21st Rencontres du Vietnam,
Neutrino Physics
(Quy Nhon, Vietnam)

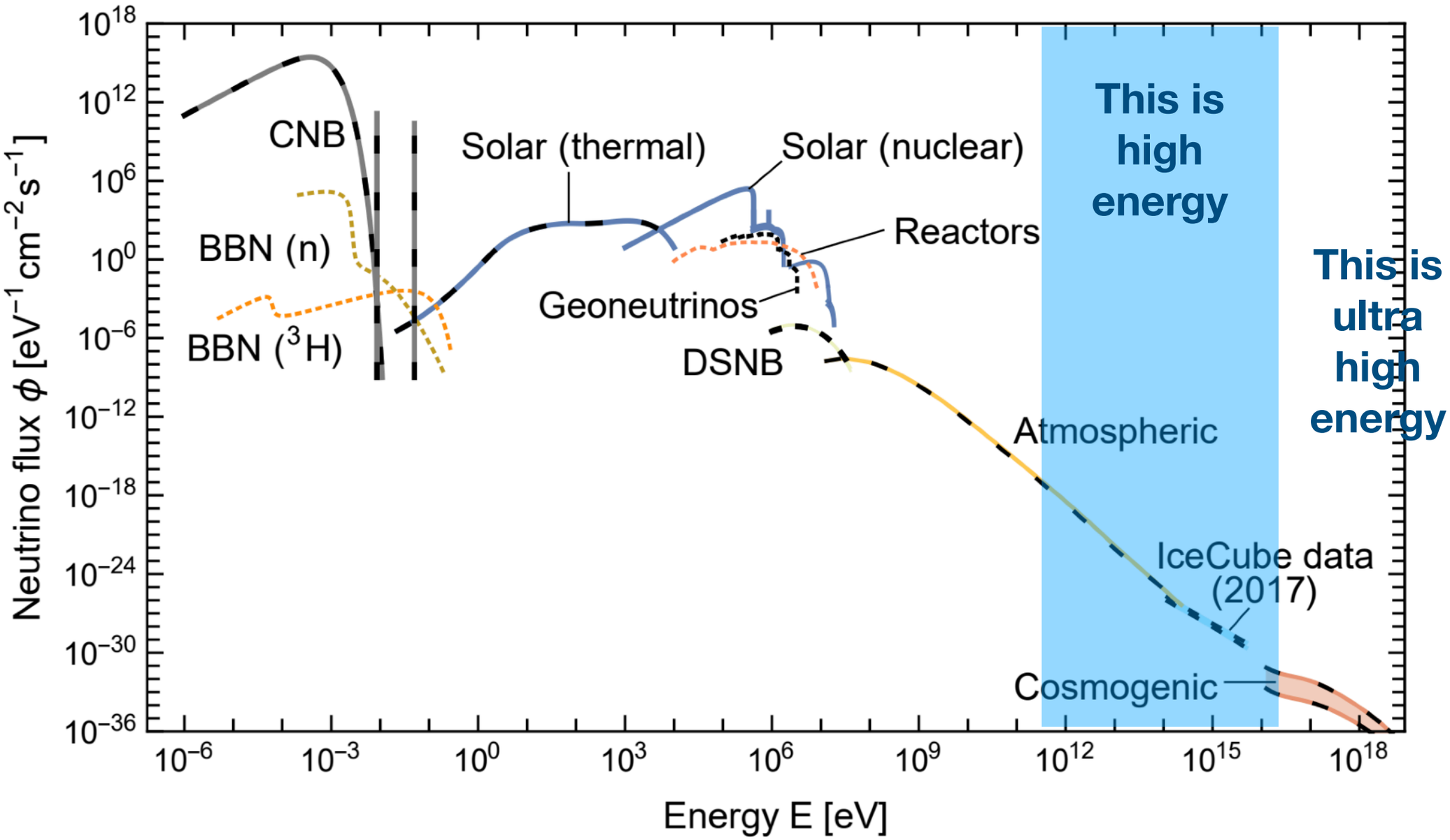
Latest Results in Neutrino Astronomy

Alfonso Garcia
alfonso.garcia@ific.uv.es

What is high energy?

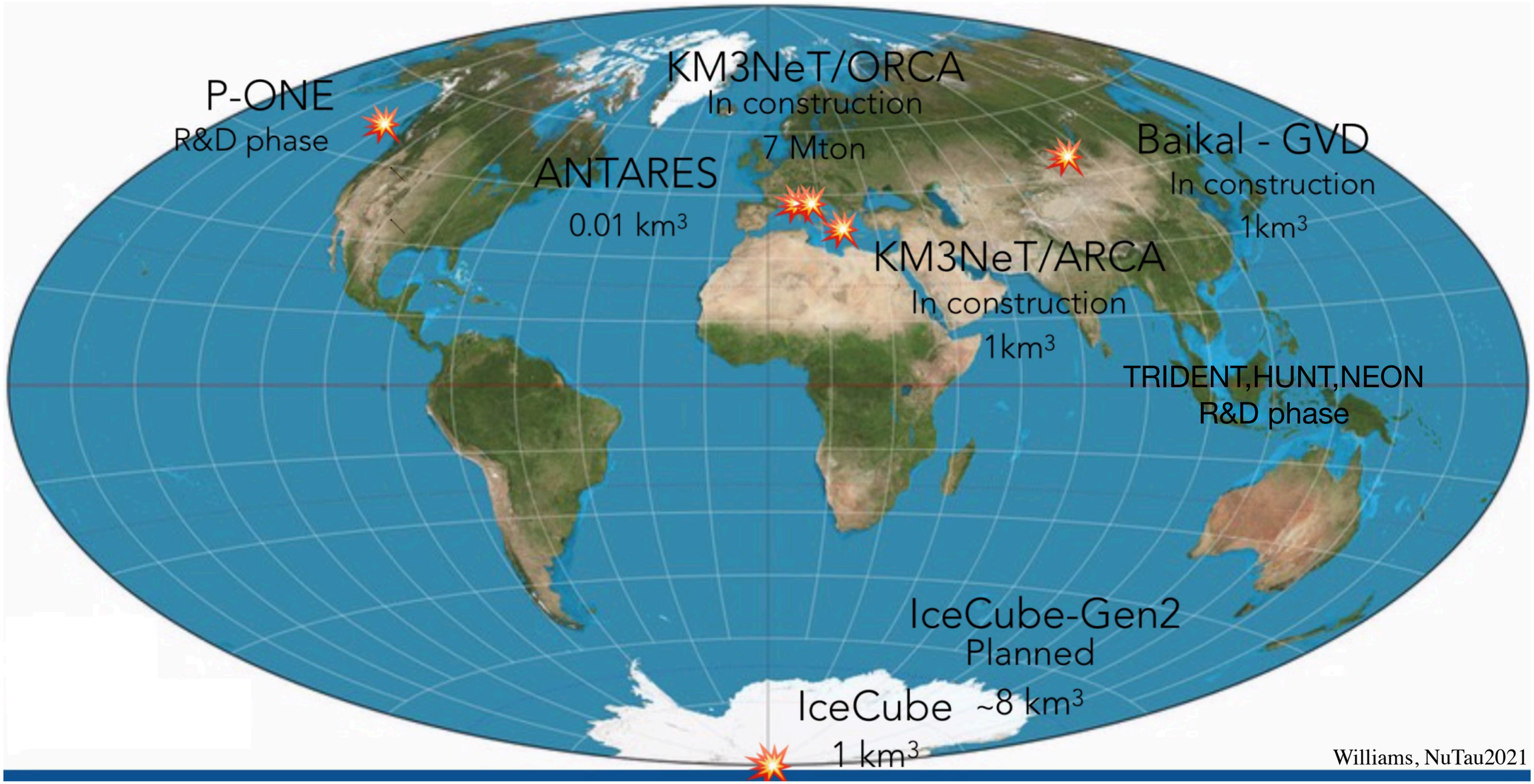
the higher in energy, the less flux….

Rev. Mod. Phys. 92, 45006 (2020)



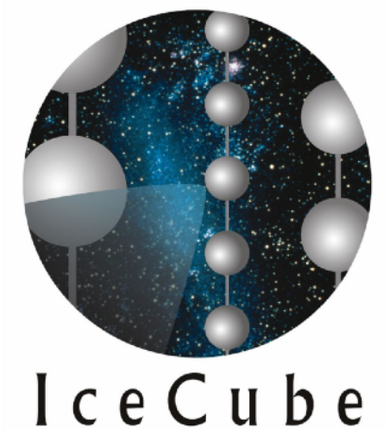
How to detect high-energy neutrinos?

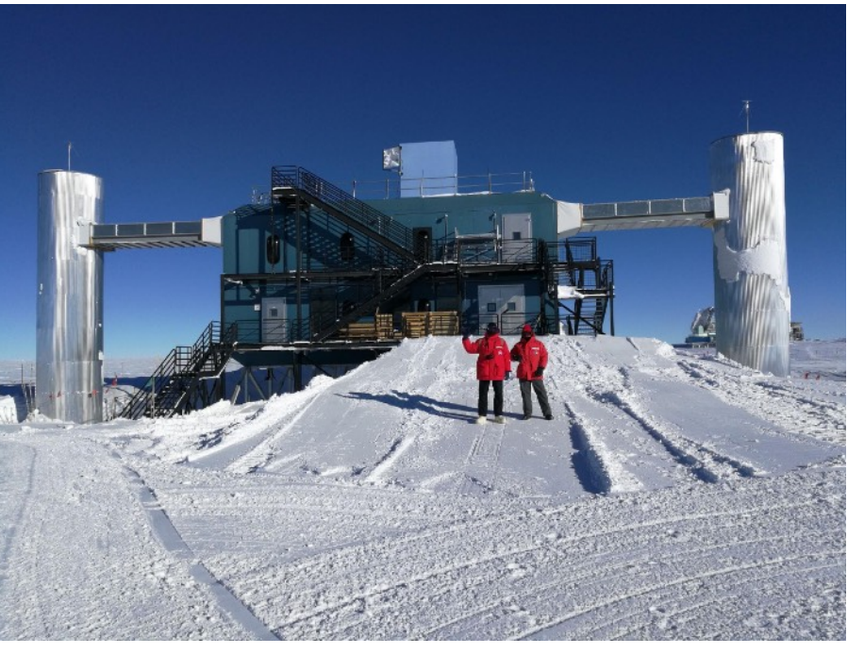
- Most common design -> Cerenkov detectors



Running detectors

- Experiments from three collaborations are currently operational





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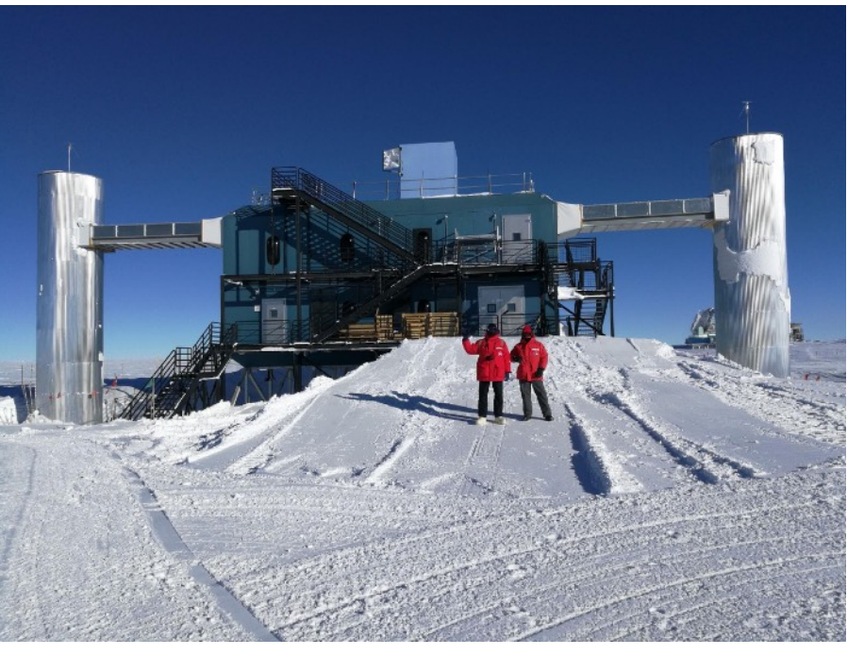
IceCube



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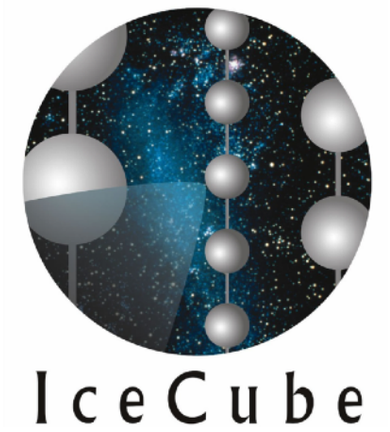
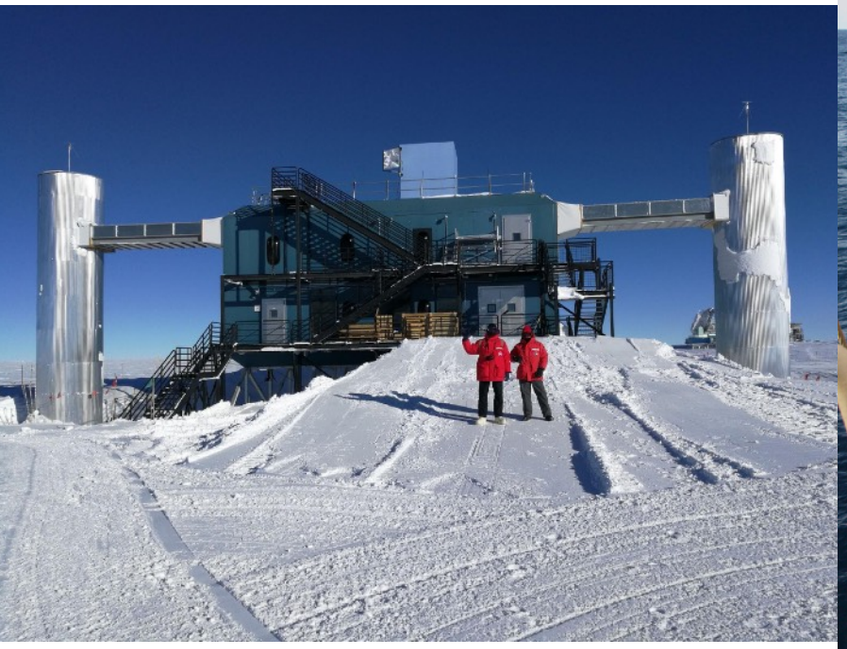
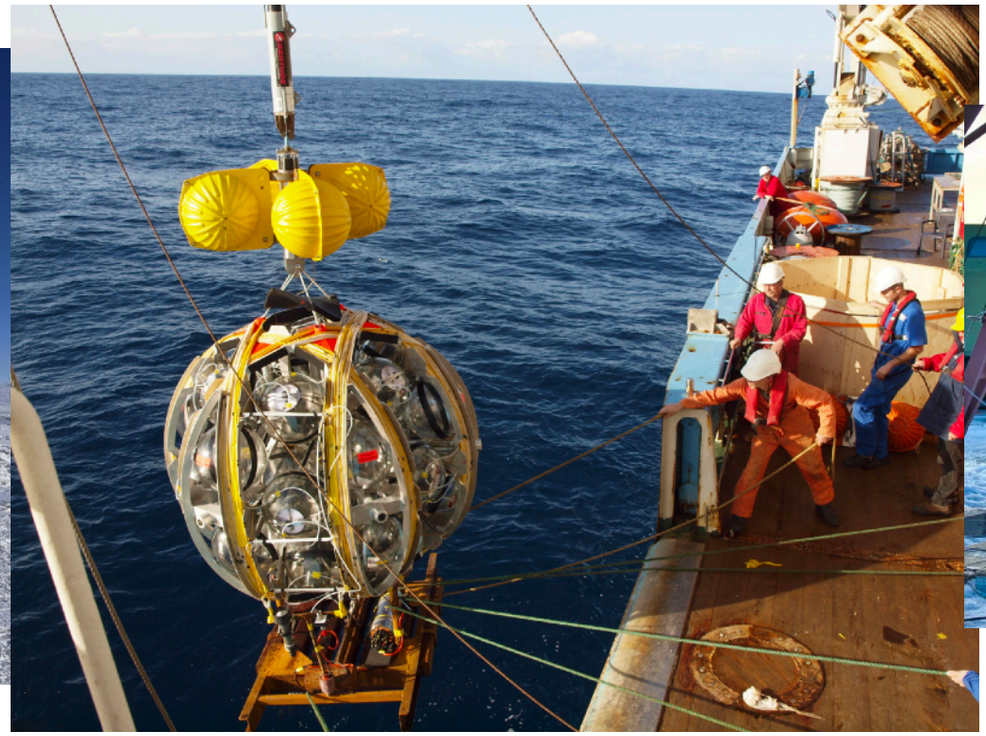
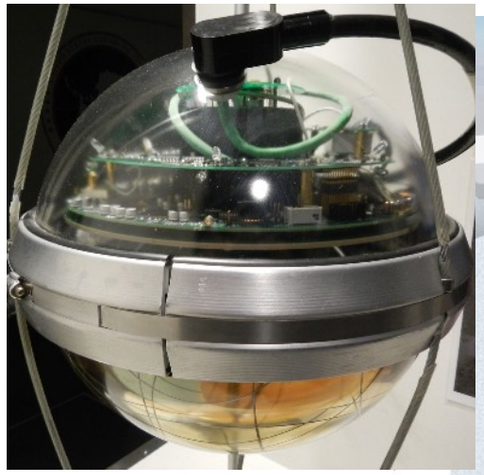






Running detectors

- Similar detector layout



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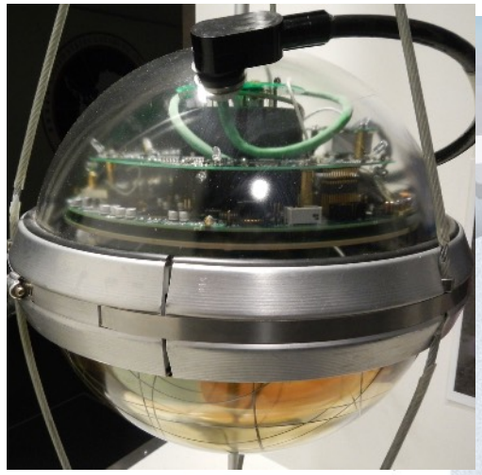
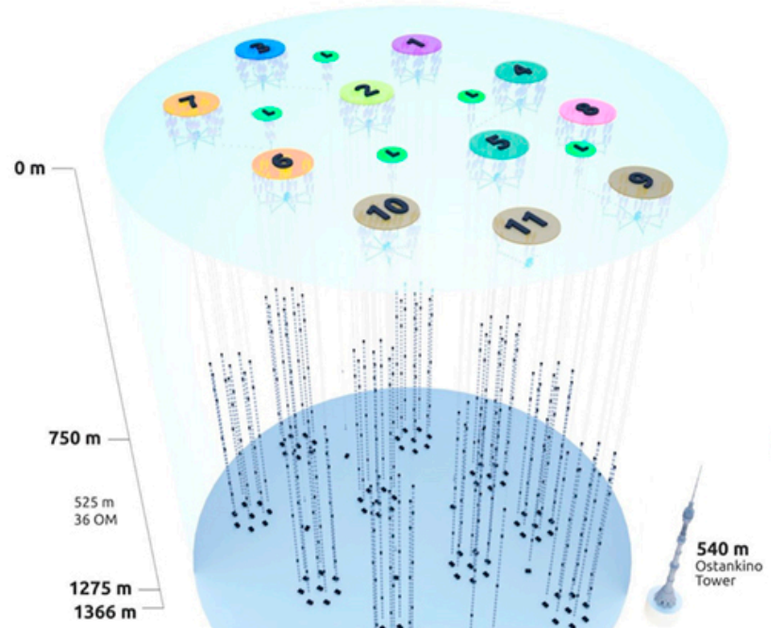


IceCube
86 lines
(1km³)



GVD-BAYKAL
117lines (0.7km³)

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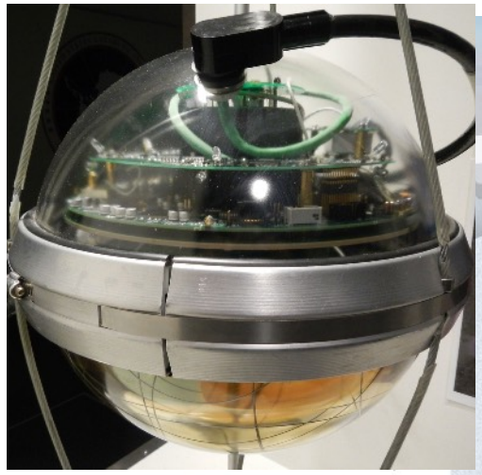

