the A03 group in Grant-in-Aid for Scientific Research on Innovation Areas
"Exploration of Particle Physics and Cosmology with Neutrinos"

Exploration of the Physics Beyond the Standard Model with Neutrinos

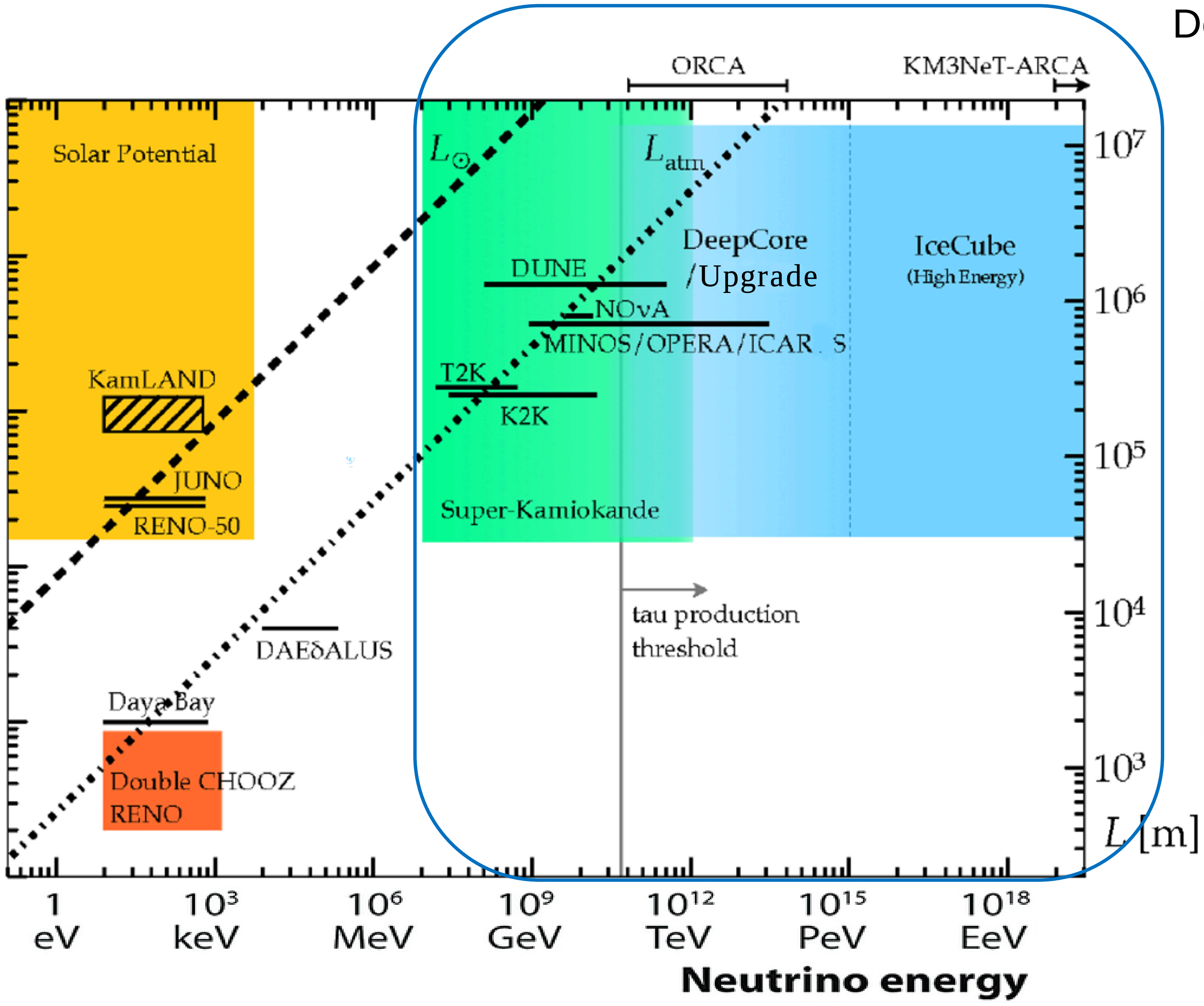
Aya Ishihara
International center for hadron astrophysics (ICEHAP), Chiba University

Kyoto, March 27-30, 2023

千葉大学 CHIBA UNIVERSITY

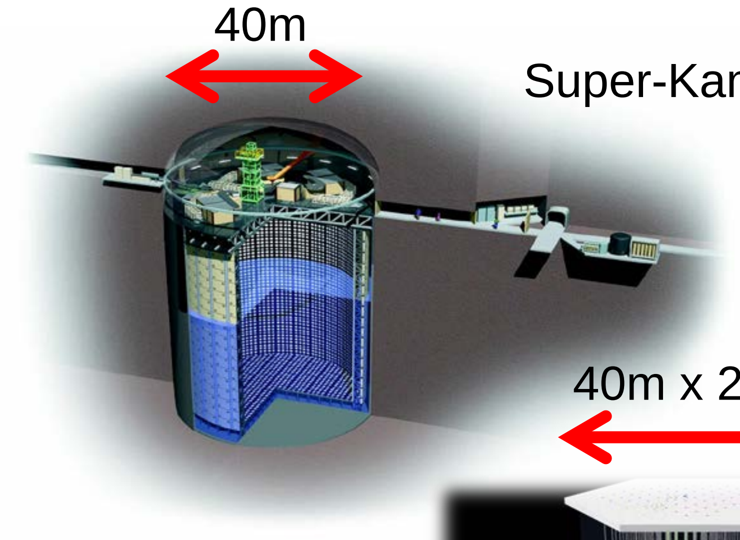
ICEHAP International Center for Hadron Astrophysics

Why NEUTRINO detectors for BSM?



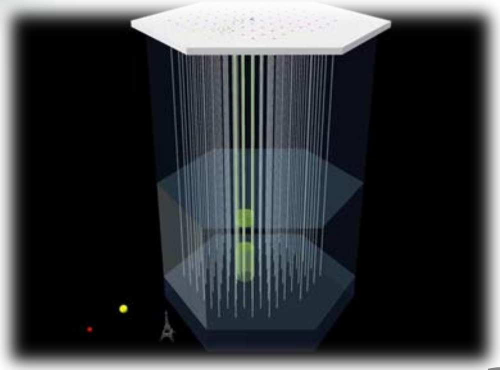
Detectors allow to measure elementary particles "neutrinos" in a very wide energy range

- with a similar detection method from sub-GeV to trans-EeV energies

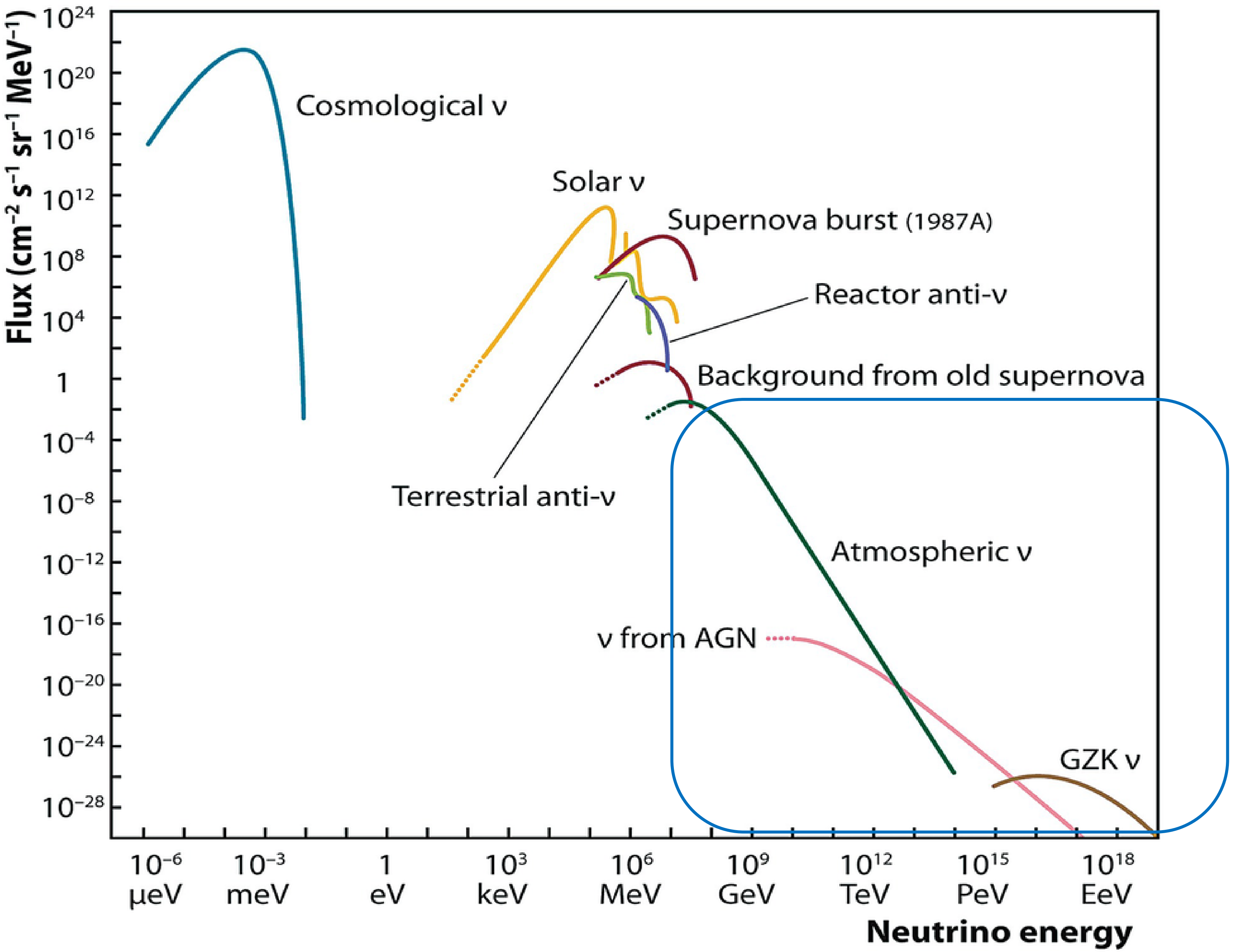


IceCube

- challenging to the systematics associated with natural Chrenkov media (glacial ice)



Why NEUTRINOs for BSM?



