High Energy Neutrino Astronomy

a promising decade ahead

Christian Spiering,
DESY , September 17, 2002

Content

- Physics Goals

2. Detection Methods and Projects

3. Amanda and Baikal:
   Physics Results

4. The next decade

1. Physics Goals

A. High Energy Neutrino Astrophysics

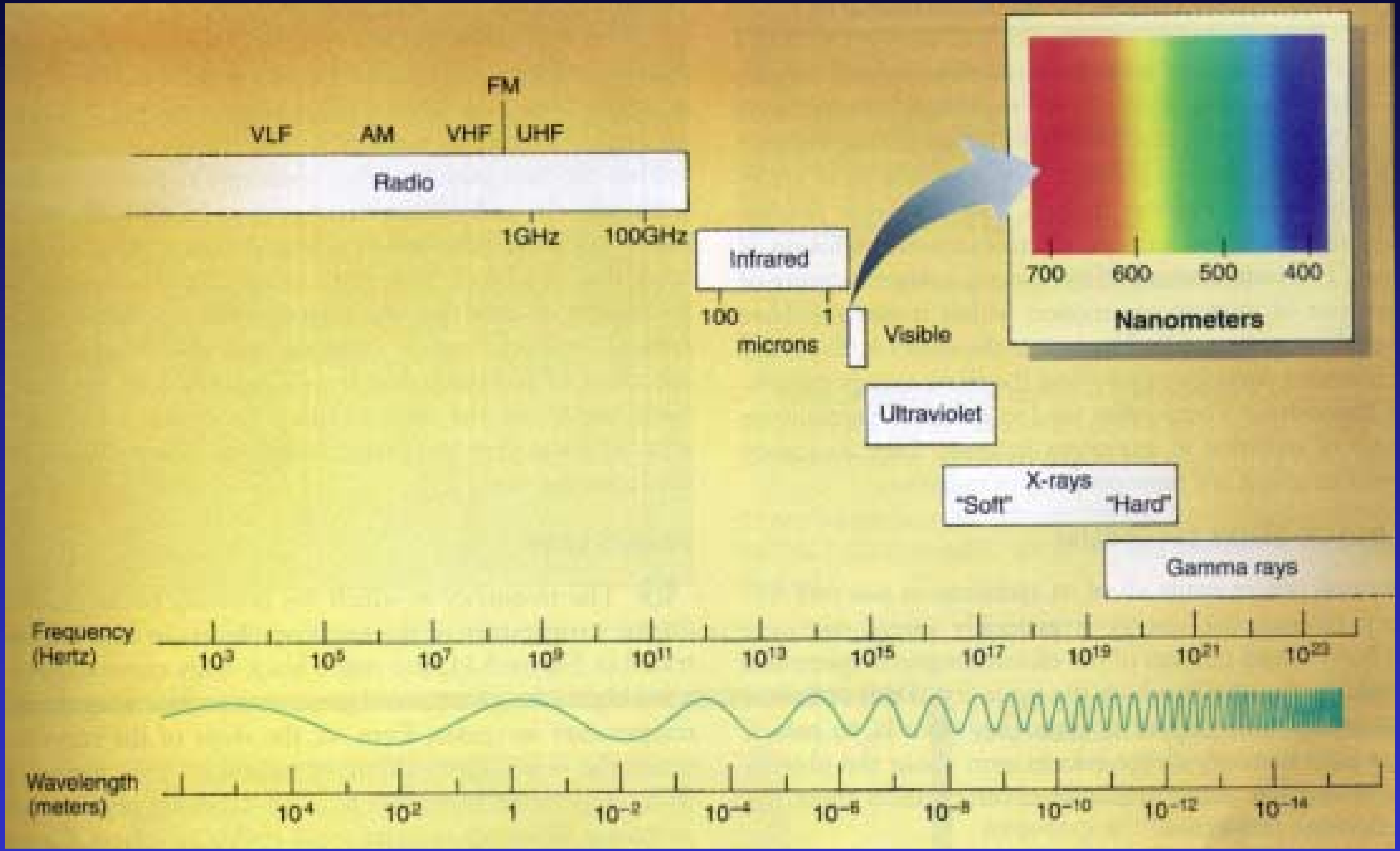
B. Particle Physics

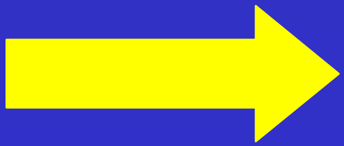
WIMPs, Magnetic Monopoles, Oscillations,
Neutrino Mass ...

C. Others

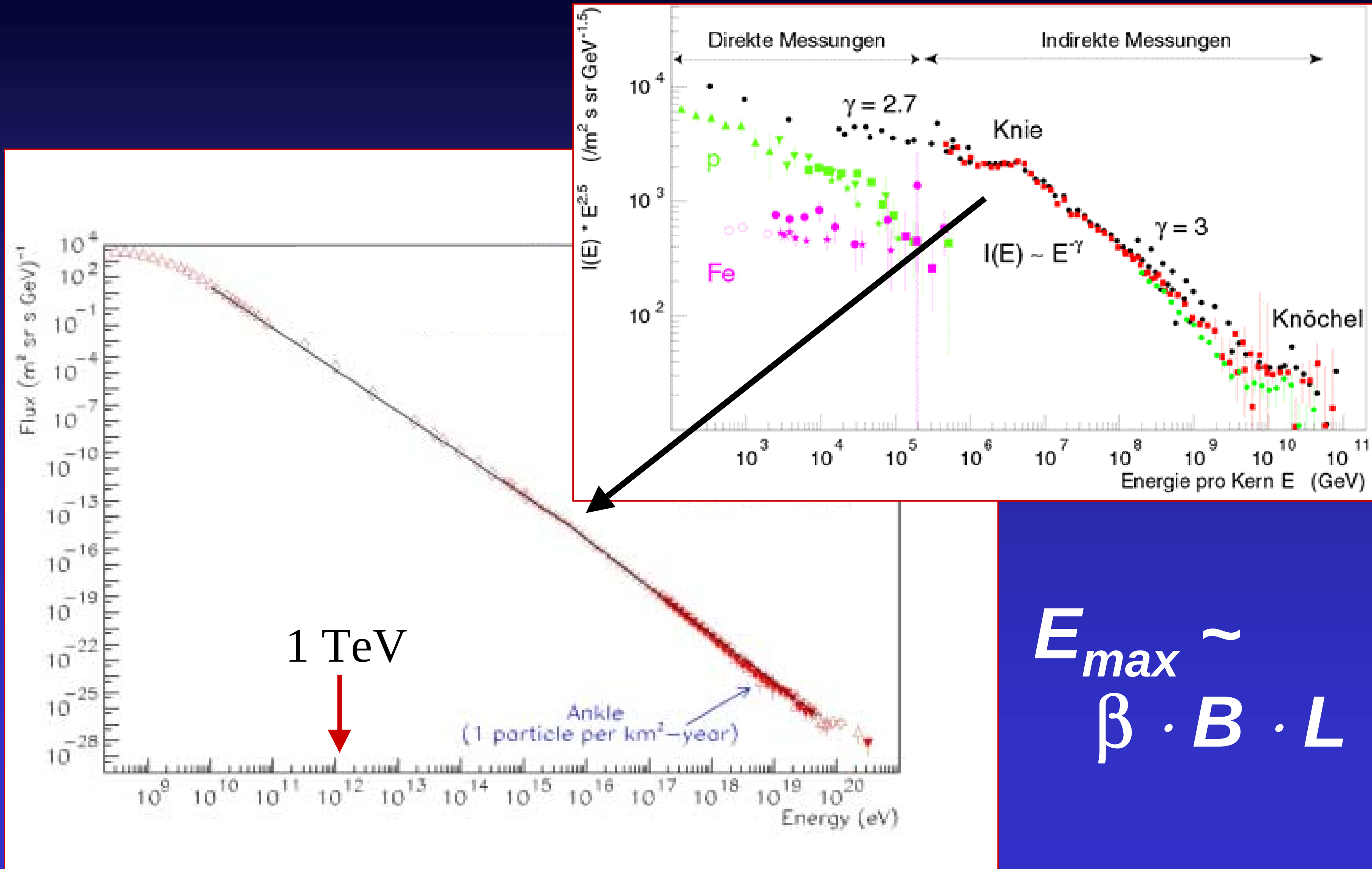
Supernova Bursts, CR composition,
Black Holes, ...

New Observational Window to Non-Thermal Universe





Cosmic Rays

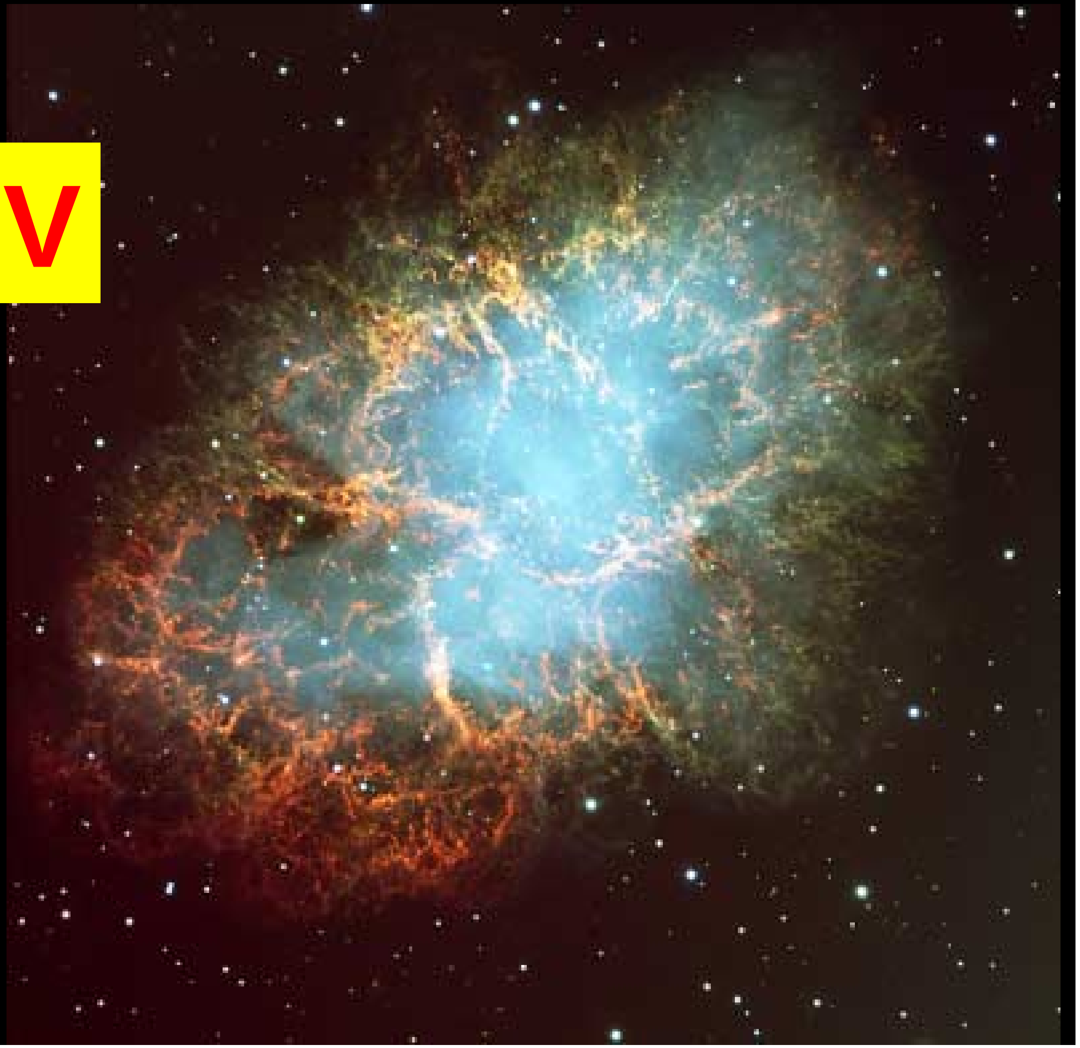


$$E_{max} \sim \beta \cdot B \cdot L$$

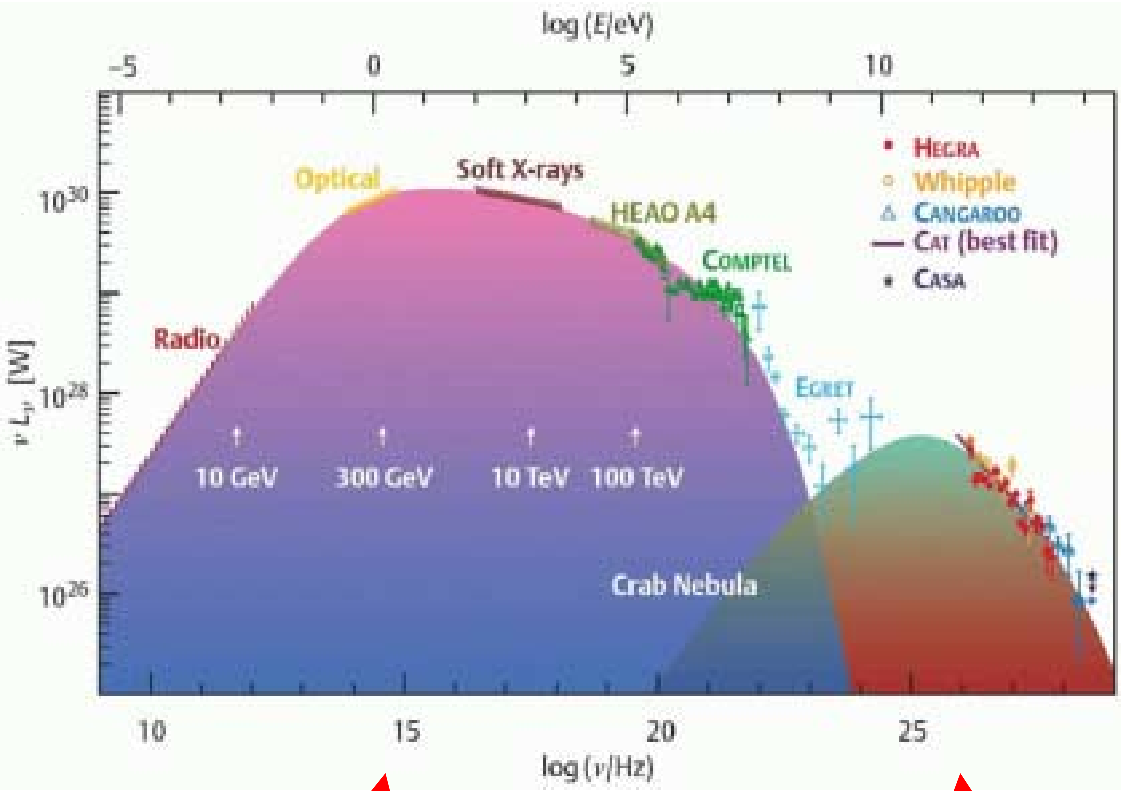
Supernova shocks expanding in interstellar medium

up to 1-10 PeV

Crab nebula



Gamma Observations: Crab is "Electron Accelerator"



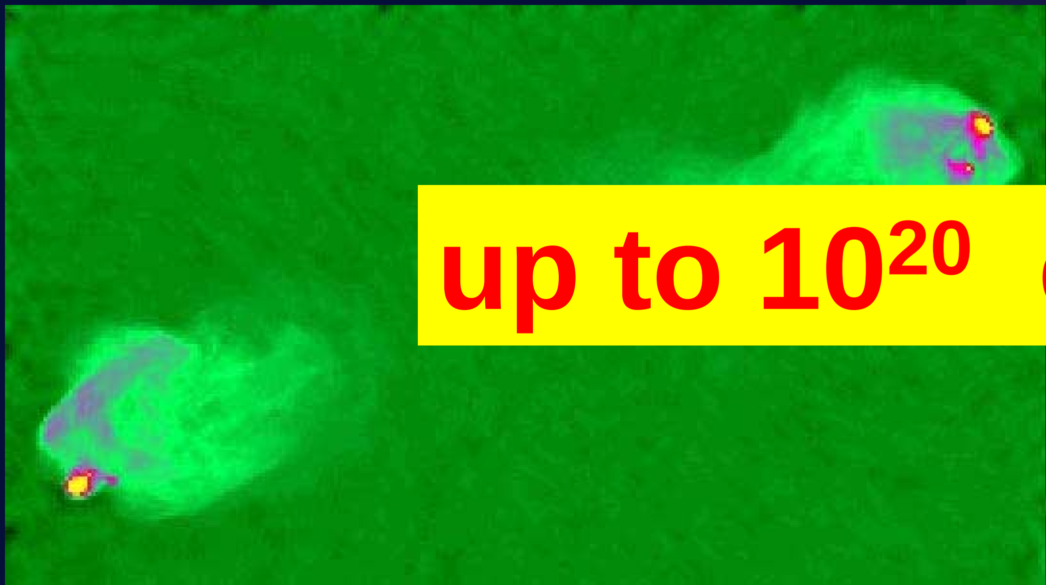
Synchrotron Inverse Compton

HEGRA

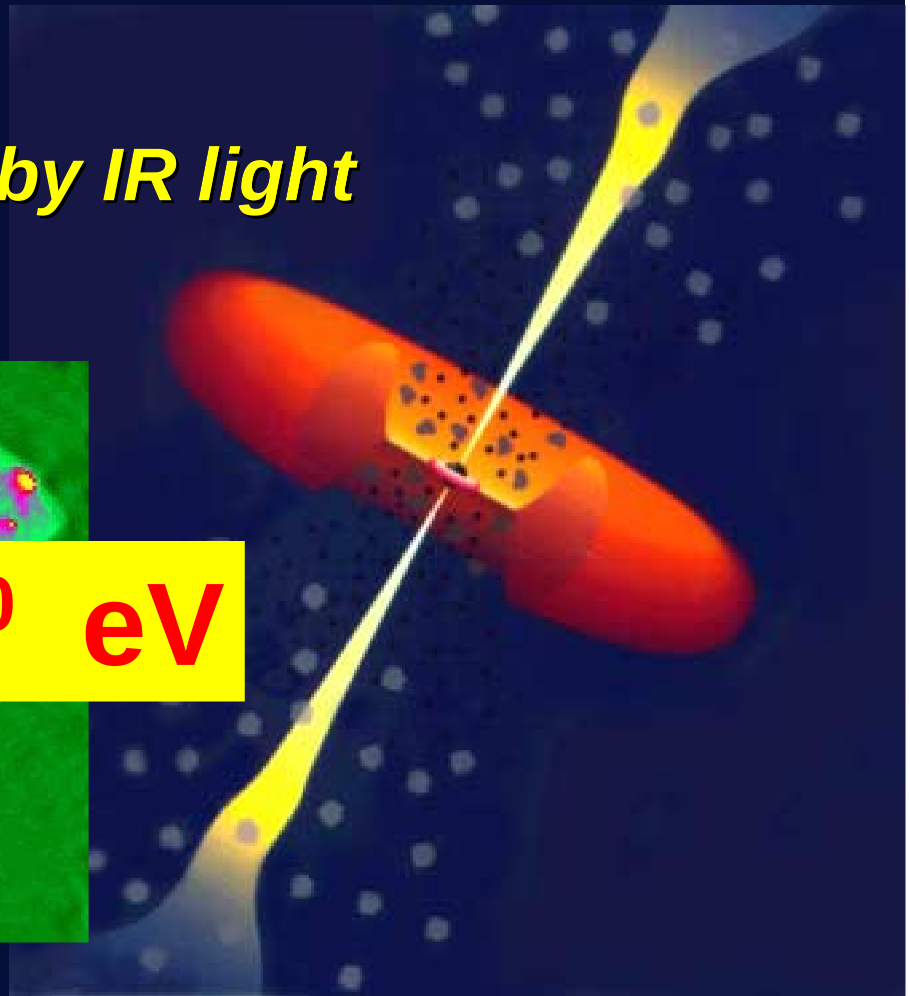
Crab

Active Galaxies: Jets

20 TeV gamma rays
Higher energies obscured by IR light

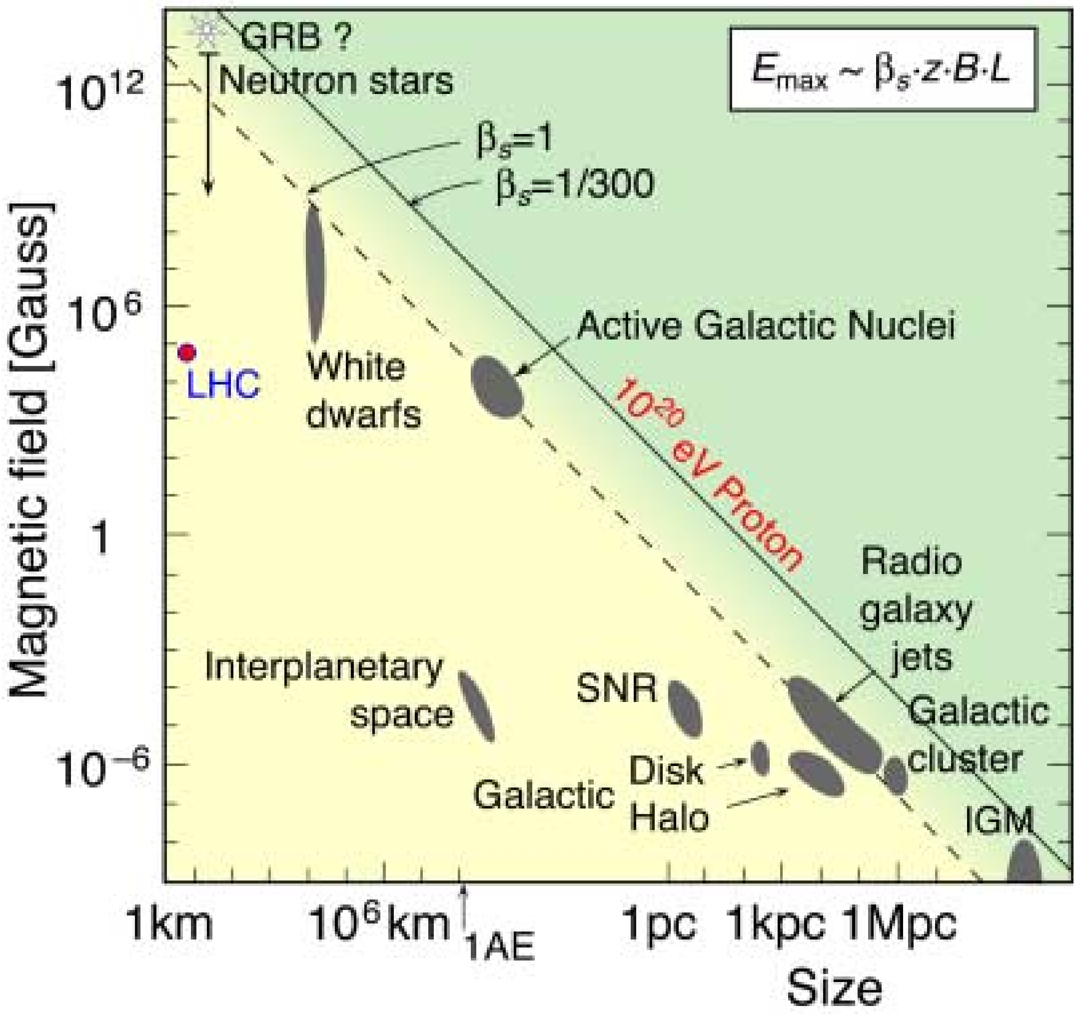


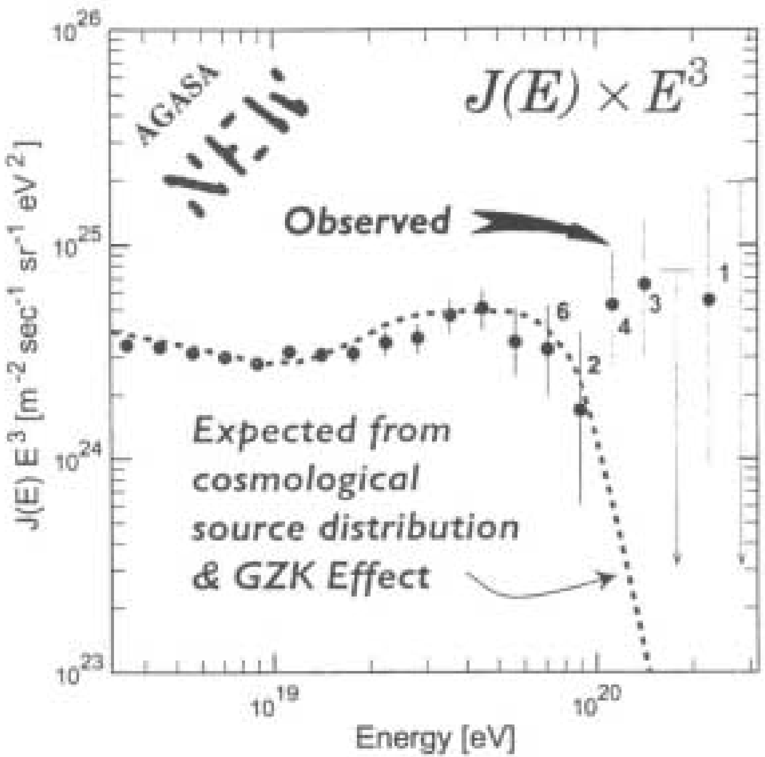
up to 10^{20} eV



VLA image of Cygnus A

Cosmic Rays with E > 10^{20} eV ? ?





