Future experiments

Albrecht Karle
University of Wisconsin-Madison

Neutrino 2012
Kyoto

Cosmic Rays and Neutrino Sources : neutrinos from accelerators

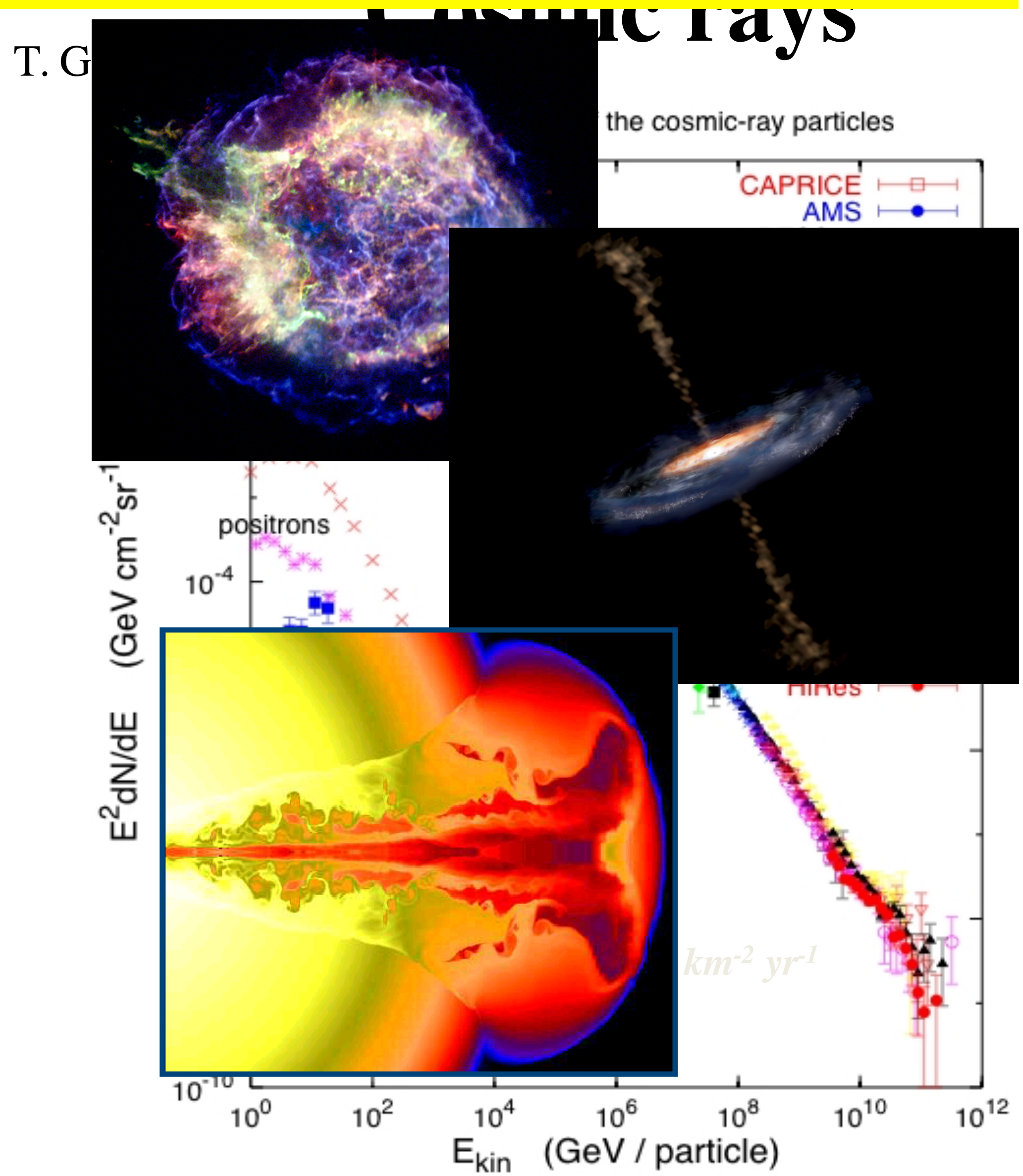
$$p\gamma \rightarrow p\pi^0, n\pi^+$$

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

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

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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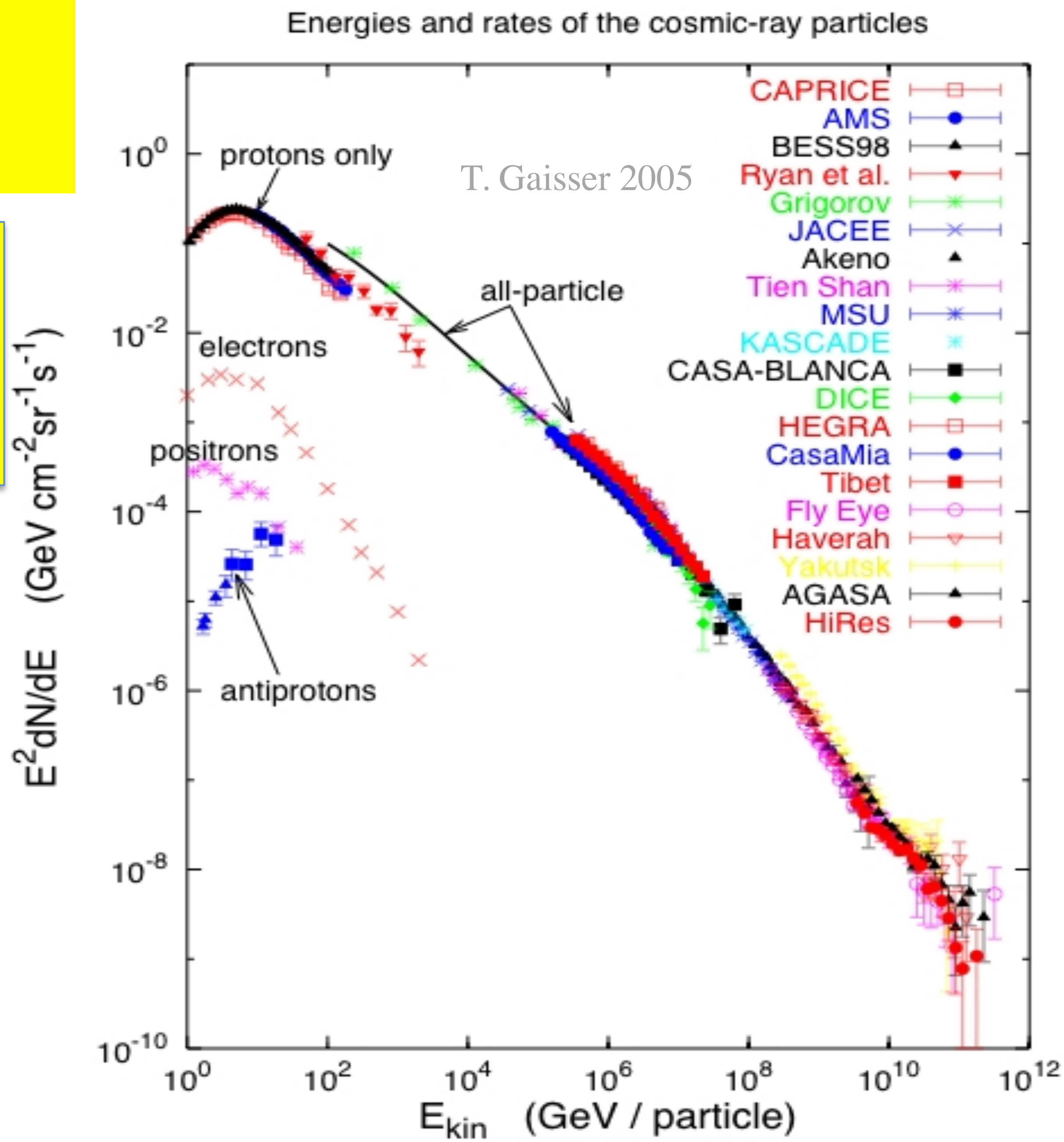
Known targets:

- 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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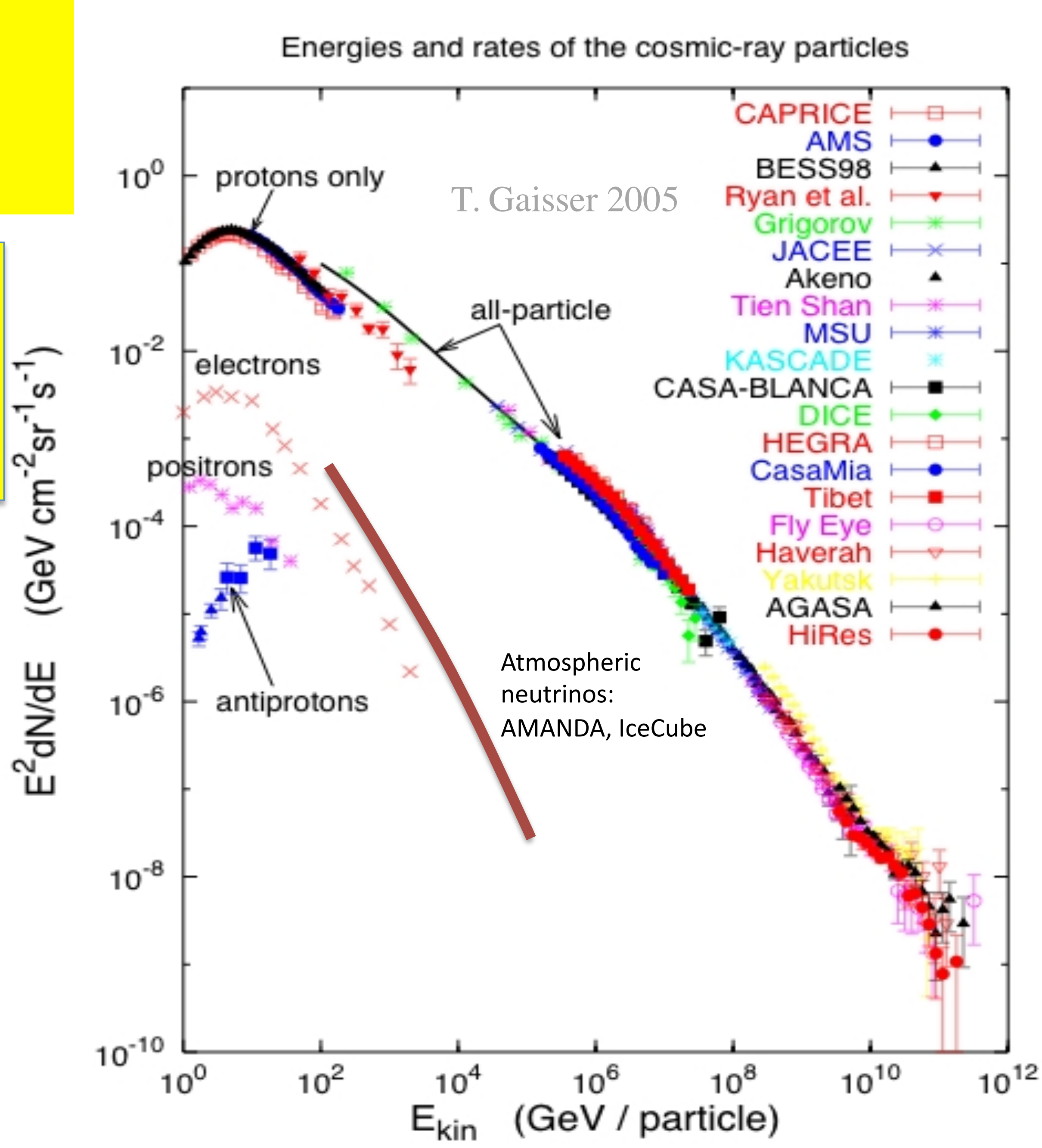

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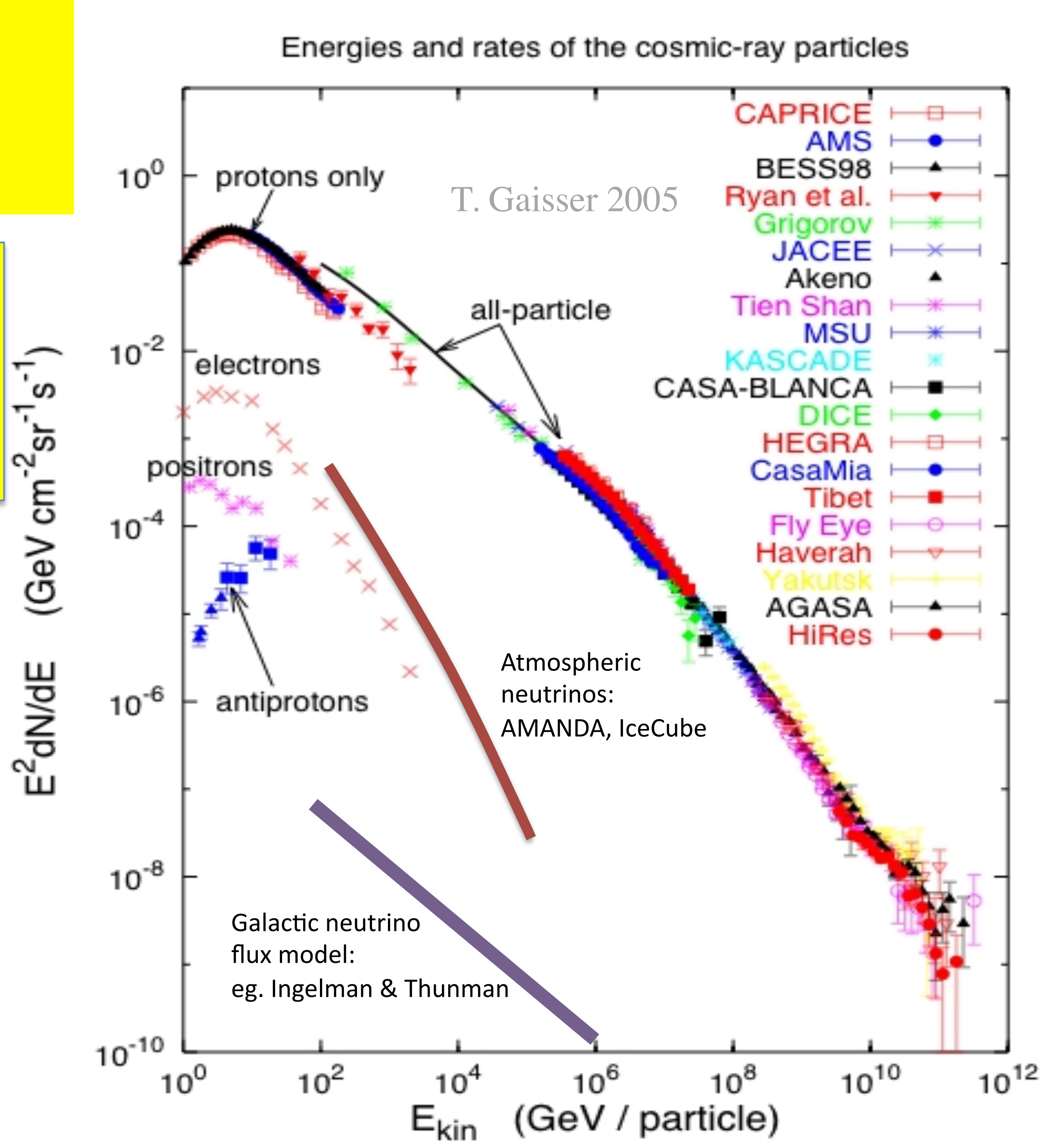

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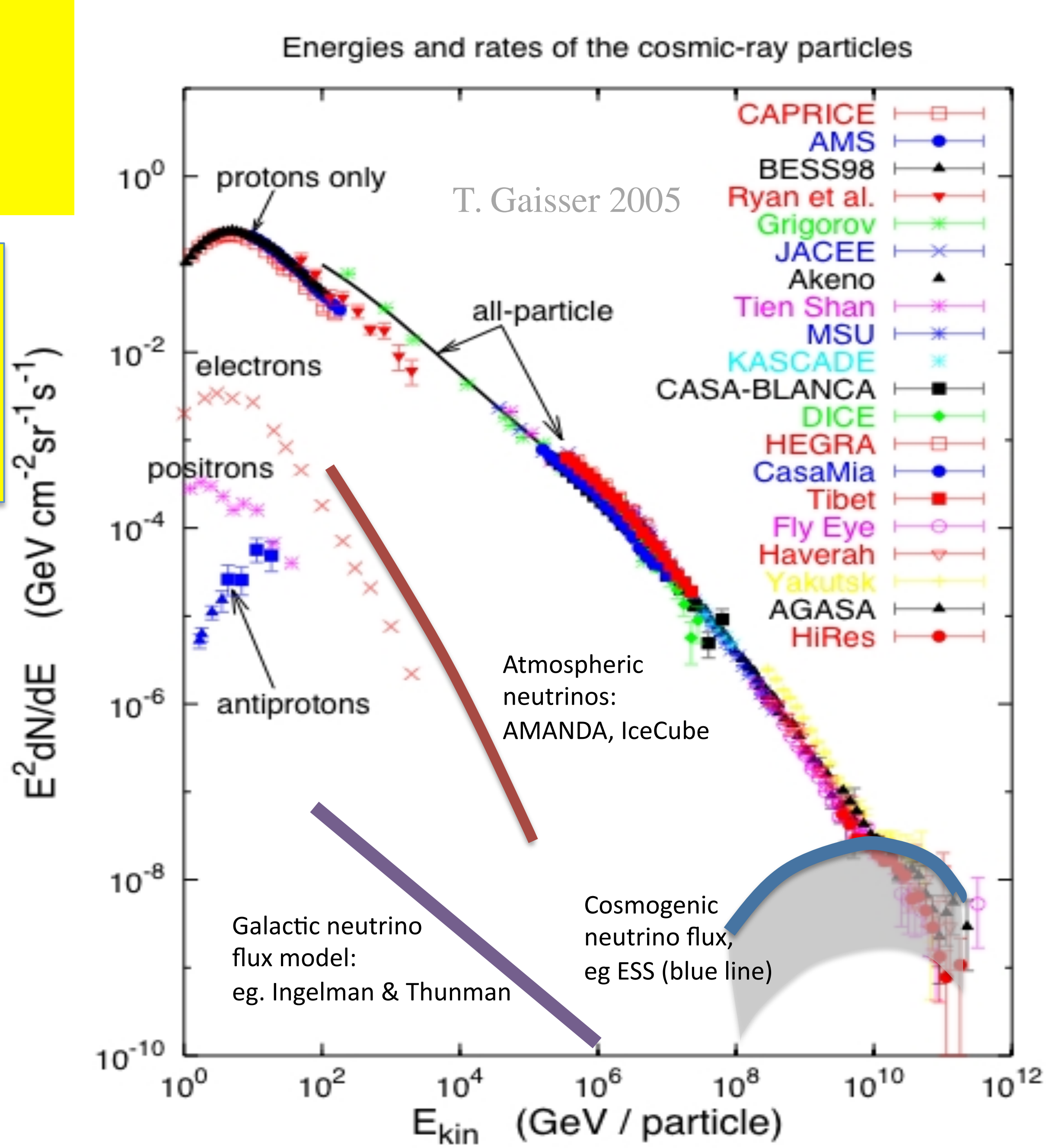

