Rapporteur: Neutrinos and Muons

Anna Nelles

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

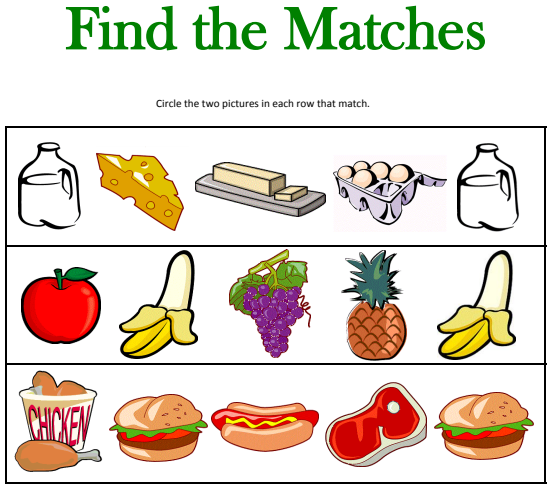
ECAP ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS

DESY.

As usual too many really interesting contribution

Or why the job of a rapporteur is really tough

- 212 contribution in the Neutrinos and Muons Track
  - 7 Plenary contributions
  - 11 discussion sessions
  - Many excellent posters, pre-recorded talks, …
- Everything recorded and viewable at any time

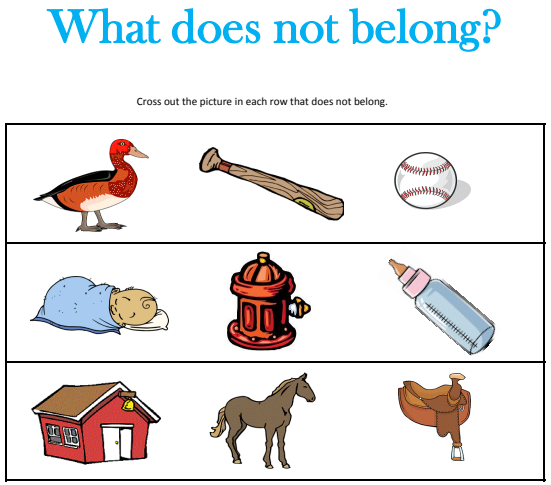


The excuse: "Sorry I couldn't attend this session, because it was double-booked!" No longer holds.

The discussion sessions already provide a sorting of topics — but using the same here would be unfair towards those not selected there

If I highlight something: "Ok, otherwise I would have complained."

If I don't highlight something: "…"



Bottom-line up front

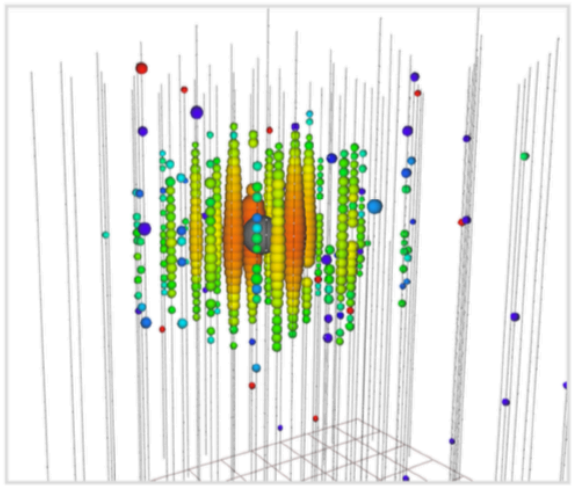
Just so that you can immediately disagree with the message of my talk

- We have exciting results with neutrinos (in particular MM), but really we don't have enough (high energy) neutrinos (yet)
- What is my evidence for this observation?
  - A flurry of ideas for new telescopes/arrays/satellites/balloons/…
  - Everyone mentions neutrinos -> even if an experiment primarily targets UHCRs, neutrinos are always mentioned too
  - Detector calibration is a serious business now, systematics become relevant
  - An incredible amount of contributions dealing with reconstructions, simulations, global frameworks, specific analyses, machine learning, source studies, transient analysis, time-integrated analyses, …

The community is doing their homework to get ready for many more neutrinos, which the broader community is excited about

Ideas

Current players and their upgrades



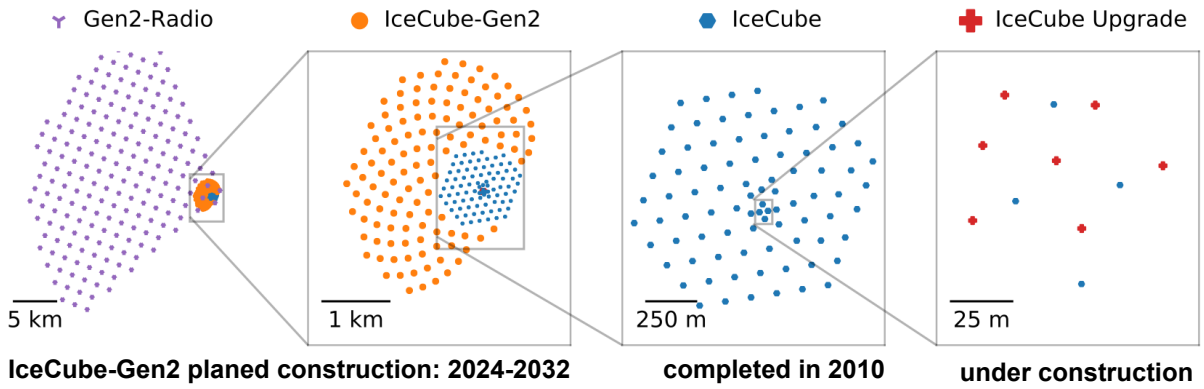
IceCube

10 years after completion still scratching the surface of neutrino astronomy

IceCube Upgrade funded and optical modules are currently being produced

IceCube-Gen2 proposed for construction after completion of the Upgrade

Highlight: Kowalski PoS(ICRC2021)022



For more ideas: Discussion session 38: Future of neutrino telescopes

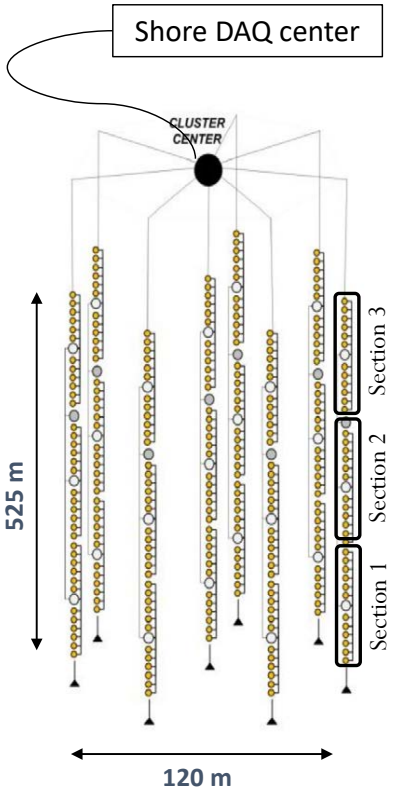
Current players under construction

12 KM3NeT detection units now operational

Highlight: Dzhilkibaev PoS(ICRC2021)002

Review: Coyle PoS(ICRC2021)042

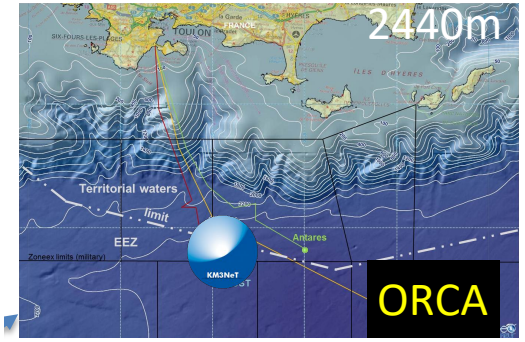
Baikal-GVD



Deployment schedule

Year	Number of clusters	Number of OMs
2016	1	288
2017	2	576
2018	3	864
2019	5	1440
2020	7	2016
2021	8	2304
2022	10	2880
2023	12	3456
2024	14	4032

Effective volume 2021: 0.40 km^3 (cascade mode)



Planned: Completion of ORCA115 array in 2025 and ARCA230 in 2027

Oscillation **R**esearch with **C**osmics In the **A**byss

Astroparticle **R**esearch with **C**osmics In the **A**byss

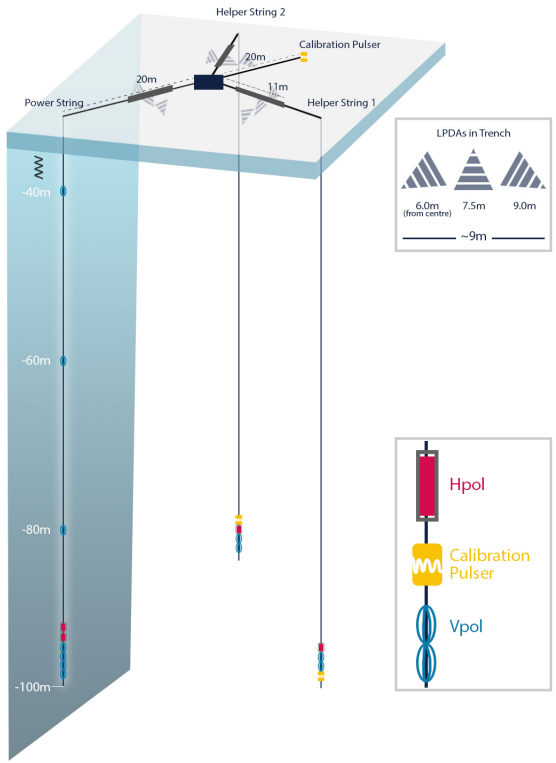
still out there,10 years of data

New players under construction

The radio crowd, PT 1
~ 100 PeV - 100 EeV

RNO-G

Radio Neutrino Observatory - Greenland



First large scale implementation of a radio neutrino array

35 stations planned and fully-funded, 1st deployment currently on-going

PUEO

Balloon payload with radio antennas.

