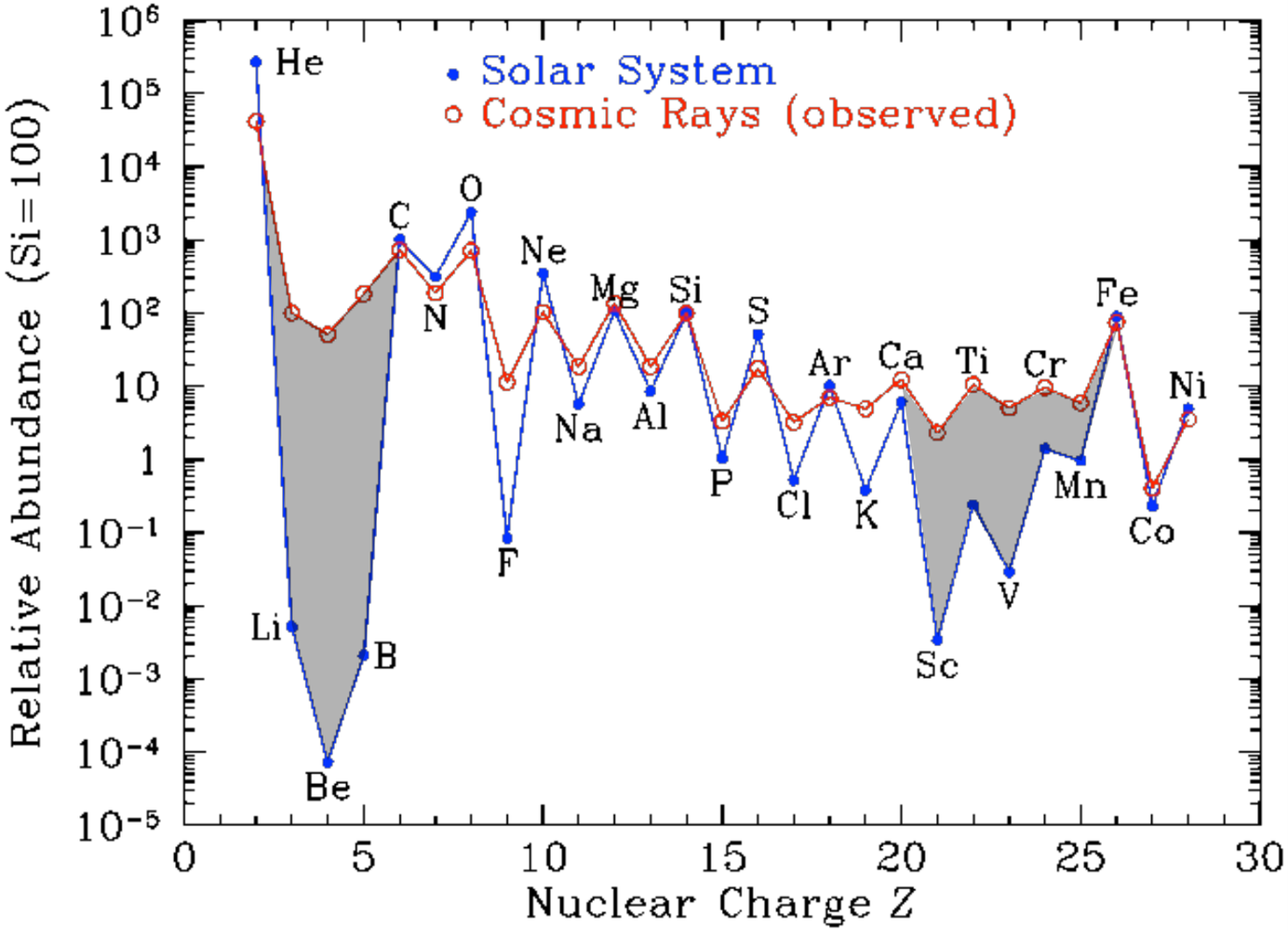
cosmic rays mass
direct observations

- cosmic rays **mass** composition **not very different** from our solar neighborhood

- differences from **nuclear fragmentation** in collisions with interstellar medium



- **isotopic composition** provides hints on origin and propagation of cosmic rays



- at high energy changes in mass composition from rigidity-escape **escape** from the Galaxy

cosmic rays spectrum
direct observations

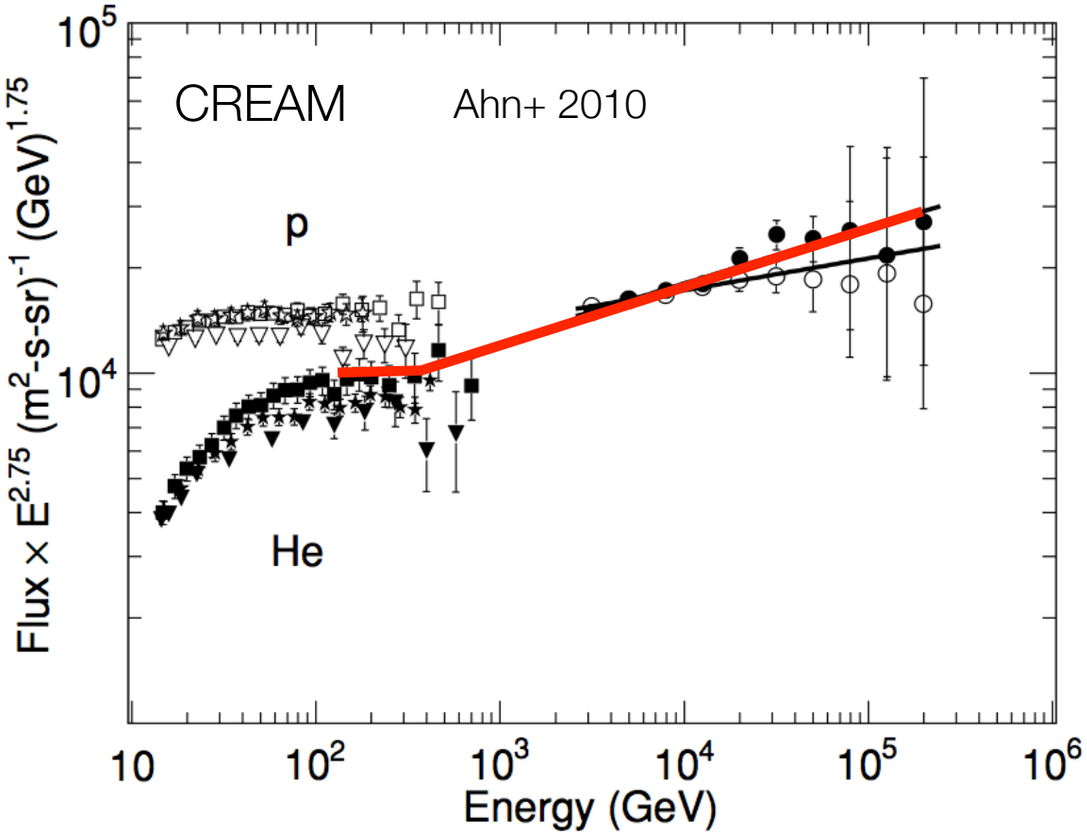
- energy spectrum has **fine** structures

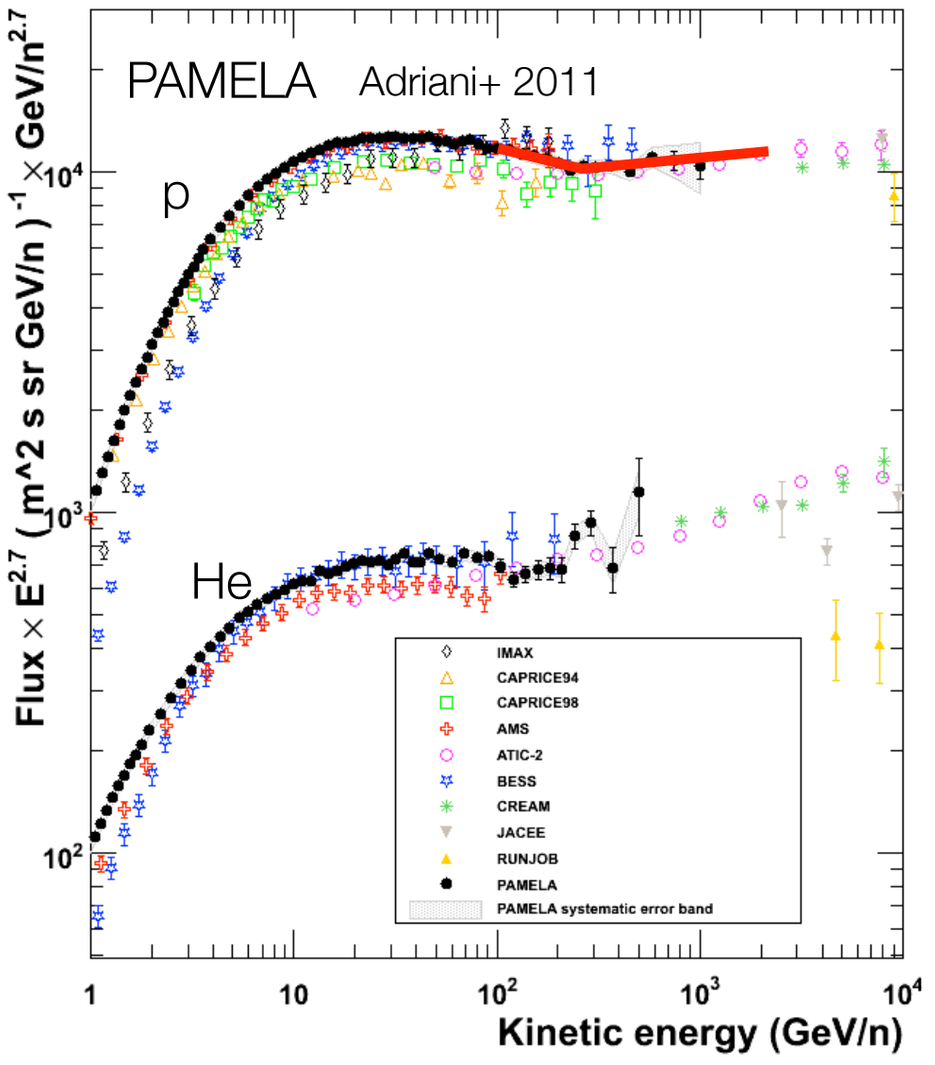
- **broken** power law or spectral **concavity**

CREAM, ATIC, Bess-Polar
TRACER, TIGER

PAMELA, Fermi,
Gamma-400,...

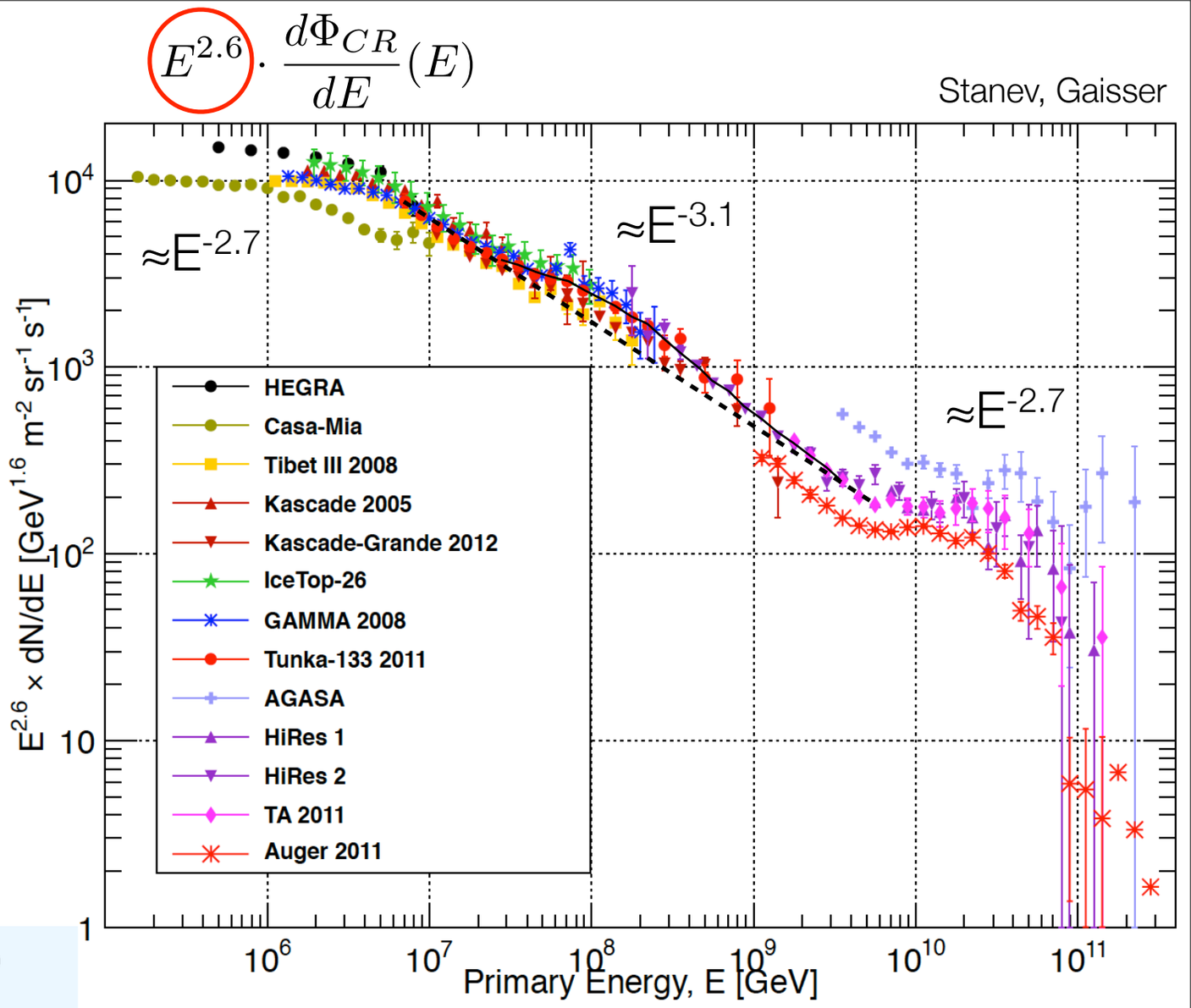
AMS2, Calet,
ISS-CREAM, ...

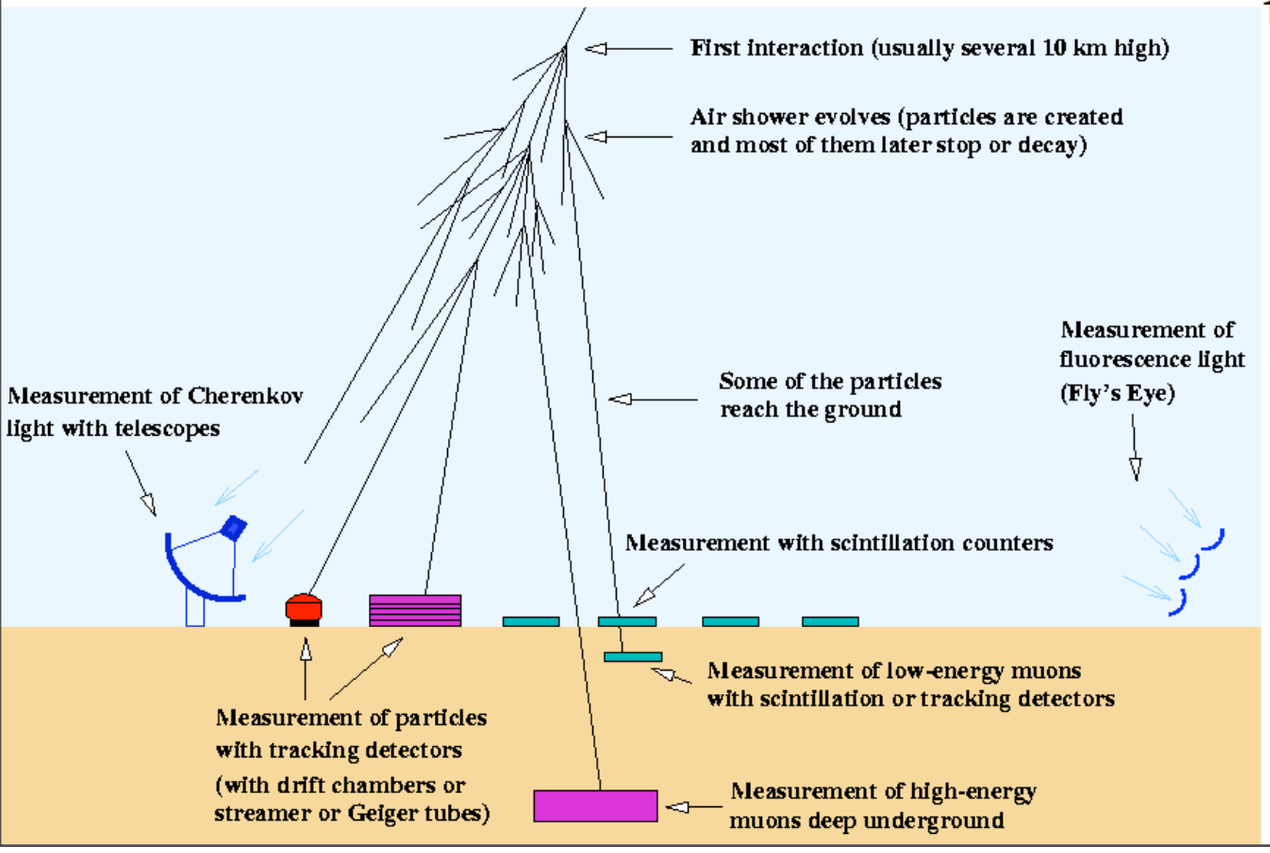




cosmic rays spectrum
indirect observations

- at **high energy** flux too small for direct observations
- ground-based, under-ground / water / ice detection





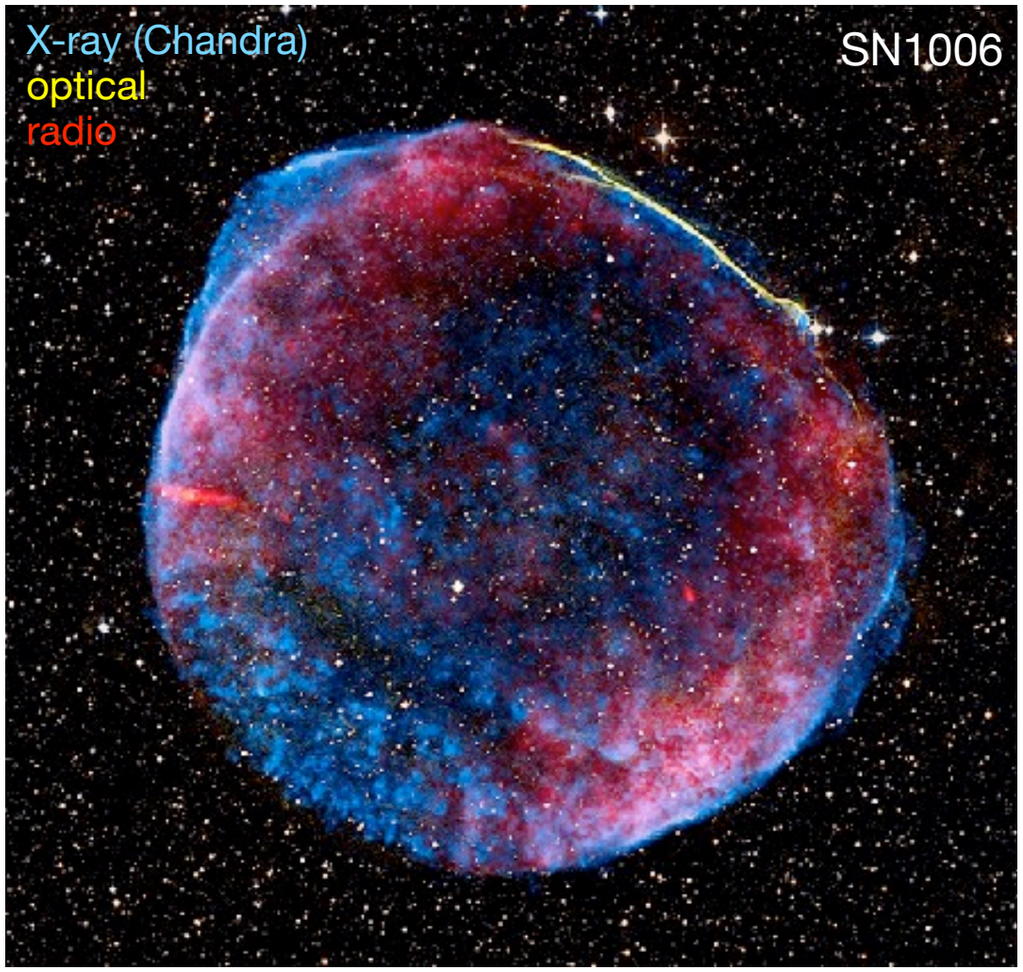
- **atmosphere** & **interaction properties**
- energy & mass observations tangled
- lower mass resolution

possible origin of
cosmic ray particles

- cosmic rays of **similar** composition of local interstellar medium

- **confined** in the Milky way for ~10 Myr ($^{10}Be/^{9}Be$ observation at low energy)

- **isotopic composition** ($^{22}Ne/^{20}Ne$) to provide a hint on the origin of a substantial fraction of low energy cosmic rays



- OB associations within superbubbles

possible origin of
cosmic ray energy

- **energy** needed to maintain galactic cosmic ray population

$$E_{GCR} \approx 10^{41}\, erg\, s^{-1} = 10^{34}\, W$$

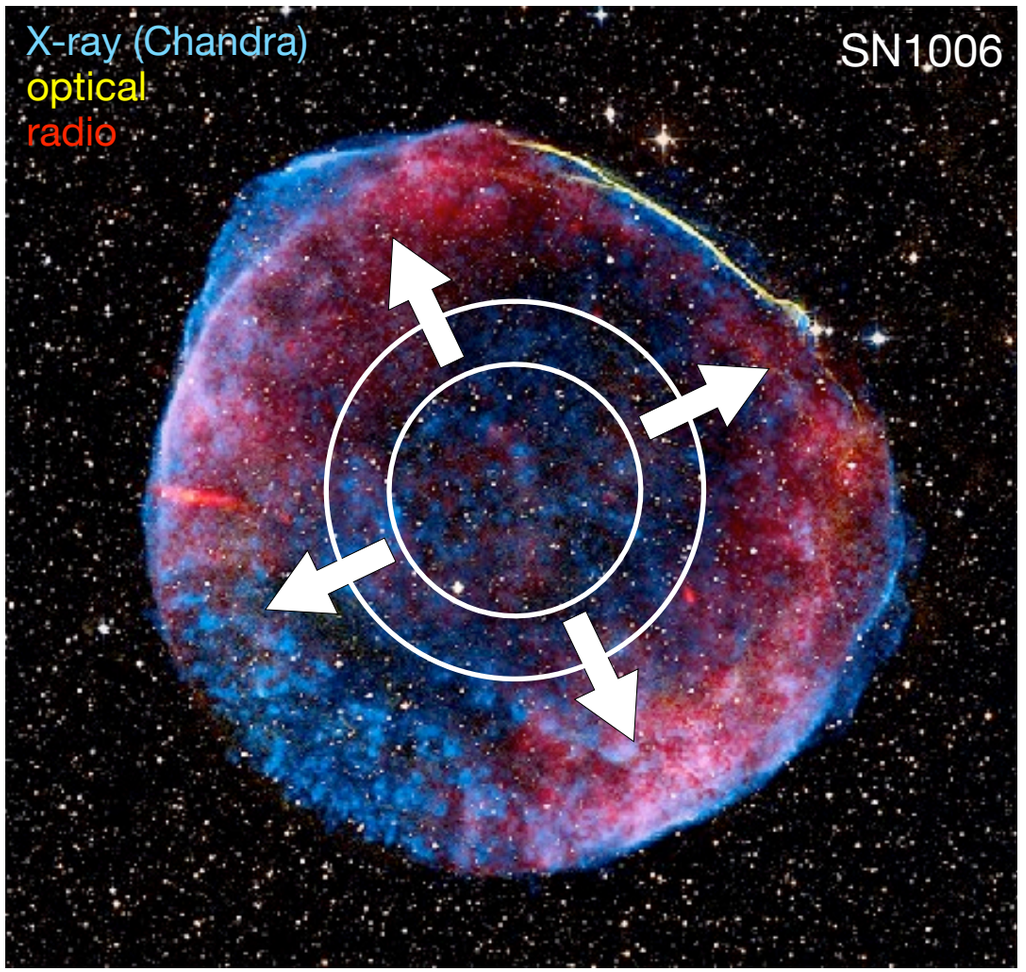
- energy released by **supernovae** that goes into particle acceleration

$$E_{SN} \approx \frac{10^{44}\, J}{30\, yr} \times 10\% \approx 10^{34}\, W$$

released mechanical energy

galactic supernova rate

energy into acceleration



- E_{max} associated to the knee of cosmic rays at ~ 3 PeV

cosmic ray acceleration
in supernova remnants

Remarks on Super-Novae and Cosmic Rays

We have recently called attention to a remarkable type of giant novae.[1] As the subject of super-novae is probably very unfamiliar we give here a few more details which are not contained in our original articles.

1. Distribution of super-novae

In our calculations we made use of the assumption that on the average one super-nova appears in each galaxy every thousand years. This estimate is based on the occurrence of super-novae in the following galaxies,

Our own galaxy	in 1572
Andromeda	1885
Messier 101	1907

These three systems are located within a sphere of radius

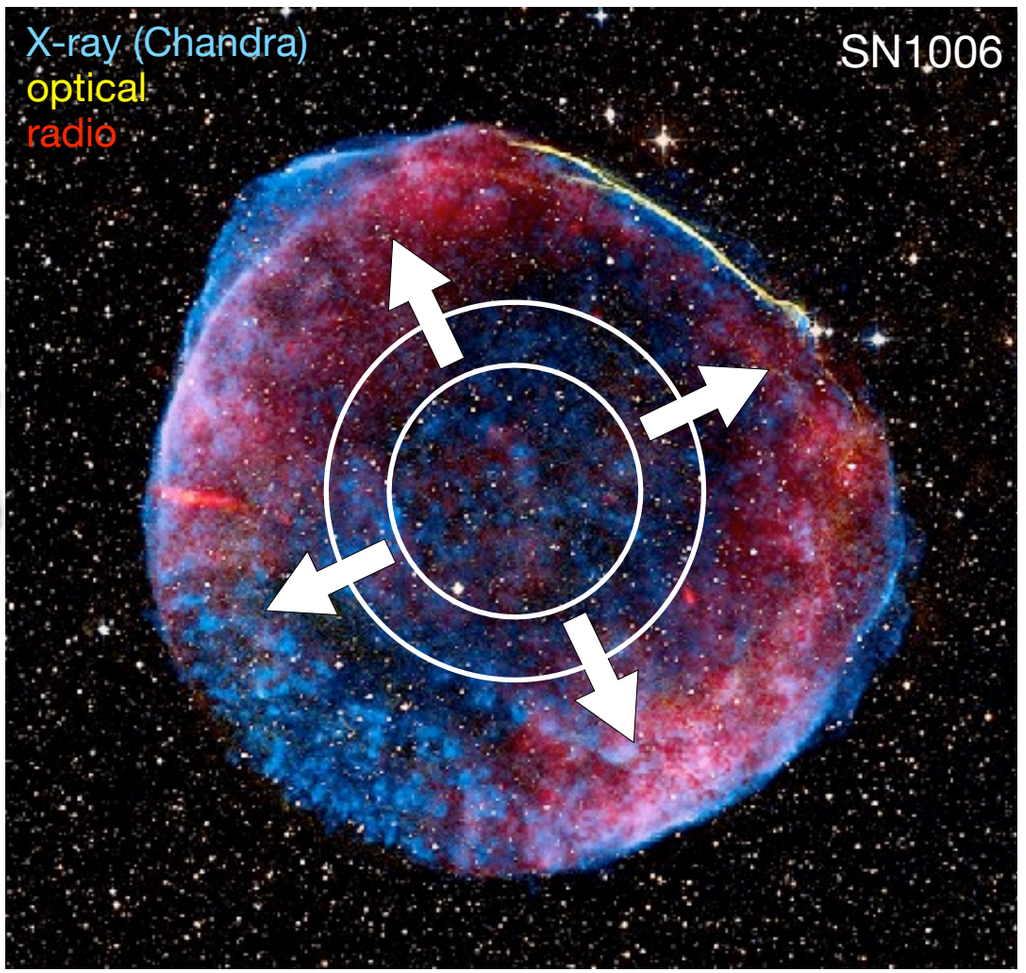
We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has been organized only recently.

From the estimate of one super-nova per galaxy per thousand years it follows that 10^7 super-novae appear per year in the 10^{10} nebulae which are contained in a sphere of 2×10^9 years radius (critical distance derived from the red shift of nebulae). If cosmic rays come from super-novae their intensity in points far away from any individual super-nova will be essentially independent of time.

2. Comparison with the lifetime of stars

The lifetime of stars is supposed to be of the order of at least 10^{12} years. A nebula contains about 10^9 stars. These estimates, combined with the frequency of occurrence of one super-nova per galaxy suggest that the

Baade & Zwicky 1934



PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

I. INTRODUCTION

IN recent discussions on the origin of the cosmic radiation E. Teller[1] has advocated the view that cosmic rays are of solar origin and are kept

where H is the intensity of the magnetic field and ρ is the density of the interstellar matter.

One finds according to the present theory that a particle that is projected into the interstellar

Fermi 1949

- diffusive shock acceleration in galactic **supernova remnants**

cosmic rays
reconstruct their history

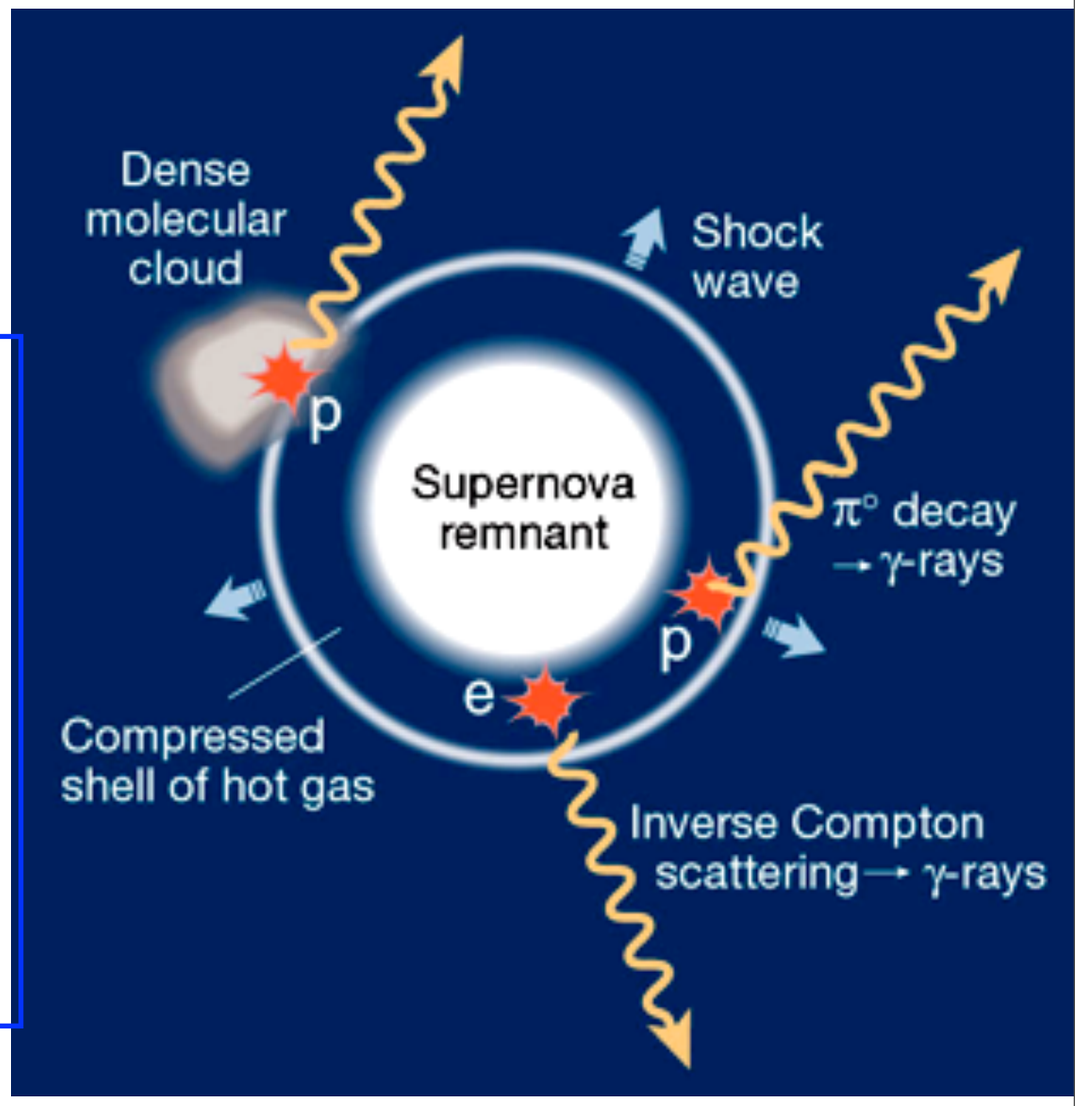
$$p + N \rightarrow p(n) + \pi^+ + \pi^- + \pi^0$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^0 \rightarrow \gamma + \gamma$$

hadronic emission



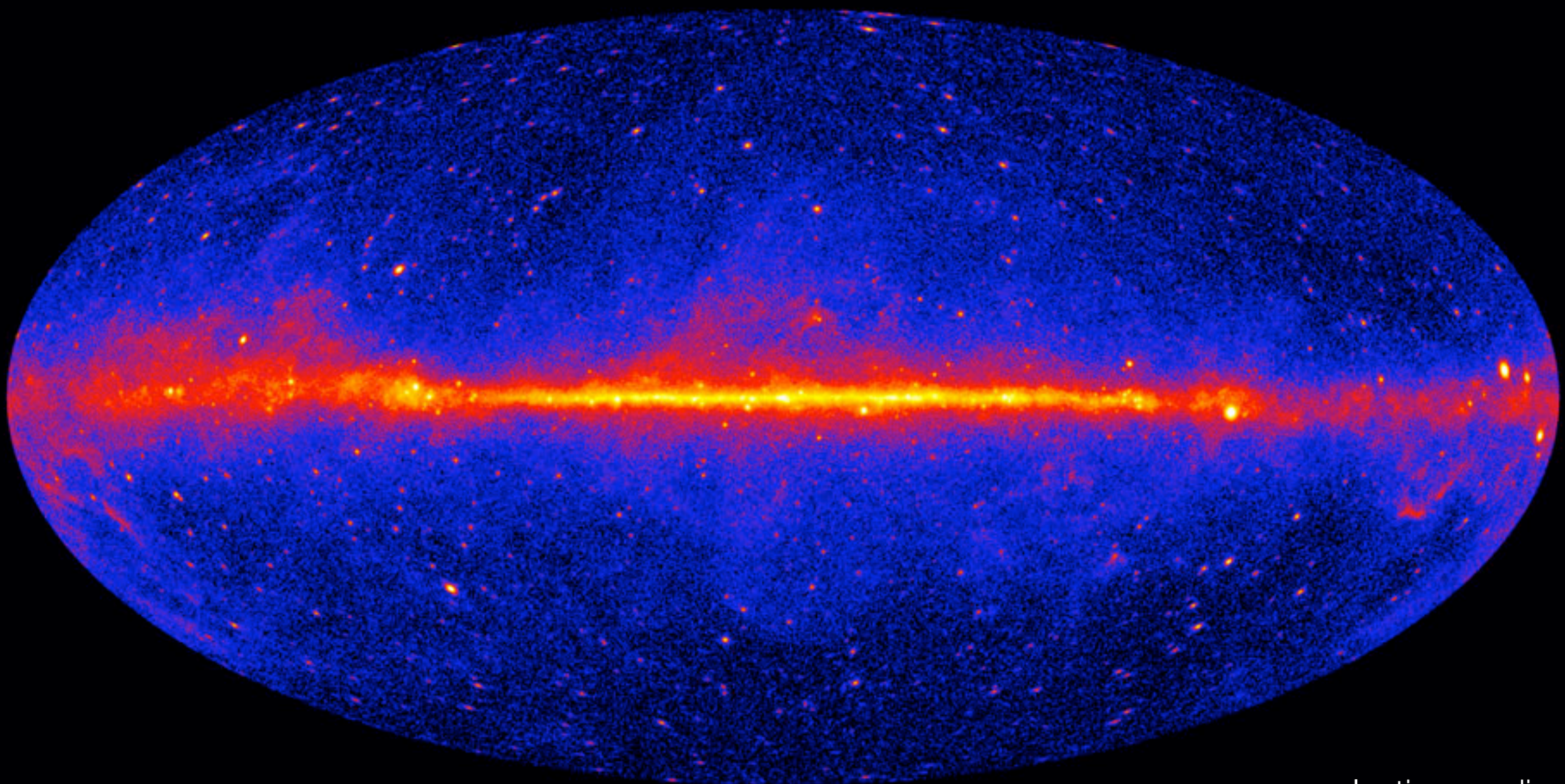
$$e^\pm + B \rightarrow e^\pm + \gamma_{synchrotron}$$

$$e^\pm + \gamma_{soft} \rightarrow e^\pm + \gamma_{Inverse\ Compton}$$

electromagnetic emission

cosmic rays
reconstruct their history: γ rays

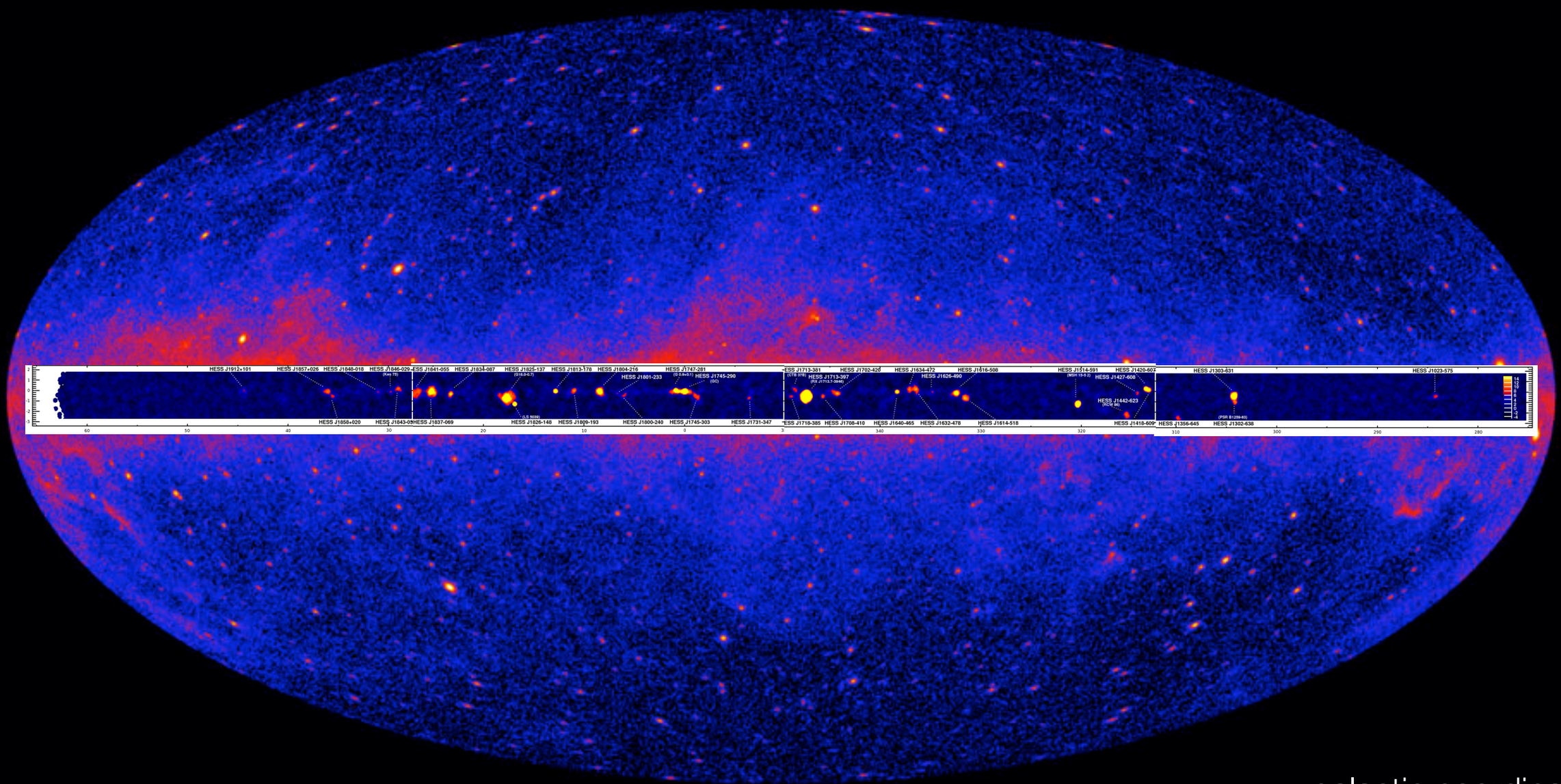
Fermi - LAT 200 MeV - 100 GeV **diffuse gamma ray** sky



galactic coordinates

cosmic rays
reconstruct their history: γ rays

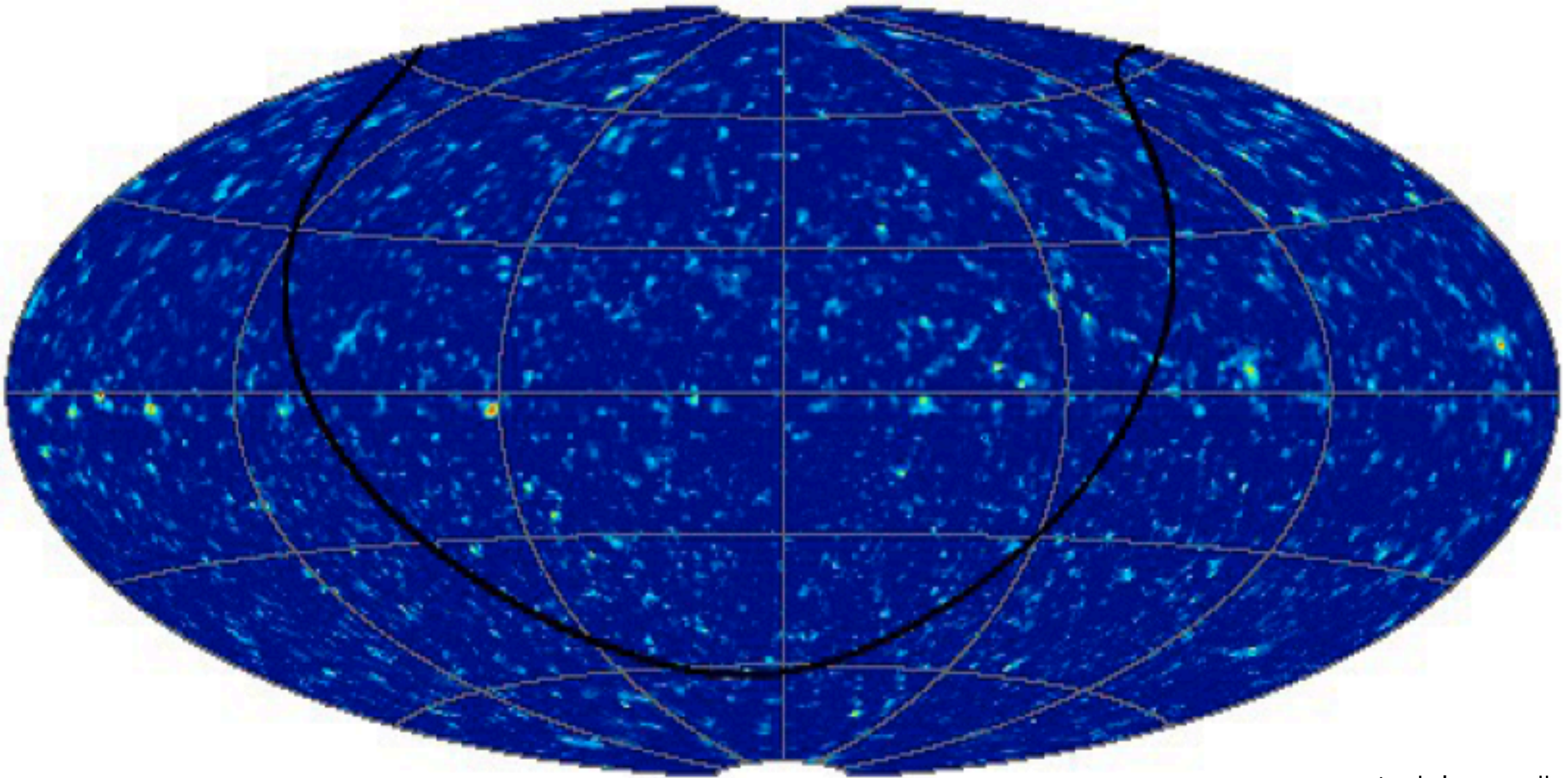
H.E.S.S. TeV **gamma ray** galactic plane



galactic coordinates

cosmic rays
reconstruct their history: neutrino

IceCube-59+40 **probability** of >100 GeV neutrino
point-like excess from random fluctuations

