The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2246-3

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Cosmic-ray spectrum and composition: implications for neutrinos

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Cosmic-ray spectrum and composition

--Implications for neutrinos

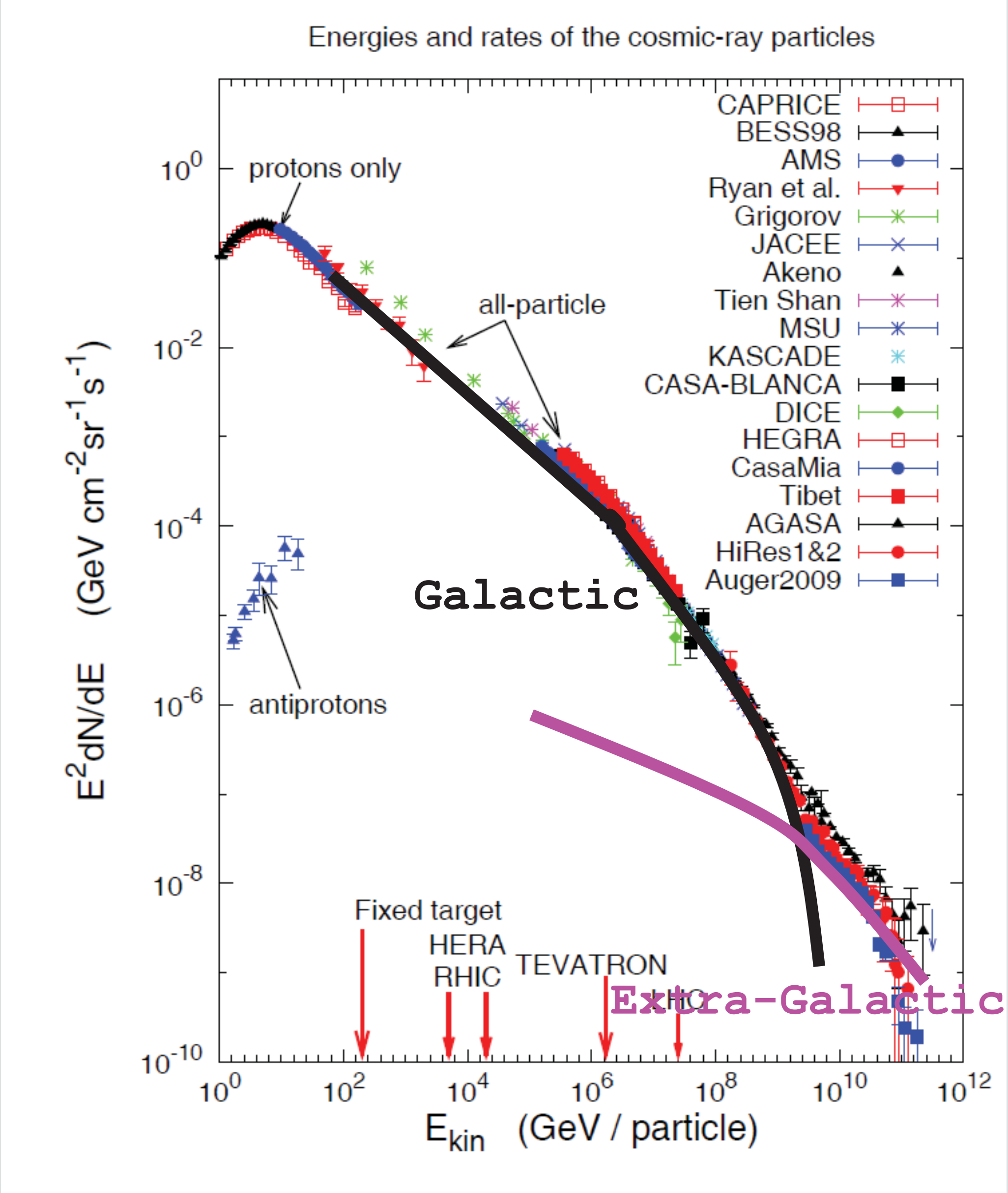
and *vice versa*

Outline

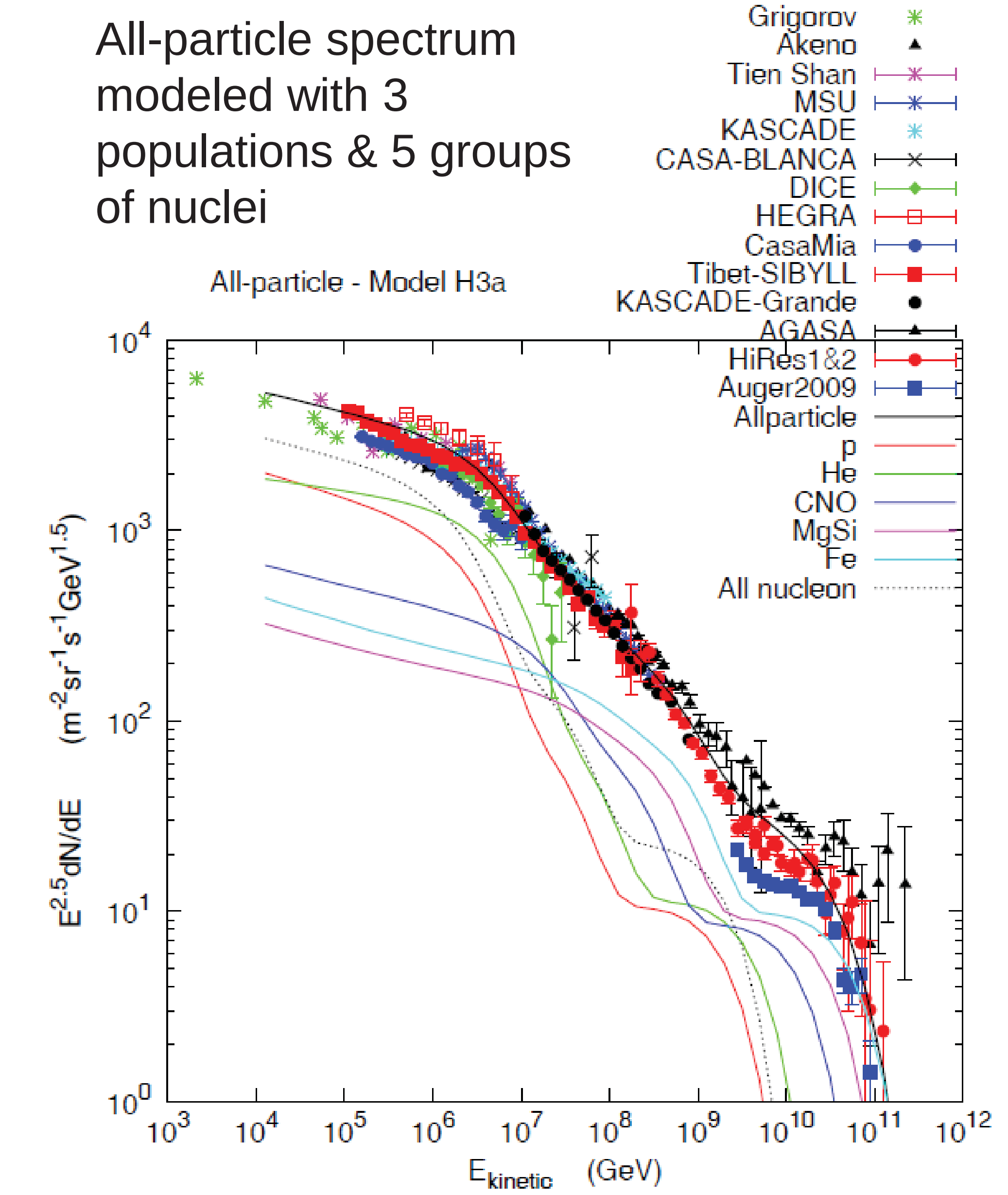
- Cosmic ray – neutrino connections
- Cosmic rays and neutrinos in IceCube
- Atmospheric neutrinos
- New limits on astrophysical neutrinos
- Implications for models of sources
- Summary

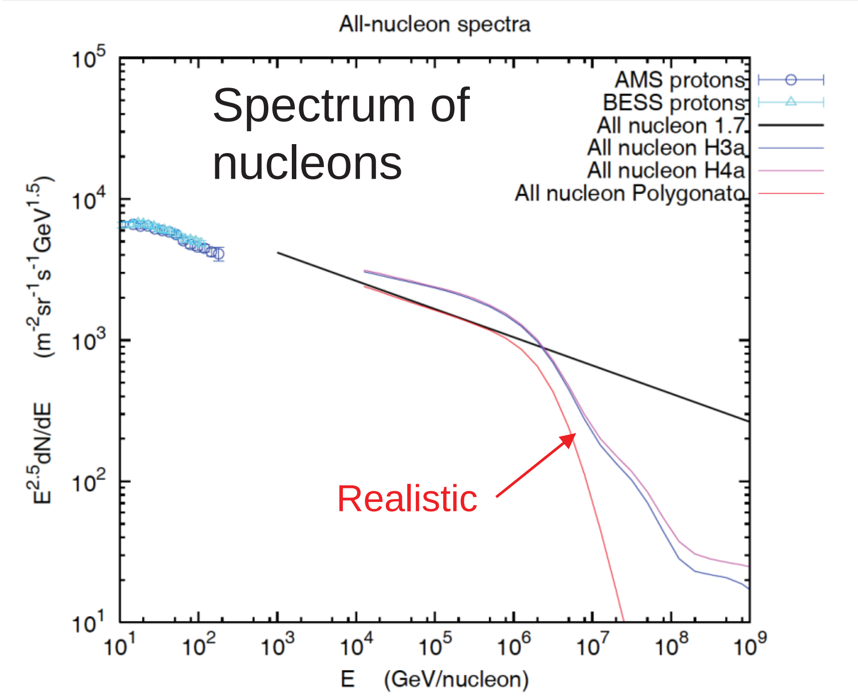
Cosmic-ray connection - I

- Galactic SNR can accelerate particles into nearby molecular clouds
- Extra-galactic jets (in AGN or GRB) may share power between c.r. & ν
- Expect a few TeV ν/ yr in a gigaton detector in hadronic scenarios
- Sets km^3 scale for HE neutrino astronomy



