IceCube Overview

IceCube Upgrade Rebaseline Review

April 26-28, 2022

Kael Hanson – IceCube Upgrade Principal Investigator

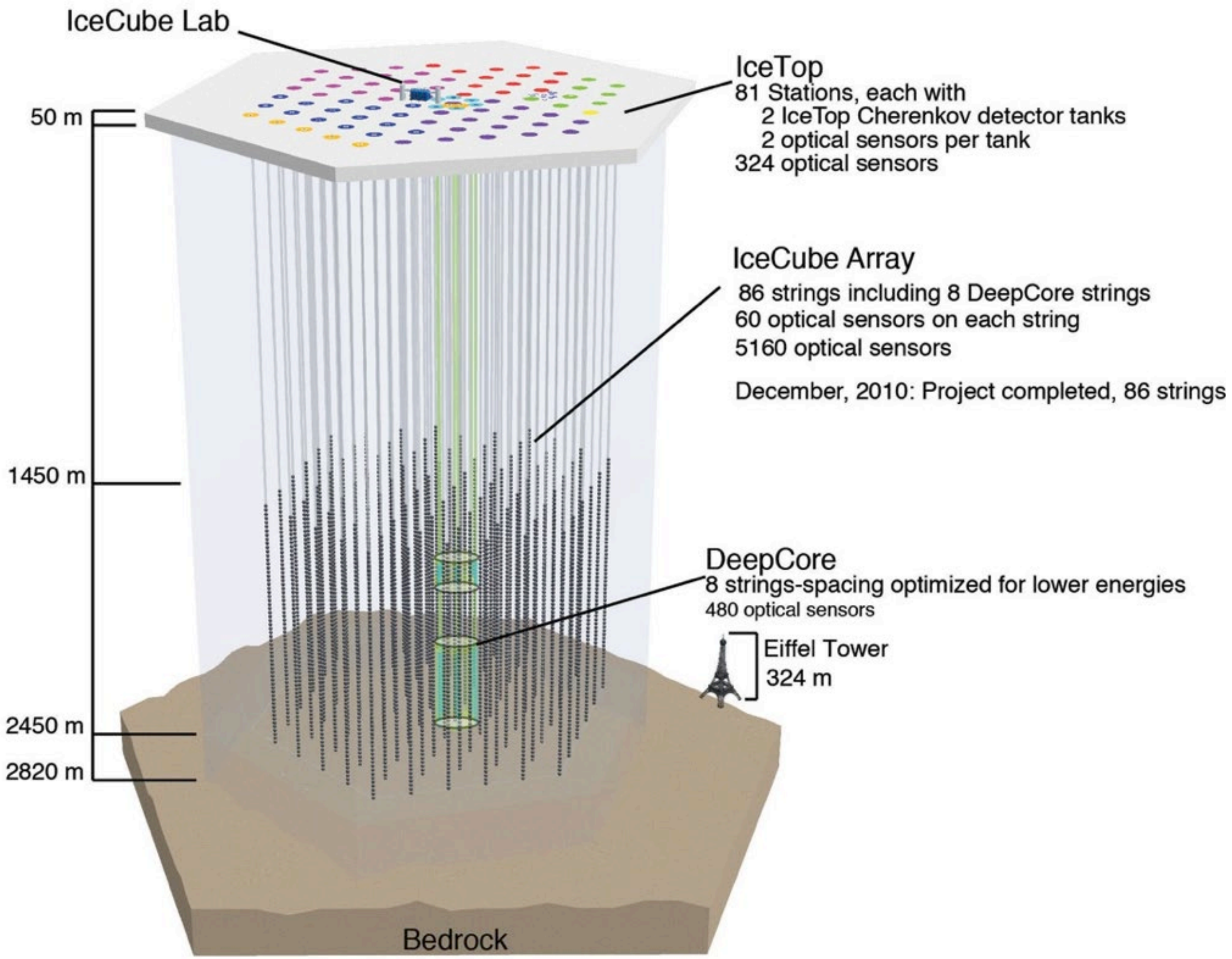
ICECUBE UPGRADE

Brief Bio – Kael Hanson

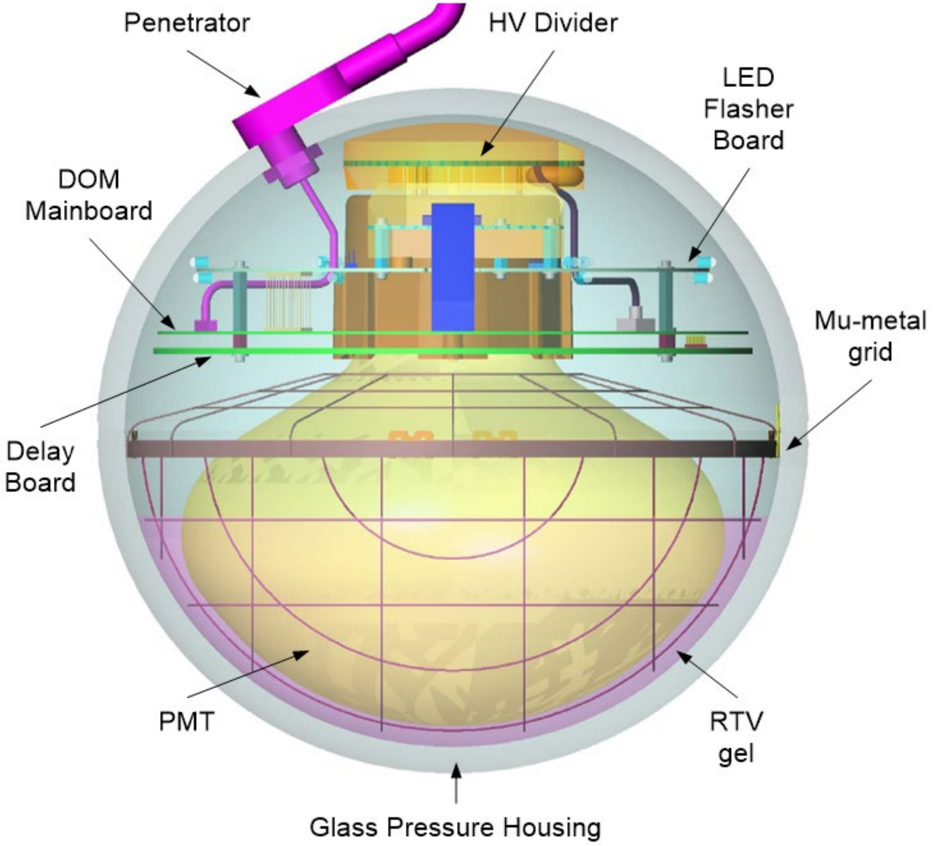
Education University of Michigan (2000) PhD Physics MACRO detector at Gran Sasso

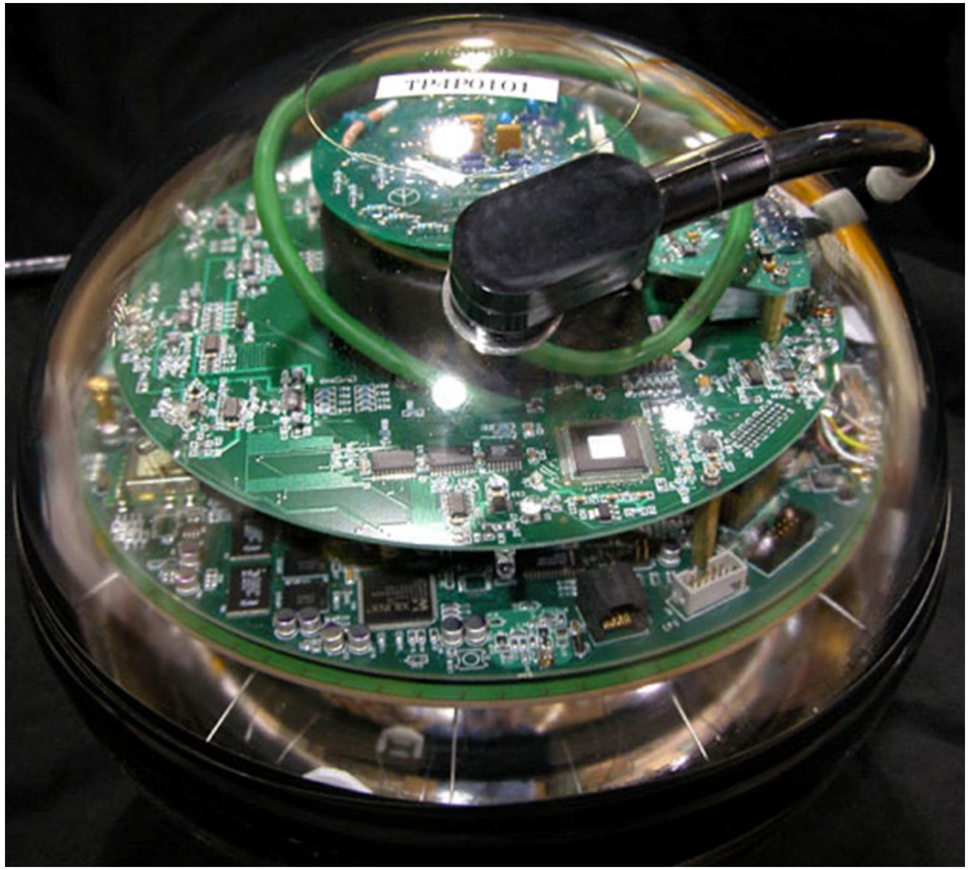
- Joined IceCube @ UPenn in 2000 when it was still AMANDA.
- Began with UW-Madison in 2002 shortly after IceCube MREFC started as postdoc.
- Led In-Ice Devices (2003-2006) and Instrumentation (2006-2008)
- Spent 6 years as faculty at Université Libre de Bruxelles (2008-2014)
- Rejoined UW-Madison as faculty / IceCube Director (2014)
- PI of Upgrade project.

