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A Vision for a wide dynamic range neutrino observatory which builds on the IceCube experience

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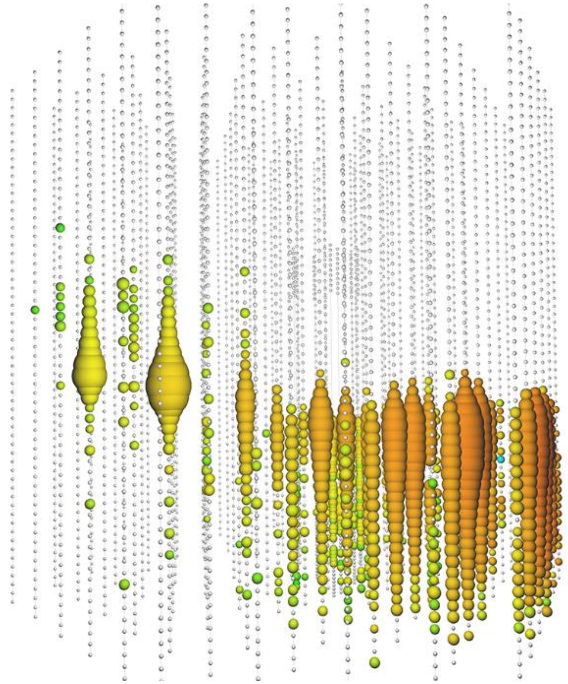
IceCube Gen2 – Scientific Vision

PeV-Scale Neutrinos

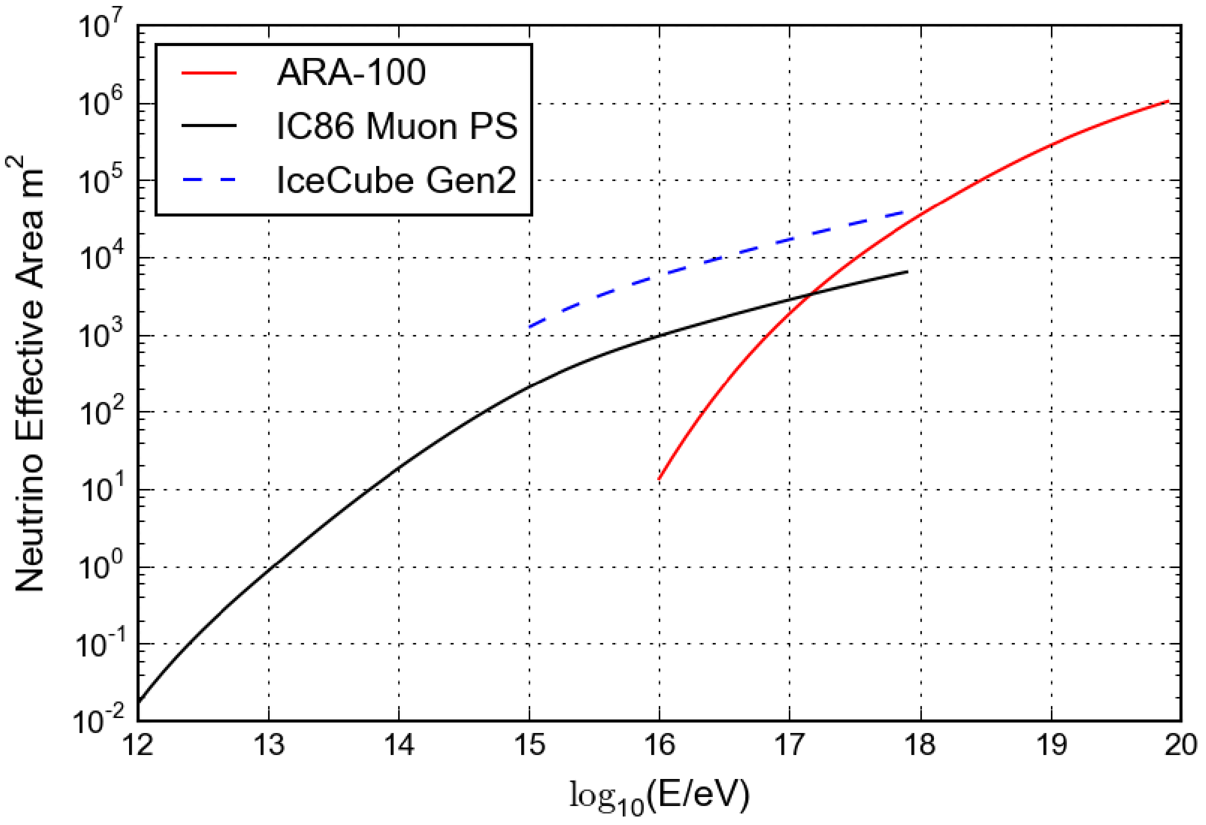
See IceCube-Gen2 Whitepaper http://arxiv.org/abs/1412.5106



A muon neutrino event recorded Jun 2014 which deposited 2.6 PeV of energy in the IceCube detector. The parent neutrino's energy is in the range 5-10 PeV.

- Background-free region for study of
  - Point sources
  - Correlation studies
  - Energy spectra
- Gen2/HEA would deliver O(10) events per year above 1 PeV
- At PeV scales new phenomena arise which help disentangle flavors providing information on source physics:
  - Tau double bangs – with separated bangs – O(1-2) per year in IceCube Gen2/HEA
  - Glashow resonance events [arXiv:1108.3163 Battacharya, et al] have pure muon, tau lollipop signatures – discrimination of pp versus pγ at source.

To EeV-Scale Neutrinos



- A combined radio – optical detector would have a powerful reach into EeV energies where GZK phenomena could be probed.
- Shown at left is a comparison of neutrino effective areas for IceCube-86, a scaling for Gen2 performance, and a putative radio deployment of 100 km^2 scaled from the ARA detector.
- At 10^{17} eV radio is the better technology. Not evident from this graph is the cost difference – radio would be more than an order of magnitude less expensive.

- PINGU
- High Energy Array
- Cosmic Ray Array
- Radio Array

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IceCube Gen2 – The Observatory

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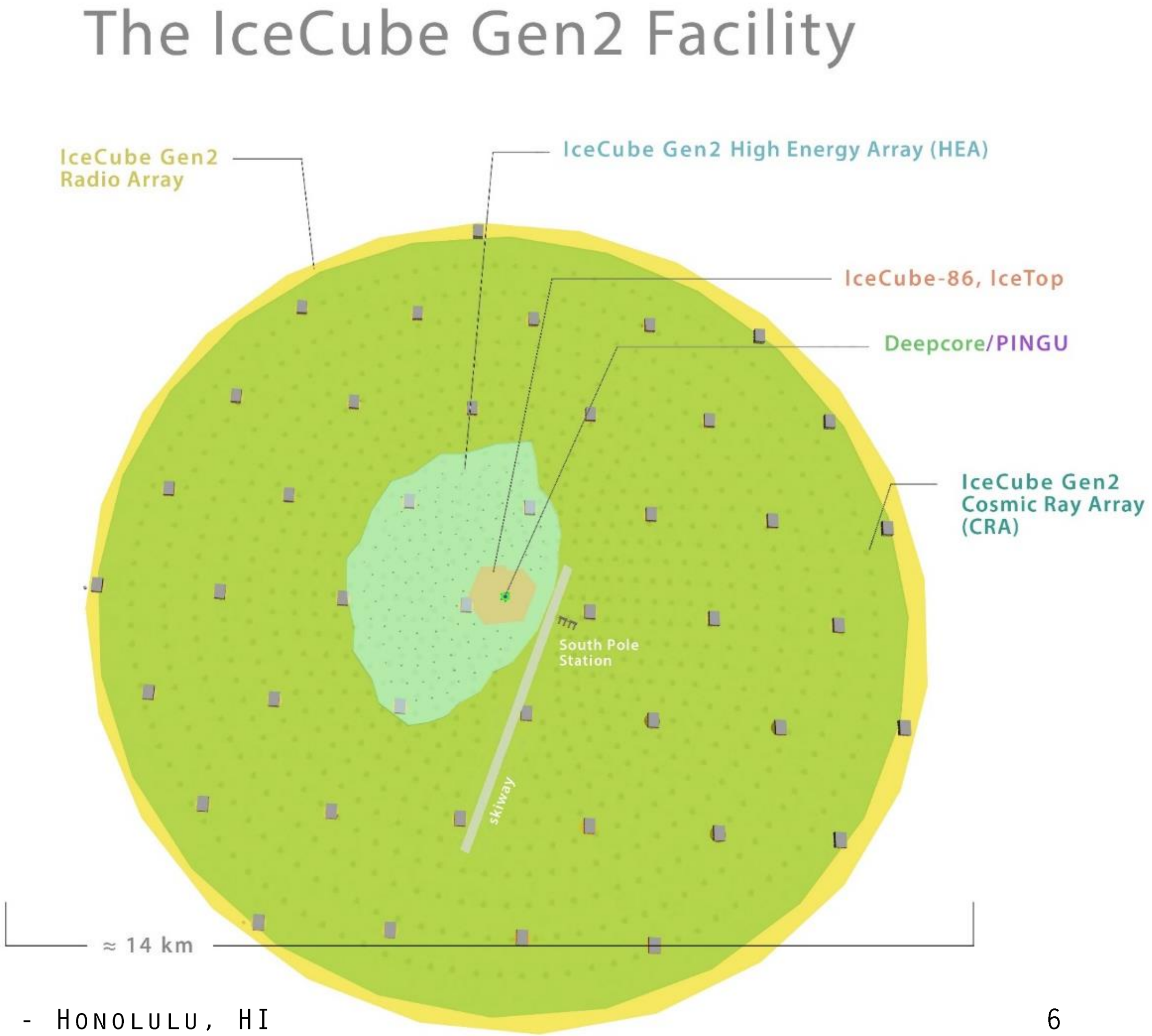
Conceptual Design

A conceptual drawing of the IceCube Gen2 Facility is shown at right. Specific points of design are likely to evolve quite a bit. However salient points are the multiple sub-detectors:

- PINGU – low energy, mass hierarchy
- High Energy Array (HEA) – PeV scale neutrino detector using optical sensors evolved from IceCube
- Cosmic Ray Array (CRA) – veto array for HEA as well as exploration of cosmic ray physics
- Radio Array (RA) – ARA-like or perhaps much denser array of RF power envelope detectors. Could even shadow CRA.



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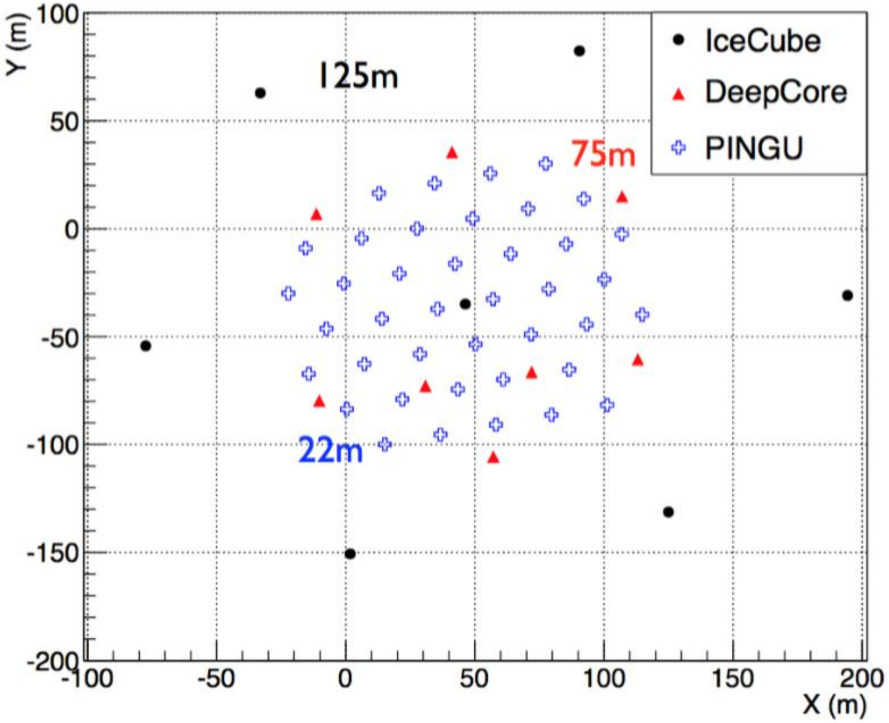
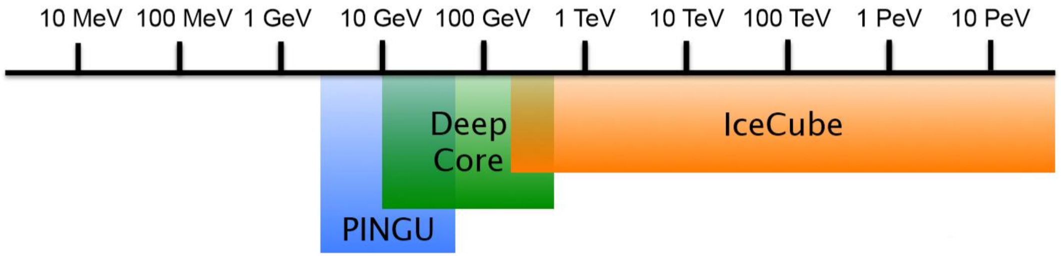
Low Energy Neutrinos and PINGU

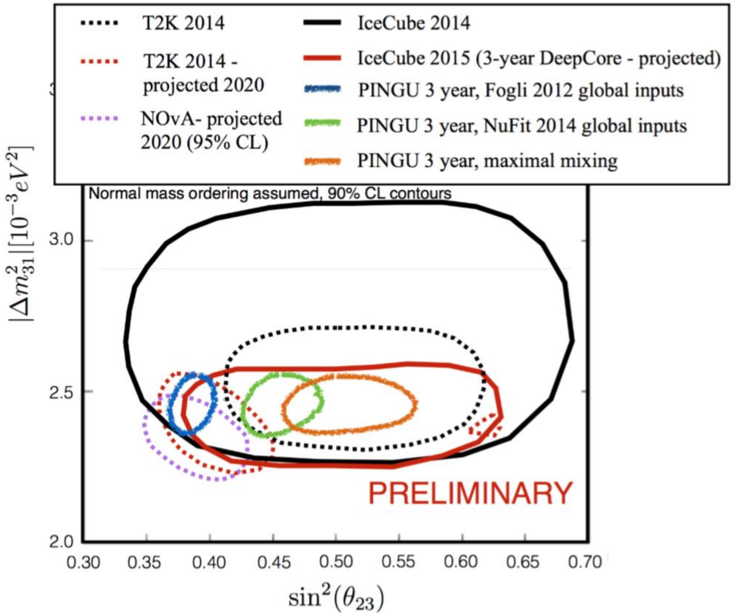
- PINGU is DeepCore infill array
- Current geometry 20 m string spacing, 3-5 m DOM spacing
- 40 Strings, 96 DOMs per string
- Major science goal NMH
- Goal is to reconstruct neutrino angle / energy below 10 GeV.
- PINGU is a time-critical deployment: to be competitive with other experiments it must start data taking in 6-8 years.