Neutrino beams are available for free!

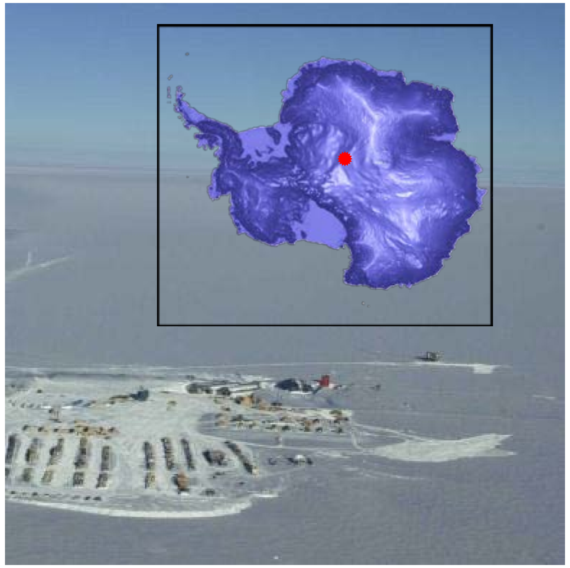
Understanding of the beam and detector systematics is crucial for the search for the hints of the BSM physics

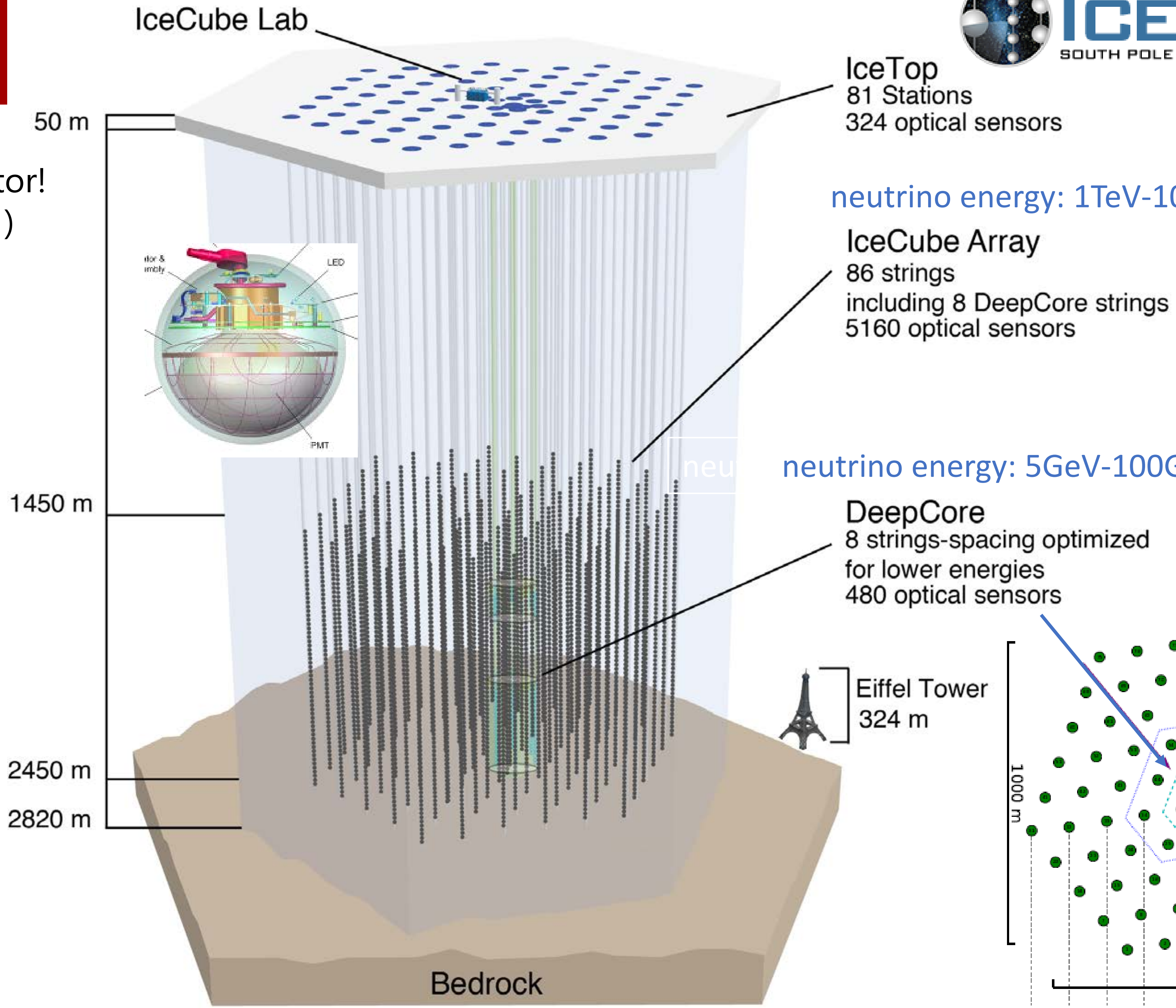
- Atmospheric neutrinos exceeding from a few tens of MeV to a few 10 TeV
- Astrophysical neutrinos dominated above a few 10-TeV

IceCube

The first km^3-scale detector!
(full operation since 2011)

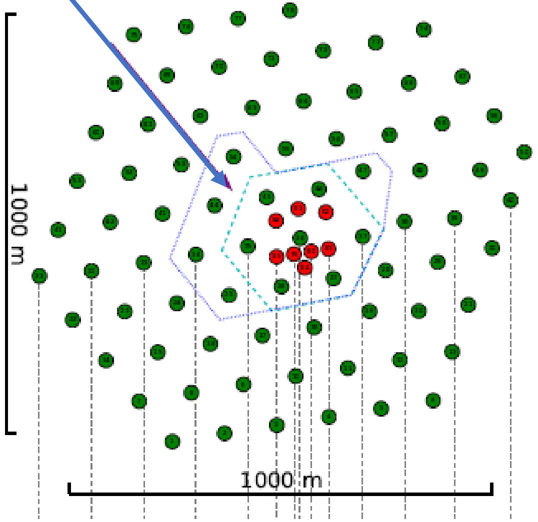
@ Amundsen-Scott South Pole station





neutrino energy: 1TeV-10EeV

neutrino energy: 5GeV-100GeV



Probing High energy (TeV-PeV) Neutrino Cross-Sections

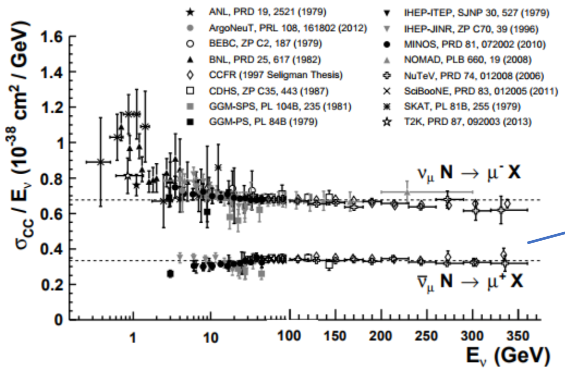
Nature ***551*** *596 (2017)*

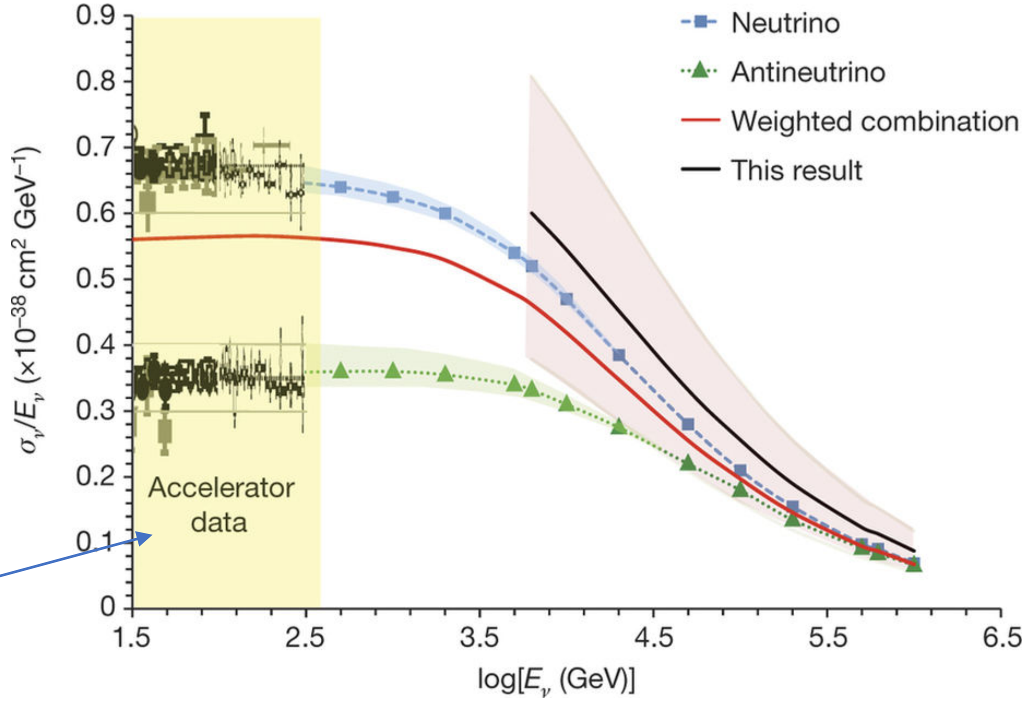
Measurement of the multi-TeV neutrino interaction cross-section with IceCube using Earth absorption

