高エネルギーニュートリノ天文学の幕開け

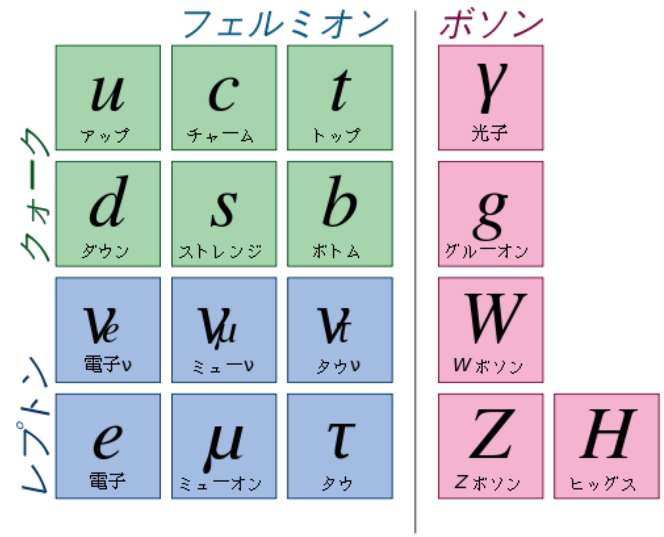
千葉大学　間瀬圭一

宇宙 ↔ 素粒子

宇宙 ↔ 素粒子

by 小柴昌俊

■ ニュートリノって何？



素粒子の一つ。

β崩壊の課程で見つかった。

中性子 → 陽子 ＋ 電子

このままではエネルギー保存則が成り立たない！

$$E_n \neq E_p + E_e$$

Pauliの予言：中性子 → 陽子 ＋ 電子 ＋中性微子（1931年）

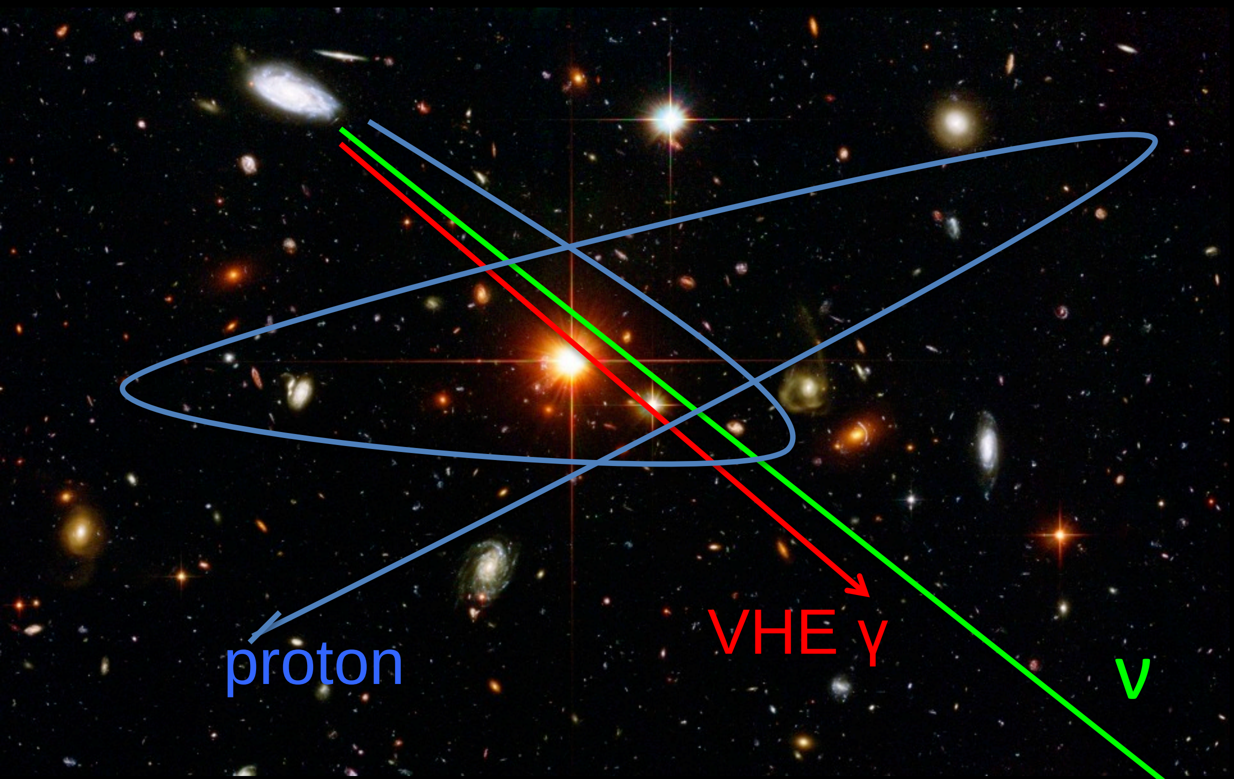
$$E_n = E_p + E_e + E_\nu$$

W. Pauli

この中性微子がニュートリノ

ほとんど物質と相互作用しない。幽霊粒子。このため実験的に確かめられたのは1950年代。

Why neutrinos?



Neutrinos are rarely interacting particles

- Arrive straight to the Earth from the deep Universe

  → **Astronomy**

- Produced through hadronic interactions

  → **Cosmic ray origin**

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Part−4: 次期計画

■ **Part-1:** 天文学とは？

■ 天文学の簡単な歴史

ガリレオ式望遠鏡

- ✓ 紀元前2000年頃：エジプト太陽暦、メソポタミア太陰暦
- ✓ 1606年：ケプラー：惑星の運動の法則
- ✓ 1610年：ガリレオ・ガリレイ：木星の衛星の観測→地動説
- ✓ 1929年：ハッブルが宇宙膨張を発見

$$v = H_0 d$$

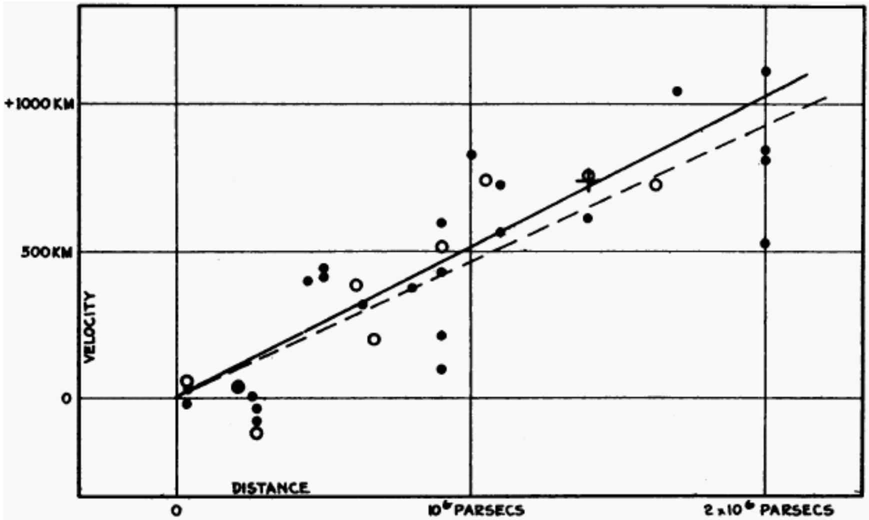


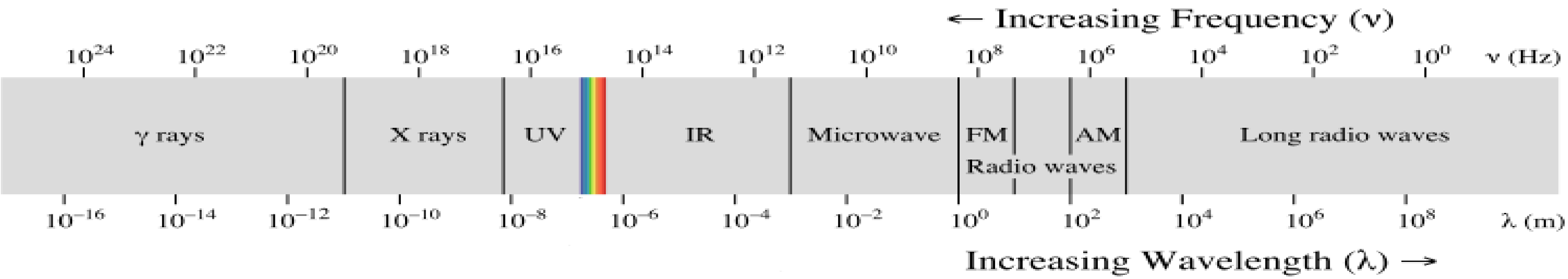
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

■ なぜ天文学？

- ✓ 知りたいという欲求（世界に対するより良い理解。なぜ我々は存在するのか？）
- ✓ 実用性（暦、将来の移住のため？）
- ✓ 宇宙の歴史が分かる（宇宙論）
- ✓ 高エネルギー現象、大スケールの現象

→ 地上で行えない素粒子理論、相対性理論等の検証、新発見の格好の場

宇宙を見る目(光)

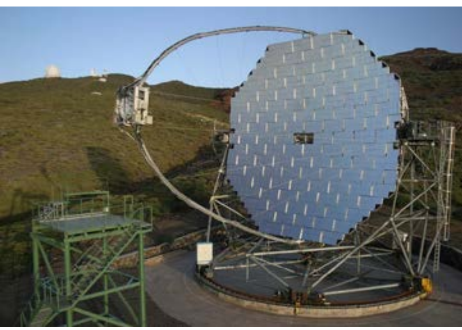


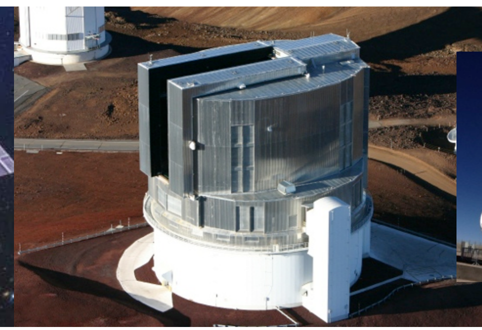
MAGIC望遠鏡

すざく衛星

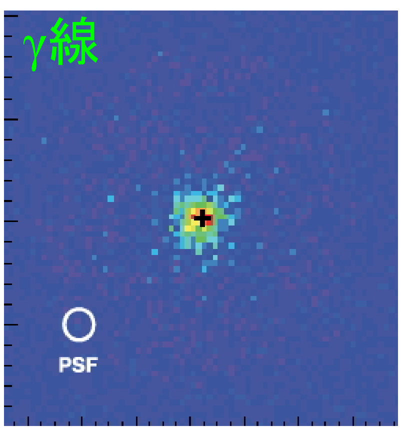
すばる望遠鏡

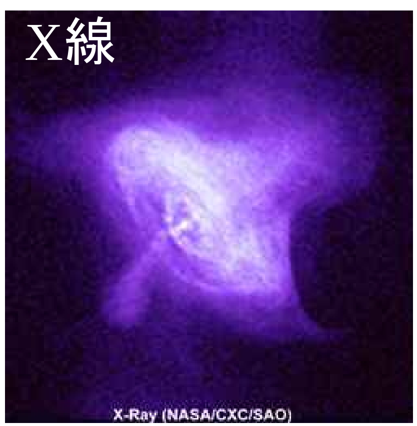
ALMA望遠鏡






かに星雲





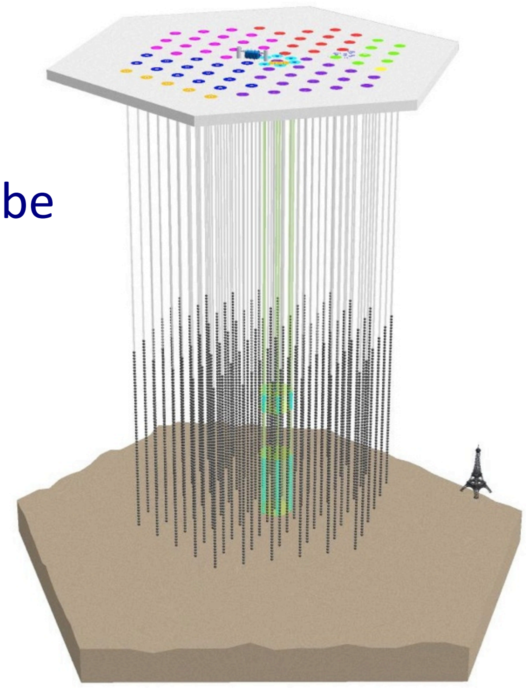
■ 宇宙を見る目 (光以外)

- ✓ **ニュートリノ**
  - ✓ 弱い相互作用しかしないレプトン
  - ✓ 深宇宙からも届く

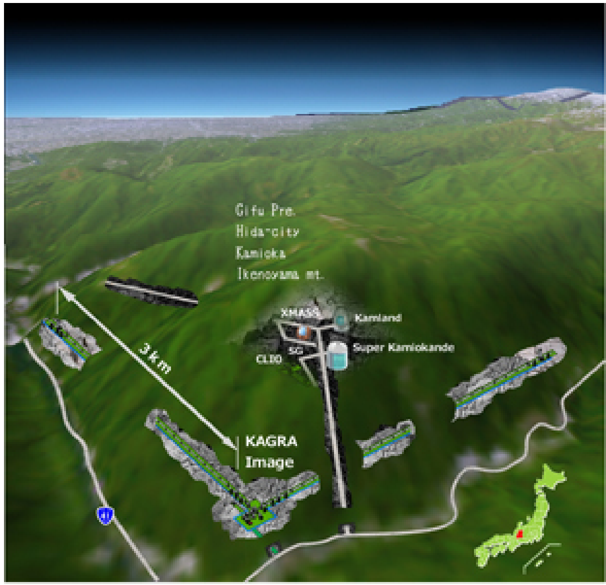
- ✓ **重力波**
  - ✓ 時空の歪みから発せられる波動

光以外の媒質を使うことで異なる物理現象を調べることができる

IceCube



KAGRA



■ 天文学が役立つ好例：暗黒物質

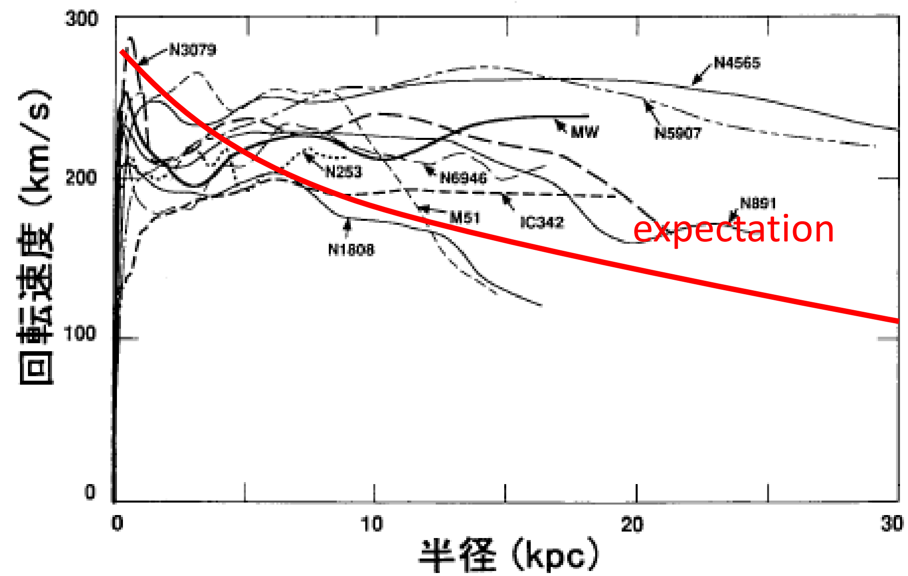
- ✓ 目には見えない物質
- ✓ 銀河の回転曲線問題

$$v = \sqrt{\frac{GM}{r}}$$

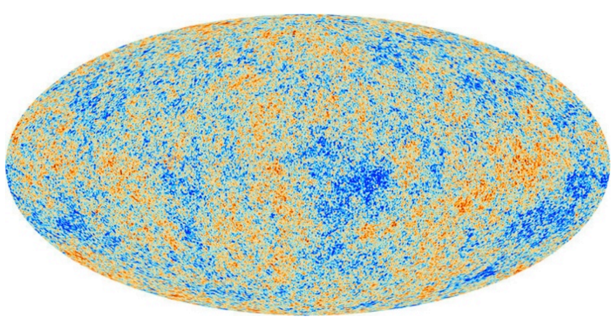
- ✓ 宇宙背景放射の揺らぎ

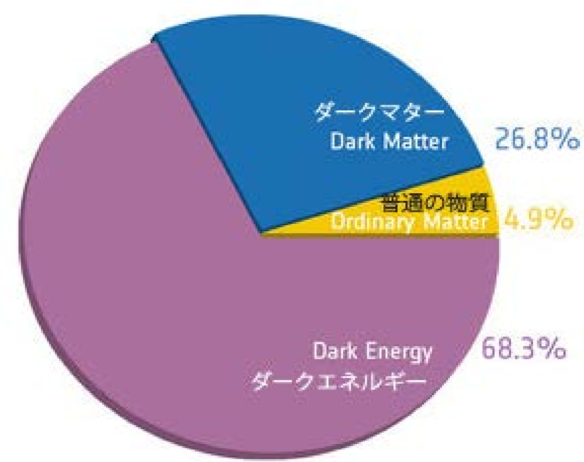
→宇宙の構成要素の約３割、冷たい（CDM）

- ✓ 超対称性理論（SUSY）から予言される素粒子（ニュートラリーノ）？



Sofue et al., AA. 296, 33 (1994)

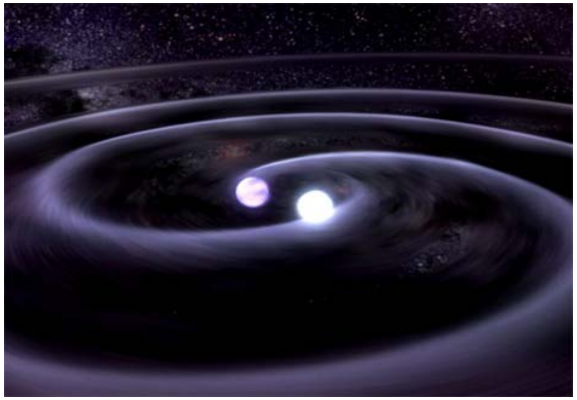




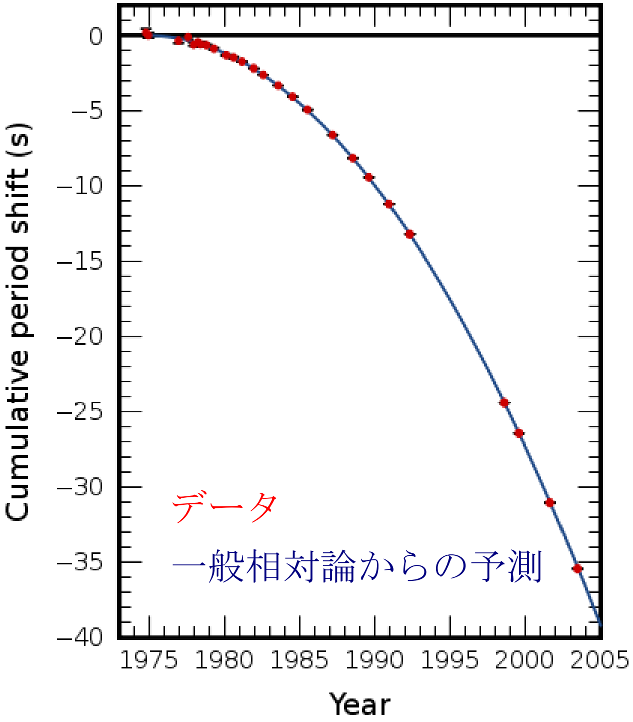
measured by Planck

■ 天文学が役立つ好例：重力波

- ✓ 時空の歪みから発せられる波動
- ✓ ２重連星パルサーの観測から間接的に検出
  →ハルス、テイラー、1993年ノーベル賞
- ✓ 一般相対性理論の検証
- ✓ 次期検出器により直接観測を狙う
  （KAGARA、advanced LIGO）



2重連星のイメージ©NASA



PSR1913+16の近星点の減衰。

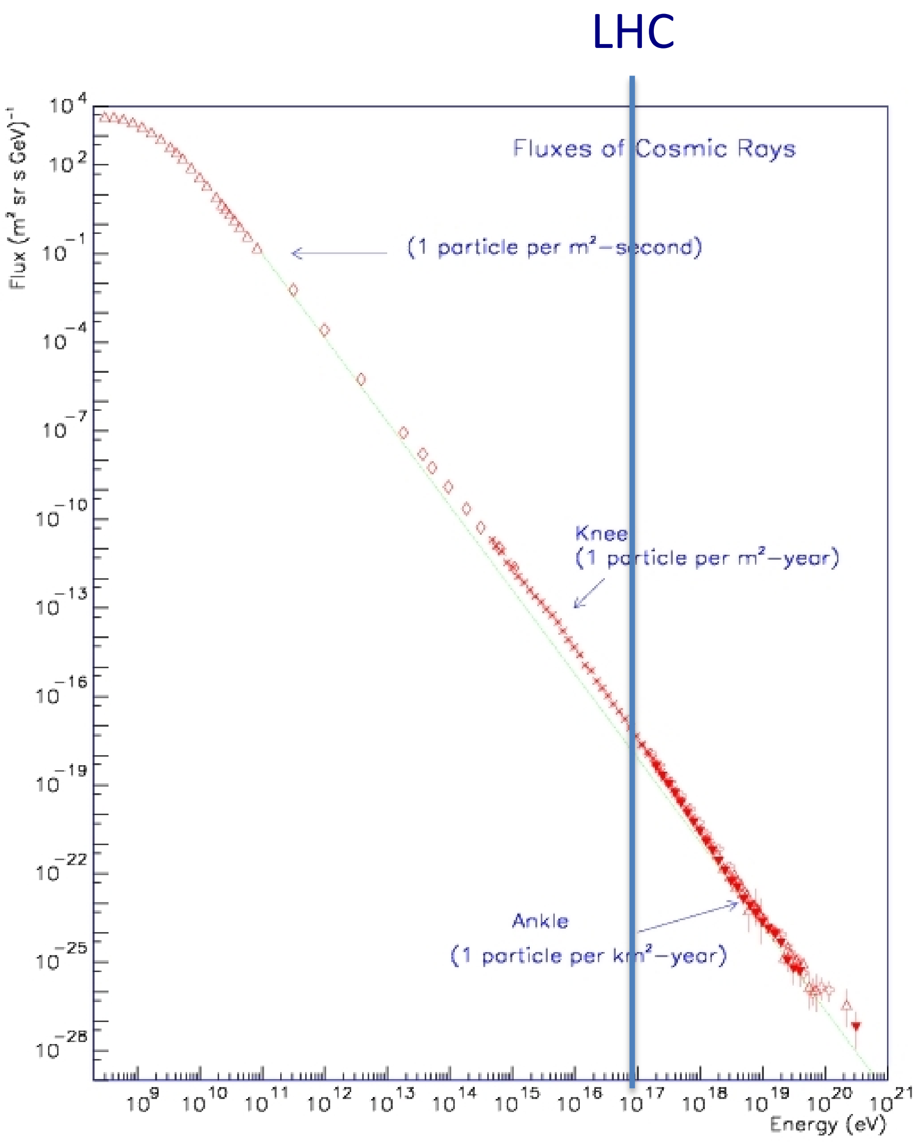
■ **Part-2:** 宇宙線とは？

宇宙線

- 宇宙からの放射線の総称。現在では宇宙からの高エネルギー粒子の総称。
- その大部分が陽子。次にHe等の重い原子核が続く。（γ 線、 ν 等も）
- 非常にありふれた粒子。我々の体を一秒間に数十発貫通。（二次宇宙線）
- 10^9eVから10^{21}eVまで幅広いエネルギースペクトラム
- 加速器で人工的に作れるエネルギーよりも高エネルギー（LHC：重心系14 TeV→実験室系10^{17}eV）

$$E = \frac{s^2}{2m_p}$$

- 大統一理論（GUT）スケール：10^{24} eV



■ 宇宙線を見る:スパークチェンバー

http://www.youtube.com/watch?v=gdk2kBKcuNY

宇宙線の歴史

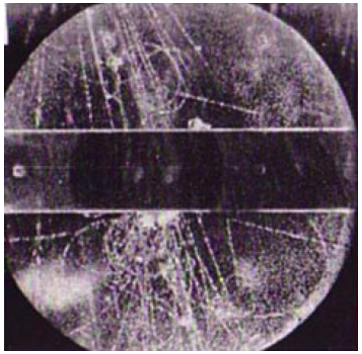
- 1912年　V. F. Hessが宇宙線を発見。（電離箱）　**100年前！**

  → 宇宙線は宇宙からの放射線。

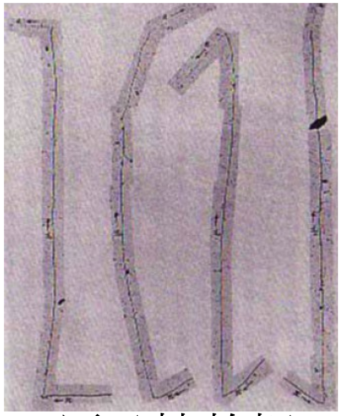
- 1930、40年代　素粒子の発見。（陽電子、パイオン、ミューオン等）（泡箱、霧箱、原子核乾板）

- 1938年 P. Augerが空気シャワーを発見。

V. F. Hess



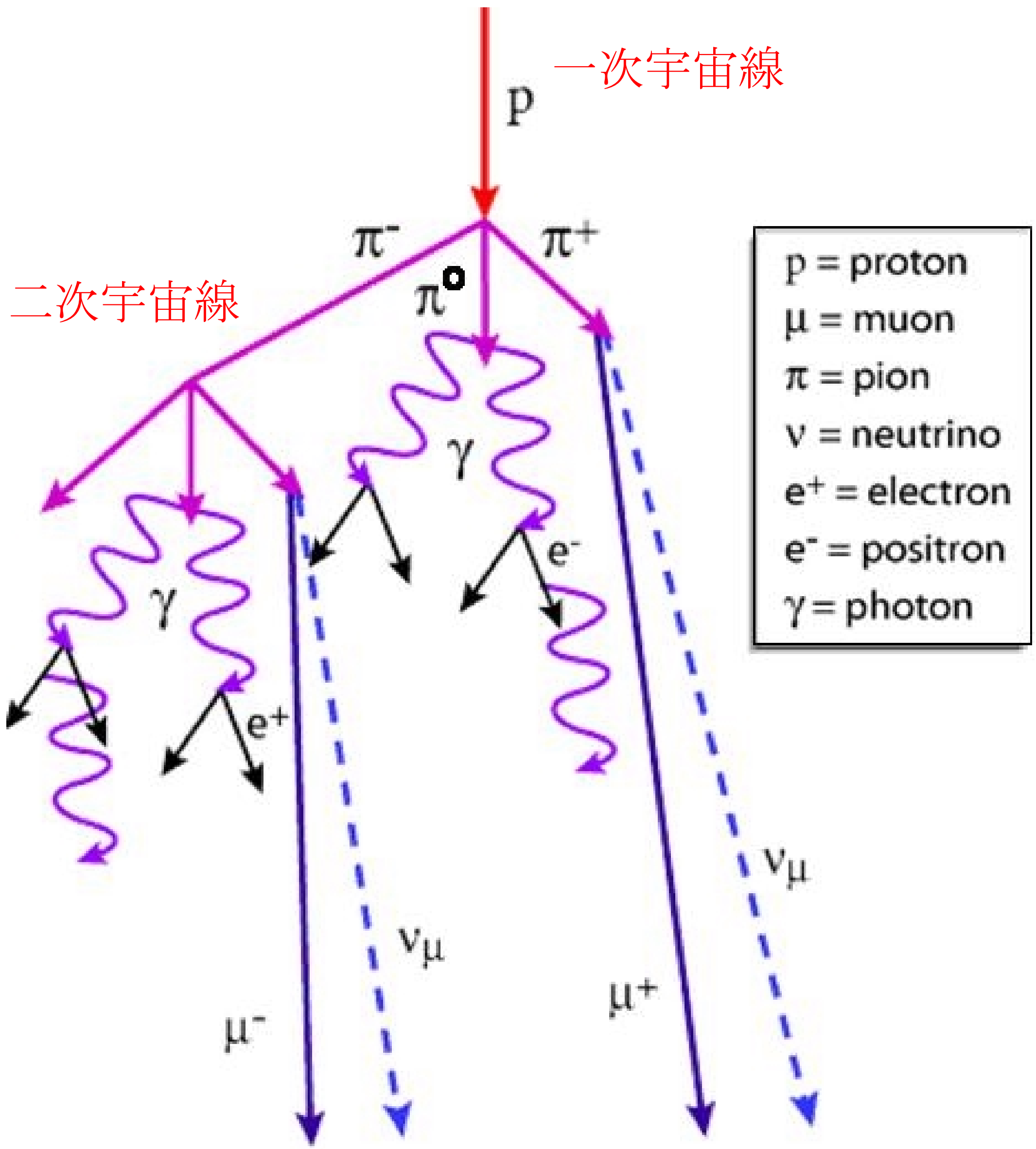
泡箱



原子核乾板

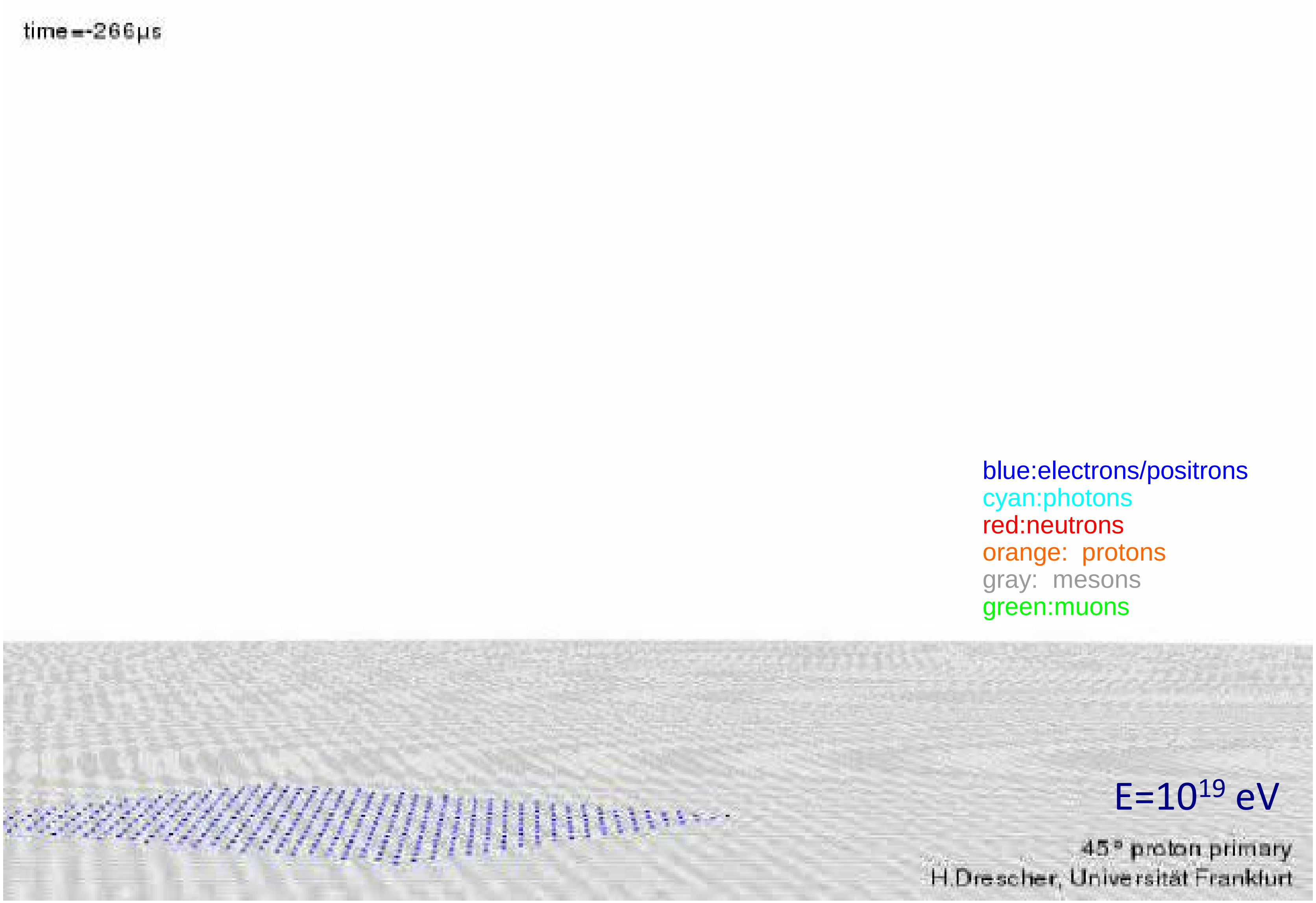
P. Auger

空気シャワー

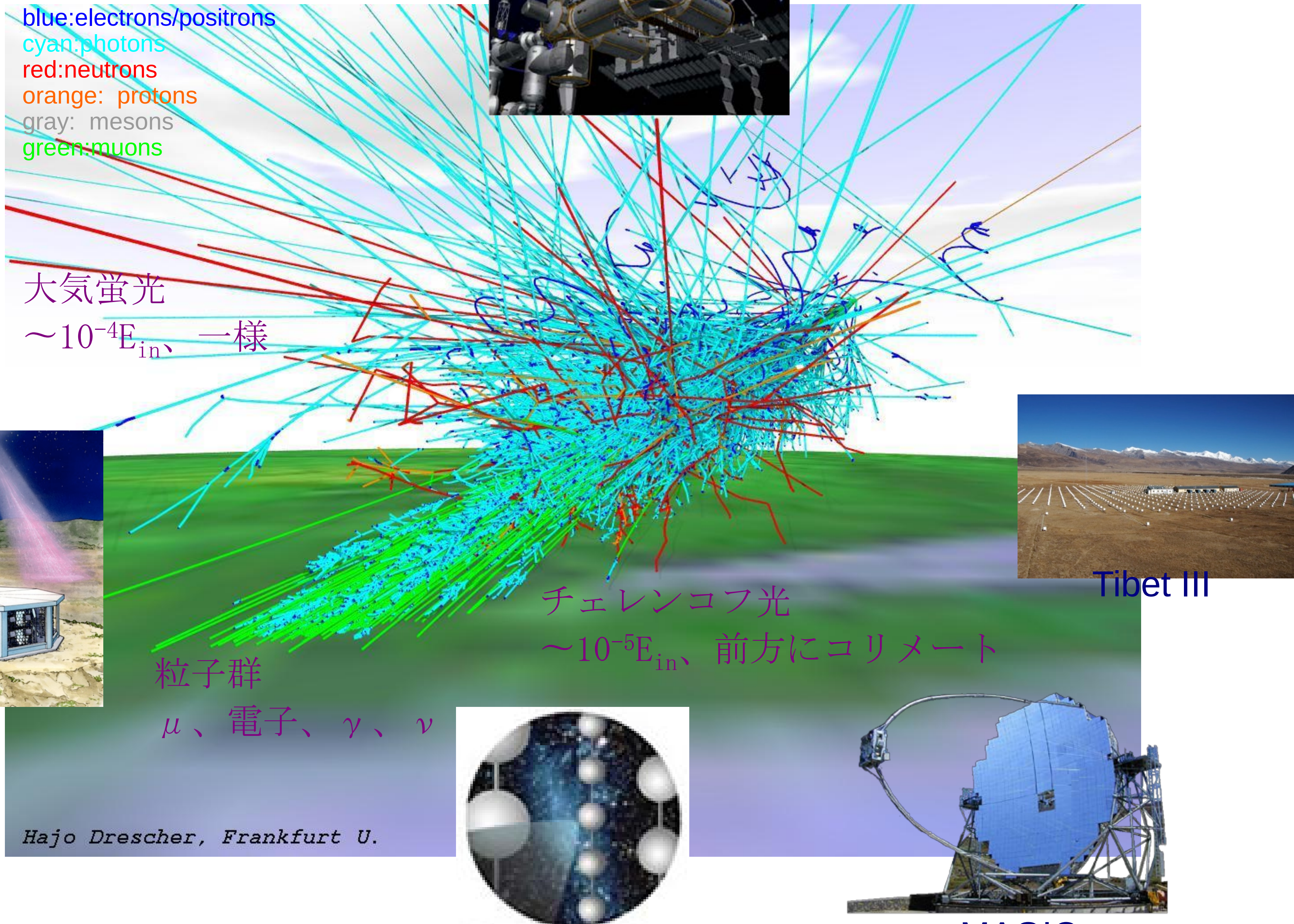


一次宇宙線
p
二次宇宙線
π⁻
π⁰
π⁺
γ
γ
e⁺
e⁻
νμ
νμ
μ⁻
μ⁺
p = proton
μ = muon
π = pion
ν = neutrino
e⁺ = electron
e⁻ = positron
γ = photon

空気シャワーシミュレーション

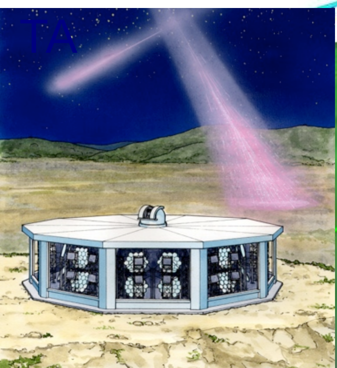


宇宙線検出器



blue:electrons/positrons
cyan:photons
red:neutrons
orange: protons
gray: mesons
green:muons
大気蛍光
～$10^{-4}E_{in}$、一様
チェレンコフ光
～$10^{-5}E_{in}$、前方にコリメート
粒子群
μ、電子、γ、ν
Hajo Drescher, Frankfurt U.
Tibet III
IceCube
MAGIC

EUSO
accommodated on ISS



TA

Fermi acceleration

Energy gain per crossing a shock front

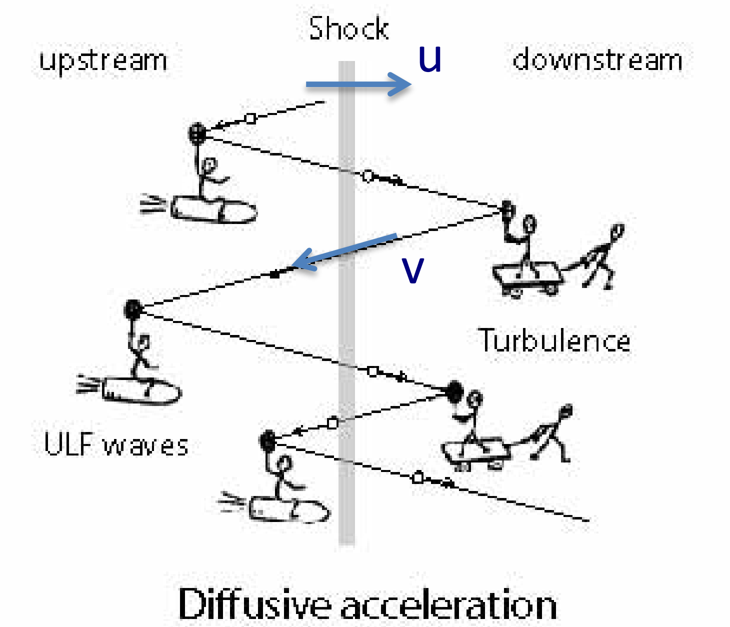
$$\Delta E = \frac{1}{2}m(u \pm v)^2 - \frac{1}{2}mv^2$$

$$\frac{\Delta E}{E} = \pm 2\frac{u}{c} + \frac{u^2}{c^2}$$

first order 2nd order

2nd order remain after many crossing

→ statistical acceleration



M. Hoshino, Progr. Theor. Phys. Suppl. **143**, 149 (2001)

Fermi acceleration (cont'd)

After k crossing

$$E_k = \beta^k E_0 \qquad \left(\beta = \frac{E_1}{E_0} = \frac{u^2}{c^2}\right)$$

$$N_k = p^k N_0$$

p: probability to remain in shock region

$$\frac{N_k}{N_0} = \left(\frac{E_k}{E_0}\right)^{\frac{\ln p}{\ln \beta}}$$

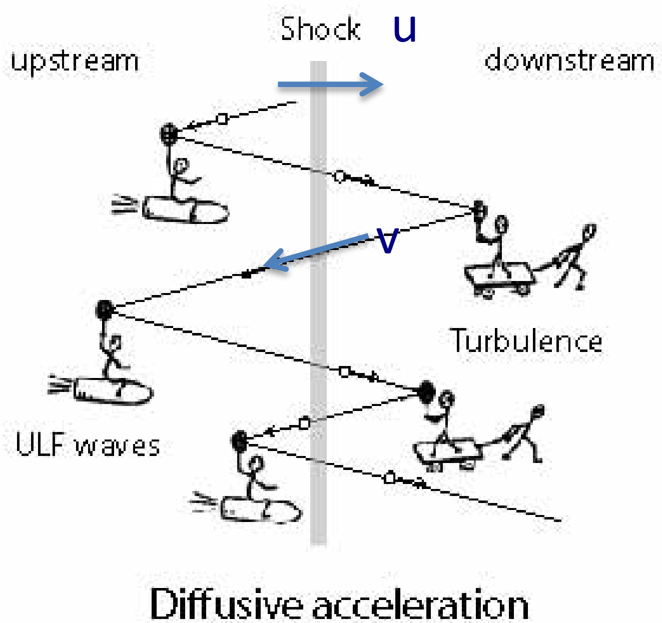
By differentiating

$$\frac{dN}{dE} \propto E^{-1+\frac{\ln p}{\ln \beta}}$$

Power law!

$$= E^{-2}$$

(standard case)



M. Hoshino, Progr. Theor. Phys. Suppl. **143**, 149 (2001)

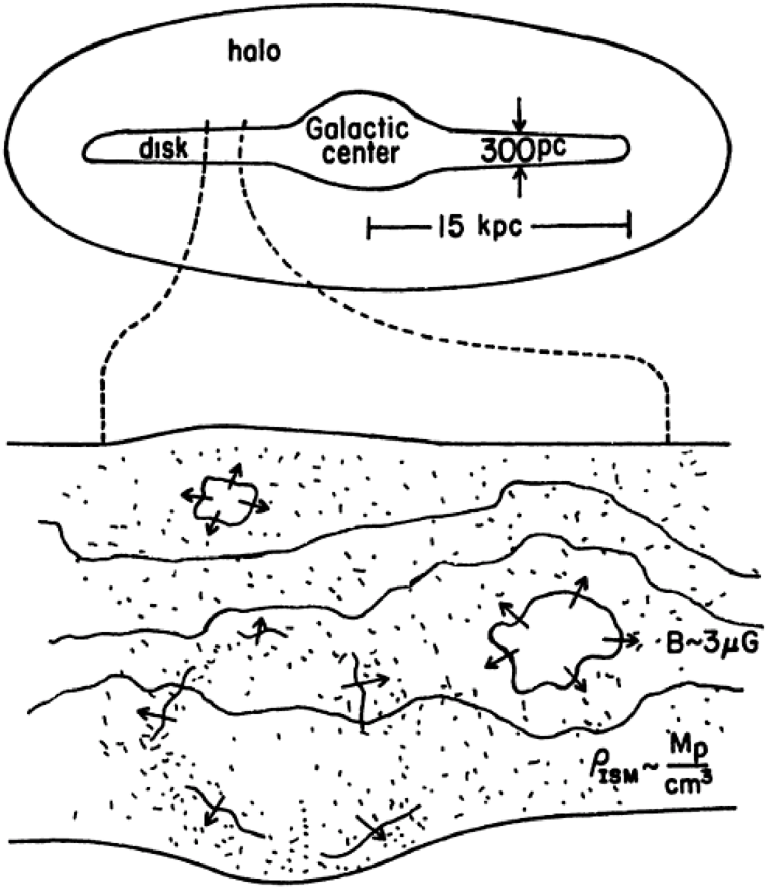
Leaky box model

- ✓ 宇宙線磁場による閉じ込め
- ✓ 高エネルギー粒子ほど逃げ出しやすい

$$\frac{dN}{dE} \propto E^{-\alpha-\delta}$$

α~2.0 from Fermi acceleration

δ~0.7 from leaky box model

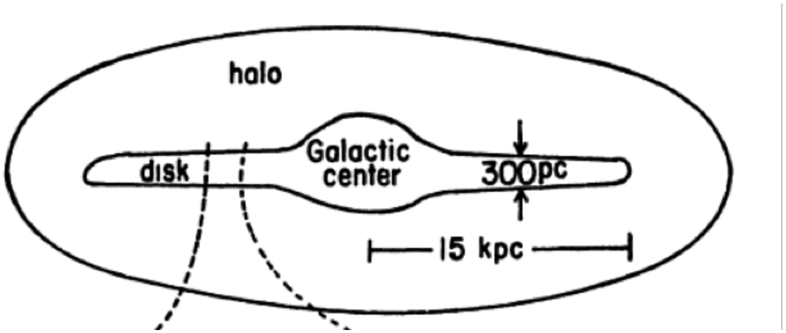


Cosmic ray and particles physics, T. K. Gaisser

Gyro-radius

$$r_g = \frac{E}{ZeB} = 400\,pc\,Z^{-1}\left(\frac{E}{10^{18}eV}\right)\left(\frac{B}{3\mu G}\right)^{-1}$$

thickness of the Galaxy: 300 pc

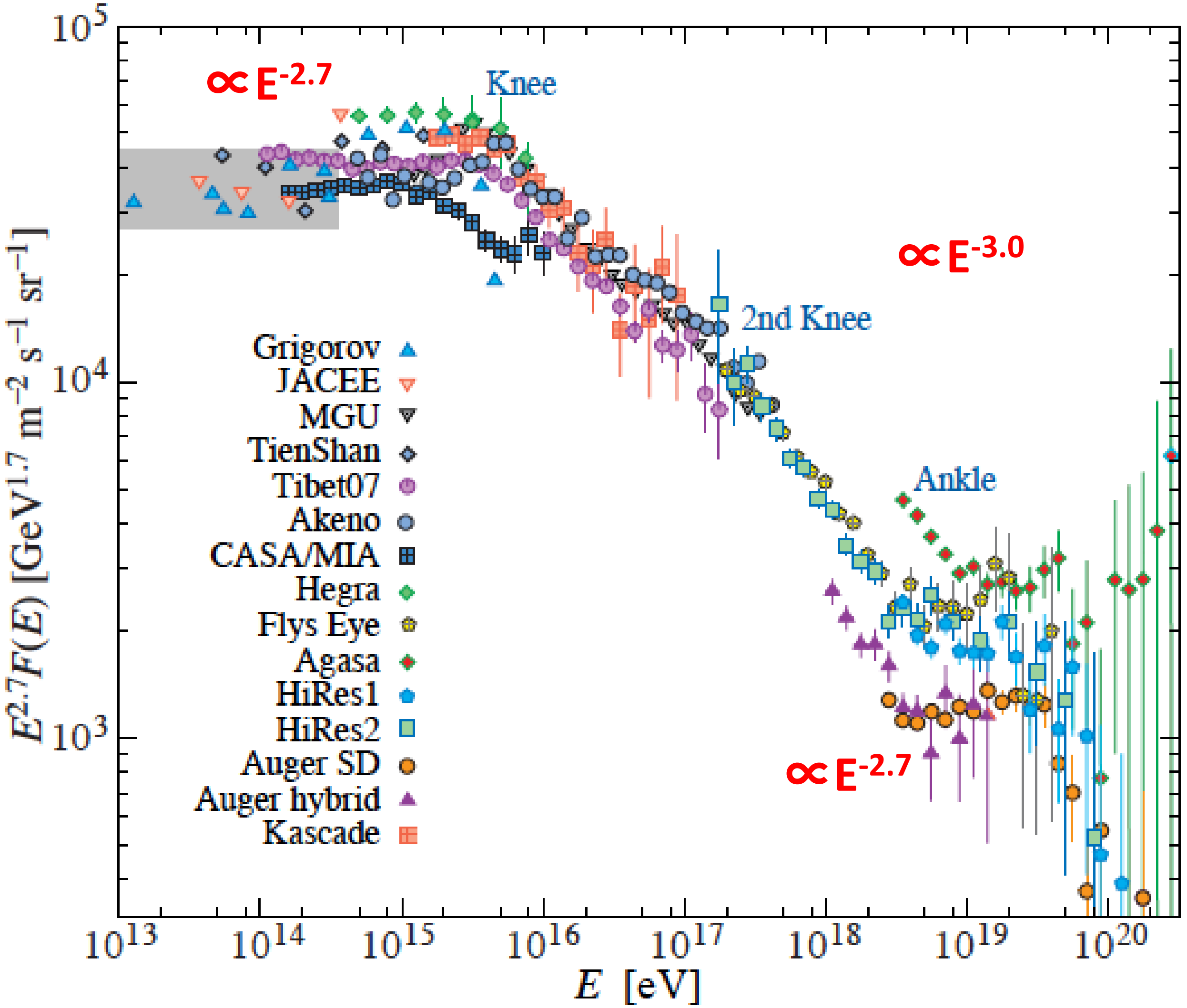


Difficult to trap high energy cosmic rays above 10^{18} eV in Galaxy

→ Extra-galactic origin

■宇宙線スペクトラムと起源

C. Amsler *et al.*, Phys. Lett. B **667** (2008) 1.



knee: $10^{15.5}$ eV

second knee: $10^{17.5}$ eV

ankle: $10^{18.5}$ eV

GZK cutoff: $10^{19.5}$ eV

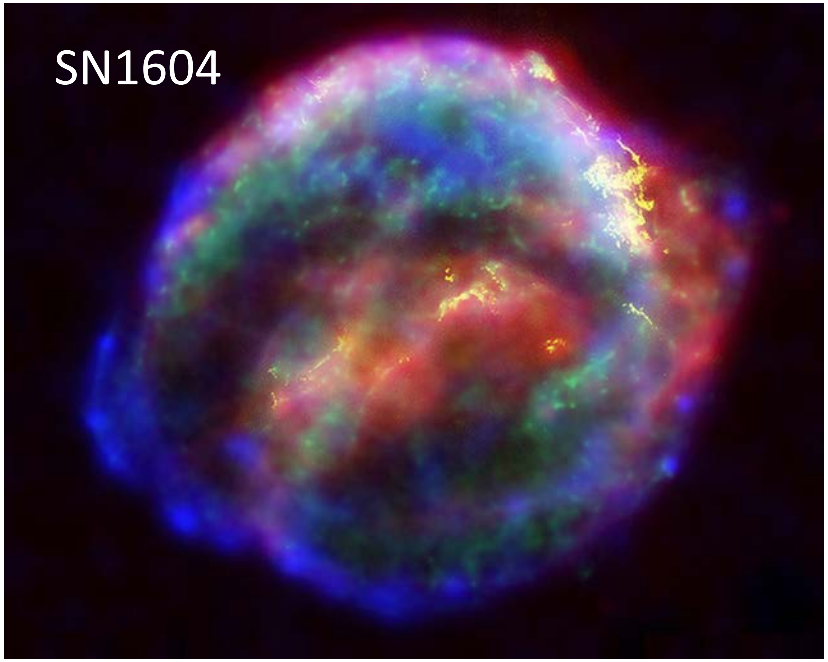
kneeまで：超新星爆発

ankleより上：銀河系外起源

その間：重い組成（鉄）？

超新星

- 星の最期の爆発（$M > 8\ M_\odot$）
- -13から-19等級増光
- $E = 10^{54}$ erg
- 殆どのエネルギーはニュートリノとして解放される（$E=10^{53}$ erg）
- $E_{kin}=10^{51}$ erg, $E_\gamma=10^{49}$ erg
- 1987Aからニュートリノ観測
- 銀河の中で約100年に一度
- $8\ M_\odot < M < 30\ M_\odot$→中性子星
- $M > 30\ M_\odot$→ブラックホール