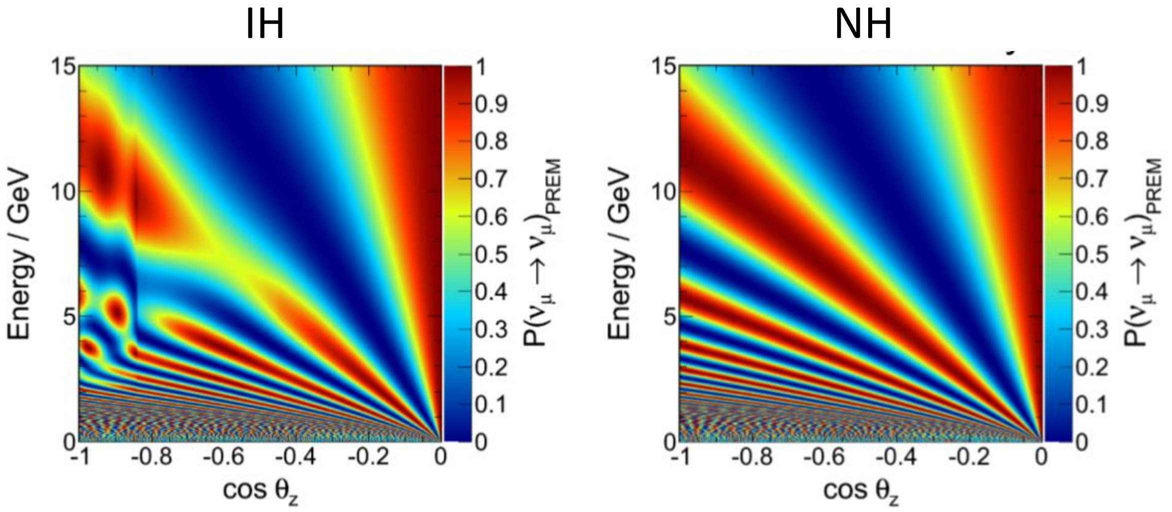


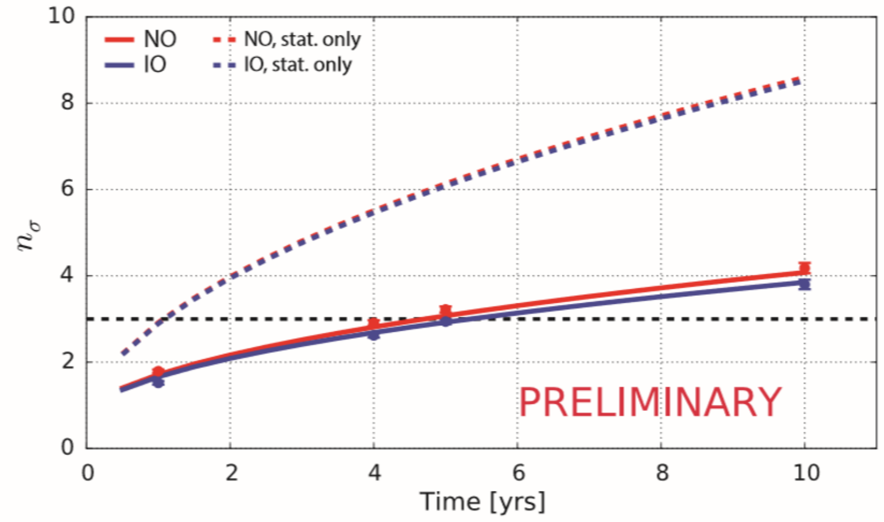


PINGU – Neutrino Physics Proper

- Uses atmospheric neutrino beam
- Discrimination of IH vs NH at X sigma level after N years (depending on neutrino mixing parameters)
- Very competitive measurement of $\sin^2\theta_{23}$
- Additional physics topics
  - Supernova neutrinos
  - Earth tomography





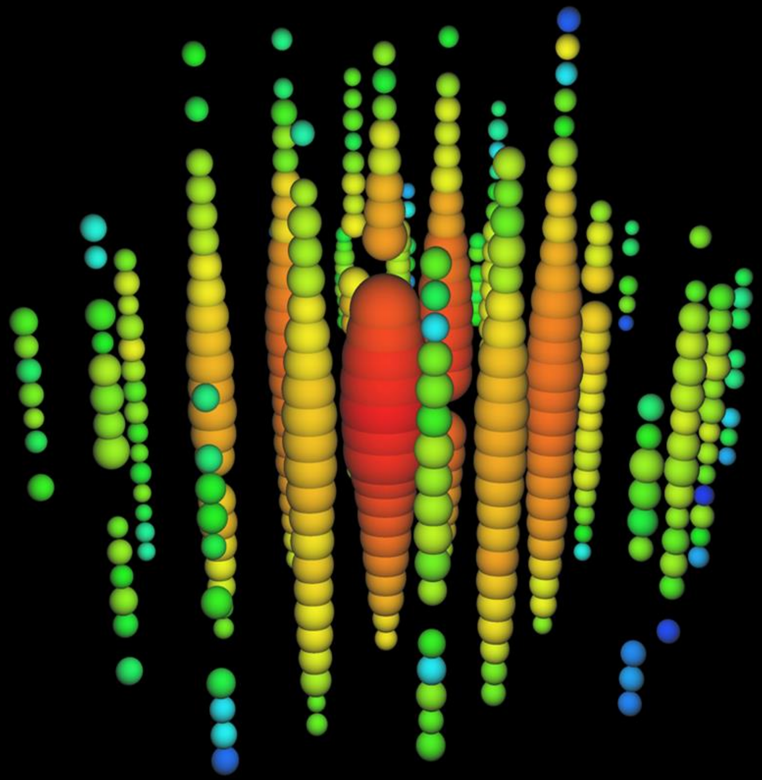


PeV neutrinos don’t need dense detector

Take Bert – one of the two original ~ 1 PeV neutrinos found in IceCube data.

Study reconstruction of this event with *real* sparse detector: IceCube with strings removed to simulate wider spacing. With 20 strings separated by 250 m

Vertex resolution	12 m
Angular resolution	30°
Energy resolution	10%



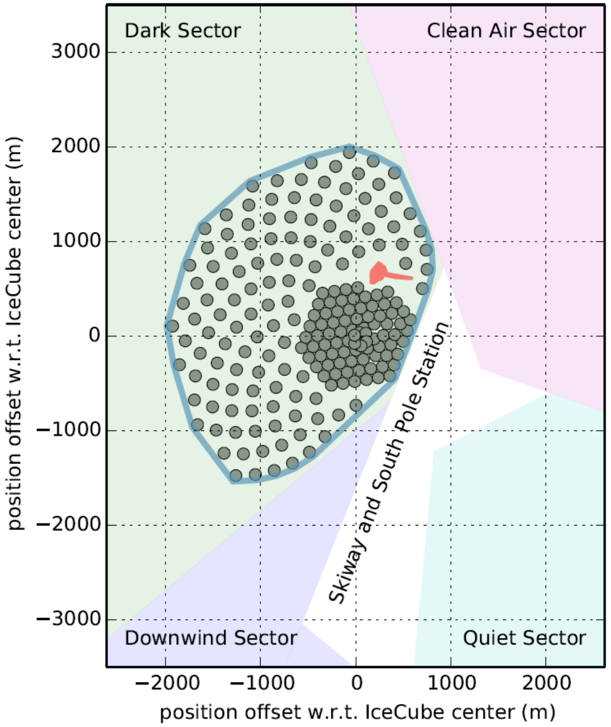
The Deep-Ice High Energy Array (HEA)

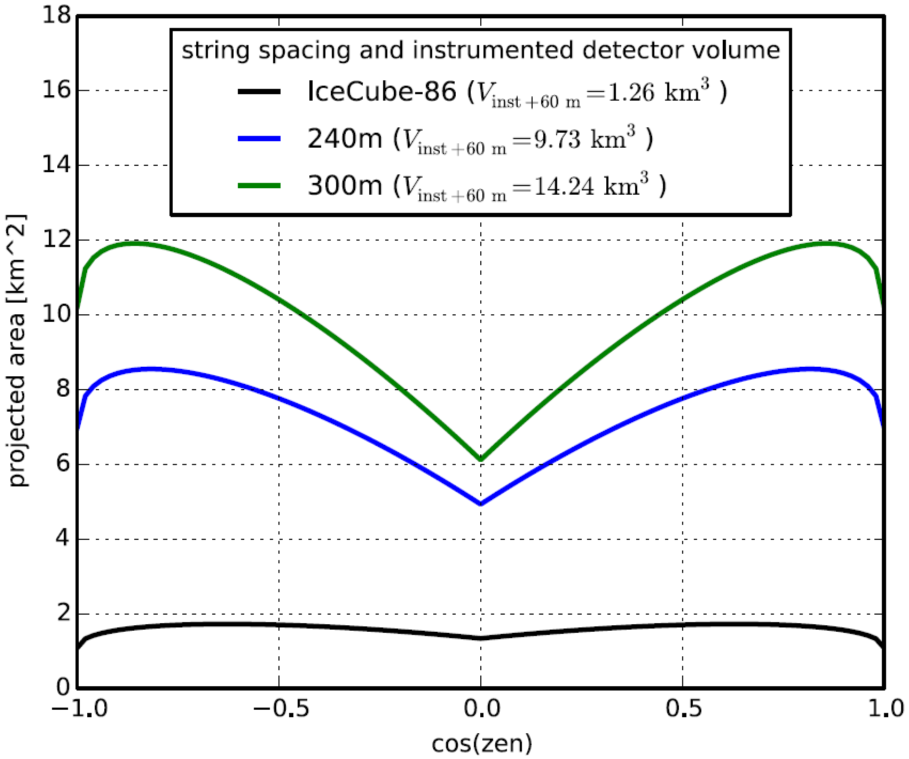
Gen2/HEA Parameters

# Strings	120
DOMs / String	80
String Length	1.3 km

Gen2/HEA Performance Characteristics

Muon $\log_{10}$ Energy Resolution	~ 0.33
Muon Angular resolution	< 0.5°
Cascade Energy Resolution	10%





Studies have focused on "sunflower" design given by Fermat spiral (no lanes). Keep-out regions at Pole limit extension to a wedge in SP Dark Sector but may be extended. Studies done simulating baseline string spacing of 240 m from IceCube data (remove strings from analysis) indicate no loss in event reconstruction for PeV-class events.

FoM Study (J. van Santen)

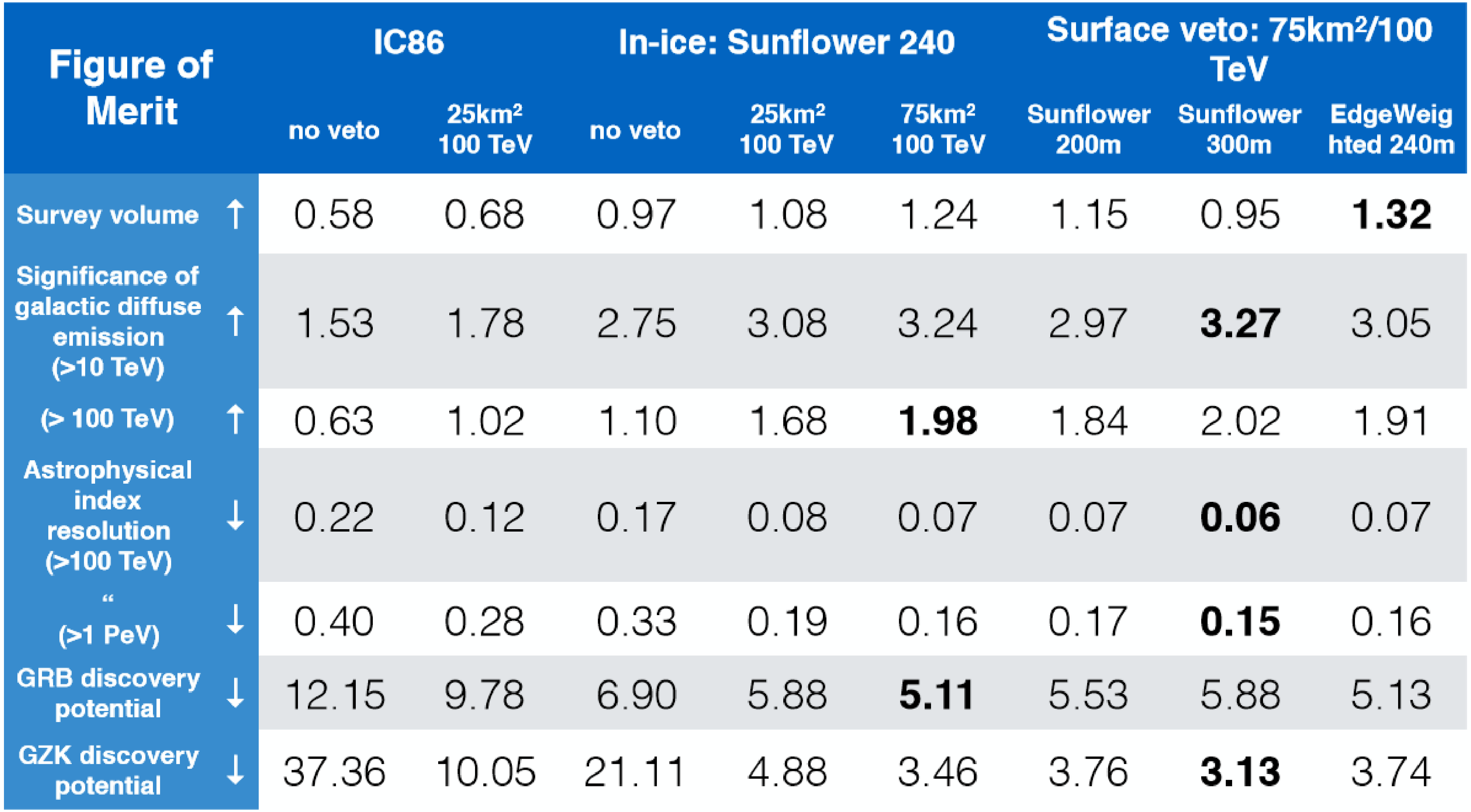


Figure of Merit	IC86		In-ice: Sunflower 240			Surface veto: 75km^2/100 TeV		
	no veto	25km^2 100 TeV	no veto	25km^2 100 TeV	75km^2 100 TeV	Sunflower 200m	Sunflower 300m	EdgeWeighted 240m
Survey volume ↑	0.58	0.68	0.97	1.08	1.24	1.15	0.95	**1.32**
Significance of galactic diffuse emission (>10 TeV) ↑	1.53	1.78	2.75	3.08	3.24	2.97	**3.27**	3.05
(> 100 TeV) ↑	0.63	1.02	1.10	1.68	**1.98**	1.84	2.02	1.91
Astrophysical index resolution (>100 TeV) ↓	0.22	0.12	0.17	0.08	0.07	0.07	**0.06**	0.07
“ (>1 PeV) ↓	0.40	0.28	0.33	0.19	0.16	0.17	**0.15**	0.16
GRB discovery potential ↓	12.15	9.78	6.90	5.88	**5.11**	5.53	5.88	5.13
GZK discovery potential ↓	37.36	10.05	21.11	4.88	3.46	3.76	**3.13**	3.74