Successor of ANITA, but with improved energy threshold and improved sensitivity (x10)

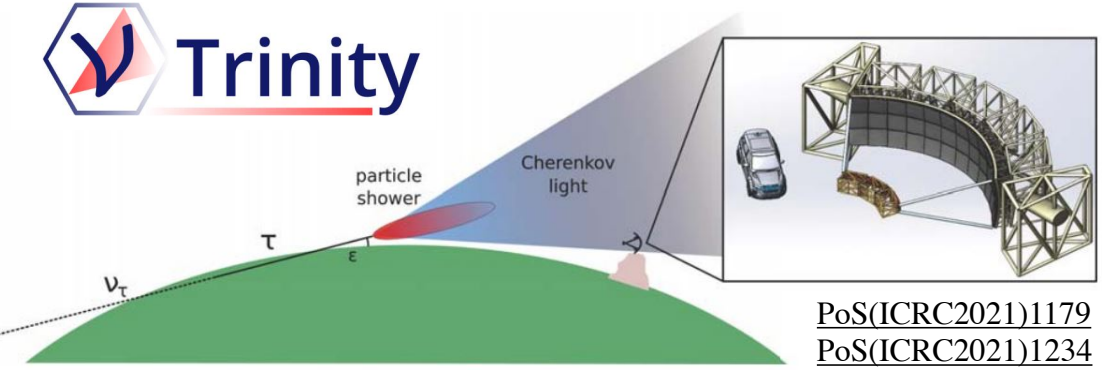
Scheduled to fly from McMurdo in 12/2024

PoS(ICRC2021)1029

Highlight: Wissel PoS(ICRC2021)001

New players in pathfinder mode

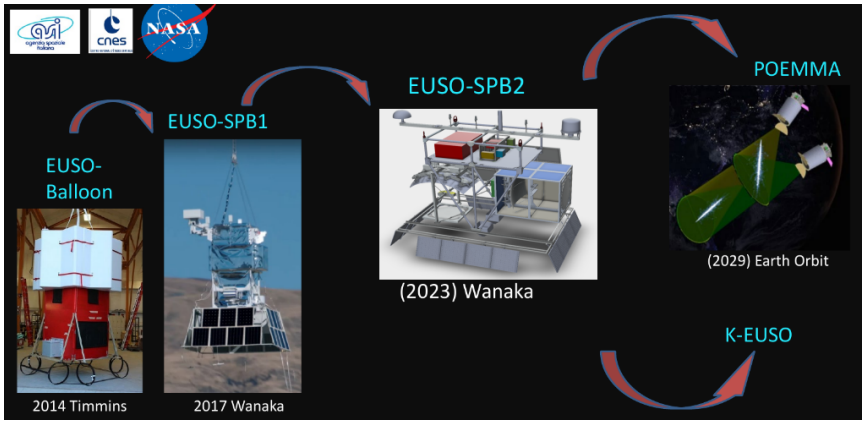
Trinity



PoS(ICRC2021)1179
PoS(ICRC2021)1234

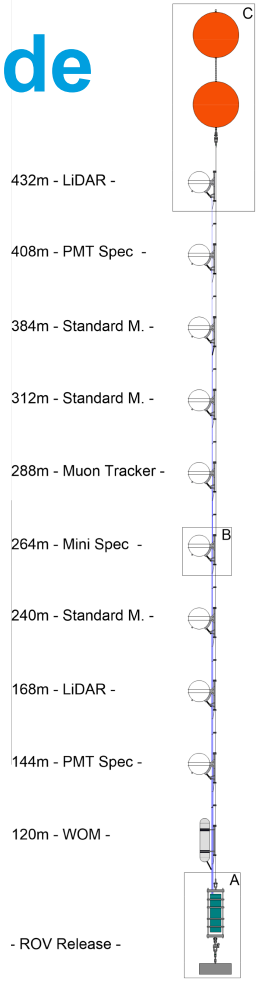
Concept: “Many times MAGIC”
Demonstrator telescope funded by NSF

Cherenkov techniques has the potential to bridge the energy region between in-ice / in-water optical arrays and radio technique



Combination of Fluorescence and Cherenkov techniques

EUSO-SPB2 targets the observation of UHECRs, works as technology demonstrator for the proposed **POEMMA** mission targeting (also) transient neutrinos



P-ONE

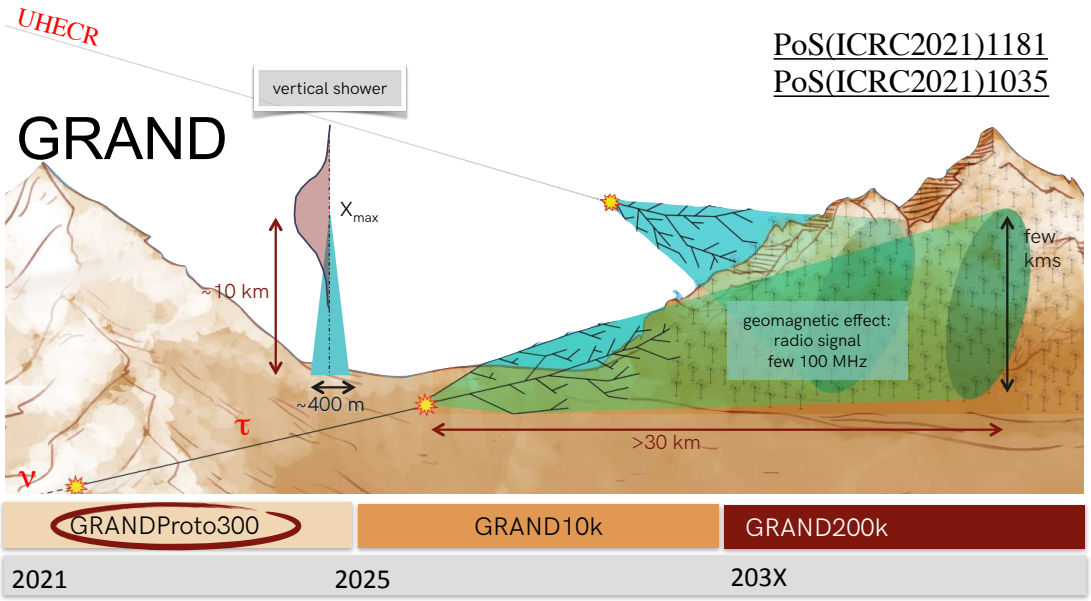
Pacific: coast of Vancouver
Potential for third large water array
Second pathfinder string deployed in 2020
First attenuation length measurements
Data is public
https://data.oceannetworks.ca

Highlight: Resconi PoS(ICRC2021)024

PoS(ICRC2021)404
PoS(ICRC2021)976

New players in pathfinder mode

GRAND



PoS(ICRC2021)1181
PoS(ICRC2021)1035

Targeting tau neutrinos emerging from the Earth using radio

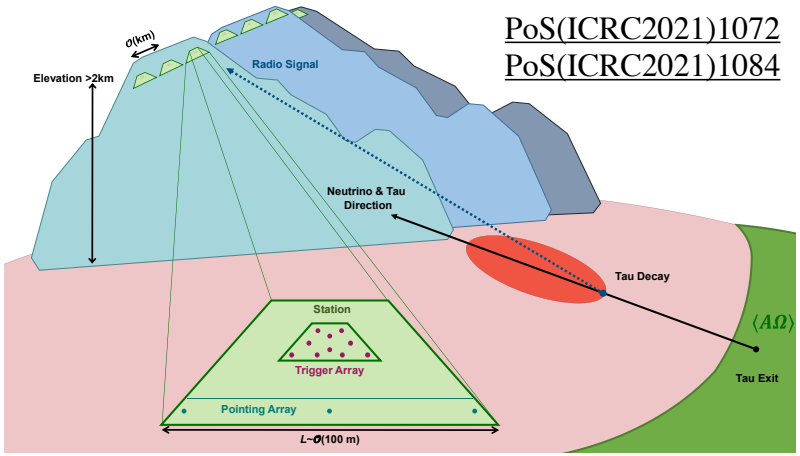
Same detection channel, but different geometry ideas

