IceCube
Kyoto 2005
UHE Neutrino Astronomy
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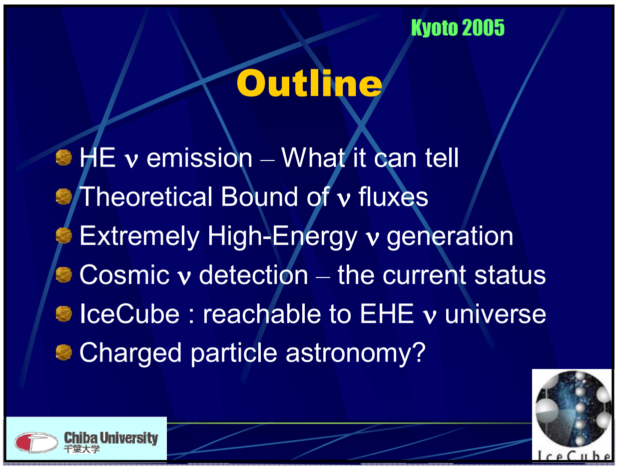
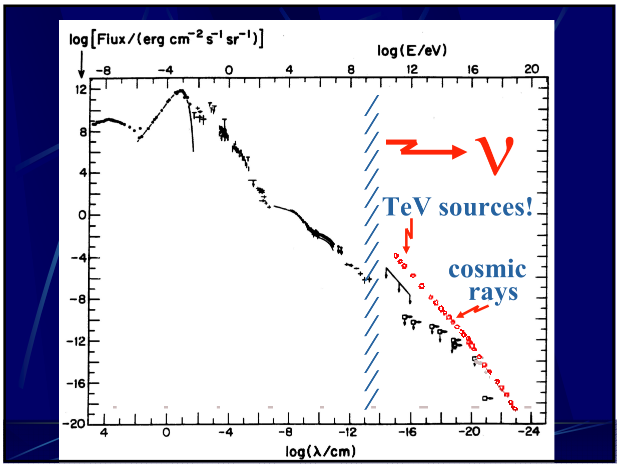
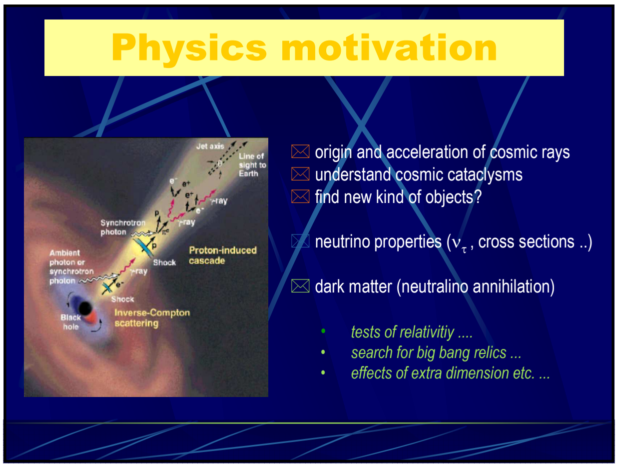
http://www.ppl.phys.chiba-u.jp/~syoshida/
Chiba University



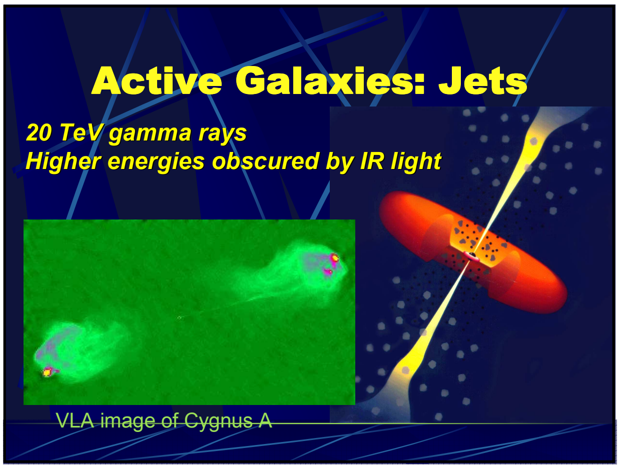
Kyoto 2005
Outline
HE ν emission – What it can tell
Theoretical Bound of ν fluxes
Extremely High-Energy ν generation
Cosmic ν detection – the current status
IceCube : reachable to EHE ν universe
Charged particle astronomy?
Chiba University
IceCube



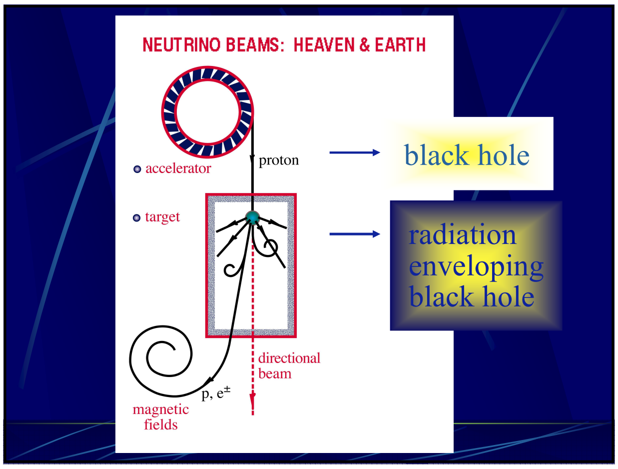
log[Flux/(erg cm^-2 s^-1 sr^-1)]
log(E/eV)
log(λ/cm)
ν
TeV sources!
cosmic rays



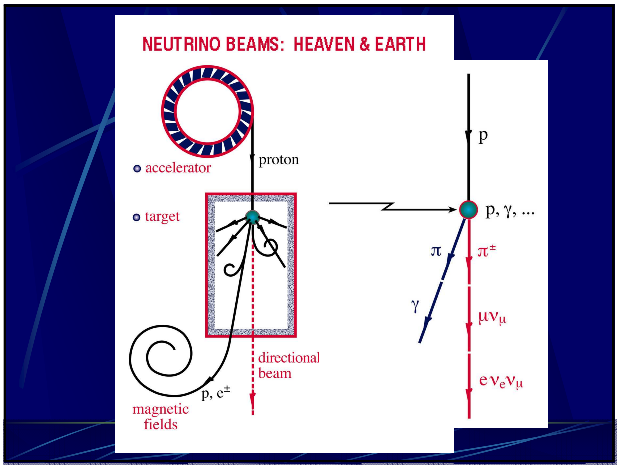
Physics motivation
origin and acceleration of cosmic rays
understand cosmic cataclysms
find new kind of objects?
neutrino properties (ν_τ , cross sections ..)
dark matter (neutralino annihilation)
tests of relativitiy ....
search for big bang relics ...
effects of extra dimension etc. ...

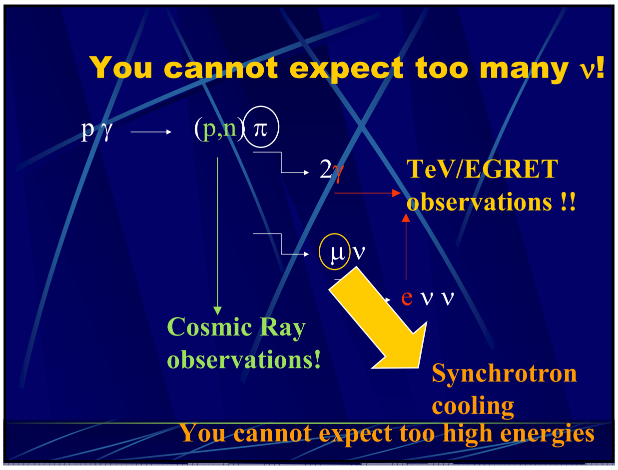


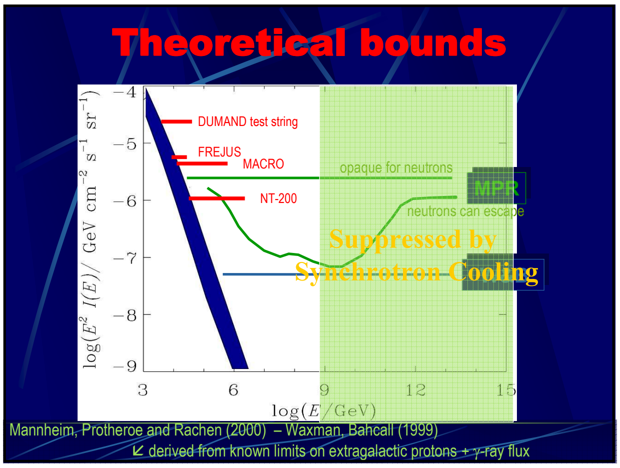
Active Galaxies: Jets
20 TeV gamma rays
Higher energies obscured by IR light
VLA image of Cygnus A

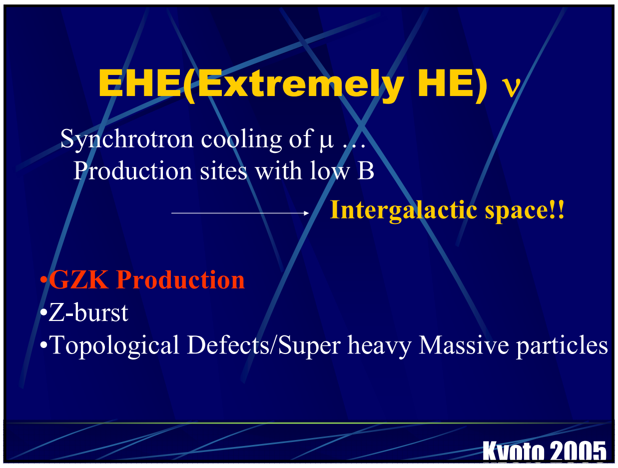


NEUTRINO BEAMS: HEAVEN & EARTH
accelerator
proton
target
magnetic fields
p, e±
directional beam
black hole
radiation enveloping black hole


