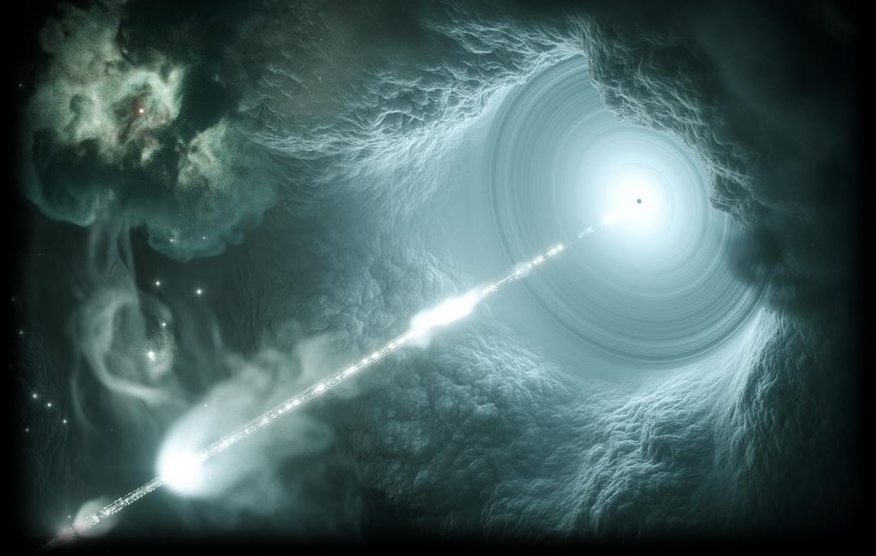
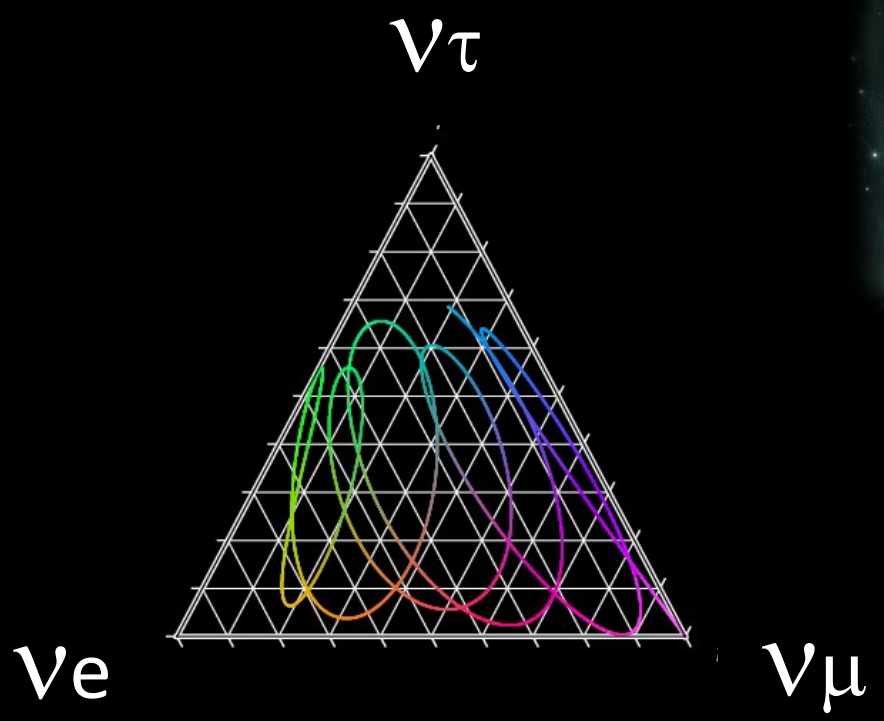
Neutrinos





Dorothea Samtleben

- **The neutrino - the unknown**

  - masses, mixing angles, CP phase
  - sterile neutrinos?

- **The neutrino - the cosmic messenger**

  - Cosmic high energy neutrino sources
  - Relic neutrinos

- **The neutrino - the unknown**

  - masses, mixing angles, CP phase
  - sterile neutrinos?

- **The neutrino - the cosmic messenger**

  - Cosmic high energy neutrino sources
  - Relic neutrinos

Experiments with Dutch involvement:

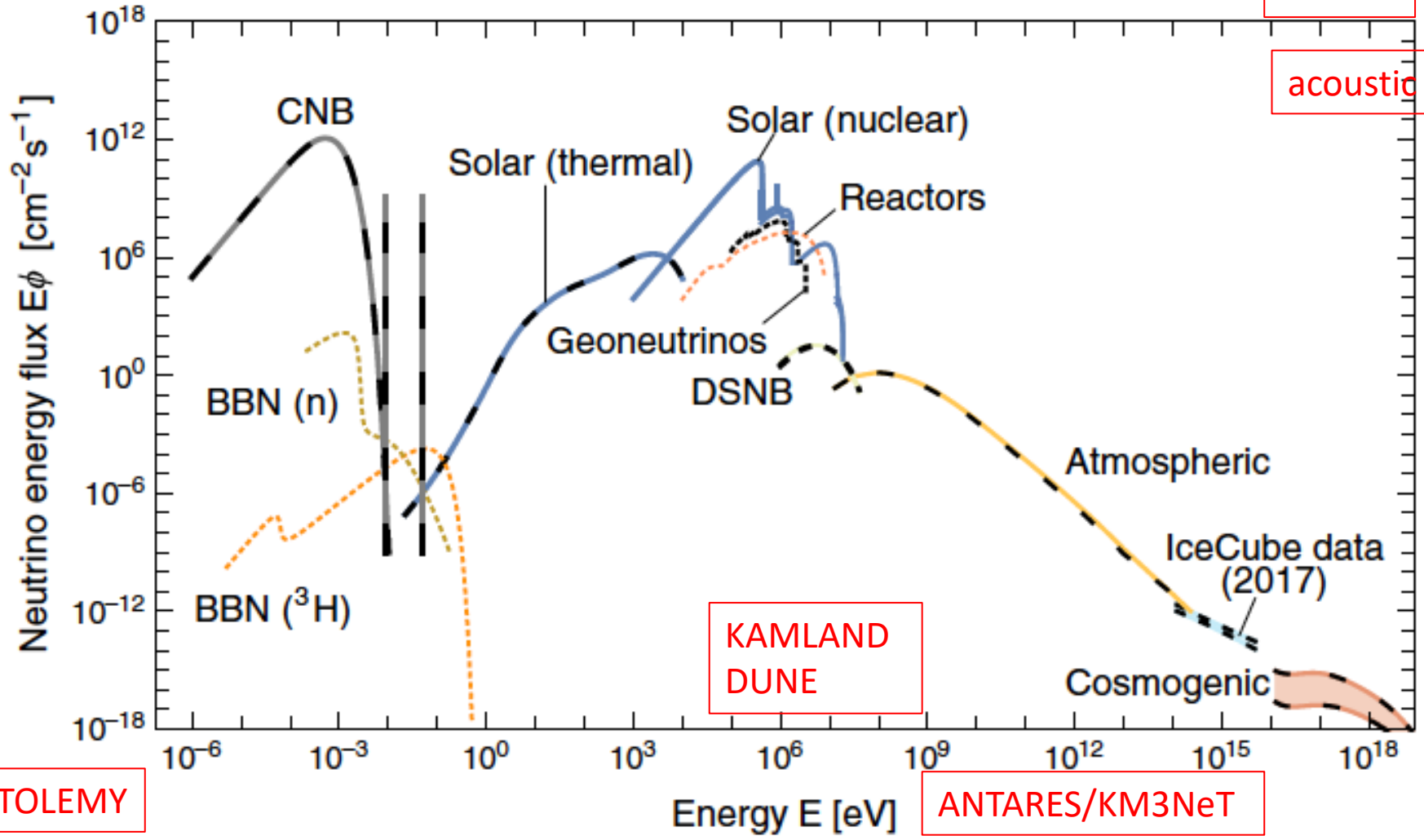
Neutrino telescopes: **KM3NeT, ANTARES*** (Global Neutrino Network)
Neutrino beam (accelerator): DUNE
Dark matter detectors: KamLand, XENONnT, XLZD
Very low energy neutrino detection: Ptolemy
Cosmic rays/neutrinos (radio): Pierre Auger Observatory, GRAND
R&D for acoustic neutrino detection

(New heavy neutral lepton searches**: **ATLAS, LHCb, FASER, SND)

* ANTARES dismantled 2022

Neutrinos from meV to PeV

Aside from cosmic exploration also rich fundamental physics potential



Auger
GRAND

acoustic R&D

KAMLAND
DUNE

PTOLEMY

ANTARES/KM3NeT

Reactor neutrinos

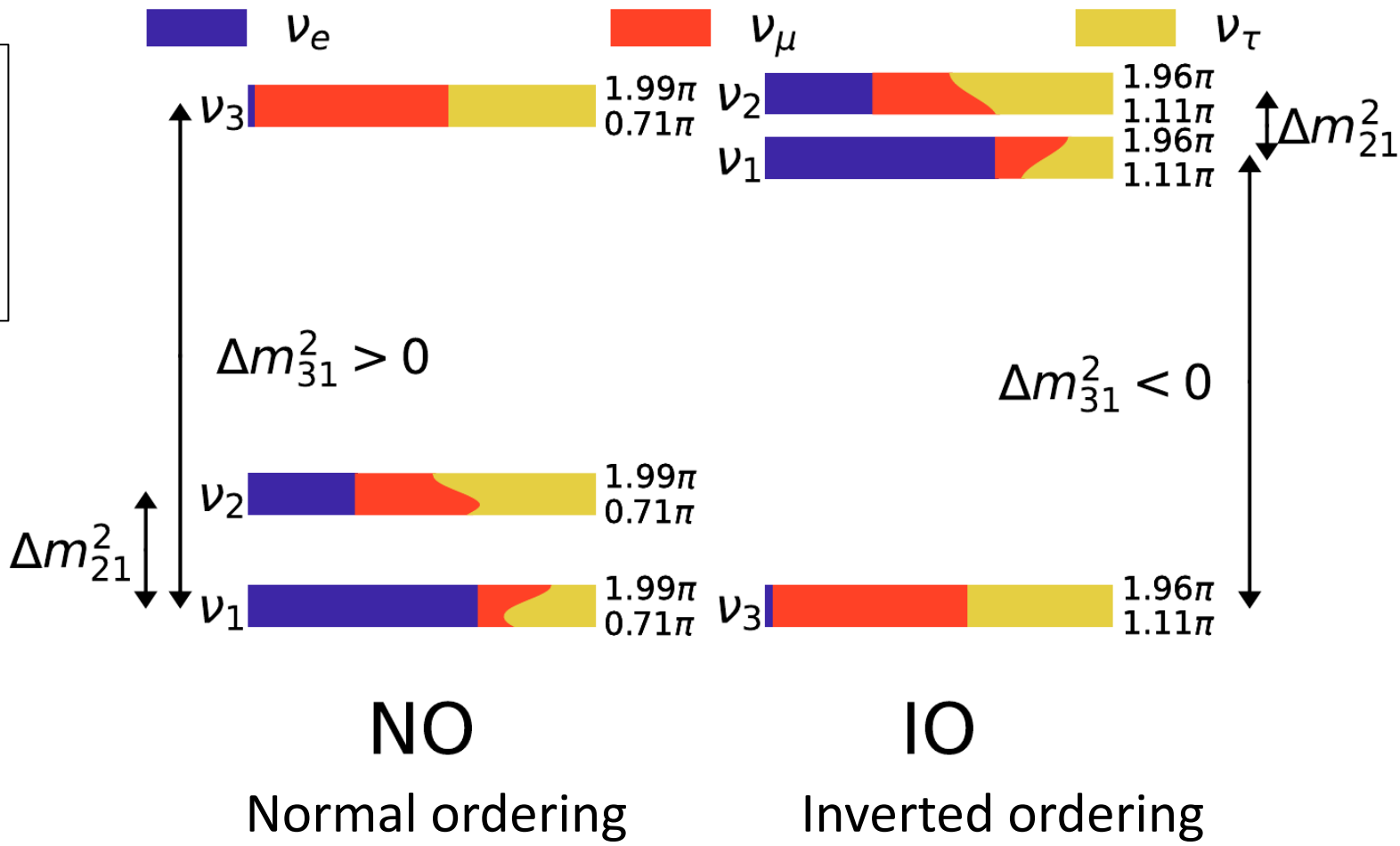
Accelerator neutrinos

Neutrino properties

Neutrino masses

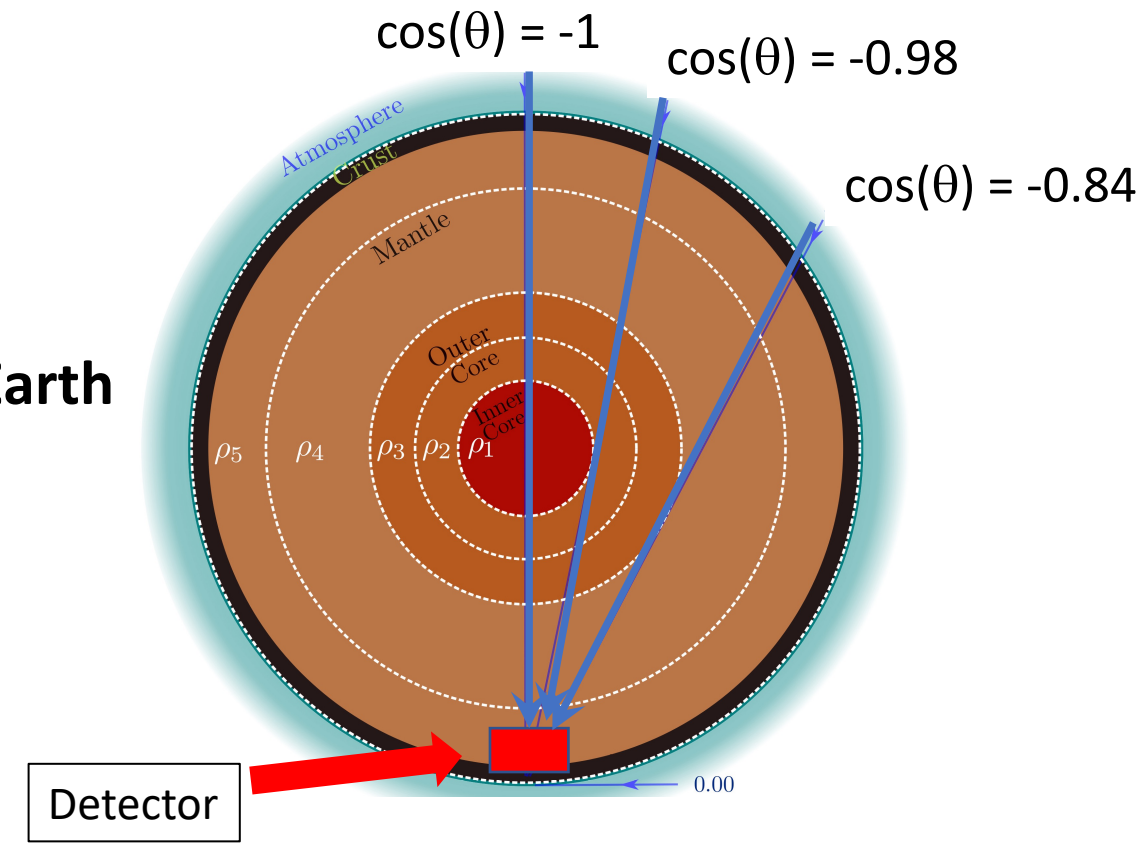
3 mass eigenstates
mixing with 3 flavor eigenstates

⇒ **Neutrino oscillations:**
2 mass differences, 3 angles, 1 phase (CP)

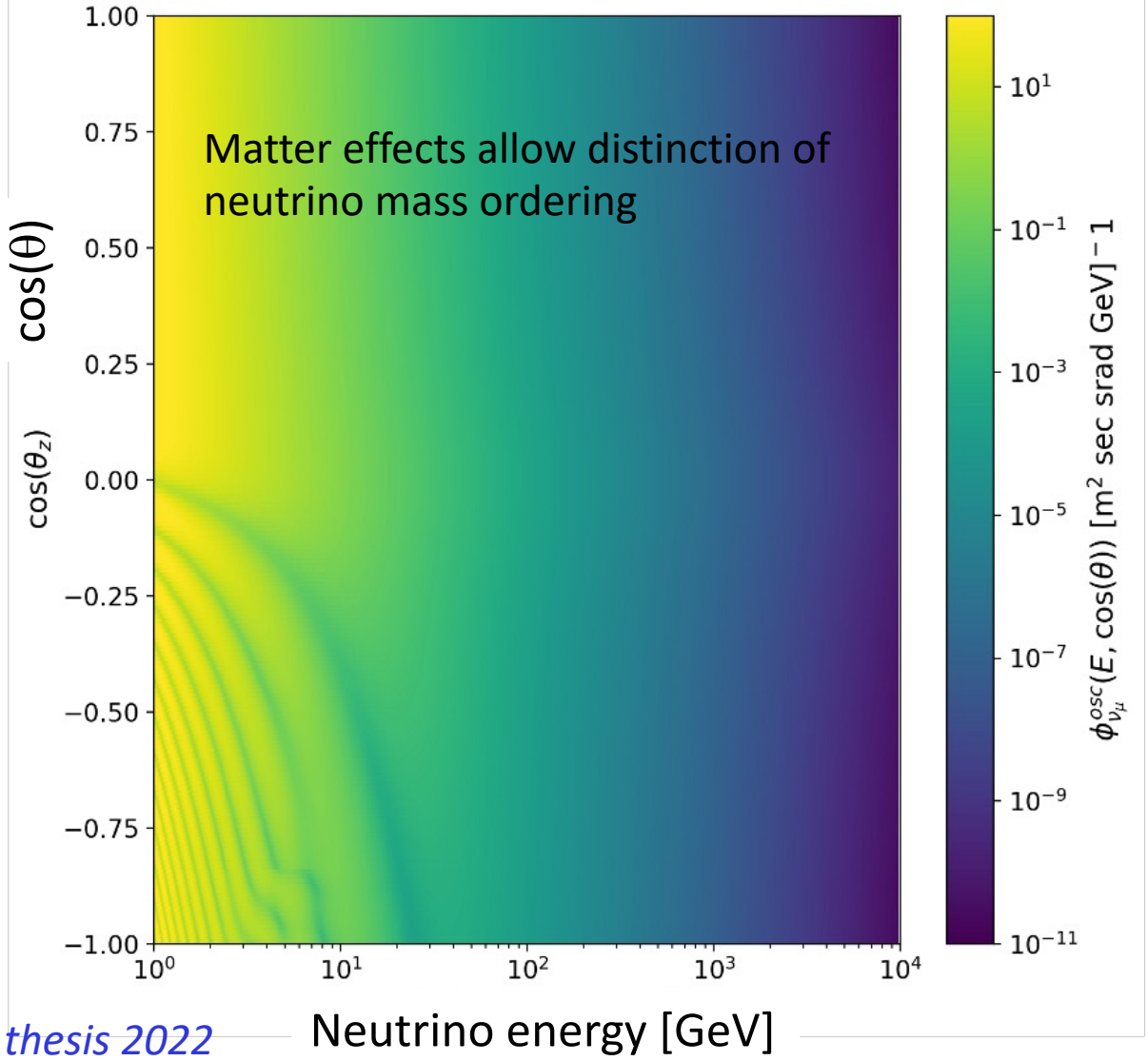


Atmospheric neutrino oscillations

Earth



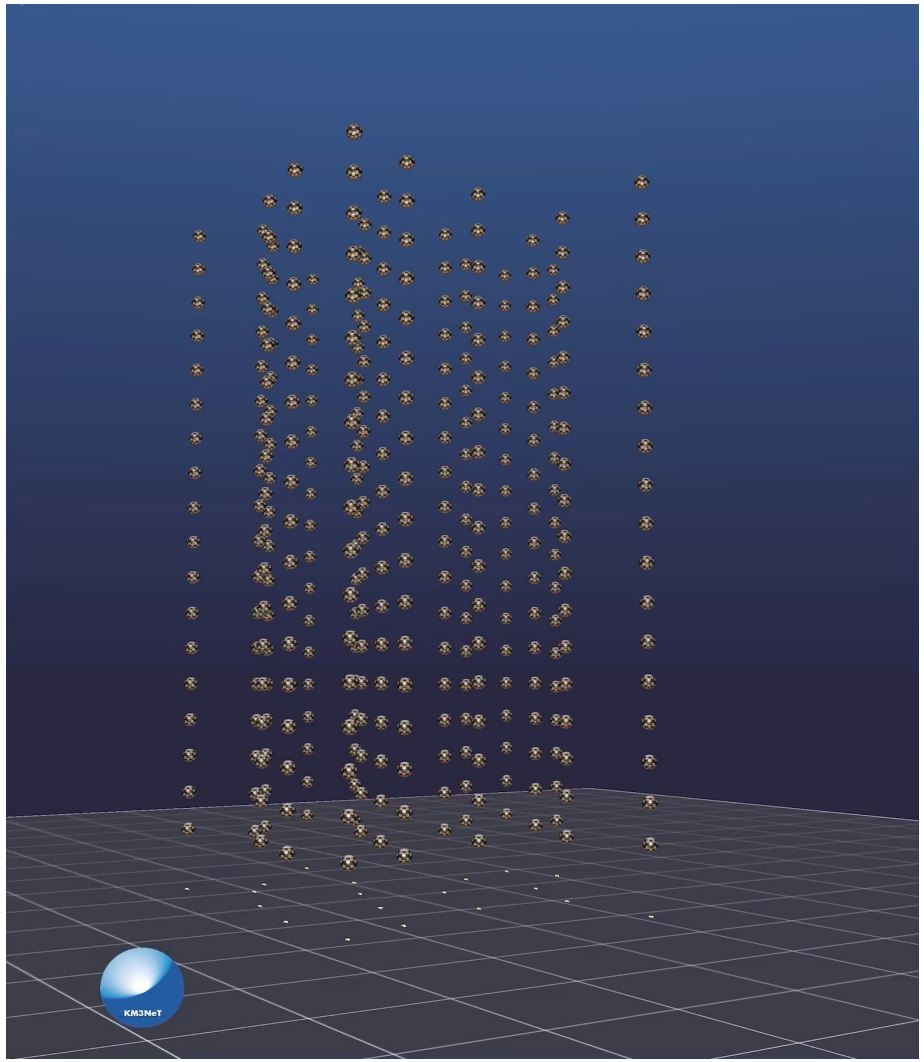
Expected oscillated muon neutrino flux



Pictures from Jerzy Manzak PhD thesis 2022

Neutrino telescope KM3NeT in the Mediterranean

ARCA: Italian site, 3.5km deep, cosmic neutrino detection
ORCA: French site, 2.5km deep, atmospheric neutrino oscillations

