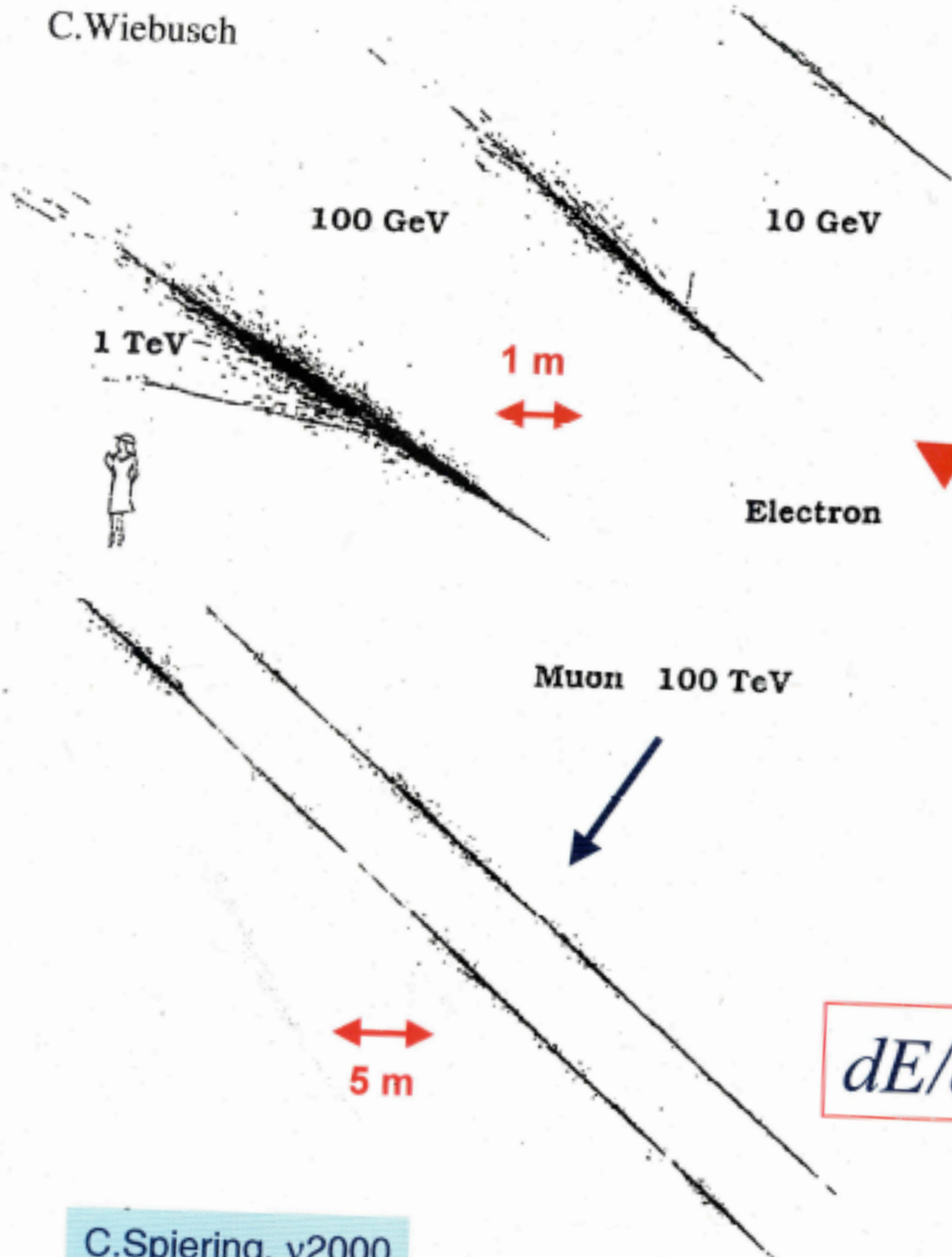
other science

Tracks and Cascades



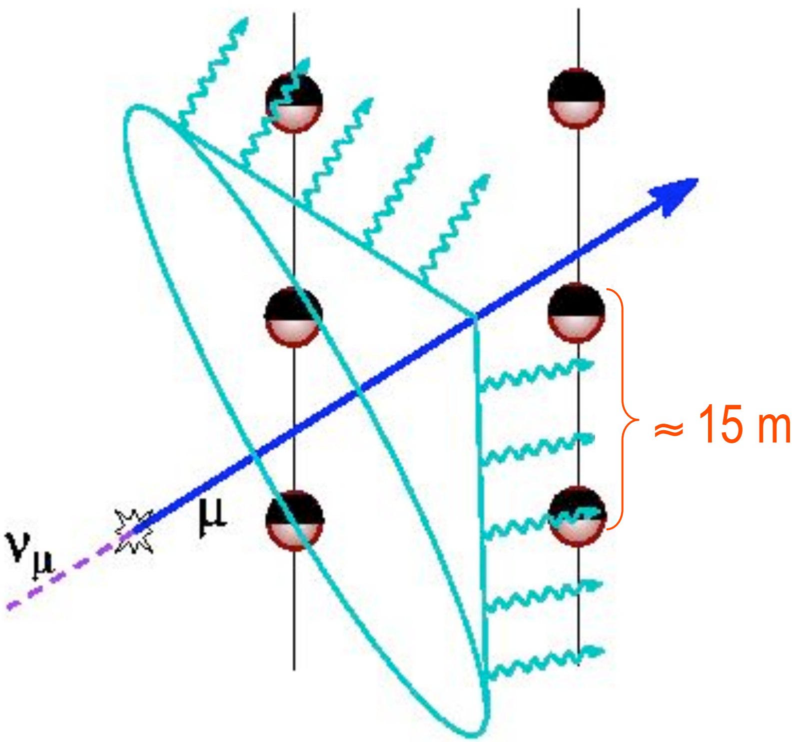
$$L_{shower} \propto \ln E_e$$

$$dE/dx \propto a + b \cdot E_\mu$$

C.Spiering, v2000

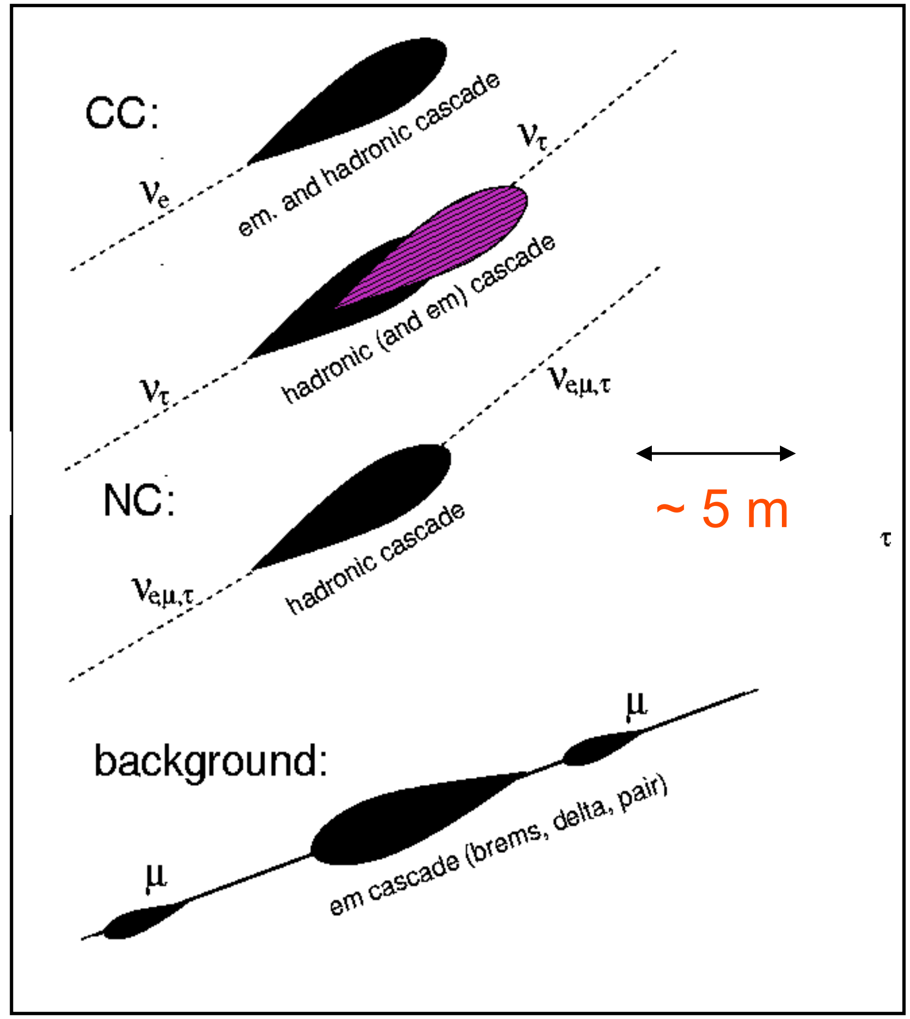
Detection of ν_e, ν_μ, ν_τ

O(km) long muon tracks

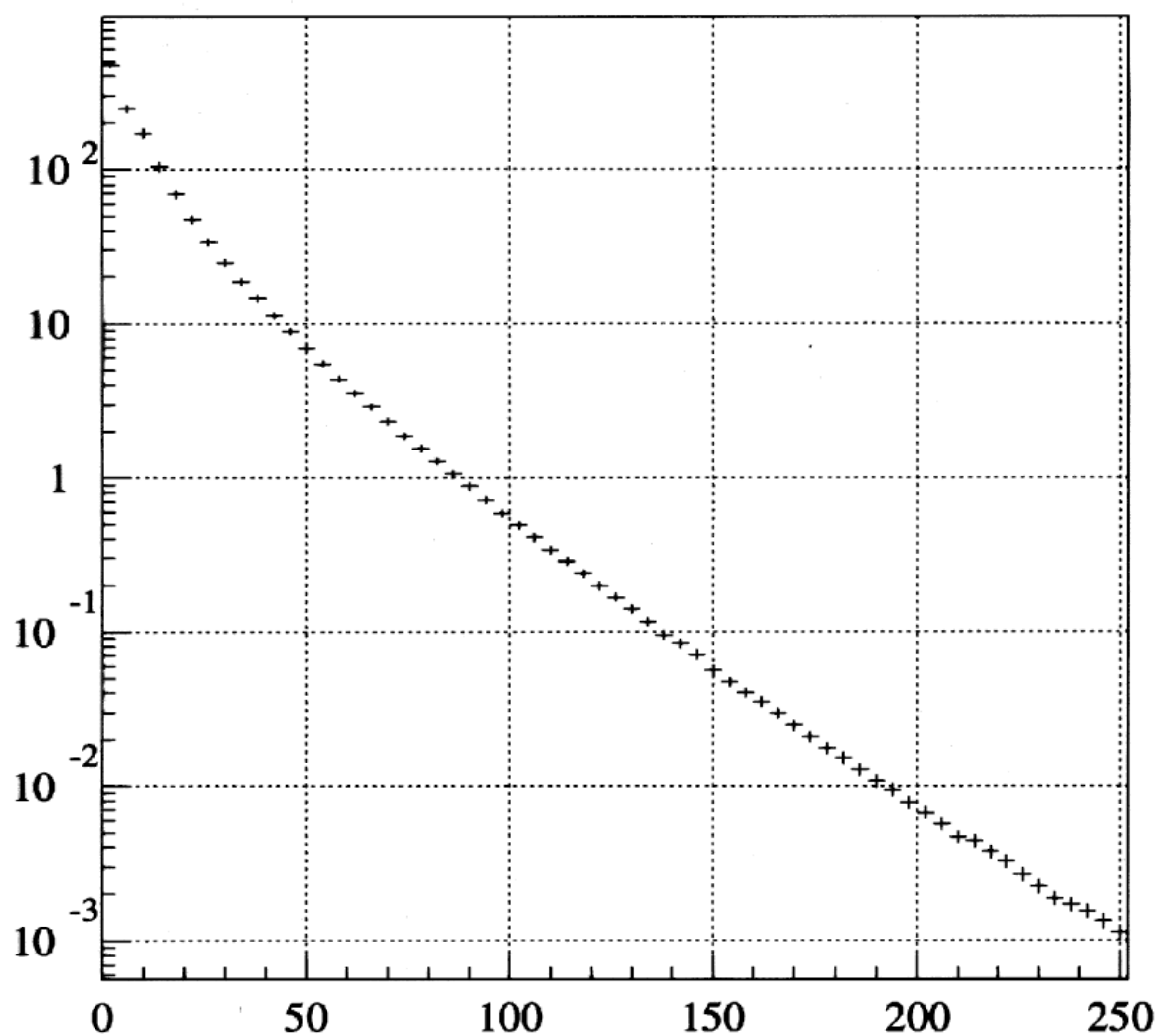


direction determination
by cherenkov light timing

Electromagnetic and hadronic cascades



1 TeV e.m. cascade - PE vs distance

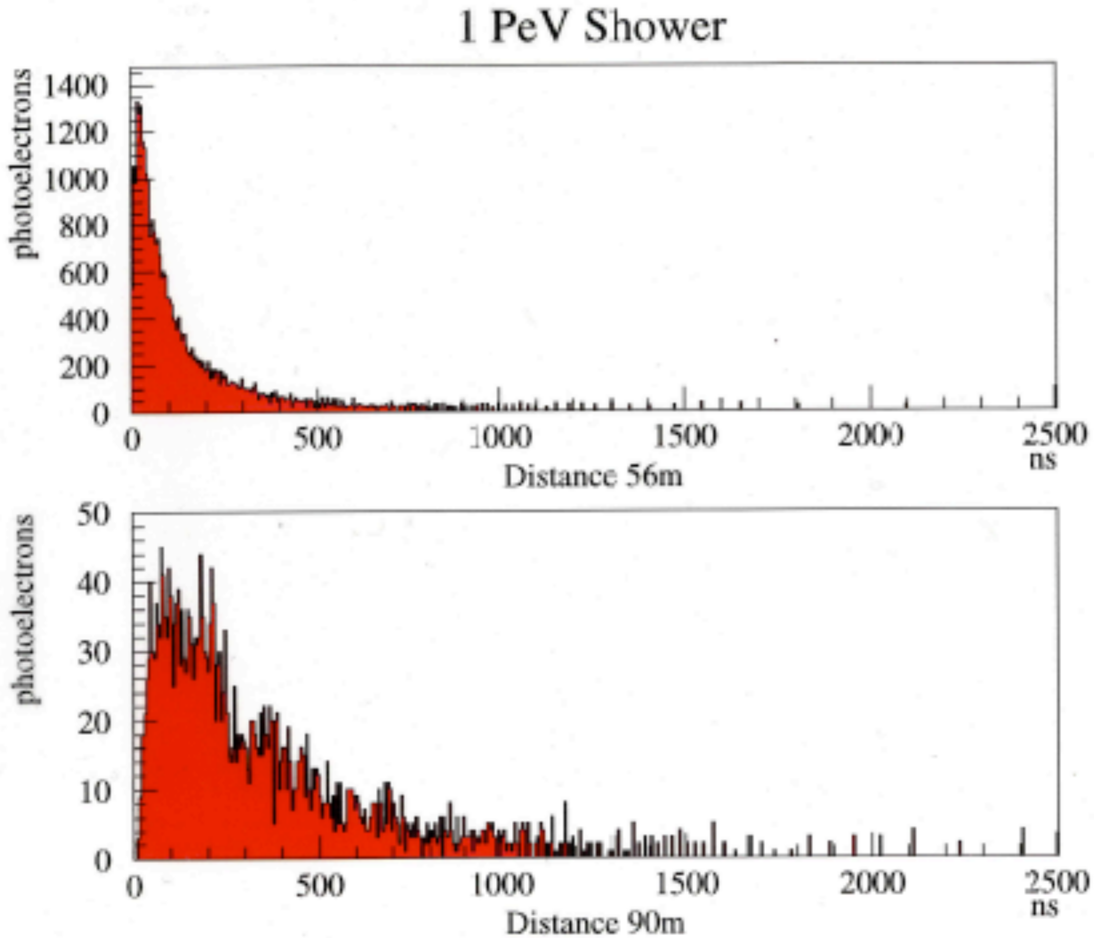


High Energy Cascades
100 TeV and beyond

Trigger volume for electromagnetic cascades

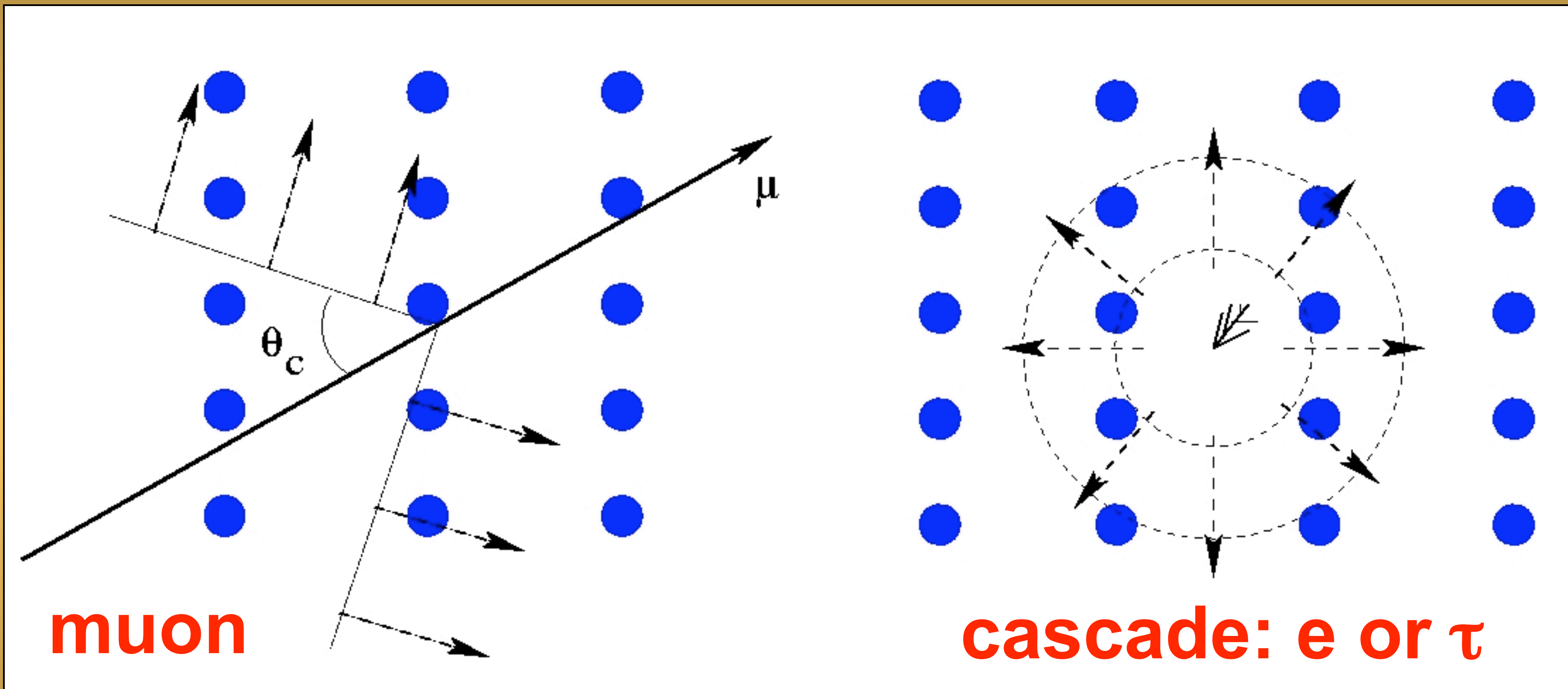
Energy	1PE radius	1PE Volume	Full MC: Trigger Volume	
(TeV)	(m)	(10^6 m^3)	(10^6 m^3) ≥16	(10^6 m^3) ≥80
0.1	44	0.35	3.6	
1	83	2.4	19	
10	133	9.8	45	
100	190	28	82	30
1000	255	69		
10000	310	124	>200	

AMANDA-B10: V_{casc}(1 PeV, 80 hits) ≈ 0.1 KM3 photoelectrons



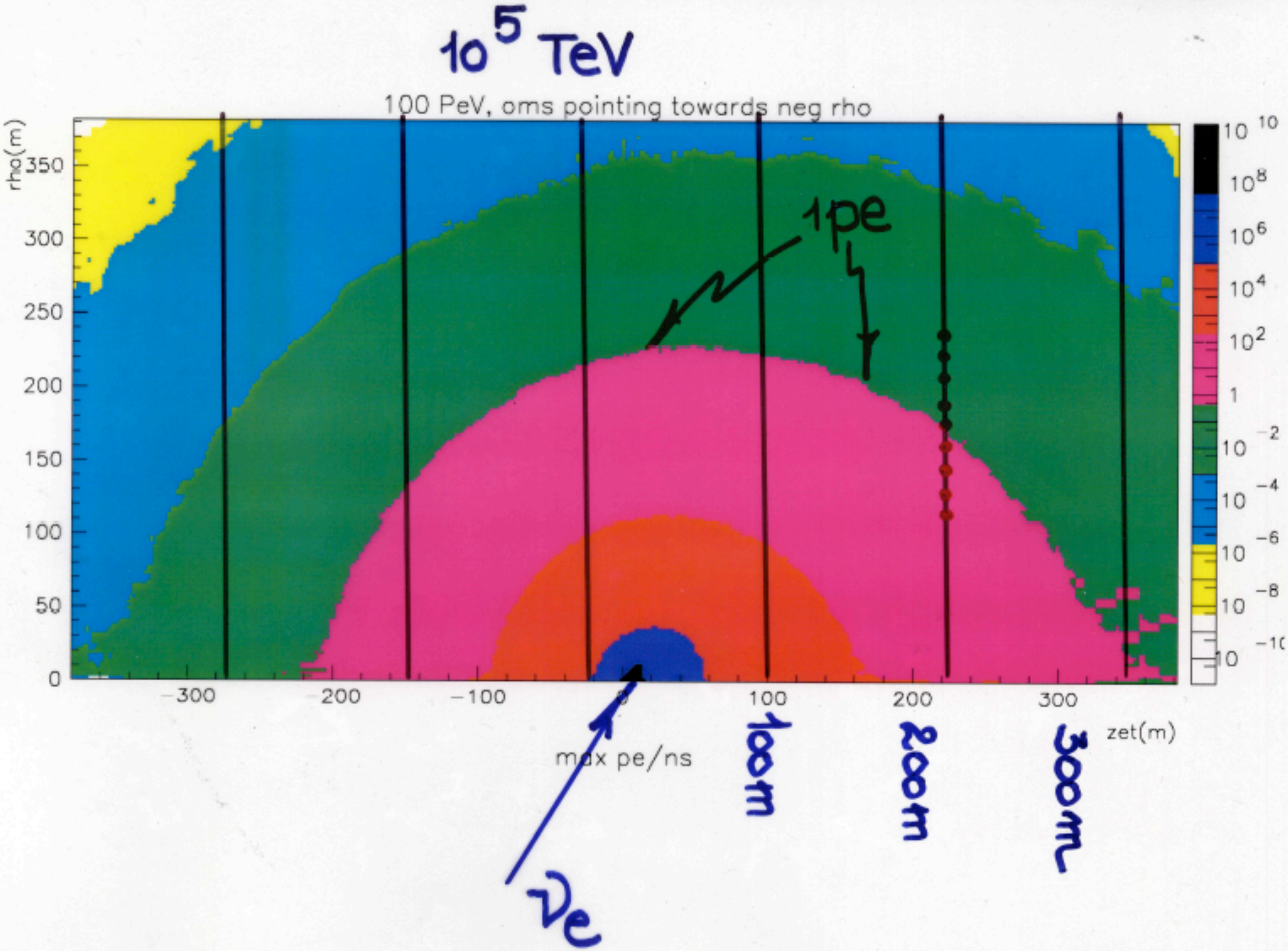
time delay (nsec)

