

# IceCube

## Recent Results and Prospects

Tyce DeYoung

Penn State University

for the IceCube Collaboration

Rome International Conference on Astroparticle Physics

June 22, 2007





I c e C u b e

# The IceCube Collaboration

University of Alaska, Anchorage

University of California, Berkeley

University of California, Irvine

Clark-Atlanta University

University of Delaware / Bartol

Research Institute

University of Kansas

Lawrence Berkeley Natl. Laboratory

University of Maryland

Pennsylvania State University

Southern University and A&M College

University of Wisconsin, Madison

University of Wisconsin, River Falls

RWTH Aachen

DESY, Zeuthen

Universität Dortmund

MPfK Heidelberg

Humboldt Universität, Berlin

Universität Mainz

BUGH Wuppertal



Stockholms Universitet  
Uppsala Universitet



Vrije Universiteit Brussel  
Université Libre de Bruxelles  
Université de Mons-Hainaut



Chiba University



University of Canterbury,  
Christchurch



Universiteit Utrecht



Oxford University





IceCube

# Outline

- The IceCube Detector
  - Design
  - Construction Status
- Recent Results
  - AMANDA
  - IceCube
- Scientific Prospects

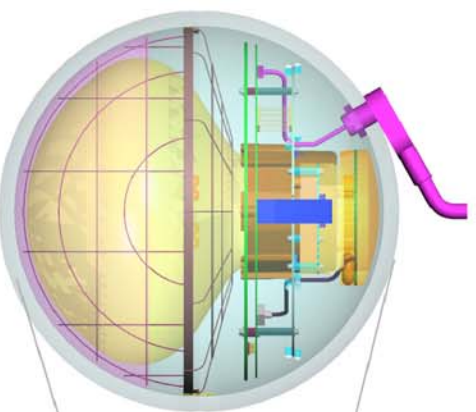
# IceCube

4800 DOMs on 80 strings

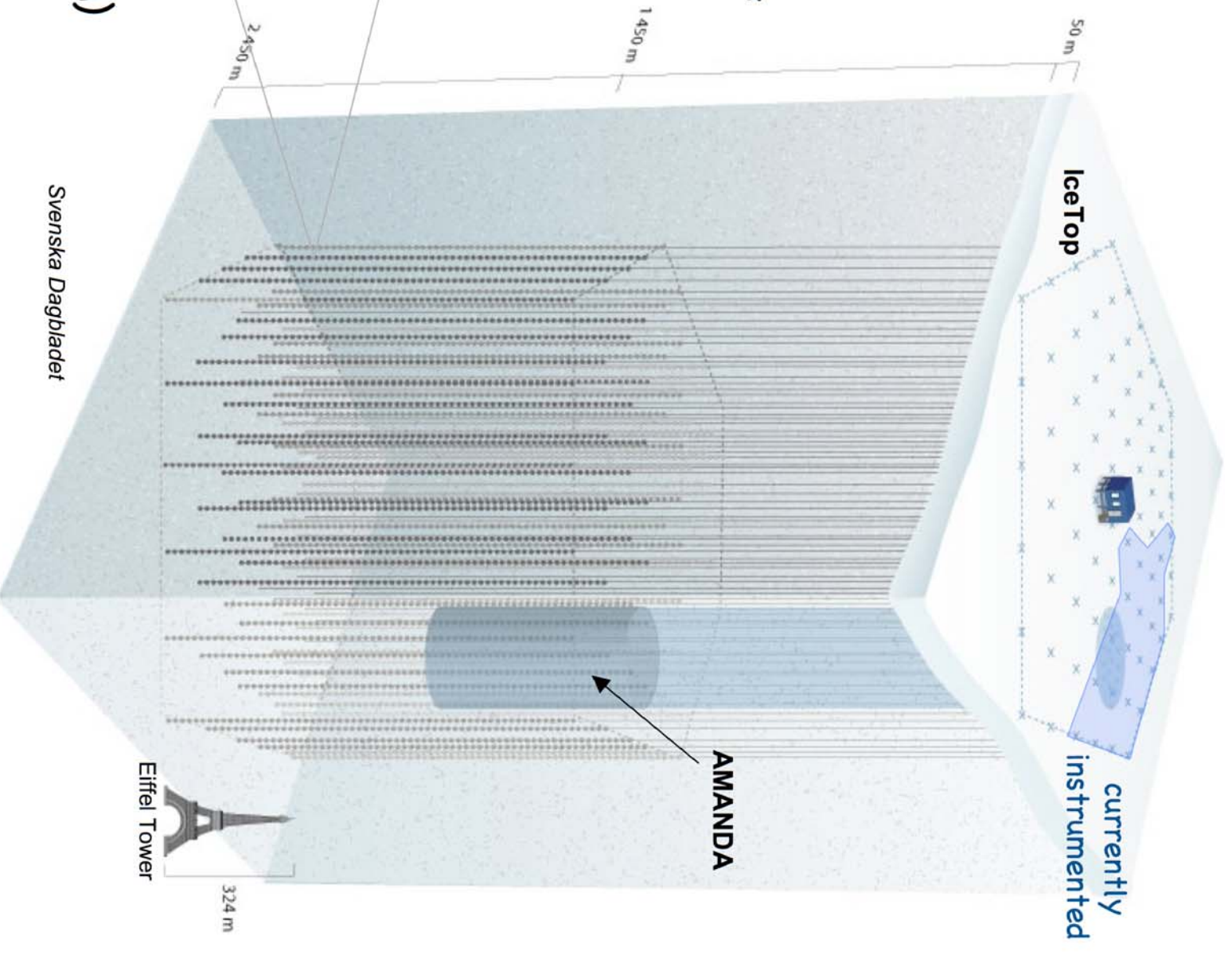
160 Ice-Cherenkov tank surface array (IceTop)

Surrounds existing AMANDA detector (677 OMs)

22 strings deployed in 3 construction seasons



Digital Optical Module (DOM)



Svenska Dagbladet

Eiffel Tower

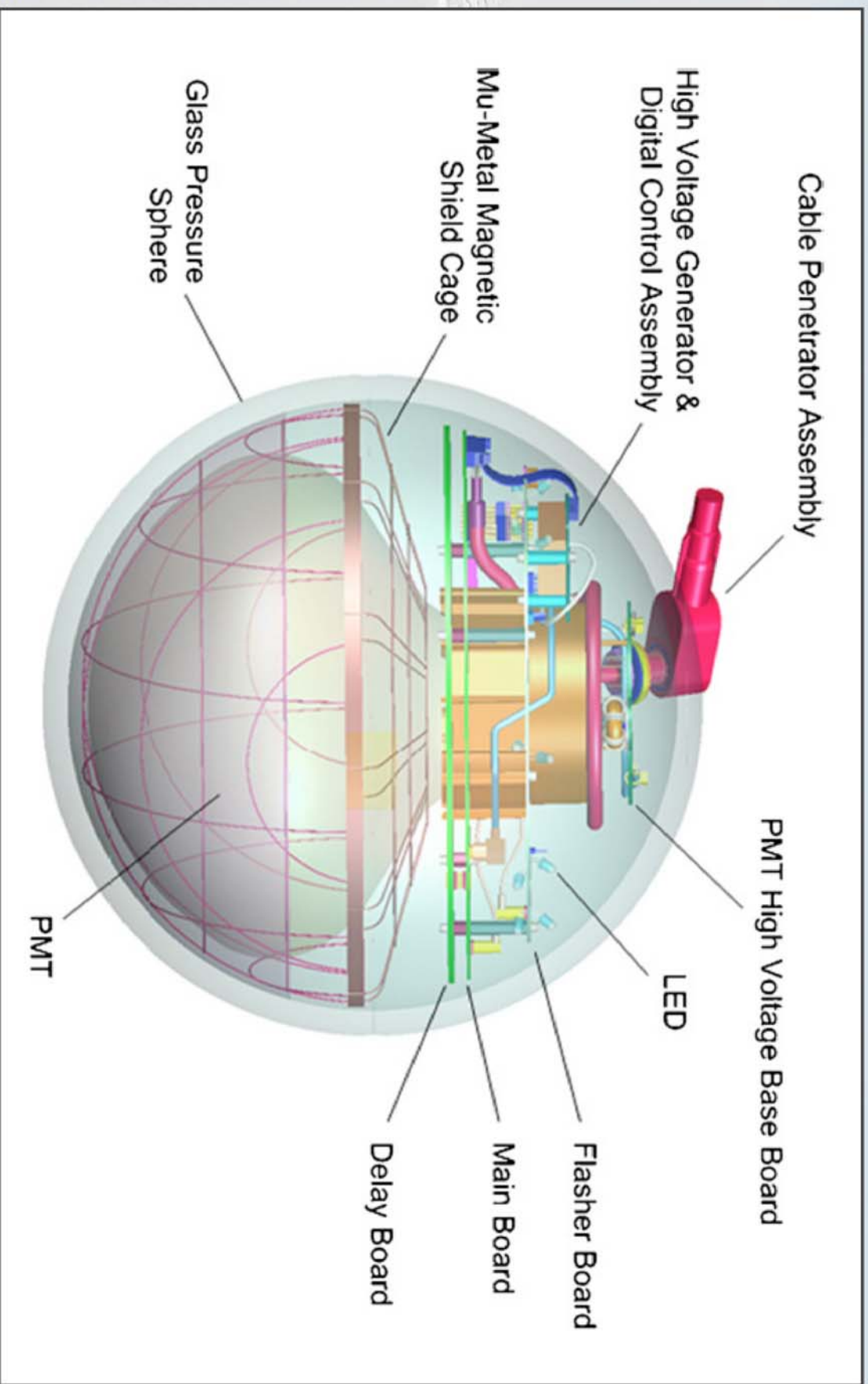
324 m





IceCube

# The Digital Optical Module (DOM)

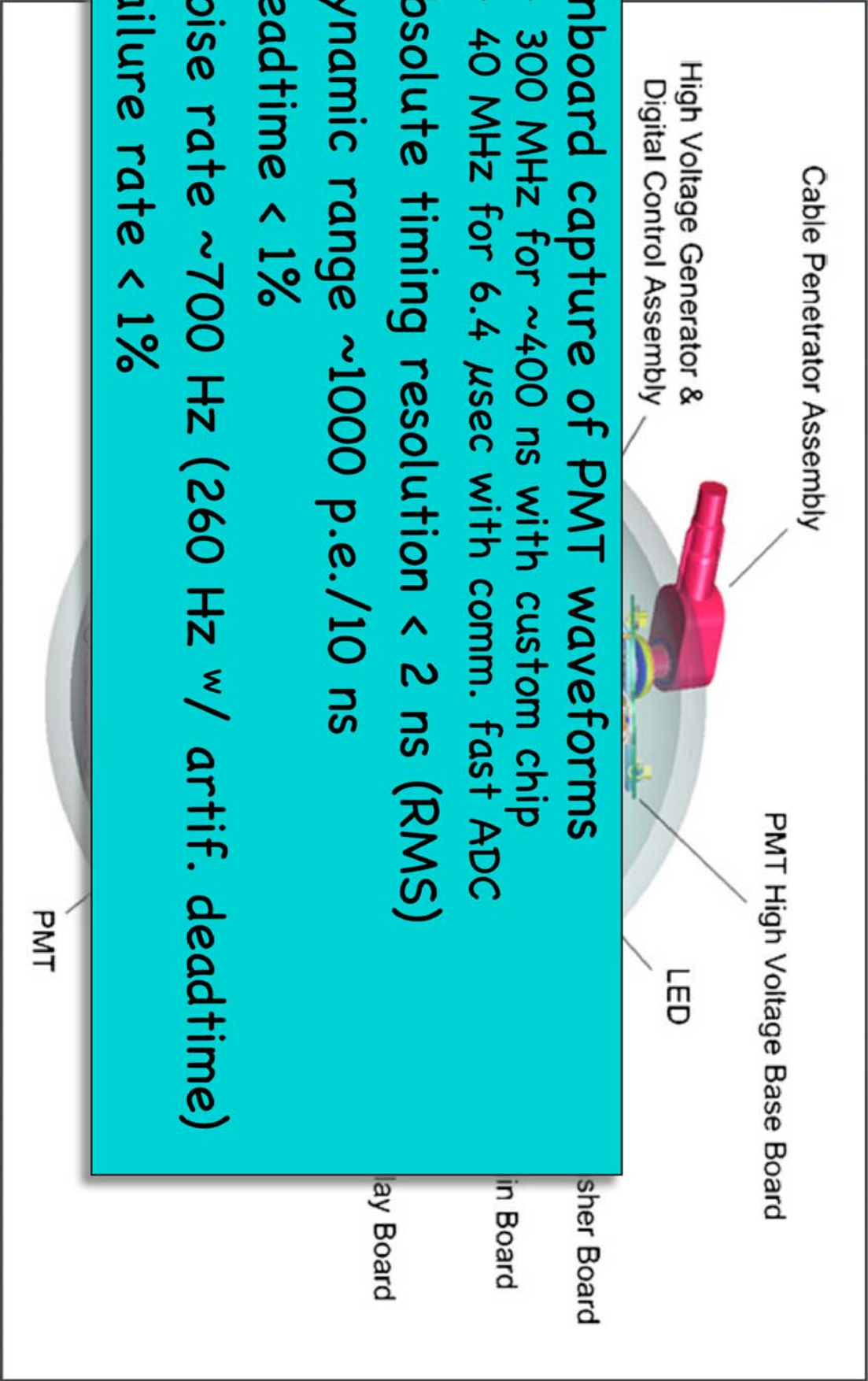




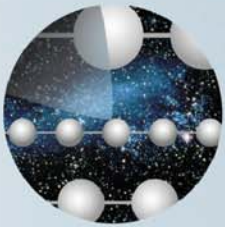
IceCube

# The Digital Optical Module (DOM)

- Onboard capture of PMT waveforms
  - 300 MHz for  $\sim 400$  ns with custom chip
  - 40 MHz for 6.4  $\mu$ sec with comm. fast ADC
- Absolute timing resolution  $< 2$  ns (RMS)
- Dynamic range  $\sim 1000$  p.e./10 ns
- Deadtime  $< 1\%$
- Noise rate  $\sim 700$  Hz (260 Hz w/ artif. deadtime)
- Failure rate  $< 1\%$



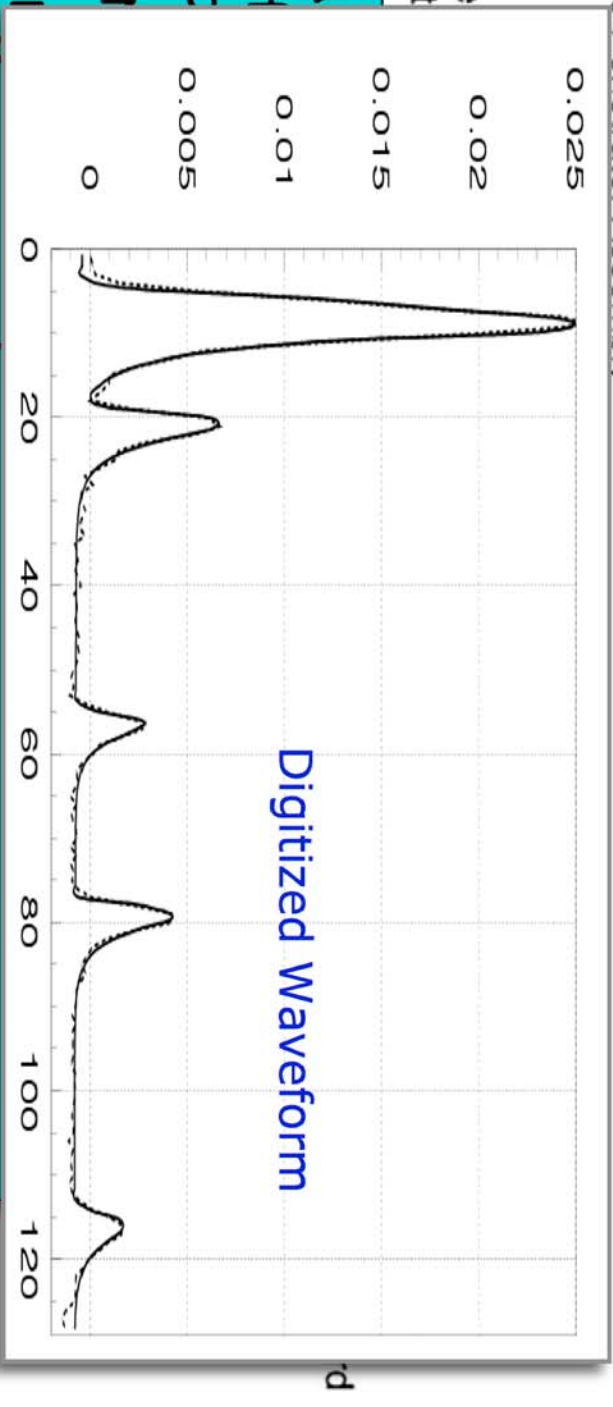




# The Digital Optical Module (DOM)

IceCube

Cable Penetrator Assembly  
High Voltage  
Digital Cont



- Onboard ca
  - 300 MHz
  - 40 MHz fc
- Absolute tim
- Dynamic ra
- Deadtime < 1%
- Noise rate ~700 Hz (260 Hz <sup>w</sup>/ artif. deadtime)
- Failure rate < 1%

PMT





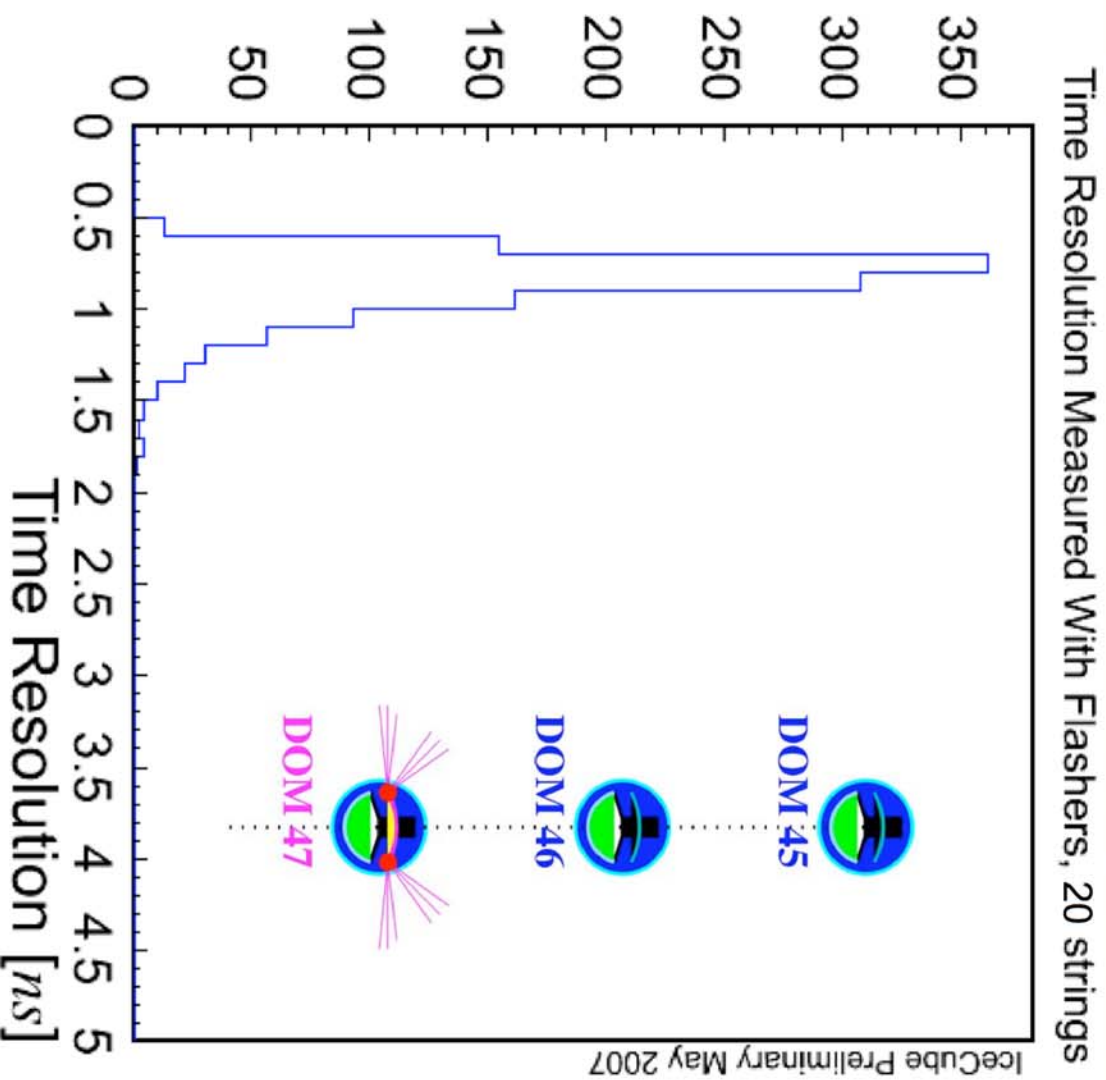


# The Digital Optical Module (DOM)

IceCube

Cable Penetration  
High Voltage Generator  
Digital Control Assembly

- Onboard capacitance
  - 300 MHz for 6.4
  - 40 MHz for 6.4
- Absolute timing
- Dynamic range
- Deadtime < 1%
- Noise rate ~70
- Failure rate < 1