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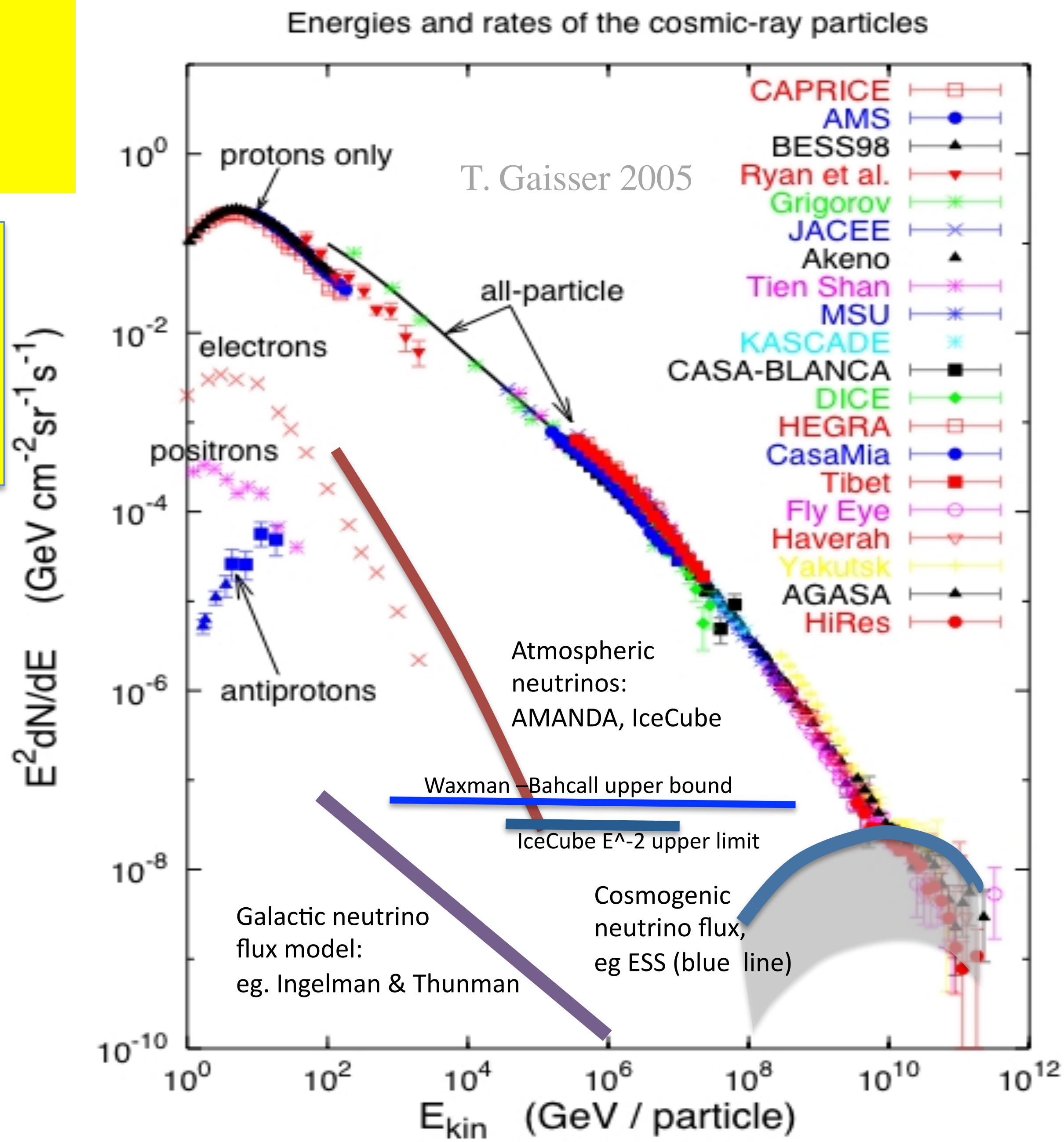
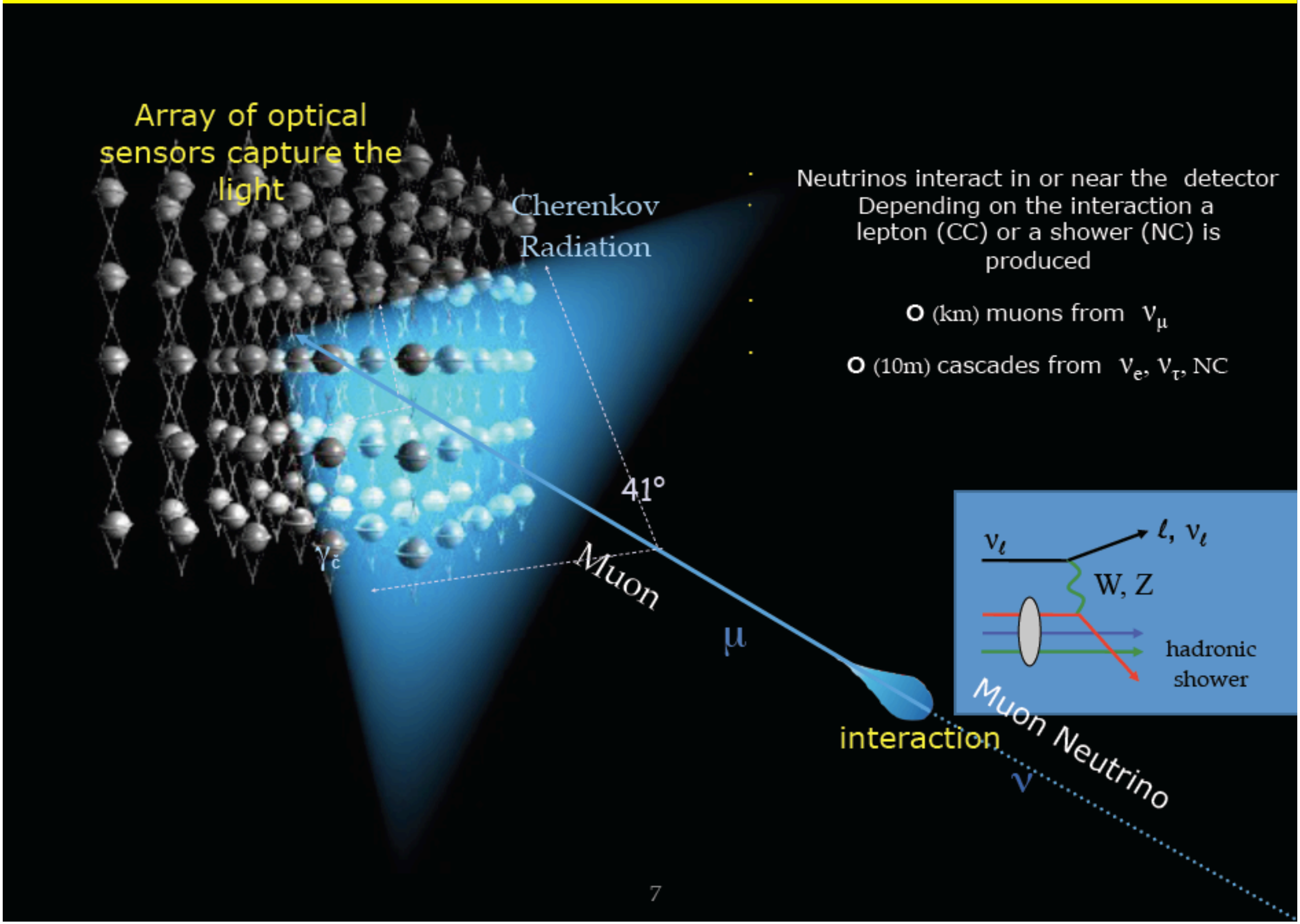


How to detect UHE high energy neutrinos? – The challenge:

- 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

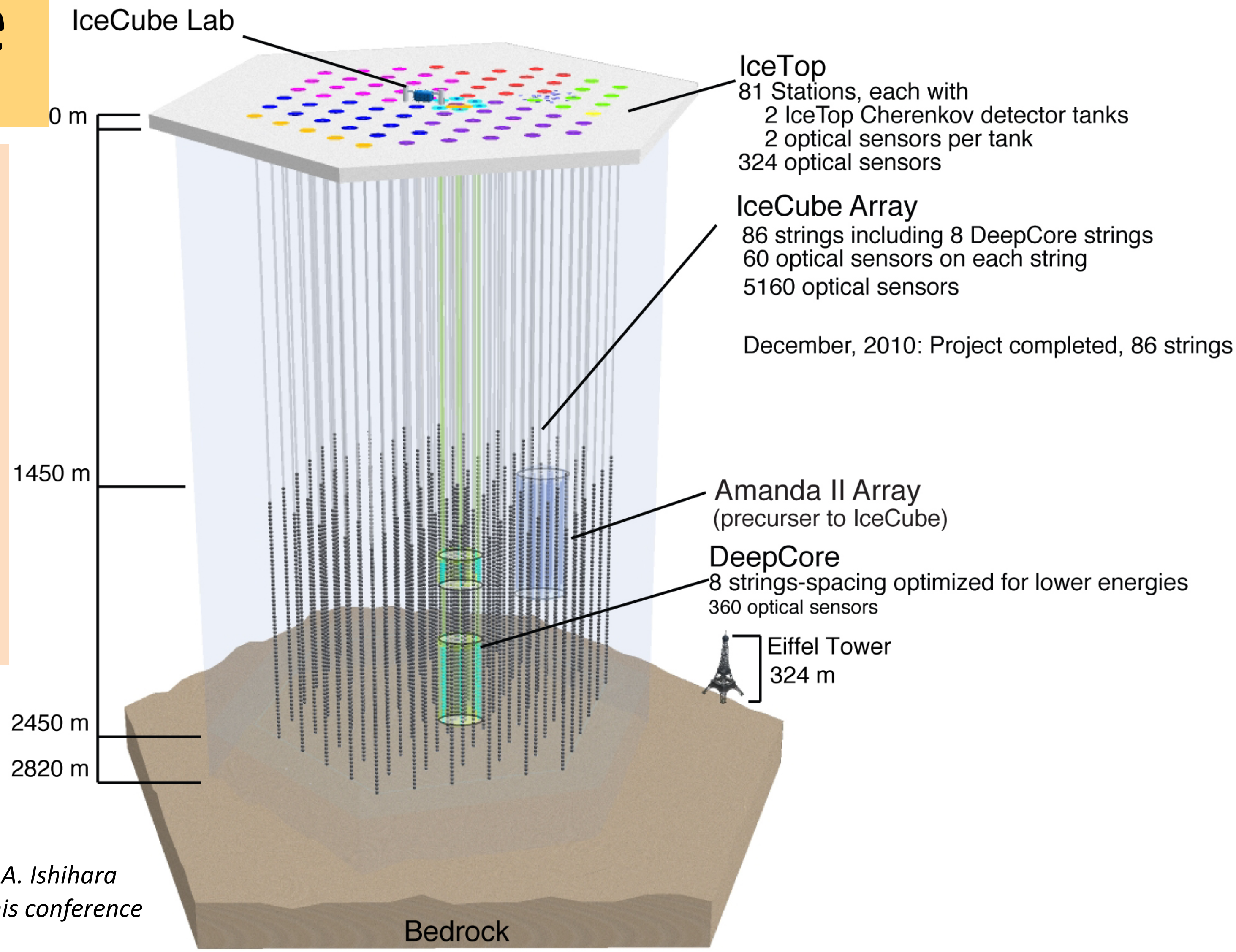
  → Challenges for Calibration

Water/ice Cherenkov detectors



IceCube

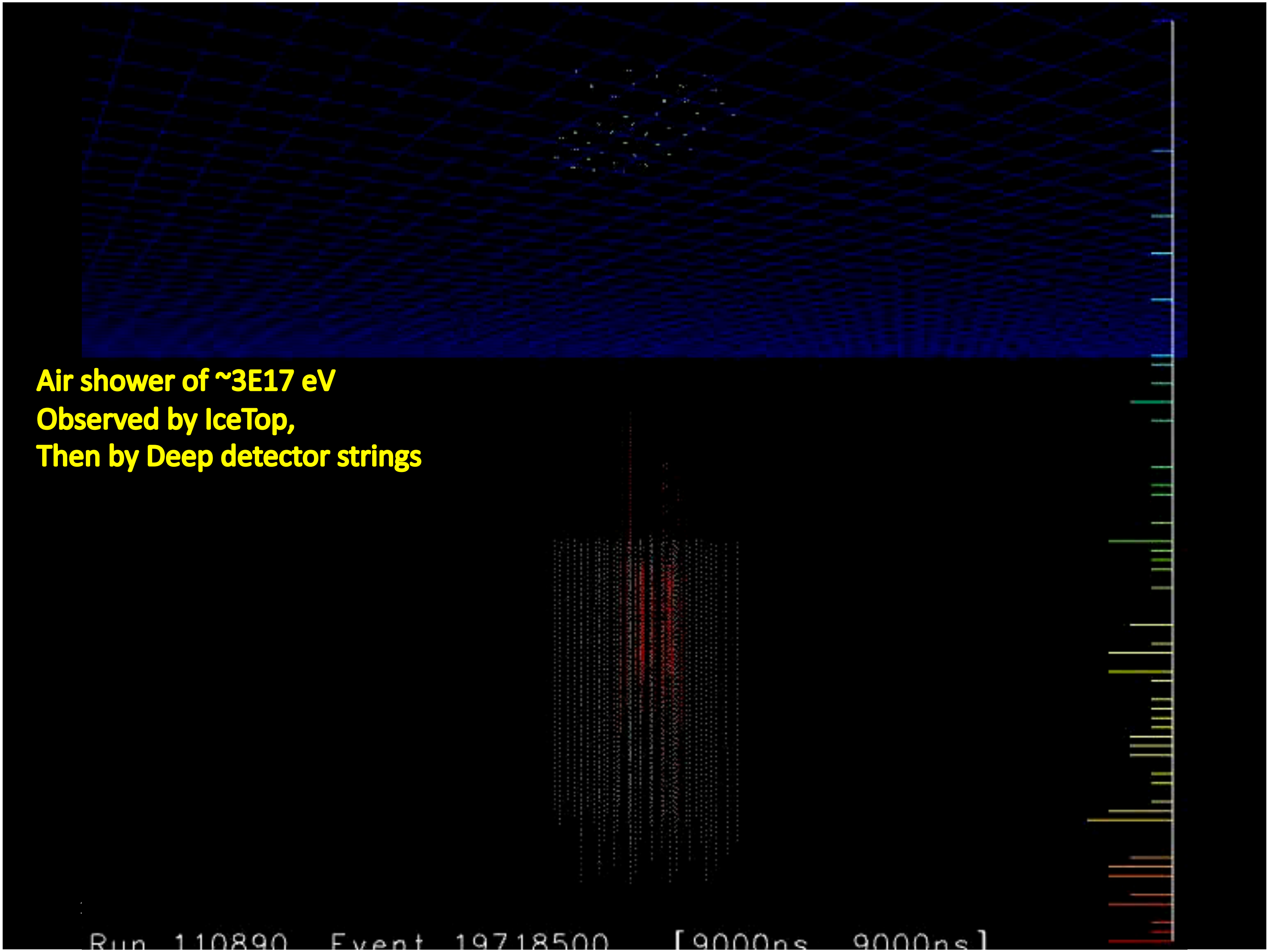
- Total of 86 strings and 162 IceTop tanks;
- Completion with 86 strings: December 2010
- Full operation with all strings since May 2011.



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

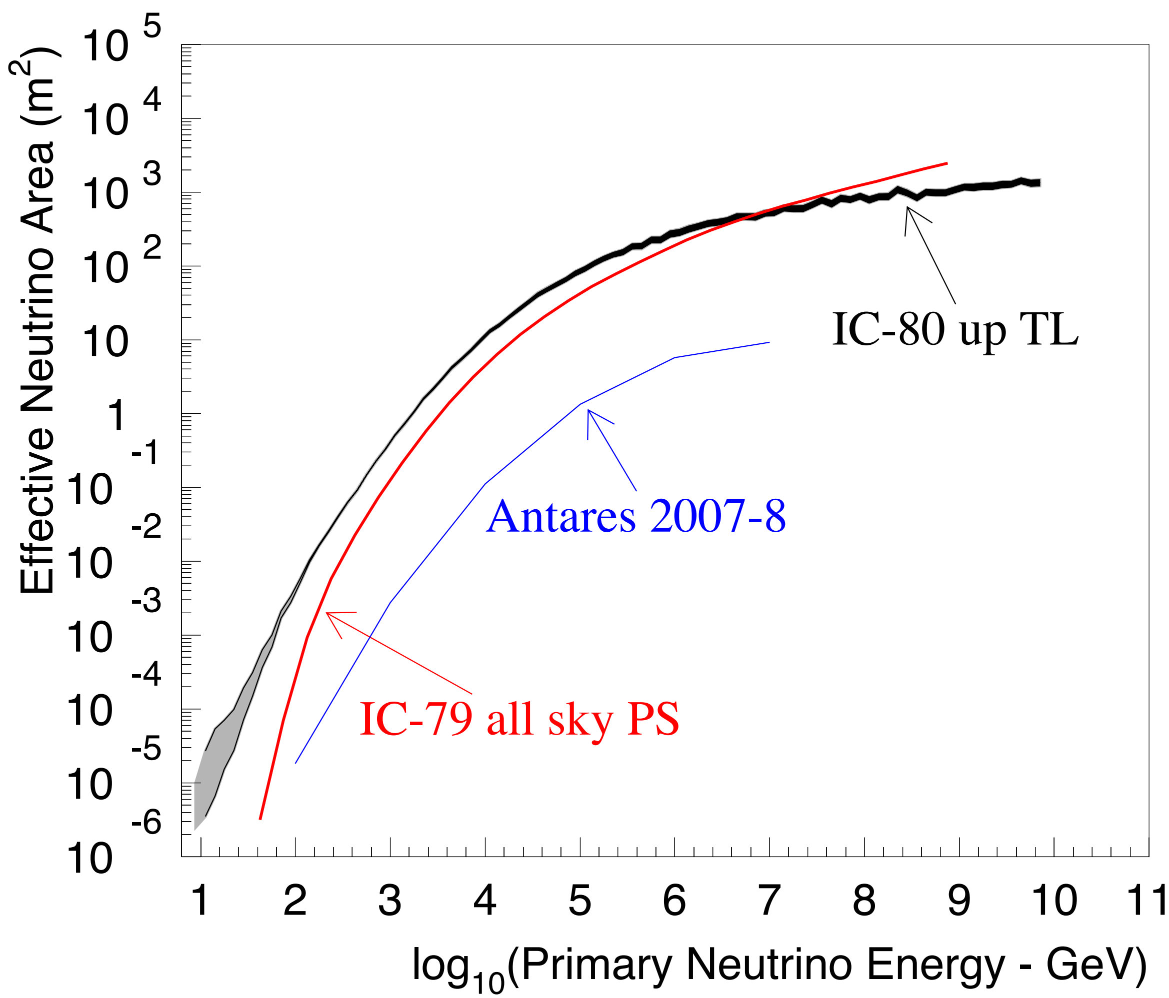
Water/ice Cherenkov detectors: Optical properties and noise characteristics

- Add a few comments on water and ice


Air shower of ~3E17 eV
Observed by IceTop,
Then by Deep detector strings
Run 110890 Event 19718500 [9000ns 9000ns]

Water/ice Cherenkov detectors: Neutrino effective areas

Wide energy range due to increase in effective area!



