IceCube

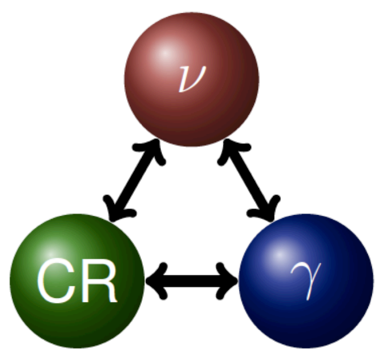
South Pole Neutrino Observatory

Air showers in IceCube

Cosmic rays

Neutrinos

Gamma rays



Cosmic rays

- Cosmic accelerators produce relativistic protons and nuclei (cosmic rays)
  - *CR sources (such as SNR, AGN, GRB) are likely neutrino sources* **Good!**
  - *Identifying CR sources by detecting high energy astrophysical neutrinos is a main goal of IceCube*
- Cosmic rays interact in the atmosphere and produce a million to one background/signal in IceCube Problem and opportunity

Neutrinos

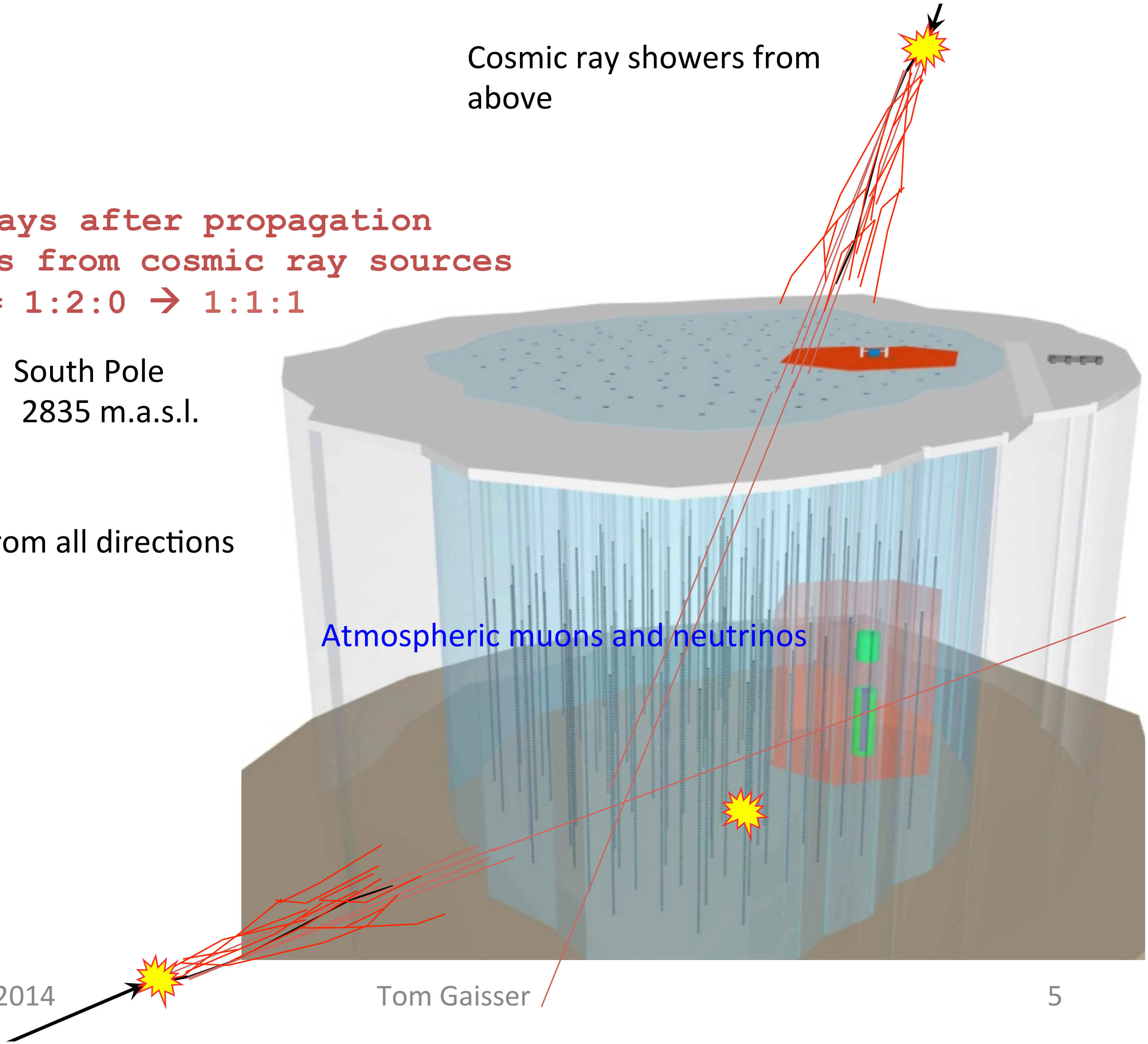
High-energy neutrinos are produced in the Universe wherever protons etc. interact with gas or light:

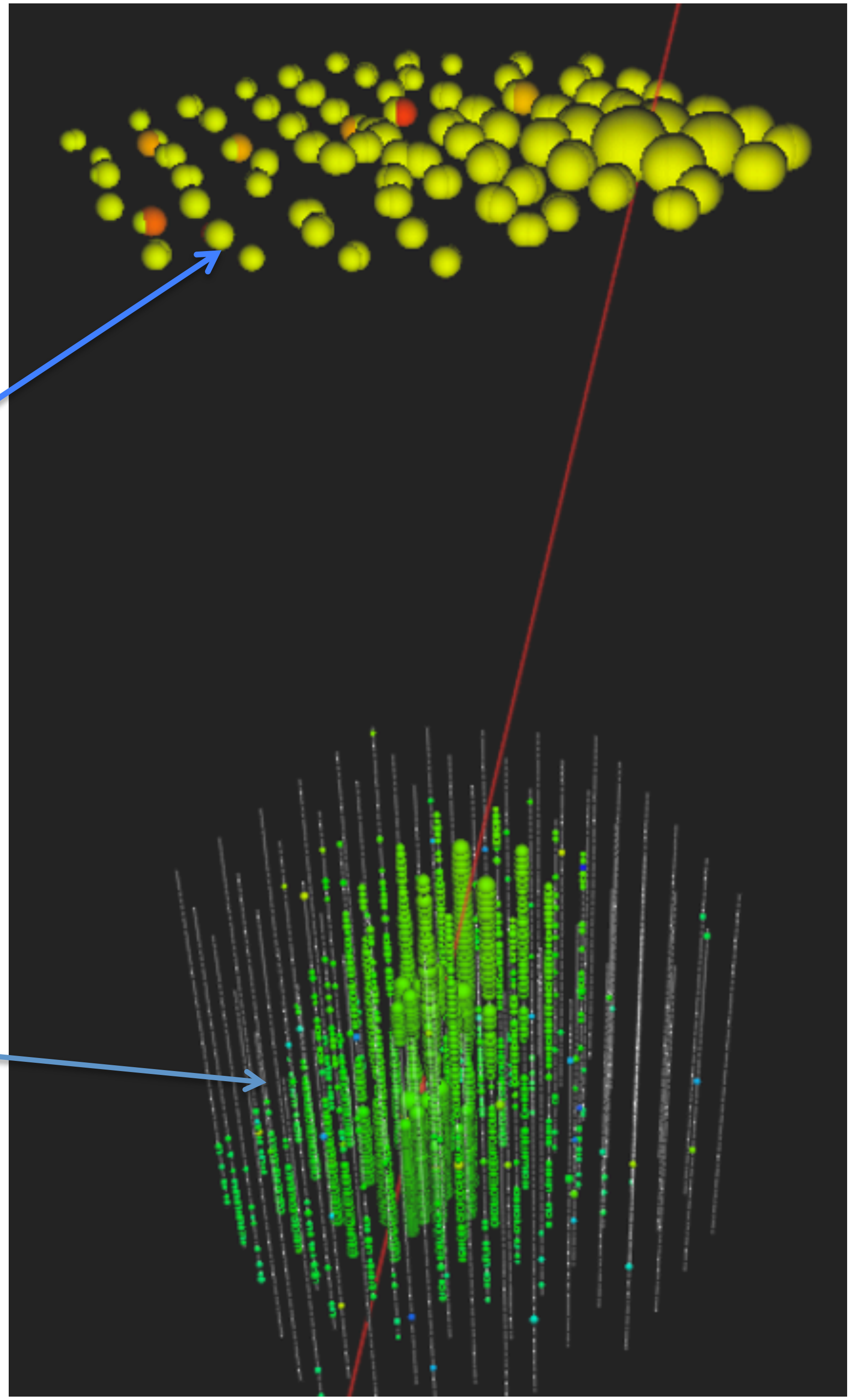
- *Near the sources of cosmic rays*
- *During propagation of cosmic-rays in the CMB*
- *But also locally by cosmic-ray interactions in the Earth's atmosphere*
- *Atmospheric neutrinos are background – but also*
    - *Calibration source and*
    - Beam for study of neutrino properties (e.g. oscillations)

Gamma rays

- Gamma-rays are a standard probe of high energy astrophysics
- Cosmic ray sources produce γ-rays in two ways
  - *From radiation by accelerated electrons*
  - *From decay of π^0 produced by interactions of accelerated cosmic-ray protons or nuclei with gas or photons*
- High energy ν are produced only in hadronic collisions:
  - *From decay of π/K produced when cosmic rays interact with gas in or near their sources*
  - *Or from photo-pion production on CMB or EBL*
  - *Neutrinos are uniquely of hadronic origin*

- **Cosmic rays after propagation**
- **Neutrinos from cosmic ray sources**
- $\nu_e : \nu_\mu : \nu_\tau$ = 1:2:0 → 1:1:1