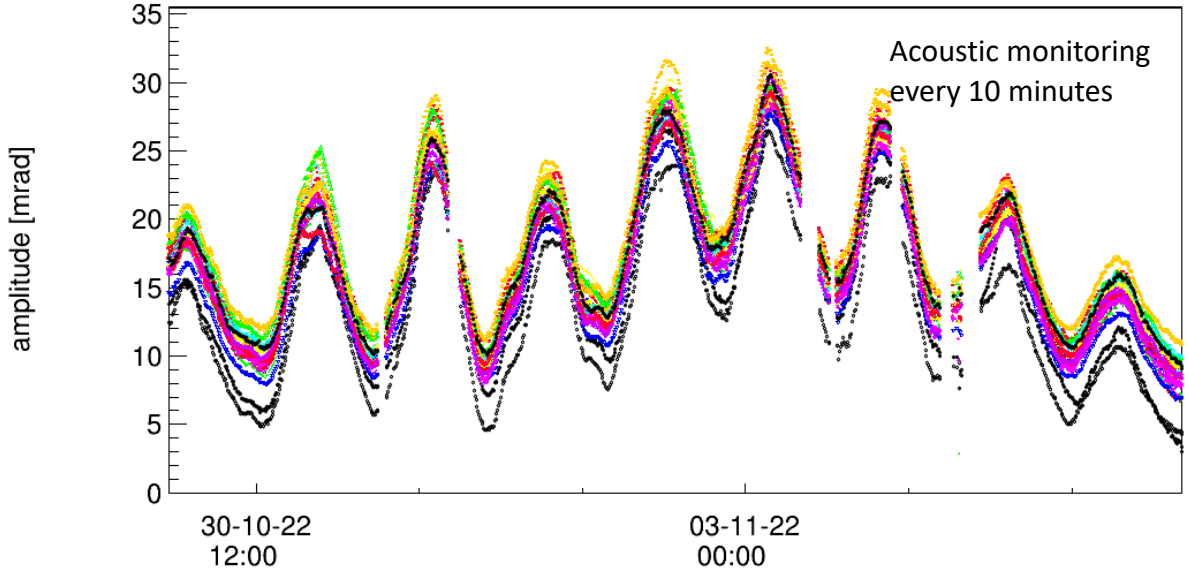


Neutrino telescope KM3NeT in the Mediterranean

ARCA: Italian site, 3.5km deep, cosmic neutrino detection
ORCA: French site, 2.5km deep, atmospheric neutrino oscillations

ARCA: 21 strings operating, 125 funded (deployment by 2025)
ORCA: 16 strings operating, 50 funded (deplyment by 2025)

A moving detector:
Tilt amplitude of the ARCA strings

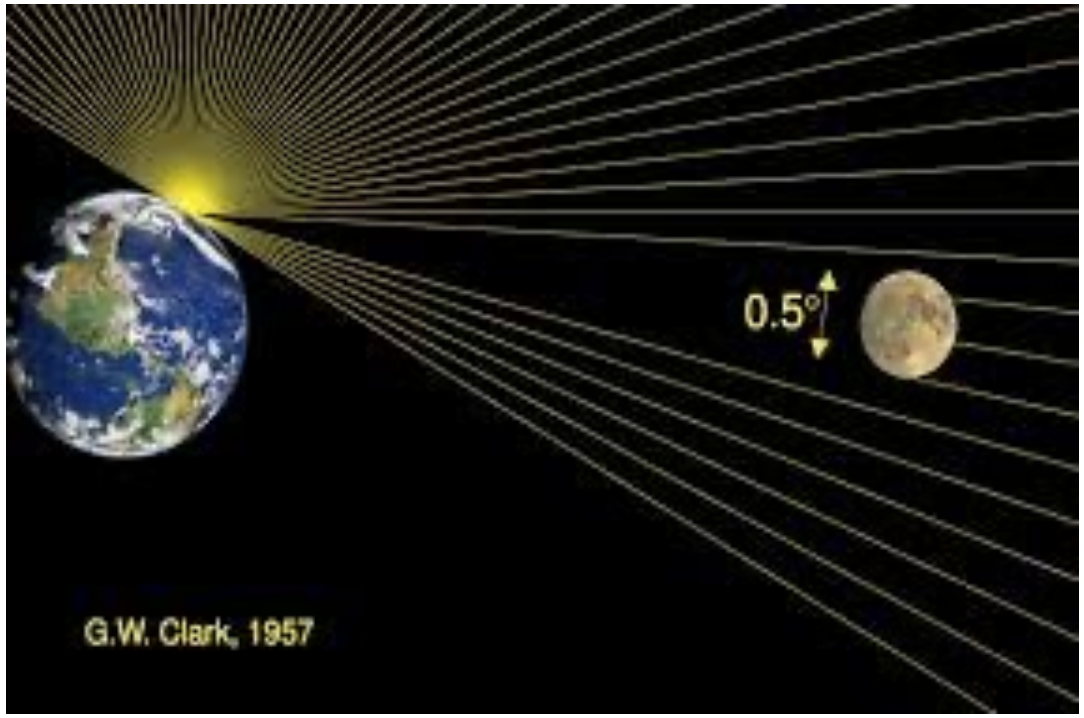


Absolute pointing check with moon/sun shadow

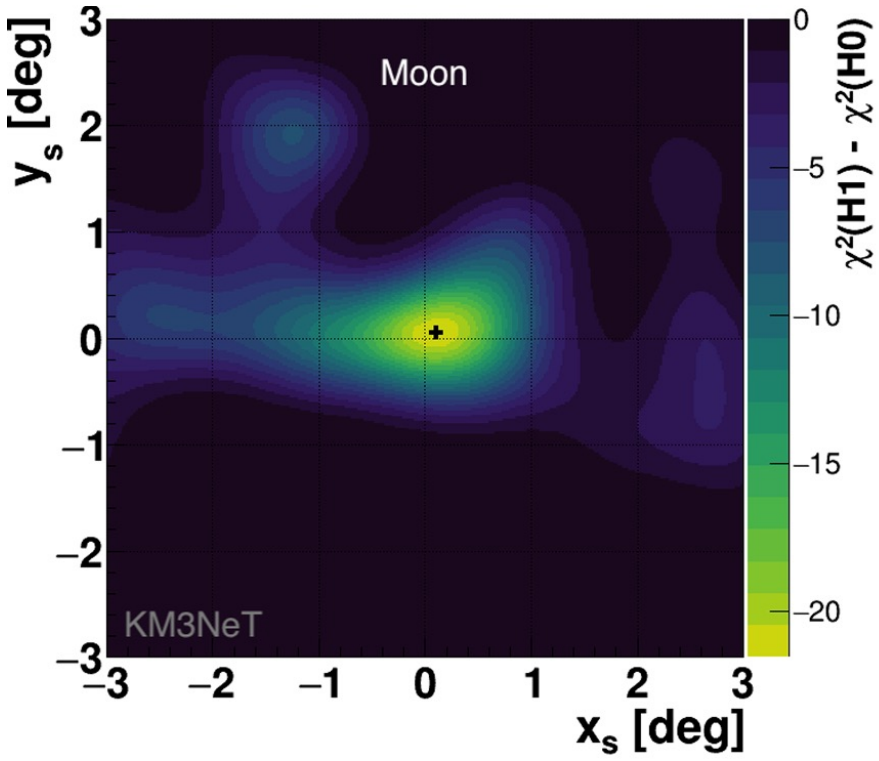
No neutrino calibration source available

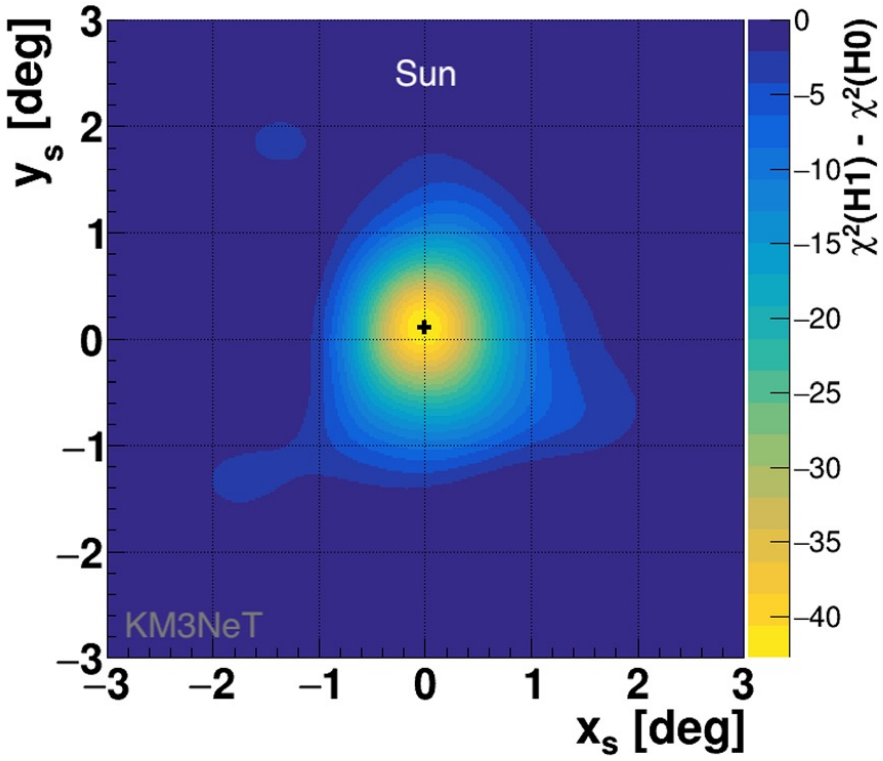
=> Use ‘negative’ signal in **atmospheric muons**

- Abundance of muons from cosmic ray interactions in the atmosphere
  -> check direction of moon/sun
  -> shadow expected



Absolute pointing check with moon/sun shadow





KM3NeT/ORCA
6 strings
1 year of data

	Sun	Moon
Significance	6.2 σ	4.2 σ
Amplitude	1.31 ± 0.34	0.71±0.27
Resolution	0.65° ± 0.13°	0.49°±0.15 °

arXiv:2211.08977
Eur.Phys.J.C 83 (2023) 4, 344

Absolute pointing check with moon/sun shadow

Peter B Denton
@jazzwhiz

Cosmic ray experiment discovers the existence of the Sun at high significance (6.2σ)! Existence of the Moon is probable (4.2σ), but more data is needed

arxiv.org/abs/2211.08977
@km3net @PlotAstro

KM3NeT/ORCA
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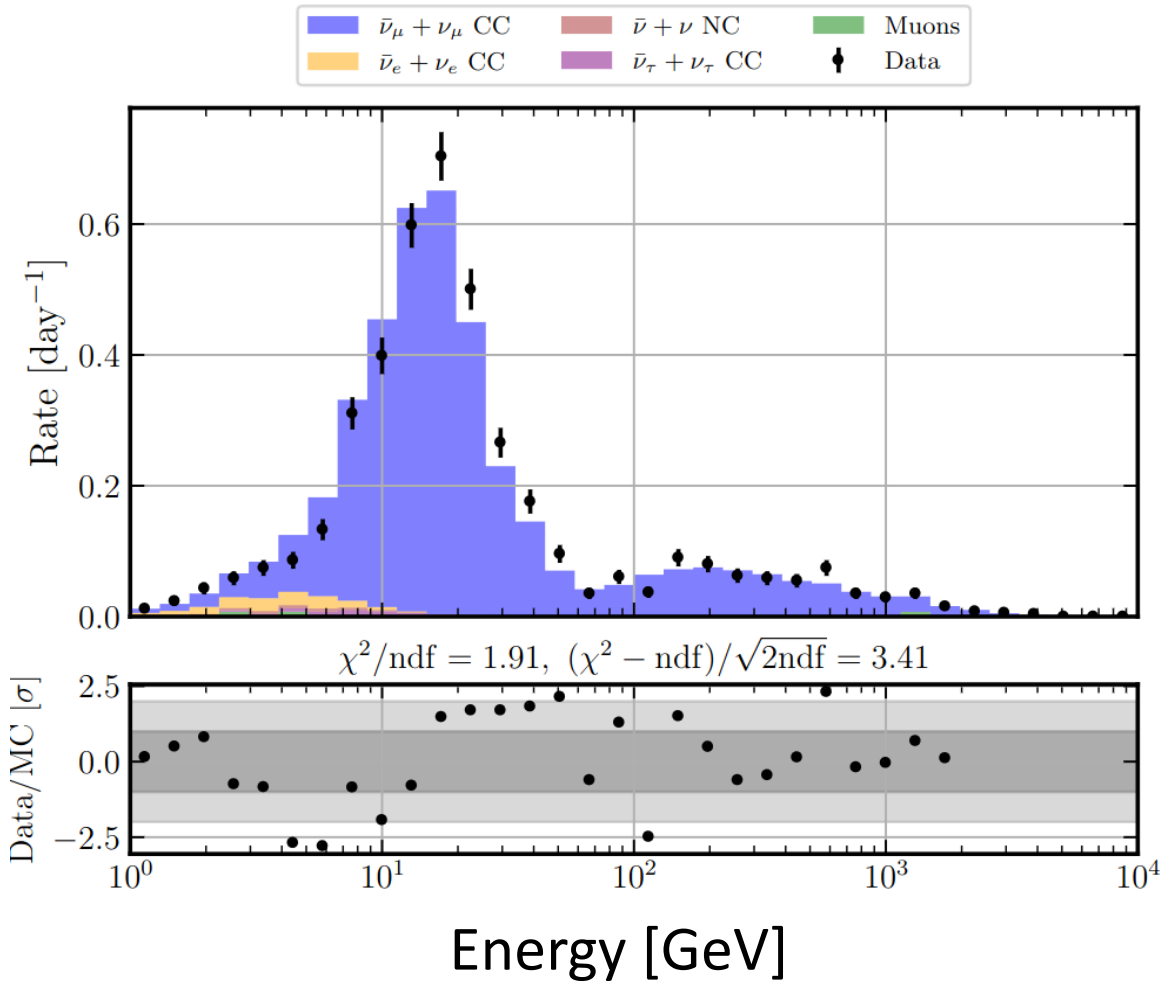
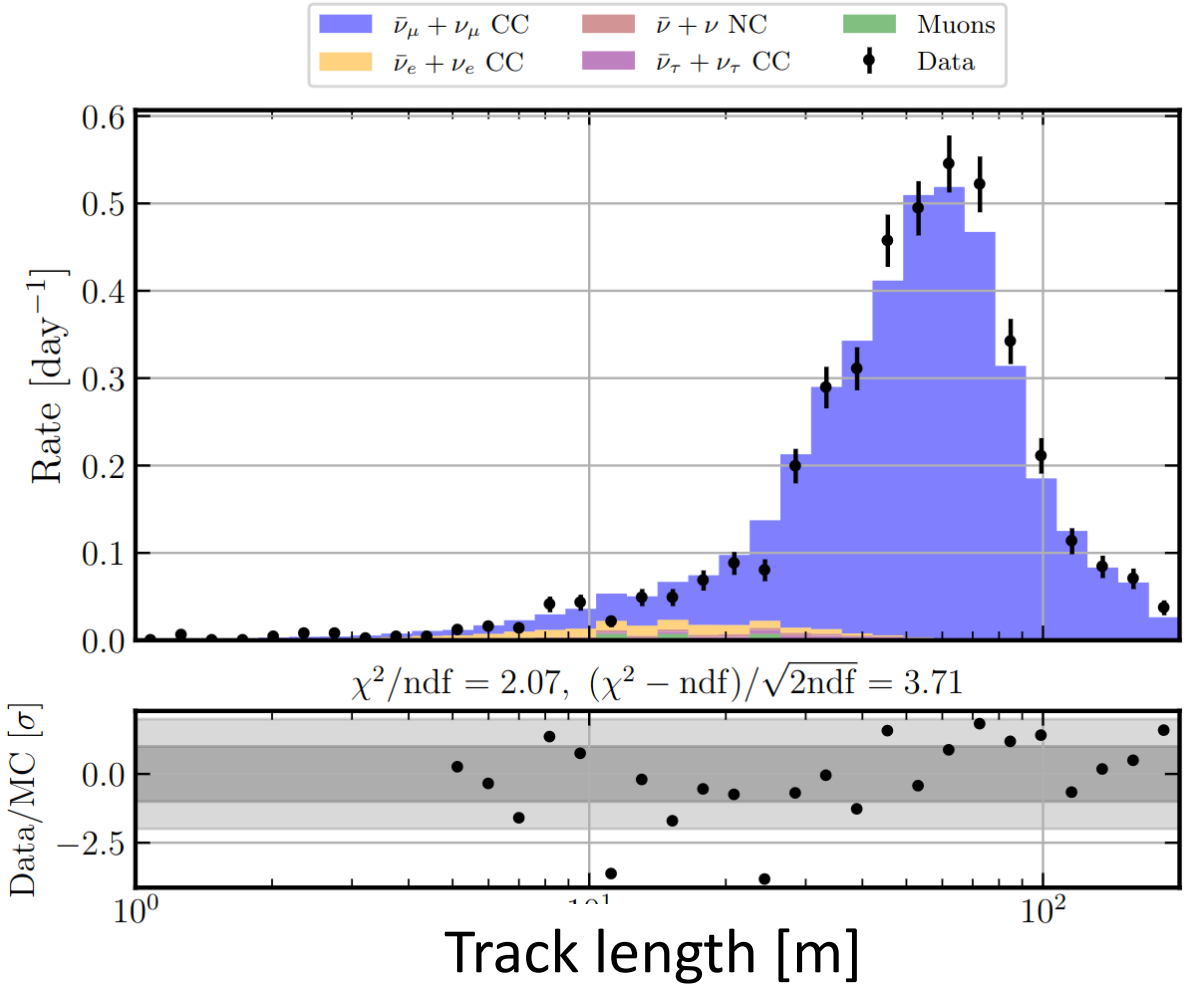
Eur.Phys.J.C 83 (2023) 4, 344

Neutrinos in KM3NeT/ORCA

Plots from 6 line detector
-> by now 16 lines taking data!

~ 4 atm. ν / day
510 days of livetime
0.3% atm. $\mu^{\pm}$ contamination

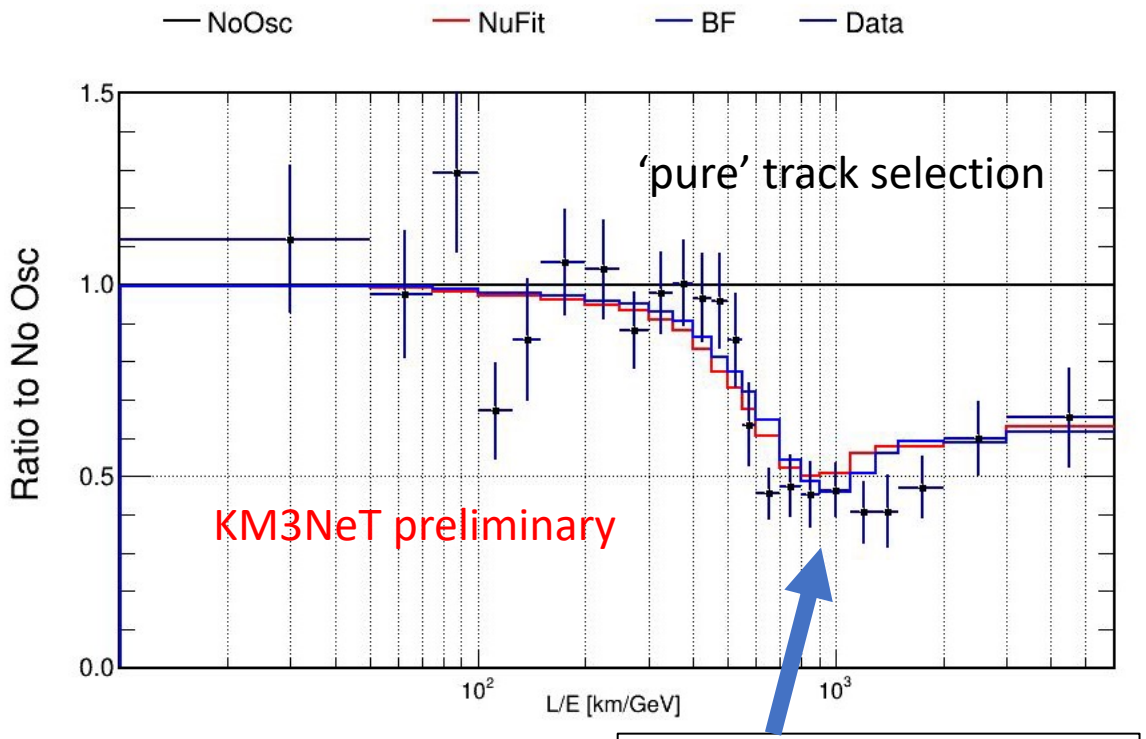




KM3NeT/ORCA oscillation analysis

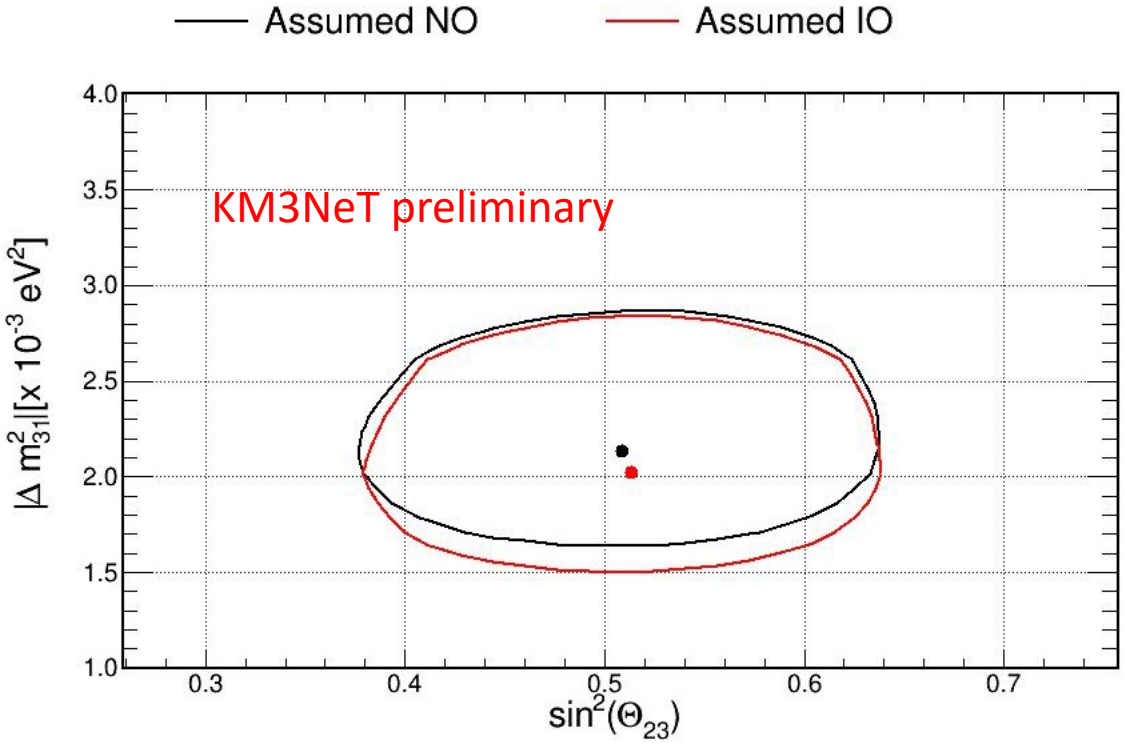
510 days ORCA 6 strings: New Unblinding

Travel length divided by Energy 'L over E'