Area at 100 TeV (1TeV)
IceCube 86: 40m² (0.3m²)

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.

Energy scales and future detectors - from low to high energy

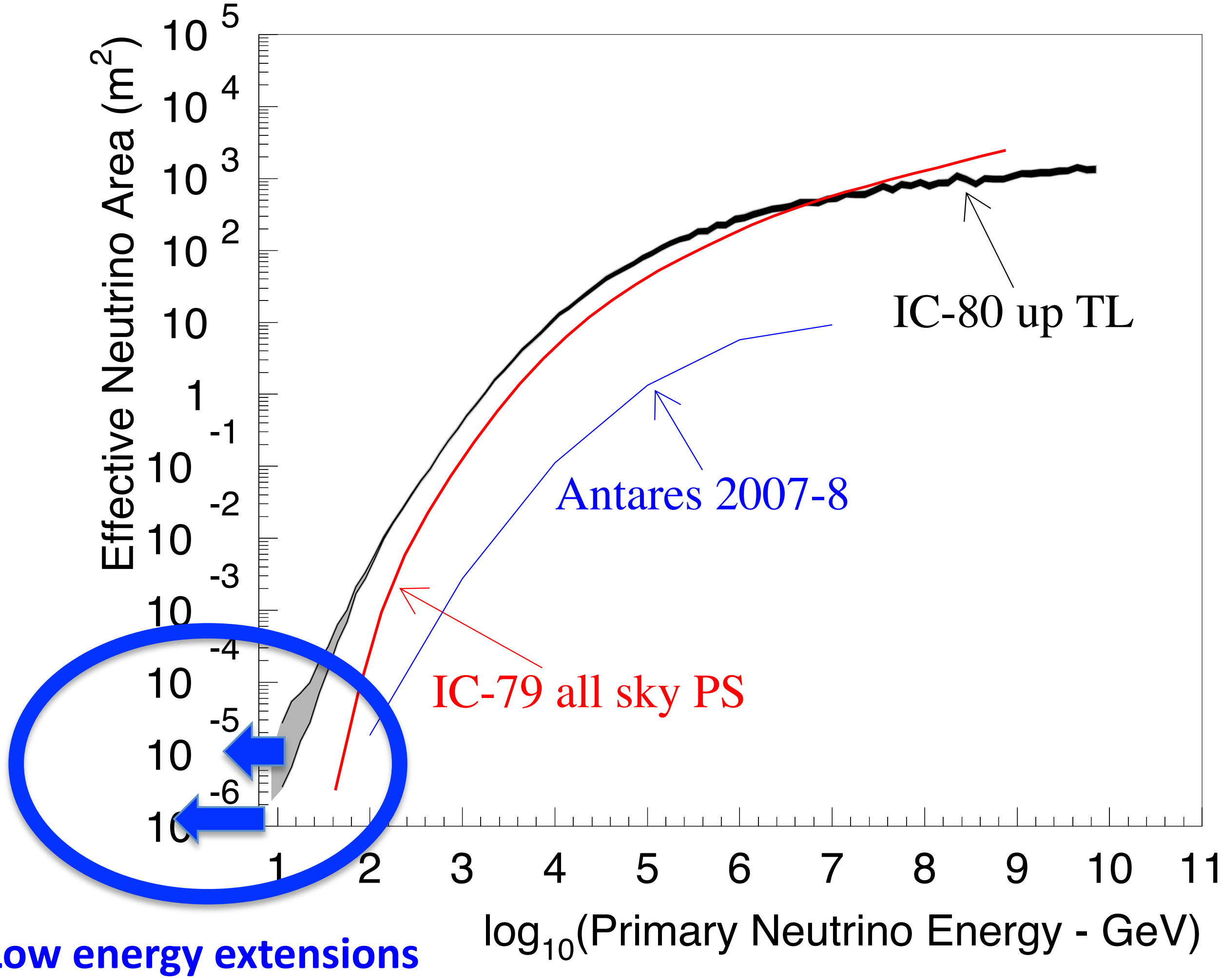
1. 1 – 100 GeV: IceCube extensions: PINGU and beyond
2. TeV – PeV plans for larger Water/ice Cherenkov detectors
   - KM3Net
   - Baikal upgrade
3. 10 PeV – 10 EeV detectors:

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

Water/ice Cherenkov detectors: Neutrino effective areas

Wide energy range due to increase in effective area!

PINGU lowers threshold to few GeV



Effective area for ν_μ

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

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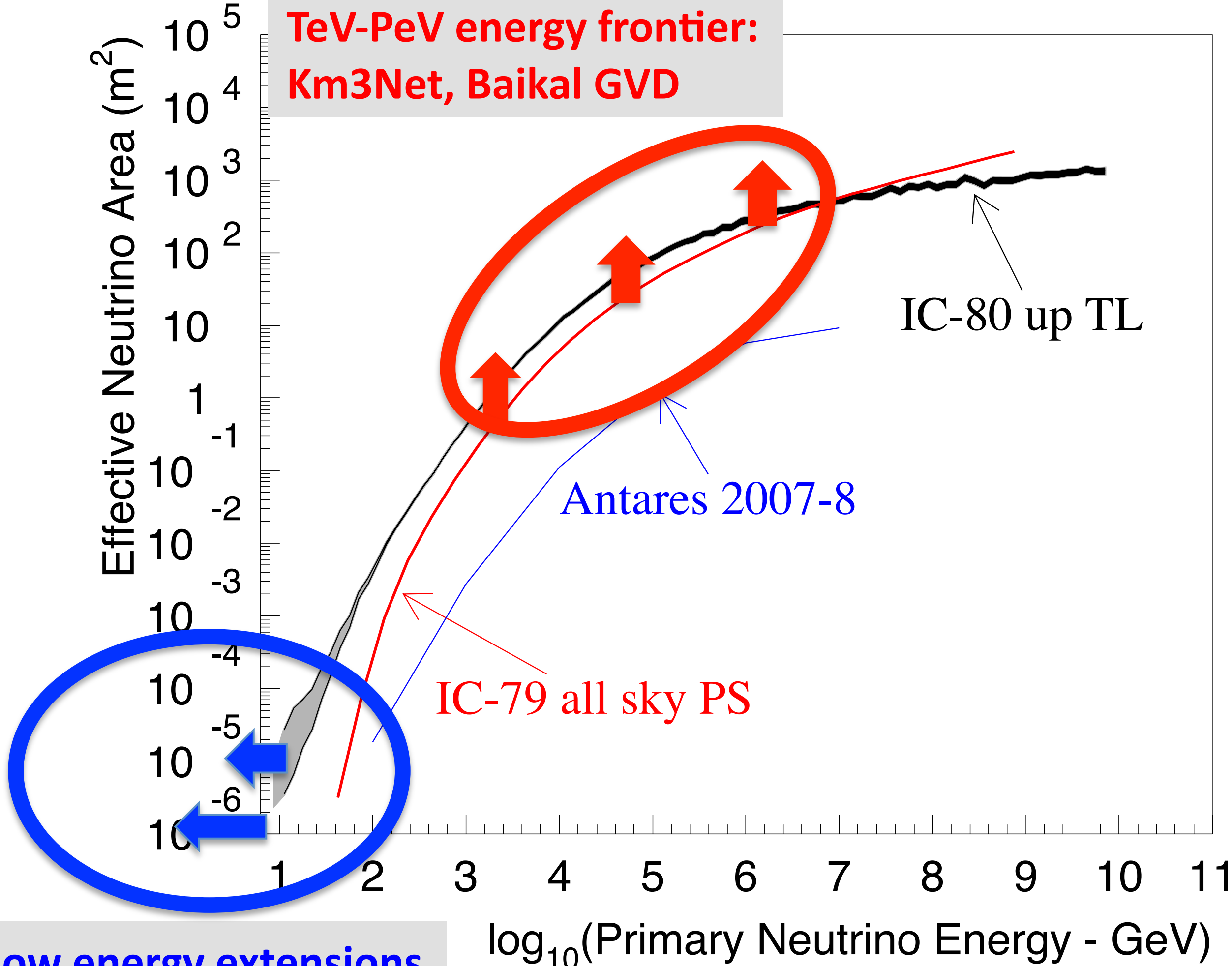

Projects with more PMT cathode area like KM3Net would establish larger detectors in Northern hemisphere:
Not only size but optimal view to Galactic Center (Southern Hemisphere)

Strong rise with energy:
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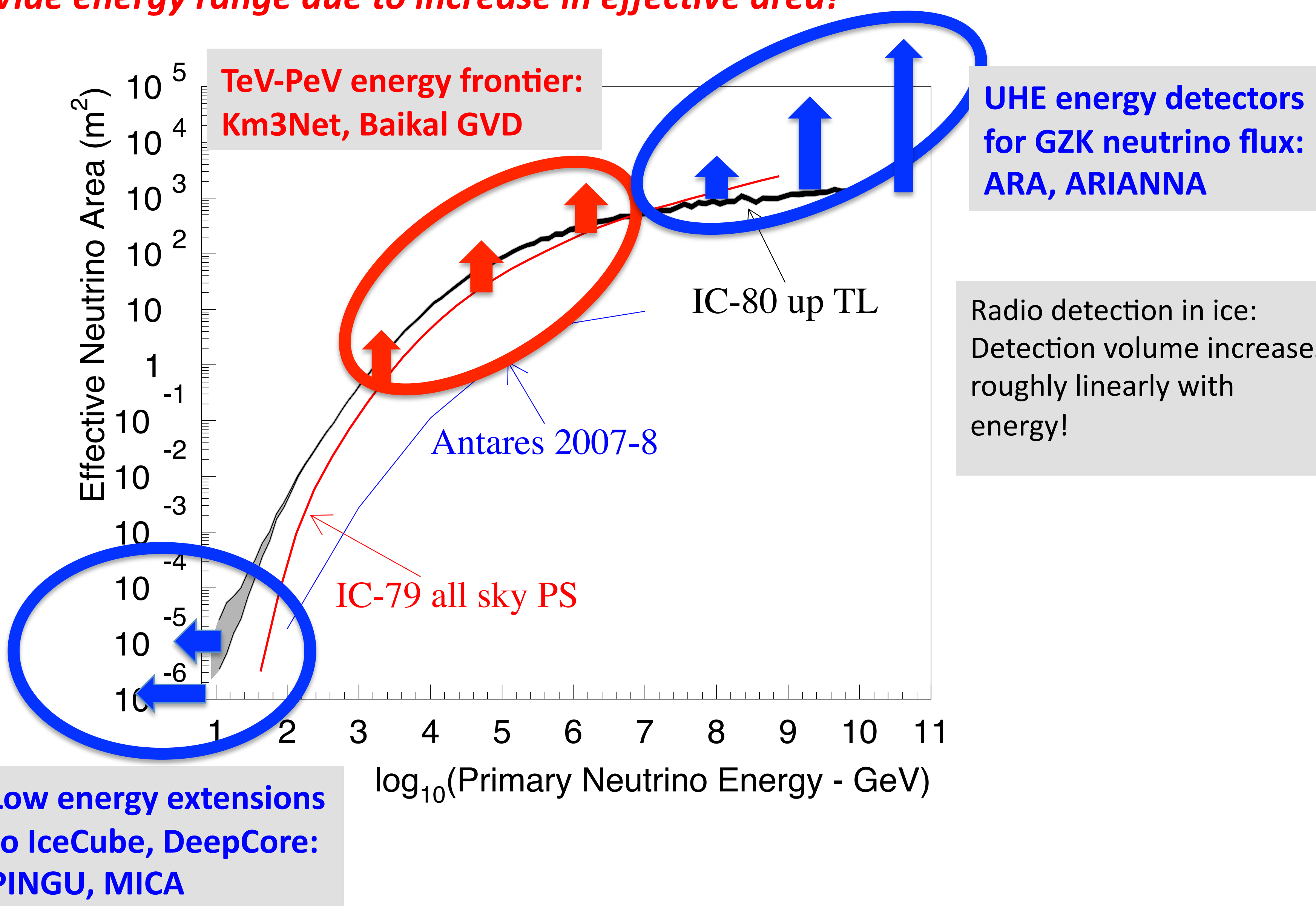
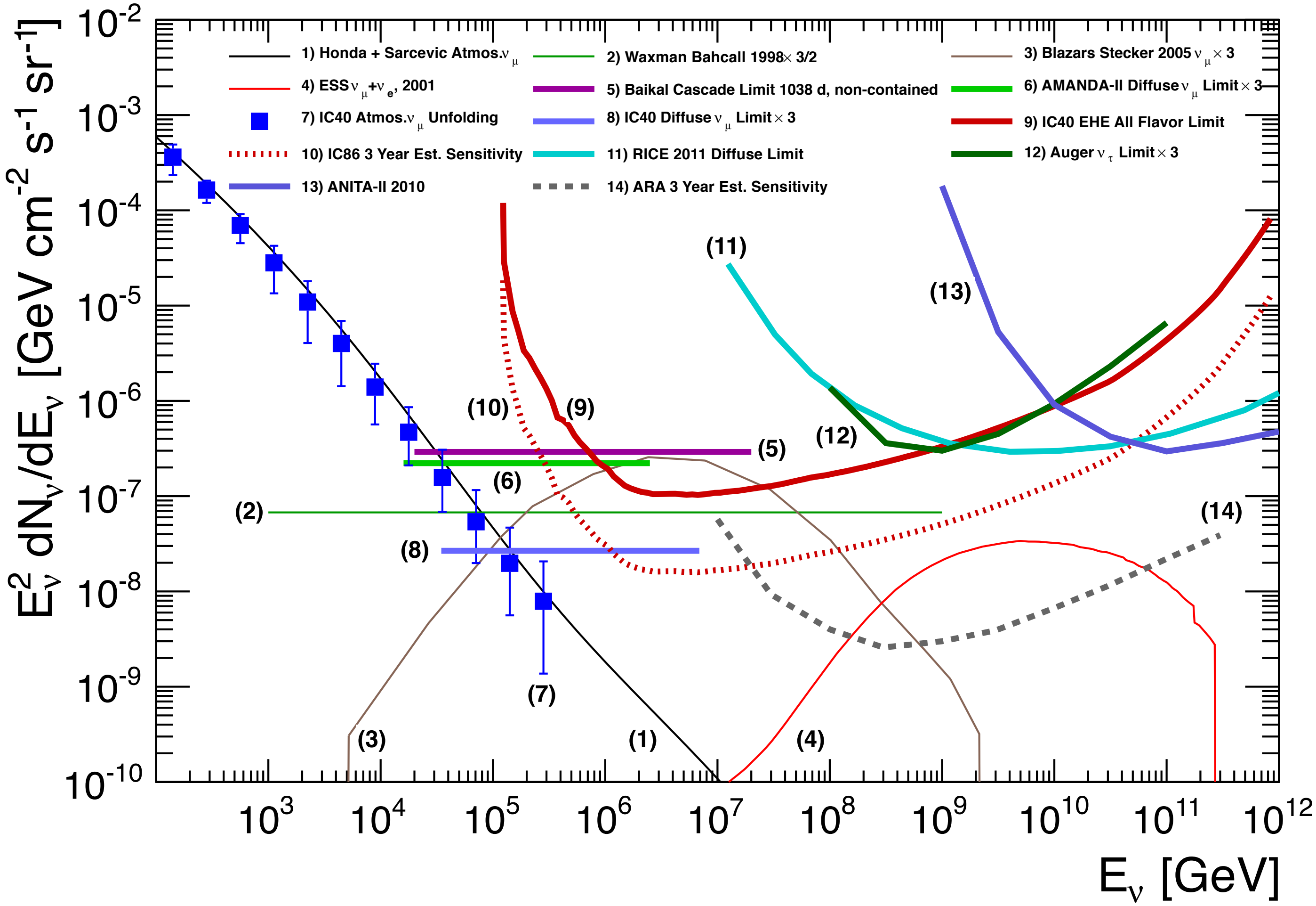


Radio detection in ice: Detection volume increases roughly linearly with energy!