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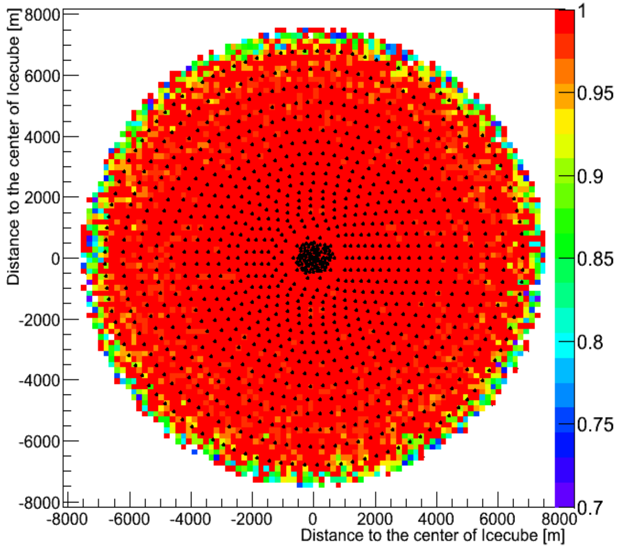
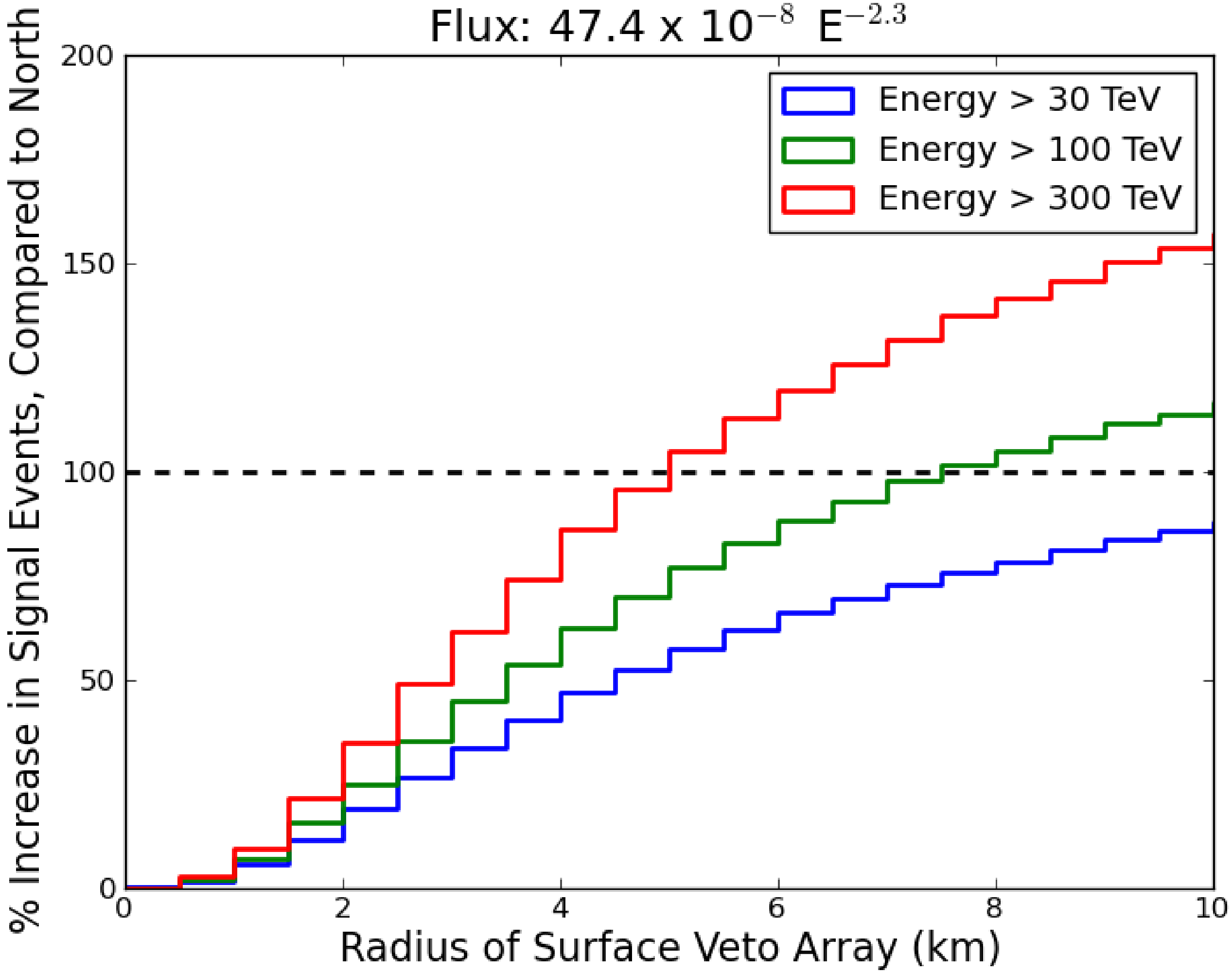
Surface Veto





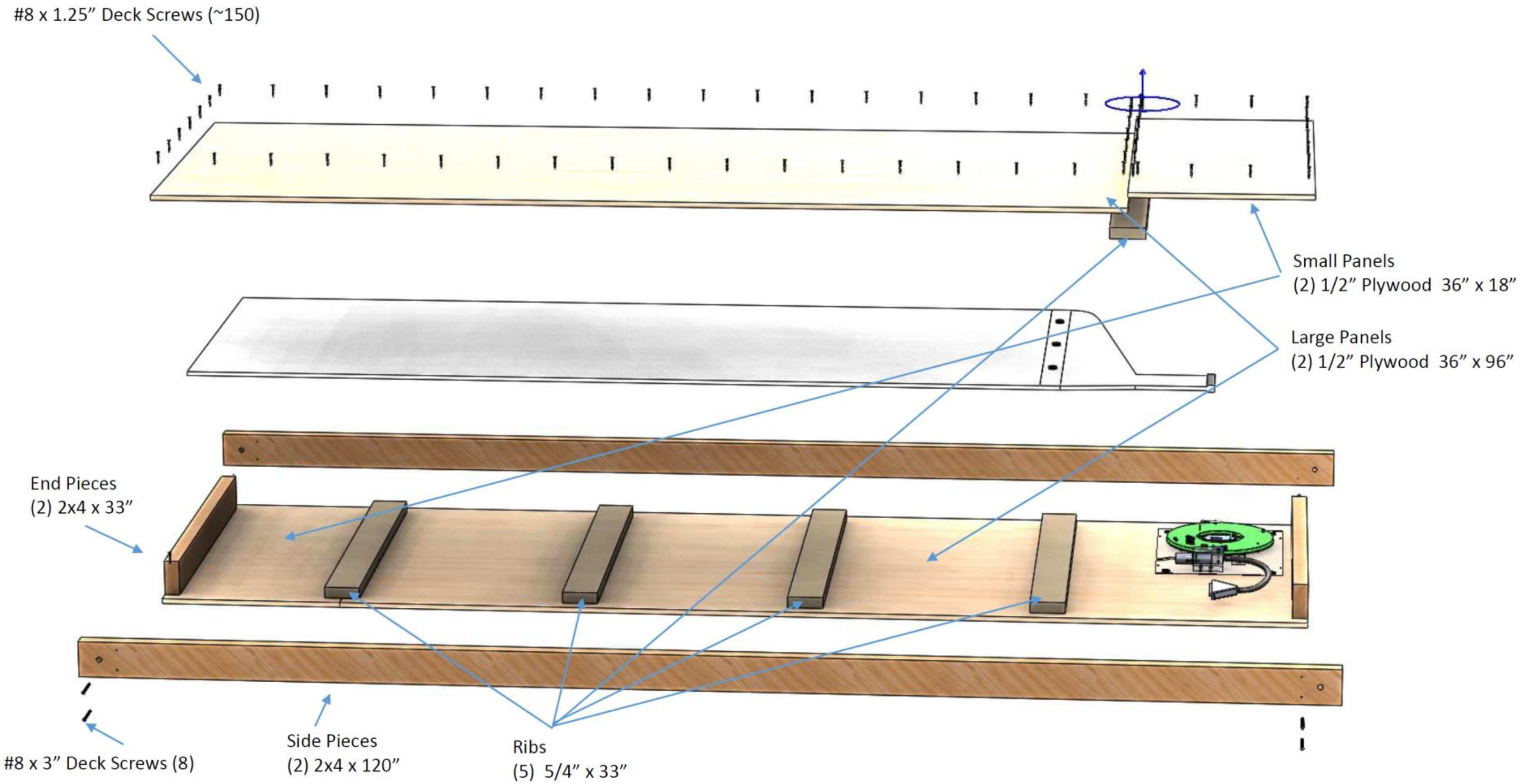
Generic surface array simulations just released at IceCube Gen2 meeting actually predict substantive gains in several FoM for CRA in the 10’s of millions price. We have just adopted a 75 km^2 CRA as baseline. Technology still unspecified: scintillator, frozen pool, IACT(??) or combo.

Scintillator Module 'Prototypes'

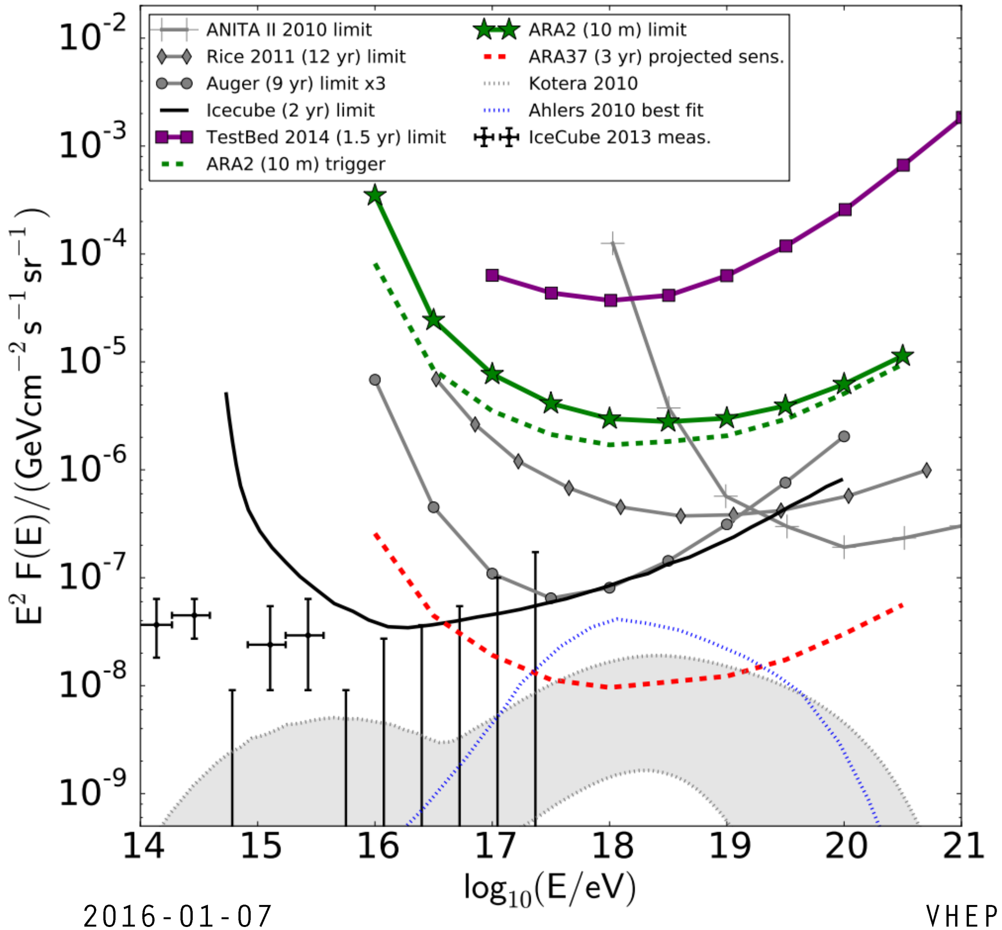
Deploying thin sheets of extruded scintillator panels from MINOS: WLS fiber readout. Being deployed for purpose of understanding snow accumulation on IceTop tanks

Panels are cheap (these are free in fact). Extruded scintillator is 10x cheaper than cast plastic.

2 sheets left for Pole Sept 2015.



The Radio Array



Absolutely clear: when measuring effective area / cost, RF detection is at least 10x better than optical above 10^{17} eV.

Not clear: what is best method for RF detection:

- Full band digitization (2-4 GSPS)
  - **Pros**: very good time resolution (50 ps)
  - **Cons**:
    - Finicky digitizers
    - Needs precise analog amplifier chain (pwr/cost)
    - Time resolution dominated by other systematics
    - Fine vertex angular resolution, no range.
- RF power envelope detection
  - **Pros**: low cost low power hardware and scalable.
  - **Cons:** unproven, is information content sufficient for background discrimination?

Also not clear: can radio techniques be improved to obtain effective areas competitive with optical at 1-10 PeV? Interferometric techniques?

See A. Karle talk Saturday.

