The IceCube Neutrino Observatory: The Perfect Muon Detector Unraveling Cosmic Secrets

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LPC – Clermont-Ferrand

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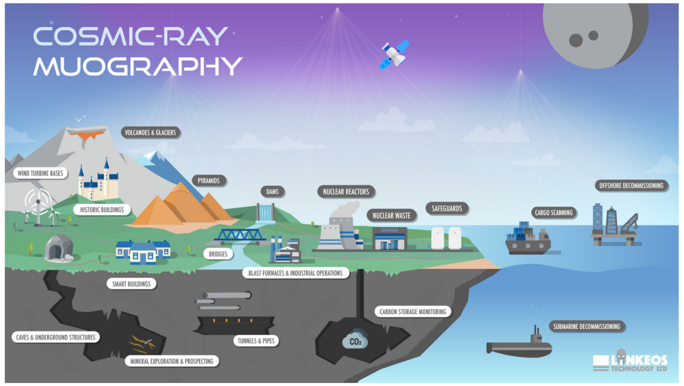
icecube..wisc.edu

Pascal Thomas Gutjahr

- B.Sc. Medical Physics
  - ATLAS
    - testing silicon strip sensors
- M.Sc. Physics
  - IceCube
    - studying and analyzing muon deflection
- PhD Student
  - IceCube
    - energy and direction reconstructions
    - cosmic ray physics – prompt component
  - Muography
    - observing water level in coal mines
  - PROPOSAL
    - software for lepton propagation

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ICECUBE
NEUTRINO OBSERVATORY
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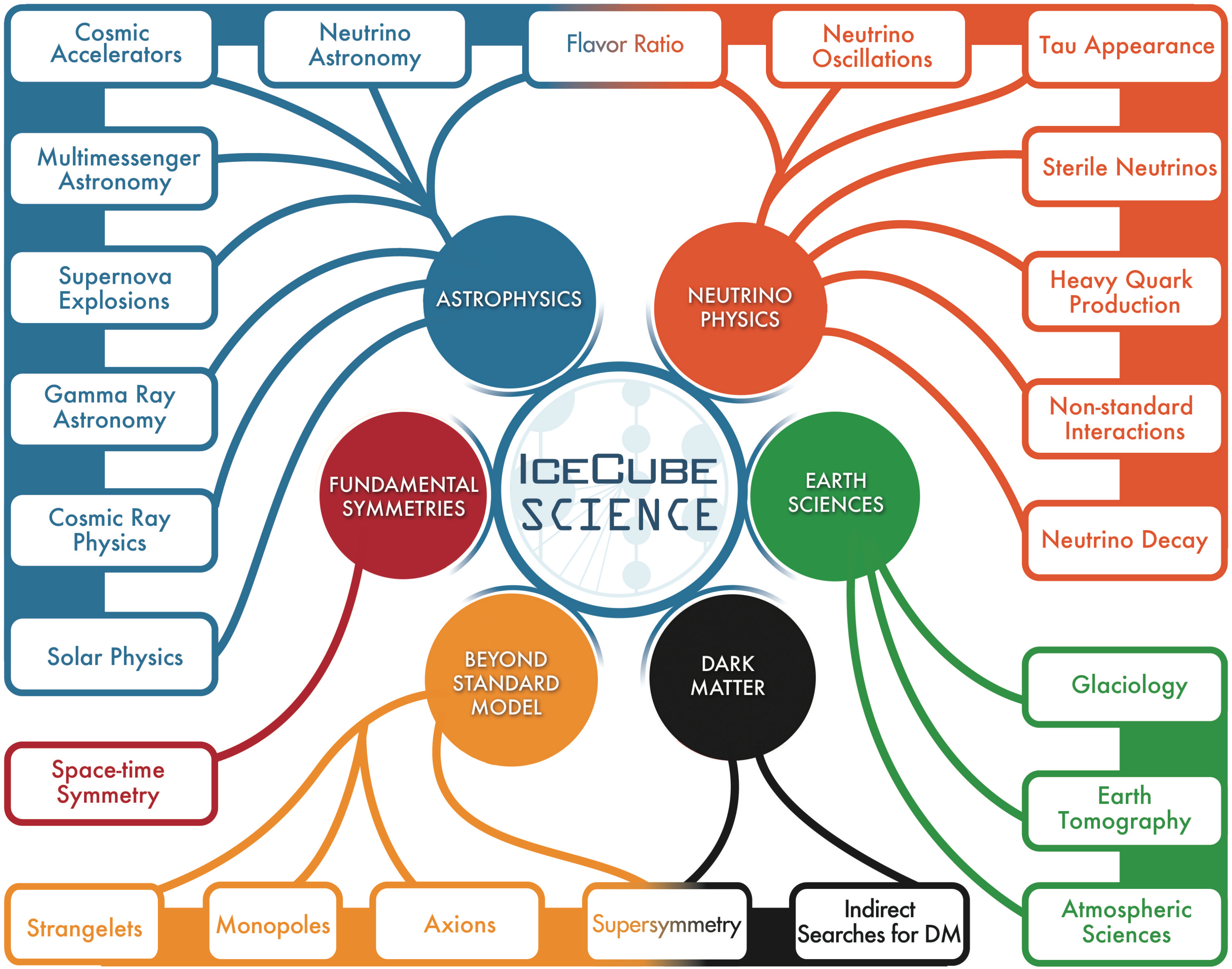

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A History of Neutrino Astronomy in Antarctica

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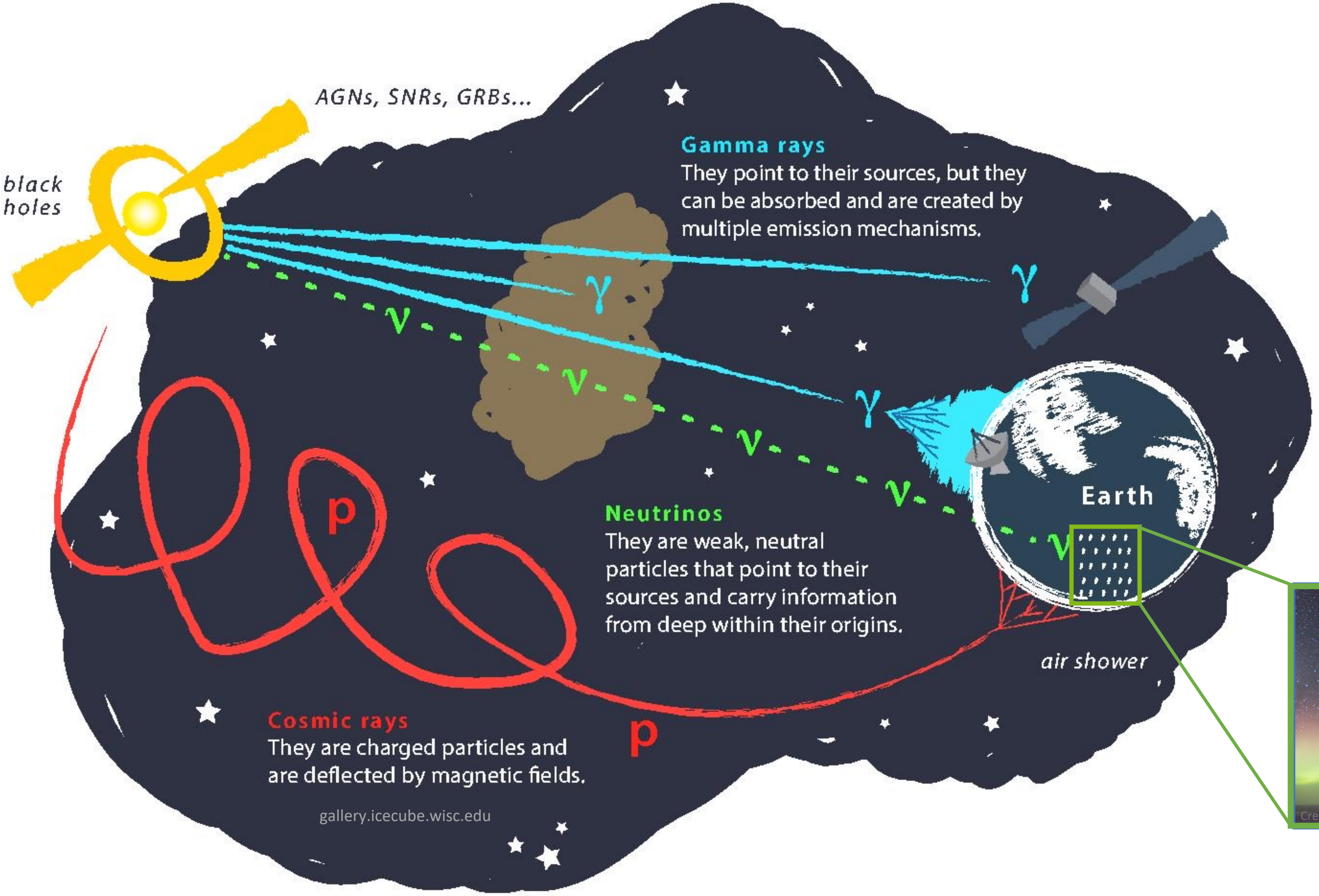
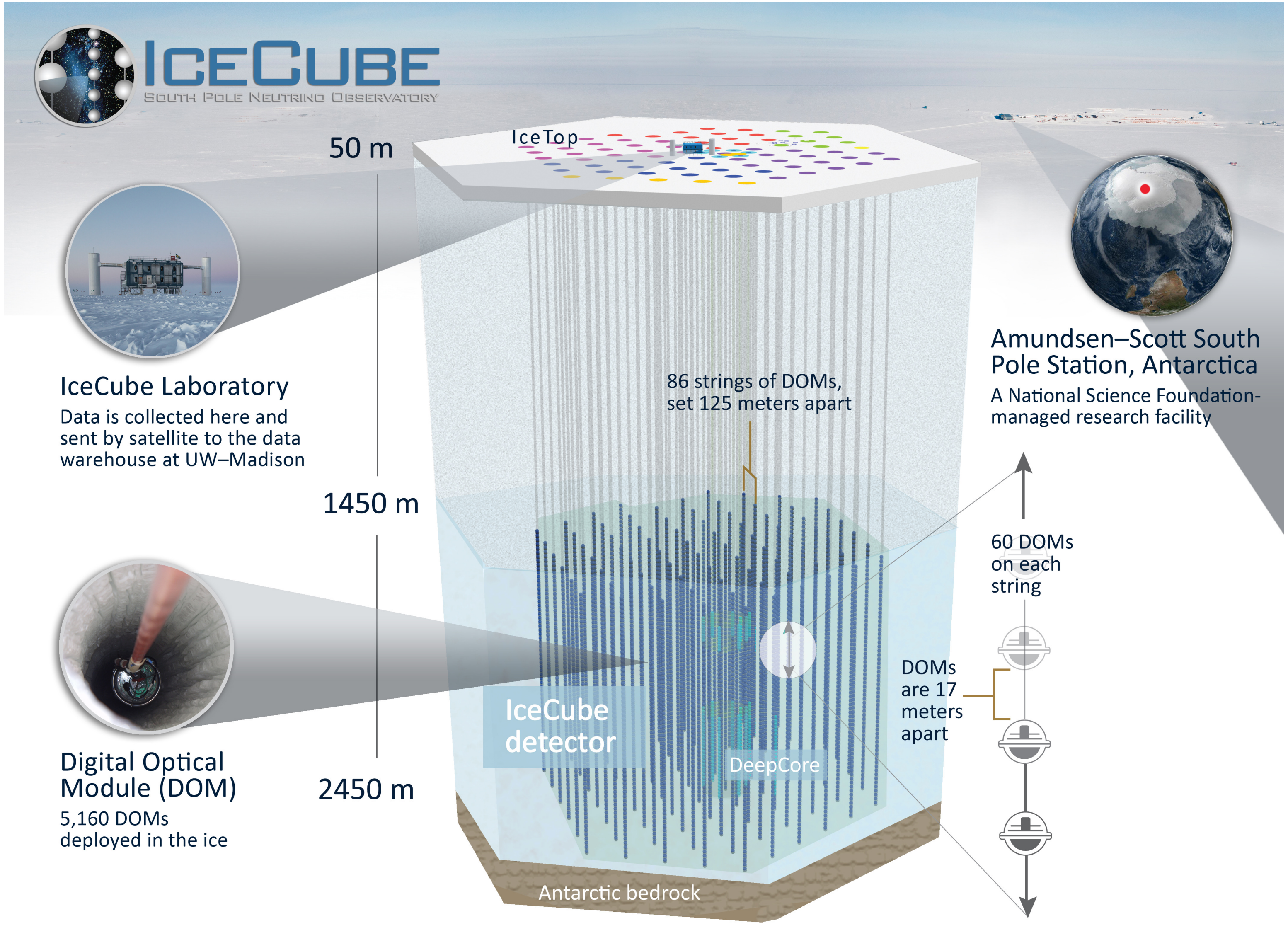
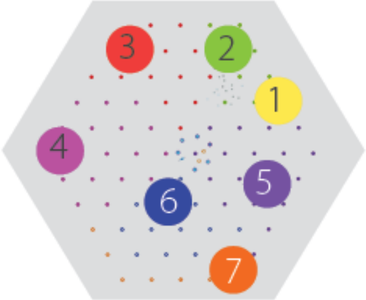
Astroparticle Physics





Detector Construction

7 seasons of construction, 2004-2011



- 28,000 person-days to complete construction, or 77 years of continuous work
- 2.1 million kilograms of cargo was shipped, 0.5 million of which was the drill
- 48 hours to drill and 11 hours to deploy sensors per hole
- 4.7 megawatts of drill thermal power with 760 liters of water per minute delivered at 88 °C and 7,600 kilopascals

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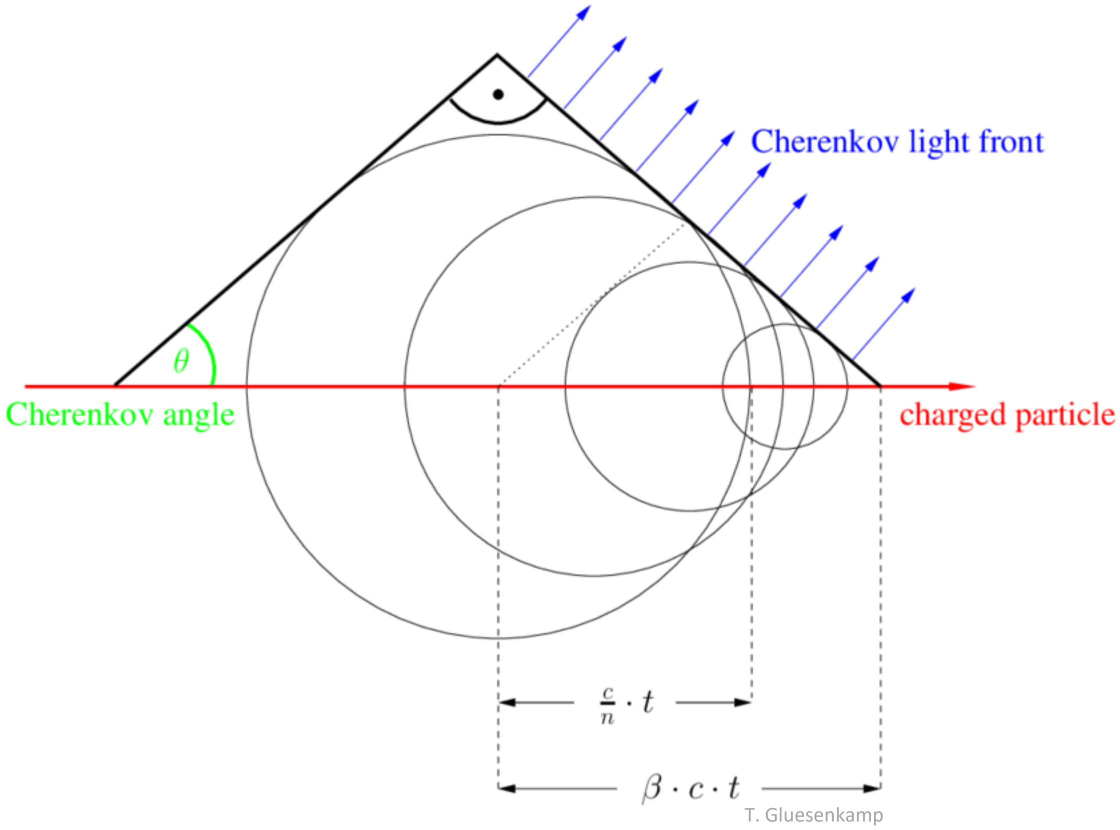
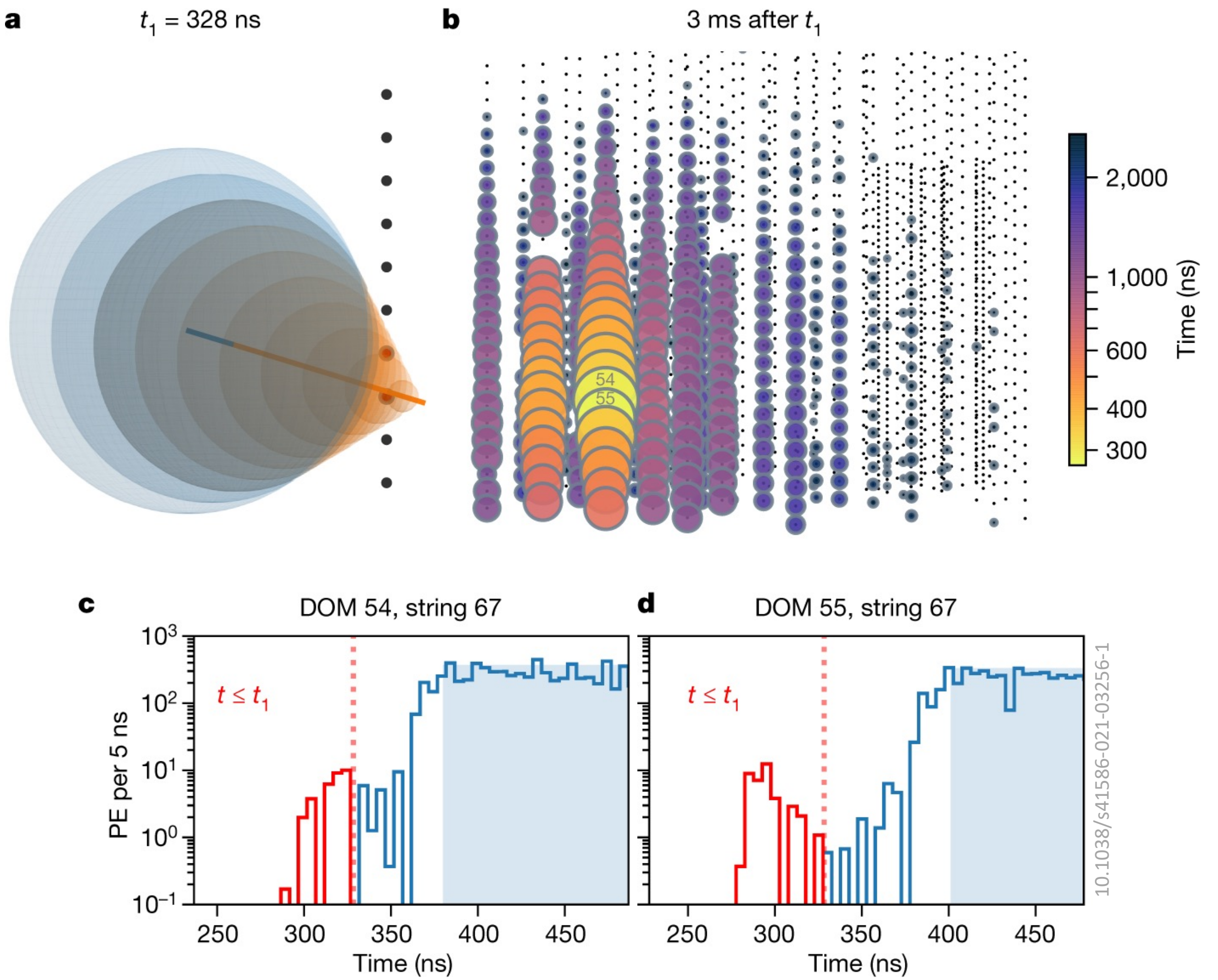
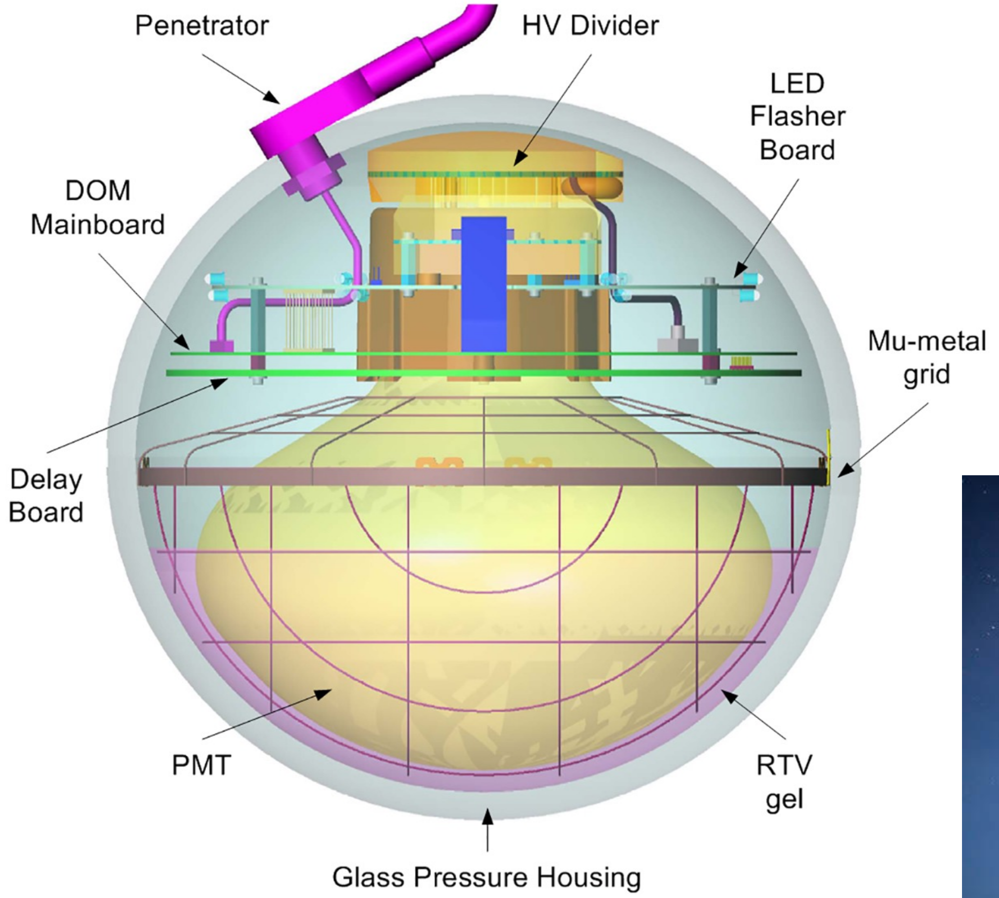
Particle Detection – Cherenkov Light





