A review of future experiments

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University of Wisconsin-Madison

Neutrino 2012
Kyoto

Outline:
- Neutrinos and Cosmic rays
- Energy scales of neutrino telescopes, next challenges
- 1 to 100 GeV: Low energy extensions: PINGU,...
- 0.1 to 10000 TeV: Neutrino telescopes for neutrino astronomy
- 10^16 to 10^20eV: Strategies for cosmogenic neutrino flux discovery

Cosmic Rays and Neutrino Sources : neutrinos from accelerators

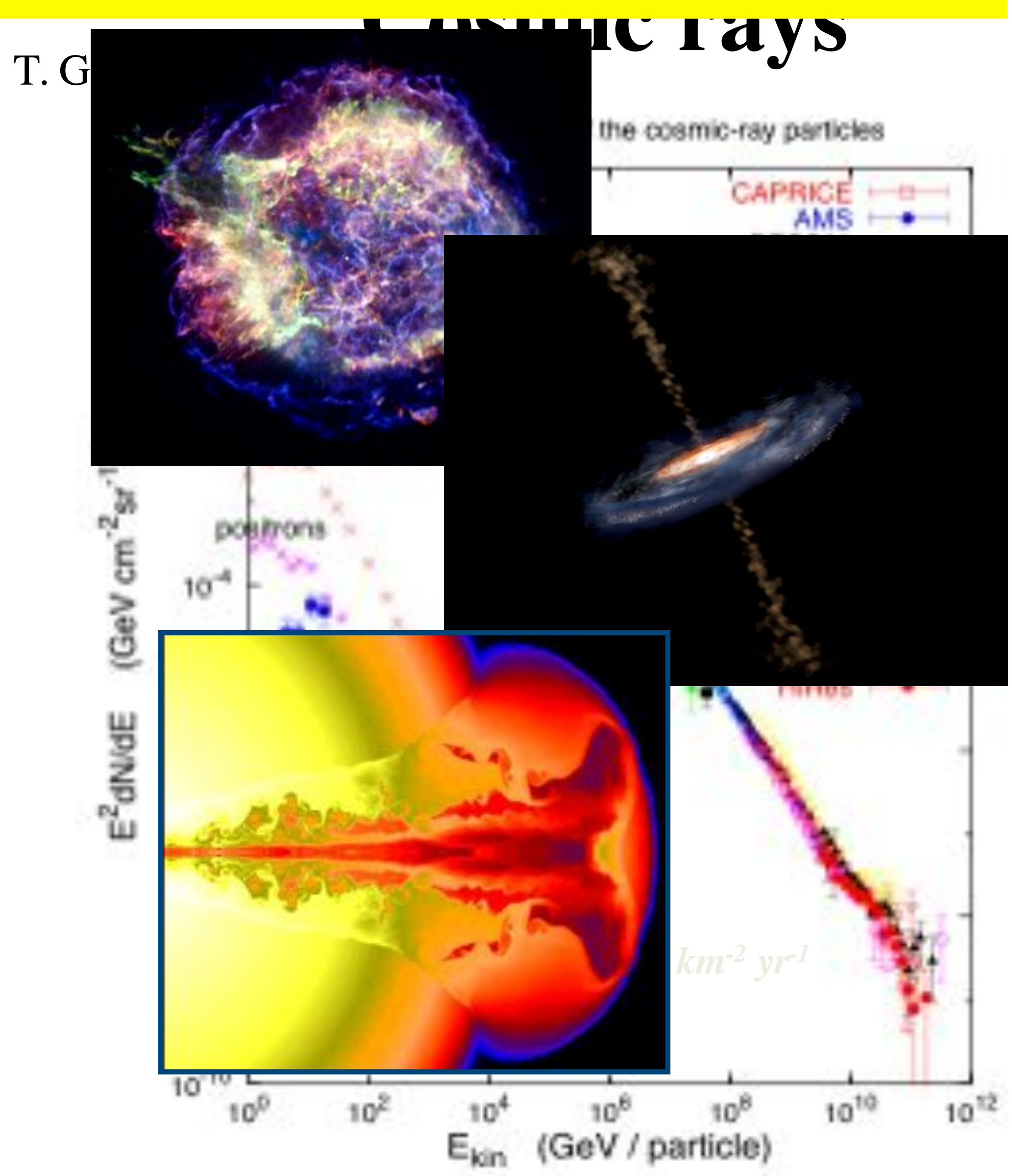
$$p\gamma \rightarrow p\pi^0, n\pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Cosmic ray interaction in accelerator region:

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts



Neutrino production from cosmic rays on known targets.

$$pp \rightarrow NN + pions; \qquad p\gamma \rightarrow p\pi^0, n\pi^+$$

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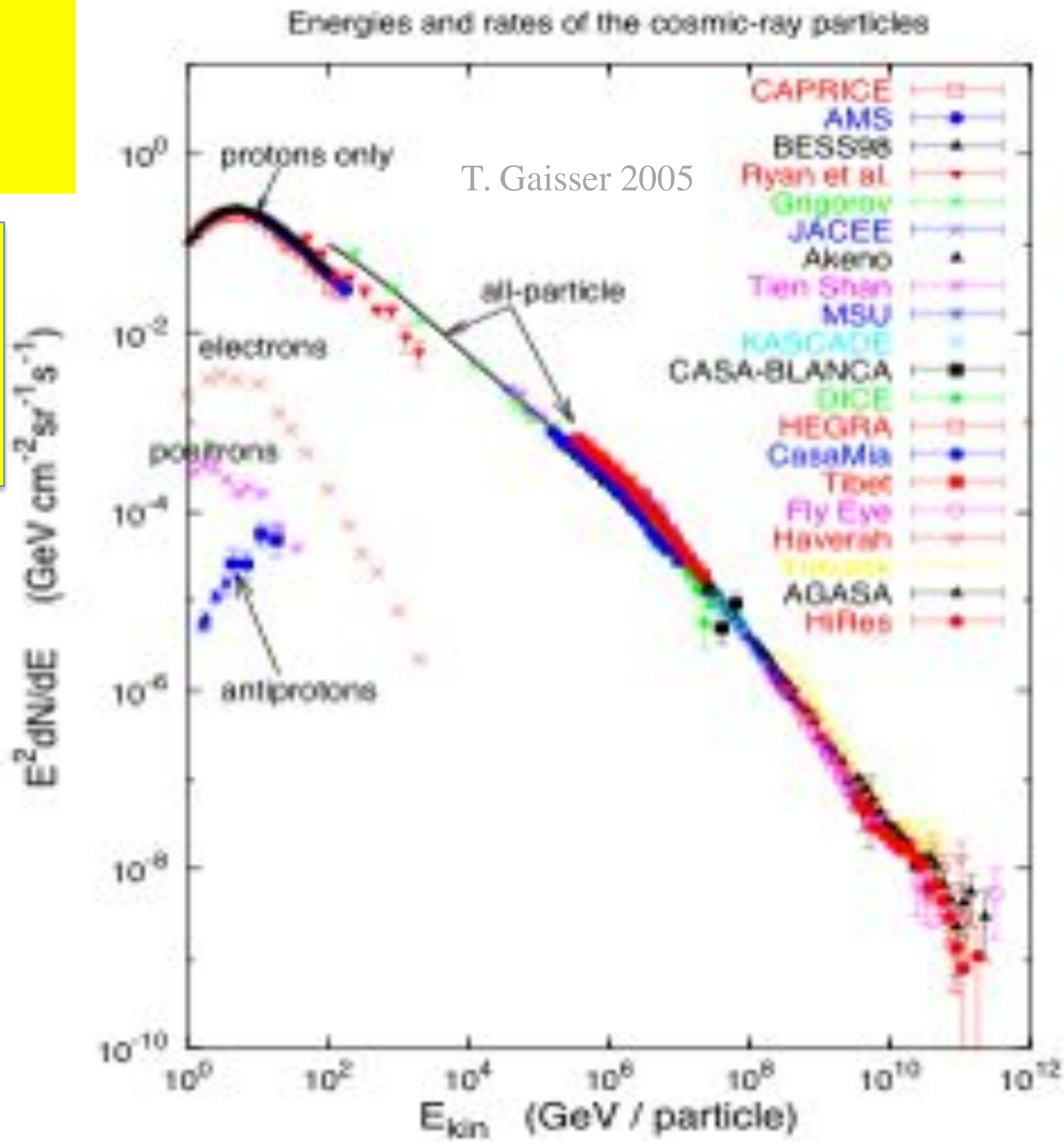
Known targets:

- Earth's atmosphere: Atmospheric neutrinos (from π and K decay)
- Interstellar matter in Galactic plane: Cosmic rays interacting with Interstellar matter, concentrated in the disk
- Cosmic Microwave background: UHE cosmic rays interact with photons in intergalactic photon fields.



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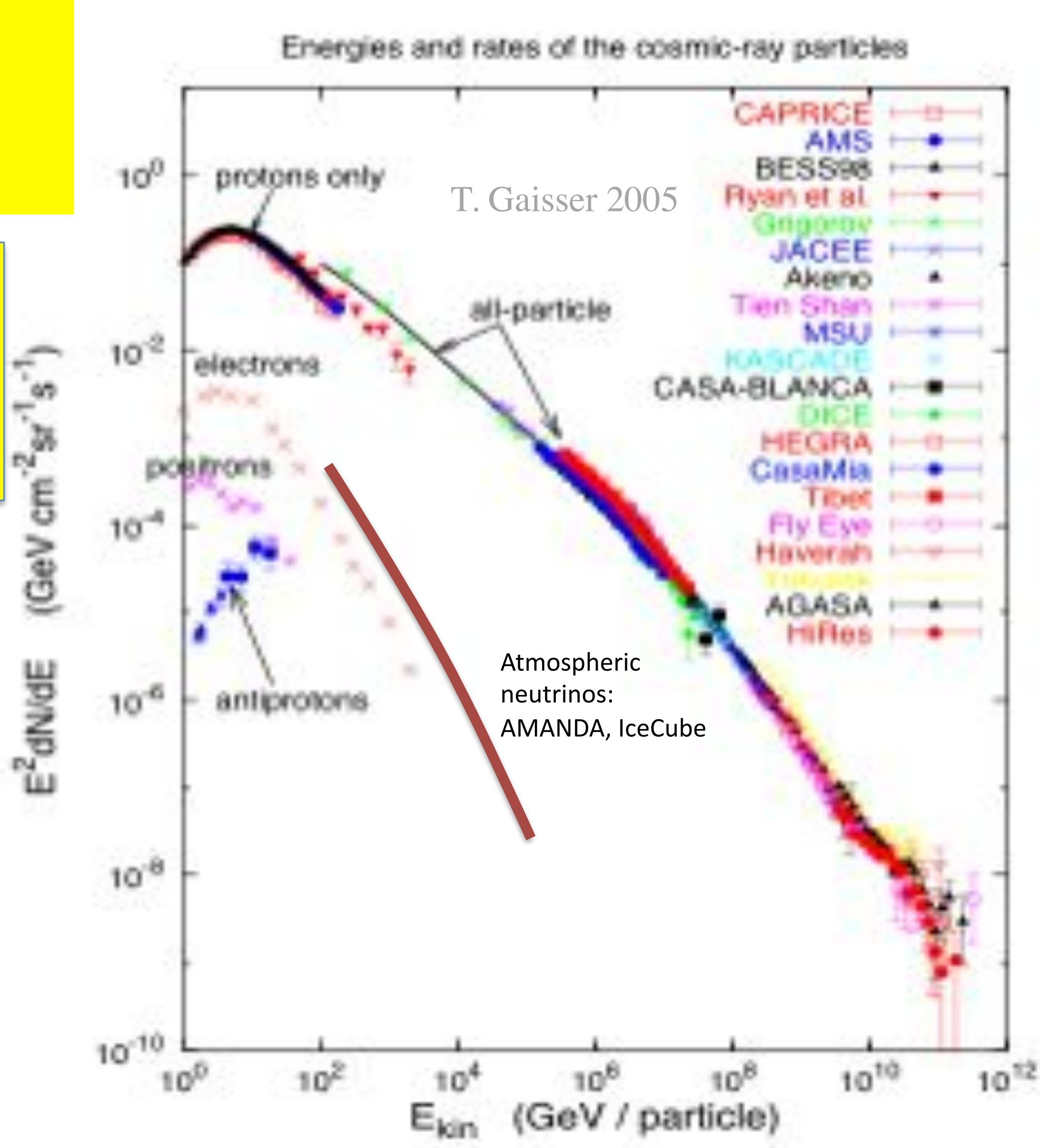

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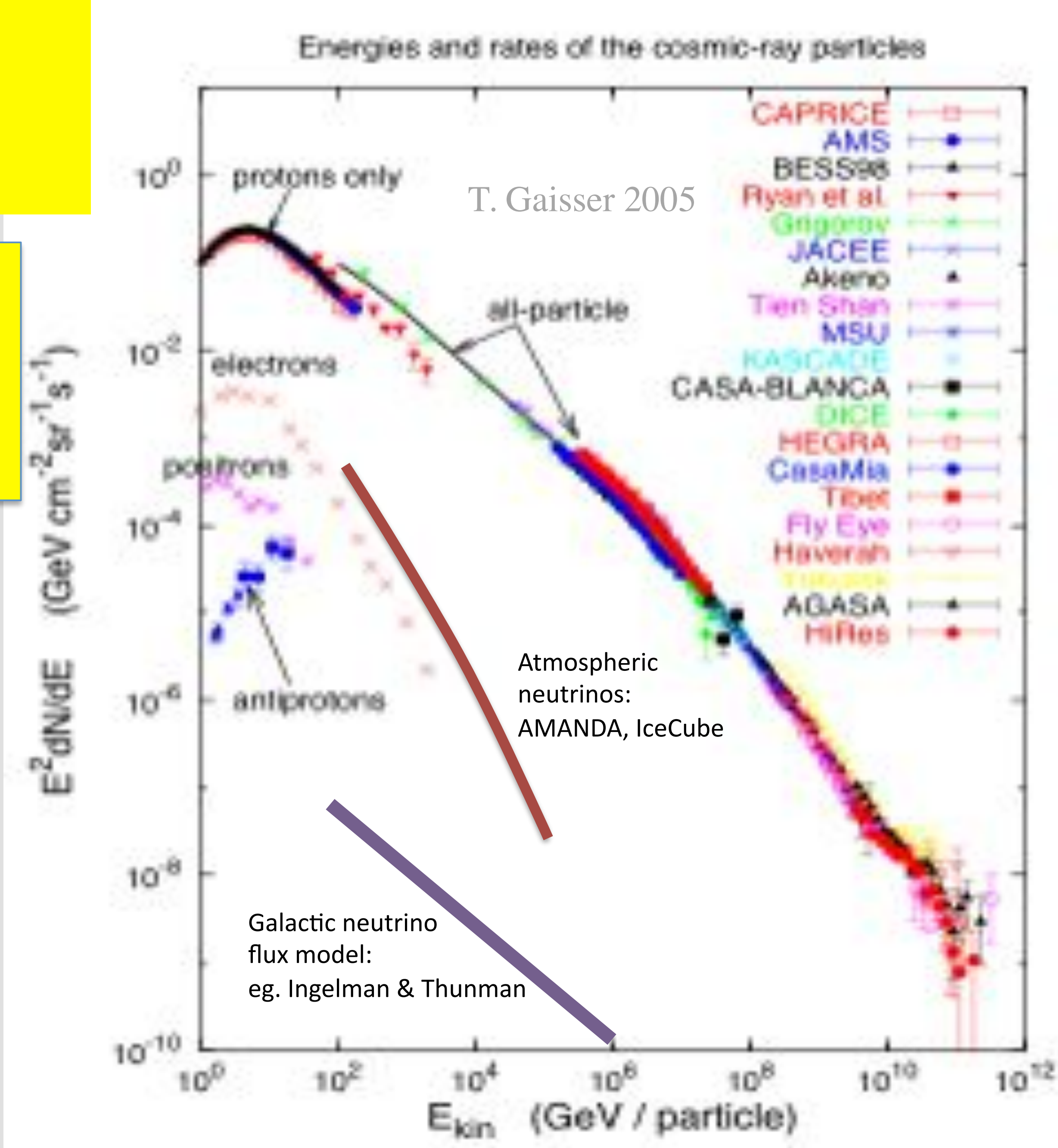

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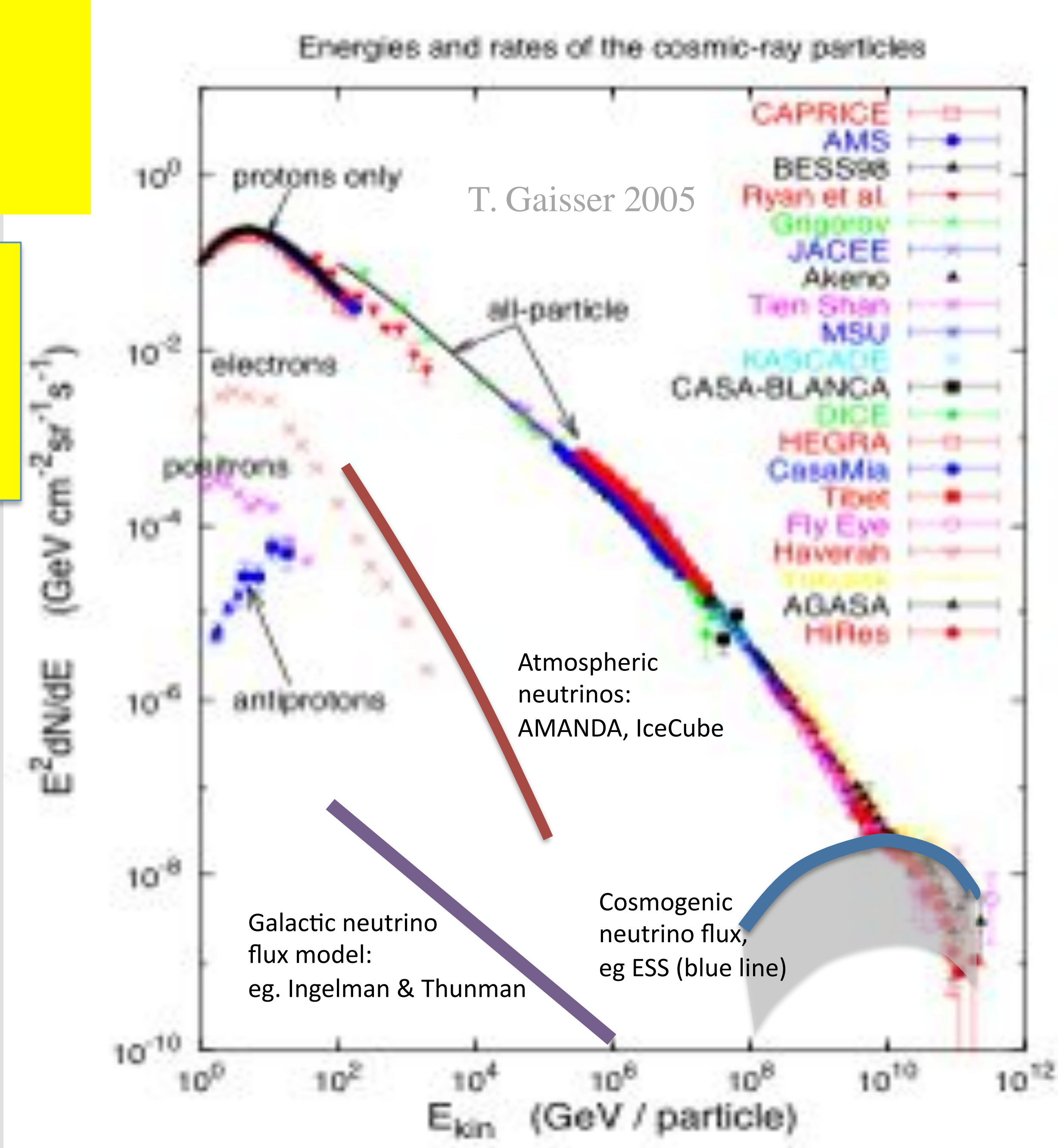

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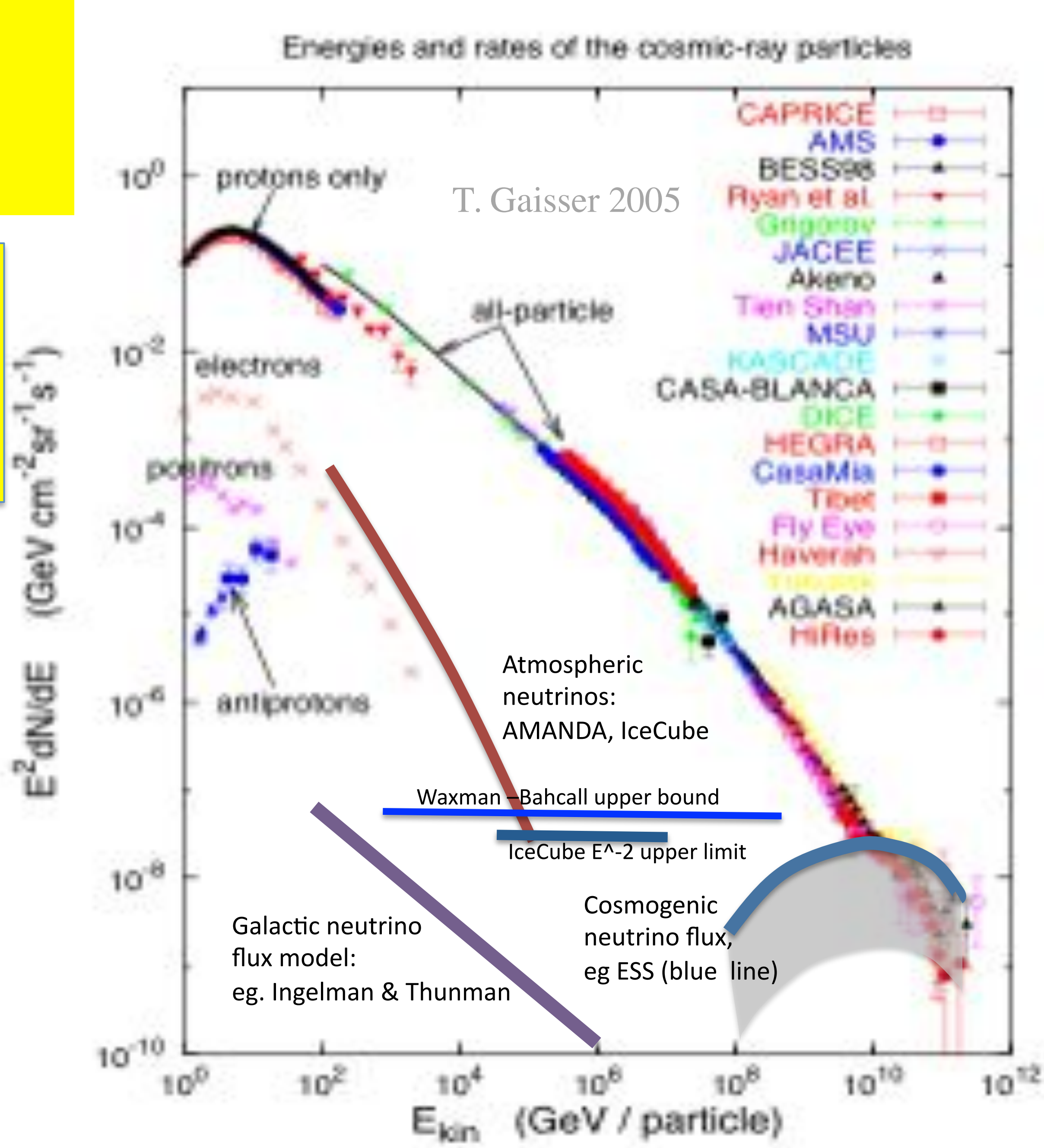