Oscillation signature:
Deficit at high L/E values

Oscillation parameter fit



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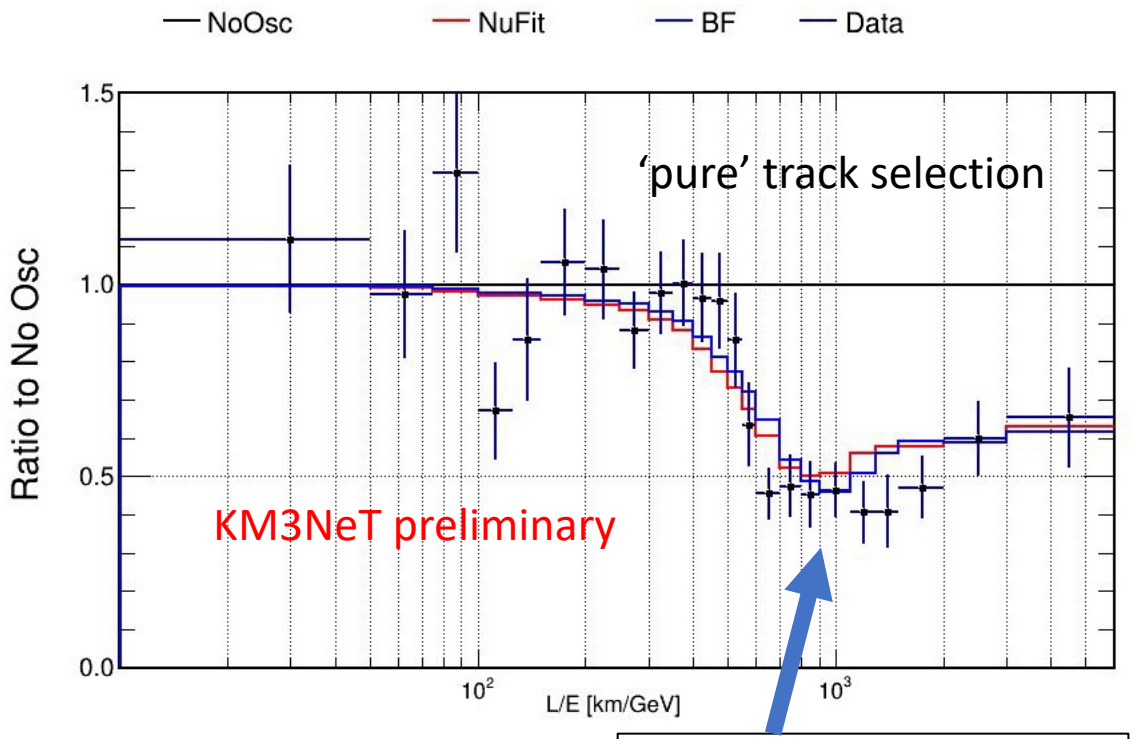
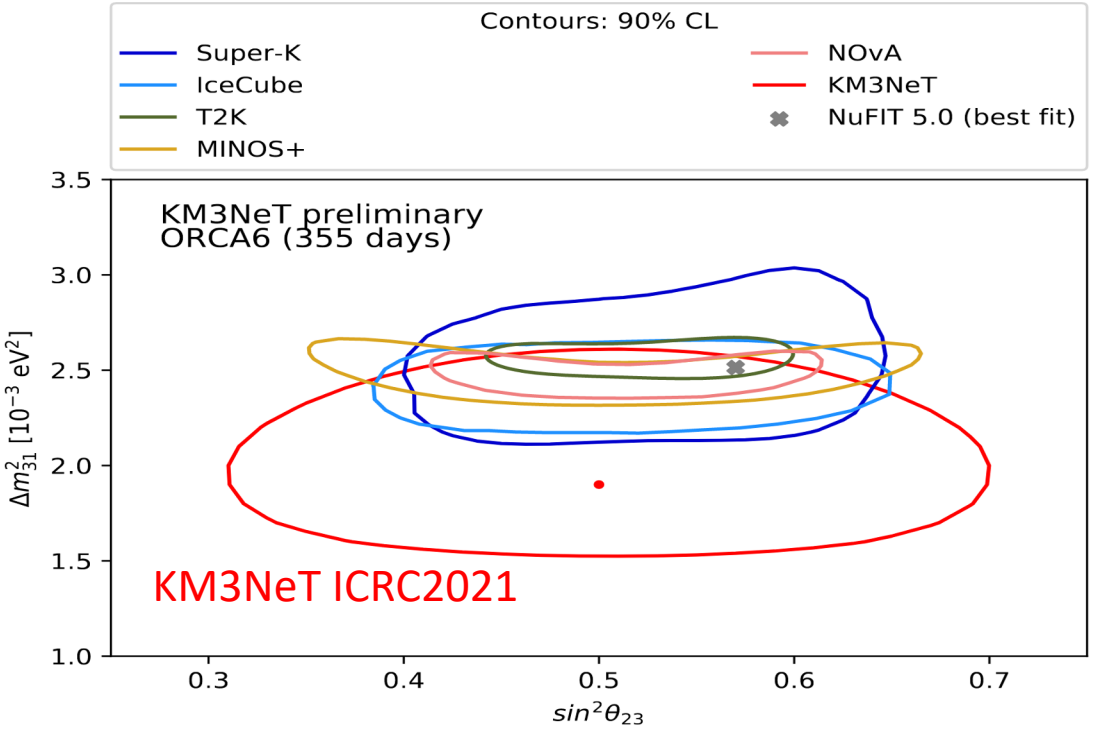


Oscillation signature:
Deficit at hgh L/E values

Oscillation parameter fit



KM3NeT/ORCA oscillation analysis

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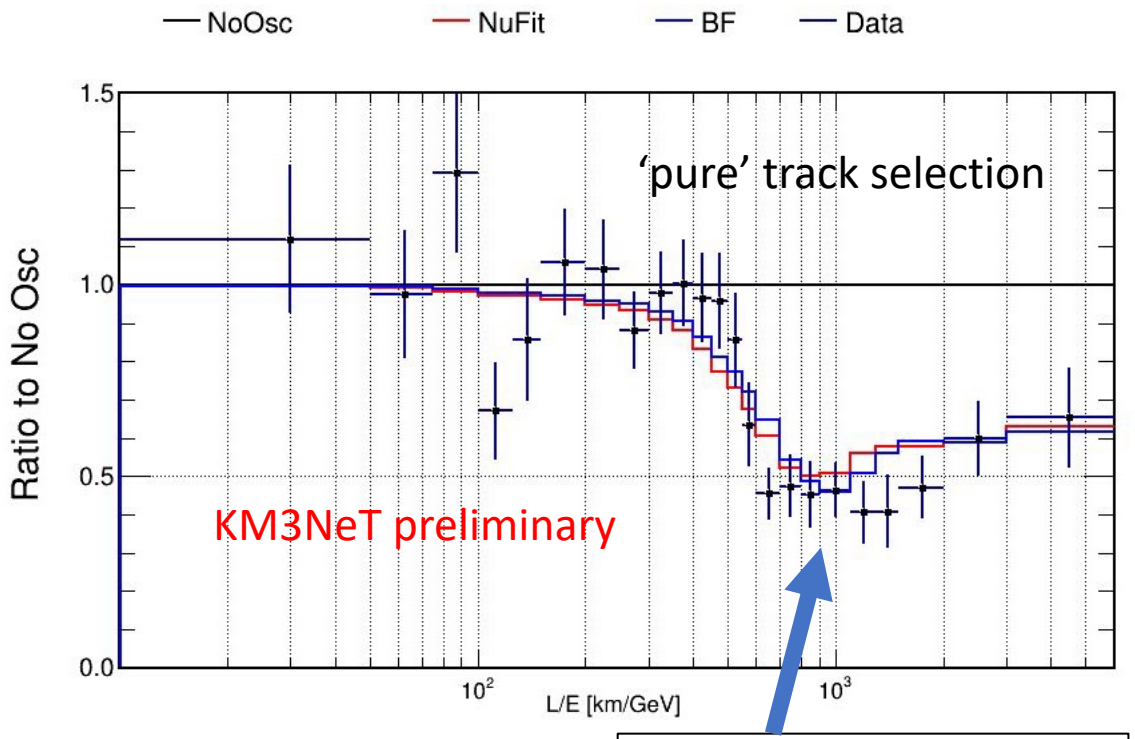

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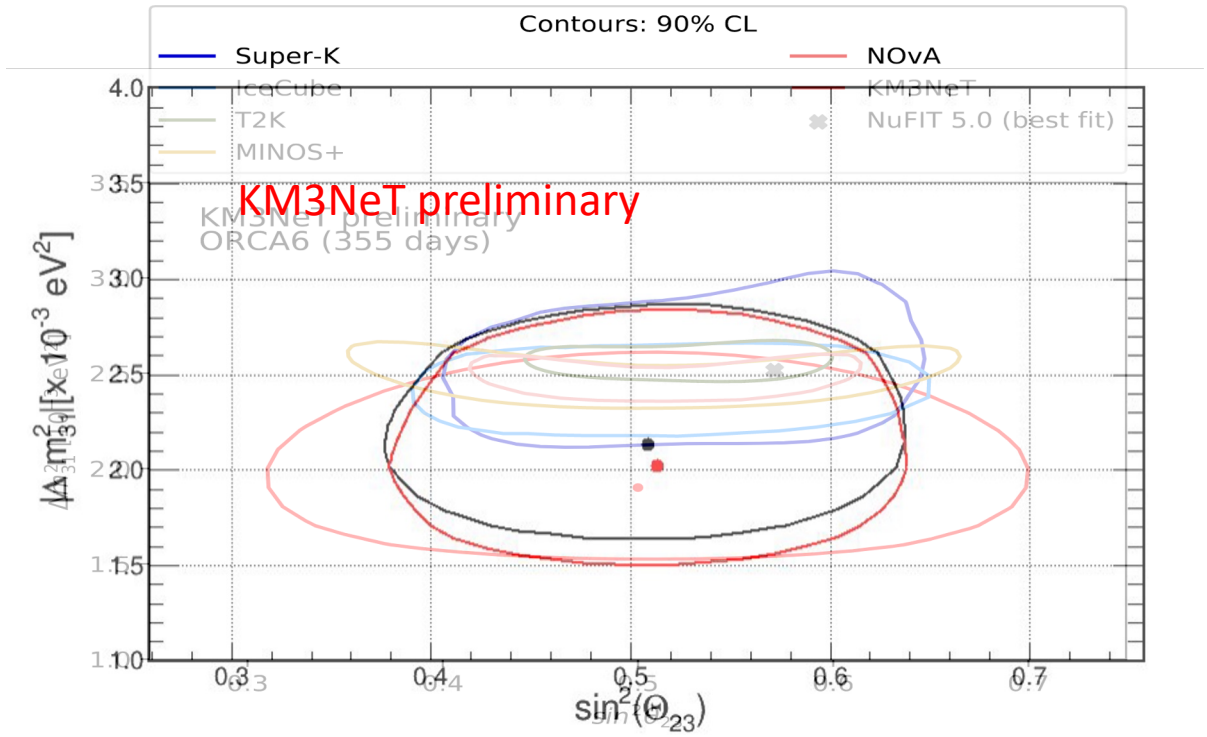
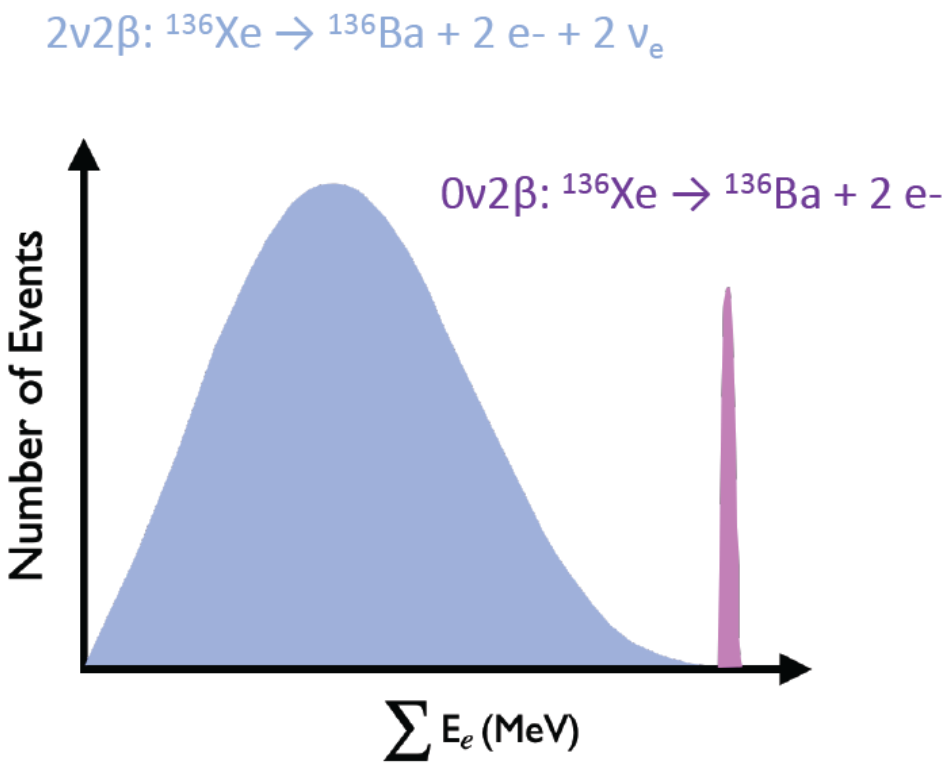
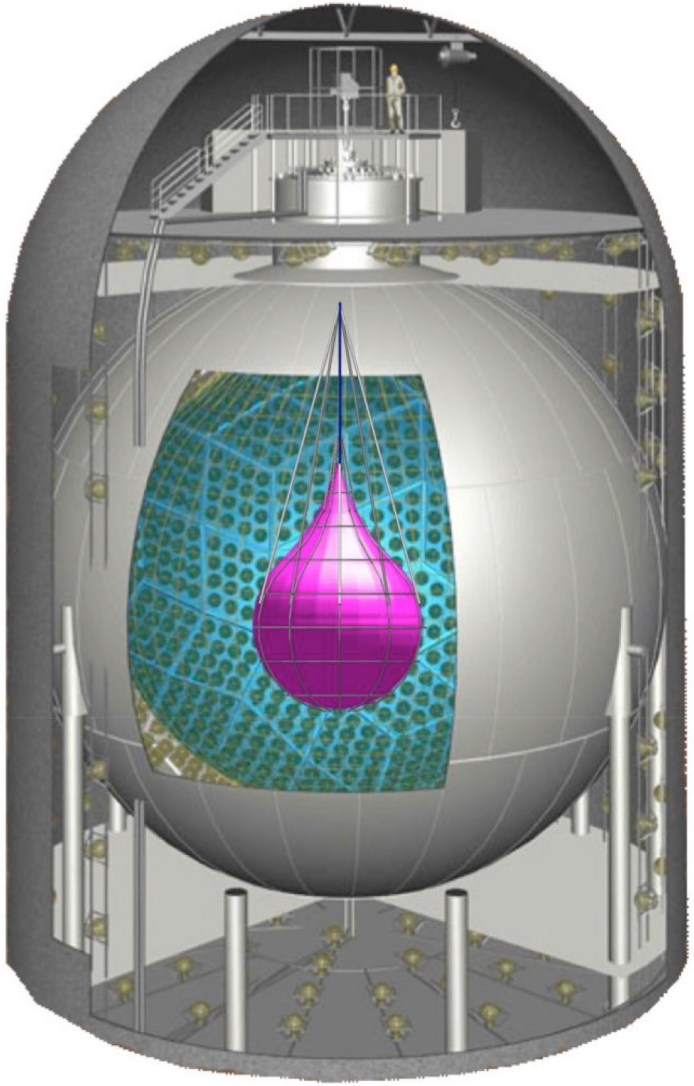


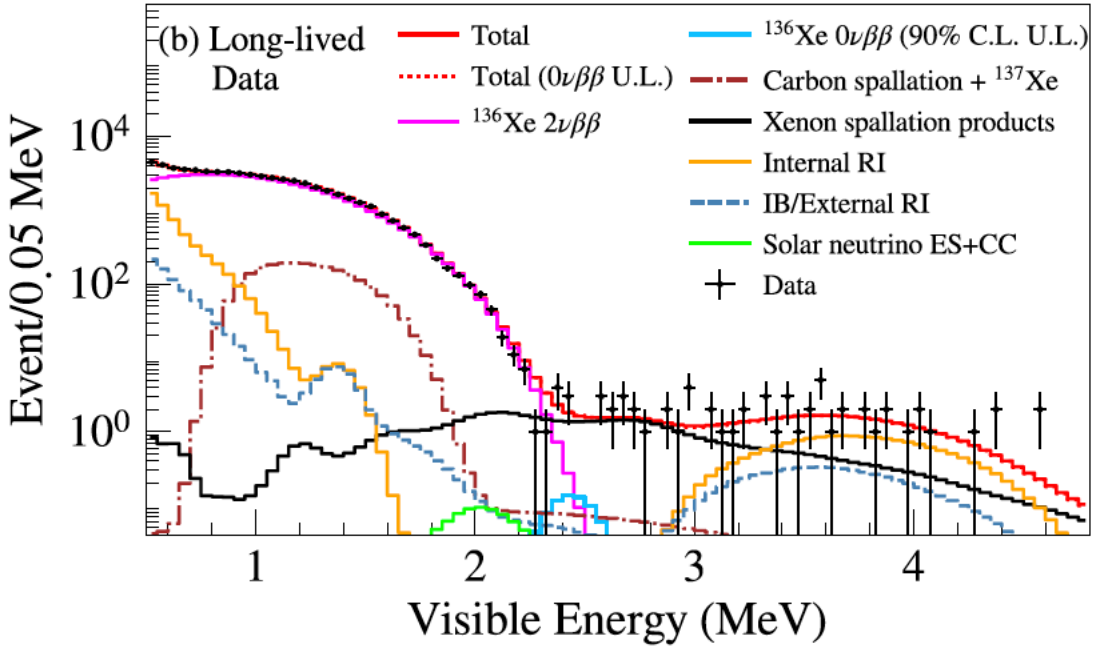
Neutrinoless double beta decay in KAMLAND-Zen

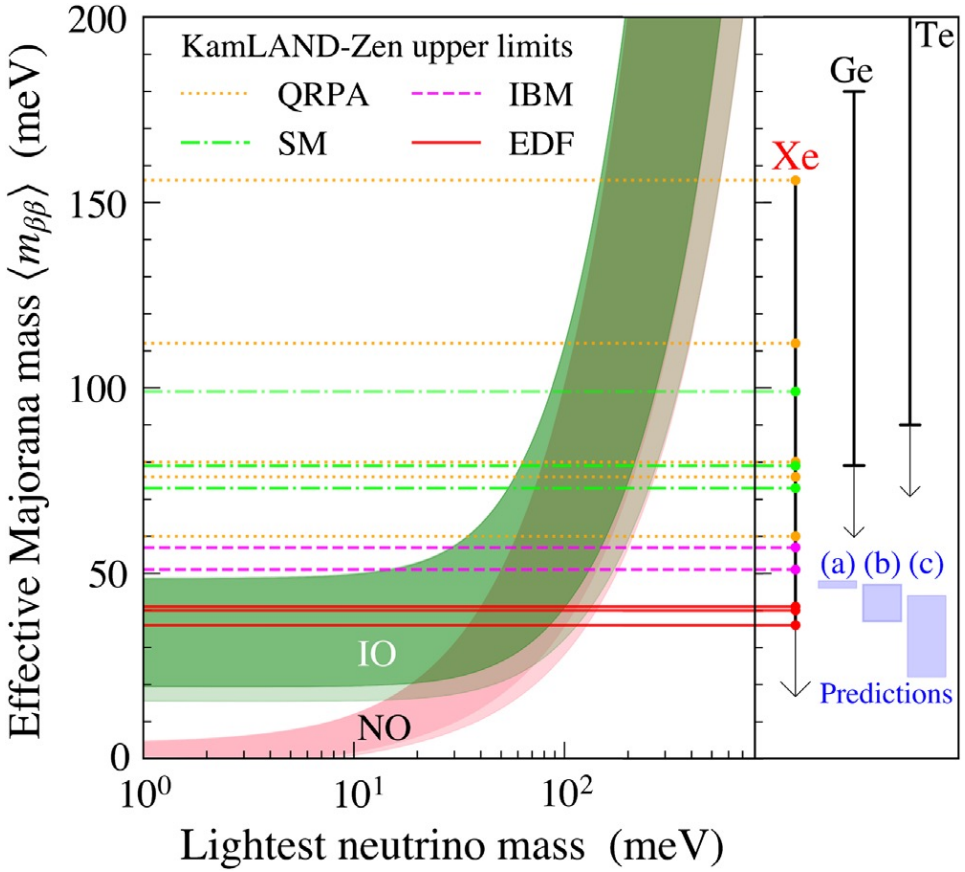




Probe Majorana character/mass of neutrino

Neutrinoless double beta decay in KAMLAND-Zen



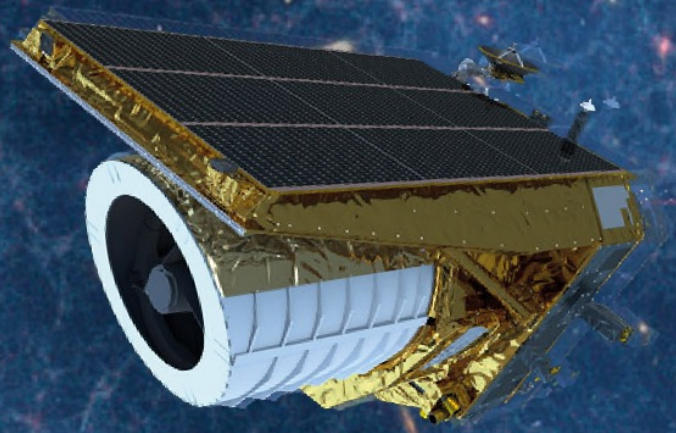


- Limits close to range expected for inverted ordering
- Improvements can help constraining ordering

Physical Review Letters **130**, *051801 (2023)*

EUCLID satellite

Launch planned 1 July 2023!

