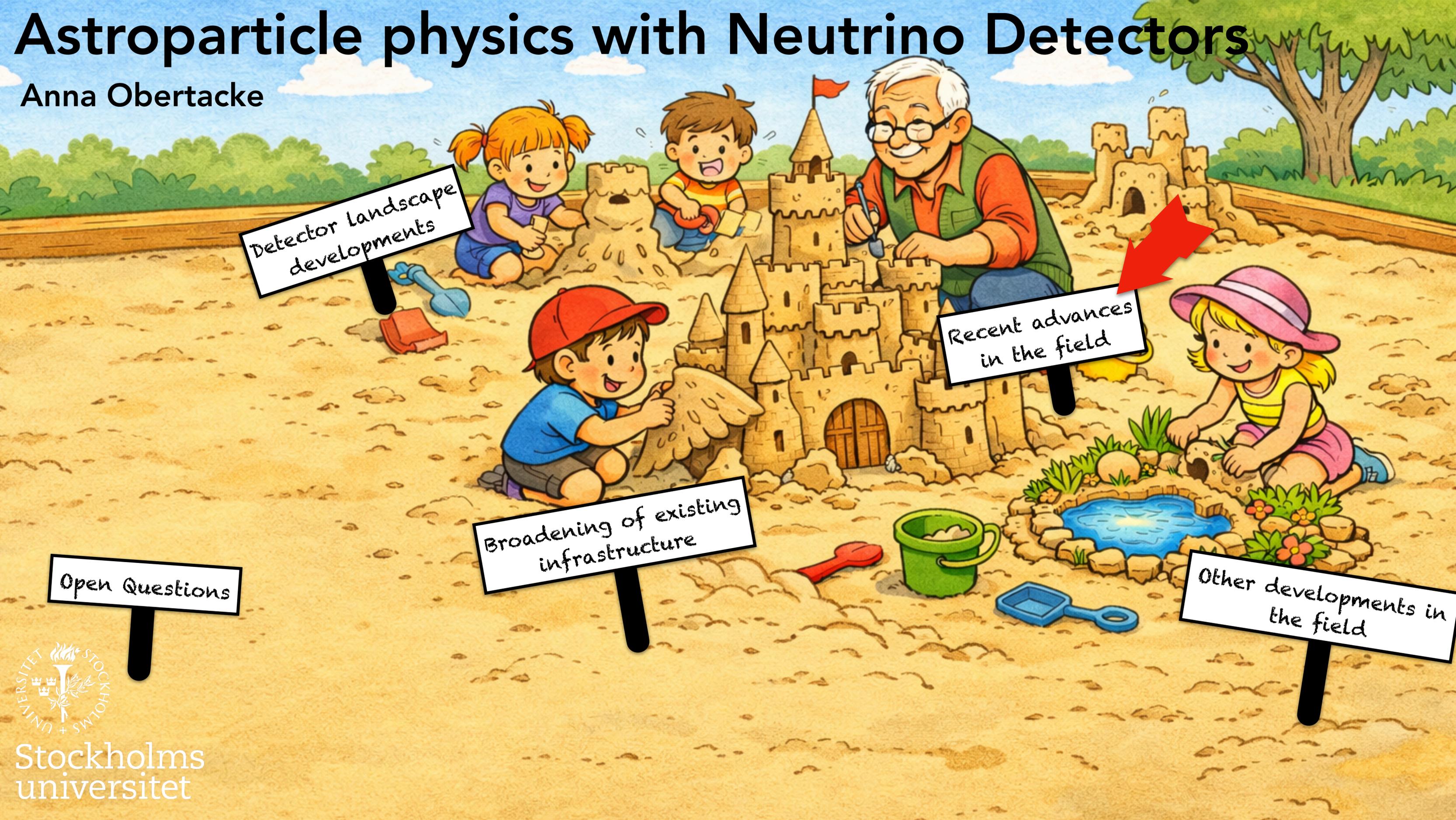


Astroparticle physics with Neutrino Detectors

Anna Obertacke



Detector landscape developments

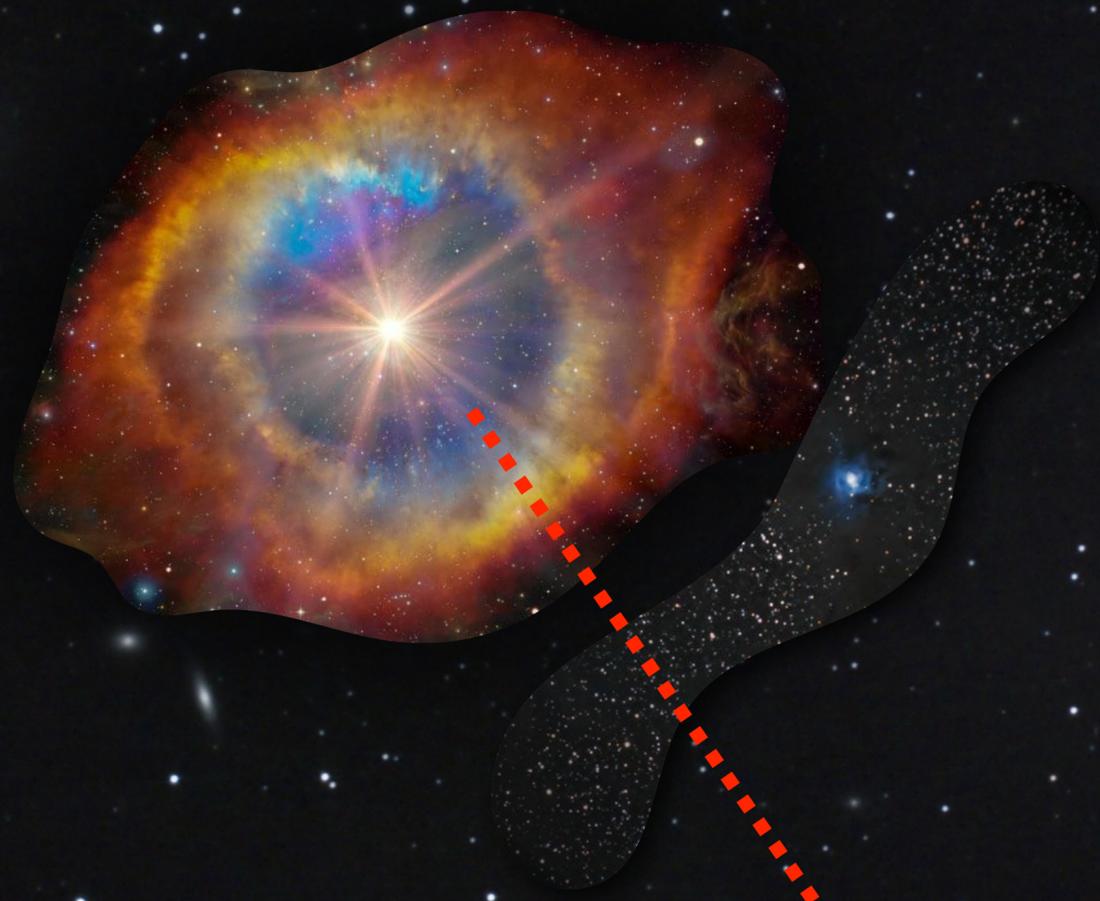
Recent advances in the field

Broadening of existing infrastructure

Open Questions

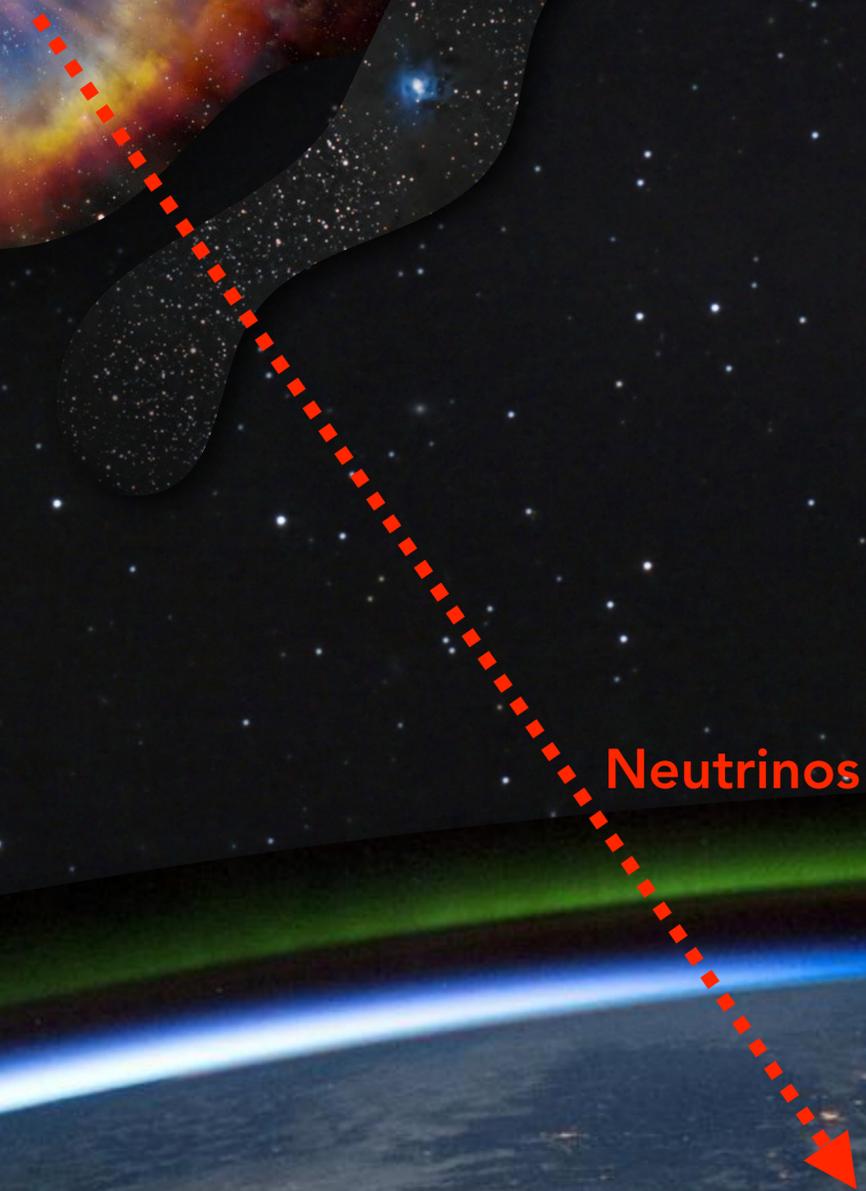
Other developments in the field

Astro-particles



Interstellar
dust cloud

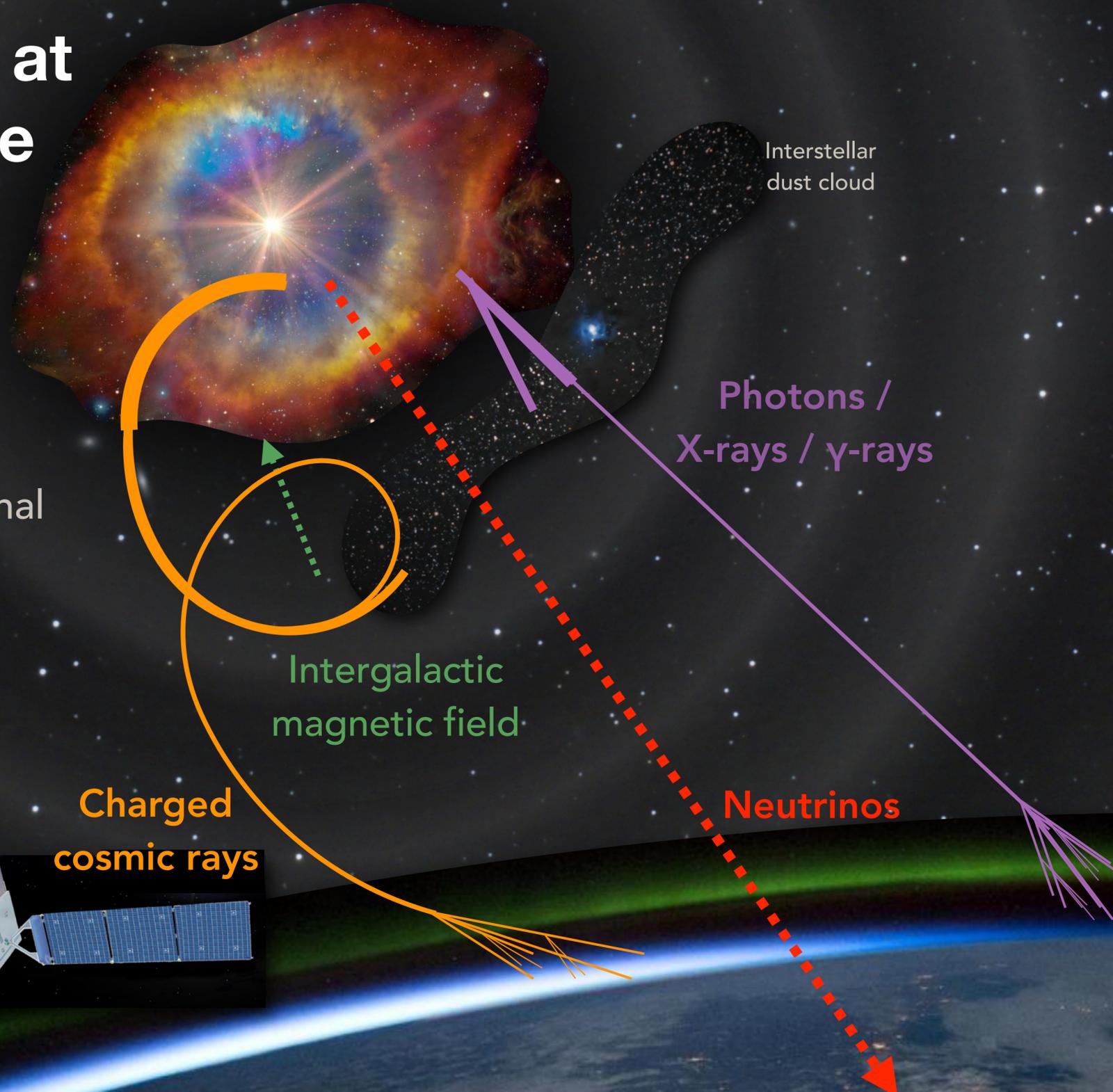
Neutrinos



Astro-particles



Linked at source



Gravitational Waves

Interstellar dust cloud

Photons / X-rays / γ -rays

Intergalactic magnetic field

Charged cosmic rays

Neutrinos