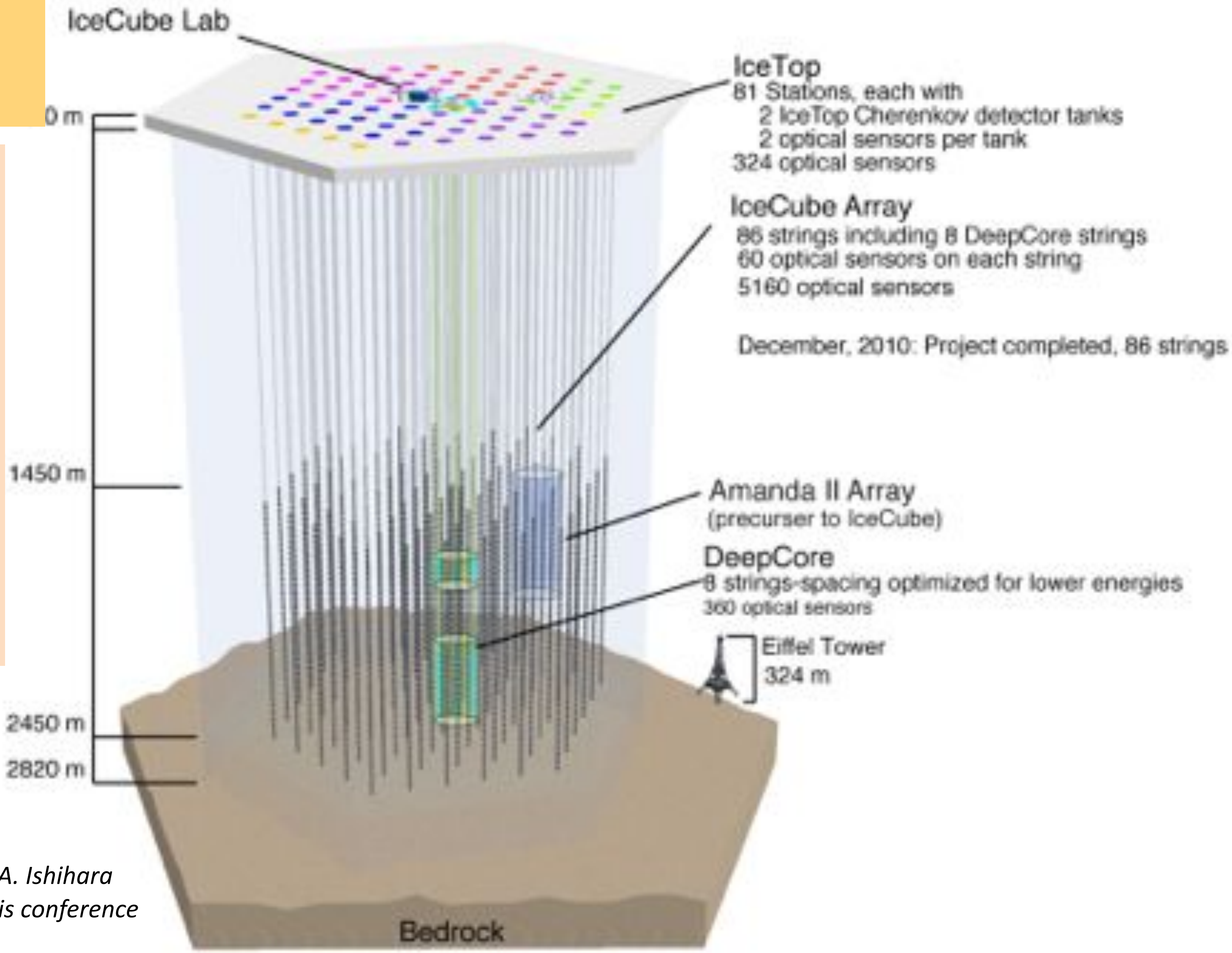
How to detect UHE high energy neutrinos? The challenge:

- Fluxes are small
- The cross section is small
  → Need to instrument/view very large target mass
- Backgrounds from cosmic rays, cosmic ray muons are high
  → Need some overburden (or other good discrimination)
- Need to use natural targets, which are free, but
  - need to deal with environmental challenges
  - no control of the medium
  - lack of infrastructure (access, power, communications)
  - possibly unstable backgrounds

  → Challenges for Calibration

IceCube

- Total of 86 strings and 162 IceTop tanks;
- Completion with 86 strings: December 2010
- Full operation with all strings since May 2011.



For results:
see talks by G. Sullivan and A. Ishihara and numerous posters at this conference

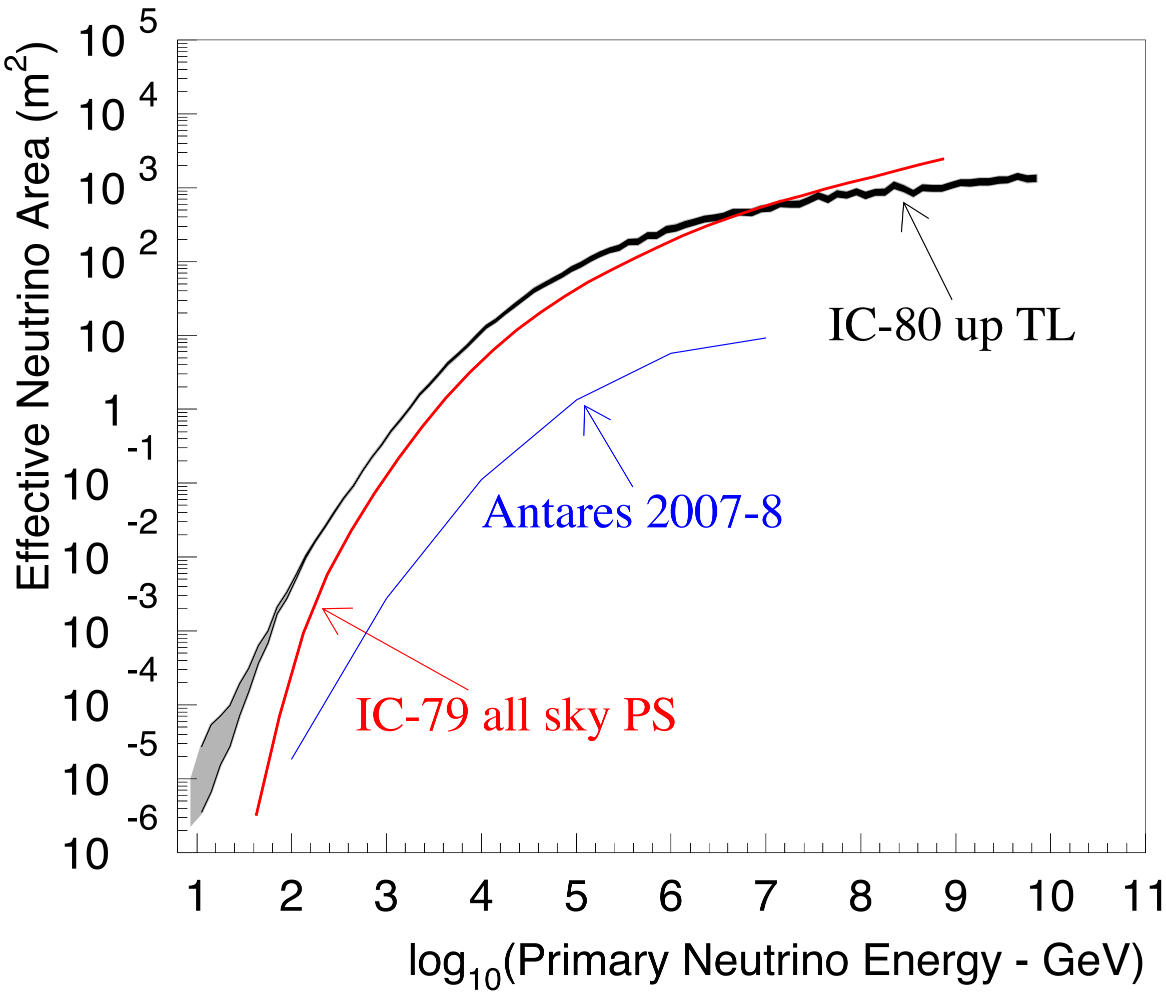
Air shower of ~3E17 eV
Observed by IceTop,
Then by Deep detector strings

Energy scales and future detectors - from low to high energy

1. 1 – 100 GeV: IceCube extensions: PINGU and beyond
2. TeV – PeV plans for larger Water/ice Cherenkov detectors
   – KM3Net
   – Baikal upgrade
3. 10 PeV – 10 EeV detectors:

   Radio detectors: ARA, ARIANNA, more ANITA flights; Auger horizontal

Wide energy range due to increase in effective area!



Area at 100 TeV (1TeV)
IceCube 86: 40m^2 (0.3m^2)

Deep Core lowers threshold from 100 GeV to 10 GeV.

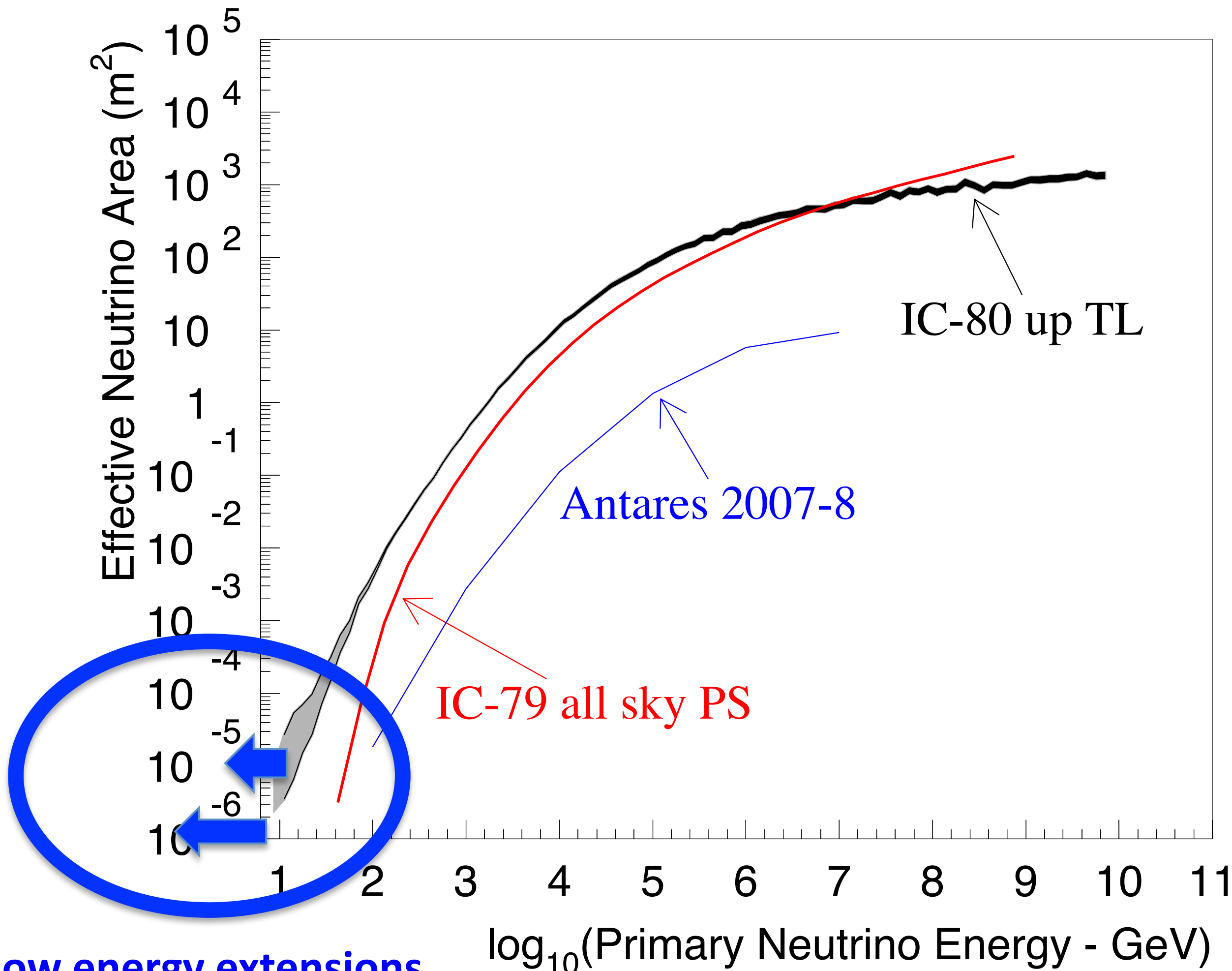
Effective area for ν_μ
Strong rise with energy:

- $\sigma \propto E_\nu$ (up to 100TeV)
- Increase of muon range with energy up to PeV
- Flattening above PeV energies.

Water/ice Cherenkov detectors: Neutrino effective areas

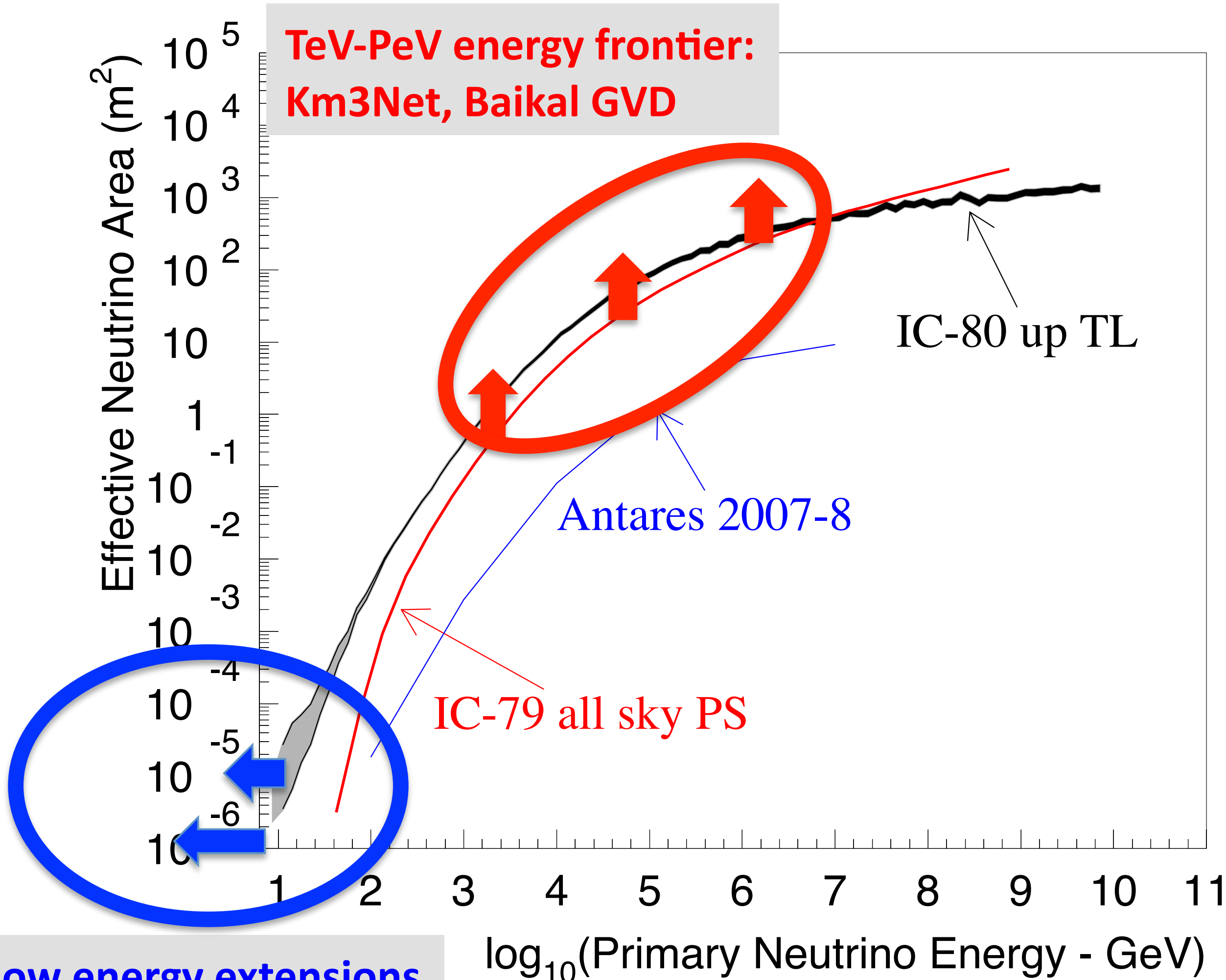
Energy scales and future detectors - from low to high energy.

PINGU: lower threshold from ~10 to few GeV



Low energy extensions to IceCube's DeepCore: PINGU, MICA

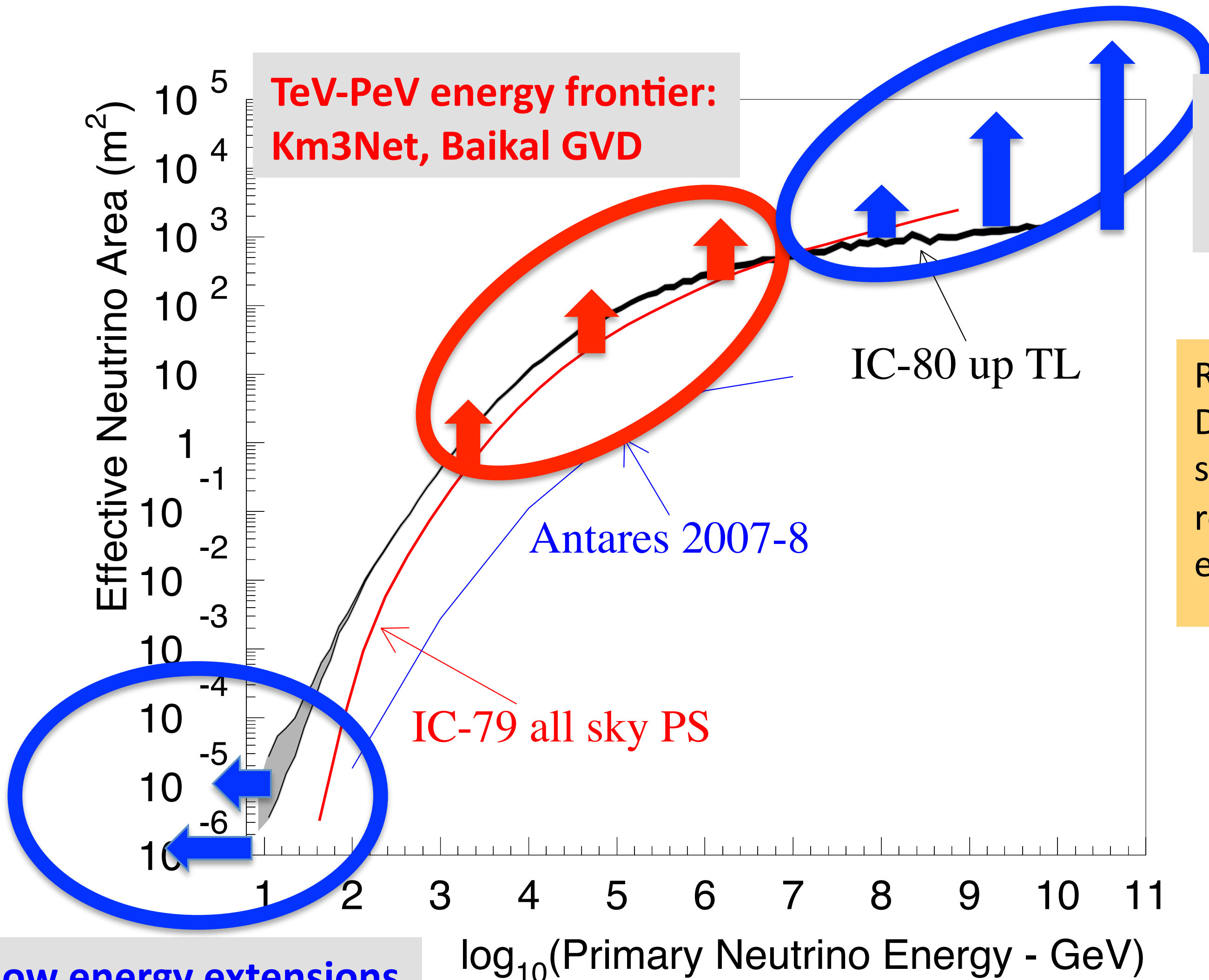
Water/ice Cherenkov detectors: Neutrino effective areas



Big neutrino telescopes like KM3Net would establish larger detectors with more sensitivity from TeV to PeV in Northern hemisphere: Optimal view to Galactic Center (Southern Hemisphere)

Low energy extensions to IceCube, DeepCore: PINGU, MICA

Water/ice Cherenkov detectors: Neutrino effective areas

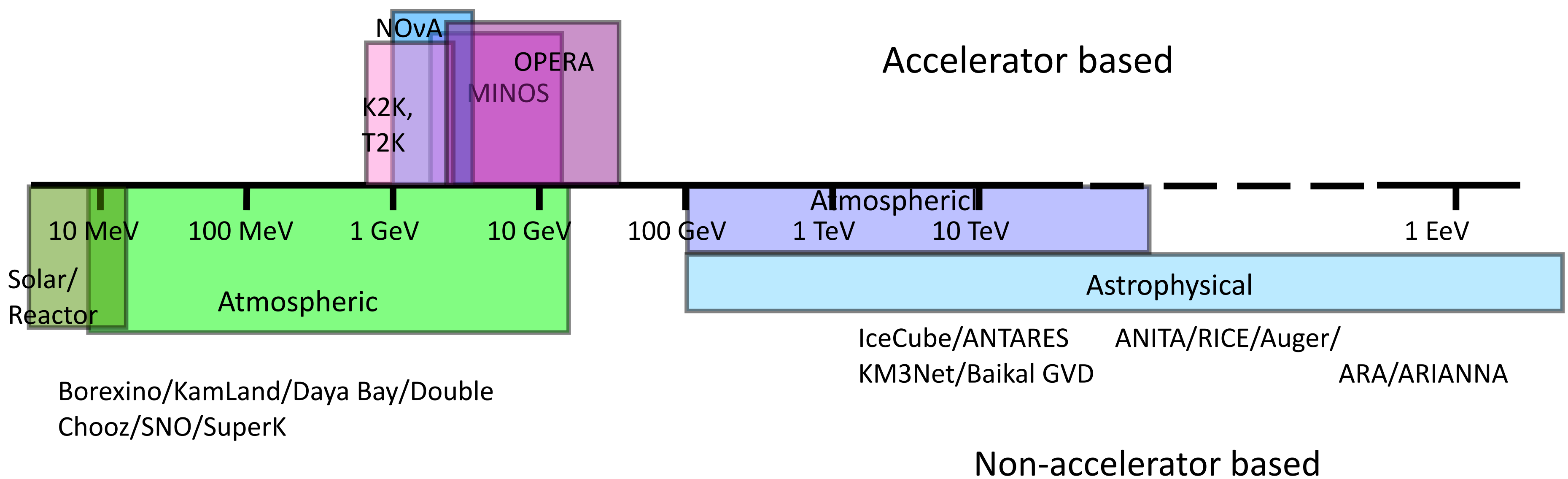


Radio detection in ice: Detection volume and thus sensitivity increases roughly linearly with energy!