NEUTRINO BEAMS: HEAVEN & EARTH
accelerator
proton
target
p
p, γ, ...
π
π±
γ
μν_μ
eν_eν_μ
directional beam
p, e±
magnetic fields


You cannot expect too many ν!
p γ → (p,n) π
2γ
TeV/EGRET observations !!
μ ν
e ν ν
Cosmic Ray observations!
Synchrotron cooling
You cannot expect too high energies


Theoretical bounds
DUMAND test string
FREJUS
MACRO
NT-200
opaque for neutrons
MPR
neutrons can escape
Suppressed by Synchrotron Cooling
log(E² I(E)/ GeV cm⁻² s⁻¹ sr⁻¹)
log(E/GeV)
Mannheim, Protheroe and Rachen (2000) – Waxman, Bahcall (1999)
derived from known limits on extragalactic protons + γ-ray flux


EHE(Extremely HE) ν
Synchrotron cooling of μ …
Production sites with low B
Intergalactic space!!
•GZK Production
•Z-burst
•Topological Defects/Super heavy Massive particles
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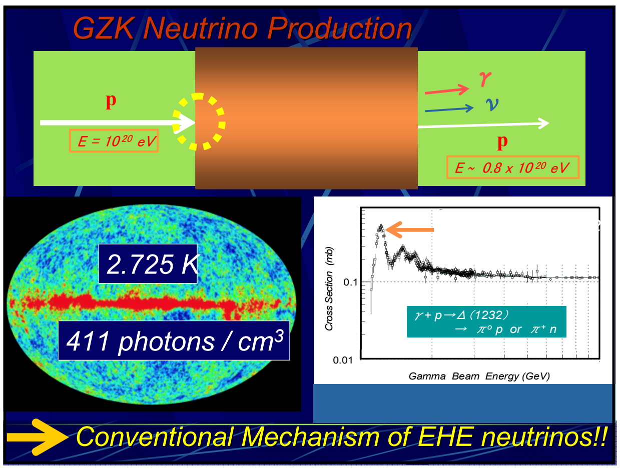
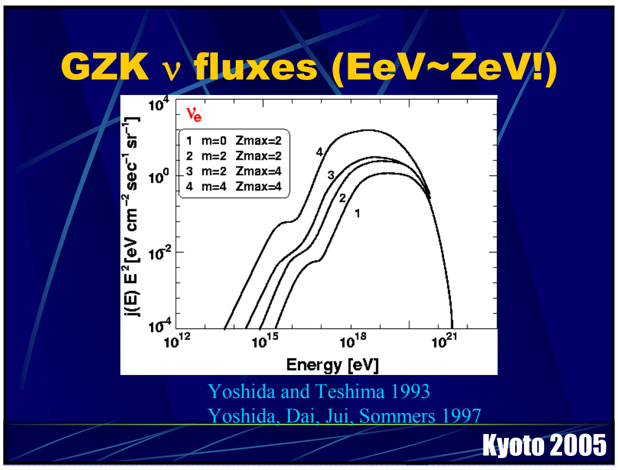

GZK Neutrino Production
p
E = 10²⁰ eV
γ
ν
p
E ~ 0.8 x 10²⁰ eV
2.725 K
411 photons / cm³
γ + p → Δ (1232) → π⁰ p or π⁺ n
Cross Section (mb)
Gamma Beam Energy (GeV)
Conventional Mechanism of EHE neutrinos!!


GZK ν fluxes (EeV~ZeV!)
ν_e
1 m=0 Zmax=2
2 m=2 Zmax=2
3 m=2 Zmax=4
4 m=4 Zmax=4
j(E) E² [eV cm⁻² sec⁻¹ sr⁻¹]
Energy [eV]
Yoshida and Teshima 1993
Yoshida, Dai, Jui, Sommers 1997
Kyoto 2005

Parameters involved in calculation. Predicted fluxes.

Parameters		Orientative order of magnitude
γ	spectral injection index	[1-3]
m	activity evolution index	[3-5]
z_{max}	z of formation of sources	[1-4]
Ω_M	density of matter	[0.2-1]
H_o	Hubble constant	[50-80 Km/s/Mpc]
B	intergalactic magnetic field	[B≤1nG]
$\eta_L\rho_L/\eta_o\rho_o$	local enhancement	[?]
E_{max}	maximum acceleration energy in source	[E_{max} >4 10^{20} eV]

(Diego González-Díaz, Ricardo Vázquez, Enrique Zas 2003)

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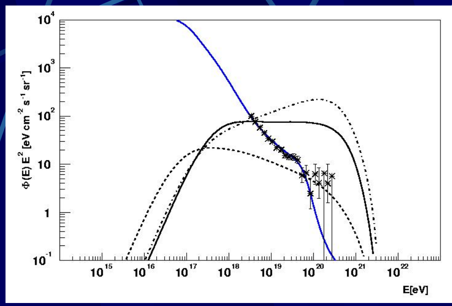
(Diego González-Díaz, Ricardo Vázquez, Enrique Zas 2003)

CR and ν fluxes for different models



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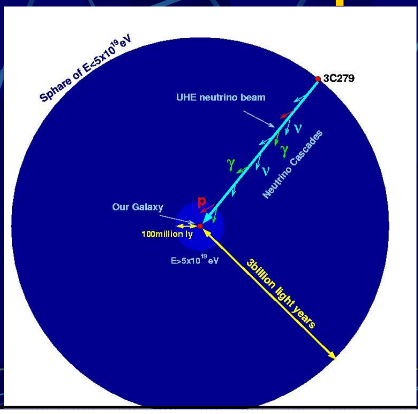
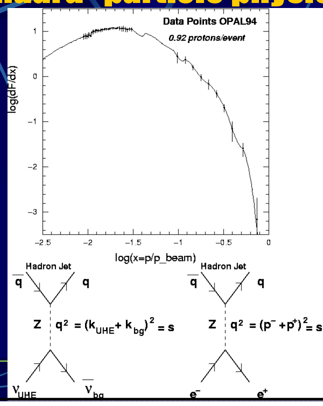
Z-bursts Concept

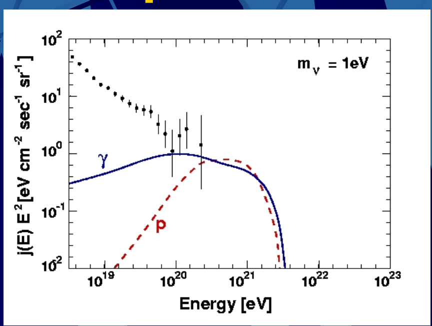


It is the "standard" particle physics

$\nu\nu \rightarrow p, \pi^+, \pi^-, \pi_0 ...$



CRs extending to superEHEs!



(Yoshida, Sigl, Lee 1998)

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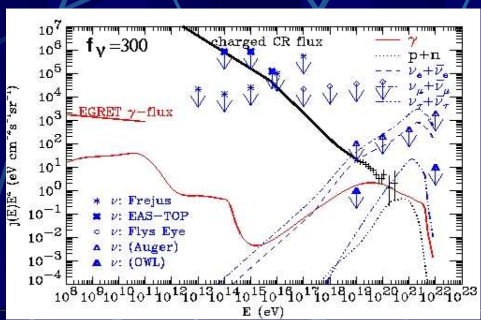
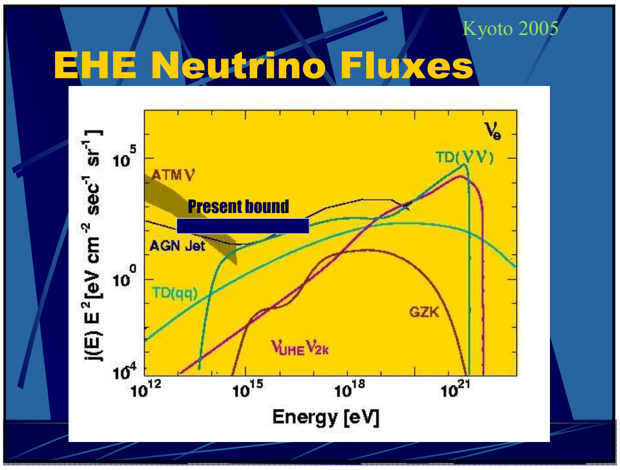
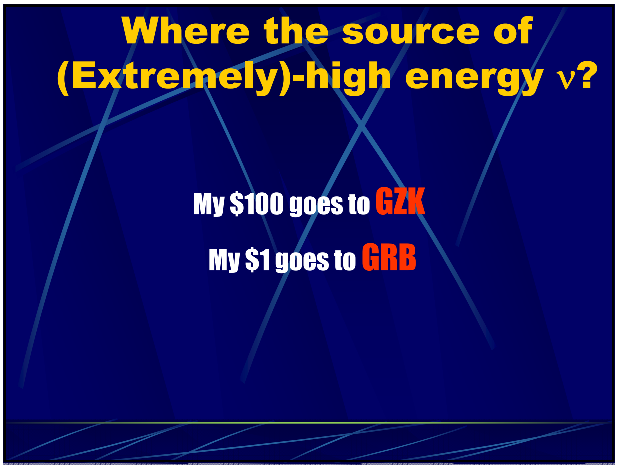
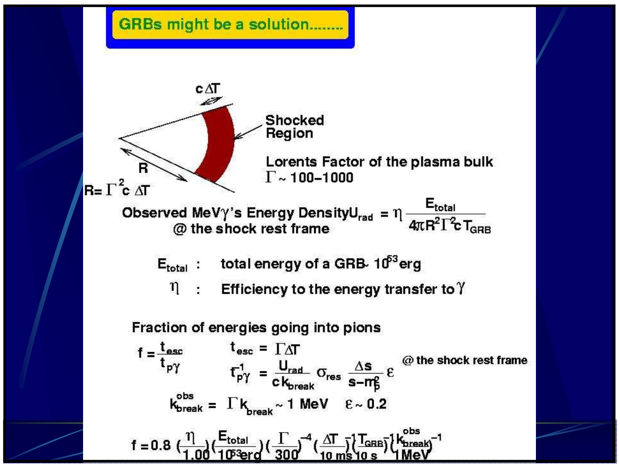
Z-burst constraints