Up on a mountain vs. covering the mountain

Implications for discovery Veff vs. angular resolution

BEACON

Prototype operational using phased array approach



PoS(ICRC2021)1072
PoS(ICRC2021)1084

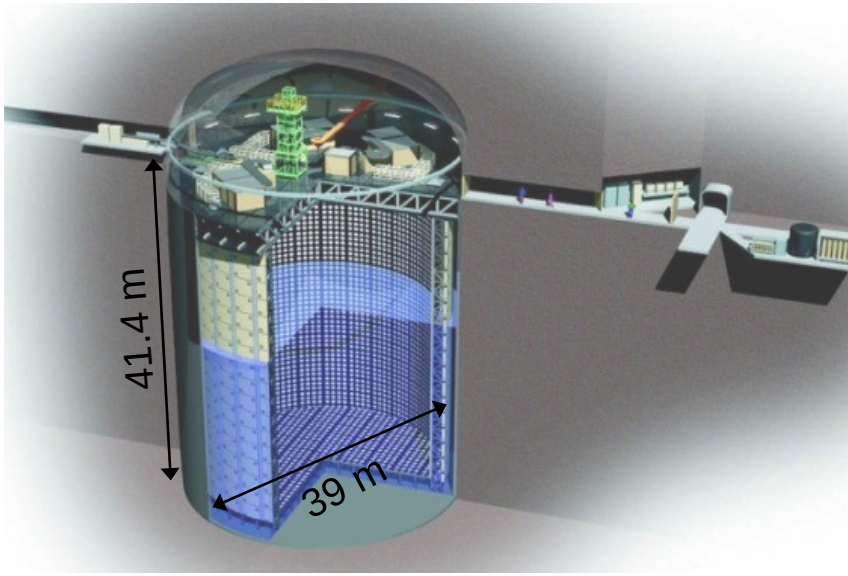
TAROGE

PoS(ICRC2021)1173

First set-up in Antarctic mountains

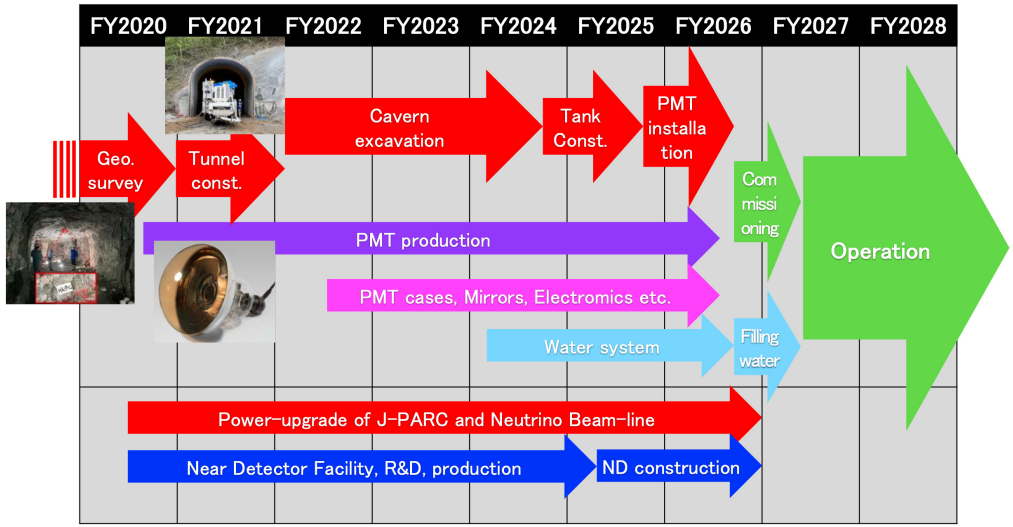
Players in the low energy regime

Super-K + Gd
Water-Cherenkov detector
25 years since it started taking data
Gadoliniumsulfate now being released for better neutrino anti-neutrino distinction



Highlight: Fernandez Menendez PoS(ICRC2021)008

Hyper-K(aminokande)
Next generation Water-Cherenkov detector
T2K -> Kamioka approved in 2020



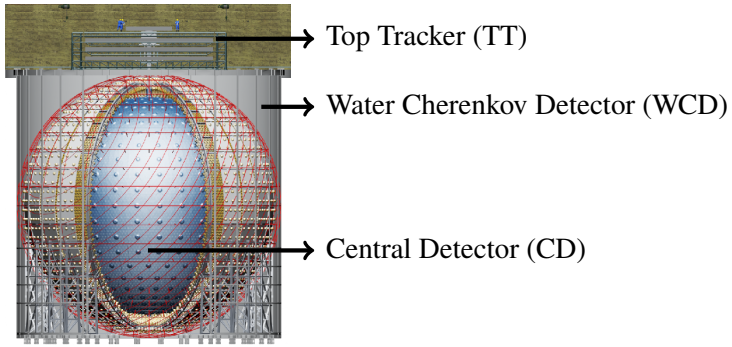
PoS(ICRC2021)1192

Players in the low(er) energy regime

PoS(ICRC2021)1194
PoS(ICRC2021)1229
PoS(ICRC2021)1076
PoS(ICRC2021)1187

JUNO

Reactor neutrino experiment
under construction in China
Interesting sensitivities if combined with
ORCA (or the IceCube-Upgrade)



BAKSAN

Multi-purpose
liquid
scintillator
detector

Current R&D at
5t, target mass
10kt, targeting
geoneutrinos
and CNO
neutrinos

PoS(ICRC2021)1188
PoS(ICRC2021)1097
PoS(ICRC2021)1100
PoS(ICRC2021)1101

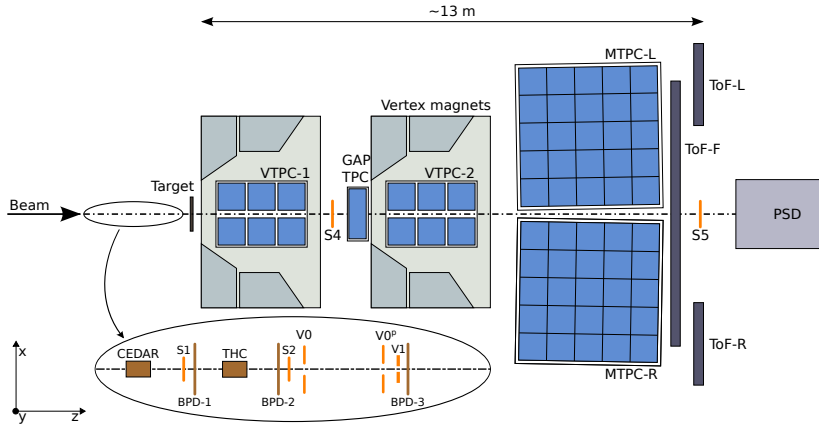
Idea: Protvino -> Km3Net
2590km baseline

Review: Coyle PoS(ICRC2021)042

Other exciting experimental endeavors

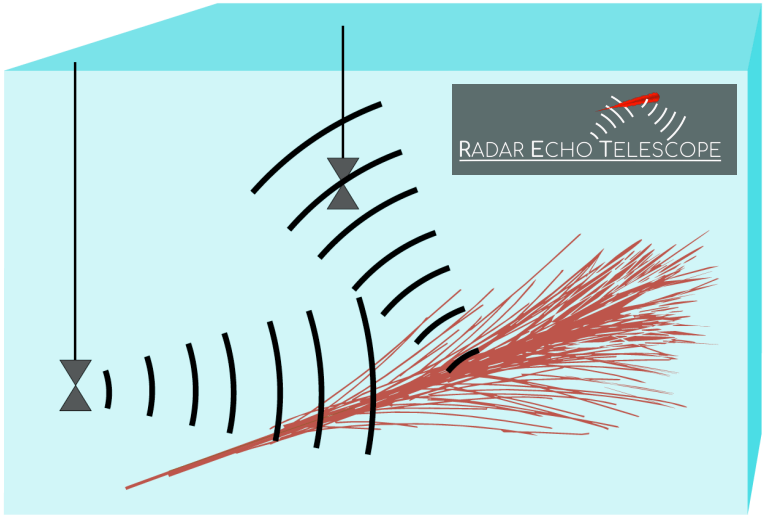
PoS(ICRC2021)416
PoS(ICRC2021)1082
PoS(ICRC2021)1195
PoS(ICRC2021)1211

NA61/SHINE

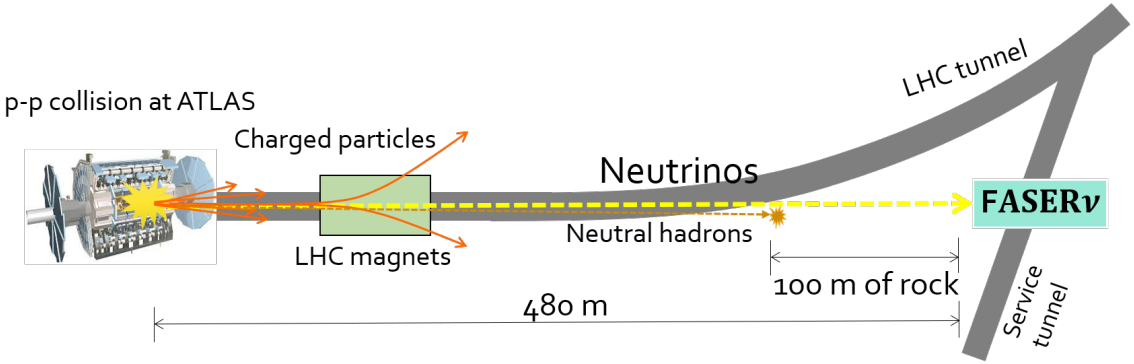


CERN fixed-target experiment, delivering input to cosmic-ray predictions, planned detector upgrades and heavy particle fragmentation

PoS(ICRC2021)102
PoS(ICRC2021)535



Concept study to use radar echo on particle showers in ice, indications for energy threshold lower than radio neutrino detection



Targeting the muon excess problems in air showers and predictions for prompt neutrinos (through forward charm meson production), starting data taking 2022

PoS(ICRC2021)1025
PoS(ICRC2021)1218

Ideas about what things to look for:

Multi-messenger astronomy was covered by Irene

- Discussion session on Fundamental Physics with neutrinos (Session 31)
- Theoretical modeling of sources, searches for neutrinos using these models
- Big picture introduction by Spencer Klein
- Some (provocative) questions:
  - What comes first: new physics or secondary corrections to our models?
  - Can one use the astrophysical flux as given?
  - Do systematic uncertainties dominate all potential searches?