IceCube: The Detector Array



IceCube Detector Element: The Digital Optical Module



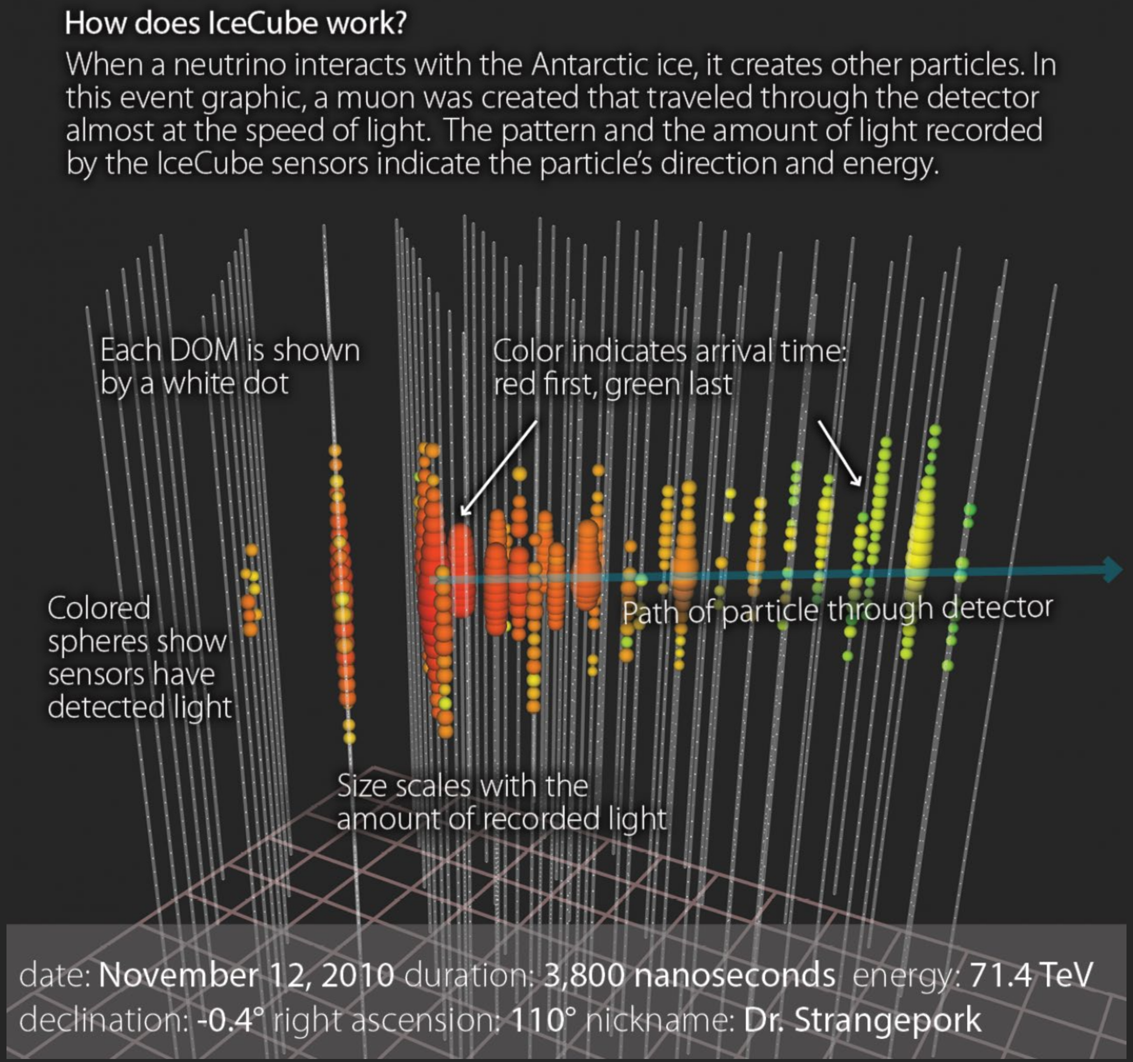


Detecting Neutrinos in the Ice

IceCube is a "water" Cherenkov detector: we detect the charged ultra-relativistic secondaries which are produced in neutrino scattering in ice or detect CR muons and their stochastic secondaries.

Ice is a good calorimetric medium.

Angular resolution for tracks is now < 0.5°, for cascades with DNN techniques can be as good as 5° : significant progress in the last 4-5 years.



The IceCube Upgrade

Infill array for neutrino physics and precision characterization of the ice.

Science Requirements

Charge Question ST1

