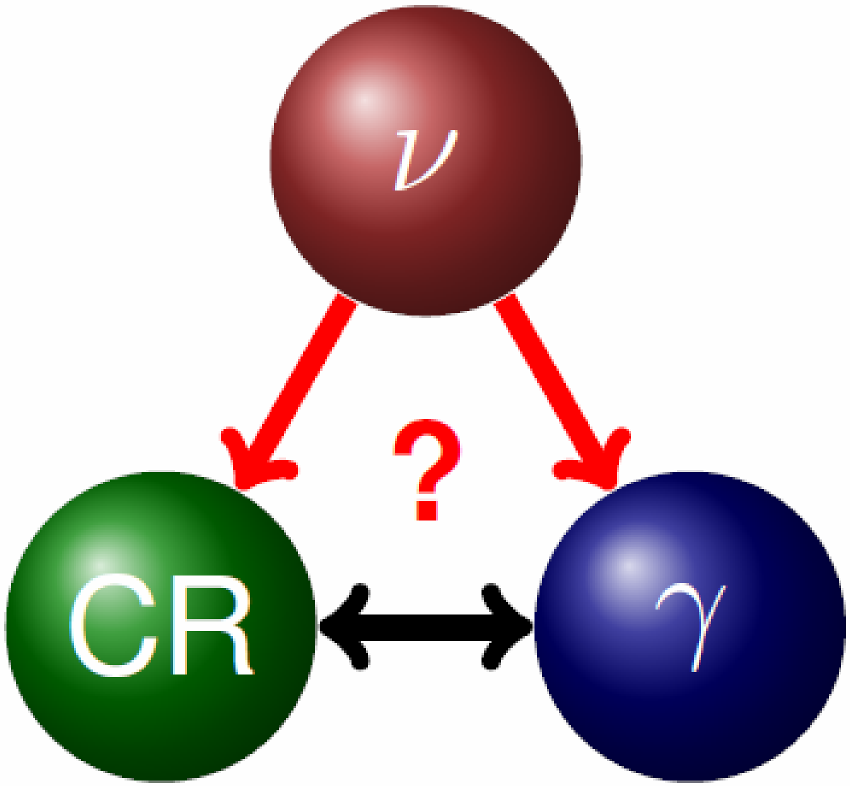
高エネルギーニュートリノ天文学将来計画への誘い

吉田滋

Multi Messenger Paradigm

- Neutrino production is closely related to the production of cosmic rays (CRs) and γ-rays.
- Flux predictions are based on CR and γ-ray observation.
- Status summary:
  - ✘ No "surprises" yet.
  - ✔ Sensitivity has reached the level of "serious" models.

➜ Implications of neutrino limits on UHE CR sources:



M. Ahlers ARENA 2012

- pion production in CR interactions with ambient radiation

$$\pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$
$$\pi^0 \to \gamma\gamma$$

- inelasticity:

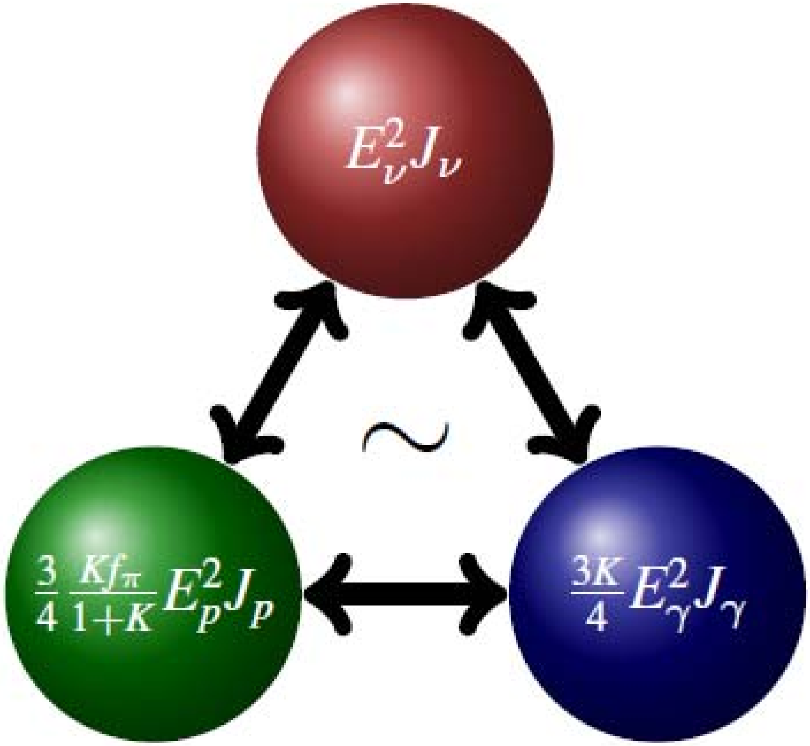
$$E_\nu \simeq E_\gamma/2 \simeq \kappa E_p/4$$

- relative multiplicity:

$$K = N_{\pi^\pm}/N_{\pi^0}$$

- pion fraction:

$$f_\pi \simeq 1 - e^{-\kappa\tau}$$



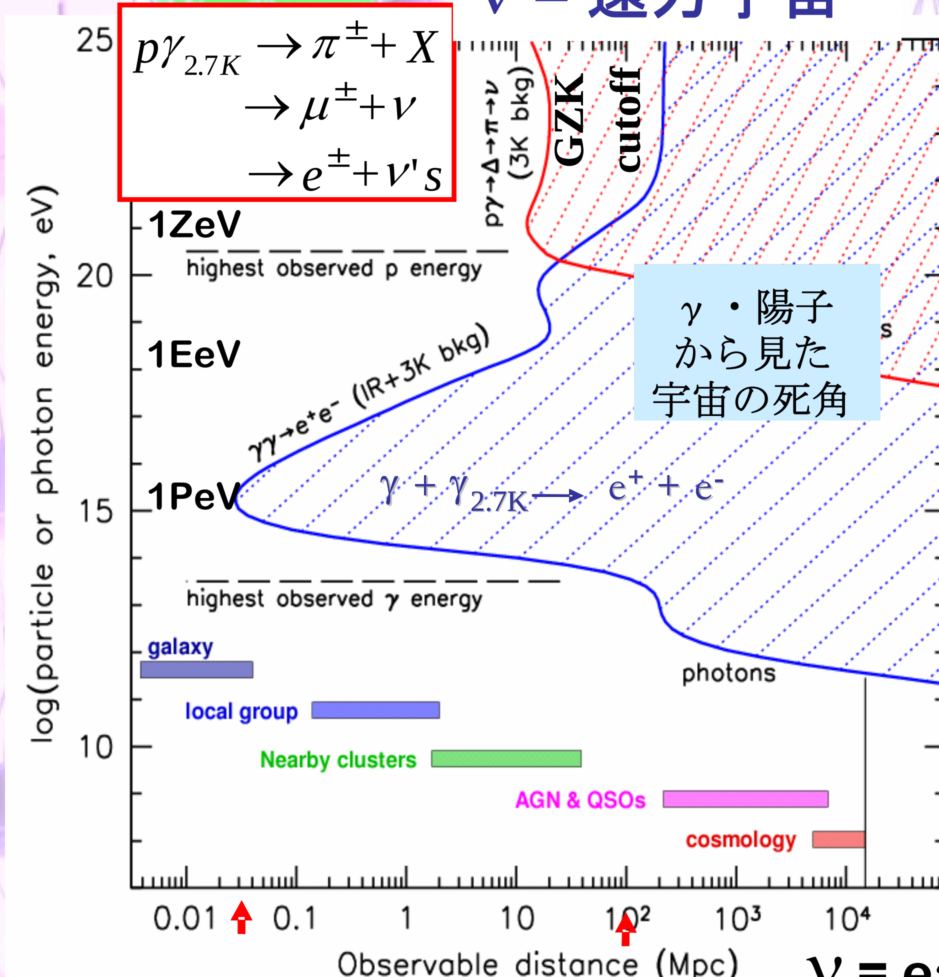
$$\omega_{\rm Fermi} \simeq 6 \times 10^{-7}\ \mathrm{eV/cm^3}$$
$$\omega_{\rm UHECR} \simeq 1 \times 10^{-7}\ \mathrm{eV/cm^3}$$
$$\omega_{\rm IC40} \lesssim 1 \times 10^{-7}\ \mathrm{eV/cm^3}$$

M. Ahlers ARENA 2012

Why Ultra-high energy ν ?

ν = 遠方宇宙

UHECR nuclei = 超局所宇宙



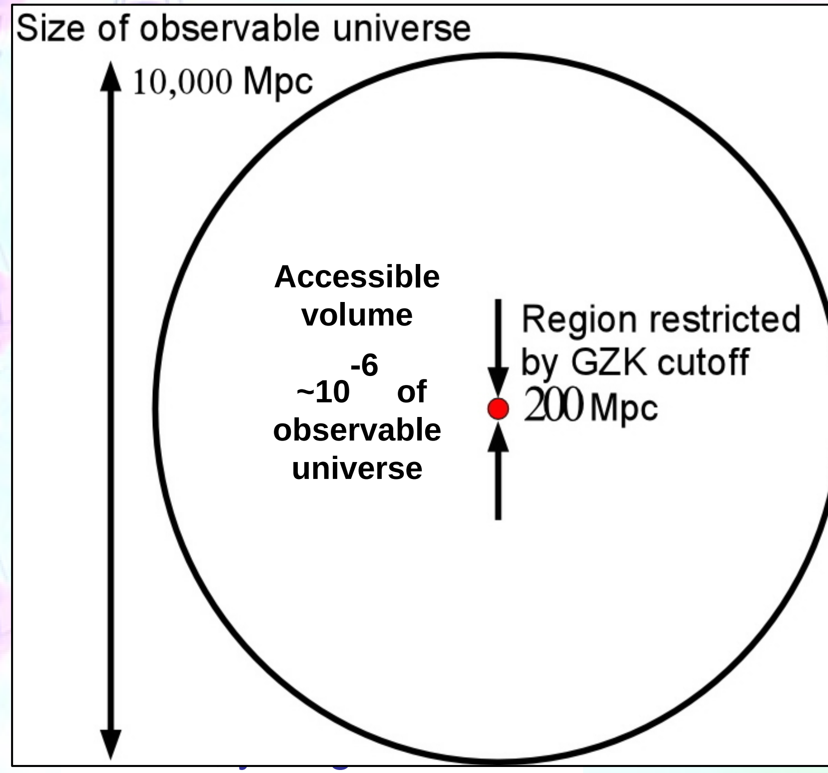
銀河直径

10 万光年

(Our Galaxy)

超銀河団直径

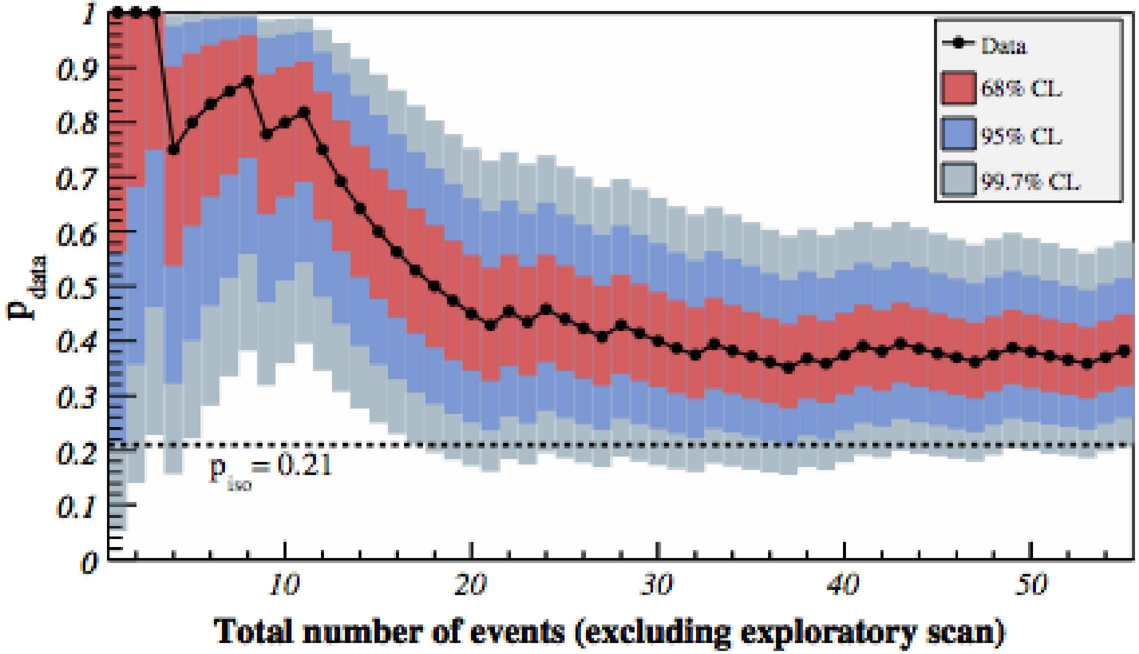
(Super Cluster)



ν = early history of cosmic radiation!

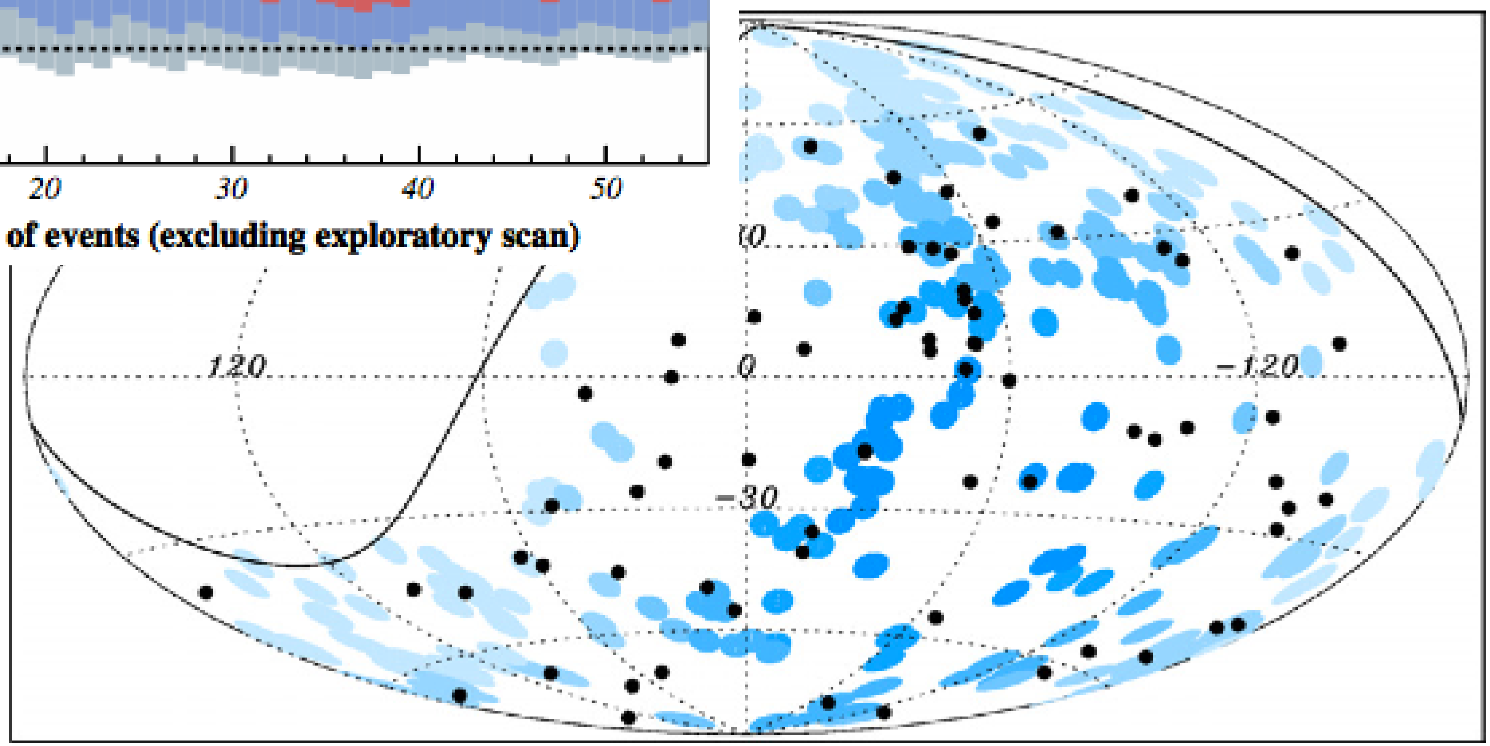
千葉大学
Chiba University

UHECR による超局所宇宙の天文学?
Yet far from conclusive!



Auger : 20,370 km^2 sr yr
||
6000 km^2 sr x 3.3 year!

HUUUUUGE !