- Discussion session on Astrophysical neutrinos (Session 39)
- Many ideas for searches and searches themselves
- Big picture introduction by Markus Ahlers
- Some (provocative) questions:
  - Too risky to assume identical sources for searches, while they are not?
  - Do we have too many fudge factors in our models, tuned to data?
  - Are we clear enough about assumptions when ruling out sources?
  - Are there enough precautions against over-interpreting correlations and bias?

Watch the summary not me summarizing the summary

Calibration
detector development

Development of photo(n) detectors

See also discussion session 33: Photodetection in Cherenkov Detectors

Trend towards more complex and segmented photodetectors

PoS(ICRC2021)1041

(a) Gen1 DOM **(b)** mDOM **(c)** D-Egg **(d)** mEgg **(e)** LOM−18

Extensive discussions about timing requirements, needs for calibration, suitability for mass-production of more complex sensors, standardization needs, cost efficiency of more complex modules, …

Discussion of scalability shows that the community is really gearing up with the next experiments

WOM
PoS(ICRC2021)1038

SiPMs
PoS(ICRC2021)1043

mDOM
PoS(ICRC2021)1070

D-Egg
PoS(ICRC2021)1062

Photon traps
PoS(ICRC2021)1039

Large vs small PMTs
PoS(ICRC2021)1104

Large area PMTs
PoS(ICRC2021)1101

Light concentrators
PoS(ICRC2021)1097

STRAW-b
PoS(ICRC2021)1092

Hardware development

The nuts and bolts you usually only find on posters and there the experts find it

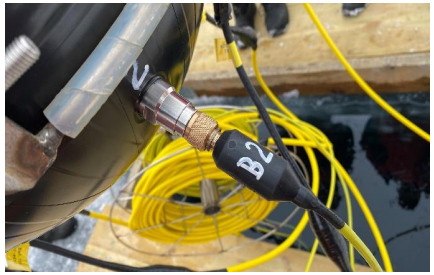
Only few hardware talks

Km3Net electronics

PoS(ICRC2021)1108

Time Sync Baikal-GVD

PoS(ICRC2021)1067



With no neutrino (yet) the radio field is a bit more into nuts and bolts still

Antennas

PoS(ICRC2021)1103

Radio trigger improvements

PoS(ICRC2021)1050
PoS(ICRC2021)1074
PoS(ICRC2021)1217

Programmable logic for trigger

PoS(ICRC2021)1028

System hardware

PoS(ICRC2021)1058

Fibre optics for data transmission are here to stay

Fibre optics IceCube

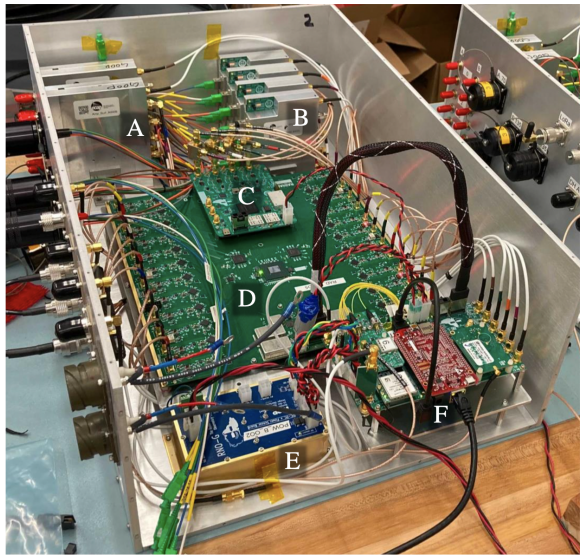
PoS(ICRC2021)1079

Fibre optics Baikal-GVD

PoS(ICRC2021)1066

Fibre optics RNO-G

PoS(ICRC2021)1058



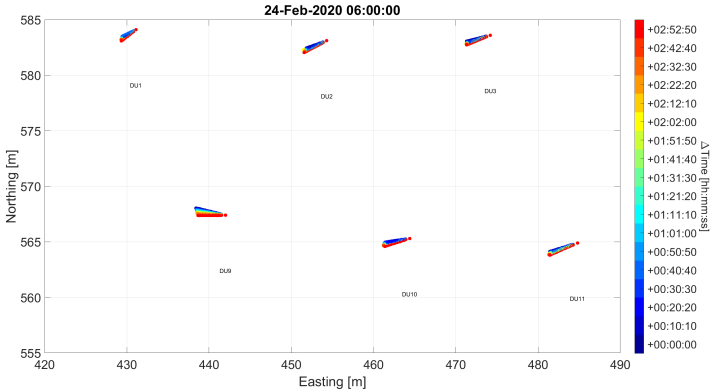
Detector calibration

See also discussion: 32 Cherenkov Media and Detector Calibration

The field has grown up, calibration is serious business now

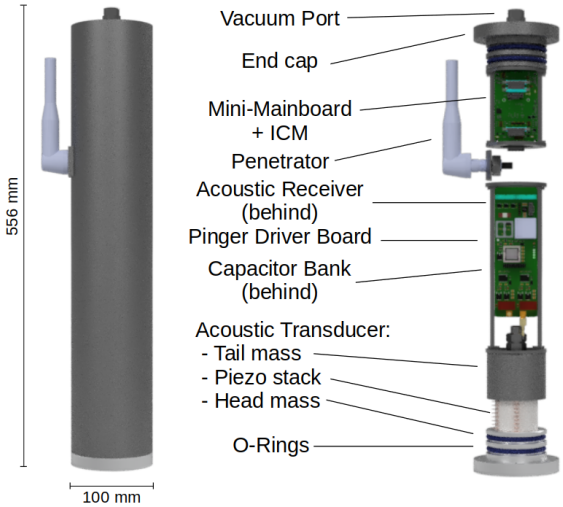
KM3NeT

PoS(ICRC2021)1052

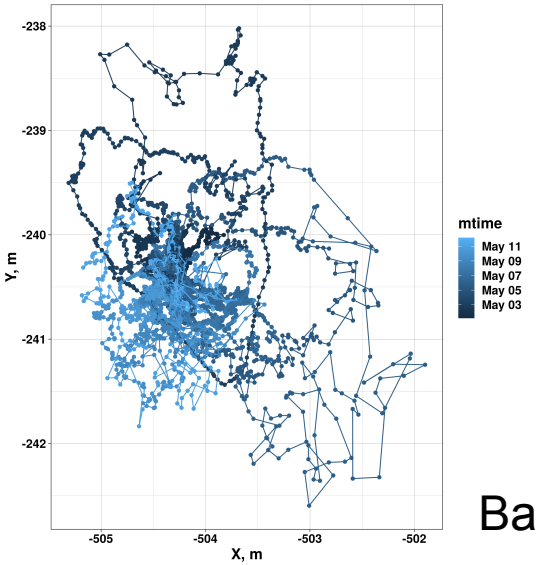


Acoustics Positioning

IceCube PoS(ICRC2021)1059



Acoustics positioning water



Baikal PoS(ICRC2021)1083

POCAM

PoS(ICRC2021)1049

Cameras in Ice

PoS(ICRC2021)1064
PoS(ICRC2021)1047

KM3NeT calibration units

PoS(ICRC2021)1096

in-situ KM3NeT

PoS(ICRC2021)1081

High-throughput testing

PoS(ICRC2021)1056

Laser for Baikal

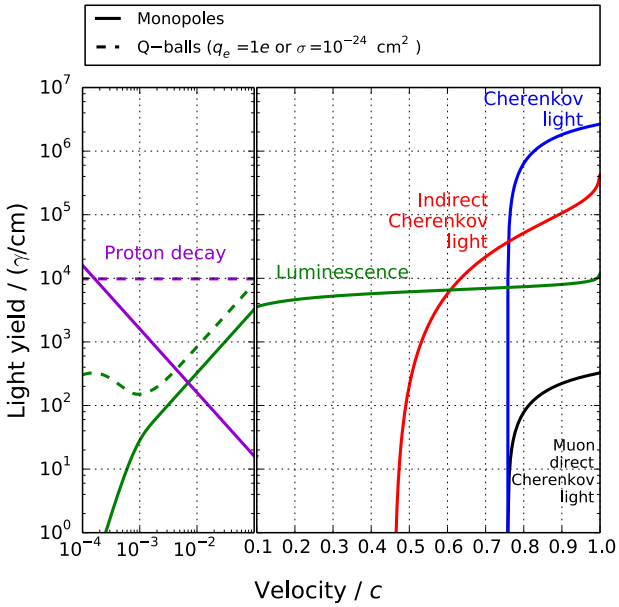
PoS(ICRC2021)1060

Calibration for Radio

PoS(ICRC2021)1086
PoS(ICRC2021)1069

Media properties

See also discussion: 32 Cherenkov Media and Detector Calibration



Luminescence properties of ice and water, a potential new detection channel for exotic “slow” particles in neutrino telescopes