Secondary photons
and low energy
charged particles

TeV muons

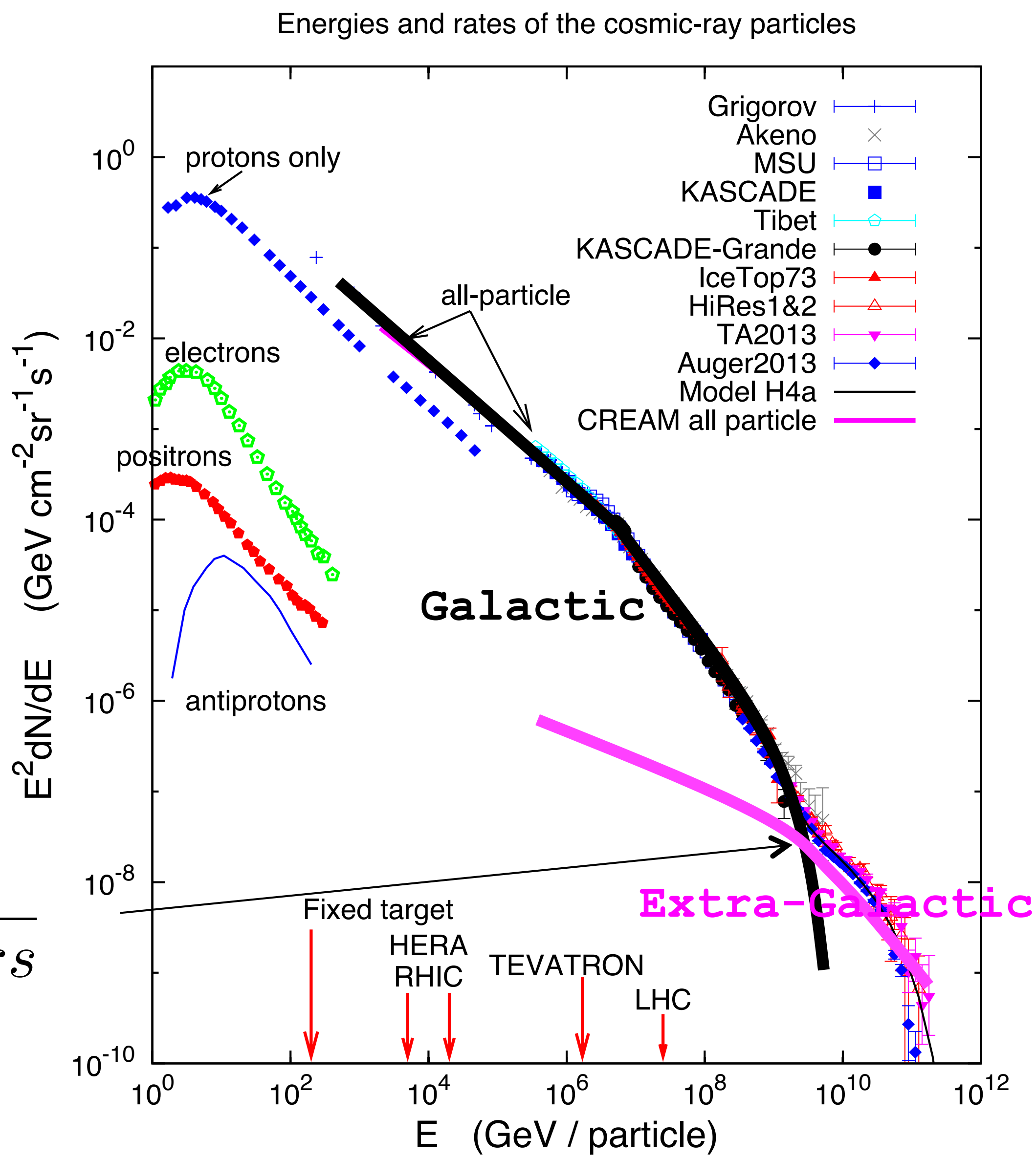
5 μs

Cosmic Rays

- Energy content of CR determines possible sources of neutrinos
- Extra-galactic origin is likely
- Location of transition from galactic to extra-galactic affects energy estimate

$$E\frac{dN}{d\ln E} \approx 3\times 10^{-8}\,\frac{\mathrm{GeV}}{cm^2 srs}$$

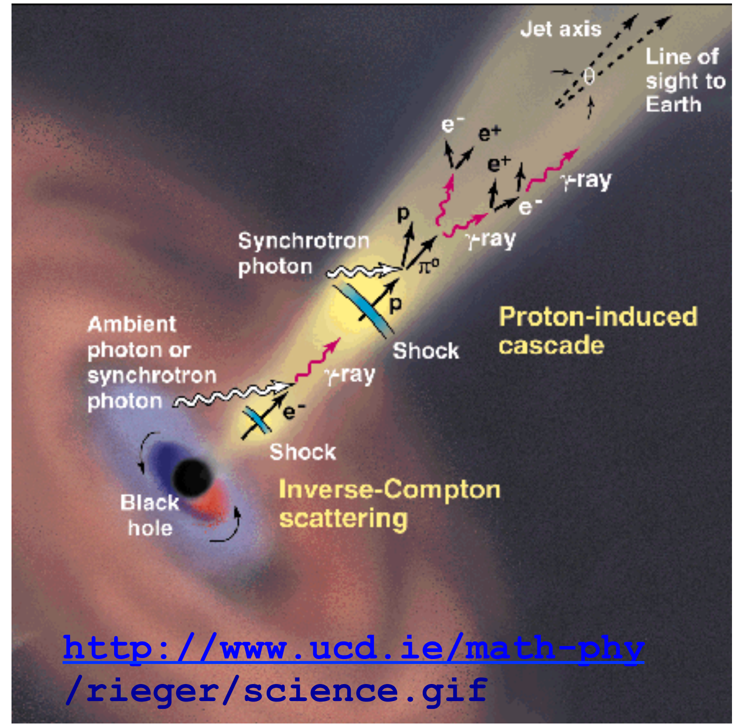
at 10^{10} GeV (10^{19} eV)



Neutrinos from sources of CR

- Galactic supernova remnants
  - Accelerated particles collide with gas in or near sources and produce neutrinos
- Extra-galactic sources (e.g. AGN, GRB,…)
  - The next two slides show two generic models
  - Neutrinos likely in the first case,
  - but less likely in the second

Generic model I



- CR acceleration occurs in jets
  - AGN or GRB
- Intense radiation fields
  - 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

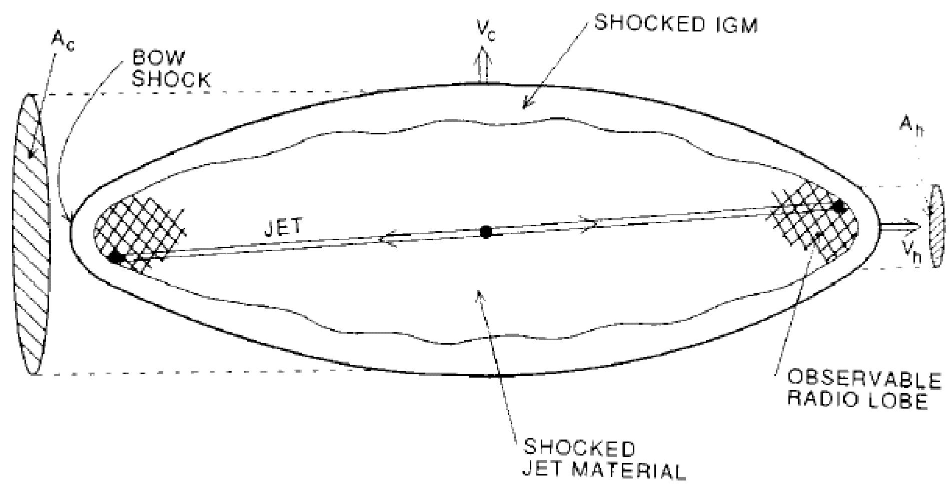
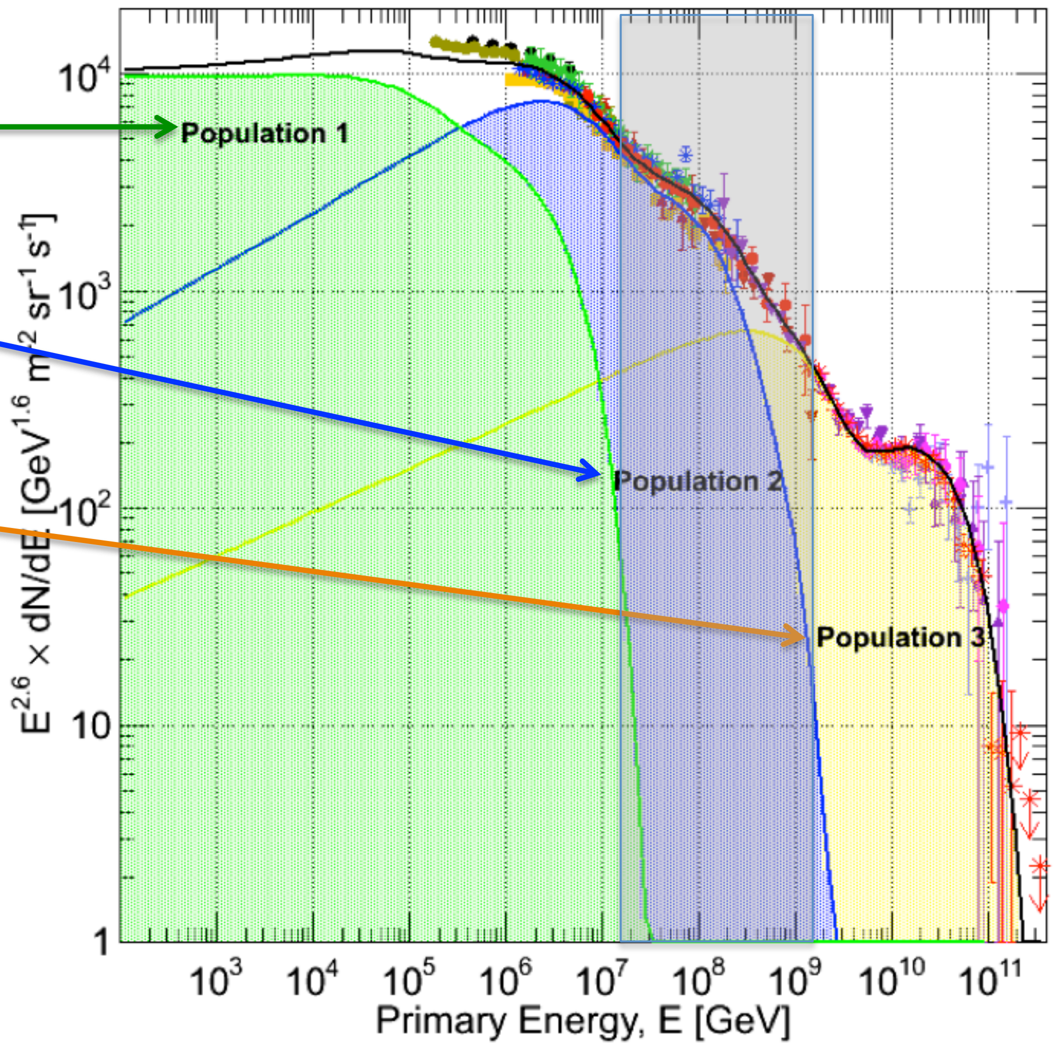