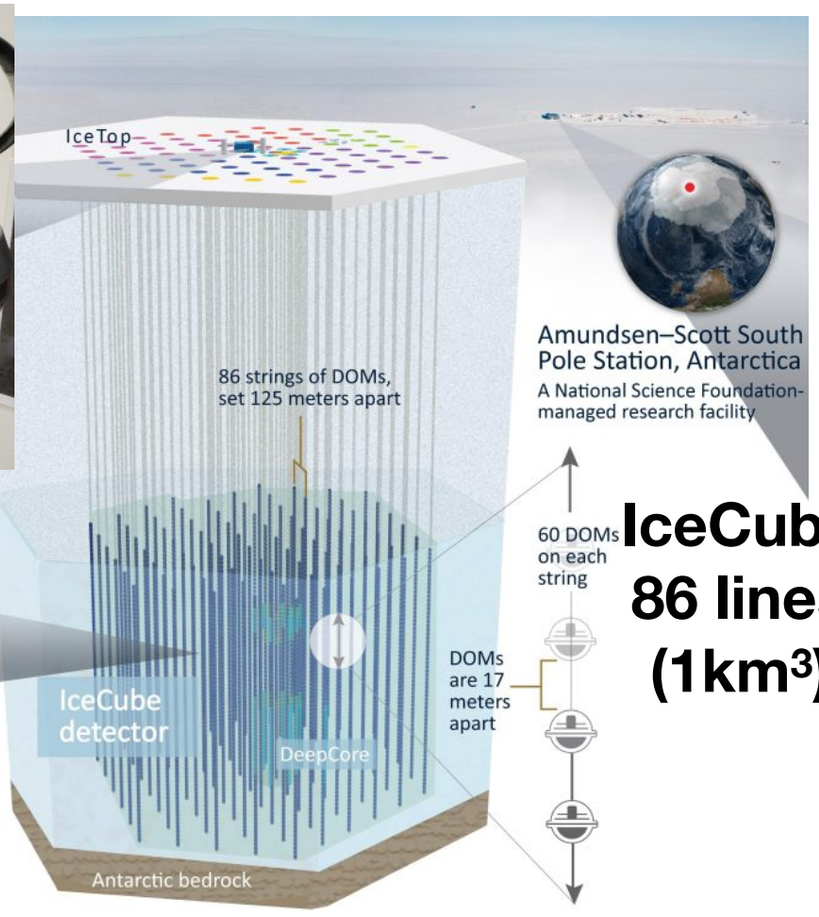

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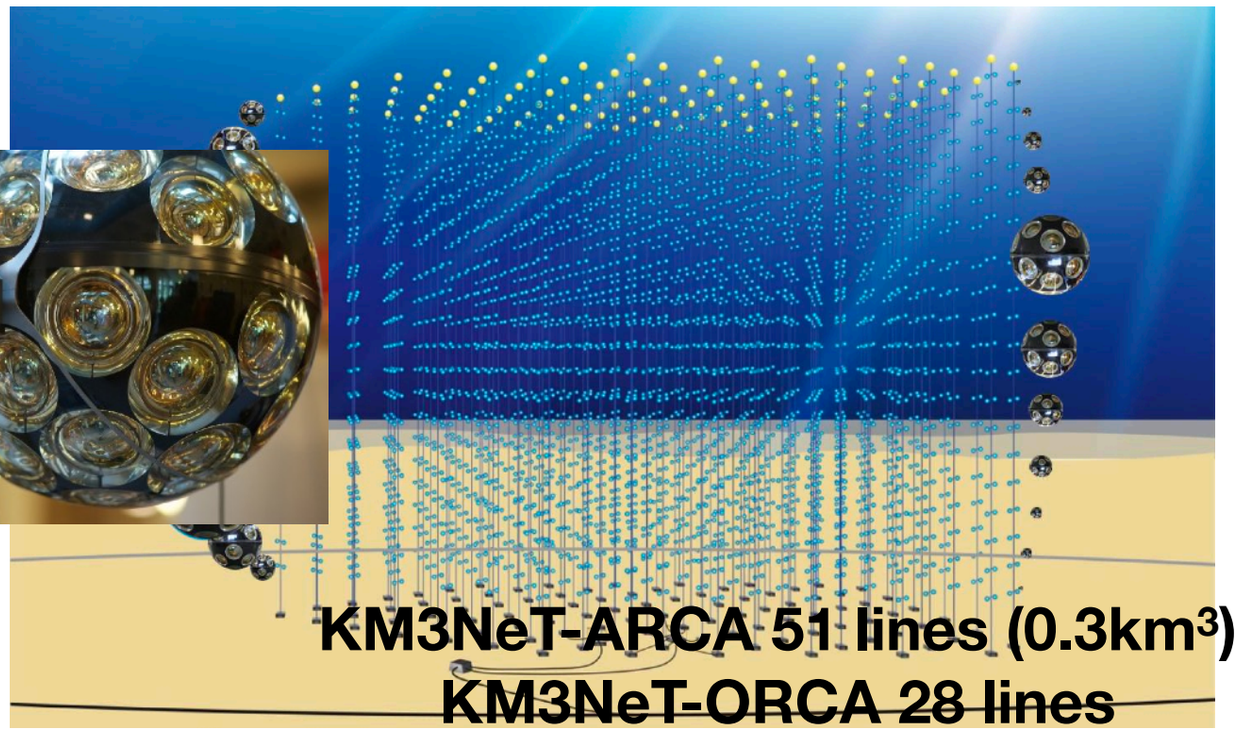
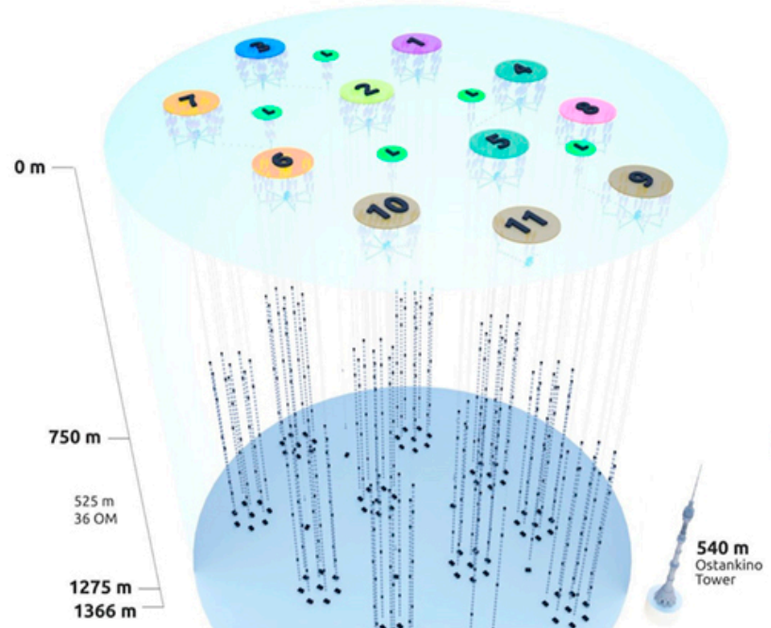


KM3NeT-ARCA 51 lines (0.3km³)
KM3NeT-ORCA 28 lines



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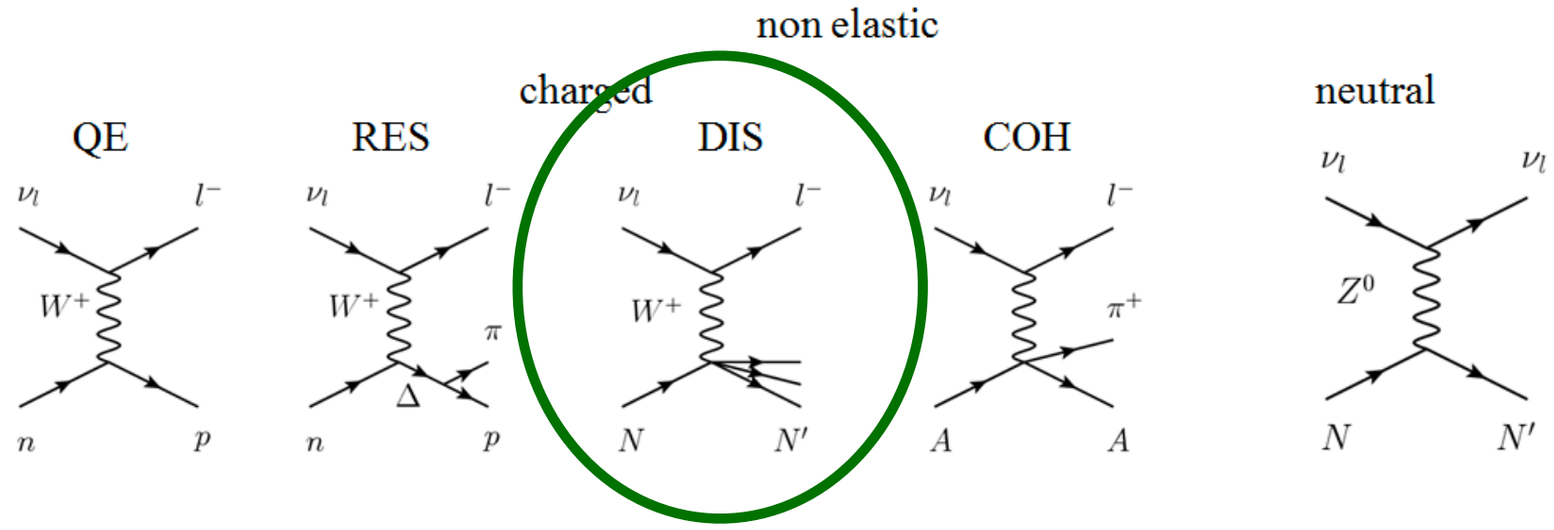
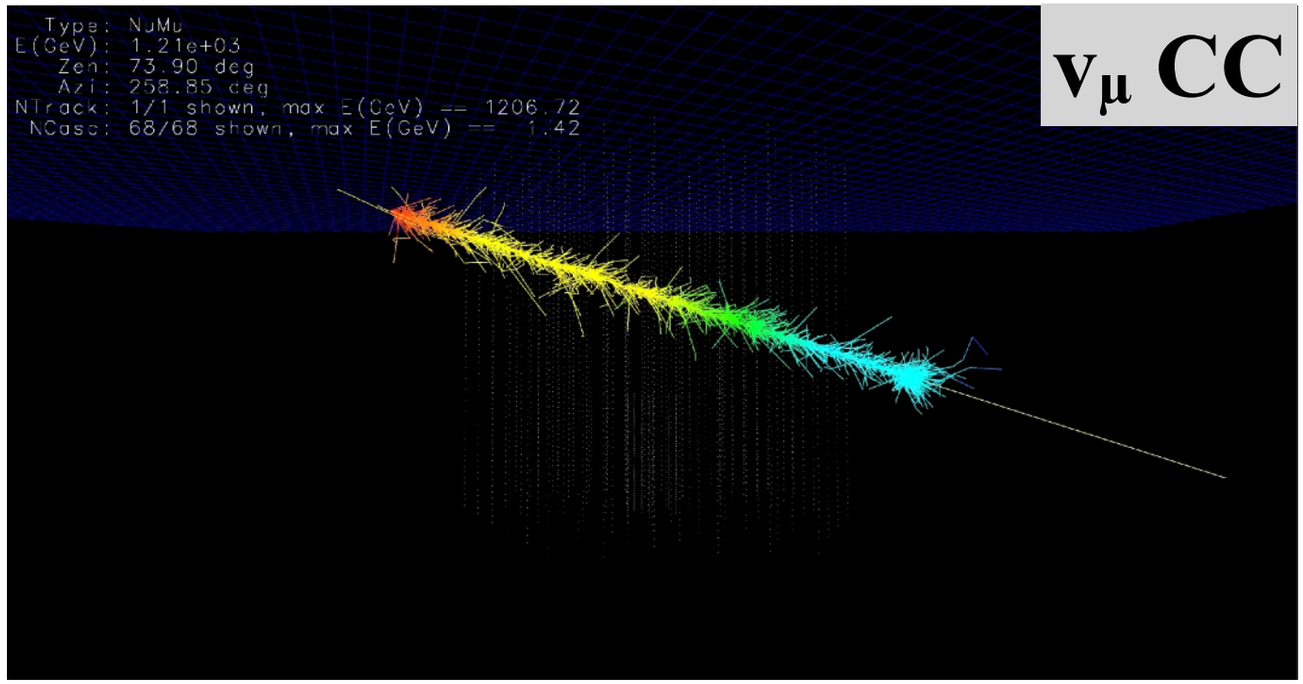
Detection principle

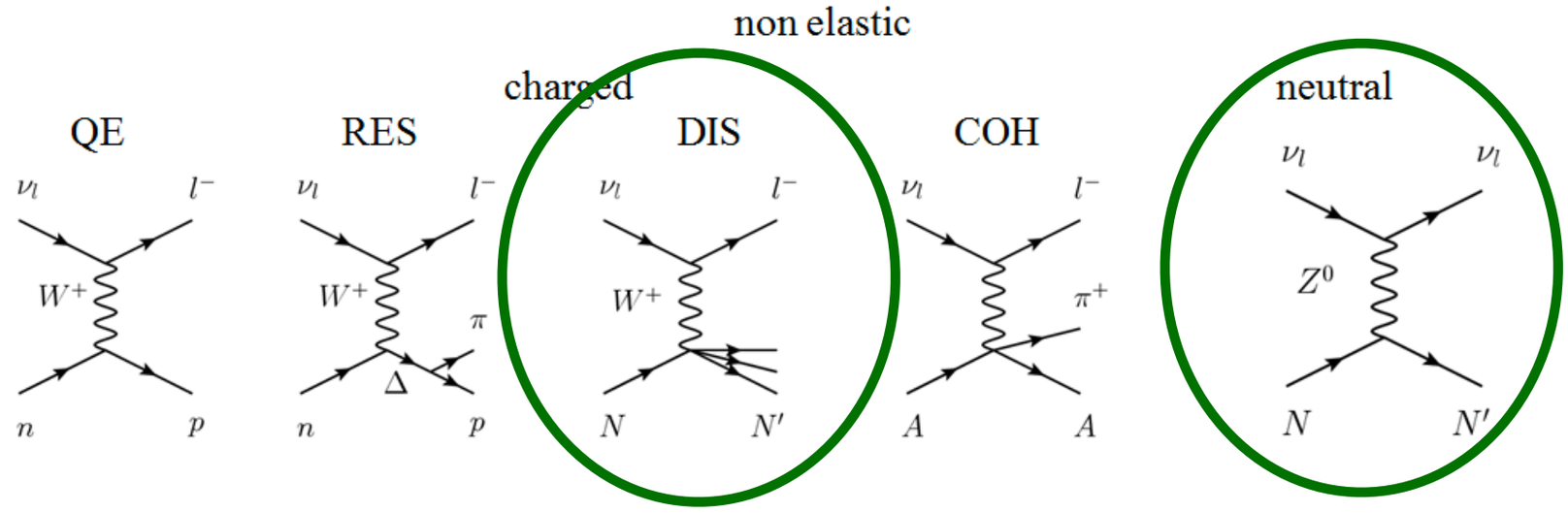


- Flavour identification using morphology of light pattern
  - Tracks → ν_μ CC

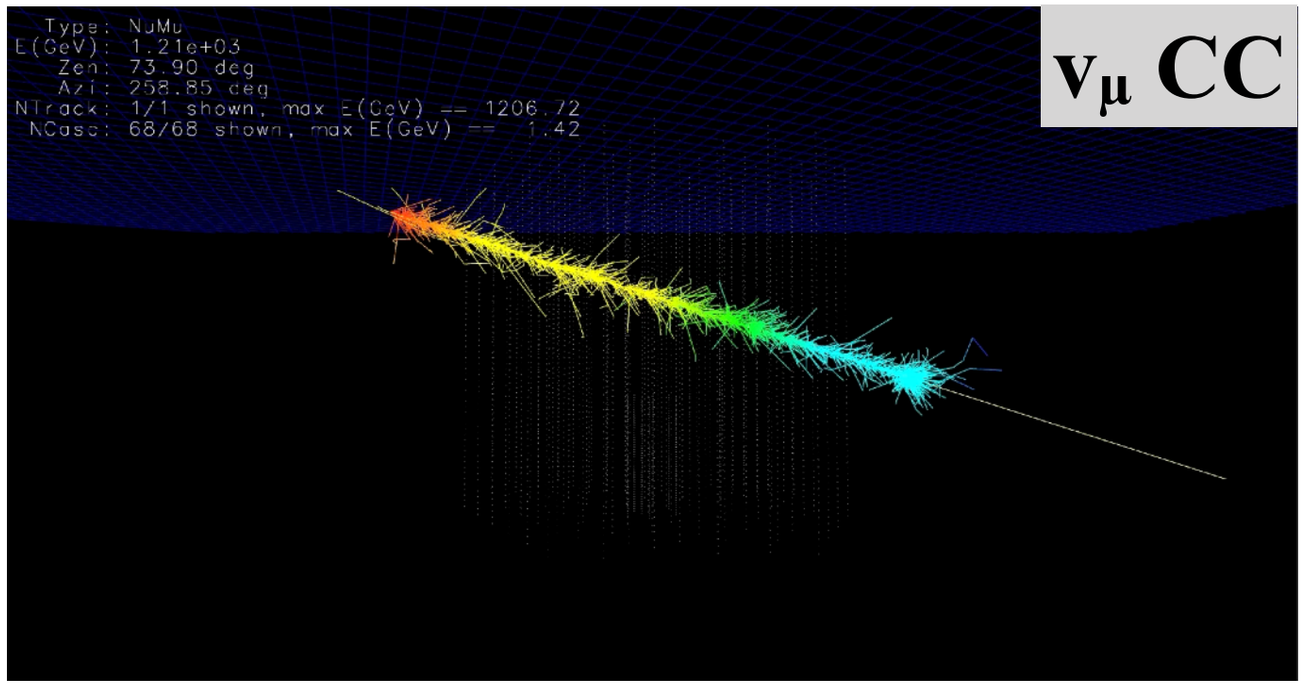


1 TeV

Detection principle



- Flavour identification using morphology of light pattern
  - Tracks → ν_μ CC
  - Showers → ν_x NC / $\nu_{e,\tau}$ CC



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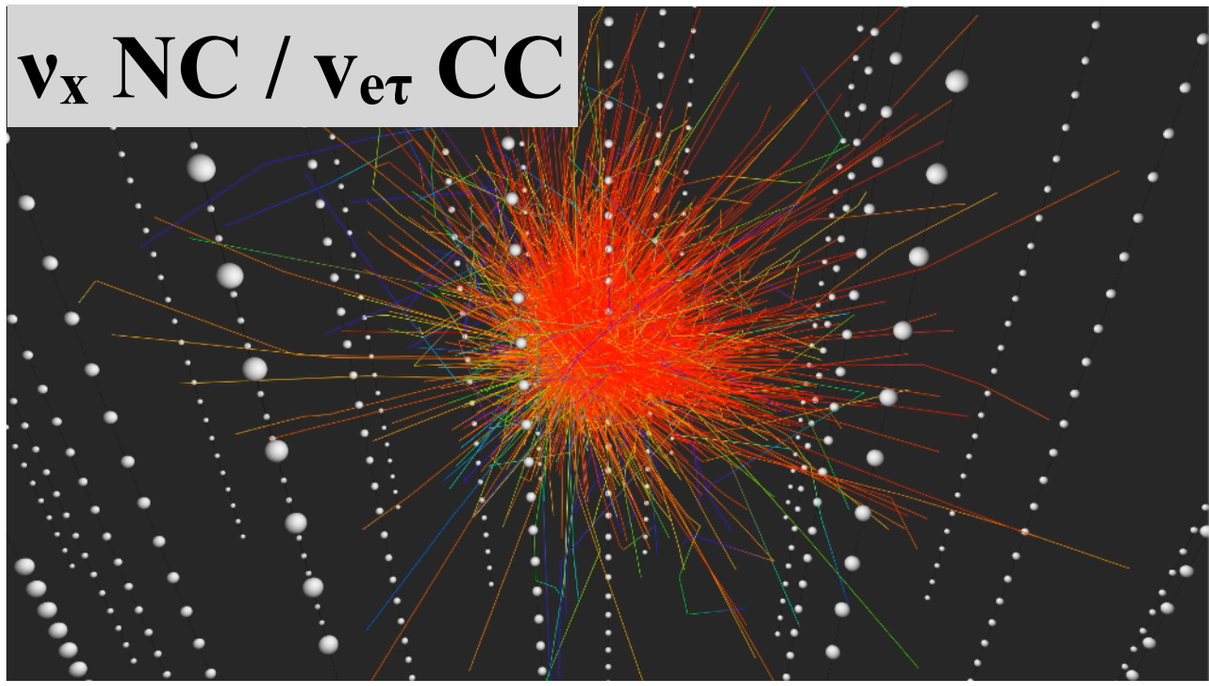
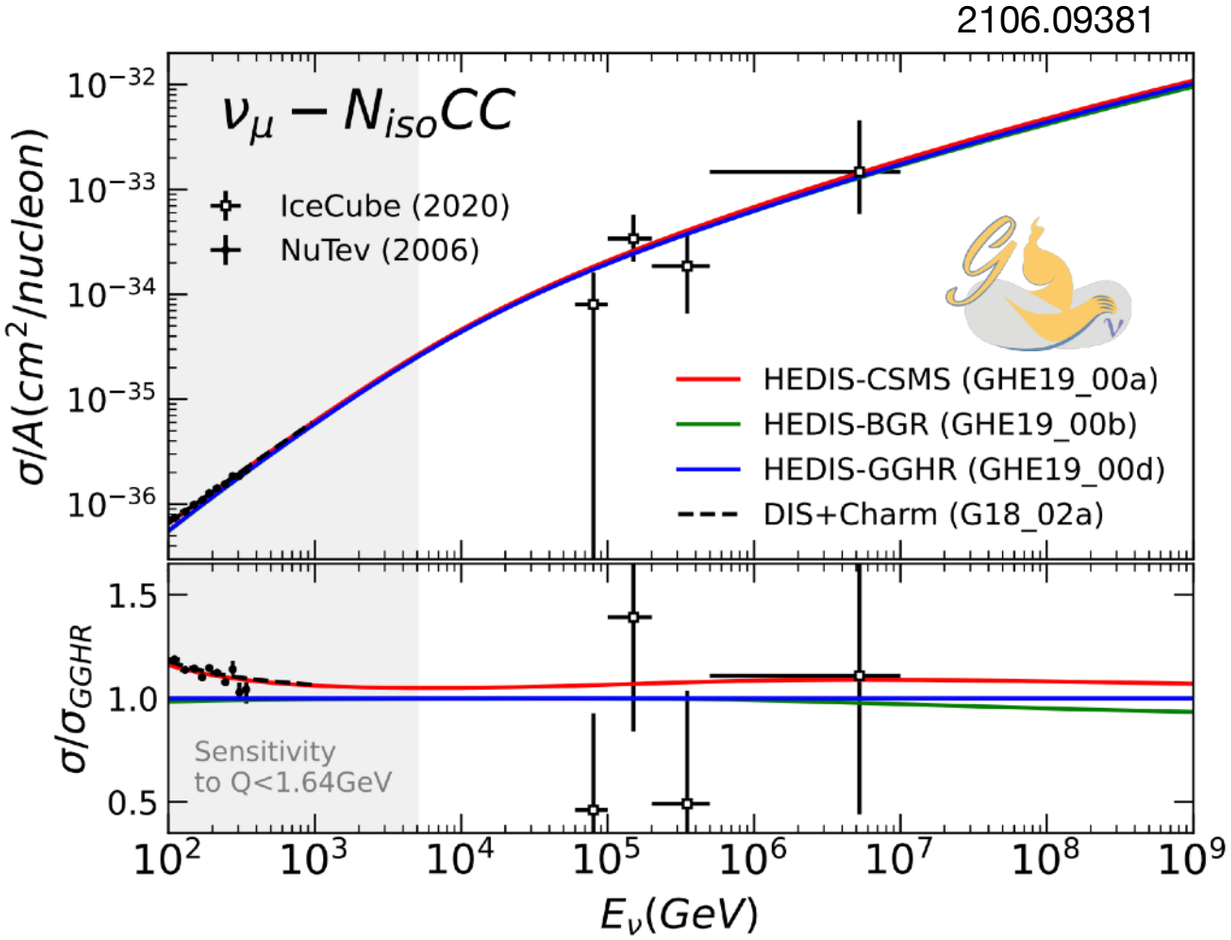


1 TeV

Neutrino cross sections

- Deep inelastic scattering
  - More precise modeling
  - FPF would help a lot!