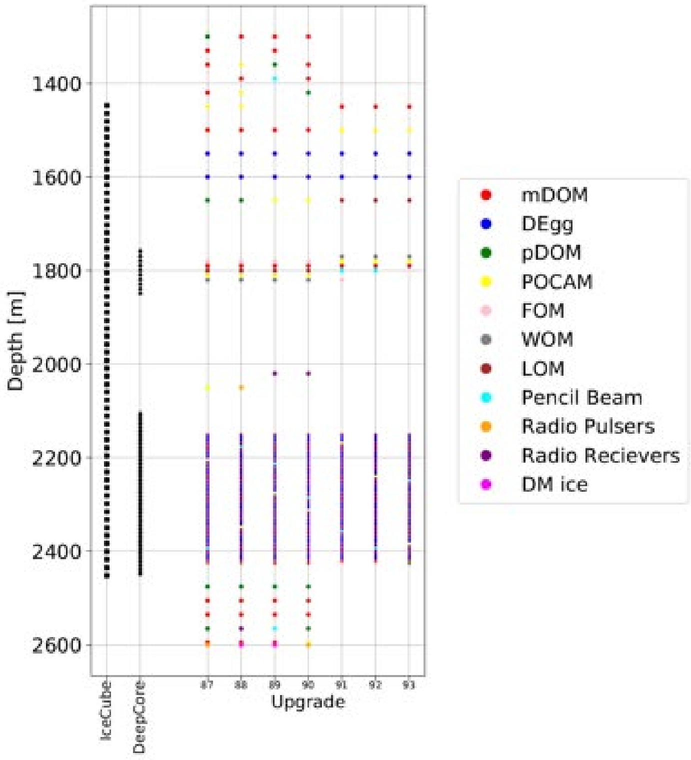
PRIMARY SCIENCE REQUIREMENTS	SCIENCE OBJECTIVES - THE ICECUBE UPGRADE: Tau Neutrino Appearance and the Unitarity of the PMNS Matrix (2.1)	Neutrino Oscillations (2.2)	Sterile Neutrinos (2.2)	Indirect Dark Matter (2.2)	Ice Characterization for better LE & HE flavor physics (2.3)		
Event Energy Range	**few to 100 GeV**	**few to 100 GeV**			**TeV to >PeV**		
Expected Detectable Event Rate	**Measurement in 2-3 years**	**5-10% tau measurement**	**Any detection/improved limit**	**Any detection/improved limit**	**100s / year**		
Desired Angular Resolution	**<5 deg at O(20 GeV)**						
Time Resolution Within Event	**2-5** ns	**2-5ns**					
Absolute Time Accuracy					50 ns		