Digital Optical Module (DOM)



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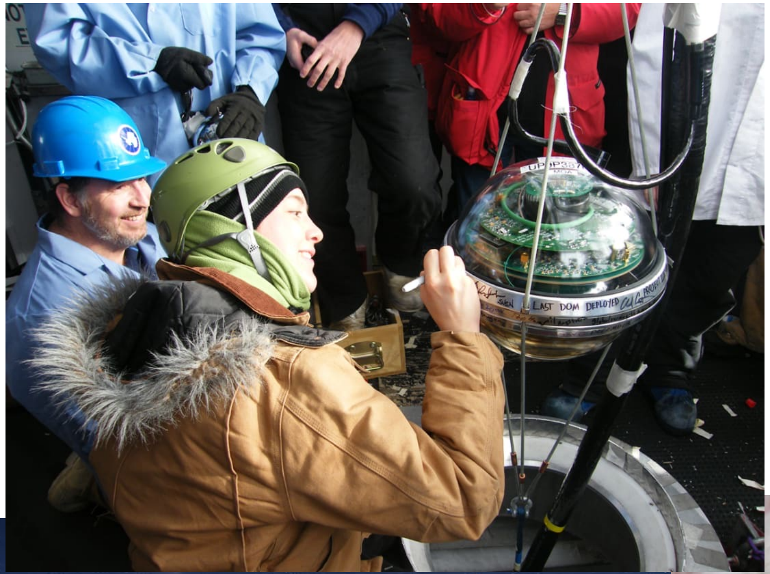
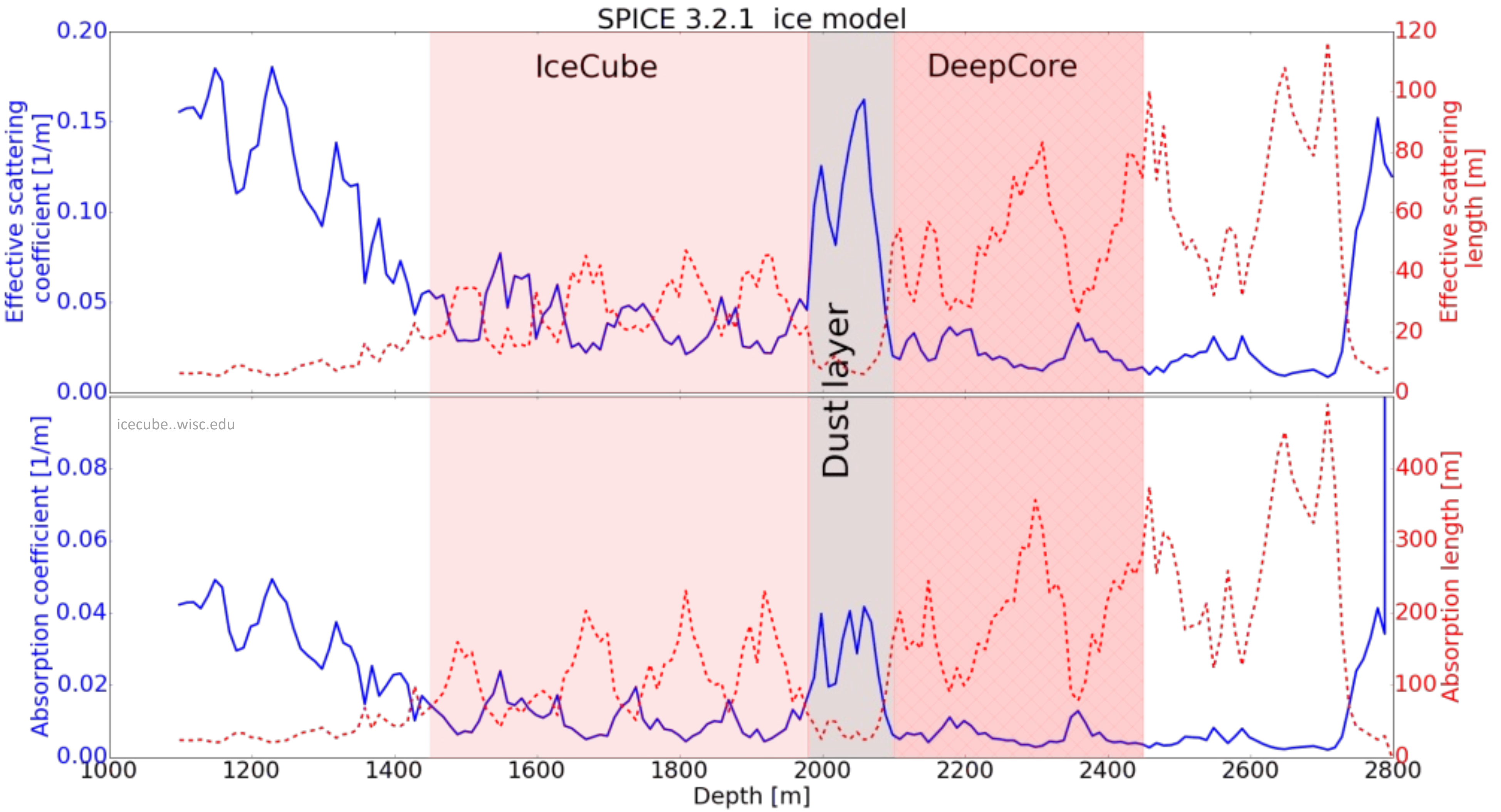
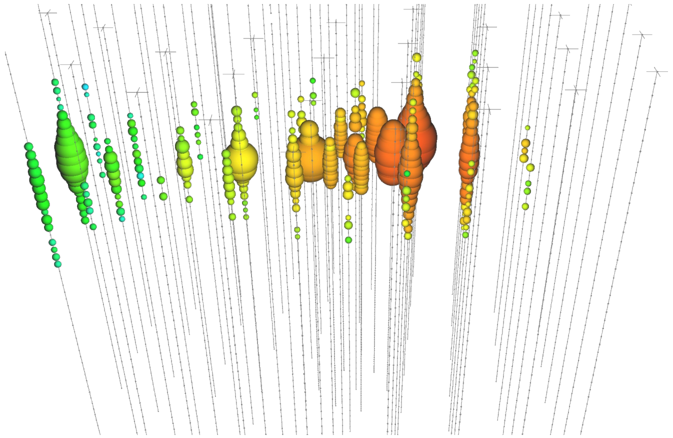
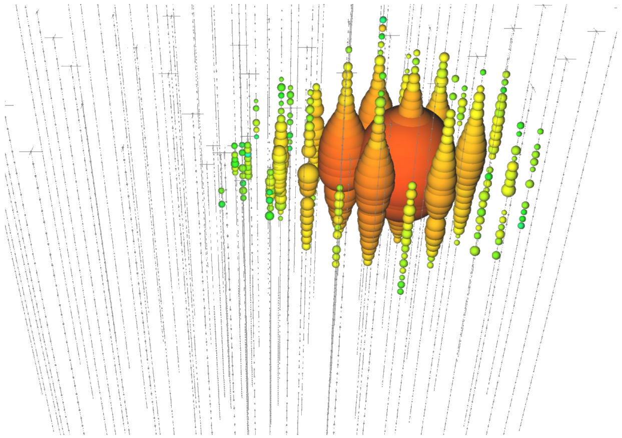
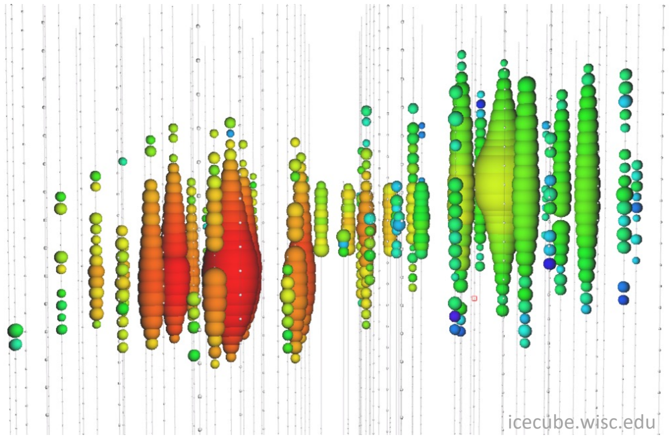


phys.org

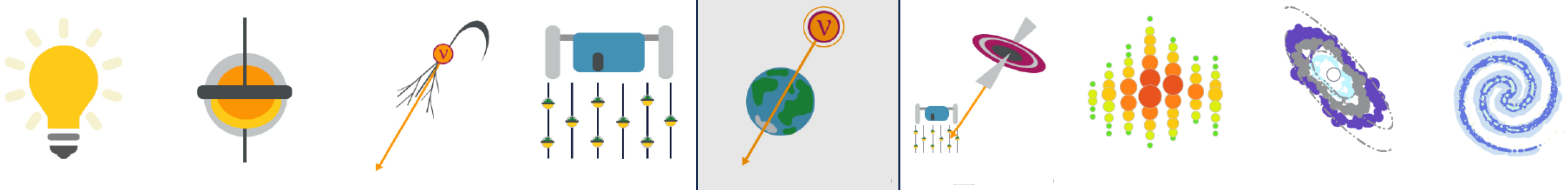
Detection Medium - Ice



Event Topologies

CC ν_μ	CC ν_e / NC ν_*	CC ν_τ
		
$\nu_\mu + N \rightarrow \mu + X$	$\nu_e + N \rightarrow \mathrm{e} + X$ $\nu_* + N \rightarrow \nu_* + X$	$\nu_\tau + N \rightarrow \tau + X,\ \tau^{\pm} + N \rightarrow \nu_\tau + W^{\pm}$
Track $(< 1°)$	Cascade ($\sim 10°$ at 10 TeV)	Cascade / Track / Double-Cascade (τ – track: ~50m/PeV)

A History of Neutrino Astronomy in Antarctica



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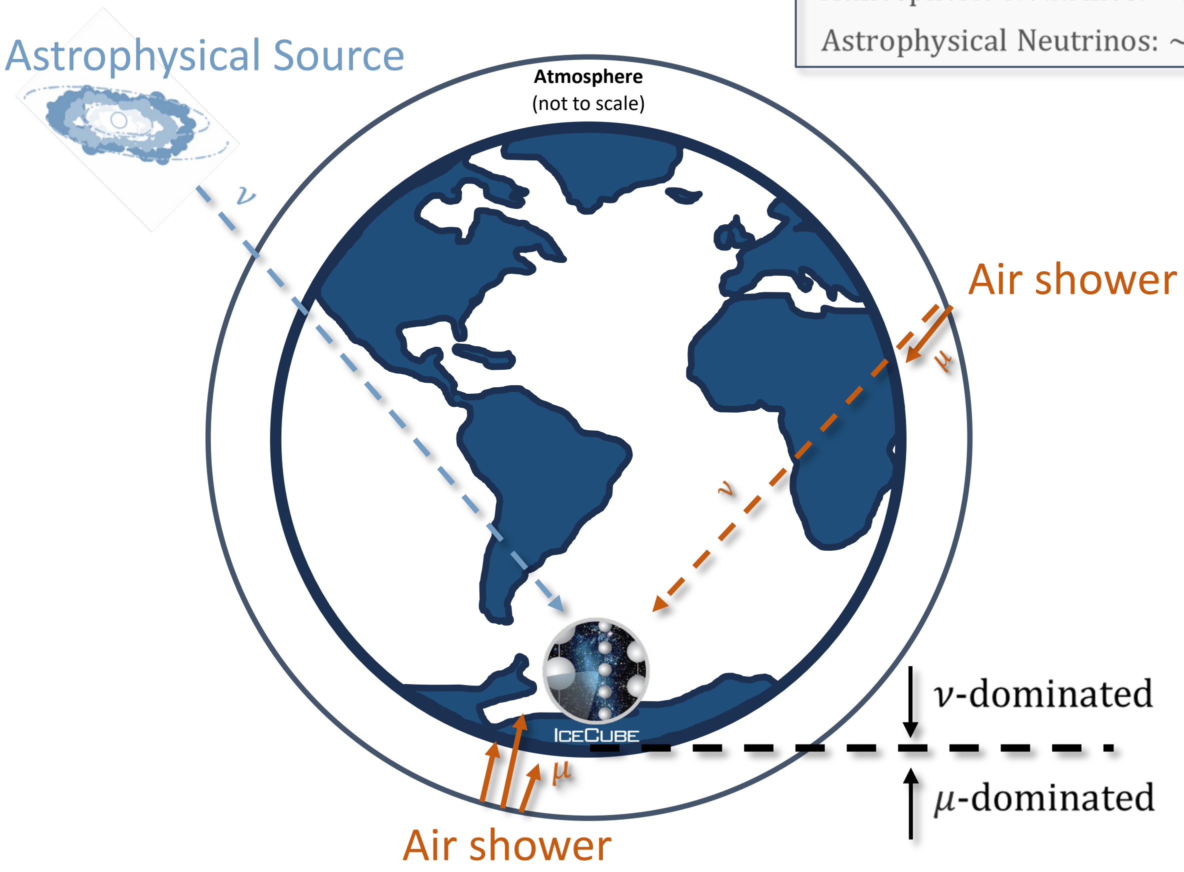
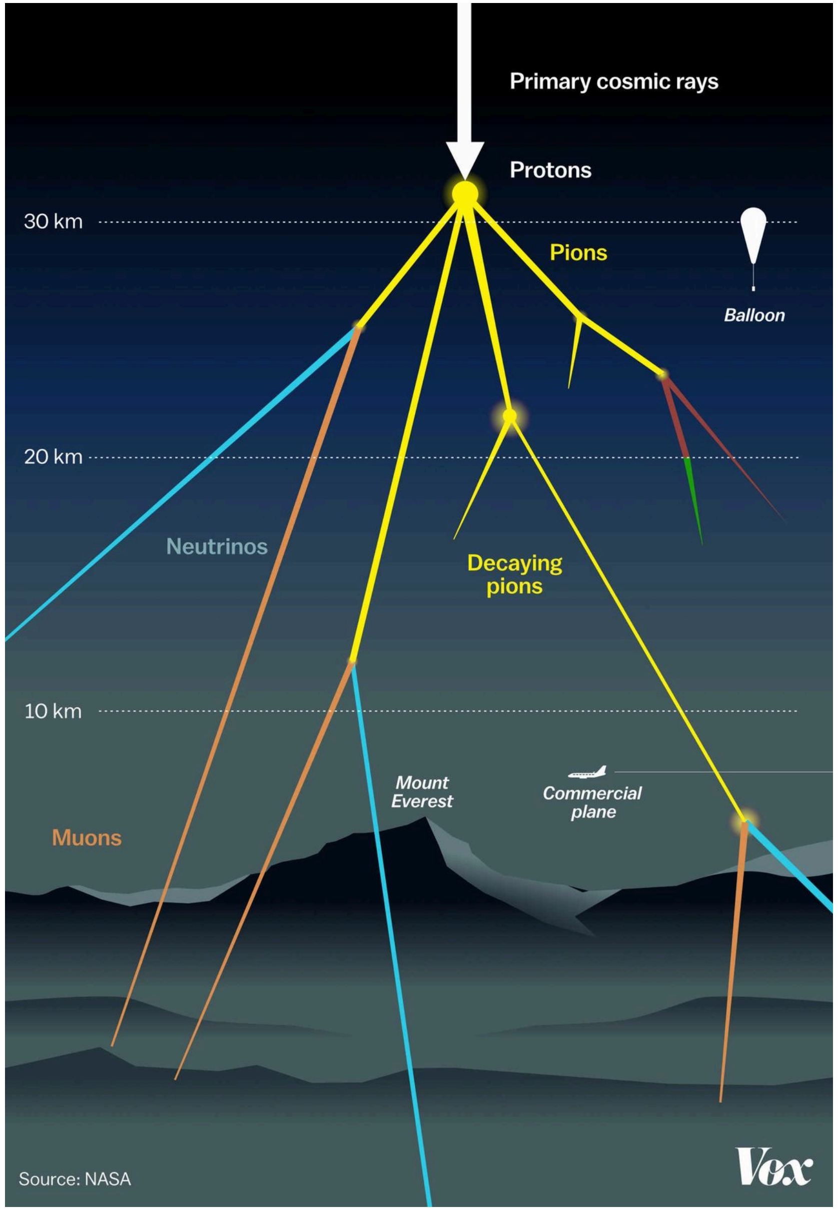
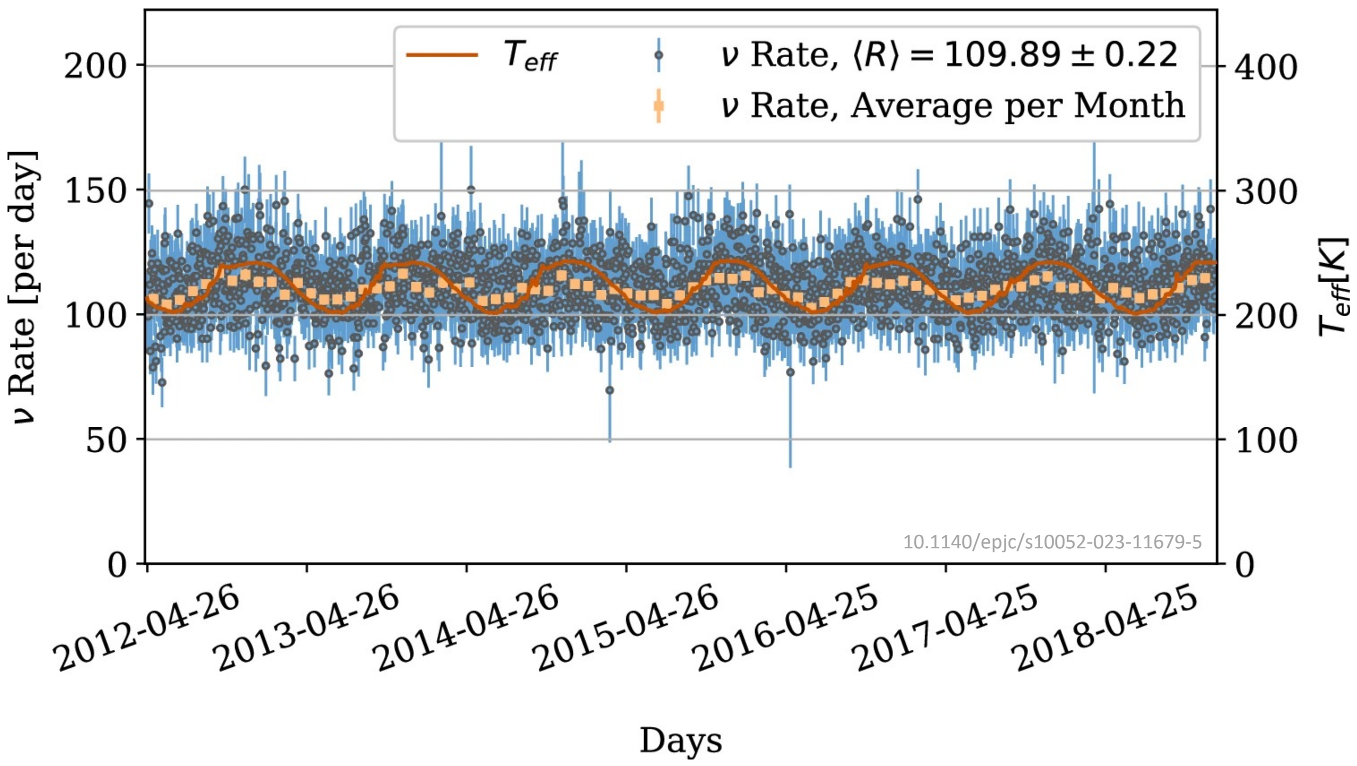
Air Shower - Background