■ 宇宙線起源としての超新星

- ✓ U_{CR}= 1 eV/cm^3
- ✓ dE_{CR}/dt

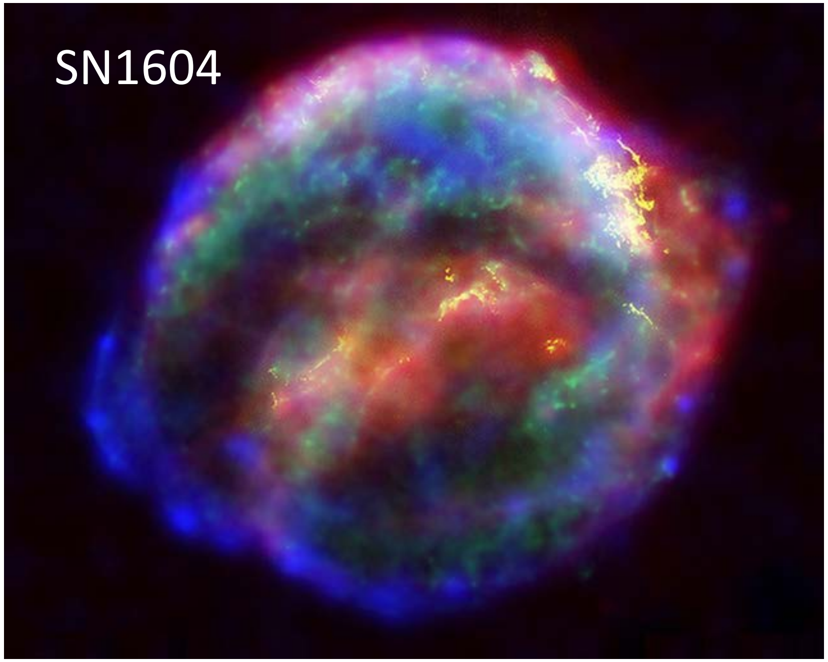
= $U_{CR}V$ (πx(10kpc)^{2}x1kpc) /t_{esc}(10^7 yr)

= 3 x 10^{40} erg/s

- ✓ dE_{SN}/dt = 10^{51} erg/100 yr

= 3 x 10^{41} erg/s

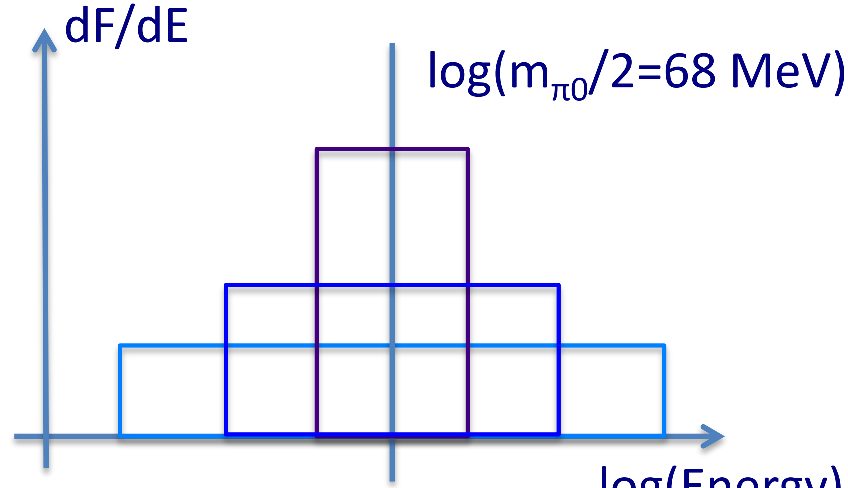
- ✓ 超新星の10%のエネルギーが宇宙線にいけば良い
- ✓ 宇宙線起源の有力候補



■ 超新星残骸が宇宙線起源である証拠

$$p + p(\gamma) \rightarrow \pi^{\pm} / \pi^{0} + anything$$

$$\pi^{0} \rightarrow 2\gamma$$



- ✓ π^{0}起源の特徴的なエネルギースペクトラムを捕らえる

ローレンツ変換

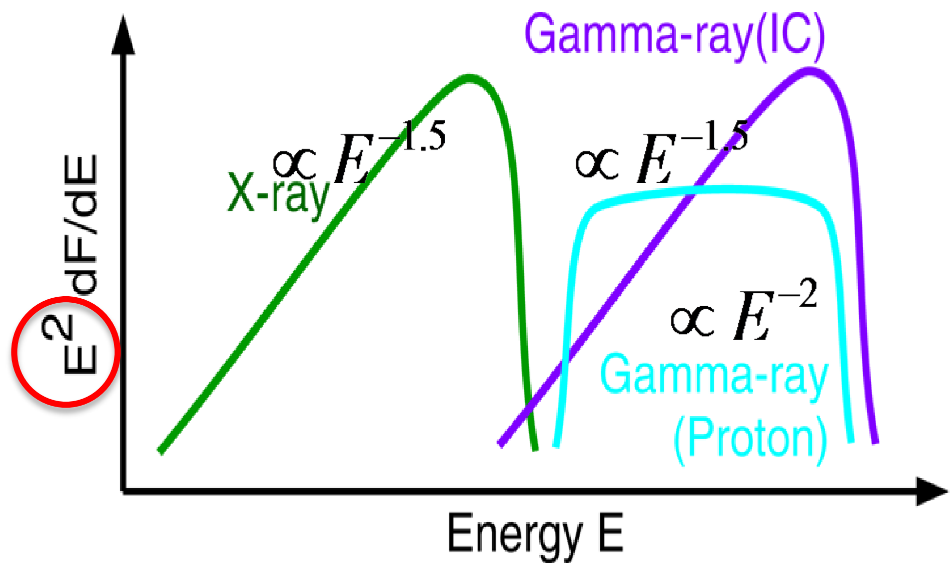
$$\frac{\gamma m_{\pi^0}}{2}(1-\beta) \leq E \leq \frac{\gamma m_{\pi^0}}{2}(1+\beta)$$

$$\frac{dn}{dE} = const.$$

E*: 重心系のエネルギー

E: 実験室系のエネルギー

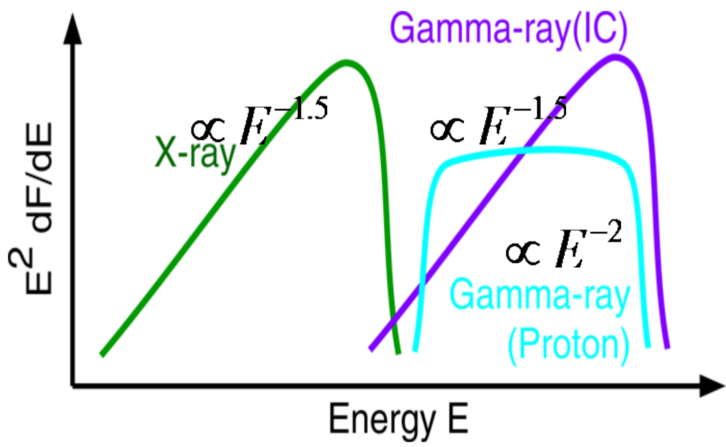
- ✓ Bremsstrahlungや逆コンプトン散乱によるγ線と区別する必要



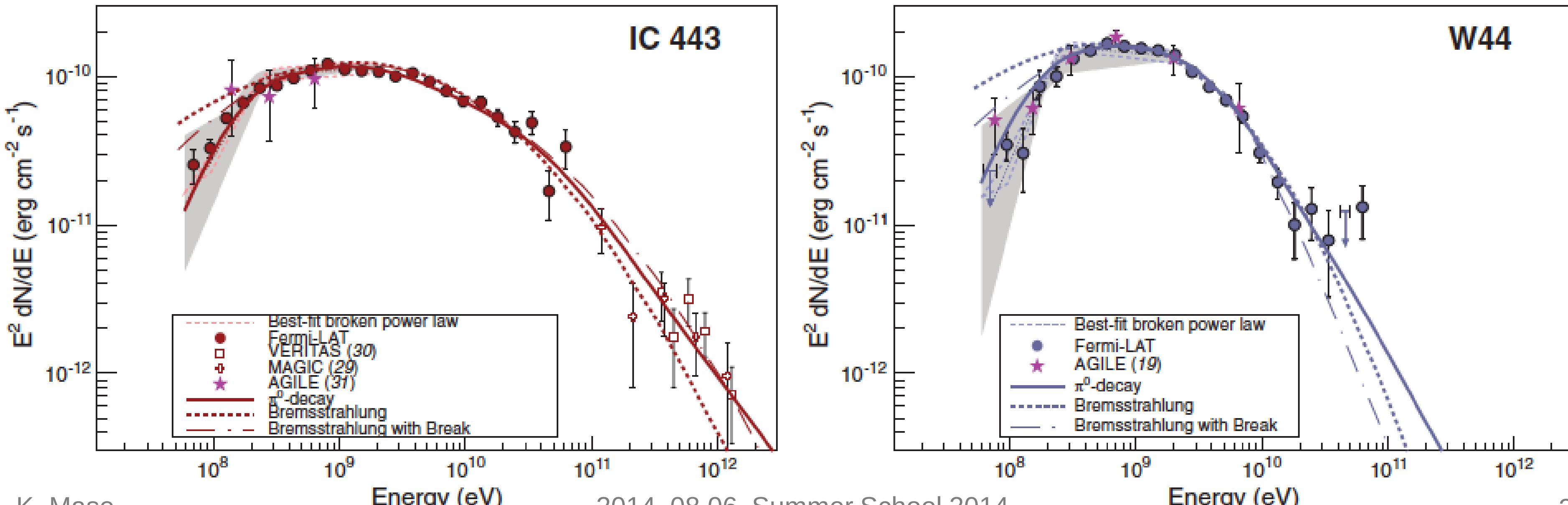
■ 超新星残骸が宇宙線起源である証拠

- ✓ Fermi衛星による宇宙線起源のγ線の観測
- ✓ π^0起源の特徴的なエネルギースペクトラムを捉えた

→超新星は宇宙線起源



M. Ackermann et al., Science 339, 807 (2013)



宇宙線組成

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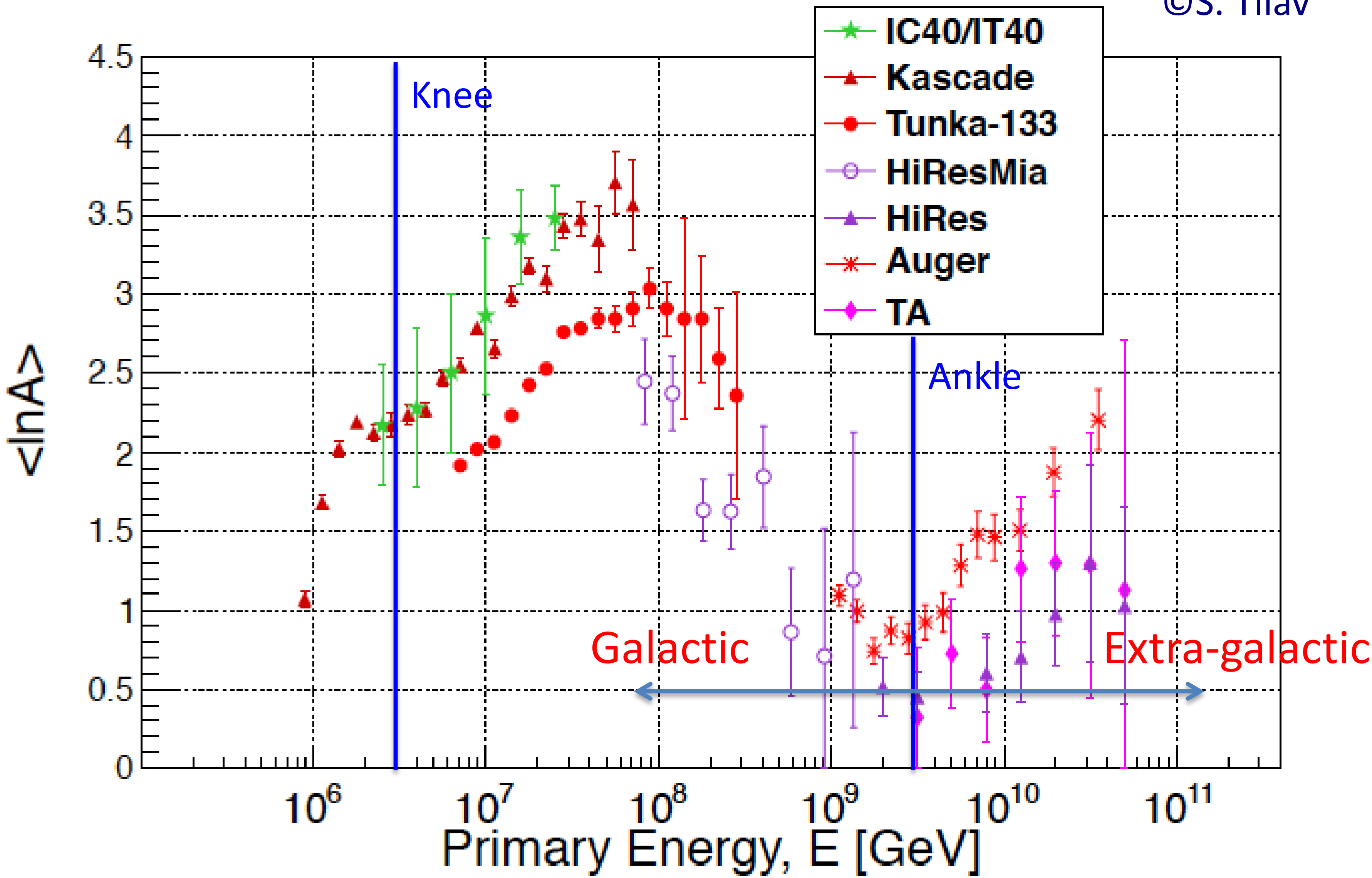
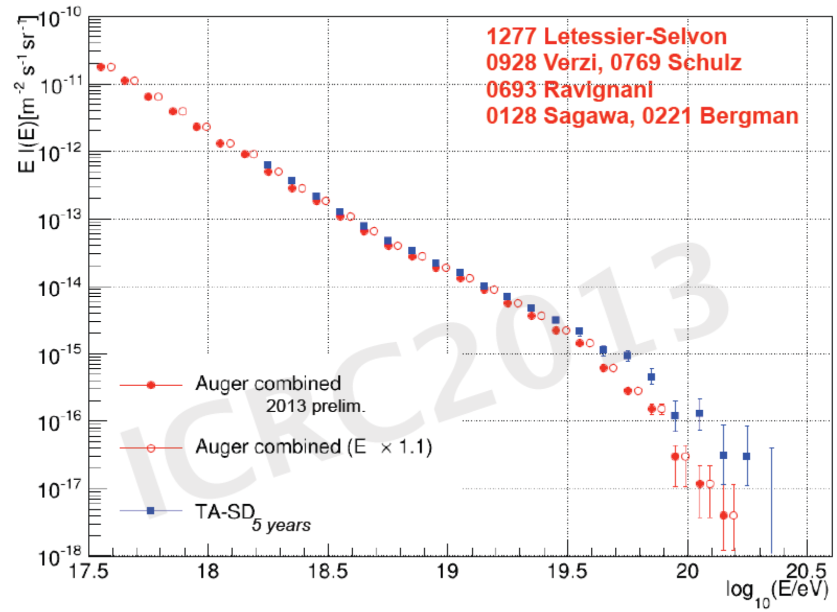
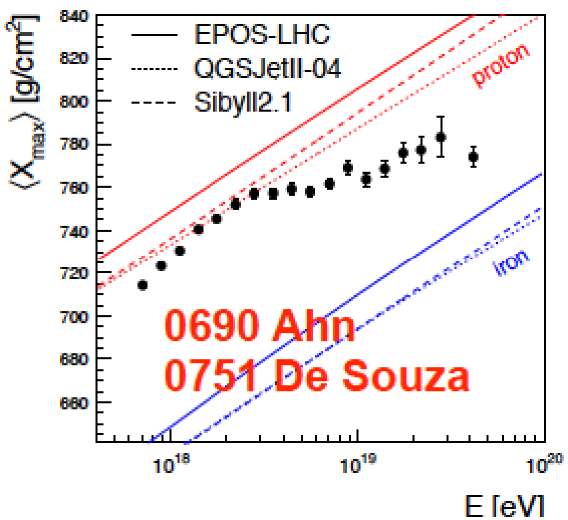


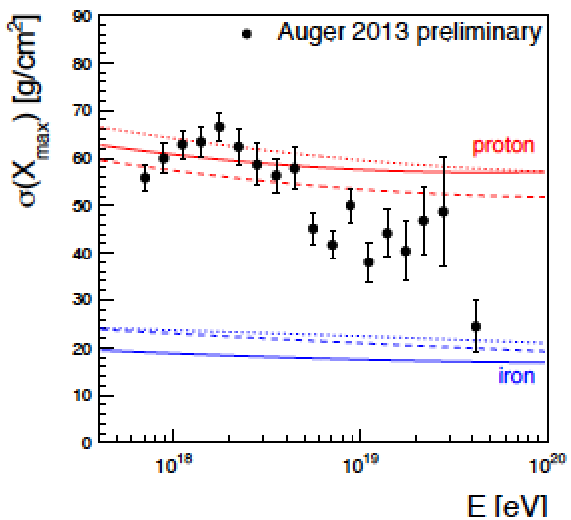
極高エネルギー宇宙線(EHECRs)

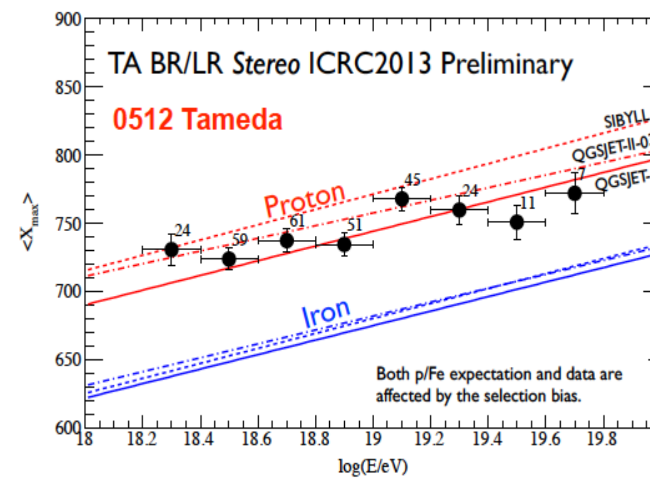
Y. Tunesada @ ICRC2013

- ✓ エネルギーが$10^{19.5}$ eV以上の宇宙線
- ✓ 1事象/100 km^2/yr
- ✓ GZK cut-off（next slide）
- ✓ スペクトラムもTAとAugerで違う
- ✓ 陽子、鉄？
- ✓ 起源は良く分かっていない





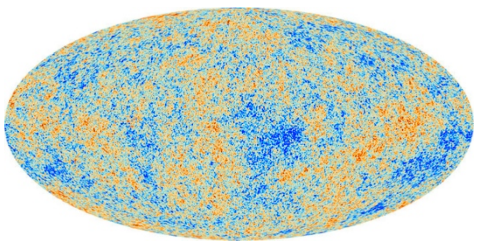




GZK cut-off

- ✓ EHECRsは3K宇宙背景放射光子と相互作用

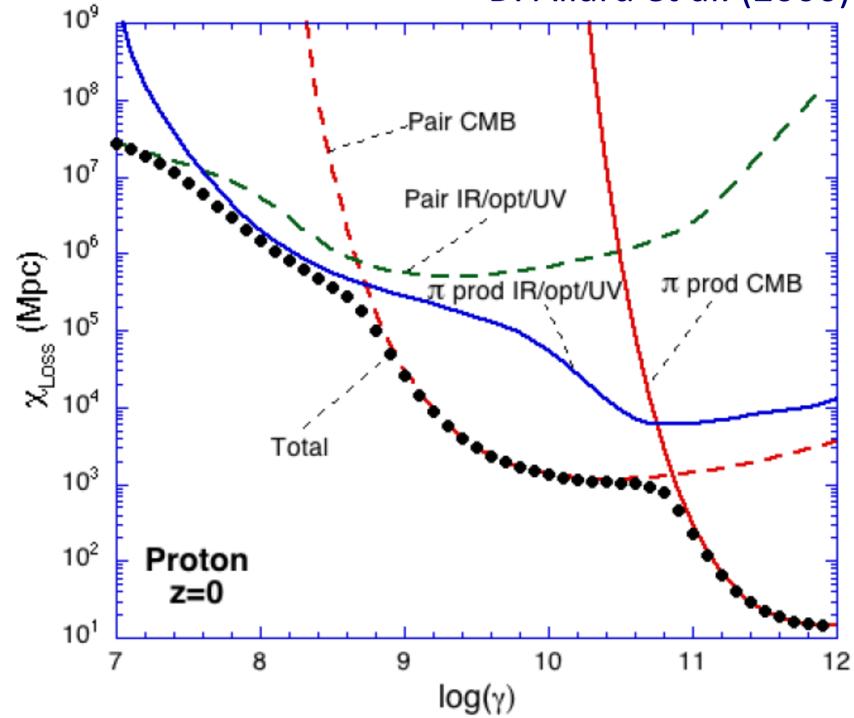
$$p\gamma_{2.7K} \rightarrow \pi^{+} + X \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}} + \nu_{\mu}$$

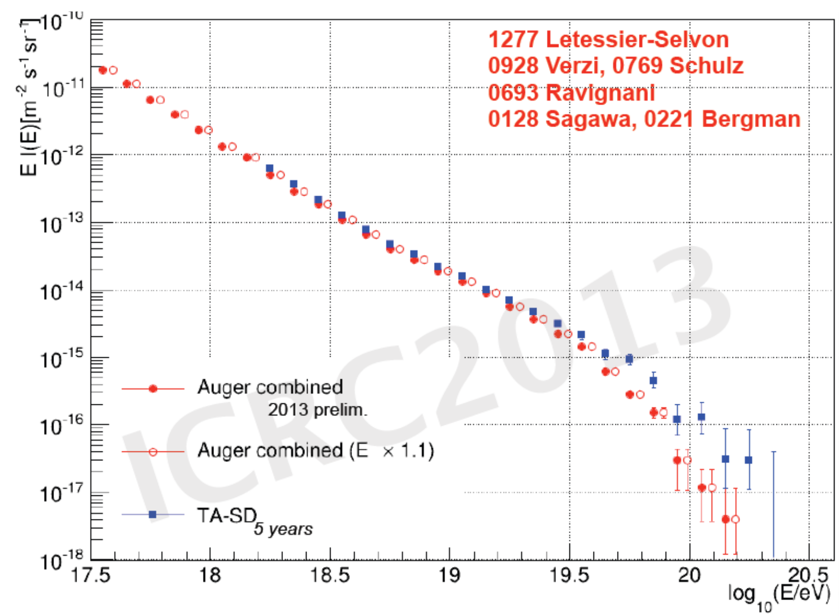


$$E_p > \frac{m_\pi^2 + 2m_p m_\pi}{4E_\gamma} \sim 10^{20} eV$$

- ✓ 50 Mpc以遠から来れない
- ✓ ニュートリノは来られる

D. Allard et al. (2006)





Y. Tunesada @ ICRC2013

EHECRs起源

- ✓ 粒子を閉じ込めるために強い磁場もしくは大きなソースサイズが必要

Maximum energy

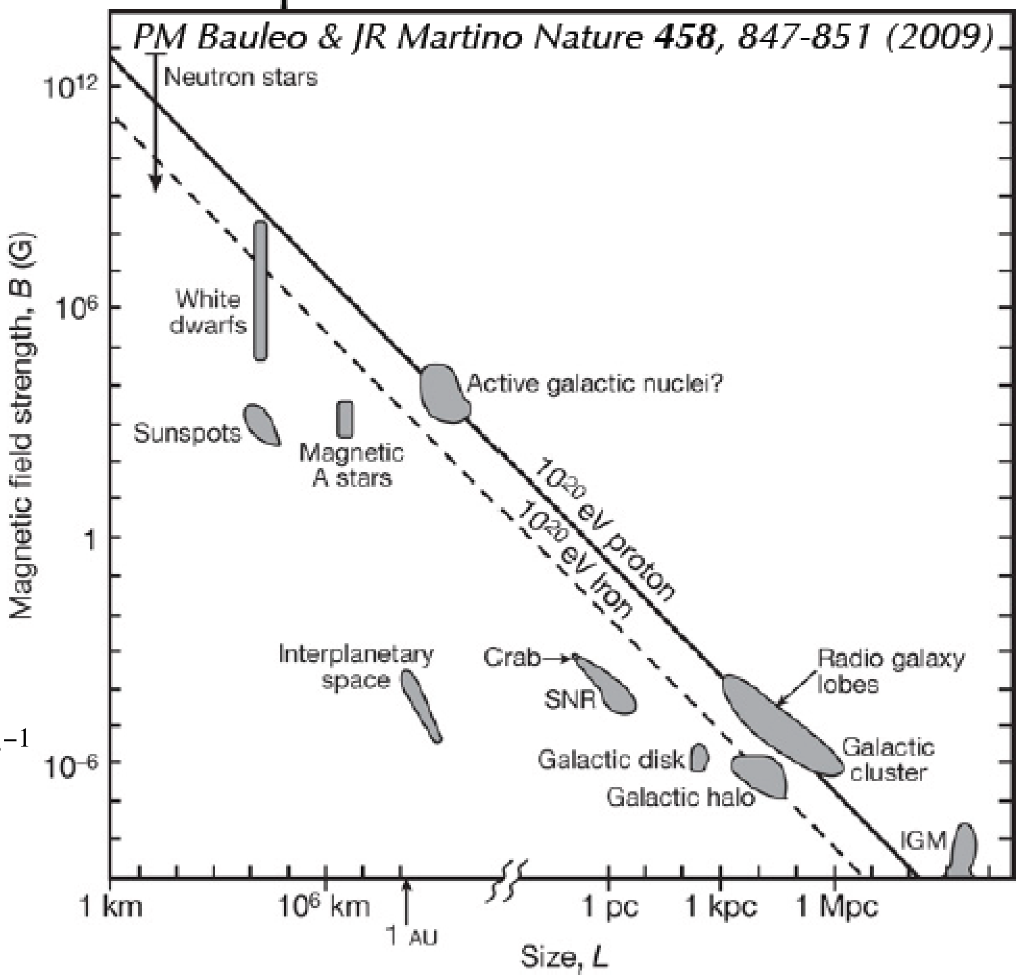
$$10^{18} eV\ Z \left(\frac{R}{kpc}\right)\left(\frac{B}{\mu G}\right)$$

- ✓ 候補天体は余りない
- ✓ エネルギー総量

$$\dot{U}_{EHECR} \sim \frac{10^{20} eV}{100 km^2 \cdot yr} \frac{2}{d_{GZK}} \sim 10^{44} erg\ Mpc^{-3} yr^{-1}$$

- ✓ 満たすのはAGN, GRBのみ

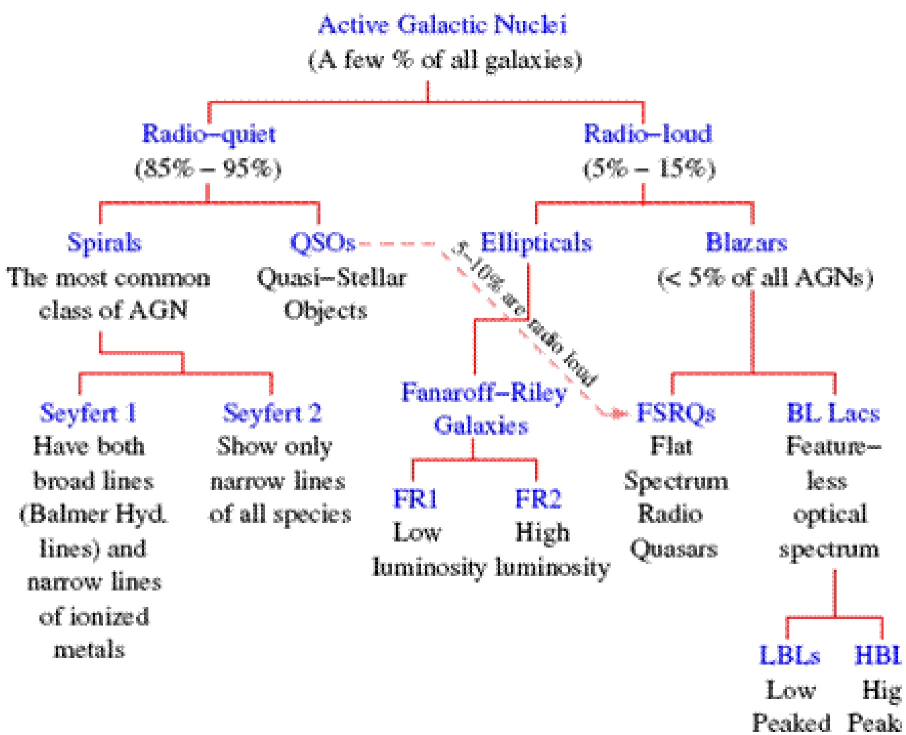
Hillas plot:

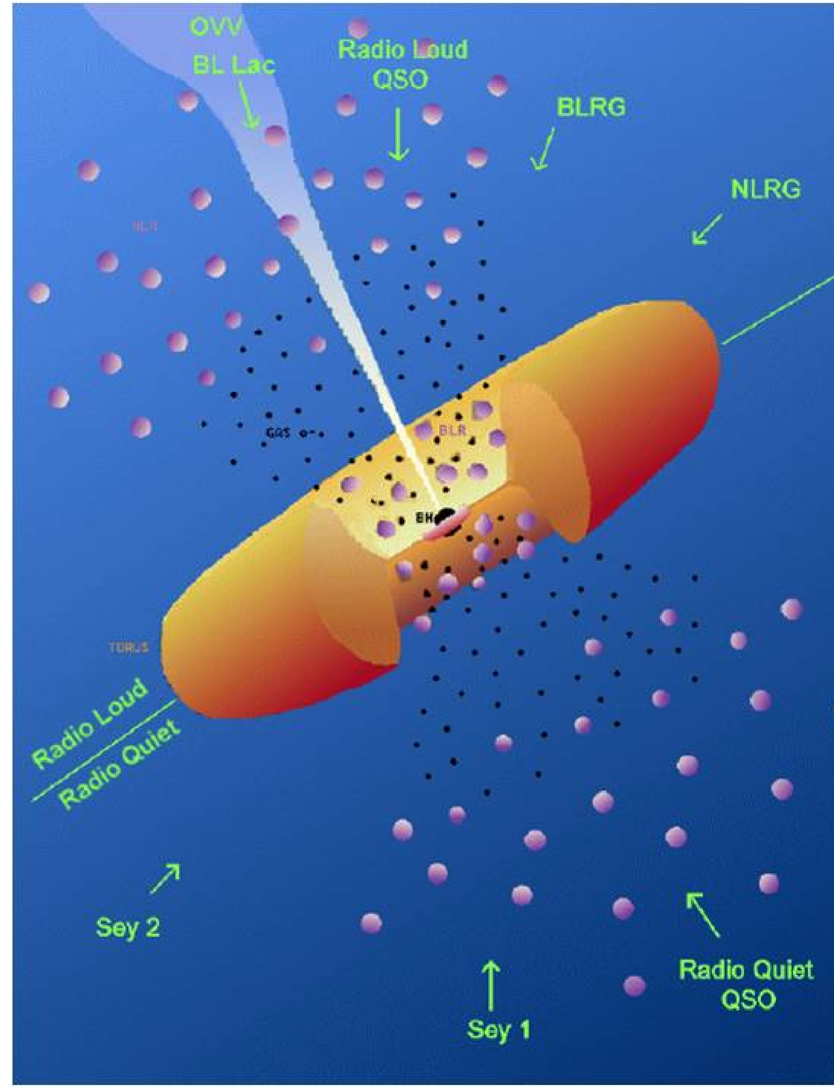


■ 活動銀河核（AGNs）

- ✓ 大質量ブラックホール（$10^{6\text{-}9}\,M_\odot$）からの放射（我々の銀河$3\text{x}10^6\,M_\odot$）

$$L_{Edd} \sim 10^{46} \frac{M}{10^8 M_\odot} erg\, s^{-1}$$

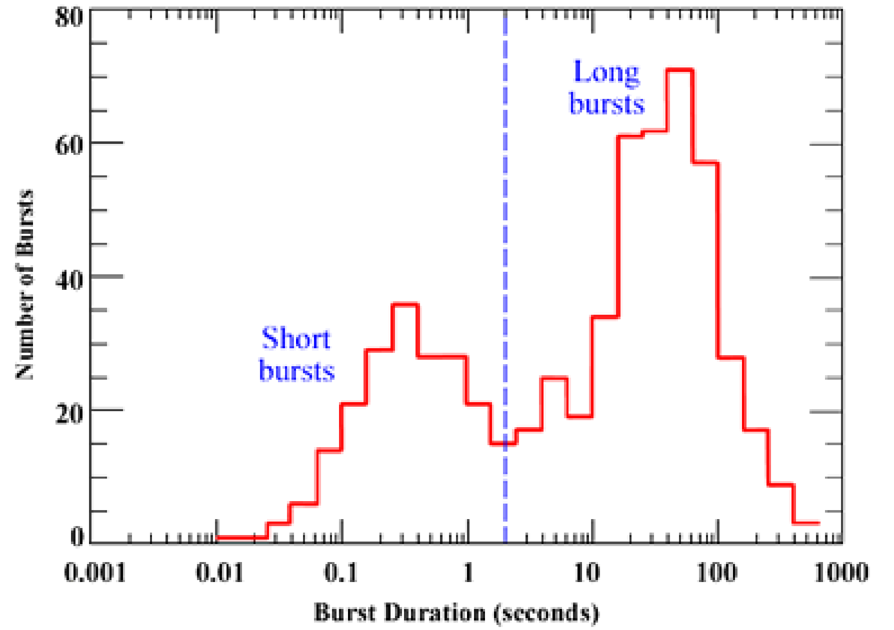


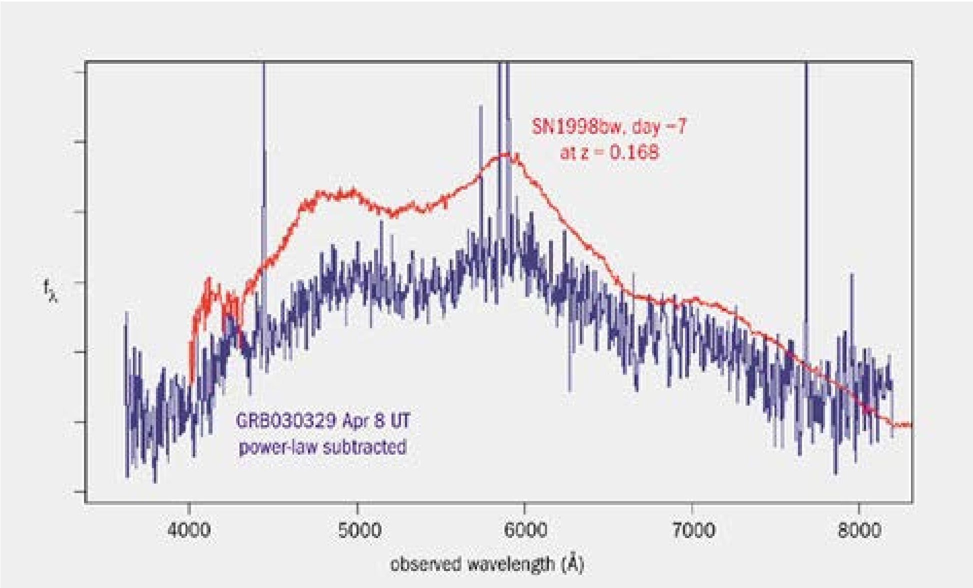


http://www.kusastro.kyoto-u.ac.jp/~iwamuro/LECTURE/AGN/agn.html

■ ガンマ線バースト（GRBs）

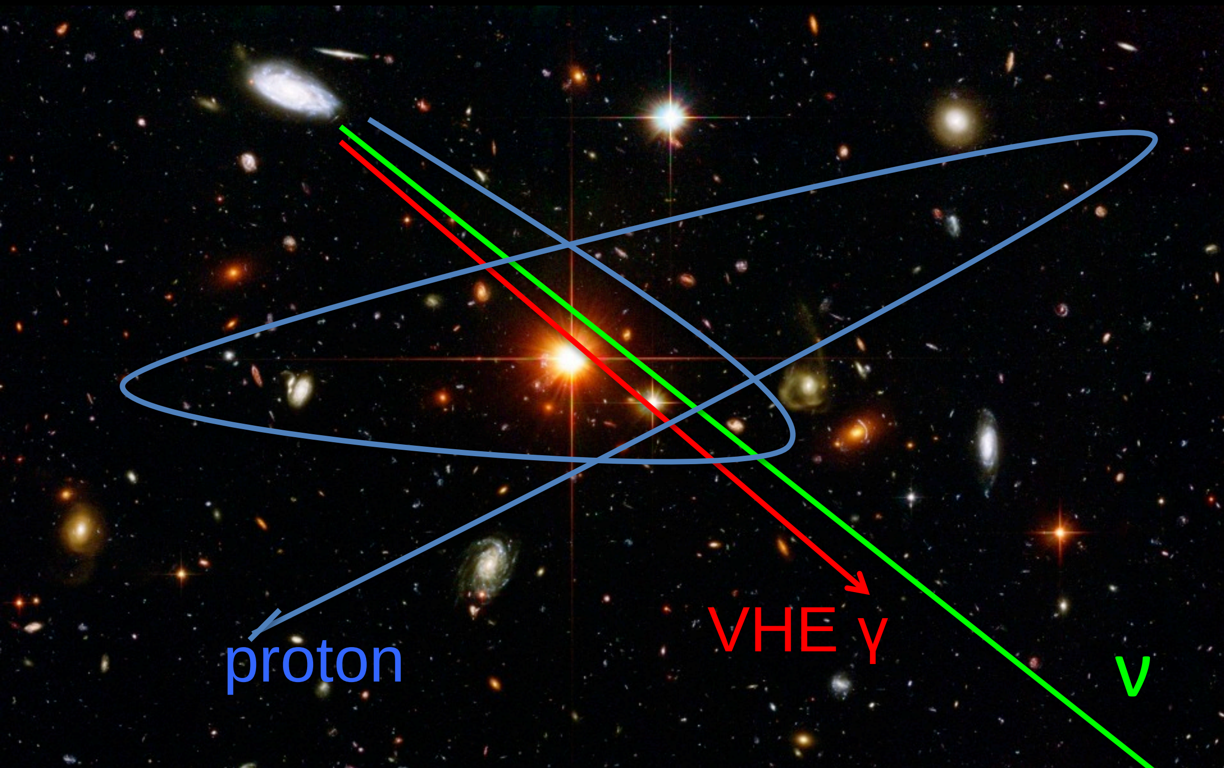
- ✓ アメリカの核施設監視衛星Velaにより発見
- ✓ 一日数回
- ✓ 非常に明るい（10^{53} erg）
- ✓ 一様→系外起源、宇宙論的距離から来る（z < 6）
- ✓ アフターグロー
- ✓ 短いバースト（< 2秒）と長いバースト（> 2秒）
- ✓ 長いバーストの一部は超新星起源
- ✓ 短いバースト：コンパクト連星の合体？





■ Part-3: IceCubeの最新結果とその意味

■ Why neutrinos?



Neutrinos are rarely interacting particles

- Arrive straight to the Earth from the deep Universe

  → **Astronomy**

- Produced through hadronic interactions

  → **Cosmic ray origin**

■ Multi messengers

Neutrino production is closely related to production of **cosmic rays** and **gamma rays**

$$p + p\,(\gamma) \rightarrow \pi^{\pm} / \pi^{0} + anything$$

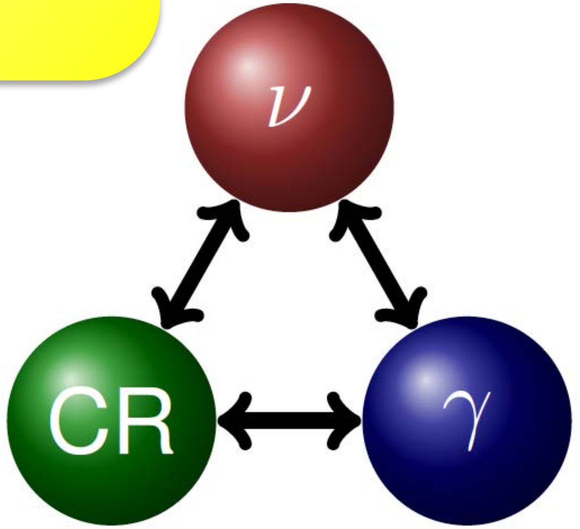
$$\pi^{+} \rightarrow \mu^{+} \nu_{\mu}$$

$$\mu^{+} \rightarrow e^{+} \nu_{e} \bar{\nu}_{\mu} \qquad E_{\nu_\mu} \approx E_{\nu_e} \approx E_{\bar{\nu}_\mu}$$

$$\pi^{0} \rightarrow 2\gamma$$

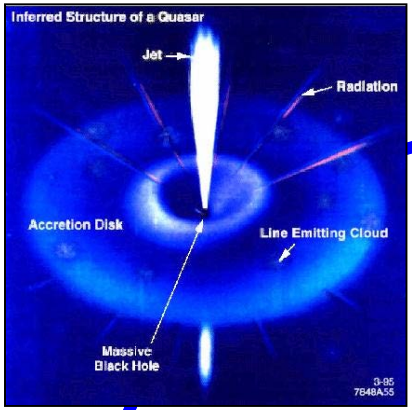
$$E_{\nu} \approx \frac{1}{20} E_{p} \qquad \square\; E_{\pi} \approx \frac{1}{5} E_{p},\; E_{\nu} \approx \frac{1}{4} E_{\pi}$$

$$E_{\nu} \approx E_{\gamma}$$

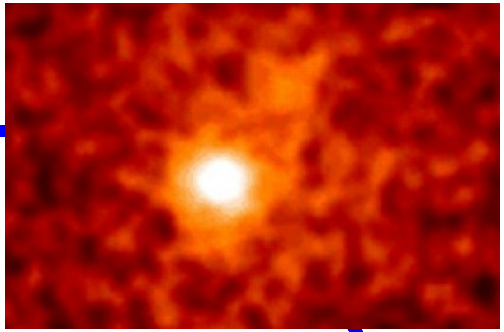


©M. Ahlers

Exploring the universe with neutrinos

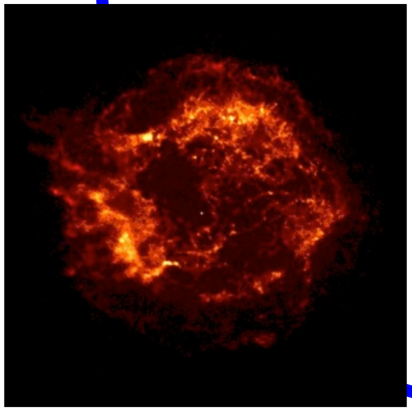


- AGNs

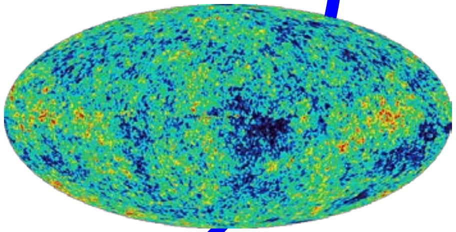


- GRBs

- Cosmic ray origin



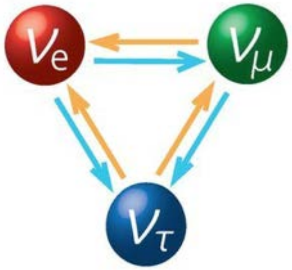
- Supernova



- Cosmogenic neutrinos

- Dark Matter

- Particle physics



- Neutrino oscillation

Neutrinos should be there…

The source of cosmic rays will be the neutrino source.

$$p + p(\gamma) \rightarrow \pi^{+} + anything \rightarrow \mu + \nu_{\mu}$$

Waxman-Bahcall limit

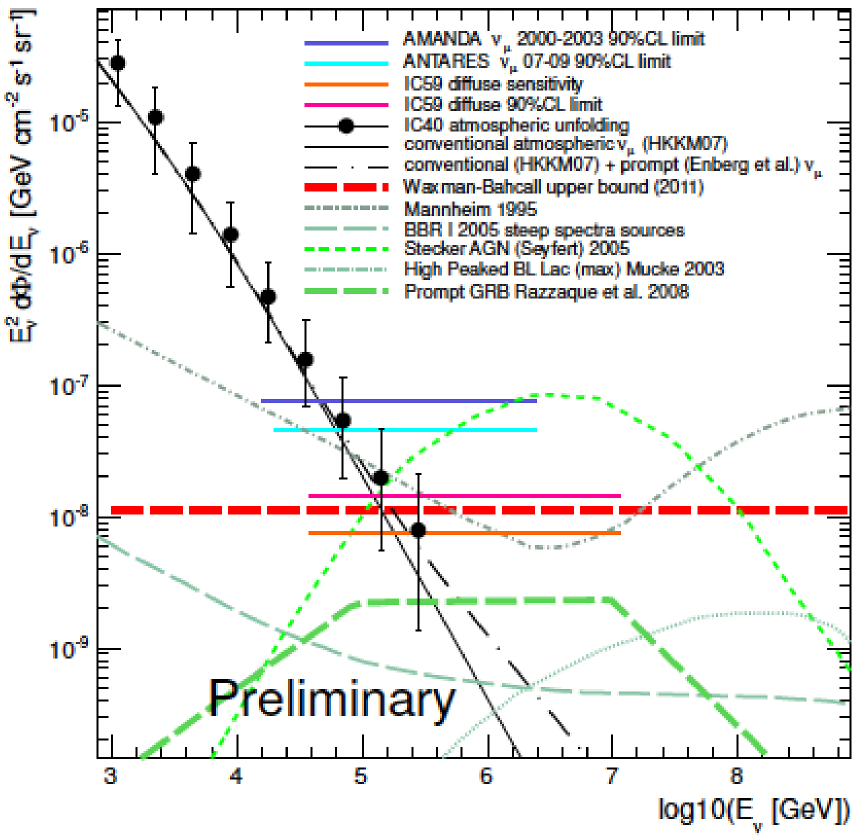
$$E_{\nu}^{2}\Phi_{\nu_{\mu}} = \frac{\varepsilon}{8}\xi_{Z}t_{H}\frac{c}{4\pi}E_{CR}^{2}\frac{d\dot{N}_{CR}}{dE_{CR}}$$

ε: fraction of energy going to neutrinos

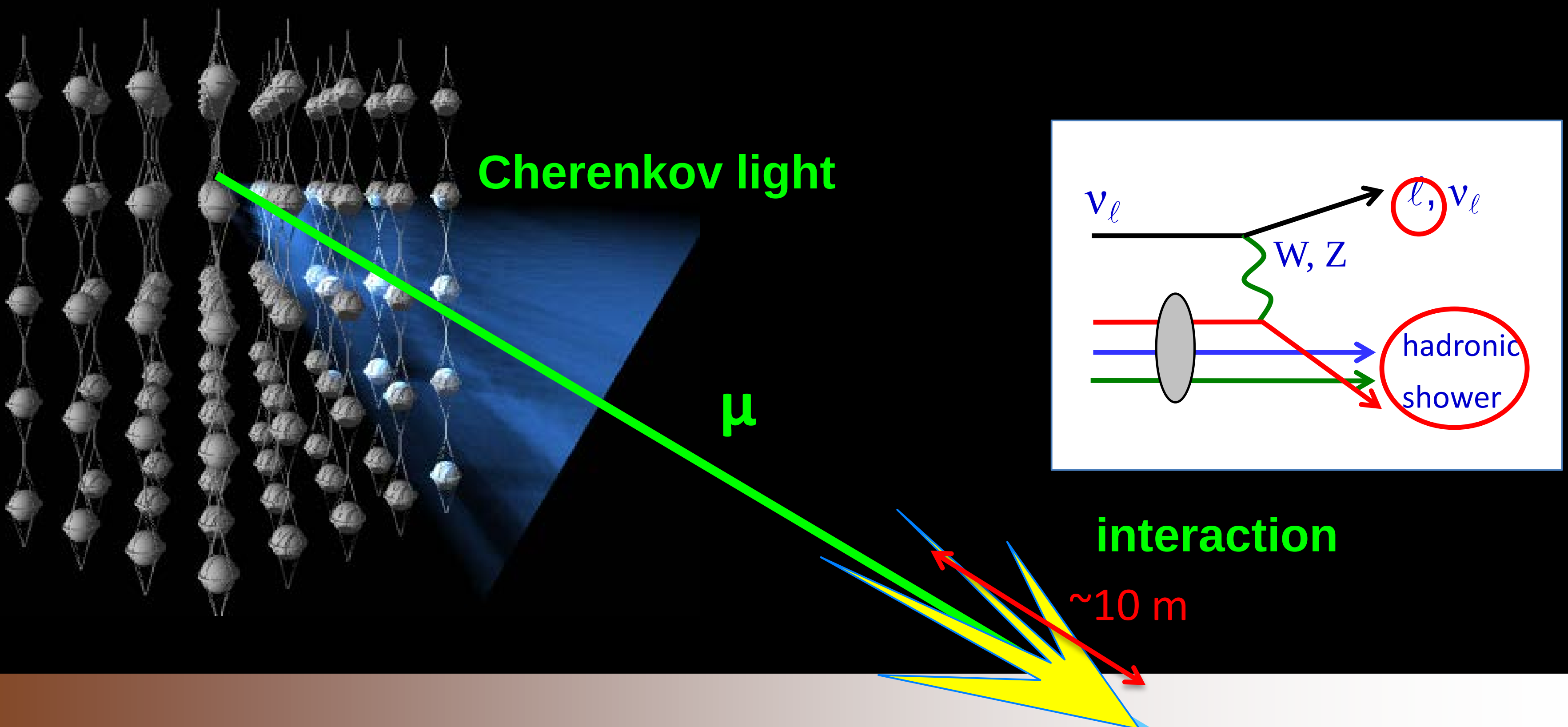
If ε=1, WB limit

$$E^{2}\phi = 10^{-8}\ GeV\ cm^{-2}s^{-1}sr^{-1}$$

The sensitivity of 1 km^3 size detector is lower than WB limit.



