Neutrino astronomy

APC 4 review, Nov 2020, Zeuthen

Markus Ackermann (Group overview / RNO-G)
Summer Blot (Neutrino properties)
Timo Karg (IceCube Upgrade)
Marek Kowalski (IceCube-Gen2 + Communications strategy)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY

The neutrino astronomy group

R&D / Sensors Karg	**LE Science** Summer Blot	**HE Science** Ackermann
IceCube Upgrade (L2 sensor lead)	IceCube Upgrade (L3 calibration lead)	IceCube group lead
IceCube R&D mDOM electronics mDOM production	IceCube Upgrade Neutrino properties Calibration	Gen2 development Spectrum / Flavor composition
2 PhD	1 PD / 2 PhD	1 PD / 2 PhD / 1 MSc

NEW

Multi-messenger Franckowiak	Radio detection Nelles
analysis	W2 professorship (FAU Erlangen)
Real-time se… …no sources Optical/Gamma follow-up	Radio Neutrino Observatory in Greenland (RNO-G)
3 PD /4 PhD / 3 MSc	1 PD / 3 PhD / 1MSc

Anna F. left DESY end of August for RU Bochum

AP Scientific Computing Van Santen
IceCube Tier-1 management AMPEL development AP Computing coordination

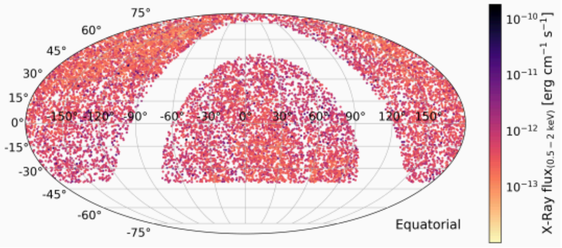
+ strong collaboration with ZTF group at HU (Nordin)

Scientific highlights

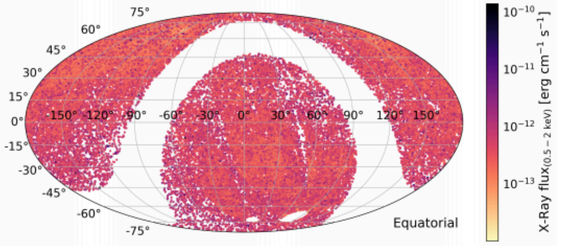
Neutrinos from AGN cores

- Search for a cumulative signal from many AGN cores.
- Selected in IR / radio.
- Model: neutrino flux ∝ soft x-rays.
- Paper in progress.

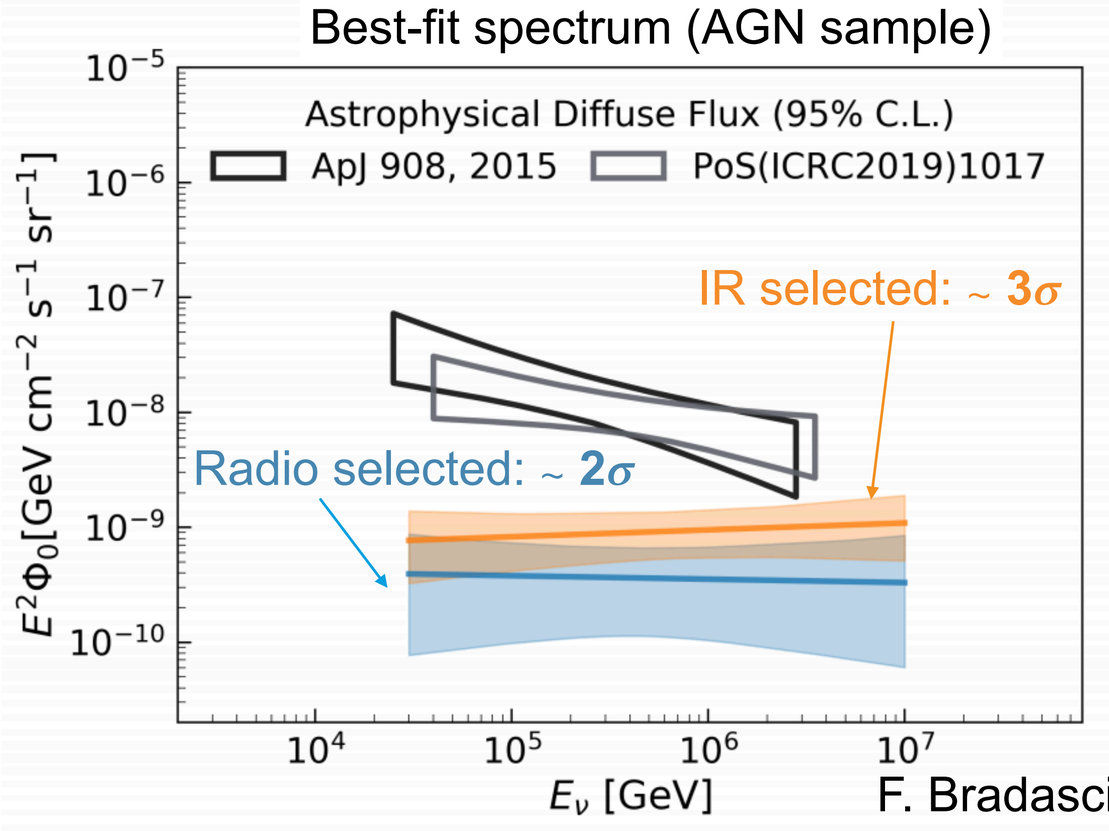
Radio-selected AGN
13927 sources



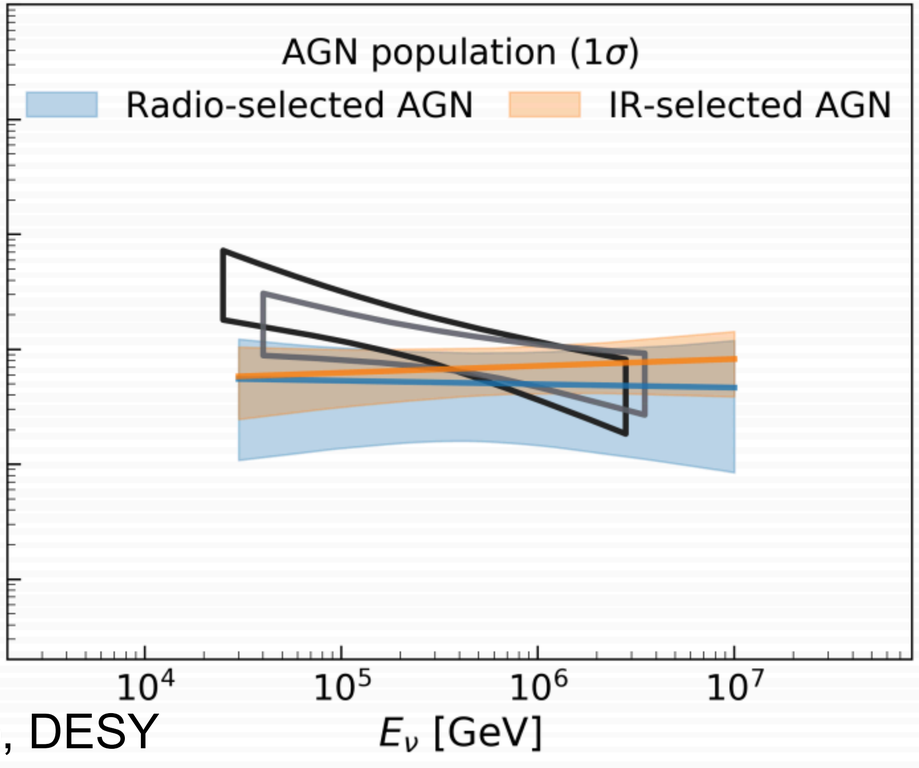
IR-selected AGN
52835 sources



Best-fit spectrum (AGN sample)



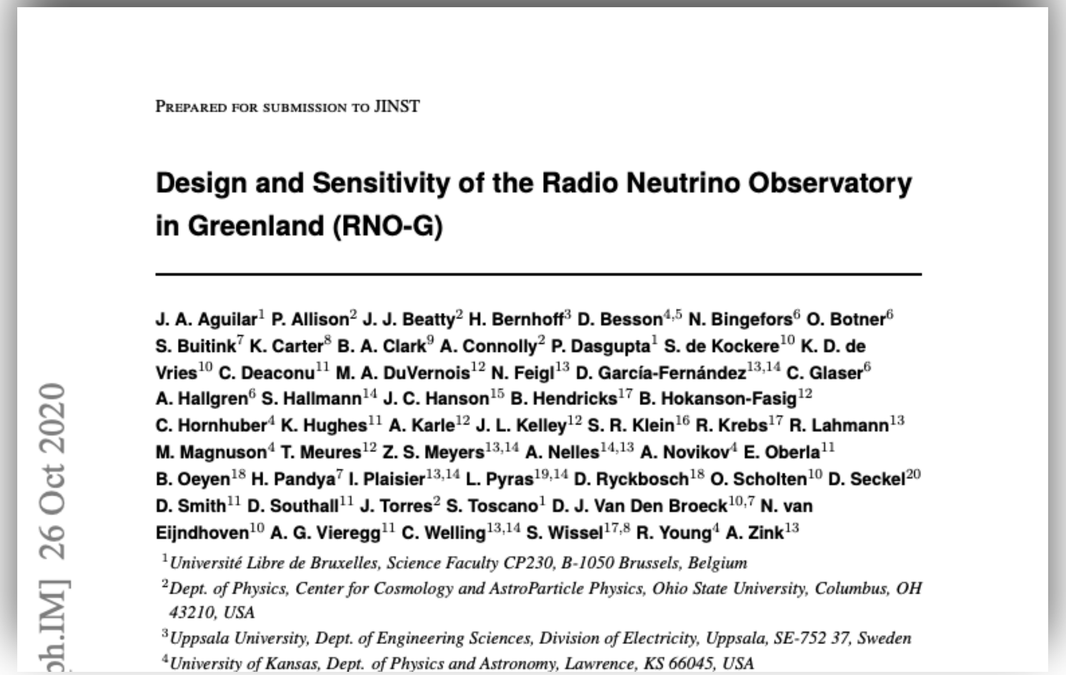
Best-fit spectrum (total population)



Selected important papers from the group

(submitted since April)

- Tau neutrino candidate observation paper (arXiv:2011.03561, submitted to PRL)
- High-energy neutrino / TDE correlation paper (arXiv:2005.05340, under review by Nature Astronomy)
- IceCube-Gen2 science white paper (arXiv:2008.04323, accepted by Journal of Physics G)
- RNO-G concept paper (arXiv:2010.12279, submitted to JINST)