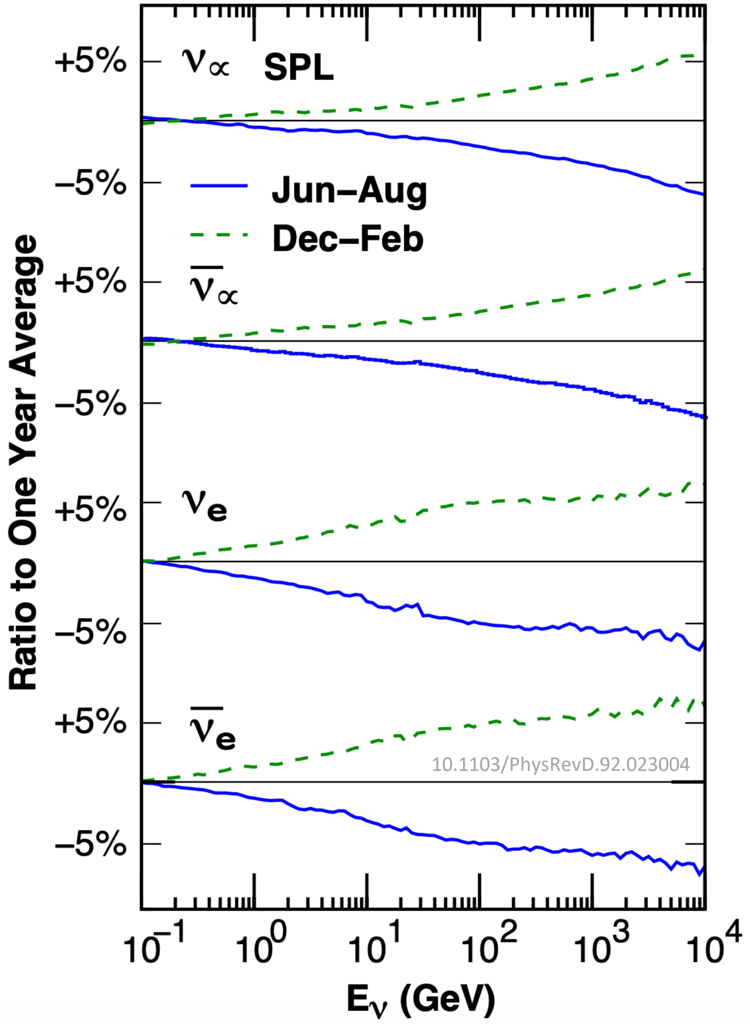
Rates:
Atmospheric Muons: ~2700 / s
Atmospheric Neutrinos: ~1 / hour
Astrophysical Neutrinos: ~1 / day



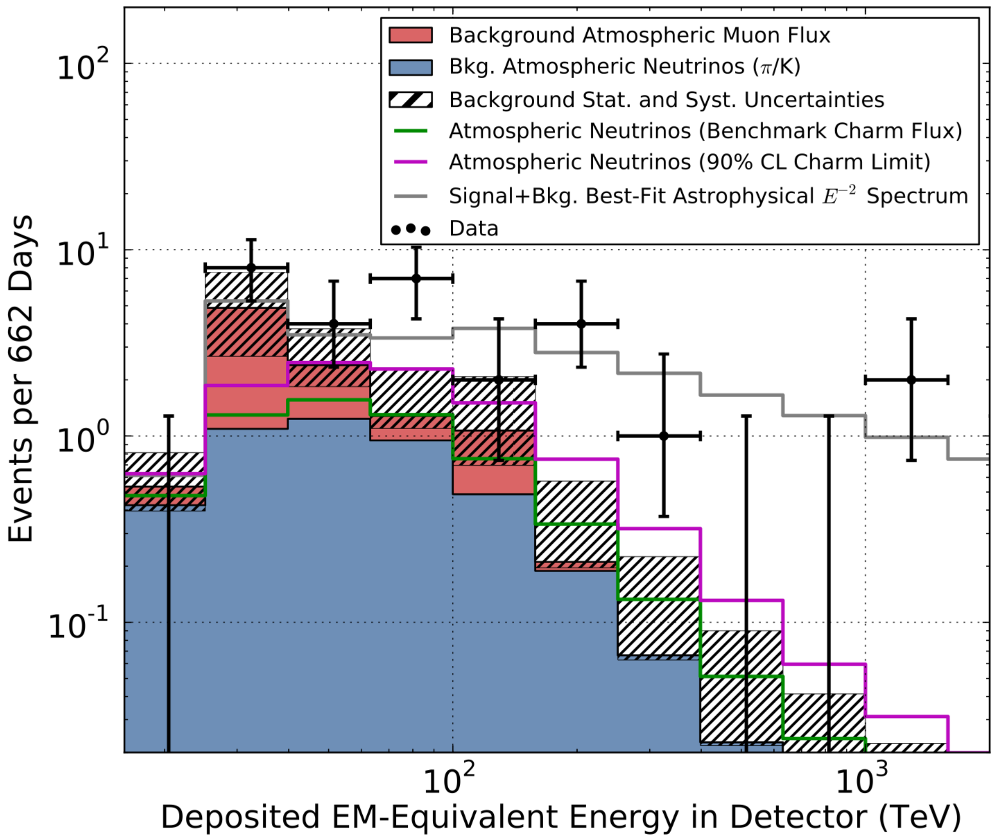


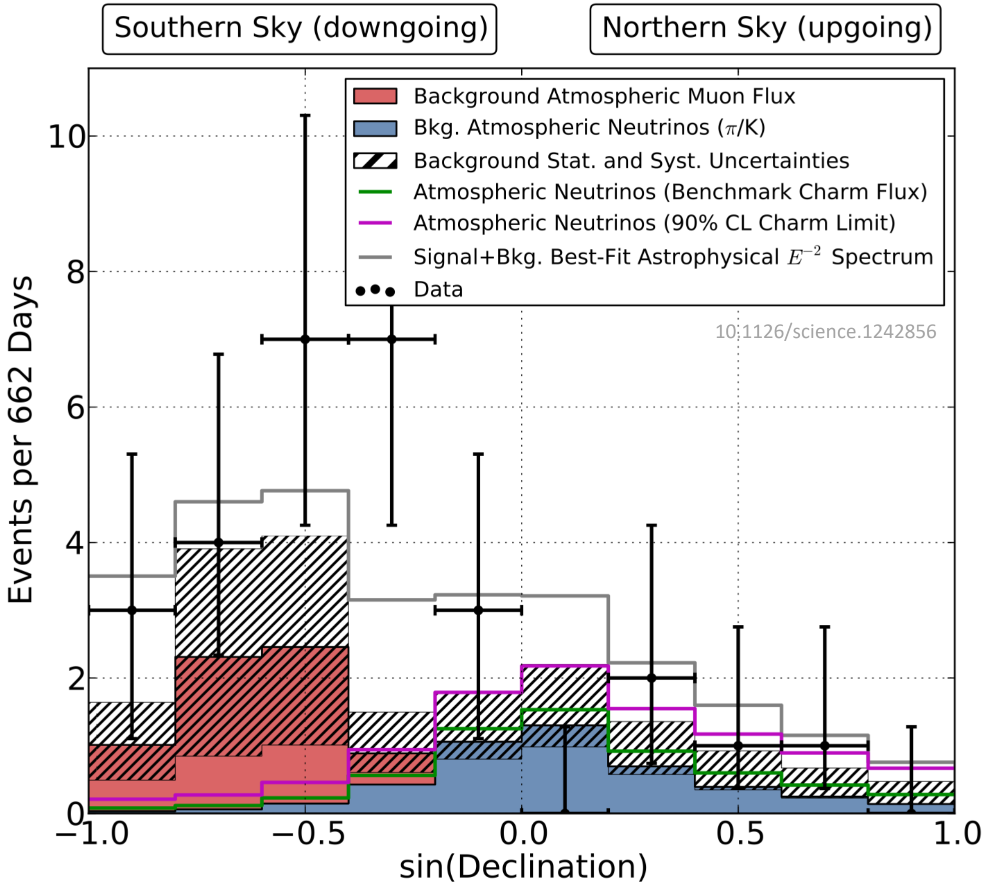
Seasonal Variations of Atmospheric Neutrinos





Astrophysical Neutrinos Discovered





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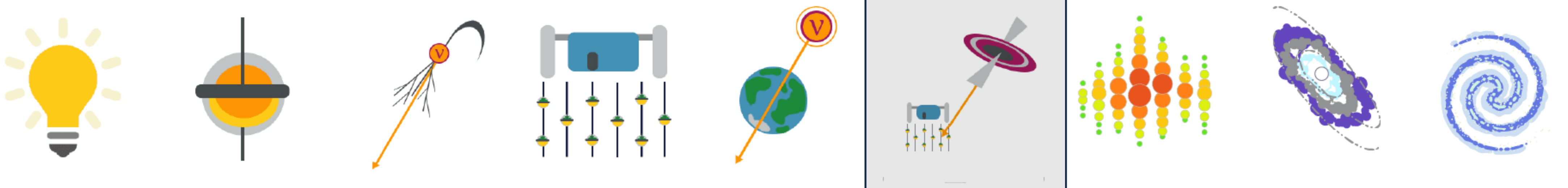

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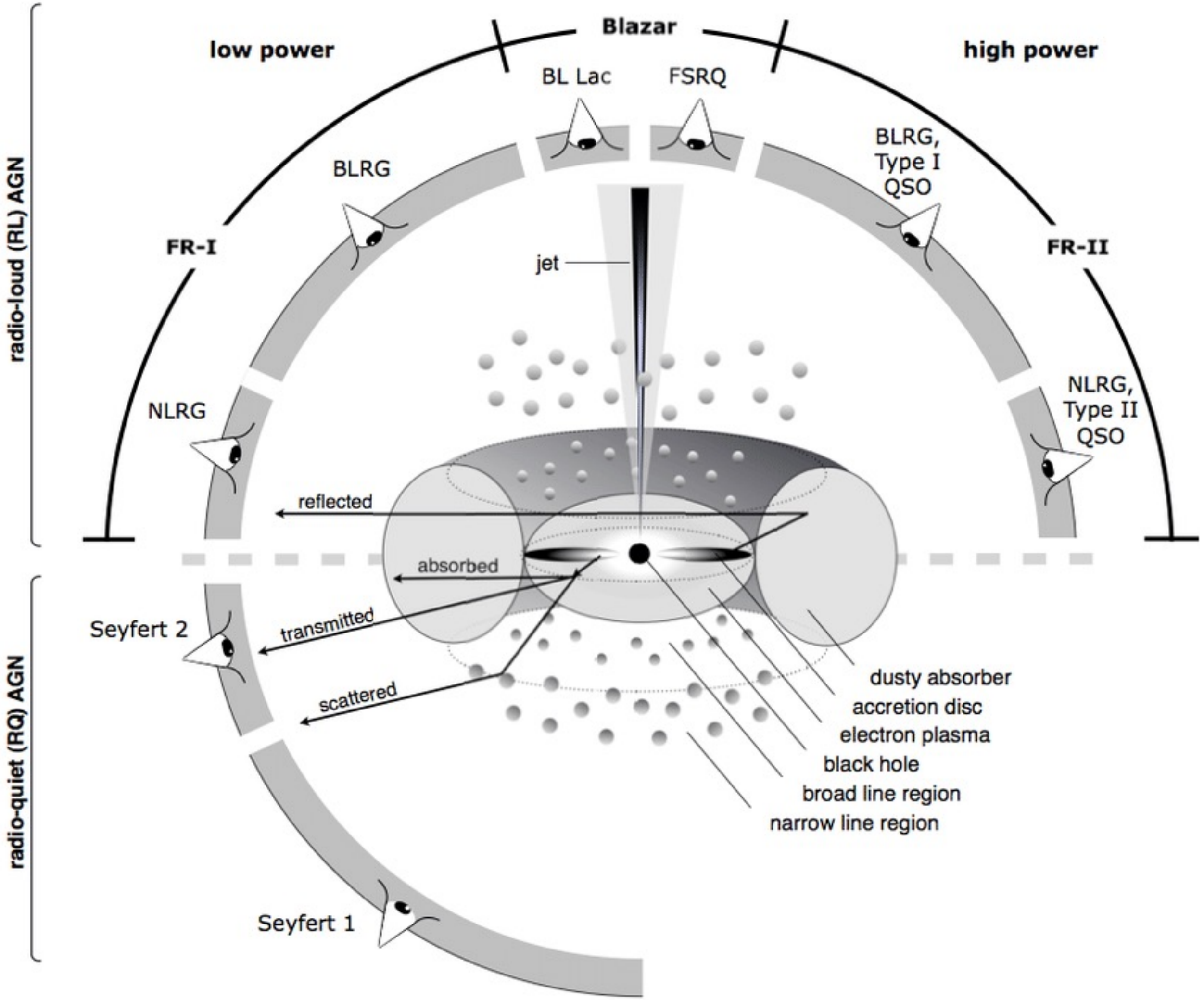
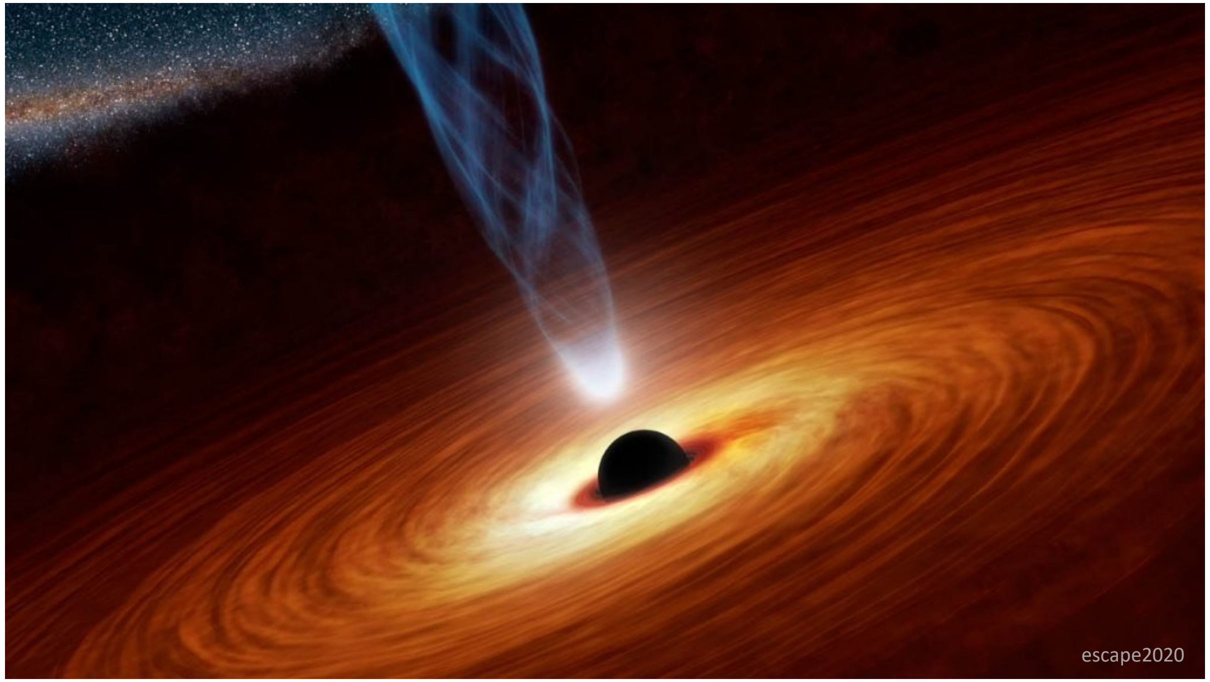
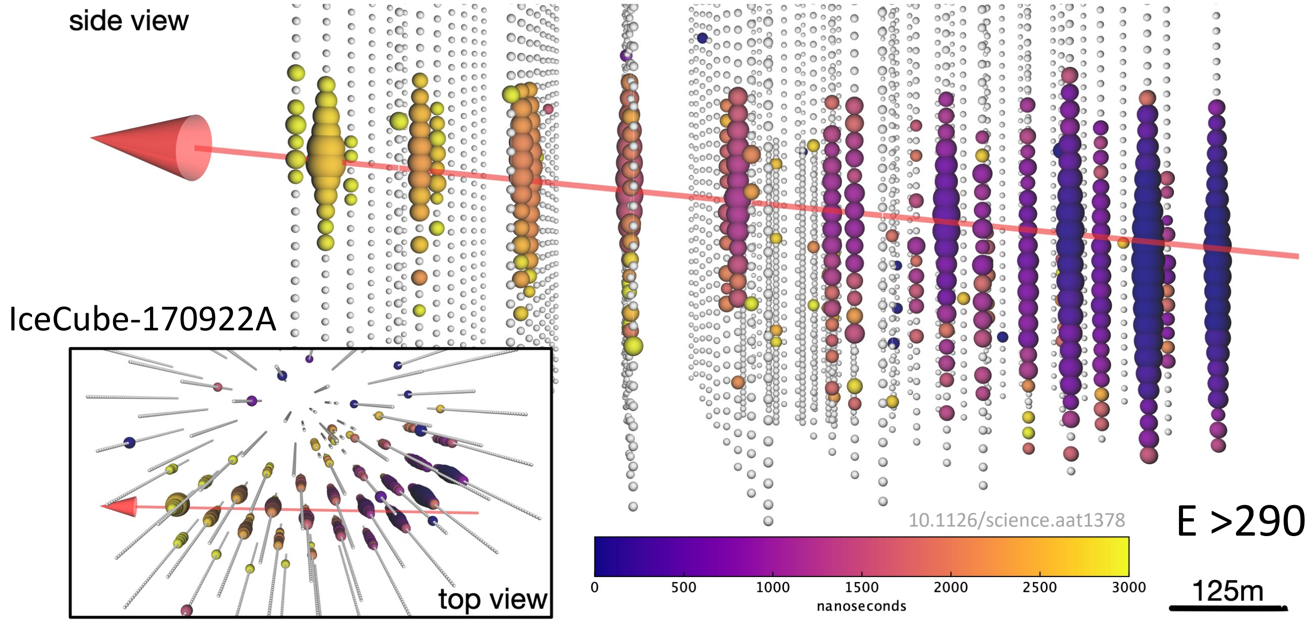
Active Galactic Nucleus (AGN)





