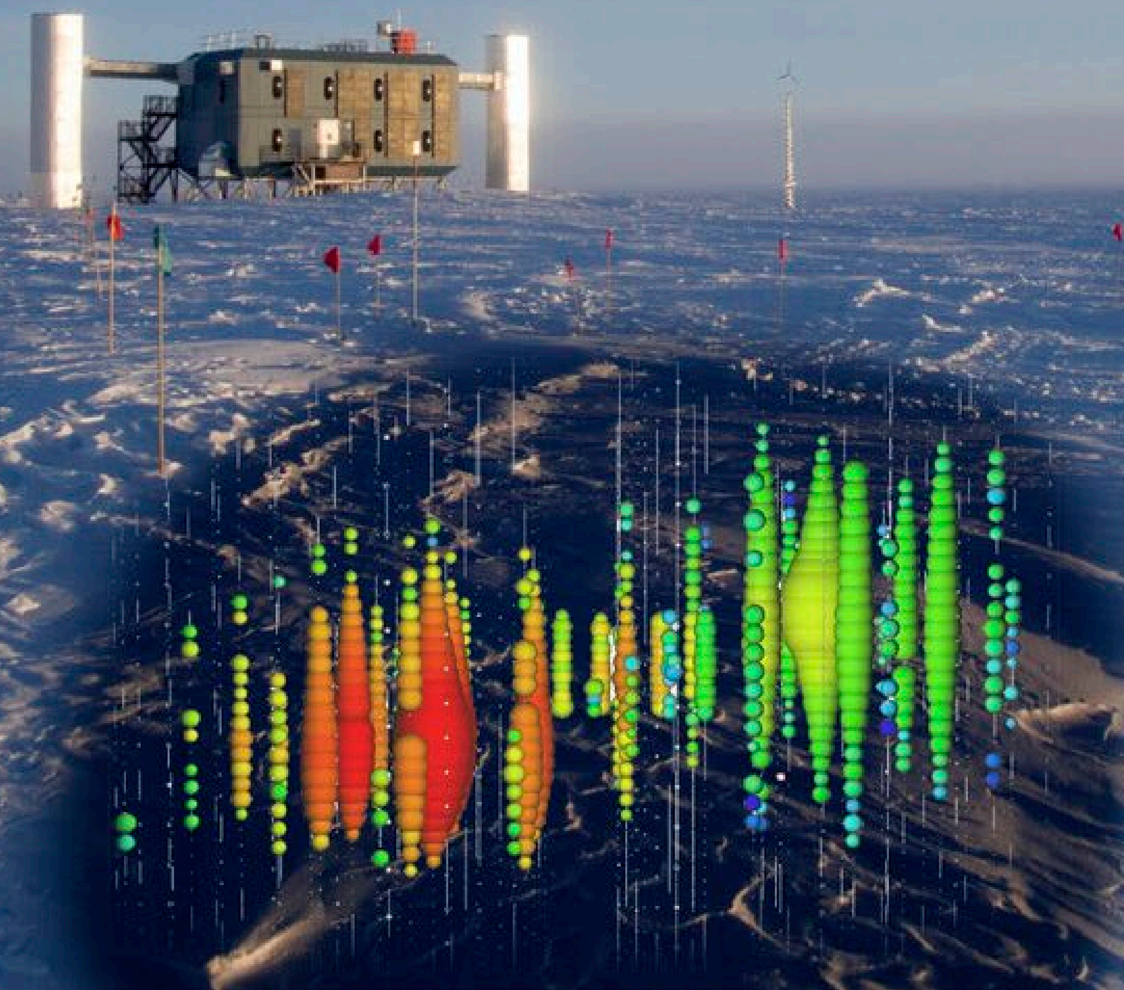
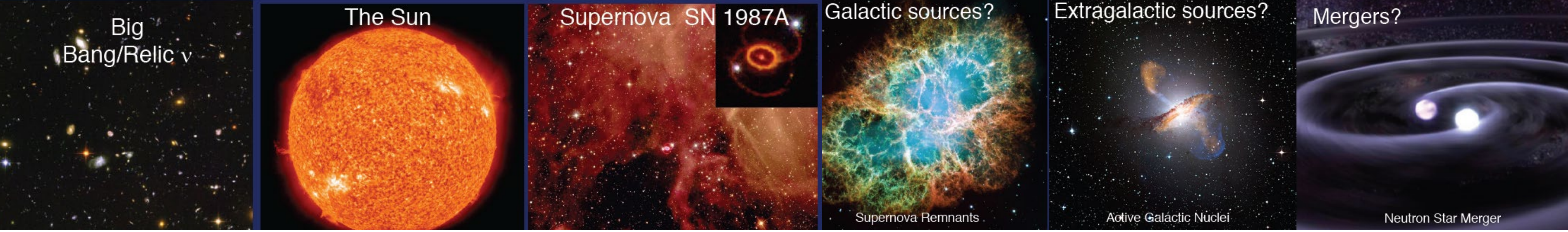
(Experimental) High-Energy Neutrino Research at KIT (at IceCube and beyond)



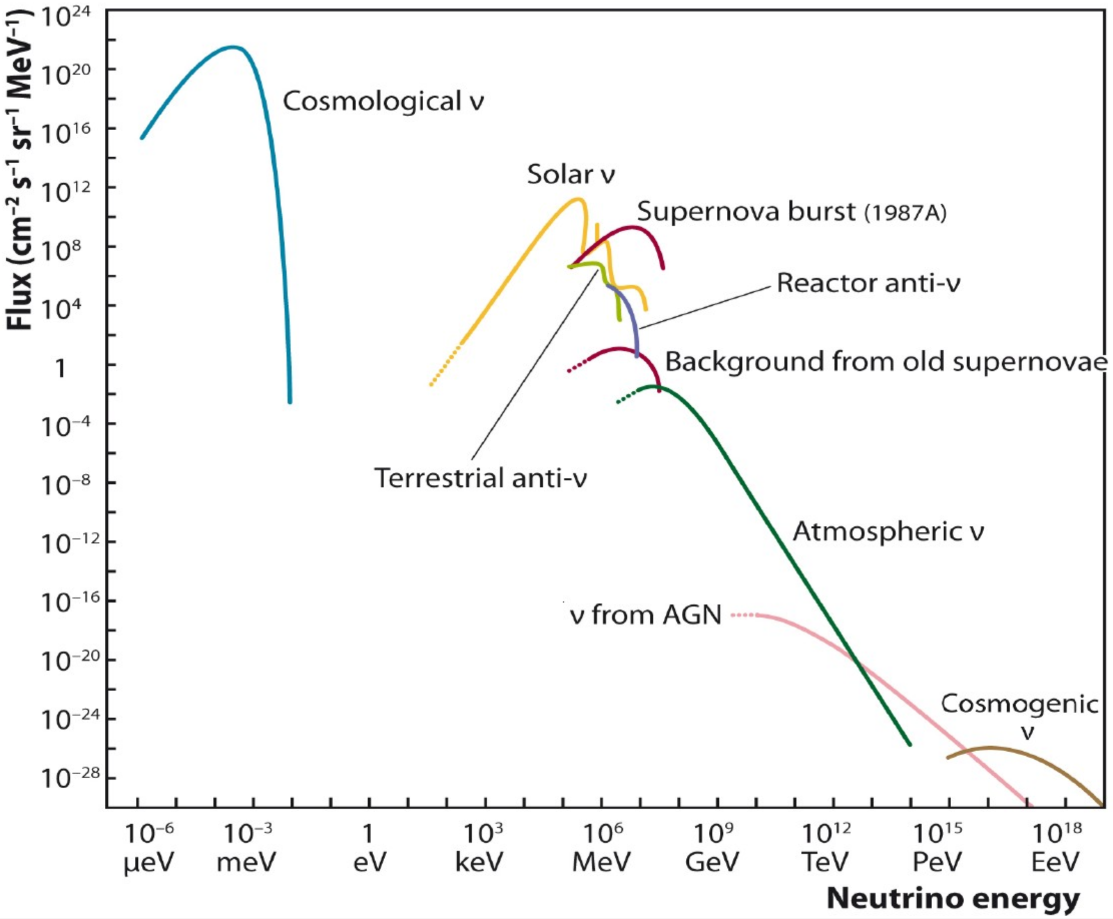
Andreas Haungs, IAP
28/11/2023 IRN@KIT

www.kit.edu



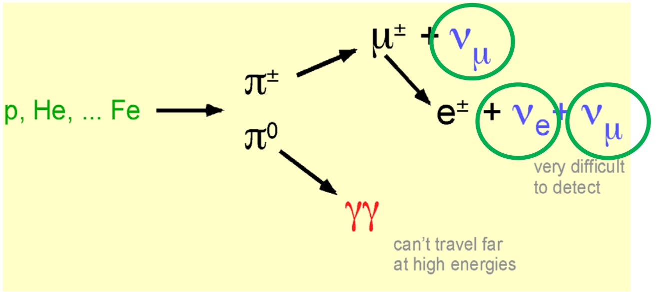
Neutrino Astronomy:

Observation of astronomical objects with neutrino detectors



Neutrino production:

1. In the (environment of) sources

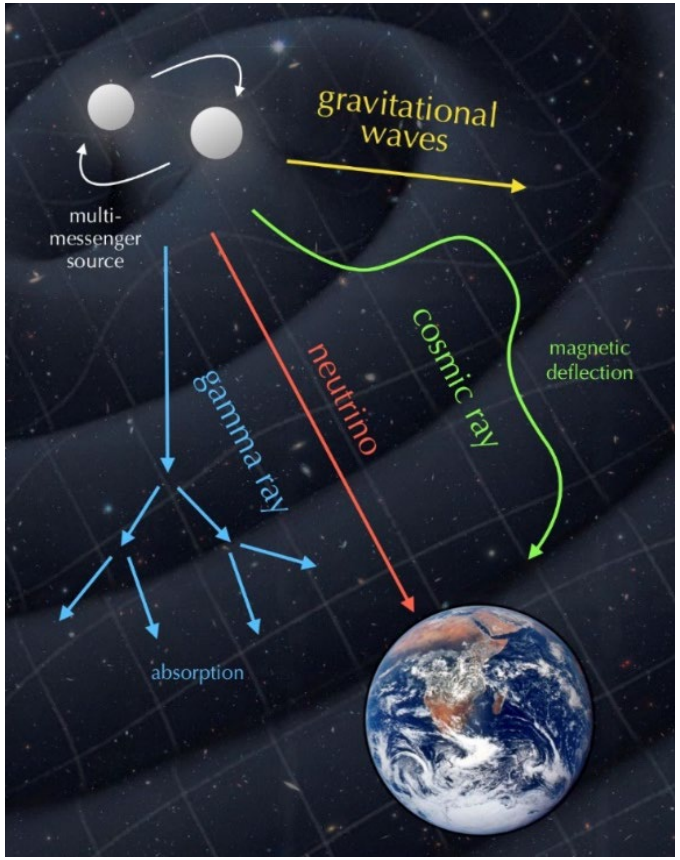


2. During Propagation

$$p + \gamma_{2.7K} \rightarrow \Delta^{+}(1232)$$
$$\rightarrow p + \pi^{0} \rightarrow p\gamma\gamma$$
$$\rightarrow n + \pi^{+} \rightarrow pe^{+}\nu$$

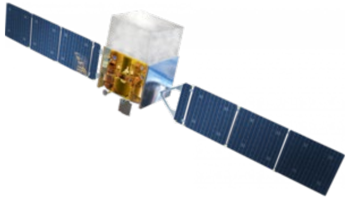
Multi-Messenger Astroparticle Physics

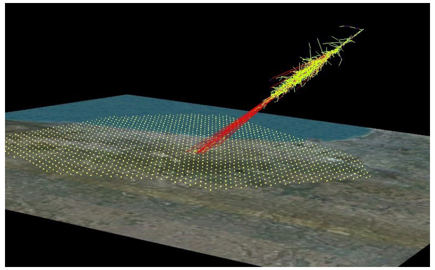
- **Required to understand the sources of cosmic rays and the physics processes in the high-energy Universe**
- **Needs long-term operational observatories**
- **And a sophisticated Big Data management: Big Data Analytics; Research Data Management; Data Curation; Open Data…… preferably in real-time!**