2106.09381



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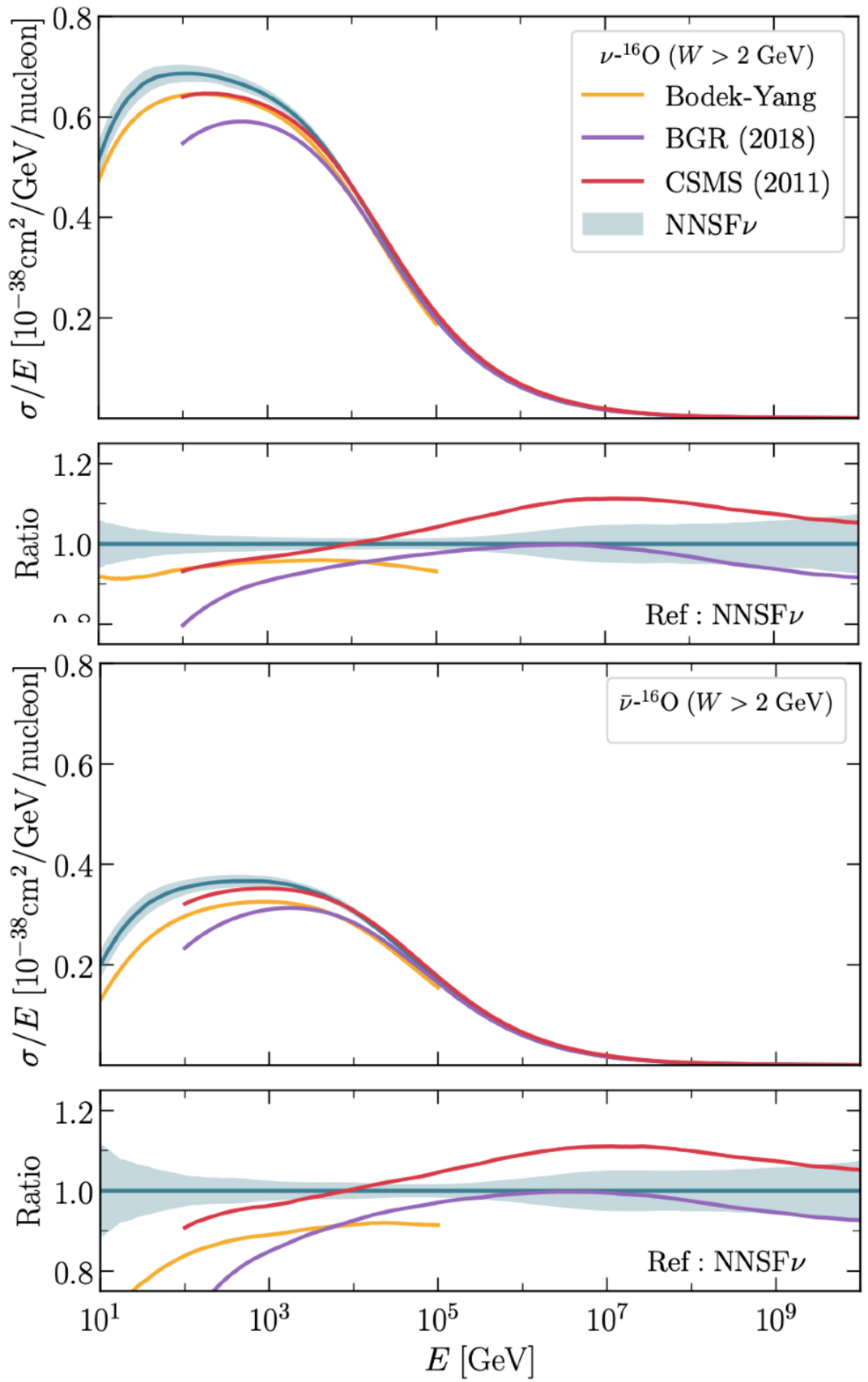
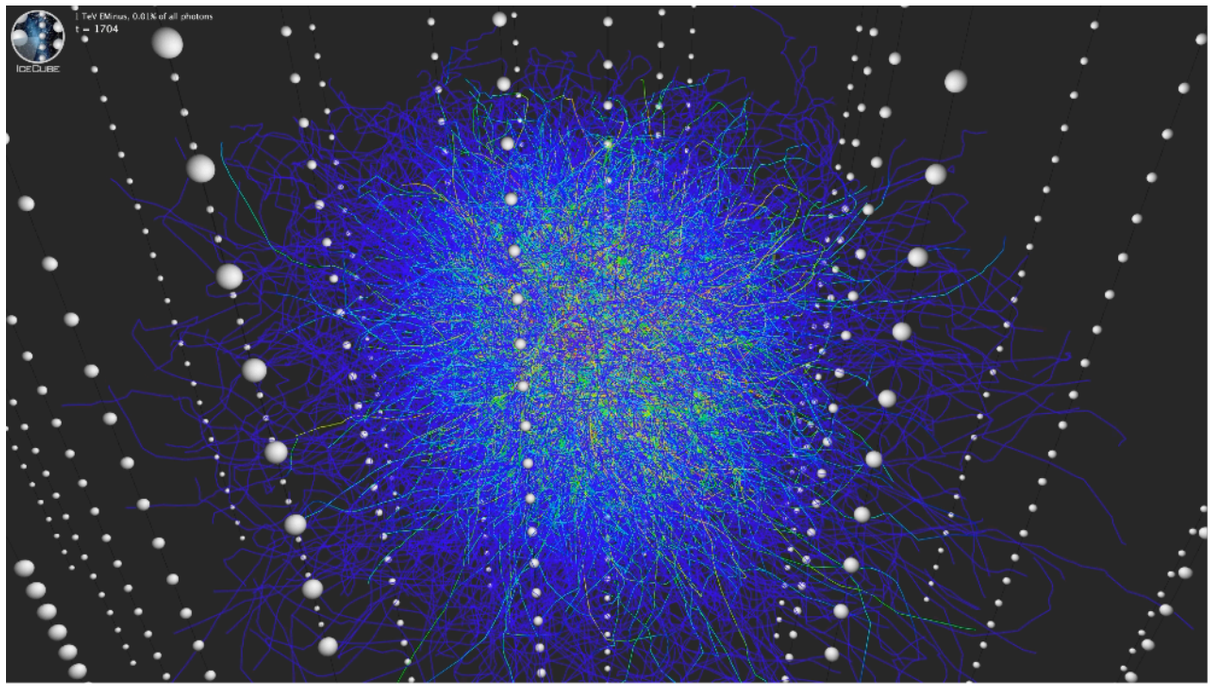


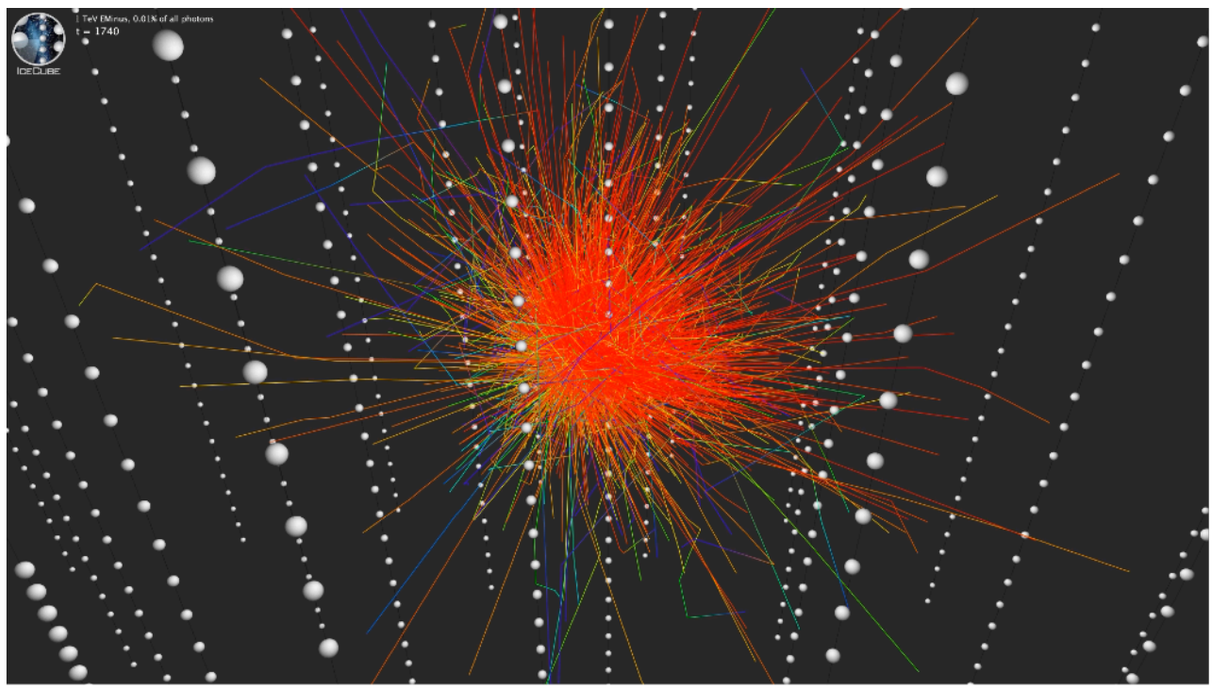
Detection principle

- Different mediums -> different light patterns



1 TeV cascade in ice

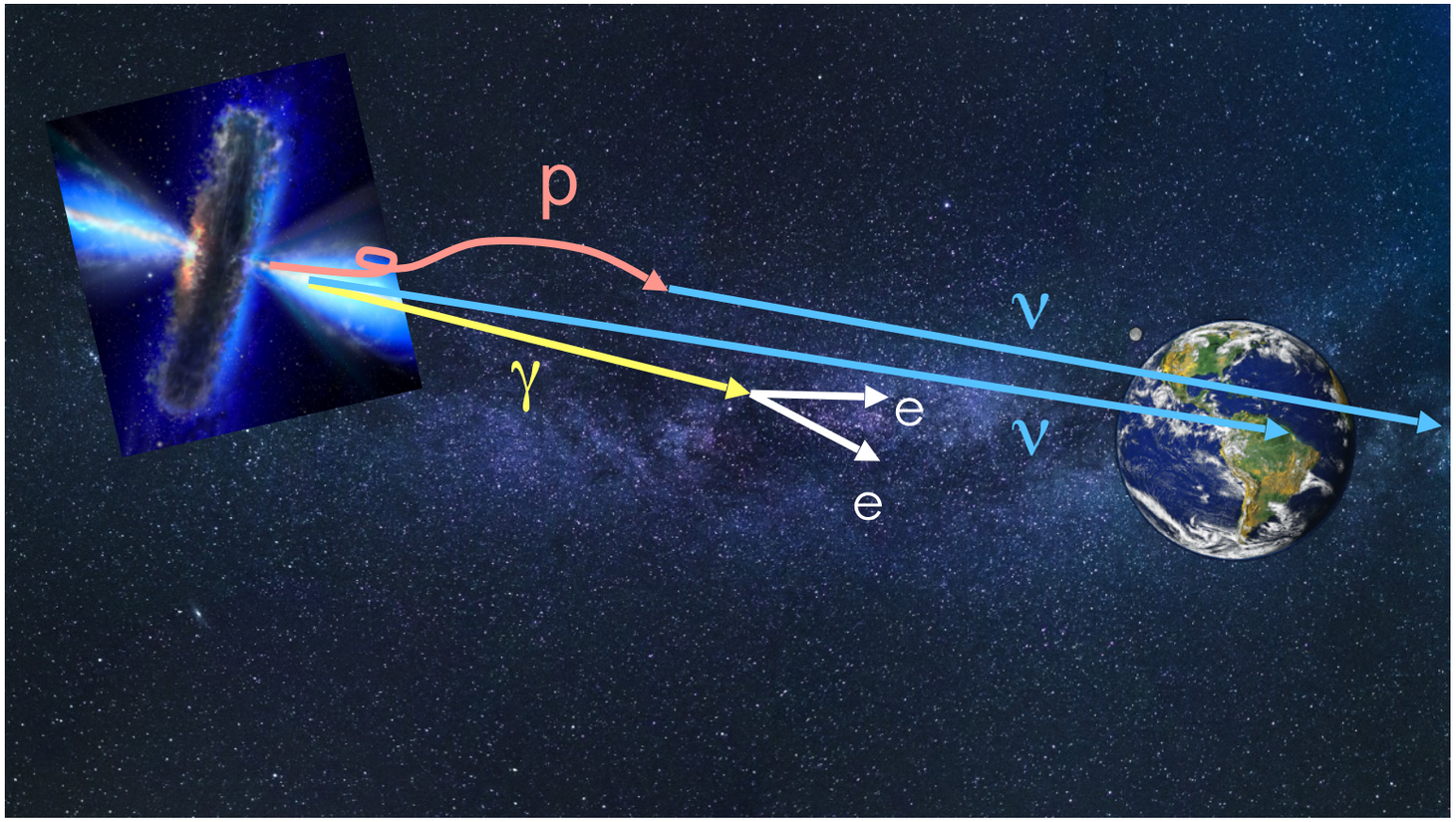
1 TeV cascade in water



How are high-energy neutrino produced?

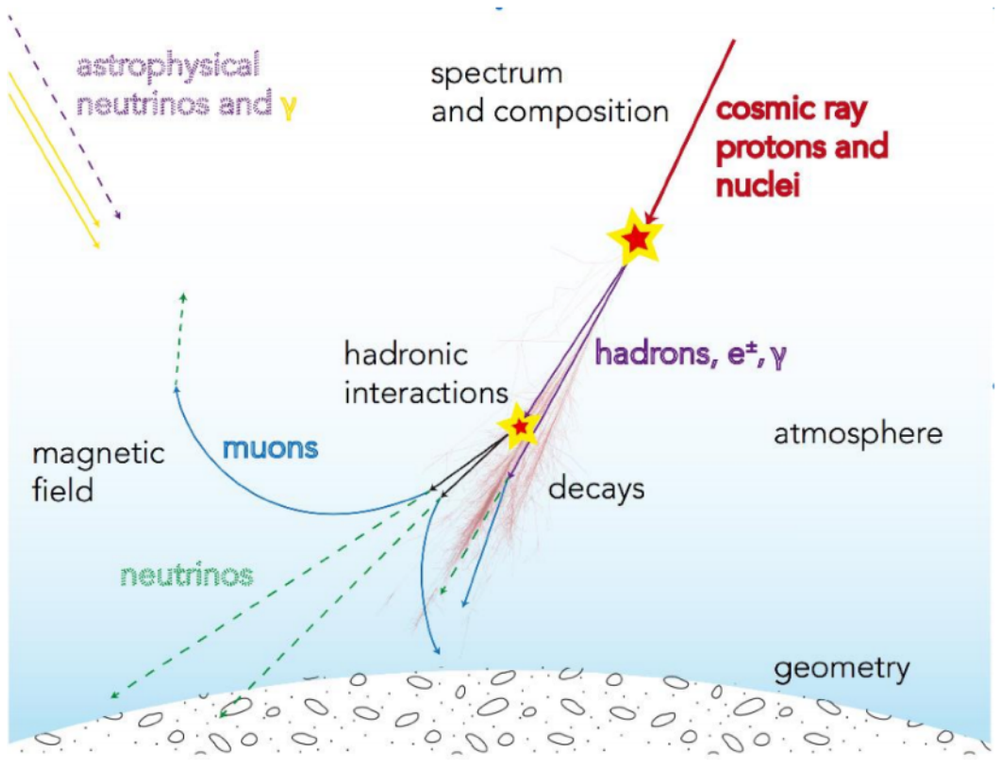
Common origin -> Hadrons

Cosmic neutrinos



"learning" how to model

Atmospheric neutrinos



"know" how to model

Atmospheric neutrinos

- Hard to model! -> multiple processes
  - Cosmic ray spectrum
  - Hadron yields
  - Atmospheric density profile
  - Hadron propagation

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  - Cosmic ray spectrum
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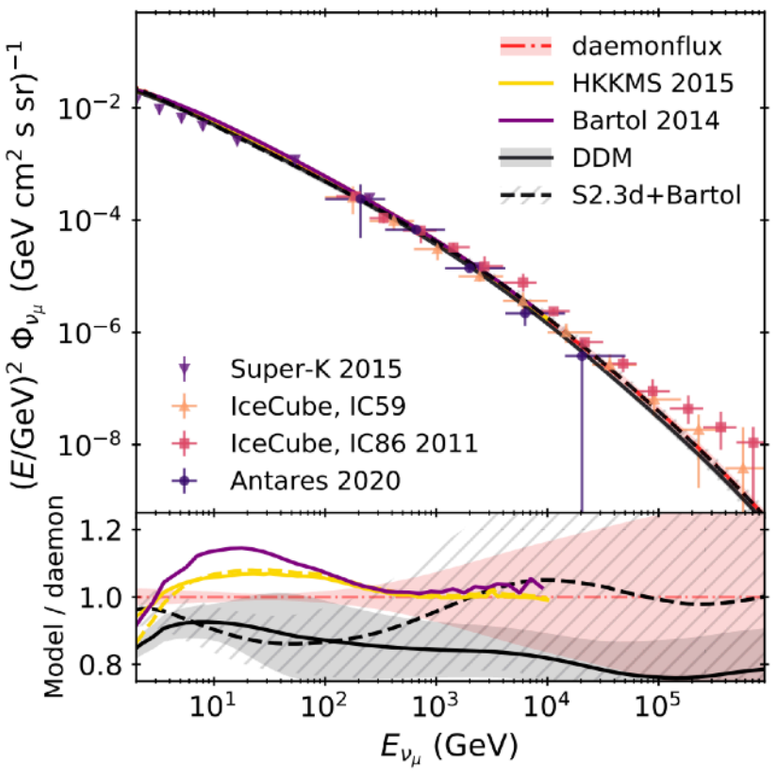
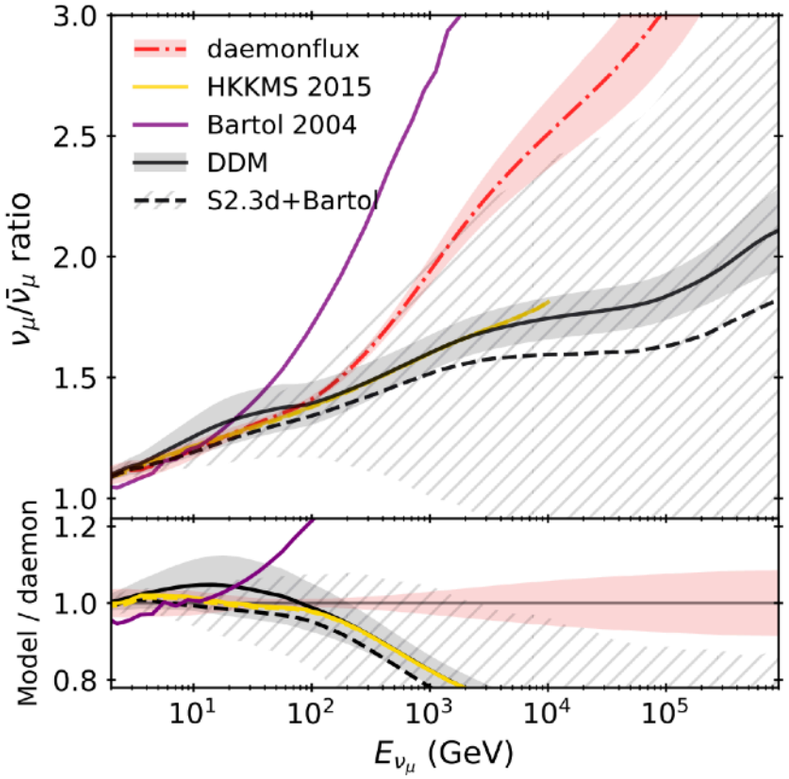
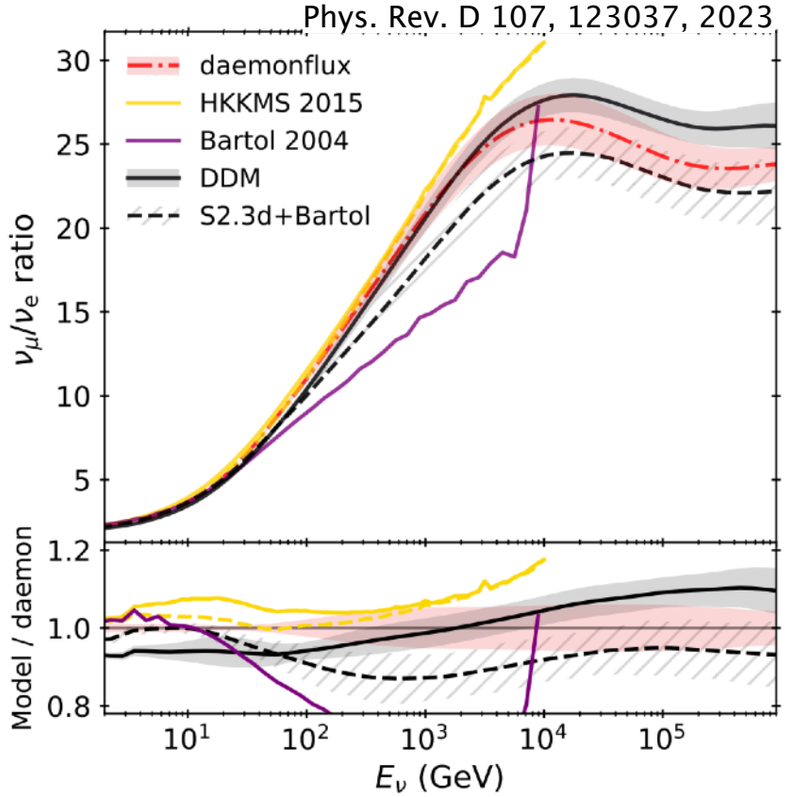
- Latest developments -> DAEMONFLUX