Diagram from Begelman & Cioffi, Ap.J. (1989) L21

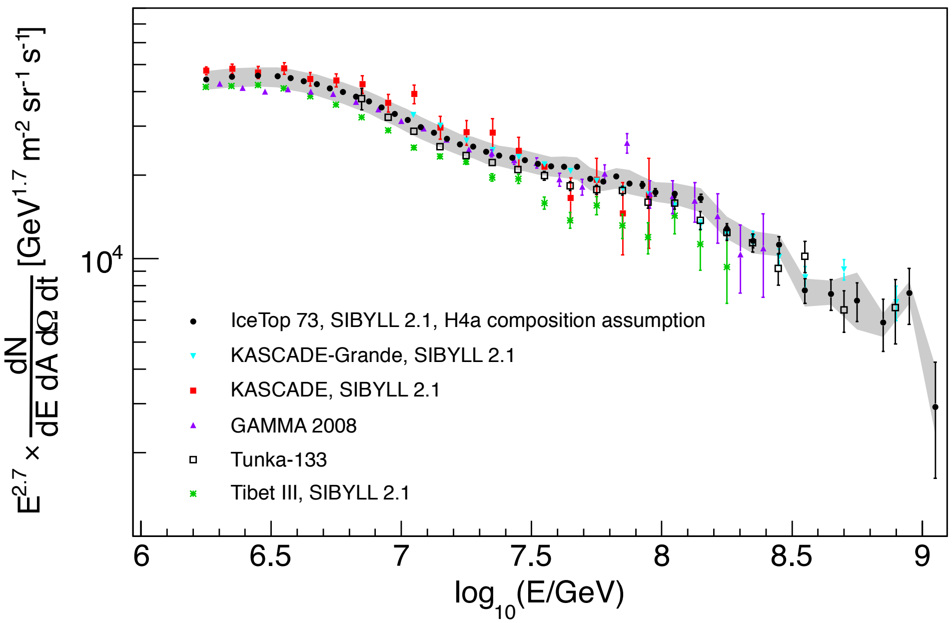
Toward a global view of CR

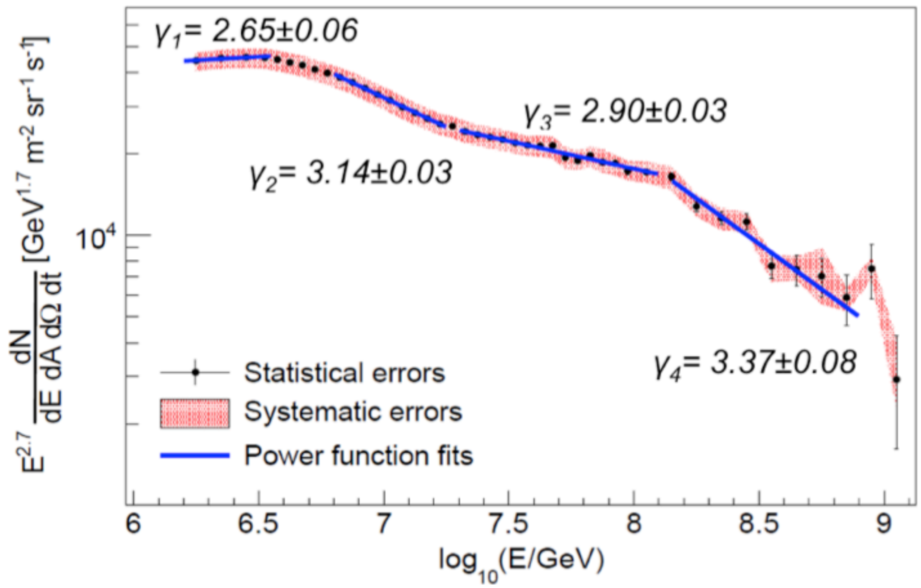
- Population 1
  - Galactic SNR ?
- Population 2
  - Is it needed ?
- Population 3
  - Extragalactic ?
  - What sources ?
- Focus: 10^7- 10^{9+} transition zone



Primary spectrum from IceTop

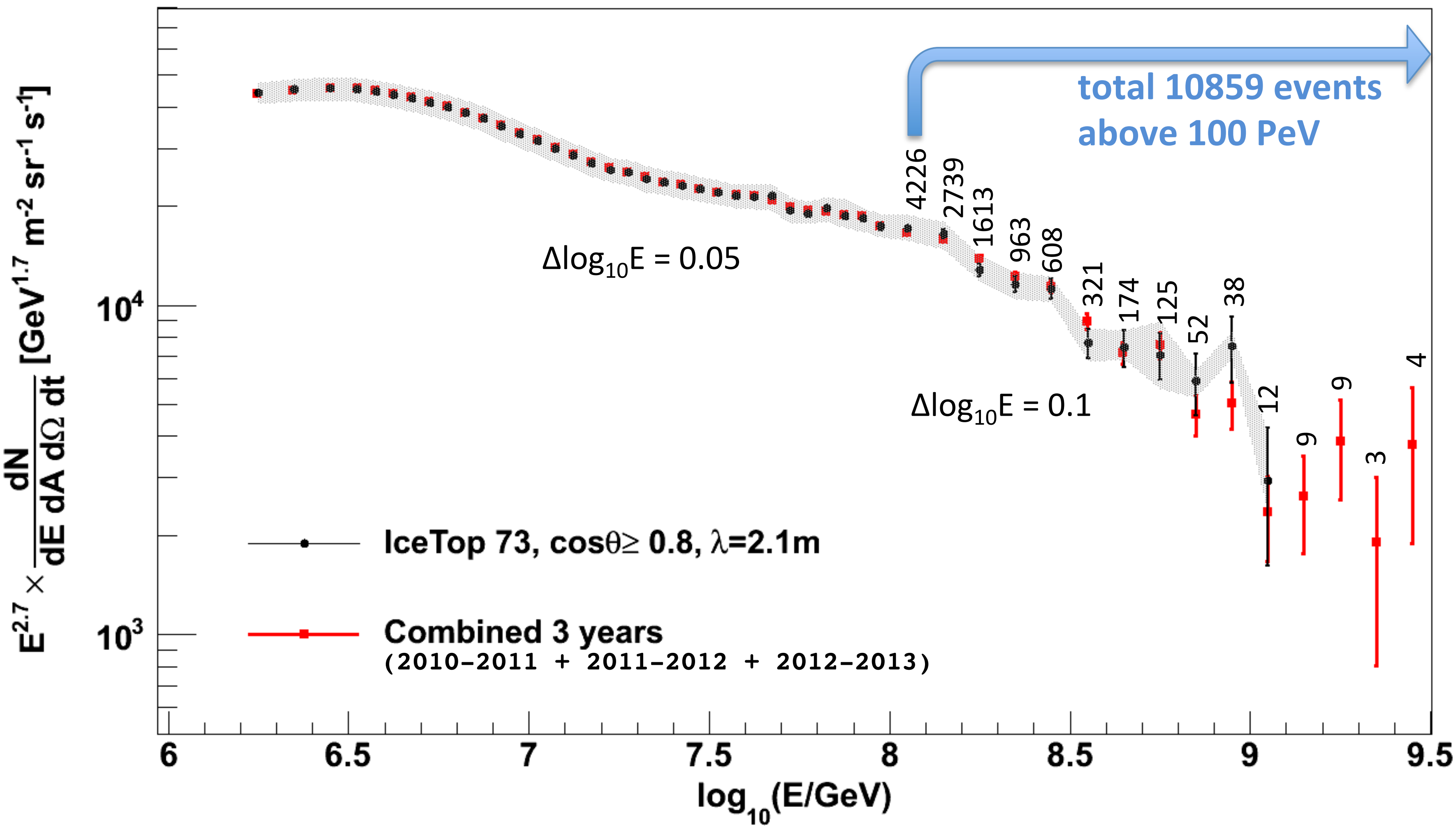
Phys. Rev. D 88, 042004 (2013). Bakhtiyar Ruzybayev is lead author



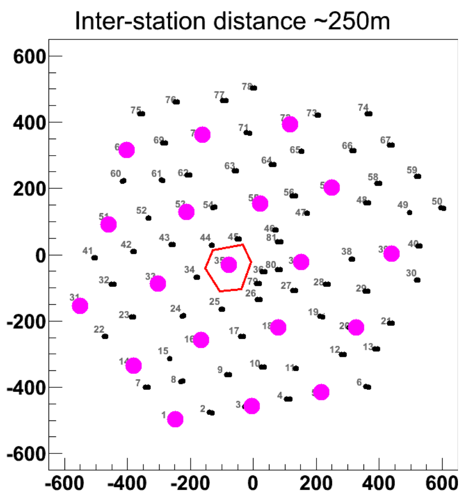


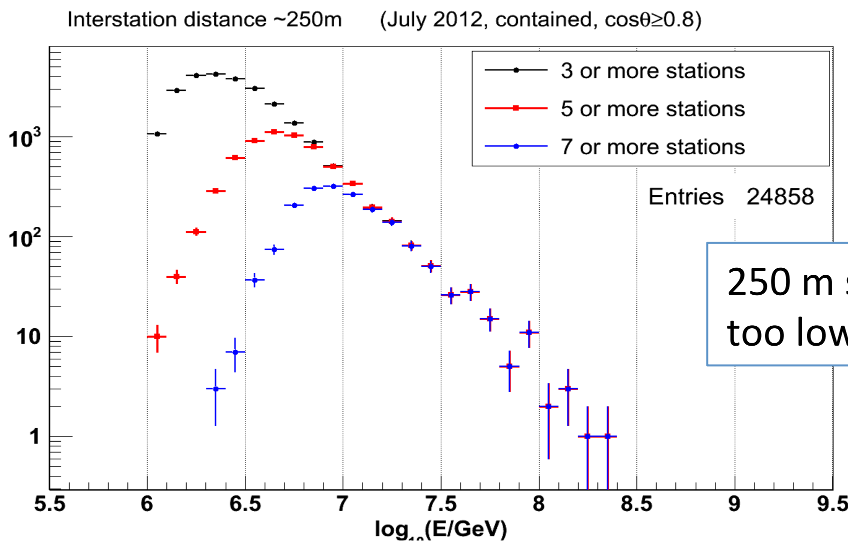
- $10^6 - 10^8$ GeV sets normalization for PeV ν
  - Directly for background atmospheric ν
  - At sources for astrophysical ν
- $10^7 - 10^9$ GeV: transition from galactic to extragalactic
  - Model dependent

Spectrum measured by IceTop
2.67 yrs livetime



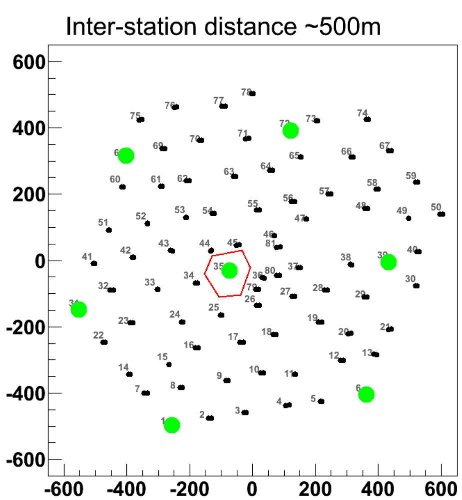
- Predefine "New" arrays with 250m and 500 m spacing
- Count stations from the "New" list participating in the event.

