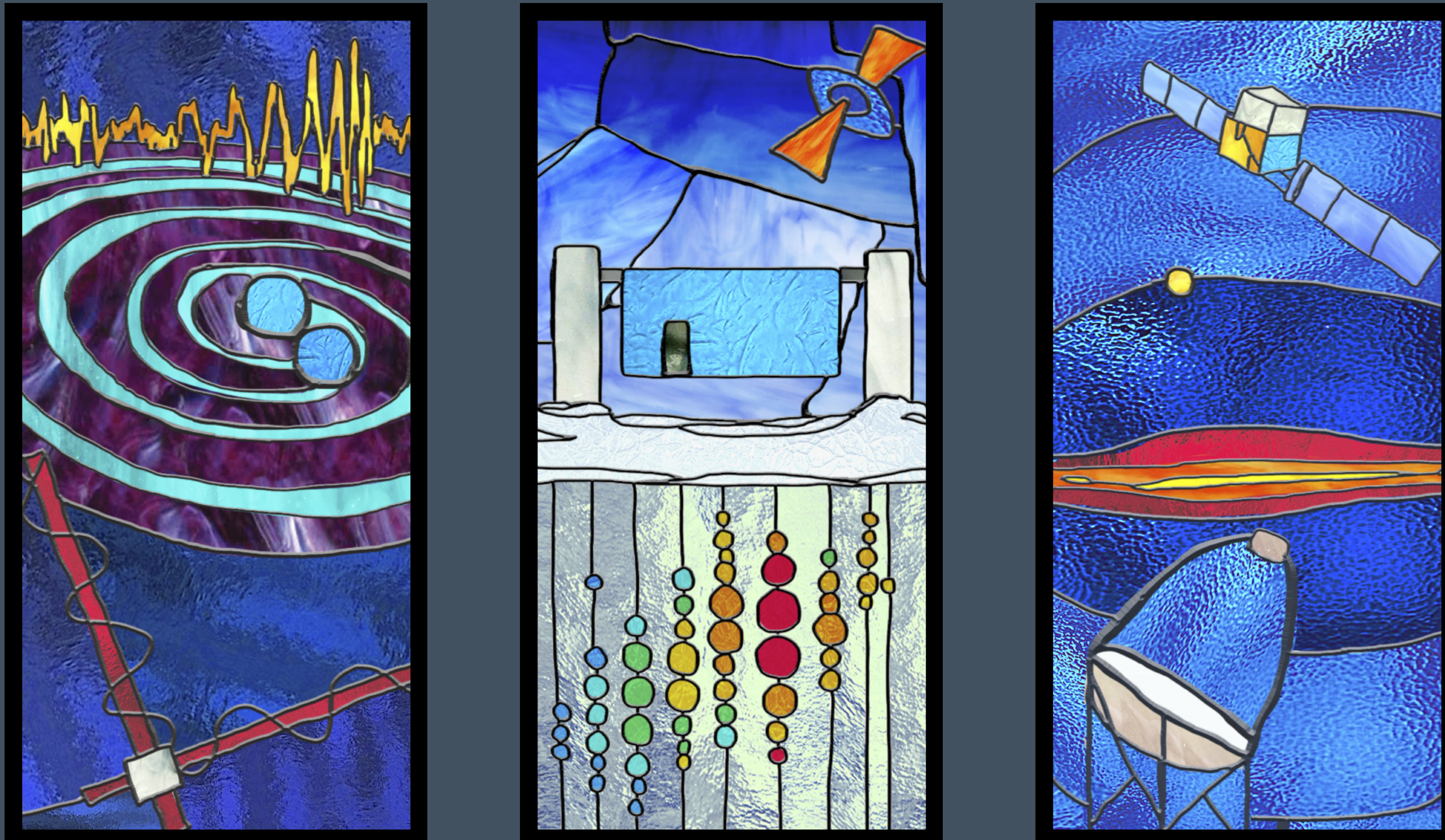


Neutrinos as Messengers

Markus Ahlers, NBI Copenhagen

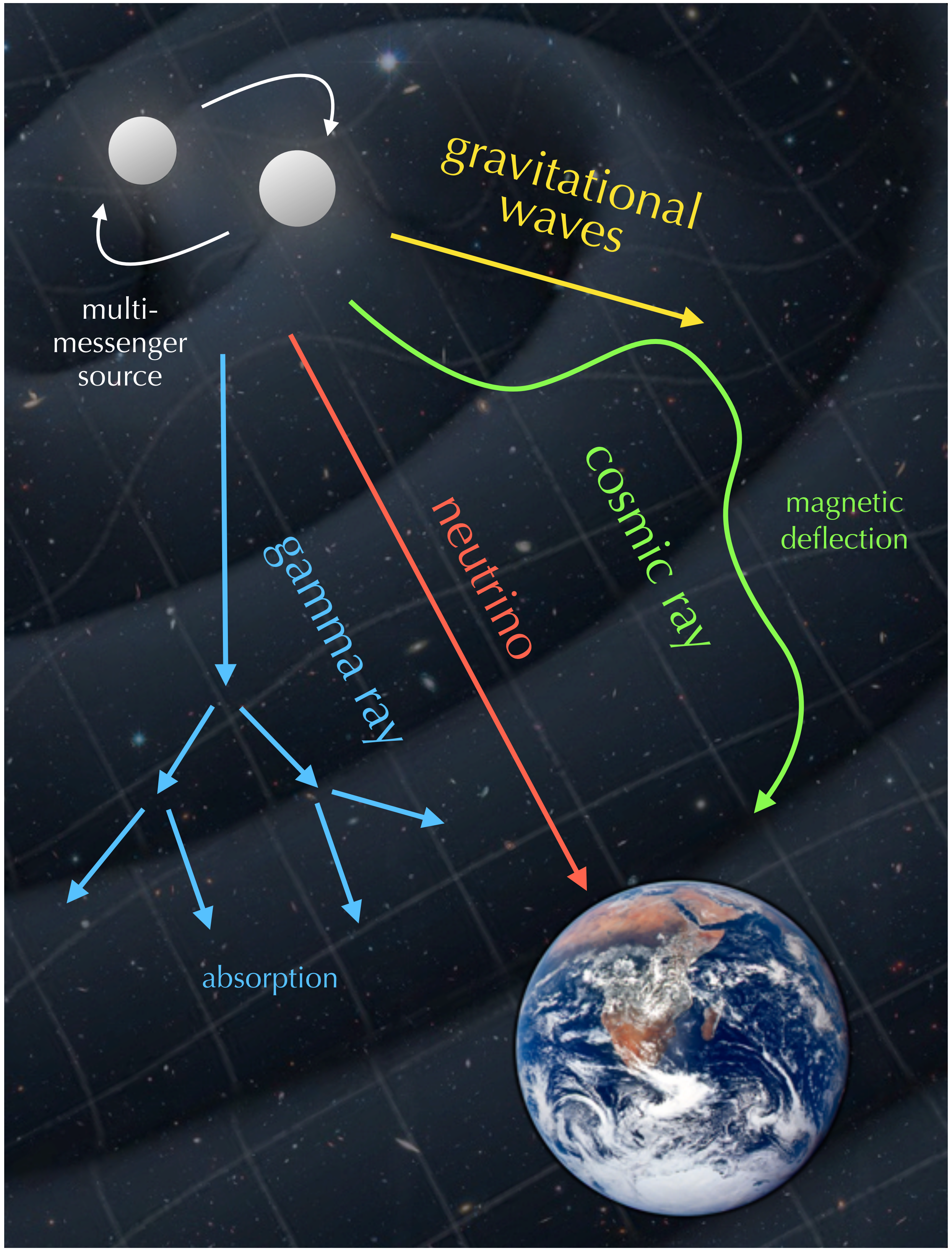
European Neutrino Town Meeting

October 22-24, 2018

VILLUM FONDEN

KØBENHAVNS UNIVERSITET

Multi-Messenger Astronomy



- **Cosmic ray** acceleration – especially in the aftermath of cataclysmic events, sometimes seen in **gravitational waves**.

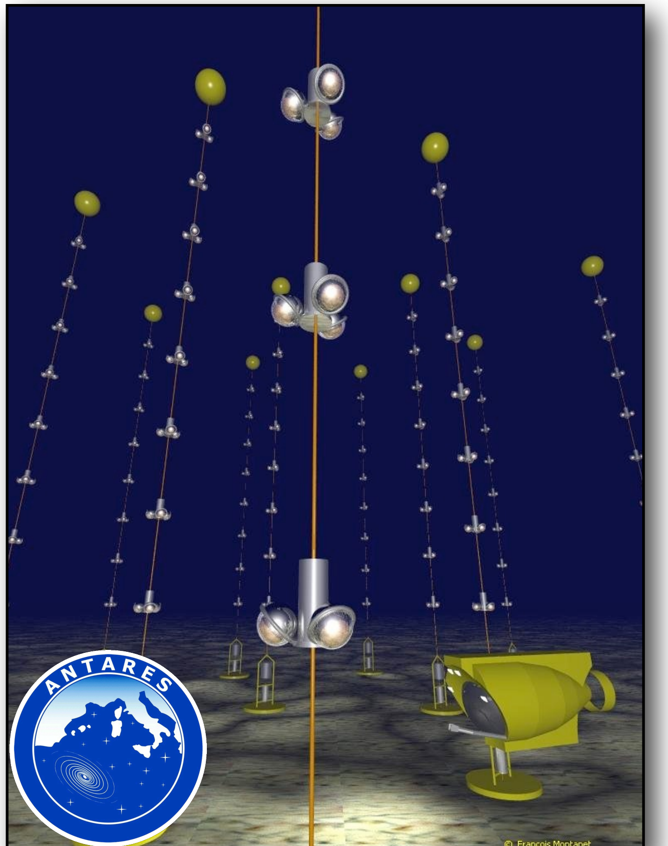
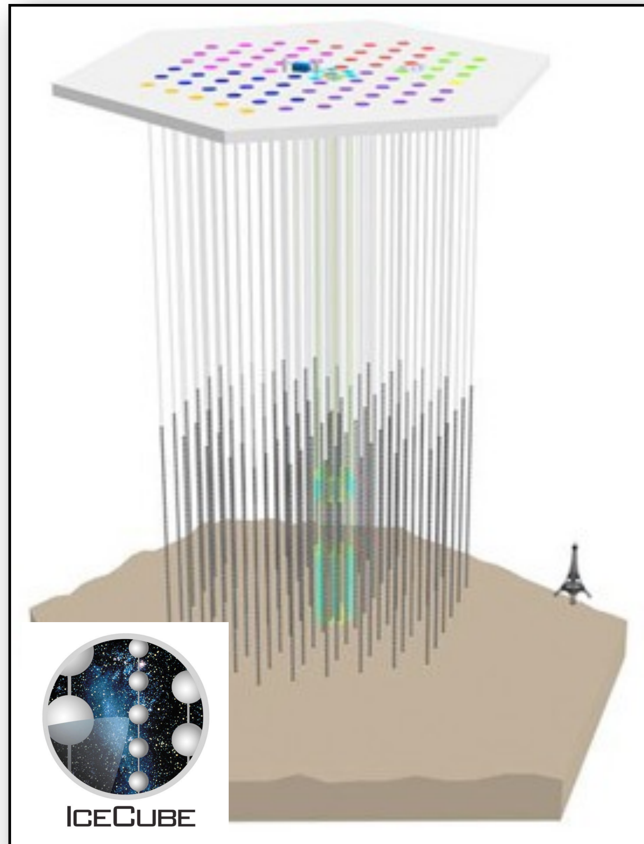
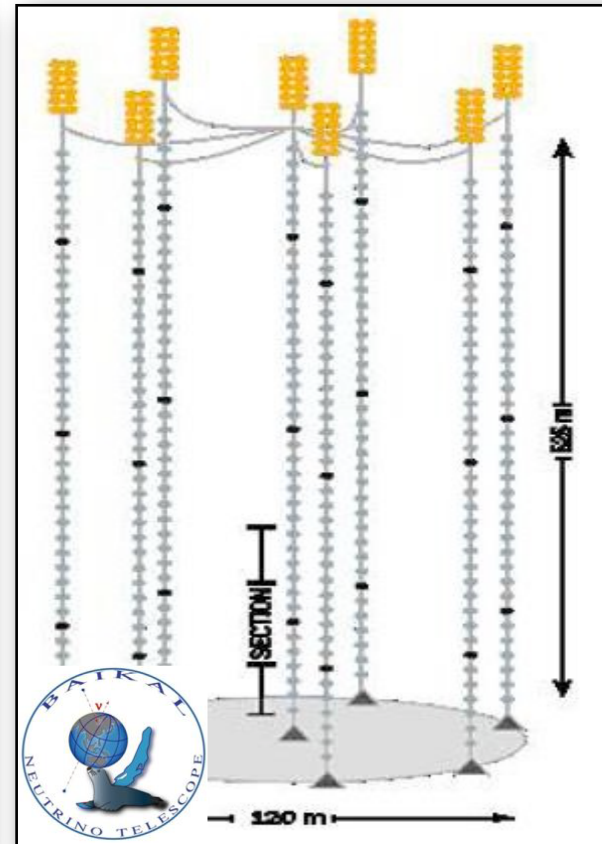
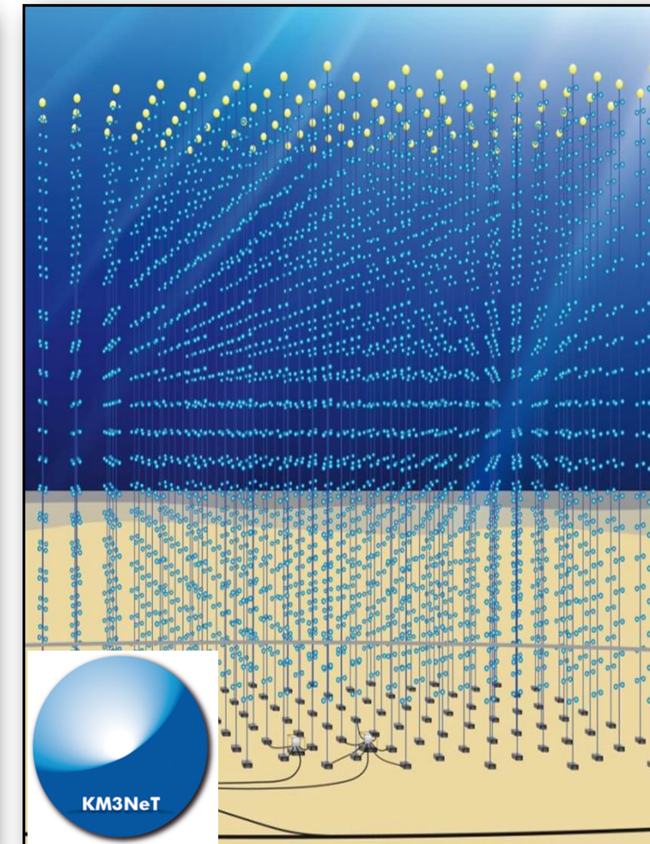
→ Inelastic collisions with radiation or gas produce **γ-rays** and **neutrinos**, *e.g.*

$$\pi^0 \to \gamma + \gamma$$

$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$$

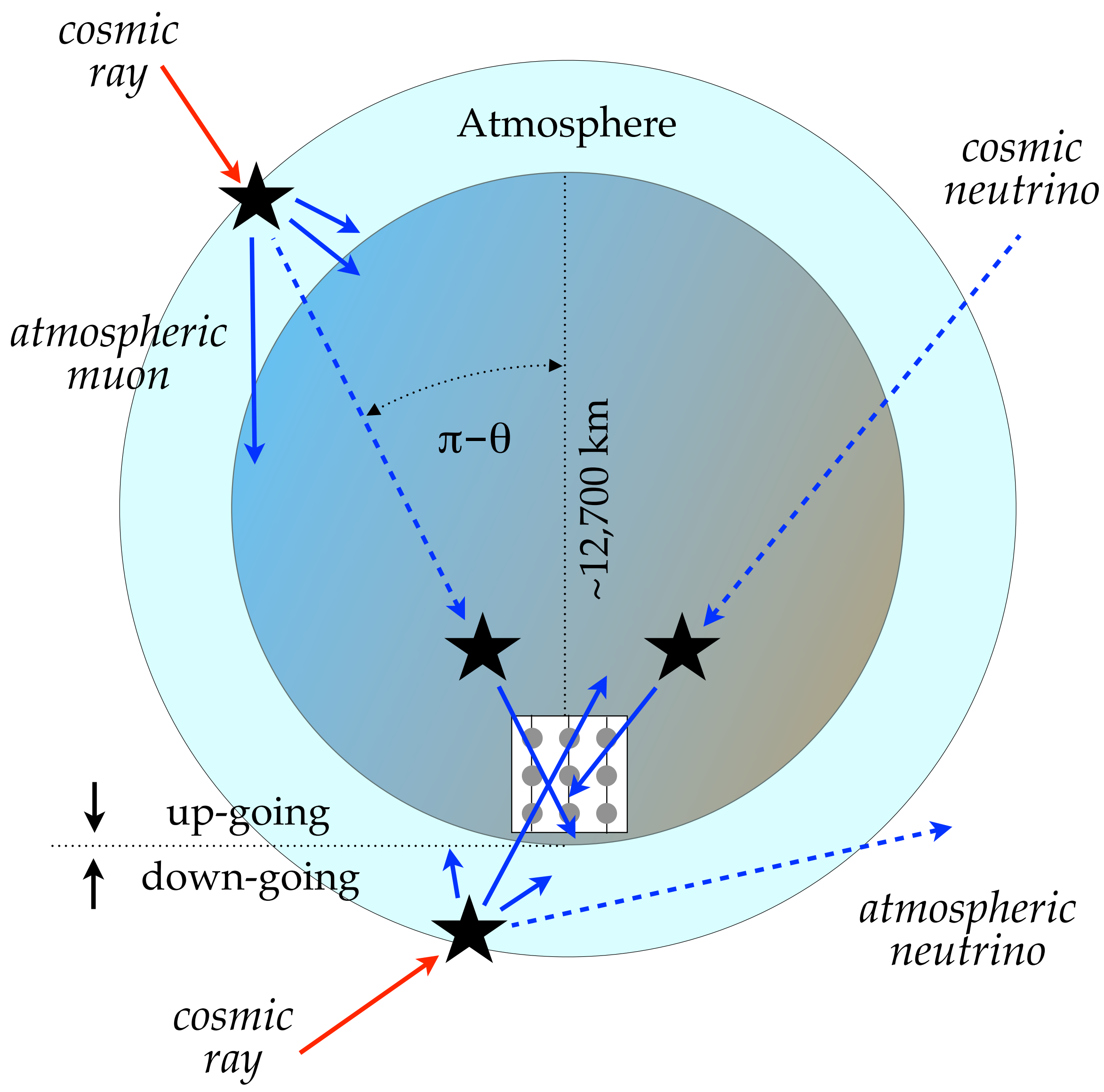
- **Unique aspects of neutrino messengers**:
  - *identify* cosmic ray sources
  - *qualifies* γ-ray emission
  - *covers blind spot* of astronomy to the very-high-energy Universe