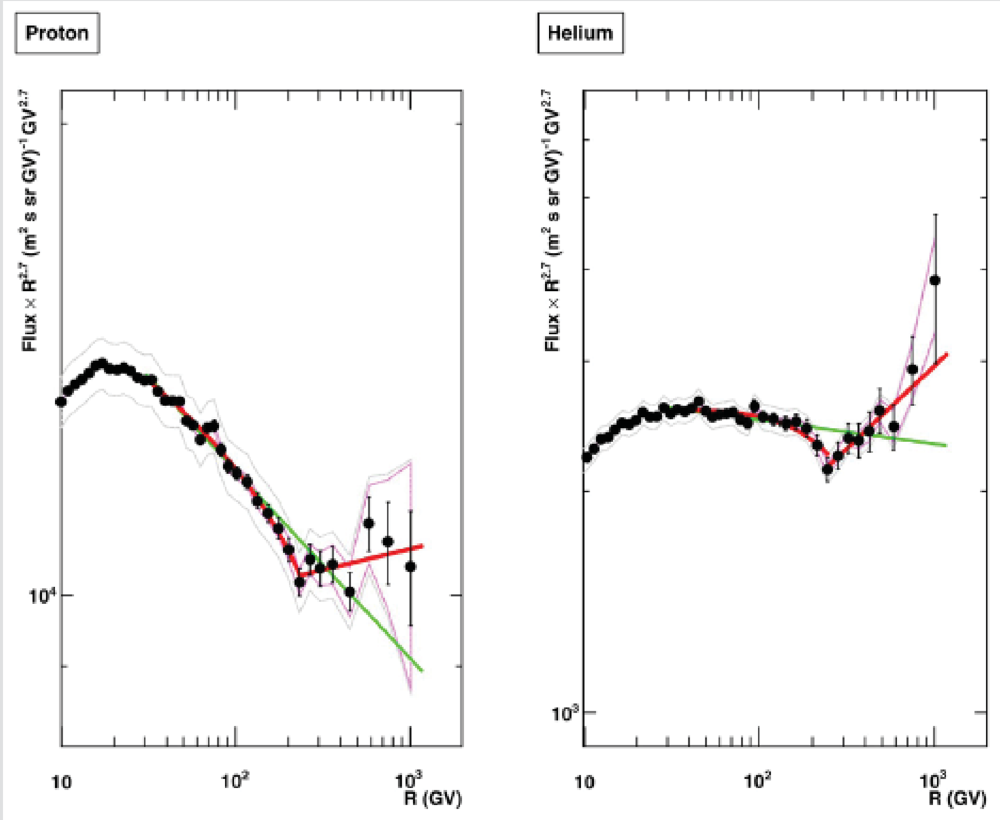
Cosmic-ray connnection – II: atmospheric ν from nucleon spectrum





New information ~TeV

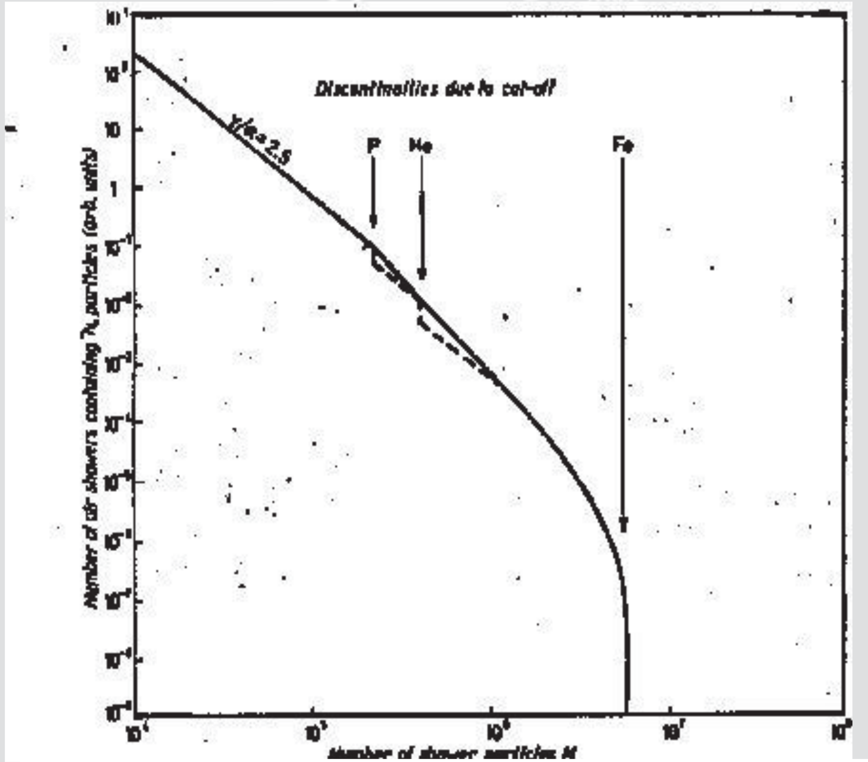
- ATIC, CREAM, PAMELA
  - Proton ≠ Helium
  - Pamela break →
    - New population?
  - Spectral hardening
    - E > 200 GeV/ A
    - Teresa, next talk



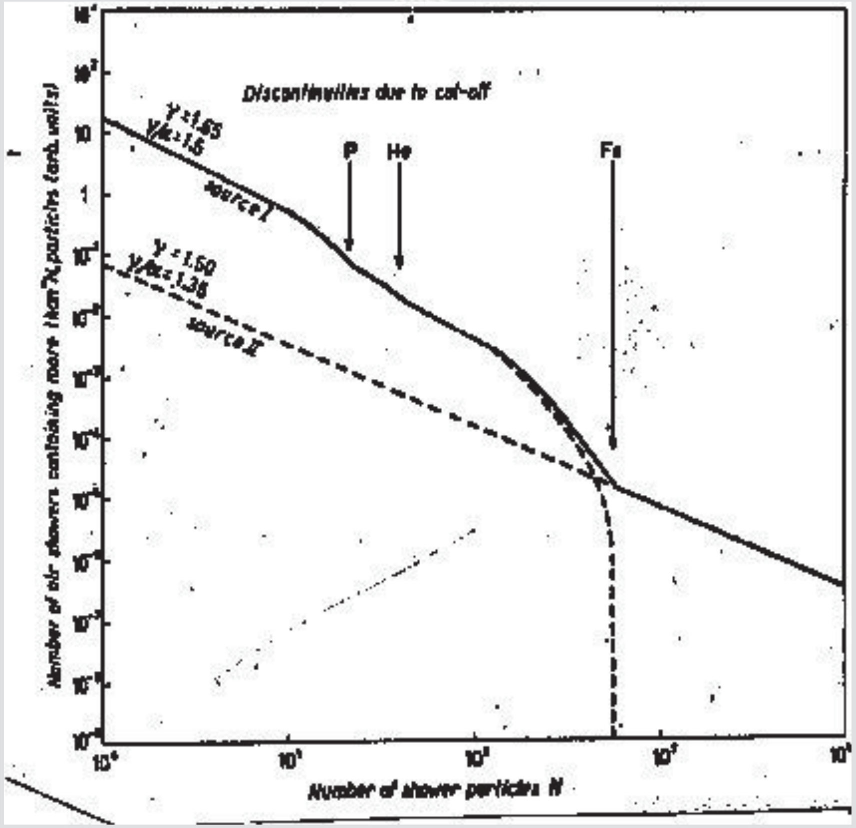
PAMELA, Adriani et al., arXiv:1103.4055

Where is the galactic – extragalactic transition?

Peters cycle: systematic increase of < A > approaching E_{max}



<A> should begin to decrease again for E > 30 x E_{knee}



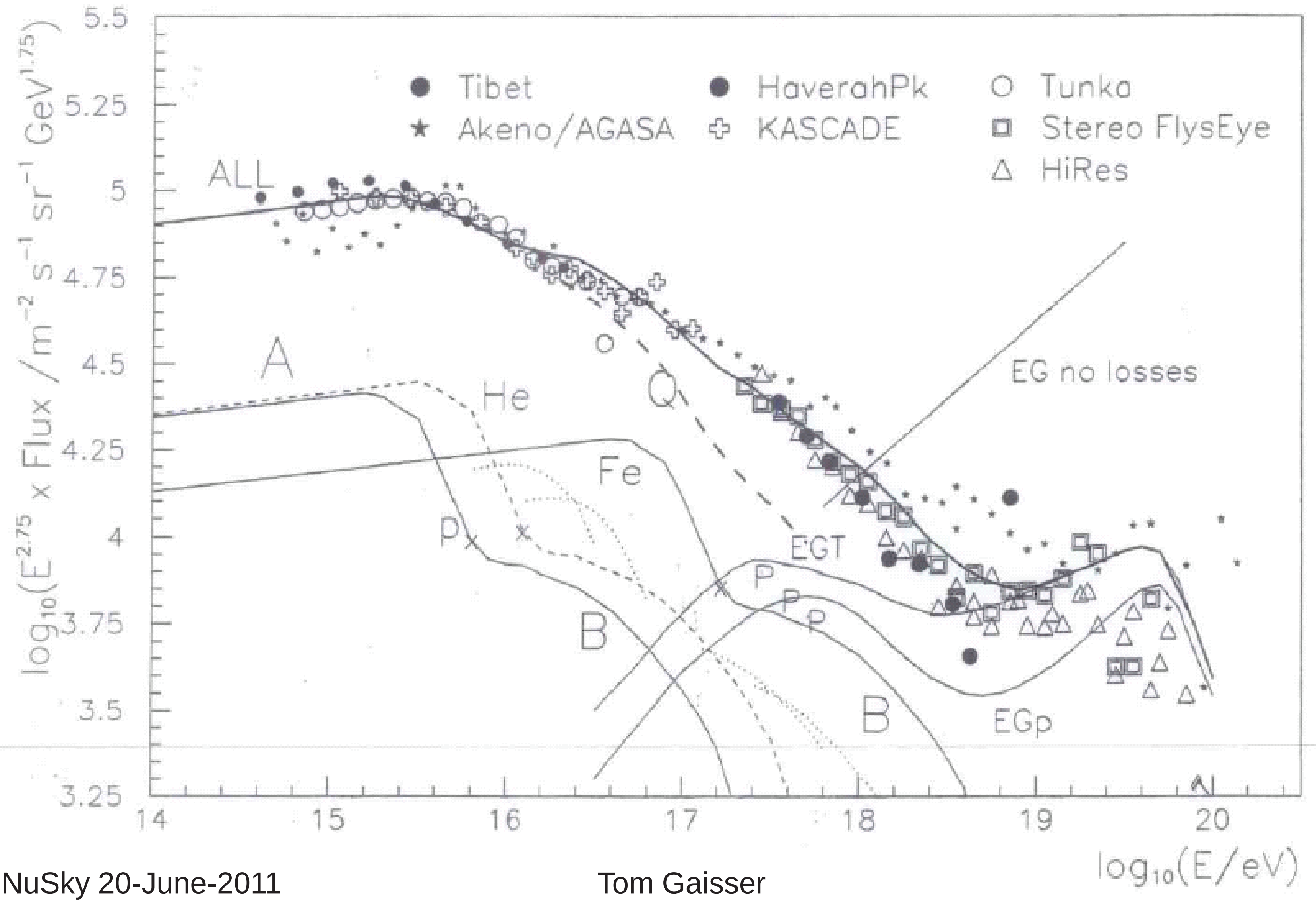
gyro-radius = Pc / ZeB ≡ R (rigidity) / B