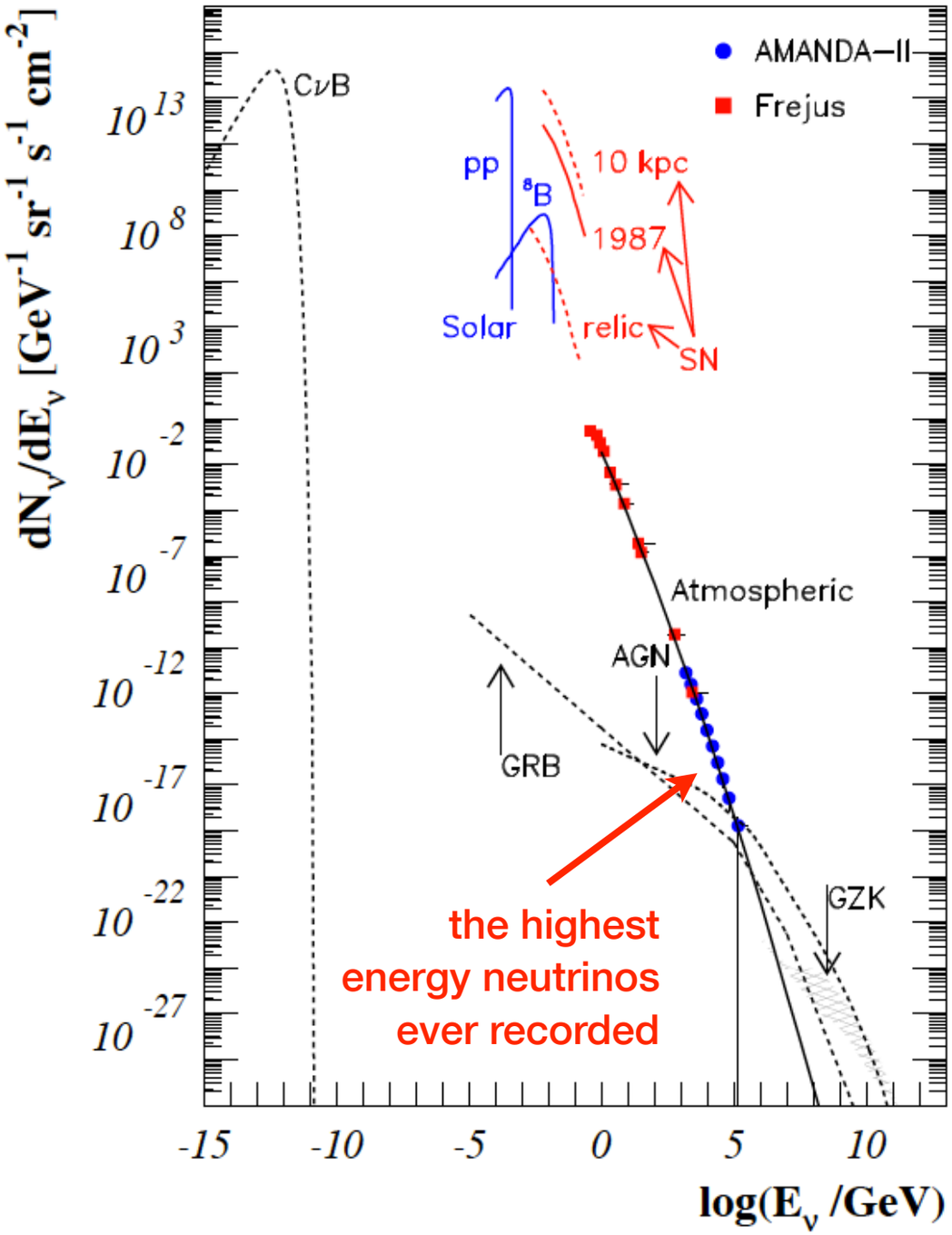


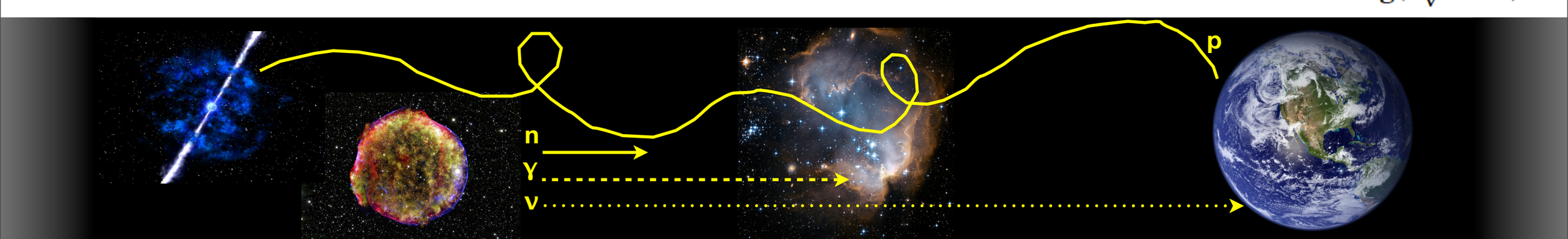
equatorial coordinates

cosmic rays
multi-messenger observations

- **neutrinos** incontrovertibly linked to proton acceleration
- neutrinos propagate **undisturbed** from dense region bringing information from the inner sources
- smoking gun for identification of cosmic ray sources

Becker J., Phys. Rept. **458**, 173 (2008)





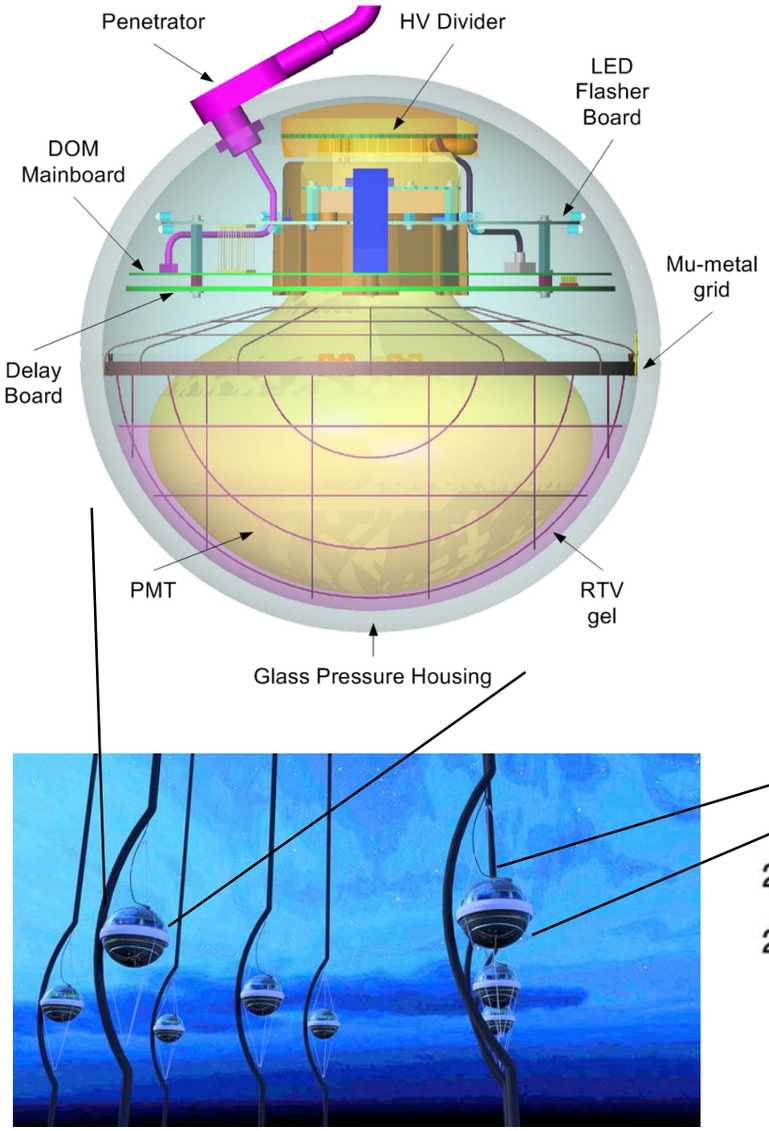
The IceCube Collaboration

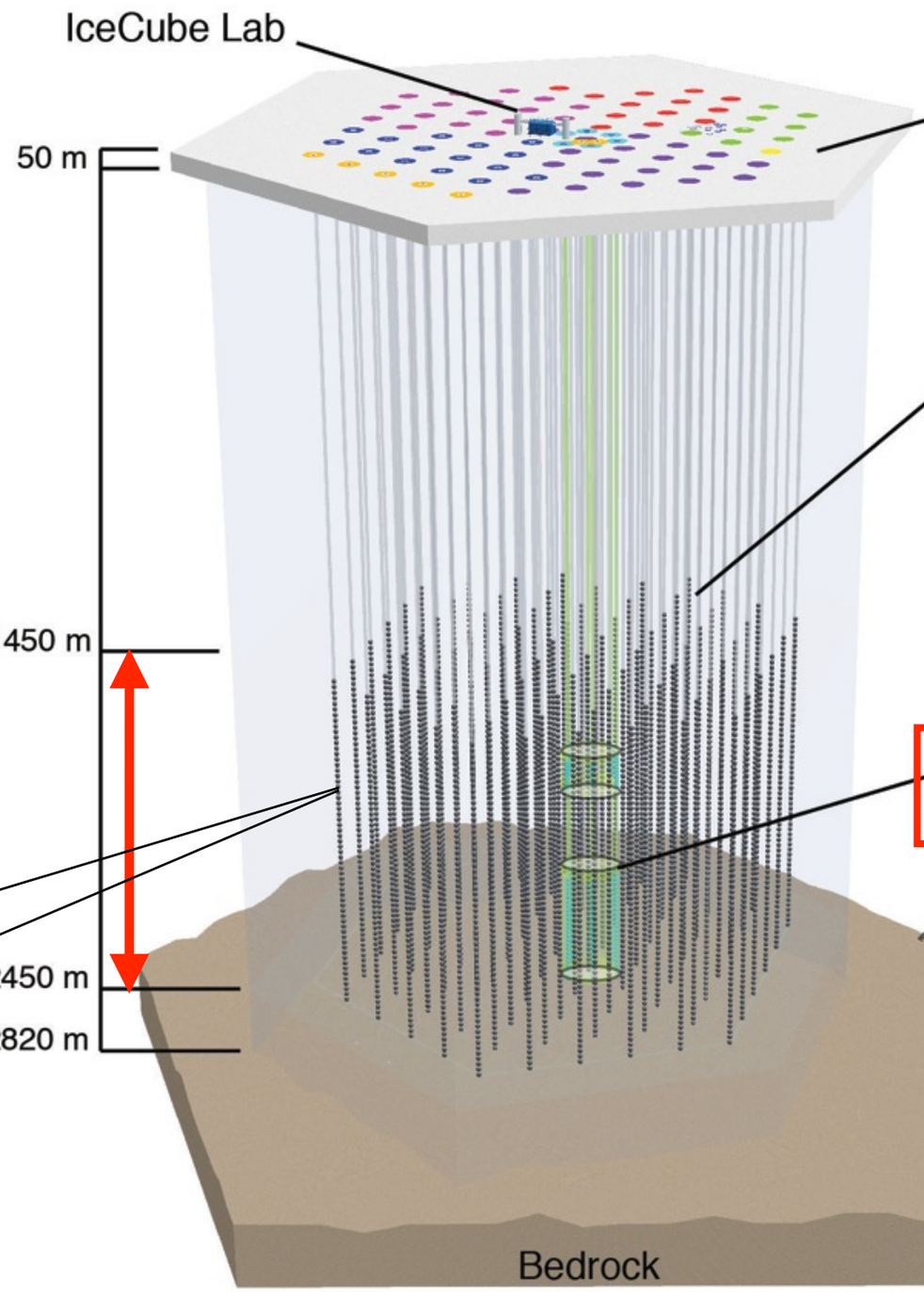
Collaborating Organizations

Chiba University
Clark Atlanta University
Deutsches Elektronen-Synchrotron
Ecole Polytechnique Fédérale de Lausanne
Georgia Institute of Technology
Humboldt Universität
Lawrence Berkeley National Laboratory
Ohio State University
Pennsylvania State University
Ruhr-Universität Bochum
RWTH Aachen University
Southern University and A&M College
Stockholm University
Stony Brook University
Sungkyunkwan University
Technische Universität München
Universität Bonn
Universität Dortmund
Universität Mainz
Universität Wuppertal
Université libre de Bruxelles
Université de Mons
University of Adelaide
University of Alabama
University of Alberta
University of Alaska Anchorage
University of California-Berkeley
University of California-Irvine
University of Canterbury
University of Delaware
University of Geneva
University of Gent
University of Kansas
University of Maryland
University of Oxford
University of Wisconsin-Madison
University of Wisconsin-River Falls
Uppsala Universitet
Vrije Universiteit Brussel

IceCube Observatory

Digital Optical Module - DOM
with 10” PMT &
local DAQ electronics





IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

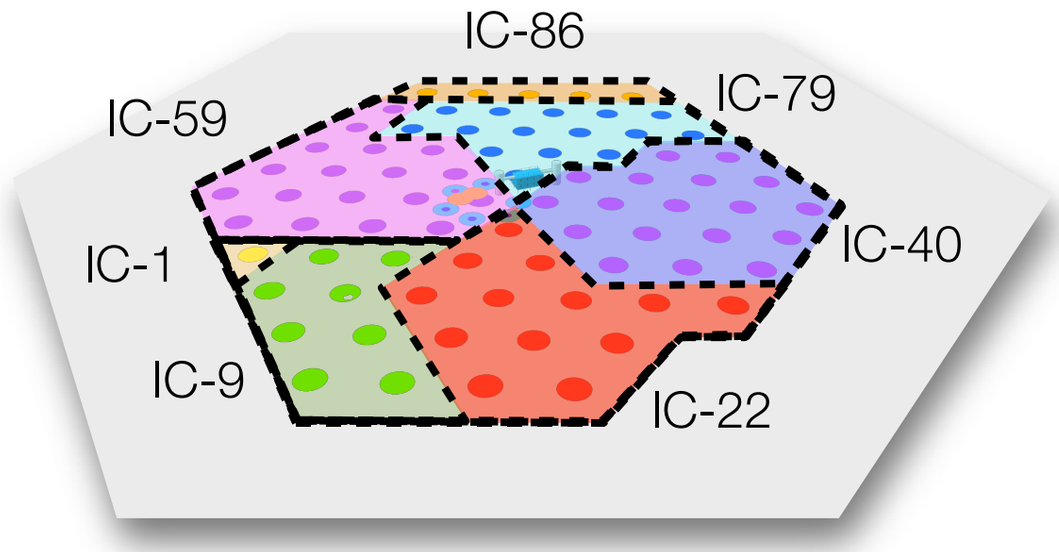
December, 2010: Project completed, 86 strings

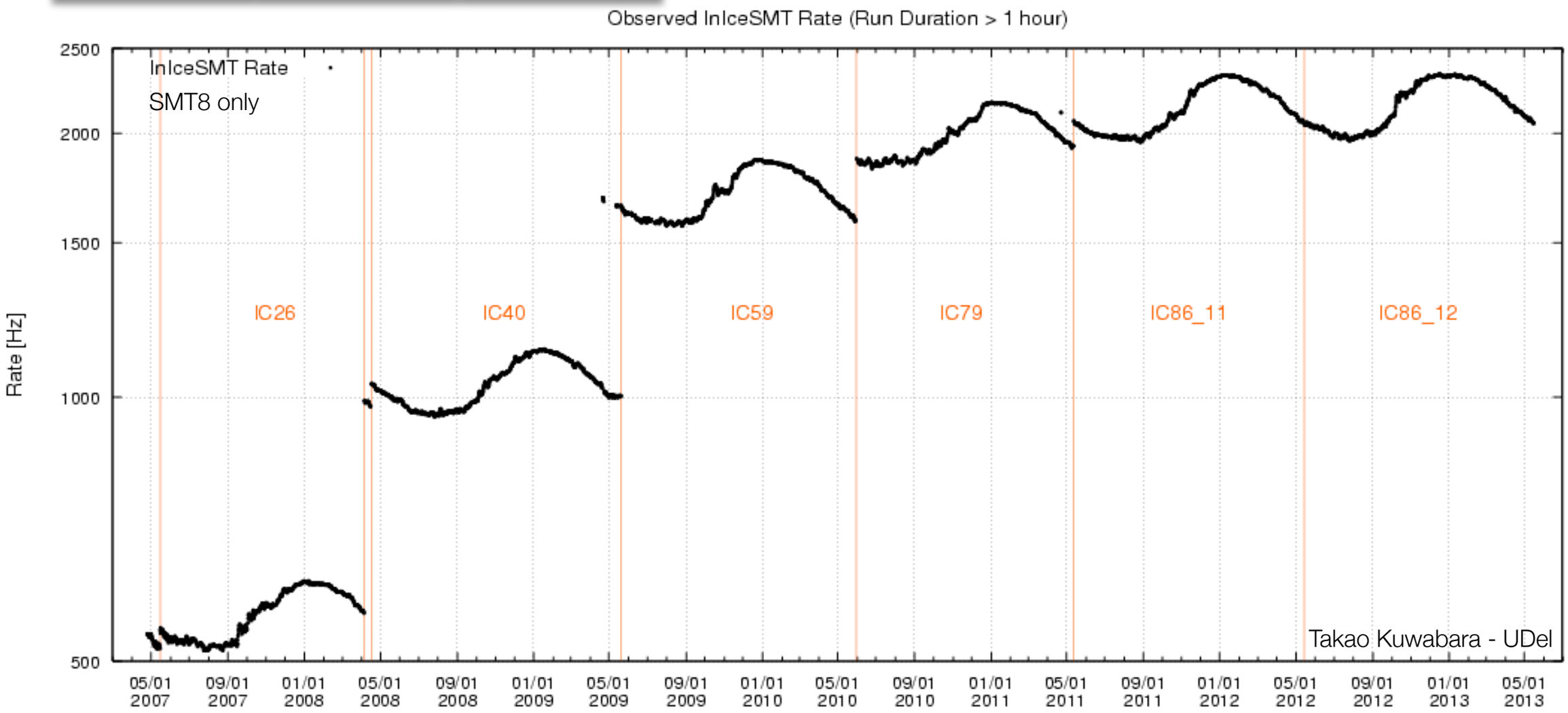
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m

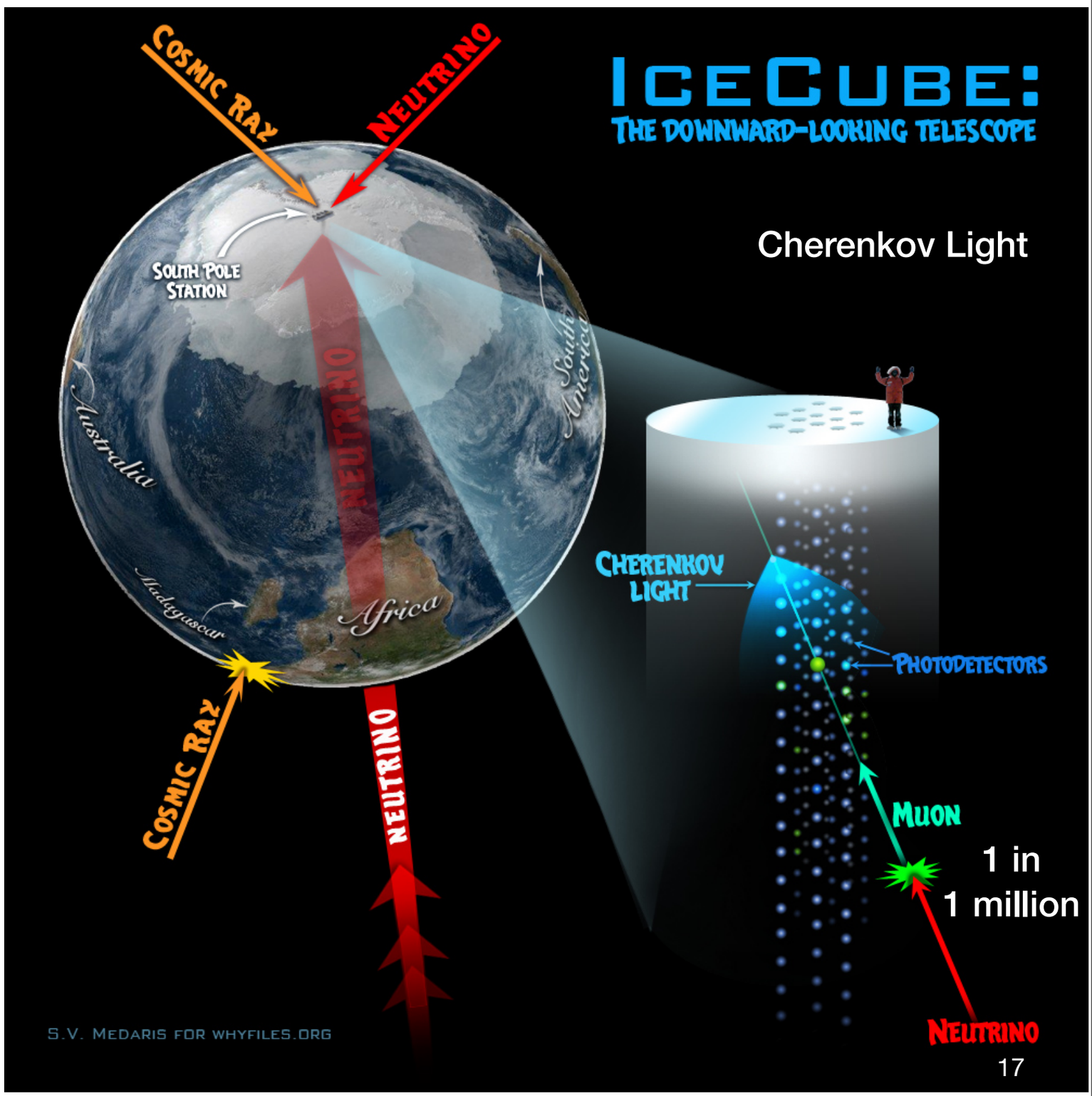
growing IceCube
& event collection

Strings	Year	μ rate
IC22	2007	500 Hz
IC40	2008	1100 Hz
IC59	2009	1700 Hz
IC79	2010	2000 Hz
IC86	2011+	2200 Hz



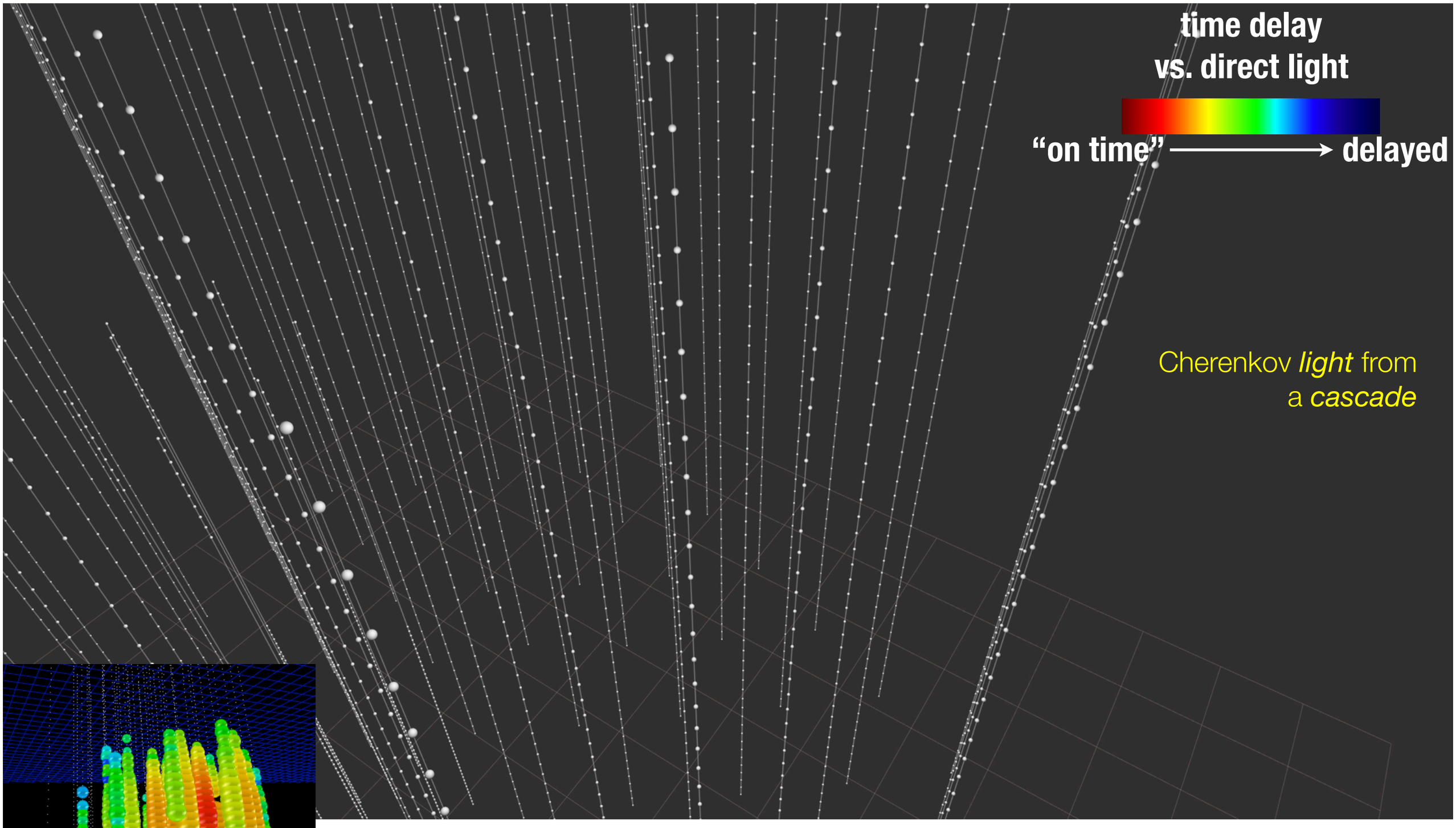


detecting neutrinos
upside-down telescope



detection principle - *cascade*

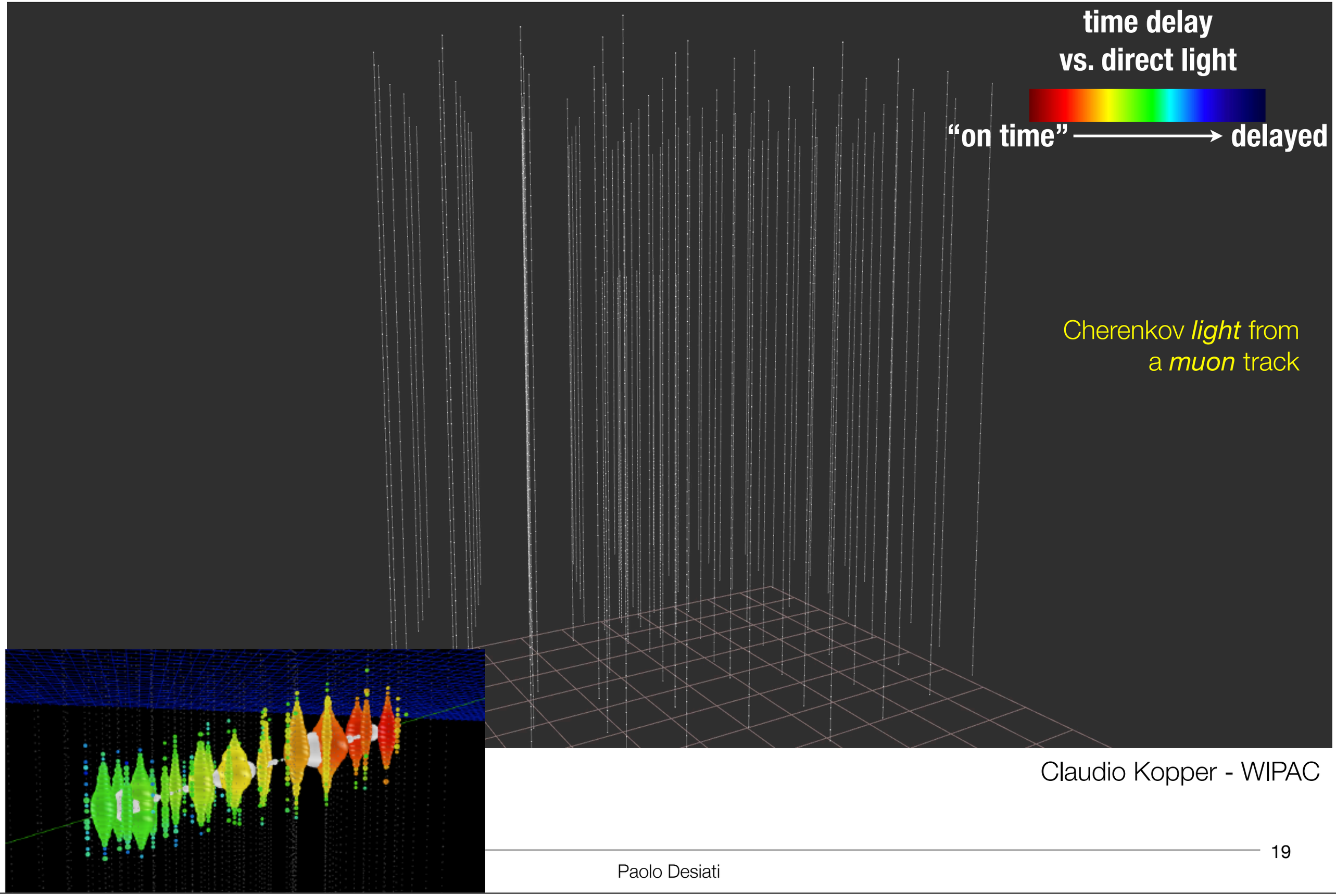
ν_e ν_τ CC-int & ν_i NC-int



Claudio Kopper - WIPAC

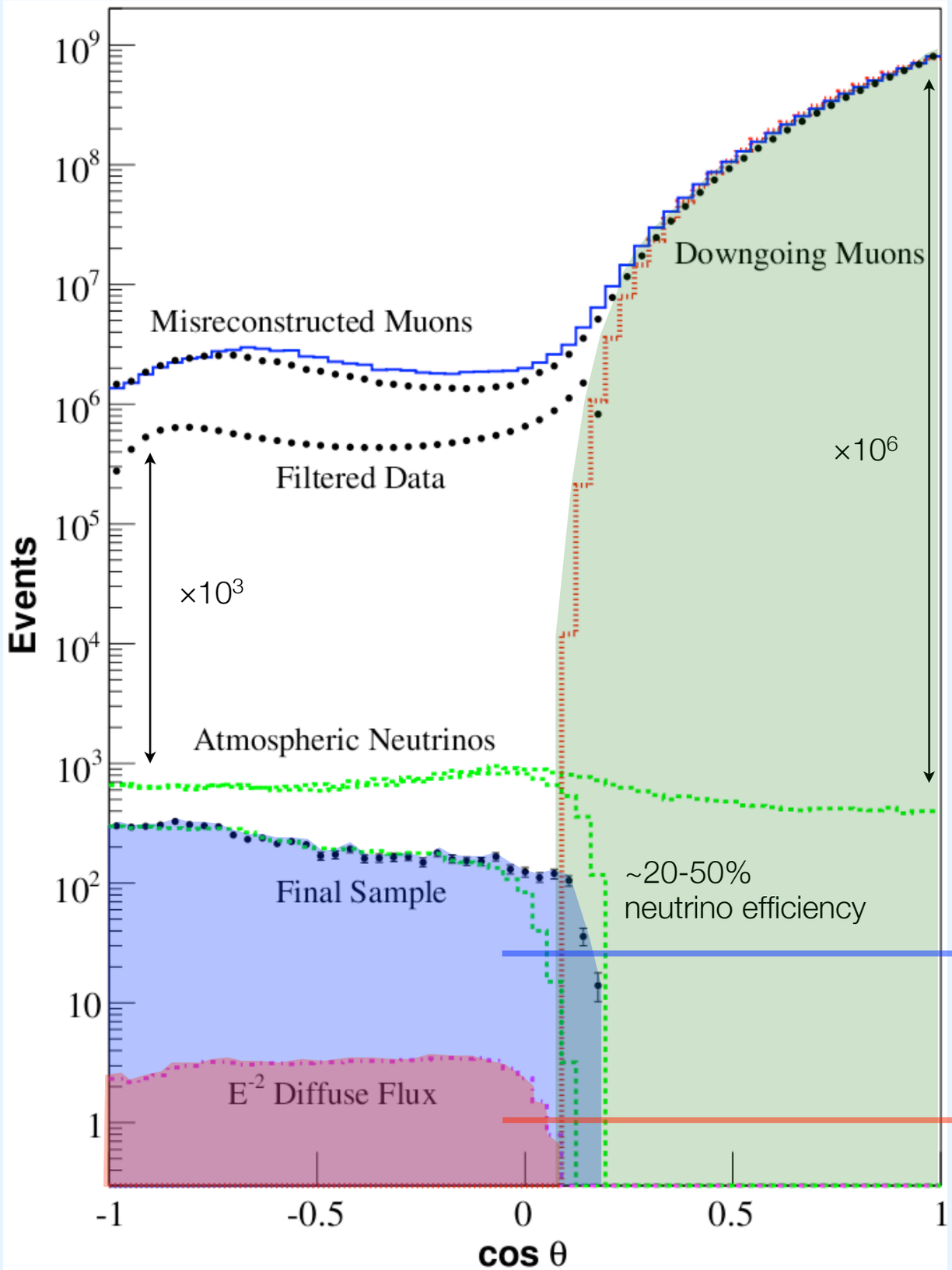
detection principle - *track*

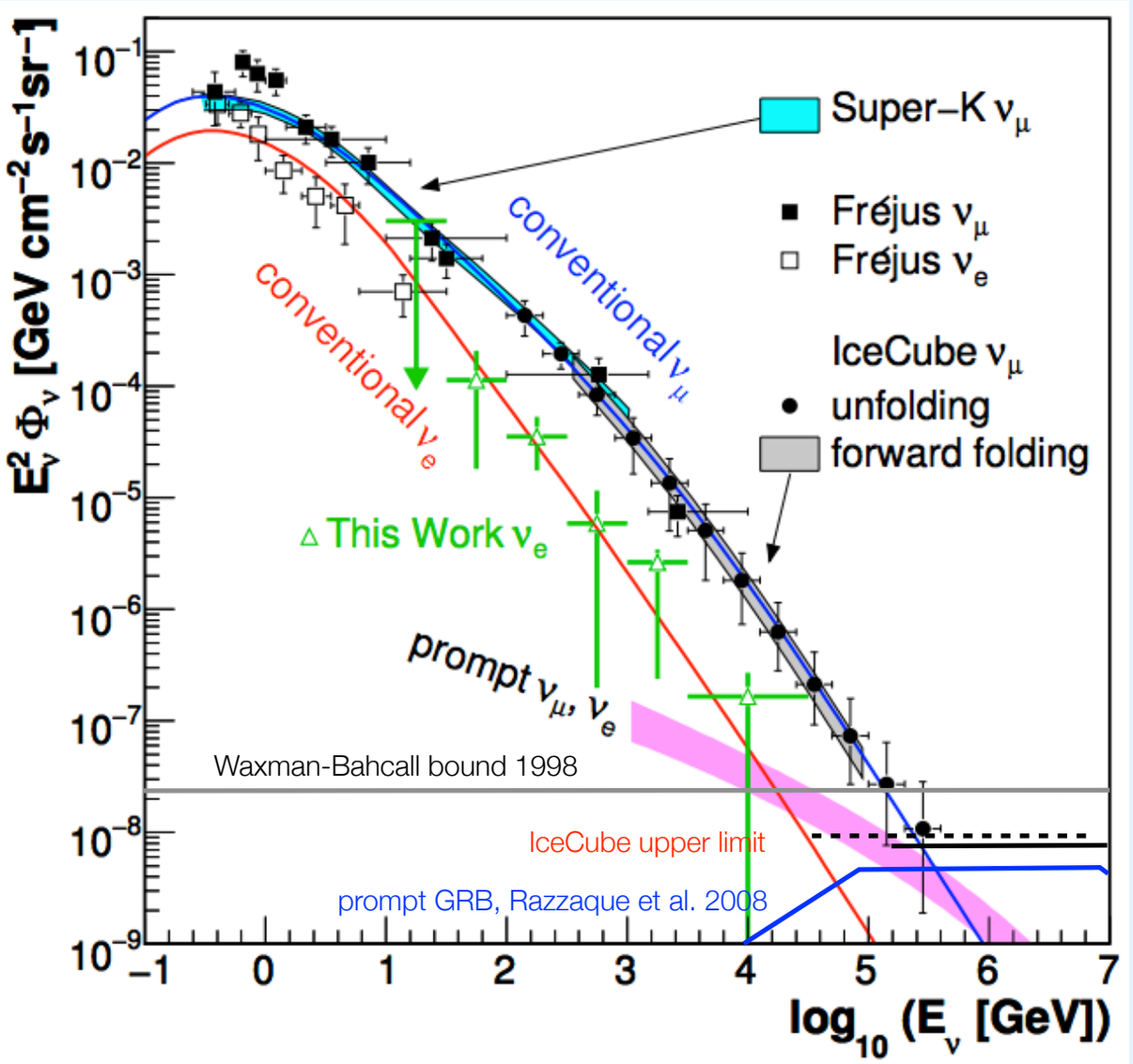
ν_μ CC-int



event identification

ν_e DeepCore - Aartsen+, 2013





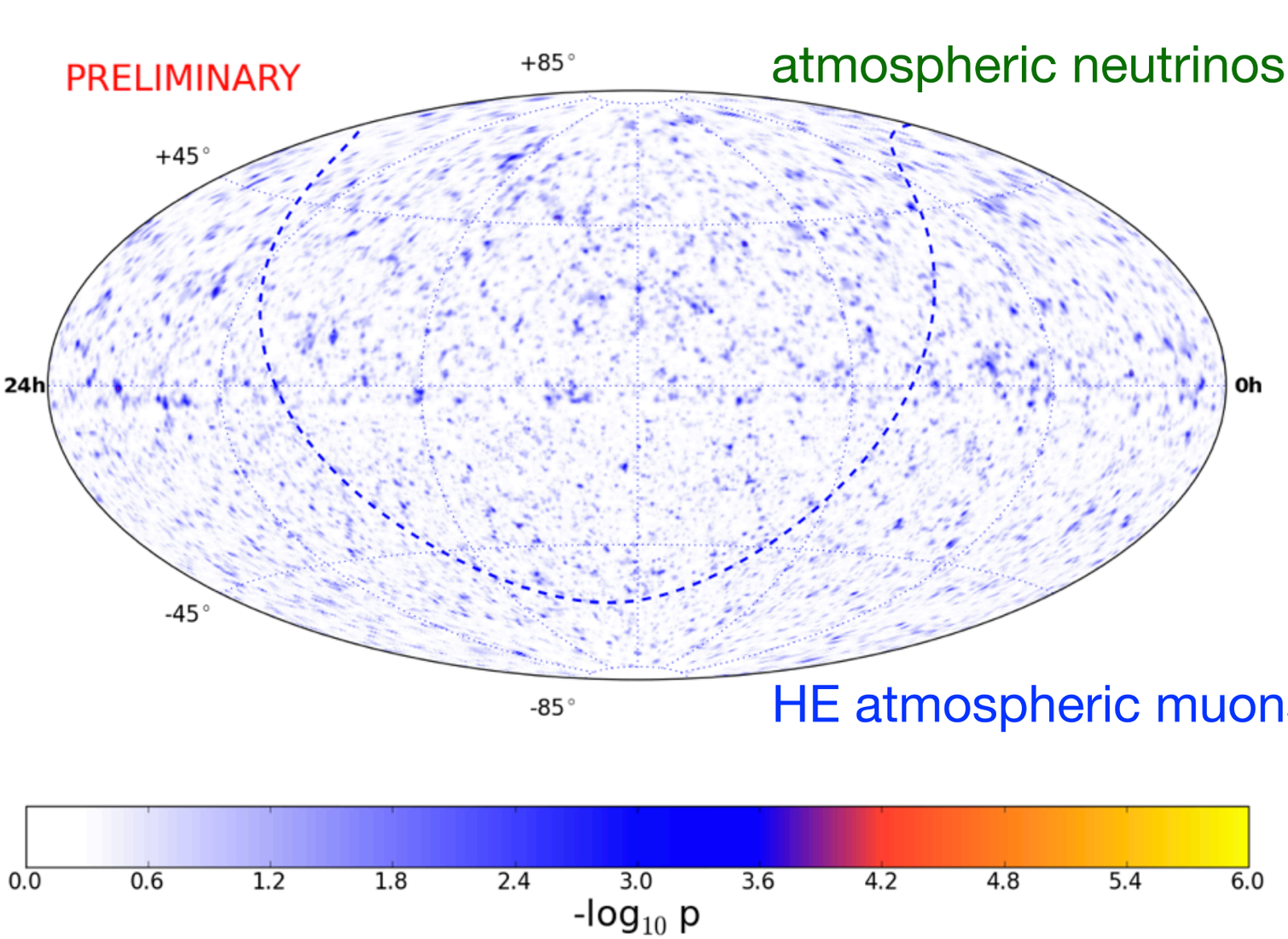
atmospheric neutrinos

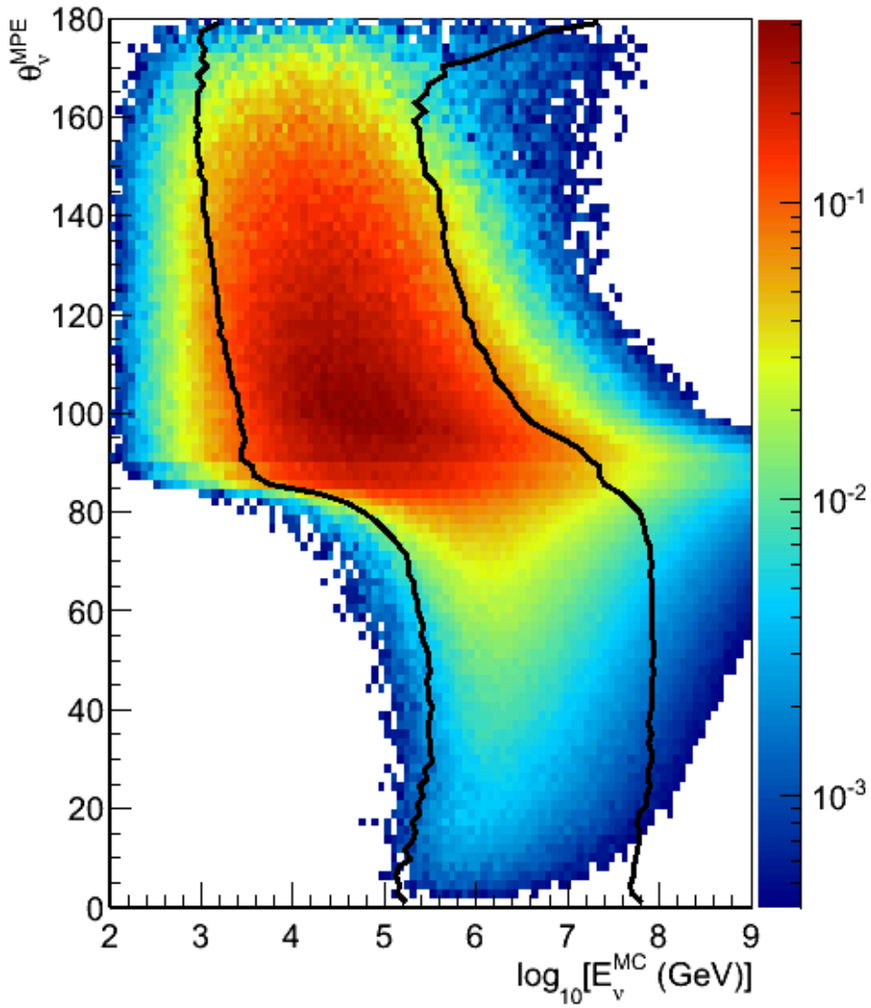
extra-terrestrial neutrinos

all-sky steady **point source** searches
IceCube-40+59+79

- **108,317** up-going events / **146,018** down-going events
- in **316** d (IC79), **348** d (IC59), **375** d (IC40)