● AGN r<75Mpc
● UHECR E>55EeV

UHECRs は local なのか?

大きな疑問として

磁場と化学組成と (local) ソースの分布という三つの不定変数の連立方程式を解けるのか？

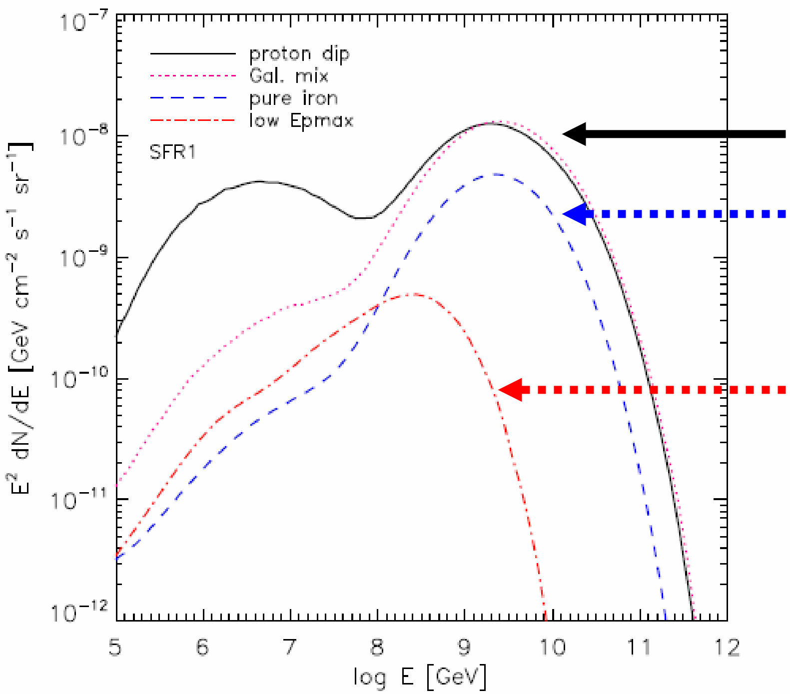
UHECR は一体何ででてきているのか**=**組成

本当に **local** なのか否かを決める決定打である

Nuclei は **10 Mpc** しか走らないから

その測定は統計誤差でなく系統誤差で決まっている！！

Kotera, Allard, Olinto JCAP **10** 013 (2010)



ニュートリノでは系統誤差が小さい

All proton case

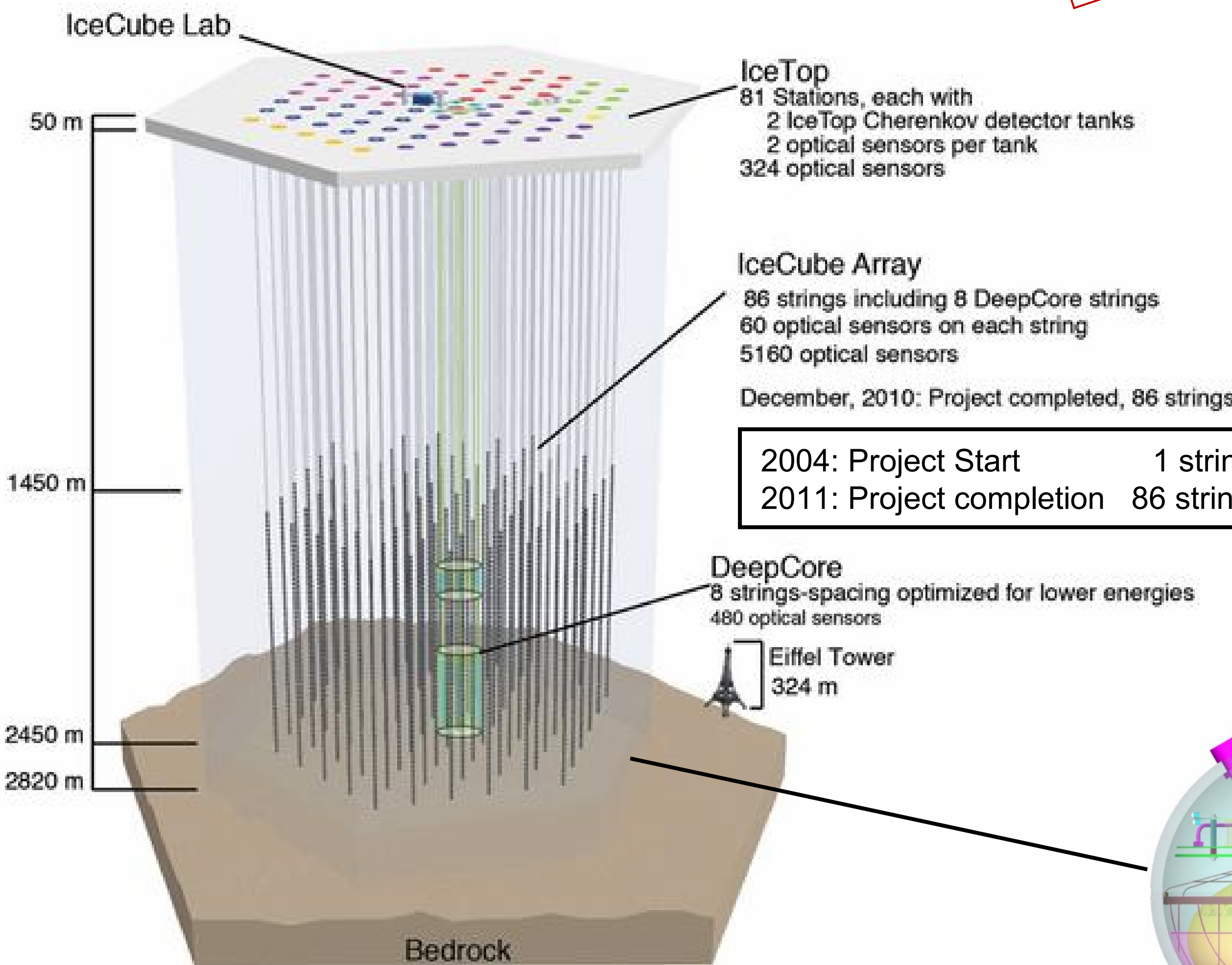
鉄で放射されたけど、地球到達時の組成は陽子・核混合組成

最高エネルギー領域で鉄として観測されるようにE_{max}を **tune = Auger** シナリオ

~ 1/30 GZK ν 強度

The IceCube Neutrino Observatory

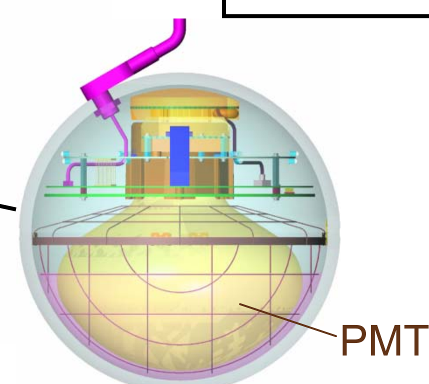
Completed: Dec 2010



2004: Project Start	1 string
2011: Project completion	86 strings

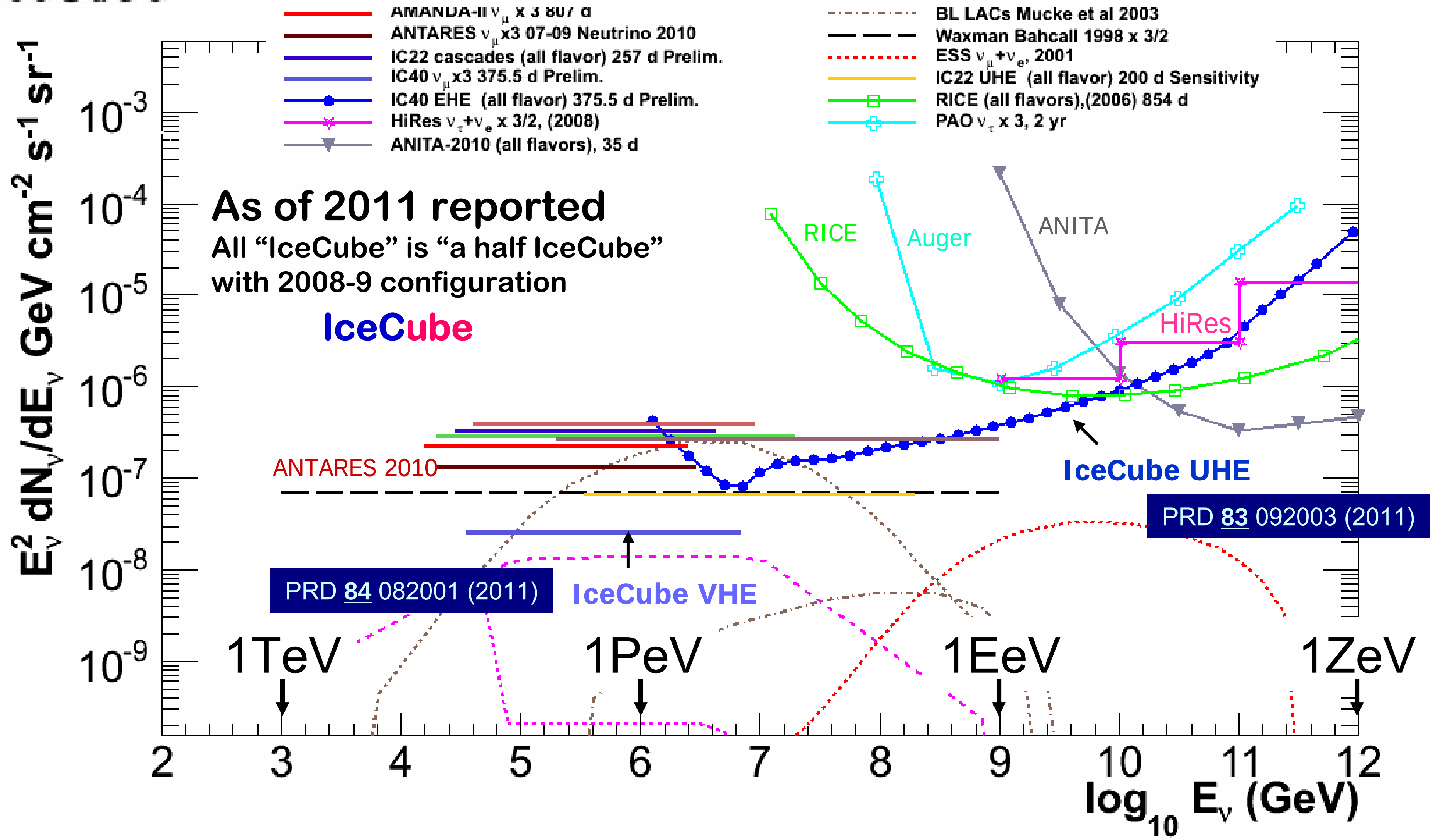
Configuration chronology

2006: IC9
2007: IC22
2008: IC40
2009: IC59
2010: IC79
2011: IC86

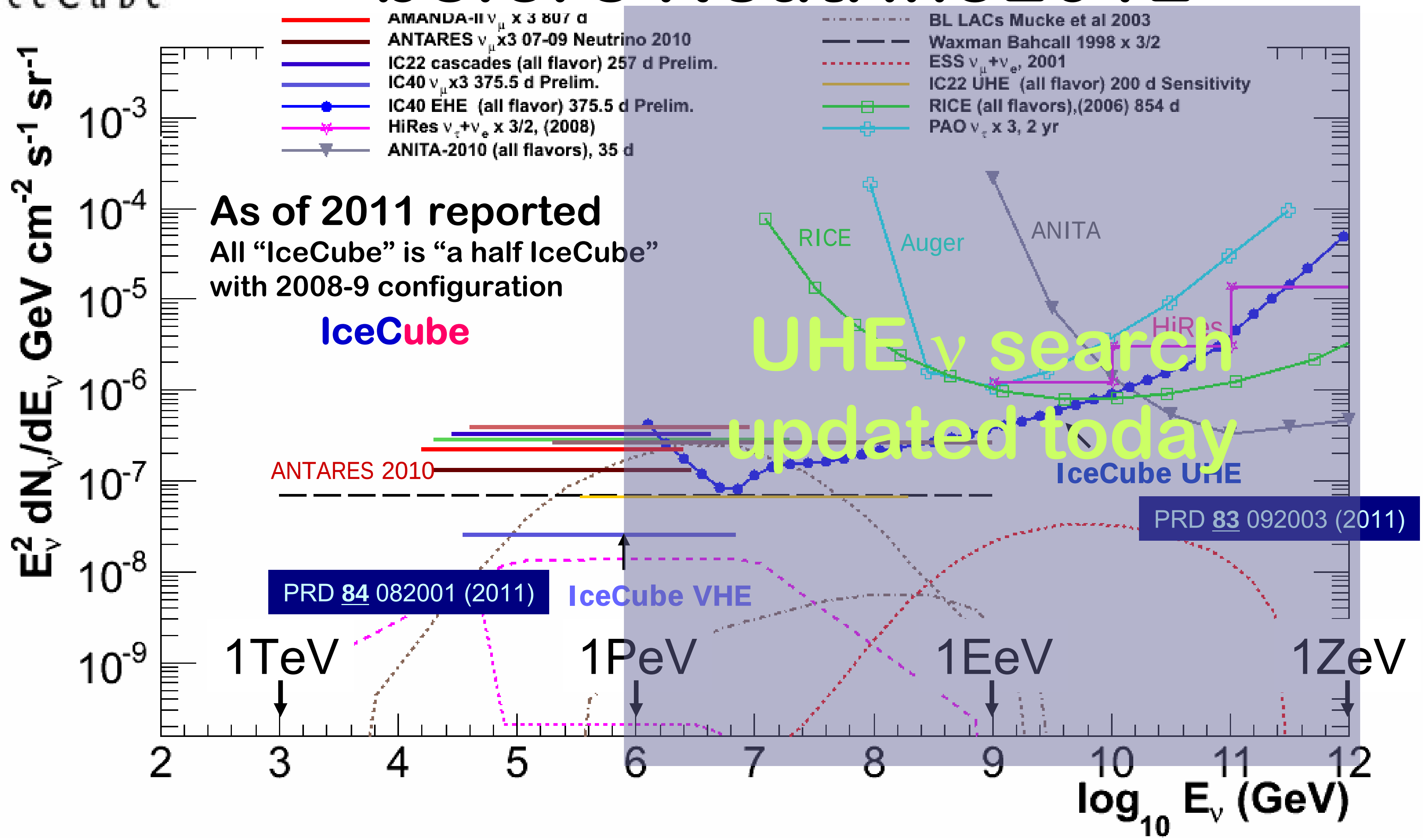


Digital Optical Module (DOM)