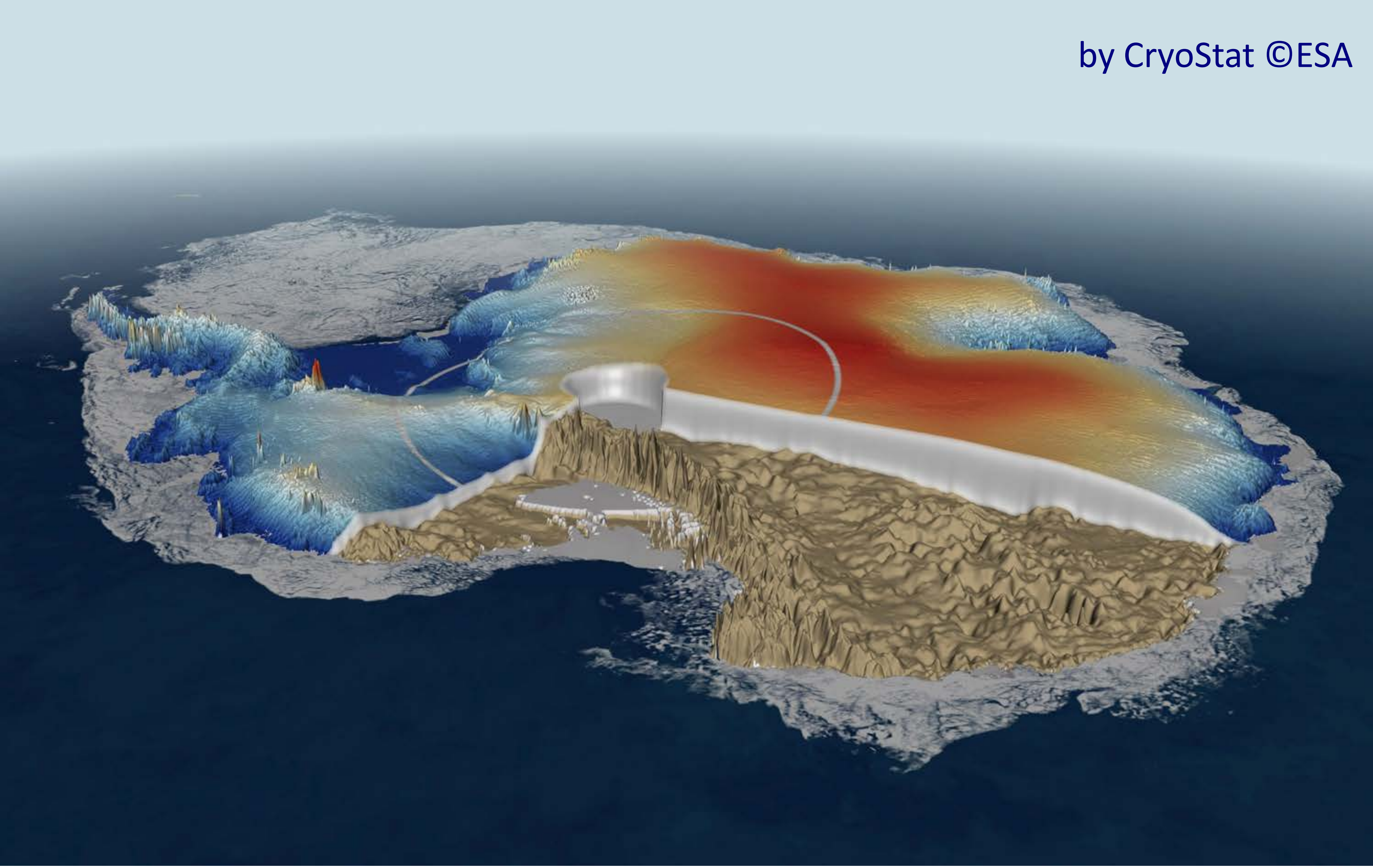
How do we detect neutrinos?



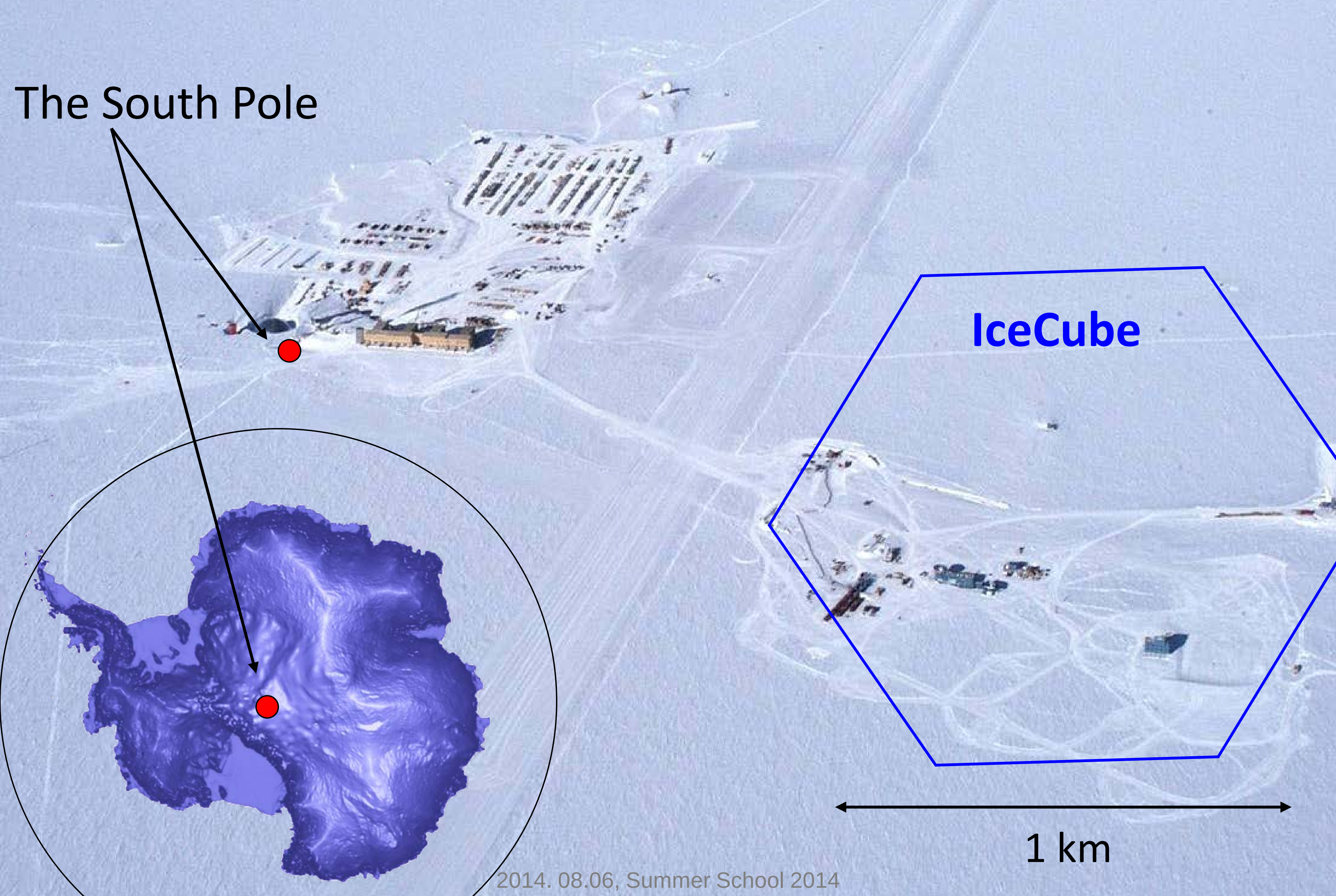
- Large volume for neutrinos to interact
- Transparent medium for light to propagate to photo-sensors

→ **Antarctica ice**

■ Part of our detector: Antarctica ice



■ The IceCube detector at the South Pole

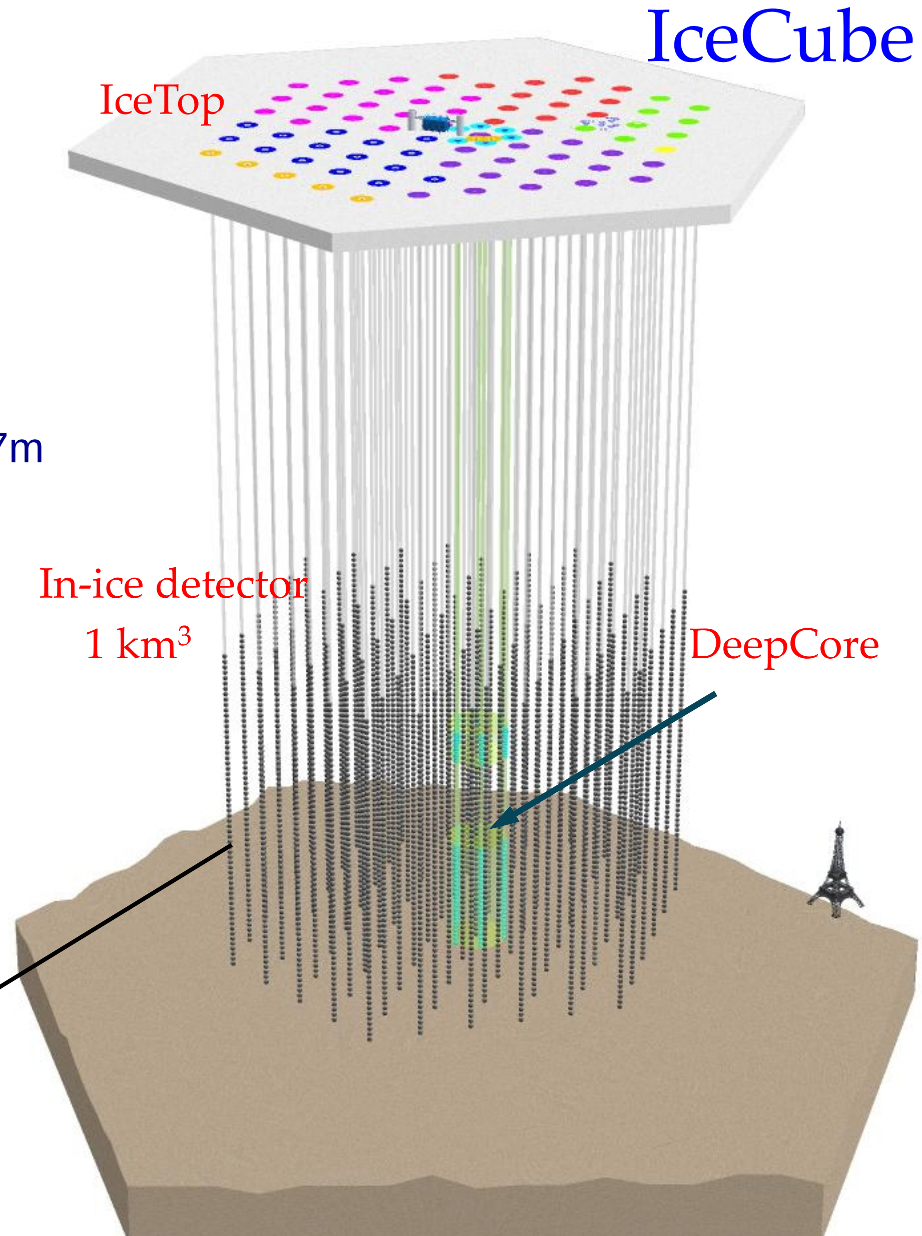


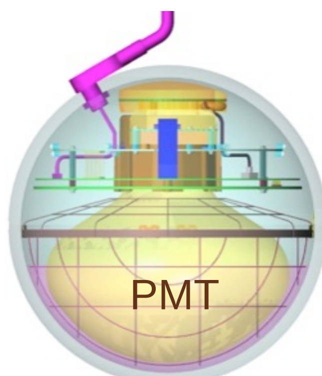
The IceCube detector

- Deployed in the Antarctica glacier
- In-ice + IceTop + DeepCore
- 86 strings (completed in 2010)
- ~ 5,160 photo-multiplier tubes (PMTs)
- Detector volume: ~ 1 km^3
- Detector spacing: horizontal 125m, vertical 17m
- ATWD 300MSPS

  3 different gains (x16, x2, x0.25)
- FADC for long duration pulse (6.4 μs)
- **Targets for cosmic high energy neutrinos**

  (mainly >~ 100 GeV)

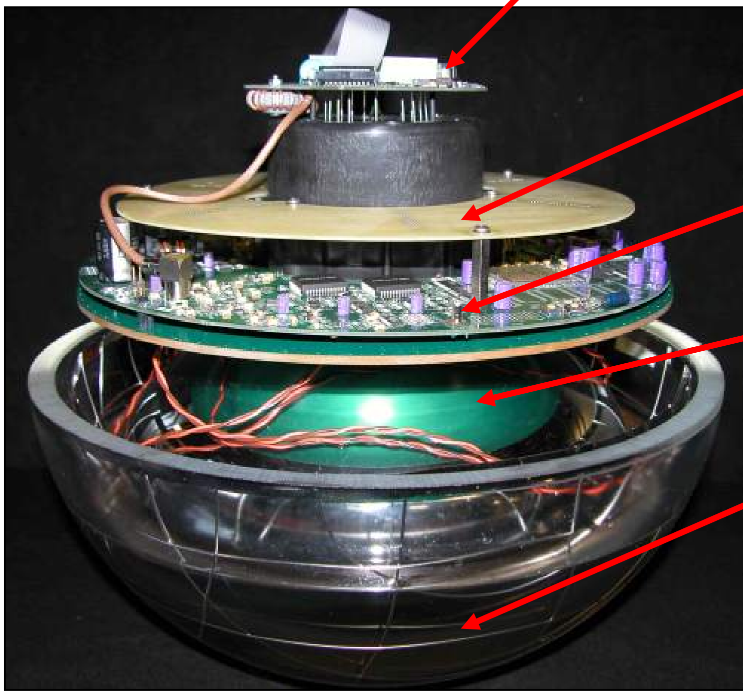




Digital Optical Module (DOM)

The Digital Optical Module (DOM)

HV Base

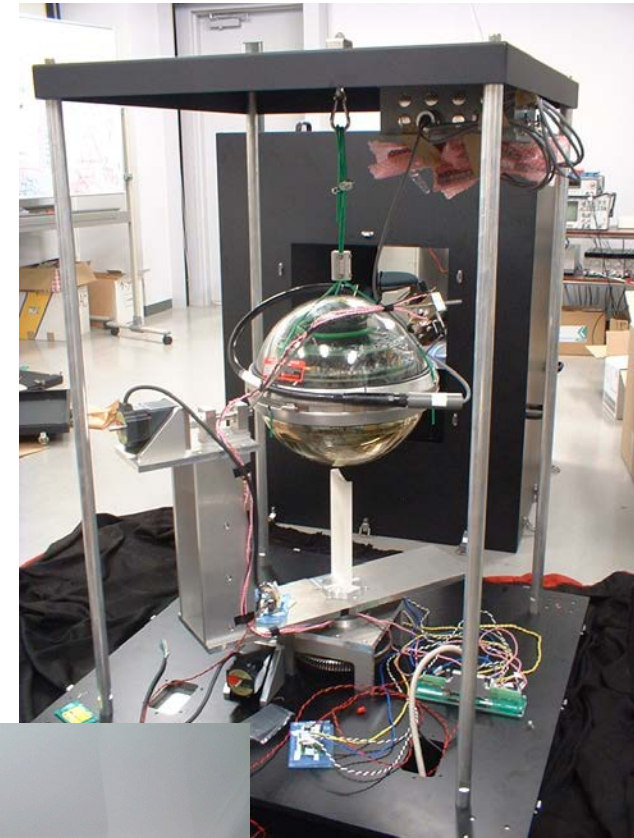


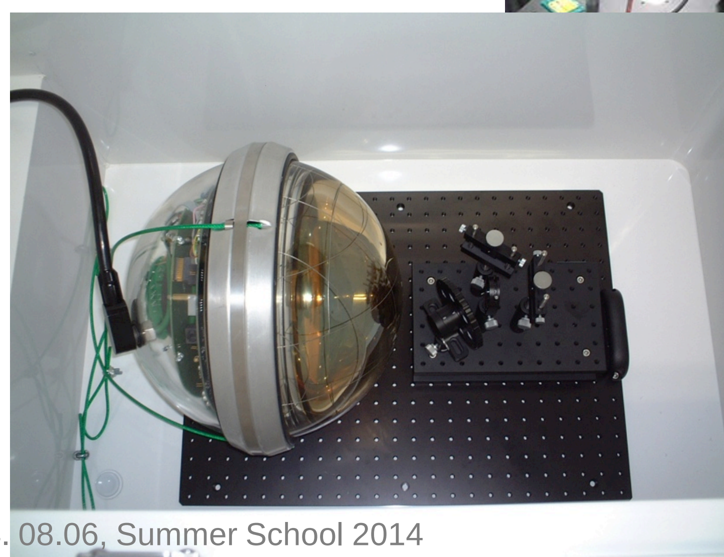
"Flasher Board"

Main Board
(DOM-MB)

10" PMT

13" Glass
(hemi)sphere

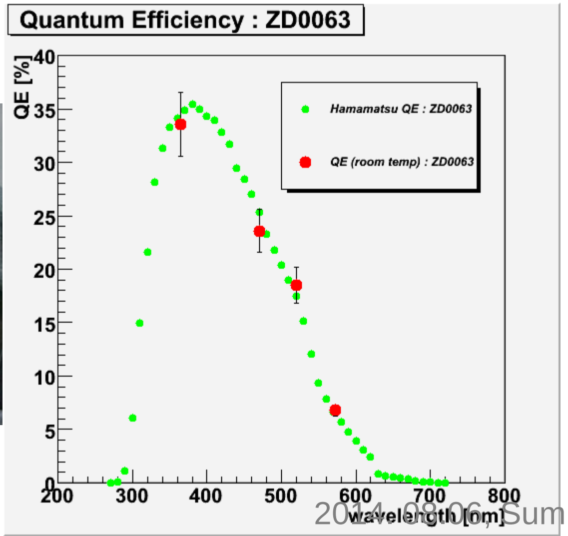


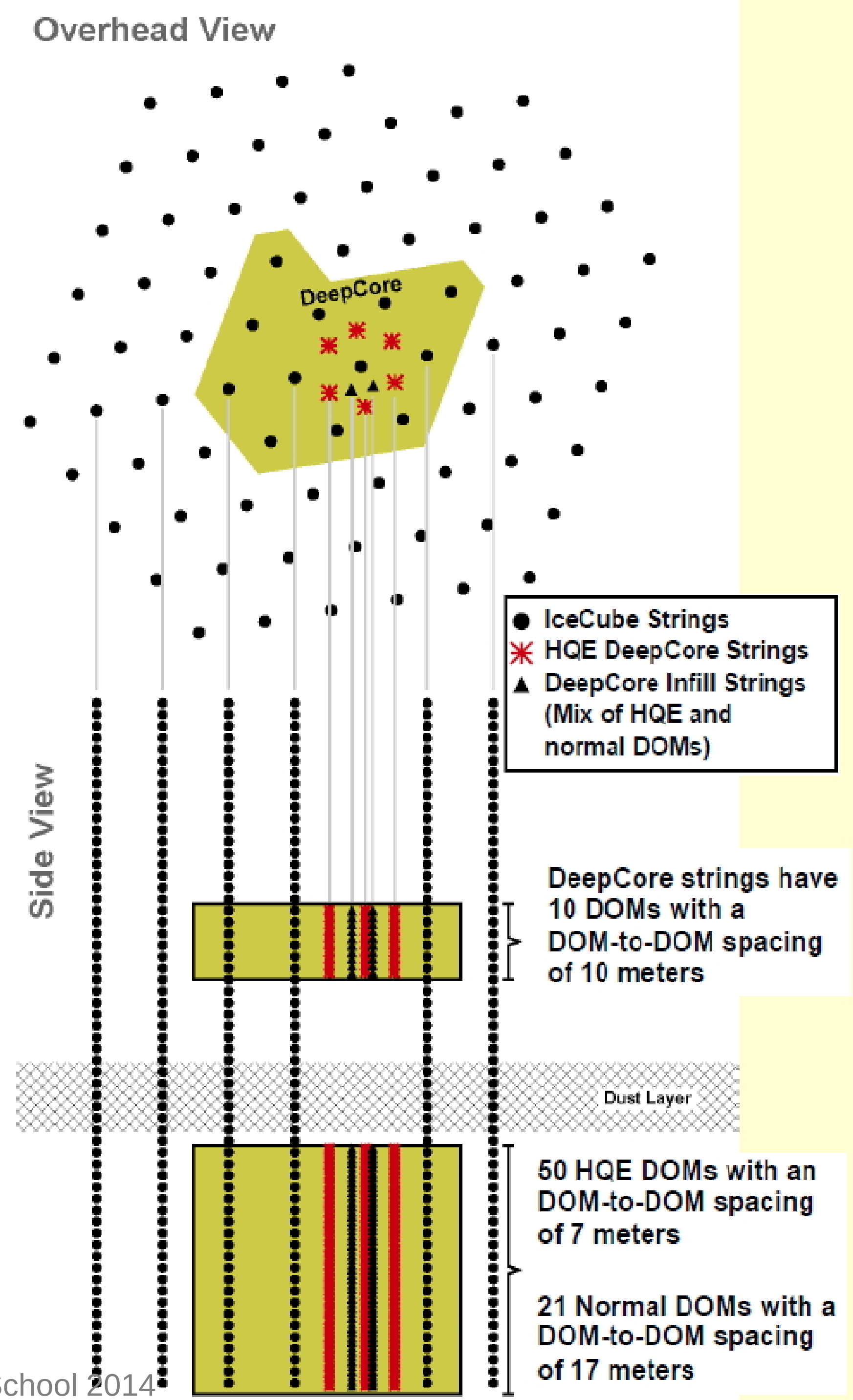


Calibrated at Chiba University

IceCube Deep Core

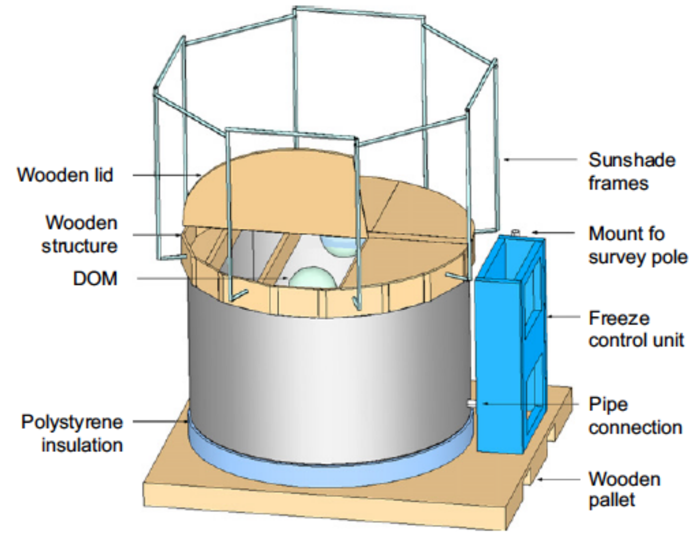
- Extend IceCube sensitivity to neutrinos with energies down to ~10 GeV
  - Six strings with 60 high-QE PMTs each (HAMAMATSU super bialkali)
  - Use very clear ice at bottom of IceCube

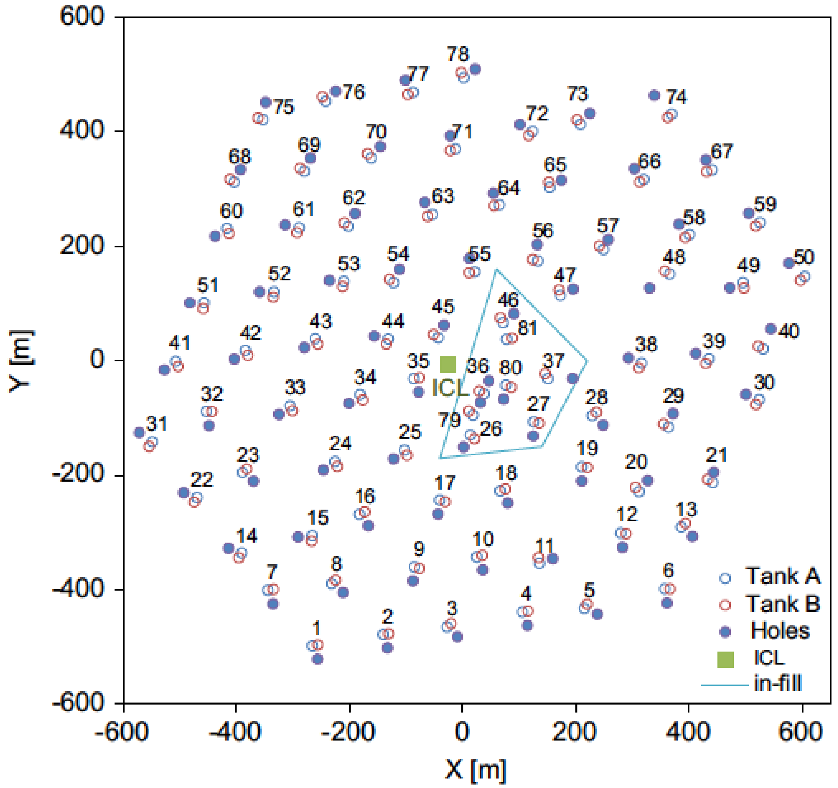




IceTop

- Surface array detector for cosmic-ray physics and veto cosmic-ray events for astrophysical search
- 1 km^2
- E_{CR} ~ $10^{15\text{-}18}$ eV
- Same DOM as IceCube
- Two DOM in a tank
- Two tanks for each string

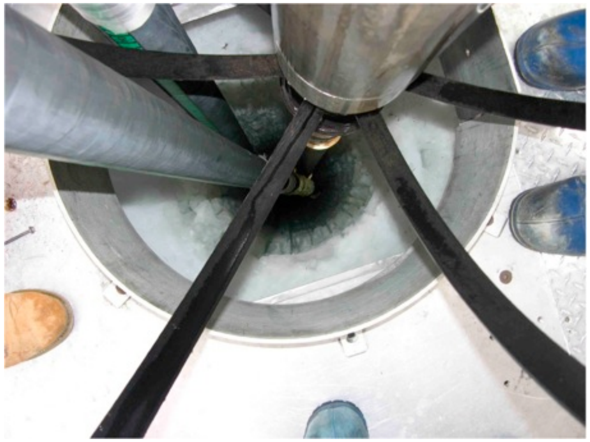


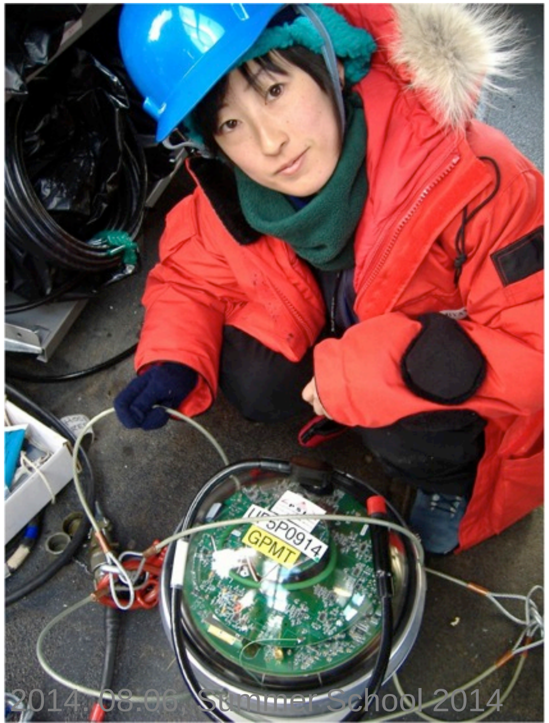


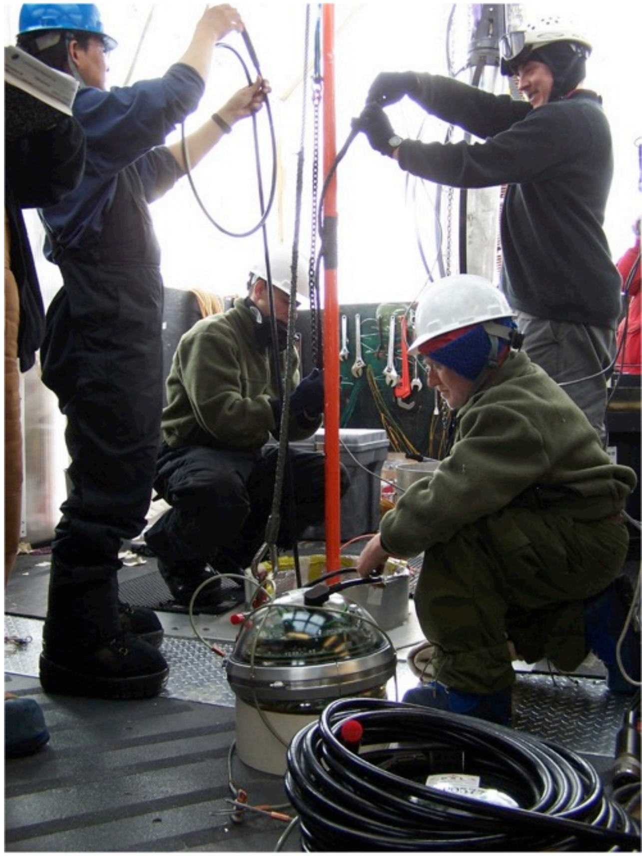
R. Abbasi et al., NIM A 700, 188 (2013)

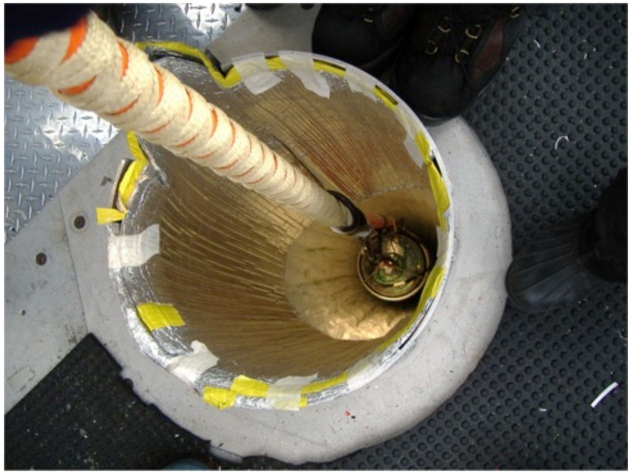
45 institutes and ~300 physicists

The deployment







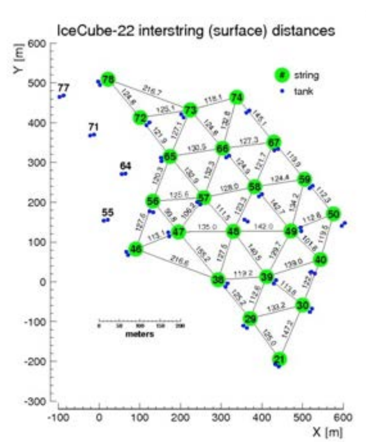


Use hot water to make a hole

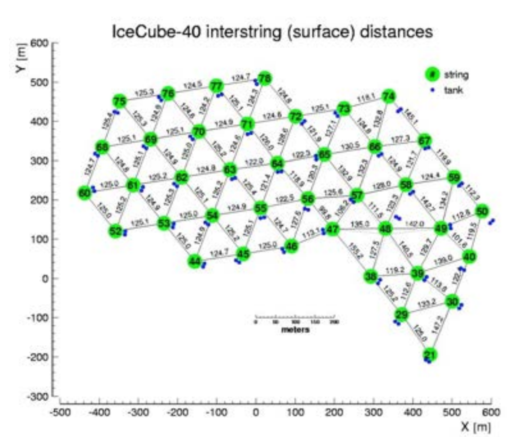
The construction

2004: project started
2006-2007: IC9
2007-2008: IC22
2008-2009: IC40
2009-2010: IC59
2010-2011: IC79
End of 2010: IceCube completed!
2011~: IC86

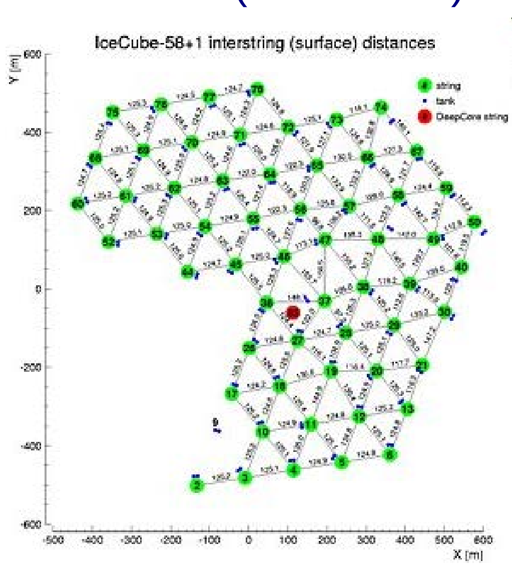
IC22 (2007-2008)



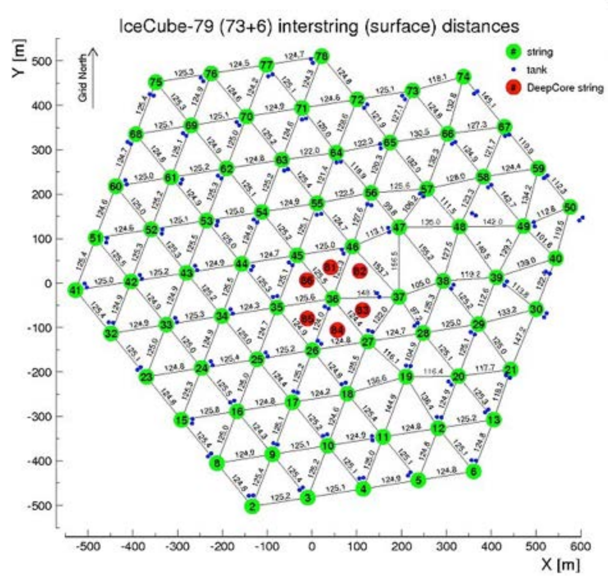
IC40 (2008-2009)



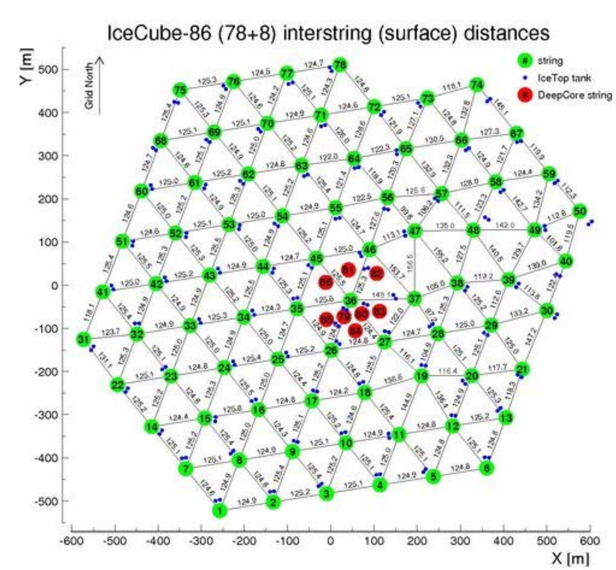
IC59 (2009-2010)



IC79 (2010-2011)

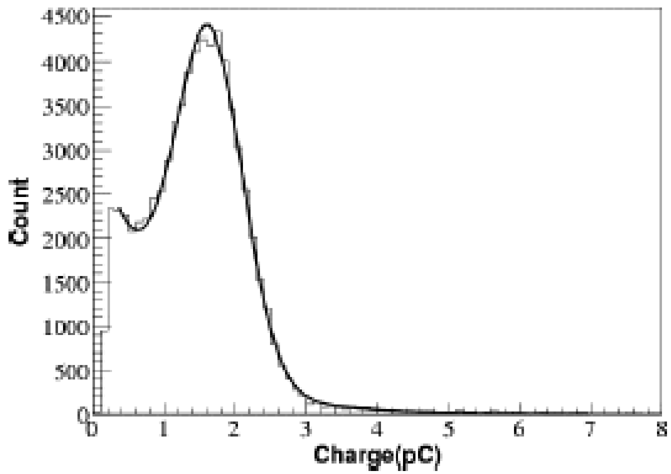


IC86 = complete IceCube (2011~)

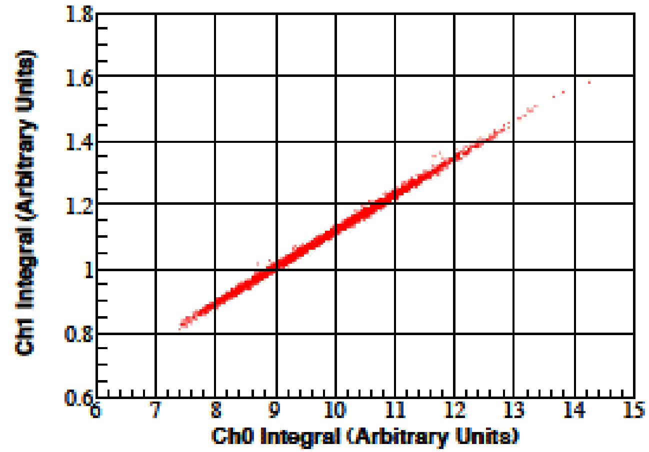


The detector performance check

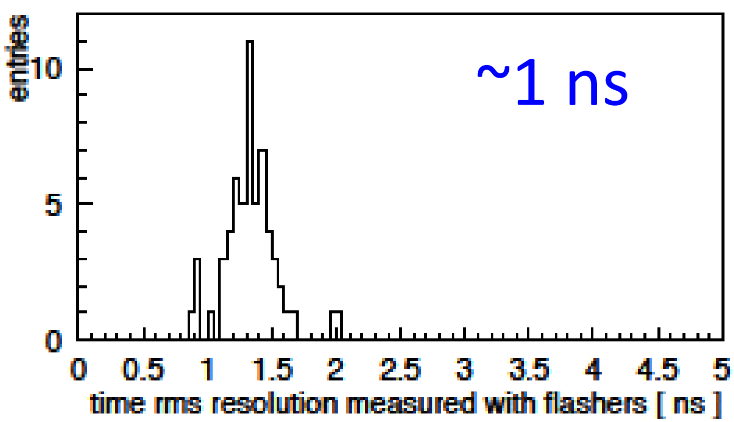
1 p.e. distribution



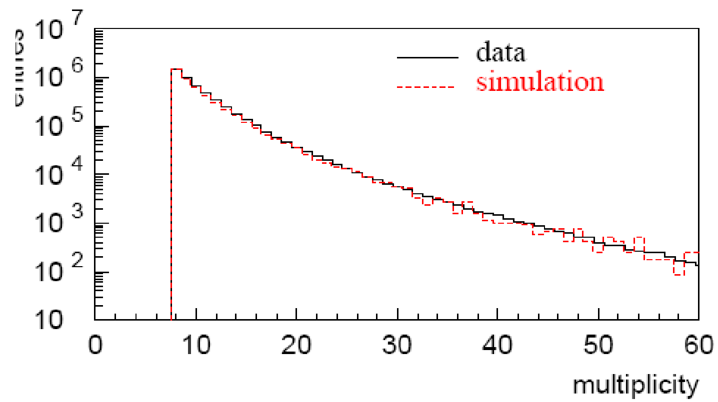
Gain check

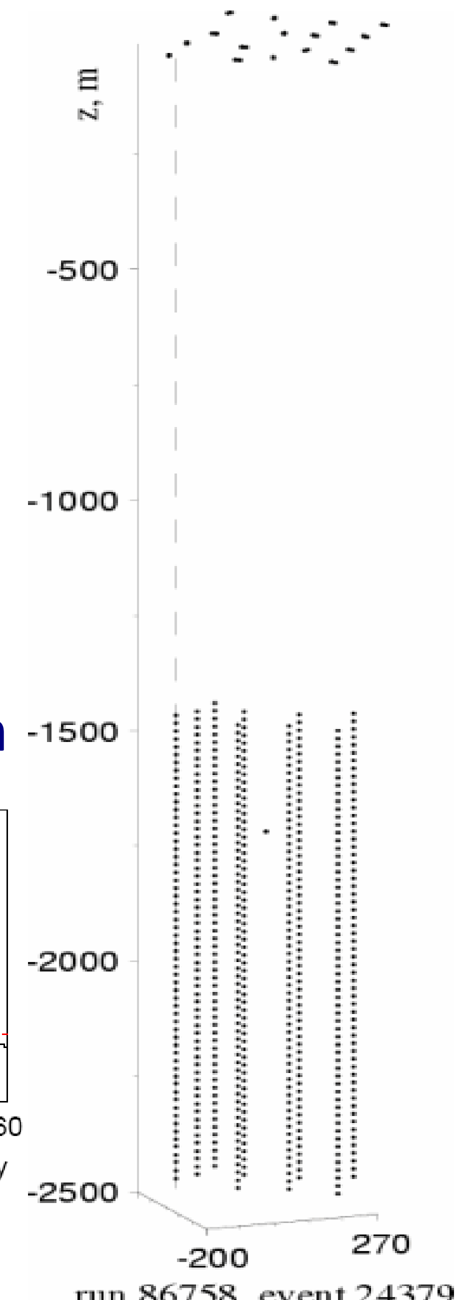


Time resolution



Multiplicity distribution



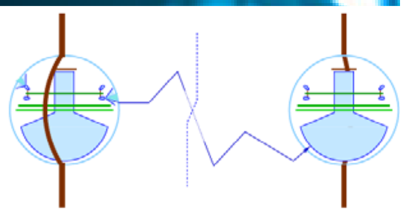


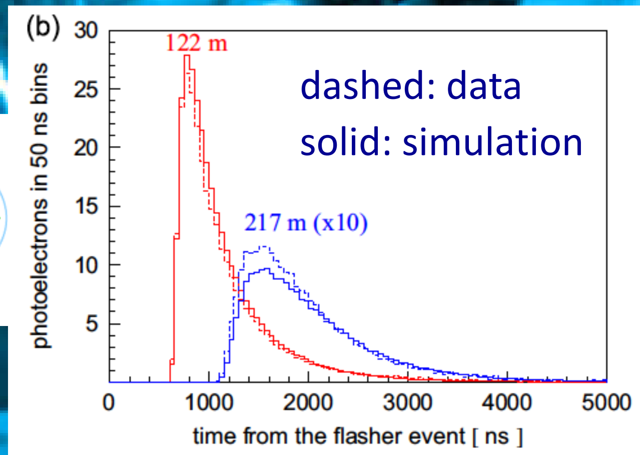
A. Achterberg et al., Astropart. Phys., 26, 3, 155-173 (2006)

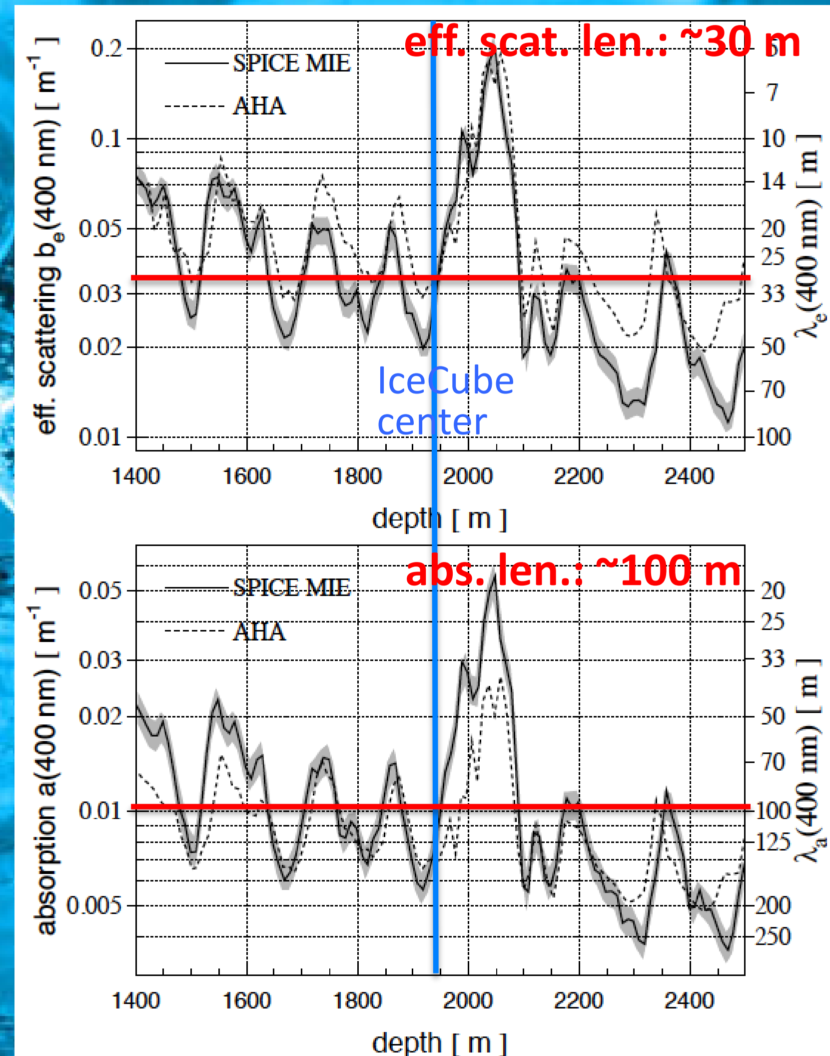
Calibration of our detector: ice

Ice properties calibrated by LEDs installed in DOMs

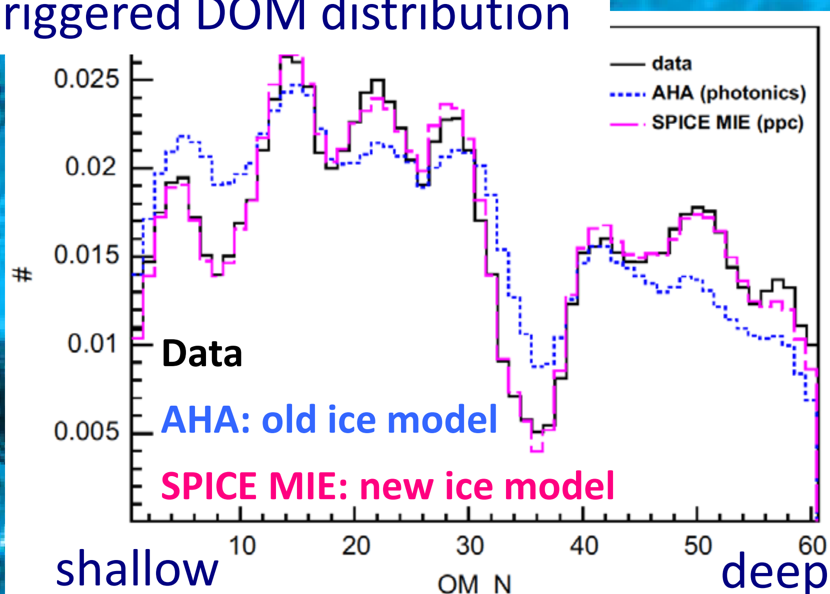
NIM A, 711, 73 (2013)







Triggered DOM distribution



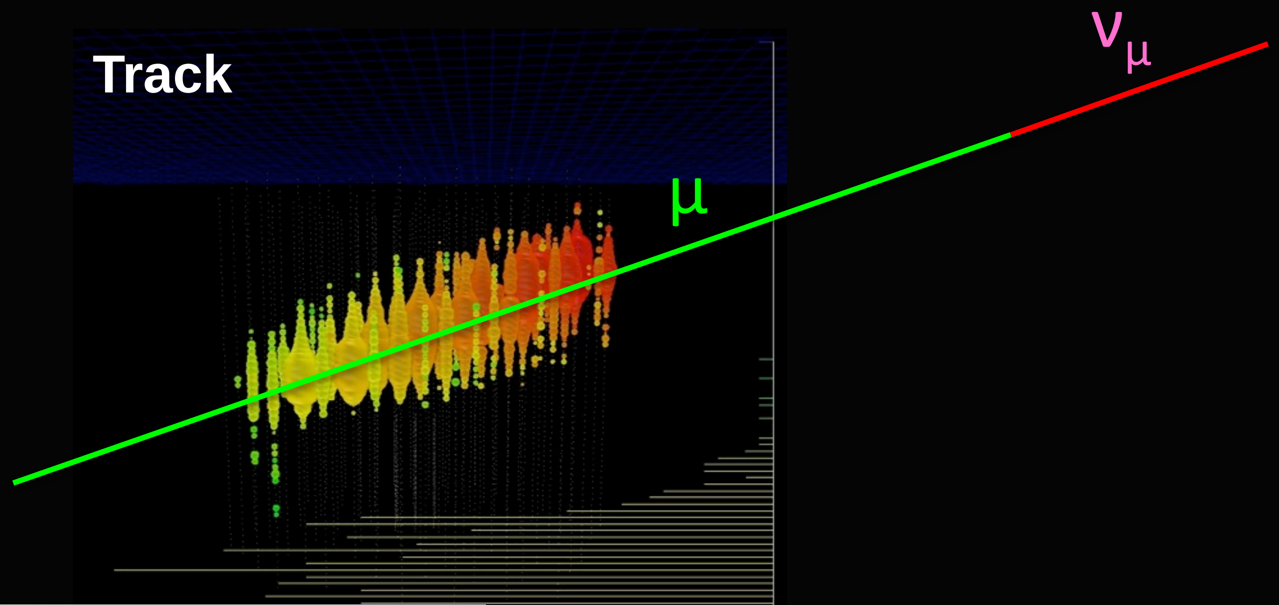
We understand the ice properties better!