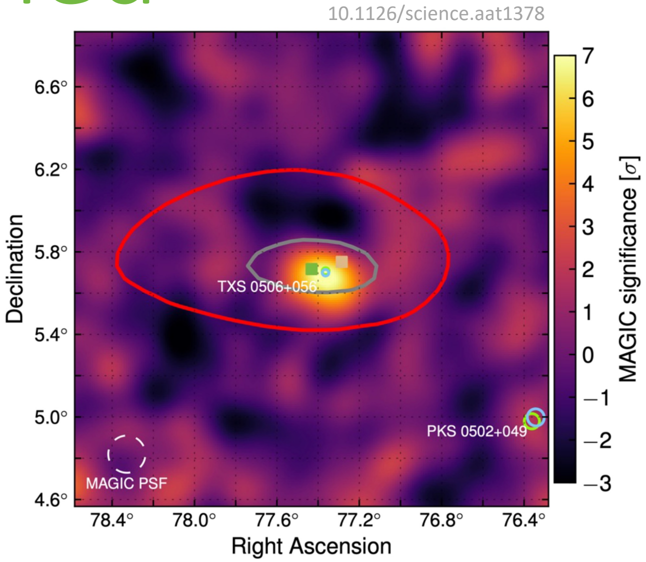
 Beckmann & Shrader 2012

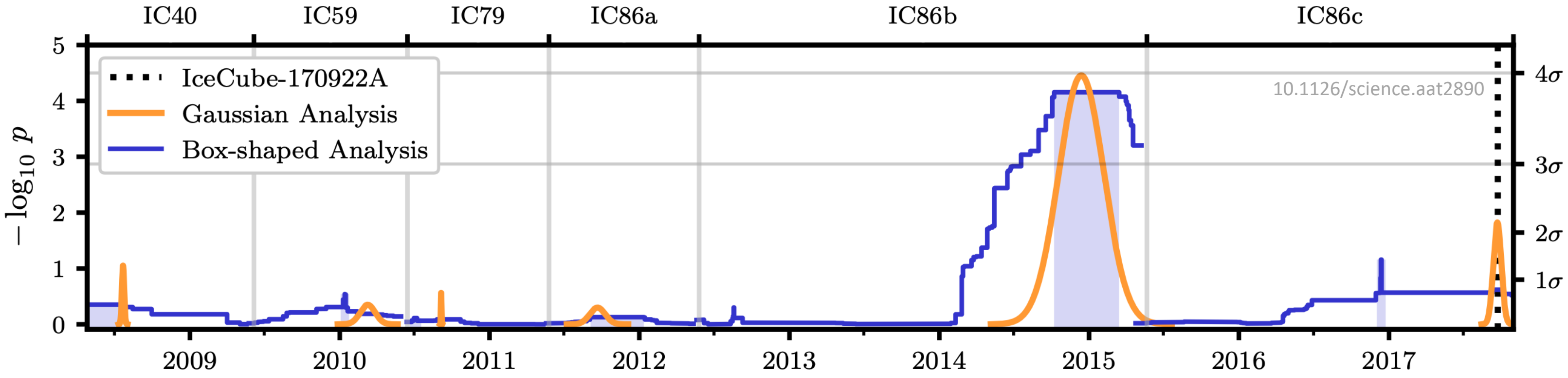
First Source TXS 0506+056 Identified

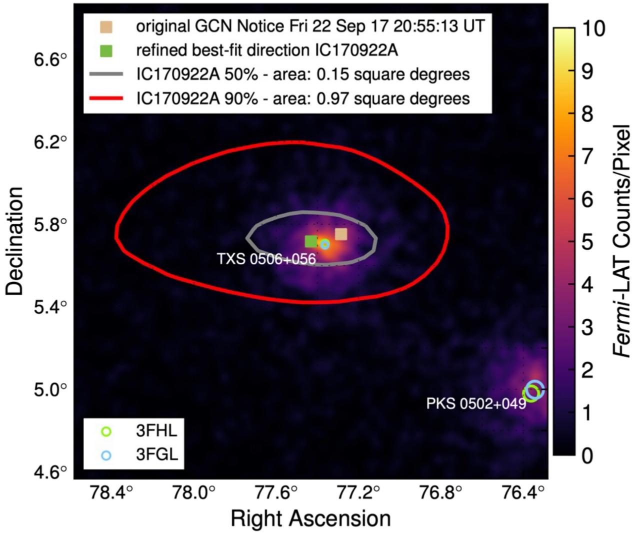


E >290 TeV

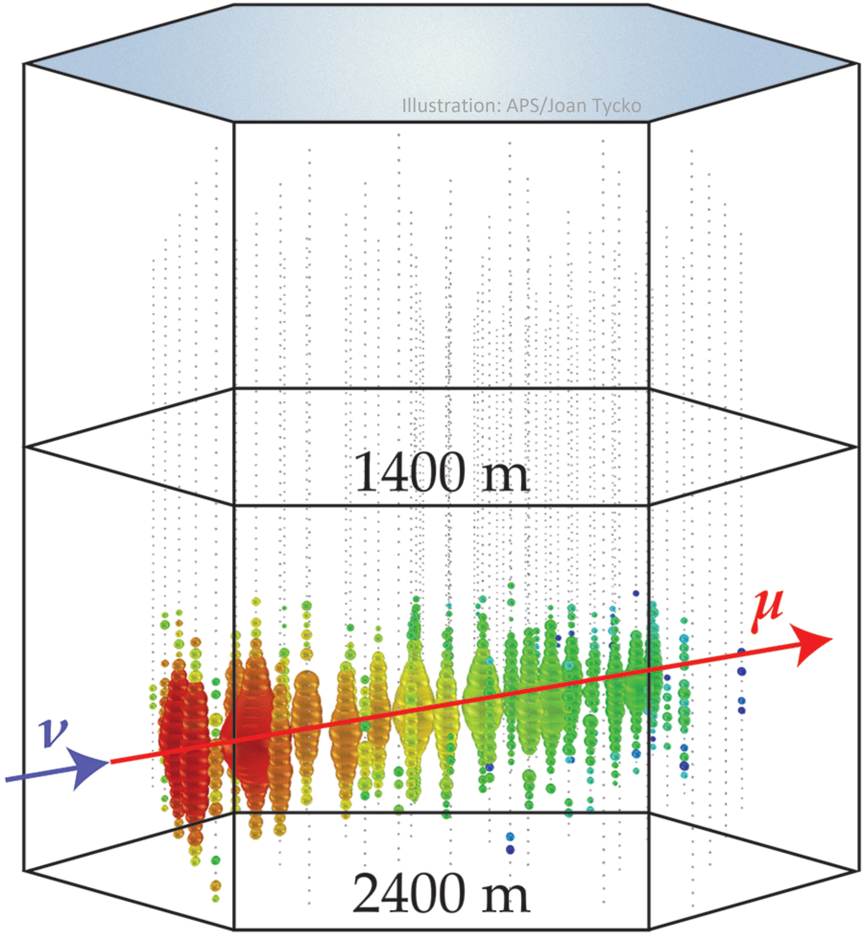
125m

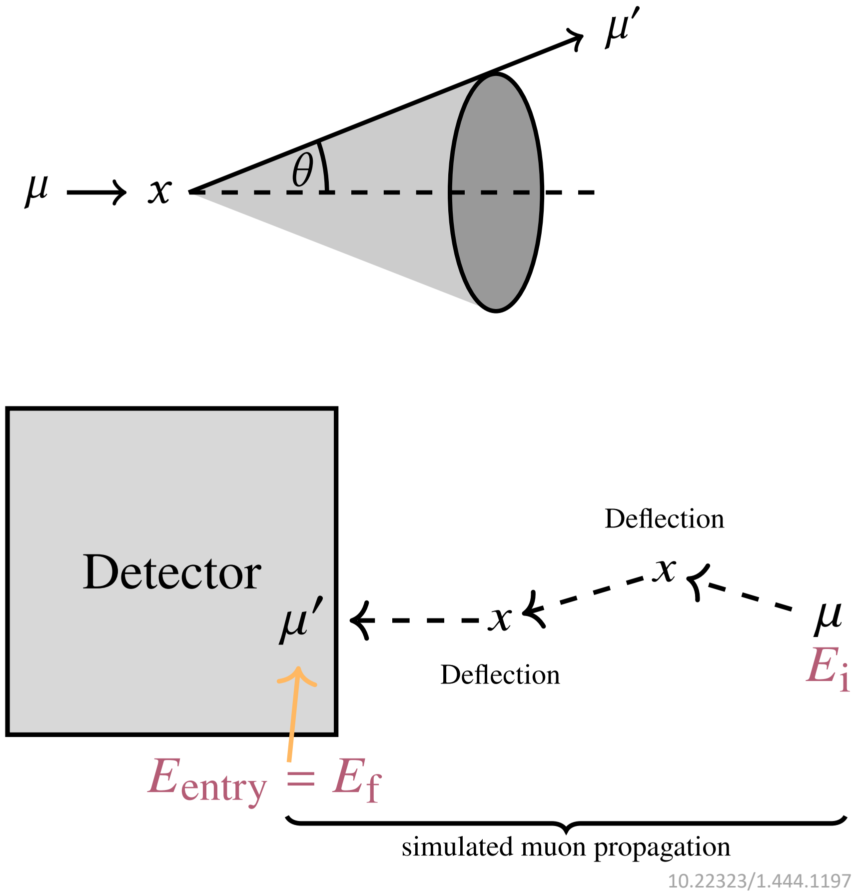




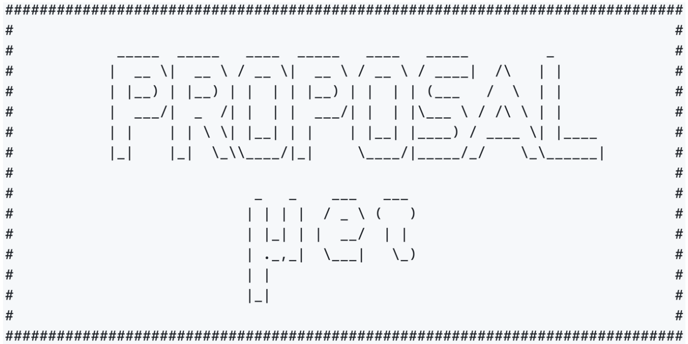


Muon Deflection – Motivation



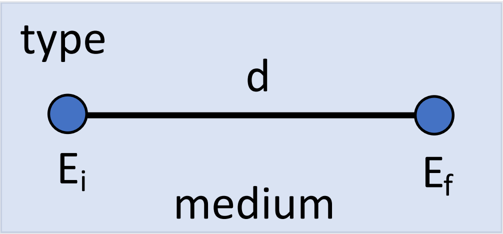


Muon Deflection – Simulation



PRopagator with Optimal Precision and Optimal Speed for All Leptons

```
# pip install proposal
```



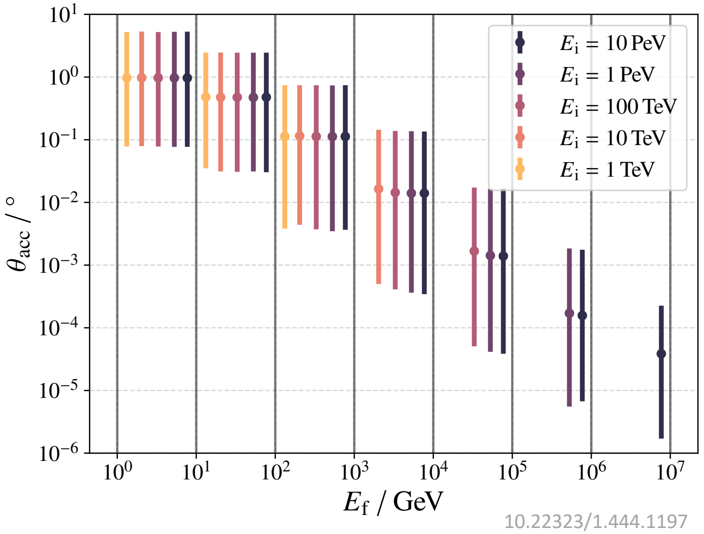
Used in:

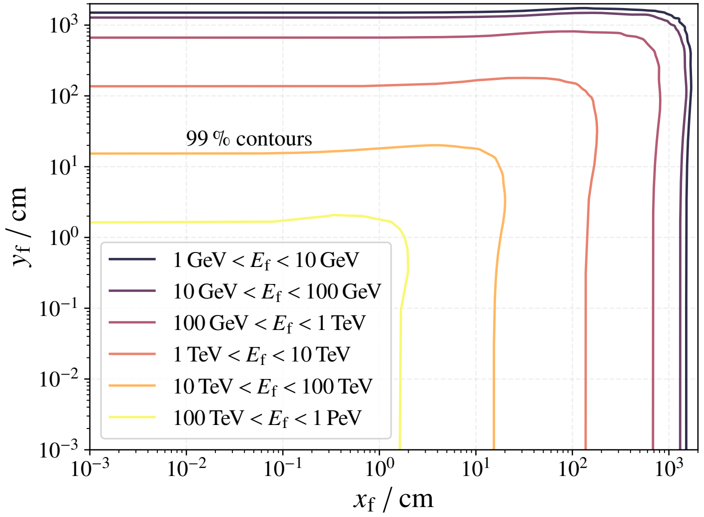
- ✓ IceCube
- ✓ KM3NeT
- ✓ NOvA
- ✓ NuRadioMC
- ✓ CORSIKA 8
- ✓ TAMBO
- ✓ Baikal-GVD
- ✓ P-One

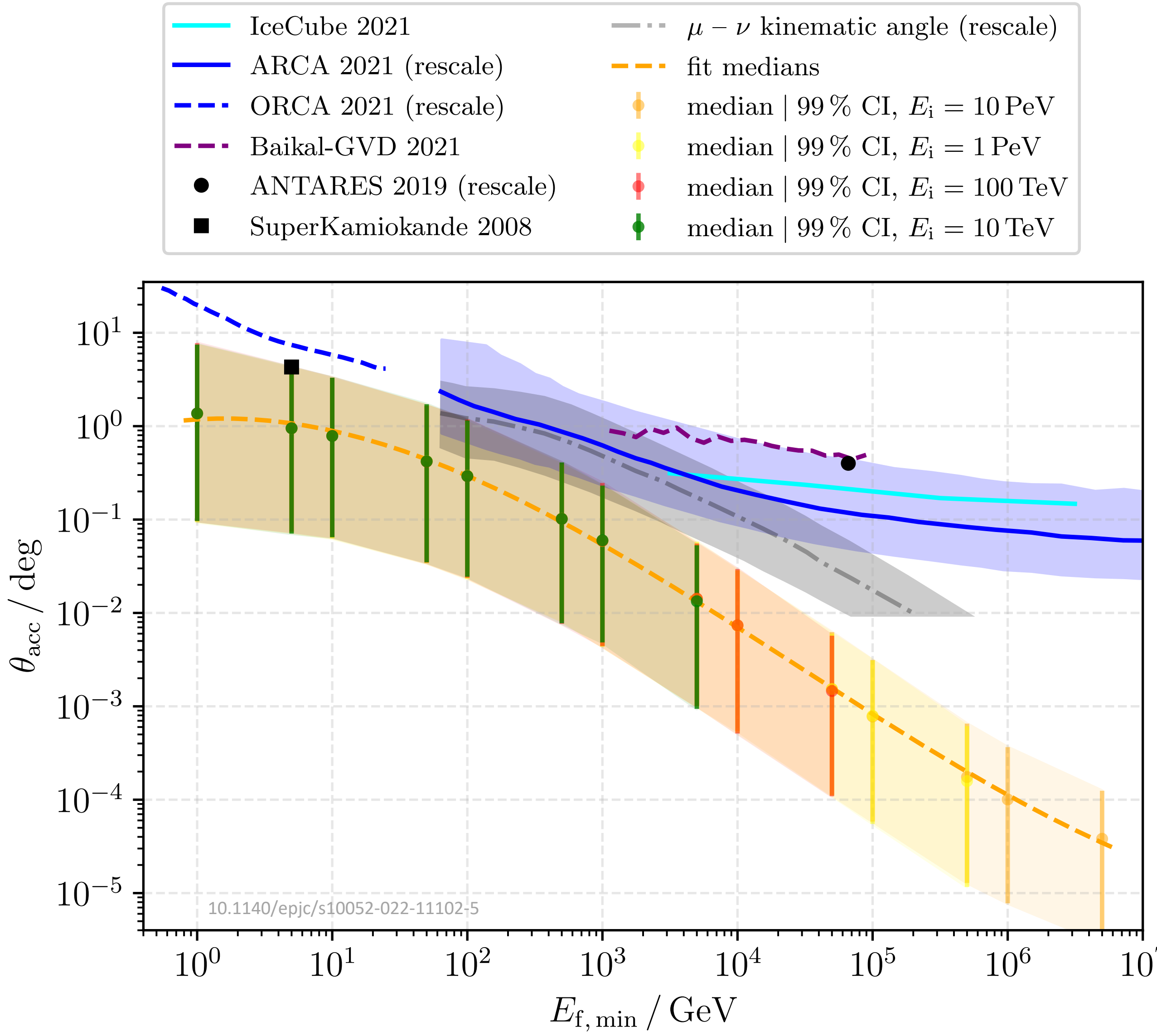
developed and mainted in Dortmund

github.com/tudo-astroparticlephysics/PROPOSAL

Muon Deflection – Results

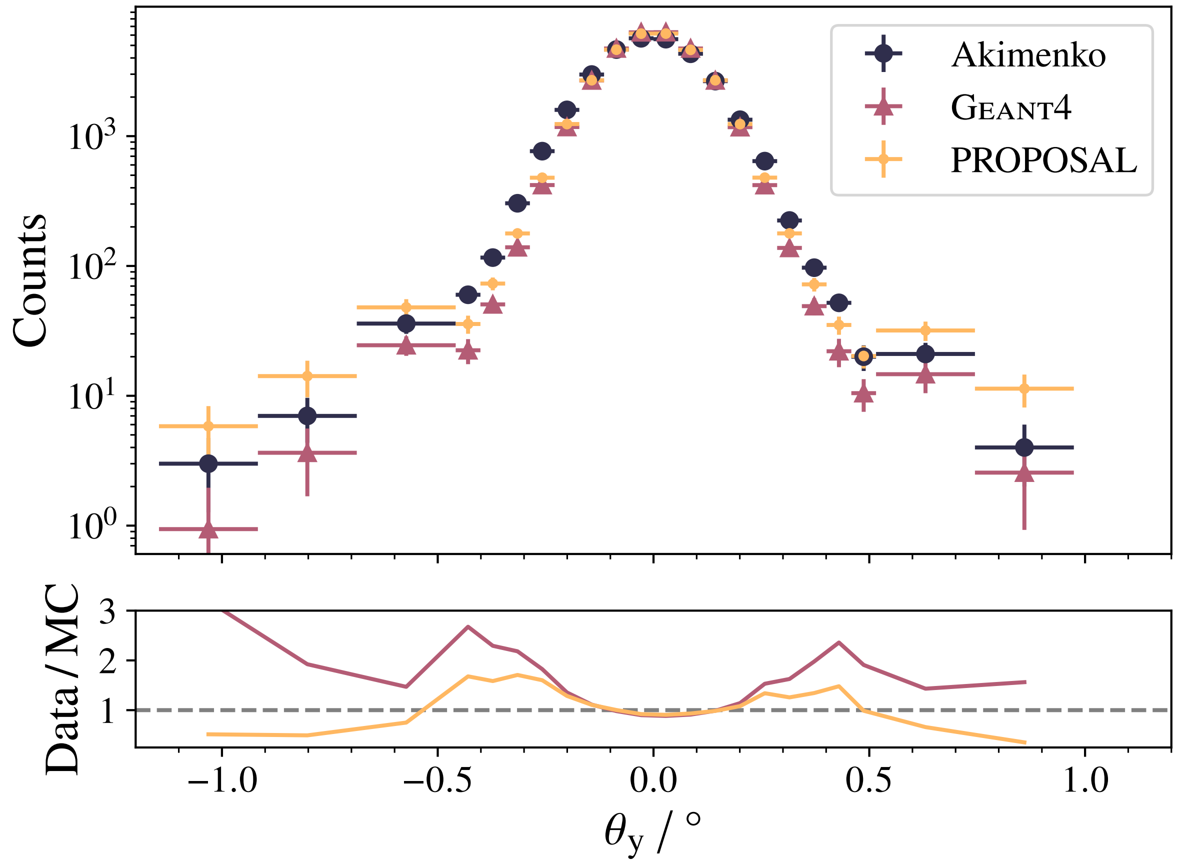




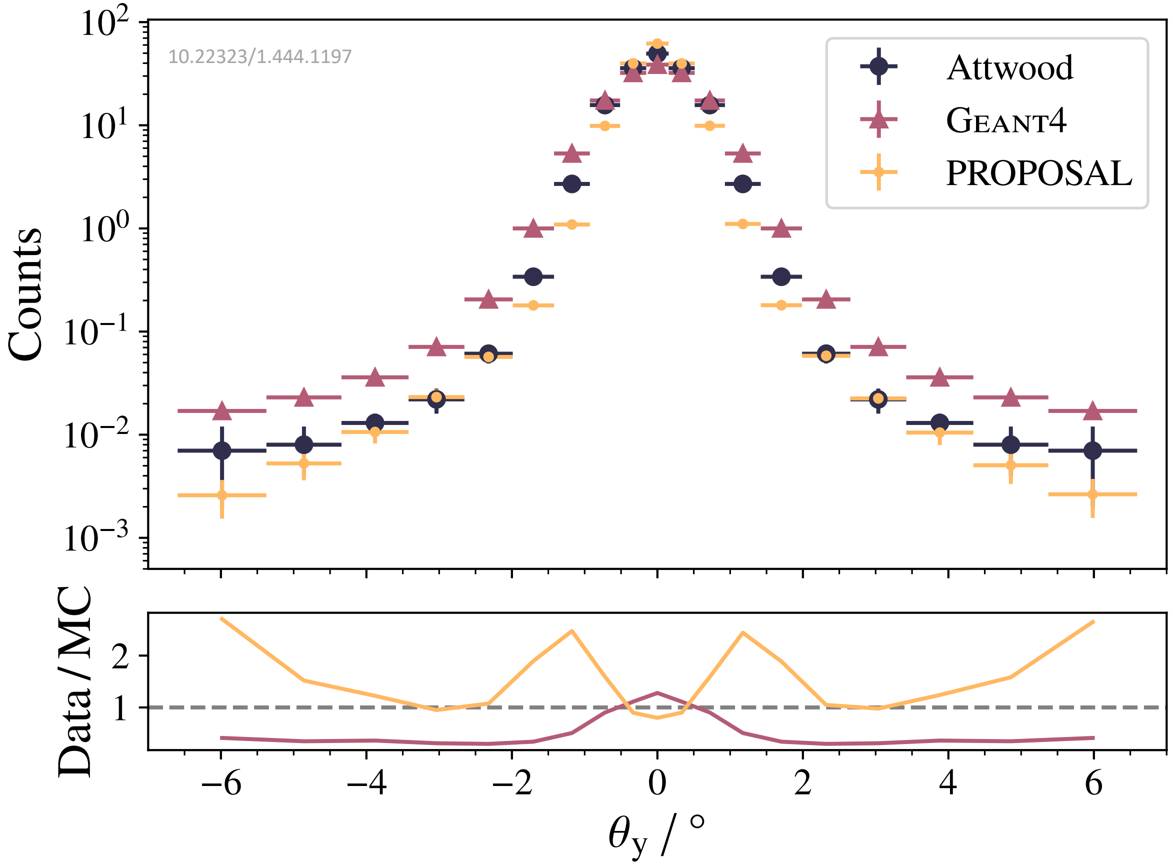


Muon Deflection – Data/MC

7.3 GeV, 1.44 cm copper



199 MeV, 1.09 cm liquid H_2



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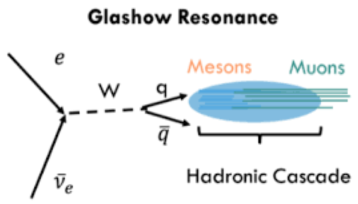
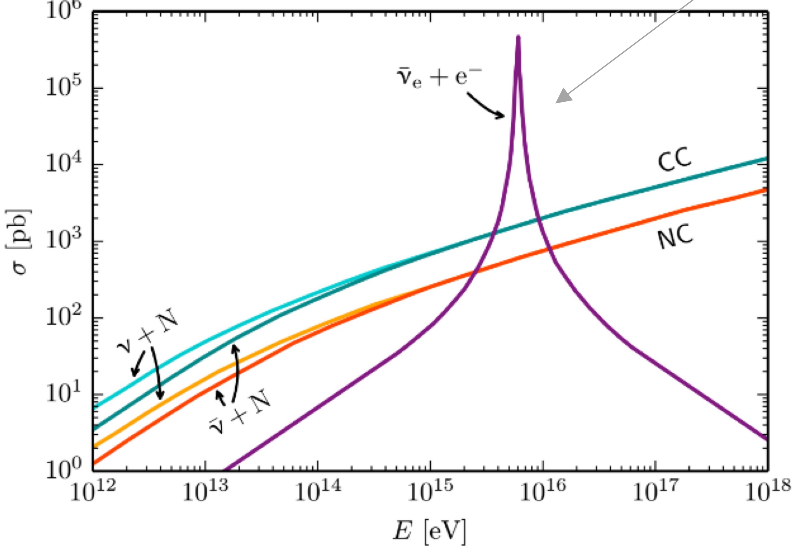
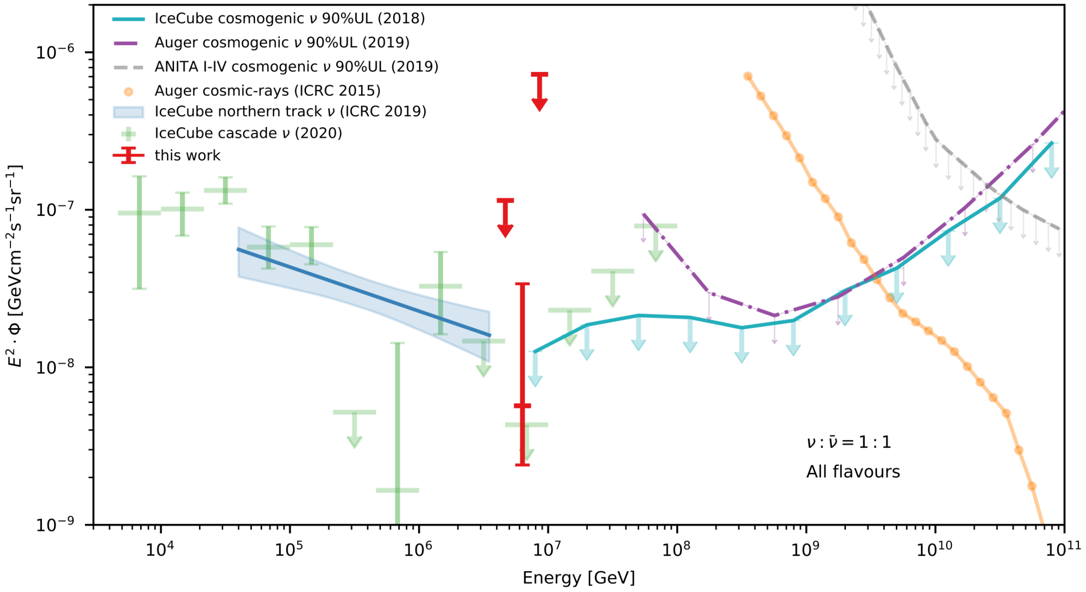