… plus all astronomy

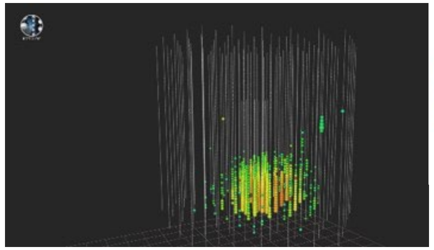
SKAO





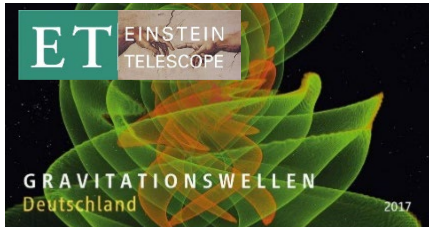
PIERRE AUGER OBSERVATORY

cta cherenkov telescope array



KM3NeT

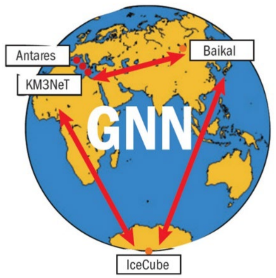
IceCube



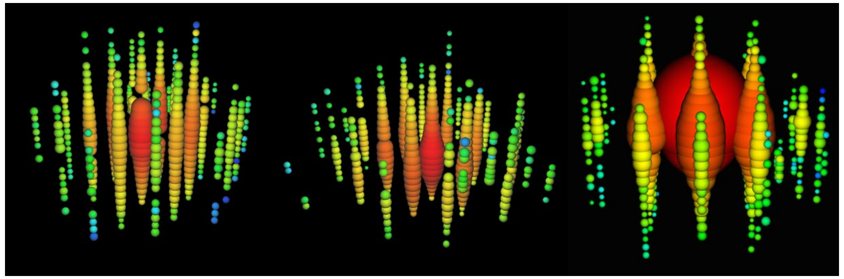
LIGO VIRGO

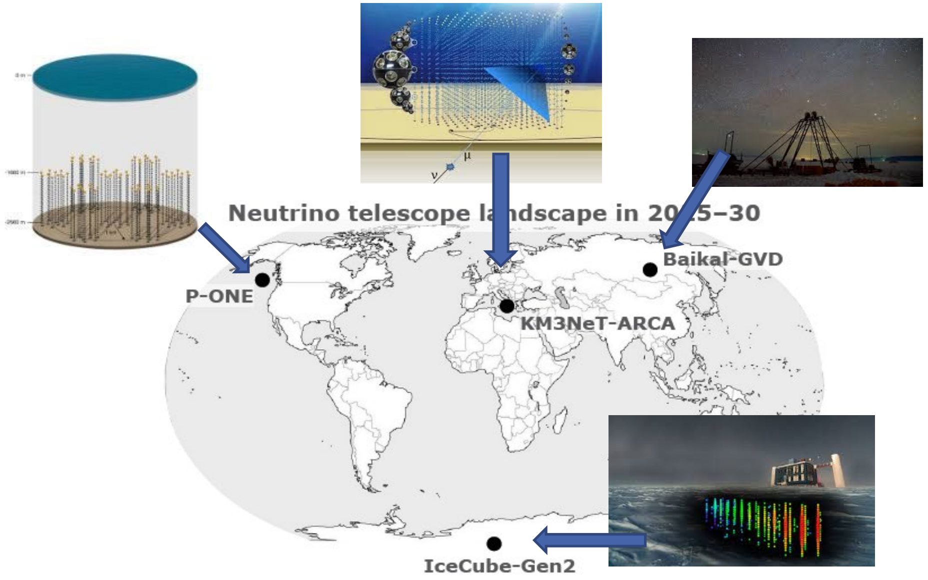
High-Energy Neutrino Astronomy

- IceCube opened in 2013 the new window of >100 TeV neutrino astronomy
- Several experiments are now organized in the Global Neutrino Network GNN:
  - IceCube ➔ IceCube-Gen2
  - Antares ➔ KM3NeT
  - Baikal-GVD (co-operation stalled)

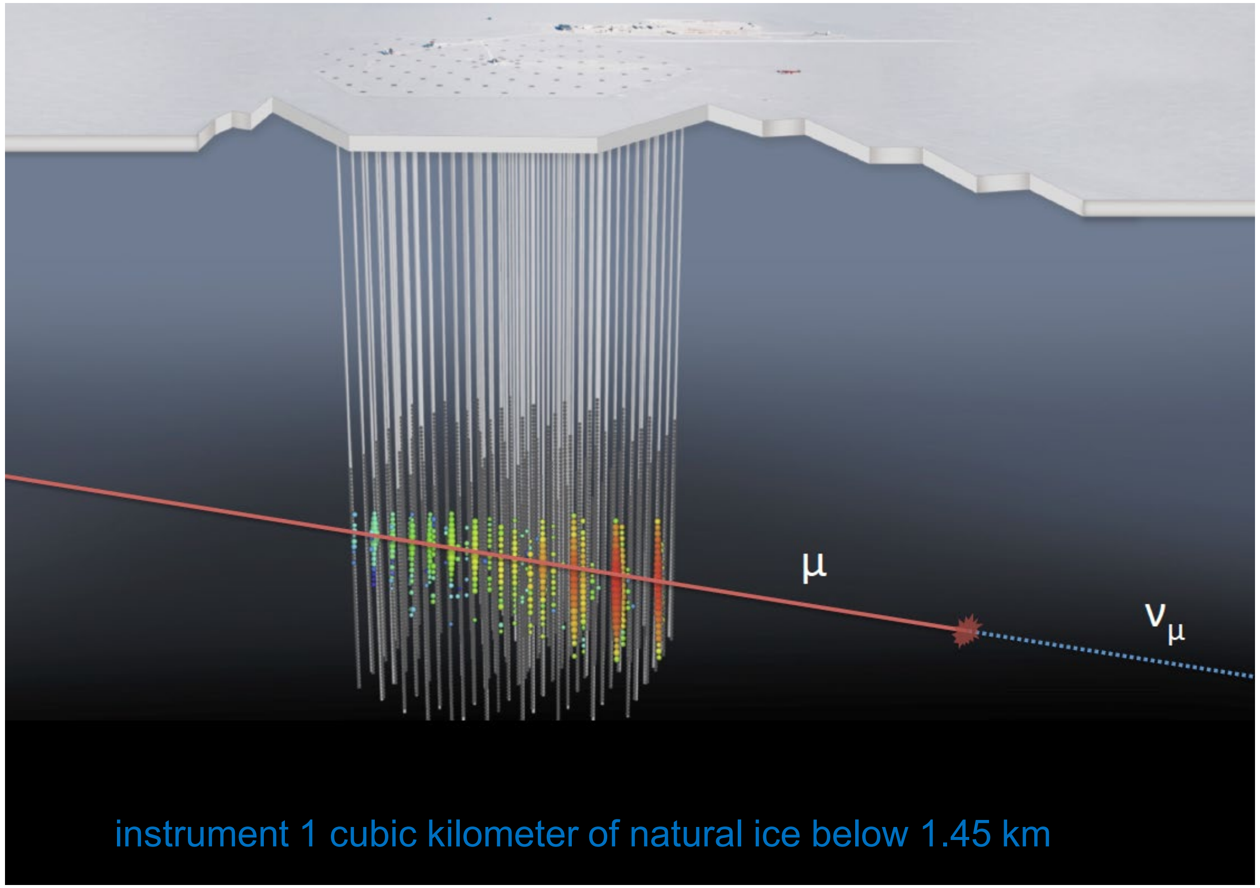


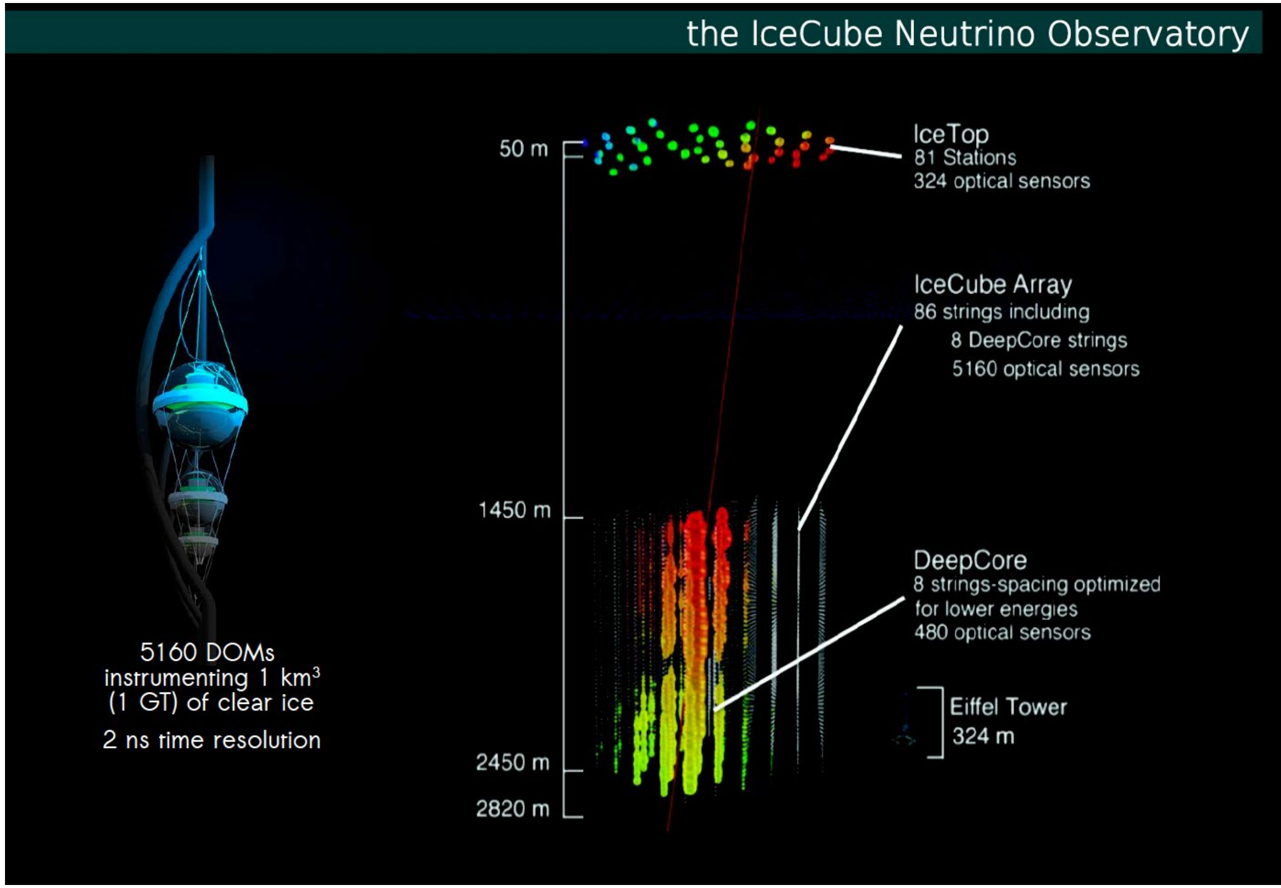
- R&D phase (in particular for cosmogenic Neutrinos): P-ONE, RNO-G, POEMMA, ANITA (PUEO), GRAND, Beacon, Trinity, Trident, …
- European flagship (ESFRI): KM3NeT
- Strong partner of US lead IceCube-Gen2