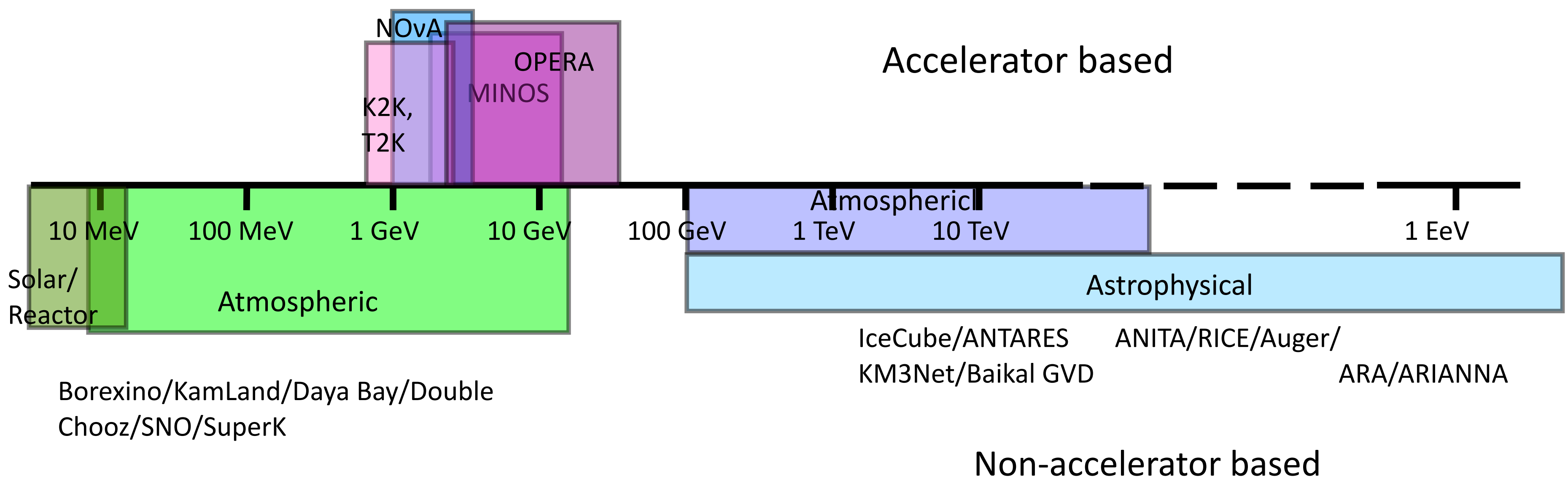
Diffuse fluxes



Notes:

Differential limits are shown as published, no corrections applied for bin size discrepancies

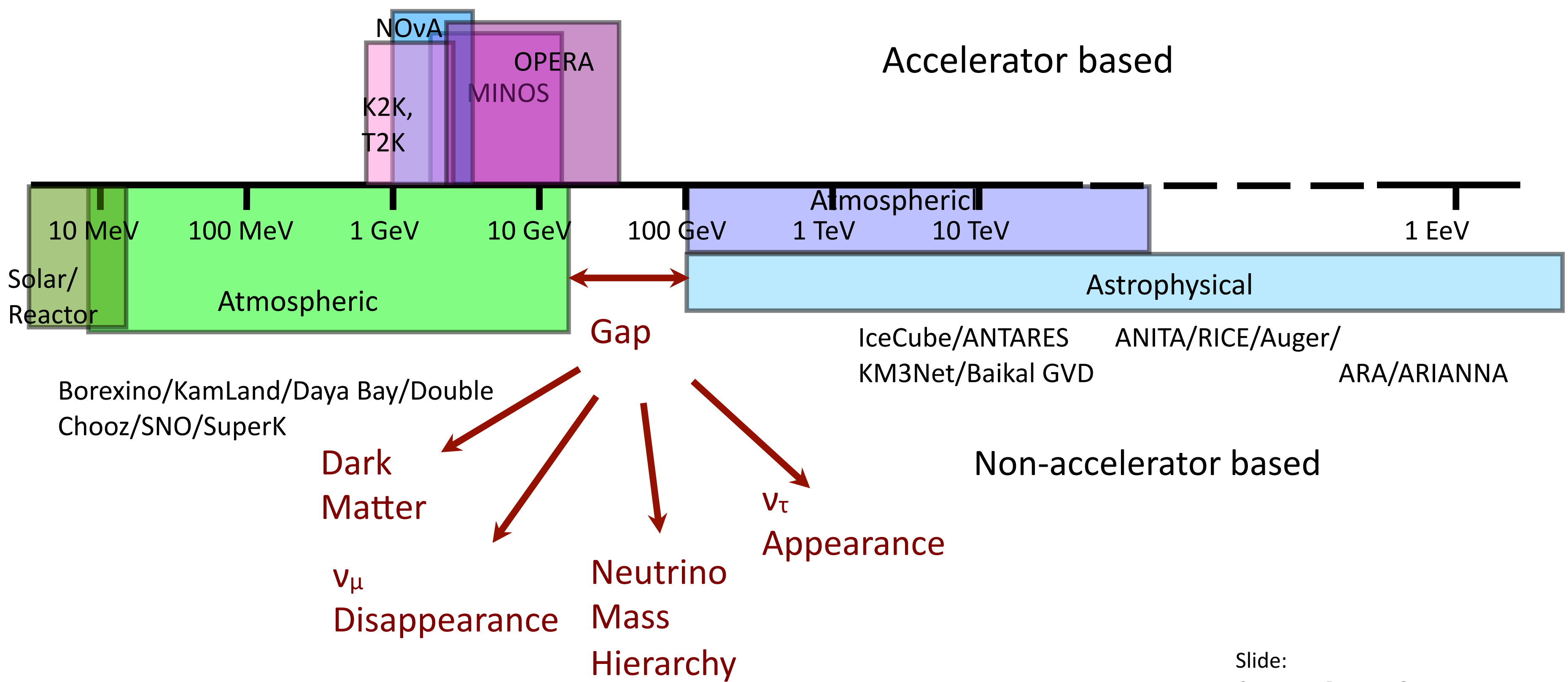
The Neutrino Detector Spectrum



Slide:
Courtesy Darren Grant
NNN 2011

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

The Neutrino Detector Spectrum



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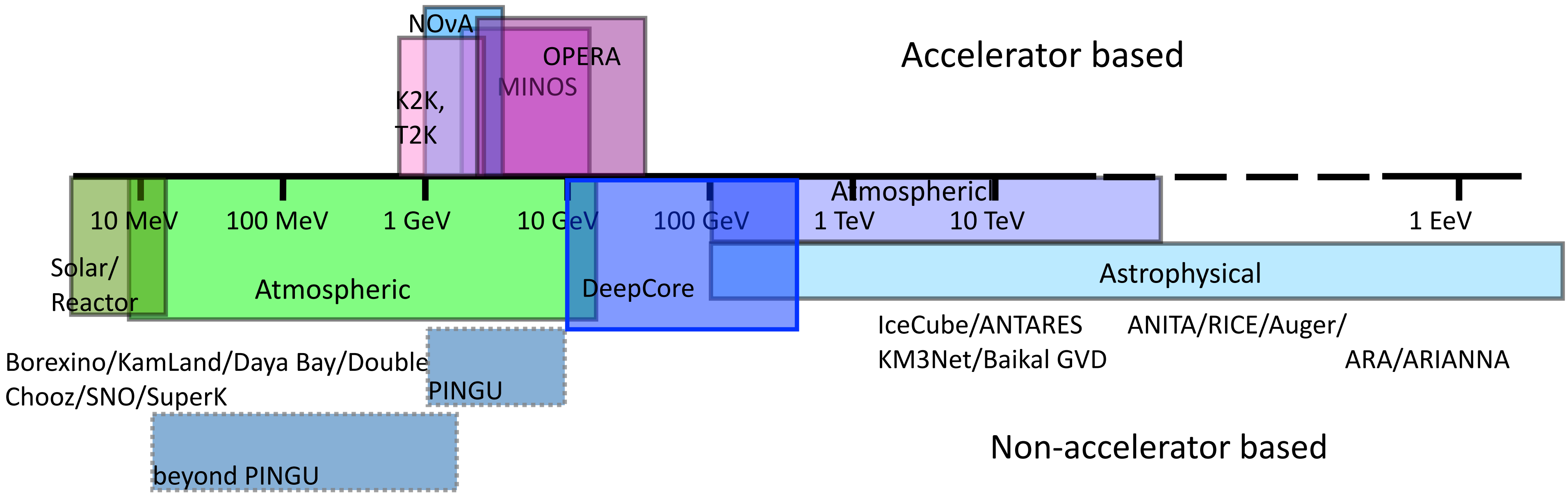


~70 active members in feasibility studies:

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)

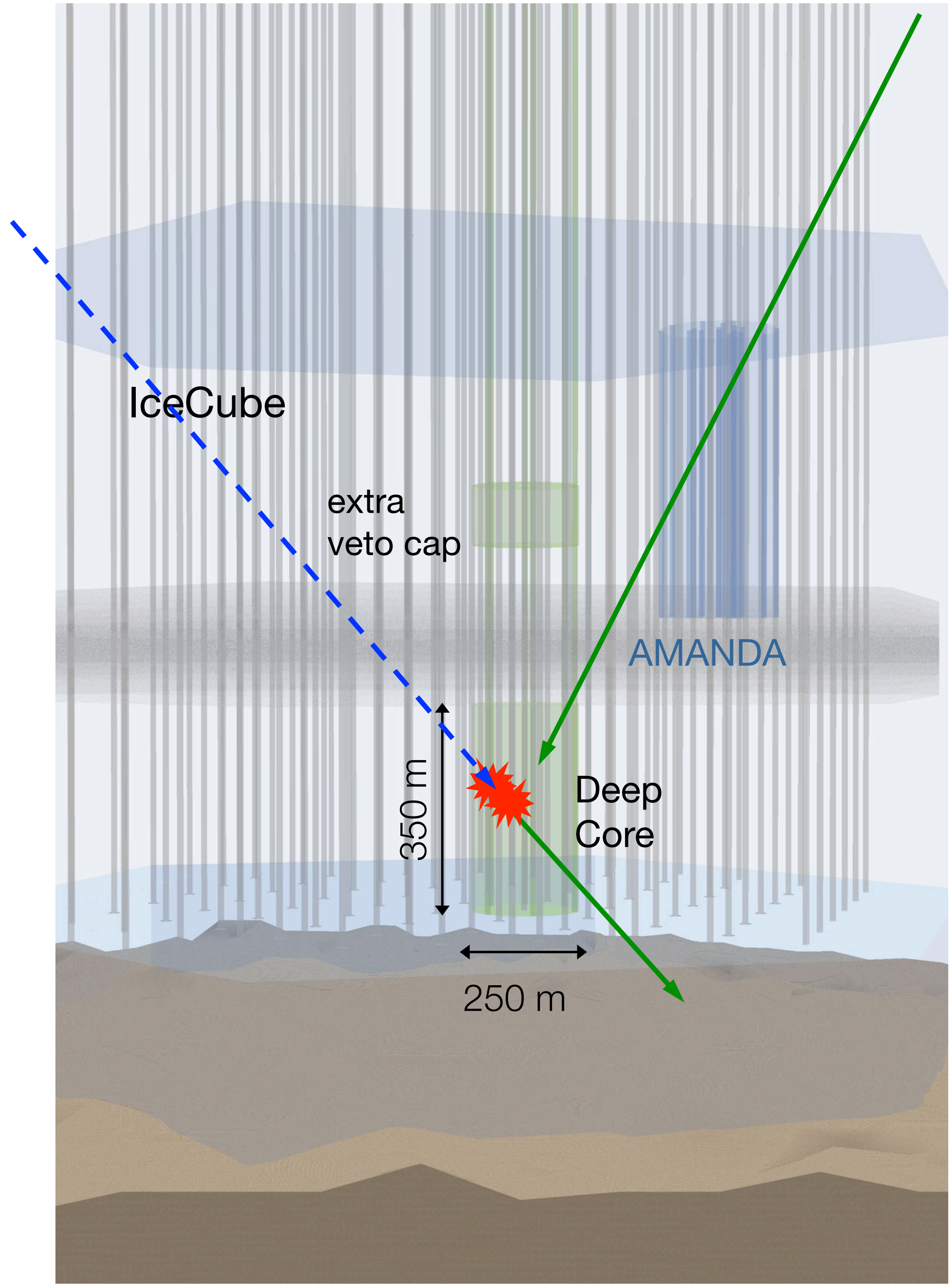
IceCube - DeepCore:

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 $\sim 10^6$
- Vetoing algorithms expected to reach well beyond 10^6 level of background rejection



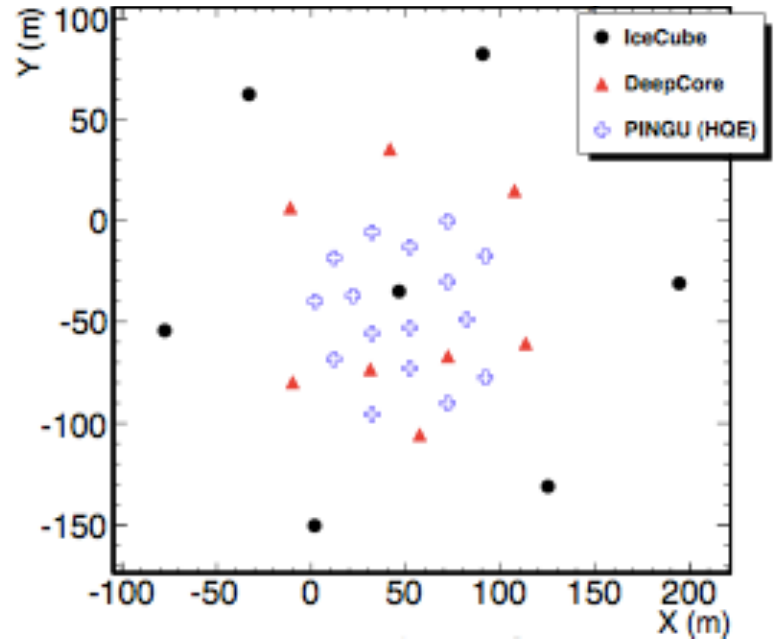
From Deep Core to PINGU
- Phased IceCube Next Generation Upgrade

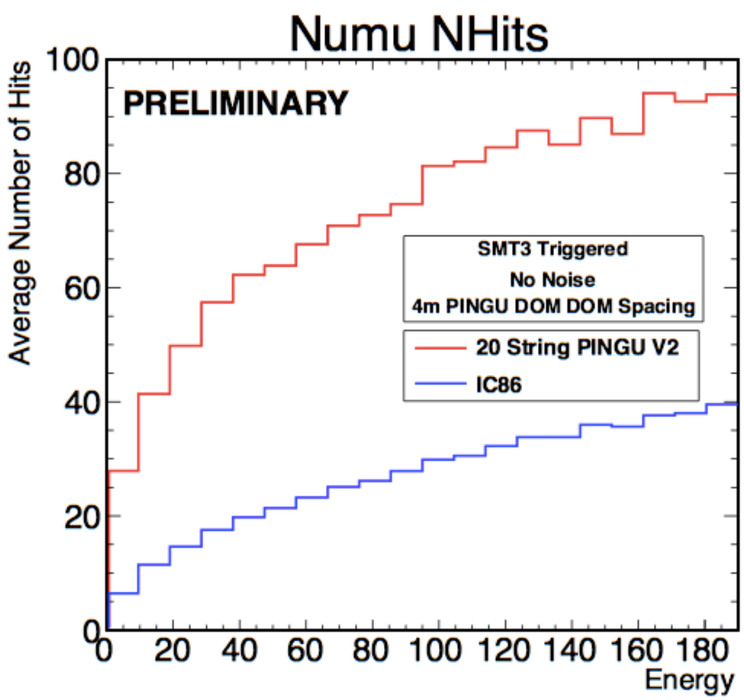
- A close look at neutrino events above ~10 GeV;
  event identification and reconstruction possible.
- Science goals:
  - improve WIMP search,
  - neutrino oscillation measurements,
  - other low energy physics, → e.g. mass hierarchy

PINGU

- Phased IceCube Next-Generation Upgrade
- Add 20 strings with ~1000 optical modules in
  Deep Core region (~400PMT)
- Expected energy threshold at 1 GeV
- R&D opportunity for future developments

PINGU geometry
(more compact version also studied)





	IceCube	w DeepCore	PINGU
String spacing [m]	125	75	25
PMT spacing	17	7	5.8
Instrumented mass [Mt]	1000	20	4
Total No of PMT	5160	500	1400
PMT/Mton	5	25	350

Simulated event in DeepCore and PINGU

DeepCore Only

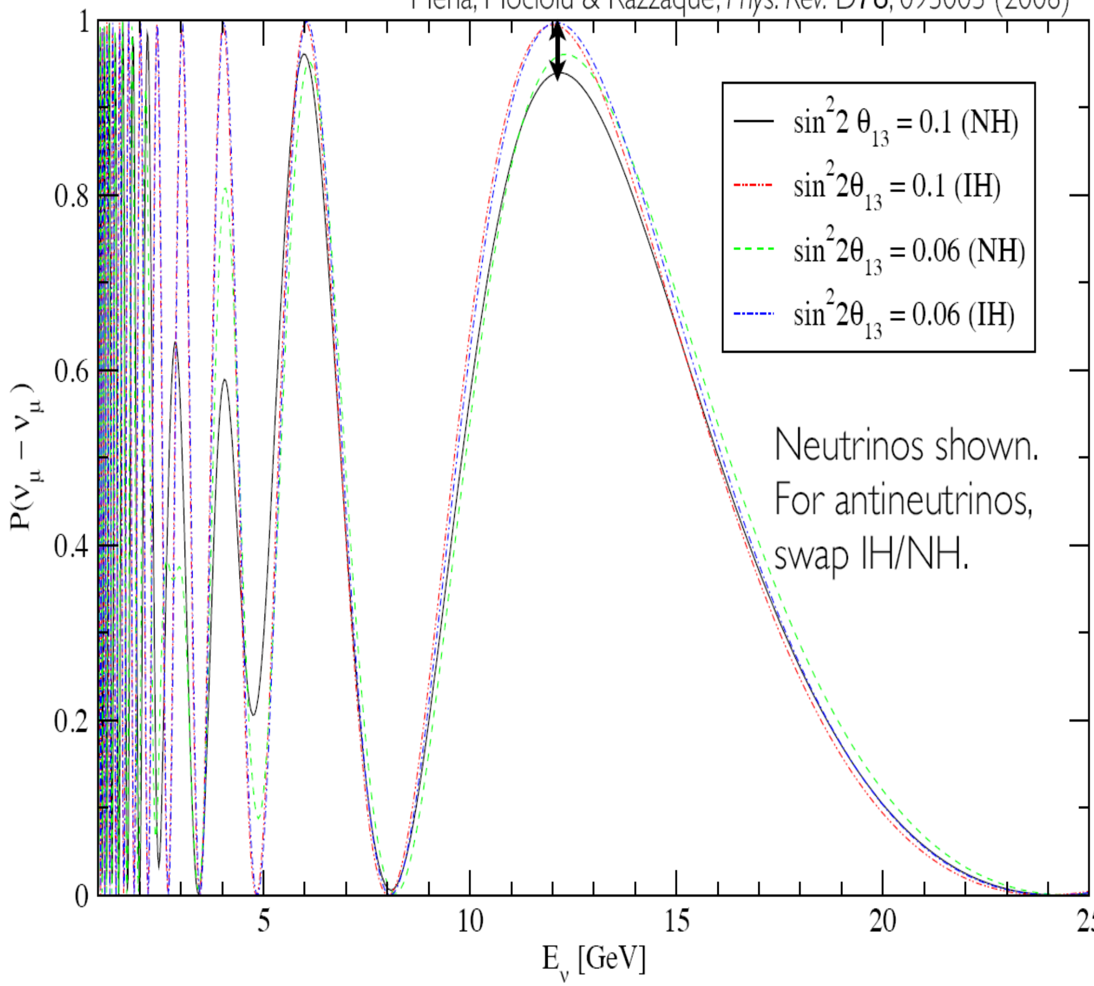
- 9.28 GeV Neutrino, 4.9 GeV muon, 4.5 GeV cascade
- Physics hits only, no noise

DeepCore + PINGU

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.)

Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)

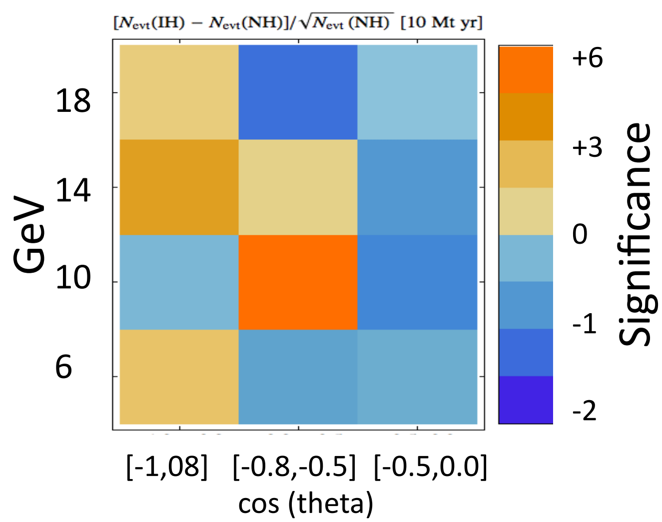


Mass hierarchy

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

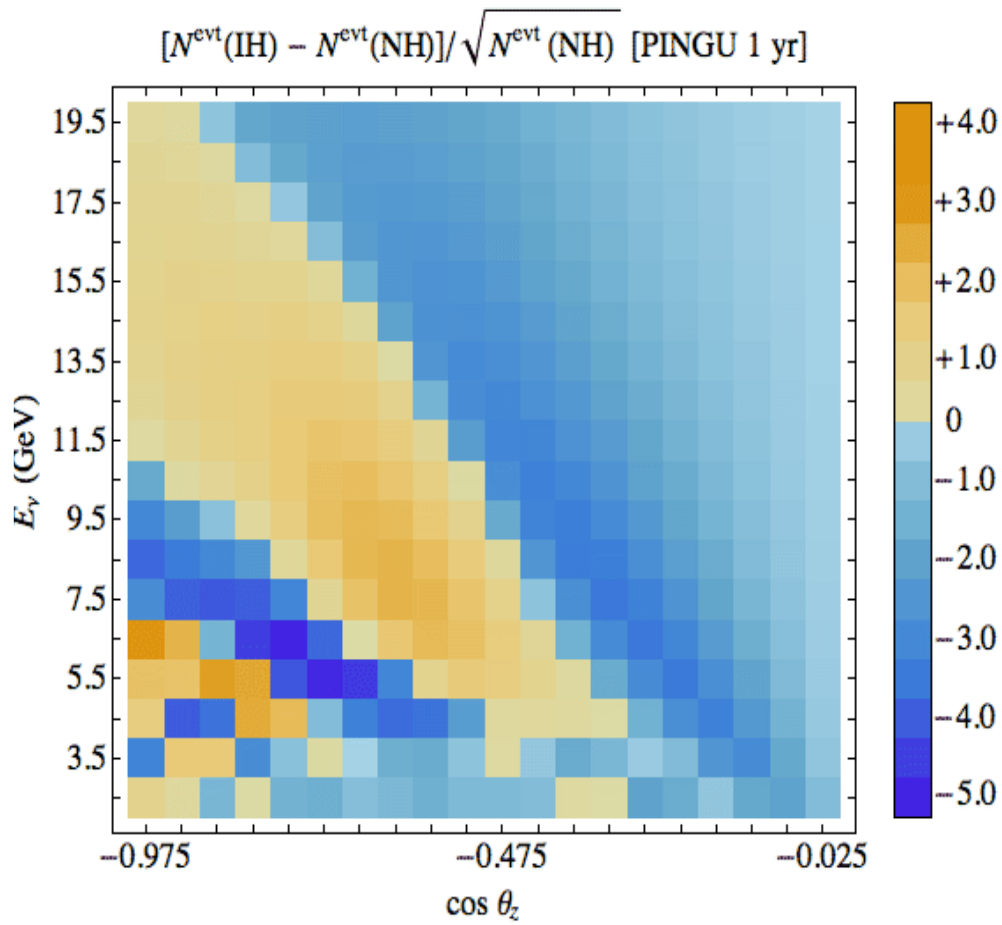


Assumed above:

Energy resolution: 4 GeV,

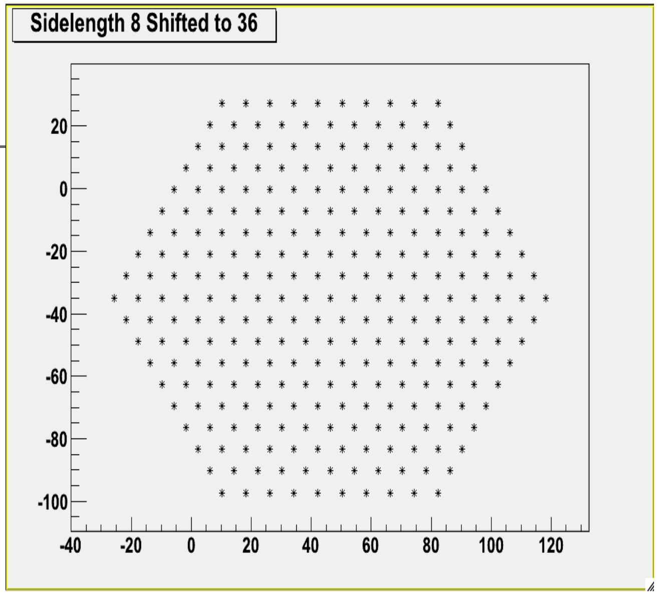
Angular resolution: 0.3 in cos(theta)

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."

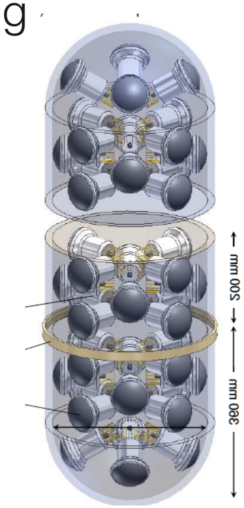
beyond PINGU Conceptual Detector

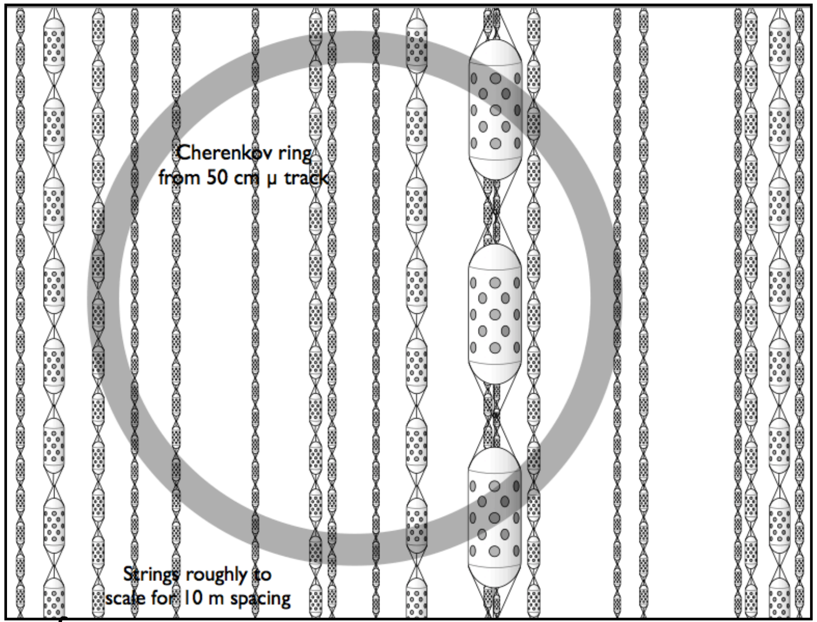


- O(few hundred) strings of detectors within DeepCore fiducial volume
- Goals: ~5 MTon scale with energy sensitivity of:
  - O(10 MeV) for bursts
  - O(100 MeV) for single events
- Physics extraction from Cherenkov ring imaging in the ice

Exploration of possibilities for:

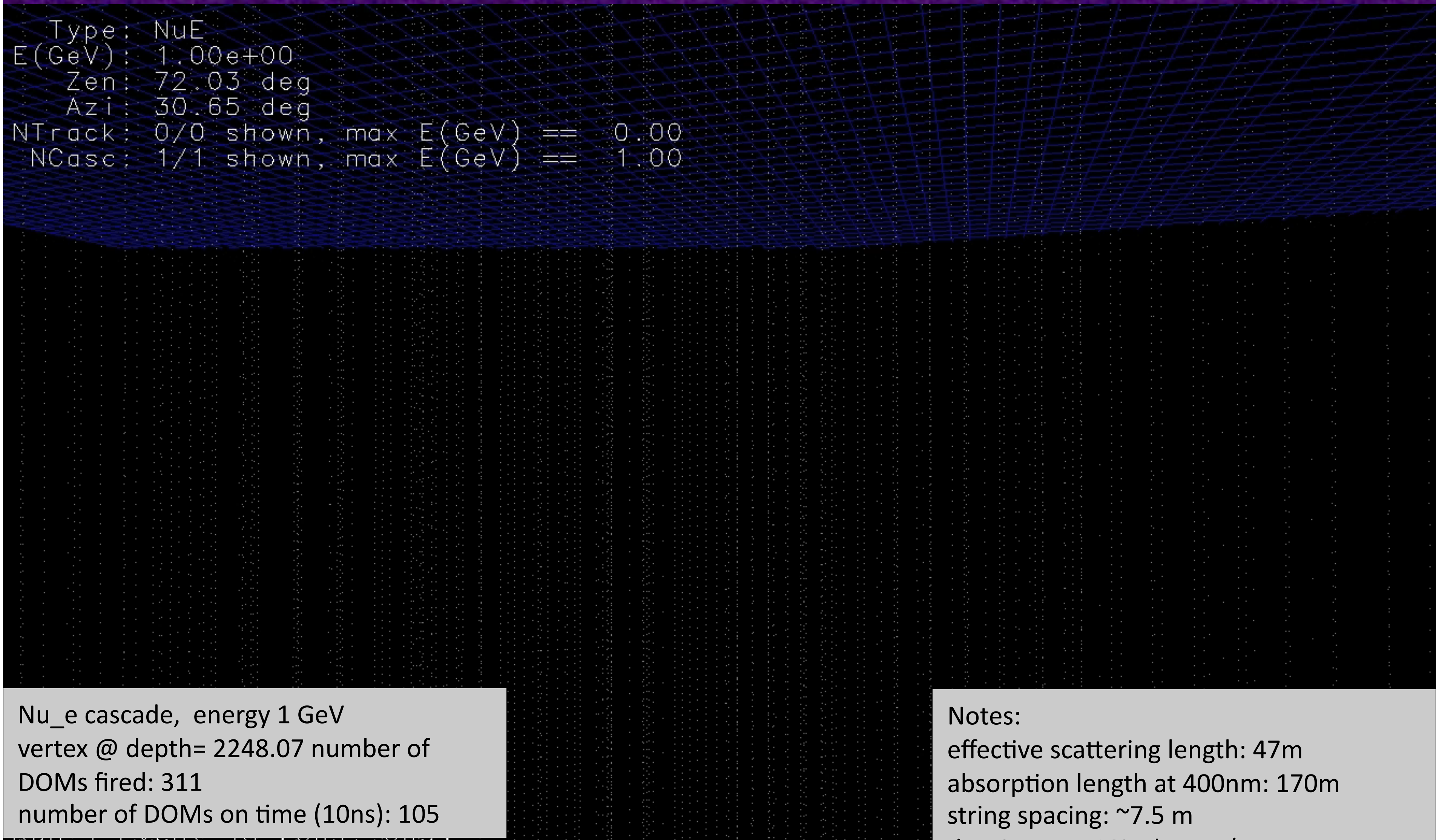
- Proton decay p -> $\pi^0 + e^+$
- Supernova to 5 Mpc





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

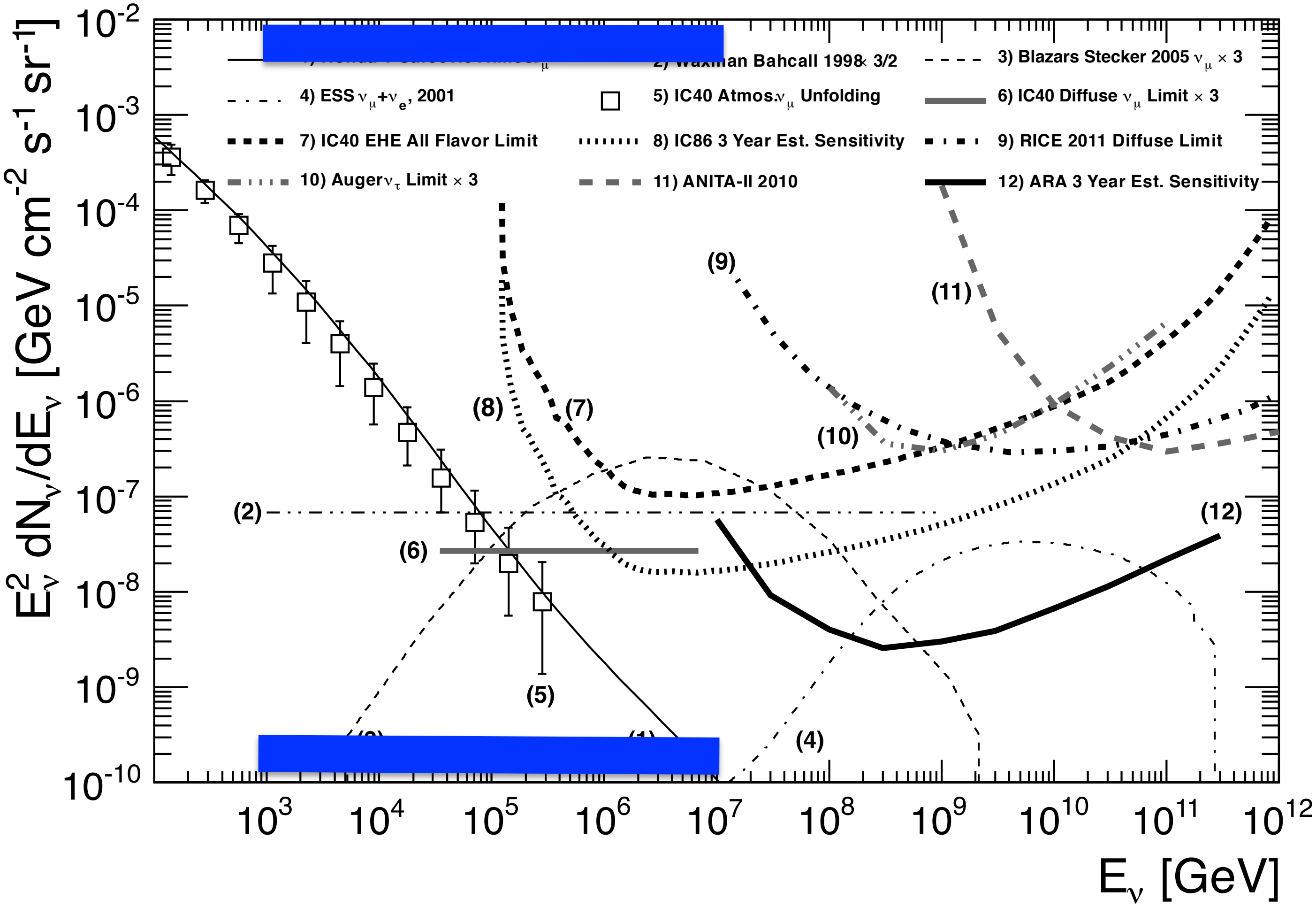
Simulated event, 1 GeV in 230 string dense array



Nu_e cascade, energy 1 GeV
vertex @ depth= 2248.07 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

TeV to 10 PeV energy scale



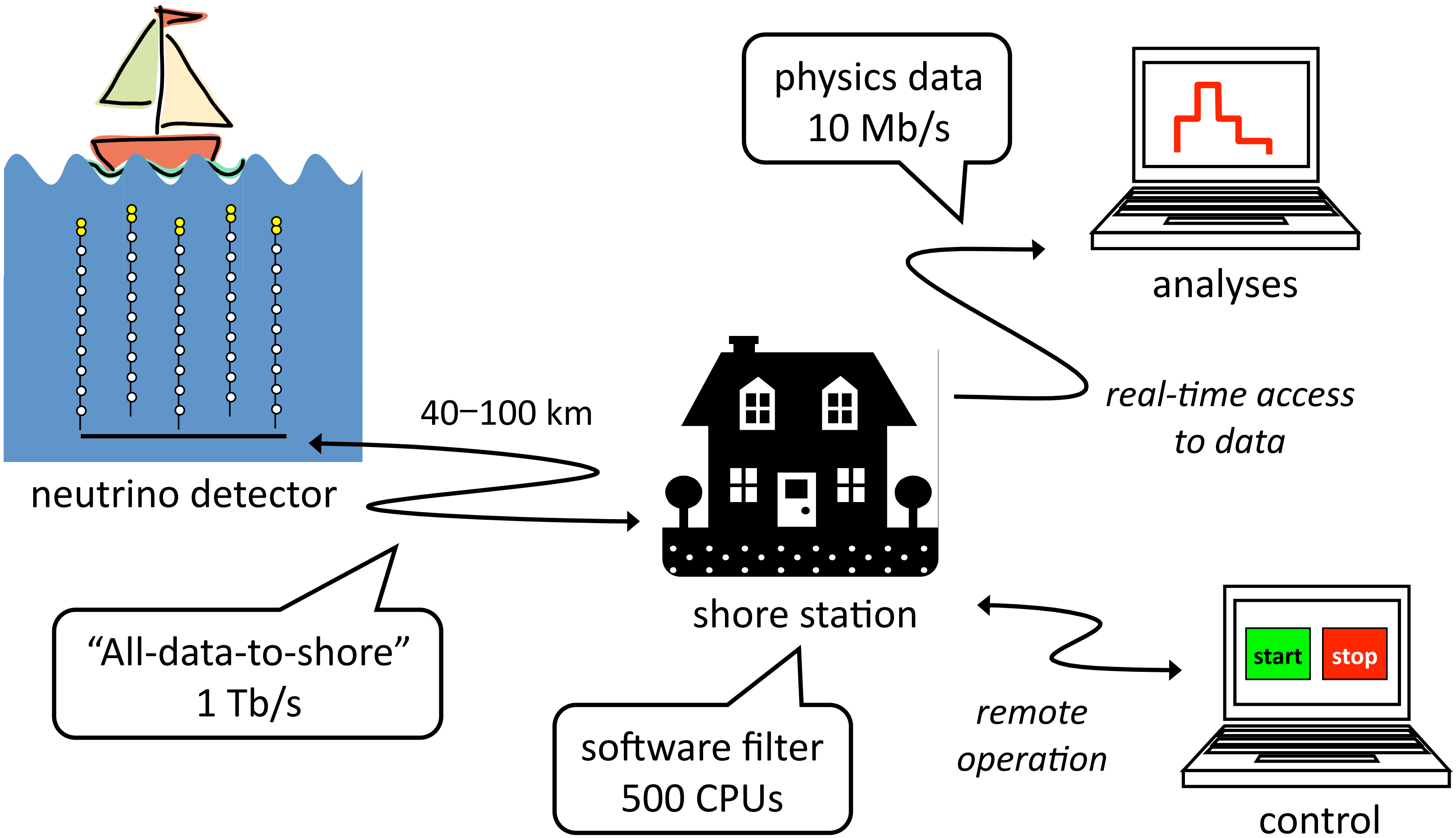
KM3Net - The next generation neutrino telescope in the Mediterranean