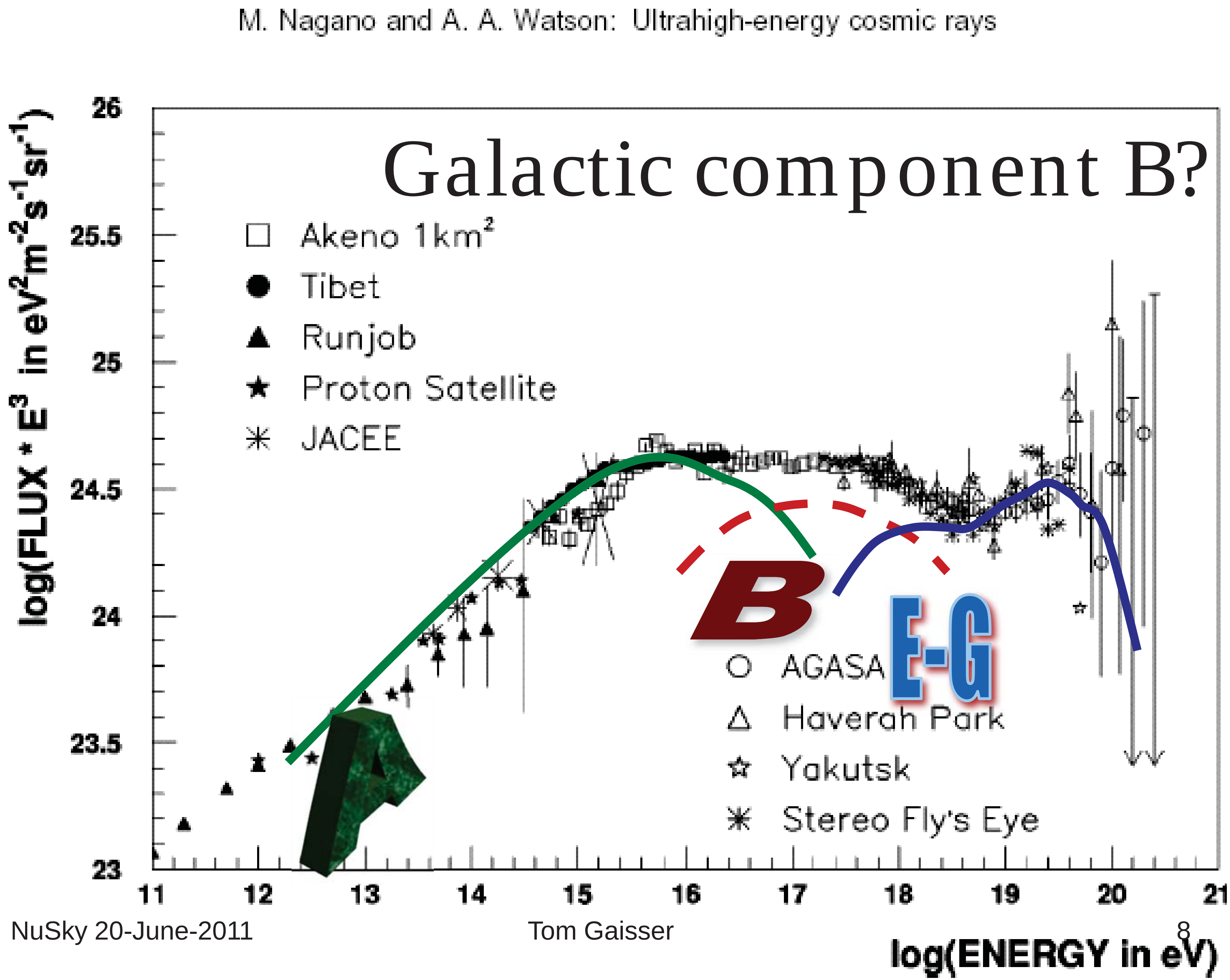
→ E_{total} (knee) ~ Z x R(knee)

B. Peters, Nuovo Cimento 22 (1961) 800

HILLAS (Aspen, 2005)

➔ Best estimate of Galactic and Extragalactic flux components:




M. Nagano and A. A. Watson: Ultrahigh-energy cosmic rays
Galactic component B?
Akeno 1km²
Tibet
Runjob
Proton Satellite
JACEE
AGASA
Haverah Park
Yakutsk
Stereo Fly's Eye
B
E-G
log(FLUX * E³ in eV²m⁻²s⁻¹sr⁻¹)
log(ENERGY in eV)
26
25.5
25
24.5
24
23.5
23
11
12
13
14
15
16
17
18
19
20
21

- # Toy model fits:

3 populations

5 nuclear groups,

Exponential cutoff in rigidity

All particle spectrum

$$\phi_i(E) \;=\; \Sigma_{j=1}^{3}\, a_{i,j}\, E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

$$\phi_{i,N}(E_N) \;=\; A \times \phi_i(A\, E_N)$$

R_c	γ	p	He	CNO	Mg-Si	Fe
γ for Pop. 1	—	1.647	1.571	1.634	1.67	1.675
Population 1: 4 PV	see line 1	7860	3550	2200	1430	2120
Pop. 2 (H3a): 30 PV	1.4	20	20	13.4	13.4	13.4
" (H4a): 30 PV	1.4	20	20	13.4	13.4	13.4
Pop. 3 (H3a): 2 EV	1.4	1.7	1.7	1.14	1.14	1.14
" (H4a): 60 EV	1.6	200.	0	0	0	0

Table 1: Normalizations constants $a_{i,j}$, spectral indices and cutoffs for Eq. 5.

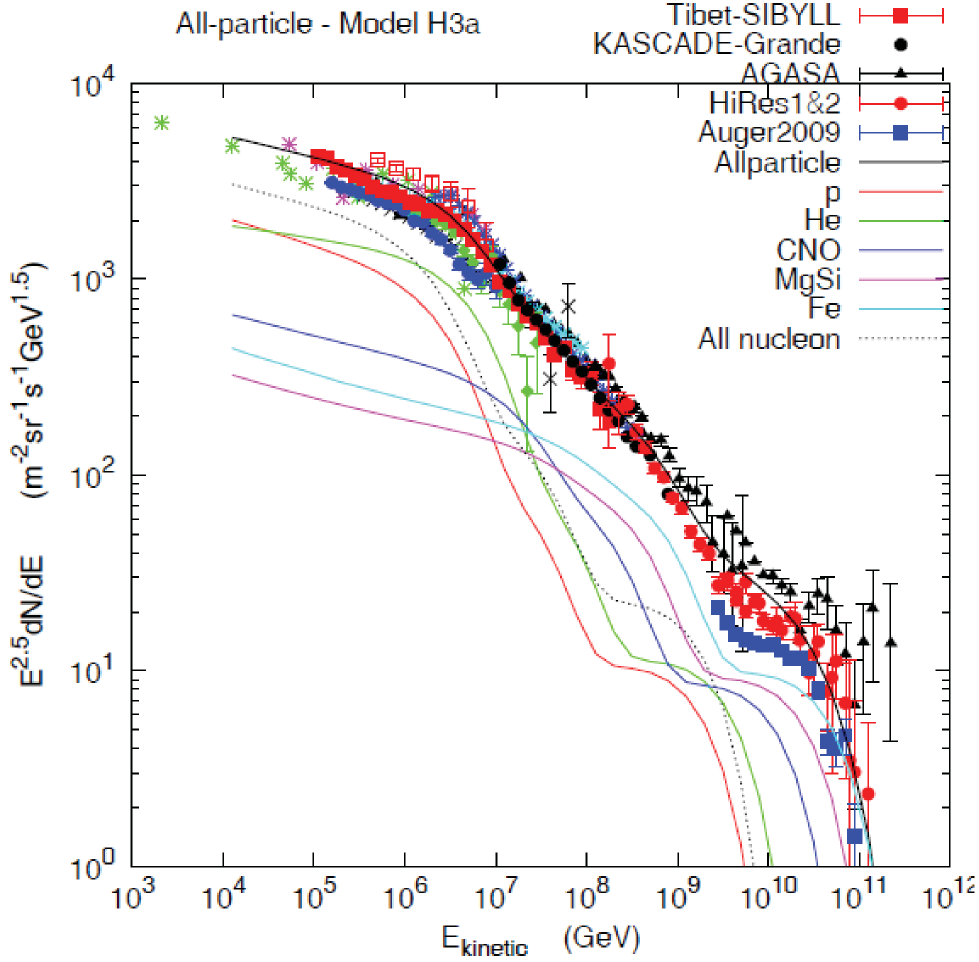
Primary spectrum & composition:

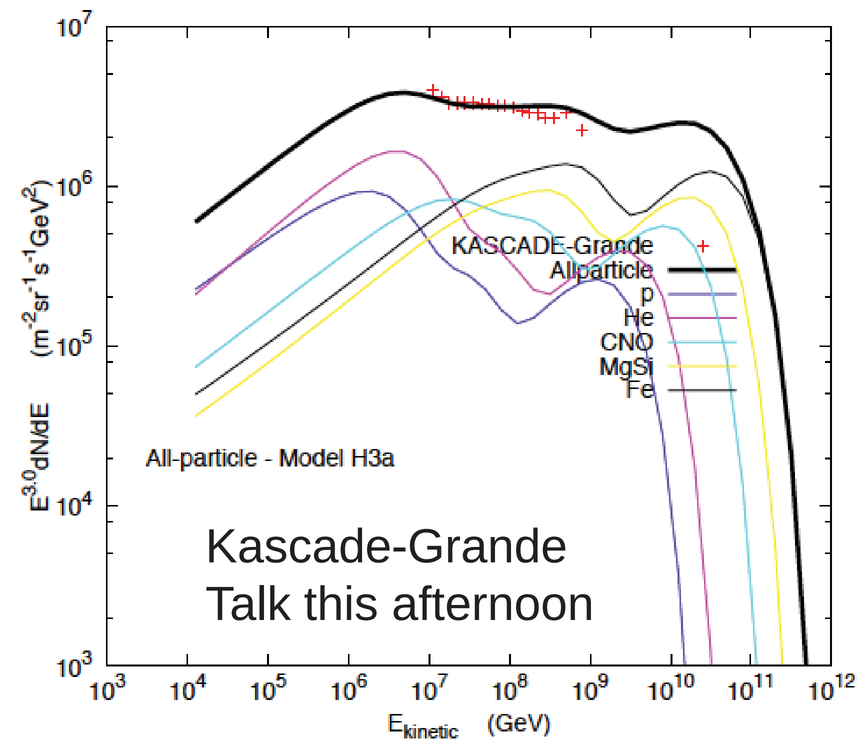
1st knee

Component B

2nd knee

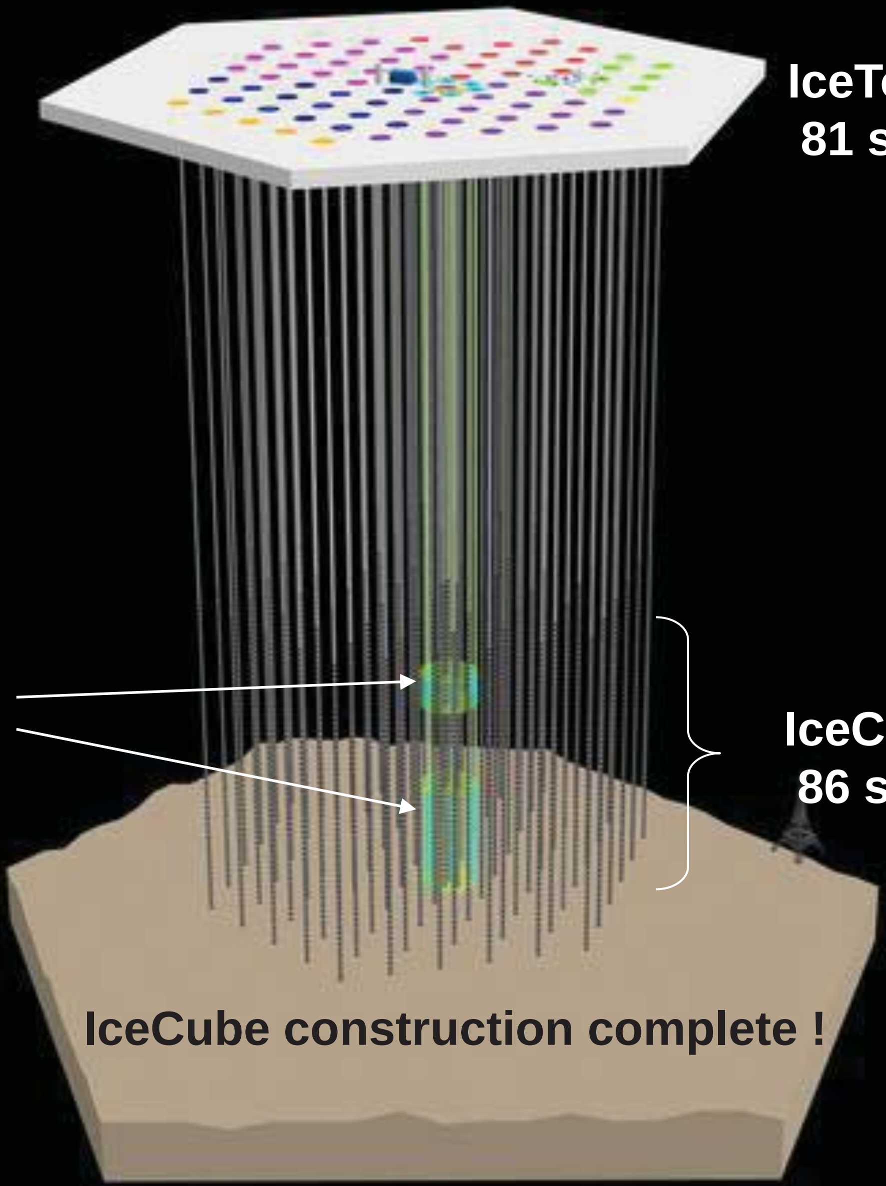
All-particle spectrum modeled with 3 populations & 5 groups of nuclei





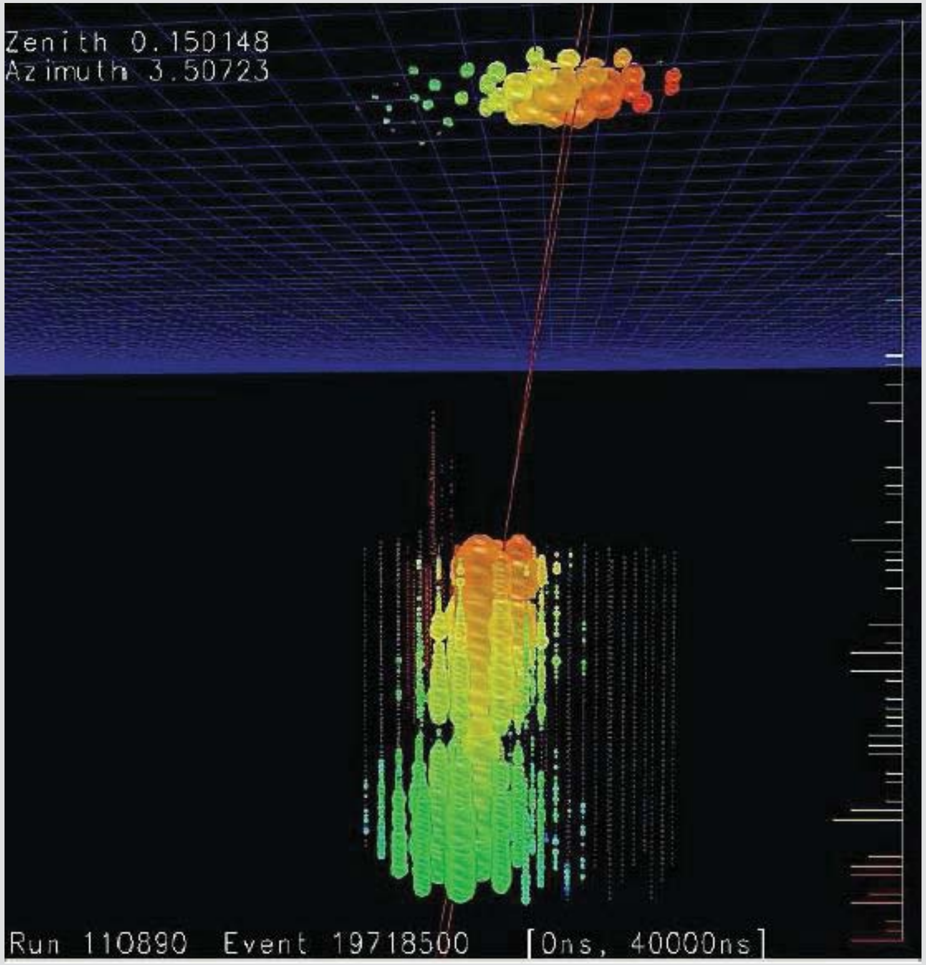
Kascade-Grande
Talk this afternoon

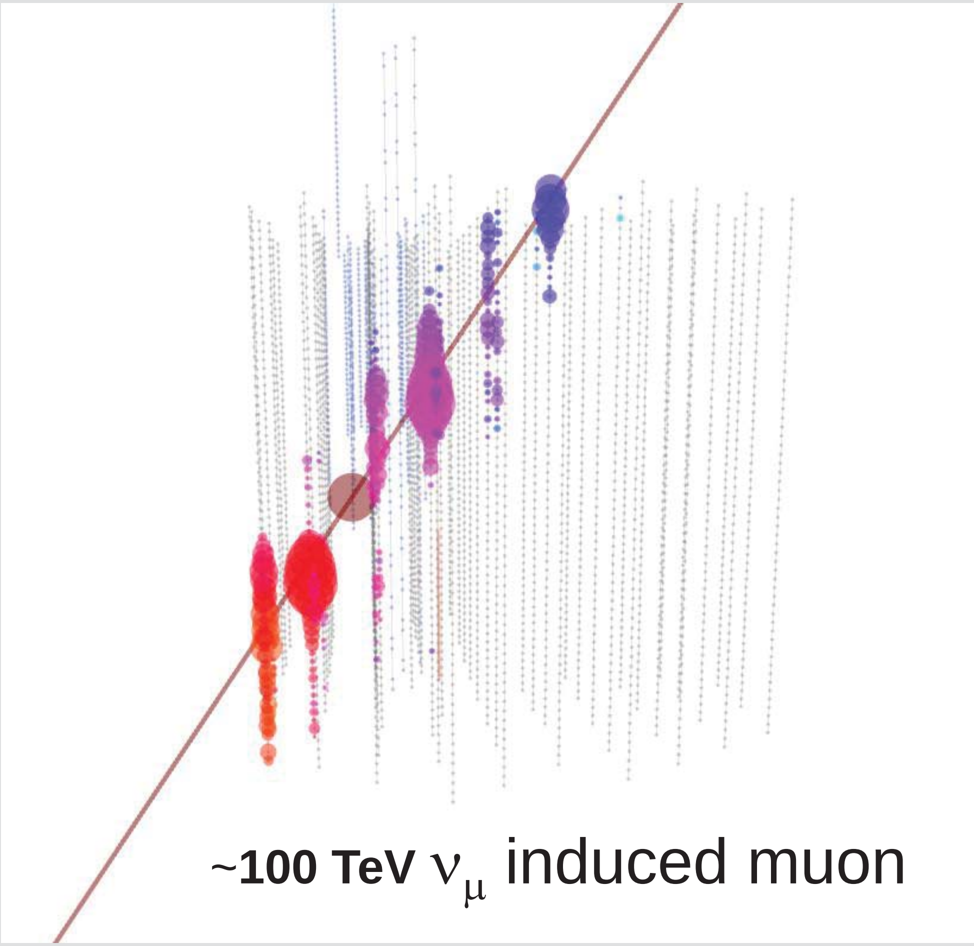
2004-05	1	1
2005-06	8	9
2006-07	13	22
2007-08	18	40
2008-09	19	59
2009-10	20	79
2010 11	7	86