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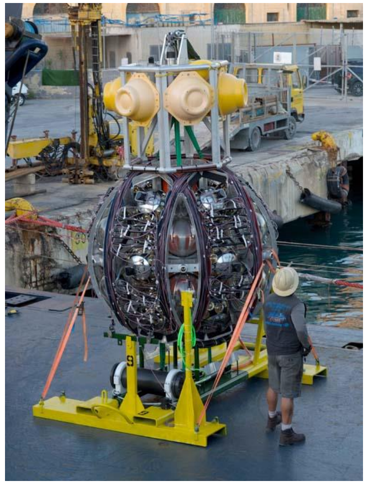
Meanwhile, in the Mediterannean

ARCA / ORCA

The new KM3NeT design baseline – blocks of 115 strings (see ORCA inset at right – ARCA spacing is O(100m)) using multi-anode optical modules. Two sites planned – ARCA (Italy) for the high-energy array and ORCA (France) for neutrino oscillations. A phased approach:

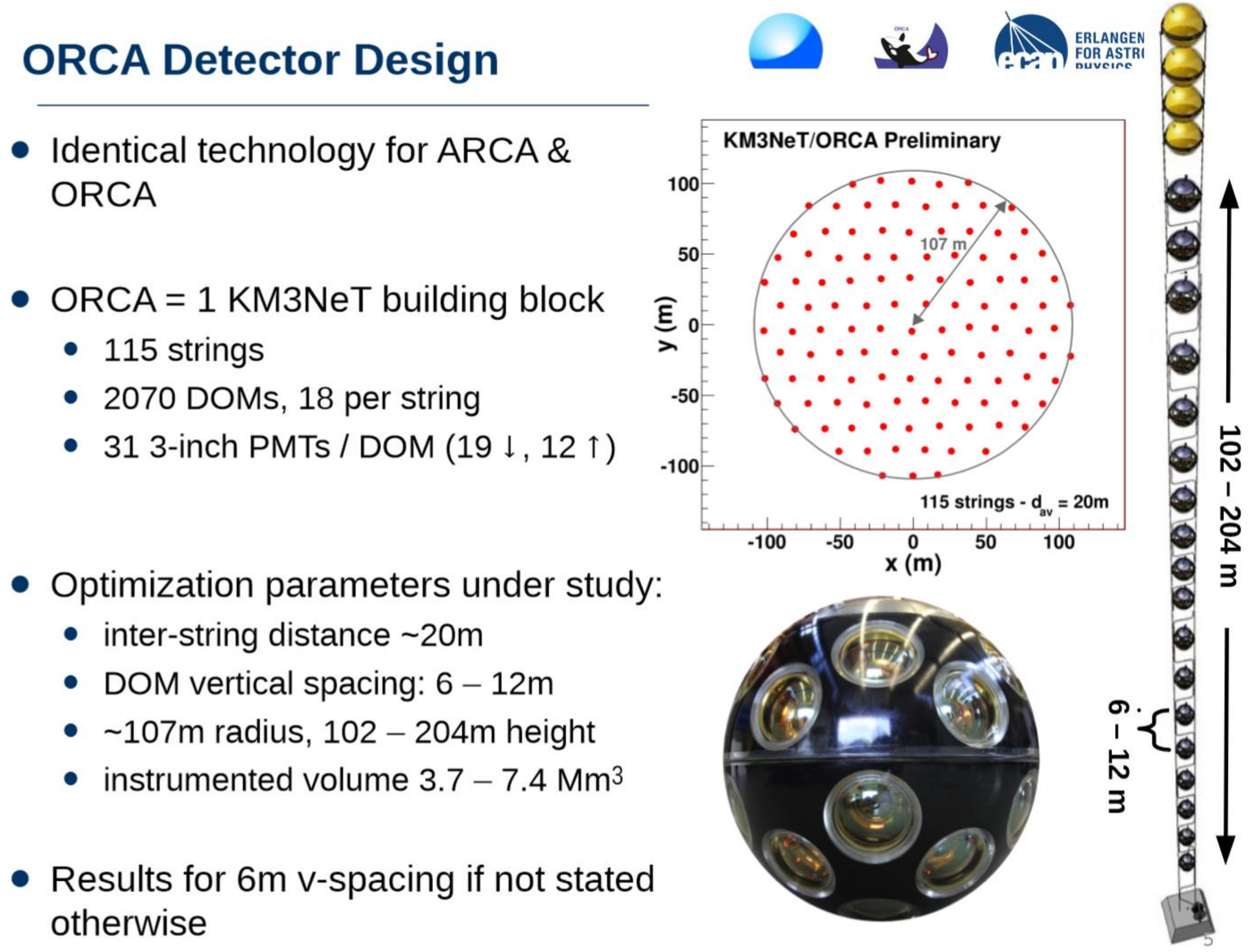
Phase	Blocks	Deliverable
1	0.2	Engineering run – first science
2	2 ARCA	Measurement of HE neutrino flux
2’	1 ORCA	NMH
3	6	Neutrino astronomy



News

On Dec 3^{rd} 2015 the first string was deployed at the Capo Passero site off SE coast of Sicily. Strings are wound up in package shown at left and dropped off deployment vessel. ROVs then connect to junction box at 3500 m depth. Reports are that string was functioning properly.

Slide from J. Hofestädt (Erlangen)



ORCA Detector Design

- Identical technology for ARCA & ORCA
- ORCA = 1 KM3NeT building block
  - 115 strings
  - 2070 DOMs, 18 per string
  - 31 3-inch PMTs / DOM (19 ↓, 12 ↑)
- Optimization parameters under study:
  - inter-string distance ~20m
  - DOM vertical spacing: 6 – 12m
  - ~107m radius, 102 – 204m height
  - instrumented volume 3.7 – 7.4 Mm^3
- Results for 6m v-spacing if not stated otherwise

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New Optical Detectors – New Electronics

Options for Future Photodetection

- **Play it safe:** current DOM works *pretty good* – certainly the lowest risk option would be to make minor tweaks to this design
  - For a fast deployment (i.e. PINGU) this might be the best option
  - Need lots of channels however for HEA
- **Higher risk:** Spend some time and effort on research into improved photo-detection methods – these also will have beneficial impacts for the entire community
  - Maybe not for PINGU, depends on time-scale
  - For Gen2/HEA we probably have some time.
- A few options on the table for better photodetectors: mDOM, WOM, and dual-PMT d-Egg

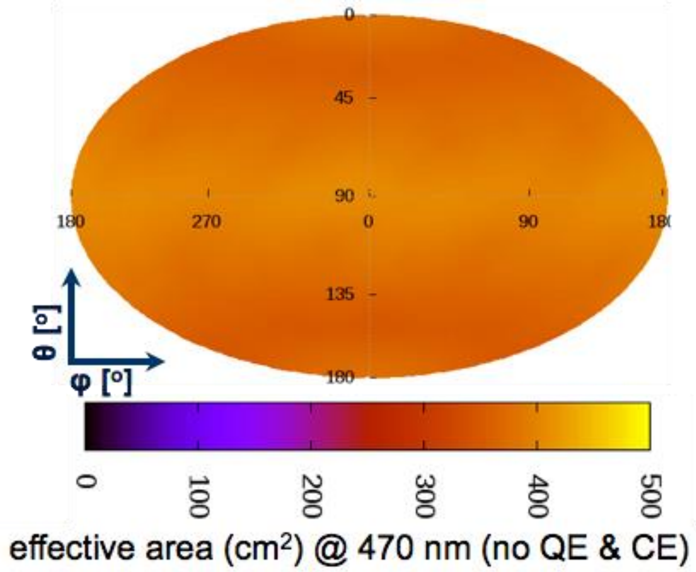
A multi-PMT optical module for IceCube-Gen2

Features

- 24× 3” PMTs (Hamamatsu 12199-02)
- 14” borosilicate glass pressure vessel rated @ 700 bar (Nautilus)
- Based on proven KM3NeT design
- Prototype to be tested in PINGU

Advantages

- Uniform 4π acceptance
- 2 times effective area of IceCube DOM @ similar price per photocathode area
- Directional sensitivity
- Local coincidences for e.g. background suppression
- Improved TTS (σ = 1.7 ns)
(important for leading-edge timing precision)



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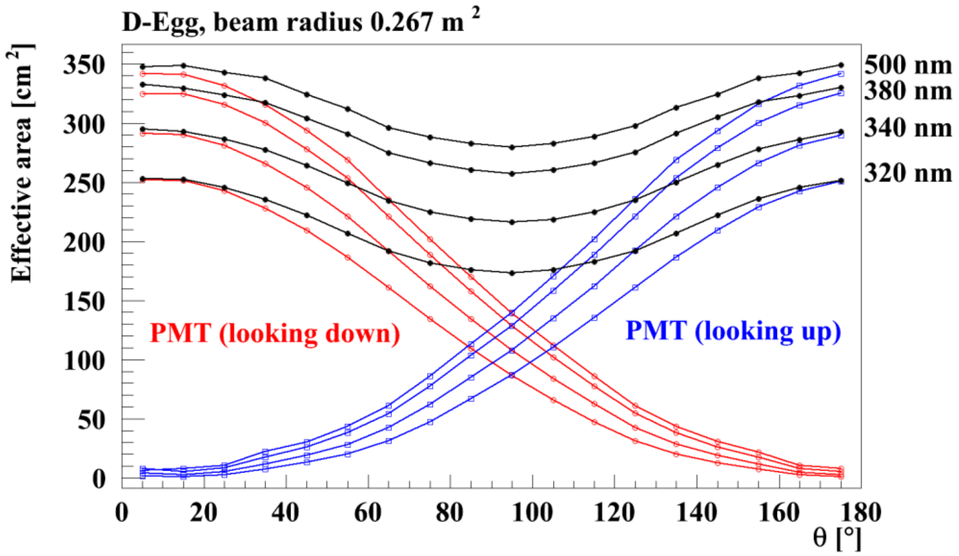
The D-Egg Dual 8” PMT + Improved Glass



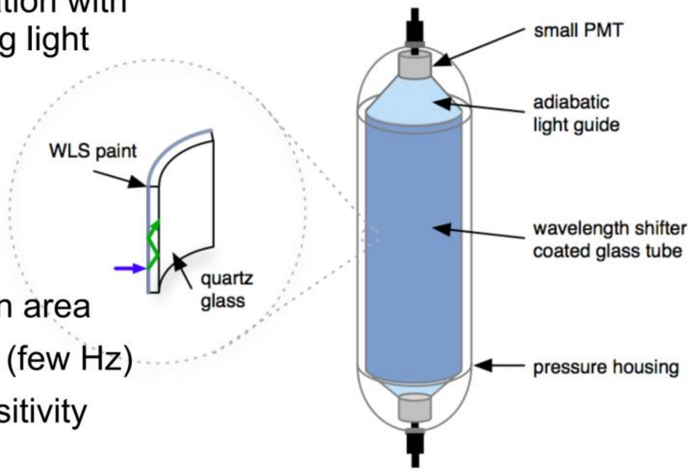
D-Egg uses 2x 8” PMTs. Naively, one would expect only about 30% enhancement in the photon effective area, however, better collection efficiency relative to 10” PMT and massive improvements in UV transparency of glass.

My personal comments:
Whether or not we decide to use 2x 8” or 1x 10” PMT, the gains in UV photon collection from better glasses is well worth the research effort and should be a priority of the photodetection R&D.

Two PMTs could probably still be readout separately with new DOM mainboards equipped with two ADC channels. TODO: investigate whether individual UP/DOWN tube hits give increase in performance versus simple ganged readout.

Wavelength-Shifting Optical Module (WOM)

Idea: light concentration with wavelength shifting light guides

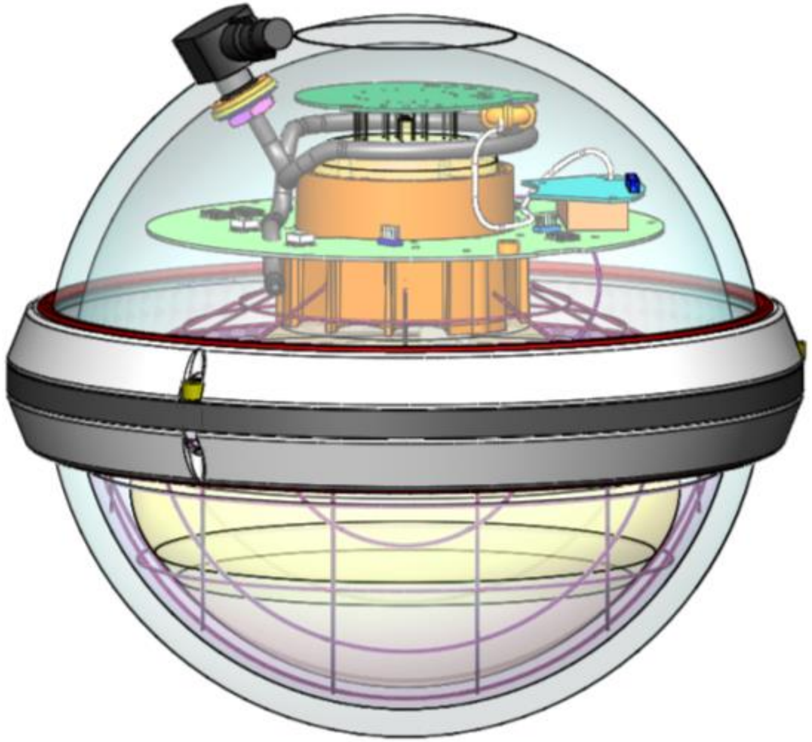


Features

- large collection area
- low noise rate (few Hz)
- better UV sensitivity
- cost effective

- Wavelength shifter painted on long cylindrical tube.
- Two small 1-2” PMTs at each end
- Time precision, if it does turn out to be worse than IceCube’s (< 5 ns) is a critical parameter for PINGU but not a critical parameter for HEA.
- WOM has potential to dramatically increase effective photo collector area.
- Still in early stages of development.