Phys. Rev. D 107, 123037, 2023



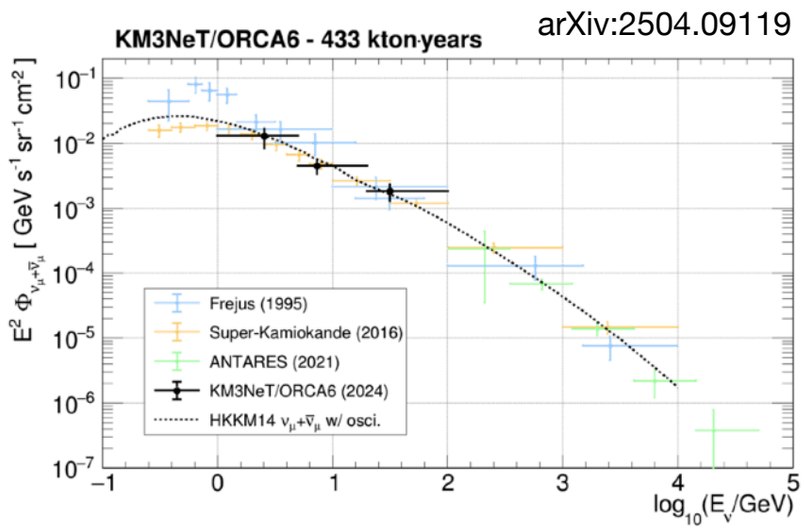




Recent results on the atmosphere

- More and more measurements of the (mostly muon-)neutrino spectrum

arXiv:2504.09119



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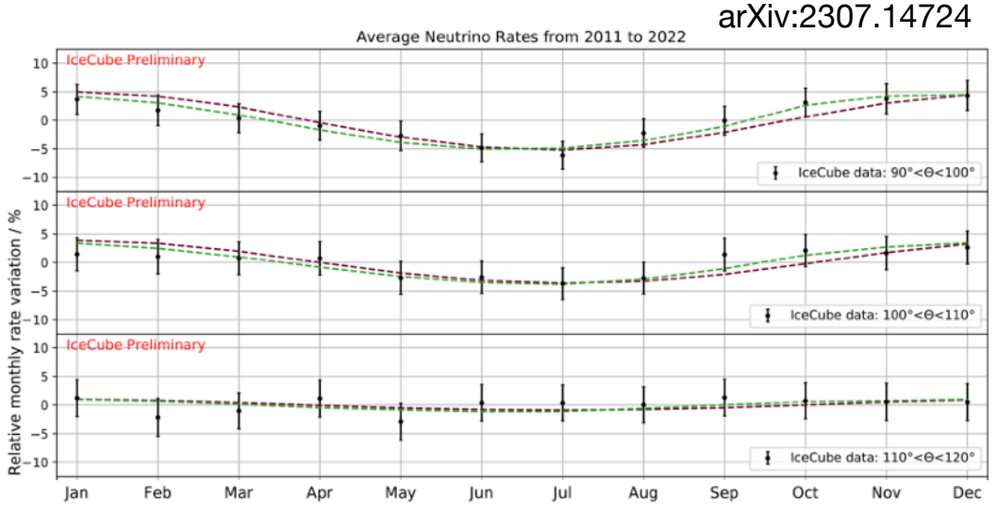
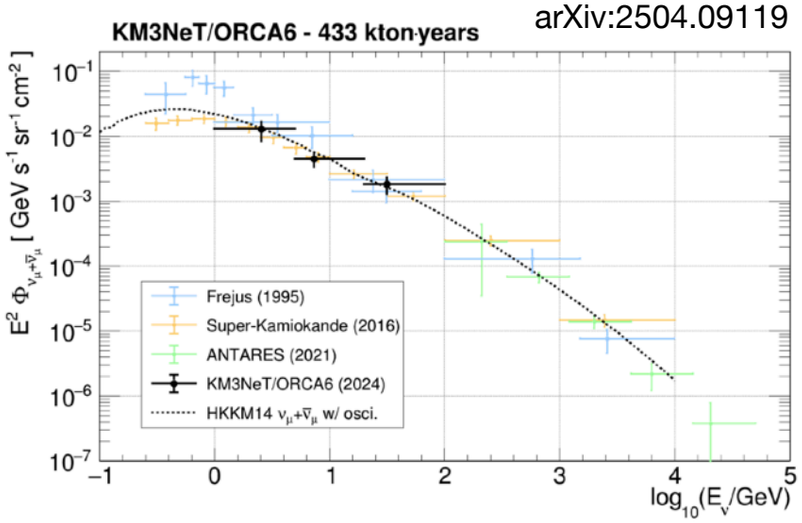


Recent results on the atmosphere

- More and more measurements of the (mostly muon-)neutrino spectrum
- No prompt found yet

arXiv:2504.09119



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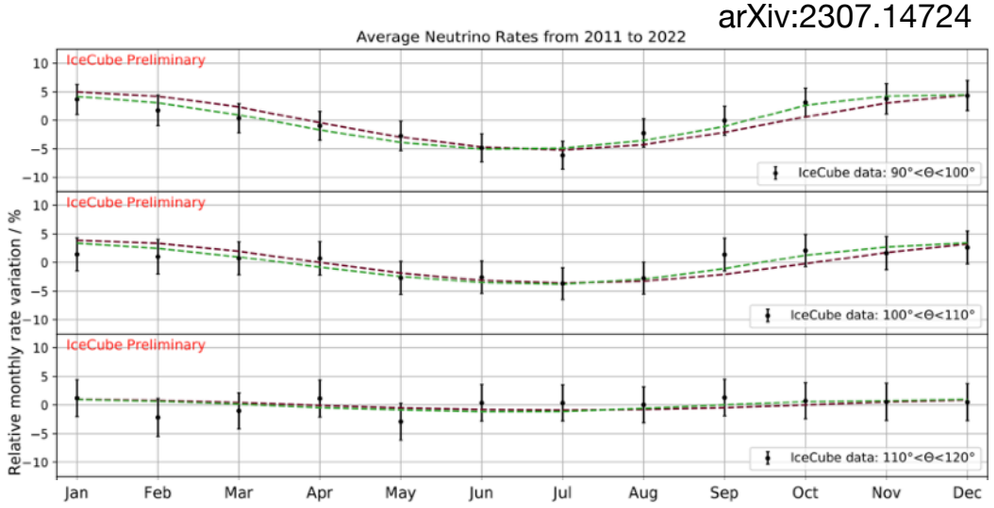
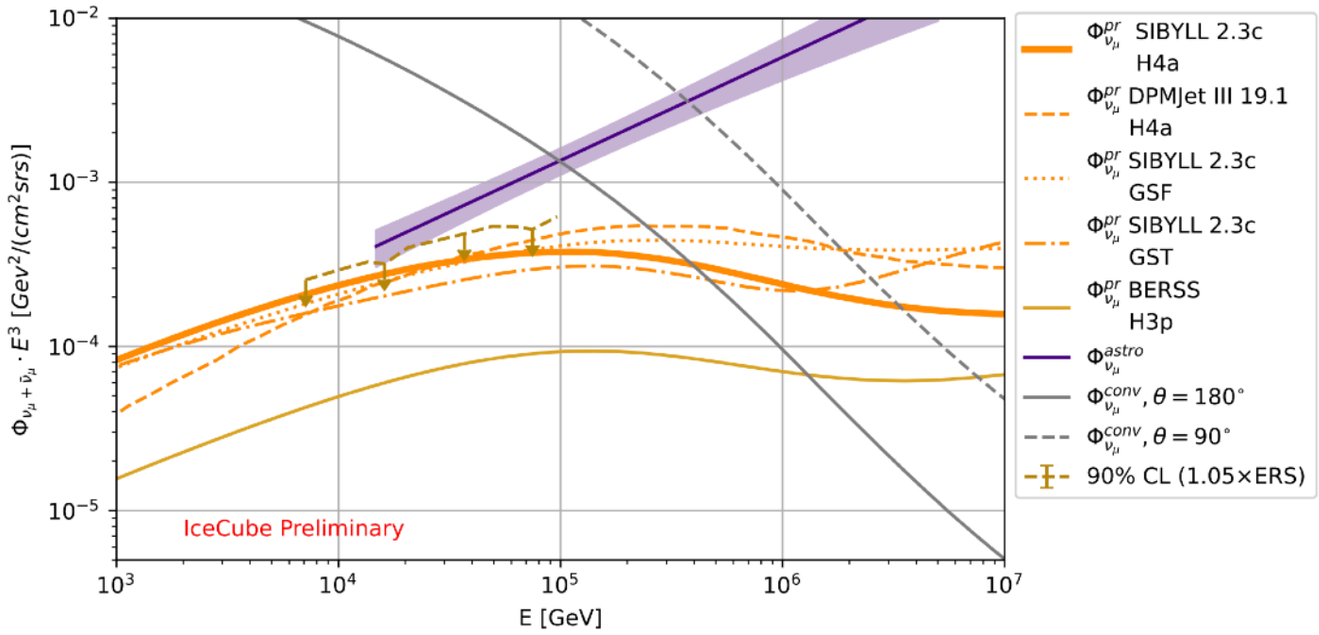


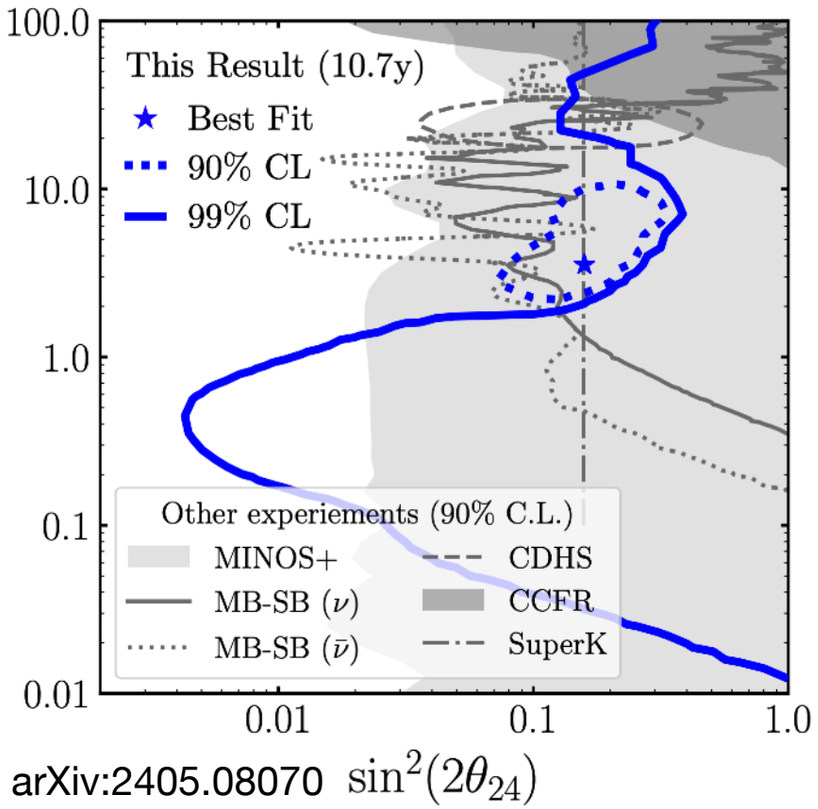
arXiv:2309.07560



Particle physics with high-energy atmospheric neutrinos

- Standard oscillations are highly suppressed at E>100GeV
- Perfect regime to study BSM scenarios

Sterile neutrinos



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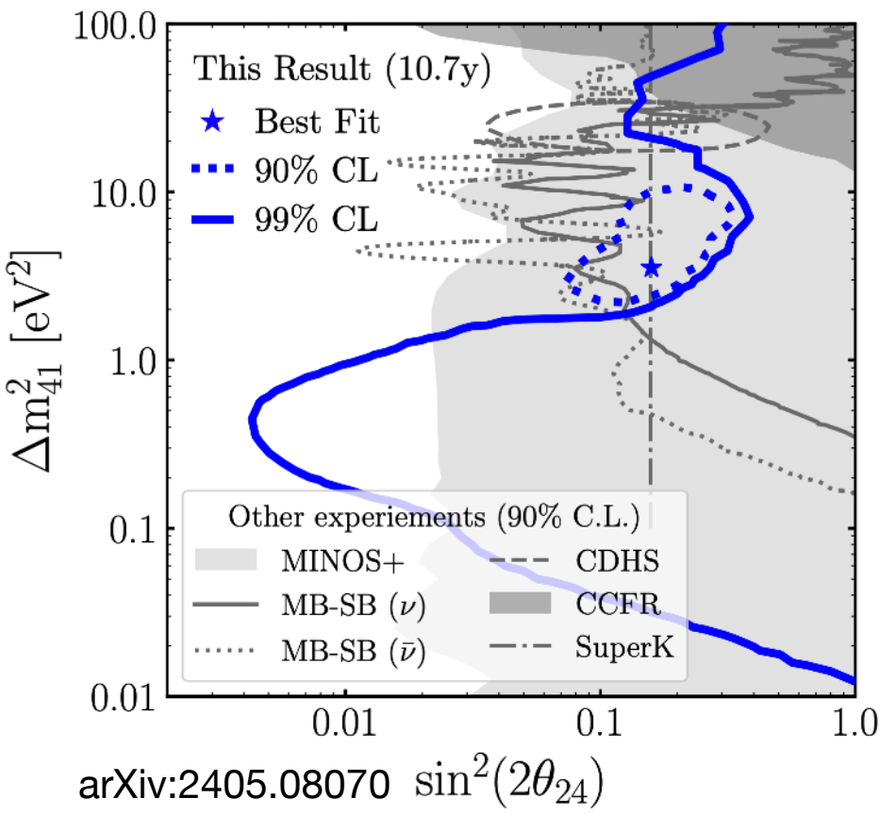

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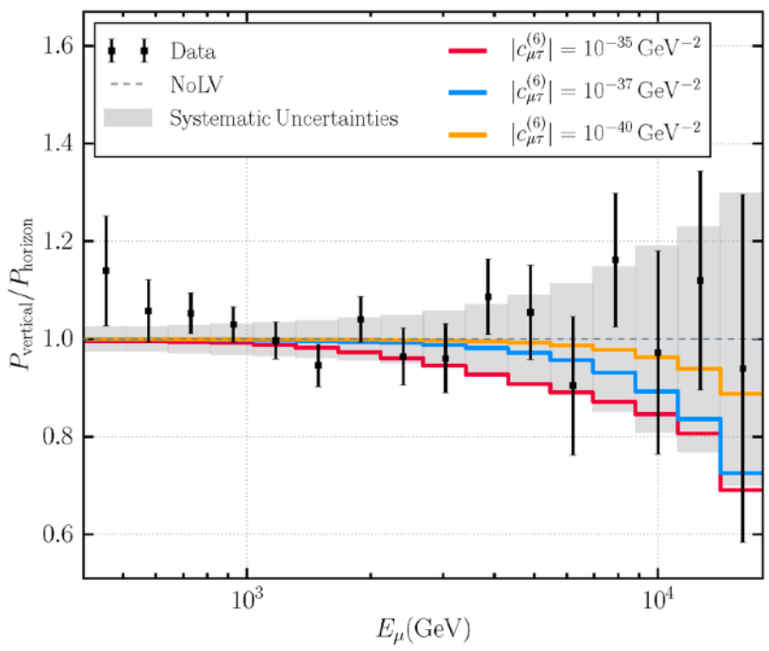

Nature Physics (2018) s41567-018-0172-2

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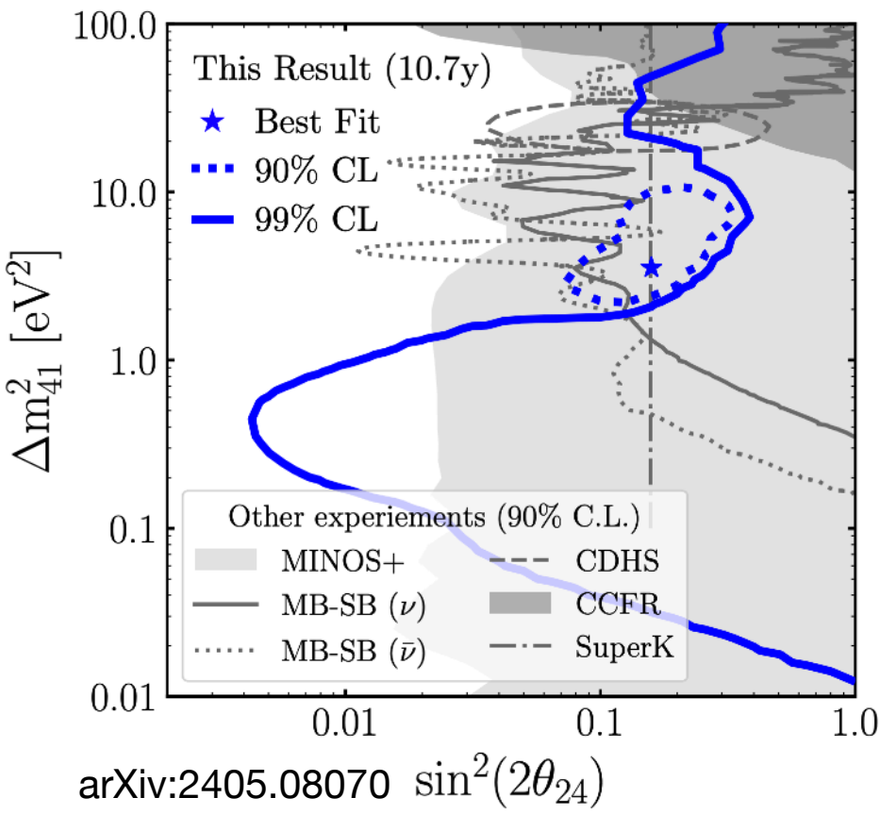

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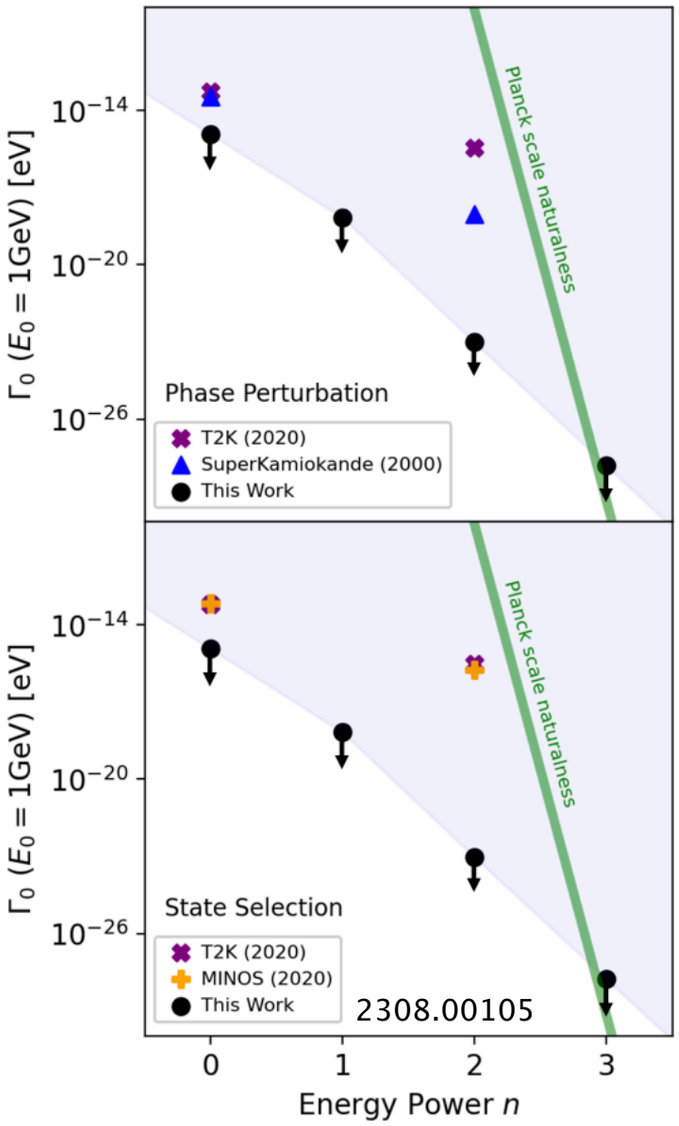
Decoherence