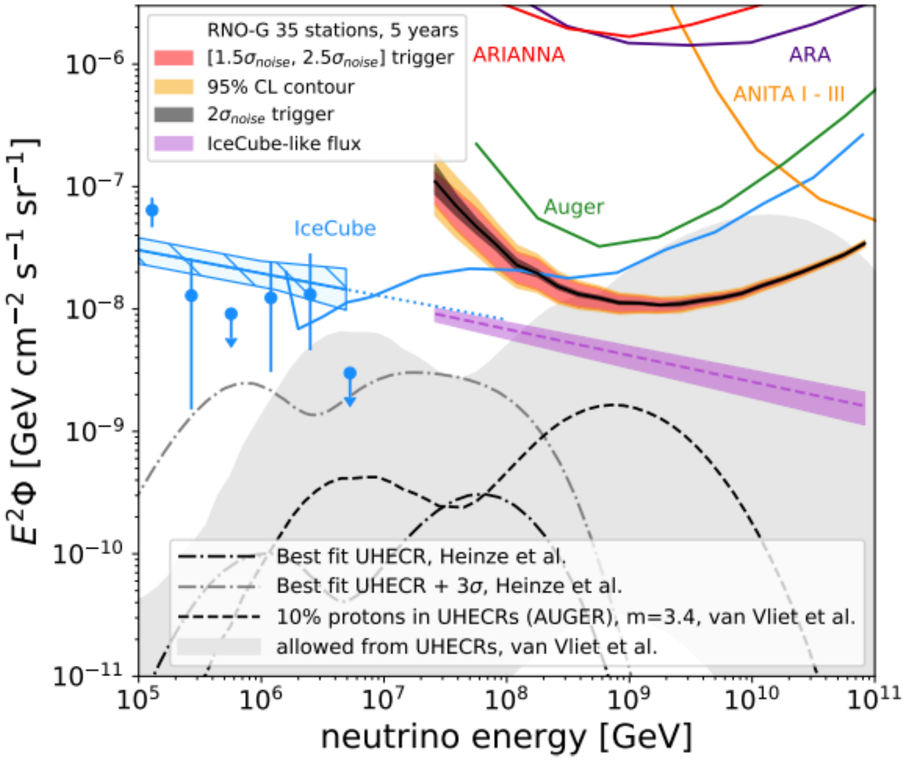


Prepared for submission to JINST

Design and Sensitivity of the Radio Neutrino Observatory in Greenland (RNO-G)

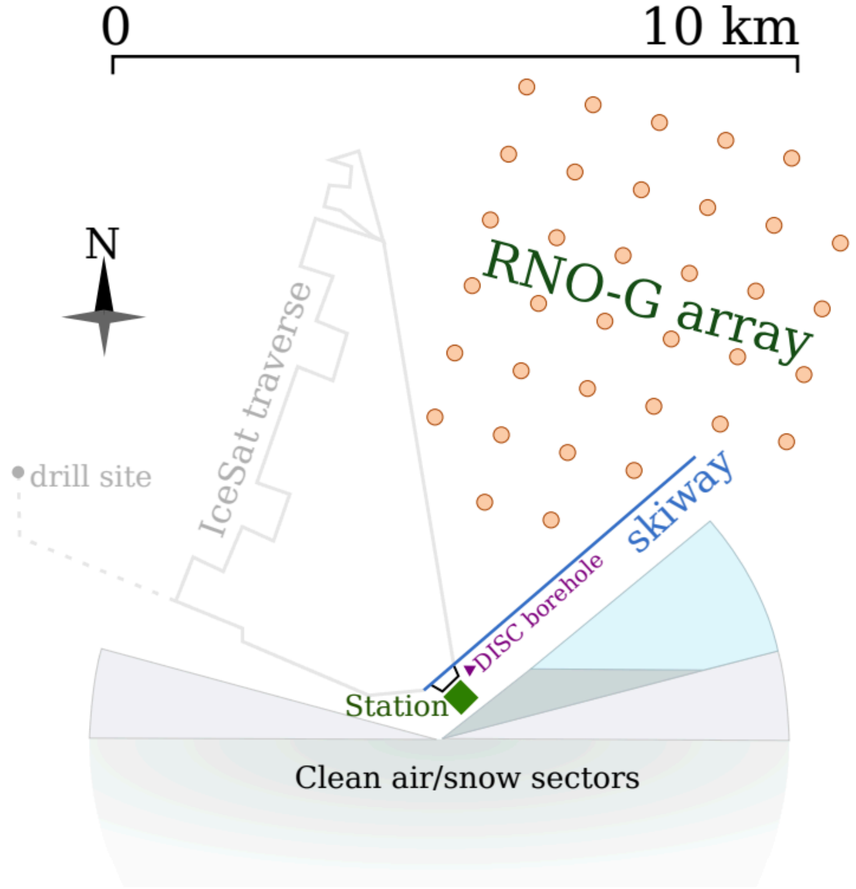
J. A. Aguilar[1] P. Allison[2] J. J. Beatty[2] H. Bernhoff[3] D. Besson[4,5] N. Bingefors[6] O. Botner[6] S. Buitink[7] K. Carter[8] B. A. Clark[9] A. Connolly[2] P. Dasgupta[1] S. de Kockere[10] K. D. de Vries[10] C. Deaconu[11] M. A. DuVernois[12] N. Feigl[13] D. García-Fernández[13,14] C. Glaser[6] A. Hallgren[6] S. Hallmann[14] J. C. Hanson[15] B. Hendricks[17] B. Hokanson-Fasig[12] C. Hornhuber[4] K. Hughes[11] A. Karle[12] J. L. Kelley[12] S. R. Klein[16] R. Krebs[17] R. Lahmann[13] M. Magnuson[4] T. Meures[12] Z. S. Meyers[13,14] A. Nelles[14,13] A. Novikov[4] E. Oberla[11] B. Oeyen[18] H. Pandya[7] I. Plaisier[13,14] L. Pyras[19,14] D. Ryckbosch[18] O. Scholten[10] D. Seckel[20] D. Smith[11] D. Southall[11] J. Torres[2] S. Toscano[1] D. J. Van Den Broeck[10,7] N. van Eijndhoven[10] A. G. Vieregg[11] C. Welling[13,14] S. Wissel[17,8] R. Young[4] A. Zink[13]

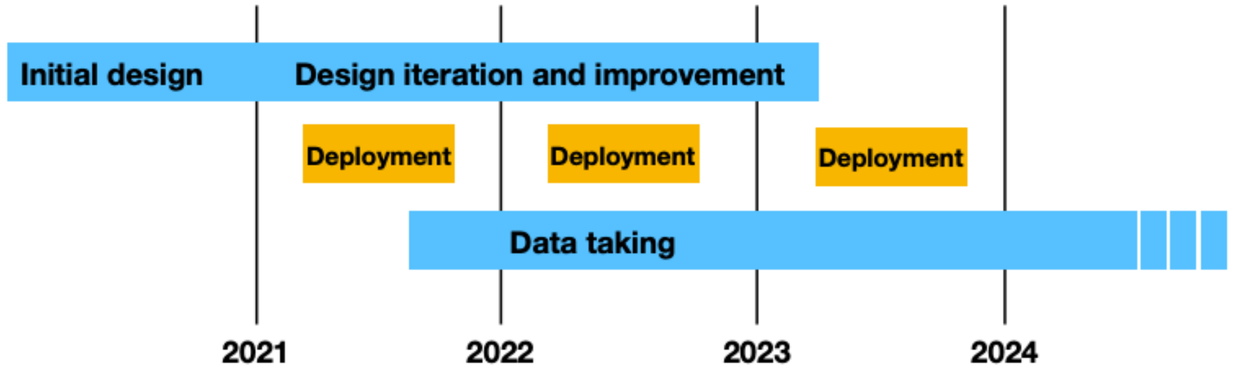
[1]*Université Libre de Bruxelles, Science Faculty CP230, B-1050 Brussels, Belgium*
[2]*Dept. of Physics, Center for Cosmology and AstroParticle Physics, Ohio State University, Columbus, OH 43210, USA*
[3]*Uppsala University, Dept. of Engineering Sciences, Division of Electricity, Uppsala, SE-752 37, Sweden*
[4]*University of Kansas, Dept. of Physics and Astronomy, Lawrence, KS 66045, USA*



Status of RNO-G efforts

- RNO-G concept paper lead by Anna Nelles submitted in October
- Hardware production for RNO-G stations nearly complete
- Deployment of RNO-G suffers from COVID-19 delays
  - Summer 2020 season has been cancelled
  - Deployment of 10 stations planned for 2021
  - Mechanical drill was purchased from British Antarctic Survey (from Belgian infrastructure grant)
- Main DESY deliverables: calibration (incl. database and software), deployment contributions

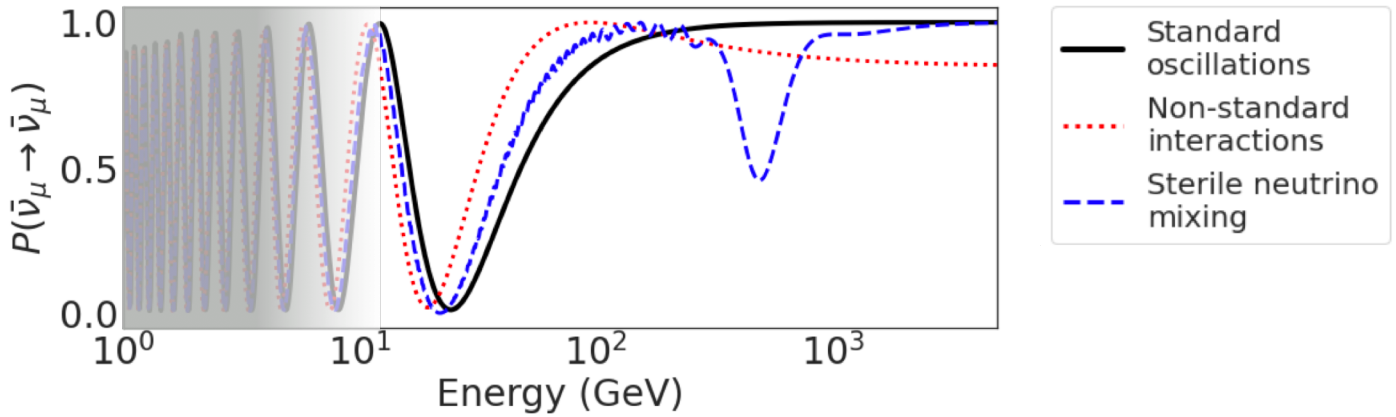


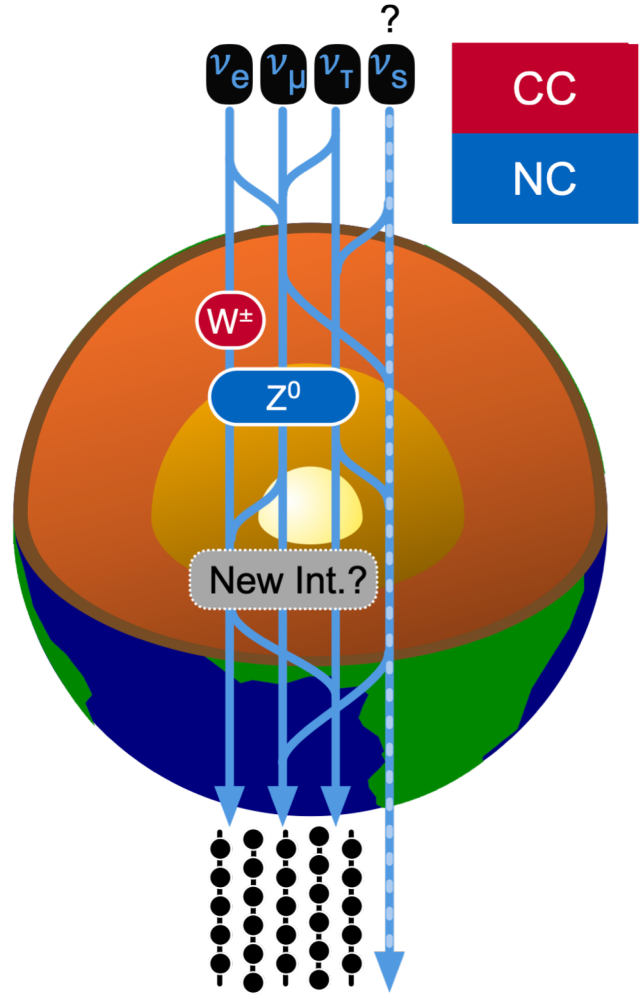


Low energy neutrino physics with IceCube

The goals

- Use IceCube DeepCore in-fill to produce World-leading measurements of atmospheric neutrino oscillations
  - 30 Mton fiducial volume, high energies and large propagation distances through complex matter profile -> unique access to non-standard oscillations physics
- Last few years have involved a massive undertaking to improve data quality -> *now complete*
  - Major DESY contributions to the revision of DeepCore event selection and development of analysis framework software
- DESY also plays a key role in generation of MC simulation and reconstruction for the future IceCube Upgrade detector