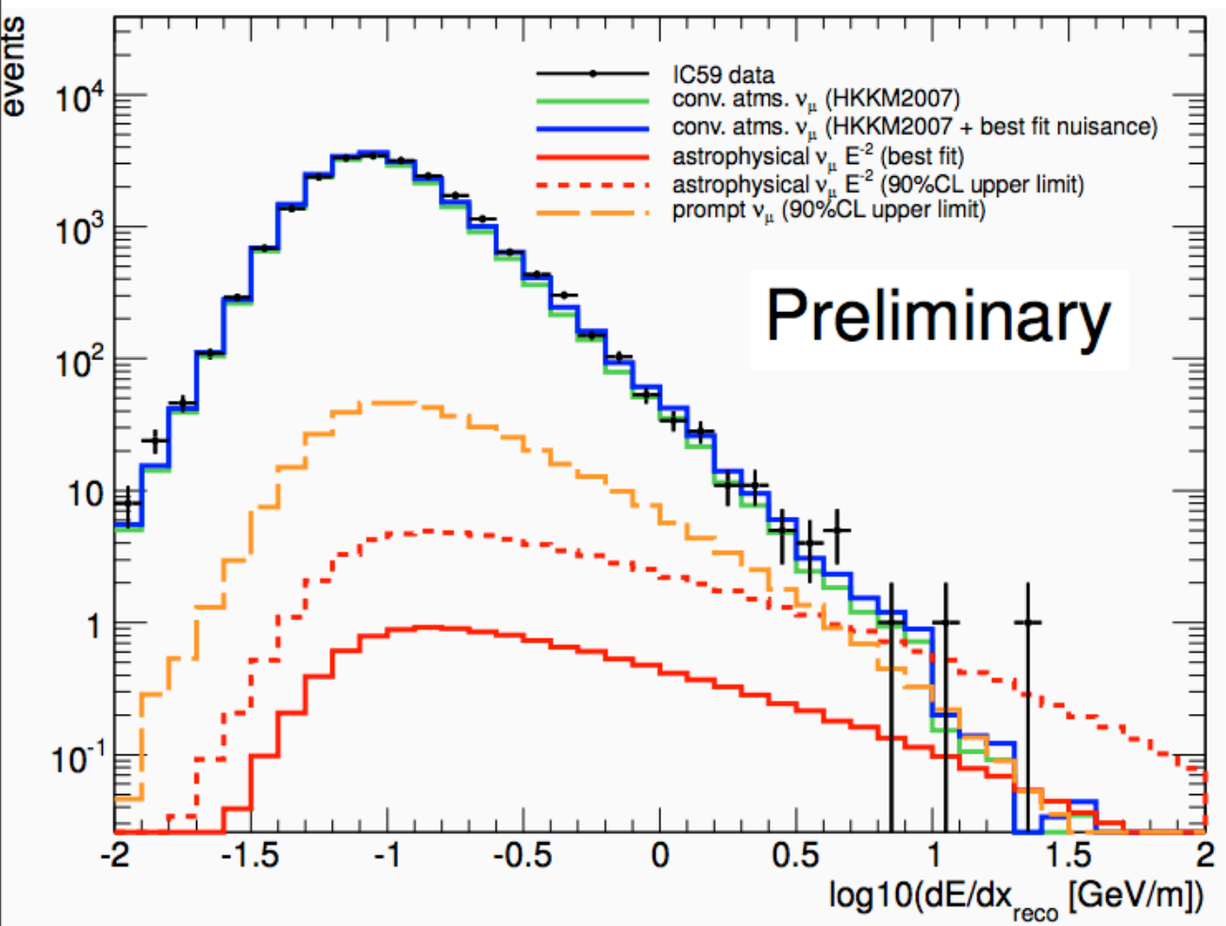
IceCube Collaboration 2013





diffuse source searches
high energy cosmic rays

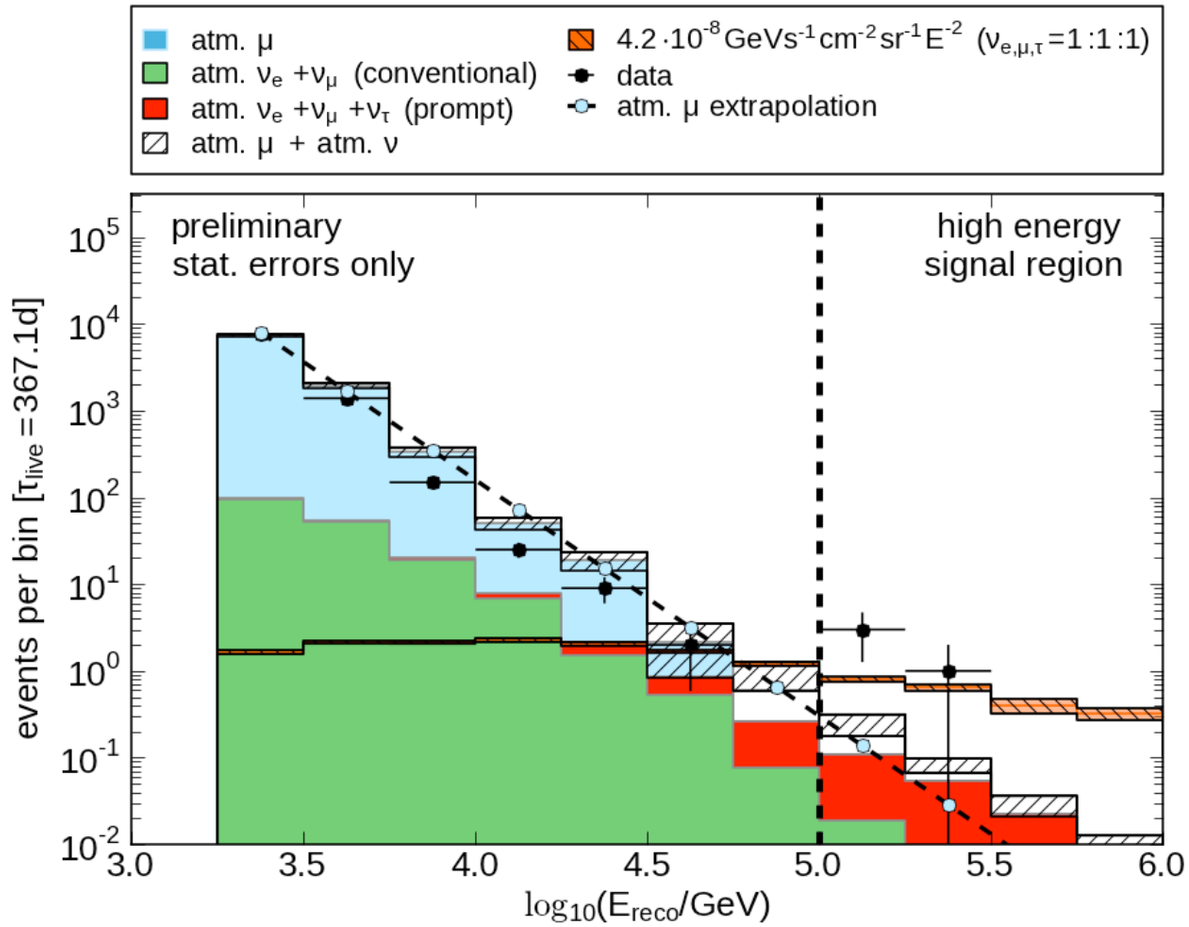
upgoing through going muons from ν_μ



IceCube-59

1.8 σ excess
over atmospheric expectation

contained cascades from ν_e



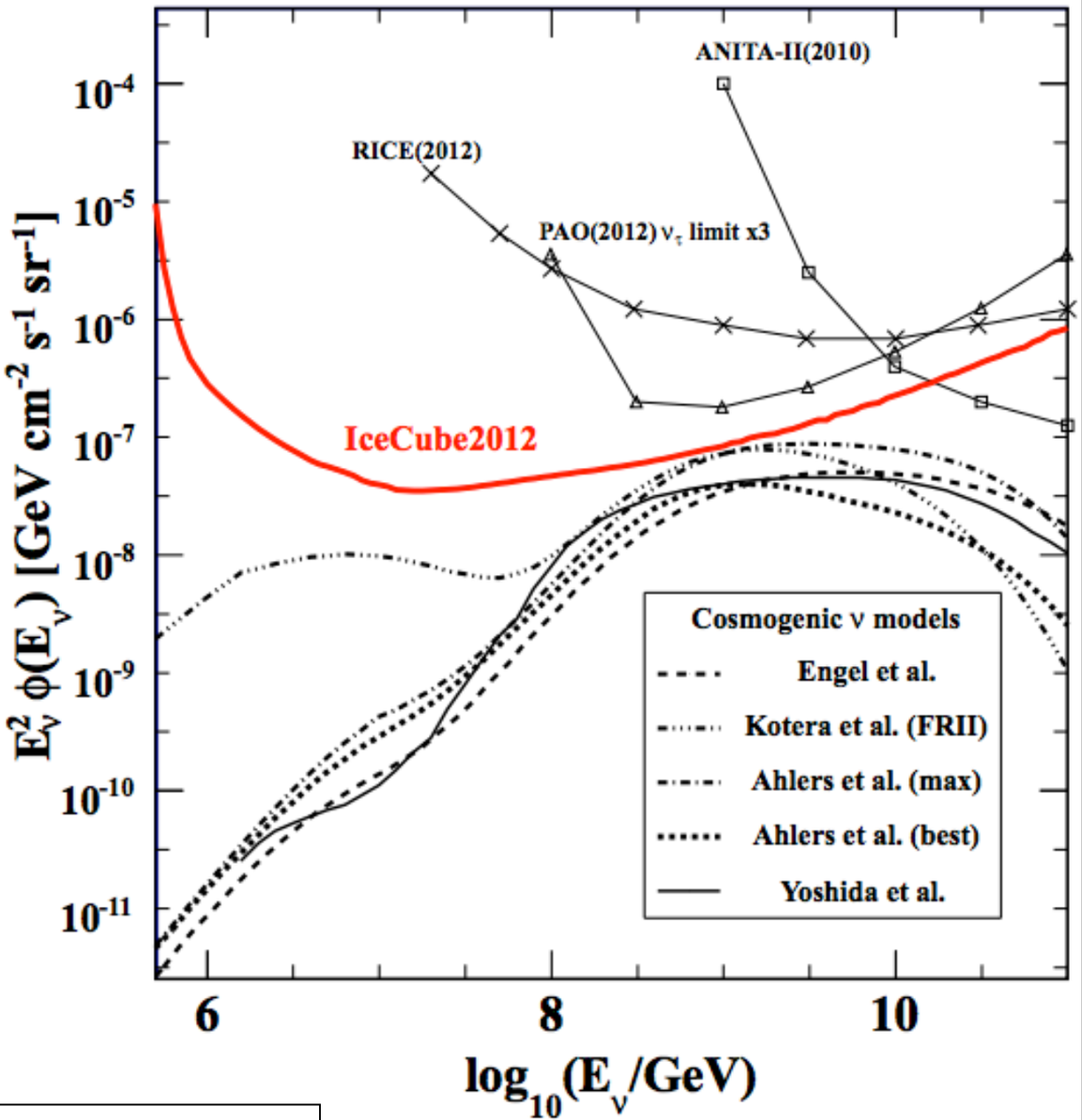
IceCube-40

2.4 σ excess
over atmospheric expectation

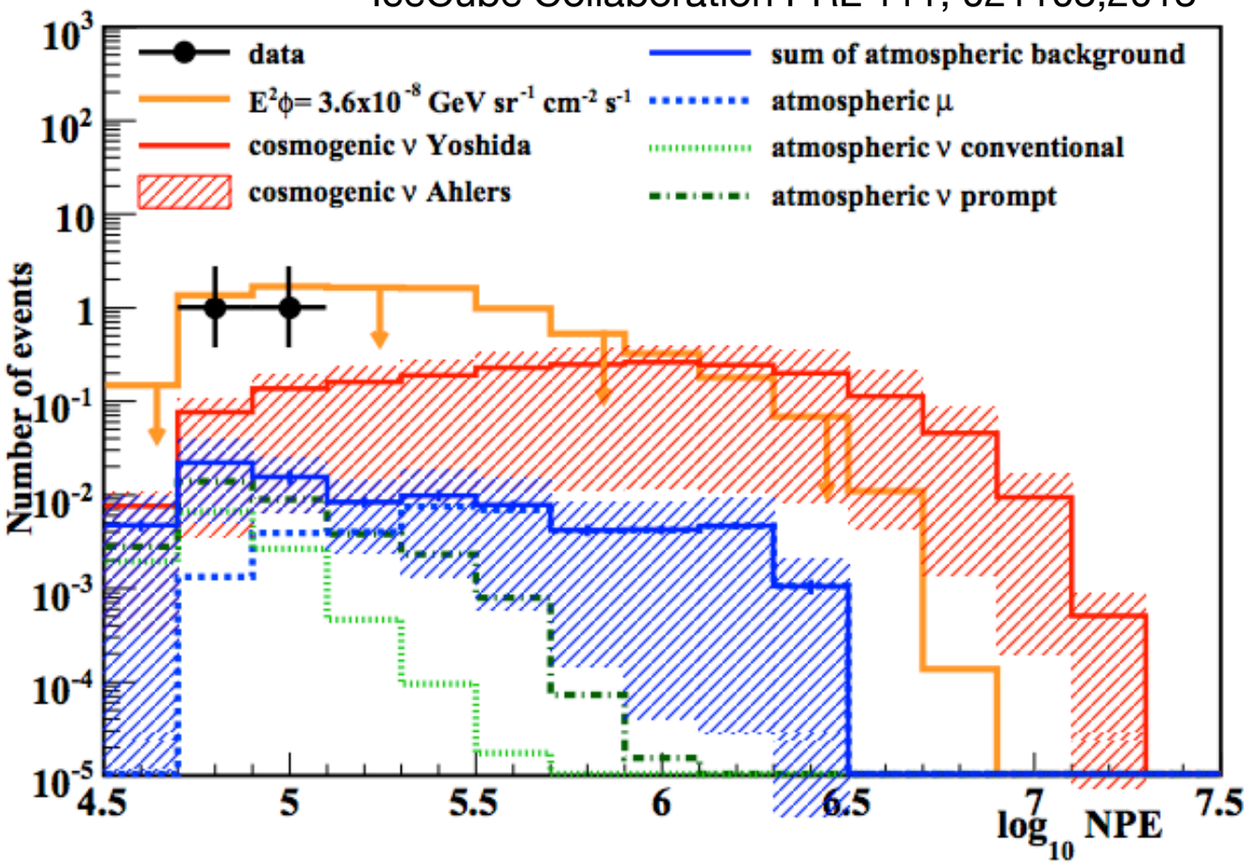
diffuse source searches
ultra-high energy frontier

- **ultra high energy** neutrinos GZK cut-off
- **616** d (IC79 + IC86 excluding burn sample)

IceCube Collaboration arXiv: 1310.5477, submitted to PRD



IceCube Collaboration PRL 111, 021103,2013



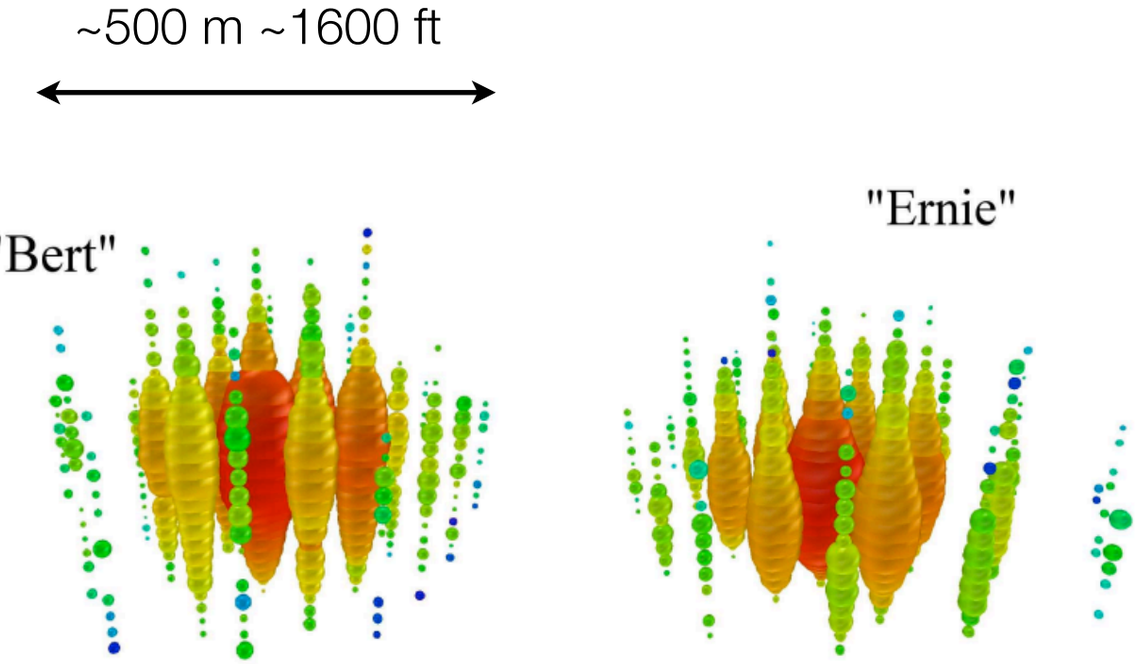
2.8 σ
over background
for GZK searches

Ahlers et al., Astrop. Phys. 34, 106 (2010)
Ahlers et al., Astrop. Phys. 35-2, 87 (2011)

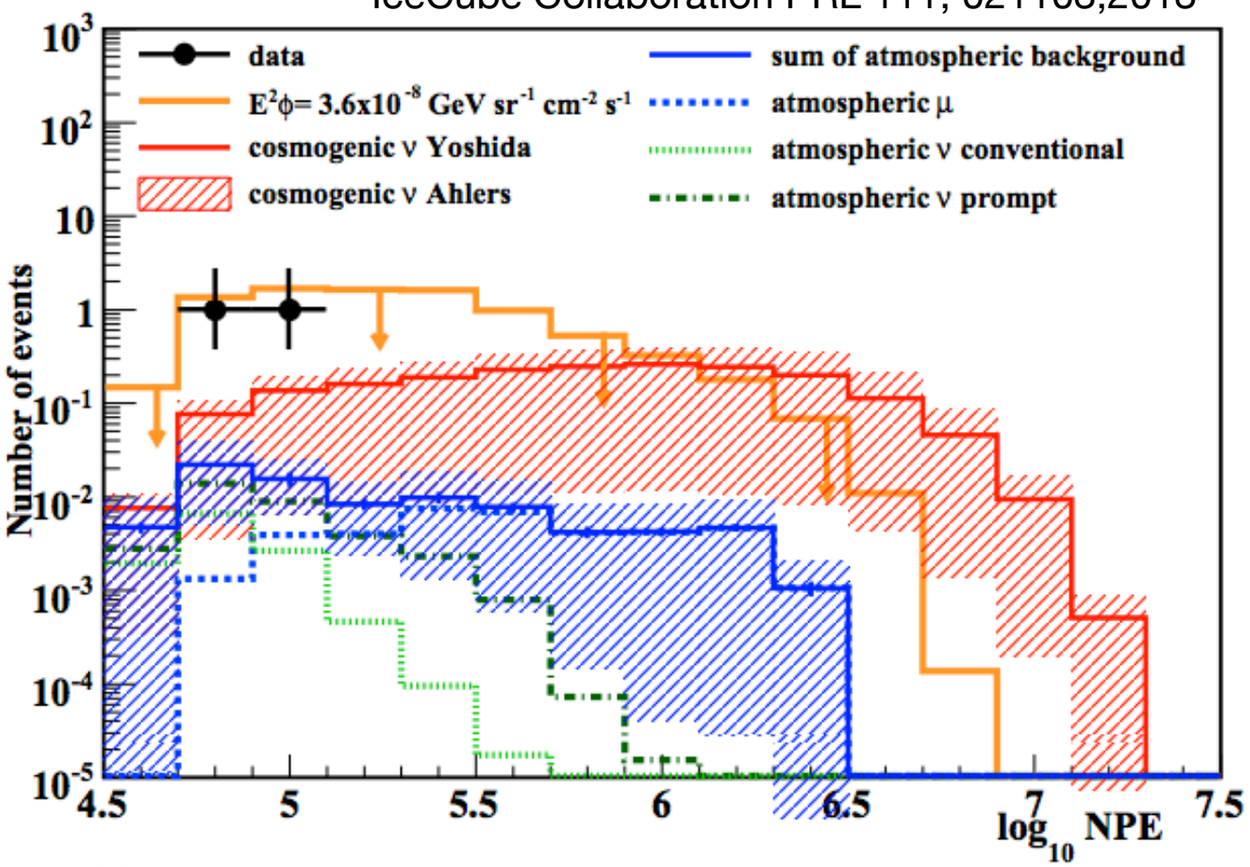
diffuse source searches
ultra-high energy frontier

- **IF** extraterrestrial associated to extreme events *(no γ counterpart ?)*

unknown origin !



IceCube Collaboration PRL 111, 021103,2013



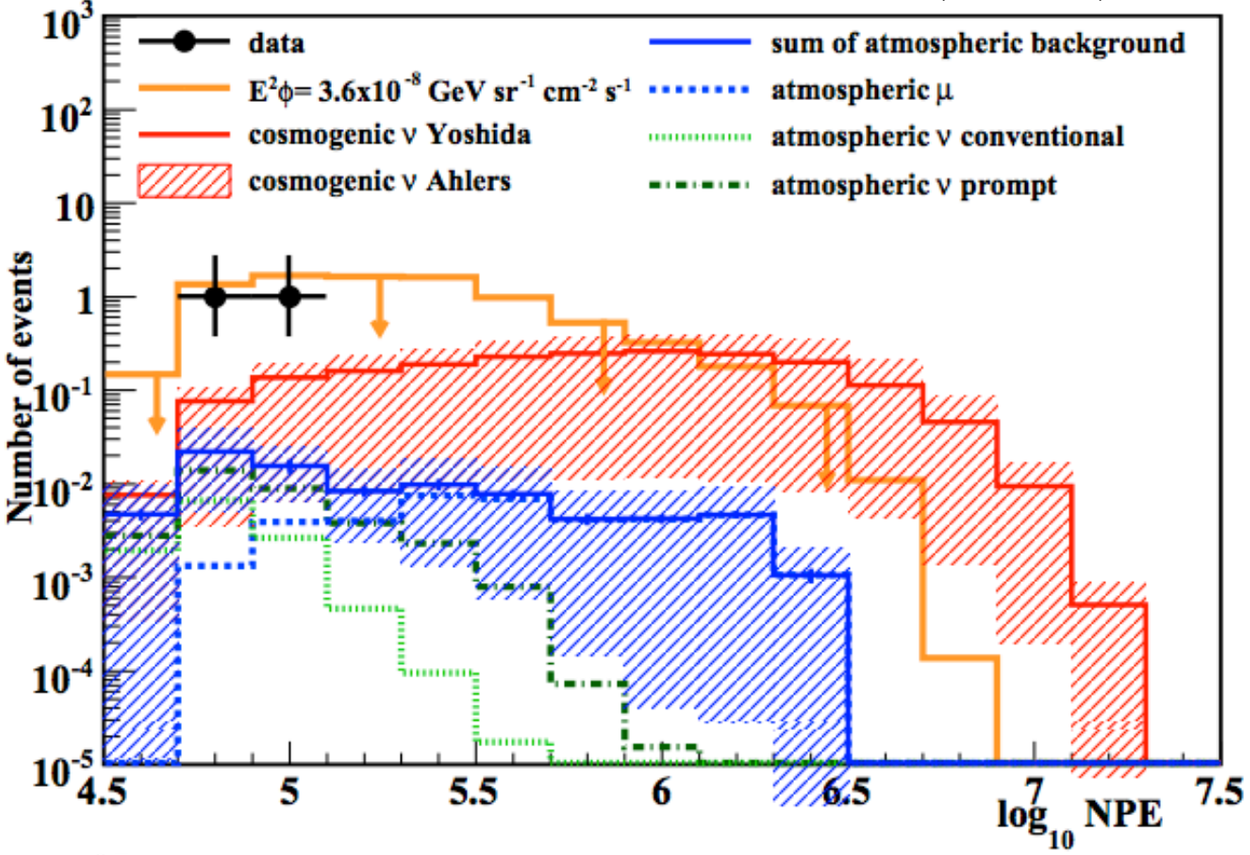
date (GMT)	Aug. 8, 2011	Jan. 3, 2012
NPE	7.0×10^4	9.6×10^4
number of recorded DOMs	354	312
reconstructed deposited energy (PeV)	1.04 ± 0.16	1.14 ± 0.17
reconstructed z vertex (m)	122 ± 5	25 ± 5

diffuse source searches
ultra-high energy frontier

2.8 σ
over background
for GZK searches

- **a PeV downgoing event / year**
- **not cosmogenic neutrino**
- **not consistent with atmospheric flux**
- **8-9 more events > 1 TeV if unbroken E^{-2} spectrum**

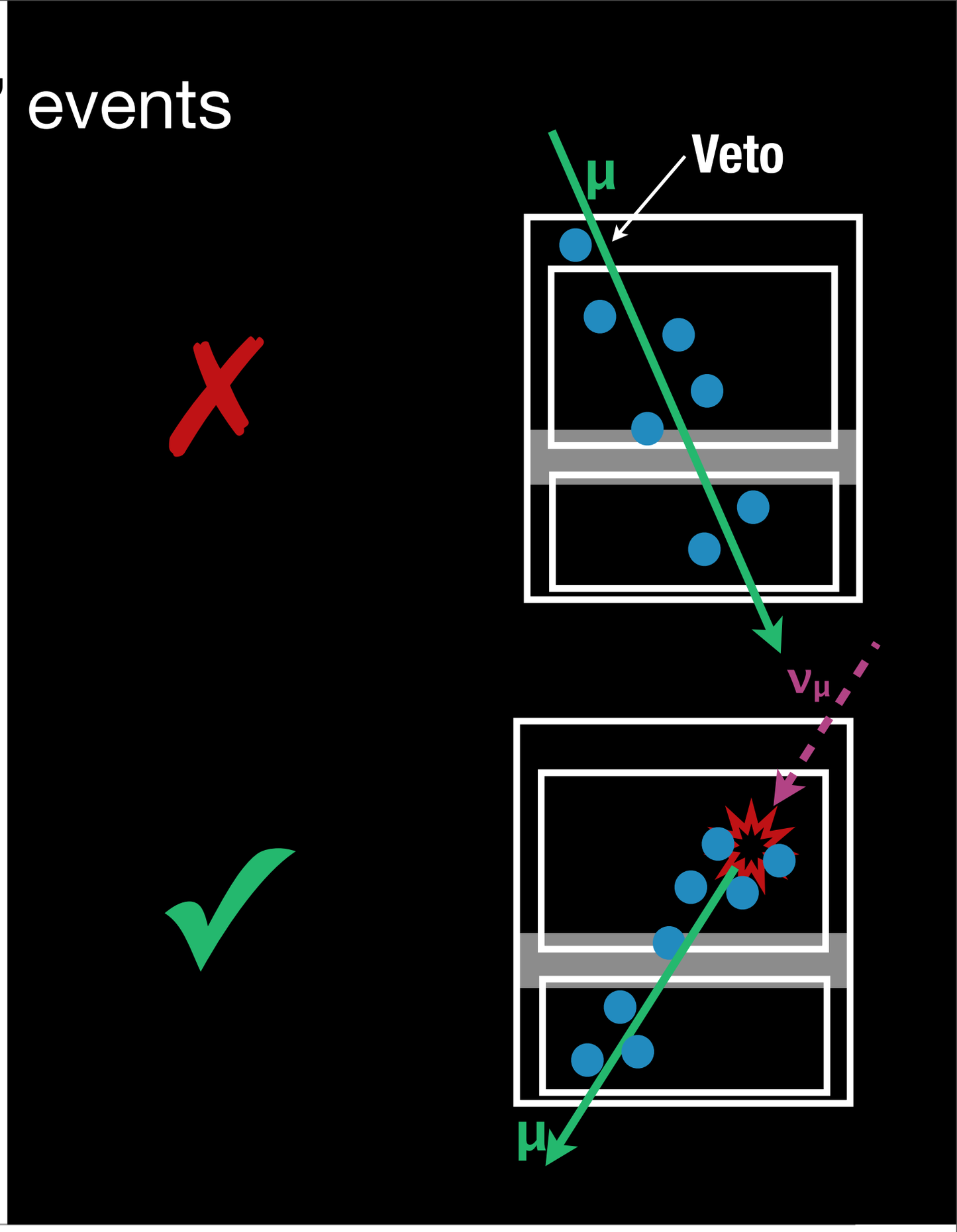
IceCube Collaboration PRL 111, 021103,2013



- are there other PeV events ?
- what's their nature ?

high energy "*starting*" events

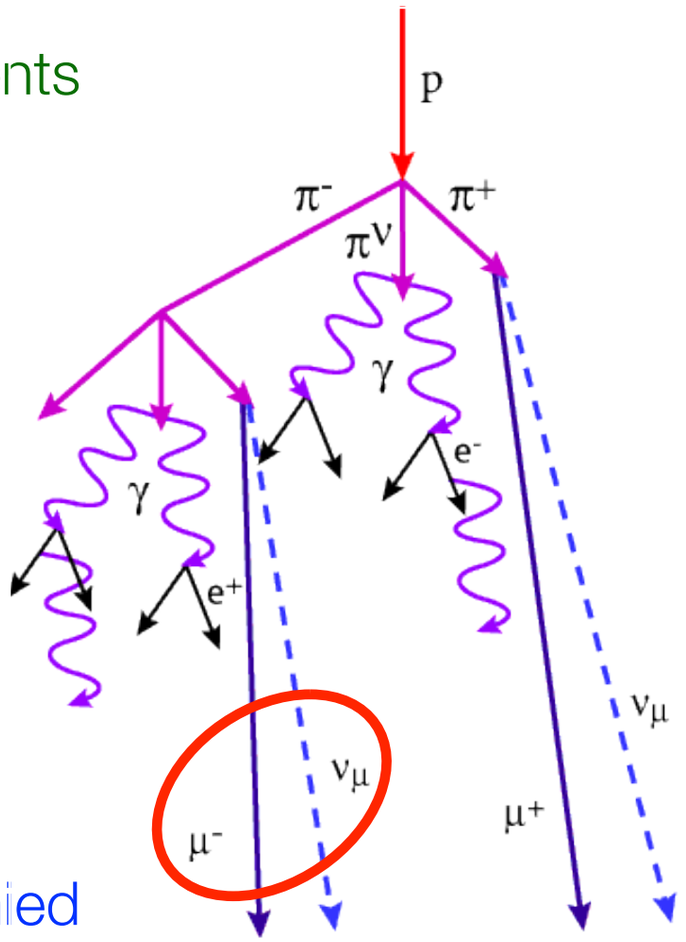
- **extension to lower energy**
- **662** d (IC79 + IC86)
- containment at HE (Q_{tot} > 6000 p.e.)
- **400 Mton** effective fiducial mass
- reject cosmic ray muons
- sensitive to all flavors > 60 TeV
- 3 times as sensitive at 1 PeV



high energy "*starting*" events
background estimation

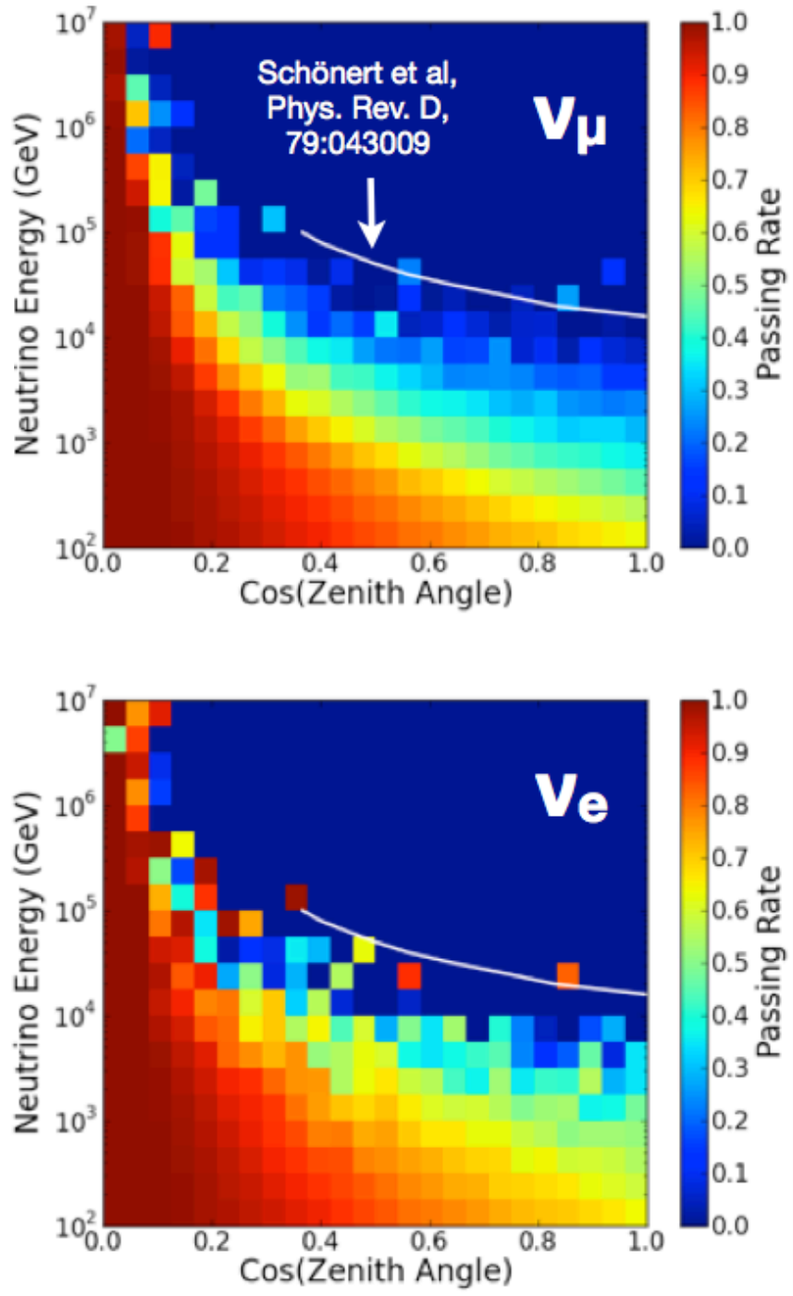
- **atmospheric muons**
  - estimated from data (tag events on outer layer)

6 ± 3.4 μ's



- **atmospheric neutrinos**
  - reject events with accompanied muons (***self-veto***)

4.6 $^{+3.7}_{-1.2}$ ν's

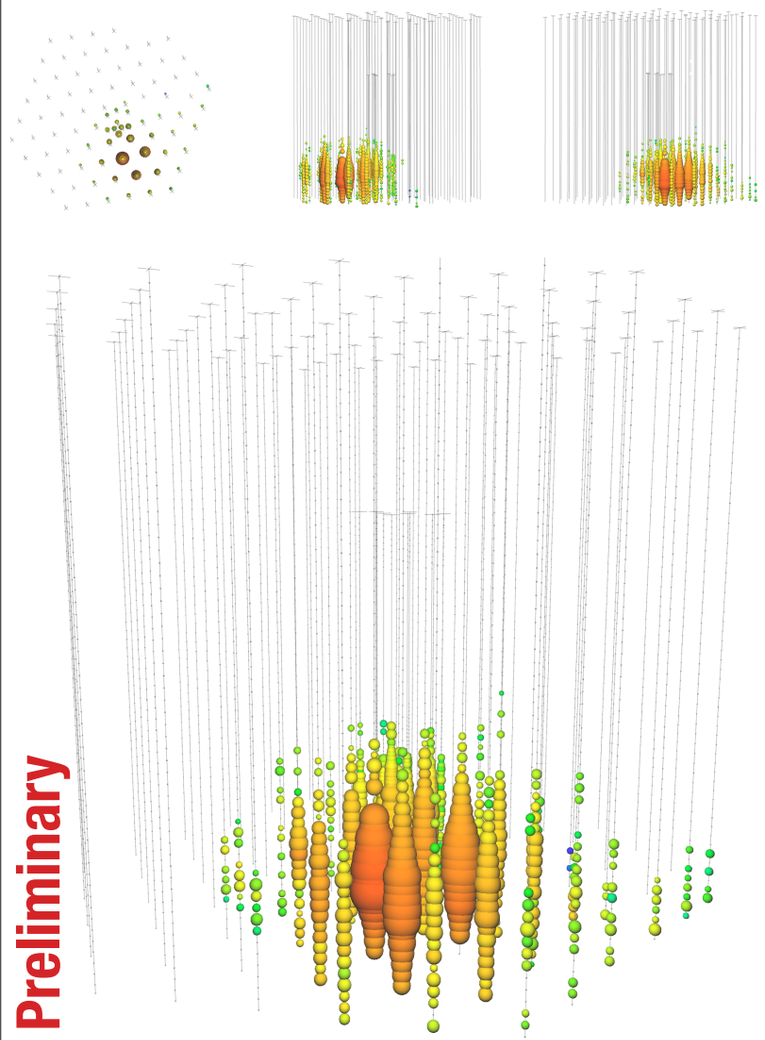


Plots courtesy of K. Jero (UW-Madison)

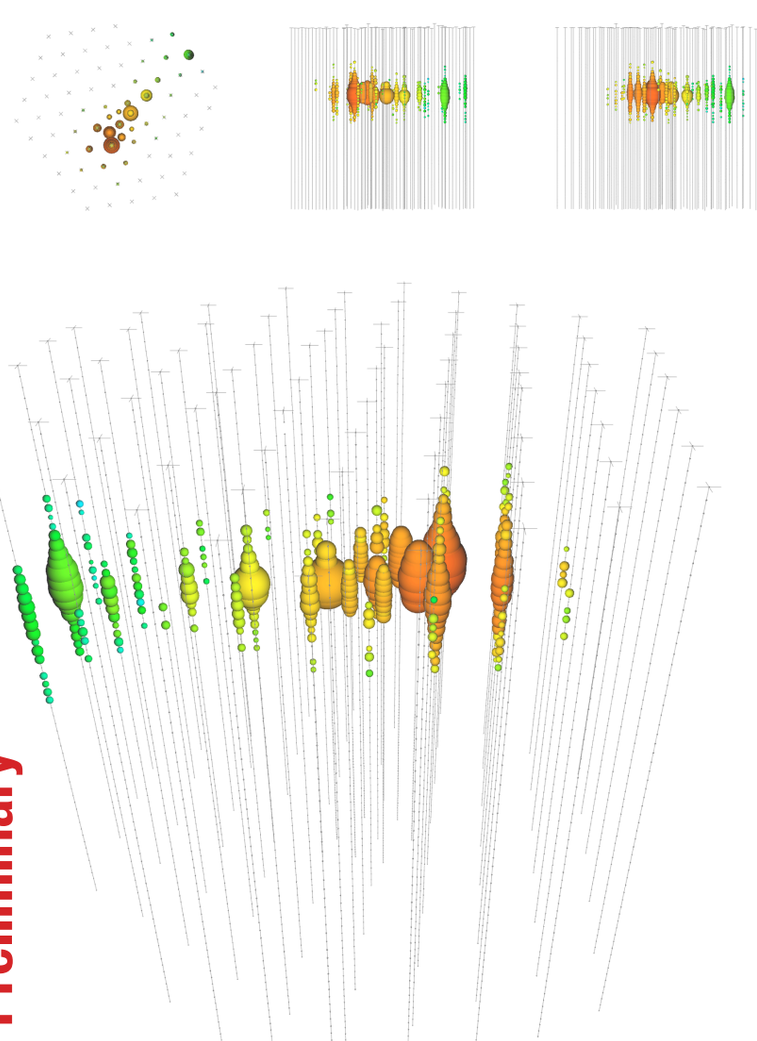
high energy "*starting*" events

some examples

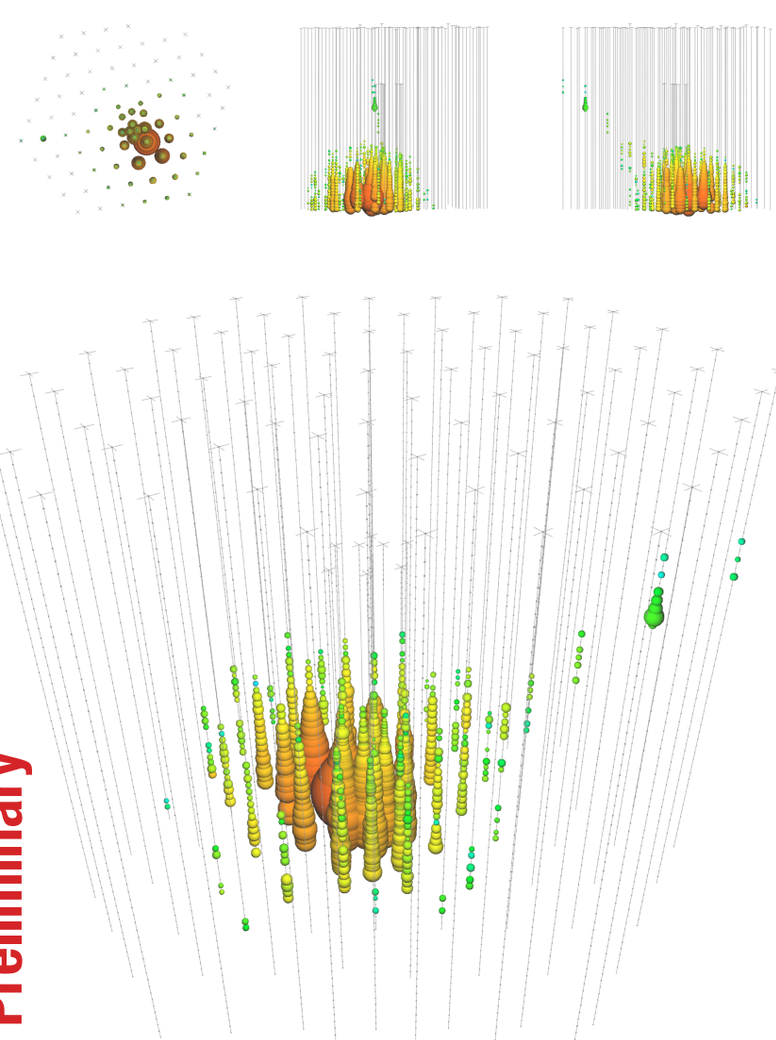
declination: -13.2°
deposited energy: 82TeV



declination: -0.4°
deposited energy: 71TeV



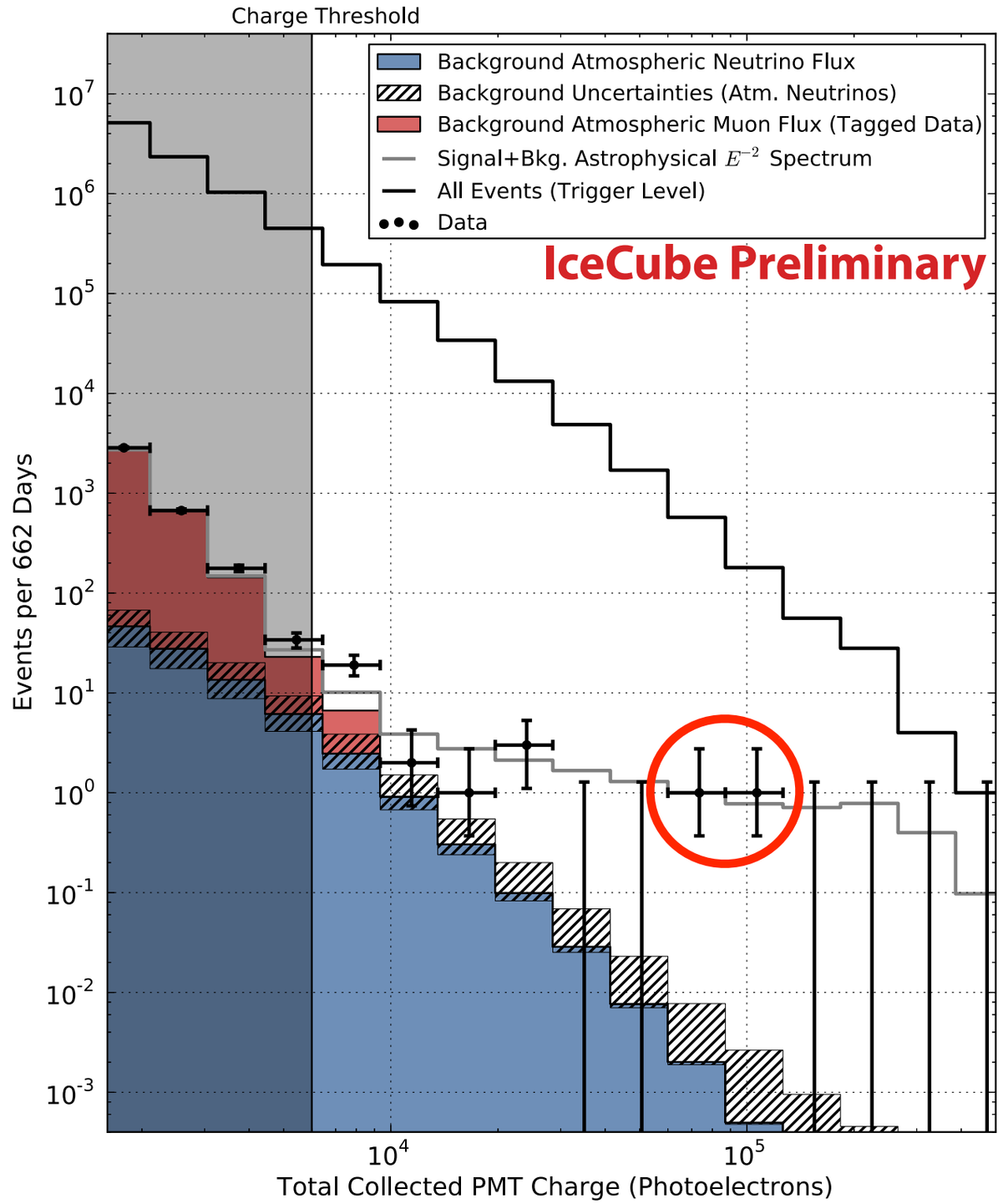
declination: 40.3°
deposited energy: 253TeV



high energy "*starting*" events

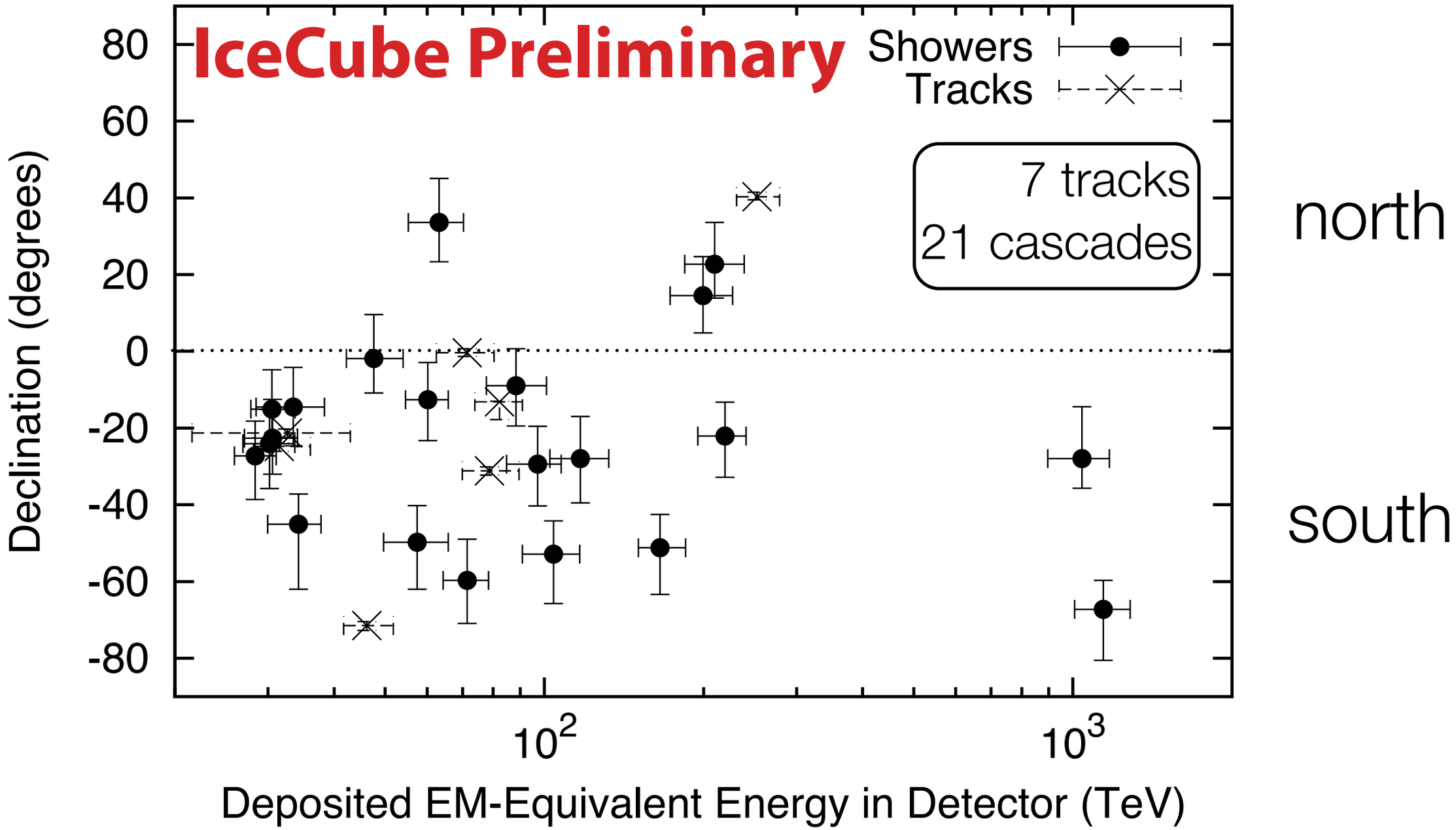
high energy all-flavor neutrino events

- **26 + 2 = 28 events found**
- good fit with tagged **muon background** (for Q_{tot} < 6000 p.e.)
- hatched region includes uncertainties from conventional and prompt (Enberg et al.) **atmospheric neutrino** flux
- total background (including models uncert's)
  - **12.1 ± 3.4** for reference flux
- **significance w.r.t. reference background**
  - **3.3 σ** (26 events) - **4.1 σ** (28 events)



