Neutrinos

Paul de Jong

Contents:

- Neutrino properties
- Neutrino astronomy

Physicist Frank Bartholomew gets a big, BIG break in his search for the ever-elusive neutrino.

Projects with NL participation:

ANTARES, KM3NeT (Global Neutrino Network)
DUNE
KamLand, XENONnT, DARWIN
Ptolemy
PAO, GRAND
R&D for acoustic neutrino detection
(New heavy neutral lepton searches: ATLAS, LHCb, FASER, SND, SHiP)

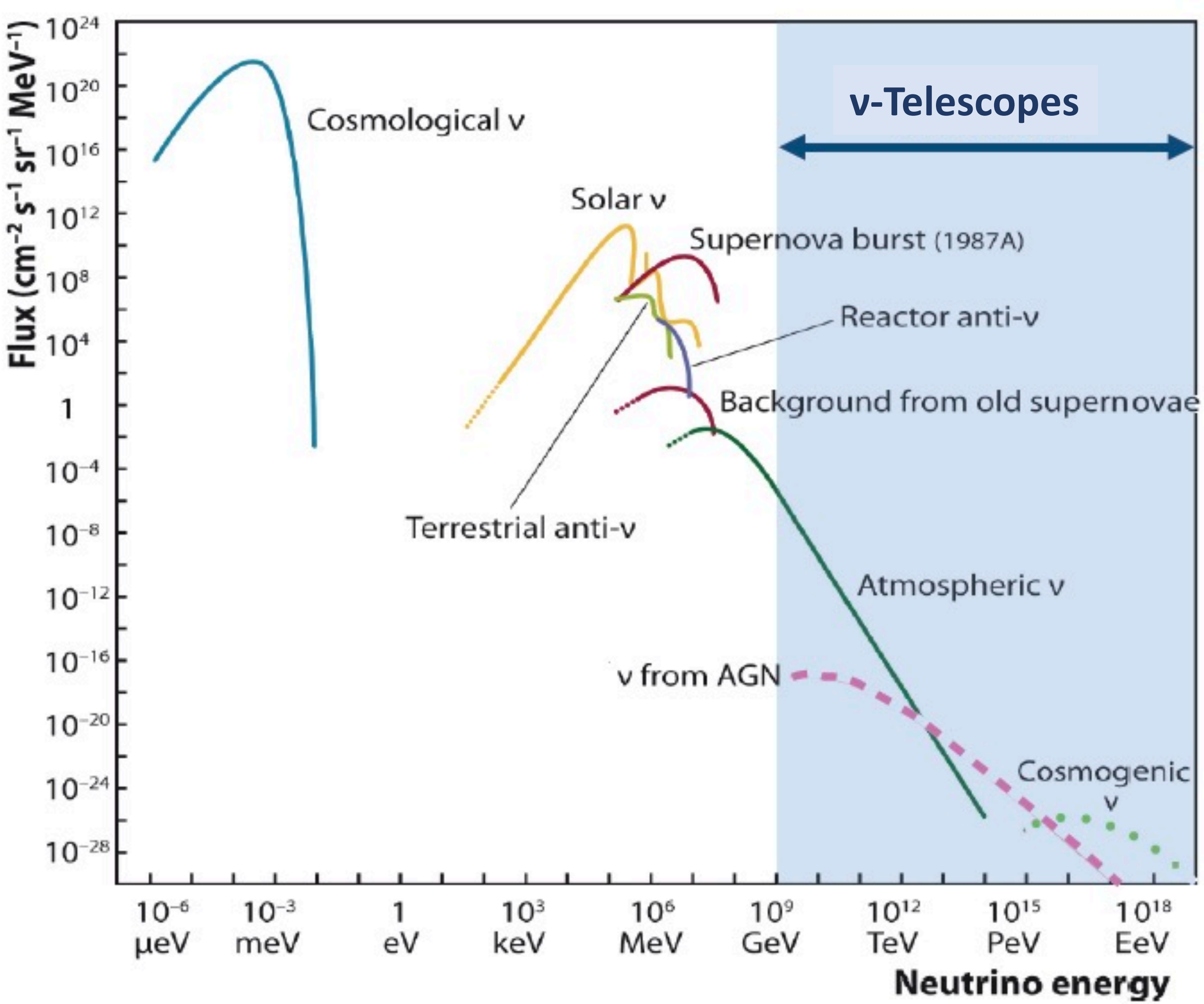
ANTARES 2006-2022

Competitive results in Southern Hemisphere
Galactic Ridge
Dark Matter

Deployment February 14, 2006

Cutting the cables: February 12, 2022

The neutrino spectrum (minus accelerators, sources)

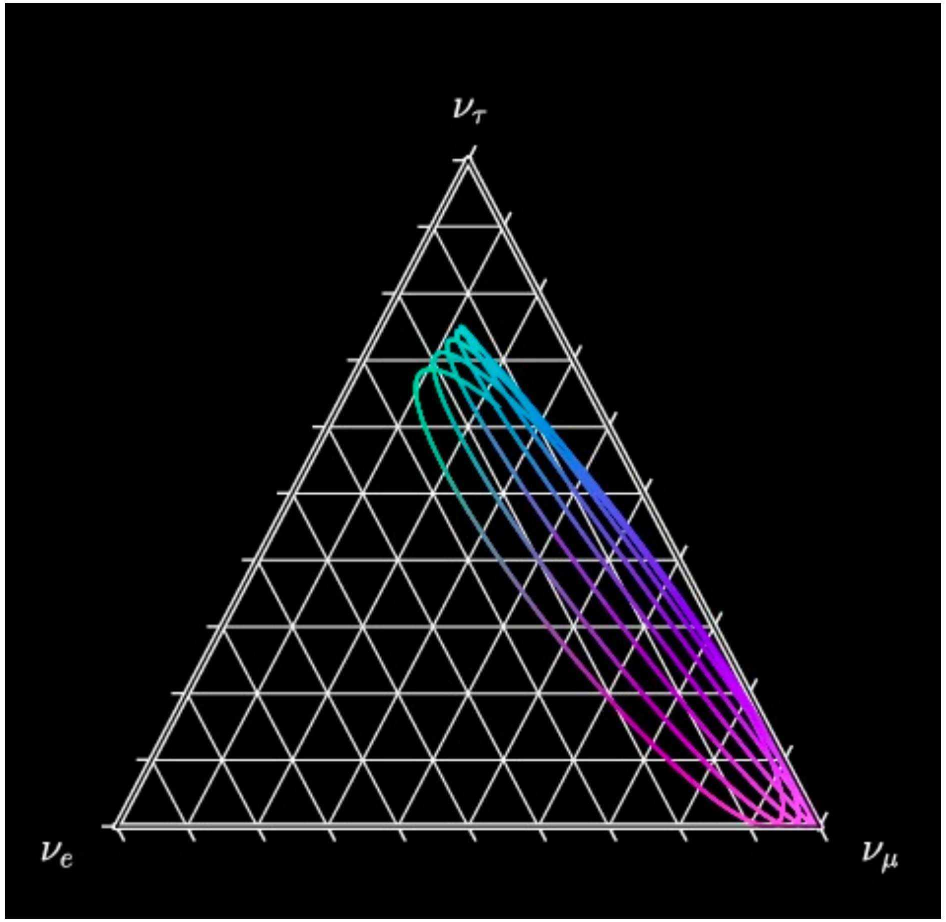


Neutrino oscillations $P(\nu_\alpha \rightarrow \nu_\beta) \neq \delta_{\alpha\beta} \quad \alpha, \beta = e, \mu, \tau$

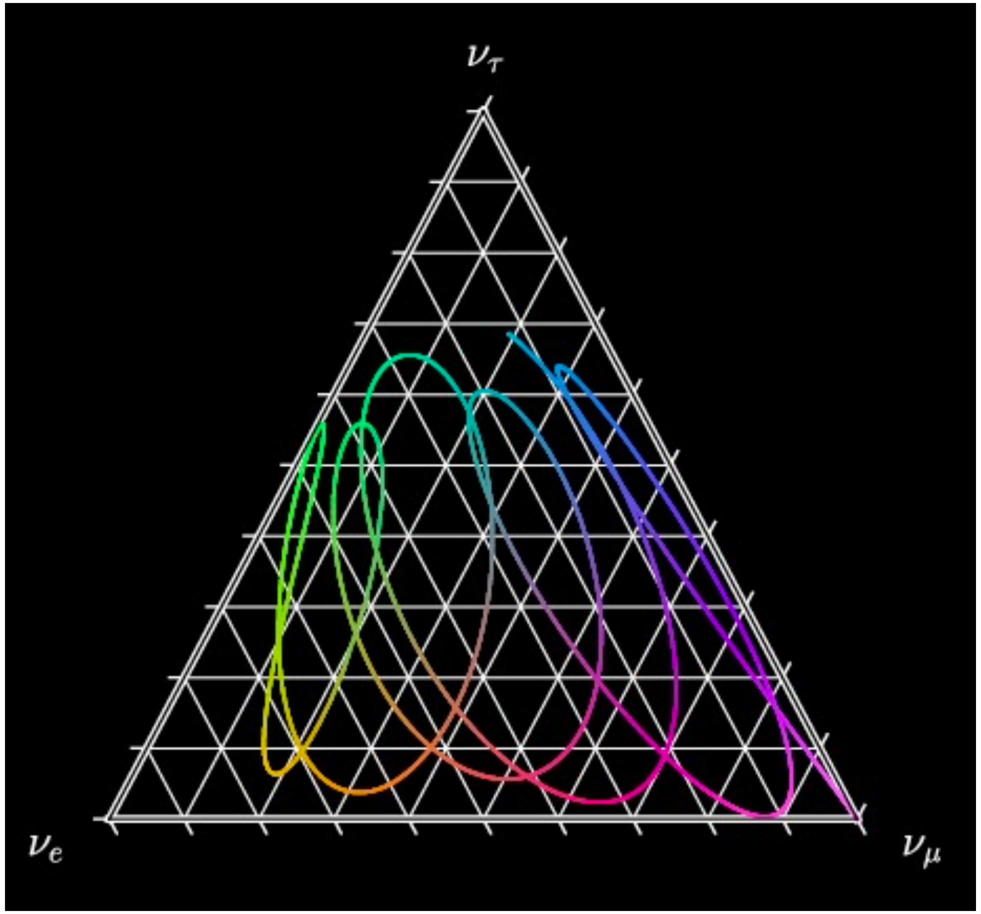
2-flavours: $P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2(1.27 \frac{\Delta m^2 L}{E})$

amplitude *frequency*

3-flavours: 3 mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$
3 mass differences $\Delta m^2_{12}, \Delta m^2_{13}, \Delta m^2_{23}$
1 CP-violating phase δ



Start with pure ν_μ, **in vacuum**



Start with pure ν_μ, **in matter (earth)**

Thesis Lodewijk Nauta

Neutrino oscillations

Neutrino 2022

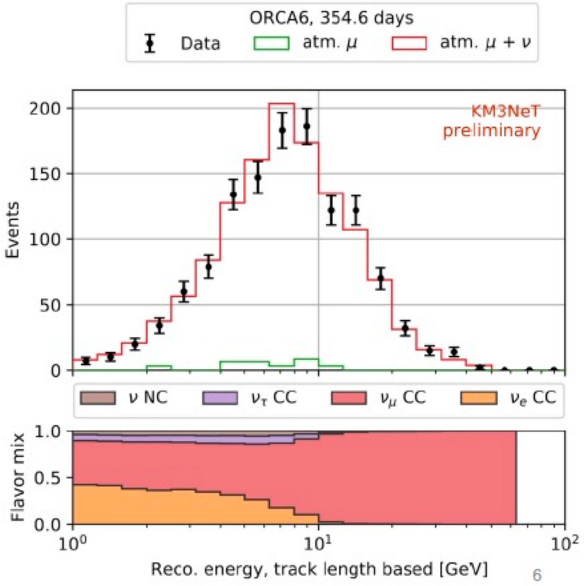
Daya Bay now measures θ_{13} with 3% precision! (Only known to be non-zero since ~10 years)

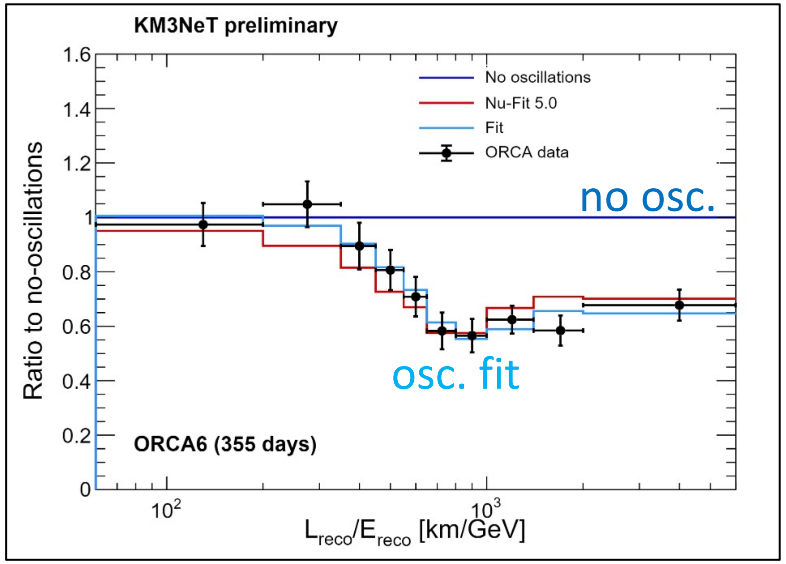
Global fit (dominated by T2K and NOvA): $\sin^2\theta_{23} = 0.57^{+0.04}_{-0.03}$, some preference for second octant (good!)
T2K and NOvA are only marginally consistent, and are saturating their sensitivity