Evolving the IceCube DOM



To Improve

- Replace transient waveform capture ASIC with modern pipelined 14-bit 250 MSPS ADC:
  - Eliminates need to pre-trigger ASIC (72 ns delay board)
  - Unify 3 disparate gain channels to single channel – tricky calibration in IceCube
  - Permit capture of arbitrarily long waveforms (currently limited to ~500 ns)
- Update FPGA to modern process, high-density (Cyclone V)
- Replace HV module (good performance but 25% efficiency)

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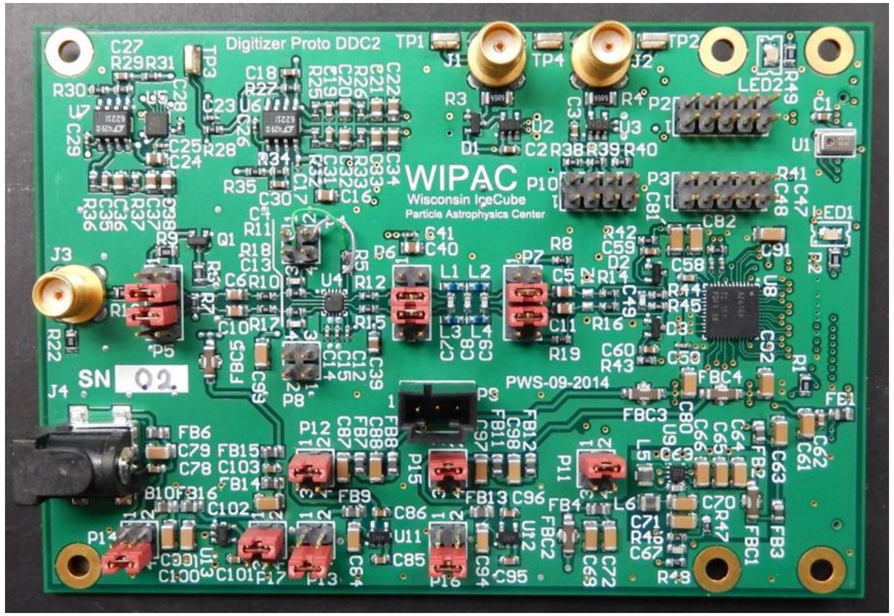
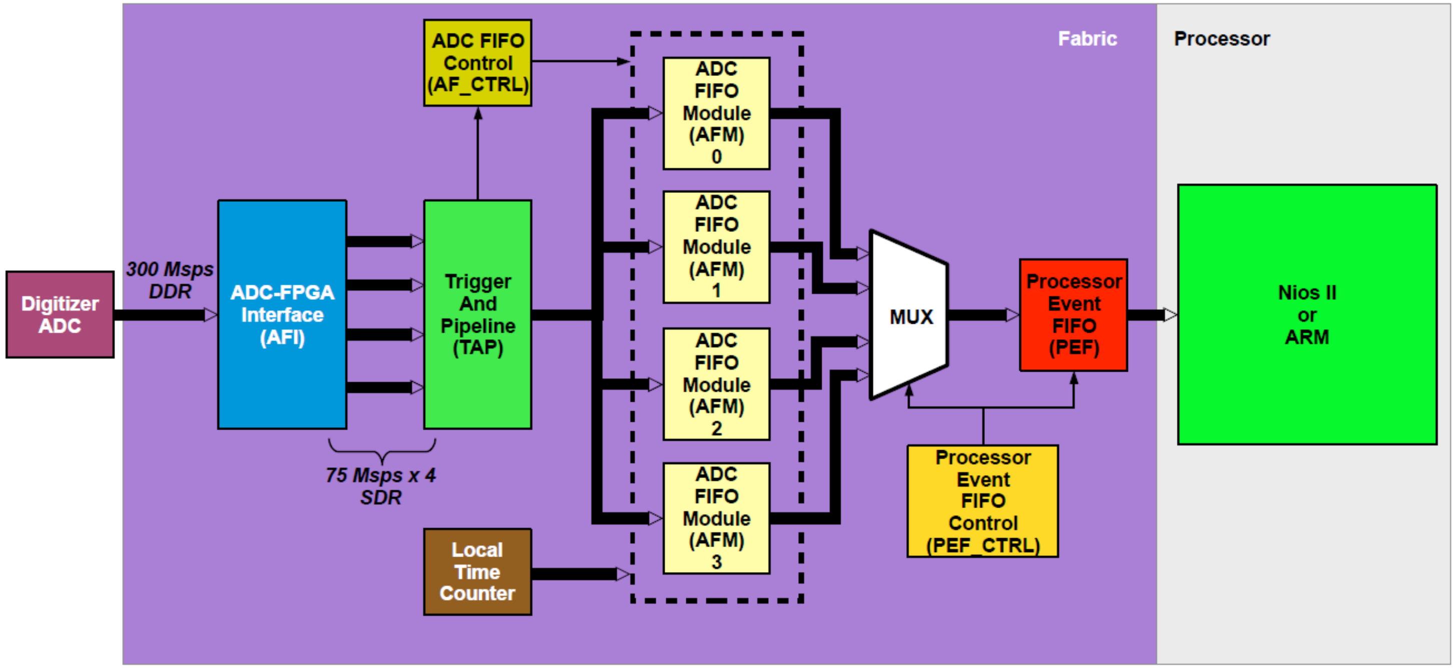
Gen2 DOM Electronics



Analog/digital front end boards fabbed 2015Q1 – good performance – 250 MSPS 14-bit, < 300 mW. Noise at 2 LSB. Plug-in via HSMC to standard FPGA development board.

P. Sandstrom - WIPAC



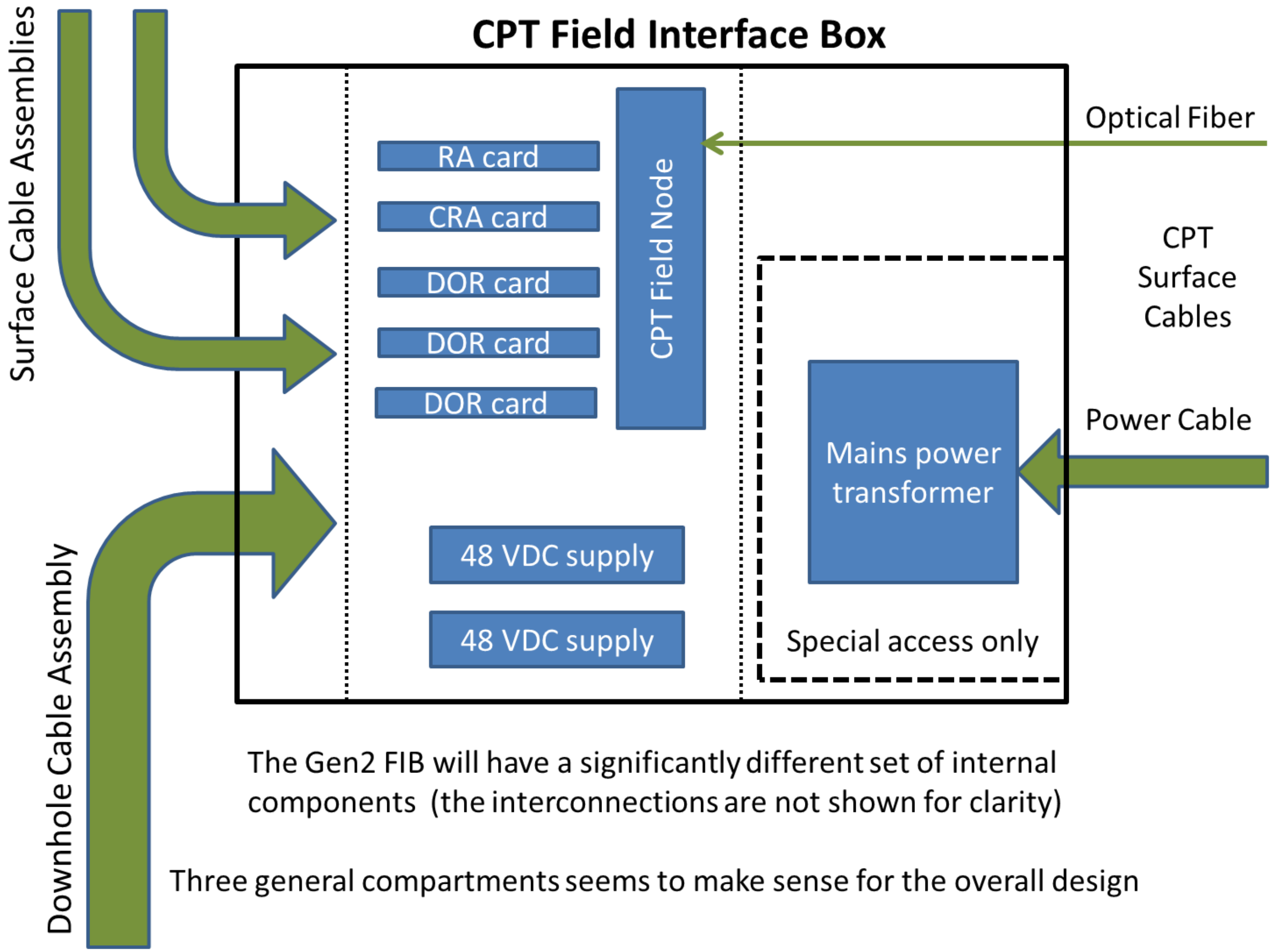
Early prototype firmware with advanced features: full throughput at 250 MSPS (quad pipeline) and control via soft core Nios on Cyclone V FPGA.

T. Anderson – Penn State

Rev0 Gen2 mainboard release planned for 2016Q1

Field Hubs and Comms

- Communications for large-scale array differ from IceCube. 3.5 km is approx. max distance → fiber out to holes (infinite BW). Downhole cables are then conceptually very similar to IceCube cables – actually shorter.
- Ericsson out of cable business. However copper cable division passed to Hexatronic – MSU working with them on Gen2 cables.
- Rev0 comms card (analog to IceCube DOR) is fabbed – in test (KH Sulanke – DESY)



The Gen2 FIB will have a significantly different set of internal components (the interconnections are not shown for clarity)

Three general compartments seems to make sense for the overall design

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Drilling

Mobile Drilling System

Meet or exceed EHWD thermal performance

- 4.7MW thermal delivery to drill nozzle
- 48 hour hole production rate
- 90% thermal efficiency

G2 Improvements

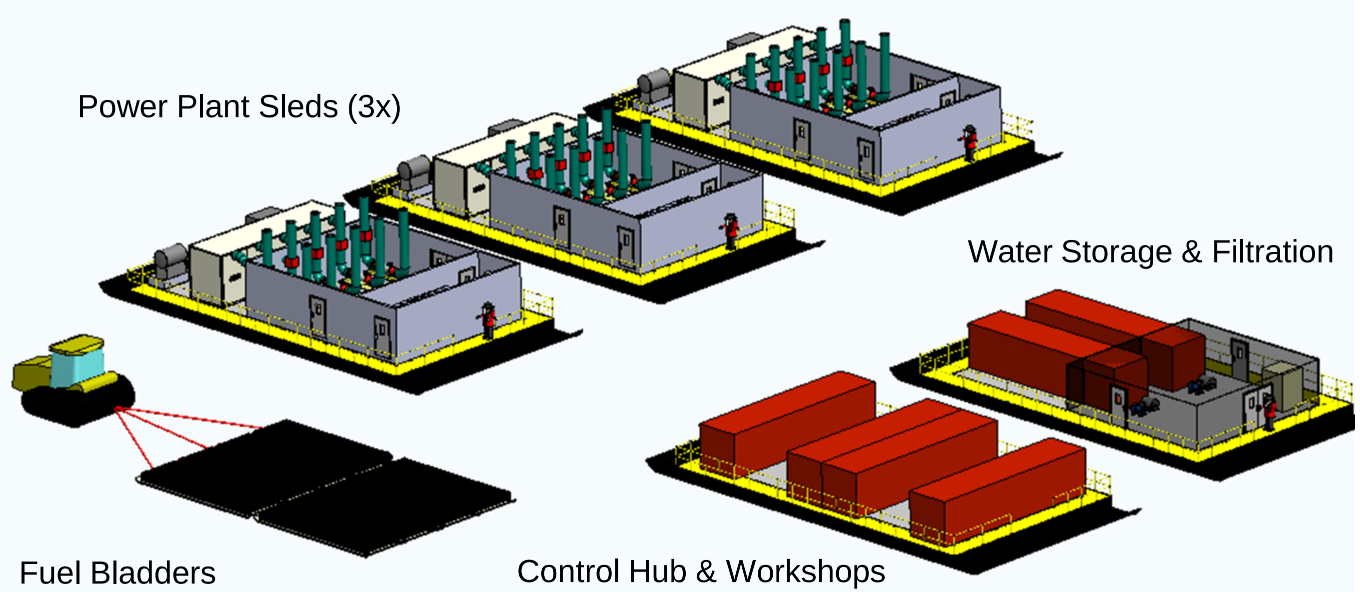
- Safety
- Mobility
- Reliability
- Degassed holes (+8 hours)
- Cleaner drill water
- Reduced manpower
- Reduced setup / decommission time

Quick Specs

Hole diameter	60 cm
Hole depth	2600 m
Hole spacing	300 m
Hole lifetime	30 hr
Total Thermal Output	5.4 MW
Nom. Thermal power delivered to nozzle	4.7 MW
Dry weight (est.)	365 tons
Fuel/hole	21,000 L
Max holes/season	20-23
Crew size	28
Construction cost	$20 M

Compatible with trending logistics

- Equipment and fuel delivered to Pole via traverse, minimize dependence on LC130s
- Reduced logistical footprint at Pole, smaller crew



EHWD-G2: Air-Ride Cargo Sleds (ARCS)

- Rigid deck atop of air bladders atop of PE panels
- Far superior to ski-based traverse designs
- In active development for high-payload traverses in Antarctic and Greenland
- Drill system is “traverse ready”

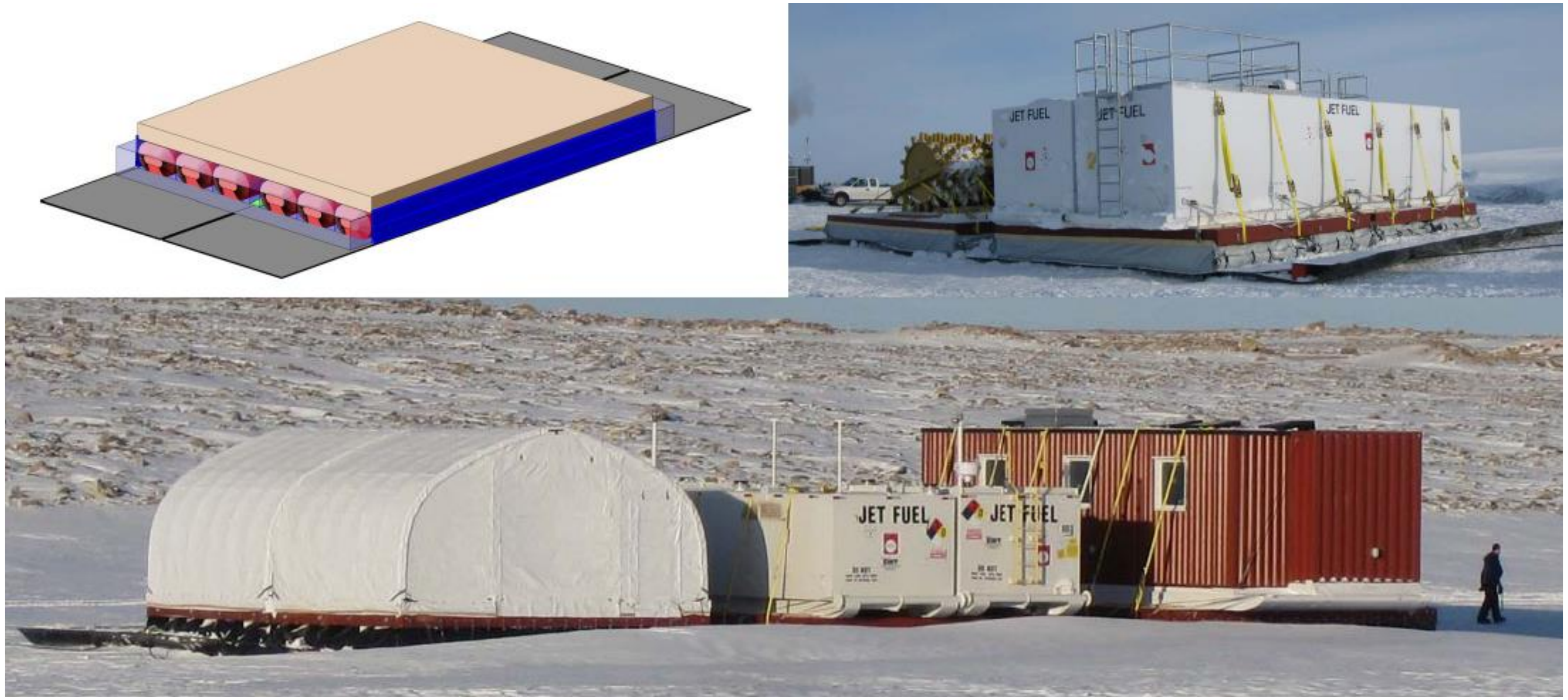


Figure from *Lightweight Cargo Sleds for Polar Traverses.* Lever, Song, Weale. Polar Technology Conference 2014