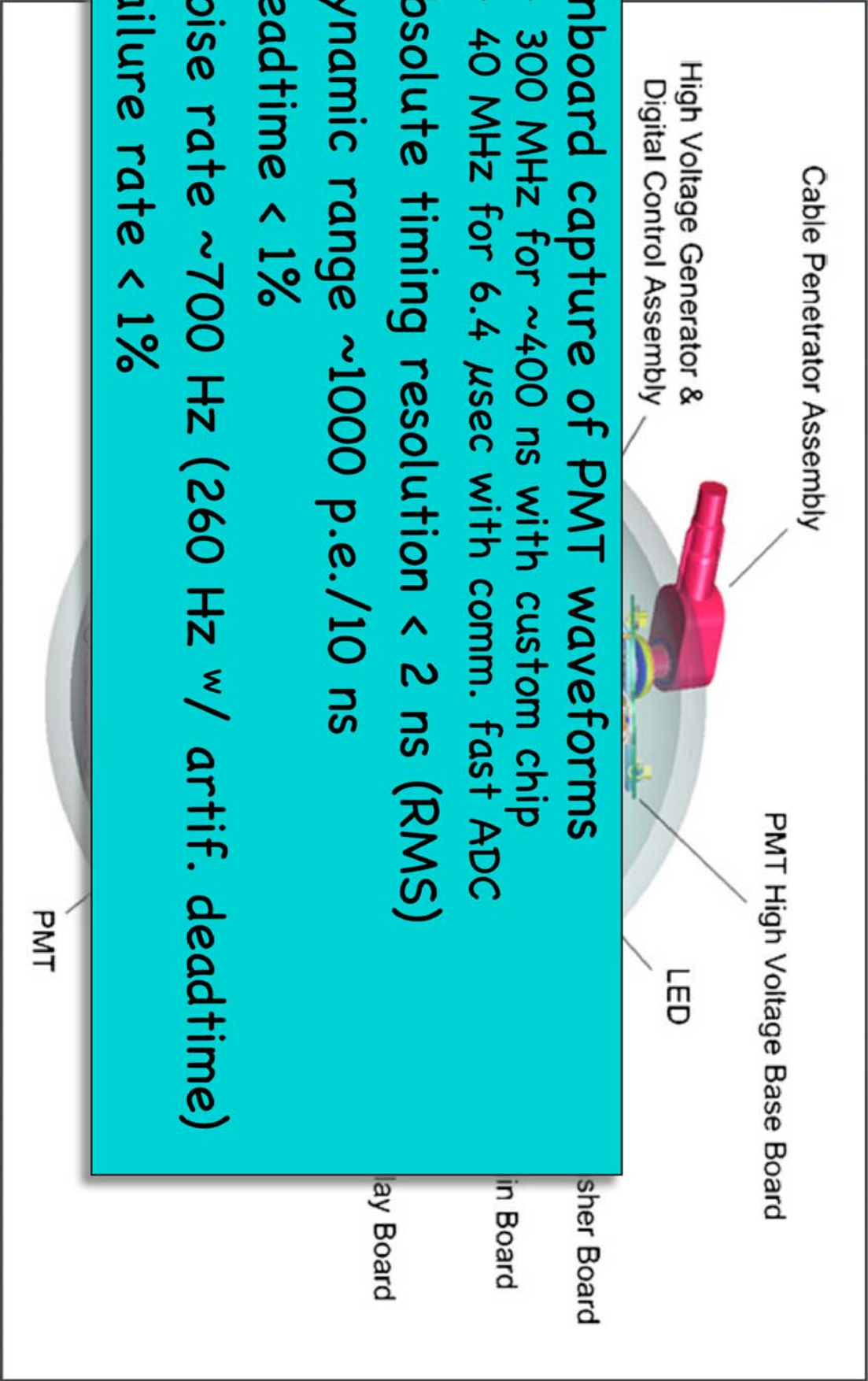




IceCube

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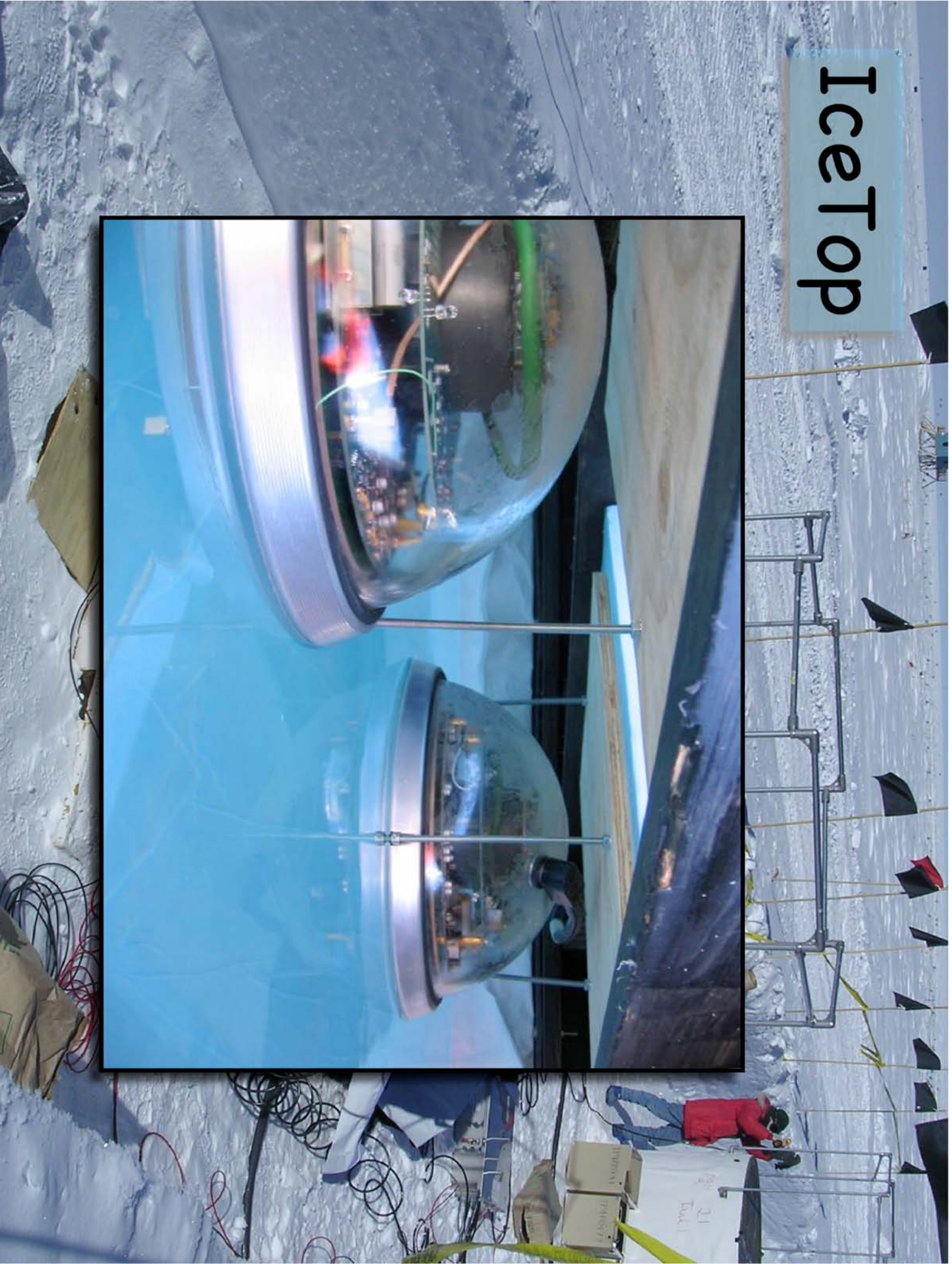


# IceTop





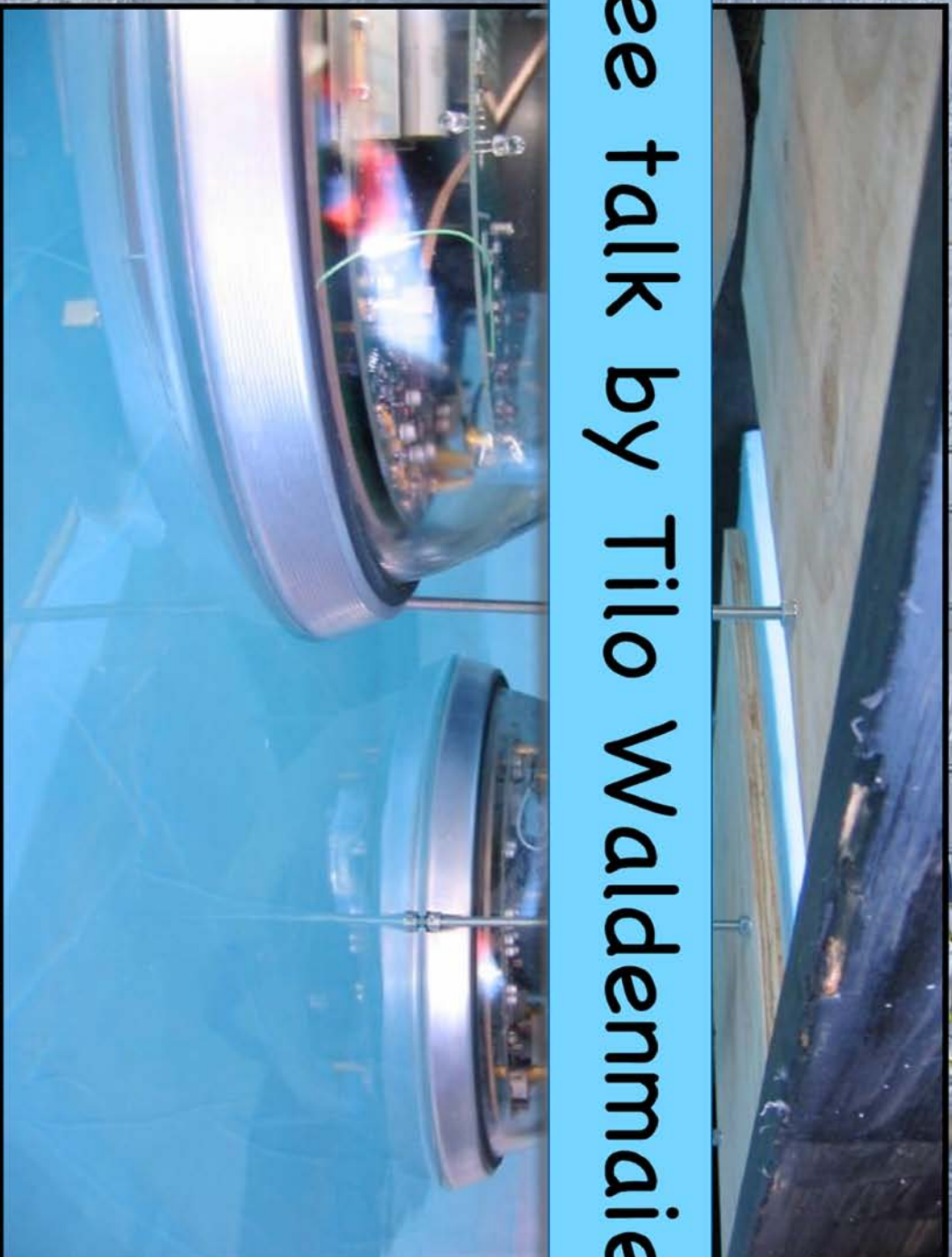
# IceTop



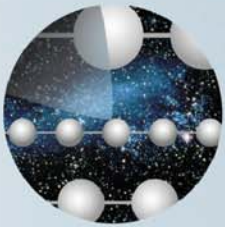


# IceTop

See talk by Tilo Waldenmaier



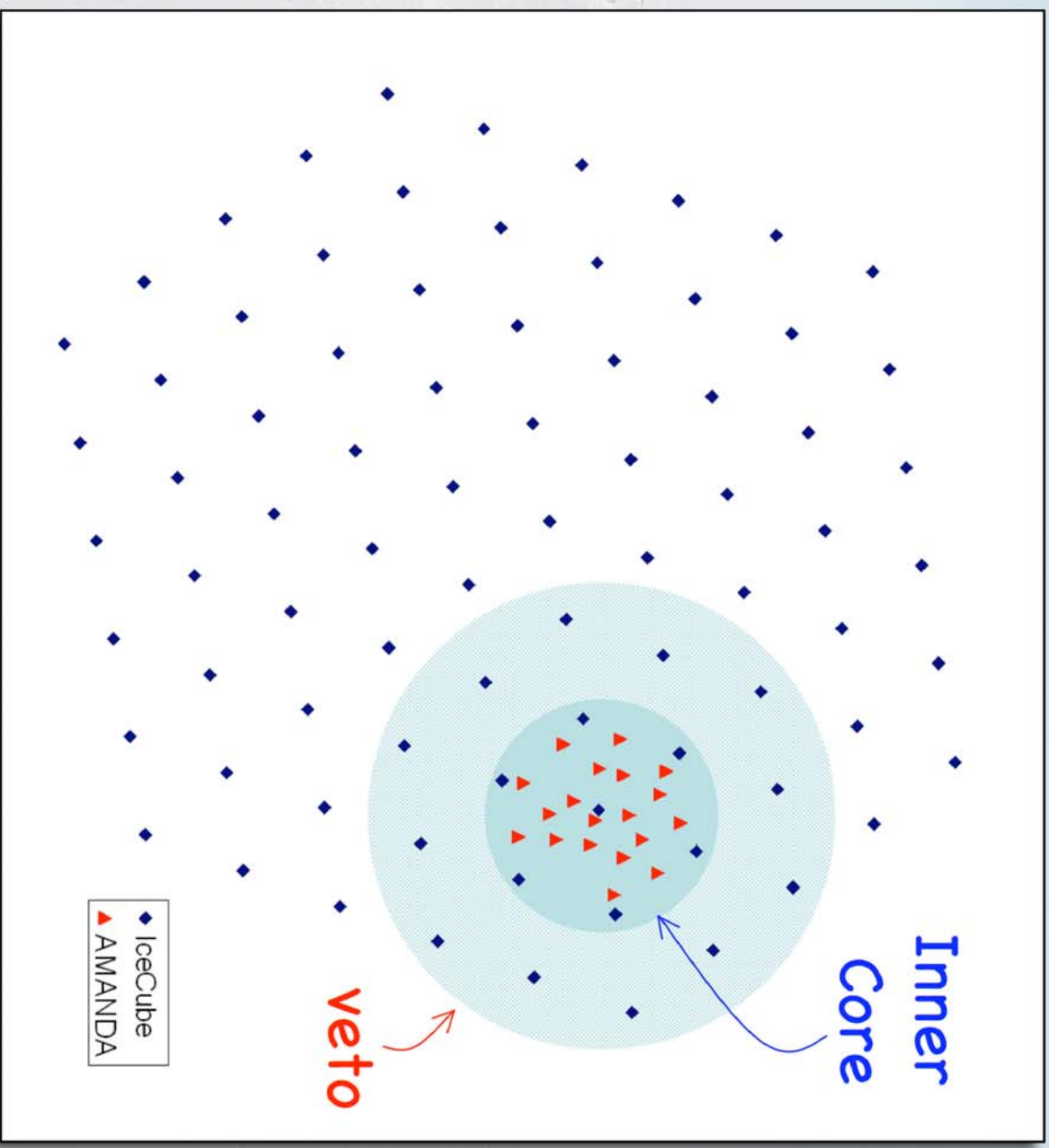




# IceCube + AMANDA

IceCube

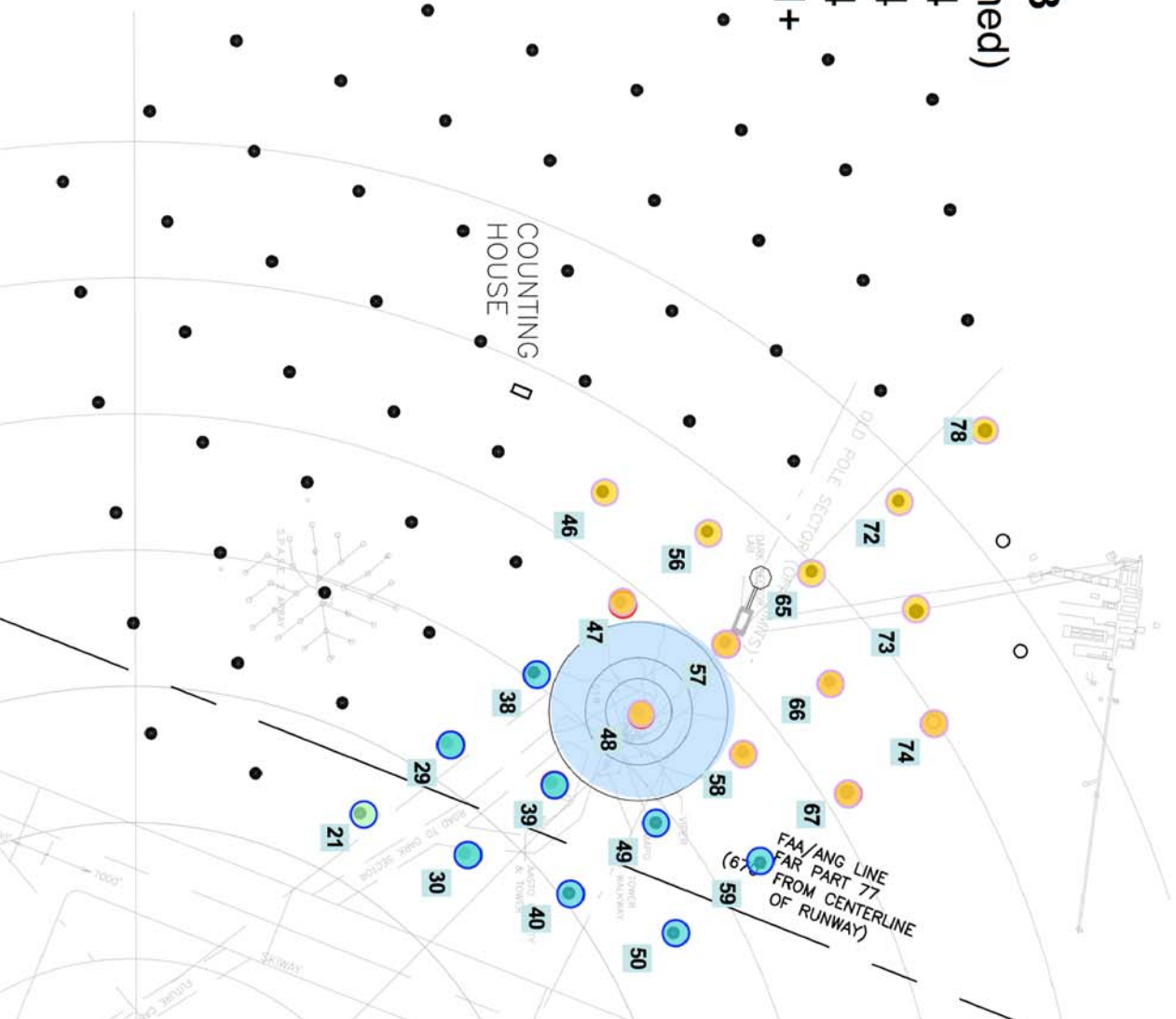
- Densely instrumented "Inner Core"
- Lower energy threshold
- 7 IceCube + 18 AMANDA strings
- 225 DOMs + 540 OMs
- Outer IceCube strings form veto volume










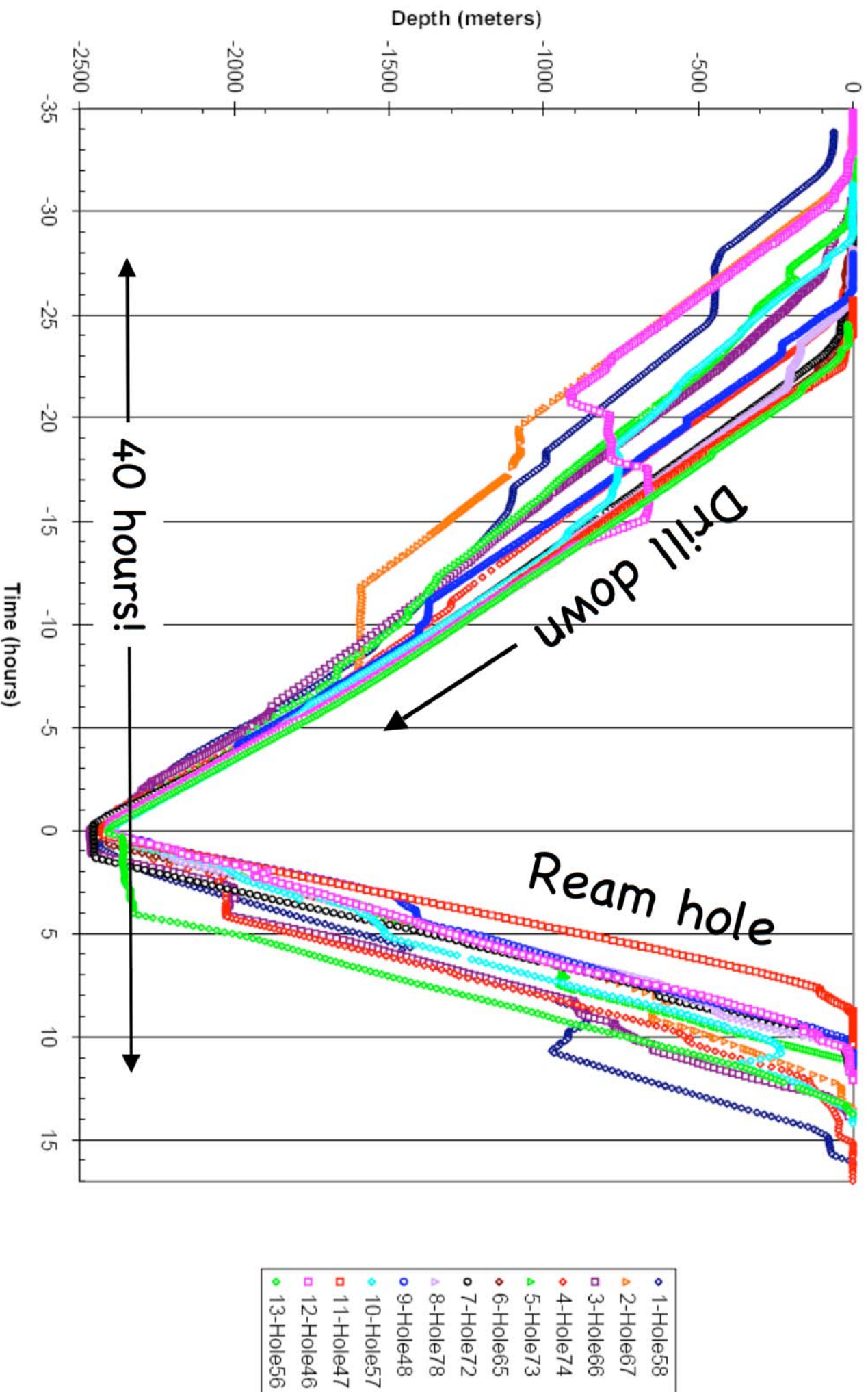
# IceCube Construction Status

- 2004/05: 1
- 2005/06: 8
- 2006/07: 13
- (12 planned)
- 2007/08: 14
- 2008/09: 14
- 2009/10: 14
- 2010/11: 11+