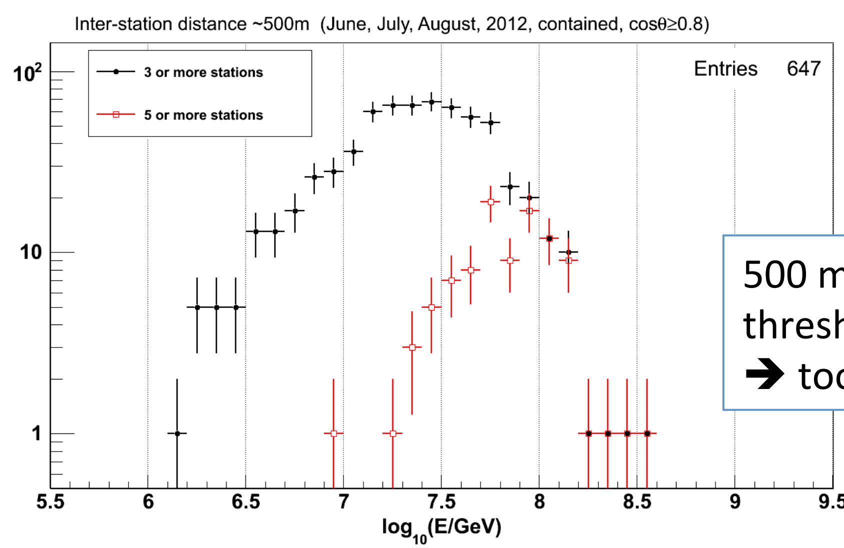




250 m spacing:
too low threshold

300-350m spacing
seems optimal
for ~50 PeV threshold

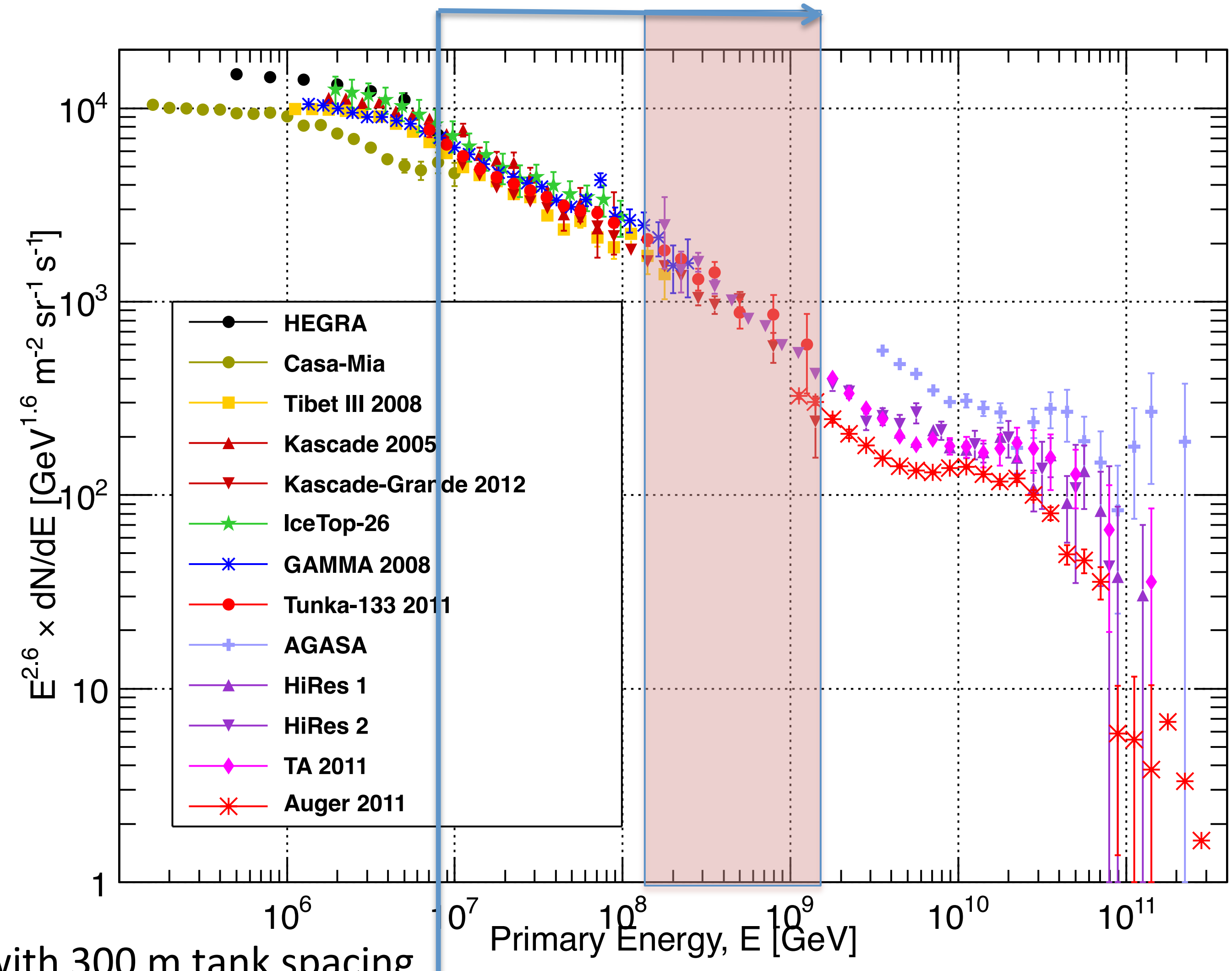




500 m spacing:
threshold moves to 100 PeV
➔ too high

Note: Auger infill: 85 detectors in two grids of 750m (covering 23.5 km2) and 433m (covering 5.9 km2) spacing.
TALE: 100 scintillator counters at 400m spacing

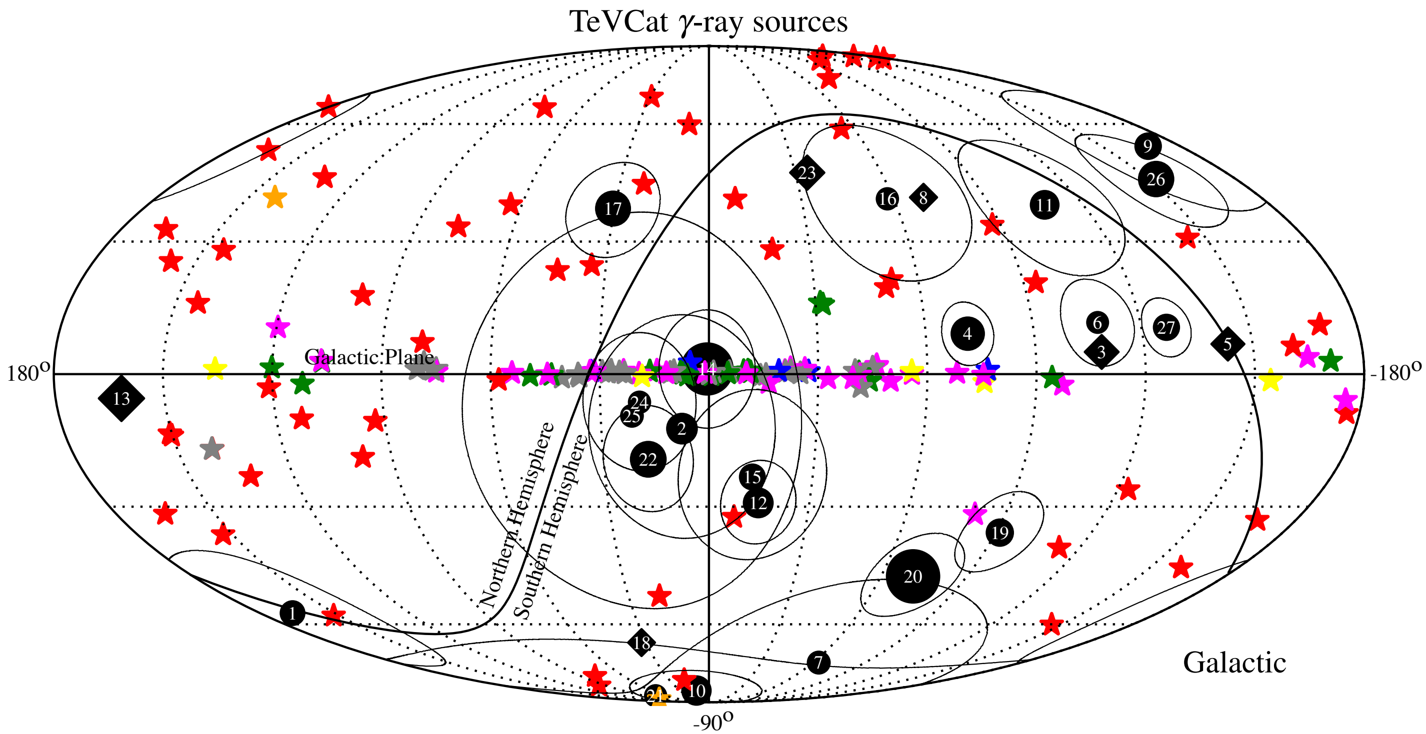
Order of magnitude increase is achievable in Galactic-extragalactic transition region



Threshold with 300 m tank spacing

ICECUBE

Multi-messenger paradigm



LBL, IBL, LBL, FRI, FSRQ Globular Cluster, Star Forming Region, Massive Star Cluster
Binary PWN Shell, SNR/Molec.Cloud, Composite SNR Starburst Others [TeVCat'14]

Slide from Markus Ahlers

Markus Ahlers (UW-Madison) Physics Goals March 3, 2014

IceCube selected sources

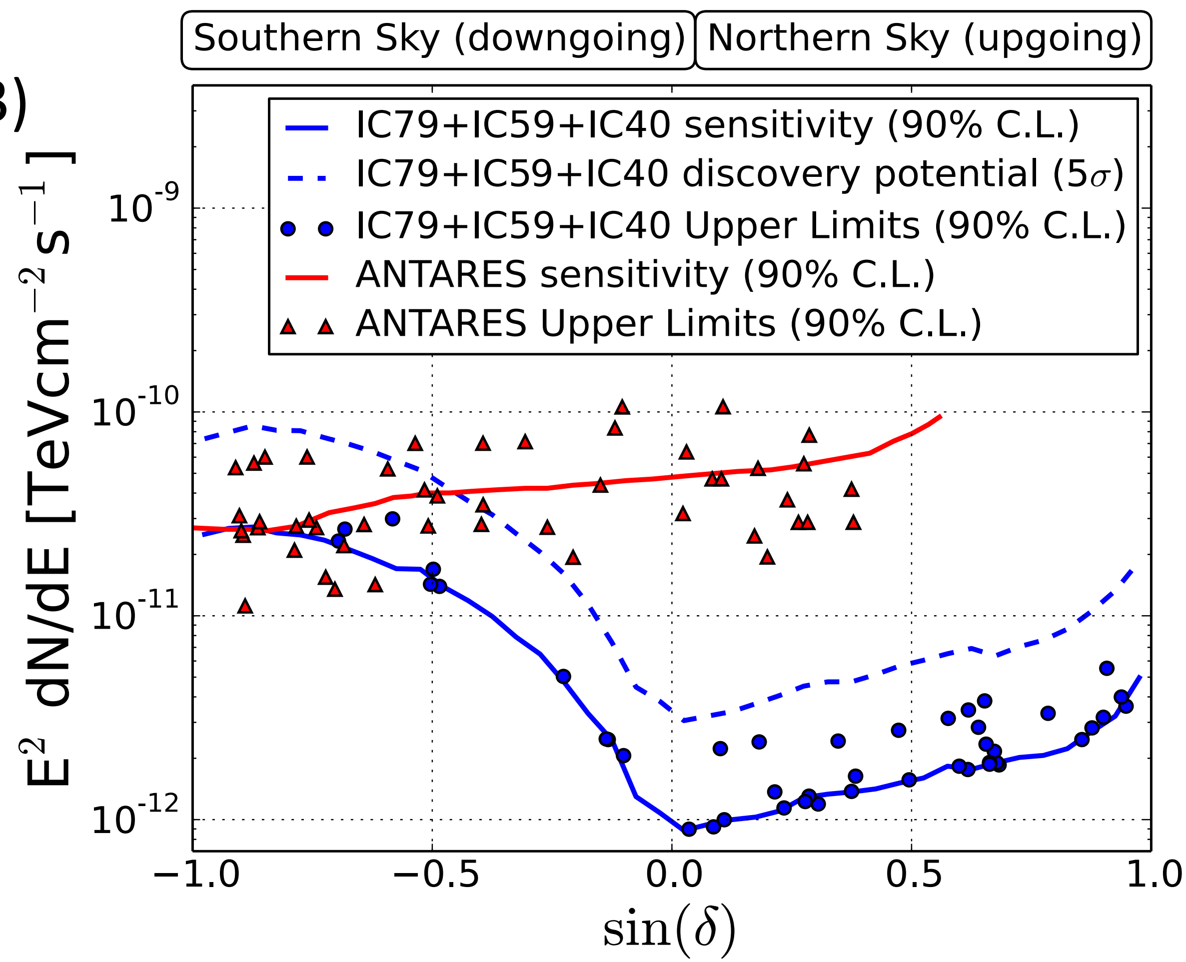
(13 galactic SNR etc, 30 extragalactic active galaxies, etc.)