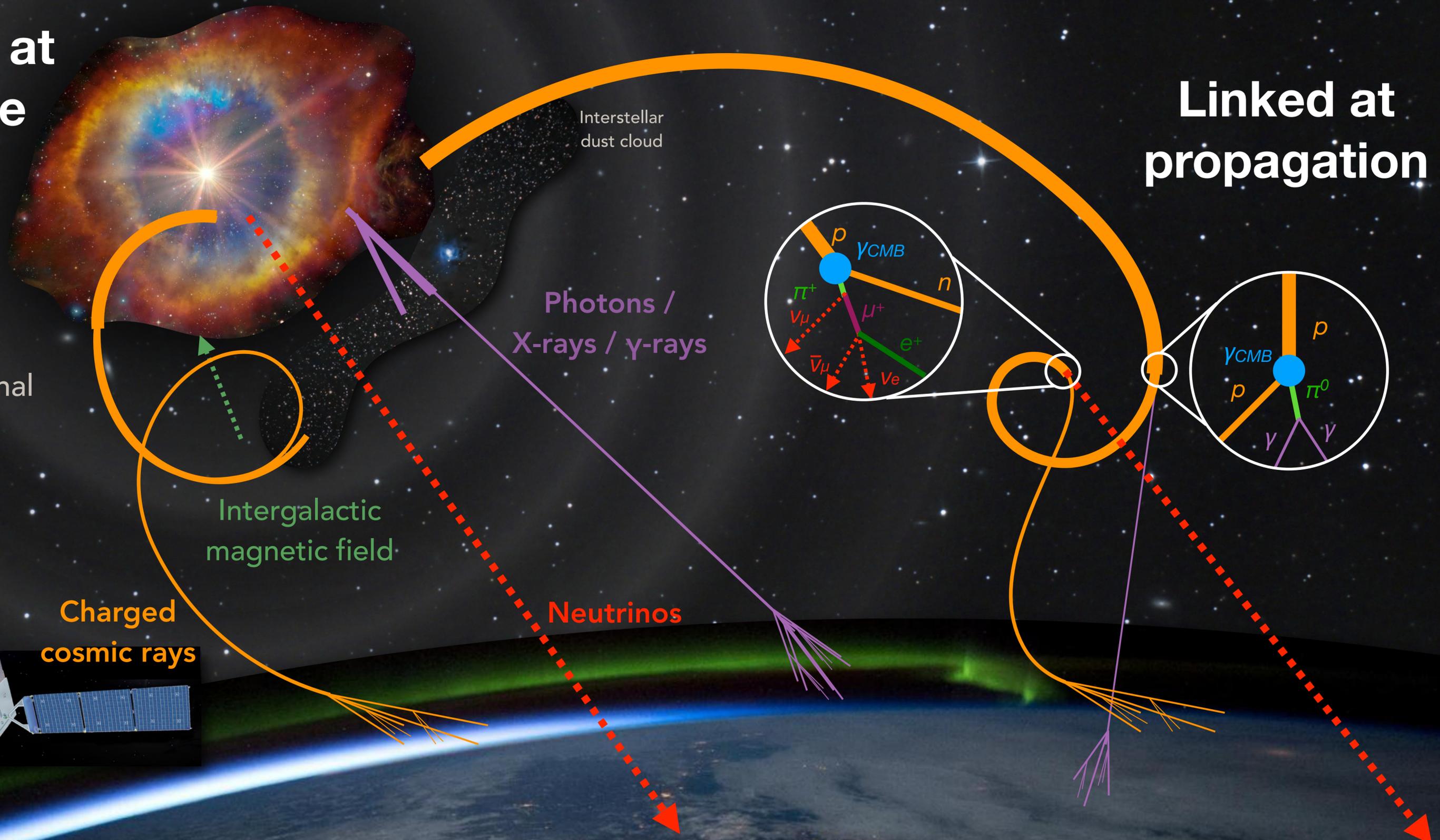


Astro-particles



Linked at source

Linked at propagation



Interstellar dust cloud

Photons / X-rays / γ-rays

Gravitational Waves

Intergalactic magnetic field

Charged cosmic rays

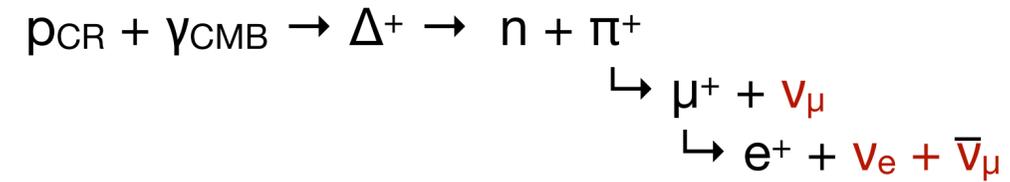
Neutrinos



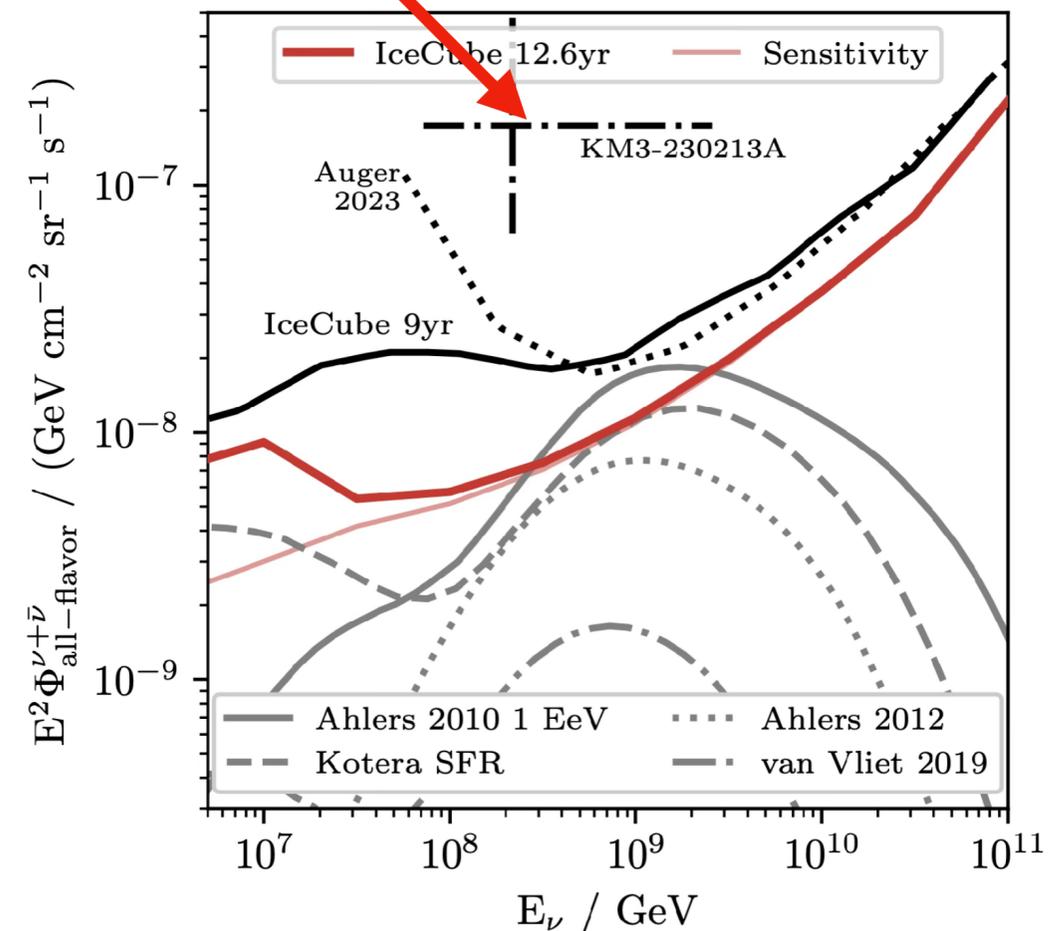
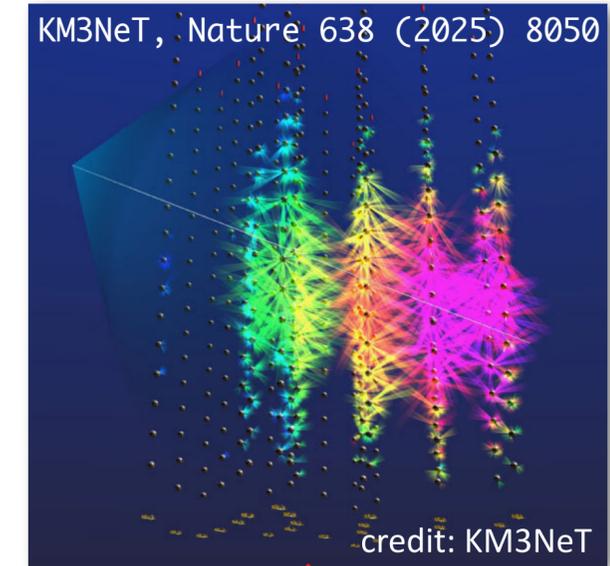
Astro-particle physics: cosmogenic neutrinos



- cosmic ray cutoff at $> 10^{20}$ eV might be due to GZK effect, giving extreme high energy neutrinos



- new data of IceCube + Auger constrains proton fraction to at most 80%
- slight tension 2.9σ with KM3NeT's ~ 220 PeV event