high energy "*starting*" events

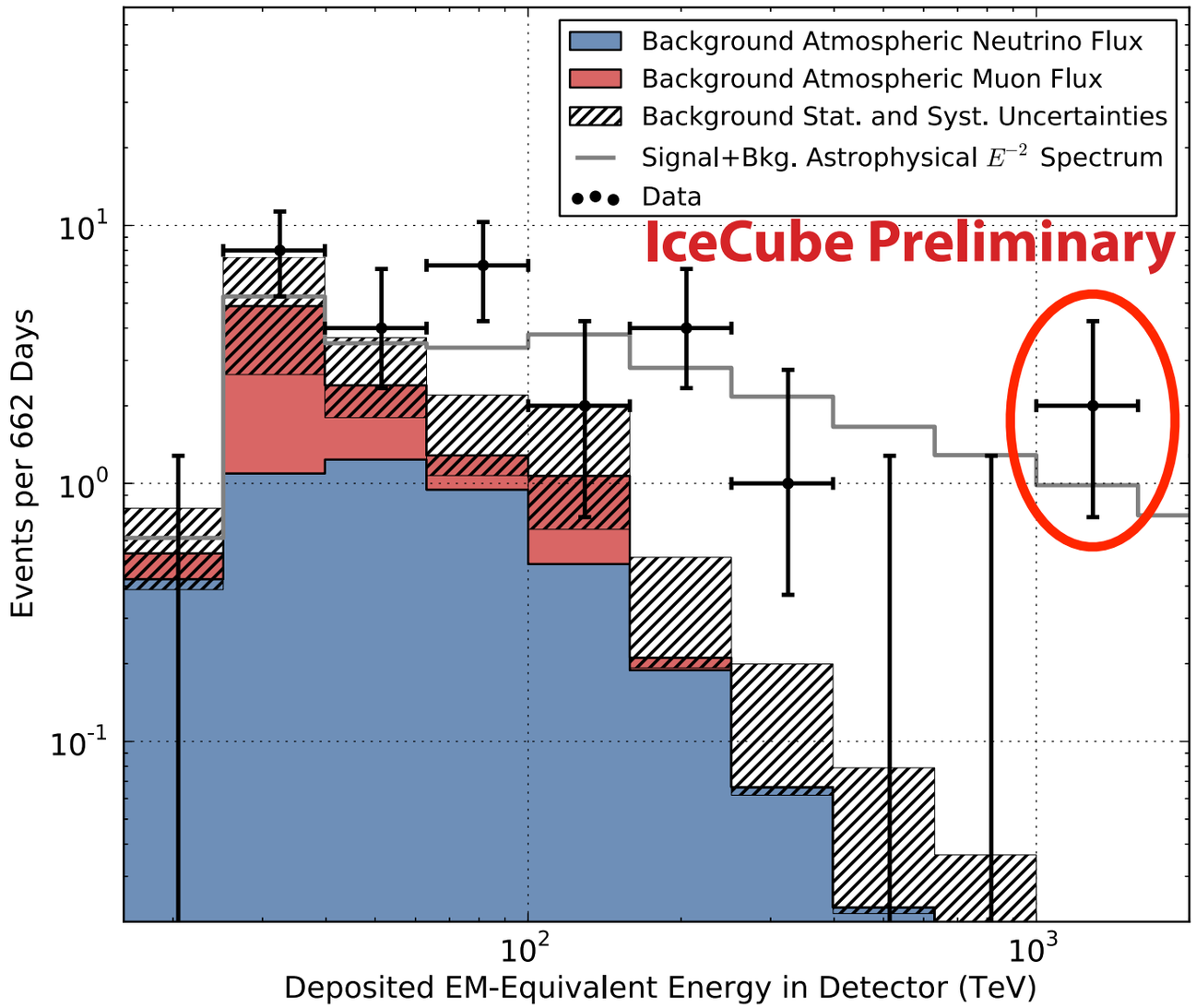
high energy all-flavor neutrino events



high energy "*starting*" events

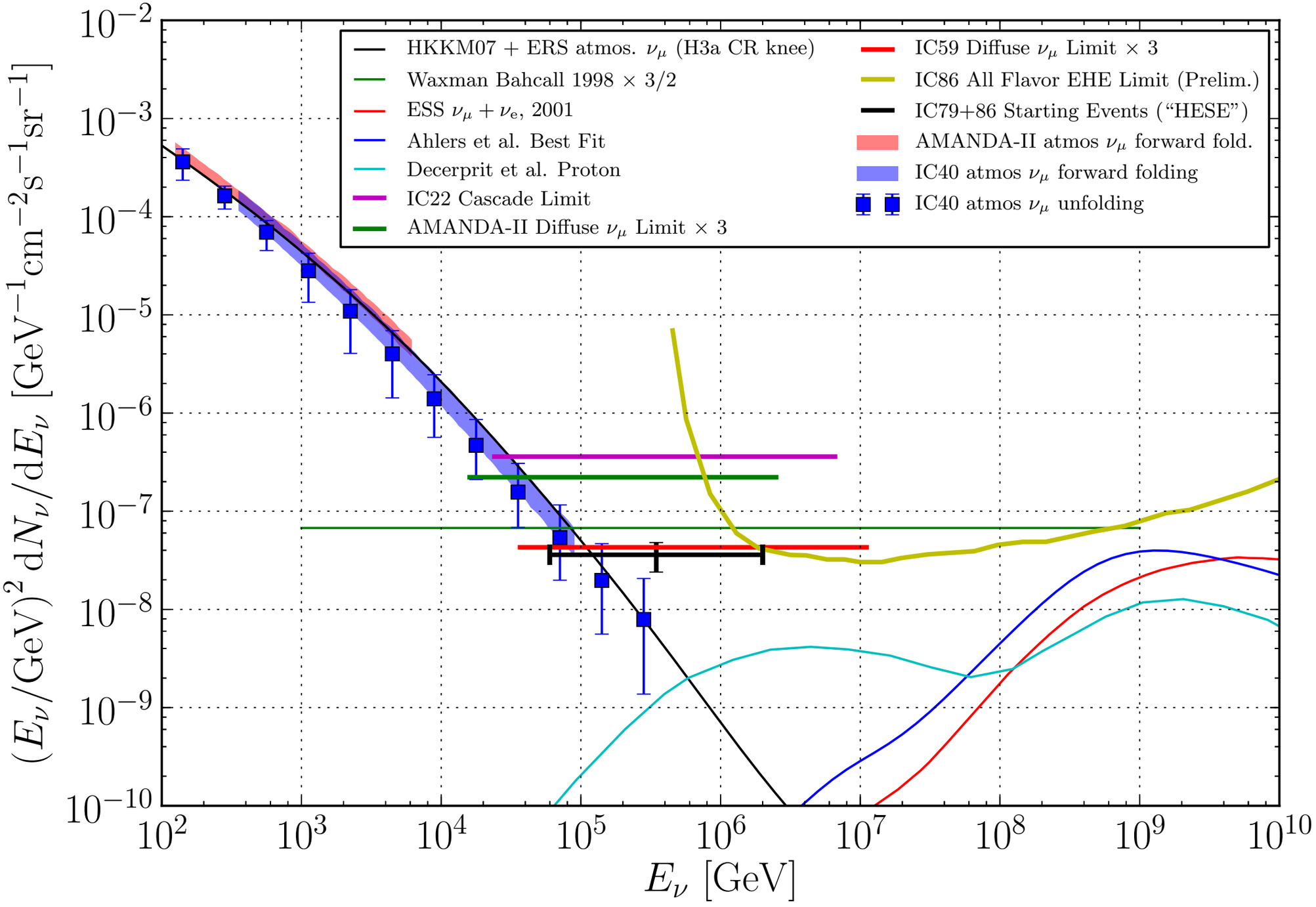
high energy all-flavor neutrino events

- **flatter spectrum than expected**
- smoothly merges into background expectation at low energy (> 30 TeV)
- **potential cutoff at 2-5 PeV**
  - $1.6\ ^{+1.5}_{-0.4}$ PeV (hard cutoff)
- **best fit**
  - $1.2 \pm 0.4 \times 10^{-8}\ E^{-2}$ GeV cm^{-2} s^{-1} sr^{-1}



high energy "*starting*" events

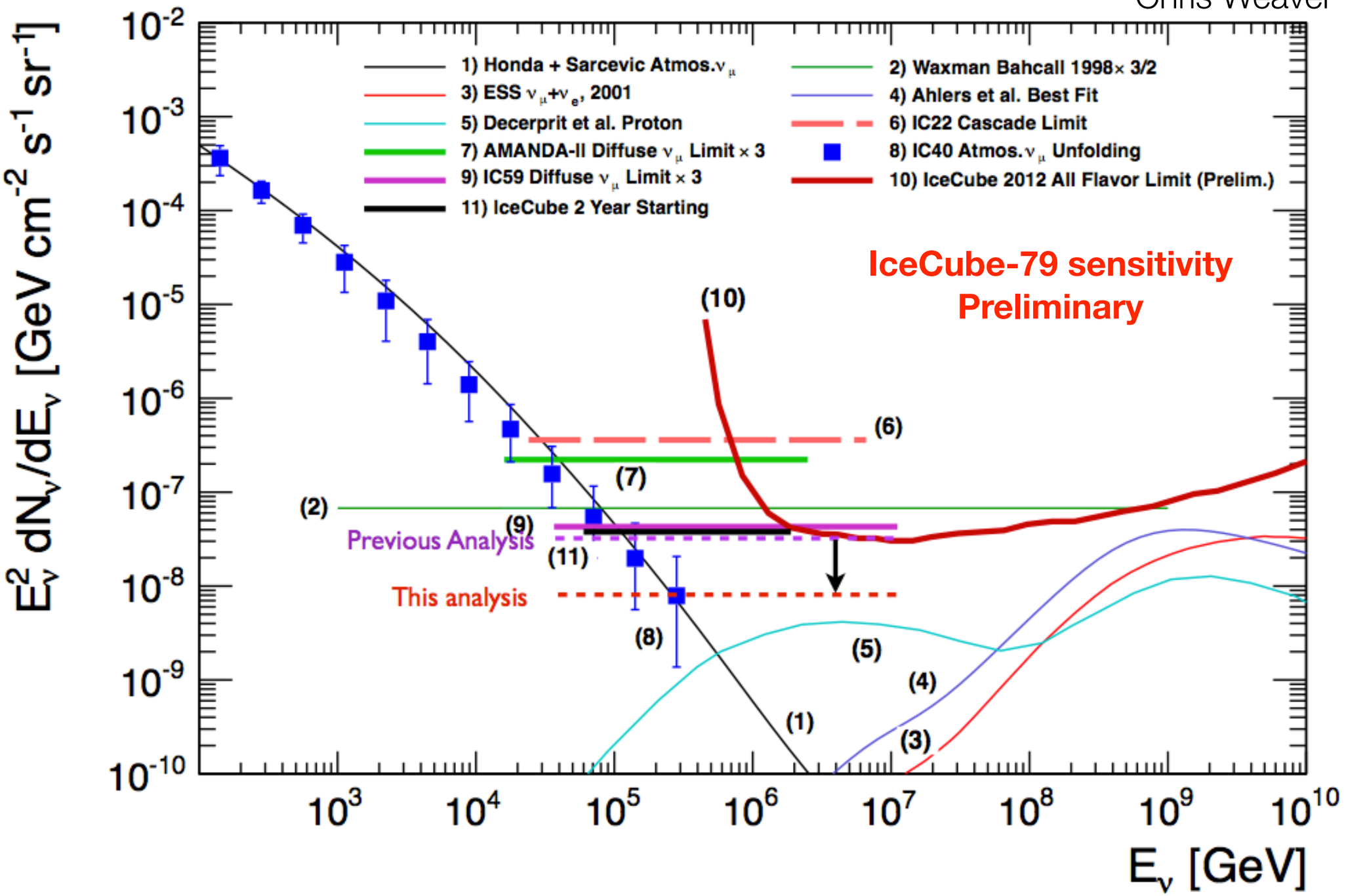
high energy all-flavor neutrino events



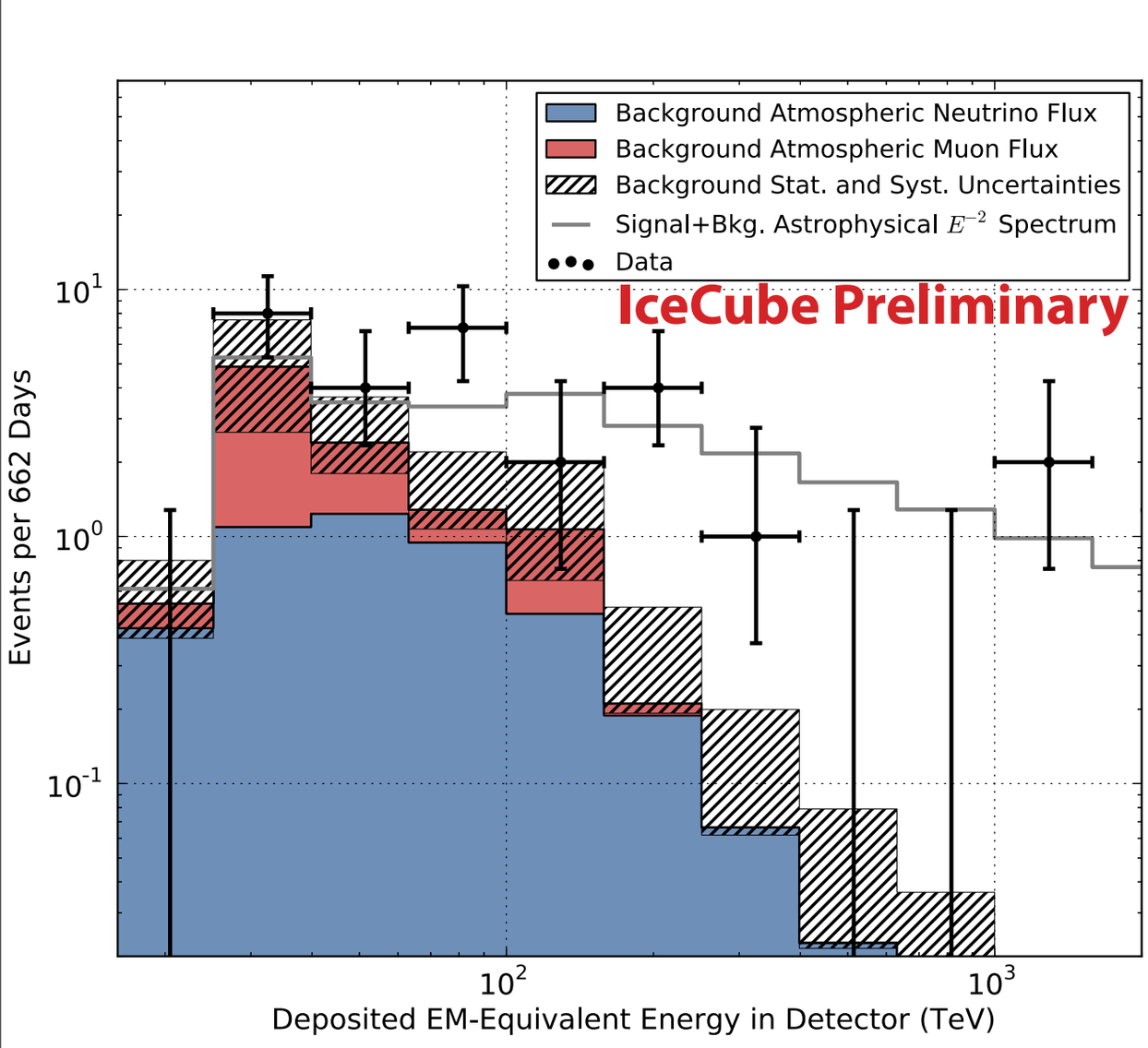
high energy "*starting*" events

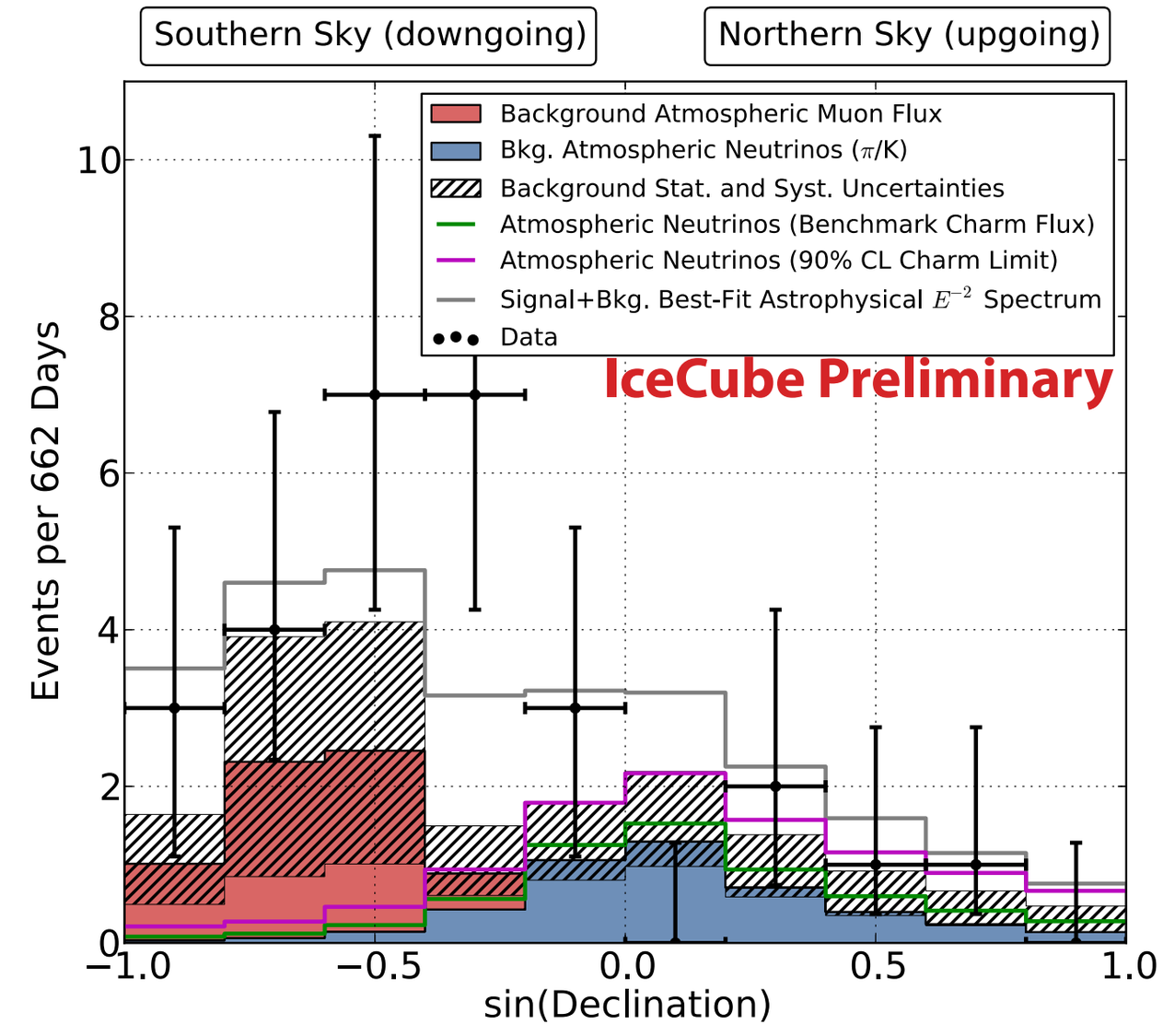
high energy all-flavor neutrino events

through-going muon tracks
Chris Weaver TAUP 2013



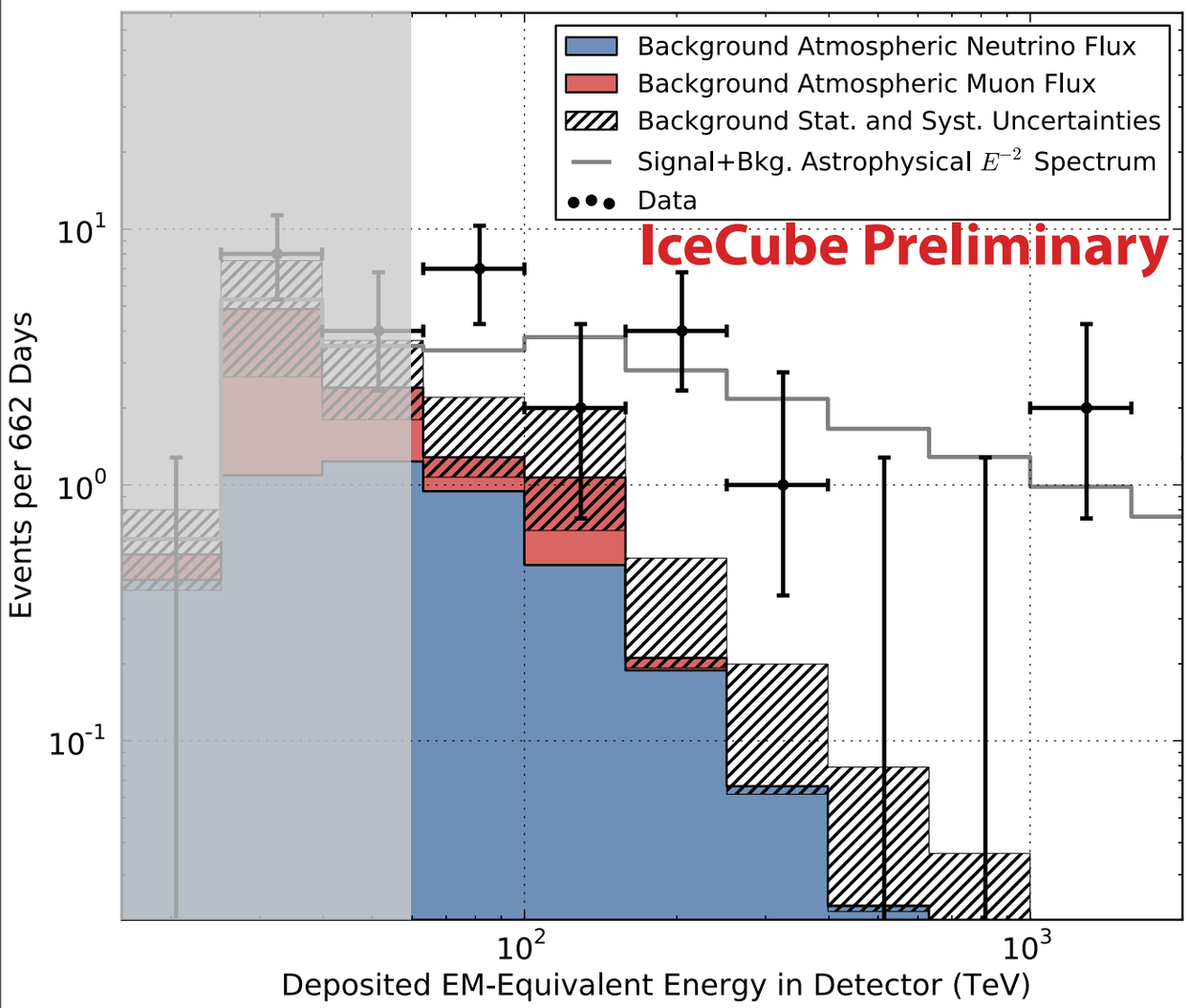
high energy "*starting*" events
angular distribution

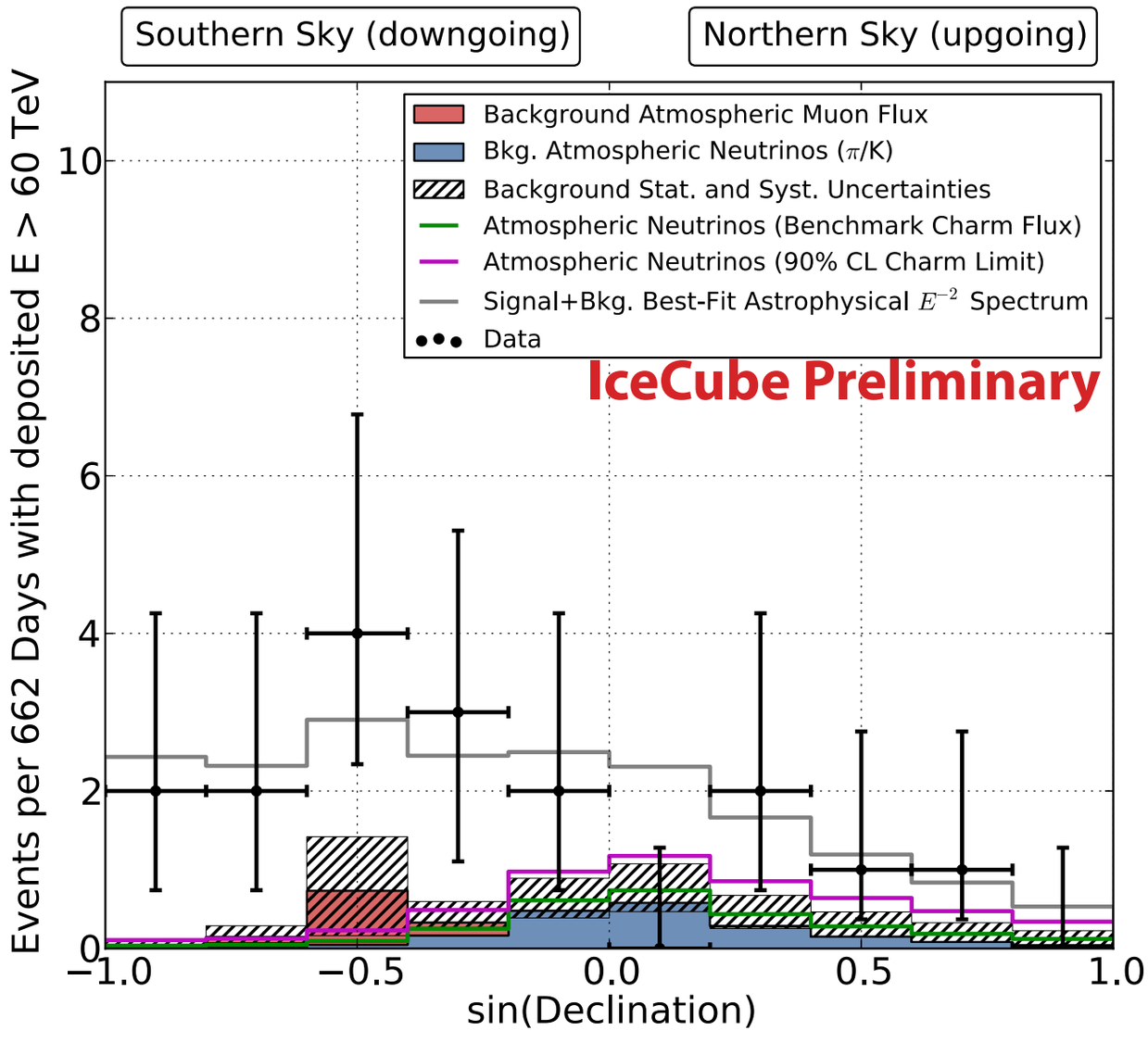




high energy "*starting*" events
angular distribution

> 60 TeV

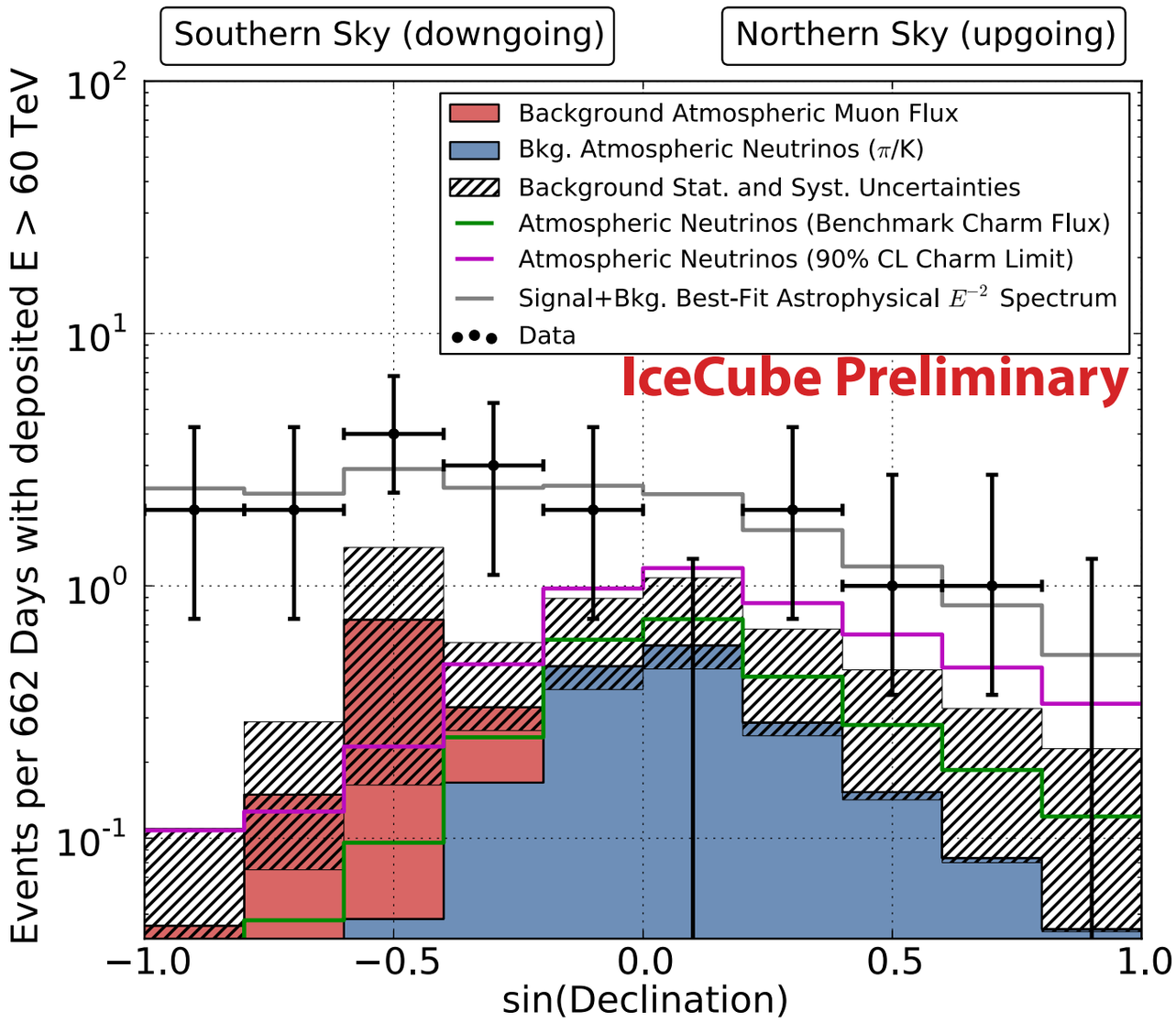




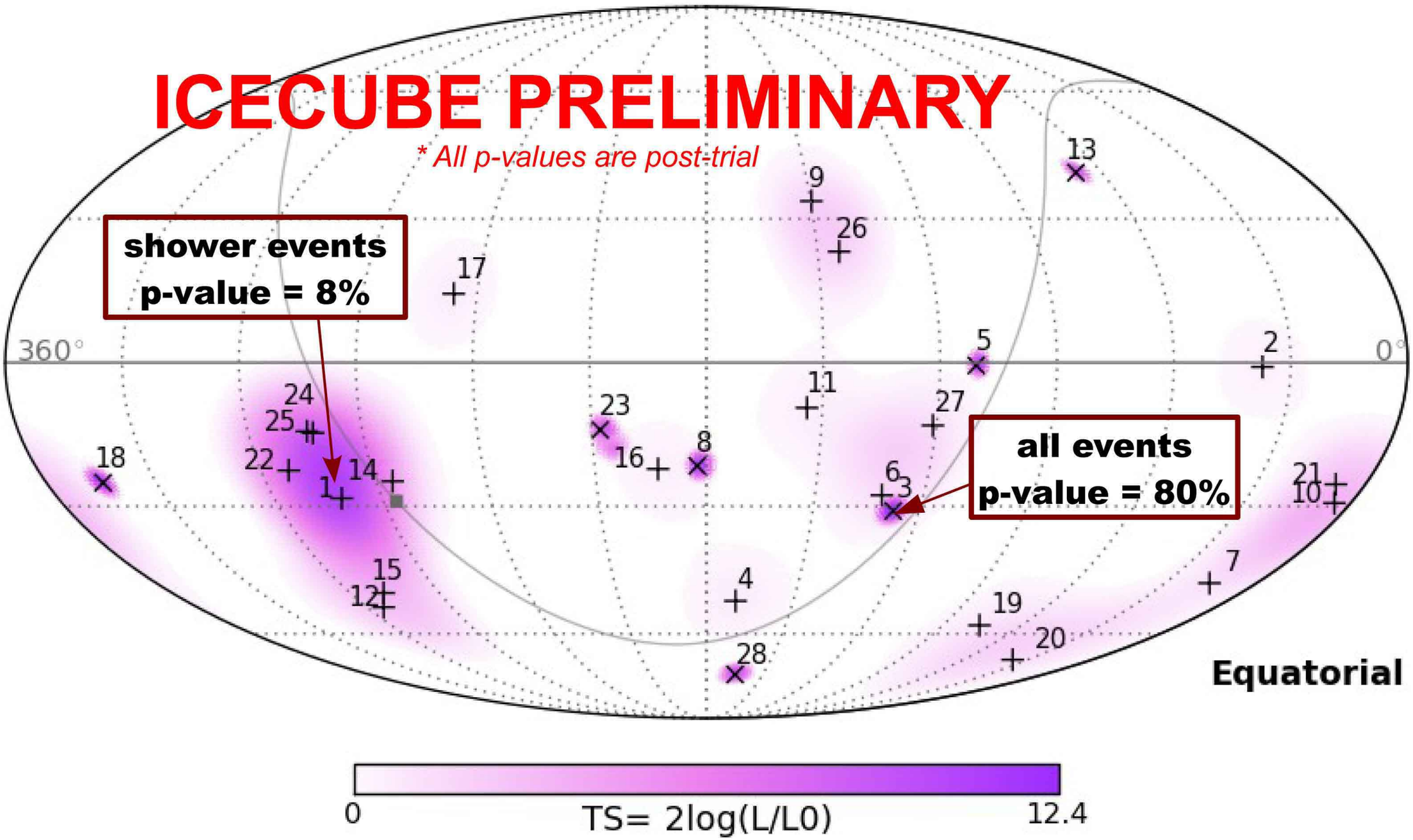
high energy "*starting*" events
angular distribution

> 60 TeV

- compatible with isotropic flux
- Earth absorption from Northern Hemisphere
- minor excess in south but not statistically significant

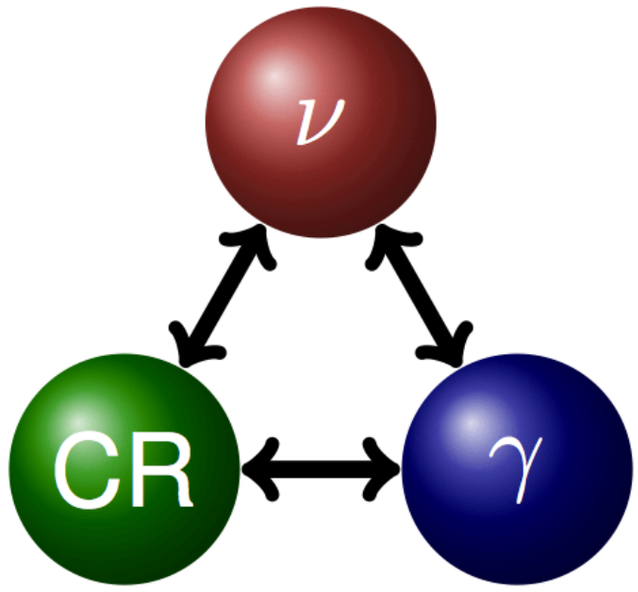


high energy "*starting*" events
arrival distribution



origin of high energy neutrinos ?

- Glashow resonance ?
- galactic or extragalactic ?
- isotropic or point sources ?
- cosmic ray composition ?
- pp or pγ origin ?
- **1 PeV neutrinos ~ 20 TeV CR nucleon ~ 2 PeV γ-rays**



origin of high energy neutrinos ?

- **extragalactic sources:**
  - relation to the sources of UHE CRs [Kistler, Stanev & Yuksel 1301.1703]
  - GZK from low $E_{\max}$ blazars [Kalashev, Kusenko & Essey 1303.0300]
  - cores of active galactic nuclei (AGN) [Stecker *et al.*'91;Stecker 1305.7404]
  - low-power γ-ray bursts (GRB) [Murase & Ioka 1306.2274]
  - starburst galaxies [Loeb&Waxman'06; He *et al.* 1303.1253; Murase, MA & Lacki 1306.3417]
  - hypernova in star-forming galaxies [Liu *et al.* 1310.1263]
  - galaxy clusters/groups [Berezinksy, Blasi & Ptuskin'97; Murase, MA & Lacki 1306.3417]

- **Galactic sources:**
  - heavy dark matter decay [Feldstein *et al.* 1303.7320; Esmaili & Serpico 1308.1105]
  - peculiar hypernovae [Fox, Kashiyama & Meszaros 1305.6606; MA & Murase 1309.4077]
  - diffuse Galactic γ-ray emission [*e.g.* Ingelman & Thunman'96; MA & Murase 1309.4077]

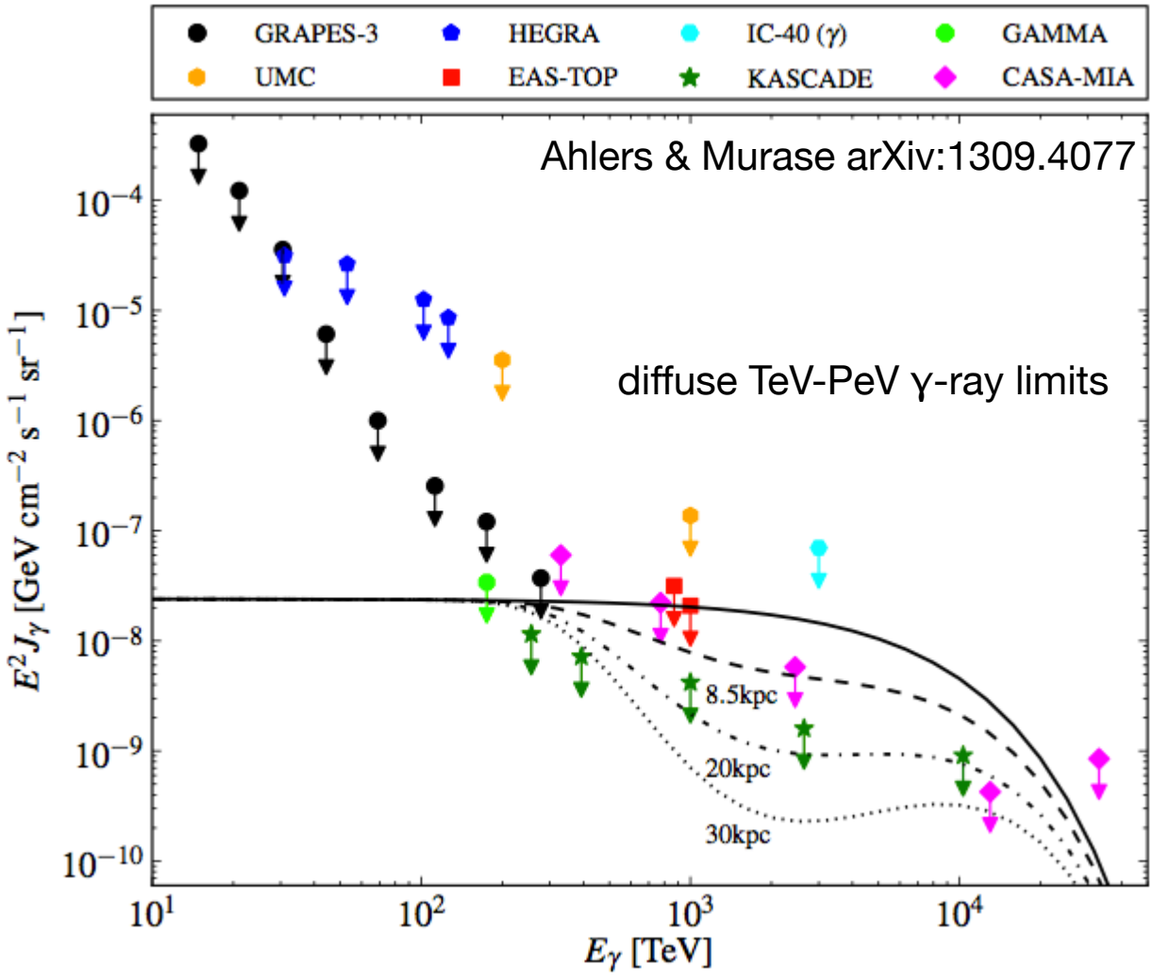
- **γ-ray association:**
  - unidentified Galactic TeV γ-ray sources [Fox, Kashiyama & Meszaros 1306.6606]
  - sub-TeV diffuse Galactic γ-ray emission [Neronov, Semikoz & Tchernin 1307.2158]

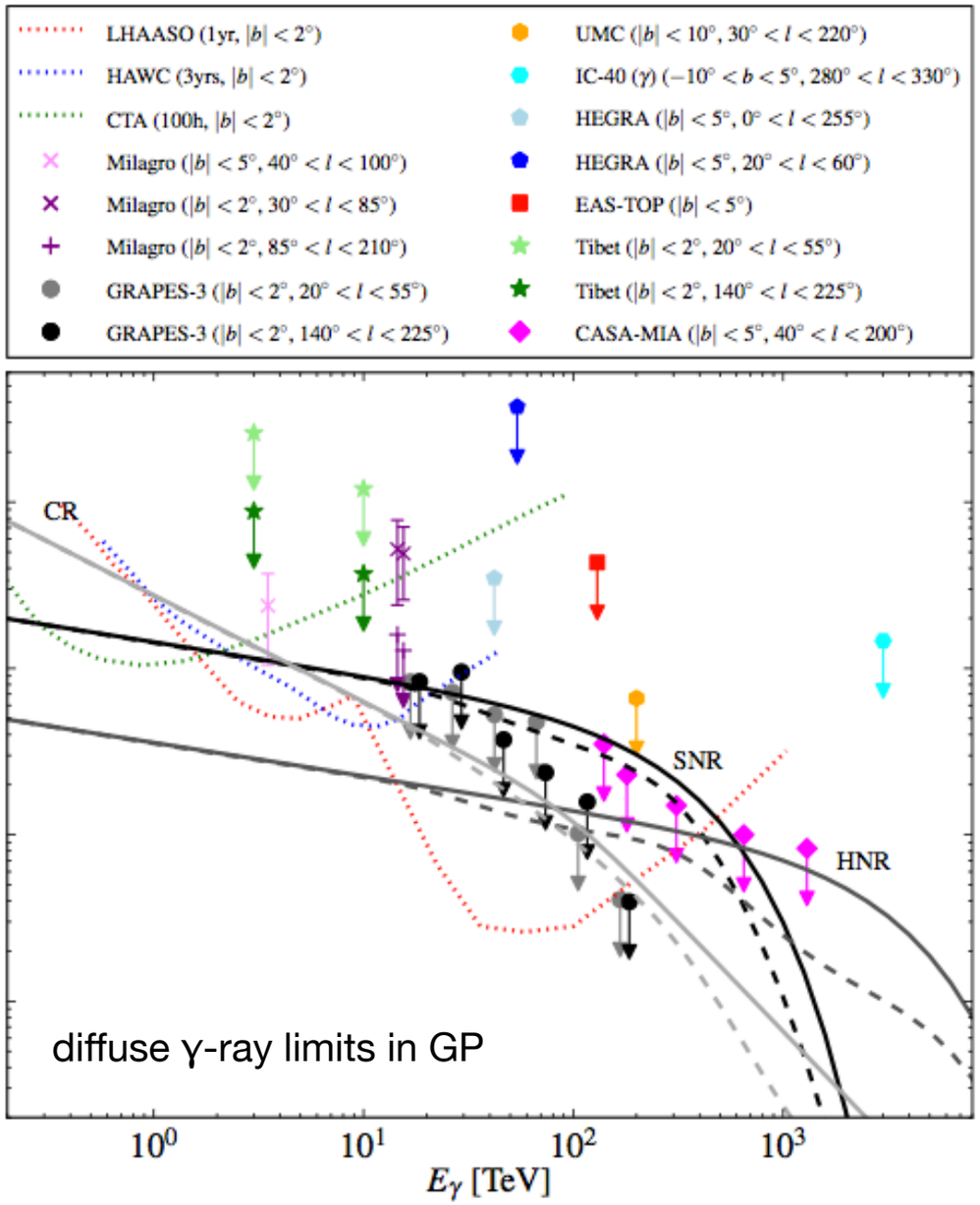
origin of high energy neutrinos ?