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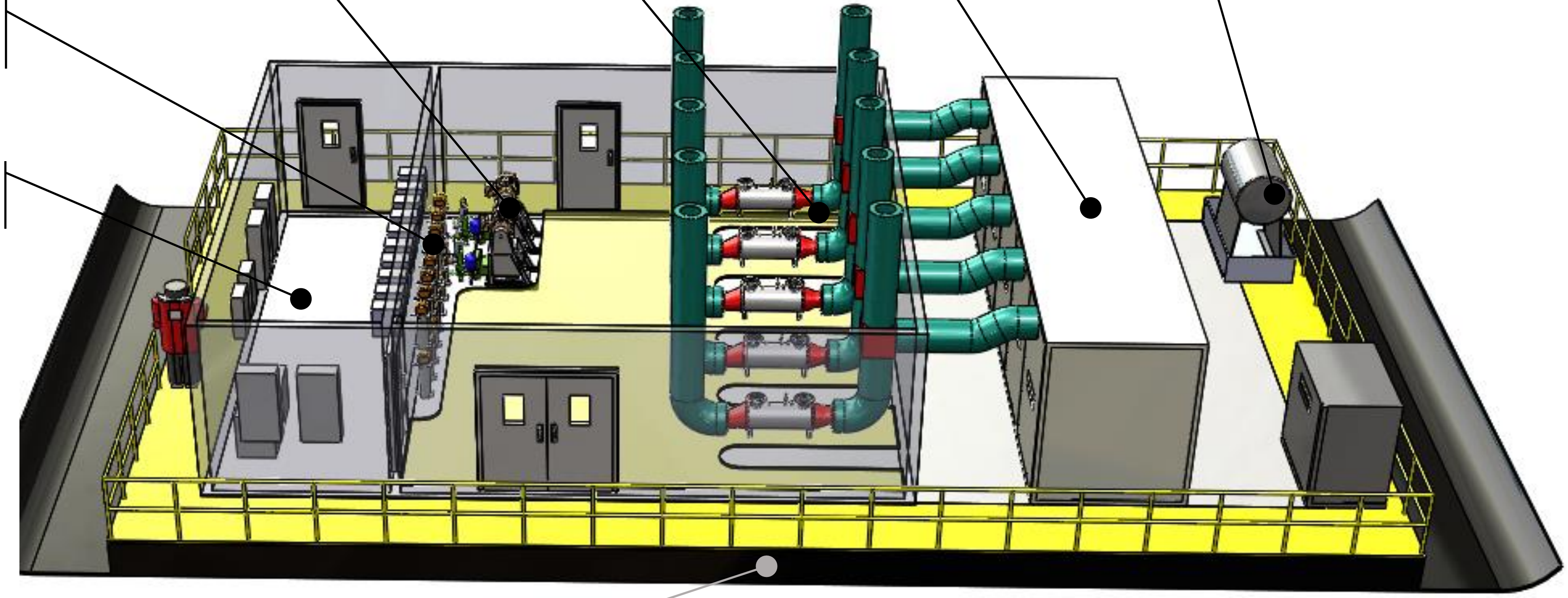
EHWD-G2 Overview: Power Plant Sled



High Pressure Pumps

Exhaust Heat Exchangers

C1000 Microturbine array

Fuel Daytank

Electrical Heater Bank

Electrical Closet

Air-Ride Cargo Sled

EHWD-G2: Microturbines

Fuel combustion in Capstone C200 microturbine. Flexible fuel – AN8 OK. High power density, low maintenance, ultra-low emissions. Easier recovery of waste heat. Combined heat and power thermal efficiency at 90%. *Turnkey solution*.

C1000 is 5 C200's in parallel. Total output @ 3 km: 1.8 MW primarily from exhaust heat recovery. 3x power plants = 5.4 MW. **Challenges:** large upfront cost – $1.5 M each; no experience in Antarctic environment. However Spring 2016 NSF is running evaluation at Summit Station in Greenland (J. Cherwinka).

Alternative Approaches to Consider

The preceding slides describe only one possible approach. Other approaches should be considered:

- Minimal EHWD Restart (PINGU drill plan from 2013)
  - Replace equipment
  - Drill up to a couple dozen holes before boilers die
- Other boiler options (fewer, larger boilers)
- Hybrid options – some microturbines, some boilers
- Alternative approaches are centered around thermal plant, whereas packaging is likely to stick with the air-ride cargo sled concept
- Build two drills and cut production time by significant amount – this is now becoming the baseline plan.

Cost & Schedule

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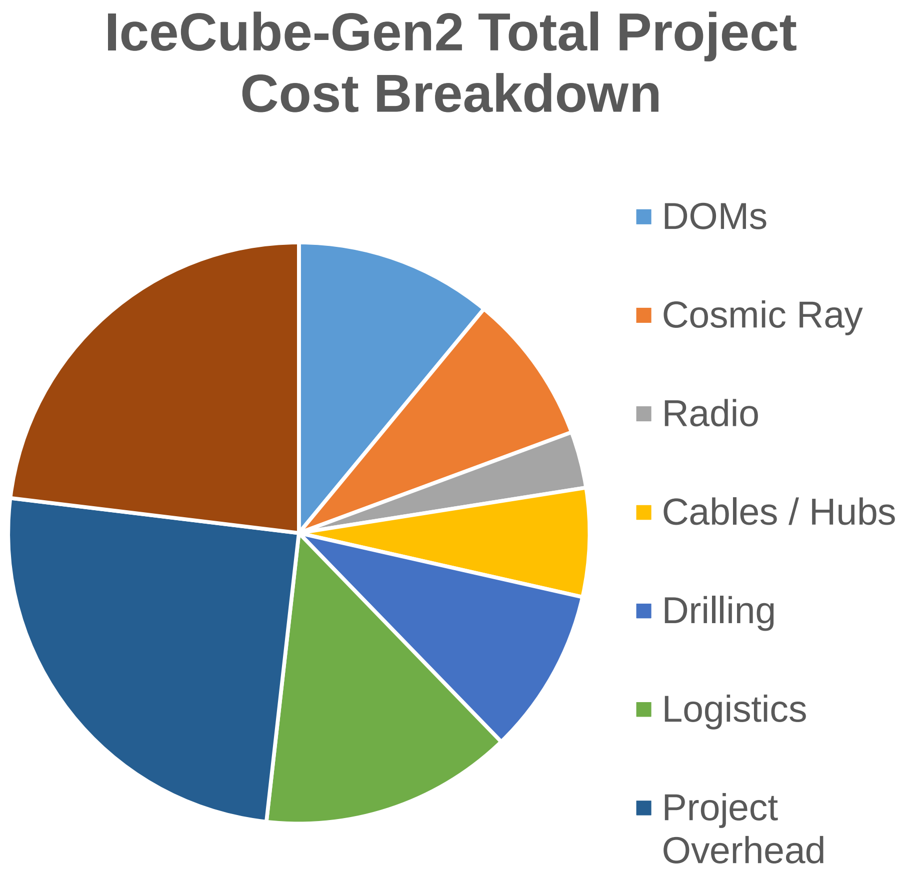
Project Matters

Total Project Cost

Project cost is 300-360 Million USD /wo/ contingency. The input to the figures in the pie chart at right are based on IceCube numbers but, given the stage of the development, putting good estimates out at this point is very difficult. Inflation has been very low, costs associated with some items should go *down*.

Instrumentation costs alone are 150 M$.


IceCube-Gen2 Total Project Cost Breakdown

Logistics

It should be noted that MREFC projects include logistical support costs. In the current USAP environment this means that many aspects of the construction must be handled by the project itself (IceCube received support from RPSC, paying for it): transportation of people and cargo, housing at SP site, heavy equipment, …

Despite concerns in a recent NAS report that IceCube Gen2 would be a logistical burden on USAP, the opposite is probably true: a large construction effort is likely to bring more resources into the logistical infrastructure.

McMurdo – Pole Traverse

The traverse has supplied S Pole with fuel and cargo for several seasons and could dramatically reduce IceCube Gen2 logistics costs. Compared to the airlift capabilities of LC-130s (11,800 kg) the traverse capacity is 30x (354,000 kg). Travel time is 30 days to Pole, 15 days return.

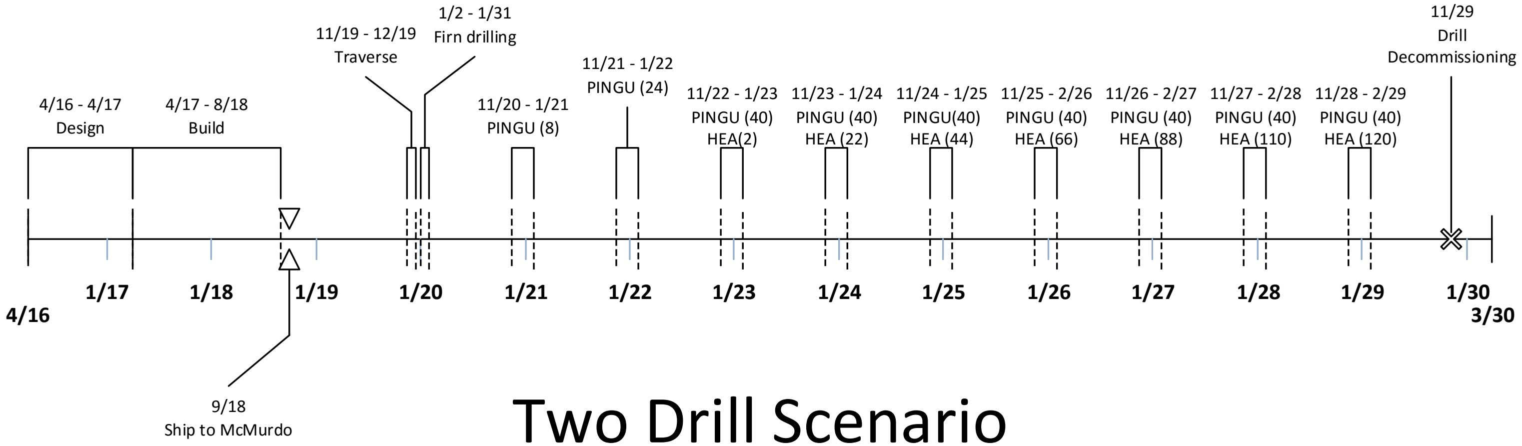
Deployment Schedule

This schedule is premised on the drill being in the critical path. Instrumentation development is not explicity listed here but assumed available when holes are delivered.

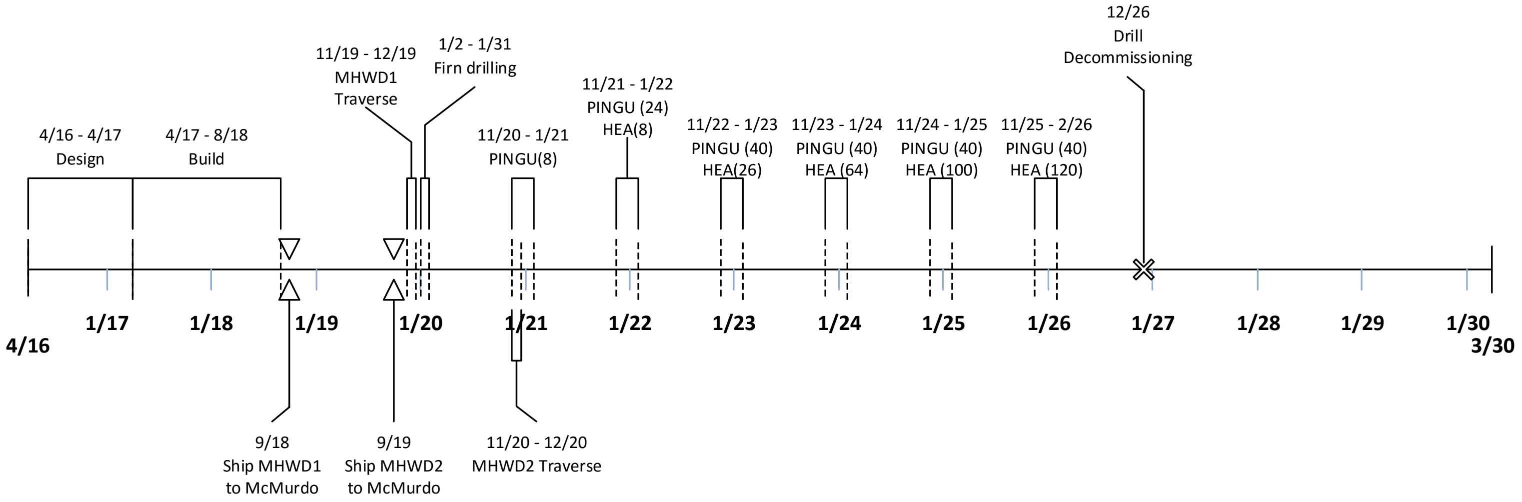
Note: this schedule is achievable but is optimistic.

Of course money (== flights) could be spent to accelerate the shipping delays.

One Drill Scenario



Two Drill Scenario



Funding Status - Projections

The MREFC Process

- A project this scale funded by NSF goes through the MREFC program (other examples: LIGO, LSST, …)
- MREFC construction funds follow only after a now very formalized sequence of design phases paid by R&RA funds:
  - Concept design: science, requirements, conceptual design plus initial cost, risk, and project execution plans;
  - Preliminary design: technology development, better cost and risk models, and PMCS development;
  - Final design: technology ready and buildable; complete bottoms up cost and risk; key staff members present.
- Must pass all reviews - only then does MREFC construction money flow. MREFC construction funds are separate from NSF Directorates and pay all logistics associated with construction activities.
- Once construction finished – operations phase again supported by the Directorates. In the case of IceCube Gen2, we anticipate only modest increase in operating budget. **IceCube is one of the most economical facilities in operation in the NSF large facilities portfolio.**

Current Status

We are still in the *development* phase – i.e. NSF has not committed any funds for design work. We are working with our program officers and expect to make a proposal for conceptual design work within the next 6-9 months.

