

# Neutrinos as Messengers

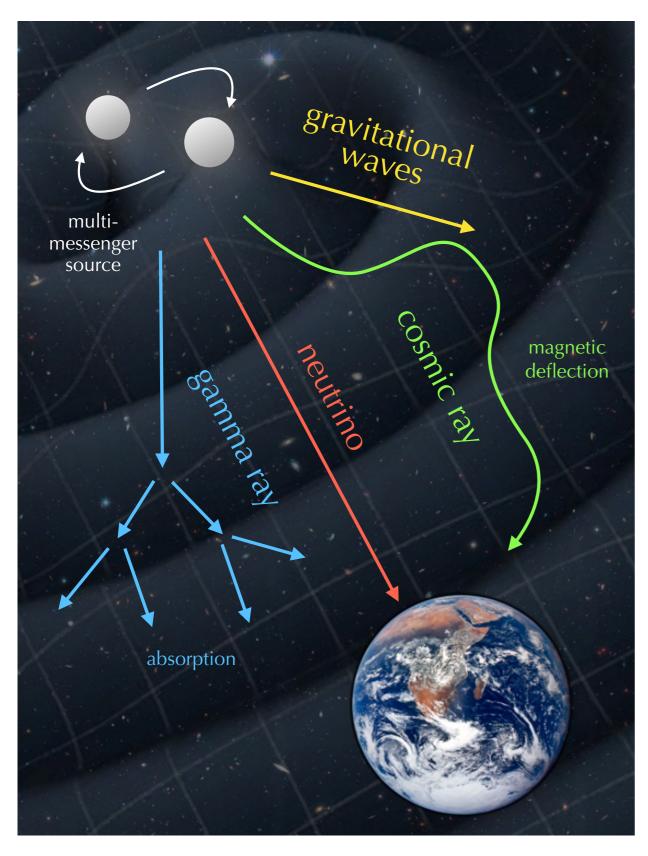
VILLUM FONDEN



Markus Ahlers, NBI Copenhagen European Neutrino Town Meeting October 22-24, 2018



# Multi-Messenger Astronomy



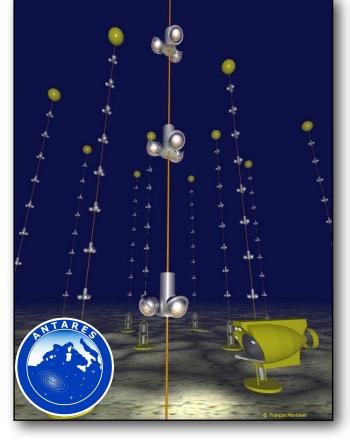
- Cosmic ray acceleration especially in the aftermath of cataclysmic events, sometimes seen in gravitational waves.
- $\rightarrow$  Inelastic collisions with radiation or gas produce  $\gamma$ -rays and neutrinos, e.g.

$$\pi^0 \to \gamma + \gamma$$
 
$$\pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \overline{\nu}_\mu + \nu_\mu$$

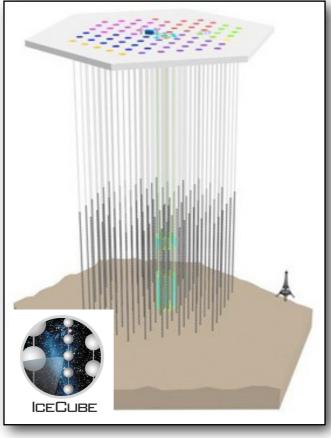
- Unique aspects of neutrino messengers:
  - identify cosmic ray sources
  - qualifies  $\gamma$ -ray emission
  - covers blind spot of astronomy to the very-high-energy Universe