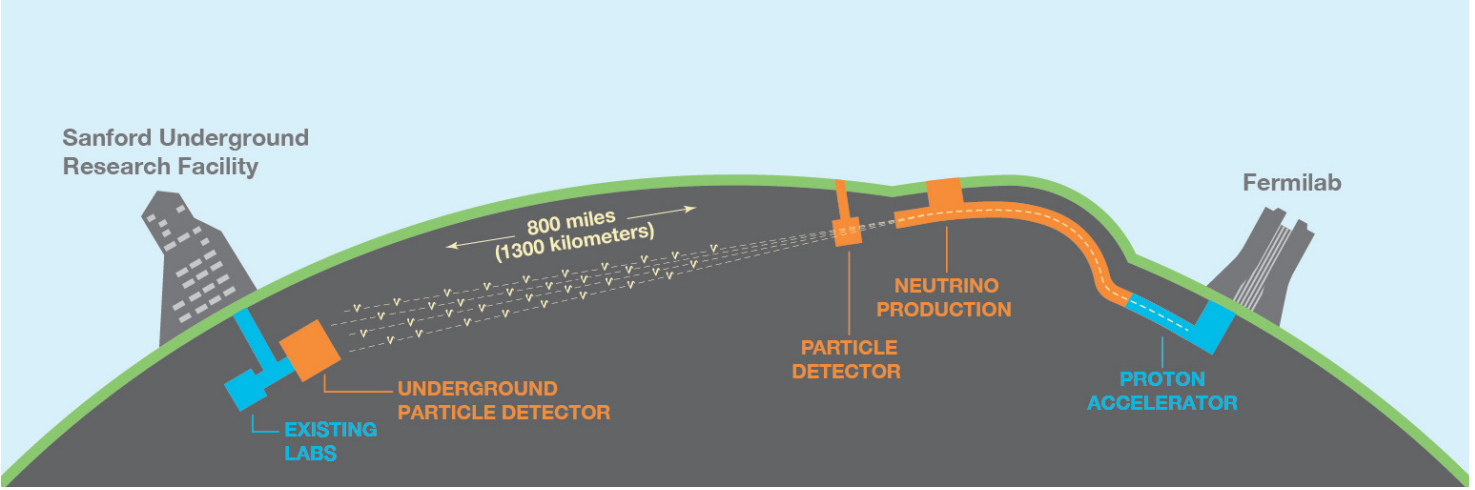


Power spectrum of structure sensitive to neutrino mass

=> Constraint on sum of neutrino masses
Expected error on sum of masses <30meV

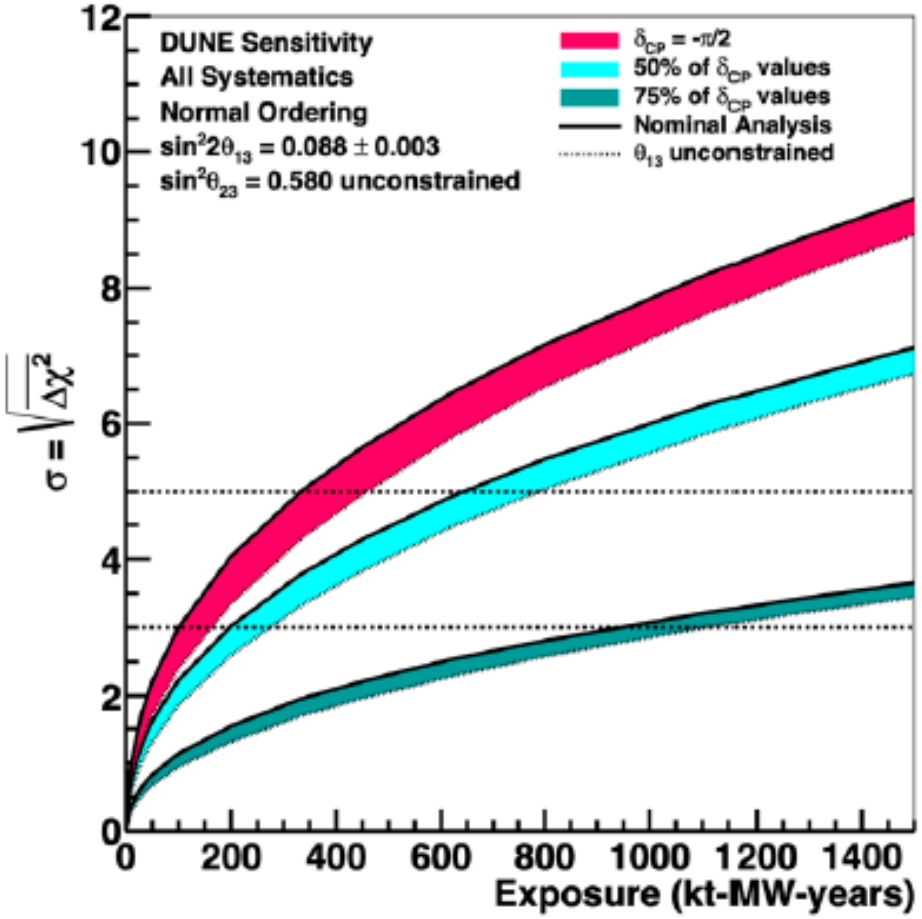
=> Interesting constraint also for mass ordering

DUNE



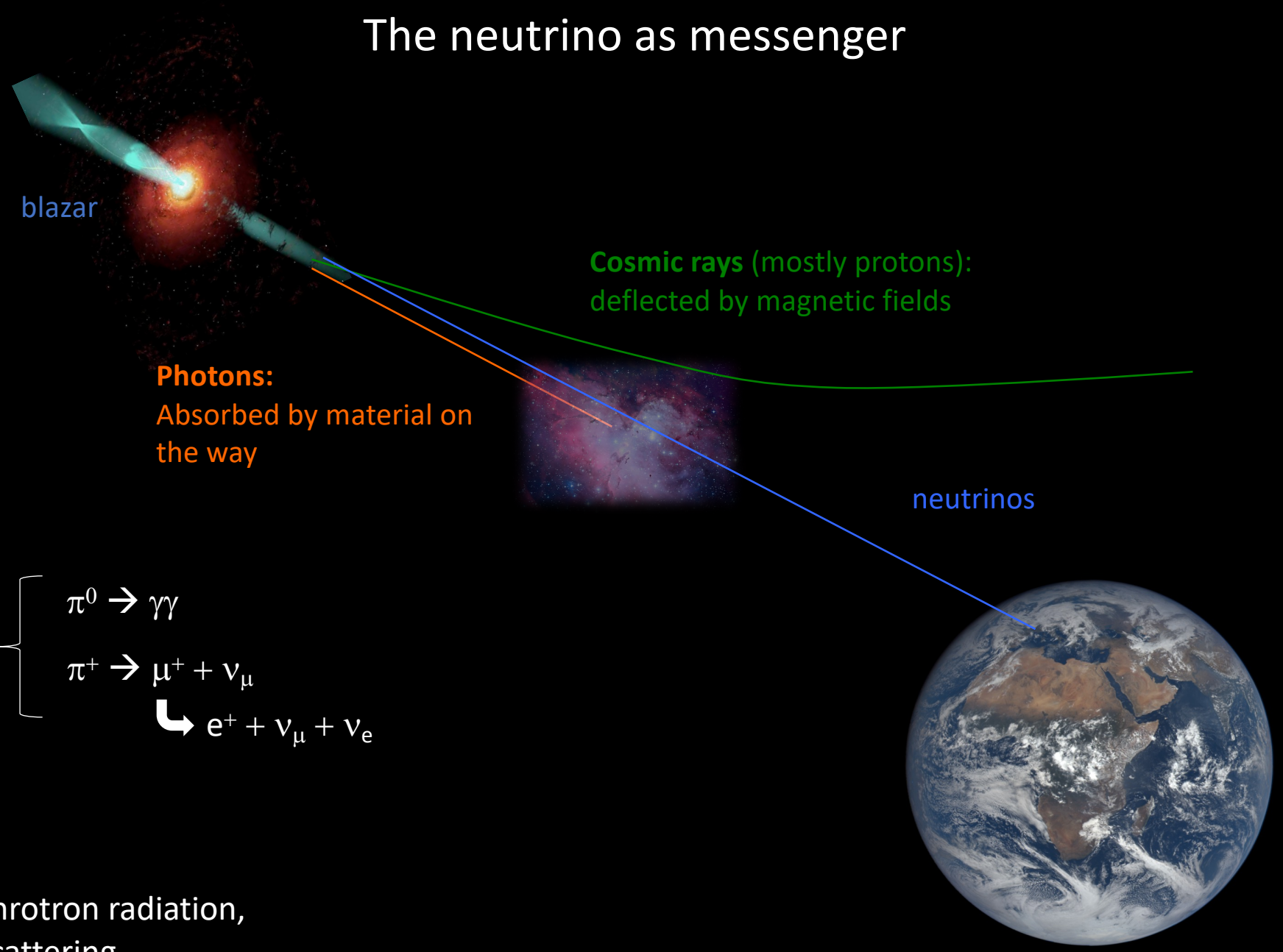
- Wide-band beam long baseline oscillation experiment.
- Far detector: 2 x 17.5 kton Liquid Argon TPC (phase 1).
- Phase 2: 20 kton more, possibly different design.
- Near Detector, several technologies.
- First far detector module 2028, beam 2030?

CP-phase sensitivity



EPJ C80 (2020) 978

The neutrino as messenger



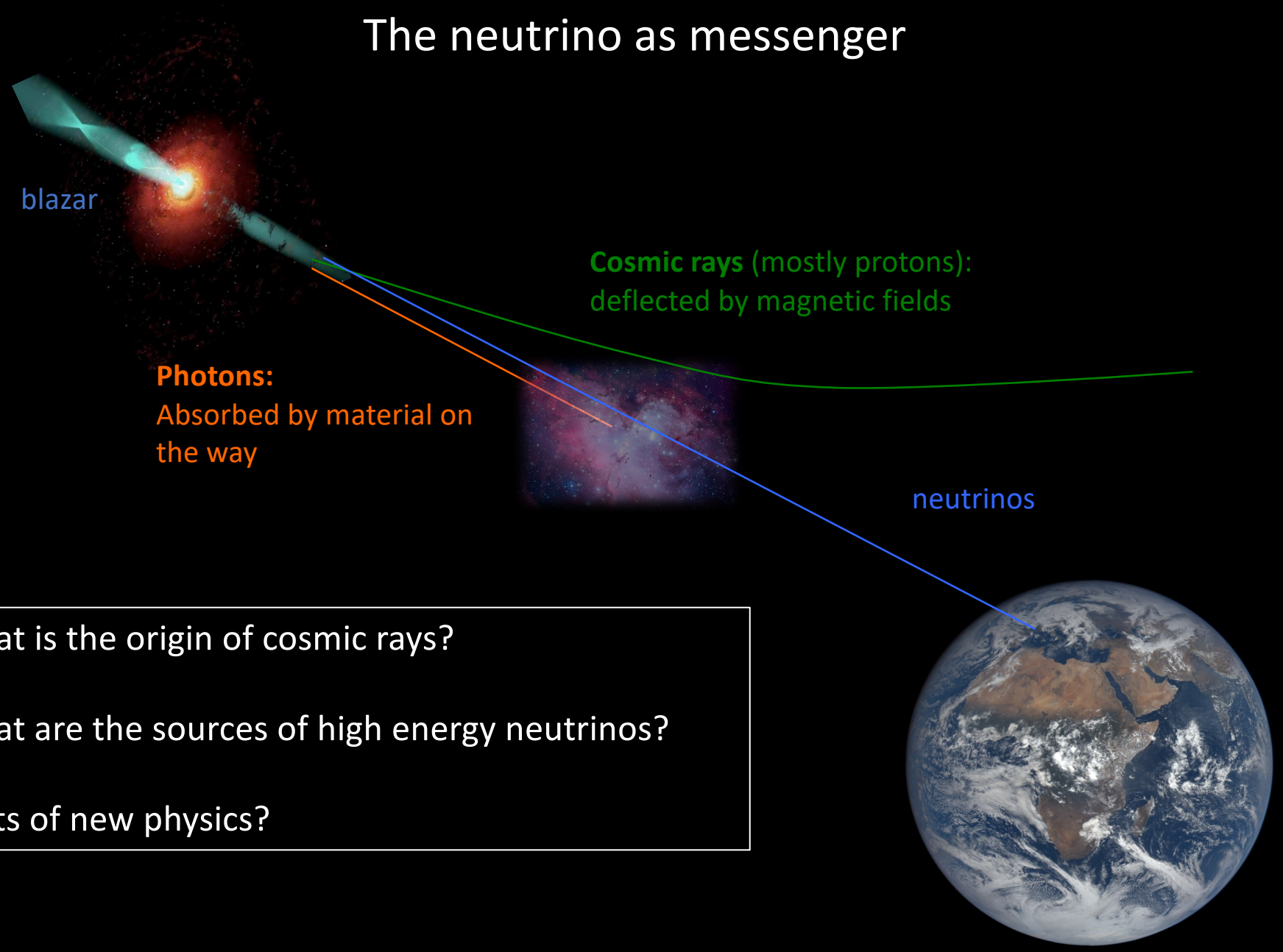
Hadronic scenario:

$$p + p/\gamma \;\text{--->}\; X + \begin{cases} \pi^0 \rightarrow \gamma\gamma \\ \pi^+ \rightarrow \mu^+ + \nu_\mu \\ \quad \hookrightarrow e^+ + \nu_\mu + \nu_e \end{cases}$$

Leptonic scenario:
Photons from synchrotron radiation,
inverse Compton scattering,
no associated neutrinos

Credit: Marscheret al., Wolfgang Steffen, Cosmovision,
NRAO/AUI/NSF, DSCOVR:EPIC/NASA

The neutrino as messenger



What is the origin of cosmic rays?

What are the sources of high energy neutrinos?

Hints of new physics?

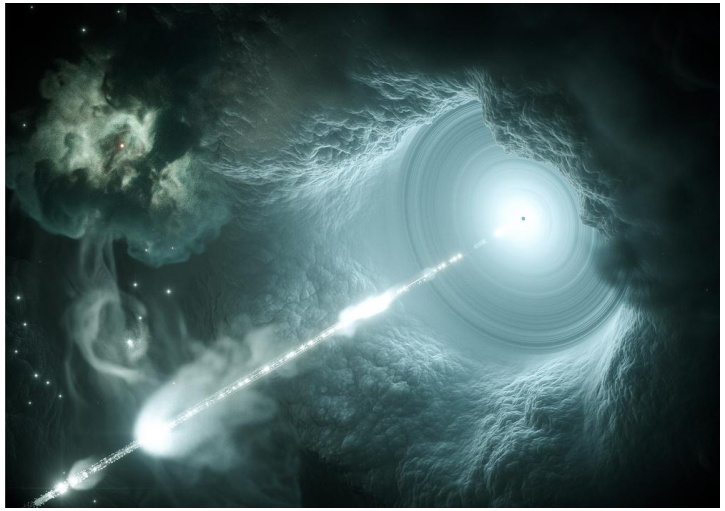
Credit: Marscheret al., Wolfgang Steffen, Cosmovision,
NRAO/AUI/NSF, DSCOVR:EPIC/NASA

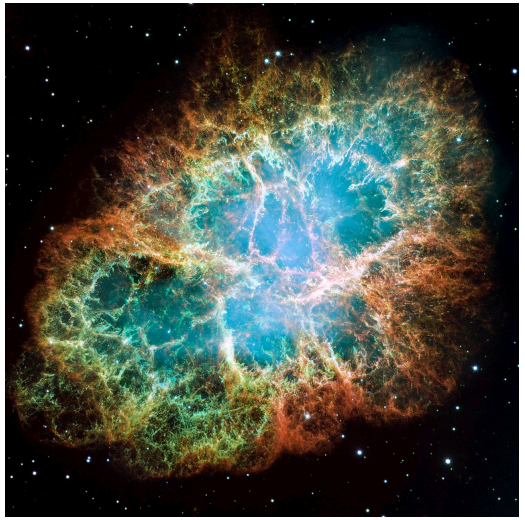
Cosmic neutrino source candidates: The usual suspects

Active Galactic Nuclei (AGN), Blazars, GRBs ,Starburst galaxies, TDEs, Supernova remnants, ….

- Best evidence so far for **blazar TXS0506**, **AGN NGC1068**,
  hints also for other neutrino correlations
  -> no clear picture yet

- Multi-messenger observation needed for understanding of production and acceleration
  -> separate unambigously leptonic/hadronic processes





New neutrino source detected by IceCube at 4.2σ

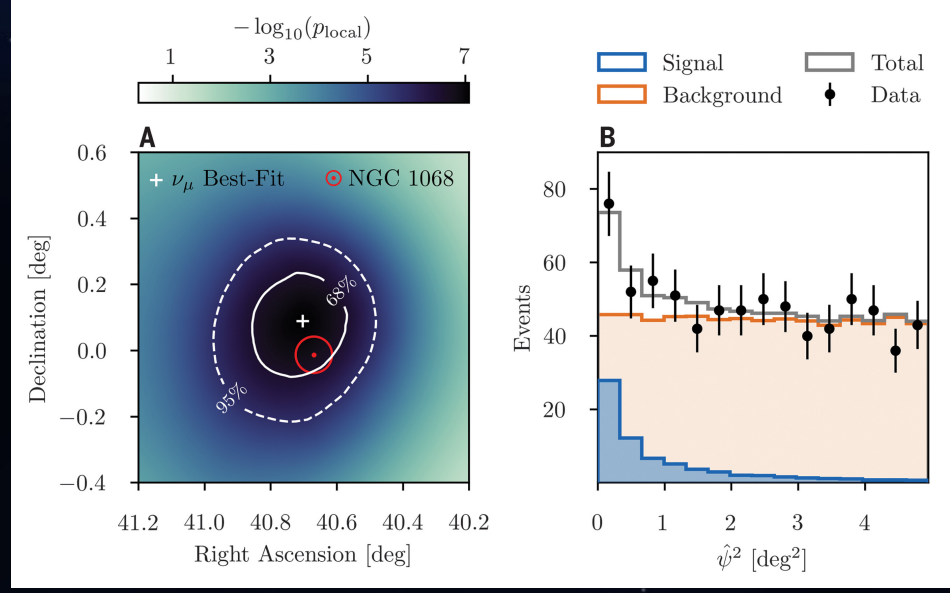


IMAGE CREDIT: NASA / ESA / A. VAN DER HOEVEN

NGC 1068
(Messier 77)
79+22(-20) events
Spectral index: γ=3.2±0.2

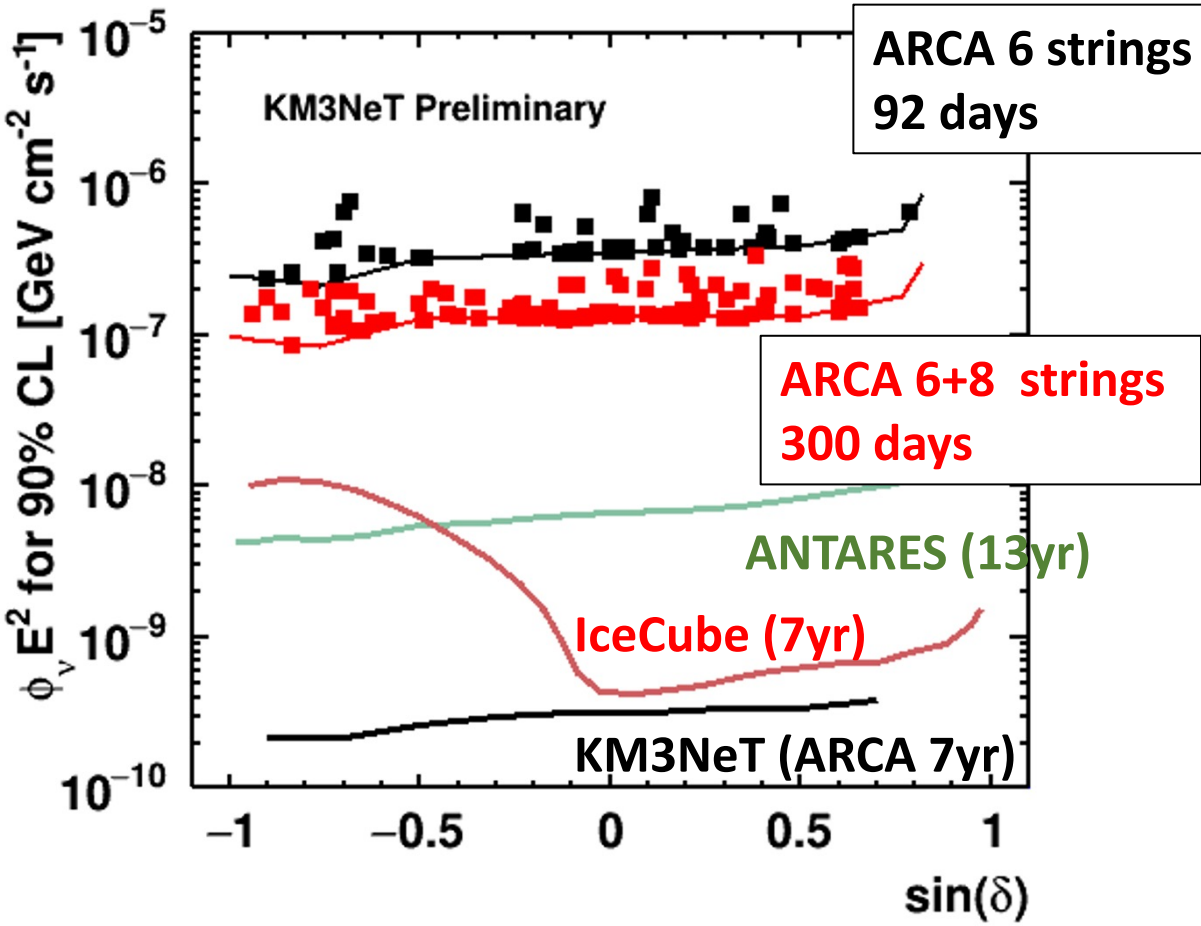
Cosmic point sources

KM3NeT/ARCA 6 + 8 strings, 300 days

New Unblinding:

- 100 source candidates
- No significant signal
- Brightest source: IC443 (Supernovae remnant)

Name	Decl	sin(decl)	TS	p-value (local)
IC 443	22°30'0.00"	0.38	1.08	.033
HESS J1614-518	-51°52'12.00"	-0.79	0.80	.053
Mkn 421	38°12'36.00"	0.62	0.47	.063
LHAASO J1908+06	6°20'60.00"	0.11	0.51	.066
J0927+3902	39°2'24.00"	0.63	0.33	.079



Probing potential neutrino sources

-> Future sensitivity sufficient to confirm/reject current hints (e.g. NGC 1068)

Unique prospects for Southern Hemisphere

ANTARES follow-up of potential neutrino flares found by IceCube

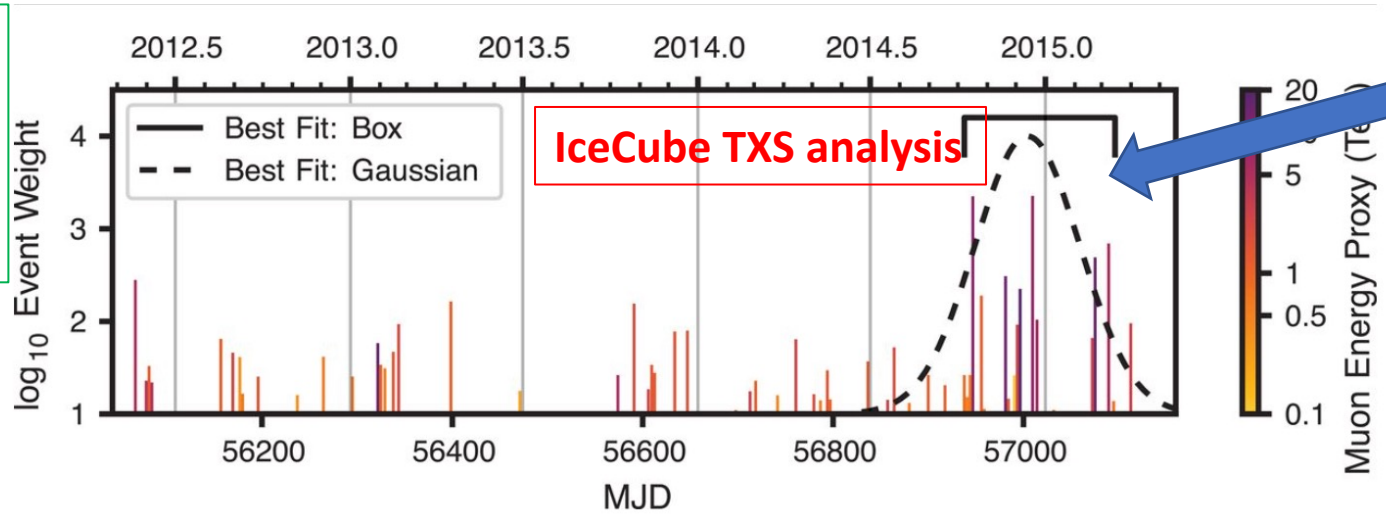
New unblinding

Source	dec RA. [deg]	Duration [days]	Signal fitted	P-value	σ	UL 90% [1/GeVcm2s]
NGC 598	(30.62 23.52)	67	1.67	$2.65\ 10^{-2}$	2.21	$1.53\ 10^{-5}$
TXS 0506+055	(5.70 77.35)	208	0.86	$3.13\ 10^{-2}$	2.15	$7.43\ 10^{-6}$
PKS 1502+106	(10.50 226.1)	45	1.26	$3.78\ 10^{-2}$	2.07	$3.56\ 10^{-5}$
B3 0609+413	(41.47. 93.22)	328	0.36	$9.63\ 10^{-2}$	1.66	$3.29\ 10^{-6}$

Of 34 potentially flaring sources in ANTARES FoV
4 with >1.6σ signal

TXS0506/PKS1502+106:
Among most significant in IceCube paper.
(2.3σ and 2.93σ)

TXS0506
Blazar with suspected neutrino emission



ANTARES neutrino candidate observed during flaring
TXS0506 also
2nd best source
In ANTARES PS search

Cosmic Neutrinos

Discovery of astrophysical neutrino flux by IceCube

~3σ/~2σ confirmation from **GVD/ANTARES**

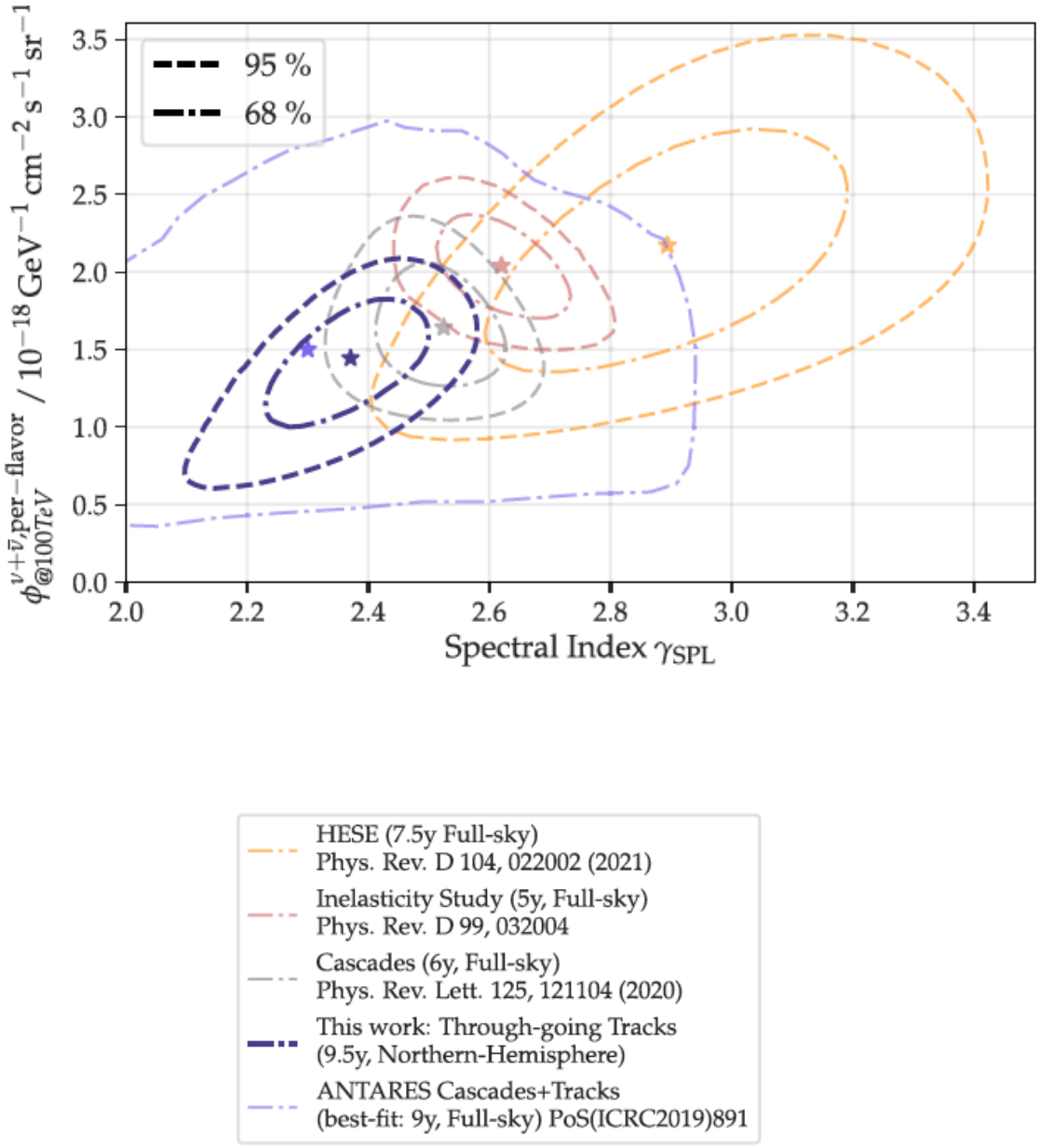
Where does it come from?