Fundamental research questions

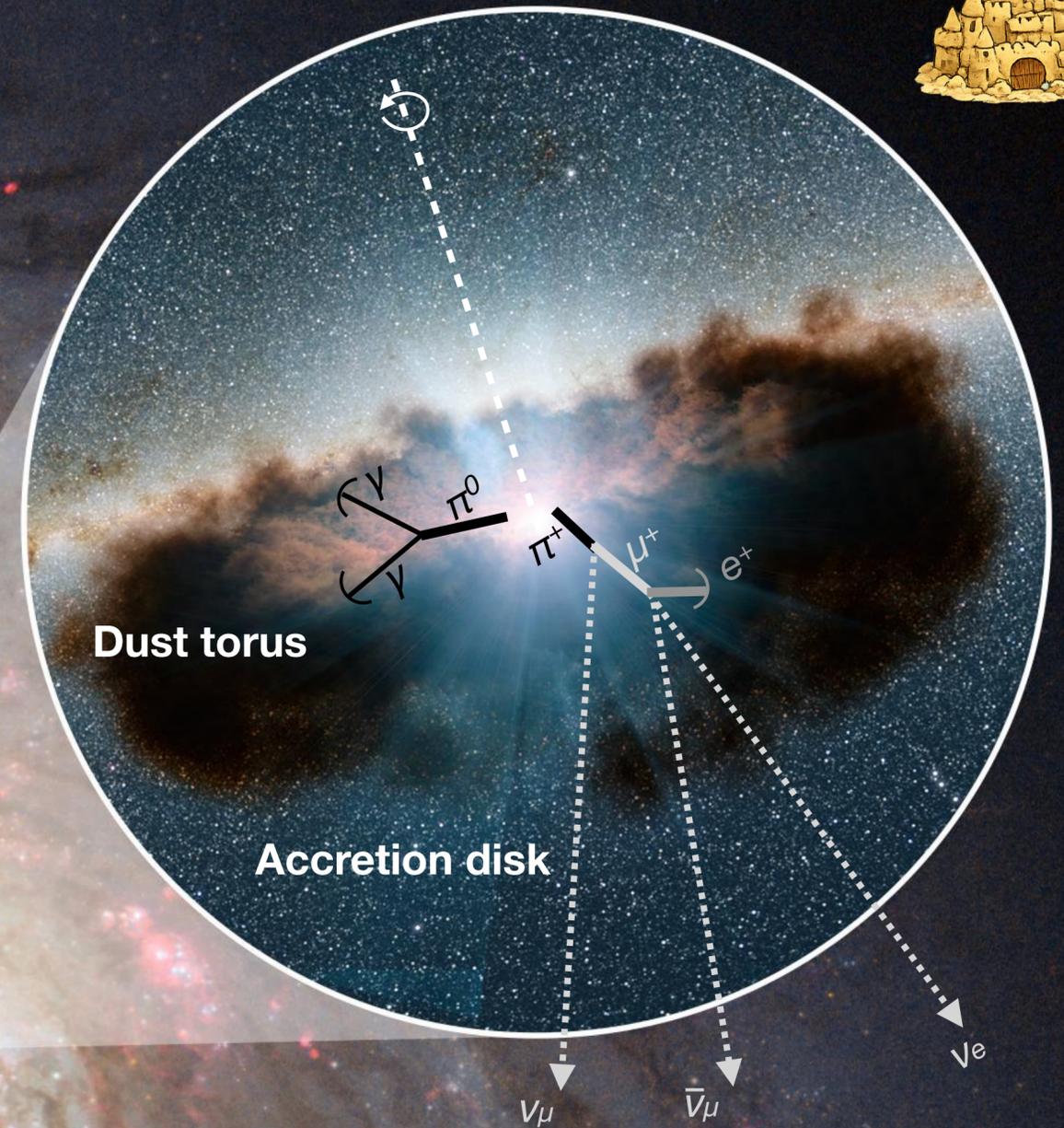
benefiting from joint astro- + particle physics effort, e.g.

- nature and origin of cosmic rays
- muon number in cosmic ray air showers
- prompt neutrino flux

Astro-physics: NGC 1068



- first evidence for a hidden galactic core
- X-ray bright AGN with a dust torus
- photo-nuclear interactions inject pions producing gamma-rays and neutrinos
- only neutrinos escape the inner core



Fundamental research questions

- acceleration mechanisms for cosmic rays
- processes in and anatomy of AGN

Multi-messenger physics: "Discovery" of TXS0506-056



Single neutrino triggered

Alarm sent out

Follow-ups start

Bright in gamma-rays during trigger

Follow-ups in all wavelengths / particles

Several further positive reports

Inspection of archival data

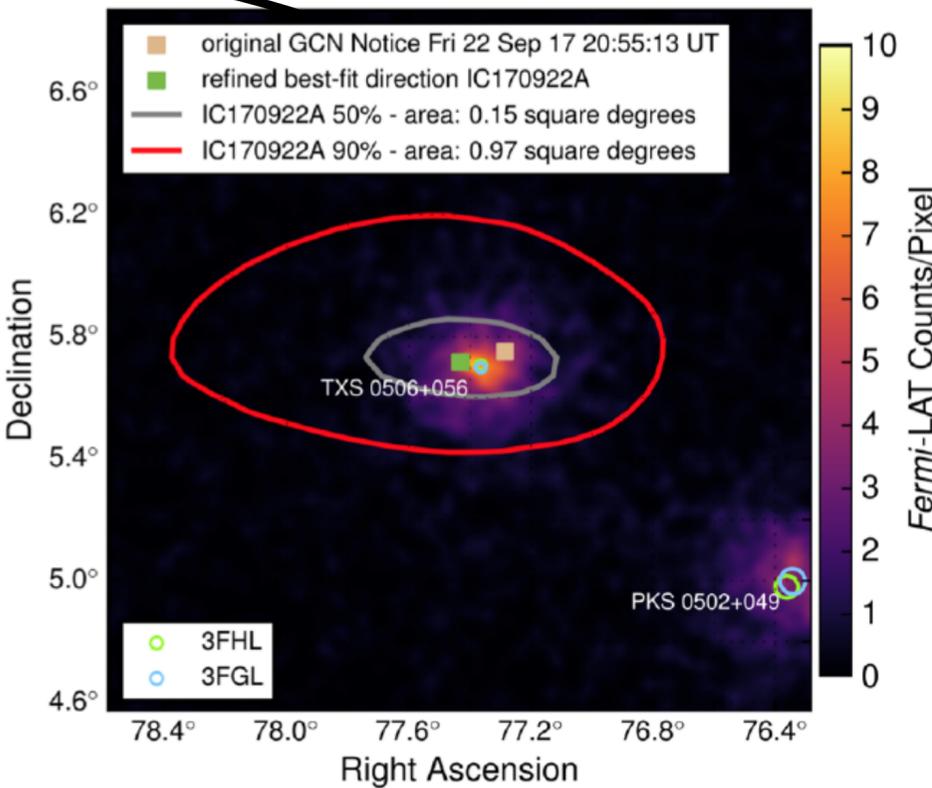
Neutrino excess in archival data found

TXS not bright in gamma-rays at earlier excess

Re-measure basic information

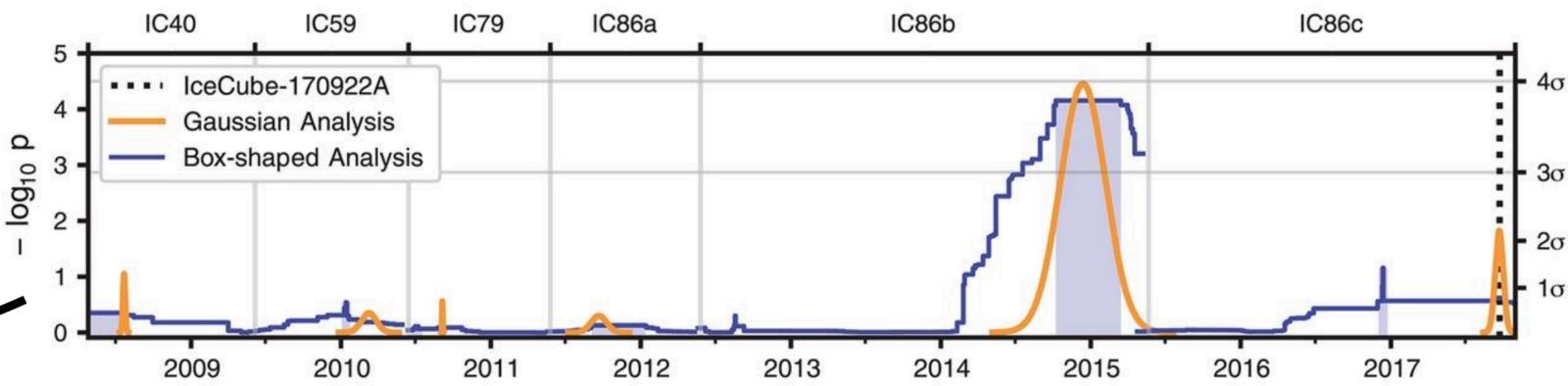
TXS distance corrected

TXS luminosity corrected



IceCube, FERMI-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S. INTEGRAL, KANATA, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift, NuSTAR, VERITAS, VLA/17B-403 teams, ...
 Science 361,6398 (2018)

IceCube, Science 361,6398 (2018)



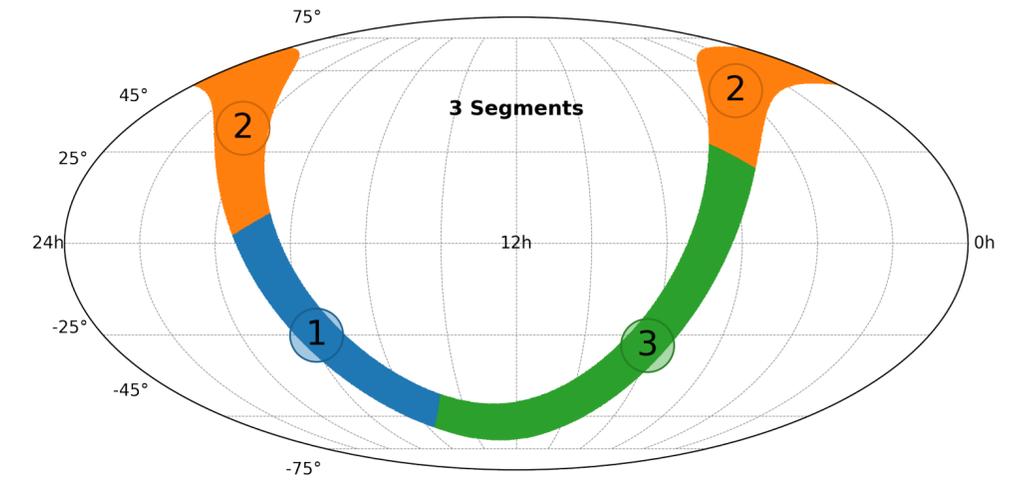
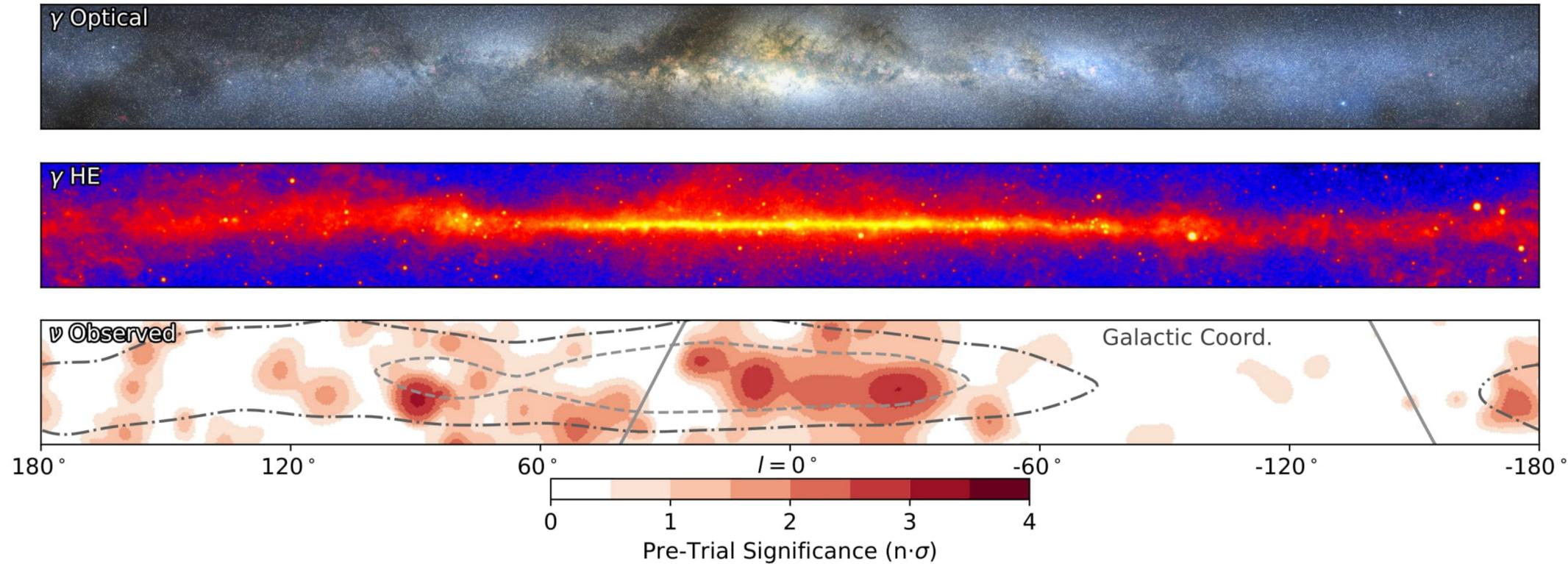
Fundamental research questions