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 on 610 strings
  - Large effective neutrino area

Architecture



Multi-PMT optical module

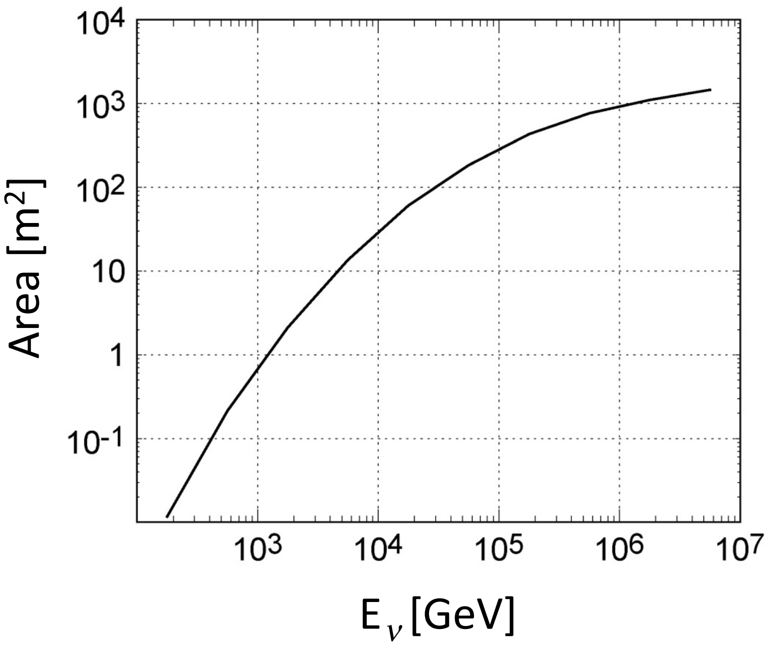
– 31 x 3” PMTs
  - larger than 3 x 10” PMTs
  - Cathode area:
– low power HV circuit
  - 10 mW / PMT
– calibration
  - LED and piezo inside glass sphere
– FPGA readout
  - sub-ns time stamping
– fibre-optic modulator
  - no lasers off-shore

(Hamamatsu R7081-2 10”) spec: 550cm^2)

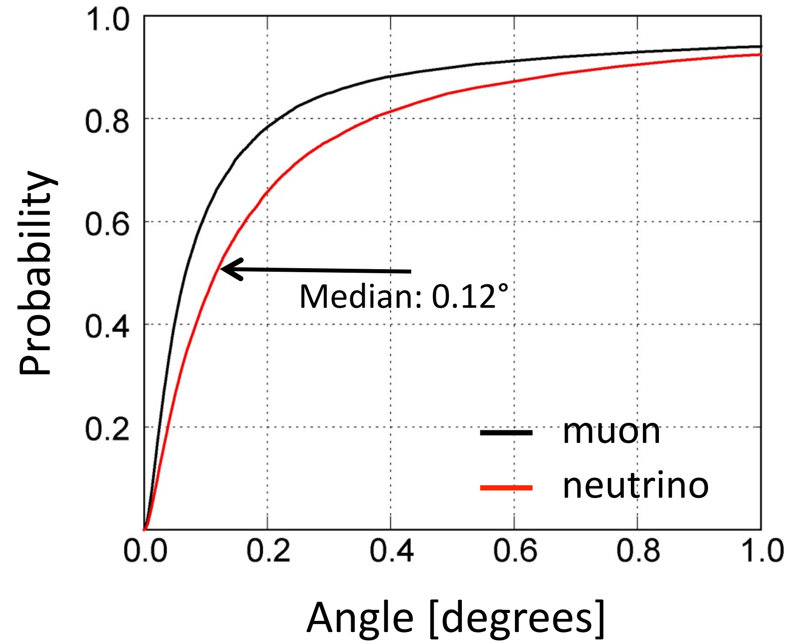
← 17 inch →

Performance

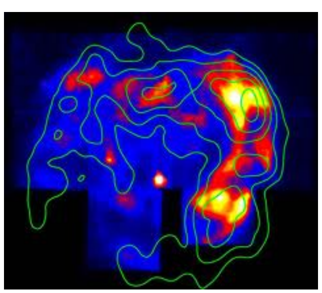
Effective neutrino area



Angular resolution



RXJ 1713

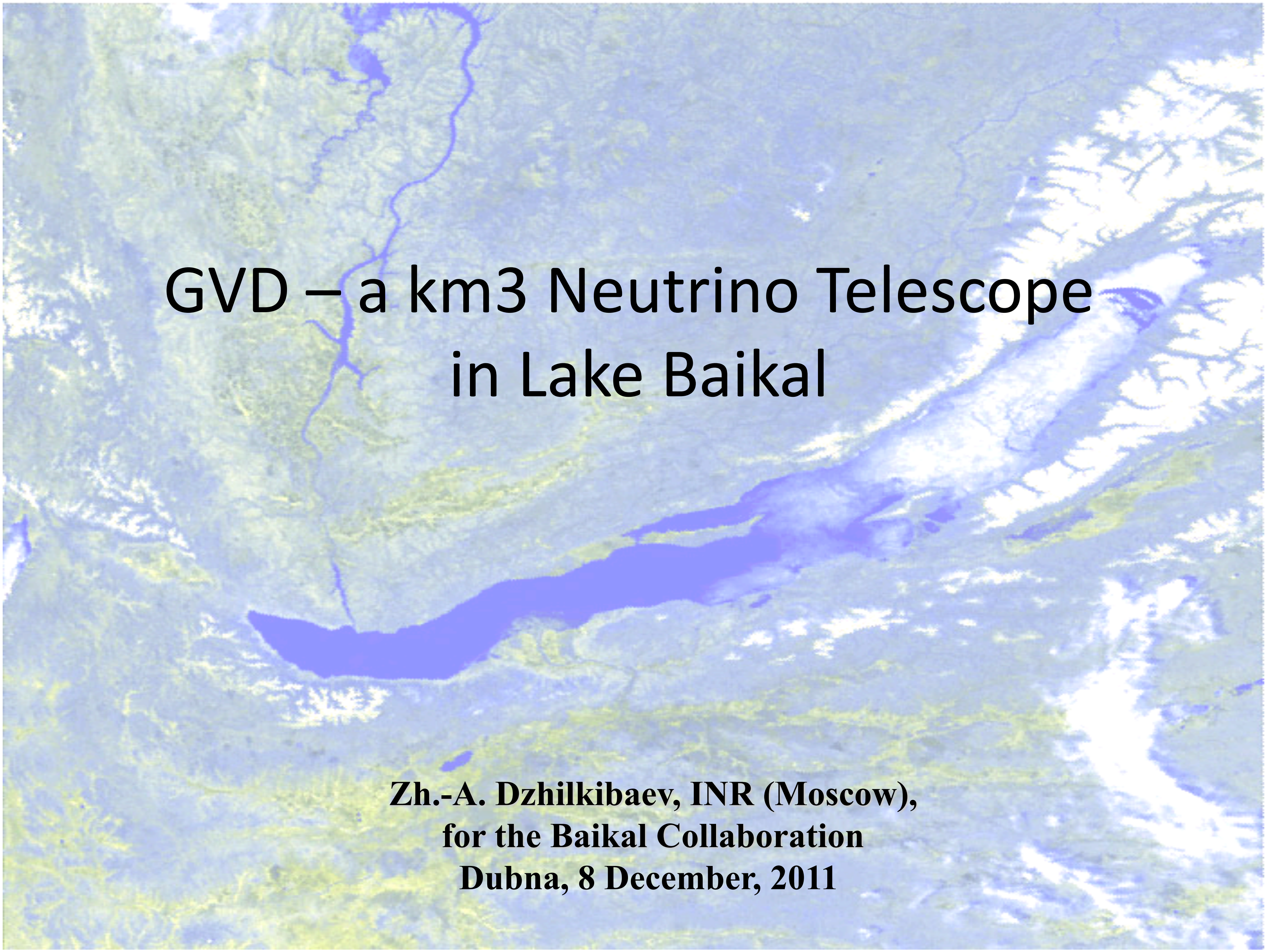


– Supernova remnants as "*origin of cosmic rays*"

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

KM3Net Summary and Status

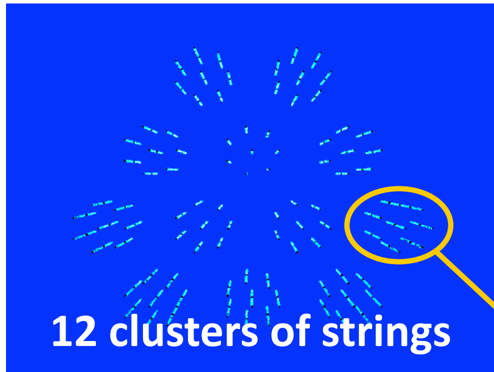
- Science case
  - discovery potential for Galactic sources
  - provides for independent observation of a possible discovery by IceCube with improved significance within reasonable amount of time
  - continuous and long-term measurements in the areas of oceanography, geophysics and marine biological 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

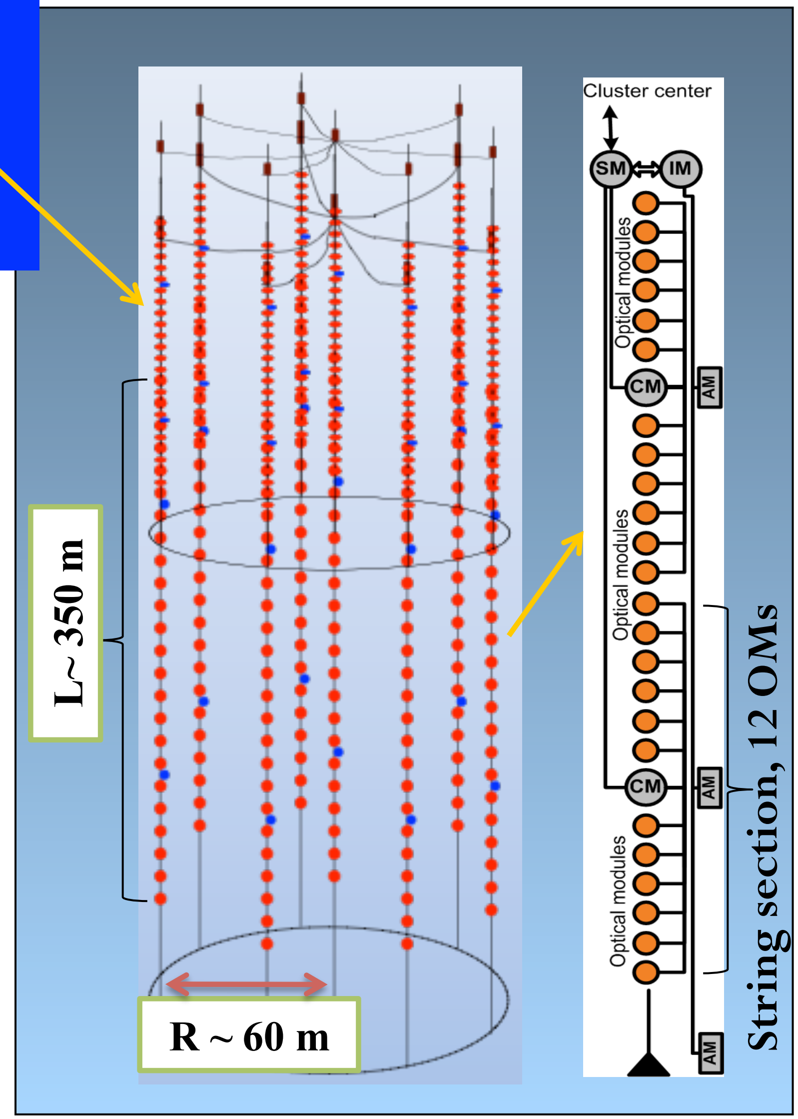
Zh.-A. Dzhilkibaev, INR (Moscow),
for the Baikal Collaboration
Dubna, 8 December, 2011

BAIKAL-GVD (minimal configuration)



Layout

96 Strings × 24 OM
String: 2 Sections × 12 OM
Clusters ⊠ 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 trigger: coincidences of nearby OMs (threshold 0.5&3 p.e.). Software selection: muons – 6 triggered channels at 3 strings; cascades – 4 channels at 3 strings.

Effective cascade volume (E > 50 TeV):

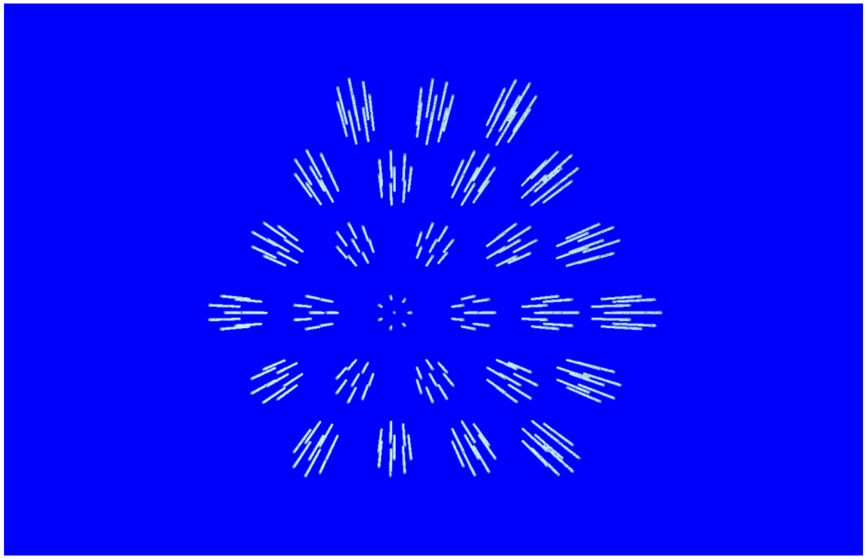
V_{eff}~0.3–0.7 km^3 , δ(lgE) ~0.1, ⊠θ_{med}~ 5^o

Effective muon area (E >3 TeV):

S_{eff} ~ 0.2 – 0.8 km^2, ⊠θ_{med} < 0.5^o

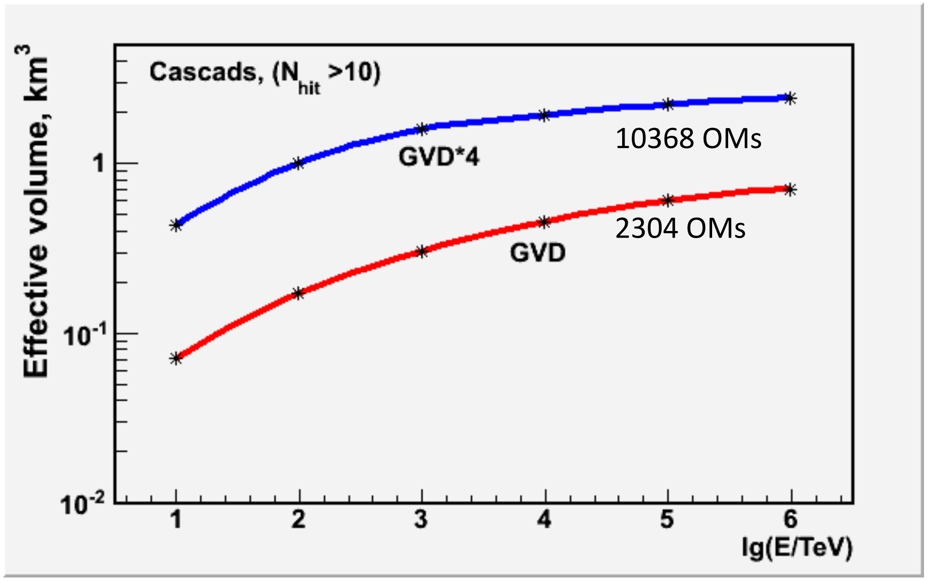
GVD*4

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

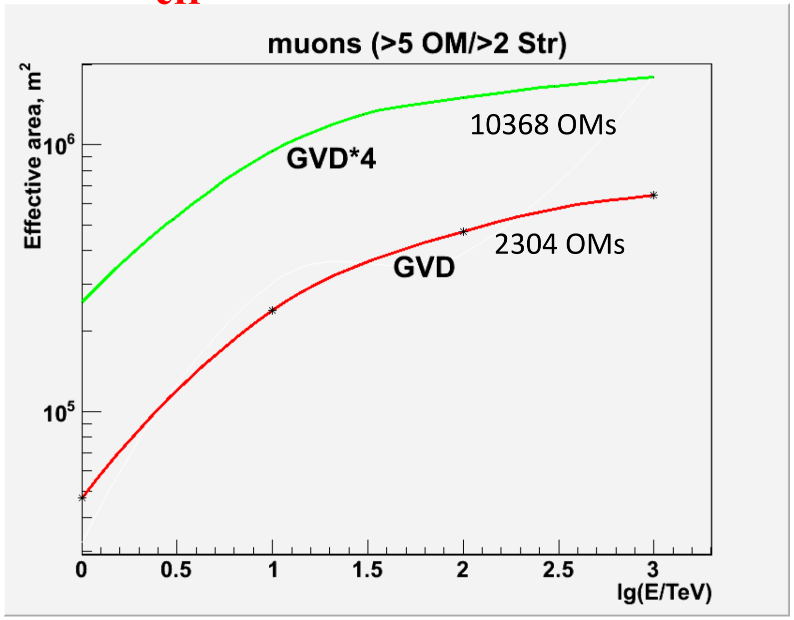


10368 Optical Modules,
216 Strings: 48 OM/Str, 3 Sec./Str
27 Clusters.: 8 Str/Cluster

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



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



The cosmic energy frontier: Cosmogenic, *GZK* neutrinos

- Need detection rates such that the the normalization of the GZK neutrino flux can be reliably determined.
- That 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