Low energy extensions to IceCube, DeepCore: PINGU, MICA

Low energies, 1 – 100 GeV, PINGU ...

The Neutrino Detector Spectrum



Slide:
Courtesy Darren Grant
NNN 2011

** boxes select primary detector physics energy regimes and are not absolute limits*

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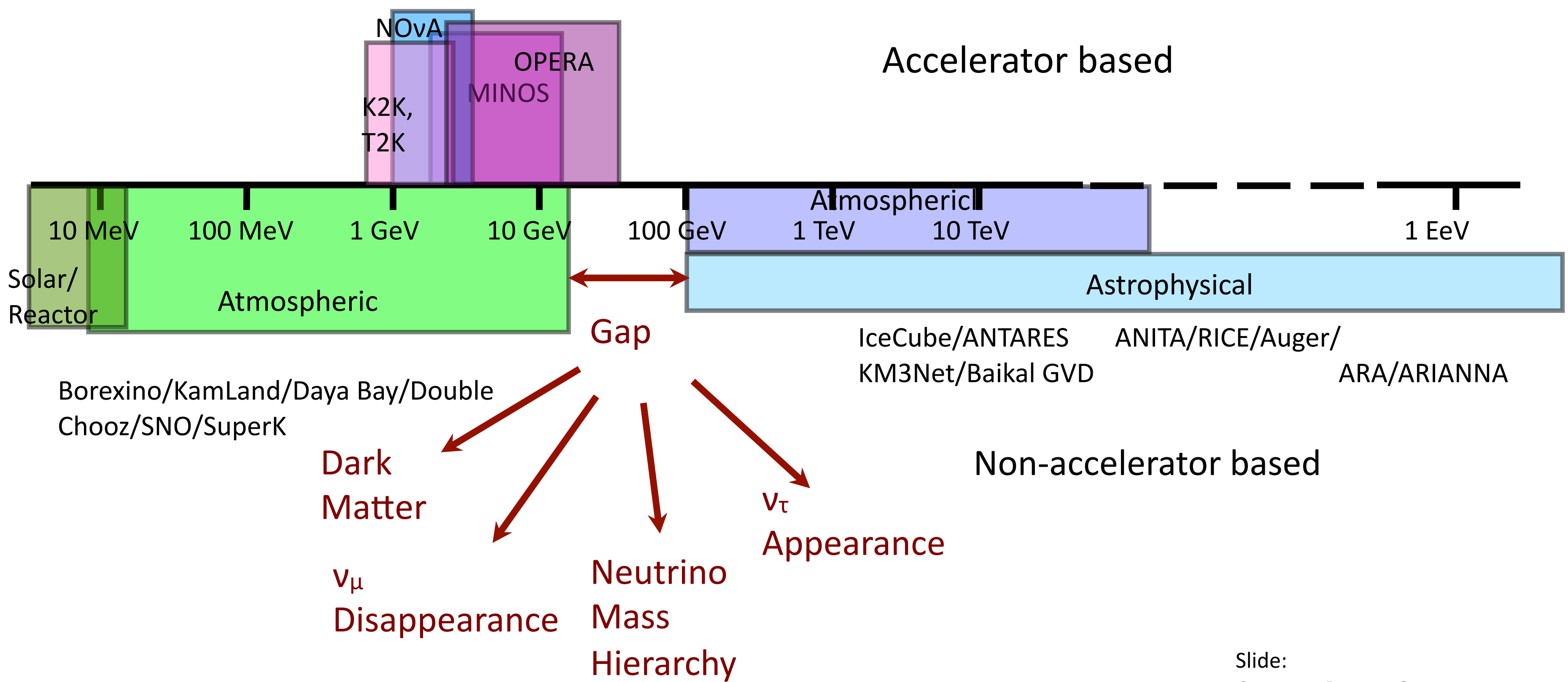

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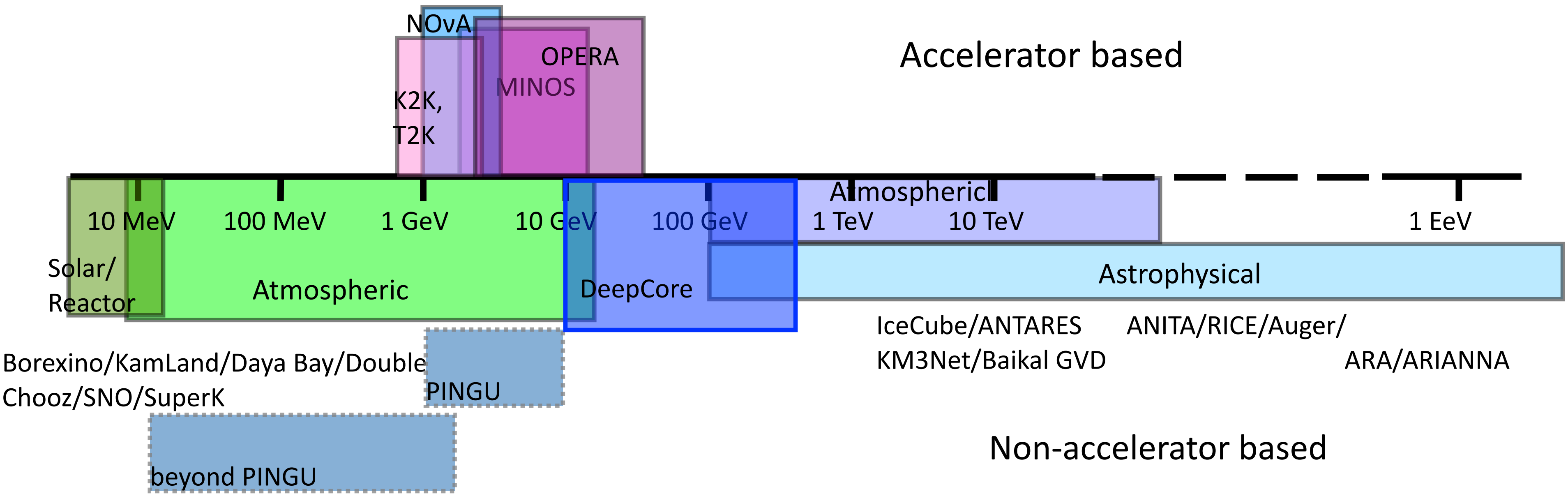


~70 active members in feasibility studies:

IceCube, KM3Net, Several neutrino experiments

Photon detector developers

Theorists

Slide after:
Darren Grant
NNN 2011

* *boxes select primary detector physics energy regimes and are not absolute limits*

IceCube-DeepCore

- IceCube extended its "low" energy response with a densely instrumented infill array: DeepCore http://arxiv.org/abs/1109.6096
- Significant improvement in capabilities from ~10 GeV to ~300 GeV (ν_μ)

- Scientific Motivations:
- Indirect search for dark matter
- Neutrino oscillations (e.g., ν_τ appearance)
- Neutrino point sources in the southern hemisphere (e.g., galactic center)

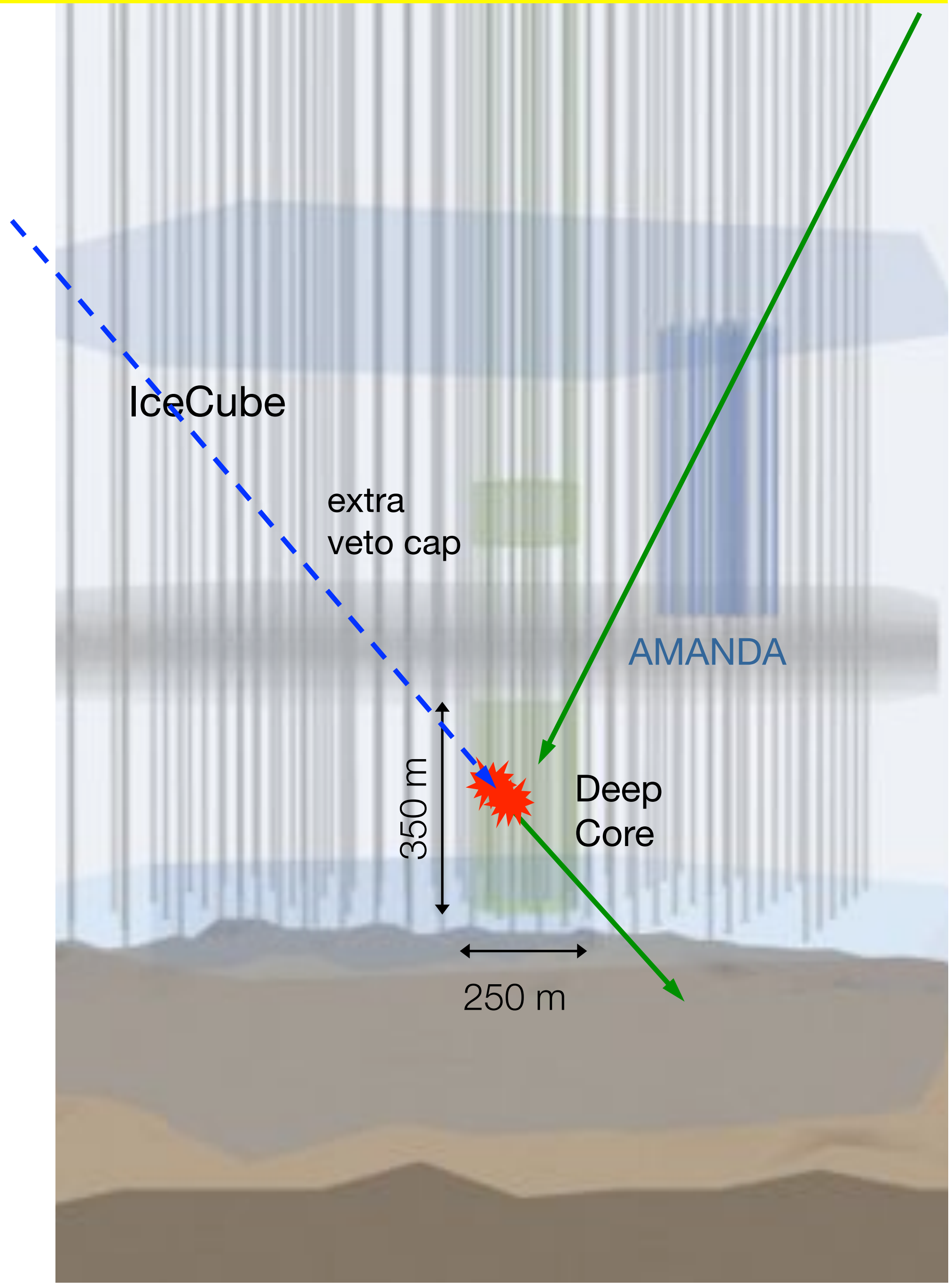
IceCube - DeepCore:

DESIGN

- Eight special strings in filled in the bottom center of IceCube
- ~5x higher effective photocathode density than regular IceCube
- Result: 30 MTon detector with ~10 GeV threshold, will collect $\mathcal{O}$(100k) physics quality atmospheric ν/yr

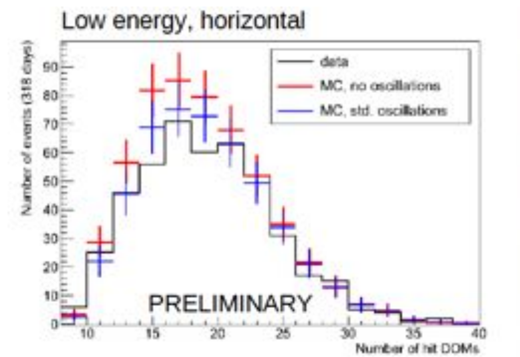
VETO

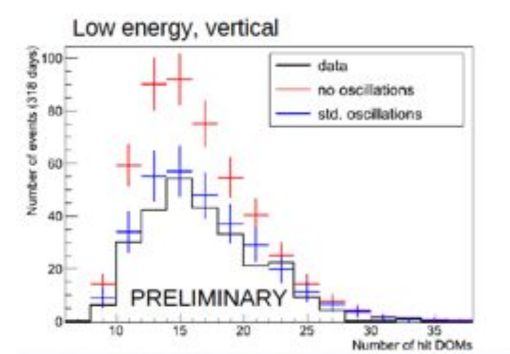
- IceCube's top and outer layers of strings provide an active veto shield for DeepCore
- Effective μ-free depth much greater
- Atm. μ/ν trigger ratio is ~10^6
- Vetoing algorithms expected to reach well beyond 10^6 level of background rejection



From Deep Core to PINGU
- Phased IceCube Next Generation Upgrade

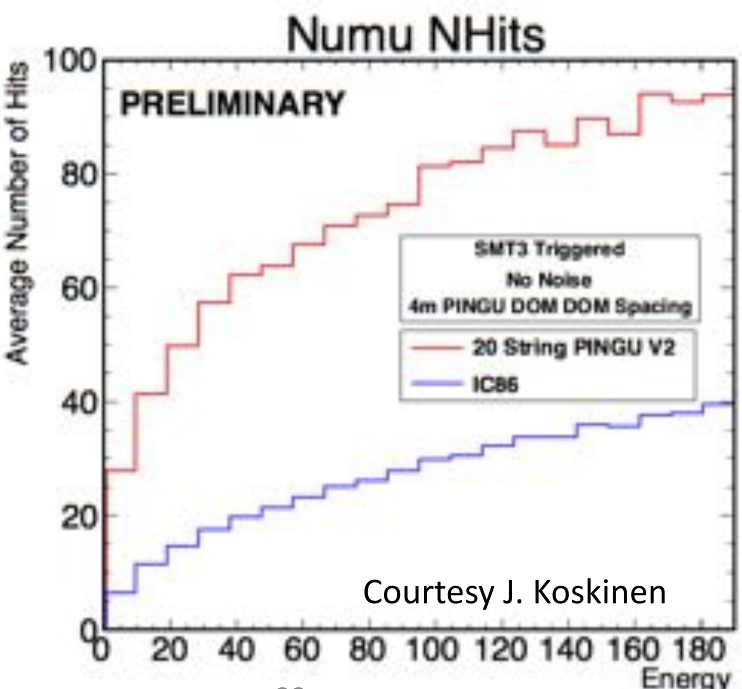
- A close look at neutrino events above ~10 GeV; event identification and reconstruction possible.
- Science goals:
  - improve WIMP search,
  - neutrino oscillation measurements,
  - other low energy physics, → e.g. mass hierarchy



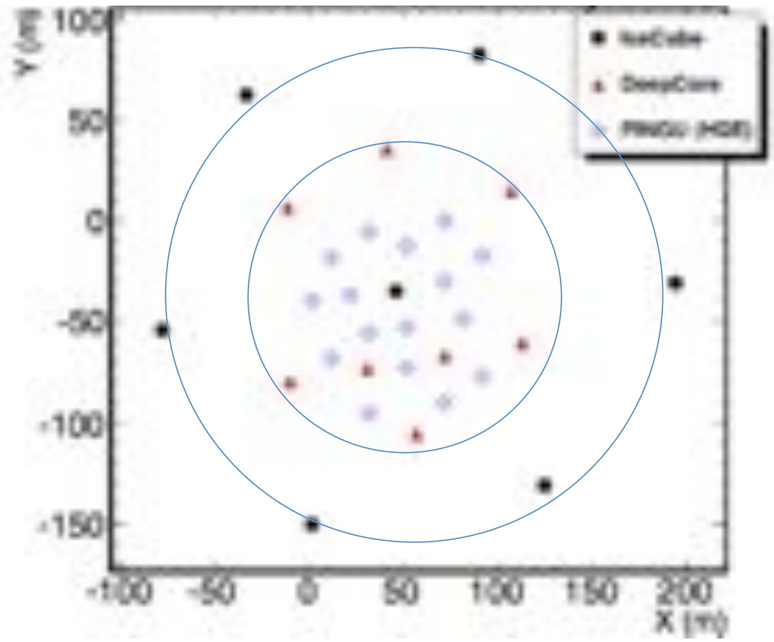


PINGU

- Phased IceCube Next-Generation Upgrade
- Add 20 strings with ~1000 optical modules inside the
  Deep Core region (~500PMT)
- Expected energy threshold ~ 1 GeV
- R&D opportunity for future developments



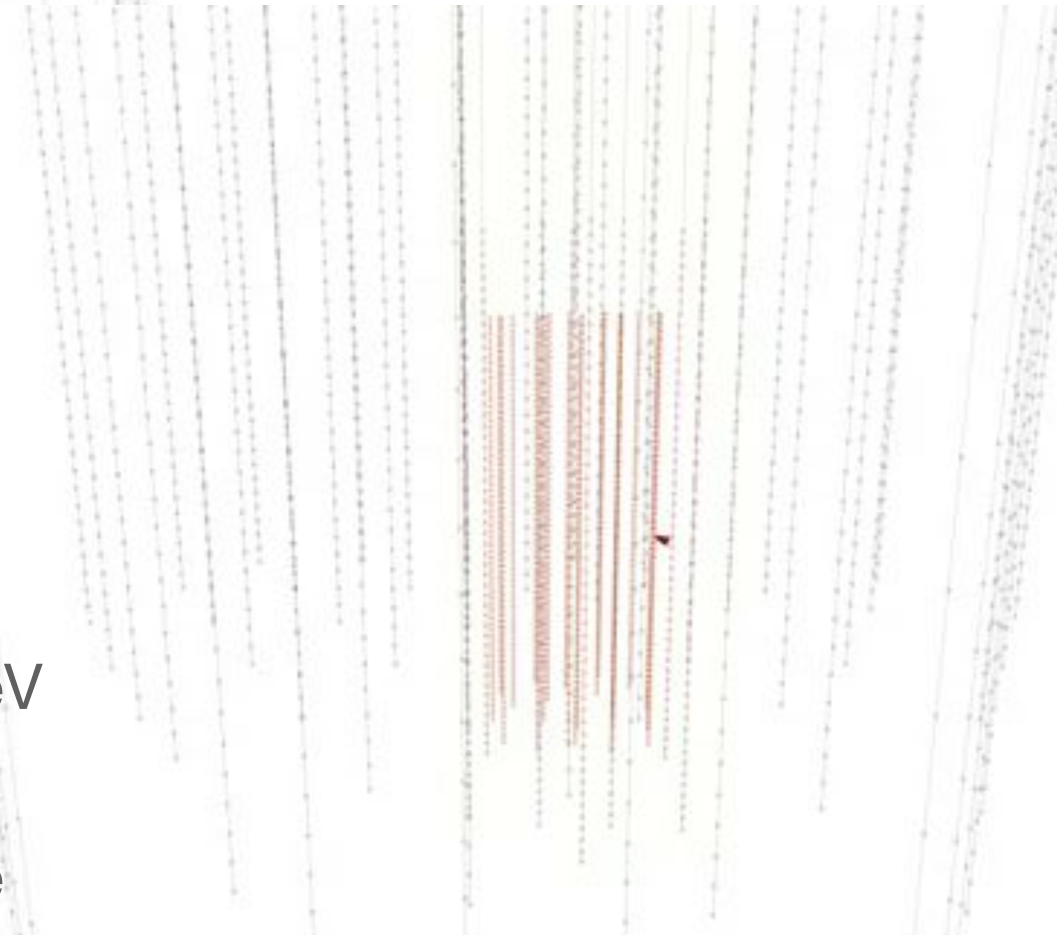
PINGU geometry
(more compact version also studied)