- new source types

Astronomy: galactic plane in neutrinos



IceCube, Science 380, 6652, 1338-1343 (2023)

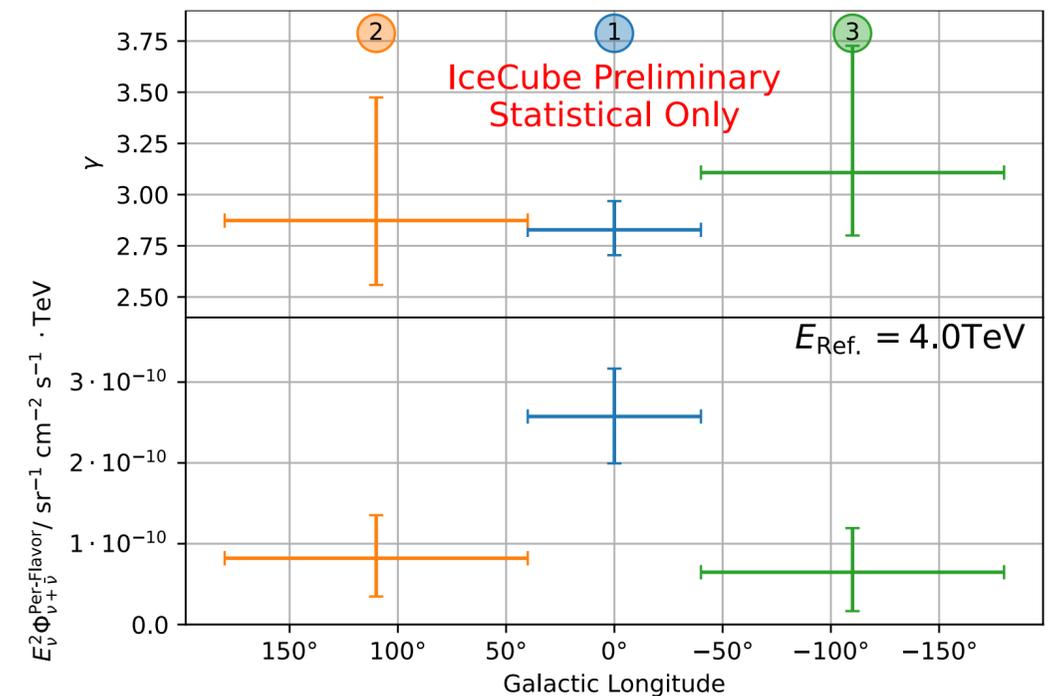


From discovery to characterization:

- model independent analysis
- first measurement of the energy spectrum slope of the neutrino flux along the galactic plane

Fundamental research questions

- propagation of cosmic rays within our galaxy
- new baseline for neutrino oscillation studies
- Dark Matter



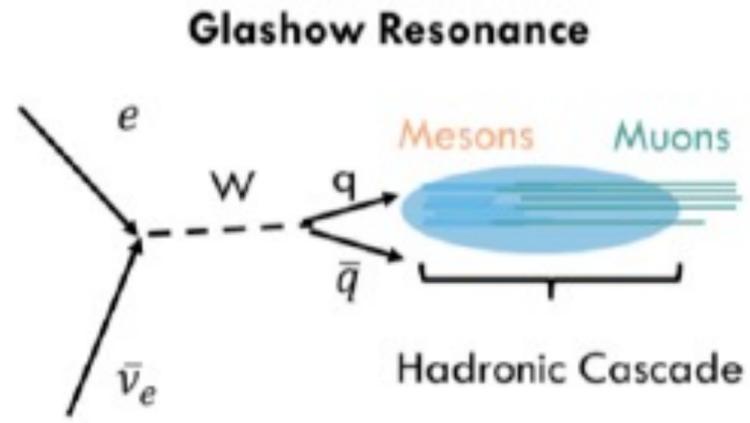
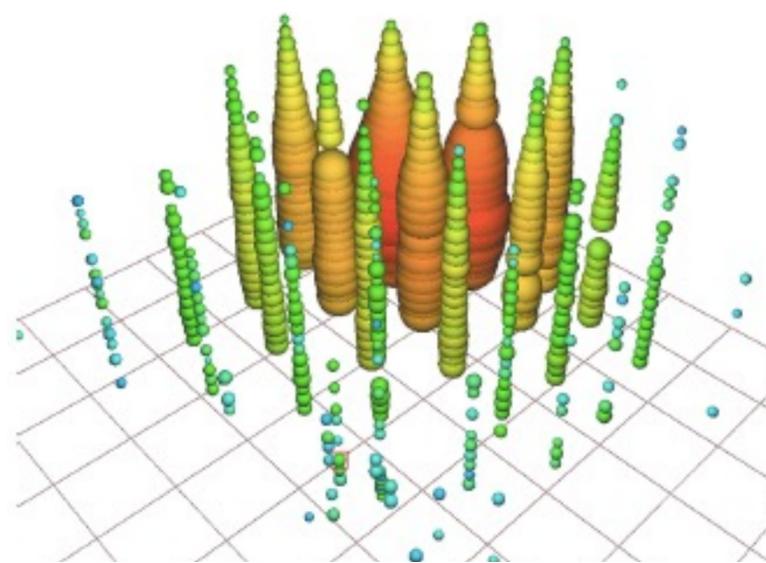
IceCube, POS 1130, ICRC 2025 (arXiv:2507.08097)

Particle physics: Glashow resonance

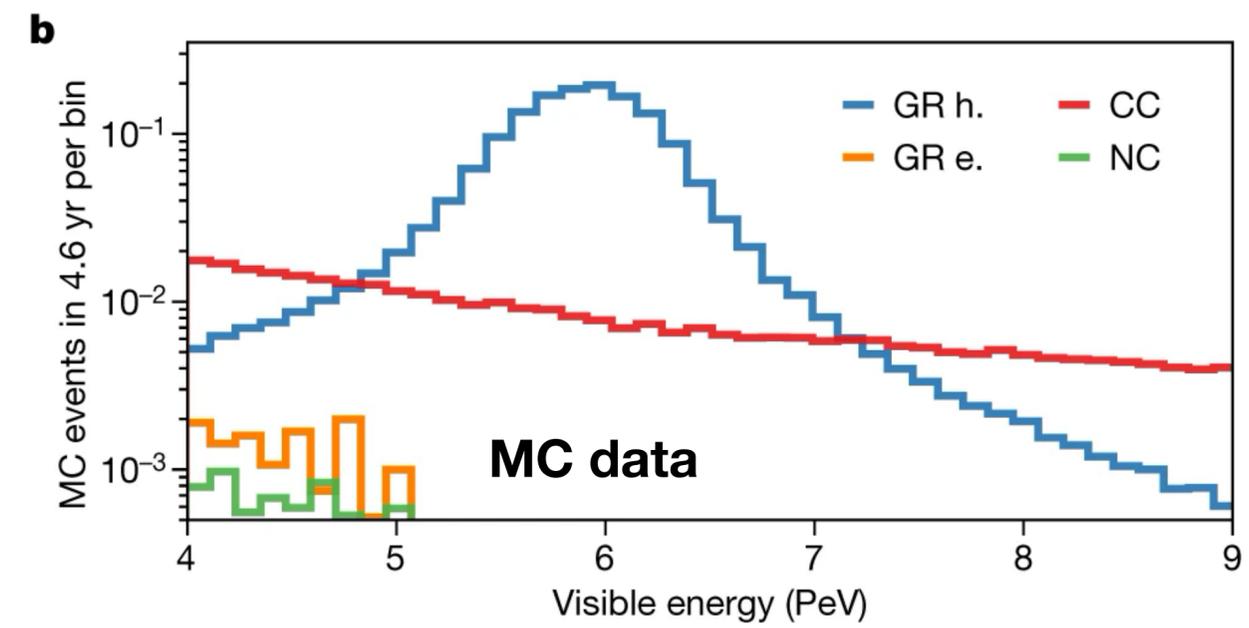
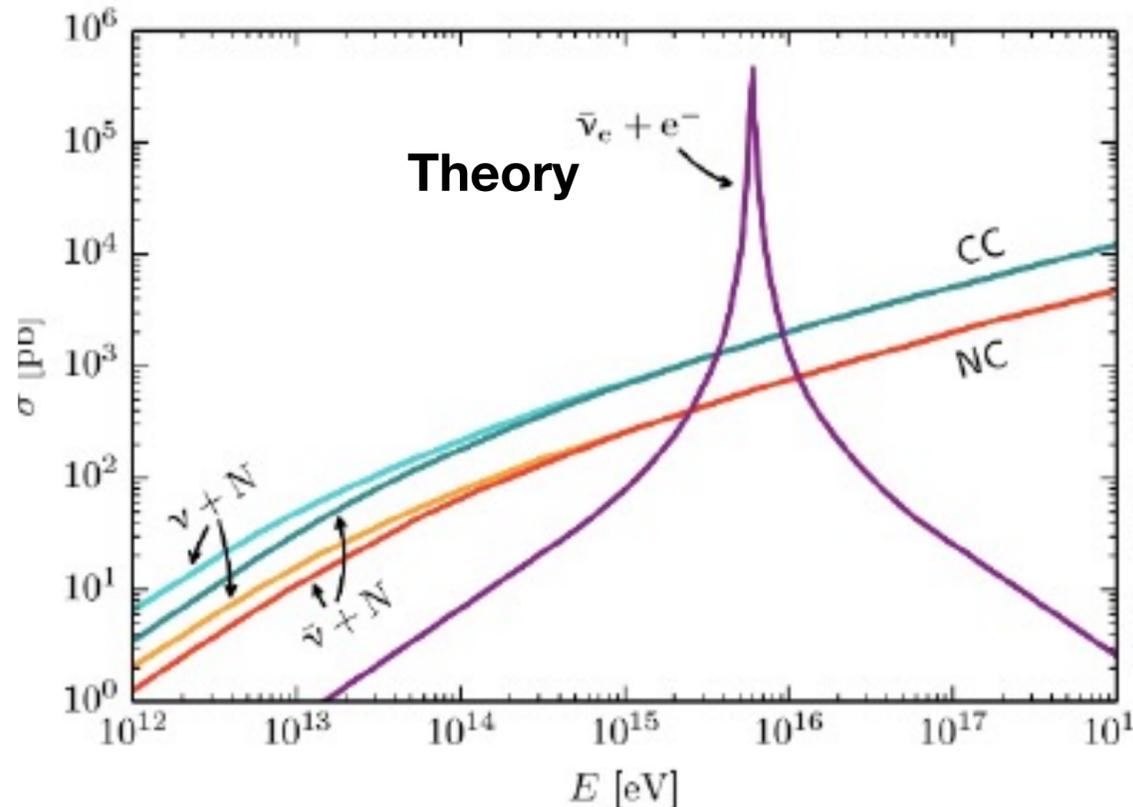