Diffuse ν limits – global picture before Neutrino2012



Diffuse ν limits – global picture before Neutrino2012



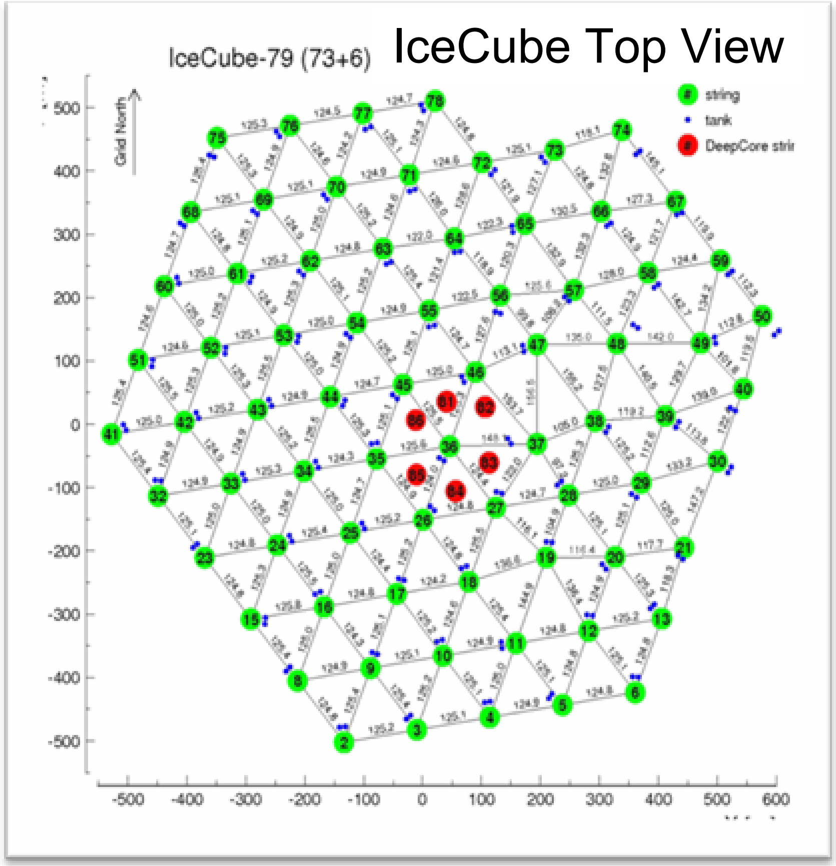
Data samples

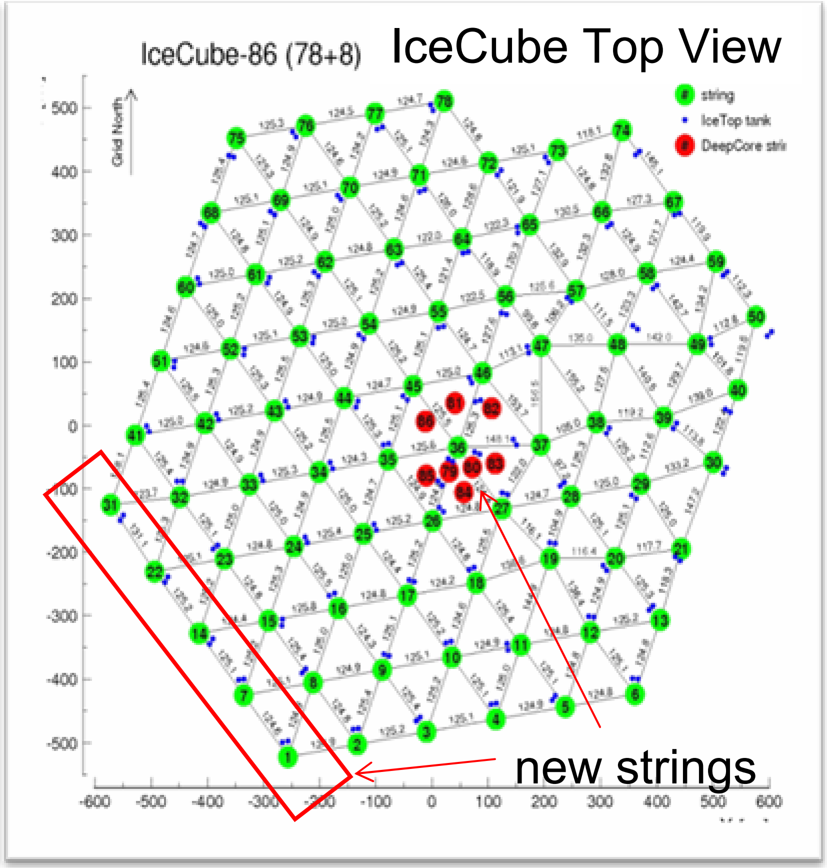
Effective livetime of 672.7days

9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

2010-2011 - 79 strings config.
May/31/2010-May/12/2011
Effective livetime 319.07days

2011-2012 – 86 strings config
May/13/2011-May14/2012
Effective livetime 353.67 days





IceCube has been in a stable operation for more than 5 years

The UHE Event Selection Criteria at the final level

IceCube

千葉大学 Chiba University

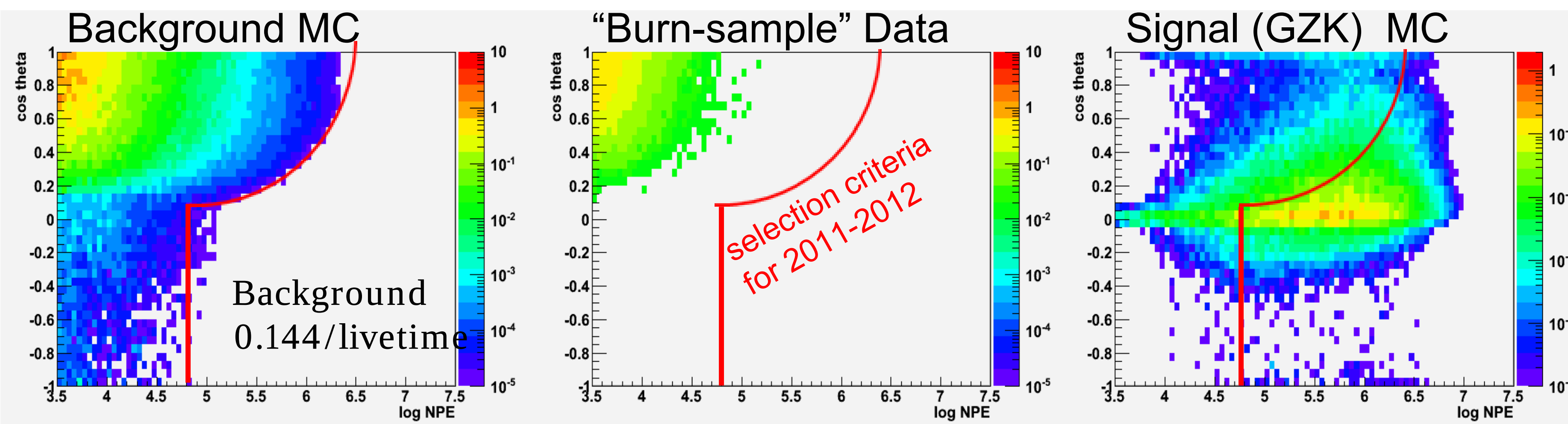
IceCube 2010-2012 (672.7 days) observation

Expected Background (atmospheric ν + μ-bundle) 0.14 events

GZK ν 0.5~ 4.0 events

Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

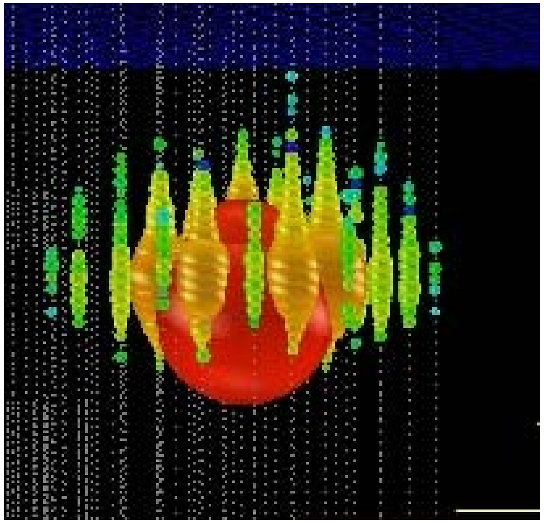
- Optimization based MC and MC verification based on 10% experimental 'burn' sample



A. Ishihara Neutrino 2012

Two events passed the final criteria

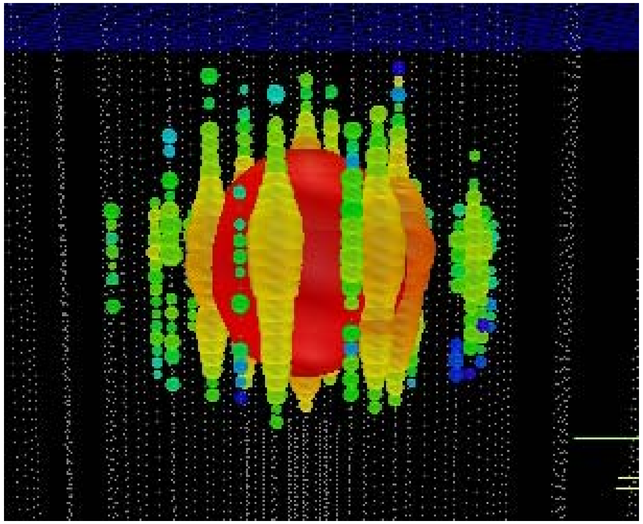
2 events / 672.7 days –
background (atm. μ + conventional atm. ν) expectation 0.14 events



Preliminary

p-value 9.4×10^{-3} (2.36σ)

Super-nicely contained cascades!



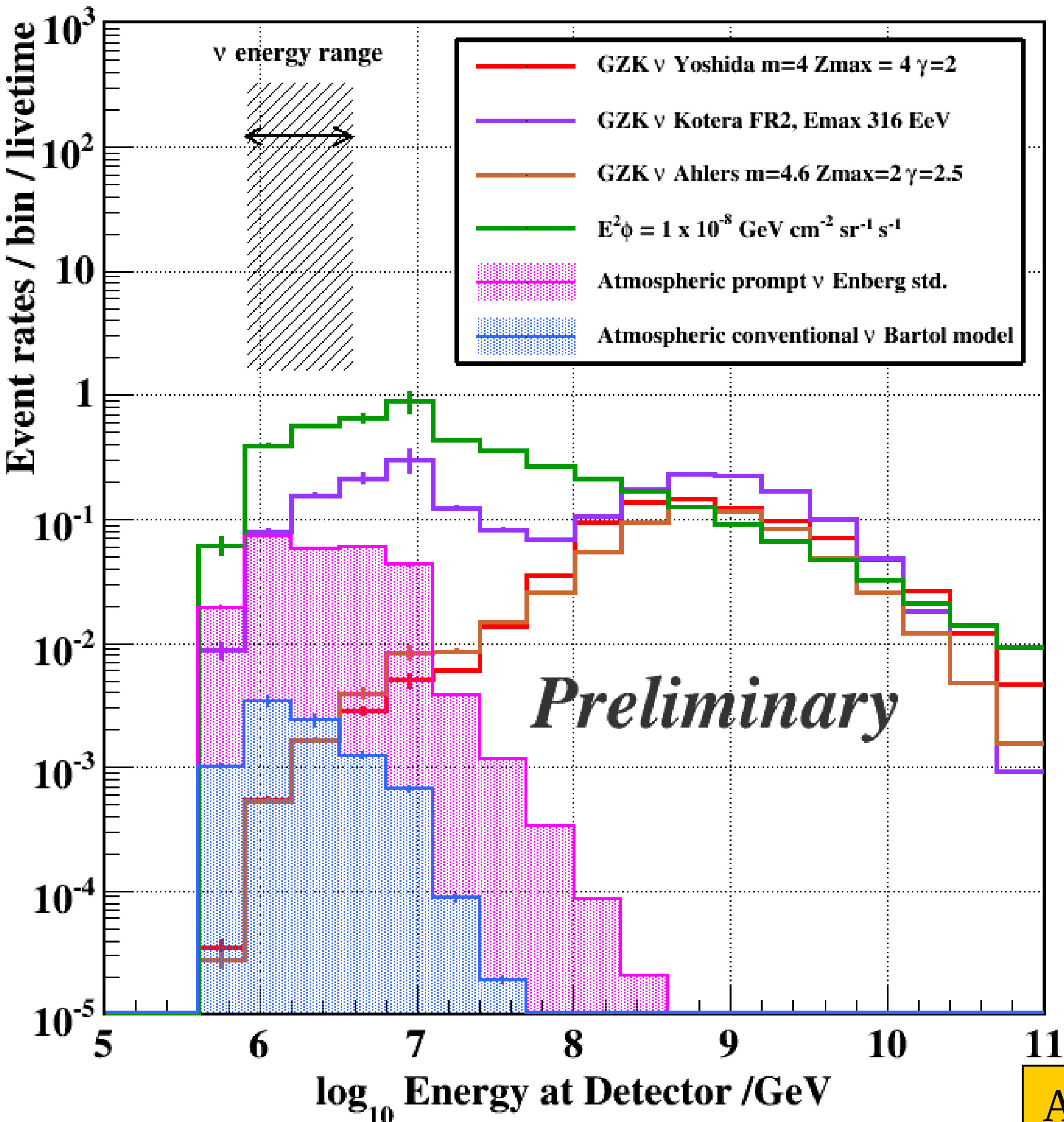
Run119316-Event36556705
Jan 3rd 2012
NPE 9.628×10^{4}
Number of Optical Sensors 312
cos(Zenith) -0.8658

Run118545-Event63733662
August 9th 2011
NPE 6.9928×10^{4}
Number of Optical Sensors 354
cos(Zenith) 0.05

Caution!!

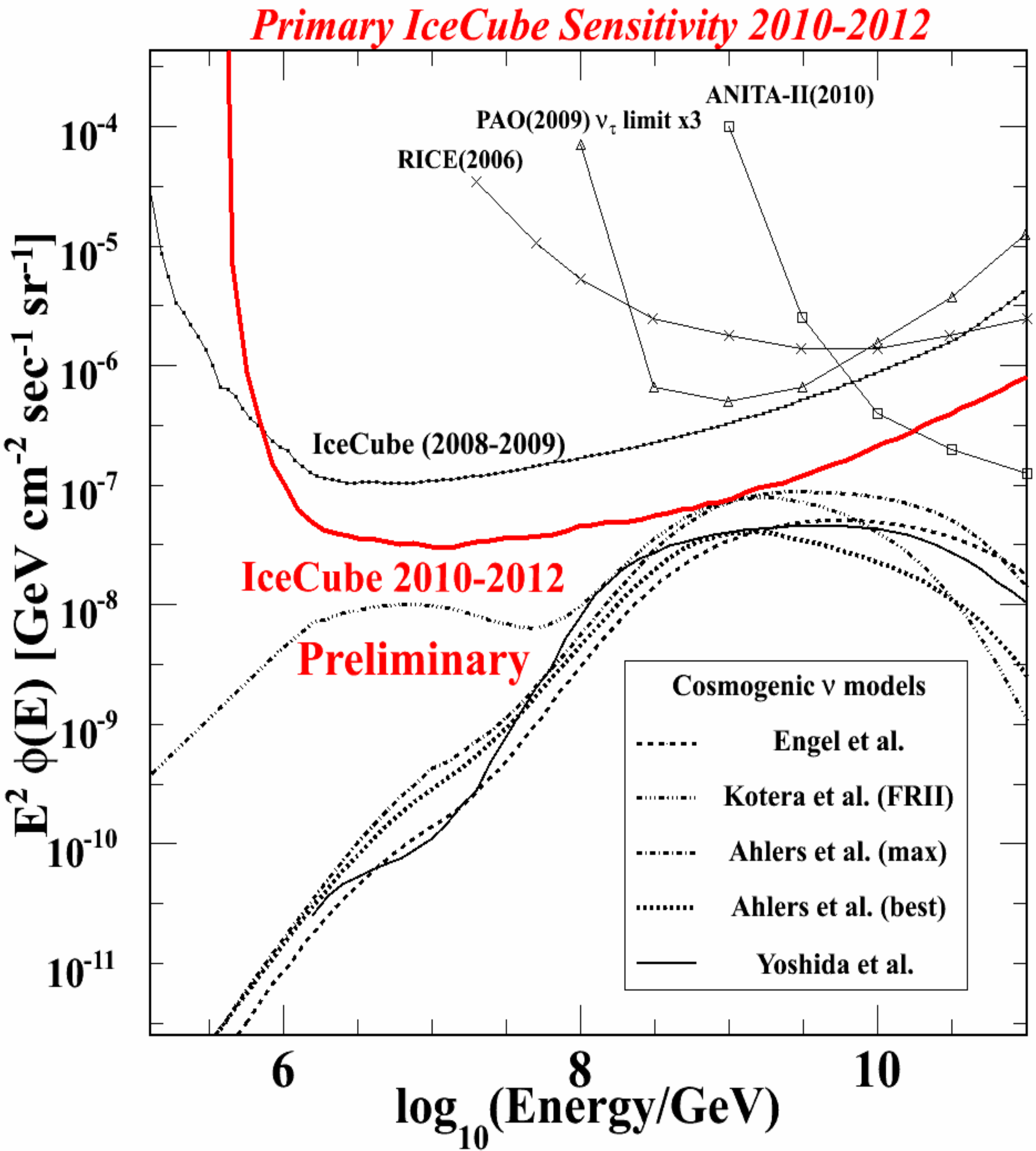
These zenith were obtained by
the "improved line-fit" used in the search process.
Large errors should be expected for these cascade-type events

Comparison with the models
-- “in-ice” Energy distribution --



A. Ishihara Neutrino 2012

IceCube UHE Sensitivity 2010-2012



- Significantly improved from the previous IceCube results
- The world’s best sensitivity!
- Will constrain (or detect) the neutrino fluxes down to mid-strong cosmological evolution models

A. Ishihara Neutrino 2012

GZK-CMB ν intensity @ 1EeV
Measurements of the evolution

Yoshida and Ishihara, PRD <u>85</u>, 063002 (2012)