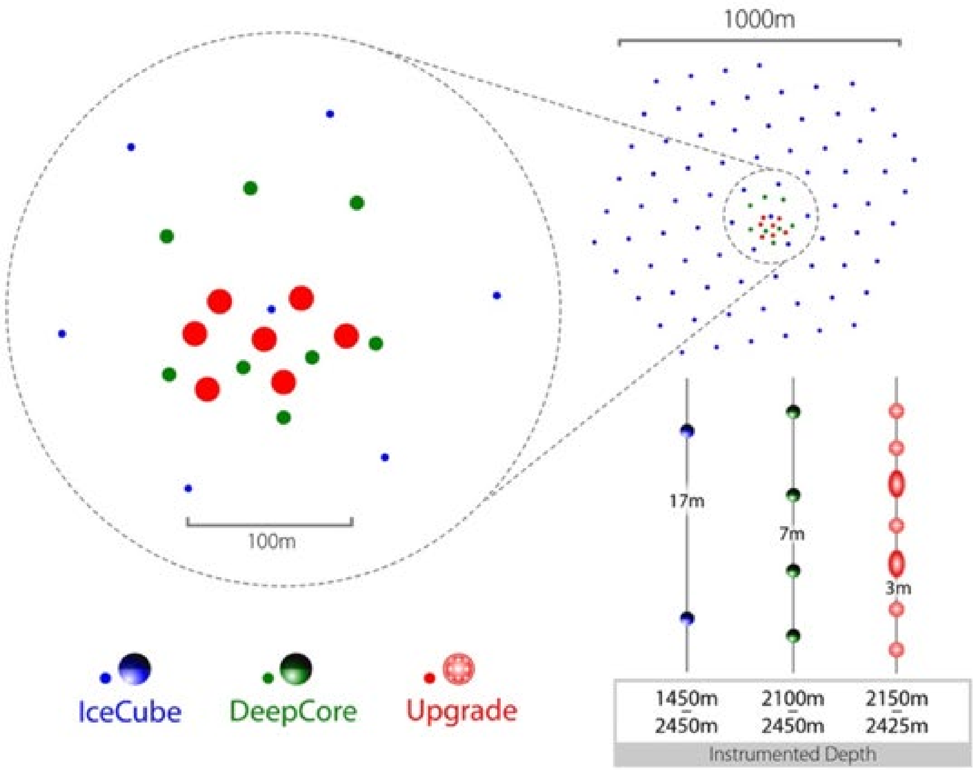
			Absolute Time Accuracy	Time Resolution Within Event	Desired Angular Resolution	Expected Detectable Event Rate	Event Energy Range
InIce Sensor Array Geometry	Instrumented Ice Volume	About 2 million cubic meters		√	√	√	√
	Array Shape	Compact		√	√	√	√
	Effective Volume	Varies with energy level and event orientation (derived from other properties)		√	√	√	√
	Number of Strings	7		√	√	√	√
	multi-PMT Digital Optical Modules (mDOM) per String	108 (90 in the dense physics region, others above and below for primarily calibration purposes) - 46 mDOMs, 38 D-Eggs, & 6 pDOMs		√	√	√	√
	Total Number of mDOM	~750 (photocathode area is key parameter here)		√	√	√	√
	mDOM Spacing - Horizontal	22 meters (compromise between closer and drill constraints)		√	√	√	√
	mDOM Spacing - Vertical	3.0 m		√	√	√	√
	Detector Depth	Physics region: 2150-2425m Upper region: 1450-2150 Deep region: 2425-2600m		√	√	√	√
Individual mDOM Performance	Sensitivity of mDOM	Single Photo Electron (SPE)		√	√	√	√
	mDOM Photon Event Dynamic Range	SPE to >200 PE / 15 ns		√	√	√	√
	mDOM Field of View	Spherical with <10% variation, except for cable shaddowing.		√	√	√	√
	Digitization Rate Waveforms < 400 ns	300 megasamples / second		√		√	√
	Digitization Rate Waveforms > 400 ns	40 megasamples / second		√		√	√
	Absolute Amplitude Calibration Accuracy	< 5 %		√	√	√	
	Timing Accuracy	< 5 ns		√	√	√	
Event / Background Discrimination (Noise Reduction)	mDOM Noise Rate	O(10kHz) total noise rate, <850 Hz per PMT				√	√
	mDOM Data Processing	Initial waveform capture and digitization in DOM, context sensitive compression of data prior to transfer		√		√	
	Local Coincidence Function	In mDOMs, might require N of 24 PMTs hit within time window to suppress noise.		√		√	
	Event Trigger Function	Global (surface) trigger logic to package event data and discriminate noise		√	√	√	√
	Veto Function	Surface Array (IceTop) allows identification and discrimination of downgoing background		√	√	√	√
Data Transport and Storage	Incoming Data Stream from Sensor Array	150 Gig / day		√	√	√	√
	Non-Volatile Storage at South Pole	1-2 Day Buffer / Archive Capacity & Full Redundancy Requirements	√			√	
	South Pole High Priority Communications	At all times, it must be possible to complete a minimum 10KB transfer to the Northern Hemisphere within 10 minute period. (SNEWS and GRB Reporting)	√			√	
	South Pole Medium Priority Communications	500 MB / day	√			√	
	South Pole High Volume Data Transfer	>30 GB / day	√			√	
	Northern Hemisphere Data Warehouse	Fully Buffered / Archive Capacity & Redundancy Requirements	√			√	