- some predicted phenomena are out of reach of artificial accelerators
- hadronic shower depositing ~ 6.05 PeV is evidence of the Glashow resonance
- so far the only chance to distinguish neutrinos from anti-neutrinos at HE

Event view
(partially contained cascade)



neutrino mixing parameters
neutrino cross section
earth tomography



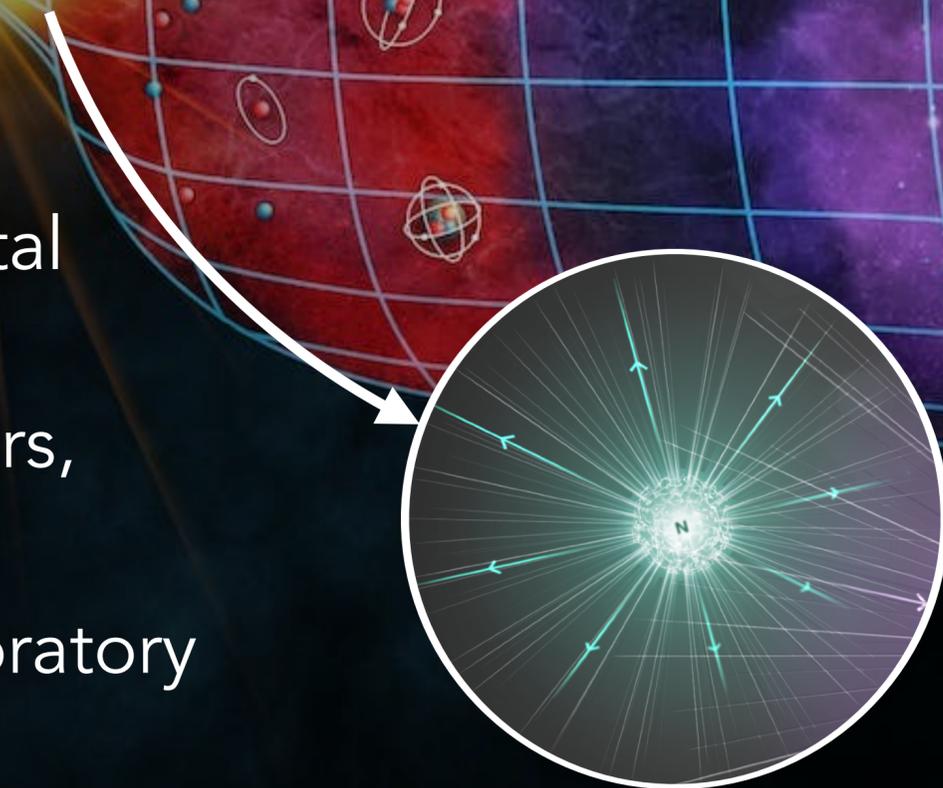
- Fundamental research questions**
- neutrino mixing parameters
 - neutrino mass (differences)
 - neutrino cross section
 - Earth tomography

Physics beyond the Standard Model



Capabilities of neutrino detectors

- world leading sensitivities in various fields (Lorentz-invariance, source flavor measurement, WIMP annihilation in the Sun, ...)
- high energy fundamental physics (neutrino cross section, heavy mediators, dark sector, ...)
- complementary to laboratory experiments



Fundamental research questions

- Nature of Dark Matter
- Nature of Dark Energy
- Extensions of the Standard Model
- Matter / Antimatter asymmetry

Neutrino physics

- neutrino mixing parameters
- neutrino mass (differences)
- neutrino cross section
- galactic center as new baseline for neutrino oscillation studies
- ...

Related topics

- Earth tomography
- ...

Astrophysics

- processes in and anatomy of AGN
- new astrophysical source classes
- ...

Cosmic ray physics

- nature and origin of cosmic rays
- acceleration mechanisms for cosmic rays
- propagation of cosmic rays (within our galaxy)
- muon number in cosmic ray air showers
- prompt neutrino flux
- ...

Beyond Standard Model Physics

- Nature of Dark Matter
- Nature of Dark Energy
- Extensions of the Standard Model
- Matter / antimatter asymmetry
- ...

Open Questions



Detector landscape developments

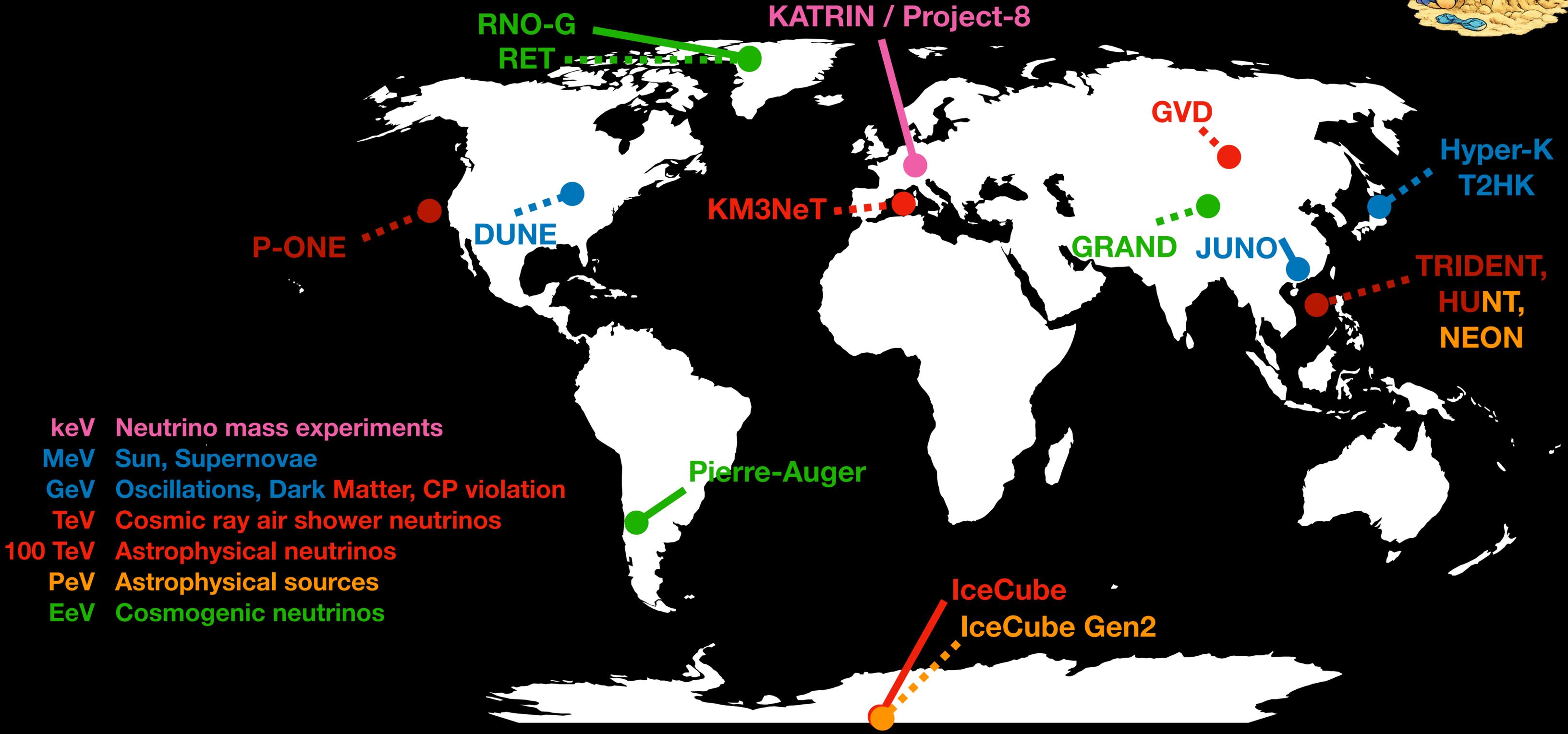
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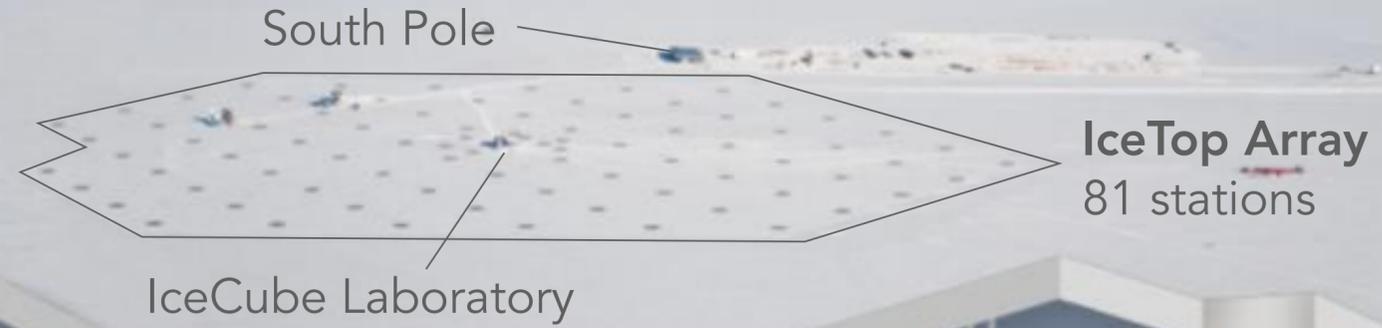
Other developments in the field

Neutrino detectors around the World



- keV Neutrino mass experiments
- MeV Sun, Supernovae
- GeV Oscillations, Dark Matter, CP violation
- TeV Cosmic ray air shower neutrinos
- 100 TeV Astrophysical neutrinos
- PeV Astrophysical sources
- EeV Cosmogenic neutrinos

IceCube



Working principle

- Particles interact with the deep clear ice
- Emitted light is detected by sensors

Fully operational since 2011

Geometry

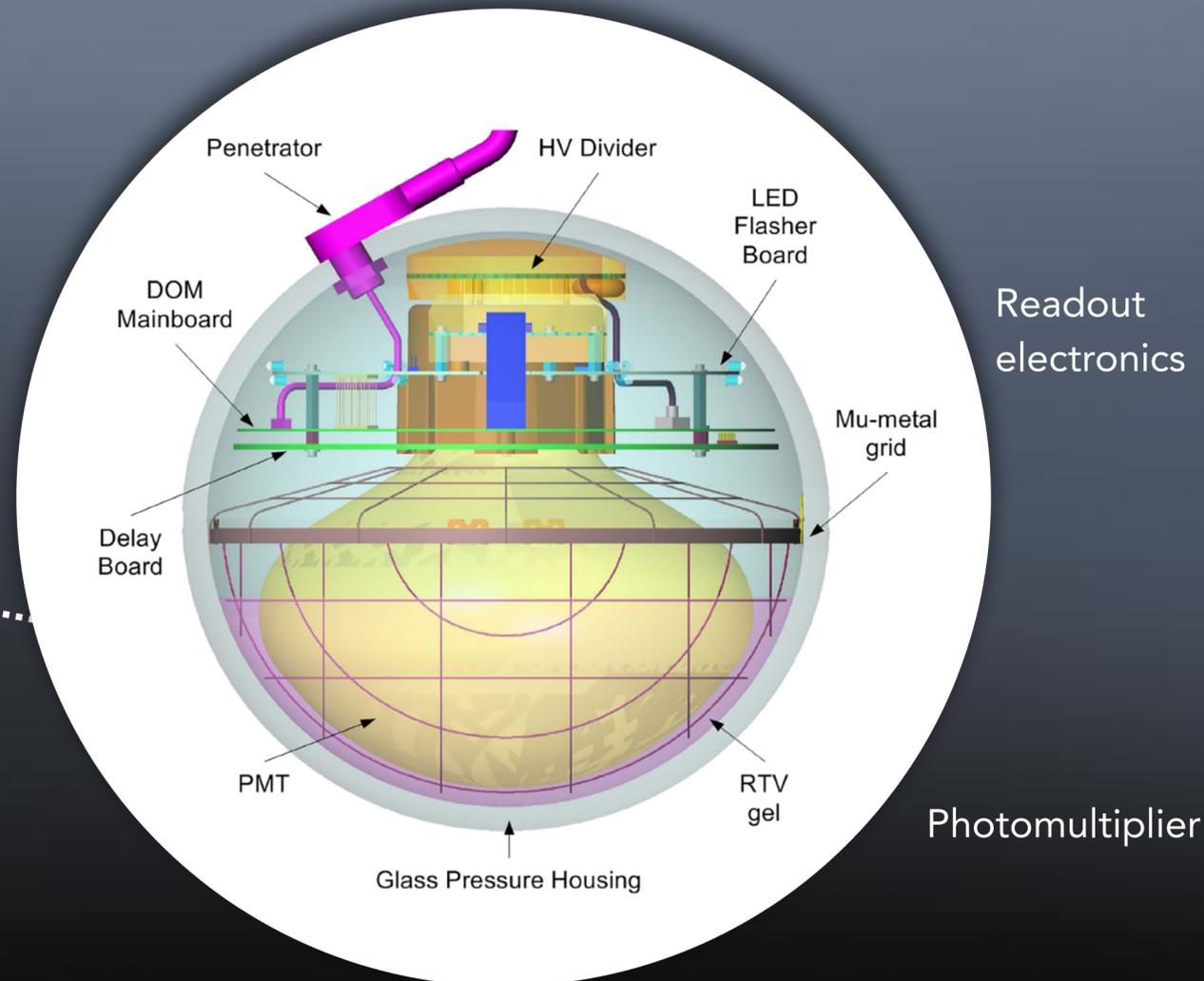
- volume 1 km³
- vertical spacing 17 m
- horizontal spacing 125 m