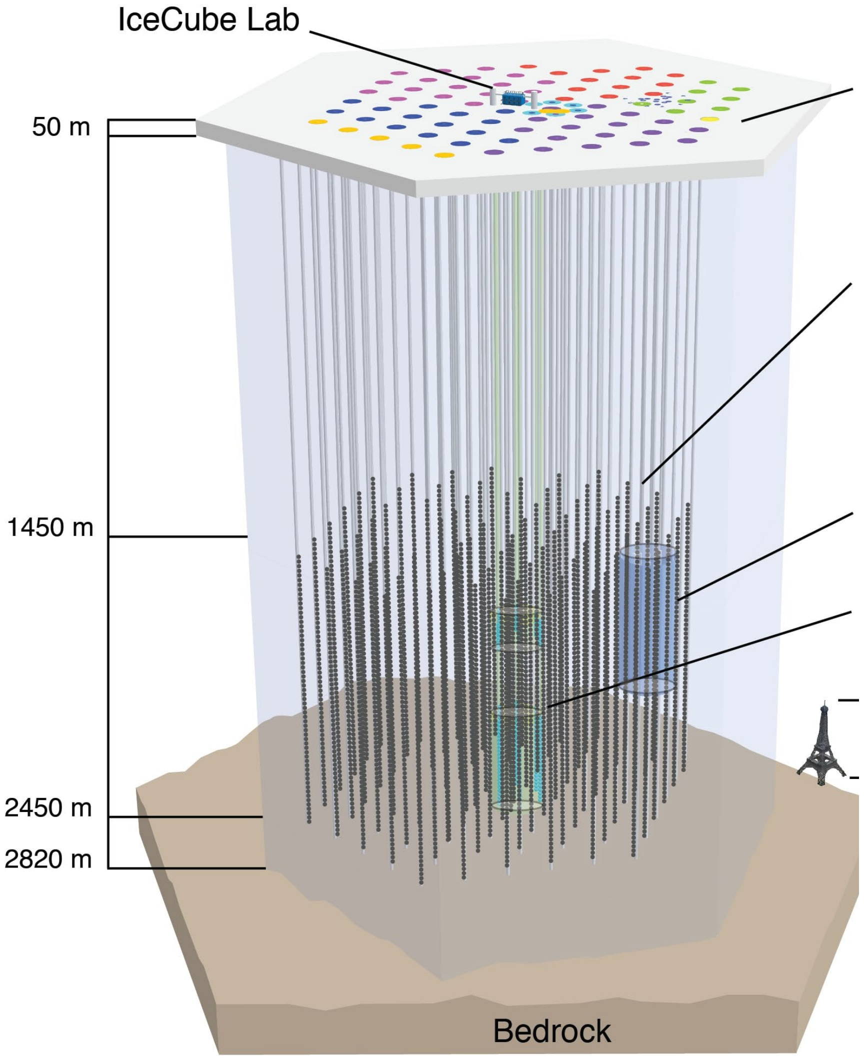
IceCube Neutrino Observatory

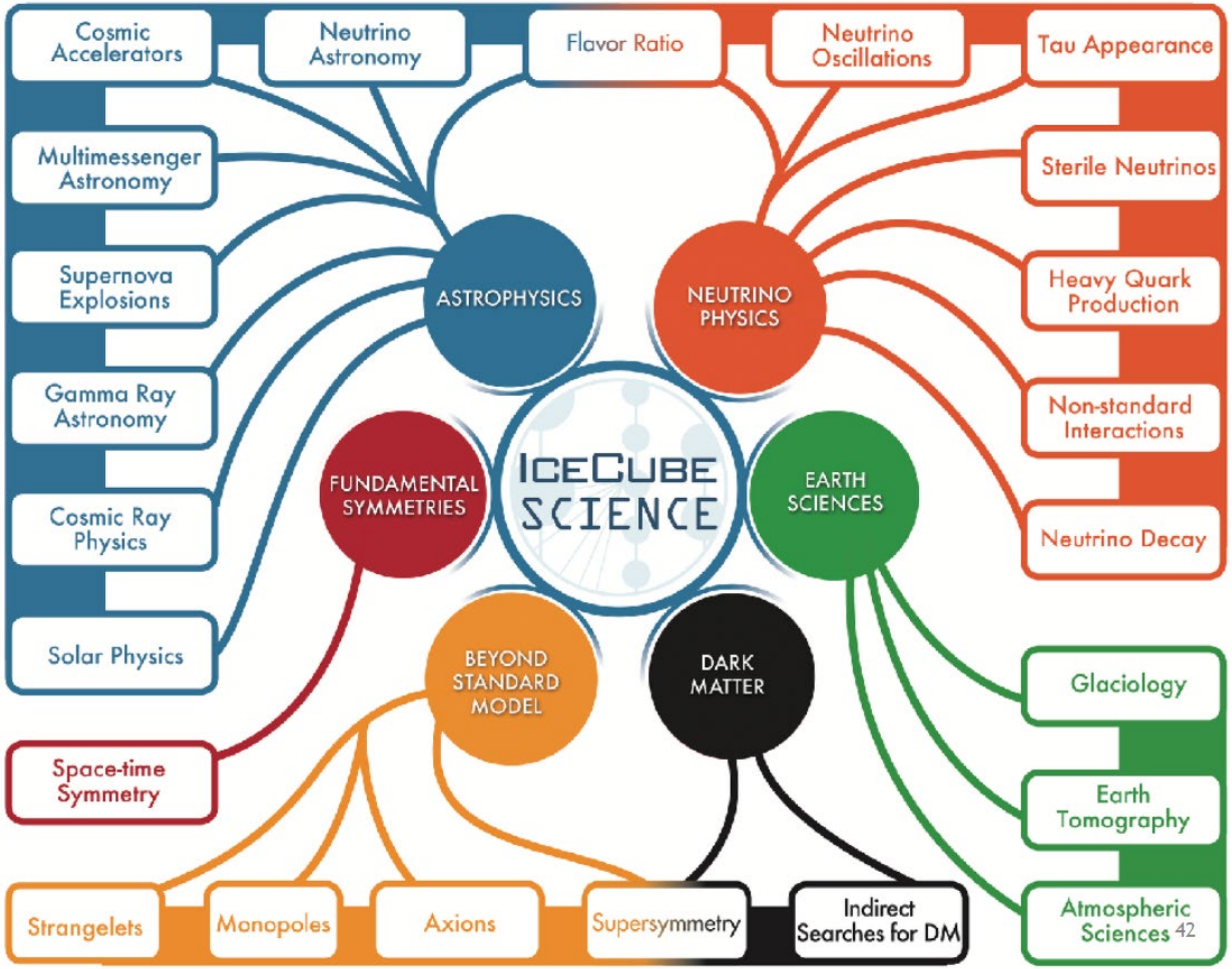




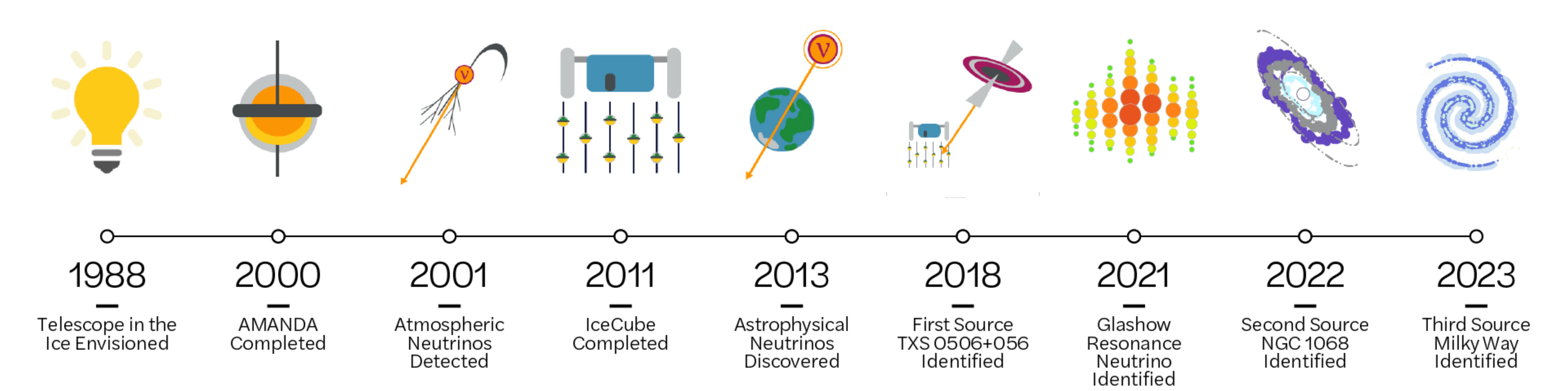
- **Amundson-Scott Station at geographic SouthPole**
- **Headquarter in Madison, Wisconsin**
- **14 Countries, 58 Institutes, ca. 350 Scientists**

IceCube Neutrino Observatory





Results of IceCube (neutrino astronomy)

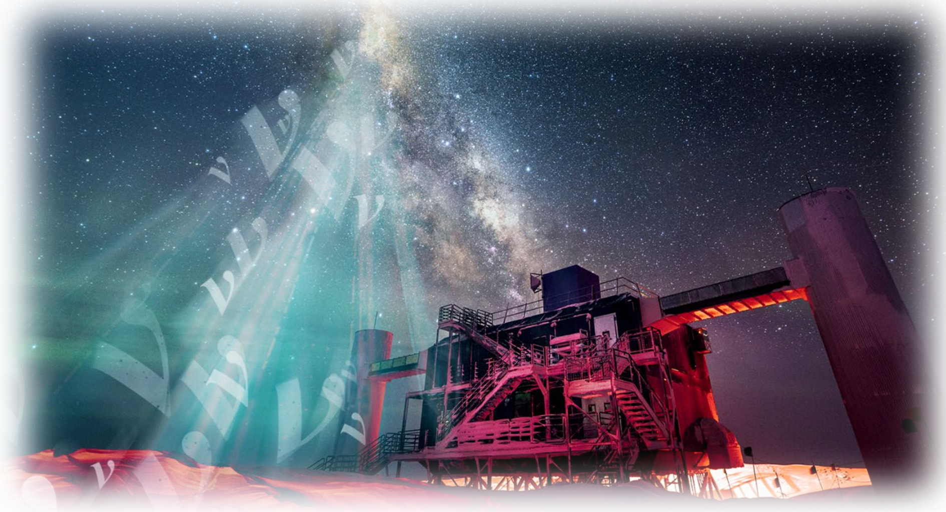


- **2013: Detection of high-energy extraterrestrial neutrinos** (Ernie and Bert)
- **2017: Discovery of the high-energy accelerator for cosmic rays** (TXS 0506+056)
- **2021: Proof of W boson generation** (Glashow Resonance)
- **2022: Detection of a neutrino source** (NGC-1068)
- **2023: Detection of the Milky Way as a neutrino source** (Milky Way)
- **The era of multi-messenger astronomy with neutrinos has begun** (Alerts)

IceCube

- **Application of machine learning in reconstruction dramatically improved resolution**
  - In particular, improved directional reconstruction now allows for "new era" in source search
  - *E.g.:* Evidence for neutrino emission from the nearby active galaxy NGC 1068; **Science** 378, 6619, 538-543 (2022); 4.2 sigma evidence
  - *E.g.:* Observation of High-Energy Neutrinos from the Galactic Plane**; Science** 380, 1338 (2023), 4.5 sigma evidence

- **KIT:**
  - Analysis IceCube / IceTop Data
  - Improvements in surface instrumentation
  - Multi-Messenger Analyses Neutrinos – Gravitational Waves
  - Air-shower simulations (CORSIKA=> C8)
  - Tier-1 computing using GridKa, HoreKa, Binac (Tübingen) - also data management
  - Winterover Nov 2022 - Dec 2023: Hrvoje Dujmovic, KIT



NGC 1068

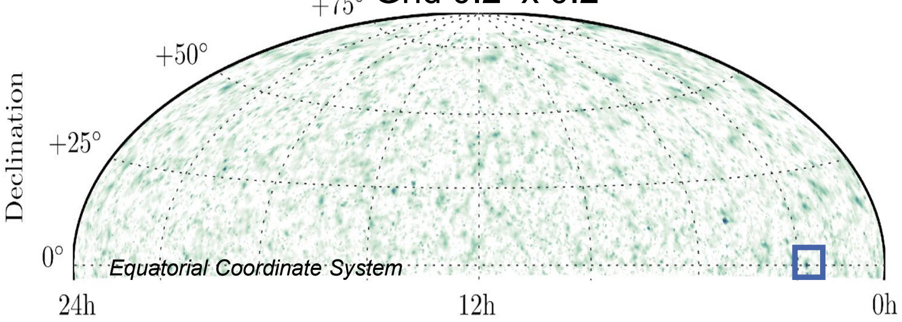
Analysis:

- **Improved detector geometry and calibration**
- **improved characterization of the optics of the ice**
- **improved angular resolution and energy reconstruction for muons using neural networks**
- **Loglikelihood analysis for each point in the sky (with energy term)**
- **search / analysis in the direction of 110 pre-selected source candidates (including NGC 1068)**

$$L(n_s, x_s, \gamma) = \prod_i^{events} \left(\frac{n_s}{N} S_i(|x_i - x_s| \sigma_i, E_i, \gamma) + \frac{N - n_s}{N} B_i(\delta_i, E_i) \right)$$

$$S_i(|\vec{x}_i - \vec{x}_s|, \sigma_i) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2} \right)$$

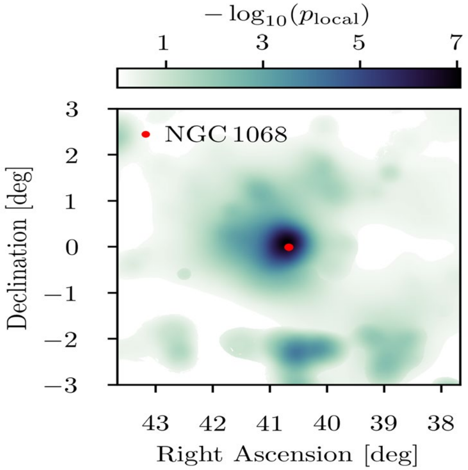
Grid 0.2° x 0.2°

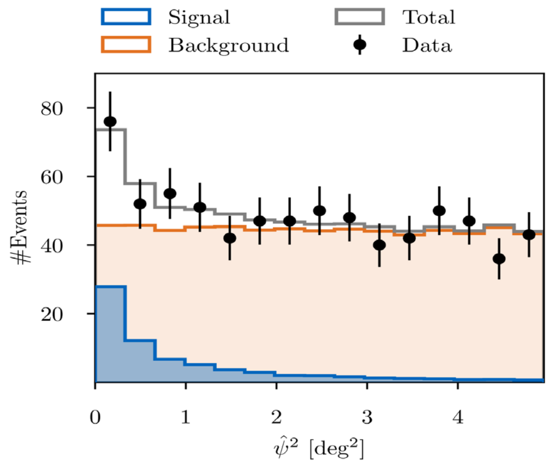


hottest spot:
c. 80 neutrinos excess
-3.2 spectral index
local significance 5.3σ

1% of scrambled data sets show ≥ 5.3σ

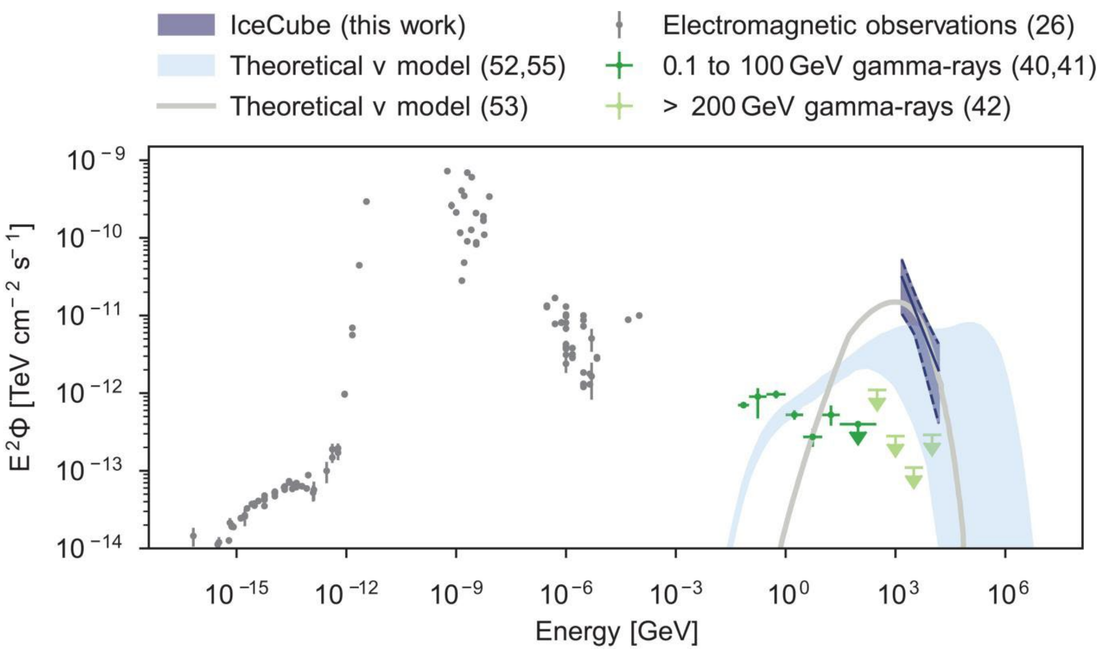
NGC1068 found as a source:
astrophysical neutrinos: 79 ± 20
spectral index γ = 3.2 ± 0.2
single source significance: 4.2σ (with tracks)
Offset to NGC1068: 0.11°