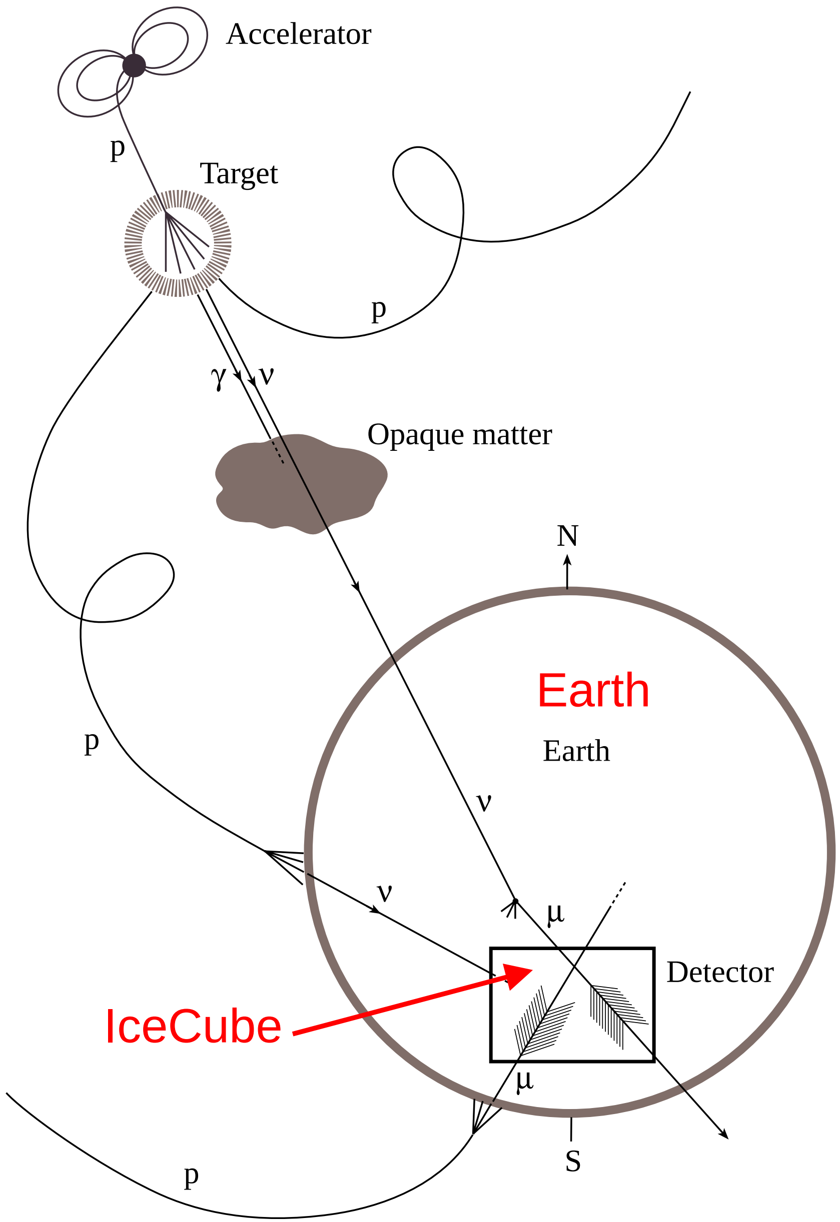
GZK effect:

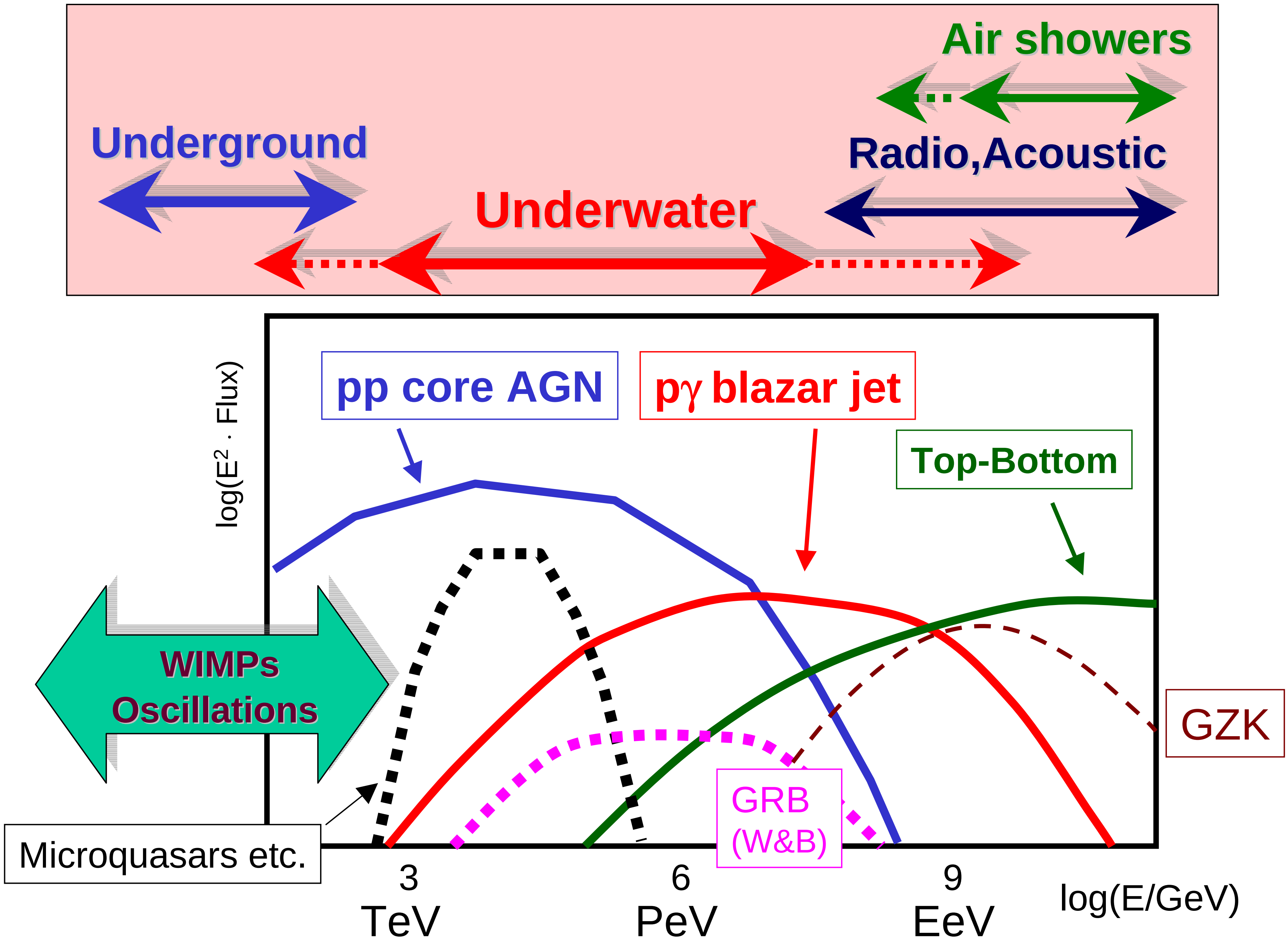
$p + \gamma_{3K} \rightarrow p + ...$

Neutrino Astronomy

measuring νs by its μ

- Stable particles: γ, p, ν
- Astrophysical Sources
  - GRB, AGN, Super Novae
  - GZK (p +CMB γ)
  - Topological defects
- Backgrounds
  - Atmospheric μ's
  - Atmospheric ν's

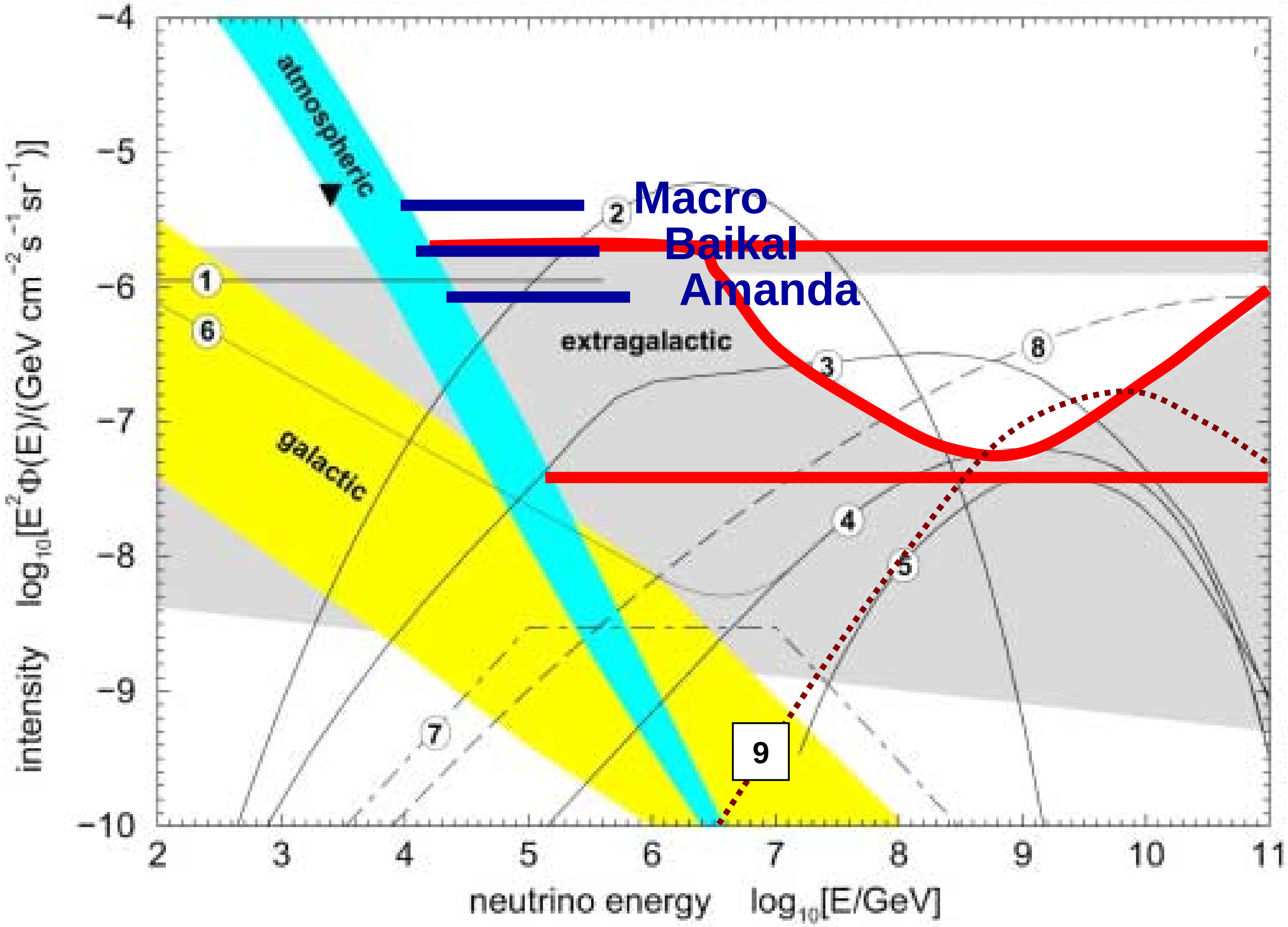




Air showers
Underground
Radio,Acoustic
Underwater
pp core AGN
pγ blazar jet
Top-Bottom
log(E² · Flux)
WIMPs
Oscillations
GZK
GRB
(W&B)
Microquasars etc.
3
TeV
6
PeV
9
EeV
log(E/GeV)

Mannheim & Learned, 2000

Diffuse Fluxes: Predictions and Bounds



1 pp core AGN (Nellen)
2 pγ core AGN Stecker & Salomon)
3 pγ „maximum model“ (Mannheim et al.)
4 pγ blazar jets (Mannh)
5 pγ AGN (Rachen & Biermann)
6 pp AGN (Mannheim)
7 GRB (Waxman & Bahcall)
8 TD (Sigl)
9 GZK

Time variations

msec

sec

hour

week

month

GRB

SN MeV burst

SN TeV bursts

Binary eclipses etc.

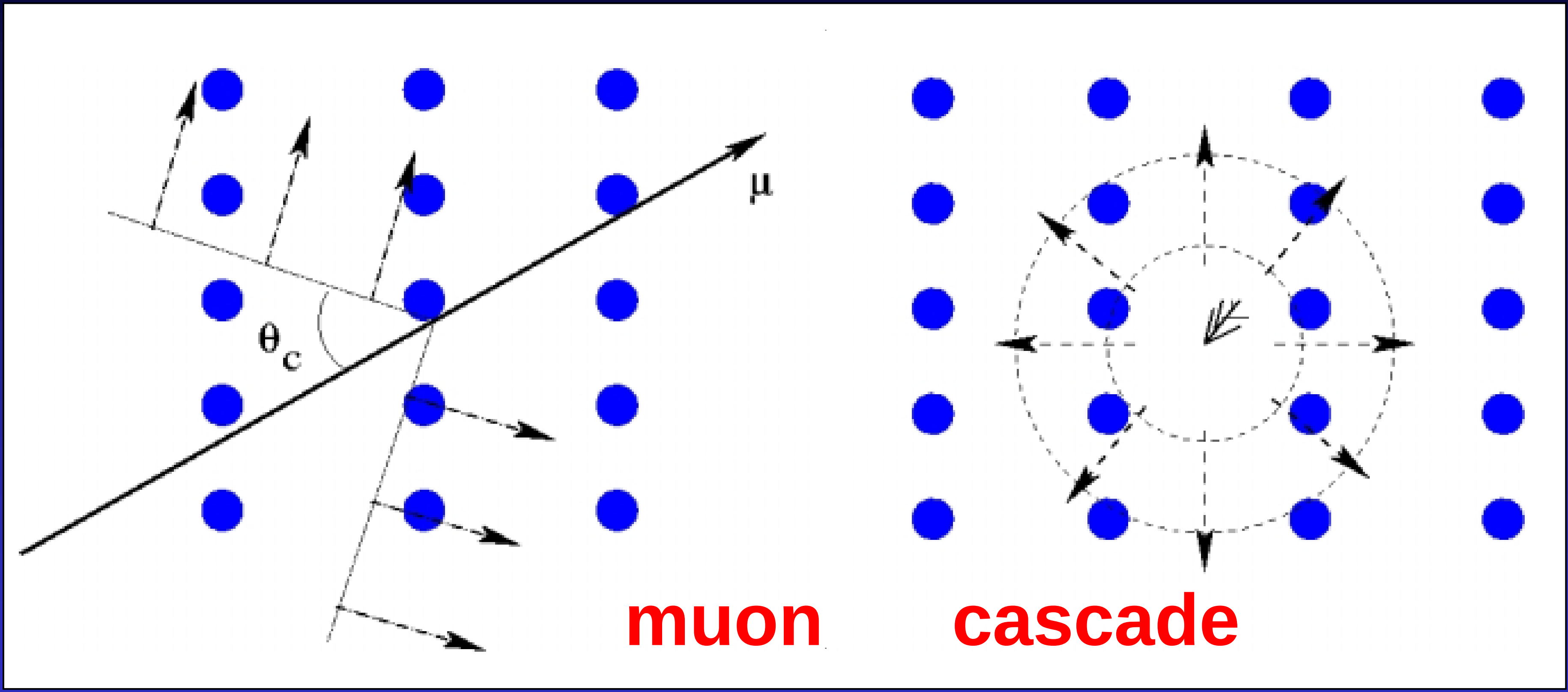
Blobs in Microquasars and blazars

young SN

2. Detection Methods and Projects

A. Underwater/Ice Cherenkov Telescopes
B. Acoustic Detection
C. Radio Detection
D. Detection by Air Showers

Underwater/Ice Cherenkov Telescopes



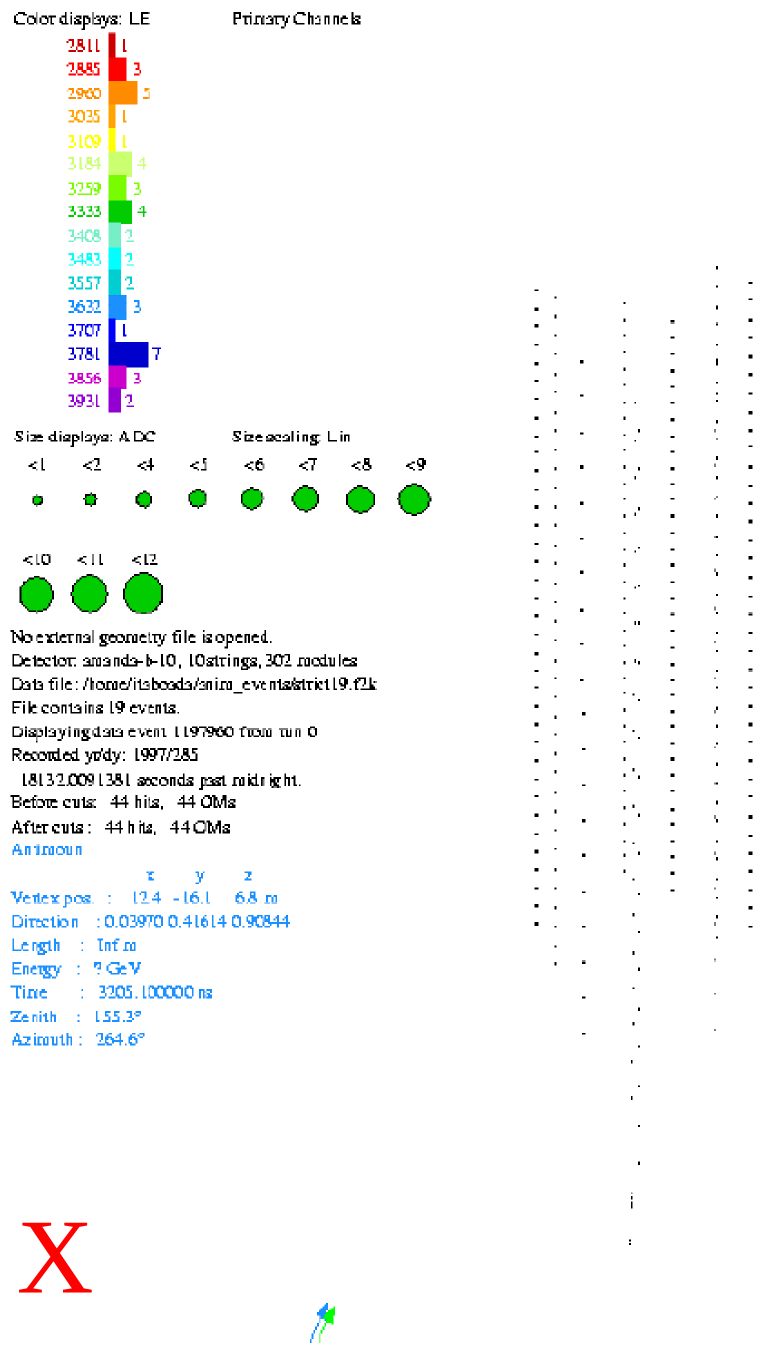
μ
θc
muon
cascade

AMANDA Event Signatures: Muons

CC muon neutrino interaction

→ **track**

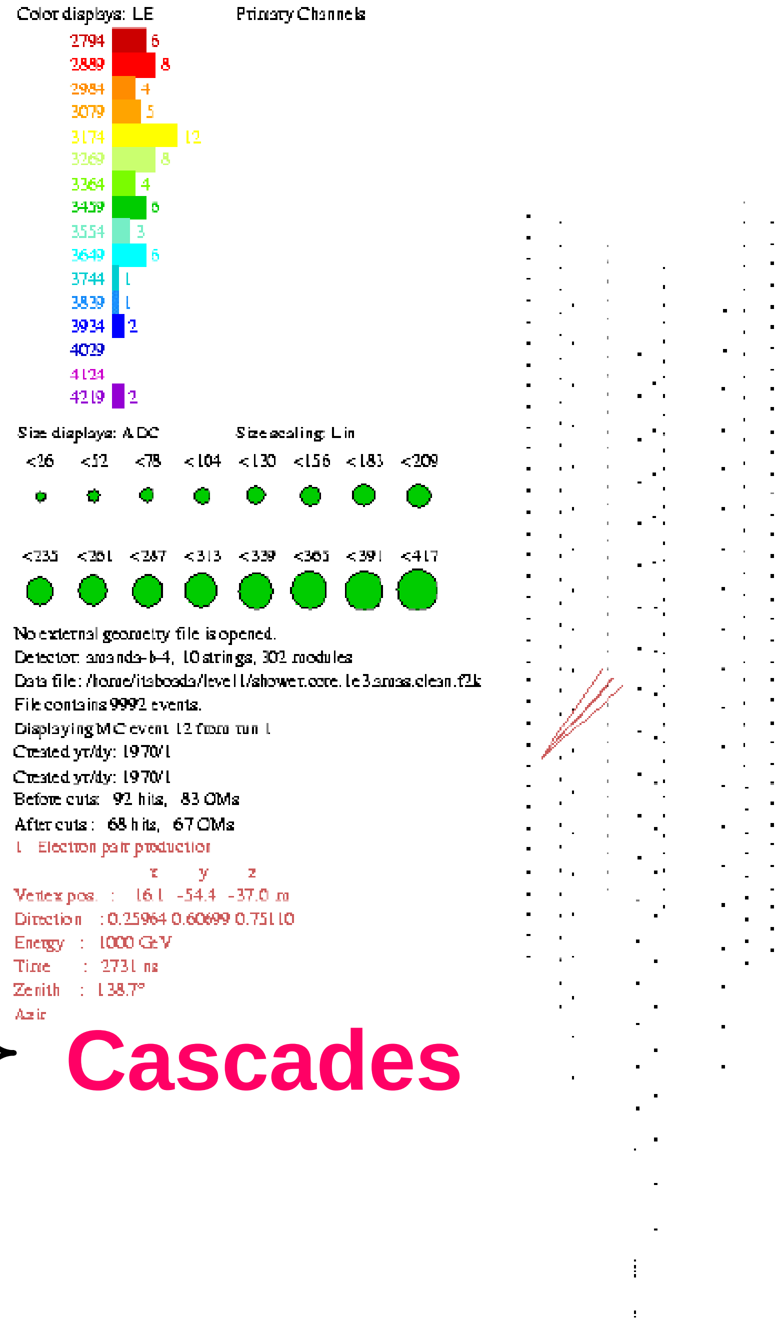
$$\nu_\mu + N \rightarrow \mu + X$$



AMANDA Event Signatures: Cascades

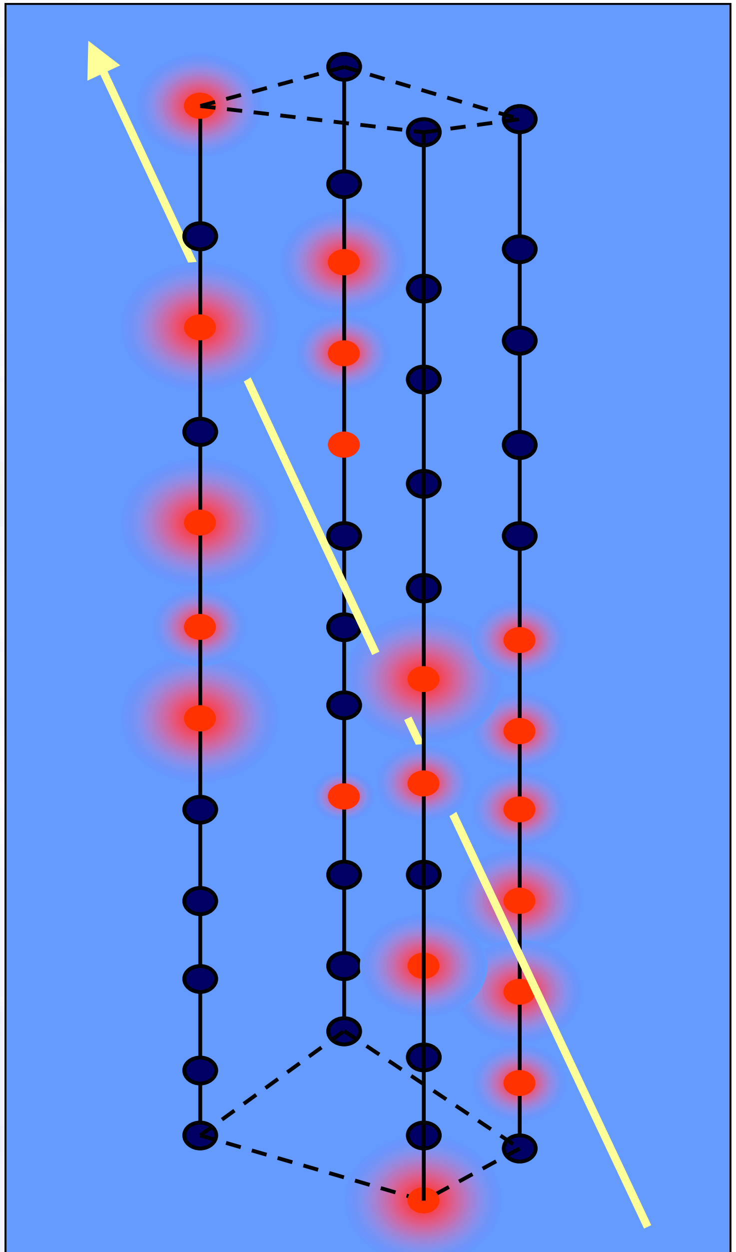
- CC electron and tau neutrino interaction:
- $\nu_{(e,\tau,)} + N \rightarrow (e, \tau) + X$
- NC neutrino interaction:

  $\nu_x + N \rightarrow \nu_x + X$



Lake Baikal

First underwater telescope
First neutrinos underwater



4-string stage (1996)

NT-200

192 PMT

>15 GeV

1997-2004

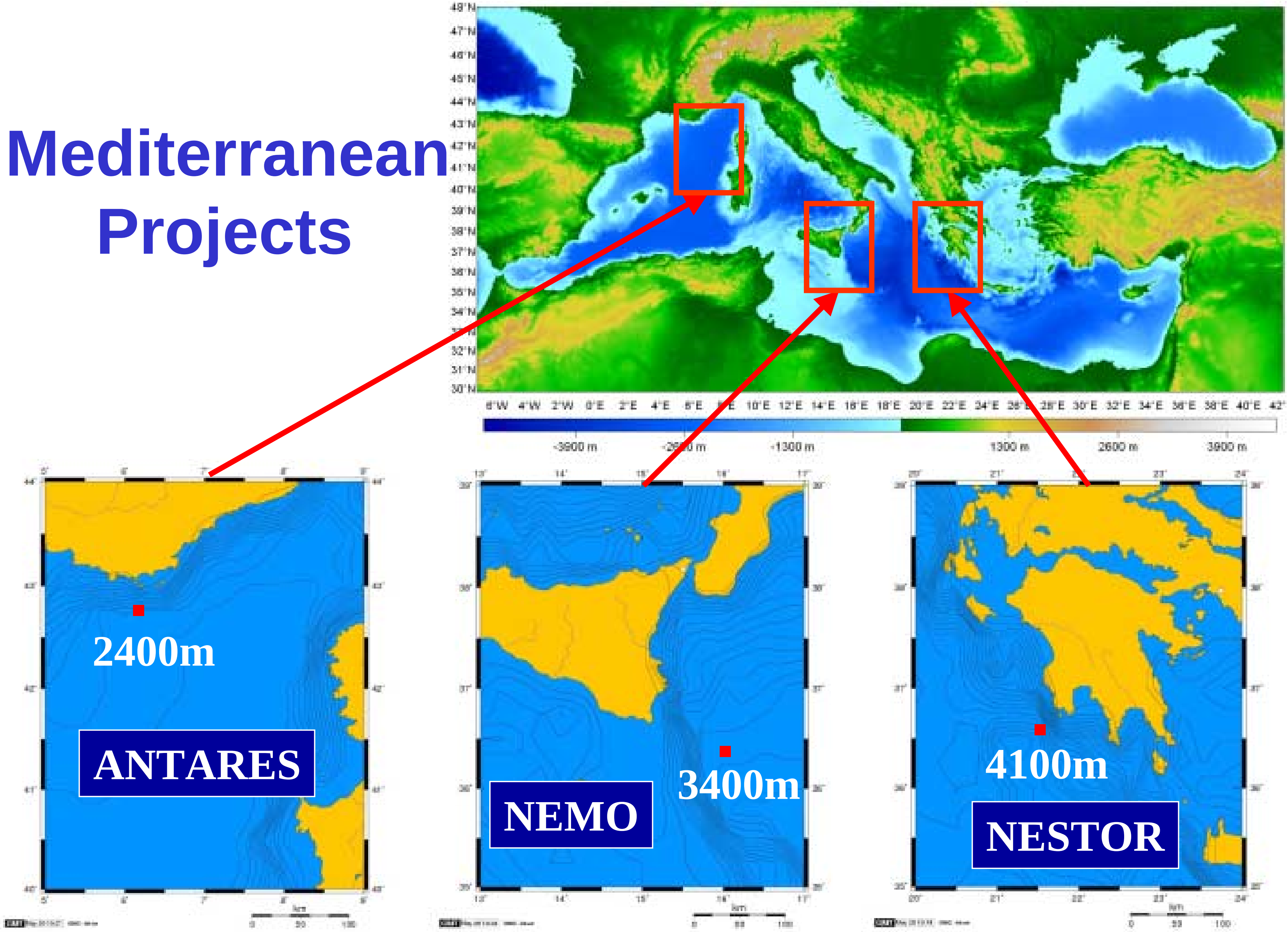
NT-200+

214 PMT

Cascades > 100 TeV

2004-2006 ...

