
THE WORLD'S WEIRDEST TELESCOPE
THE WORLD'S LARGEST ICECUBE
THE WORLD'S COLDEST LABORATORY
A NEXT GENERATION NEUTRINO TELESCOPE
IceCube

IceCube complete - Dec 18 2010

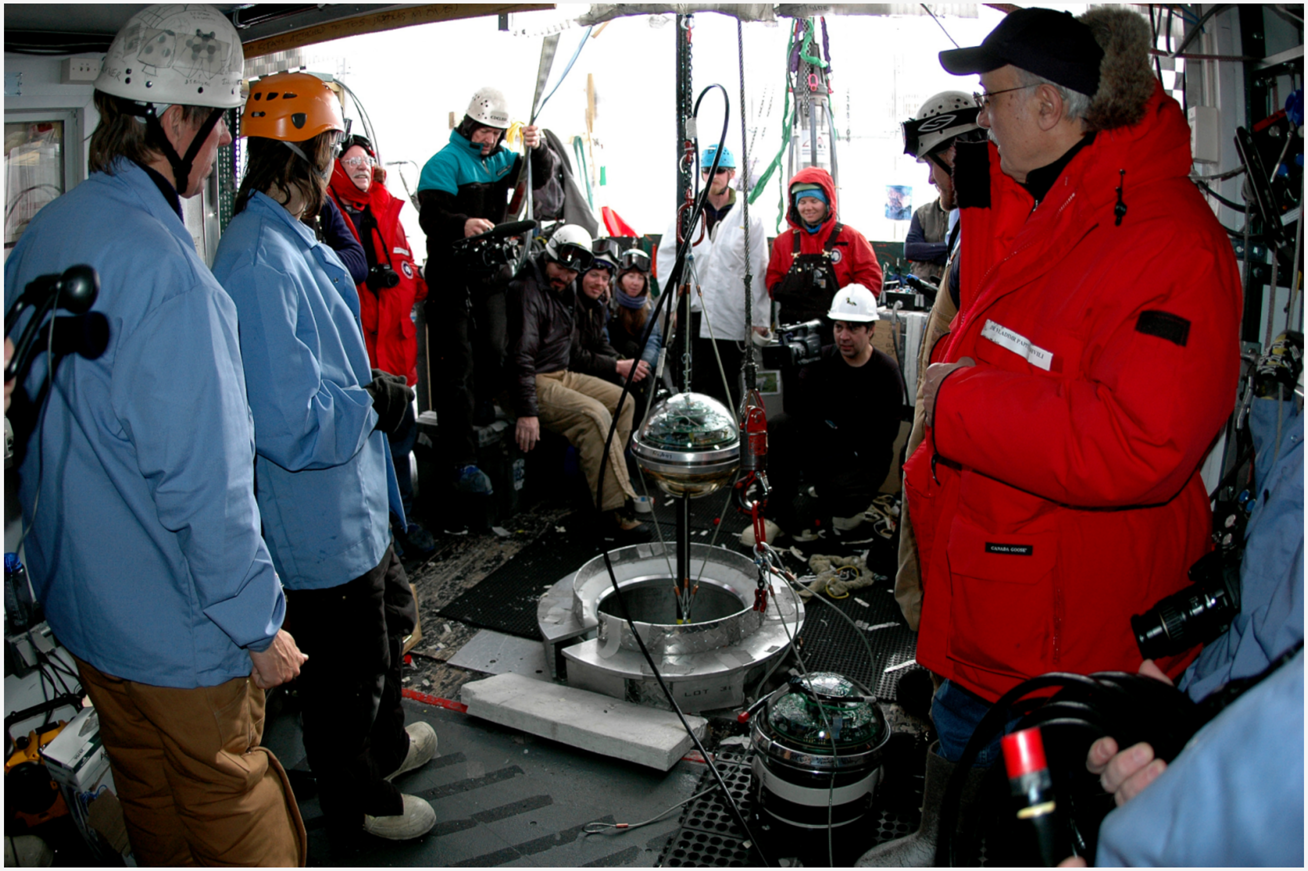


Photo: P. Rejcek, NSF

IceCube collaboration 33 institutions worldwide w. ~250 scientists

The beginnings

the pioneers

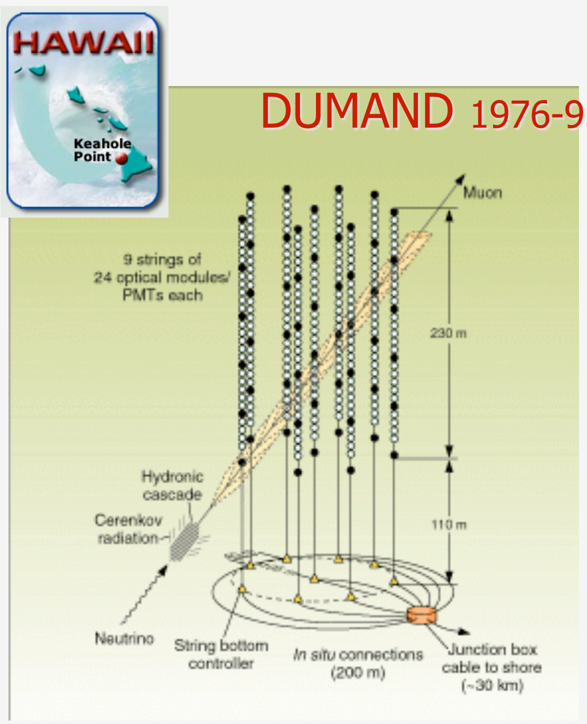
Moisey Markov

Fred Reines

Ken Greisen

- Proc. of 10th ICHEP 1960
- Ann. Rev. Nucl. Sci. 1960

- deep ocean cosmic n det.s
- a kton or more required



The beginnings

NEUTRINO ASTRONOMY

Francis Halzen
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John Learned
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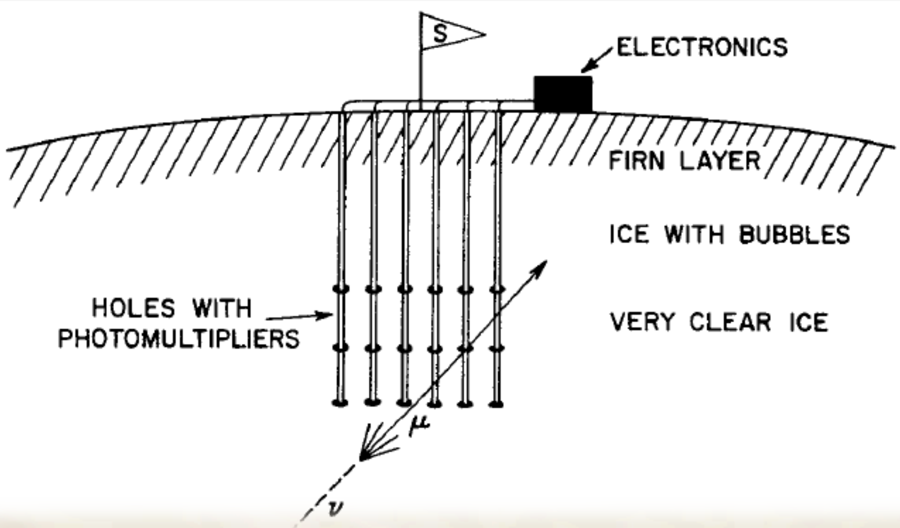
Todor Stanev
Bartol Research Institute, University of Delaware, Newark, DE 19716

AIP Conf. Proc.
vol. 198 (1990)
Astrophysics in Antarctica



Inspired by pre-1985
observations of
Cygnus X-3
in the TeV and PeV bands

In conclusion, we suggest that field investigations begin as soon as possible to examine the relevant optical properties of deep Antarctic ice. It is amusing to envisage the Antarctic ice sheet as a giant neutrino telescope, with the whole earth as its rotating neutrino bandpass filter.

The prototype

August 1990 – first tests in Greenland

l_{abs} >18 m (clear ice)

Lett. to Nature vol. 353 (1991) 331

1993-94 AMANDA-A (800 – 1000 m)

bubbles! – but expect l_{abs} >60 m (clear ice)

Science vol. 267 (1995) 1147

1996 – 2000 constructing AMANDA II (1450 – 2000m)

clear ice! l_{abs} ~ 110 m

OBSERVATION OF HIGH-ENERGY NEUTRINOS USING ČERENKOV DETECTORS EMBEDDED DEEP IN ANTARCTIC I

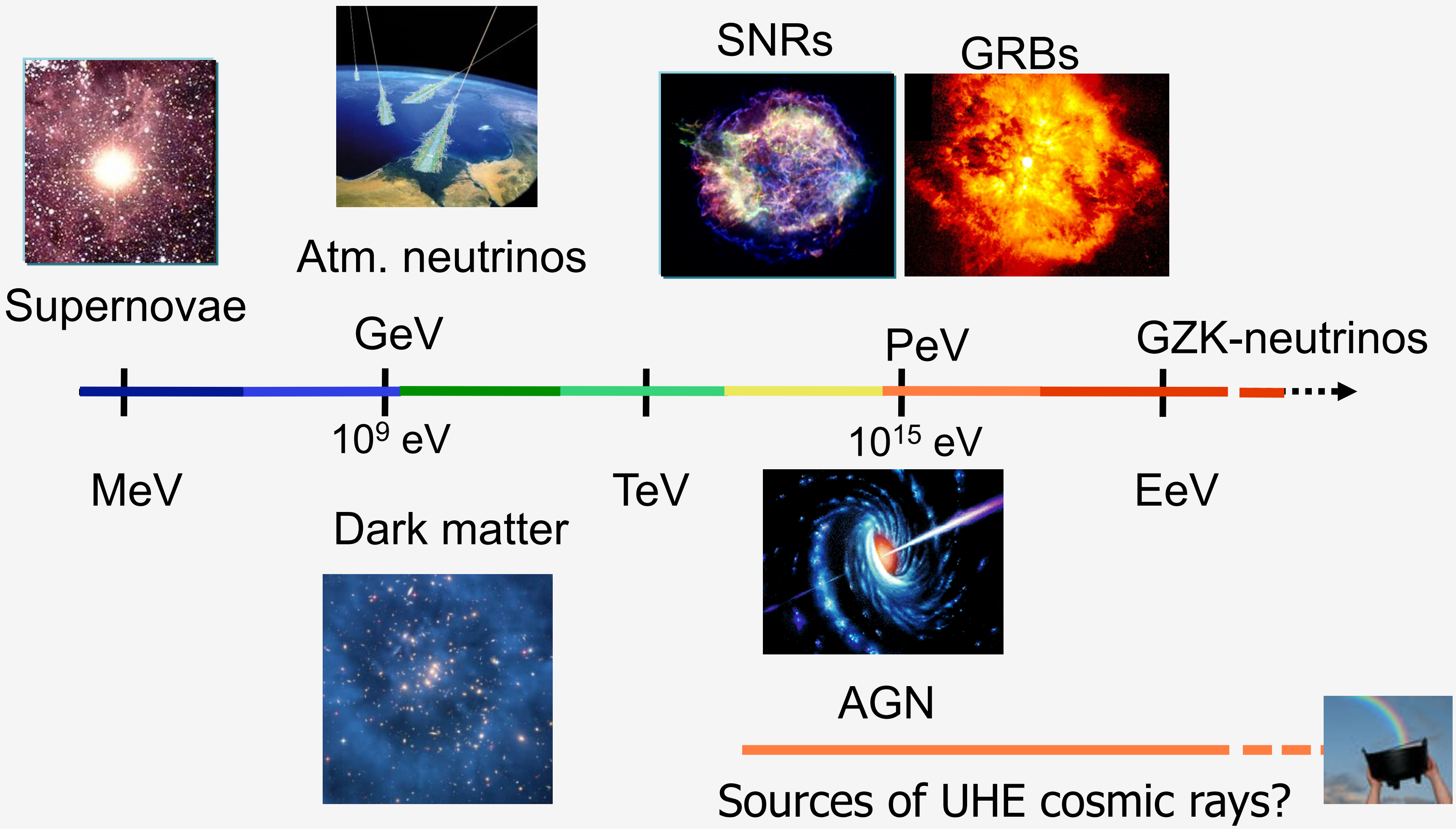
Nature vol. 410 (2001) 441

measuring water transparency in Torneträsk, northern Sweden

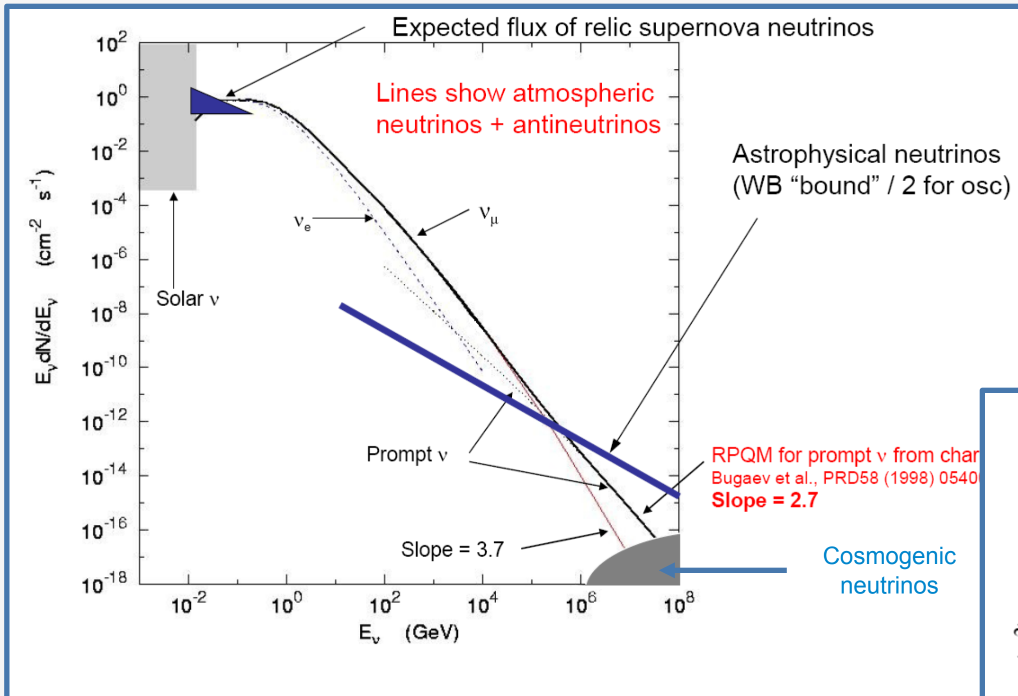
Stockholm/Uppsala join UCB-UW-UCI in 1992