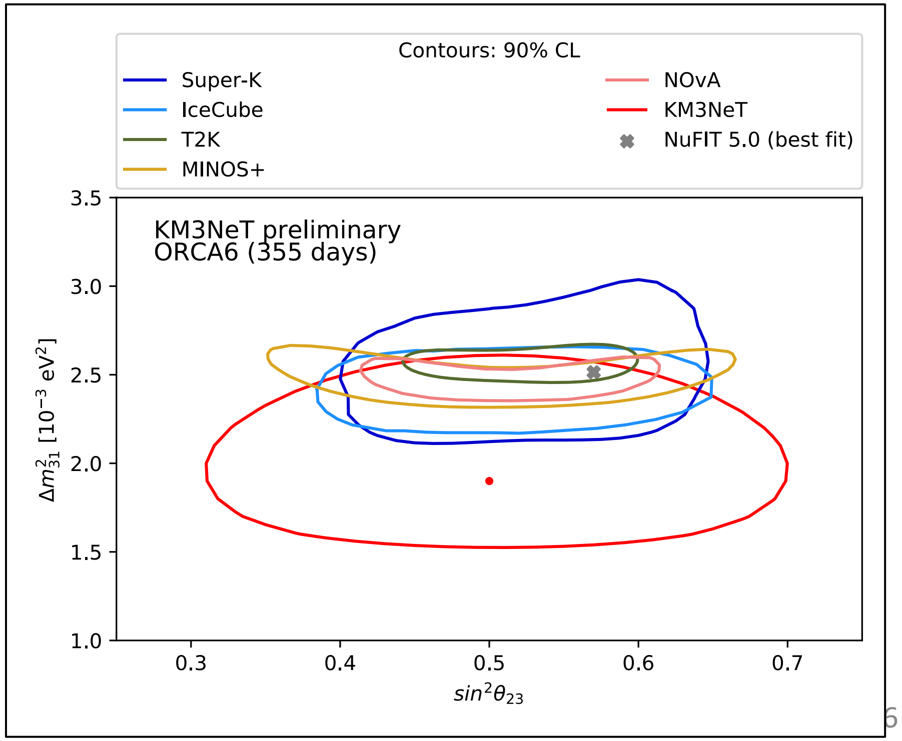
→ ***Comeback of the atmospheric neutrino experiments!***

One year ORCA data with only 6 lines:

PoS ICRC2021 (2021) 1123



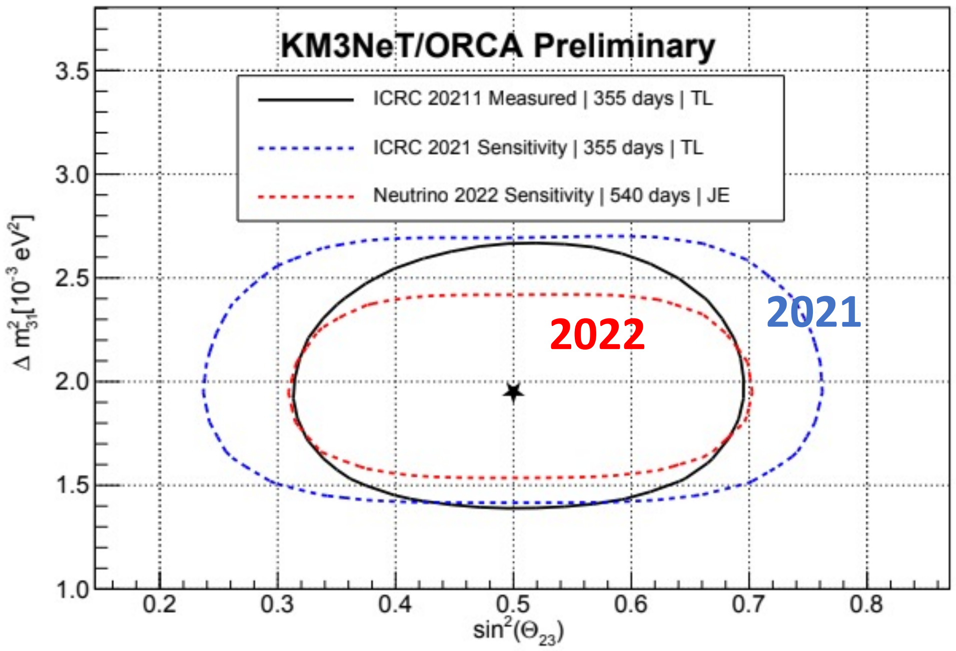




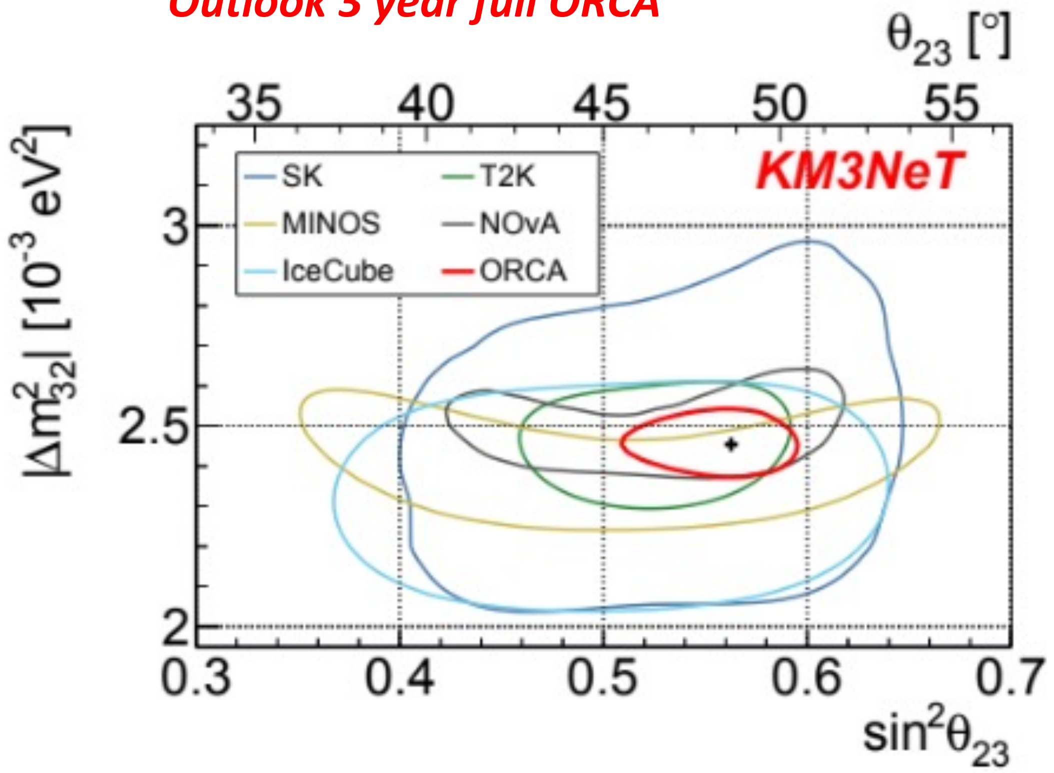
Neutrino oscillations

- *Super-Kamiokande new results: impact on neutrino mass ordering (next slide)*
- *IceCube will soon unblind new data, new analysis. <u>Sensitivity similar to T2K/NOvA</u> !*
- *KM3NeT/ORCA sensitivity improvement and outlook:*

Sensitivity improvements for Neutrino 2022



Outlook 3 year full ORCA



→ θ_{23} will be dominated by neutrino telescopes soon

Neutrino Mass Ordering

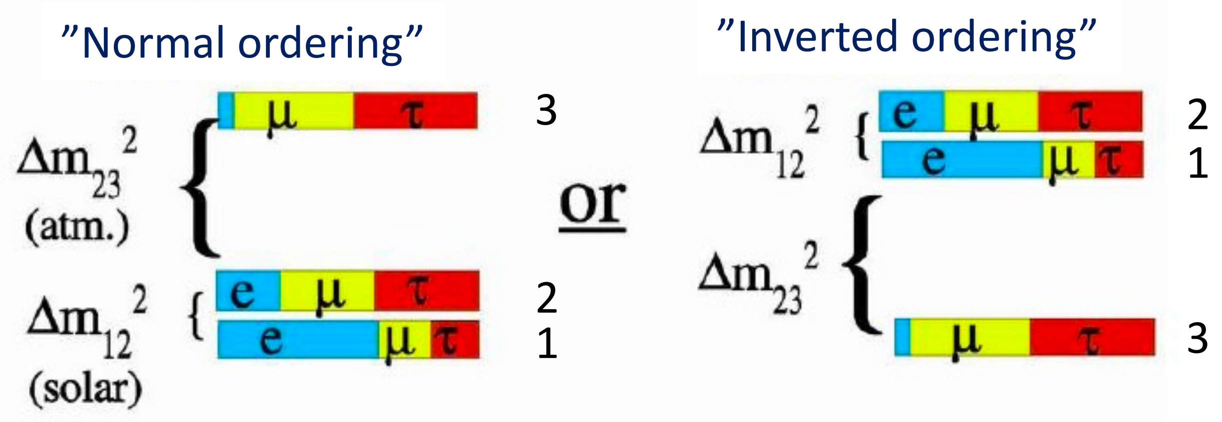
Global Fit with ”SM”-assumptions:

$$\Delta\chi^2(NO - IO) = 6.2 \rightarrow 2.7 \rightarrow 7.1$$

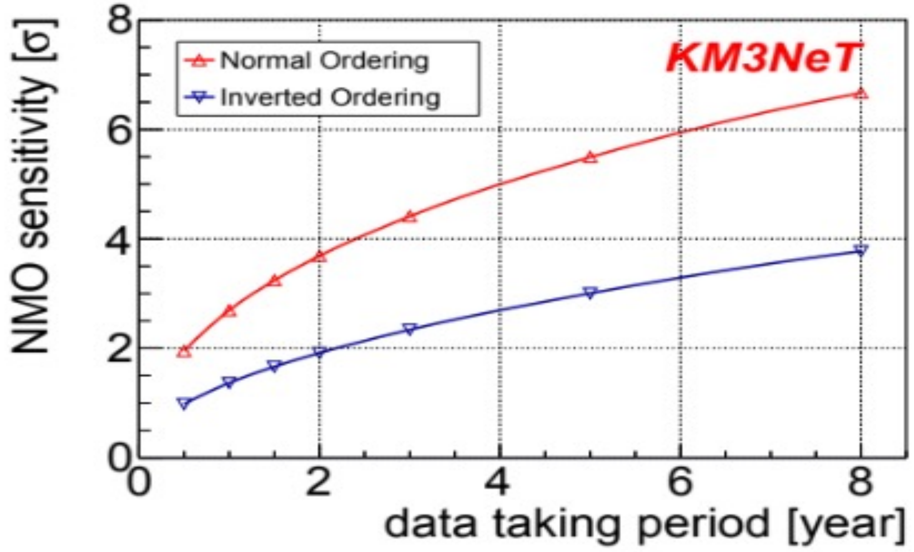
2019 *2021* *2022*

effect of new Super-K data

T2K/NOvA agree better if IO
LBL/reactor expts. agree better if NO

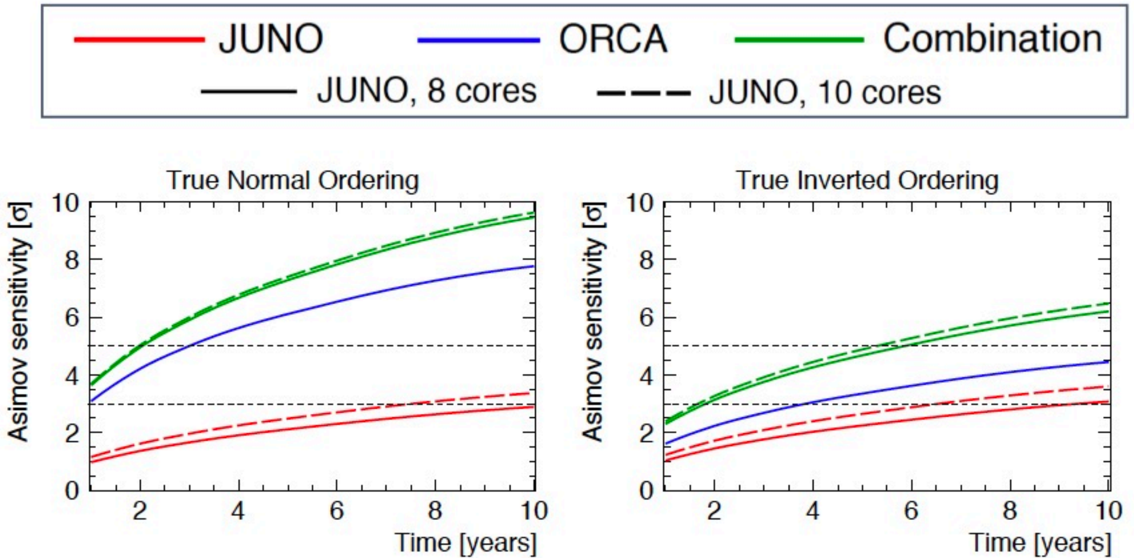


Full KM3NeT/ORCA



Eur.Phys.J.C 82 (2022) 1, 26

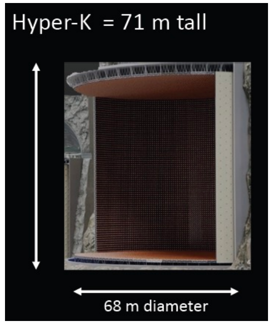
Powerful: combination with JUNO



JHEP 03 (2022) 055

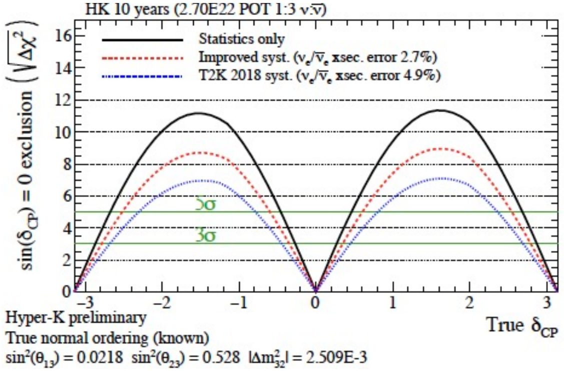
CP-violation in the lepton sector: δ

CP is violated if $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$: $\delta \neq 0, \pi$
"Holy grail" of future neutrino experiments. Easier with $\nu/\bar{\nu}$ beam.