Simulated event in DeepCore and PINGU

DeepCore Only

- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- Physics hits only, no noise

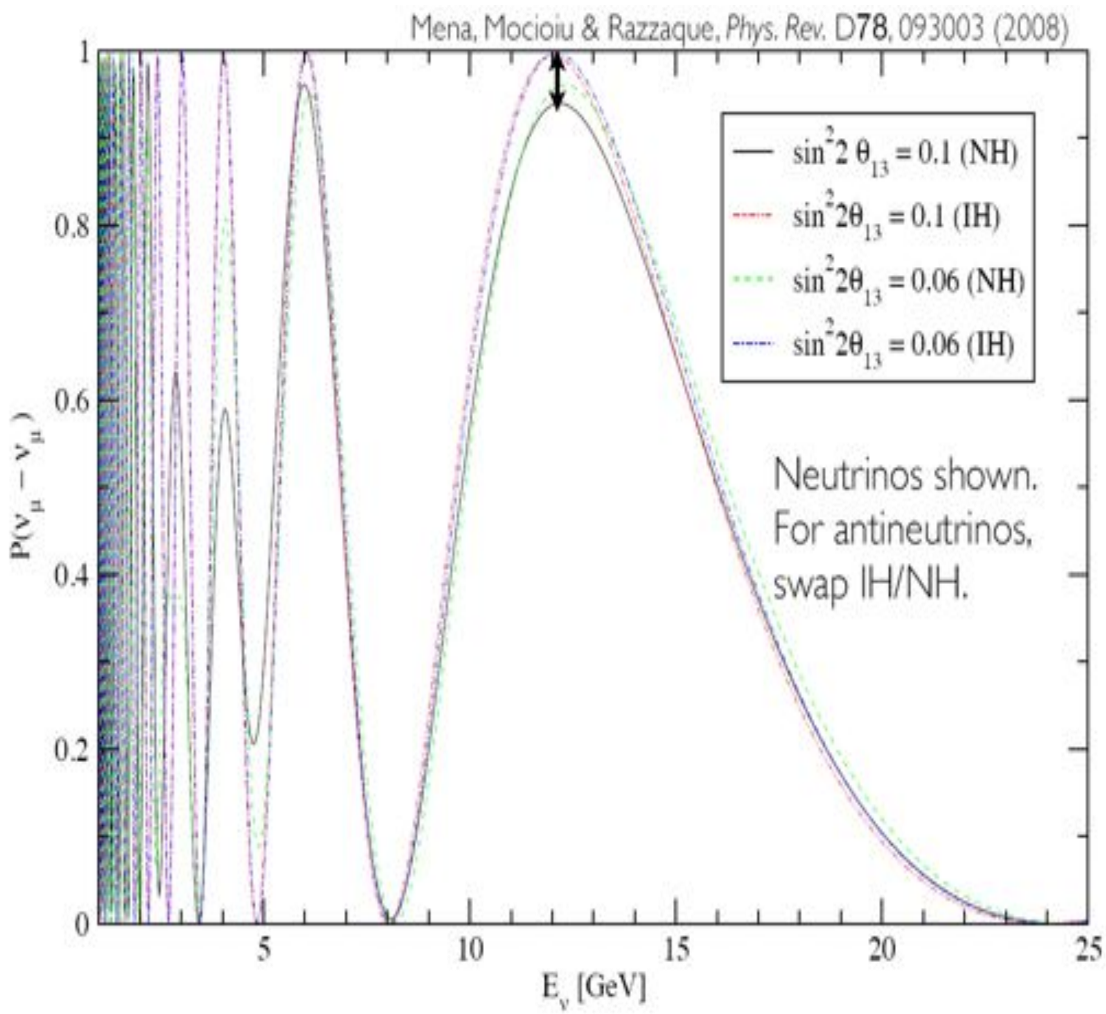


DeepCore + PINGU

Courtesy J. Koskinen

Mass hierarchy in atmospheric neutrinos

- MSW effect in Earth induces difference $\nu/\overline{\nu}$ in ν oscillations
- Note: first maximum for $\mu \longrightarrow \mu$ is at 12 GeV for $L = d_{\text{Earth}}$
- Could be measurable since at these energies $\sigma(\nu) \approx \sigma(\overline{\nu})$
- Advanced analysis: "oscillograms" (A. Smirnov et al.)

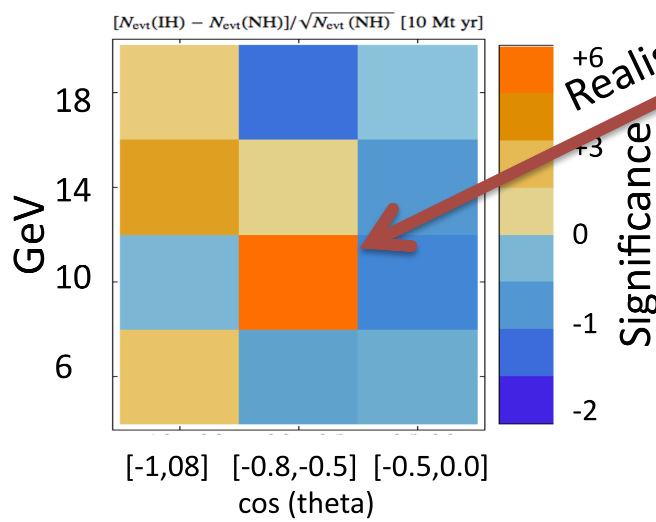


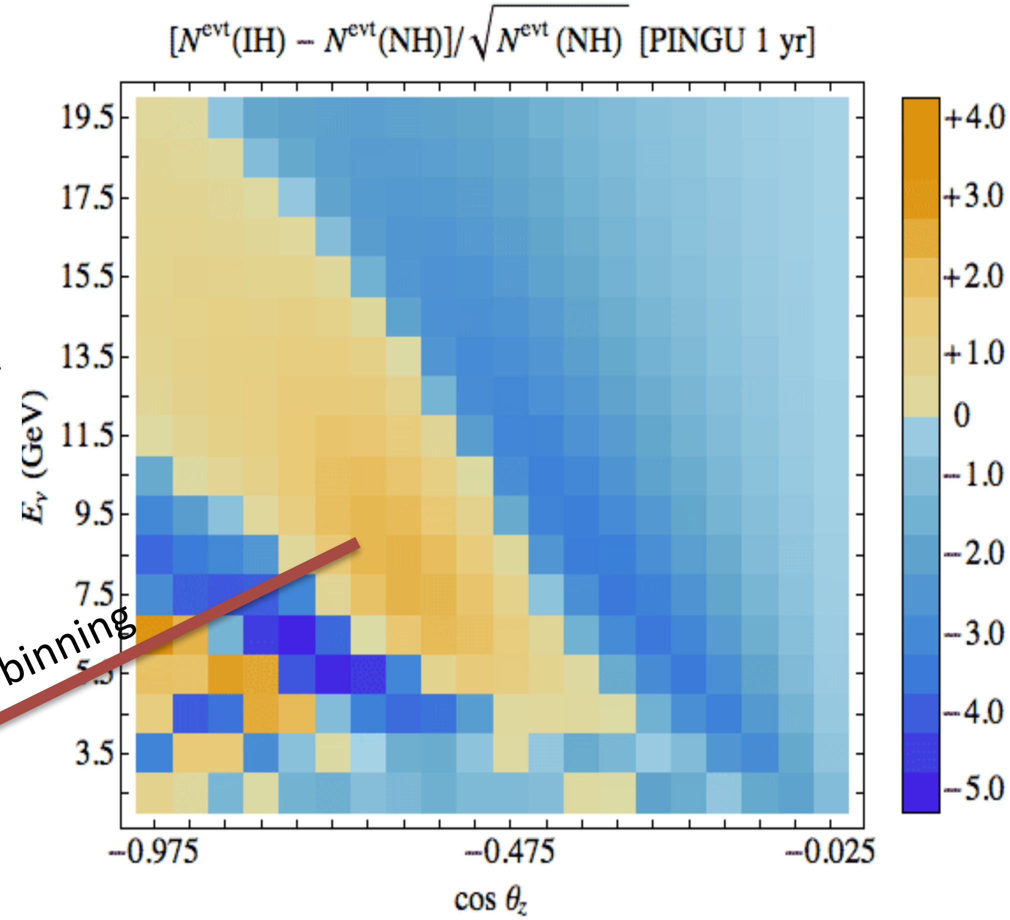
Mass hierarchy

Figure and Analysis from:
Akhmedov, Razzaque, Smirnov, arXiv: 1205.7071
See poster by E. Resconi et al. (IceCube and PINGU)

- Expected significance for observed number of events for IH vs NH are shown in energy vs. zenith plot
- If required energy and directional resolution is achievable:

  → high statistical significance





Assumed above:

Energy resolution: 4 GeV,

Angular resolution: 0.3 in cos(theta)

Exposure: 10 Mt yr

Conclusion (Akhmedov et al.):
"Our preliminary estimates show that after 5 years of PINGU 20 operation the significance of the determination of the hierarchy can range from 3 to 11 (without taking into account parameter degeneracy), depending on the accuracy of reconstruction of neutrino energy and direction."

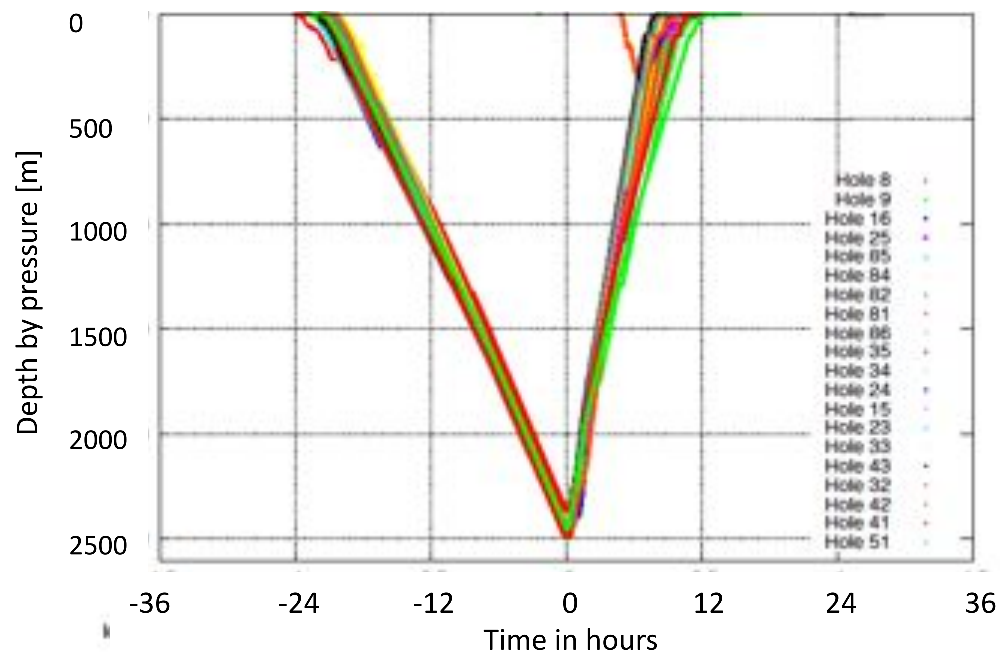
Drilling and installation in ice

- Optical properties of ice is well understood.
- Drilling and deployment method well established.

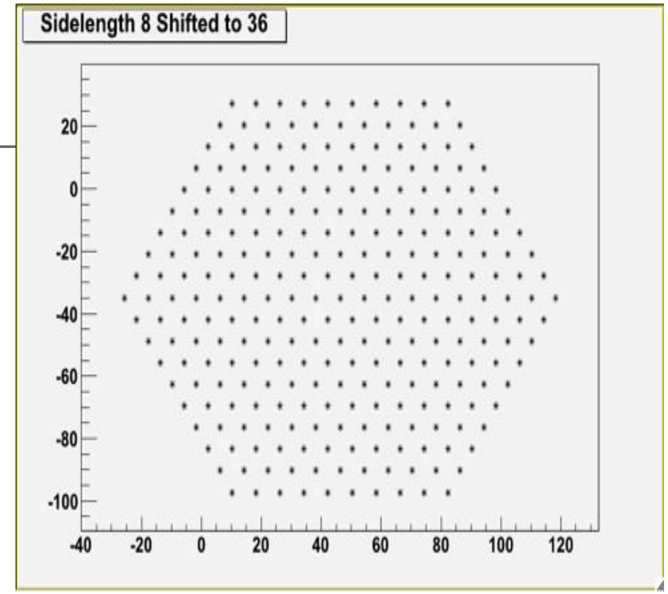
  32 h of drilling/string

  20 holes in 2 month season
- Cost to deploy PMT in ice:
  - drilling
  - Glass pressure housings, etc

Depth versus time profile
Overlay of 20 IceCube holes drilled in < 2 months



beyond PINGU Conceptual Detector

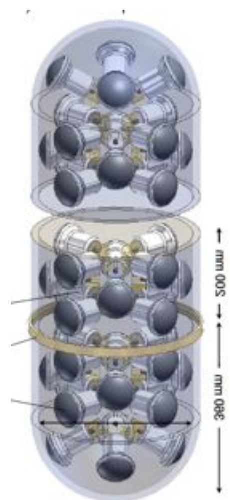


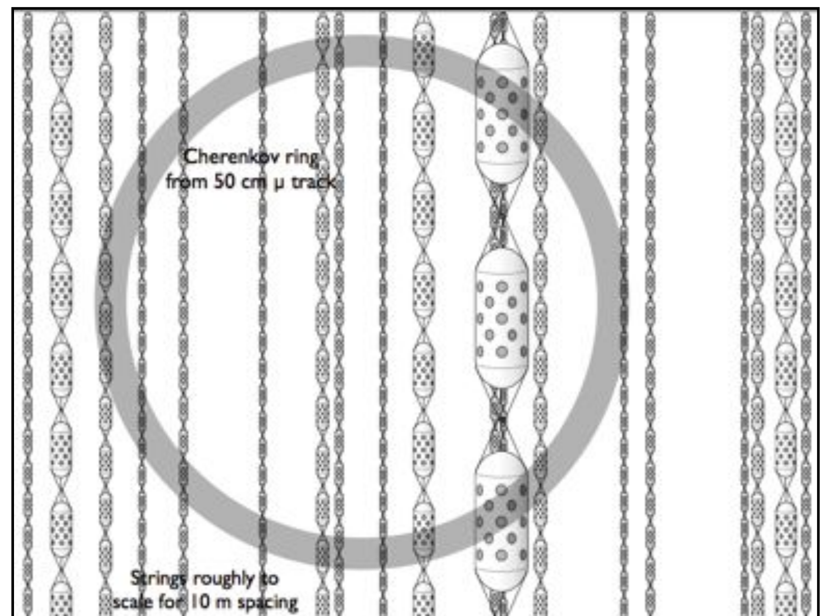
- O(few hundred) strings of detectors within DeepCore fiducial volume
- Goals: ~5 MTon scale with energy sensitivity of:
    - O(10 MeV) for bursts
    - O(100 MeV) for single events

- Physics extraction from Cherenkov ring imaging in the ice

Exploration of possibilities for:

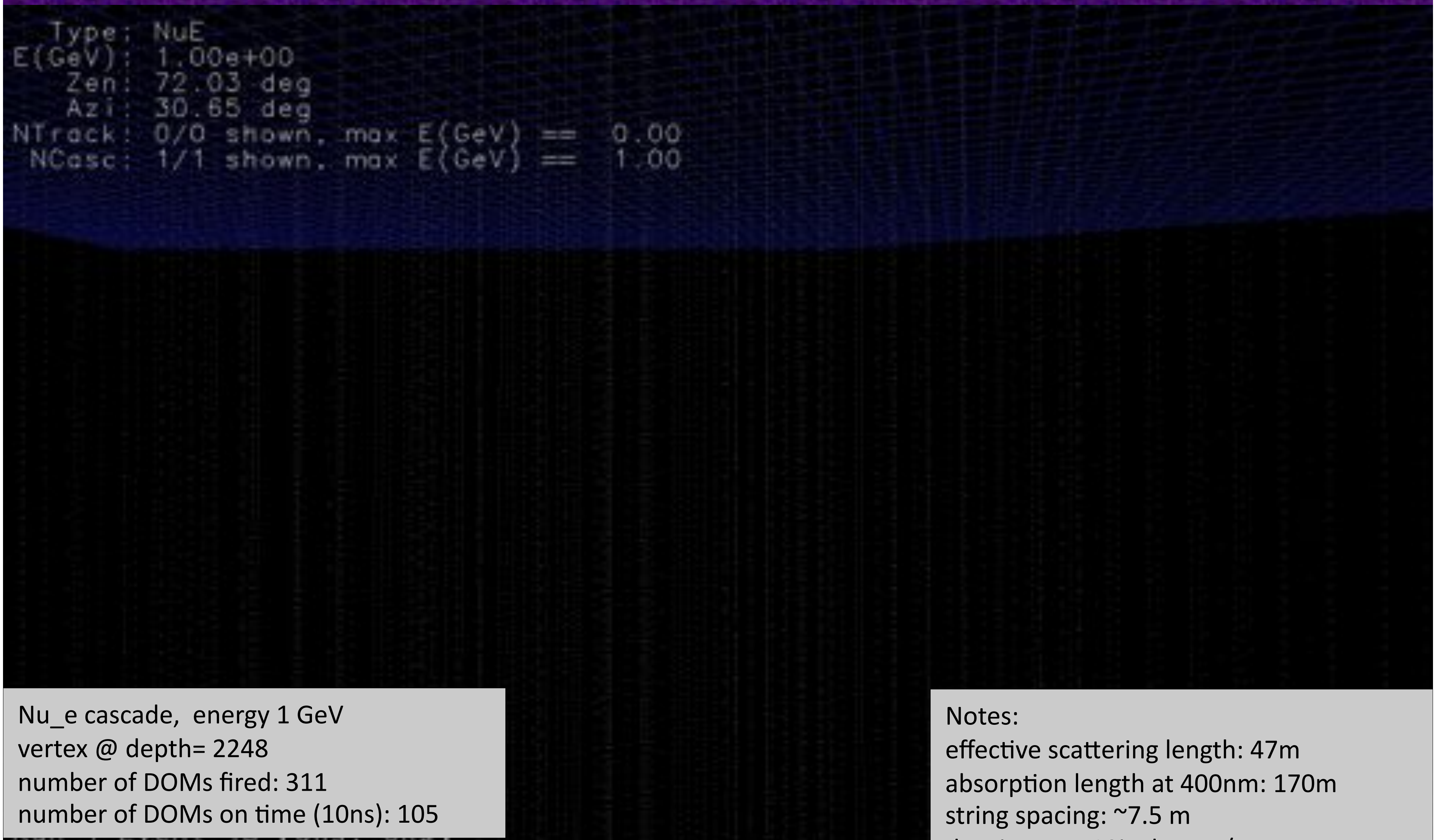
- Proton decay p -> $\pi^0 + e^+$
- Supernova to 5 Mpc





→Poster ay this conference
by L. Classen, O. Kalekin, U. Katz, P. Kooijman, E. de Wolf.