Scientific Goals → Technical Requirements

- Module design (segmented PMT) + array geometry (photocathode density) determine reconstruction accuracy in function of E
- Array geometry (instrumented volume) determines event rate
- IceCube provides surrounding veto for background elimination
- New calibration instruments (cameras, flashers, POCAM, Pencil Beam) probe ice properties on baselines shorter than 1 scattering length and with enhanced precision.
- Increased instrumentation density → more modules per wire pair → power + B/W constraints
- Upgrade array must interoperate seamlessly with IceCube (“just another string or set of strings”) – module communication standardized by ICM (“all devices speak DOM”)

Project Objectives (Unchanged Since 2016)





7 strings - 693 Optical sensors:

- 277 D-Eggs (2x 8” PMT)
- 402 mDOMs (24x 3” PMT)
- 14 PDOMs
- Calibration devices

2 Mton effective volume for LE neutrino events:

- trigger down to 1 GeV
- 90% efficient at 3 GeV

Single Drill / Install Season

1. **Neutrino Properties**
2. **Recalibration and Reanalysis of IceCube Data**
3. **IceCube-Gen2 Research and Development**

The Four Pillars of the Upgrade

Charge Questions R4; M1

National Science Foundation

MPS/PHY Funded ($22.983M original TPC)

GEO/OPP provides logistics support including cargo, fuel, on-ice field work and population support **not costed in Project budget.**

IceCube Upgrade Project	IceCube M&O	IceCube Collaboration
• Project Management • Drilling & Installation • Sensors • Cable Systems • Calibration • M&O Data Systems Integration	Supports integration of Upgrade Project into IceCube Detector and Software Systems– much of M&O Data Systems labor resources are supported by the M&O program. **Upgrade will transition into mature operations program at little additional cost.**	Collaboration in-kind contributions of instrumentation: D-Eggs, mDOMs, calibration devices, and downhole raw cable – approx. $14M. Collaboration labor and computing resources coordinated through M&O structures.

THE ICECUBE COLLABORATION

AUSTRALIA
University of Adelaide

BELGIUM
Université libre de Bruxelles
Universiteit Gent
Vrije Universiteit Brussel

CANADA
SNOLAB
University of Alberta–Edmonton

DENMARK
University of Copenhagen

GERMANY
Deutsches Elektronen-Synchrotron
ECAP, Universität Erlangen-Nürnberg
Humboldt–Universität zu Berlin
Karlsruhe Institute of Technology
Ruhr-Universität Bochum
RWTH Aachen University
Technische Universität Dortmund
Technische Universität München
Universität Mainz
Universität Wuppertal
Westfälische Wilhelms-Universität Münster

JAPAN
Chiba University

NEW ZEALAND
University of Canterbury

REPUBLIC OF KOREA
Sungkyunkwan University

SWEDEN
Stockholms universitet
Uppsala universitet

SWITZERLAND
Université de Genève

UNITED KINGDOM
University of Oxford

UNITED STATES
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Harvard University
Lawrence Berkeley National Lab
Loyola University Chicago
Marquette University
Massachusetts Institute of Technology
Mercer University
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines and Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
University of California, Berkeley
University of California, Irvine
University of Delaware
University of Kansas
University of Maryland
University of Rochester
University of Texas at Arlington
University of Utah
University of Wisconsin–Madison
University of Wisconsin–River Falls
Yale University