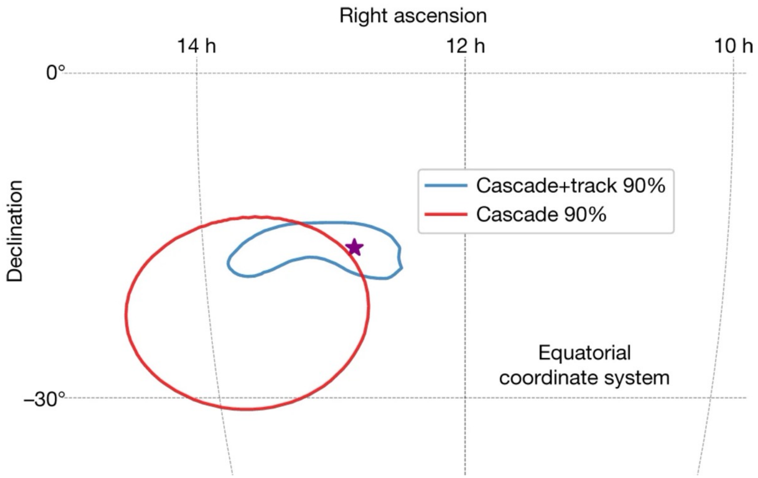
$$E_\nu = \frac{M_W^2 c^2 - (m_e^2 + m_\nu^2)c^2}{2m_e} \approx \frac{M_W^2 c^2}{2m_e}$$

6.3 PeV



10.1038/s41586-021-03256-1





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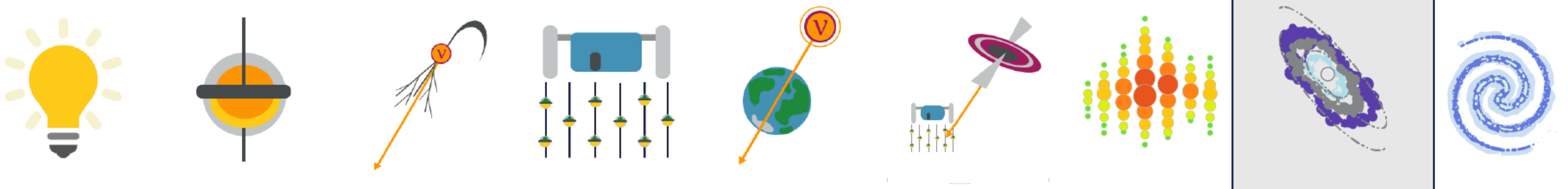

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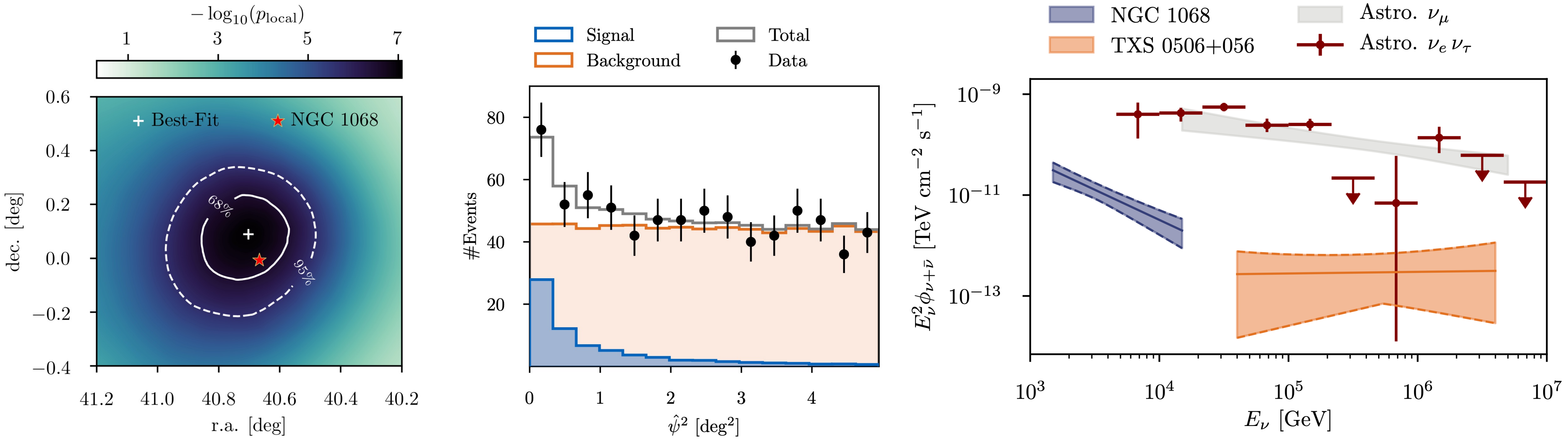

10.1126/science.abg3395

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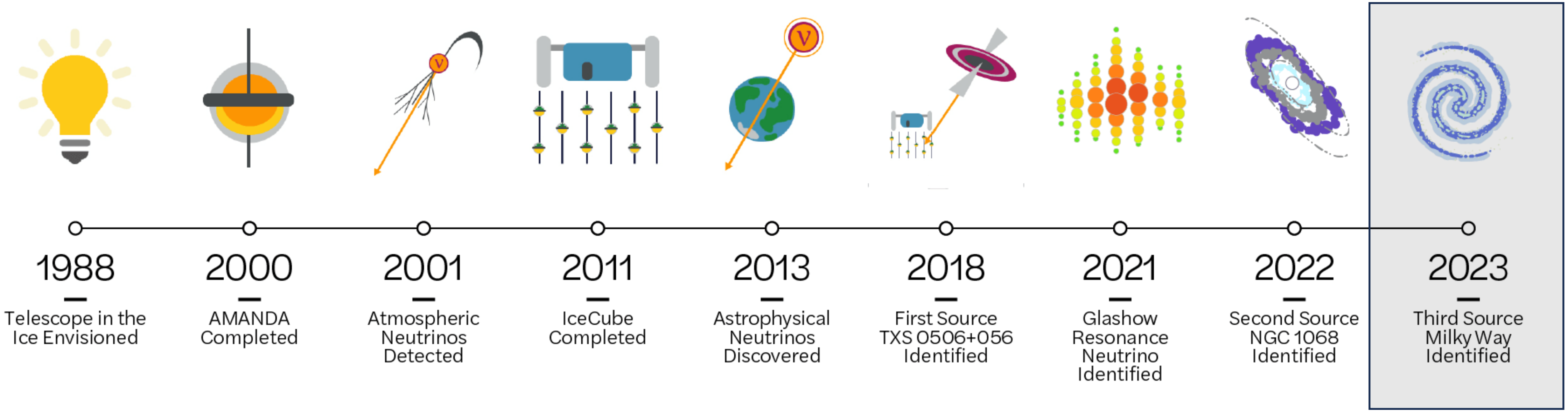
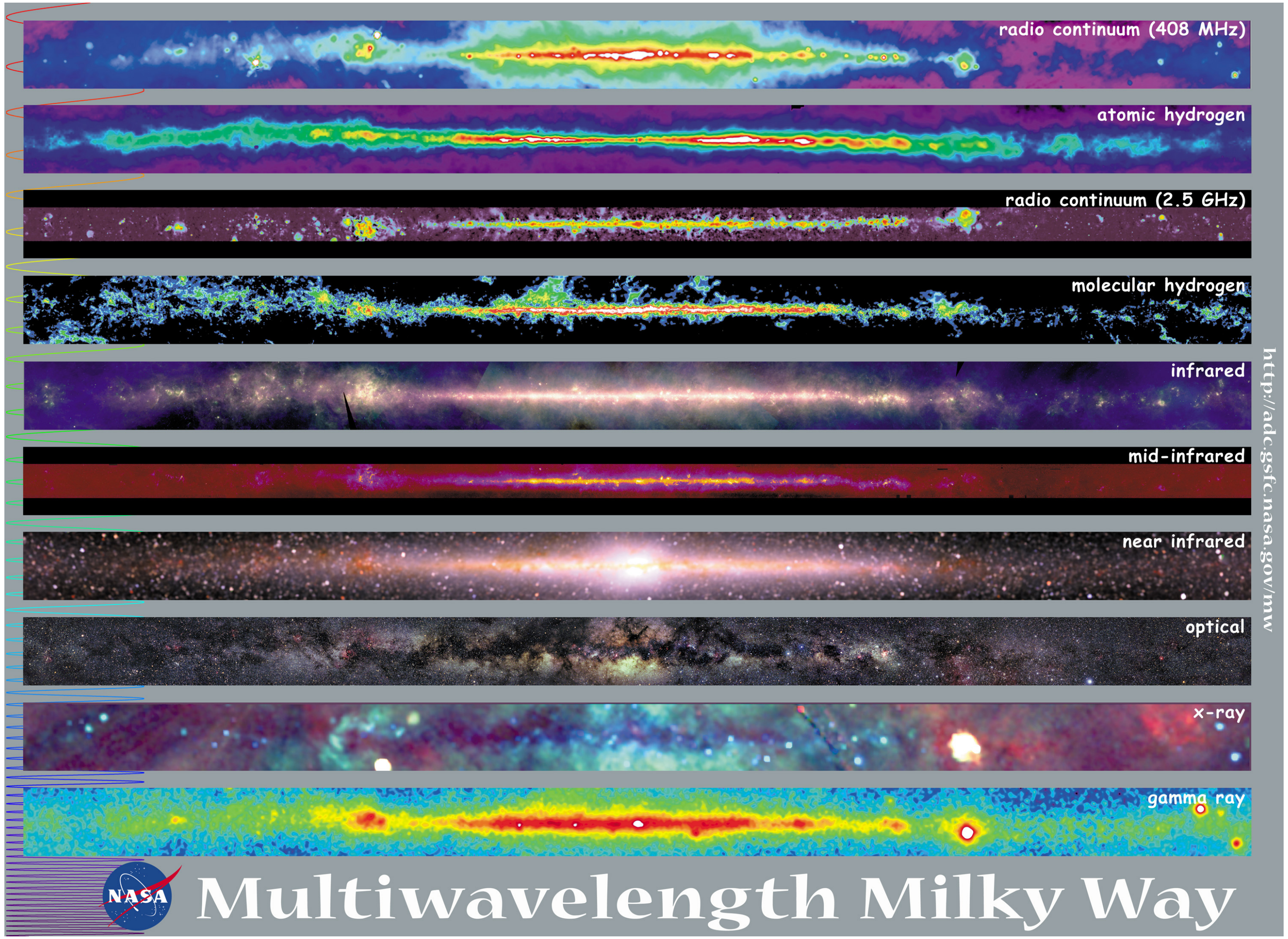


Multiwavelength Milky Way



Why was our galaxy not been detected before?

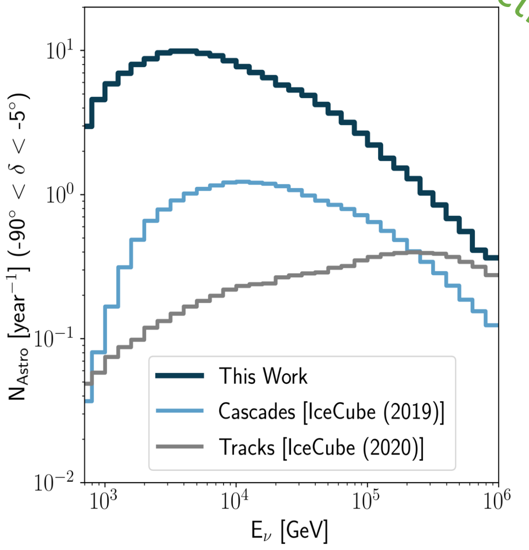
Rates:

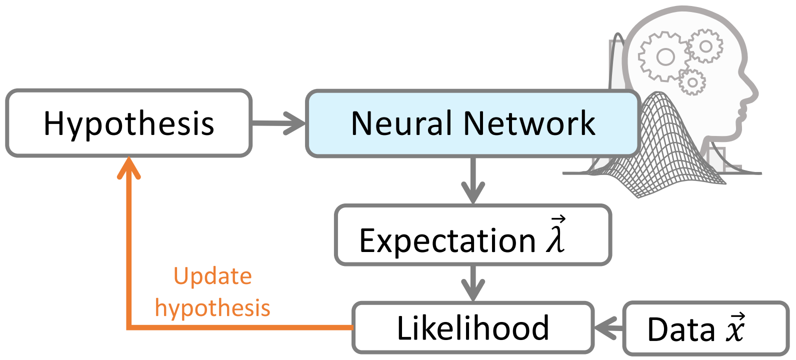
Atmospheric Muons: ~2700 / s

Atmospheric Neutrinos: ~1 / hour

Astrophysical Neutrinos: ~1 / day

Selection

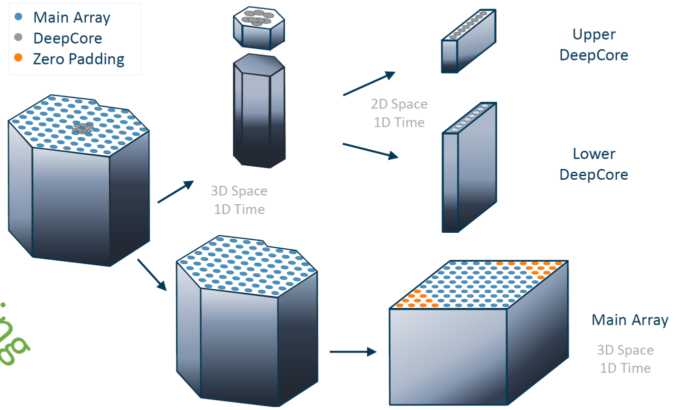




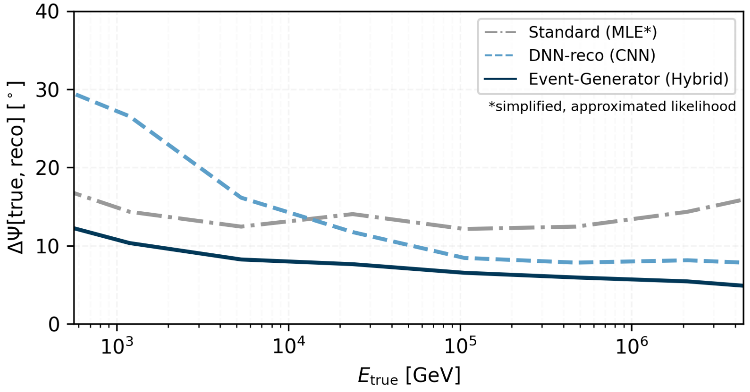
Hybrid reconstruction method:

- Combines maximum-likelihood estimation with deep learning
- Modeling of high-dimensional PDFs via neural networks
- Exploits available information and symmetries
- **Improved resolution over entire energy range**

Machine Learning

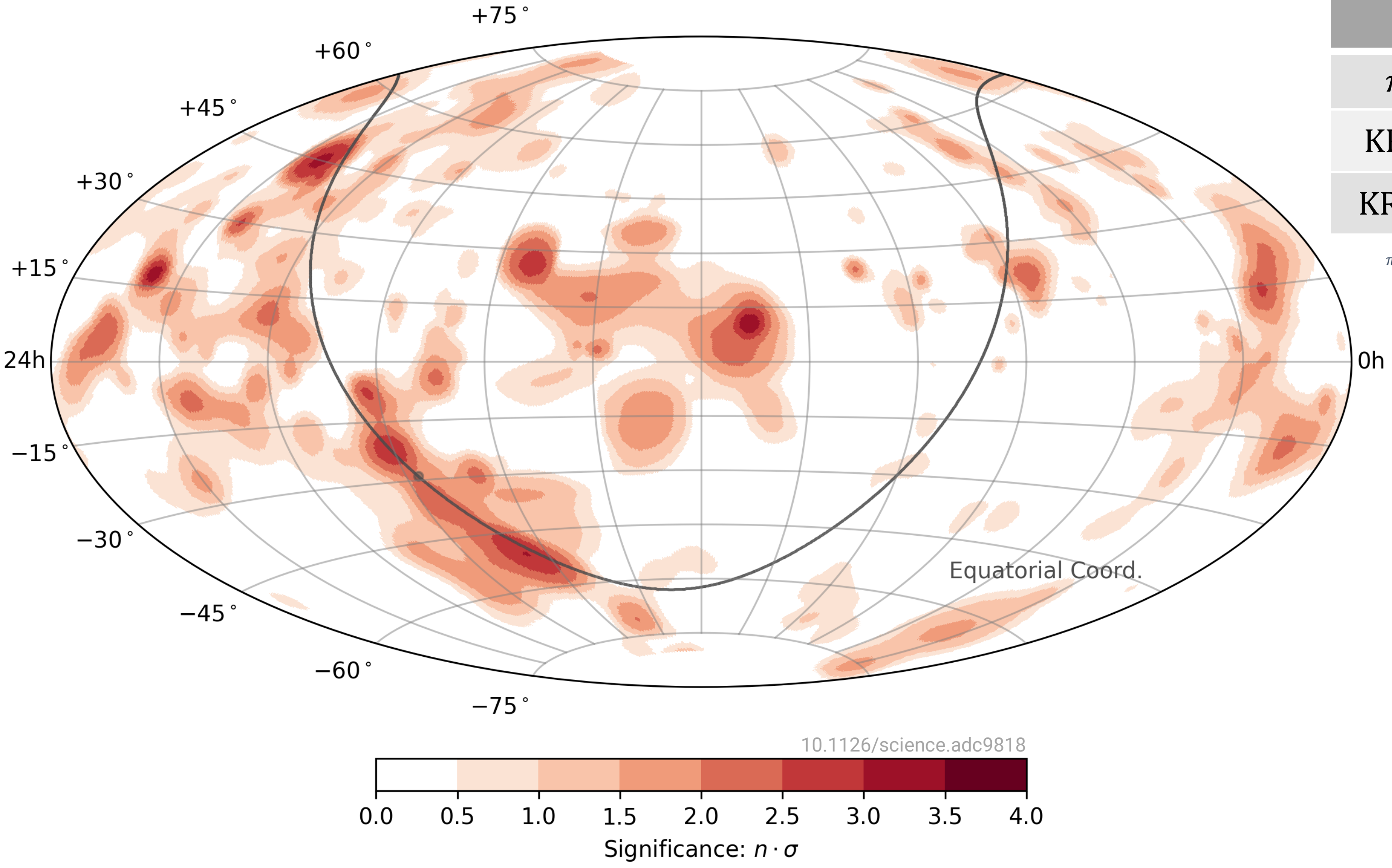


DOI: 10.22323/1.395.1065



Reconstruction

Third Source Milky Way Identified

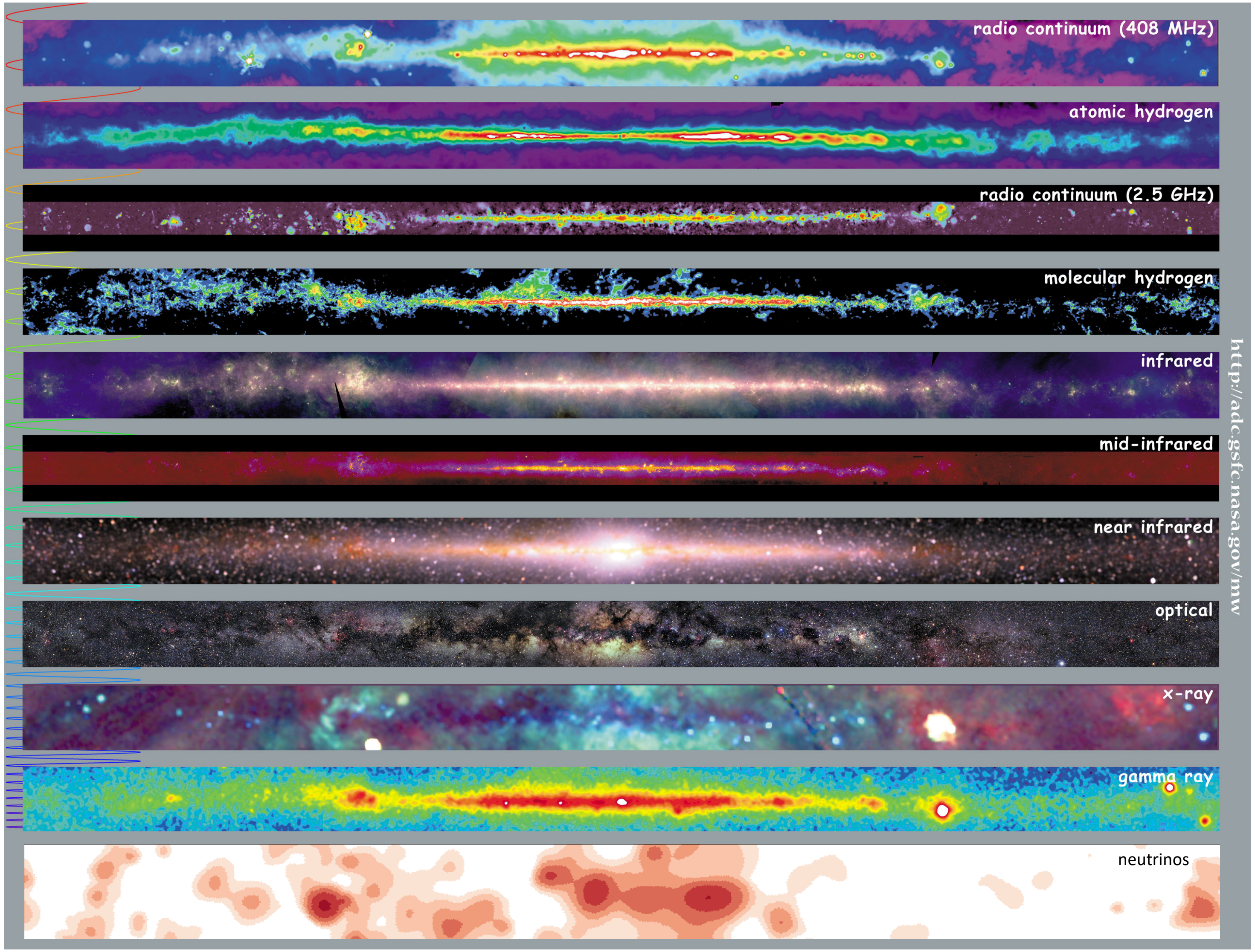


After trial-correction: 4.5σ

Model	Signal Events	Pre-trial p-value ($N\sigma$)
π^0	748	1.26×10^{-6} (4.71σ)
KRA_γ^5	276	6.13×10^{-6} (4.37σ)
KRA_γ^{50}	211	3.72×10^{-5} (3.96σ)