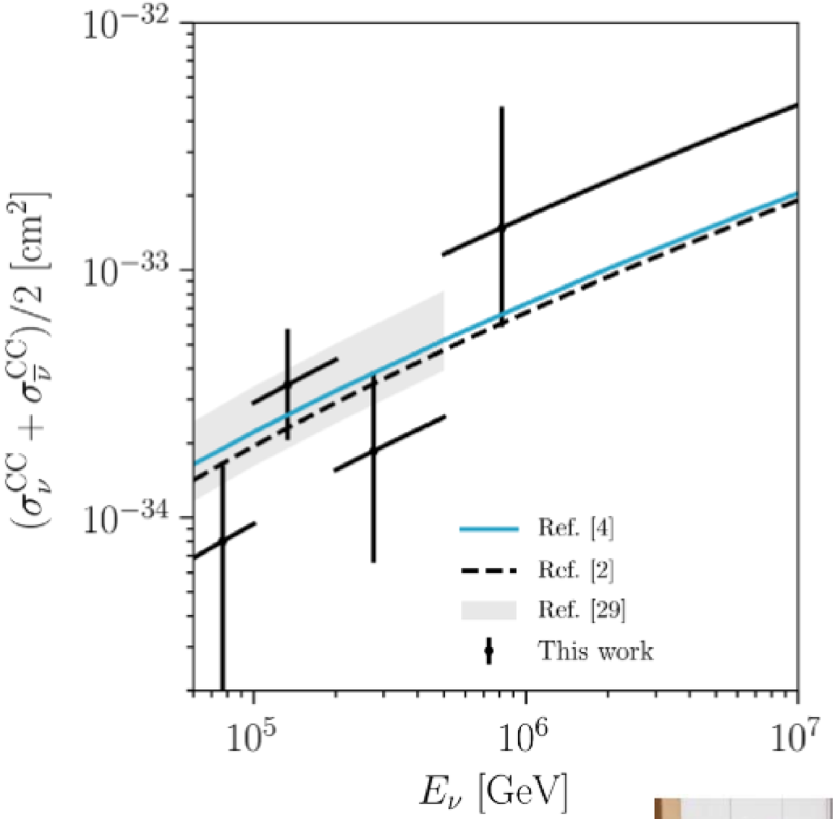
PHYSICAL REVIEW D **104**, 022001 (2021)

Measurement of the high-energy all-flavor neutrino-nucleon cross section with IceCube

PDG







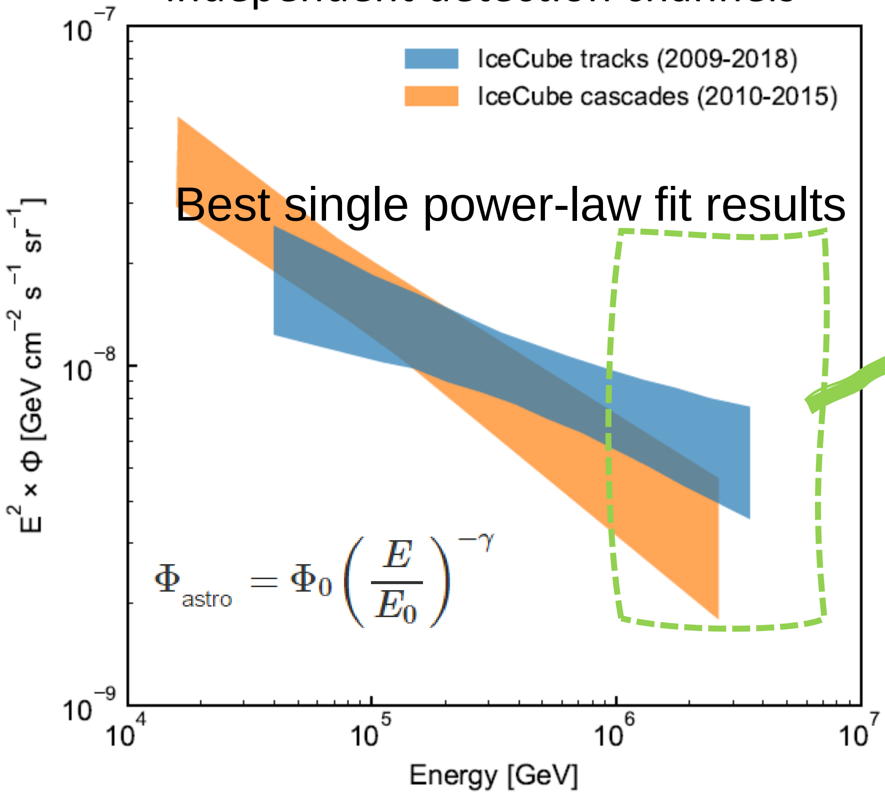
Extending further understanding of PeV cross section using multiple-detection channel, improved and larger sample

C. Hill (Chiba)

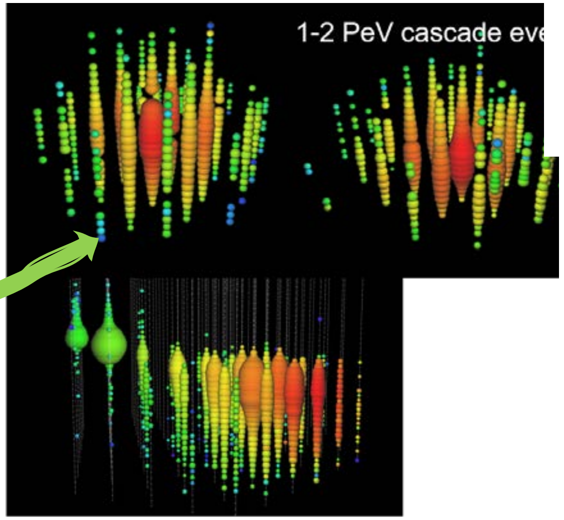
Energy Frontier: PeV energies

The Astrophysical Journal,928:50 (2022)
Improved Characterization of the Astrophysical Muon–neutrino Flux with 9.5 Years of IceCube Data

cosmic neutrinos measured in two independent detection channels



New extremely high energy neutrino analysis by M. Meier (Chiba)

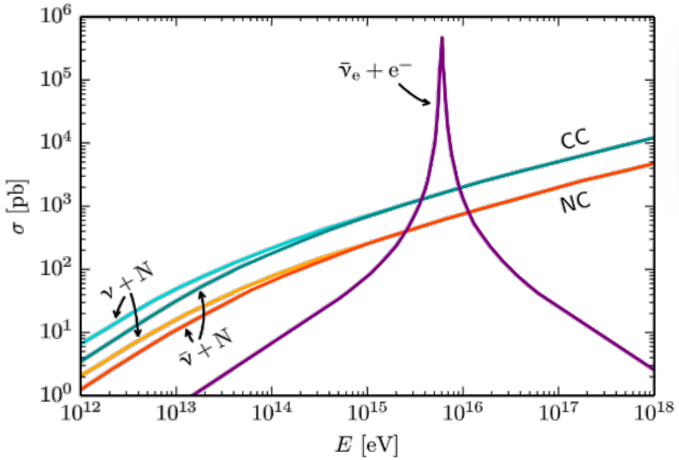


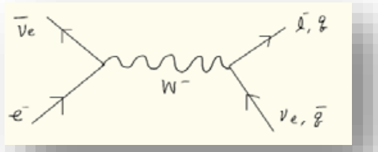
Highest energy event to date, an upward-going track.

- Deposited energy 2.6±0.3 PeV
- Median neutrino energy 8.7 PeV
- Observed photoelectrons 130,000 pe

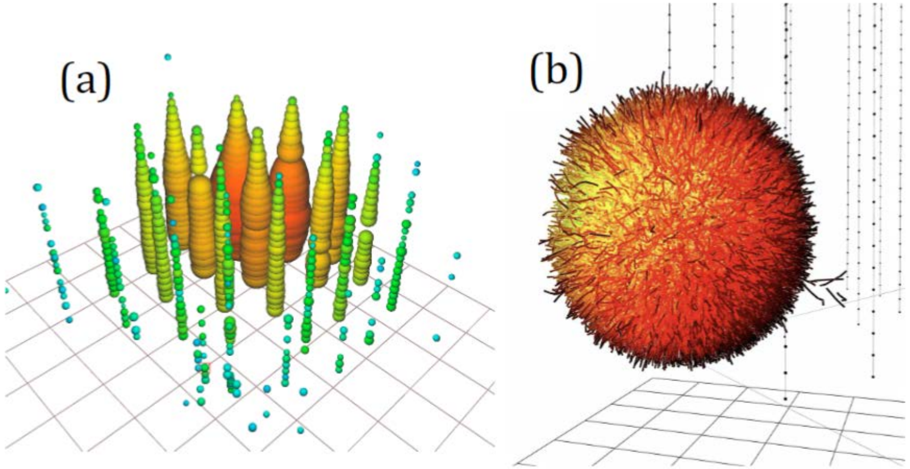
NATURE volume 591, 220 (2021)
Detection of a particle shower at the Glashow resonance with IceCube

L.Lu (Chiba➡UW)