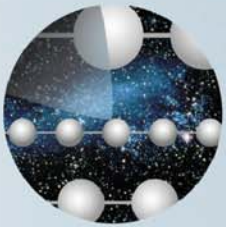


-  AMANDA 01/2000
-  IceCube string and IceTop station 01/05
-  IceCube string and IceTop station 01/06
-  IceTop station only 2006
-  IceCube string and IceTop station 02/07

# Drilling Performance 2007





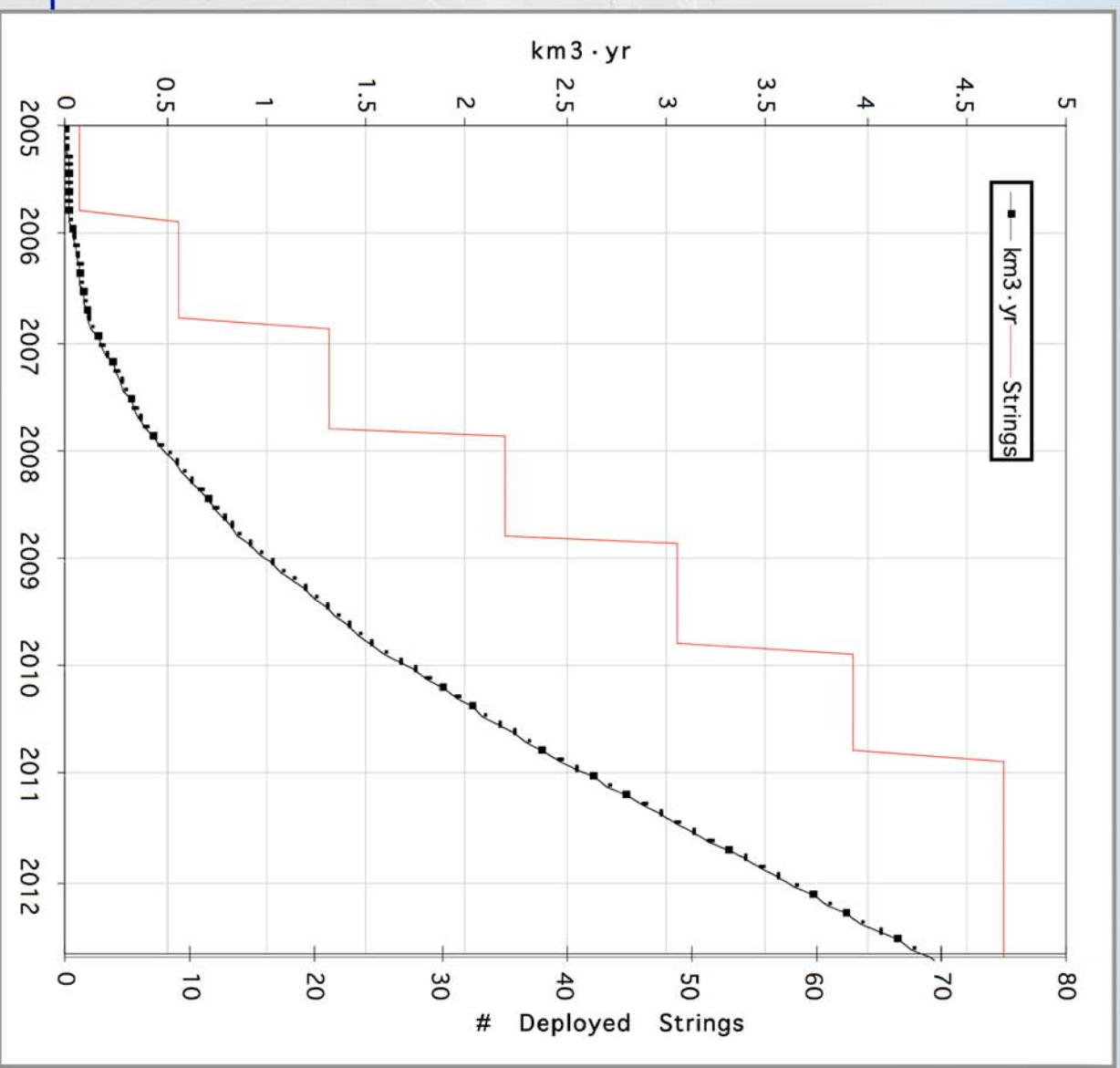


IceCube

# Integrated Exposure

- 1 km<sup>3</sup>·yr by early 2009

- Close to 4 km<sup>3</sup>·yr after one year of operations with full detector



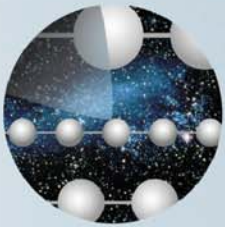


IceCube

# Outline

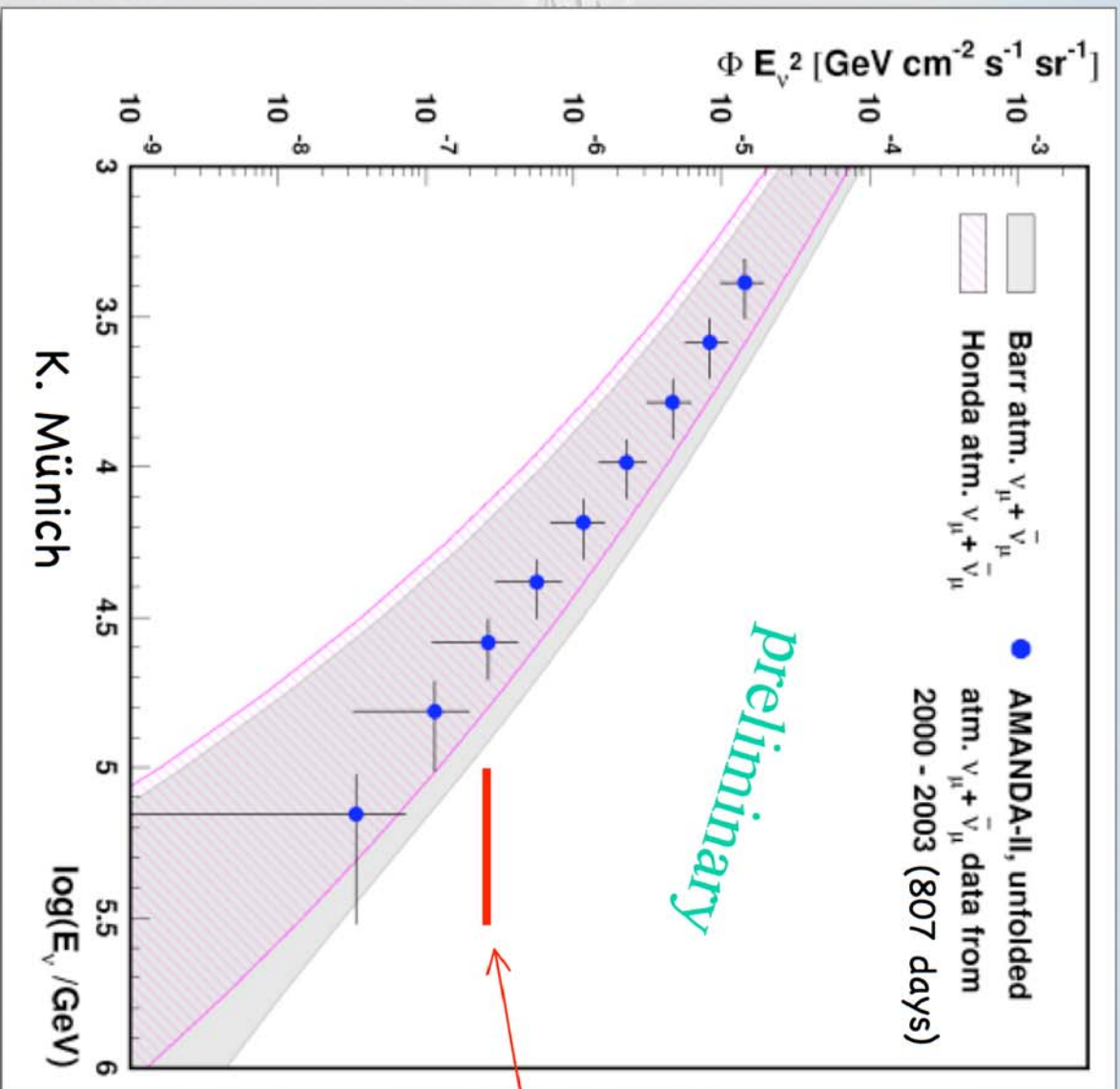
- The IceCube Detector
  - Design
  - Construction Status
- Recent Results
  - AMANDA (See talk by Kirsten Münich)
  - IceCube
- Scientific Prospects





IceCube

# AMANDA Atmospheric Neutrinos



K. Münich

Preliminary

● AMANDA-II, unfolded  
atm.  $\nu_\mu + \bar{\nu}_\mu$  data from  
2000 - 2003 (807 days)

□ Barr atm.  $\nu_\mu + \bar{\nu}_\mu$   
▨ Honda atm.  $\nu_\mu + \bar{\nu}_\mu$

$\Phi E_\nu^2 [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}]$

$\log(E_\nu/\text{GeV})$

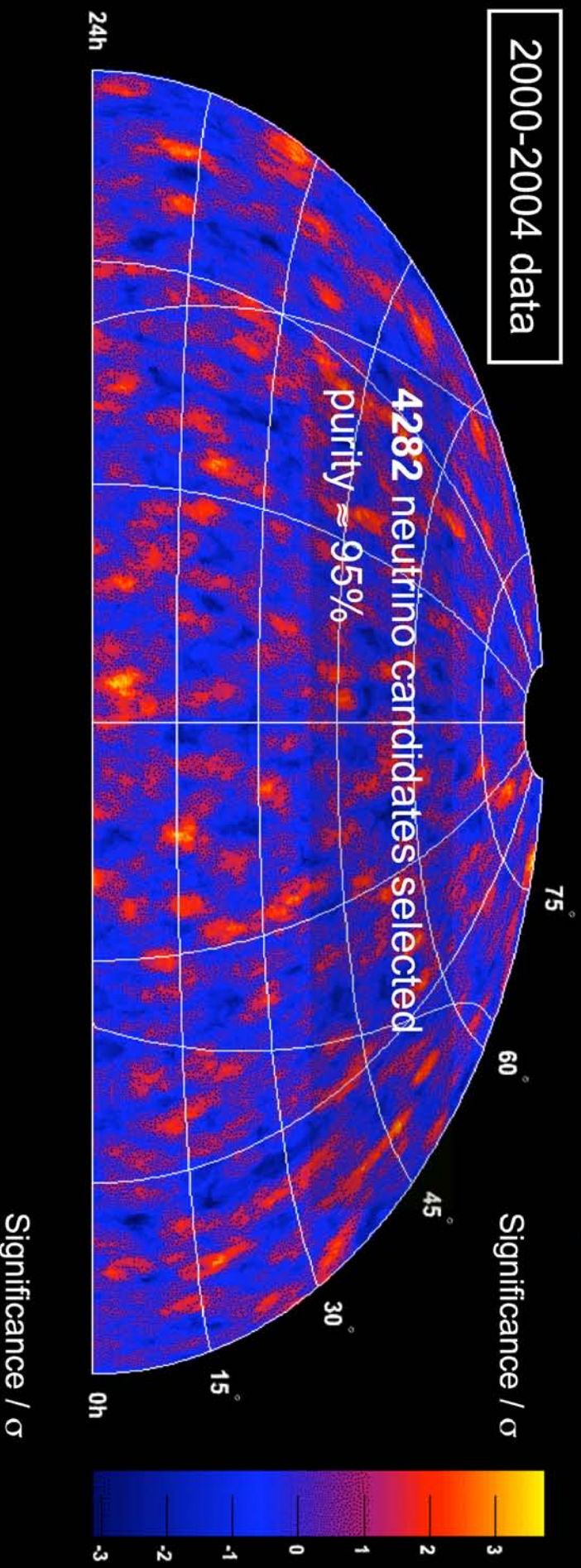
Limit based on only  
2000 data:

$$E^2 \Phi_\nu < 2.6 \cdot 10^{-7} \text{ GeV/cm}^2 \text{s sr}$$

Unfolded neutrino  
energy spectrum  
based on observed  
muon energies

# AMANDA Sky Map

2000-2004 data

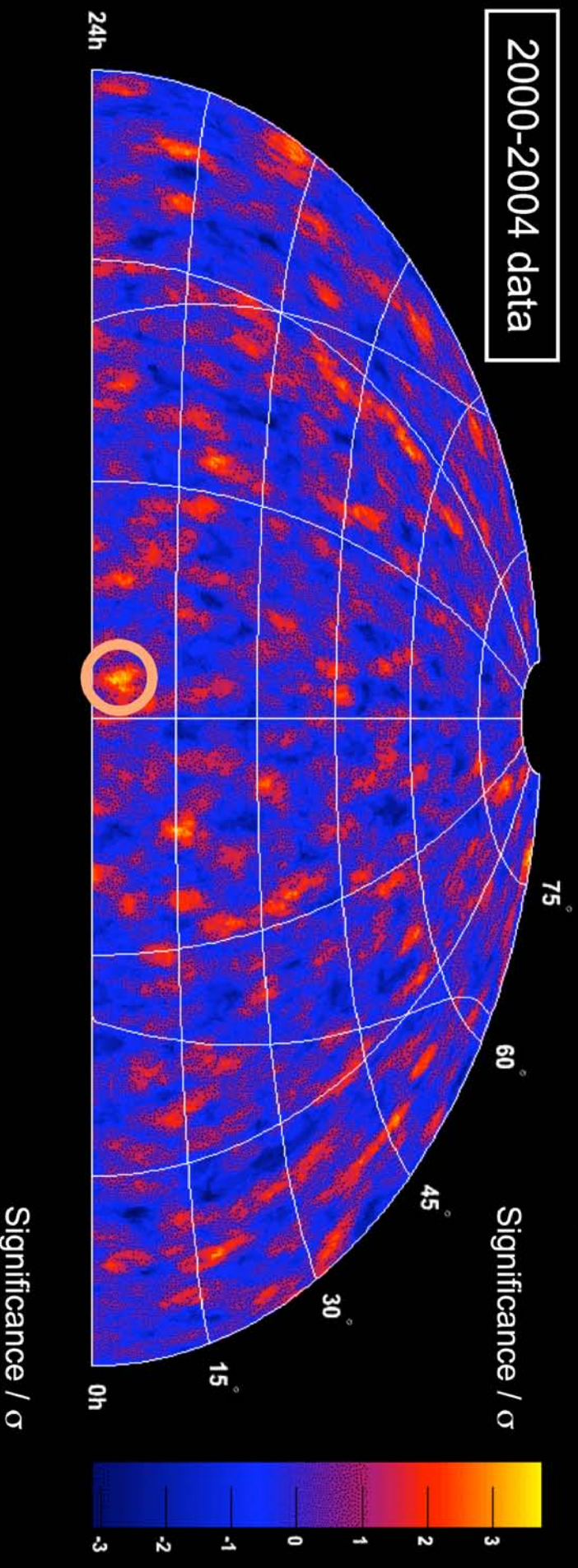


Achterberg et al. 2007, astro-ph/0611063



# AMANDA SKY MAP

2000-2004 data

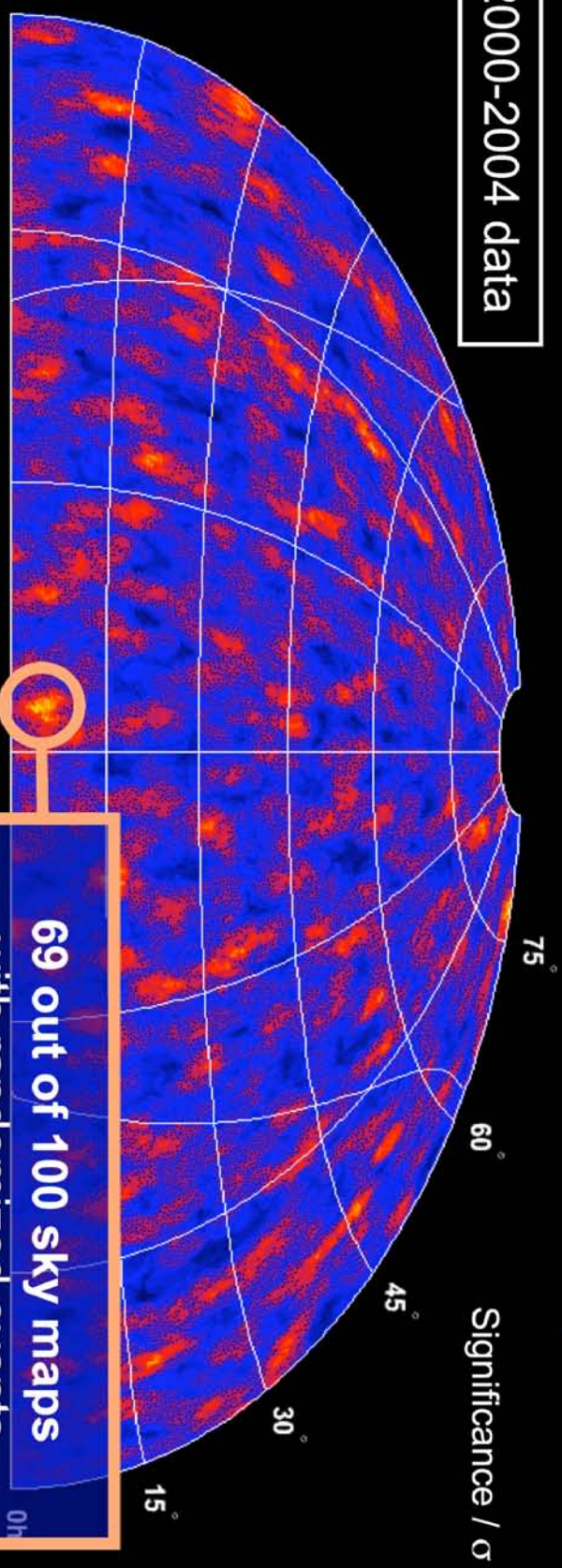


Achterberg et al. 2007, astro-ph/0611063



# AMANDA Sky Map

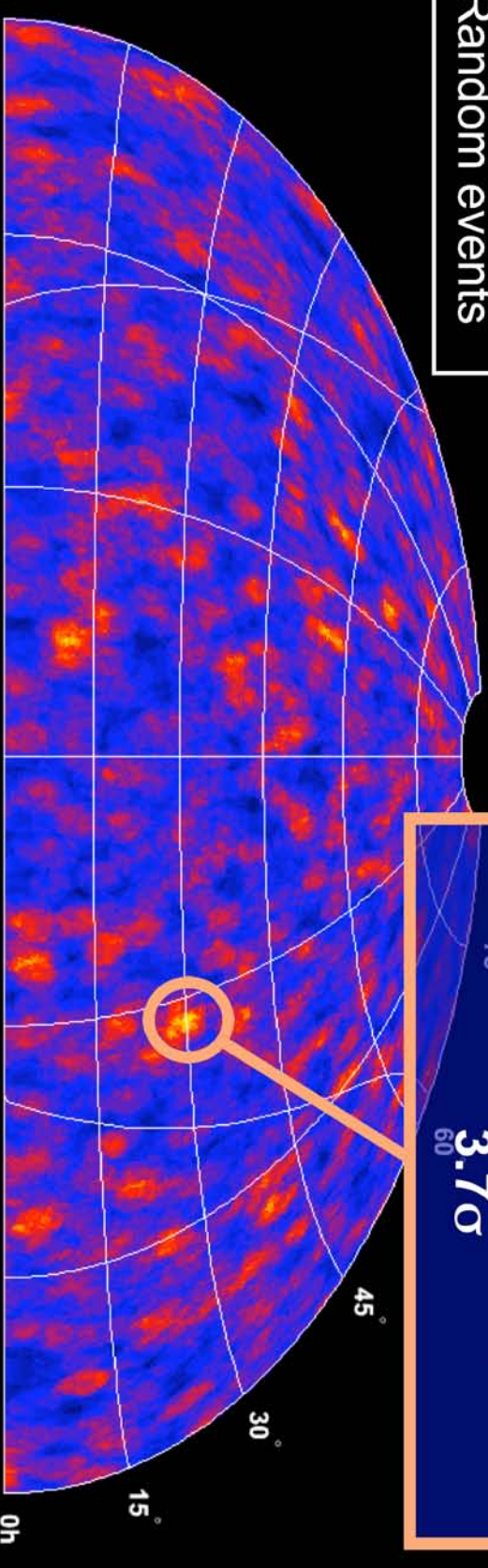
2000-2004 data



69 out of 100 sky maps  
with randomized events  
show an excess higher than

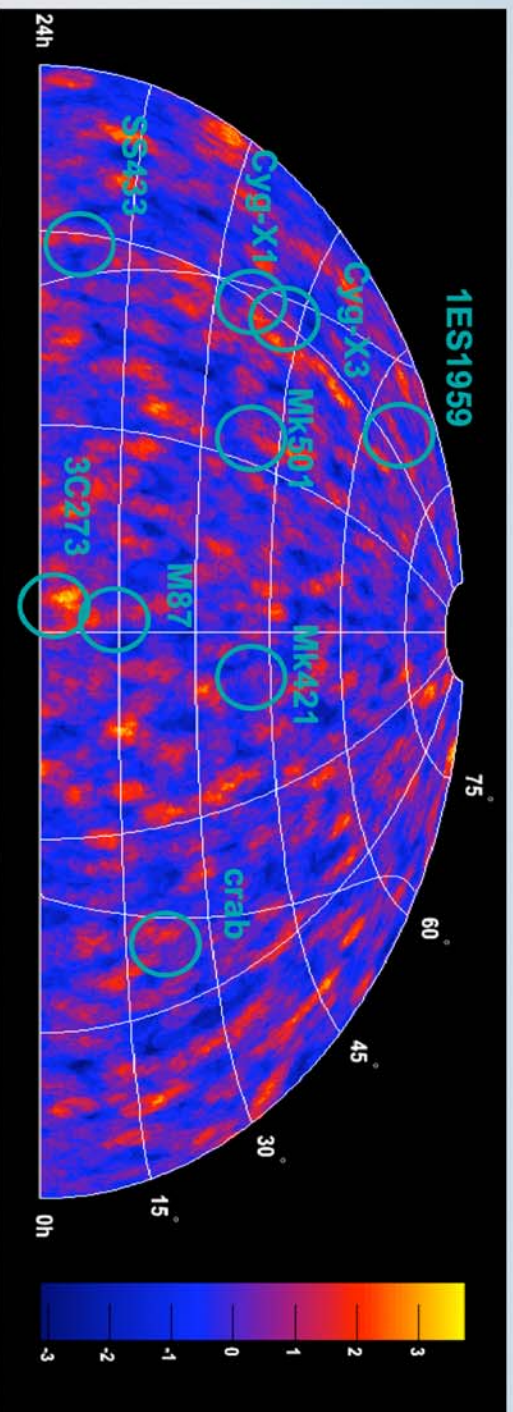
$3.7\sigma$

Random events





# Search for neutrinos from 32 candidate sources



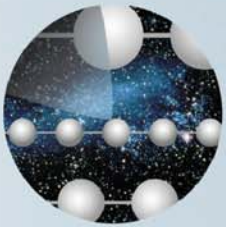
event selection optimized for both  $\text{dN/dE} \sim E^{-2}$  and  $E^{-3}$  spectra

source	nr. of $\nu$ events (5 years)	expected background (5 years)	$E^{-2}$ flux upper limit (90% c.l.) $\Phi_{\nu_e+\nu_\tau}$ [ $10^{-11} \text{ TeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$ ]
Markarian 421	6	7.4	7.4
M87	6	6.1	8.7
1ES 1959+650	5	4.8	13.5
SS433	4	6.1	4.8
Cygnus X-3	7	6.5	11.8
Cygnus X-1	8	7.0	13.2
Crab Nebula	10	6.7	17.8
3C 273	8	4.72	18.0

1.2 $\sigma$   
equiv.  
(random maps)

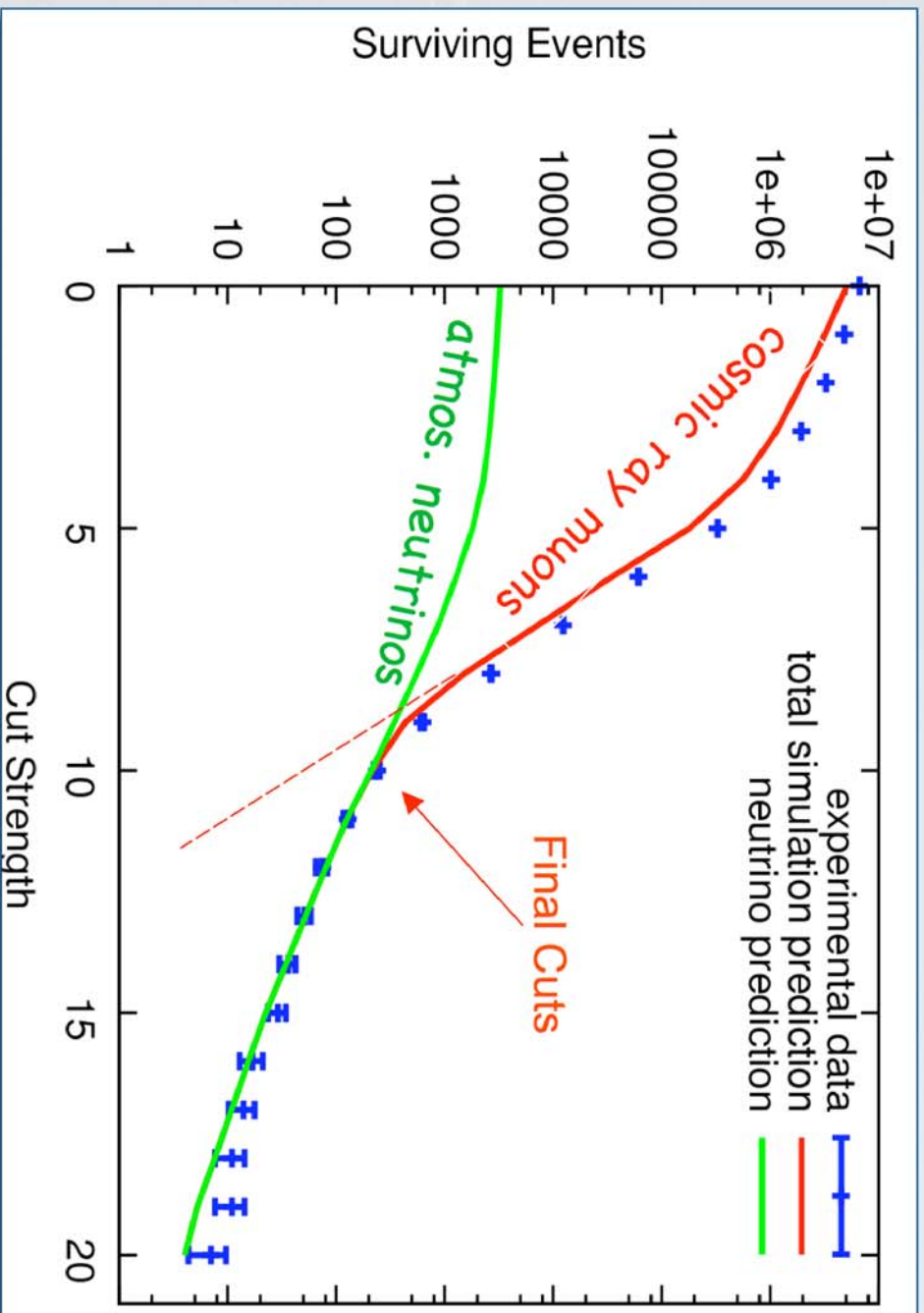
No significant excess observed

Achterberg  
et al. 2007,  
astro-ph/  
0611063



IceCube

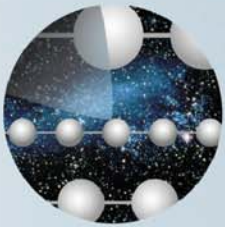
# IceCube Neutrino Observations



- 9-string data (2006)
- Cosmic ray background seen with weak cuts
- Atmospheric neutrinos seen with strong cuts
- Agreement in event rate over 6 decades

Achterberg et al. astro-ph/0705.1781



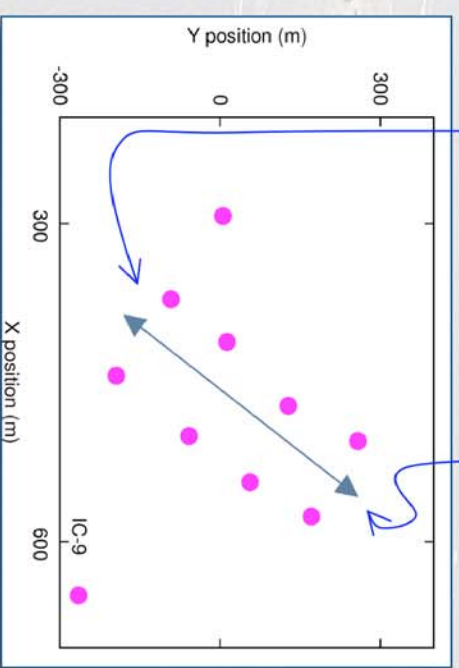
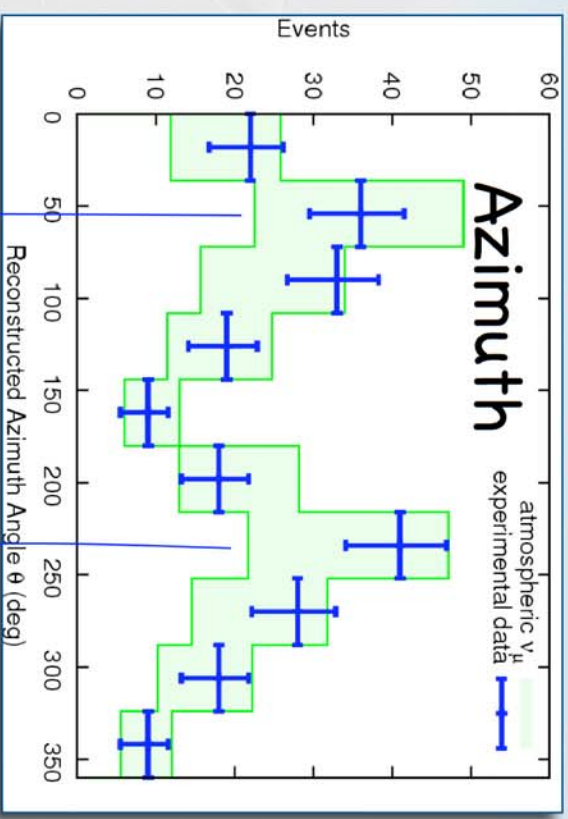
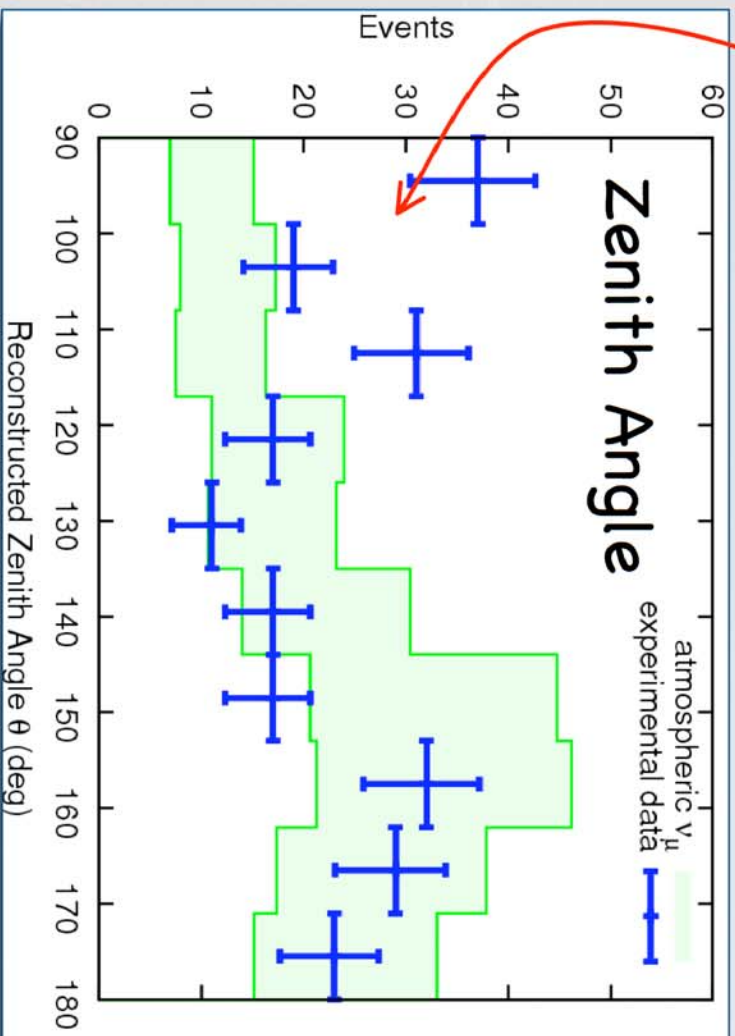


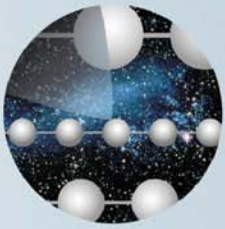
# IceCube-9 Neutrinos

IceCube

Achterberg et al. astro-ph/0705.1781

- Residual background near horizon ( $\sim 10\%$  of total set)
- Peaks in azimuth along detector long axis





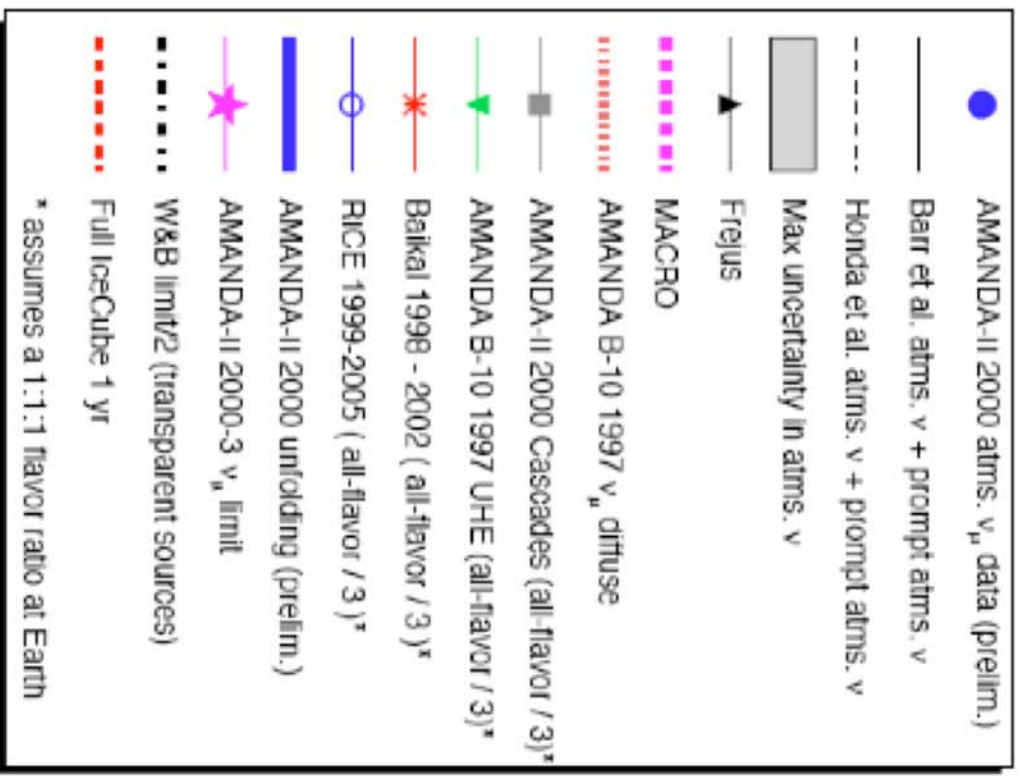
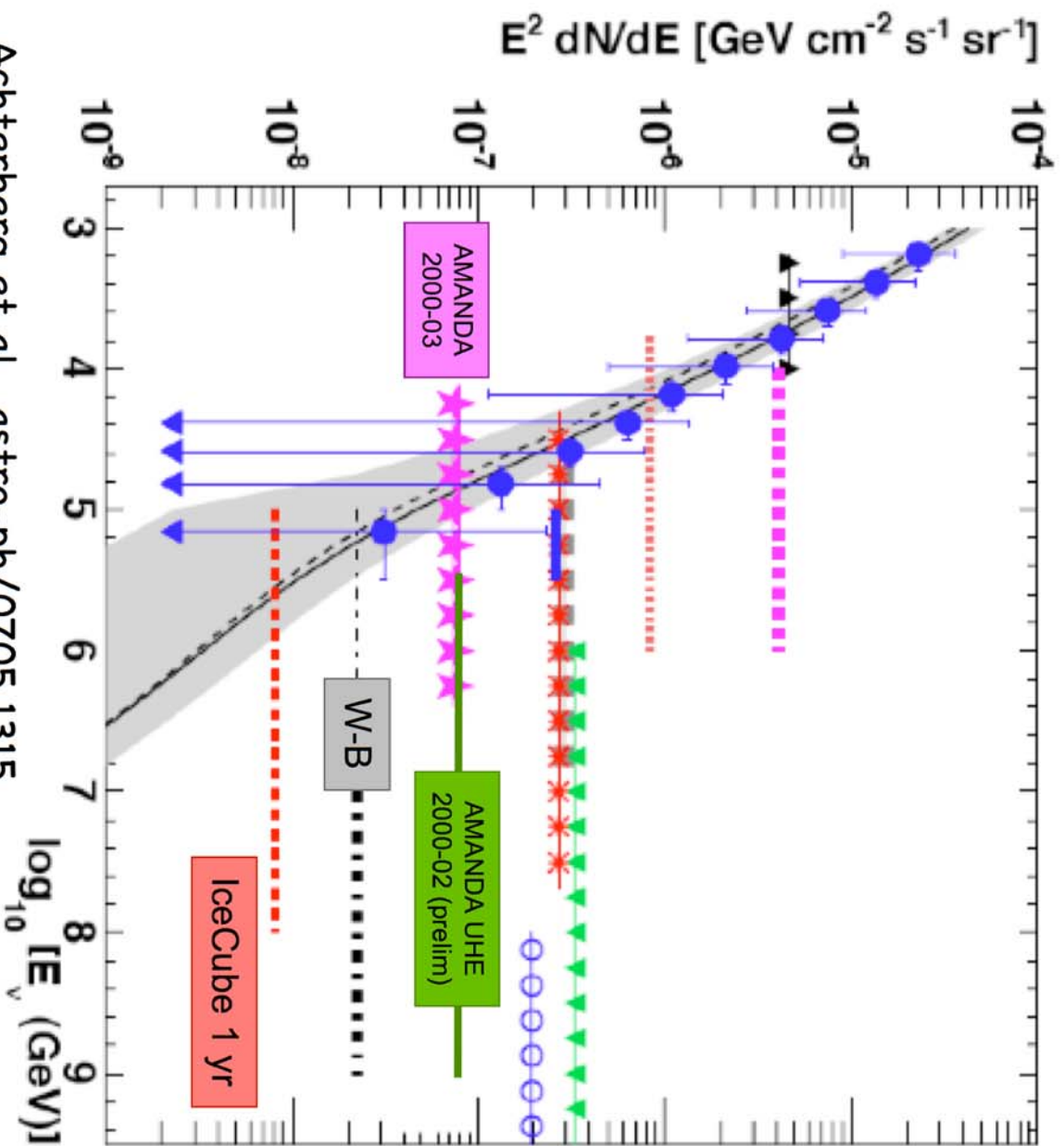
IceCube

# Outline

- The IceCube Detector
  - Design
  - Construction Status
- Recent Results
  - AMANDA
  - IceCube
- Scientific Prospects