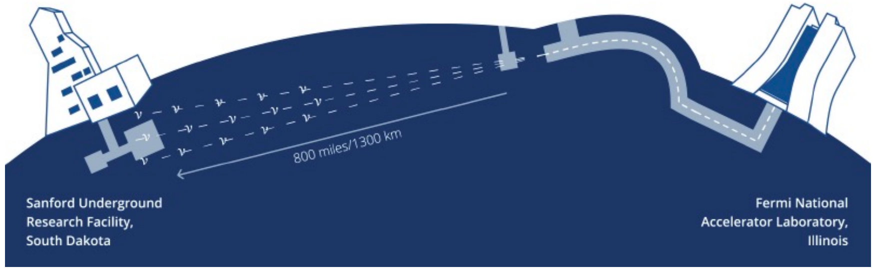


200 kton H_2O

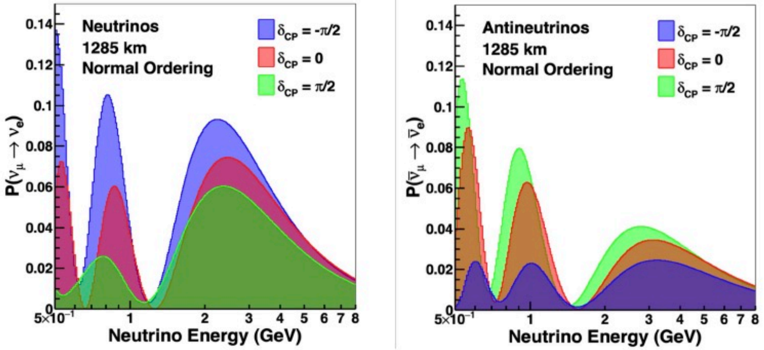
2028?



Hyper-Kamiokande

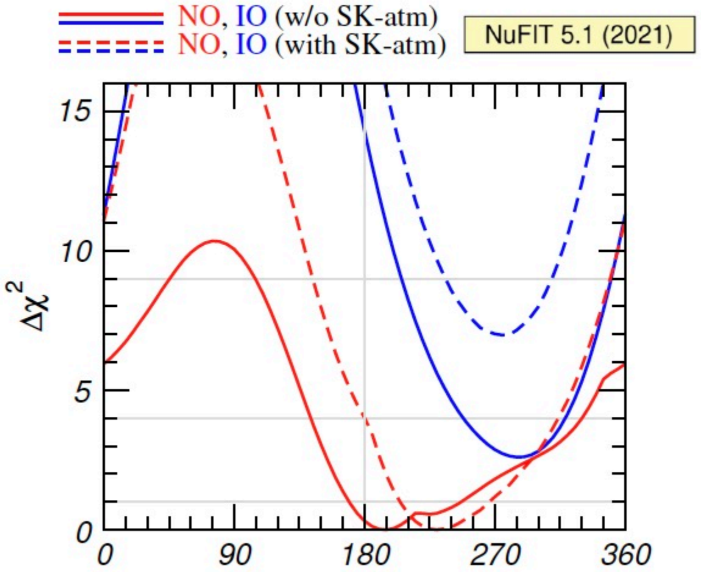


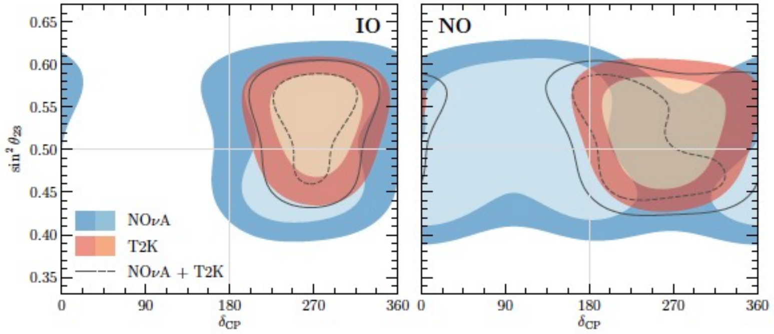
4 x 10 kton LAr **2030?**



Deep Underground Neutrino Experiment (DUNE)

Current data marginally sensitive to δ





(Also: P2O: beam from Protvino to KM3NeT/ORCA, with neutrino tagging. Now politically difficult…)

Absolute neutrino mass

KATRIN: ^{3}H decay: $m_{"\nu_e"} < 0.8$ eV   Future: a.o. Project 8 (Cyclotron Radiation Emission Spectroscopy): < 0.05 eV?

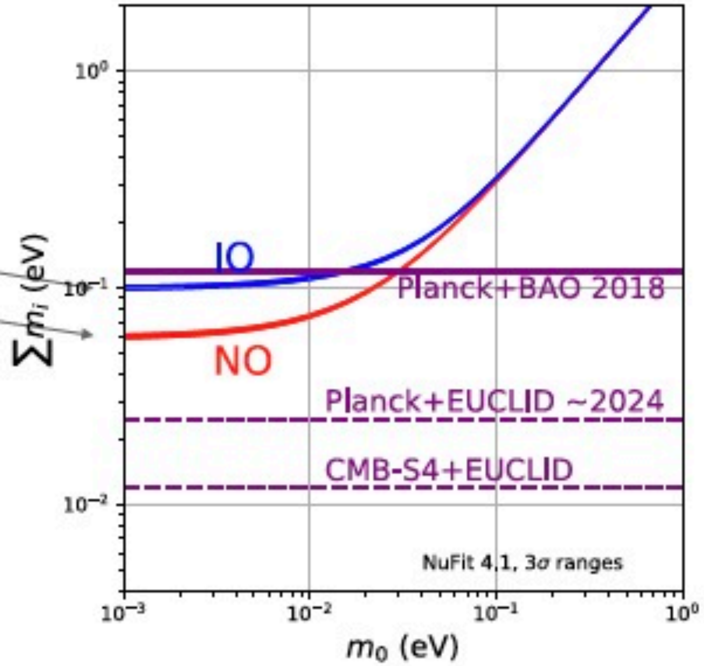
Cosmology:

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} & \text{(IO)} \end{cases}$$

- minimal values predicted from oscillation data for $m_0 = 0$:

$$\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \\ 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \end{cases}$$

- **detection of non-zero neutrino mass expected soon!**
- **current limit close to IO minimum**

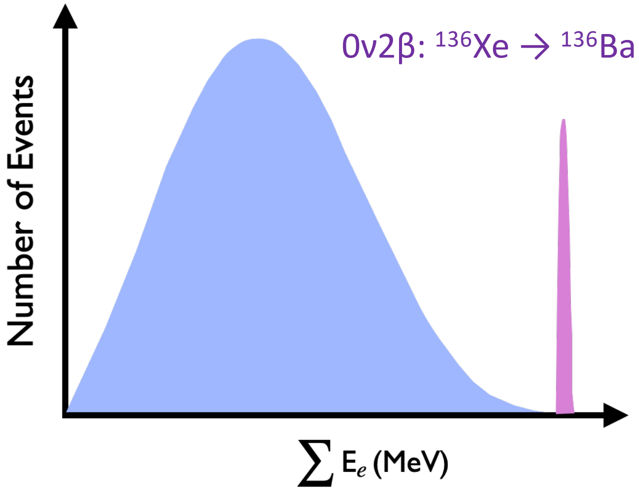


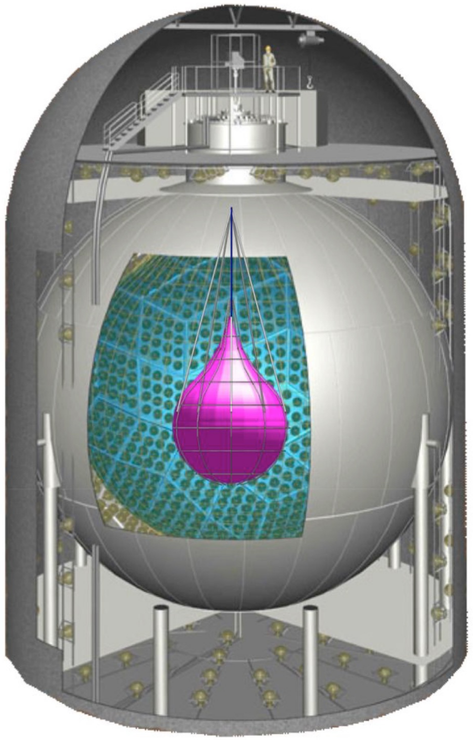
Neutrinoless double beta decay

A number of isotopes undergo (rare) double beta decay.
If neutrinos are Majorana: possibility of $0\nu\beta\beta$

2ν2β: ^{136}Xe → ^{136}Ba + 2 e- + 2 ν_e

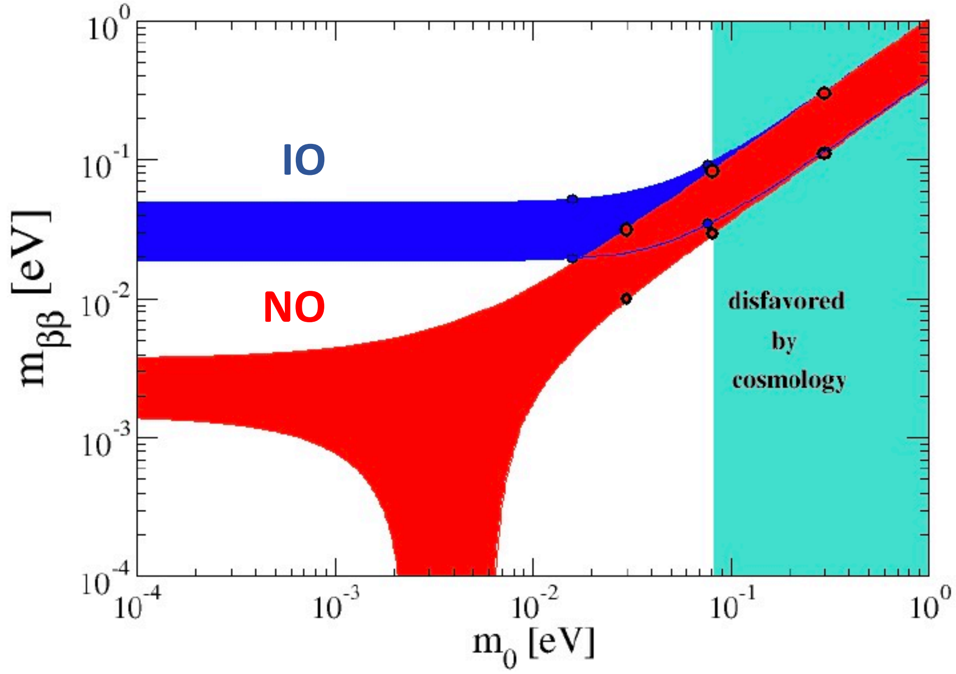
0ν2β: ^{136}Xe → ^{136}Ba + 2 e-





KamLAND-Zen experiment in Kamioka
745 kg of ^{136}Xe dissolved in central balloon