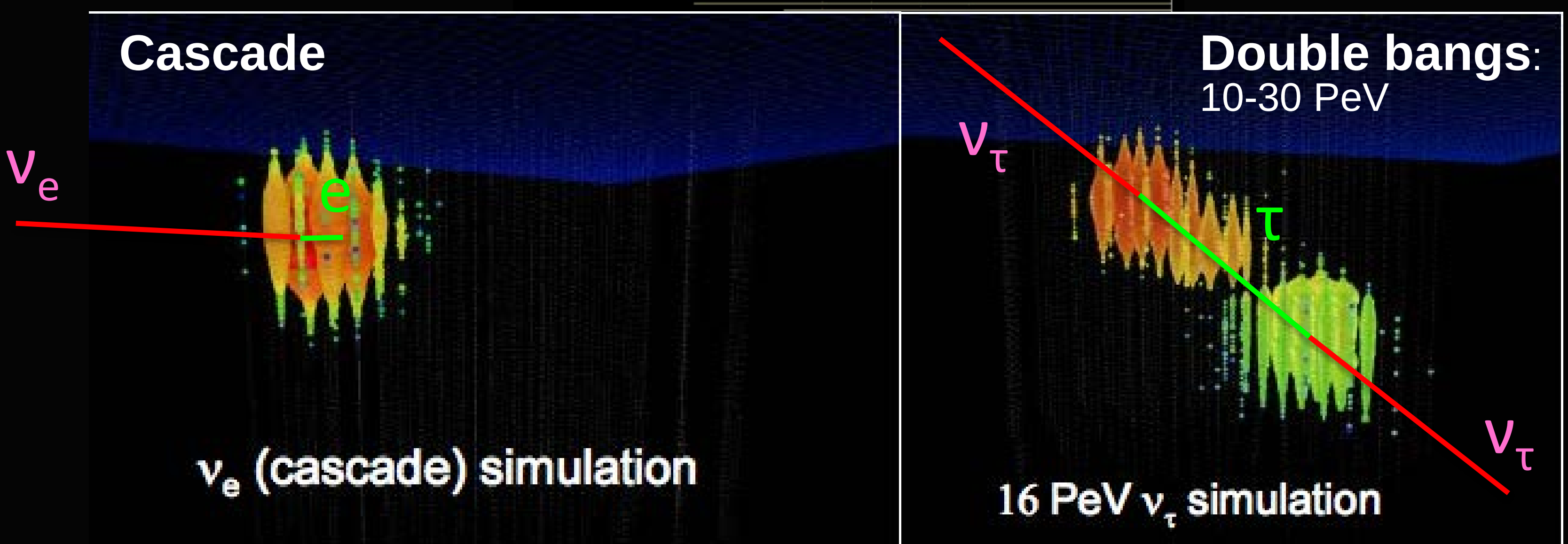
Particle identification

Angular resolution

Tracks: ~1°

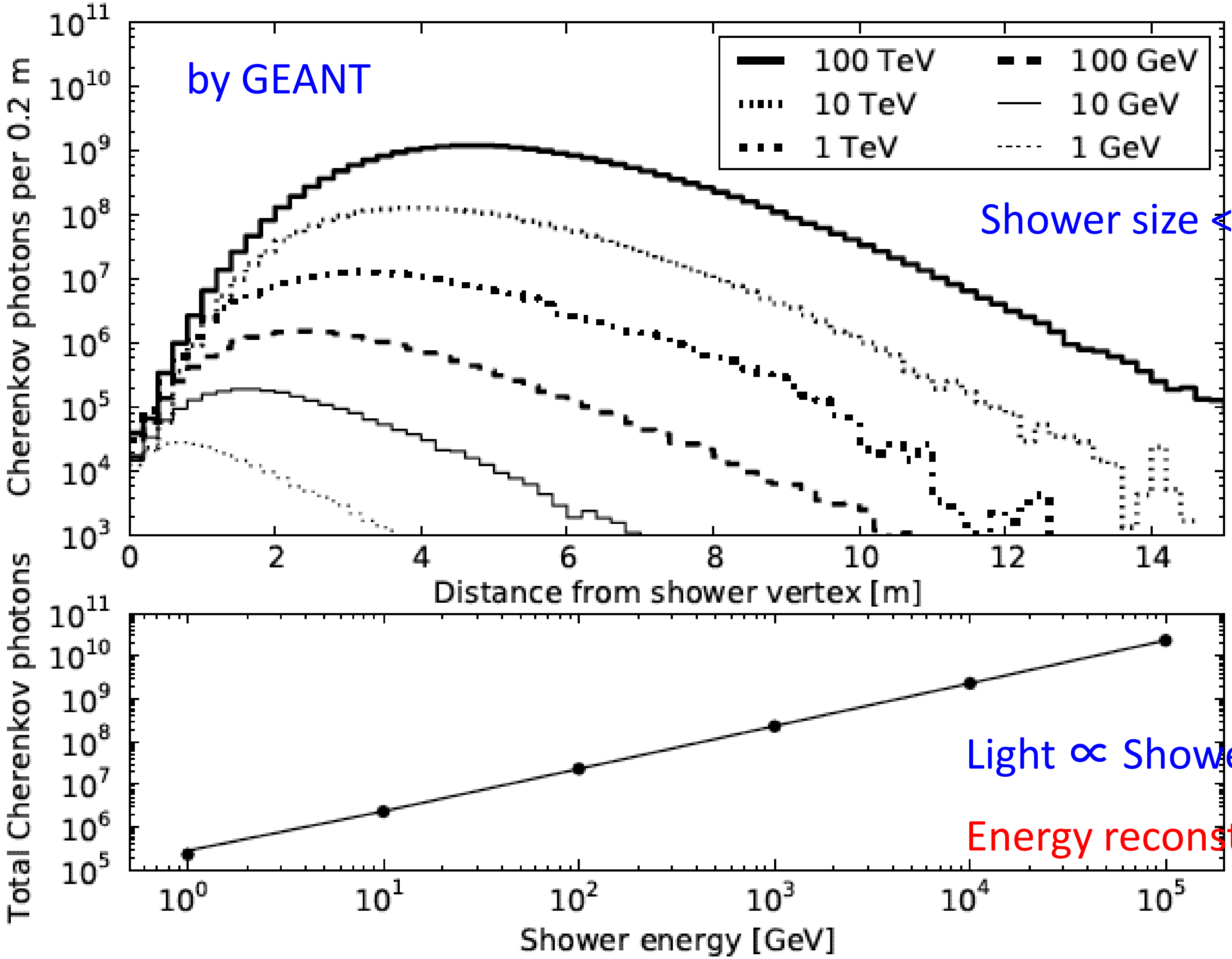
Cascades: ~10°





Note: neutral current events also generate cascades

Shower development in ice



Shower size < detector interval

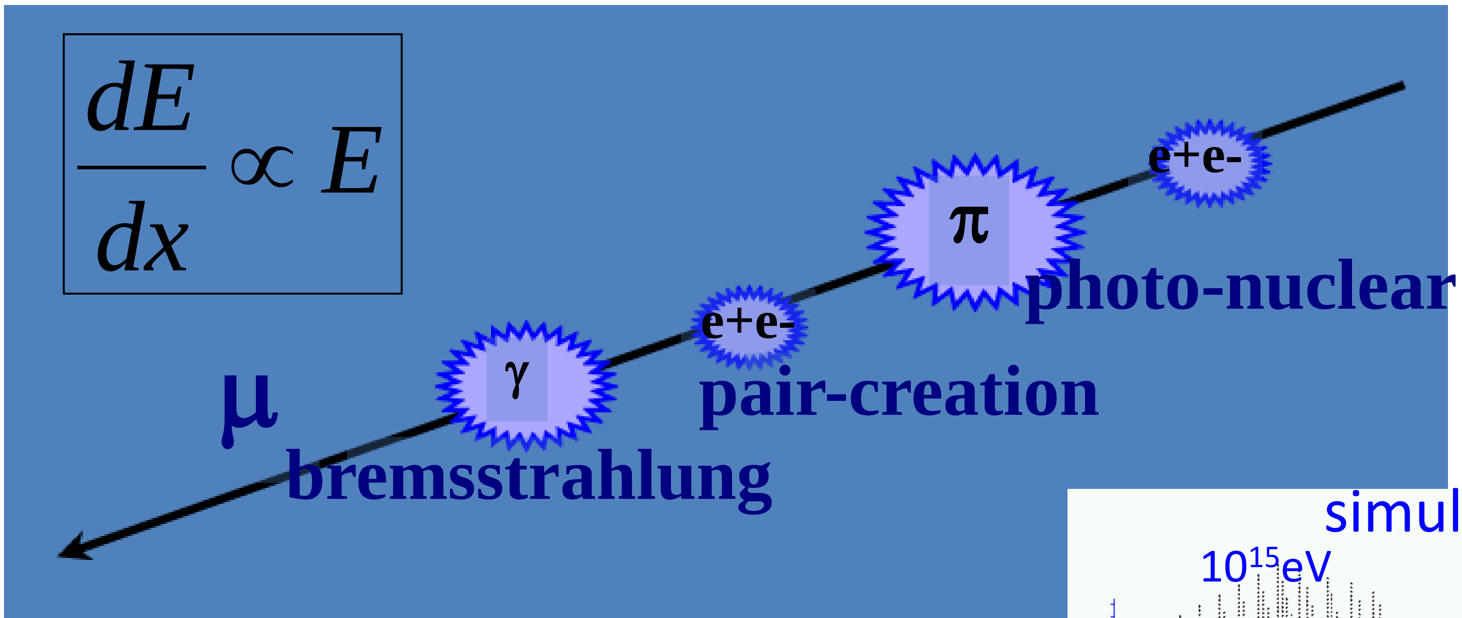
Light ∝ Shower energy

Energy reconstruction possible

❑ High energy muon track

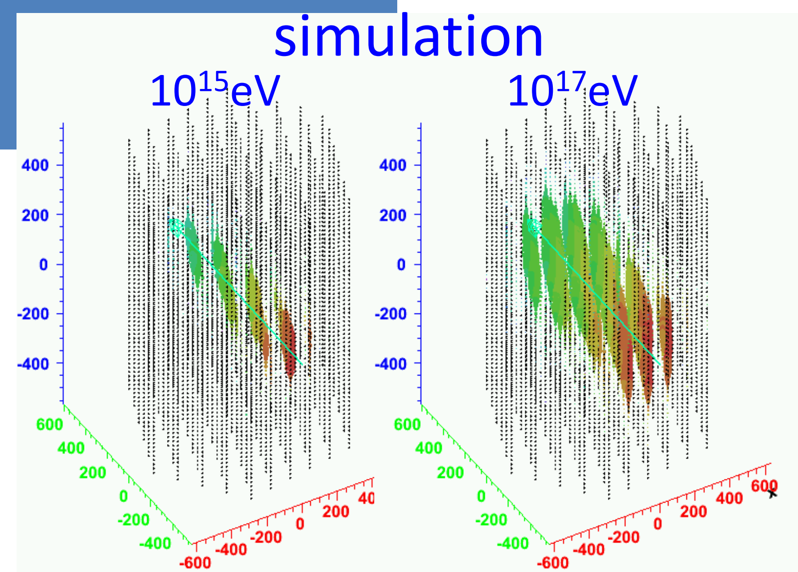
Not a minimum ionizing particle,

But generates cascades continuously!



$$\frac{dE}{dx} = \beta E \; (E > 1TeV) \quad \beta \approx const.$$

→ The energy reconstruction possible

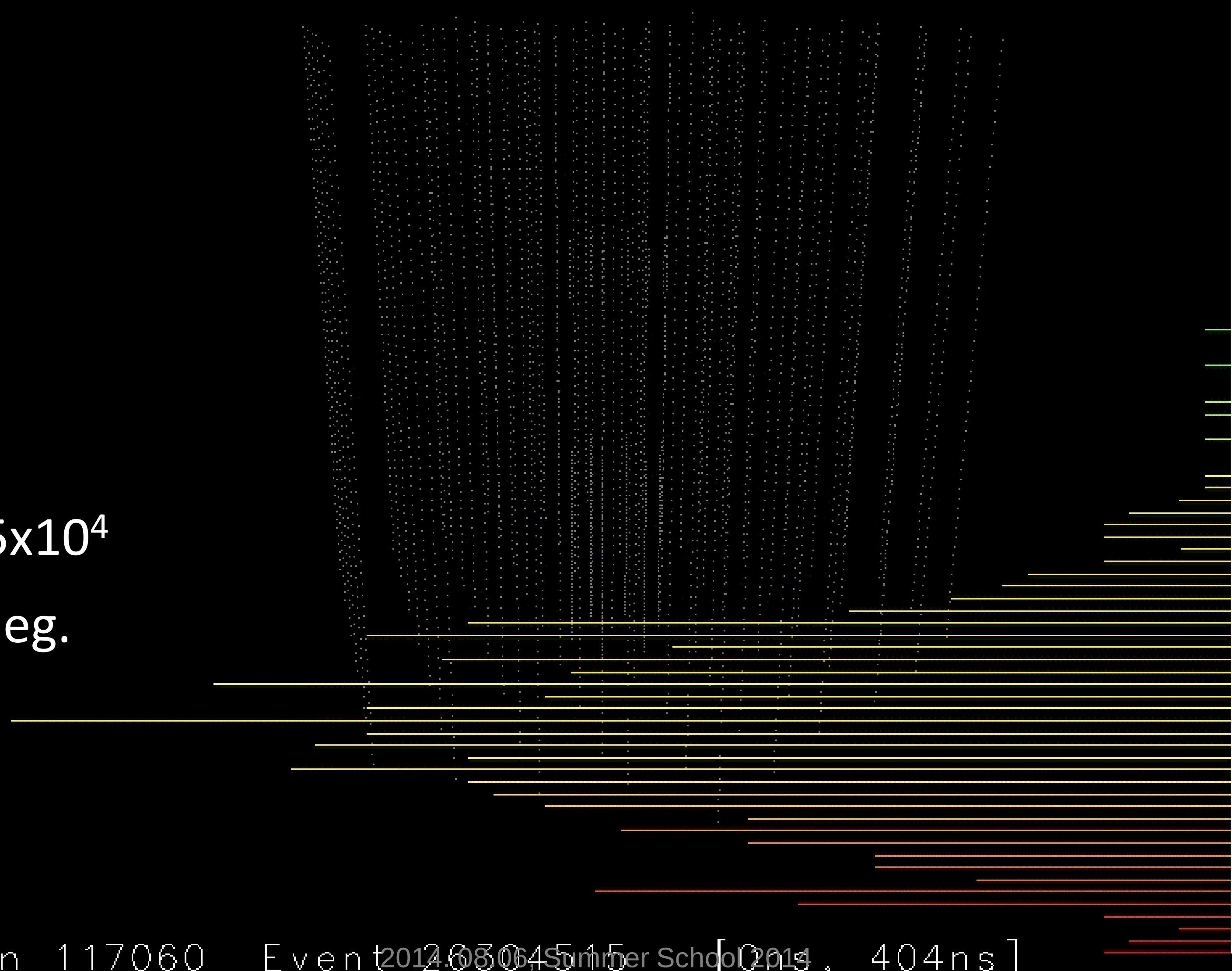


Example of an event

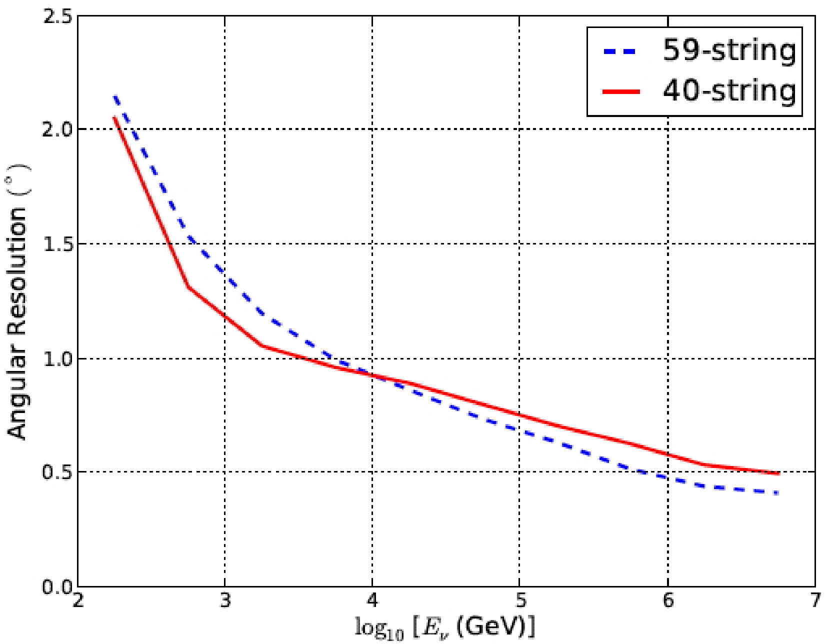
Observation data (IC-79 (IceCube with 79 strings))

NPE: 7.5×10^4

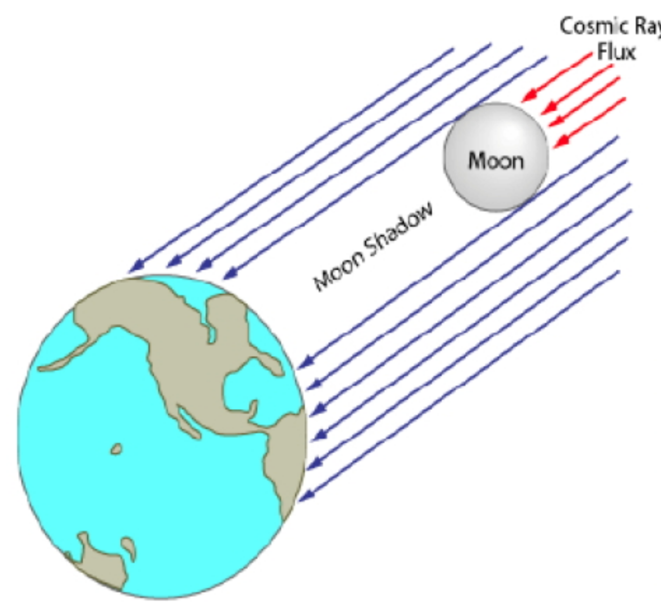
ZA: 70 deg.

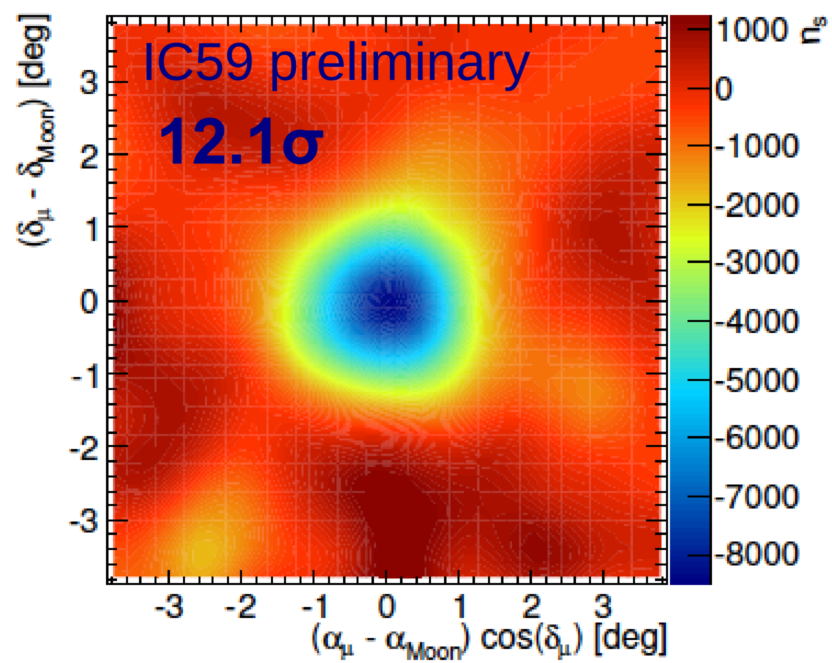


The angular resolution



arXiv:1111.2741

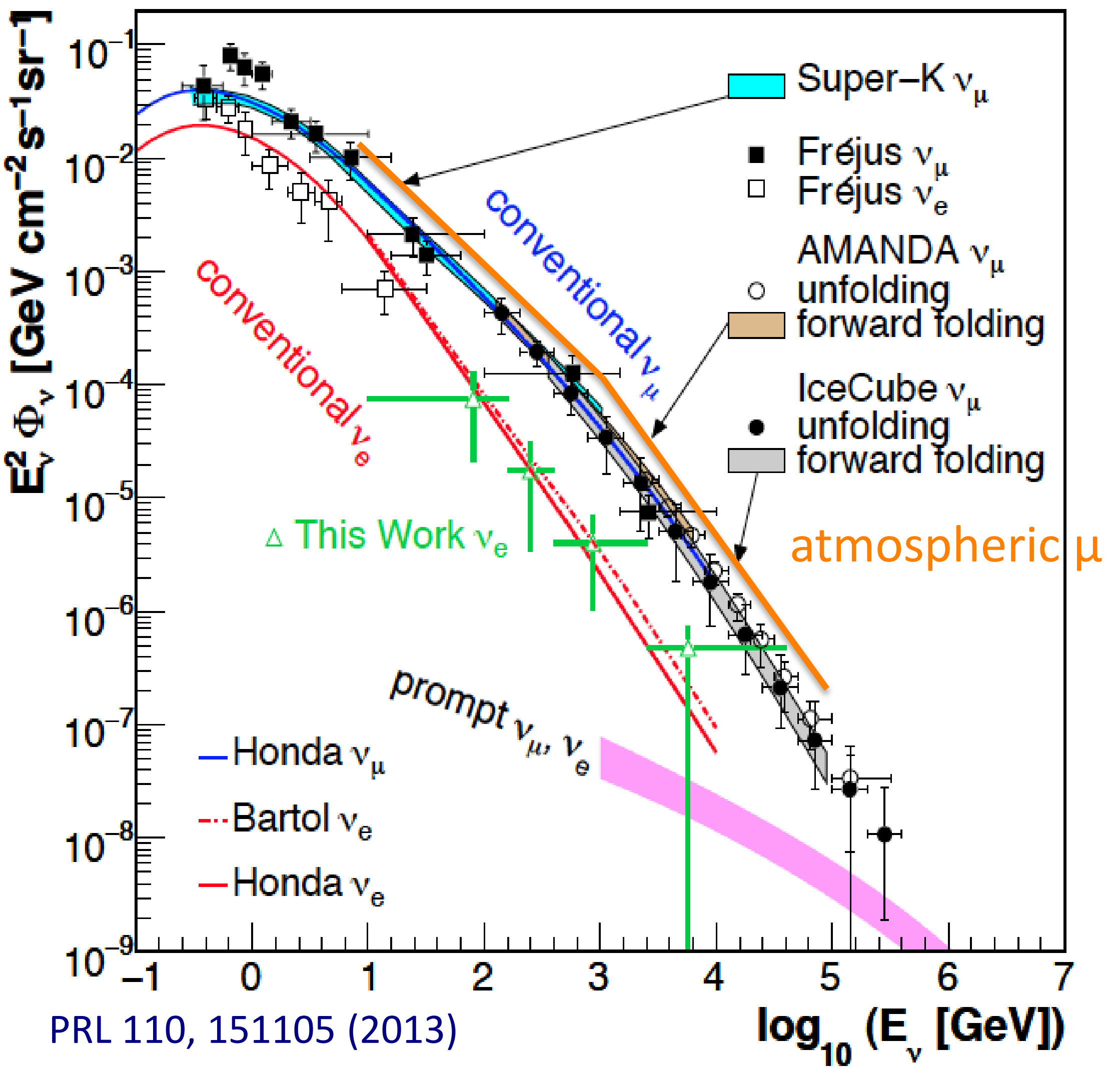




- Angular resolution < 1° (> 10 TeV)
- Systematic angular shift < 0.2°
- Confirmed by moon shadow

Backgrounds

Energy spectra @ surface



PRL 110, 151105 (2013)

$$\frac{dN}{dE} \propto \frac{dN_{CR}}{dE} \frac{A}{1 + B\cos\theta \frac{E}{\varepsilon}}$$

θ: zenith angle, ε: critical energy

- atmospheric μ

$$\frac{dN_\mu}{dE} \propto E^{-3.7} \; (> \varepsilon_\pi = 115\, GeV)$$

- atmospheric ν

$$\frac{dN_\nu}{dE} \propto E^{-3.7} \; (> \varepsilon_\pi = 115\, GeV)$$

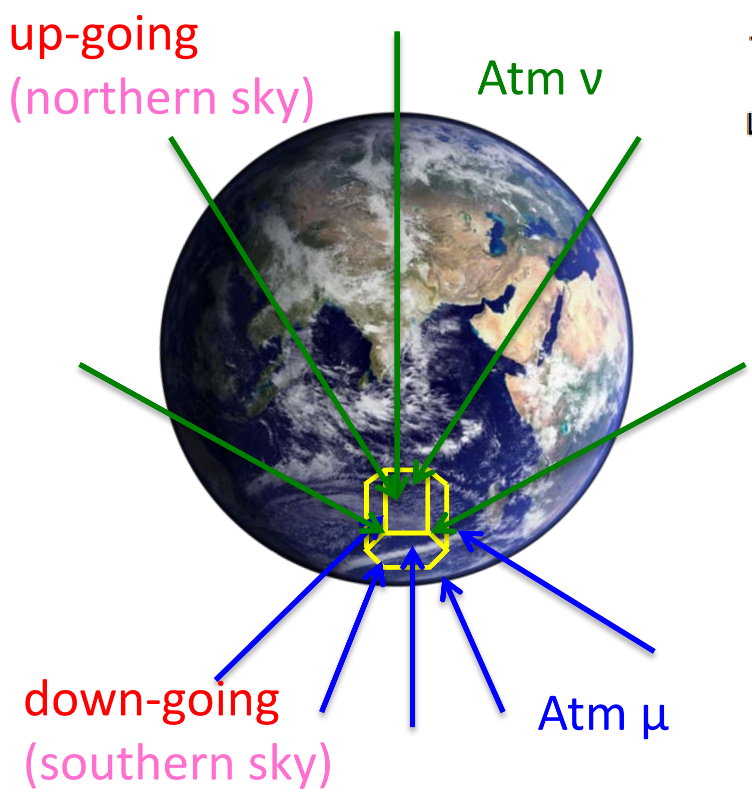
- prompt ν
  - decay from charmed particles

$$\frac{dN}{dE} \propto E^{-2.7} \; (< \varepsilon_{charm} = 10\, PeV)$$

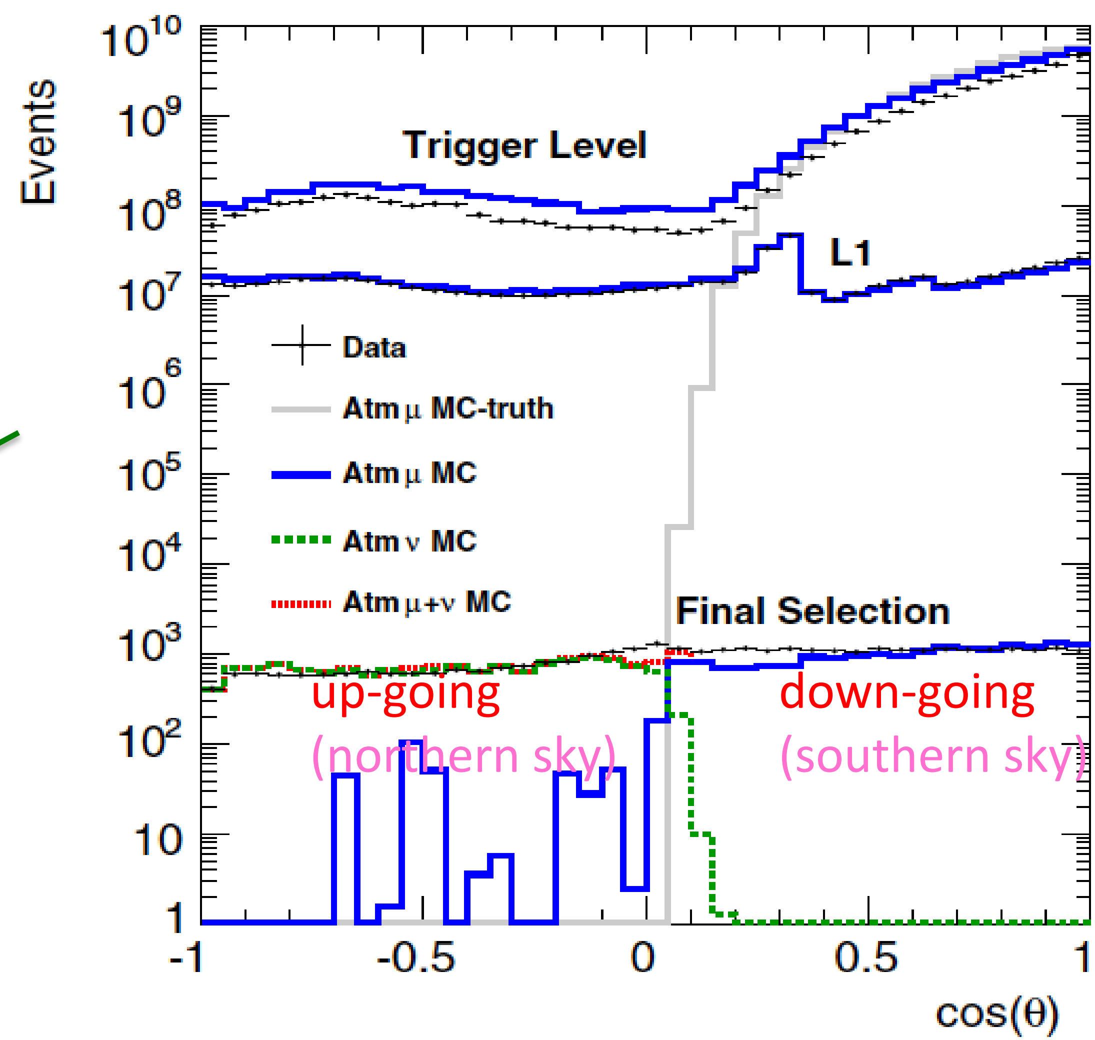
- Three main backgrounds: Atm μ, Atm ν, prompt ν (all CR originated)

Backgrounds (cont'd)

IC40 Point source analysis
ApJ, 732, 18 (2011)



Zenith angle distribution @ detector



➢ Essentially energy and zenith angle information used for signal searches

Point source search

Sensitive: > ~1 TeV

Search for muon neutrinos by using mainly the directions (energy info also used)

4-year data (IC40+IC59+IC79+IC86-I): 1371.7 days

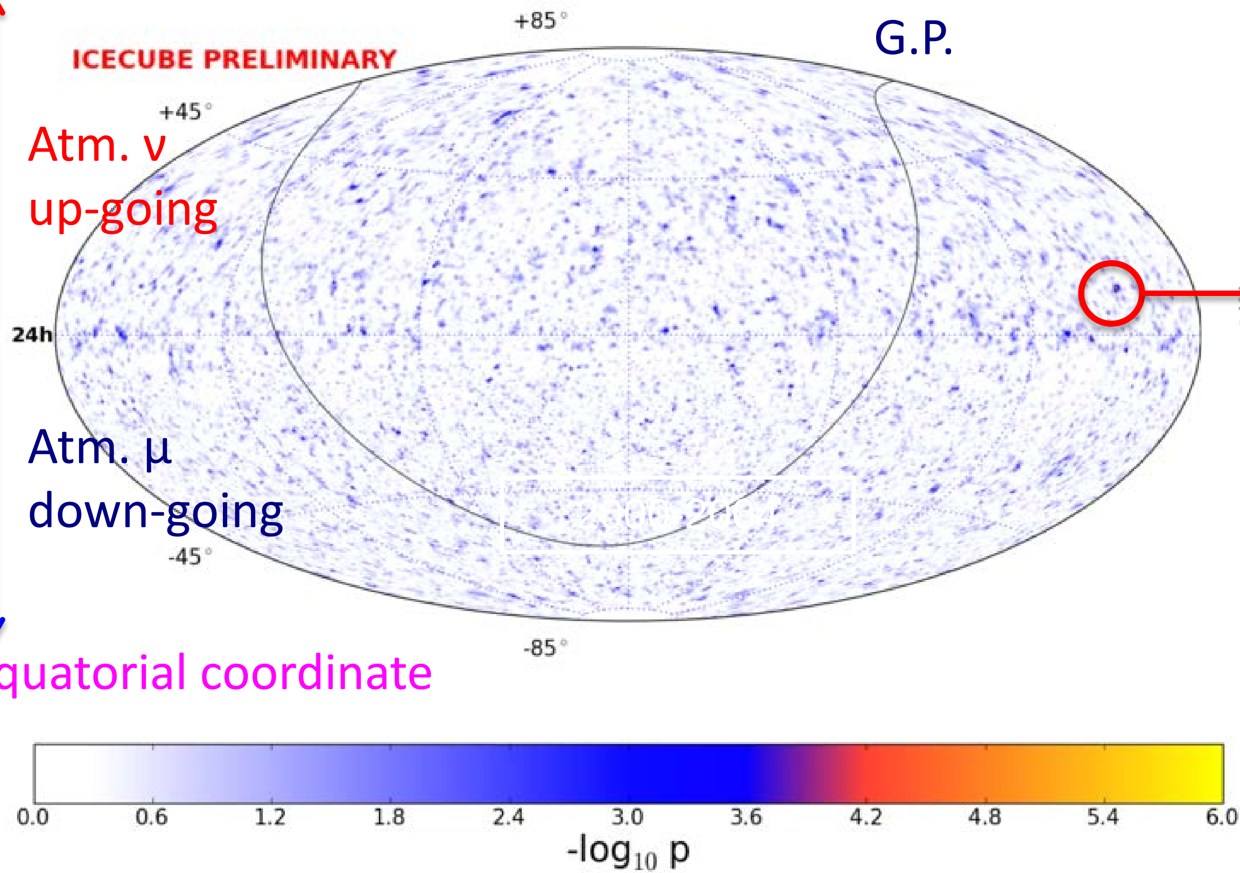
Test null hypothesis of no signal against one with signals

178000 ν + 216000 μ

G.P.

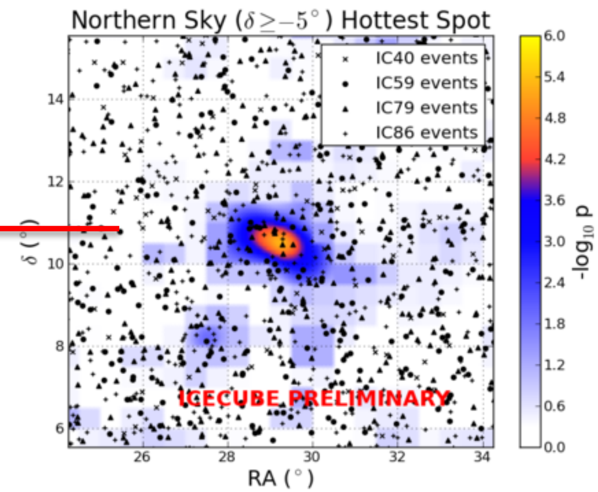
Atm. ν up-going

Atm. μ down-going



Equatorial coordinate

Hottest spot



post-trial after scrambling data

→ P-value: 22.6%

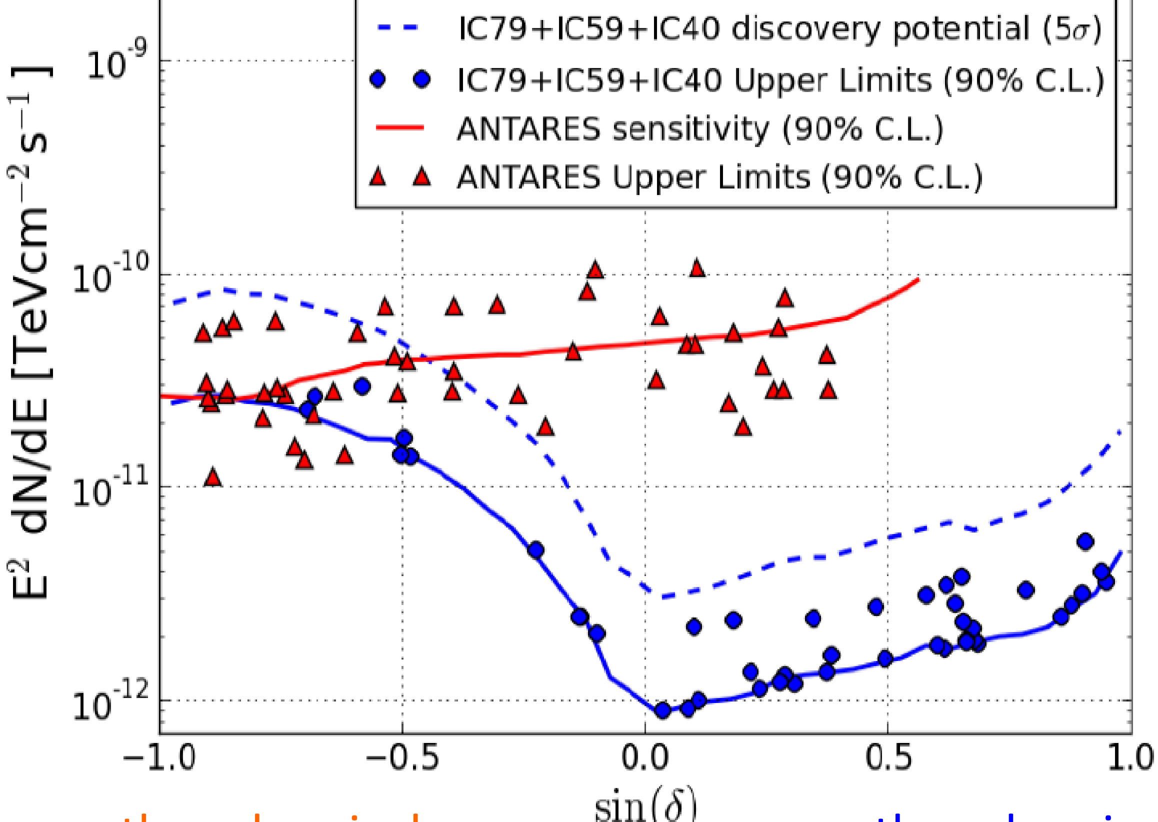
Not significant

Upper limit for selected sources

Most significant 44 sources are selected a priori to reduce the number of trials

The list was determined by a modeling producing neutrinos

arXiv:1307.6669



southern hemisphere

northern hemisphere

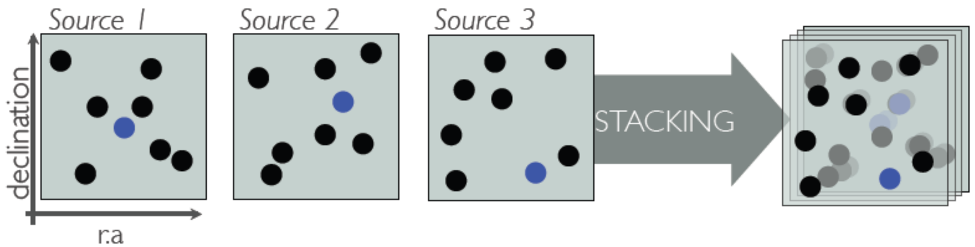
S5 0716+71
M82
1ES 1959+650
TYCHO
LSI 303
Cas A
1ES 2344+514
3C66A
H 1426+428
BL Lac
NGC 1275
Cyg OB2
Cyg X-3
Cyg A
Mrk 501
Mrk 421
4C 38.41
MGRO J2019+37
Cyg X-1
3C 123.0
W Comae
IC443
Crab Nebula
1ES 0229+200
Geminga
PKS 0235+164
3C 454.3
PKS 0528+134
M87
PKS 1502+106
MGRO J1908+06
HESS J0632+057
SS433
3C 273

3C279
QSO 2022-077
PKS 1406-076
QSO 1730-130
Sgr A*
PKS 1622-297
PKS 2155-304
PKS 1454-354
Cen A
PKS 0537-441

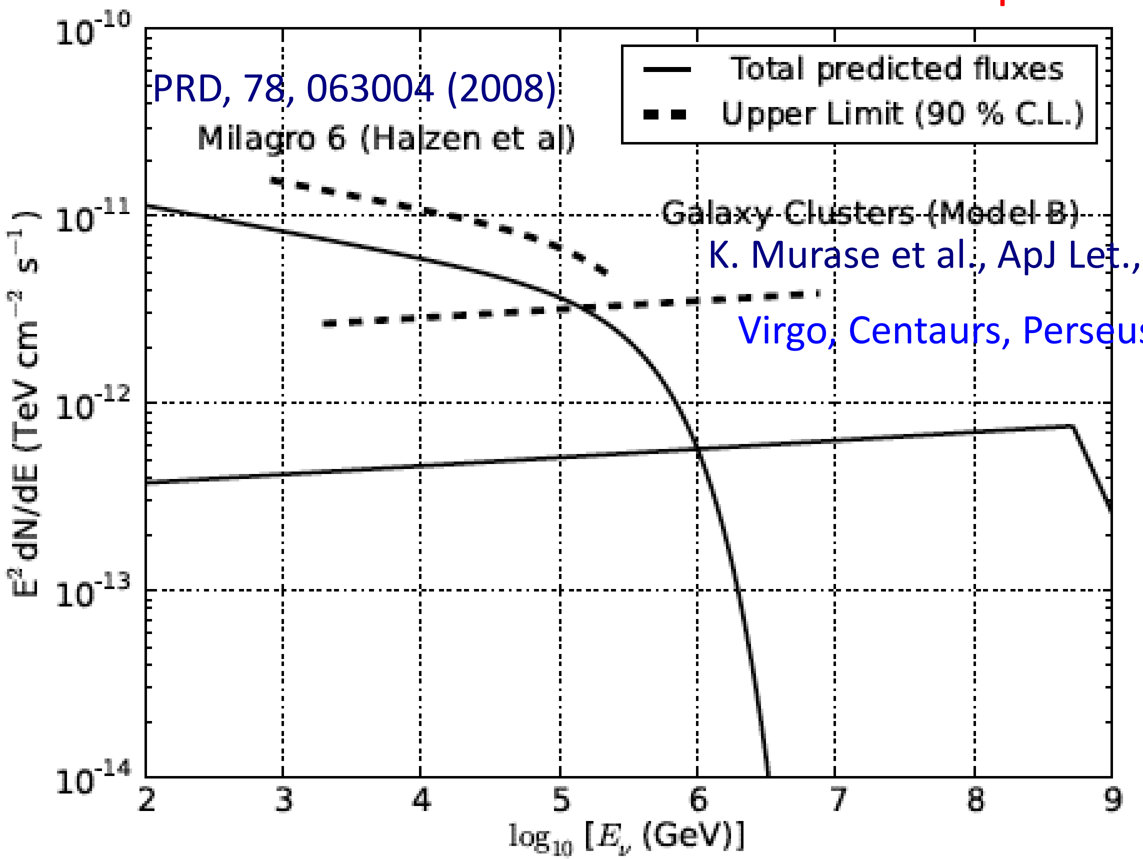
Stacking analysis

arXiv:1307.6669

Increase the ability by stacking a specific source class



Pp interactions

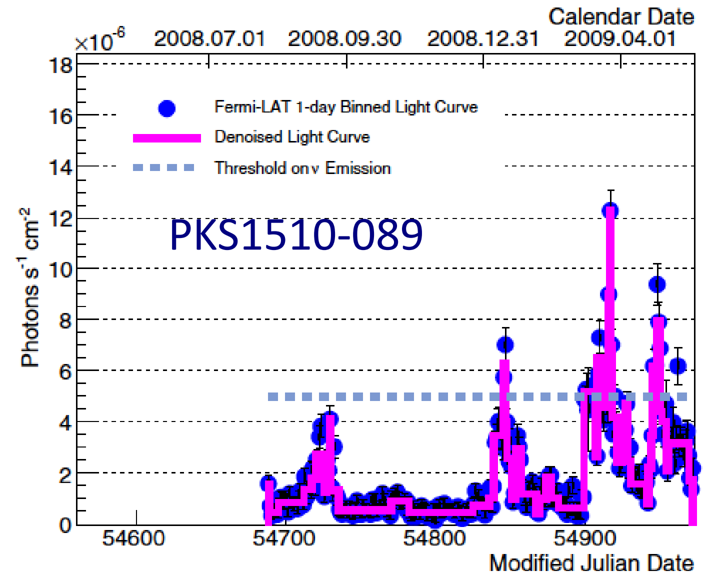


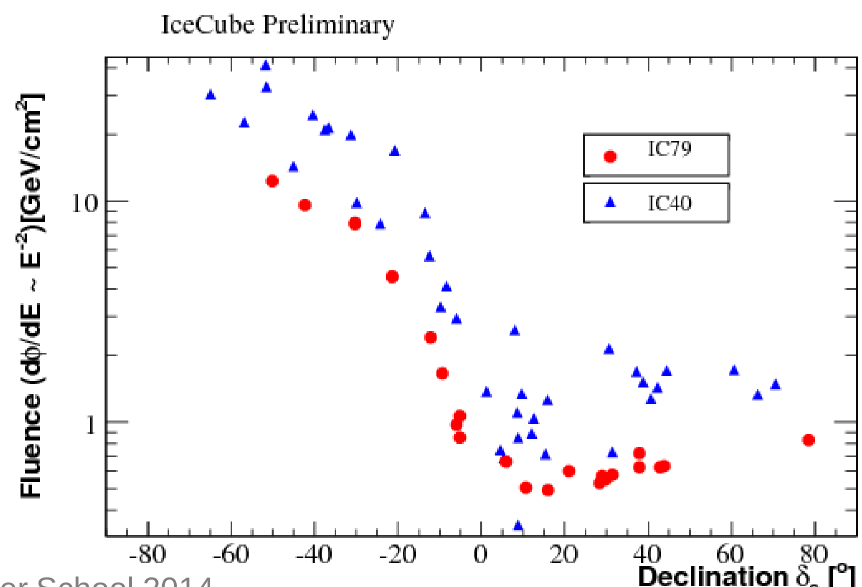
CRs generated inside virial radius of clusters

Close to model prediction

Search for neutrinos from AGN flares

- ✓ Use timing information of AGN flares to reduce background
- ✓ Fermi data used for selecting sources and the light curve
- ✓ Selected hard spectrum BL-Lacs, and FSRQs
- ✓ No significant signal was found

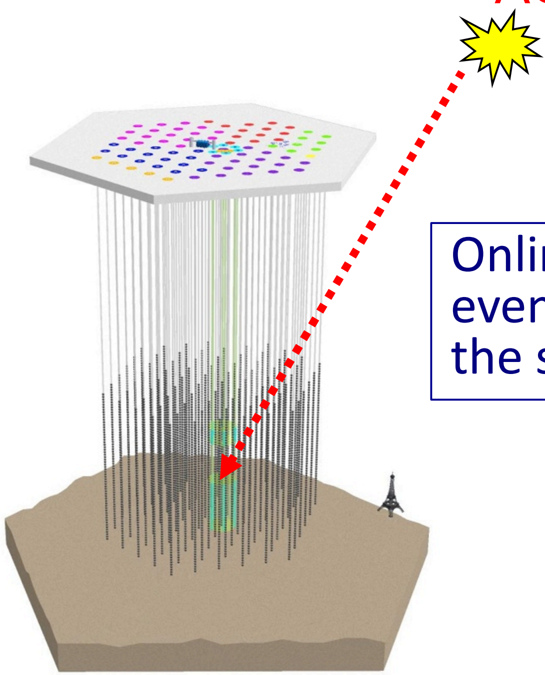




IceCube follow-up programs

- ✓ Send alerts to satellites/telescopes
- ✓ Multi messenger approach
- ✓ Few alerts per year

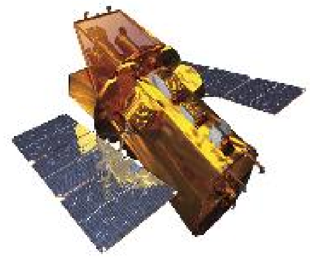
AGN/SN/GRB



Online neutrino event selection at the south pole

Alert

Swift (X-ray)



PTF (optical)

ROTE (optical)

MAGIC (γ-ray)

VERITAS (γ-ray)

EHE online alert is coming

Search for neutrinos from GRBs

neutrino (ν_μ) searches by using the direction and the timing information of GRBs