## Cherenkov Observatories

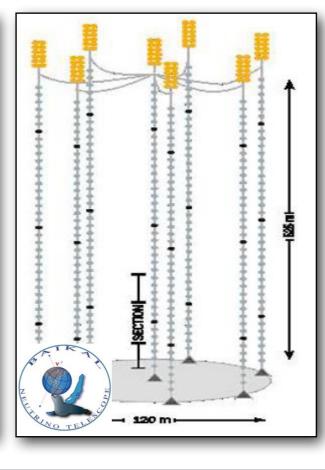
**Antares** 



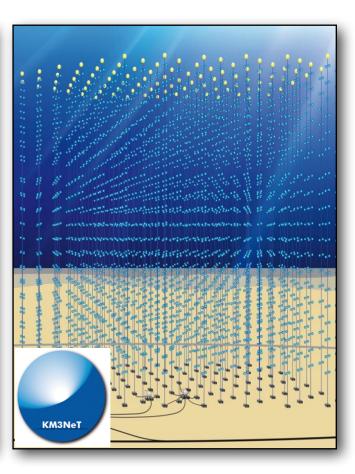
IceCube



Baikal-GVD



KM3NeT/ARCA



Mediterranean 2008–2019

~0.01 km<sup>3</sup>

885 OMs (10")

South Pole fully instrumented

~1 km<sup>3</sup>

since 2011

5160 OMs (10")

Lake Baikal under construction

(3 out of 8 clusters)

~0.4 km<sup>3</sup> (Phase 1) ~1km<sup>3</sup>

2304 OMs (10")

Mediterranean

under construction

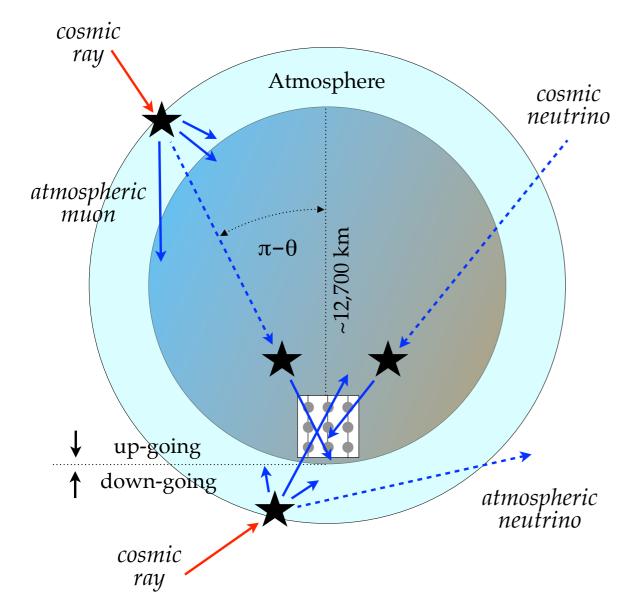
(3 out of 230 DUs)

~0.1 km<sup>3</sup> (Phase 1) ~1 km<sup>3</sup>

4140 OMs (31x3")

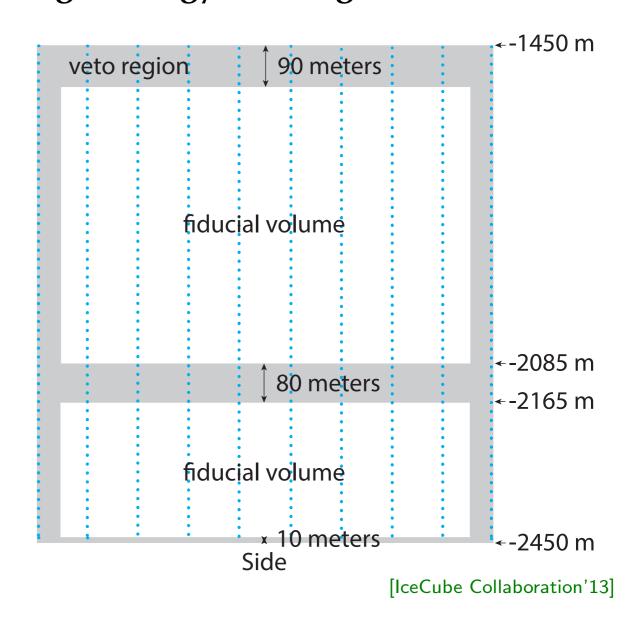
#### Detection Methods

#### **Up-going Muon-Neutrino Tracks**



- 10,000,000,000 atmospheric muons
- 100,000 atmospheric neutrinos
- 10 cosmic neutrinos (per year and km<sup>3</sup>)