Desy/Zeuthen joins 1994

Neutrino sources

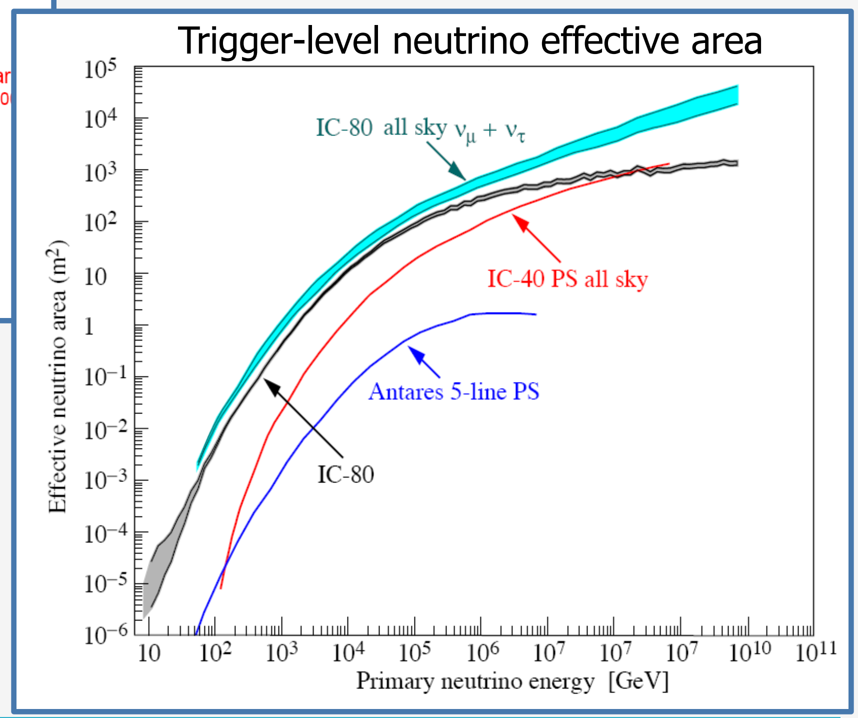


The neutrino landscape



T. Gaisser, Arequipa, Peru 2008

A. Karle,PDG 2010



The challenges: DOMs

designed for reliability
- life time > 10 yrs
- temperatures [-55°C,20°C]

each DOM an autonomous detector
- high sampling speed (300 MSPS)
- low power consumption (3.5 W)
- low noise (300 Hz)

DOM mainboards - designed and delivered by Berkeley Lab

5160 DOMs assembled & verified at three production sites

PSL at Stoughton, WI · DESY/Zeuthen · Stockholm/Uppsala

The challenges: DOM surface cable

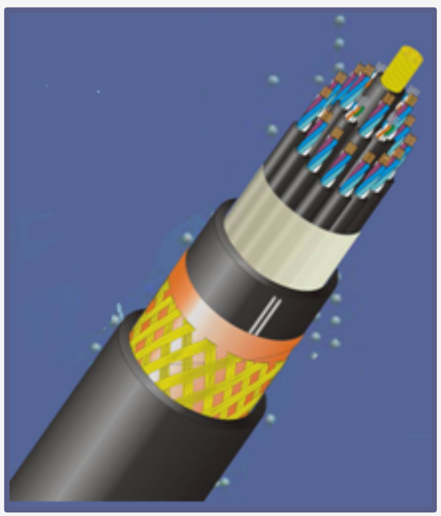
optimized twisted quad configuration, low attenuation over 3 km

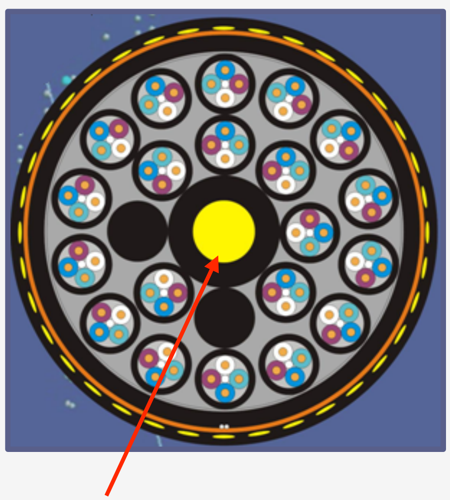
- unsheathed, 0.9 mm copper

low cross talk, low EMI sensitivity

careful mechanical construction

low weight





structural strength core

Quality control at
Ericsson Network Technologies, Sweden

The ”data challenge”

seeing to it that data get to ICL – also a challenge!

Goals for IceCube

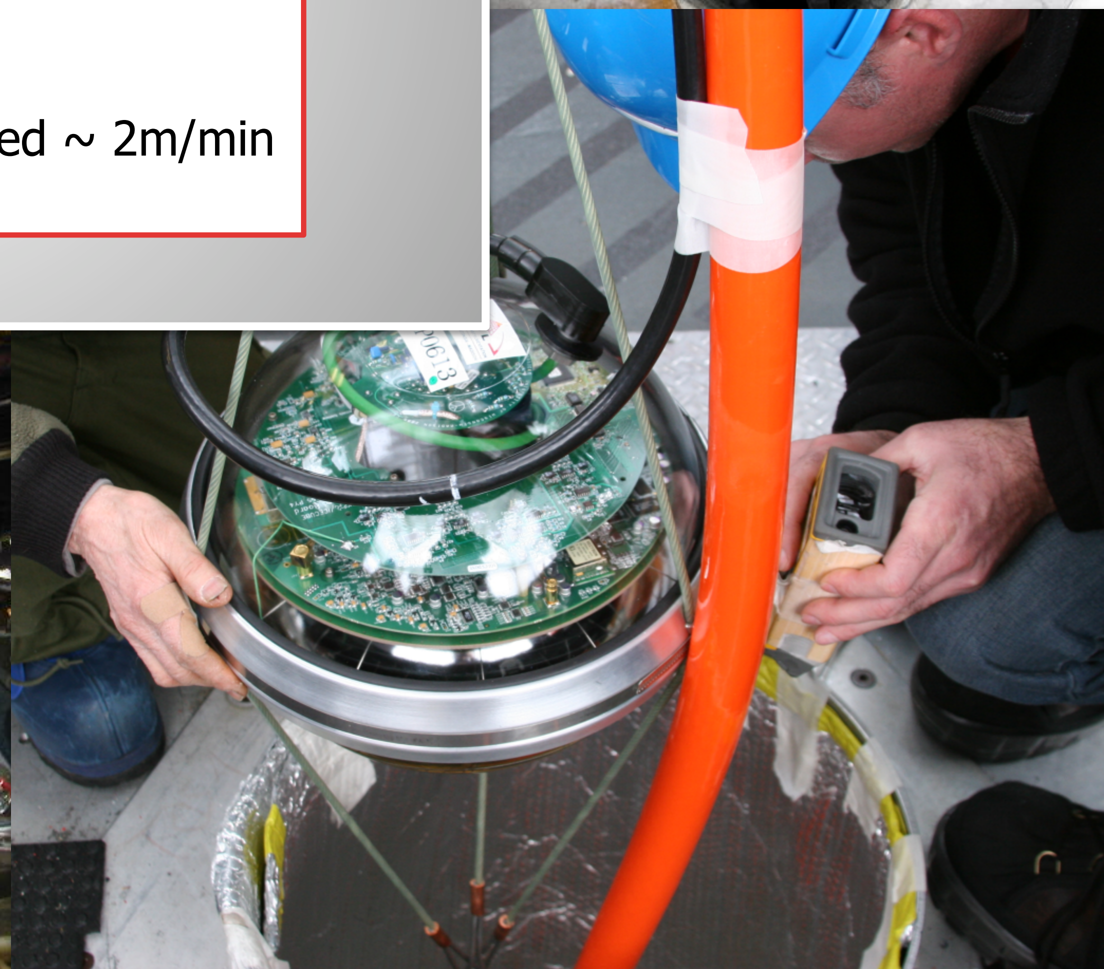
- 18 holes/season
- 2450 m deep
- straight within 1 m
- fuel 25000-30000 ℓ/hole

Cf. AMANDA

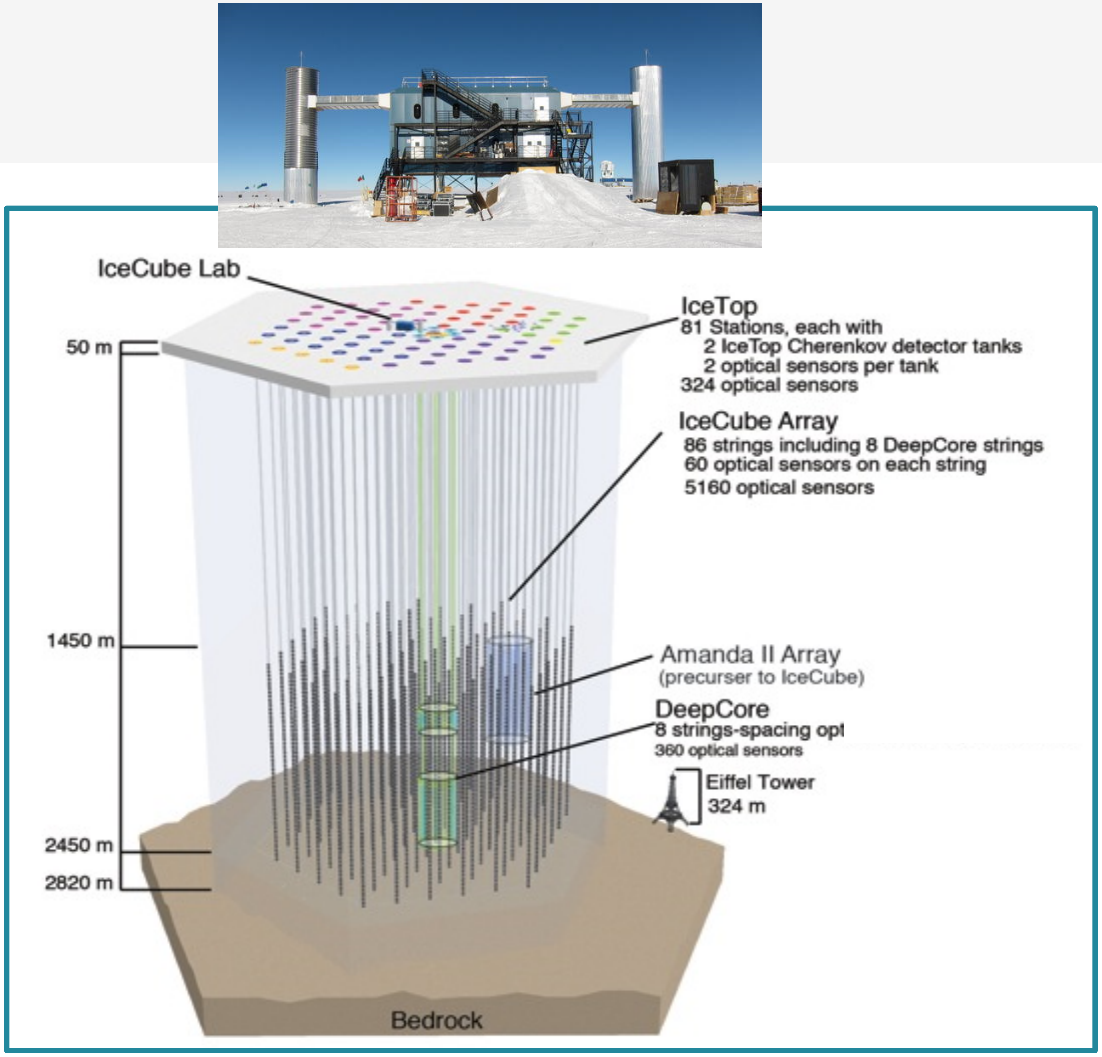
- eventually 90 hrs/hole
- fuel ~40000 ℓ/hole