→ Very low backgrounds

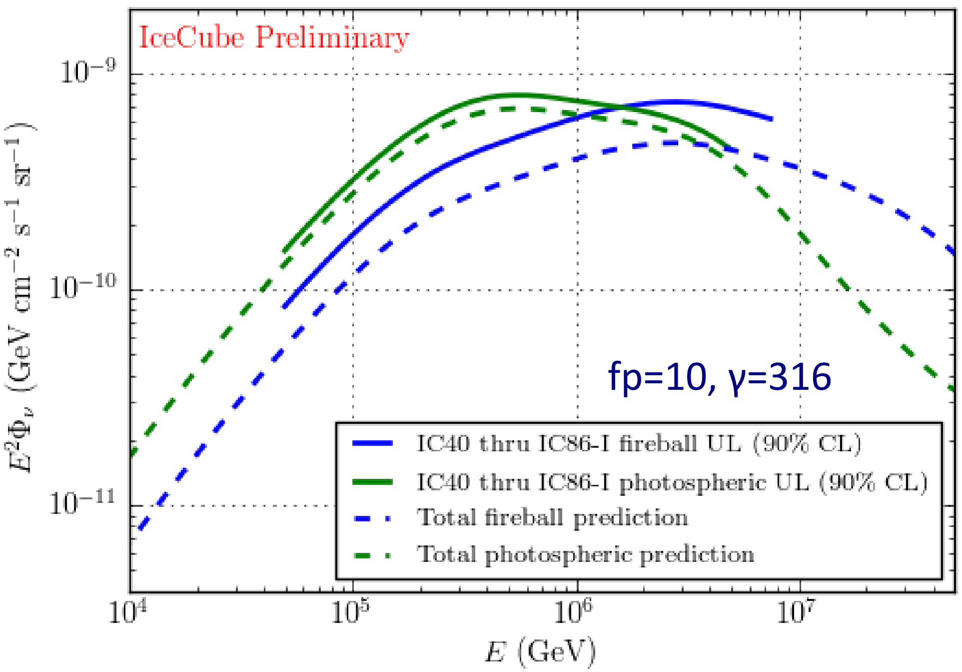
arXiv: 1309.6979

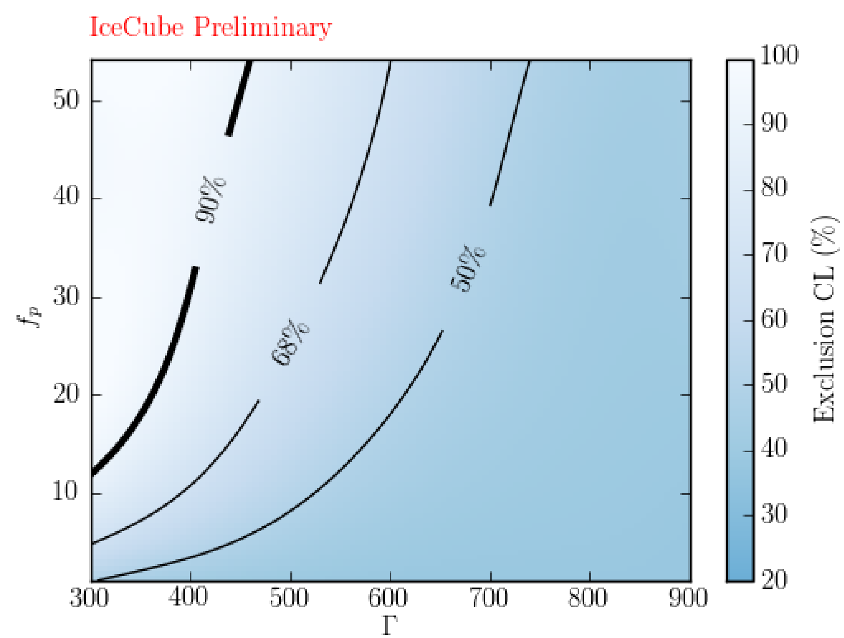
4 year data (IC40+IC59+IC79+IC86-I) ~540 GRBs

No significant neutrino signal → limits on radiation mechanism

$$\Phi \propto \frac{f_p}{\Gamma}$$

fp: baryon loading factor



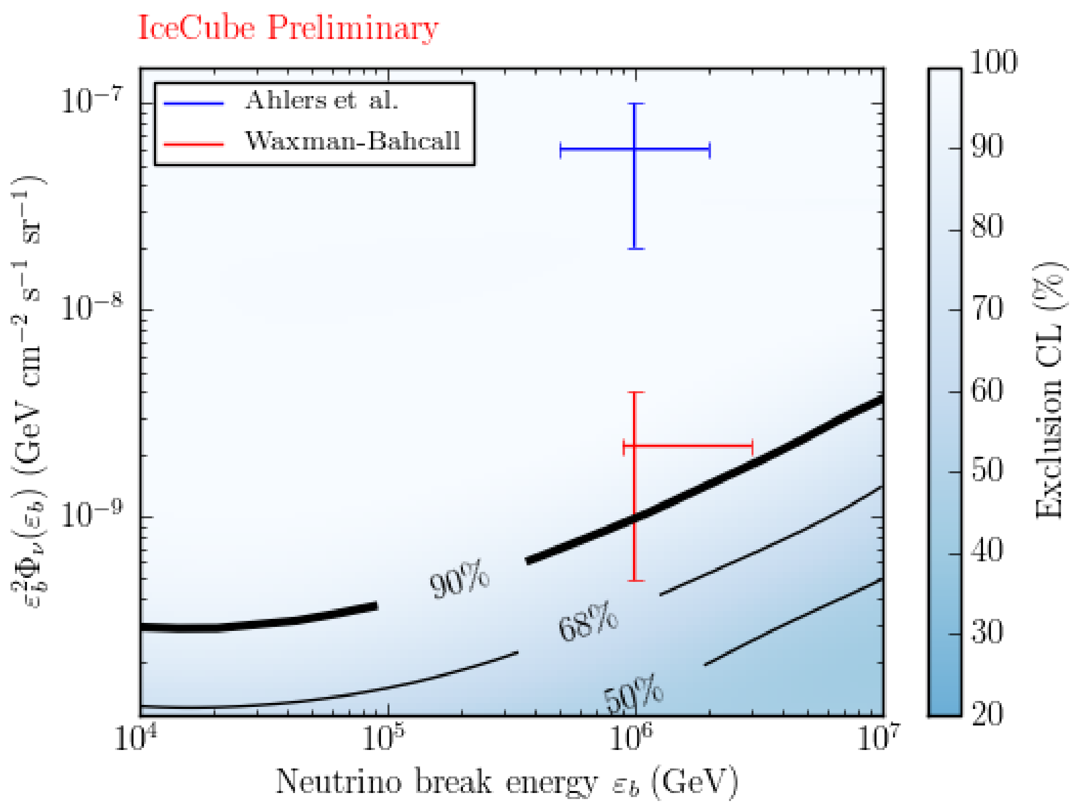


Search for neutrinos from GRBs

4 year data (IC40+IC59+IC79+IC86-I) ~540 GRBs

No significant neutrino signal → limits on UHECR origin

arXiv: 1309.6979



Either GRBs are not the main source for UHECRs

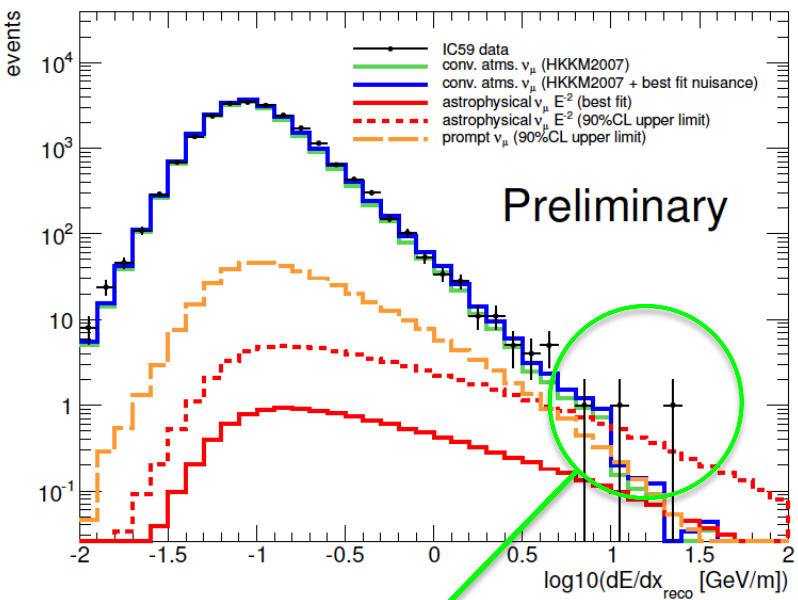
Or, theoretical models may need modifications

Diffuse neutrino search

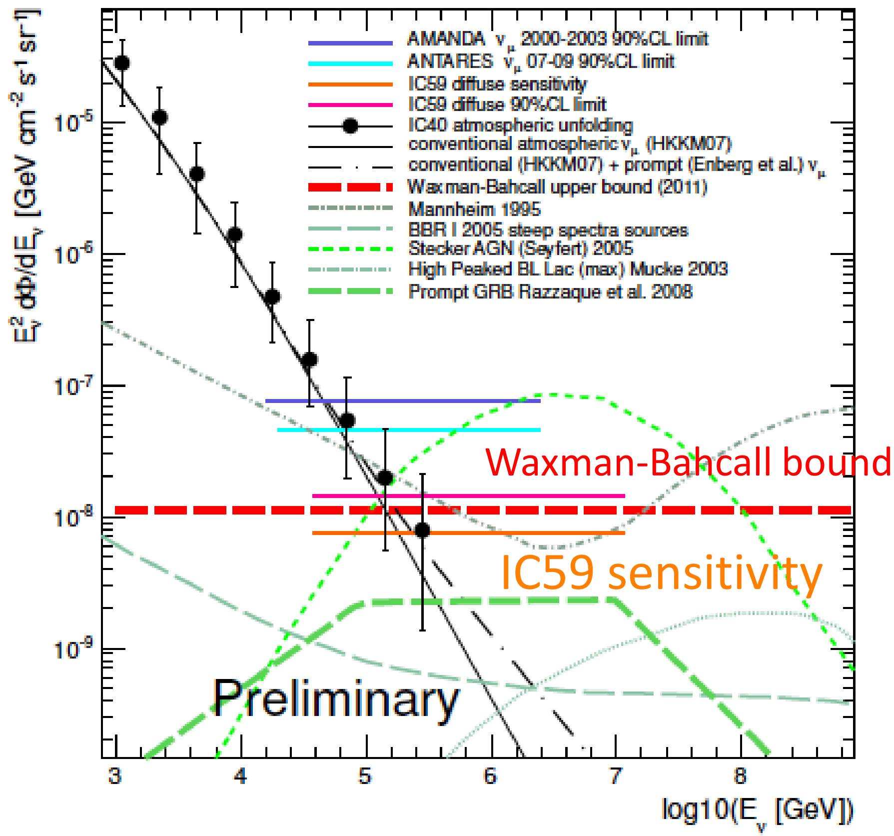
Idea to integrate weak neutrino flux
Search for diffuse muon neutrinos by using mainly energy information
Signal slope is harder than background slope

Sensitive: 30 TeV-10 PeV

arXiv:1302.0127



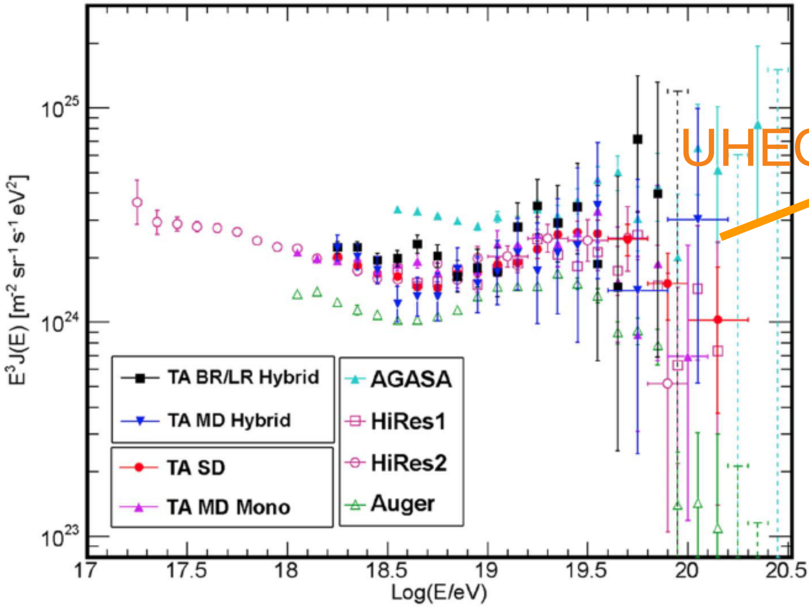
Significance: 1.8σ

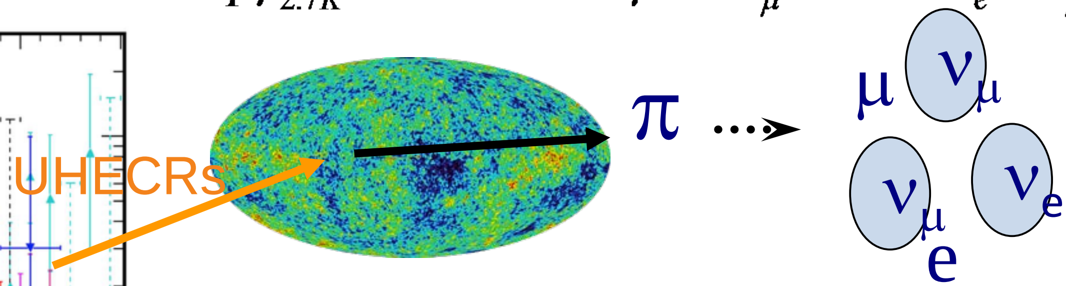


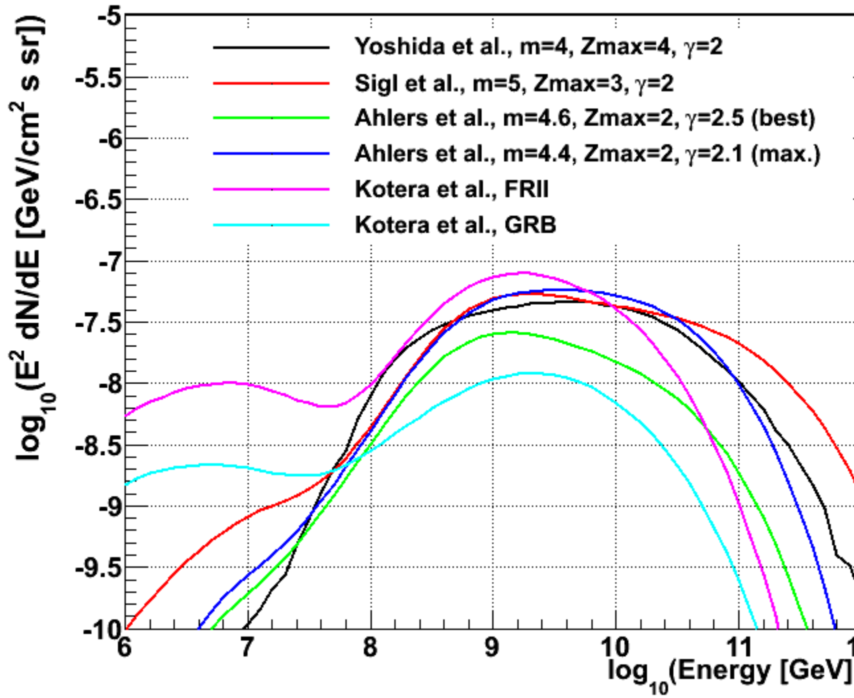
- Sensitivity is below Waxman-Bahcall bound
- Atmospheric neutrinos measured from 100 GeV - 300 TeV
  → Consistent with previous measurements

The extremely high energy (EHE) cosmogenic neutrino search

$$p\gamma_{2.7K} \rightarrow \pi^{+} + X \rightarrow \mu^{+} + \nu_{\mu} \rightarrow e^{+} + \nu_{e} + \overline{\nu_{\mu}} + \nu_{\mu}$$





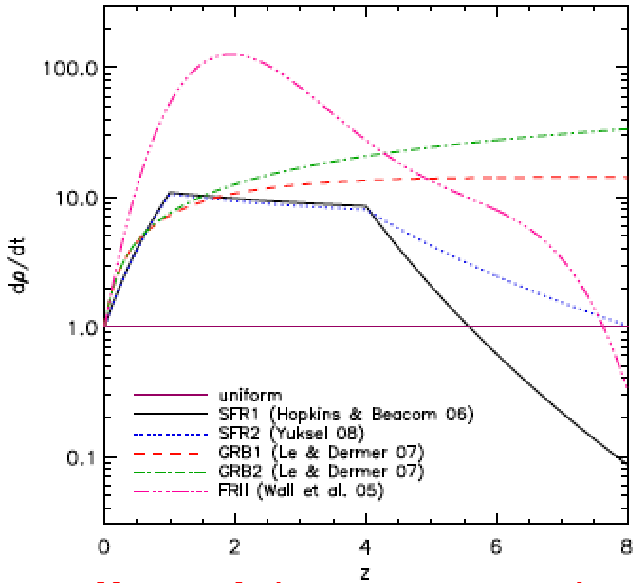


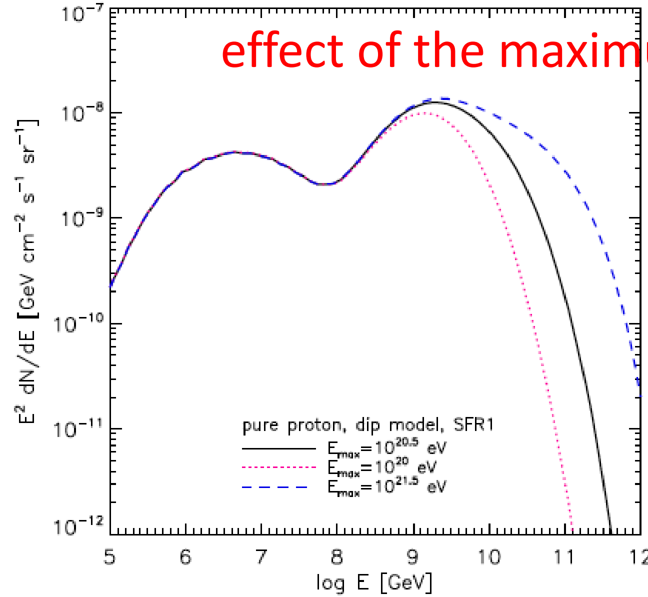
Shed light on the UHECR origin

- Source position
- Composition (proton/iron)?
- Source evolution / when the UHECR generation started

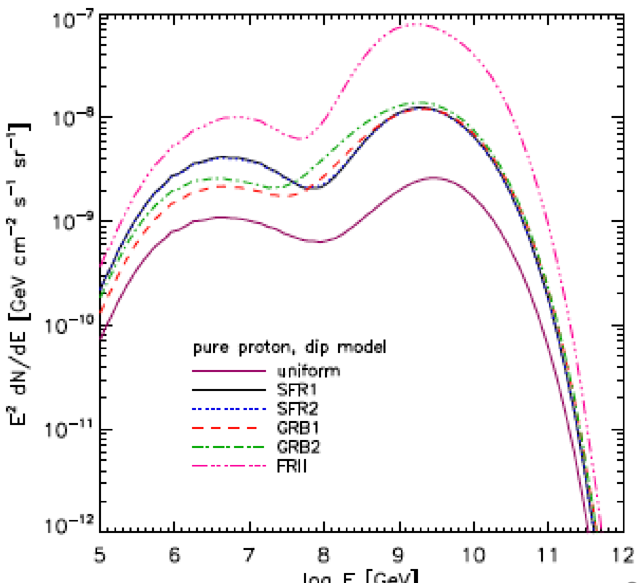
All flavor sensitive, Energy > 1 PeV

❑ Effect of source evolution and maximum energy on neutrino flux





effect of the source evolution

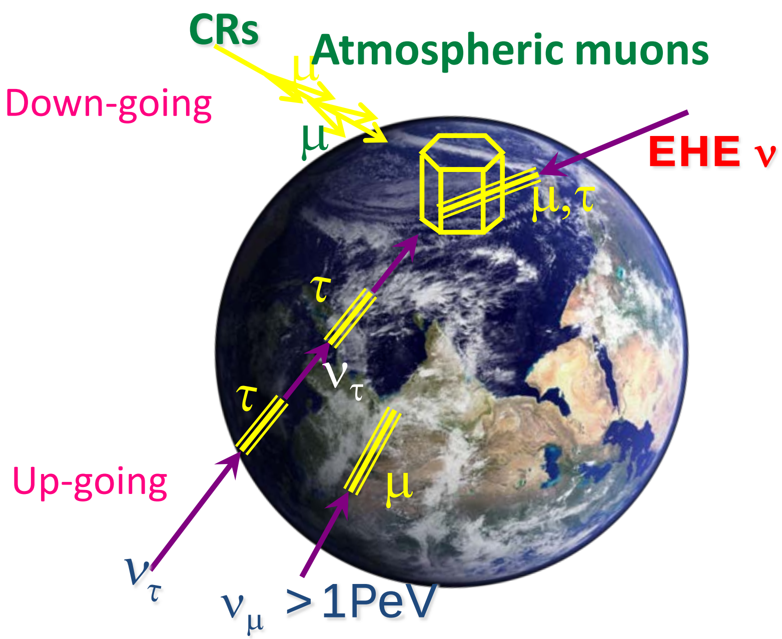


neutrino flux depend on the source evolution and maximum energy

-> constraint on the parameters

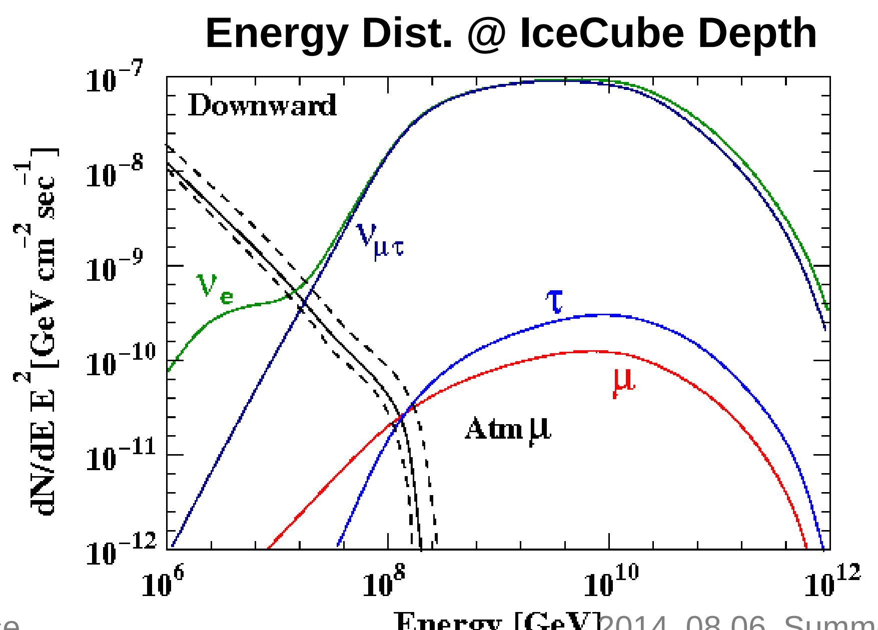
Kotera et al., JCAP 10 (2010) 013

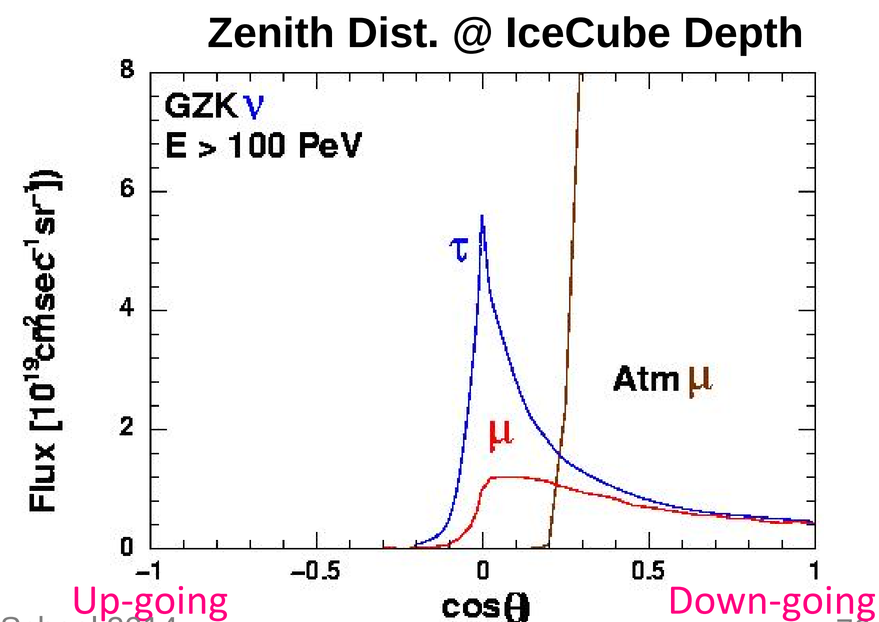
The detection principle



- ✧ **EHE neutrino signal (all flavor)**
  - ✧ Horizontal (opaque to the earth)
  - ✧ High energy (> 10^8 GeV)
- ✧ **Atmospheric muon background**
  - ✧ Down-going
  - ✧ Low energy (the energy spectrum is steep ($\sim E^{-3.7}$))

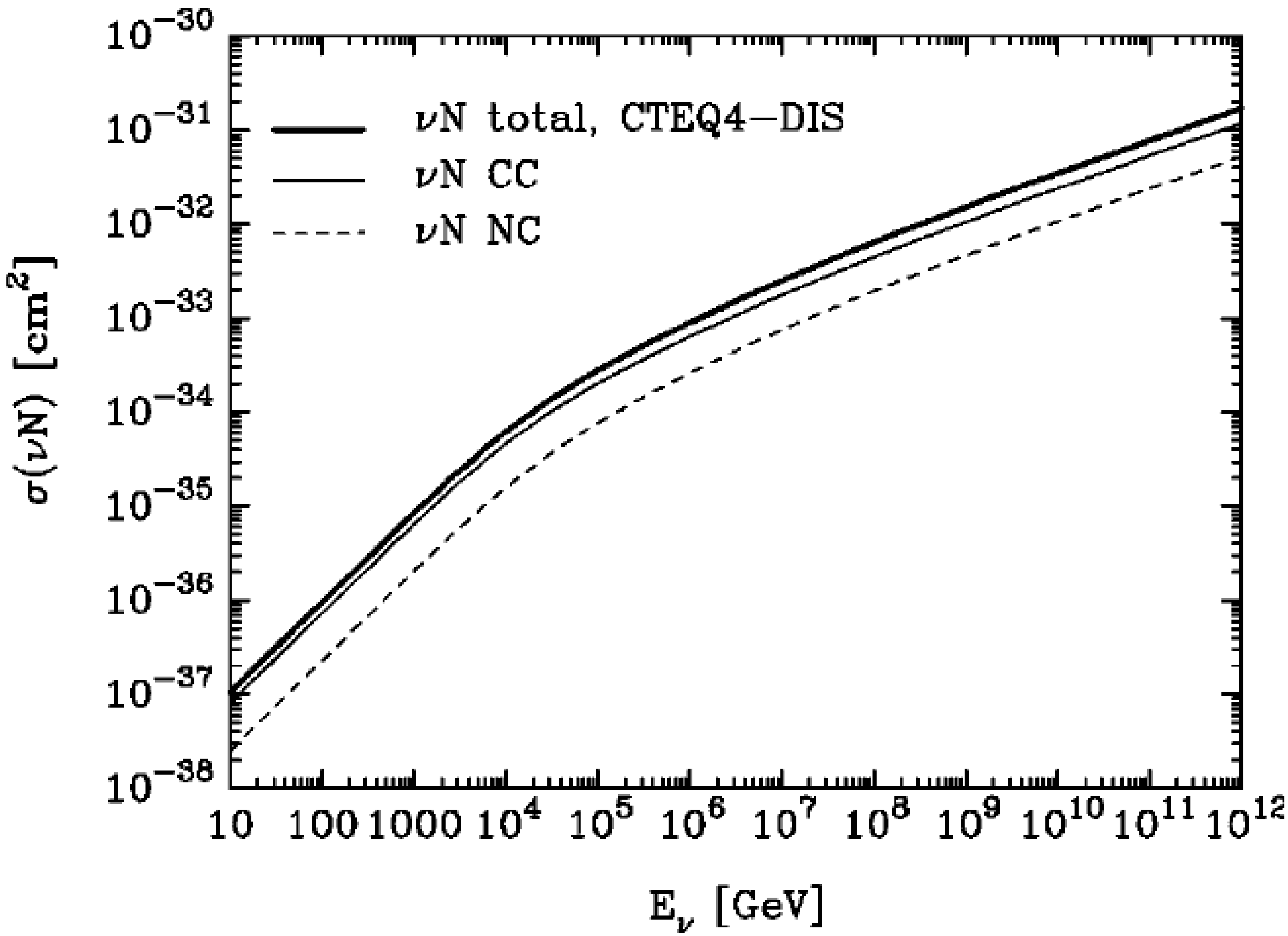
Yoshida et al PRD **69** 103004 (2004)





The cross section

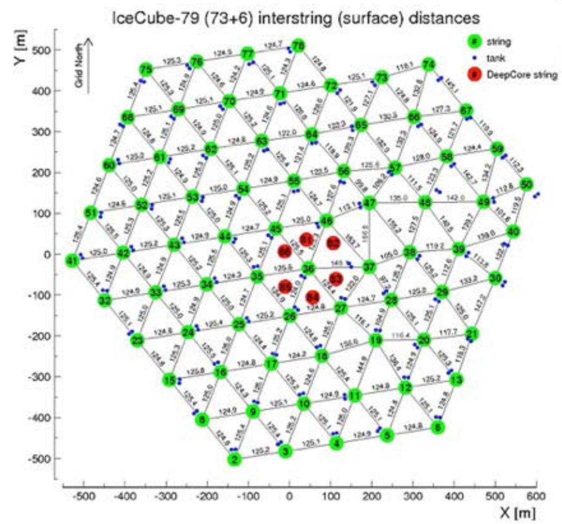
PRD, 58, 093009 (1998)



Datasets

Five datasets are used in this analysis:

IC79 (2010-2011)



1. Observational data (two years data)

taken in 2010-2011 (319.2 days) with 79 string configuration (IC79)
taken in 2011-2012 (350.9 days) with the complete detector (IC86)
EHE on-line filter data (NPE > 1000)
~100M events, ~ 1.7 Hz

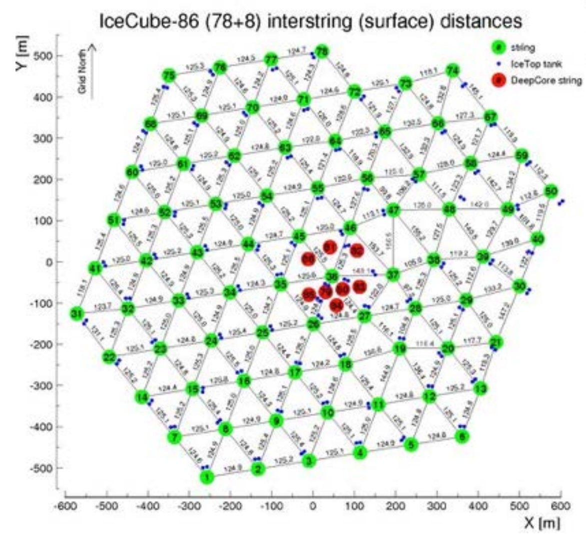
2. Signal MC data (JULIeT)

10^5-10^{11} GeV, $dN/dE = E^{-1}$
20k events for μ, τ, ν_e, ν_μ, ν_τ

3. Atmospheric muon background MC data (CORSIKA data)

10^5-10^{11} GeV, $dN/dE = E^{-1}$
15k events for proton and iron
SIBYLL HE interaction model

IC86 = complete IceCube (2011~)



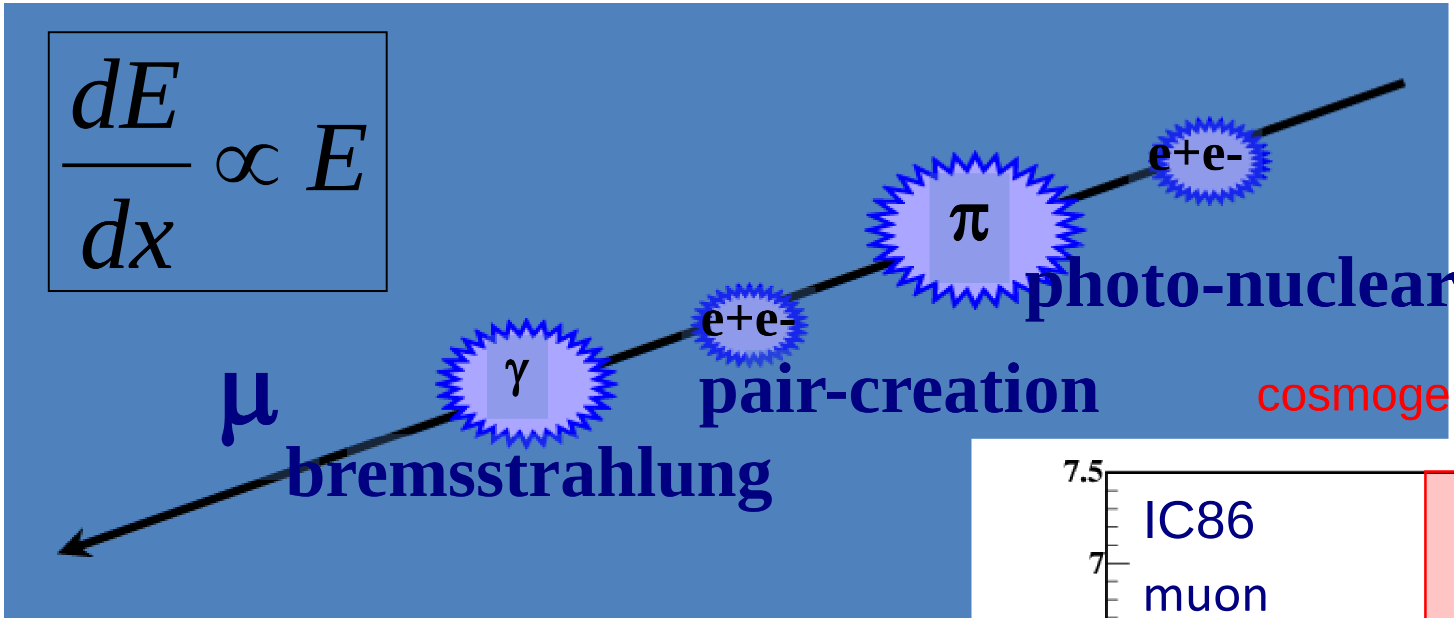
4. Coincidence muon MC data (CORSIKA data)

600-10^{11} GeV, $dN/dE = E^{-1.7}$, polygonate model (J. R. Hoerandel (2003))
10G events
SIBYLL HE interaction model

5. Atmospheric neutrino background MC data

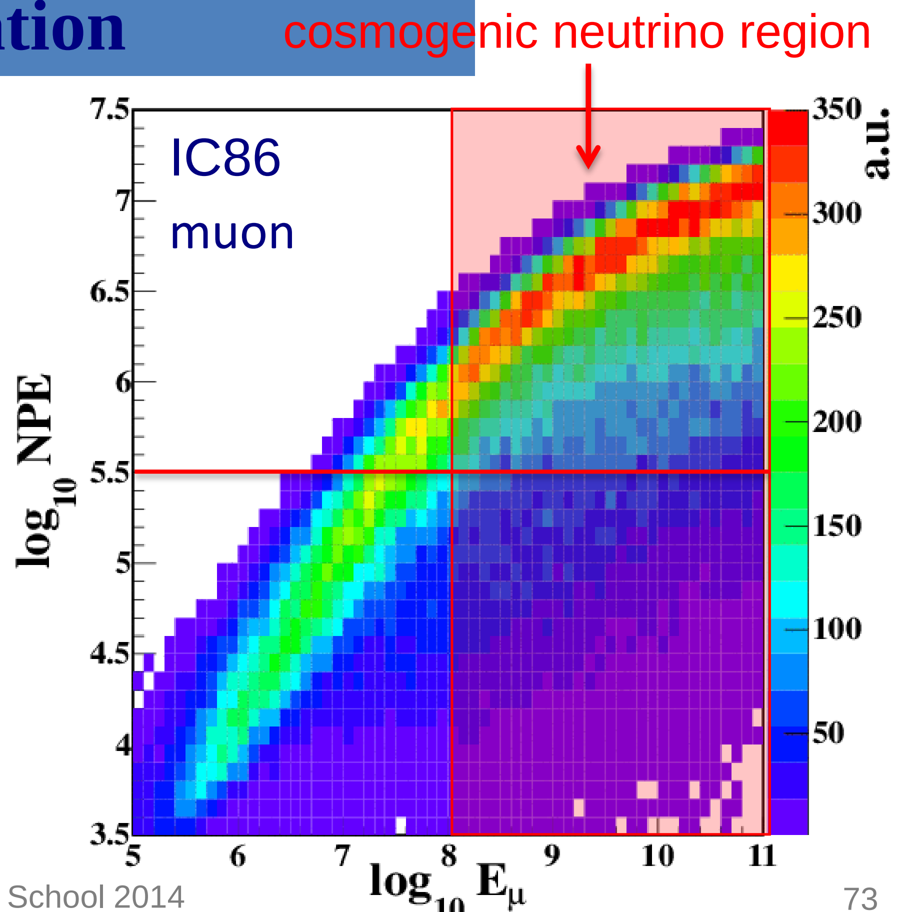
10^3-10^9 GeV, $dN/dE = E^{-1}$, ν_μ, ν_e
10M events
atmospheric neutrinos: including knee (T. K. Gaisser (2012))
prompt neutrinos: perturbative QCD model (Enberg et al. (2008))

Energy indicator



Detected total number of photo-electrons (NPE) ∝ Energy

NPE is used for the energy indicator

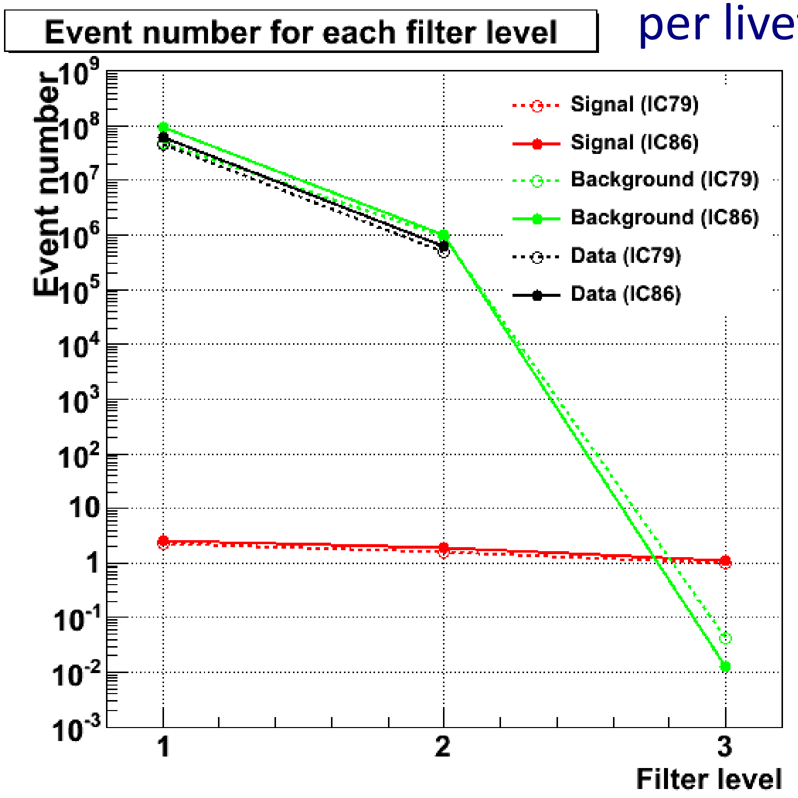


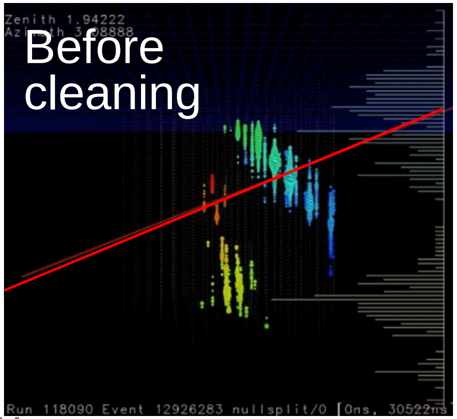
Analysis scheme

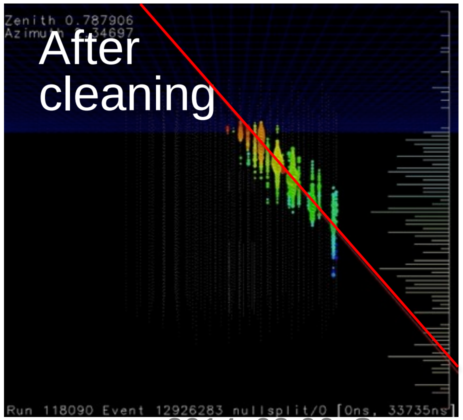
Blind analysis

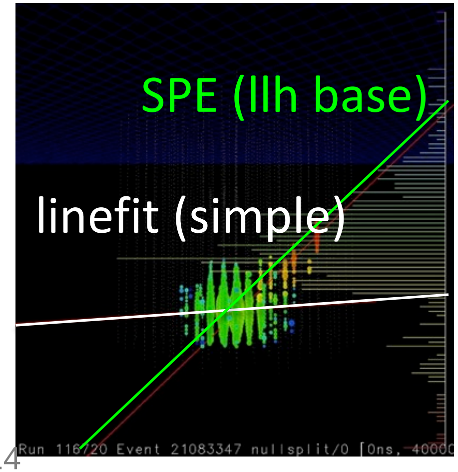
1. Online filter level (EHE):
   NPE > 1000
   ↓
2. Analysis level:
   NPE > 3200
   NDOM > 300
   coincident muon cleaning
   improved geometry reconstruction
   ↓
3. Final level:
   NPE and zenith angle information

per livetime

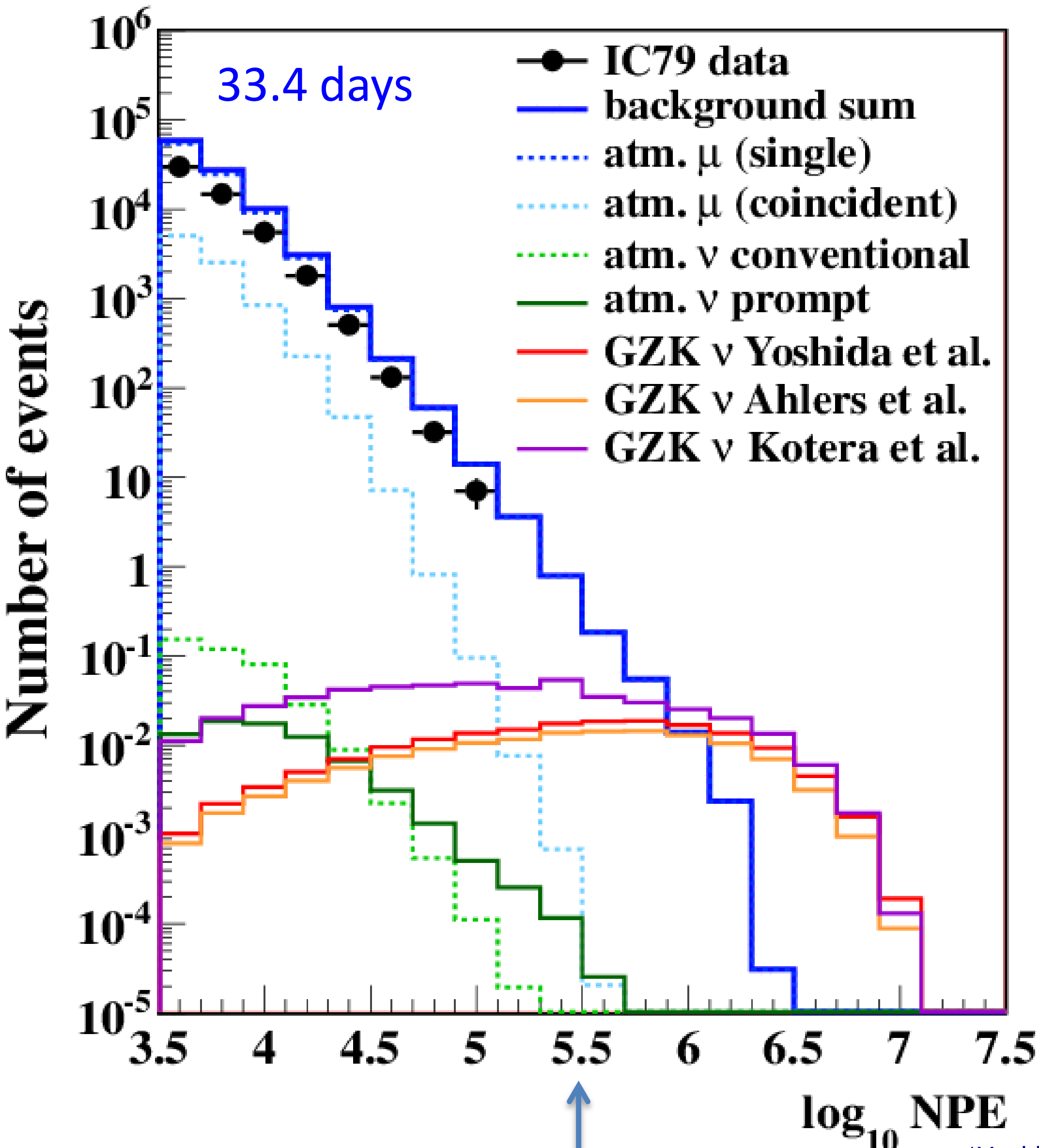






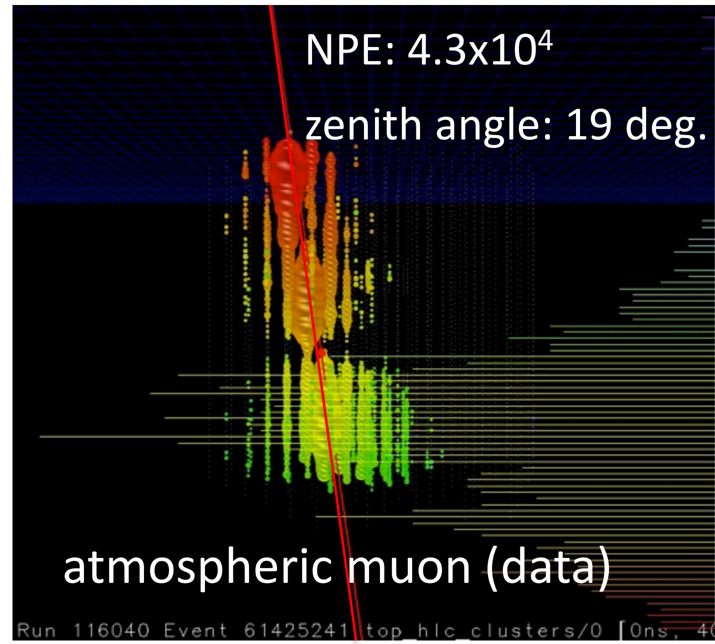


NPE distribution at analysis level (IC79)



10^8 GeV (cosmogenic neutrinos (at surface))
10^{10} GeV (CR primary)

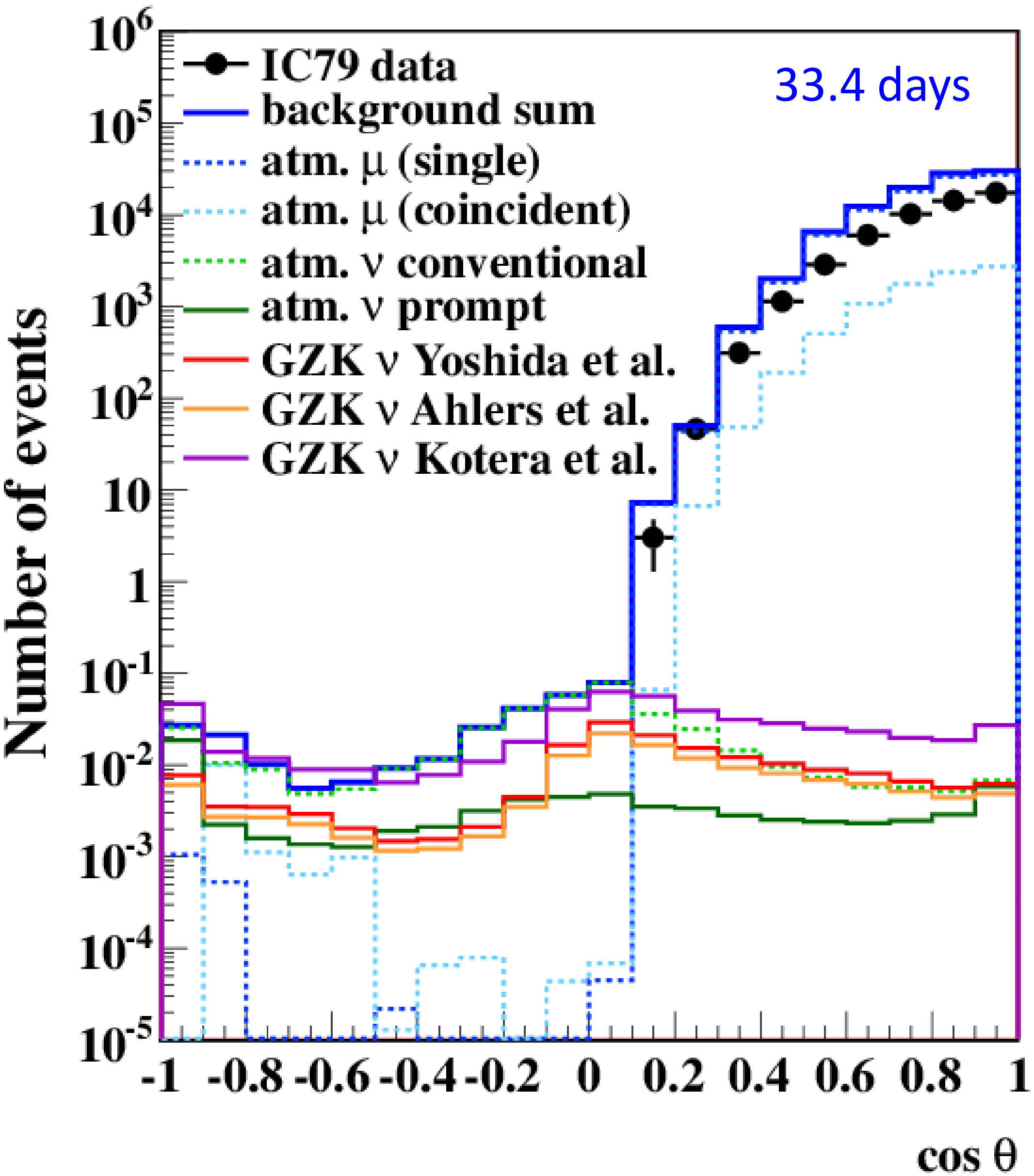
NPE > 3200 && NDOM > 300



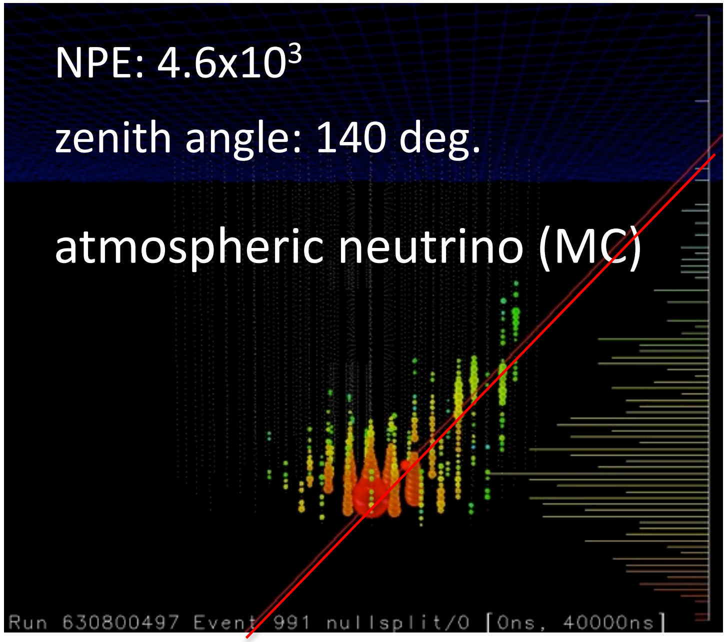
Dominated by atmospheric muons
Reasonable MC/data agreement

*Yoshida and Teshima, Prog.Theor. Phys. 89, 833795 (1993), m=4, Zmax=4
**Ahlers et al., Astropart. Phys. 34, 106867 (2010), m=4.6, Zmax=2 (best)
***Kotera et al., JCAP 1010, 013869 (2010), FRII

Zenith angle distribution at analysis level (IC79)



NPE > 3200 && NDOM > 300



Geometry for atmospheric muons is reconstructed reasonably well

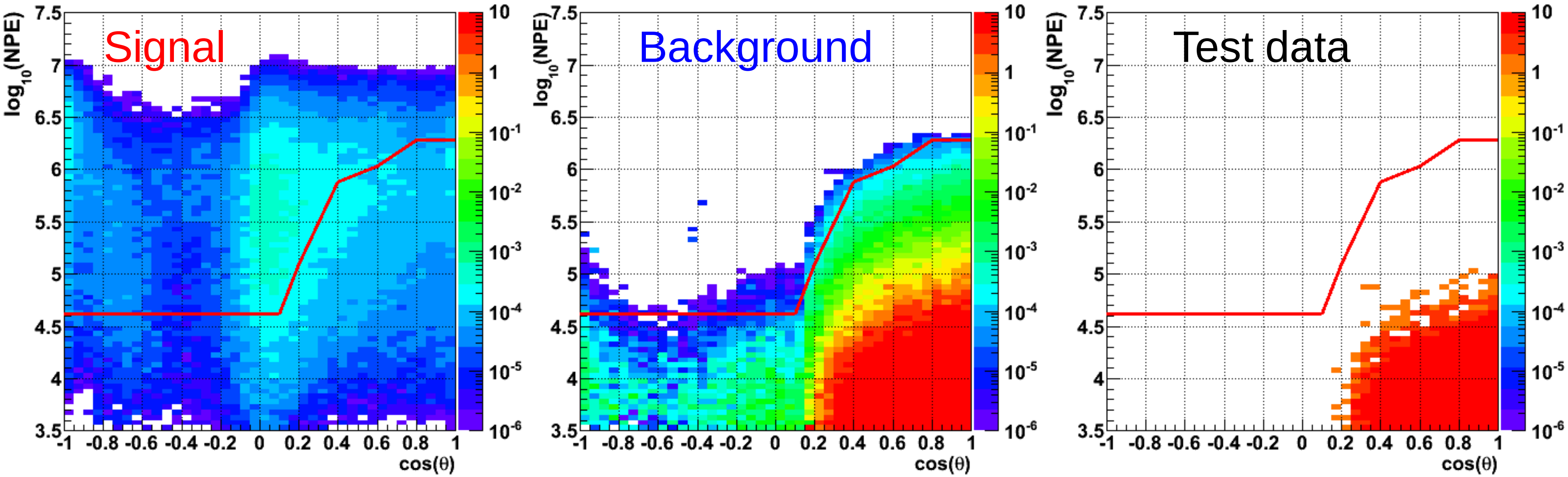
Atmospheric neutrinos also come from horizontal direction, but low energy

Final selection criteria (IC79)

Model discovery potential method used

G.C. Hill et al., in the Proceedings of PHYSTAT2005 (2006) 108–111.