Source	RA (deg)	Dec (deg)	Type	Distance	P-value
Cyg OB2	308.08	41.51	UNID	-	--
MGRO J2019+37	305.22	36.83	PWN	-	--
MGRO J1908+06	286.98	6.27	SNR	-	0.38
Cas A	350.85	58.81	SNR	3.4 kpc	--
IC443	94.18	22.53	SNR	1.5 kpc	--
Geminga	98.48	17.77	Pulsar	100 pc	--
Crab Nebula	83.63	22.01	SNR	2 kpc	--
1ES 1959+650	300.00	65.15	HBL	z = 0.048	--
1ES 2344+514	356.77	51.70	HBL	z = 0.044	--
3C66A	35.67	43.04	Blazar	z = 0.44	0.42
H 1426+428	217.14	42.67	HBL	z = 0.129	--
BL Lac	330.68	42.28	HBL	z = 0.069	0.4
Mrk 501	253.47	39.76	HBL	z = 0.034	0.19
Mrk 421	166.11	38.21	HBL	z = 0.031	--
W Comae	185.38	28.23	HBL	z = 0.1020	--
1ES 0229+200	38.20	20.29	HBL	z = 0.139	0.39
M87	187.71	12.39	BL Lac	z = 0.0042	0.38
S5 0716+71	110.47	71.34	LBL	z > 0.3	0.49
M82	148.97	69.68	Starburst	3.86 Mpc	--
3C 123.0	69.27	29.67	FRII	1038 Mpc	--
3C 454.3	343.49	16.15	FSRQ	z = 0.859	0.48
4C 38.41	248.81	38.13	FSRQ	z = 1.814	0.3
PKS 0235+164	39.66	16.62	LBL	z = 0.94	0.18
PKS 0528+134	82.73	13.53	FSRQ	z = 2.060	0.49
PKS 1502+106	226.10	10.49	FSRQ	z = 0.56/1.839	--
3C 273	187.28	2.05	FSRQ	z = 0.158	--
NGC 1275	49.95	41.51	Seyfert Galaxy	z = 0.017559	--
Cyg A	299.87	40.73	Radio-loud Galaxy	z = 0.056146	0.44
Sgr A*	266.42	-29.01	Galactic Center	8.5 kpc	0.49
PKS 0537-441	84.71	-44.09	LBL	z = 0.896	0.44
Cen A	***201.37***	***-43.02***	***FRI***	***3.8 Mpc***	***0.14***
PKS 1454-354	***224.36***	***-35.65***	***FSRQ***	***z = 1.42***	***0.14***
PKS 2155-304	329.72	-30.23	HBL	z = 0.116	--
PKS 1622-297	246.53	-29.86	FSRQ	z = 0.815	0.27
QSO 1730-130	263.26	-13.08	FSRQ	z = 0.902	--
PKS 1406-076	212.24	-7.87	FSRQ	z = 1.494	0.36
QSO 2022-077	306.42	-7.64	FSRQ	z = 1.39	--
3C279	194.05	-5.79	FSRQ	z = 0.536	0.45
TYCHO	6.36	64.18	SNR	2.4 kpc	--
Cyg X-1	299.59	35.20	MQSO	2.5 kpc	--
Cyg X-3	308.11	40.96	MQSO	9 kpc	--
LSI 303	40.13	61.23	MQSO	2 kpc	--
SS433	287.96	4.98	MQSO	1.5 kpc	0.48

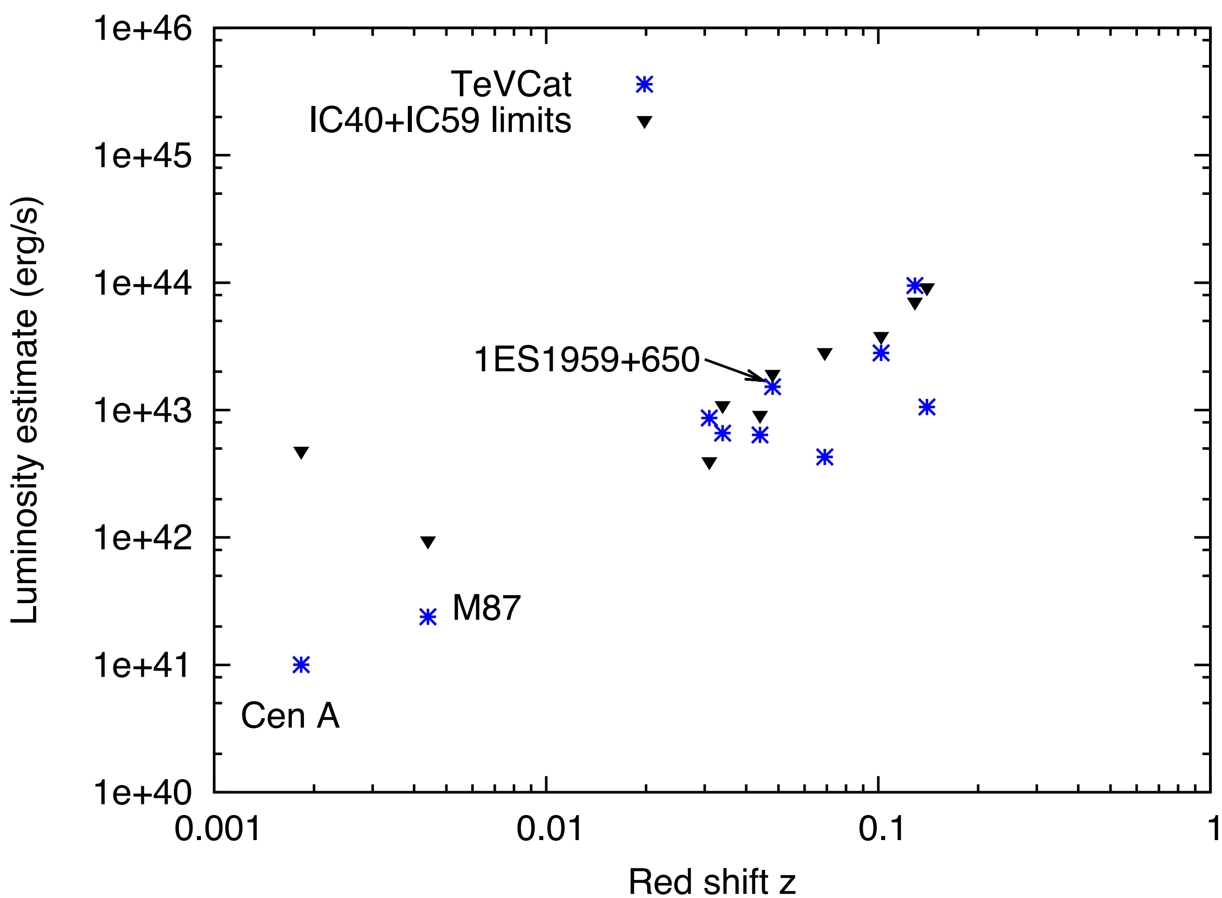
Upper limits on selected sources

IC40 + 59 +79

Ap.J. 779, 132 (2013)