IceCube season 2009-10

- 20 holes delivered
- fuel ~15000 ℓ/hole
- ~ 20 hrs/hole ☞ drill speed ~ 2m/min
- ~ 10 hrs/deployment



IceCube complete



Feb 2004 - NSF baseline review
GO AHEAD

successful deployment

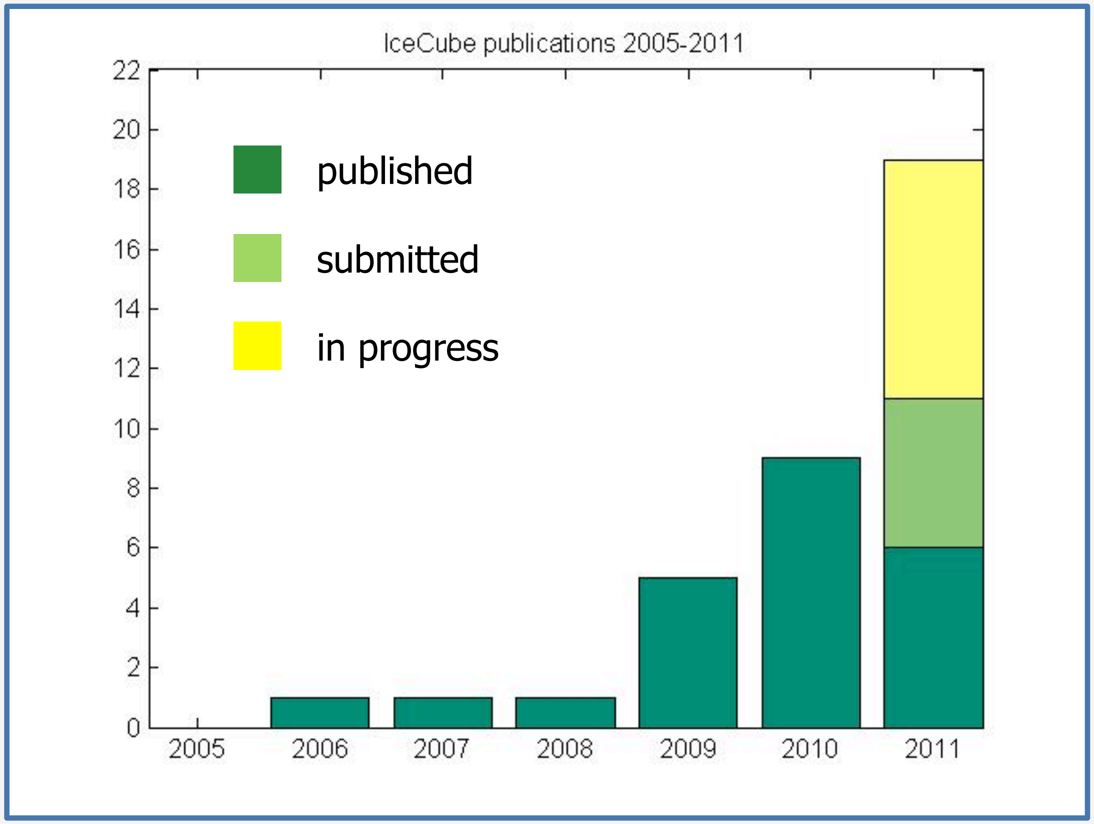
season	# strings
2004/5	1
2005/6	8
2006/7	13
2007/8	18
2008/9	18 + 1 DC
2009/10	15 + 5 DC
2010/11	7

98% of all sensors working

IceCube science

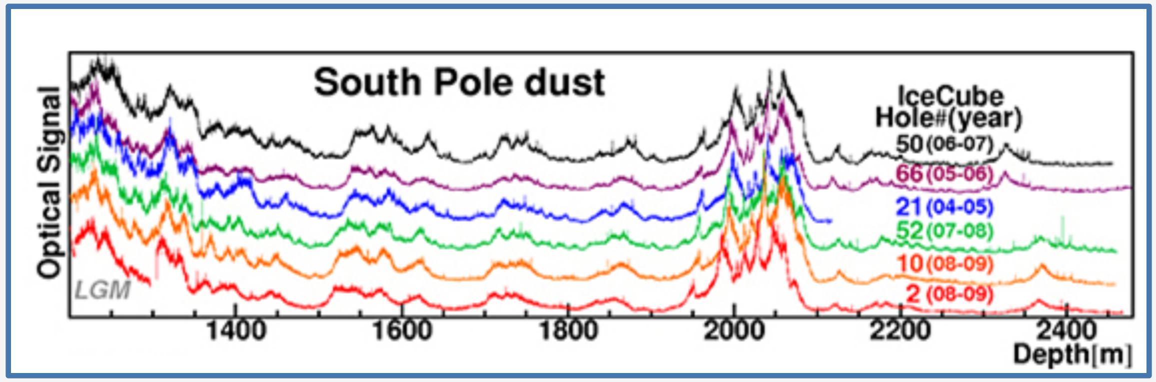
science output during construction

2006: *First Year Performance of the Icecube Neutrino Telescope*
2007: *Detection of Atmospheric Muon Neutrinos with the IceCube 9-String Detector*
2008: *Solar Energetic Particle Spectrum on 13 December 2006 Determined by IceTop*



The ice – a continuing challenge

- analyses depend on careful mapping of optical ice properties
- LEDs, lasers, dust loggers



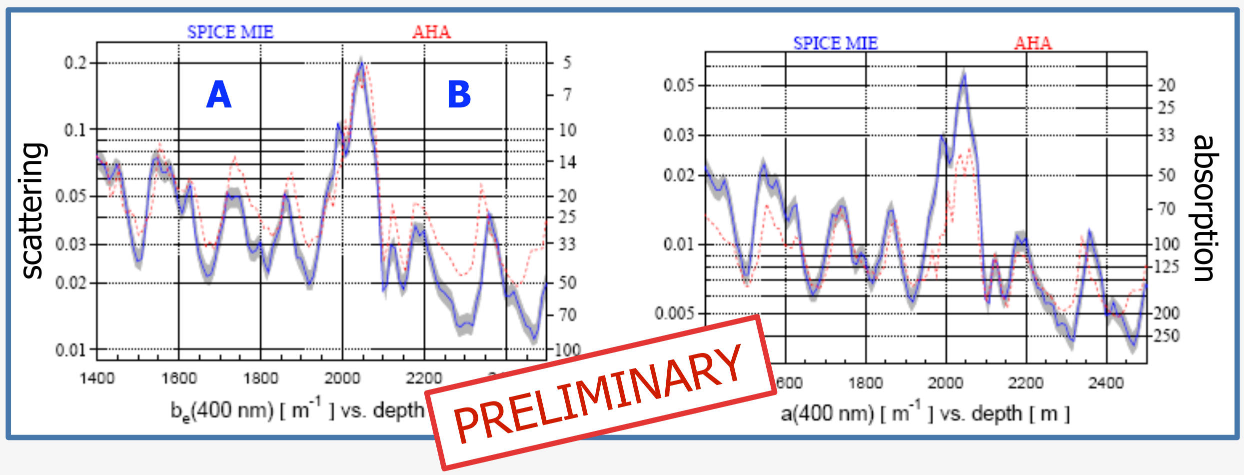
Averages at 400 nm

region A

l_{abs}~ 110m, l_{sca}~ 25m

region B

l_{abs}~ 220m, l_{sca}~ 40m



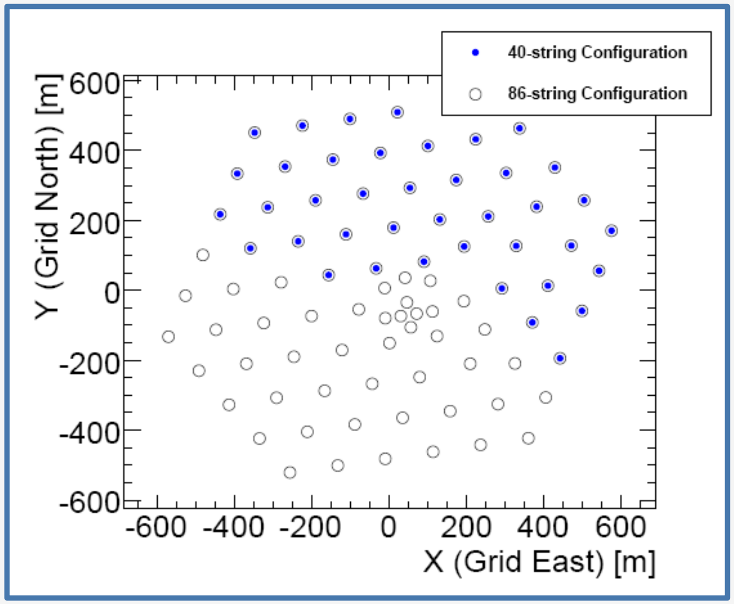
IceCube performance

discussed in terms of physics results for IC40 (& IC59)

- point sources
- GRBs
- dark matter searches
- diffuse n_m flux
- cascades
- downgoing muons

IC40 data taking

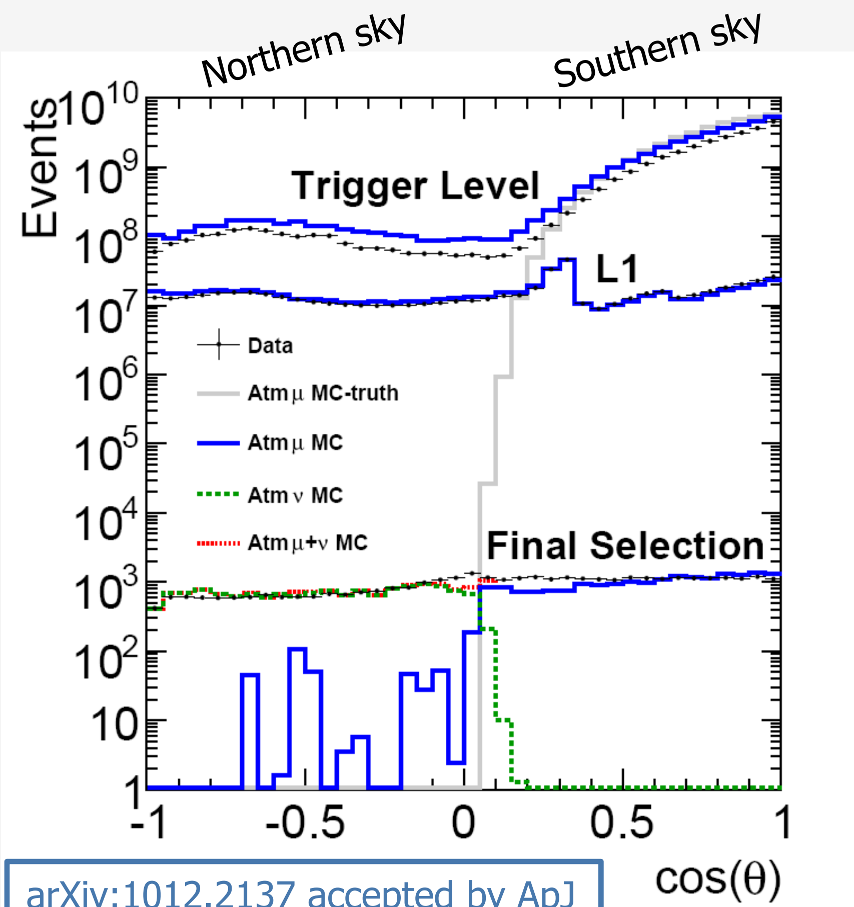
- April 2008 – May 2009
- 375.5 days (92% livetime)
- 3.3×10^{10} triggers
- trigger rate 950 Hz