#### **High-Energy Starting Events (HESE)**



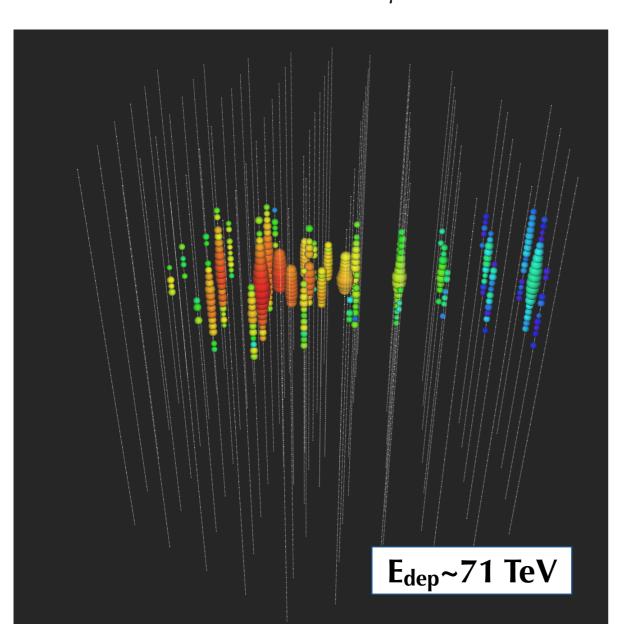
- virtual veto region triggered by atmospheric muons
- self-veto of coincident atmospheric neutrinos
- cosmic neutrino events are required to start inside [Schoenert et al. PRD79 (2009) 043009]

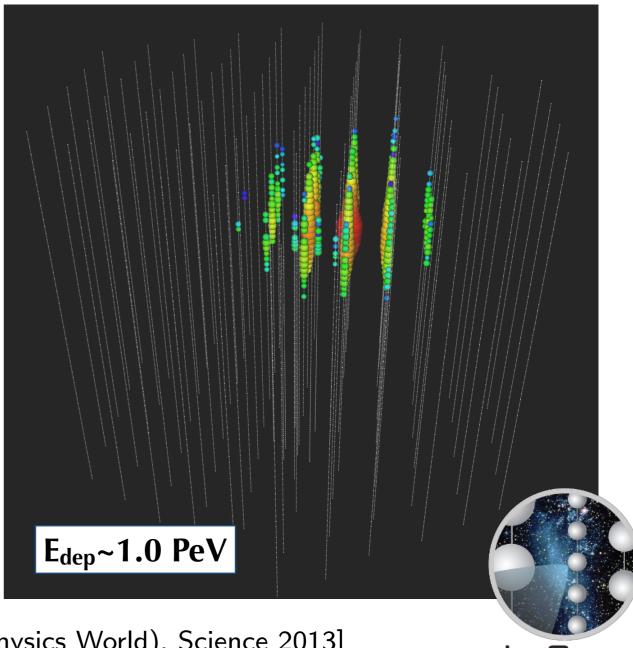
# Breakthrough in 2013

#### First observation of high-energy astrophysical neutrinos by IceCube!

"track event" (from  $\nu_{\mu}$  scattering)

"cascade event" (from all flavours)