Compare IceCube limits on ν to TeV photons from active galaxies

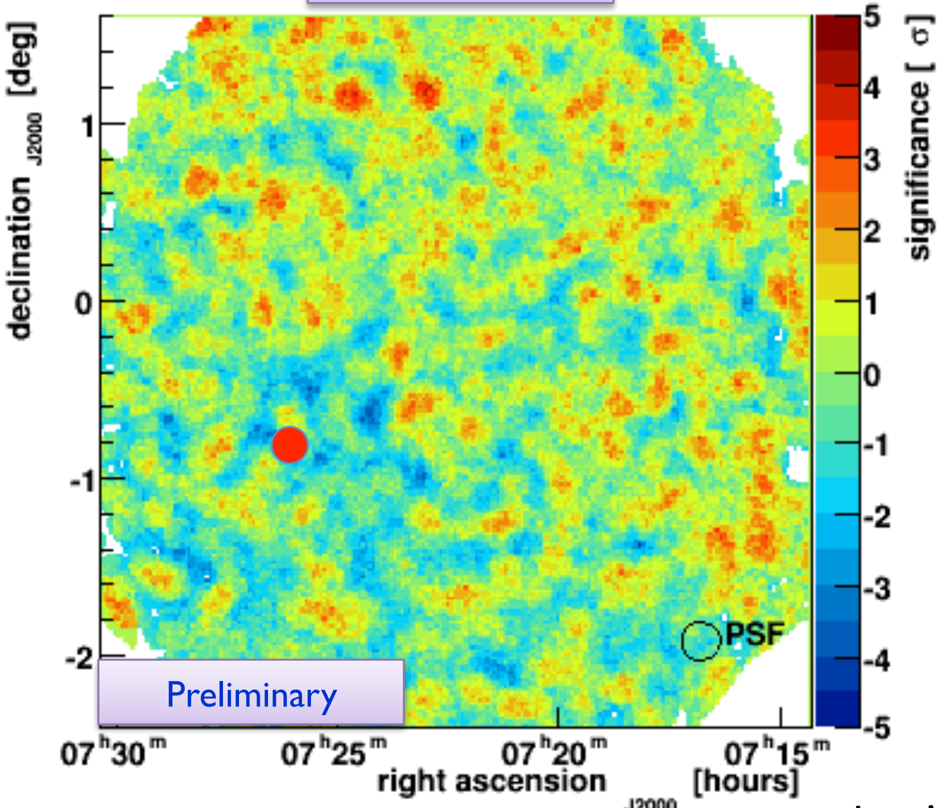


Follow-up by VERITAS

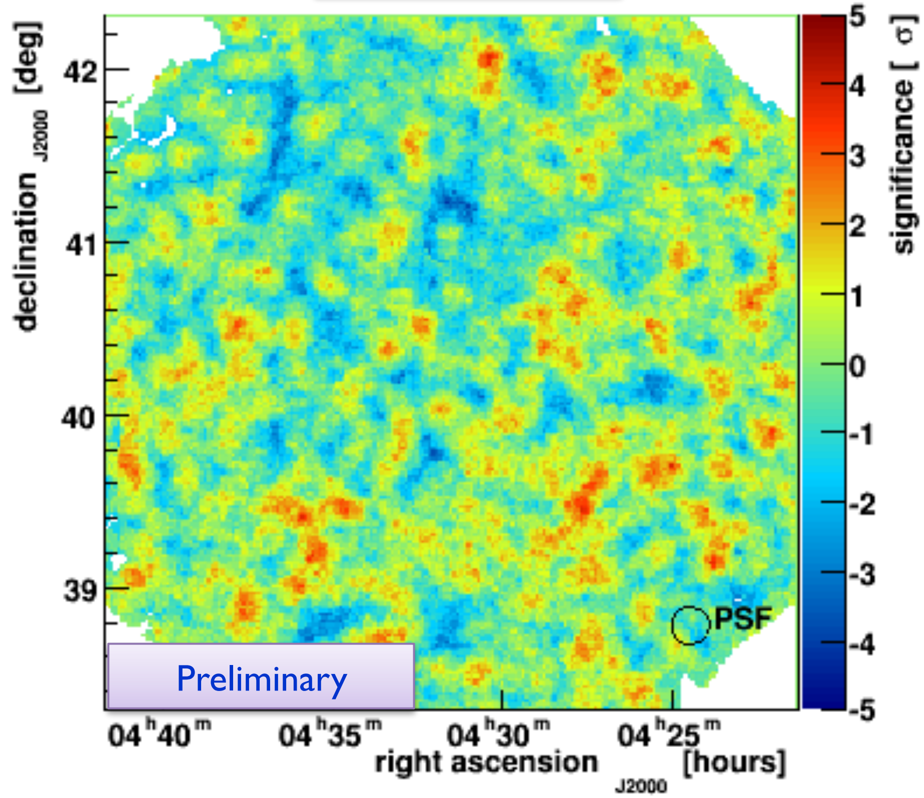
- Look for TeV gamma-rays from two HESE events (#5 and #13)
- Both are starting muon tracks with ~ 1 degree resolution
- Event 5 has a Fermi blazar within 2 deg (PKS 0723-008, z=0.128)
- Observe each for several hours

- 3.5 hours on Event ID 5, offset by 0.7 degrees NSEW
- UL(99%) = 1.55 x10^{-8} m^{-2} s^{-1} above 300 GeV (~ 1.2% Crab)
- 2.5 hours on Event ID 13
- UL(99%) = 2.00 x10^{-8} m^{-2} s^{-1} above 300 GeV (~ 1.6% Crab)
- Nothing elsewhere in the field(including PKS 0723-008)

Event ID 5



Event ID 13



Jamie Holder, IceCube Collaboration Mtg, Mar. 2014

Air showers from cosmic γ-rays

SEARCH FOR GALACTIC PeV GAMMA RAYS WITH THE . . . PHYSICAL REVIEW D **87,** 062002 (2013)

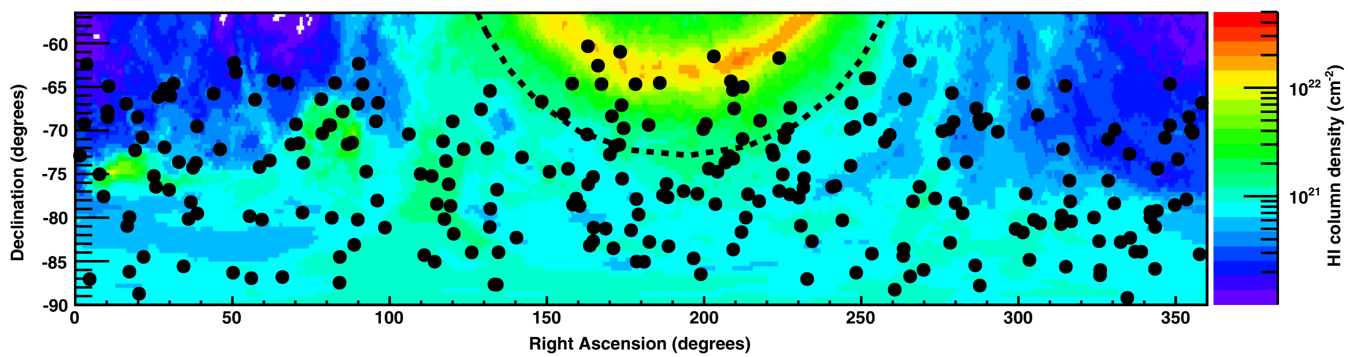


FIG. 8 (color online). Equatorial map of the 268 candidate gamma-ray events of the IC40 data set superimposed on HI column densities based on Ref. [14]. The dotted black curve encloses the source region, defined as within 10° of the Galactic plane.

- Signature: few μ in deep IceCube in coincident events
- Search with present IceCube limited by narrow aperture for coincident events (<30^o zenith) and high energy threshold
- Larger aperture would allow better sky coverage (closer to Galactic center)
- ID of muons at the surface improves sensitivity

Cosmic-ray neutrinos (aka atmospheric neutrinos)

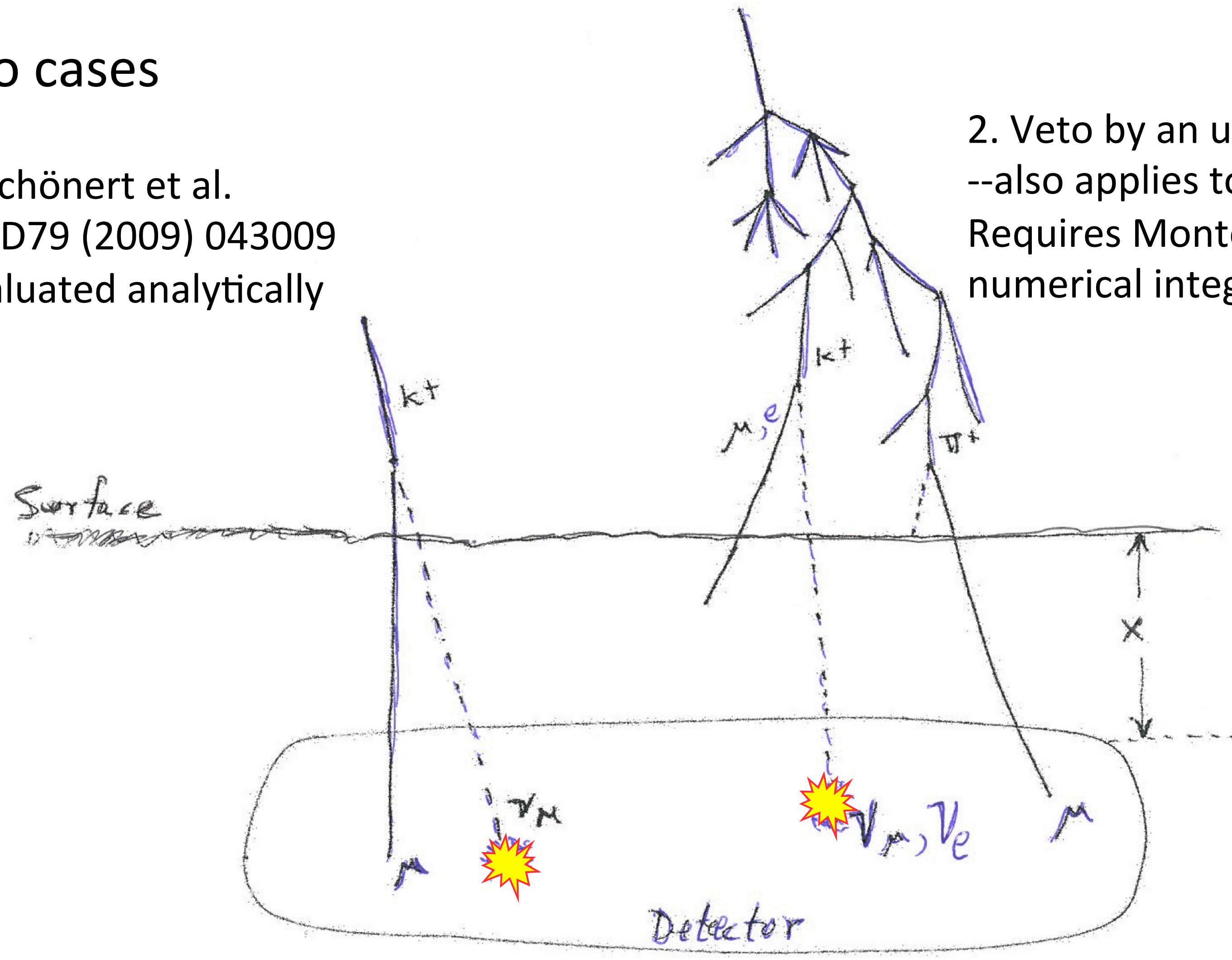
- Atmospheric neutrinos produced in air showers above IceCube
  - "Conventional" ν (from K and π decay)
  - "Prompt" ν (from decay of charm)
  - Muons produced in the same shower as ν provide a partial self-veto in Southern sky
  - IceTop also provides a partial veto

Atmospheric neutrino self veto

Two cases

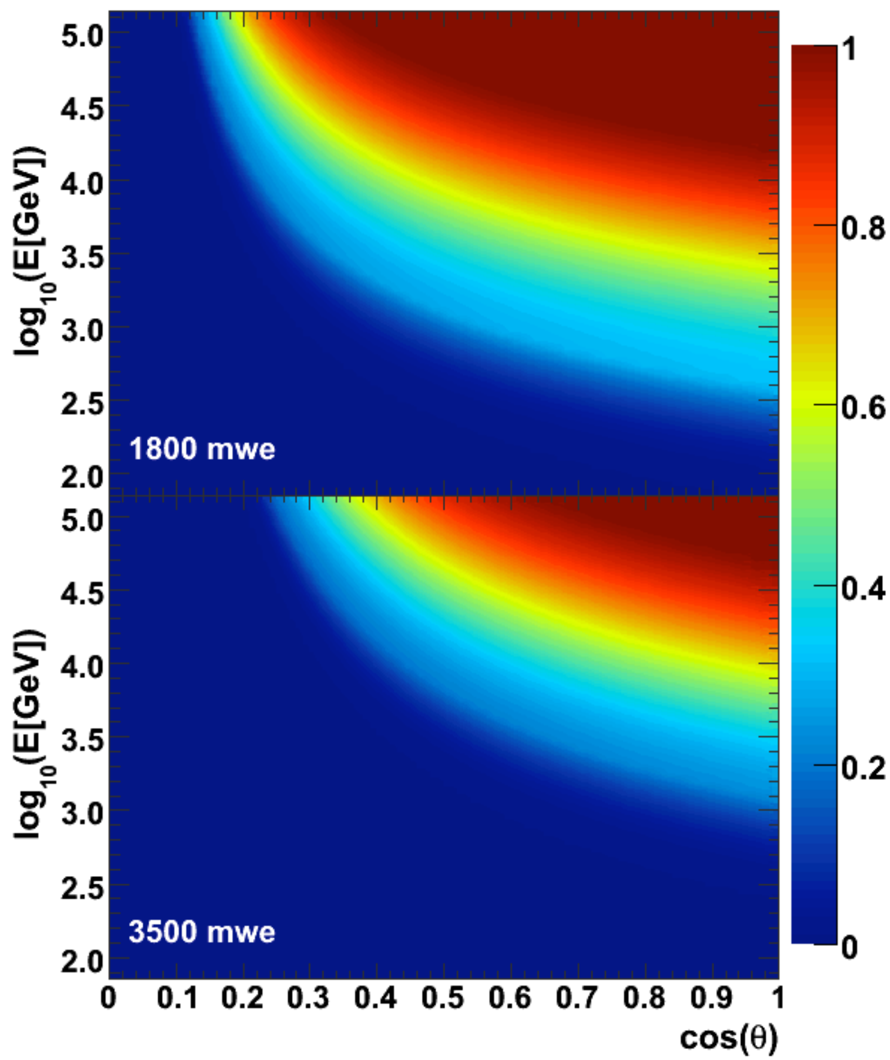
1. Stefan Schönert et al.
Phys. Rev. D79 (2009) 043009
Can be evaluated analytically