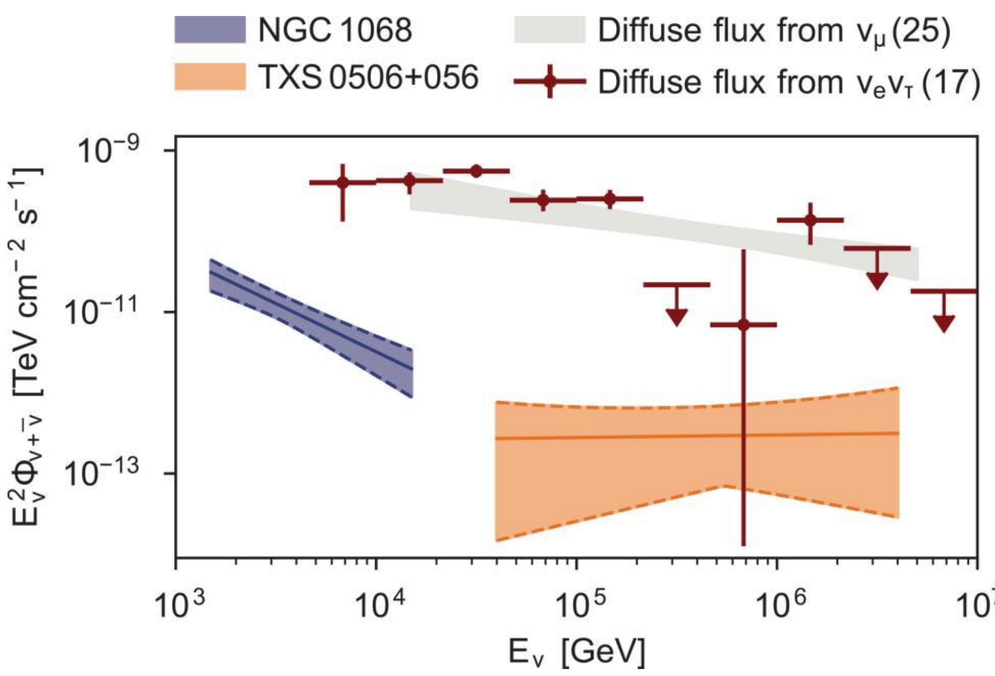




Science **378**, 538 (2022)

NGC 1068 as neutrino source





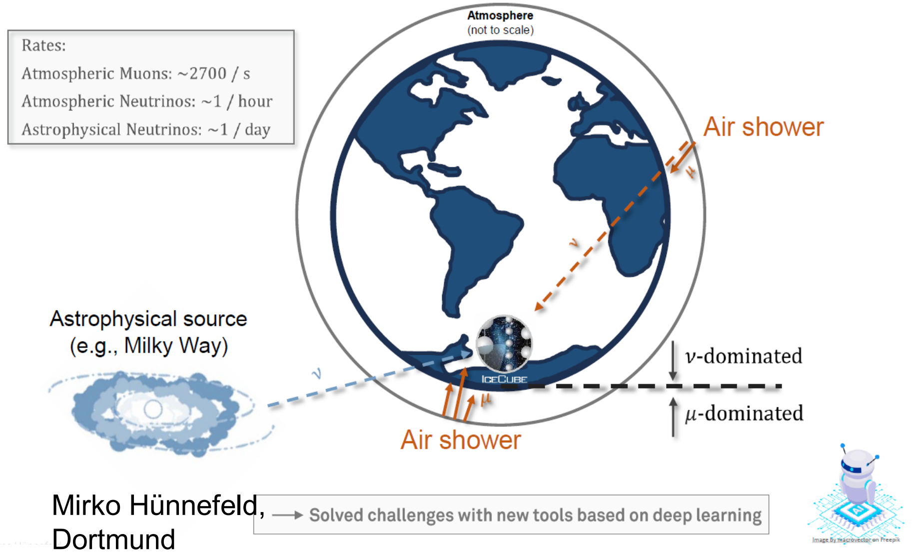
- Close-by Spiral Galaxy (Messier 77) at 14,4 Mpc distance with Compton-thick and bright AGN
- X-Ray Corona at accretion disc might allow neutrino production and gamma-ray absorption

➔ Neutrinos are produced in the gamma-ray-darkened core of NGC 1068

- NGC1068 contributes max. 10% to the astrophysical neutrino flux (1-10 TeV)
- Search with the help of source catalog (X-ray bright AGNs) shows possible second source (NGC 4151)
- However, X-ray bright AGNs cannot explain the total neutrino flux

Milky Way as Neutrino Source

- **Deep learning methods:**
  - Improved reconstruction (more events)
  - Improved directional reconstruction (3 times better chance of point sources)
  - Likelihood analysis assuming theoretical predictions based on gamma-ray observations of the Milky Way

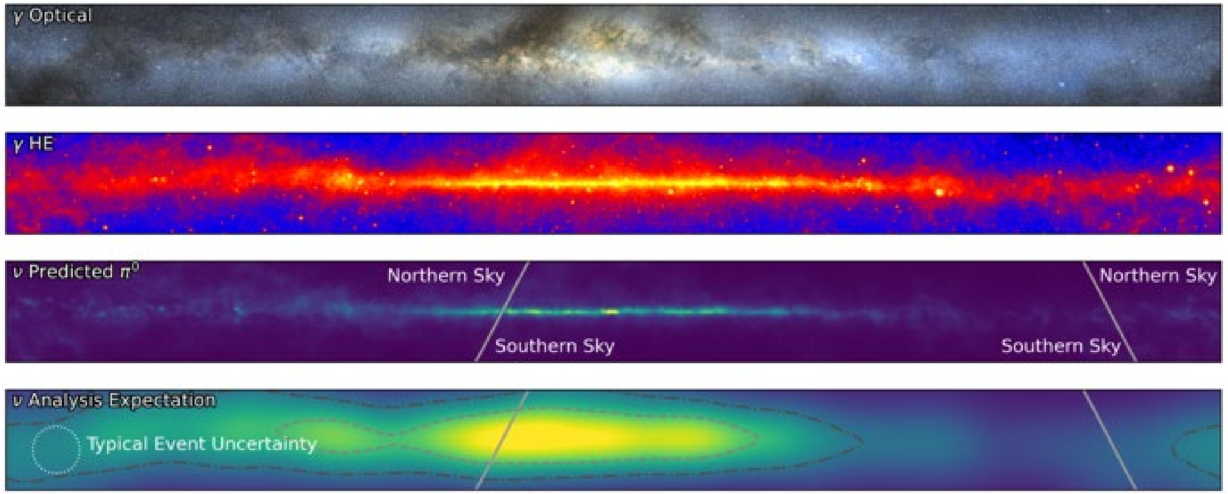


optical

HE-γ

ν-Theorie

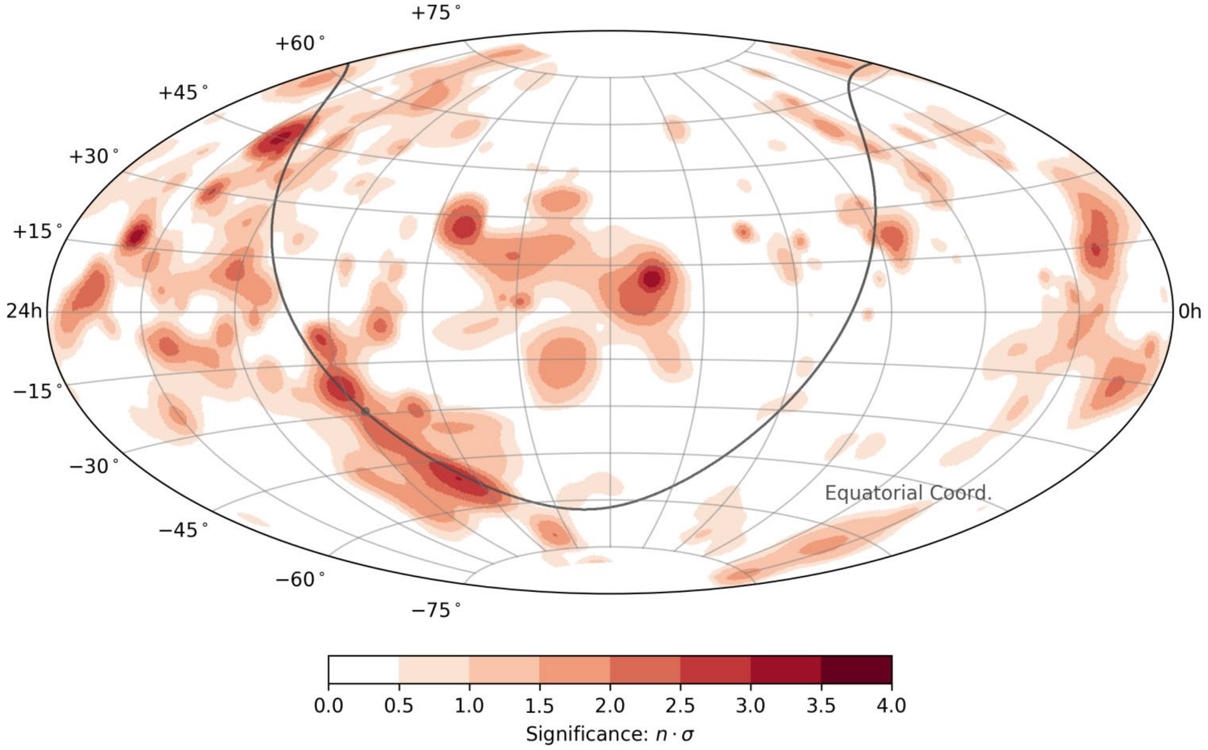
ν-Theorie
Incl. Exp.