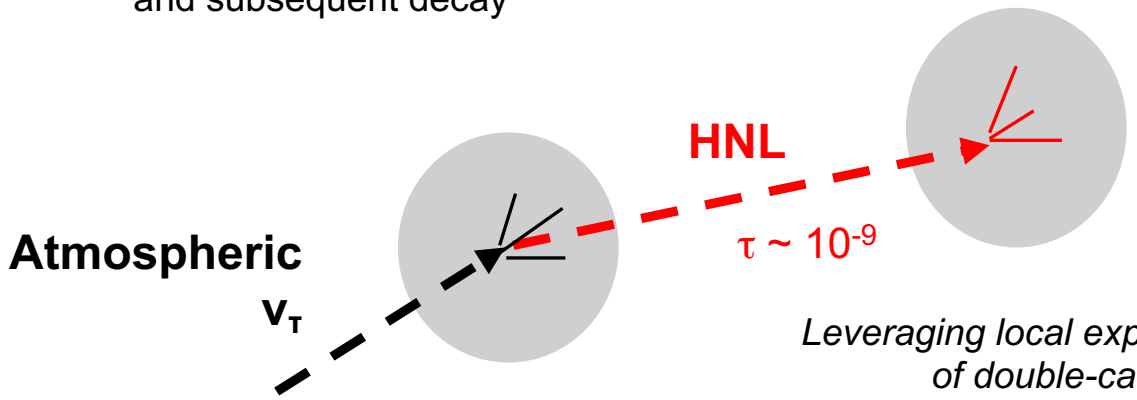


$$\hat{H} = \frac{1}{2E} U\hat{M}^2U^\dagger + \hat{V}_{int}$$

Low energy neutrino physics with IceCube

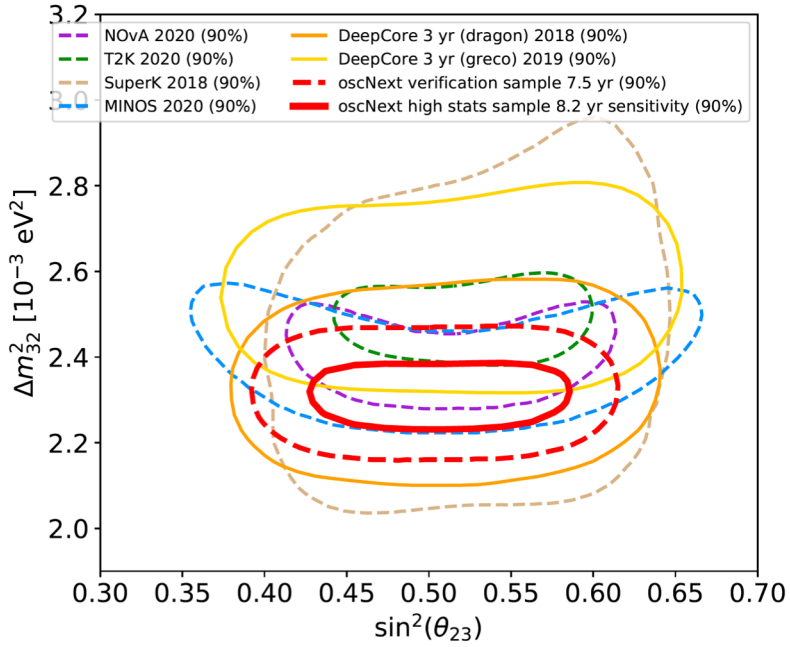
Science highlights

- DESY is leading the way in the first measurement of θ_{23} and Δm_{32}^2 with 8 years of data
  - So-called verification sample analysis stepping stone to higher statistics analysis
- Update to search for light (eV) scale sterile neutrinos also underway
- New search for heavy neutral lepton (HNL) production and decay inside DeepCore volume
  - Unique sensitivity to $U_{\tau 4}$ mixing for ~GeV scale sterile neutrinos
  - Signature of BSM physics, with implications for neutrino mass generation
  - Low energy double-bang signature produced by tau-neutrino “up-scattering” to HNL and subsequent decay

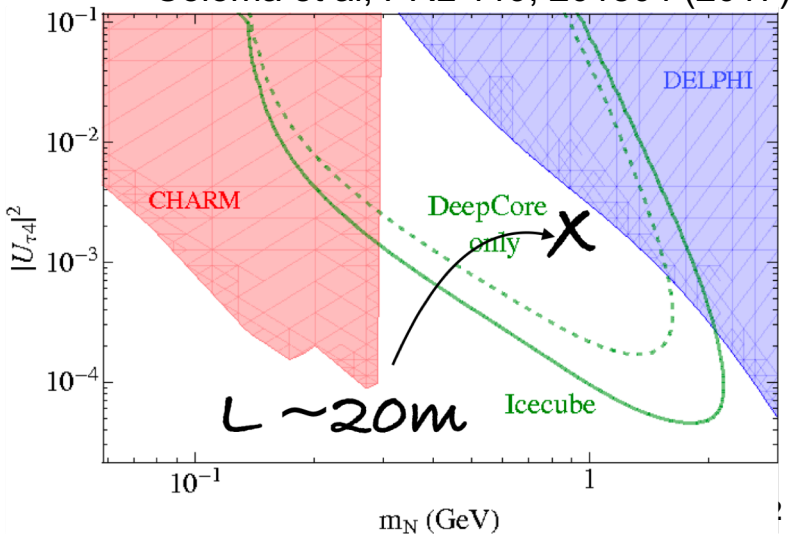


Leveraging local expertise in reconstruction of double-cascade topology

Red lines: new expectations from DeepCore



Coloma et al, PRL 119, 201804 (2017)

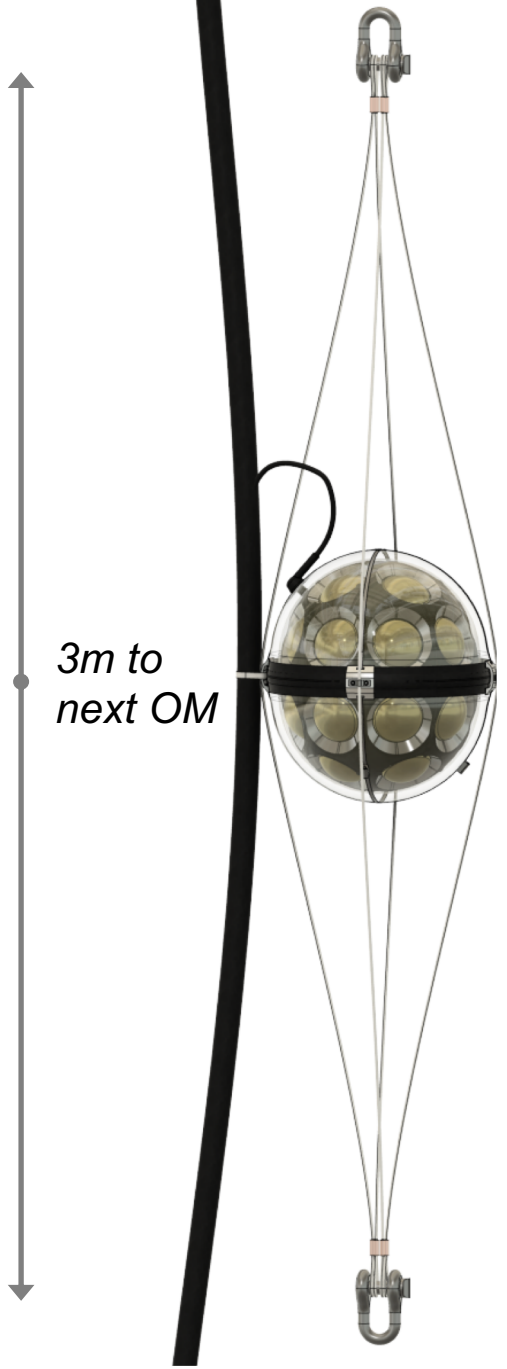


Low energy neutrino physics

Group structure and scope of activities

- IceCube Upgrade will enable unprecedented precision in atmospheric neutrino measurements
- Over the next years, will slowly shift focus from DeepCore-only analyses to combined DeepCore + Upgrade reconstruction and analysis
- Upgrade construction enables a healthy mix of analysis and hardware training for a well-rounded education of all group members

	Personnel	DeepCore: Standard oscillations	DeepCore: Sterile neutrino searches	IceCube Upgrade/Gen2
	Staff, S. Blot	25%	25%	50%
	PD 1, W. Ma	70%		30%
new	PD 2, S. Mechbal			100%
	PhD 1, A. Trettin	50%	50%	
	PhD 2, L. Fischer		70%	30%
2021	PhD 3, N. Fiegl			100%



IceCube Upgrade

News Since APC 3

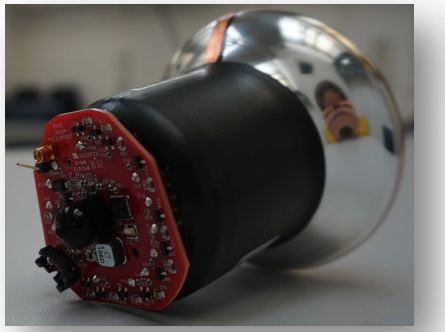
- S. Blot hired as staff scientist
  (50% Upgrade management / 50% Upgrade science)
- mDOM close to Final Design Review
  - Missing item are the PMTs
  - Production now ramping up slowly at Hamamatsu;
    delayed due to Covid-19
- Tendering process for pressure vessels finished
  - Pressure vessels for series production will come from Nautilus
- Large-scale procurement for optical gel in preparation
- Tender for Schönefeld integration site (HVAC) published
  - Bidding closes on Nov. 26th
  - Expect Schönefeld site to be operation on April 1, 2021
  - Temporary integration lab established on Zeuthen campus

Half-mDOM with working LED flashers

Integration of D-Eggs in Japan

mDOM integration lab at MSU

First batch of D-Eggs ready for testing



mDOM PMT

IceCube Upgrade Project

Impact of Covid-19

- Impact Project is behind schedule due to the pandemic, impact varies by subsystem
- Field season for 2020-2021 has been cancelled, we had planned much of drill repair this year to be ready for drill hot test next year
- USAP resupply vessel to McMurdo was cancelled, main drill hose will not ship to McM this year, may ship to Christchurch and remain
- No cargo flights from McM to SP, and overland traverse to SP oversubscribed, generators will remain in McM
- Technical progress continues to be excellent, collaborating institutions have been able to continue work
- A plan for project year 3 (Oct. 2020 – Sep. 2021), as a stand-alone plan, has been developed to continue the work with following focus:
  - Continue production and testing of D-Eggs and start production of mDOMs
  - Procure main and surface cables, penetrators
  - Advance drill repairs and control system, northside work can advance more with staff not travelling
  - Move cargo southward – to McMurdo Station and to South Pole (this now looks very improbable)

IceCube Upgrade Project Advisory Panel Meeting Report
Oct. 30, 2020

Panel: B. Flaugher (Chair), A. Lazzarini, D. Nygren, J. Jacobsen

Farshid Feyzi presented a talk on the overall project status and impact of COVID. Field season 2020-2021 for the Upgrade has been cancelled and shipments to McMurdo and the Pole have largely stopped. Technical progress has been good on all fronts but missing this season will extend the project. NSF has scheduled a review for Feb. 16-17, 2021. The main topic will be rebaselining.