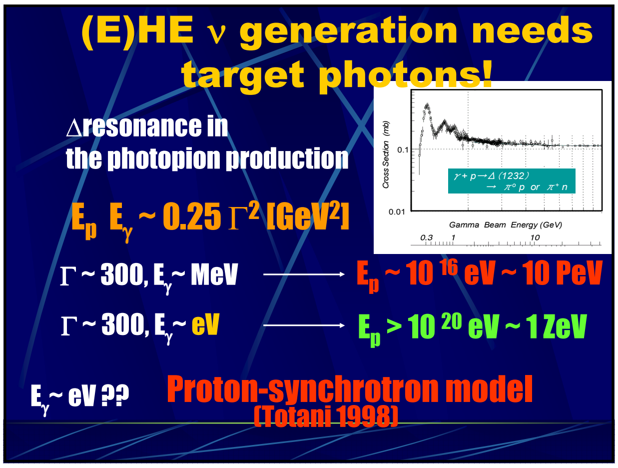


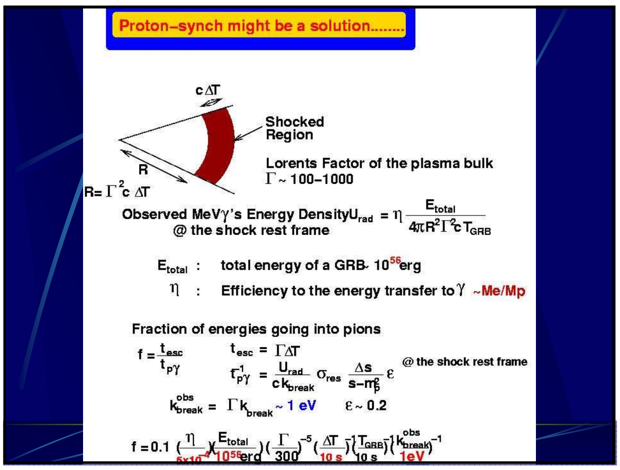
(Yoshida, Sigl, Lee 1998)

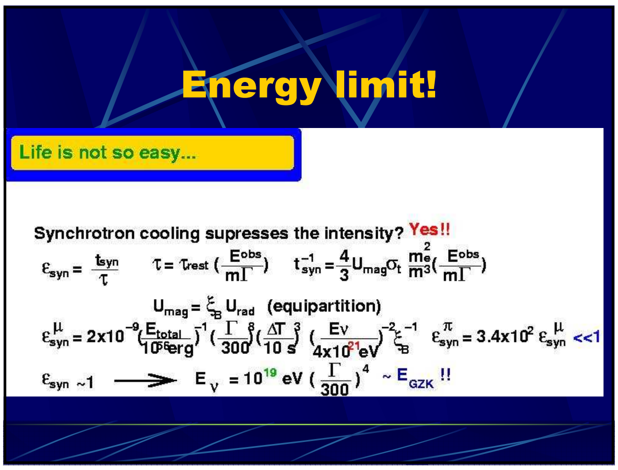

Kyoto 2005
EHE Neutrino Fluxes
ν_e
TD(νν)
ATM ν
Present bound
AGN Jet
TD(qq)
GZK
ν_UHE ν_2k
j(E) E²[eV cm⁻² sec⁻¹ sr⁻¹]
Energy [eV]

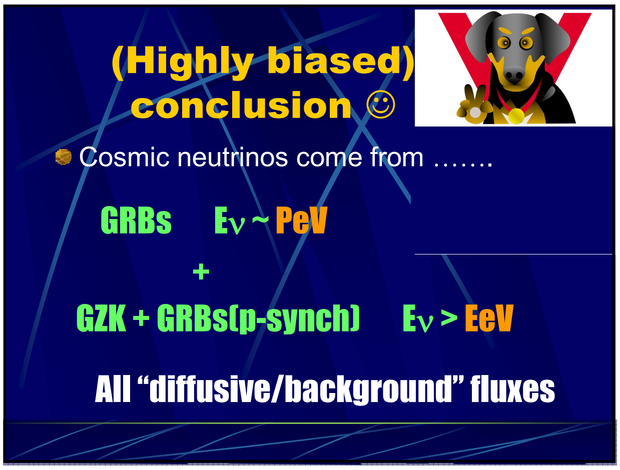

Where the source of (Extremely)-high energy ν?
My $100 goes to GZK
My $1 goes to GRB

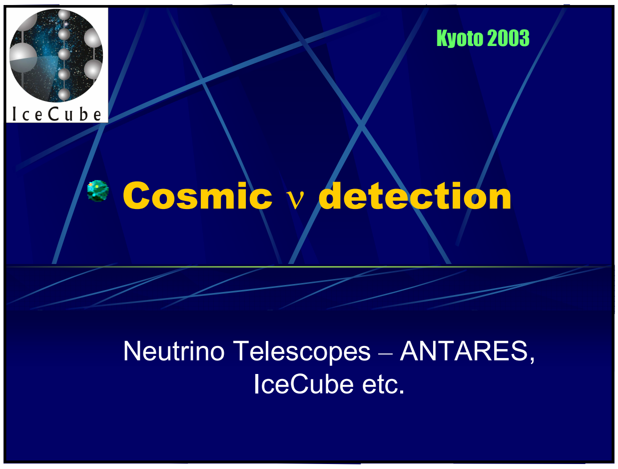

GRBs might be a solution........
cΔT
Shocked Region
Lorents Factor of the plasma bulk
Γ ~ 100–1000
R= Γ²c ΔT
Observed MeVγ's Energy Density
@ the shock rest frame
E_total : total energy of a GRB- 10⁵³erg
η : Efficiency to the energy transfer to γ
Fraction of energies going into pions
@ the shock rest frame
~ 1 MeV ε ~ 0.2

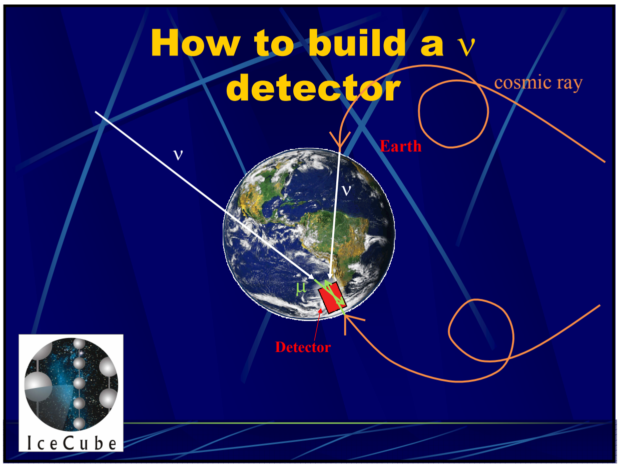

(E)HE ν generation needs target photons!
Δresonance in the photopion production
E_p E_γ ~ 0.25 Γ² [GeV²]
Γ ~ 300, E_γ ~ MeV → E_p ~ 10¹⁶ eV ~ 10 PeV
Γ ~ 300, E_γ ~ eV → E_p > 10²⁰ eV ~ 1 ZeV
E_γ ~ eV ??
Proton-synchrotron model
[Totani 1998]
γ + p → Δ (1232) → π⁰ p or π⁺ n
Cross Section (mb)
Gamma Beam Energy (GeV)

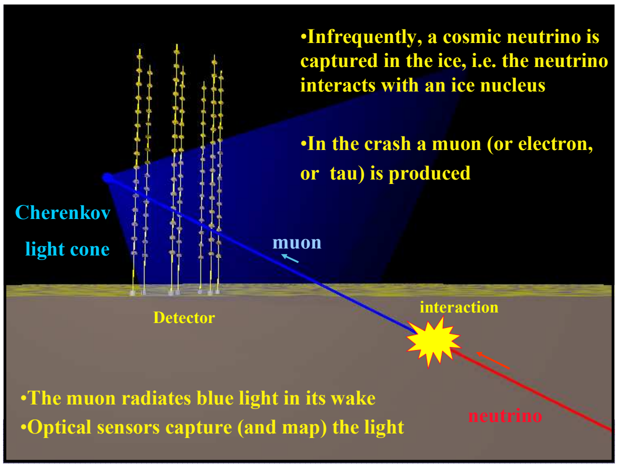

Proton–synch might be a solution........
cΔT
Shocked Region
Lorents Factor of the plasma bulk
Γ ~ 100–1000
R= Γ²c ΔT
Observed MeVγ's Energy Density
@ the shock rest frame
E_total : total energy of a GRB- 10⁵⁶erg
η : Efficiency to the energy transfer to γ ~Me/Mp
Fraction of energies going into pions
@ the shock rest frame
~ 1 eV ε ~ 0.2

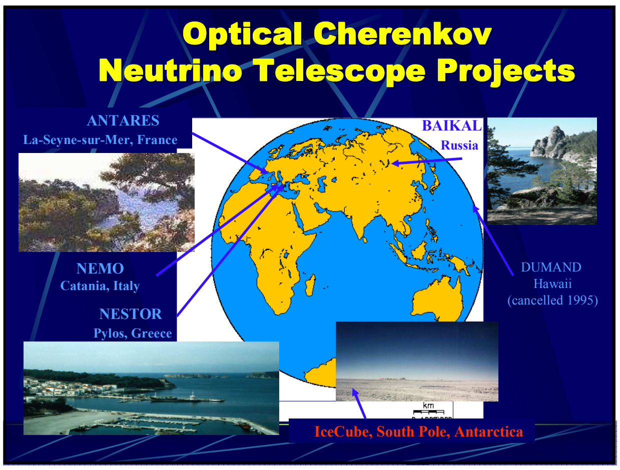

Energy limit!
Life is not so easy...
Synchrotron cooling supresses the intensity? Yes!!
U_mag = ξ_B U_rad (equipartition)
ε_syn ~1 → E_ν = 10¹⁹ eV (Γ/300)⁴ ~ E_GZK !!