1450m -

2450m -

InIce Array
86 strings,
each with 60 optical
sensors

Digital Optical Module (DOM)



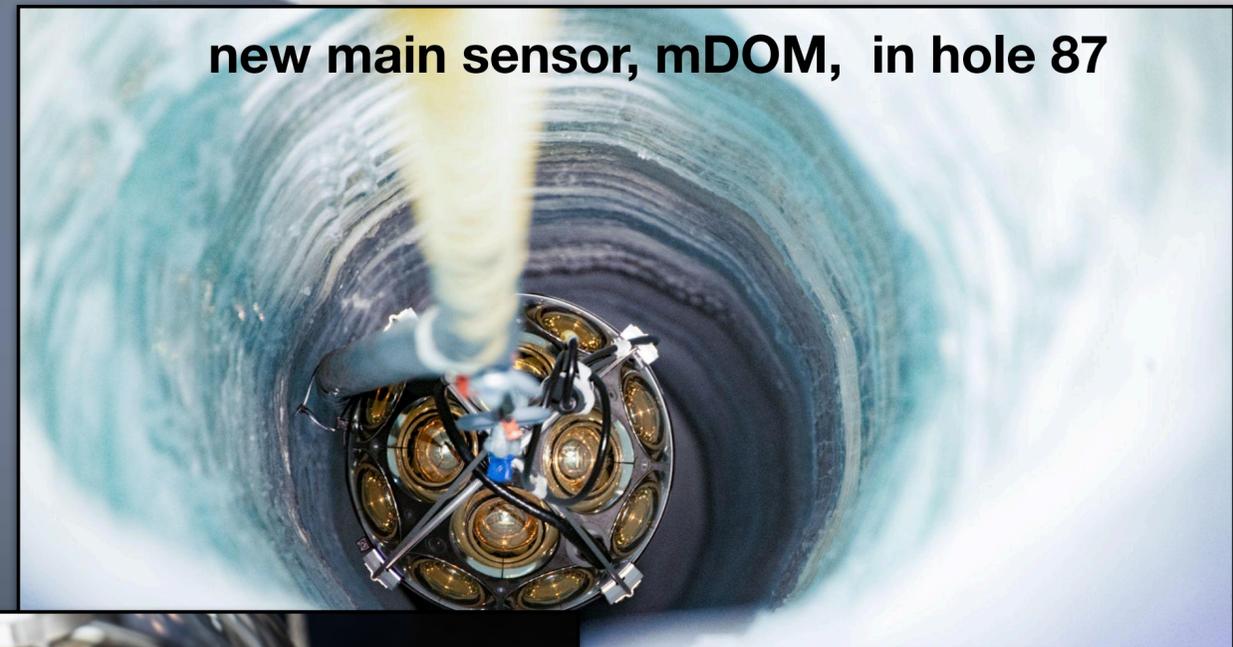
IceCube Upgrade (construction this winter)



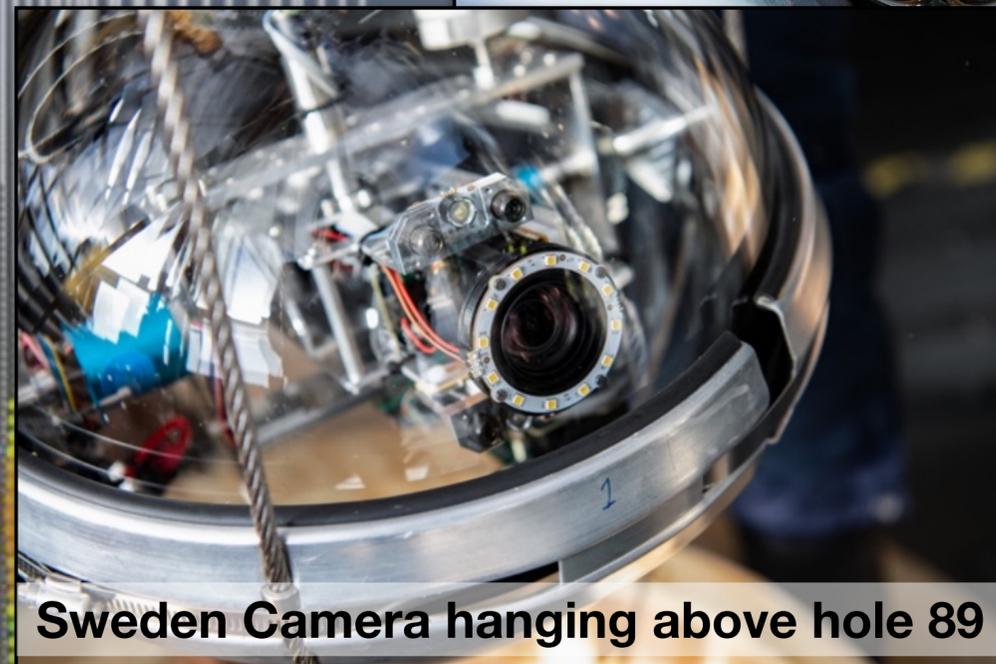
- low energy extension of IceCube down to ~ 1 GeV
- 6 new holes
- ~ 660 new sensors in a dense pattern
- science goals: oscillation, unitarity, calibration

1450m –

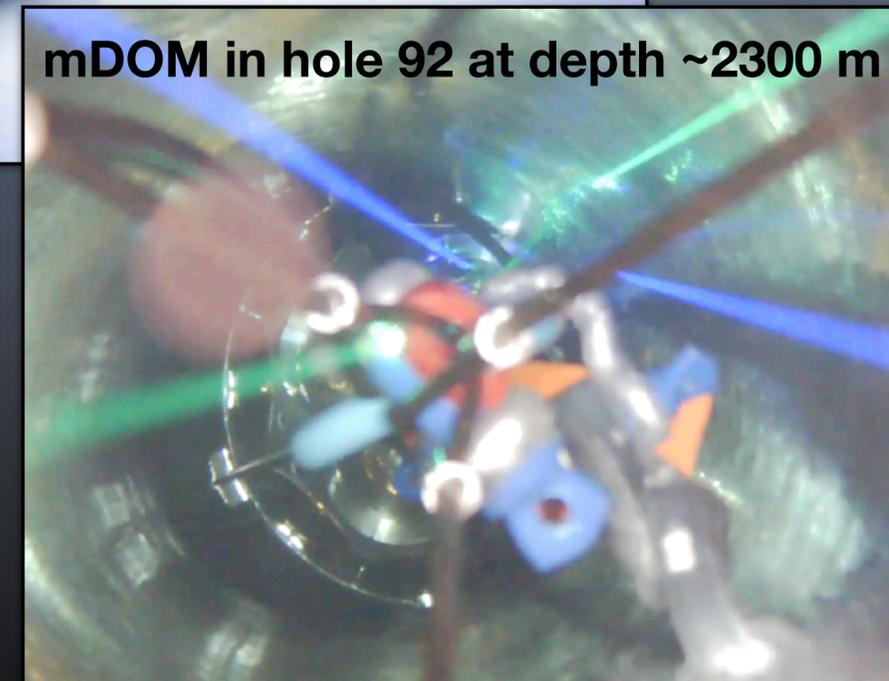
2450m –



new main sensor, mDOM, in hole 87



Sweden Camera hanging above hole 89



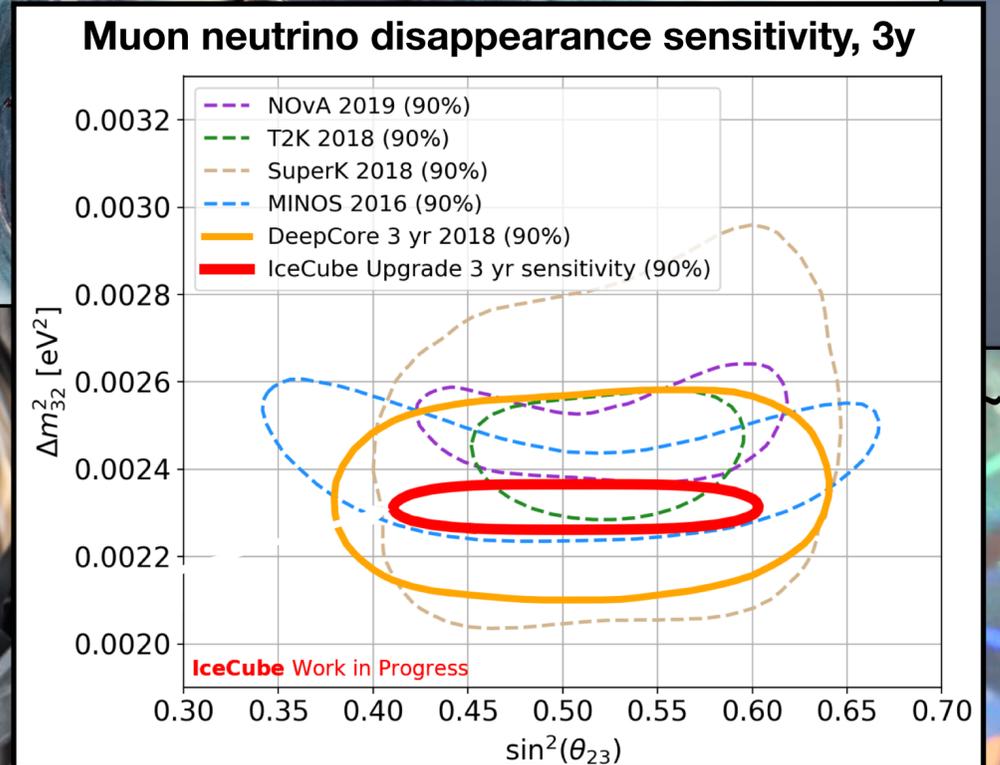
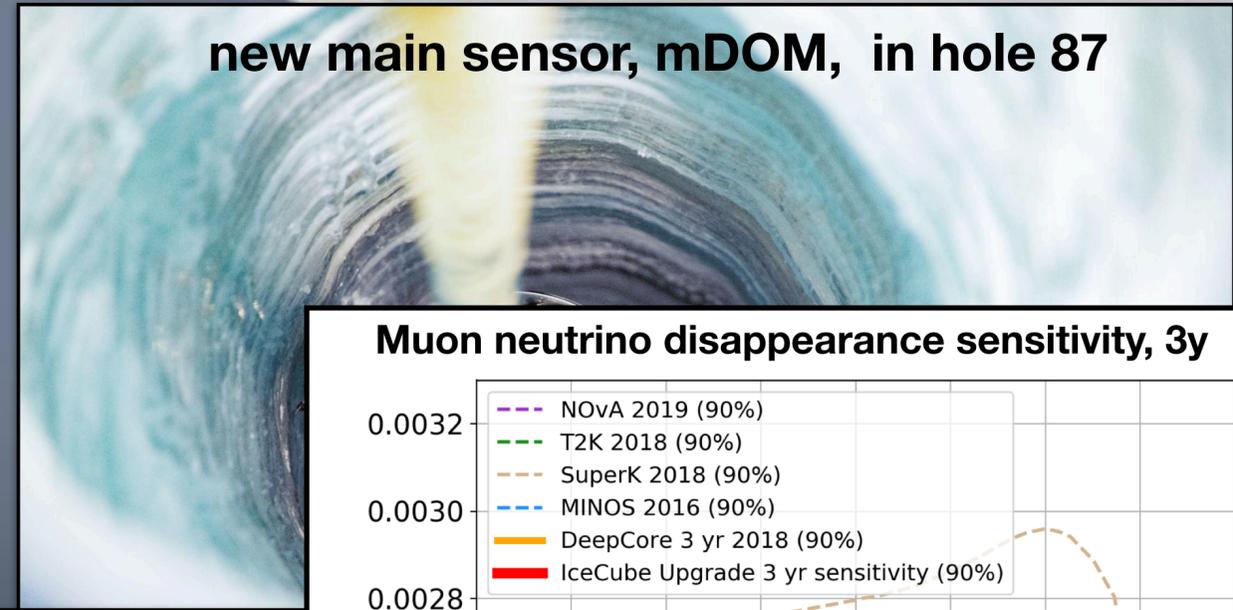
mDOM in hole 92 at depth ~ 2300 m