Point source searches

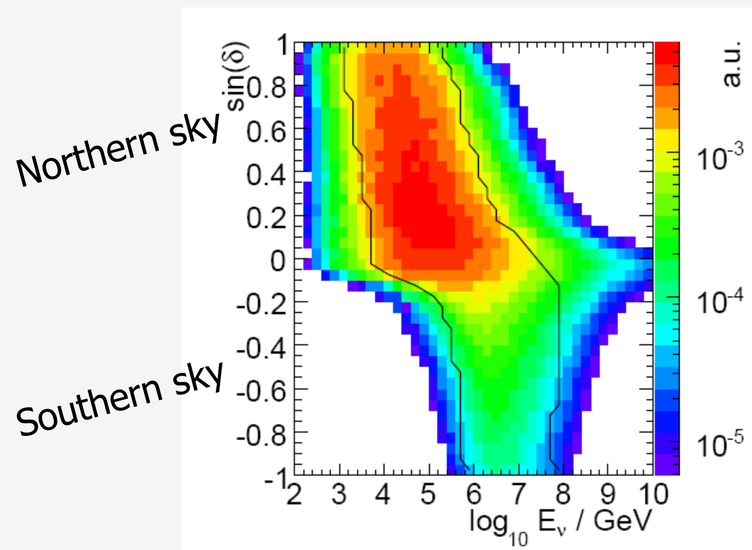
- search for neutrino induced muons

- severe bckg from atm. m's
- irreducible bckg from atm. n's



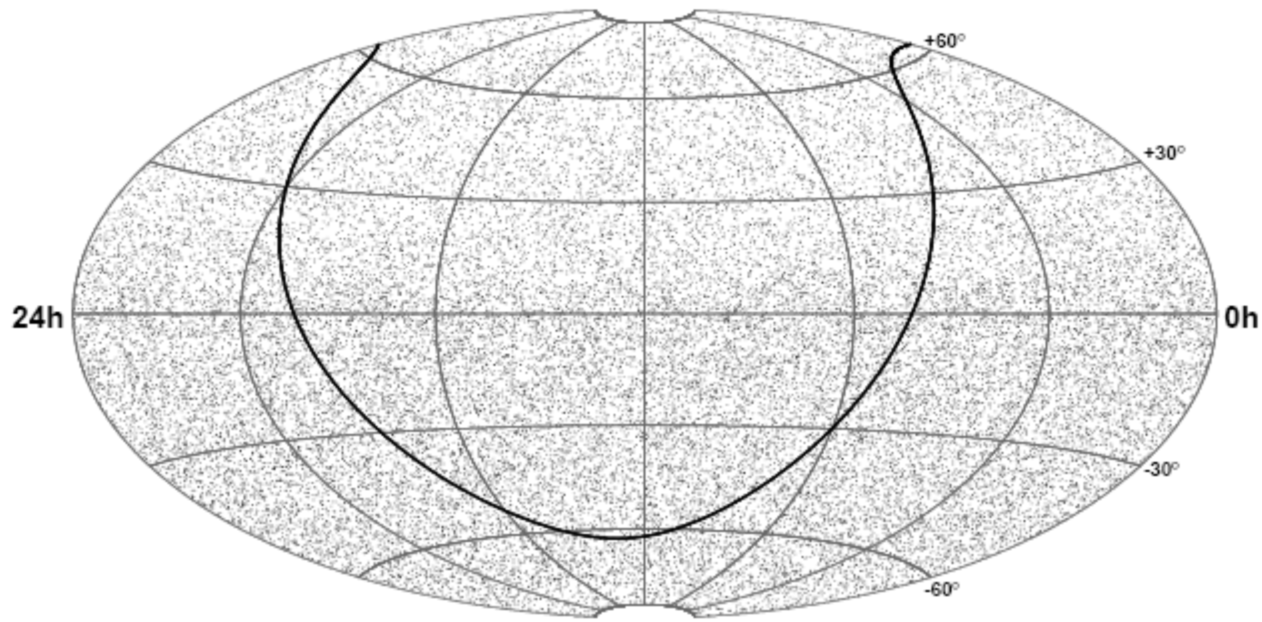
arXiv:1012.2137 accepted by ApJ

- northern sky
  - remove misreconstructions
- southern sky
  - stronger quality cuts
  - energy selection



Energy distribution , final selection
E^{-2} flux of neutrinos

All-sky point source scan

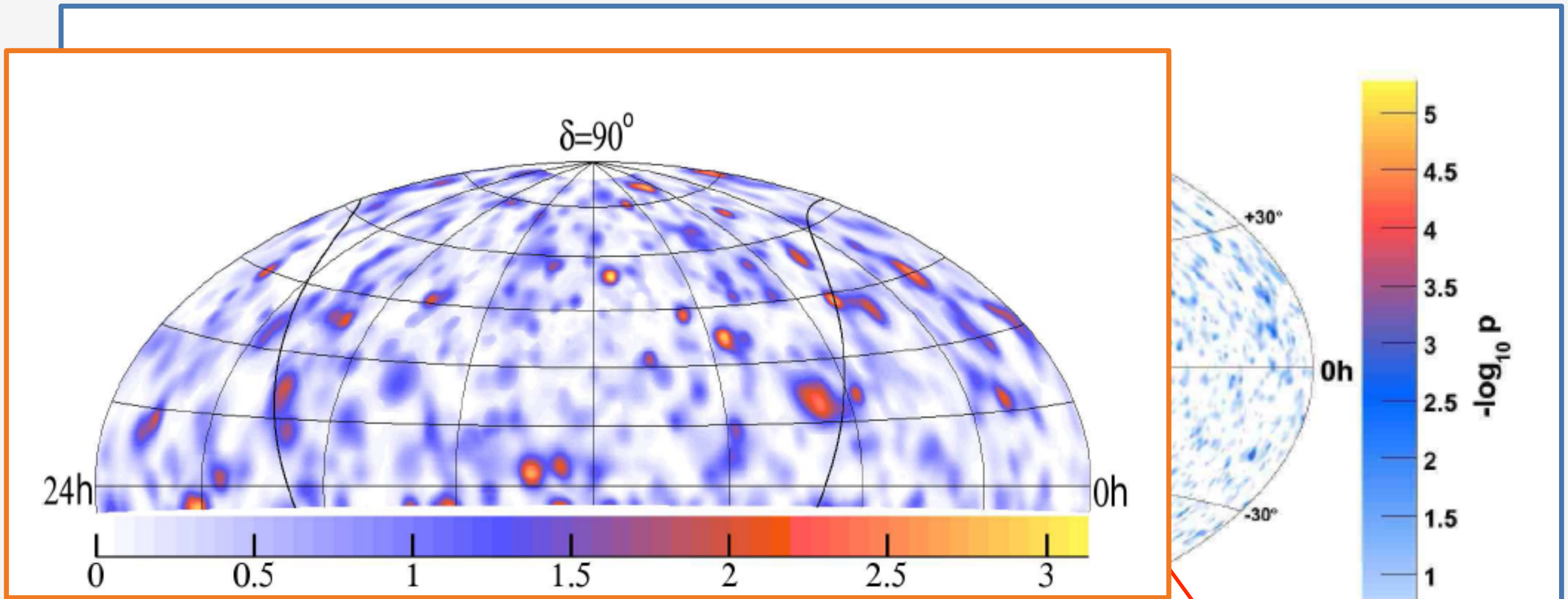


36 900 events

Northern sky – 14 121 events, pre-dominantly n_m m (> 97%)

Southern sky – 22 779 events, pre-dominantly atm. m's (> 95%)

All-sky point source scan



final AMANDA all-sky map (1387 d) – 6595 events

pre-trial significances (p-values)
color indicates compatibility with bckg

most significant hot-spot at r.a.=113.75°, d=15.15°

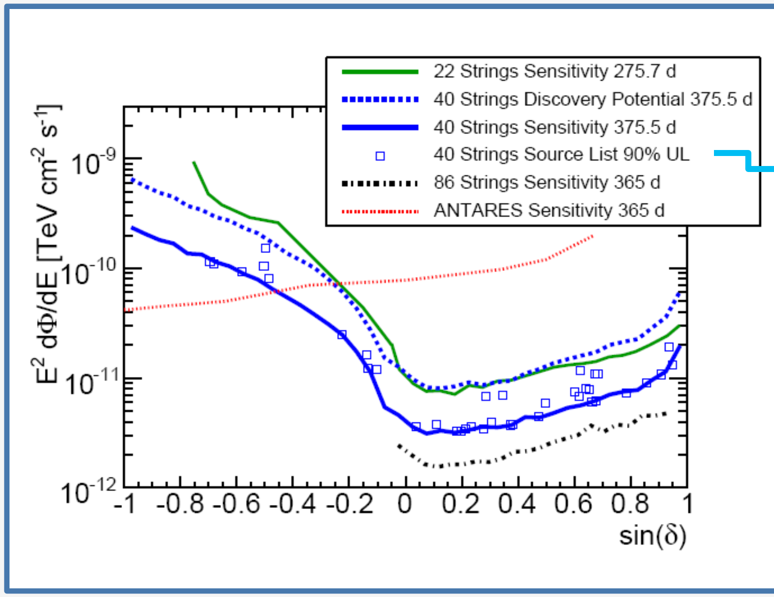
random probability 18%

Point source searches

- selected sources
- stacked sources

exp. sensitivity IC80 (2004) northern sky
$5.5 \times 10^{-12} TeVcm^{-2}s^{-1}/1y$

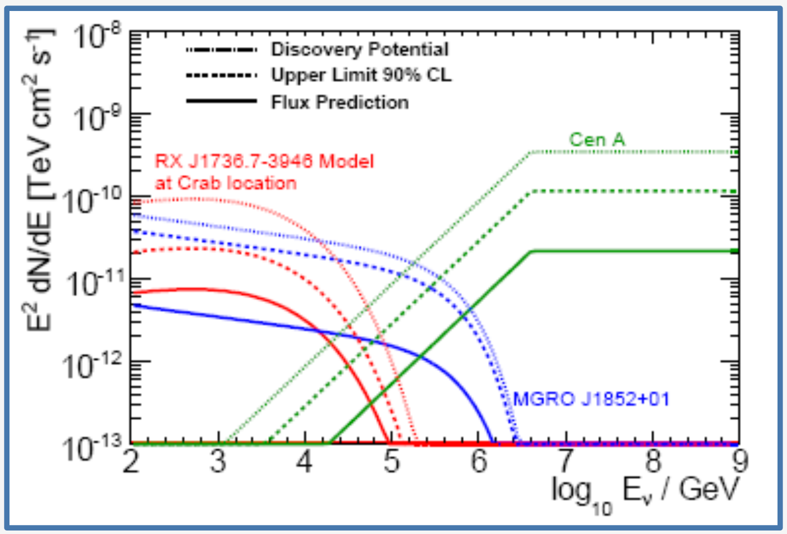
currently expect at least ***a factor 2 better***



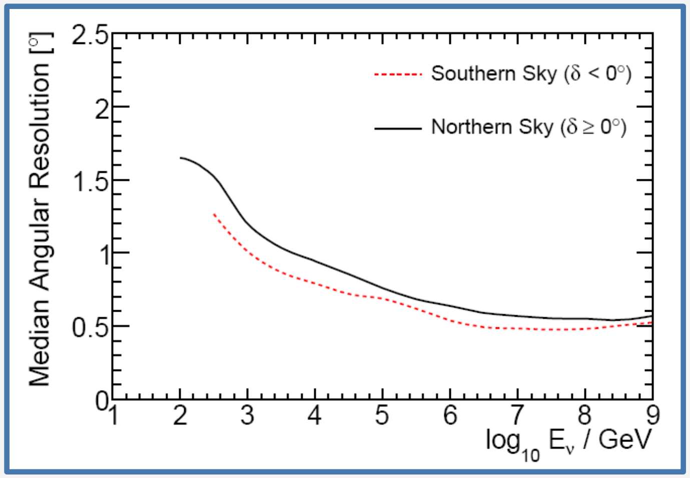
	$\Phi^{90}_{\nu_\mu}$	$\Phi^{90}_{\nu_\mu+\nu_\tau}$	
Cyg OB2	6.04	10.54	–
MGRO J2019+37	7.50	13.3	0.44
MGRO J1908+06	3.73	6.82	0.43
Cas A	9.04	15.92	–
IC443	3.80	6.62	–
Geminga	3.91	6.66	0.48
Crab Nebula	3.70	6.58	–
1ES 1959+650	10.74	19.18	–
1ES 2344+514	7.24	12.96	–
3C66A	10.89	19.70	0.24
H 1426+428	6.14	10.94	–
BL Lac	10.80	18.70	0.25
Mrk 501	8.11	14.14	0.41
Mrk 421	11.71	20.14	0.15
W Comae	4.46	8.06	–
1ES 0229+200	6.89	12.06	0.19
M87	3.42	5.98	–
S5 0716+71	13.28	23.56	–
M82	19.14	32.84	0.4
3C 123.0	5.59	10.66	0.44
3C 454.3	3.42	5.92	–
4C 38.41	6.77	11.86	0.48
PKS 0235+164	6.77	11.62	0.15
PKS 0528+134	3.63	6.72	–
PKS 1502+106	3.26	5.78	–
3C 273	3.61	6.54	–
NGC 1275	6.04	10.54	–
Cyg A	7.84	13.44	0.46
IC-22 maximum	3.26	5.86	–
Sgr A*	80.56	139.26	0.41
PKS 0537-441	113.90	201.82	–
Cen A	109.51	191.56	–
PKS 1454-354	92.56	156.74	–
PKS 2155-304	105.41	182.90	0.28
PKS 1622-297	152.28	263.86	0.048
QSO 1730-130	24.83	43.30	–
PKS 1406-076	16.04	28.72	0.42
QSO 2022-077	12.18	21.78	–
3C279	11.94	21.36	0.33