Cherenkov Observatories

Antares	IceCube	Baikal-GVD	KM3NeT/ARCA
			
Mediterranean	South Pole	Lake Baikal	Mediterranean
2008–2019	fully instrumented since 2011	under construction (3 out of 8 clusters)	under construction (3 out of 230 DUs)
~0.01 km³	~1 km³	~0.4 km³ (Phase 1) ~1km³	~0.1 km³ (Phase 1) ~1 km³
885 OMs (10″)	5160 OMs (10″)	2304 OMs (10″)	4140 OMs (31x3″)

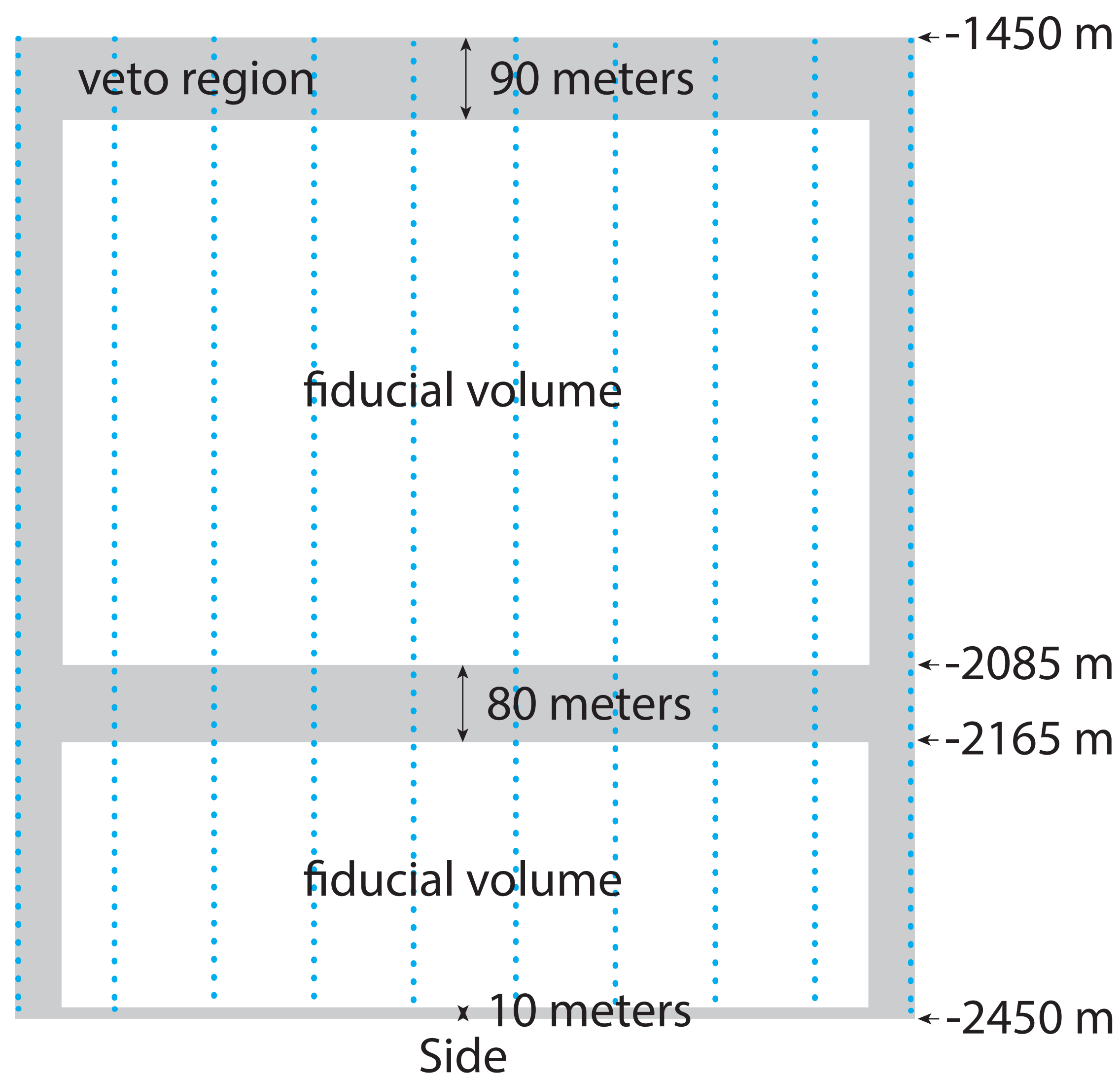
Detection Methods

Up-going Muon-Neutrino Tracks



- **10,000,000,000** atmospheric muons
- **100,000** atmospheric neutrinos
- **10** cosmic neutrinos (per year and km³)

High-Energy Starting Events (HESE)



[IceCube Collaboration'13]

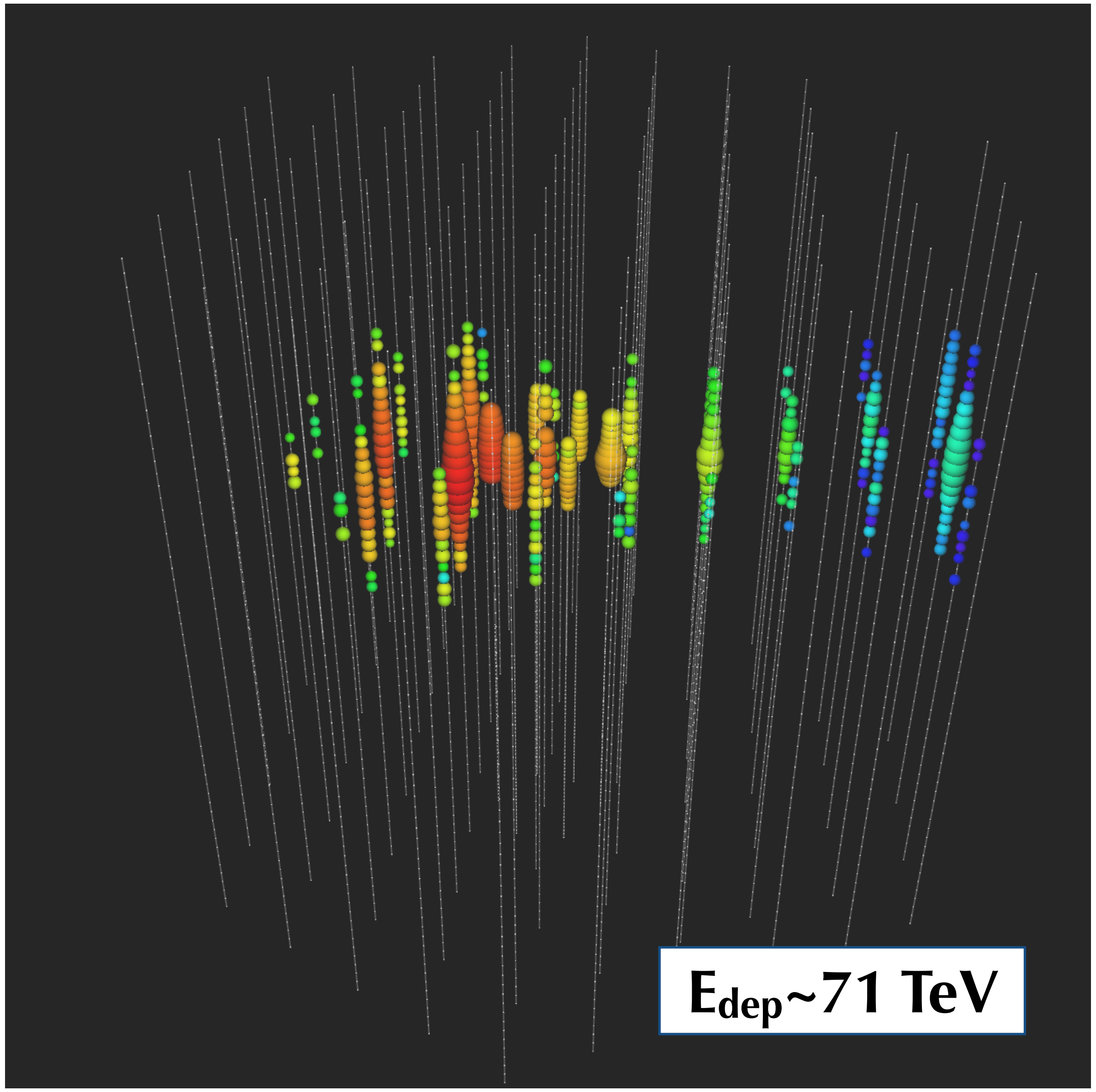
- **virtual veto region** triggered by atmospheric muons
- **self-veto** of coincident atmospheric neutrinos
- **cosmic neutrino events are required to start inside**

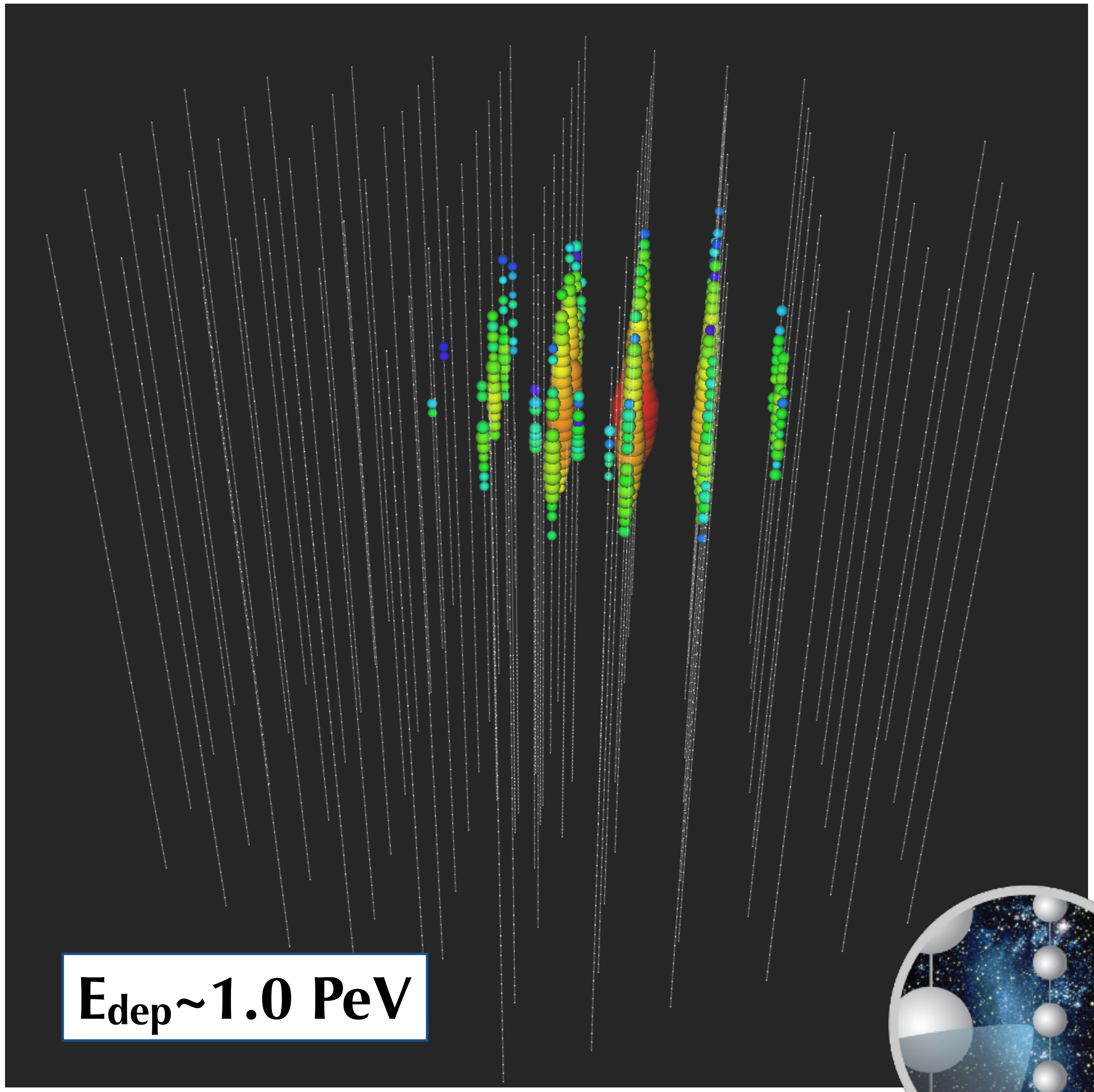
[Schoenert et al. PRD79 (2009) 043009]

Breakthrough in 2013

First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from ν_μ scattering) **"cascade event"** (from all flavours)



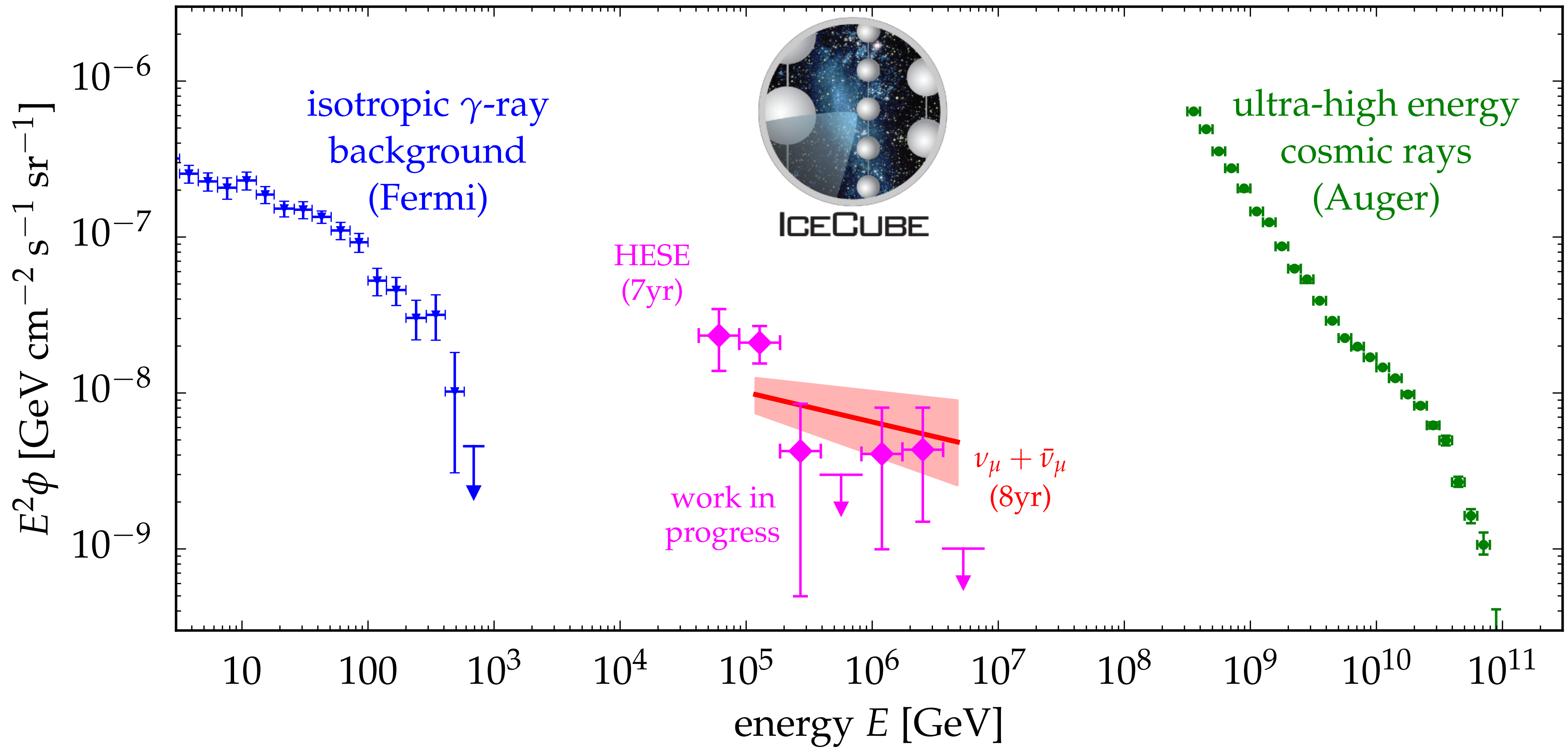


["Breakthrough of the Year" (Physics World), Science 2013]
(neutrino event signature: early to late light detection)