IceCube Coll. PRD 87, 062002, 2013

- strong **constraints** of galactic isotropic emission of γ-rays

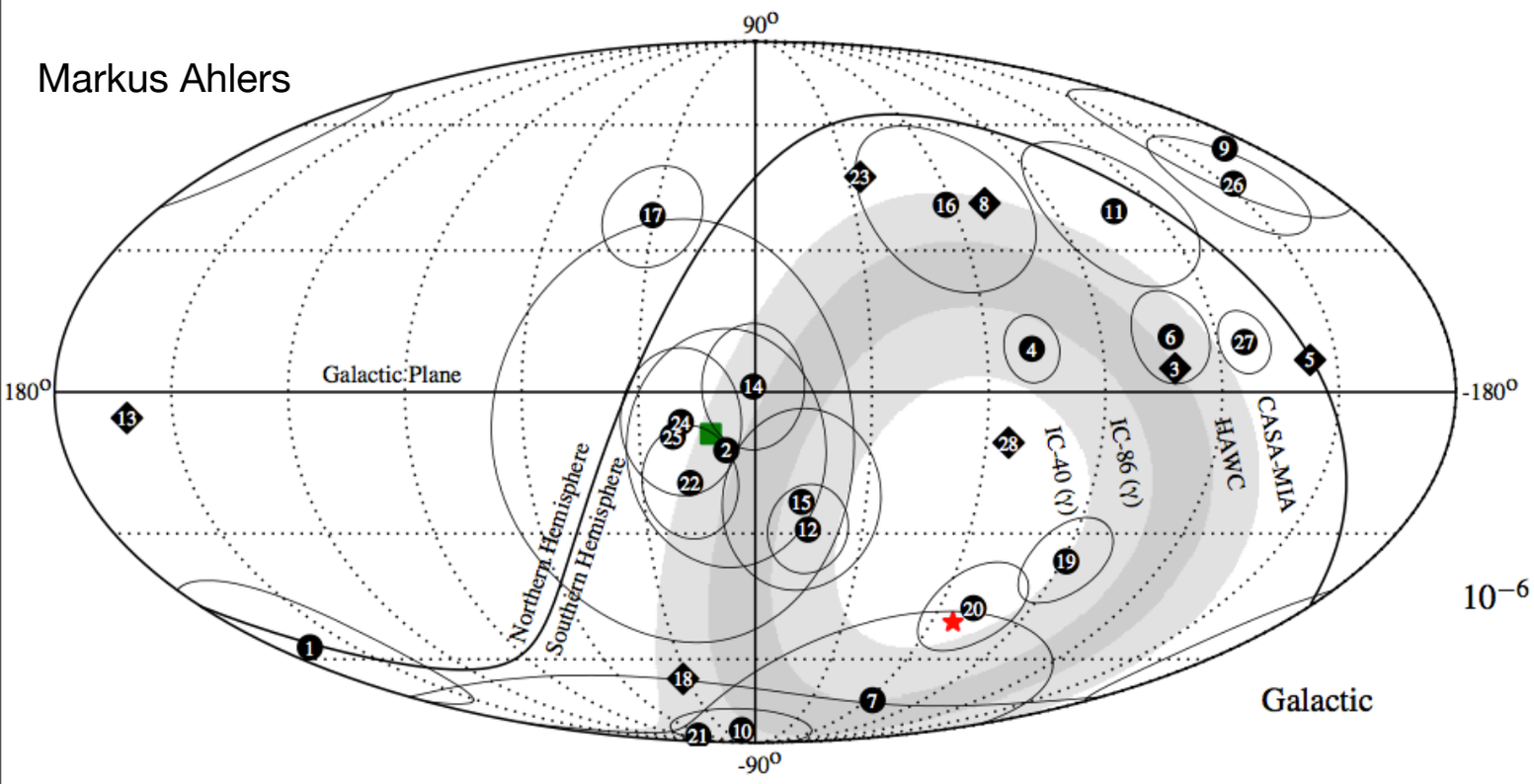
- **disfavor** contribution from SNR & HyperNovae



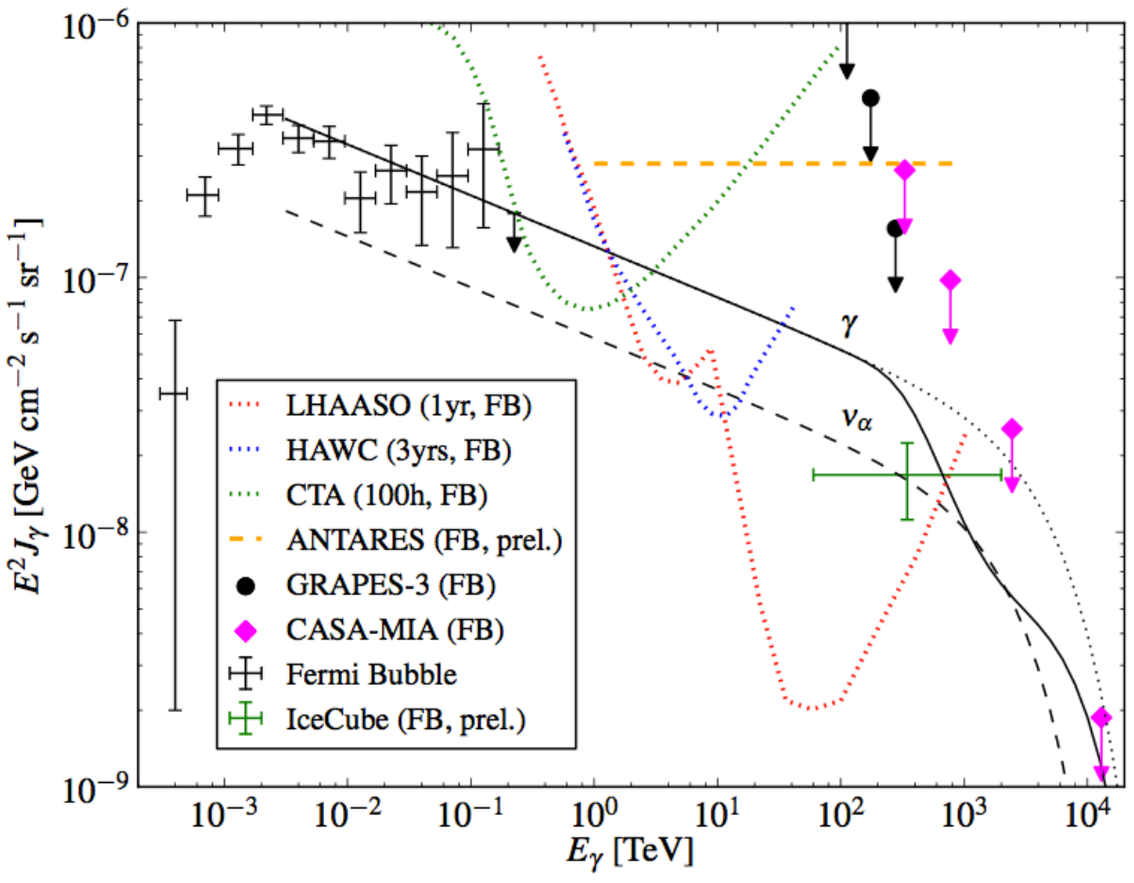


origin of high energy neutrinos ?

Markus Ahlers



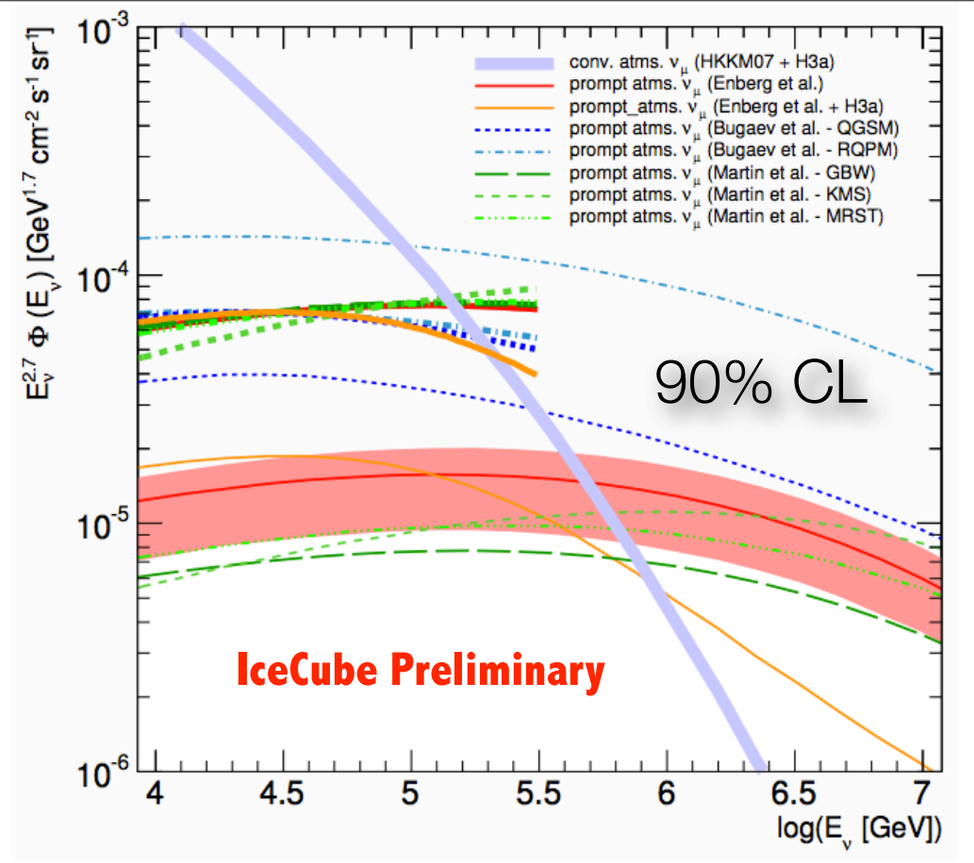
Ahlers & Murase arXiv:1309.4077



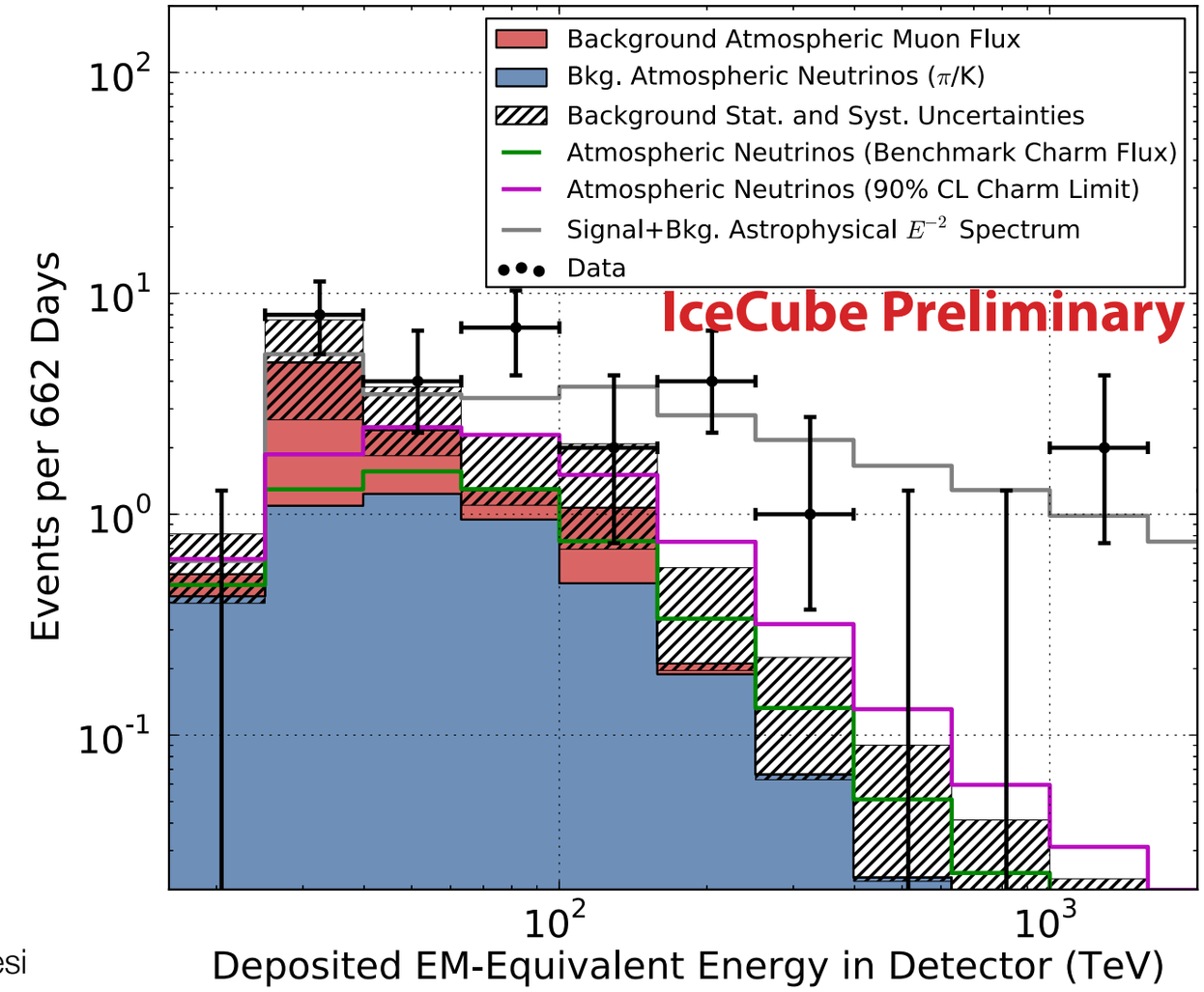
- 15 high energy neutrino in **blind region**
- **Fermi Bubble** to explain southern excess ?

atmospheric neutrinos
charm and astrophysical neutrinos

- how easy is to measure an **astrophysical** signal ? It depends on its spectrum



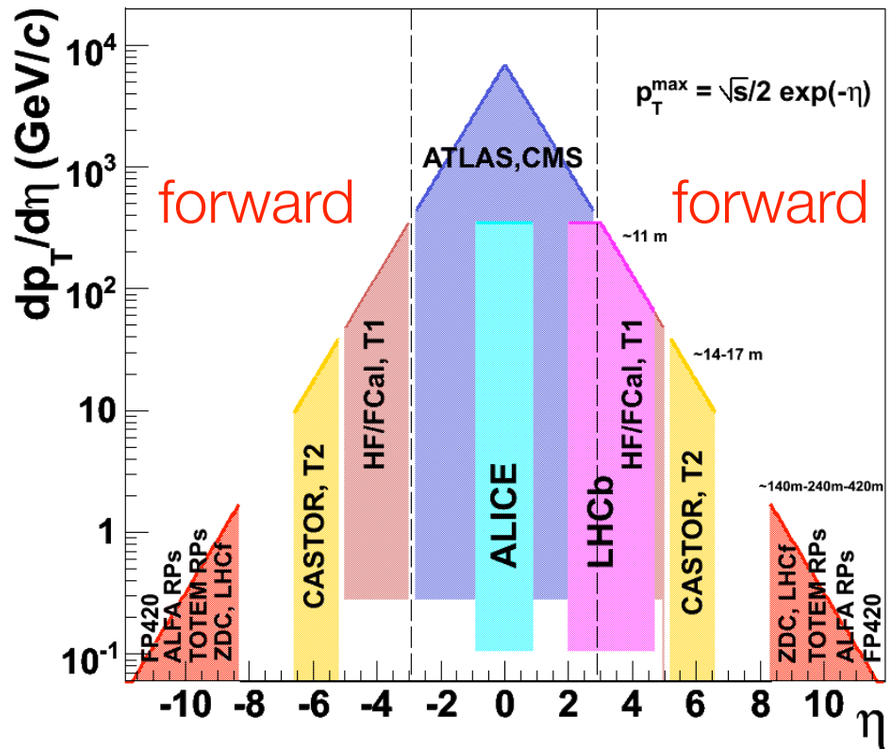
- can neutrino telescopes ***observe*** neutrinos from **charm** ? And constrain models ? And break **degeneracy** between charm & astrophysics ?

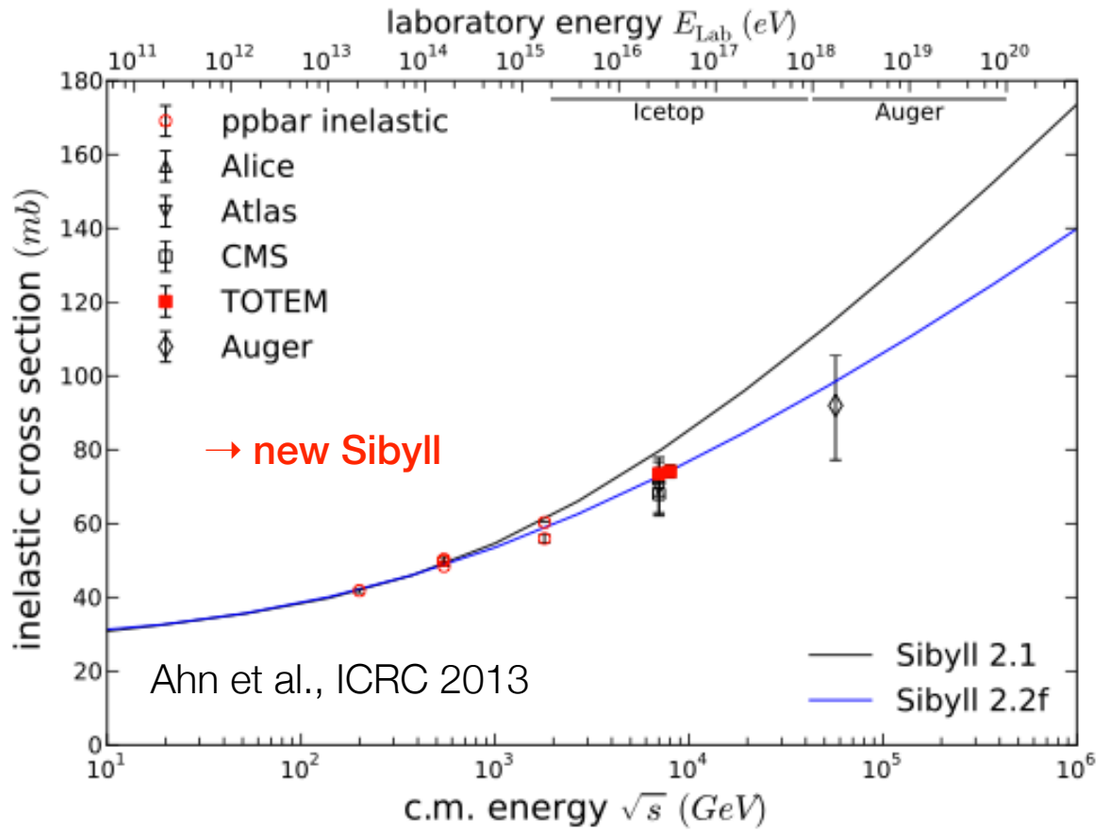


hadronic interactions
forward physics

- CR showers dominated by **soft component with small p_T** (*non-perturbative QCD*)
- **hard component (heavy quarks) with high p_T** (pQCD)
- **phenomenological** descriptions of hadronic interactions with minijet production for hard component
- **models** to describe soft/hard **interactions** in **forward region** & **extrapolated to high energy**

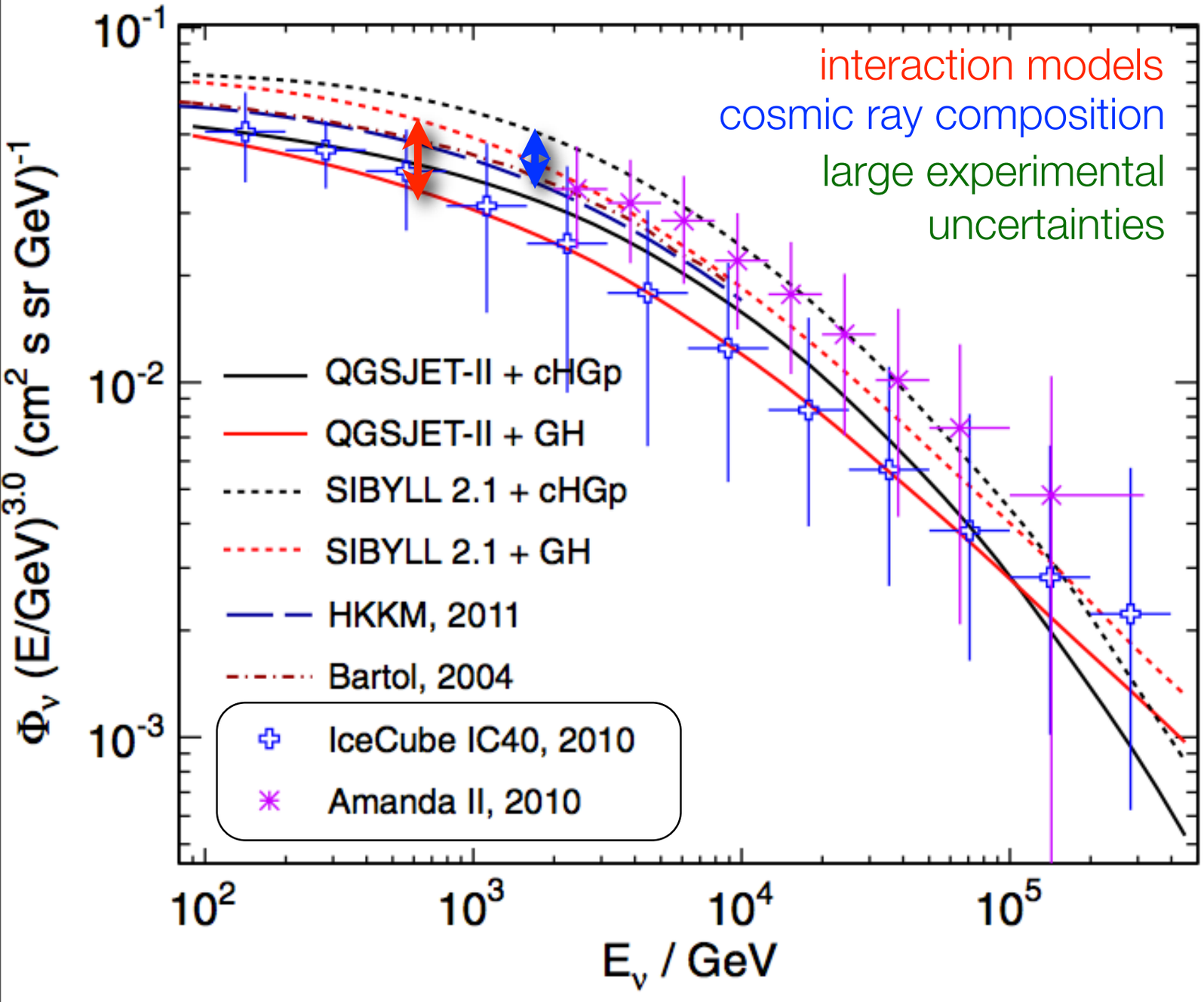
transverse momentum p_T
vs
pseudo-rapidity

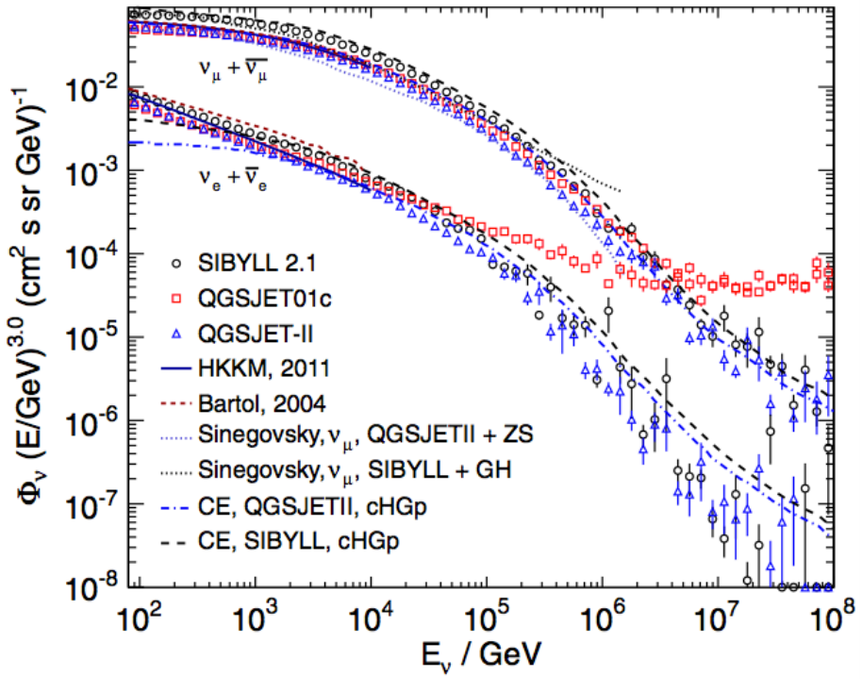




atmospheric neutrinos
experimental observations

observed through-going $\nu_\mu + \bar{\nu}_\mu$





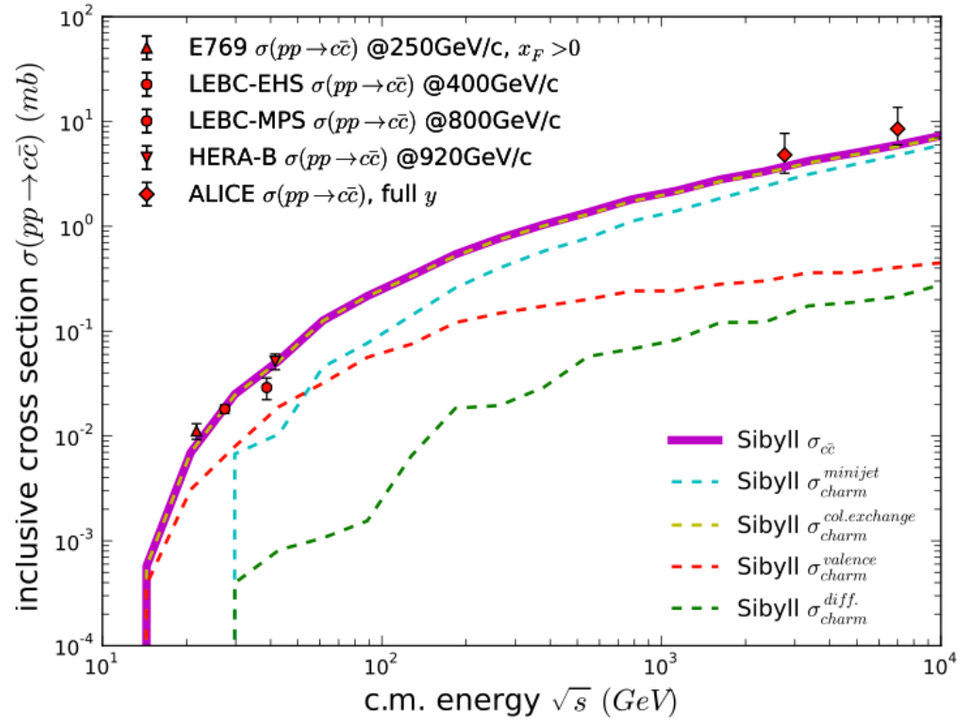
uncertainties from

- hadronic interaction models (K physics and heavy quark physics)
- primary cosmic ray composition

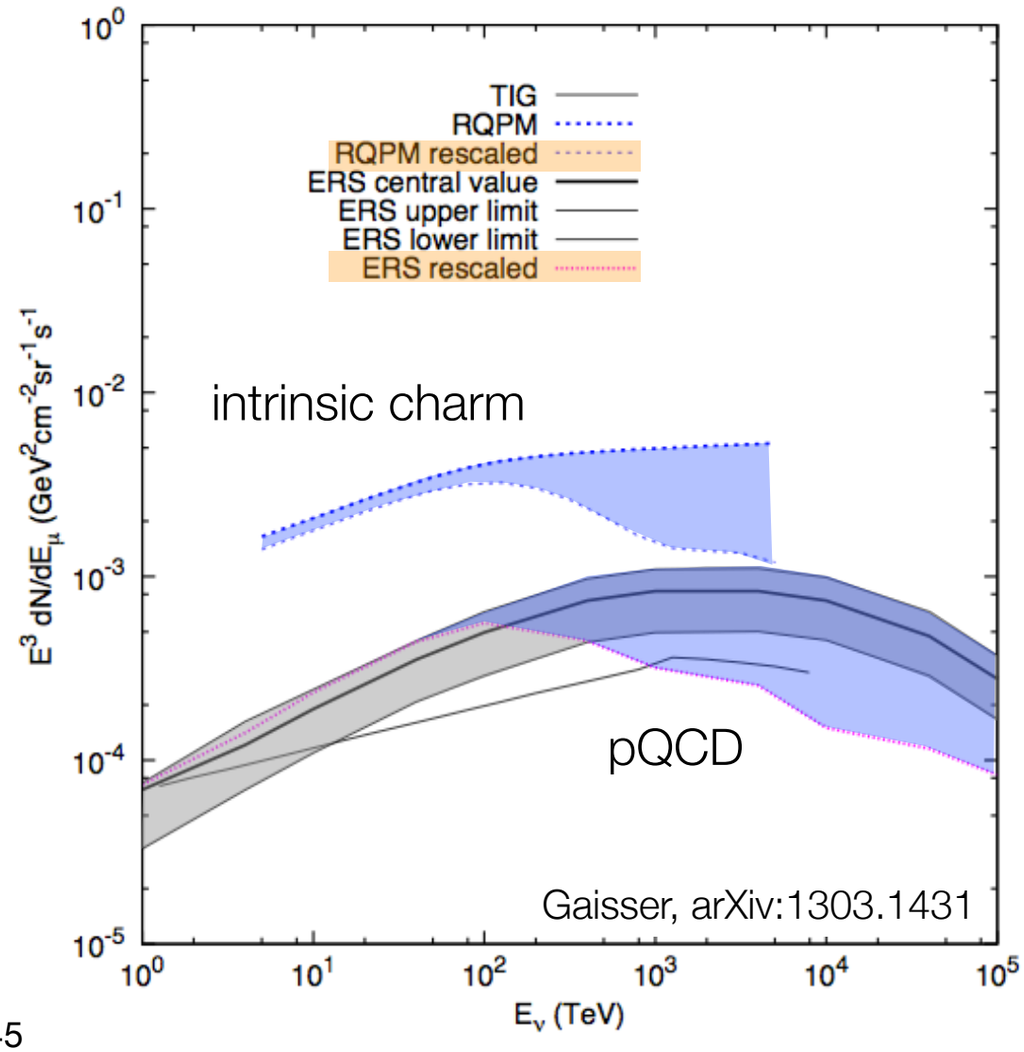
Fedynitch, Becker Tjus, PD 2012

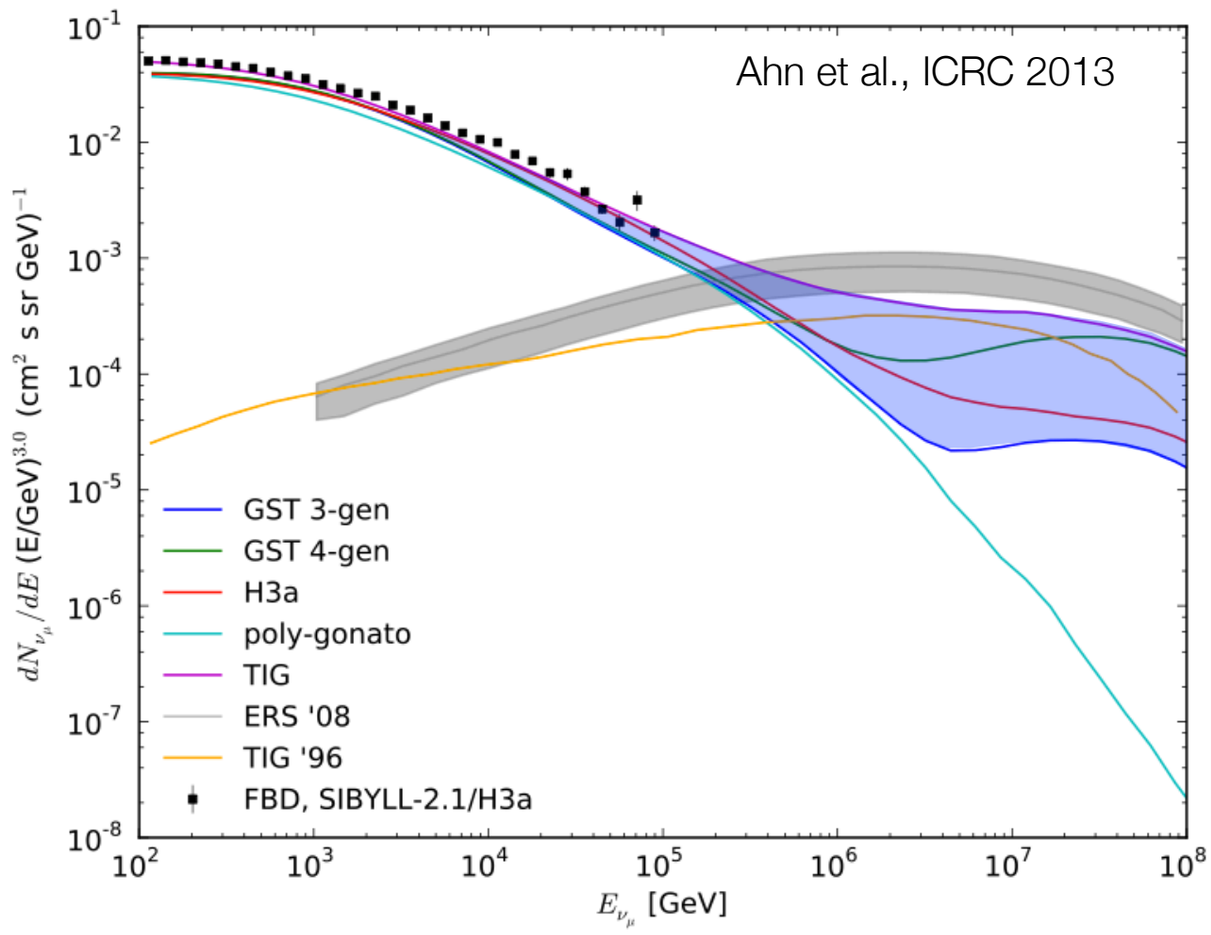
atmospheric neutrinos
charm production

- effect of charm production **models**
- effect of primary **cosmic ray spectrum**



Sibyll 2.2 - PRELIMINARY



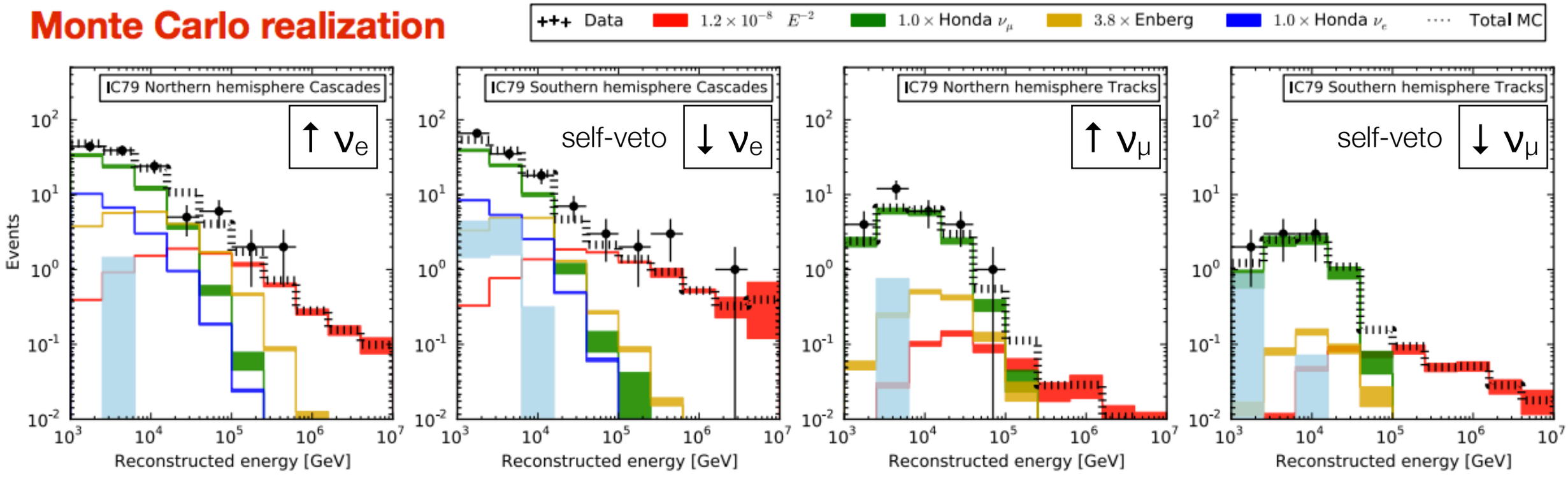


atmospheric neutrinos
charm and astrophysical neutrinos

- lower energy threshold to search for all flavor starting events
- <10 TeV constrains conventional atmospheric contribution
- 10-50 TeV constrains onset of charm component
- north/south weakens degeneracy between hard atmospheric and additional components

J. van Santen - TAUP 13

Monte Carlo realization

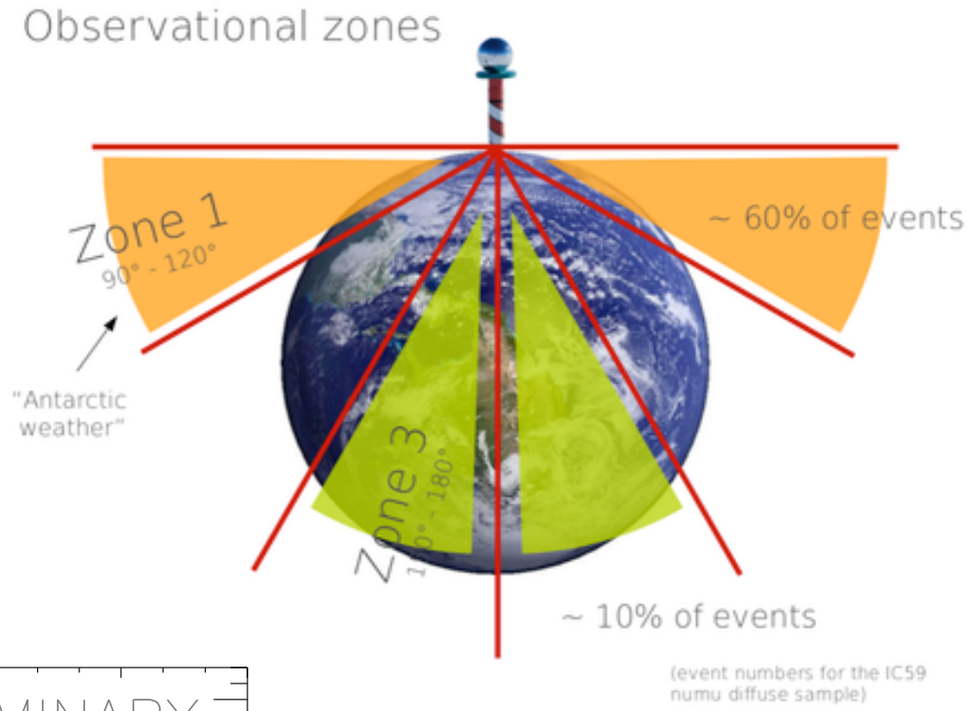


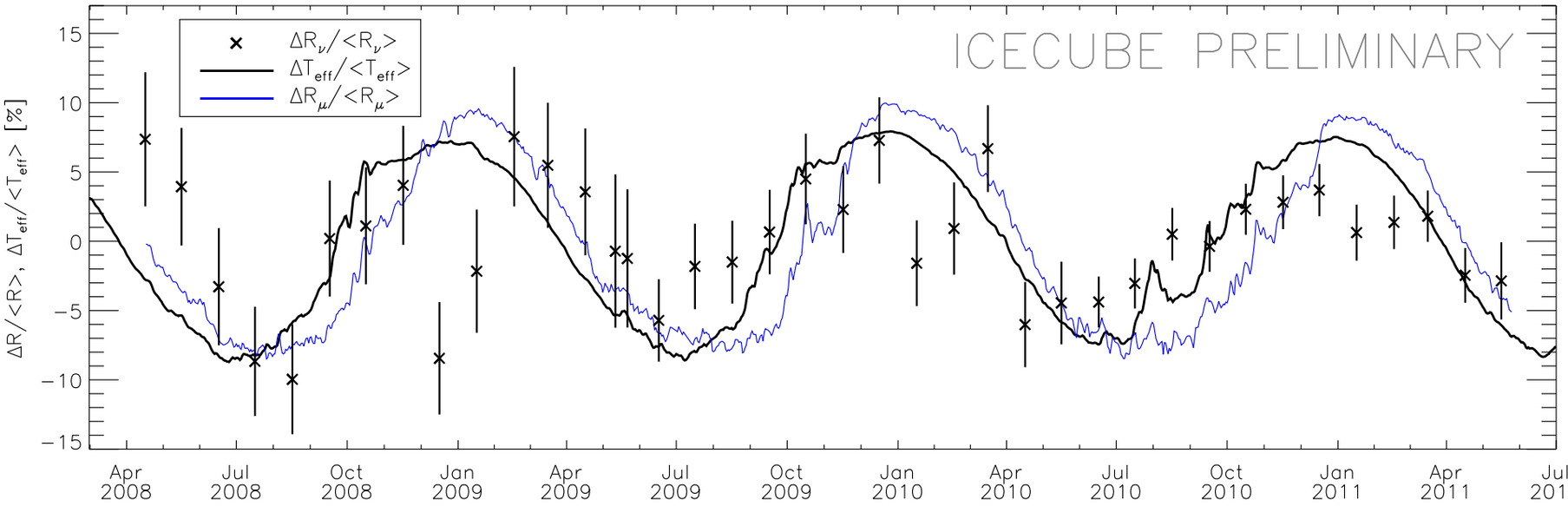
atmospheric neutrinos

charm & **ν** seasonal variations

effective temperature

$$T_{eff}(\theta) = \frac{\int dE_\nu \int dX \; A_{eff}(E_\nu,\theta) P(E_\nu,\theta,X) T(\theta,X)}{\int dE_\nu \int dX \; A_{eff}(E_\nu,\theta) P(E_\nu,\theta,X)}$$





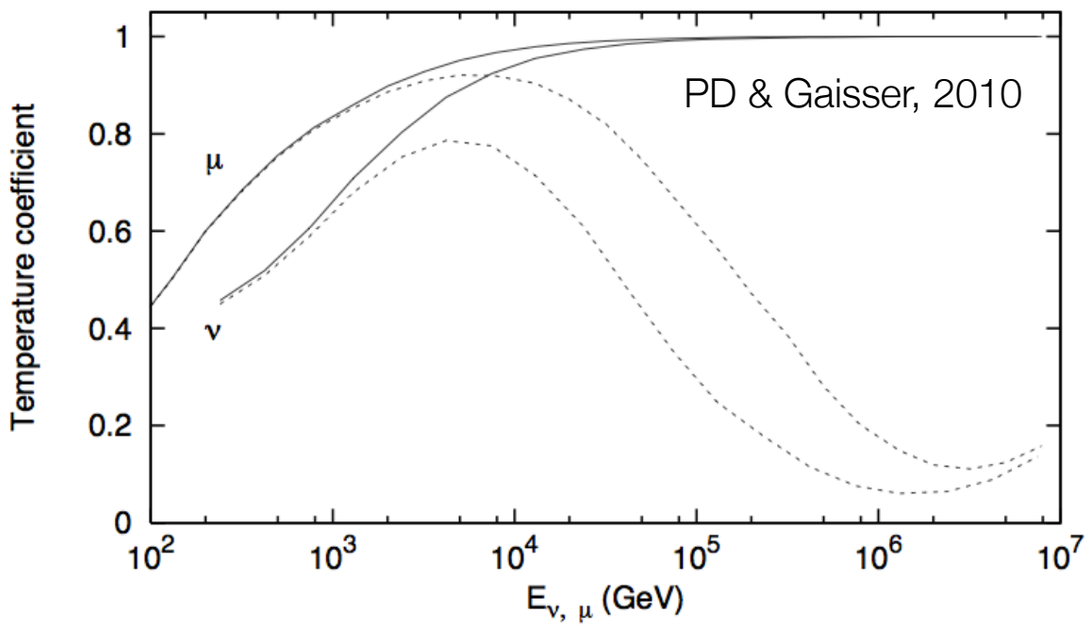
Tilav et al., ICRC 2009
PD et al., ICRC 2011
PD et al., ICRC 2013

seasonal variations decrease with prompt component

temperature coefficient

$$\alpha_T^{th}(\theta) = \frac{T \cdot \frac{\partial}{\partial T} \int dE_\nu \, \phi_\nu(E_\nu,\theta) A_{\rm eff}(E_\nu,\theta)}{\int dE_\nu \, \phi_\nu(E_\nu,\theta) A_{\rm eff}(E_\nu,\theta)}$$

$$\frac{\Delta R_\nu}{\langle R_\nu \rangle} = \alpha_T^{exp} \frac{\Delta T_{\rm eff}}{\langle T_{\rm eff} \rangle}$$