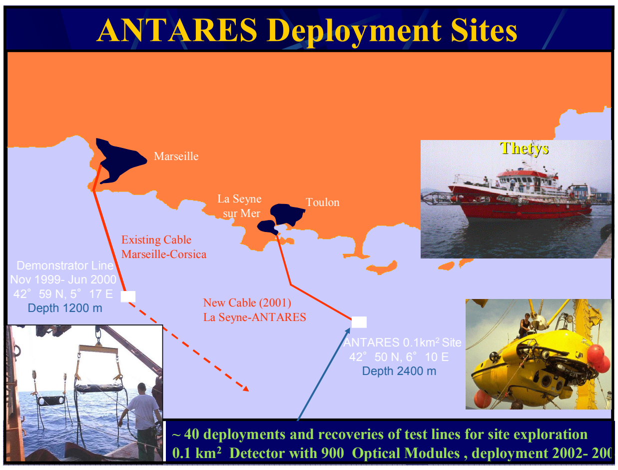

(Highly biased) conclusion ☺
Cosmic neutrinos come from …….
GRBs Eν ~ PeV
+
GZK + GRBs(p-synch) Eν > EeV
All "diffusive/background" fluxes

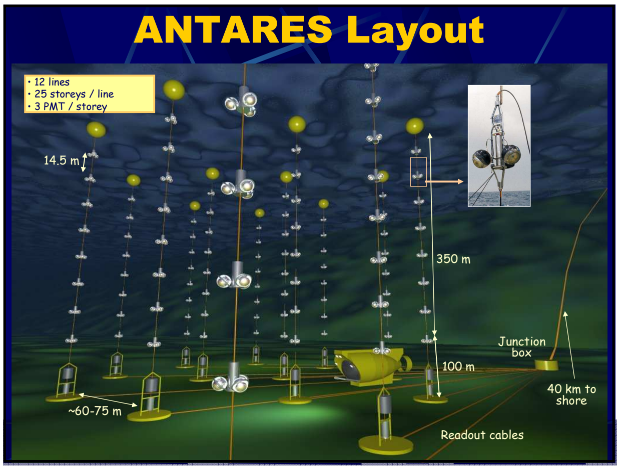

IceCube
Kyoto 2003
Cosmic ν detection
Neutrino Telescopes – ANTARES, IceCube etc.

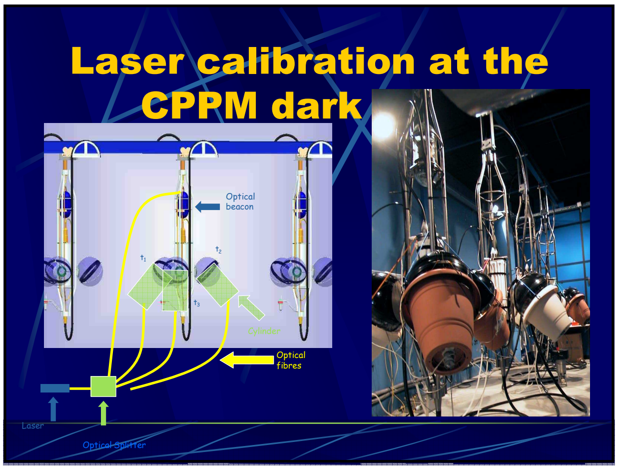

How to build a ν detector
cosmic ray
Earth
ν
ν
μ
Detector
IceCube

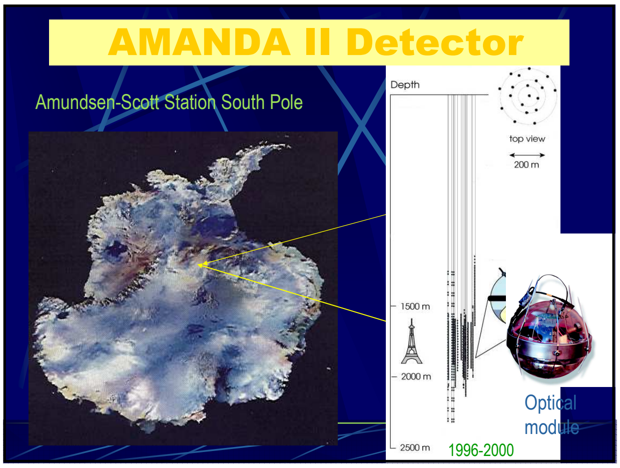

•Infrequently, a cosmic neutrino is captured in the ice, i.e. the neutrino interacts with an ice nucleus
•In the crash a muon (or electron, or tau) is produced
Cherenkov light cone
muon
Detector
interaction
•The muon radiates blue light in its wake
•Optical sensors capture (and map) the light
neutrino

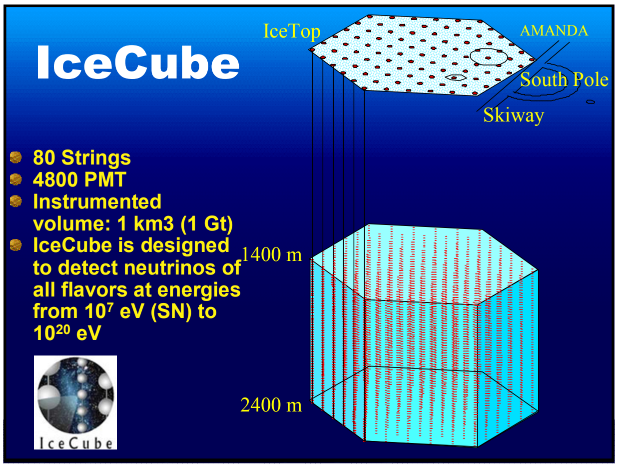

Optical Cherenkov Neutrino Telescope Projects
ANTARES
La-Seyne-sur-Mer, France
BAIKAL
Russia
NEMO
Catania, Italy
NESTOR
Pylos, Greece
DUMAND
Hawaii
(cancelled 1995)
IceCube, South Pole, Antarctica

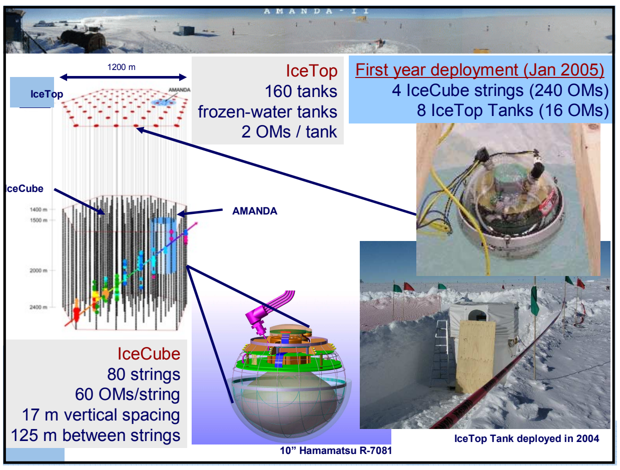

ANTARES Deployment Sites
Marseille
Thetys
La Seyne sur Mer
Toulon
Existing Cable Marseille-Corsica
Demonstrator Line
Nov 1999- Jun 2000
Depth 1200 m
New Cable (2001)
La Seyne-ANTARES
ANTARES 0.1km² Site
Depth 2400 m
~ 40 deployments and recoveries of test lines for site exploration
0.1 km² Detector with 900 Optical Modules , deployment 2002- 20

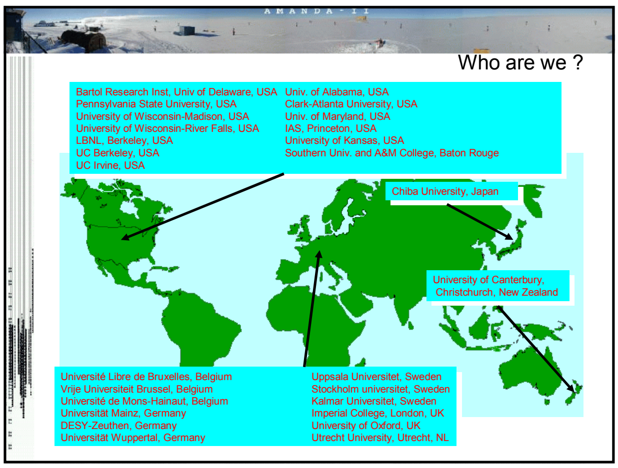

ANTARES Layout
• 12 lines
• 25 storeys / line
• 3 PMT / storey
14.5 m
350 m
Junction box
100 m
40 km to shore
~60-75 m
Readout cables

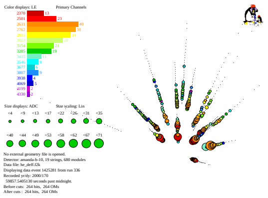

Laser calibration at the CPPM dark
Optical beacon
Optical fibres
Laser
Optical splitter