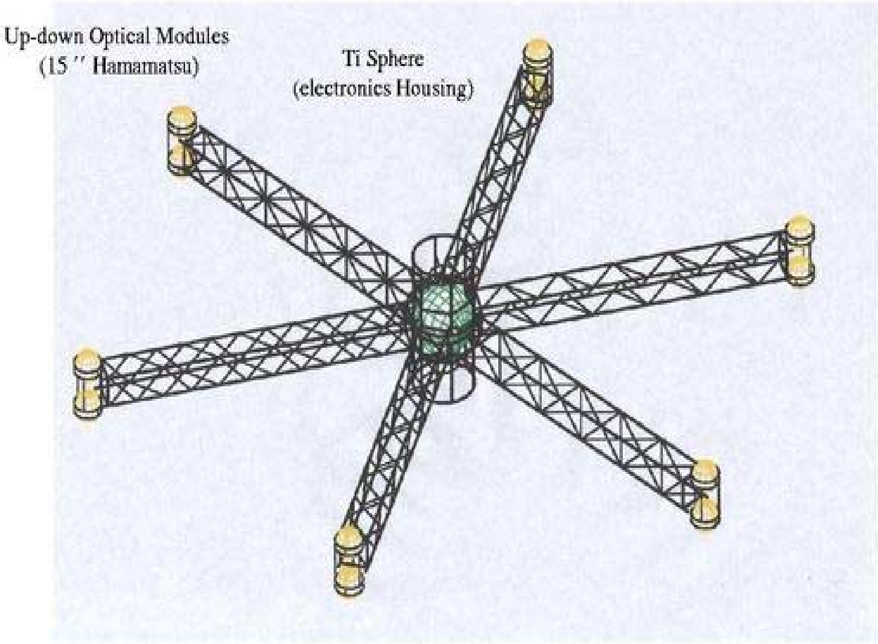
Mediterranean Projects



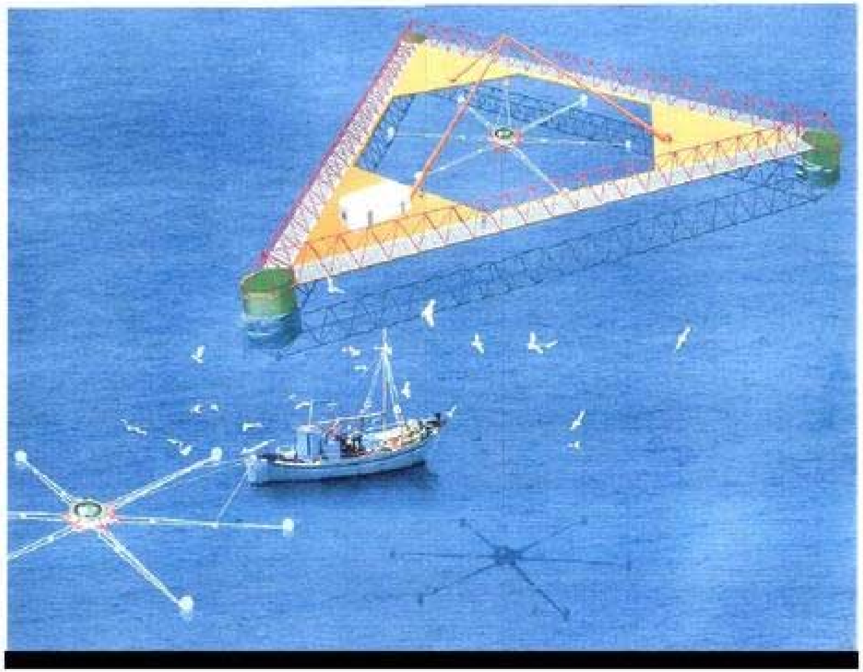
NESTOR

Site: Pylos (Greece), 3800m depth

towers of 12 titanium floors each supporting 12 PMTs

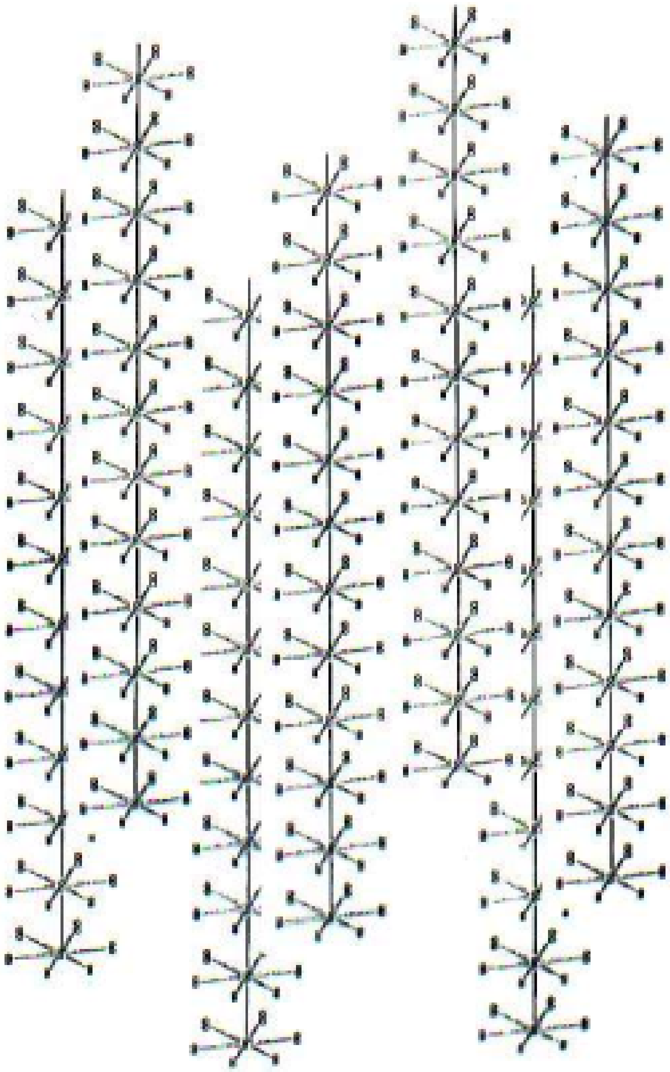


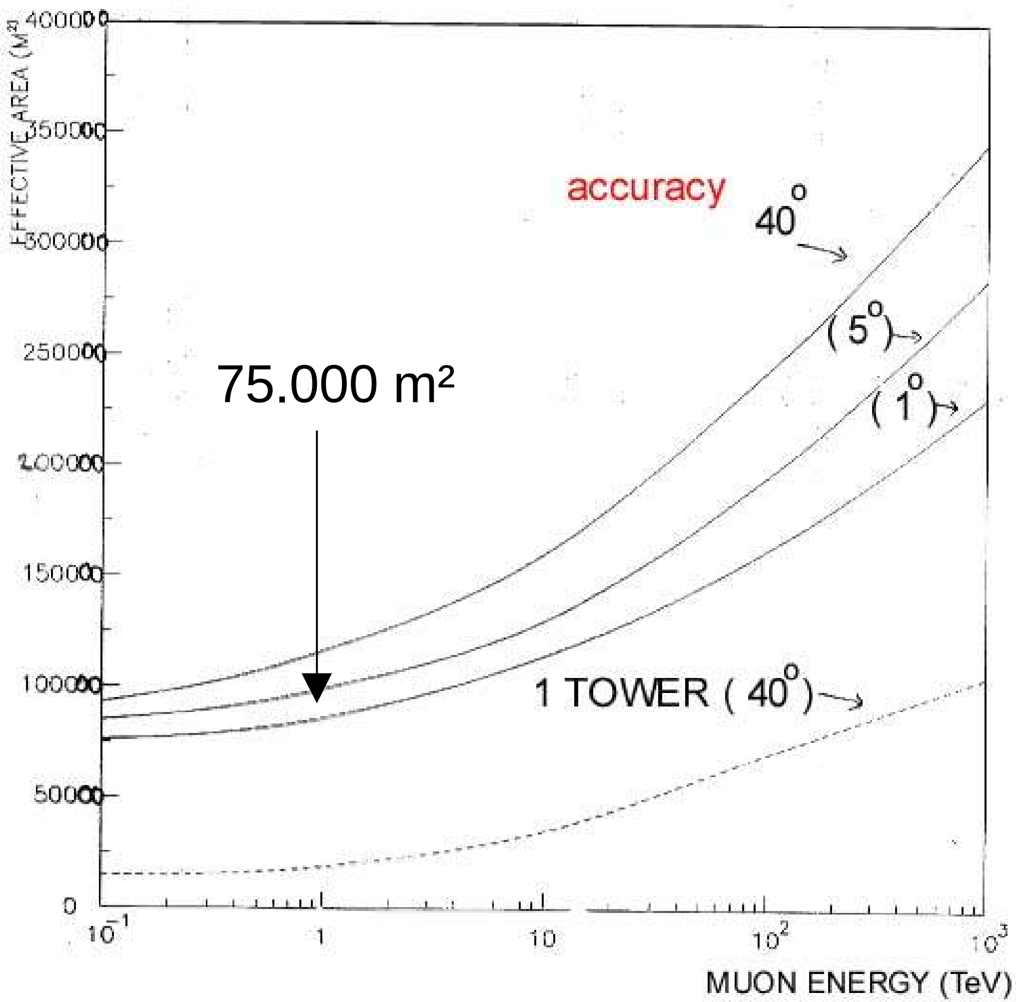
SHORT ARM (1/3 the usual diameter)
HEXAGONAL TITANIUM FLOOR

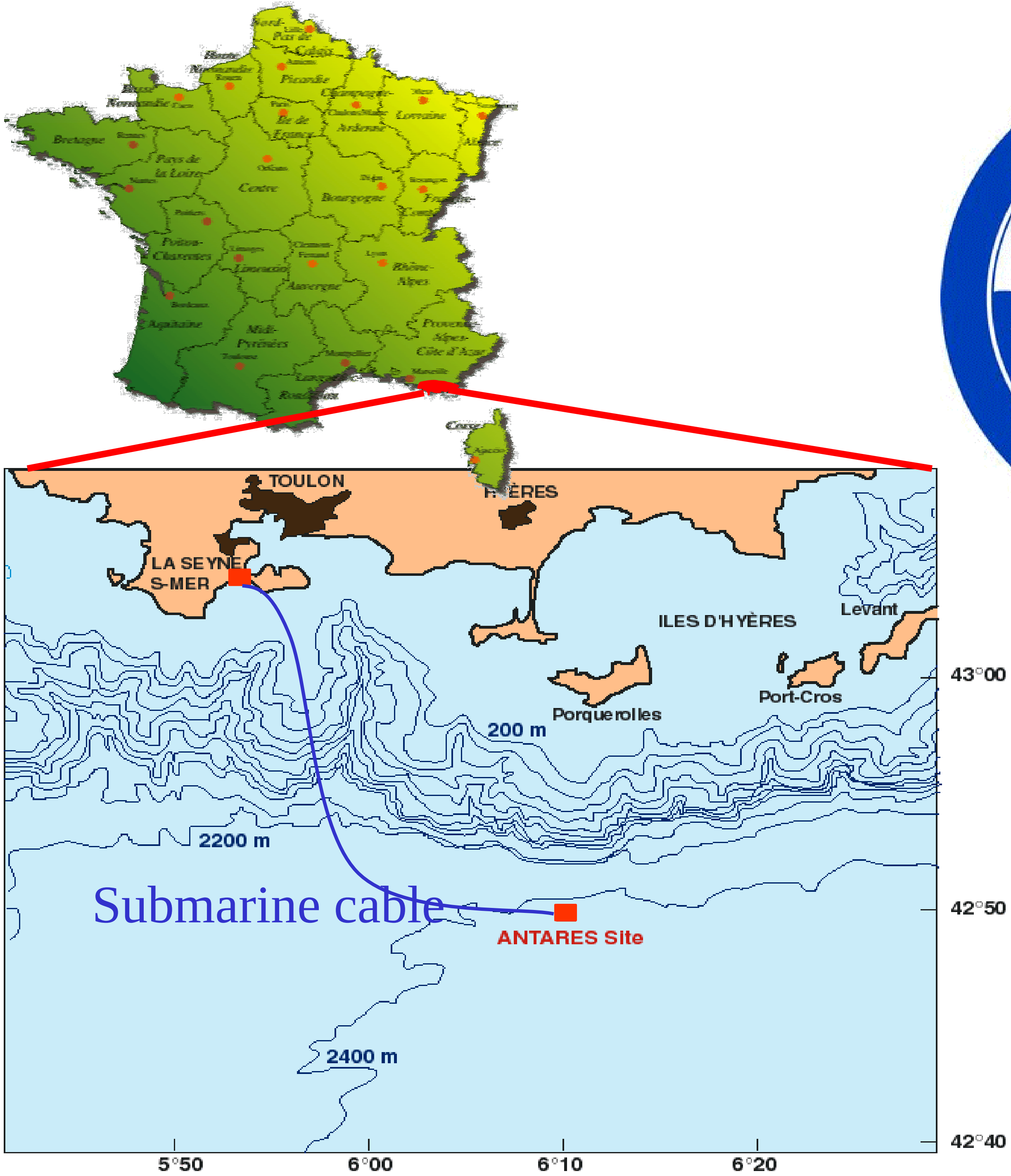


DELTA BERENIKE

7 NESTOR towers ?   75 000 m² at 1 TeV

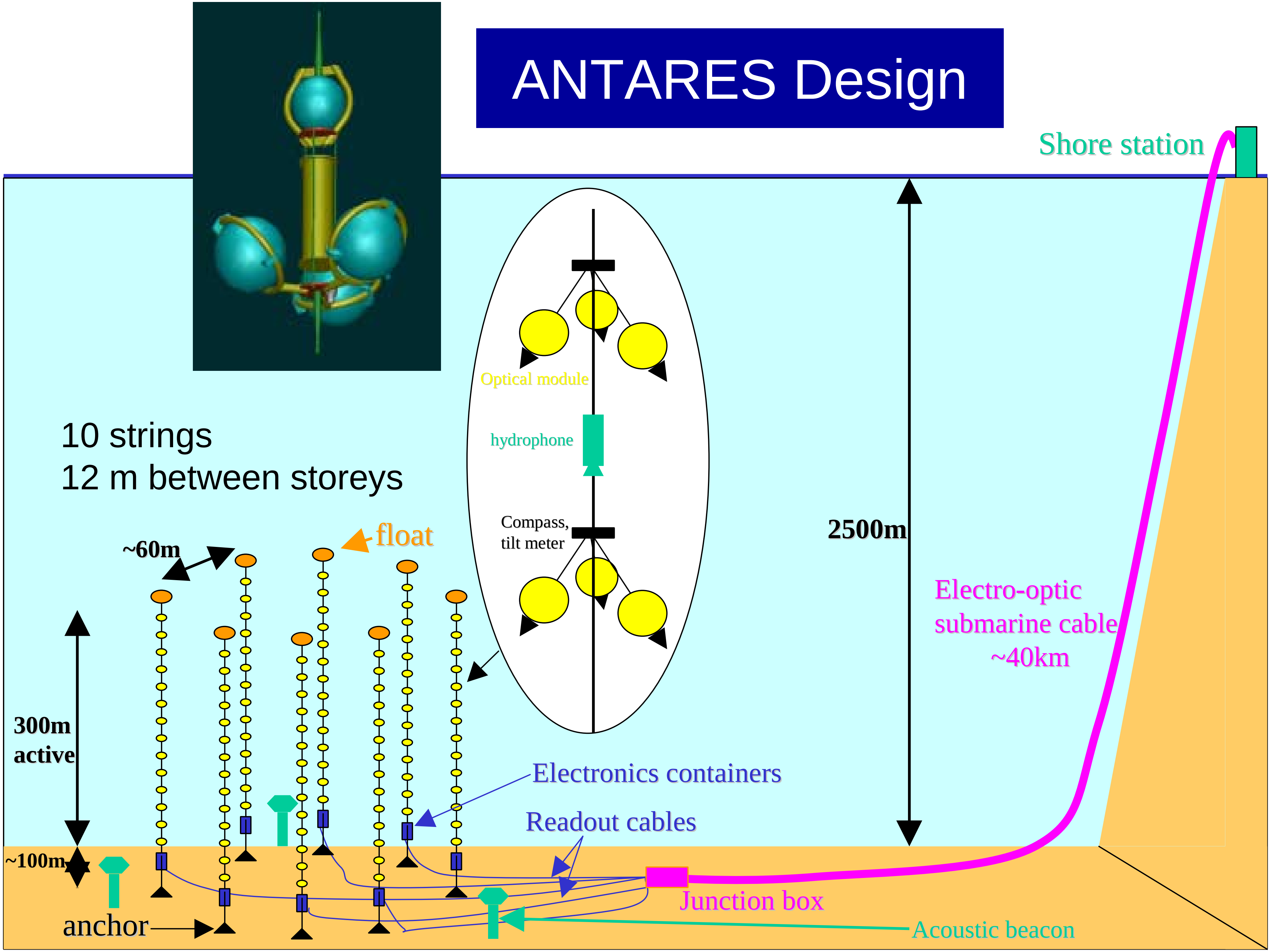




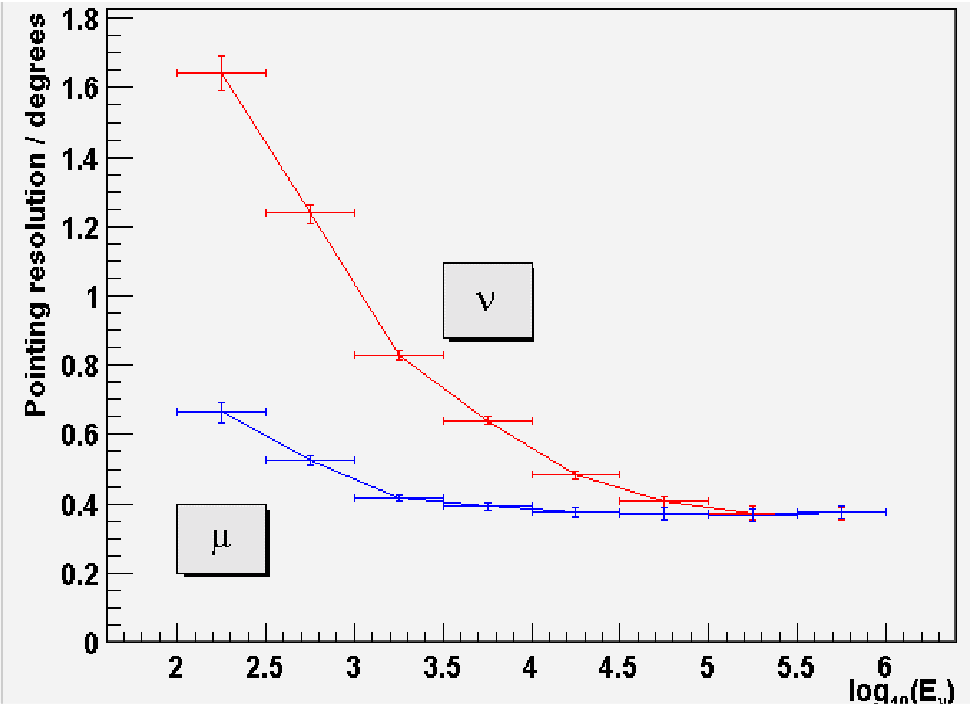

TOULON
HYÈRES
LA SEYNE
S-MER
ILES D'HYÈRES
Levant
Porquerolles
Port-Cros
200 m
2200 m
2400 m
Submarine cable
ANTARES Site
43°00
42°50
42°40
5°50
6°00
6°10
6°20

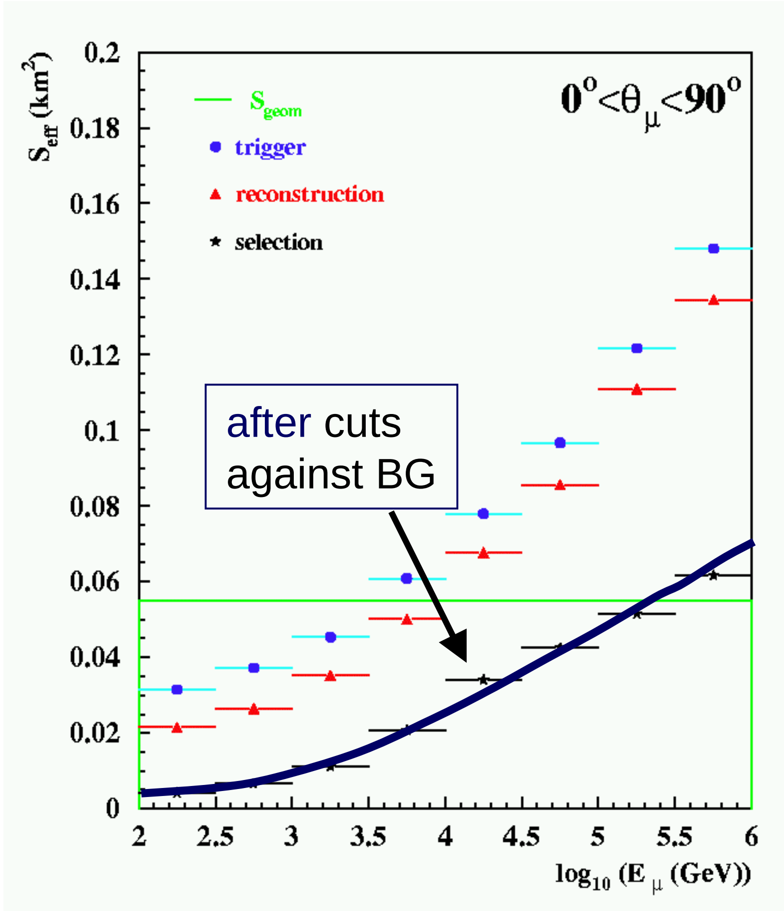
ANTARES Design

10 strings
12 m between storeys



ANTARES Performance





Very good angular accuracy

below 3 TeV angular error is dominated by kinematics, above 3 TeV by recon-struction error (~ 0.4°)

Effective area:

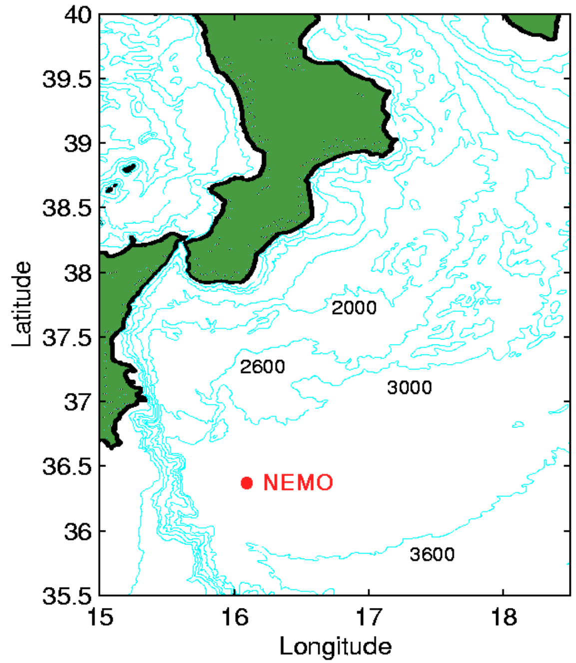
~ 10 000 m^2 at 1 TeV

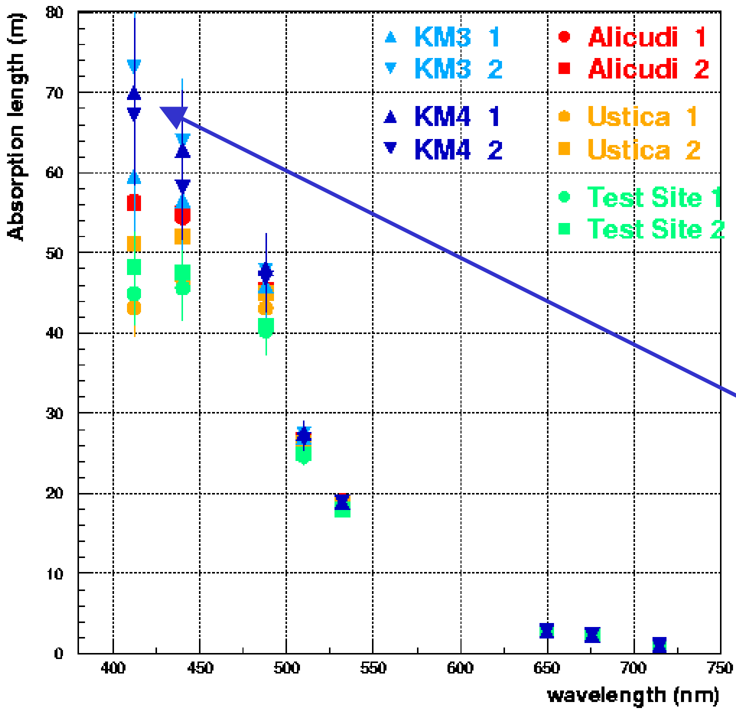
~ 50 000 m^2 at 100 TeV

NEMO Neutrino Mediterranean Observatory

The Capo Passero Site

- Very good optical properties (light absorption length about 70 m)
- ~ 80 km from coast
- about 3400 m deep
- Very low sedimentation and biological activity

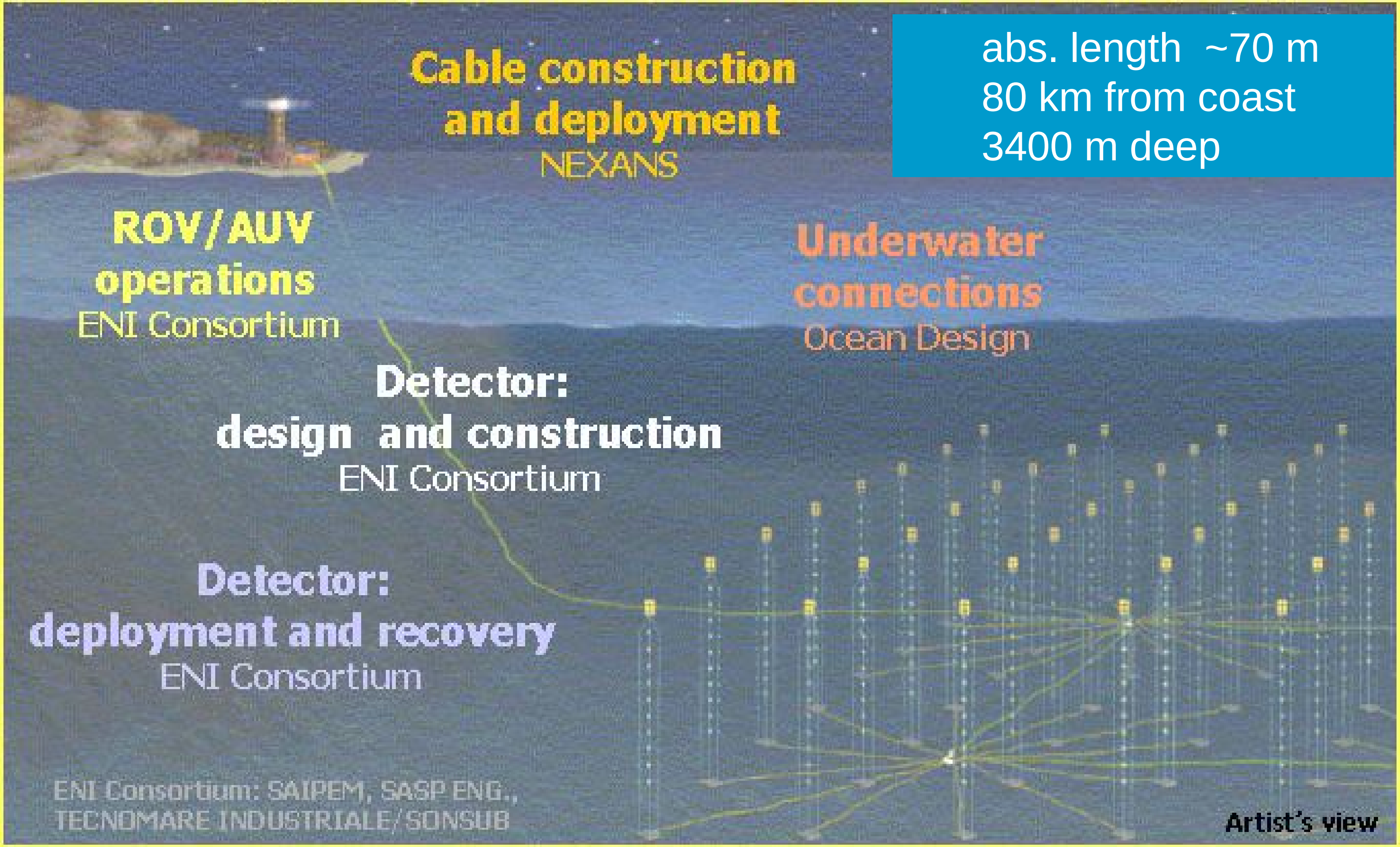




absorption length ~ 70 m at 400 nm

NEMO *Neutrino Mediterranean Observatory*

Coordinated by INFN, in collaboration with SACLANTcen-NATO, CNR, OGS



NESTOR

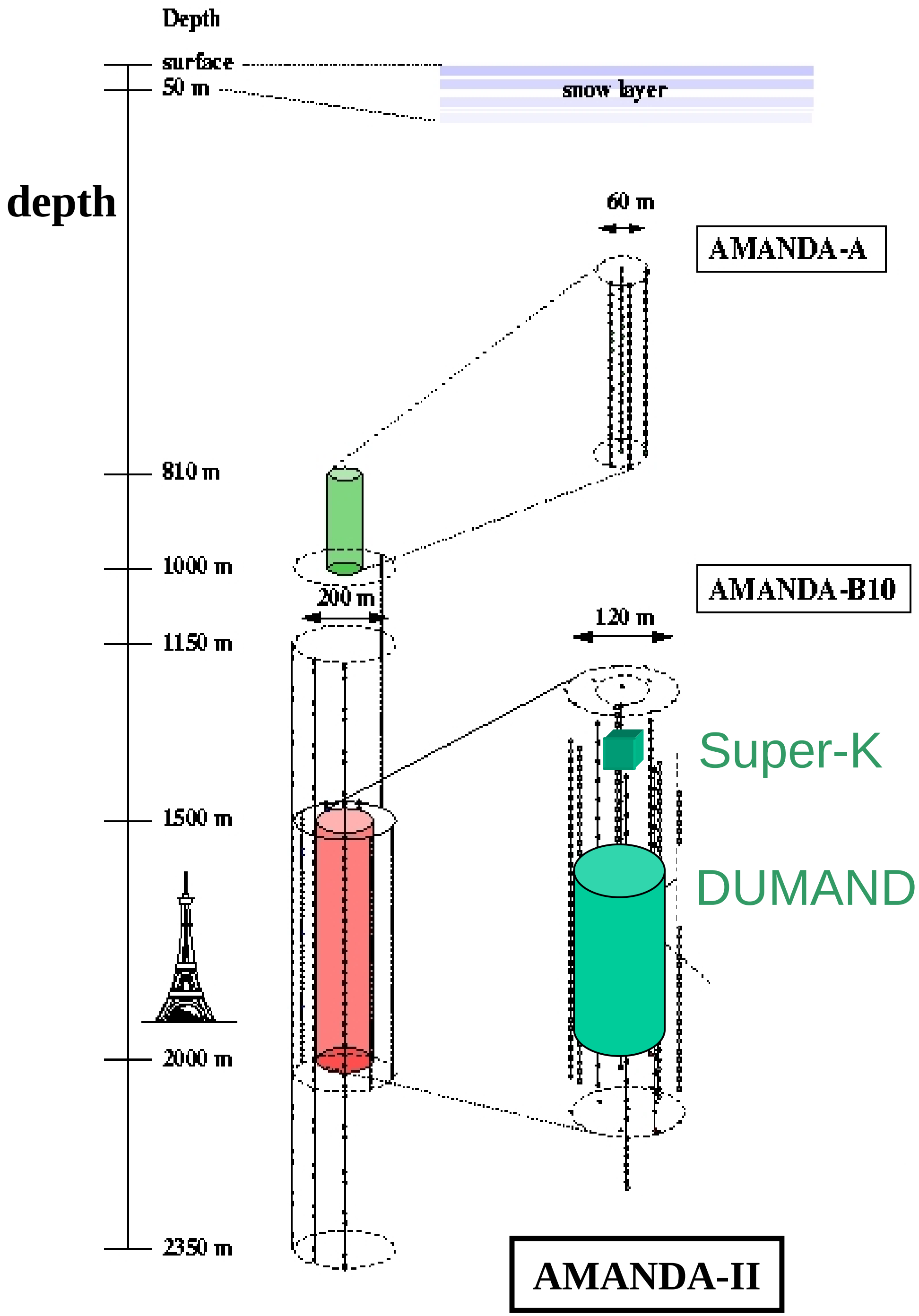
	1991 - 2000	R & D, Site Evaluation
Summer	2002	Deployment 2 floors
Winter	2003	Recovery & re-deployment with 4 floors
Autumn	2003	Full Tower deployment
	2004	Add 3 DUMAND strings around tower
	2005 - ?	Deployment of 7 NESTOR towers