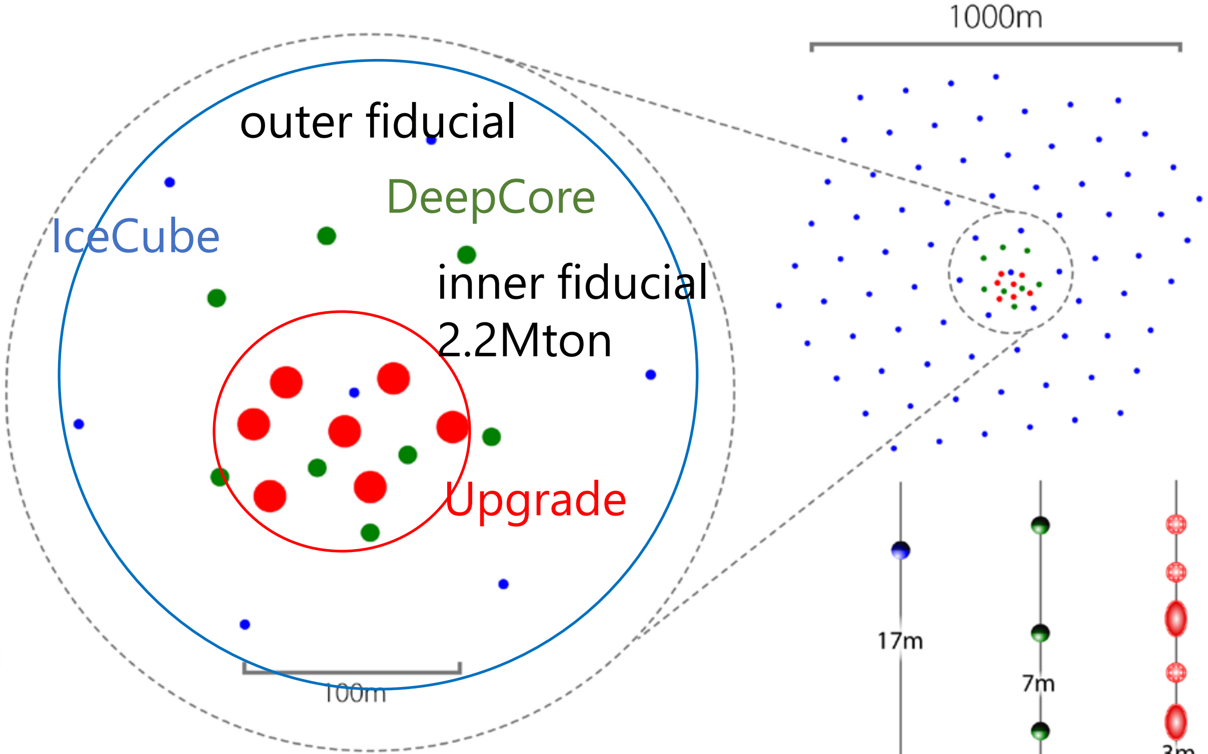
A 6PeV cascade consistent with Glashow resonance

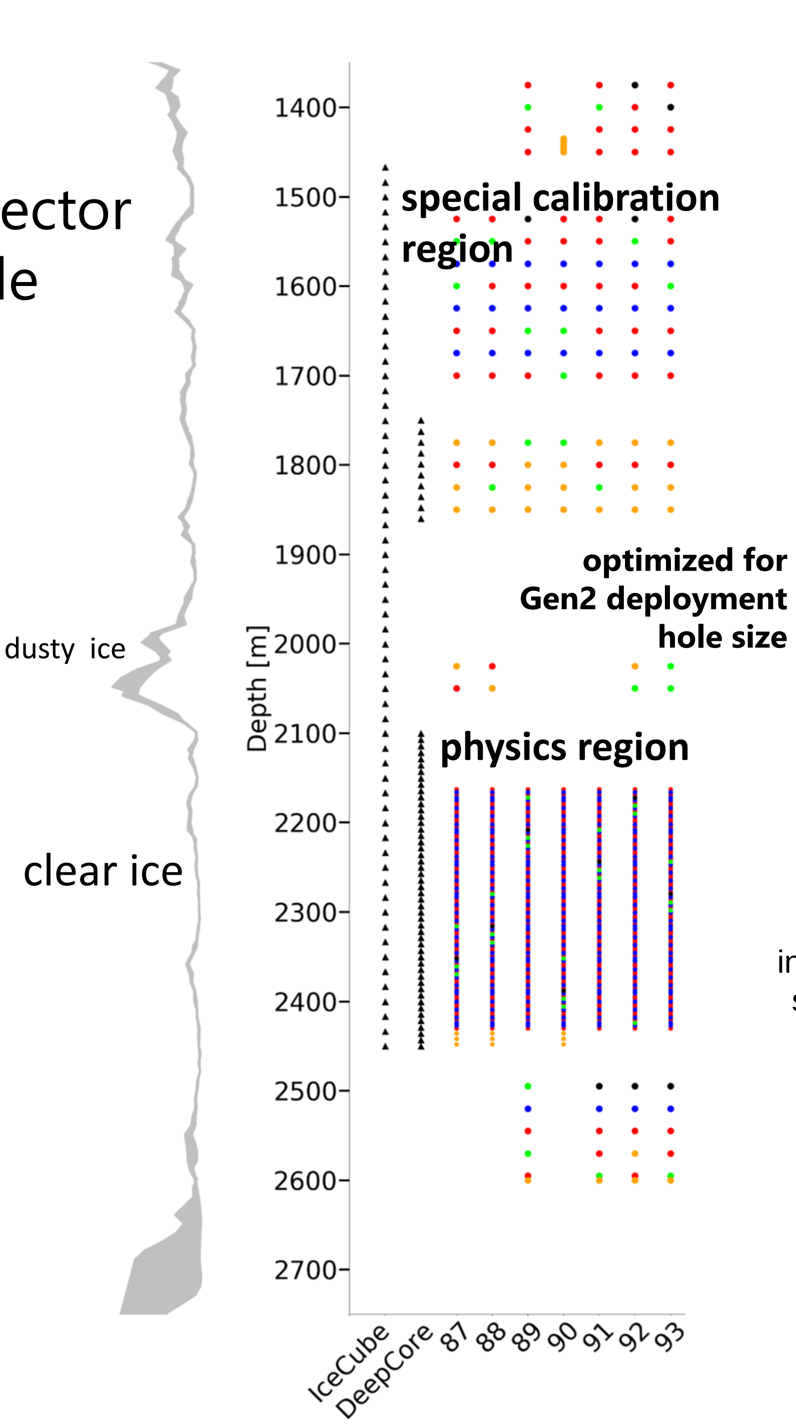


IceCube Gen2 Phase1 (Upgrade)

Geometry optimized for
- GeV neutrinos
- Calibration of the IceCube detector for improve systematics in wide energy regions

AI “The IceCube Upgrade -- Design and Science Goals”
arxiv:1908.09441, PoS-ICRC2019-1031 (2019)



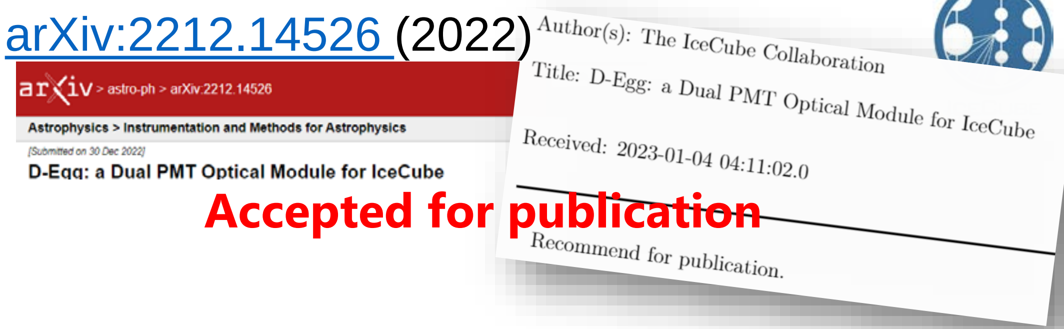


D-Egg: ~300 produced in Japan shipping 2024

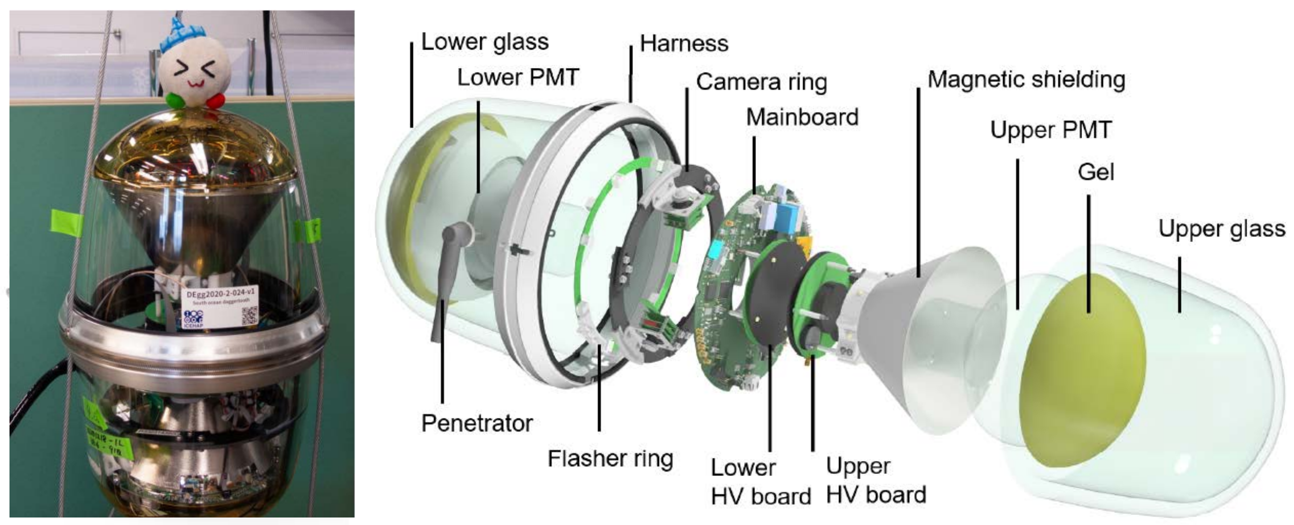
mDOM:~400
to be produced
in US and Germany
shipping 2024, 25

D-Egg: Dual optical sensors in an Ellipsoid Glass for Gen2

arXiv:2212.14526 (2022)