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

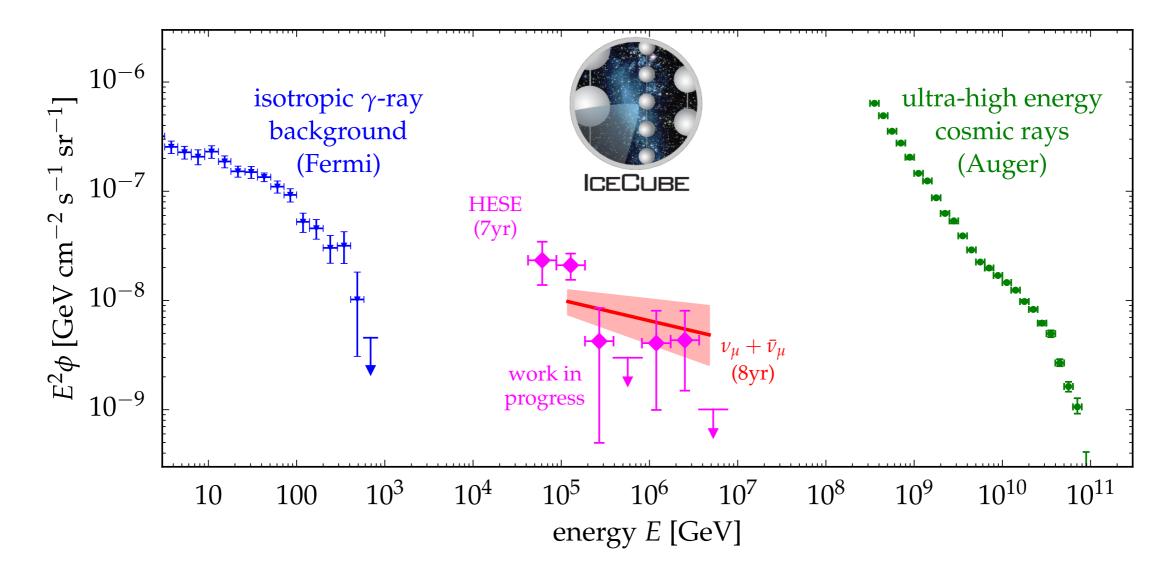
#### Diffuse TeV-PeV Neutrinos

- High-Energy Starting Events (HESE) (7yrs):
- [Science 342 (2013); work in progress]

- bright events ( $E_{\rm th} \gtrsim 30 {\rm TeV}$ ) 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



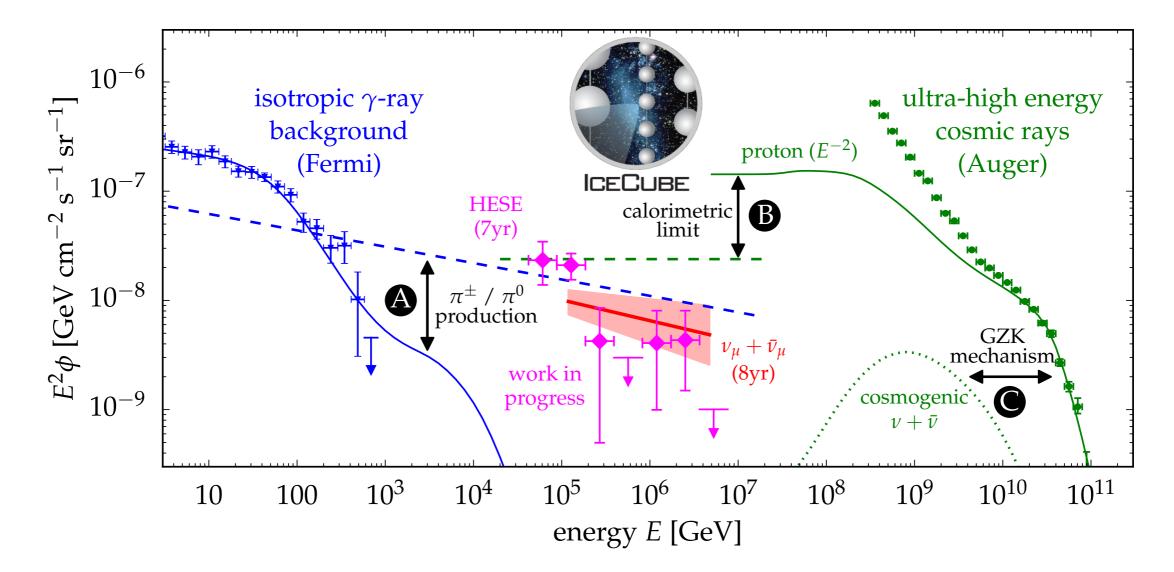
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## Astrophysical Flavors

CUBE Heren 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:

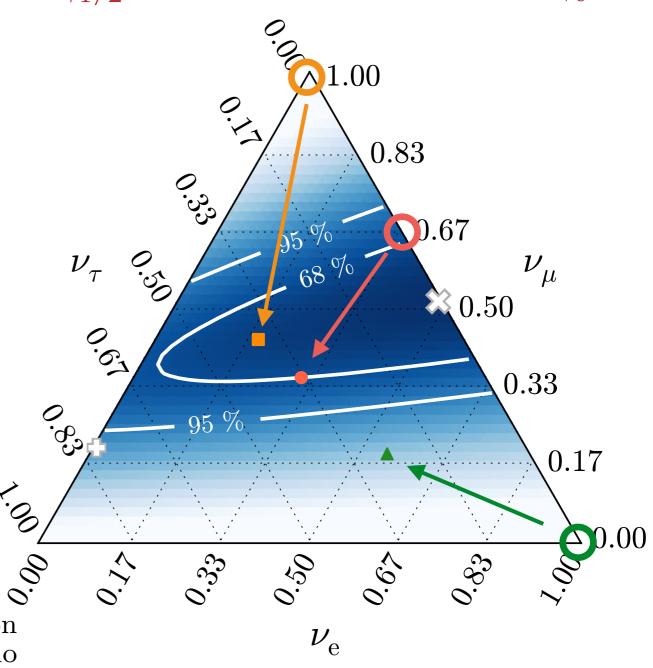
$$P_{\nu_{\alpha} \to \nu_{\beta}} \simeq \sum_{i} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

• initial composition:  $v_e: v_{\mu}: v_{\tau}$  pion & muon decay: 1:2:0 muon-damped decay: 0:1:0 neutron decay: 1:0:0

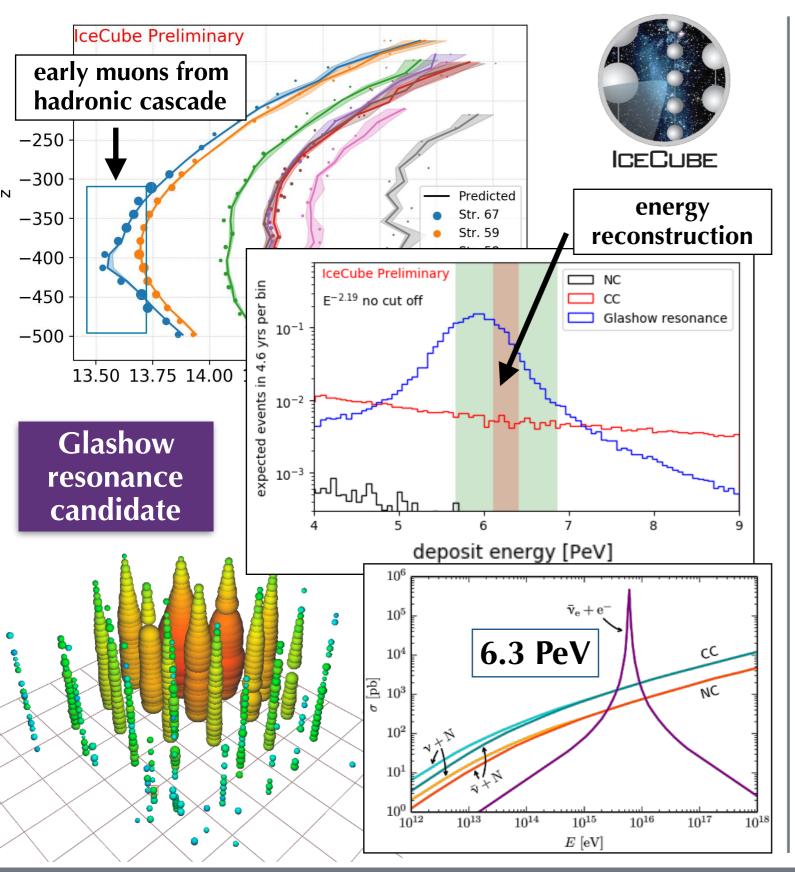
[**Astrophys.J.** 809 (2015) no.1, 98]