ANTARES

	1996 - 2000	R&D, Site Evaluation
	2000	Demonstrator line
	2001	Start Construction
September	2002	Deploy prototype line
December	2004	10 (14?) line detector complete
	2005 - ?	Construction of km^3 Detector

NEMO

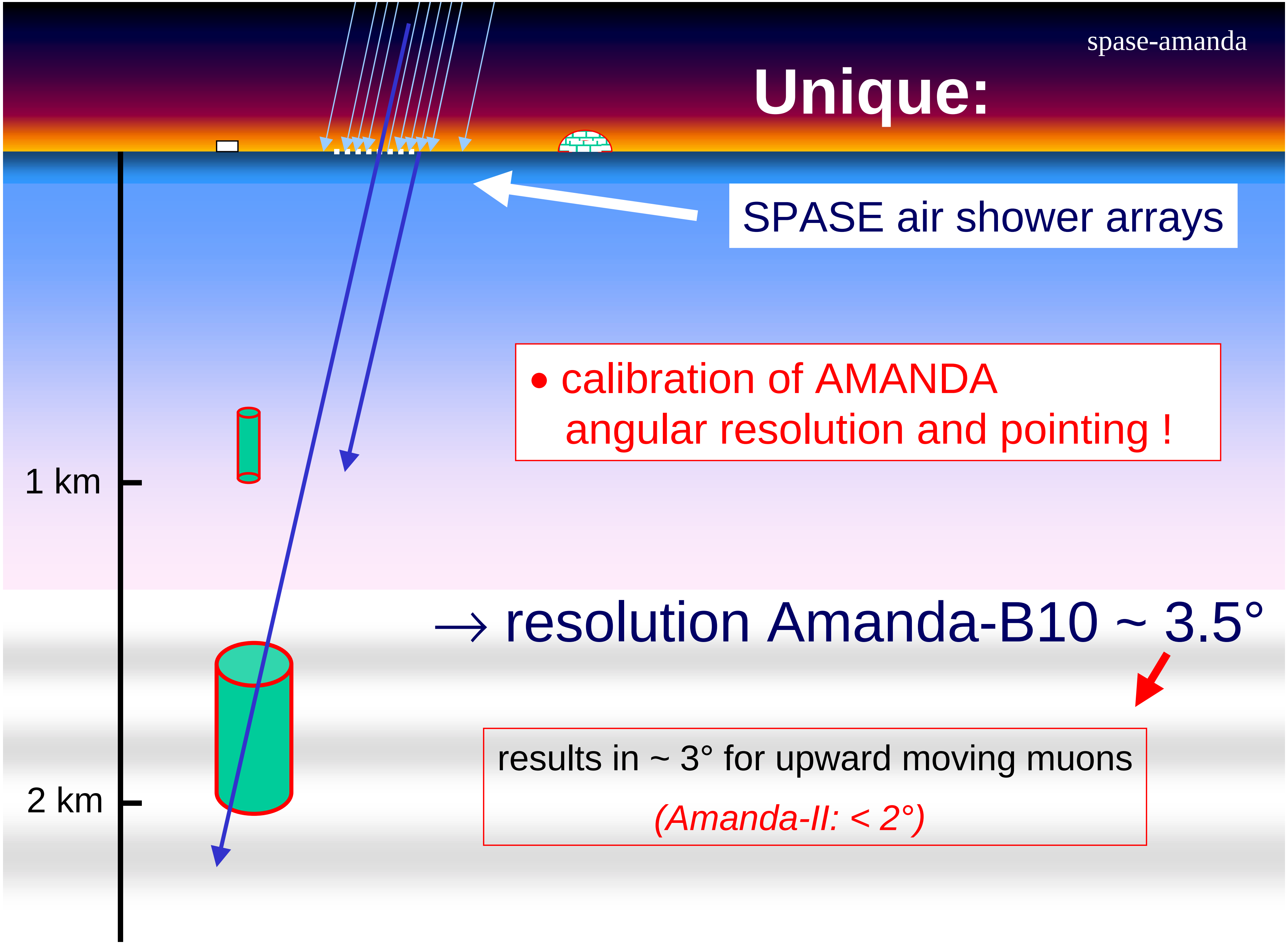
1999 - 2001	Site selection and R&D
2002 - 2004	Prototyping at Catania Test Site
2005 - ?	Construction of km^3 Detector



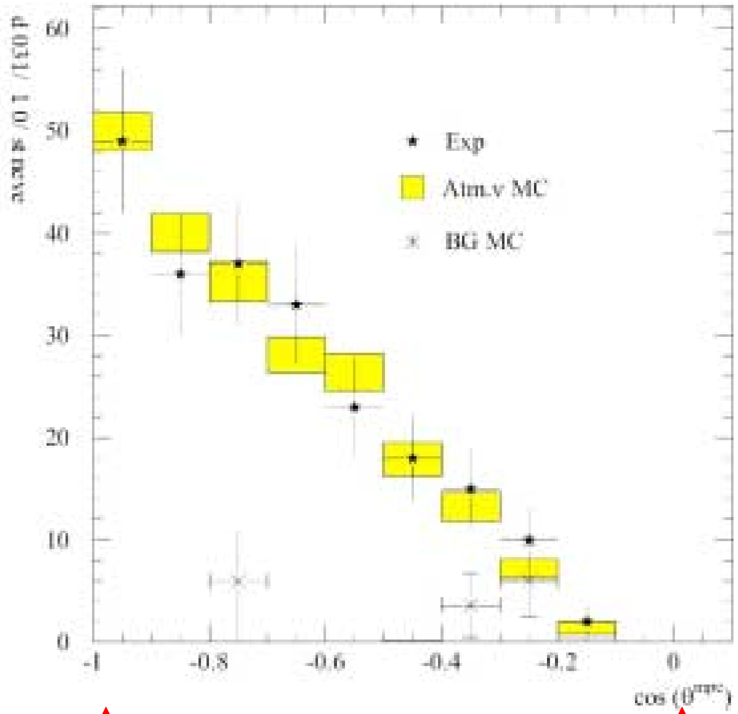
AMANDA

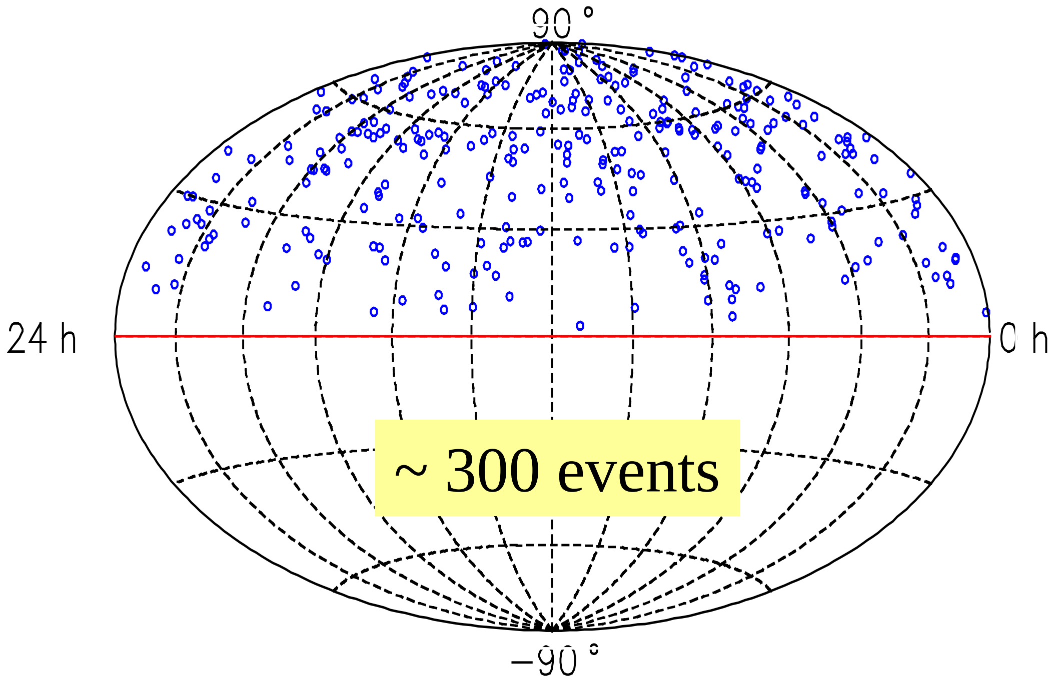
Amanda-II:
677 PMTs
at 19 strings

(1996-2000)


spase-amanda
Unique:
SPASE air shower arrays
• calibration of AMANDA
angular resolution and pointing !
1 km
2 km
→ resolution Amanda-B10 ~ 3.5°
results in ~ 3° for upward moving muons
(Amanda-II: < 2°)

Atmospheric Neutrinos, 97 data





vertically up

horizontally

→ AMANDA sensitivity understood
down to normalization factor of ~ 40%
(modeling of ice ...)

2002 real time analysis at Pole

On line reconstruction and filtering with 2 high end PCs at SP

→ 2 % minimum bias

→ upward tracks

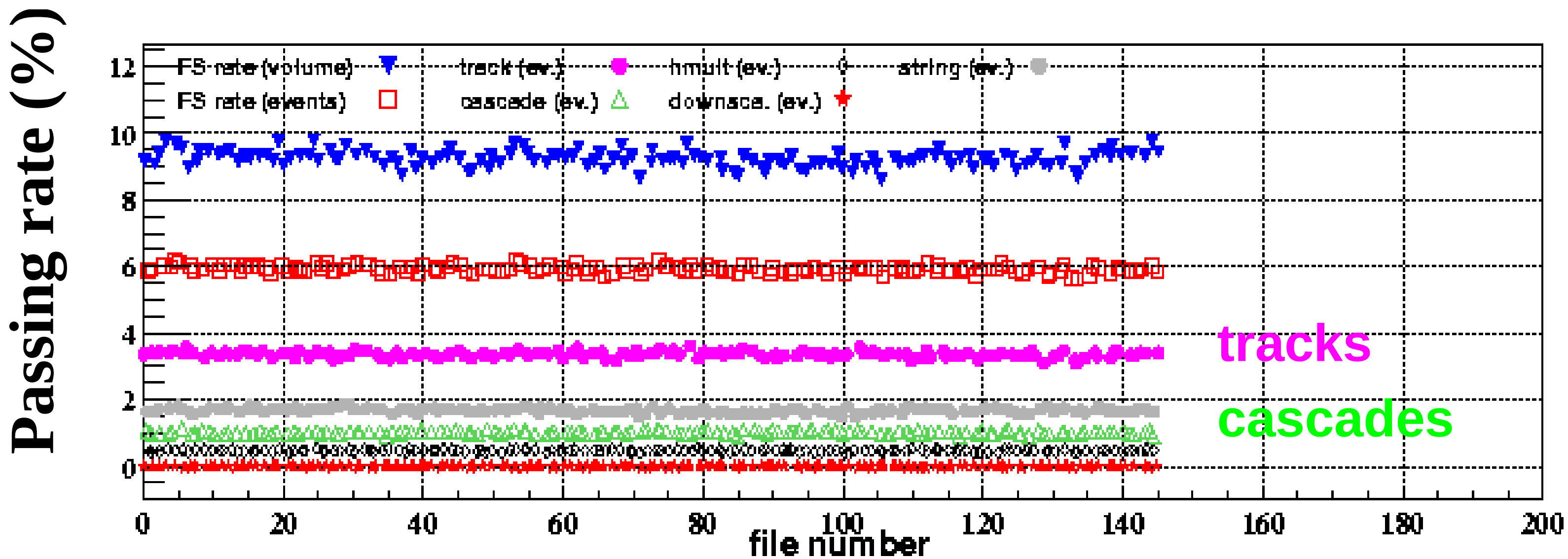
→ cascades

→ high multiplicities

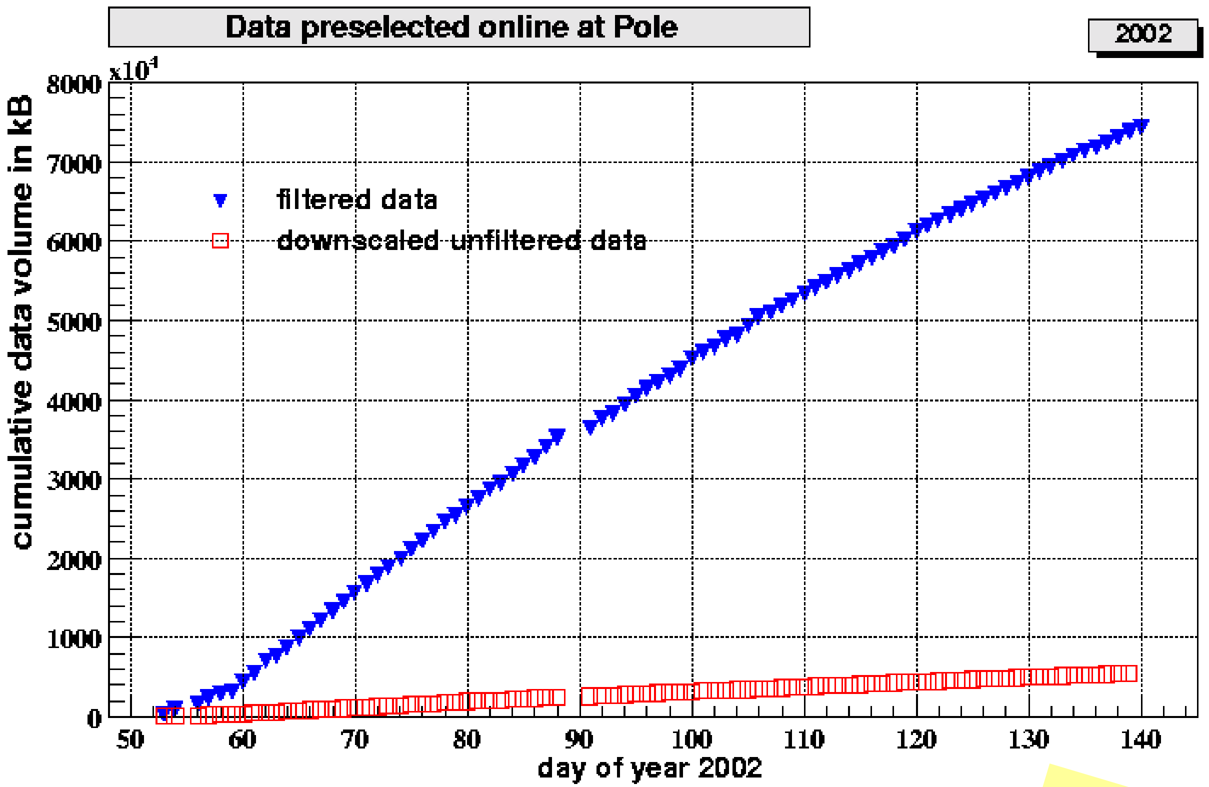
→ string trigger

→ Spase-Amanda

Friday, 14 June, 2002



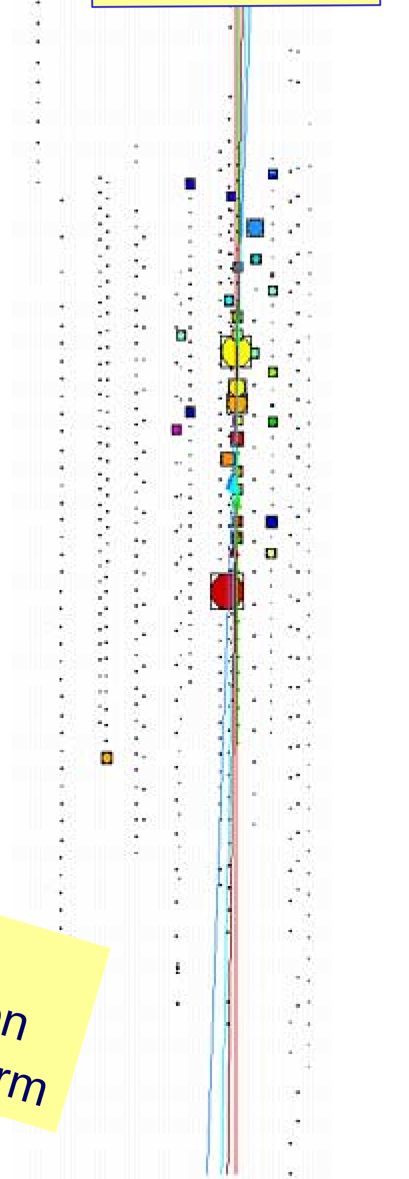
2002 real time analysis



Daily transmission ~ 1 GB via satellite
Full data to tape (available next polar summer)
Monitoring shifts in home labs

From 02/03:
Iridium connection
for supernova alarm

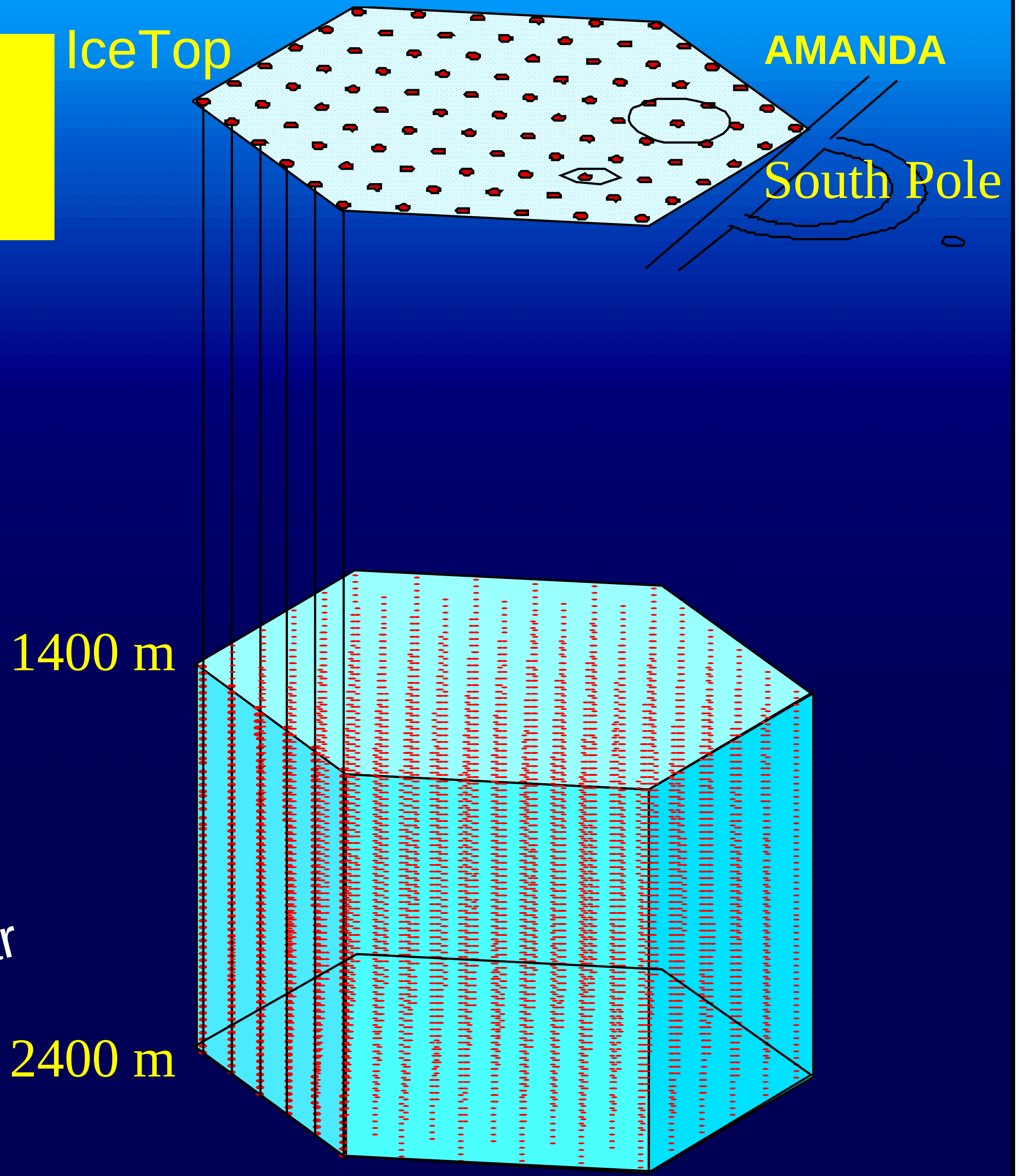
ν event June 14



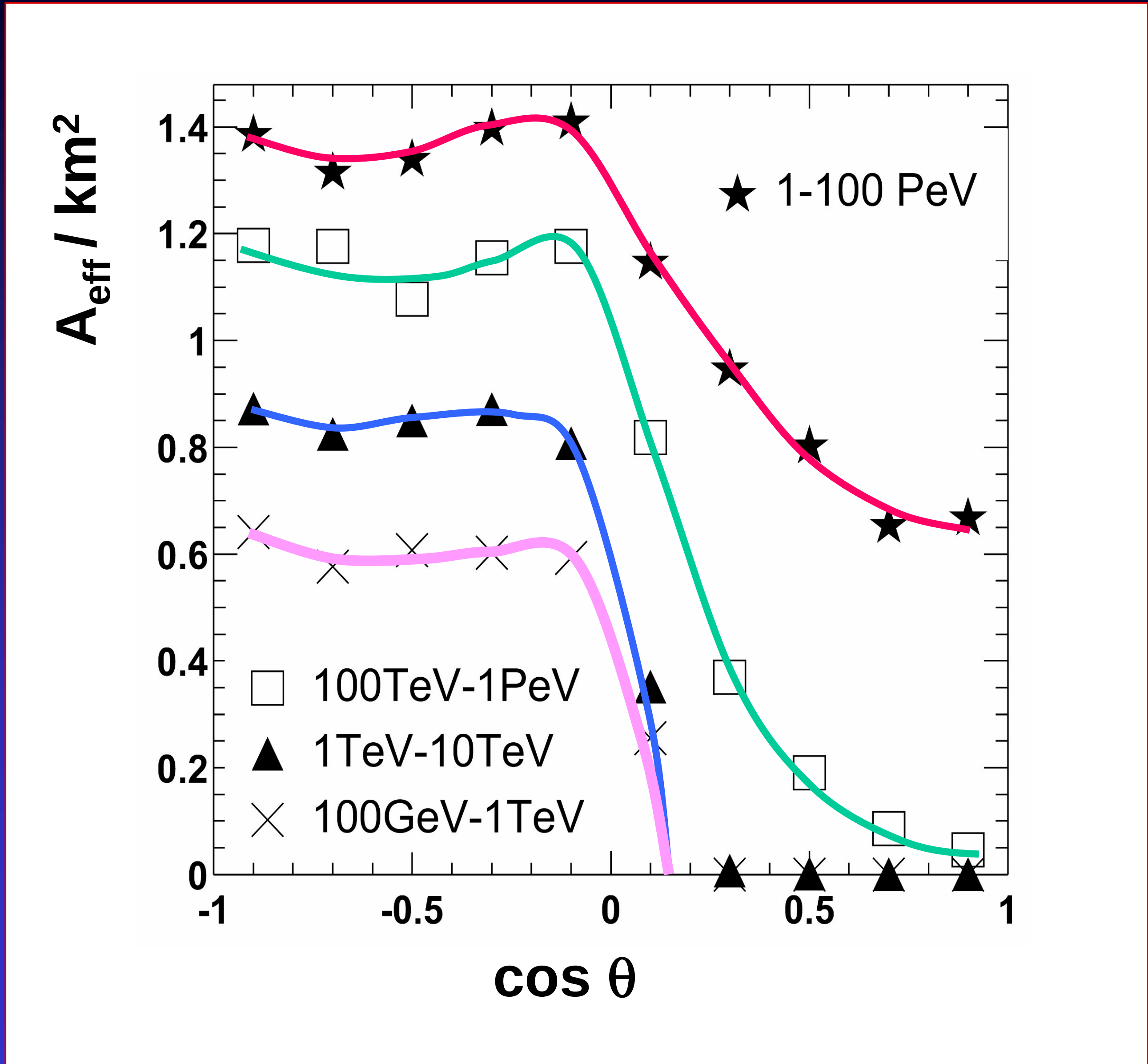
IceCube

- 80 Strings
- 4800 PMT
- Instrumented volume: 1 km^3
- Installation: 2004-2010

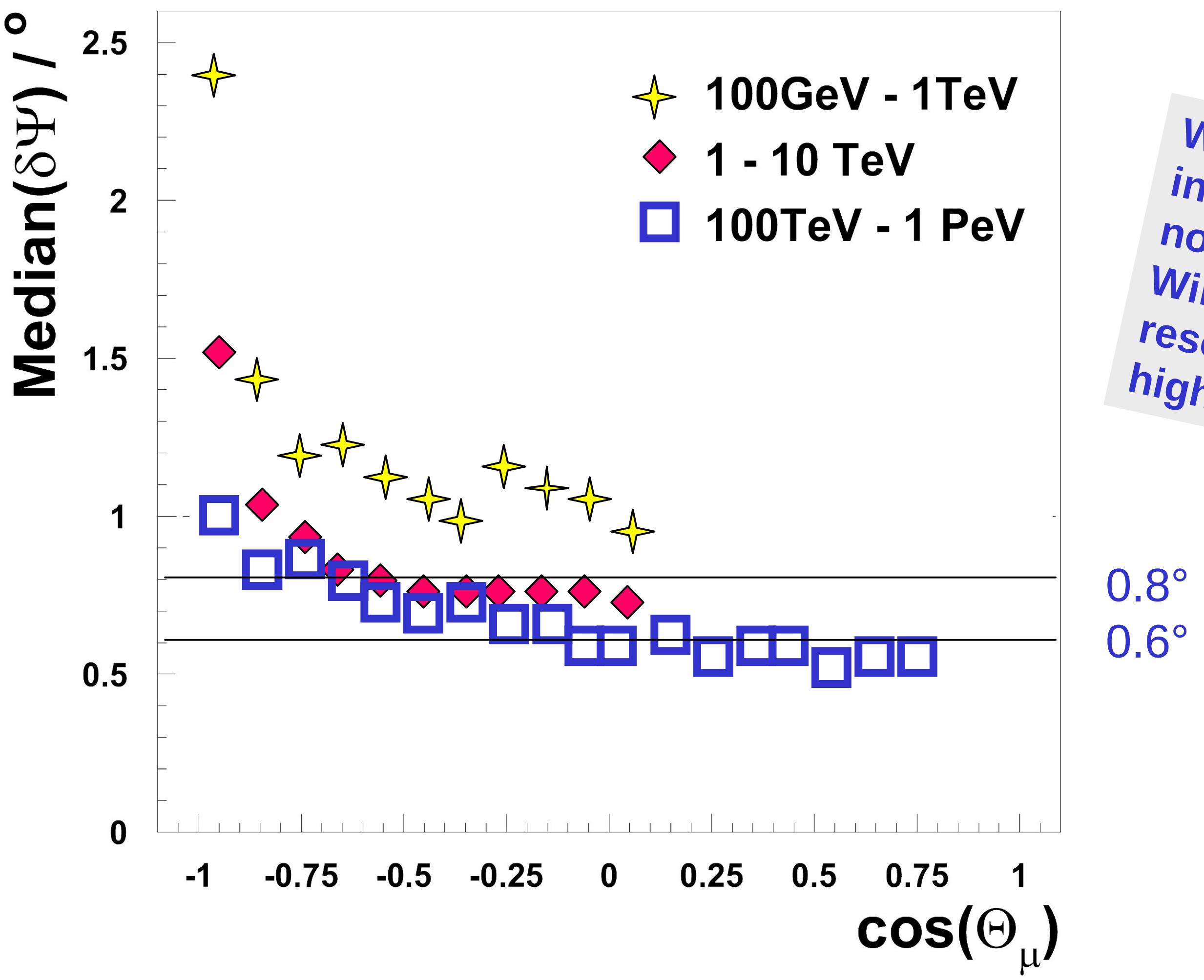
~ 80.000 atm.ν per year



Effective area of IceCube



Angular resolution as a function of zenith angle



Waveform information not used. Will improve resolution for high energies !