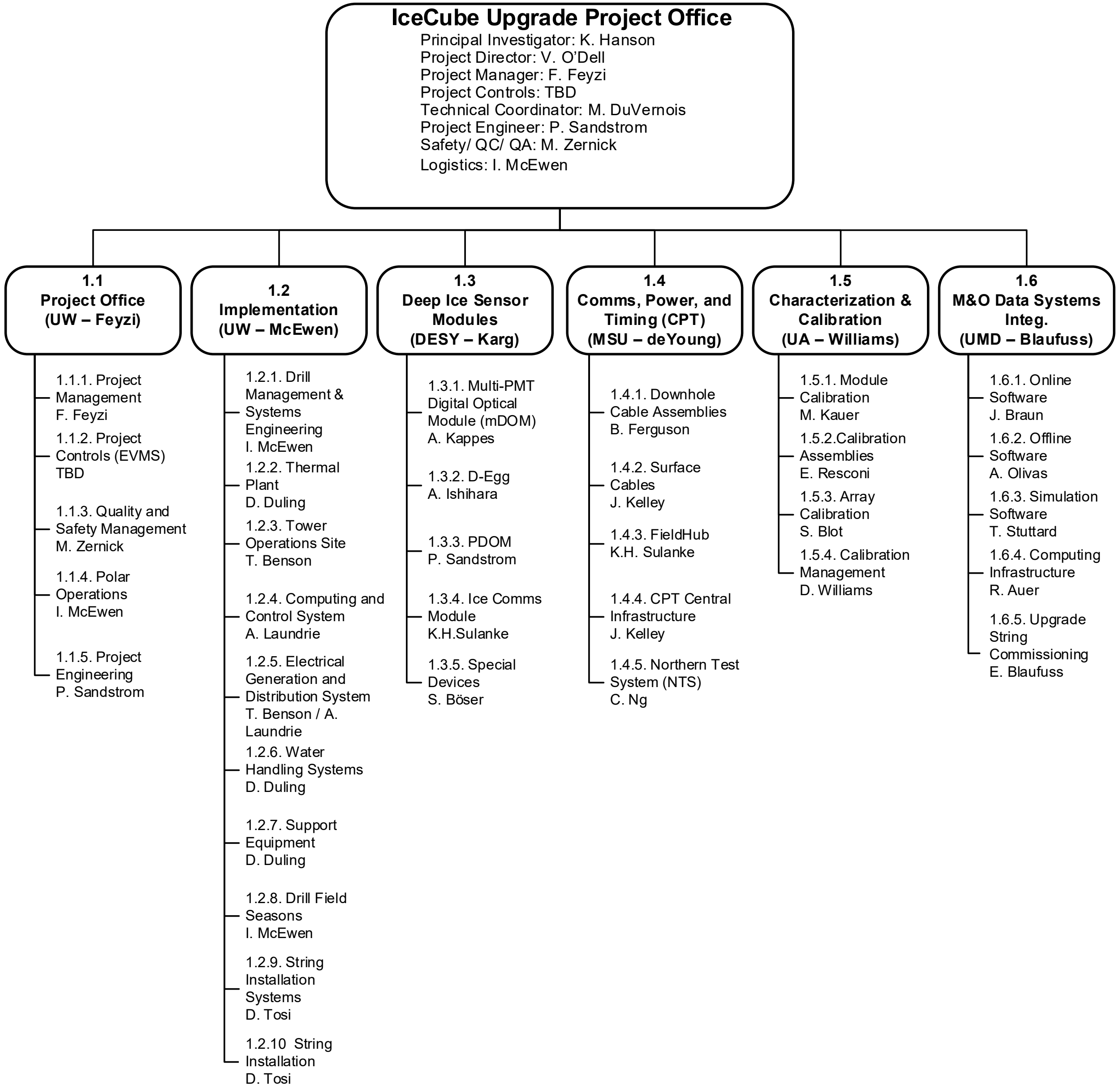
FUNDING AGENCIES

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education and Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

Following talks by L2 managers will go into further detail on major deliverable areas. WBS deliverables defined through *WBS Dictionary* to L4 *and* under change control.

WBS Tree structured functionally not by institution.



Cost (vs Time)

Increased On-Project Cost

2018 Initial Cooperative Agreement Budget
$20.1M Base
$2.8M Contingency

Add PO & technical staff
Surface cables

COVID
Loss of 3 field seasons
60 months → 91 months

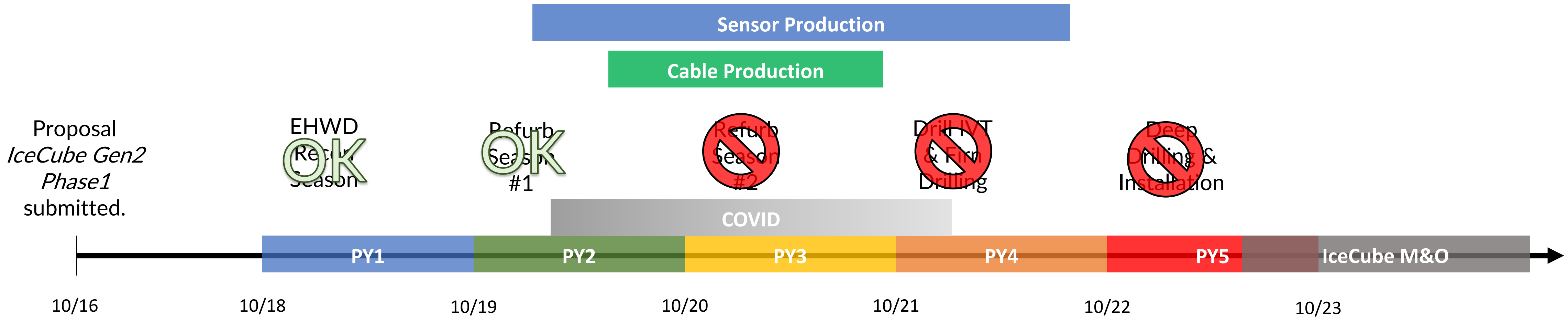
Additional in-kind contribution of PMTs from KIT