$\rho \sim (1+z)^m$

$0<z<z_{max}$

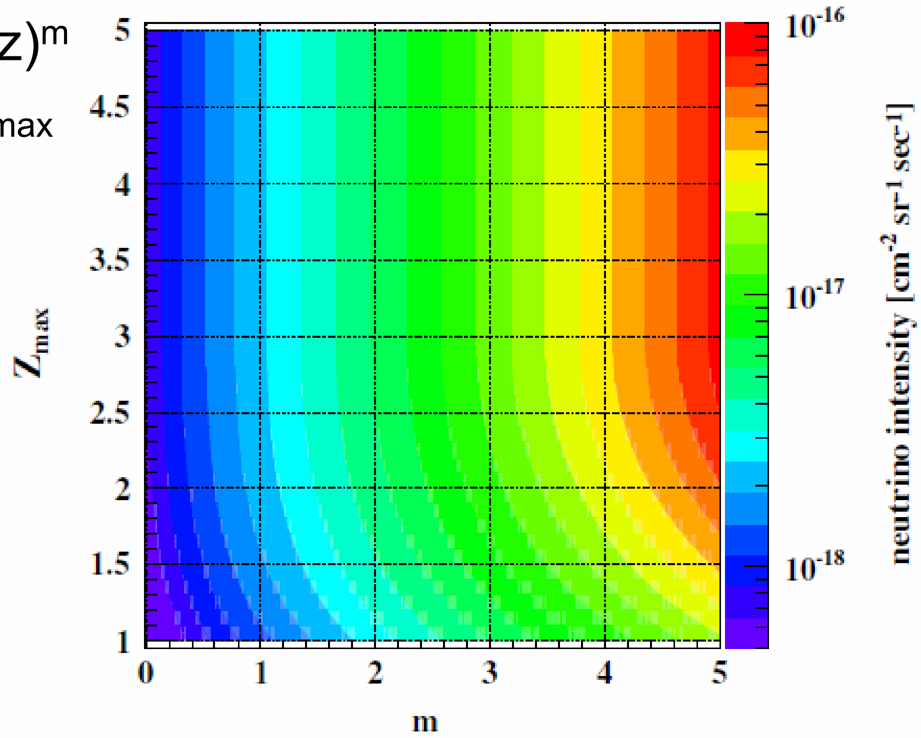


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

GZK(-CMB) ν flux

x IceCube Exposure

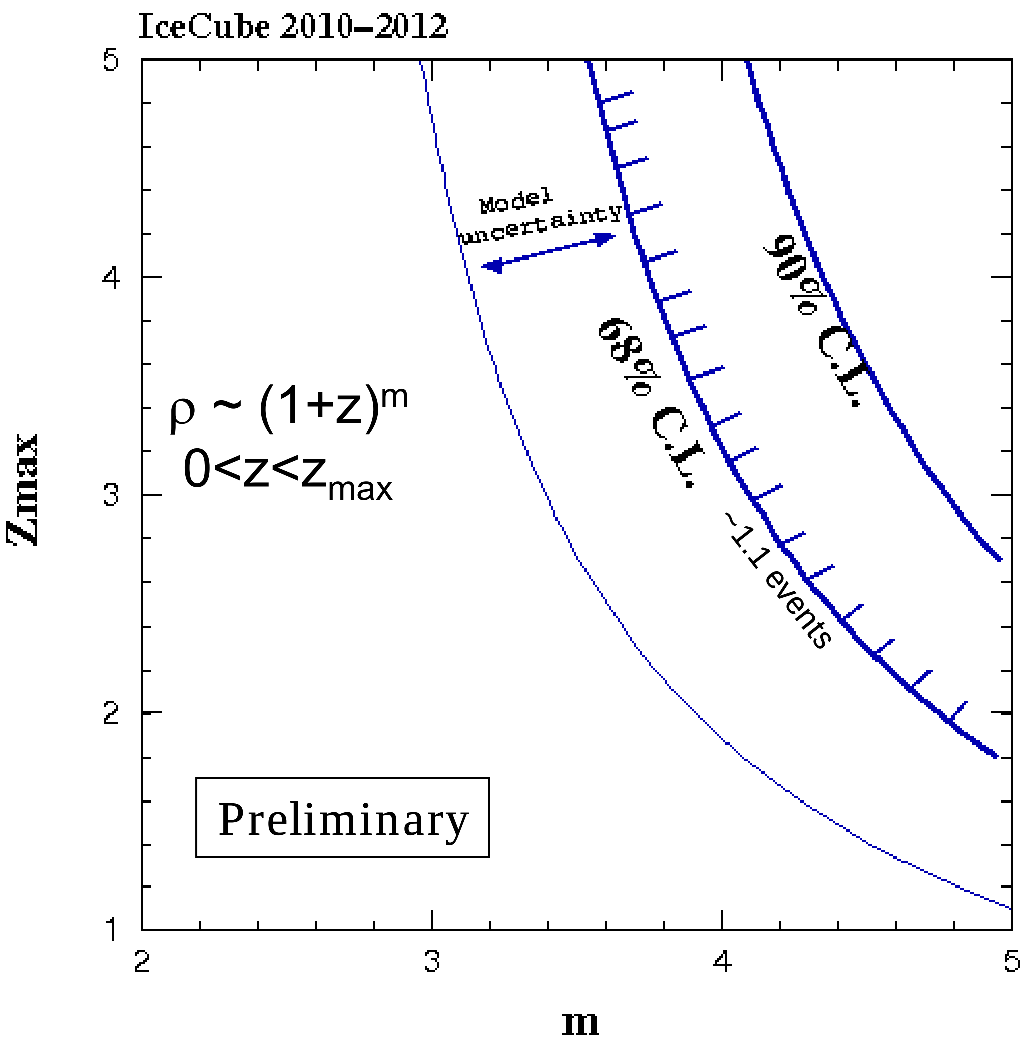
Number of events we should have detected

Evolution of UHECR sources

Identify classes of astronomical objects responsible for UHECRs

千葉大学 Chiba University

Constraints on the evolution



- A strongly evolved astronomical object (like FR-II radio galaxy) has already been disfavored

- any scenario involving sources evolved stronger than SFR will soon be ruled out by IceCube if we see no events in EeV rage.

是非セミナーに呼んでください。
そこで詳細を議論しましょう。

今夏の国際会議

- **Neutrino 2012 (June 4-9) by A. Ishihara ← 1st announcement**
- **ARENA 2012 (June 19-22) by S. Yoshida**
- **Centenary Symposium (June 26-28) by T. Gaisser**
- **Gamma 2012 (July 9-13) by I. Taboada**
- **VHESS Symposium (August 6-8) by F. Halzen**

超高エネルギーニュートリノは存在する

ARA-Collaboration

- ARA is an international Collaboration
  - 14 institutions
  - ~50 authors

Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole

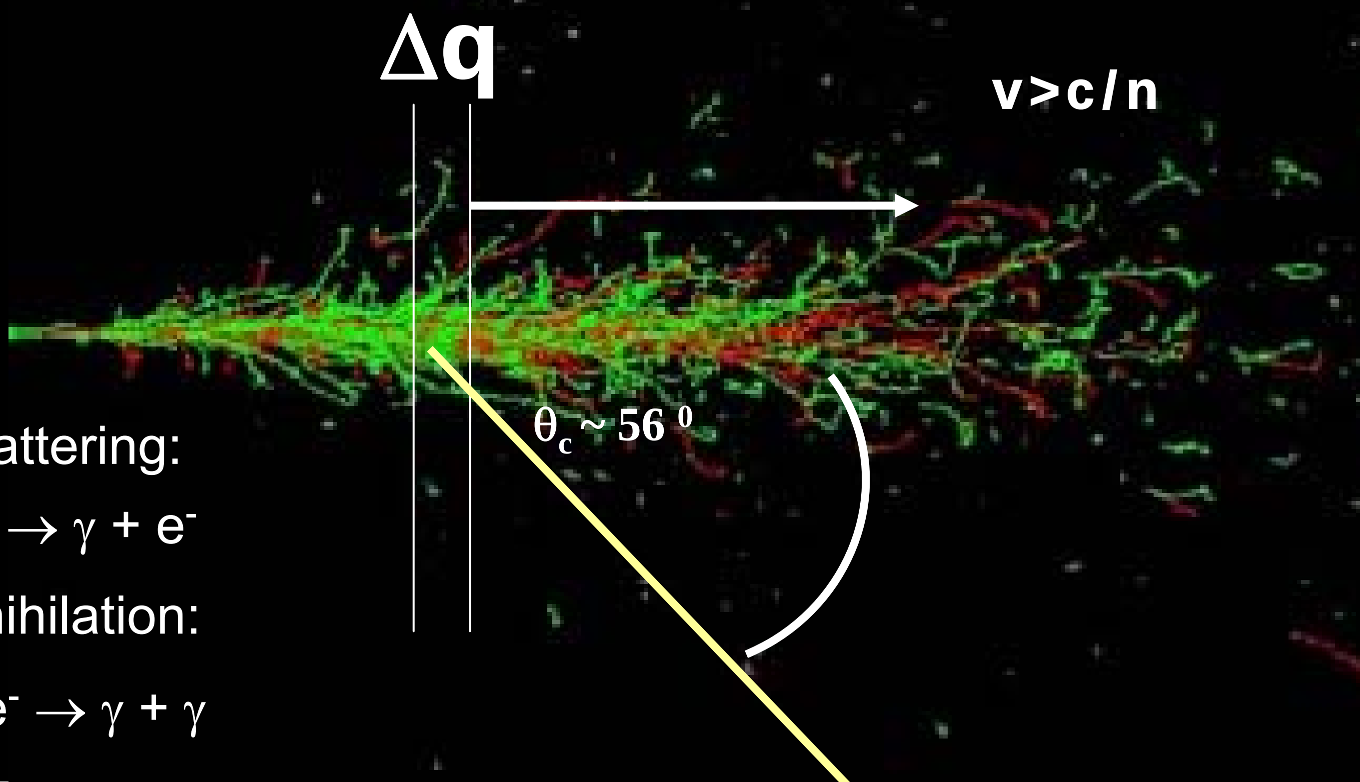
P. Allison,[1] J. Auffenberg,[2] R. Bard,[3] J. J. Beatty,[1] D. Z. Besson,[4] S. Böser,[5] C. Chen,[6] P. Chen,[6] A. Connolly,[1] J. Davies,[7] M. DuVernois,[2] B. Fox,[8] P. W. Gorham,[8] E. W. Grashorn,[1] K. Hanson,[9] J. Haugen,[2] K. Helbing,[10] B. Hill,[8] K. D. Hoffman,[3] M. Huang,[6] M. H. A. Huang,[6] A. Ishihara,[11] A. Karle,[12] D. Kennedy,[4] H. Landsman,[2] A. Laundrie,[2] T. C. Liu,[6] L. Macchiarulo,[8] K. Mase,[11] T. Meures,[9] R. Meyhandan,[8] C. Miki,[8] R. Morse,[8] M. Newcomb,[2] R. J. Nichol,[7] K. Ratzlaff,[13] M. Richman,[3] L. Ritter,[8] B. Rotter,[8] P. Sandstrom,[2] D. Seckel,[14] J. Touart,[3] G. S. Varner,[8] M. -Z. Wang,[6] C. Weaver,[12] A. Wendorff,[4] S. Yoshida,[11] and R. Young[13]

(ARA Collaboration)

[1] Dept. of Physics, Ohio State Univ., Columbus, OH 43210, USA.
[2] IceCube Research Center, Univ. of Wisconsin- Madison WI 53703.
[3] Dept. of Physics, Univ. of Maryland, College Park, MD, USA.
[4] Dept. of Physics and Astronomy, Univ. of Kansas, Lawrence, KS 66045, USA.
[5] Dept. of Physics, Univ. of Bonn, Bonn, Germany.
Dept. of Physics, Grad. Inst. of Astrophys., & Leung Center for Cosmology and Particle Astrophysics, National
[7] Dept. of Physics and Astronomy, Univ. College London, London, United Kingdo
[8] Dept. of Physics and Astronomy, Univ. of Hawaii, Manoa, HI 96822, USA.
[9] Dept. of Physics, Univ. Libre de Bruxelles, Belgium.
[10] Dept. of Physics, Univ. of Wuppertal, Wuppertal, Germany.
[11] Dept. of Physics, Chiba university, Tokyo, Japan.
[12] Dept. of Physics, Univ. of Wisconsin Madison, Madison, WI, USA.
[13] Instrumentation Design Laboratory, Univ. of Kansas, Lawrence, KS 66045, US
[14] Dept. of Physics, Univ. of Delaware, Newark, DE 19716.

Radio Pulses from Neutrino

EM cascade resembles a large negative excess charge moving exceeding speed of light (Askaryan effect)



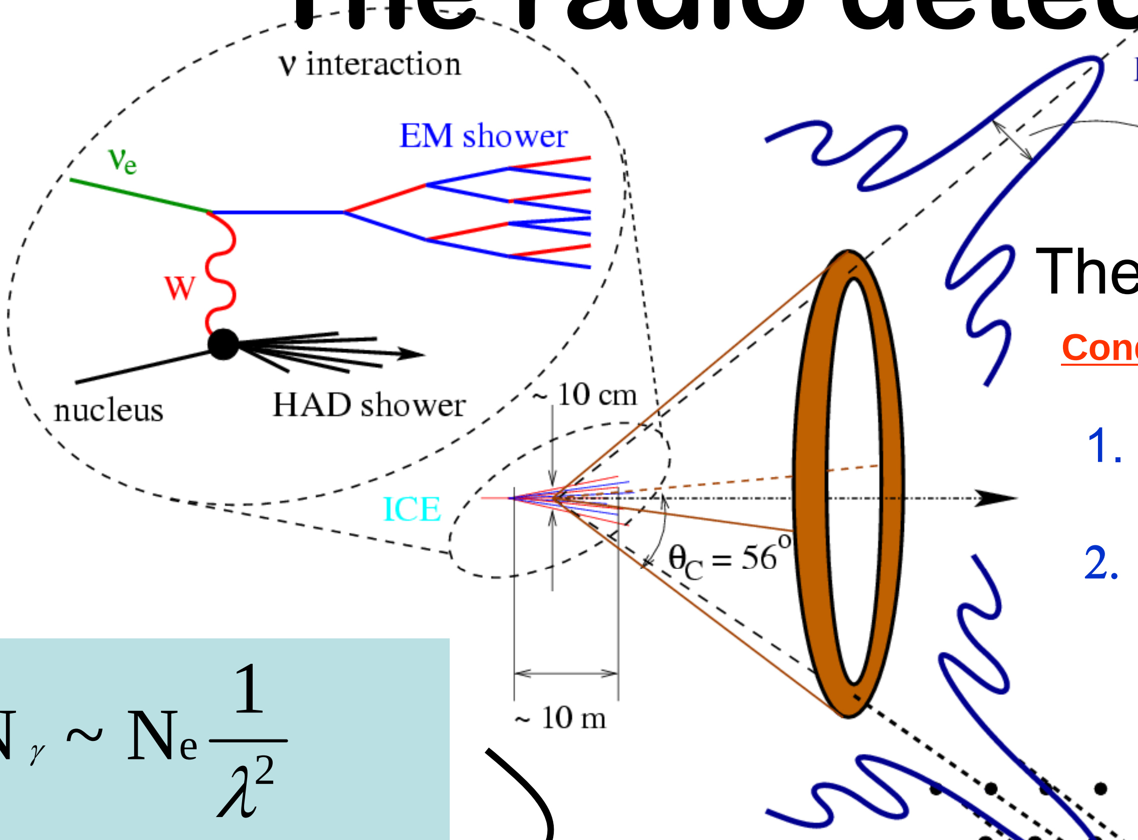
Compton scattering:

$\gamma + e^- \rightarrow \gamma + e^-$

Positron annihilation:

$e^+ + e^- \rightarrow \gamma + \gamma$

The radio detection



The Askaryan effect

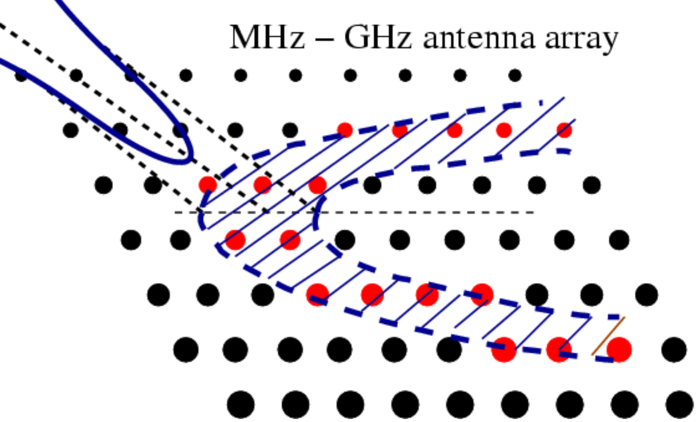
Conditions for coherent radio emission

1. Net exccess charge
2. λ_{obs} > shower dimensions

$$N_\gamma \sim N_e \frac{1}{\lambda^2}$$

$$W \sim (N_e \Delta q)^2 \frac{1}{\lambda^2}$$

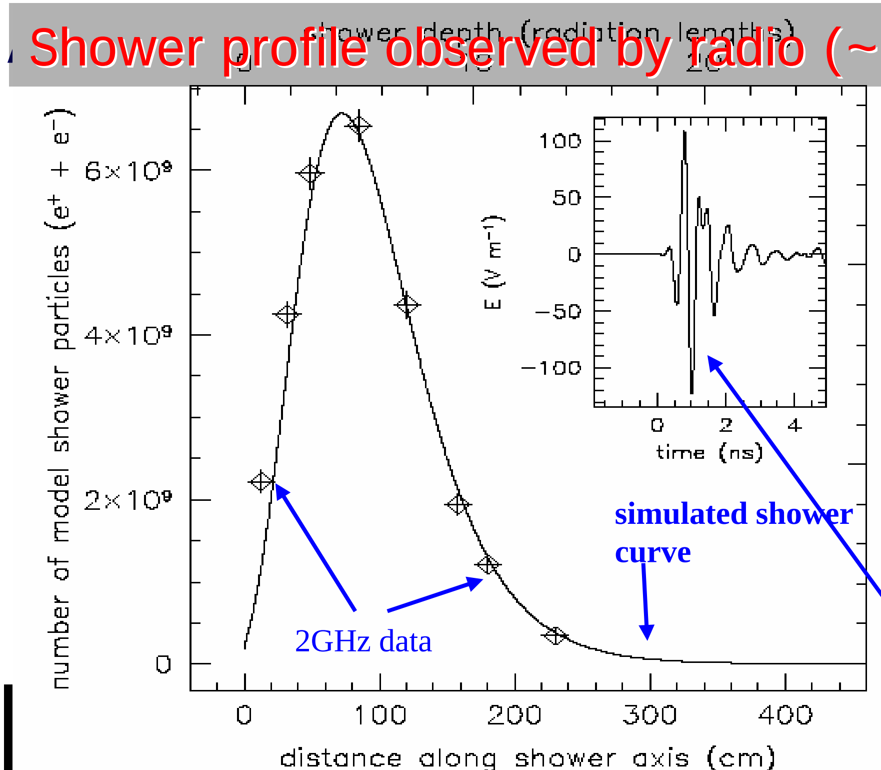
Coherence!!