High-energy events in IceCube-40

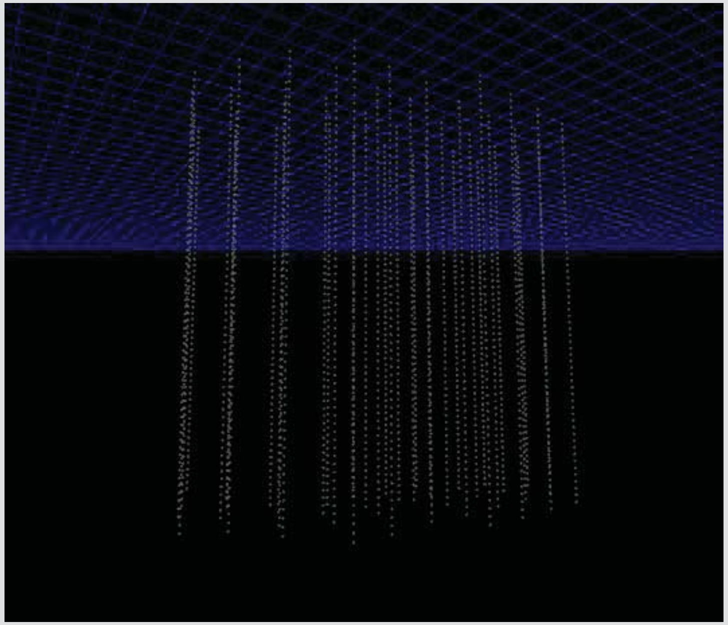
~ EeV air shower

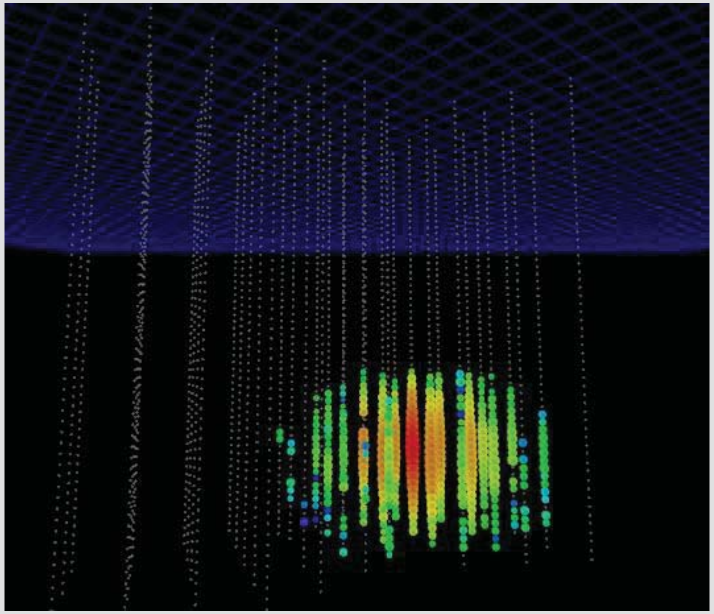


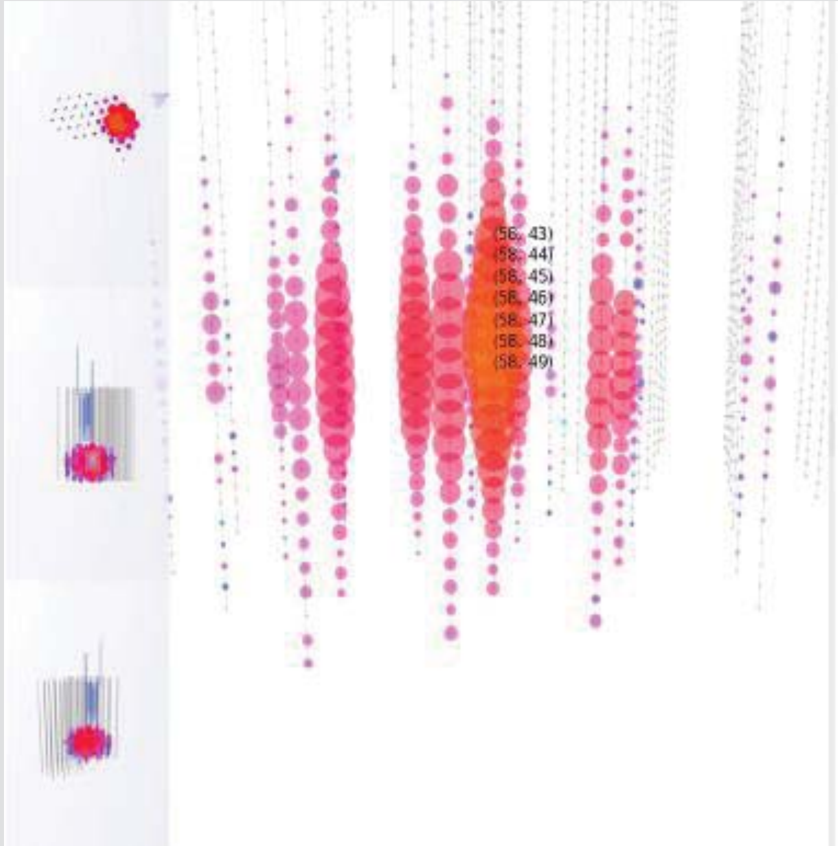


~**100 TeV** ν_μ induced muon

More events



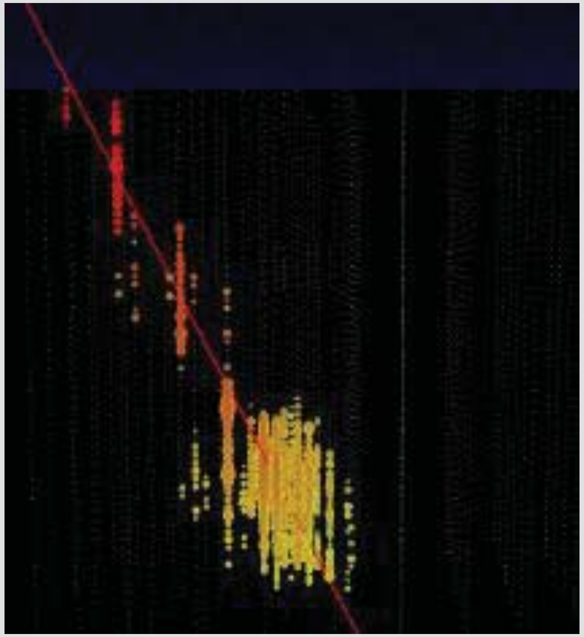




A cascade event, candidate for a high energy ν_e ~50 TeV

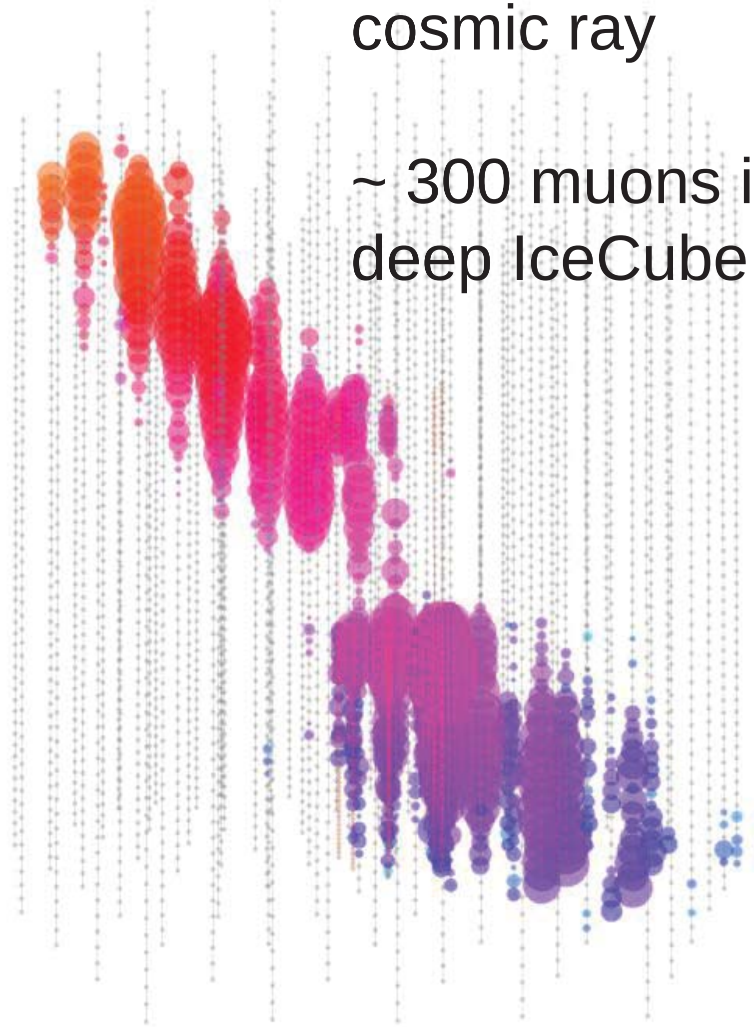
IC-79 event: downward muon bundles

IceCube Deep Core talk by Doug Cowen Friday



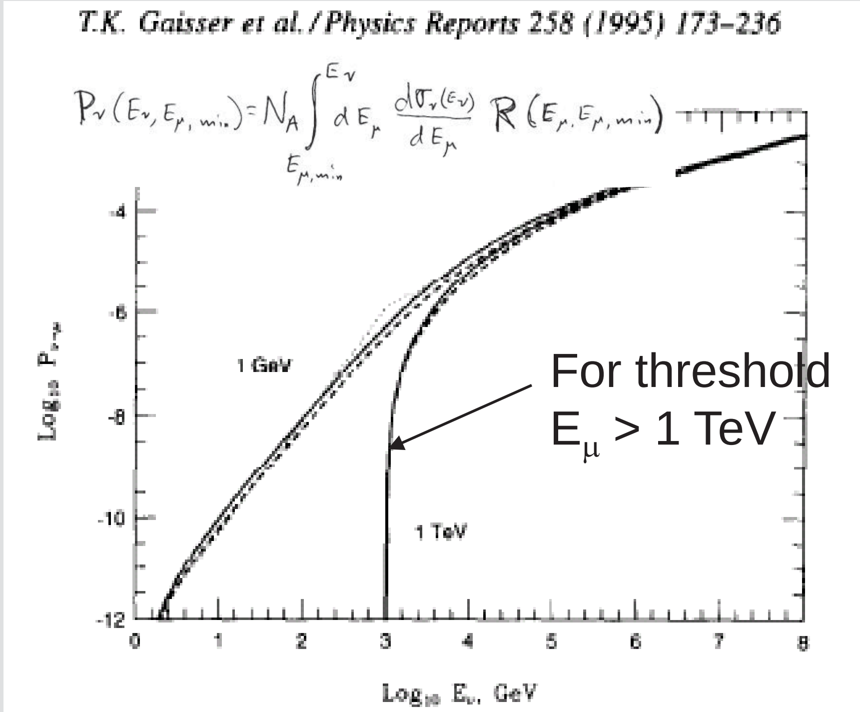
~100 PeV primary cosmic ray

~ 300 muons in deep IceCube



Detecting neutrinos

- Rate = Neutrino flux
  - x Absorption in Earth
  - x Neutrino cross section
  - x Size of detector
  - x Range of muon (for ν_μ)
- Range favors ν_μ
  - – ~4 to 15 km.w.e. for E_ν ~ 10 to 1000 TeV