We encourage the project to proceed with development of a plan (cost and schedule) to add a year to the project and rebaseline. We are concerned that the rebaselining effort is a significant undertaking -- IceCube needs to start this ASAP.

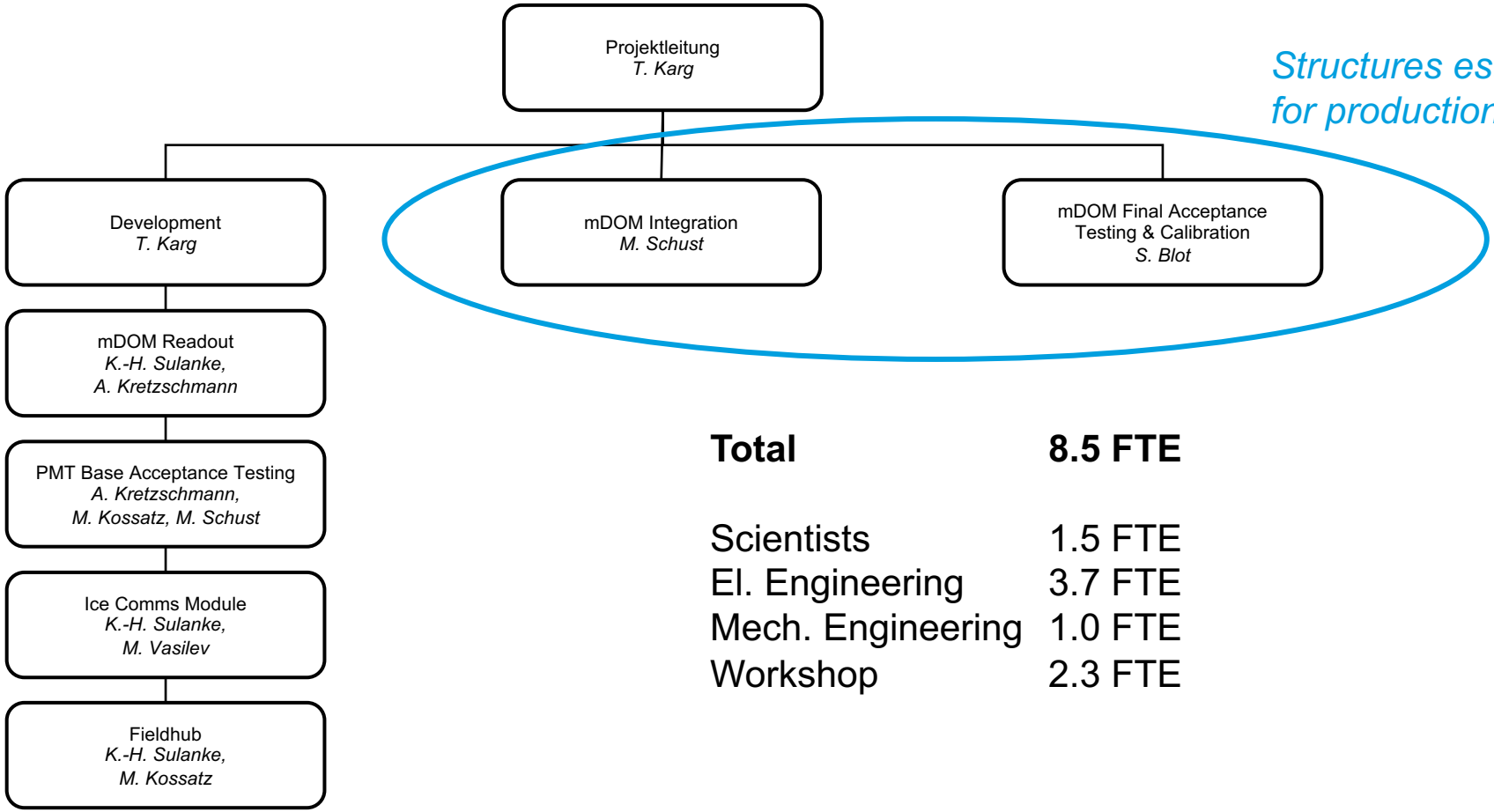
Revise the Year 3 plan to fit within the currently approved profile. Prioritize the work that can be completed this year with high confidence. Include a detailed justification for how you will credibly spend the full amount (given that you underspent the past two years). If you want to exceed the approved Year 3 amount then present a detailed description (scope cost and schedule) and justification for why this work should be done in year 3.

Review and evaluate the impact of the new year 3 plan on years 4, 5 and 6.

Review your schedule/cost variances and allocate them to 3 categories:
(i) Normal project issues that you would have incurred even without COVID-19,
(ii) Logistics issues outside of IceCube's control, and
(iii) Directly COVID related.
If possible, estimate future cost/schedule impacts in these categories in year 3, 4 and 5 (and 6).

IceCube Upgrade @ DESY

Personnel and Organization



Structures established for production and testing

Total	**8.5 FTE**
Scientists	1.5 FTE
El. Engineering	3.7 FTE
Mech. Engineering	1.0 FTE
Workshop	2.3 FTE

IceCube Upgrade @ DESY

Impact of Covid-19

- Minor (typical one to two months) delays in development all subsystems since many people worked partly from home
- Interruptions in electronics parts supply chains have slowed down prototyping of mDOM readout
- Largest impact is on PMT-base production by Hamamatsu
  - Design was approved for production in February 2020
  - Delivery times for some parts (connectors, SMD resistors) in mass production quantities as late as September 2020
  - First articles inspected in September / October 2020
  - Expect first shipment of PMT for design verification mDOMs in November 2020

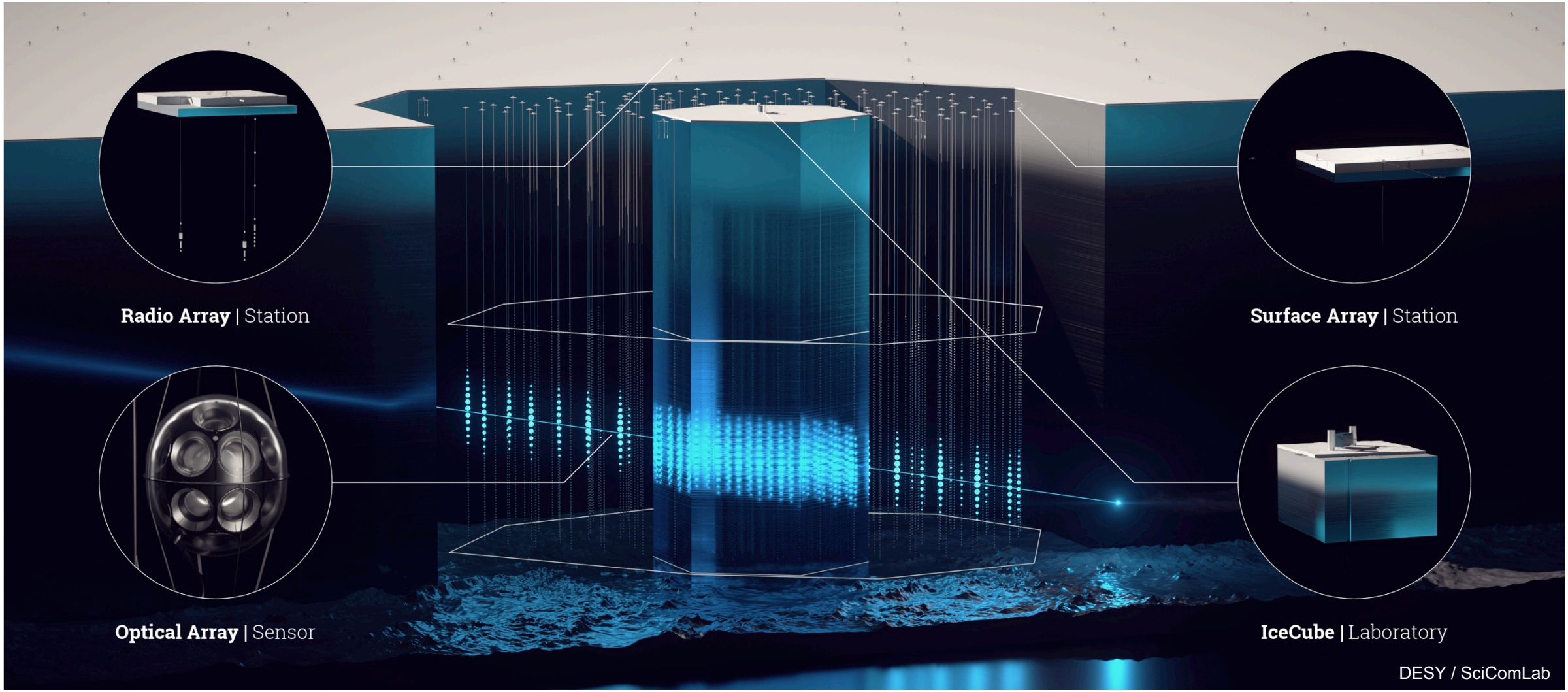
IceCube Upgrade @ DESY

Key Milestones and Schedule Performance

• Dec 2018	mDOM Preliminary Design Review “mechanics”		(report)
• Feb 2019	Interfaces btw. Ice Comms Module and DOMs defined		
• Jun 2019	mDOM Preliminary Design Review “electronics”	(Aug 2019)	(report)
• Oct 2019	Start of mass production of Ice Comms Modules	(Dec 2019)	
• Apr 2020	mDOM Final Design Review	expected Dec 2020	
• Jul 2020	mDOM Production Readiness Review		
• Jan 2021	Start of mDOM production	expected Mar 2021	
• Sep 2021	All DOMs ready to ship to Pt. Hueneme	expected Jan 2022	
• Dec 2022	Deep drilling and deployment at South Pole		