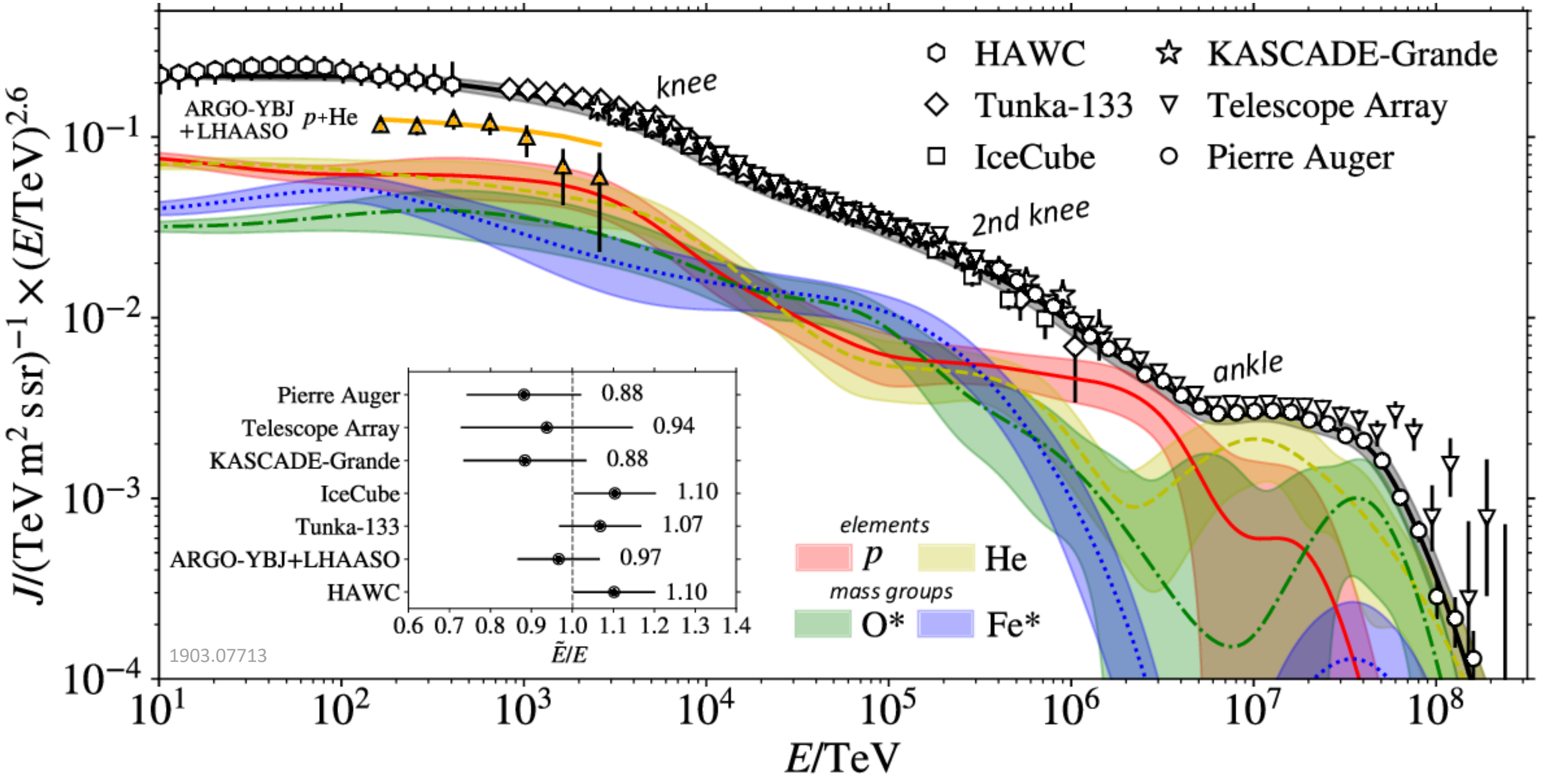
π^0: based on Fermi-LAT gamma-ray measurements (DOI: 10.1088/0004-637X/750/1/3)
$\mathrm{KRA}_\gamma^{5/50}$: based on Gaggero et. *al* (DOI 10.1088/2041-8205/815/2/L25)

~~Multiwavelength~~ Multimessenger Milky Way



The Muon Puzzle

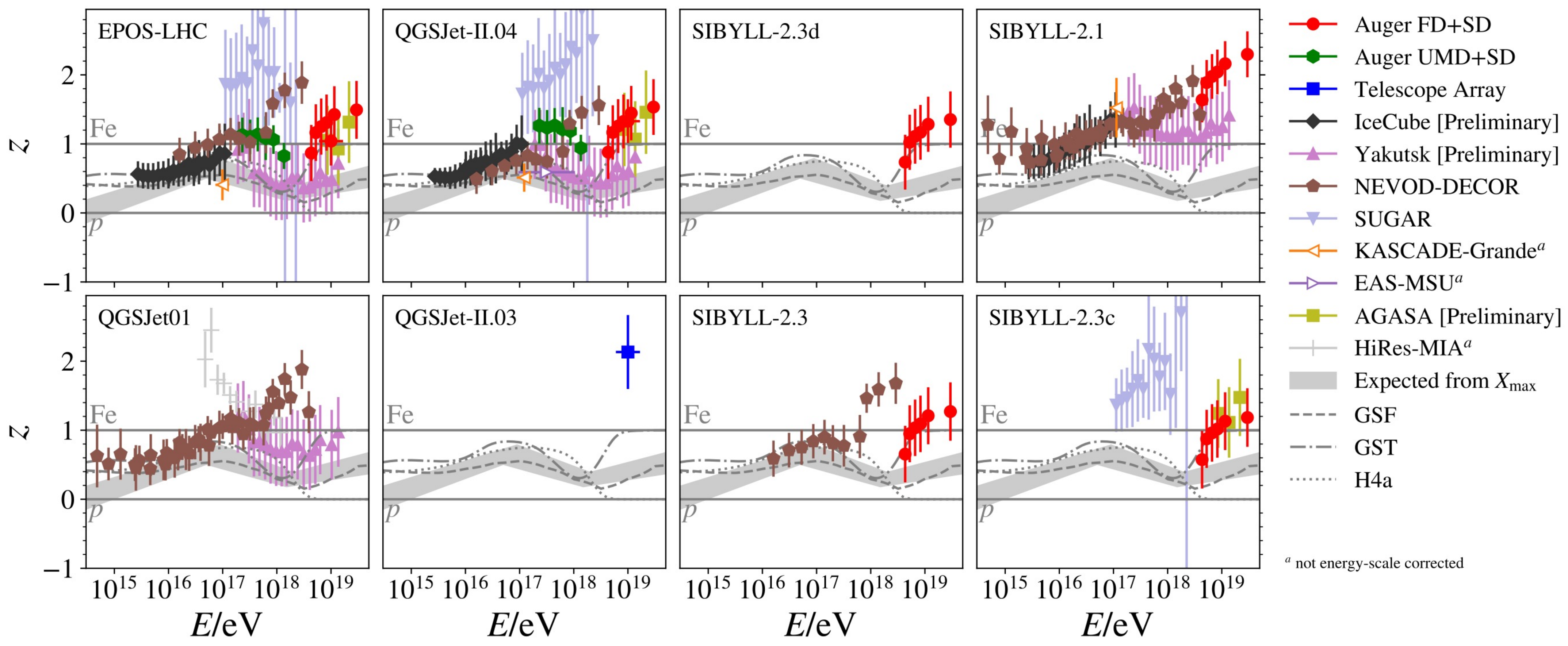
Cosmic Ray Flux



The Muon Puzzle

"muon number"

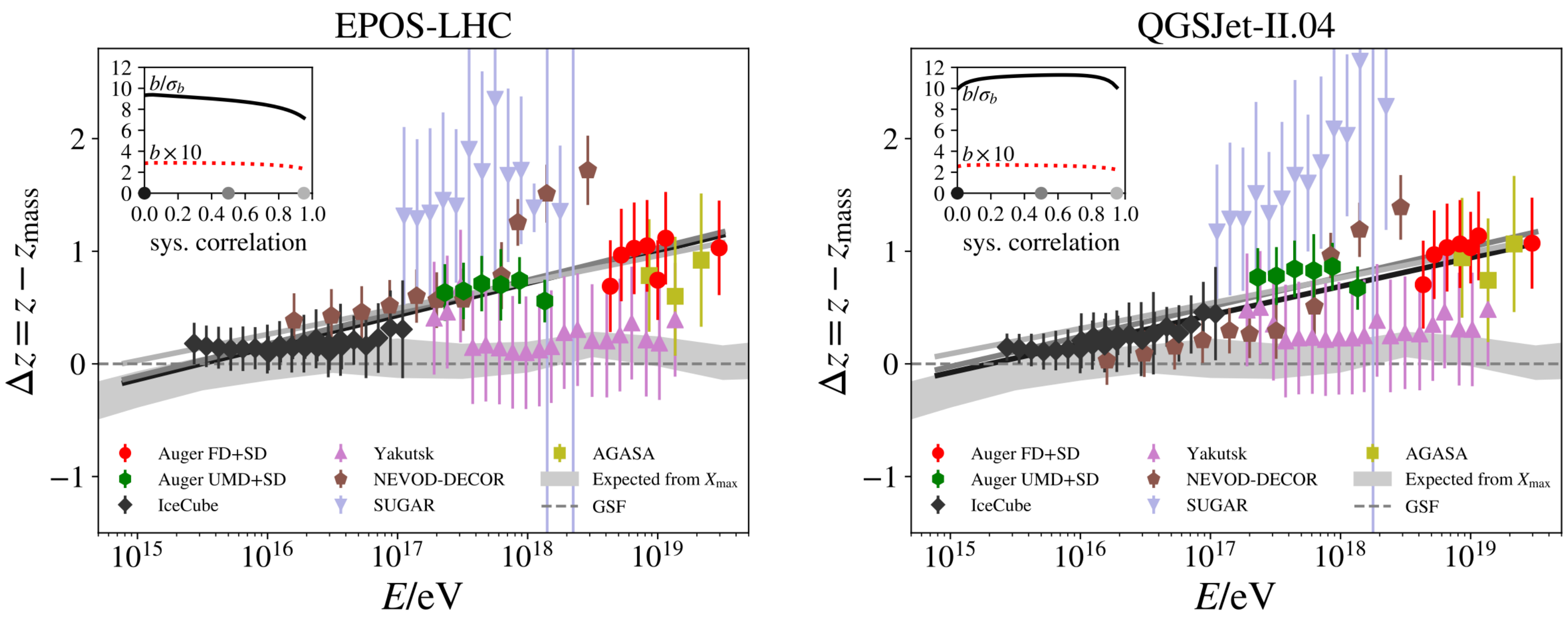
$$z = \frac{\ln\langle N_\mu \rangle - \ln\langle N_\mu \rangle_p}{\ln\langle N_\mu \rangle_{\mathrm{Fe}} - \ln\langle N_\mu \rangle_p}$$



2108.08341

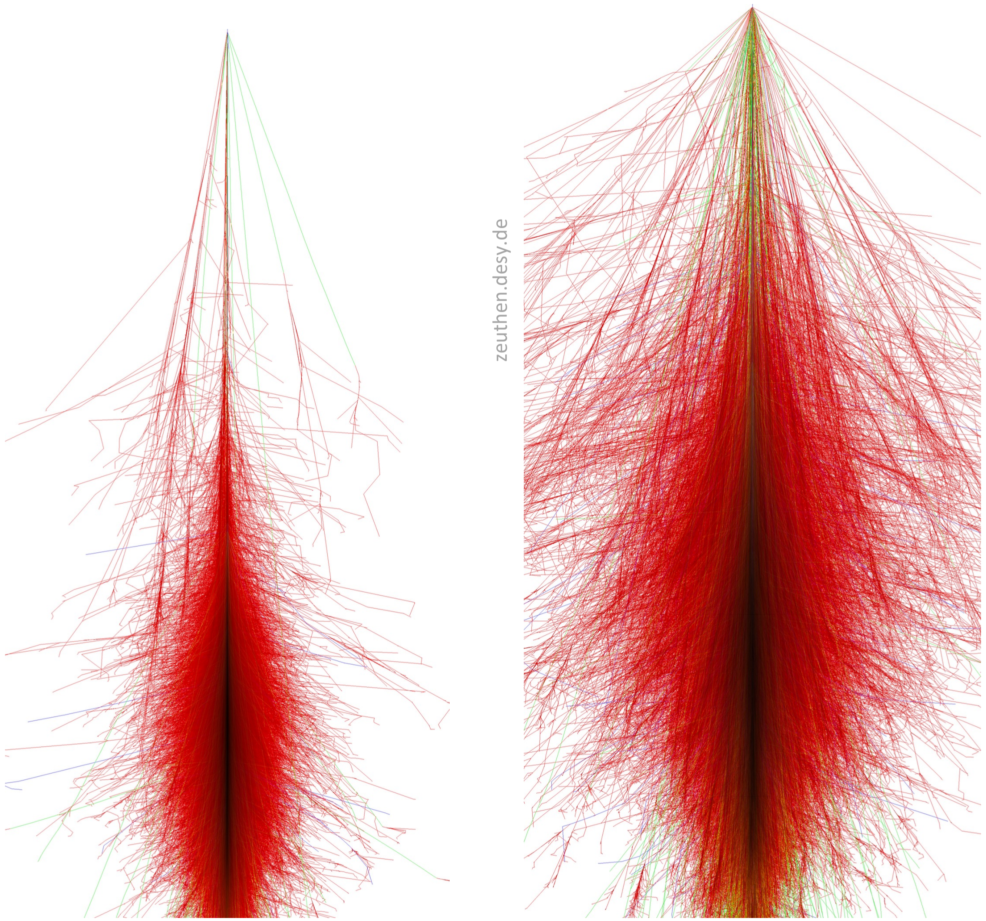
The Muon Puzzle

Expected z



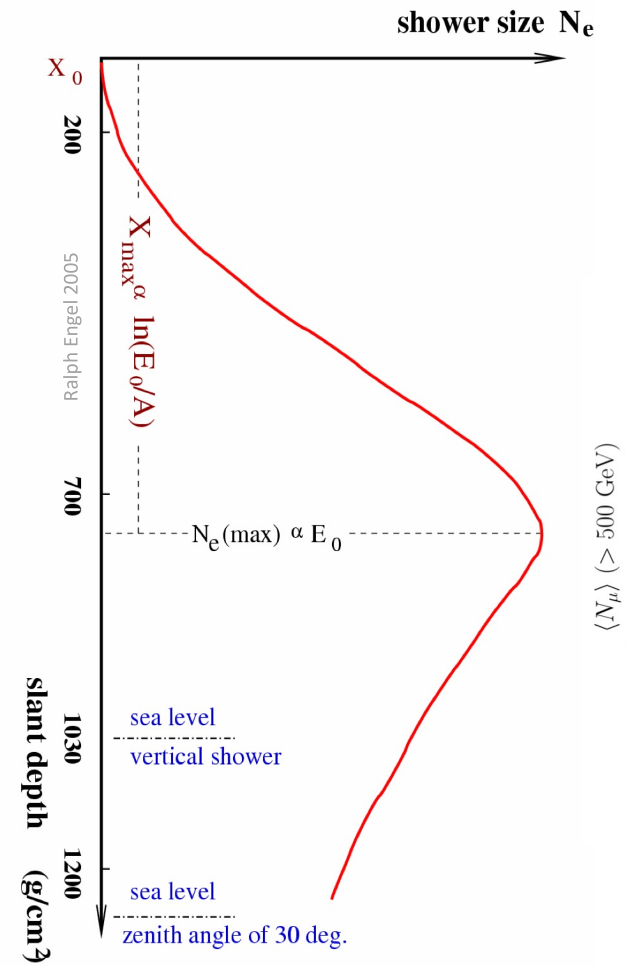
2108.08341

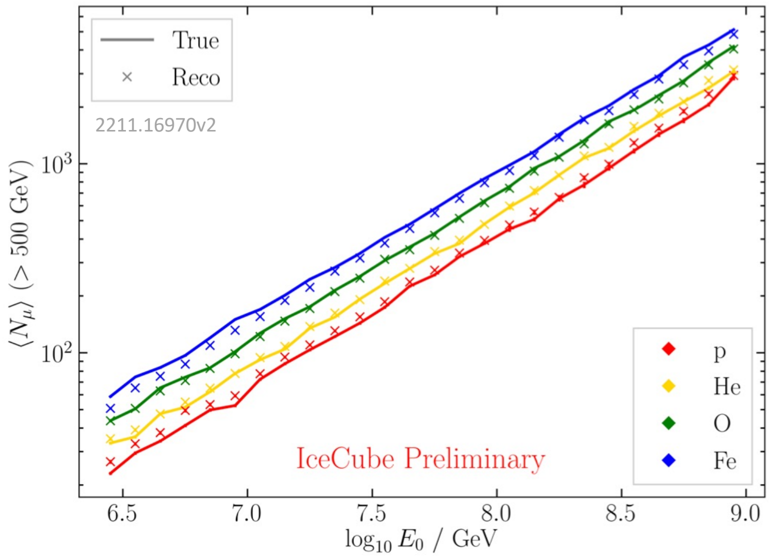
Air Shower Profiles – 10 TeV



Proton

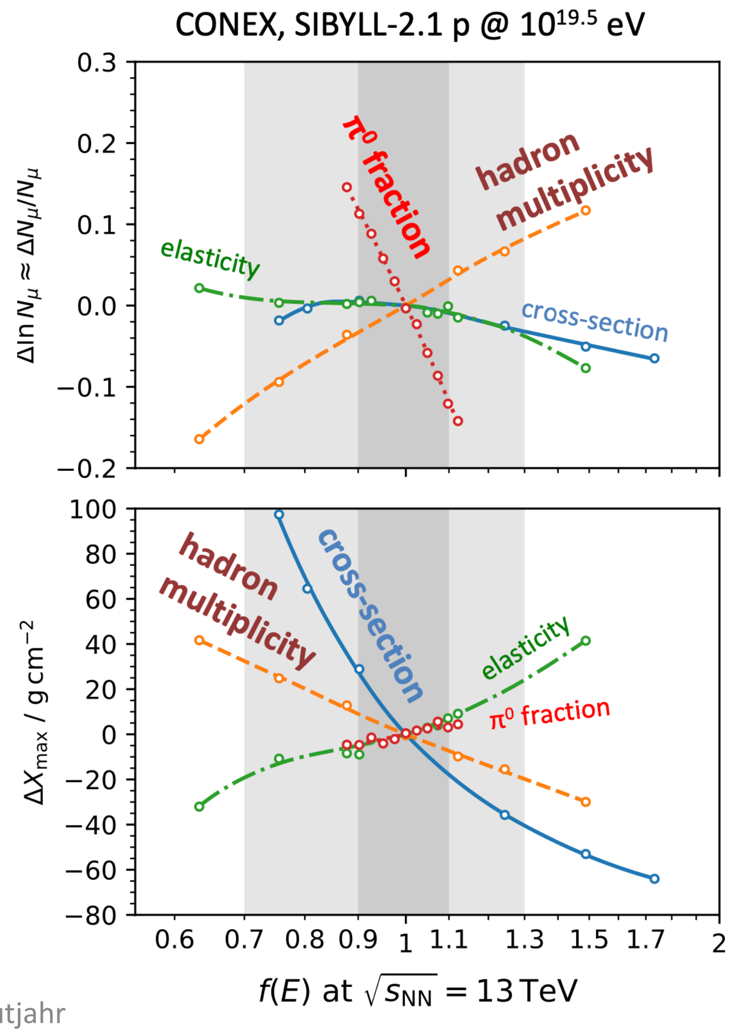
Iron



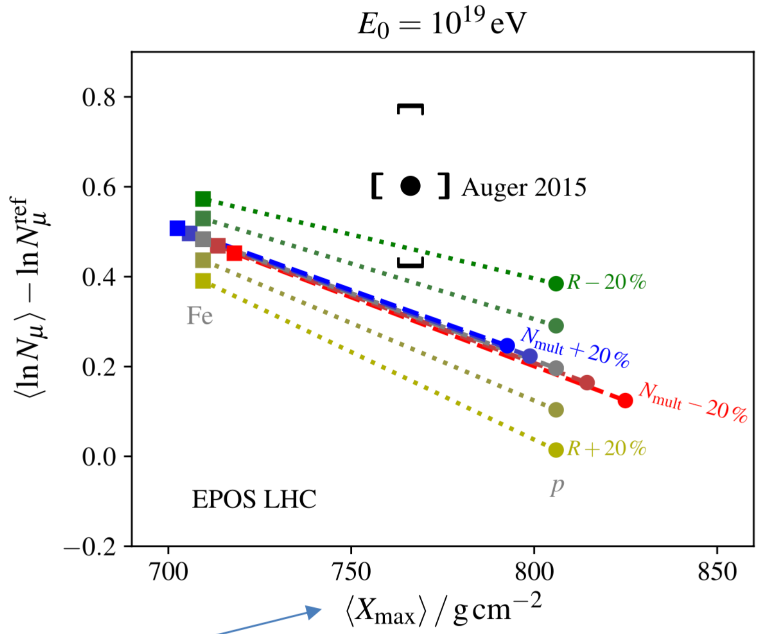


Possible Solutions

R. Ulrich, R. Engel, M. Unger, PRD 83 (2011) 054026



S. Baur, HD, M. Perlin, T. Pierog, R. Ulrich, K. Werner, arXiv:1902.09265



$$R = \frac{E_{\pi^0}}{E_{\text{other hadrons}}}$$

- Only changes to R can solve muon puzzle
- Small changes have large effect,
  R needs to be known to about 5 %