Cherenkov light from muons and cascades



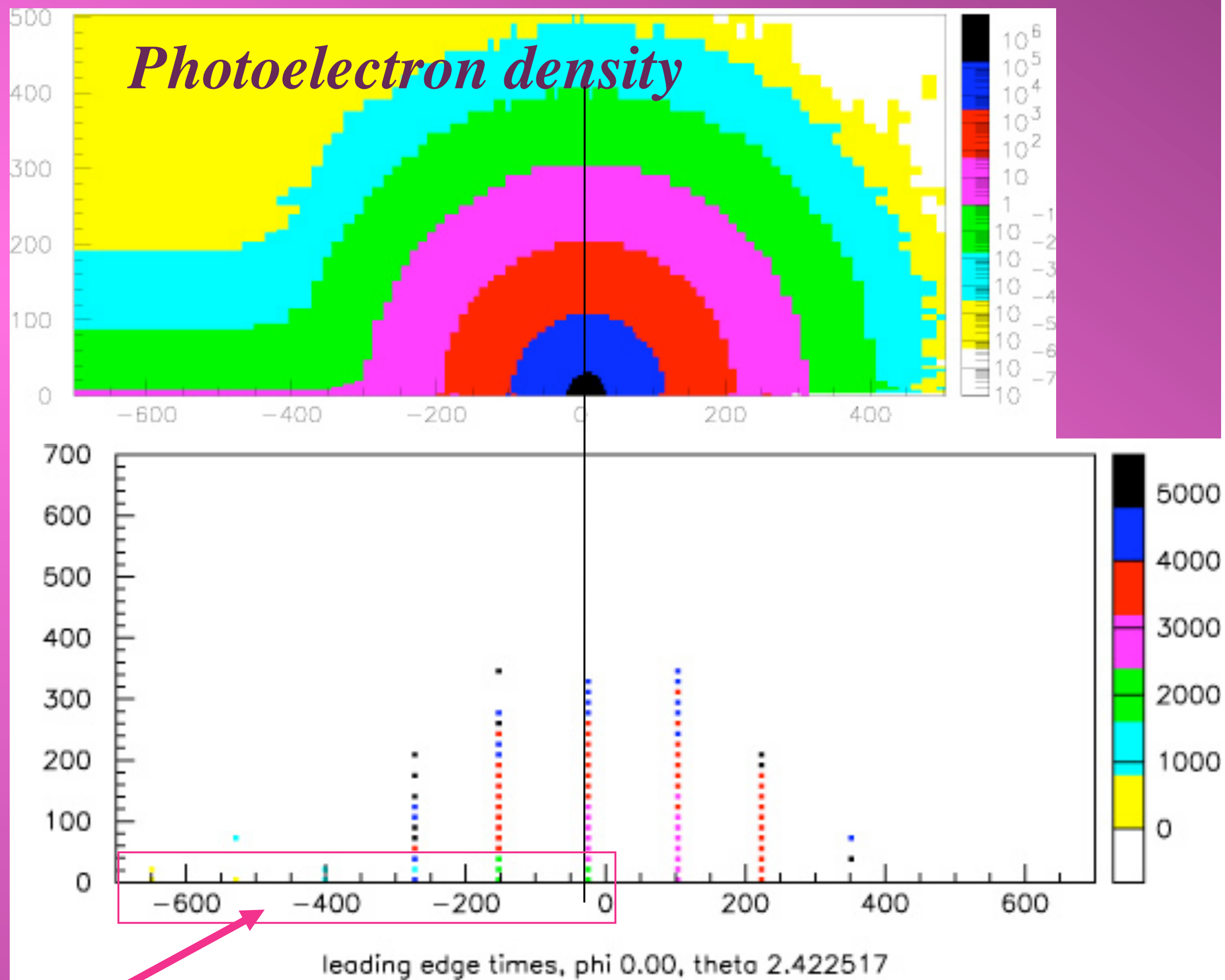
Reconstruction

- Maximum likelihood method
- Use expected time profiles of photon flight times


10^5 TeV
100 PeV, oms pointing towards neg rho
rho(m)
350
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
zet(m)
max pe/ns
1pe
100m
200m
300m
νe
10^10
10^8
10^6
10^4
10^2
1
10^-2
10^-4
10^-6
10^-8

ν_τ at E > PeV: Partially contained

- The incoming tau radiates little light.
- The energy of the second cascade can be measured with high precision.
- Signature: Relatively low energy loss incoming track: would be much brighter than the tau (compare to the PeV muon event shown before)



Result: high effective Volume, only second bang needs to be seen in Ice3

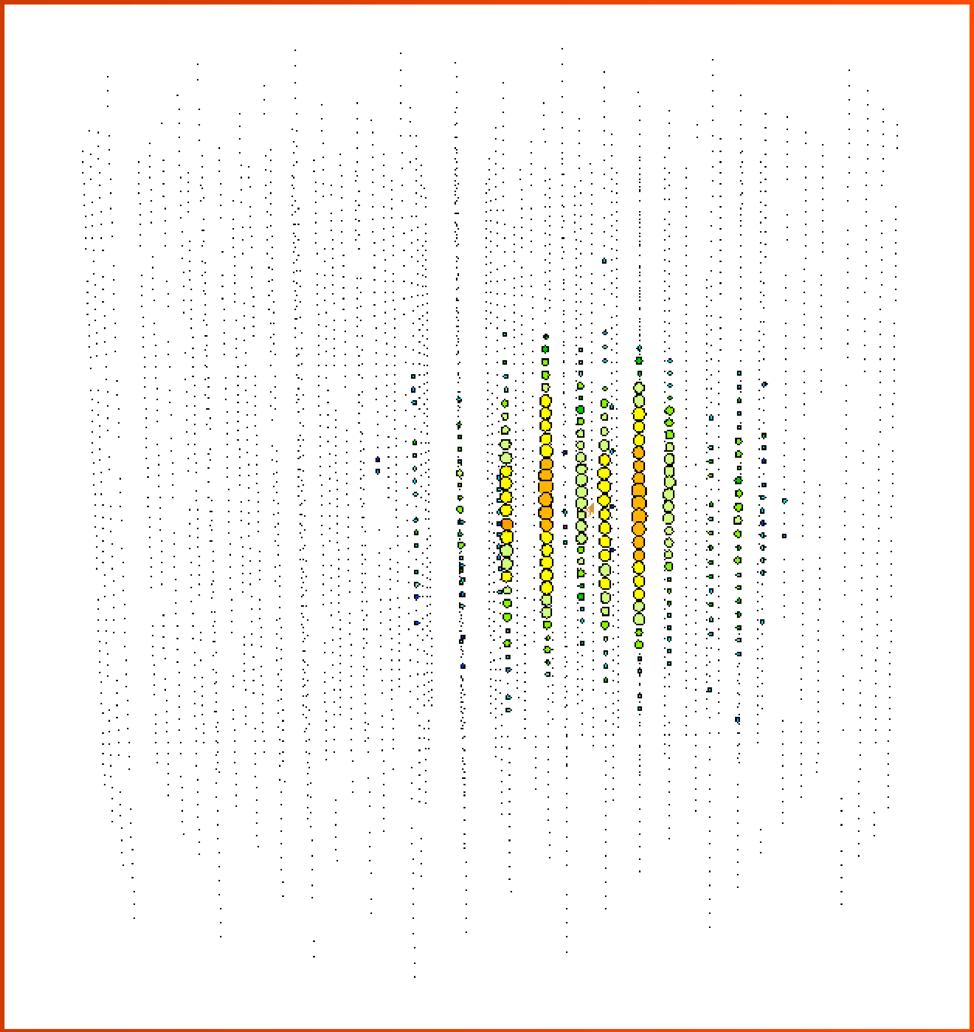
10-20 OM early hits measuring the incoming τ-track

Cascade event

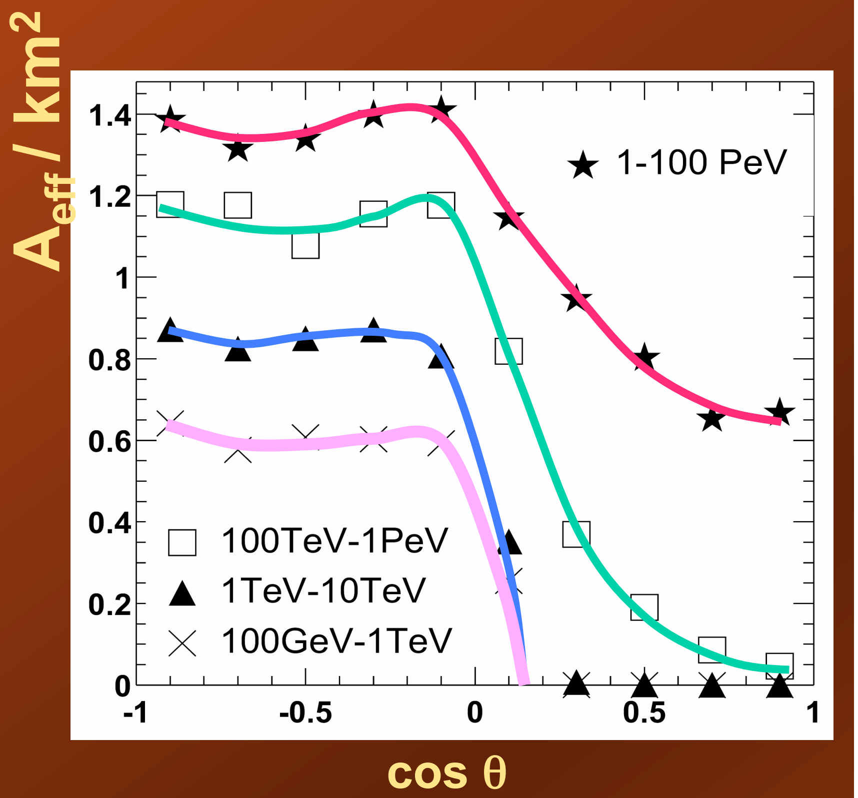
• the length of the e^- cascade is small compared to the spacing of sensors.
• roughly spherical density distribution of light.
• 1 PeV ≈ 500 m diameter, additional 100 m per decade of energy
• linear energy resolution

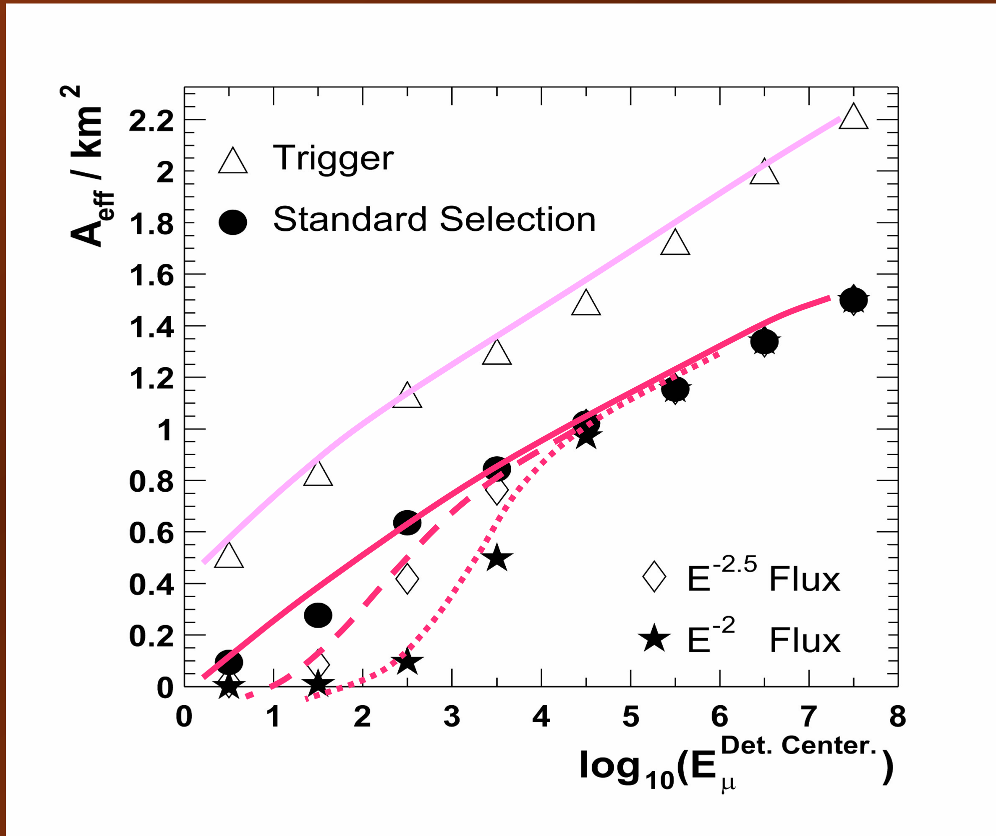
ν_e + N --> e- + X

Energy = 375 TeV



Effective area of IceCube

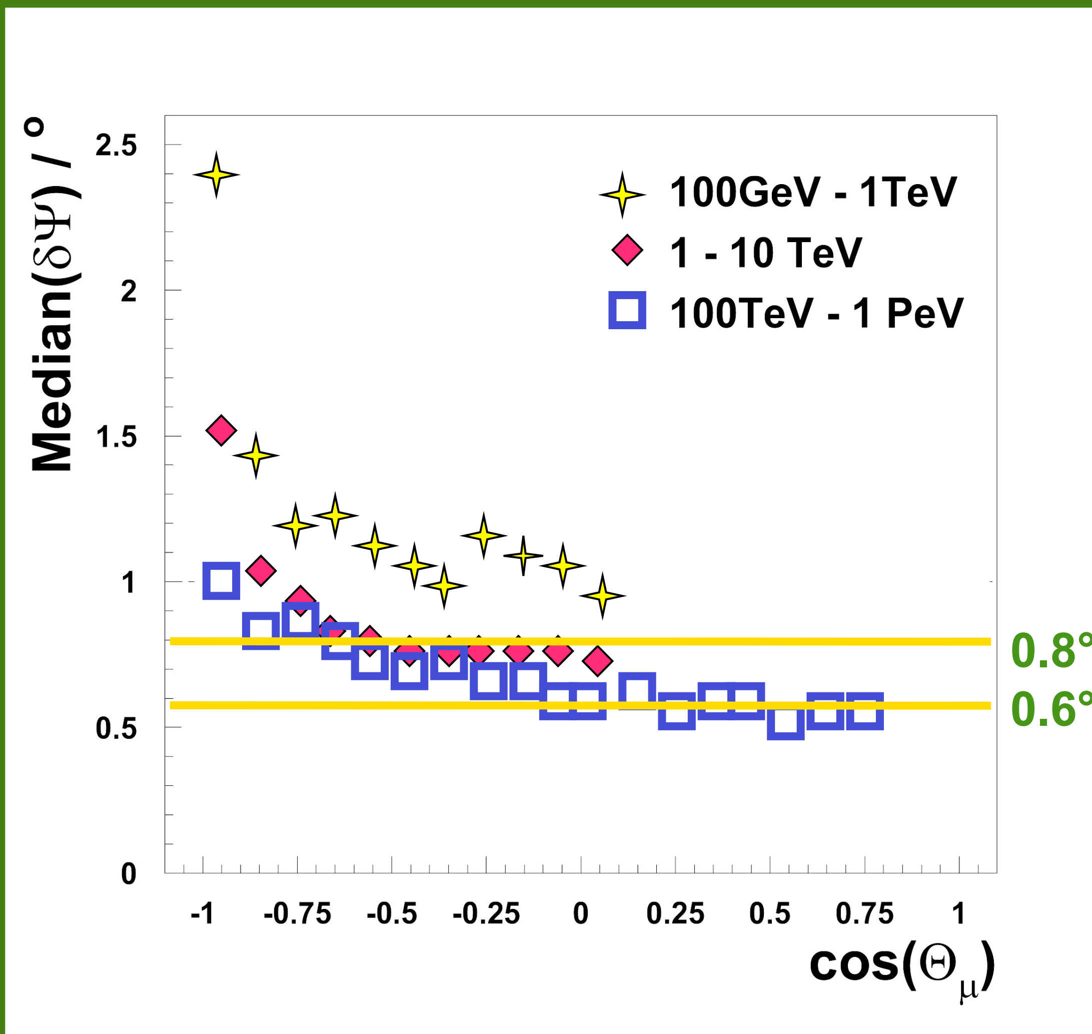




Effective area vs. zenith angle (downgoing muons rejected)

Effective area vs. muon energy (trigger, atm μ, pointing cuts)

angular resolution as a function of zenith angle

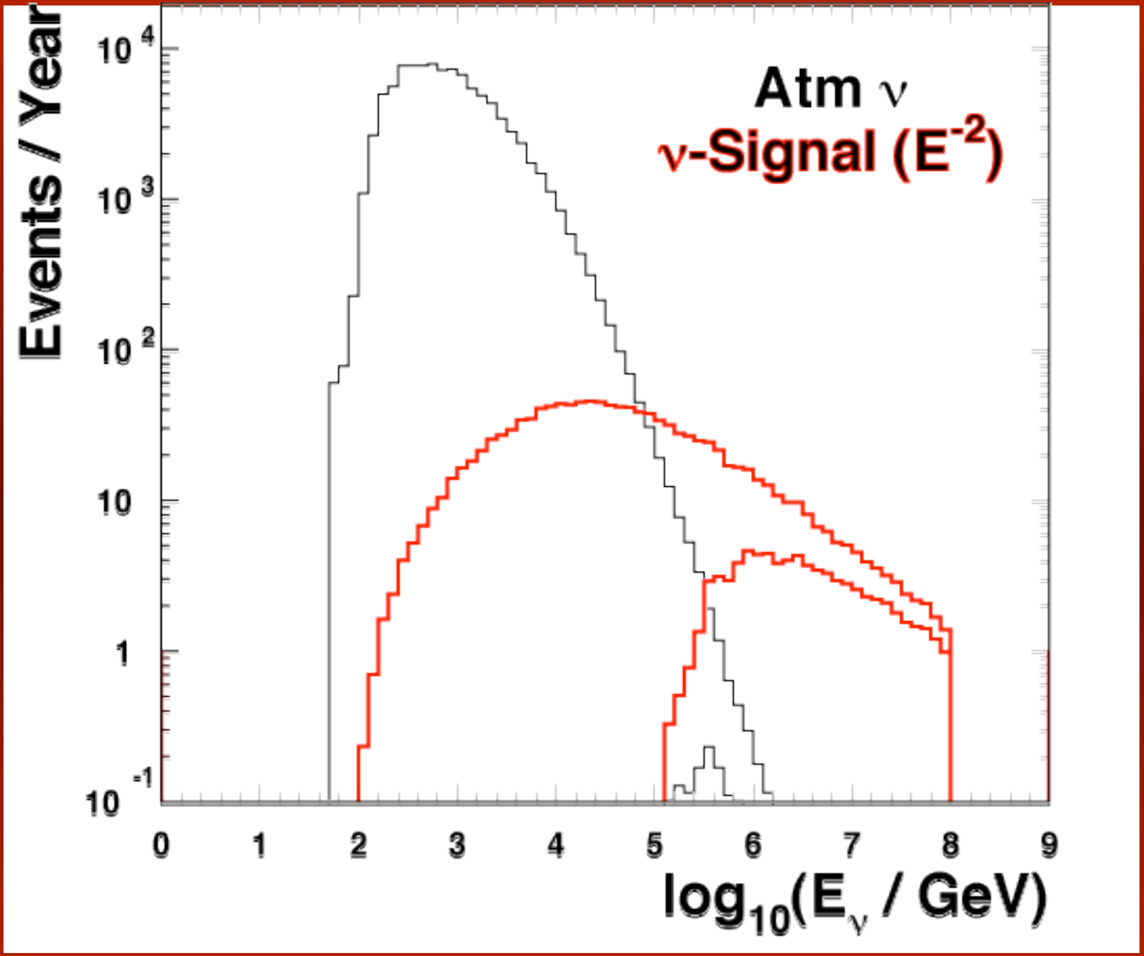


Waveform information not used. Will improve resolution for high energies !

→ above 1 TeV, resolution ~ 0.6 - 0.8 degrees for most zenith angles

event rates before and after energy cut

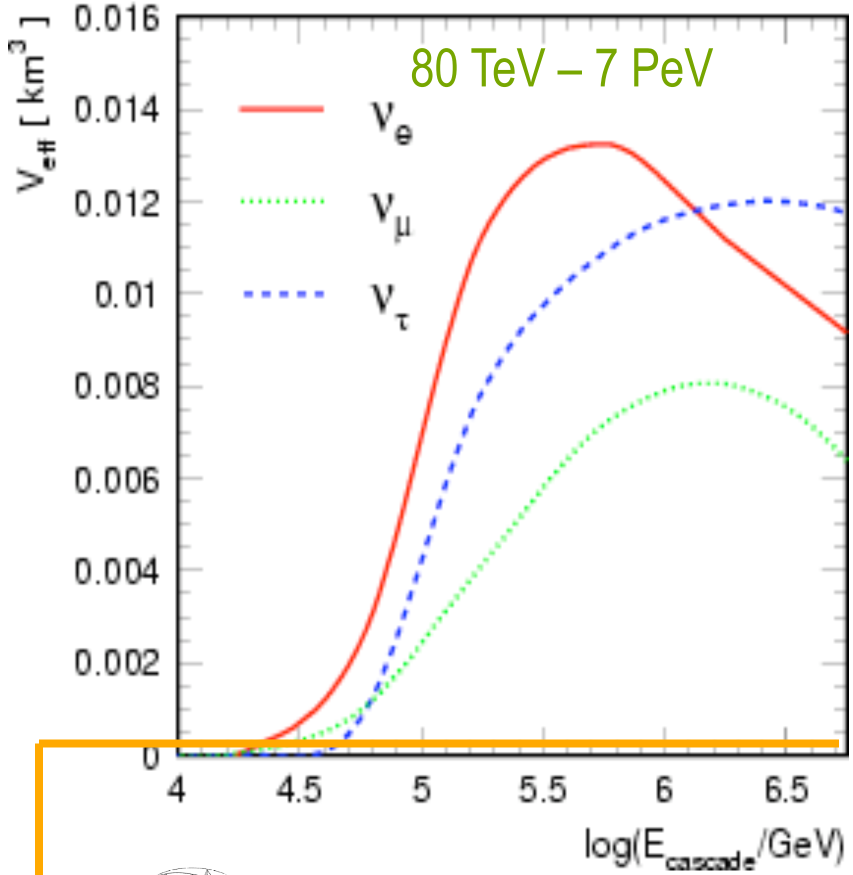
Events per year at the ultimate AMANDA sensitivity

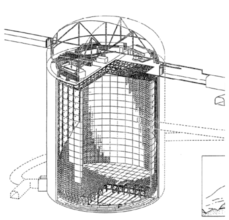


Note: 300,000 atmospheric neutrinos per year (TeV range)

diffuse limit cascades

Effective volume





- For $E^2\Phi(E) = 10^{-6}$ GeV cm^{-2}s^{-1}sr^{-1} flux would expect:

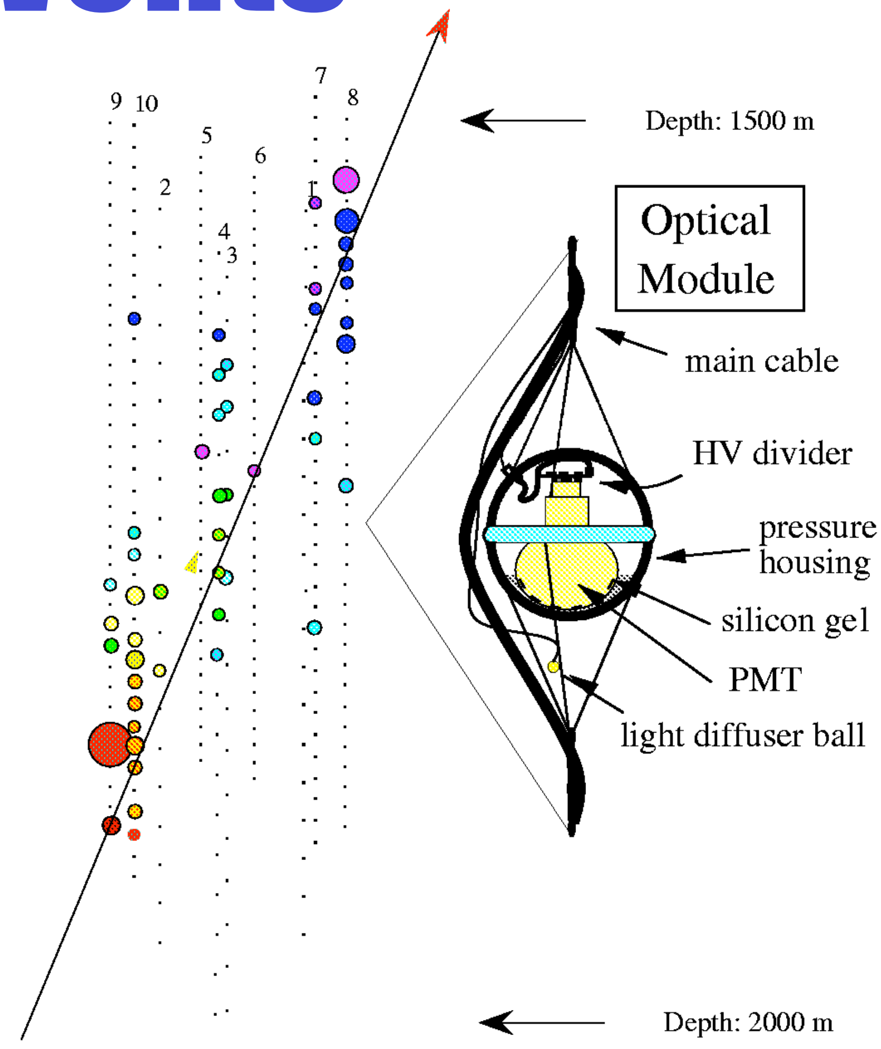
  9.3 ν_e , 6.2 ν_μ , 8.0 ν_τ events

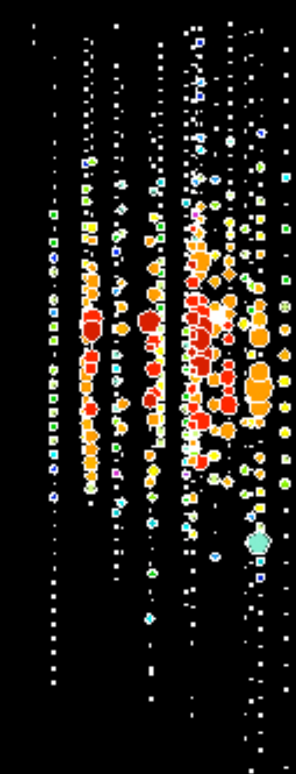
2 candidate events total observed

90% CL limit, assuming ν_e:ν_μ:ν_τ=1:1:1

$E^2\Phi_{all\ \nu}$ (E) < $9 \cdot 10^{-7}$ GeV cm^{-2}s^{-1}sr^{-1}

Two Events

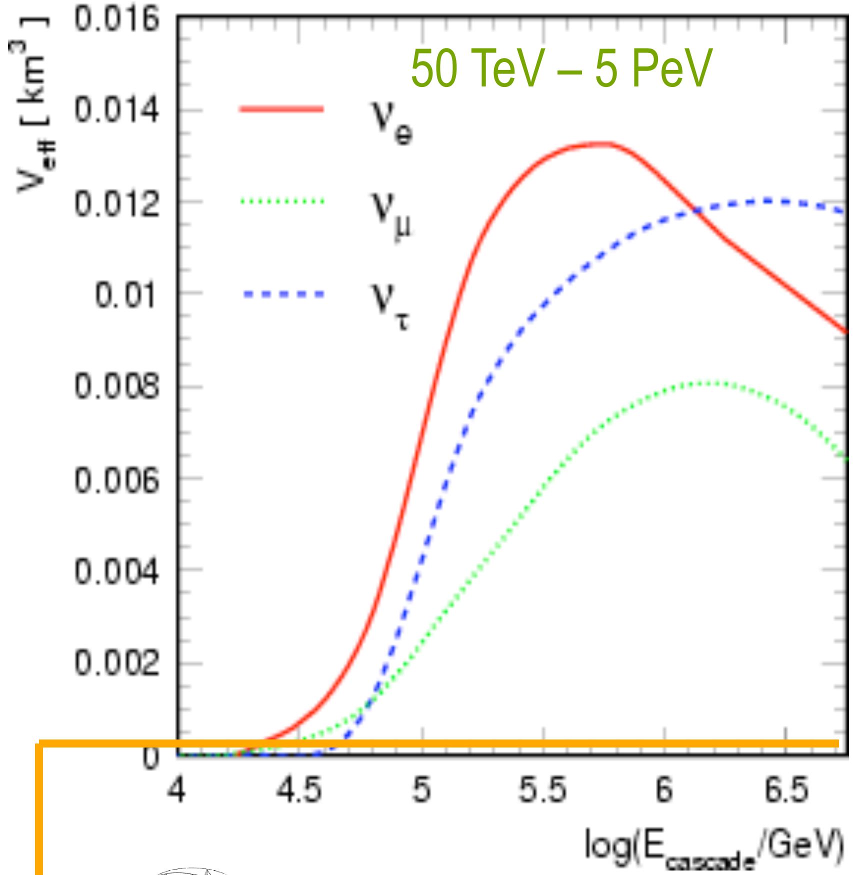


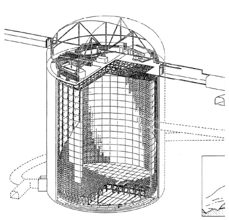


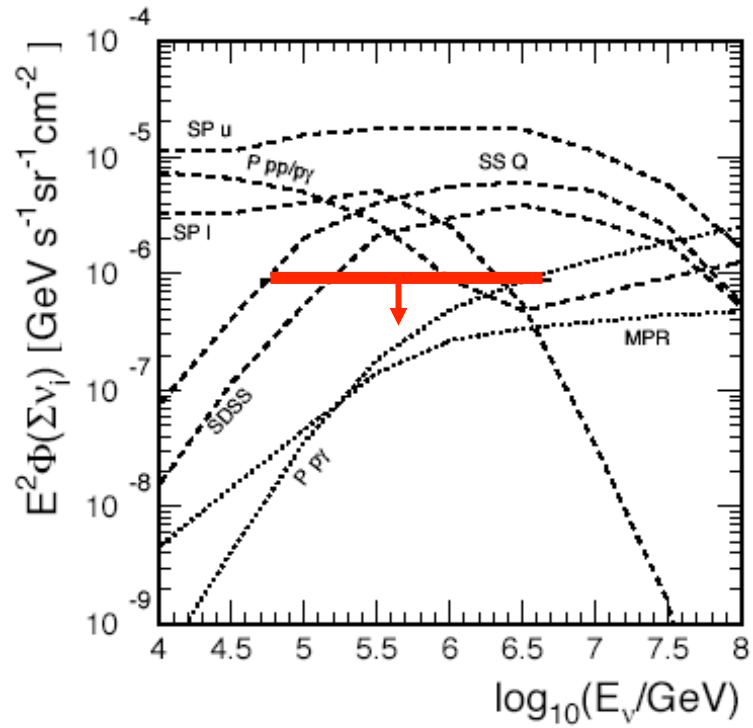
200 TeV ν_e

Diffuse limit cascades

Effective volume





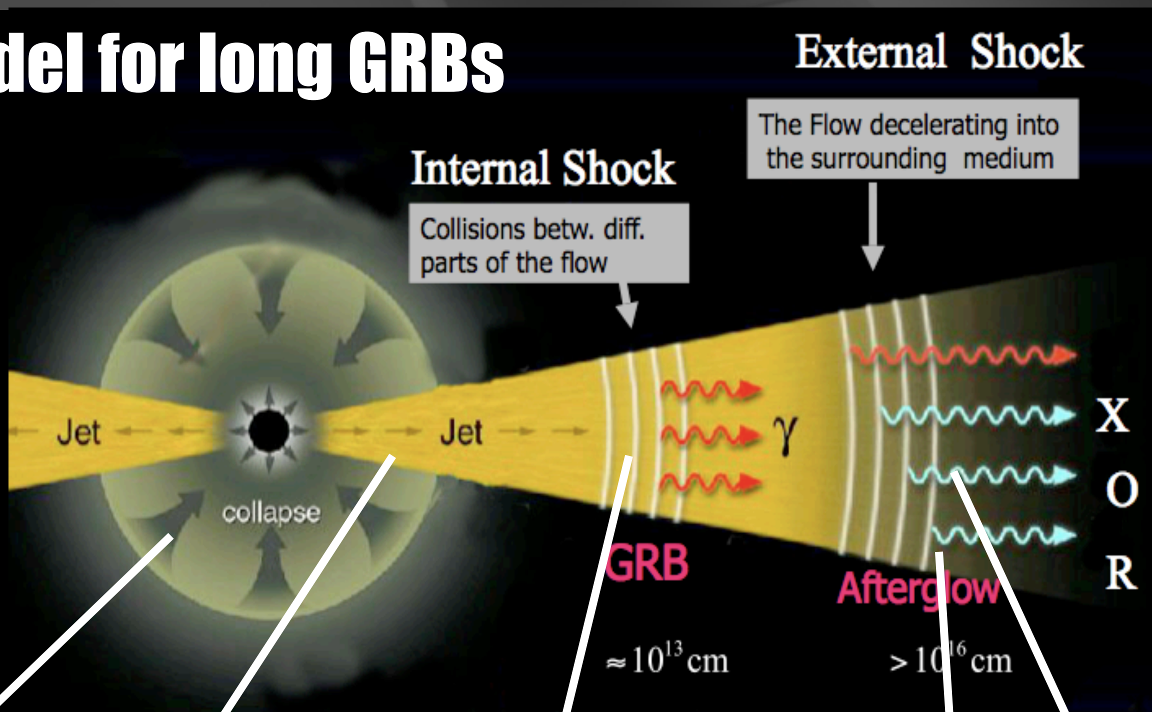


90% CL limit, assuming ν_e:ν_μ:ν_τ=1:1:1 :

$E^2\Phi_{all\ \nu}$ (E) < 8.6 · 10^{-10} TeV cm^{-2}s^{-1}sr^{-1}

GRBs as sources of high-energy neutrinos

Fireball model for long GRBs



MeV neutrinos at collapse

TeV neutrinos from inside the star

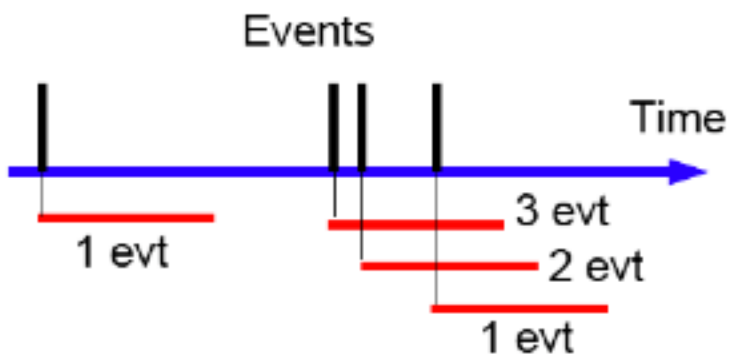
PeV neutrinos from internal shock

EeV neutrinos from external shocks

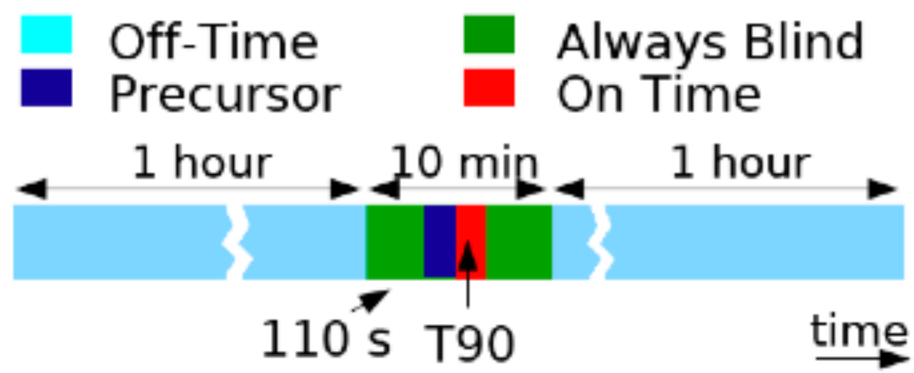
PeV-EeV neutrinos from flares

[Murase & Nagataki 2006]

GRB/transient search strategies



Rolling Search

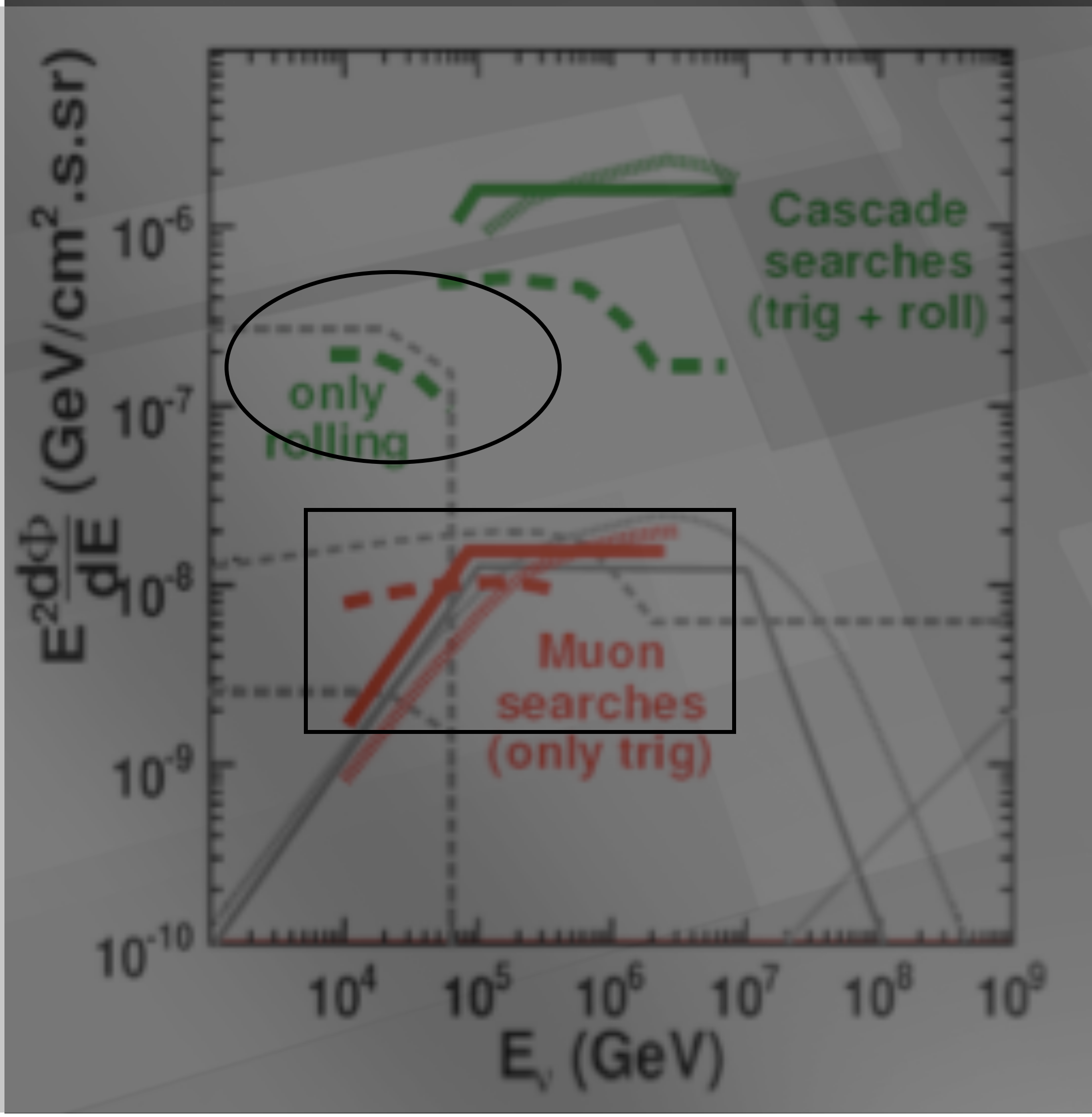


Satellite Triggered Search

time and directional correlation reduces background and increases sensitivity

Optical Follow-up

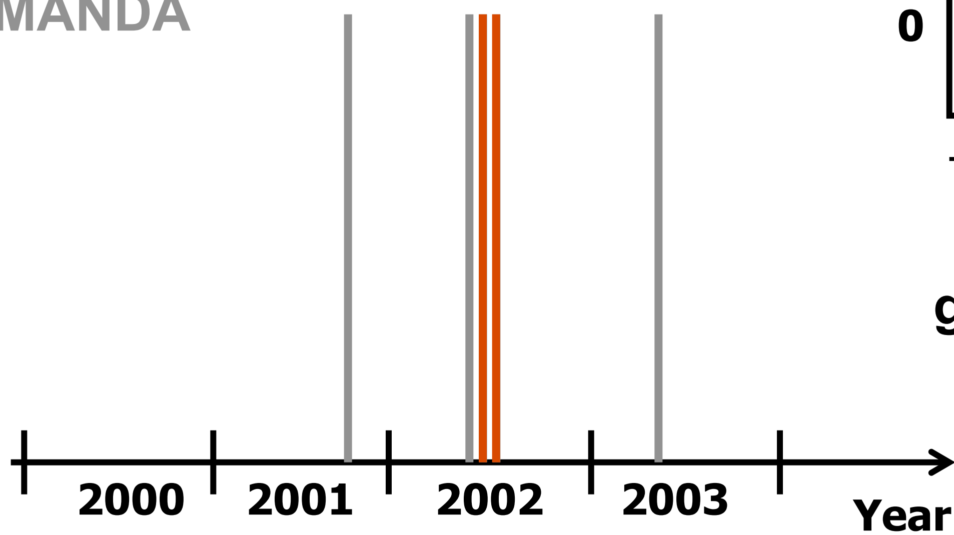
420 GRB searched

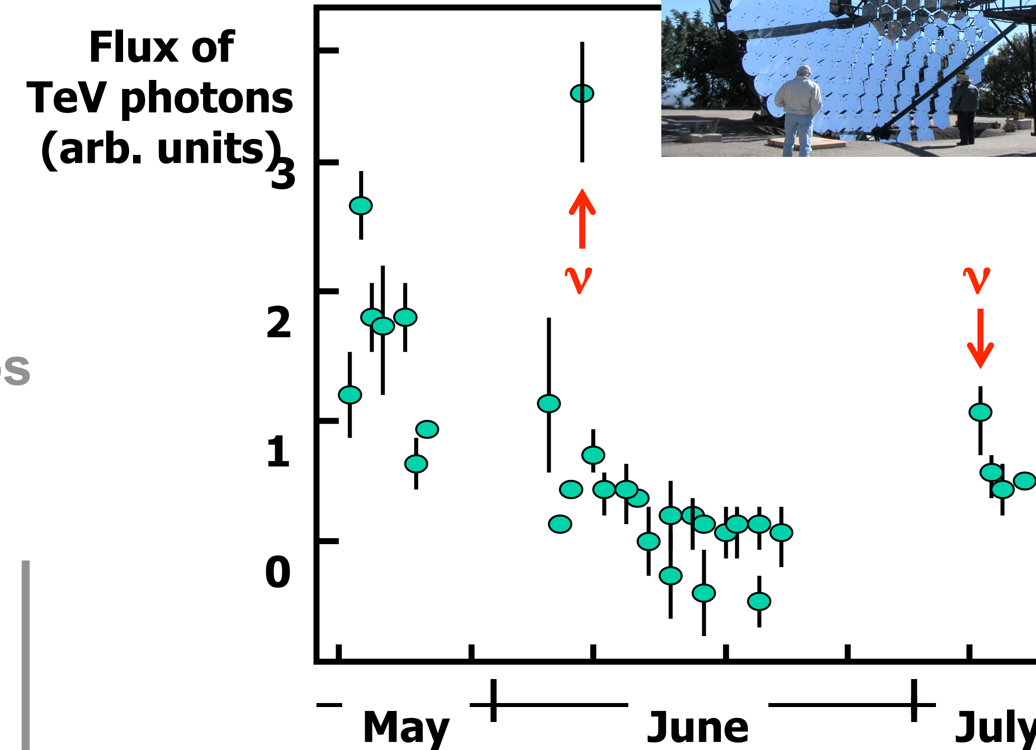


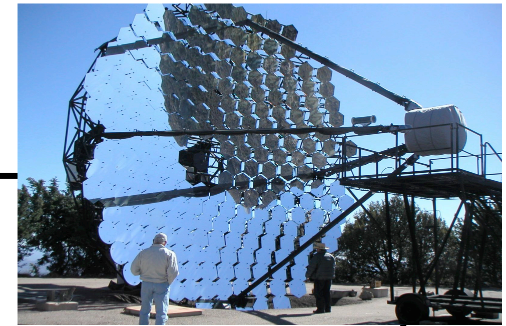
- AMANDA starts to exclude models
- IceCube will reach 70 times the instrumented volume in 2009

need a larger detector

Arrival time of the neutrinos from the direction of ES1959+650 detected by AMANDA