Future DARWIN underground observatory



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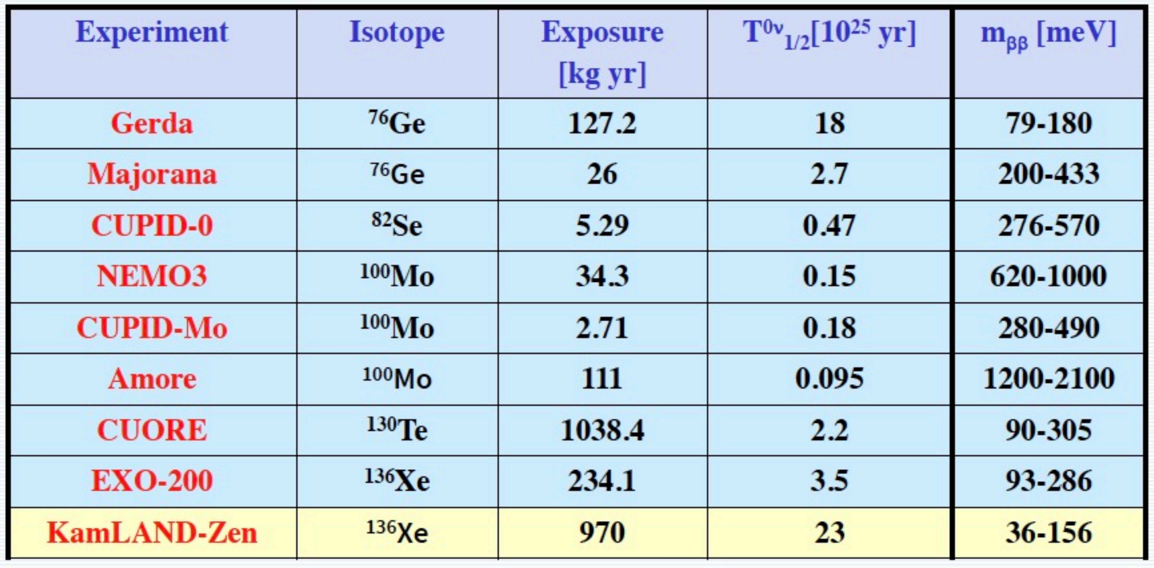
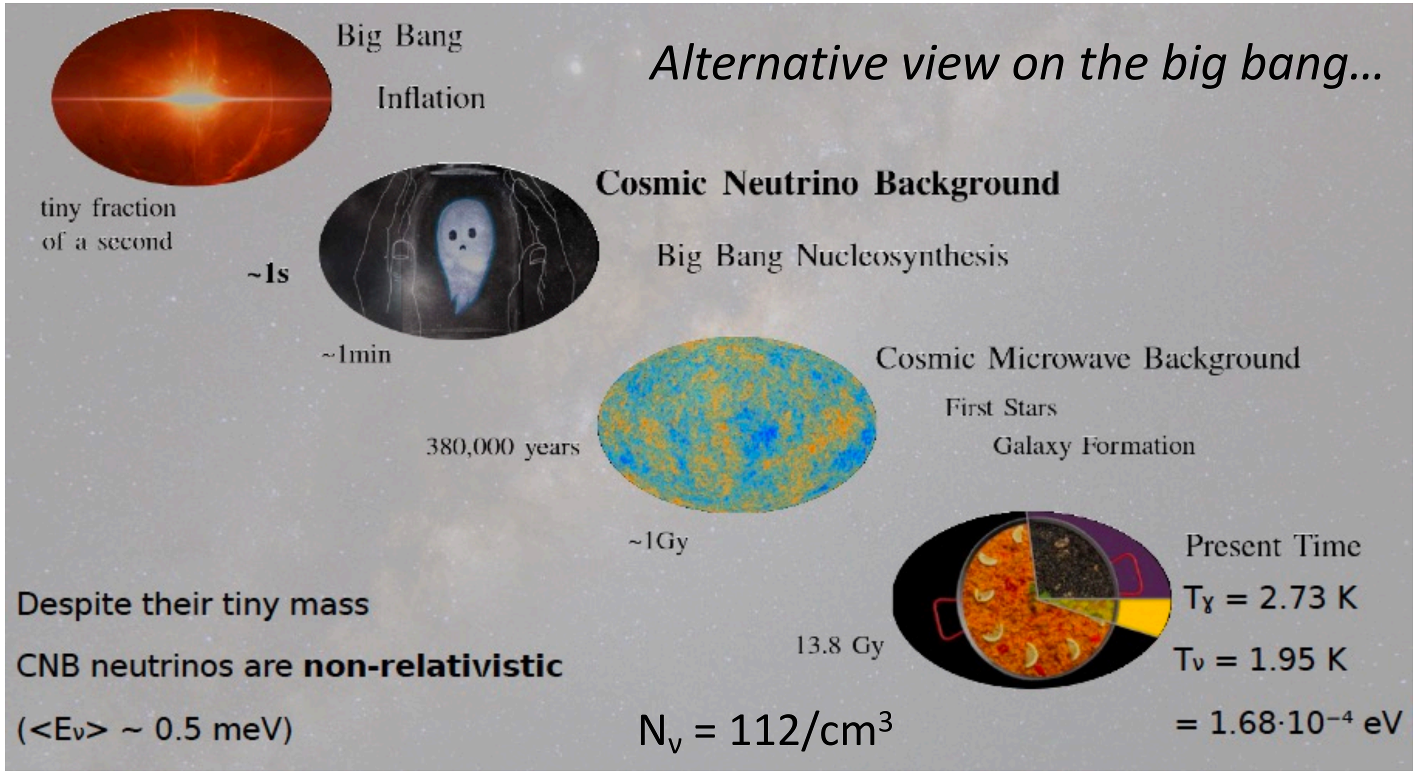


Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}[10^{25}$ yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
CUPID-0	^{82}Se	5.29	0.47	276-570
NEMO3	^{100}Mo	34.3	0.15	620-1000
CUPID-Mo	^{100}Mo	2.71	0.18	280-490
Amore	^{100}Mo	111	0.095	1200-2100
CUORE	^{130}Te	1038.4	2.2	90-305
EXO-200	^{136}Xe	234.1	3.5	93-286
KamLAND-Zen	^{136}Xe	970	23	36-156

Cosmic neutrino background



Alternative view on the big bang…

Despite their tiny mass

CNB neutrinos are **non-relativistic**

(<Eν> ~ 0.5 meV)

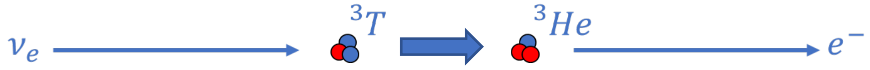
$N_\nu = 112/cm^3$

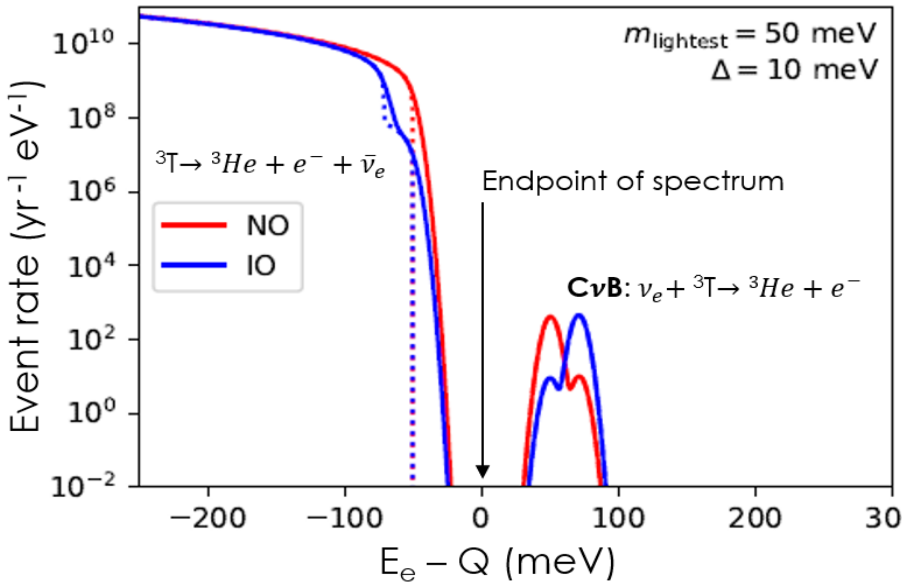
$T_\gamma = 2.73$ K

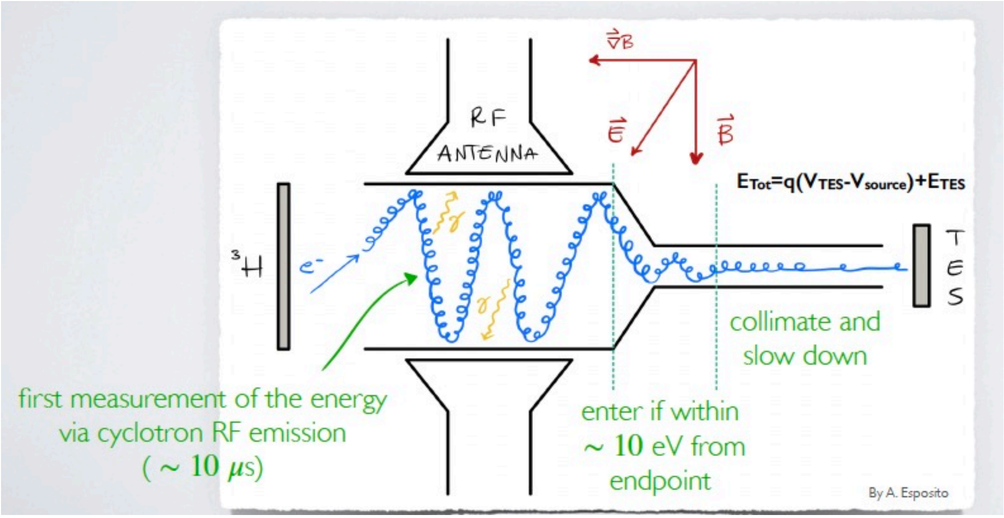
$T_\nu = 1.95$ K

$= 1.68 \cdot 10^{-4}$ eV

Ptolemy: $\nu_e + {}^3_1H \rightarrow {}^3_2He + e$

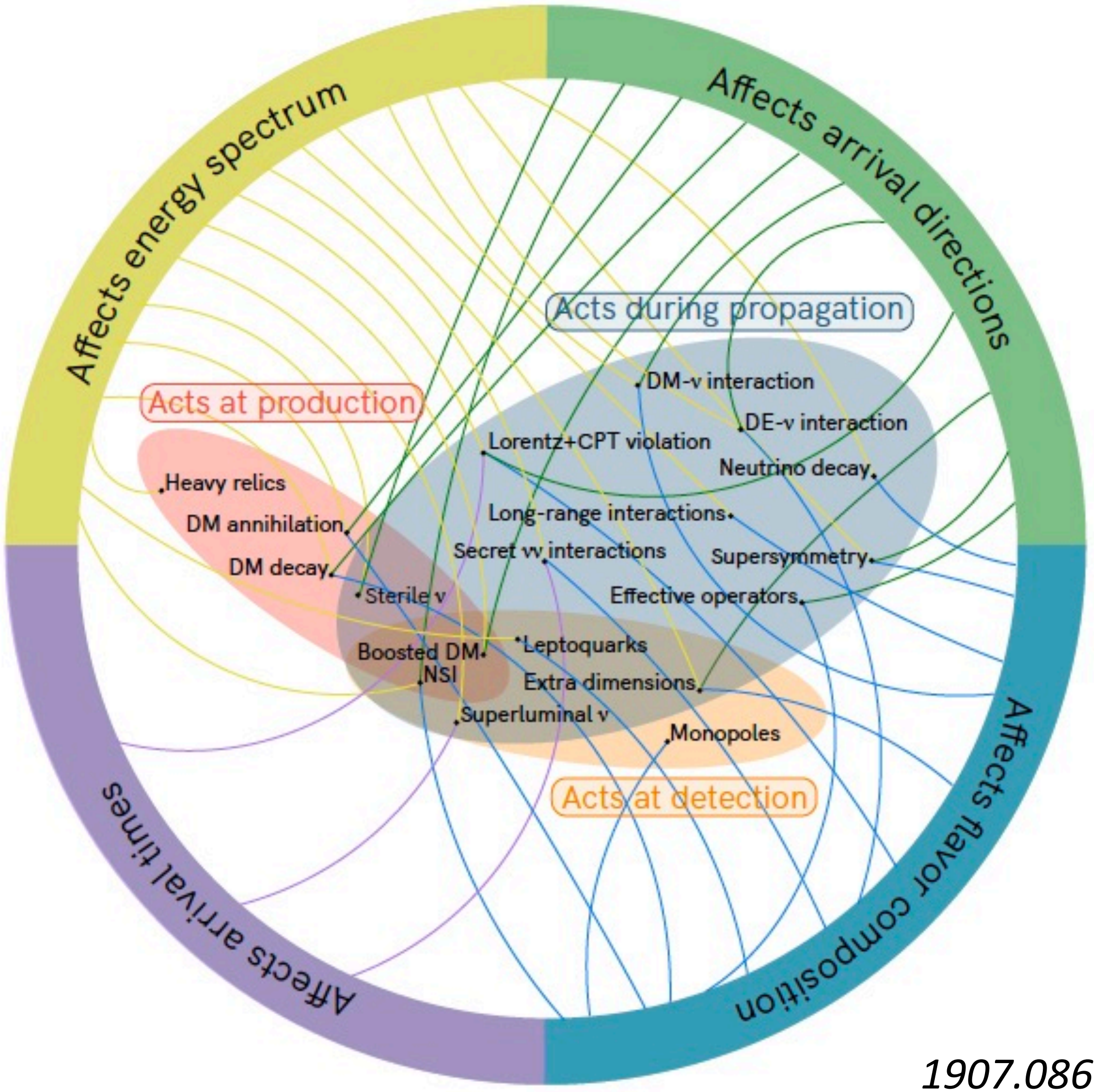






Tritium on sheets of graphene.
Measure e energy very precisely.
Extremely challenging experiment.