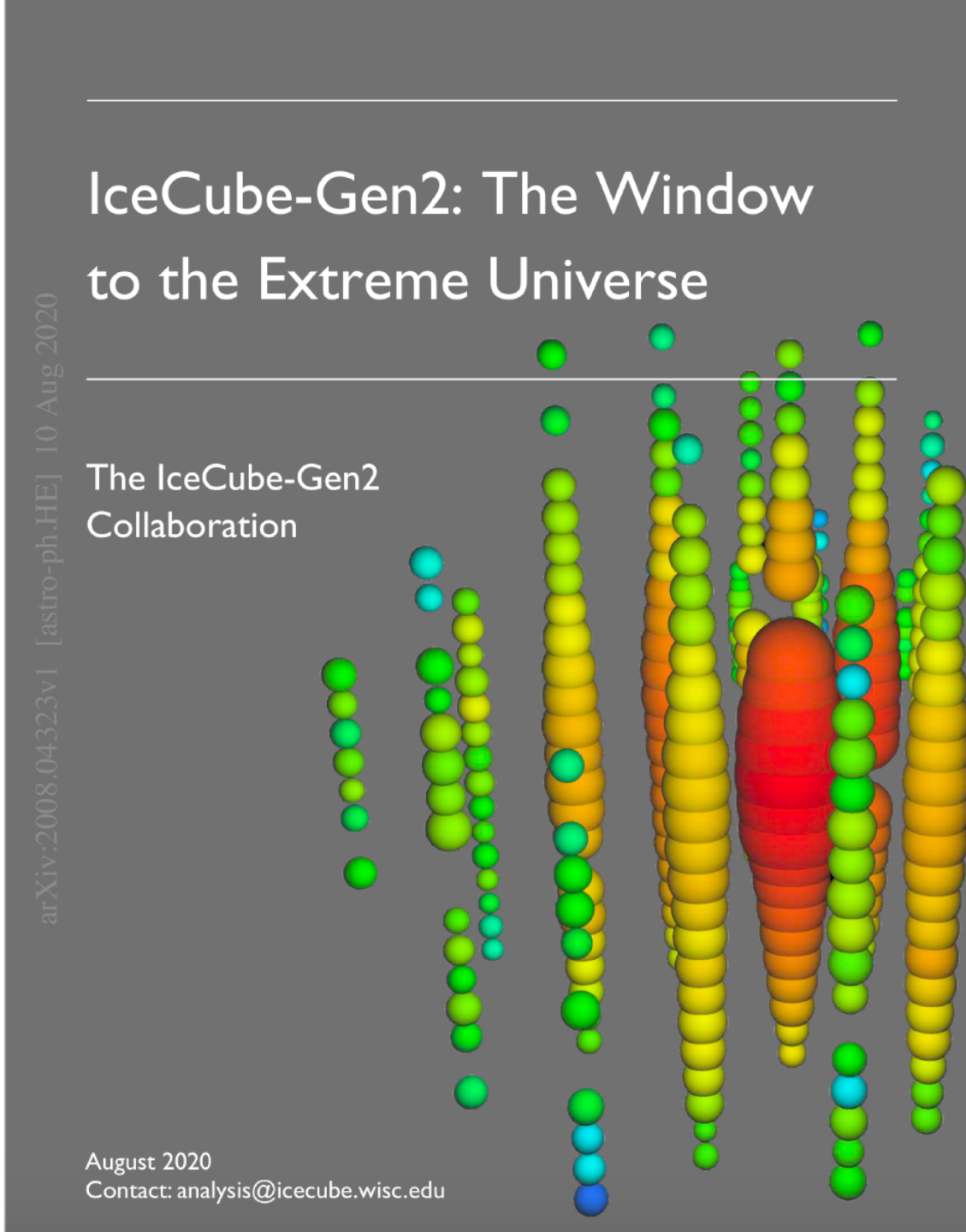
IceCube-Gen2

Gen2 Update


Radio Array | Station
Surface Array | Station
Optical Array | Sensor
IceCube | Laboratory
DESY / SciComLab

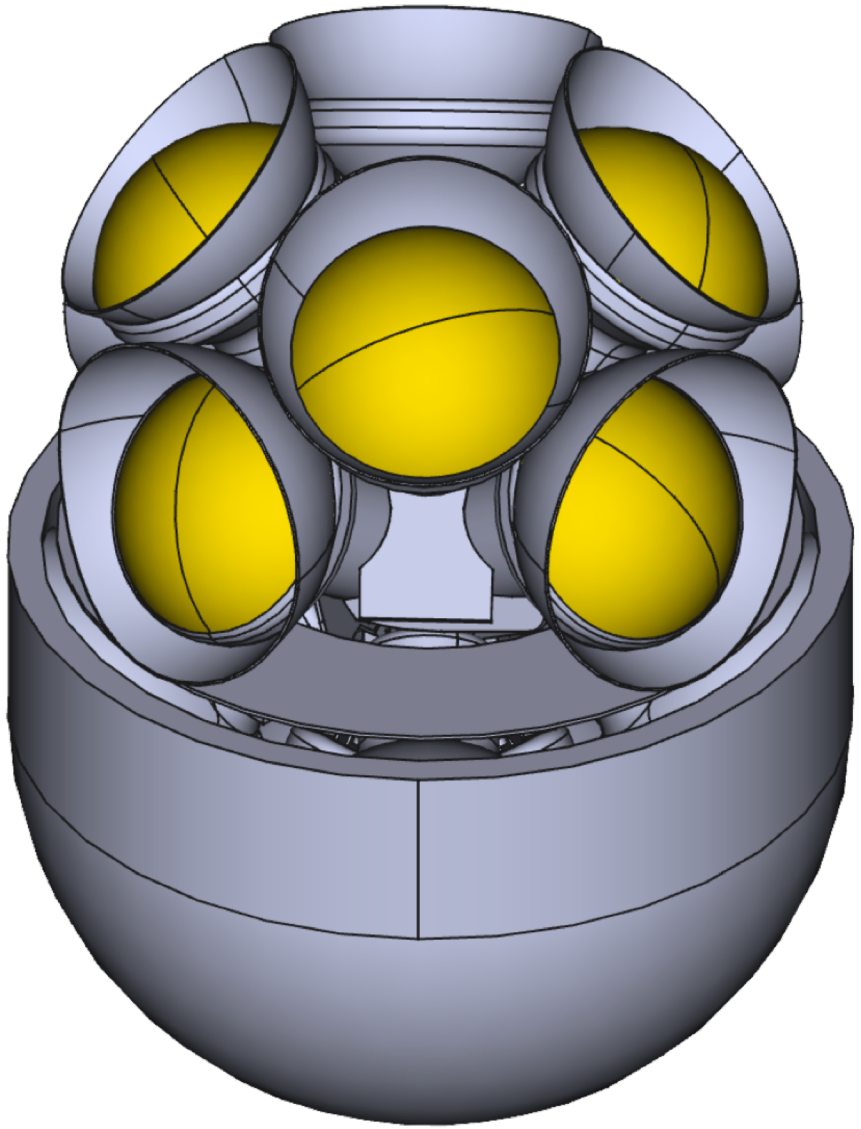
Gen2 white paper(s)

- The comprehensive Gen2 science white paper published on the archive and accepted for publ. in Journal of Physics G. (lead by M.Ackermann, remaining milestone in PoFIII plan now completed)
- It lays out the science case, derives requirements and presents sensitivity. It also serves as a documentation of our conceptual design.
- Other white paper efforts: Gen2 submission to Snowmass2021 (Karle, Kowalski et al.). US Decadal Survey has seen several iterations with the panel in the spring (100+ extra pages had been written), expect results in April 2021.

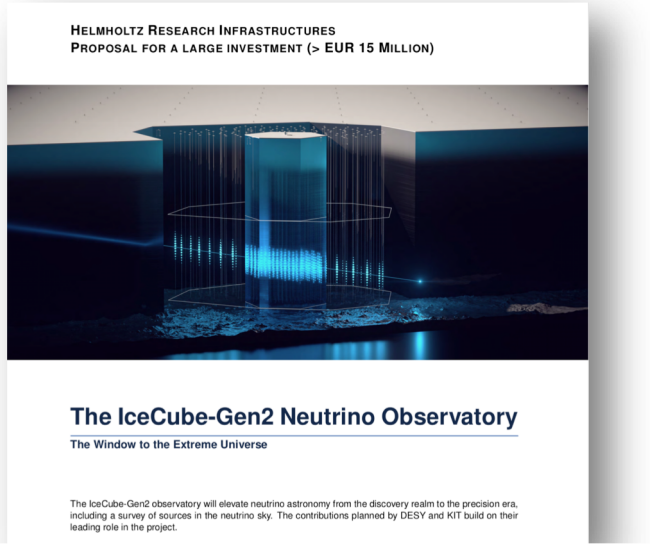


Gen2 development towards a PDR

- Informal suggestion by NSF to complete a Preliminary Design Review (PDR) by fall 2021. This is a requirement for being considered for funding.
- CMB-S4 plans similar scale project for South Pole, and PDR would close the planning gap between us and them.
- Gen2 optical sensor design is being developed by a team from DESY, UW Madison and Chiba. It follows the mDOM concept but will be more compact and cost optimized.
- Radio less mature and behind in planning: We established a Gen2 radio working group / task force under the leadership of Anna Nelles and Abby Vieregg.
- Relation to IceCube Upgrade / Gen2 Phase 1 is that we build on its R&D, but do not require deployment for verification.



Preproposal for Helmholtz investments (FIS)



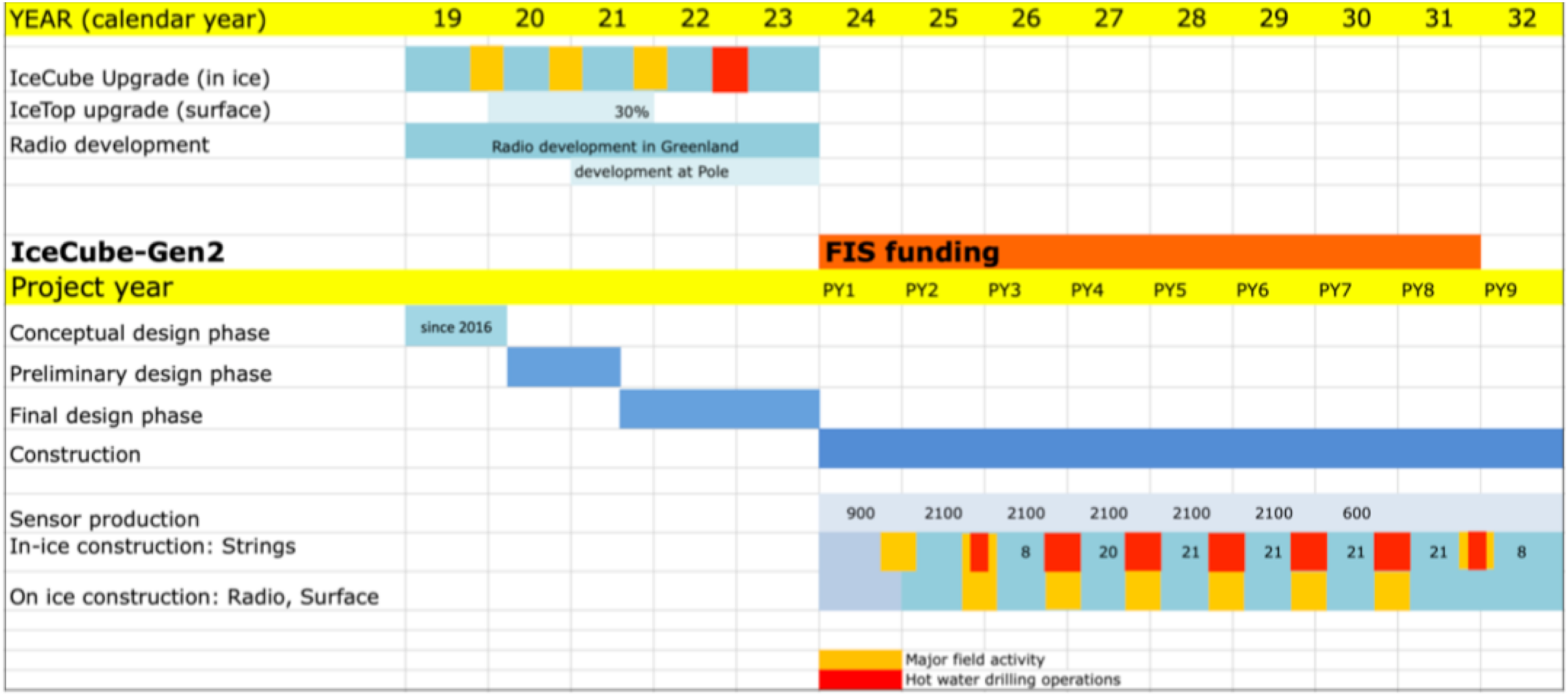
- Preproposal for Gen2 to enter Helmholtz roadmap submitted Oct 31; request 20.77 MEuro for instrumentation
- Lead by DESY (Kowalski), KIT major partner.
- DESY leads work packages on sensors and radio, KIT on surface array
- Discussion started with AWI to join Gen2. Mutual benefits: For AWI: a very detailed measurements of the ice over the 500 km2 footprint of Gen2, while IceCube-Gen2 would gain extra access to logistic support

Table 1: Comparison of the actual costs of building IceCube, the total projected costs for the construction and deployment of the IceCube-Gen2 observatory, the investments requested in this proposal, and DESY/KIT contributions to labor and operations. Contributions are divided into investments for instrumentation and other support to allow proper comparison between US and European accounting.