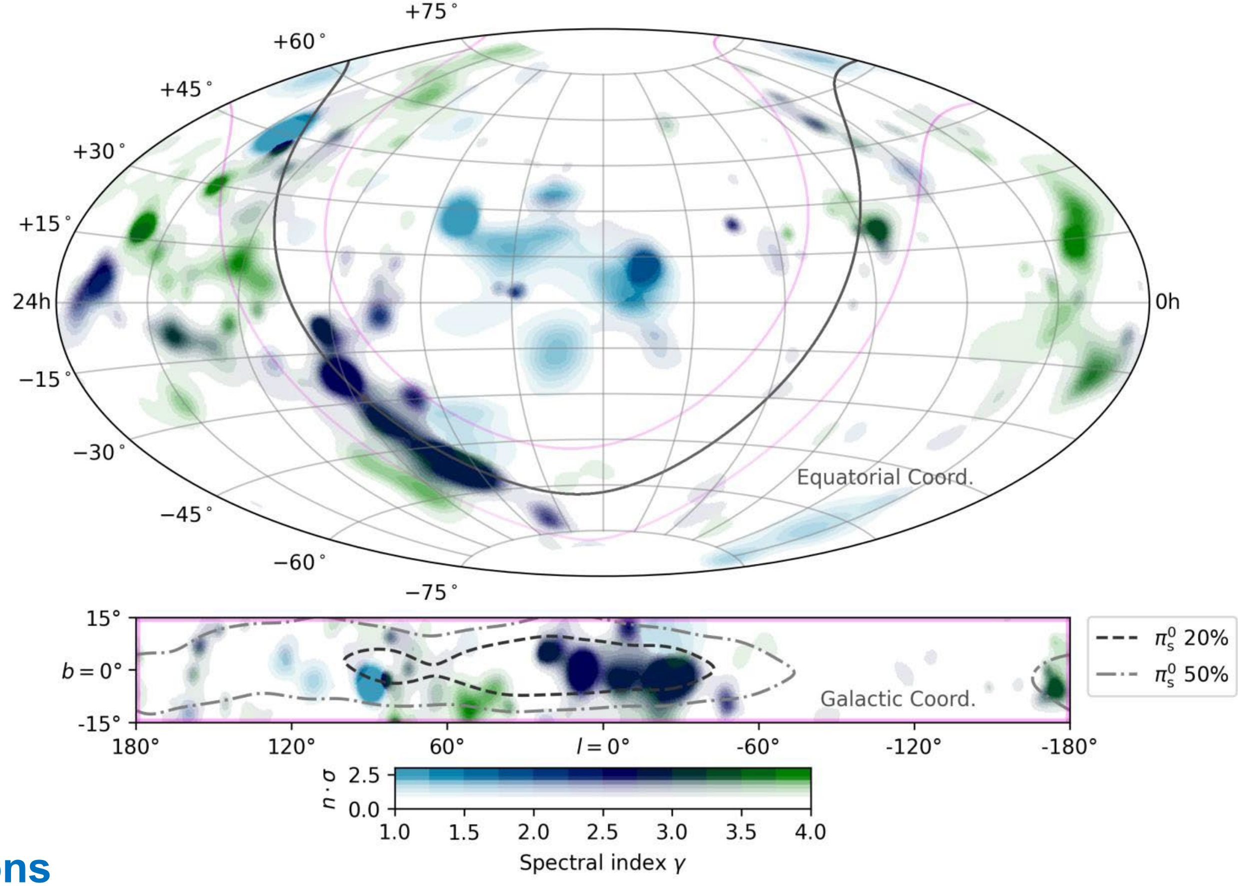
Science **380**, 1338 (2023)

Milky Way as Neutrino Source

Local significance:

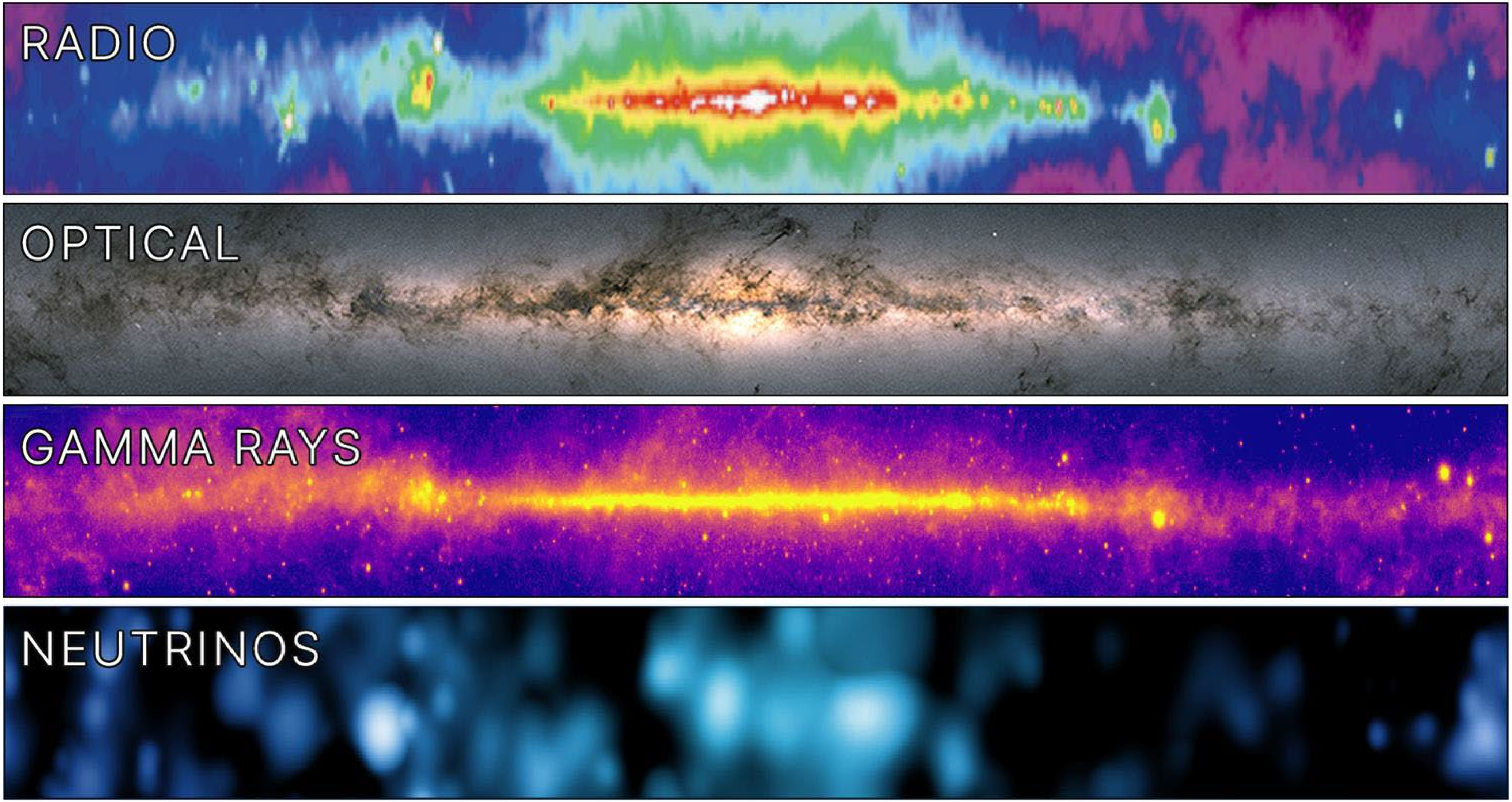


Spectral index:



- **Individual hotspots compatible with background fluctuations**
- **Analysis under theoretical assumption and correlation with gammas: evidence for neutrinos from the Milky Way with a significance of 4.5σ**

Science **380**, 1338 (2023)

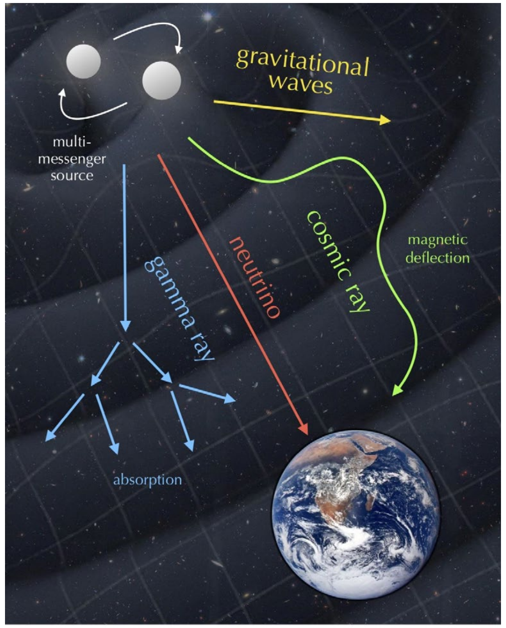

RADIO
OPTICAL
GAMMA RAYS
NEUTRINOS

Milky Way as Neutrino Source

- Proof of the acceleration of cosmic rays in our Milky Way is an important milestone
- Milky Way is a neutrino desert compared to the universe, i.e. strong accelerators are in other galaxies
- We find that only a maximum of 15% of the total cosmic neutrino flux reaches us from our own galaxy (at 30 TeV)

Multimessenger Studies Neutrinos - Grav. Waves

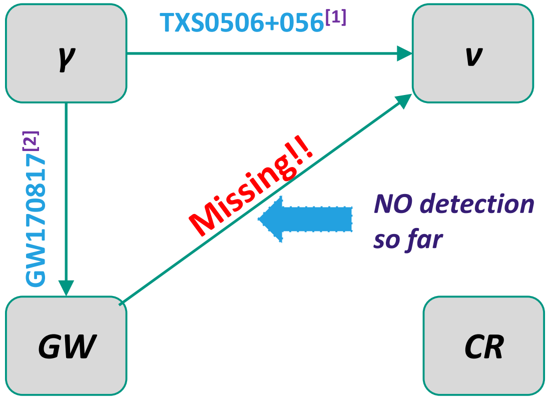
Tista Mukherjee, IAP
(A. Haungs, R. Engel)

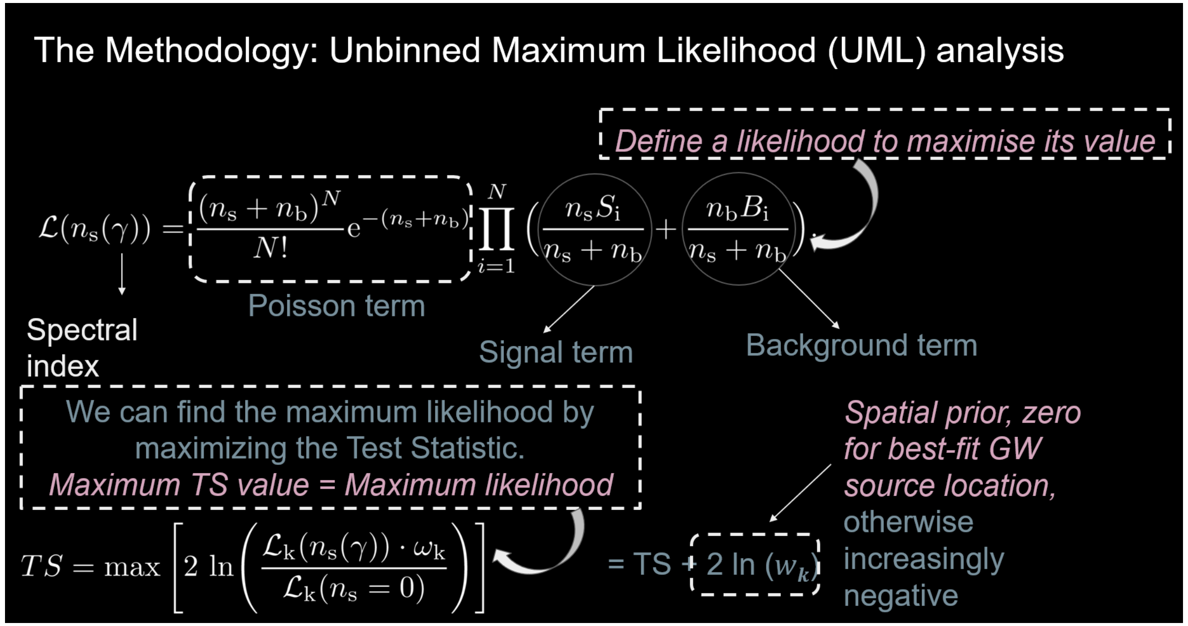


With multi-messenger studies, we access *maximum information* that we get from nature to unveil the unknowns of the Universe.

IceCube, PoS (ICRC 2023) 1504

- **No O3 sub-threshold GW candidate was followed in real-time or archival studies.**
- **We want to do archival studies with these candidates to look for neutrino counterparts.**
- **The knowledge we can gain from sub-threshold candidates is crucial for planning future real-time campaigns.**
- **We can improve our understanding about the 'threshold' for GW detection, helping future detectors.**
- **A selection of sub-threshold candidates has been made for archival studies with sub-TeV neutrinos.**





Ref: [1]Aartsen et al., Science 361 (2018) [2]Abbot et al. 2017b, PhRvL 119, 161101