Accepted for publication

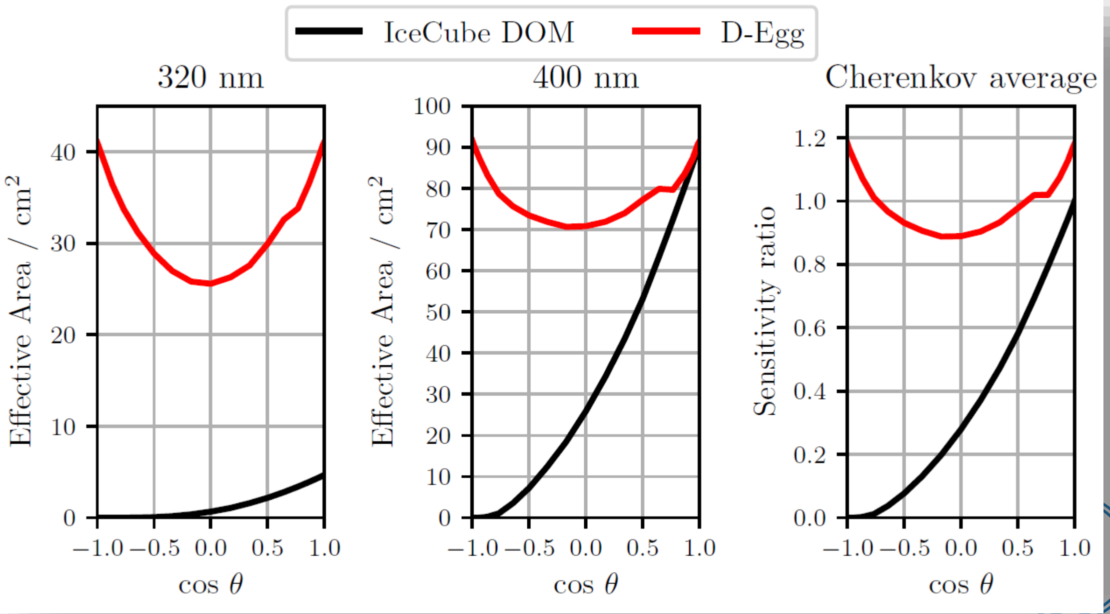


A factor of 2.8 better photon detection efficiency (>0.25 pe) compared to the current IceCube optical module with an improved 4pi sensitivity

Table 1. Effective areas for the optical modules.*

	IceCube DOM	D-Egg
Effective area (320 nm)	1.3 cm^2	31 cm^2
Effective area (400 nm)	32 cm^2	77 cm^2
Cherenkov-averaged sensitivity (Ratio to IceCube DOM)	1	2.8

* An efficiency due to the threshold of 0.25 PE is included in the detection efficiency of PMTs.



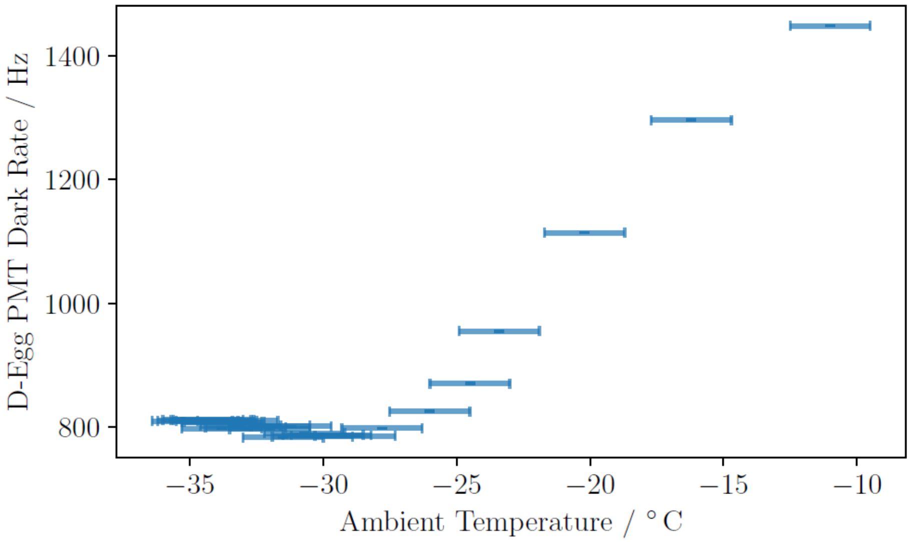
Production and final acceptance test (FAT)

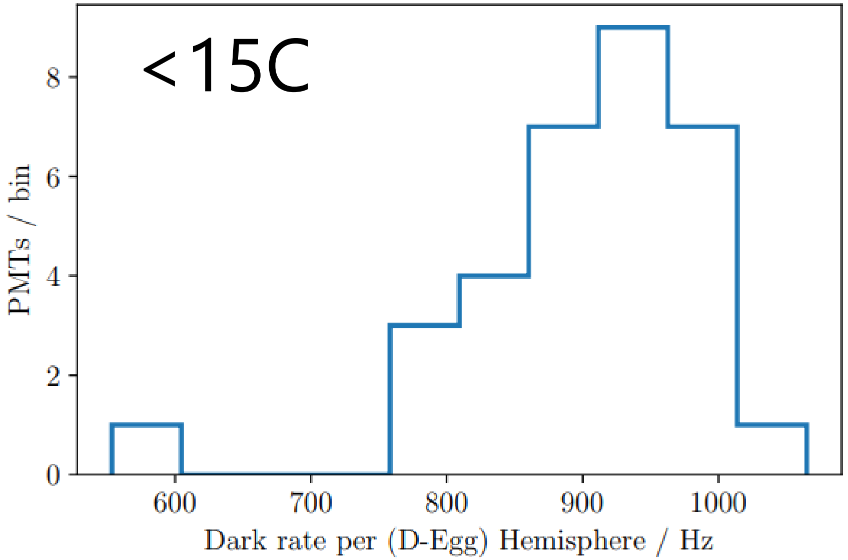
- Production of 310 D-Eggs and 10 extra for lab testing completed by the end of 2021 almost on the pre-covid schedule but the upgrade schedule delayed due to covid…
- The Final Acceptance Test (FAT) is a high-standard screening test that lasts for 20-day cycle at -40℃, with temperature cycling between cold environment and room temperature
- 91 D-Eggs underwent FAT (Two failure modules so far)

On-going Final Acceptance Test Results

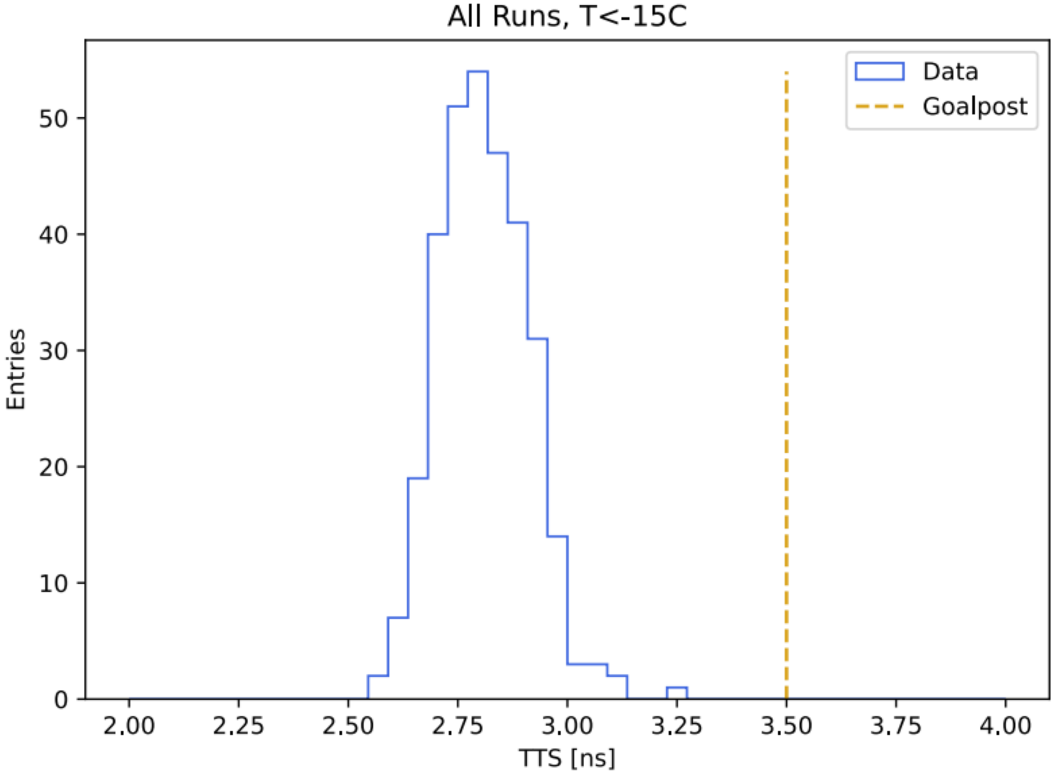
All modules goes to the South Pole are confirmed to pass the goal post we set