Budget item	**IceCube** (actual, in M$)	**IceCube-Gen2** (total projected, in M$)	**This proposal** (investments, in M€)	
Optical/surface array (Instrumentation)	111.9	151.9	17.65	(a)
Radio array (Instrumentation)		25.9	3.12	(b)
Total instrumentation	**111.9**	**177.8**	**20.77**	
Project support	27.9	28.1		(c)
Implementation	46.6	61.6	program	(d)
Data systems	27.1	13.1	contributions	(e)
Commissioning & Verification	20.8	12.2	from	(e)
Polar support	36.3	53.9	DESY + KIT	(f)
Pre-operations	7.1	0		(e)
Total	**277.7**	**346.7**	**20.77**	

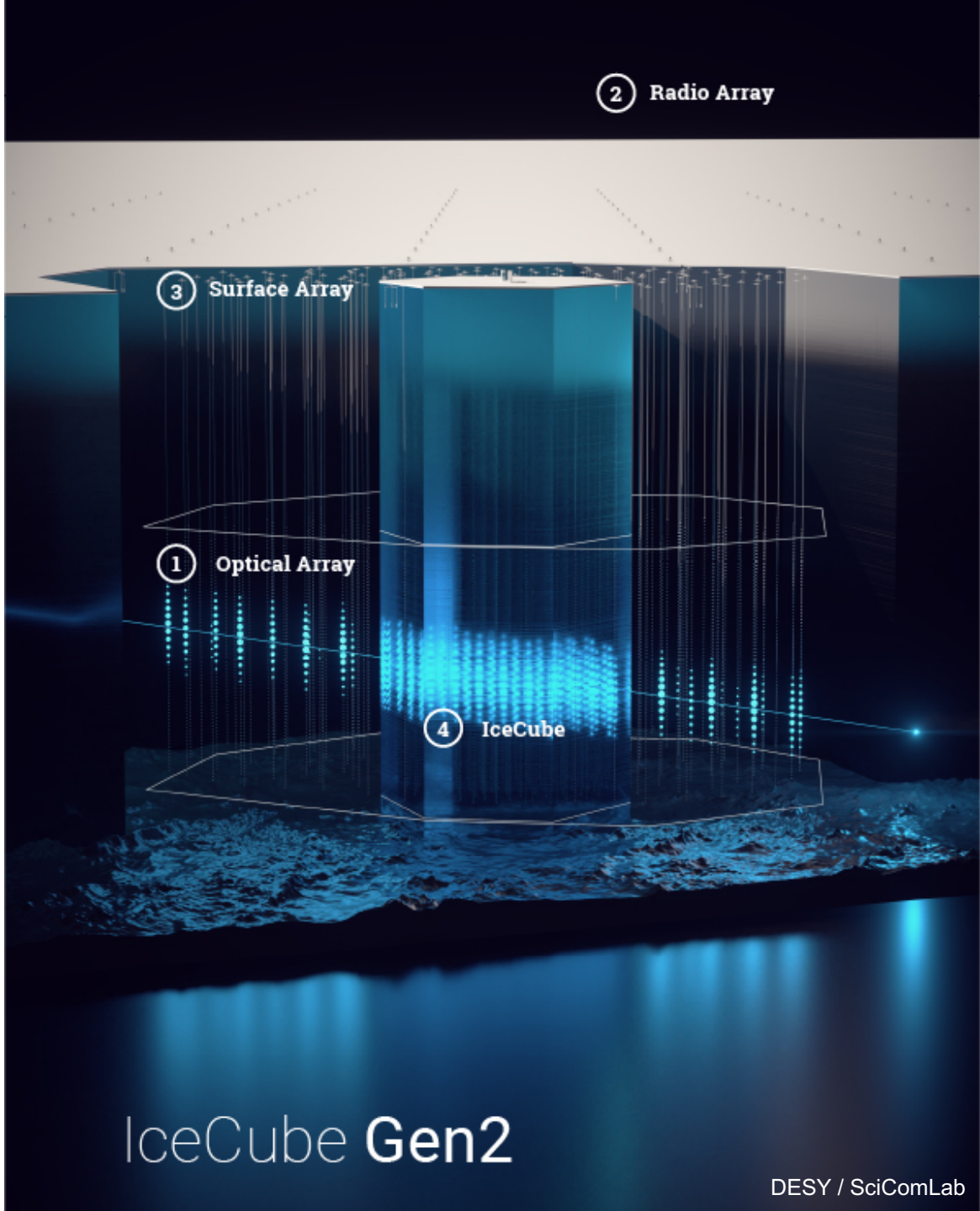
(a) Significantly higher sensor coverage per string than IceCube
(b) Component was not available for IceCube
(c) Build on IceCube structure approach
(d) Drilling and deployment
(e) Savings due to existing IceCube infrastructure / M&O structure
(f) Increased efforts on the ice (more strings, radio array)

Timeline


YEAR (calendar year)
19
20
21
22
23
24
25
26
27
28
29
30
31
32
IceCube Upgrade (in ice)
IceTop upgrade (surface)
30%
Radio development
Radio development in Greenland
development at Pole
IceCube-Gen2
FIS funding
Project year
PY1
PY2
PY3
PY4
PY5
PY6
PY7
PY8
PY9
Conceptual design phase
since 2016
Preliminary design phase
Final design phase
Construction
Sensor production
900
2100
2100
2100
2100
2100
600
In-ice construction: Strings
8
20
21
21
21
21
8
On ice construction: Radio, Surface
Major field activity
Hot water drilling operations

Other developments

- Started discussion within German community (within KAT) to receive additional project funding for participation of Universities (goal ~20MEuro).
- Preparation for launch of icecube-gen2.de website early December ongoing (editorial board: Haungs, Helbing, Kowalski, Resconi, Rhode, Wiebusch).
- Promotion event planned for spring/summer 2021, once Decadal Survey results are known.
- New advisory board to IceCube / Gen2 being set up; Barry Barish agreed to (continue) chairing it.



Backup

IceCube Upgrade @ DESY

Planned Cost

Deliverable	Qty.	Est. Cost / pc. [EUR]	October 2020 Cost Est. [EUR]	Basis of Estimate	March 2019 Cost Est. [EUR]	
mDOM w/o PMTs	430	4 555	1 958 650	*(cf. next slide)*	1 961 660	No spares included here
mDOM Production Facility	1		435 113	HOAI planning	200 000	
mDOM FAT Facility	1		275 000	HOAI pre-planning		
mDOM DVT Modules	10	13 340	133 400	mDOM +30% for low qty.	126 420	
Ice Comms Module	900	100	90 000	in production	80 000	
Field Hub	7	10 000	70 000	engineering est.	70 000	
PMT Incoming Test Facility			—	engineering est.	35 000	Verbundforschung (Aachen, Dortmund)
Subtotal			**2 962 163**		**2 473 080**	
R&D WOM			—	engineering est.	180 000	Verbundforschung (Mainz, Wuppertal)
R&D Radio Instrumentation			—	engineering est.	50 000	
Total			**2 962 163**		**2 703 080**	

IceCube Upgrade @ DESY

mDOM Cost and Basis of Estimate

	October 2020 Cost Est. [EUR]	Basis of Estimate	March 2019 Cost Est. [EUR]	
Mainboard	1 000.00	engineering est.	1 000.00	
PMT base incl. soldering to PMT	—	included in PMT	840.00	
PMT Support Structure	1022.72	vendor quote	810.86	
Optical Gel	462.00	vendor quote	624.42	
Pressure Vessel	780.00	purchased	587.00	
Penetrator	590.00	vendor quote	400.00	
Harness	—		100.00	
Miscellaneous	700.00	engineering est.	200.00	
Total	**4 554.72**		**4 562.28**	
PMT	5 592.00	purchased (includes PMT base)	5 162.16	purchased by KIT
Harness	115.00	engineering est.	—	will be purchased by Verbundforschung (Wuppertal)

IceCube Upgrade @ DESY

Production and Final Acceptance Testing Facilities

- These facilities account for the largest cost increase
- Original plan: refurbish production and testing facilities from IceCube Gen1 on the Zeuthen campus

Production facility

- Is now been used as optical calibration lab; it was decided to not move the lab
- New hall rented in Schönefeld together with CTA
- Significant effort required, especially on HVAC to fulfill work safety and cleanliness requirements

Acceptance Test Facility

- Chillers in worse condition than anticipated
- Noise emission to neighboring residential area requires relocation of chillers