Ice vs. Water

Ice

- **Proven technology**
- **Stable deployment surface**
- **Stable detector geometry**
- **Longer absorption length**
- **Sterile, low noise medium**

Water

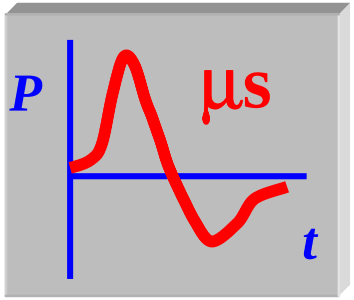
- **Longer deployment season**
- **More accessible locales**
- **Changeable detector geometry**
- **Longer scattering length**
- **More uniform medium**

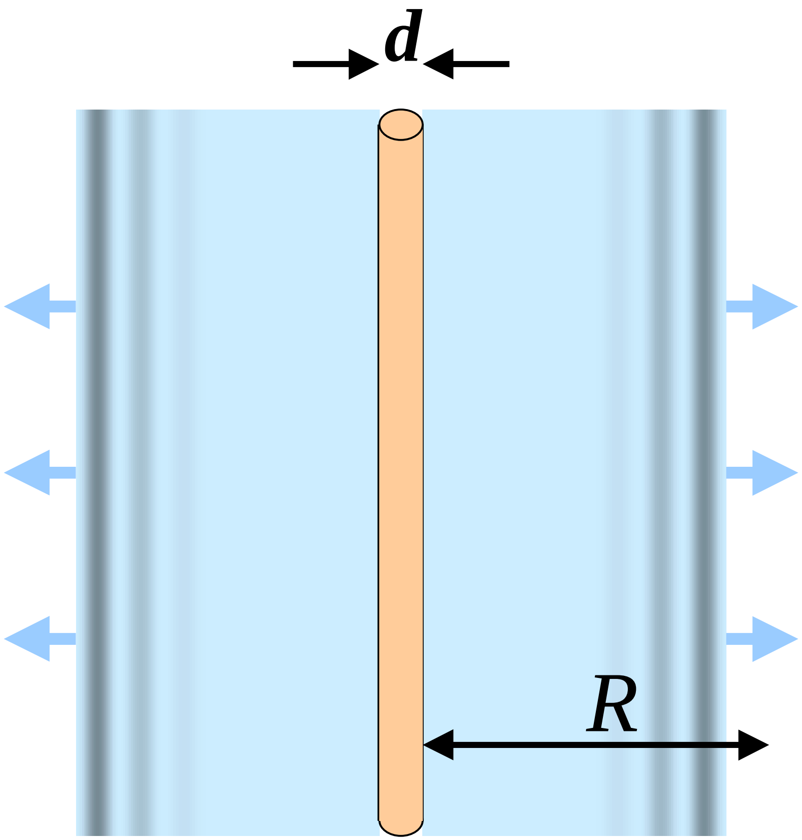
Acoustic Detection

Particle cascade → ionization

→ heat

→ pressure wave





Maximum of emission at ~ 20 kHz

Attenuation length of sea water at 15-30 kHz: **a few km**
(light: a few tens of meters)

? given a large initial signal, huge detection volumes can be achieved.

Threshold > 10 PeV

Renewed efforts along acoustic method for GZK neutrino detection

Greece: SADCO
Mediterannean, NESTOR site, 3 strings with hydrophones

Russia: AGAM antennas near Kamchatka:
existing sonar array for submarine detection

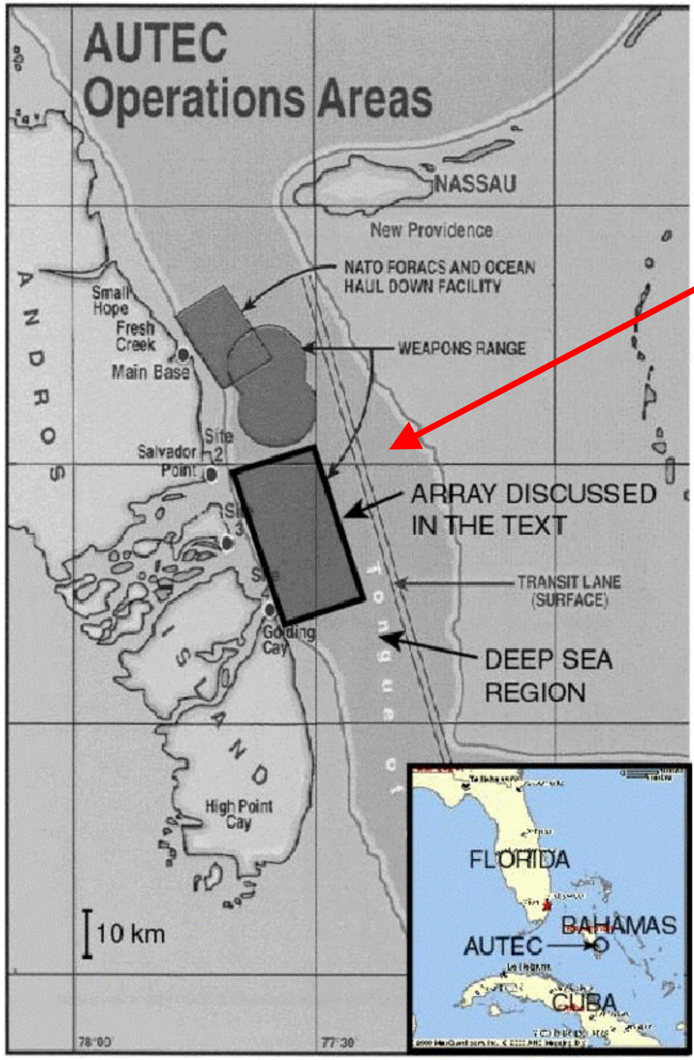
Russia: MG-10M antennas:
withdrawn sonar array for submarine detection

AUTEC: US Navy array in Atlantic:
existing sonar array for submarine detection

Antares: R&D for acoustic detection

IceCube: R&D for acoustic detection

AUTEC array in Atlantic

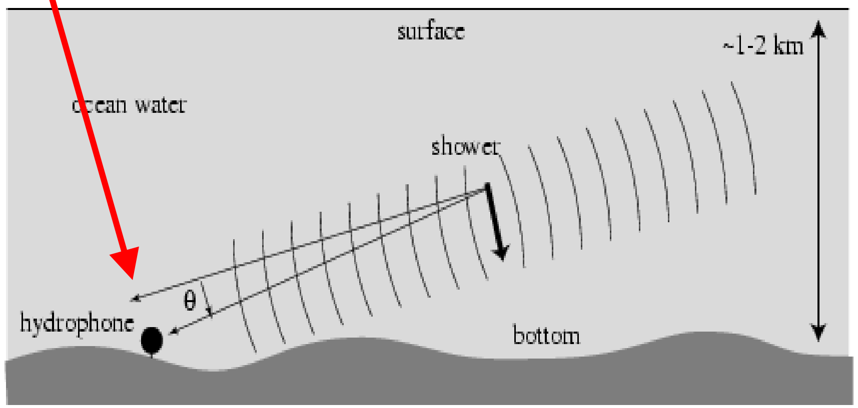


Atlantic Undersea Test and Evaluation Center

52 sensors on 2.5 km lattice (250 km^2)

4.5 m above surface

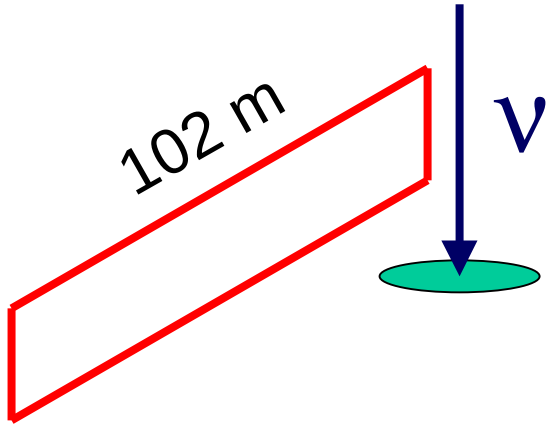
1-50 kHz !



AGAM and MG-10m antennas

AGAM: Existing sonar array for submarine detection
Shore of Kamchatka, 2400 hydrophones, 102 m × 17.3 m × 4.5 m

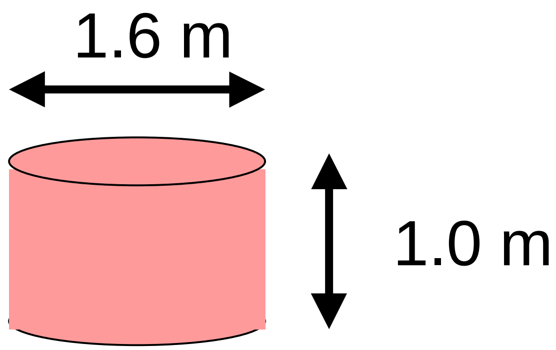
f a few hundred Hz
→ small signals
→ large attenuation length
→ hundreds of km^3 above 10^{20} eV ?



First test measurements started !

MG-10M: cyindric modules, each with 132 hydrophones.

Bandwidth up to 25 kHz
→ better suited for e.m. shower detection!



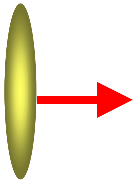
Radio Detection

$\nu_e + n \rightarrow p + e^-$

$e^- \rightarrow$ ... cascade

negative charge is sweeped into developing shower, which acquires a negative net charge $Q_{net} \sim 0.25\ E_{cascade}$ (GeV).

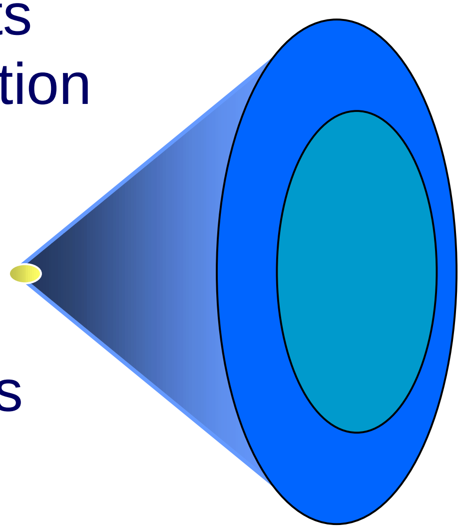
$\Rightarrow$ relativist. pancake
~ 1cm thick, ∅ ~10cm



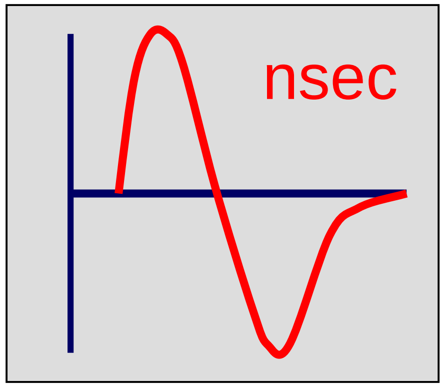
$\Rightarrow$ for λ >> 10 cm (radio)
coherence

$\Rightarrow$ each particle emits
Cherenkov radiation

$\Rightarrow$ C signal is
resultant of
overlapping
Cherenkov cones

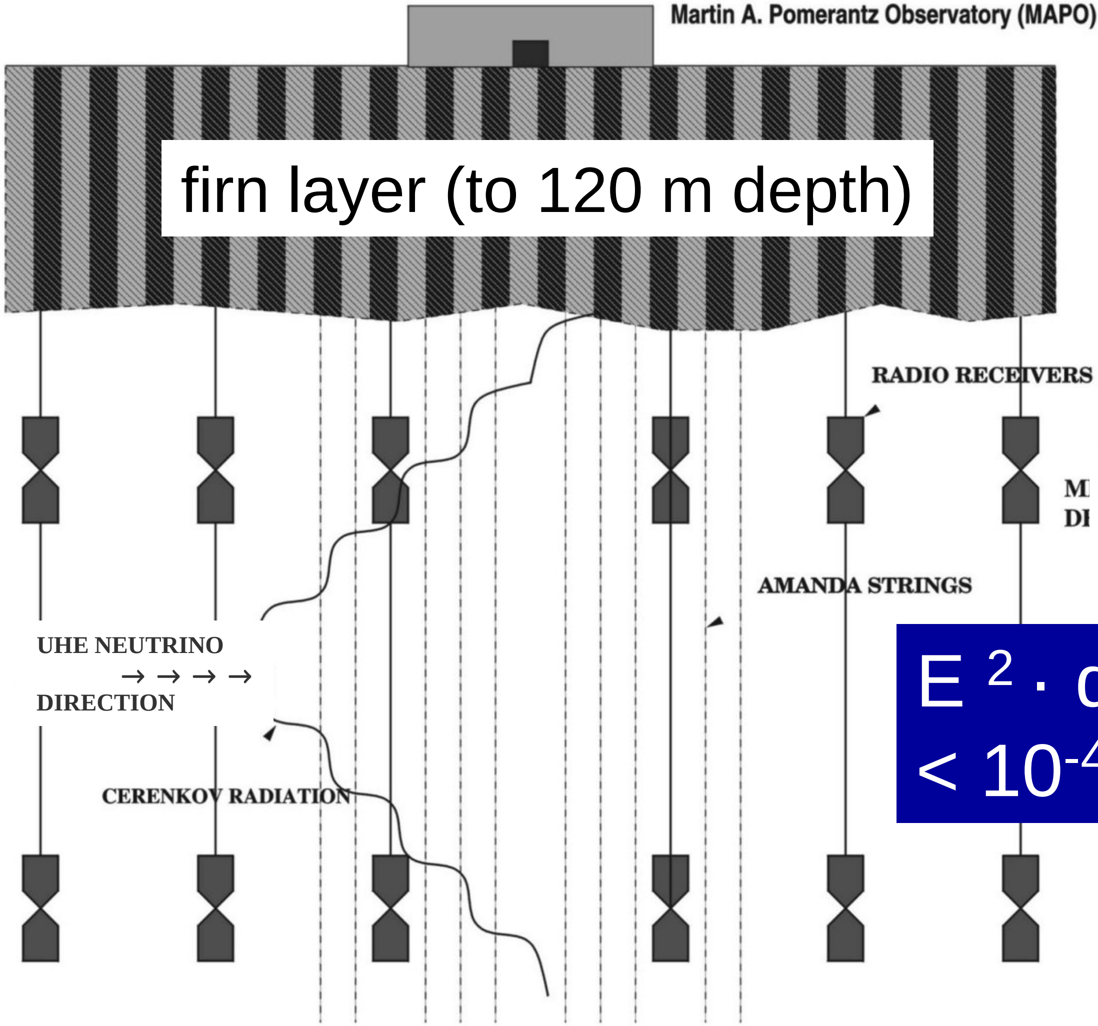


$\Rightarrow$ C-signal ~ E^2



Threshold > 10 PeV

RICE **R**adio **I**ce **C**herenkov **E**xperiment



South Pole

20 receivers + transmitters

$E^{2} \cdot dN/dE$
$< 10^{-4}$ GeV $\cdot$ cm$^{-2} \cdot$ s$^{-1} \cdot$ sr^{-1}

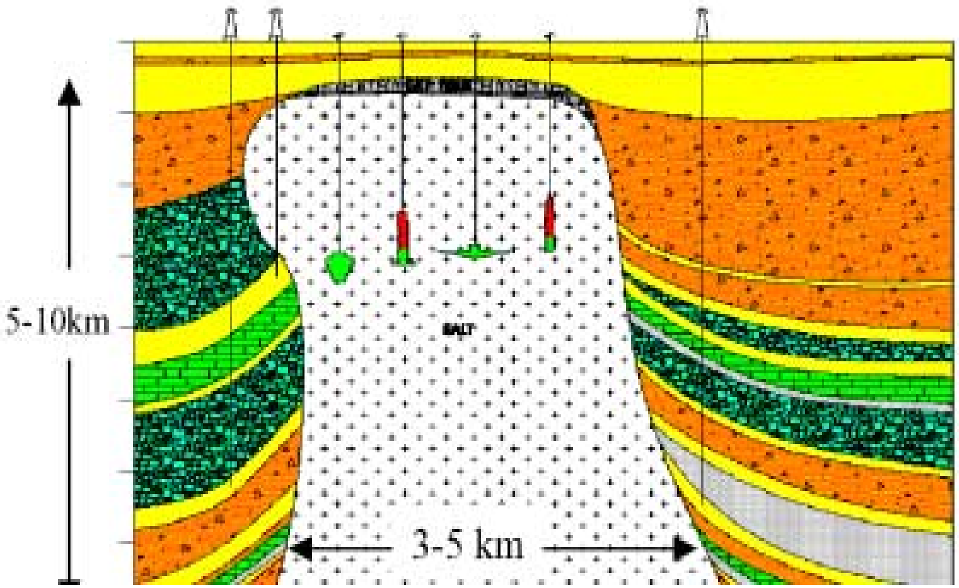
at 100 PeV

300 METER DEPTH

Natural Salt Domes: Potential PeV-EeV Neutrino Detectors

- Natural salt can be extremely low RF loss: ~ as clear as very cold ice, 2.4 times as dense

- Typical salt dome halite is comparable to ice at -40C for RF clarity



SalSA

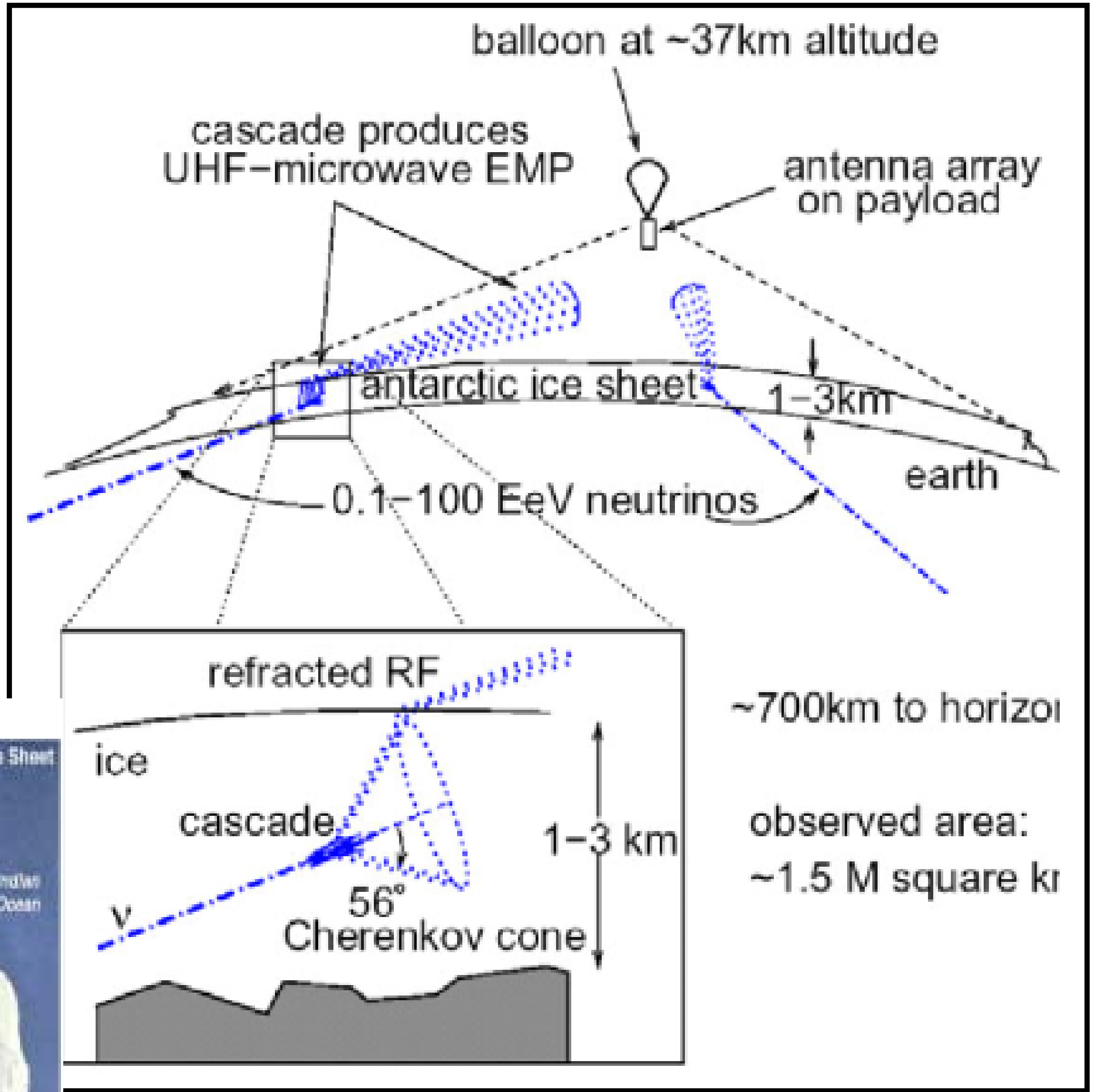
Salt Dome

Shower

Array

ANITA

Antarctic
Impulsive
Transient
Array

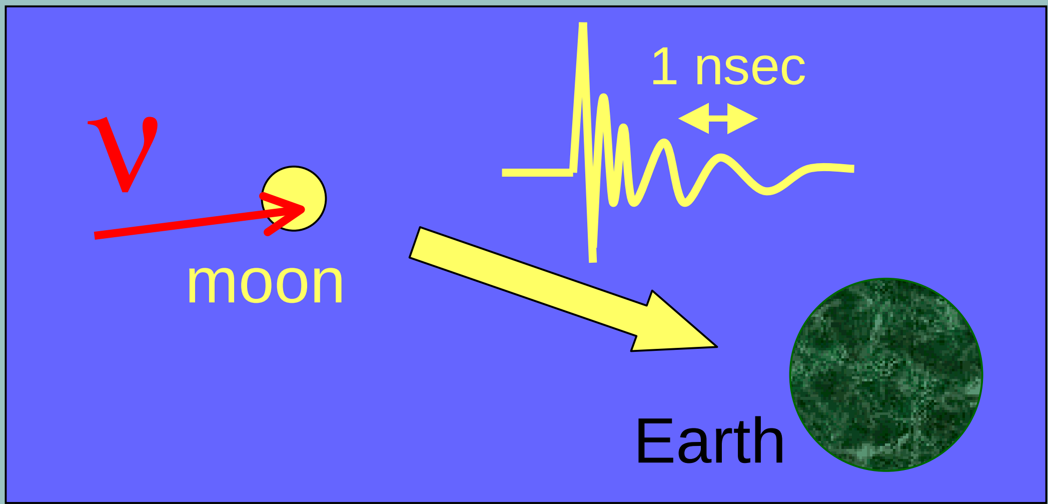


Flight in 2006

GLUE **G**oldstone **L**unar **U**ltra-high Energy Neutrino **E**xperiment

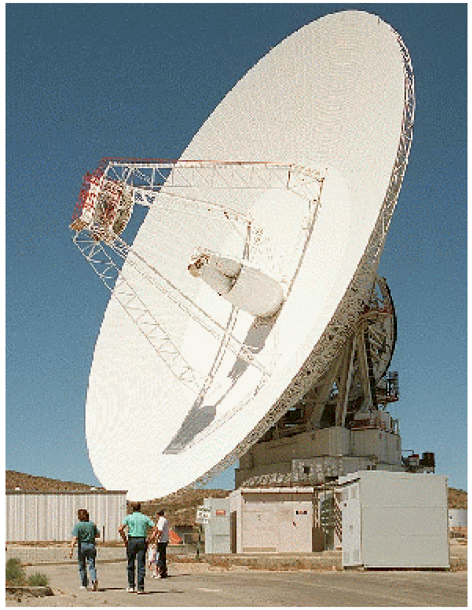
Lunar Radio Emissions from Interactions of ν and CR with > 10^{19} eV

Gorham et al. (1999), 30 hr NASA Goldstone 70 m antenna + DSS 34 m antenna



→ $E^2 \cdot dN/dE < 10^{-4}$ GeV·cm^{-2}·s^{-1}·sr^{-1}

at 10^{20} eV



Effective target volume
~ antenna beam (0.3°)
× 10 m layer

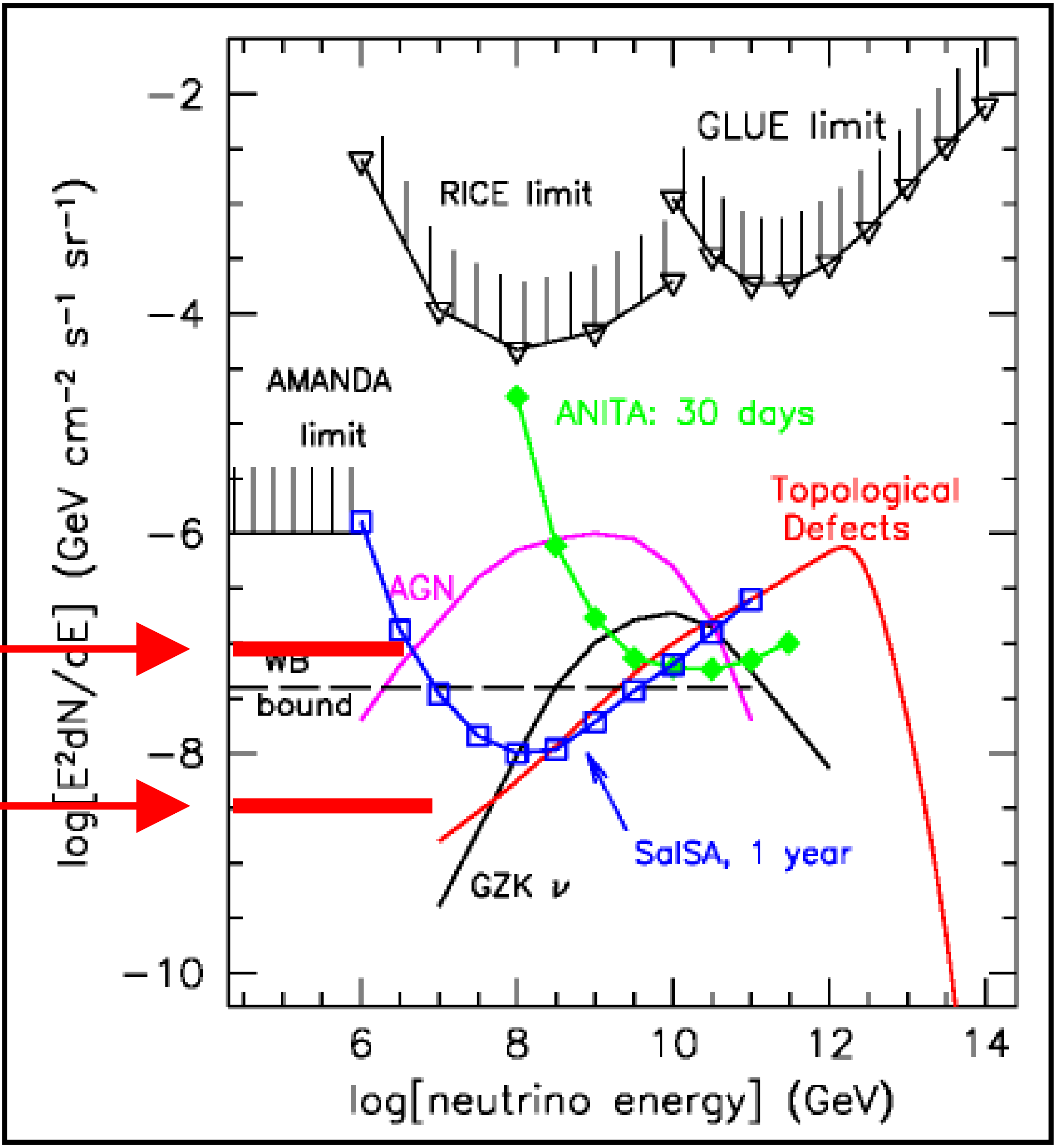
→ 10^5 km^3

Measured & Predicted Radio Limits

- Radio is competitive with optical km3 arrays for E >10 PeV
- Required detection times are small, a benefit of the enormous volumes radio detectors can view
- But: background ??