Beyond-the-Standard-Model physics with neutrinos



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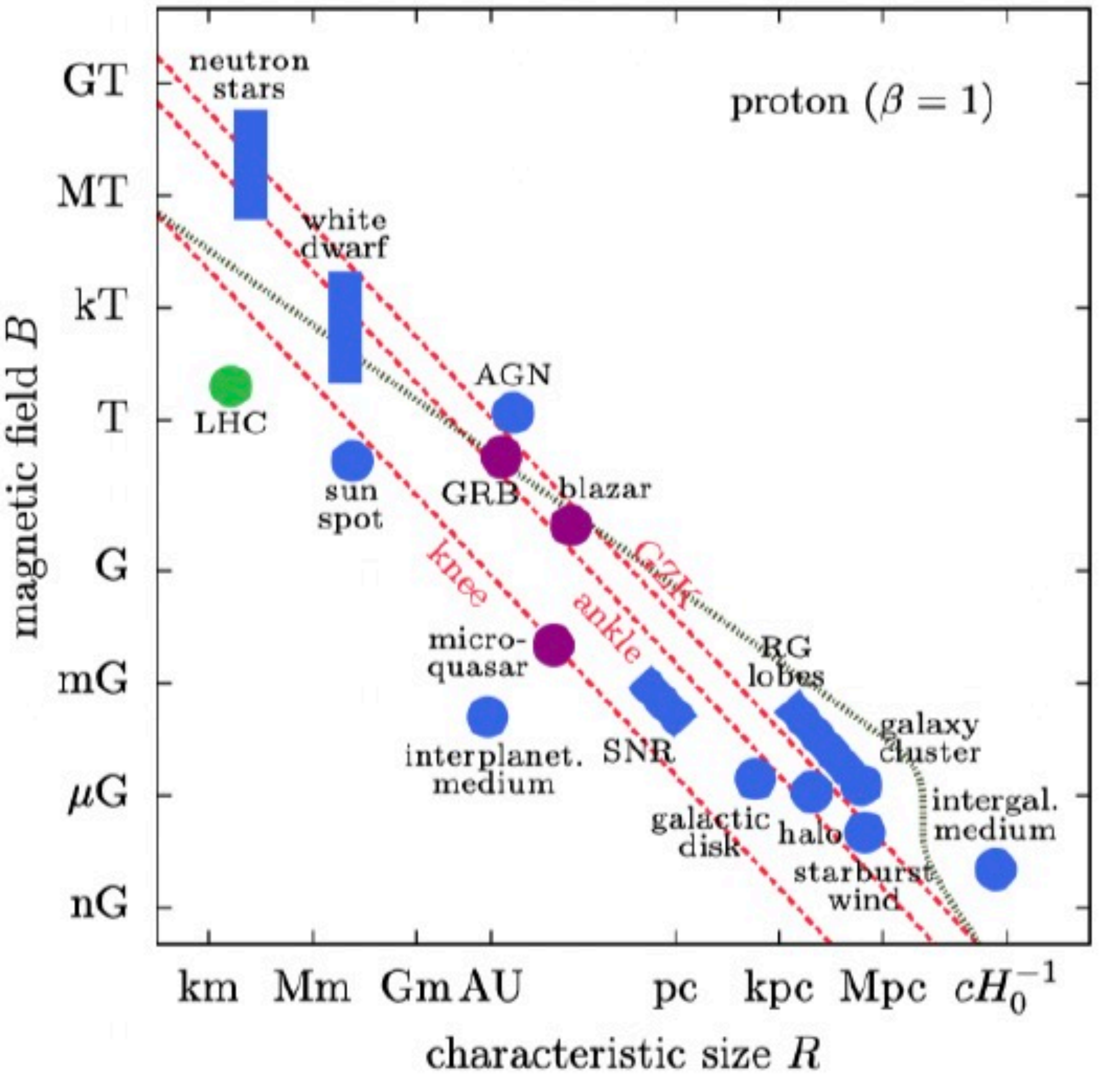
KM3NeT/ORCA one year data, 6 lines:

Neutrino decay
Non-standard interactions
Sterile neutrinos
Quantum decoherence

ANTARES/IceCube:

Dark matter
Unstable sterile neutrinos
Quantum gravity
Lorentz violation
Magnetic monopoles
Neutrino cross section deviations
Staus
Nuclearites
…

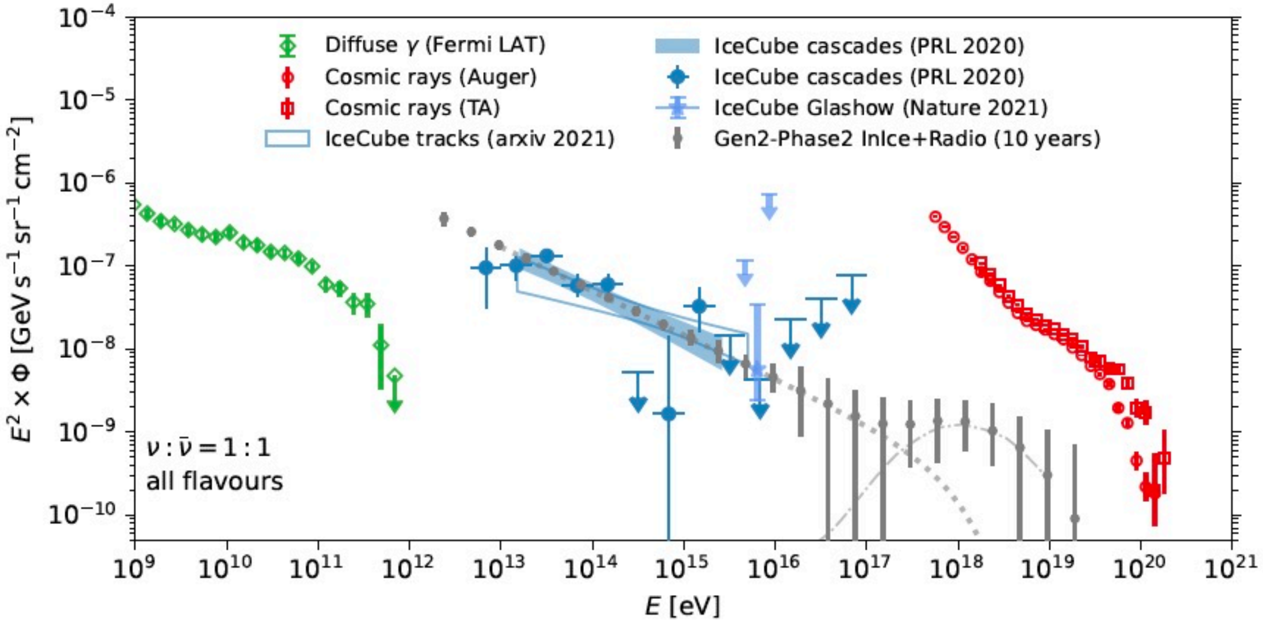
Neutrinos for astronomy



"Elk nadeel heb z'n voordeel", *J. Cruijff*

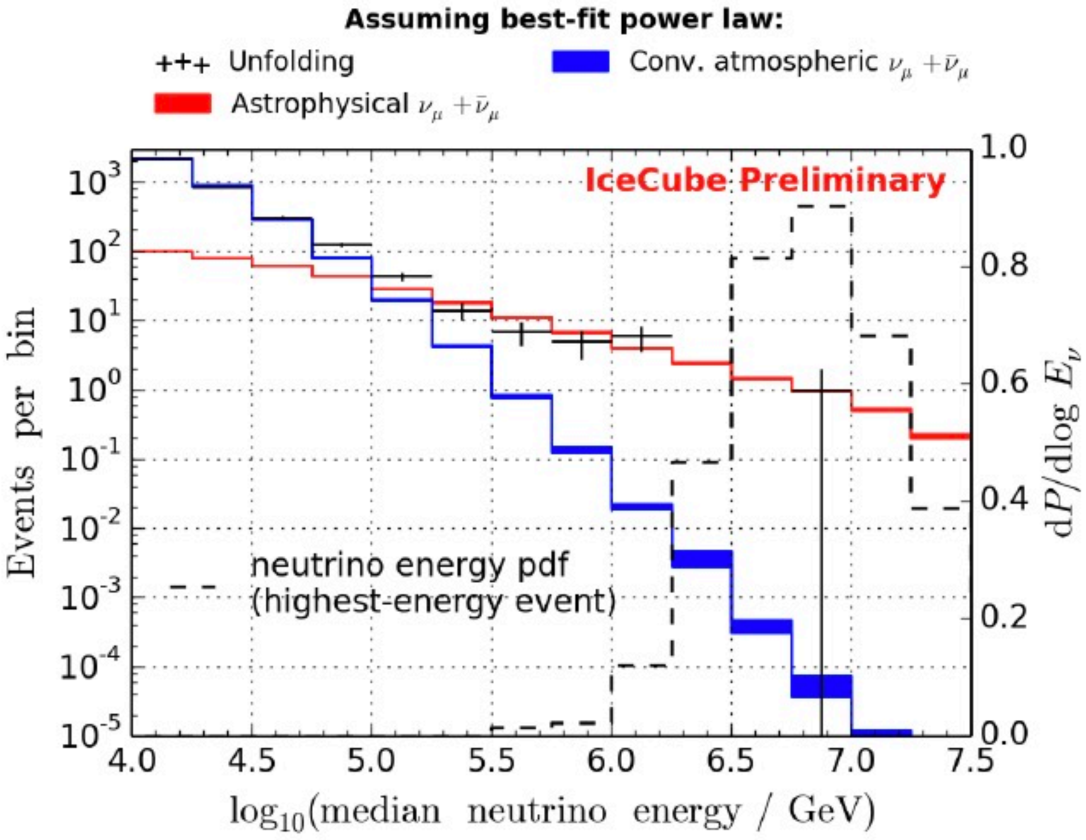
(Every disadvantage comes with an advantage)

- ν are very hard to measure
- ν are very hard to absorb



gamma-rays, neutrinos, CRs must be related

Diffuse cosmic flux



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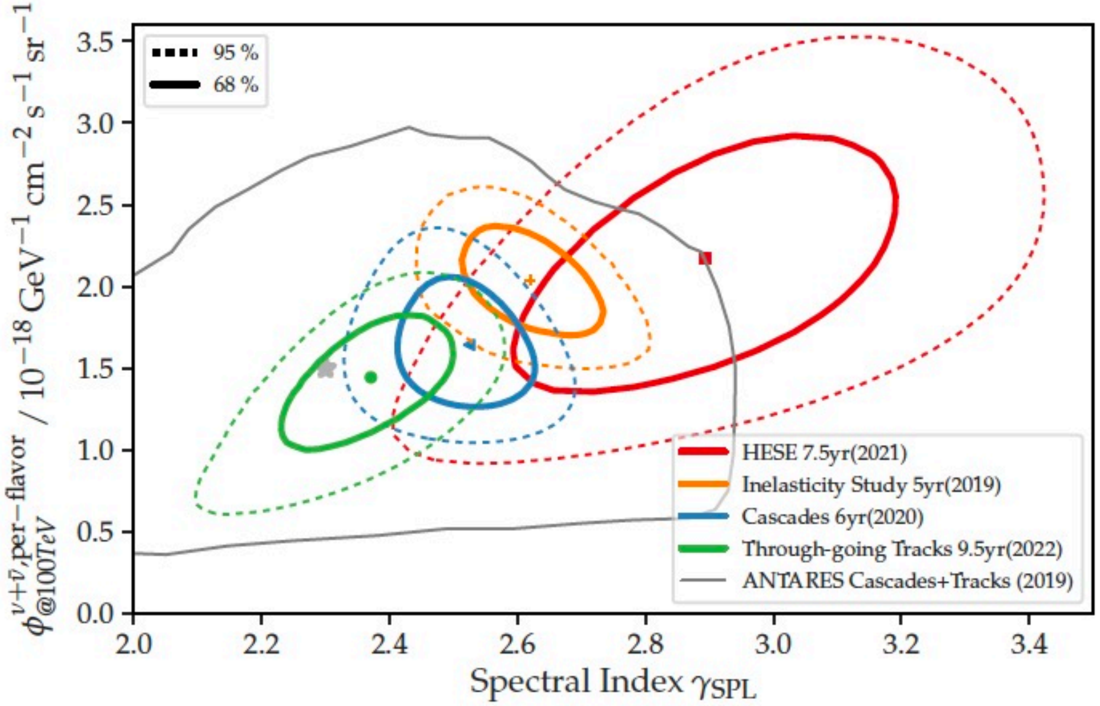

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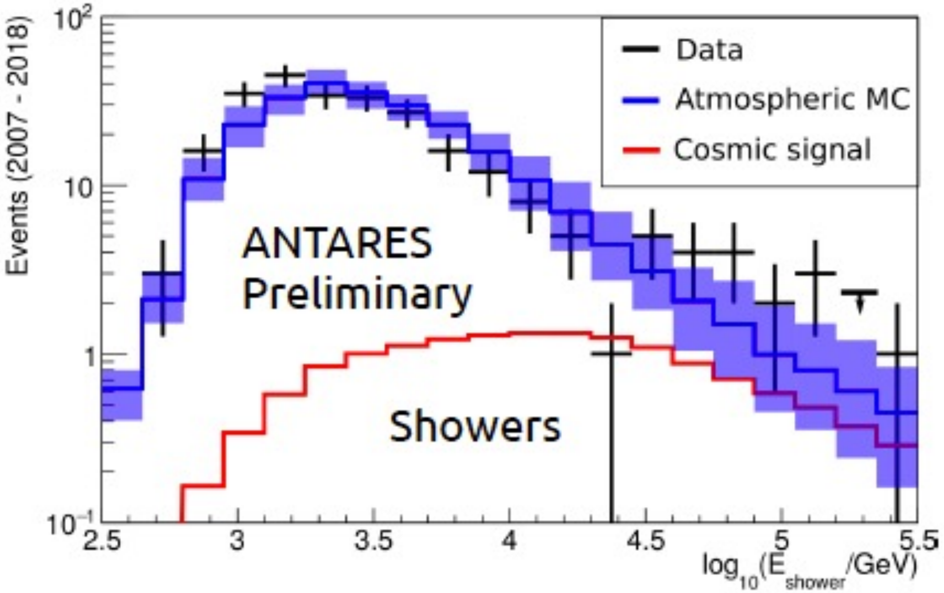
Diffuse cosmic flux