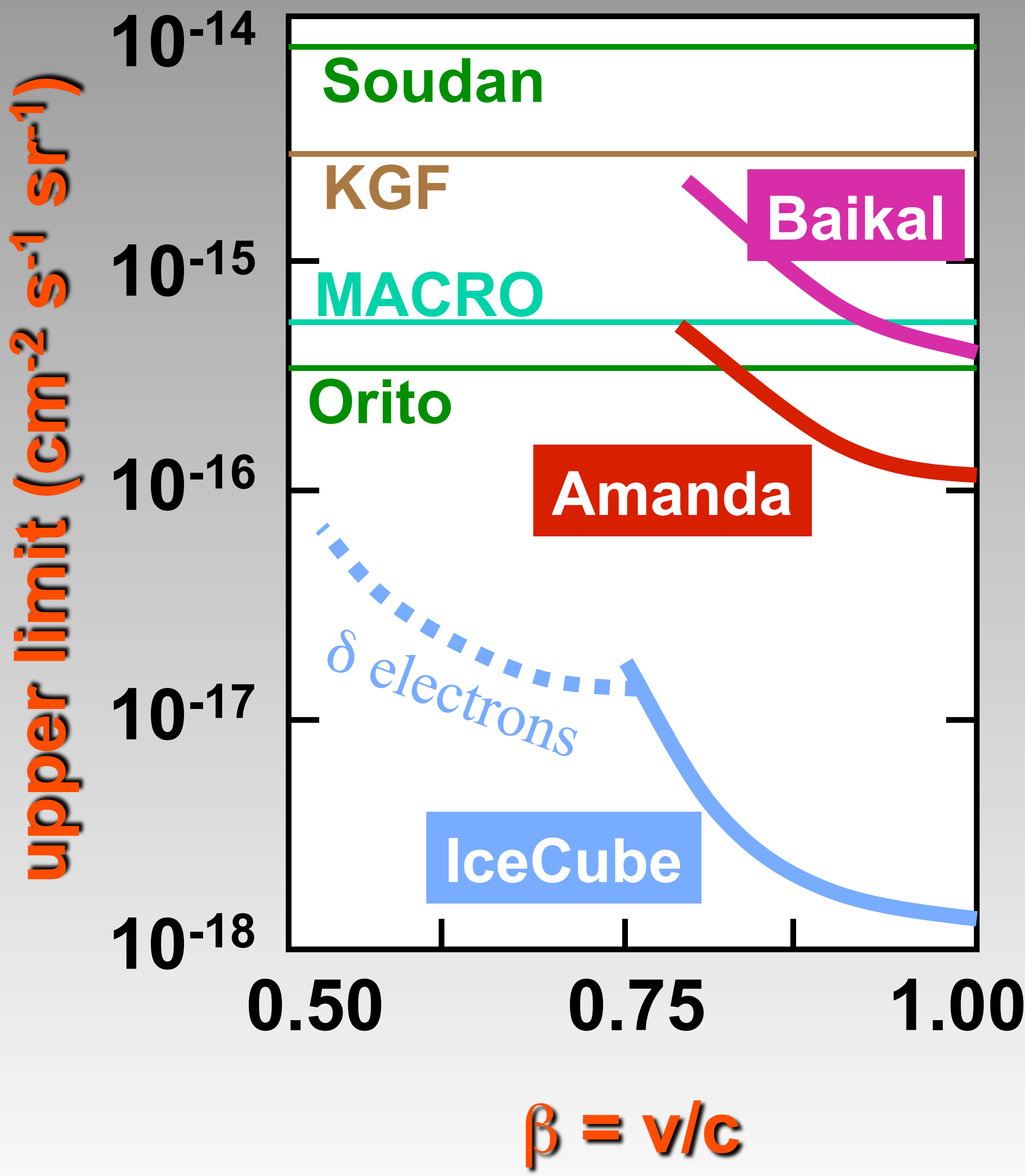






gamma-rays detected by TeV gamma telescopes

Relativistic Magnetic Monopoles



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

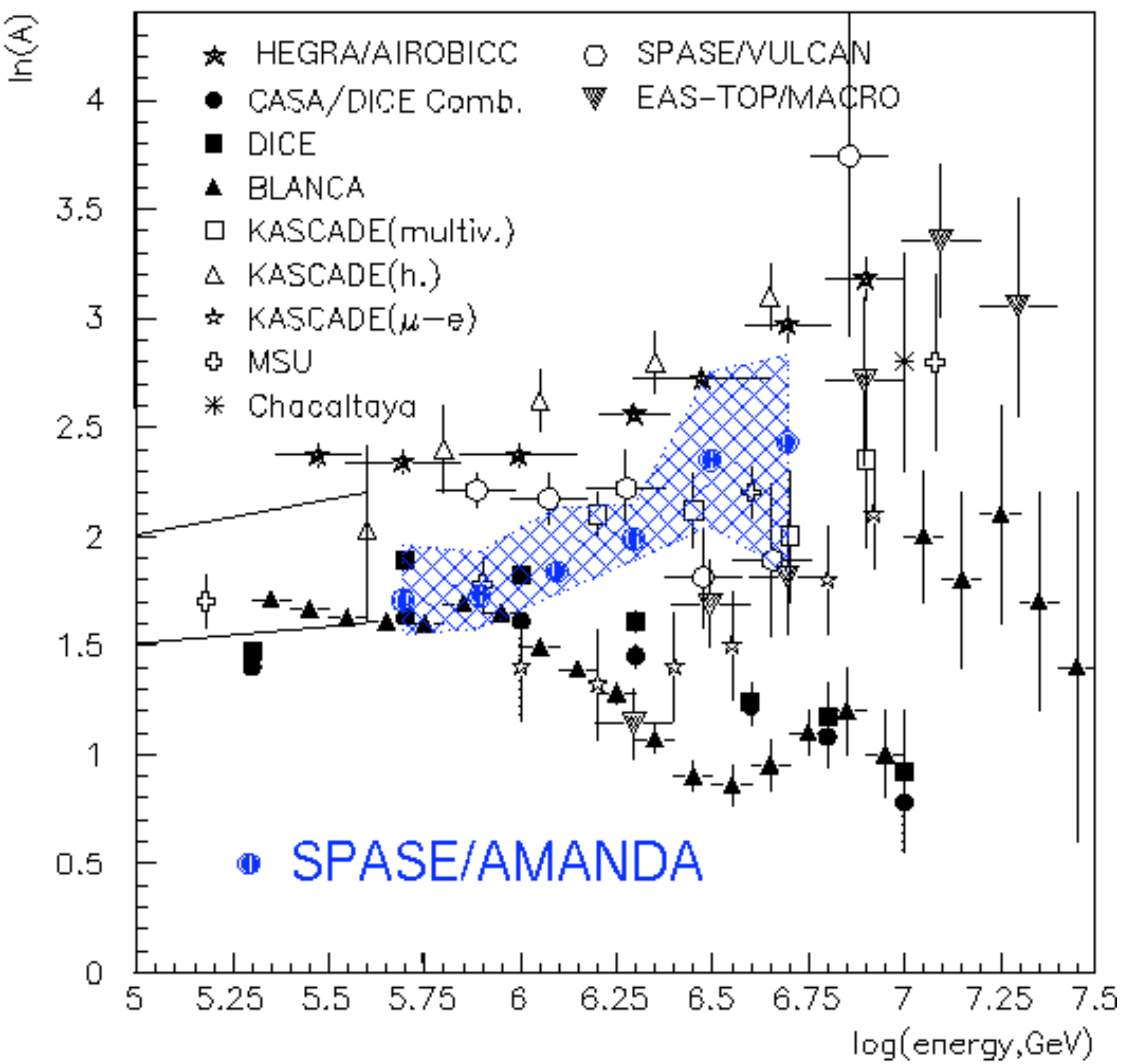
$n = 1.33$

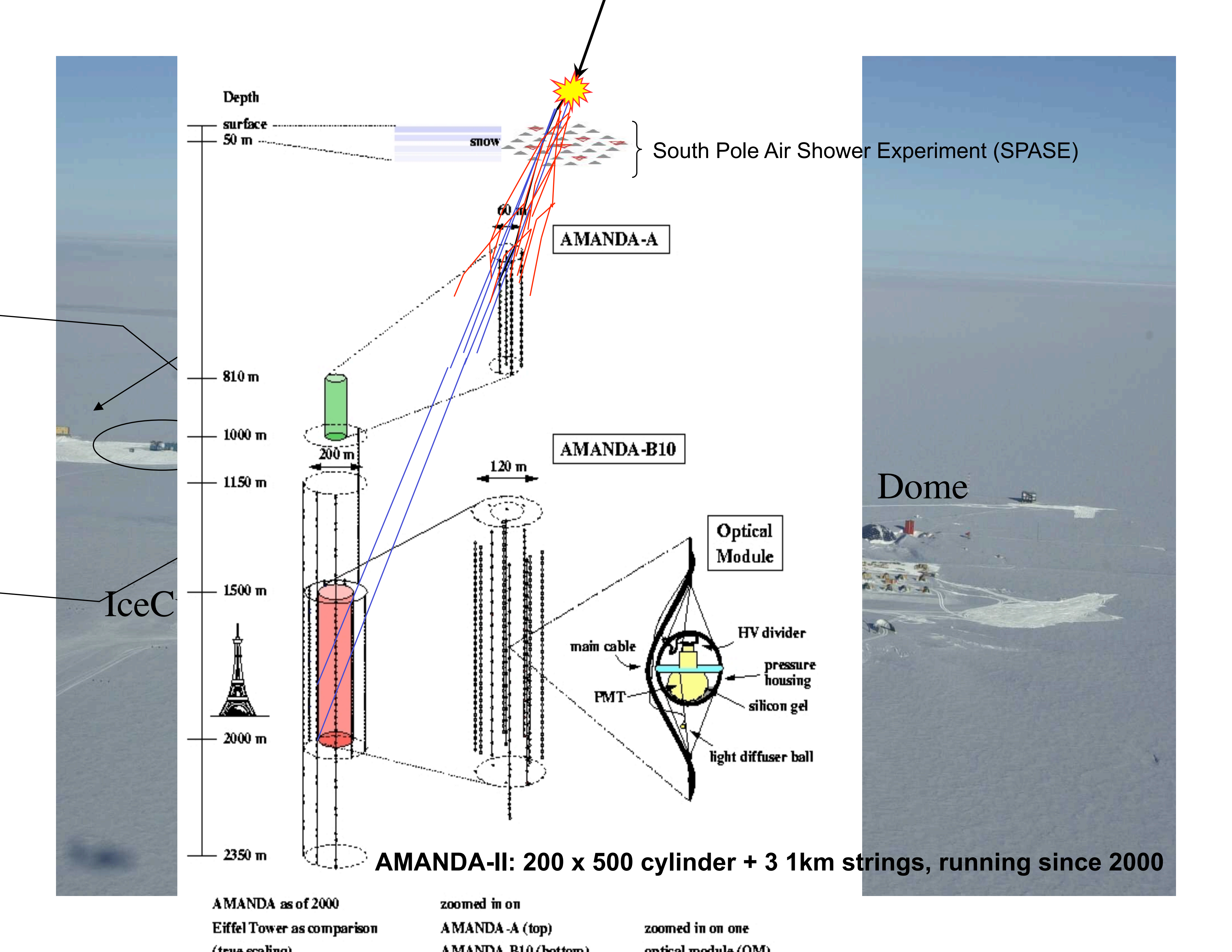
$(g/e) = {}^{137}/_{2}$

≈ 8300

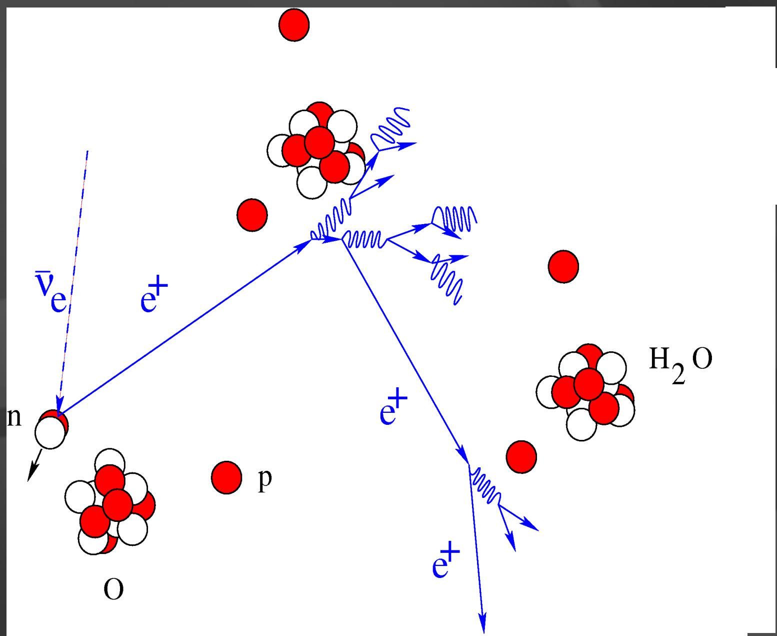
Composition Near the "knee"

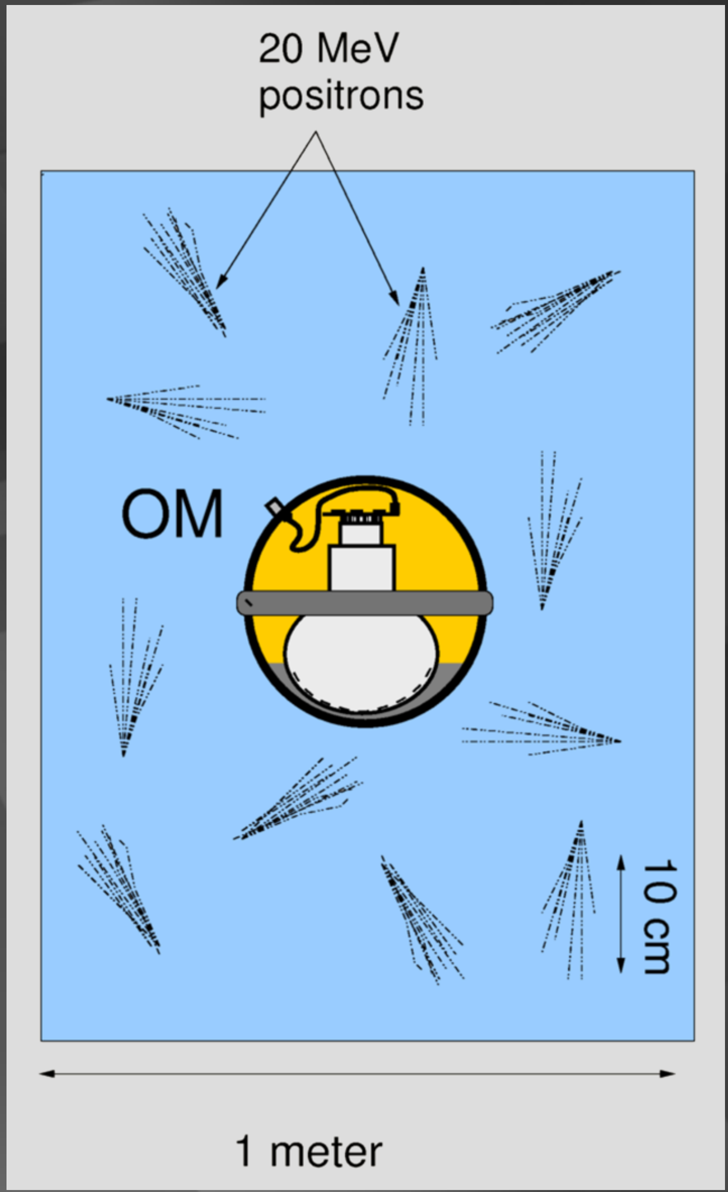
Atomic Number Vs Energy




Depth
surface
50 m
snow
810 m
1000 m
200 m
1150 m
1500 m
2000 m
2350 m
South Pole Air Shower Experiment (SPASE)
60 m
AMANDA-A
AMANDA-B10
120 m
Optical Module
main cable
HV divider
pressure housing
PMT
silicon gel
light diffuser ball
Dome
AMANDA-II: 200 x 500 cylinder + 3 1km strings, running since 2000
AMANDA as of 2000
Eiffel Tower as comparison
zoomed in on
AMANDA-A (top)
zoomed in on one

AMANDA/IceCube as MeV ν detector





- ☞ PMT noise low (~ 300 Hz)
- ☞ ice uniformly illuminated
- ☞ detect correlated rate increase on top of PMT noise

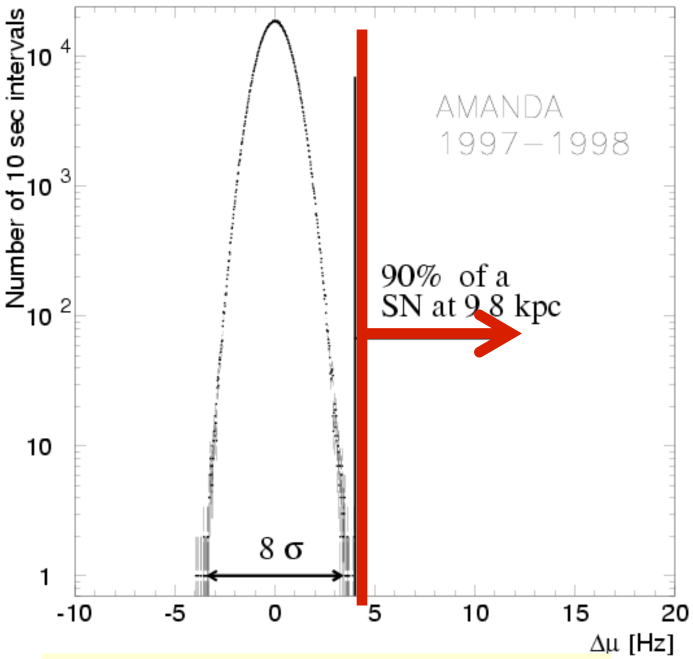
SUPERNOVA SEARCH ’97 + ‘98

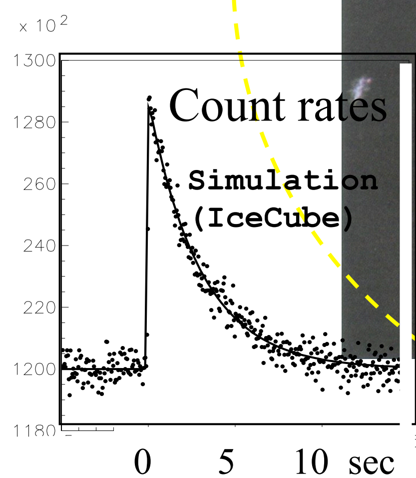
AMANDA-B10 with 302 OMs
Selection of very stable OMs → AMANDA-II with 677 OMs

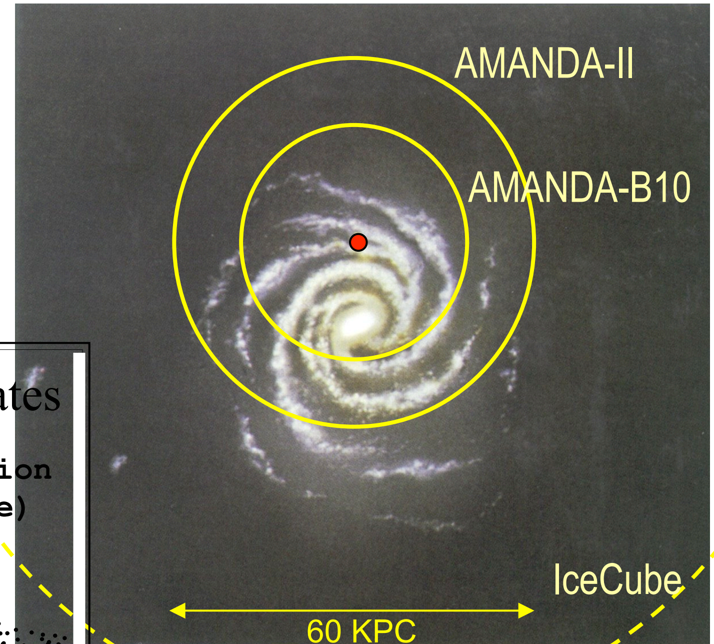
SN Signal proportional
To number of OMs !

CRUCIAL = LOW NOISE

215 Days live time; 90% = **9.8 kpc**







Astropart.Phys. 16 (2002) 345

70% of Galaxy coverage

$\Phi_{sn} < 4.3$ Event yr^{-1}

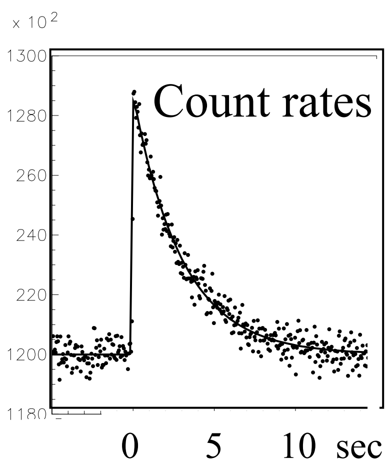
- IceCube: < 500Hz/OM
- 1 string = AMANDA

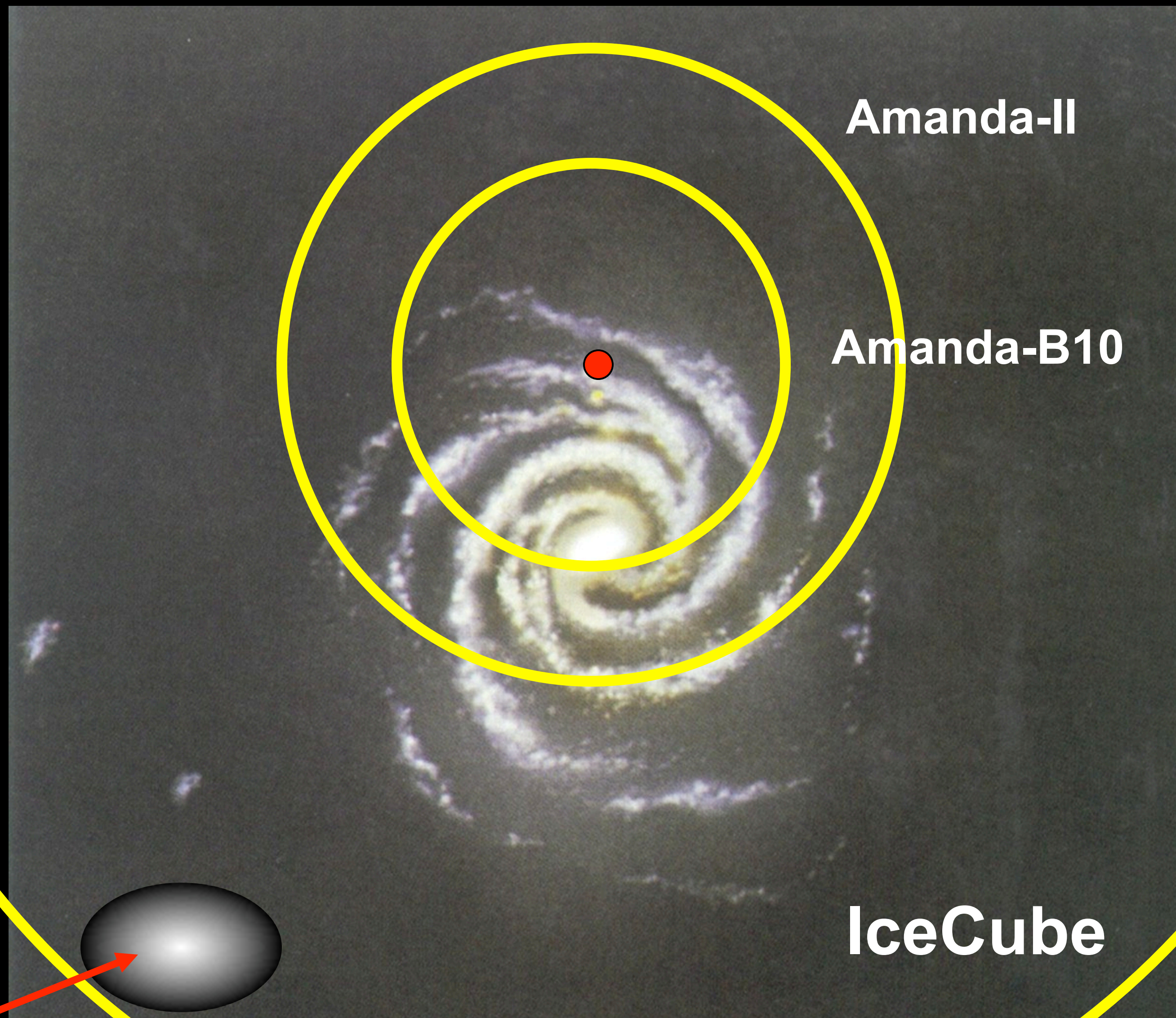
Joined SNEWS (**SuperNova Early Warning System**)
[with Super-K, SNO, Kamland, LVD, Boone]