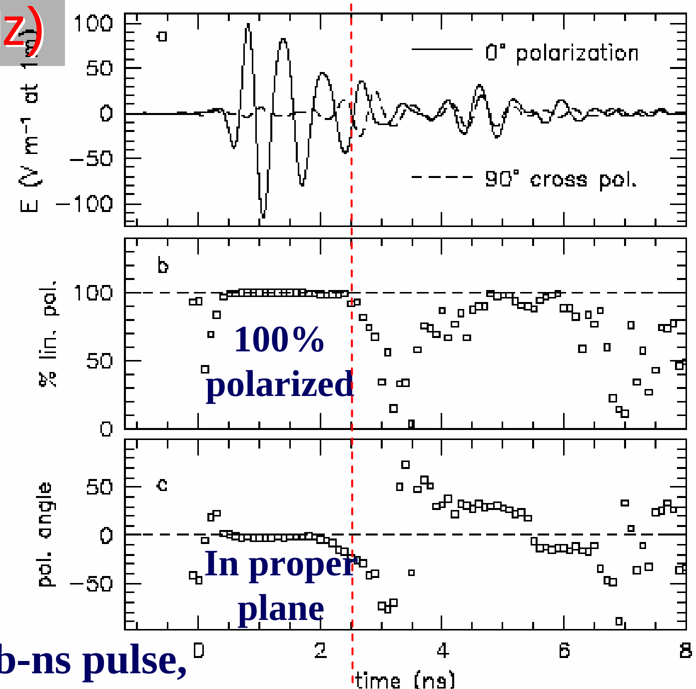


J. Alvarez–Muñiz & E. Zas (2005)

Cherenkov Radio Pulse measurement

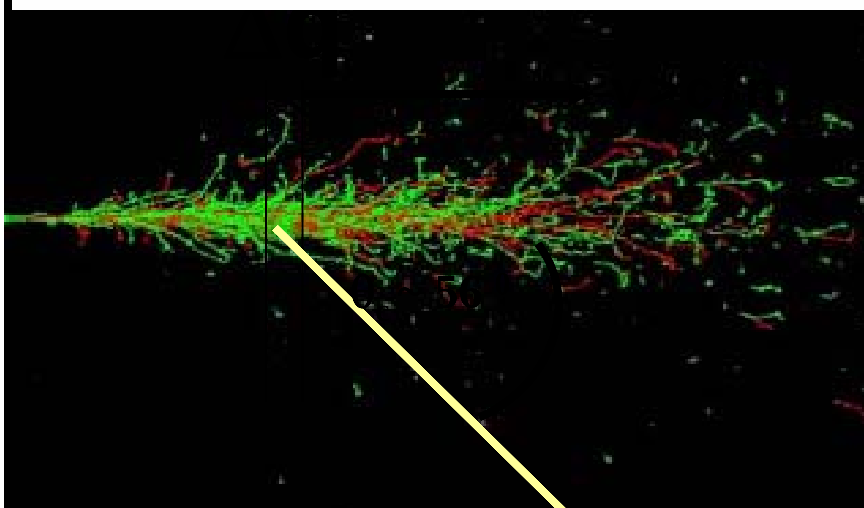
Shower profile observed by radio (~2GHz)

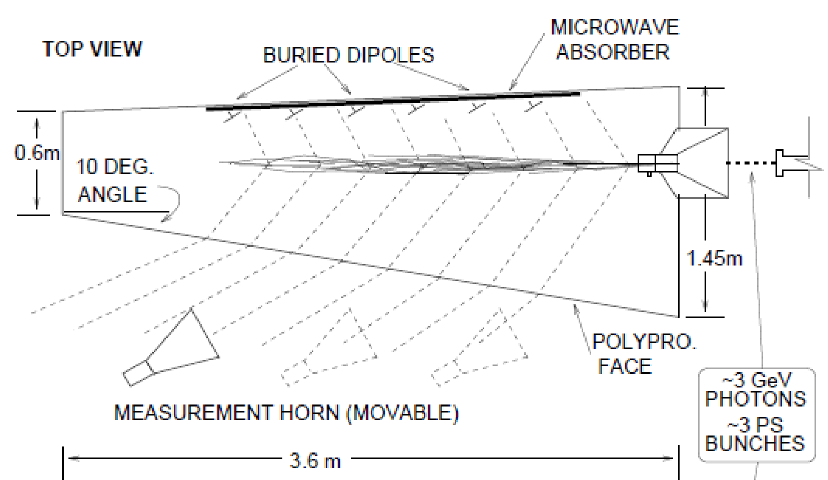




Sub-ns pulse,
Ep-p~ 200 V/m

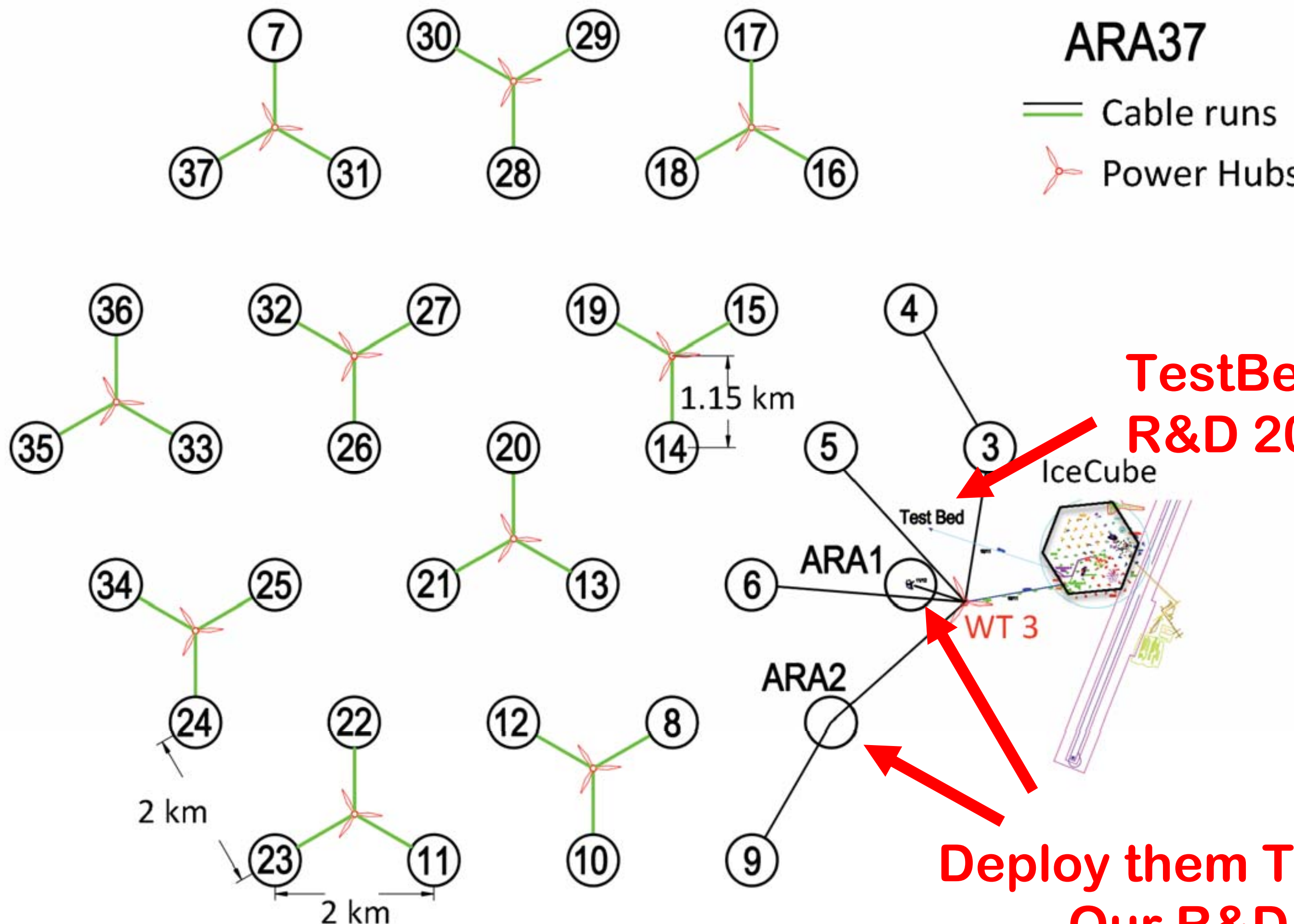
←**Reflection from side wall**





ARA 37 geometry

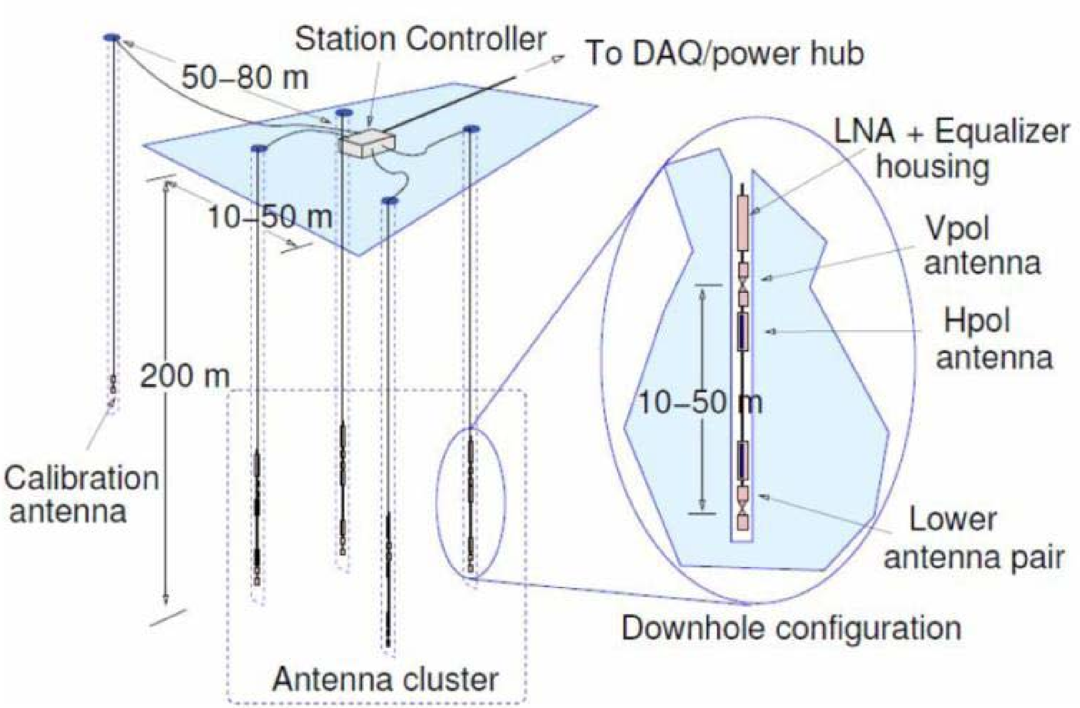
~ 200 km^2 !



TestBed
R&D 2010-

Deploy them THIS YEAR!
Our R&D base

Components of a single station



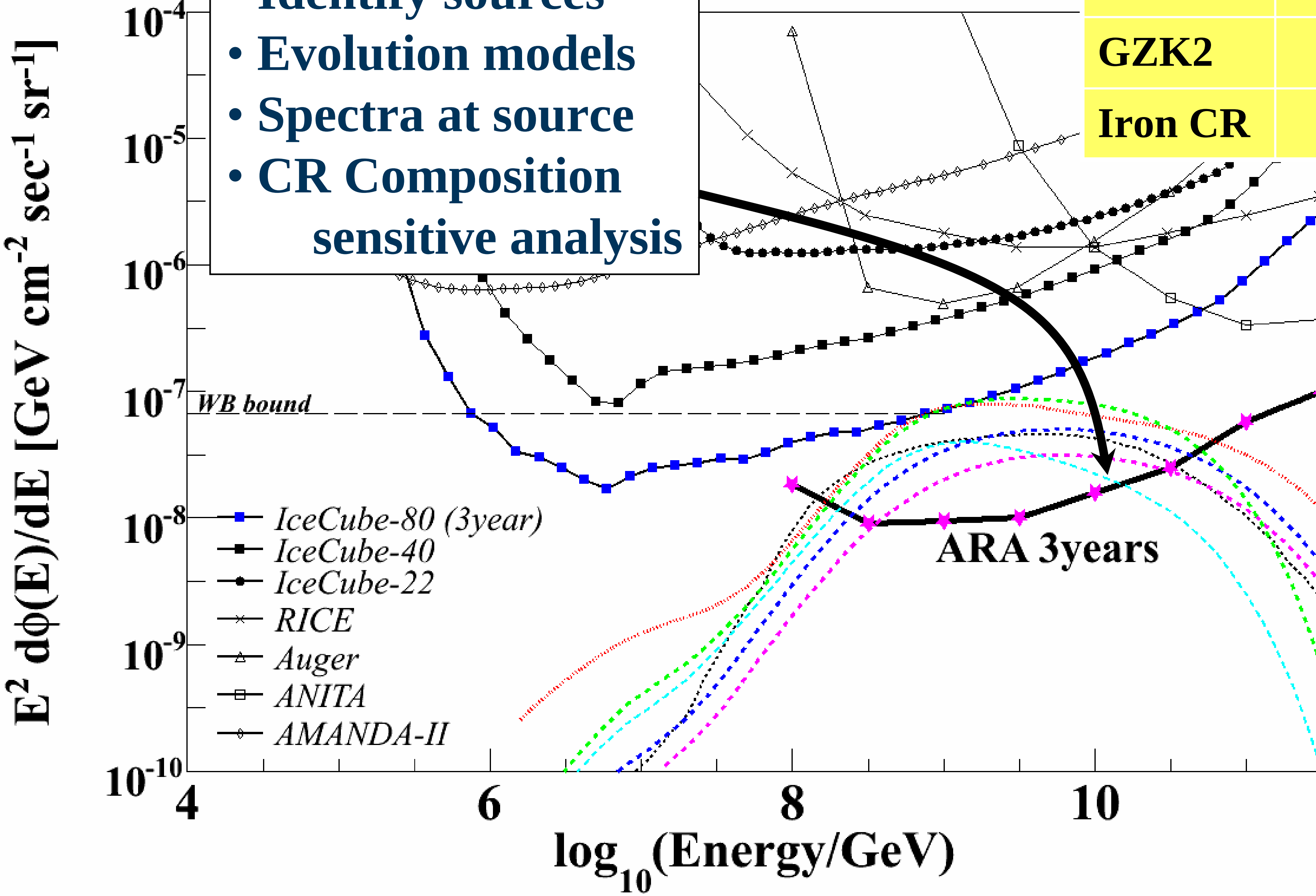
- **5holes 200m depth**
- **16+2 antennas**

(8 h-pol, 8 v-pol, 2 cals)