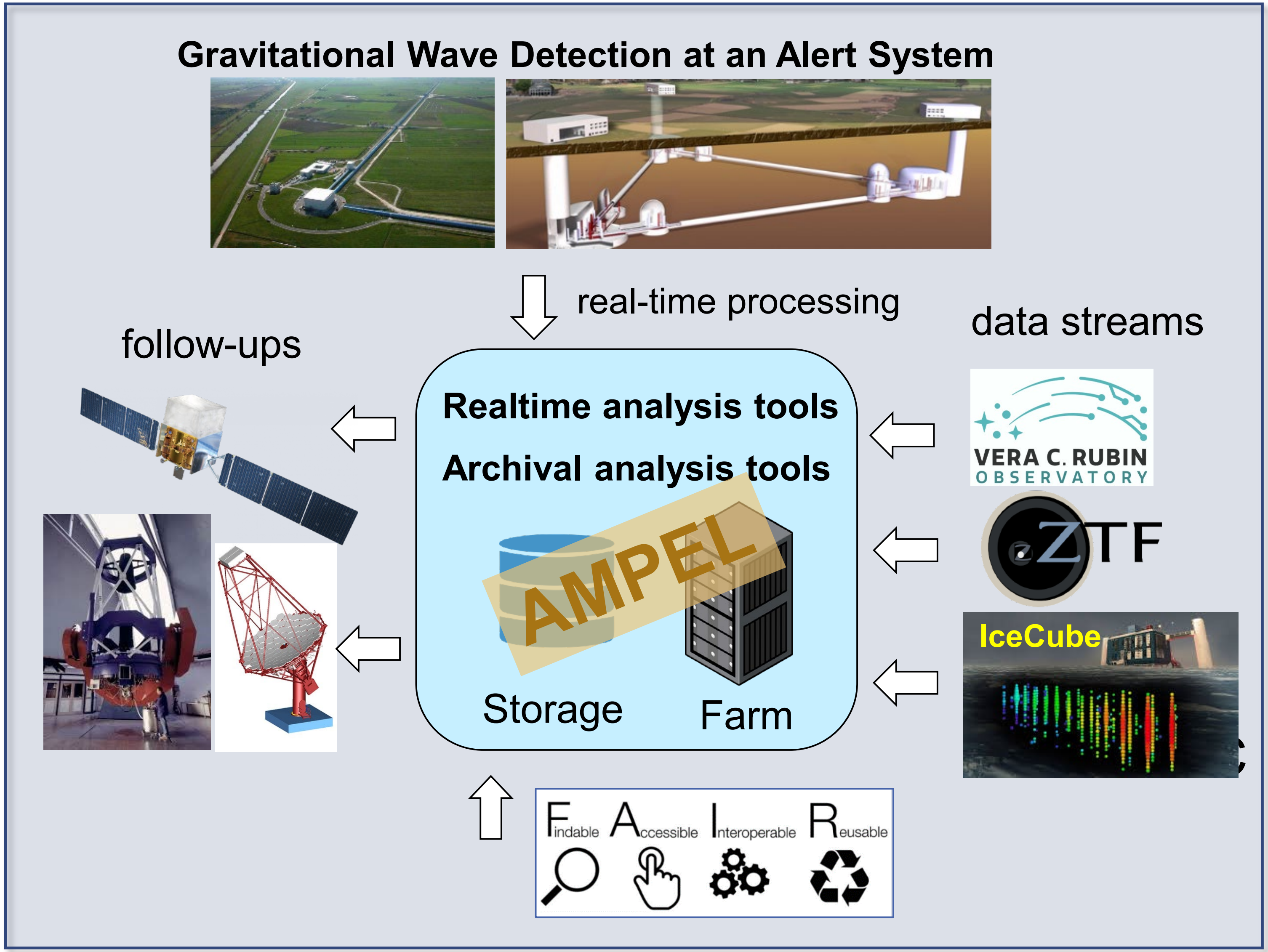
Realtime Multimessenger

Tista Mukherjee, IAP
(A. Haungs, R. Engel)
Karlsruher Institut für Technologie

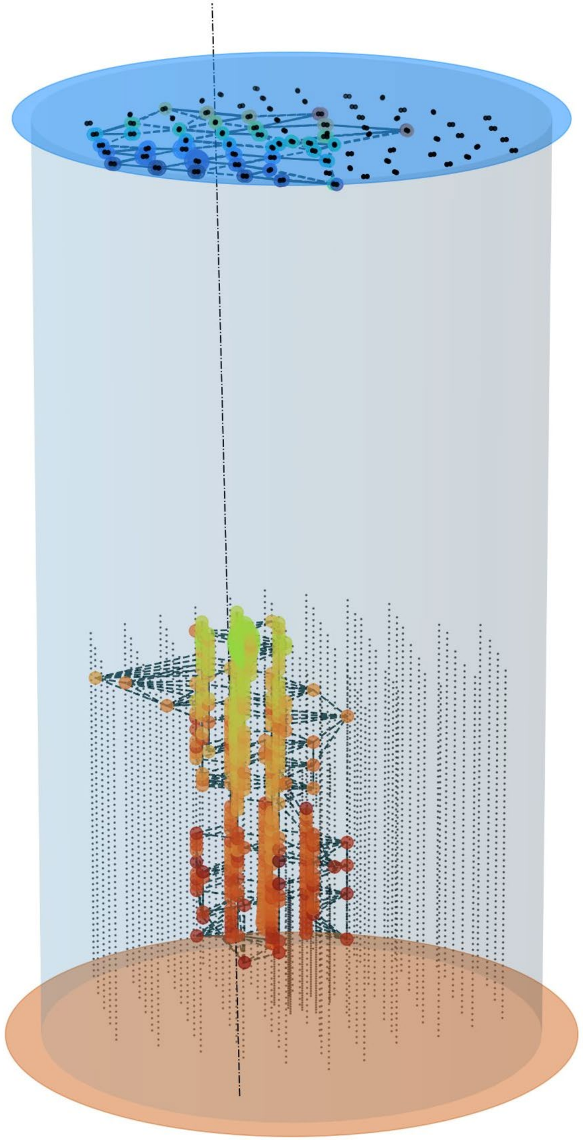
Preparation of multi-messenger follow-up studies of gravitational wave or neutrino events

1. Multi-messenger follow-up studies of gravitational wave and neutrino events (alert systems)
2. Enhancement of environmental monitoring system at Virgo and Einstein Telescope
3. Gravitational wave observations as part of a multi-messenger astroparticle physics data center

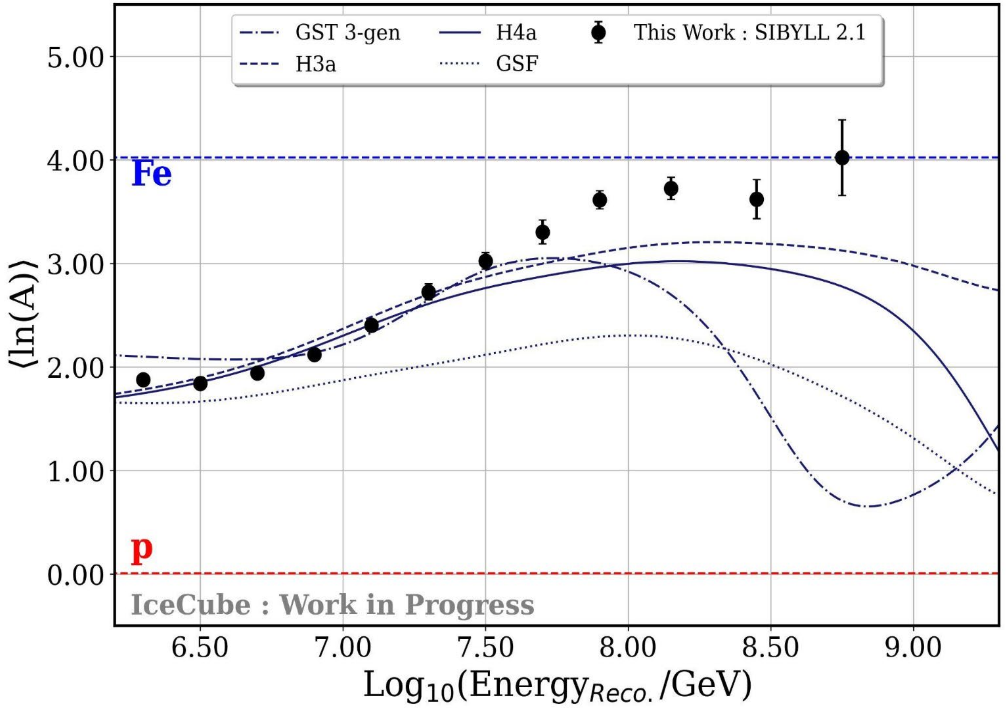
- is based on expertise and competences available at Helmholtz
- has close cooperation of Einstein Telescope, CTA, IceCube and Pierre Auger groups
- preparatory work by AMPEL group [J.Nordin et al., Astron.Astrophys. 631 (2019) A147 e-Print:1904.05922]



IceCube: Cosmic Ray Composition Analysis

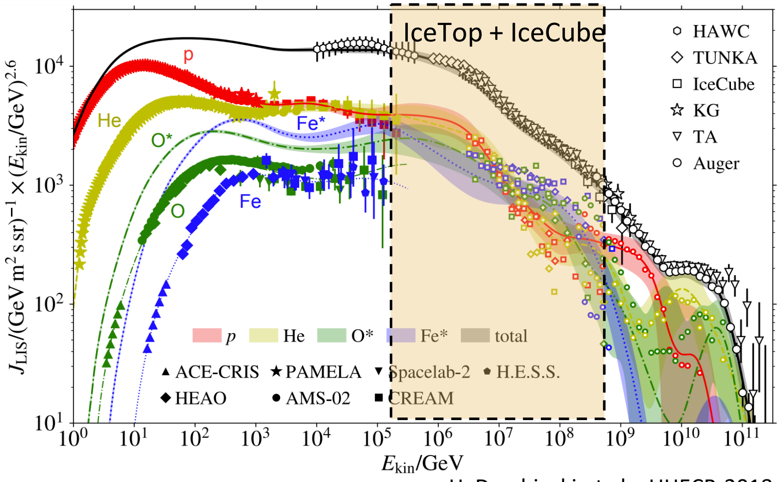


- Cosmic ray composition analysis based on Graph Neural Network application
- Sensitive to details of hadronic interaction models (in CORSIKA)
- First application results in (too?) heavy composition at high-energies (> 10^{17} eV)



Paras Koundal, KIT
PhD thesis, defended on July, 14, 2023

IceCube, PoS (ICRC 2023) 334

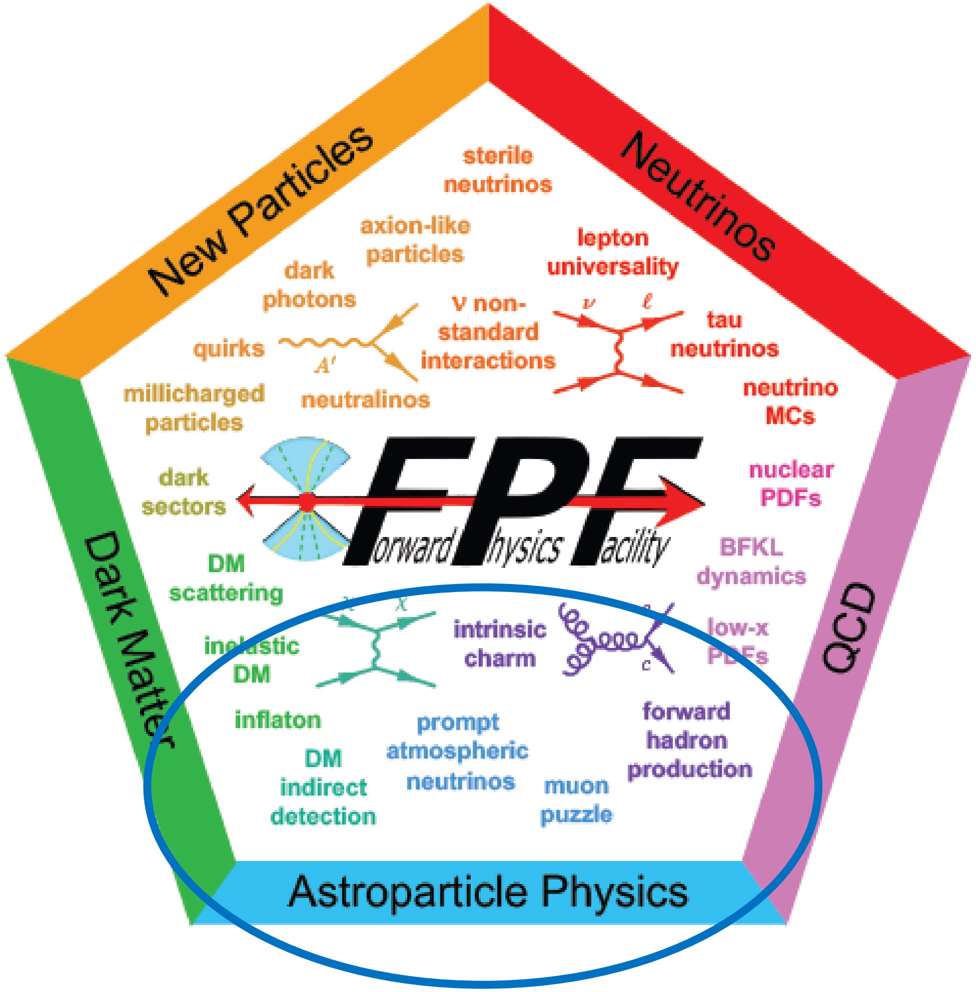


H. Dembinski et al. , UHECR-2018

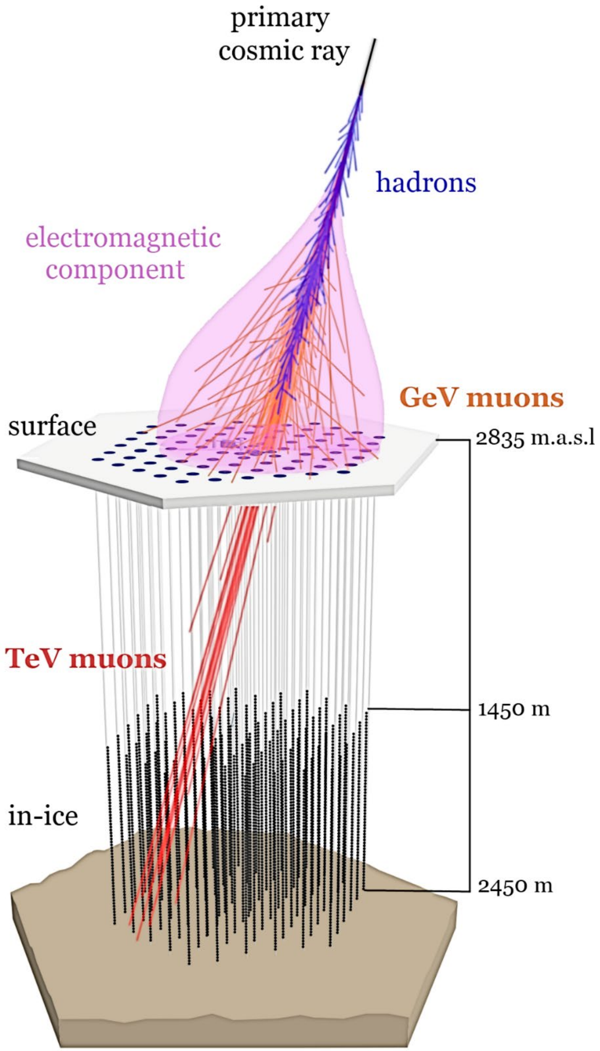
IceCube Connection to particle physics: FPF