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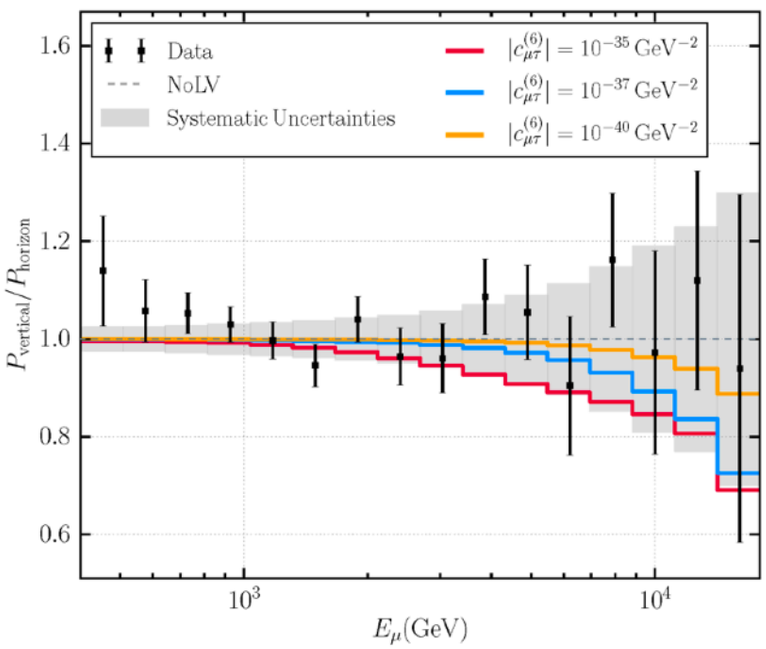

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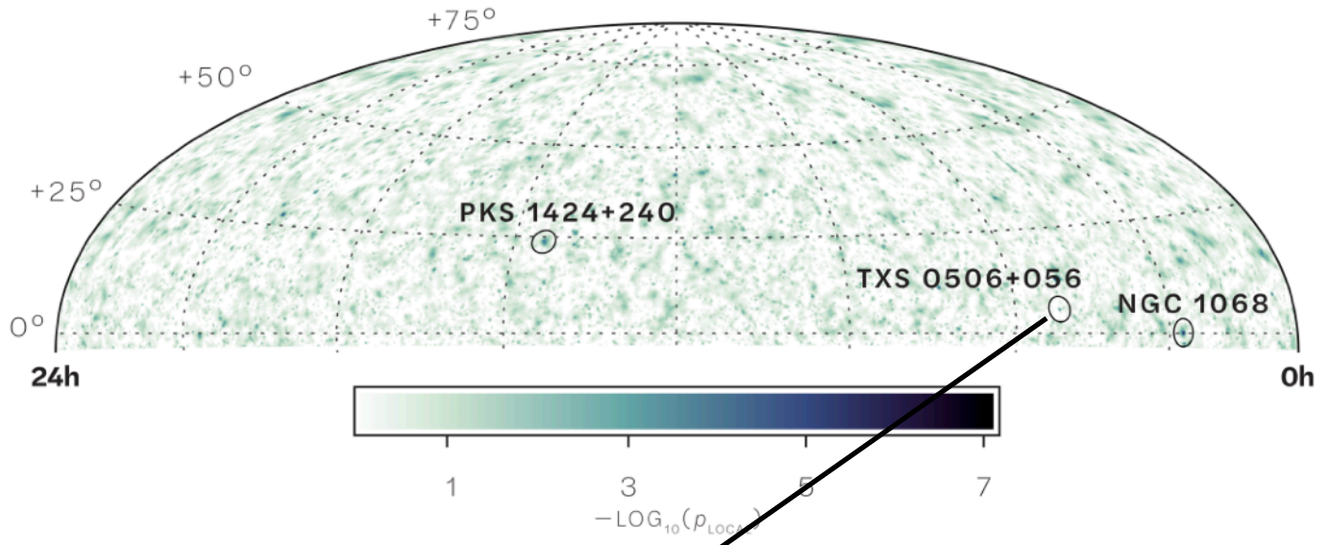
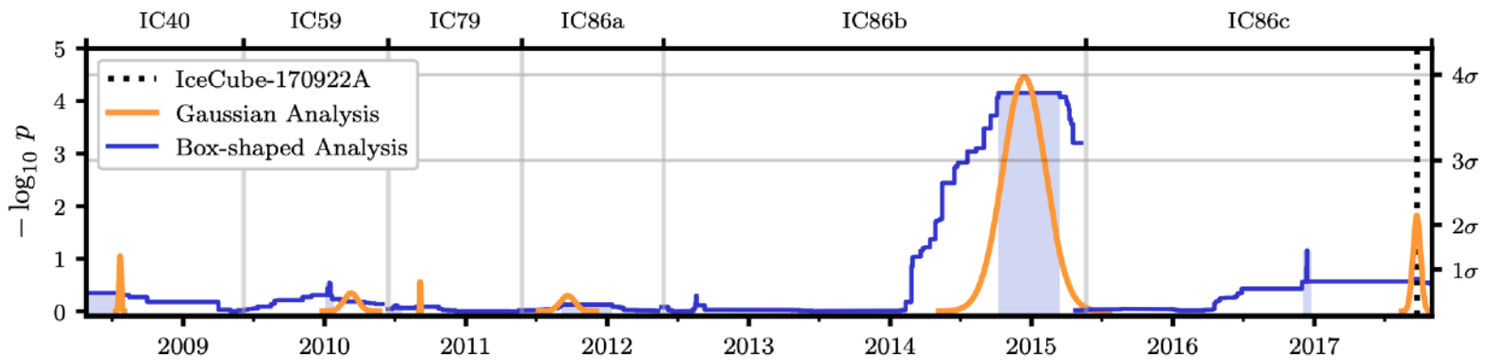
Astrophysical neutrinos

- IceCube have identified two point sources -> not bright in gammas



Science 361 (2018)



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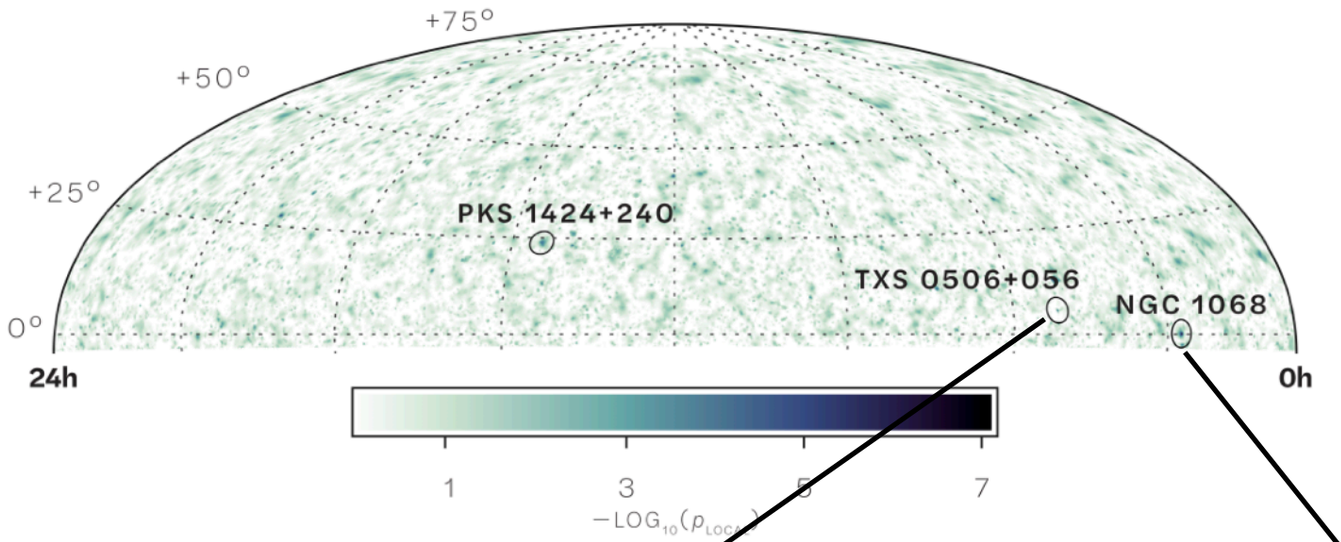

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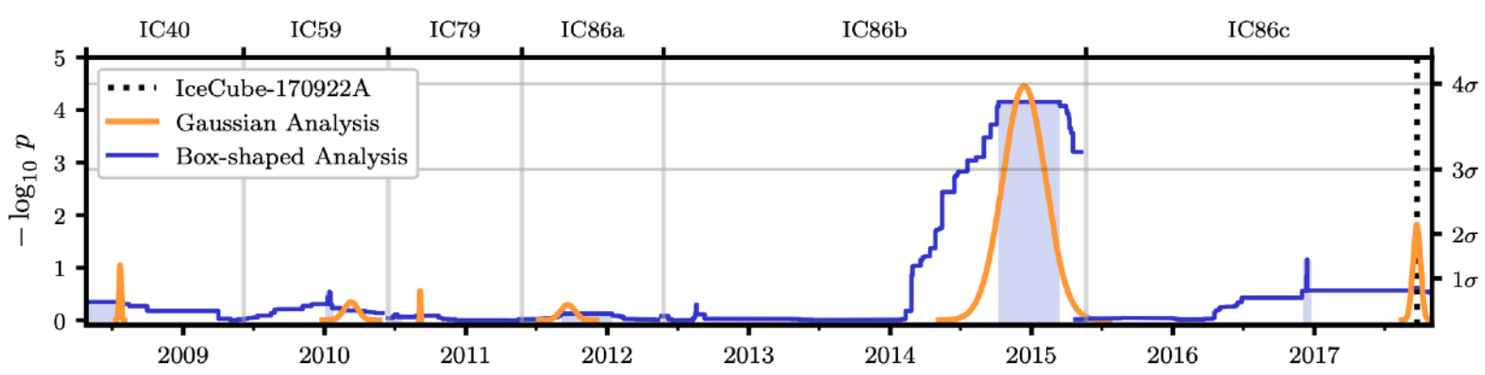
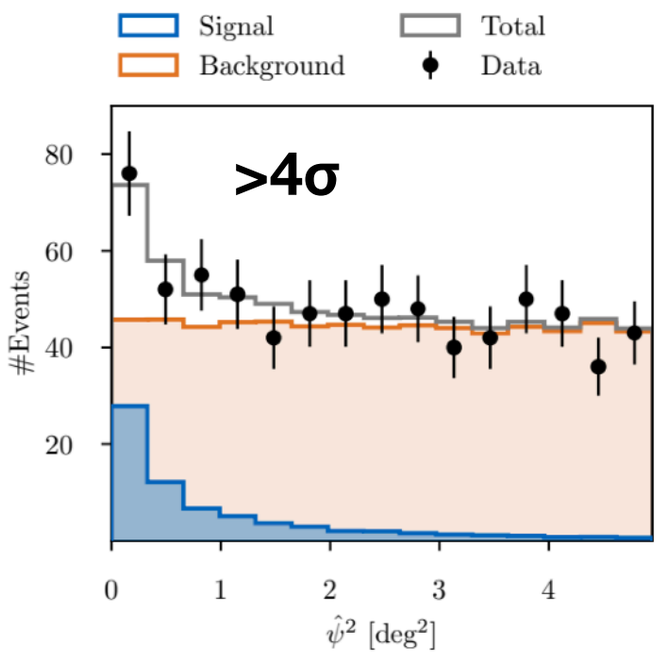
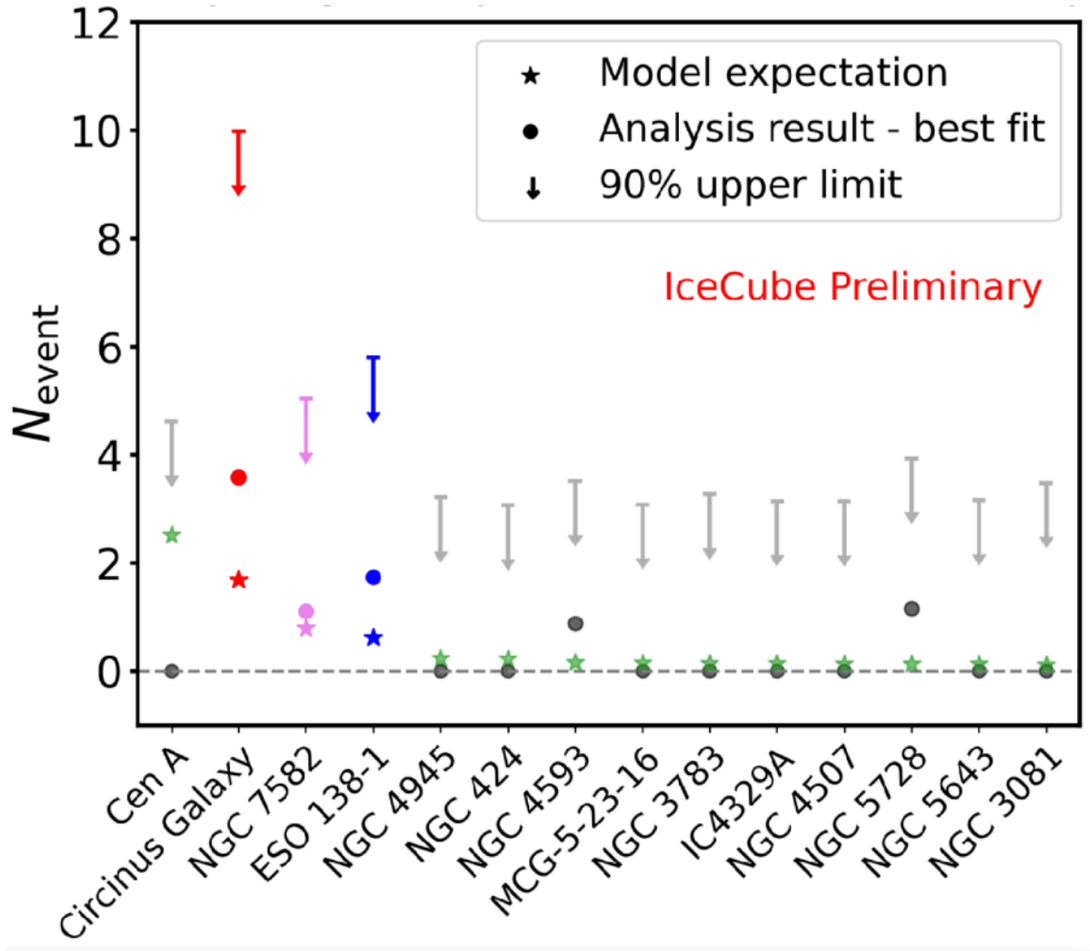


Science 378 (2022)



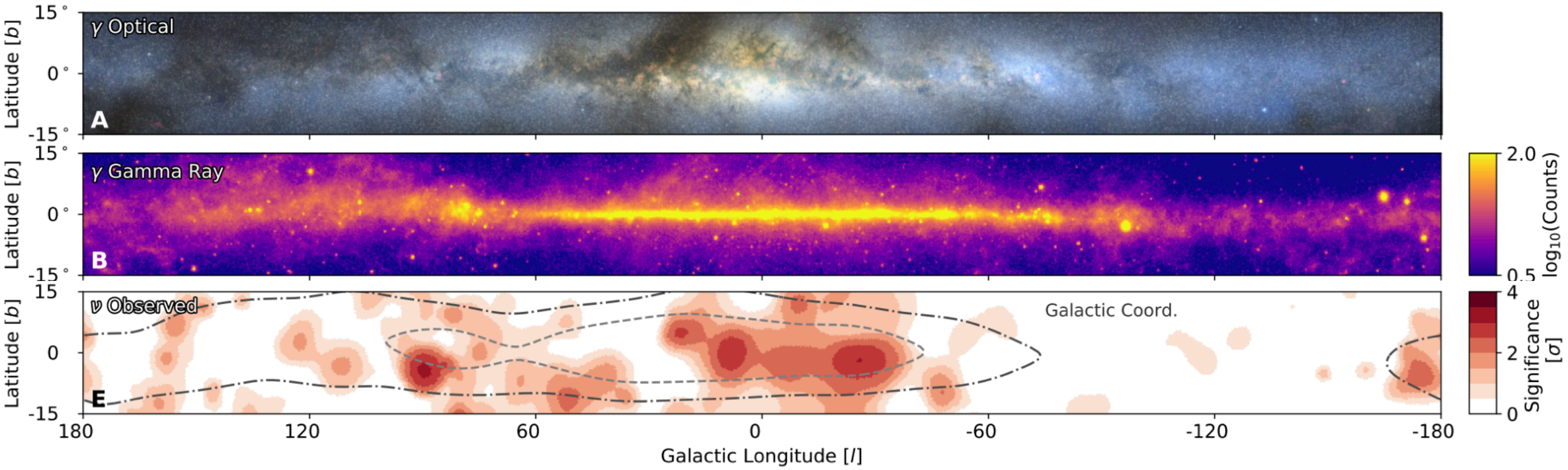
Obscured AGNs

- Multiple analysis are finding a consistent picture -> targets that block gammas are needed for nu production!
  - Multiple analysis show a ~3σ preference for X-ray bright AGNs (NGC4151,++) in the Northern sky.
  - And also evidences in the Southern sky. Stacked analysis over 3σ.



Galactic neutrinos

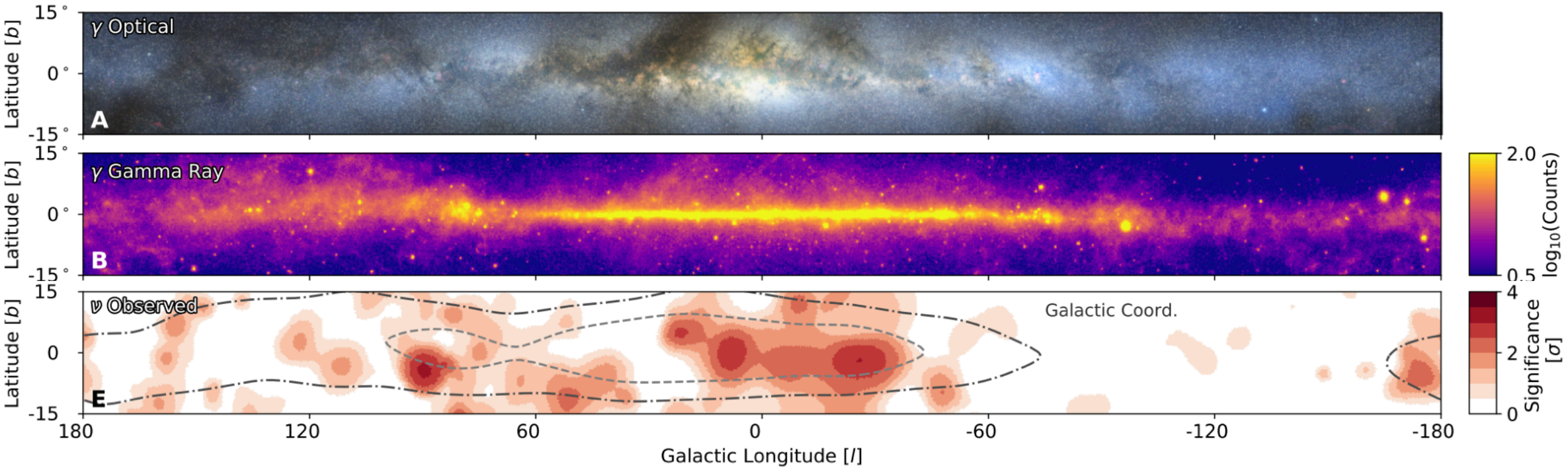
Science 380 (2023)



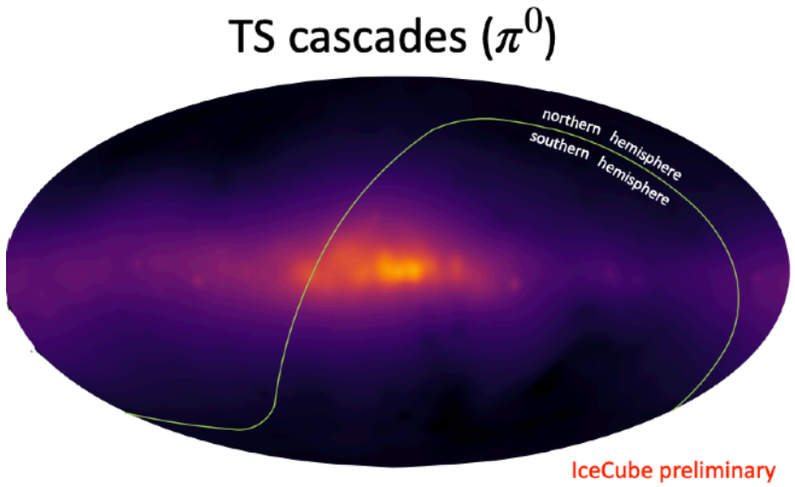
- Observed by IceCube (4.5σ)

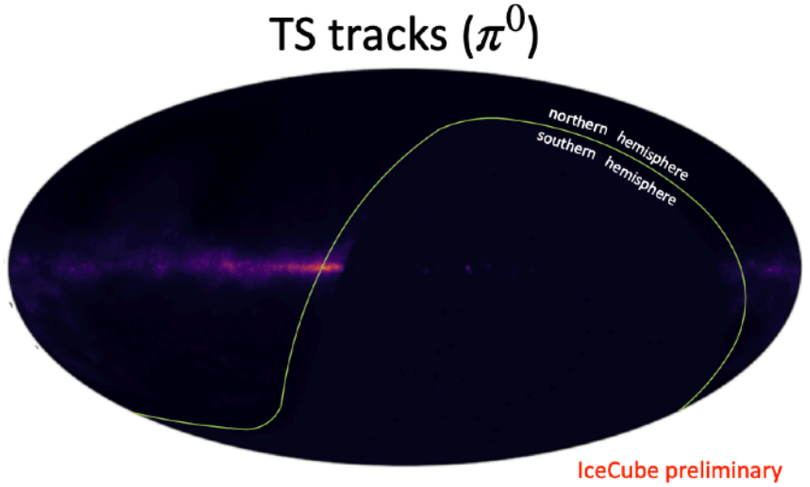
Galactic neutrinos

Science 380 (2023)



- Observed by IceCube (4.5σ)
- Now combining cascades and tracks >5σ
- Sources or diffuse?