PoS(ICRC2021)1093

Baikal monitoring

PoS(ICRC2021)1034

PoS(ICRC2021)1094

Baikal luminescence

PoS(ICRC2021)1113

Optical Ice Properties

PoS(ICRC2021)1057

PoS(ICRC2021)1023

PoS(ICRC2021)1119

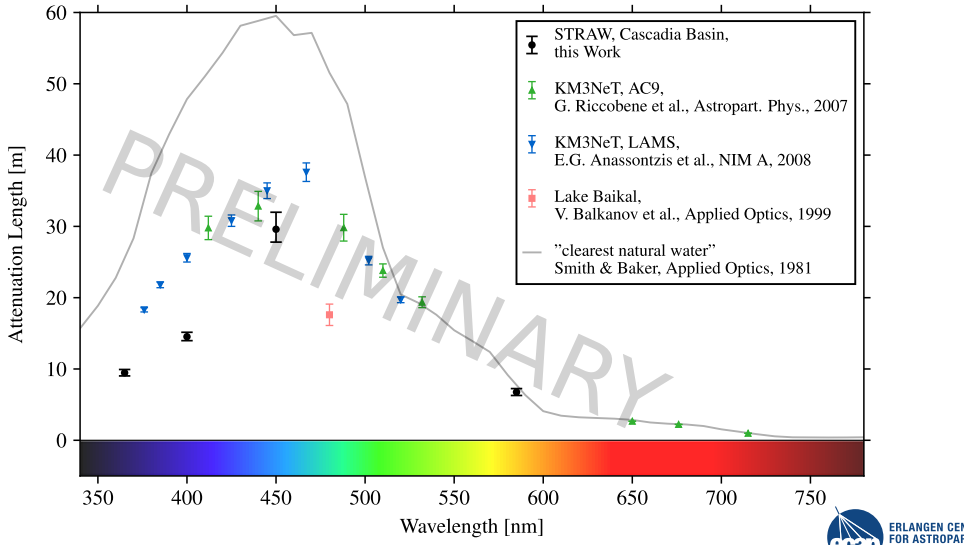
Radio Ice Modeling

PoS(ICRC2021)1027

PoS(ICRC2021)1206

Attenuation length P-ONE

PoS(ICRC2021)1160



Reconstruction and simulations

Neutrino pointing

See also discussion session 36: Shower reconstruction and pointing

Multi-messenger observations are helped by accurate pointing both for finding counterparts and calculating coincidences

Observation: Lots of ongoing work to develop new ideas, improve pointing, understand pointing, understand uncertainties and input for searches

Muontracks Baikal
PoS(ICRC2021)1080

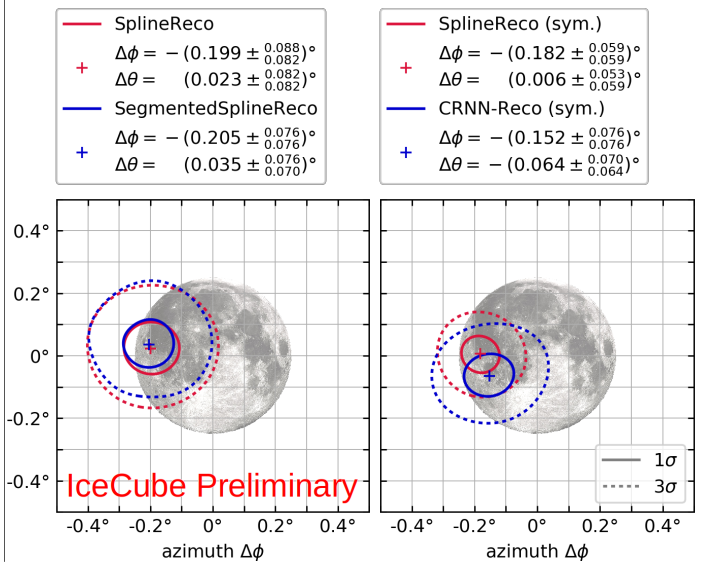
skyLLH for IceCube
PoS(ICRC2021)1073

IceCube Uncertainties
PoS(ICRC2021)1045

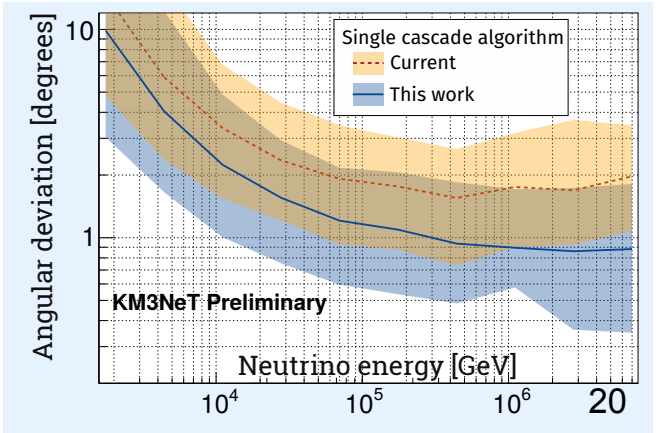
Antares Moon Shadow
PoS(ICRC2021)1124

Radio + Optical
PoS(ICRC2021)1182

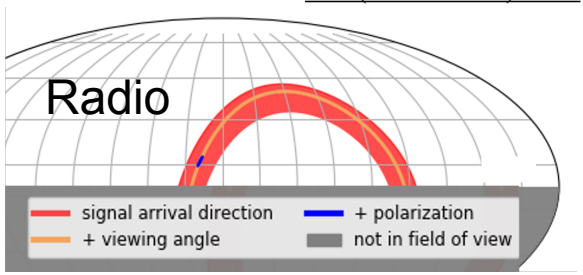
PoS(ICRC2021)1087



PoS(ICRC2021)1089



PoS(ICRC2021)1026



Reconstruction techniques

See also discussion session 37: Reconstruction and Analysis Techniques

Observation: Many, many excellent contributions in the bowels of the experiments in event reconstruction and simulations

Double-cascades GVD
PoS(ICRC2021)1167

Background suppression
PoS(ICRC2021)1114

Hit finding Baikal
PoS(ICRC2021)1063

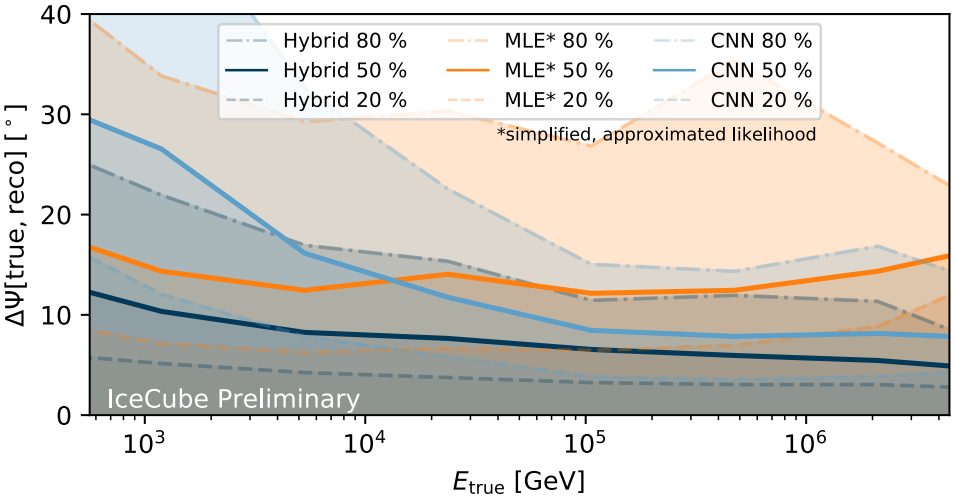
Functional data analysis
PoS(ICRC2021)1095

Angular power spectrum
PoS(ICRC2021)1198

Uncertainties framework
PoS(ICRC2021)1180

MM framework IceCube
PoS(ICRC2021)1098

Trend towards modern machine learning techniques, however, established techniques still going strong