IceCube Upgrade (construction this winter)



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1450m –



~2300 m

2450m –



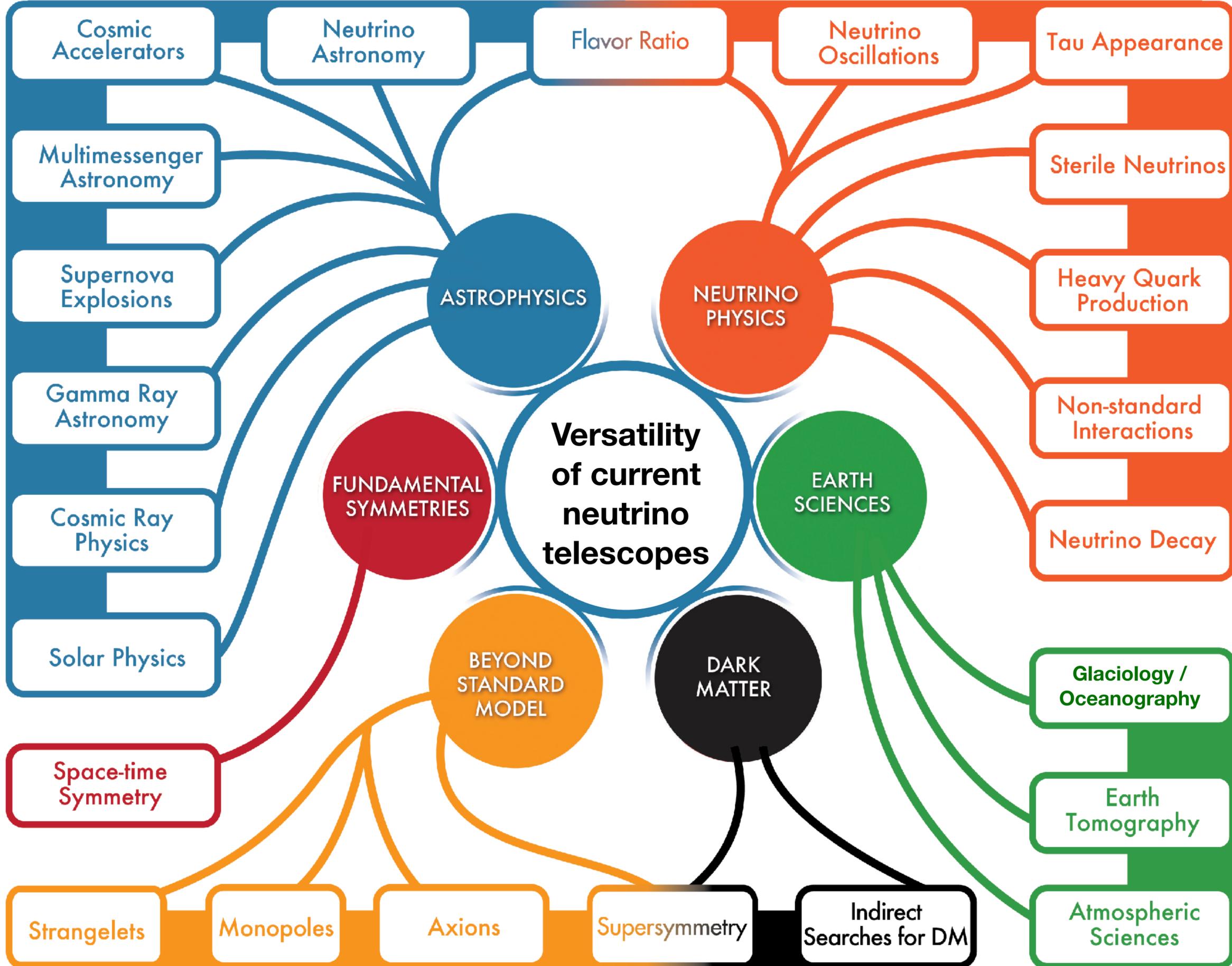
Detector landscape developments

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Other developments in the field

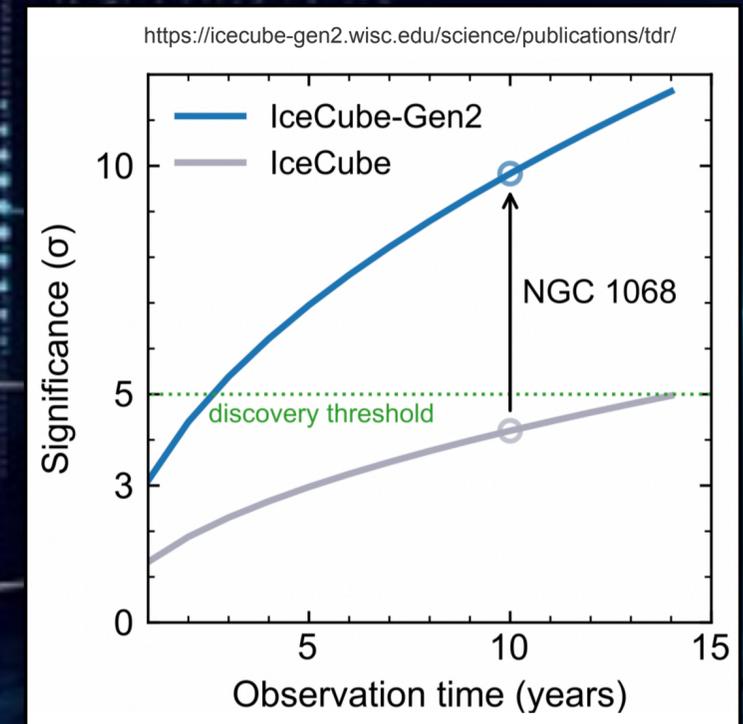
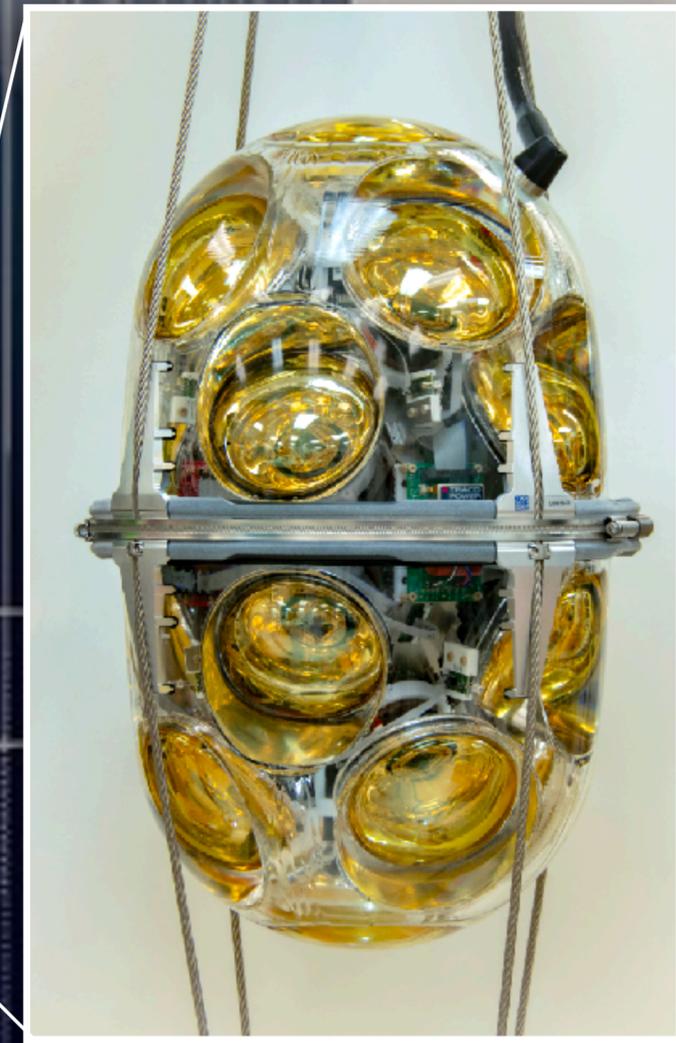


- **What is not covered by OKC?**
- **What else is covered at accelerator based experiments?**

IceCube Gen-2



- eight times the volume of IceCube
- enabling astronomy with neutrino detectors
- many new sensor technologies improving sensitivity and broadening the possibilities
- construction in the 2030s
- significant commitments from Germany and Japan (sensor production lines prototyping)