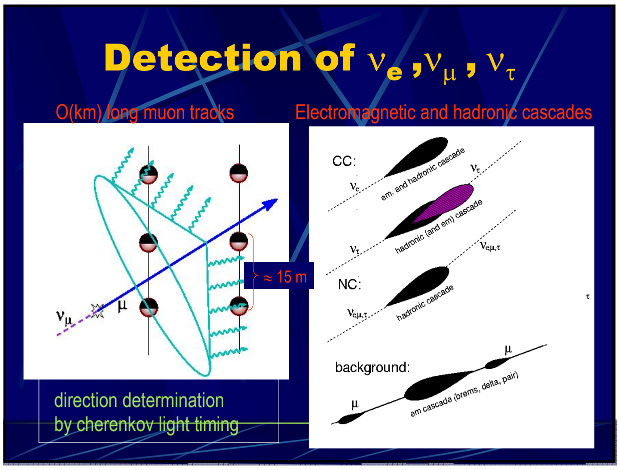

AMANDA II Detector
Amundsen-Scott Station South Pole
Depth
top view
200 m
1500 m
2000 m
2500 m
Optical module
1996-2000


IceCube
IceTop
AMANDA
South Pole
Skiway
80 Strings
4800 PMT
Instrumented volume: 1 km3 (1 Gt)
IceCube is designed to detect neutrinos of all flavors at energies from 10^7 eV (SN) to 10^{20} eV
1400 m
2400 m
IceCube

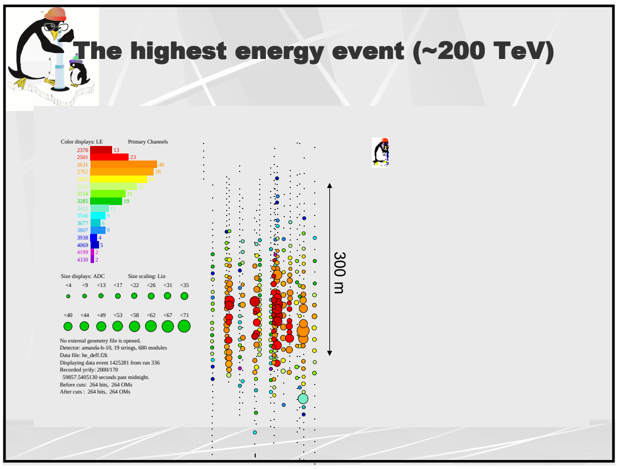

A M A N D A - I I
1200 m
IceTop
AMANDA
IceCube
IceTop
160 tanks
frozen-water tanks
2 OMs / tank
First year deployment (Jan 2005)
4 IceCube strings (240 OMs)
8 IceTop Tanks (16 OMs)
IceCube
80 strings
60 OMs/string
17 m vertical spacing
125 m between strings
10" Hamamatsu R-7081
IceTop Tank deployed in 2004


A M A N D A - I I
Who are we ?
Bartol Research Inst, Univ of Delaware, USA
Pennsylvania State University, USA
University of Wisconsin-Madison, USA
University of Wisconsin-River Falls, USA
LBNL, Berkeley, USA
UC Berkeley, USA
UC Irvine, USA
Univ. of Alabama, USA
Clark-Atlanta University, USA
Univ. of Maryland, USA
IAS, Princeton, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge
Chiba University, Japan
University of Canterbury, Christchurch, New Zealand
Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universität Mainz, Germany
DESY-Zeuthen, Germany
Universität Wuppertal, Germany
Uppsala Universitet, Sweden
Stockholm universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Utrecht, NL

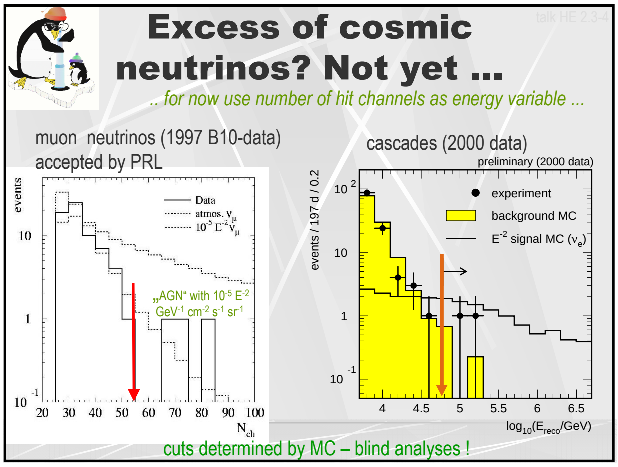




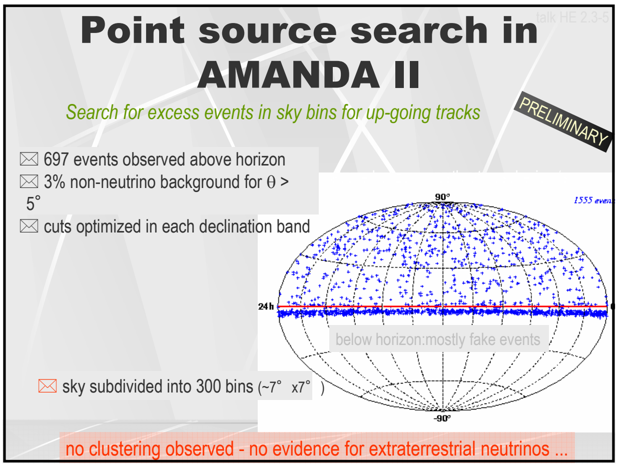
Detection of ν_e, ν_μ, ν_τ
O(km) long muon tracks
Electromagnetic and hadronic cascades
ν_μ
μ
≈ 15 m
CC:
ν_e
em. and hadronic cascade
ν_τ
hadronic (and em) cascade
$\nu_{e,\mu,\tau}$
NC:
hadronic cascade
background:
μ
em cascade (brems, delta, pair)
direction determination
by cherenkov light timing



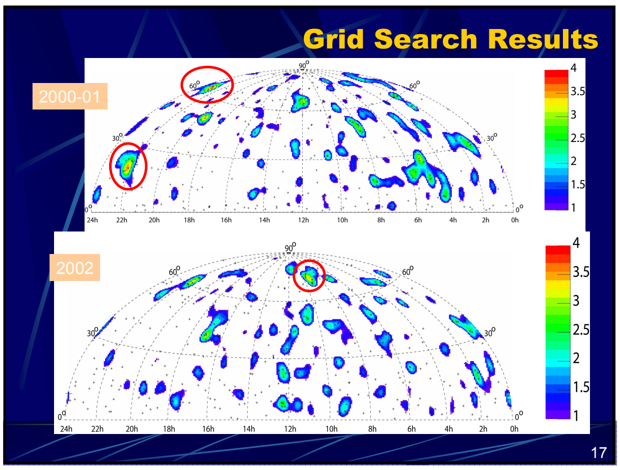
The highest energy event (~200 TeV)
300 m



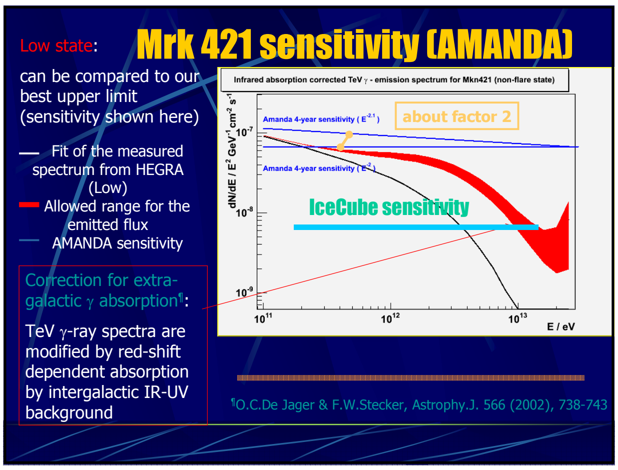
Excess of cosmic
neutrinos? Not yet ...
.. for now use number of hit channels as energy variable ...
muon neutrinos (1997 B10-data)
accepted by PRL
cascades (2000 data)
preliminary (2000 data)
events
Data
atmos. ν_μ
10^{-5} E^{-2} ν_μ
„AGN" with 10^{-5} E^{-2}
GeV^{-1} cm^{-2} s^{-1} sr^{-1}
N_{ch}
events / 197 d / 0.2
experiment
background MC
E^{-2} signal MC (ν_e)
$\log_{10}(E_{reco}/GeV)$
cuts determined by MC – blind analyses !



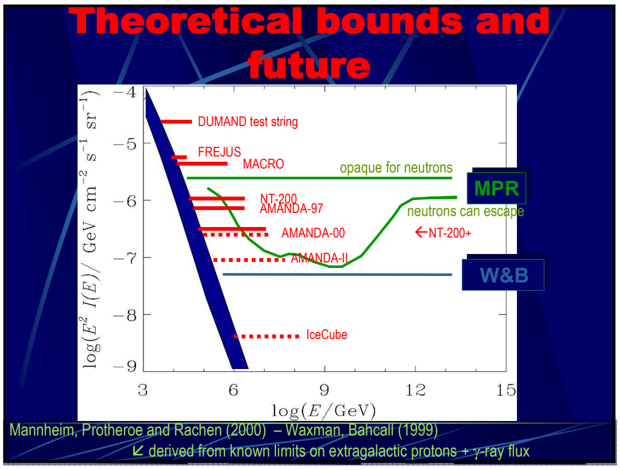
Point source search in
AMANDA II
Search for excess events in sky bins for up-going tracks
PRELIMINARY
697 events observed above horizon
3% non-neutrino background for θ > 5°
cuts optimized in each declination band
sky subdivided into 300 bins (~7° x7°)
below horizon:mostly fake events
90°
-90°
24 h
no clustering observed - no evidence for extraterrestrial neutrinos ...