And the others in the North?

- ANTARES also observed a 2.2σ excess (ON-OFF technique)
  - They dont see a significant preference using templates

Model	$\hat{r}$	$\widehat{TS}$	p-value (nσ)	UL	Sensitivity
DiffUSE	0.7 [8.9]	0.2	0.22 (1.23)	2.2 [28.4]	1.3 [17.3]
CRINGE	0.7 [8.1]	0.3	0.21 (1.26)	2.2 [24.8]	1.3 [15.1]
$KRA_\gamma^{\max}$	0.4 [6.2]	0.6	0.11 (1.59)	1.2 [20.7]	0.6 [9.6]
$KRA_\gamma^{\min}$	0.4 [6.4]	0.5	0.15 (1.46)	1.4 [22.5]	0.7 [11.9]
$KRA_\gamma^{5\,\mathrm{PeV}}$	0.5 [6.4]	0.7	0.10 (1.65)	1.5 [19.5]	0.7 [9.4]
π^0	3.0 [10.3]	0.2	0.20 (1.28)	9.5 [33.2]	5.7 [19.7]

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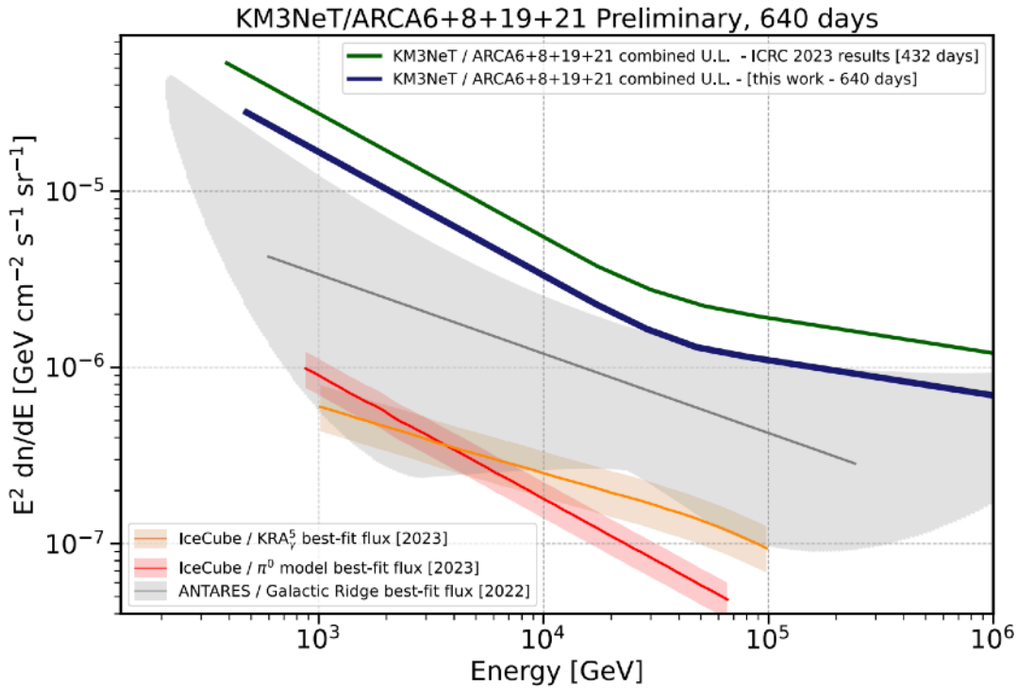
- KM3NeT/ARCA still not sensitive (also ON-OFF)



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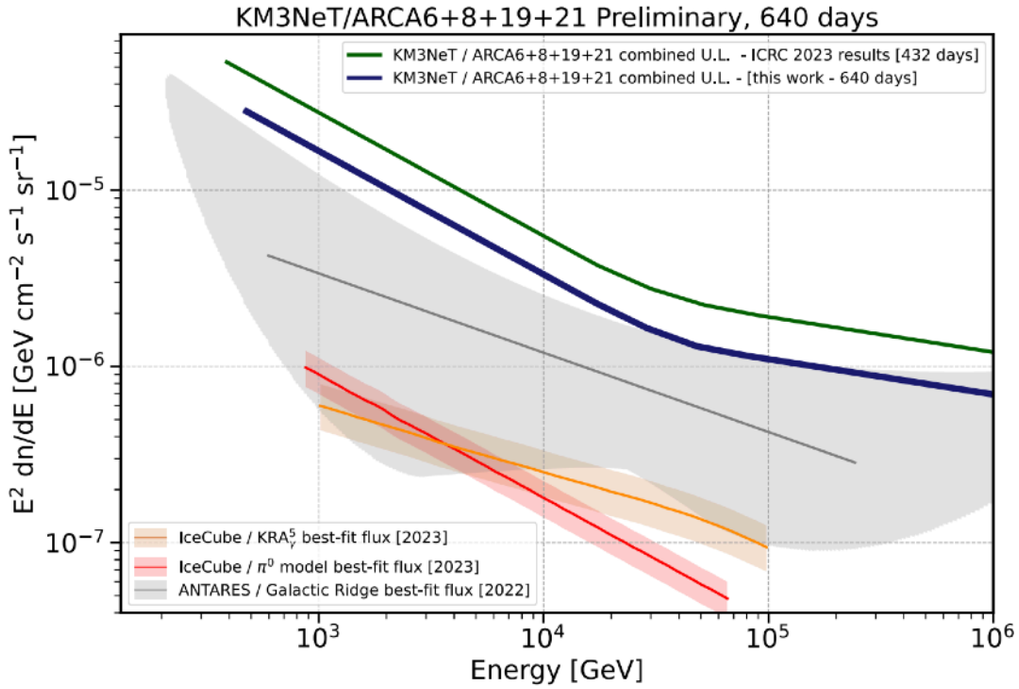
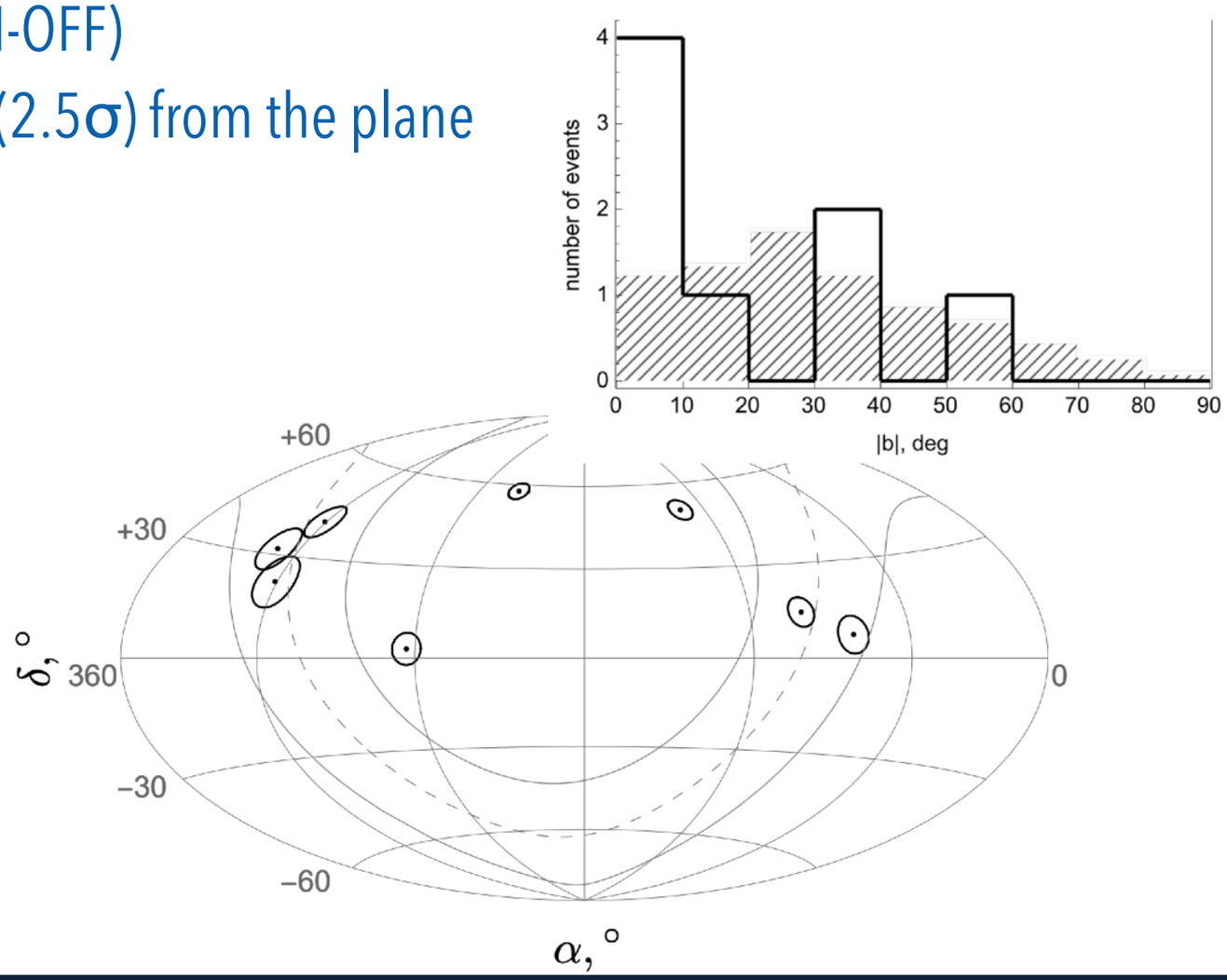
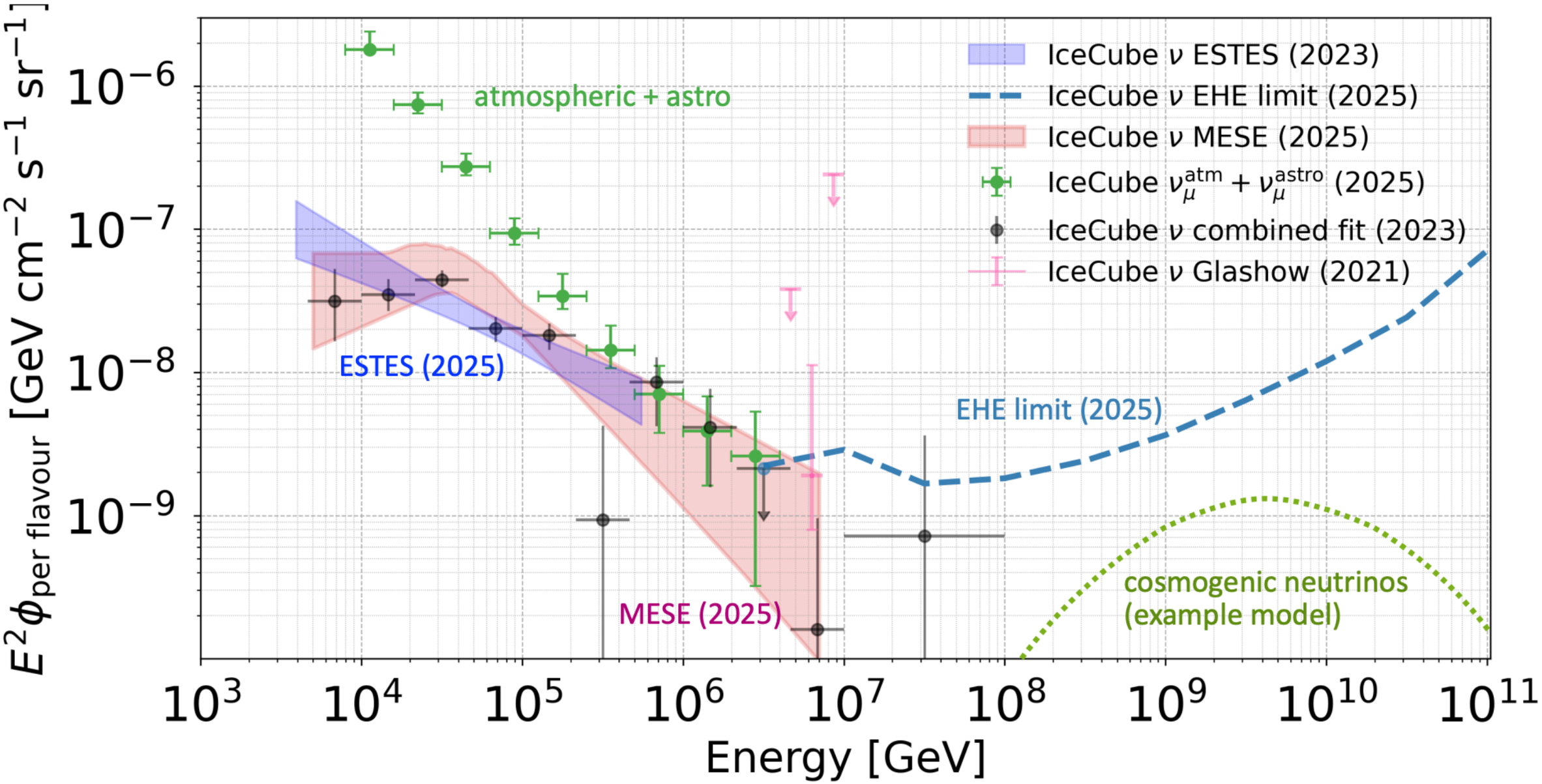
- KM3NeT/ARCA still not sensitive (also ON-OFF)
- Baykal preliminary analysis show excess (2.5σ) from the plane





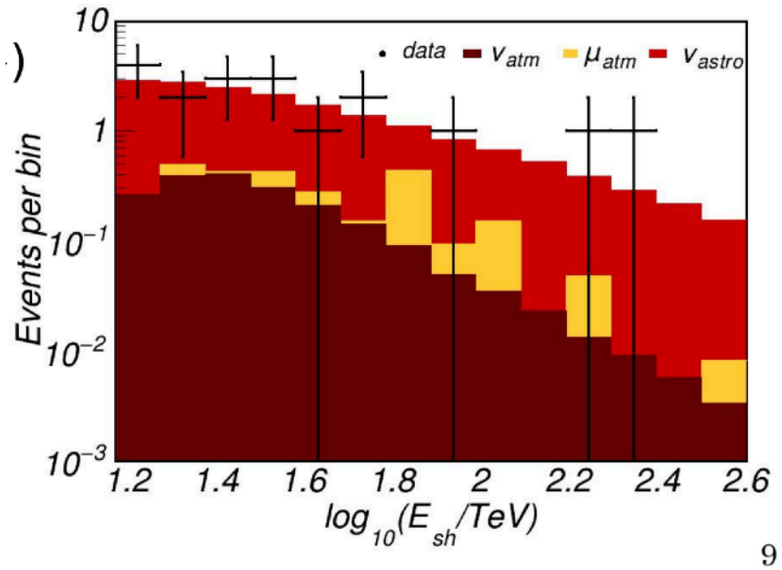
Diffuse flux

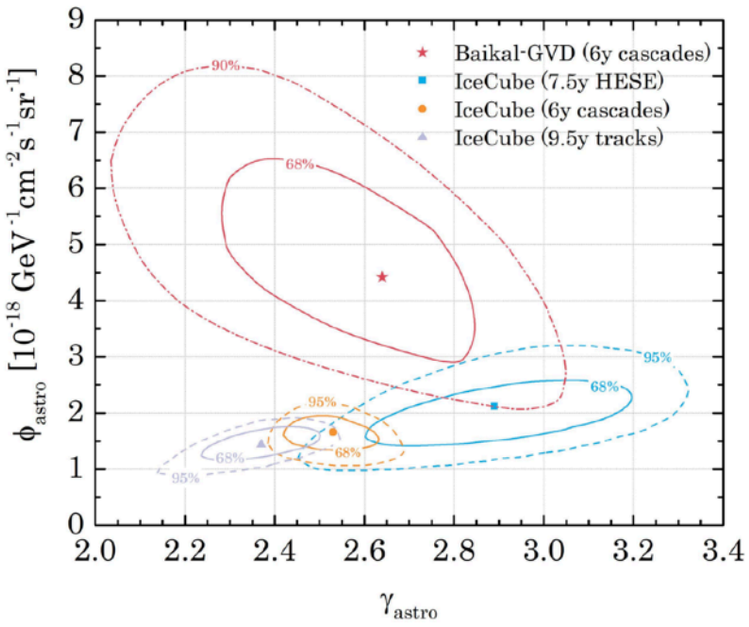
- IceCube has entered the era of characterization!
  - Interesting features observed in the TeV regime



The new partners are coming

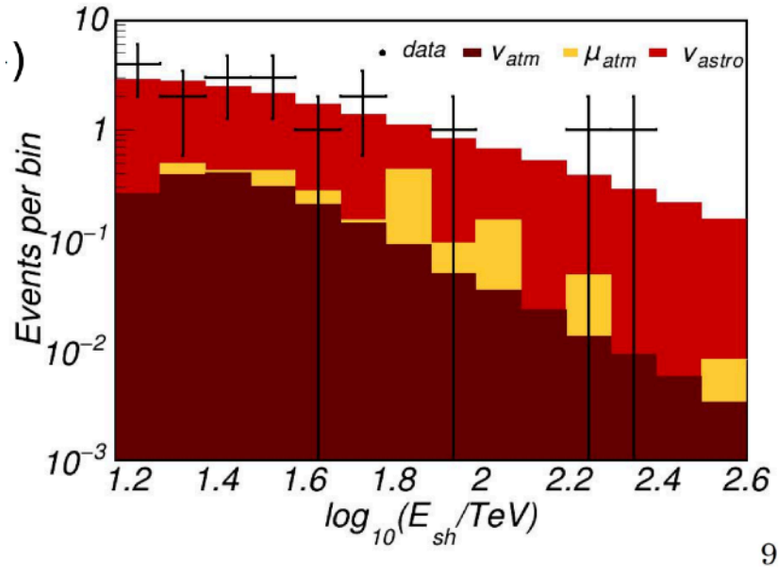
- GVD-Baykal claims observation (>5σ with upgoing cascades) -> too many

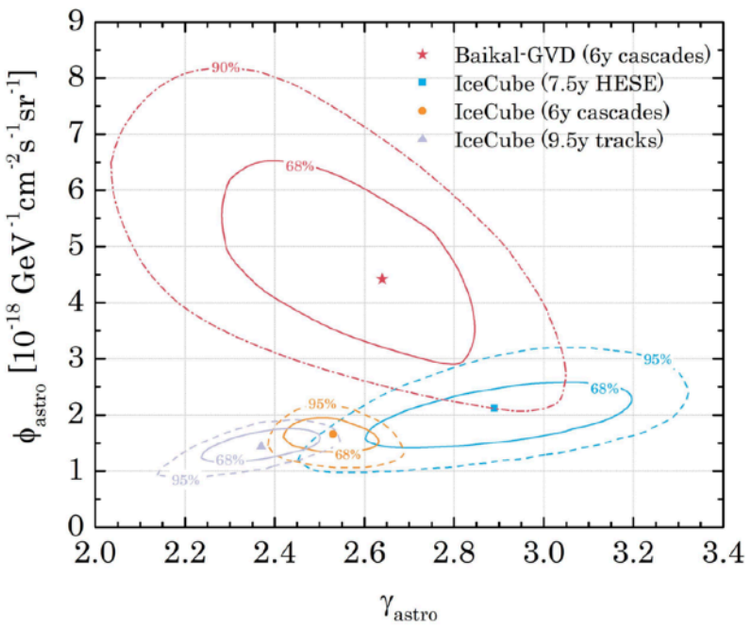


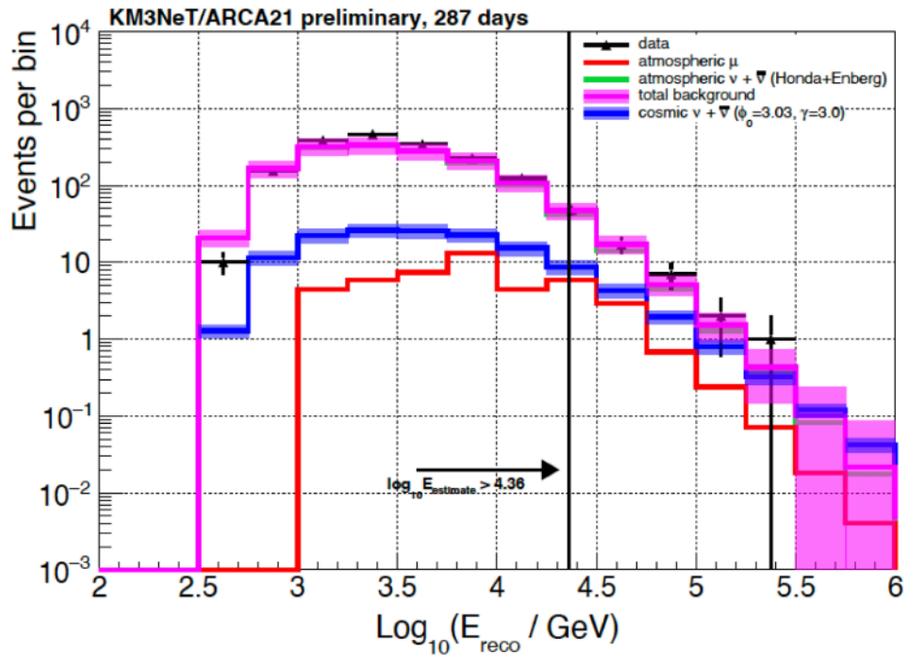


The new partners are coming

- GVD-Baykal claims observation (>5σ with upgoing cascades) -> too many
- ARCA will start seeing then soon (only upgoing tracks have been analyzed).