ICECUBE

Diffuse TeV-PeV Neutrinos

- **High-Energy Starting Events (HESE) (7yrs):** [Science 342 (2013); work in progress]
  - bright events ($E_{\rm th} \gtrsim 30$TeV) starting inside IceCube
  - efficient removal of atmospheric backgrounds by veto layer
- **Up-going muon-neutrino tracks (8yrs):** [Astrophys.J. 833 (2016); update ICRC 2017]
  - large effective volume due to ranging in tracks
  - efficient removal of atmospheric muon backgrounds by Earth-absorption



Diffuse TeV-PeV Neutrinos

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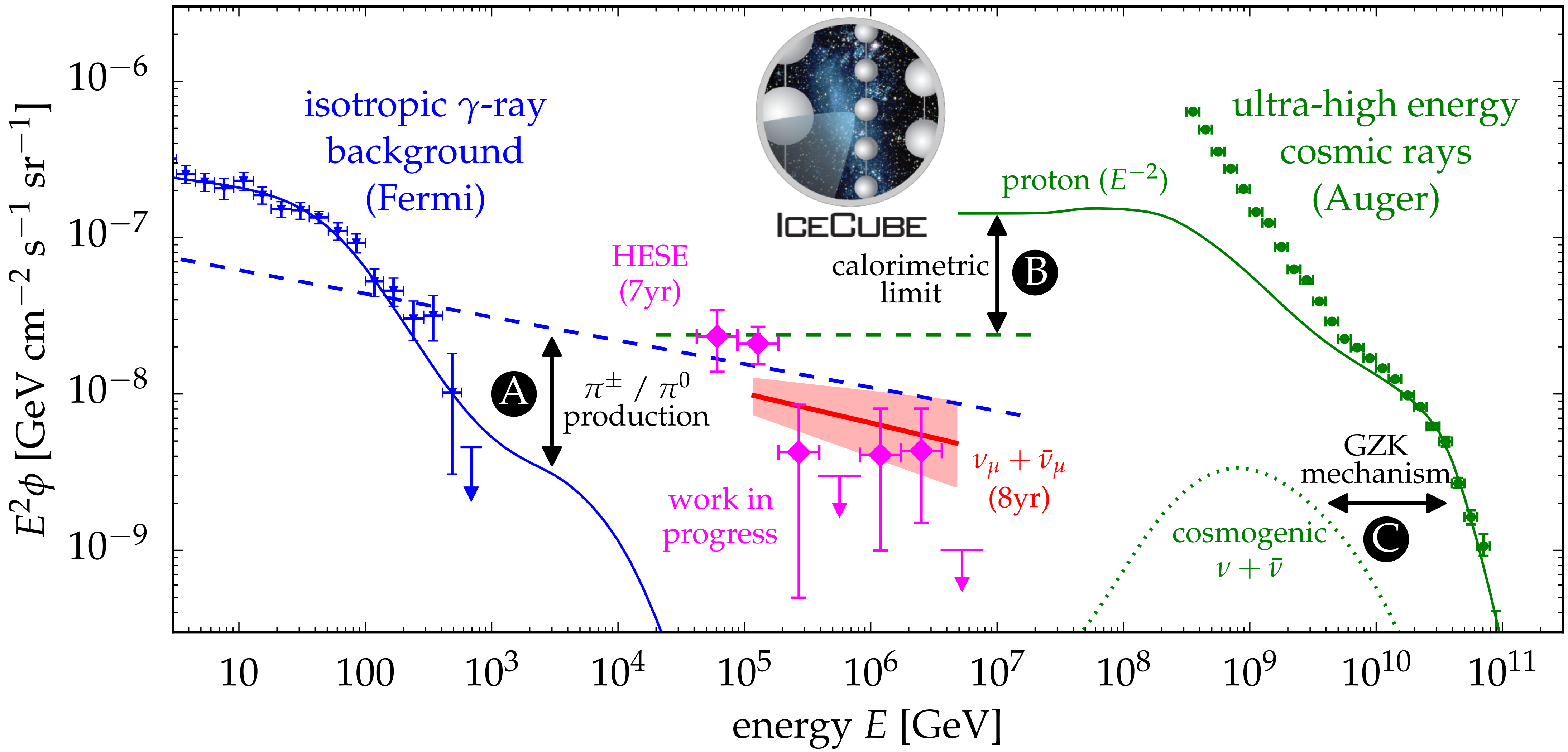


Astrophysical Flavors

- Energy resolution of detectors is limited and neutrino source is distant.

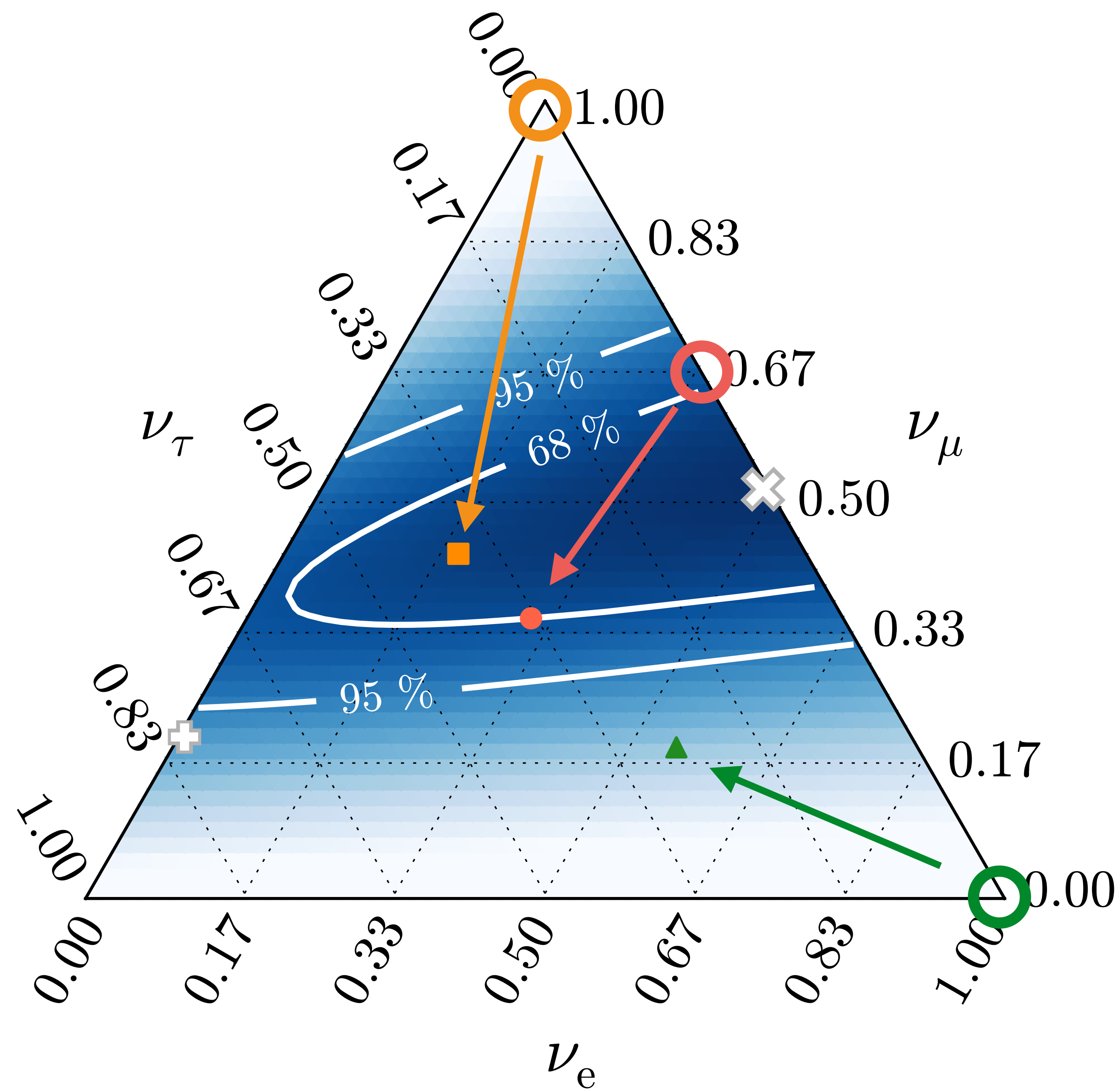
$$P_{\nu_\alpha\to\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\Re(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin^2\Delta_{ij}}_{\to 1/2} + 2\sum_{i>j}\Im(U^*_{\alpha i}U_{\beta i}\,U_{\alpha j}U^*_{\beta j})\underbrace{\sin 2\Delta_{ij}}_{\to 0}$$

→ oscillation-averaged probability:

$$P_{\nu_\alpha\to\nu_\beta} \simeq \sum_i |U_{\alpha i}|^2|U_{\beta i}|^2$$

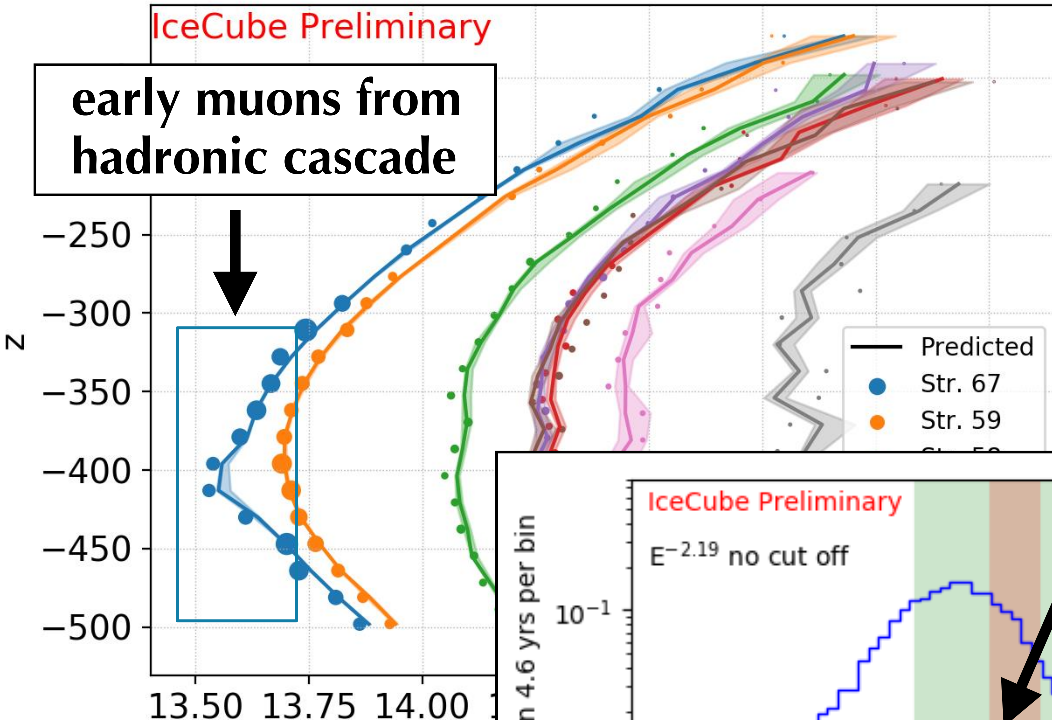
- initial composition: $\nu_e : \nu_\mu : \nu_\tau$
  pion & muon decay: $1:2:0$
  muon-damped decay: $0:1:0$
  neutron decay: $1:0:0$

[**Astrophys.J.** 809 (2015) no.1, 98]