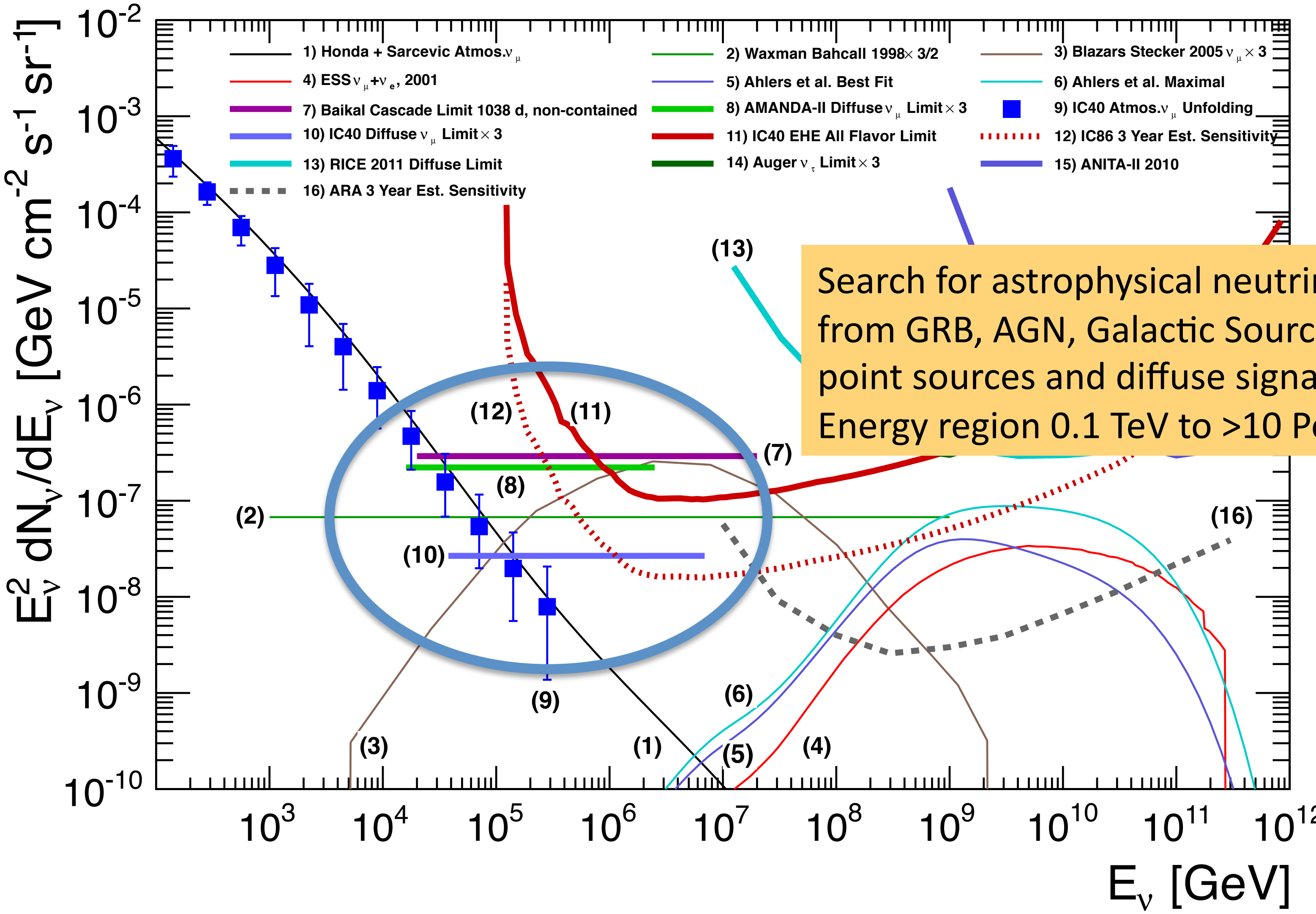
Simulated event, 1 GeV in 230 string dense array



Nu_e cascade, energy 1 GeV
vertex @ depth= 2248
number of DOMs fired: 311
number of DOMs on time (10ns): 105

Notes:
effective scattering length: 47m
absorption length at 400nm: 170m
string spacing: ~7.5 m
density: one 10inch PMT/m

1 TeV to 10 PeV: future optical neutrino telescope arrays



Search for astrophysical neutrinos from GRB, AGN, Galactic Sources, point sources and diffuse signals
Energy region 0.1 TeV to >10 PeV

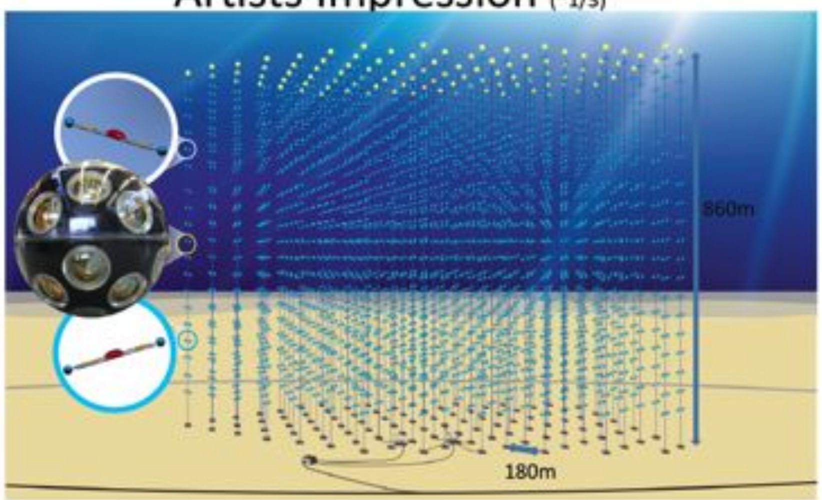
KM3Net –
The next generation neutrino telescope in the Mediterranean

Based on update from: Uli Katz, Erlangen and Maarten DeJong, NIKHEF

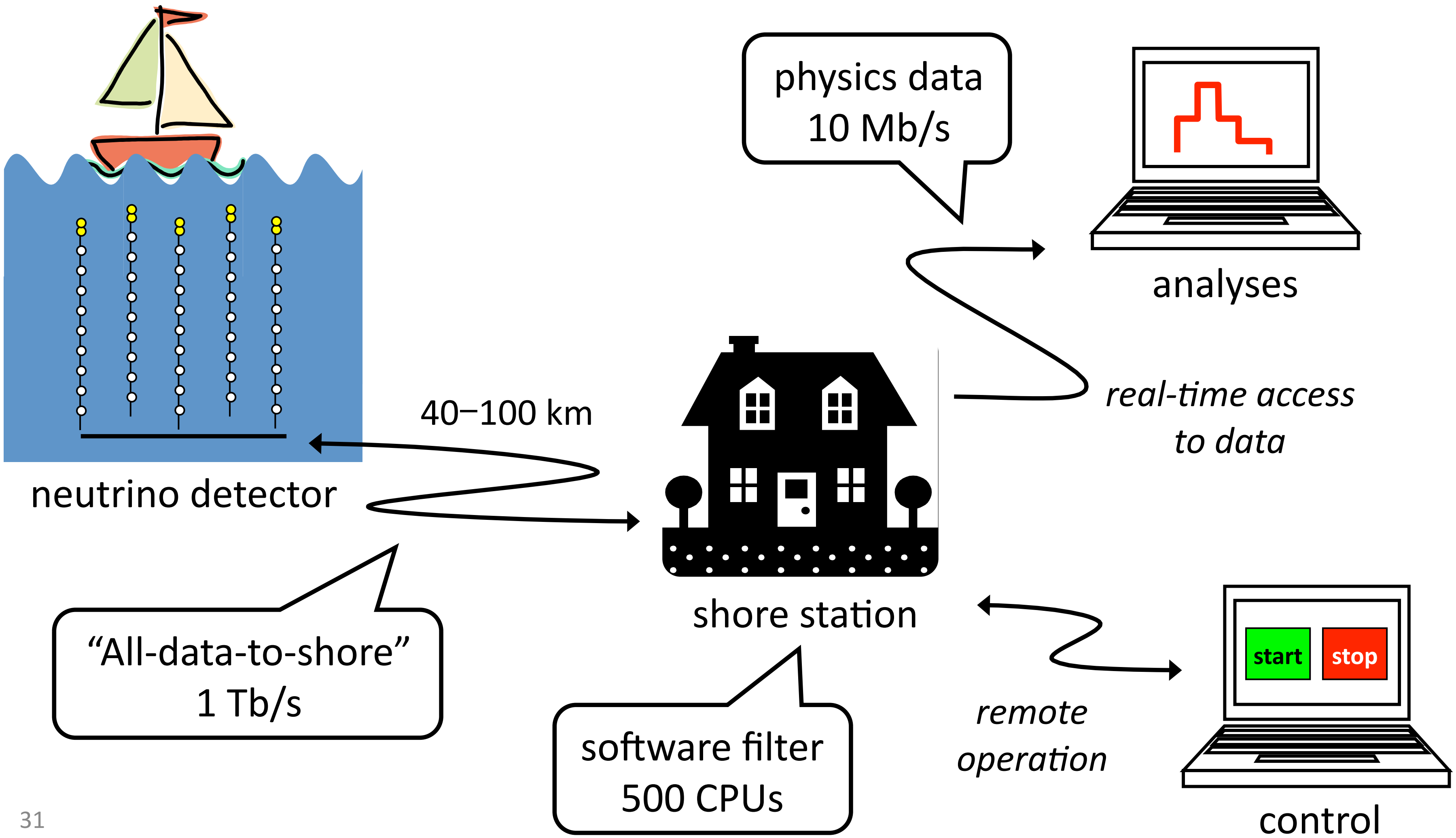
Scientific focus: Observation of Galactic neutrino sources

- Geographical location
  - Mediterranean Sea
  - Field of view includes Galactic centre
- Optical properties of deep-sea water
  - Excellent angular resolution
- Envisaged budget 220–250 M€
  - Full detector (according to design study):
    - 12800 Optical Modules 610 strings
    - Instrumented volume: ~5 km^3
    - string spacing and geometry not completely final yet
  - Large effective neutrino area

Artists Impression (~1/3)



Architecture



Multi-PMT optical module

KM3NeT

17 inch

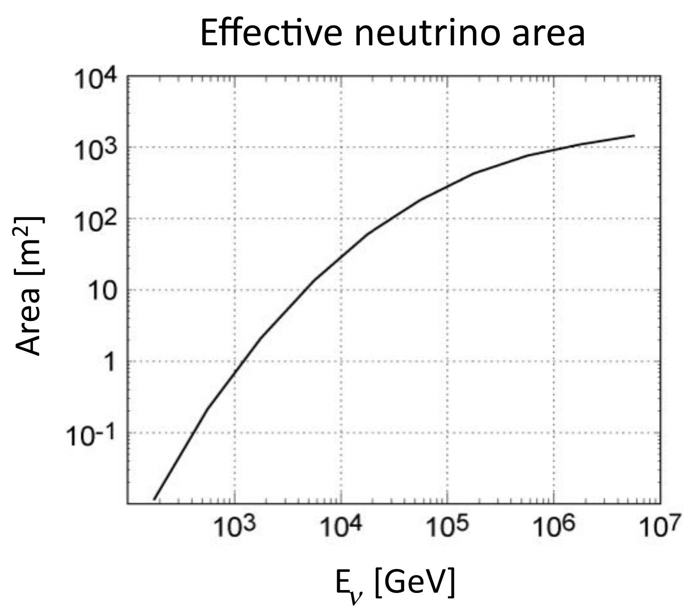
- 31 x 3” PMTs
  - Cathode area ~2.4 x 10” PMTs
- low power HV circuit
  - 10 mW / PMT
- calibration
  - LED and piezo inside glass sphere
- FPGA readout
  - sub-ns time stamping
- fibre-optic modulator
  - no lasers off-shore

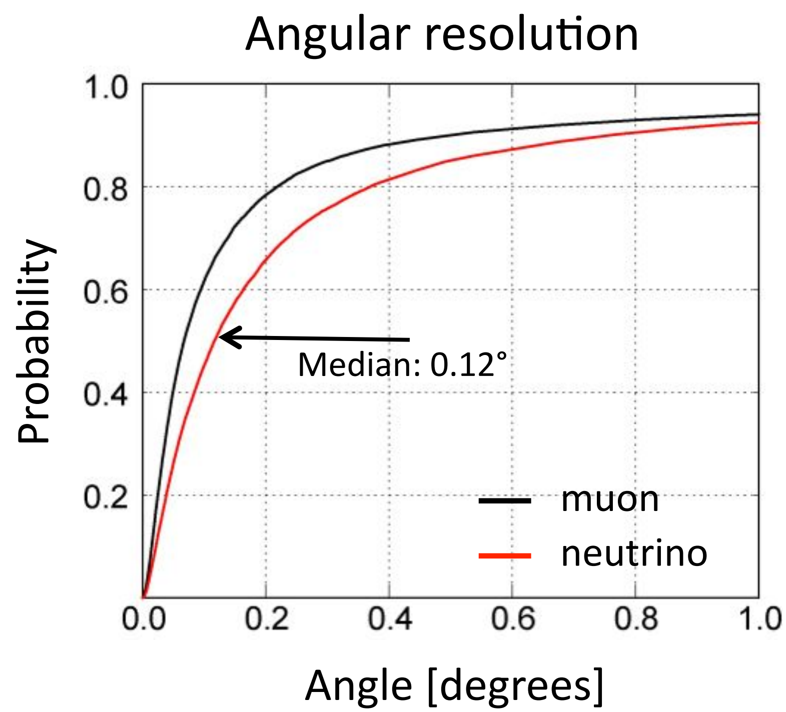
Use of many small PMT
- cost per cathode area seen comparable to large hemispherical PMT, eg 10 inch.
- directional information

Performance

Reference design with 12800 modules
on 610 strings.

total photocathode area
about 6 x IceCube



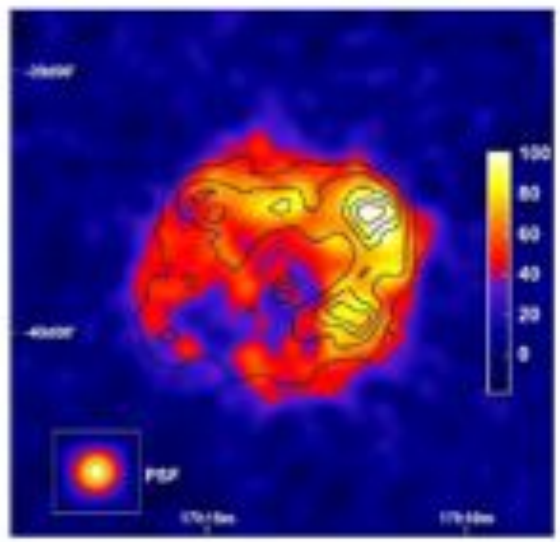


Galactic sources

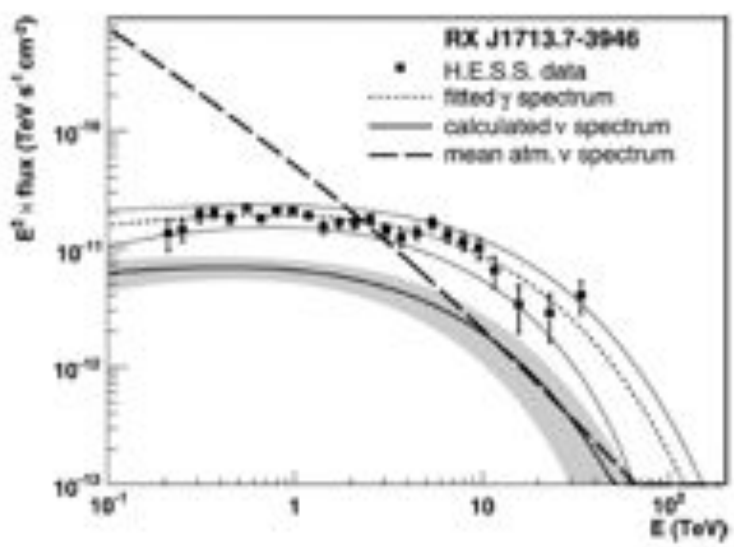
KM3Net will have optimal view of Southern hemisphere with galactic sources

Supernova remnants as "*origin of cosmic rays*"

Supernova remnant RXJ 1713



Observed gamma rays from supernova remnant RXJ 1713 at TeV energies.

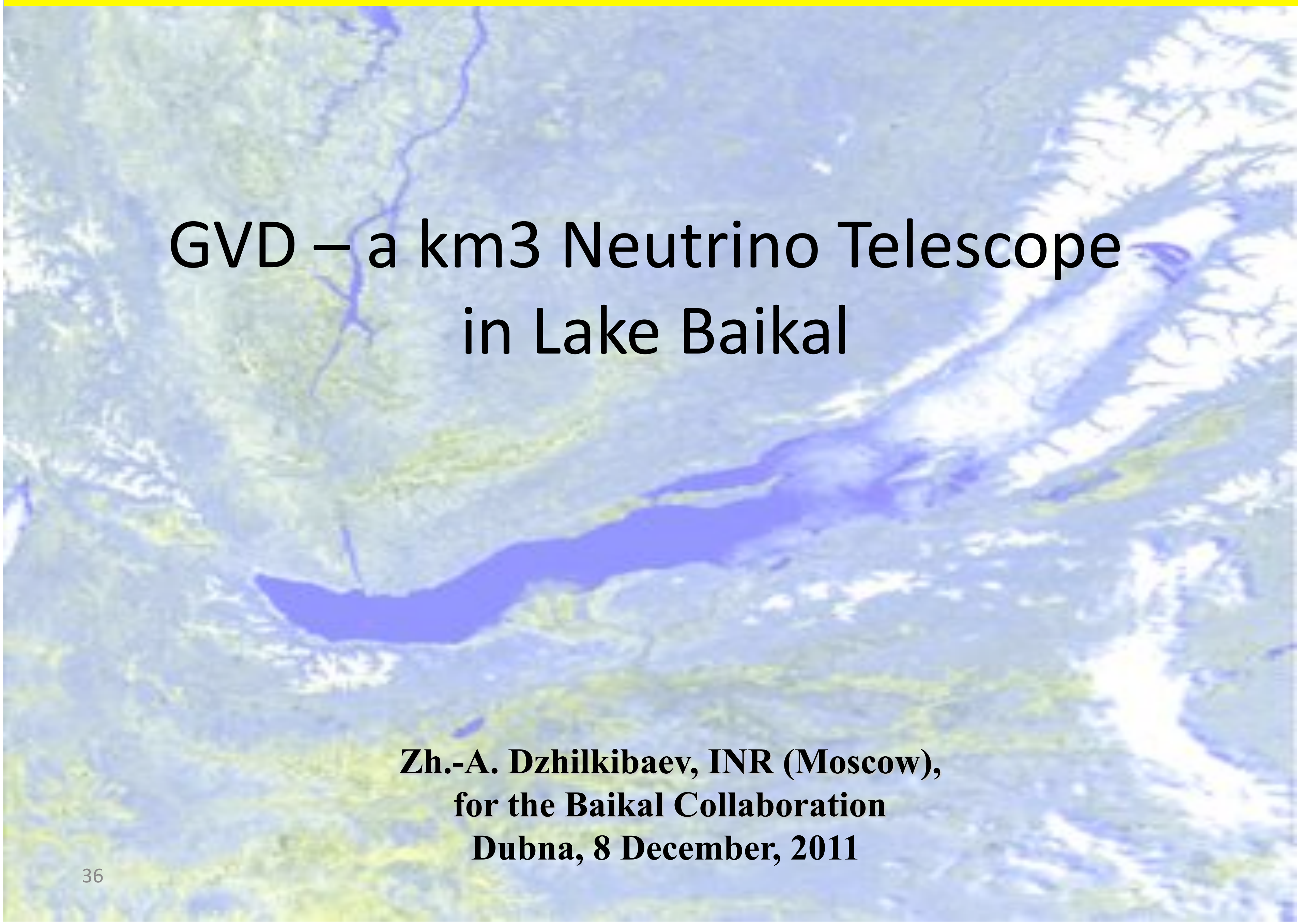


Energy spectrum in gamma rays and predicted neutrino flux

– KM3NeT can make 5 (3) sigma discovery in 5 (2.5) years

KM3Net Summary and Status

- Science case
  - discovery potential for Galactic sources
  - provides for independent observation of a possible discovery by IceCube with improved significance within reasonable amount of time
  - continuous and long-term measurements in the areas of oceanography, geophysics and marine biological sciences
- ANTARES detector proved feasibility of (high-energy) neutrino astronomy in Mediterranean Sea
  - see presentation P. Coyle at this conference
- Major investments paved the way for KM3NeT
  - site preparations, shore stations, ROV, assembly lines, prototyping, logistics, ...
- Planning
  - start capital of 40 M€ available
  - deployment of first multi-PMT optical module this summer at Antares site
  - first phase of construction will start later this year in Italy and France
  - complete construction by 2020; final site locations and construction schedule subject to future funding



GVD – a km3 Neutrino Telescope in Lake Baikal

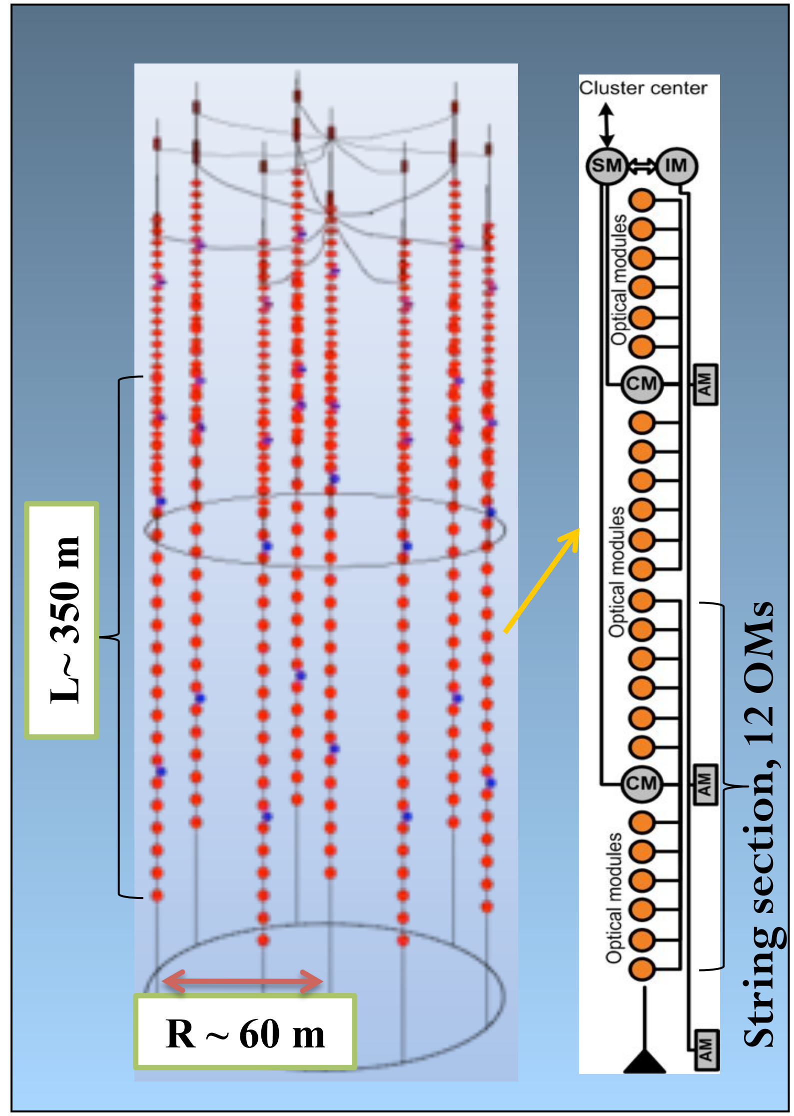
Zh.-A. Dzhilkibaev, INR (Moscow),
for the Baikal Collaboration
Dubna, 8 December, 2011

BAIKAL-GVD (minimal configuration)

Layout
96 Strings × 24 OM
String: 2 Sections × 12 OM
Clusters with 8 strings
2304 Optical Modules in total

Optimization results
Z = 15 m – OMs spacing on strings
R = 60 m – the Cluster radius
H = 300 m - the distance between Clusters.