Differences in flux size and spectral index for different subsets of neutrinos?

To be taken into account:

- different energy ranges
- different parts of the sky probed
- different interaction and observation channels
- different. systematic uncertainties

KM3NeT will probe neutrino flux with complementary view



Abbasi et al , ApJ 928 50, 2022

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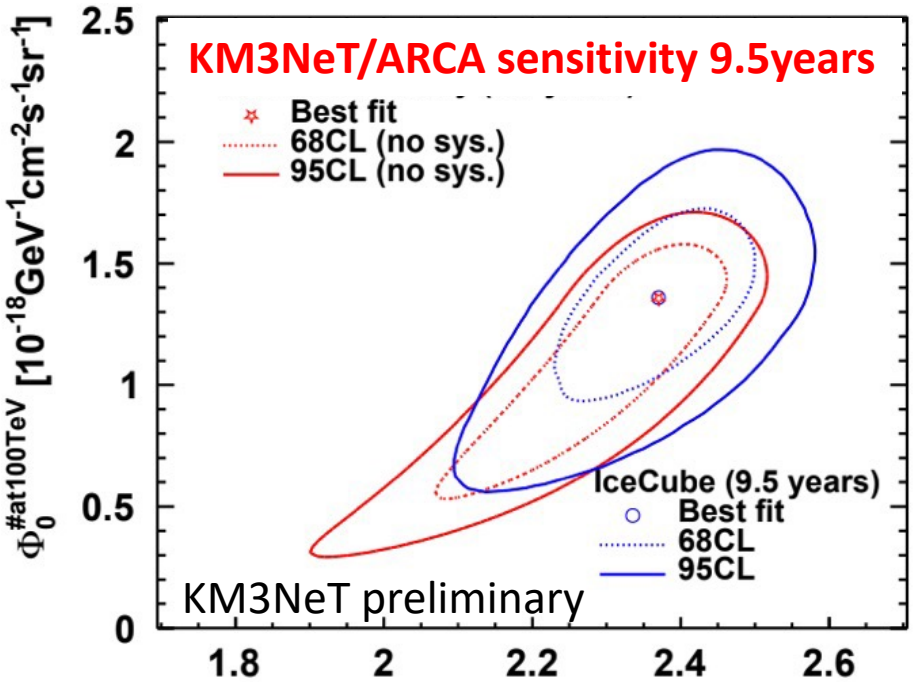
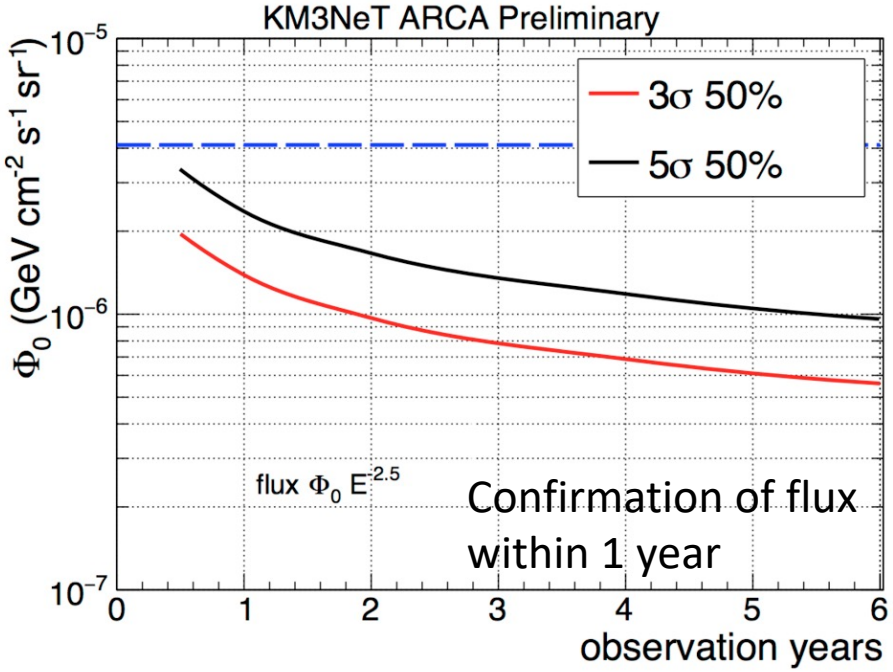


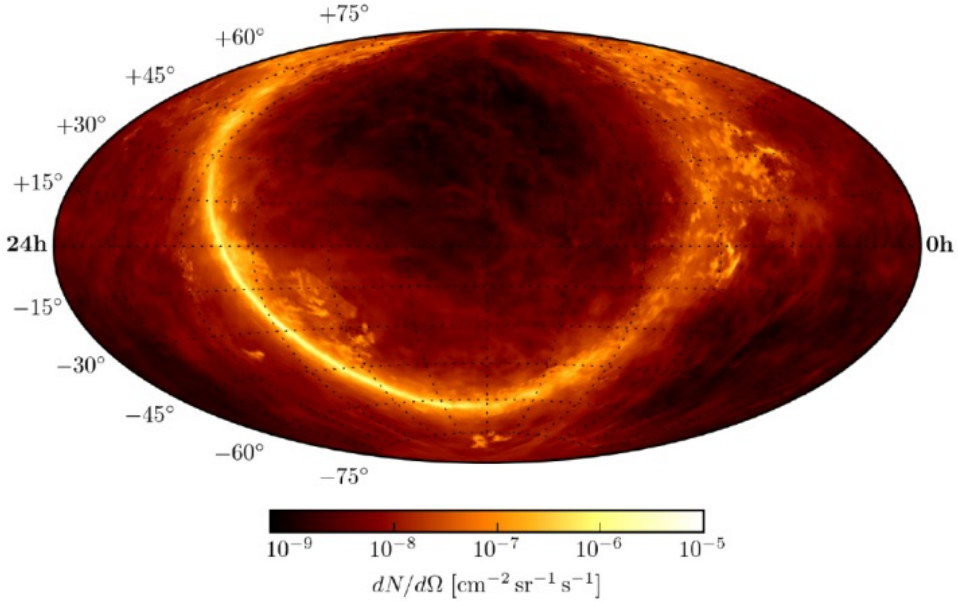


Galactic contribution

Neutrinos expected from Cosmic Ray interactions with interstellar gas in Galactic Plane

IceCube&ANTARES analyses show
excess in Galactic Plane

-> KM3NeT has direct view of Galactic Centrum
=> Measurement / constraint of flux



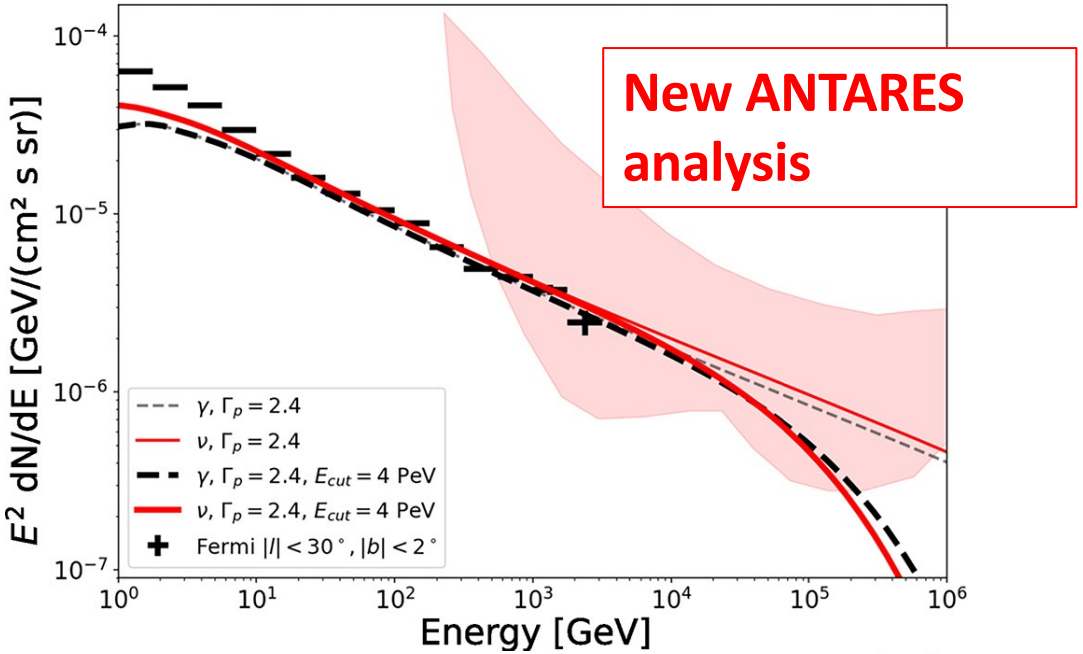
Model based on γ ray data

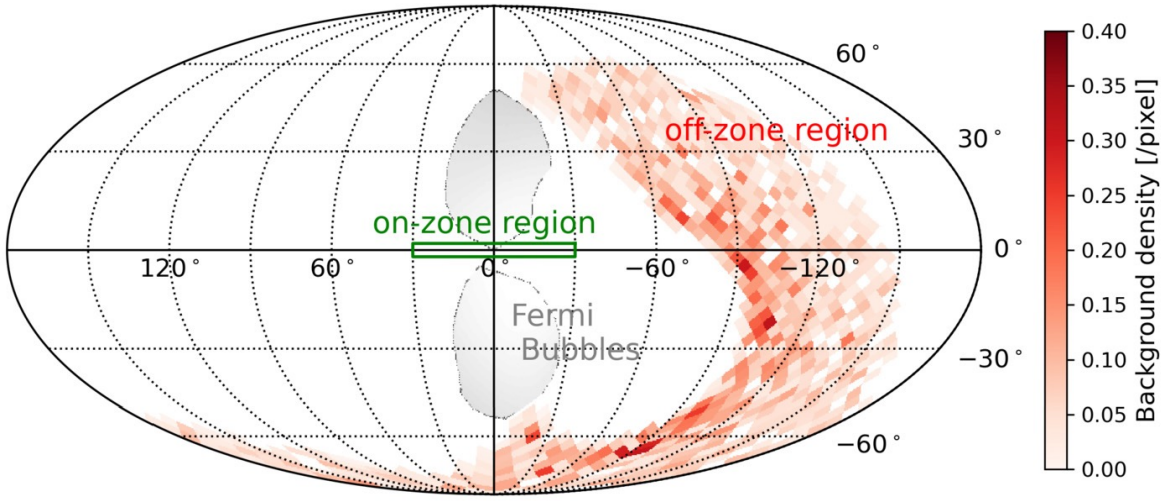
Galactic contribution

Neutrinos expected from Cosmic Ray interactions with interstellar gas in Galactic Plane

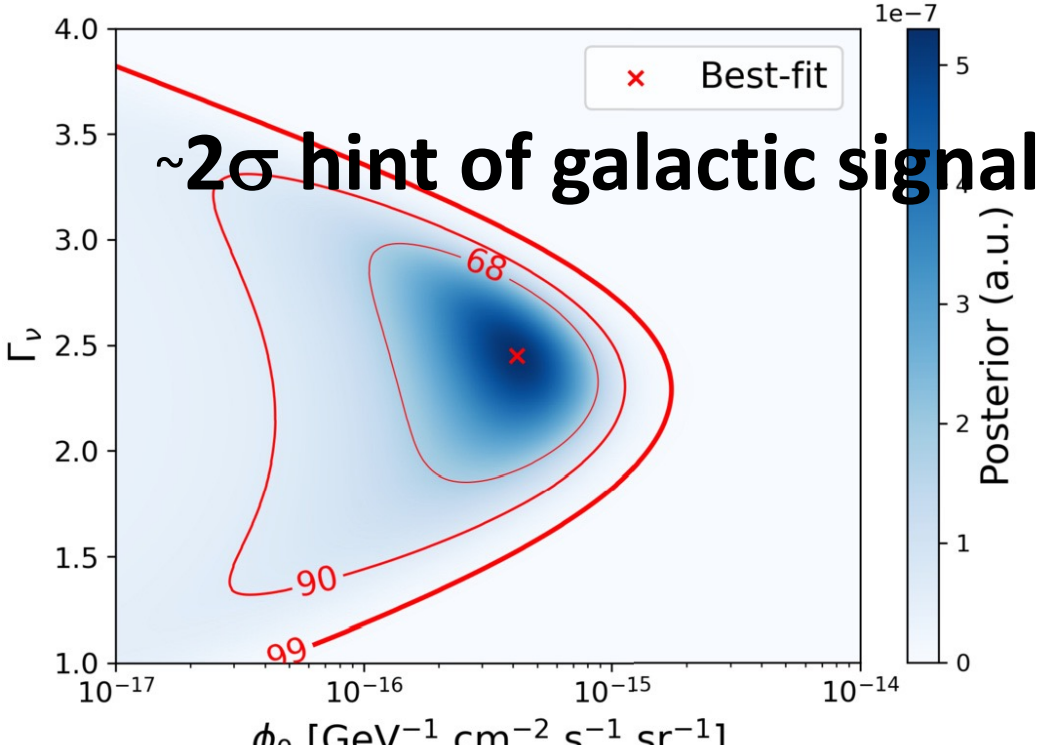
IceCube&ANTARES analyses show excess in Galactic Plane

-> KM3NeT has direct view of Galactic Centrum
=> Scrutinize galactic signal!

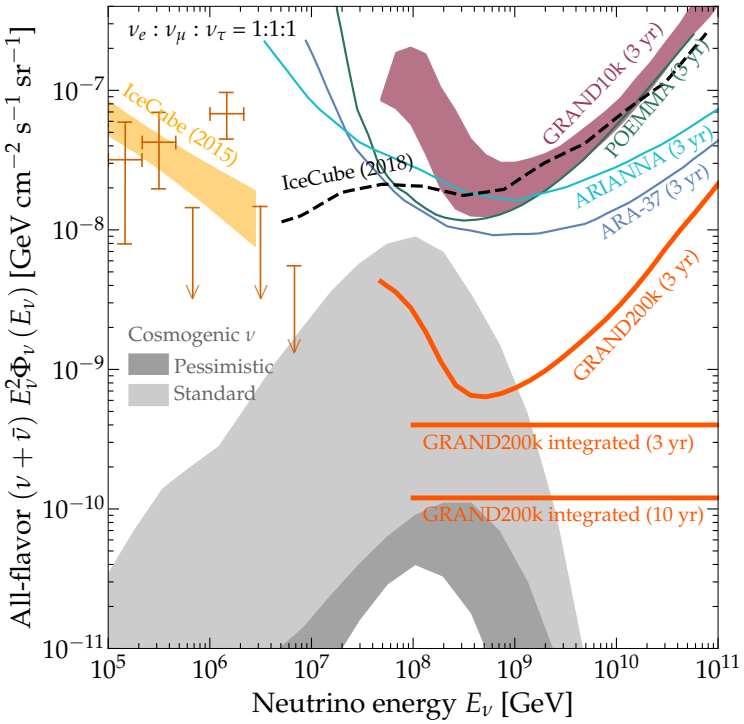


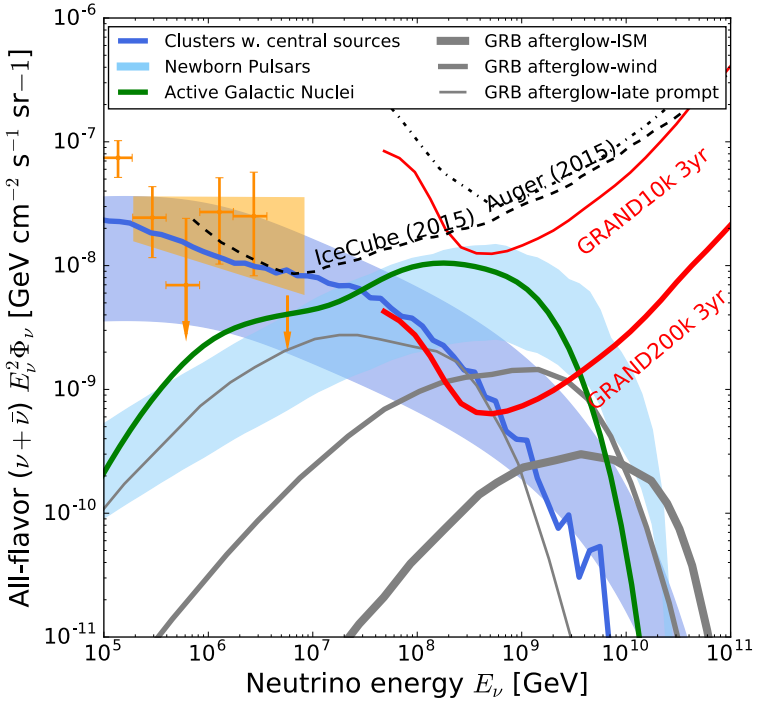


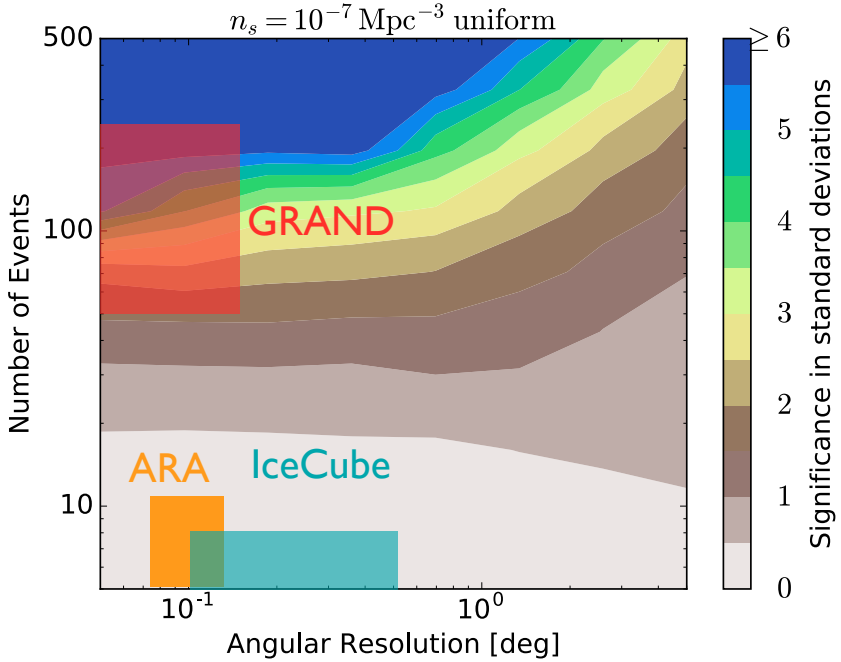
Physics Letters B
Volume 841, 10 June 2023, 137951



GRAND:
A multimessenger experiment focussed on neutrino sensitivity





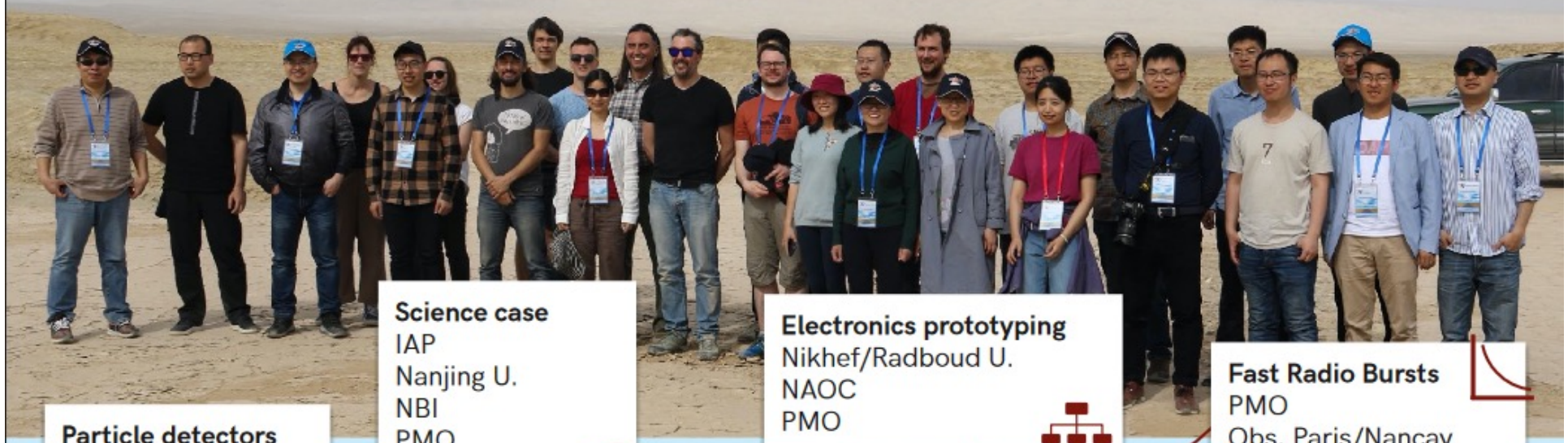


GRAND collaboration:
Sci. China Phys.Mech.Astron. 63 (2020) 1, 219501

GRAND will be located in many places around the world to cover 200000 km² in total

GRAND Today

~90 collaborators from 11 countries

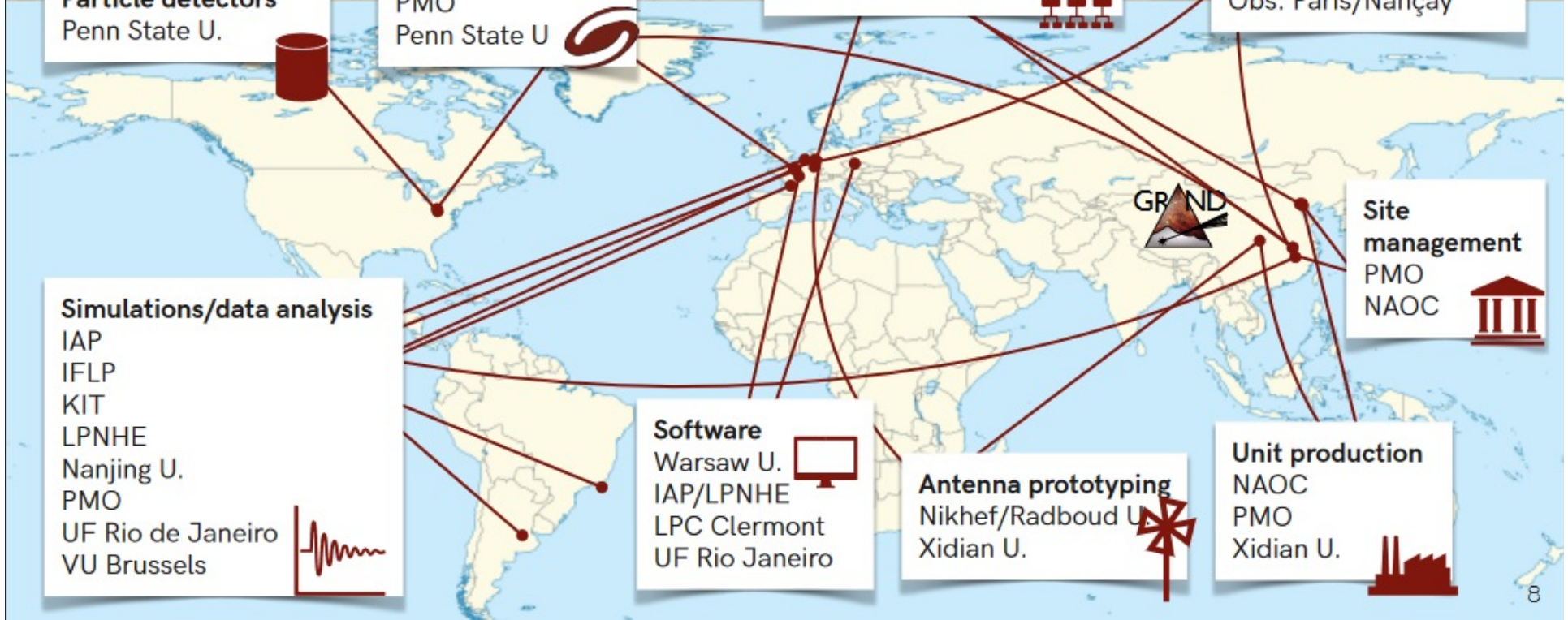


Science case
IAP
Nanjing U.
NBI
PMO
Penn State U

Electronics prototyping
Nikhef/Radboud U.
NAOC
PMO

Fast Radio Bursts
PMO
Obs. Paris/Nançay

Particle detectors
Penn State U.