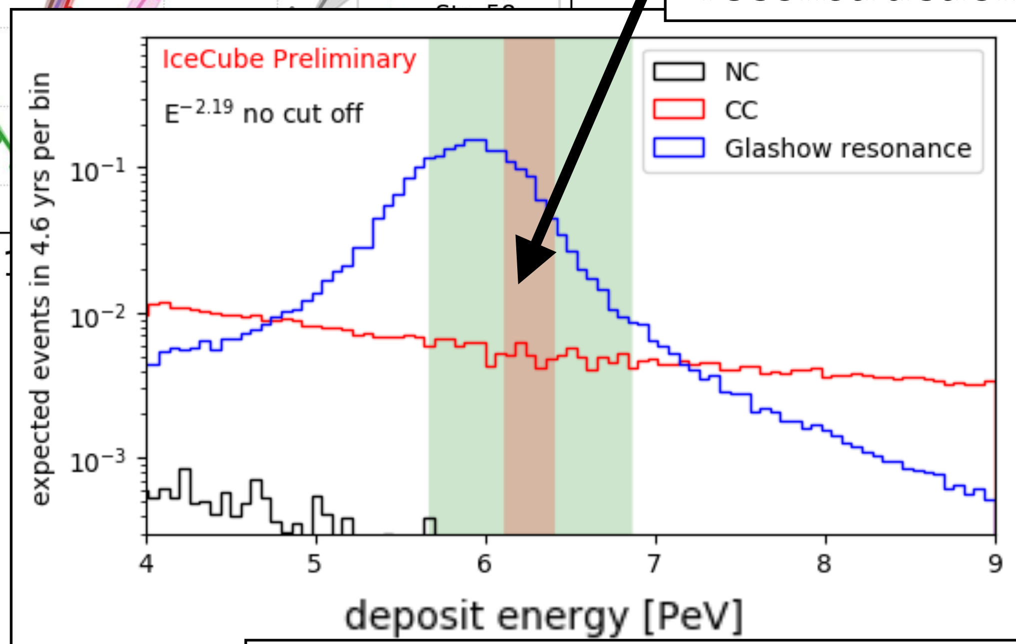


Astrophysical Flavors

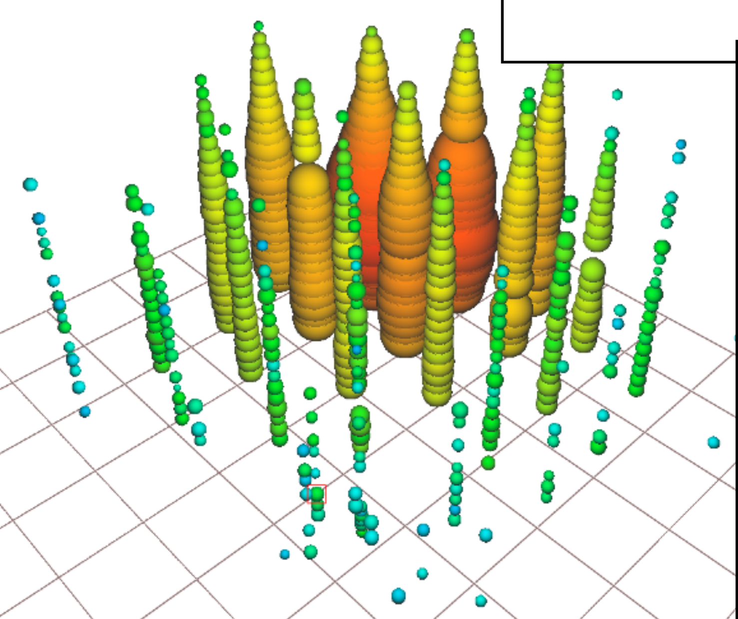
early muons from hadronic cascade



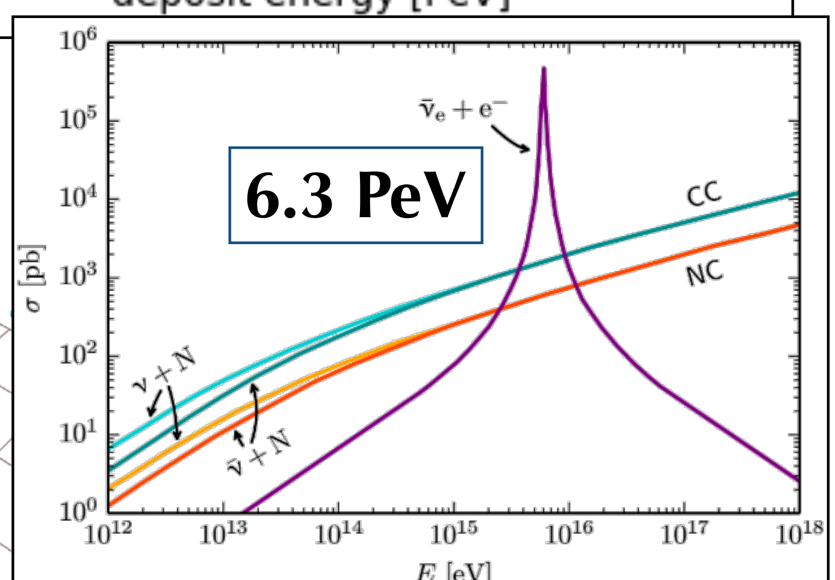
energy reconstruction



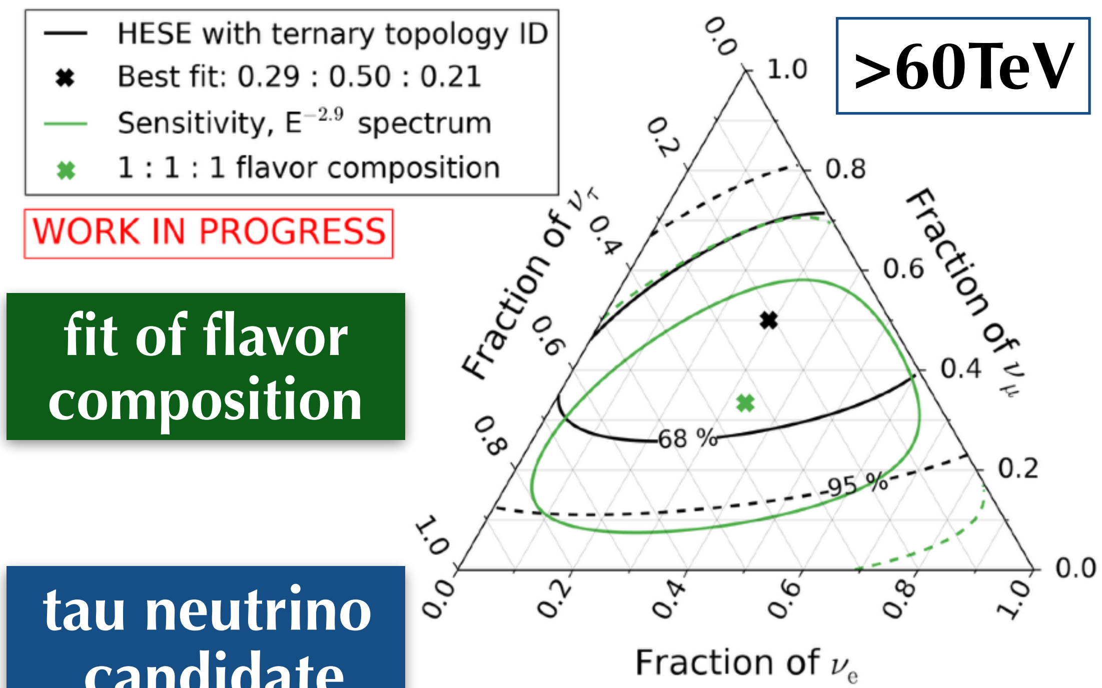
Glashow resonance candidate



6.3 PeV



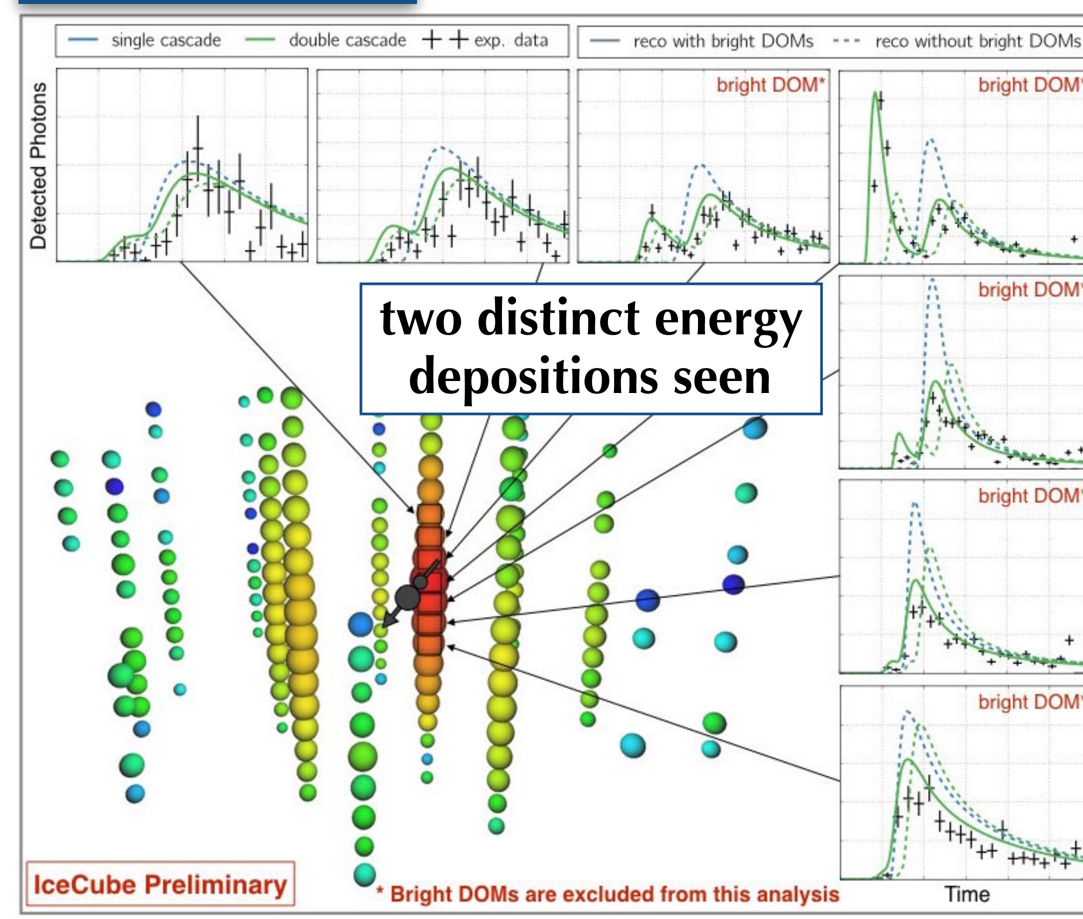
>60TeV



fit of flavor composition

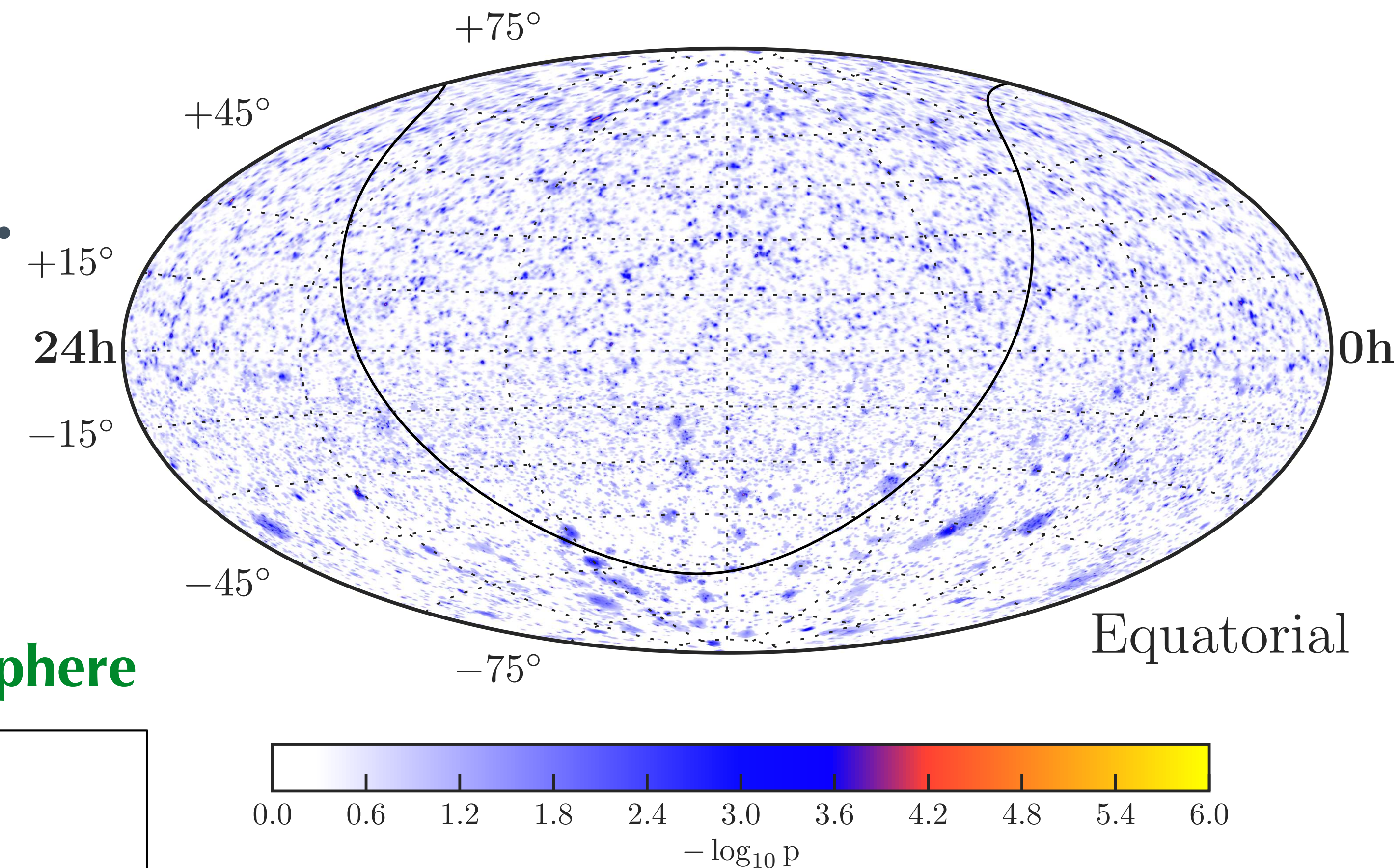
tau neutrino candidate

two distinct energy depositions seen



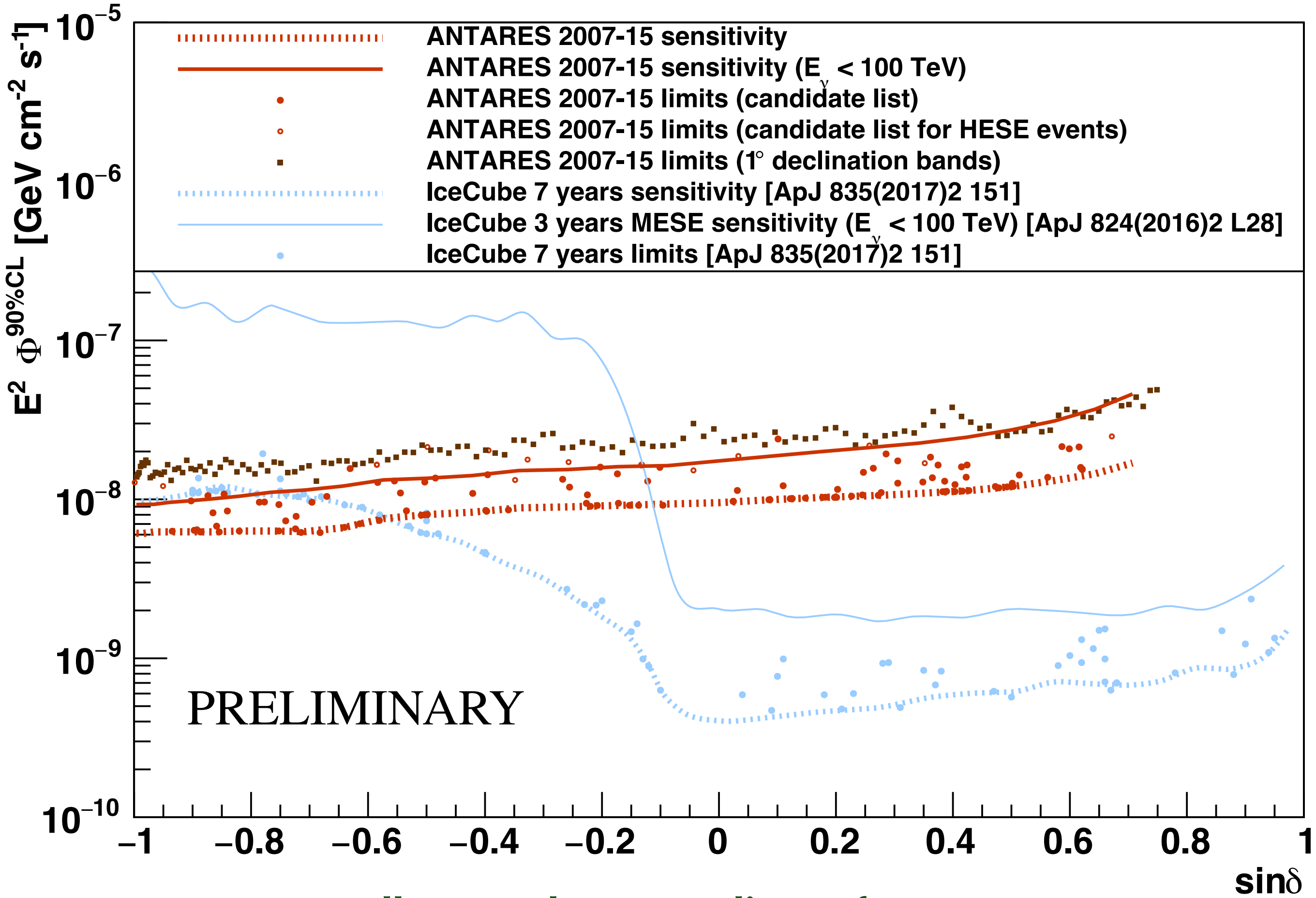
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.



[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]

Southern Hemisphere | Northern Hemisphere



[Albert et al., Proceedings of ICRC 2017]

- **No significant** time-independent point sources emission in all-sky search.
- **No significant** time-independent emission from known Galactic and extragalactic high-energy sources.

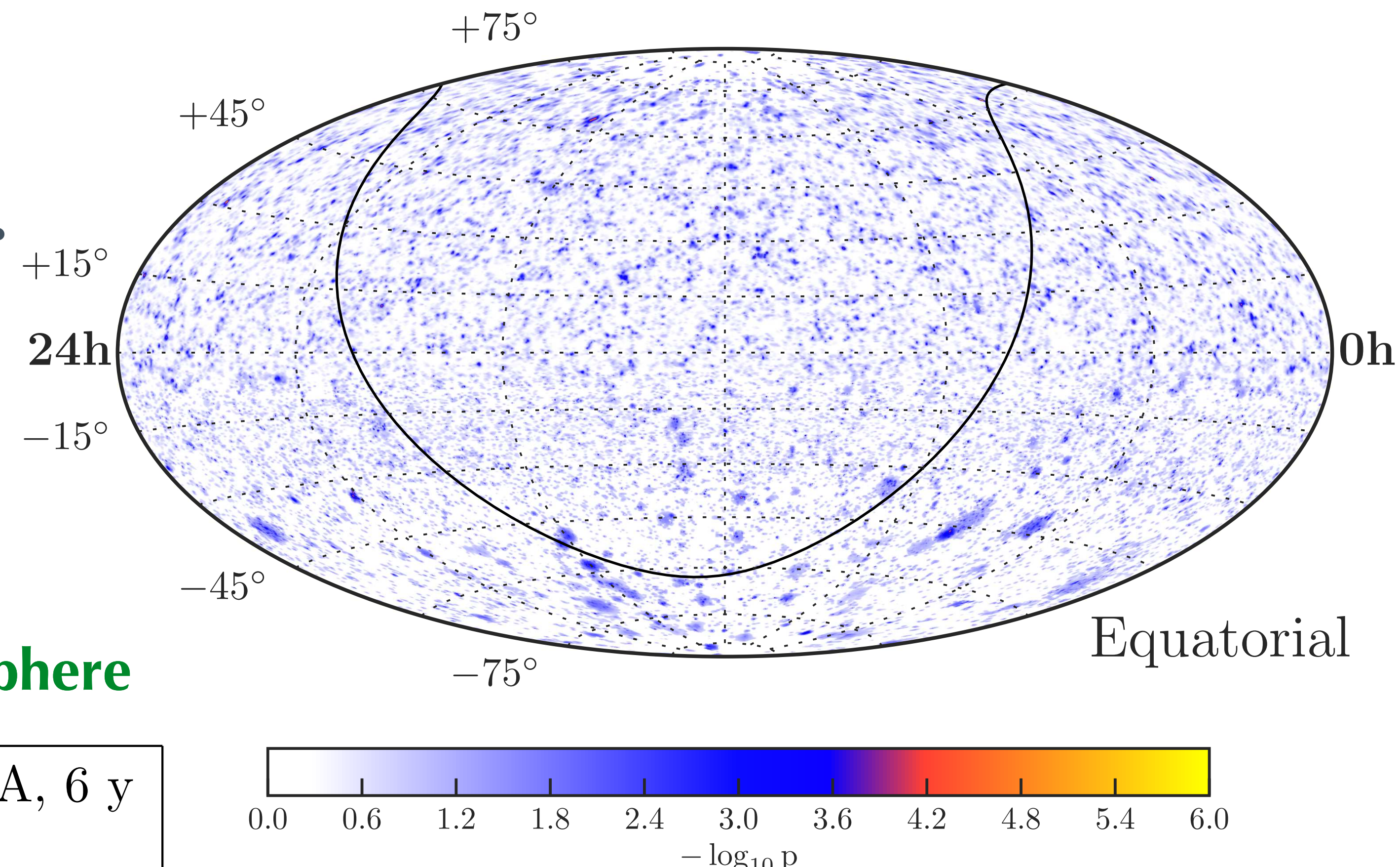
Search for Neutrino Sources

IceCube and ANTARES/KM3NeT with complementary field of views.