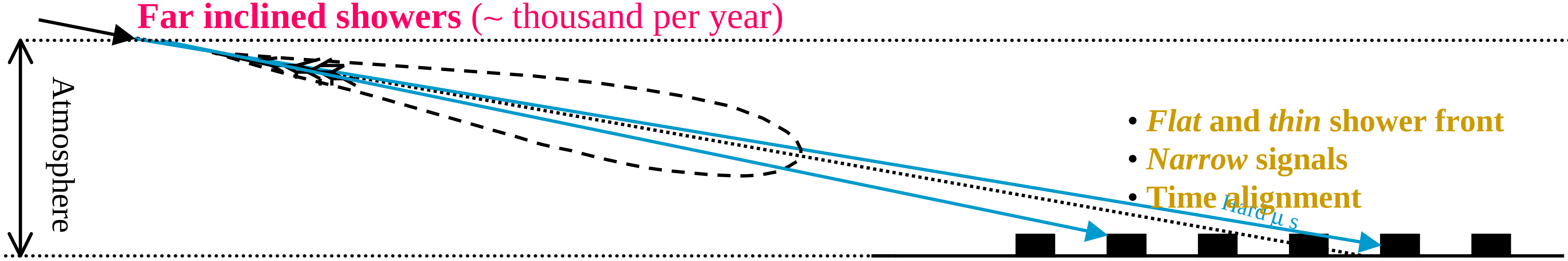
AMANDA-II 3 years expected

km3 , 3 years expected

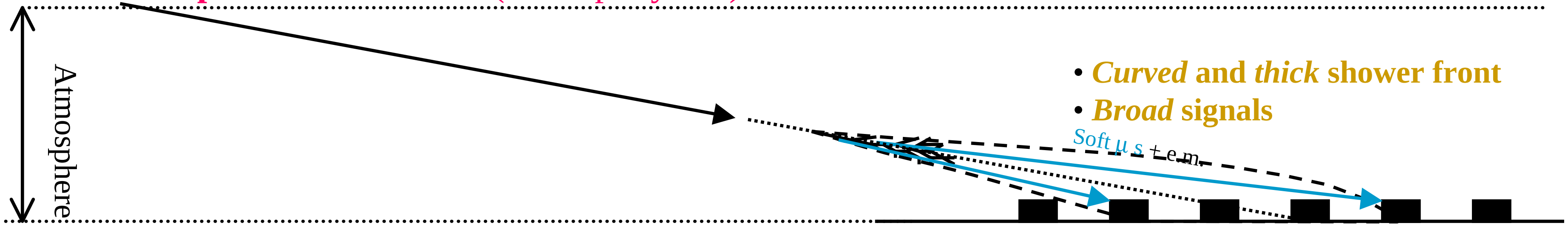


Detection of neutrino induced air showers

Far inclined showers (~ thousand per year)



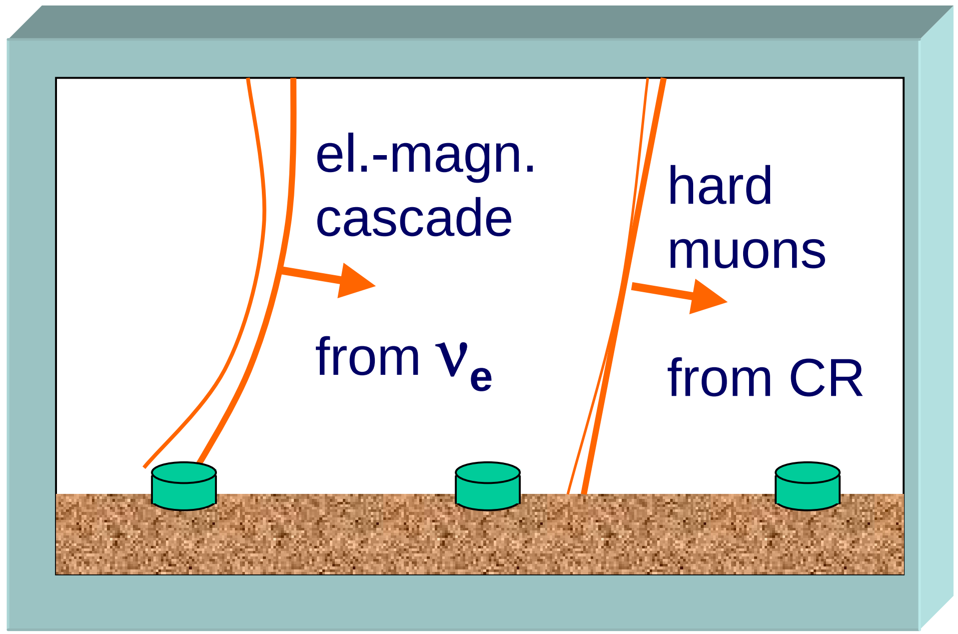
Deep inclined showers (~ one per year?)



AGASA 2001:

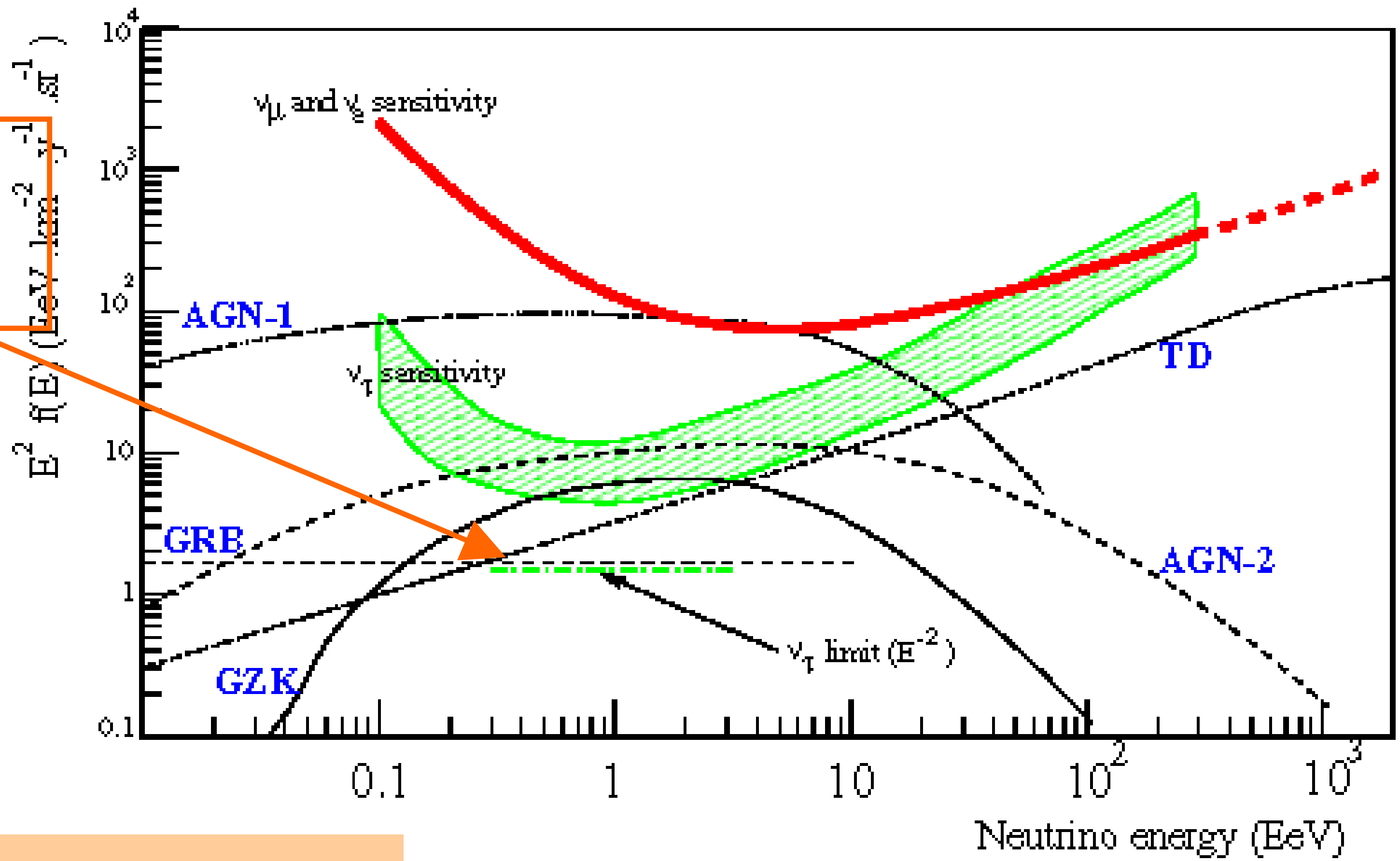
$< 10^{-5}$ GeV·cm^{-2}·s^{-1}·sr^{-1}

for E > 10 EeV



Predicted Auger Sensitivities

Comparable to 3-year optical km3 limit

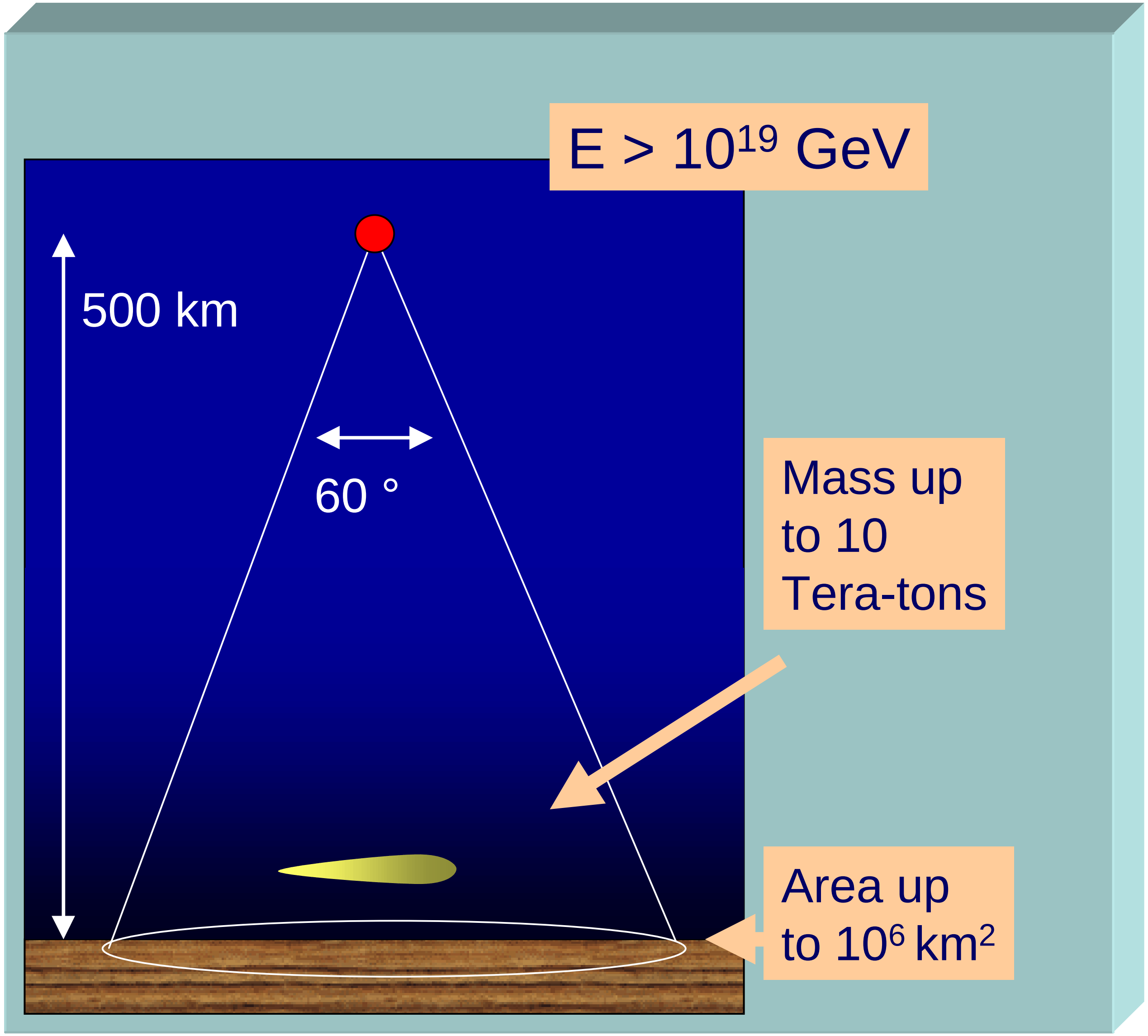


Mass for ν_μ and ν_e ~ 15 Gigatons

sensitivity ≈ $3 \cdot 10^{-7}$ GeV·cm^{-2}·s^{-1}·sr^{-1}

Skimming ν_τ
high acceptance at ~EeV !

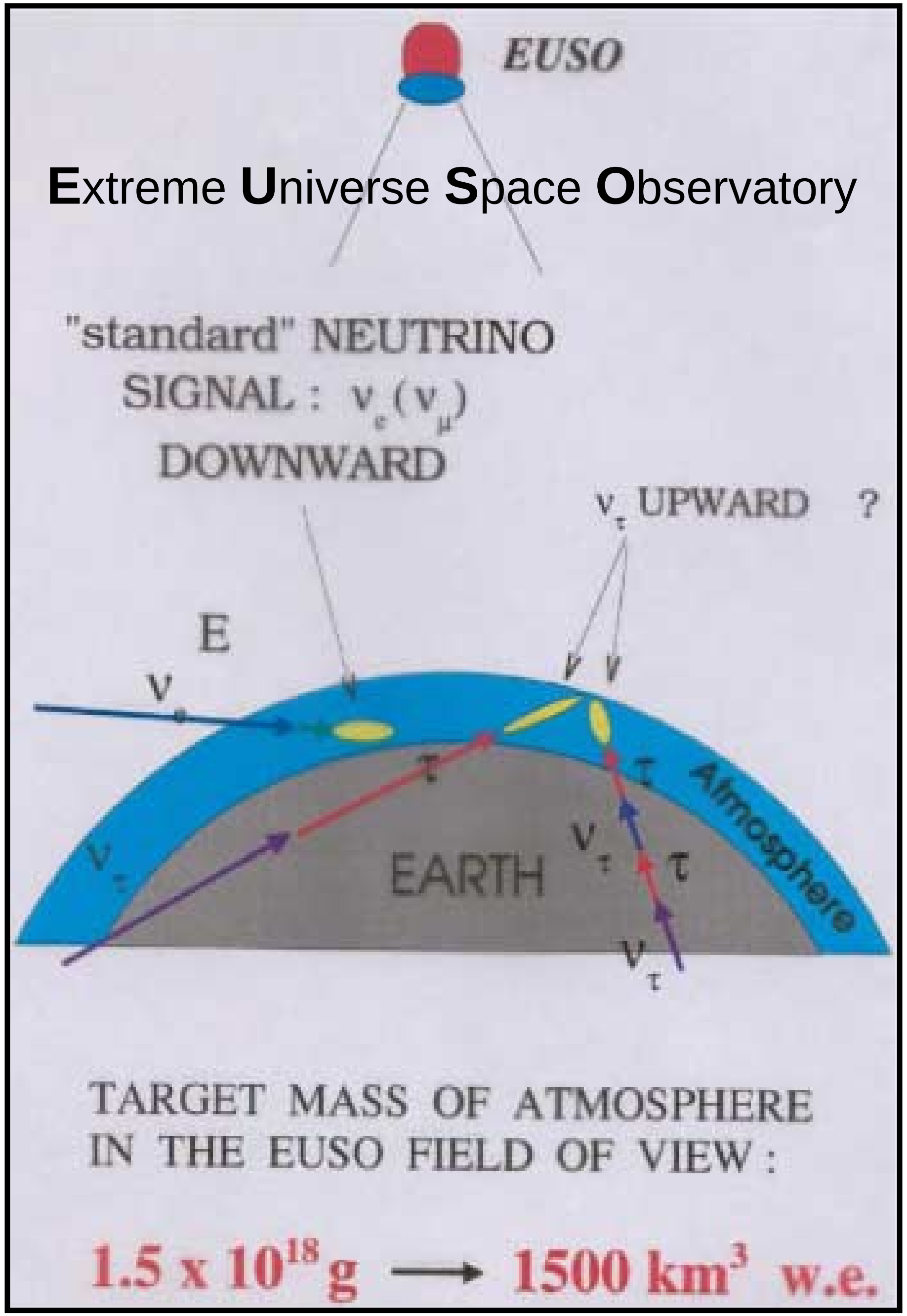
Horizontal Air Showers seen by Satellite

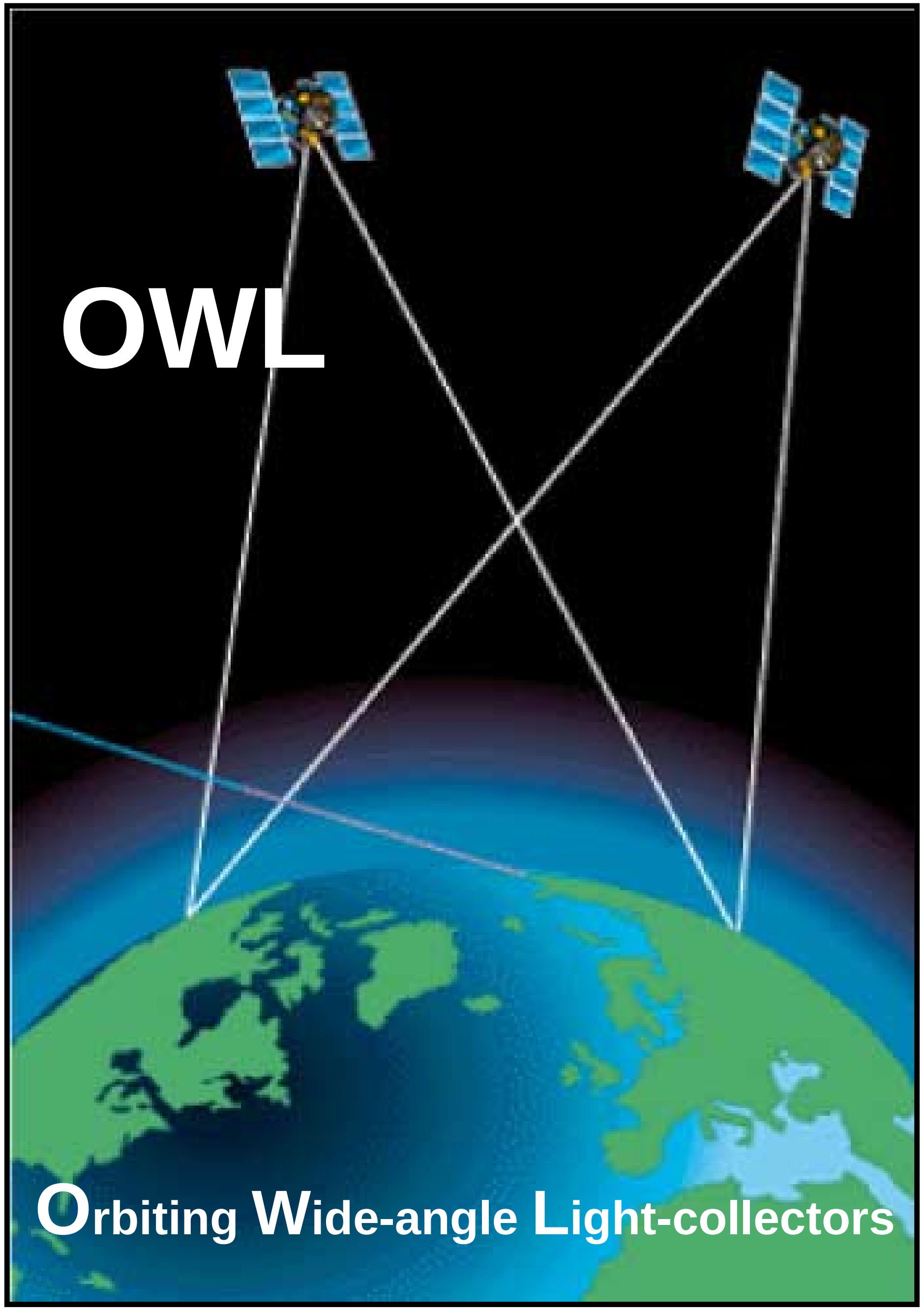


Horizontal air shower initiated deep in atmosphere

1 - 20 GZK ev./y

5 - 50 TD ev./y


EUSO
Extreme Universe Space Observatory
"standard" NEUTRINO
SIGNAL : $\nu_e(\nu_\mu)$
DOWNWARD
ν_τ UPWARD ?
E
ν_e
τ
τ
Atmosphere
ν_τ
EARTH
ν_τ
τ
ν_τ
TARGET MASS OF ATMOSPHERE
IN THE EUSO FIELD OF VIEW :
1.5×10^{18} g ⟶ 1500 km^3 w.e.


OWL
Orbiting Wide-angle Light-collectors

OWL Preliminary Electron Neutrino Event Rates

640 km Orbits, 10% Duty Cycle, 2.5 m Optical Aperture

Interaction	2 Satellites Independently `Looking Down'	Stereo 500 km Sat. Sep.	Stereo 2000 km Sat. Sep.
$p\gamma_{2.7K}$ (1)	16 Events/Year	5 Events/Year	1 Events/Year
Topological Defects (2)	46 Events/Year	17 Events/Year	13 Events/Year
Z_{Burst} (3)	20 Events/Year	9 Events/Year	20 Events/Year
$E_{Threshold}$	10^{19} eV	2×10^{19} eV	10^{20} eV
No. of Satellites Viewing Event	1	2	2

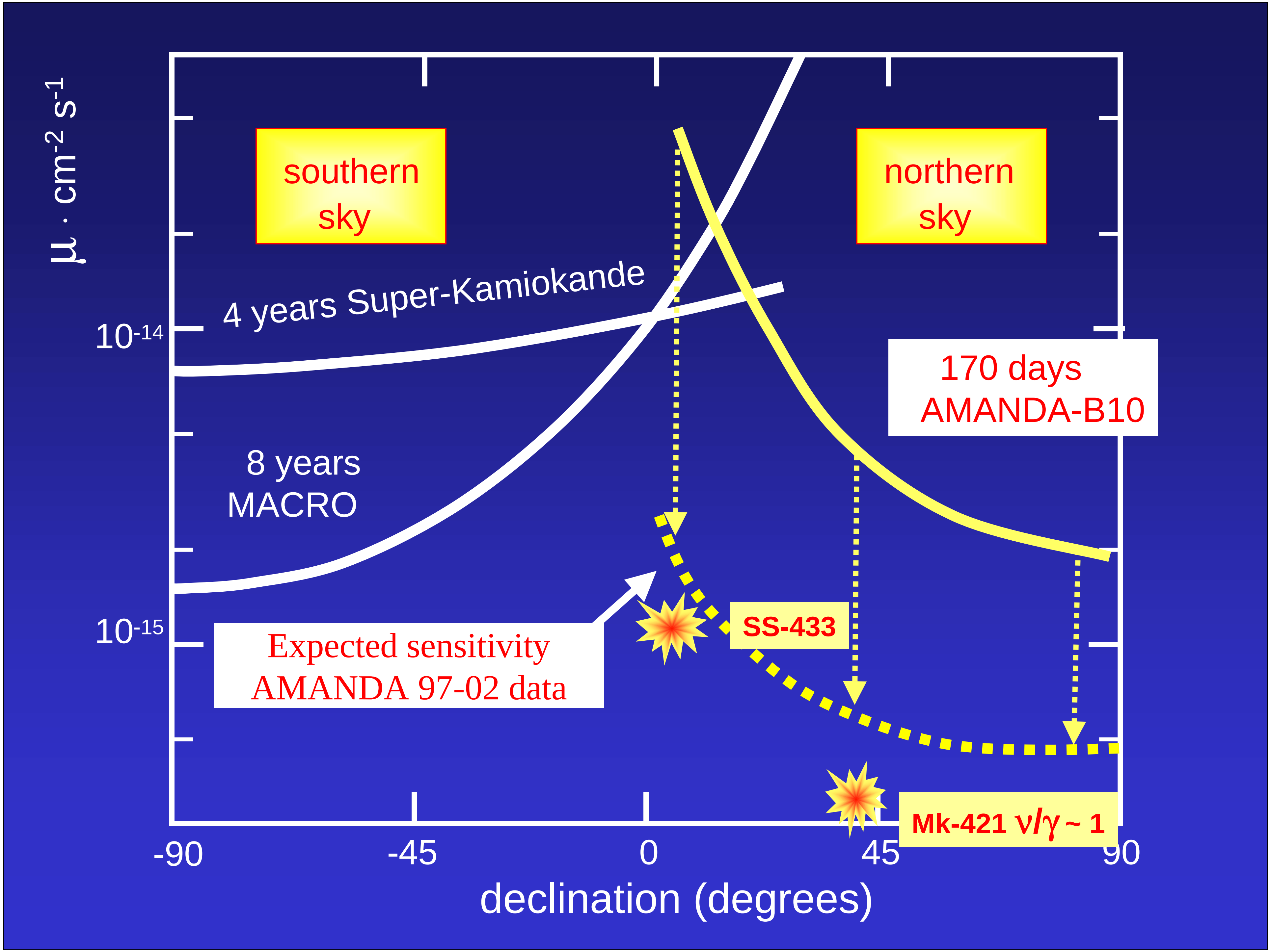
1 Stecker, Done, Salamon, &Sommers, PRL 66 (1991)
2 Sigl, Lee, Bhattacharjee, & Yoshida, Phys Rev D 59 (1998), $m_X = 10^{16}$ GeV, X -> q+ q, SuperSymmetric fragmention
3 Yoshida, Sigl, & Lee, PRL 81 (1998), $m_\nu = 1$ eV, Primary $\Phi_\nu \sim E^{-1}$

3. Physics from

AMANDA

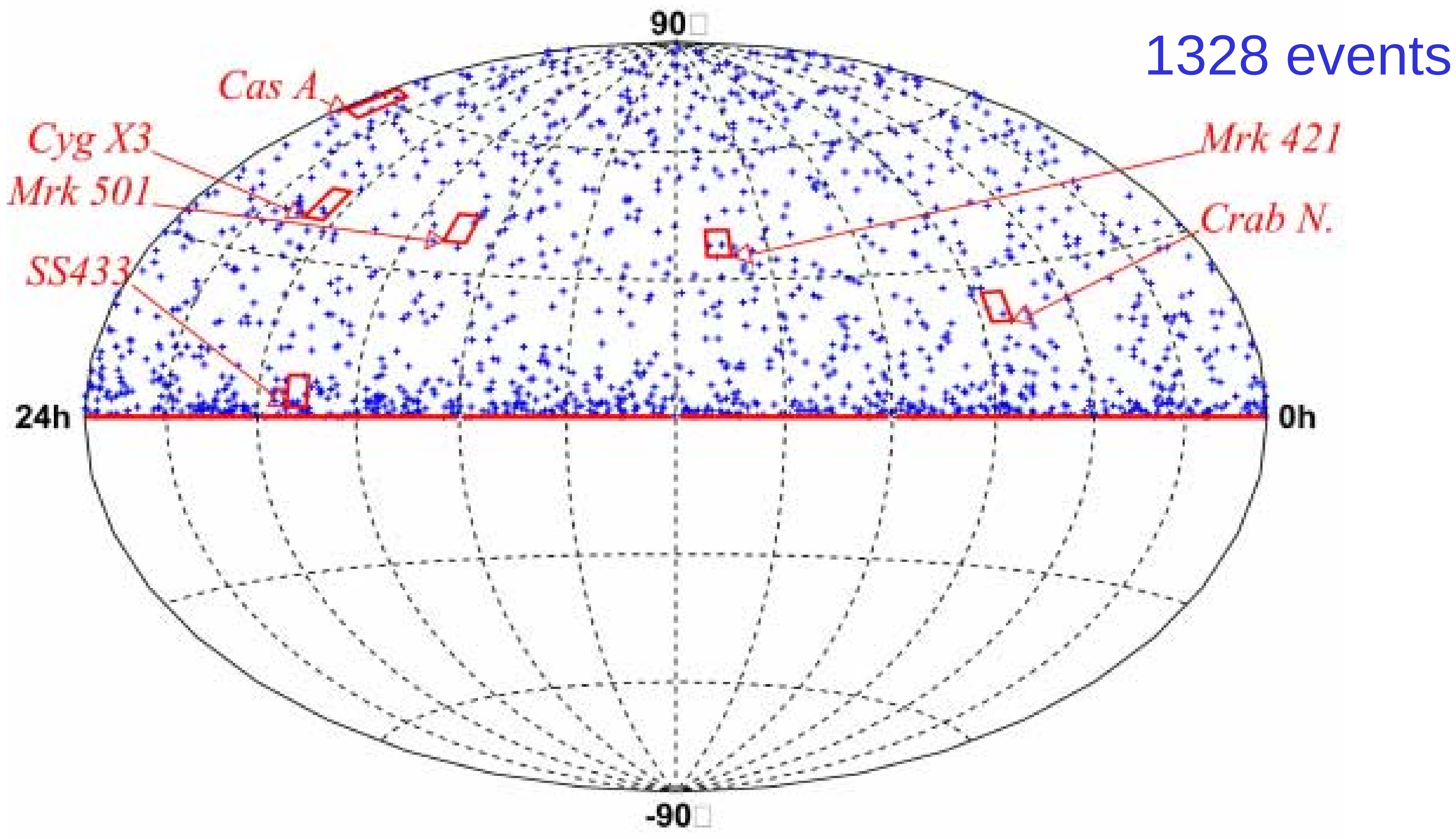
and

BAIKAL



μ · cm-2 s-1
southern sky
northern sky
4 years Super-Kamiokande
10-14
10-15
170 days AMANDA-B10
8 years MACRO
Expected sensitivity AMANDA 97-02 data
SS-433
Mk-421 ν/γ ~ 1
-90
-45
0
45
90
declination (degrees)