Foreign Funding

Support from international collaborators is an important asset and it appears that significant non-US funding contributions are not only possible but likely. Of course everyone, including NSF, acknowledges that NSF must be the first to commit resources toward such a project.

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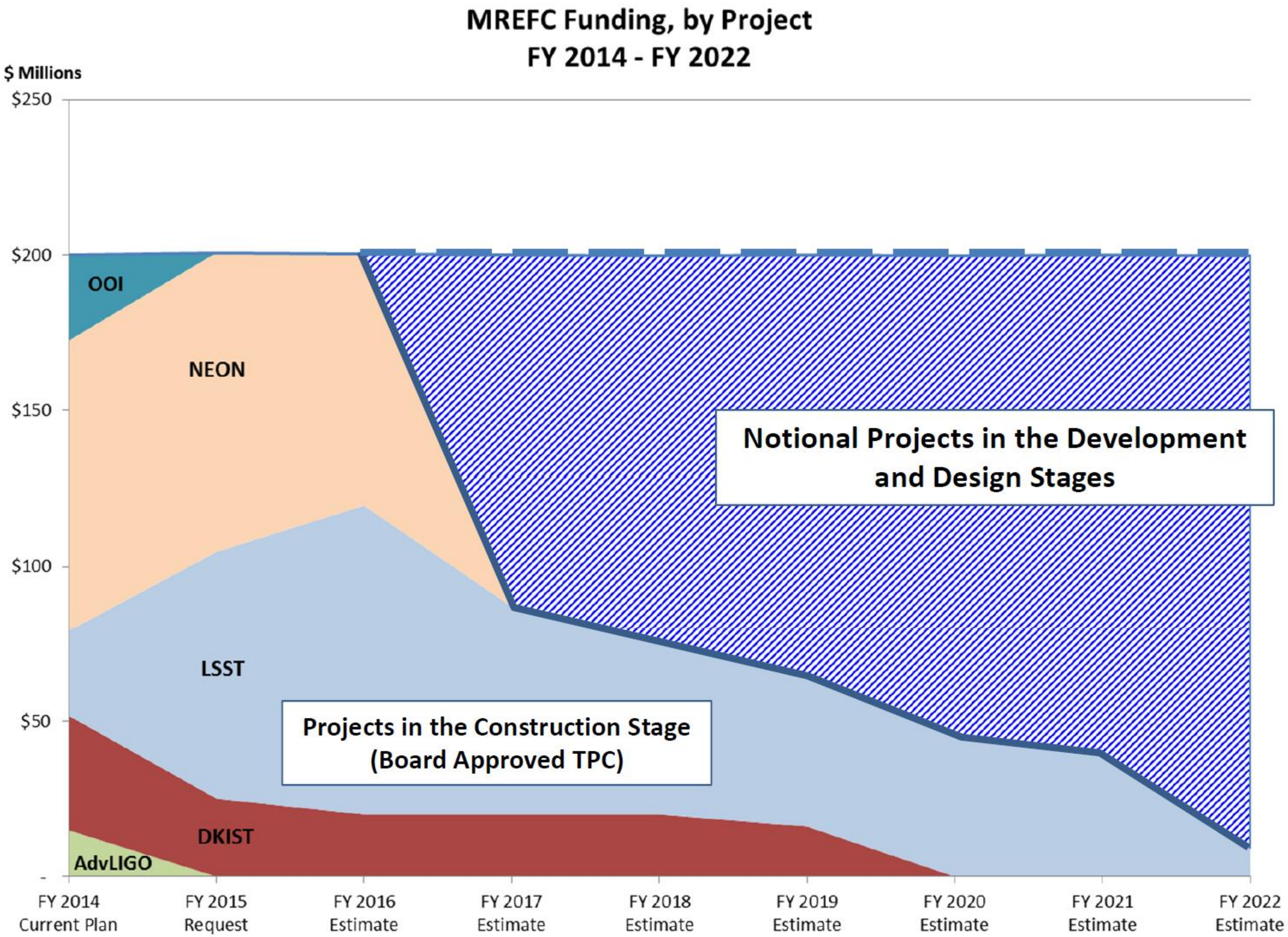
MREFC Budget

Figure at right shows NSFs long-range MREFC planning. NEON was recently de-scoped and may end sooner than planned.

No projects aside from AIMS and RCRV – both GEO division – in MREFC queue. There could be others in development stage like IceCube Gen2.

Assuming budget stays flat, there is budget in MREFC account past 2018.



Summary

- Neutrino astrophysics has come from limit setting to detection to confirmation in just over 2 years. The field is alive and invigorated – we now have events but what are their origins?
- The Collaboration is looking to issue a more detailed LoI to follow the Whitepaper using our current baseline.
- IceCube Gen2 is not just more DOMs. It is a wide band neutrino observatory (MeV – EeV) that will use a number of detection technologies – optical, radio, and surface veto – to achieve the science in this rapidly evolving new field.
  - The initiative has stimulated research into new photodetection – multi-anode PMTs, better glasses, and wavelength shifting materials for use in ice.
  - Rethinking radio detection, in particular with an eye on scalability to large arrays is also prudent.
  - Surface arrays may help significantly – we need R&D money to fully explore our options
- In every possible scenario, this is a large-scale project which will not be completed within ten years from this point.
- Technically the project is feasible given the long experience with IceCube.
- Funding is challenging and spans many constraints in many countries, however a window exists.
- NEW! KM3NeT is happening – this is great news we congratulate them and look forward to data from the Med.

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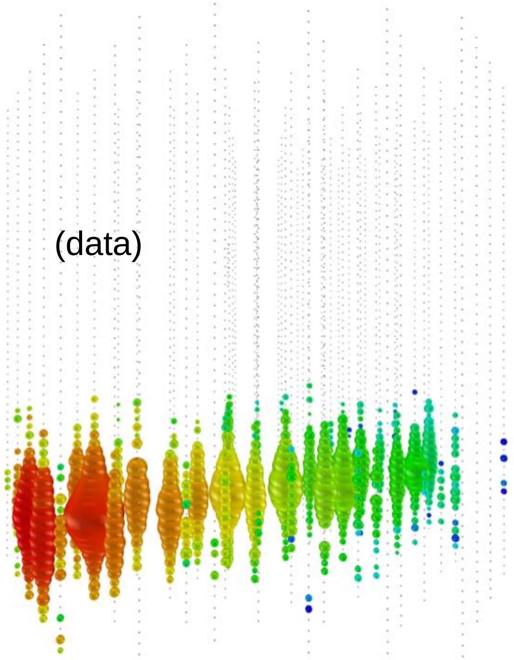
The END – Mahalo!

Neutrino event signatures

Charged-current ν_μ

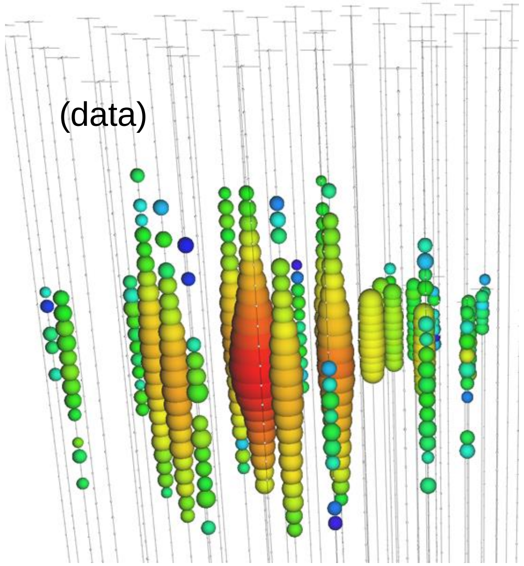


(data)

Up-going track

Factor of ~2 energy resolution
< 1 degree angular resolution

Neutral-current / ν_e

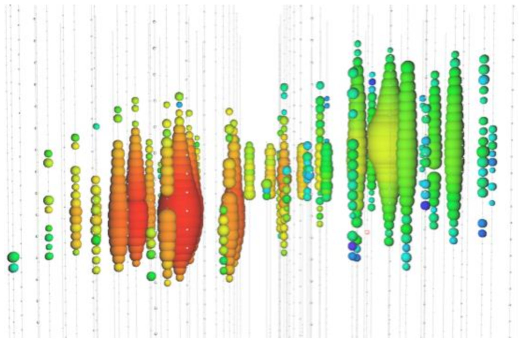


(data)

Isolated energy deposition
(cascade) with no track

15% deposited energy resolution
10 degree angular resolution (above 100 TeV)

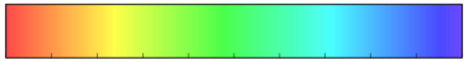
Charged-current ν_τ



(simulation)

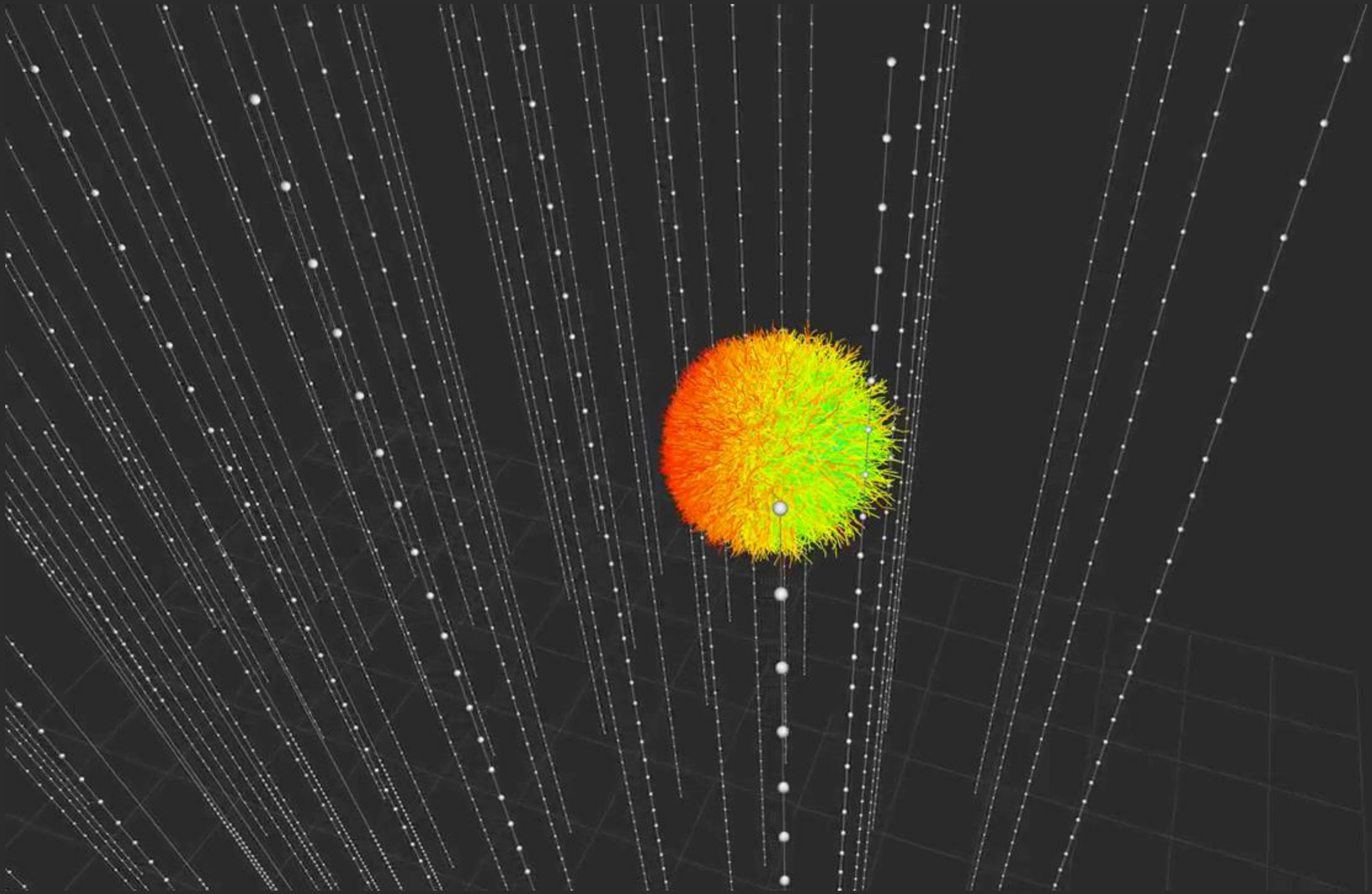
“Double-bang”

(none observed yet: τ decay
length is 50 m/PeV)

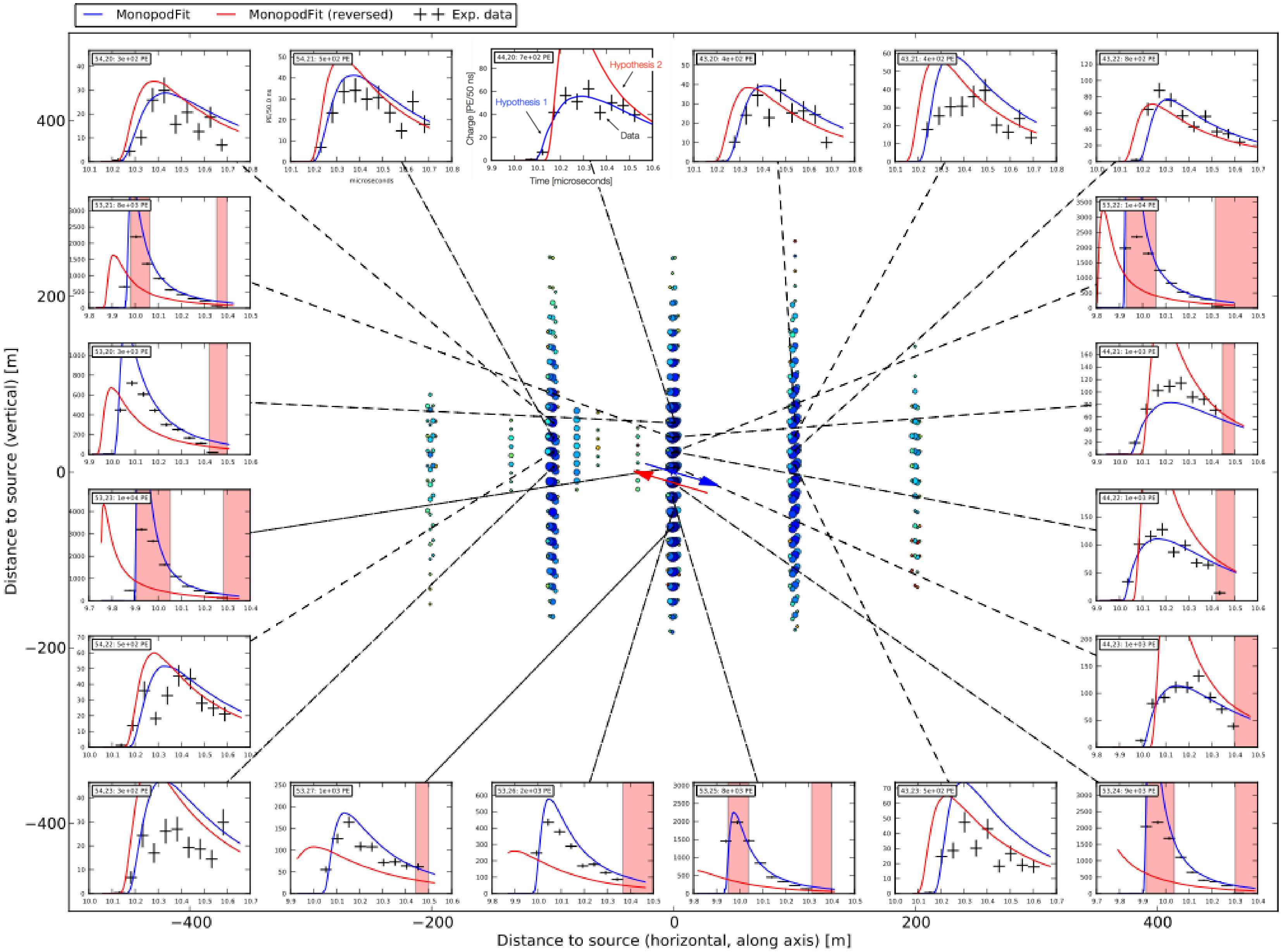


An electromagnetic cascade in ice

(C. Kopper)