Forward Physics Facility at LHC

- *Particle production in the far-forward region (EAS) have large uncertainties*
  - Limits measurements of the cosmic ray mass composition (e.g. Pierre Auger Observatory, IceCube Neutrino Observatory, …)
  - Prompt atmospheric neutrino production is important background for astrophysical neutrino searches (e.g. IceCube Neutrino Observatory, KM3NeT, …)
  - Limits the validity of air-shower simulations with CORSIKA, C8
- *Measurements at the FPF will reduce associated uncertainties!*
  - FPF Short Paper: Phys. Rep. 968 (2022) arXiv:2109.10905
  - FPF White Paper: J. Phys. G: Nucl. Part. Phys. 50 (2023) arXiv:2203.05090



Dennis Soldin, KIT (=> Utah)
Convener FPF Working Group for Light Hadron Production



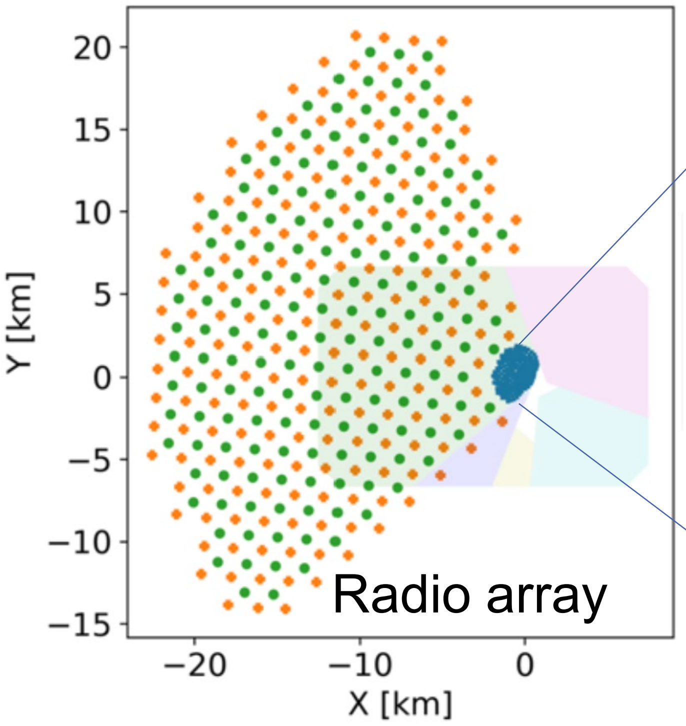
IceCube Upgrade

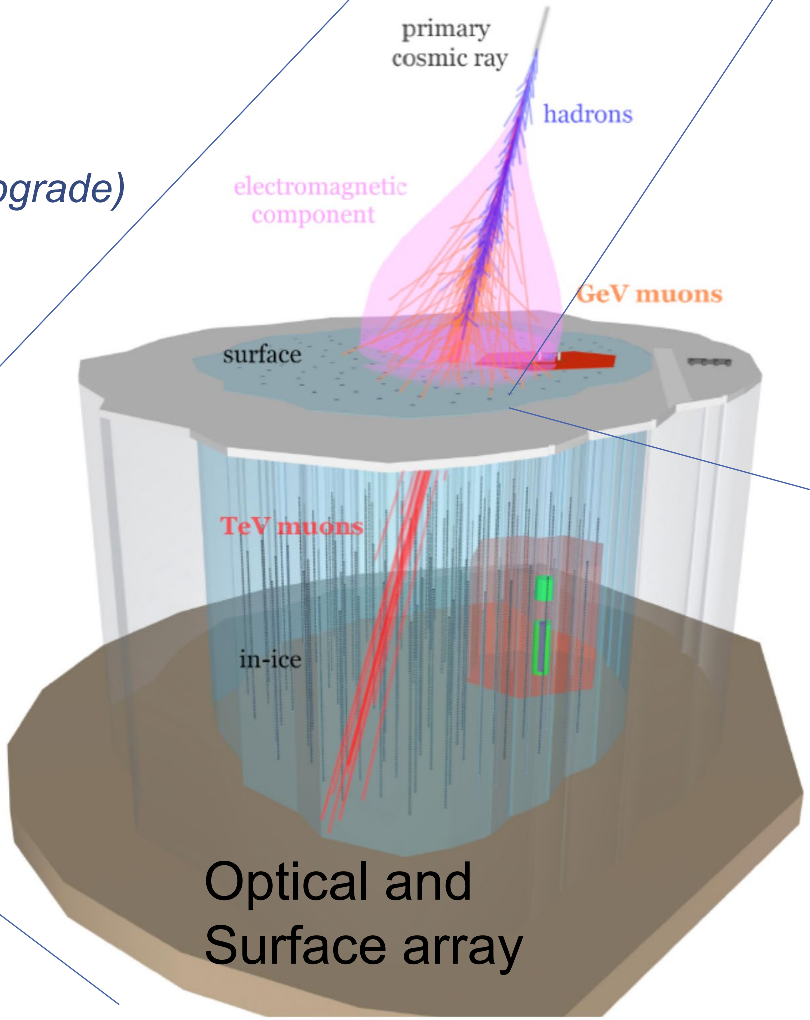
- *NSF Rebaseline of Upgrade Project (7 new strings + Surface Array Enhancement (in Germany))*
  - 7 new strings / 795 new modules
    - Originally Funded for '19-'23, but logistical challenges at the South Pole (COVID etc) => Now funded for '25/26 completion
    - Main Physics Goals:
      - Better understand optical properties of the IceCube ice (largest systematic in most analysis!)
      - Low energy neutrino physics
    - KIT investment: 10,000 PMTs for mDOMs
  - 32 hybrid surface stations (each 8 scintillator panels, 3 radio antennas, 1 DAQ)
    - construction of surface stations at KIT
    - Prototype station in operation

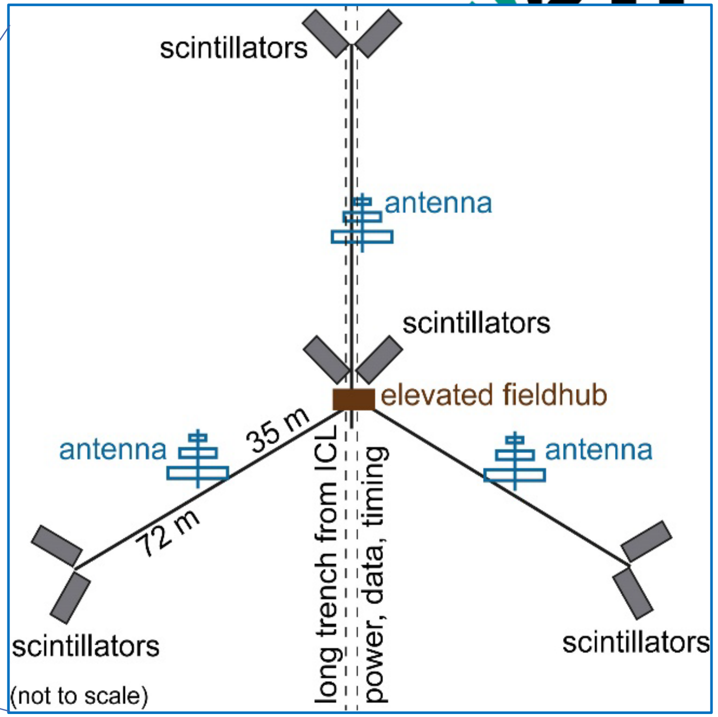
mDOM:402+22
(5.5% spares)

IceCube-Gen2

- *IceCube-Gen2 consists of 4 components:*
  - *Optical in-ice Array*
  - *Surface Array (scintillators and radio)*
  - *In-ice radio array*
  - *IceCube (with IceTop, Deep Core and Upgrade)*







Surface Station

- Design is advanced and being documented in the Technical Design Report (submission 2023) consisting of 3 parts:
  - Science
  - Instrumentation
  - Logistics, Deployment, Operation

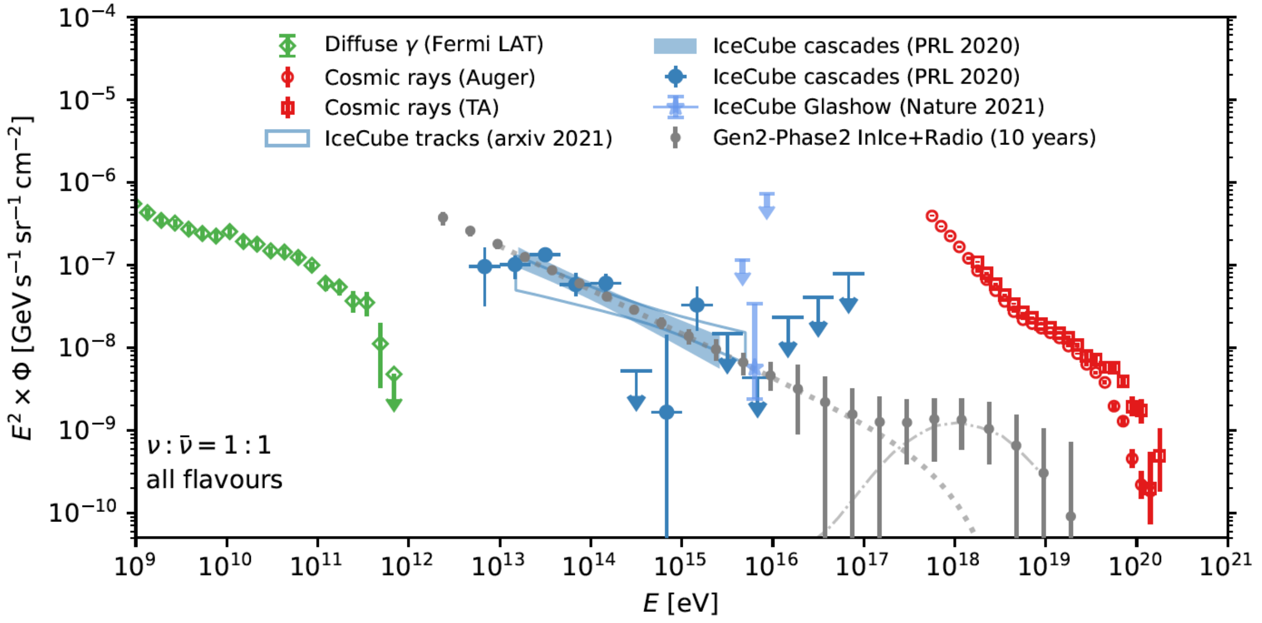
(KIT scientists involved in all parts)

IceCube-Gen2

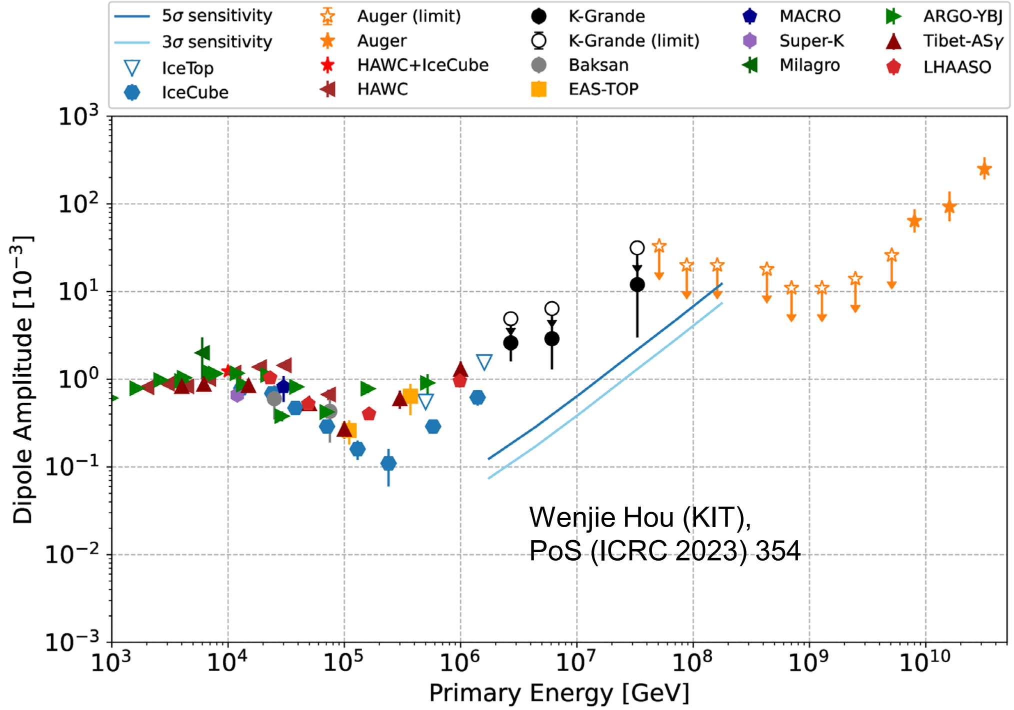
KIT is committed to IceCube-Gen2

- *Search for Point Sources*
- *Neutrino Oscillations*
- *Sterile Neutrinos*
- *Indirect Dark Matter Search*
- *High-energy Cosmic Rays 100 TeV – 1 EeV*