Hans Dembinski

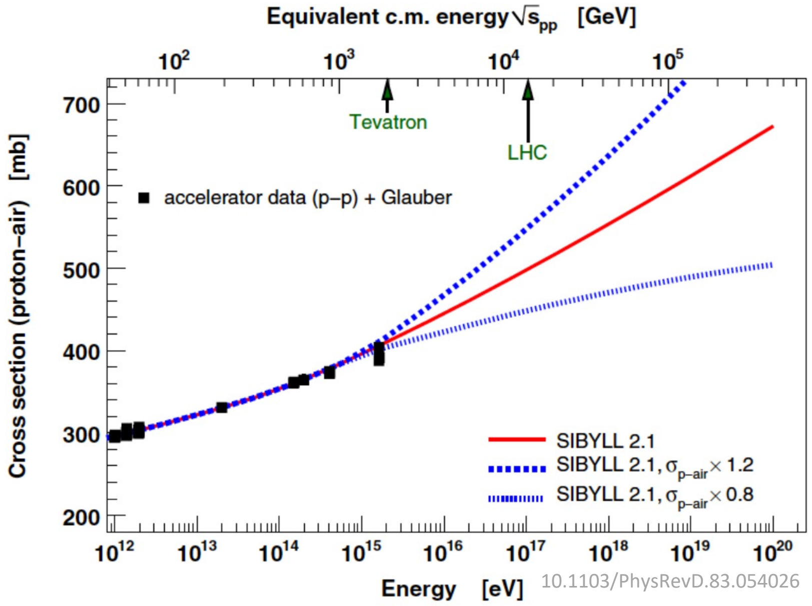
Connection to LHC

Deviations start at 40 PeV -> cms 8 TeV

Fixed target data at sub-TeV

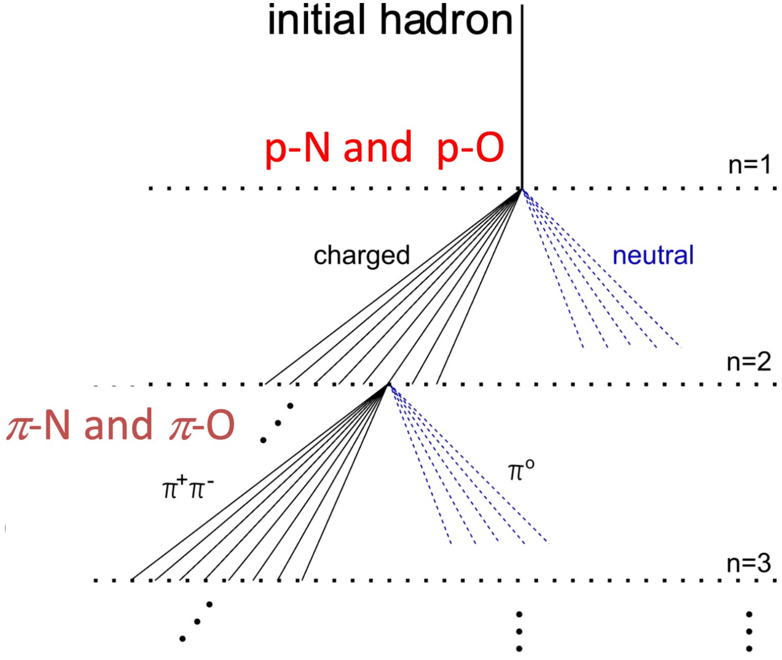
- p+(p,…,O,N,…) @ 0.11 TeV
- Pb+(p,…,O,N,…) @ 0.07 TeV
- O+O, O+p @ 0.08 TeV (in Run 3)

$\eta \gg 2$



10.1103/PhysRevD.83.054026

Air shower collision systems

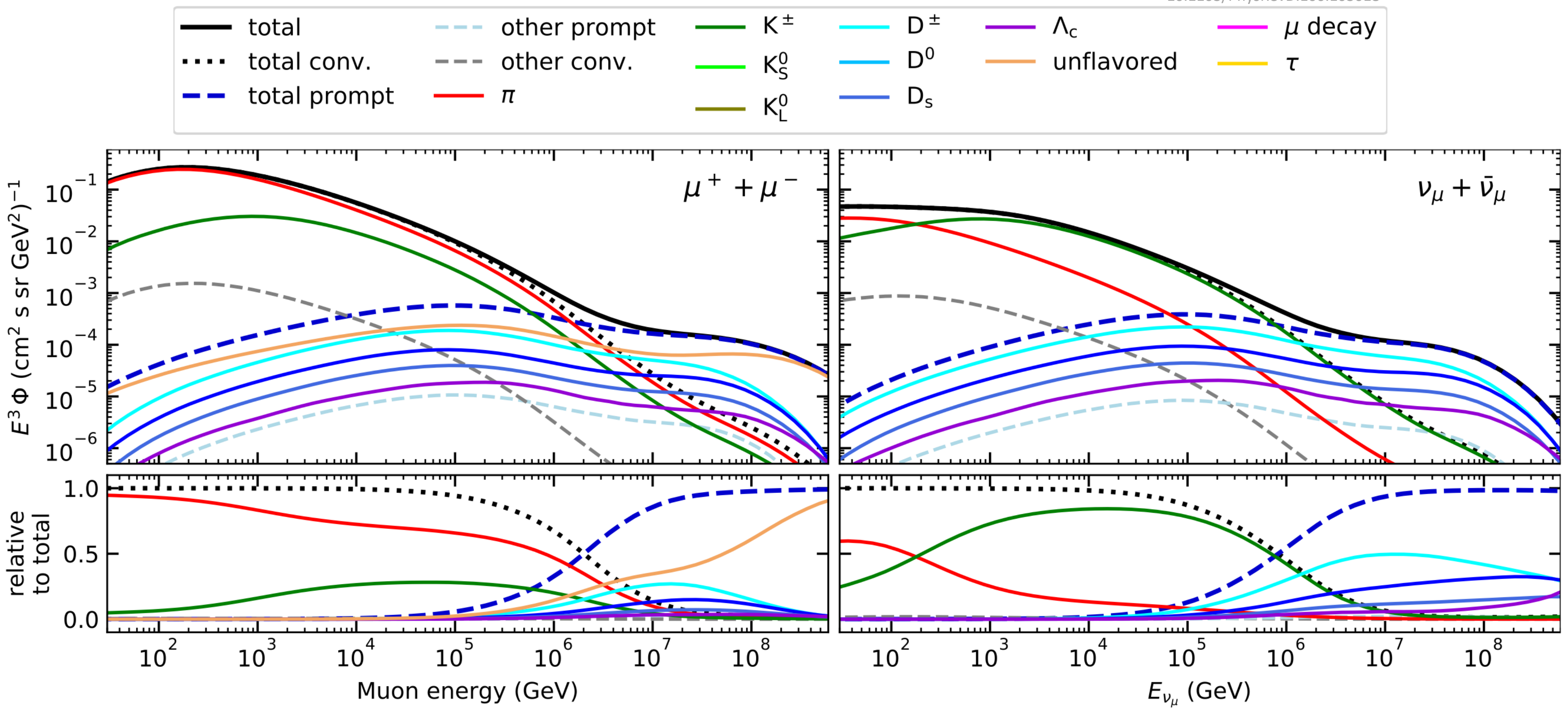


p-O collisions mimic air shower interactions

Hans Dembinski

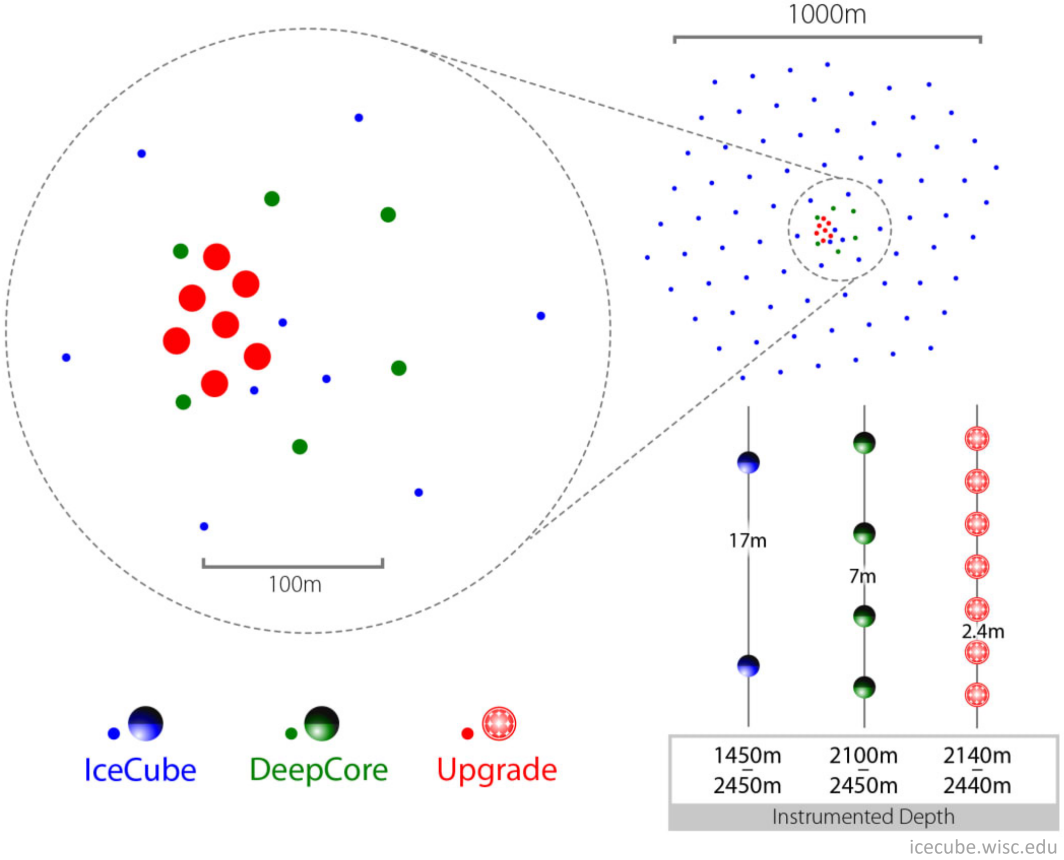
Atmospheric Prompt Muons and Neutrinos

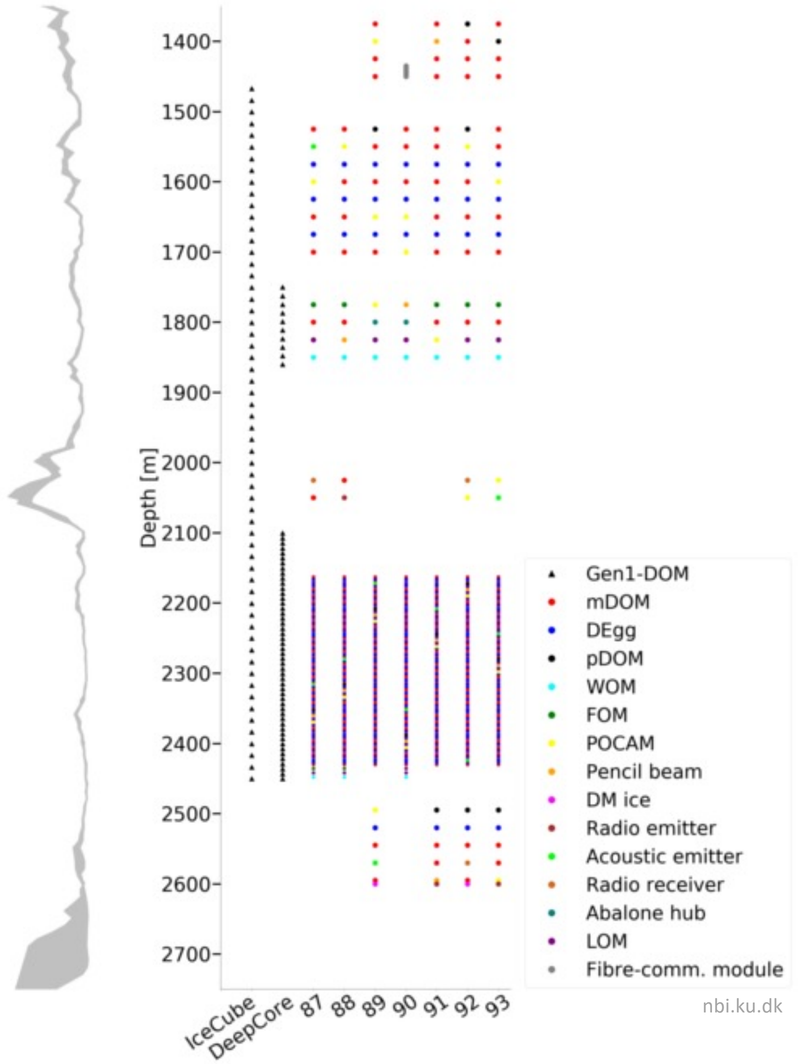
10.1103/PhysRevD.100.103018



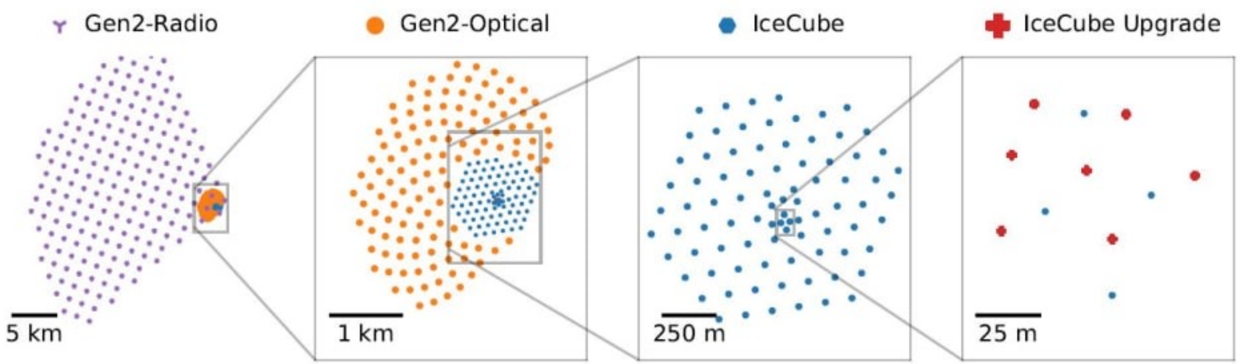
The Future of IceCube

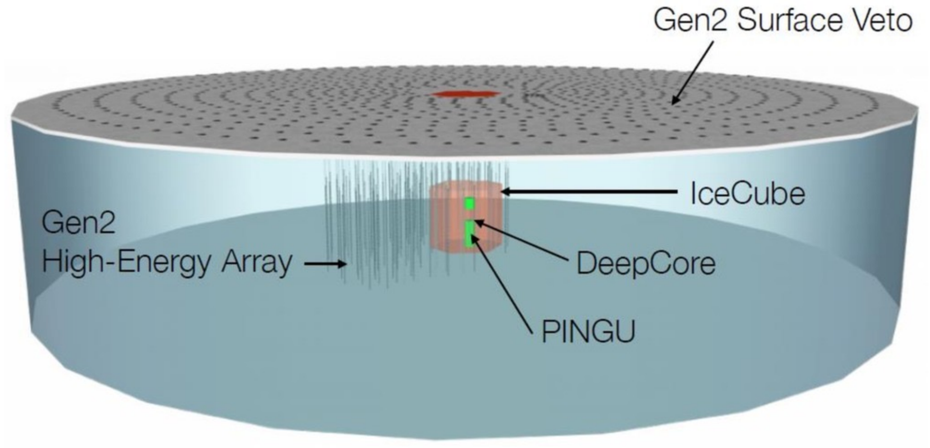
IceCube Upgrade

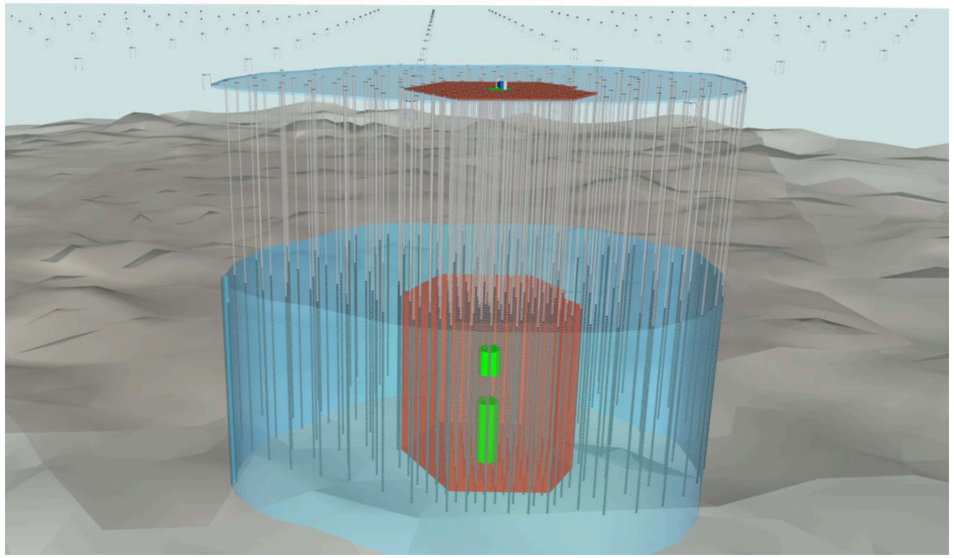




IceCube Gen-2





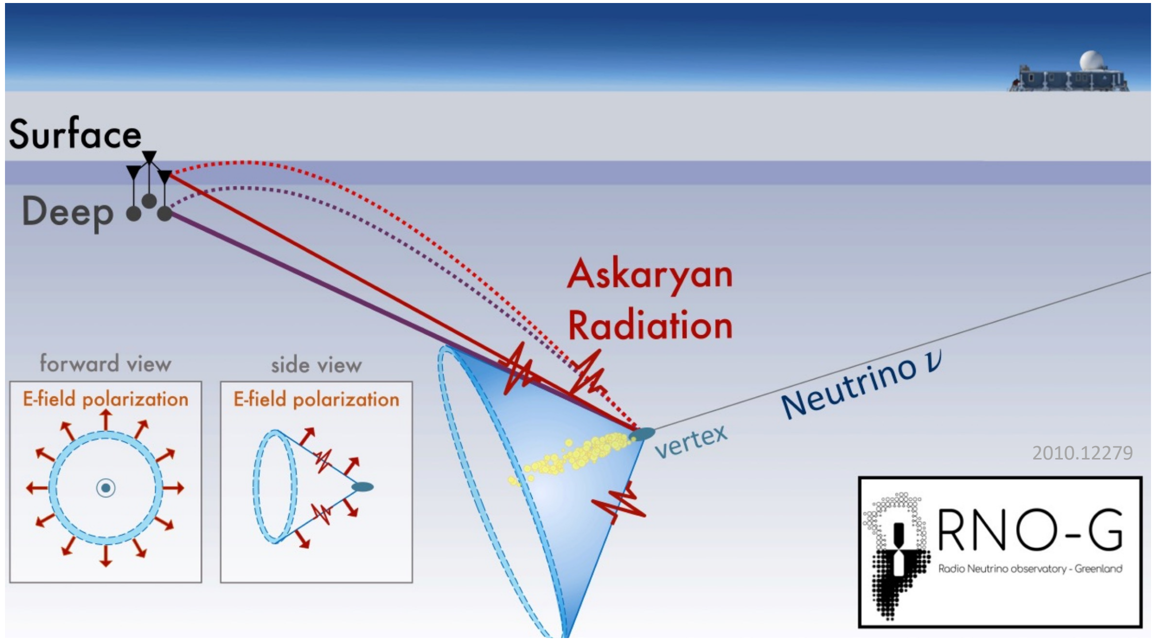


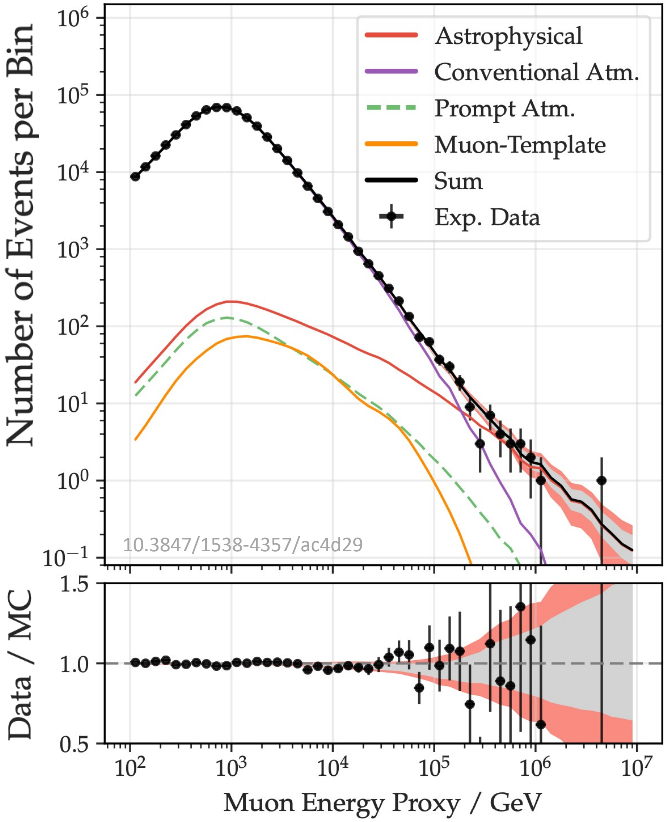
icecube.wisc.edu

Radio Neutrino Astronomy

Radio:
- larger attenuation length
- covers bigger volume
- detect higher energies