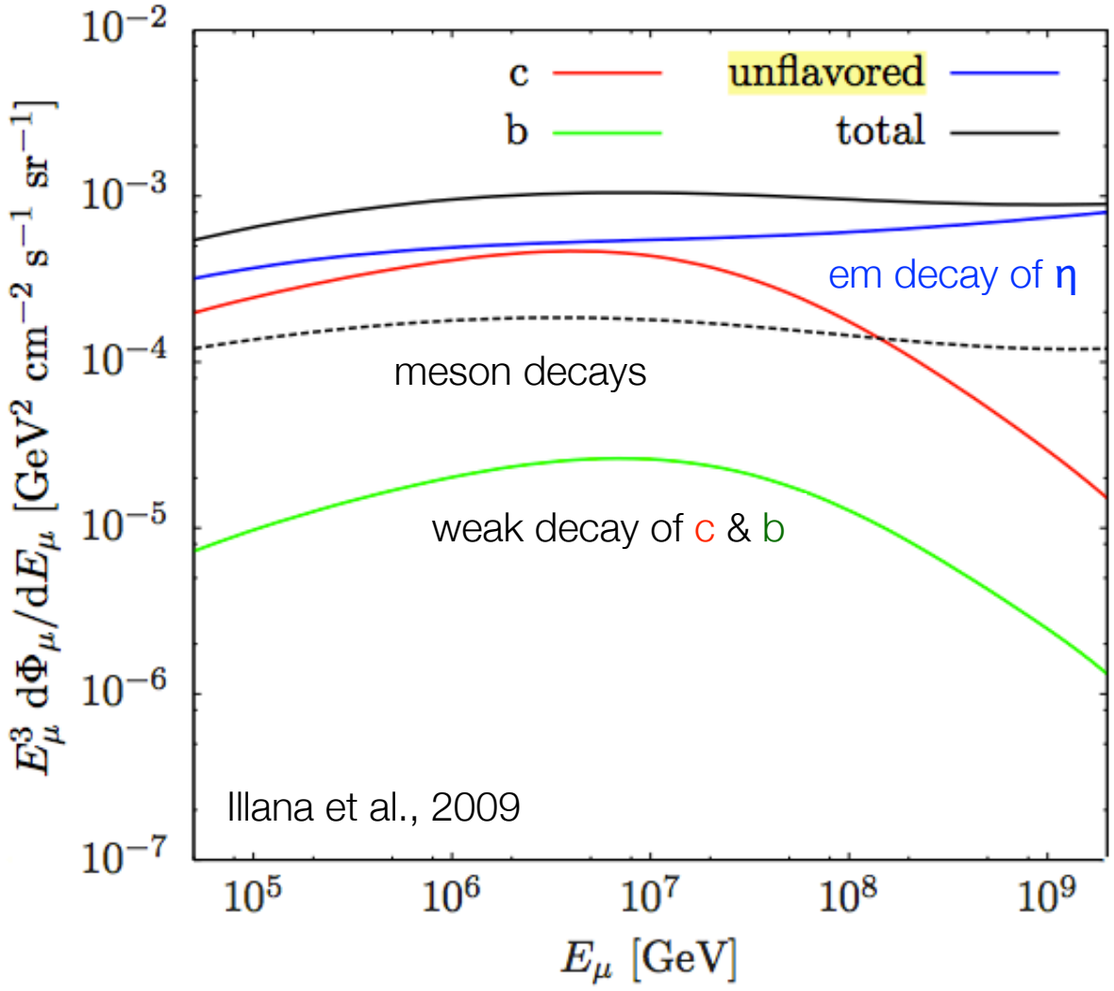


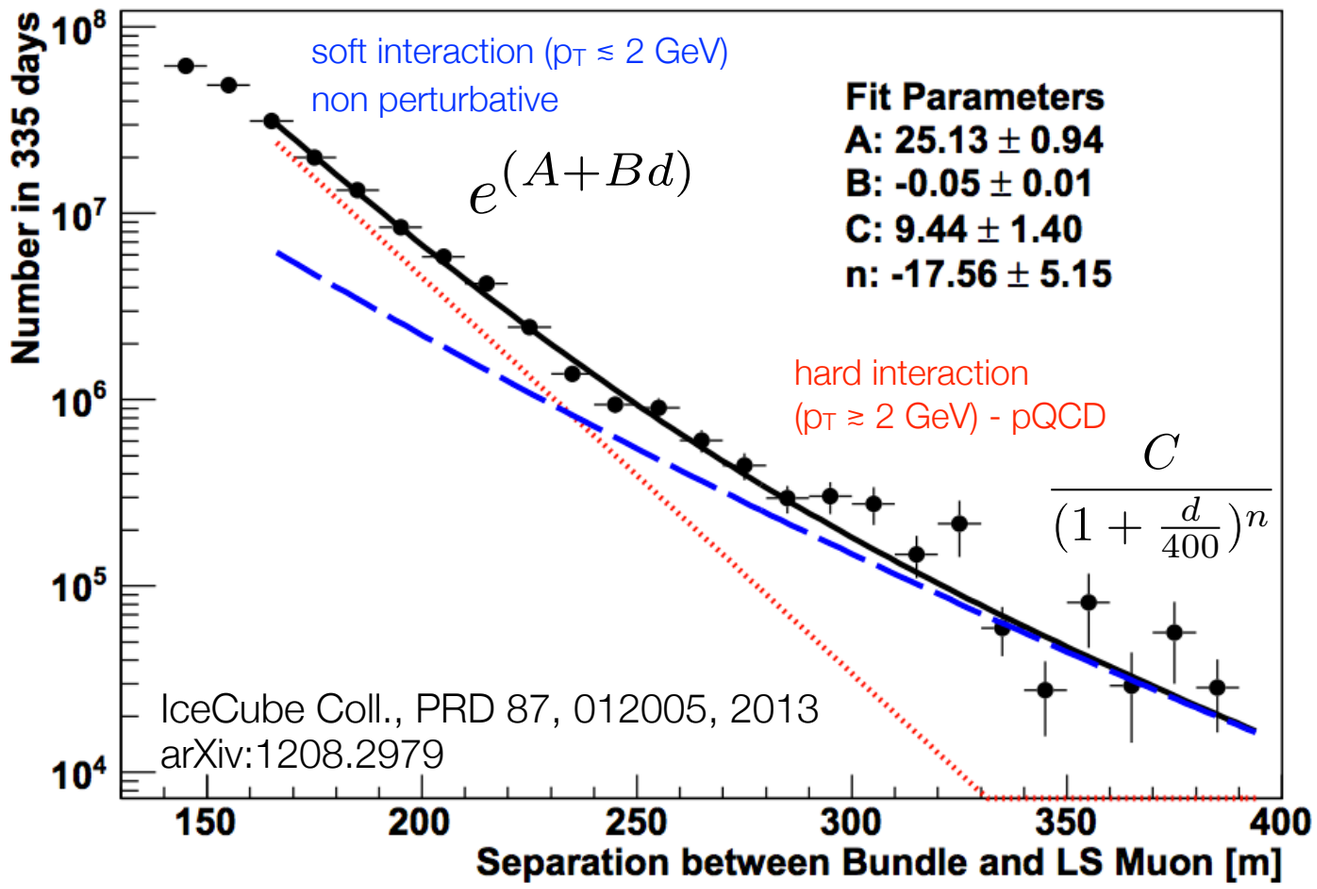
μ not *contaminated* by astrophysical signal
BUT multiplicity

charm production in the atmosphere

breaking the degeneracy with astrophysical signal

- μ produced by **same processes** as ν
- BUT not *contaminated* by HE signal
- hadronic model **uncertainties** (effect of unflavoured mesons)





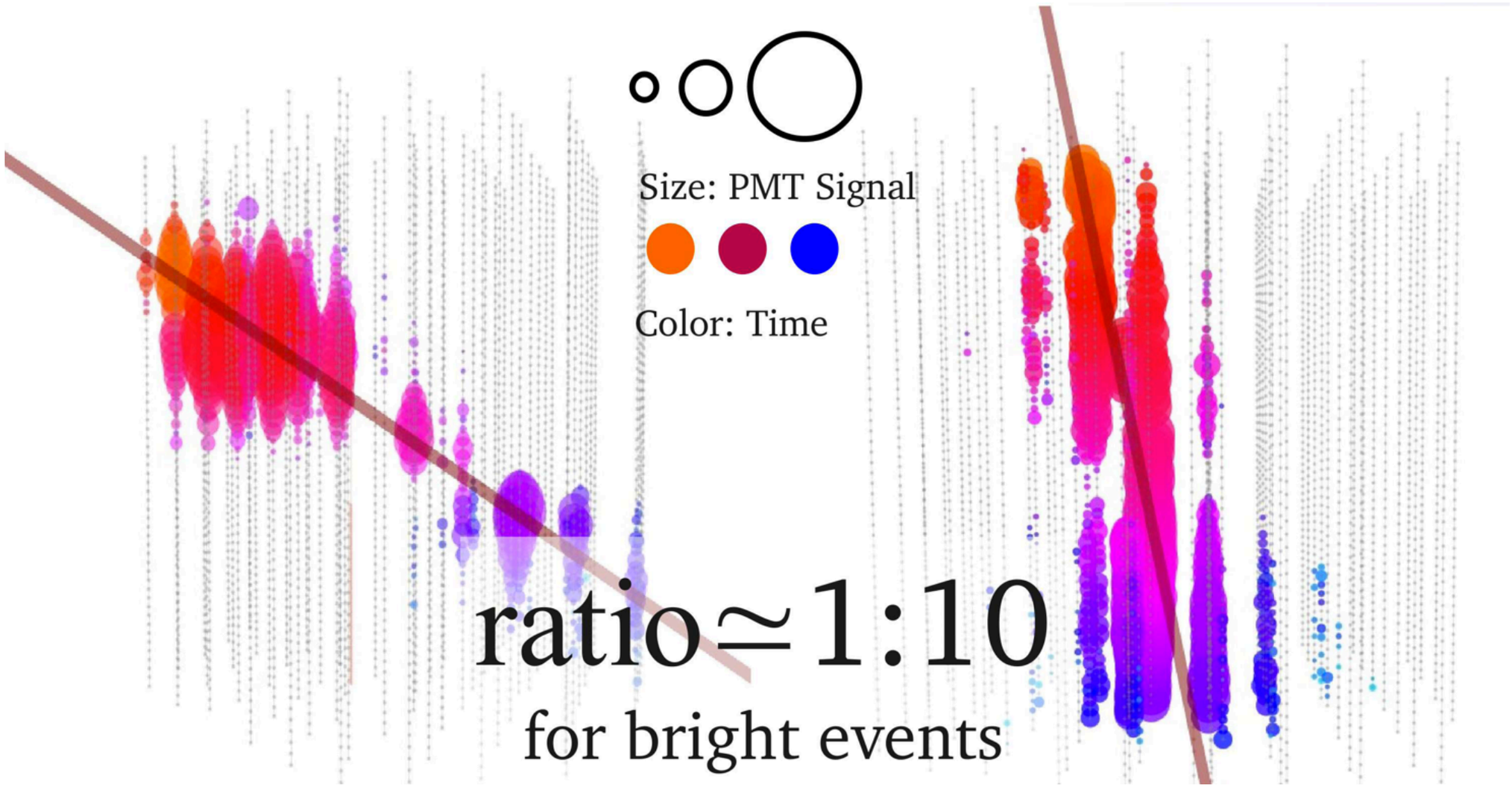
$$d_T \approx \frac{p_T H c}{E_\mu cos(\theta)}$$

charm production in the atmosphere

breaking the degeneracy with astrophysical signal

- separate μ bundles (smooth) from high energy μ (stochastic energy losses)

- measure energy spectrum up to PeV scale



HE muon

High multiplicity bundle

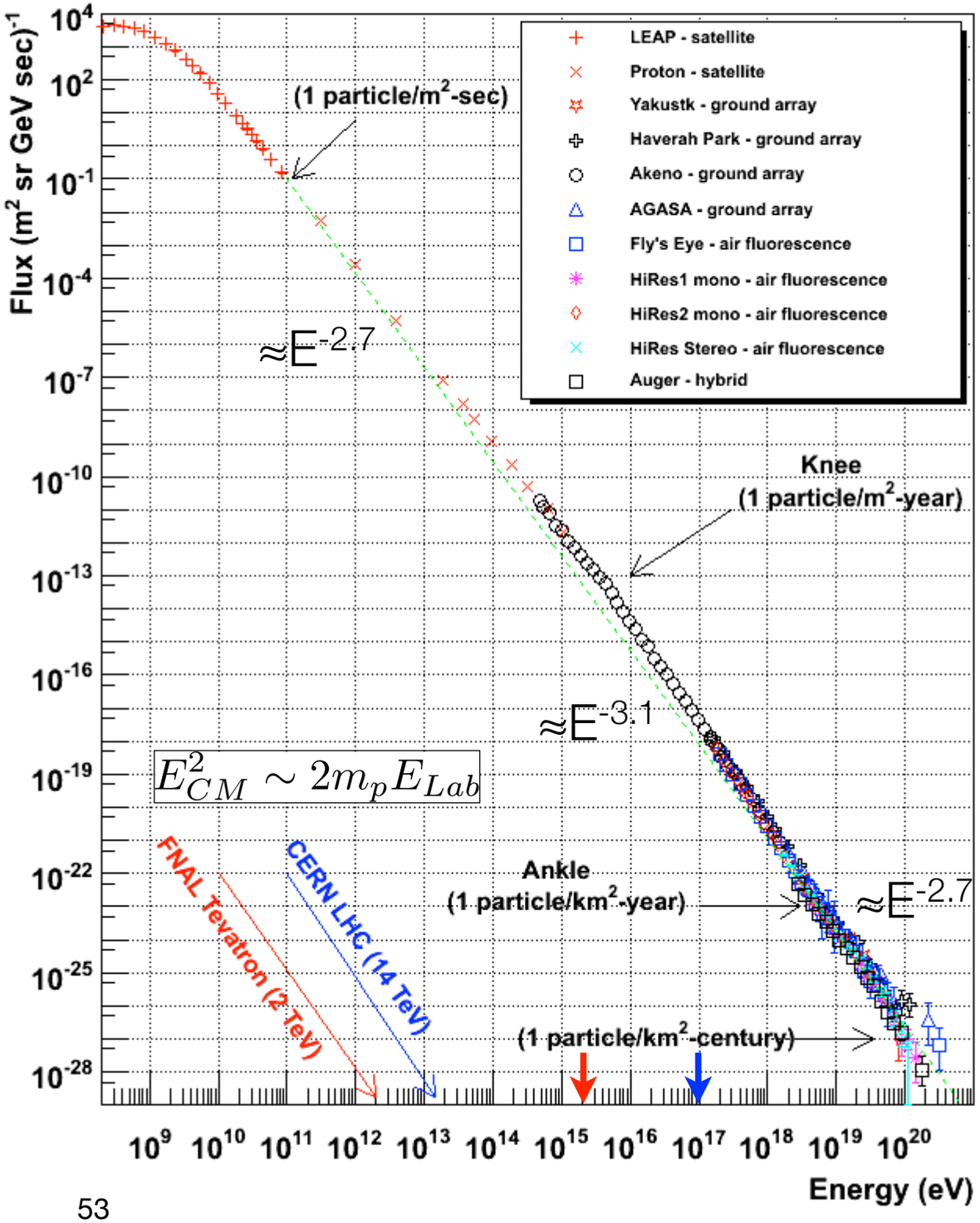
summary

- are we at the beginning of **neutrino astrophysics** ?
- more data will help understand the nature of **PeV neutrinos**
- a better understanding of **charm** production in the atmosphere
- break **degeneracy** between prompt and an additional high energy component
- IceCube is working in **probing** charm production in the atmosphere
- need **forward physics** observations at high energy

Grazie !

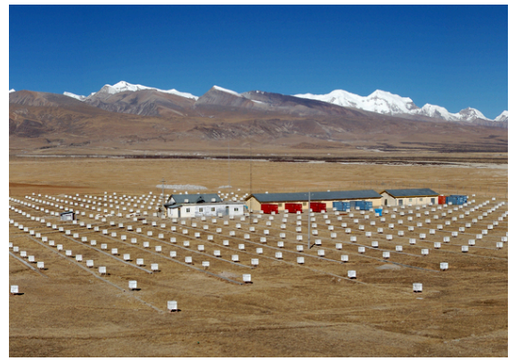
spare slides

primary cosmic rays
spectrum & composition

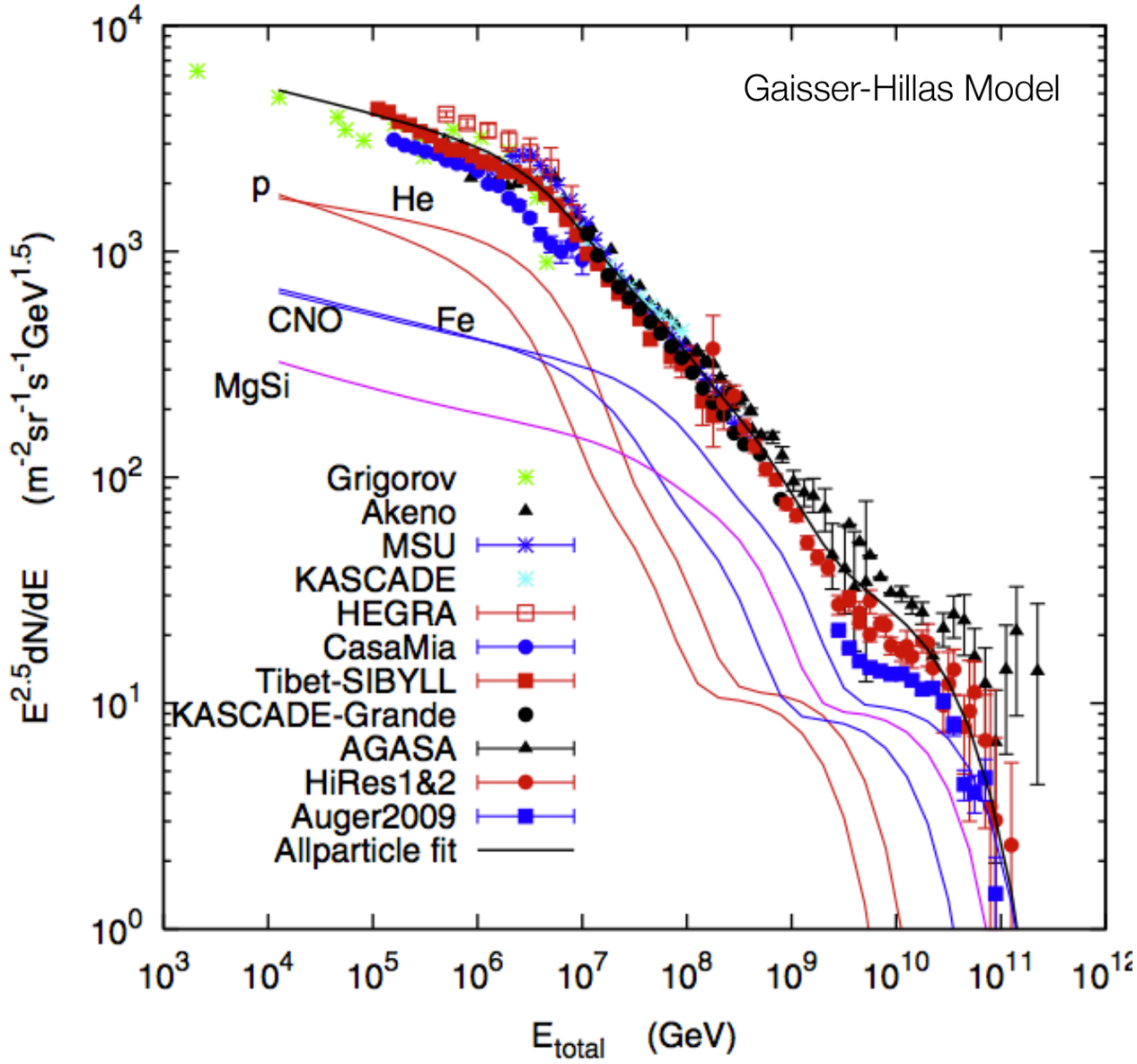


direct measurements

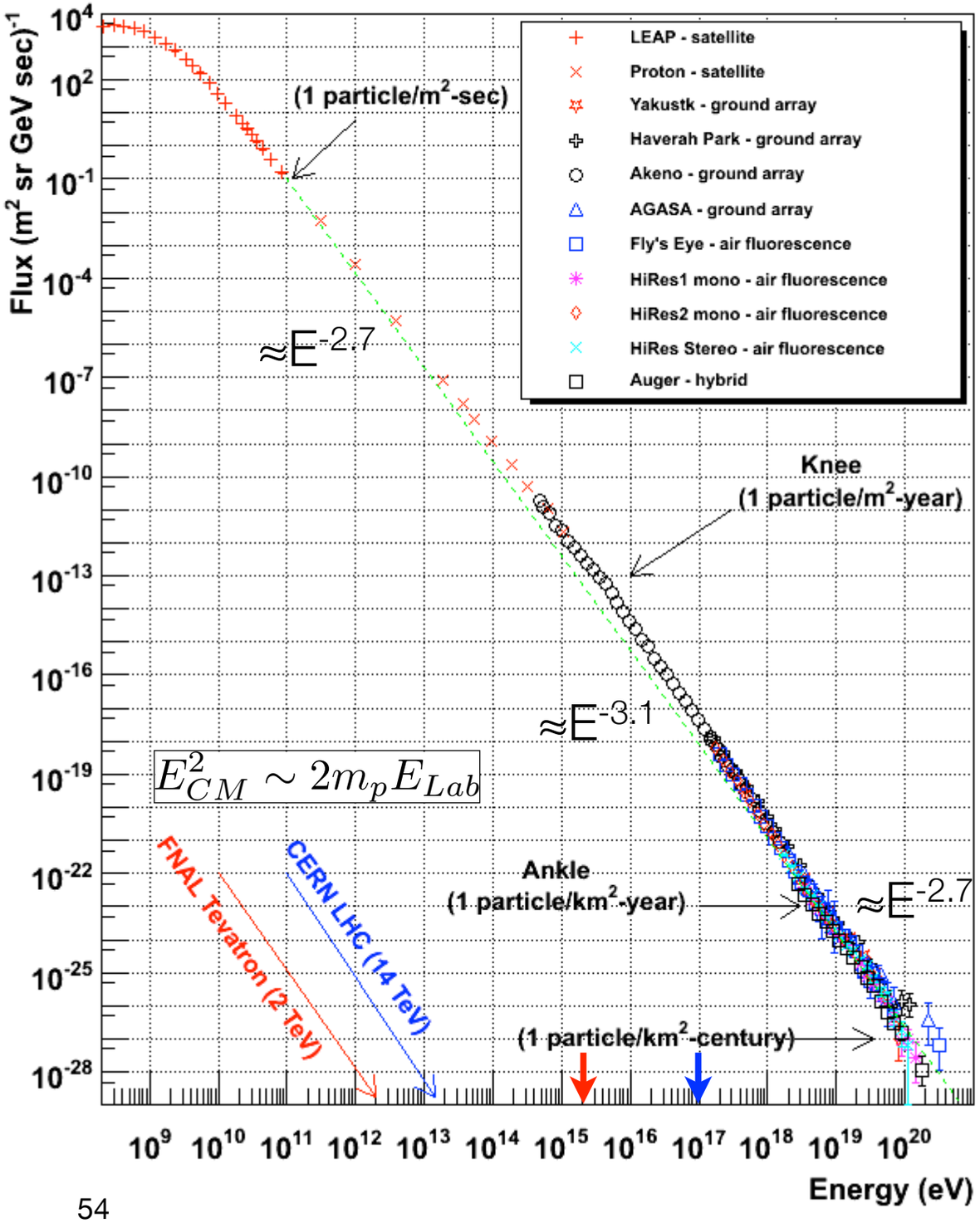
indirect measurements



Gaisser, Astropart. Phys. 35 (2012) 801

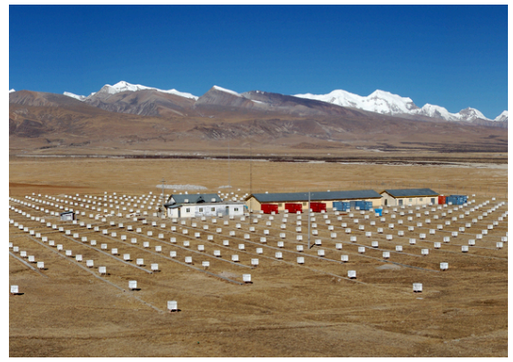


primary cosmic rays
spectrum & composition

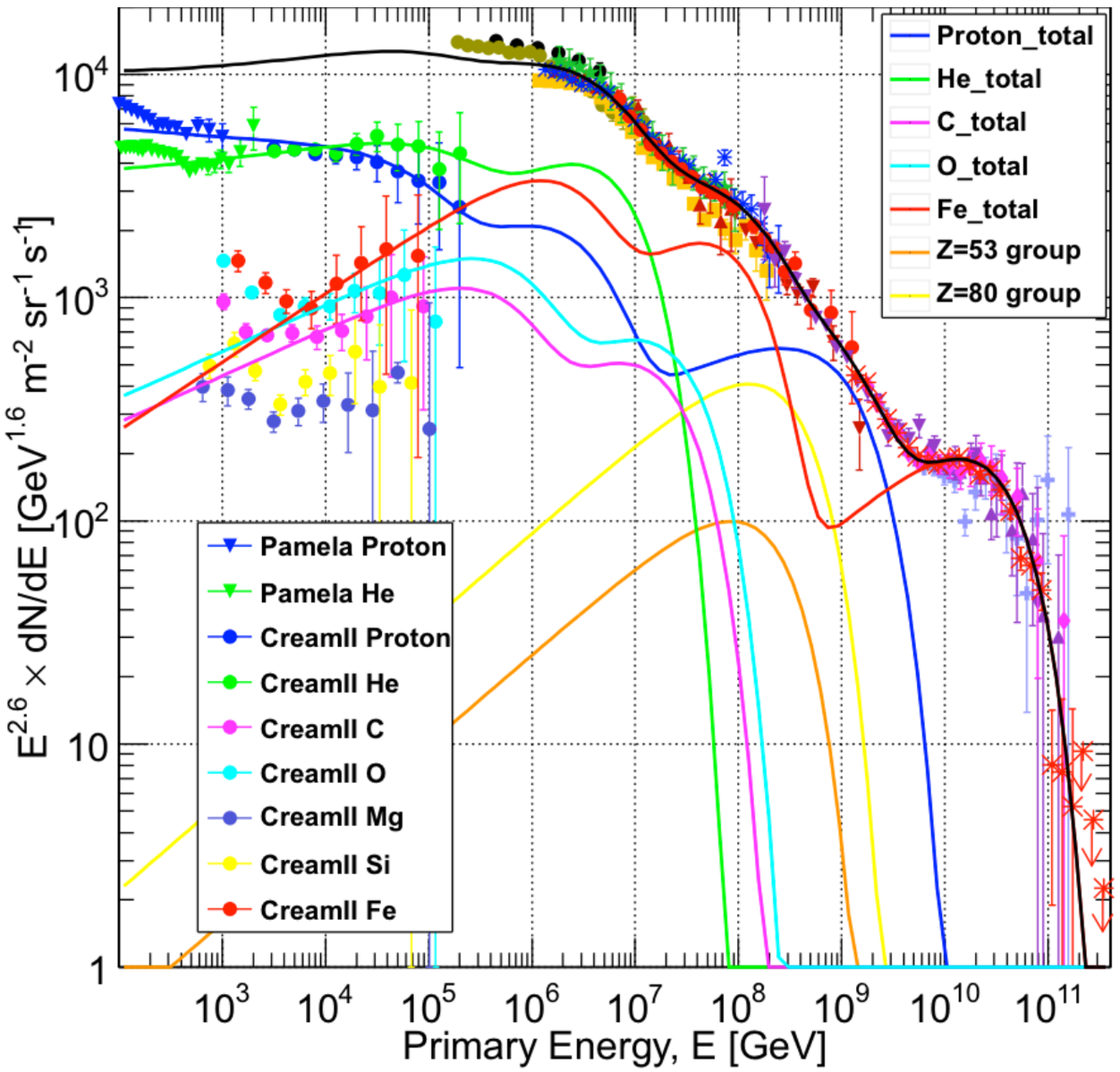


direct measurements

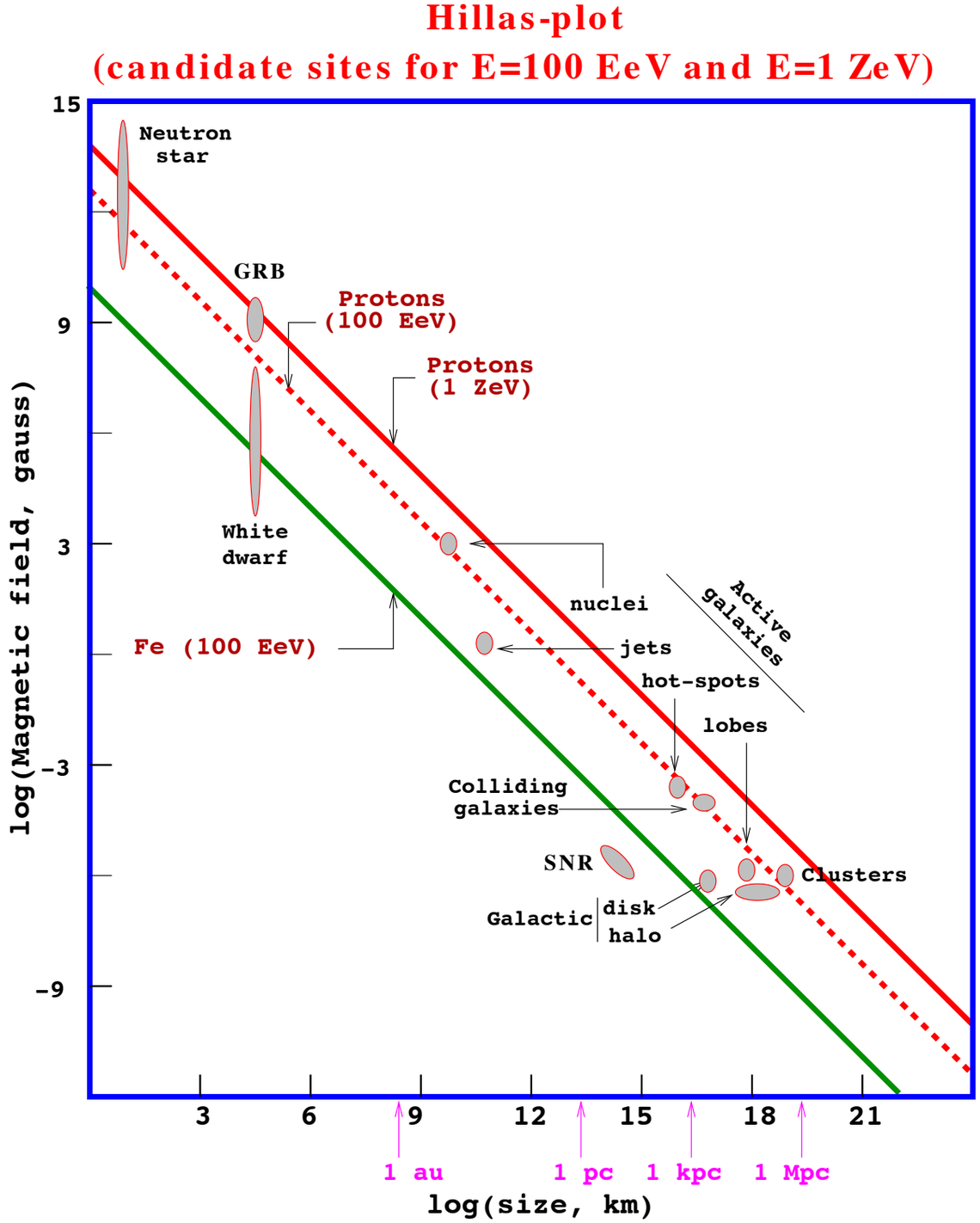
indirect measurements



Gaisser, Stanev & Tilav, 2013 - arXiv:1303.3565

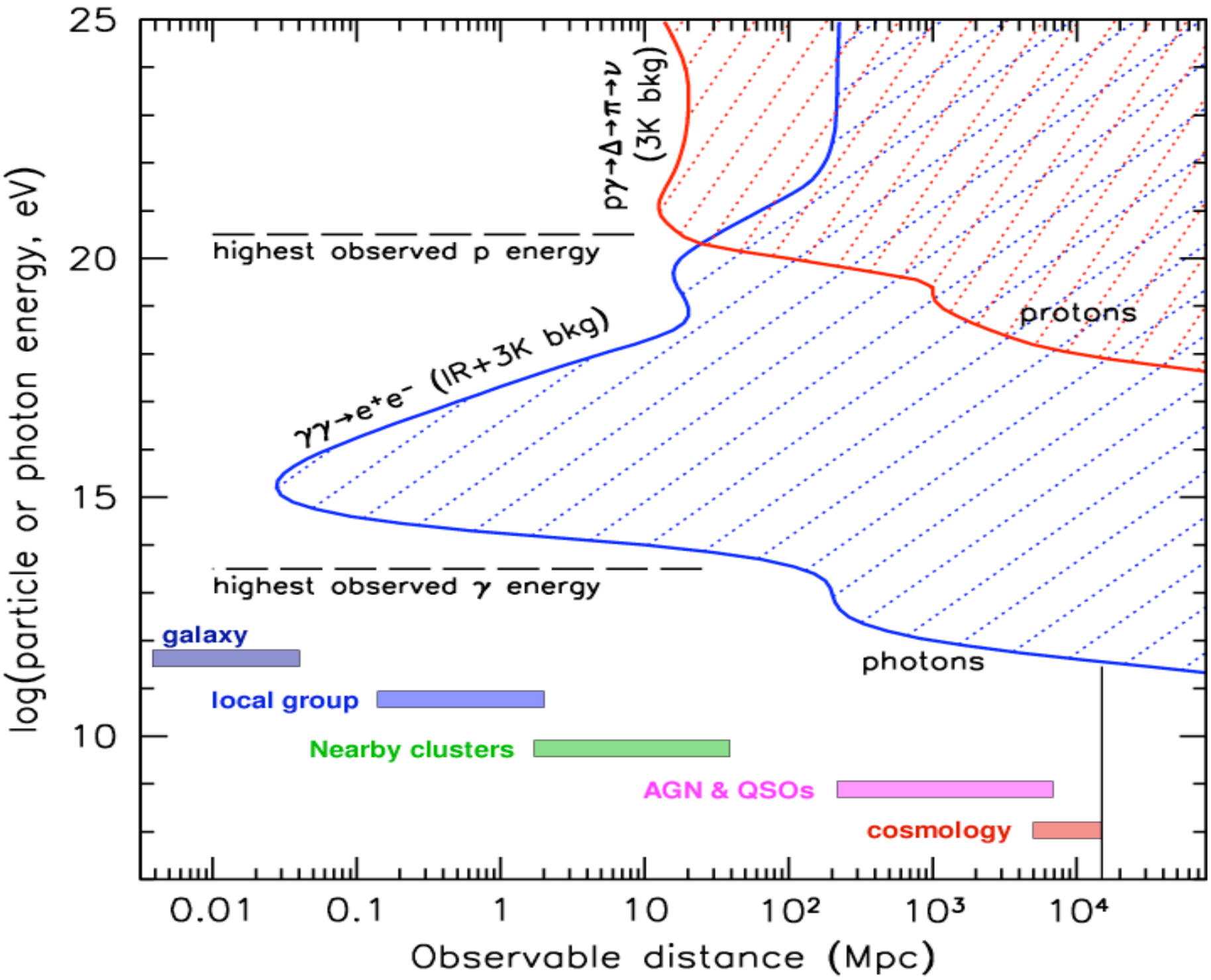


cosmic ray acceleration in supernova remnants



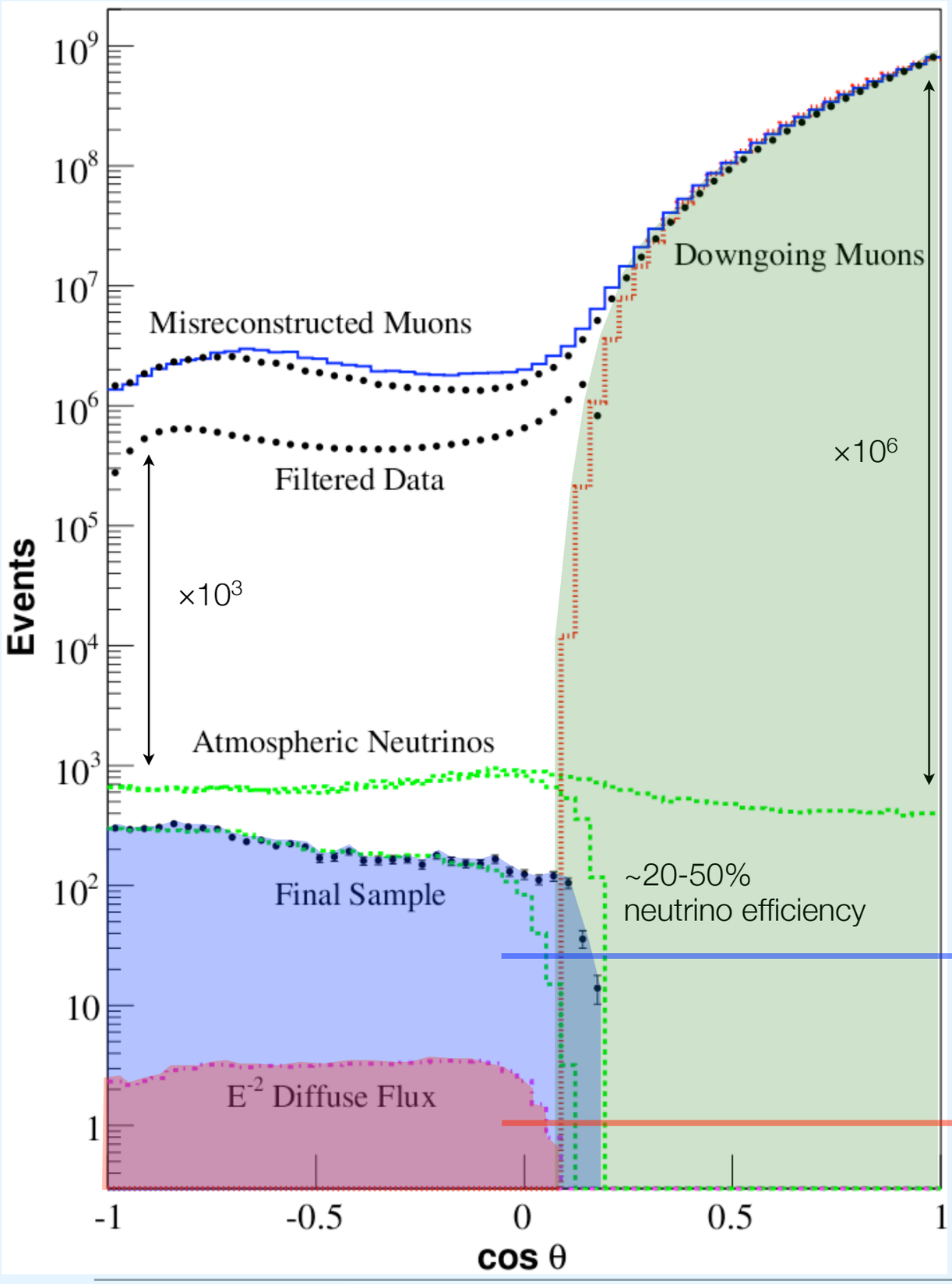
$E_{max} \sim ZBL$ (Fermi)

$E_{max} \sim ZBL\,G$ (Ultra-relativistic shocks-GRB)



propagation depth of protons and gamma rays

event identification

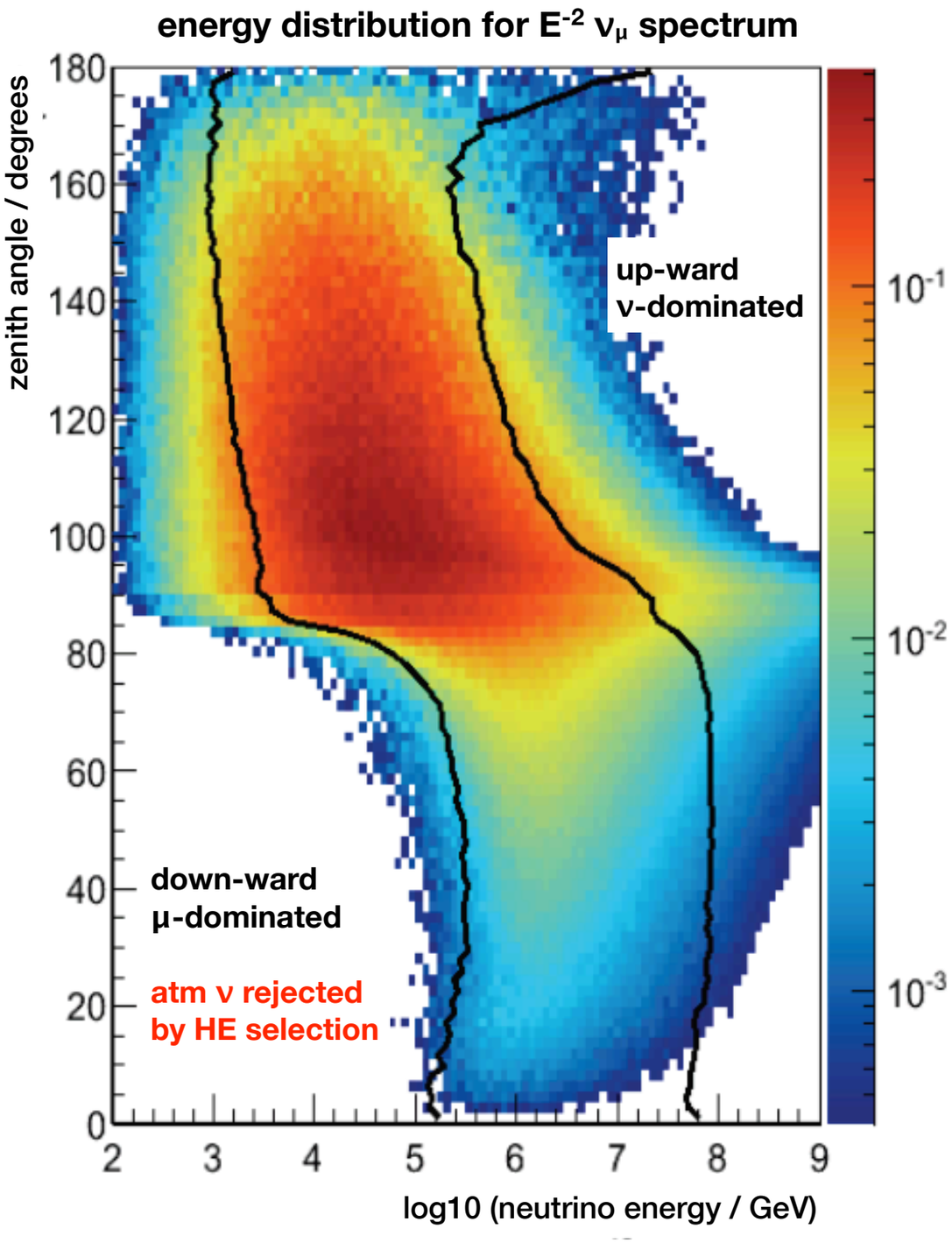


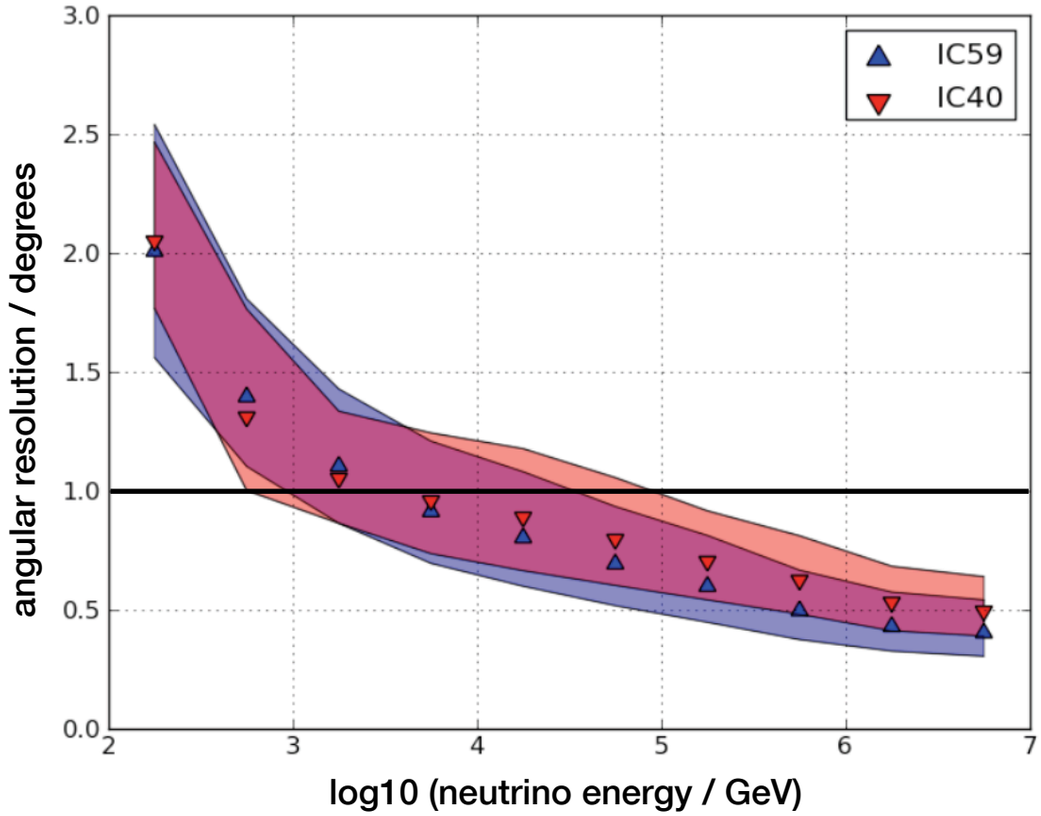
Strings	Year	μ rate	final ν_μ rate
IC22	2007	500 Hz	18 / day
IC40	2008	1100 Hz	40 / day
IC59	2009	1700 Hz	130 / day
IC79	2010	2000 Hz	*~170 / day*
IC86	2011	2100 Hz	*~200 / day*