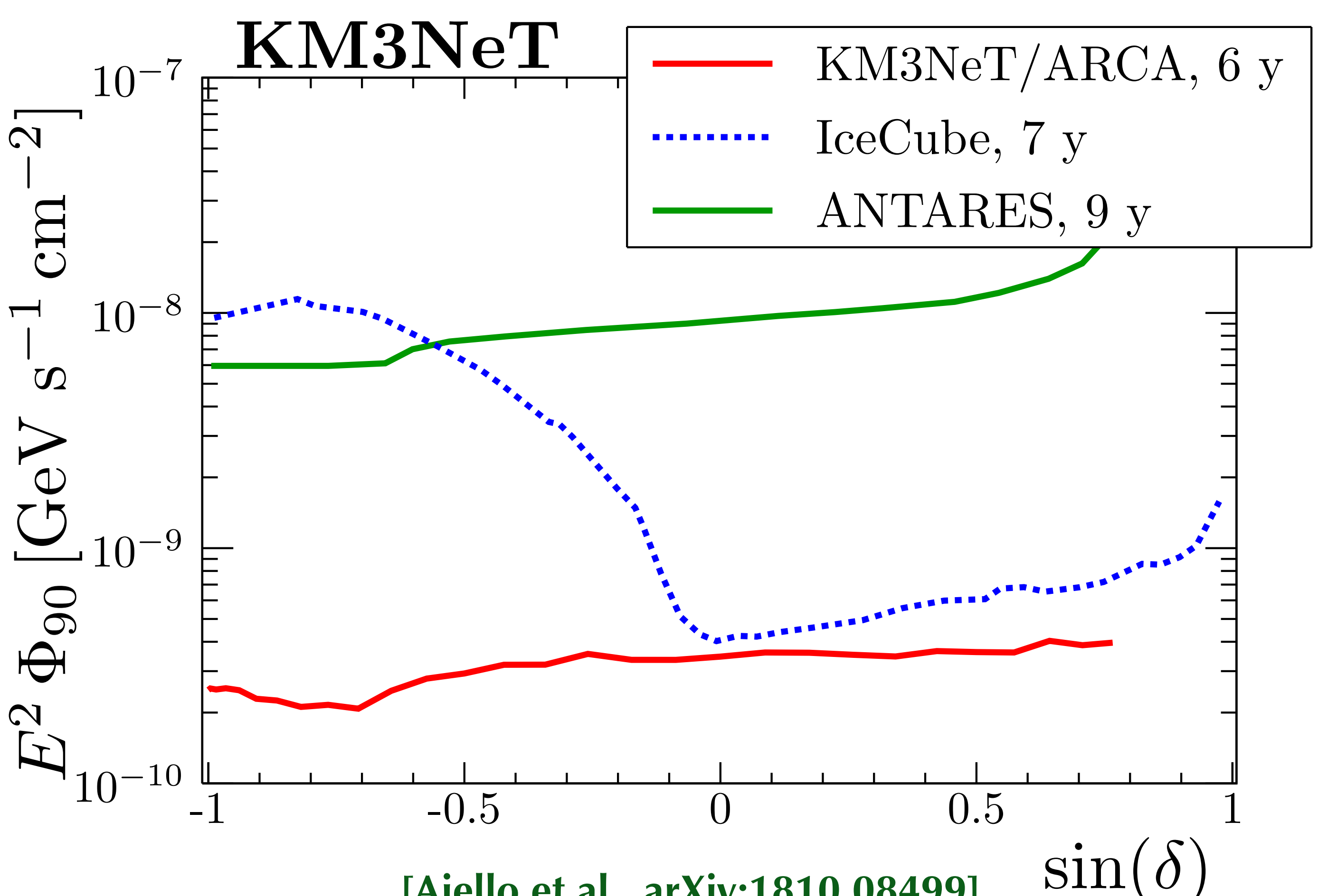
KM3NeT

ICECUBE

Southern Hemisphere | Northern Hemisphere



[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]

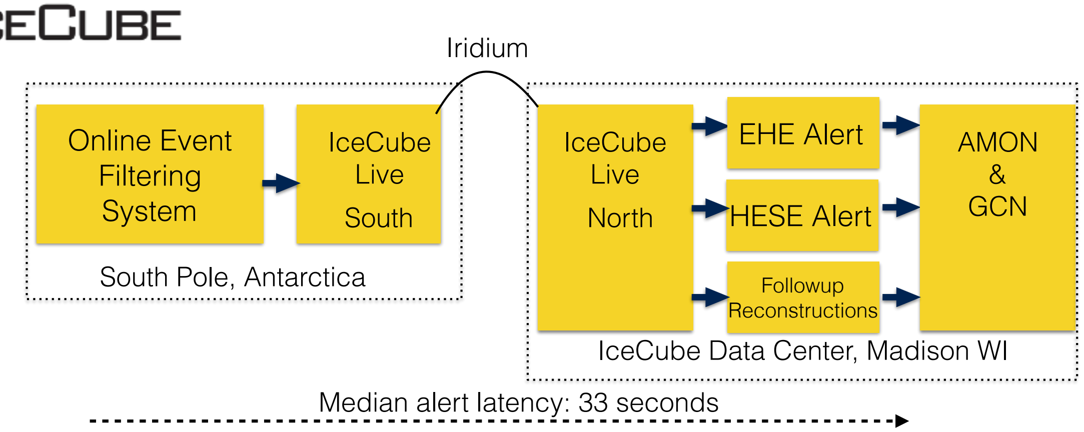


[Aiello et al., arXiv:1810.08499]

- **No significant** time-independent point sources emission in all-sky search.
- **No significant** time-independent emission from known Galactic and extragalactic high-energy sources.

Realtime Neutrino Alerts

IceCube and ANTARES issue realtime neutrino alerts to multi-messenger partners for rapid follow-up.



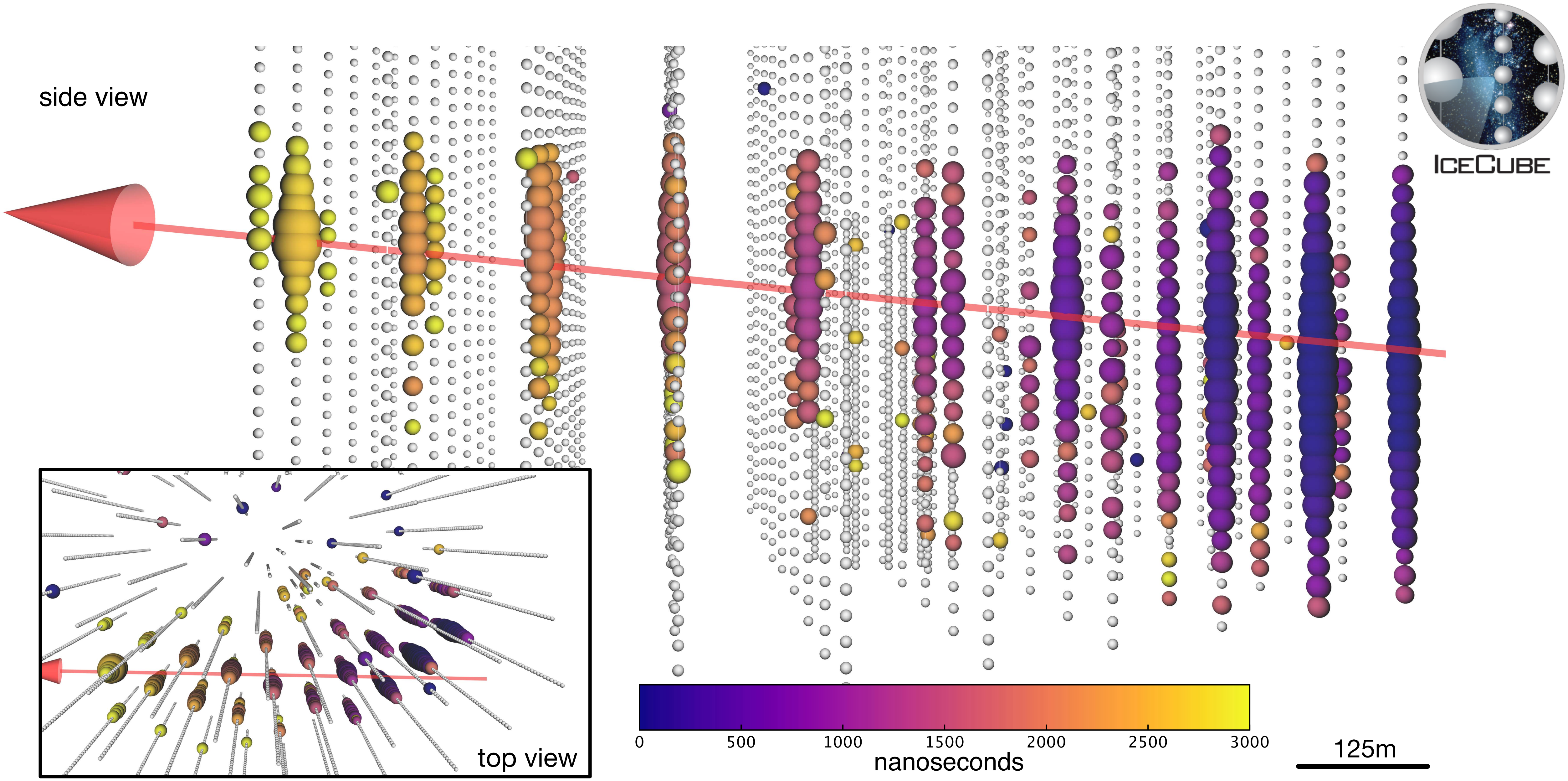
- 50% astrophysical neutrino fraction
- angular resolution 0.5-2deg
- **high-energy starting tracks** (>60TeV)
  - 4.8 alerts/year (1.1 signal/year)
- **through-going muons** (>100TeV)
  - 4-5 alerts/year (2.5-4 signal/year)

[Blaufuss et al., Proceedings of ICRC 2017]

- time to issue alert: 5s
- median angular resolution 0.5deg
- **neutrino doublets**
  - 0.04 alerts/year
- **neutrinos from local galaxies** (>1TeV)
  - 10 alerts/year
- **high-energy neutrinos** (>5TeV)
  - 20 alerts/year
- **very high-energy neutrinos** (>30TeV)
  - 3-4 alerts/year

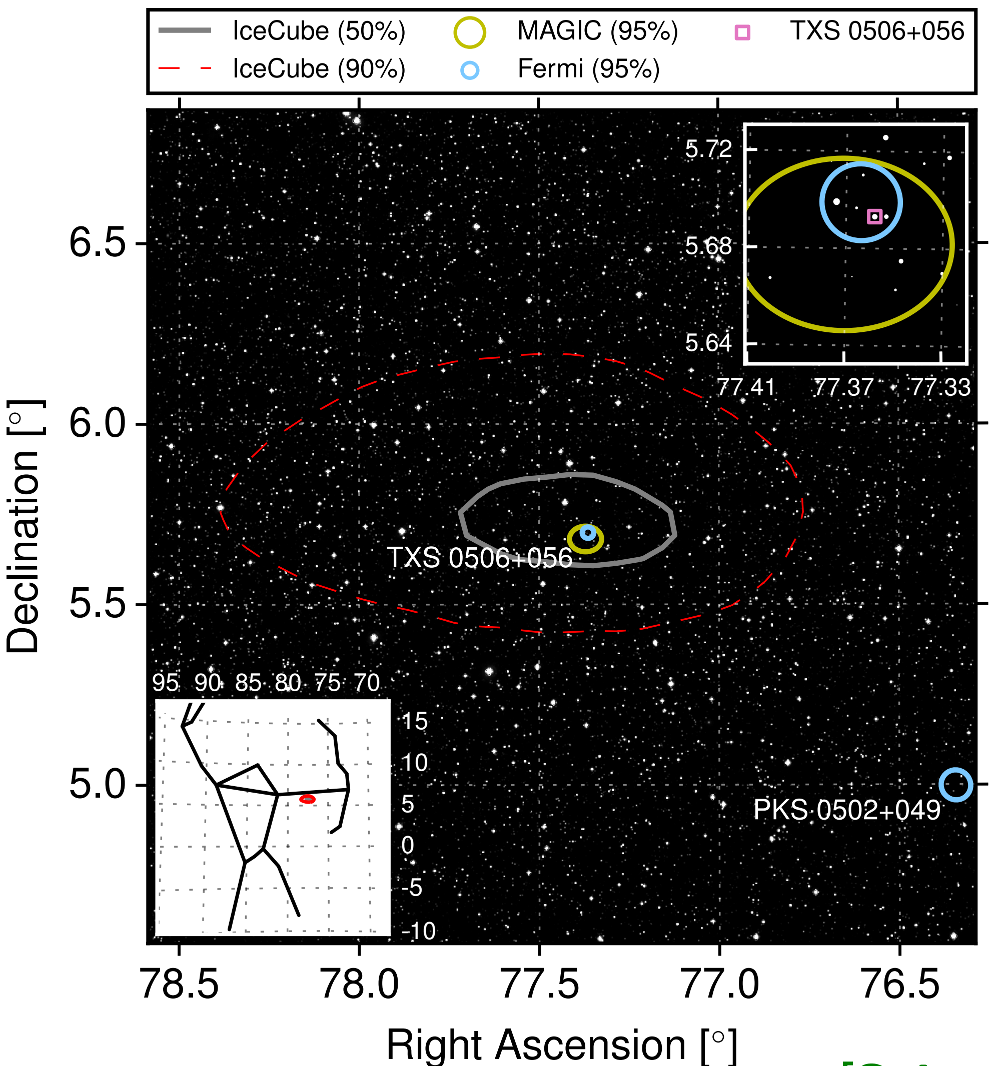
[Dornic et al., Proceedings of ICRC 2017]

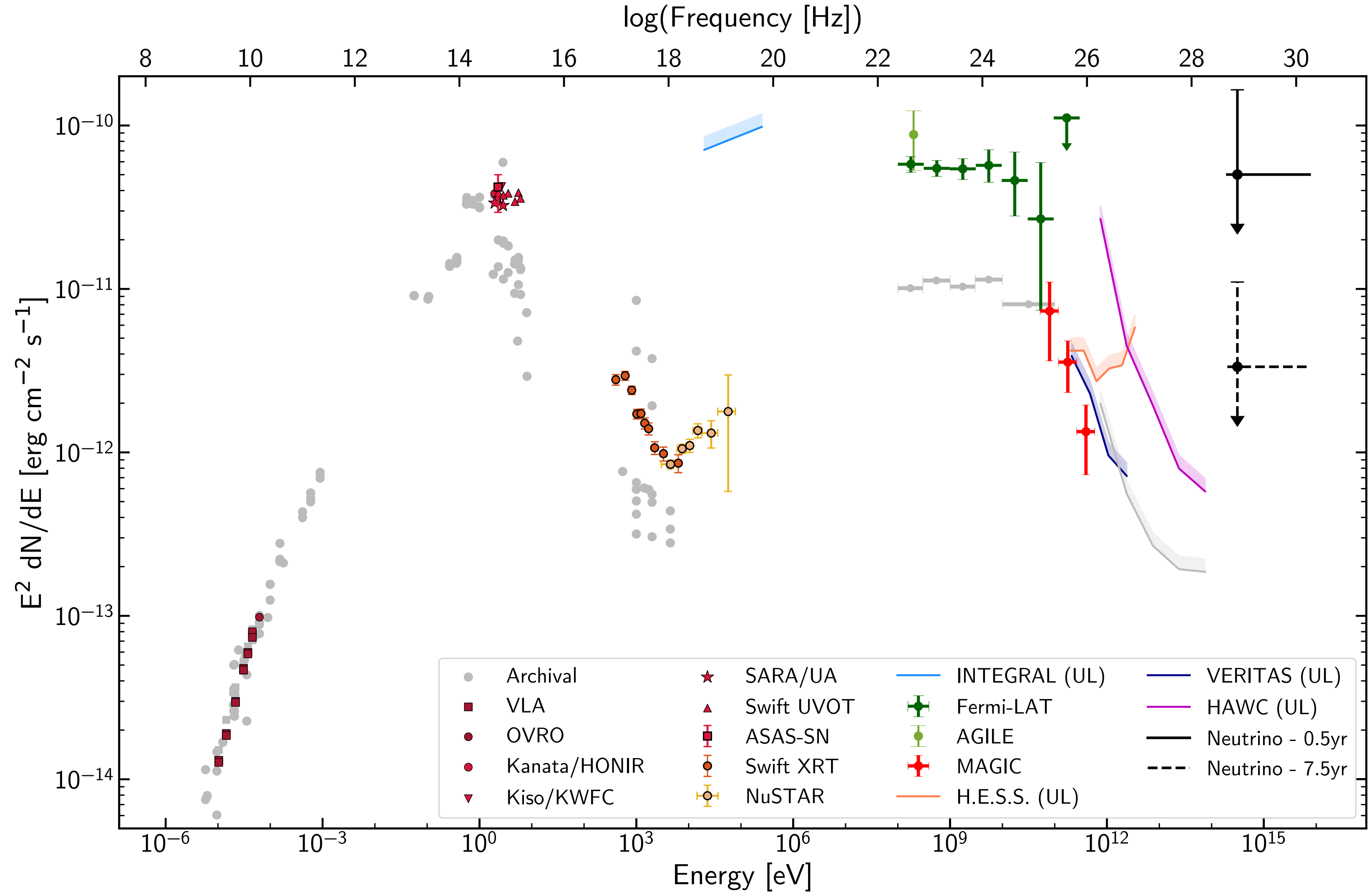
Realtime Neutrino Alerts



IceCube EHE ("extremely-high energy") alert IC-170922A
Up-going muon track (5.7° below horizon) observed on September 22, 2017.
The best-fit neutrino energy for an E^{-2}-spectrum is 311 TeV.