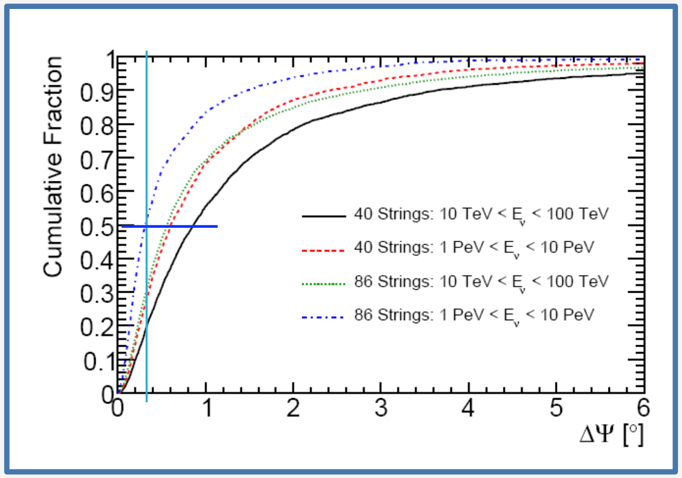
IC40
upper limit/disc. potential

- optimistic models

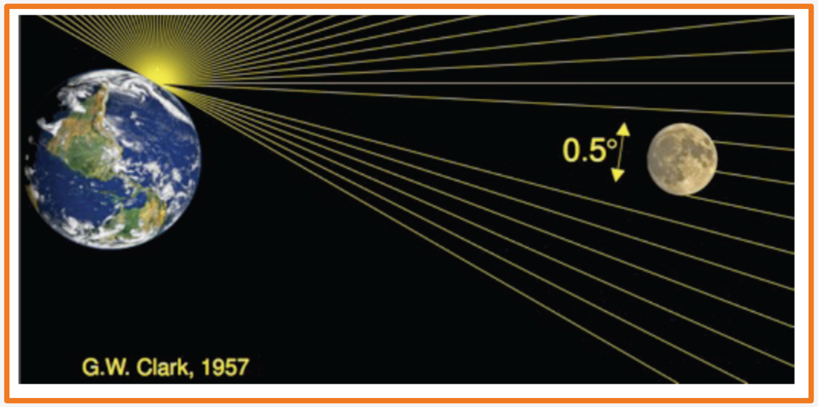


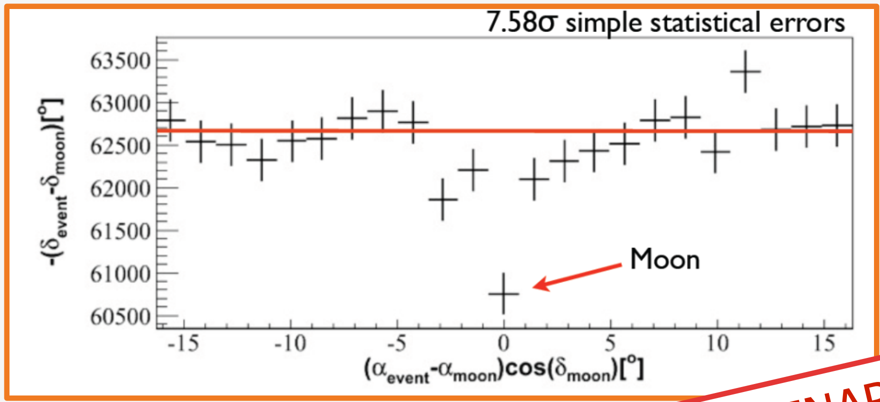
Point source performance





verification of angular resolution and absolute pointing

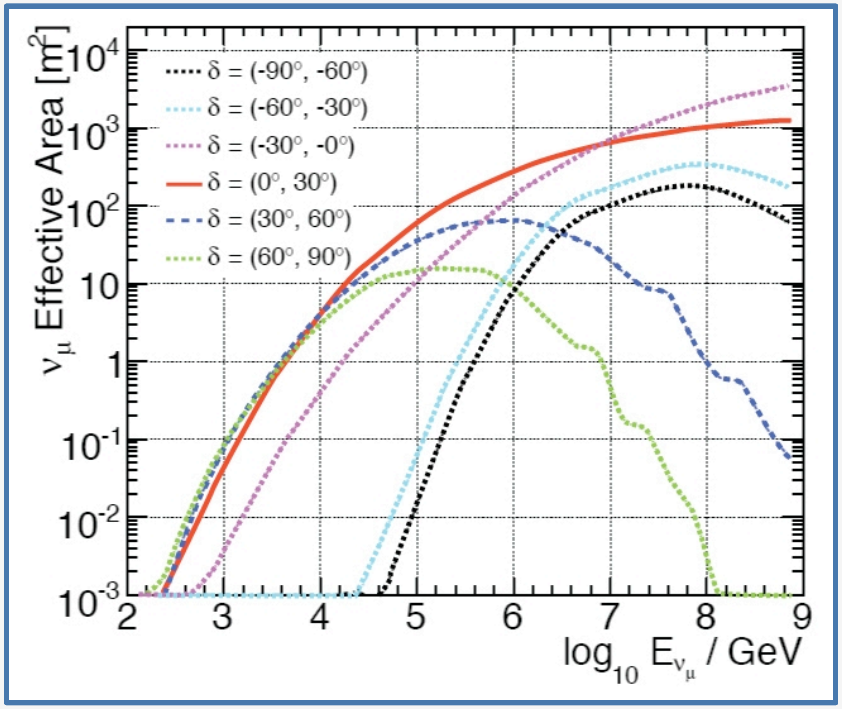




PRELIMINARY

moon shadow observed in muons

Point source performance



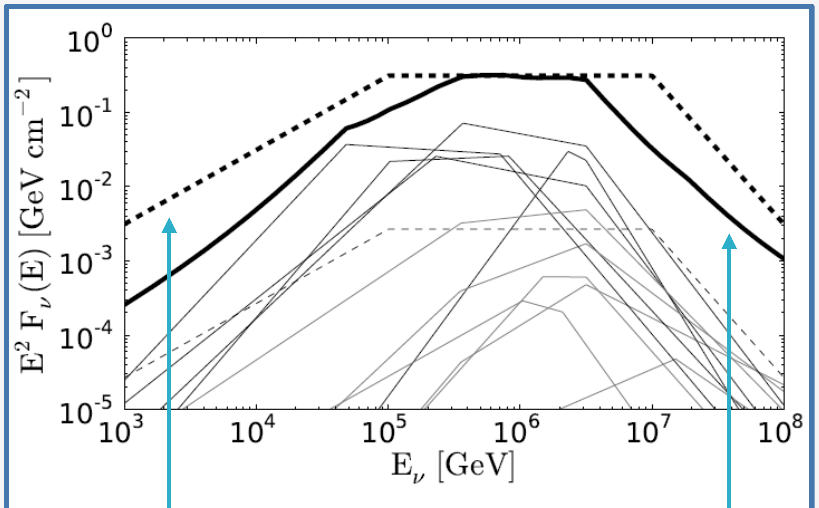
a view to the GC
at the highest energies

Galactic center
at $\delta = -29°$

solid angle averaged effective area for E^{-2} flux

Gamma Ray Bursts

n spectra of selected bursts



Waxman 2003 prediction

sum of all 117 bursts

exp. sensitivity IC80 (2004)
northern sky
~ 0.2 F_{WB} in 1 year

117 GRBs analyzed (d>0)

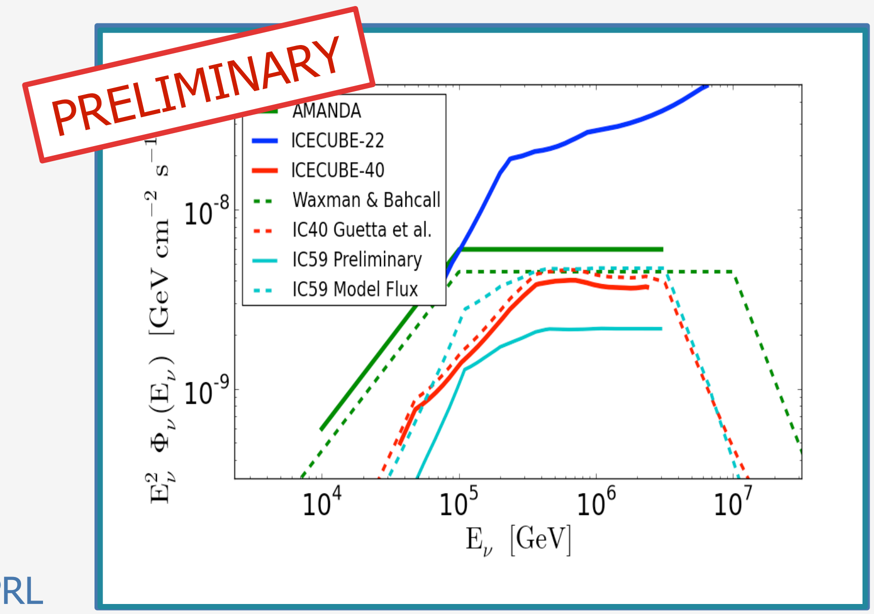
April 2008 – May 2009

Model independent: time window

[-10s;10s] [-1d;1d]

Model dependent: unbinned LLH

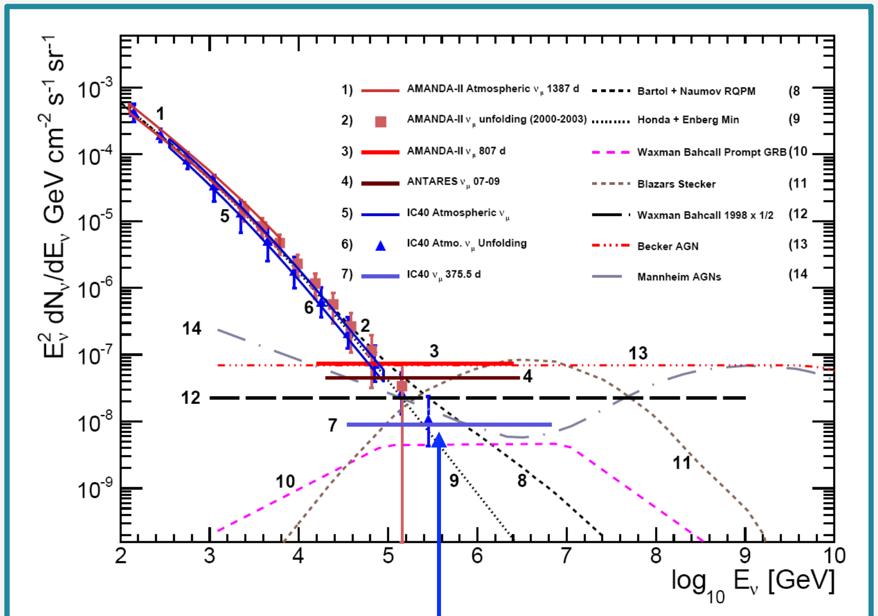
n's w. energy spectrum à la Guetta et al



arXiv:1101.1448 subm. to PRL

Diffuse flux of astrophysical n_m

- search for n_m signal integrated over the northern sky
- energy measurement crucial



IC40: 8.9×10^{-12} TeVcm^{-2}s^{-1}sr^{-1}
34.7 TeV -6.9 PeV

exp. sensitivity IC80 (2004)
☞ 8.1×10^{-12} TeVcm^{-2}s^{-1}sr^{-1}/1y

- atm. n_m spectrum (332 GeV – 84 TeV)
  – consistent with p, K decays
  – no evidence for charm