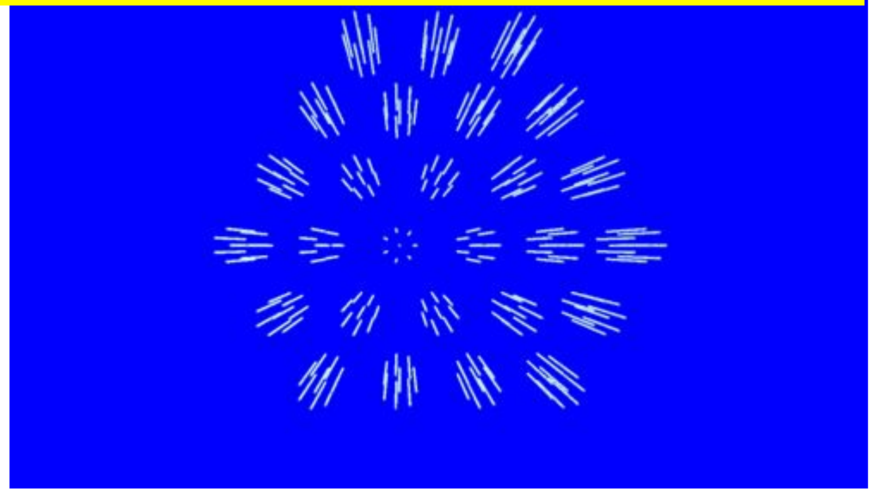
Trigger conditions
Hardware: coincidences of nearby OMs
+ software trigger



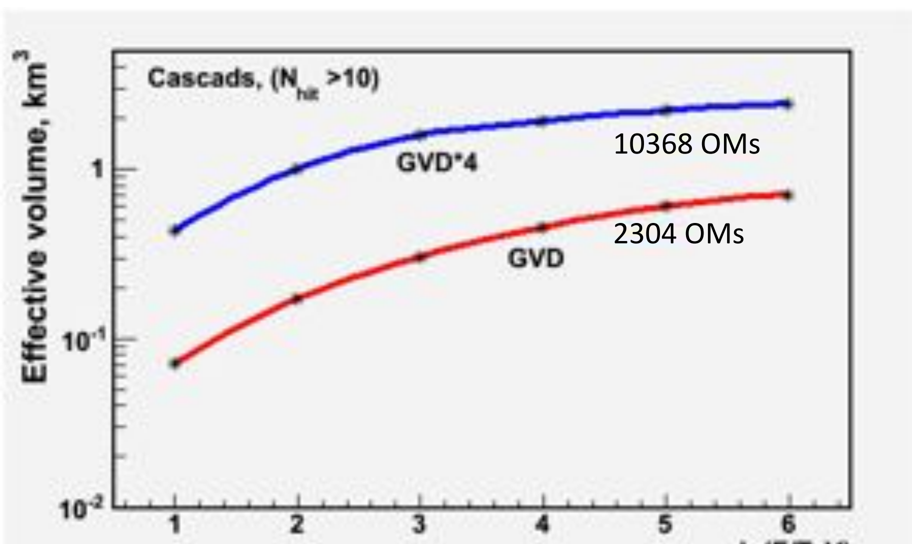
KM scale: Baikal GVD 4

Instrumented volume: 1.5 km^3
Depth: 600-1300 m (705 m long strings)

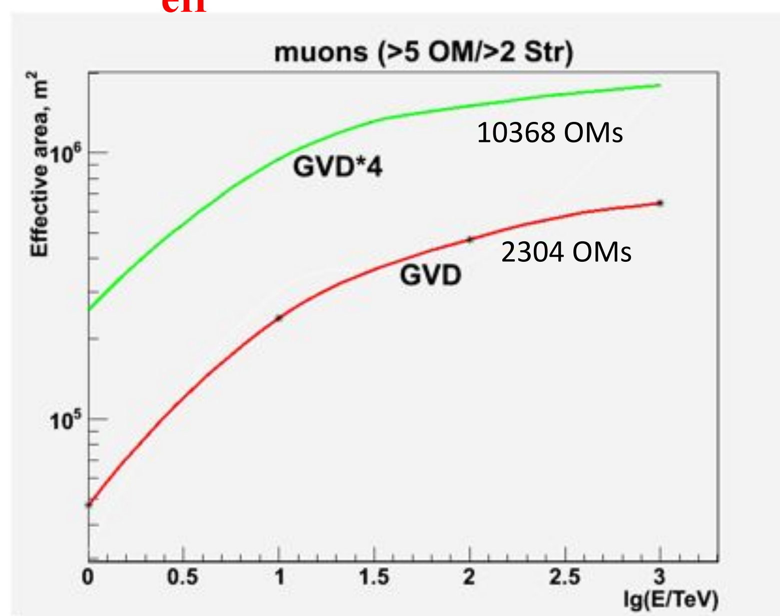
10368 Optical Modules,
216 Strings: 48 OM/Str, 3 Sec./Str
27 Clusters.: 8 Str/Cluster



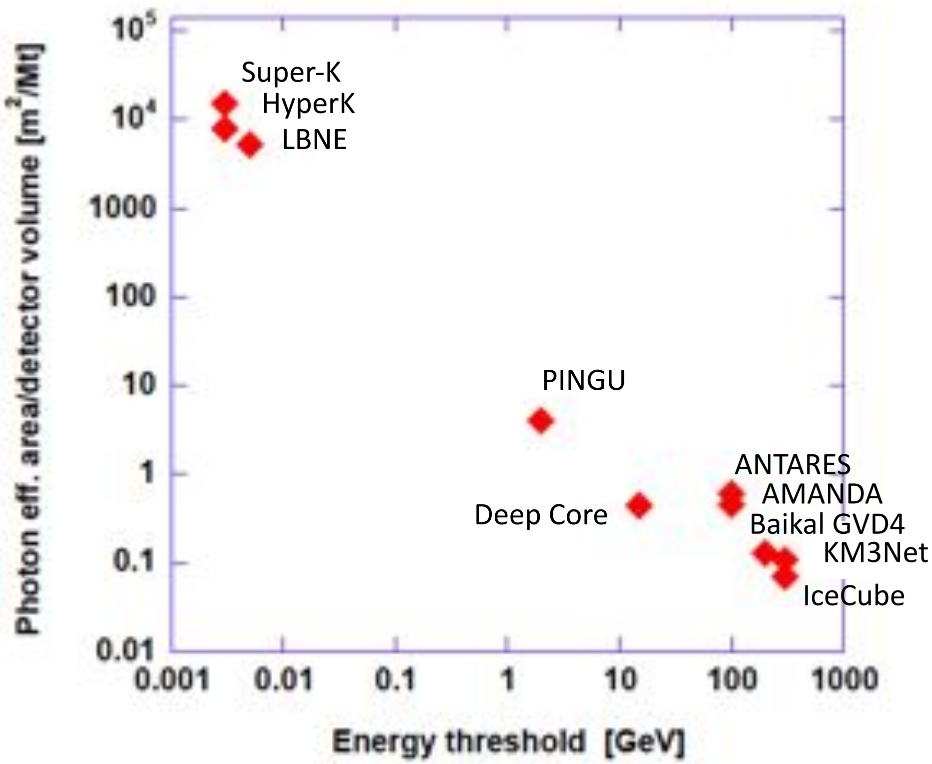
Cascades: (E>10 TeV):
V_{eff}~0.4–2.4 km^3



Muons: (E>1 TeV):
S_{eff} ~ 0.3–1.8 km^2



Water Cherenkov detectors PMT coverage vs threshold



Define:

Photon effective area =

Number of PMT

x Cathode area

x Quantum efficiency

= equivalent area of 100% photon detection.

(collection efficiency not included here.)

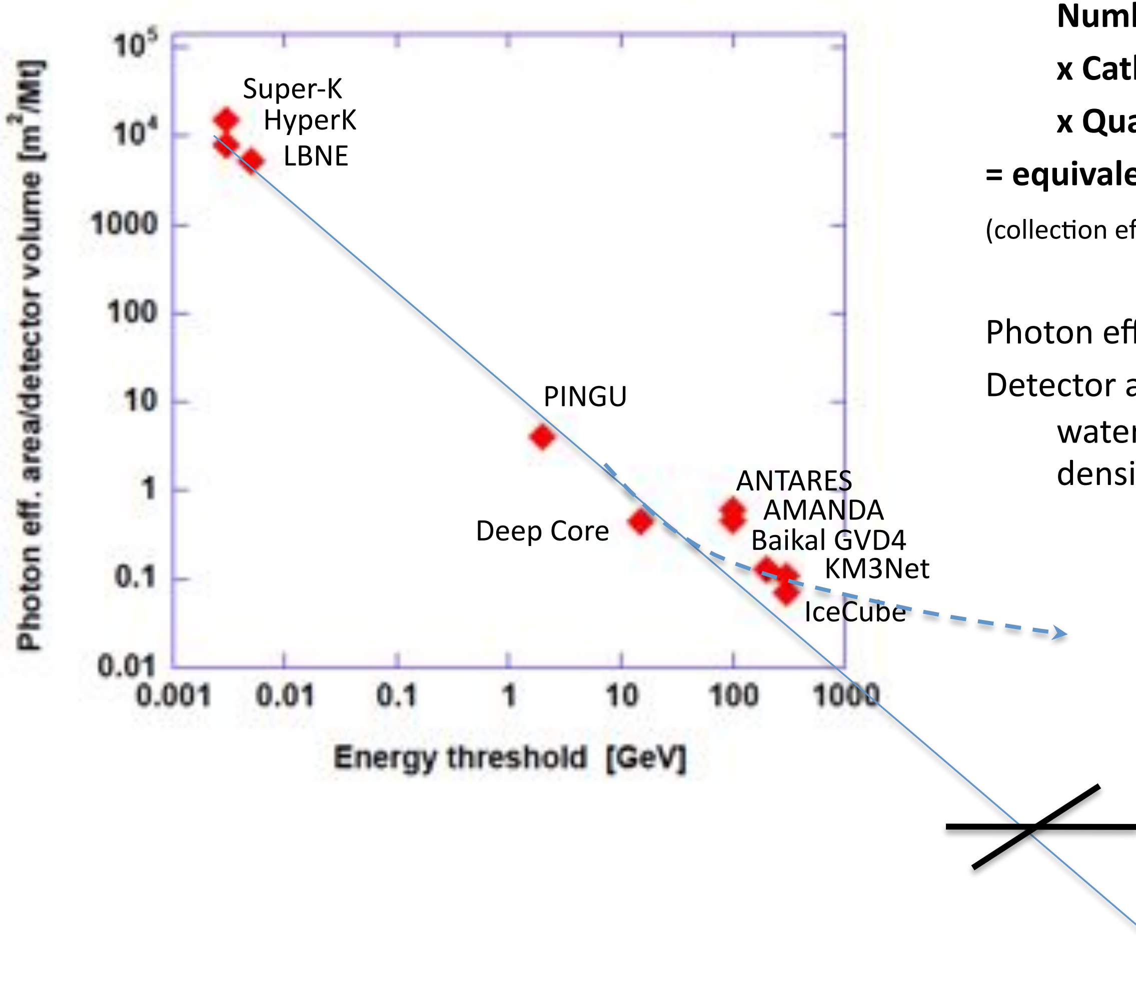
Photon effective area prop. ~ 1/Energy threshold.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

	IceCube	DeepCore	PINGU	AMANDA	ANTARES	KM3Net	BAIKAL GVD4	LBNE	SuperK	HyperK
String spacing [m]	125	75	25	70	45			7.5		
PMT spacing [m]	17	7	4	12	15					
Instrumented mass [Mt]	1000	20	6	12	16	5000	1500	0.2	0.04	1
Total No of PMT, OMS	5160	500	1400	677	885	12800	10368	29000	11410	100000
Cathode area	530	530	530	300	530	1271	530	1080	2400	2400
No. of PMT or OMs/Mton	5	25	233	55	57	3	7	145000	285250	100000
Photon eff. area/mass [m2/Mt]	0.07	0.46	4	0.409	0.603	0.114	0.128	5481	17115	8400
Energy "threshold" [GeV]	300	15	2	60	40	300	200	0.005	0.003	0.003

Footnote/Disclaimer: Some figures are estimates. Definitions of threshold vary somewhat within factor of two in some cases. Threshold for nu telescopes above Deep Core are for muon neutrinos only.

Water Cherenkov detectors PMT coverage vs threshold



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(collection efficiency not included here.)

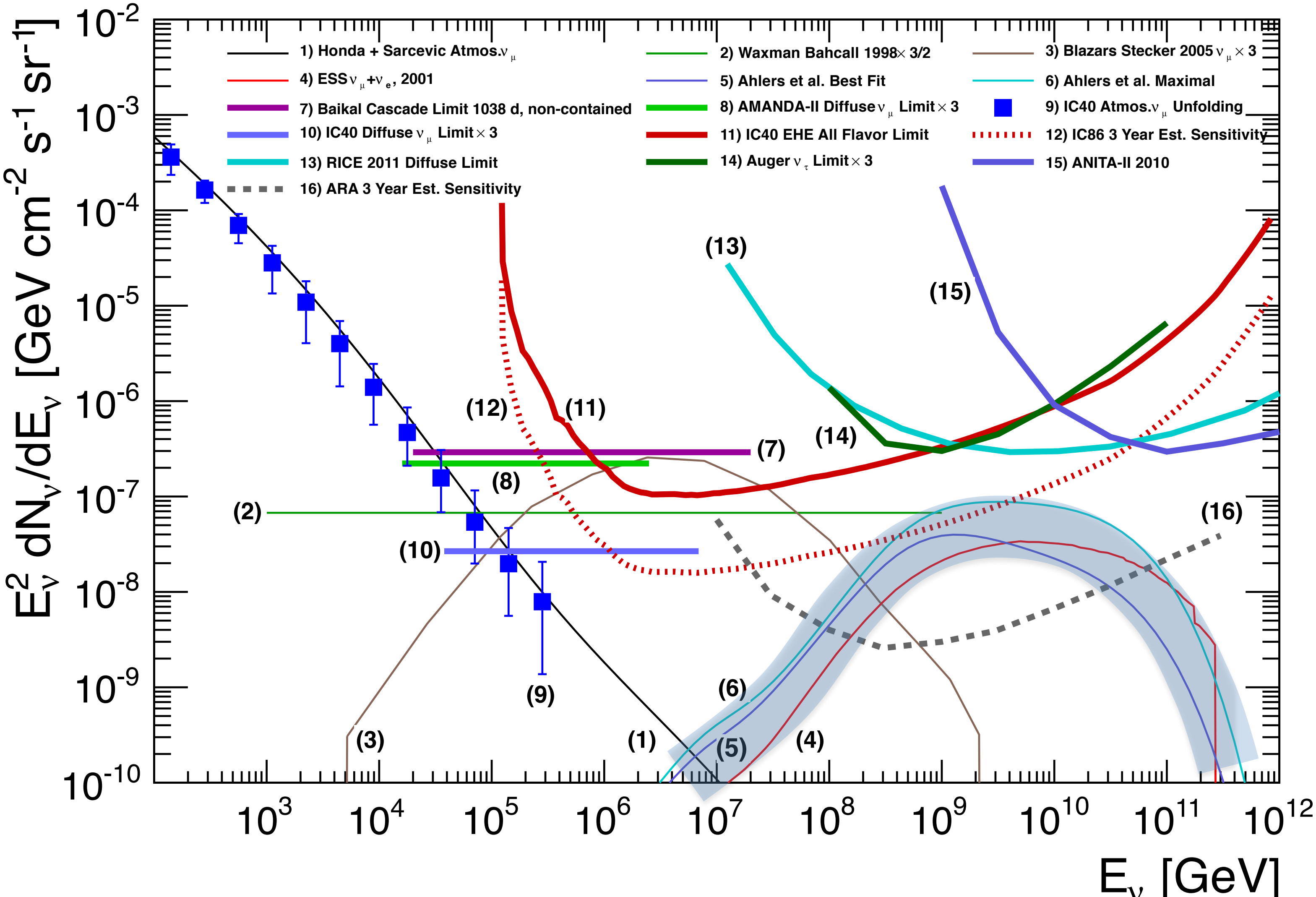
Photon effective area prop. ~ 1/Energy threshold.

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.

Continue this strategy to >PeV energies?

Not practical to extend this path, reducing the PMT density by orders of magnitude.
Attenuation of light and infrastructure cost will dominate at some point.

The cosmic energy frontier, 10^7 to 10^{11} GeV
Cosmogenic or *GZK* neutrinos



The Challenge

- Need detection rates such that the the normalization of the GZK neutrino flux can be reliably determined.
- Requires more than 100 times better sensitivity than published results and more than 10 times the sensitivity of IceCube at 1E18 eV.
- Alternatives to water/ice based optical Cherenkov detectors:
  - Radio detection in the Antarctic ice

Other alternatives have been and are being pursued, eg. acoustic detection, radio telescopes pointing at the moon, and other.
They seem less competetive in the foreseeable future, one problem being too high thresholds.
I am not covering any of these.

Future projects with based on Askaryan radio signature in ice.

ARA:
Location: South Pole
Area: 150 – 200 km2
embedded detector
Ice sheet: 2.8 km
Prototype array in installation

ARIANNA:
Location: Ross Ice Shelf
Area: 1000km2
Shelf thickness: 600m
Surface detector

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Detection principle: Coherent radio emission from e.m. cascade

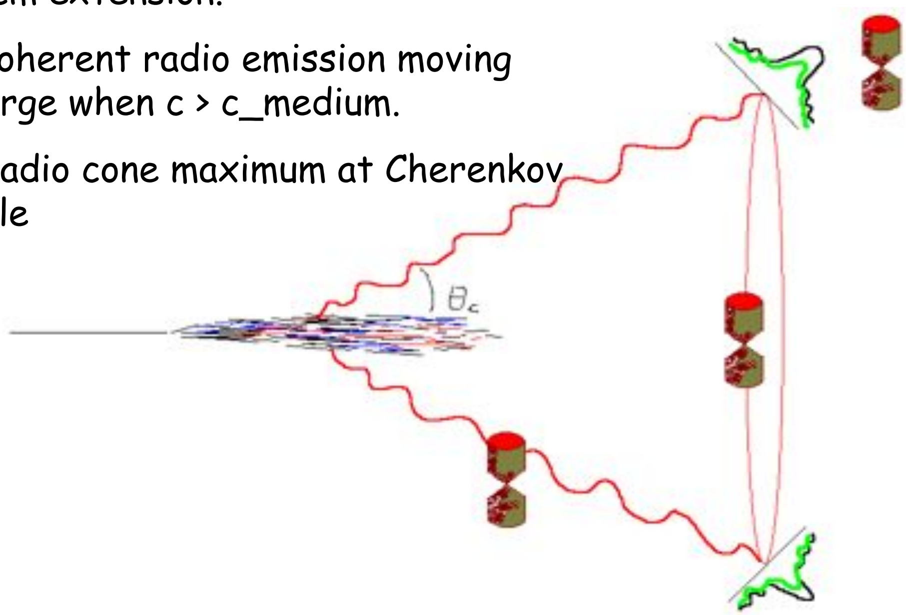
Gurgen Askaryan, 1962
proposes radio detection of showers

Principle:

Charge asymmetry in particle shower development produces a net charge of cm extension.

→coherent radio emission moving charge when c > c_medium.

→Radio cone maximum at Cherenkov angle

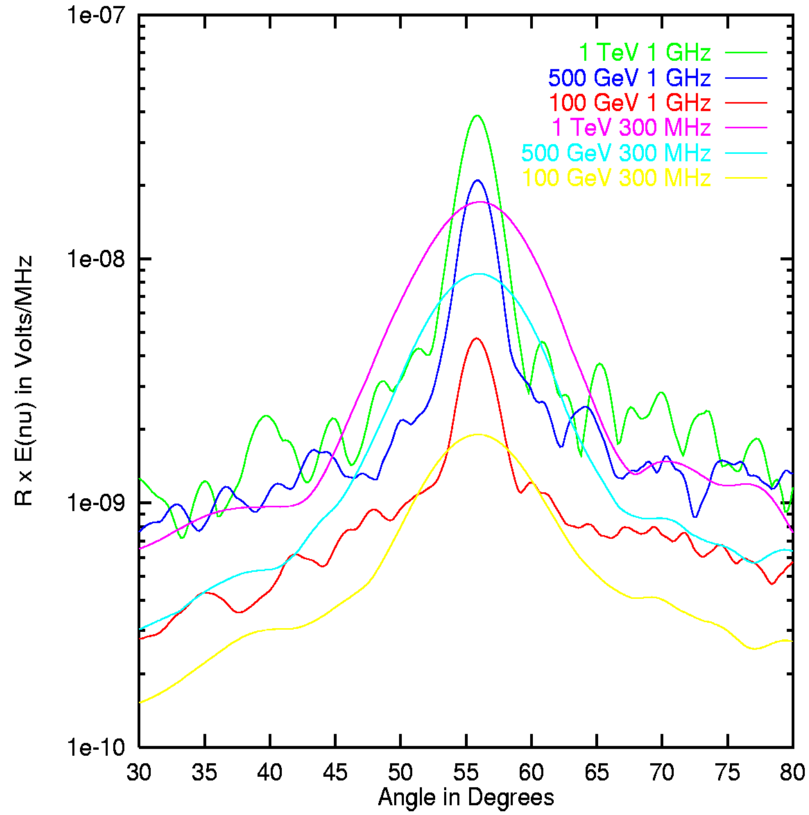


$\lambda >> \ell$

Add coherently!