33.4 days



Expected event rates

319.2 days

GZK signal*	Bg total	(Atm. μ)	(Atm. ν)
0.98±0.01	0.041±0.003	(0.033±0.003)	(0.008±0.001)

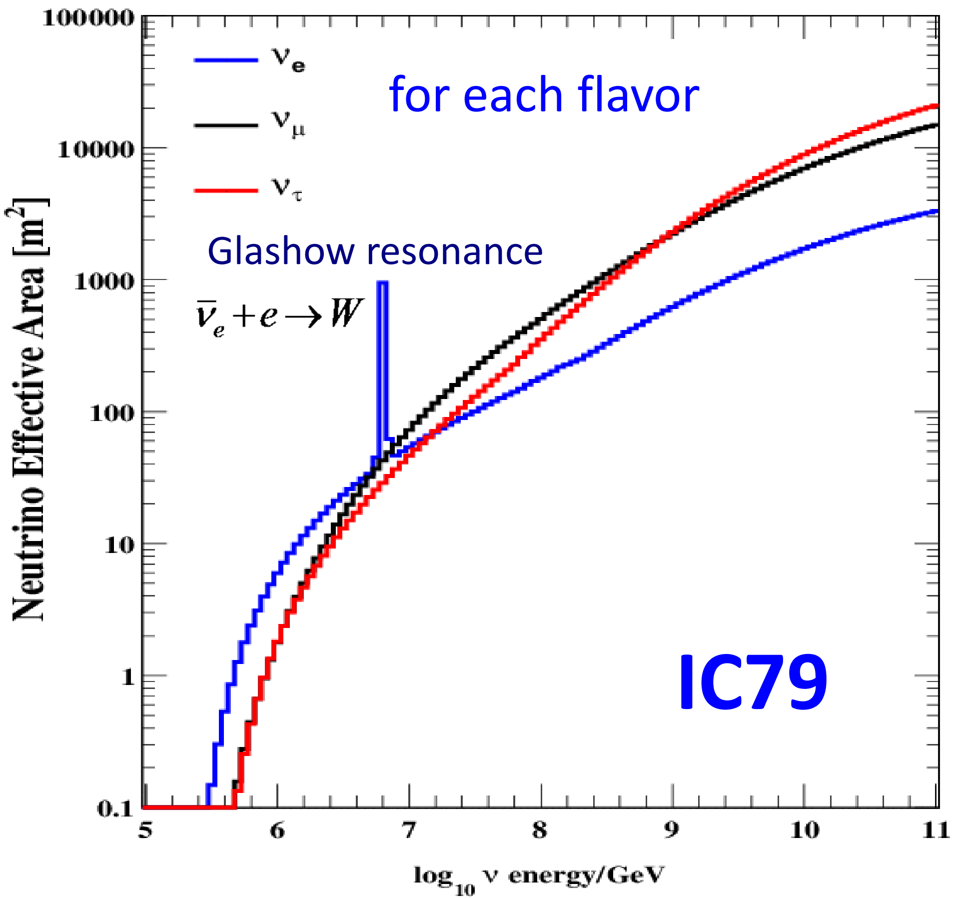
*Yoshida and Teshima, Prog.Theor. Phys. 89, 833795 (1993), m=4, Zmax=4

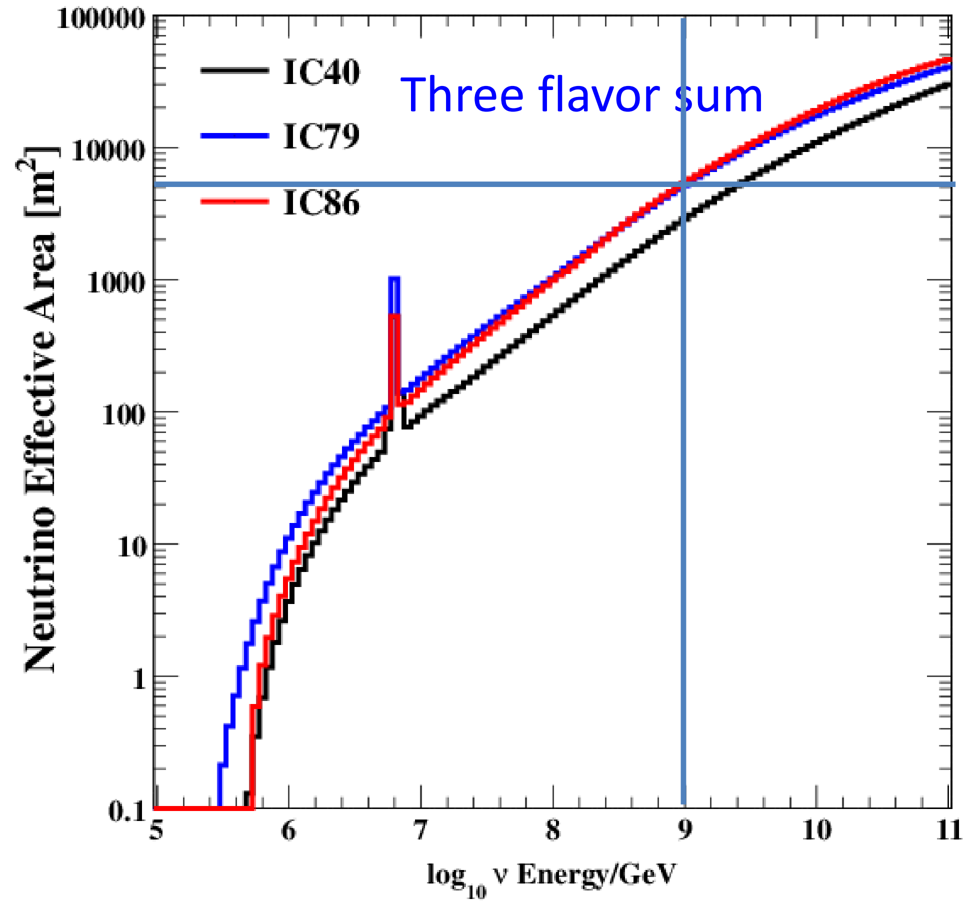
0.57 per 333 days for IC40

~1 event/yr

Effective area

$A_{IC79} \approx A_{IC86} \approx 2 \times A_{IC40}$





- Increases with energy
- ~5000 m^2 @ EeV

Two cascade like events found in 2011-2012 data

May, 2011 - May, 2012 (350.9 days), IC86 configuration

PRL 111, 021103 (2013)

Either CC interaction of ν_e or NC interaction of any flavor ν

''Bert''
Aug., 9th, 2011
Run 118545
-Event 63733662
NPE: 7.0×10^4
NDOM: 354
1.04±0.16 PeV

''Ernie''
Jan, 3rd, 2012
Run 119316
-Event 36556705
NPE: 9.6×10^4
NDOM: 312
1.14±0.17 PeV

	event rate in 615.9 days
Atmospheric muons	0.038 ± 0.004
conventional atmospheric neutrinos	0.012 ± 0.001
prompt neutrinos*	0.033 ± 0.001
total background	**0.082 ± 0.004**

* R. Enberg et al., PRD78, 043005 (2008)

Significance: 2.8σ

Highest energy neutrinos ever seen!

The August event ("Bert")

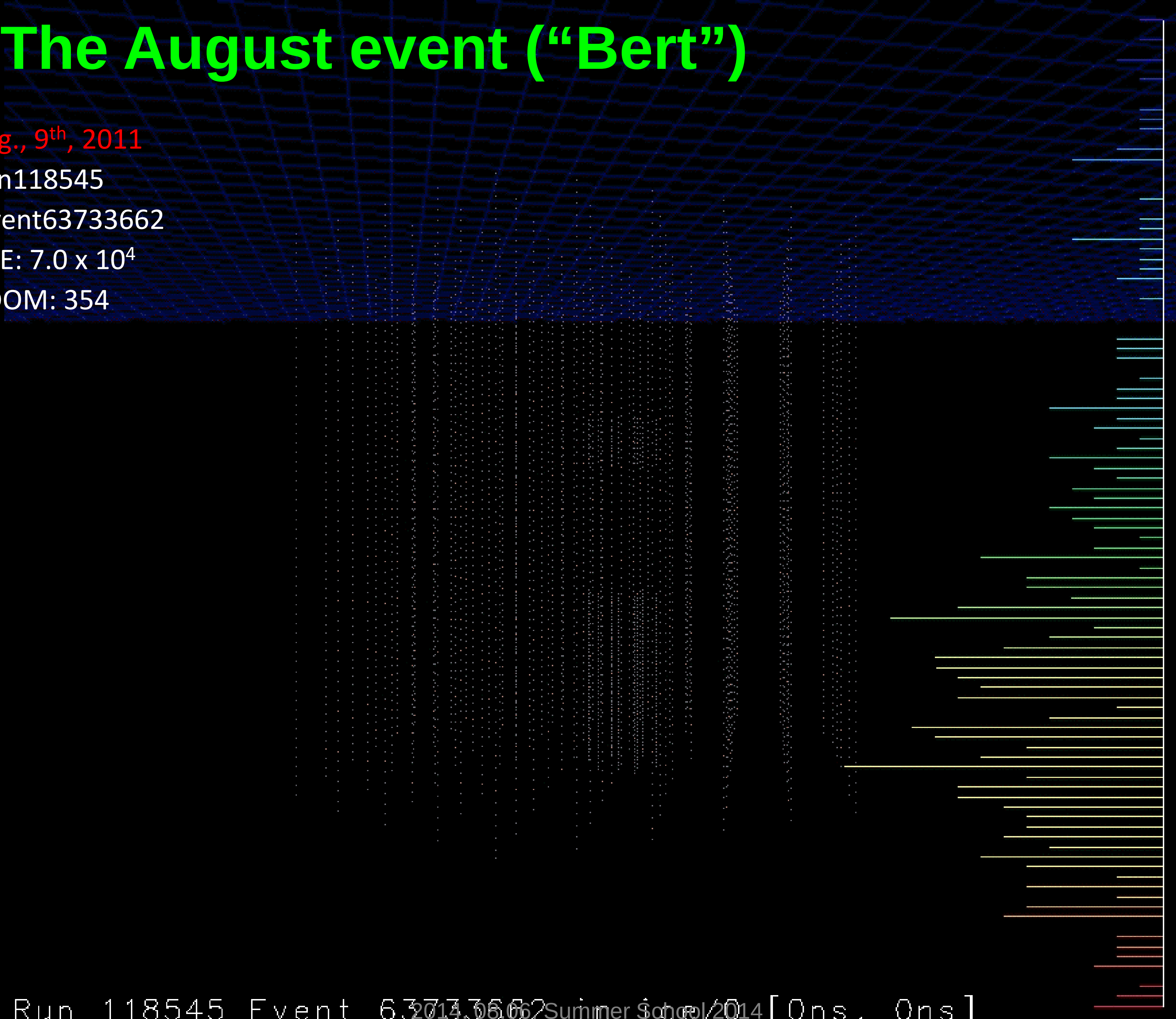
Aug., 9th, 2011

Run118545

-Event63733662

NPE: 7.0 x 10^4

NDOM: 354



The January event ("Ernie")

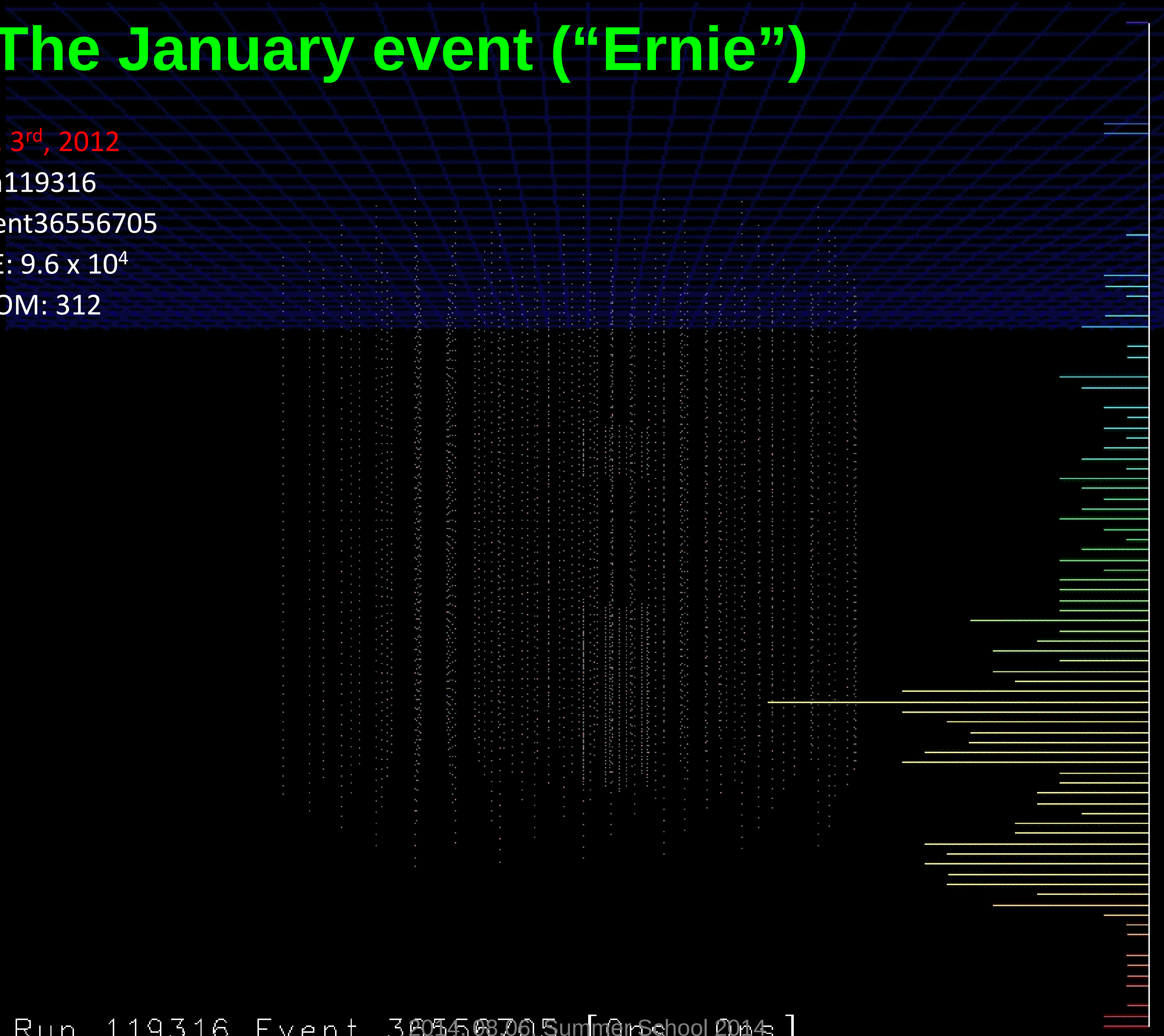
Jan, 3rd, 2012

Run119316

-Event36556705

NPE: 9.6×10^4

NDOM: 312

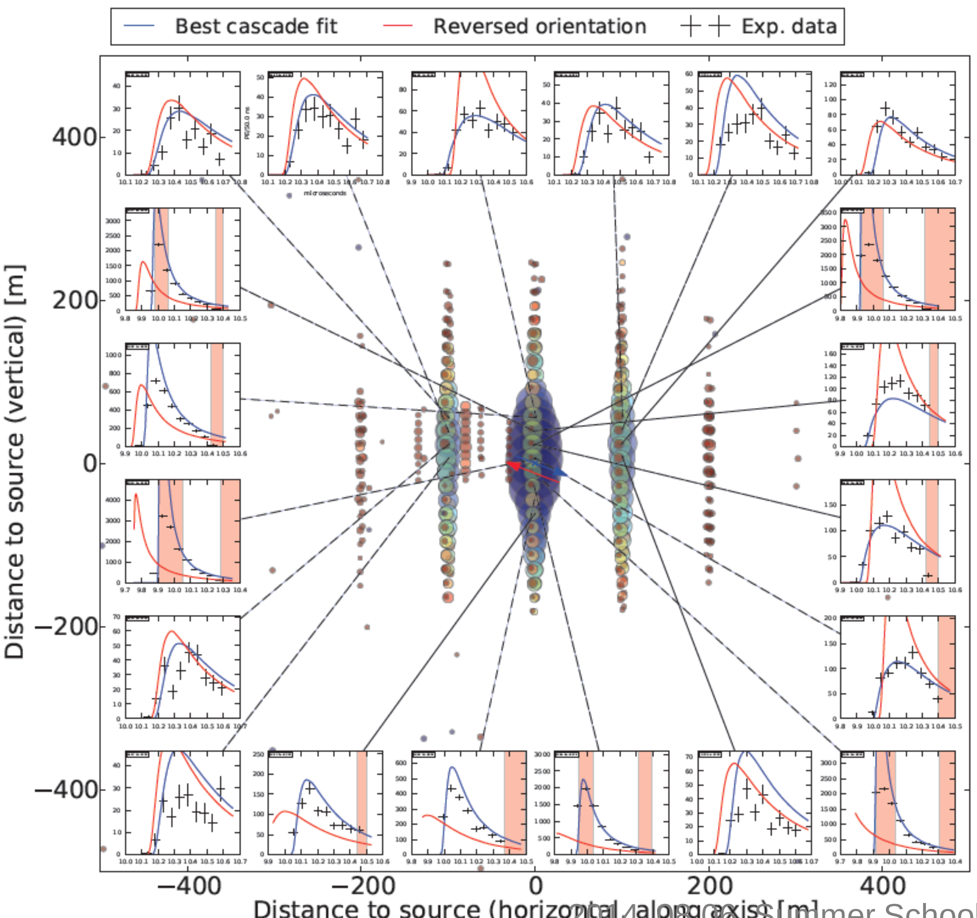


Bert visits Tokyo

The energy deposit reconstruction

Aug. ("Bert")

1.0±0.2 PeV



Jan. ("Ernie")

1.1±0.2 PeV

energy resolution for these specific events

including systematics (ice + DOM eff.)

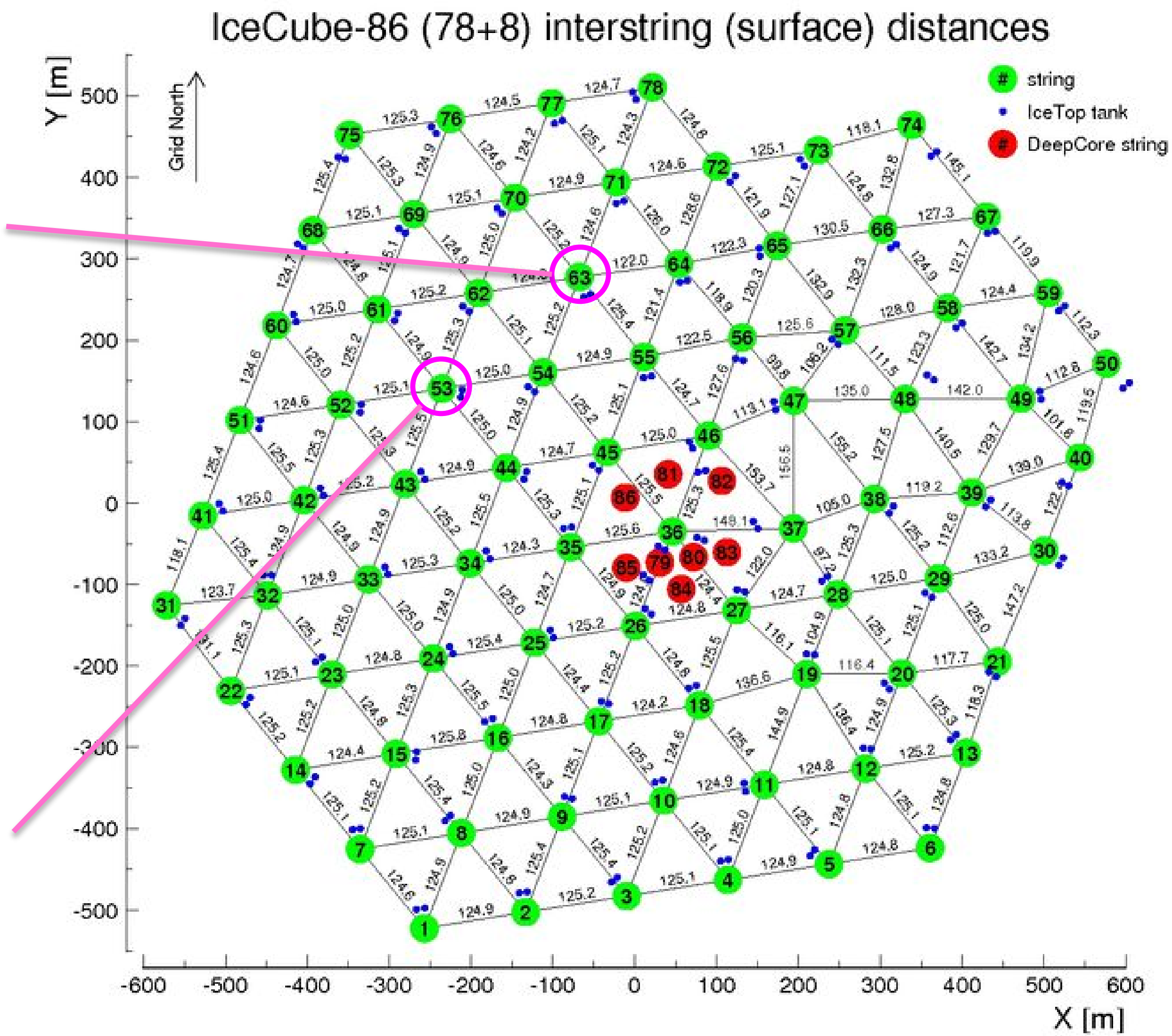
Closest string positions for the vertices

Jan. ("Ernie")

Z: 25 m

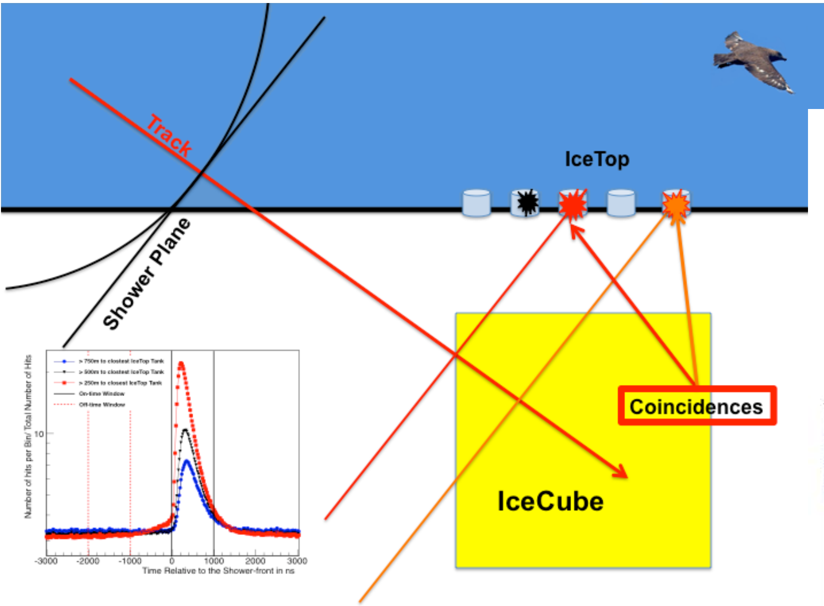
Aug. ("Bert")

Z: 122 m

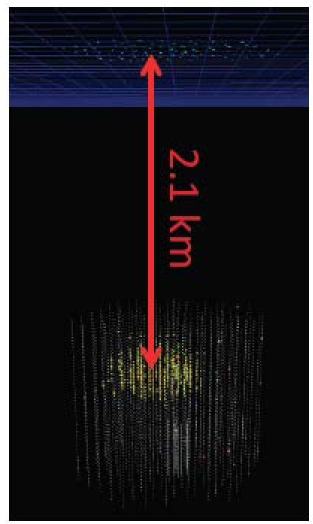


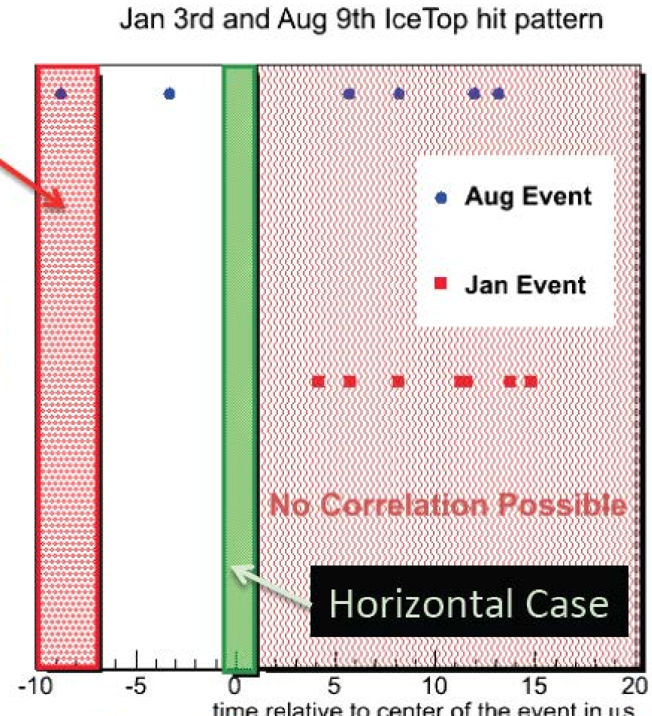
Well contained!

❑ IceTop (surface array) veto information



Geometrical not possible as Cascades 2 .1km deep





Before first Hit: Correlation possible

After the Event no Down-going correlation possible

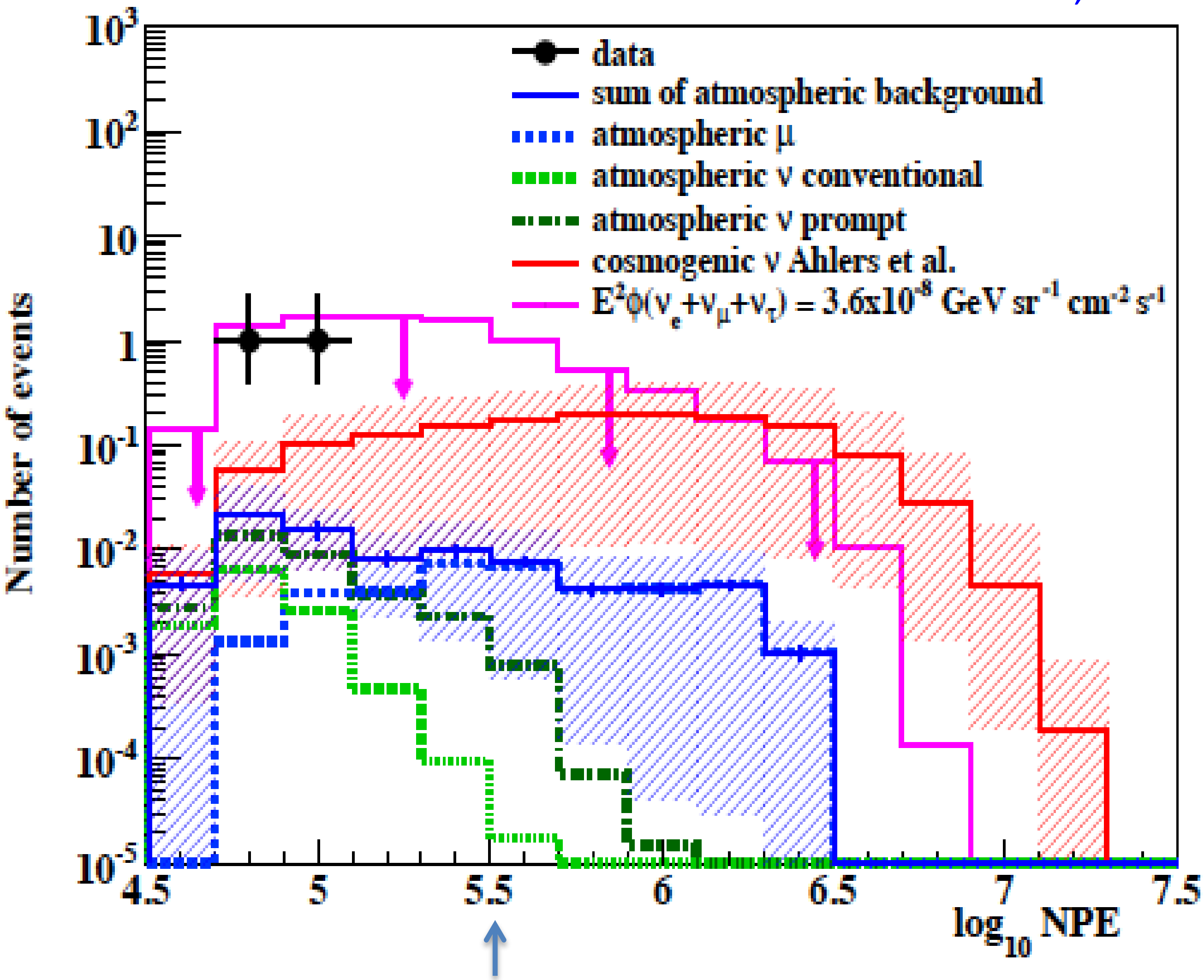
- ✧ IceTop veto information was checked
- ✧ hits search in allowed 8µs time window
- ✧ 0 and 1 hit observed again 2.1 hits expected

-> No CR shower

NPE distribution at final level

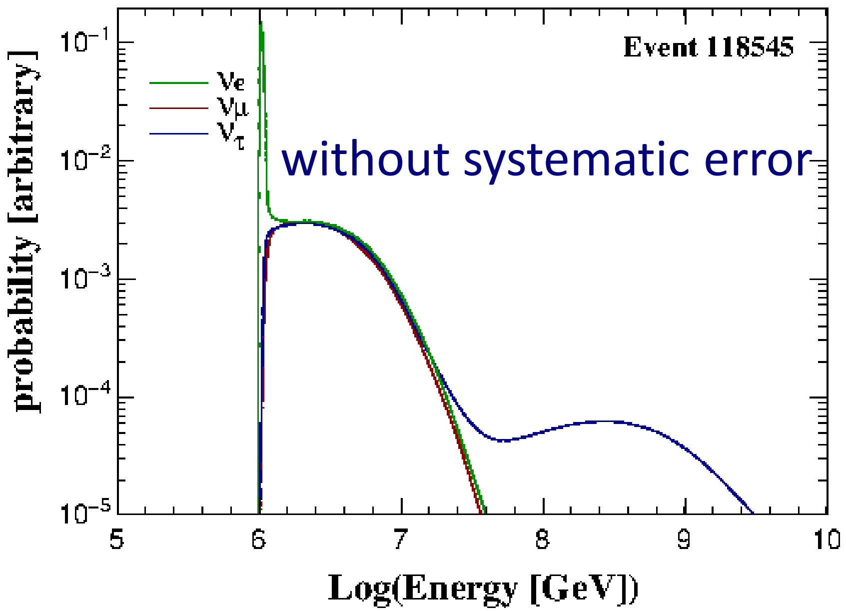
IC79/86 combined (615.9 days)

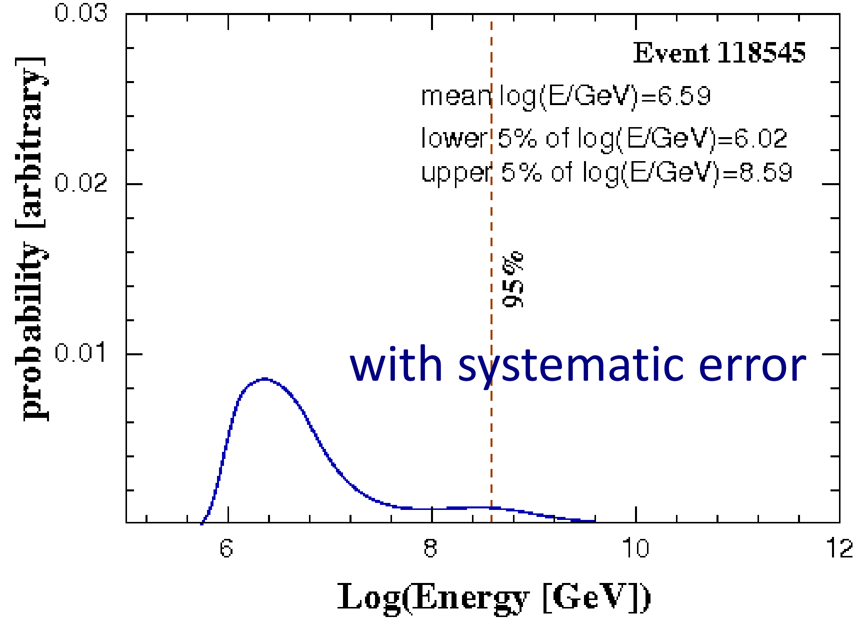
PRL 111, 021103 (2013)



corresponds to ~10^8 GeV neutrinos at surface with a cosmogenic neutrino spectrum

❑ Reconstructed energy at surface





GZK flux assumed

Top-down approach (in-ice) + propagation to surface

In case of ν_e CC, full energy deposit

Other case of NC, partial energy deposit by Bjorken y

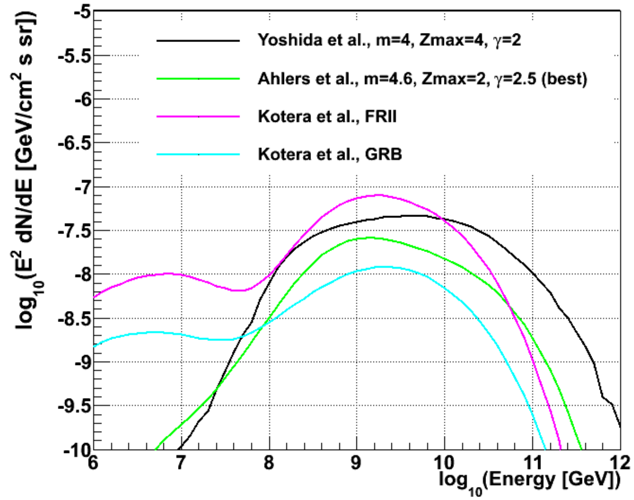
Aug.
0.81 < E < 7.6 PeV (90%)

Jan.
0.93 < E < 8.9 (90%)

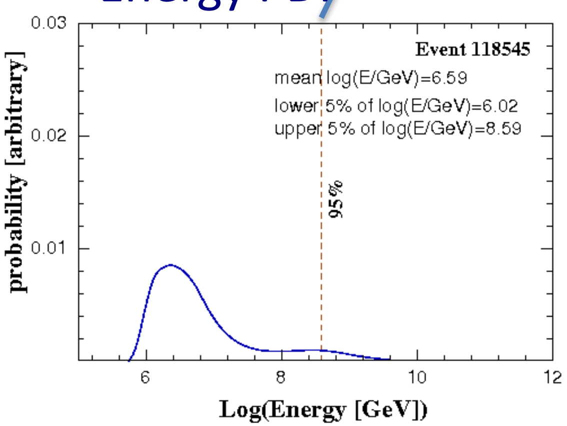
Two events compatible with EHE cosmogenic neutrino models?

Whether cosmogenic models can explain the two event observation was tested

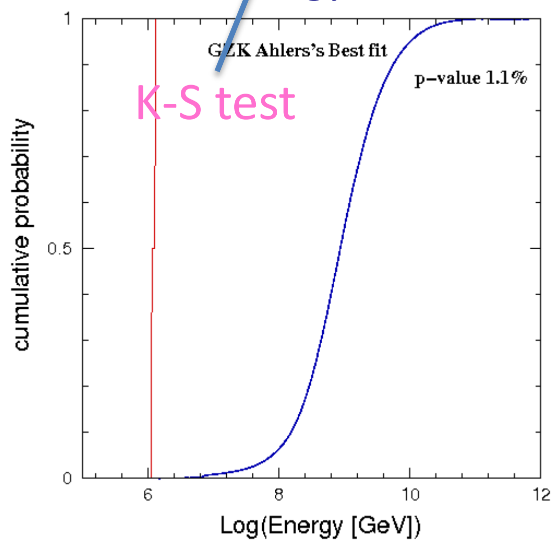
$$P_E = \int dE_1 \rho_1(E_1) \int dE_2 \rho_2(E_2) P_{KS}(E_1, E_2),$$



Energy PDF



Cumulative energy distribution



K-S test

IC40+IC79+IC86

neutrino model	p-value
GZK Yoshida and Teshima	0.077
GZK Ahlers Fermi best	0.075
GZK Kotera FR-II	0.039
GZK Kotera GRB	0.052

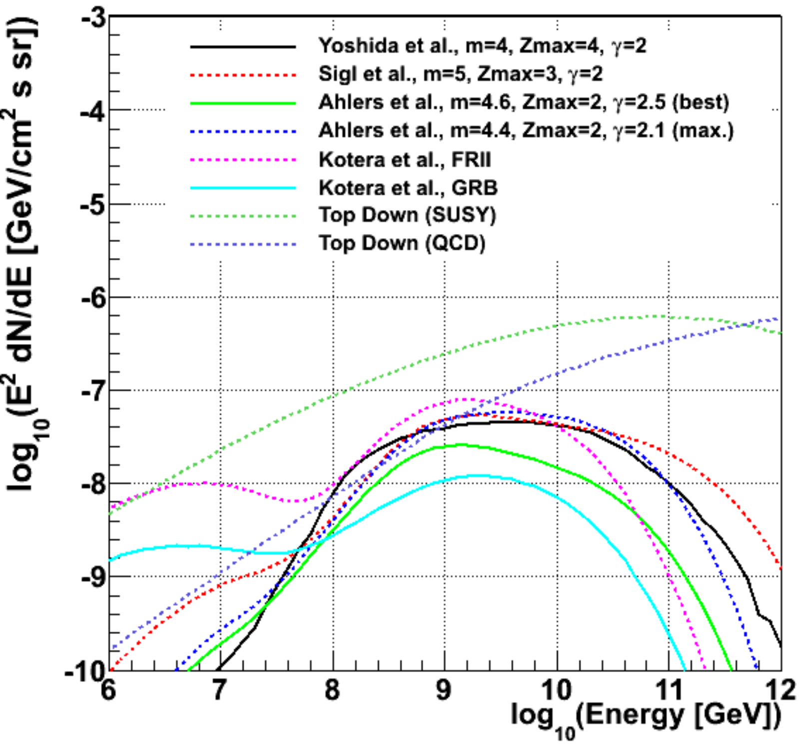
Cosmogenic neutrino models can not explain the two event observation

Constraint on EHE cosmogenic neutrino models

Compared the event rate with observation

PRD 88, 112008 (2013)

Essentially no event observation above 100 PeV, though the effect of the two events considered by the energy PDF



IC40+IC79+IC86

model	expected rate (>100 PeV)	p-value
GZK Yoshida Teshima, m=4, Zmax=4	2.0	0.14
GZK Sigl, m=5, Zmax =3*	3.1	**0.045**
GZK Ahrlers, Fermi best	1.5	0.22
GZK Ahrlers, Fermi max	3.1	**0.044**
GZK, Kotera, GRB	0.48	0.66
GZK, Kotera, FRII	2.9	**0.052**
Top-down SUSY**	16	**<< 0.002**
Top-down QCD**	3.9	**0.021**

*O. E. Kalasheve et al., Phys. Rev. D66, 063004 (2002)

**G. Sigl et al., Phys. Rev. D59, 043504 (1999)

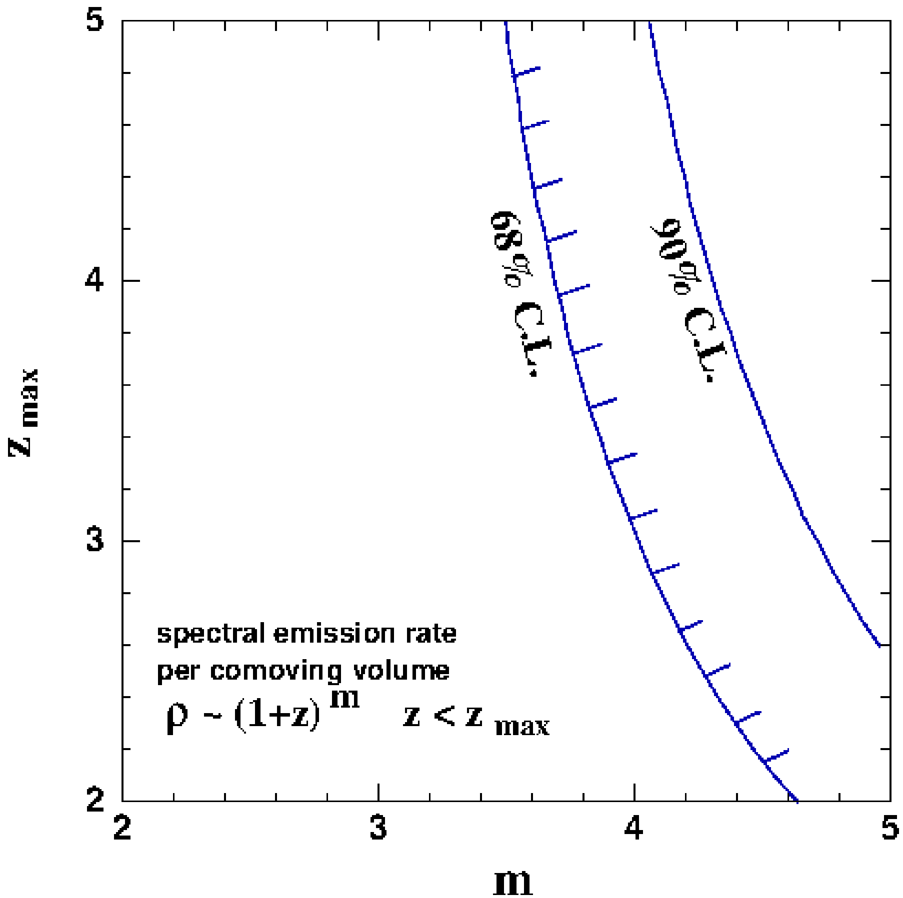
high evolution models (m>4) are mostly ruled out such as FRII

Limit on evolution parameters

Energies of two PeV events are too low to be explained by cosmogenic neutrinos

No events observed above 100 PeV

PRD 88, 112008 (2013)



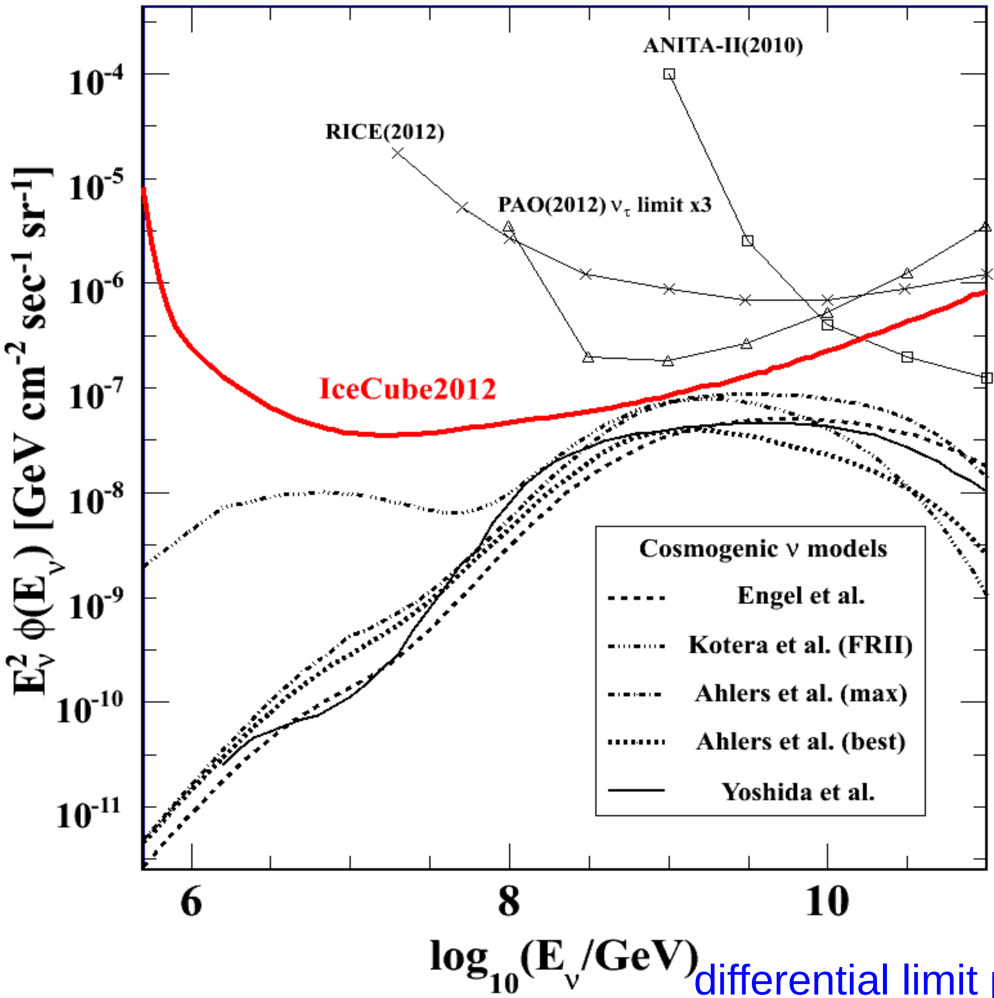
High evolution models (m>4) are mostly ruled out such as FR-II class of AGN