Site management
PMO
NAOC

Simulations/data analysis
IAP
IFLP
KIT
LPNHE
Nanjing U.
PMO
UF Rio de Janeiro
VU Brussels

Software
Warsaw U.
IAP/LPNHE
LPC Clermont
UF Rio Janeiro

Antenna prototyping
Nikhef/Radboud U.
Xidian U.

Unit production
NAOC
PMO
Xidian U.

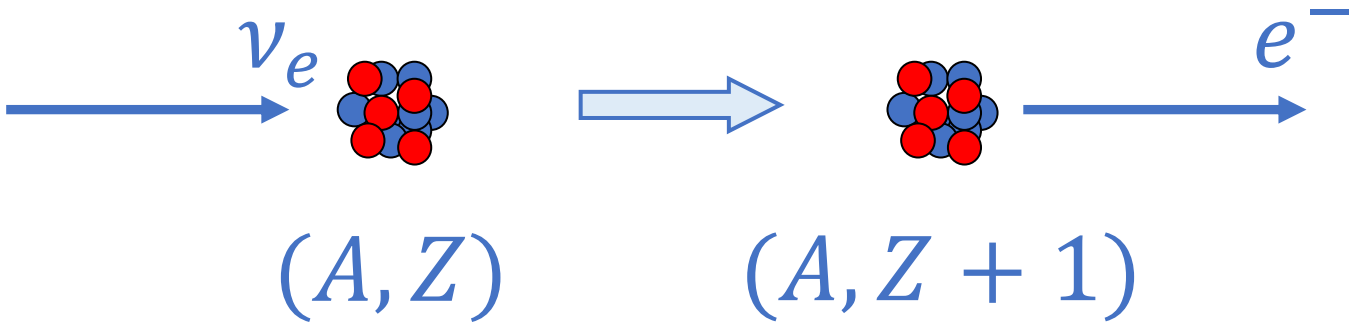
GRAND@Auger

GRAND in China

First prototypes are in the field and are being commissioned

Relic neutrinos

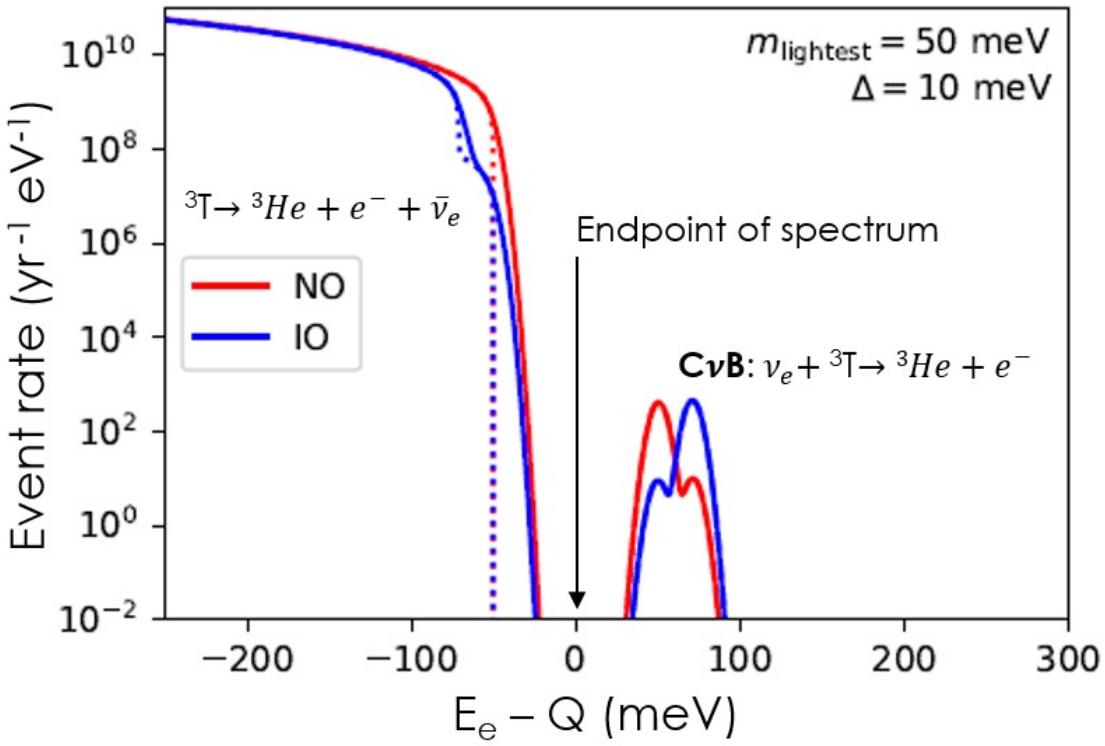
Abundant, but very low energy
-> hard to detect



Detection via inverse beta decay of tritium

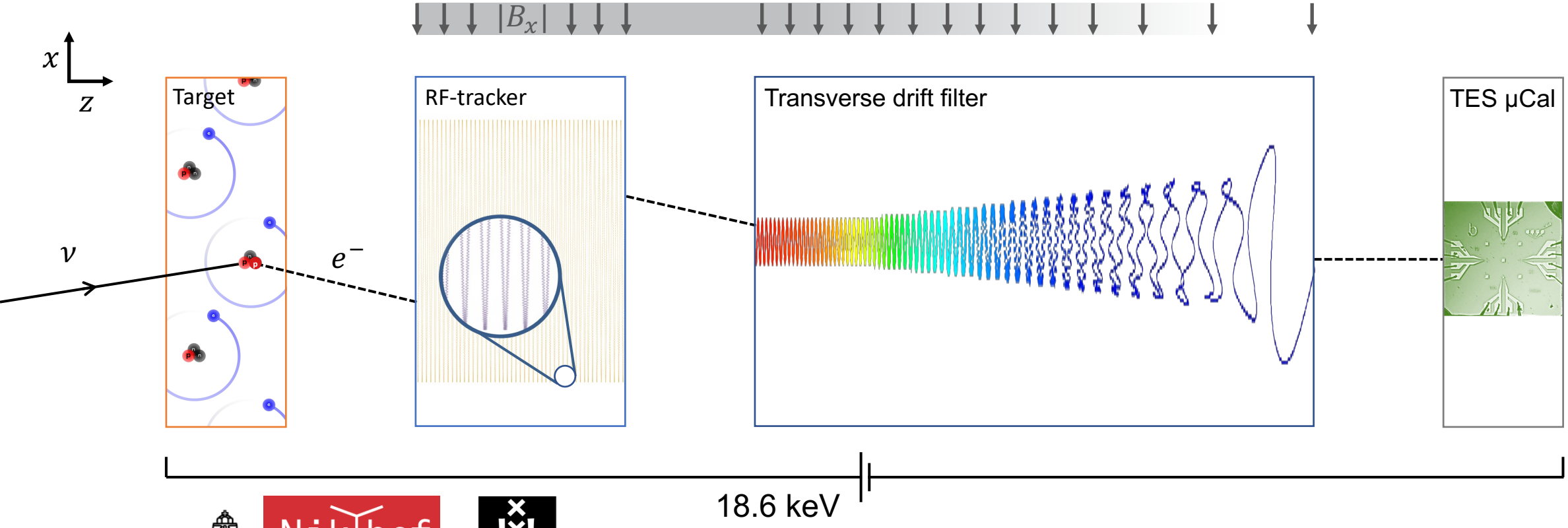
- High cross-section for neutrino capture
- **No energy threshold**
- Sizeable lifetime
- Low Q-value of 18.6 keV

- **Tritium beta decay ~10^{15} Bq/gram**



PTOLEMY

R&D at Nikhef, UvA, RU…… building prototypes

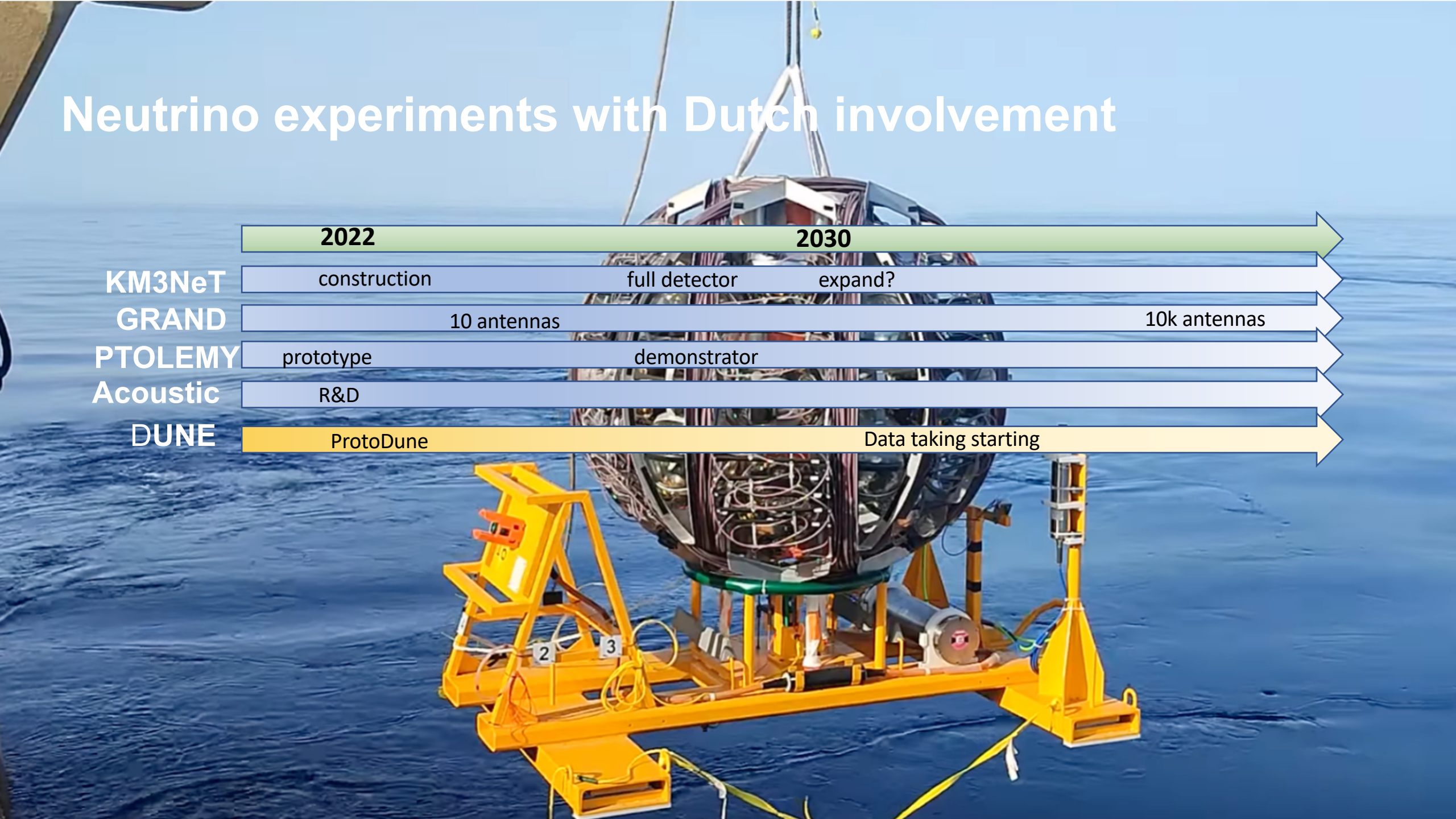


Radboud University

Nikhef

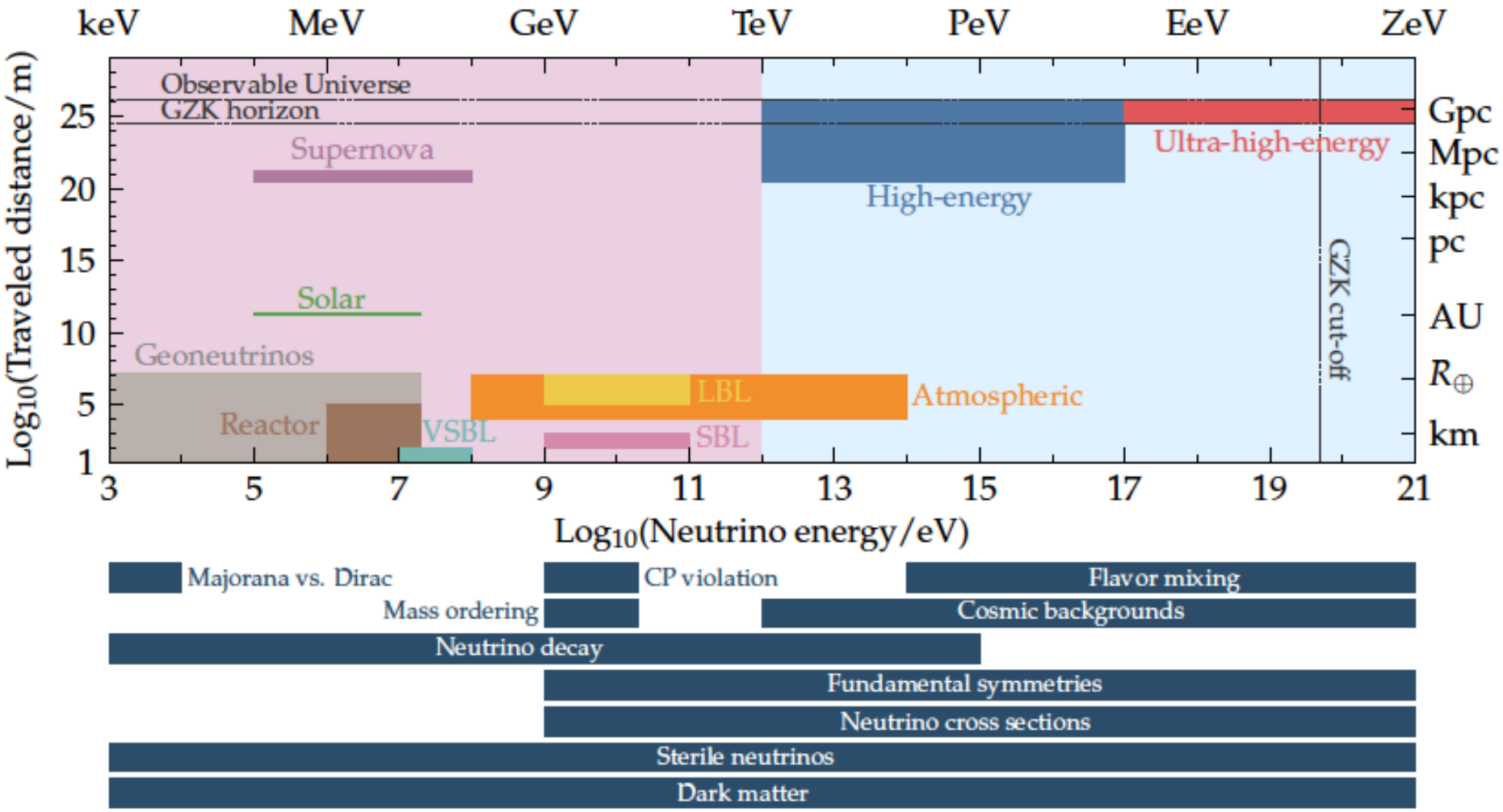
$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

Neutrino experiments with Dutch involvement



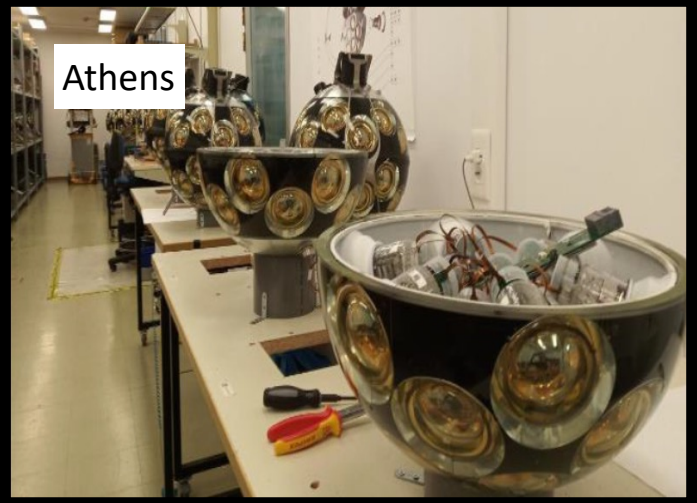
Backup

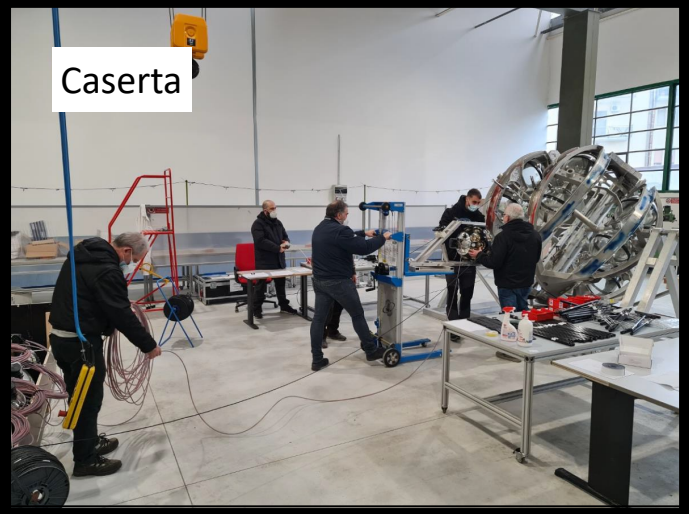
Aside from cosmic exploration also rich fundamental physics potential