SLAC 25 GeV electrons on a block of ice make radio pulses in good agreement of theory with data:
D. Saltzberg *et al.,* PRL **86**, 2802 (2001)

cone narrows for higher frequencies
- analogous to single slit diffraction



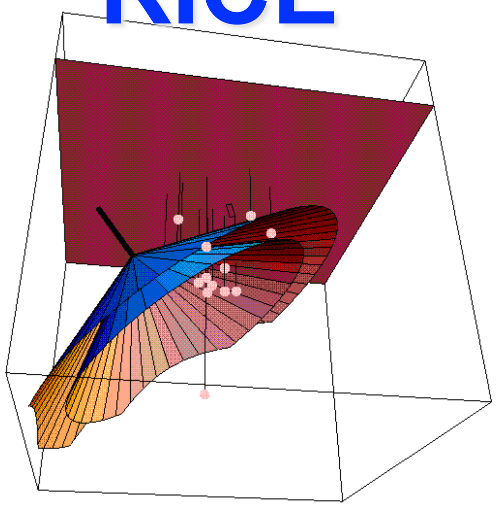
see eg.: J. Alvarez-Muniz et al., Astrop. Phys. 35 (2012) 287-299 and references therein

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Existing and previous instruments using radio in Polar ice

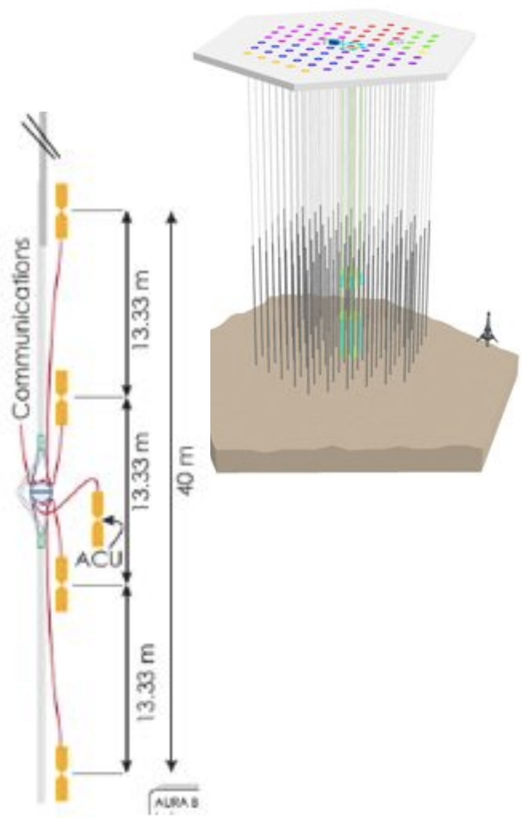
Experiences for ARA, Collaborators from all three experiments joined ARA

RICE



- array of single dipole antennas deployed between 100 and 300m near the Pole
- much of the instrumentation was deployed in AMANDA holes
- Pioneered technique in the ice

Special radio detectors and pulsers in IceCube



ANITA

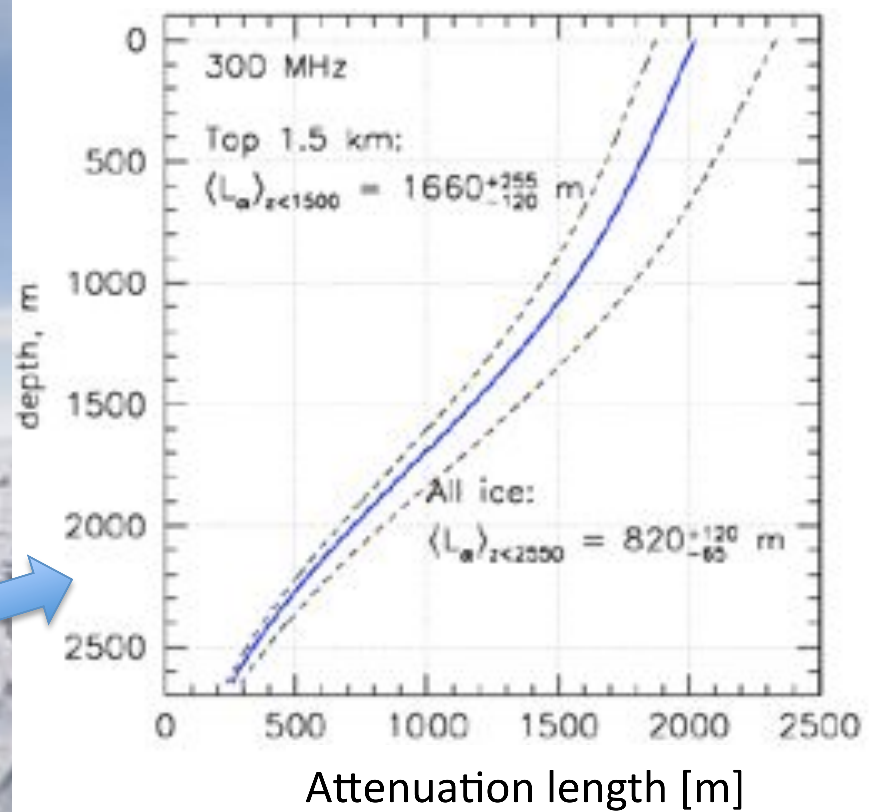
- balloon payload of horn antennas
- surveys the ice cap from high altitude for RF refracted out of the ice
- → high fidelity data acquisition system >Gs/sec waveform capture

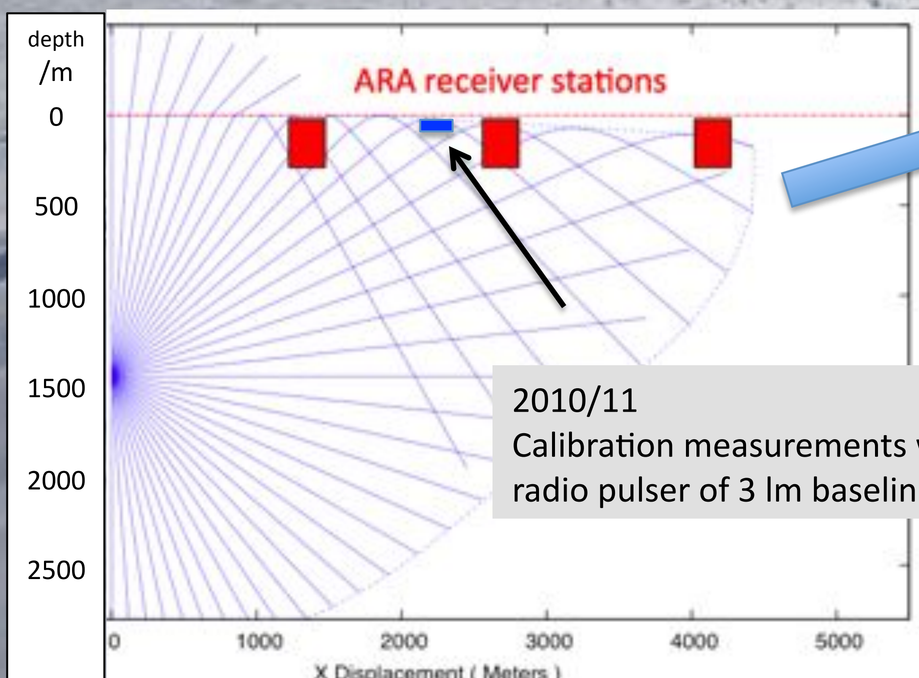
10^7 to 10^{11} GeV: Radio ice Cherenkov detection

South Pole glacial ice – 2.8km, cold and RF transparent

- Thickness: 2800m
- Temperature: -55°C at top, -40°C at 1500m
- Attenuation length at 300MHz: ~ 1.7 km at depths 0 – 1.5 km.
  → Slightly better than expected
- Very low electromagnetic noise

from: Allison et al., Astropart.Phys. 35 (2012) 457-477
arXiv:1105.2854





2010/11
Calibration measurements with embedded radio pulser of 3 lm baseline.

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

- a very large radio neutrino detector at the South Pole

Ref: Allison et al., Astropart.Phys. 35 (2012) 457-477, arXiv:1105.2854 (Design and performance paper)

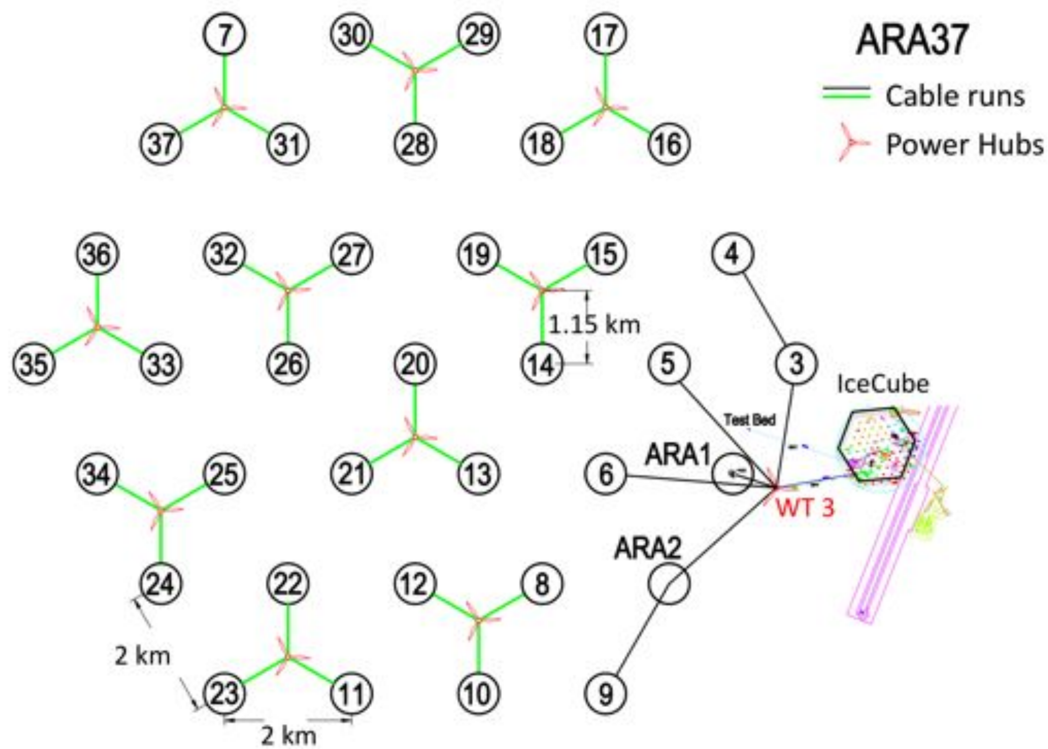
Poster session at this conference:
→ H. Landsman, ARA Design and Status
→ J. Davies, ARA prototype and first station

Scientific Goal:

- Discover and determine the flux of highest energy cosmic neutrinos.
- Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:

Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick and radio transparent ice sheet at the South Pole



Areal coverage: ~150km^2

ARA station geometry

Design goals and choices:

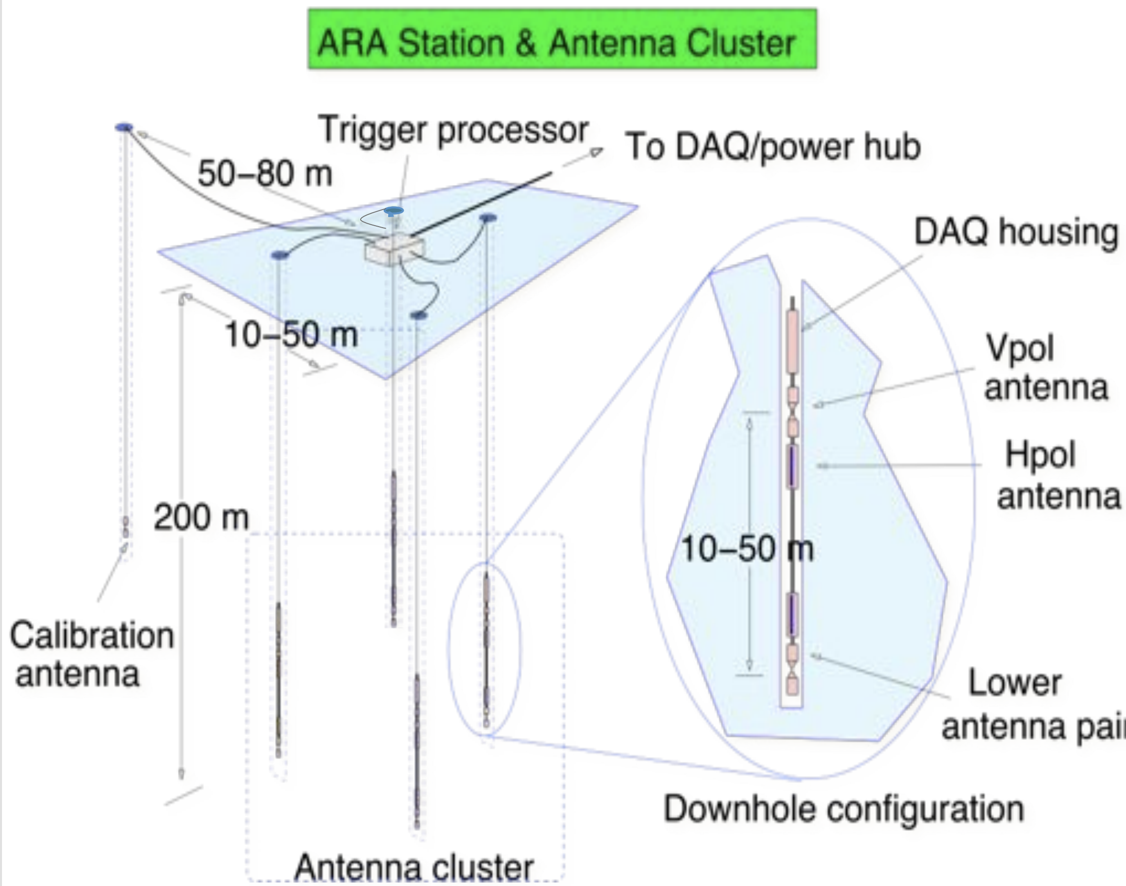
- Every station is a fully functioning detector.

→ Lower energy threshold: nearby events (300m) can be reconstructed.

Background rejection:

→ Embedded strings: Allow good vertex resolution and high vertical resolution for background rejection

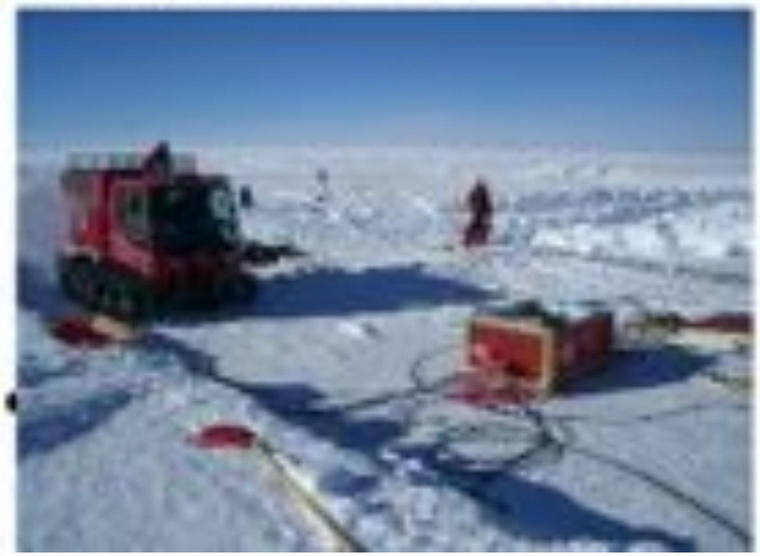
→ Depth at 200m: below firn, Increase acceptance (factor 1.5 compared to 100m).



10^{7} to 10^{11} GeV: Radio ice Cherenkov detection

ARA field activities on the ice

Status:
2011/12 season: Second test detector deployed.
2012/13: Plan for two more stations
- 3 stations Comparable to sensitivity of IceCube at 1E18eV
Goal for full array by 2016/17

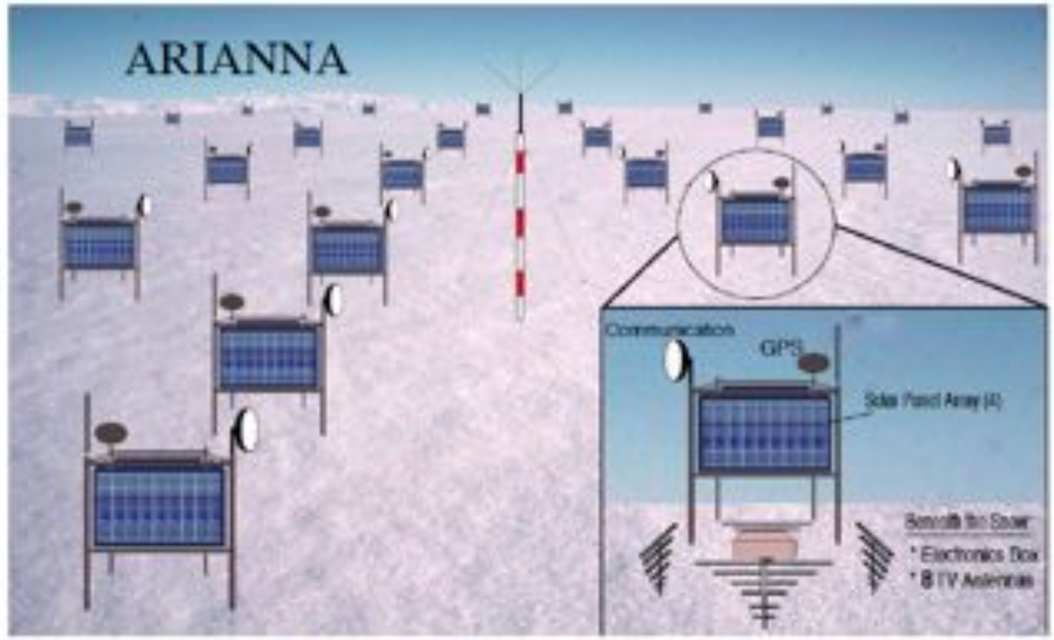


10^7 to 10^{11} GeV: Radio ice Cherenkov detection

ARIANNA

L. Gerhardt et al., Nucl.Instrum.Meth. A624 (2010) 85-91

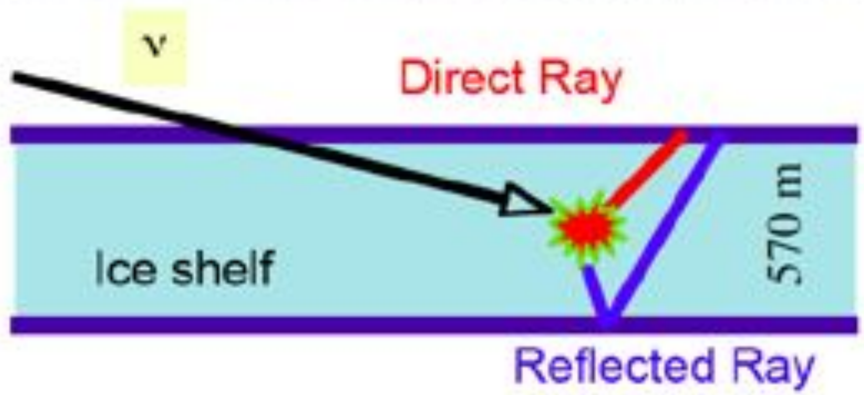
31 x 31 array
[30 km x 30 km]



ARIANNA

US, S. Korea, England, New Zealand

Barwick, astro-ph/0610631

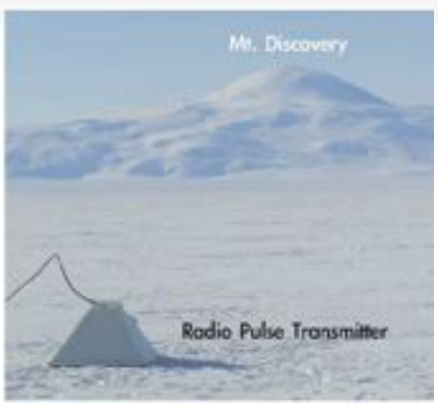


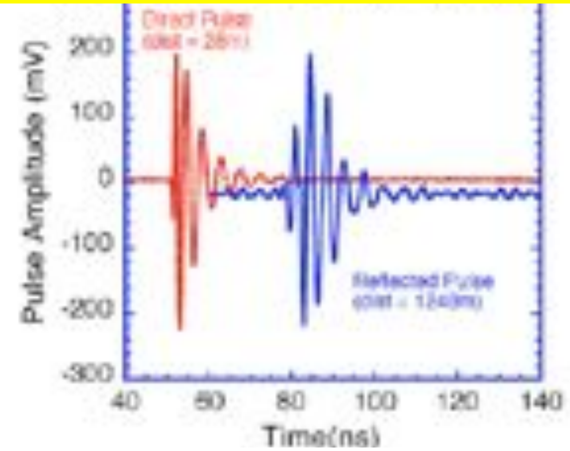
10^7 to 10^{11} GeV: Radio ice Cherenkov detection

ARIANNA: Field studies - ice properties

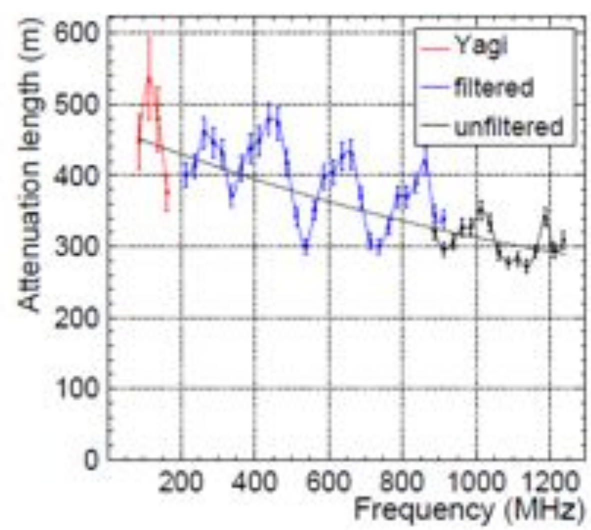
courtesy: Spencer Klein

- Measure reflected signals from ice-water interface
  - Horn antennas
  - Ice thickness 572 m
- Signal loss at interface and in-transit
- Absorption length 300-500 m
  - With conservative assumption – full reflection at interface
    - Ice-water interface attenuation < 3 db
  - Systematic uncertainty 15-55 m
- 183 MHz oscillations not well understood