- astrophysical limits depend on extrapolation of atm. n_m spectrum

change of slope of the CR spectrum influences the atm. n_m spectrum

- data needed in the knee region
  ☞ IceTop+IceCube

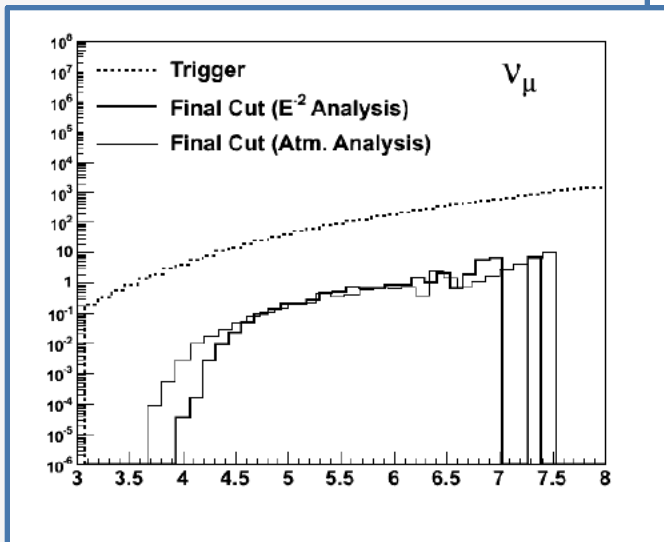
an astrophysical $E^{-2}n_m$ flux at the current limit will take 3 yrs of full IC for a 5s discovery

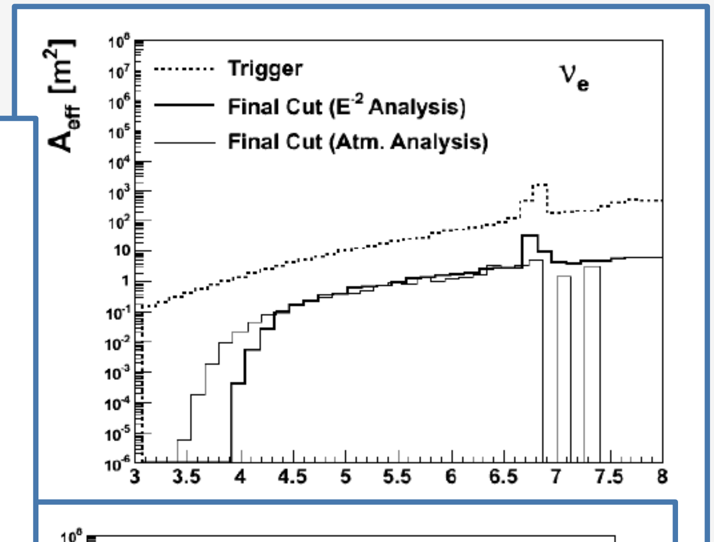
Cascades

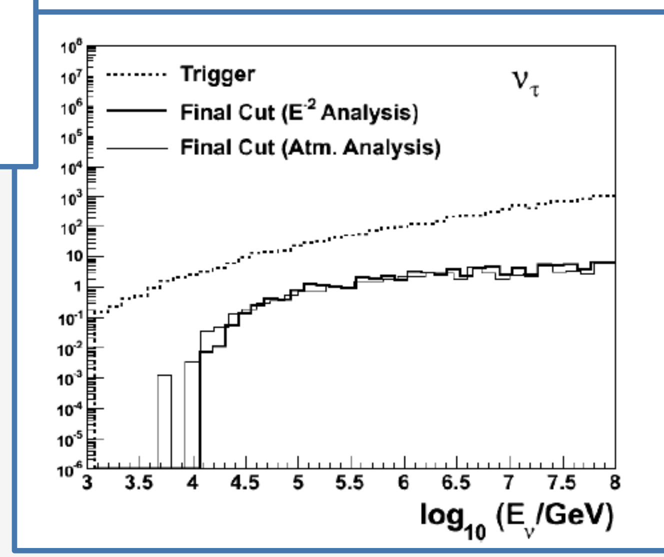
- sensitivity to all flavors
- 4p coverage

results for IC22

arXiv:1101.1692
subm. to PRD







- similar A_{eff} for all flavors

for diffuse flux expect similar sensitivity
in the cascade channel as in the muon channel
☞ considerable improvement of overall sensitivity

Diffuse flux of EHE neutrinos

arXiv:1103.4250 acc. by PRD

- search for n's with E> 1 PeV
- simple robust observables

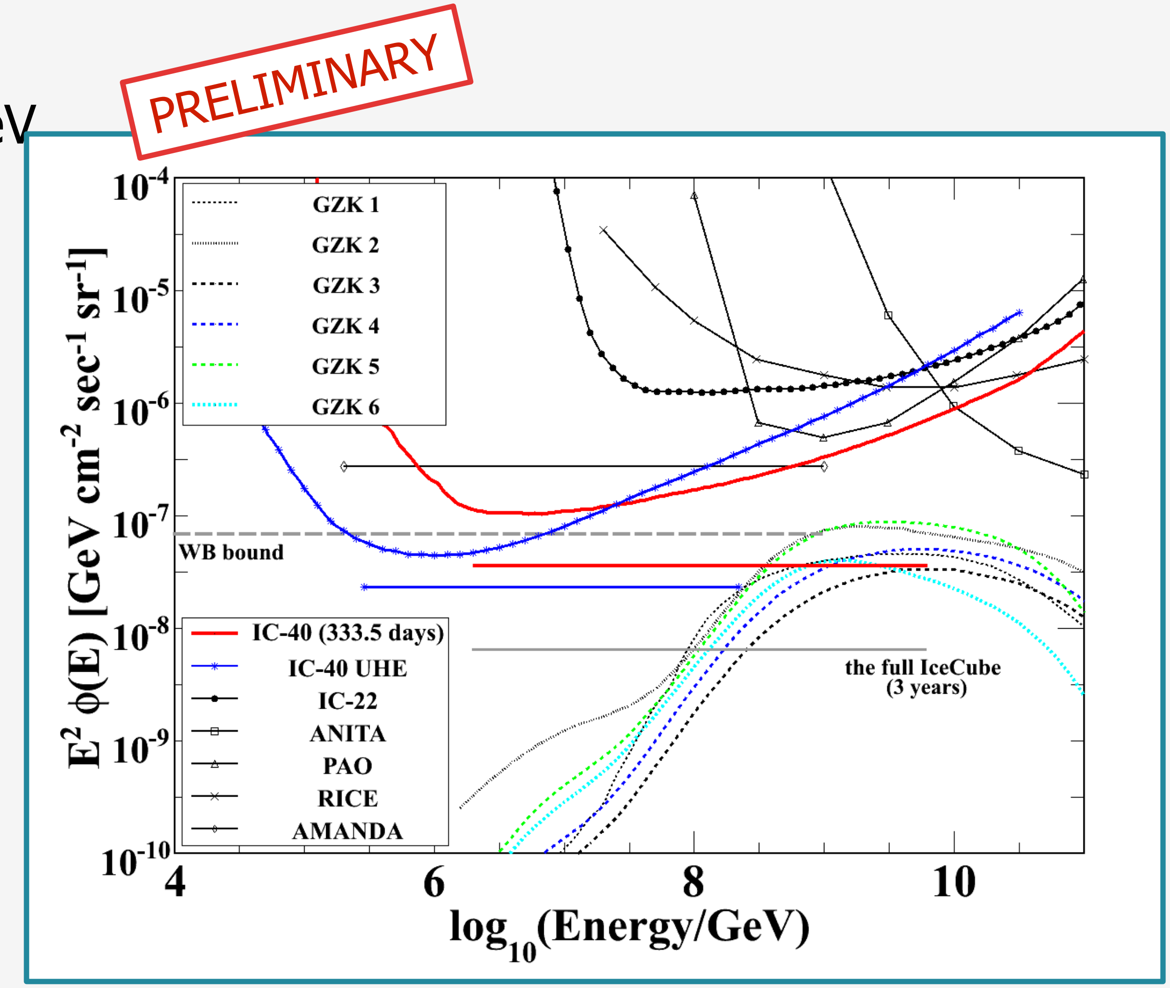
- bright events (NPE> 10^6)
- close to the horizon