Genova

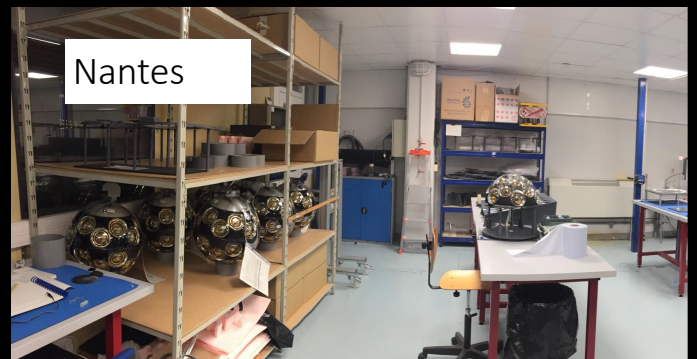

Catania


Athens


Caserta


Bologna


Erlangen

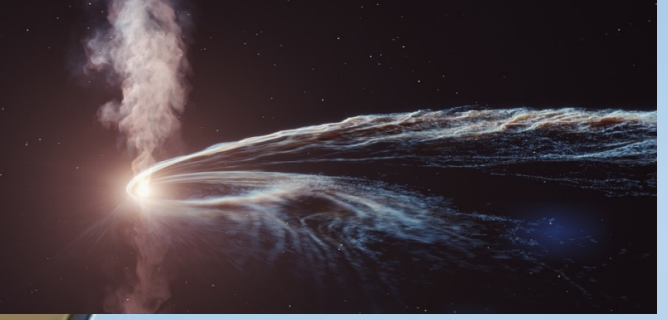

Nantes


Marseille

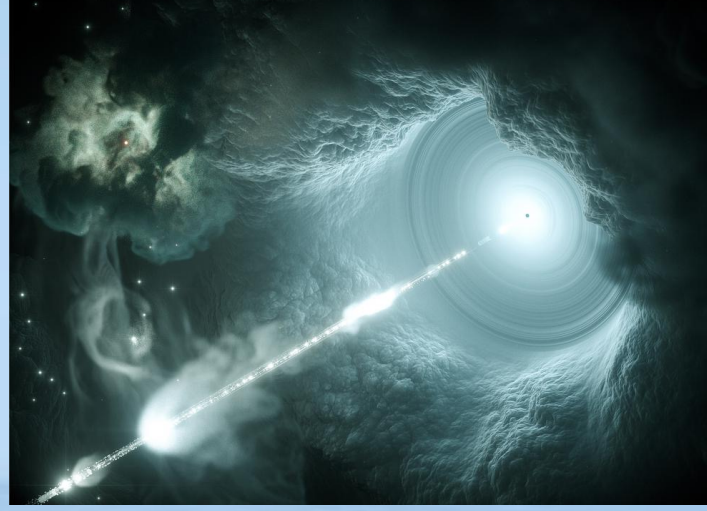

Strasbourg

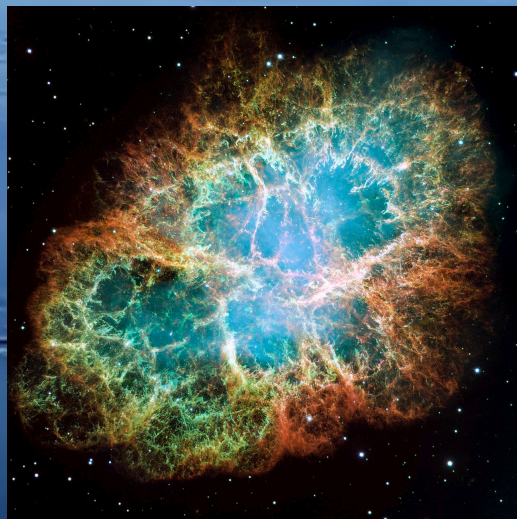
Detection Units in staging area @ Malta


KM3NeT
Opens a new window on our universe

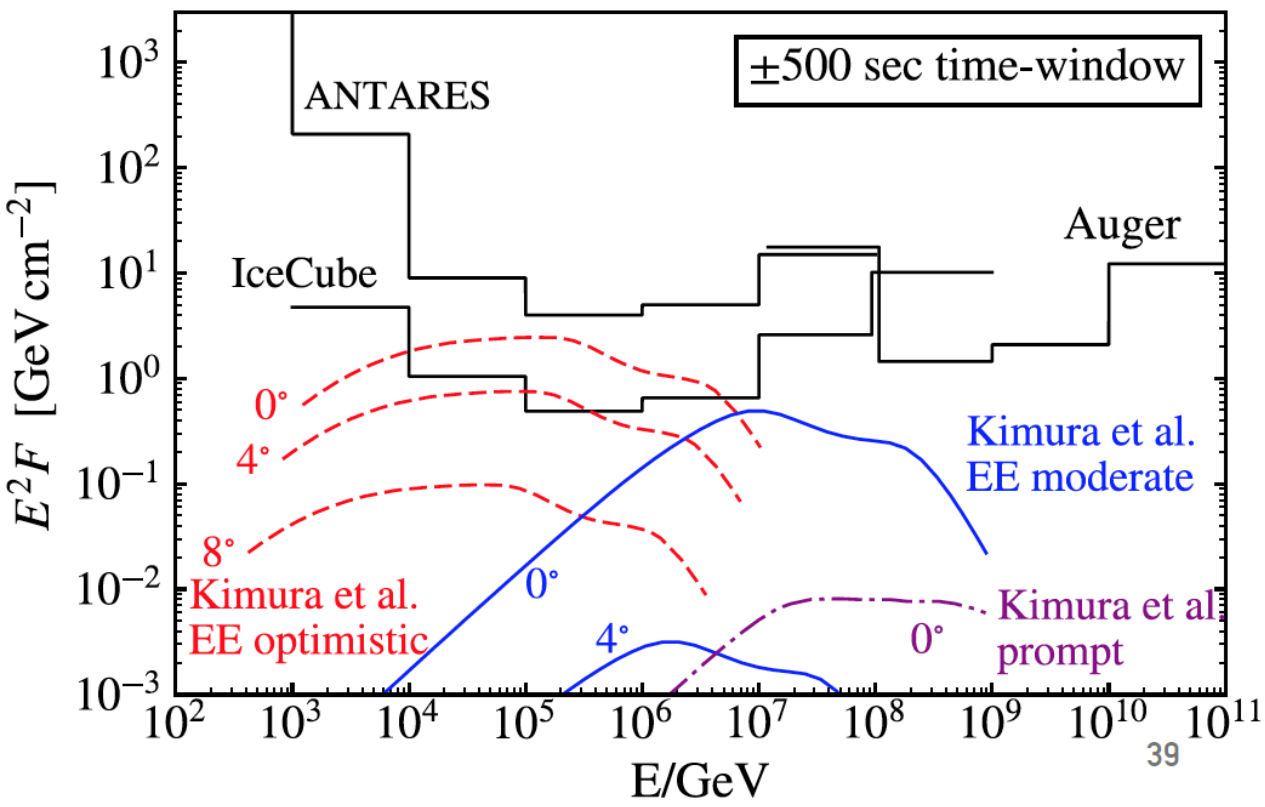


A decade of discoveries lies ahead!

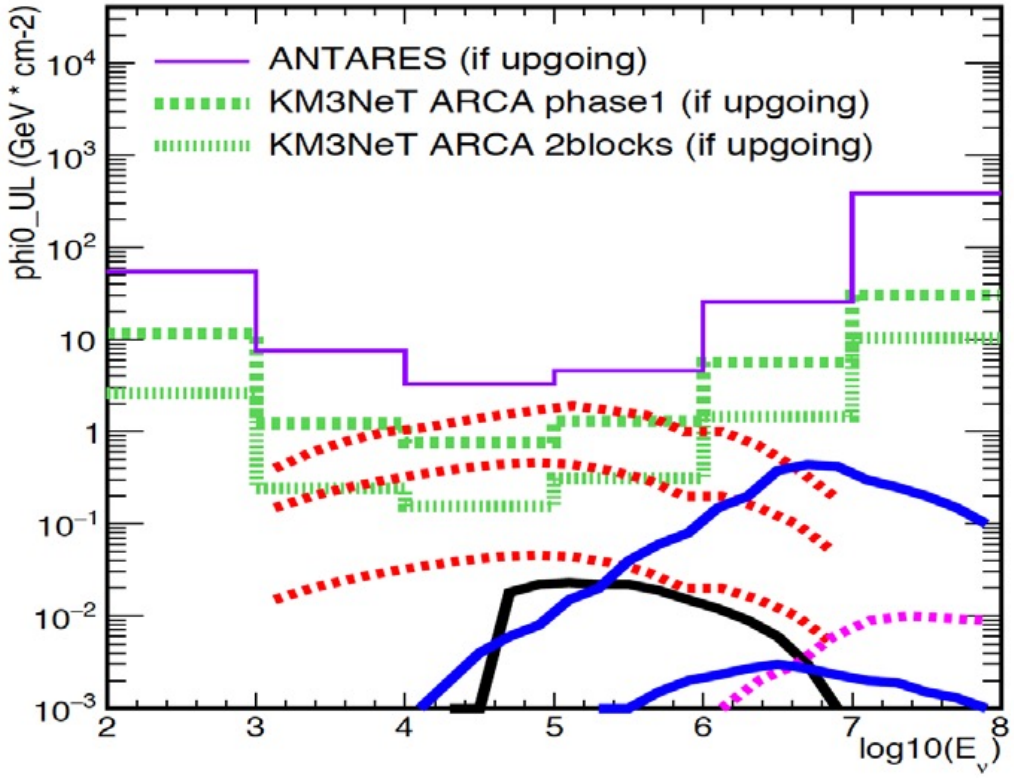




Models for neutrino fluence
from **GW170817 (binary neutron star merger)**
with measured upper limits by
Auger, IceCube, ANTARES



Expectation for **KM3NeT** sensitivity

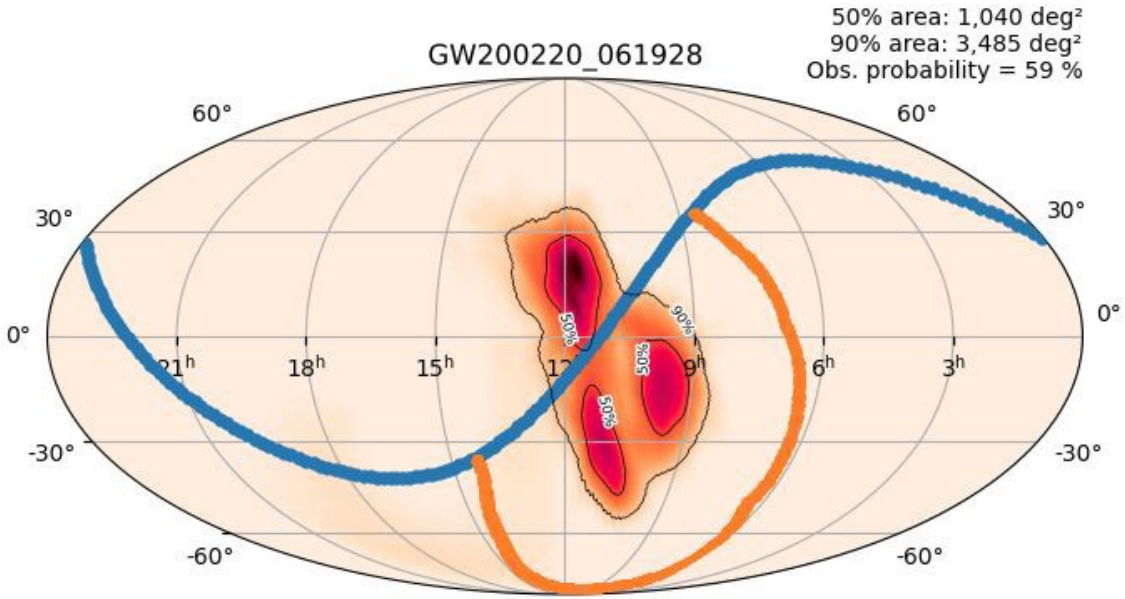


EPJ Web of Conferences **207**, 02009 (2019) *VLVnT-2018*

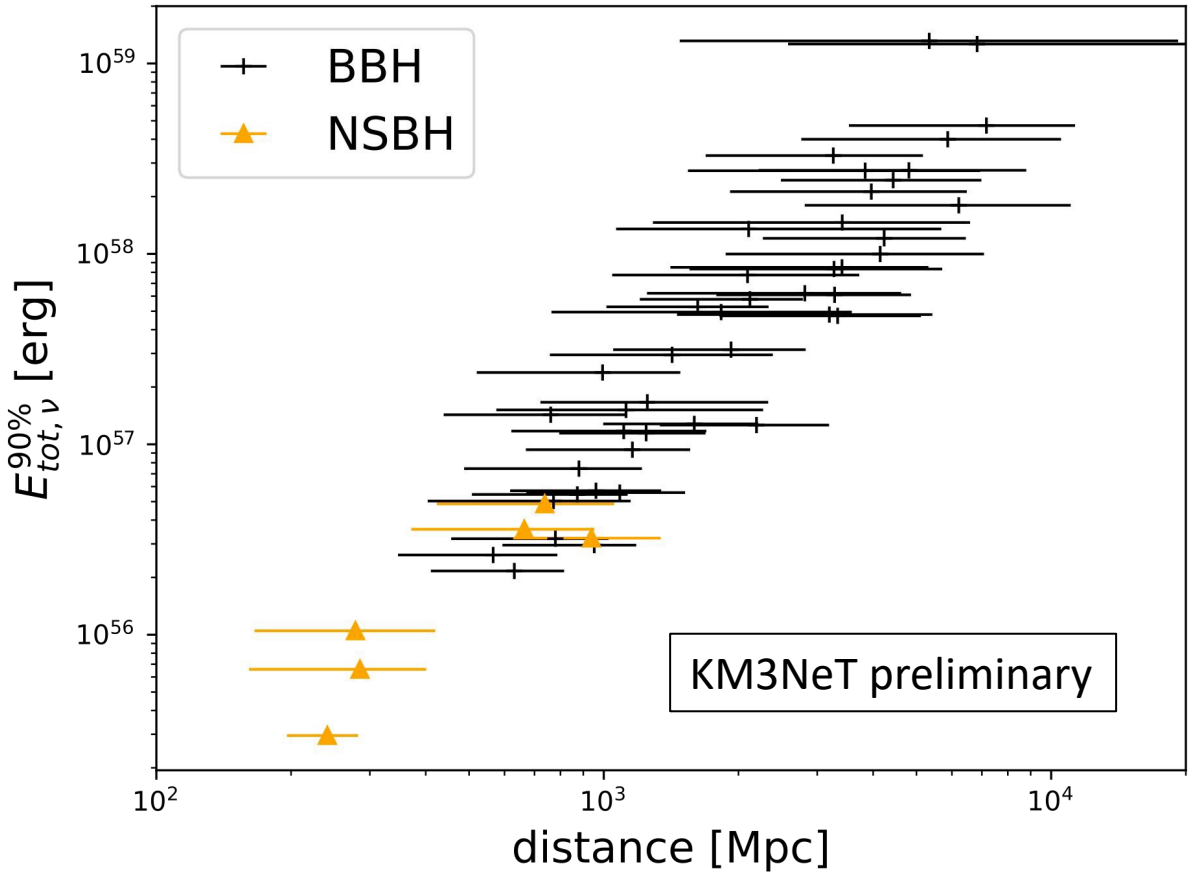
Transient sources

Results for KM3NeT/ORCA follow-up of 55 GW events in MeV and GeV-TeV

=> no significant correlation



Limits in GeV-TeV range



D. Dornic et al.
NEUTRINO 2022

Real-time follow-up with KM3NeT

Goals:

- Core-Collapse Supernova monitoring for prompt alerts
- Receive external electromagnetic / gravitational wave / neutrino alerts

  => search for correlated neutrinos
- Send all flavor, all-sky neutrino alerts (multiplets, HE) to external observatories for follow-up

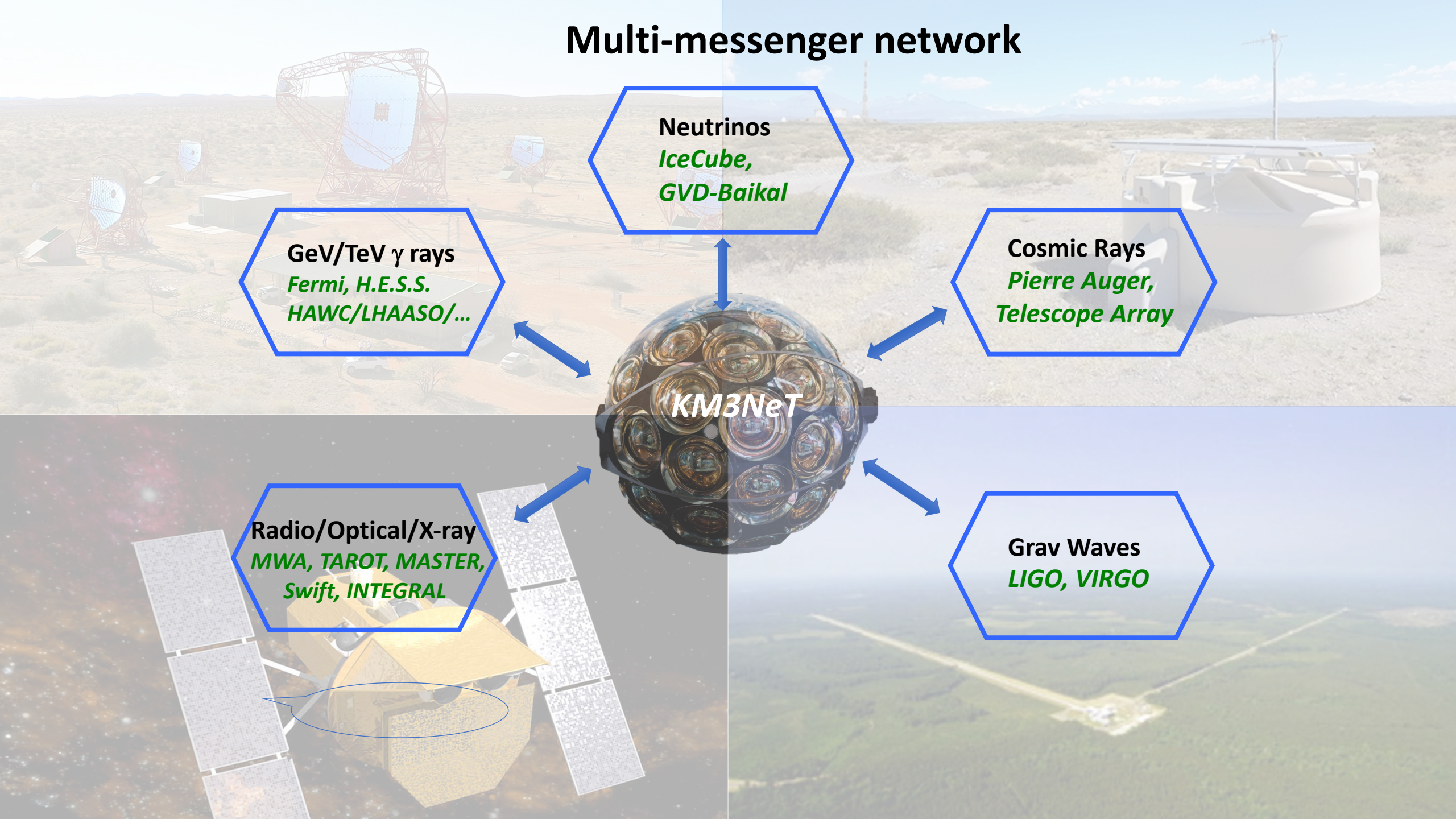
Correlation analyses:

- Two unmodeled **GWs** follow-ups with MeV neutrinos
  GCN Circulars 26249 and 26751
- Multiple correlation analyses **with IceCube neutrino** events associated with blazars,
  follow-up of PKS-0735+178 in ATeL #15290
- Search for coincident neutrinos at both MeV level and above GeV for **GRB221009A**, no neutrinos found (*GCN Circular 32741*) refined offline analyses underway

Fermi data
>10 hours **γ-rays**>100MeV
~20 degree wide image

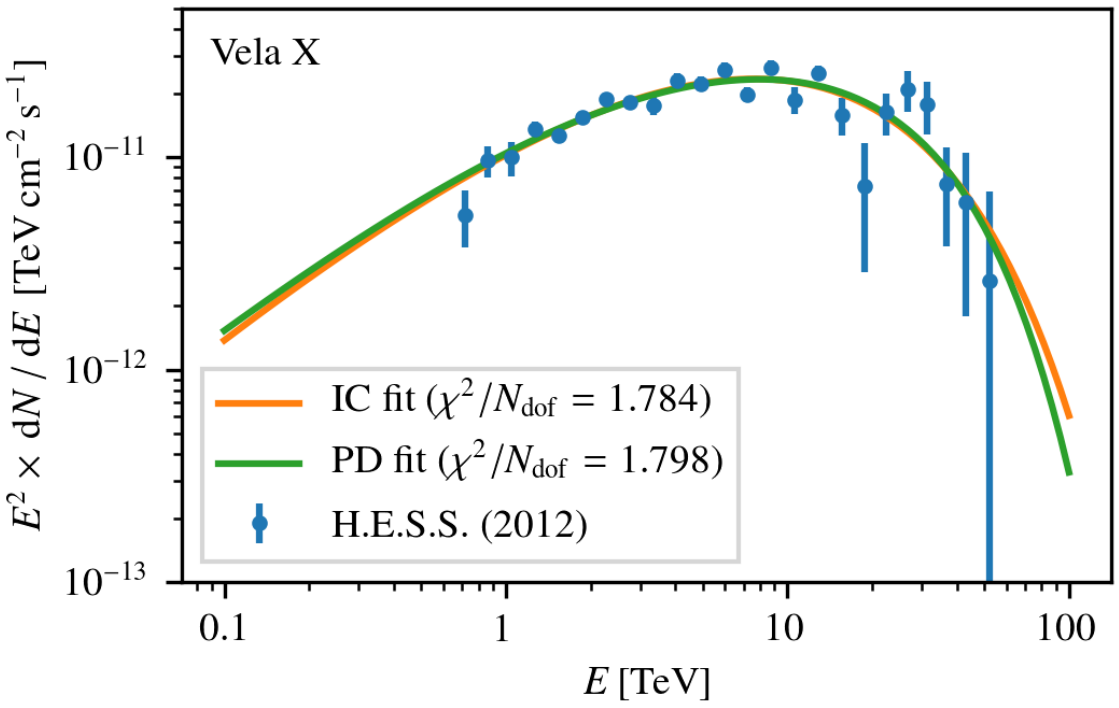
Credit: NASA/DOE/Fermi LAT Collaboration

Multi-messenger network

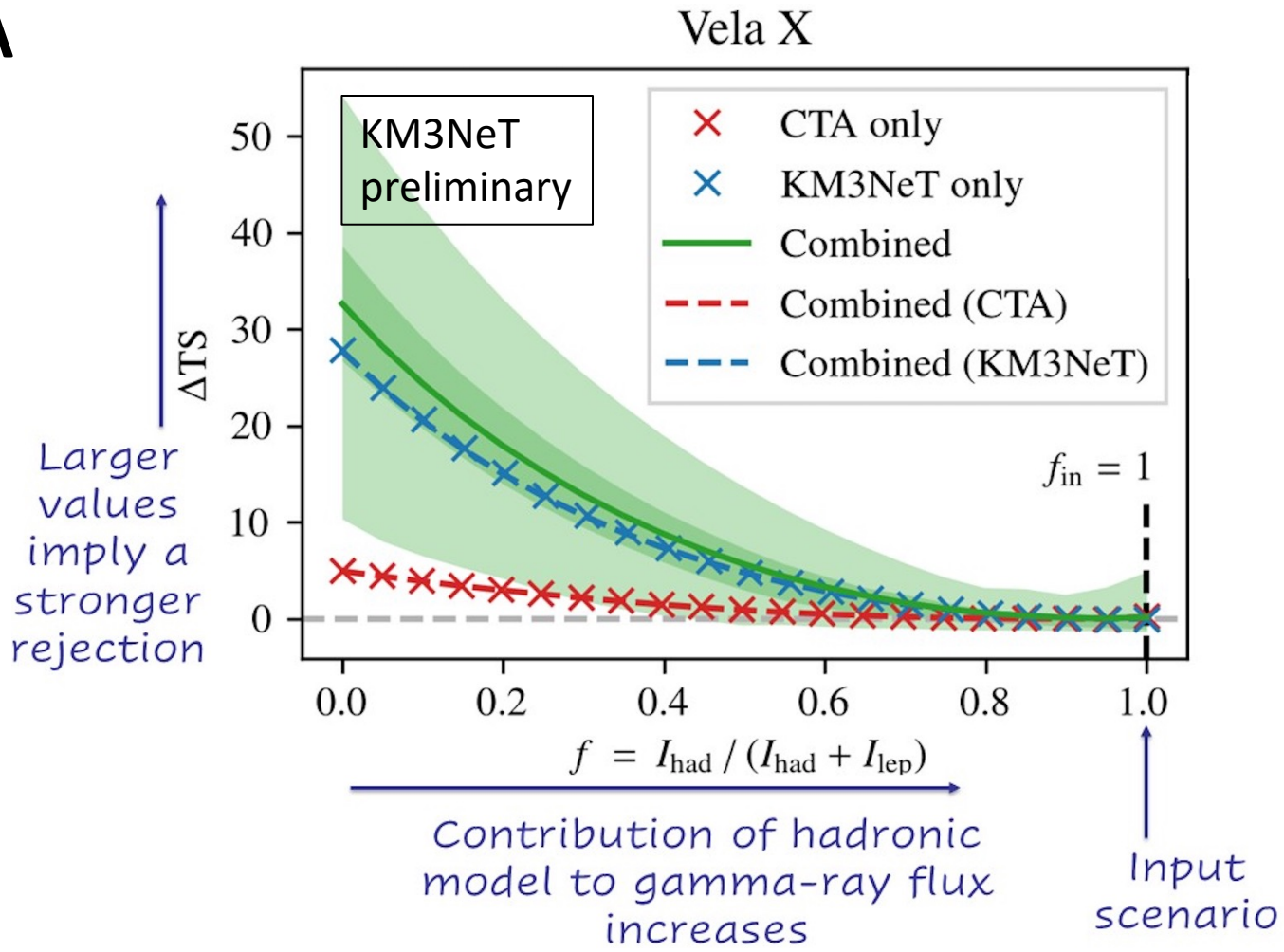


Probing leptonic/hadronic scenarios in combination with CTA

Inverse Compton (IC) / Pion decay (PD) model fits to HESS data



Combination with γ–ray information (CTA) strengthens power to **discriminate leptonic and hadronic scenarios**