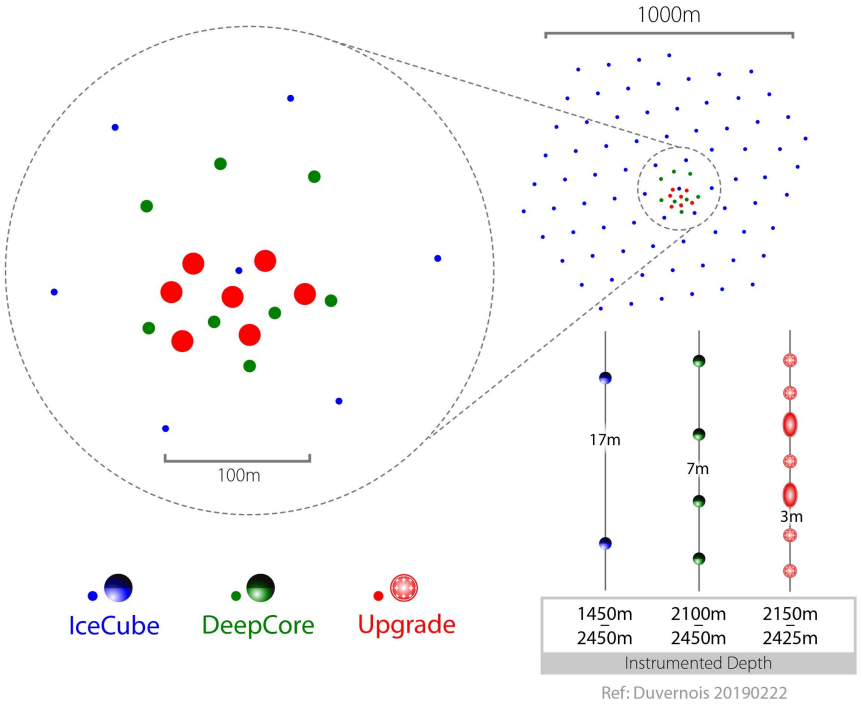
Measures

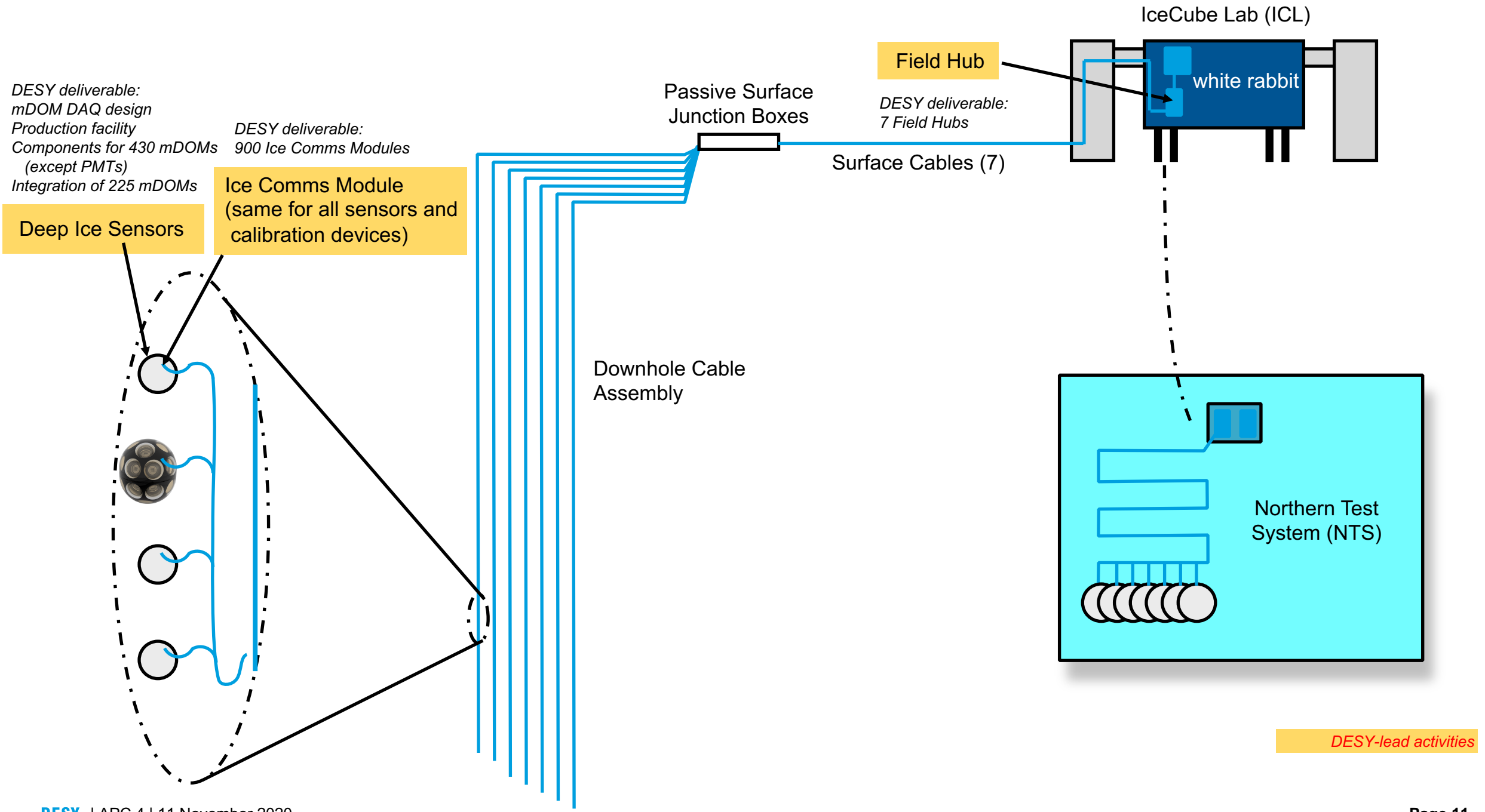
- Some of the cost increase covered by university Verbundforschung funds
- Reevaluation of requirements for Final Acceptance Testing to reduce facility cost

The IceCube Upgrade Project

- IceCube Upgrade will significantly increase the sensitivity of the experiment from 2023
- Seven new, densely instrumented strings inside the DeepCore volume
- New sensors and calibration devices haven been developed, profiting from 10 years of IceCube experience
- Important step towards the next-generation observatory IceCube-Gen2

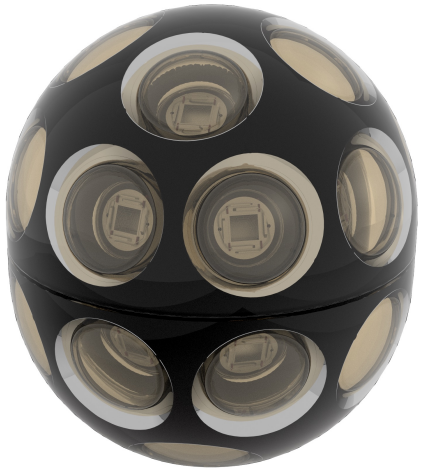
- Main physics goals
  - Neutrino mixing parameters (esp. ν_τ appearance)
  - Calibration of ice optical properties




IceCube Lab (ICL)
Field Hub
white rabbit
DESY deliverable:
7 Field Hubs
Passive Surface
Junction Boxes
Surface Cables (7)
DESY deliverable:
mDOM DAQ design
Production facility
Components for 430 mDOMs
(except PMTs)
Integration of 225 mDOMs
DESY deliverable:
900 Ice Comms Modules
Ice Comms Module
(same for all sensors and
calibration devices)
Deep Ice Sensors
Downhole Cable
Assembly
Northern Test
System (NTS)
DESY-lead activities

The IceCube Upgrade Project – Deep Ice Sensors

mDOM
(DESY, U Erlangen, U Münster)
Diameter: 14 inch
(24) 3-inch PMTs
2.2 A_{eff} of IceCube DOM
adapted from KM3NeT



D-Egg
(Chiba U)
Diameter: 12 inch
(2) 8-inch HQE PMTs
1.5 A_{eff} of IceCube DOM

for comparison:

IceCube DOM*
Diameter: 13 inch
single 10-inch PMT (DeepCore: HQE)

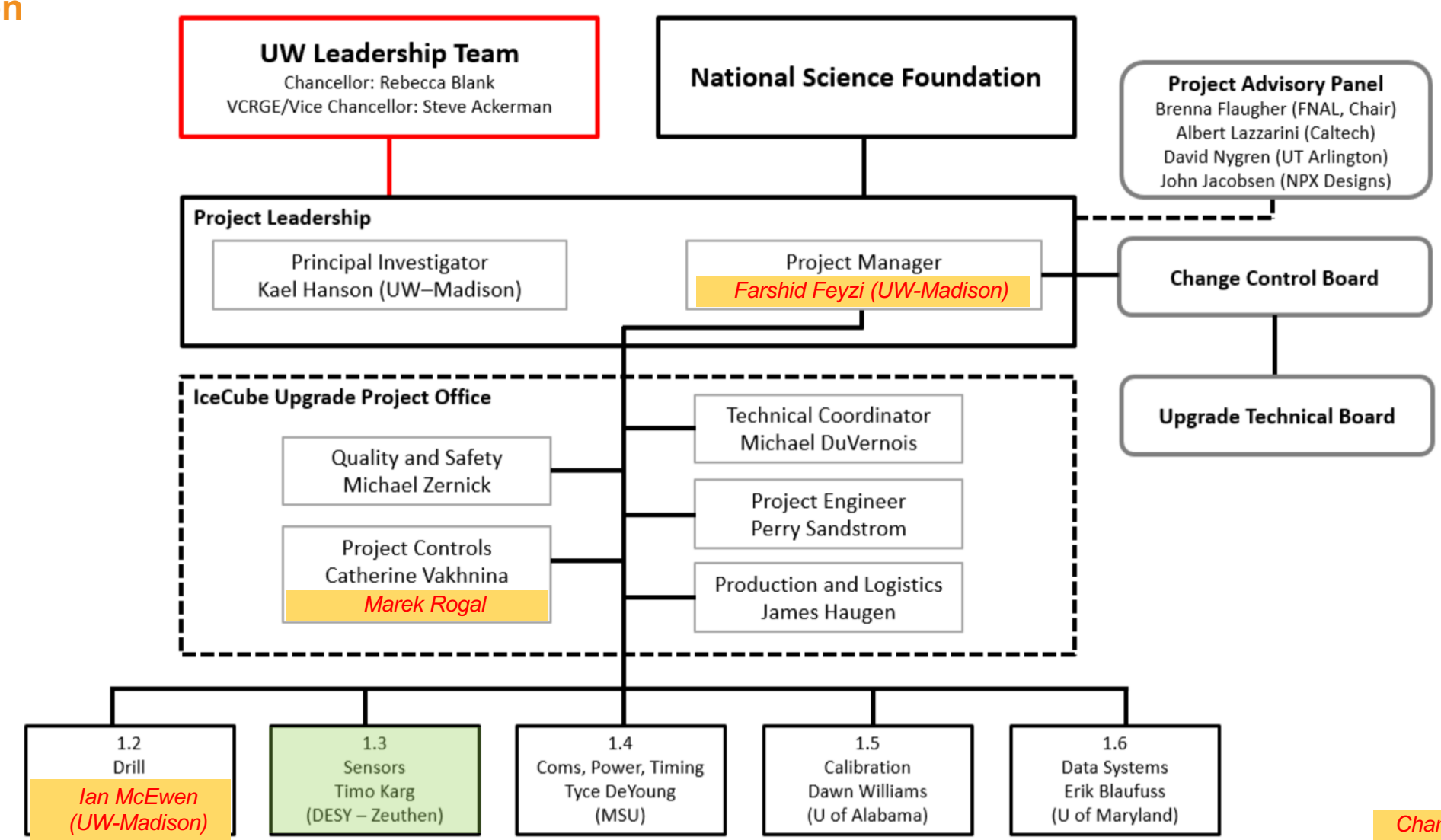
**DOM: Digital Optical Module*

D-Egg

- Final Design Review in Feb. 2020
- Pre-production of 50 D-Eggs completed
  - Sealing postponed due to missing ICM Golden Image firmware
- Preparations for Final Acceptance Testing well underway
  - (16) D-Eggs sealed and loaded into freezer in Oct. 2020
- D-Egg Batch #2 integration (Qty. 200) started on Oct 29, 2020
- About 4 months delay compared to PY2 schedule
  - D-Egg schedule always driven by Japanese funding
  - D-Eggs are well in time for installation in the Upgrade