➔ *Deployment planned for 2027-35*



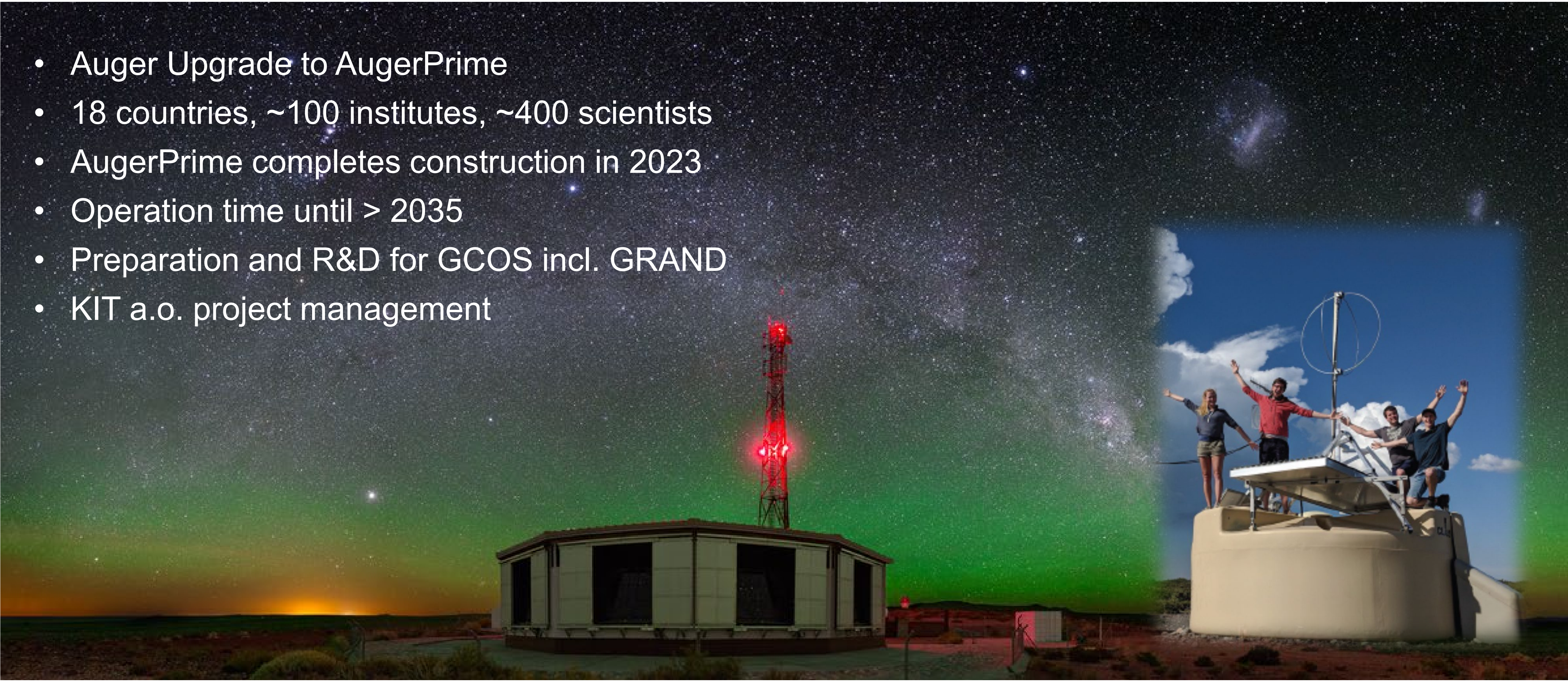
Predicted neutrino spectrum for 10 years IceCube-Gen2



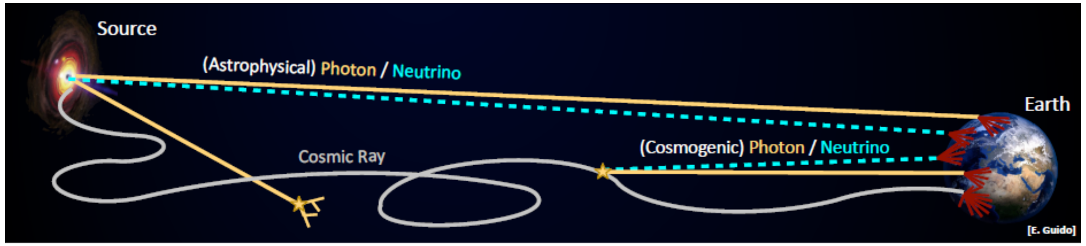
Predicted sensitivity to cosmic ray anisotropy for 10 years IceCube-Gen2

Pierre Auger Observatory

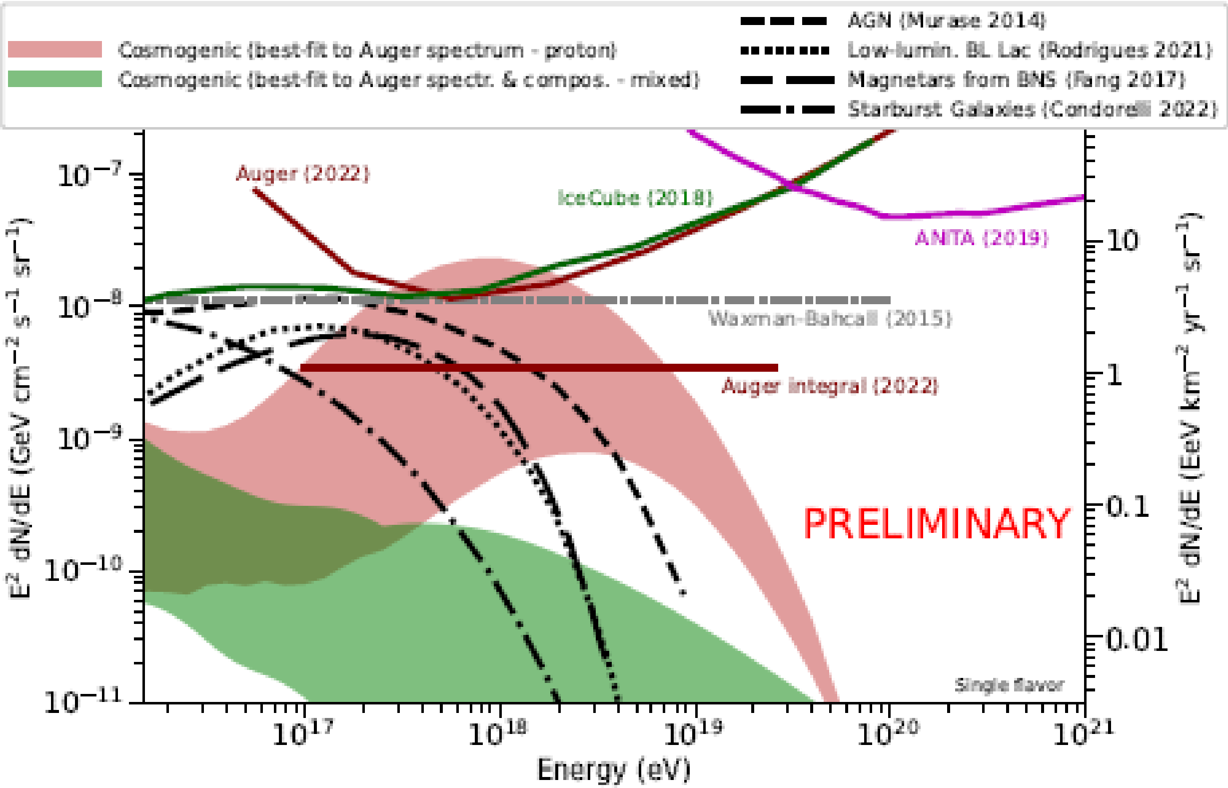
- Auger Upgrade to AugerPrime
- 18 countries, ~100 institutes, ~400 scientists
- AugerPrime completes construction in 2023
- Operation time until > 2035
- Preparation and R&D for GCOS incl. GRAND
- KIT a.o. project management



Pierre Auger Observatory – HE Neutrino Limit



- *Best sensitivity to UHE neutrinos slightly below 10^{18} eV*
- *Integral limit for neutrino energies between 10^{17} eV and 2.5×10^{19} eV: 3.5×10^{-9} GeV cm^{-2} s^{-1} sr^{-1}*
- *Corresponding limits on point-like sources of neutrinos complement IceCube and ANTARES*



Auger, PoS (ICRC2023)1488

GRAND - the Giant Radio Array for Neutrino Detection

Karlsruher Institut für Technologie

At KIT NUTRIG project (with France):

→ Development of autonomous radio trigger

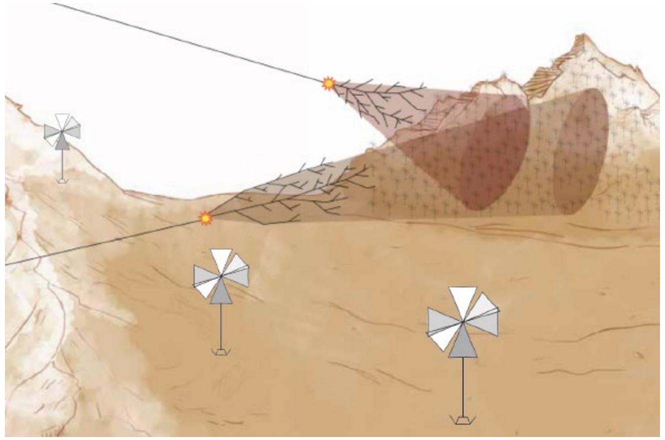
Signal Model
- Update model for GRAND sites
- Frequency band of 50-200 MHz
- Characterise behaviour of signal

First-Level Trigger
- On antenna level
- Exploit air shower radio pulse characteristics
- Trigger rate of 100Hz to limit data bandwidth

Second-Level Trigger
- On detector level
- Combine signal model & FLT info
- Reduce transient noise

L. Gülzow, J. Köhler, IAP
(T. Huege, M. Roth)

NUTRIG, PoS (ICRC 2023) 990

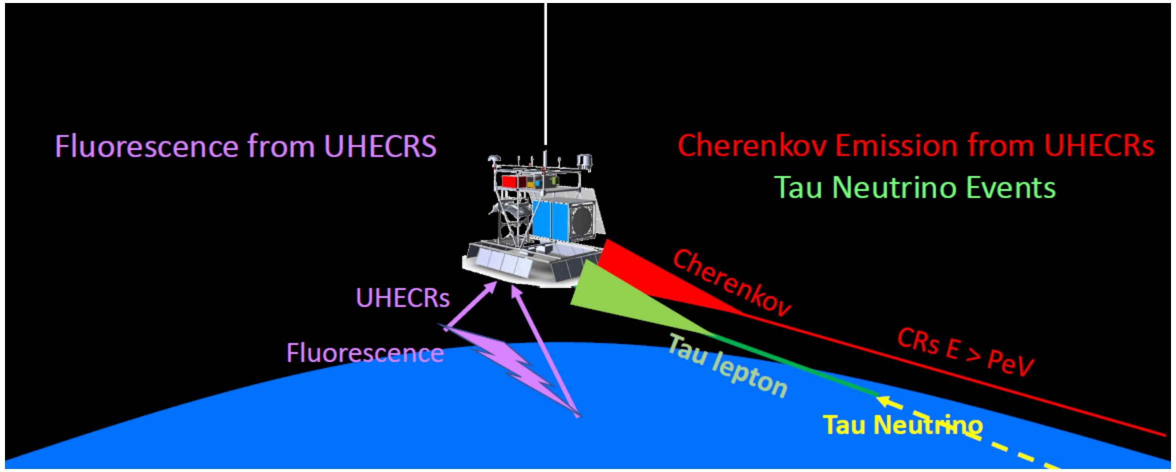


GRAND@Auger site in Malargüe, Argentina

Mountainous area near Ulastai, West China

POEMMA -- SPB-SBR

POEMMA, PoS (ICRC2023)1159



- *POEMMA, 2 satellites, 4 m mirror, design study funded by NASA, launch foreseen mid 30ies*
- *Detection of UHECR and neutrinos*
- *SuperPressureBalloon flight foreseen 2027 as POEMMA testbed*
- *KIT involved in SiPM camera*

Neutrino Astronomy:
The window for observing the universe with high-energy neutrinos is now open!