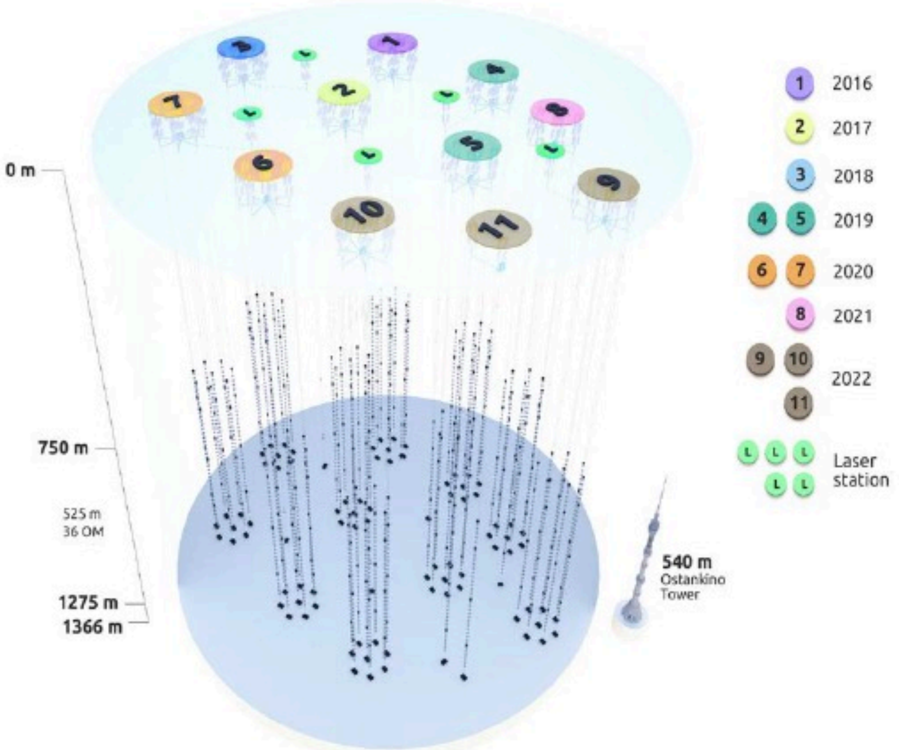


Antares data fully compatible with cosmic flux

- Data: 50 events (27 tracks + 23 showers)
- Background : 36.1 ± 8.7

significance 1.8σ

PoS ICRC2019 (2020) 891



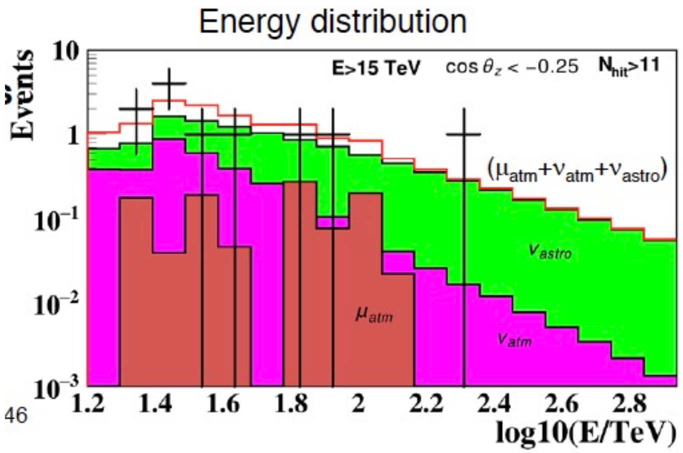
Lake Baikal
Gigaton Volume Detector

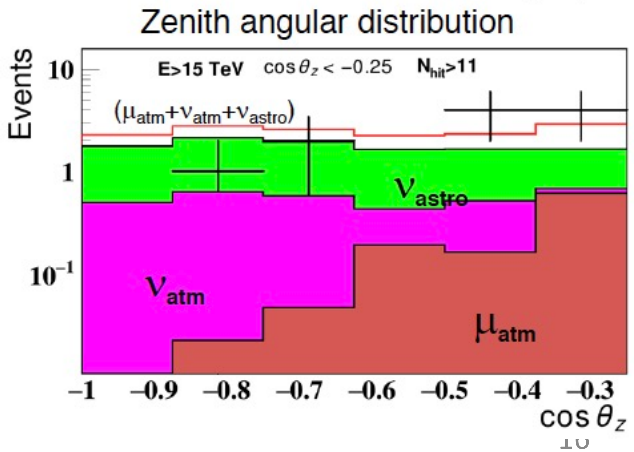
combined upward +
downward HE showers:

25 data
9.7 muons
3.4 atmosph. ν
16 cosmic ν ($E^{-2.46}$)

→ 3 sigma evidence

Neutrino 2022



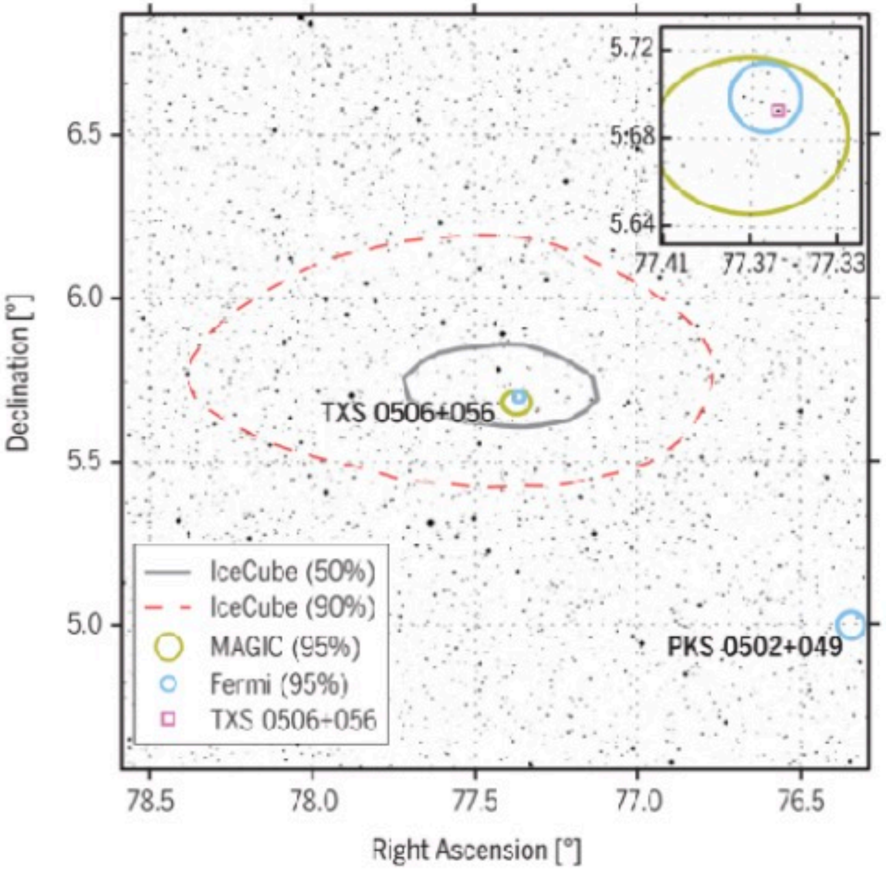


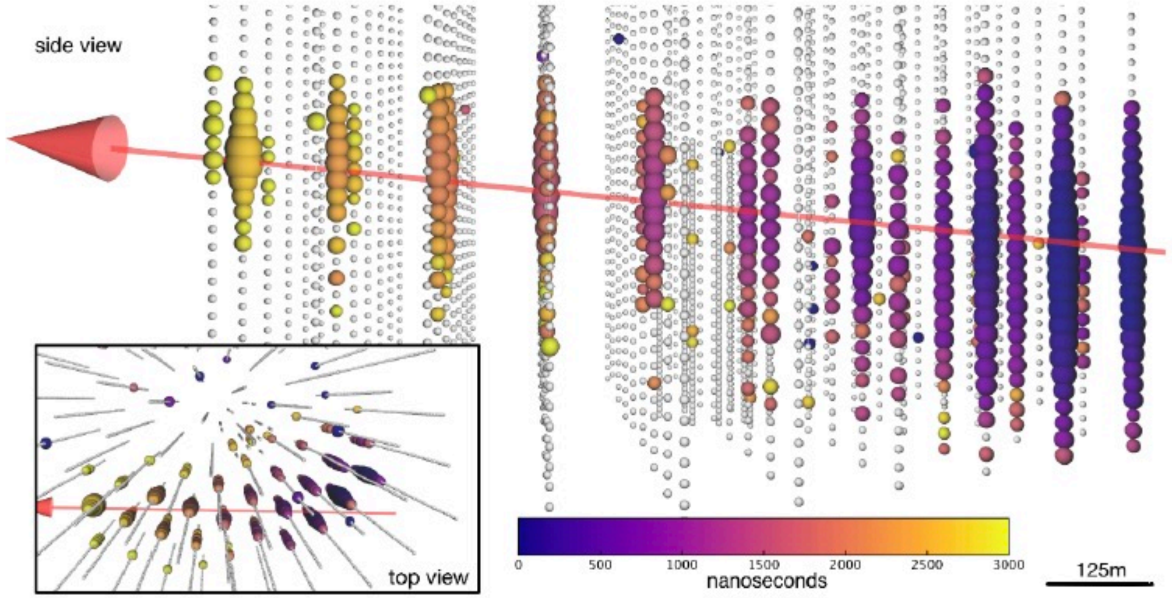
Sources?

blazar

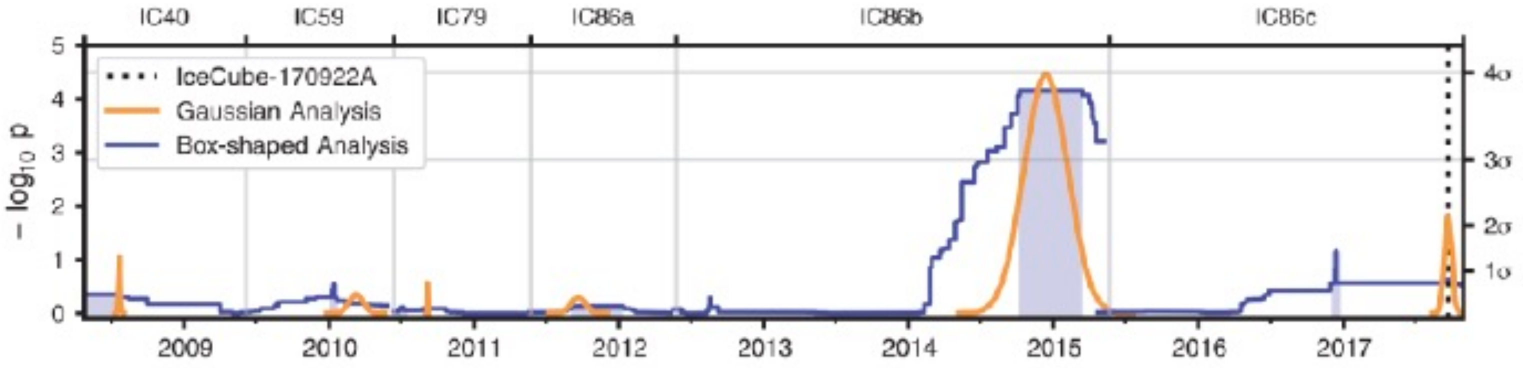
Association **IC170922A – TXS0506+056**

*Sci **361** eaat1378* *Sci **361** 147* (2017)



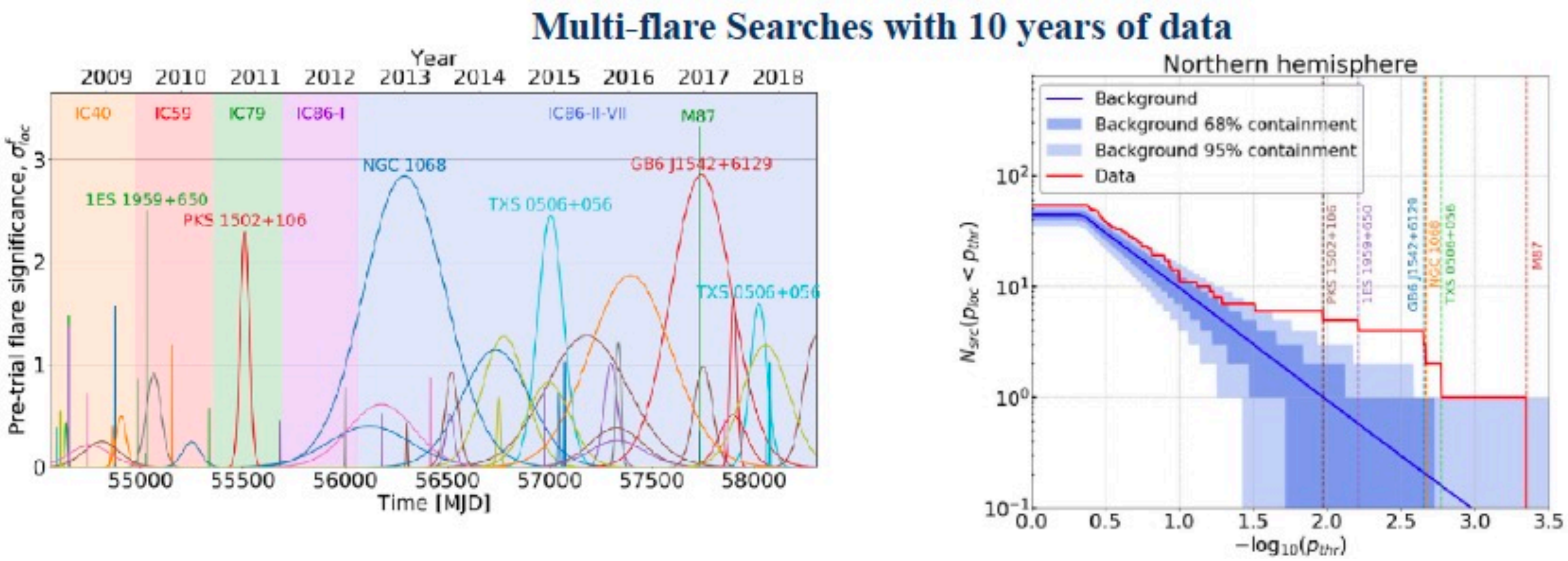


◉ 13 ± 5 events above the background over 100 days: significance of 3.5σ



ANTARES followup: ApJL 863, L30 (2018)

Other associations under scrutiny



IceCube

ApJ 920 (2021) 2, L45

IC190730A (300 TeV ν_μ) -- blazar PKS 1502+106 ?