effective area increases to
~ $10^4 – 10^5$ m^2
at the highest energies

- differential limit
- integrated limit

- for an assumed E^{-2} spectrum

3.6×10^{-11} TeVcm^{-2}s^{-1}sr^{-1}
2 PeV – 6.3 EeV

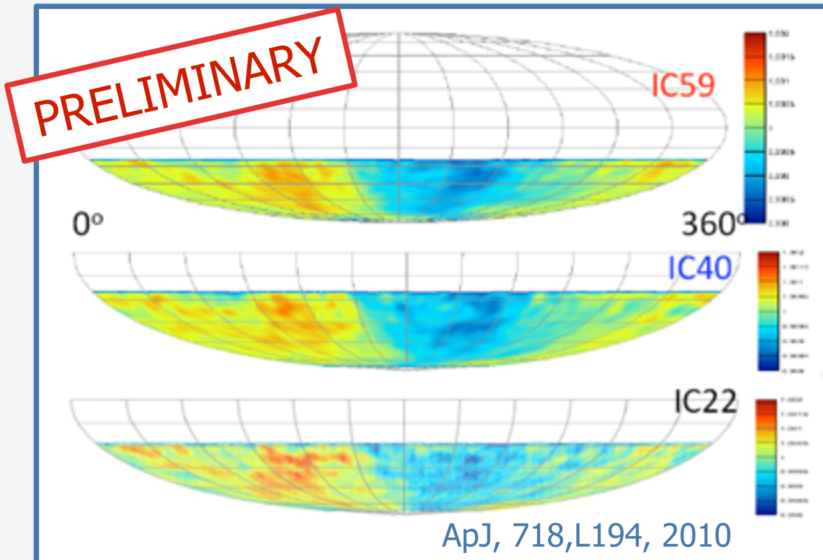


all flavor limits with $n_e:n_m:n_t$=1:1:1

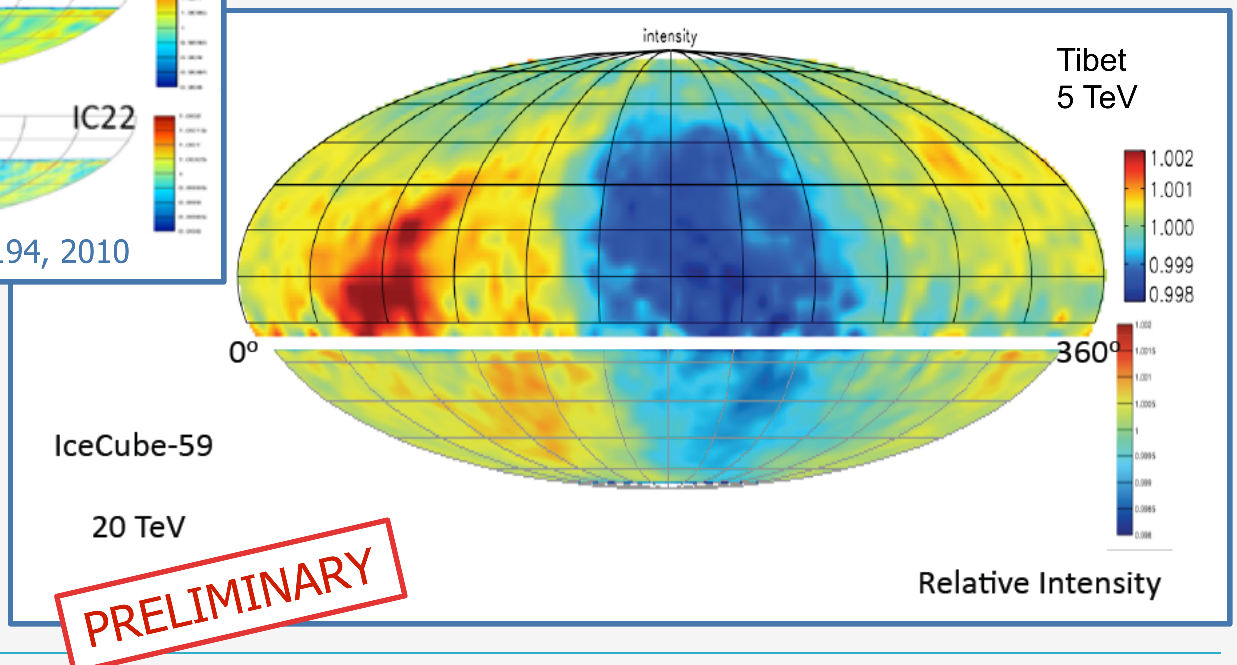
CR anisotropy – large scale

IceCube collects ~O (10^{10}) m’s per year

high statistics study of arrival directions in the southern sky



a continuation of previously measured northern sky anisotropy

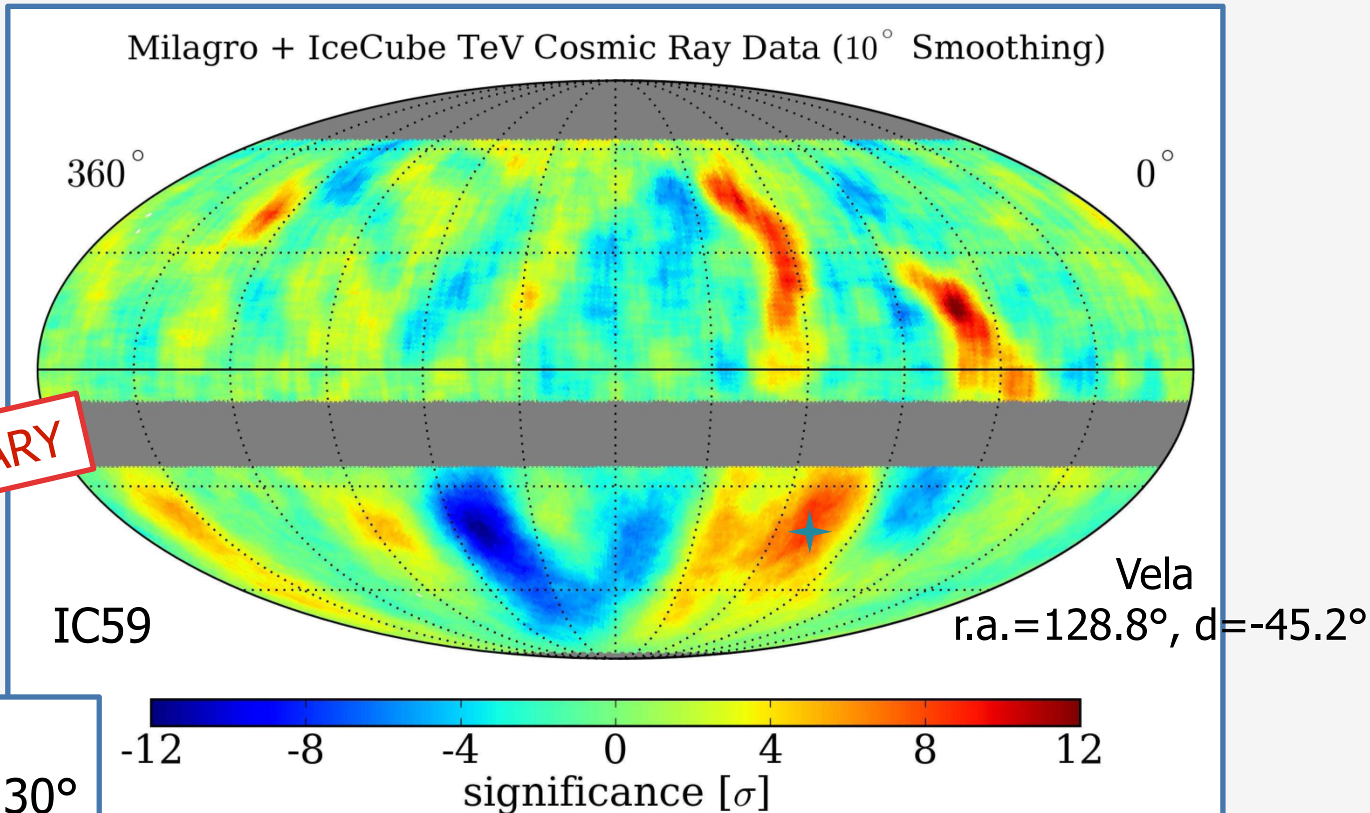


rel. intensity of the CR event rate

- modulation at the level 10^{-3}

CR anisotropy – medium scale

- ongoing high sensitivity analyses at varying ang. scales and energy bands

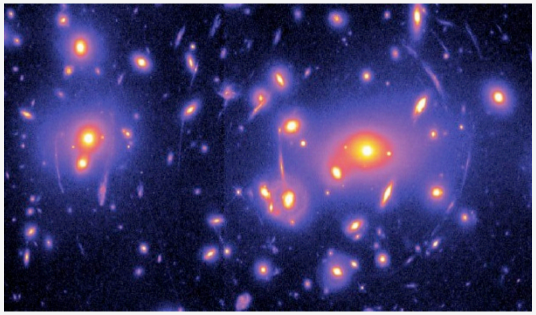


PRELIMINARY

structures on scales 15° - 30°

currently no explanation for the structure

Dark matter searches


dark matter exists! – but what is it?

new fundamental particle produced in the early universe – WIMP ??

leading candidate for dark matter: the neutralino
predicted by MSSM

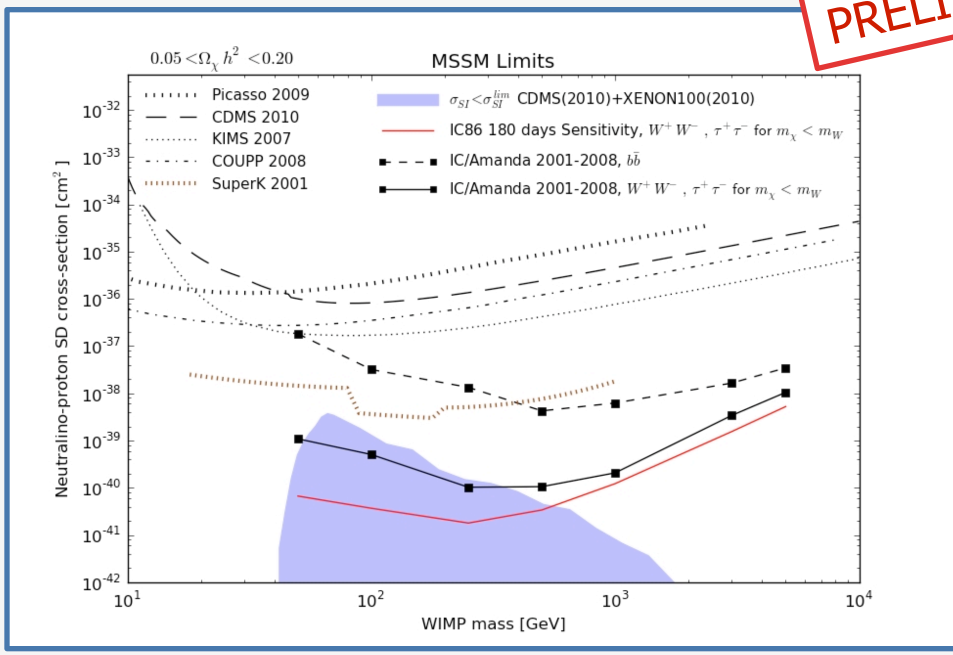
$$\tilde{\chi}^0 = N_1\tilde{B} + N_2\tilde{W}^3 + N_3\tilde{H}_1^0 + N_4\tilde{H}_2^0$$

- ☞ weakly interacting, stable, mass O(GeV-TeV)
- ☞ give the required relic density without fine-tuning
- ☞ accumulate in celestial bodies

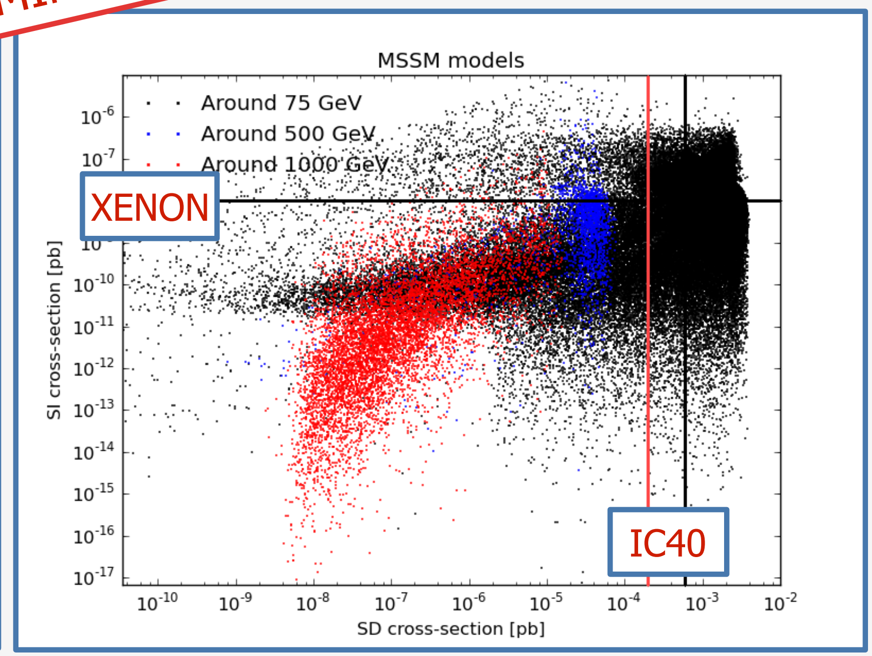
WIMP searches

- Sun
- Earth
- galactic halo
- galactic center

PRELIMINARY

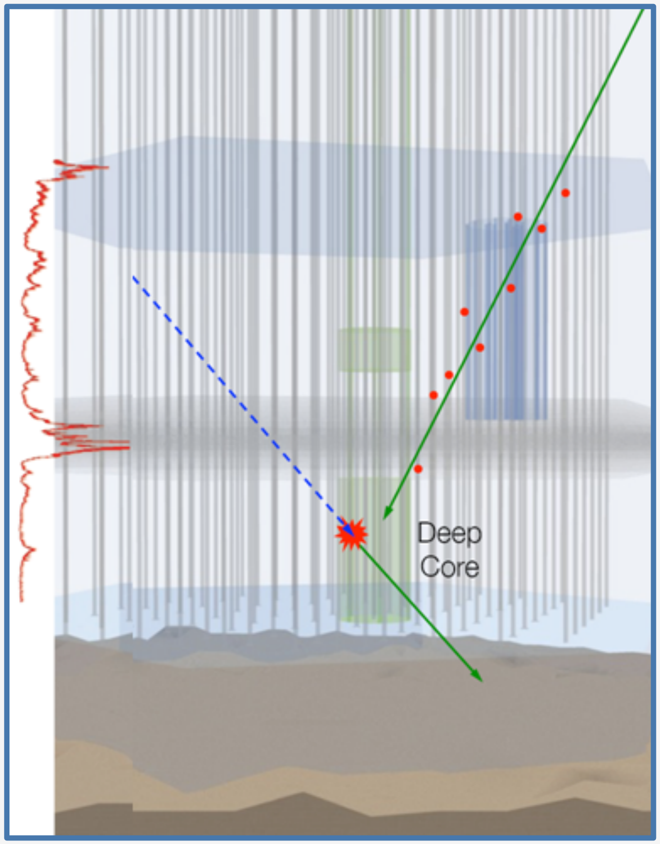


solar WIMP searches
90% CL limit on χ-p SD cross section

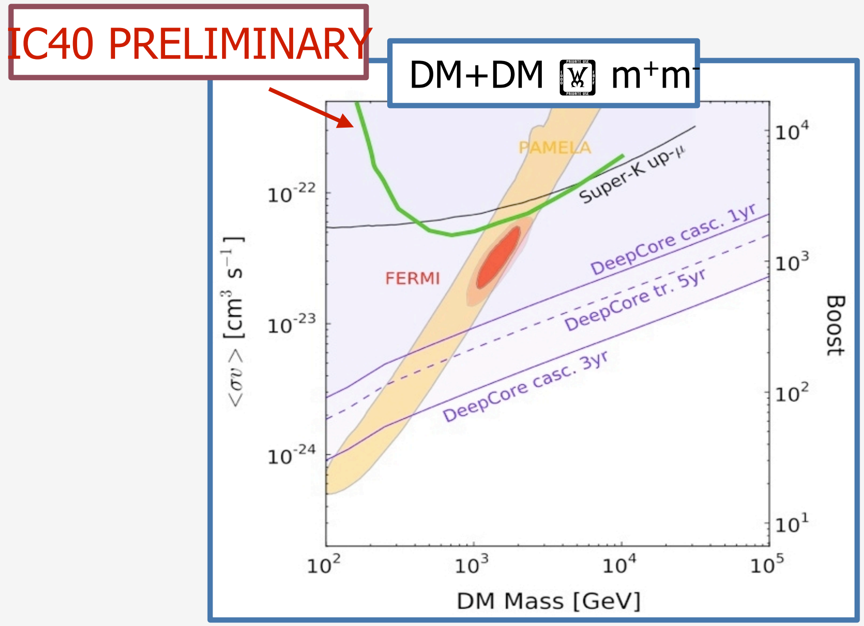


χ-p SI vs SD cross section

Deep Core



- improved sensitivity for low mass WIMPs
- enhanced acceptance for low energy n
- sensitivity for Southern sky sources