Dark rate temperature scan

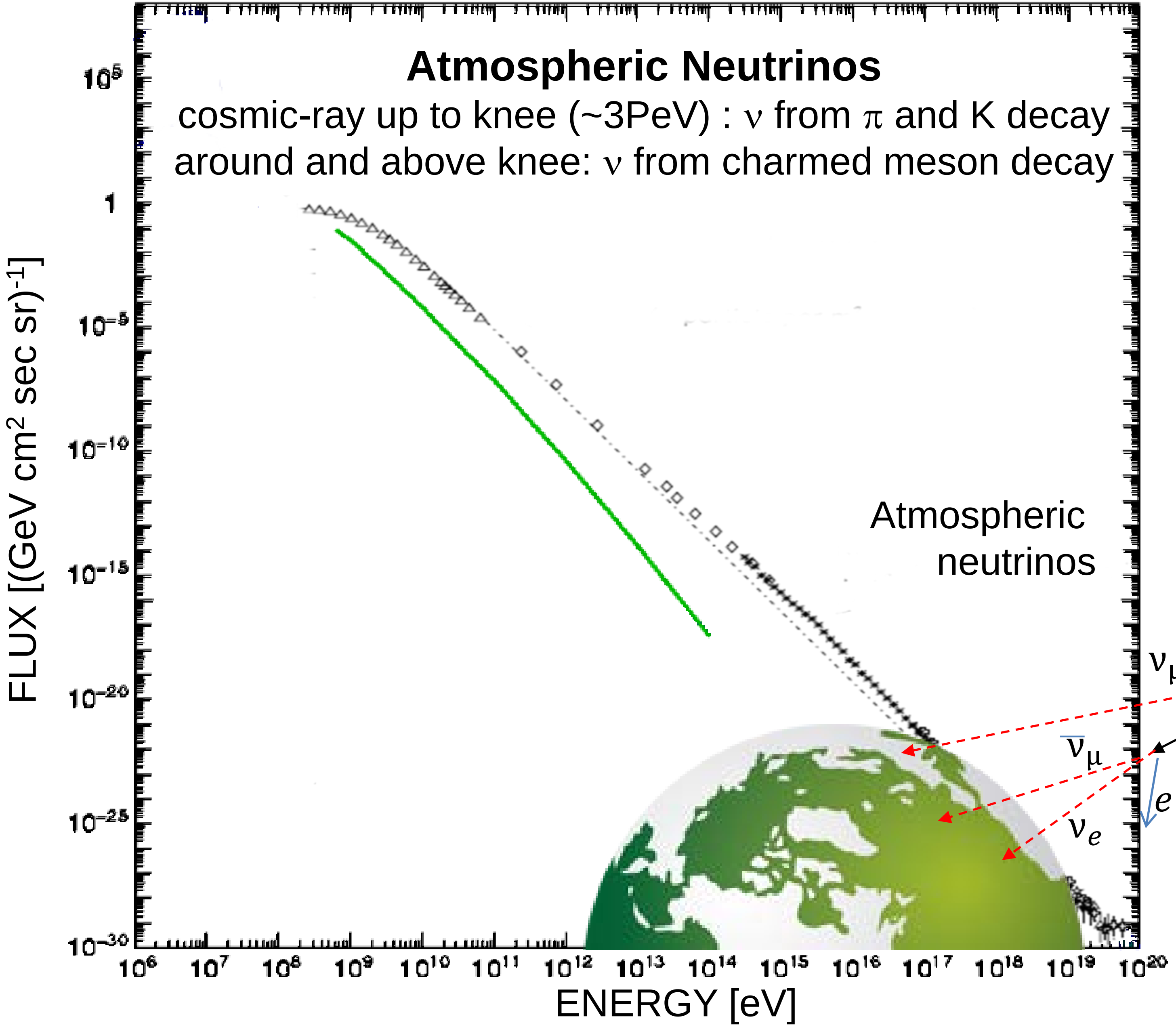




transit time spread

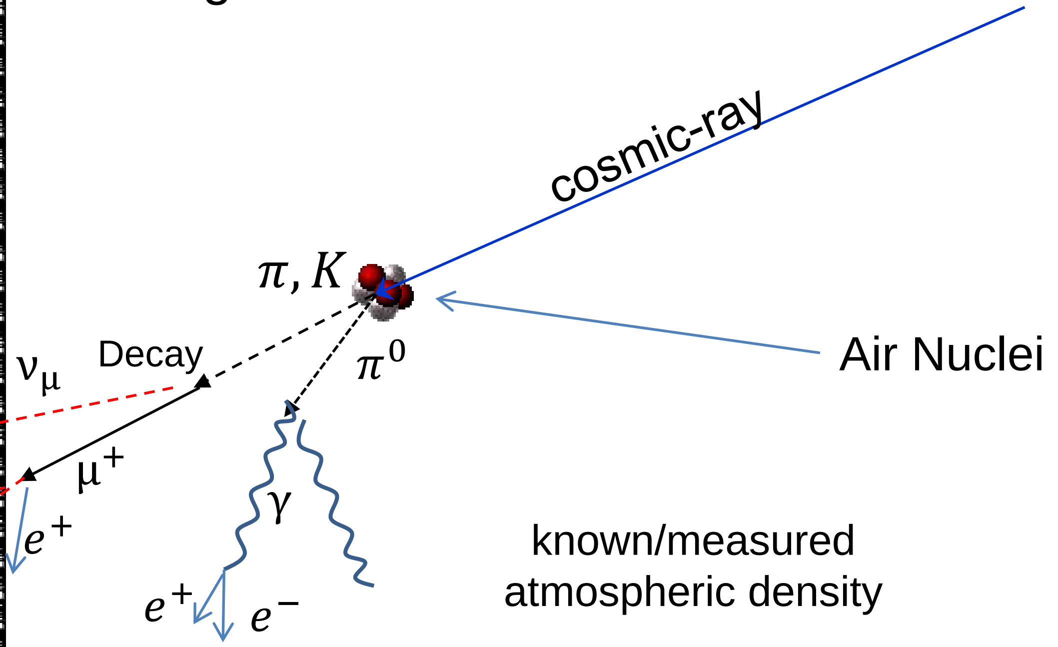


Common systematics and calibration beam



Uncertainties

- Primary cosmic ray flux, composition
- ***Hadronic interaction***
- Atmosphere
- Magnetic field

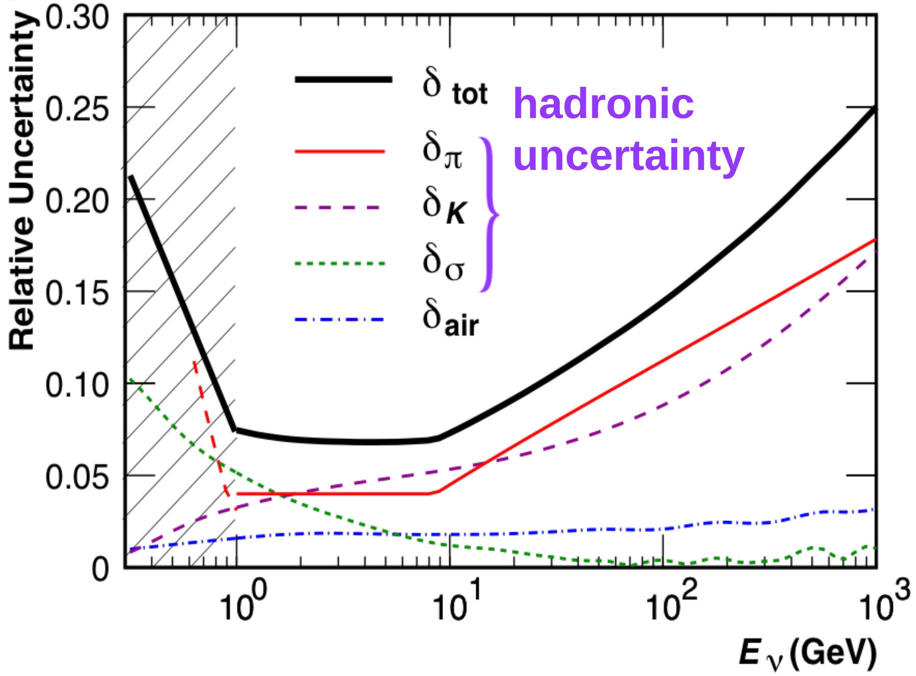


Improvements of the standard atmospheric neutrino model

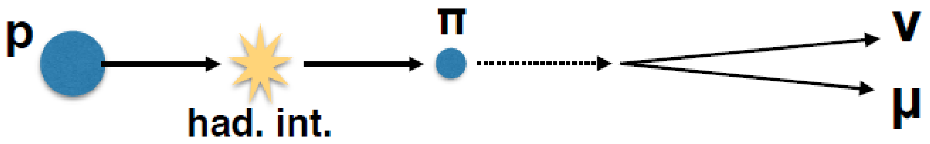
Kazufumi Sato (ICRR)

Systematics reduction of widely used “Honda model” [PRD 83, 123001(2011)]
using **hadron production data measured in beam experiments**

uncertainty of ATMNC flux
[M. Honda et. al, PRD75, 043006(2007)]



Main sources of uncertainty: Hadron interaction (evaluated with atmospheric muon data)



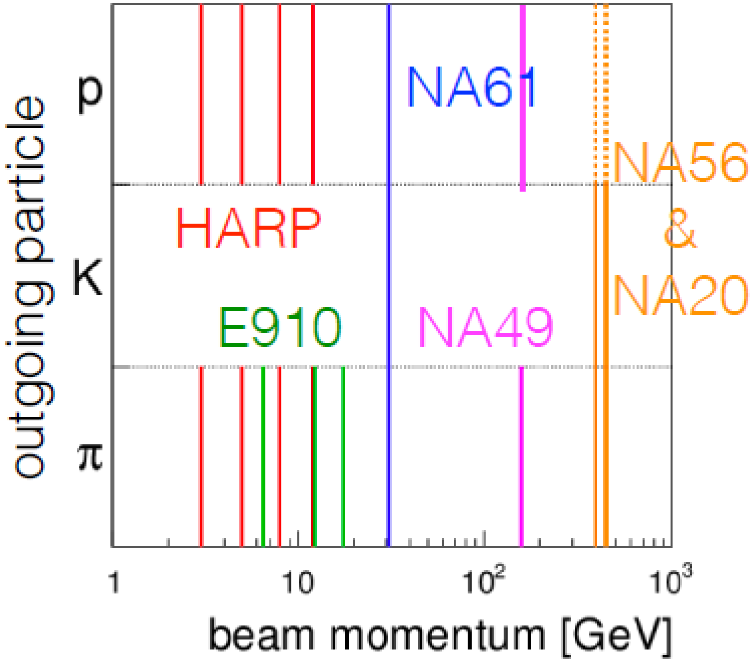
E_ν < 1GeV uncertainty
→Limited low-E μ data
E_ν > *O*(10 GeV) uncertainty
→ Kaon contribution

Estimation of hadronic interaction uncertainty using accelerator experiments
p_{beam} = 3 GeV/c -- 450 GeV/c from HARP, E910, NA61, NA49, NA56