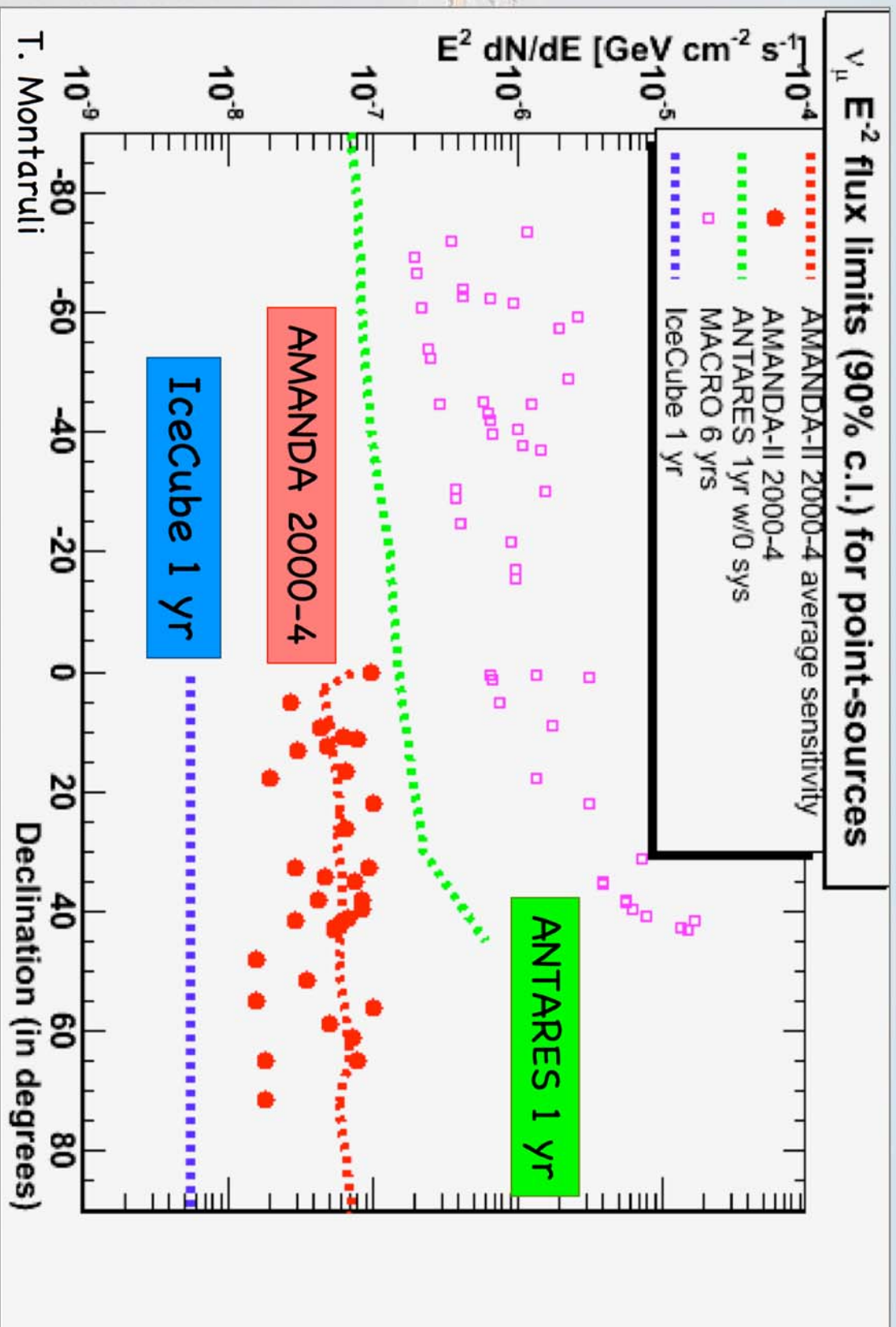
# Diffuse Neutrino Fluxes





IceCube

# Point Source Sensitivity



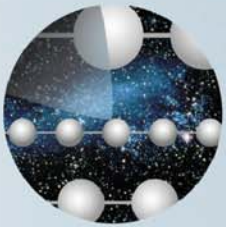
MACRO:  
astro-ph/  
0002492

AMANDA:  
astro-ph/  
0611063

ANTARES  
(binned):  
E. Carmona,  
Ph.D. thesis

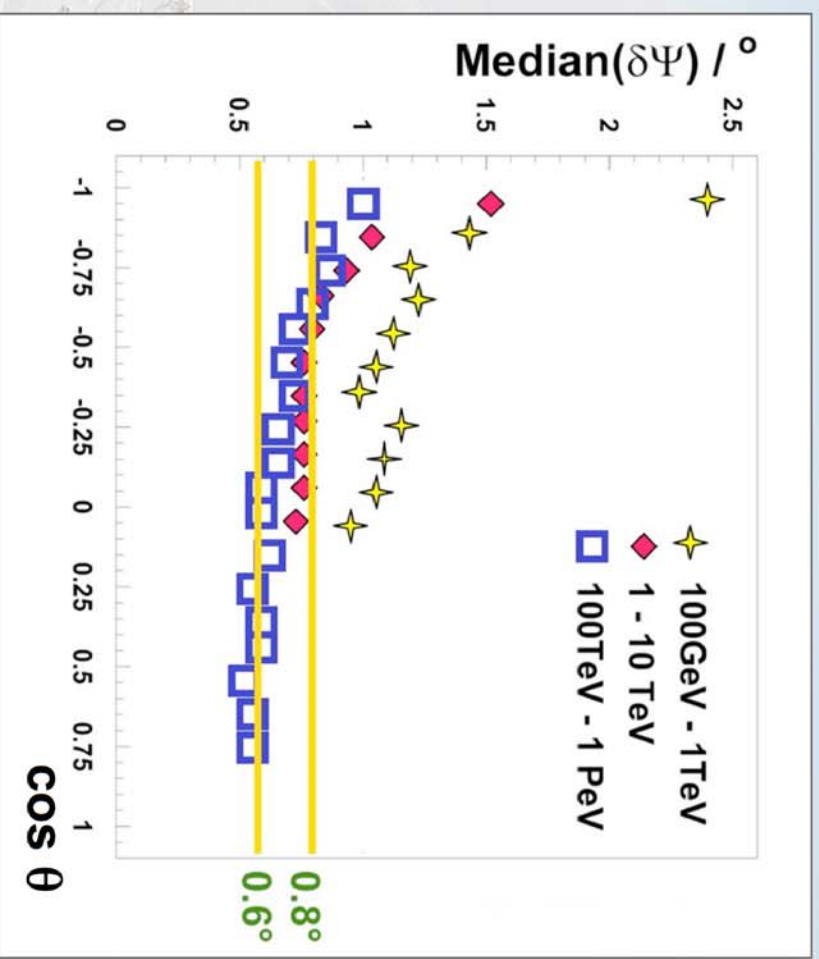
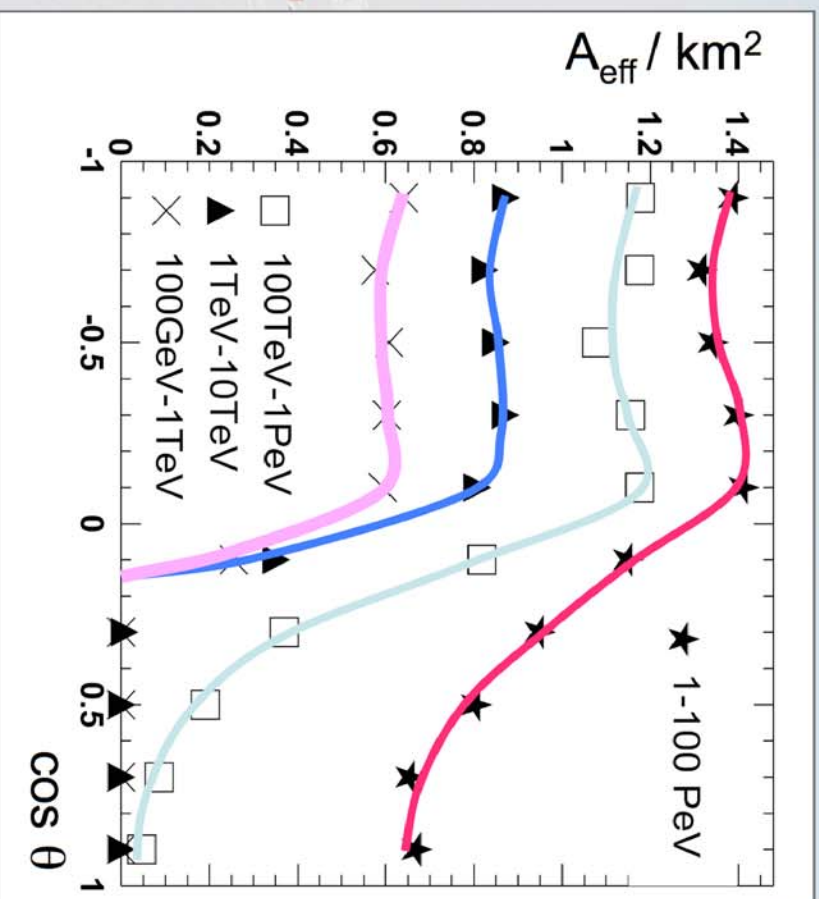
IceCube:  
astro-ph/  
0305196





# IceCube Muon Response

IceCube

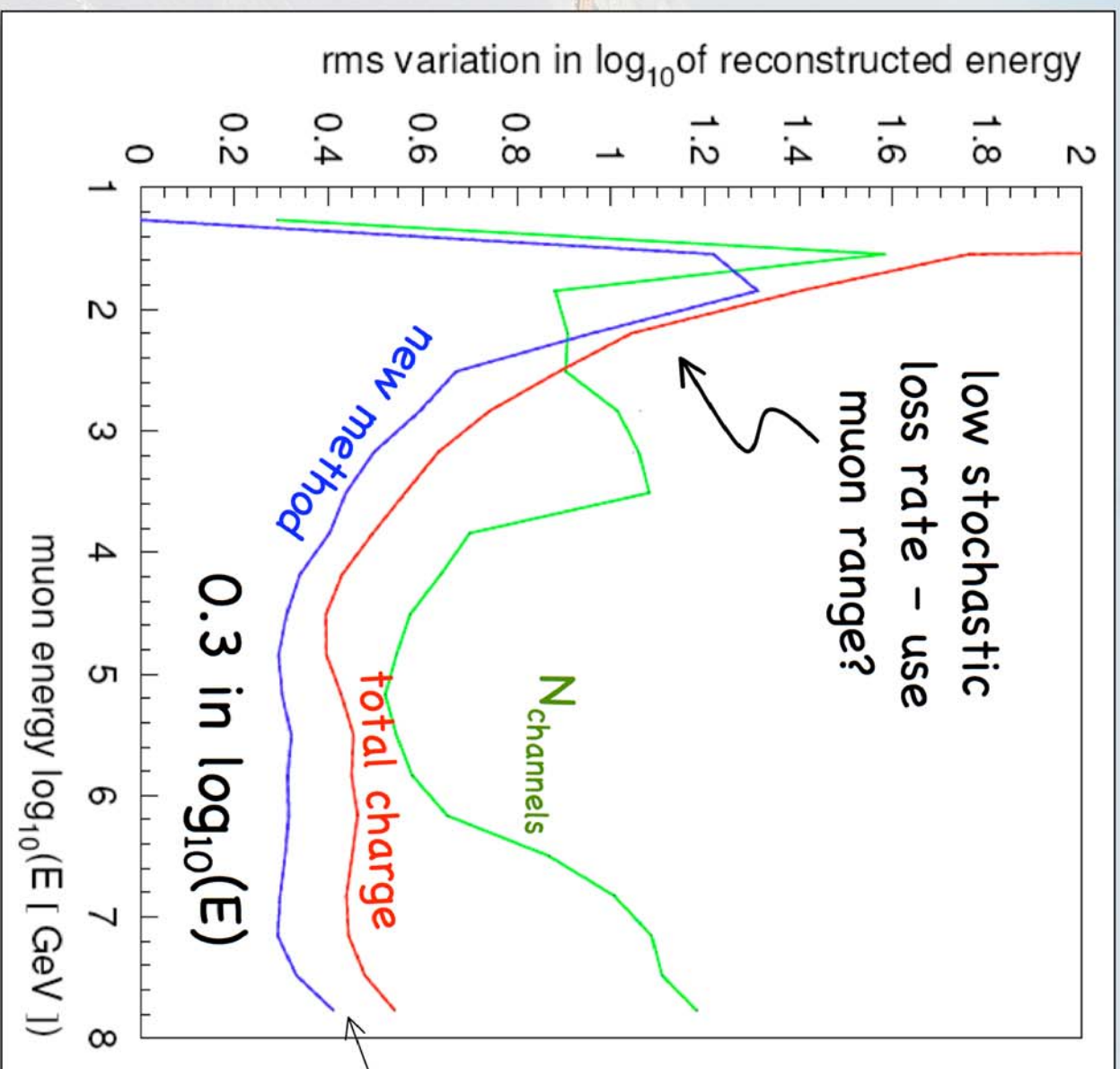


- Simulations and analysis techniques based on AMANDA
- Big improvements possible – waveforms, more hits, better noise reduction, reconstruction techniques



IceCube

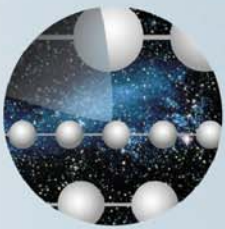
# Muon Energy Resolution



saturation  
- can be  
corrected

Zornoza,  
Chirkin et al.  
ICRC 2007





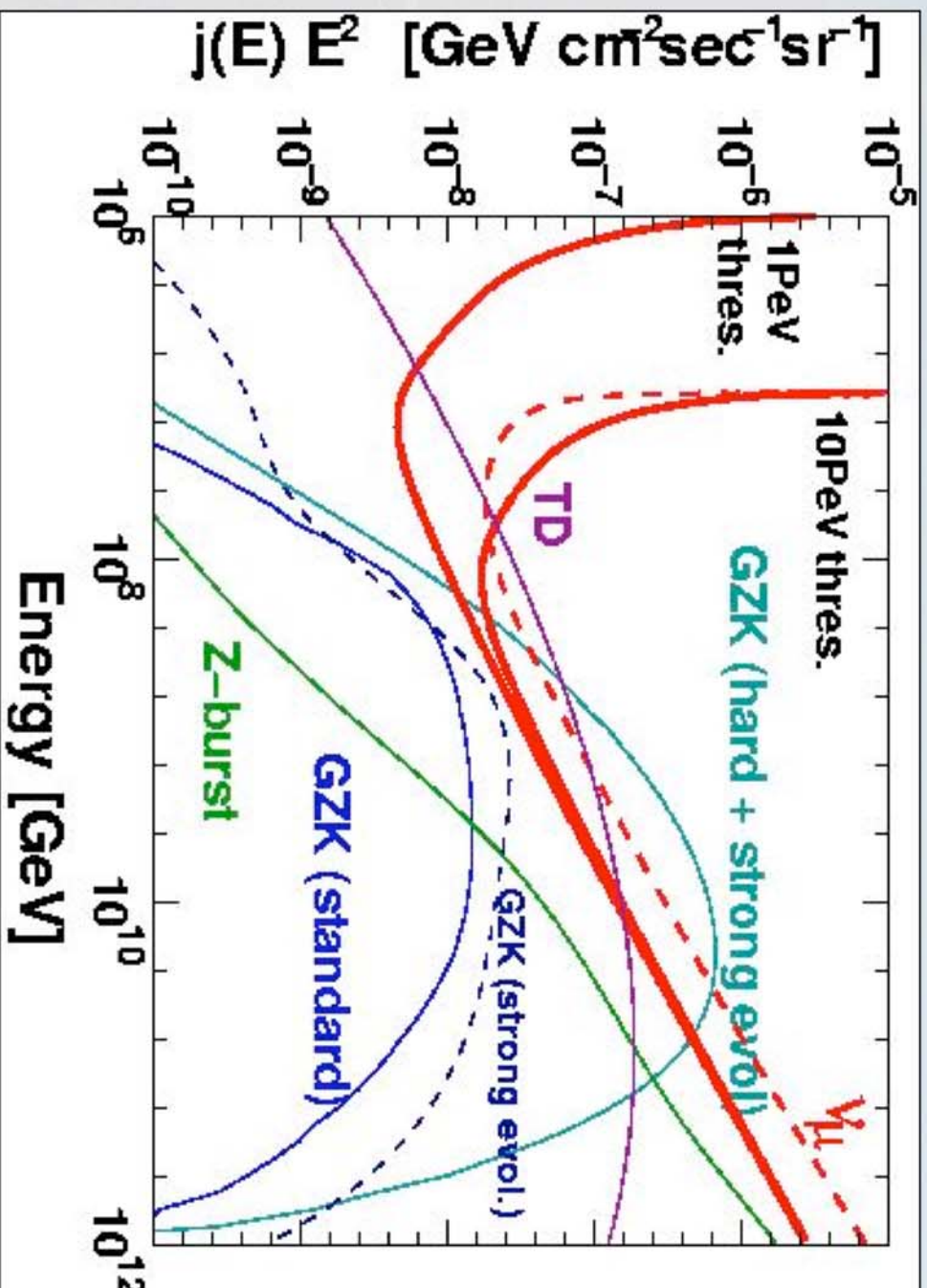
IceCube

# Extremely High Energies

5 year search for muon events depositing more than 10 PeV in the detector

Detector response not yet included!

- gZK** (hard, strong evol.) Kalashev et al. 2002
- gZK** (standard) Yoshida & Teshima '93
- TD** - Sigl et al. 1999
- Z-burst** - Yoshida et al. 1998



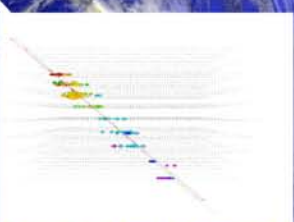
# Neutrinos from GRBs, AGN, and supernovae

Swift, GLAST,  
HETE, etc.)

ROSE

$\nu$

IceCube



HAWC

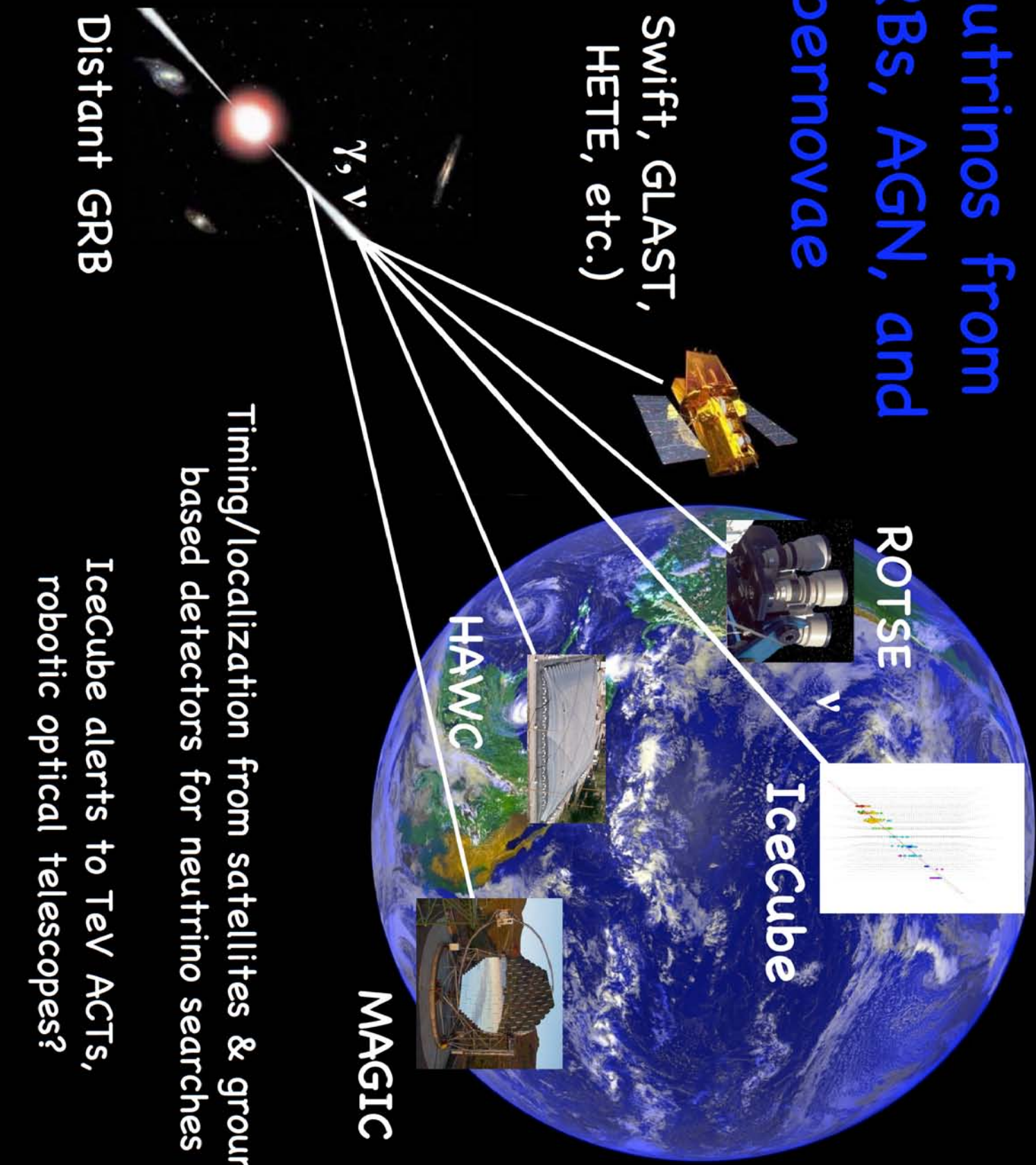
MAGIC

Timing/localization from satellites & ground-based detectors for neutrino searches

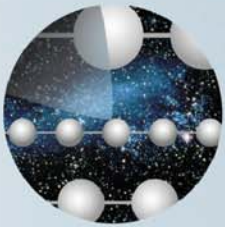
IceCube alerts to TeV ACTs,  
robotic optical telescopes?