2. Veto by an unrelated μ
--also applies to ν_e
Requires Monte Carlo or numerical integration



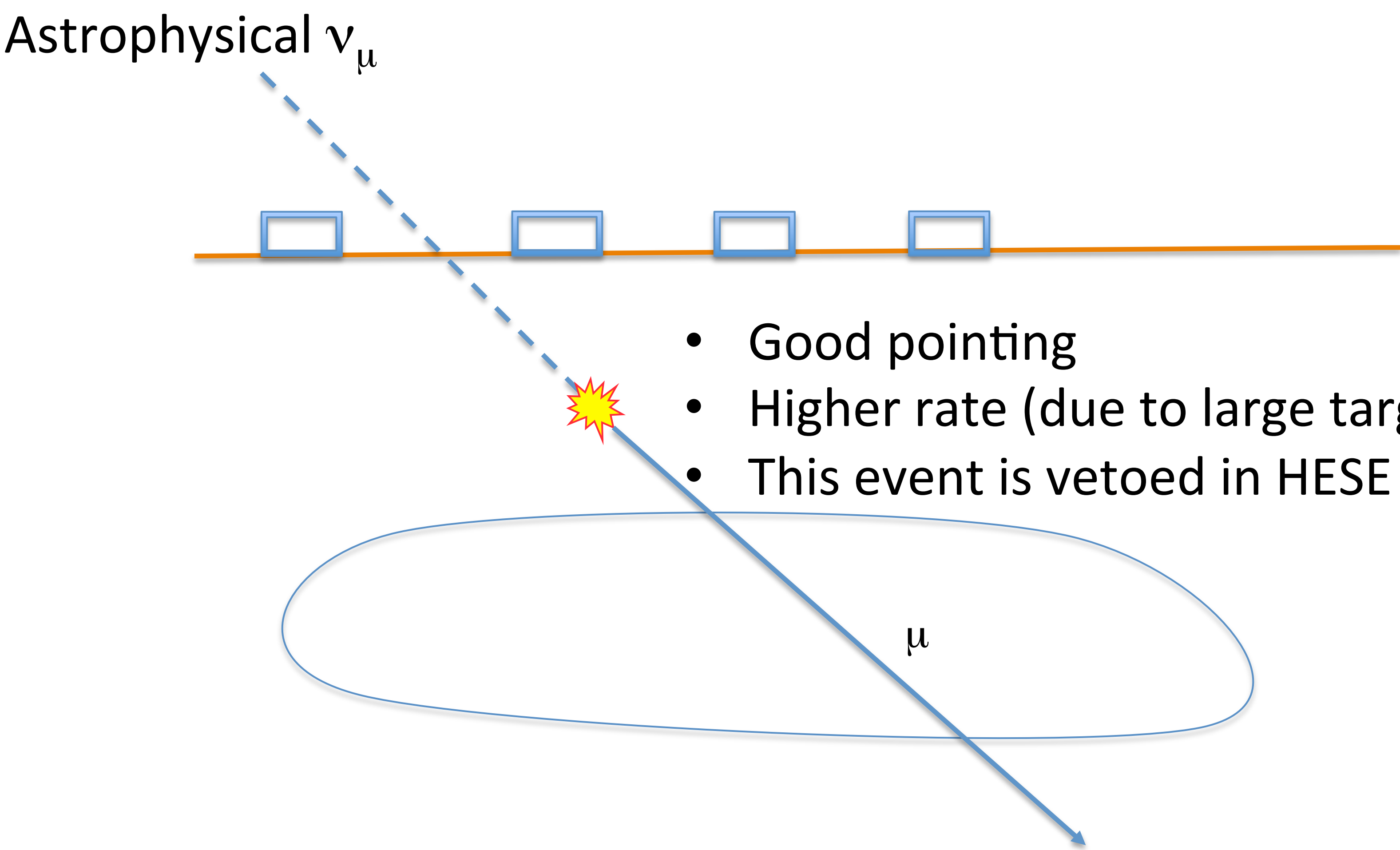
Angular/energy dependence

- Analytic calculation:
  - Applies to ν_μ only
  - For E_ν > 100 TeV
  - Passing rate < 10% for cosθ > 0.3
  - 70% of downward phase space
  - Even better at higher E
  - Works best at modest depth



Schönert et al. PR D79 (2009) 043009

Surface veto needed to enhance ν_μ signal starting in ice



- Good pointing
- Higher rate (due to large target)
- This event is vetoed in HESE analysis

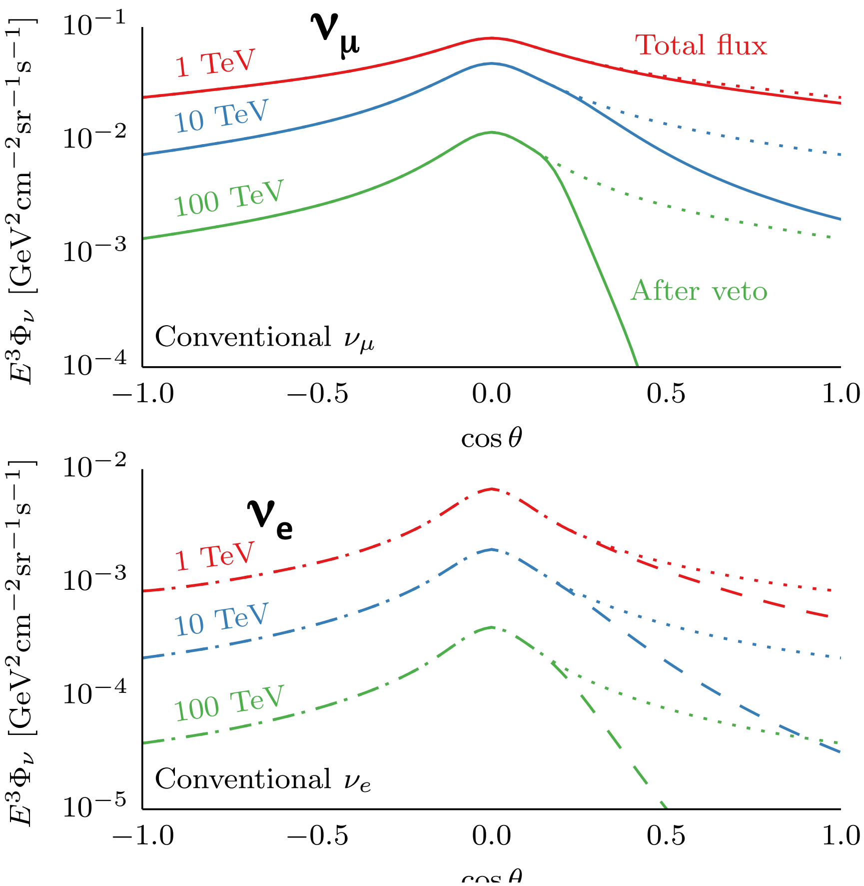
Veto concept

- Yields: $Y_\nu(A, E_0, E_\nu, \theta)$ and $Y_\mu(A, E_0, E_\mu, \theta)$
  - Use Monte Carlo simulations
  - Extend to higher energies numerically
- Response (ν): $R(A, E_0, E_\nu, \theta) = \phi_A(E_0) \cdot Y_\nu(A, E_0, E_\mu, \theta)$
- Passing rate:

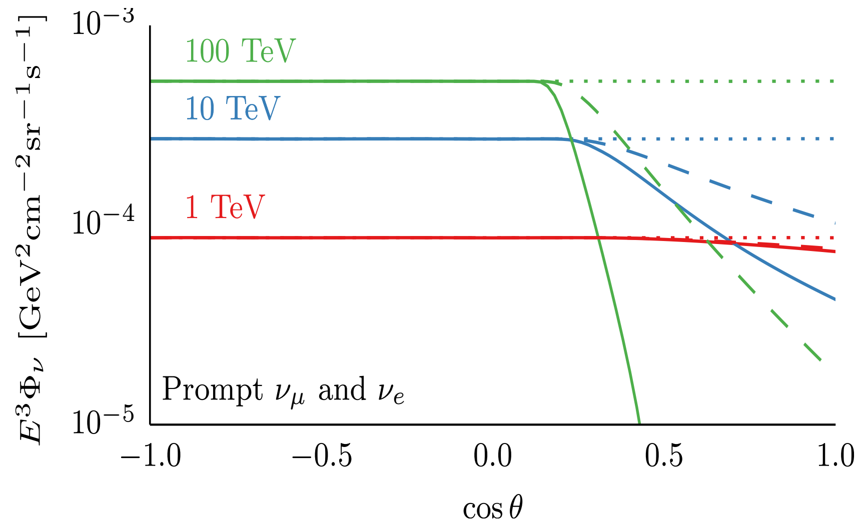
$$P_\nu(E_\nu, \theta) = \Sigma_A \int \mathrm{dE_0 R_\nu(A, E_0, E_\nu,} \theta) \, \mathrm{P(veto = \{no\})}$$