Upgrade of Honda atmospheric neutrino flux calculation with implementing recent hadron interaction measurements

K. Sato et al. **PoS-ICRC2021-1210 (2021)**

beam momentum and on-going particle type



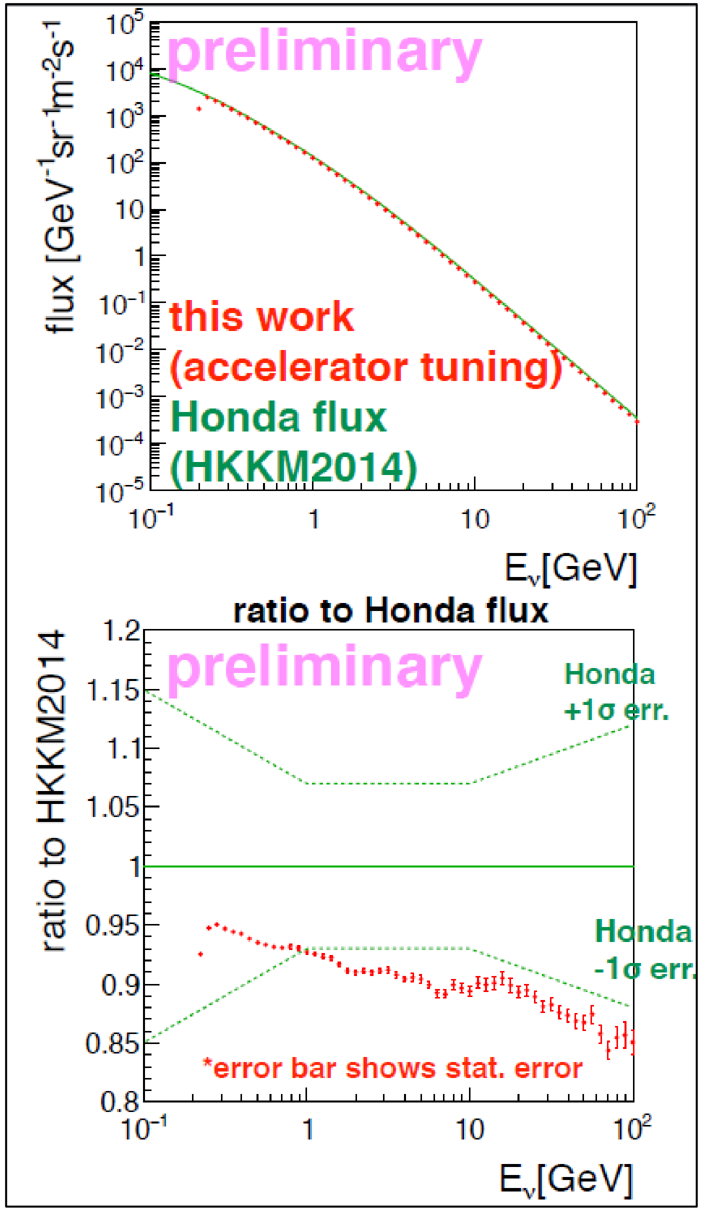
h_{out}	Beam momentum [GeV/c] 3	5	6.4	8	12	12.3	17.5	31	158	400	450
$\pi^{\pm}$	Be, C, Al [6]	Be, C, Al [6]	Be [8]	Be, C, Al [6]	Be, C, Al [6]	Be [8]	Be [8]	C [9]	C [10]	Be [11]	Be [11]
$K^{\pm}$	–	–	–	–	–	–	–	C [9]	–	Be [11]	Be [11]
p	Be, C, Al [7]	Be, C, Al [7]	–	Be, C, Al [7]	Be, C, Al [7]	–	–	C [9]	–	Be [11]	Be [11]

- discrete beam momentum
- limited phase space

dividing into groups based on p_{beam} and fitting for each group to extract cross section correction factor

Correction factor applied ν flux: **consistent within error** (5-10% smaller than Honda flux)

atm. μ simulation shows same tendency

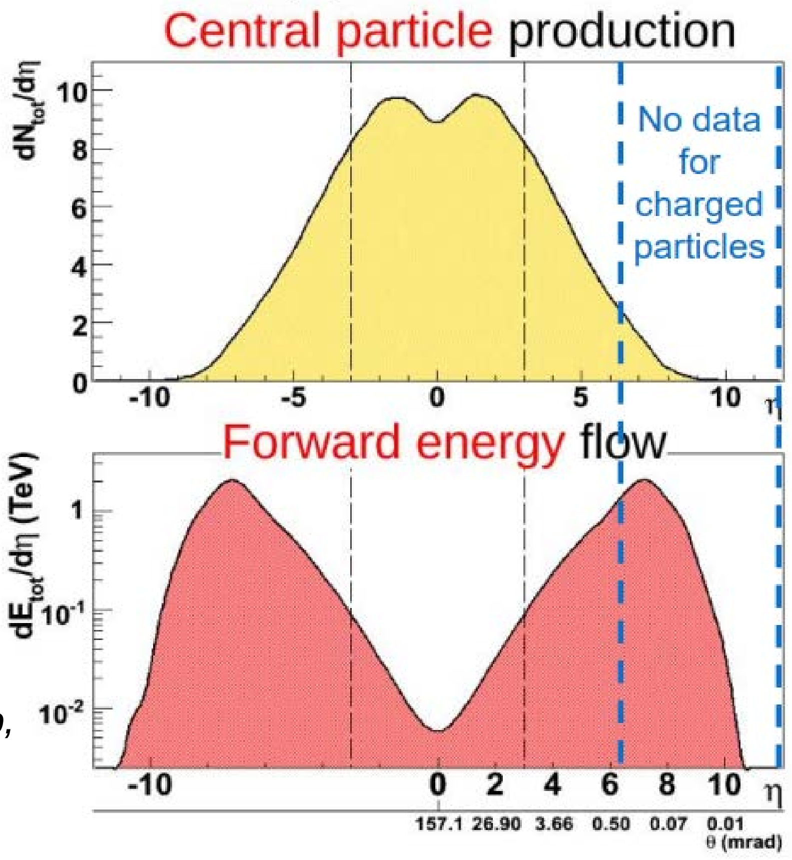


CR interaction data from collider experiments: LHCf and RHICf

Hiroaki Menjo and Yoshitaka Itow (ISEE)

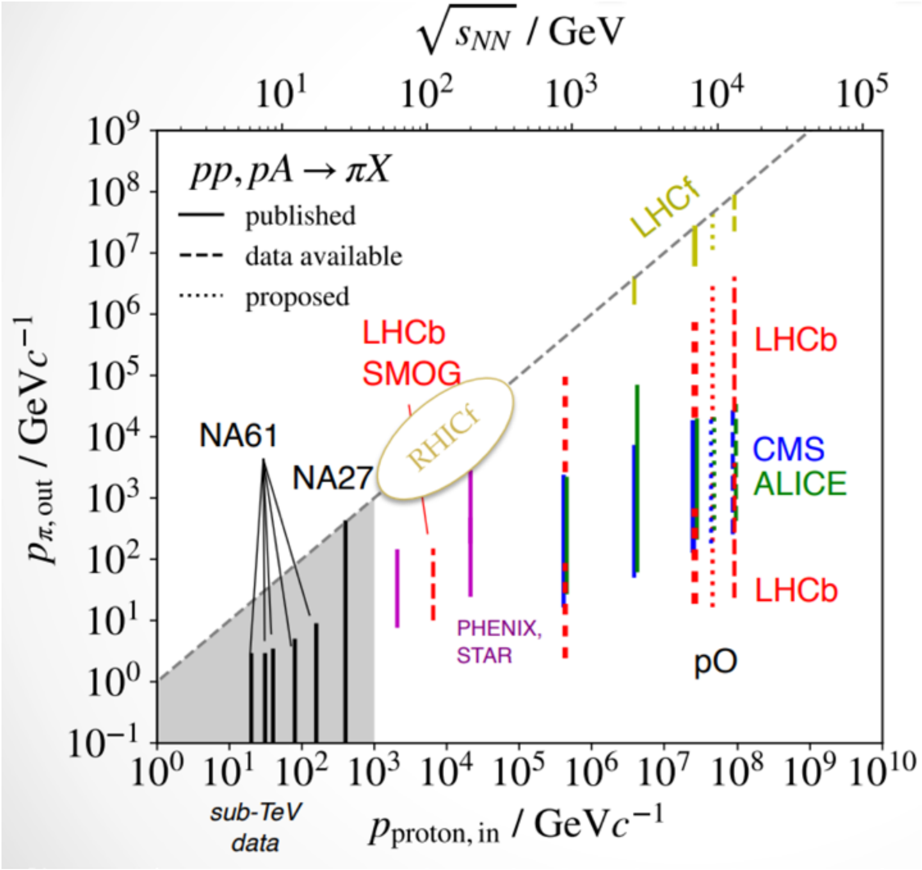
Measurement of very forward regions is essential ***→ LHC forward (LHCf) and RHIC forward (RHICf) experiments***

Pseudo-rapidity dependence of particle production and energy flow in p-p @ 14 TeV