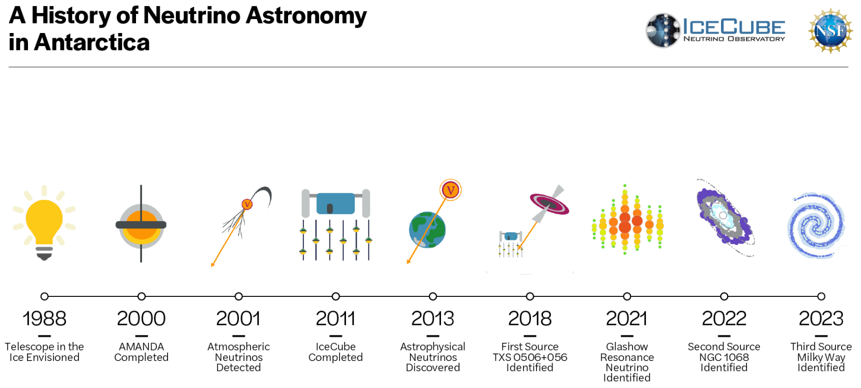
Askaryan effect -> similar to Cherenkov effect -> charge anisotropy -> emission of radio radiation -> particle energy scales with frequency

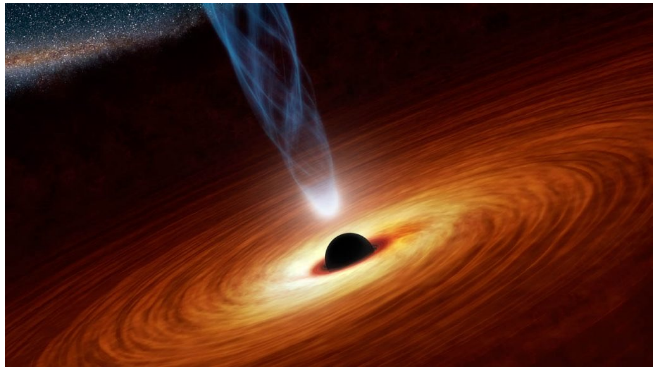


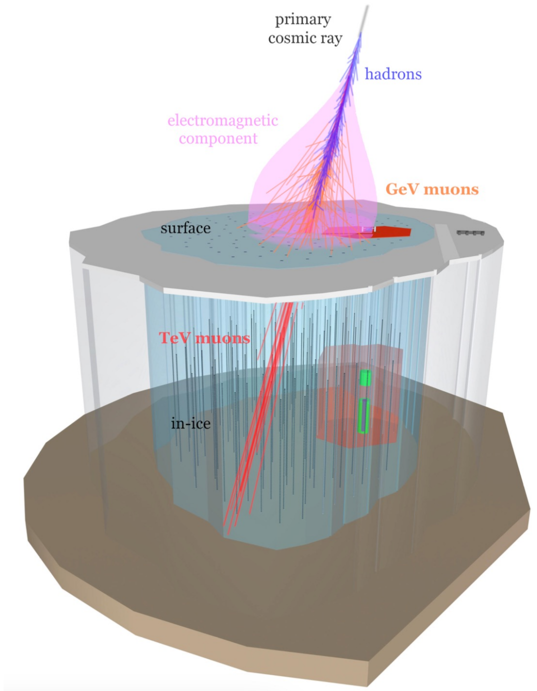


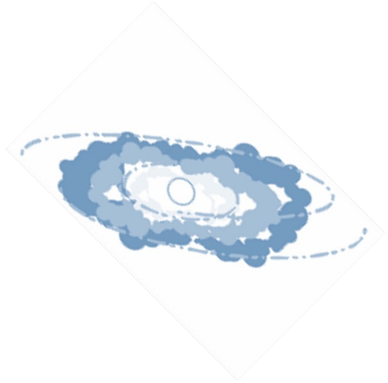
dortmund university

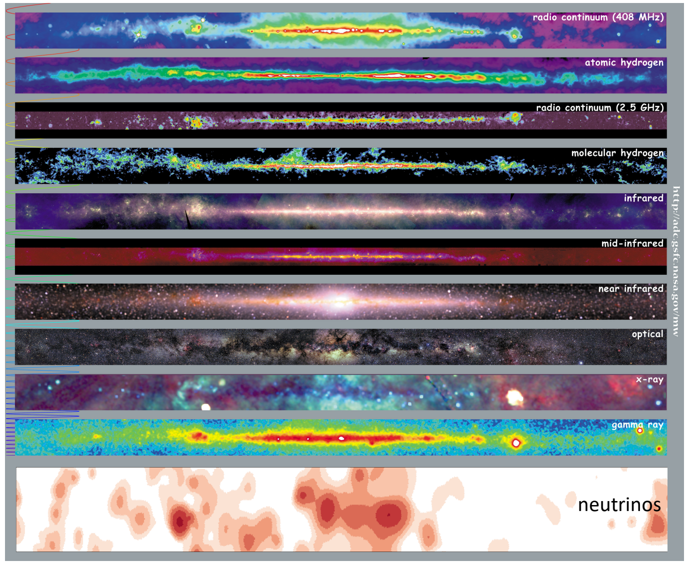
Conclusion

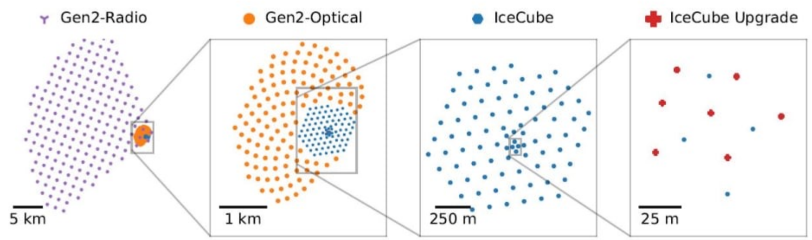






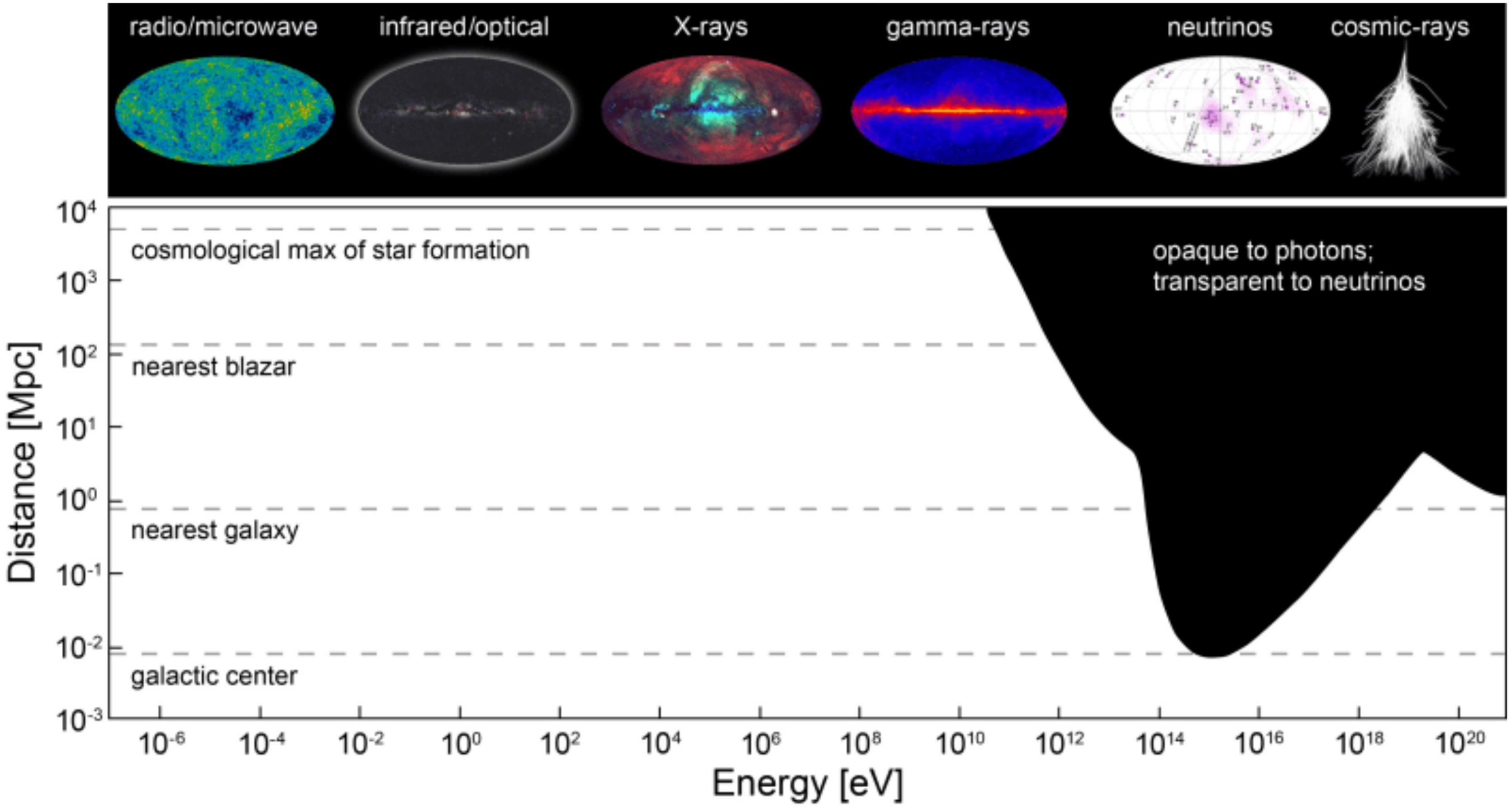






Backup

Messenger


radio/microwave
infrared/optical
X-rays
gamma-rays
neutrinos
cosmic-rays
cosmological max of star formation
opaque to photons;
transparent to neutrinos
nearest blazar
nearest galaxy
galactic center
Distance [Mpc]
Energy [eV]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-6}
10^{-4}
10^{-2}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}

Gen2 Modules

IceCube DOM

35 cm

mDOM

36 cm

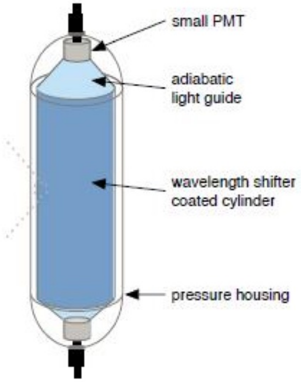
- Directional information
- More sensitive area per module

D-Egg

30 cm

- Directional information
- More sensitive area per module
- Smaller geometry

WOM



11 cm

- more sensitive area per $
- Small diameter
- Lower noise rate

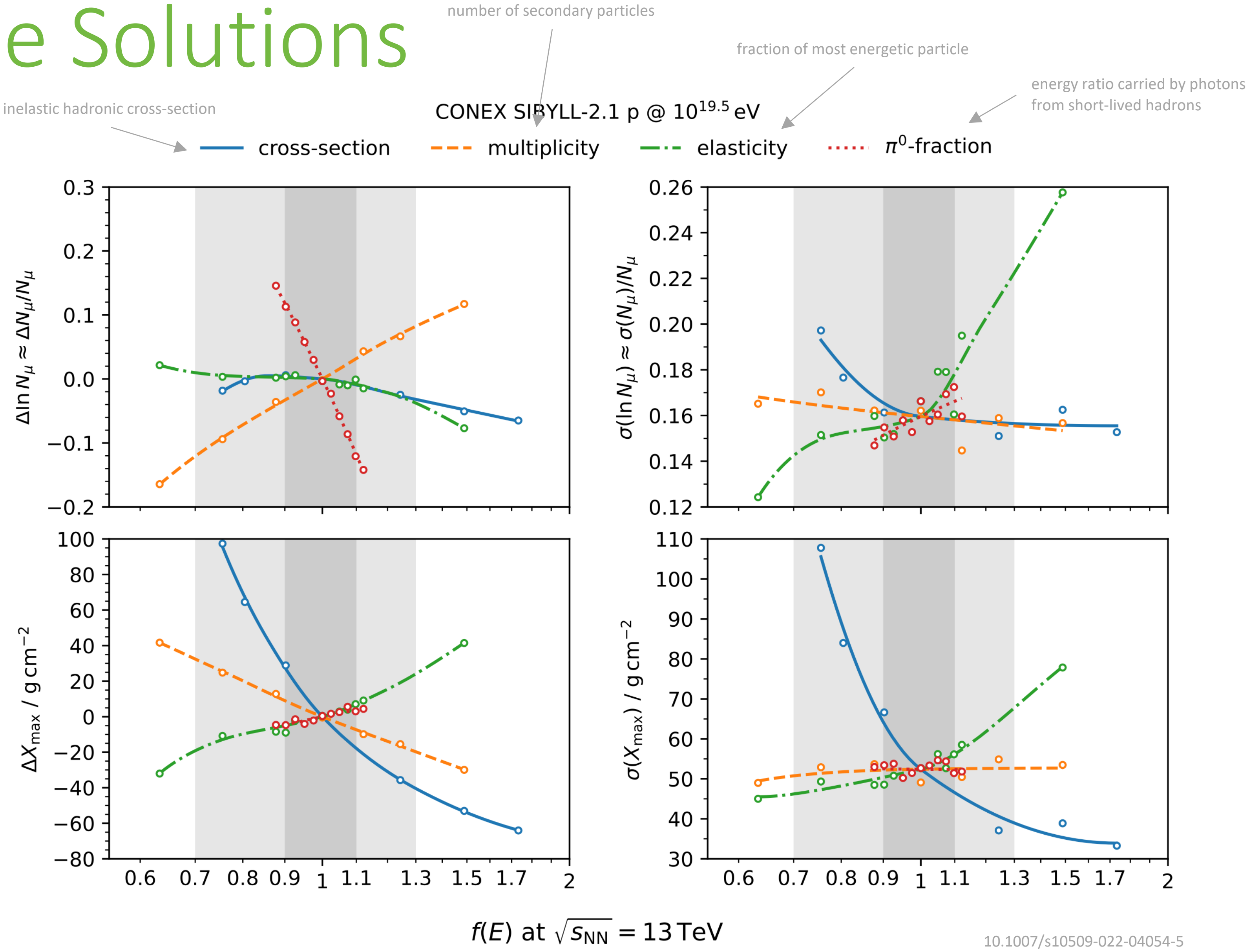
LOM

13 cm

- Small diameter
- Directional info.
- More area per module

icecube.wisc.edu

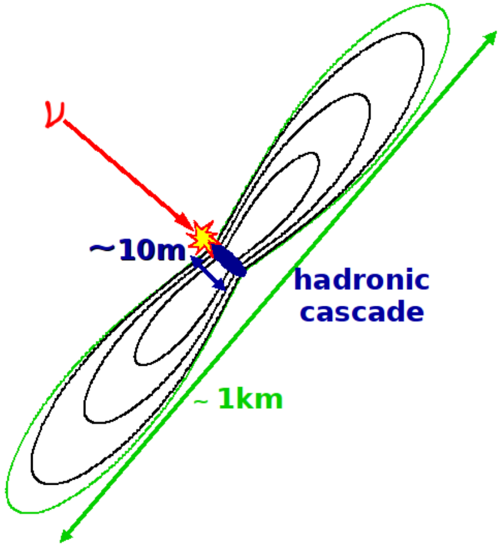
Possible Solutions



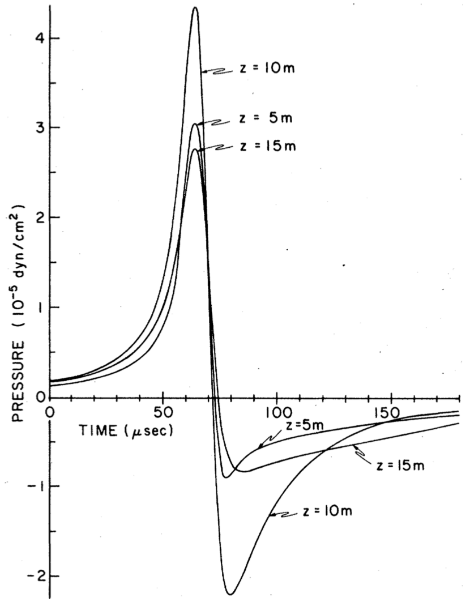
10.1007/s10509-022-04054-5

Acoustic Neutrino Detection

hadronic cascade
- ➢ medium heats up
- ➢ thermal expansion
- ➢ acoustic signal (see Askaryan 1957)



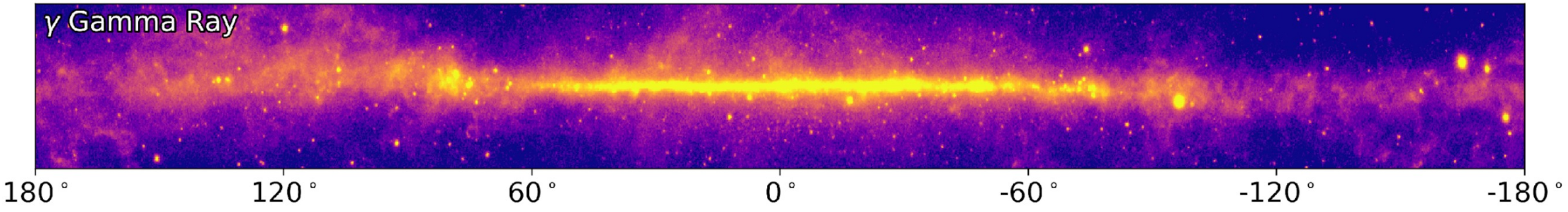
(a)



(b)

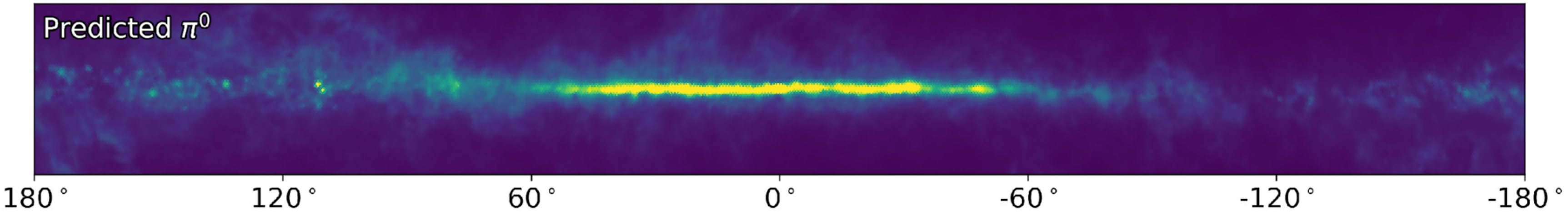
Figure 3.6: *(a) Illustration of the thermo-acoustic effect for a neutrino-induced hadronic cascade, from [86]. The typical length of a high-energy cascade with* 10^{10} GeV *is about* 10 m*, resulting in a flat disc-shaped radiation pattern. (b) Calculated bi-polar pressure pulse arising from a* 10^{16} eV *cascade in sea water with a radial symmetric heat deposit. Pressure pulses are shown in different positions* (z) *in* 400 m *distance along the cascade axis, from [87].*

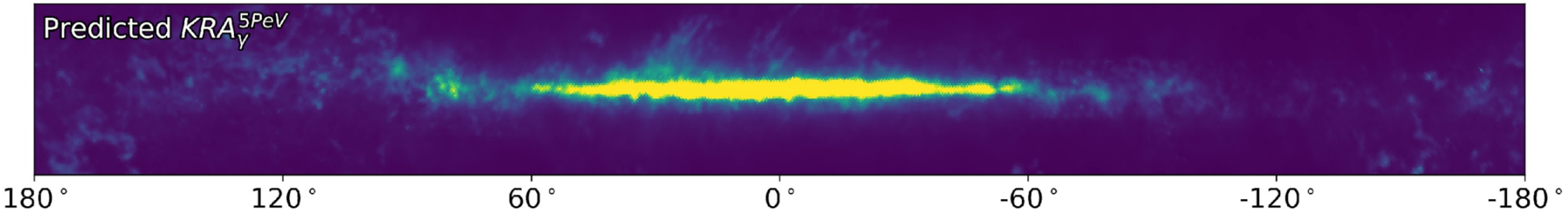
Galactic Plane Analysis



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

$$\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$





1. Ackermann et al. *The Astrophysical Journal* 750, no. 1 (April 2012): 3.
2. Gaggero et al *The Astrophysical Journal* 815, no. 2 (December 2015): L25.

Galactic Plane Analysis