IceCube GNN
PoS(ICRC2021)1044

KM3Net GNN
PoS(ICRC2021)1048

IceCube CNN
PoS(ICRC2021)1053
PoS(ICRC2021)1054

Liquid Argon NN
PoS(ICRC2021)1075

Radio NN
PoS(ICRC2021)1051
PoS(ICRC2021)1055
PoS(ICRC2021)1157

combining both worlds
PoS(ICRC2021)1065

Radio reconstruction

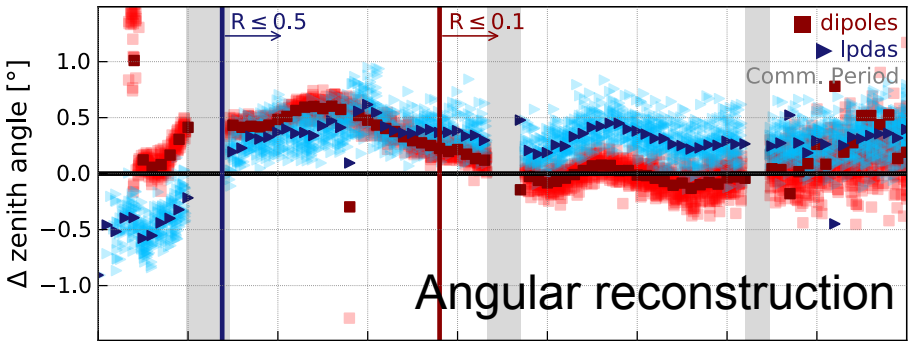
Highlight: Hoffman PoS(ICRC2021)014

see also discussion session 34: Radio detection of neutrinos

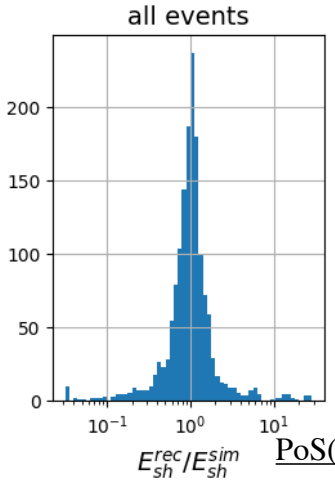
Encouraging development: radio is now also grouped with “mainstream” analysis discussion

However, some challenges remain unique to radio, lots of progress:

PoS(ICRC2021)1151



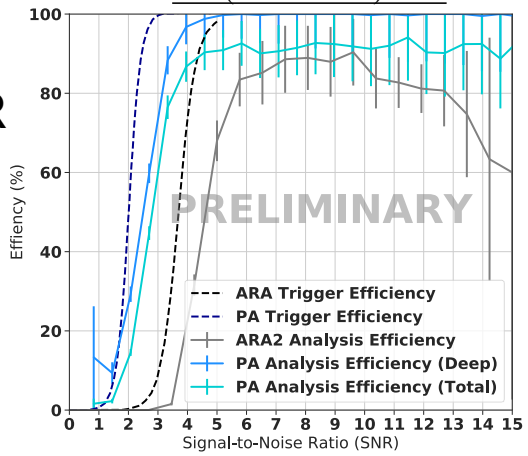
Energy reconstruction



PoS(ICRC2021)1033

PoS(ICRC2021)1153

Low SNR Analysis threshold



NuMoon
PoS(ICRC2021)1148

Template search
PoS(ICRC2021)1147

Flavor in radio
PoS(ICRC2021)1231

Air shower background in ice
PoS(ICRC2021)1032

Polarization ARIANNA
PoS(ICRC2021)1156

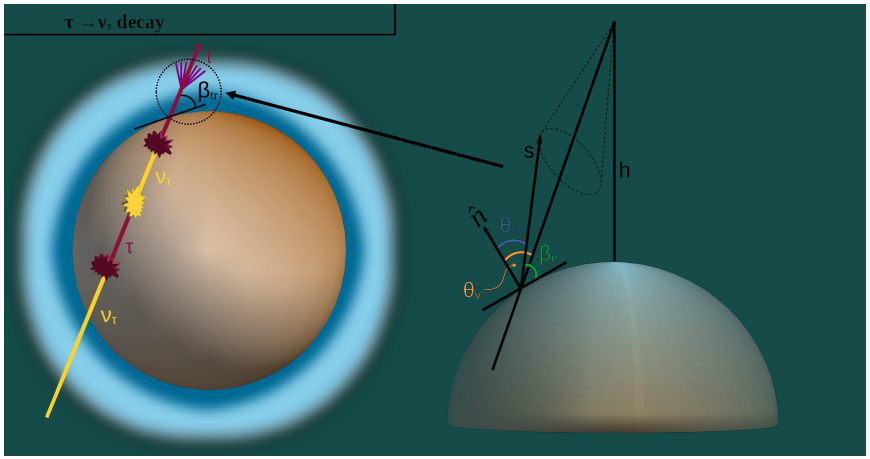
see also discussion session 35 Upgoing Tau Neutrinos: Present and Future

Tau neutrinos

Flavor physics and UHE simulations

The field of upward going tau neutrinos is booming (see also the experimental ideas)

Discussion session: Currently **7** independent codes to calculate the tau propagation through the Earth



https://pos.sissa.it/395/1203

Not a lot of discussion about the ANITA mystery events, but interesting follow up and limits from Auger

ANITA tau

PoS(ICRC2021)1110

Upward Tau Auger

PoS(ICRC2021)1140
PoS(ICRC2021)1145

UHE IceCube

PoS(ICRC2021)1170

TauRunner

PoS(ICRC2021)1030

nupyProp

PoS(ICRC2021)1203

nuSpaceSim

PoS(ICRC2021)1205

Cherenkov for tau

PoS(ICRC2021)1201

Upward tau
and moon shadow

PoS(ICRC2021)1208

Horizontal tracks
HAWC

PoS(ICRC2021)1036

ZHAireS for tau

PoS(ICRC2021)1031

Flavor in total

PoS(ICRC2021)1178

Muons

No dedicated muon session, natural overlap to air showers

The category is called “Neutrinos AND MUONS”

Muon related- problems:
(as background for neutrino detectors)

- too many in air showers (as compared to simulations)
- prompt neutrino production (and related muons) uncertain, lacking solid quantitative predictions

Different simulations, all geared toward upgrading more seasoned models:

- MCEq widely used for flux predictions and keeps being improved
- CORSIKA 8 anticipated for comparison
- PROPOSAL for lepton propagation widely used
- small flux differences may be observable for neutrino telescopes, but need a dedicated effort, not a by-product of neutrino analyses
- Input from experiments at accelerators like FASER-nu and NA61/SHINE eagerly anticipated

Km3NeT Muons
PoS(ICRC2021)1112
PoS(ICRC2021)1176

Uncertainty of muon energy loss
PoS(ICRC2021)1221

2d muons sims
PoS(ICRC2021)1209

Analytic calculations
PoS(ICRC2021)1230

Underground muons
PoS(ICRC2021)1226

Seasonal variations
PoS(ICRC2021)1202

Hadronic interaction uncertainties
PoS(ICRC2021)1227

Atm. neutrino predictions
PoS(ICRC2021)1149

Global and combined analyses

Joining forces?

- Future neutrino telescopes discussion session: Should we be like particle physics and have **ONE BIG** telescope only?

- Reconstruction discussion session: Should we collaborate better to more **sustainably write code** and make analyses more reproducible across collaborations?
- Do we give **enough credit** to those developing all our codes?
- Do we **educate future students** well enough to become efficient physicists in the modern world (data analysis, simulations development) ?

Plenum

PoS(ICRC2021)1185

IceCube-Gen2

PoS(ICRC2021)1183
PoS(ICRC2021)1184
PoS(ICRC2021)1186

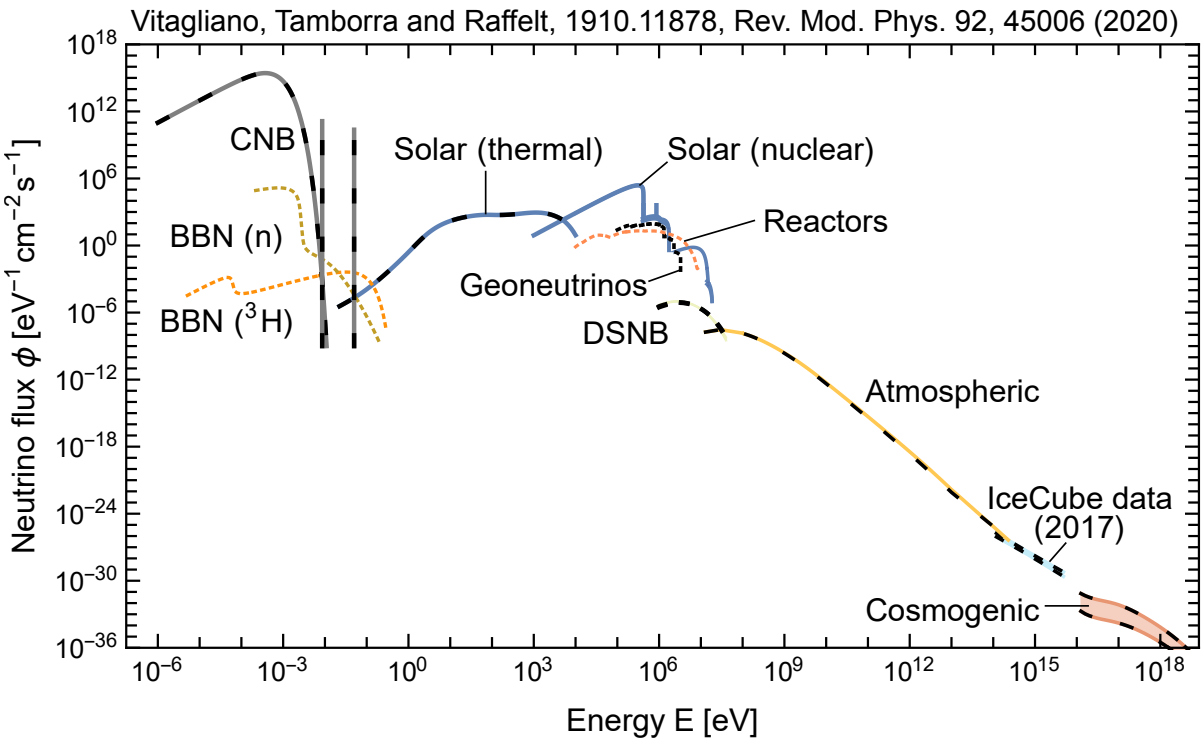
End-to-end forecasting

PoS(ICRC2021)1222

No result at this conference would have been possible without software; good software speeds up results, improves everyone's work satisfaction, and simplifies cross-instrument verification and collaboration