A Distant GRB

$\gamma, \nu$



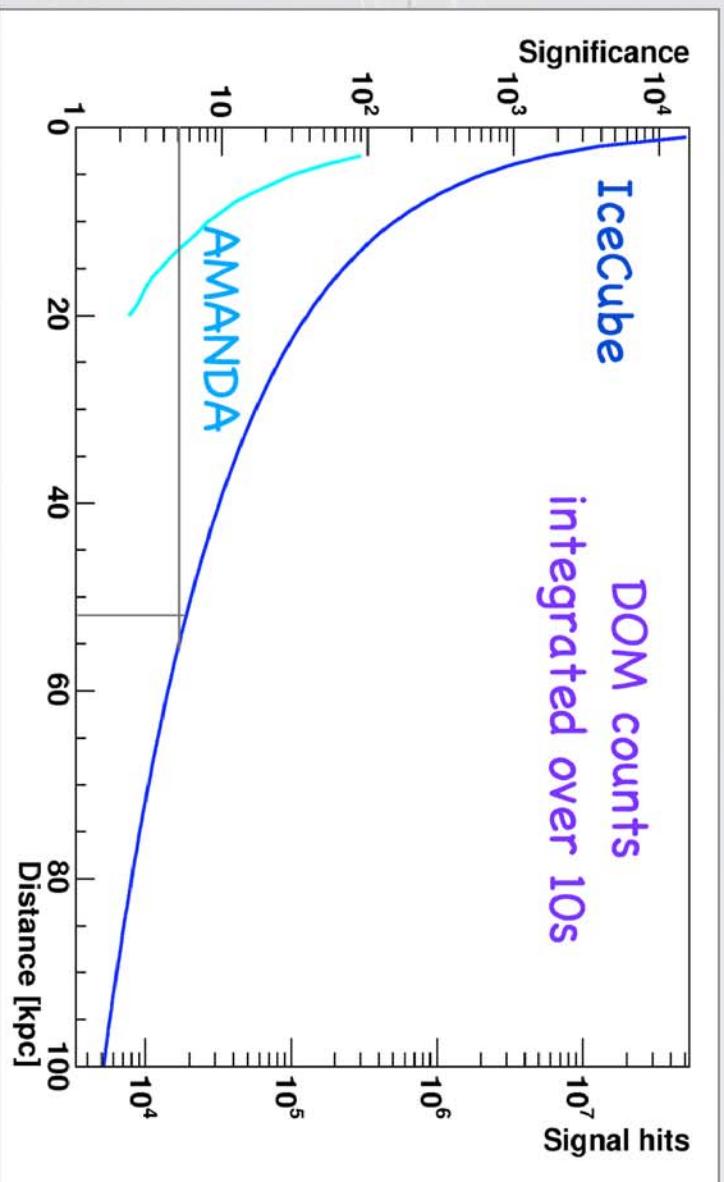




IceCube

# MeV Supernova Neutrinos

Significance of observation vs distance



L. Köpke

PENNSSTATE



RICAP 2007

Visibility out to Large Magellanic Cloud ( $\sim 5 \sigma$  signal)

Tyce DeYoung

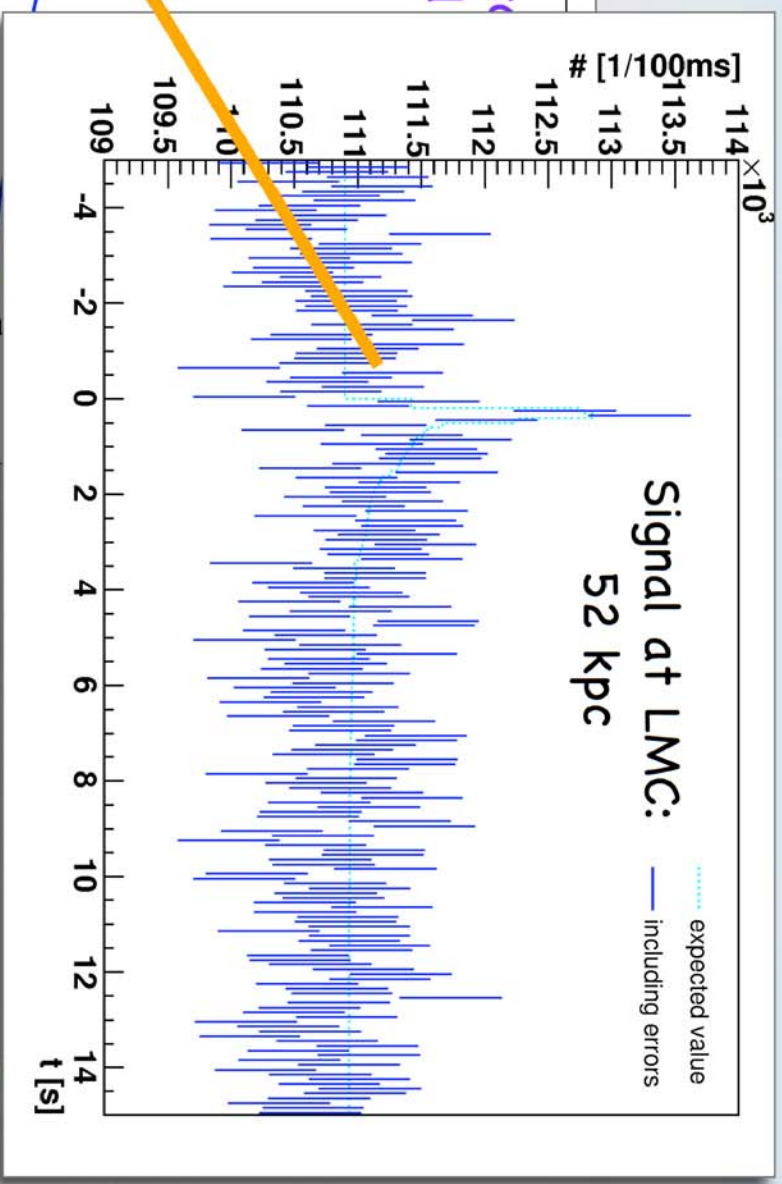
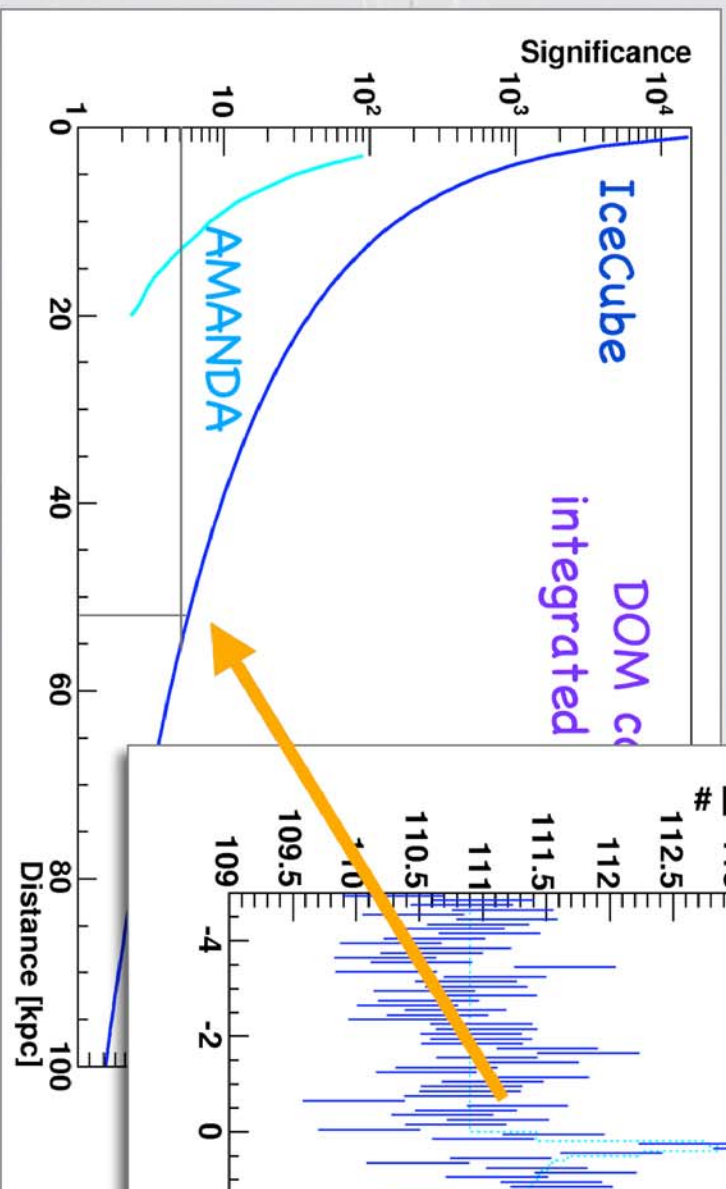
June 22, 2007



IceCube

# MeV Supernova Neutrinos

Significance of observation



L. Köpke

PENNSSTATE



RICAP 2007

Visibility out to Large Magellanic Cloud ( $\sim 5 \sigma$  signal)

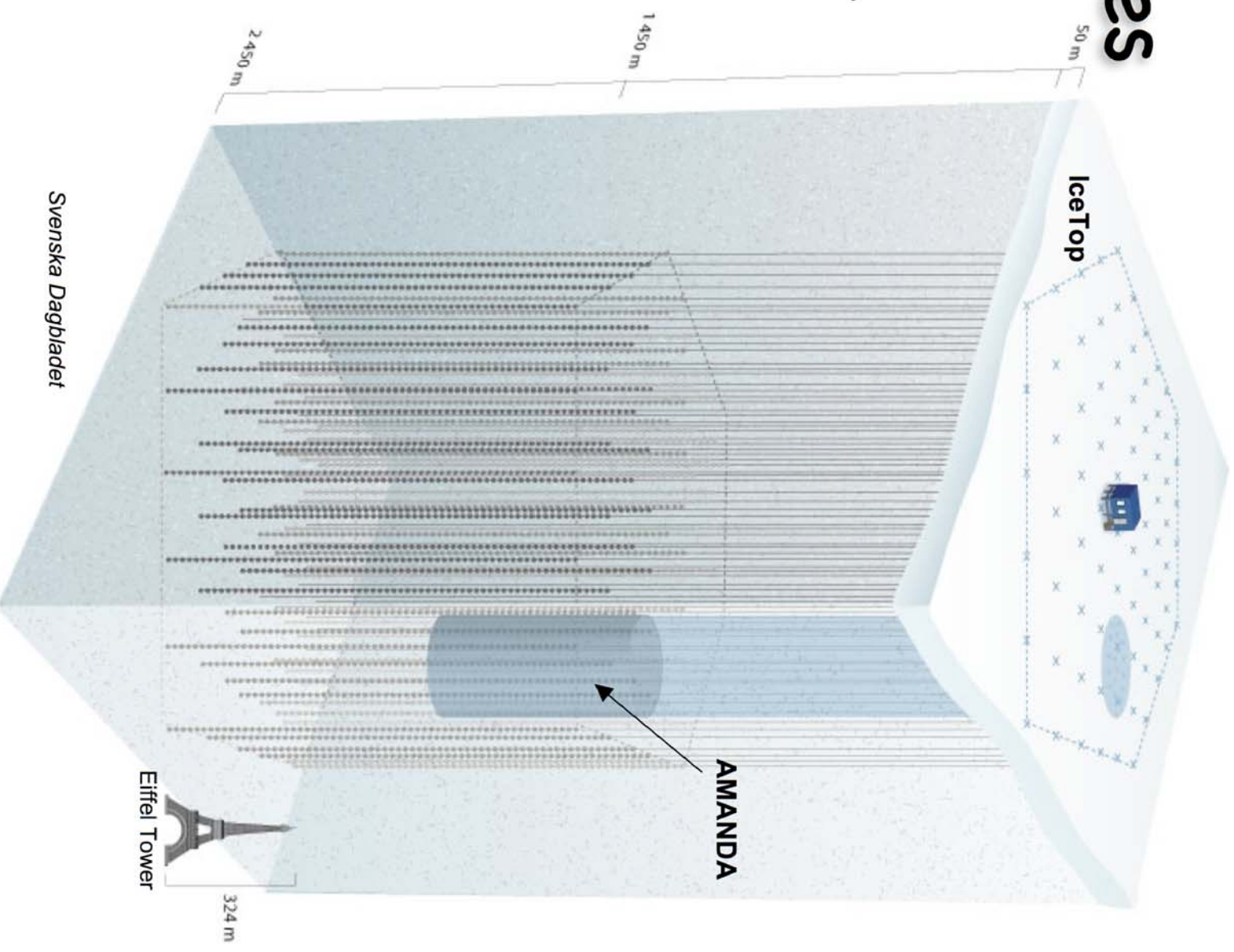
Tyce DeYoung

June 22, 2007



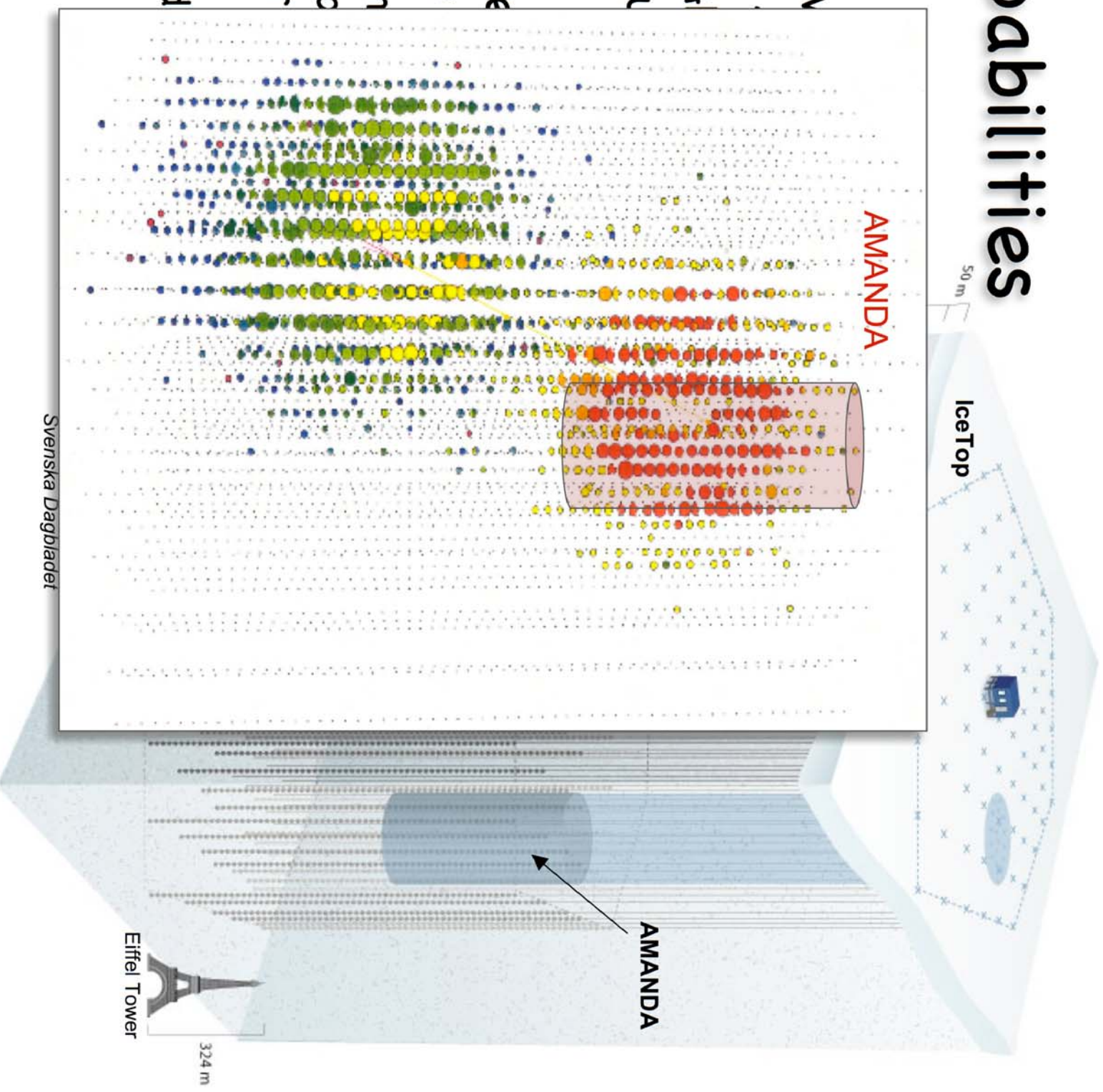
# New Capabilities

- IceCube will be a factor of  $\sim 60$  larger than AMANDA (instr. volume)
- Better events, not just more events
  - Fully contained, well away from edge of detector
  - More of event observed

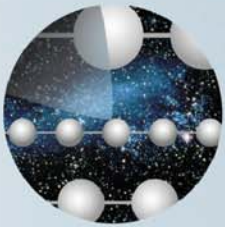


# New Capabilities

- IceCube with a factor of 10 more than AMANDA (instr. vol.)
- Better event reconstruction
  - Fully contained
  - Away from detector
  - More of observed