ARA 37 sensitivity

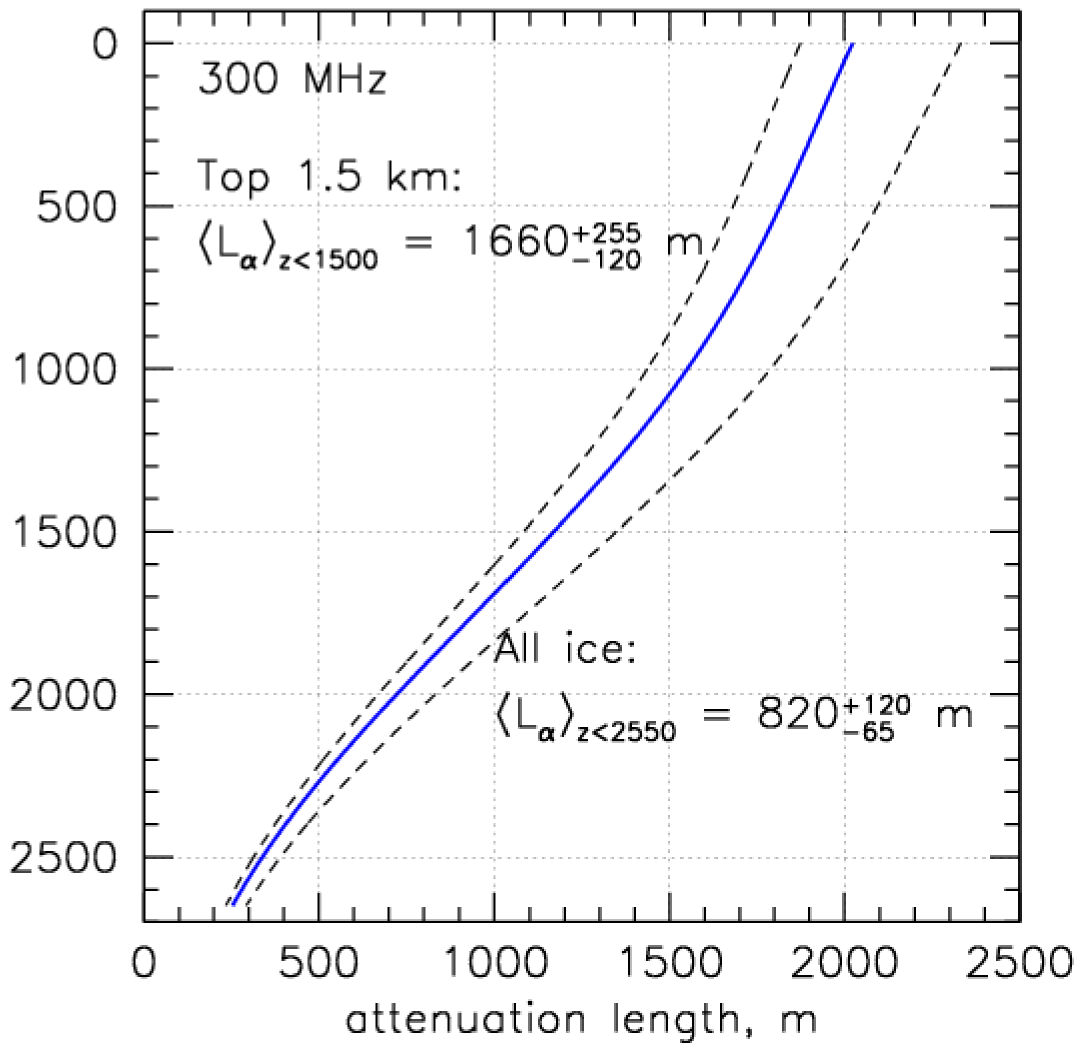
Model	#/year
GZK1	7.0
GZK2	11.1
Iron CR	~1

- Identify sources
- Evolution models
- Spectra at source
- CR Composition sensitive analysis

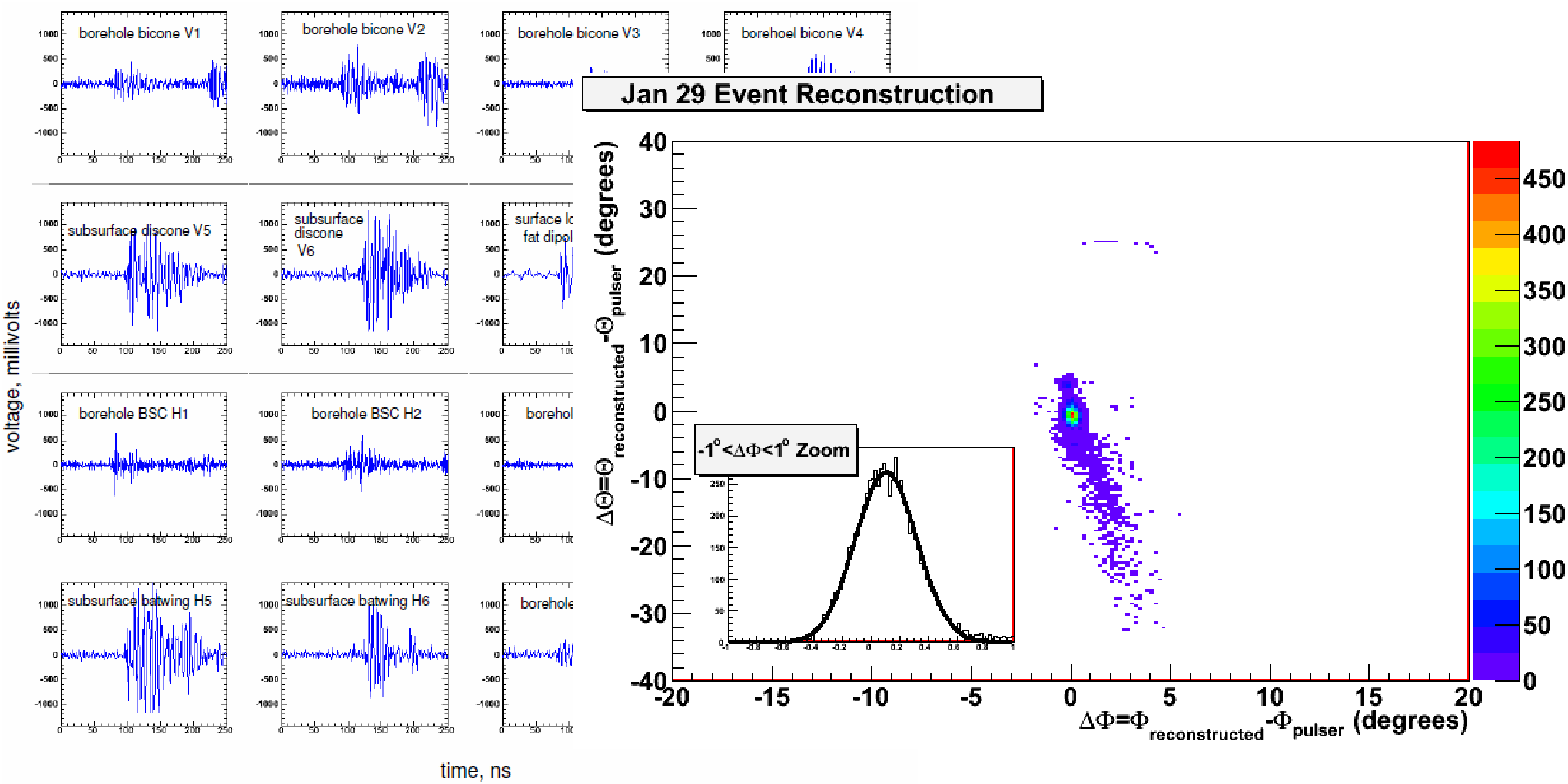


R&D 2010-2011

Deep Radio Pulser – Radio Attenuation length



R&D 2010-2011
event reconstruction from the pulser

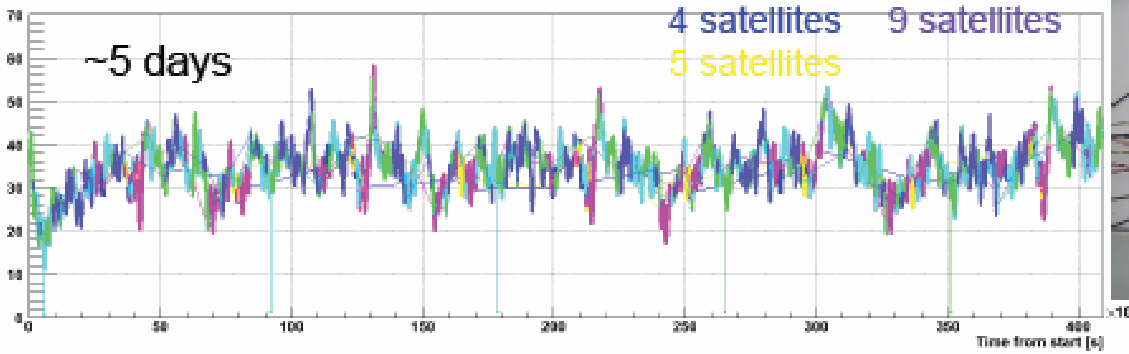


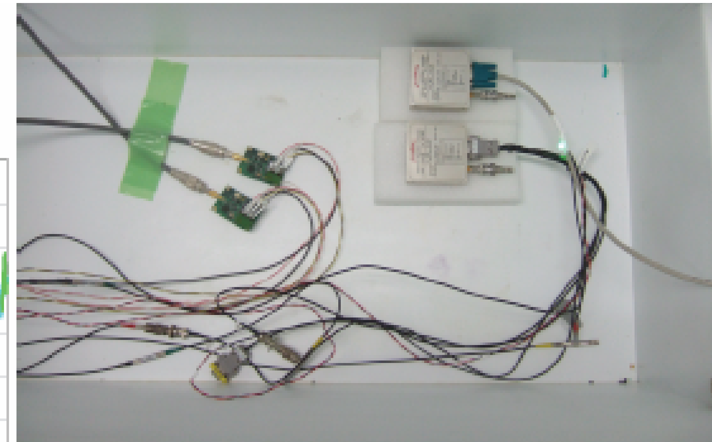
R&D 2010- 2011

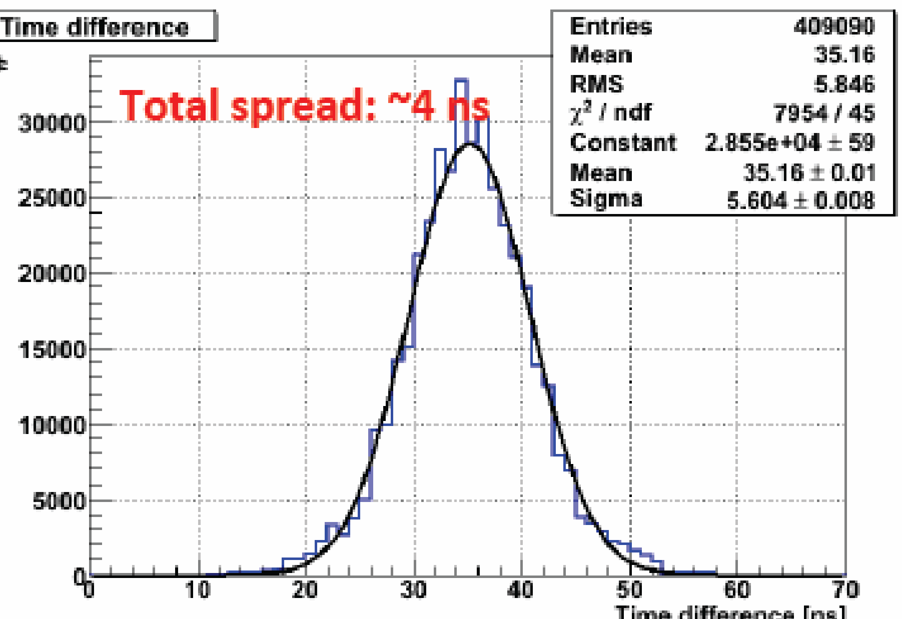
千葉大学 Chiba University

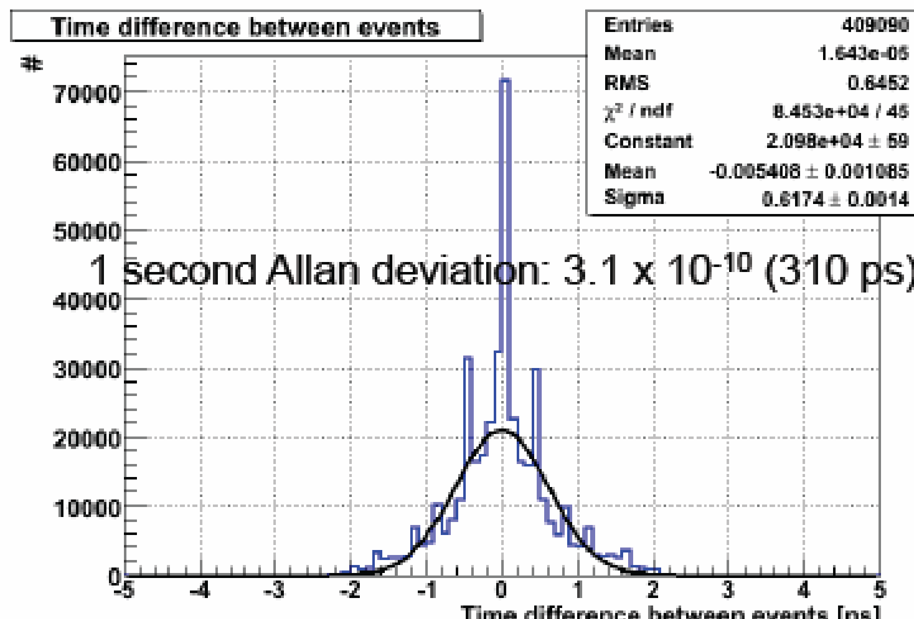
Japan’s program – Detector Synchronization

- The results did not change.









2012 polar season
Drilling and deployment #1 station

ARA 2012 (Japan)

- 台湾グループと共同で、ARA station 2 のアッセンブリと較正(来月からスタート)
- GPS の組み立て・設置

電波実験室の整備

- 電波暗室
- スペクトルアナライザー
- ネットワークアナライザー

ASKARYAN RADIO ARRAY

千葉大学 Chiba University

Schedule Toward ARA37

NSF (MRI-R2) grant funded ~$2,000,000
Total $3,000,000 (3years) for Phase I+II
Kickoff meeting March, 2010

Phase I: Testbed (2010-2011)
A prototype antenna station closest to IceCube lab.
Measure RF noise off the IceCube
    Deploy a deep pinger in an IceCube final string
        □ measure refraction index in the shallower ice
    Develop Hpol + Vpol dipole antenna

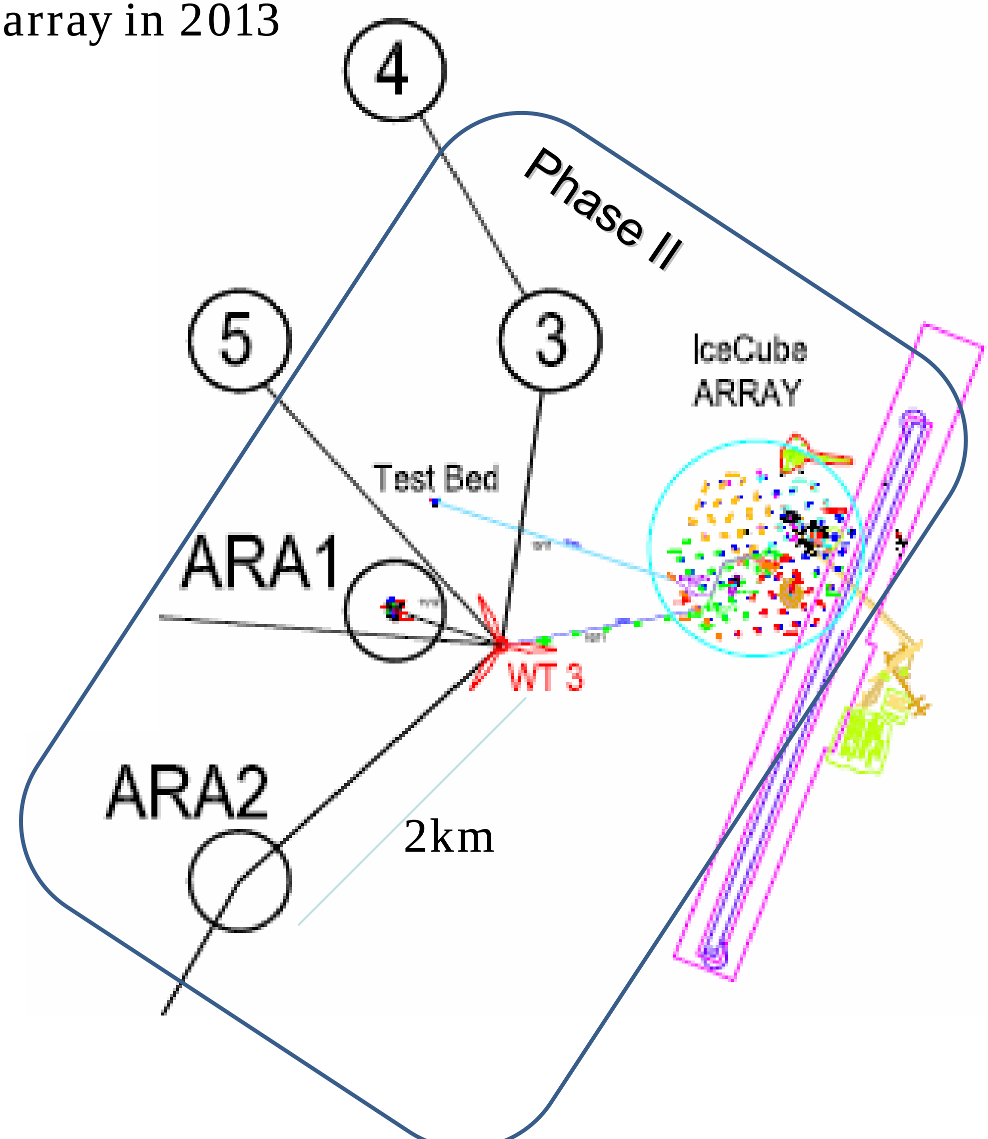
Phase II: ~10 km^2 Radio Antenna Array (2011-2013) ← 今、ここの段階
Testing communication + DAQ, Turbine, Inter-station sync.
    finalize the antenna + front-end readout