Cosmic Physics

The world of neutrinos



This conference covers all known of these

And more

Nuclearites KM3Net
PoS(ICRC2021)1152

Magnetic monopoles
PoS(ICRC2021)1127

Exotic neutrinos XMASS
PoS(ICRC2021)1155

various DM contributions

Solar neutrinos

Stuck somewhere between the neutrino and the solar session

JUNO Solar neutrinos

PoS(ICRC2021)1229

Solar ANTARES

PoS(ICRC2021)1122

Solar flare search Kamland

PoS(ICRC2021)1163

Solar flares Super-K

PoS(ICRC2021)1299

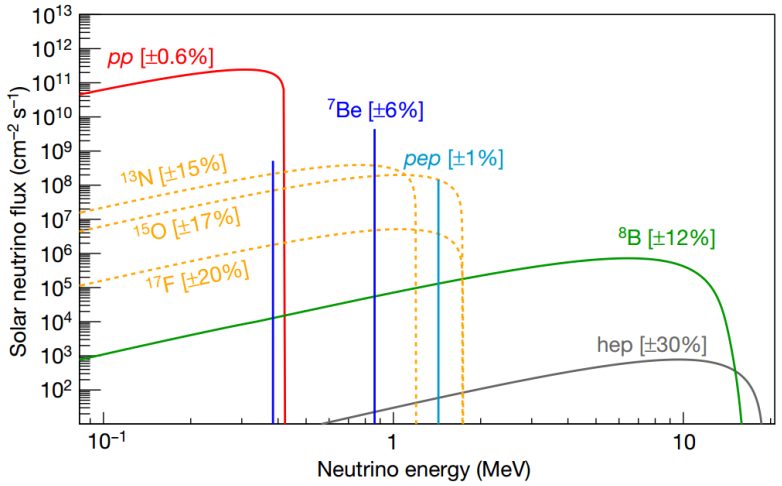
Solar atmospheric IceCube

PoS(ICRC2021)1174

CNO Borexino

PoS(ICRC2021)1109

PoS(ICRC2021)1109



Borexino sees first evidence for CNO neutrinos.

All other searches at this point still compatible with background

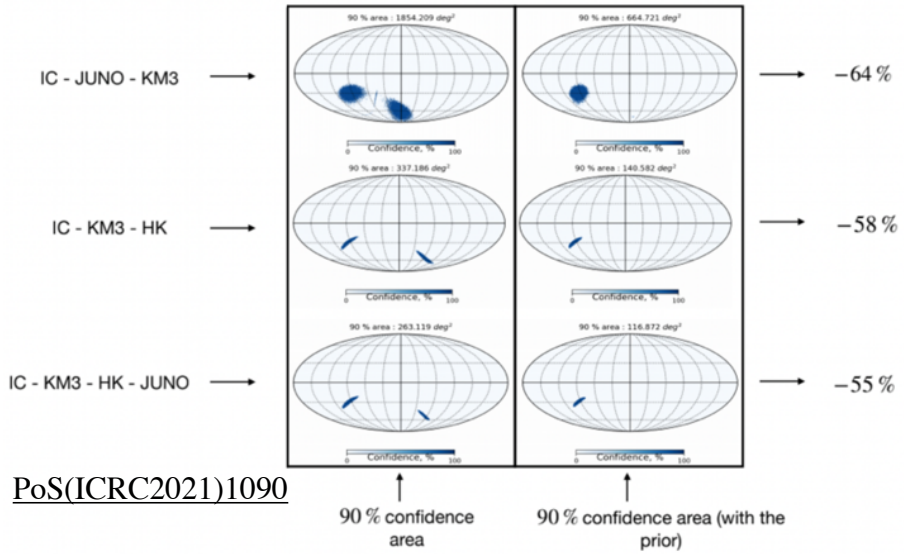
JUNO has the potential to resolve B^8

Supernova neutrinos

Everyone is getting ready to see **“the ONE”**

A supernova in our own Galaxy will certainly be a game changer for the field, so we better not miss it!

Supernova Early Warning System will alert the astronomical community to what is coming, many neutrino telescopes are (in the process of) joining forces



PoS(ICRC2021)1090

SNEWS

LHAASO

PoS(ICRC2021)1037

JUNO

PoS(ICRC2021)1076
PoS(ICRC2021)1187

IceCube

PoS(ICRC2021)1116
PoS(ICRC2021)1085

KM3Net

PoS(ICRC2021)1102

LVD

PoS(ICRC2021)1111

Diffuse SN BG SuperK

PoS(ICRC2021)1139
PoS(ICRC2021)1154

Atmospheric neutrinos

Background and signal

Atmospheric spectra keep improving, a measurement of the prompt flux seems within reach, putting pressure on the models to increase precision as well

KM3NeT Oscillations
PoS(ICRC2021)1123

KM3NeT performance
PoS(ICRC2021)1172

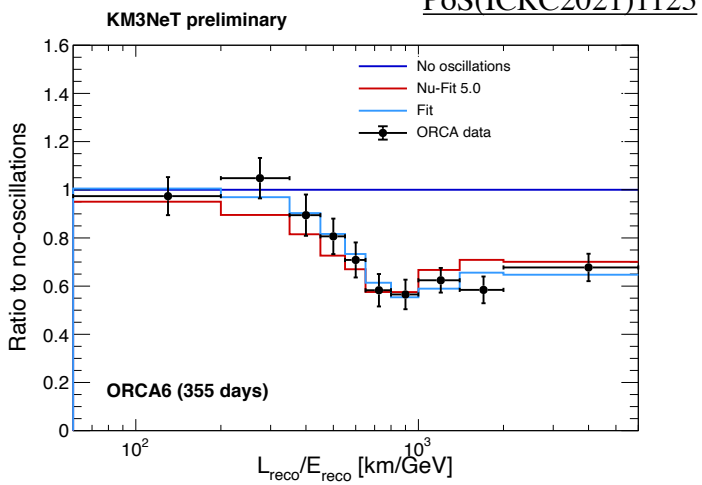
KM3NeT mass ordering
PoS(ICRC2021)1166

JUNO with ORCA
PoS(ICRC2021)1196

KM3NeT non-standard interactions
PoS(ICRC2021)1165

IceCube cross-sections
PoS(ICRC2021)1132
PoS(ICRC2021)1158

PoS(ICRC2021)1123



Prompt neutrino predictions
PoS(ICRC2021)1235

Seasonal variations
PoS(ICRC2021)1159

Influence of composition on flux
PoS(ICRC2021)1220

Update HONDA model
PoS(ICRC2021)1210

KM3NeT Flux
PoS(ICRC2021)1125

Km3Net ARCA
PoS(ICRC2021)1134

Results of oscillation physics and other neutrino properties keep improving

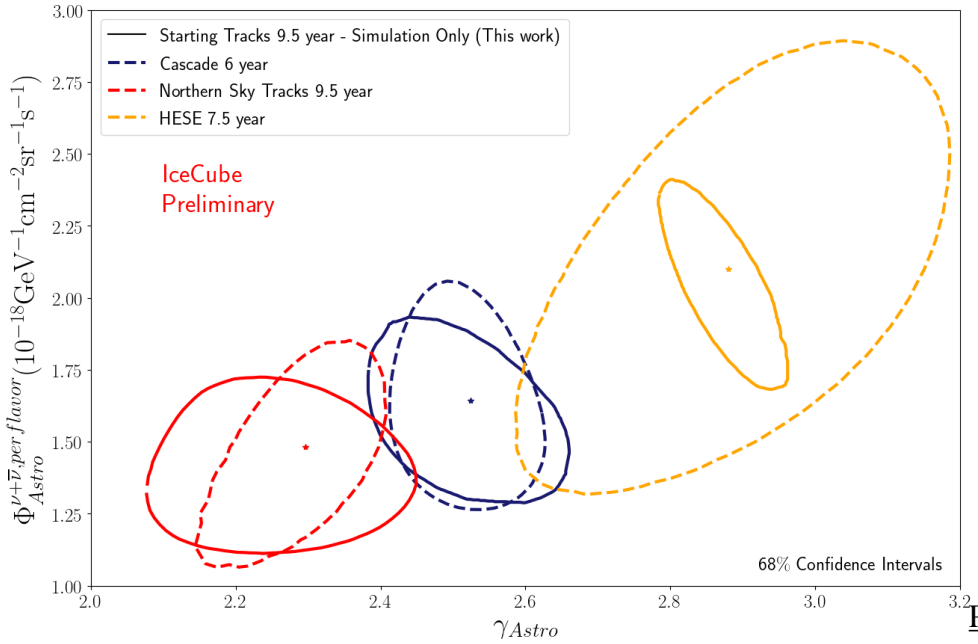
Astrophysical neutrinos

The astrophysical spectrum

Baikal-GVD and Antares/KM3NeT almost there

IceCube increases effort to provide the community with one estimate and consistent reporting