TXS 0506+056

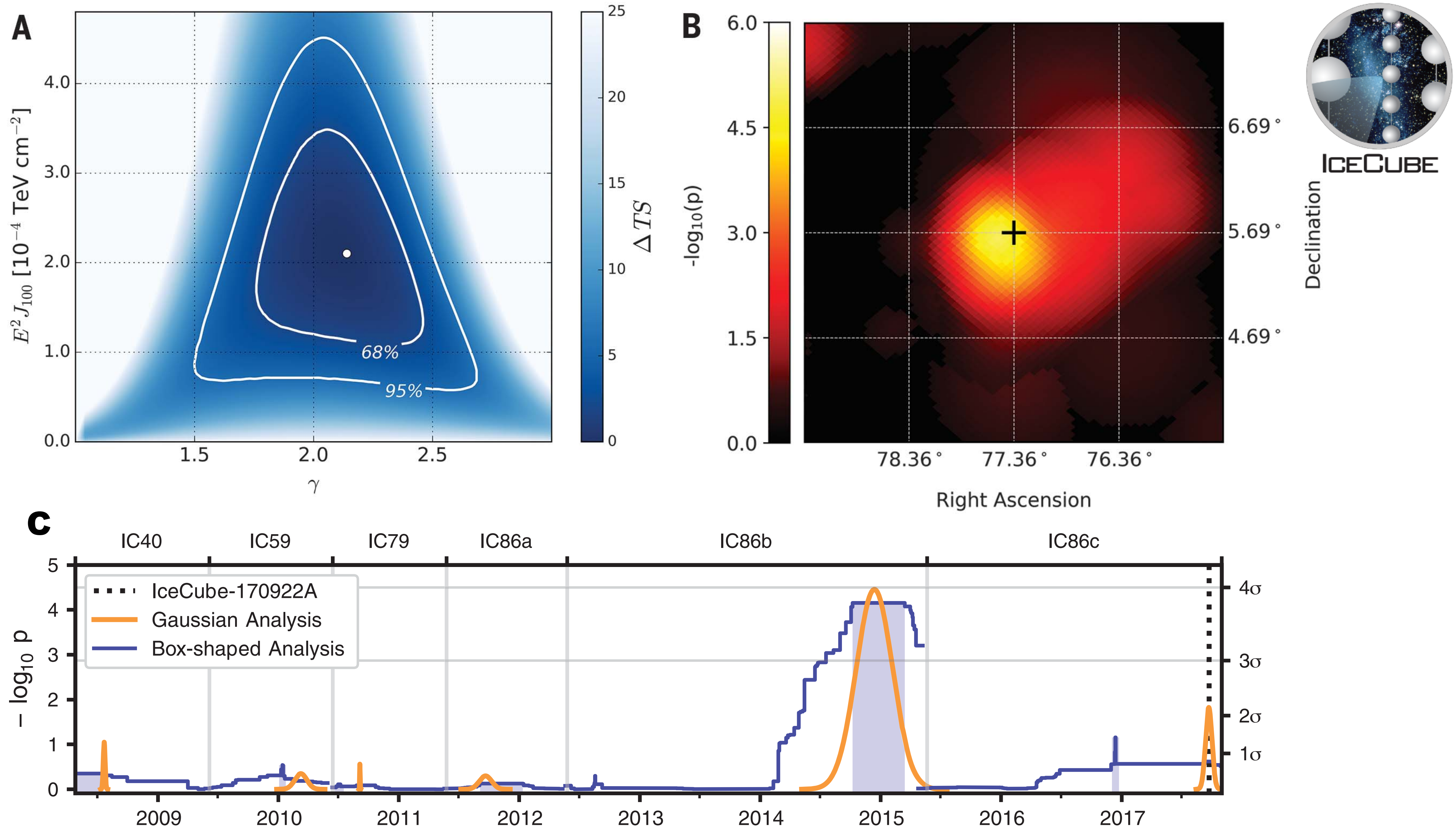




[**Science** 361 (2018) no.6398, eaat1378]

- IC-170922A observed in coincident with flaring blazar TXS 0506+056.
- Chance correlation can be rejected at the 3σ-level.
- TXS 0506+056 is among the 3% brightest Fermi-LAT blazars and one of the most luminous BL Lacs (2.8×10^{46} erg/s).

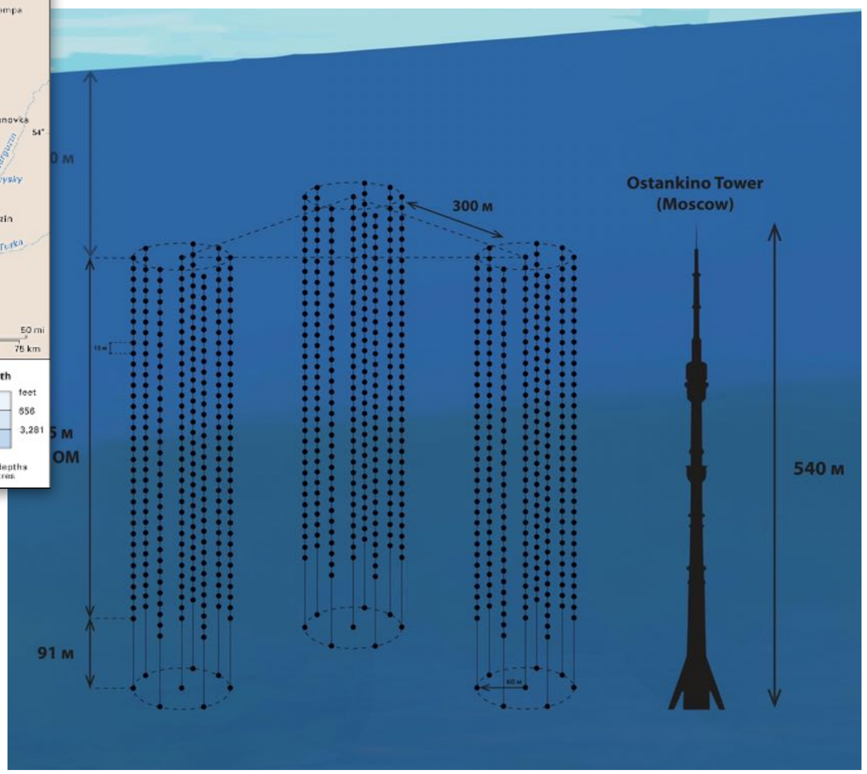
TXS 0506+056



[**Science** 361 (2018) no.6398, 147-151]

- Independent 3.5σ evidence for neutrino flare (13 ± 5 events) in 2014/15.
- Implies neutrino luminosity of 1.2×10^{47} erg/s over 158 days ($\simeq 4 \times L_{\rm Fermi}$).

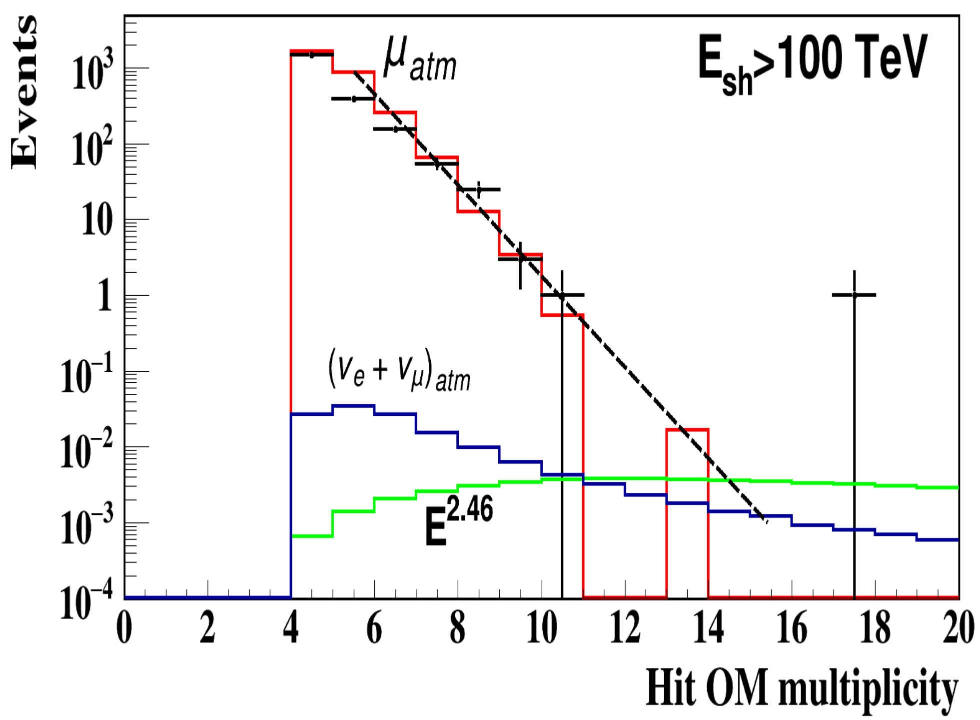
Outlook: Baikal-GVD



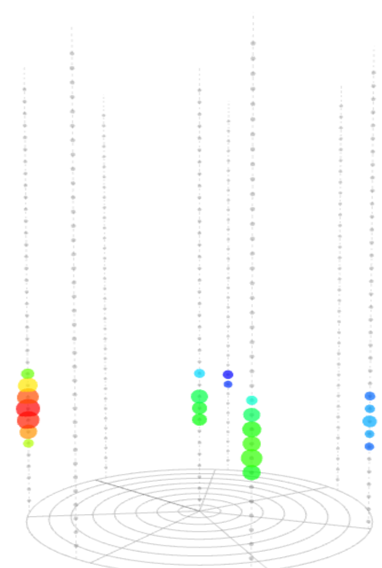
BAIKAL-GVD

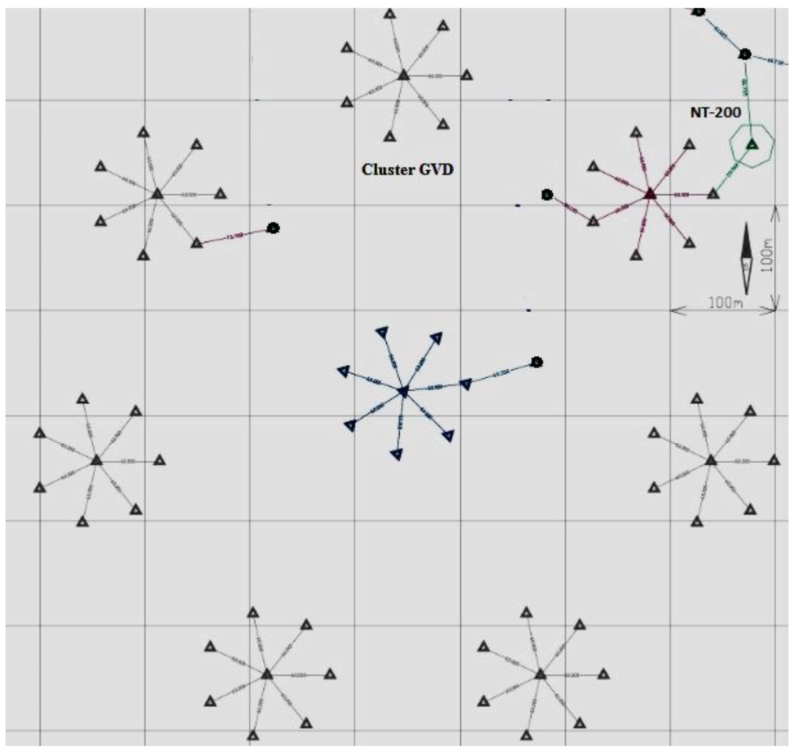
present detector outline (2018)

- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km³)
- cluster depth: 735–1260 m
- 3 clusters deployed 2016–18
- **final goal**: 27 clusters (~1.4 km³)



first physics results: cascade spectrum / cascade event in 2015 data



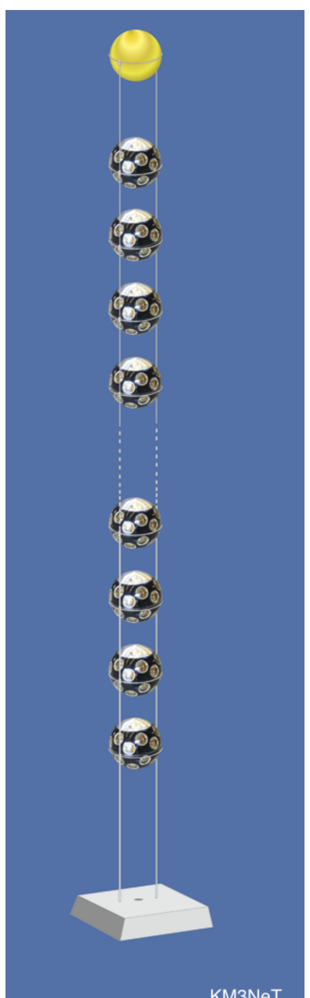


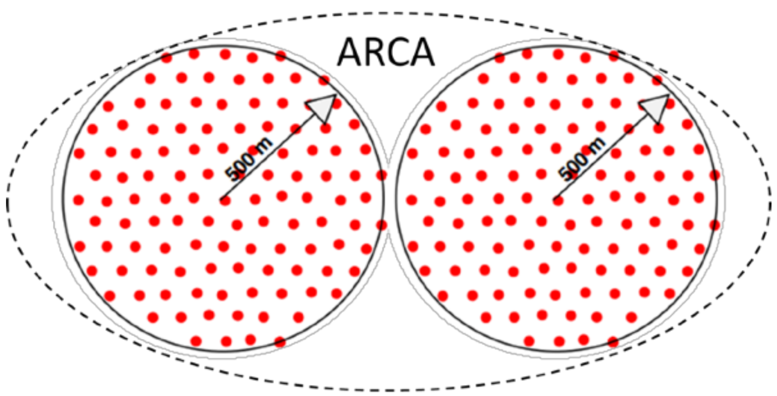
GVD-Phase 1

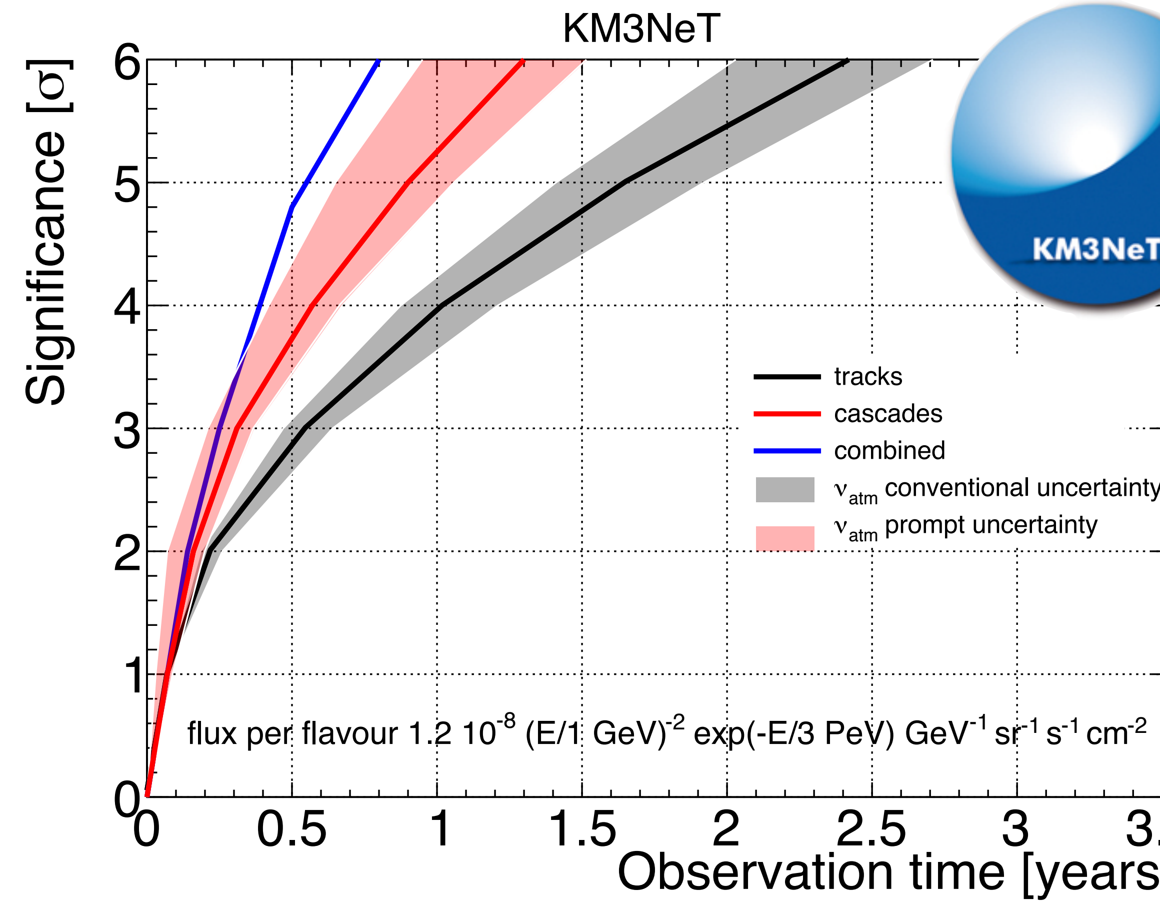
Outlook: KM3NeT/ARCA

- **ARCA :** 2 building blocks of 115 detection units (DUs)
- 24 DU funded (**Phase-1**, ~0.1 km^3)
- 3 DU deployed off the coast of Italy (1 DU recovered after shortage)
- 2 DUs operated until March 2017