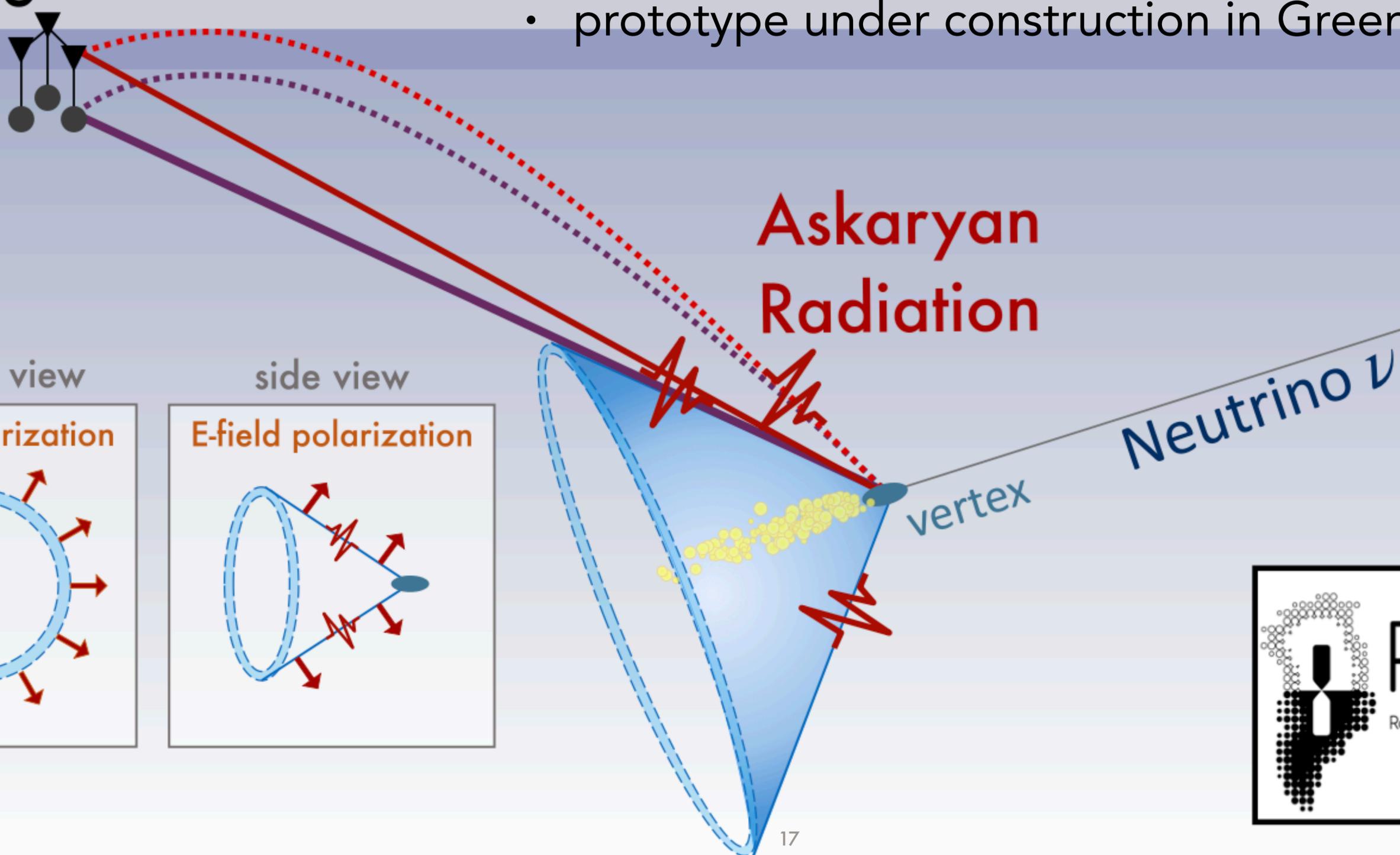
Askaryan detectors



- into the exascale
- prototype under construction in Greenland

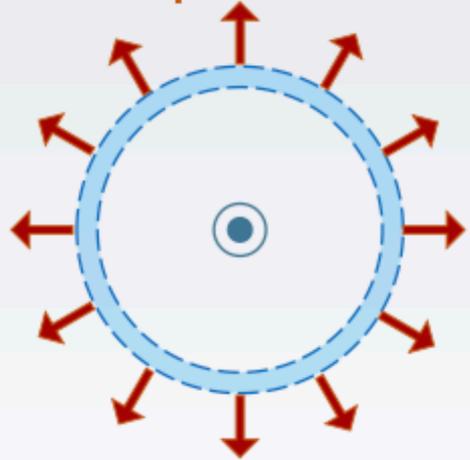
Surface

Deep



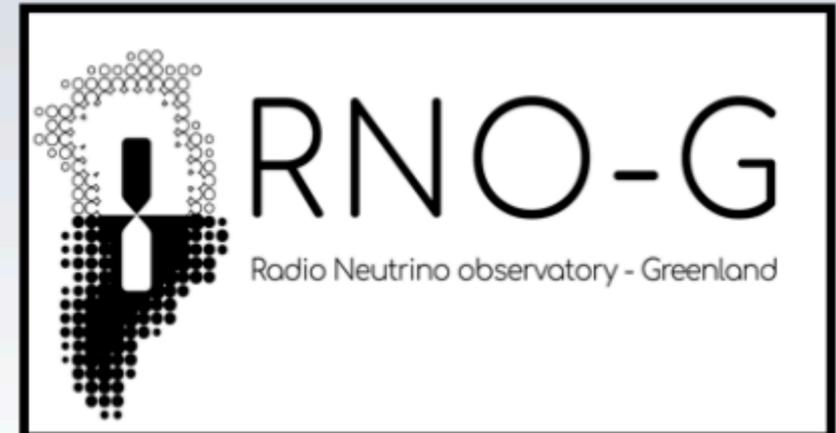
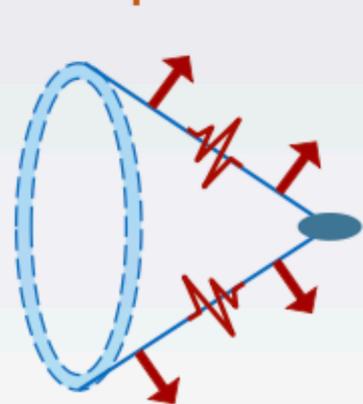
forward view

E-field polarization

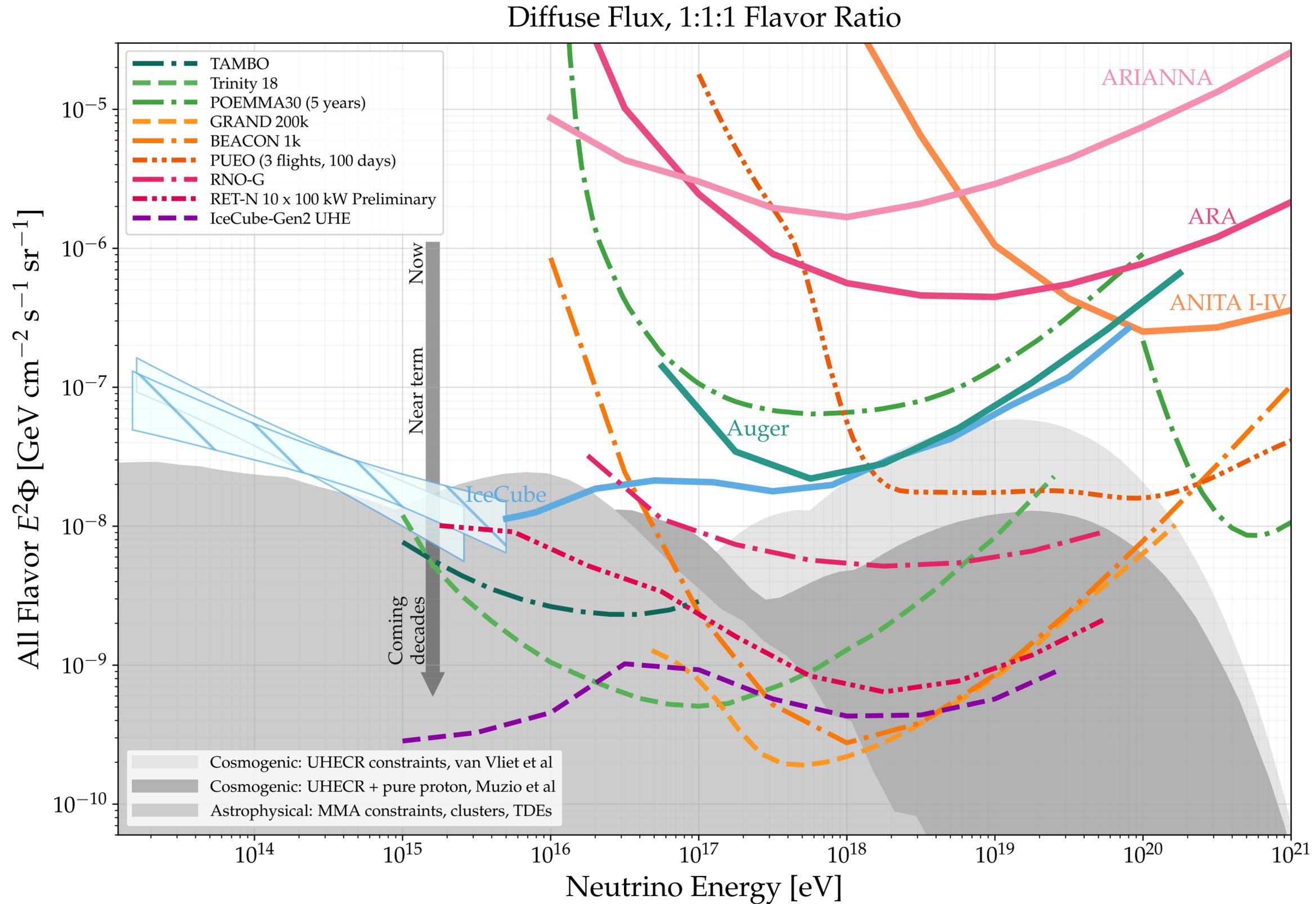


side view

E-field polarization



Future landscape of TeV to EeV neutrino detectors





Detector landscape developments

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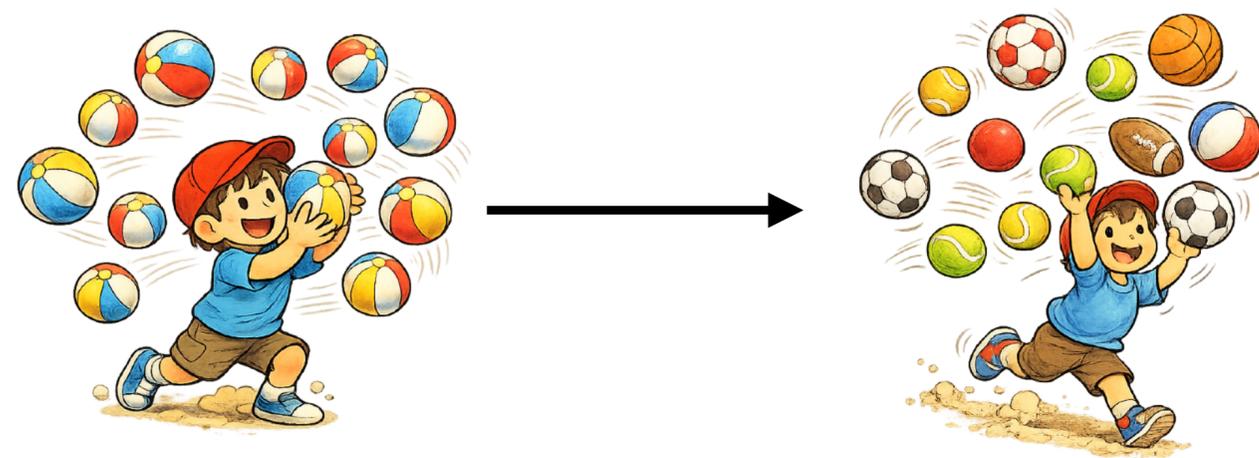
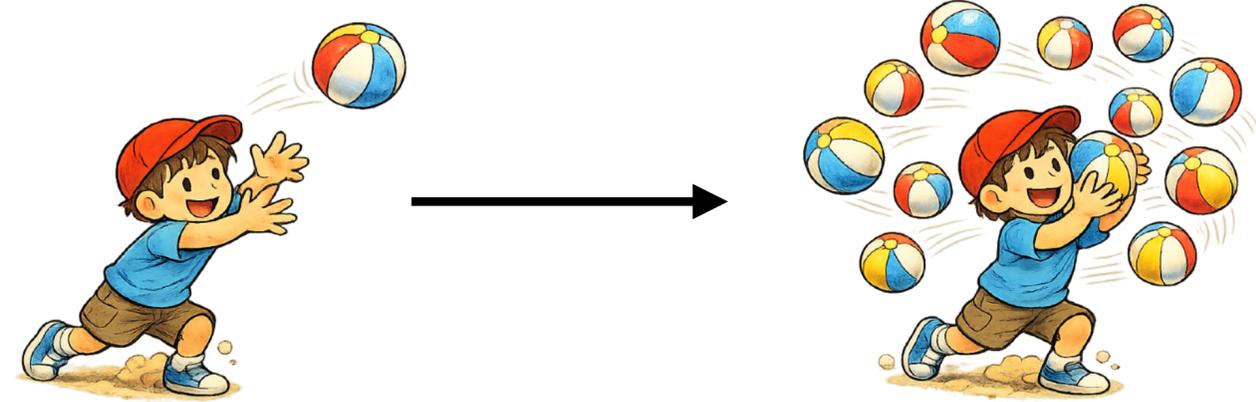


General foreseeable developments



From detection → characterization

- flavor, directionality, energy systematics
- composition of astrophysical flux
- atmospheric neutrinos as precision tools



From single-messenger → multi-messenger

- neutrinos + GW + gamma + EM follow-up
- real-time alerts, rapid analysis pipelines

From cuts/fits/drawing board → AI

- anomaly detection
- detector-aware generative models
- AI detector design





OKC