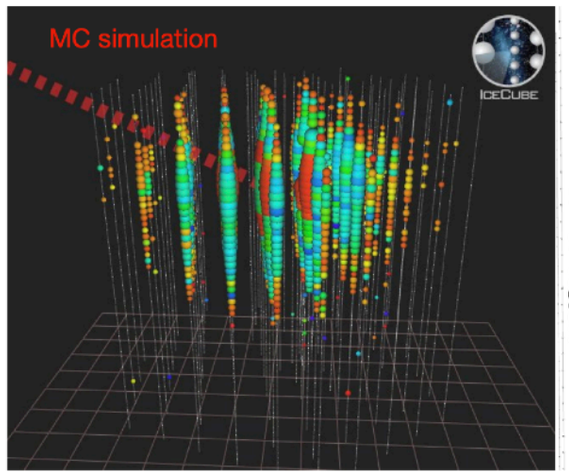




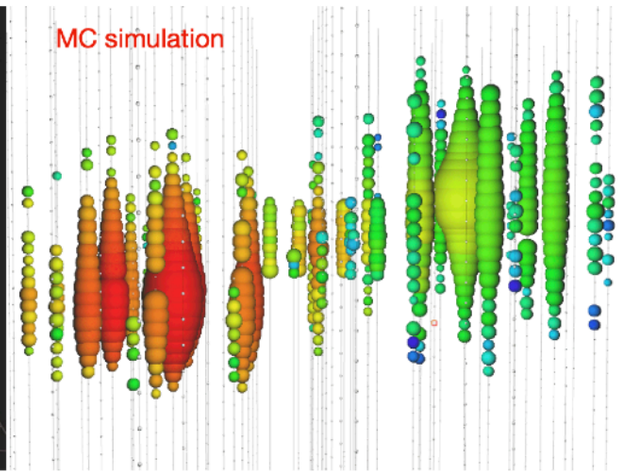


What about the flavor composition?

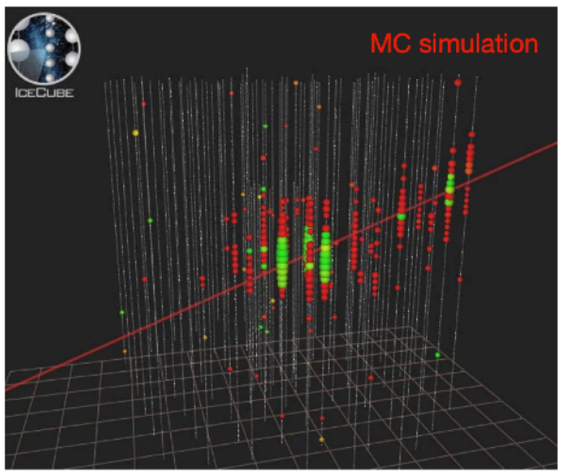
- Right now only IceCube is able to do this (access to tau-neutrino candidates).

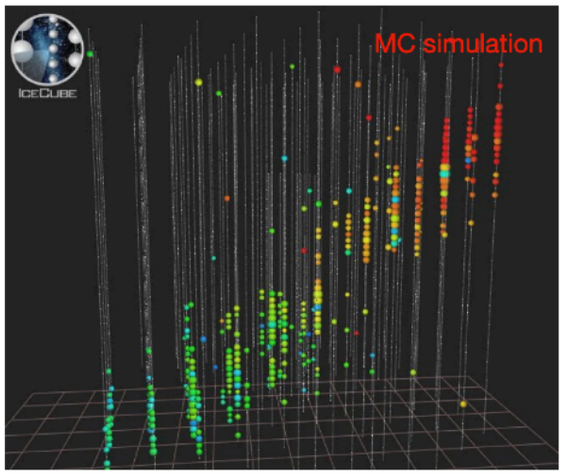


Cascade



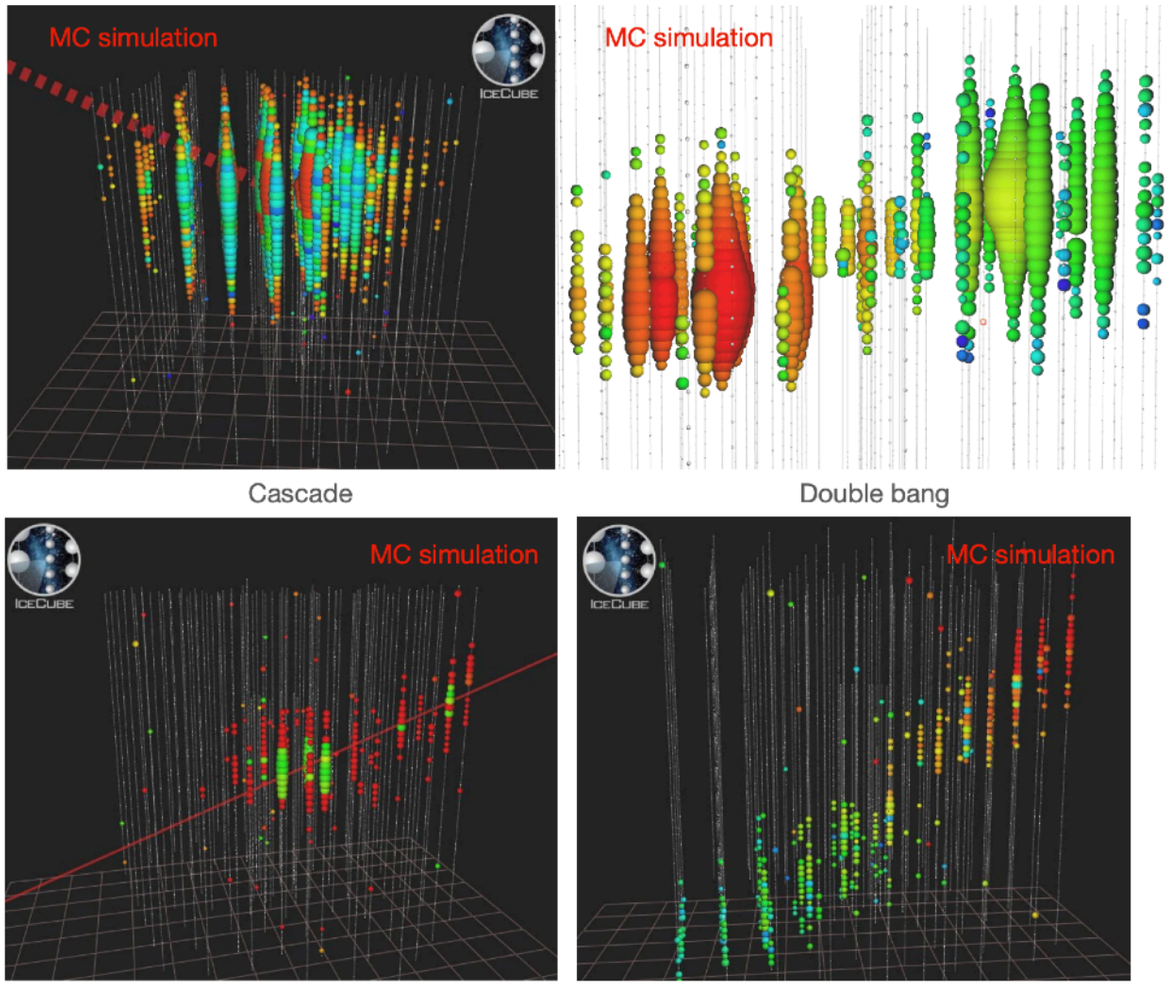
Double bang

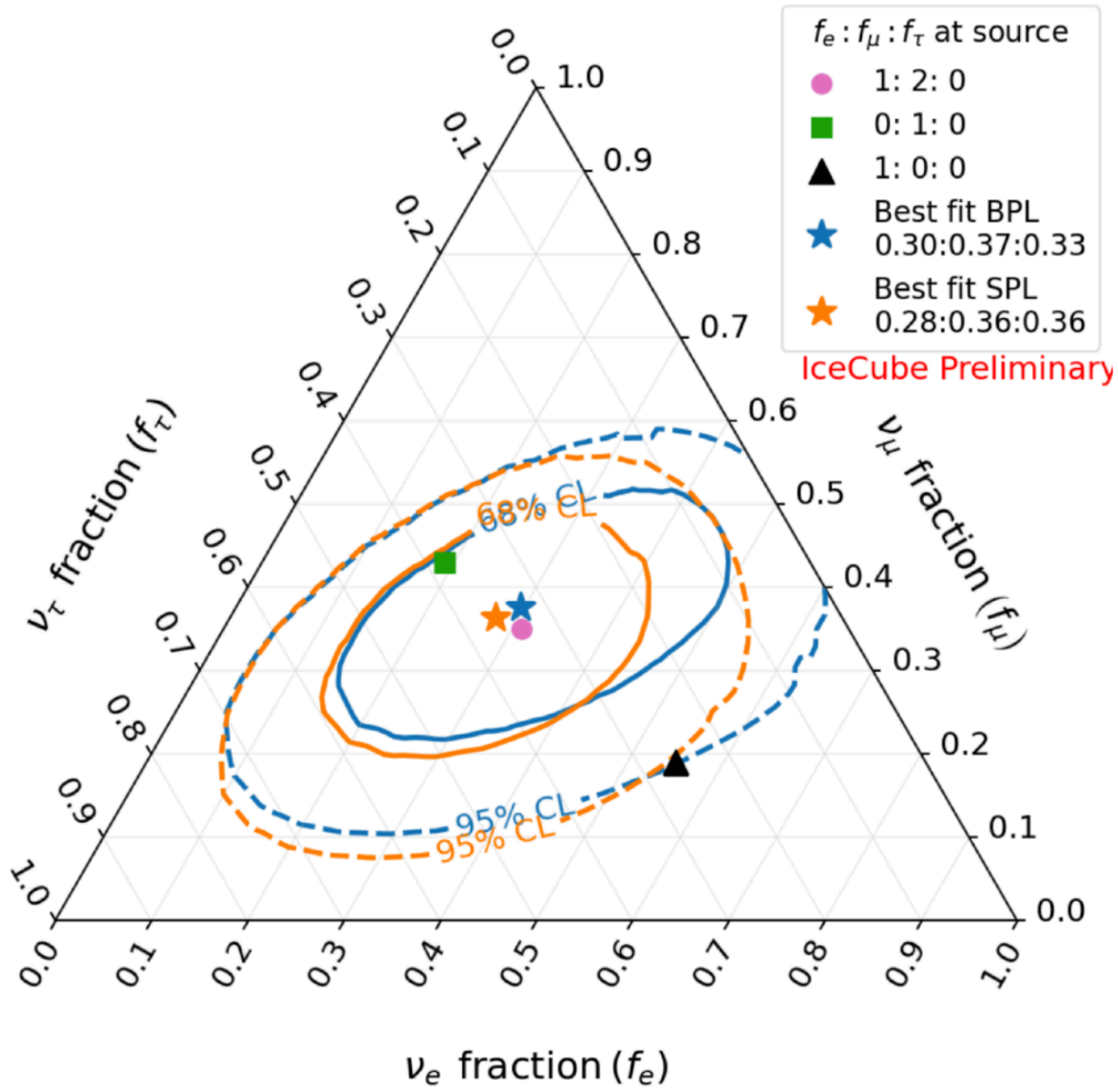




What about the flavor composition?

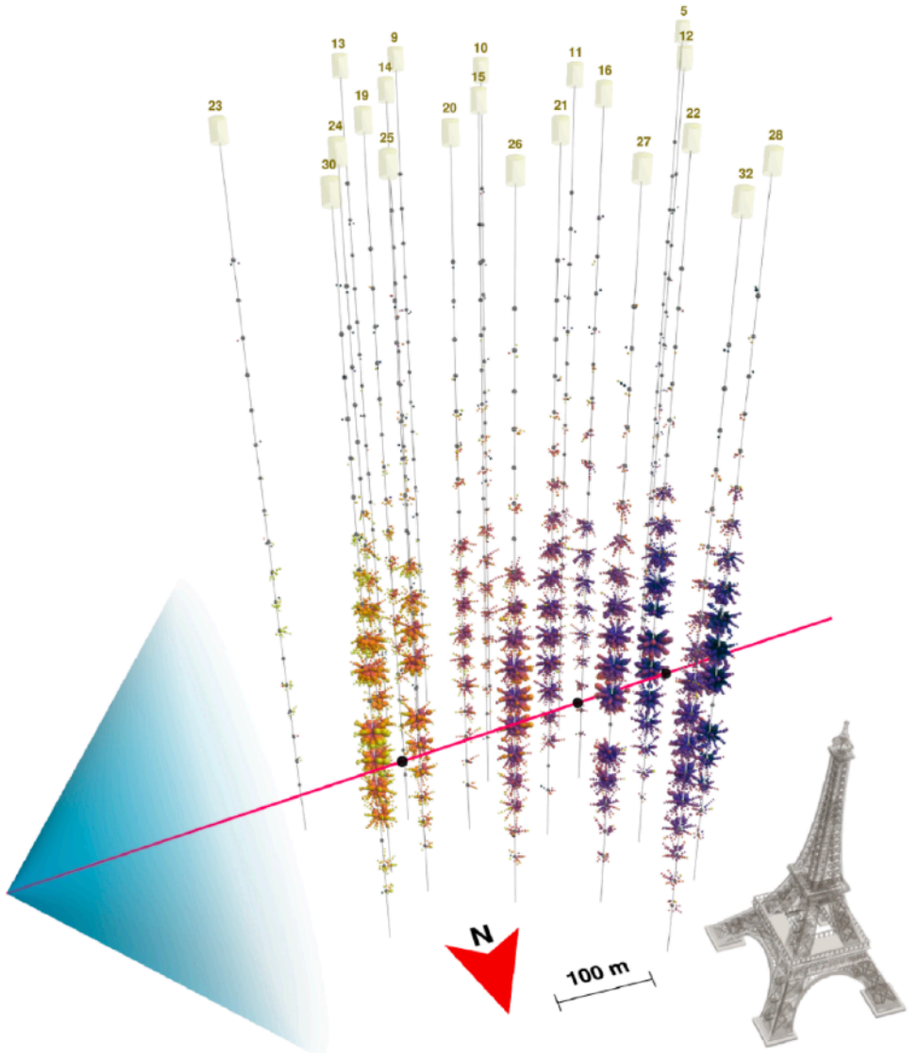
- Right now only IceCube is able to do this (access to tau-neutrino candidates).
- Latests analysis using MESE sample start disfavoring neutron production

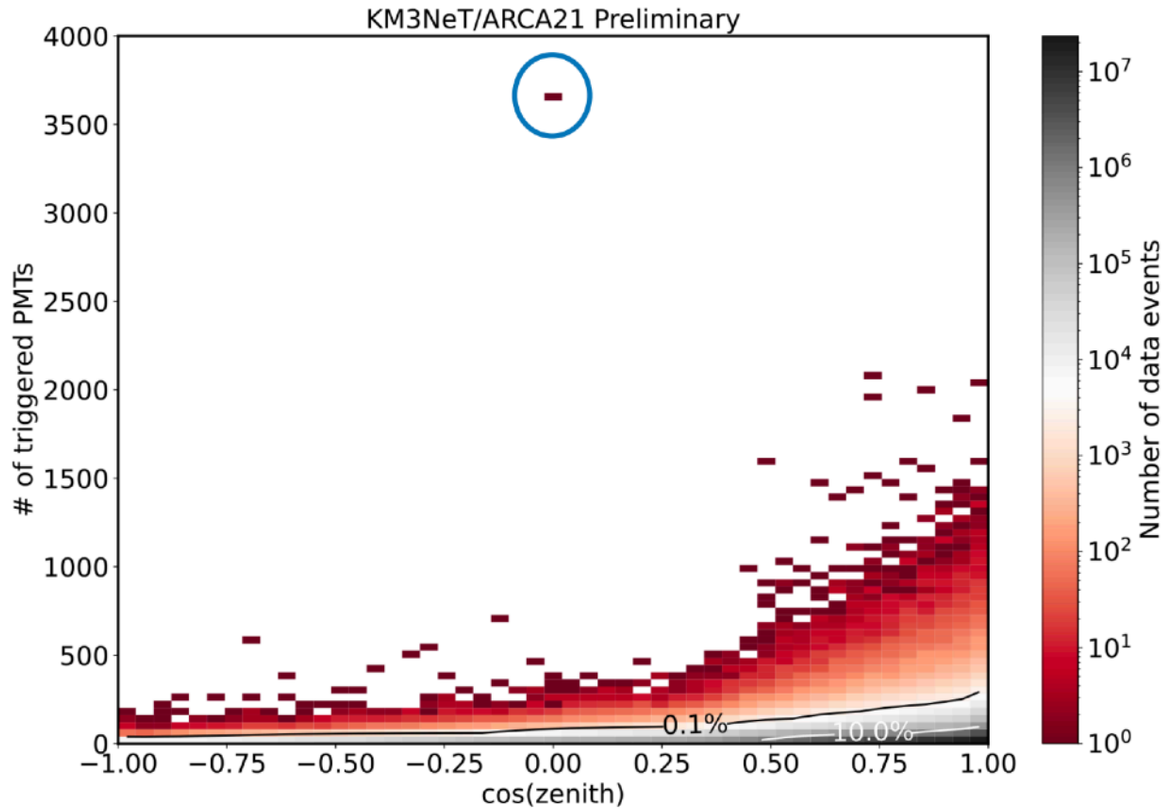




The unexpected

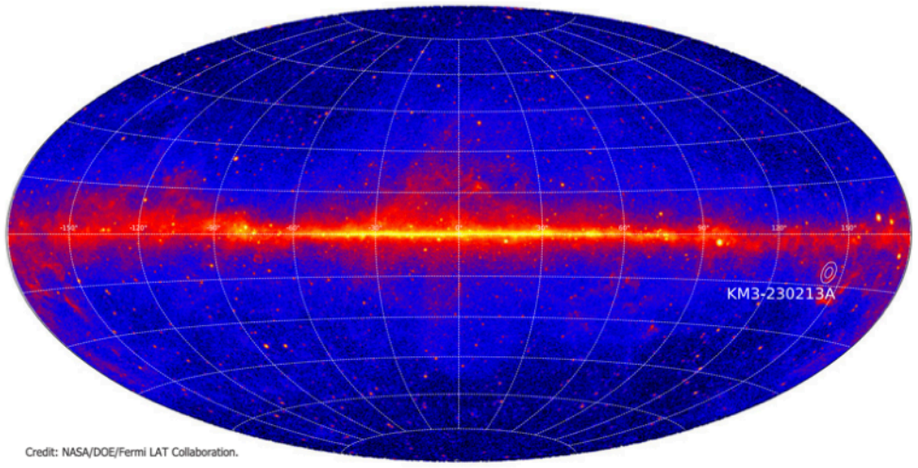
- KM3NeT observed an very bright muon crossing the detector horizontally
  - Coming from a neutrino the median energy is 220PeV -> new energy regime!





The unexpected

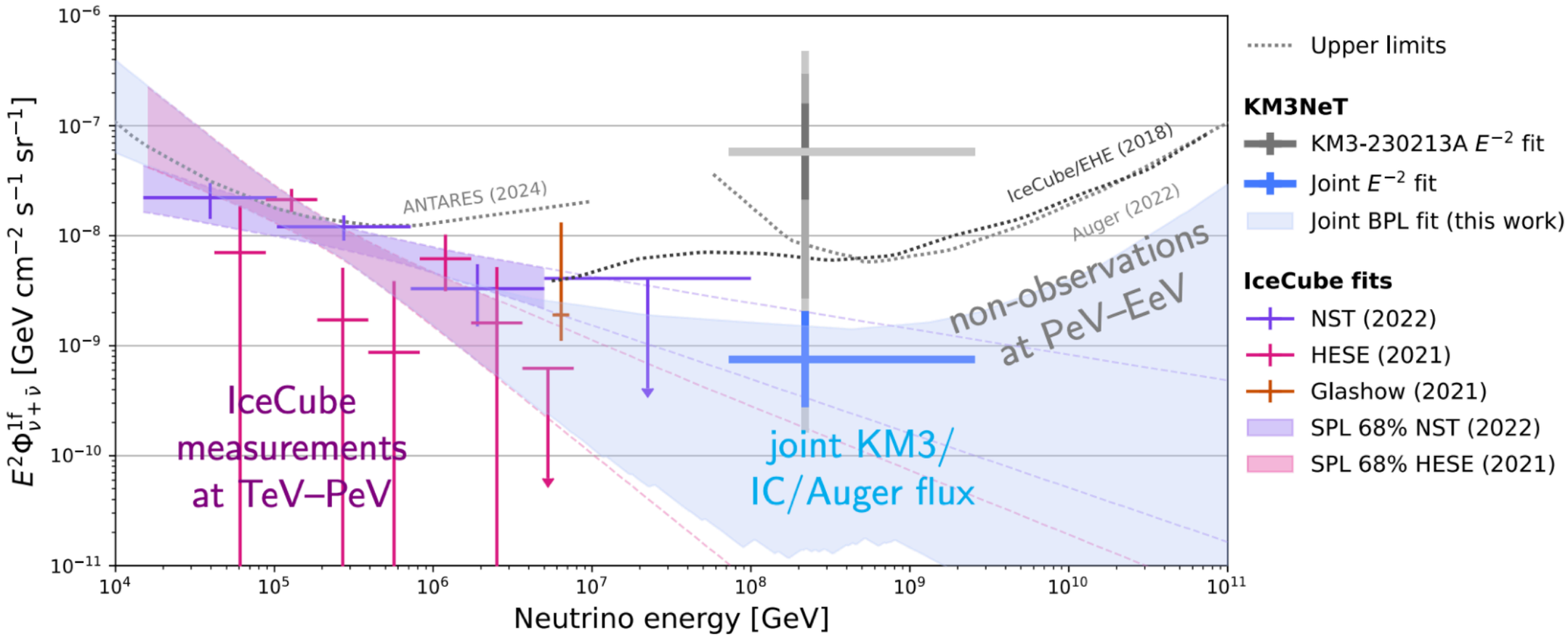
- No sources identified (still large angular error).