Future experimental goals

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

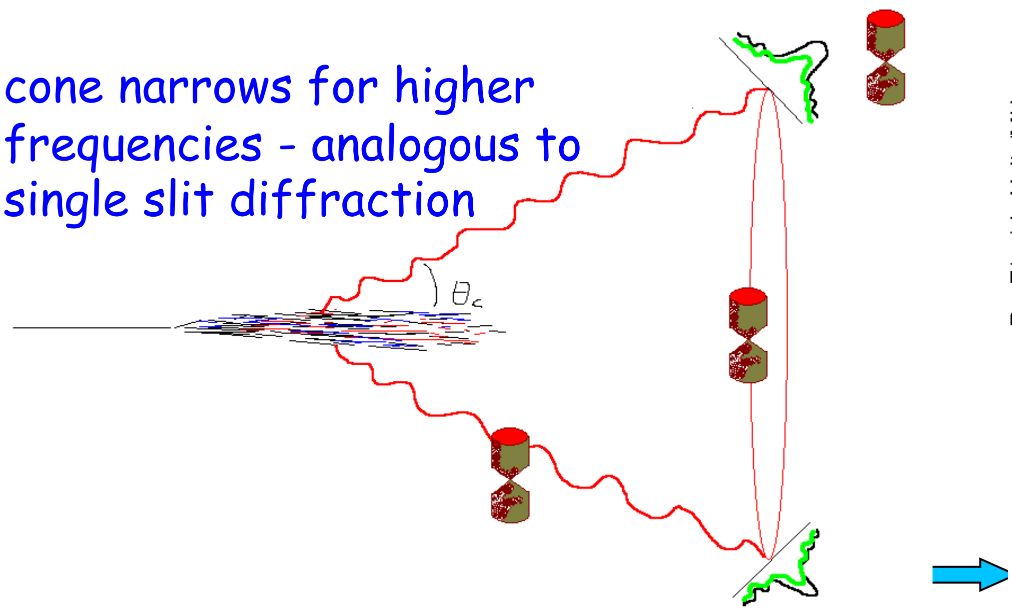
Detection principle:
Coherent radio emission from e.m. cascade

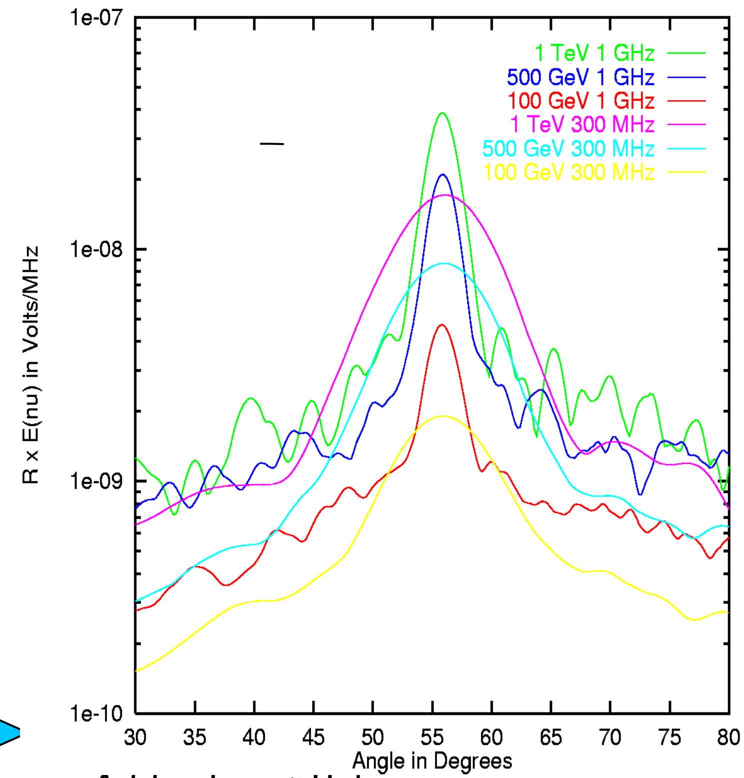
Gurgen Askaryan, 1960ies

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

→ coherent radio emission from c > c_medium moving charge

cone narrows for higher frequencies - analogous to single slit diffraction



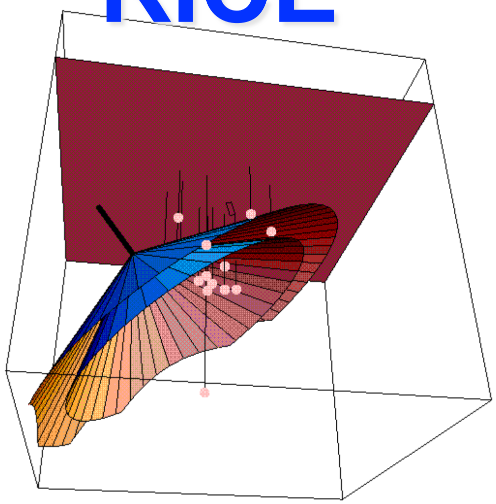


Add coherently!

Existing and previous instruments using radio in Polar ice

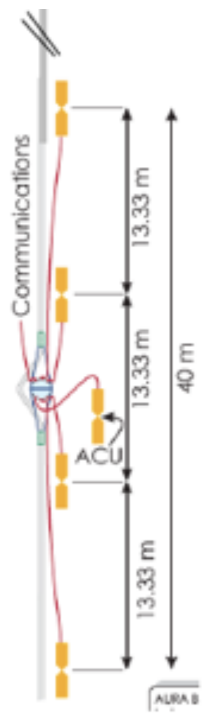
Experiences for ARA, Collaborators from all three experiments joined ARA

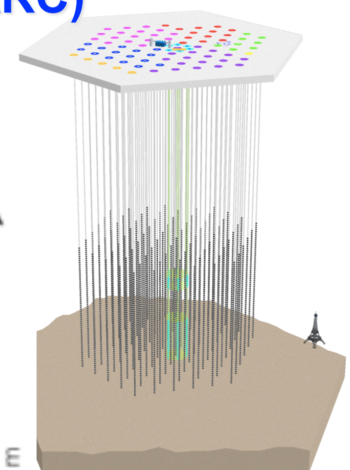
RICE



- 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 instruments In IceCube (AURA, NARC)



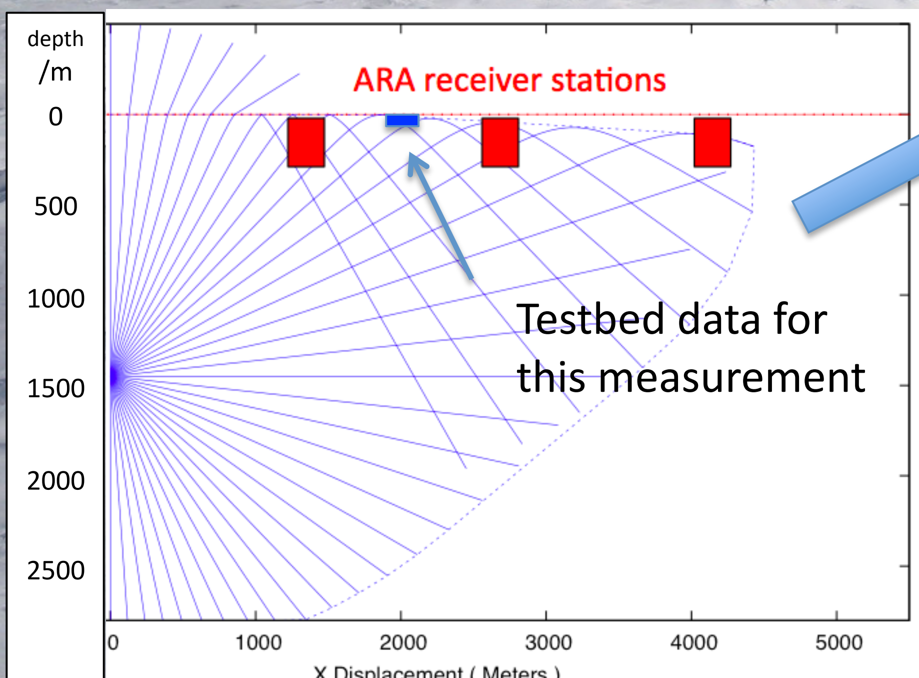


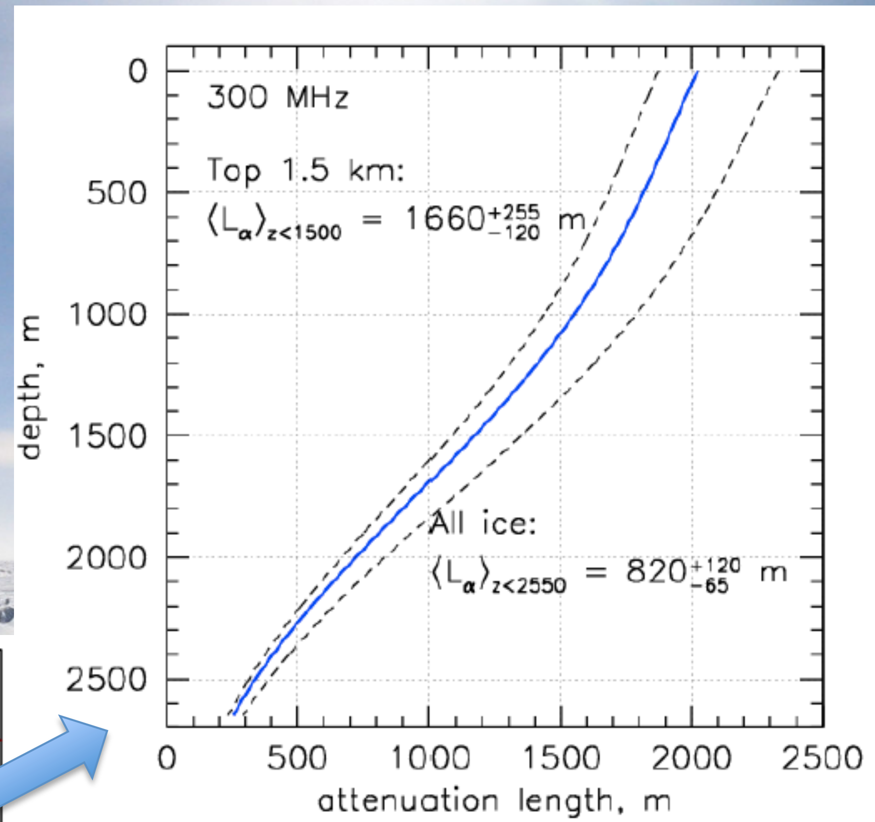
ANITA

- balloon payload of horn antennas
- surveys the ice cap from high altitude for RF refracted out of the ice

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: ~ 1.5km at depths < 1500m.
  - → Slightly better than expected
- Very low electromagnetic noise





Askaryan Radio Array (ARA)
- a very large large radio neutrino detector at the South Pole

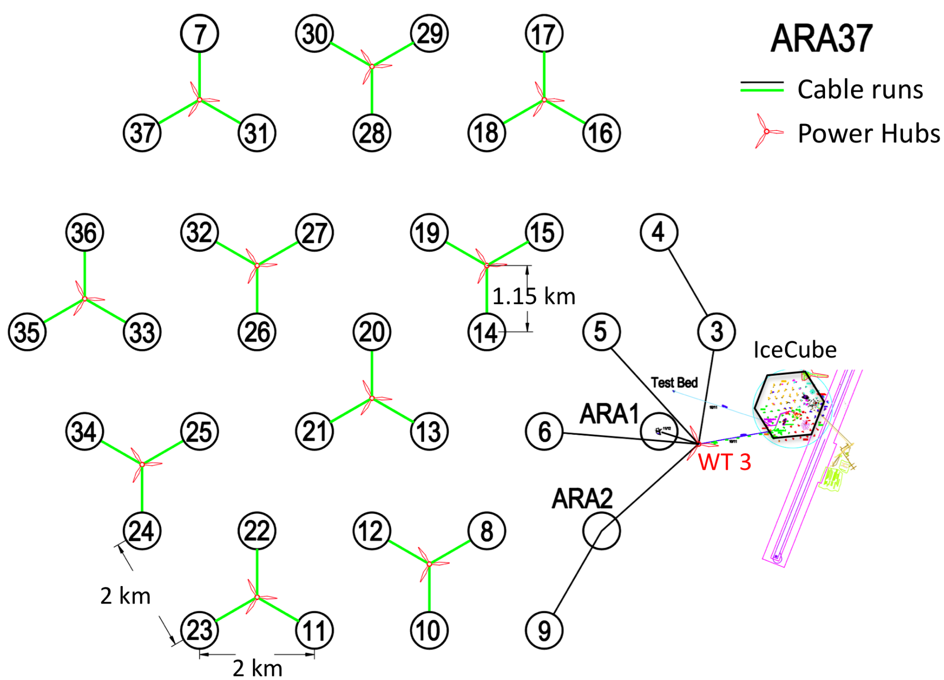
Poster session at this conference:
→ H. Landsman, ARA Design and Status
→ J. Davies, ARA prototype and first station

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:

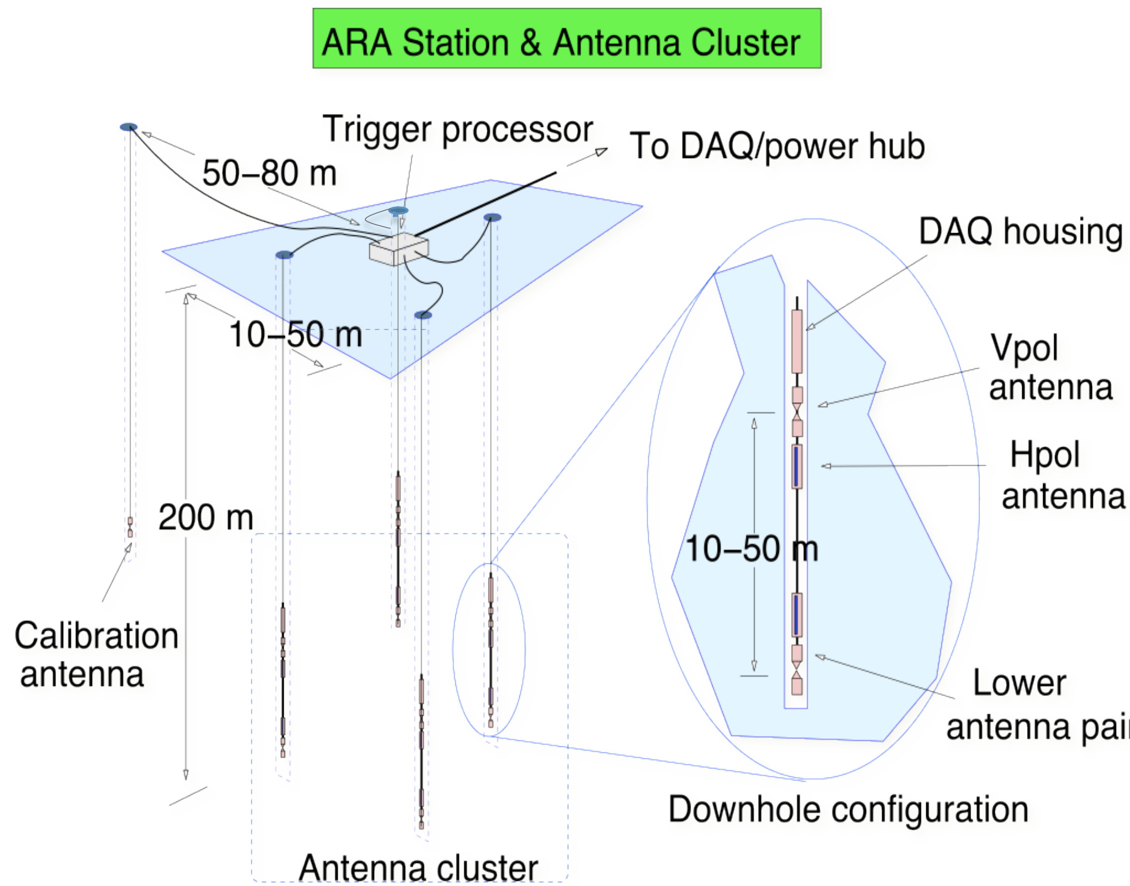
- Every station is a fully functioning detector.

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

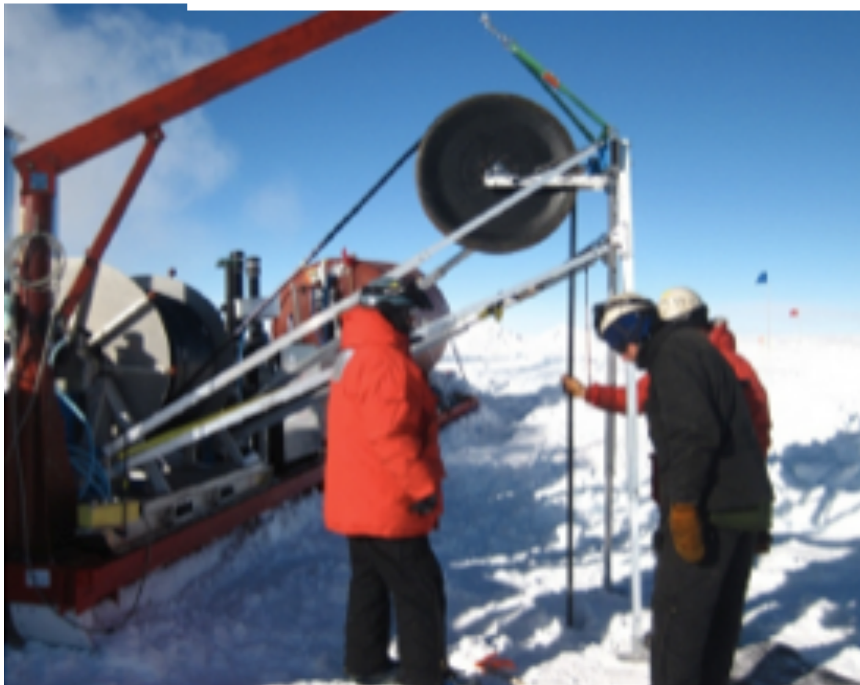
Background rejection:

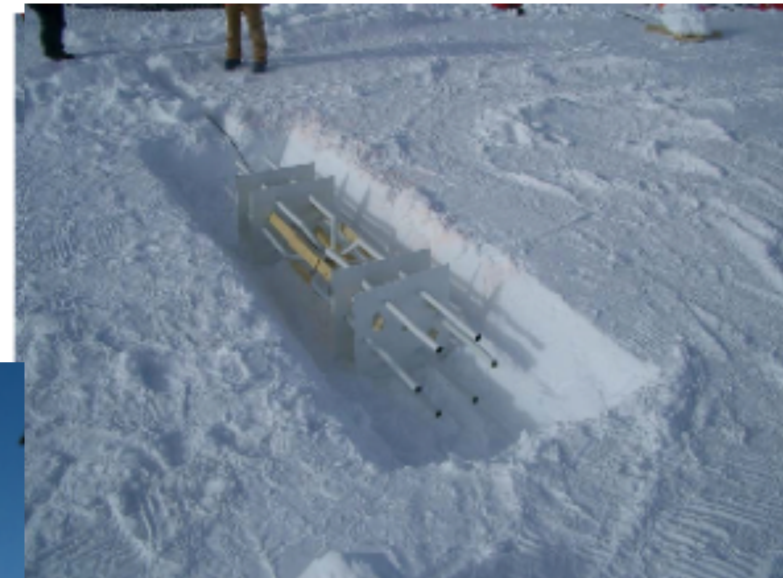
→ Embedded strings: Allow good vertex resolution and high vertical resolution for background rejection

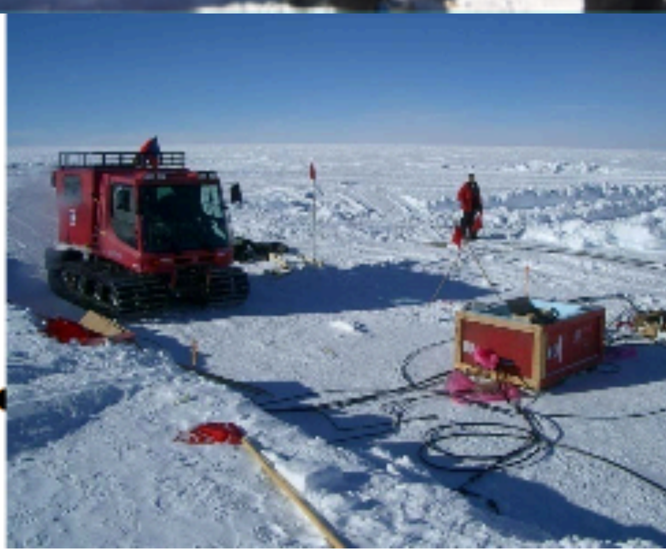
→ Depth at 200m: below firn, Increase acceptance (factor 1.5 compared to 100m).