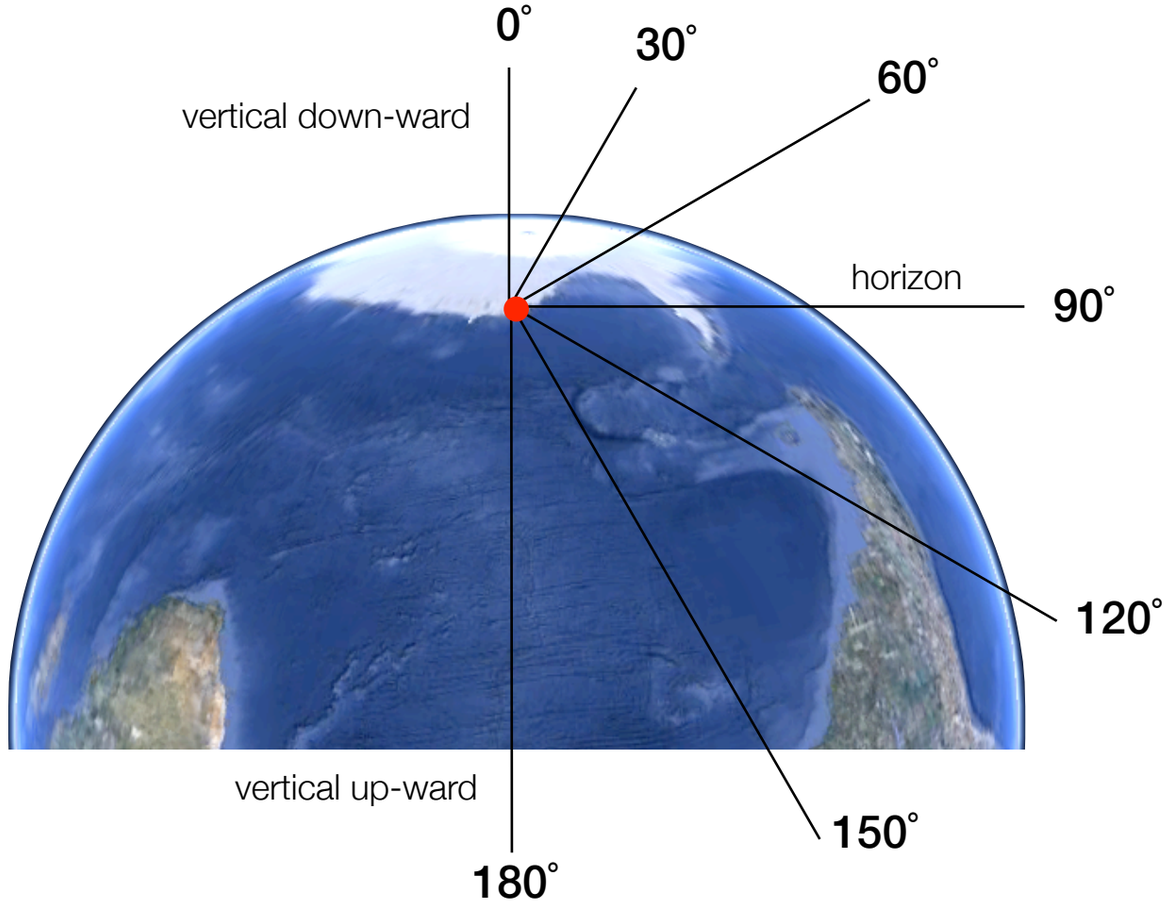
atmospheric neutrinos

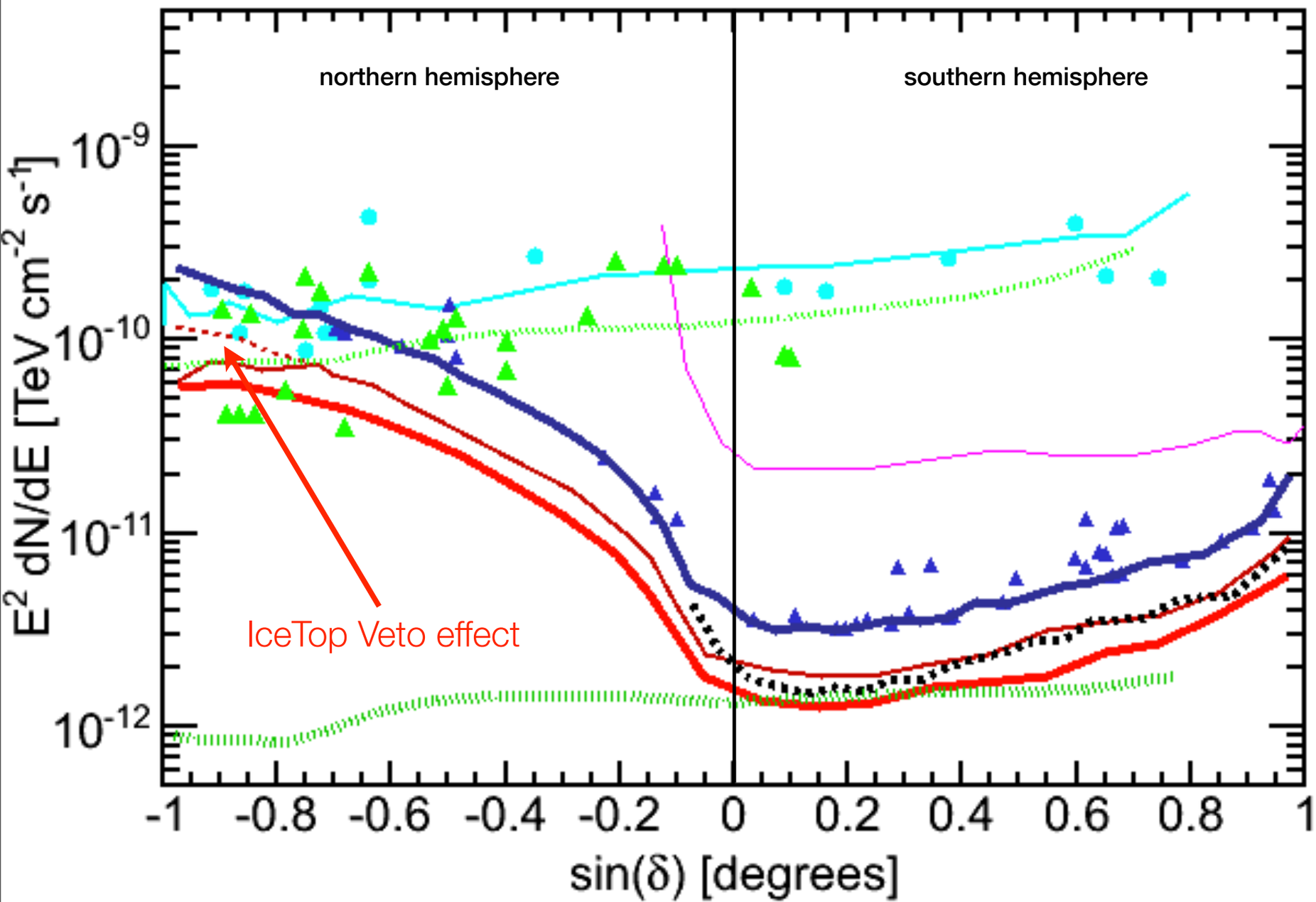
extra-terrestrial neutrinos

all-sky
steady point sources









SuperK

Antares (304 days)

AMANDA-II (1387 days)

IceCube-40 (375 days)

IceCube-59 (348 days)

IceCube-40+59 (723 days)

IceCube-80 (predicted)

KM3Net (predicted)

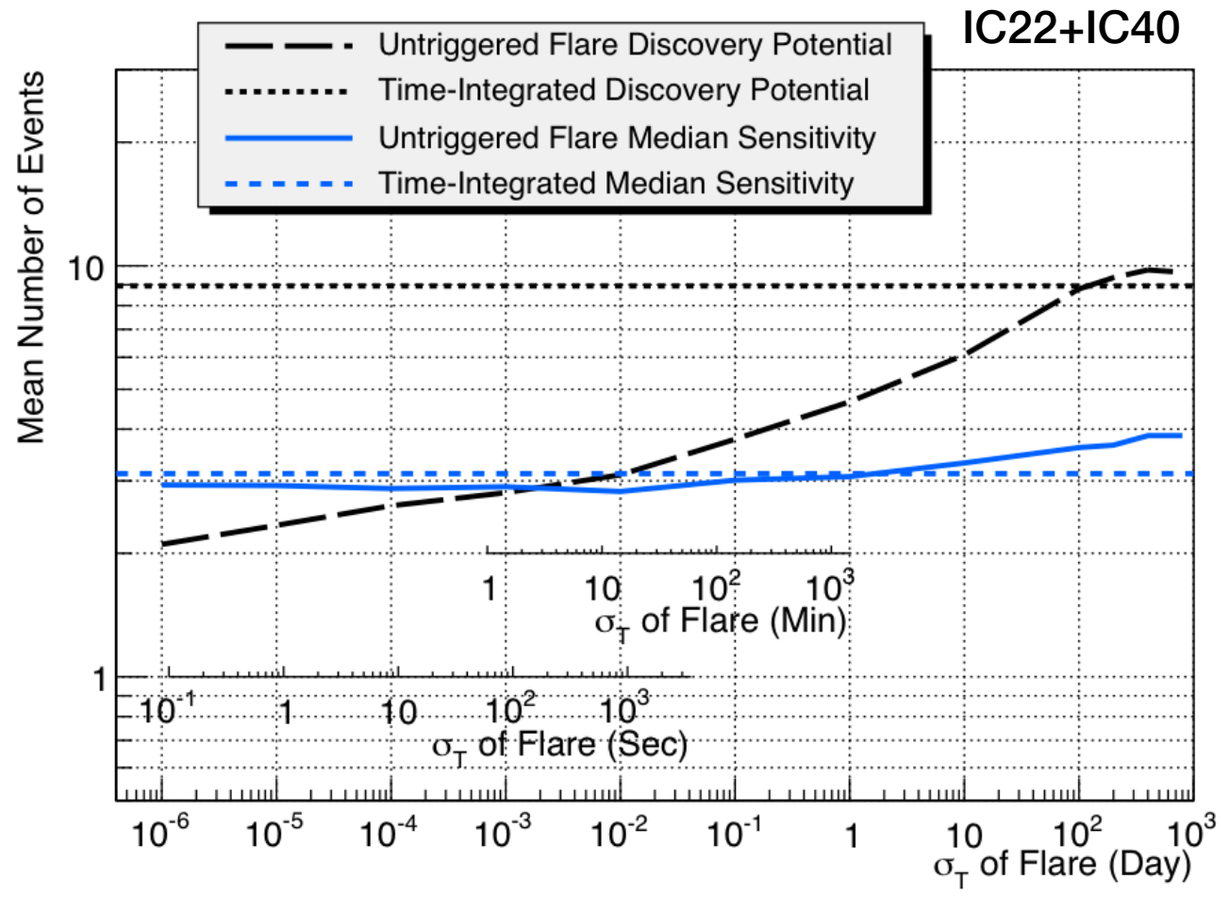
90% CL sensitivity for E^{-2} steady point sources

discovery potential (5σ, 50% of trials) is about ×3

other point source searches

- time varying sources
  - untriggered all-sky time scan →
  - time scan for candidate variable sources from Fermi-LAT Bright Source List
  - triggered search based on flaring sources observed by Fermi (alerts from Public Release), H.E.S.S., MAGIC and VERITAS

number of events needed for 5σ (50%) all-sky discovery potential at different flare scales



ApJ 744, 1, 2012 - arXiv:1104.0075

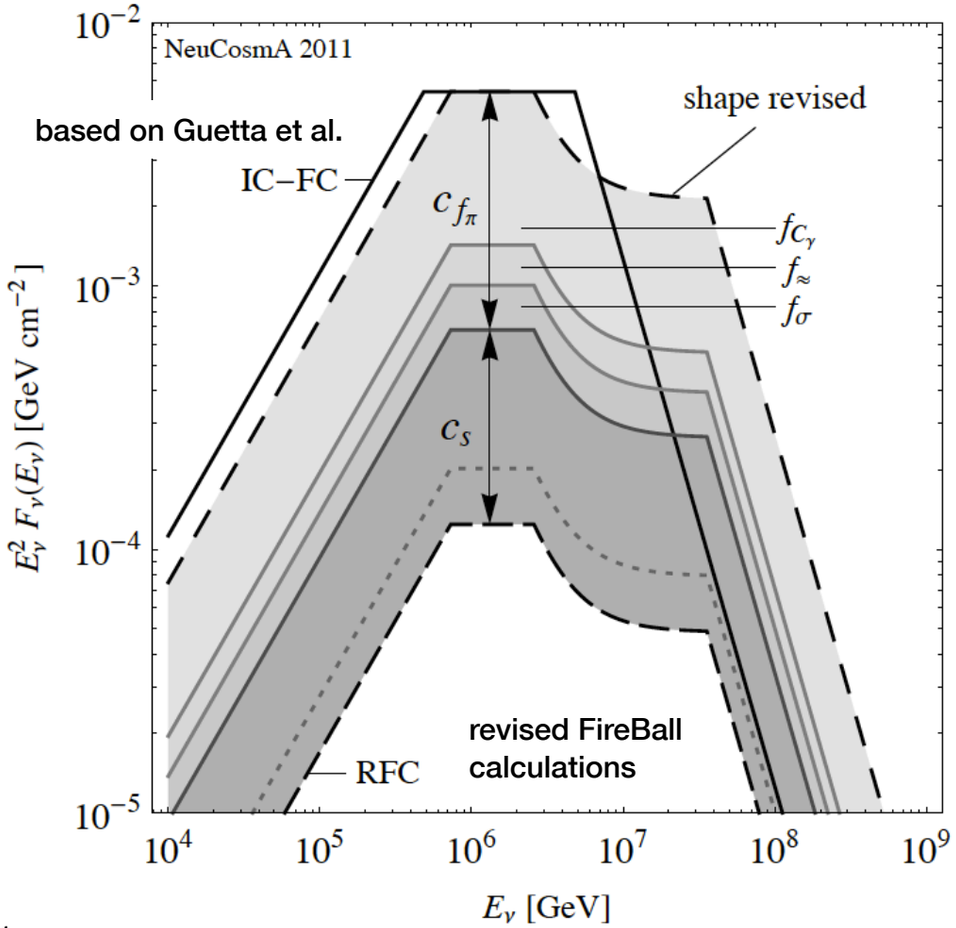
- periodic sources from catalogue of GeV-TeV binary systems

ApJ 748, 118, 2012 arXiv:1108.3023

neutrinos from Gamma Ray Bursts

- search for stacked neutrinos in coincidence with observed γ ray from GRB in the northern hemisphere

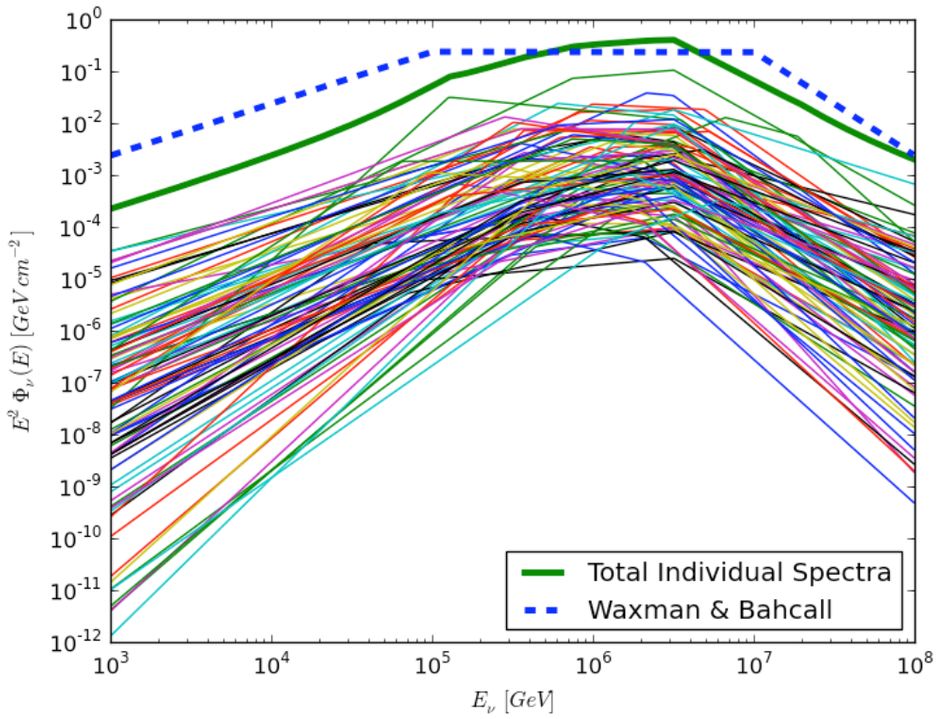
- per-burst neutrino spectra calculated from γ ray spectra based on prescription by Guetta et al. Astrop. Phys. 20, 429 (2004)



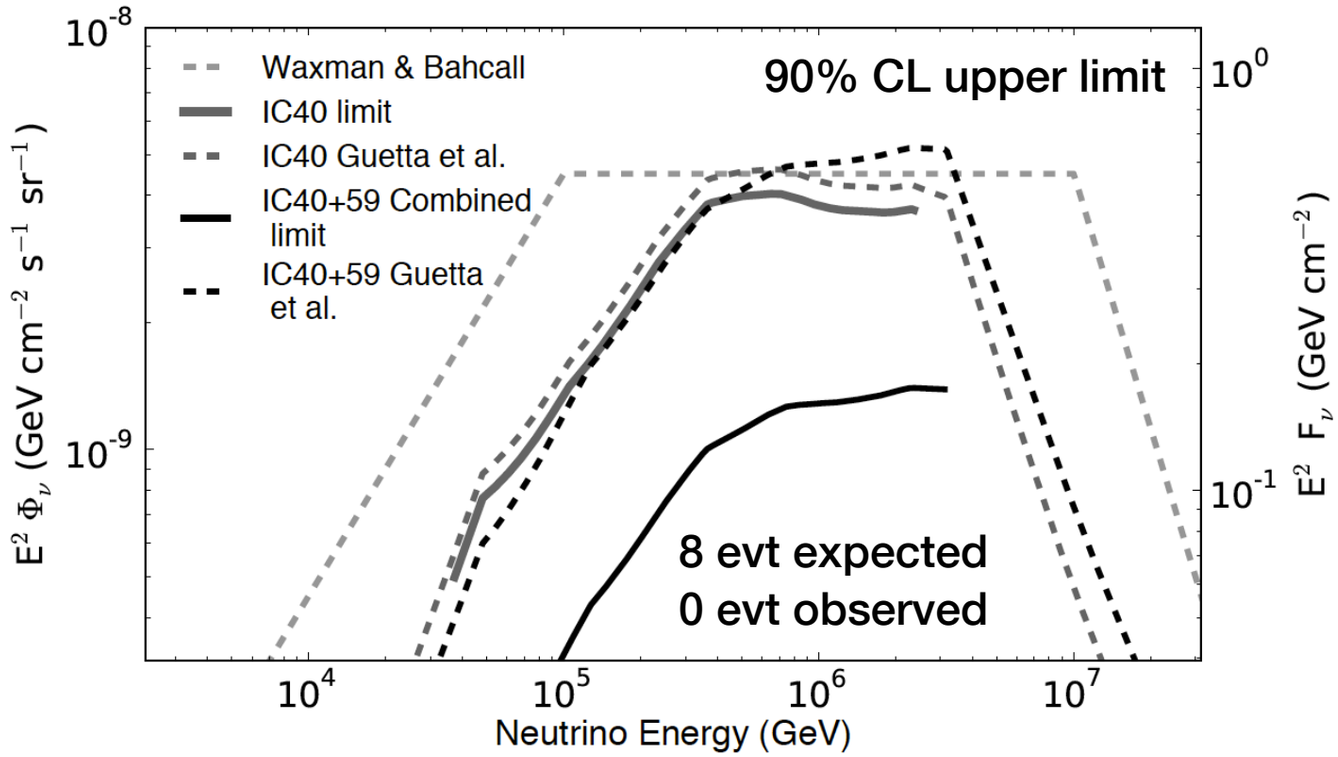
Hümmer et al. arXiv:1112.1076

assuming GRB as sources of UHE cosmic rays

e.g. Ahlers et al., Astrop. Phys. 35-2, 87 (2011)

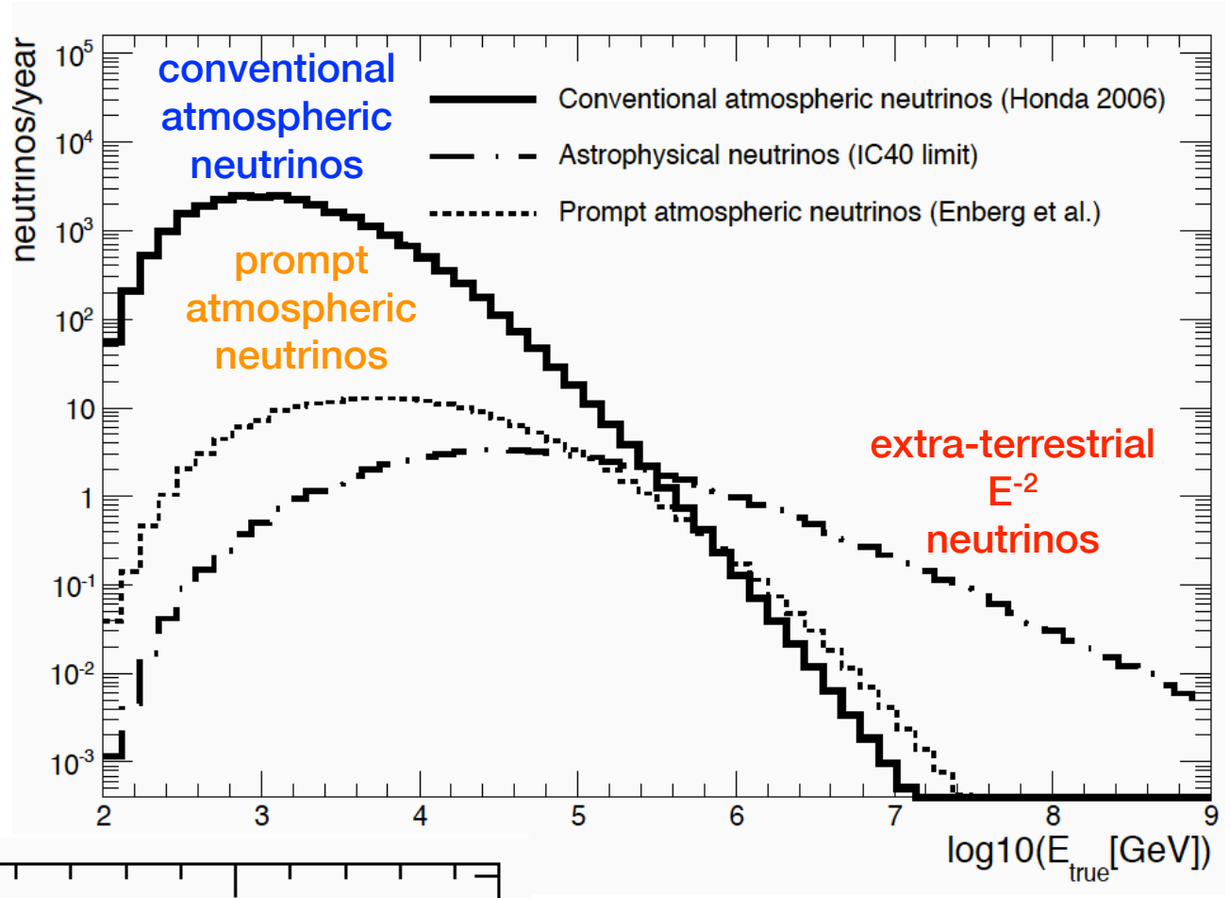


Nature, 484, 351 (2012)

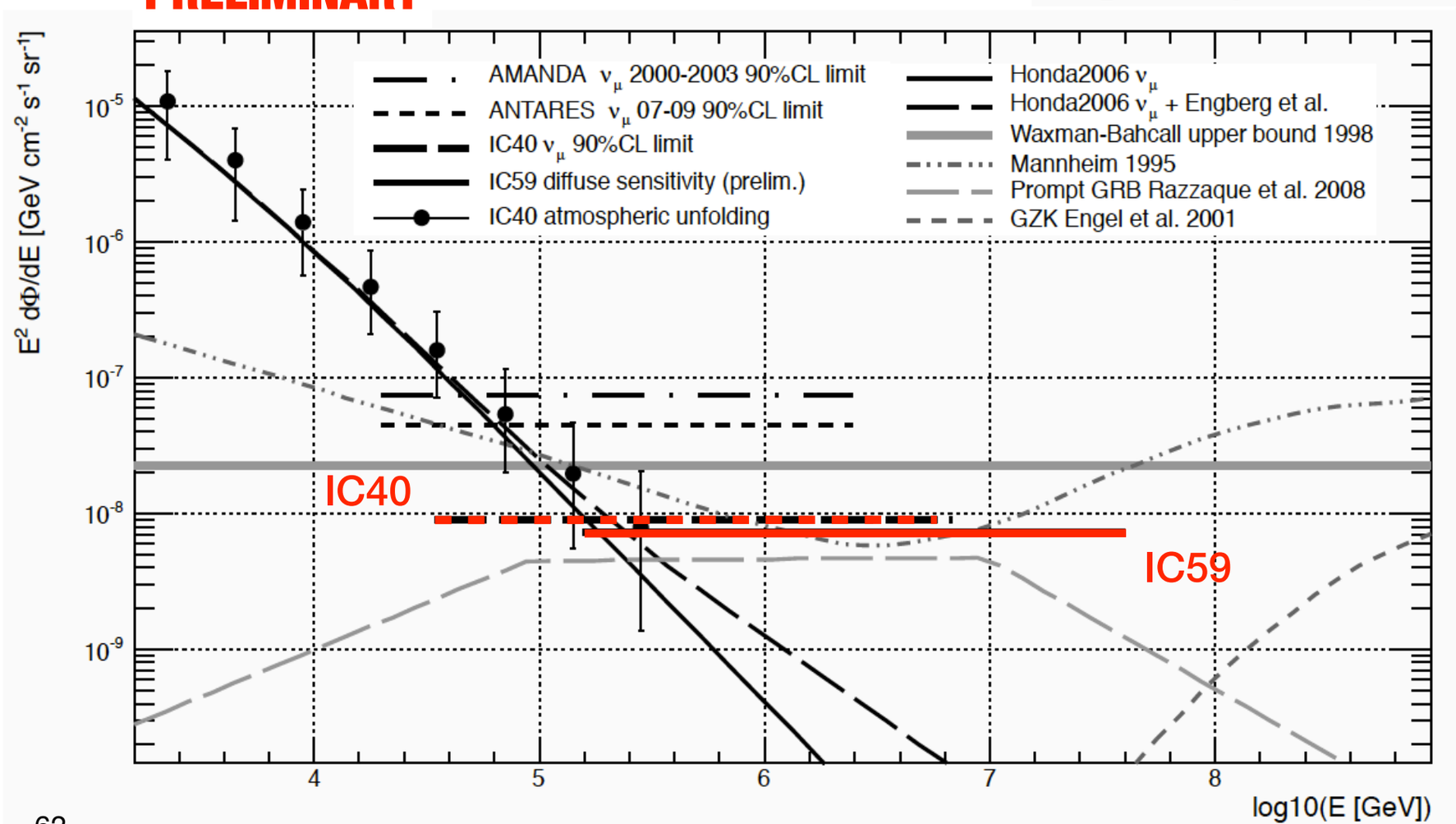


neutrinos from diffuse sources

- search for neutrinos from unresolved sources in the Universe (e.g. AGN)



PRELIMINARY



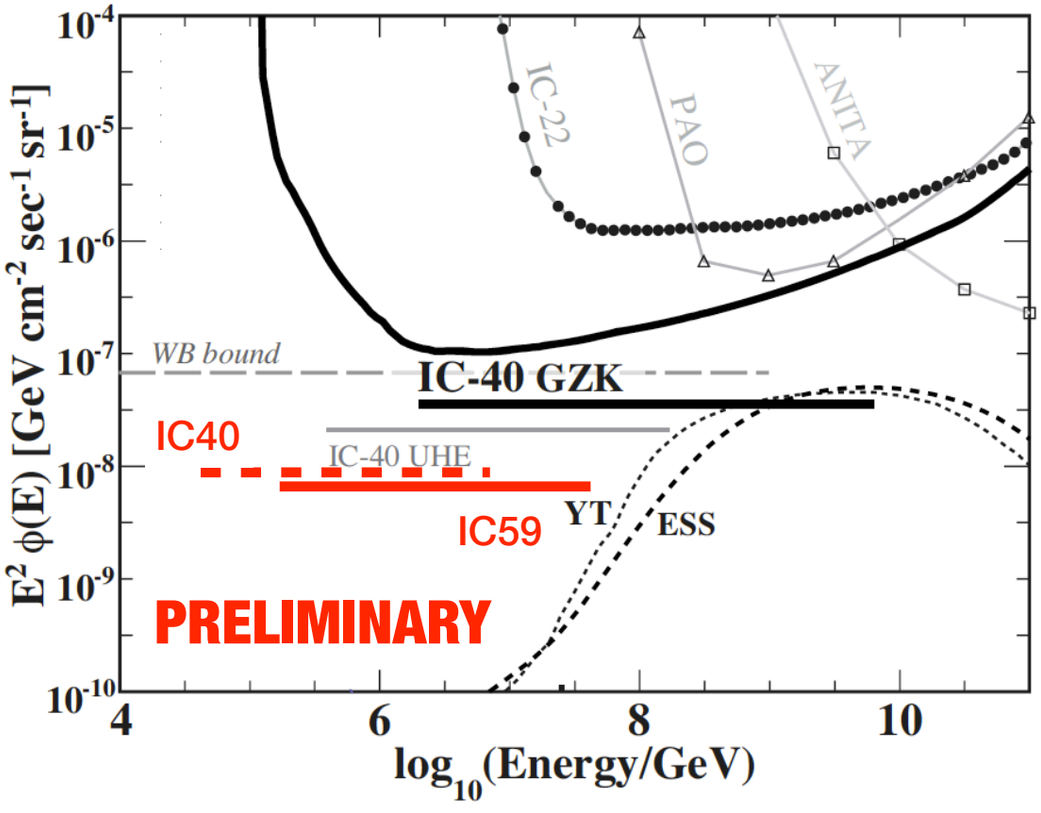
Schukraft, Grullon, Wallraff, et al. ICRC 2011

cosmogenic neutrinos

- cosmogenic neutrinos from photo-hadronic interactions of UHECR protons with the CMB

- constrain through the e^-, e^+ and γ-rays cascading on the CMB and intergalactic magnetic fields to lower energies and generating a γ-ray background in the GeV-TeV region

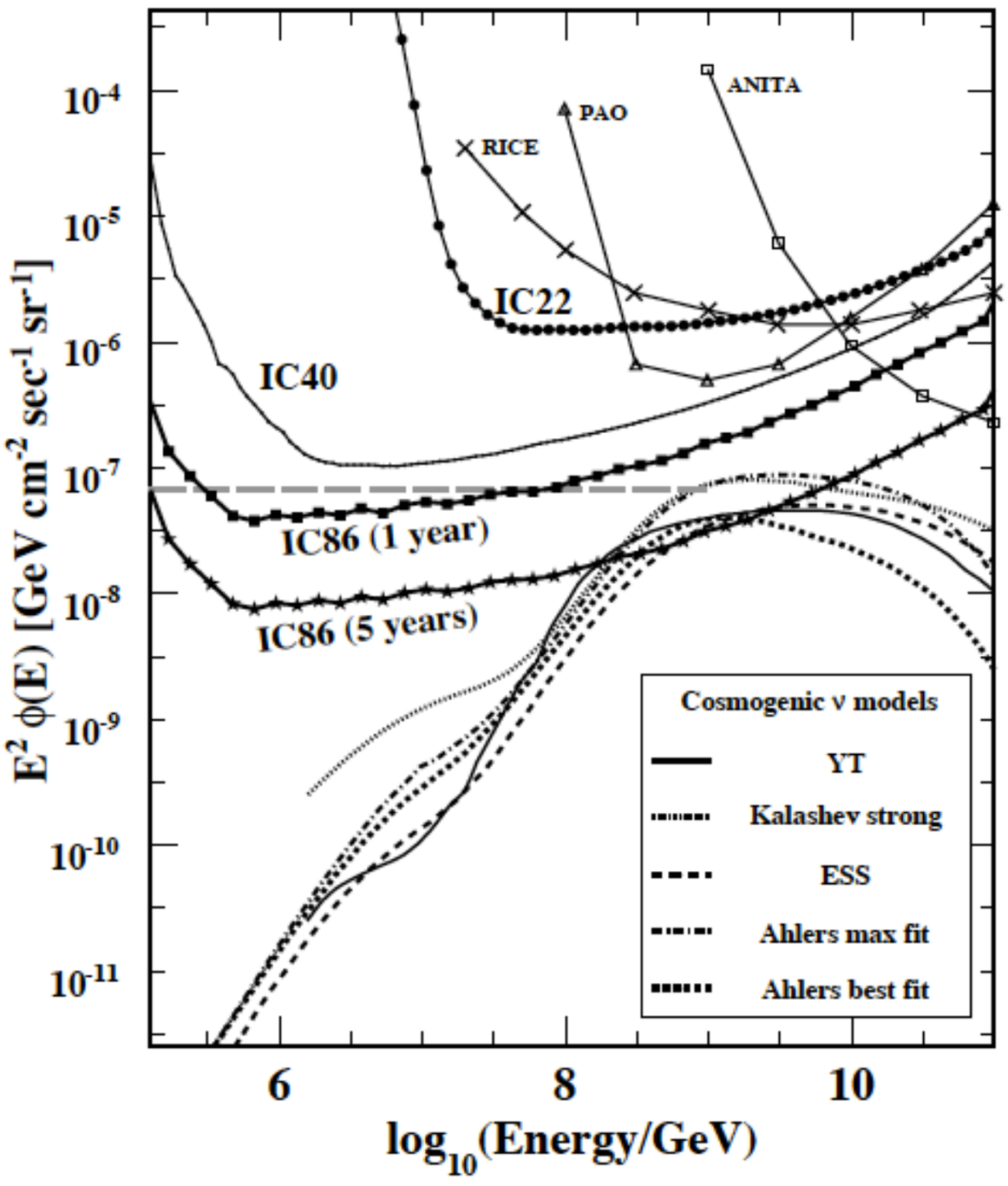
Wissing, Ishihara, et al. ICRC 2011



IC40
PRD 83, 092003 (2011)
PRD 84, 079902 (2011)

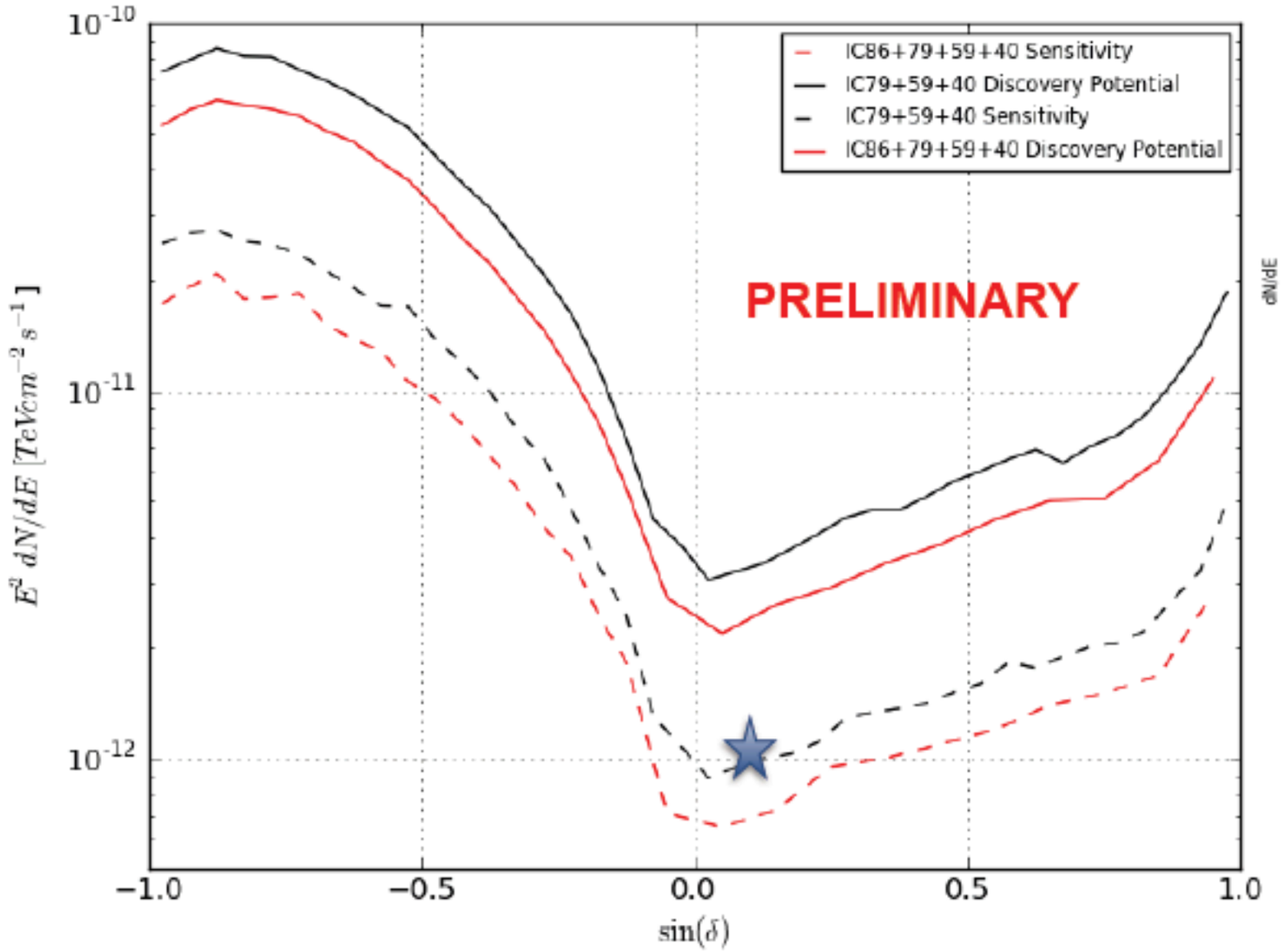
PRELIMINARY

Ishihara, et al. ICRC 2011

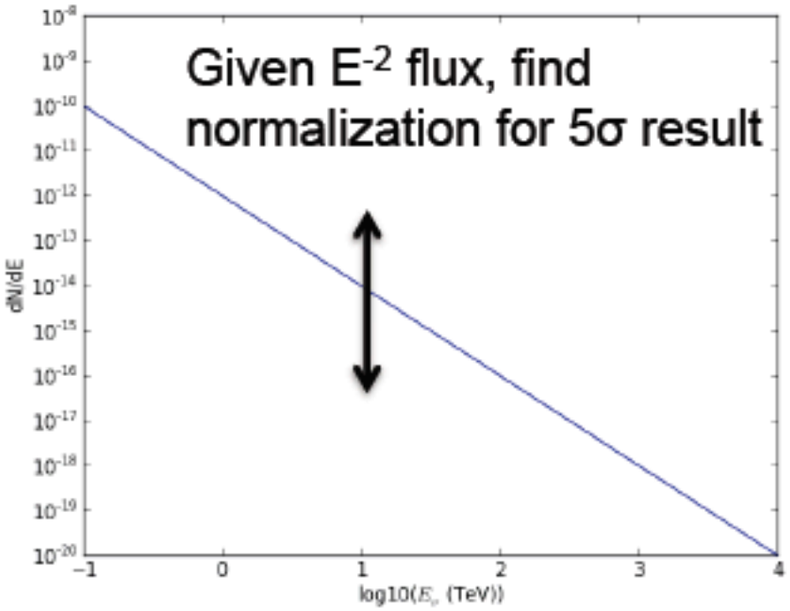


Ahlers et al., Astrop. Phys. 34, 106 (2010)
Ahlers et al., Astrop. Phys. 35-2, 87 (2011)

Discovery potential for 4 years of IceCube



Normalization of MGRO J1908+06 model from Halzen et. al. '08 (arxiv 0803.0314)

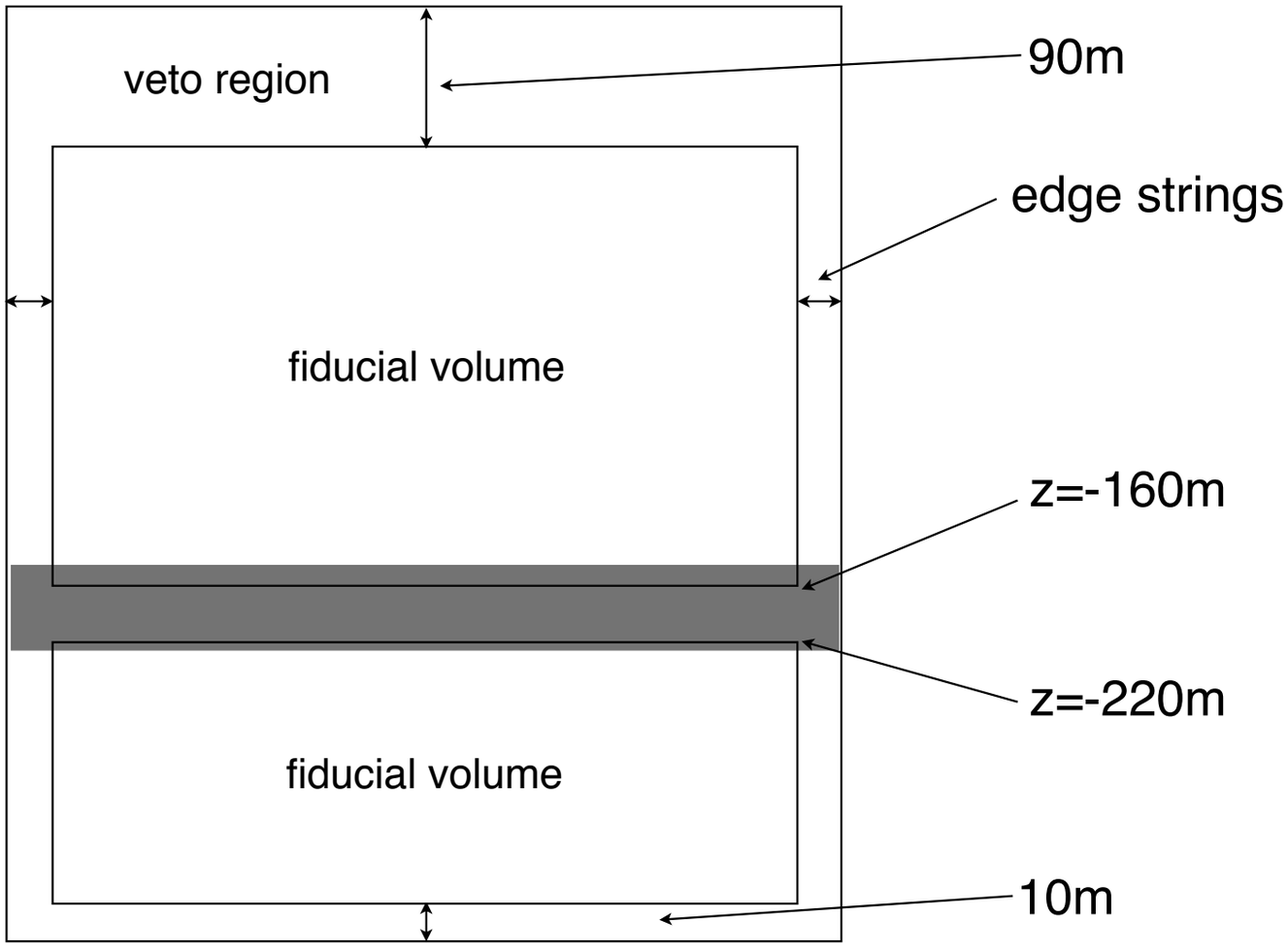


Discovery potential improves because of:

- More livetime
- Better angular resolution
- Bigger effective area
  - detector size, event selection
- Improved understanding of systematics

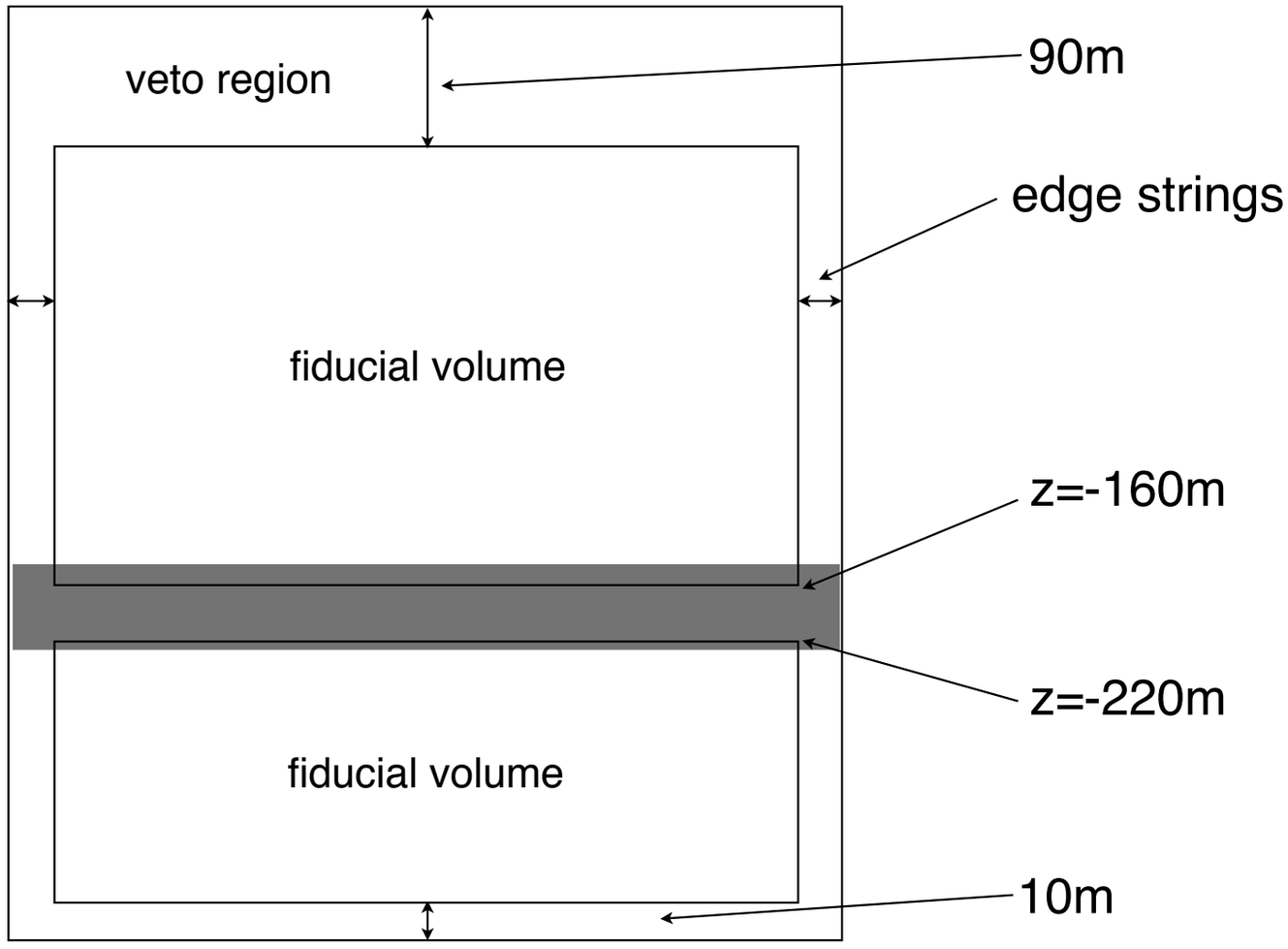
high energy "*starting*" events

- **extension to lower energy**
- **662** d (IC79 + IC86)
- containment at HE (Q_{tot} > 6000 p.e.)
- 400 Mton effective fiducial mass
- reject cosmic ray muons
- sensitive to all flavors > 60 TeV
- 3 times as sensitive at 1 PeV
- background estimation from data



high energy "*starting*" events

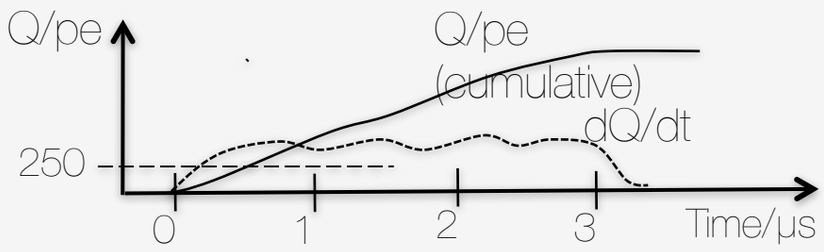
- reject through going muons when "*early charge*" in veto region is detected