ARA-37

Phase III: 2013～
~200 km^2 Radio Antenna Array

2012-13: ARA phase-II 10km^3 Detector

The first results expected from Ara1-3 2km x 6km antenna array in 2013



Budget Breakdown

日本グループ責任分

Hardware only – Software, 人件費除く

1 station あたり

Detector sync. (時間同期系) 250万円

Data comm. (データ伝送系) 150万円

Radio Detector (電波検出器) 1000万円

日本グループ 12台の commit

Excerpt from the collaboration breakdown sheet

116	CAL-	2	Microcontroller		2		ea	$200	$400		UMD	UMD	procu
117	CAL-	3	Internal splitters/combiners	ZX10-2-12+	2		ea	$60	$120		UMD	UMD	procu
118	CAL-	4	downhole RF cable	LDF2-50 3/8" diameter	2		ea	$1,320	$2,640		UMD	UMD	procu
119	CAL-	5	Hpol borehole pulser antennas		4		ea	$500	$2,000	rough costs	UH	NTU	build
120	CAL-	6	Vpol borehole pulser antennas		4		ea	$500	$2,000	rough costs	UH	NTU	build
121	CAL-	7	internal RF cable parts		2		est	$200	$400		UMD	UMD	procu
122	CAL-	8	5V supply	LMZ1200 series switcher	2		ea	$100	$200		UMD	UMD	procu
123	CAL-	9	TTL boost	TTL-BOOST	2		ea	$50	$100		UMD	UMD	procu
124	CAL-	10	Noise source	NMA2510-2T	2		ea	$1,825	$3,650	small quantity quote	UMD	UMD	procu
125	CAL-	11	Feedthru adapters	SM4233	8		ea	$50	$400		UMD	UMD	procu
126	CAL-	12	pulser module	RFPOCV3	2		ea	$200	$400	engineering estimate	UMD	UMD	build
127	CAL-	13	pulser boost amplifier	ZKL-1R5	2		ea	$150	$300		UMD	UMD	procu
128	CAL-	14	antenna TX RF cable	LMR-600	8		ea	$35	$280		UMD	UMD	procu
133	Subtotal			*SUBTOTAL*					*$14,290*		UMD	UMD	
134	**ARA station cable (ASC)**												
135	ASC	1	power connector plug	FG24PN	1	1	ea	$85	$85		KU	KU	procu
136	ASC	2	testbed connector backshell		1	1	ea	$150	$150	estimate	KU	KU	procu
137	ASC	3	ferrites		20	10	ea	$3	$60	rough costs	KU	KU	procu
138	ASC	5	Junction box plug	MS3312 type	3		ea	$40	$120		KU	KU	procu
143	Subtotal			*SUBTOTAL*					*$415*		KU	KU	
144	**data-archiving system (DAS)**												
145	DAS-	1	Comms TX		1		ea	$250	$250	guess	Chiba	Chiba	procu
146	DAS-	2	Comms TX antenna + mount		1		ea	$100	$100	guess	Chiba	Chiba	procu
147	DAS-	3	Comms RX antenna + mount		1		ea	$100	$100	guess	Chiba	Chiba	procu
148	DAS-	4	Comms RX		1		ea	$250	$250	guess	Chiba	Chiba	procu
153	Subtotal			*SUBTOTAL*					*$700*		Chiba	Chiba	

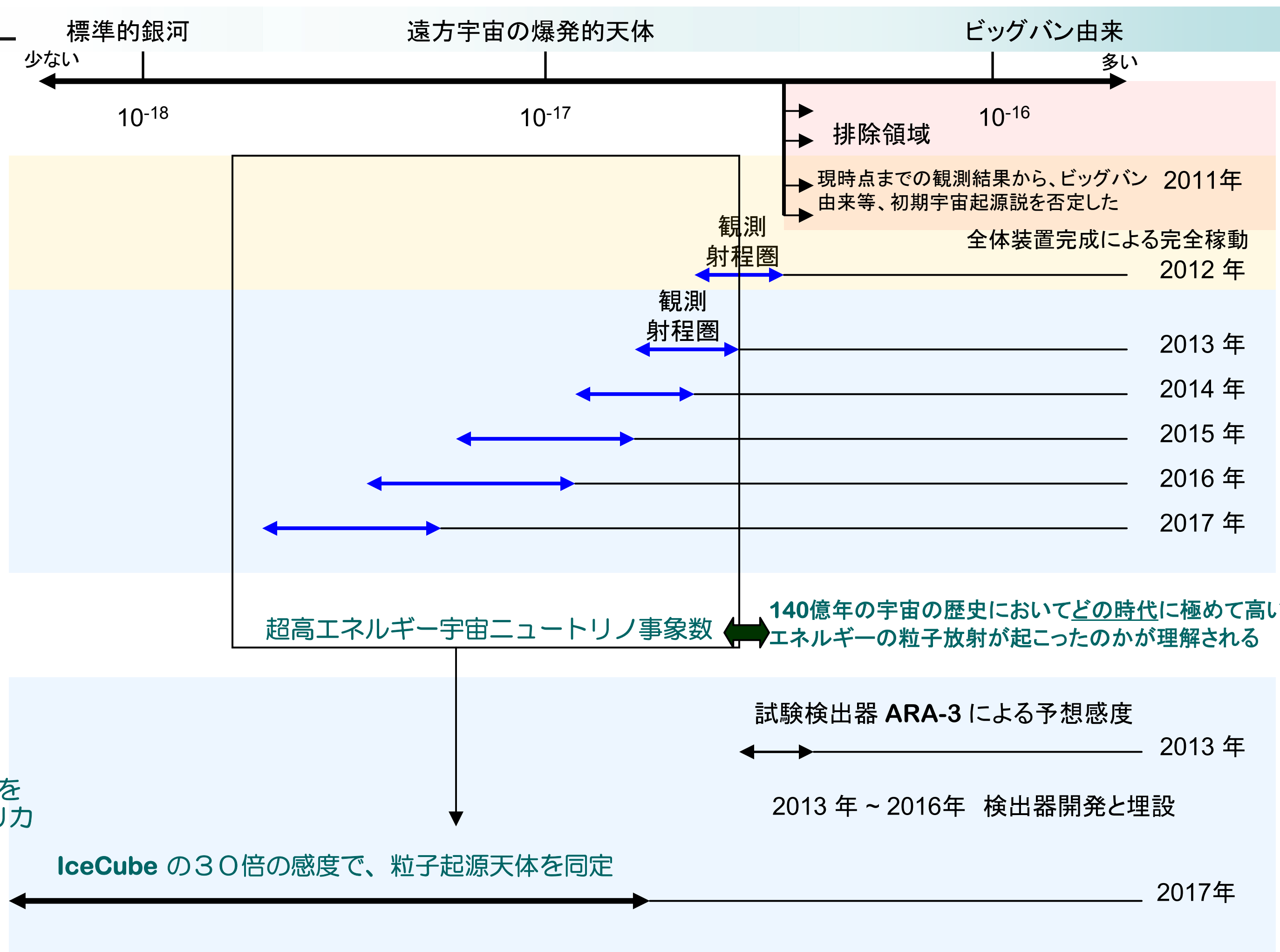
IceCube and ARA: Milestone

究極の目標　超高エネルギー帯における未知の宇宙像
「なぜ宇宙はかくも高いエネルギーの粒子を産むのか?」

予想される超高エネルギー
宇宙ニュートリノの量
[cm^{-2} sec^{-1} sr^{-1}]

UHE 帯の解析を
日本が主導

IceCube



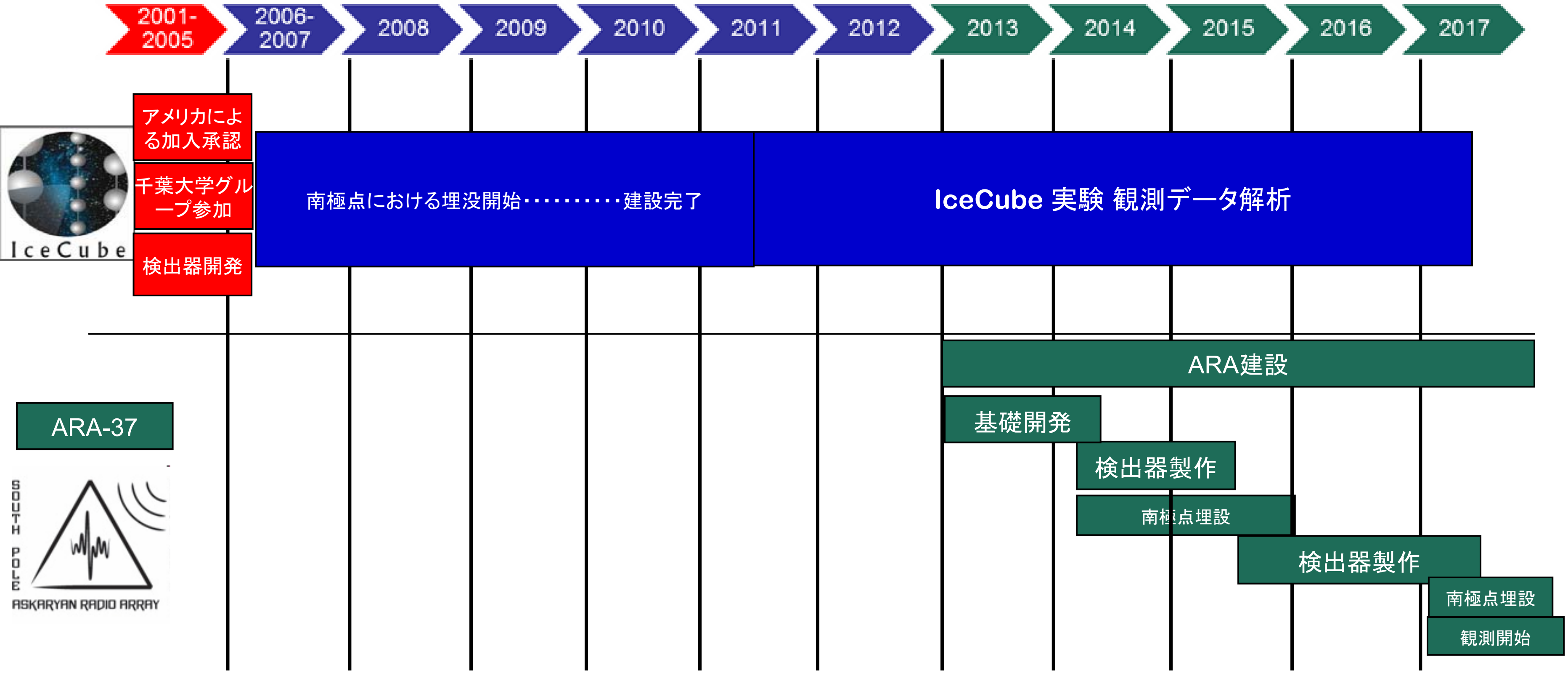
IceCube における実績を背景に、基幹検出器となるマイクロ波検出器を建造しARA 実験をアメリカと共に主導する。