ARA field activities on the ice

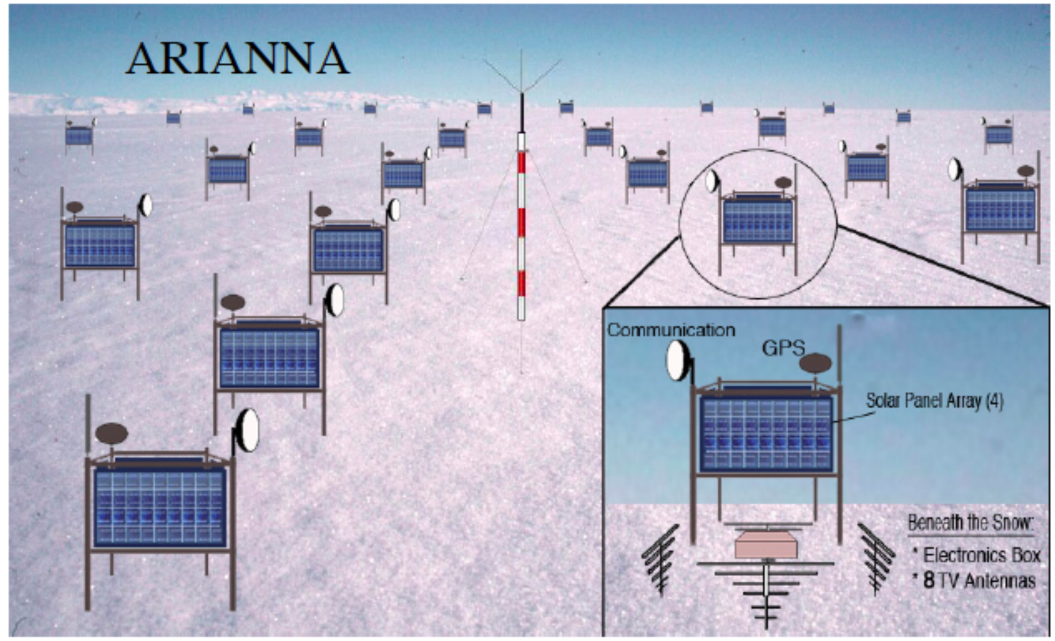






ARIANNA

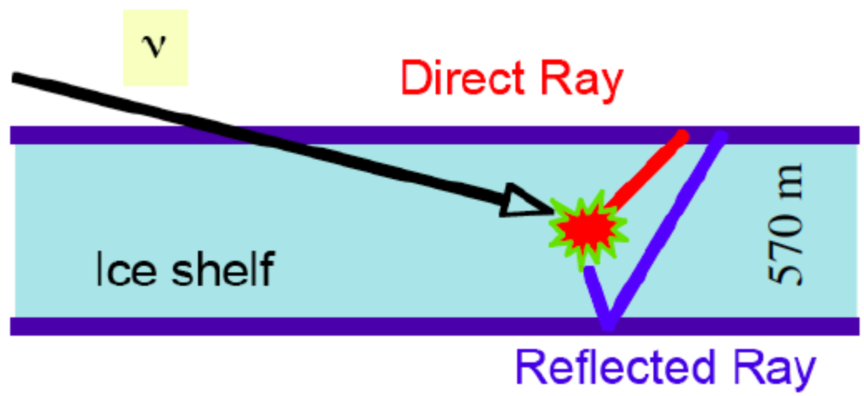
31 x 31 array
[30 km x 30 km]



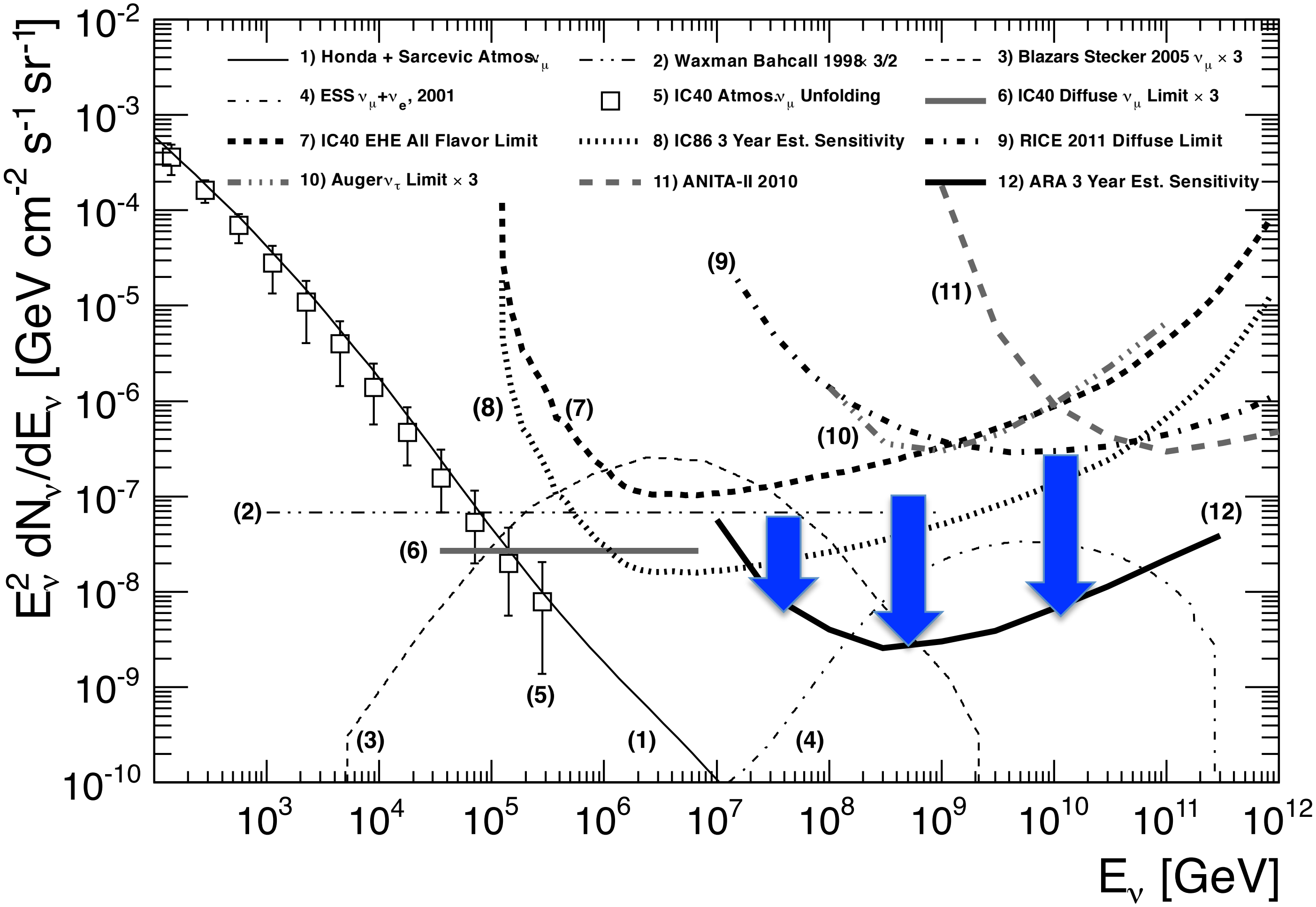
ARIANNA

US, S. Korea, England,
New Zealand

Barwick, astro-ph/0610631



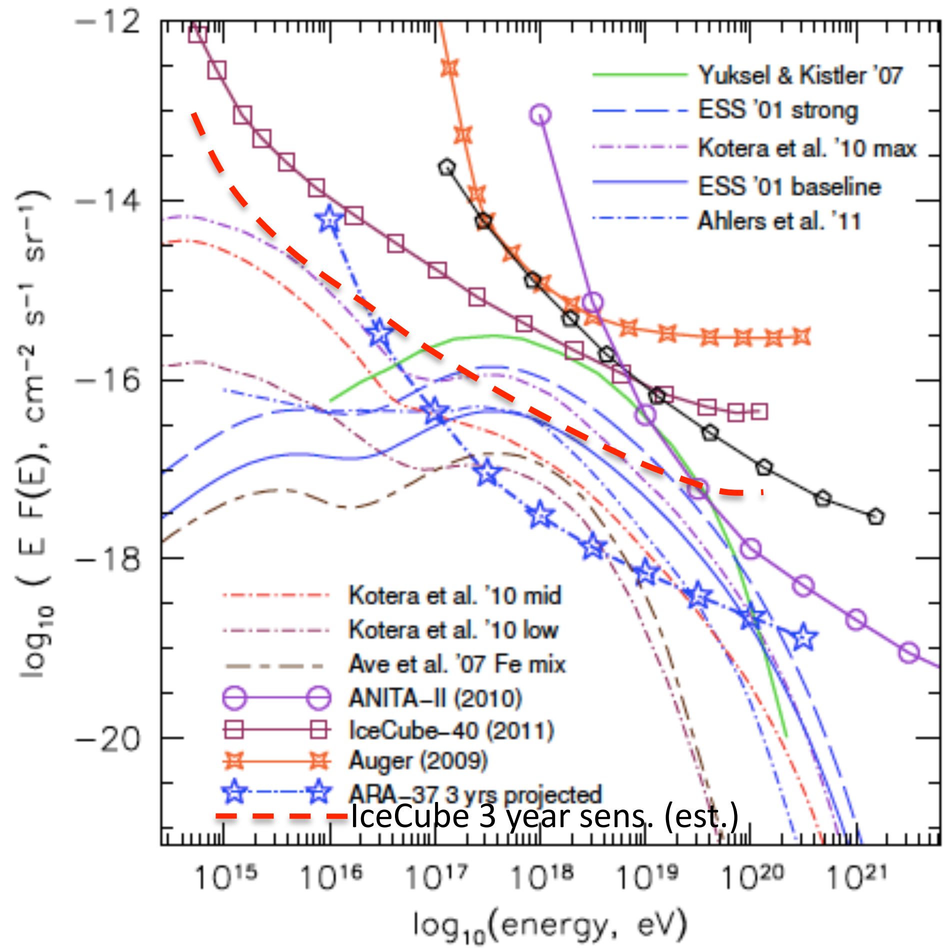
10^16 – 10^20 eV energy scale



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!



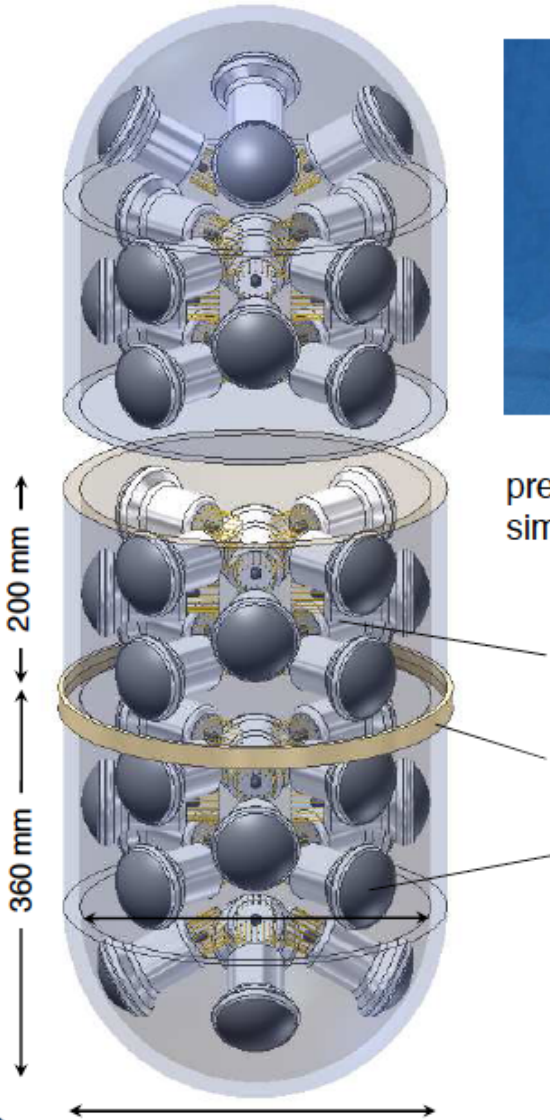
Summary

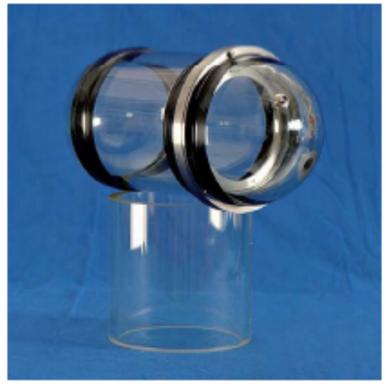
- Big quantum leap in sensitivity with the realization of IceCube.
- Future detectors on three energy scales with different science goals
  - GeV energies: PINGU precision atmospheric neutrino physics with multi Mton target
  - TeV to PeV energies: Projects with goals to expand sensitivity overall and especially towards Southern hemisphere, eg Galactic Center
  - 100 PeV to 100 EeV: Radio Cherenkov neutrino detectors using Antarctic Ice are inprototype/ 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.
    - Very realistic chance to clarify cosmogenic neutrino flux level.

Acknowledgments

- Thanks to
  - M. DeJong, U. Katz, S. Barwick, Ch. Spiering, D. Grant, J. Koskinen, C. Kopper, D. Chirkin, Ch. Weaver, and many of my IceCube and ARA collaborators for useful discussions and materials.

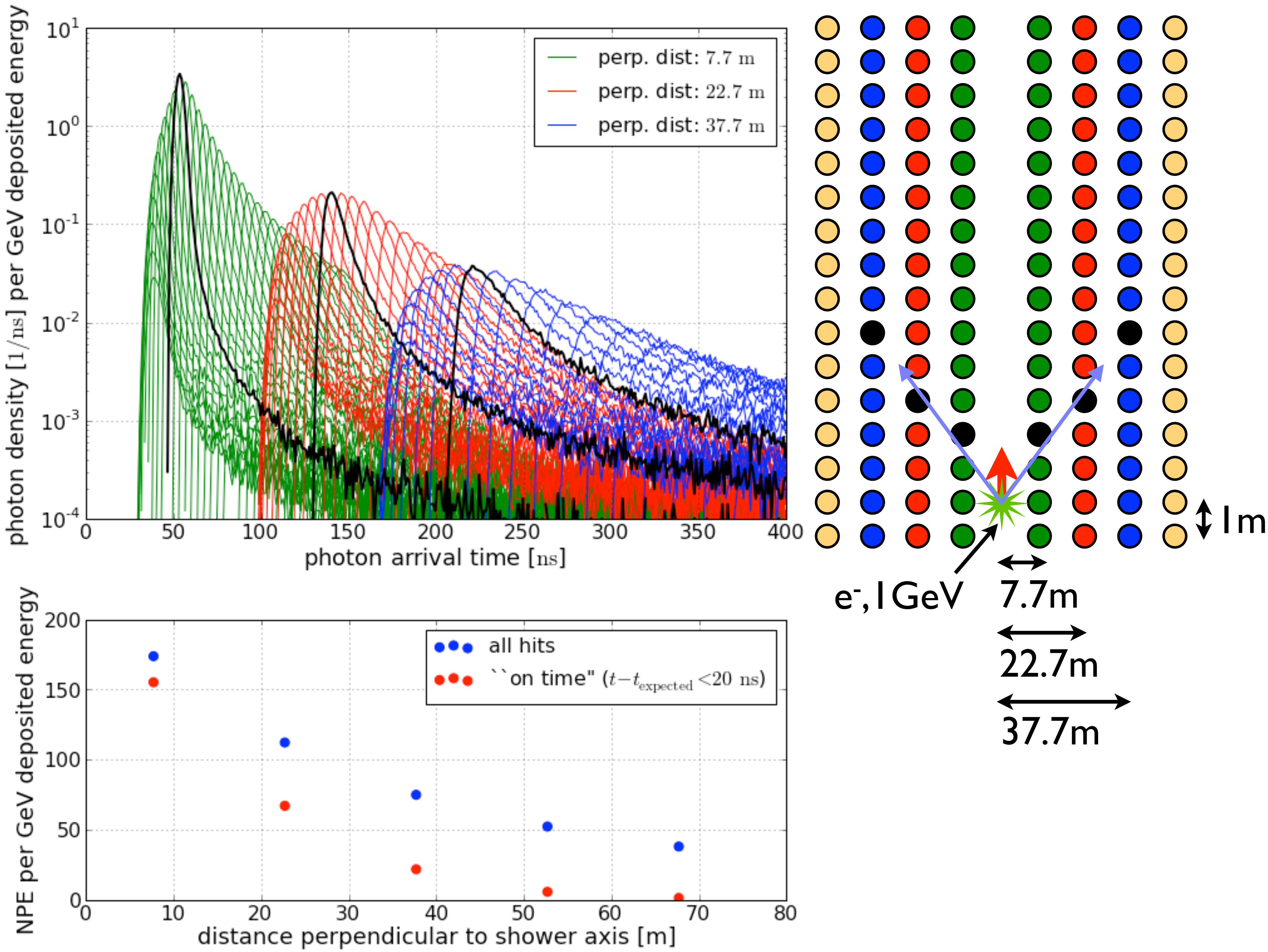
currently considered layout of PINGU/MICA
multi-PMT optical module (44 × 3-inch PMT)





pressure vessel by Nautilus,
similar to planned layout

available 3-inch PMT prototypes,
presently tested by ECAP & NIKHEF


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