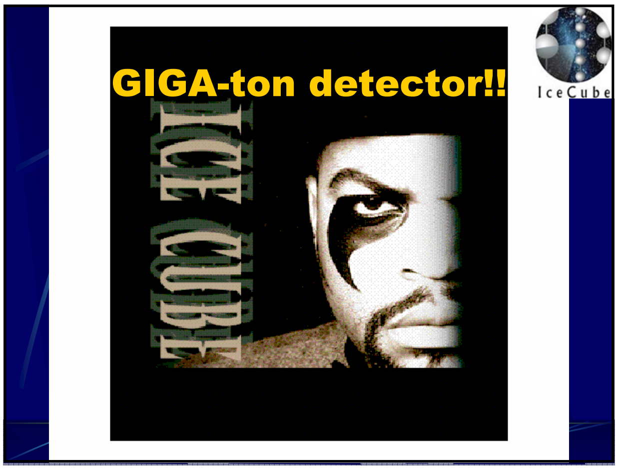


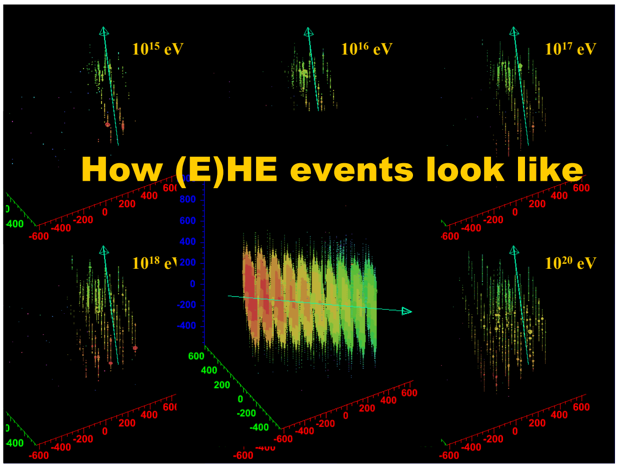
Grid Search Results
2000-01
2002
17

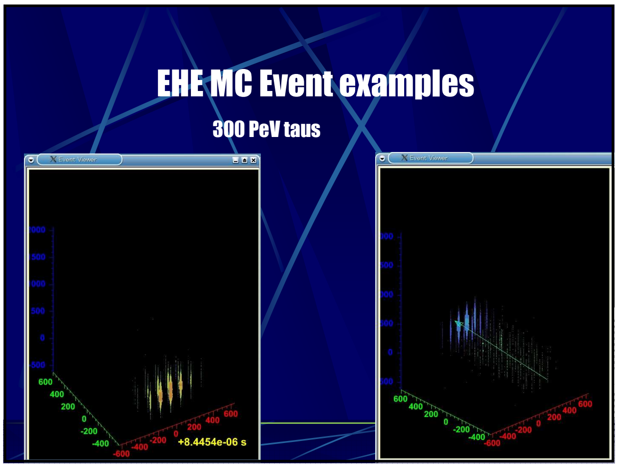


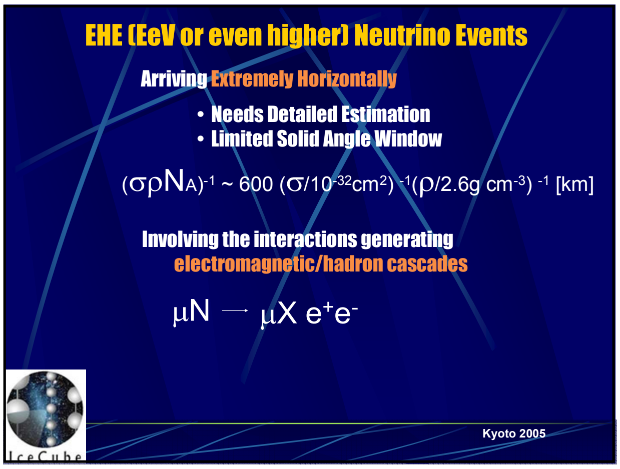
Low state:
Mrk 421 sensitivity (AMANDA)
can be compared to our best upper limit (sensitivity shown here)
Fit of the measured spectrum from HEGRA (Low)
Allowed range for the emitted flux
AMANDA sensitivity
Correction for extra-galactic γ absorption¶:
TeV γ-ray spectra are modified by red-shift dependent absorption by intergalactic IR-UV background
Infrared absorption corrected TeV γ - emission spectrum for Mkn421 (non-flare state)
about factor 2
IceCube sensitivity
dN/dE / E^2 GeV^{-1} cm^{-2} s^{-1}
E / eV
¶O.C.De Jager & F.W.Stecker, Astrophy.J. 566 (2002), 738-743

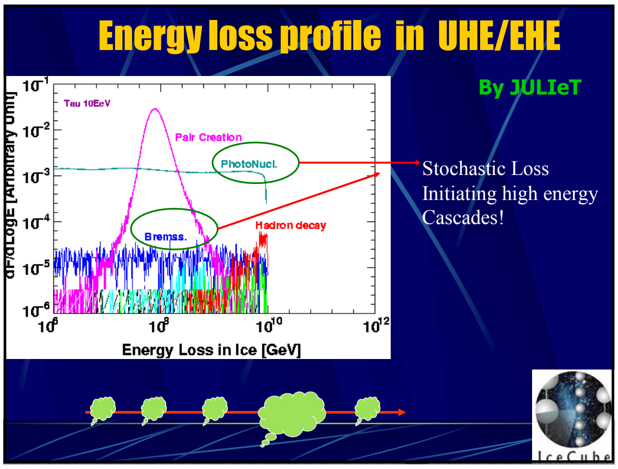

Theoretical bounds and future
DUMAND test string
FREJUS
MACRO
opaque for neutrons
MPR
NT-200
AMANDA-97
neutrons can escape
AMANDA-00
←NT-200+
AMANDA-II
W&B
IceCube
log(E² I(E)/ GeV cm⁻² s⁻¹ sr⁻¹)
−4
−5
−6
−7
−8
−9
3
6
9
12
15
log(E/GeV)
Mannheim, Protheroe and Rachen (2000) – Waxman, Bahcall (1999)
⇙ derived from known limits on extragalactic protons + γ-ray flux

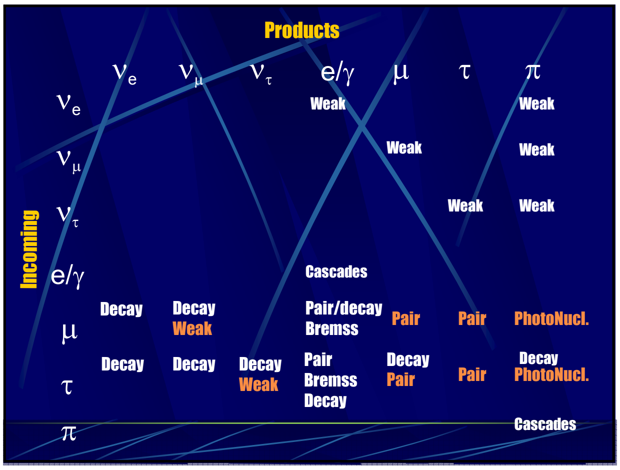

GIGA-ton detector!!
ICE CUBE
IceCube


10¹⁵ eV
10¹⁶ eV
10¹⁷ eV
How (E)HE events look like
10¹⁸ eV
10²⁰ eV

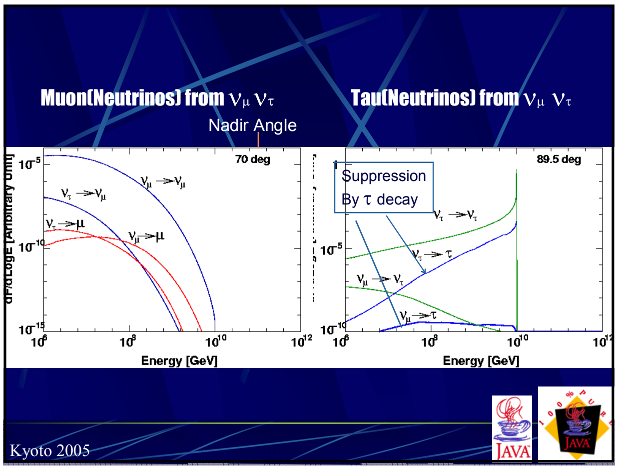

EHE MC Event examples
300 PeV taus
+8.4454e-06 s

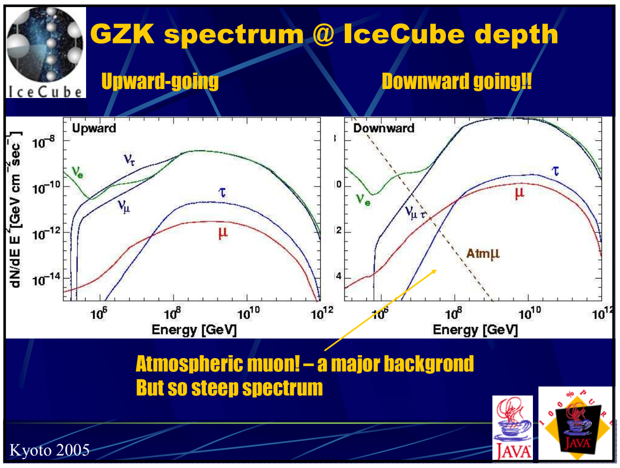

EHE (EeV or even higher) Neutrino Events
Arriving Extremely Horizontally
• Needs Detailed Estimation
• Limited Solid Angle Window
(σρN_A)⁻¹ ~ 600 (σ/10⁻³²cm²)⁻¹(ρ/2.6g cm⁻³)⁻¹ [km]
Involving the interactions generating
electromagnetic/hadron cascades
μN → μX e⁺e⁻
IceCube
Kyoto 2005