Supernova Monitor

B10:
60% of Galaxy

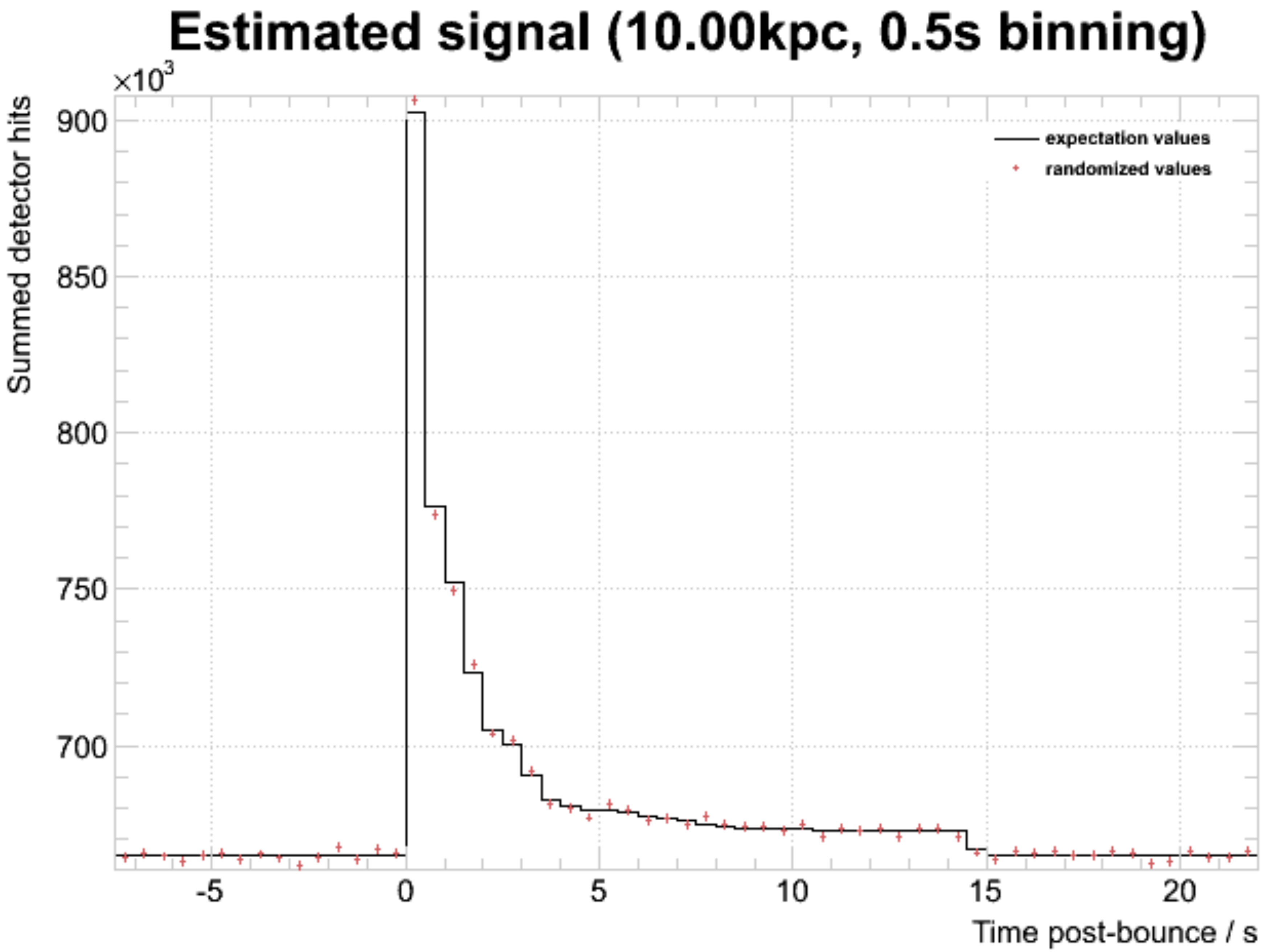
A-II:
95% of Galaxy





IceCube:
up to LMC

10^6 events in millisecond bins from 8 kpc



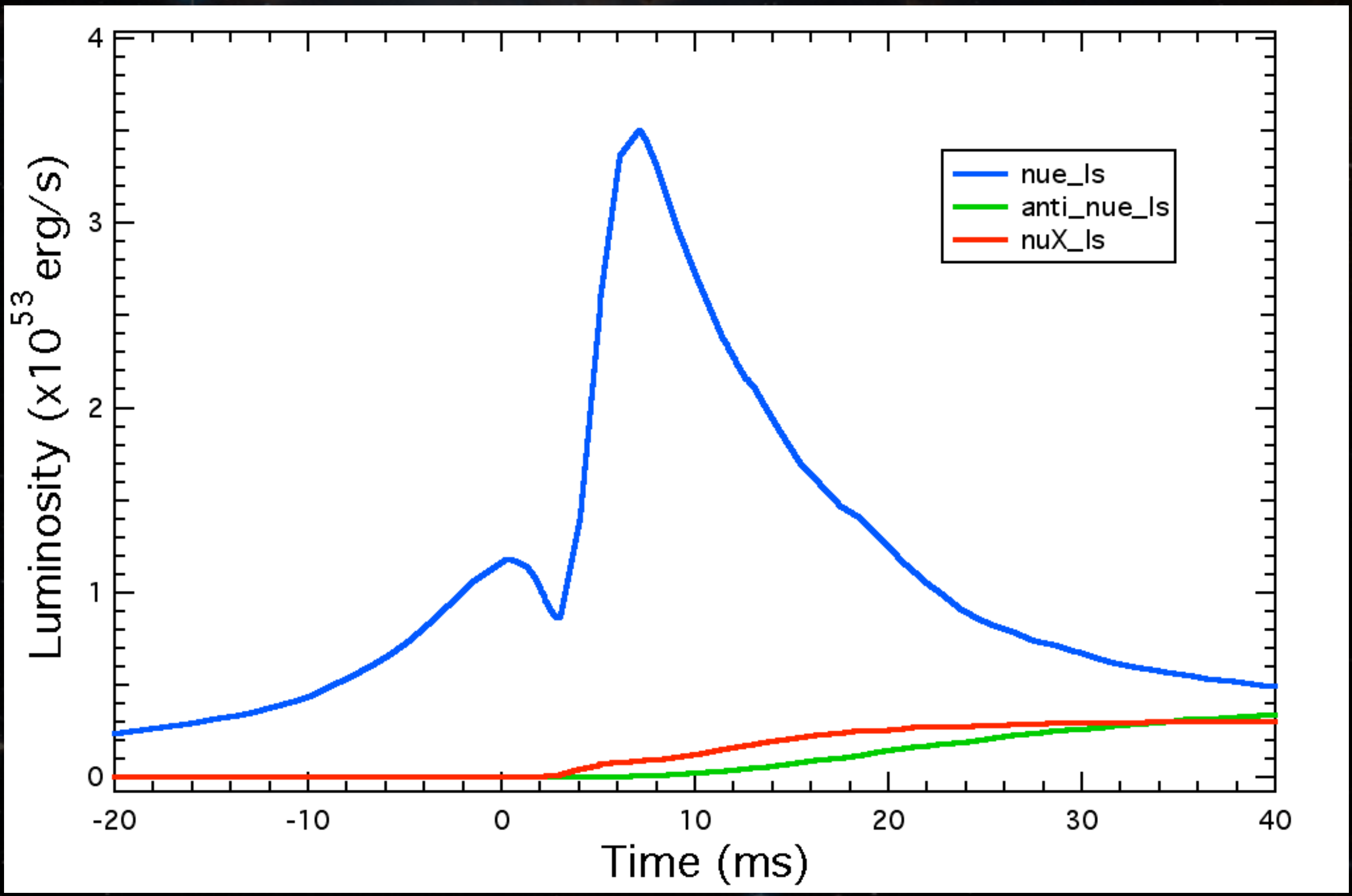
1 million events with millisecond resolution from 8 kpc

Simulation Data

Kitaura, Janka, Hillebrandt (Astron. Astrophys. 450 (2006) 345)

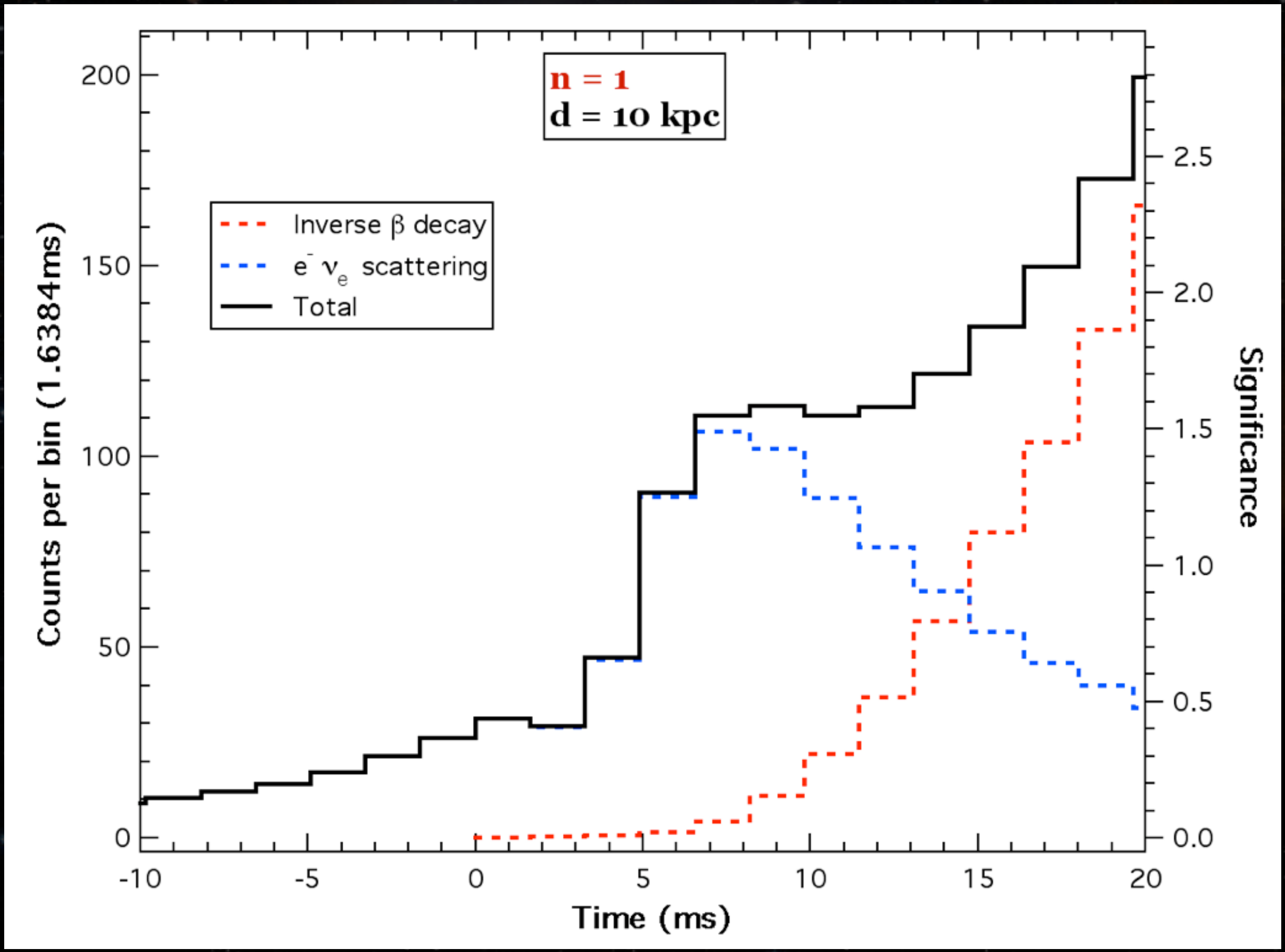
Garching

Luminosities



Random noise: 71^2 hits per bin

Expected IceCube signal (D=10kpc, M =10M$_\odot$)
(Without oscillations)



gamma rays from the Southern sky

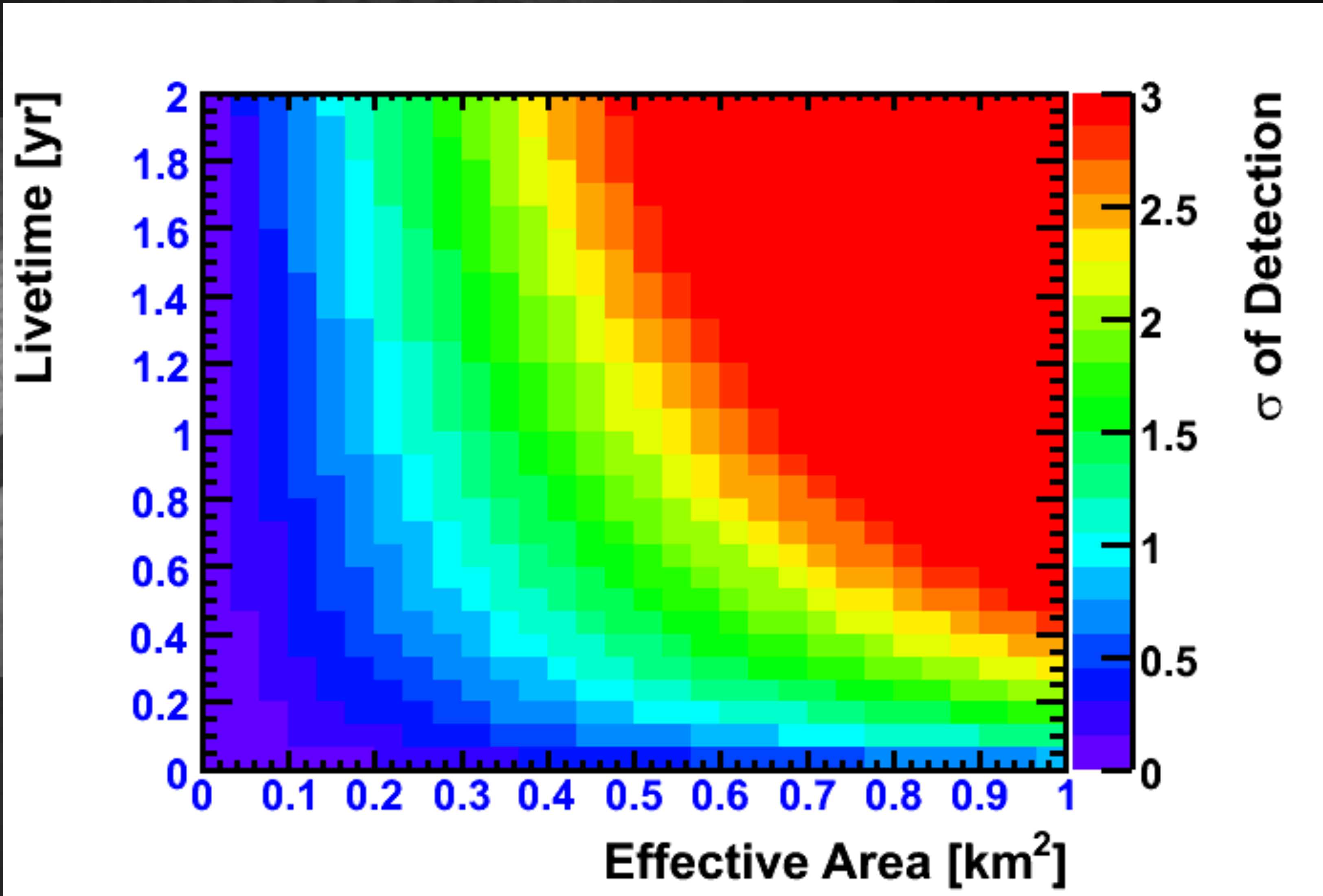
- **for a gamma source spectrum**

$$\frac{dN_\gamma}{dE_\gamma} = \frac{A_\gamma}{E_\gamma^\alpha}\ cm^{-2} s^{-1} TeV^{-1}$$

- **the number of muons reaching the detector depth from the source is**

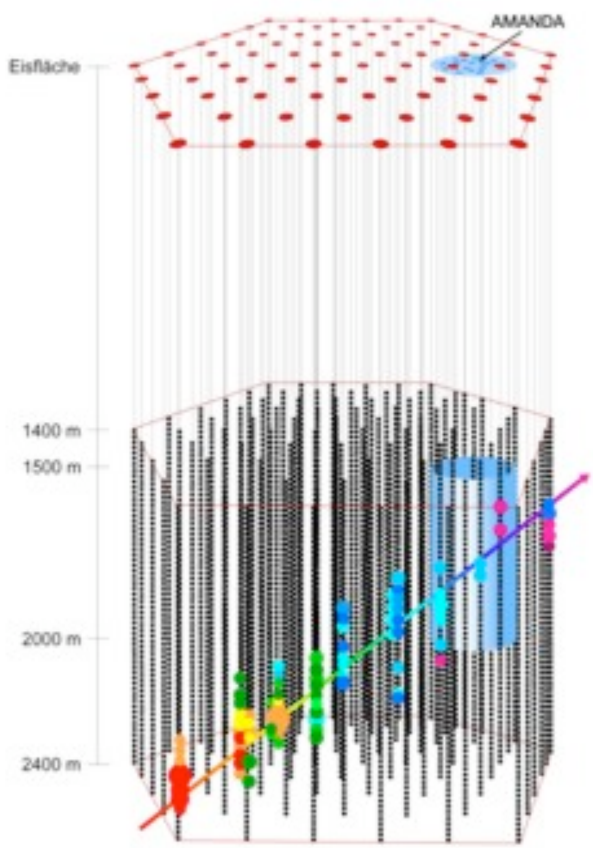
$$N_\mu(\geq E_{\mu,sur}) \cong \int_{E_{\gamma,min}}^{E_{\gamma,max}} dE_\gamma \frac{dN_\gamma}{dE_\gamma} N_\mu(E_\gamma \geq E_{\mu,sur})$$

IceCube as a gamma ray detector: significance for 1 Crab



particle physics

IceCube



• in the next 10 years IceCube will observe

~ 10^6 neutrinos with energies 0.1—1,000 TeV
~ 10 neutrinos with energy > 10^6 TeV

made in the interactions of cosmic rays with the Earth's atmosphere and microwave photons.

• with m~0.01 eV and E~100 TeV
the gamma factor of the neutrino is

$$\gamma = \frac{E_\nu}{m_\nu} \approx 10^{16}$$

neutrino "astronomy"

• in the next 10 years IceCube will observe

~ 10^6 neutrinos with energies 0.1—1,000 TeV
~ 10 neutrinos with energy > 10^6 TeV

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• with m~0.01 eV and E~100 TeV
the gamma factor of the neutrino is

$$\gamma = \frac{E_\nu}{m_\nu} \approx 10^{16}$$

natural particle beams

- **Sun: resolution of solar neutrino puzzle**

  → ν's have mass
  → John Bahcall understands how the sun shines

- **Supernova 1987A: ~ 20 events only!**

  → confirmed basic scenario for the death of a star
  → set records on neutrino properties

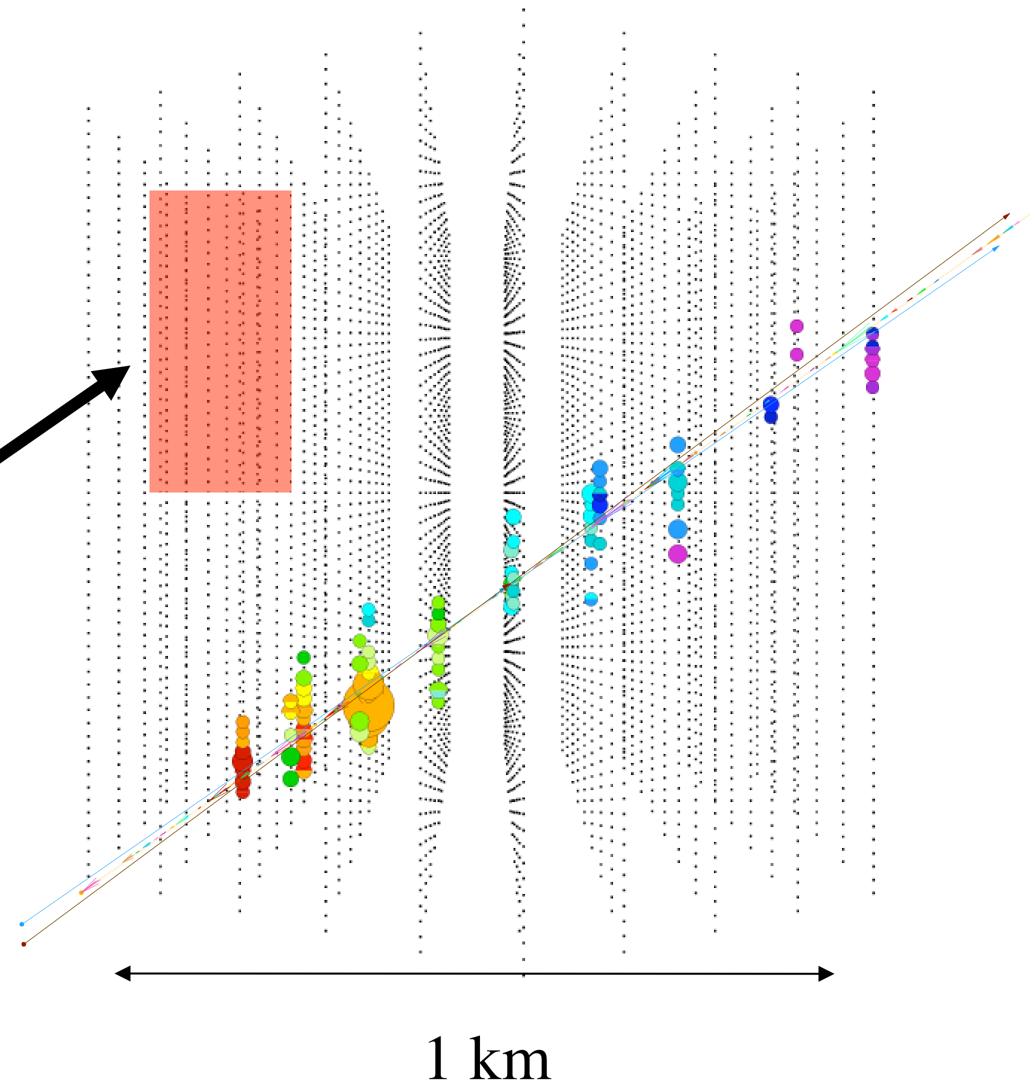
- **Cosmic neutrinos? Discovery instrument, but also ~ 10^6 atmospheric and ~ 10^3 supernova neutrinos**

  → origin of cosmic rays
  → beam for particle physics

μ-event in IceCube

300 atmospheric neutrinos per day

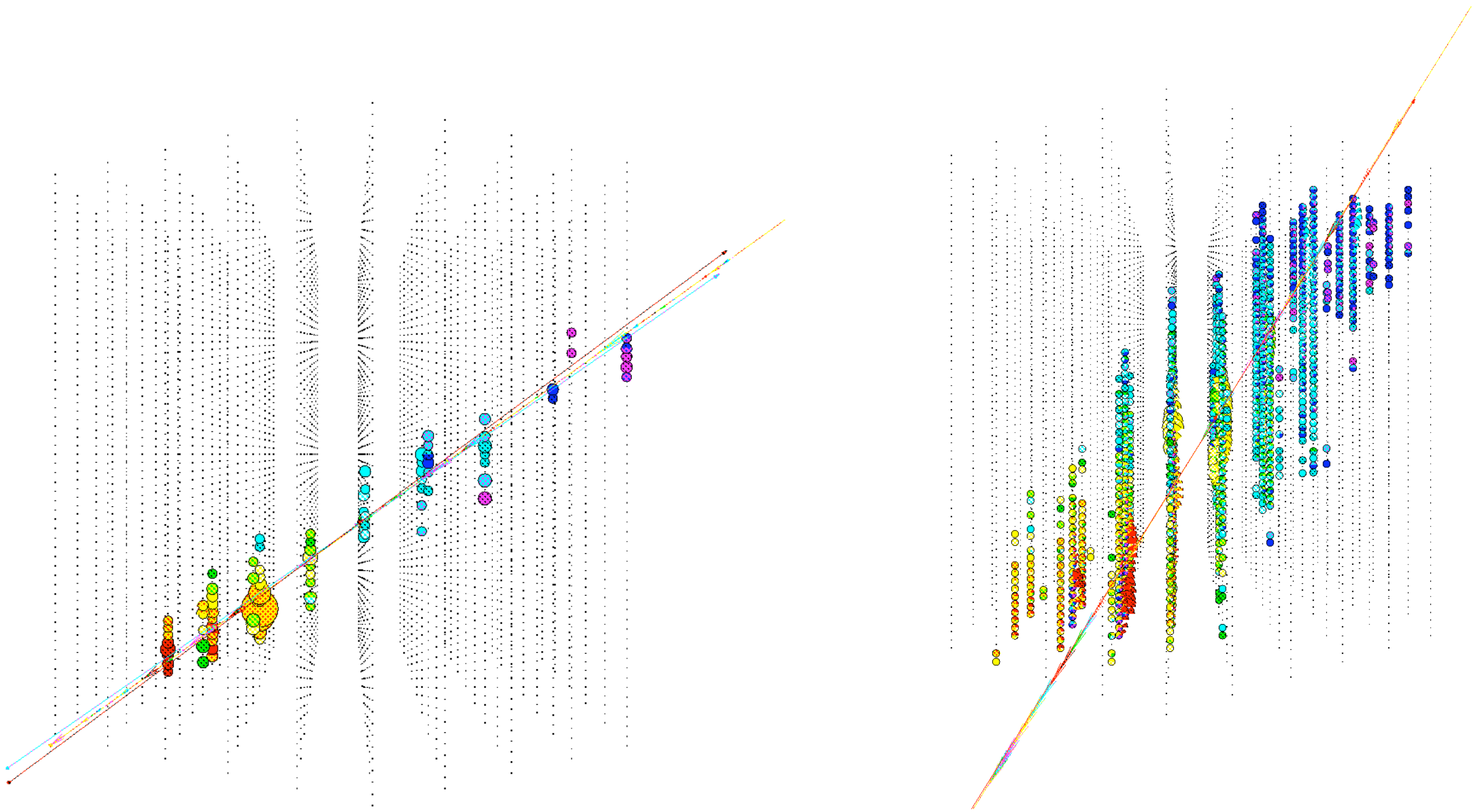
AMANDA II



IceCube:

Larger Telescope
Superior Detector

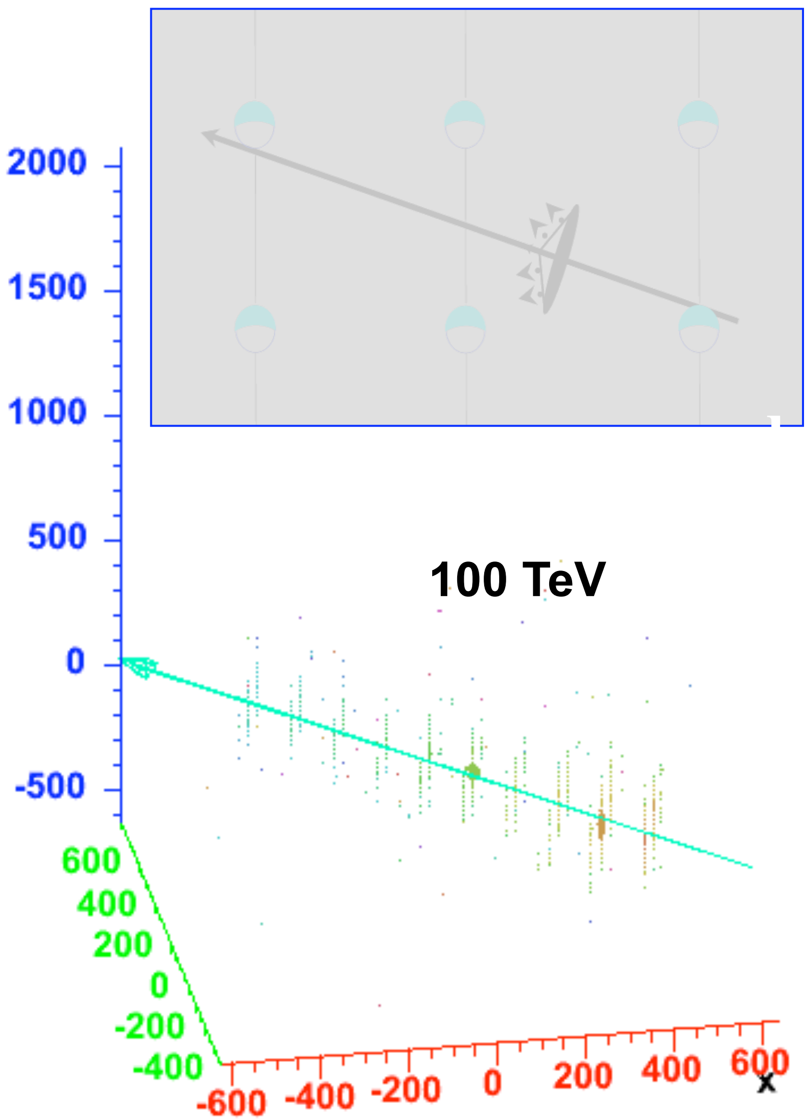
ν_μ detection in IceCube

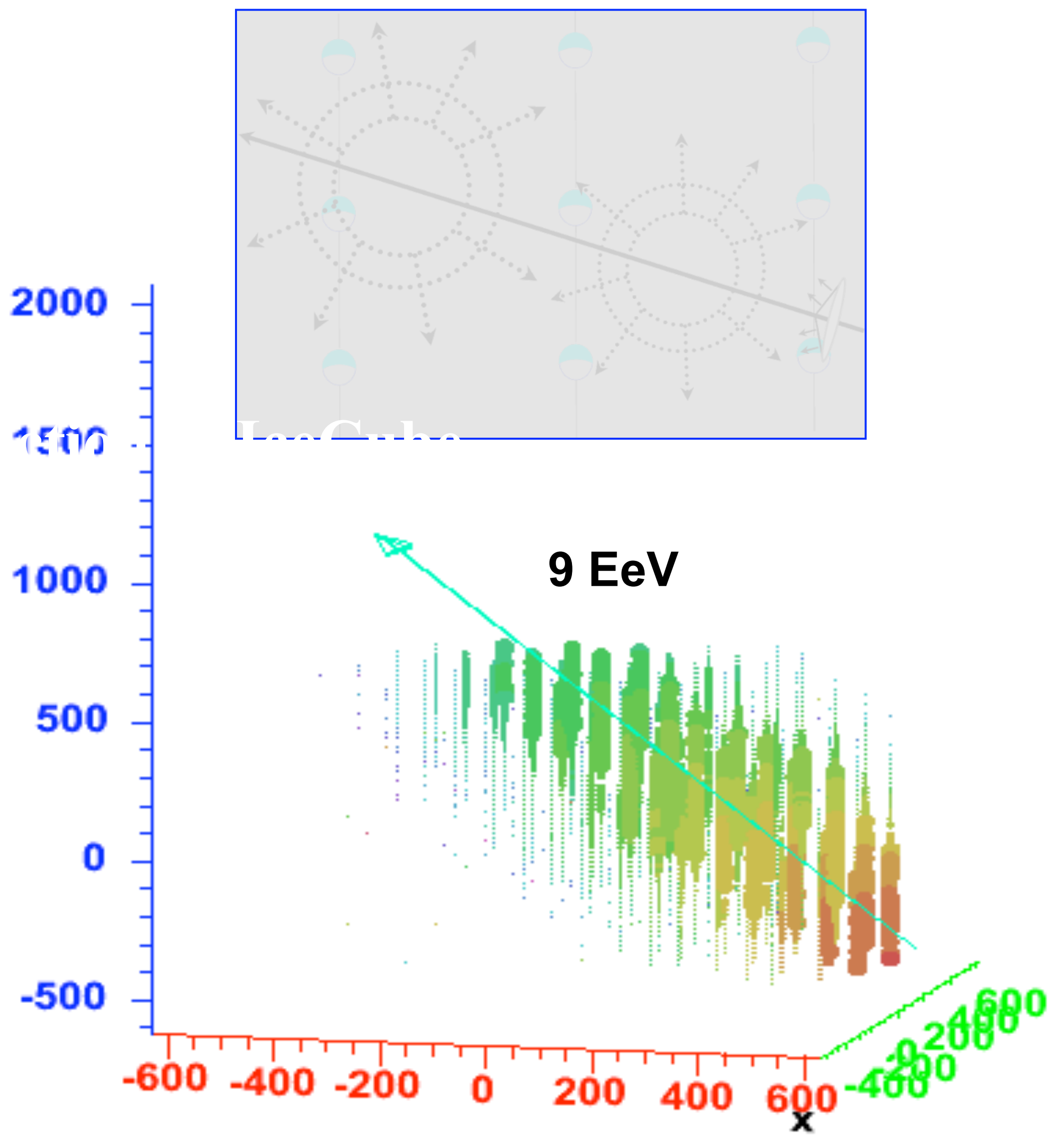


E = 6 TeV   E = 6400 TeV

ν_μ detection in IceCube

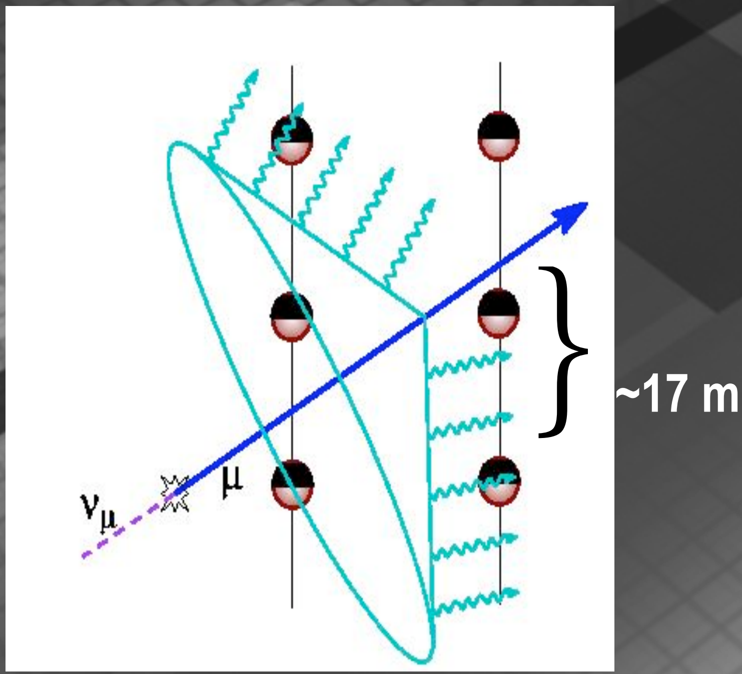
→ energy measurement from MeV to EeV

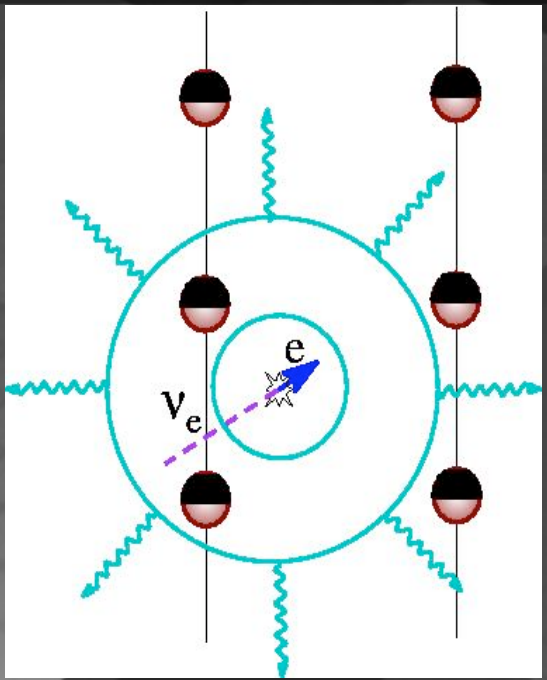




Neutrino Detection

event reconstruction by Cherenkov light timing



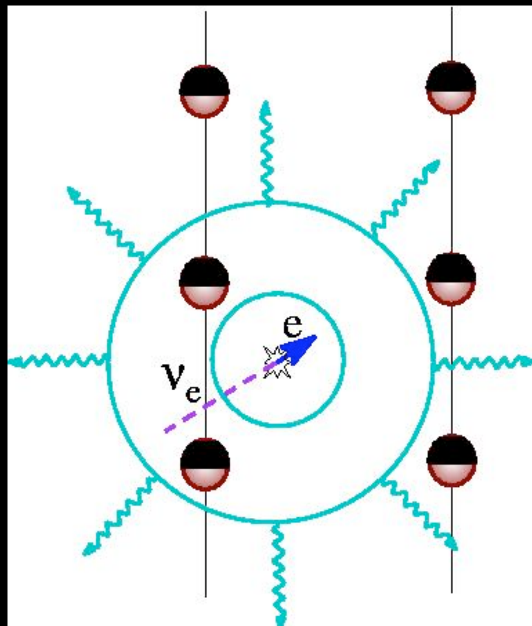


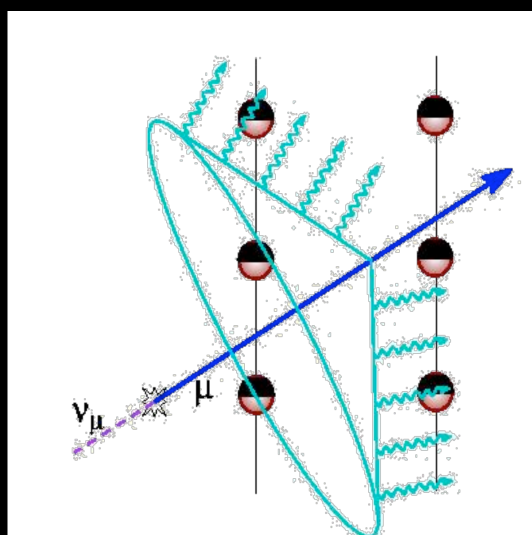
~ km-long muon tracks from ν_μ

~10m-long cascades, ν_e ν_τ neutral current

Longer absorption length => larger effective volume

neutrino flavor





Poi

ν_e C
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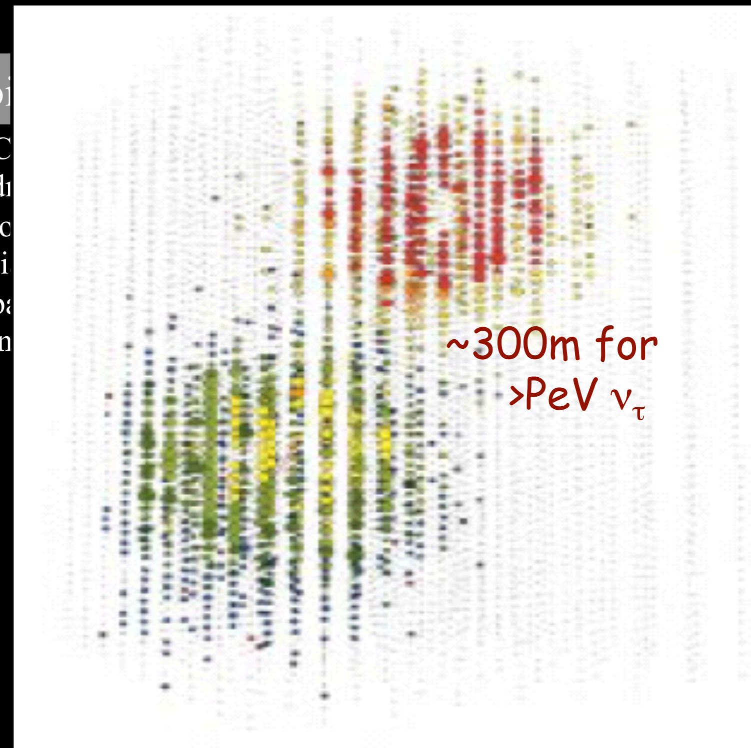
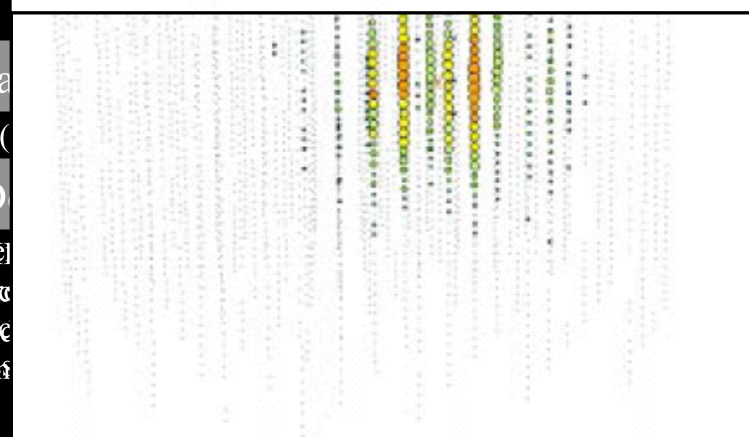


Tra

ν_μ (

"D

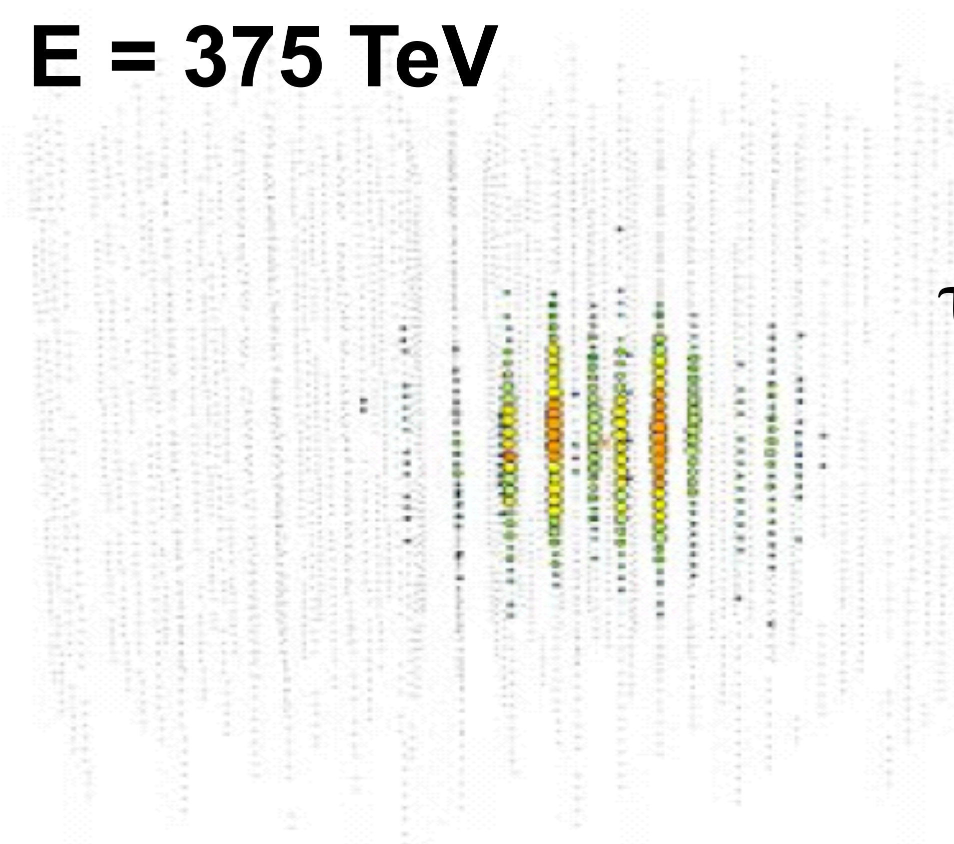
coil
id



ν_e and ν_τ detection in IceCube

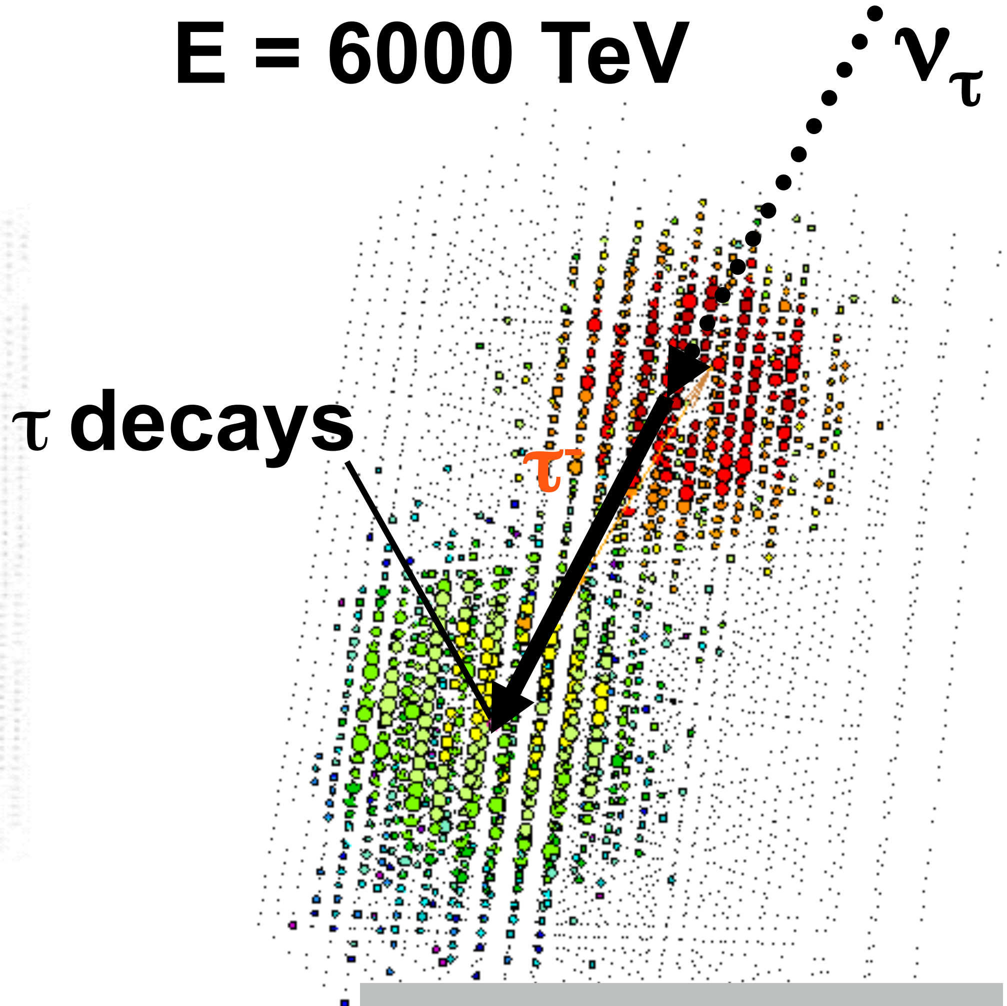
→ identify ν flavor

E = 375 TeV



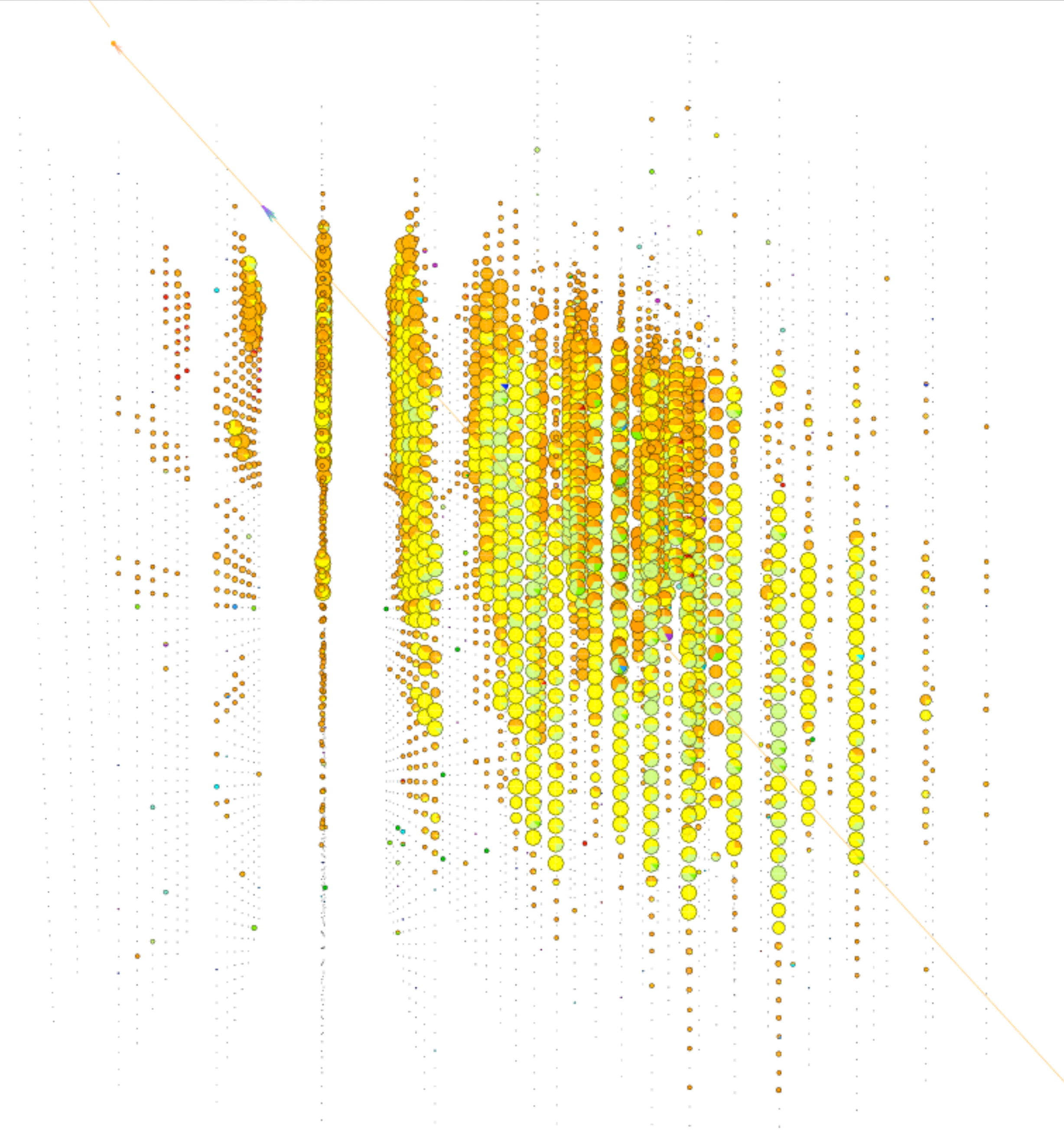
$$\nu_e + N \rightarrow e^- + X$$

E = 6000 TeV



$$\nu_\tau + N \rightarrow \tau^- + X$$

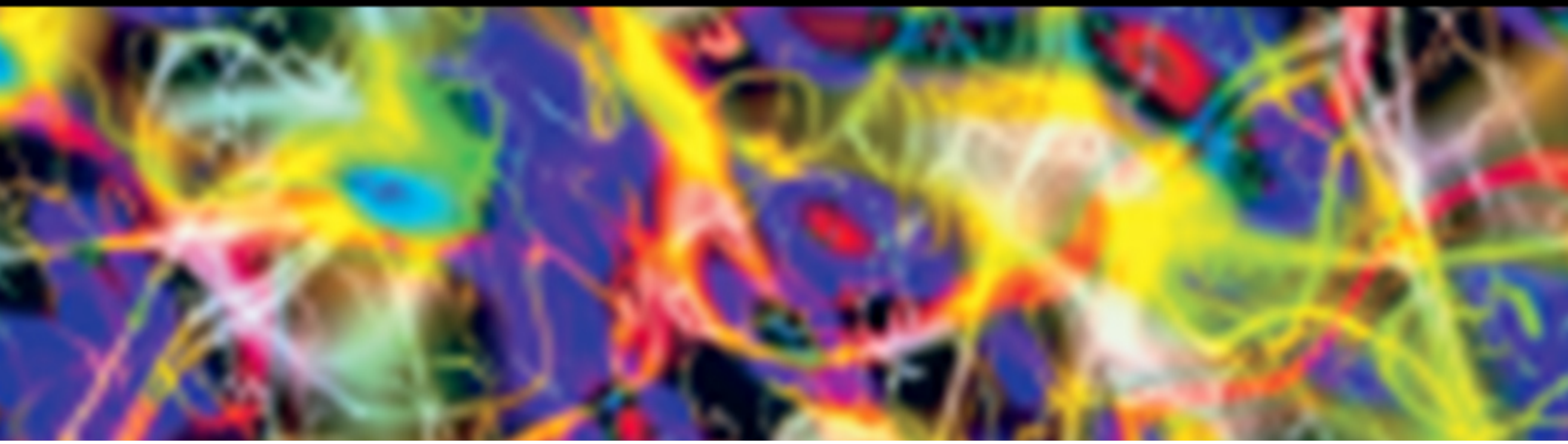
GZK event: cosmic ray + cmb photon → 10 EeV neutrino



IceCube : particle physics with one million atmospheric neutrinos

- **Astronomy**: new window on the Universe
- **Physics**:
- measurement of the high-energy neutrino cross section
- TeV-scale gravity, quantum decoherence
- physics beyond 3-flavor oscillations
- test special and general relativity with new precision
- search for magnetic monopoles
- search for neutralino (or other) dark matter
- search for topological defects and cosmological remnants
- search for non-standard model neutrino interactions
- …

quantized space: matter where the geometry is activated



quantized space: matter where the geometry is activated

violation of Lorentz invariance may be a tool to study Planck scale physics

→ interaction with Planck mass particles distort spacetime

→ Planck scale vacuum fluctuations probed by high energy neutrinos

$$E^2 = p^2 + m^2 \pm E^2 \left(\frac{E}{M_{Planck}}\right)^n \pm \ldots$$

modification to dispersion relation leads to an energy dependent speed of light.