detection unit with multi-PMT DOMs



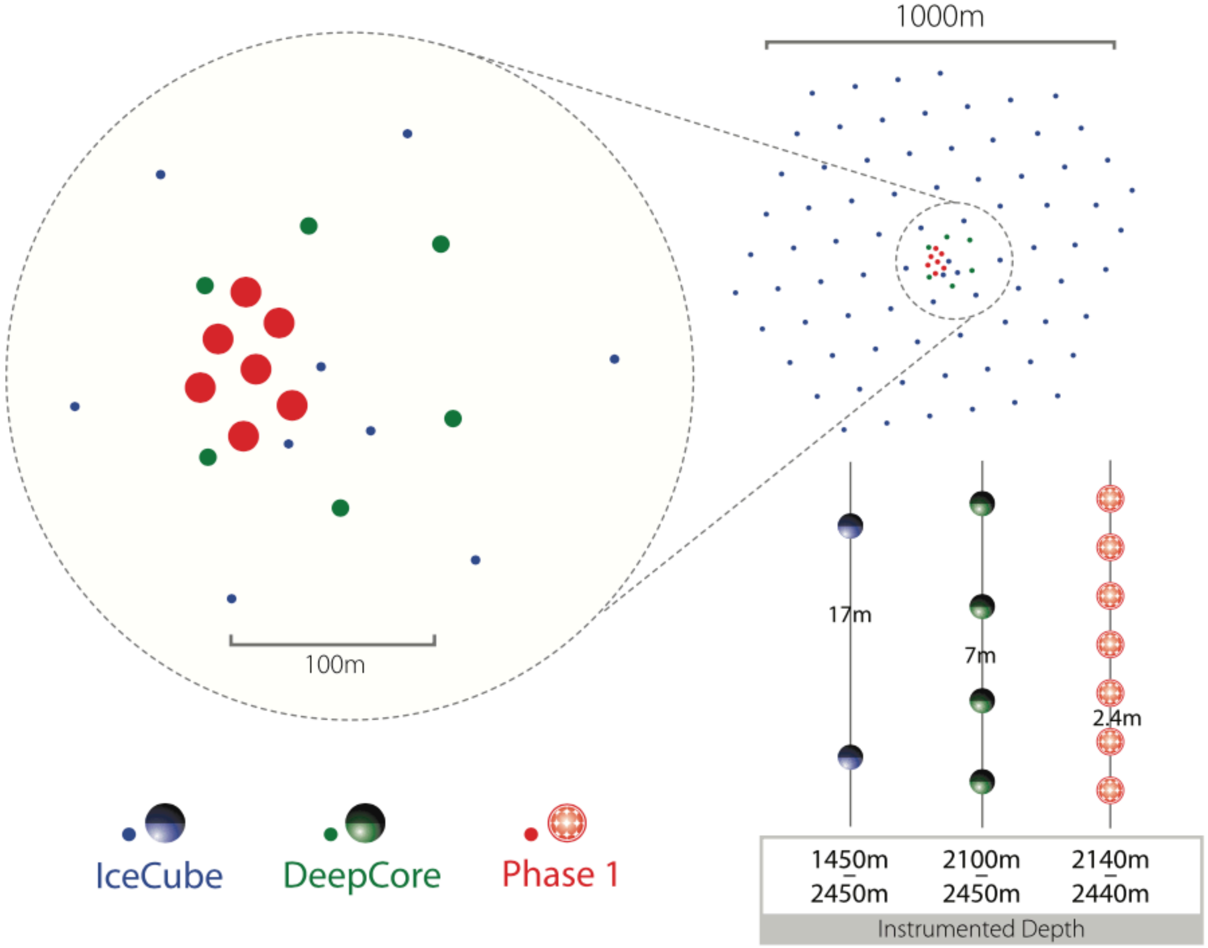


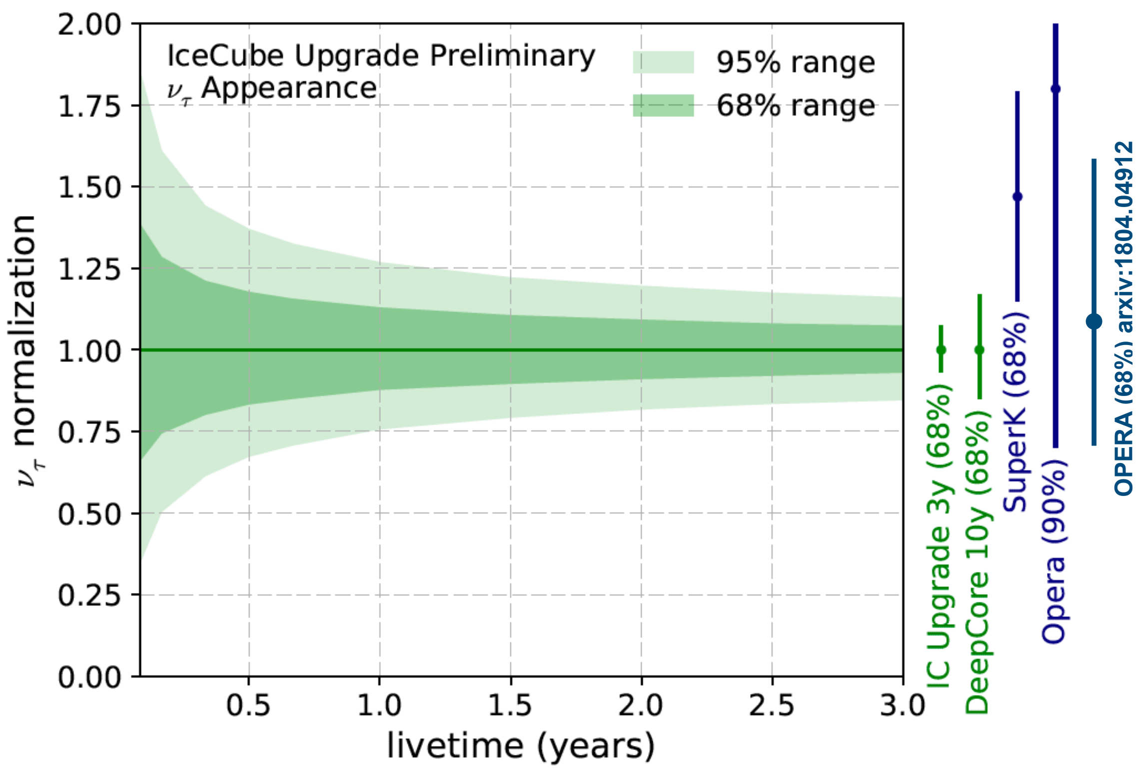


- **Improved angular resolution** for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- **Complementary field of view** ideal for the study of point sources.

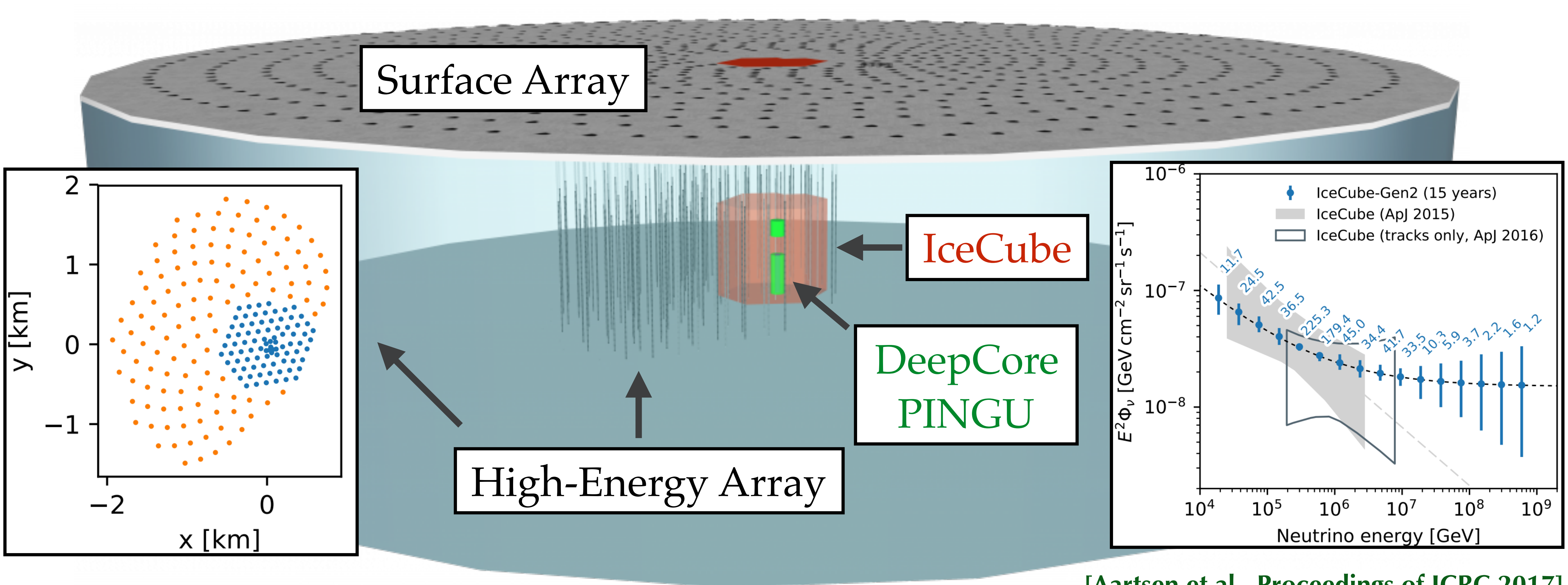
Outlook: IceCube Upgrade

- **7 new strings** in the DeepCore region (~20m inter-string spacing) with improved optical modules.
- **New calibration devices**, incorporating lessons from a decade of IceCube calibration efforts.
- **Precision measurement** of atmospheric neutrino oscillation.
- Midscale NSF project with an estimated total cost of $23M.
- deployment in 2022/23
- **October 1st: first $1M increment**
- additional $9M in capital equipment alone from partners





- **Multi-component facility** (low- and high-energy & multi-messenger).
- In-ice **high-energy Cherenkov array** with 6-10 km³ volume.
- **Under investigation:** Surface arrays for in-ice radio Askarayan and cosmic ray veto (air Cherenkov and/or scintillator panels).



[Aartsen et al., Proceedings of ICRC 2017]

Summary

- The future of neutrino astronomy is bright:
  - Diffuse TeV-PeV neutrino flux of unknown origin.
  - Intensity comparable to cosmic-ray and gamma-ray observations.
  - First compelling evidence of neutrino emission from blazars.
- With next-generation telescopes we will go from discovery to astronomy!
- Many more avenues, that could not be covered in this talk:

  supernova neutrinos, GZK neutrinos, BSM physics, neutrino-nucleon cross-section mesurements, dark matter indirect signals, …

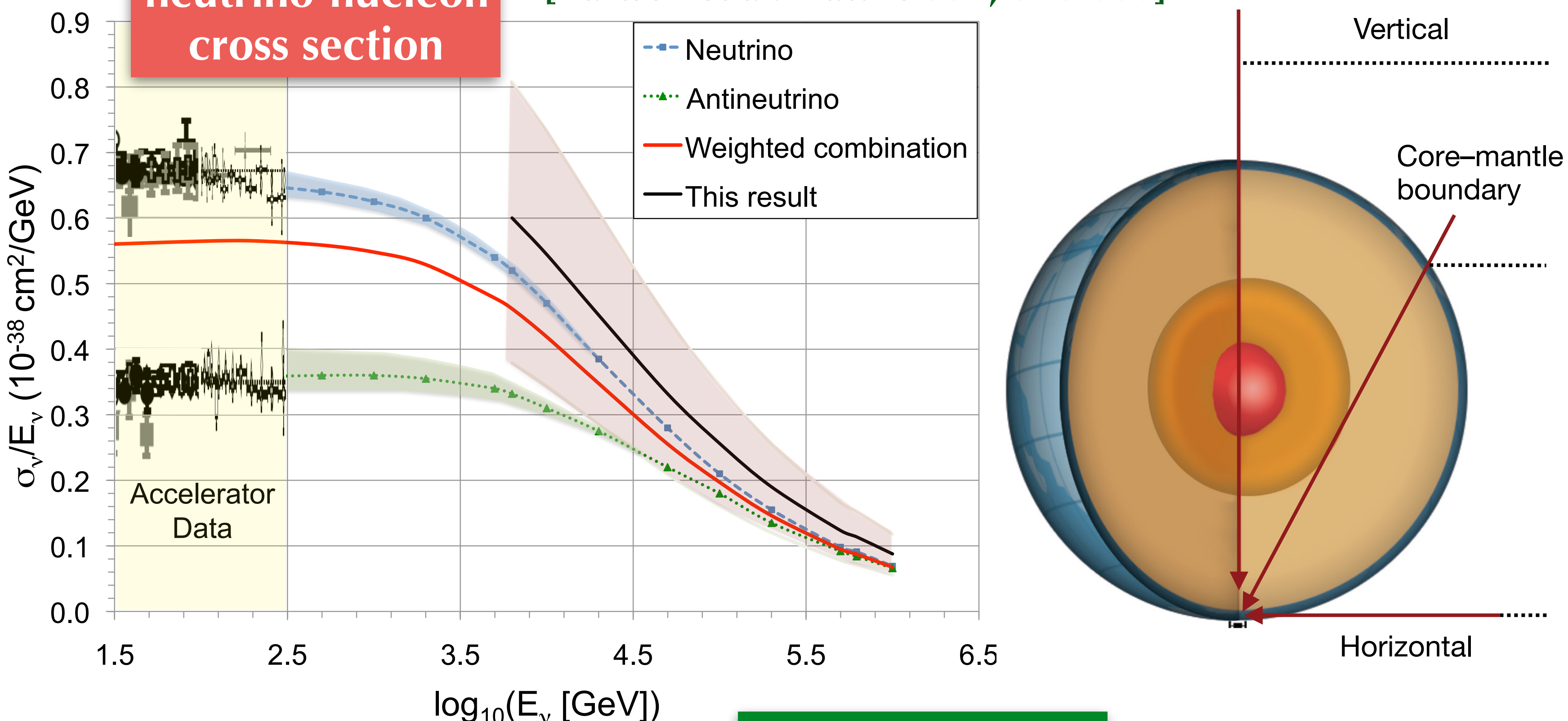
Thank you for your attention!

Backup Slides

Neutrino Physics

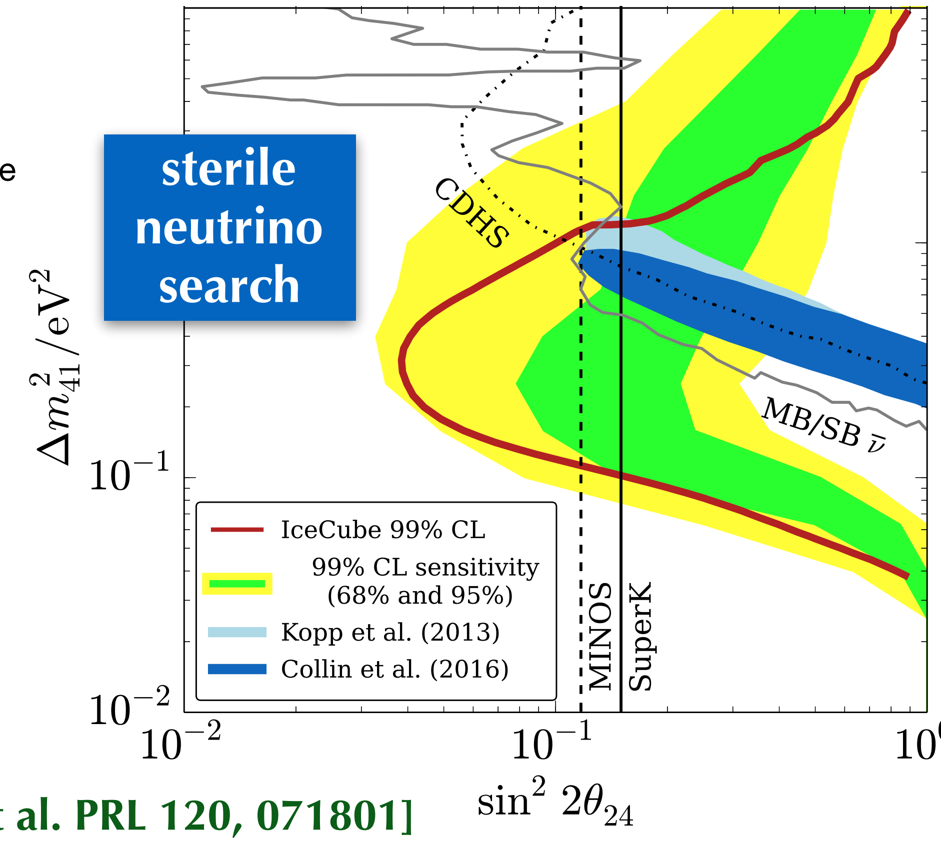
neutrino-nucleon cross section

[Aartsen et al. Nature 551, 596-600]