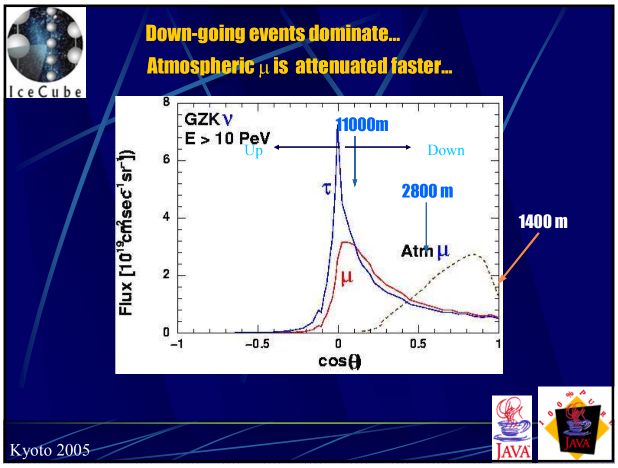

Energy loss profile in UHE/EHE
By JULIeT
Tau 10EeV
Pair Creation
PhotoNucl.
Bremss.
Hadron decay
Stochastic Loss
Initiating high energy
Cascades!
10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁶
10⁸
10¹⁰
10¹²
Energy Loss in Ice [GeV]
IceCube

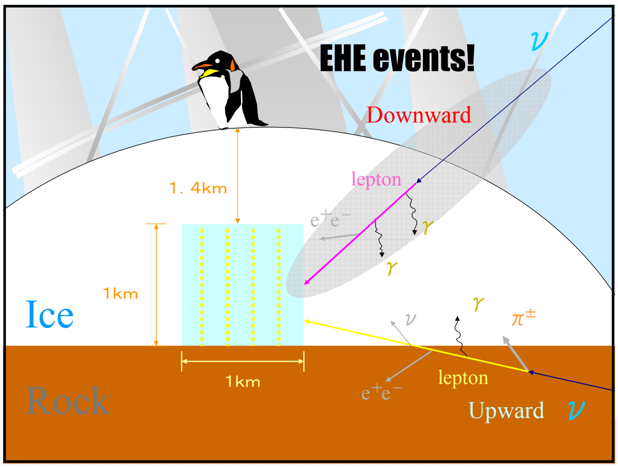


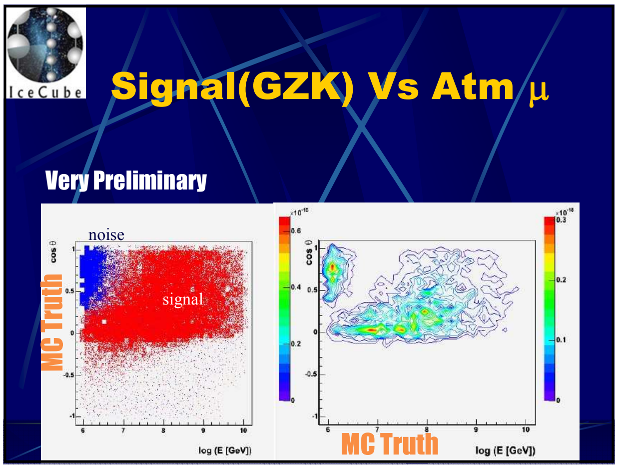
Incoming	ν_e	ν_μ	ν_τ	e/γ	μ	τ	π
ν_e				Weak			Weak
ν_μ					Weak		Weak
ν_τ						Weak	Weak
e/γ				Cascades			
μ	Decay	Decay Weak		Pair/decay Bremss	Pair	Pair	PhotoNucl.
τ	Decay	Decay	Decay Weak	Pair Bremss Decay	Decay Pair	Pair	Decay PhotoNucl.
π							Cascades

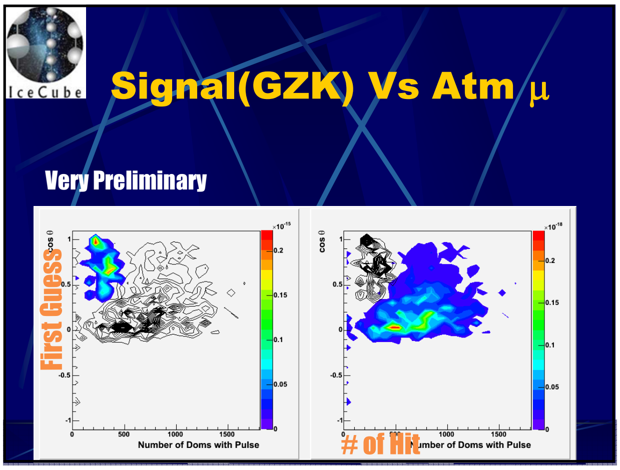


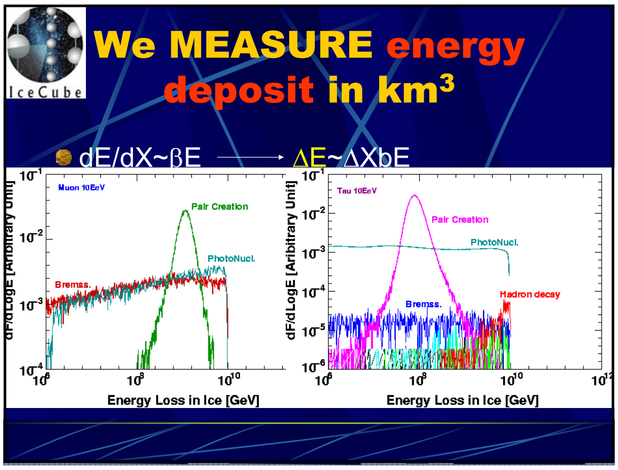


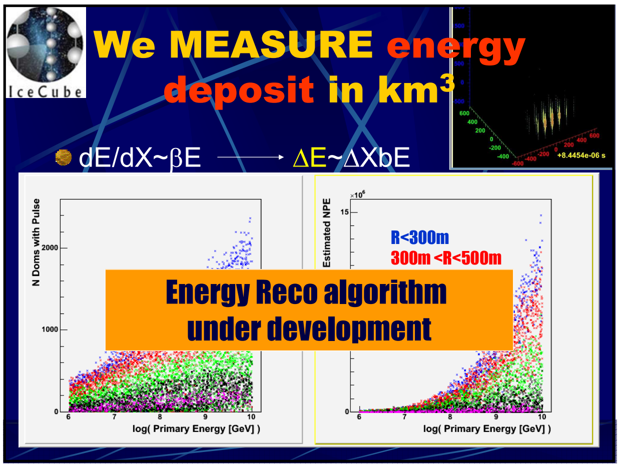


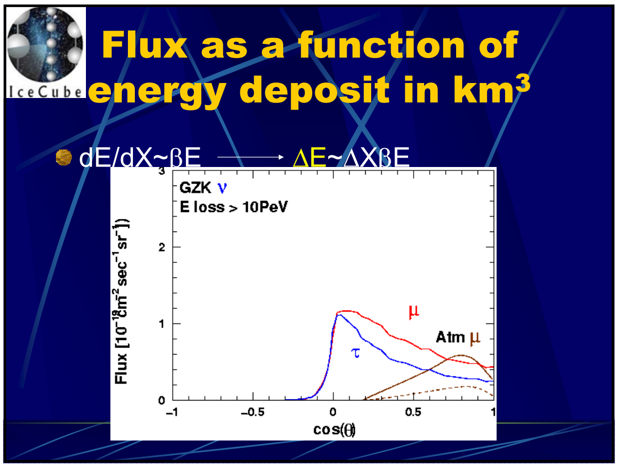










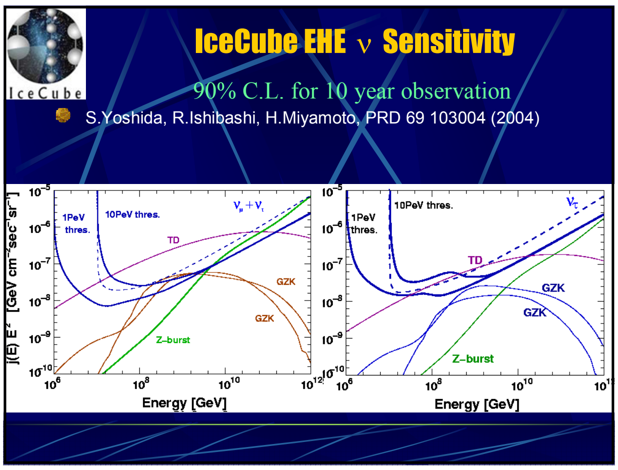


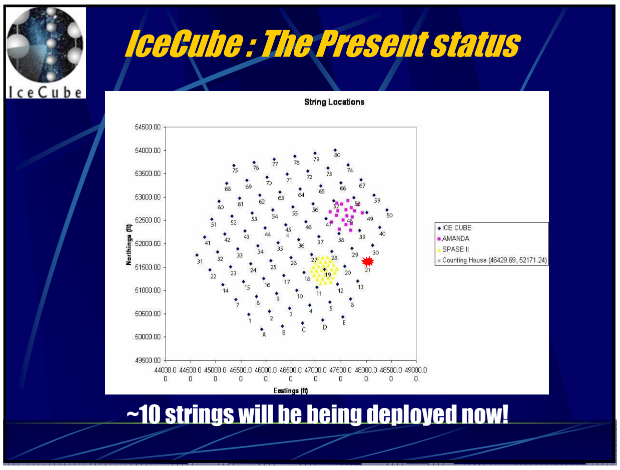
Intensity of EHE μ and τ

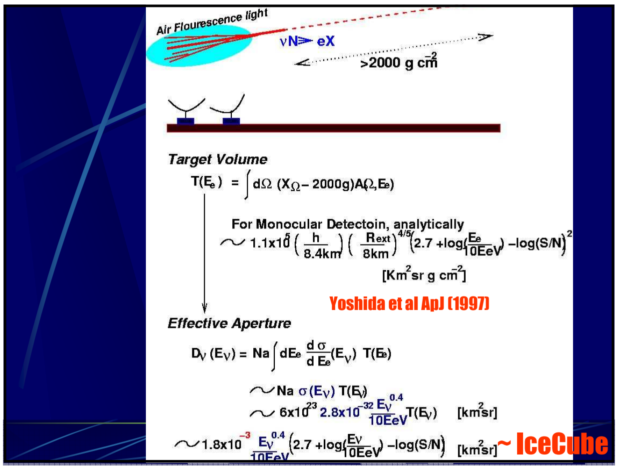
[cm^{-2} sec^{-1}]