Limit on flux

Energies of two PeV events are too low to be explained by cosmogenic neutrinos

No events observed above 100 PeV

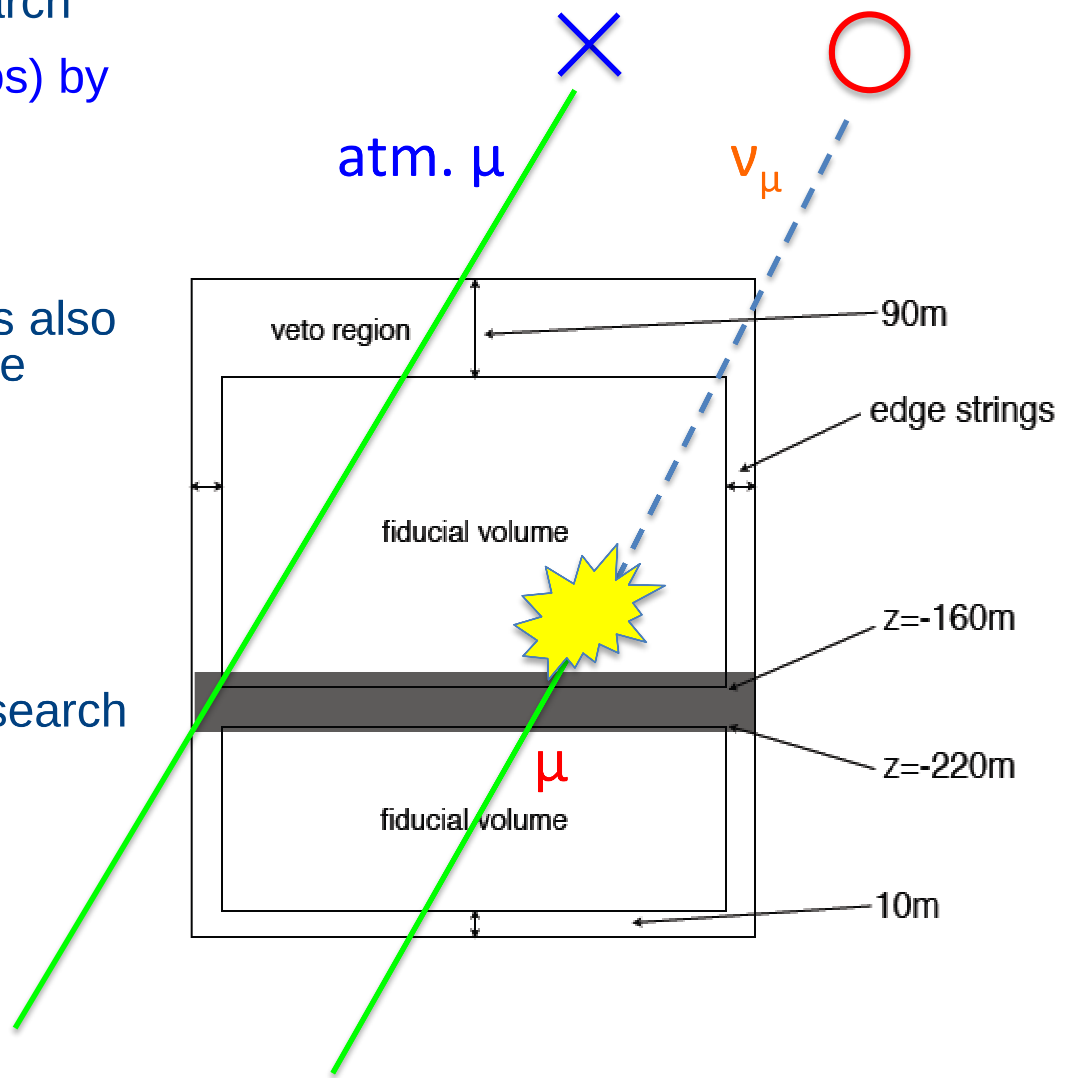
PRD 88, 112008 (2013)



differential limit per one energy decade

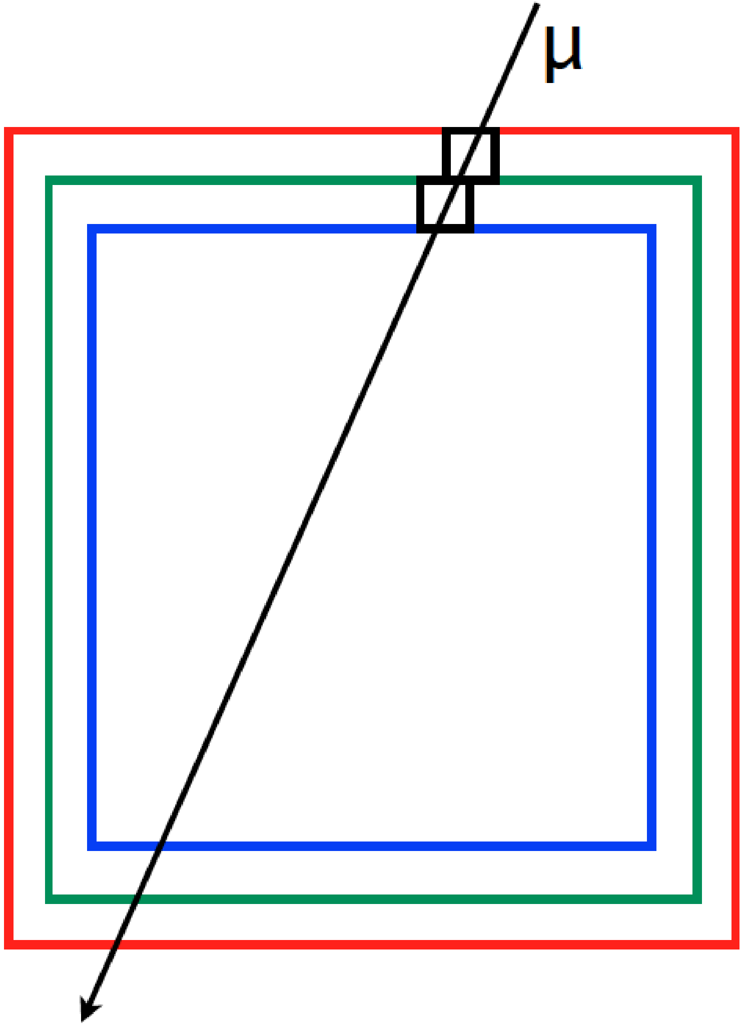
High energy starting event search

- Follow-up of the EHE neutrino search
- Search contained events (neutrinos) by using outer layers as veto
- Atmospheric muon backgrounds reduced
- Atmospheric neutrino backgrounds also reduced as atmospheric muons are normally accompanied
- 420 Mton fiducial mass
- All flavor
- > 30 TeV
- 3 times better than EHE neutrino search @ 1 PeV



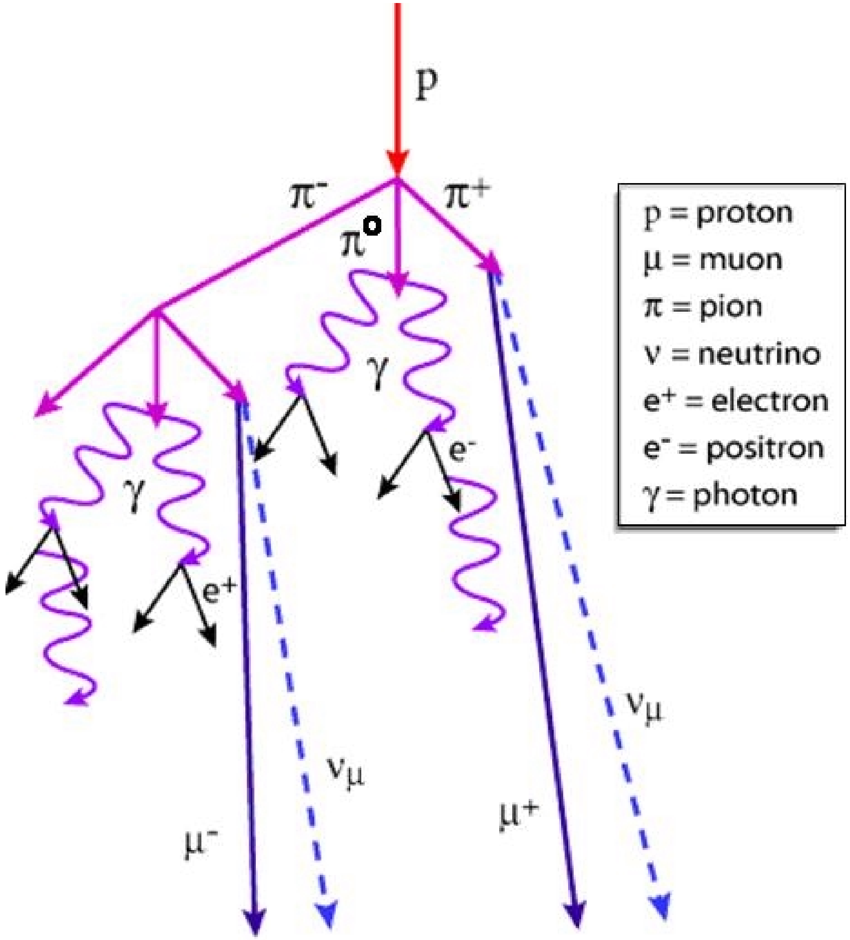
Atmospheric muon background

- Dominant down-going background
- Estimated by using data
- Second veto layer introduced
- veto power: at least 3 orders of magnitude
- 4 muon events passed the inner layer
→ 8.4 ± 4.2 events / 3 years with geometrical volume correction



Atmospheric neutrino background

- Low rate at PeV energy (0.1 event/year)
- Reduced by 70% by the muon veto
- Uncertainty ~30% from CR composition and hadronic interaction
- Large uncertainty from unmeasured charm contribution Enberg et al. (2008) employed (NLO perturbative QCD)
- Estimated bg rate: $6.6^{+5.9}_{-1.6}$ events / 3 years



Deposited energy and zenith angle distributions

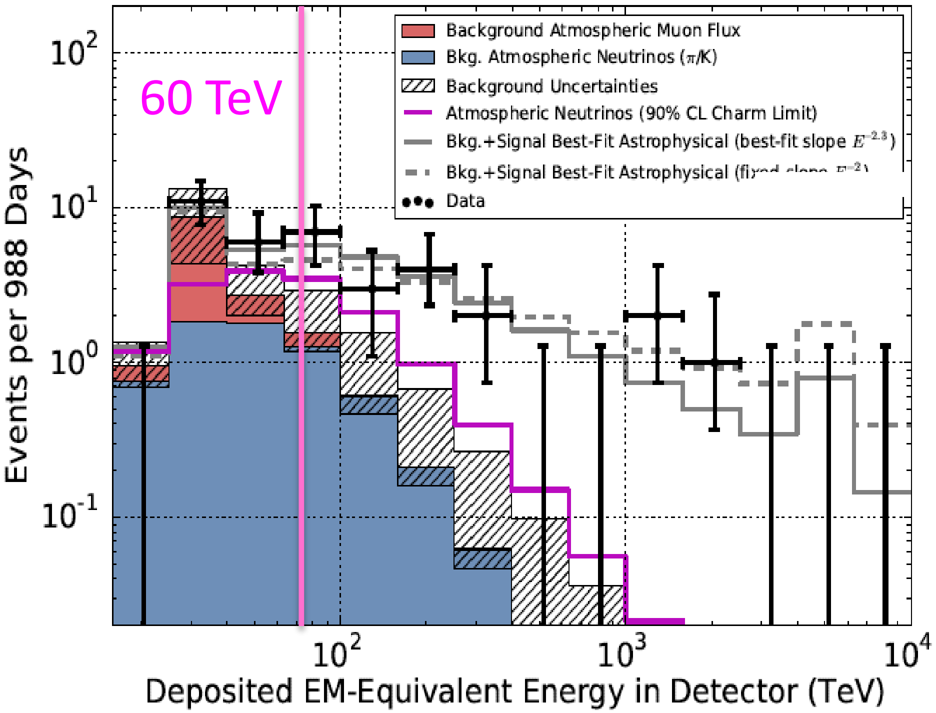
Other 37 events found! (28 cascades, 9 tracks) 3 year data

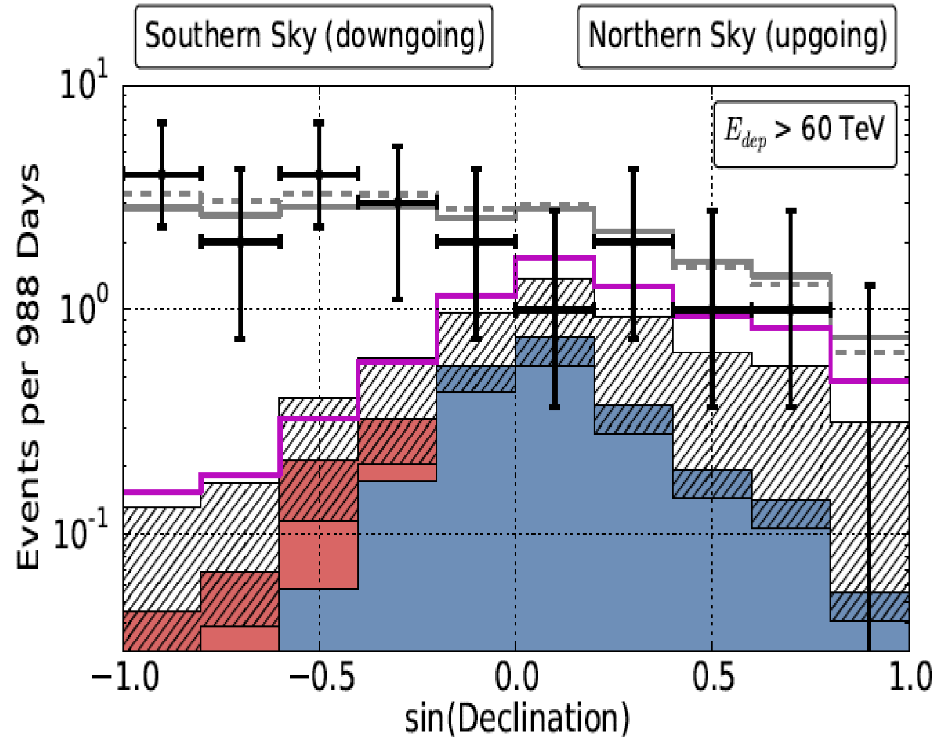
Significance: 5.7σ

arXiv:1405.4303

Expected BG: 15.0

E > 60 TeV

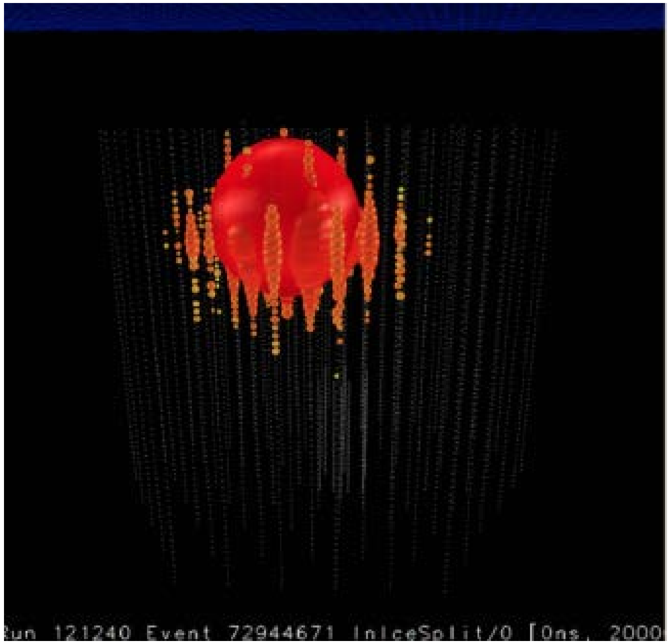


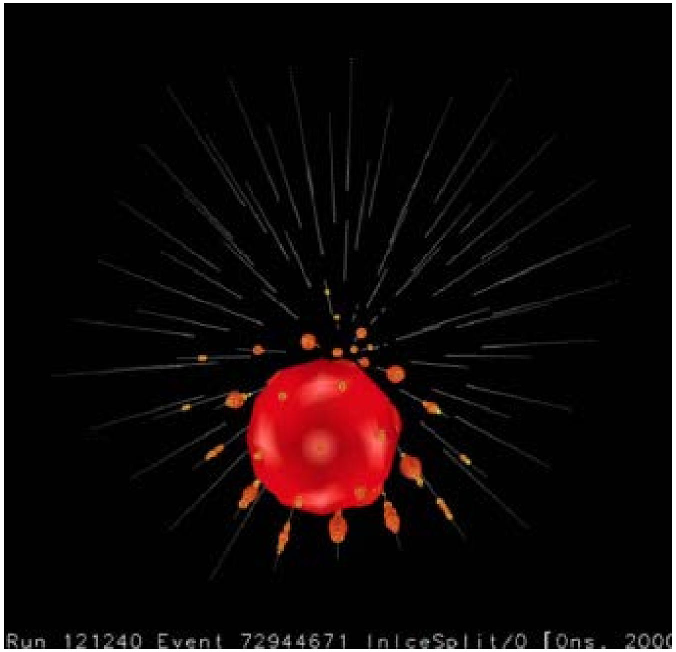


- Energy spectrum harder than that of backgrounds
- Spectral index: -2.0 ~ -2.3
- $E^2\varphi = 0.95 \pm 0.3 \times 10^{-8}$ GeV/cm^2/s/sr (per flavor)

Big Bird

- Another PeV event found in the 2012 data
- 2.0 PeV
- The highest energy neutrino!





Sky map and the significance

Test null hypothesis against the most likely

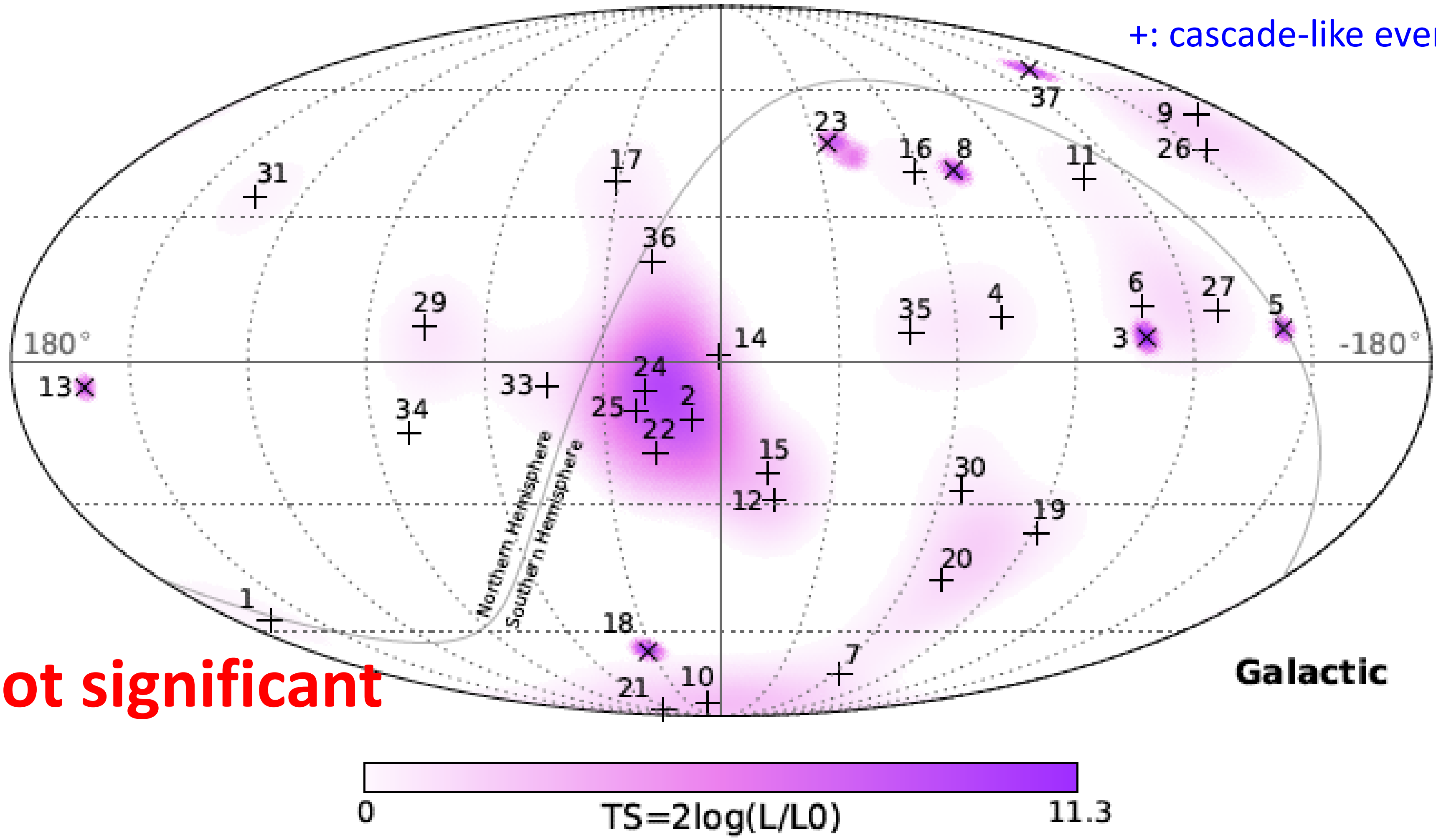
L0: null hypothesis

L: maximized likelihood

arXiv:1405.4303

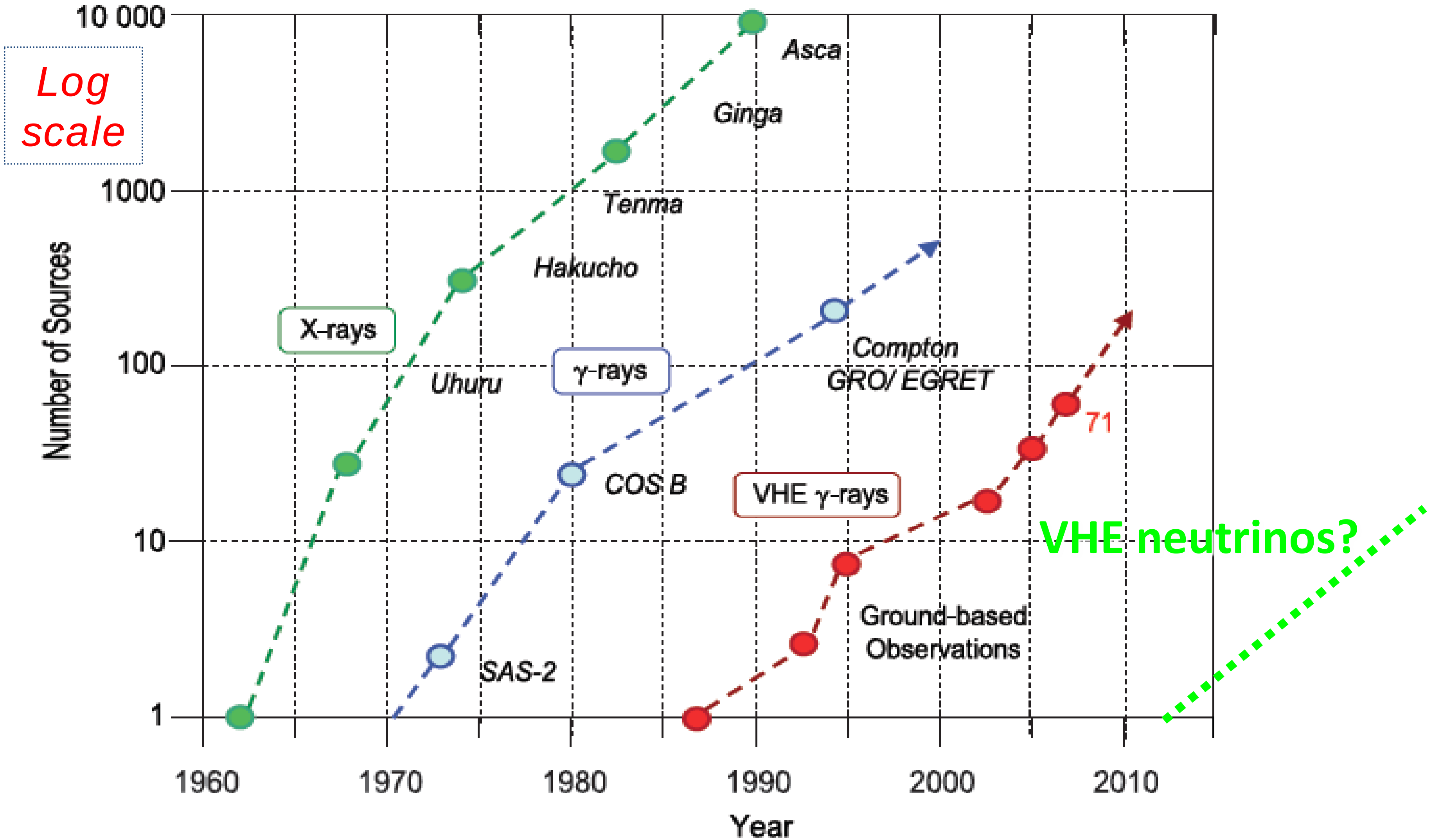
x: track-like events

+: cascade-like events



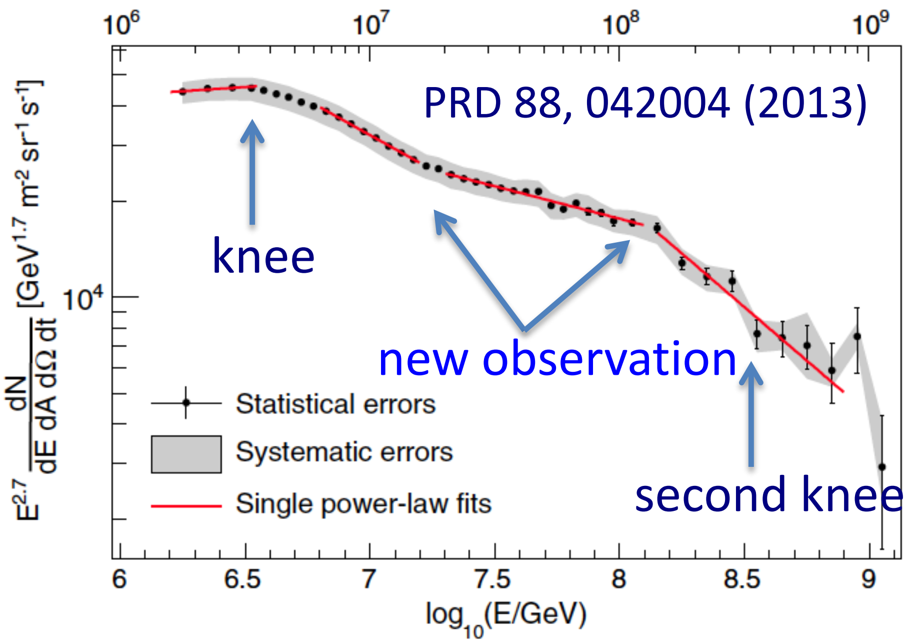
Not significant

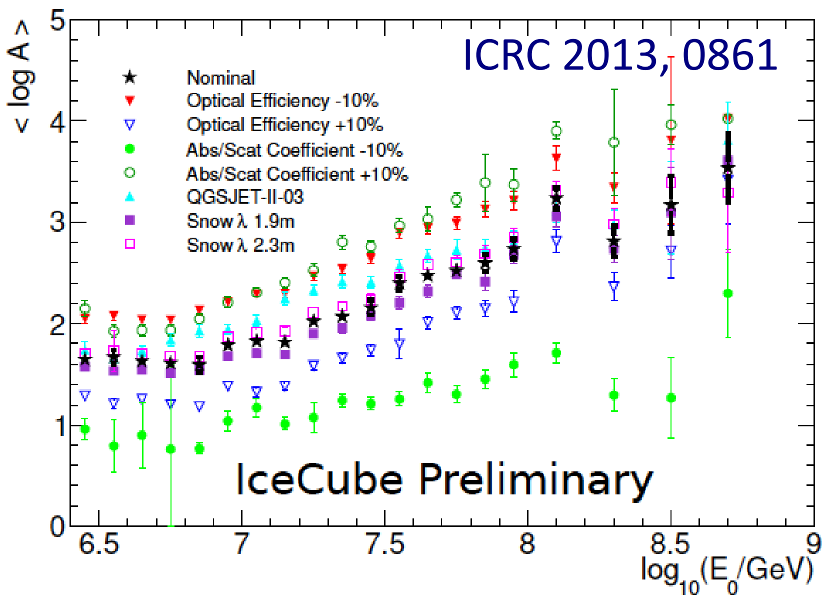
How Kifune plot will be for VHE neutrinos?



First detection is most important!

Cosmic ray measurements by IceTop

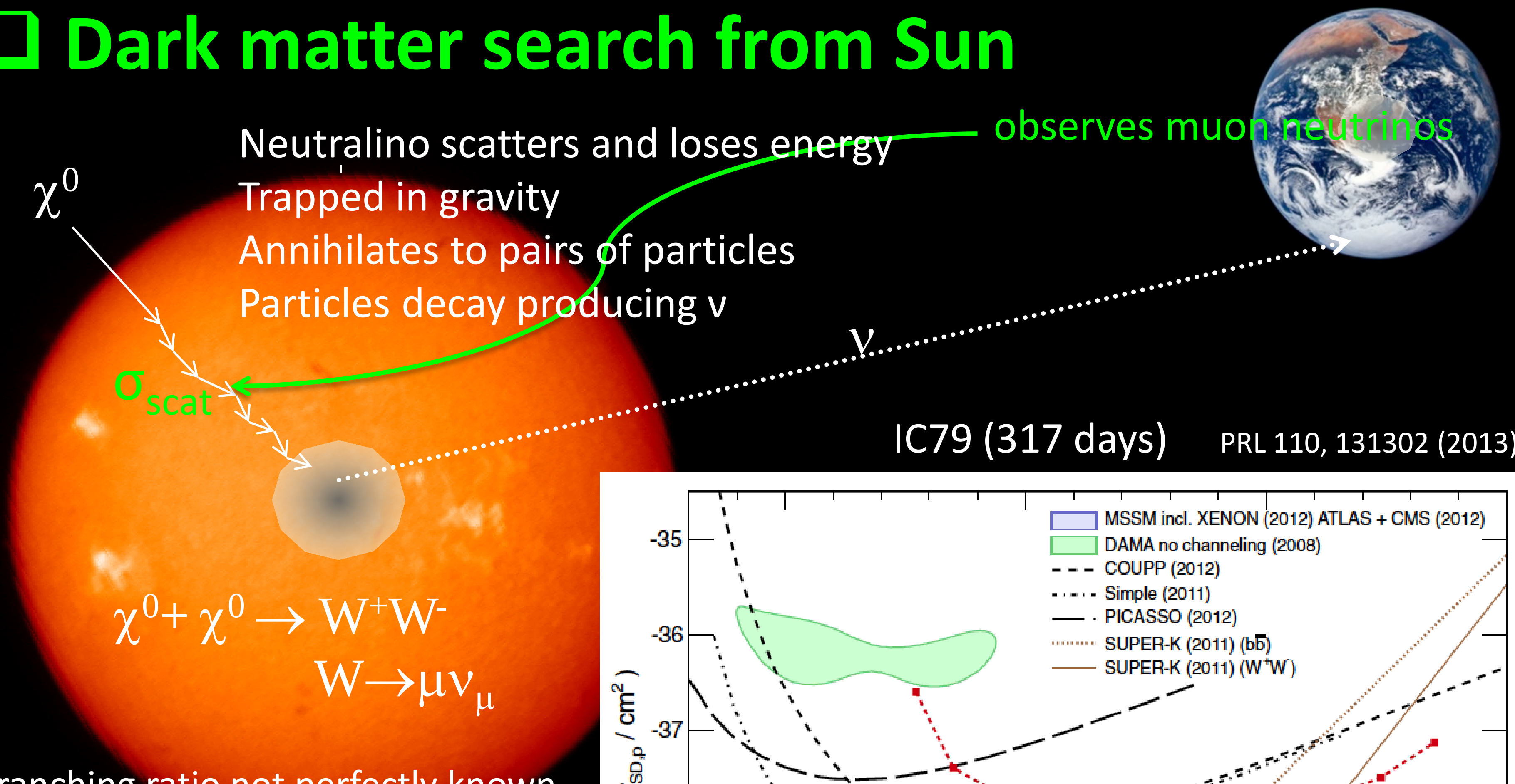




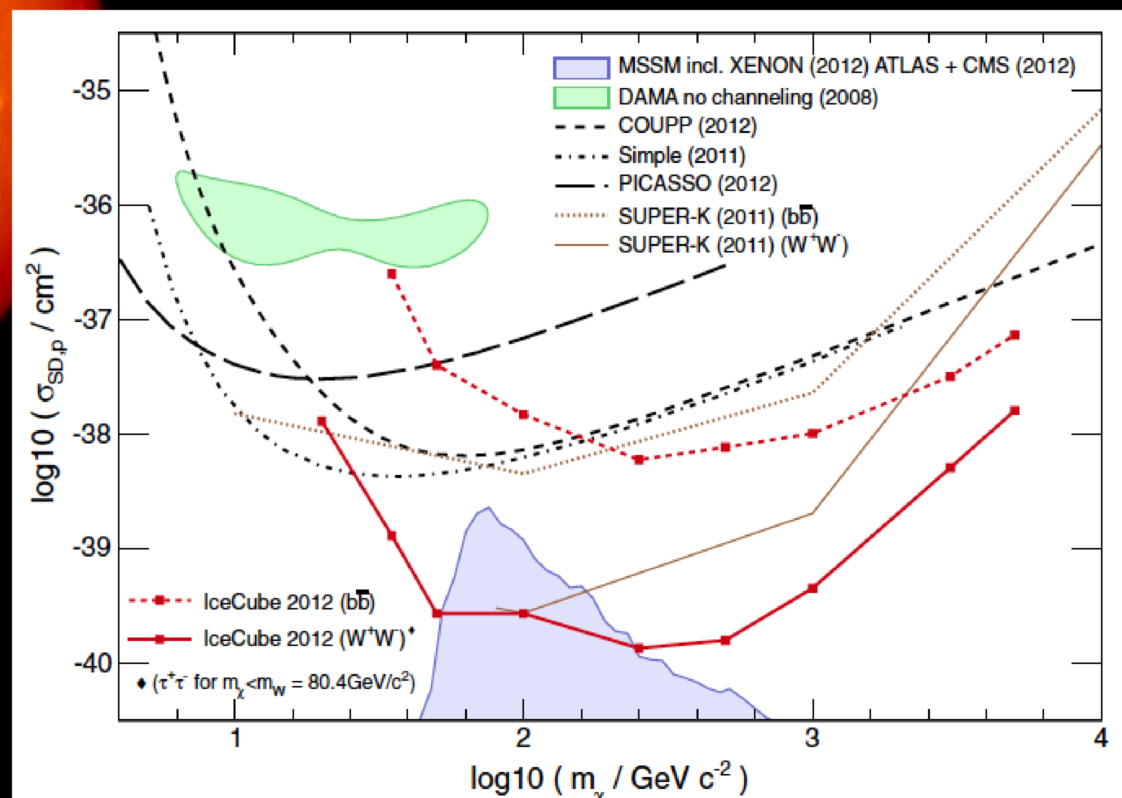
- 1 year cosmic ray energy spectrum measured by IceTop-73 configuration from 1.6 PeV to 1.3 EeV
- Precise measurement: uncertainty 12% above 10 PeV
- Consistent with other experiments
- 4 characteristic energy slopes found
- May indicate composition change
- Mass number increases with energy up to 100 PeV

❑ Dark matter search from Sun

Neutralino scatters and loses energy
Trapped in gravity
Annihilates to pairs of particles
Particles decay producing ν



IC79 (317 days) PRL 110, 131302 (2013)



Branching ratio not perfectly known

$\chi^0 + \chi^0 \rightarrow W^+W^-$ (hard channel, typical)

$\chi^0 + \chi^0 \rightarrow b\bar{b}$ (soft channel, conservative)

χ^0: neutralino

Supersymetry particle

Mixture of super-partner of zino, photino, higgsino

❑ Dark matter search in the Milky Way

$$\frac{d\Phi_\nu}{dE} = \frac{<\sigma_A \upsilon>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

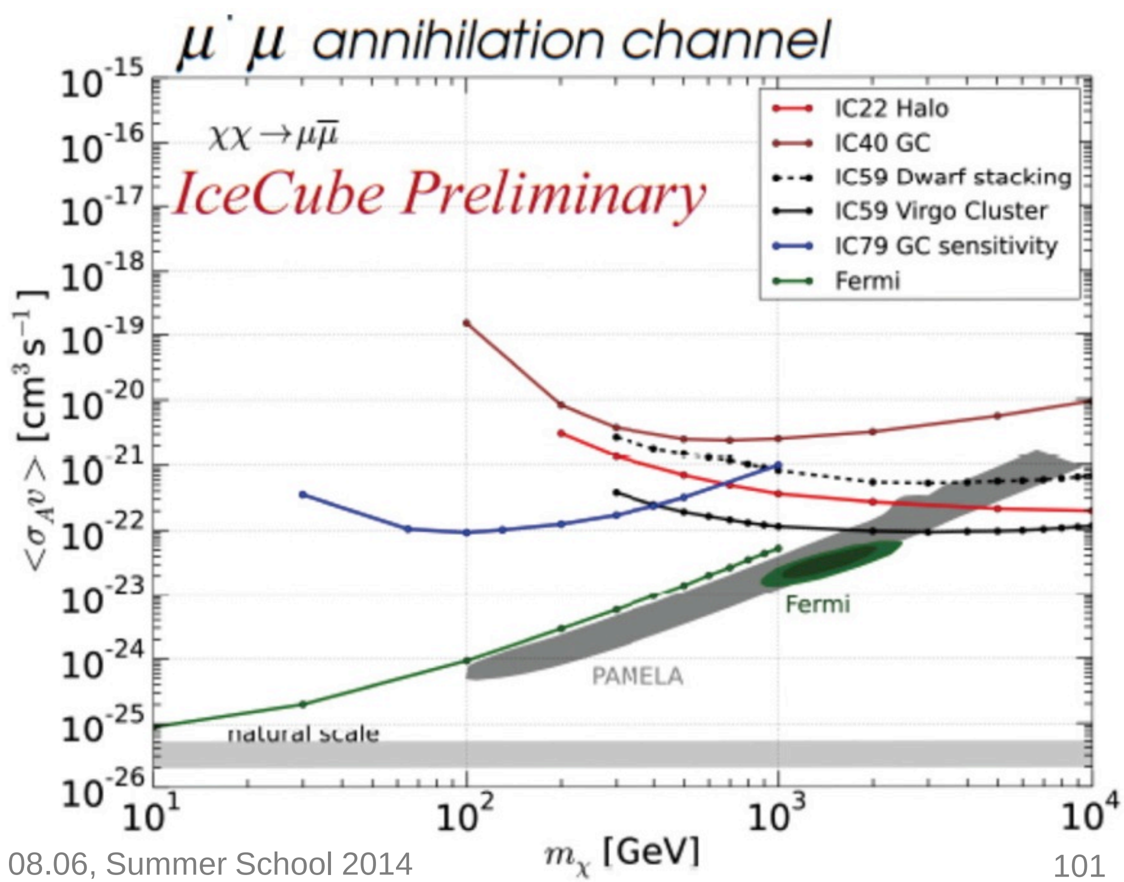
Dark matter density profile
(model dependent.
NFW model as benchmark.)

SUSY model (model dependent)

Measure of muon neutrinos

cross section to be constrained

IC79 (320 days)
found no excess



Neutrino oscillation

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = M(3\times 3) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Flavor eigen state   Mass eigen state

In case of 2 flavors

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Time evolution

$$|\nu_1(t)\rangle = e^{-iE_1 t}|\nu_1(t=0)\rangle$$

$$|\nu_2(t)\rangle = e^{-iE_2 t}|\nu_2(t=0)\rangle$$

$$|\nu(t)\rangle = e^{-iE_1 t}\cos\theta|\nu_1\rangle + e^{-iE_2 t}\sin\theta|\nu_2\rangle$$

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix}$$

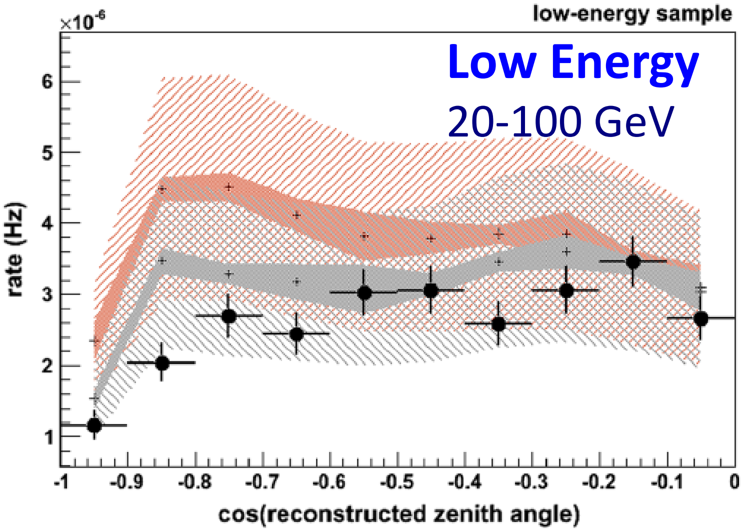
$$|\nu(t)\rangle = \left[e^{-iE_1 t}\cos^2\theta + e^{-iE_2 t}\sin^2\theta\right]|\nu_\alpha\rangle + \cos\theta\sin\theta\left[e^{-iE_2 t} - e^{-iE_1 t}\right]|\nu_\alpha\rangle$$

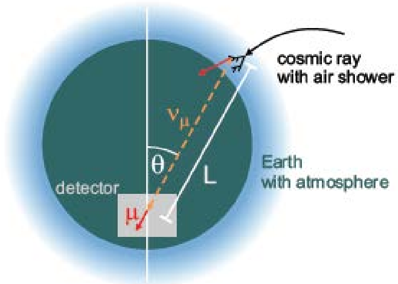
$$P(\nu_\alpha \to \nu_\beta) = \left|\langle \nu_\beta | \nu(t)\rangle\right|^2 = \sin^2 2\theta \sin^2\left(1.27 \times \Delta m^2 \frac{L}{E}\right)$$

Atmospheric neutrino oscillation

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}L/E)$$

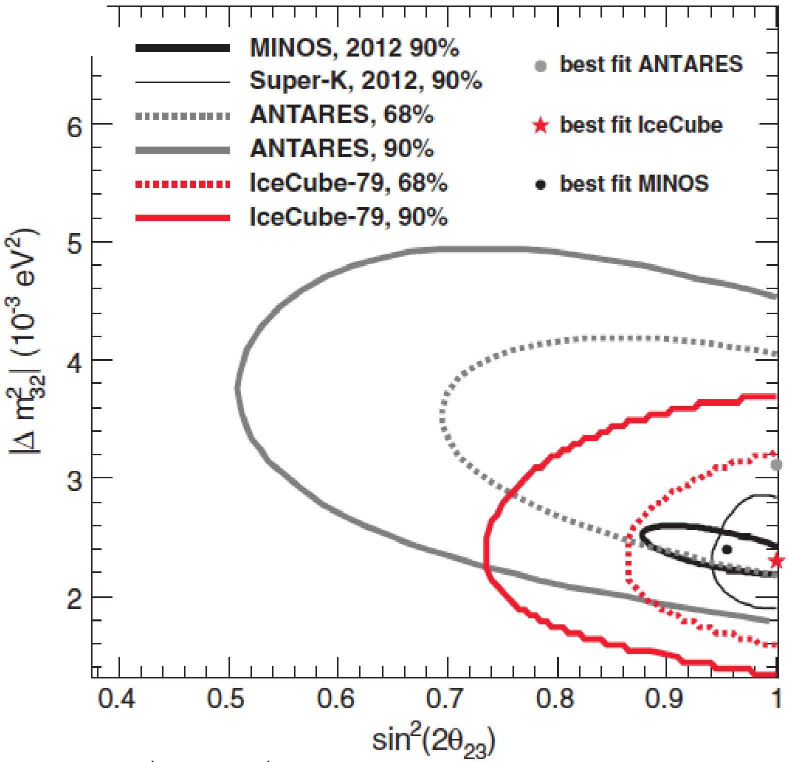
PRL, 111, 081801 (2013)

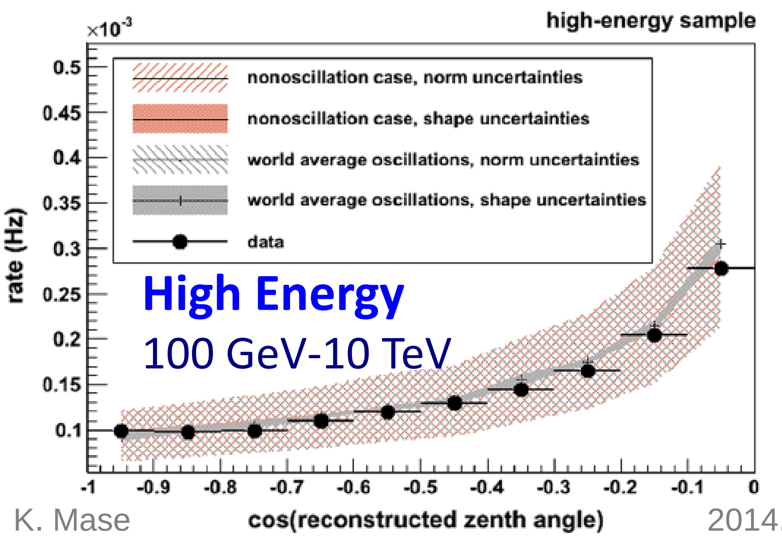




No oscillation scenario rejected by 5.6σ

IC79 (318.9 days)



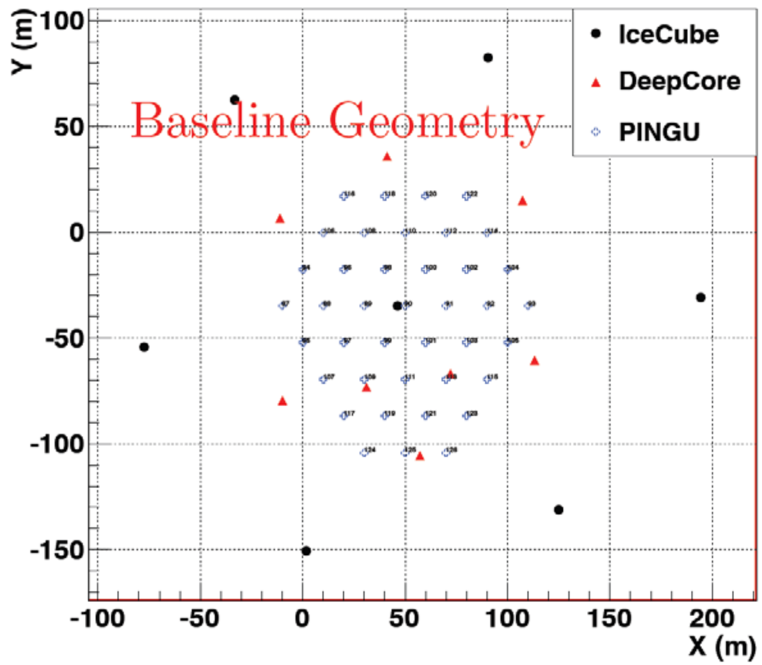


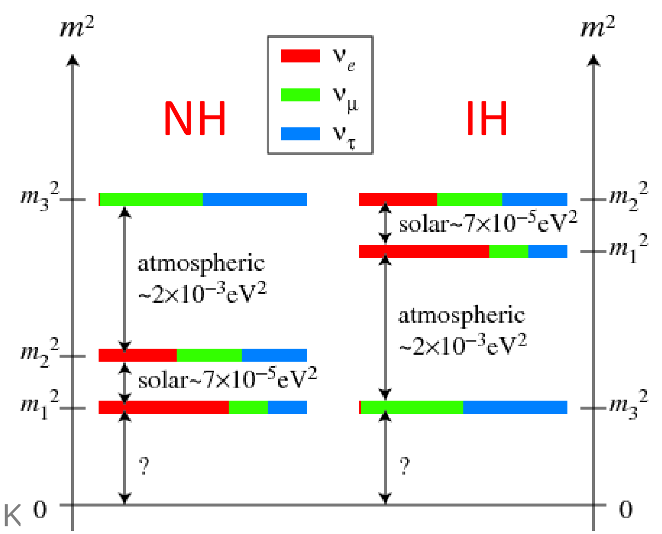
$$\left|\Delta m^2_{32}\right| = (2.3^{+0.6}_{-0.5})\times 10^{-3}\ eV^2$$
$$\sin^2(2\theta_{23}) > 0.93\ (68\%\ C.L.)$$