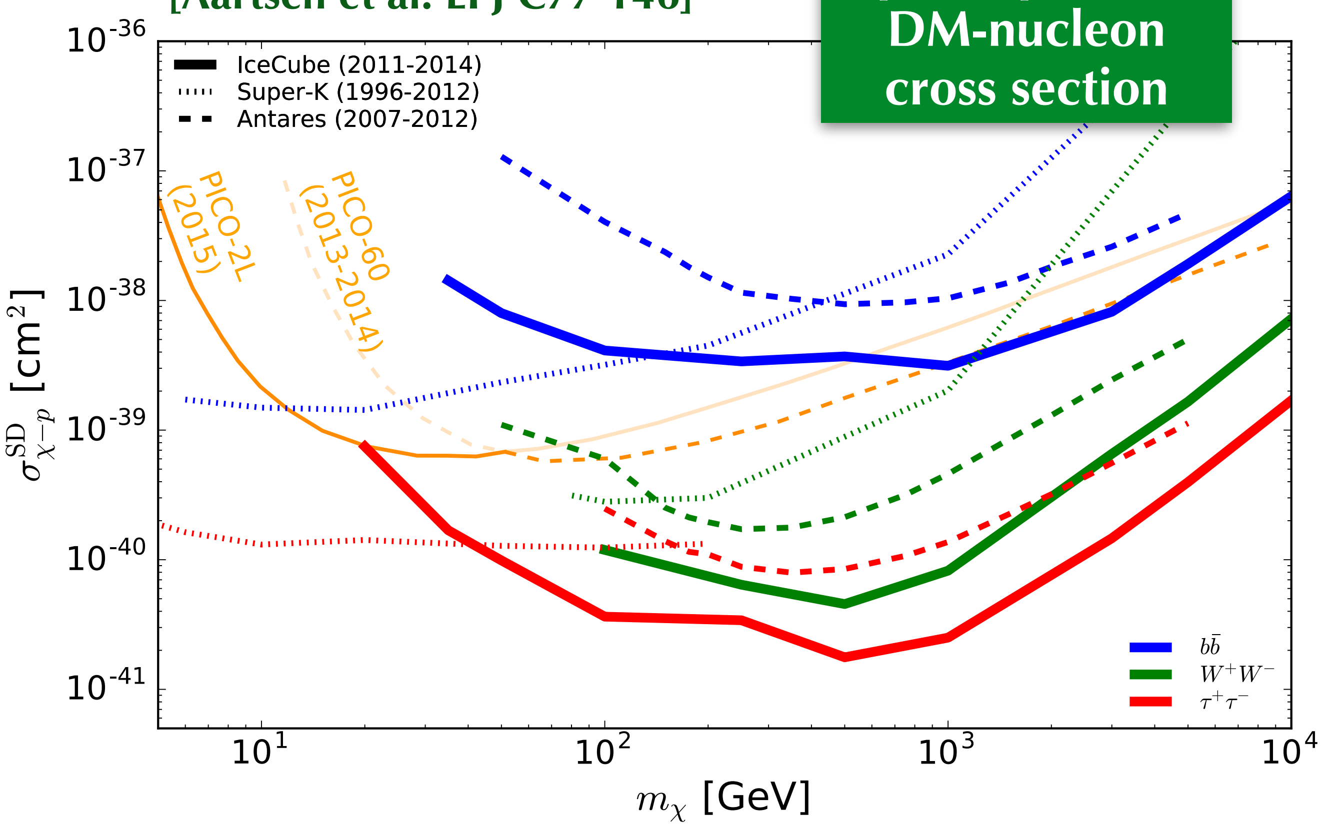
sterile neutrino search

[Aartsen et al. PRL 117, 071801]



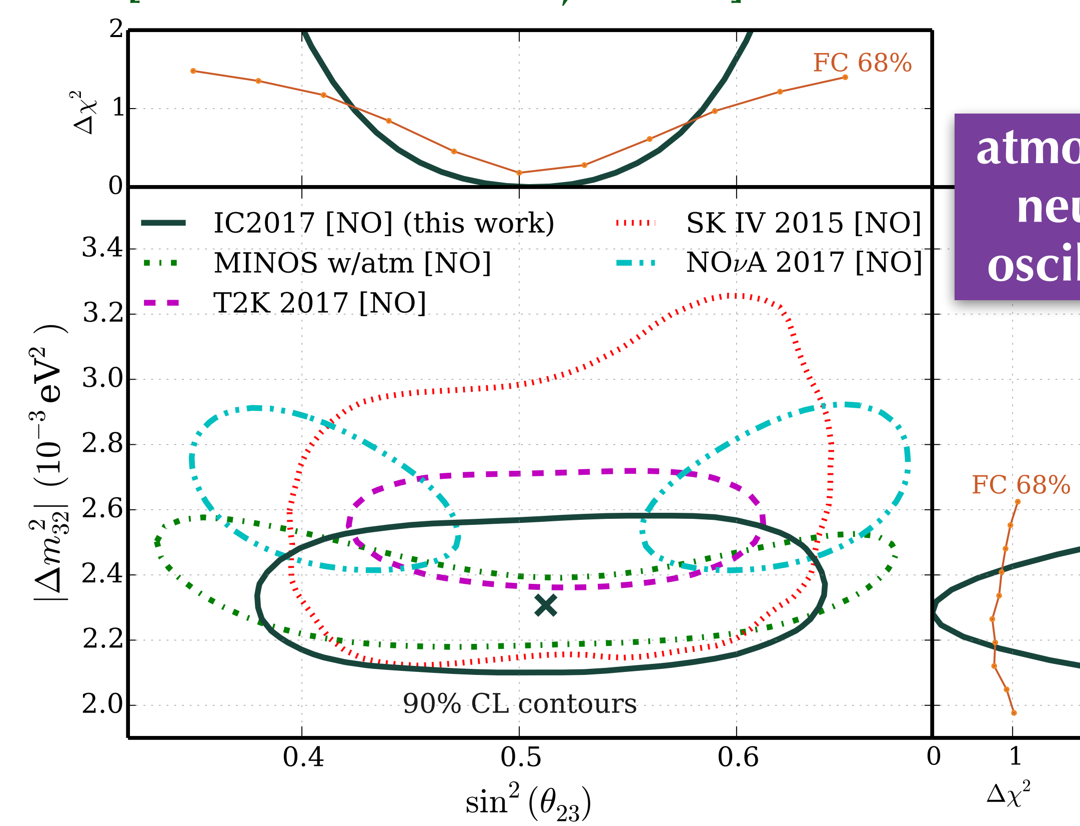
spin-dependent DM-nucleon cross section

[Aartsen et al. EPJ C77 146]

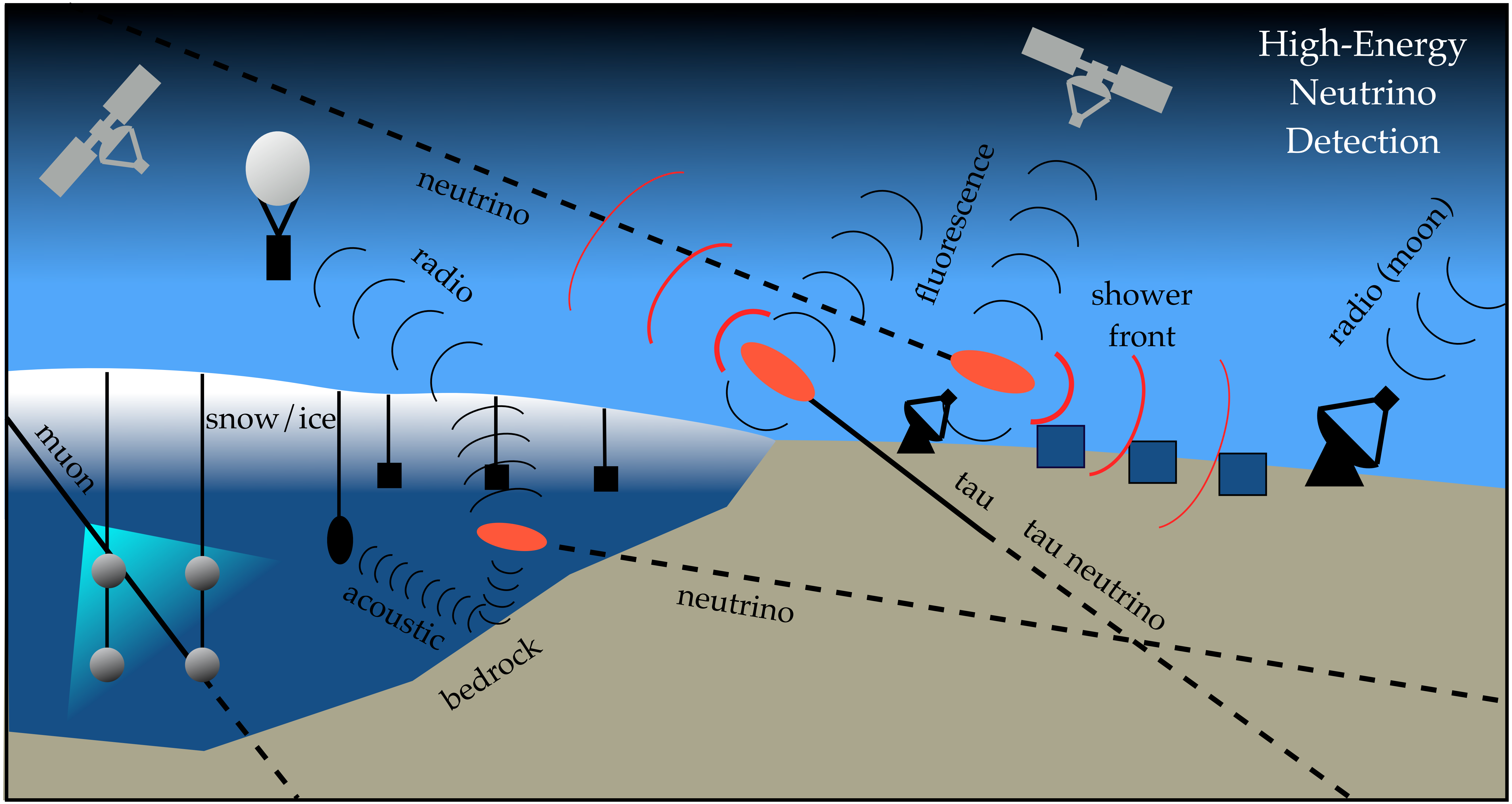


atmospheric neutrino oscillations

[Aartsen et al. PRL 120, 071801]

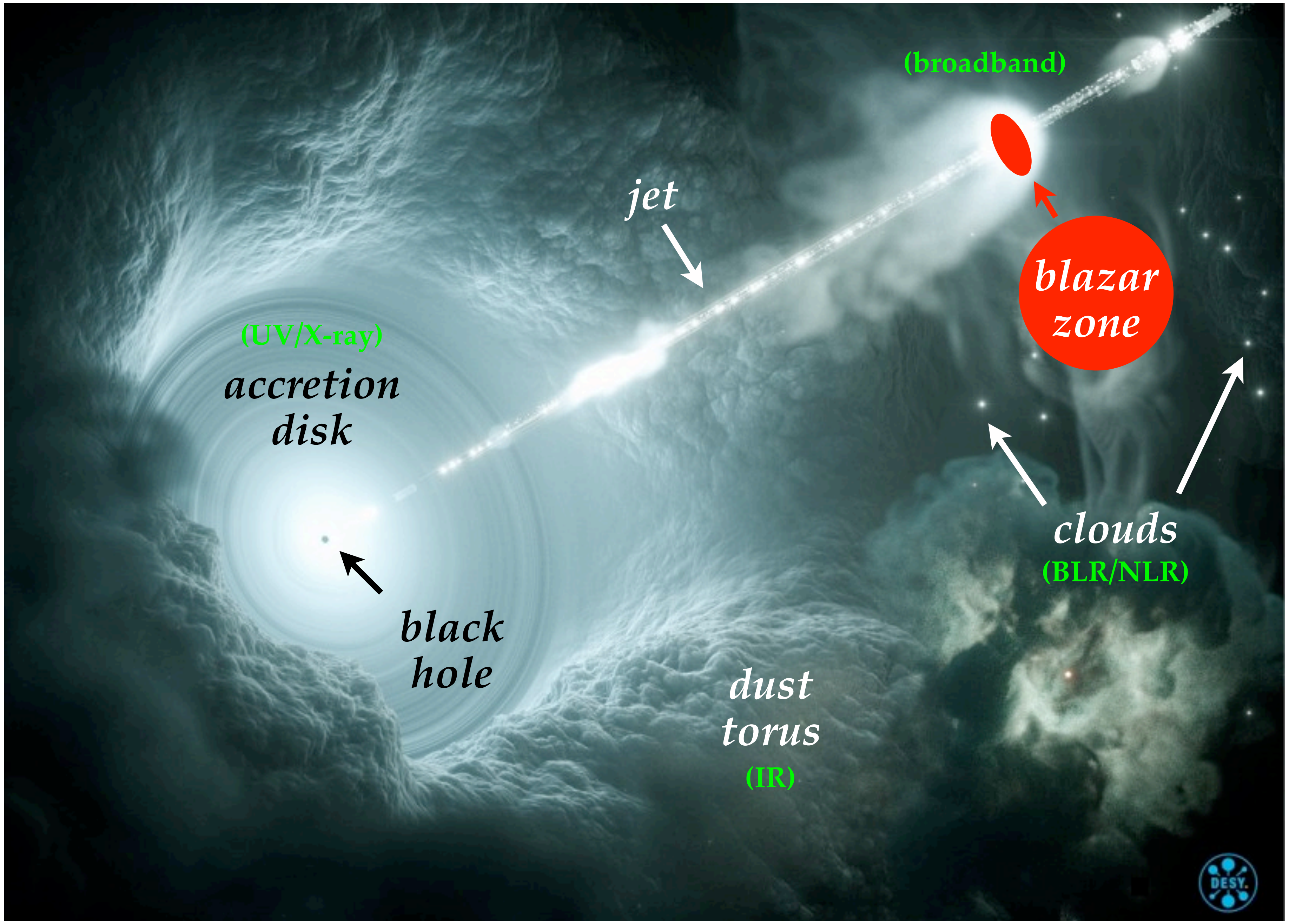


Detection Principles



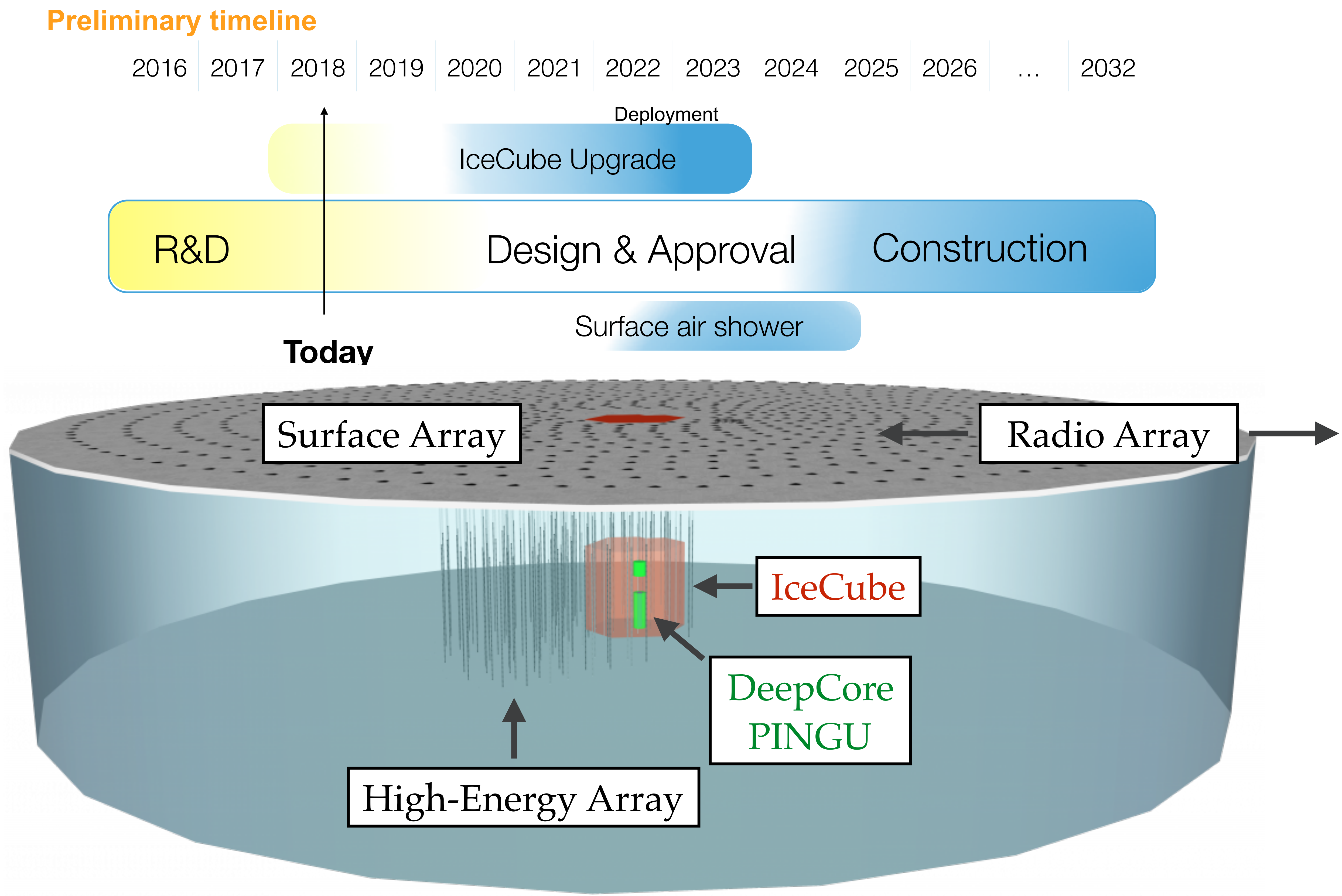
Blazars as Neutrino Factories

- **Active galaxies** powered by accretion onto a supermassive black hole expel **relativistic jets pointing into our line of sight**.
- **Cosmic ray acceleration** and p-gamma interaction in blazar zone leads to neutrino beam.
- Predicted neutrino spectra have a **strong energy dependence** following photon target spectra.



[Stecker et al.'91; Mannheim'96; Halzen & Zas'97]

IceCube-Gen2 Timeline



Supernova Forecast

From K. Scholberg, J. Phys G 45:2017

Detector	Type	Mass (kt)	Location	Events [10 kpc]
IceCube	**long string**	**600**	**South Pole**	**1,000,000**
*Hyper-K**	H_2O	*374*	*Japan*	*75,000*
*DUNE**	*Ar*	*40*	*USA*	*3,000*
Super-K	H_2O	32	Japan	7,000
*JUNO**	C_nH_{2n}	*20*	*China*	*6,000*
NOvA	C_nH_{2n}	15	USA	4,000
LVD	C_nH_{2n}	1	Italy	300
KamLAND	C_nH_{2n}	1	Japan	300
SNO+	C_nH_{2n}	0.8	Canada	300
Baksan	C_nH_{2n}	0.33	Russia	50
Daya Bay	C_nH_{2n}	0.33	China	100
Borexino	C_nH_{2n}	0.3	Italy	100
MicroBooNE	Ar	0.17	USA	17
HALO	Pb	0.08	Canada	30