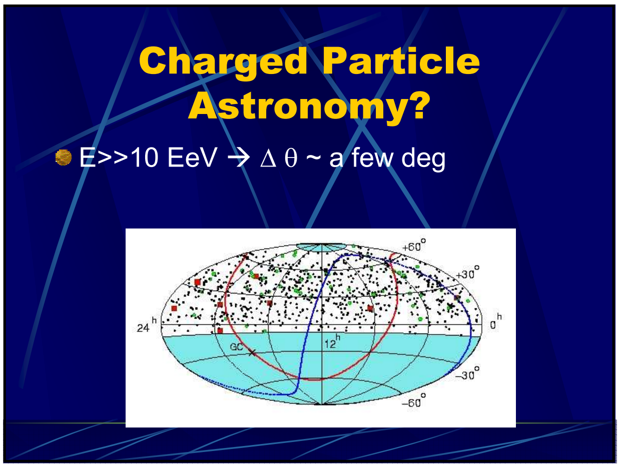
GZK m=4 Zmax=4		Iμ(E>10PeV)	Iτ(E>10PeV)	RATE [/yr/km²]
Down		5.90 10^{-19}	5.97 10^{-19}	0.37
Up		3.91 10^{-20}	6.63 10^{-20}	0.03
		Iμ(E>10PeV) Energy Deposit	Iτ(E>10PeV) Energy Deposit	
Down		4.75 10^{-19}	3.28 10^{-19}	0.25
m=7 Zmax=5 Down		7.21 10^{-17}	4.83 10^{-17}	37.9
Atm μ		1.74 10^{-19}		0.05

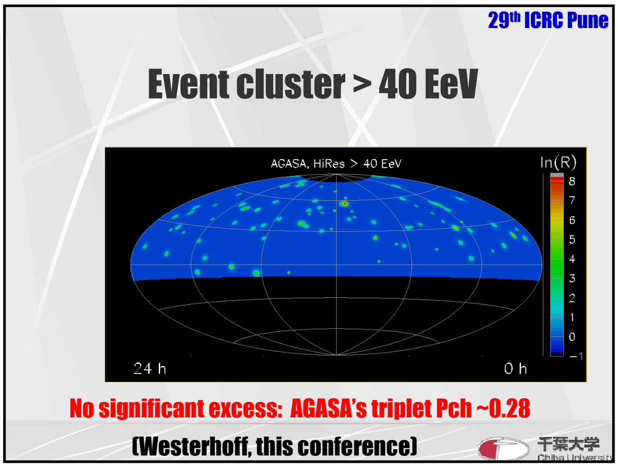
RESCEU 2003

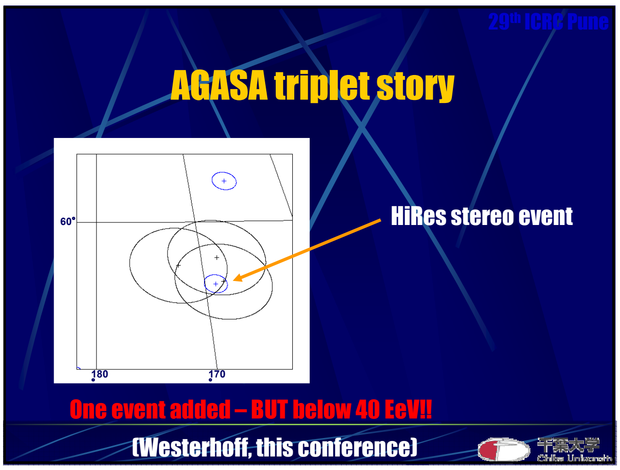


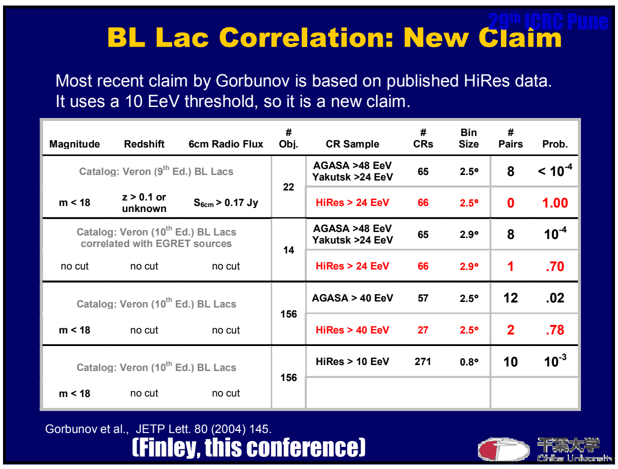




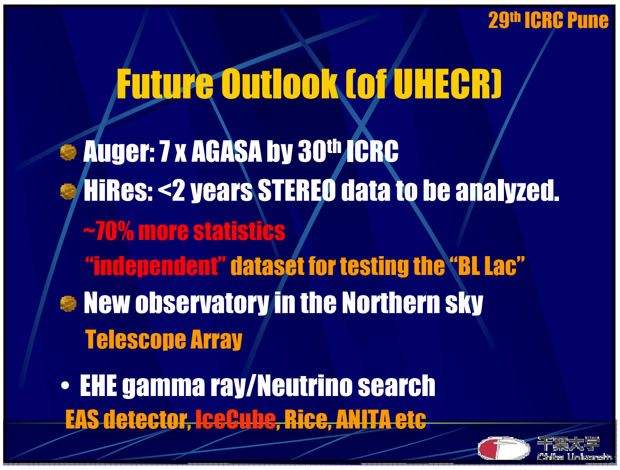


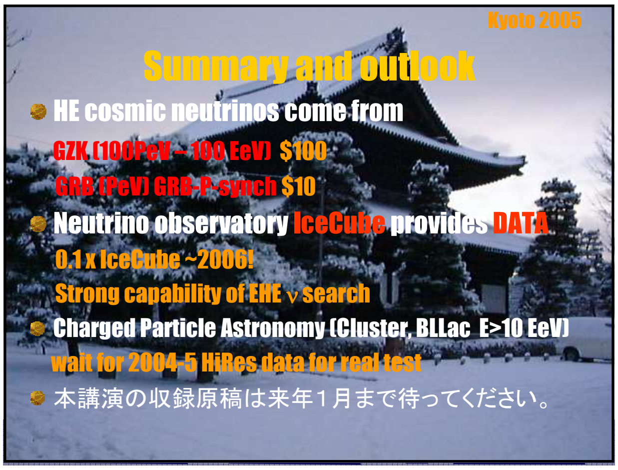






Magnitude	Redshift	6cm Radio Flux	# Obj.	CR Sample	# CRs	Bin Size	# Pairs	Prob.
Catalog: Veron (9th Ed.) BL Lacs			22	AGASA >48 EeV Yakutsk >24 EeV	65	2.5°	8	$< 10^{-4}$
m < 18	z > 0.1 or unknown	$S_{6cm} > 0.17$ Jy		HiRes > 24 EeV	66	2.5°	0	1.00
Catalog: Veron (10th Ed.) BL Lacs correlated with EGRET sources			14	AGASA >48 EeV Yakutsk >24 EeV	65	2.9°	8	10^{-4}
no cut	no cut	no cut		HiRes > 24 EeV	66	2.9°	1	.70
Catalog: Veron (10th Ed.) BL Lacs			156	AGASA > 40 EeV	57	2.5°	12	.02
m < 18	no cut	no cut		HiRes > 40 EeV	27	2.5°	2	.78
Catalog: Veron (10th Ed.) BL Lacs			156	HiRes > 10 EeV	271	0.8°	10	10^{-3}
m < 18	no cut	no cut						


29th ICRC Pune
Future Outlook (of UHECR)
Auger: 7 x AGASA by 30th ICRC
HiRes: <2 years STEREO data to be analyzed.
~70% more statistics
"independent" dataset for testing the "BL Lac"
New observatory in the Northern sky
Telescope Array
• EHE gamma ray/Neutrino search
EAS detector, IceCube, Rice, ANITA etc


Kyoto 2005
Summary and outlook
HE cosmic neutrinos come from
GZK (100PeV ~ 100 EeV) $100
GRB (PeV) GRB-P-synch $10
Neutrino observatory IceCube provides DATA
0.1 x IceCube ~2006!
Strong capability of EHE ν search
Charged Particle Astronomy (Cluster, BLLac E>10 EeV)
wait for 2004-5 HiRes data for real test
本講演の収録原稿は来年１月まで待ってください。