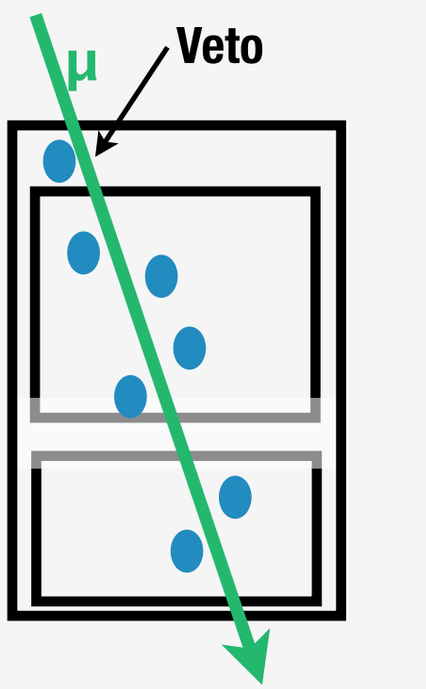
high energy "*starting*" events
atmospheric muon background

Throughgoing muon

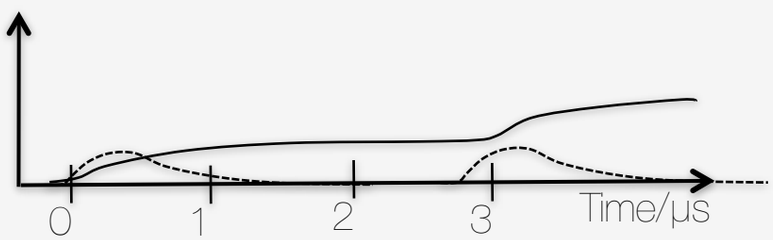
Total detector



Veto region



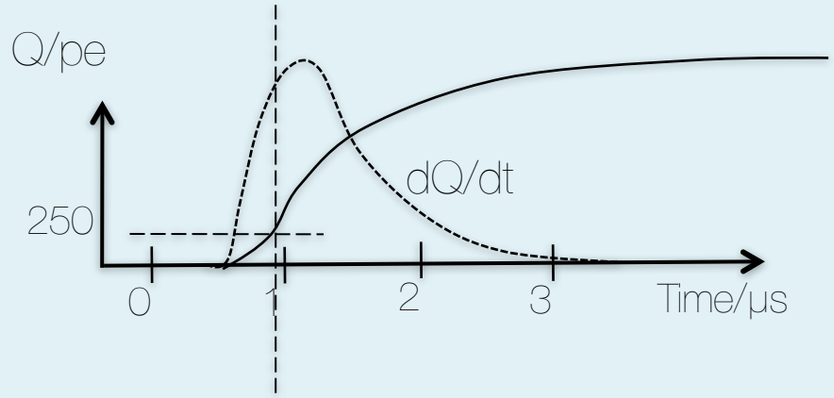
Q/pe

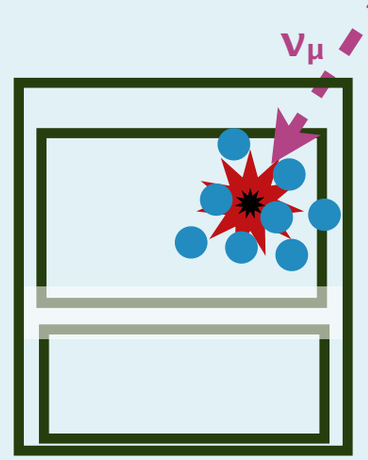


T_{250}= time at which Q= 250 pe

Contained cascade

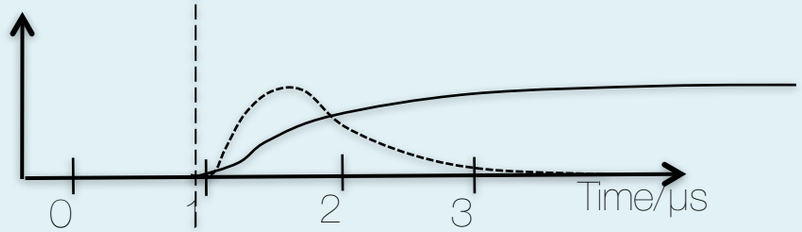
Total detector





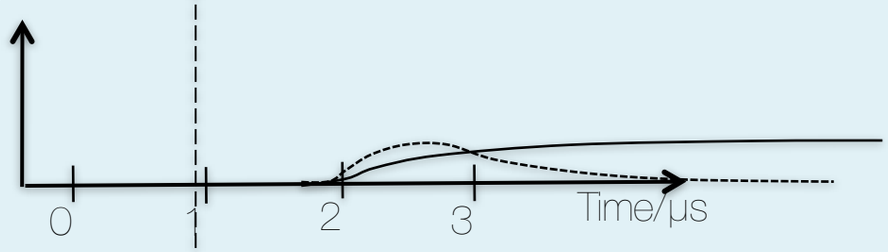
Veto region – barely contained cascade

Q/pe



Veto region – well contained cascade

Q/pe

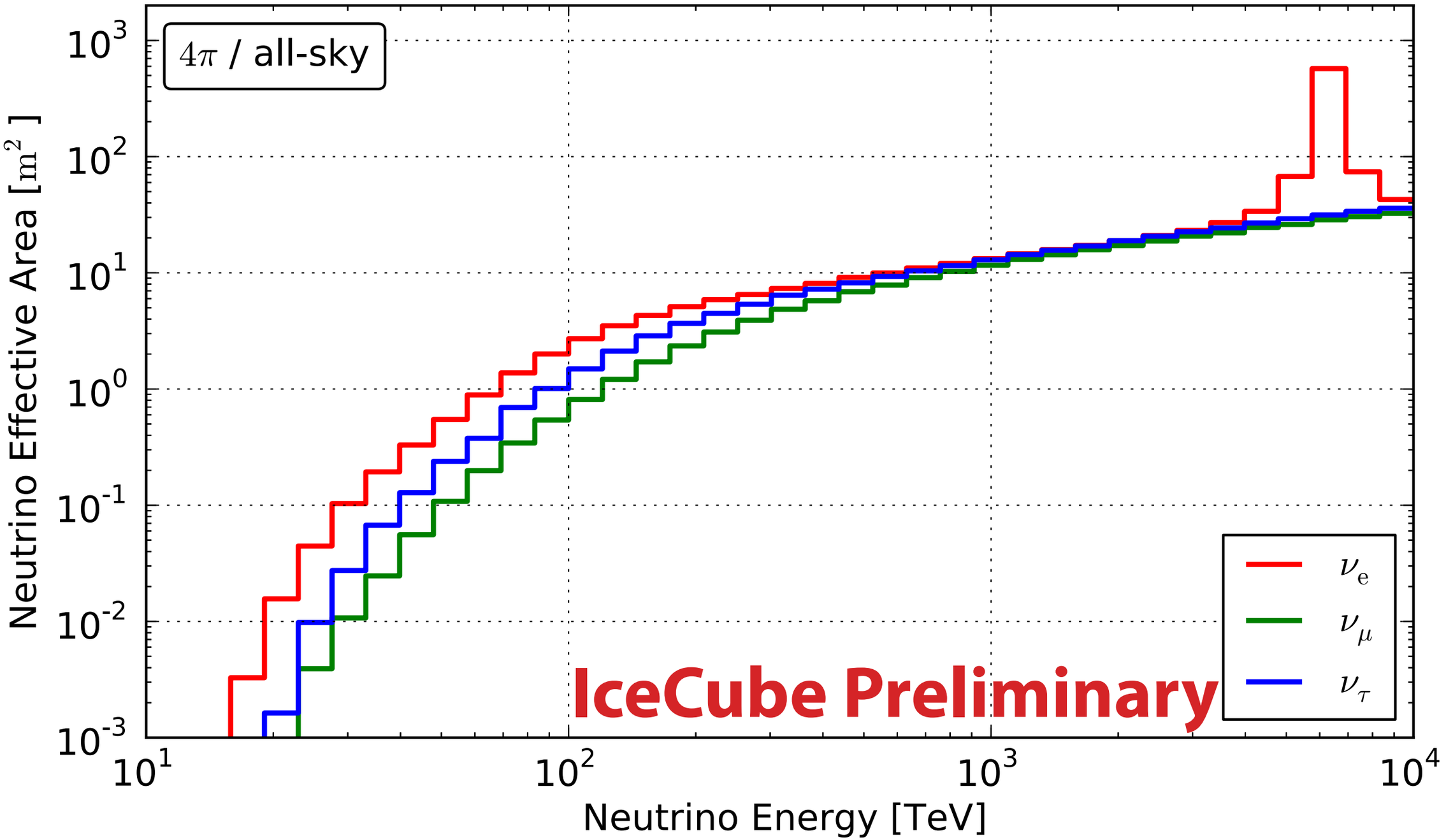


T_{250}= time at which Q= 250 pe

IceCube Preliminary

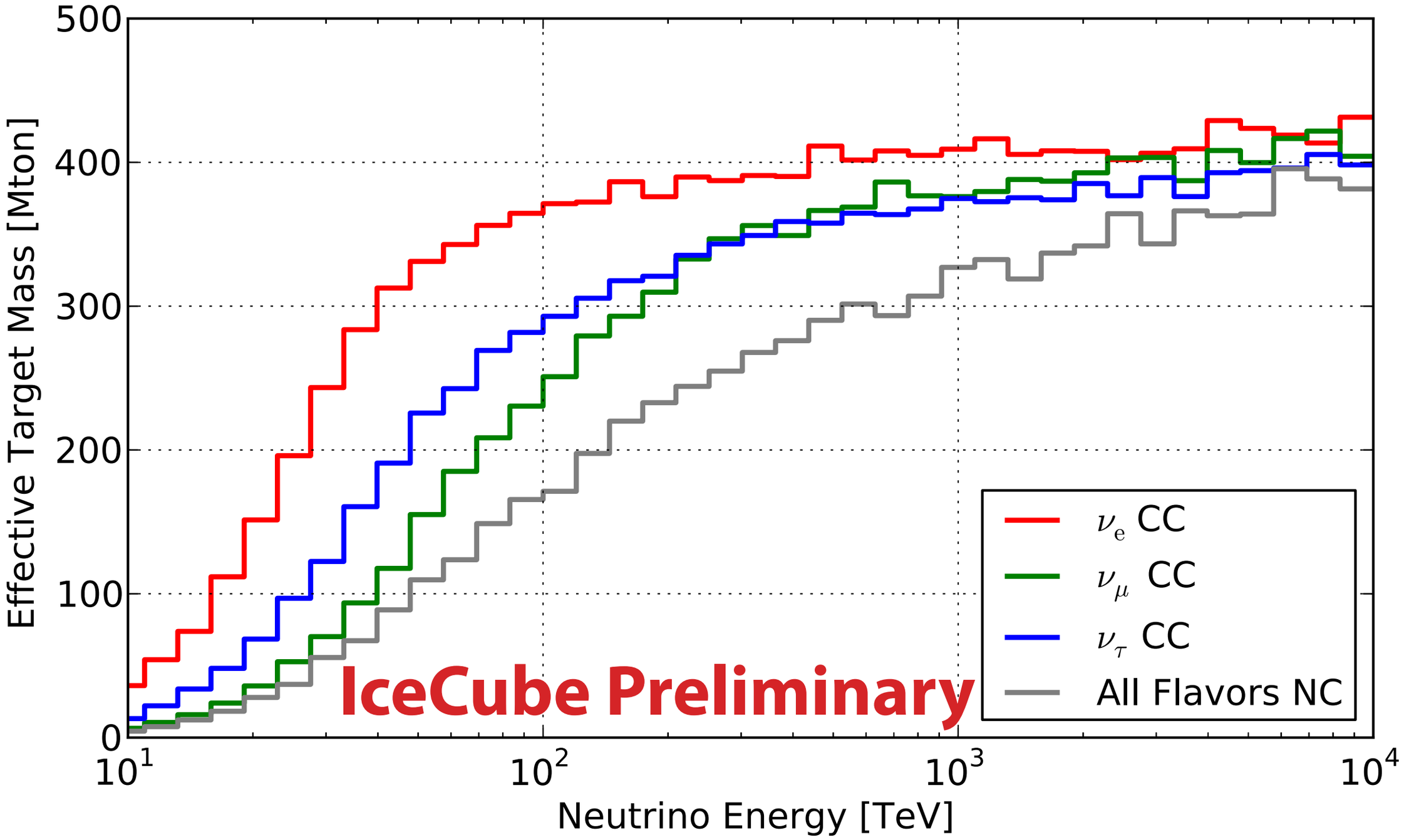
high energy "*starting*" events

effective area



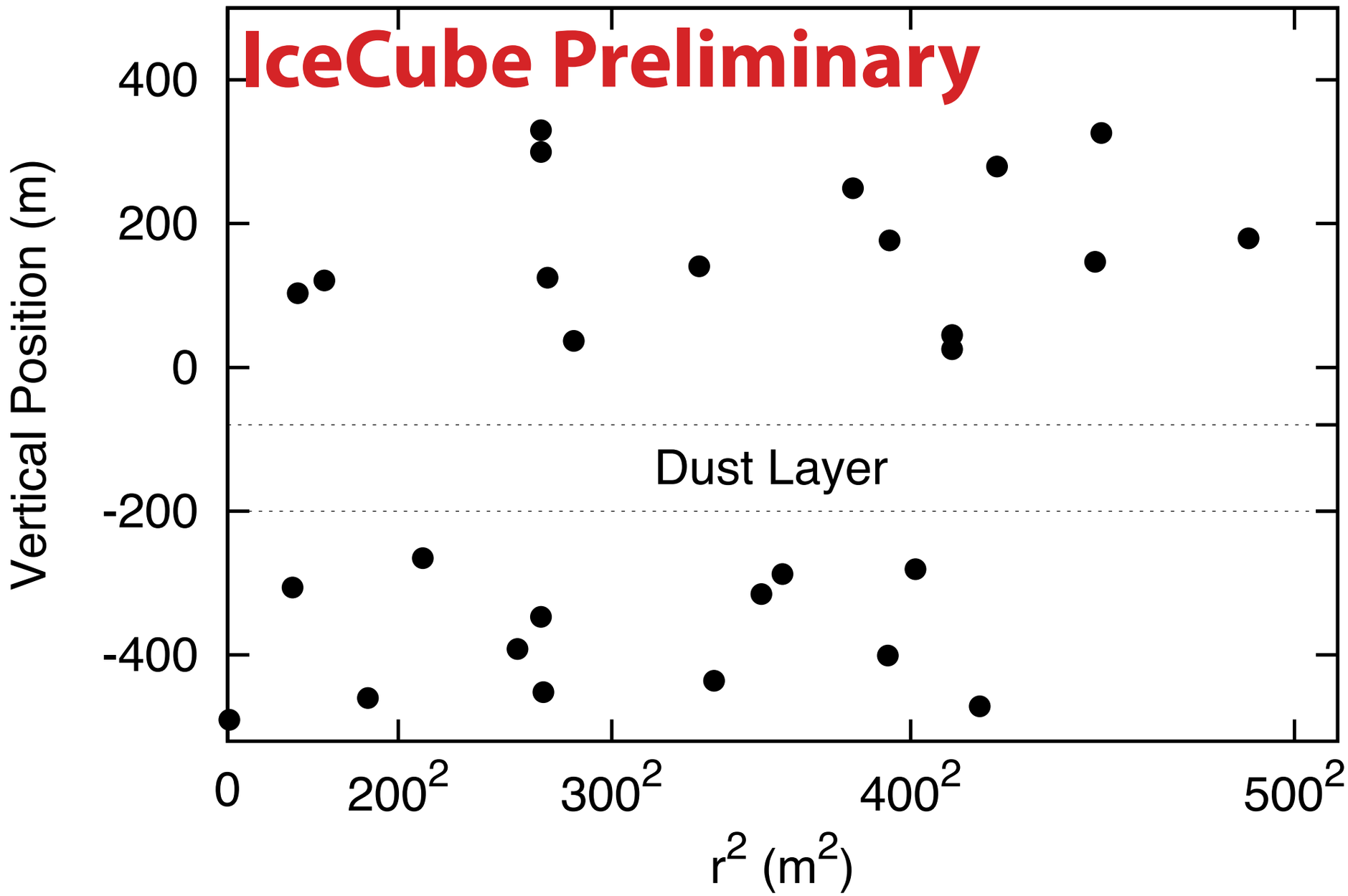
high energy "*starting*" events

effective volume

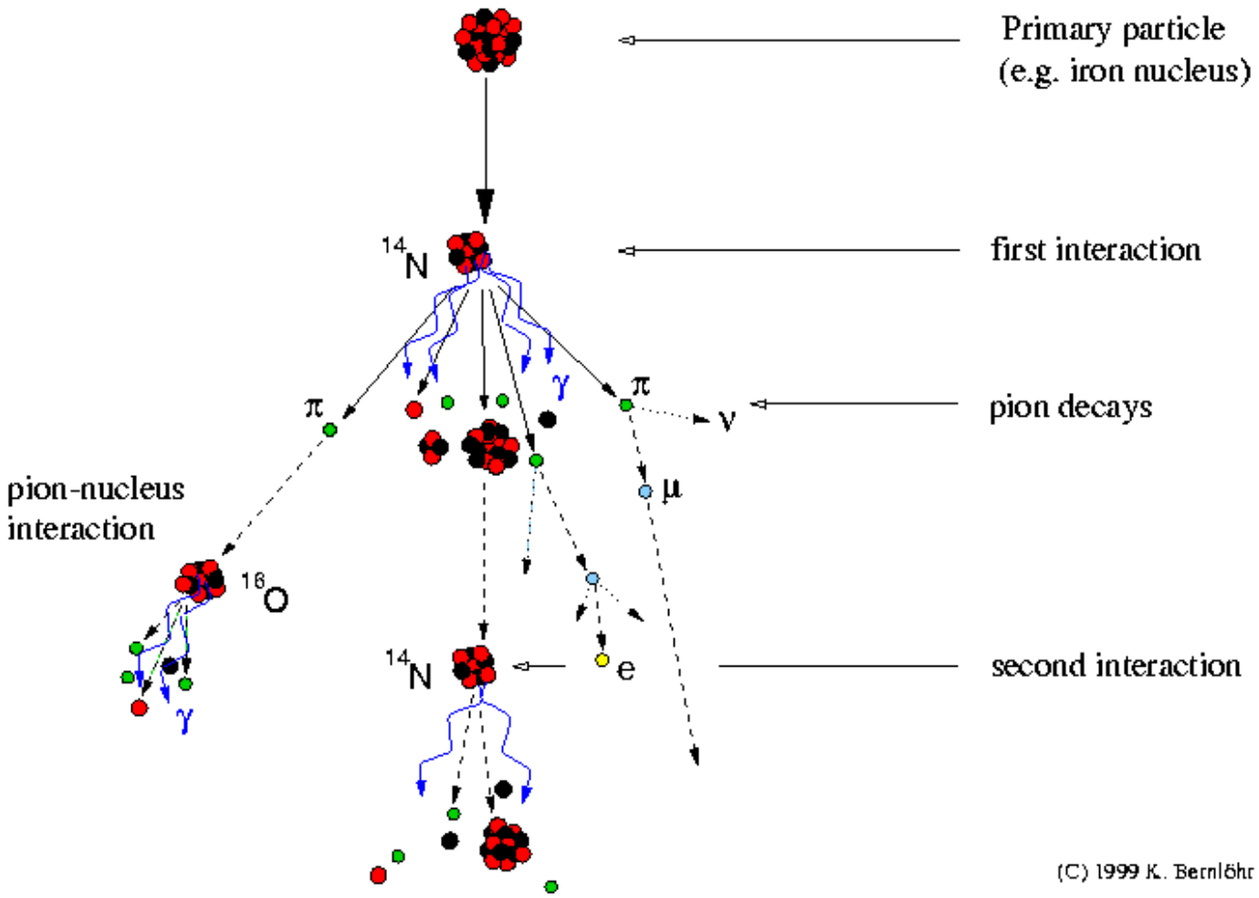


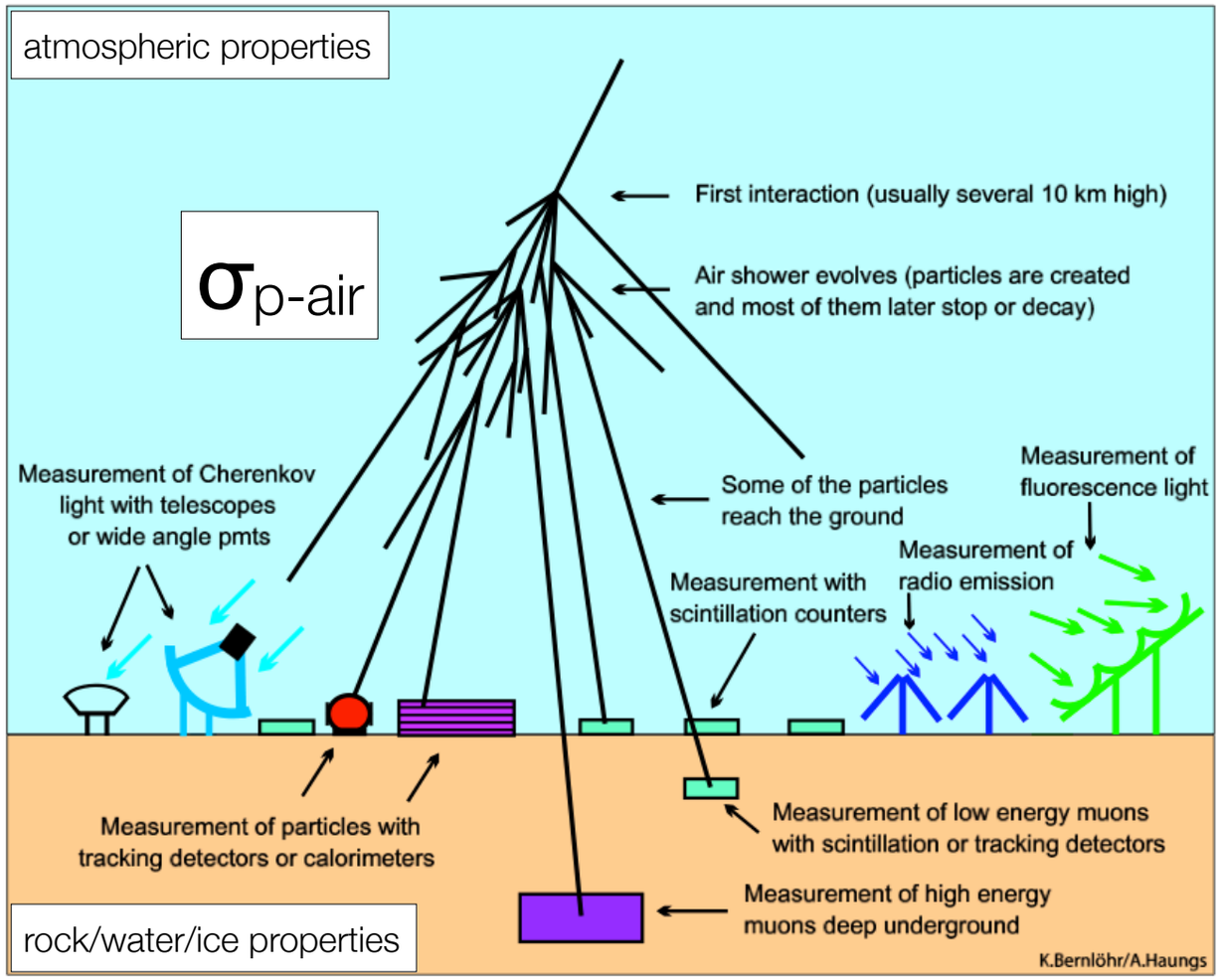
high energy "*starting*" events

no background accumulated at the boundary



detection of high energy cosmic ray

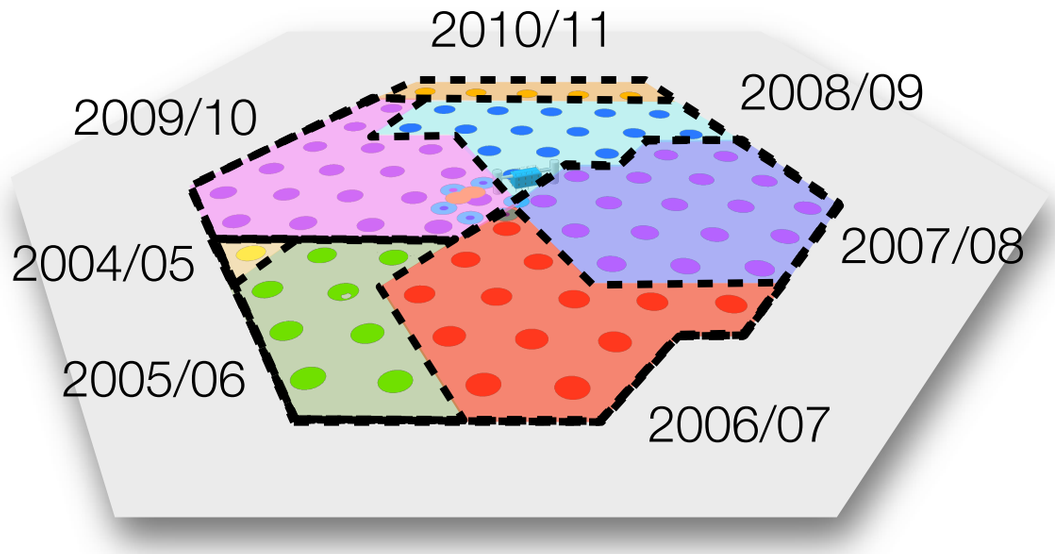


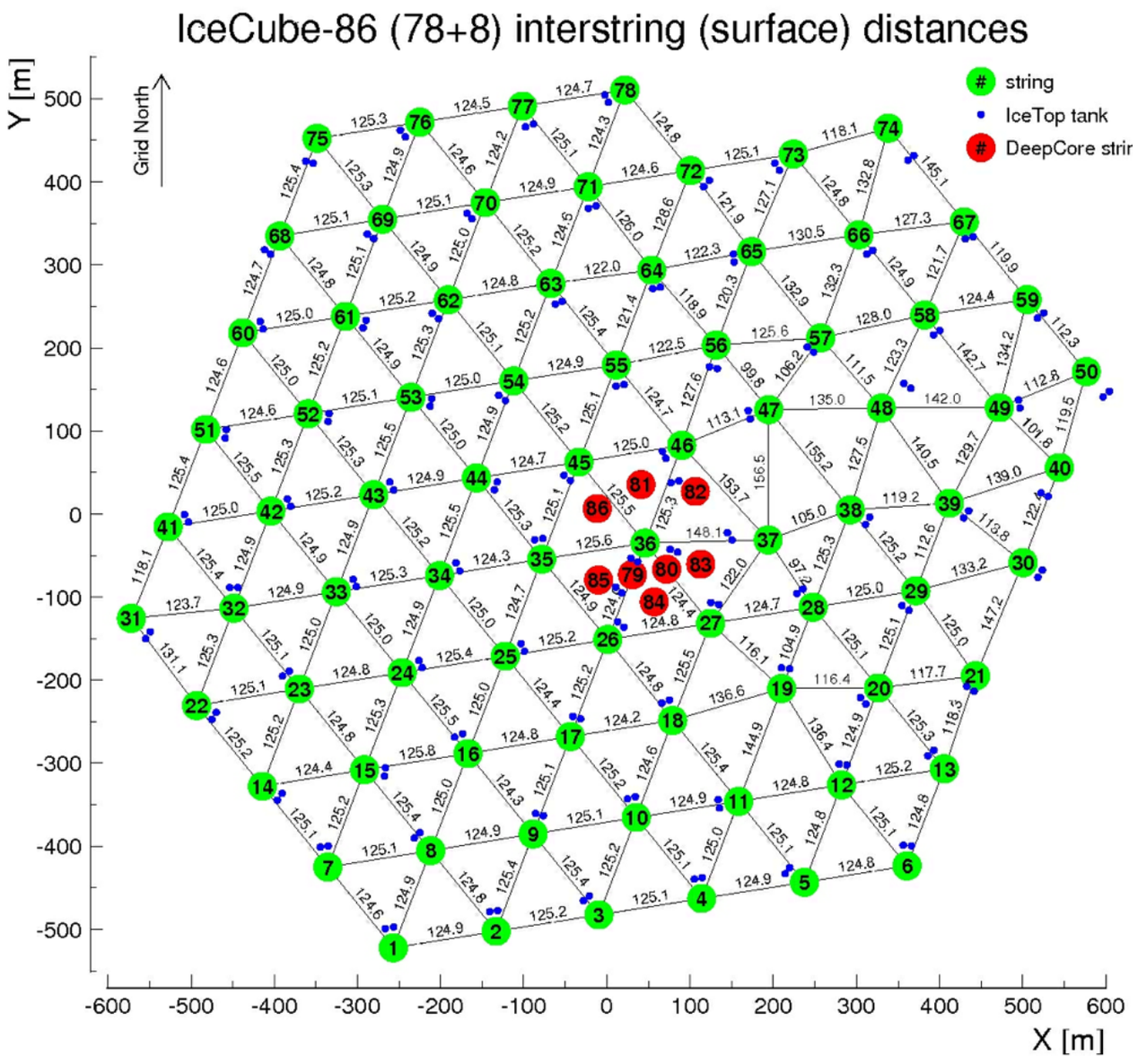


- indirect measurements > 10^{14} eV
- **model-dependent** measurement spectrum for individual mass components

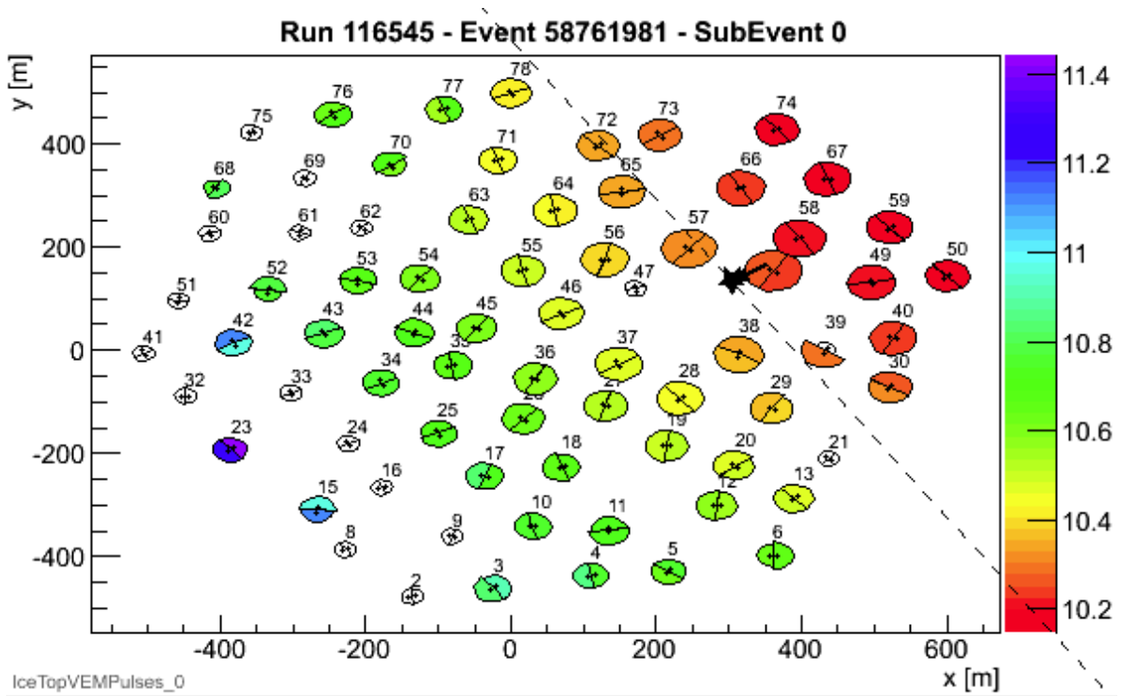
growing observatory

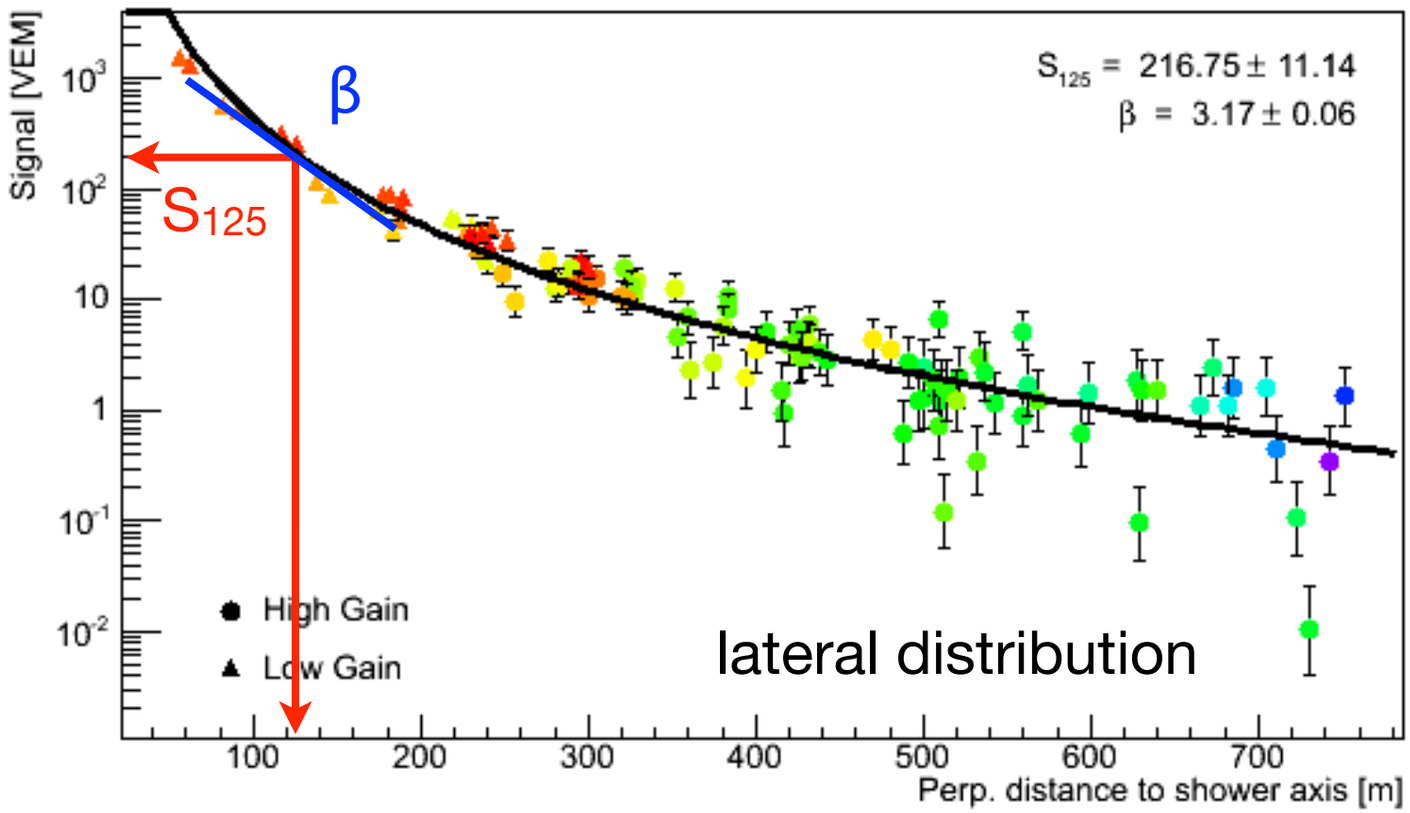
season	no. strings no. stations	array configuration
2004-2005	1 string 4 stations	
2005-2006	9 strings 16 stations	
2006-2007	22 strings 26 stations	IT26/IC22
2007-2008	40 strings 40 stations	IT40/IC40
2008-2009	59 strings 59 stations	IT59/IC59
2009-2010	79 strings 73 stations	IT73/IC79
2010-2011	86 strings 81 stations	IT81/IC86

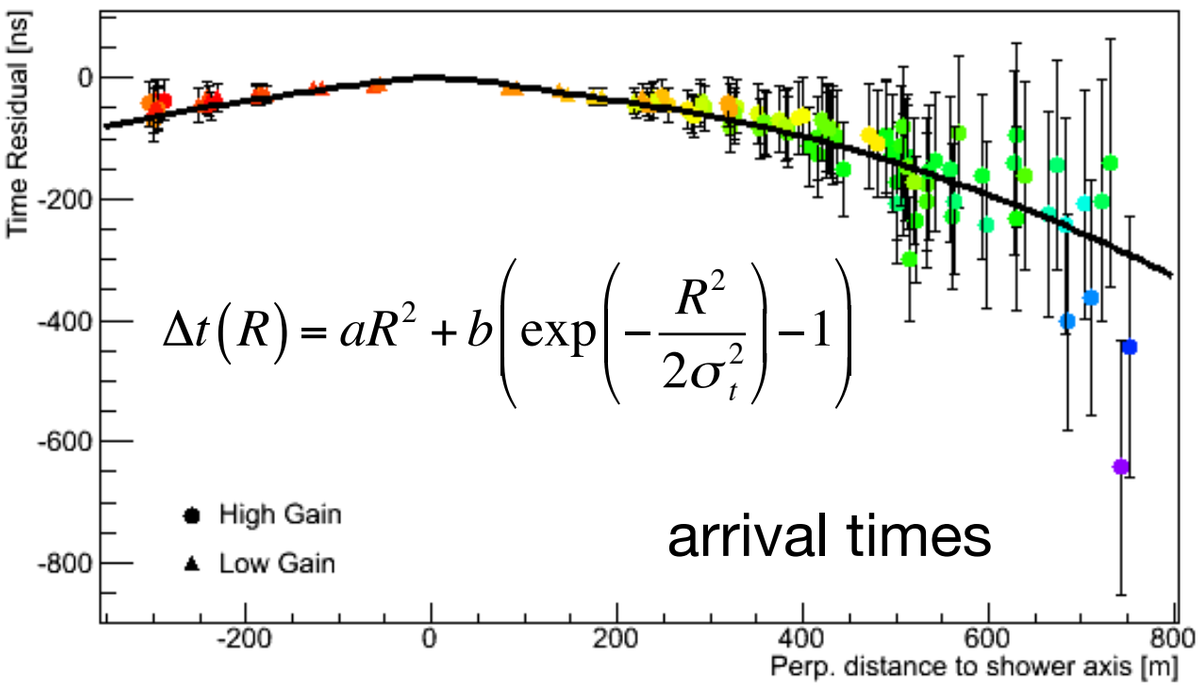




IceTop shower reconstruction







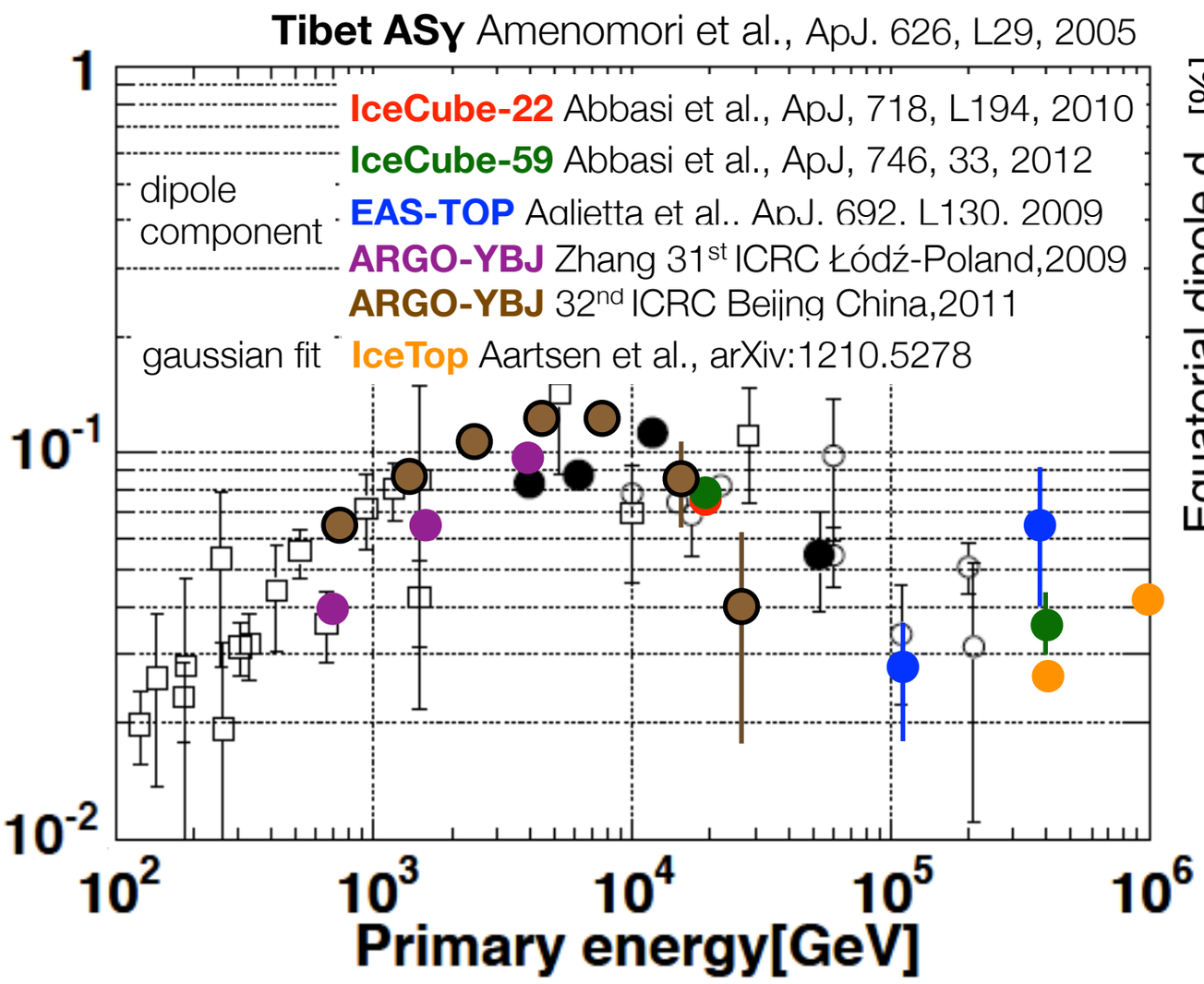
$$S(R) = S_{125}\left(\frac{R}{125m}\right)^{-\beta-\kappa\log(R/125m)}$$

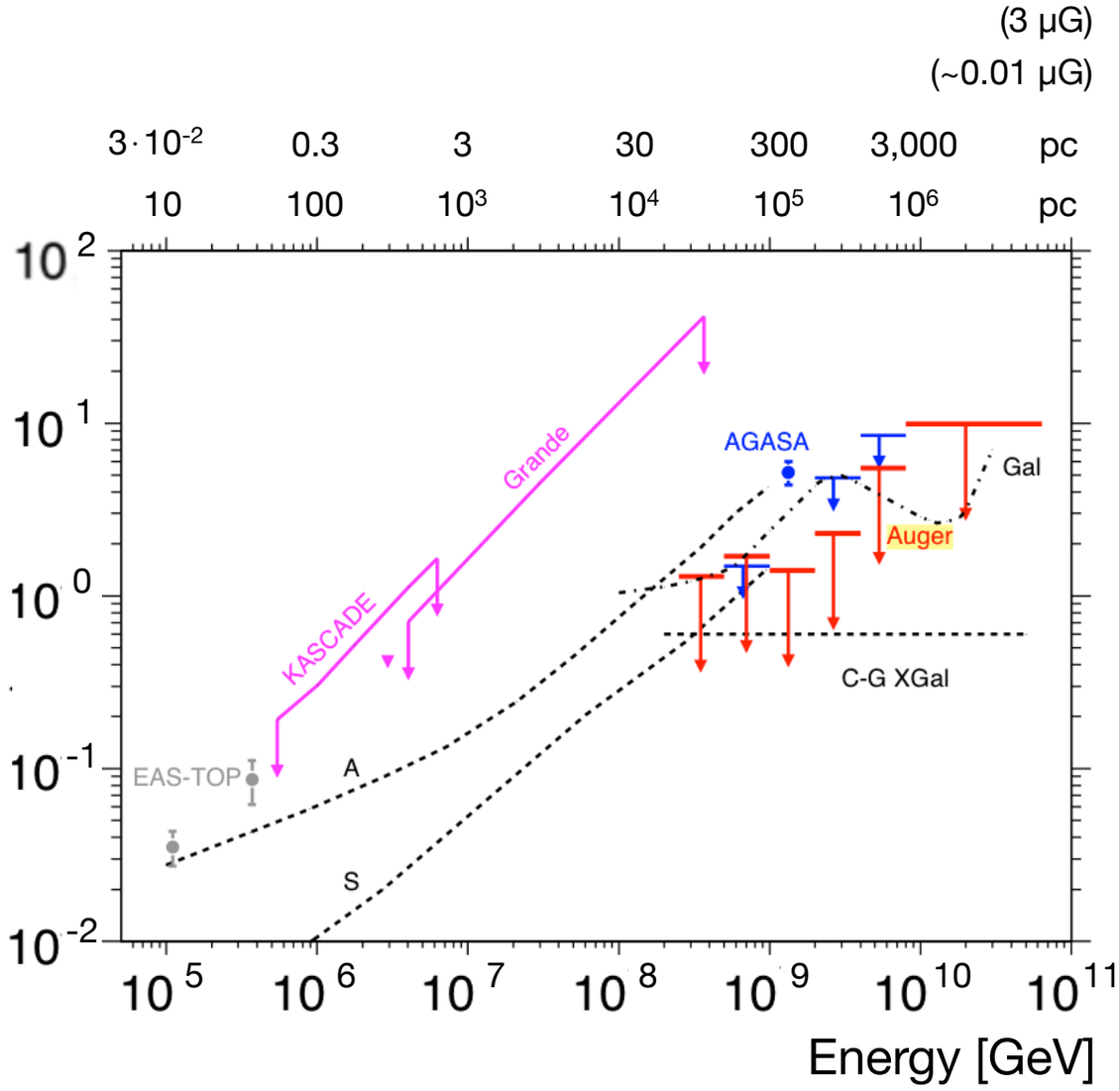
S_{125} : signal at r = 125m

β : slope at r = 125m

κ = 0.303 fixed

cosmic ray anisotropy large scale energy dependency





Abreu et al., Astrop. Phys., 34, 627, 2011

(3 μG)

$3\cdot10^{-5}$	$3\cdot10^{-4}$	$3\cdot10^{-3}$	$3\cdot10^{-2}$	0.3	gyro-radius (pc)
7	70	700	7,000	70,000	gyro-radius (AU)