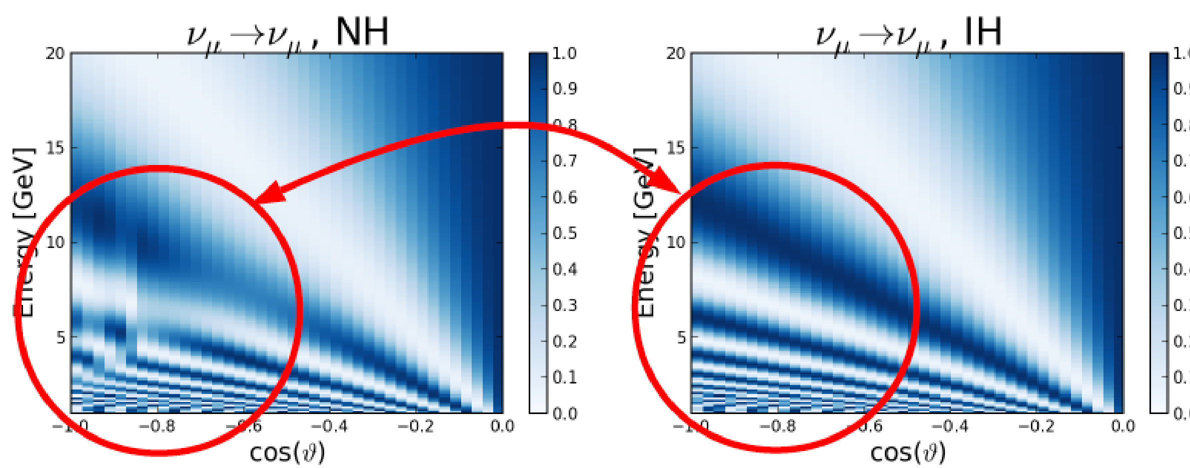
■ Part-4: 次期計画

Precision IceCube Next Generation Upgrade (PINGU)

- High detector density (40 strings with 20 m spacing)
- Energy threshold: a few GeV
- Measures neutrino mass hierarchy by the precise measurements of 3 flavor neutrino oscillation
- Normal mass hierarchy with 3 sigma after 3.5 years
- Resolutions: ΔE ~ 20%, Δθ ~ 10° (depends on energy and flavor)







High energy extension

Increase the sensitivity at high energy (> 10 TeV)

IceCube (120 m): 1 km^2

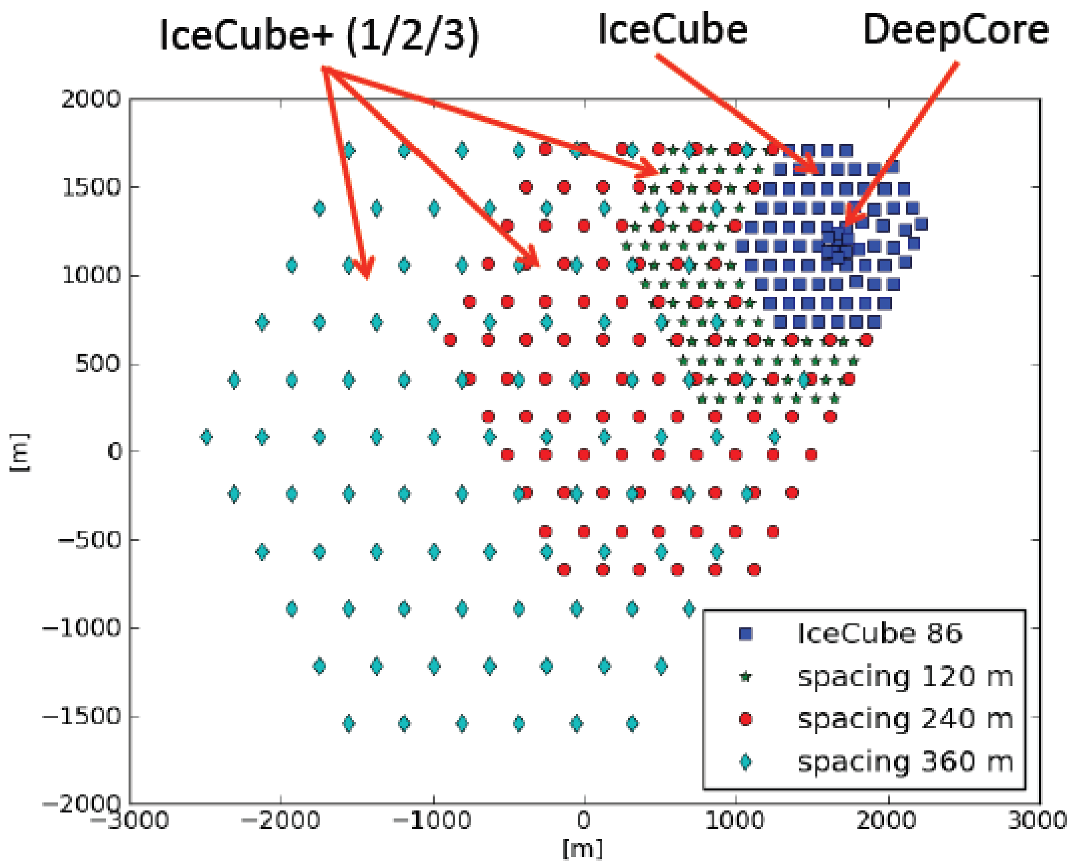
+HEX (120 m): 2.3 km^2

+HEX (240 m): 6.3 km^2

+HEX (360 m): 12.6 km^2

The optimization is on-going

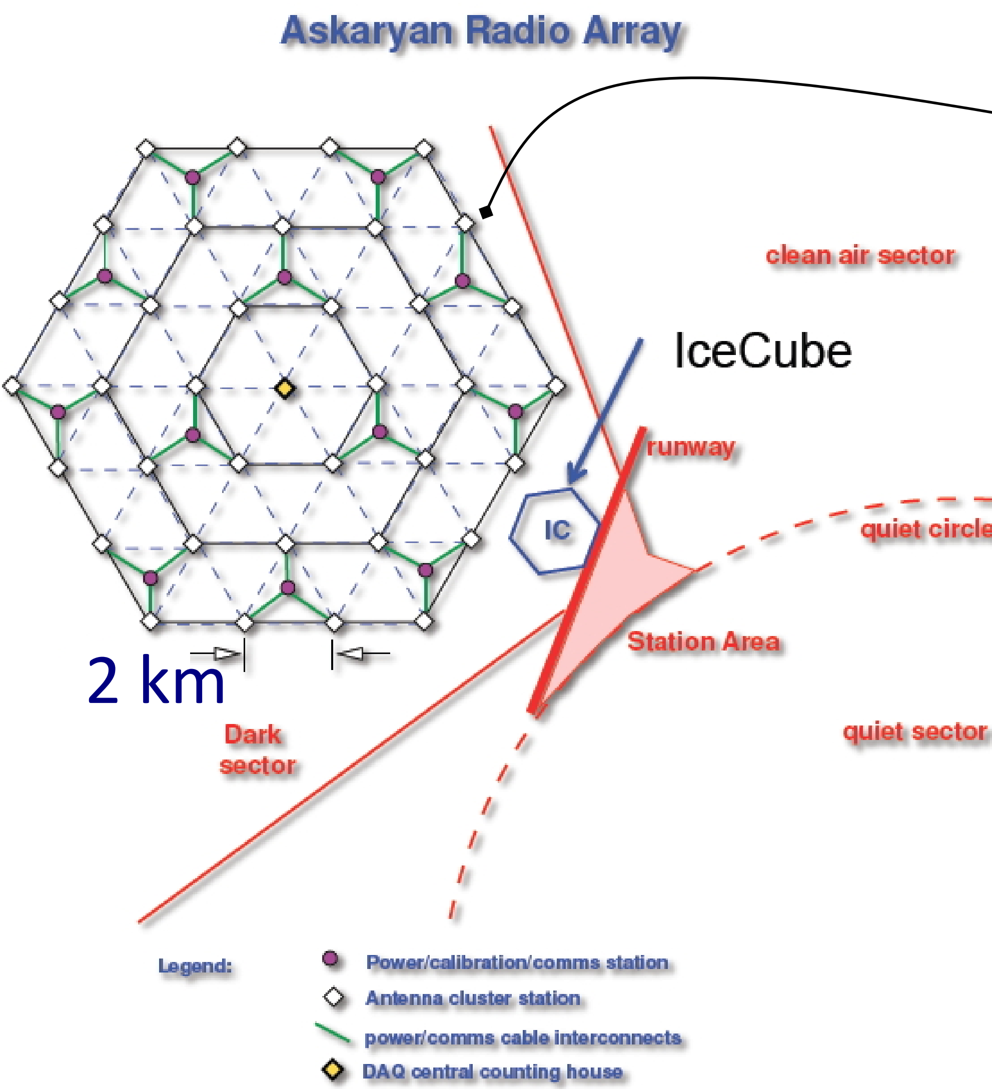
Additional idea to extend
surface tanks for veto

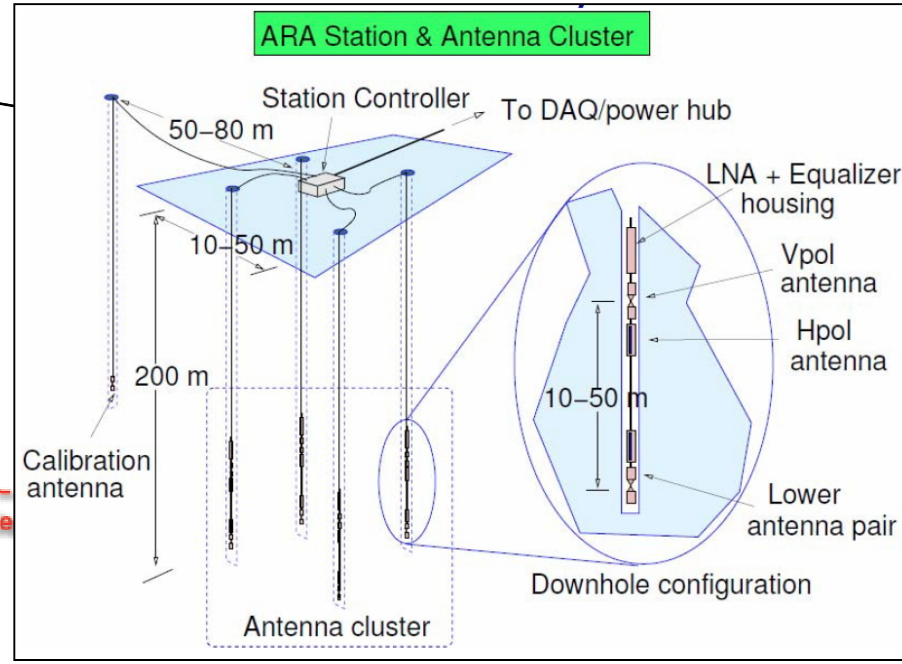


~100 new strings

Askaryan Radio Array (ARA)

Astroparticle Physics **35** (2012) 457–477





37 stations

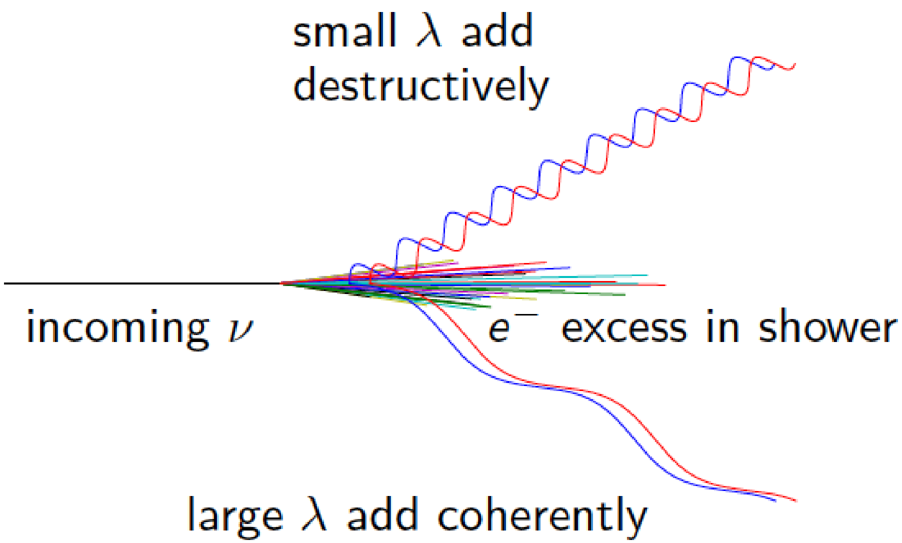
- Each cluster has 4 strings of 200m depth
- Each string has 2 Vpol + 2Hpol broadband antennas (200–800 MHz)
- **Total surface area ~200 km^2**

Askaryan effect

✧ 1962: Askaryan predicted coherent radio emission from excess negative charge in an EM shower (~20% due to mainly Compton scattering and positron annihilation)

→ **Askaryan effect**

G. Askaryan



Shower size << λ to be coherent

Cherenkov emission (Frank-Tumm result)

$$\frac{d^2W}{d\nu dl} = \frac{4\pi^2\hbar}{c}\alpha z^2 \nu \left(1 - \frac{1}{\beta^2 n^2}\right)$$

in case N electrons,

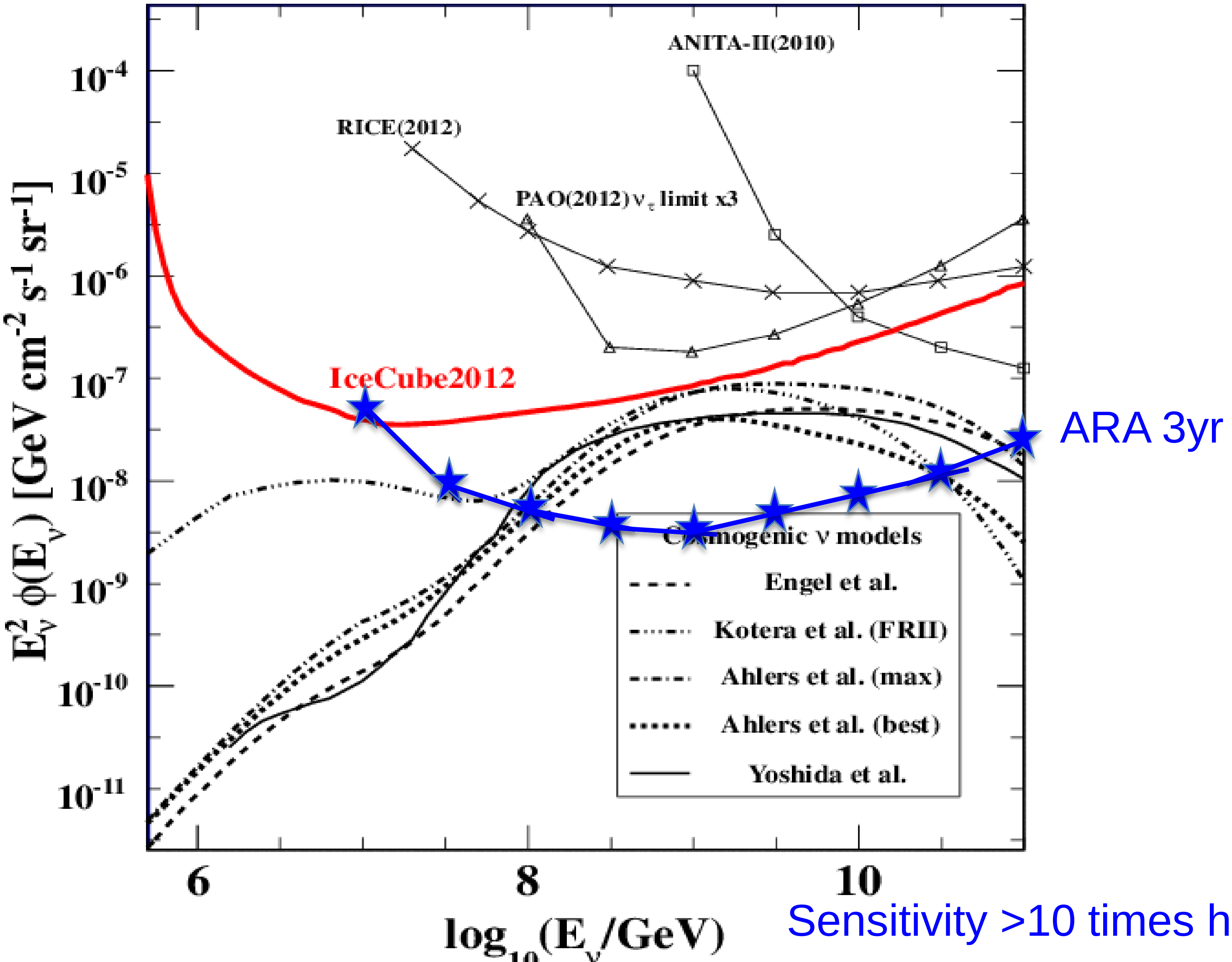
z=1 (not coherent) → W ∝ N

z=N (coherent) → W ∝ N^2

Power ∝ Δq^2, thus prominent at EHE (>~ 10 PeV)

Attenuation length in ice ~ 1 km

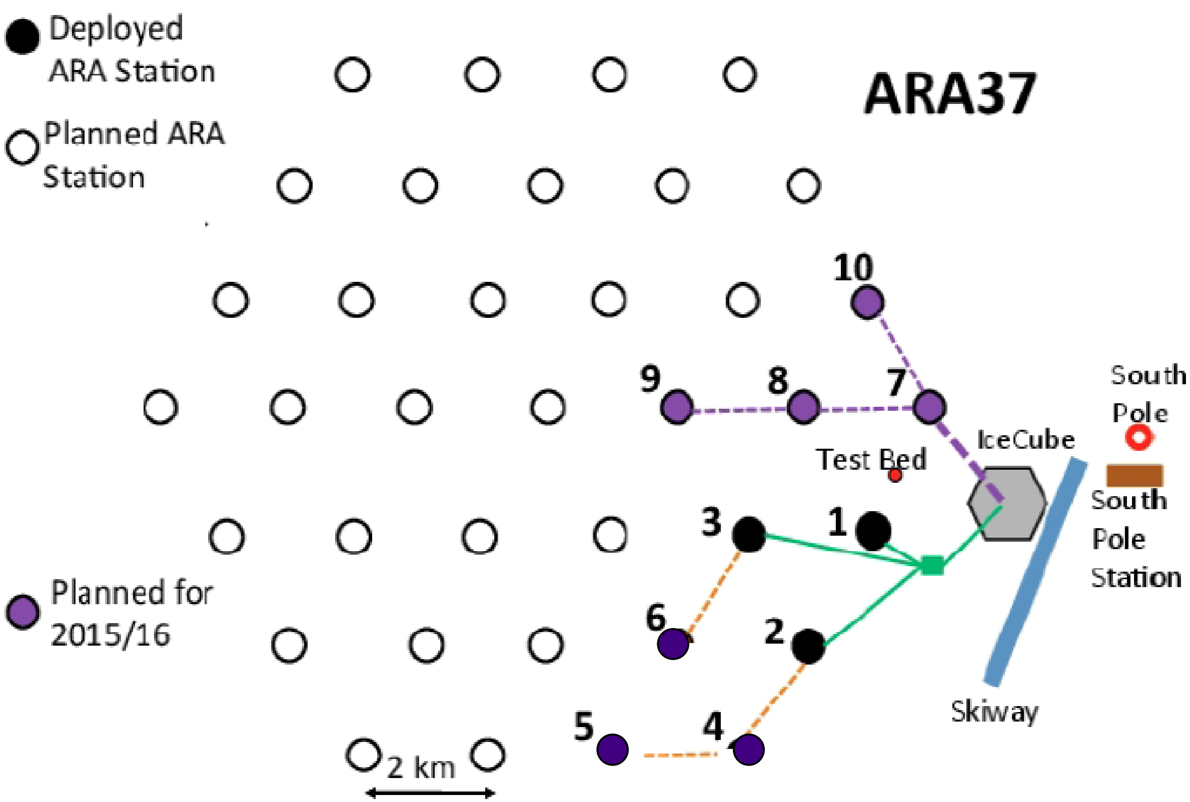
The ARA sensitivity



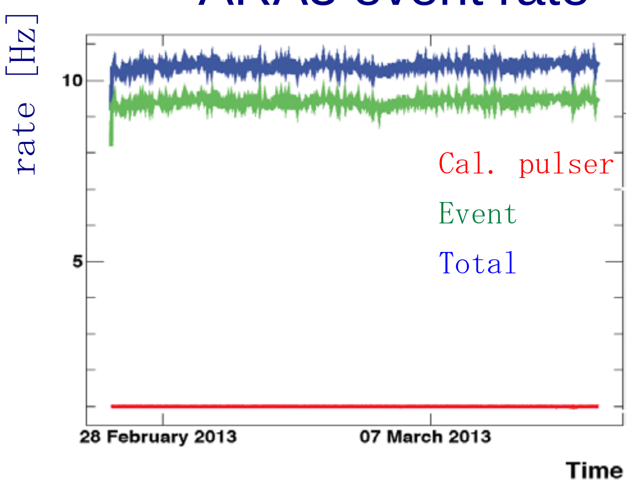
Sensitivity >10 times higher

>~10 events/yr

Current status and further plan



ARA3 event rate



- ✧ 3 stations operational
- ✧ More to come

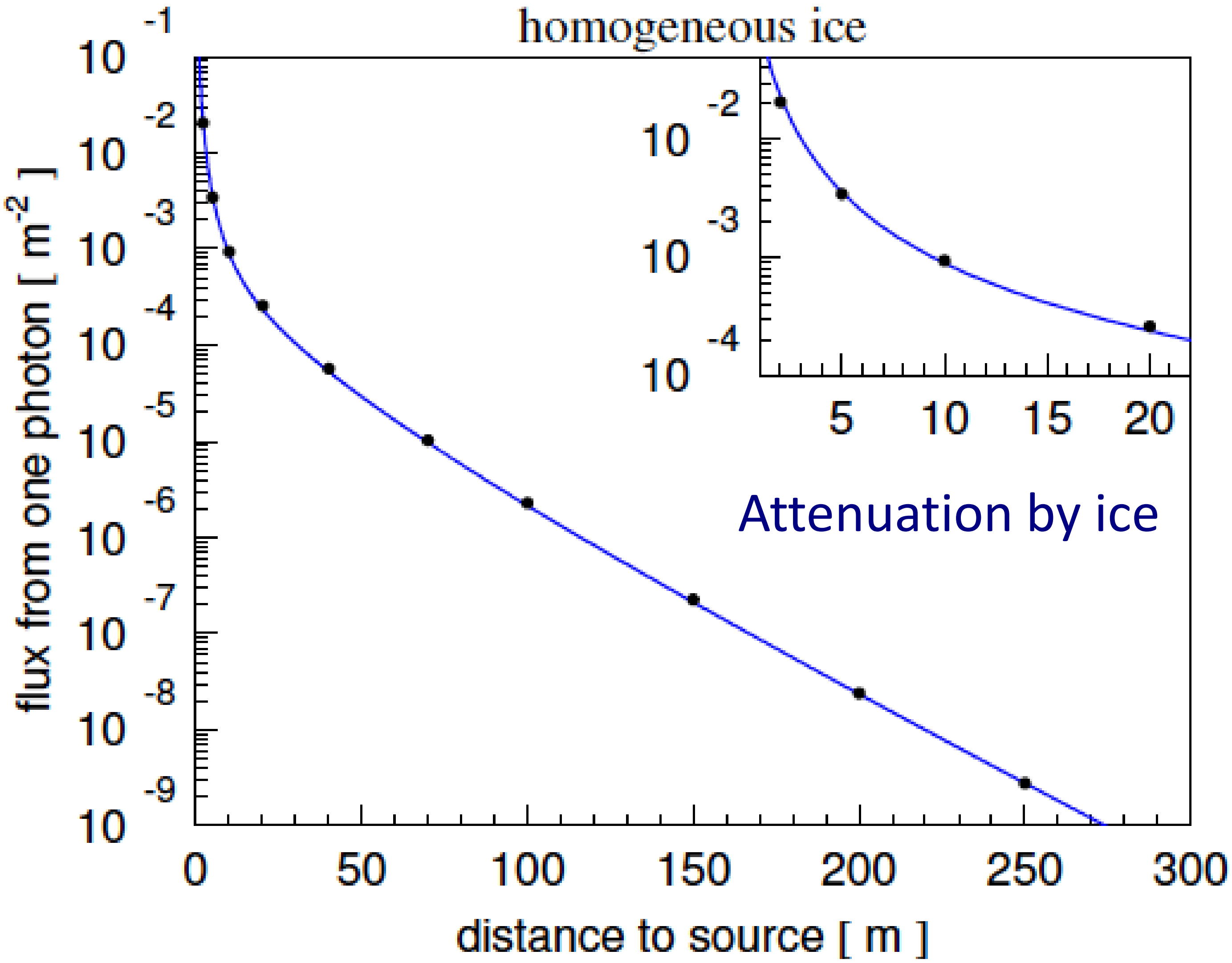
❑ Summary

- 宇宙は地上で行えない理論検証、新発見の格好の場
- IceCubeはバックグラウンドではない宇宙からのニュートリノを検出
→ ニュートリノ天文学の幕開け
- IceCubeは素粒子物理にも寄与する
- 長年謎に包まれた宇宙線起源に迫る

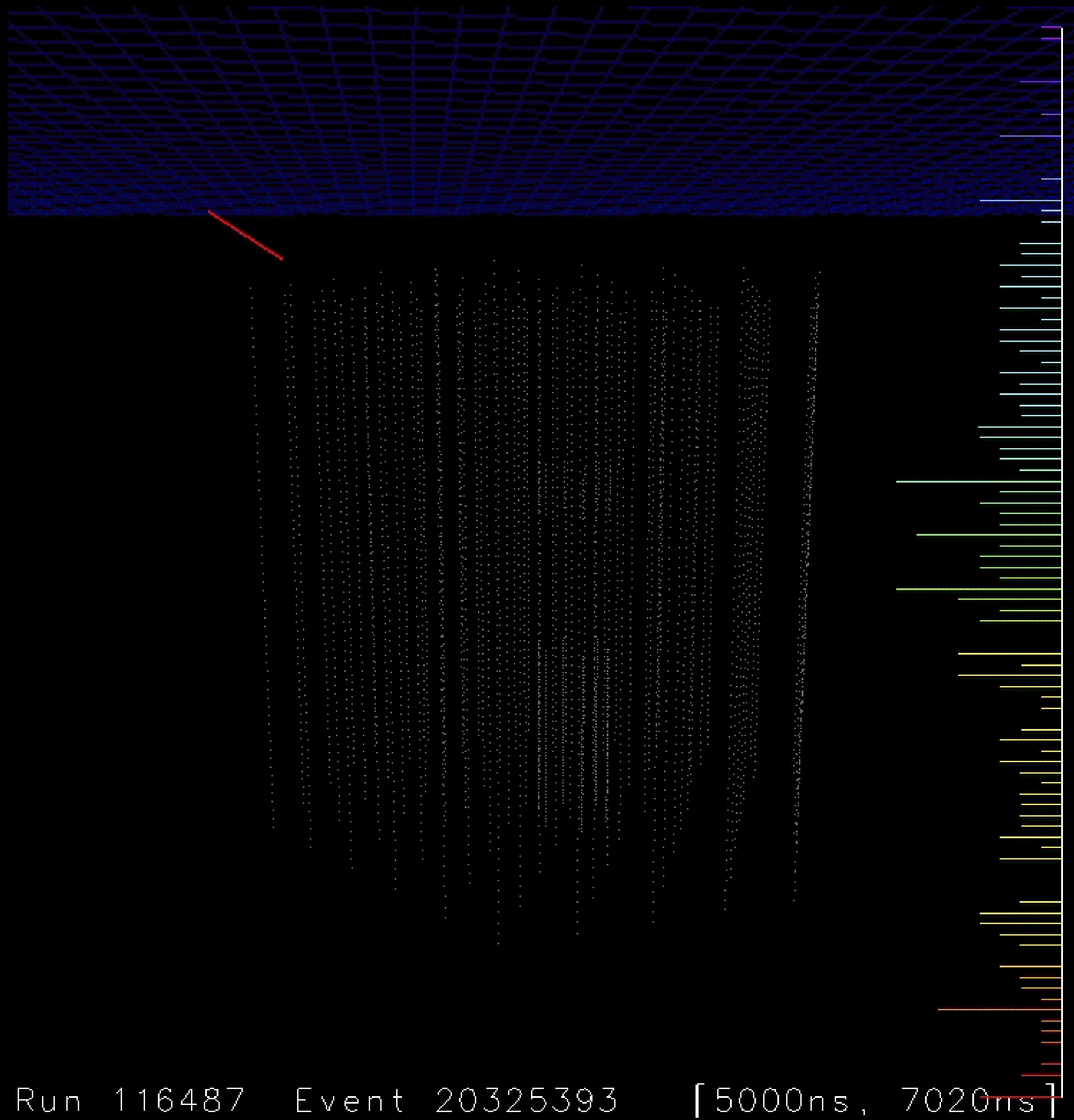
氷を掘ると宇宙、素粒子が見える？

backups

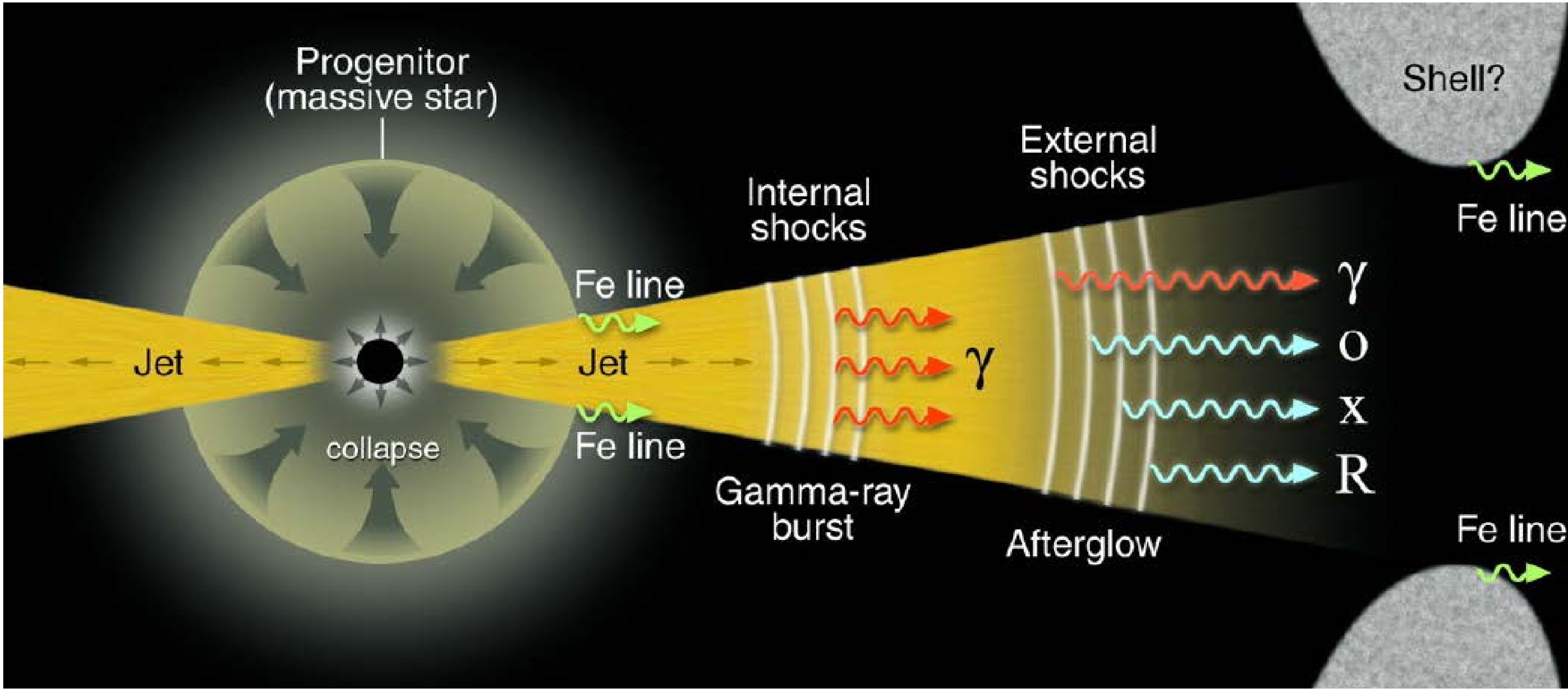
Light yield vs. distance for a point-like source



■実際のデータ



■ ガンマ線バースト（GRBs）



Likelihood method translates events on the sky into p-values

Signal: Astrophysical neutrinos clustering in space
Background: Isotropic atmospheric neutrinos

Maximize the likelihood function:

$$\mathcal{L}(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} \mathcal{S}_i(\gamma) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}_i \right)$$

Braun et. al., arXiv: 0801.1604

Test statistic:

$$\lambda = \log\left(\frac{L(\hat{\gamma}, \hat{n}_s)}{L(n_s = 0)} \right)$$

Obtain **p-value** by comparing test statistic for real data to random trials from scrambled data

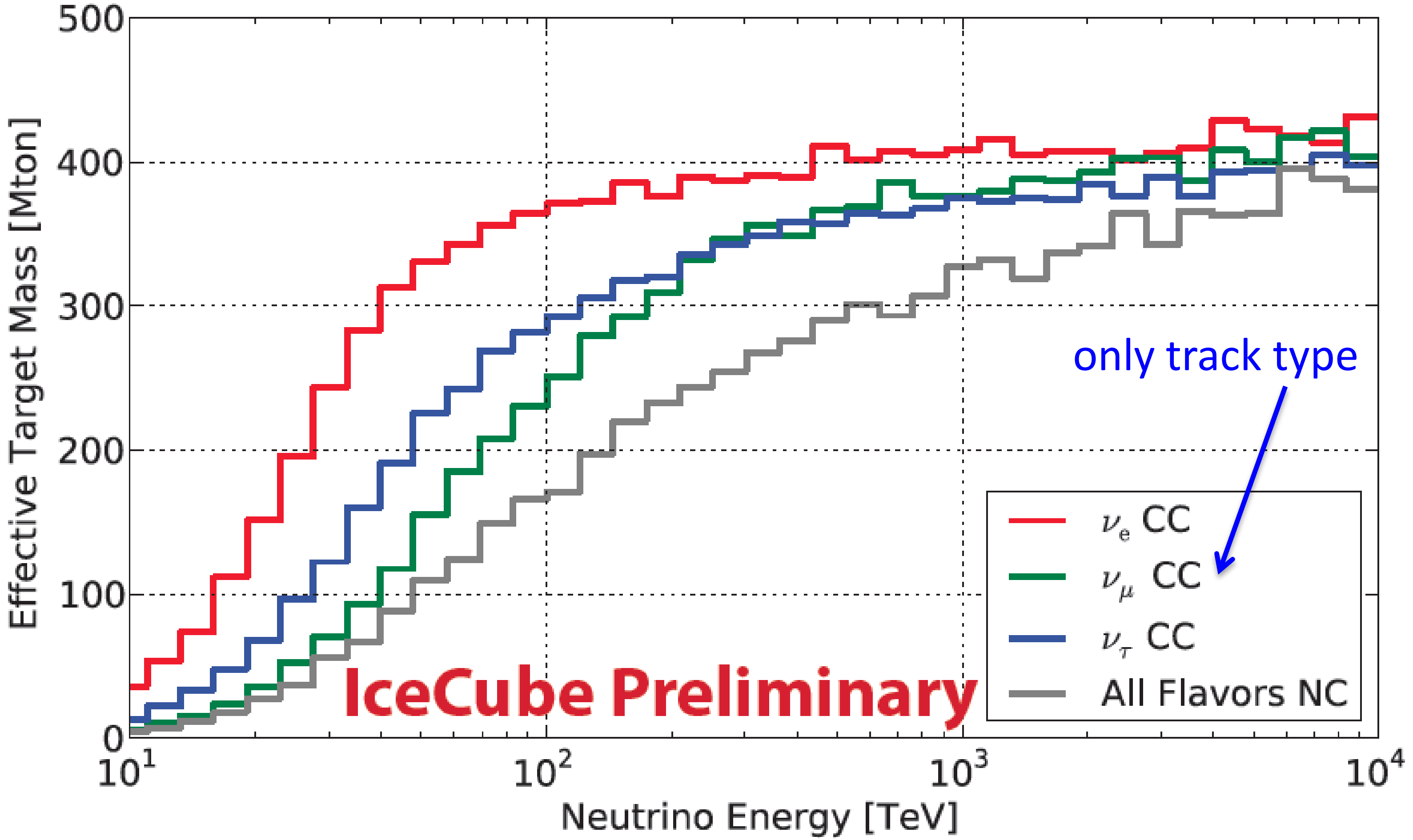
Fit for:
- **n_s**, # of signal events
- **γ**, neutrino spectral index

■ The systematic uncertainties

PRD 88, 112008 (2013)

Sources	Cosmogenic ν signal (%)	Atmospheric muon (%)	Conventional Atmospheric neutrino (%)	Prompt neutrino (%)	Total background (%)
Statistical error	± 0.4	± 9.1	± 9.8	± 1.1	± 4.5
DOM efficiency	$^{+1.5}_{-5.1}$	$^{+41.9}_{-42.7}$	$^{+73.2}_{-17.9}$	$^{+33.6}_{-9.6}$	$^{+43.1}_{-26.1}$
Ice properties/detector response	-7.2	-47.7	-44.8	-30.8	-41.7
Neutrino cross section	± 9.0	...	...	...	...
Photonuclear interaction	$+10.0$	...	...	...	...
LPM effect	± 1.0	...	...	...	...
Angular shift for cascades	-0.5	...	...	...	...
Cosmic-ray flux variation	...	$^{+30.0}_{-50.0}$	± 30.0	± 30.0	$^{+18.7}_{-26.3}$
Cosmic-ray composition	...	-79.1	...	...	-36.7
Hadronic interaction model	...	$+17.7$	...	...	$+8.1$
ν yield from cosmic-ray nucleon	...	...	± 15.0	...	± 2.2
Prompt model uncertainty	...	...	...	$^{+31.6}_{-40.4}$	$^{+12.6}_{-16.1}$
Total	± 0.4(stat)	± 9.1(stat)	± 9.8(stat)	± 1.1(stat)	± 4.5(stat)
	$^{+13.6}_{-12.4}$(syst)	$^{+54.5}_{-100}$(syst)	$^{+80.5}_{-58.7}$(syst)	$^{+55.0}_{-59.8}$(syst)	$^{+49.3}_{-68.7}$(syst)

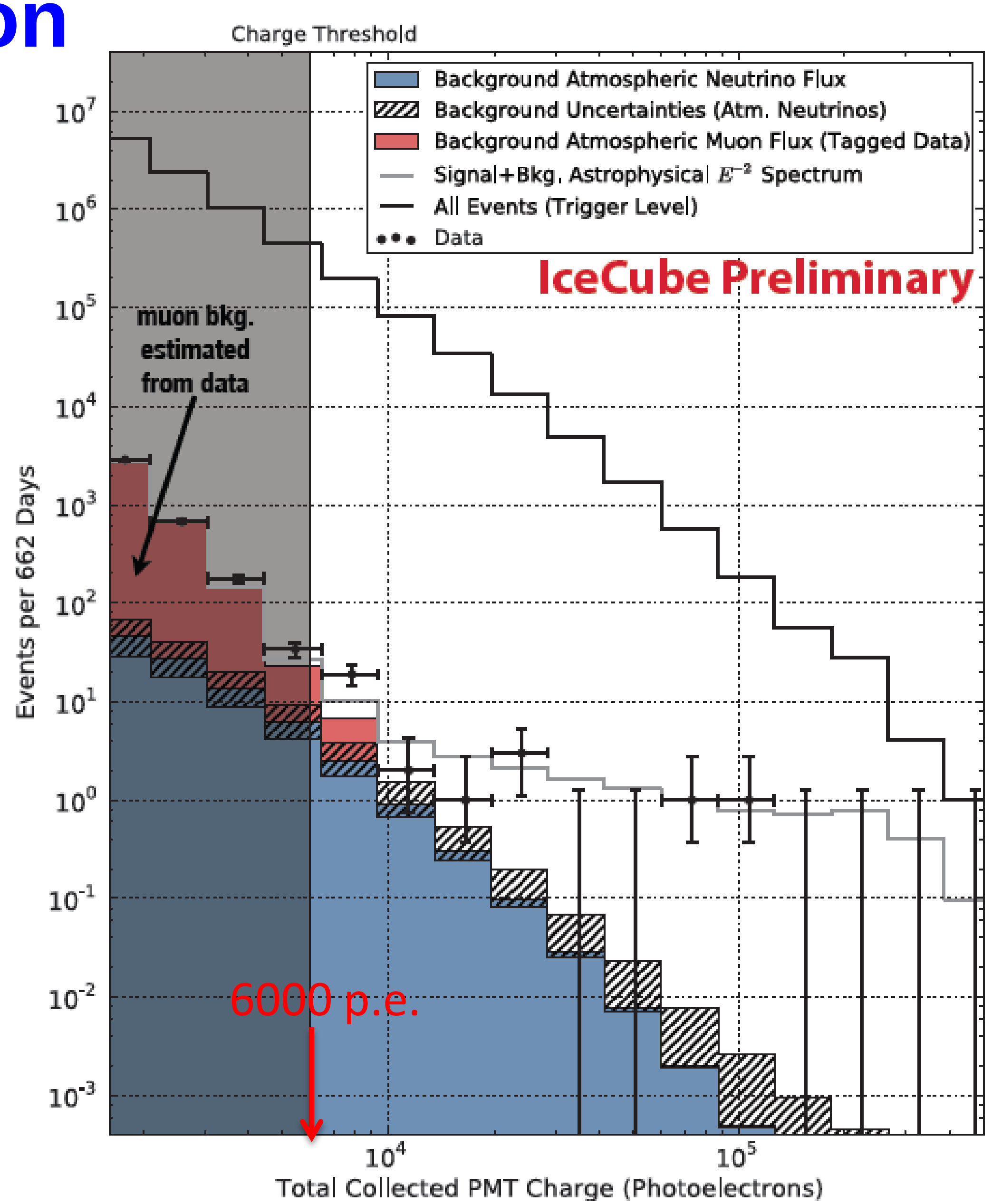
Effective volume



This analysis is more sensitive to cascade events

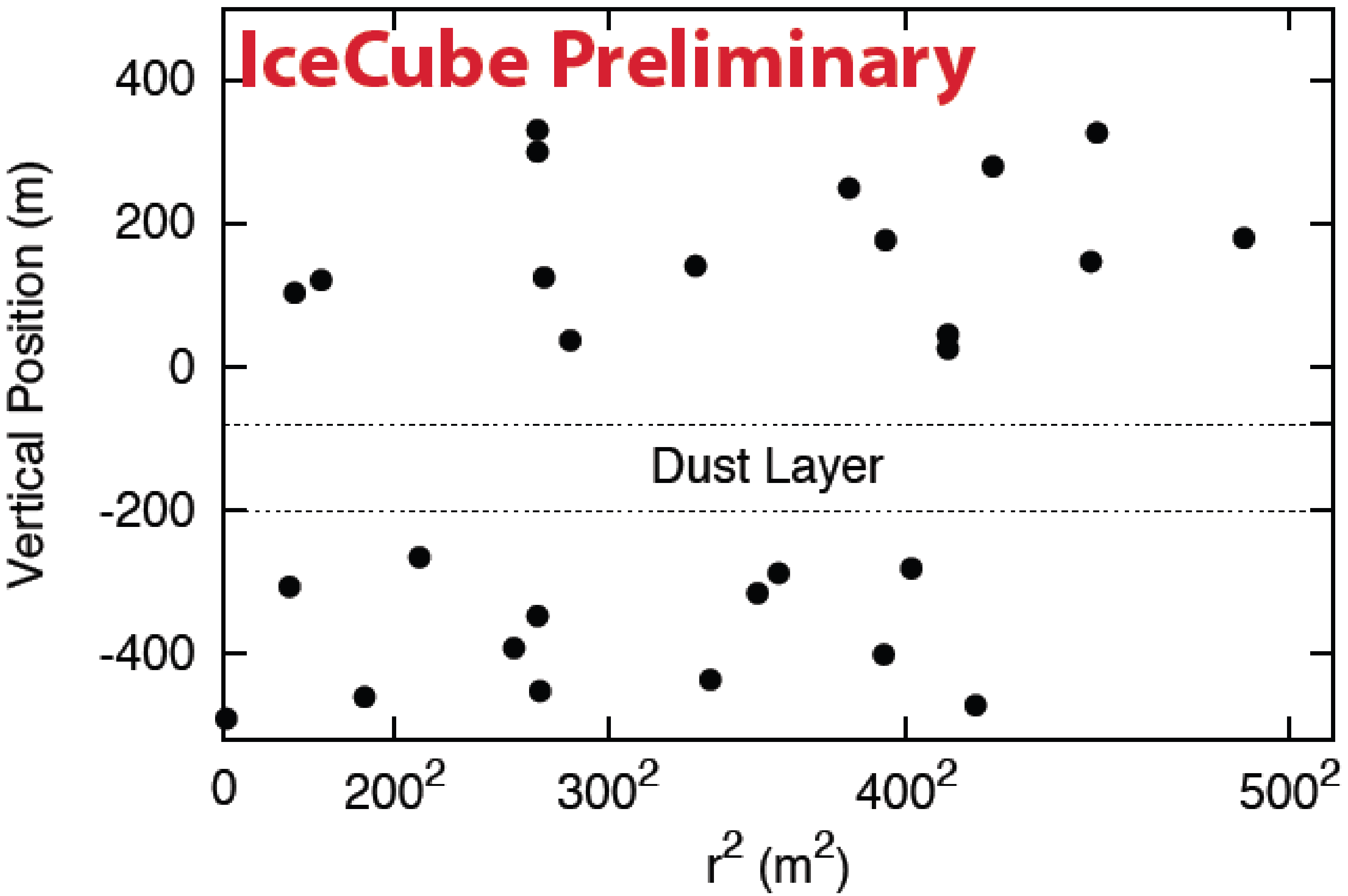
Charge distribution

- 28 events observed above selection criteria
- Total bg: $10.6^{+4.5}_{-3.9}$
- Significance: 3.3σ (HESE analysis alone wo two PeV events)
- Including EHE result (2.8 σ): 4.1σ
- A posteriori (including two PeV events): 4.8σ
- Atmospheric muons are largely reduced
- Data and MC agree well at low charge



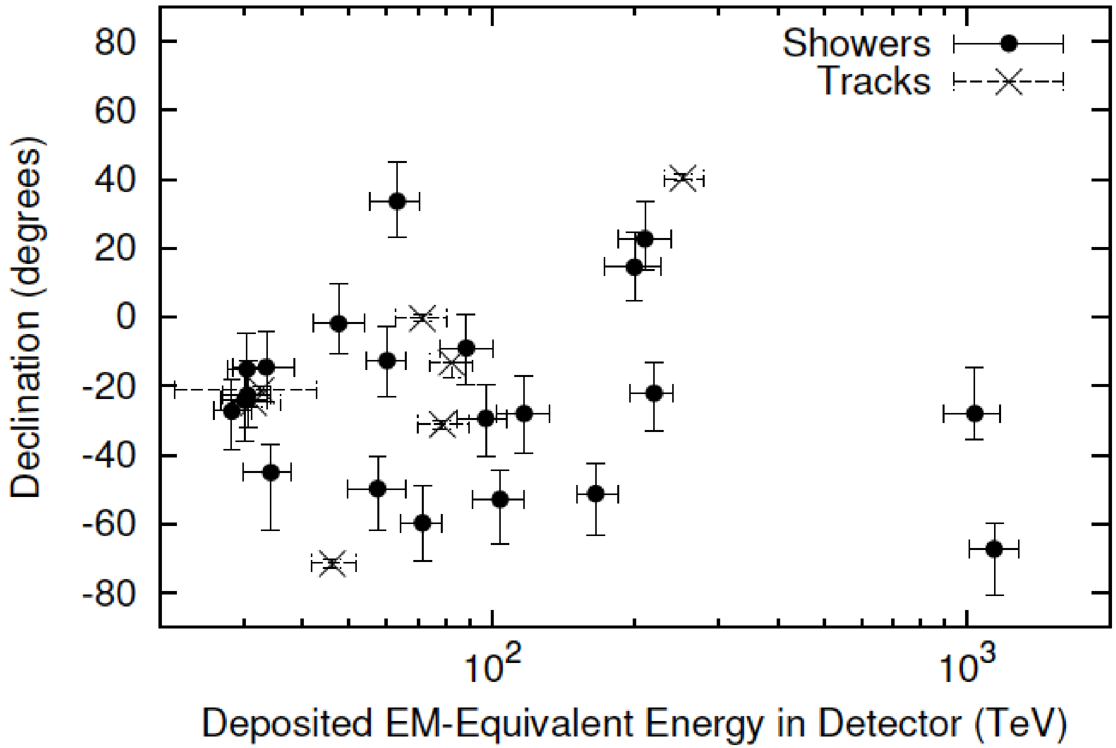
Coordinate of the first detected light

- Uniformly distributed



Declination vs deposited energy

- 21 showers vs 7 tracks
  Suggesting signals.
- In case of conventional atmospheric:
  track : cascade = 2:1
- Most of events come from southern sky because events from north are absorbed by the Earth
- Excess in south is not due to atm. ν since they are reduced in south by our muon veto
- low energy 4 tracks look atmospheric origin (consistent with the prediction of 6±3.4)
- Neutrino energy for track events can be very high compared to the deposited energy

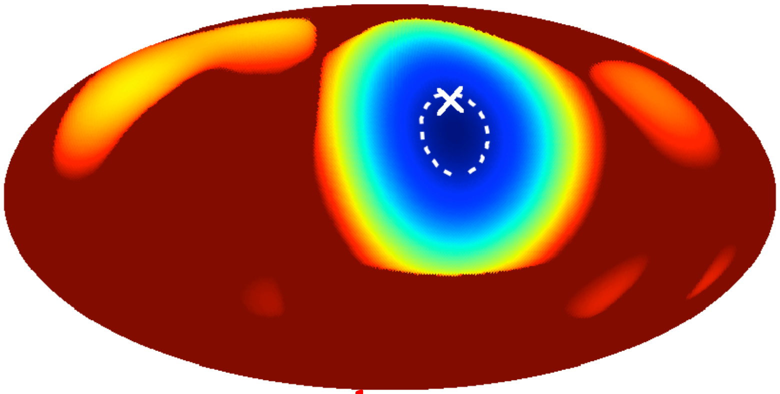


HESE GRB correlation

- Investigated correlation between HESE events and GRBs
- Model independent (10s to 15 days)
- 568 GRBs
- “Best” time window: 80340 s (~ 22.3 hours)
- “Best” pre-trial p-value: 17%
- Post-trial p-value: 77%
- Not significant

Bert (1.04 PeV)
74.304 s after GRB
9.8 deg. apart

Spatial PDF



Preliminary

Oscar (63.2 TeV)
80.336 s after GRB
22.9 deg. apart

Spatial PDF