The unexpected

- No sources identified (still large angular error).

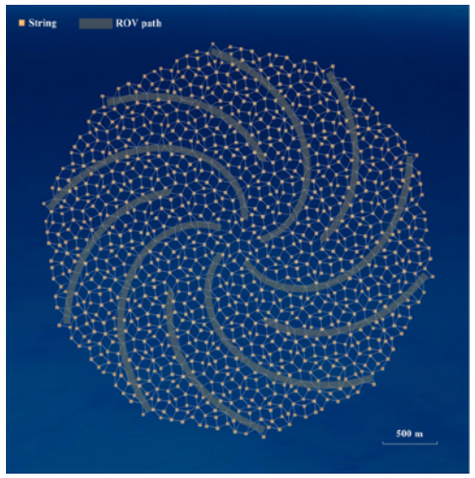
- No observation of similar events by IC or Baykal.
  - Current tension at the level of 3σ

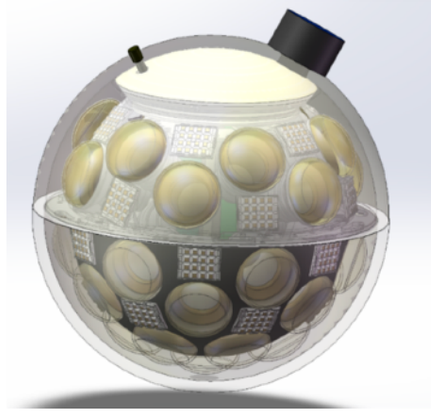


Future for Cerenkov detectors

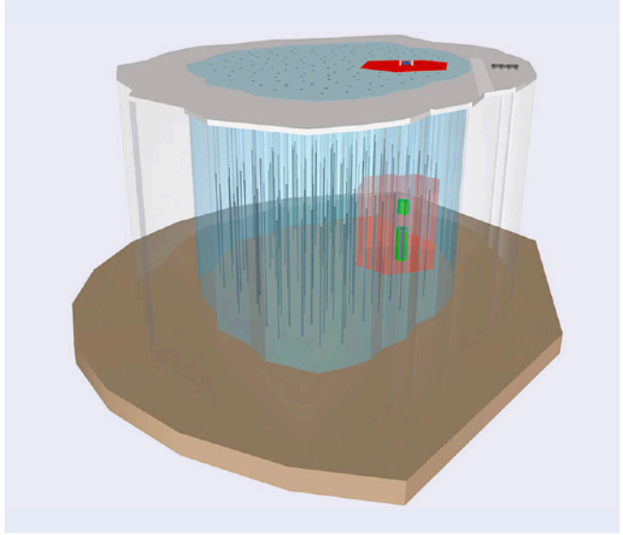
- GVD-Baykal and ARCA will be completed before the end of the decade
- New friends are planning to join!

TRIDENT





IC Gen2 - Optical



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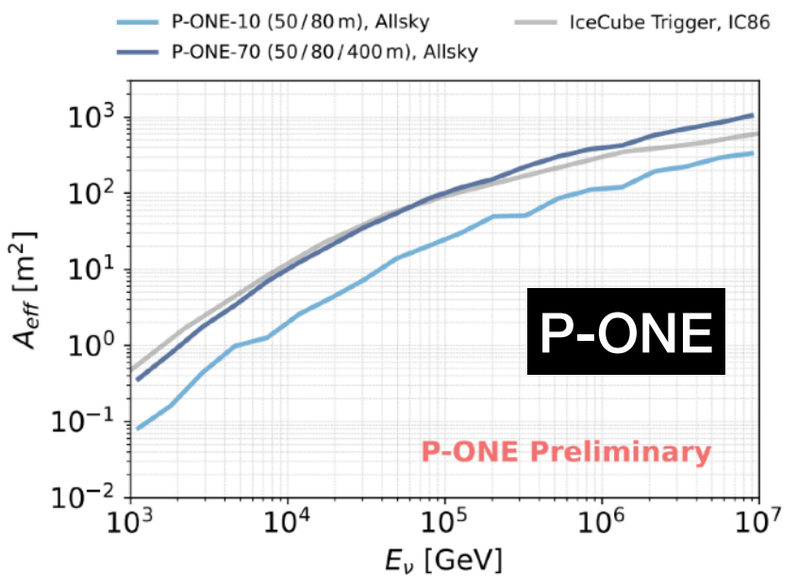
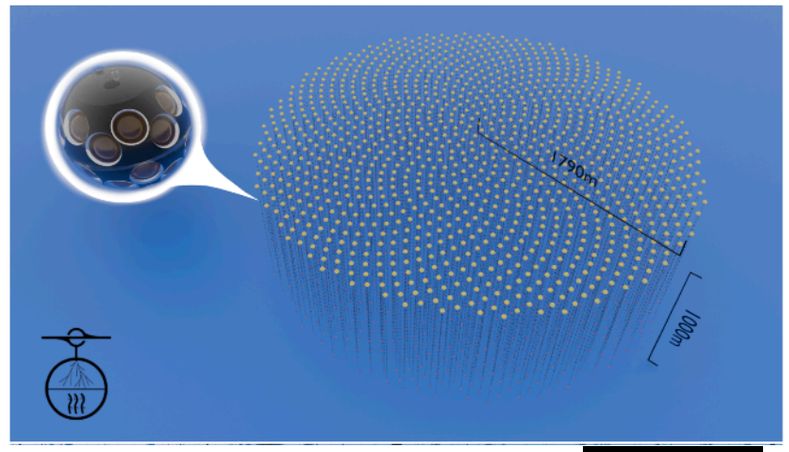
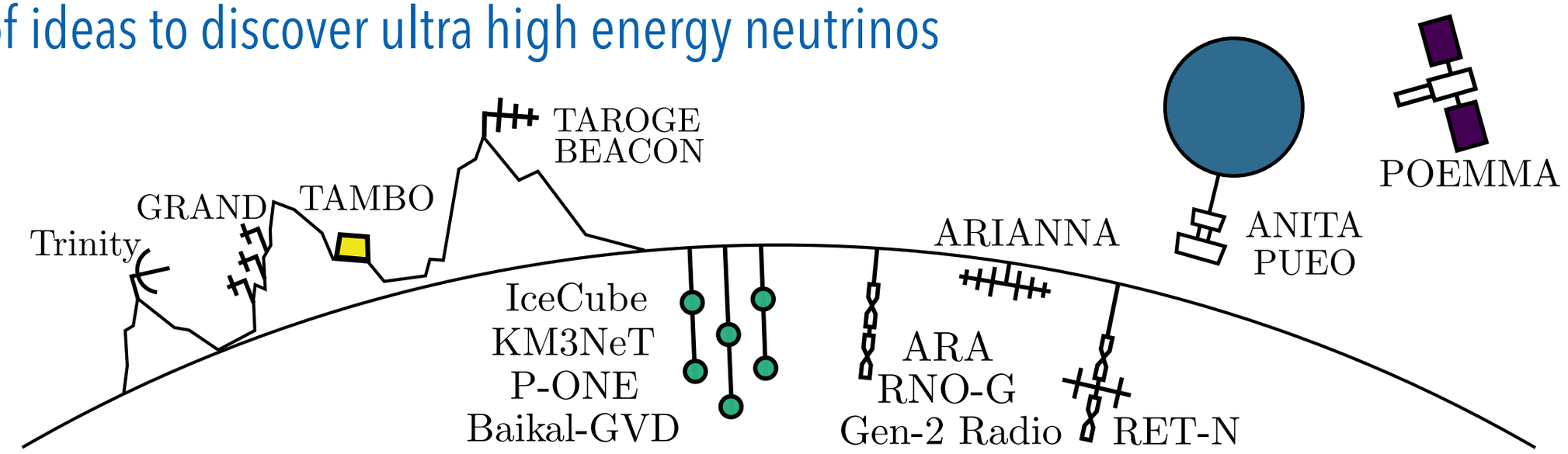




NEON

Going to even higher energies

- A plethora of ideas to discover ultra high energy neutrinos



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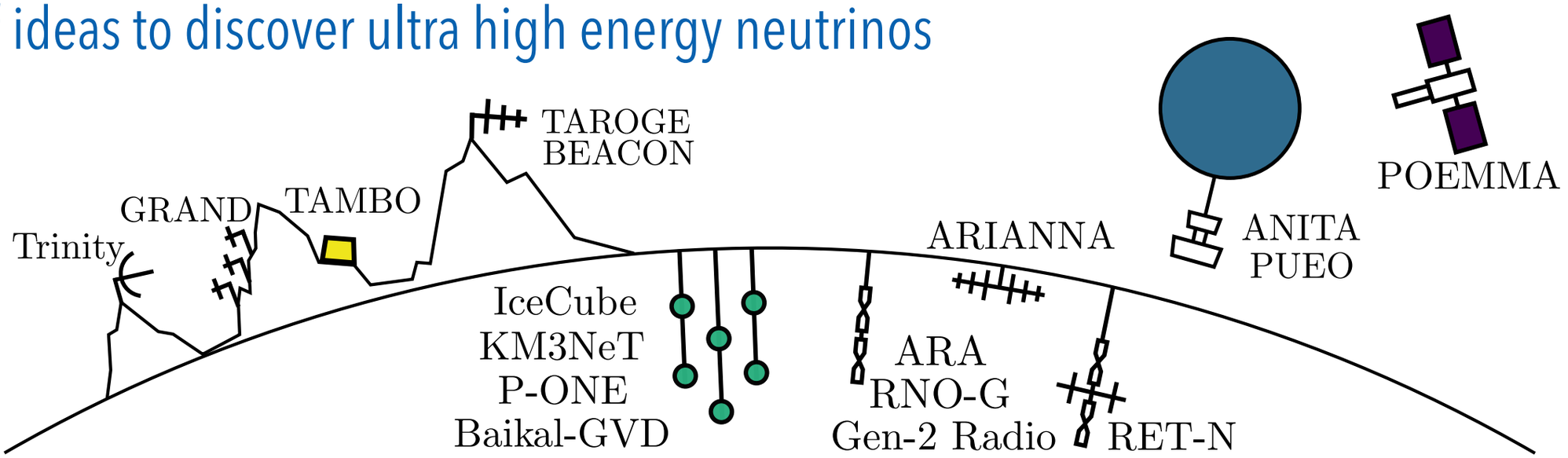
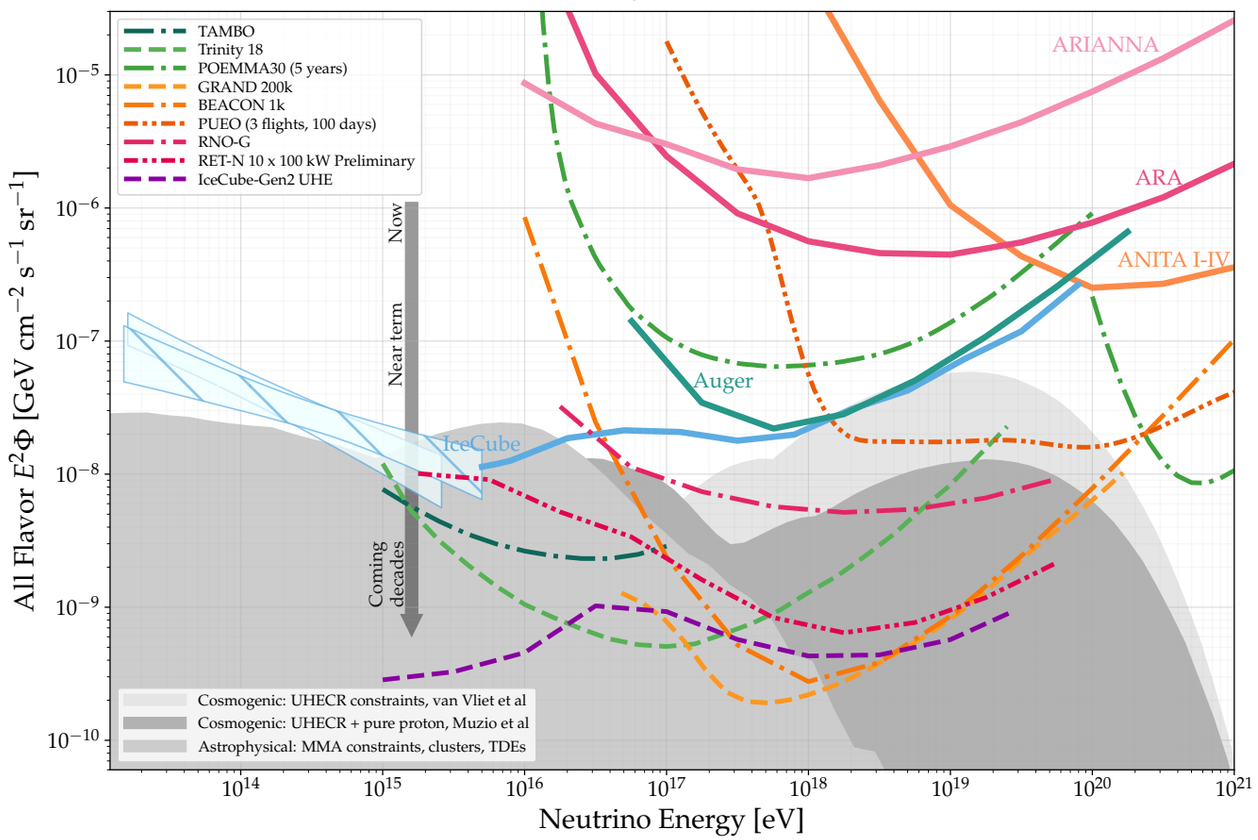
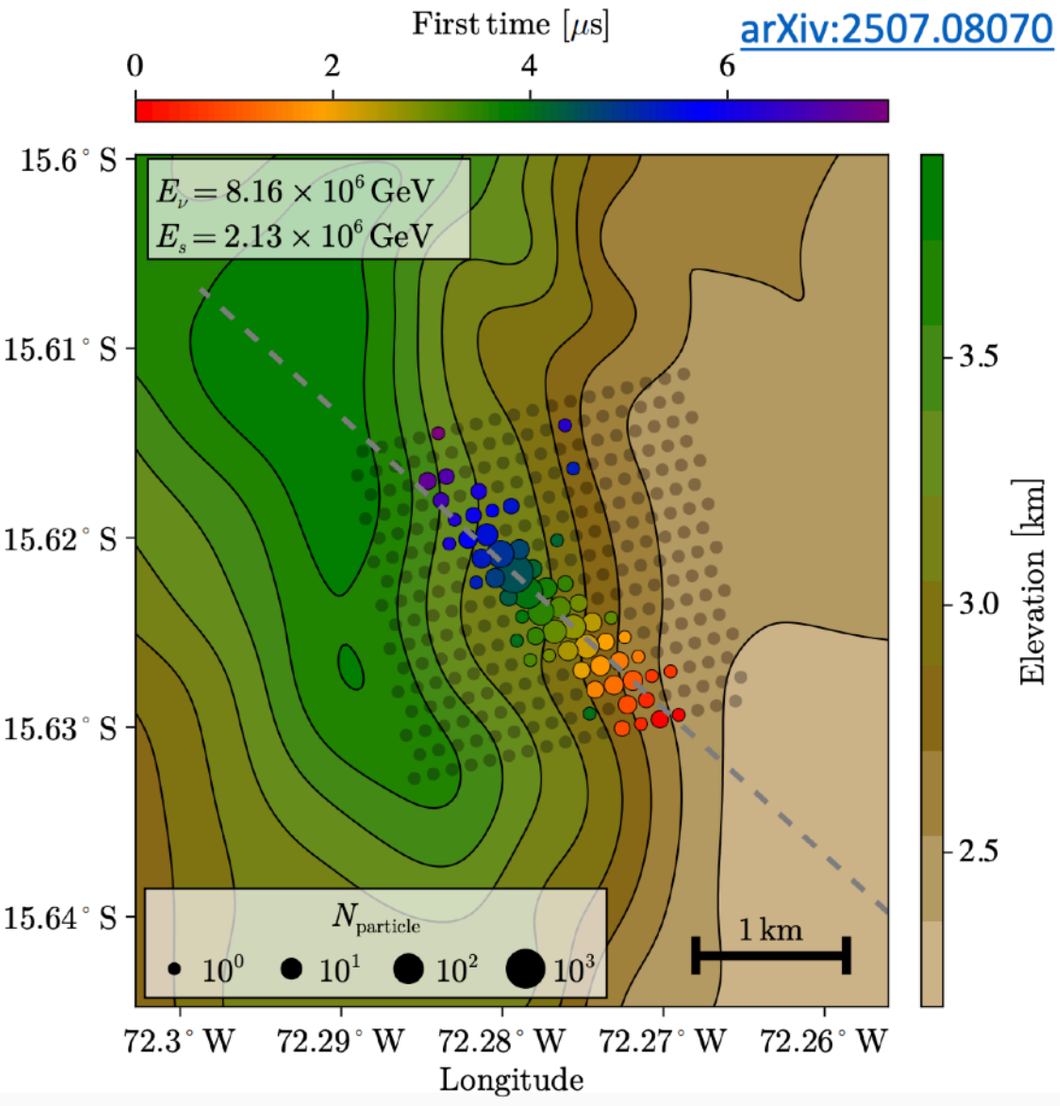
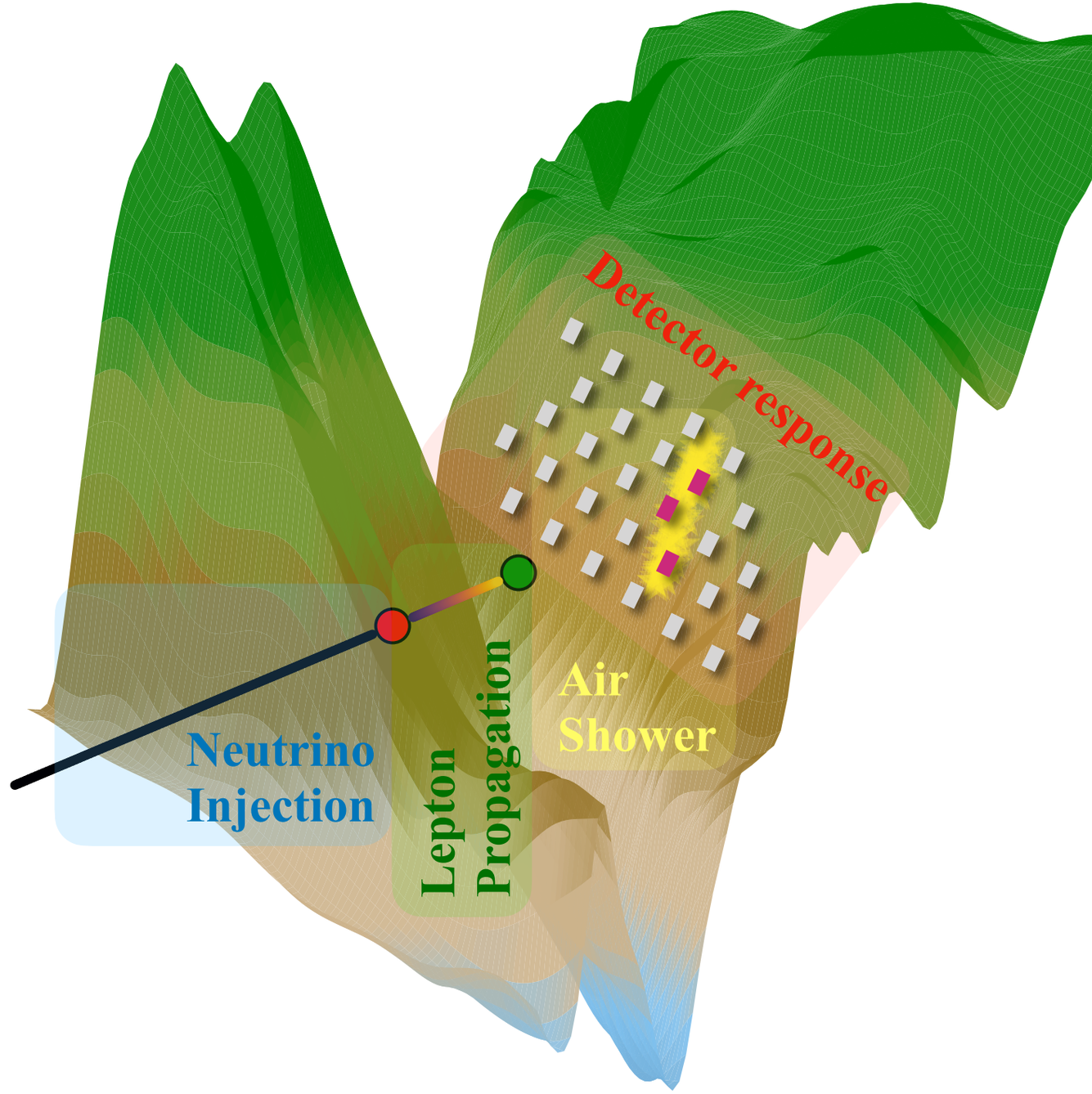




My favourite… TAMBO

- Founded first prototype!!!





Conclusions

- The era of the high-energy neutrinos has just started
- Multiple breakthrough measurements in the last years.
- New technologies are coming online!

THANKS!