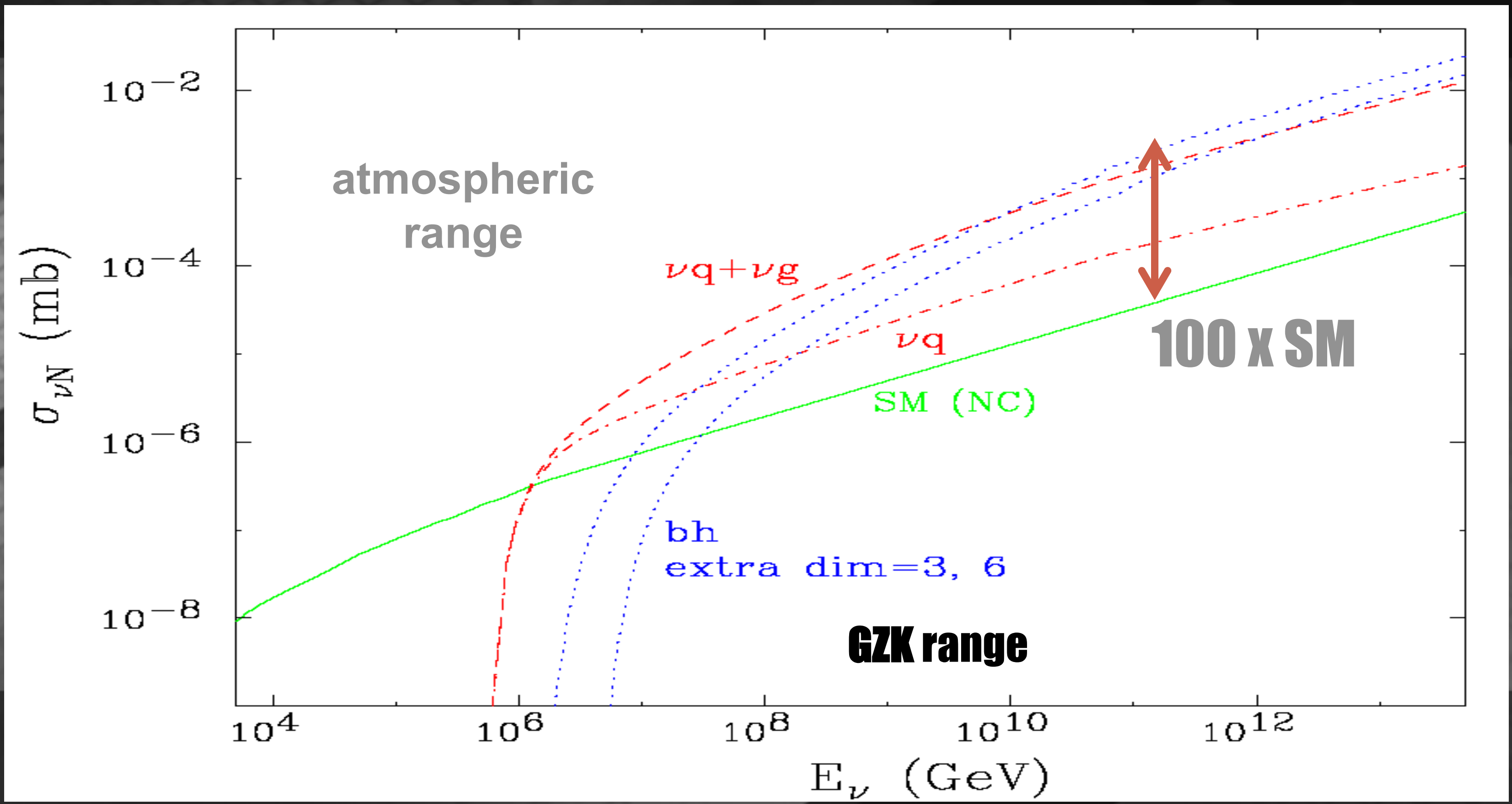
Lorentz violation: ΔE vs Δt

violation of Lorentz invariance because of Planck scale physics can be detected through time delays of high energy neutrinos relative to low energy photons

$$energy\ scale \cong \frac{d}{c}\frac{\Delta E}{\Delta t} \cong M_{Planck}$$

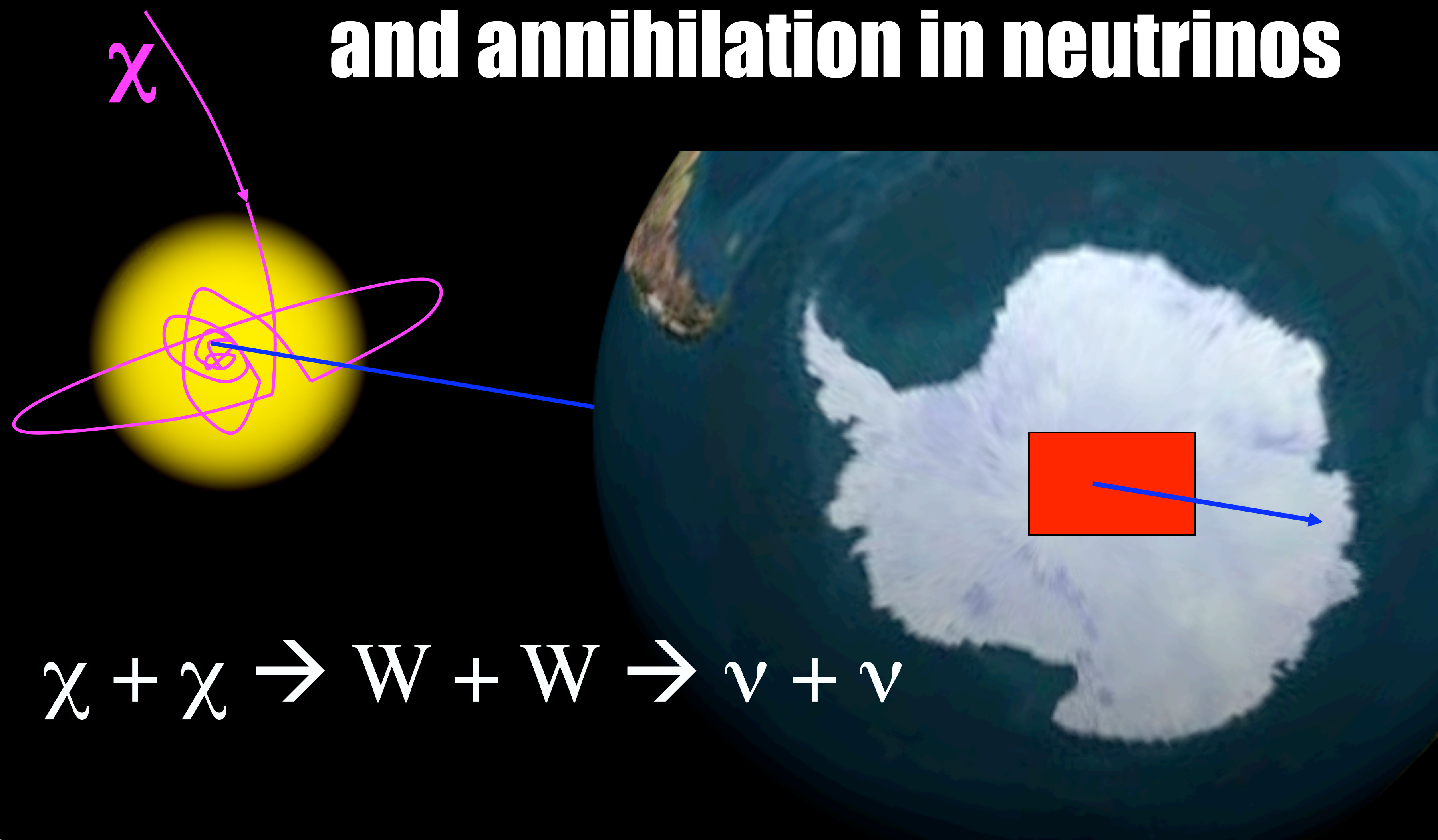
from a source at a distance d; for instance a GRB.

Neutrino Astronomy Explores Higher Dimensions



TeV-scale gravity increases PeV ν-cross section

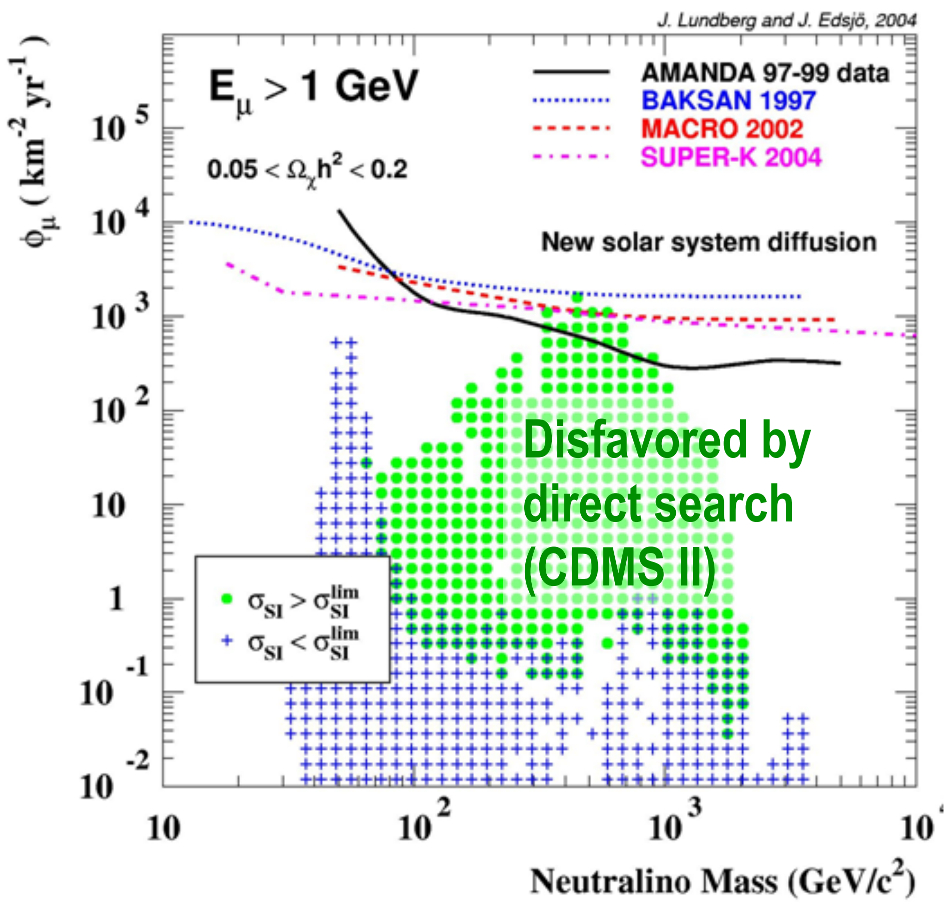
WIMP capture in the sun
and annihilation in neutrinos