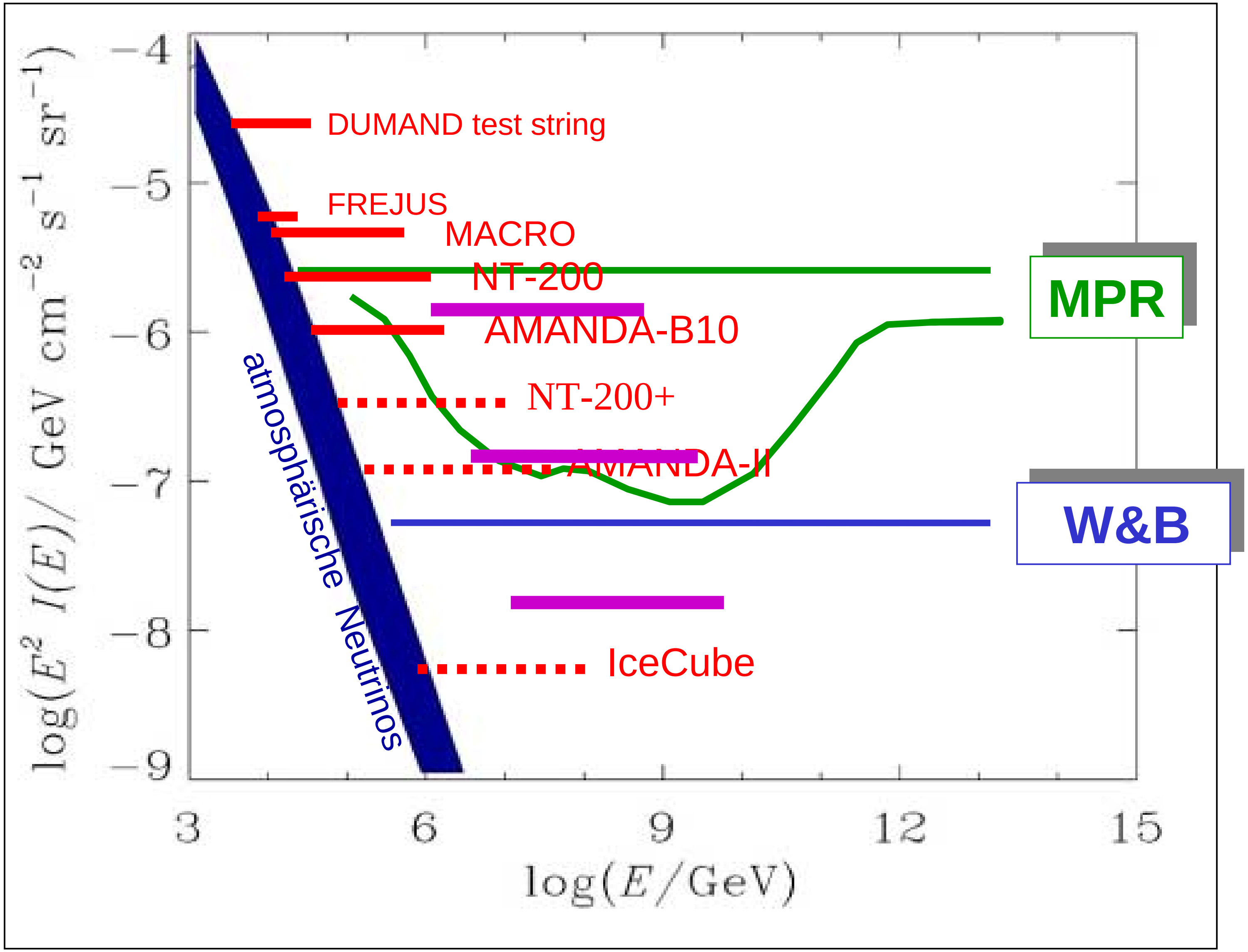
Point Sources Amanda II (2000)



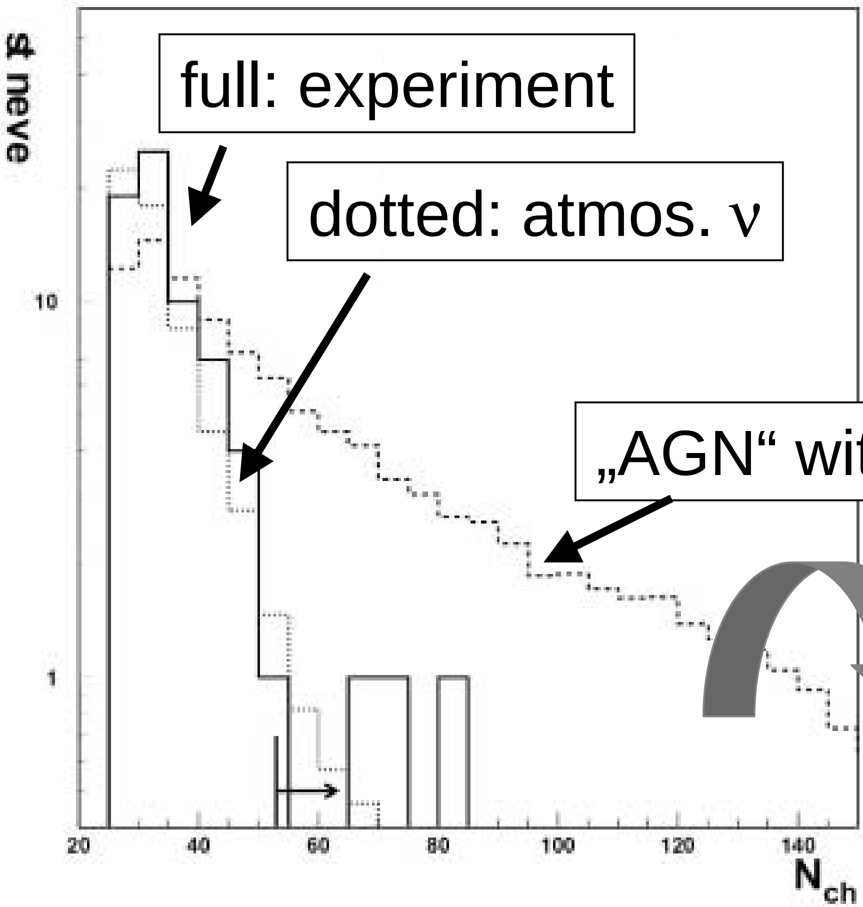
Preliminary limits (in units of 10^{-15} muons cm^{-2} s^{-1}):

Cas A: **0.6** *Mk421:* **1.4** *Mk501:* **0.8** *Crab:* **6.8** *SS433:* **10.5**

Diffuse fluxes: theoretical bounds and experimental limits



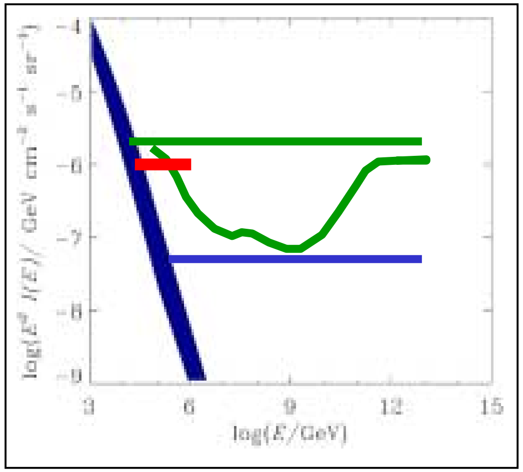
Amanda 97: Upper limit on the diffuse flux of h.e. upward muon neutrinos



full: experiment

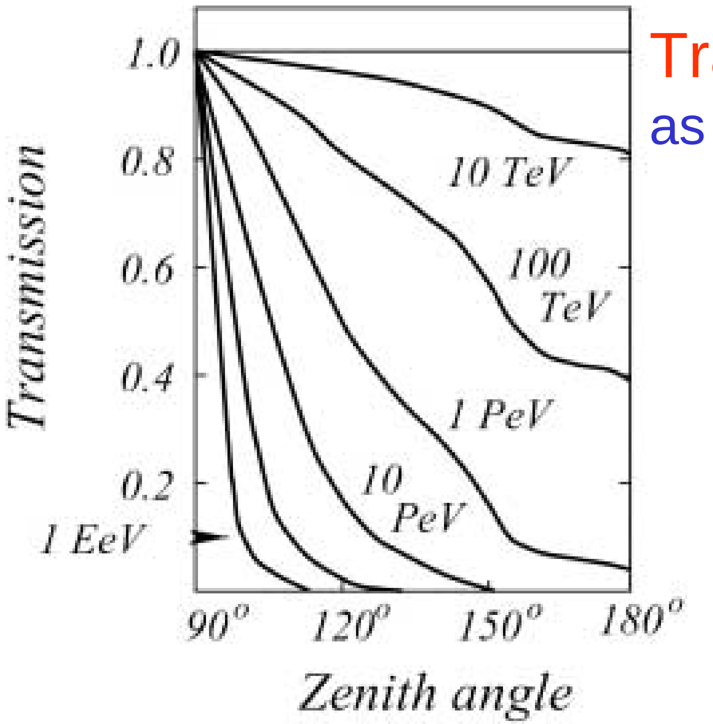
dotted: atmos. ν

„AGN“ with $10^{-5}\ E^{-2}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$



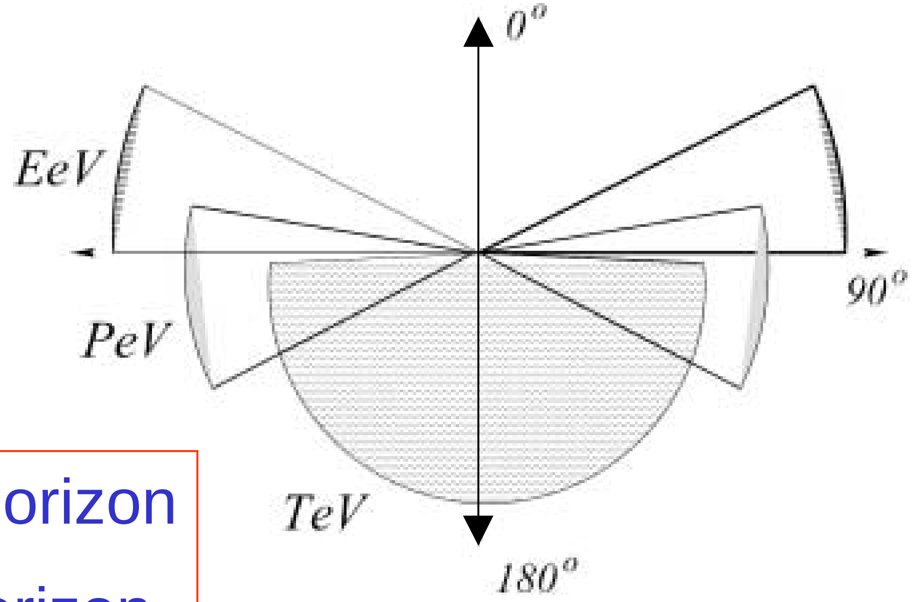
$E^2\ \Phi$
$< 0.9 \cdot 10^{-6}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$

EeV neutrinos underwater



Transmission of Earth for Neutrinos
as a function of zenith angle and energy

→ *Earth opaque above a few PeV*



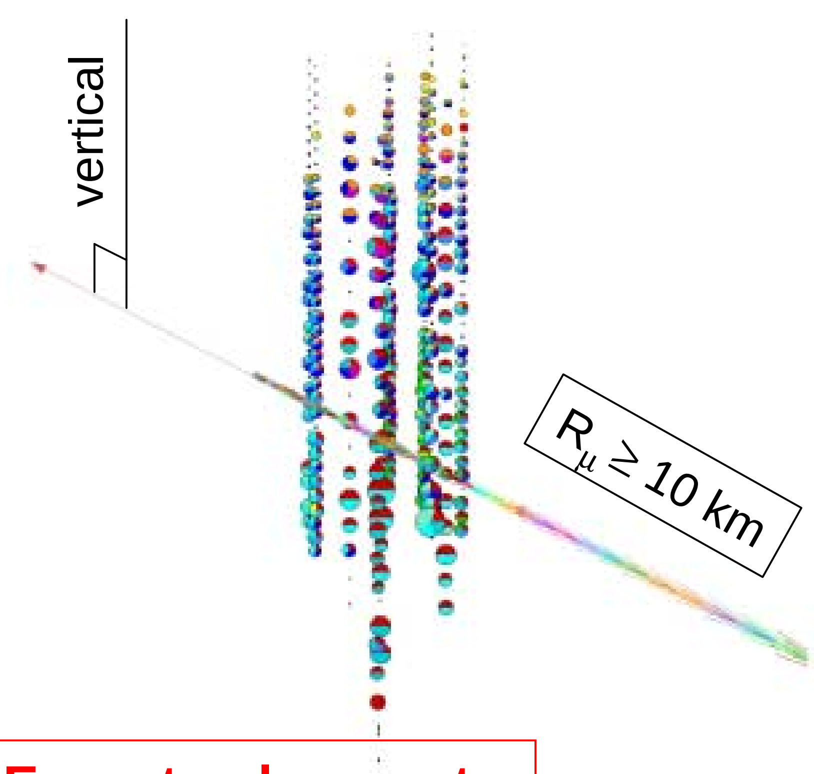
Downward-background at high energies is small.

PeV acceptance around horizon

EeV acceptance above horizon

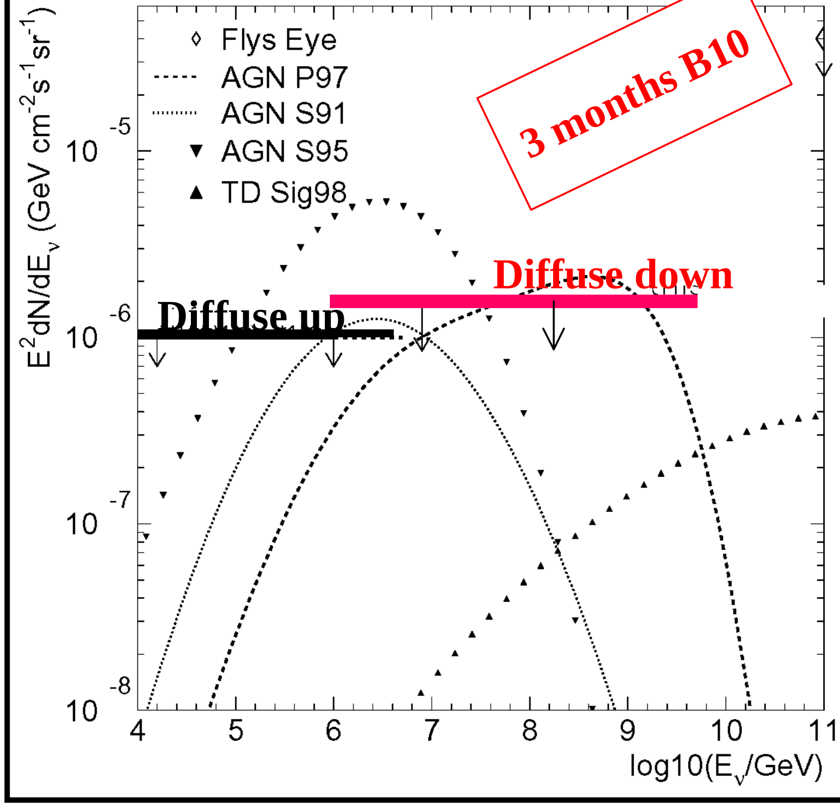
AMANDA 97 : EHE $(E \geq 10^{16}$ eV) Search

EHE events very bright; many PMTs detect multiple photons

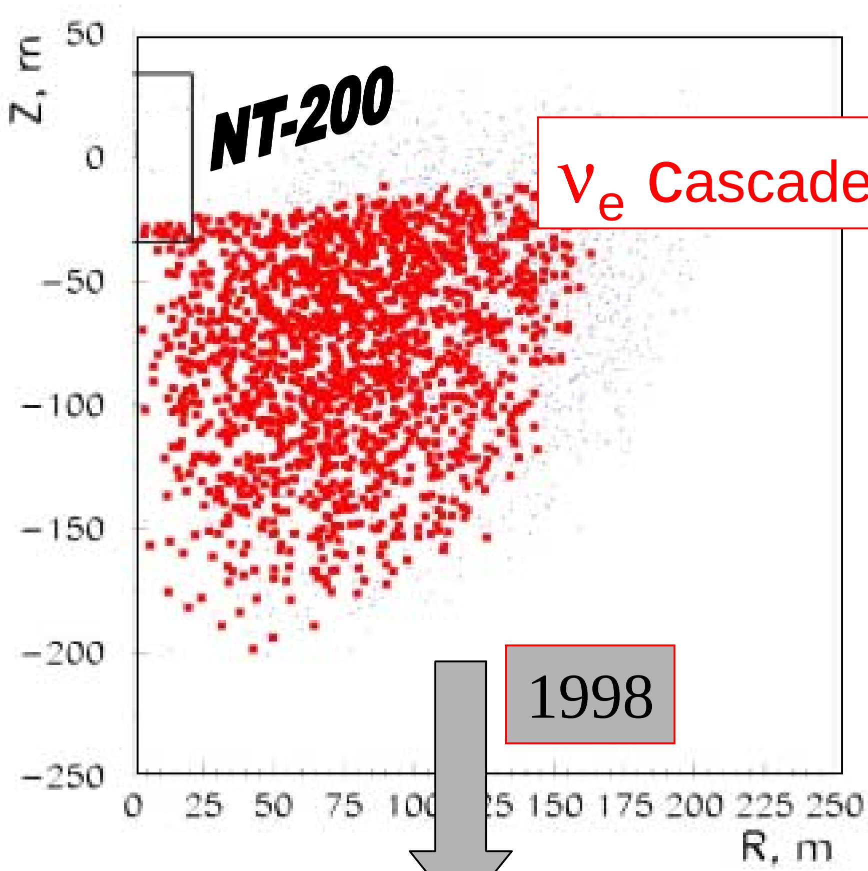


Expect only events near horizon

- Main background: muon "bundles"
- Comparable N_{PMT} but smaller amplitudes



... and Baikal



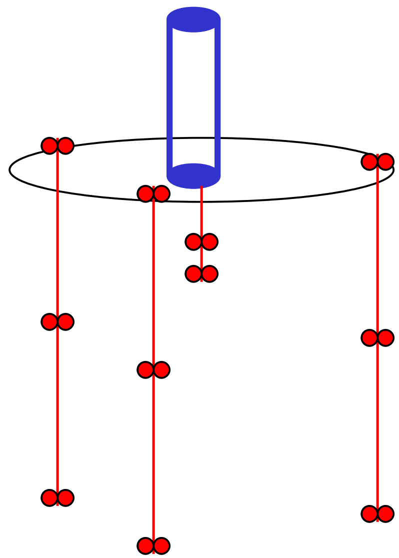
ν_e Cascades

1998

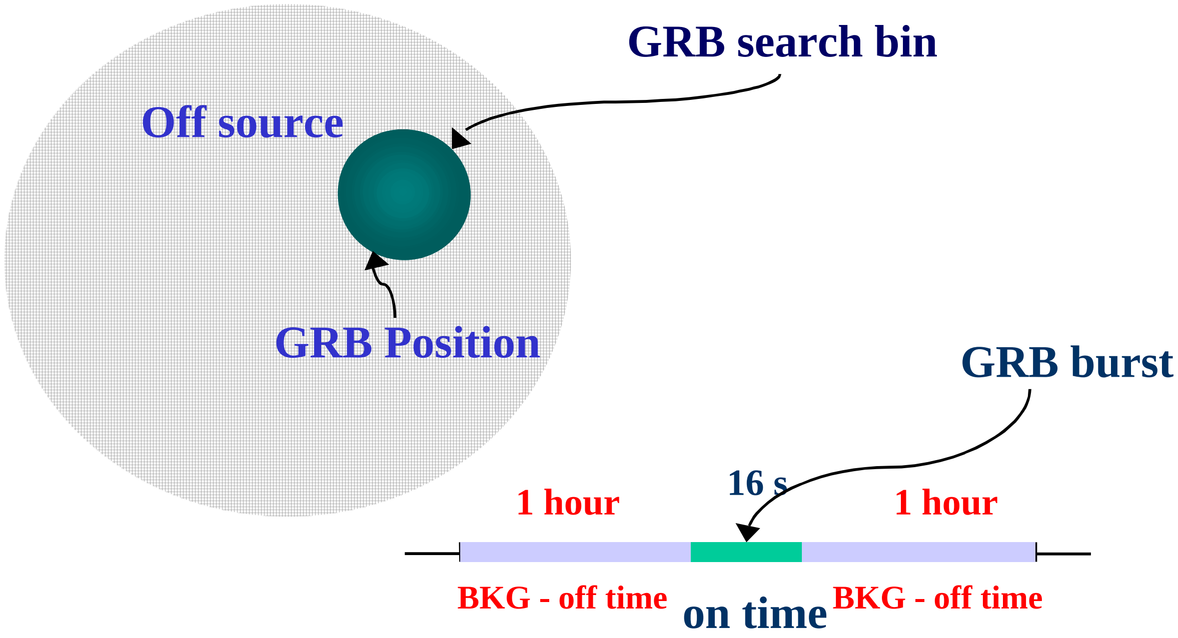
$\Phi \cdot E^2 < 1.9 \cdot 10^{-6}$ cm^{-2} s^{-1} sr^{-1} GeV

NT-200+

Upgrade with only 22 PMTs
→ factor 4 in sensitivity

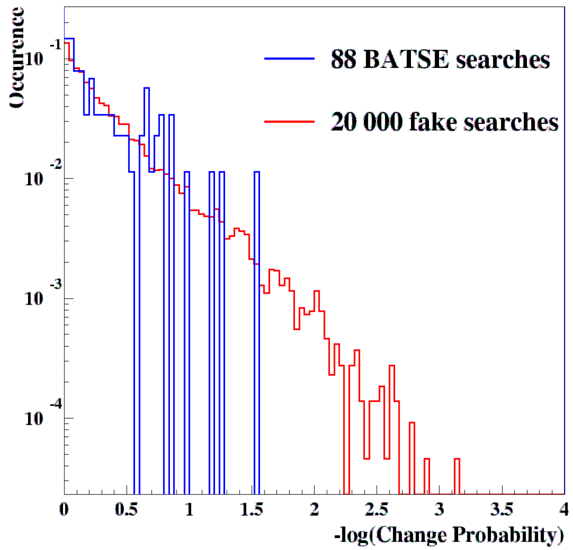


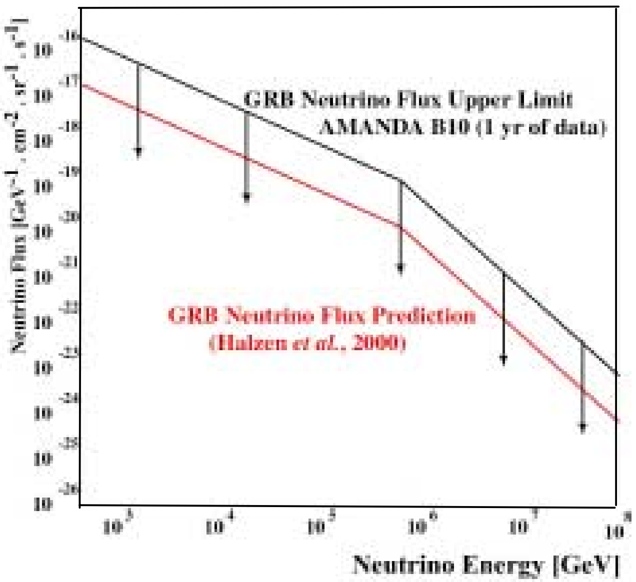
AMANDA: Correlations to GRB



Background cuts can be loosened considerably
$\rightarrow$ high signal efficiency

78
BATSE bursts
in 1997





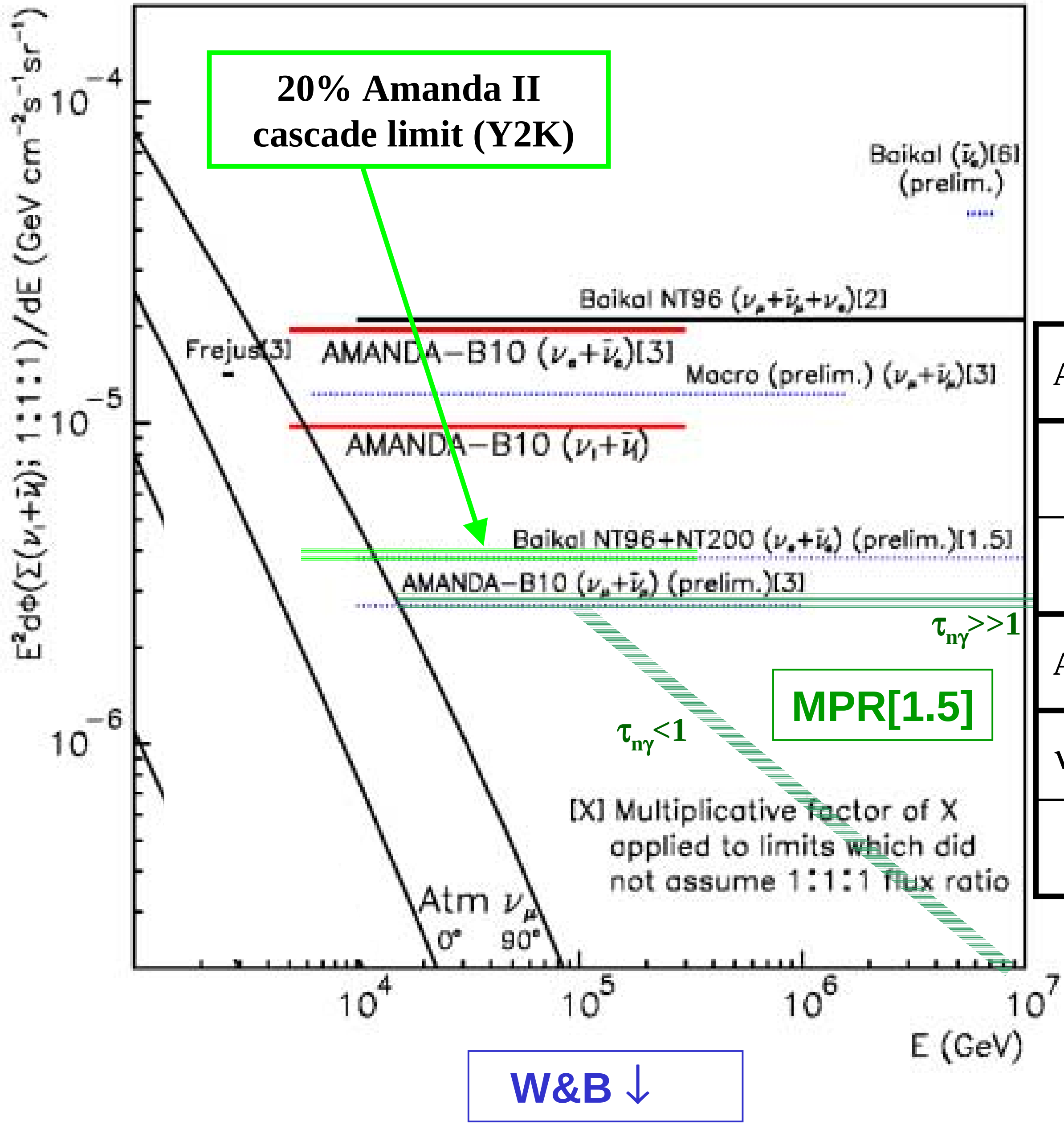
EM & Hadronic Showers: "Cascades"

- Motivations for searching for cascades:
  - oscillations: $\nu_\mu \rightarrow \nu_{e,\tau}$
  - better E_ν measurement
  - less cosmic-ray background
  - contained events give sensitivity over 4π
  - easier to calibrate
  - Glashow resonance
  - at E > 100 TeV, only ν_τ can penetrate the Earth

- Drawbacks:
  - effective volume smaller than for ν_μ
  - angular resolution worse than for tracks