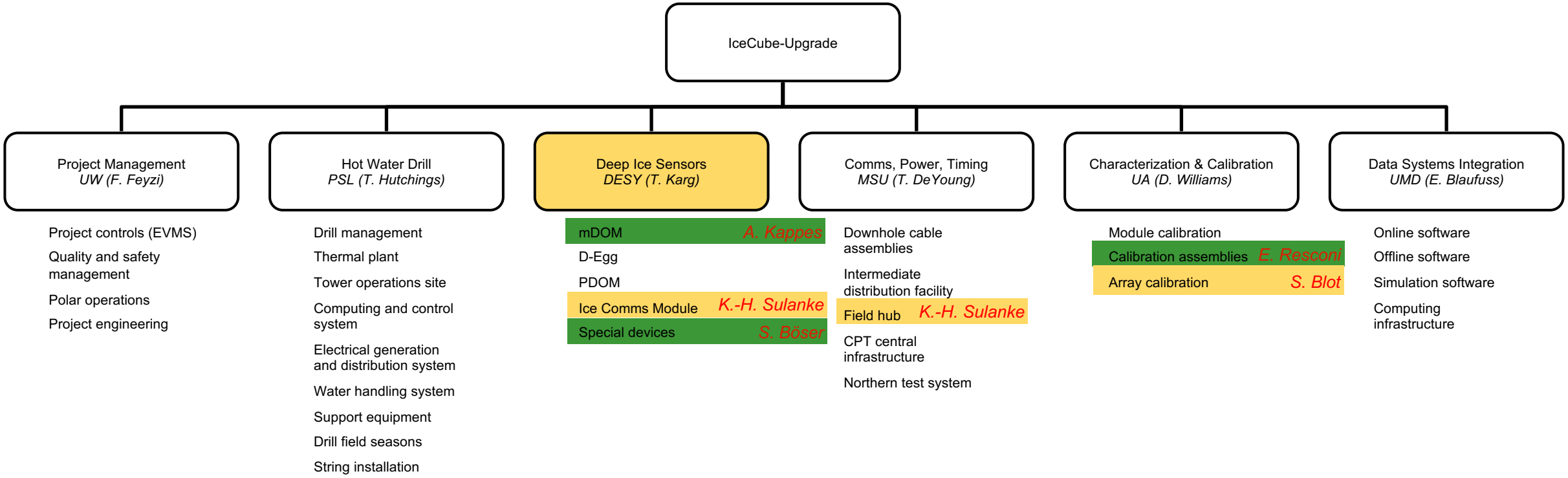
IceCube Upgrade Project

Organization



Changes since last mtg.

IceCube Upgrade Project – Organization



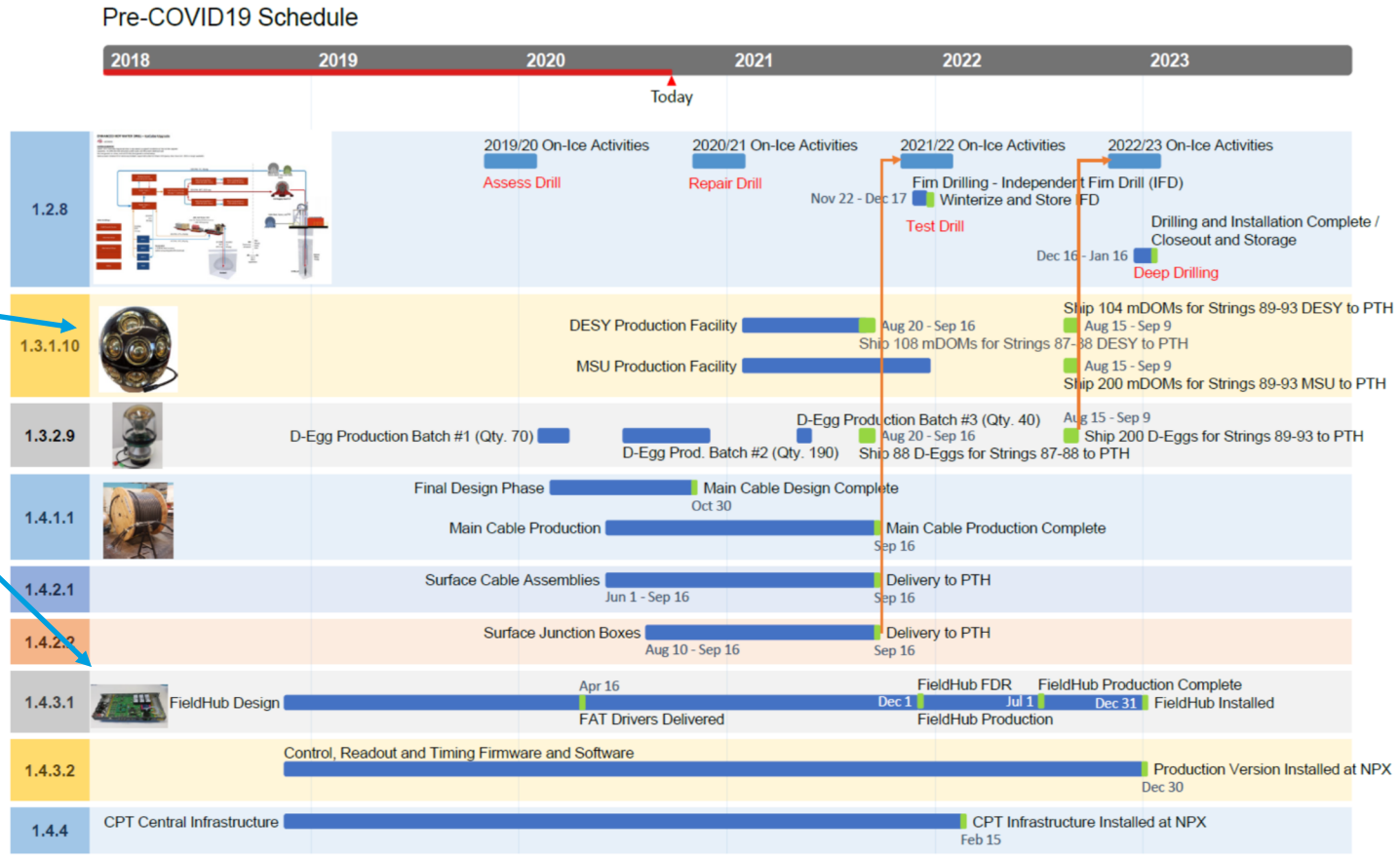
DESY-lead activities

German University-lead

IceCube Upgrade Project

Funding and Schedule Overview

- NSF: 23 M$
  - incl. 2.9 M$ contingency
- Helmholtz
  - DESY: 2.85 MEUR invest
  - KIT: 2.33 MEUR invest
- Chiba University
  - 300 D-Egg sensors (approx. 3 M$ invest)
- Michigan State University
  - approx. 3 M$
- Multiple university in-kind contributions

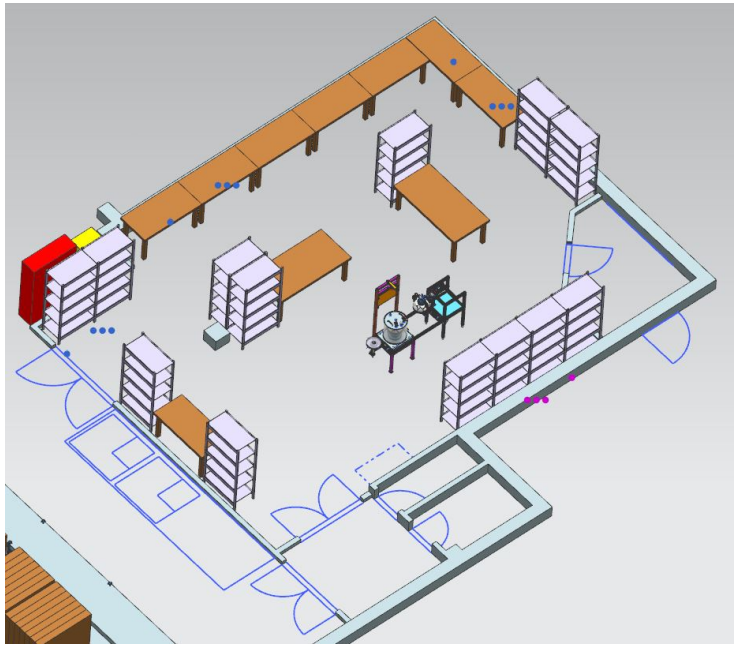


Production

- Production at two sites: DESY and MSU
- Planned rate: 9 mDOMs / week / site

DESY Site

- Rented 844 m^2 hall in Schönefeld
  (~20 min. by car from campus)
- Shared by IceCube and CTA
  (pre-assembly of mid-scale telescopes)
- 105 m^2 area walled off for mDOM integration
- Start of construction: November 2019
- *Requirement: 4 air changes per hour* ← *est. cost: 177 kEUR*



Final Acceptance Testing

- Operate all mDOMs at −40°C for three weeks before shipping to Pole
- IceCube Gen1 Dark Freezer Lab (DFL) still existing in Zeuthen, but cooling aggregates reworked for CTA mirror testing
- Also noise emission problems towards neighbours

→ Major refurbishment of DFL required

- Trade study performed by Ingenieurbüro Helm Option:
  - Refurbish existing DFL ← *Best option est. cost: 239 kEUR*
  - Construction of new DFL in Zeuthen experimental hall
  - Construction of new DFL in Schönefeld

IceCube Gen1 FAT @ DESY (capacity 64 DOMs)

DESY IceCube
Vergleichsmatrix

		Varianten	I		II		III		IV	
			Var. 1a Sanierung Bestand, Verdichter innnen		Var. 1b Sanierung Bestand, Verdichter außen		Var. 2, Aufbau in Halle		Var. 3, Schönefeld	
No	Ziele	Gewichtung [%]	Wert	gewichtet	Wert	gewichtet	Wert	gewichtet	Wert	gewichtet
1	niedrige Gesamtkosten (Energie- und Investkosten)	20	1	0,20	1	0,20	0	0,00	-1	-0,20
2	geringer zusätzlicher Platzbedarf	20	0	0,00	1	0,20	-1	-0,20	1	0,20
3	kurze Wege für Bedienung und Einbringung	20	1	0,20	1	0,20	1	0,20	-1	-0,20
4	flexible Beeinflussung von Sollwerten und Parametern	5	1	0,05	1	0,05	1	0,05	-1	-0,05
5	weitere Nutzbarkeit nach Experiment gegeben	10	1	0,10	1	0,10	1	0,10	-1	-0,10
6	keine Probleme mit Nachbarn zu erwarten (Schall)	5	0	0,00	-1	-0,05	0	0,00	1	0,05
7	niedrige Schallbelastung im Gebäude	15	-1	-0,15	0	0,00	0	0,00	1	0,15
8	Einbindung in Siclimat möglich	5	1	0,05	1	0,05	1	0,05	-1	-0,05
9										
		100								
	Summe, ungewichtet		4		5		3		-2	
	Summe, gewichtet		0,45		0,75		0,20		-0,20	
	Rangfolge, ungewichtet		2		1		3		4	
	Rangfolge, gewichtet		2		1		3		4	

Legende
- Eingabefelder, veränderbar
- Ergebnisfelder
- begünstigend für Zielerreichung (1)
- neutral für Zielerreichung (0)
- verschlechternd für Zielerreichung (-1)

DFL trade study

mDOM Project – Organization

Integrated mDOM	WWU Münster
• Pressure vessel, PMT support structure, Optical Gel	WWU Münster (procurement and pre-assembly of PMT support structure)
• Harness	BU Wuppertal (design, procurement, pre-assembly)
mDOM electronics	DESY
• Readout electronics	DESY
• High-voltage system	UW Madison
• LED Flasher production	JGU Mainz
mDOM PMTs	
• PMT selection	FAU Erlangen, WWU Münster
• PMT Acceptance Testing	RWTH Aachen, TU Dortmund, BU Wuppertal
mDOM integration	DESY
mDOM Final Acceptance Testing	DESY, FAU Erlangen, JGU Mainz