IC191001A -- AT2019dsg
IC200530A -- AT2019fdr

Tidal disruption events?
2021 NatAs ***5*** *510*

Antares followup: no significant signal ApJ 920 (2021) 50

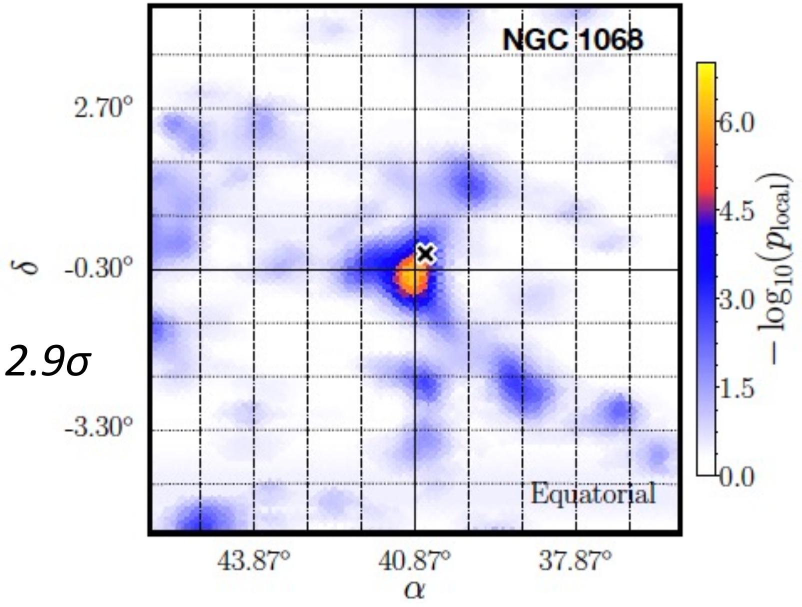
IC211208A – blazar PKS 0735+17 ? **First KM3NeT/ARCA followup analysis!** No significant signal

Many followups on GW events from LIGO/VIRGO: no signal seen.

Baikal GVD: possible association of ν candidates with a number of ANTARES alerts. (*PoS* ICRC2021 (2021) 1121)

Source searches

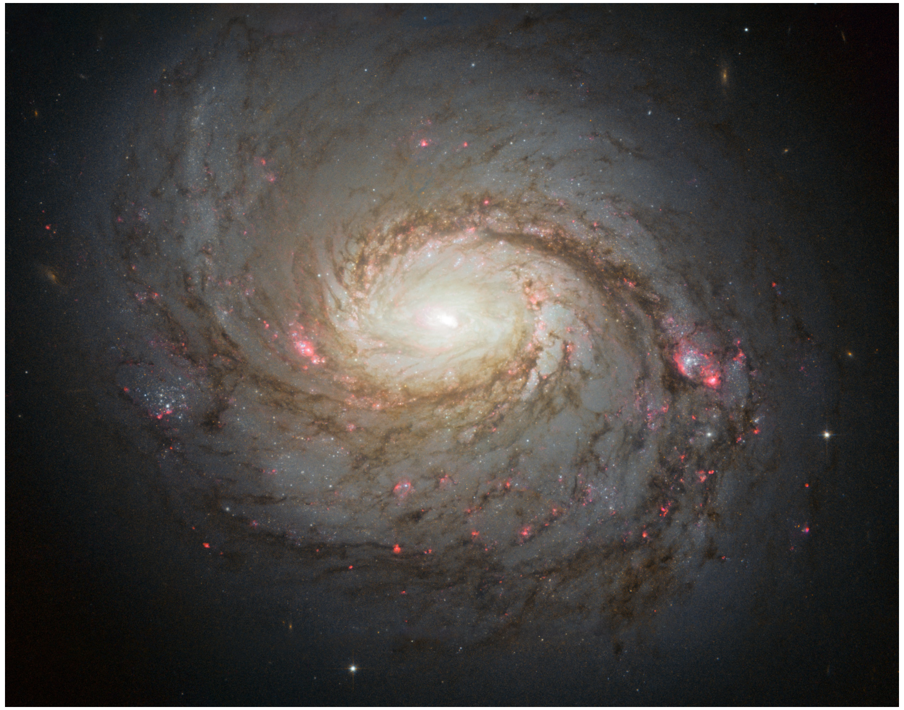
IceCube search for correlations in their own data.
Most significant hot-spot coincides with NGC 1068



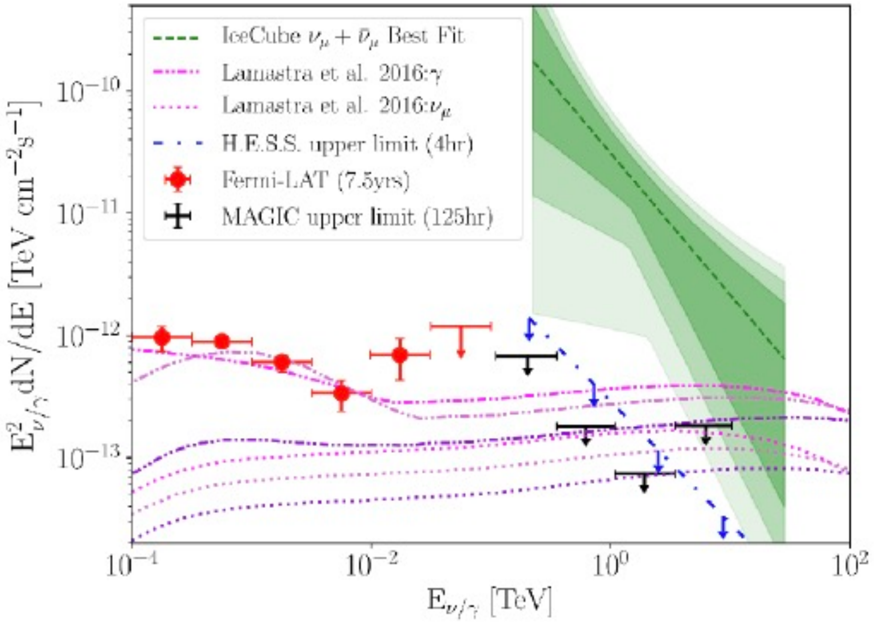
post-trial significance 2.9σ

Phys.Rev.Lett. 124 (2020) 5, 051103

NGC 1068 = Messier 77 (Seyfert galaxy)

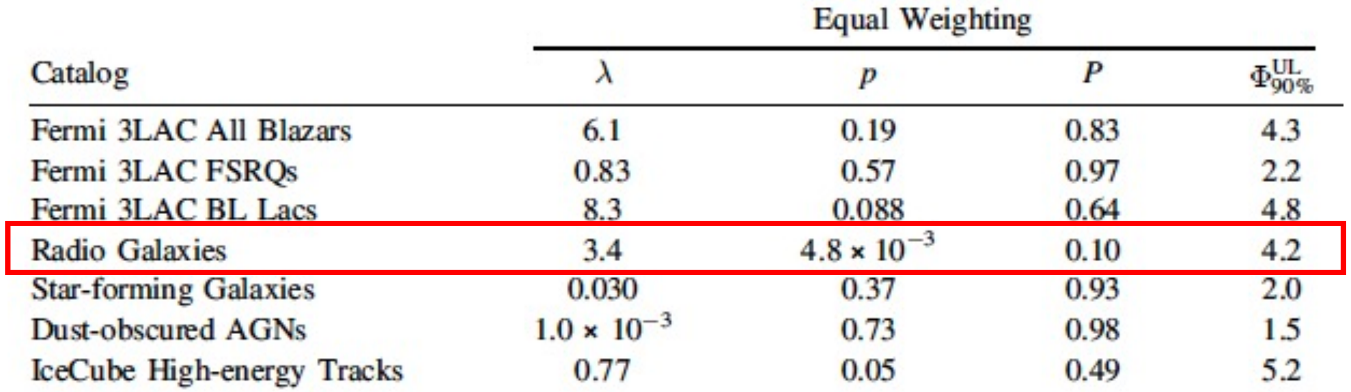


If real, ν luminosity exceeds photon luminosity



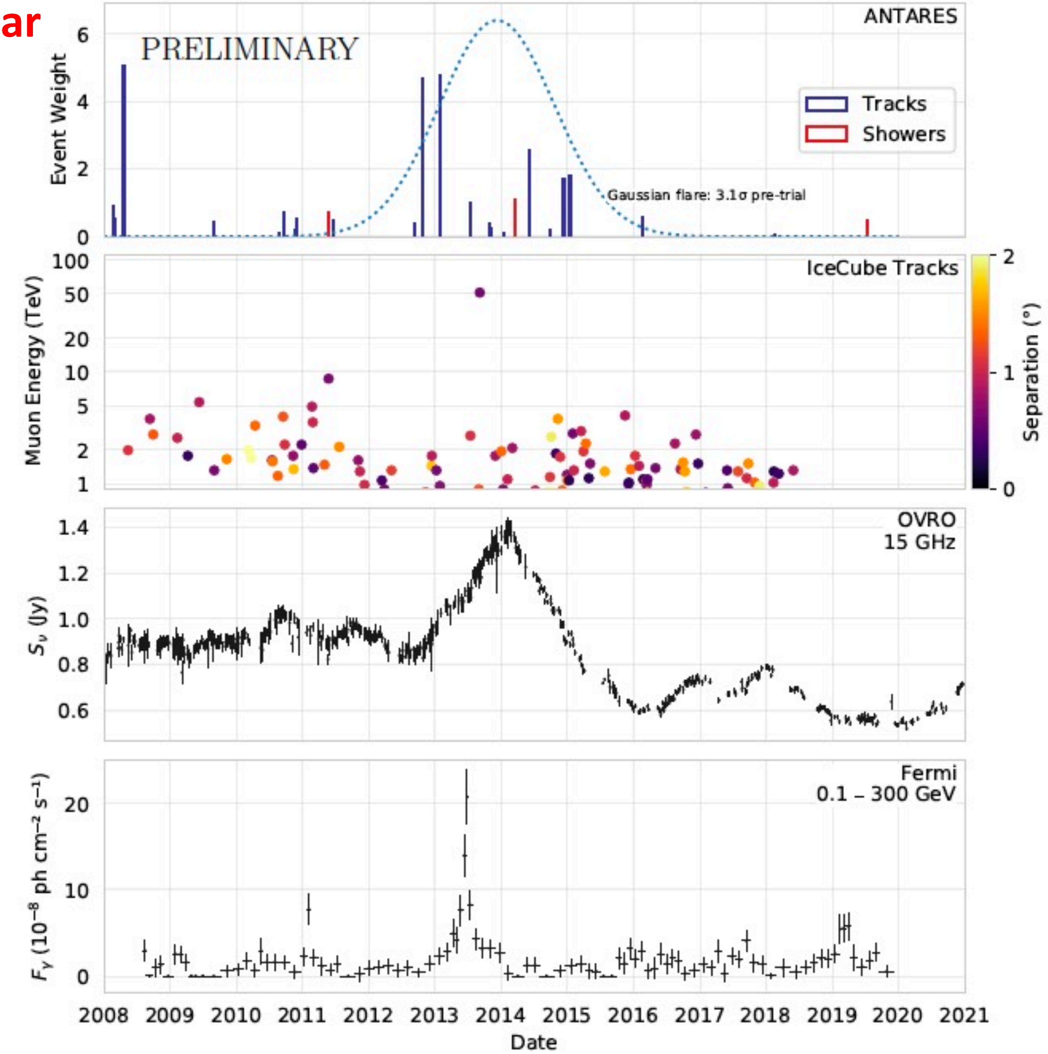
Source searches

ANTARES: [ApJ 911 (2021) 48]



Catalog	Equal Weighting			
	λ	p	P	$\Phi^{\mathrm{UL}}_{90\%}$
Fermi 3LAC All Blazars	6.1	0.19	0.83	4.3
Fermi 3LAC FSRQs	0.83	0.57	0.97	2.2
Fermi 3LAC BL Lacs	8.3	0.088	0.64	4.8
Radio Galaxies	3.4	4.8×10^{-3}	0.10	4.2
Star-forming Galaxies	0.030	0.37	0.93	2.0
Dust-obscured AGNs	1.0×10^{-3}	0.73	0.98	1.5
IceCube High-energy Tracks	0.77	0.05	0.49	5.2

flaring radio-blazar



J0242+1101 (PKS0239+108)