Likelihood fit: Millipede/Monopod



Jakob van Santen - Contained cascade reconstruction - Aachen, October 2012

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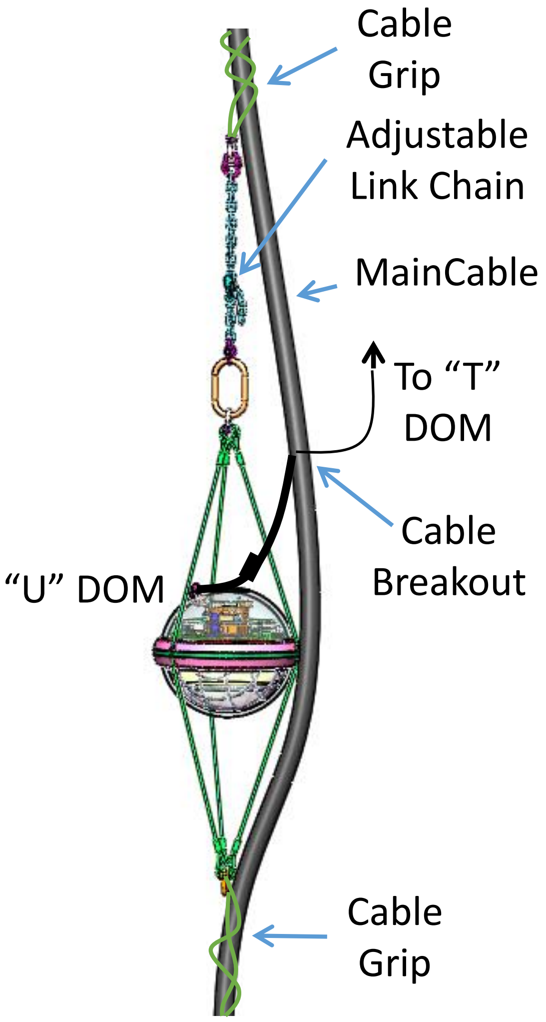
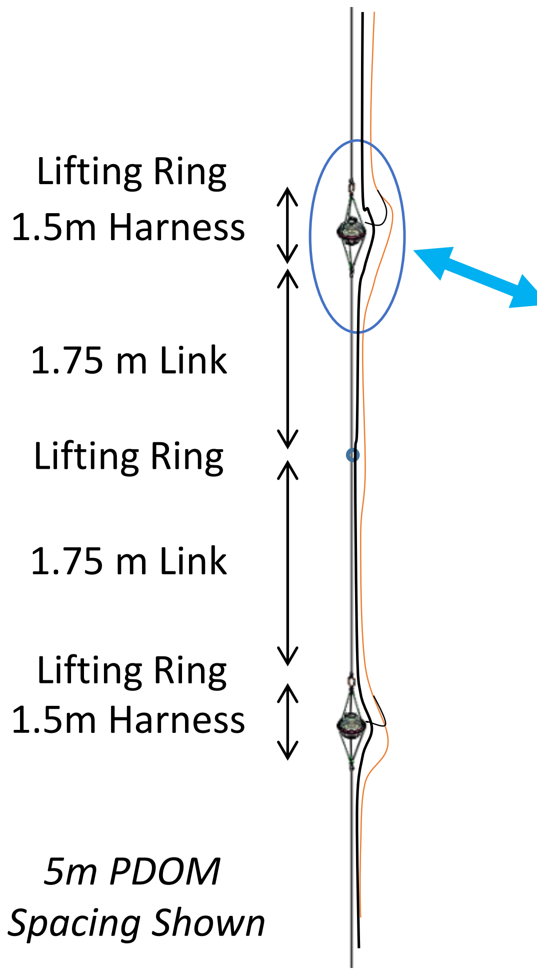
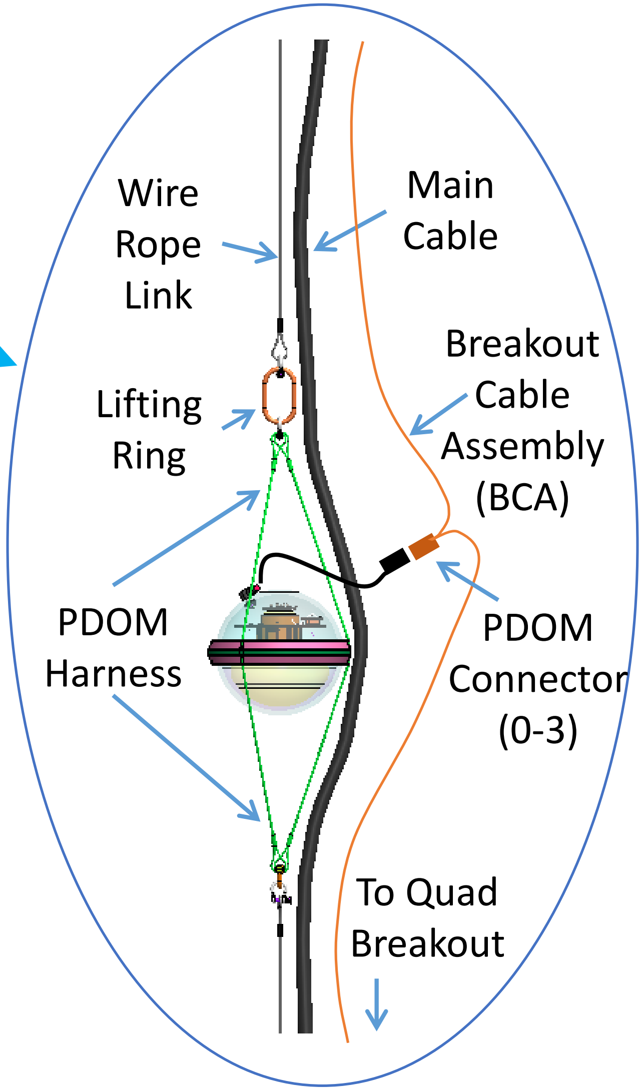
Proposed PINGU String Architecture



IceCube Detail



PINGU String



PINGU Detail

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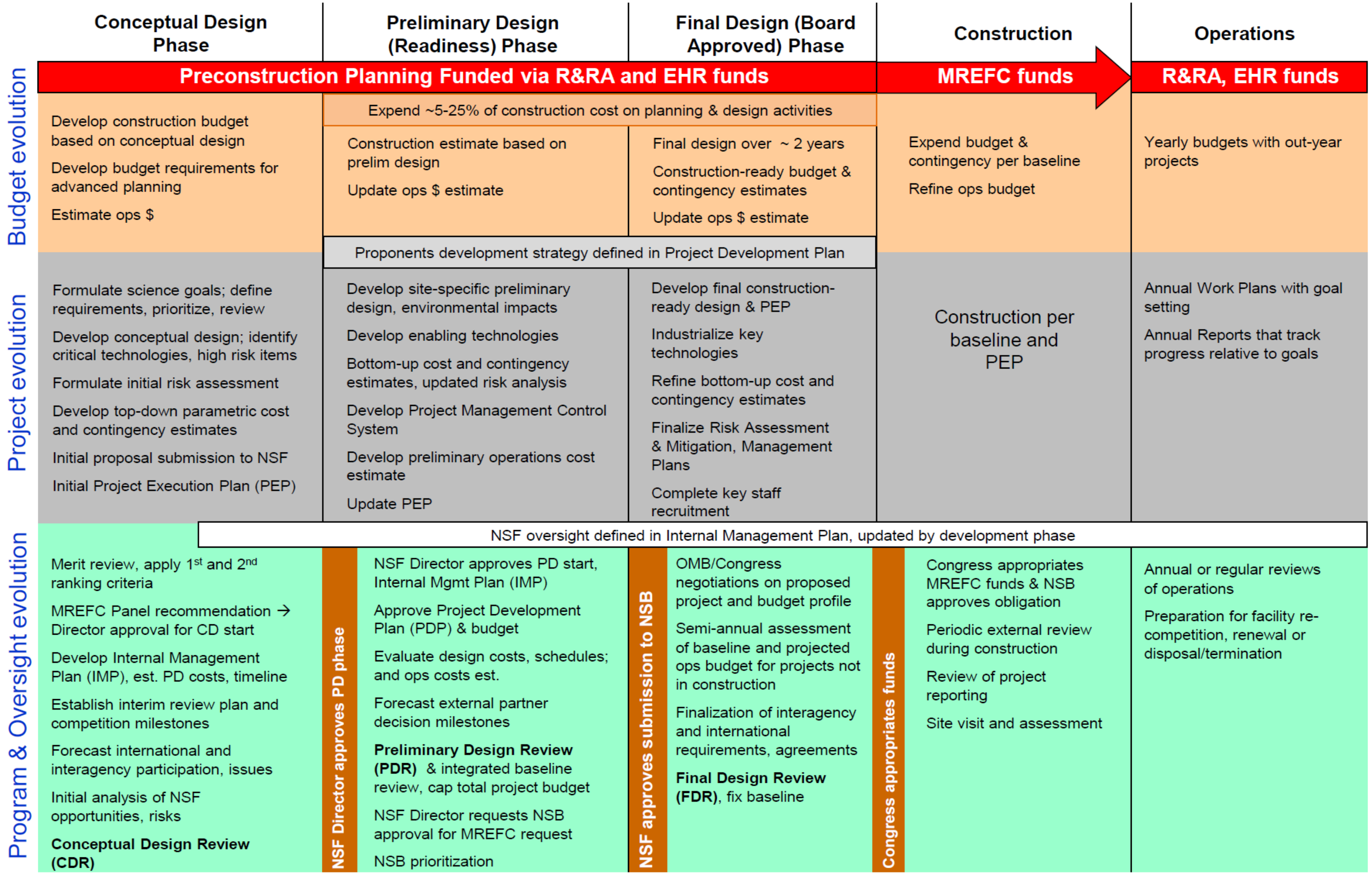
Drill Costs (EHWD-G2, 1 Drill Scenario)

Drill development and construction	$25 M
9 field seasons	9 * $1.2 M
Setup / teardown	$1.8 M

- Costing for the 2 drill scenario has not been worked out …
- Cost reduction of 3 seasons will be eaten up by larger drill crew footprint per season.
- It's going to be significantly more expensive building and operating 2 drills vs 1.

MREFC Process



	Conceptual Design Phase	Preliminary Design (Readiness) Phase	Final Design (Board Approved) Phase	Construction	Operations
	Preconstruction Planning Funded via R&RA and EHR funds			**MREFC funds**	**R&RA, EHR funds**
Budget evolution	Develop construction budget based on conceptual design Develop budget requirements for advanced planning Estimate ops $	Expend ~5-25% of construction cost on planning & design activities		Expend budget & contingency per baseline Refine ops budget	Yearly budgets with out-year projects
		Construction estimate based on prelim design Update ops $ estimate	Final design over ~ 2 years Construction-ready budget & contingency estimates Update ops $ estimate		
		Proponents development strategy defined in Project Development Plan			
Project evolution	Formulate science goals; define requirements, prioritize, review Develop conceptual design; identify critical technologies, high risk items Formulate initial risk assessment Develop top-down parametric cost and contingency estimates Initial proposal submission to NSF Initial Project Execution Plan (PEP)	Develop site-specific preliminary design, environmental impacts Develop enabling technologies Bottom-up cost and contingency estimates, updated risk analysis Develop Project Management Control System Develop preliminary operations cost estimate Update PEP	Develop final construction-ready design & PEP Industrialize key technologies Refine bottom-up cost and contingency estimates Finalize Risk Assessment & Mitigation, Management Plans Complete key staff recruitment	Construction per baseline and PEP	Annual Work Plans with goal setting Annual Reports that track progress relative to goals
	NSF oversight defined in Internal Management Plan, updated by development phase				
Program & Oversight evolution	Merit review, apply 1st and 2nd ranking criteria MREFC Panel recommendation → Director approval for CD start Develop Internal Management Plan (IMP), est. PD costs, timeline Establish interim review plan and competition milestones Forecast international and interagency participation, issues Initial analysis of NSF opportunities, risks **Conceptual Design Review (CDR)**	**NSF Director approves PD phase** NSF Director approves PD start, Internal Mgmt Plan (IMP) Approve Project Development Plan (PDP) & budget Evaluate design costs, schedules; and ops costs est. Forecast external partner decision milestones **Preliminary Design Review (PDR)** & integrated baseline review, cap total project budget NSF Director requests NSB approval for MREFC request NSB prioritization	**NSF approves submission to NSB** OMB/Congress negotiations on proposed project and budget profile Semi-annual assessment of baseline and projected ops budget for projects not in construction Finalization of interagency and international requirements, agreements **Final Design Review (FDR)**, fix baseline	**Congress appropriates funds** Congress appropriates MREFC funds & NSB approves obligation Periodic external review during construction Review of project reporting Site visit and assessment	Annual or regular reviews of operations Preparation for facility re-competition, renewal or disposal/termination