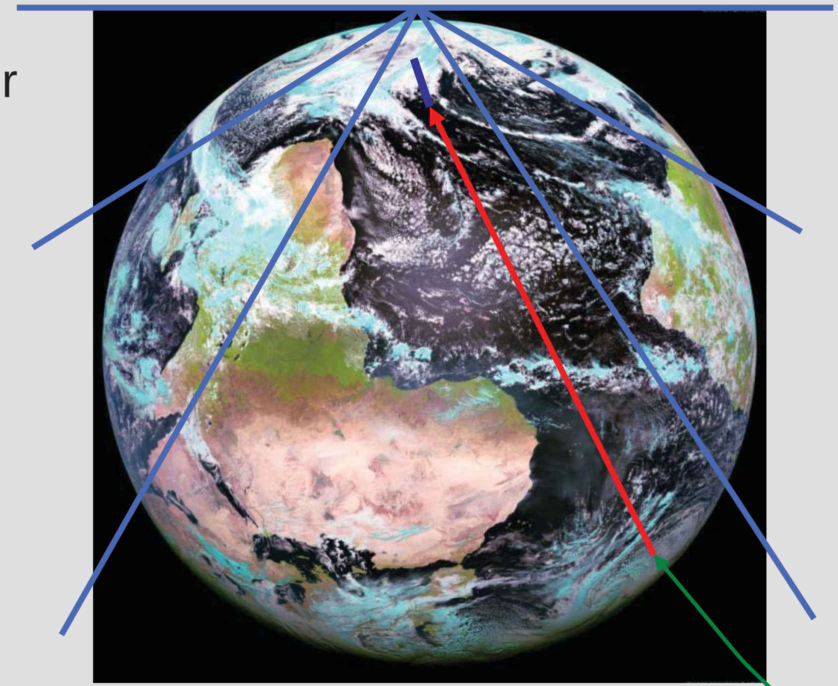


Probability to detect ν_μ-induced μ

$$A_{eff}(\theta, E_\nu) = \epsilon(\theta) A(\theta) P_\nu(E_\nu, E_{\mu,min}) e^{-\sigma_\nu(E_\nu) N_A X(\theta)}$$

Atmospheric ν in IceCube

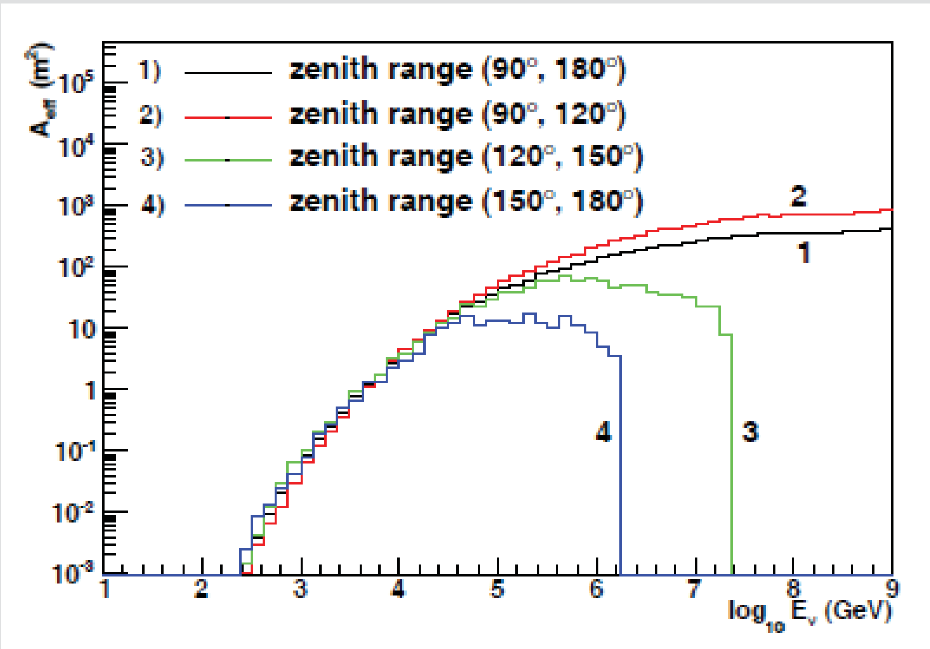
S.P.



Zone 1, l: -30 to -90 ; 3.14 sr
Zenith: $90 < \theta < 120^o$
(40% of Zone 1 is over the Antarctic continent)

Zone 2, l: -30 to +30; 2.30 sr
Zenith $120 < \theta < 150^o$

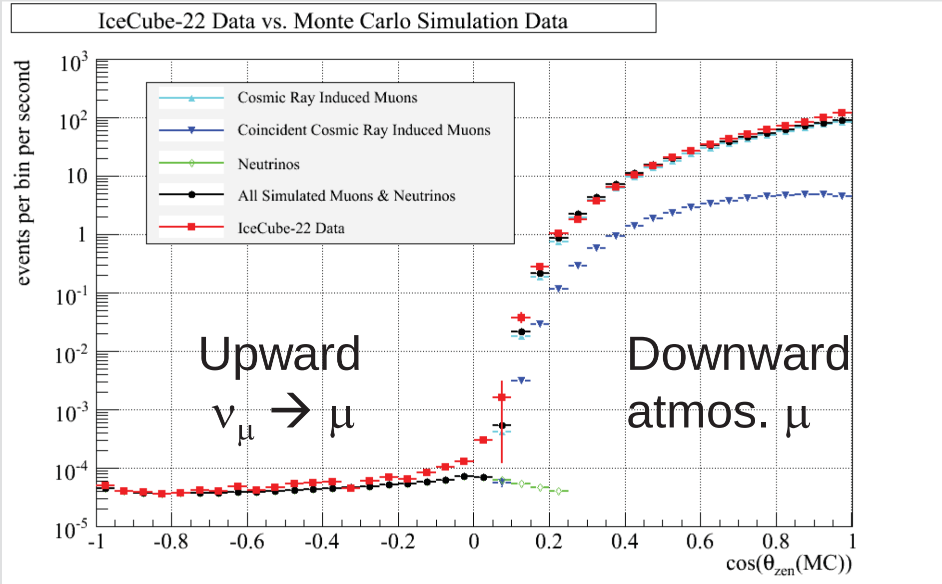
Zone 3, l: +30 to +90, 0.84 sr
Zenith: $150 < \theta < 180^o$



Cosmic ray produces ν in atmosphere that puts a **muon** into the detector

Cuts and event reconstruction

- 40-string IceCube:
  - 375 days livetime in 08/ 09 @1 kHz $=3.3\times10^{10}$ triggers, 99.9999% muons
  - 8 x 10^8 filtered & sent over satellite from S.P.
  - Quality cuts applied to get ~14,000 upward ν_μ induced muons



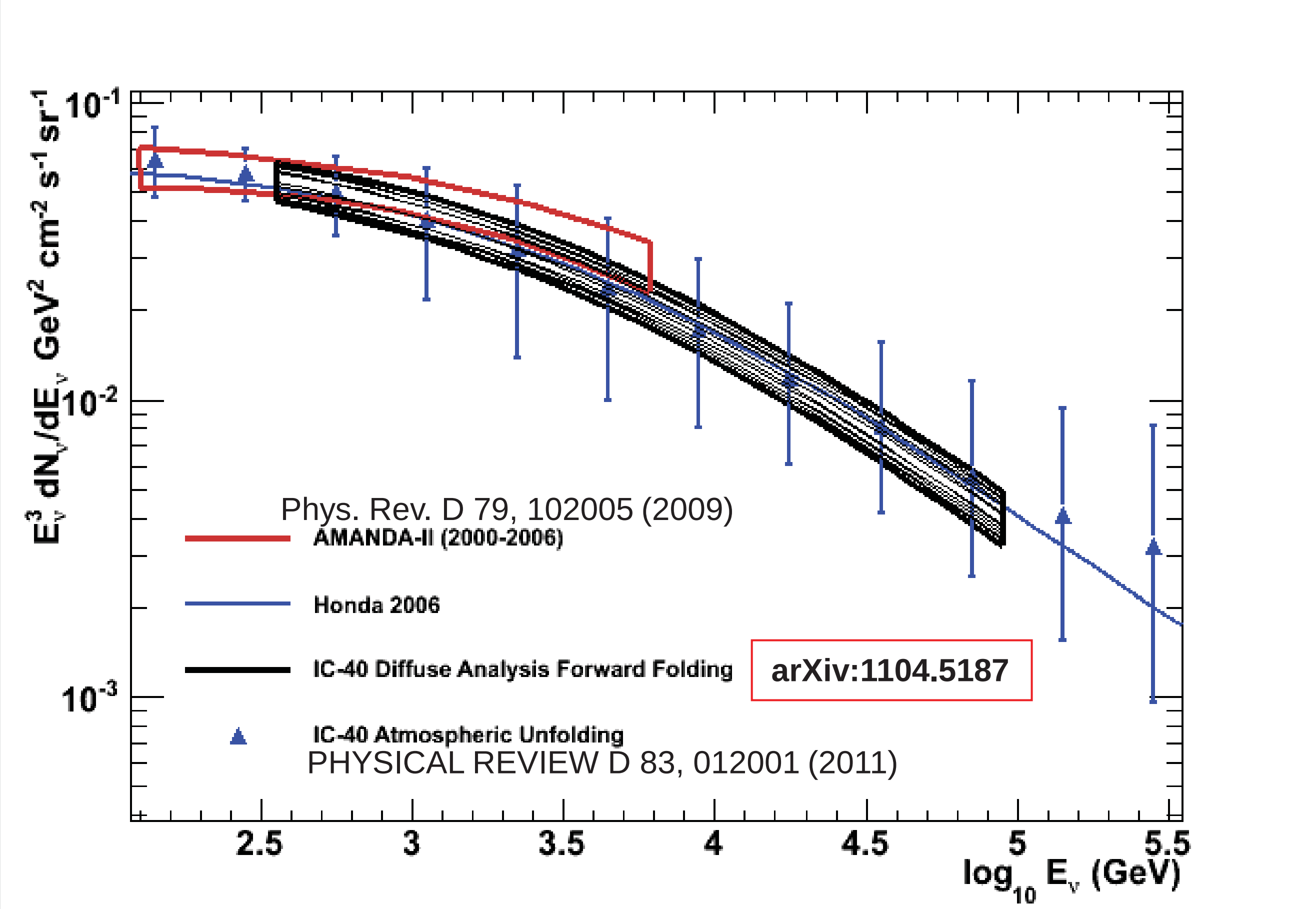
All-sky plot of muons in IceCube-22 from 2007 (P. Berghaus, IceCube, ISVHECRI-2008 arxiv.org/abs/0902.0021)

Atmospheric ν_μ with IceCube-40

Two analyses:

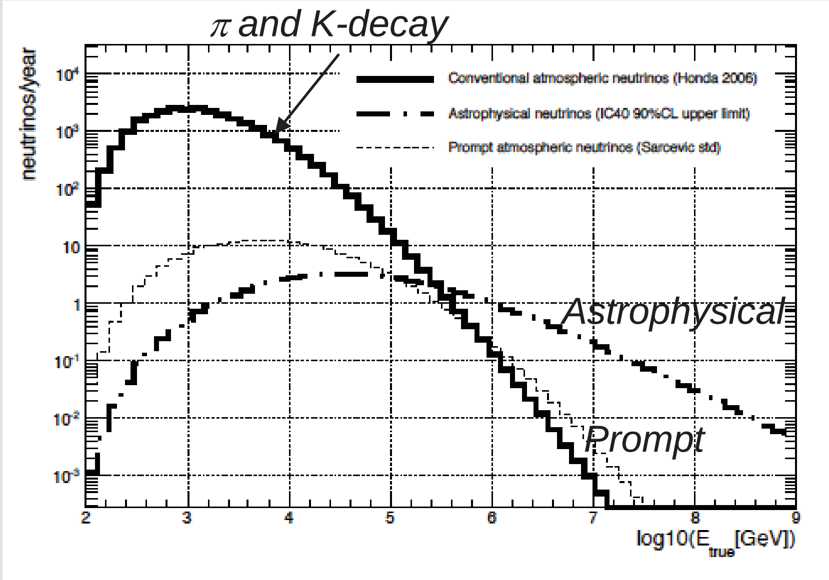
1. Unfolding
2. Forward folding as a by-product of a search for diffuse astrophysical ν

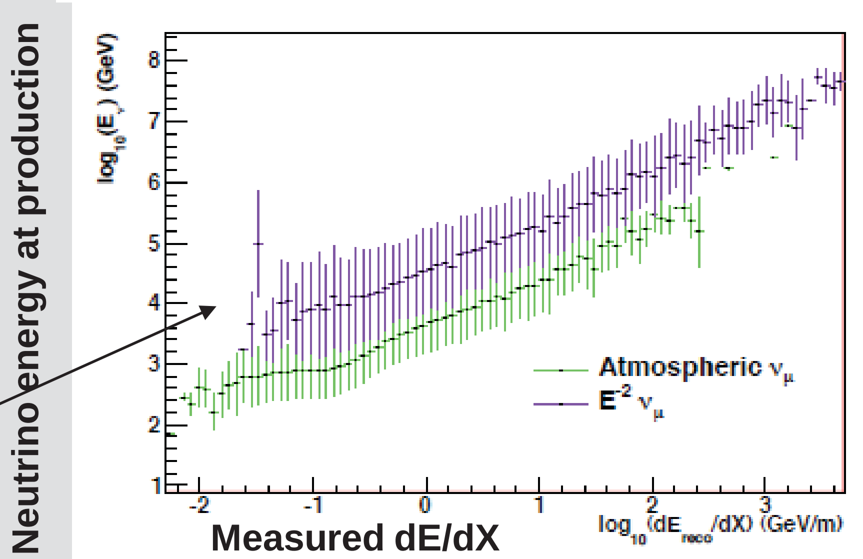
Look in detail at 2



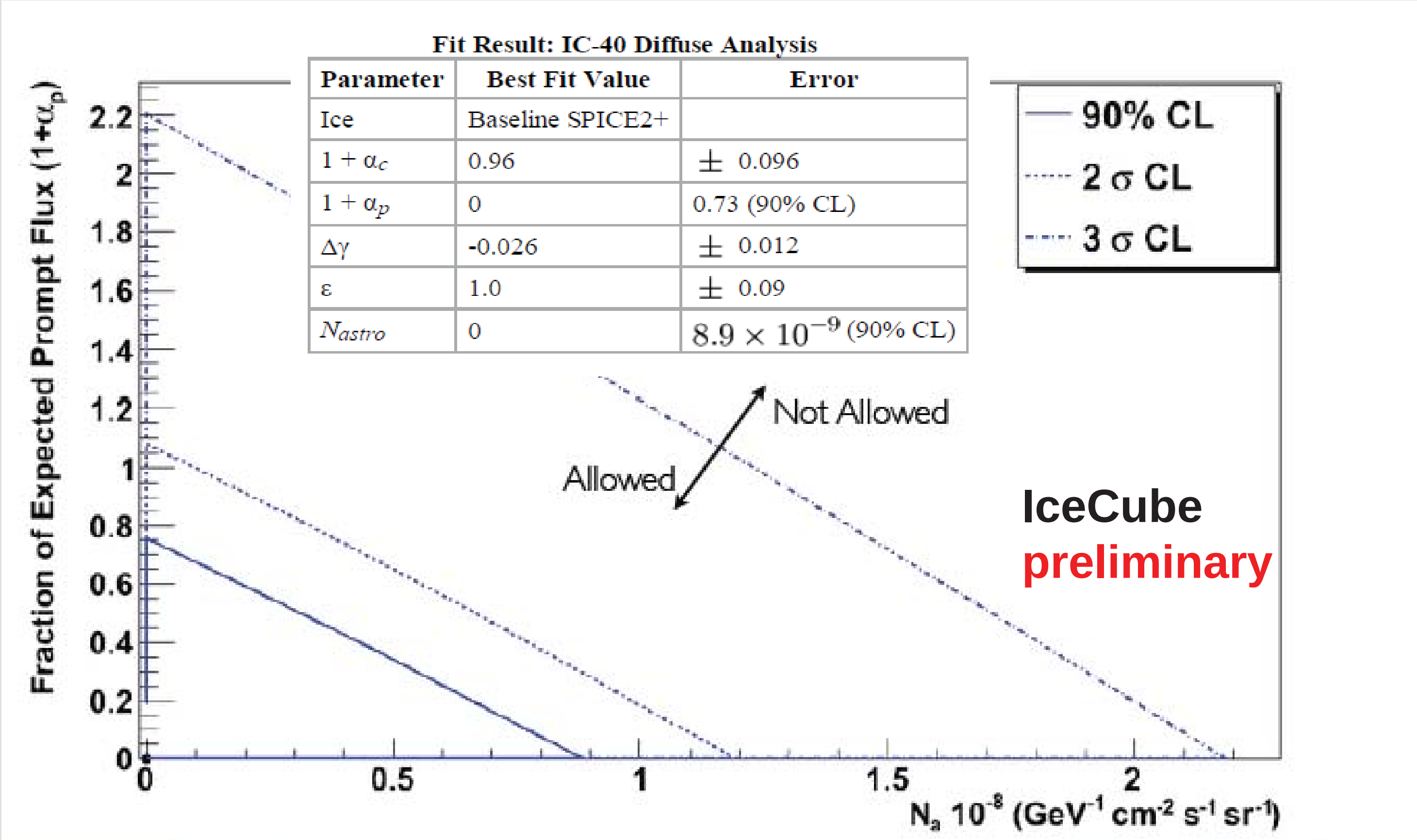
Measurement of ν_μ-induced μ

- Fit 3 components:
  - Atmospheric ν from $K^\pm$ and $\pi^\pm$ (0.3 – 85 TeV)
    - Use Honda 2007 to 10 TeV
    - + power-law extrapolation
    - $\sim \cos^{-1}(\theta)$
  - Prompt ν (10 – 600 TeV)
    - Harder spectrum to > 10^7 GeV ($\sim E^{-2.7}$), isotropic
  - Astrophysical ν
    - Isotropic, with E^{-2} spectrum assumed (35 – 7000 TeV)
  - Note different response for astro. ν *vs* atmos. ν





Results of likelihood fit



Fit Result: IC-40 Diffuse Analysis

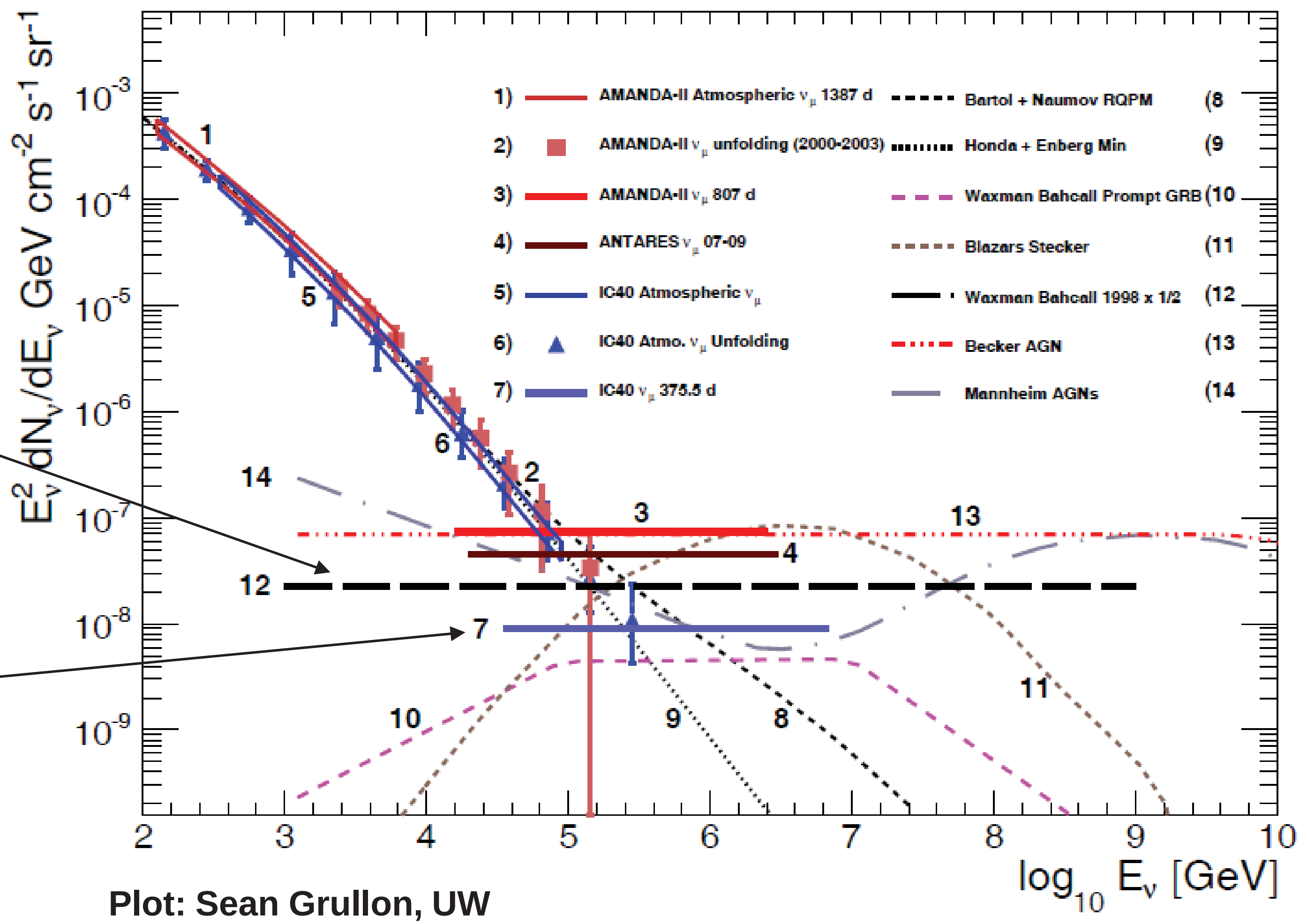
Parameter	Best Fit Value	Error
Ice	Baseline SPICE2+	
$1+\alpha_c$	0.96	$\pm$ 0.096
$1+\alpha_p$	0	0.73 (90% CL)
$\Delta\gamma$	-0.026	$\pm$ 0.012
ε	1.0	$\pm$ 0.09
N_{astro}	0	8.9×10^{-9} (90% CL)