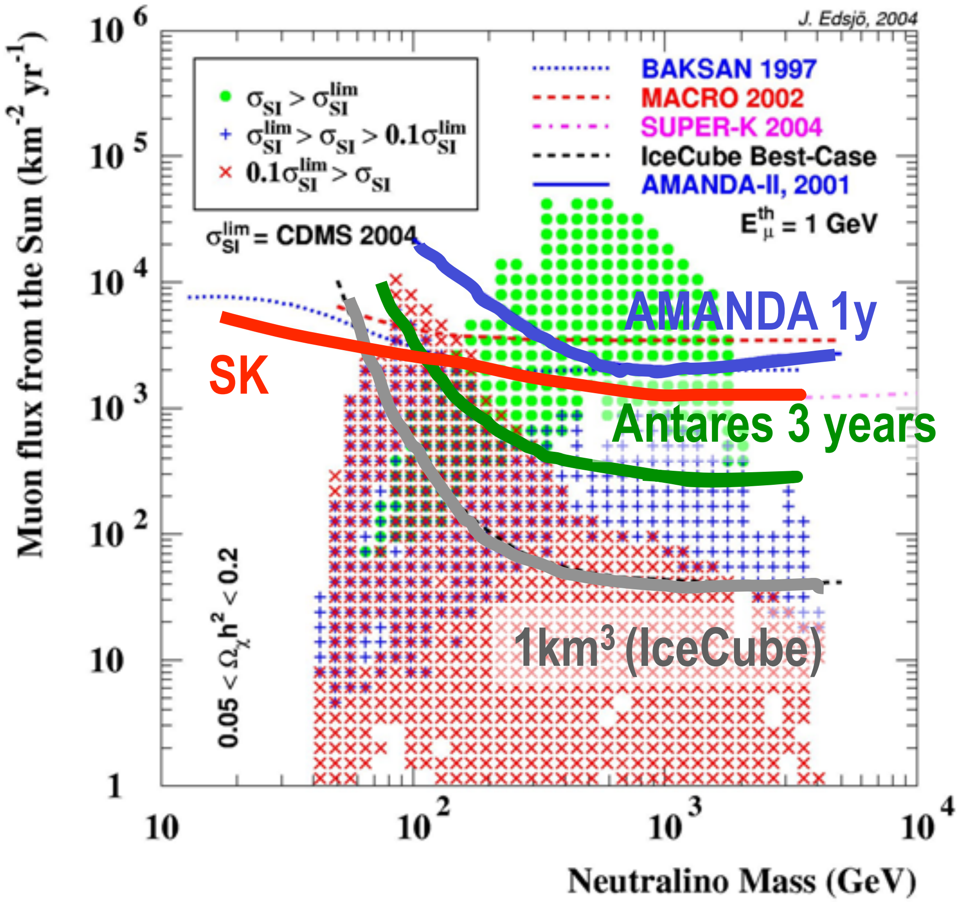


$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

WIMP search

PRELIMINARY

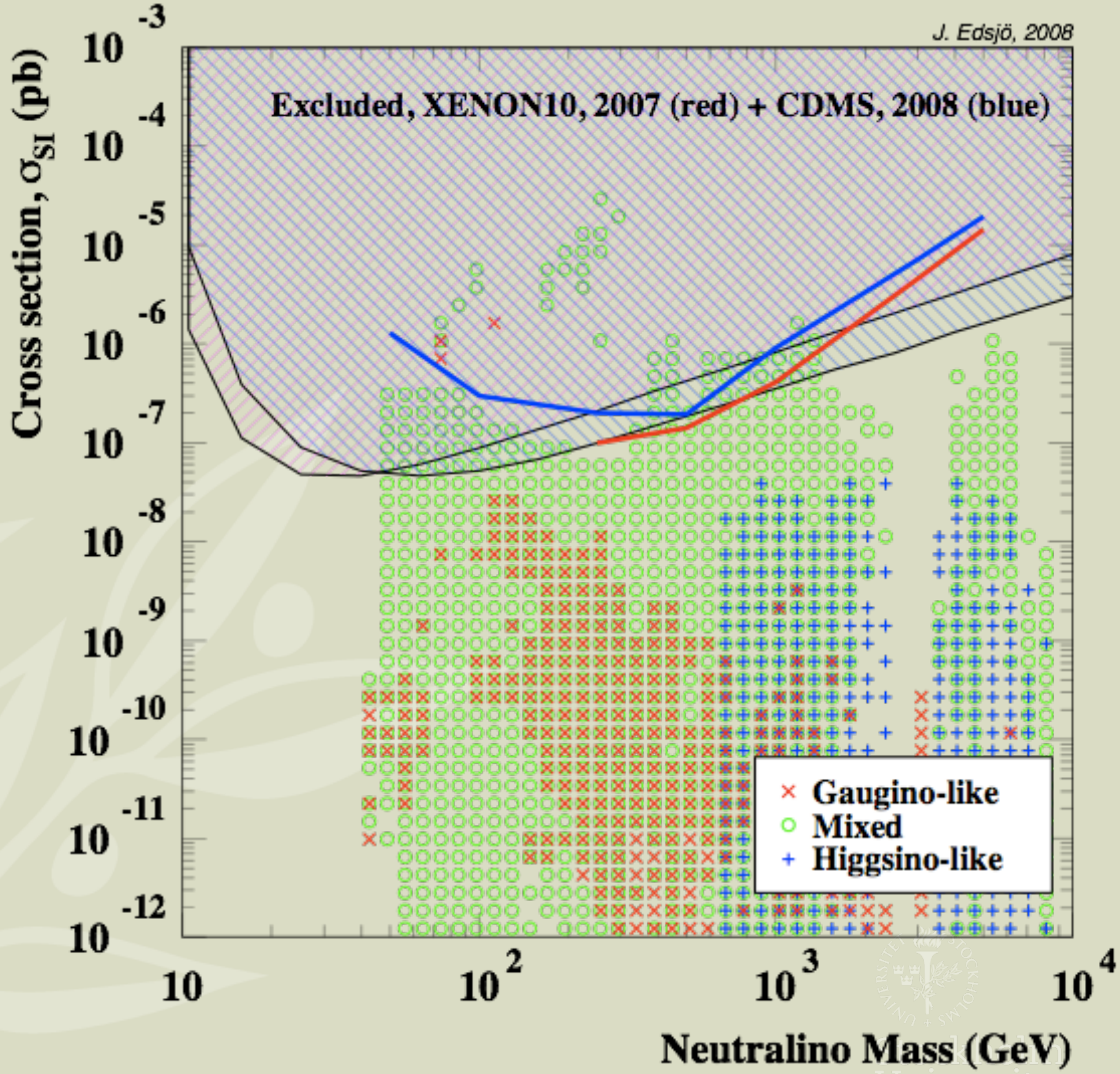




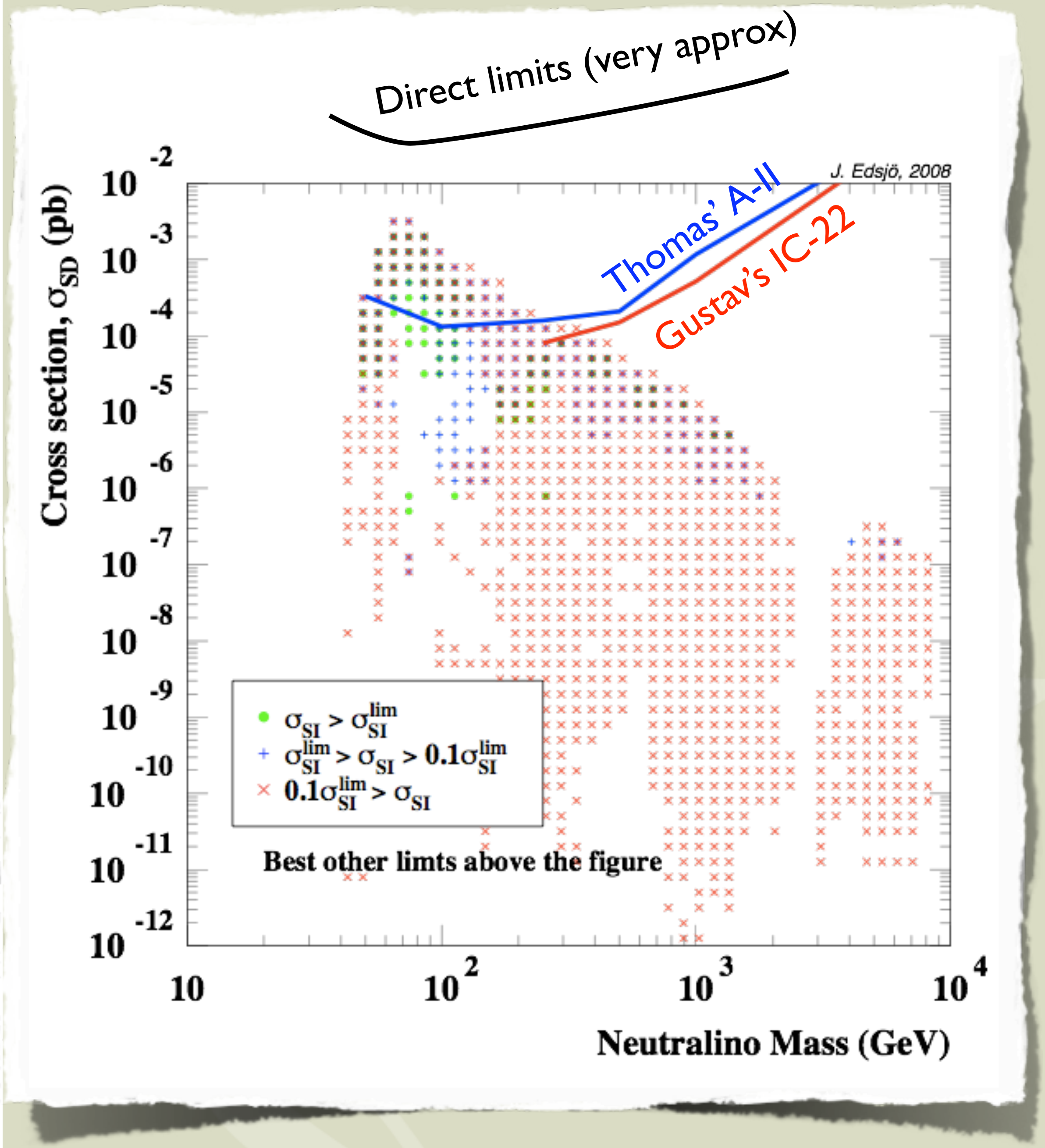
Limits on muon flux from Earth

Limits on muon flux from Sun

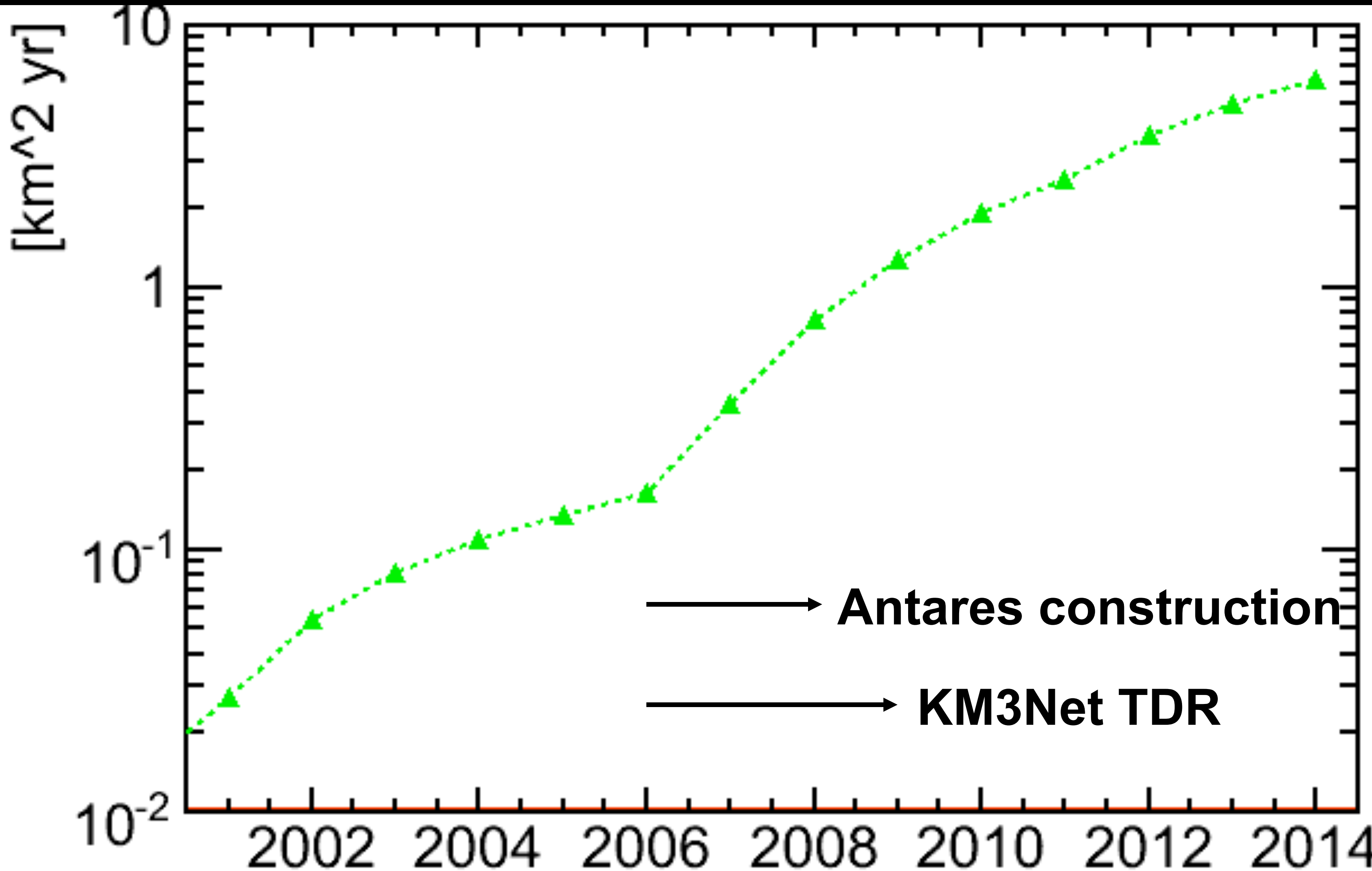
spin-independent scattering



spin dependent scattering



IceCube
accumulated exposure at 100 TeV



radio detection of neutrinos

Radio Emission from neutrino-induced electromagnetic cascades

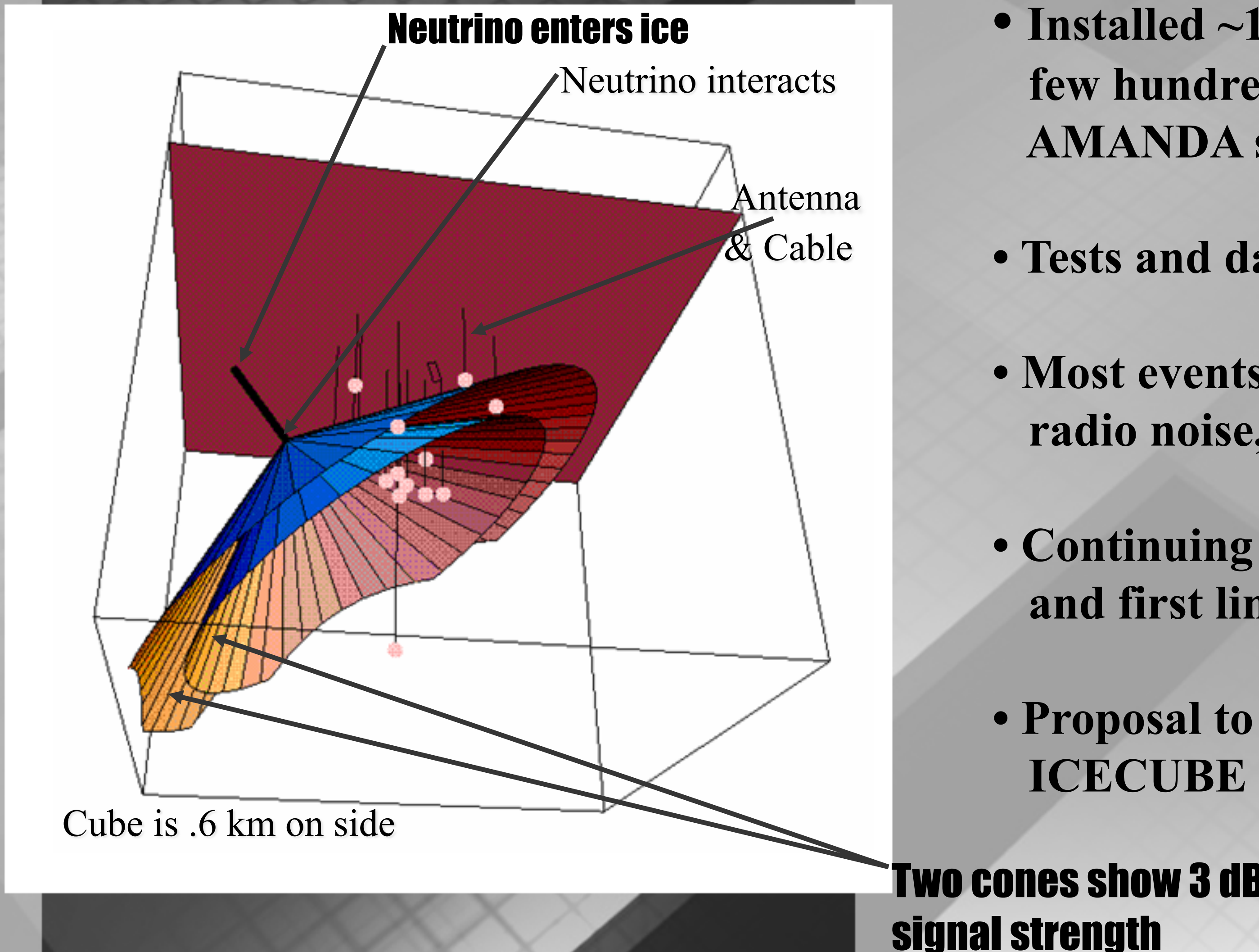
• Electromagnetic cascades: electron-positron pairs and (mostly) gammas → electrically neutral, no radio emission.

• But, Compton scattering of photons on atomic electrons creates negative charge excess of ~ 20%

• Negative charge radiates coherently at MHz ~ GHz → Power = Energy ^{2}

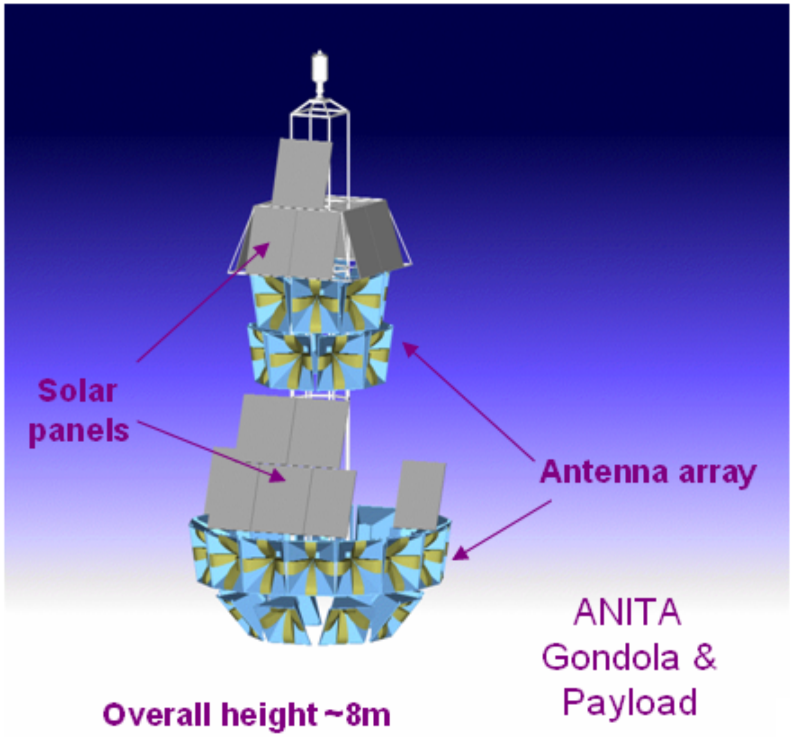
• Askarian effect demonstrated at SLAC: consistent with calculations

RICE
Radio Detection in South Pole Ice

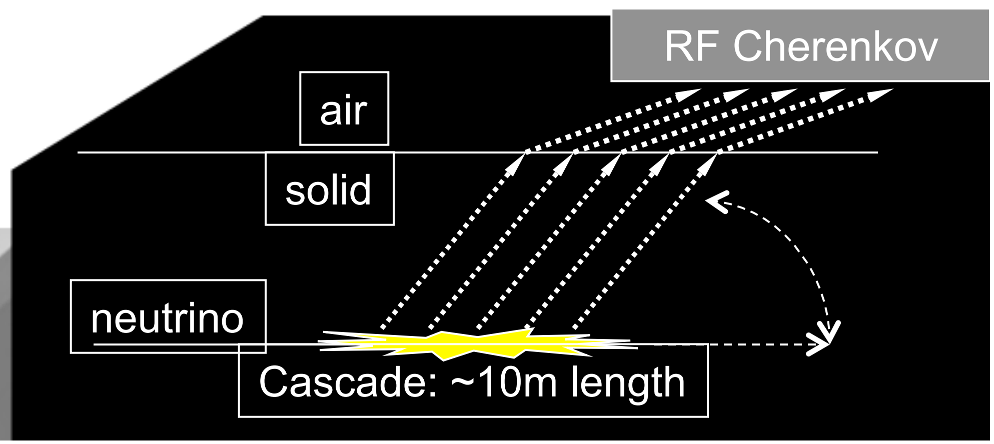


- Installed ~15 antennas few hundred m depth with AMANDA strings.
- Tests and data since 1996.
- Most events due to local radio noise, few candidates.
- Continuing to take data, and first limits prepared.
- Proposal to Piggyback with ICECUBE

Antarctic Impulsive Transient Antenna Experiment
ANITA



searching for GZK neutrinos with radio detection in Antarctic ice

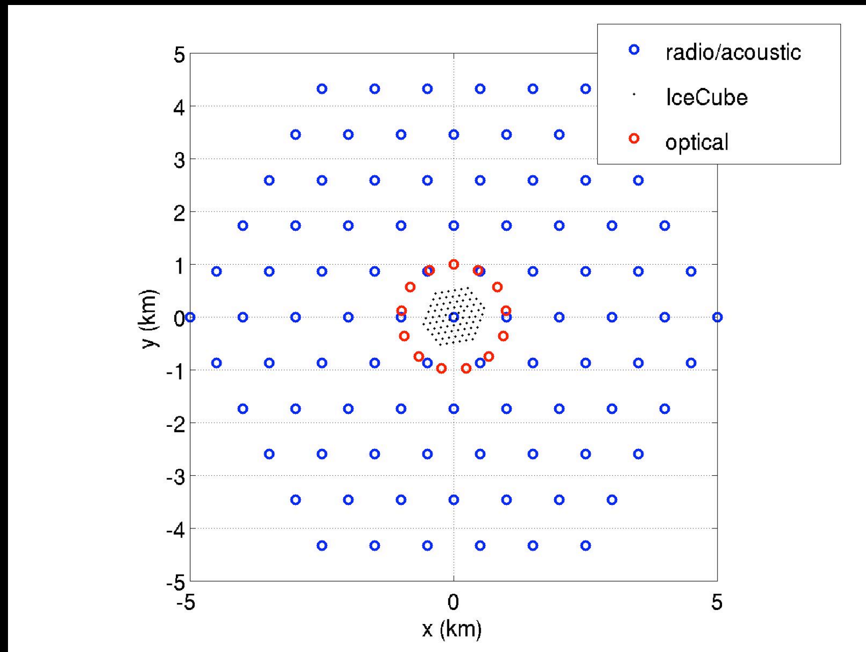


ICECUBE EXTENSION
optical-radio-acoustic detector

IceCube Collaboration, ICRC2005

instrumented volume :

~(110 +3) km^3



Optical:
80 IceCube + 13 IceCube-Plus strings at a 1 km radius, 1.5-2.5 km depth

Radio/Acoustic:
91 holes, 1 km spacing, 1.5 km depth
5 radio + 300 acoustic receivers per hole

EVENT RATES

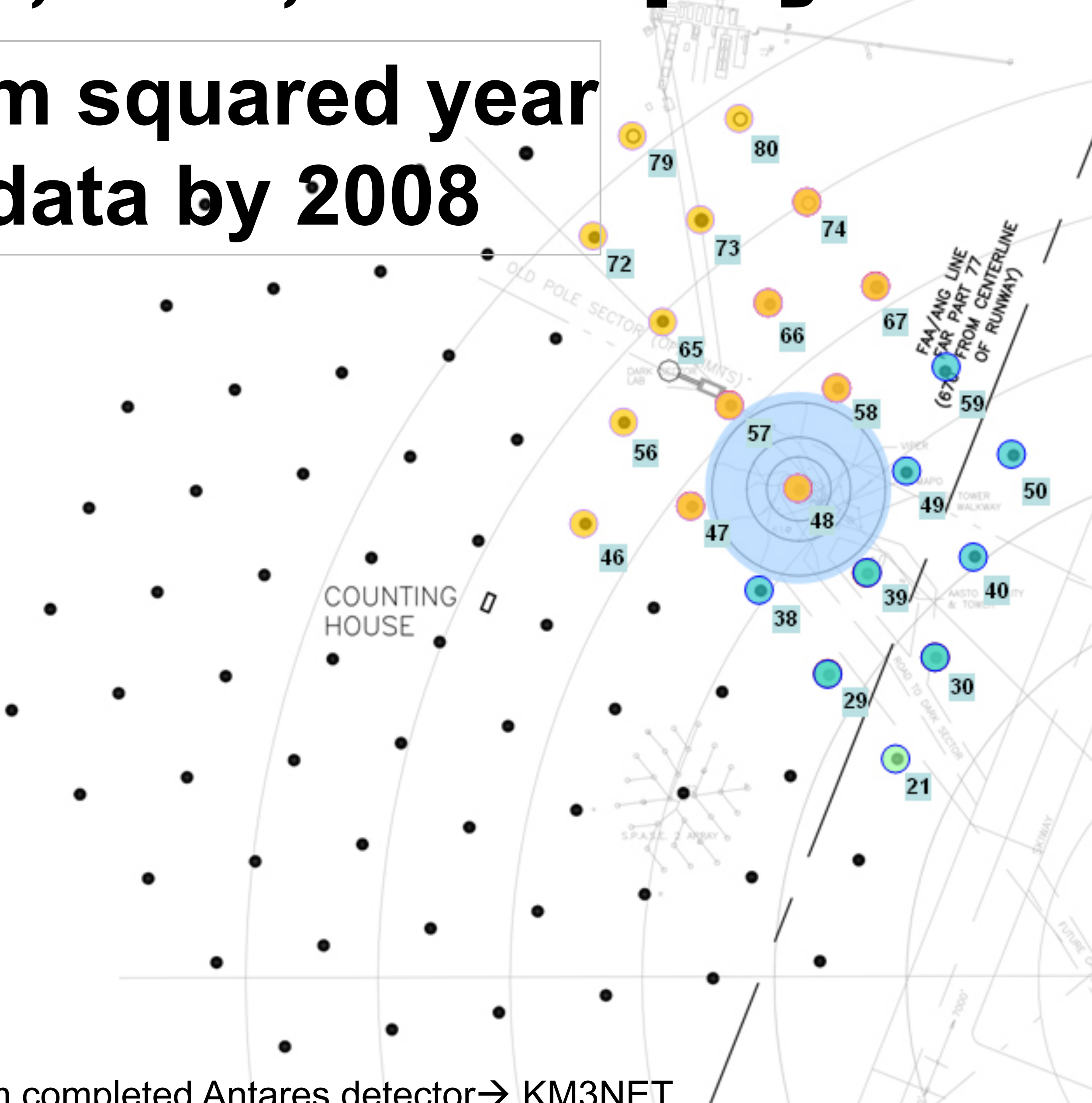
IceCube Colllaboration, ICRC2005

Detection option	GZK events/year*)
IceCube	0.7
Optical	1.2
Radio	12.3
Acoustic	16.0
Optical+Radio	0.2
Optical+Acoustic	0.3
Radio+Acoustic	8.0 !!!
Opt.+Rad.+Acou.	0.1
TOTAL	21.1

*Numbers calculated, folding effective volumes with ESS GZK neutrino flux model

2005, 2006, 2007 deployments

a km squared year
data by 2008



AMANDA

IceCube string and IceTop station deployed 01/05

IceCube string and IceTop station deployed 12/05 – 01/06

IceTop station only 2006

IceCube string and IceTop station to be deployed 12/06 – 01/07

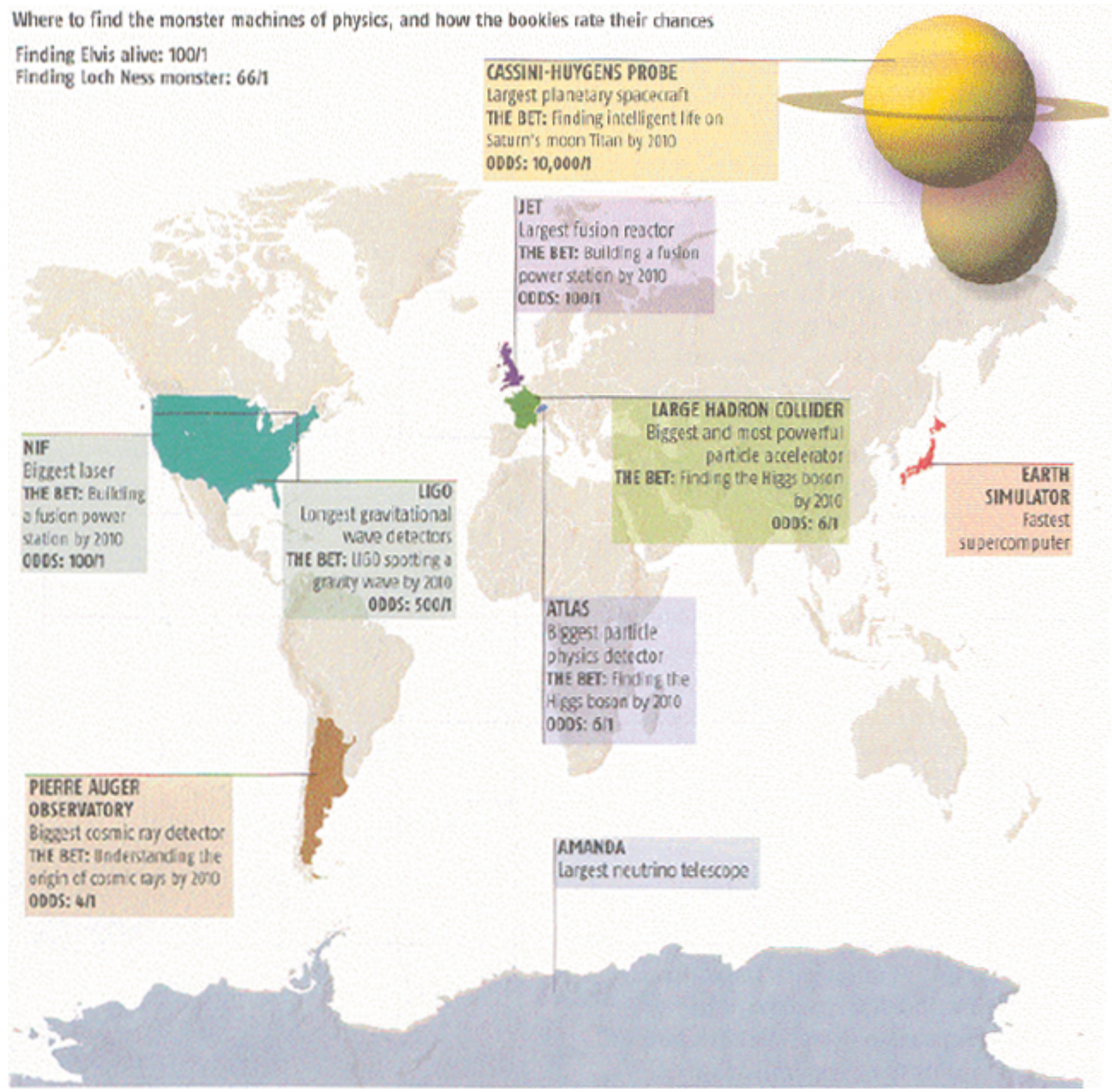
- 604 DOMs deployed to date
- Want to achieve steady state of 14 strings / season.

Data from completed Antares detector→ KM3NET

The Worlds Biggest Physics Experiments

From New Scientist:

AMANDA discovers cosmic neutrinos 6/1

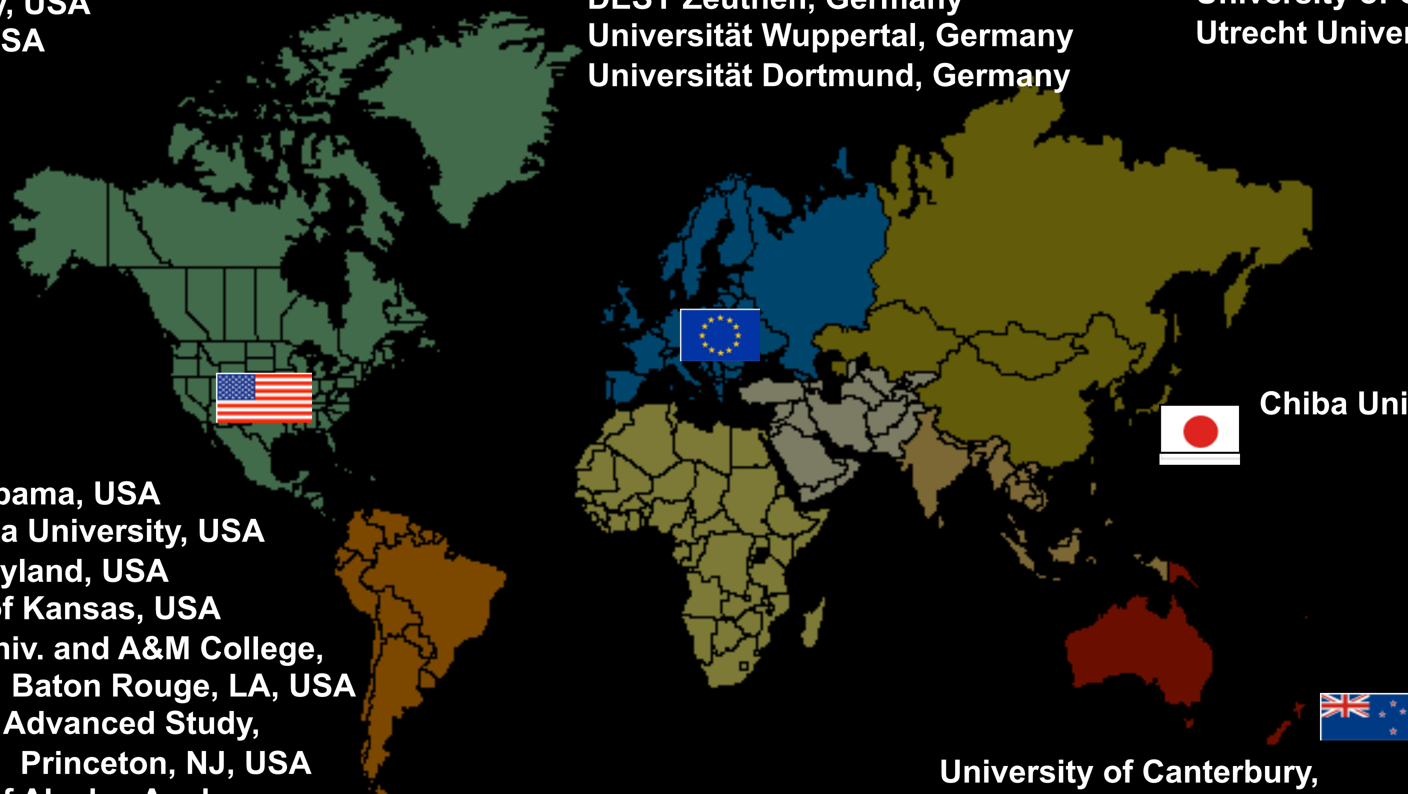


IceCube Collaboration

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

Université Libre de Bruxelles, Belgium
Vrije Universiteit Brussel, Belgium
Université de Mons-Hainaut, Belgium
Universiteit Gent, Belgium
Universität Mainz, Germany
DESY Zeuthen, Germany
Universität Wuppertal, Germany
Universität Dortmund, Germany

Humboldt Universität, Germany
MPI, Heidelberg
Uppsala Universitet, Sweden
Stockholm Universitet, Sweden
Kalmar Universitet, Sweden
Imperial College, London, UK
University of Oxford, UK
Utrecht University, Netherlands



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Clark-Atlanta University, USA
Univ. of Maryland, USA
University of Kansas, USA
Southern Univ. and A&M College, Baton Rouge, LA, USA
Institute for Advanced Study, Princeton, NJ, USA
University of Alaska, Anchorage

University of Canterbury, Christchurch, New Zealand

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