ARA

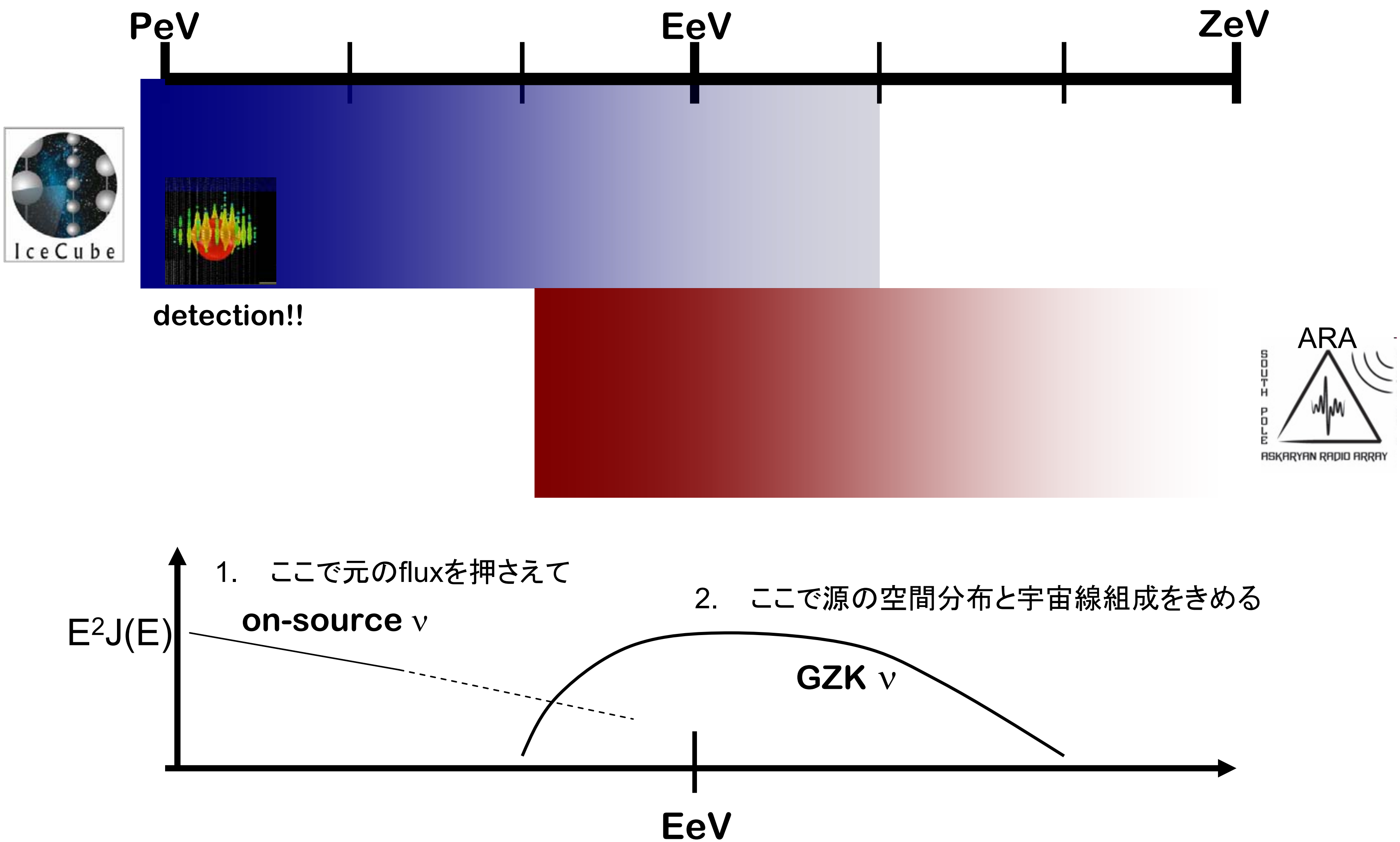
追求する科学は IceCube で日本が主導するものと合致

年表 2001-2017

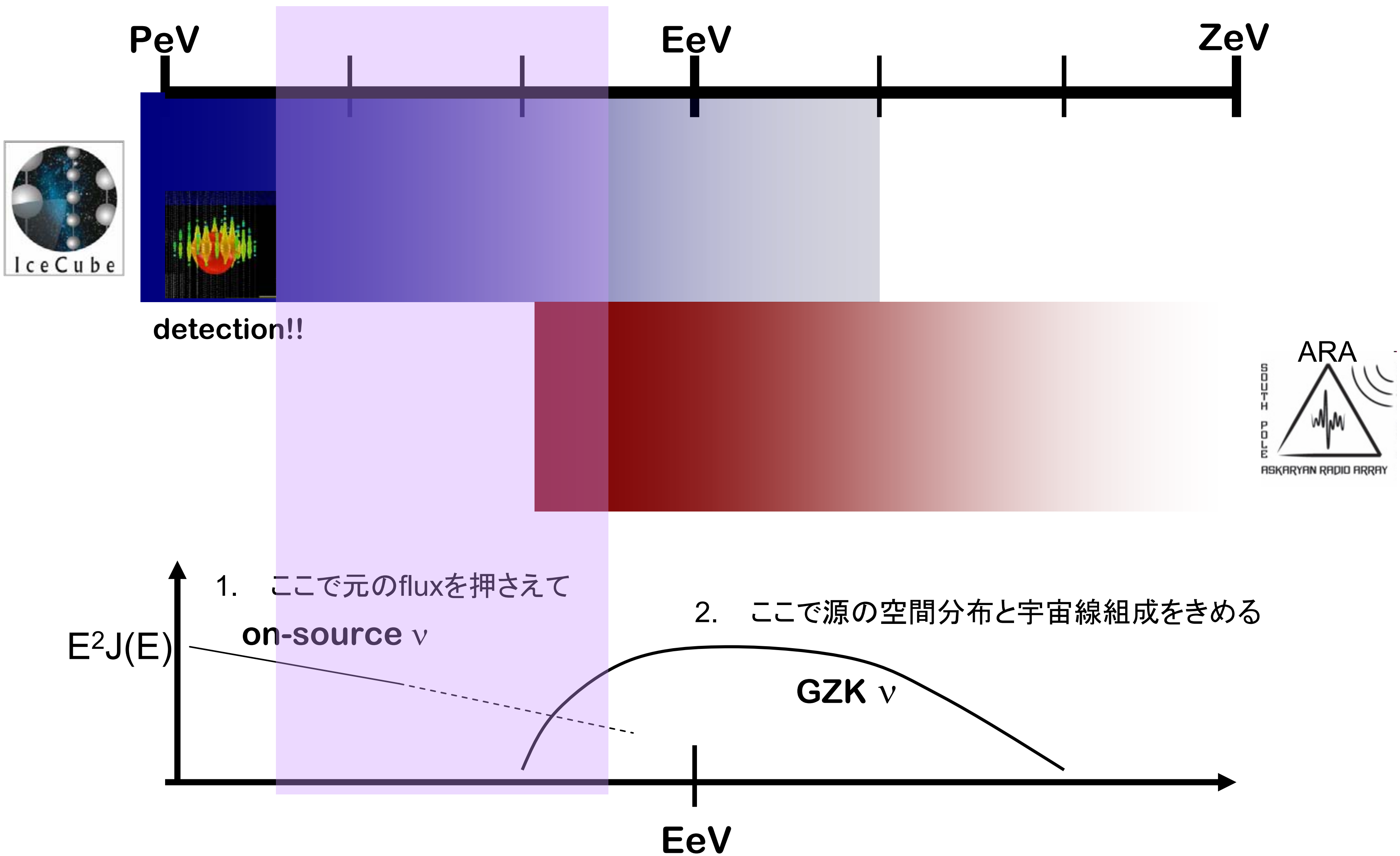
千葉大学 Chiba University



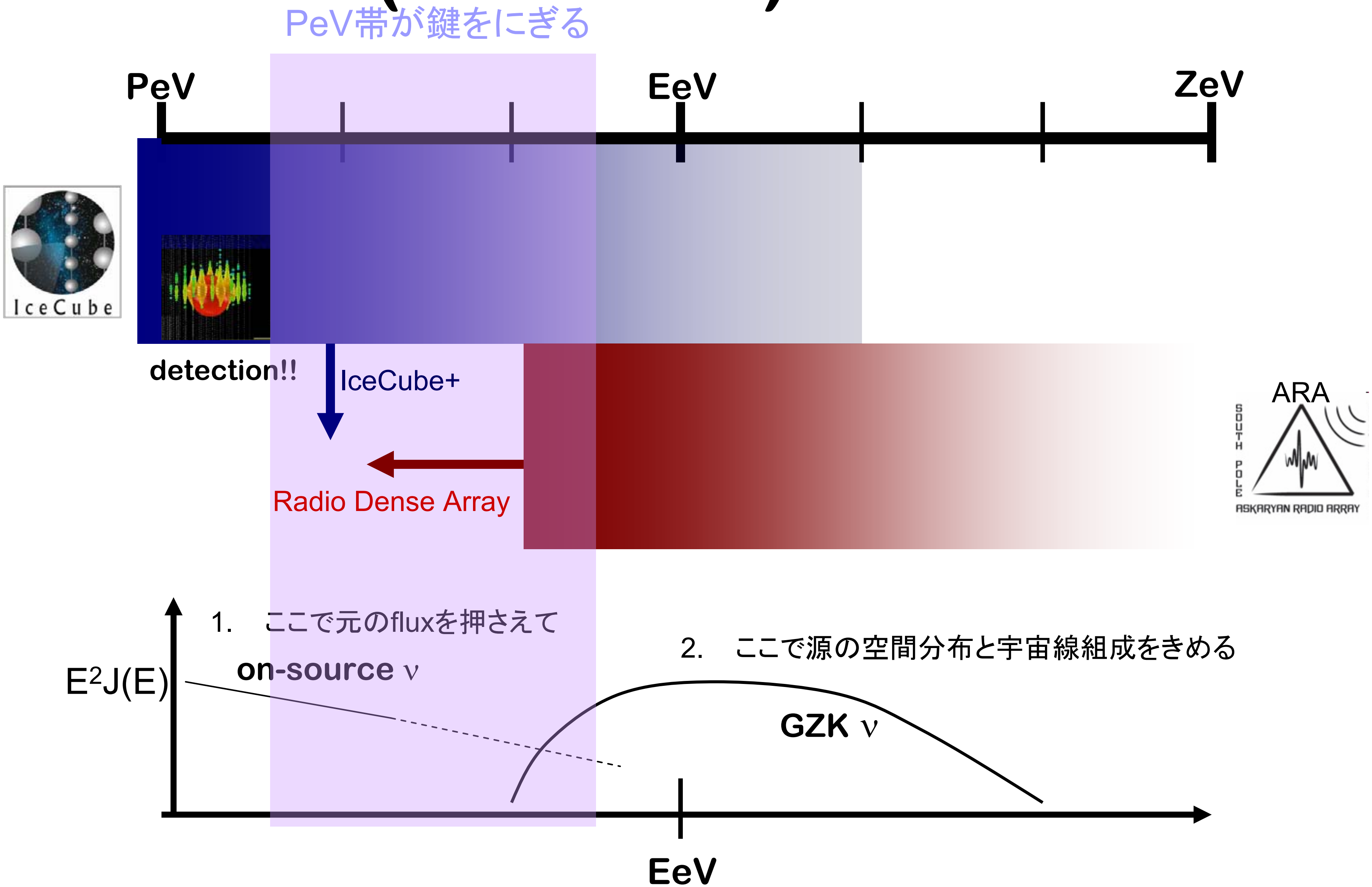
基本的に5ヵ年計画


PeV
EeV
ZeV
IceCube
detection!!
ARA
SOUTH POLE
ASKARYAN RADIO ARRAY
1.　ここで元のfluxを押さえて
2.　ここで源の空間分布と宇宙線組成をきめる
on-source ν
E²J(E)
GZK ν
EeV

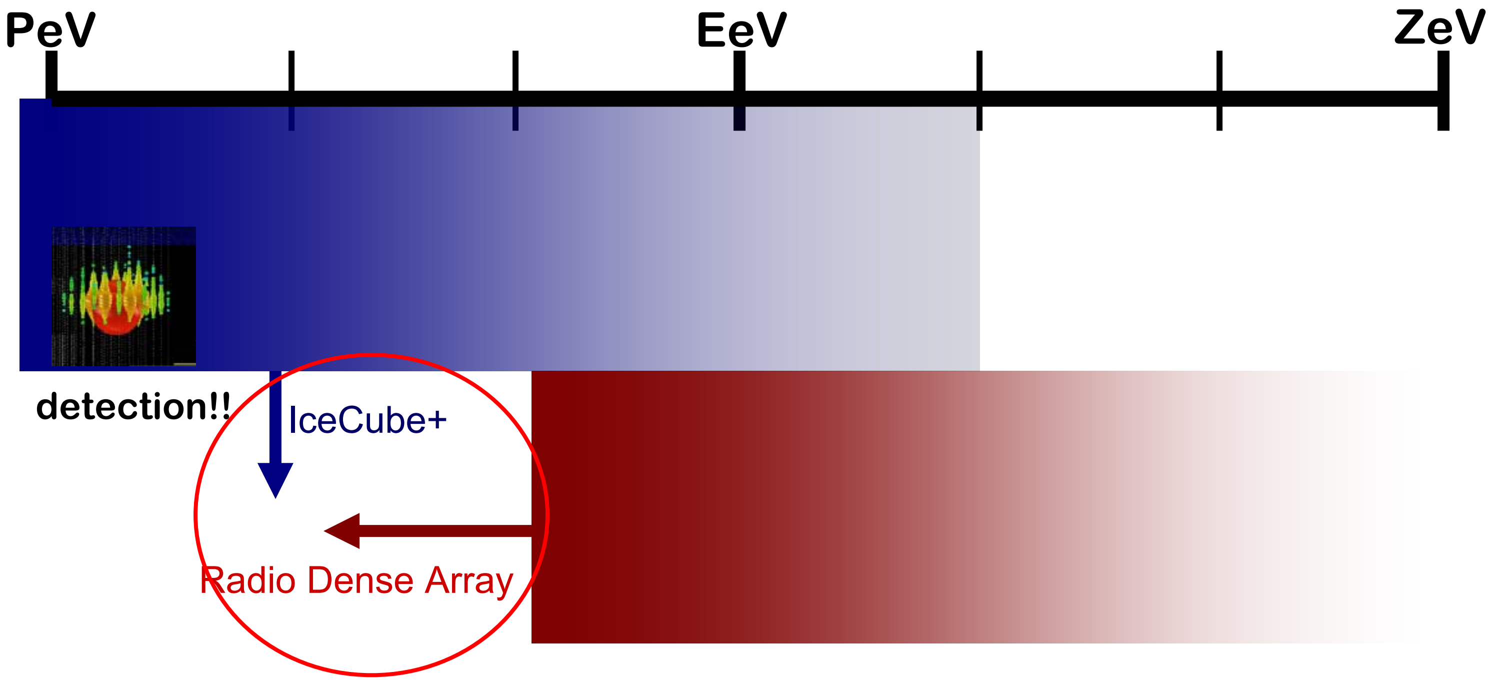
PeV帯が鍵をにぎる


PeV
EeV
ZeV
IceCube
detection!!
ARA
SOUTH POLE
ASKARYAN RADIO ARRAY
1.　ここで元のfluxを押さえて
on-source ν
2.　ここで源の空間分布と宇宙線組成をきめる
$E^2J(E)$
GZK ν
EeV

PeV (sub-EeV) detector?



PeV (sub-EeV) detector

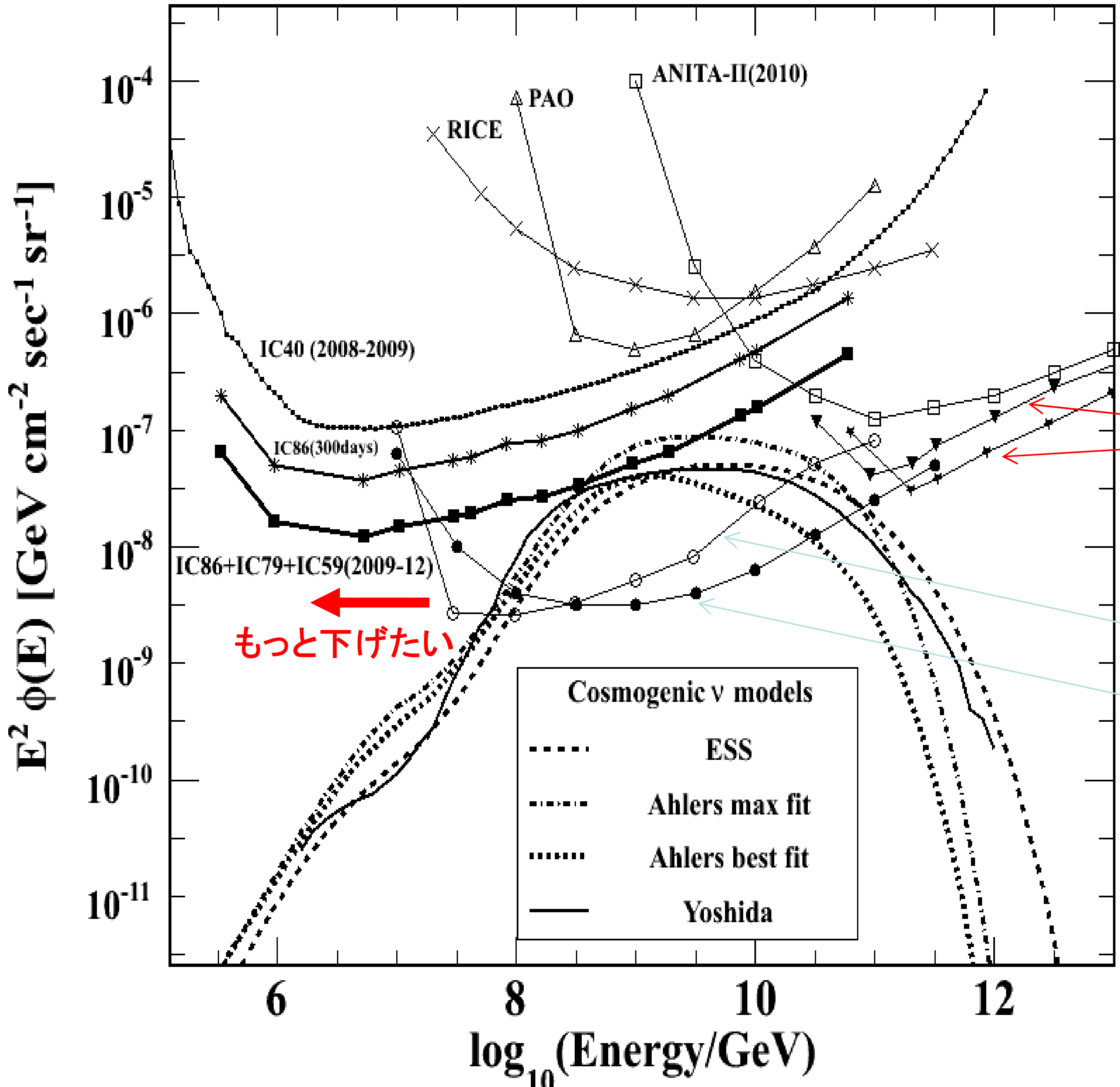


- 詳細設計はこれから。光検出器、エレキ
- 日本が旗を掲げるドンピシャリのタイミング
- 宇宙線起源を<u>本当に</u>解明するチャンスがある。

ν の優位性は絵に描いた餅ではない

日本として手を挙げてコミットしませんか?

Summary of Future Sensitivities



$> 10^{11}$GeV neutrinos
high E_{max} physics

EUSO

P. Gorodetzk, NIMA (2011)

ARIANNA

ARA

Main stream energy region
- Competitive as designed
- O(50-100) gzk neutrinos/year
- cosmic-ray sources
- composition

今日、最も言いたかったこと

Before Neutrino 2012…

ニュートリノねえ。いいんだけど、どうせ見つからないんだろう、吉田くん

Now

いや、あったんですよ! 砂漠じゃなかったんです。

$\boxed{\text{今が参入の絶好の機会}}$

この結果を出したUHE 解析は日本が主要な寄与。
このモーメンタムを生かさない手はない。
しかもcontribution する場所はたくさんある。

(Published) Reference

- Calculations of UHE ν propagation and the tactics for their detection by IceCube

  SY et al Phys.Rev.D 69 103004 (2004)
- The detailed description of GZK ν search by IceCube and the 1st results using 2007-2008 data

  IceCube collaboration, Phys.Rev.D 82 072003 (2010)
- The follow up results using 2008-2009 data: The world tightest limit as of today

  IceCube collaboration, Phys.Rev.D 83 092003 (2011)
- An analytical approach to constrain UHECR origin with ultra-high energy ν flux

  SY and A.Ishihara, Phys.Rev.D 85 063002 (2012)

千葉大学
Chiba University