Spectrum is needed/used as input for many estimates for sources or BSM physics, so an important ingredient



PoS(ICRC2021)1130

Track-like GVD
PoS(ICRC2021)1177

Baikal Search
PoS(ICRC2021)1144

Diffuse search ANTARES
PoS(ICRC2021)1126

KM3NeT sensitivity estimate
PoS(ICRC2021)1077
PoS(ICRC2021)1162

Starting tracks IceCube
PoS(ICRC2021)1130

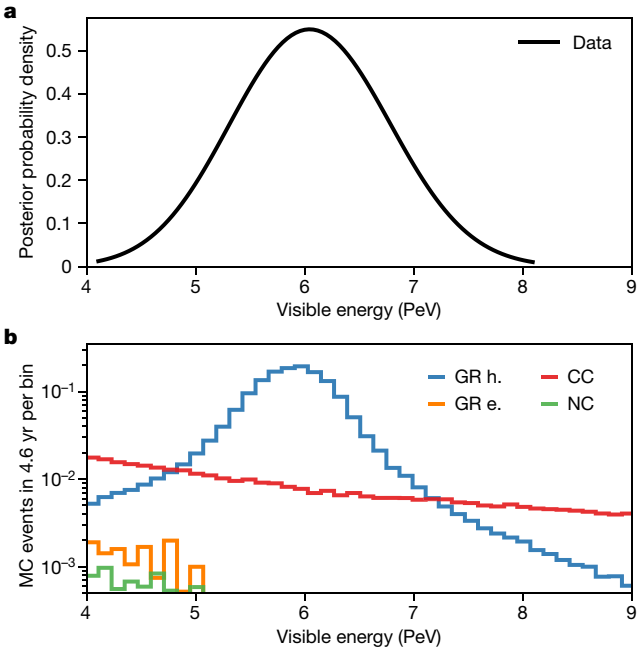
Downgoing tracks IceCube
PoS(ICRC2021)1137

Combined fit (sim)
PoS(ICRC2021)1129

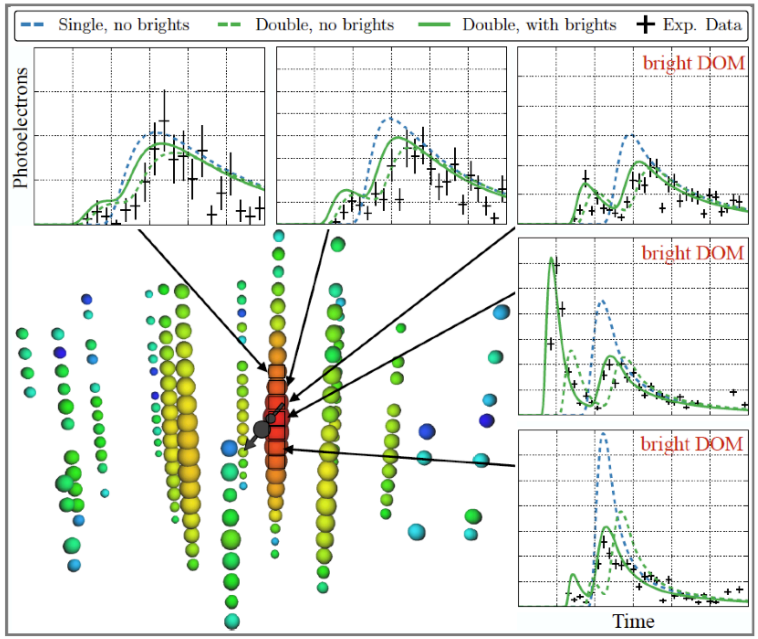
Astrophysical neutrinos

New since last ICRC

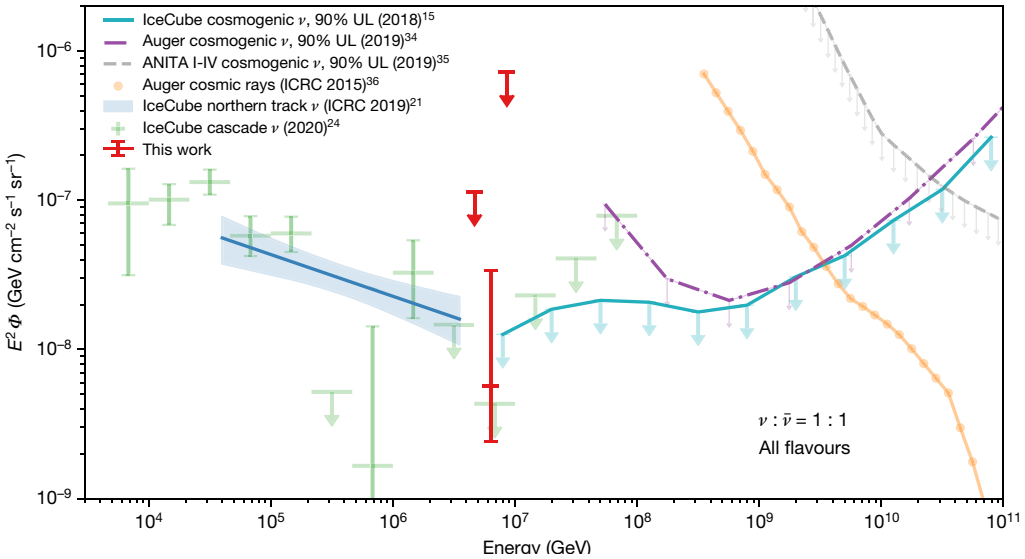
First identifiable electron-anti-neutrino



Glashow resonance



First identifiable tau neutrino



https://doi.org/10.1038/s41586-021-03256-1

Astrophysical neutrinos

The theoretical community is giving it all

Modeling shocks
PoS(ICRC2021)1219

Modeling afterglows
PoS(ICRC2021)1214

Modeling clusters
PoS(ICRC2021)1212

Modeling GRB progenitors
PoS(ICRC2021)1233

Modeling choked GRB
PoS(ICRC2021)1223

MM Starburst Galaxies
PoS(ICRC2021)1232

Galactic sources
PoS(ICRC2021)1215

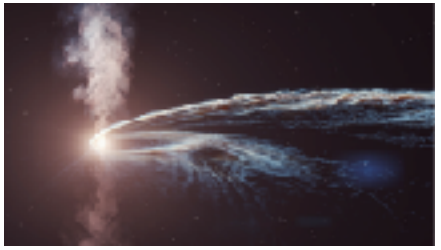
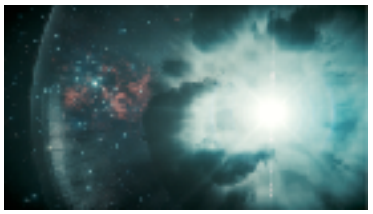
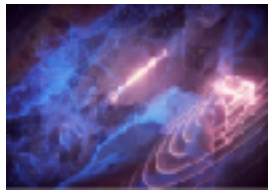
UHE cross-section
PoS(ICRC2021)1200

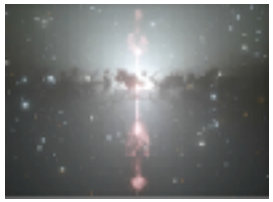
see also discussion session: 39 Astrophysical Neutrinos – Theoretical and Experimental Results

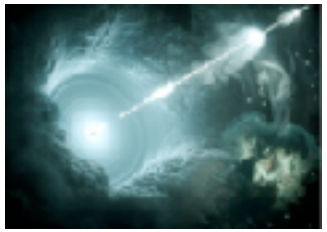
No shortage in ideas of what to look for

Models are being refined, data is combined from multiple observatories to predict interesting objects to look at

No “knock-it-out-of the-park” suggestion






Images: DESY, Sci comm lab

Astrophysical neutrinos

And so are the experimentalists

For "Signals" see the MM rapporteur talk

Many searches, nothing conclusive (yet)

Point-sources ANTARES
PoS(ICRC2021)1161

Intriguing

Time-variability IceCube
PoS(ICRC2021)1141

Radio-selected Blazars vs Antares
PoS(ICRC2021)1164

"Stay-tuned"

IceCube Magnetars
PoS(ICRC2021)1135

IceCube Cascades for sources
PoS(ICRC2021)1150

Point-source search IceCube
PoS(ICRC2021)1138

X-Binaries IceCube
PoS(ICRC2021)1136

Km3Net Starburst sensitivity
PoS(ICRC2021)1168

IceCube transient search
PoS(ICRC2021)1128

IceCube Transients < 1 TeV
PoS(ICRC2021)1131

Hard X-ray AGN IceCube
PoS(ICRC2021)1142

Antares vs Baikal
PoS(ICRC2021)1121

Transients DeepCore
PoS(ICRC2021)1143

IceCube infrared Galaxies
PoS(ICRC2021)1115

IceCube Galaxy clusters
PoS(ICRC2021)1133

IceCube GRBs
PoS(ICRC2021)1118

Bottom-line

We need more neutrinos

Neutrinos

Ideas

Calibration and detector development

Reconstruction and simulations

Cosmic Physics

ICRC 2021

Looking forward to ICRC 2023.