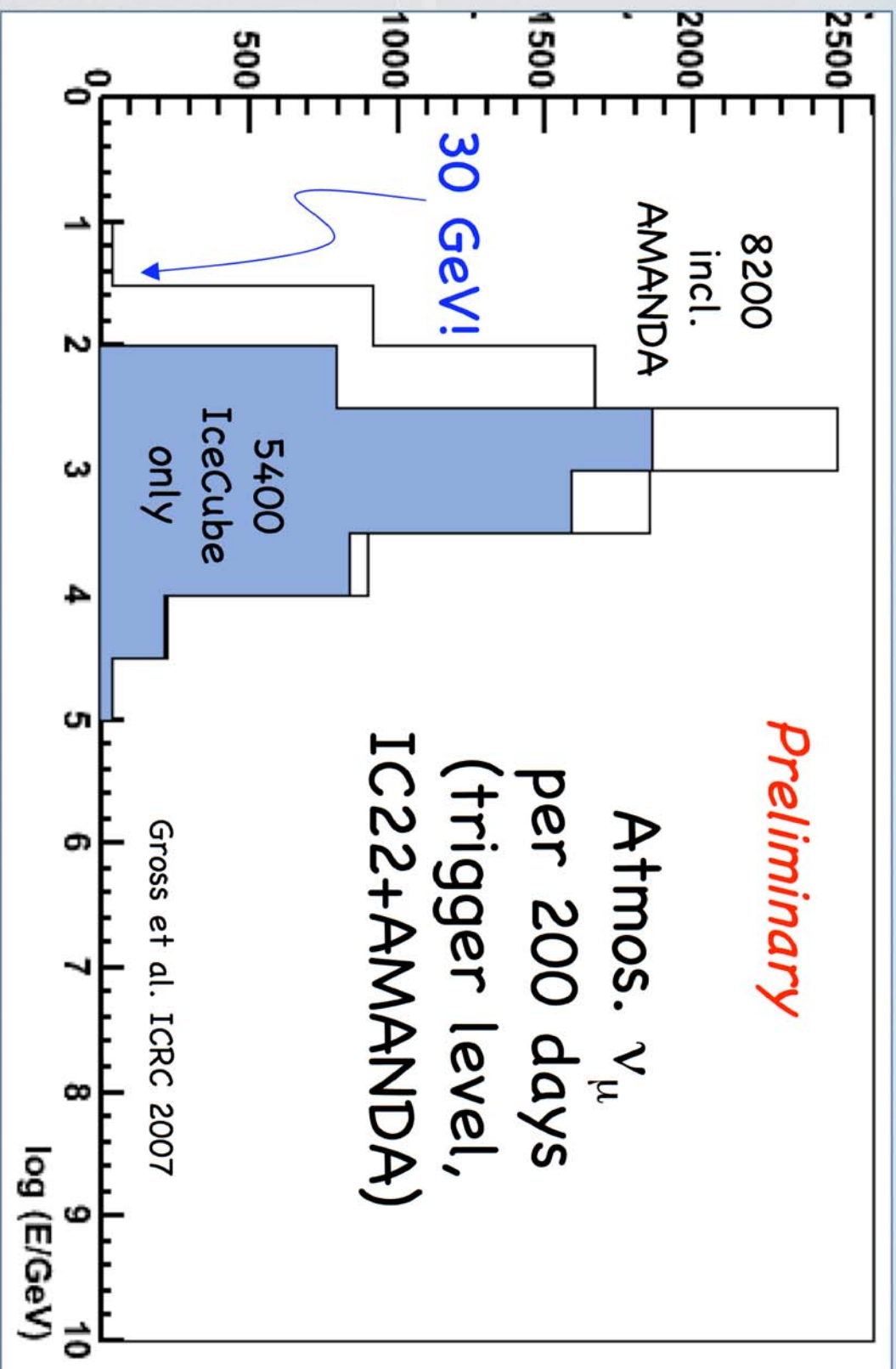






# Low Energy Physics

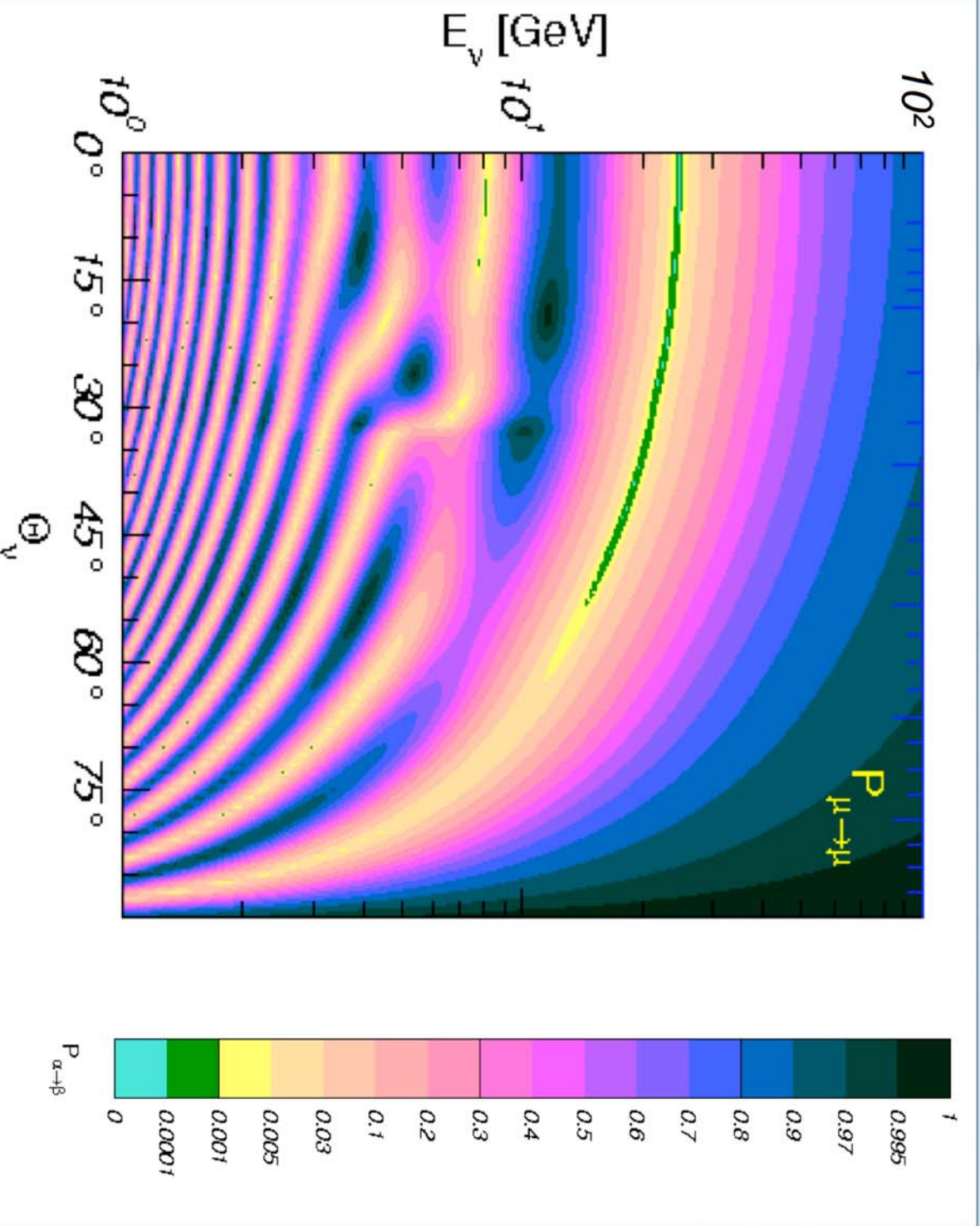
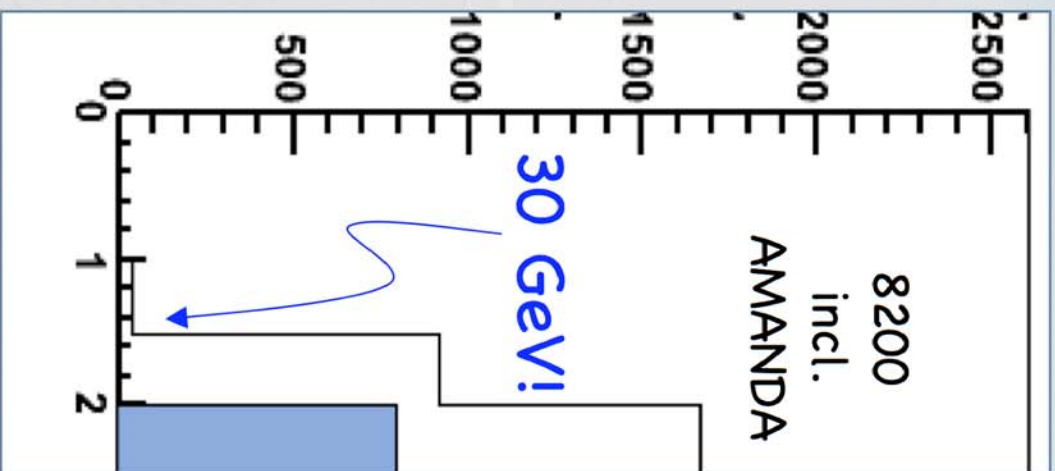
IceCube





# Low Energy Physics

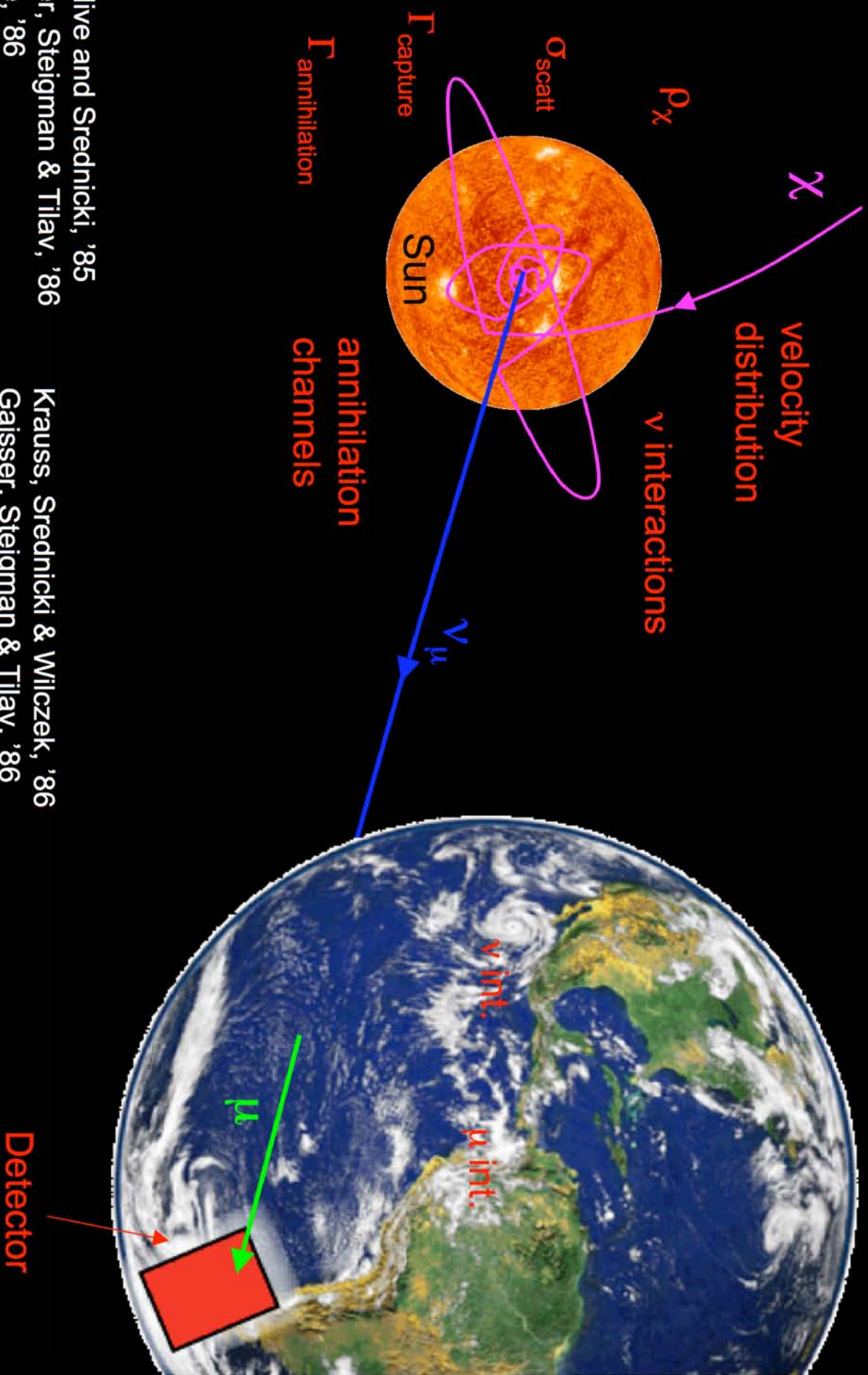
IceCube



Akhmedov, Maltoni & Smirnov, hep-ph/0612285



# Indirect WIMP detection



Silk, Olive and Srednicki, '85  
Gaisser, Steigman & Tilav, '86  
Freese, '86

Krauss, Srednicki & Wilczek, '86  
Gaisser, Steigman & Tilav, '86

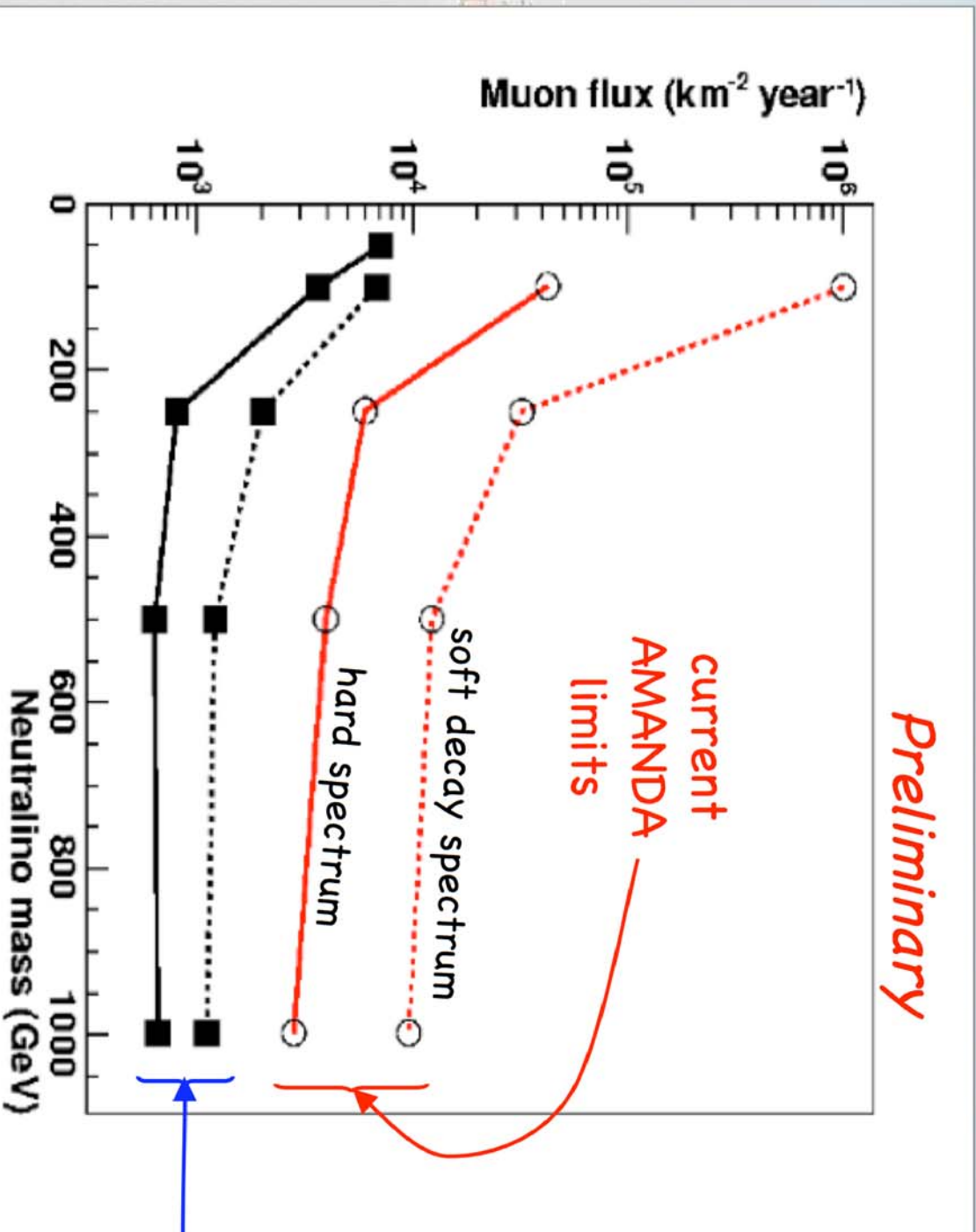


IceCube

# Solar WIMP Sensitivity

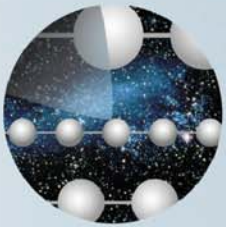
AMANDA limits (144 days, 2001):  
astro-ph/0508518