- Consistent with only K, π atmospheric ν to 100 TeV
- Charm component not yet seen; "intrinsic" charm in doubt?
- No astrophysical neutrinos seen yet

IceCube ν_μ: measurements & limits

Waxman -Bahcall Limit

IceCube 40
arXiv:1104.5187

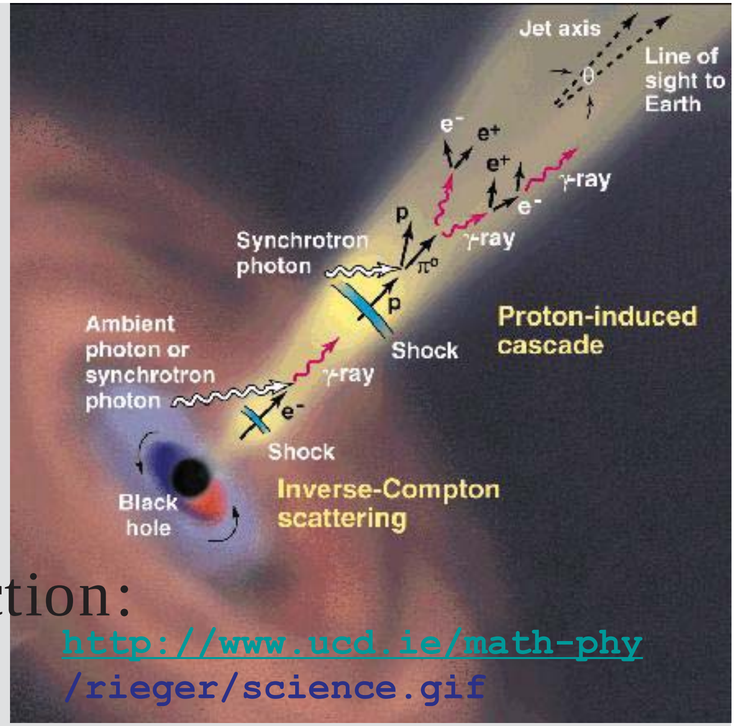


Plot: Sean Grullon, UW

Comments on diffuse ν results

- Input to analysis
  - Specific spectrum assumed for atmospheric ν from decay of π and K (Honda et al., PR D75:043006,2007)
    - Extrapolate with power law for E_ν > 10 TeV up to 10 PeV
  - For prompt ν use Enberg et al.. PR D 78, 043005, 2008
  - Overall normalization fitted for each component with a single fitted slope for both components
- Limitations of this analysis
  - Limits depend on simple power-law extension of conventional atmospheric ν_μ to E_ν > PeV
  - Neutrino spectrum must steepen to some extent above 100 TeV to reflect the knee in the primary spectrum
  - Bounds on prompt and astrophysical ν will be relaxed to some extent with a more realistic assumption for shape of atmospheric ν
  - Recent calculation extends calculation of ν_μ to > PeV
    - Illana, Lipari, Masip, Meloni, Astropart. Phys. 34 (2011) 663

Generic model I



http://www.ucd.ie/math-phy/rieger/science.gif

- CR acceleration occurs in jets
  - AGN or GRB
- Abundant target material
  - Most models assume photo-production:
    - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma\,\gamma$
    - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Ideal case (~ "Waxman-Bahcall limit")
  - Strong magnetic fields retain protons in jets
  - Neutrons escape, decay to protons & become UHECR
  - Extra-galactic cosmic rays observed as protons
  - Energy content in neutrinos ≈ energy in UHECR
- This picture disfavored as limits go below W-B

Waxman, Bahcall, PRD 59, 023002 (1998). Also TKG astro-ph/9707283v1

Generic model II

- UHECR are accelerated in external shocks analogous to SNR
  - See E.G. Berezhko, 0809.0734 & 0905.4785
  - mixed composition (accelerate whatever is there)
  - Low density of target material
  - → lower level of TeV-PeV neutrino production

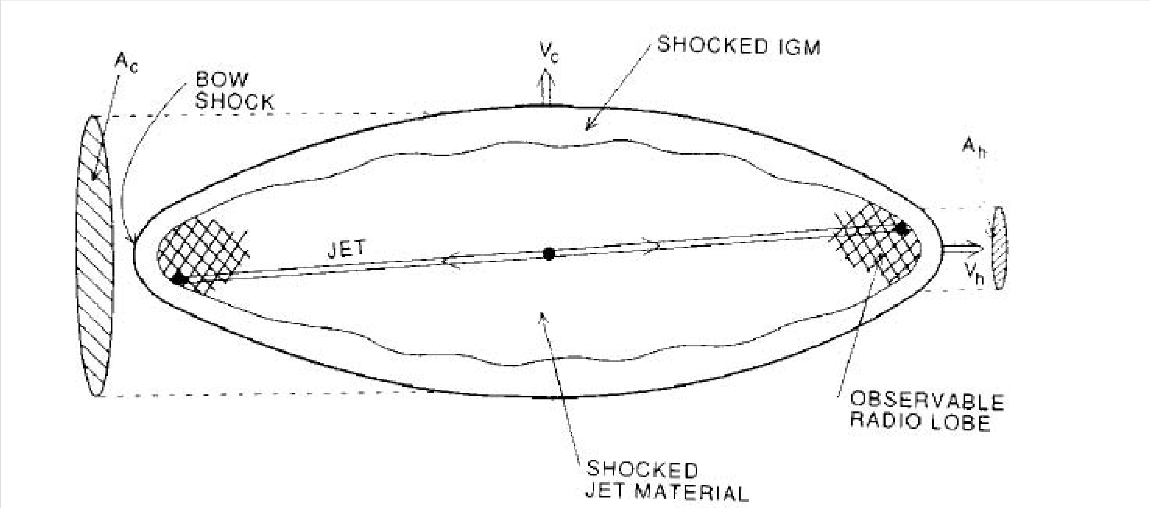
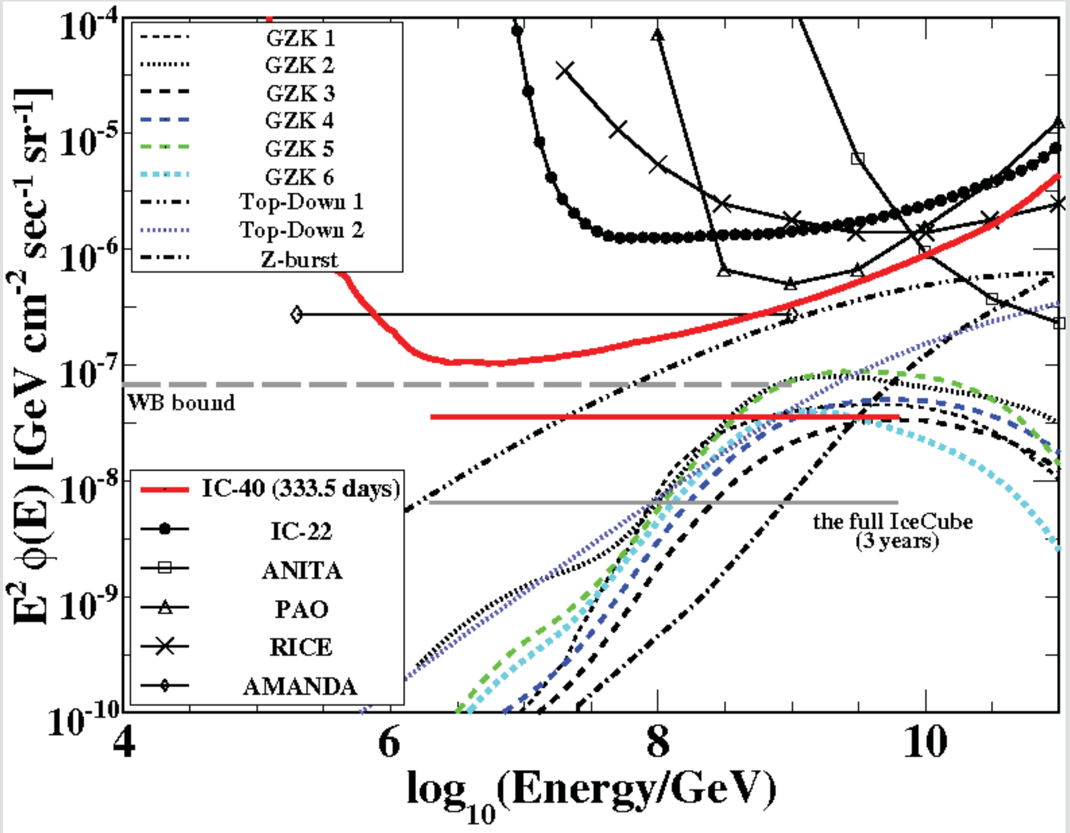


Diagram from A.Ferrari, Ann Revs A&A 36 (1998) 539

IceCube limits on cosmogenic ν

- GZK search looks for
  - Very bright events
  - Near the horizon
  - with compact initial burst of light
- Range of sensitivity
  - PeV – EeV
  - Complementary to diffuse ν_μ search that starts by measuring atmospheric ν_μ
  - Model 6 (Fermi max): expect 0.4 events

IceCube-40 arXiv:1103.4250



All-flavor limits assuming $\nu_\mu \sim \nu_\tau \sim \nu_e$

Summary

- Pushing below Waxman-Bahcall “limit” in 100 TeV – 10 PeV range disfavors proton dominance in 1 – 100 PeV range
- Expect significant improvements in IceCube sensitivity to astrophysical ν:
  - IC59 + IC79 in analysis; IC86 running
  - Better analysis
    - Use more realistic atmospheric neutrino spectrum
    - Use angular dependence
    - Better understanding of systematics