- Check against full Monte Carlo and extrapolate to $E_\nu \geq$ PeV

Neutrino self-veto

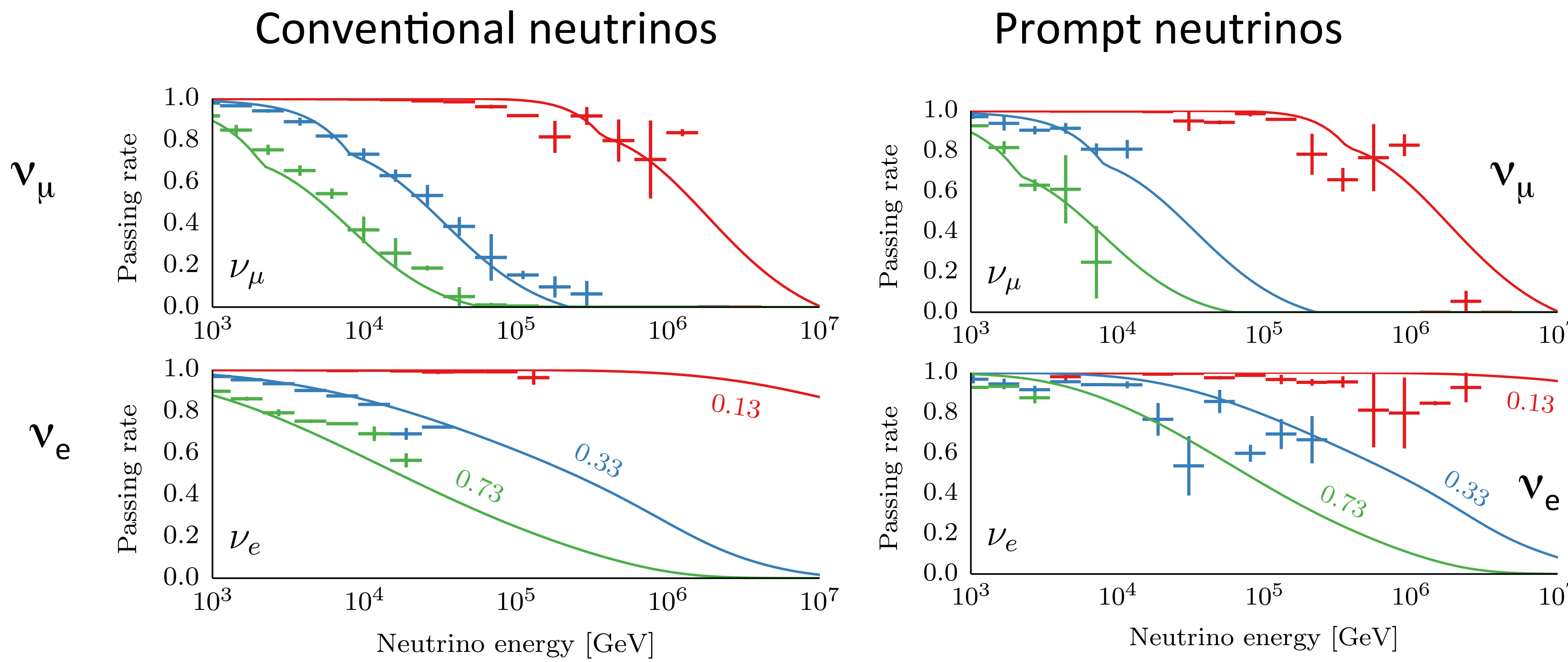


Prompt ν_μ (solid) and ν_e (dashed)

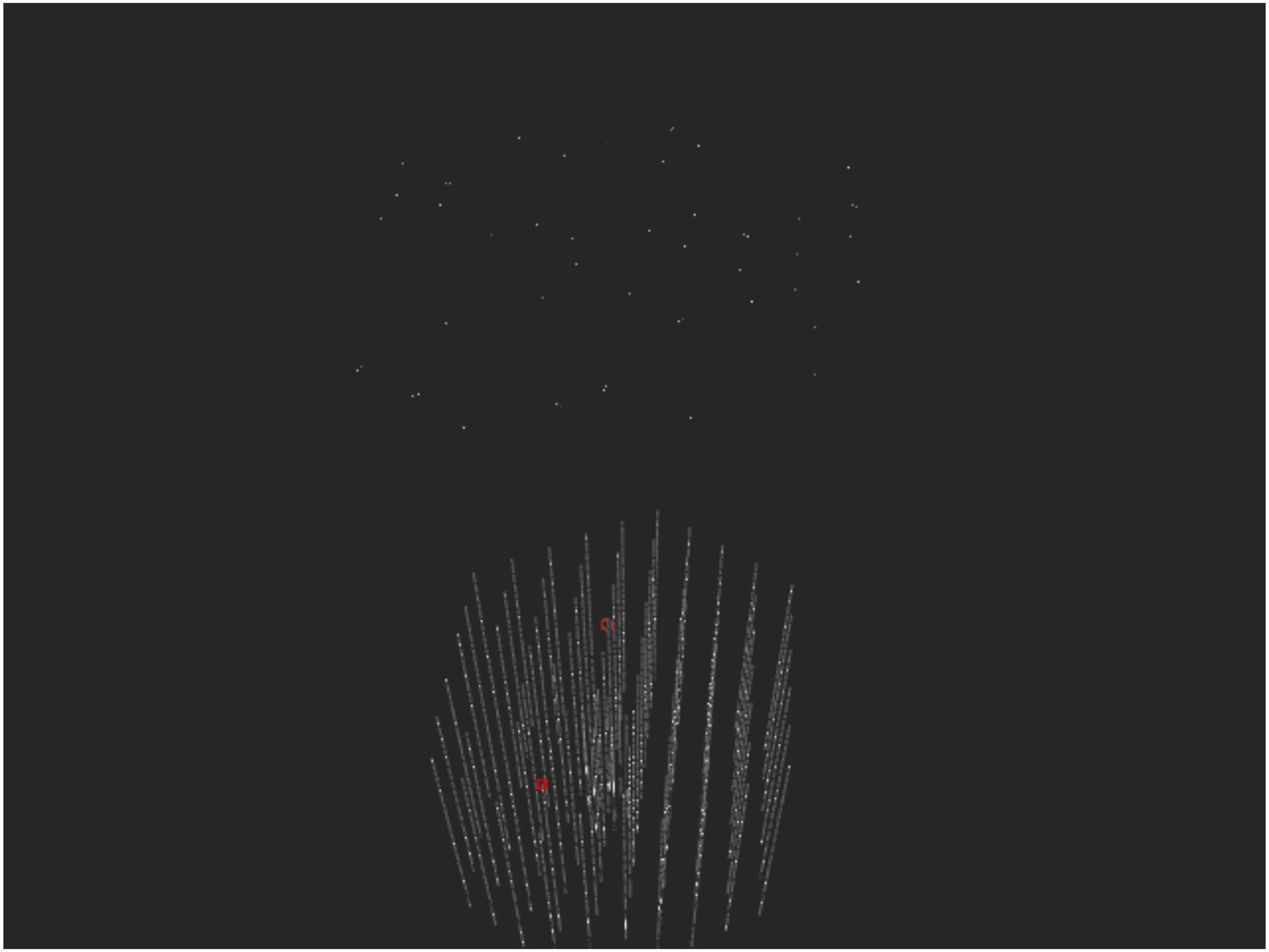


TKG, Jero, Karle, van Santen

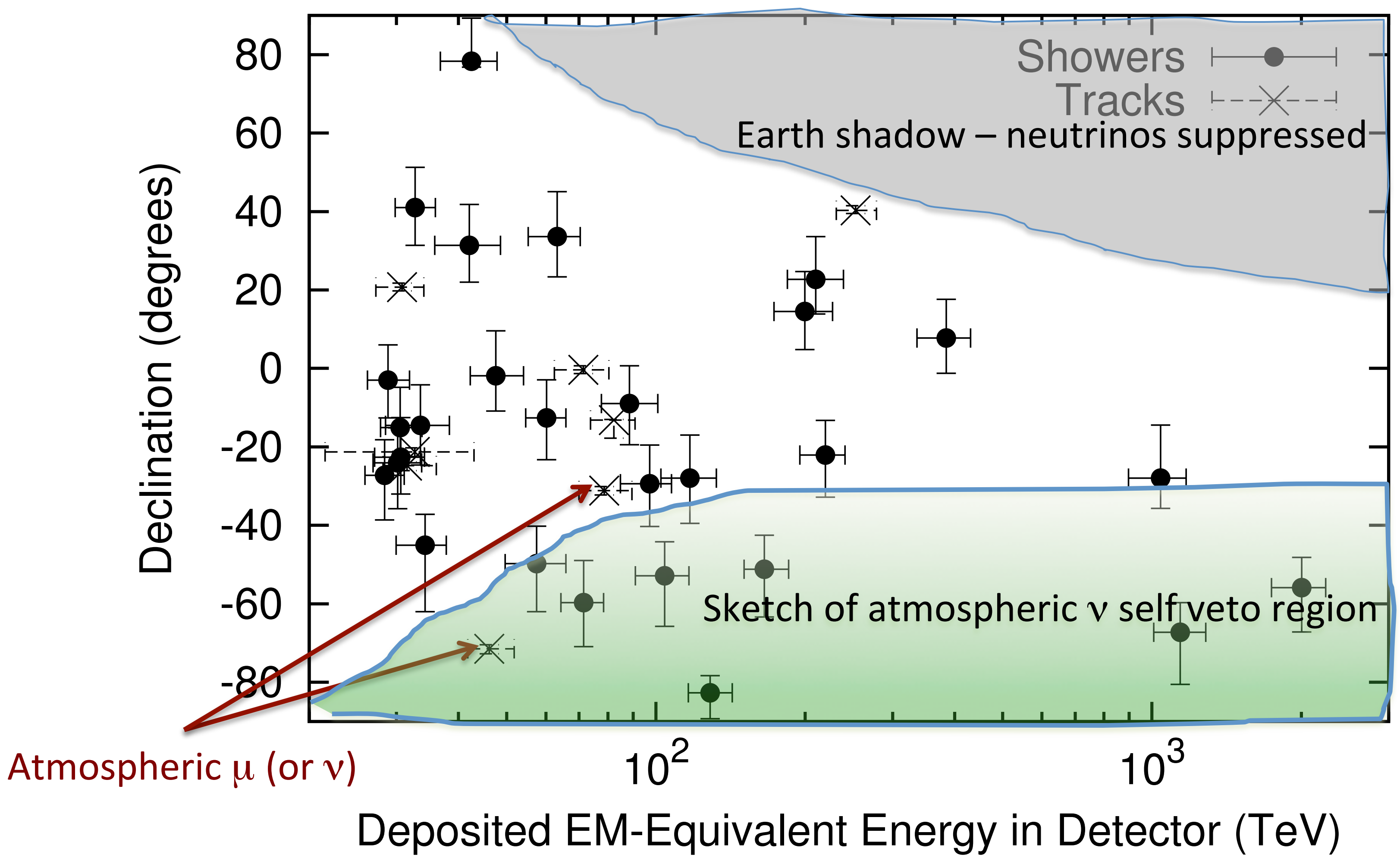
Comparison with full MC



Surface veto example (Event 28)



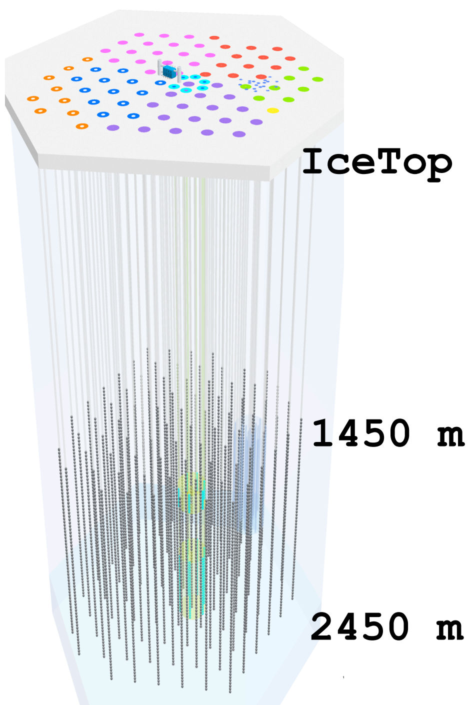
3 yrs



Declination (degrees)
80
60
40
20
0
-20
-40
-60
-80
Showers
Tracks
Earth shadow – neutrinos suppressed
Sketch of atmospheric ν self veto region
Atmospheric μ (or ν)
10^2
10^3
Deposited EM-Equivalent Energy in Detector (TeV)

Aperture for coincident events: ν, γ, cosmic rays

0.26 km^2 sr



~ 10 km^2 sr