Expected sensitivity for 1/2 year: Lic. thesis, G. Wikström



Expected sensitivity with IC22 + AMANDA



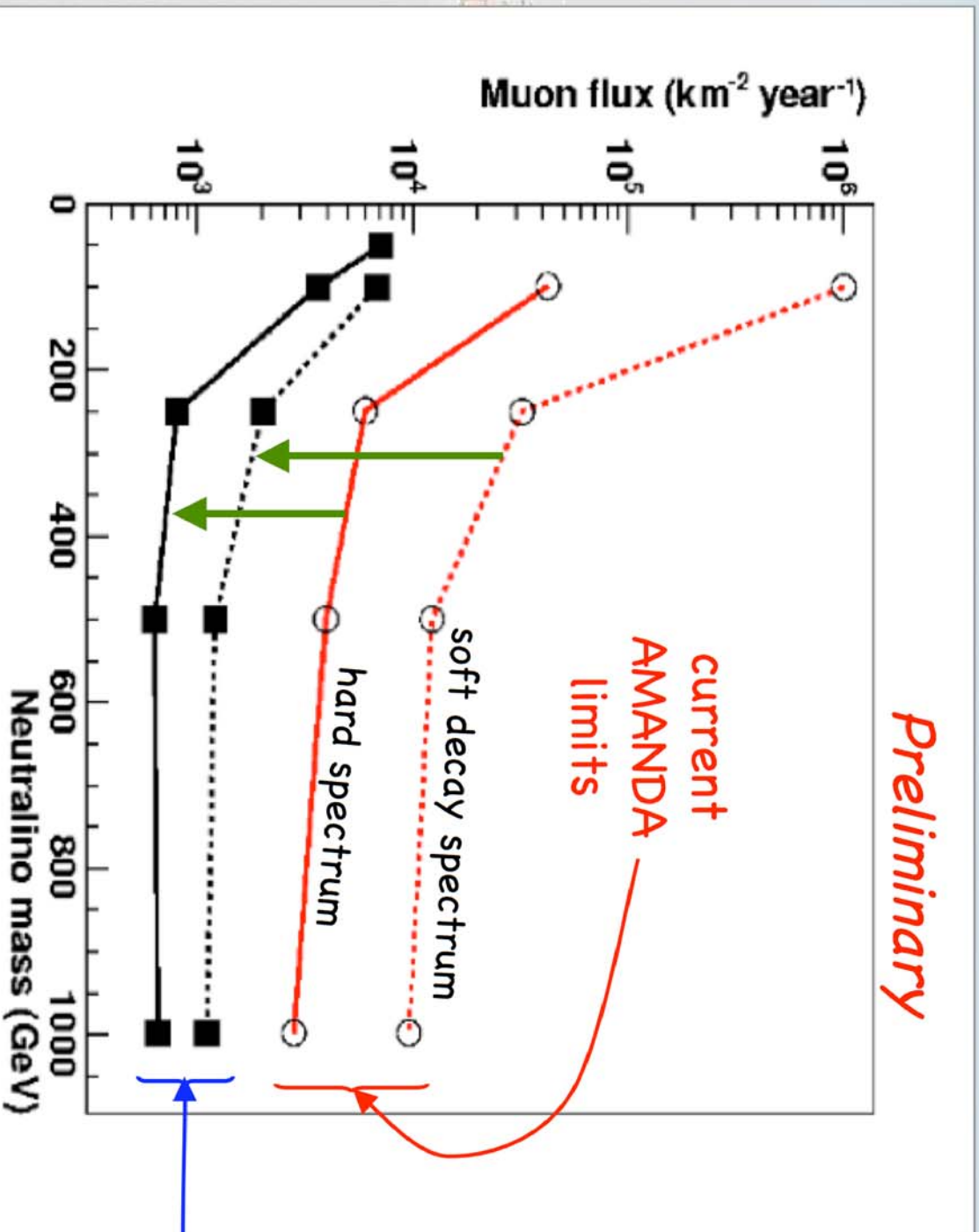


IceCube

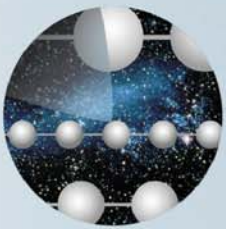
# Solar WIMP Sensitivity

AMANDA limits (144 days, 2001): astro-ph/0508518

Expected sensitivity for 1/2 year: Lic. thesis, G. Wikström



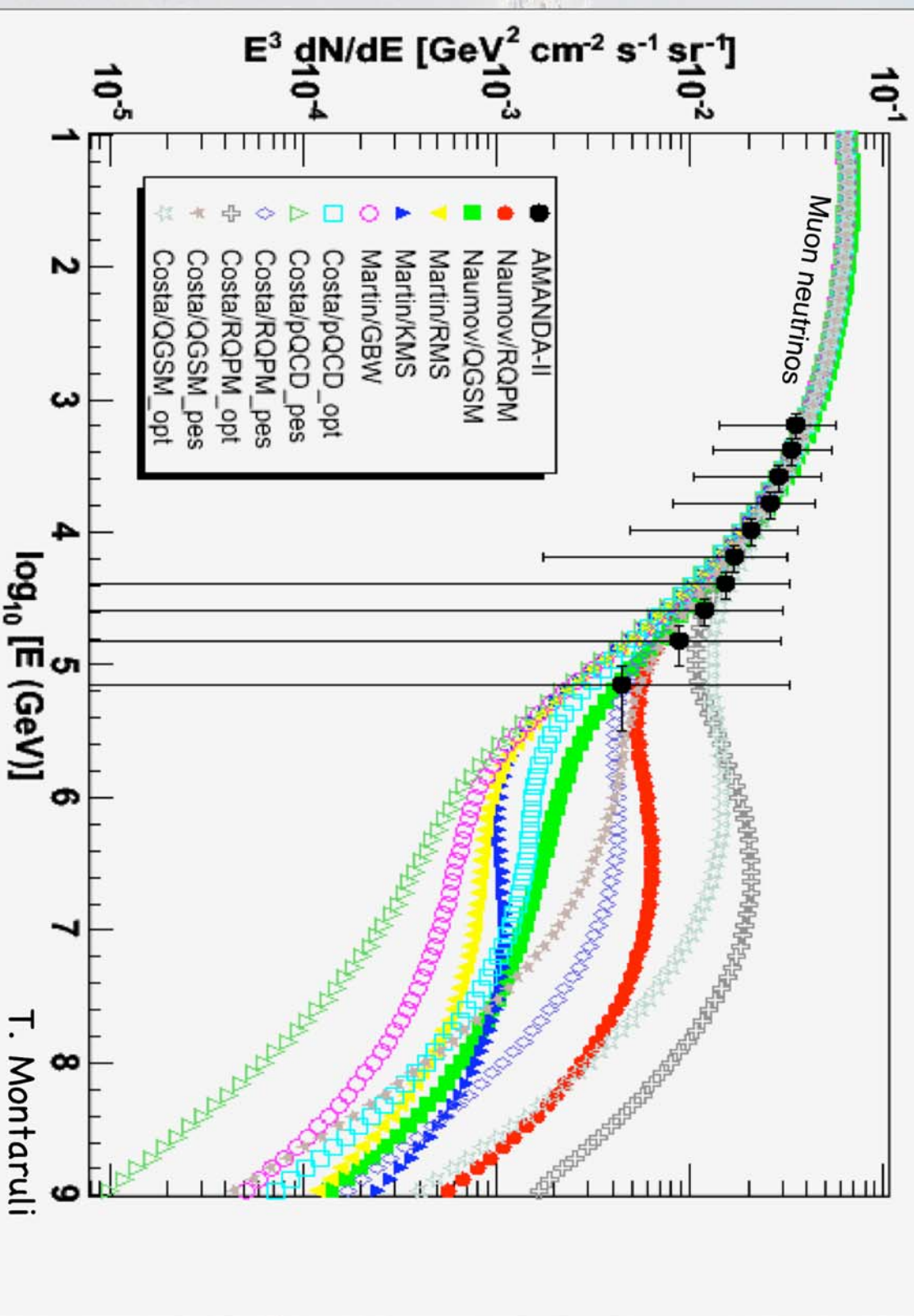
Expected sensitivity with IC22 + AMANDA



I c e C u b e

# Prompt Neutrino Flux

Spectrum of atmospheric neutrinos with Bartol+prompt and AMANDA-II



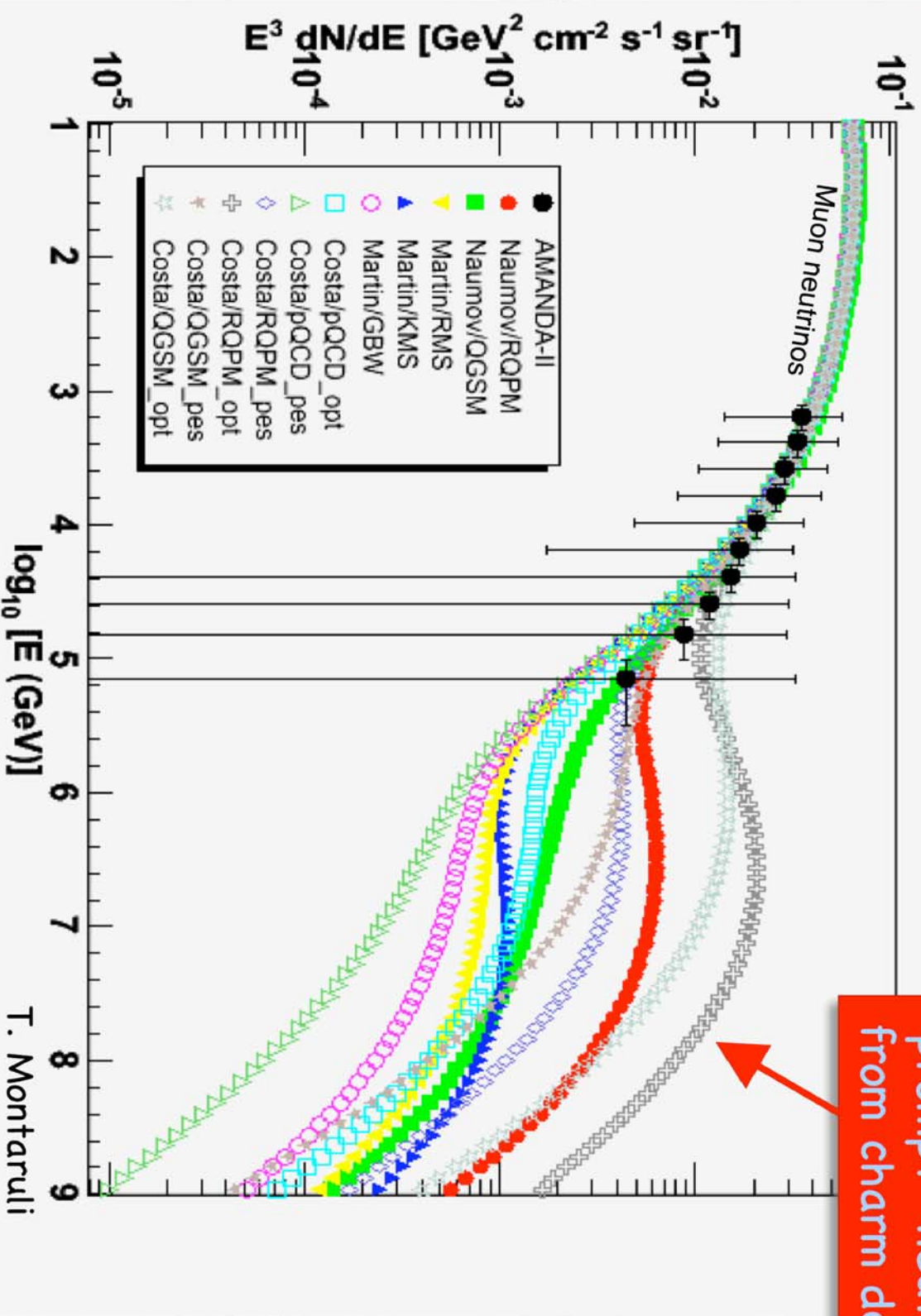


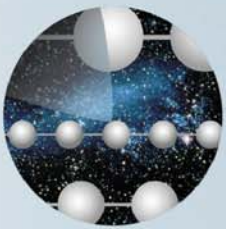


I c e C u b e

# Prompt Neutrino Flux

Spectrum of atmospheric neutrinos with Bartol+prompt and AMANDA-II

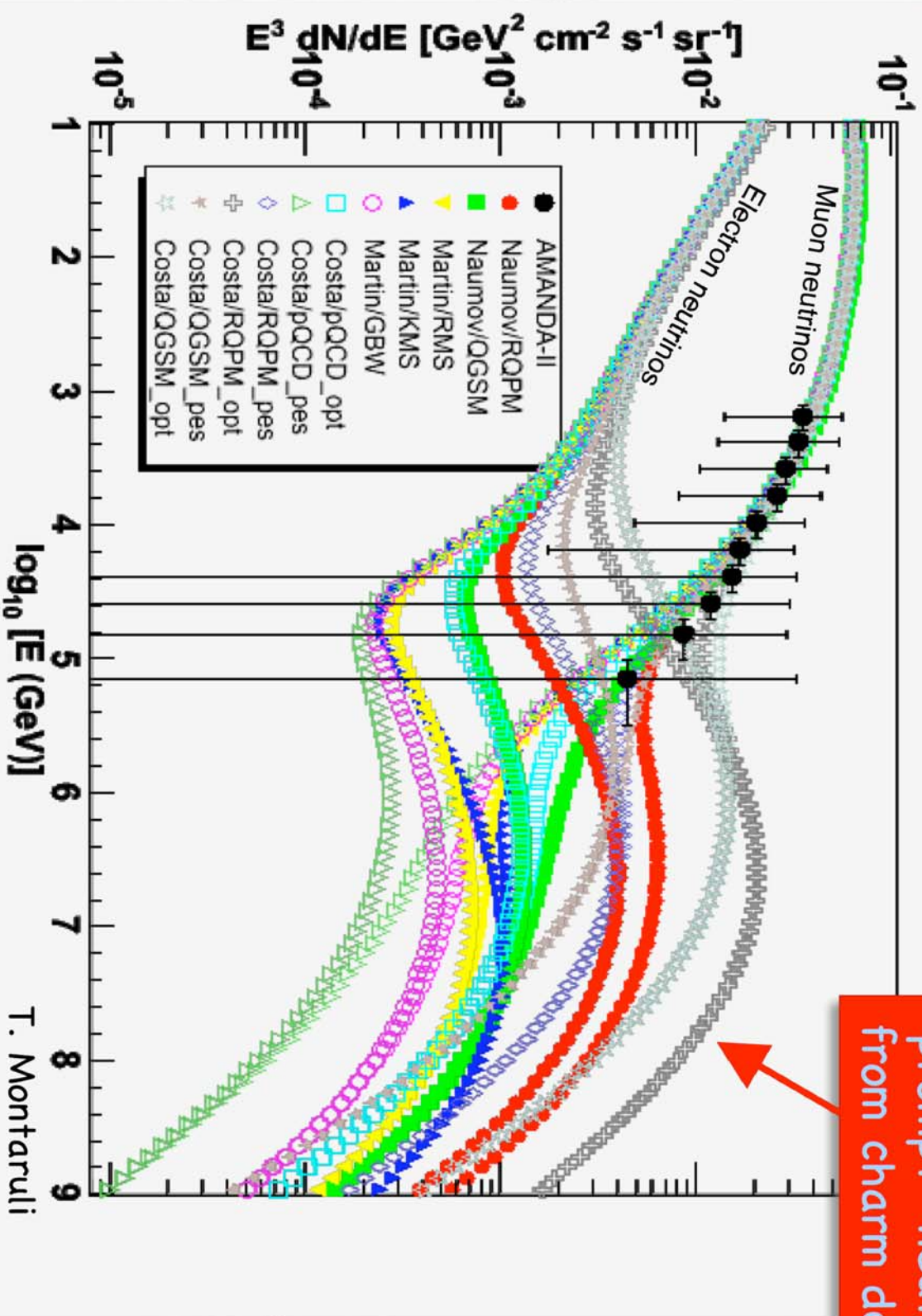




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# Prompt Neutrino Flux

Spectrum of atmospheric neutrinos with Bartol+prompt and AMANDA-II



"prompt" neutrinos  
from charm decay

T. Montaruli





IceCube

# Tau Neutrino Detection

- Negligible intrinsic tau neutrino flux from accelerated hadrons

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$$

- Oscillations over astrophysical distances lead to flavor equality (we think)

$$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$$

- Essentially zero physics background to astrophysical tau neutrinos at relevant energies
  - Only background is misidentified events
    - « 1 yr<sup>-1</sup> above 1 PeV (TDY, Razaque & Cowen 2007)



# Tau Neutrino Signatures

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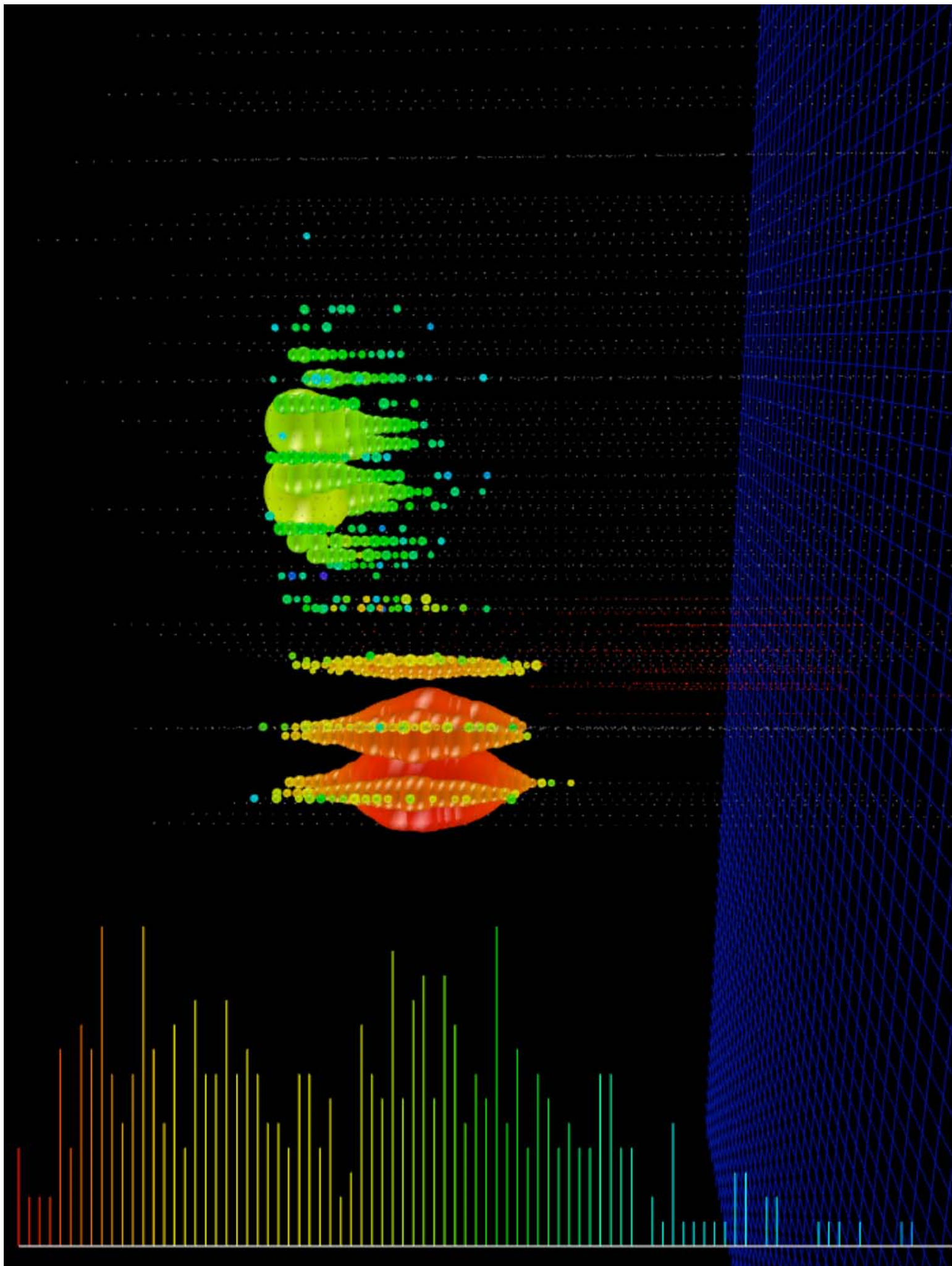


"Double Bang"  
 Learned & Pakvasa  
 hep-ph/9405296

"Lollipop"  
 Beacom et al.  
 hep-ph/0307025

"Sugar Daddy"  
 TDY, Razzaque  
 & Cowen  
 astro-ph/0608486



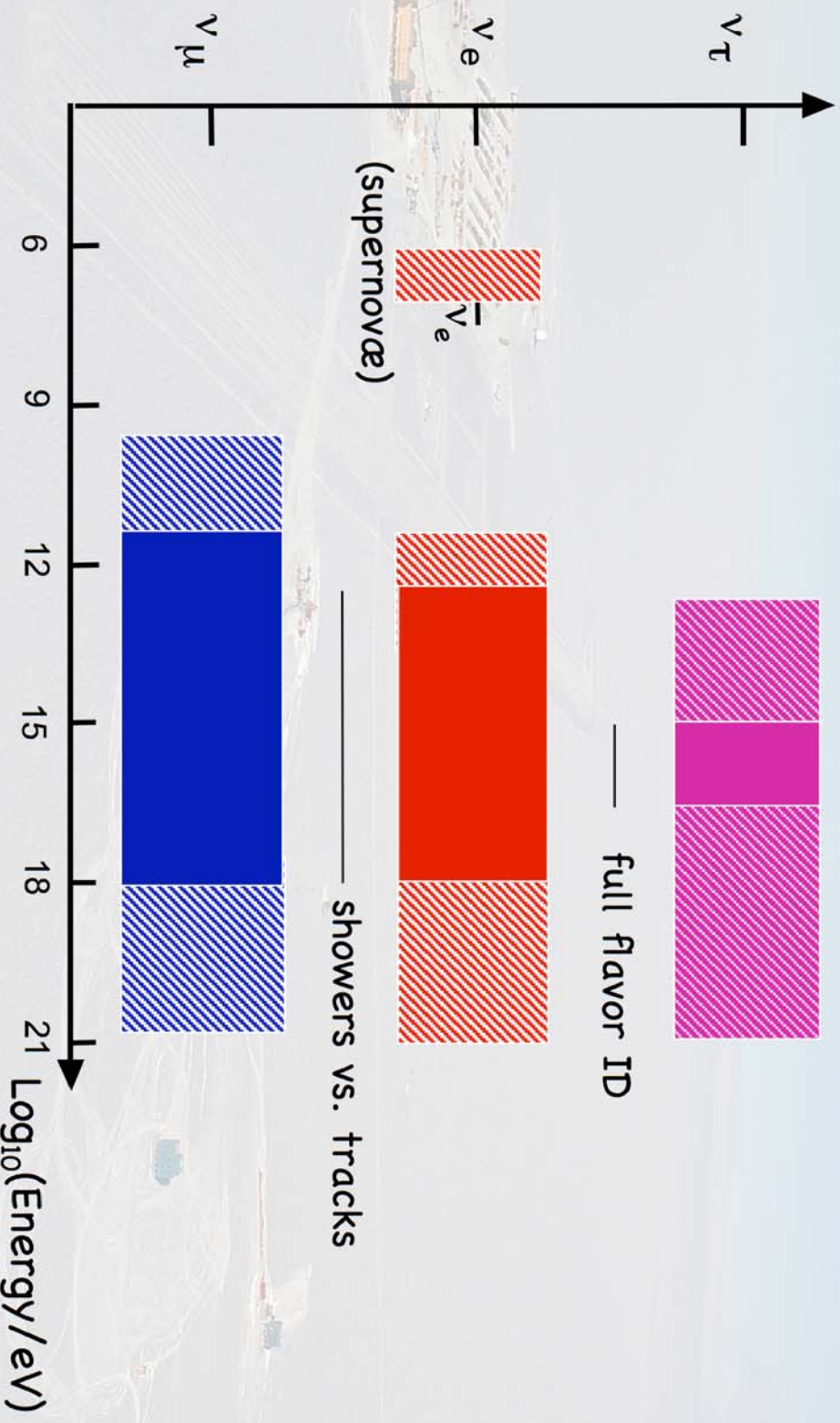




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# Energy Windows by Flavor

Neutrino flavor



Expect 1:1:1 from oscillations – if not...?



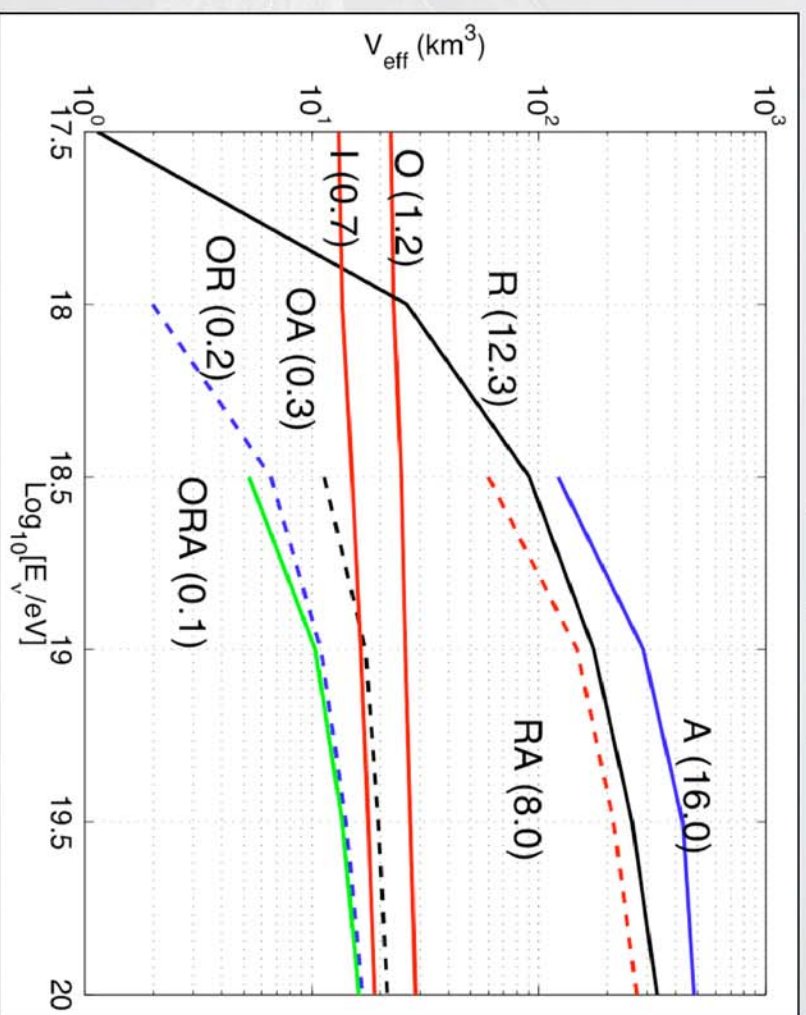
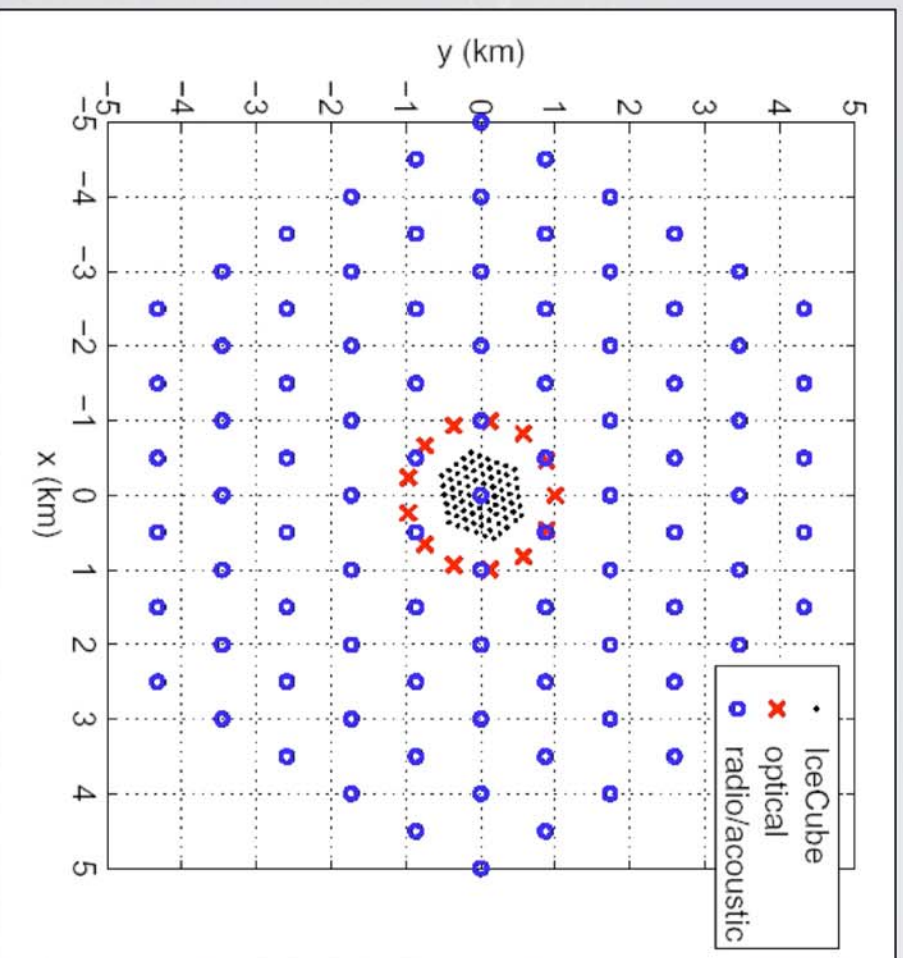


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# Beyond IceCube?

Very low attenuation of radio, acoustic waves in ice

Effective volumes and number of GZK neutrinos detected per year (ESS flux)



Besson et al., astro-ph/0512604



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# I Didn't Have Time to Talk About...

- Cosmic ray composition
- Diffuse extraterrestrial neutrino fluxes
- Sources of ultrahigh energy cosmic rays
- Neutrino point sources (AGN, microquasars, magnetars, SNRs,...)
- Neutrinos from GRBs (afterglow, precursors, choked GRBs, neutrons)
- Ultrahigh energy cosmogenic neutrinos (GZK interactions)
- Non-neutralino dark matter (Kaluza-Klein, sleptons,...)
- Neutrino oscillations ( $\theta_{13}$ )
- Tests of Lorentz invariance, weak equivalence principle
- Exotic massive particles (topological defects, relic particles)
- TeV-scale extra dimensions, electroweak instantons,...
- Magnetic monopoles, nuclearites, Q-balls,...
- Fundamental physics with flavor ratios

PENNSSTATE



RICAP 2007

Tyce DeYoung

June 22, 2007





IceCube

# Conclusions

- IceCube construction is going well
  - On target for completion in 2011
- 22 IceCube strings now deployed, working well and taking data
- AMANDA analysis is continuing
  - Now integrated into IceCube
- First IceCube physics papers are starting to appear
- Stay tuned!