KM3NeT/ARCA also started source searches, but cannot yet outperform ANTARES

Understanding the sources

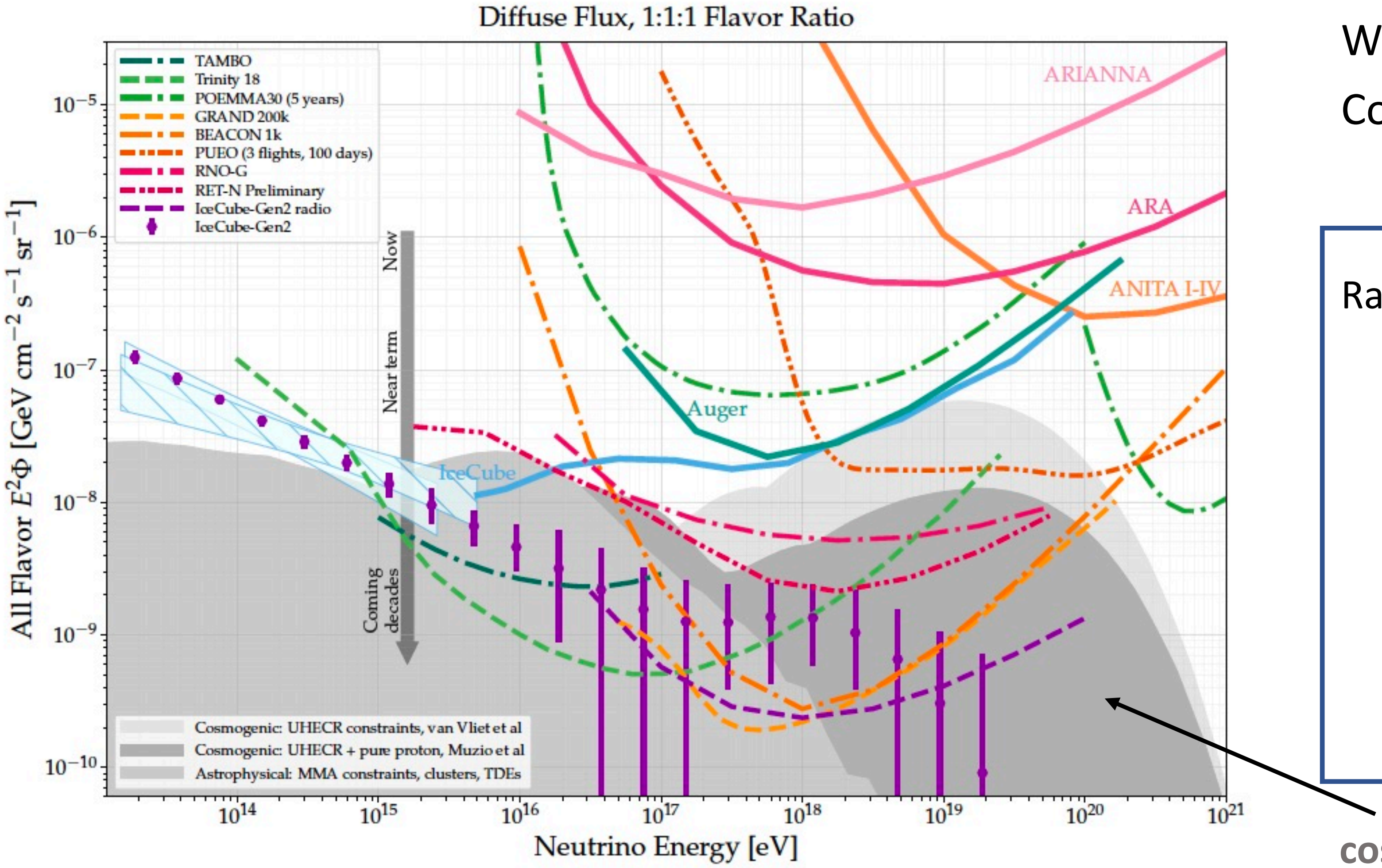
Assignments of neutrino candidates to sources not solid yet.

High fraction of blazars in candidate sources seems at odds with earlier limits on blazar contribution to diffuse flux, but perhaps that is telling us something on the physics in blazars.

Various source modelling attempts ongoing.

Perhaps tension between requirements for strong neutrino signal and strong gamma ray signal from sources. Neutrinos: calorimetric thick source, gamma rays: transparent source.

Ultra-High Energy neutrinos



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cosmogenic

Will give insight to UHECR sources

Cosmogenic neutrinos: from GZK cutoff

Radio detection of showers in air/water/ice

Balloons
Antenna arrays

PAO
IceCube-Gen2
GRAND

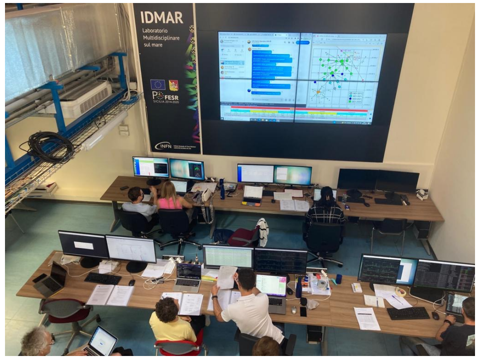
R&D for acoustic detection in water

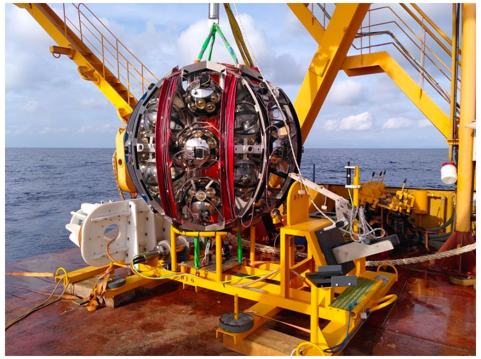
Some of the projects with NL participation

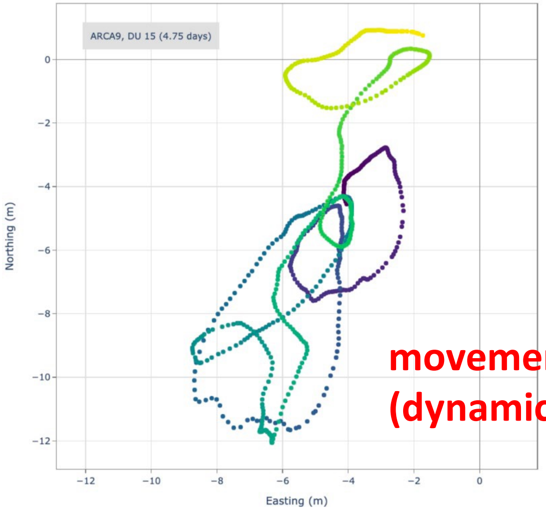
KM3NeT

all going on now in parallel!

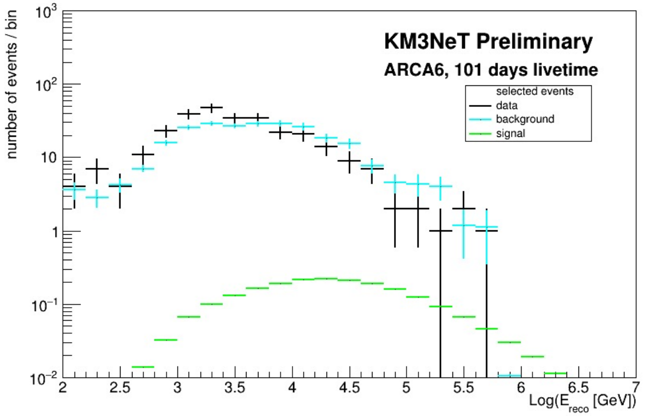
construction → deployment → commissioning → calibration → science







movement of top DOM in a line over time (dynamic acoustic positioning, 10 x 10 m)



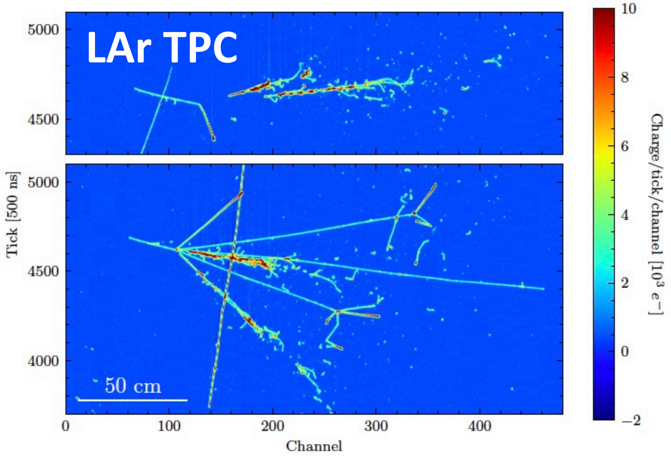
In the last two weeks: ARCA7 → ARCA19 !

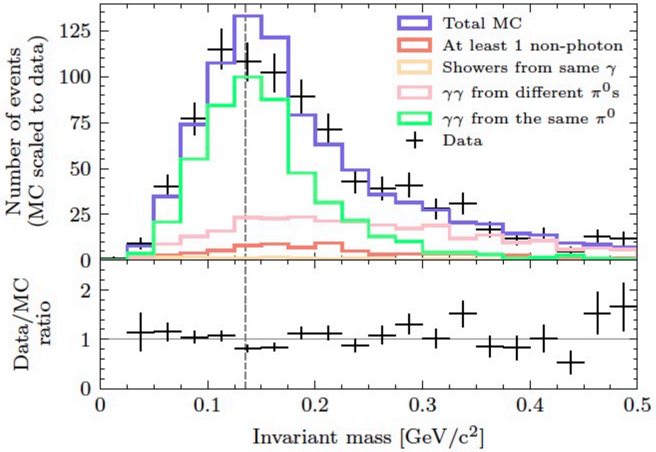
DUNE

Original contribution to the ProtoDUNE DAQ (evolved to DUNE DAQ baseline)

ProtoDUNE data analysis, ProtoDUNE II e-π^0 separation, calibration

VUV setup (with XENON) for studies of fluorescence/reflection of UV light

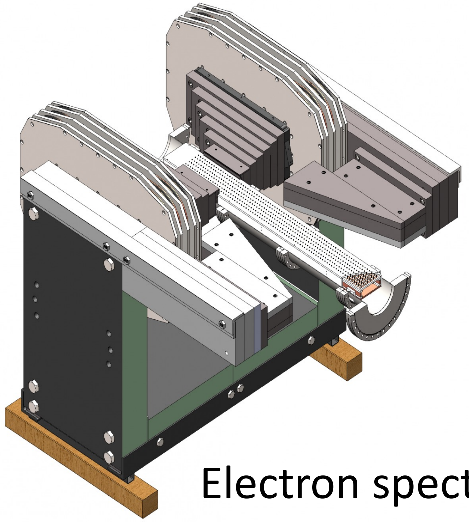


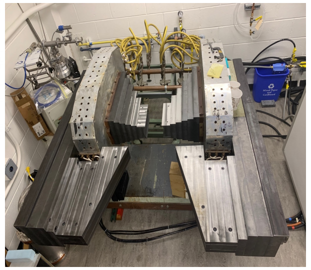


$\pi^0 \rightarrow \gamma\gamma$

Ptolemy

- Dutch relic neutrino R&D effort
- Building a community: UvA, RU, TNO, THUAS, NNV
- Developing cutting edge electron spectrometer with Princeton, Gran Sasso, TNO
- Target development at RU + KIT





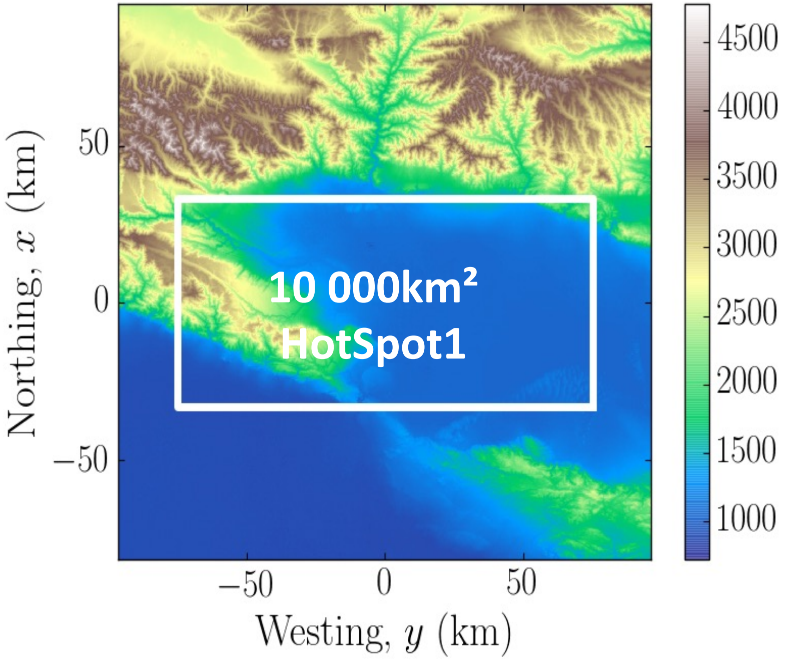
Electron spectrometer R&D

GRAND (Giant Radio Array for Neutrino Detection)

on a 10000 antennas hotspot (GRAND10k)

➔ Sensitivity in IceCube2015 range.

- **Go for x20!! ➔ Network of O(20) subarrays of O(10000) antennas with sparse density (1/km²) at various favorable locations around the world (« hotspots »)**
- Sensitivity of full array good enough for GRAND to detect cosmogenic neutrinos for standard hypothesis
- **GRAND white paper**




Not contractual!

- GRAND in China
  - COVID has hampered deployment
  - Manufactured pieces are now sent across the world for
  - The prototype stage is now spreading over the world
- GRAND in Nijmegen
  - Single antenna setup (May 2022) to debug problems from around the world
- GRAND In Nançay
  - ~4 antenna setup (July 2022) in radio quiet environment in France for further prototyping
- GRAND in Argentina
  - Looking for possibilities in San Juan for array of ~100 antennas
  - GRAND@Auger: discussing option to install ~10 antennas within the Auger observatory in 2023


That's all Folks!