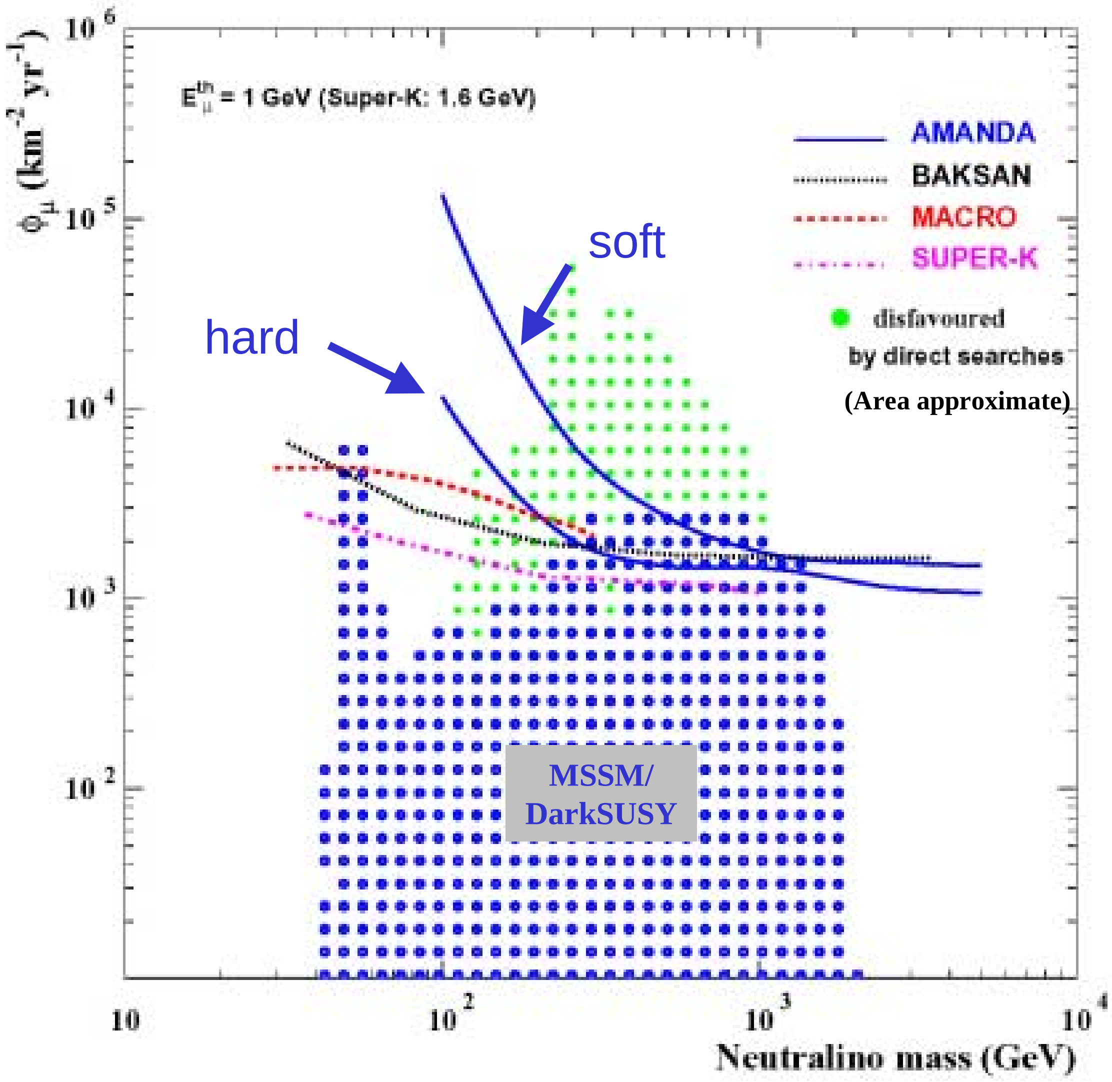
Analysis gets easier and more competitive with muons as detector grows in size.
Amanda-B $\rightarrow$ Amanda-II

Cascade limits

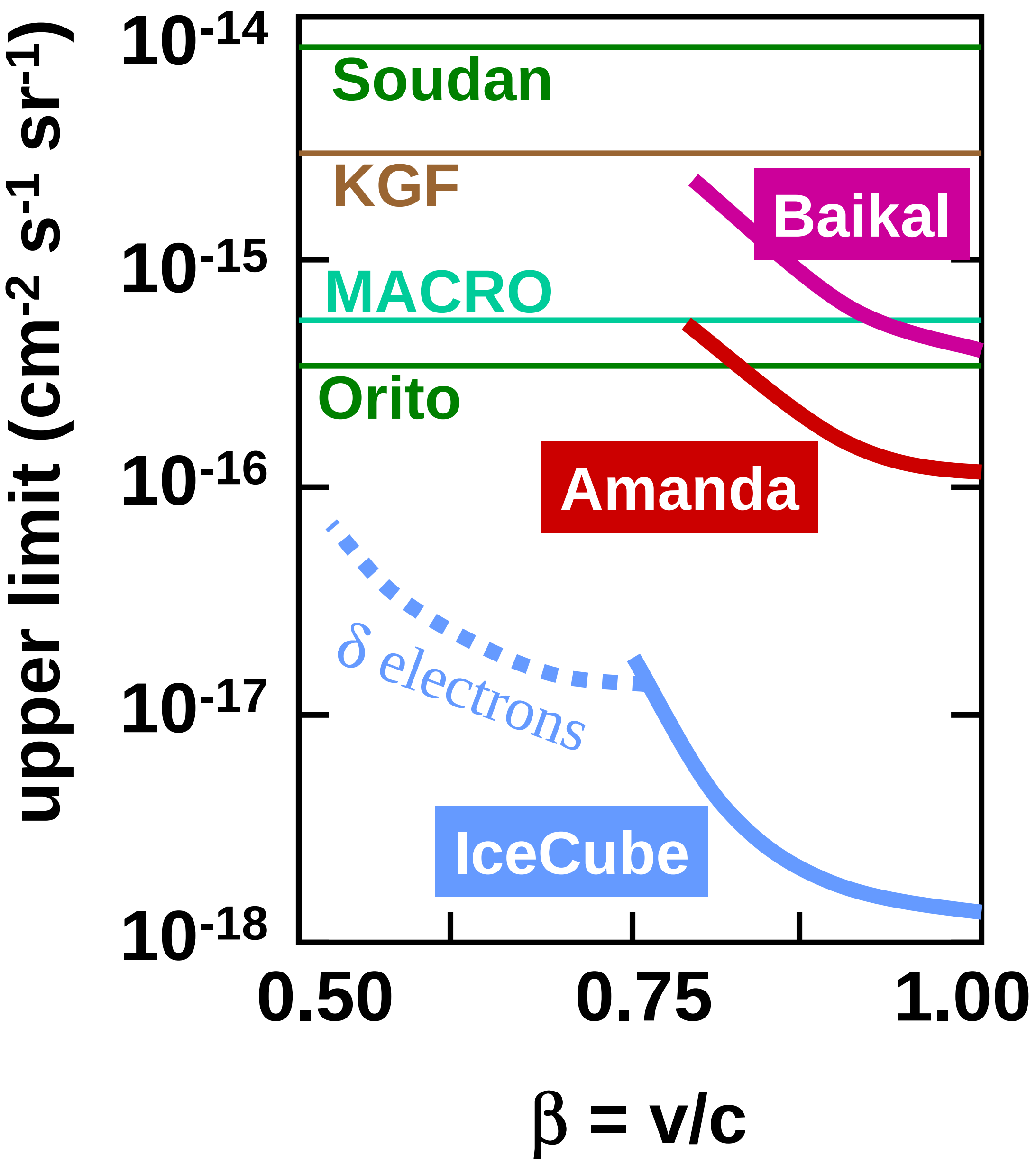


Astrophysical ν's	*Predicted* events in 100% of 2000 data
$\Phi_{\nu_e+\nu_e} = 10^{-6} E^{-2}$ GeV cm^{-2} s^{-1}	5.5
$\Phi_{\nu_\tau+\nu_\tau} = 10^{-6} E^{-2}$ GeV cm^{-2} s^{-1}	3.2
Atmospheric ν's	***Predicted* events in 100% of 2000 data**
ν_e (CC), $\nu_e+\nu_\mu$ (NC)	0.15
Prompt charm (RQPM)	0.50

WIMP Search



E_μ^{th} = 1 GeV (Super-K: 1.6 GeV)
AMANDA
BAKSAN
MACRO
SUPER-K
disfavoured
by direct searches
(Area approximate)
soft
hard
MSSM/
DarkSUSY
Φ_μ (km^{-2} yr^{-1})
Neutralino mass (GeV)
10^6
10^5
10^4
10^3
10^2
10
10^2
10^3
10^4



Relativistic Magnetic Monopoles

C - light output ∝ $n^2 \cdot (g/e)^2$

$n = 1.33$

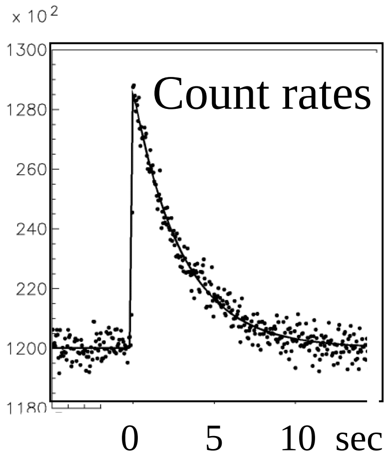
$(g/e) = {}^{137}/_{2}$

≈ 8300

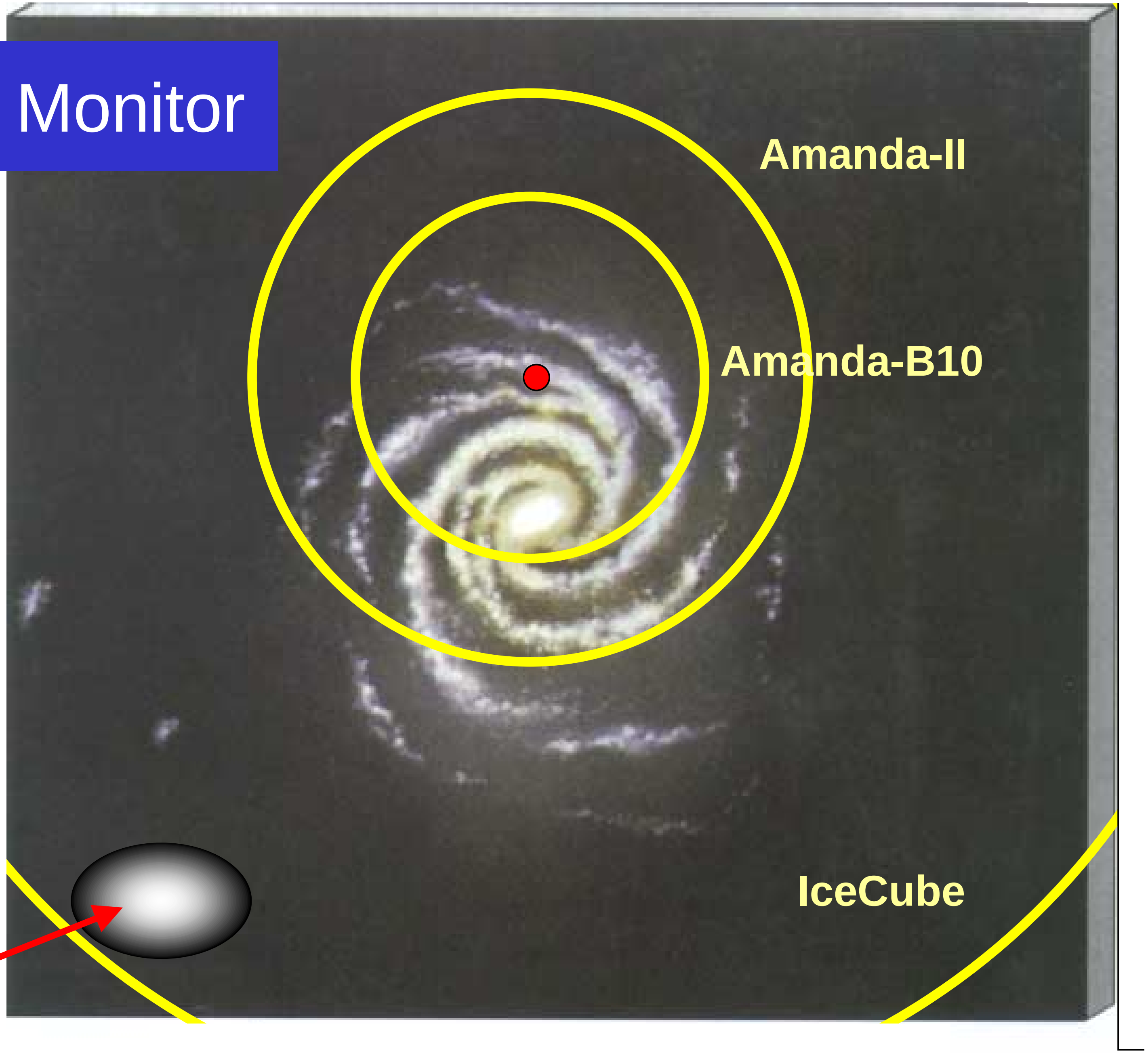
Supernova Monitor

B10:
60% of Galaxy

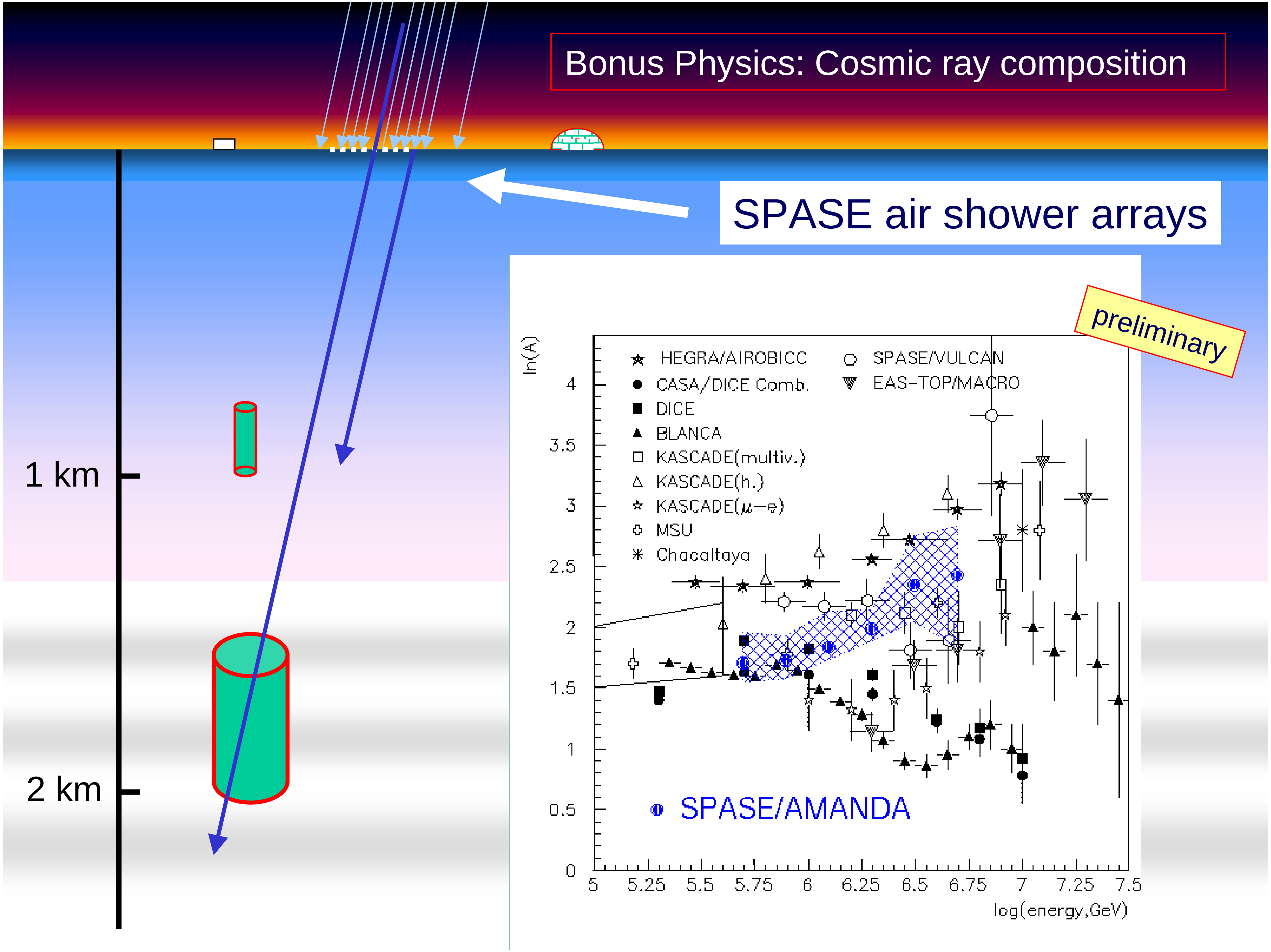
A-II:
95% of Galaxy



IceCube:
up to LMC

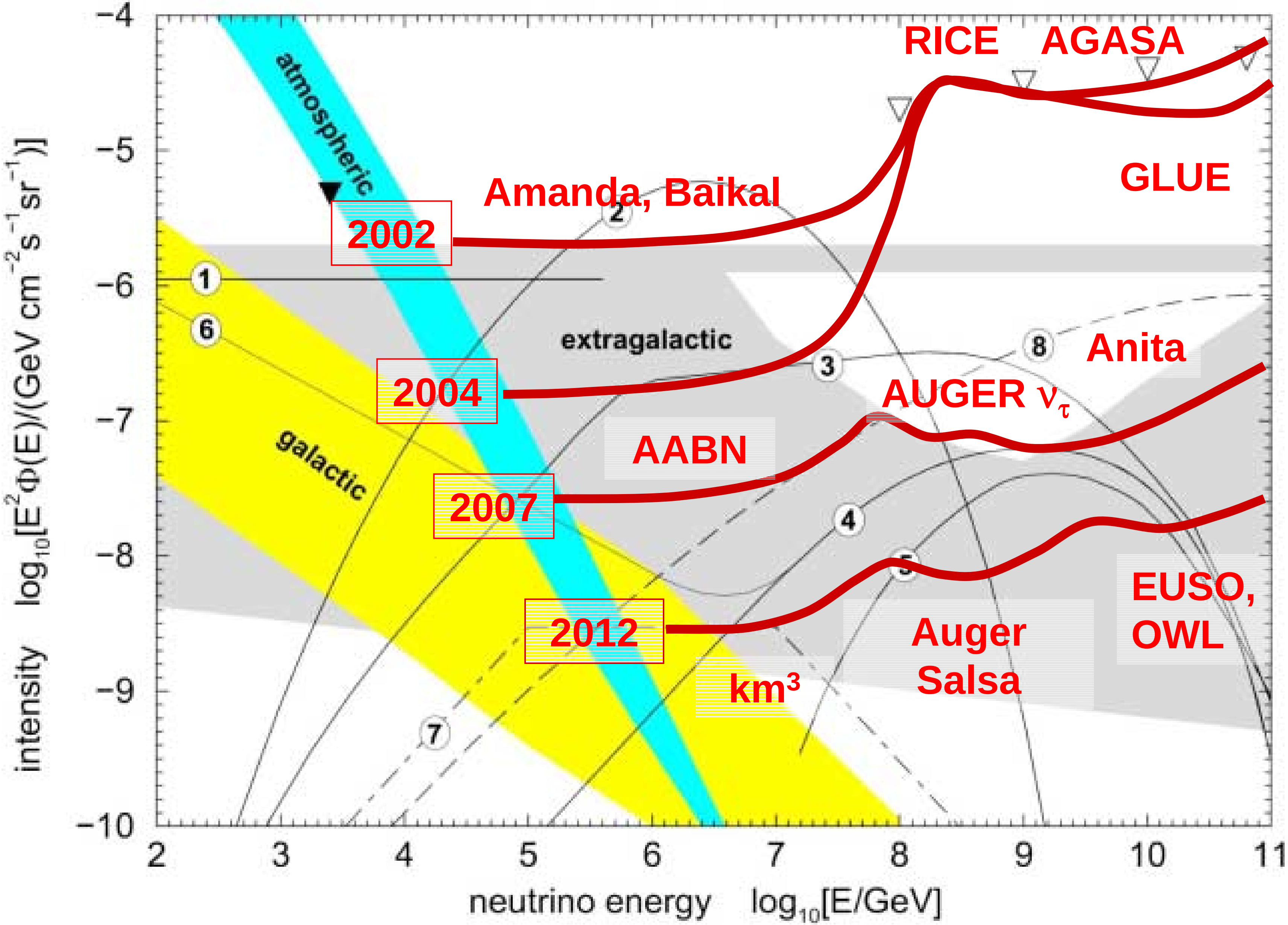


Bonus Physics: Cosmic ray composition



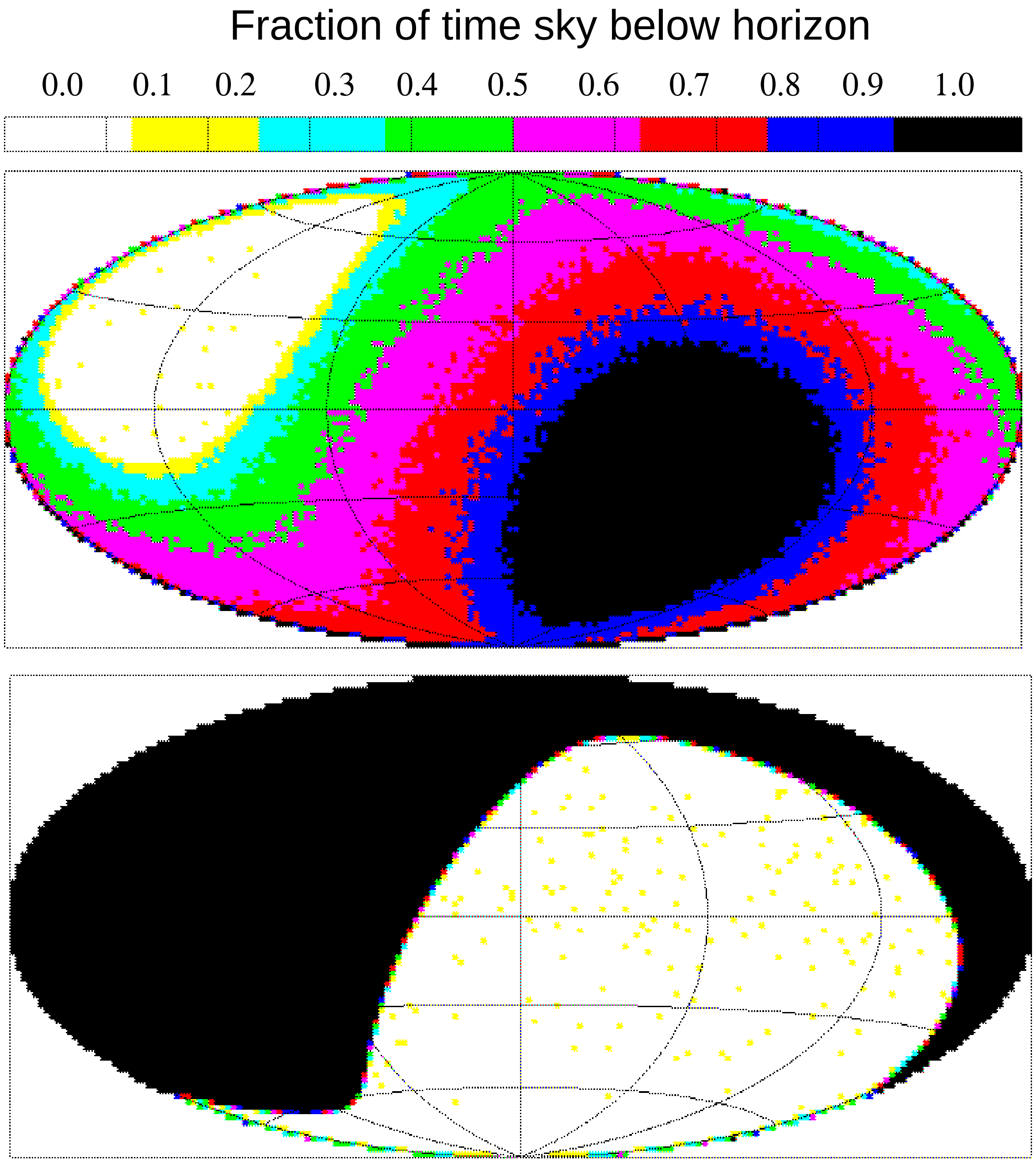
5.

The next decade



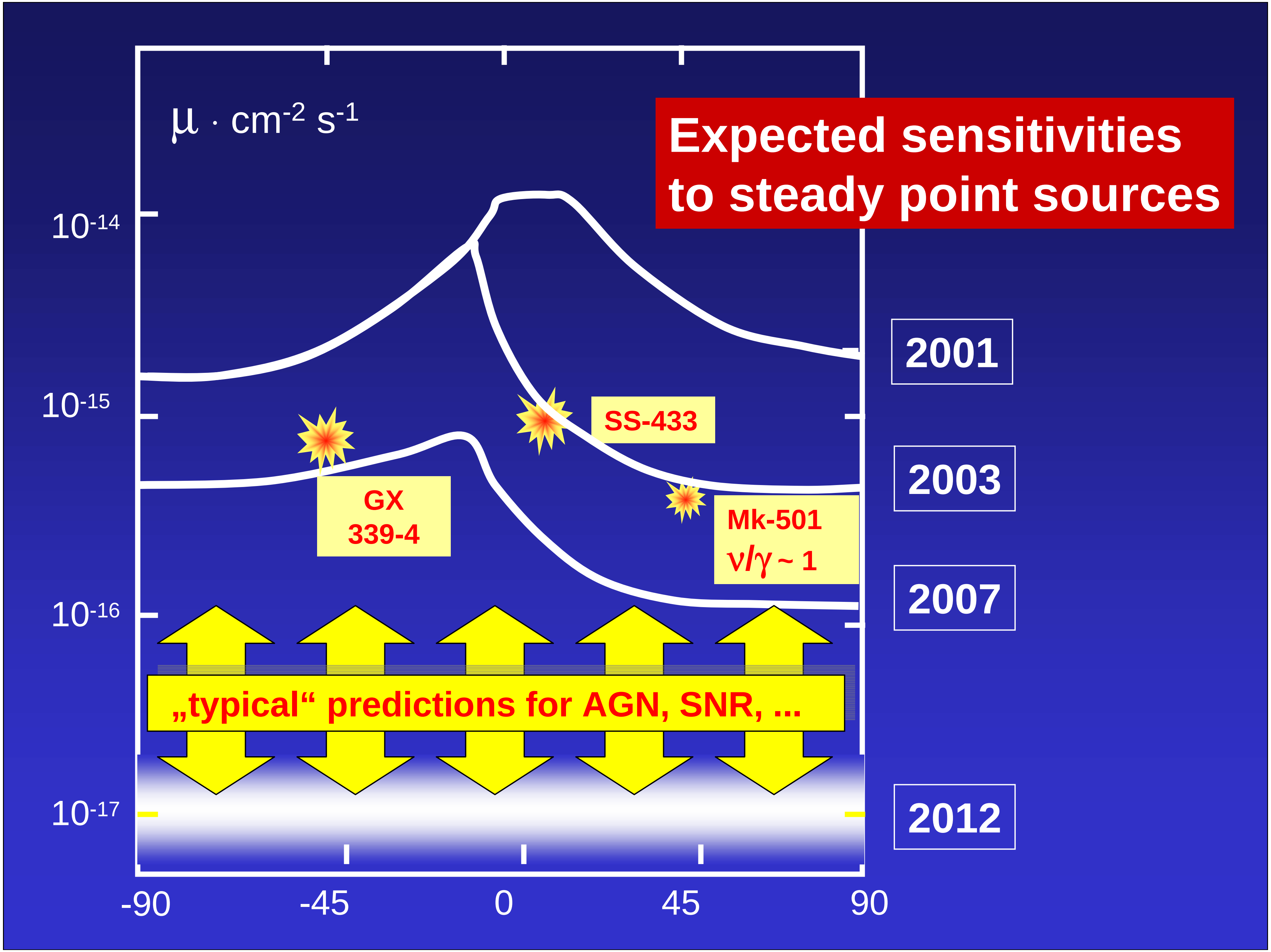
RICE
AGASA
GLUE
Amanda, Baikal
2002
atmospheric
extragalactic
Anita
AUGER ν_τ
2004
AABN
galactic
2007
EUSO,
OWL
2012
Auger
Salsa
km³
1
2
3
4
5
6
7
8
−4
−5
−6
−7
−8
−9
−10
2
3
4
5
6
7
8
9
10
11
intensity $\log_{10}[E^2\Phi(E)/(\mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}})]$
neutrino energy $\log_{10}[E/\mathrm{GeV}]$

Point sources: detector South + detector North



Mediterannean

South Pole


Expected sensitivities
to steady point sources
μ · cm-2 s-1
10-14
10-15
10-16
10-17
SS-433
GX
339-4
Mk-501
ν/γ ~ 1
„typical“ predictions for AGN, SNR, ...
2001
2003
2007
2012
-90
-45
0
45
90

We are close to some predictions !

Most promising: point sources

0.1 km² and 1 km² detectors underwater and ice

Huge step in GZK region

Exciting decade ahead