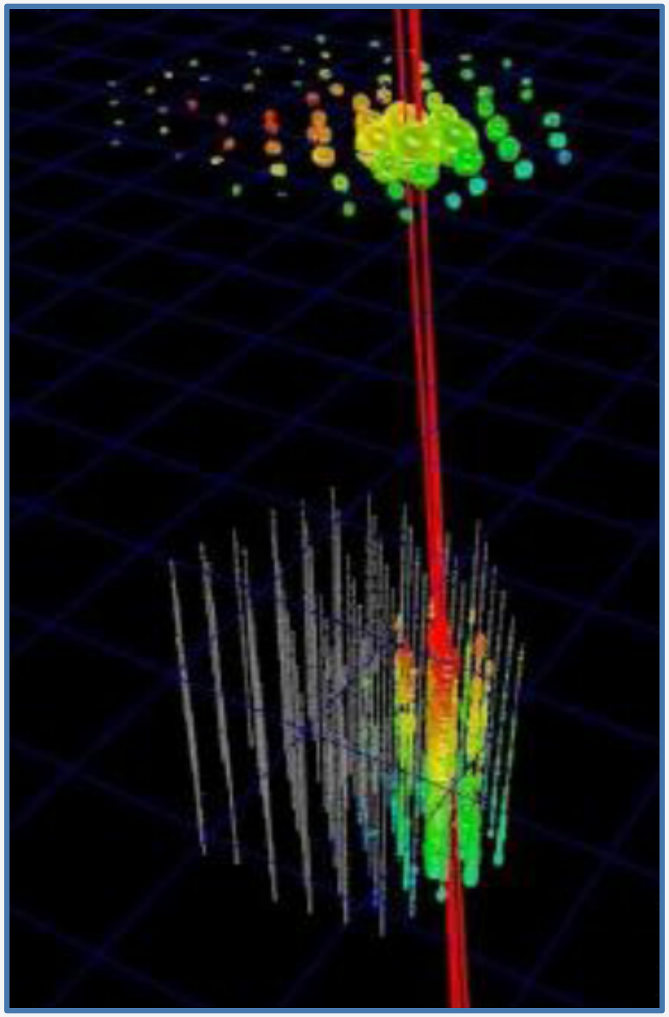
all sky sensitivity

☞ use surrounding IceCube strings as veto

constraints on leptophilic DM

PRD 81, 043508 (2010)

IceTop



IceTop/IceCube coinc. event June 2010

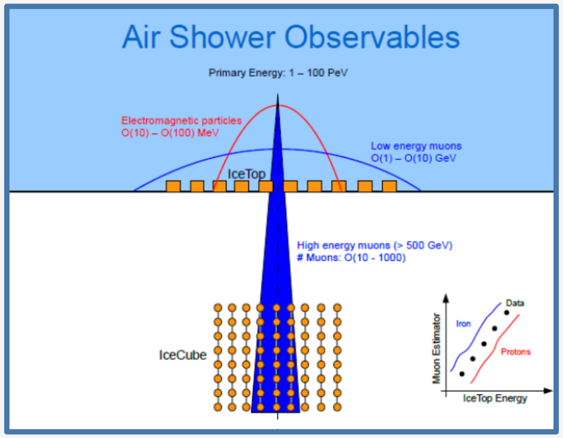
surface array completed 81 stations w. 324 DOMs

energy range > 0.3 PeV

geom. extent A[illegible]W $3\ km^2sr$ IceTop only

$0.3\ km^2sr$ IceTop + IceCube

~10^9 air showers/y



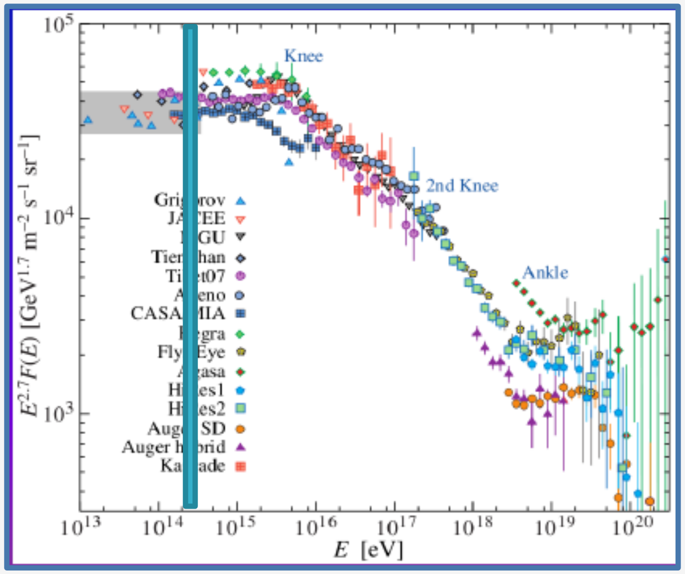
IceTop+IceCube
- veto
- calibration

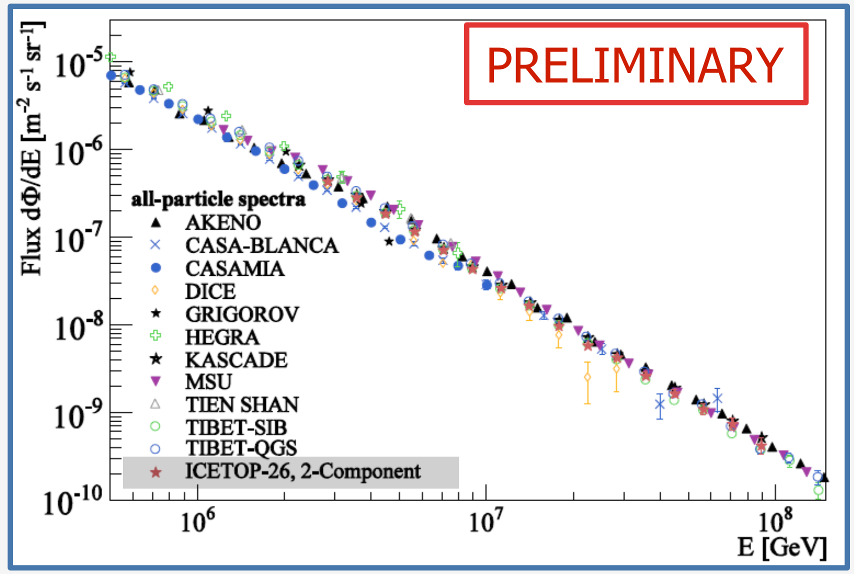
Primary goals

- CR spectrum
- mass composition

in the "knee" region

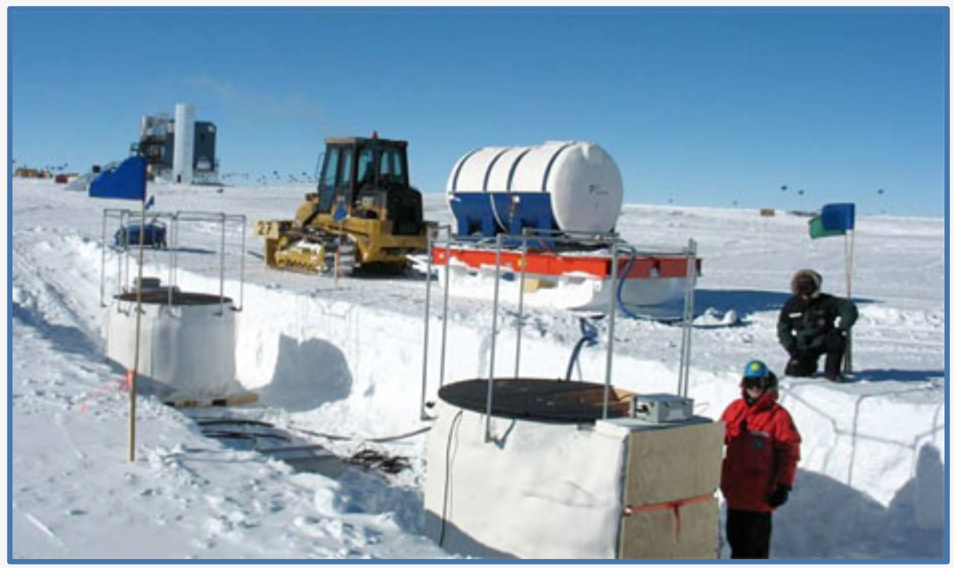
IceTop





analyses underway ☞ ICRC

- ★ composition
- ★ search for PeV g rays
- ★ search for high-p_T muons
- ★ solar flare physics
- ★ atmospheric physics



There is nothing like a dream to create the future.

Victor Hugo

projects investigated or considered

- SPATS: acoustic detection of UHE neutrinos
- AURA: under-ice radio detection of UHE neutrinos

- ARA: a radio array (~100 km^2) for GZK neutrinos
- DM-ICE: a DM detector for direct searches in the center of IceCube
- Beyond-DC: an extended dense array inside IceCube
  for DM physics, SN detection beyond the Milky Way, proton decay (?)
- RASTA: an extended air shower array

Summary

★ ICECUBE is a unique observatory hoping to detect the elusive cosmic neutrinos

★ COMPLETED – on time, within budget

★ PERFORMANCE – exceeding design goals

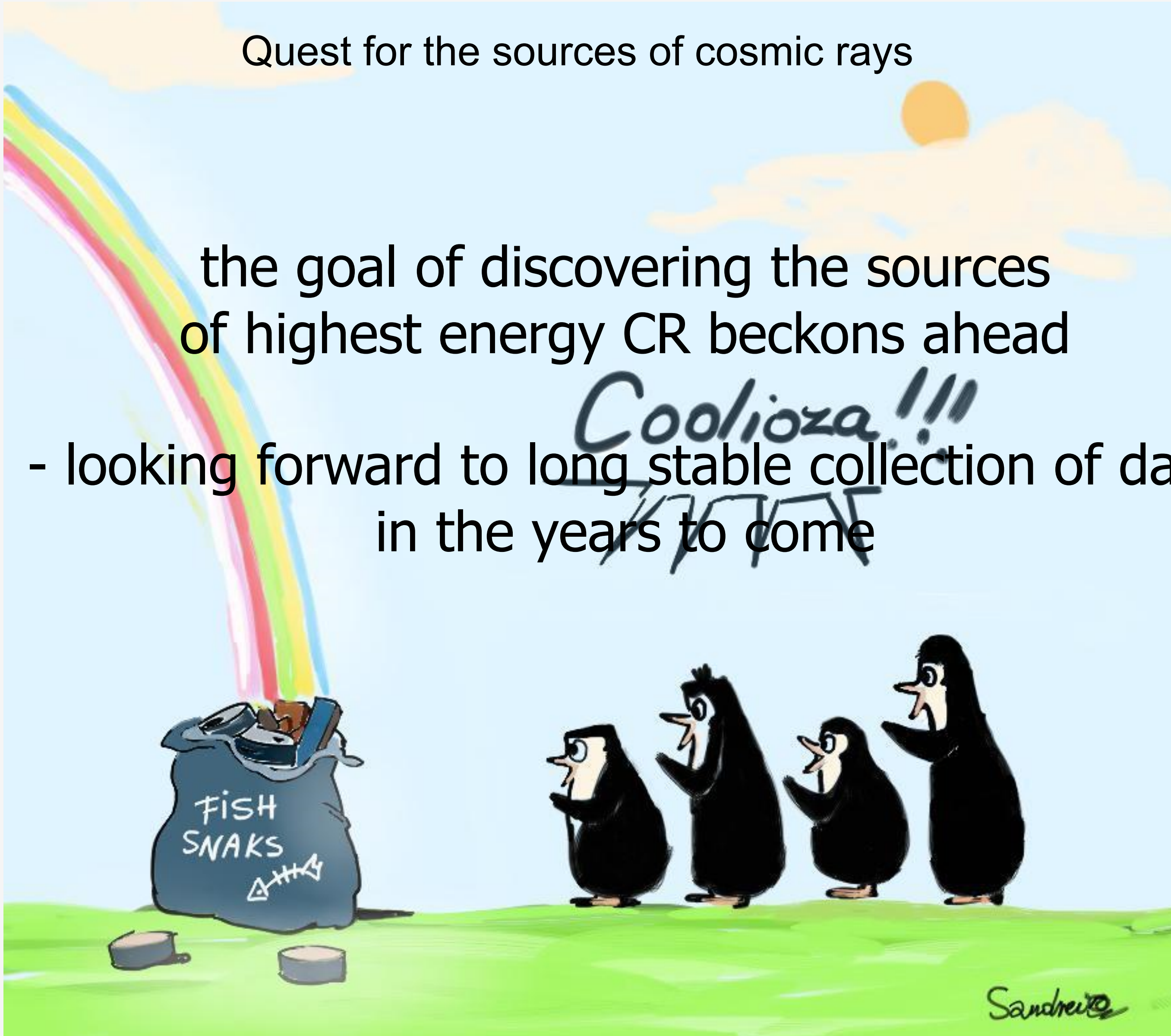
★ ICETOP+ICECUBE a unique tool for CR physics

★ many science results
– already excluding the most optimistic models

- atm. n spectrum extended
- diffuse limit below the WB bound
- GRB limits below the WB bound
- no evidence yet for point sources with 0.5 km^3yr data

★ multi-messenger programs in place: Magic, LIGO, ROTSE, SWIFT

Quest for the sources of cosmic rays



the goal of discovering the sources
of highest energy CR beckons ahead

- looking forward to long stable collection of data
in the years to come