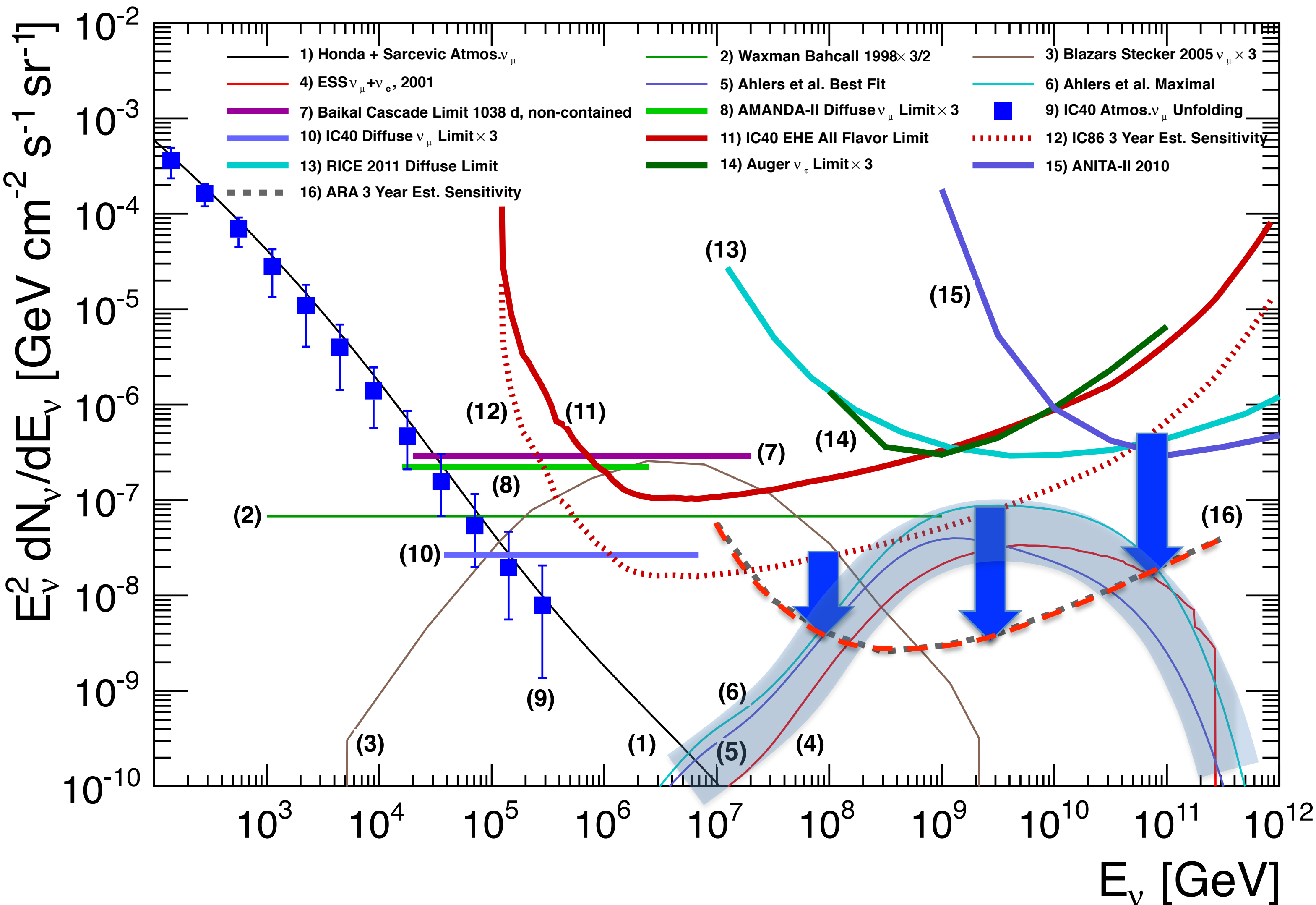


Signal reflection from interface



T. Barrella, S. Barwick, D. Saltzberg, 2010

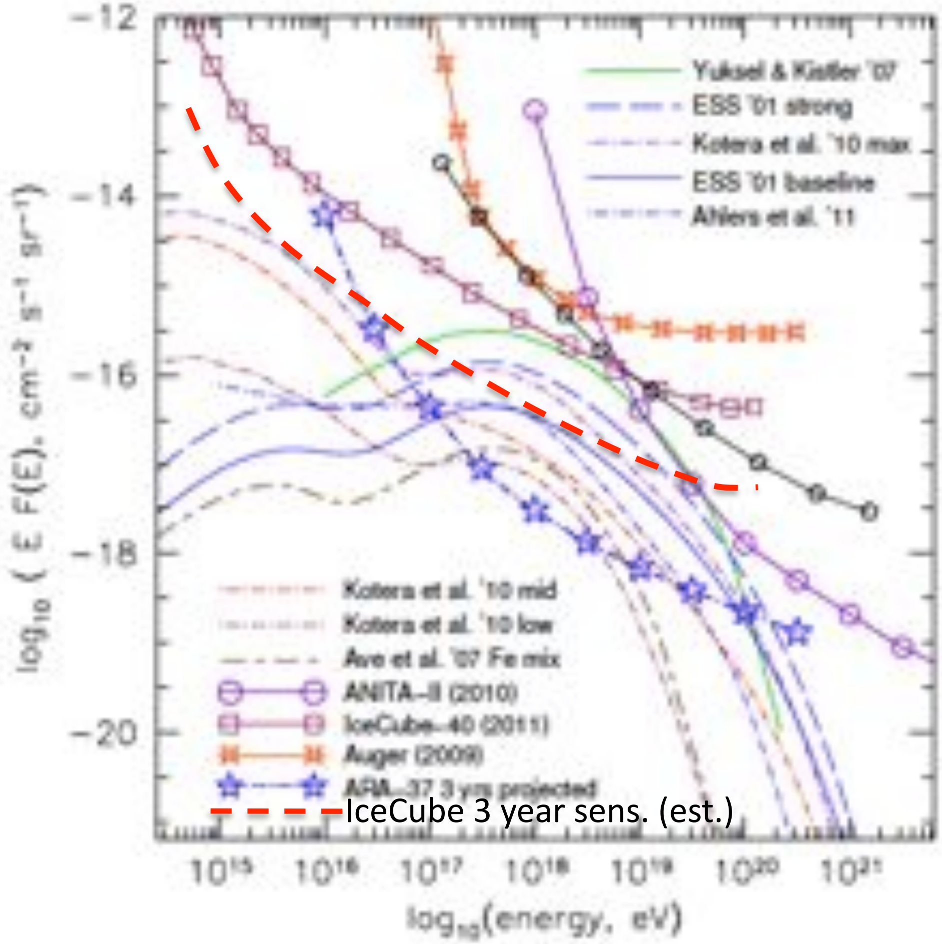
10^16 – 10^20 eV energy scale



Search for cosmogenic (GZK) neutrino flux

- 3 years of IceCube has a good chance of seeing a few events.

- → A larger detector and different technology is needed to have good prospects of measuring this flux!



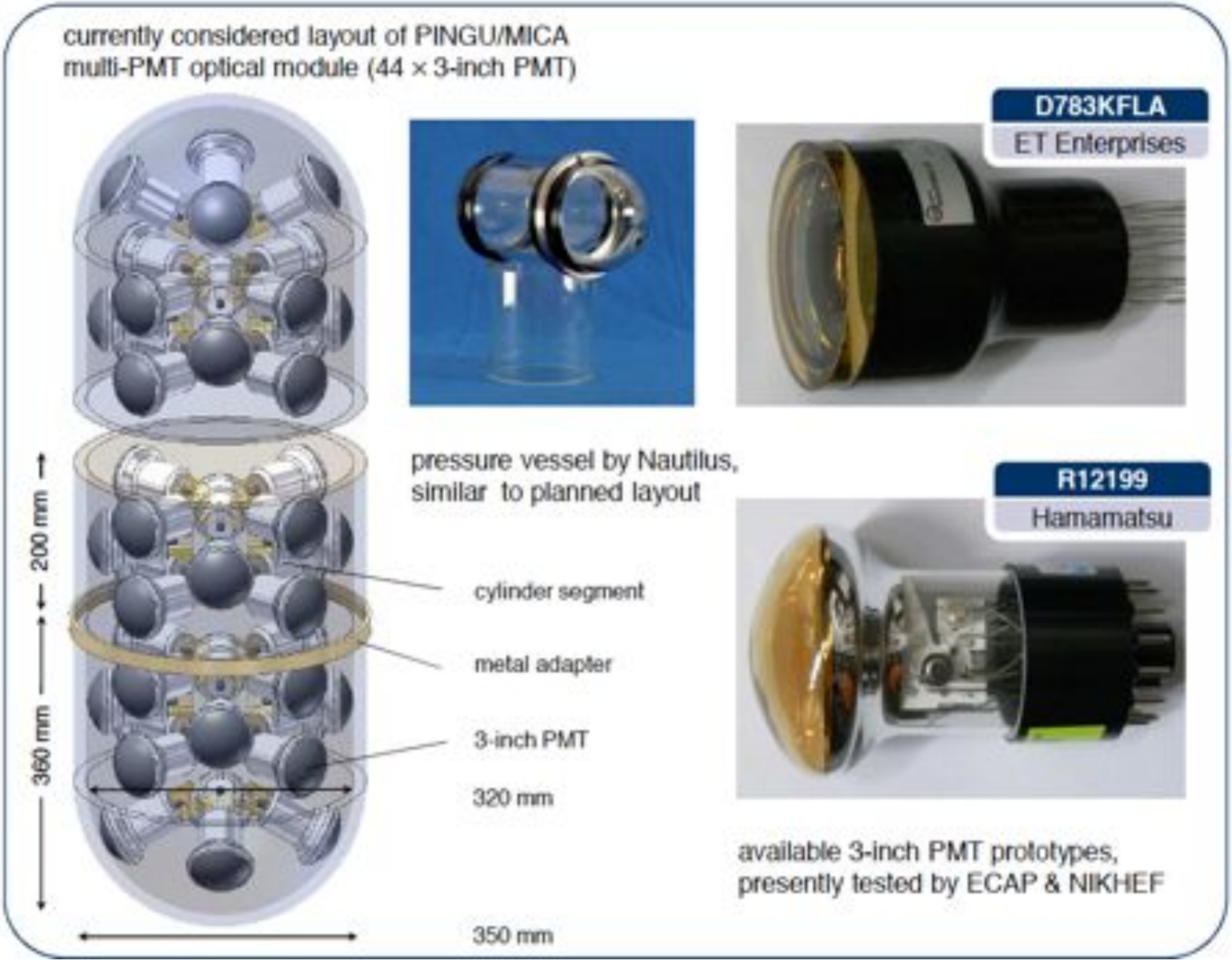
Summary

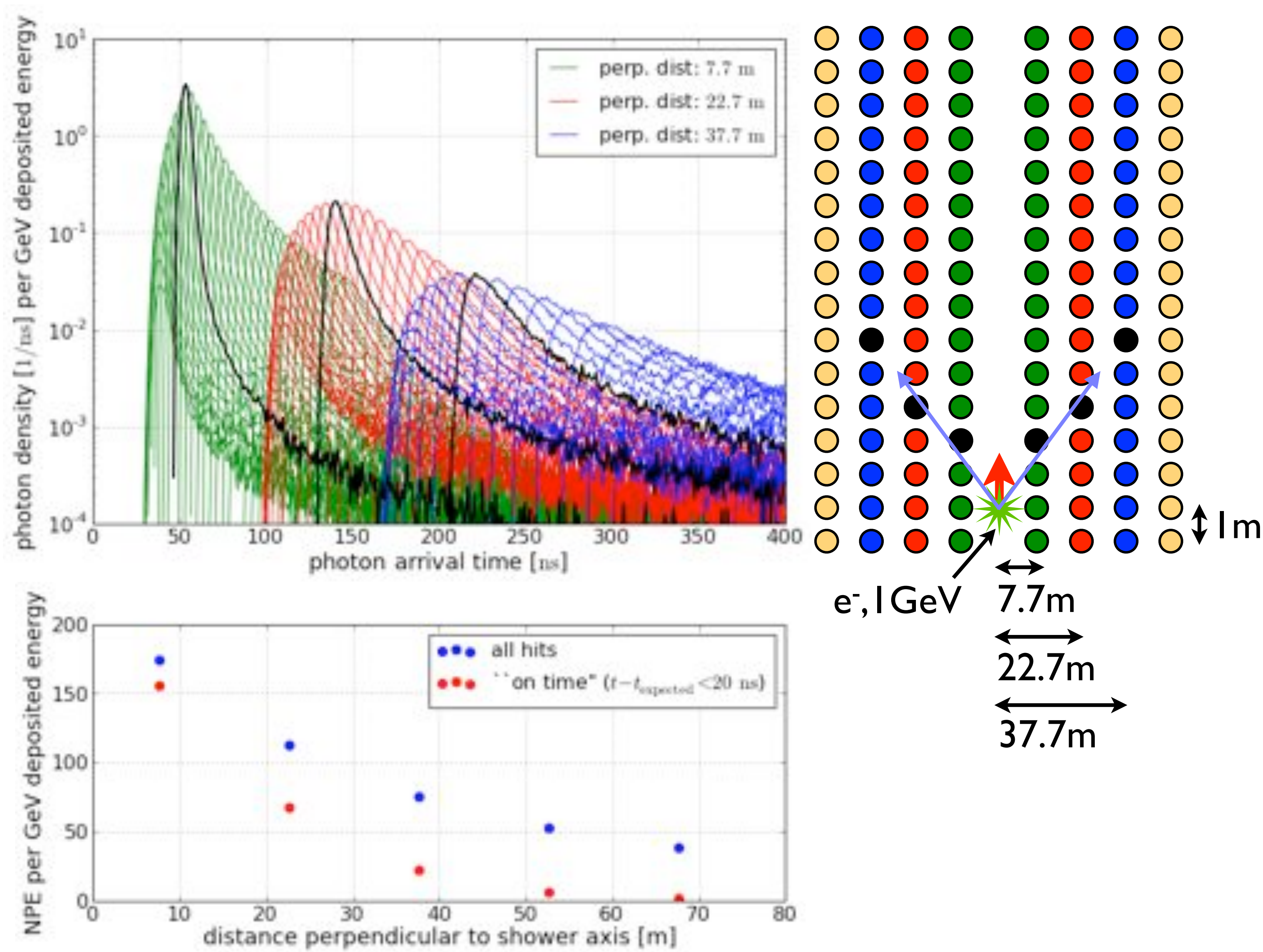
- Big quantum leap in sensitivity with the realization of IceCube.
- Future detectors on three energy scales with different science goals
  - GeV energies: PINGU precision atmospheric neutrino physics with multi Mton target
  - TeV to PeV energies: Projects with goals to expand sensitivity overall and especially towards Southern hemisphere, eg Galactic Center
  - 100 PeV to 100 EeV: Radio ice Cherenkov neutrino detectors using Antarctic Ice are in prototype/ 1st phase to detect cosmogenic neutrino flux
    - ARA, a full large radio array (150km^2) for highest energy (GZK) neutrinos will surpass IceCube substantially in sensitivity with scalable technology.
    - ARIANNA on Ross Ice Shelf
    - Background rejection critical
    - Realistic chance to clarify cosmogenic neutrino flux level in this decade.

Acknowledgments

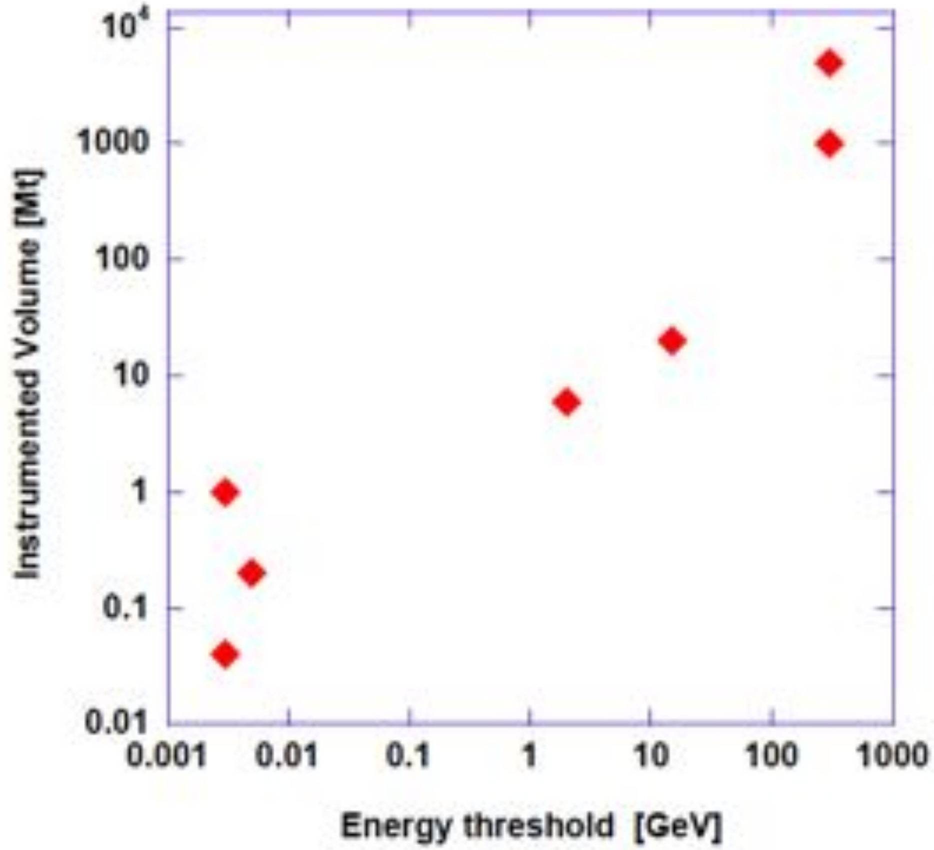
- Thanks to

  M. DeJong, U. Katz, P. Sapienza, Zh.-A. Dzhilkibaev, S. Barwick, S. Klein, Ch. Spiering, D. Grant, J. Koskinen, C. Kopper, D. Chirkin, Ch. Weaver, and many of IceCube and ARA collaborators for useful discussions and materials.

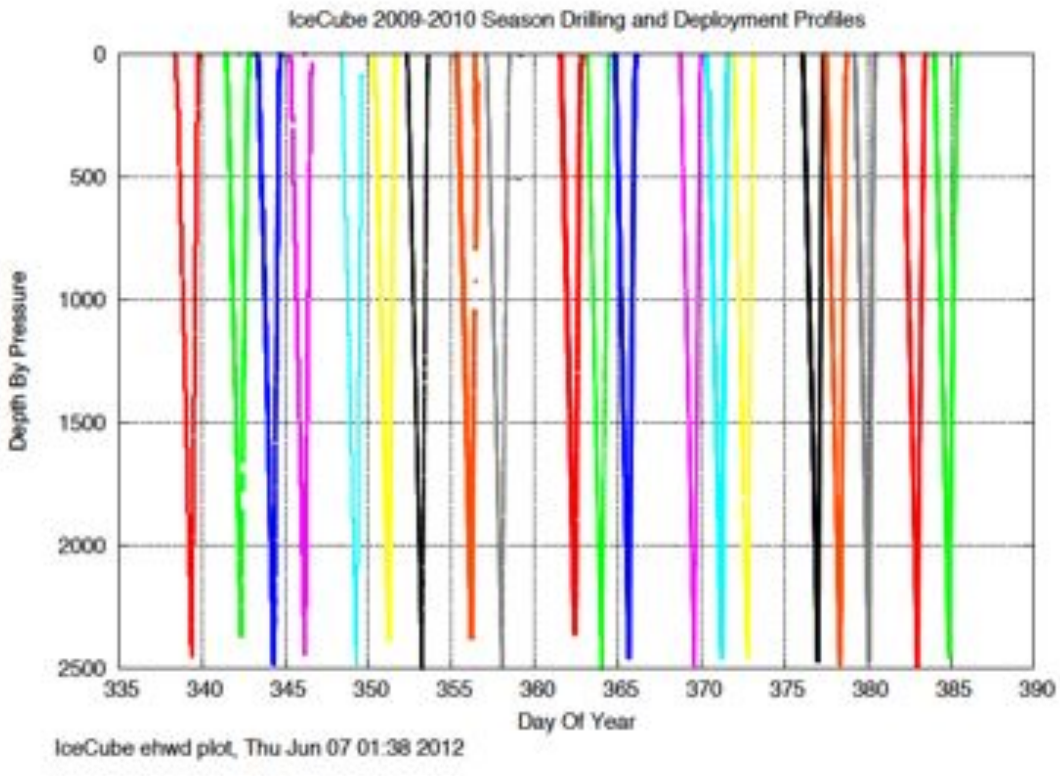

currently considered layout of PINGU/MICA
multi-PMT optical module (44 × 3-inch PMT)
pressure vessel by Nautilus,
similar to planned layout
D783KFLA
ET Enterprises
R12199
Hamamatsu
200 mm
360 mm
cylinder segment
metal adapter
3-inch PMT
320 mm
350 mm
available 3-inch PMT prototypes,
presently tested by ECAP & NIKHEF



photon density [1/ns] per GeV deposited energy
photon arrival time [ns]
perp. dist: 7.7 m
perp. dist: 22.7 m
perp. dist: 37.7 m
NPE per GeV deposited energy
distance perpendicular to shower axis [m]
all hits
``on time" ($t - t_{expected} < 20$ ns)
1m
e⁻, 1GeV
7.7m
22.7m
37.7m



10^4
1000
100
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
1000
Instrumented Volume [Mt]
Energy threshold [GeV]


IceCube 2009-2010 Season Drilling and Deployment Profiles
0
500
1000
1500
2000
2500
Depth By Pressure
335
340
345
350
355
360
365
370
375
380
385
390
Day Of Year
IceCube ehwd plot, Thu Jun 07 01:38 2012