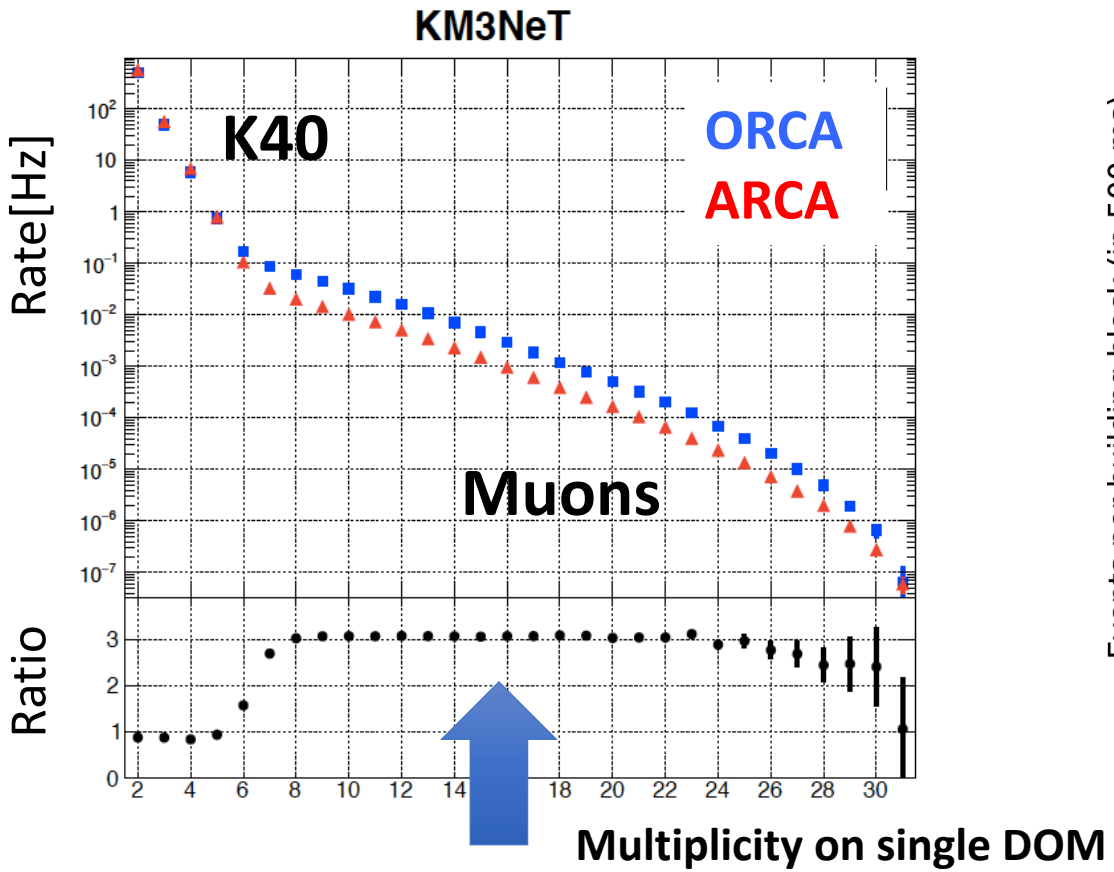


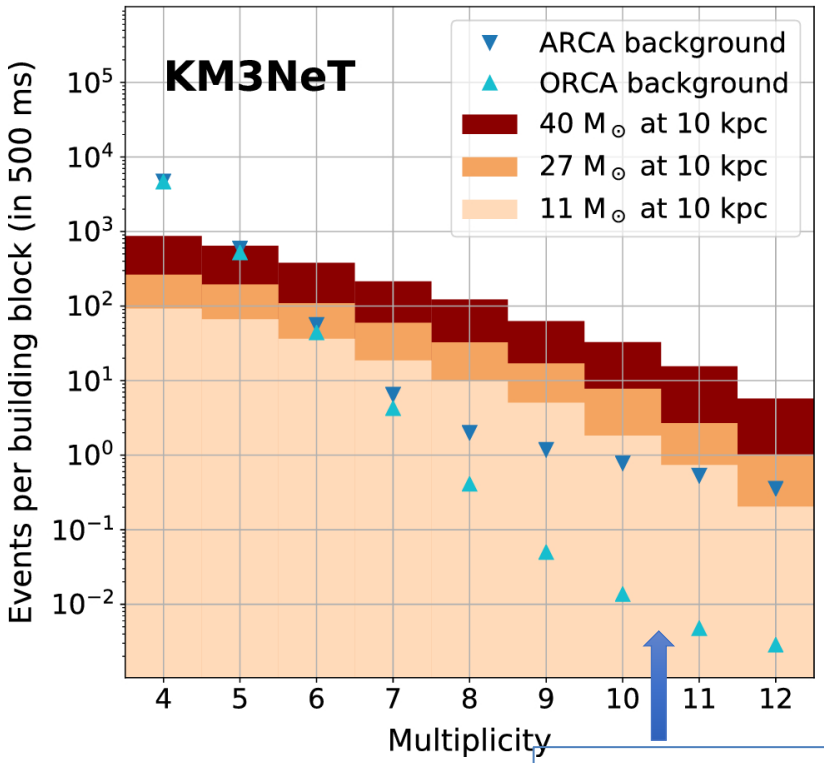
Unbehaun et al., NEUTRINO 2022

Supernova (SN) monitoring in KM3NeT

Supernova MeV neutrinos => collective excess of multi-fold coincidences on all DOMs

Real-time monitoring of activity



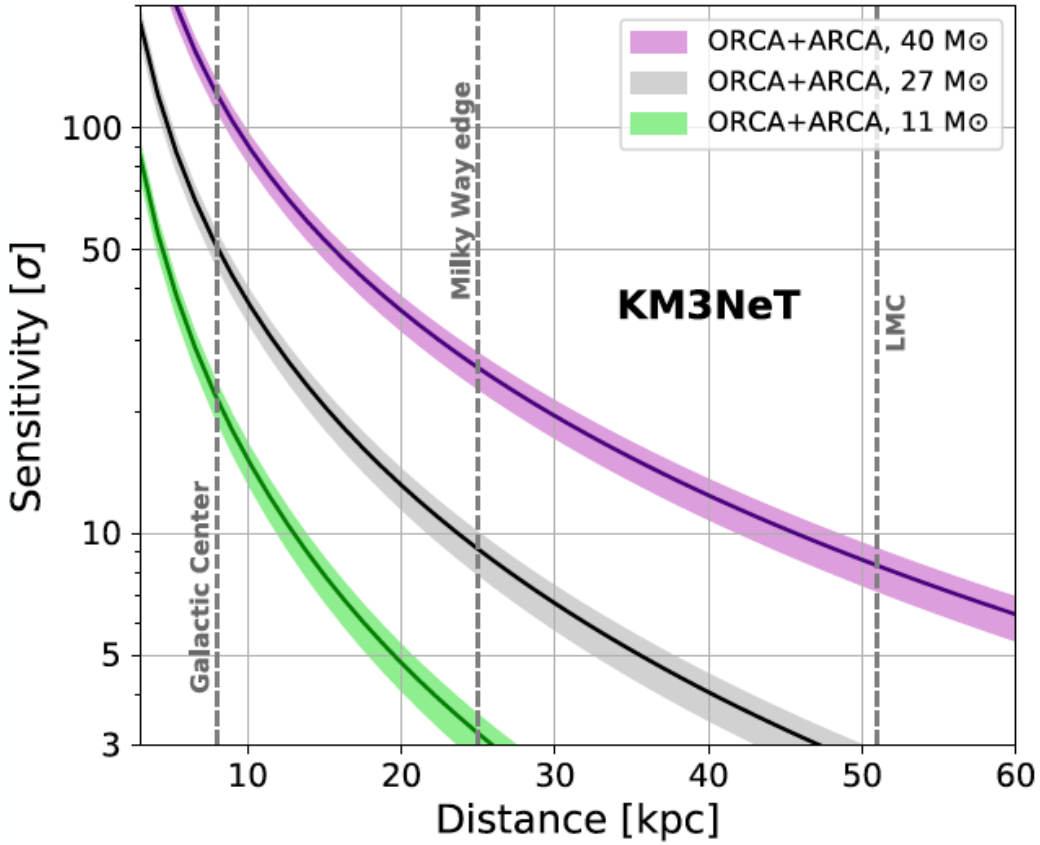


ARCA: ~3 times lower muon rate

Muon veto
-> ORCA less background

Aiello et al., Eur. Phys. J. C81, 445, 2021

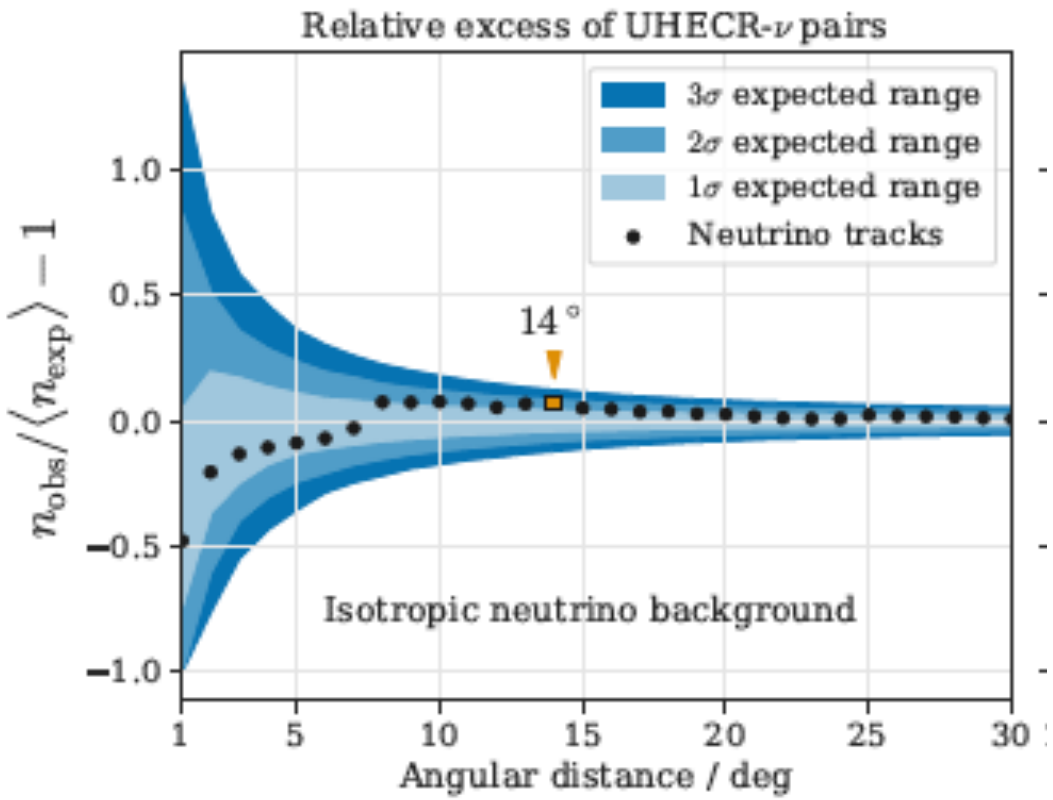
Expected KM3NeT sensitivity to CCSN



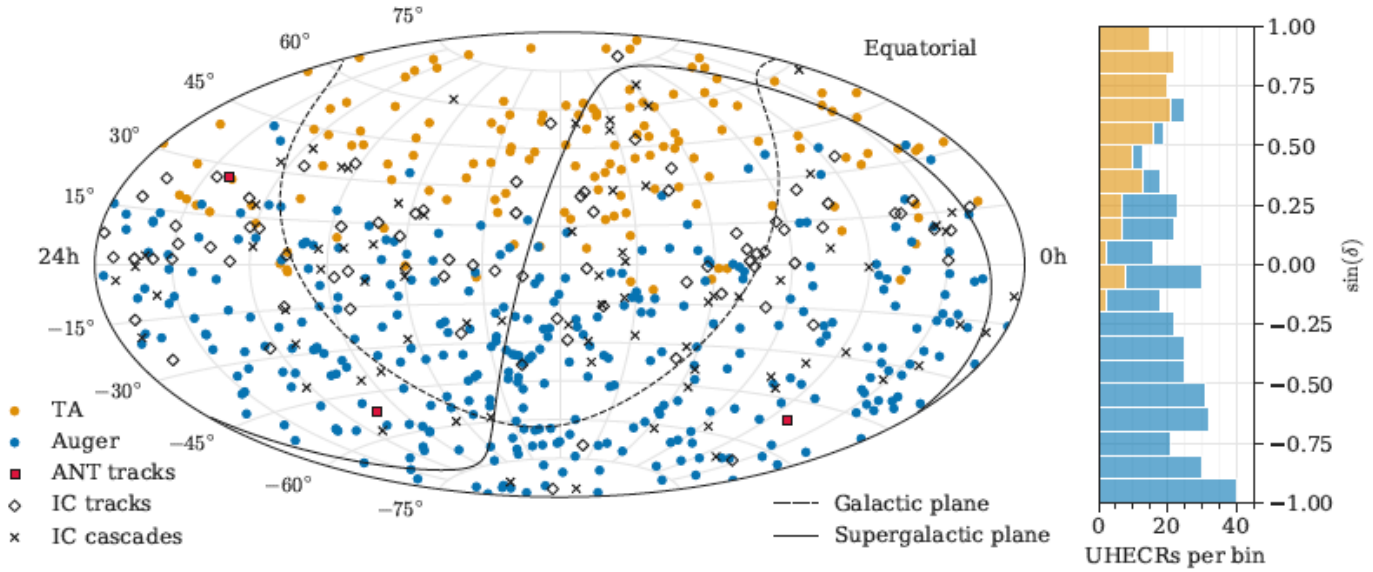
- KM3NeT already in **SNEWS**:
  SN alerts sent and followed up

Super-K (Japan), **LVD** (Italy), **Ice Cube** (South Pole), **KamLAND** (Japan), **Borexino** (Italy) , **Daya Bay** (IChina , **KM3NeT** (Mediterranean), HALO (Canada).

Cosmic Rays and Neutrinos



Search for correlations of neutrinos and UHECRs



TA & Auger & IceCube & ANTARES

Evaluation difficult due to CR deflections in magnetic field

=> So far no direct correlation identified

- UHECR horizon much closer than for neutrinos
- Sources could be transient
  -> couple of decades delay for CRs in galactic magnetic field
- Mass composition uncertainty (different deflection)

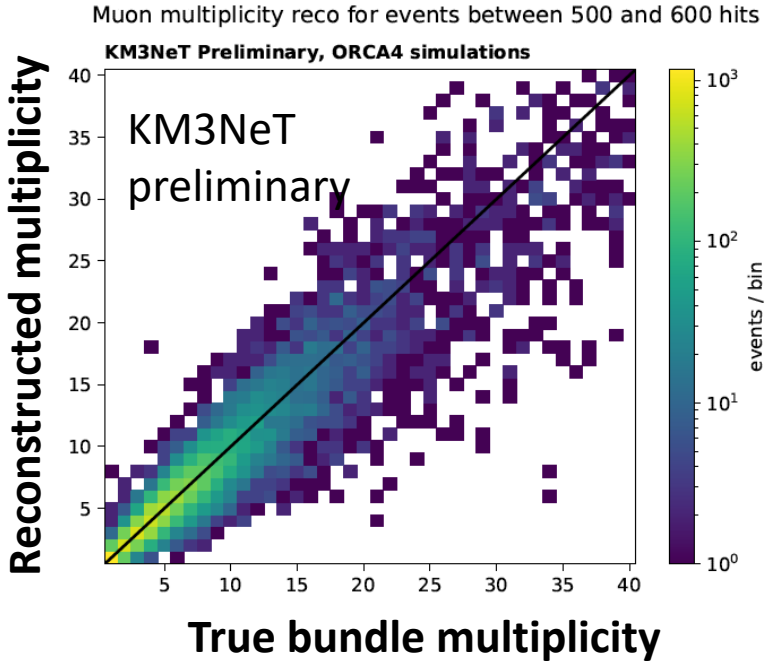
Cosmic Ray characterization with KM3NeT

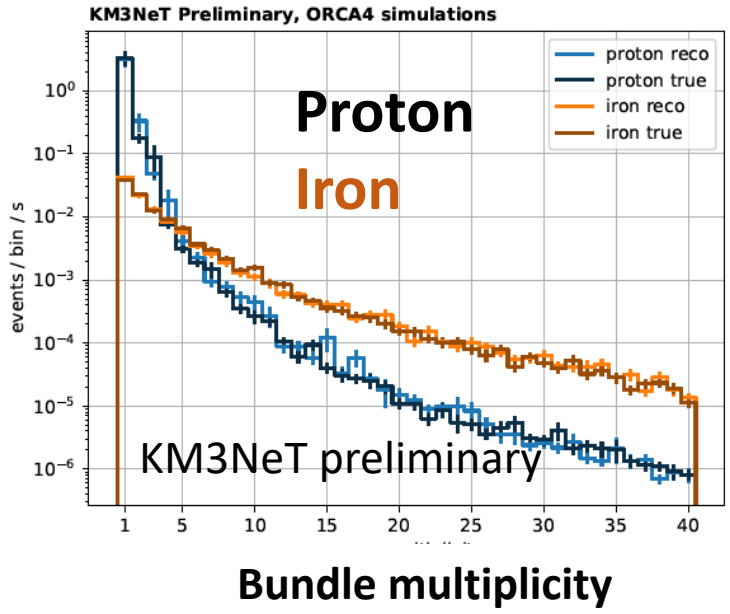
Most signals (muons & neutrinos) in detector from atmospheric cosmic ray interactions

=> information on hadronic interaction models
=> measurement of muon prompt flux
=> information on cosmic ray composition

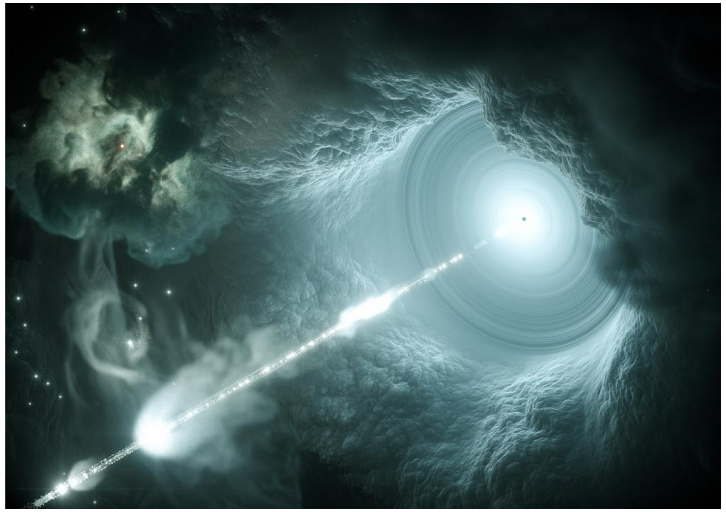
Observables:
- muon bundle multiplicity/diameter/zenith/energy
  => First promising reconstructions using GNNs on few-string detector simulations

Excellent resolutions of event topologies already with few strings



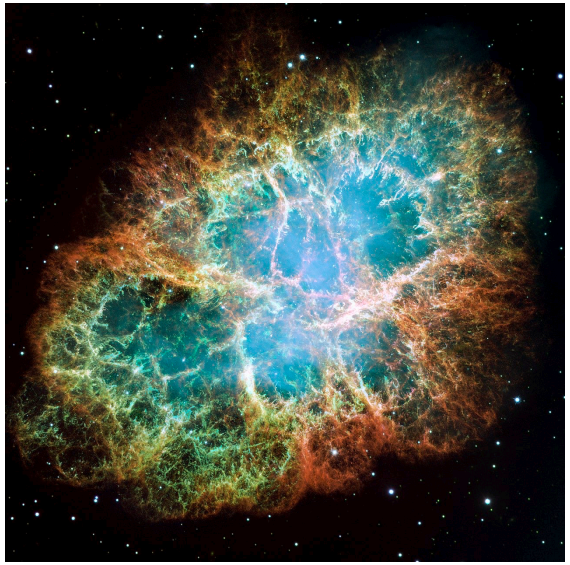


TDE, artists view
DESY, Science Communications Lab

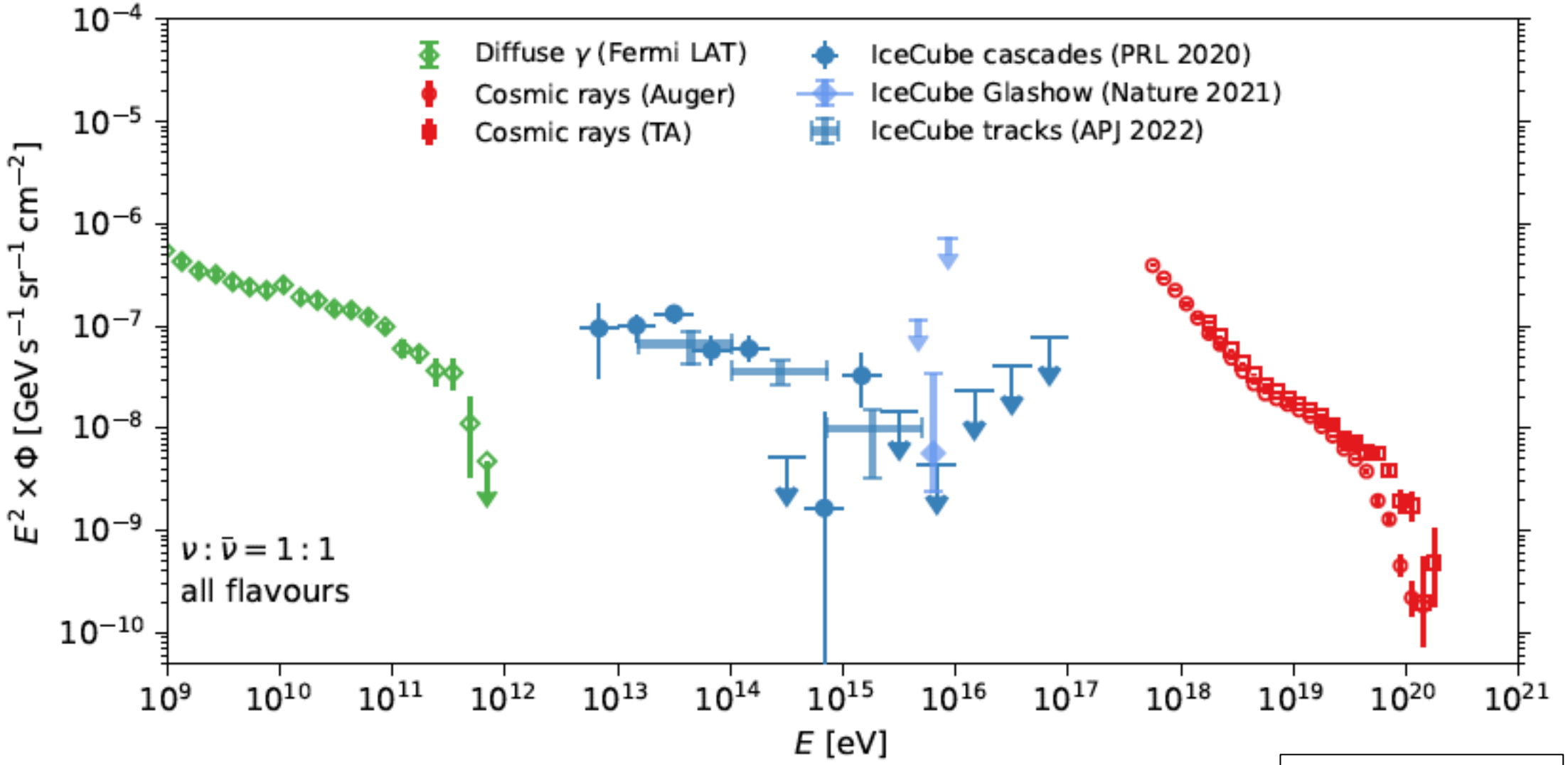


Blazar, artists view
DESY, Science Communications Lab

Starburst Galaxy: M82
NASA, ESA, and The Hubble Heritage Team (STScI/AURA)



SN remnant: Crab Nebula
NASA and STScI



Ackermann et al., Snowmass 2021