A. Fedynitch YITP Workshop, 2020

Experimental coverage



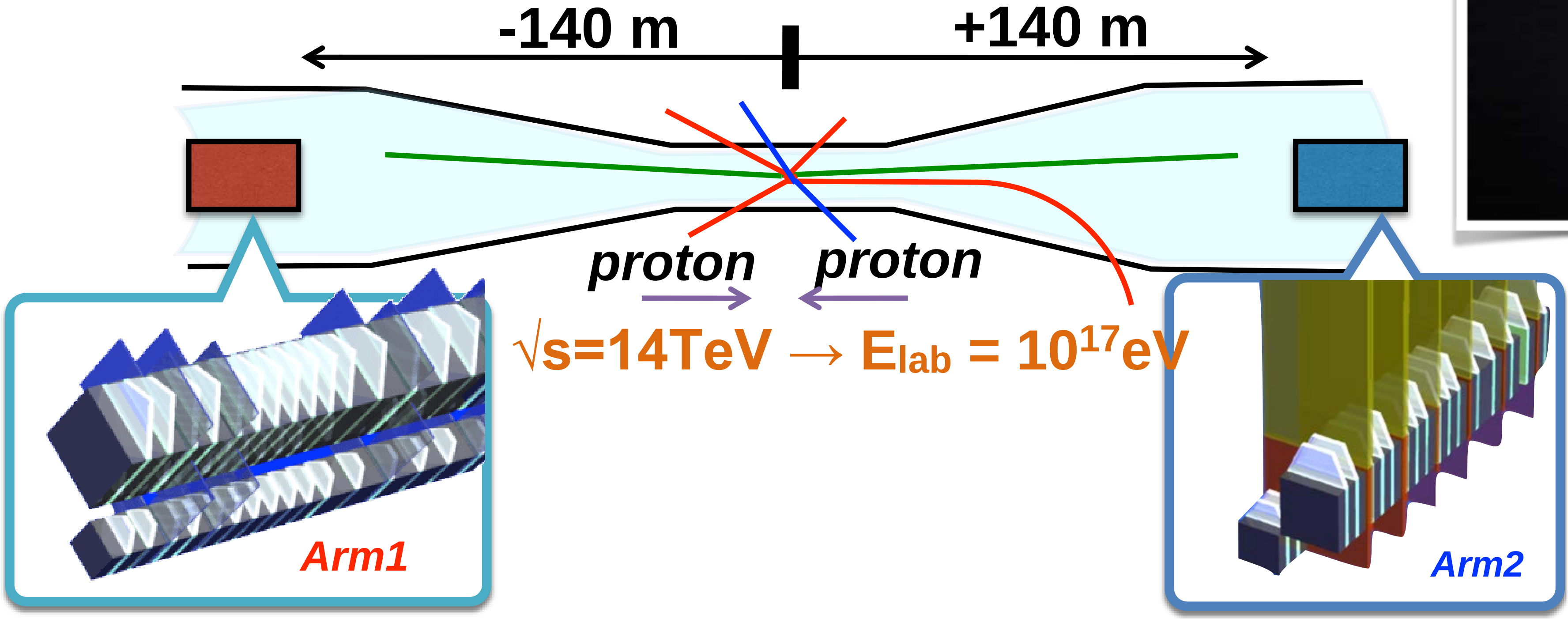
H. Dembinski ISVHECRI 2018

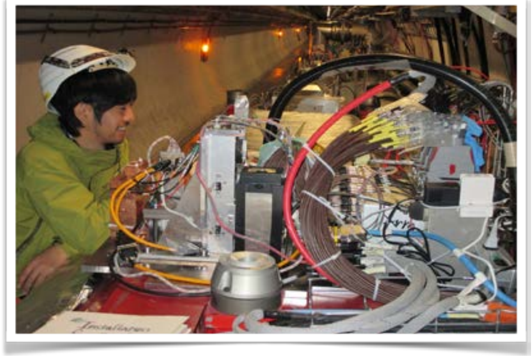
CR interaction data from collider experiments: LHCf and RHICf

Hiroaki Menjo and Yoshitaka Itow (ISEE)

LHCf detectors

- Sampling and positioning calorimeters
- ATLAS interaction point
- +/- 140m from the IP
- Cover Zero degree of collisions pseudo-rapidity η > 8.4





Analysis and publication status: LHCf and RHICf

Hiroaki Menjo and Yoshitaka Itow

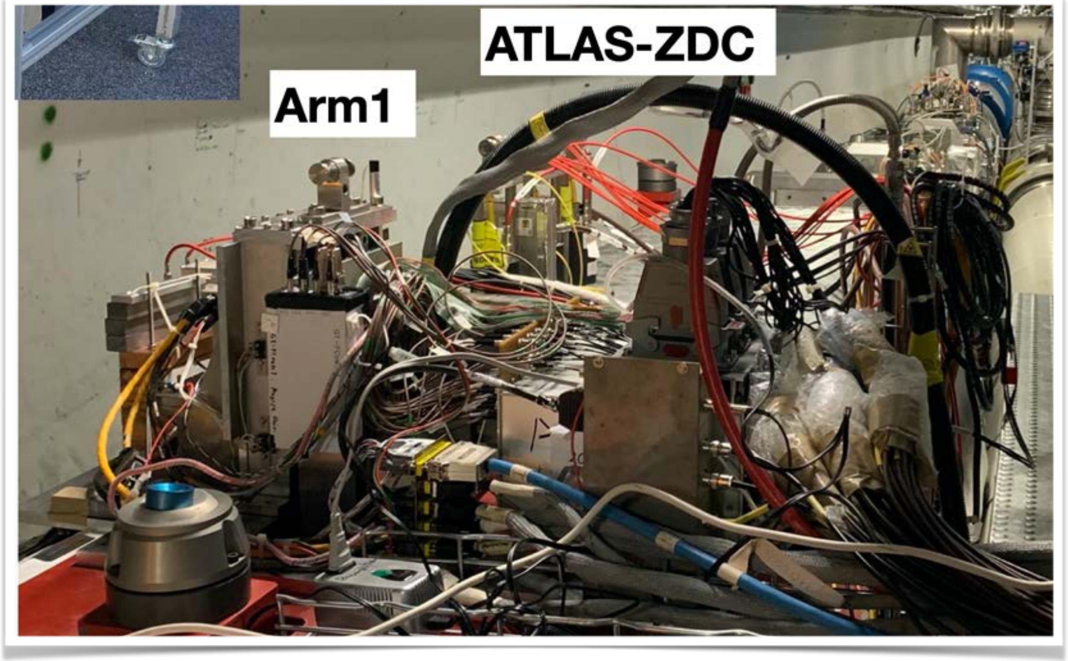
Run	E_{lab} (eV)	Photon	Neutron	π^0		LHCf-ATLAS joint analysis
p-p $\sqrt{s}$=0.9TeV (2009/2010)	4.3×10^{14}	PLB 715, 298 (2012)		-		
p-p $\sqrt{s}$=2.76TeV (2013)	4.1×10^{15}			PRC 86, 065209 (2014)	PRD 94 032007 2016)	
p-p $\sqrt{s}$=7TeV (2010)	2.6×10^{16}	PLB 703, 128 (2011)	PLB 750 360 (2015)	PRD 86, 092001 (2012)		
p-p $\sqrt{s}$=13TeV (2015)	9.0×10^{16}	PLB 780, 233 (2018)	JHEP 2018, 73 (2018) JHEP 2020, 016 (2020)	preliminary		Photon in diffractive coll. Preliminary: ATLAS-CONF-2017-075, Final: under internal review
p-Pb $\sqrt{s_{NN}}$=5TeV (2013,2016)	1.4×10^{16}			PRC 86, 065209 (2014)		
p-Pb $\sqrt{s_{NN}}$=8TeV (2016)	3.6×10^{16}	prelimiary				
RHICf p-p $\sqrt{s}$=510GeV (2017)	1.4×10^{14}	Submitted ArXiv:2203.15416		Spin Asymmetry PRL 124 252501 (2021)		with STAR

LHCf 2022 operation

Hiroaki Menjo and Yoshitaka Itow (ISEE)

- $K^{+/-}$ are dominant source of Atm. ν in 100 GeV < $E_ν$ < 1 PeV range

Hardware upgrade
✓ Improved readout speed of silicon DAQ
✓ New trigger for high energy π^0, η, K_S^0



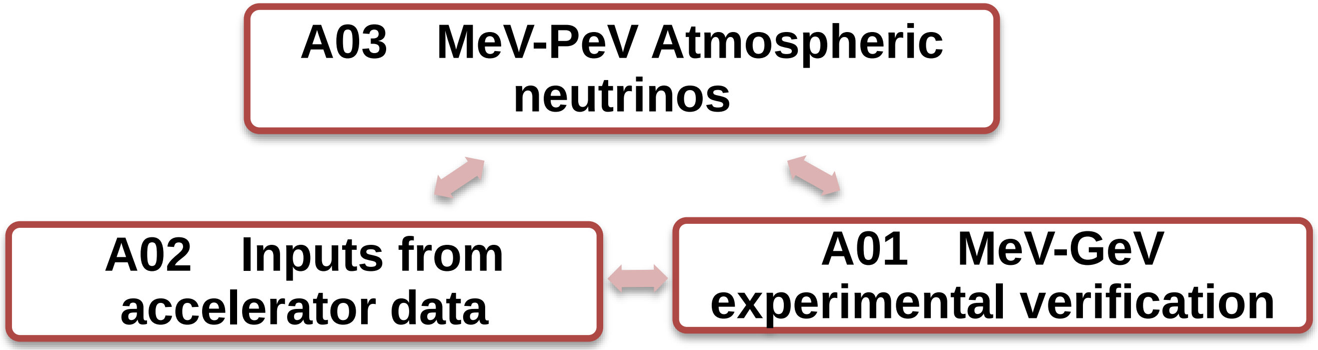
- Successful operation of obtained 300 M events in September 2022!

Improve/open many analysis channels with high statistics including K^0_s and Λ measurements

LHCf events: Obtained η events: ~ 1500 events x 4
(⇔ ~ 100 events in 2015 data set)
LHCf-ATLAS common events: ~300 M events
(⇔ ~7 M events in 2015 data)

Summary

- Wide energy range neutrino beams in the Universe / Detectors available in Earth
- Common and systematic understanding of ”Beam and Detector” is crucial for discovery of signature from beyond-standard model physics
  - With the scheme in the Grant-in-Aid for Scientific Research on Innovation Areas



1. Unique methods for the atmospheric neutrino model tuning using accelerator data established
2. LHCf and RHICf data for the further improvements of the atmospheric neutrino model
3. Optical modules for the IceCube Upgrade project have been produced and being calibrated.

Ready for the 2025 installation of the post-covid re-defined schedule (shipping in 2024)