Reuse EHWD Generators instead of MicroTurbines

2022 Rebaseline
$32.2M Base
$3.7M Contingency

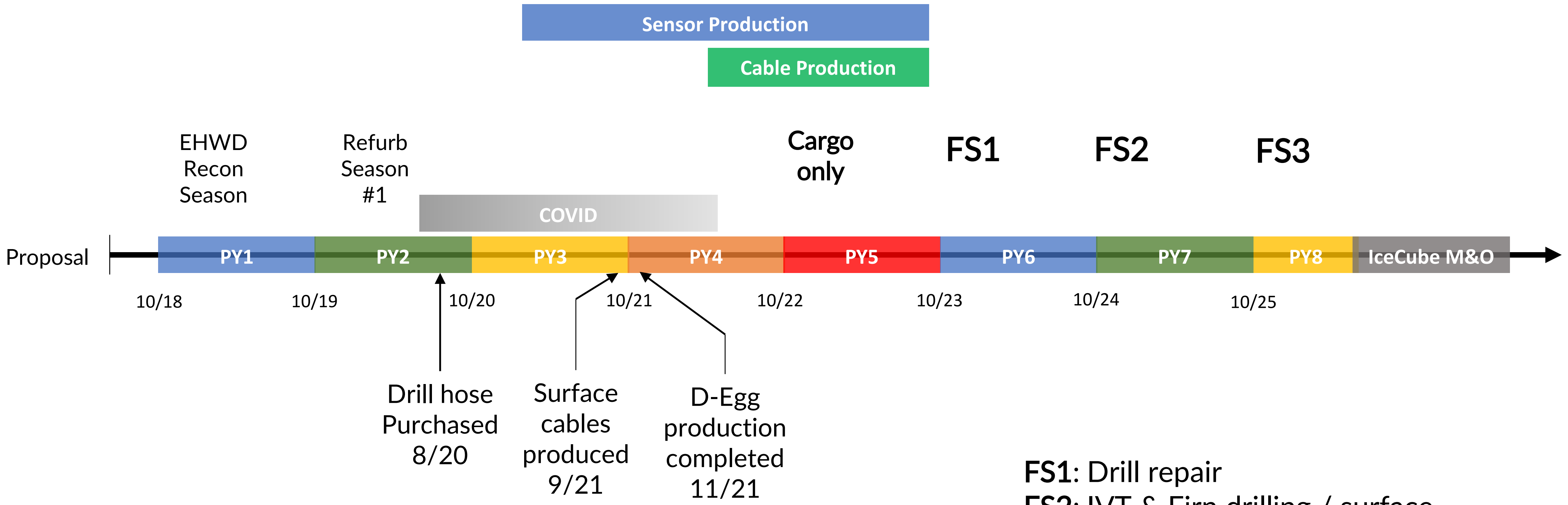
Decreased On-Project Cost

Simplified Project Timeline – Baseline Plan



Charge Questions S5, L1

Simplified Project Timeline – Rebaseline 2022



FS1: Drill repair
FS2: IVT & Firn drilling / surface
FS3: Deep drilling & installation

Charge Question S5

Hand-Off To IceCube Operations

- Handoff to IceCube M&O following FY26 drilling, installation, commissioning of strings : Milestone date is 04/06/2026 – this is within the first week of the next M&O cycle.
- Project complete 04/30/2026.
- Drill equipment packed during FY26 season, ready to retro.
- Retro to occur with small field team under M&O following season, or, alternatively equipment could remain on site for IceCube-Gen2 activities.

Considerations for the Next 2 Days

- Upgrade scientific objectives and technical scope remain unchanged 5 years after original proposal.
- The project has made significant progress: 300 of the 700 DOMs are completed; drill has completed recon and repair seasons; over $2.5M in major equipment purchases.
- Three-year delay principally due to COVID – the project has matured as a result and developed the rigor not only to complete the Upgrade scope, but also to transition to future larger-scale endeavors.