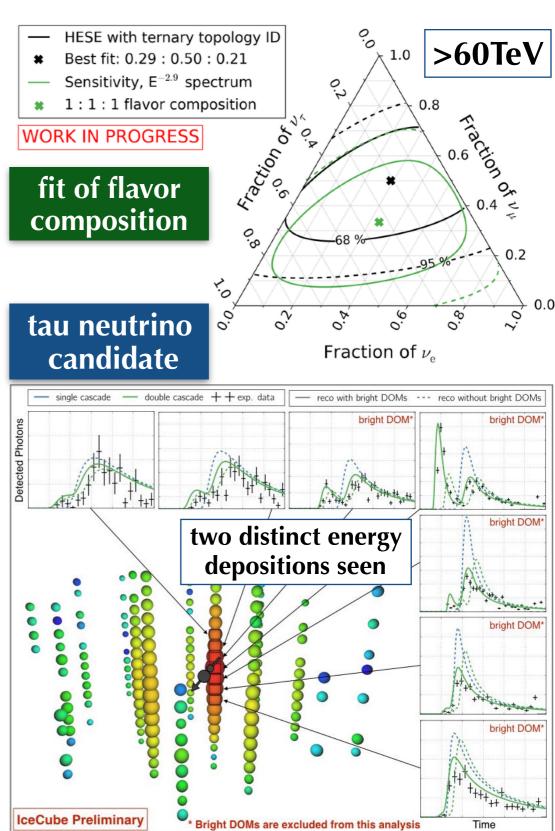
Profile likelihood scan of the flavor composition Each point in the triangle corresponds to a ratio as measured on Earth, the individual contribu-

d Markhe Ahles, sidesCopetheageiangle. Theutbests fit Messengers



## Astrophysical Flavors



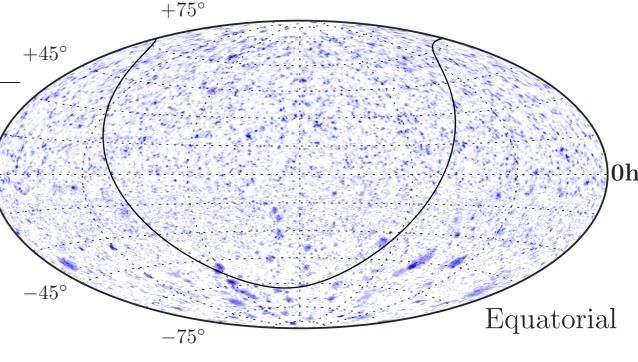


## Search for Neutrino Sources

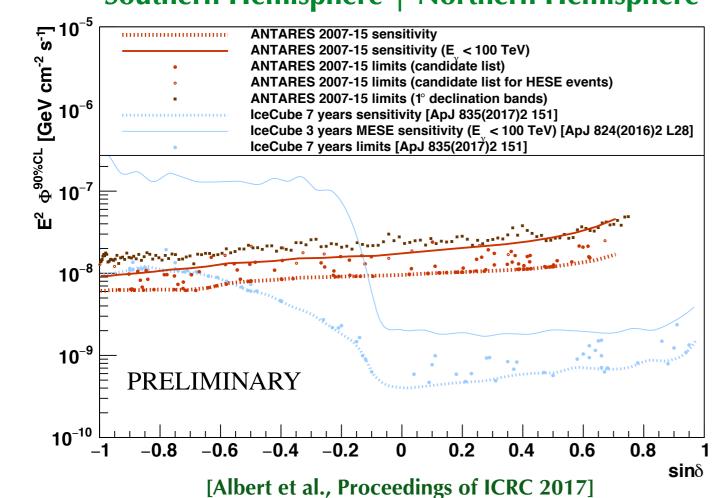
IceCube and ANTARES/KM3NeT with complementary field of views.

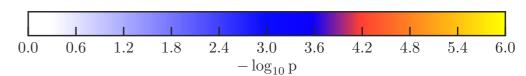








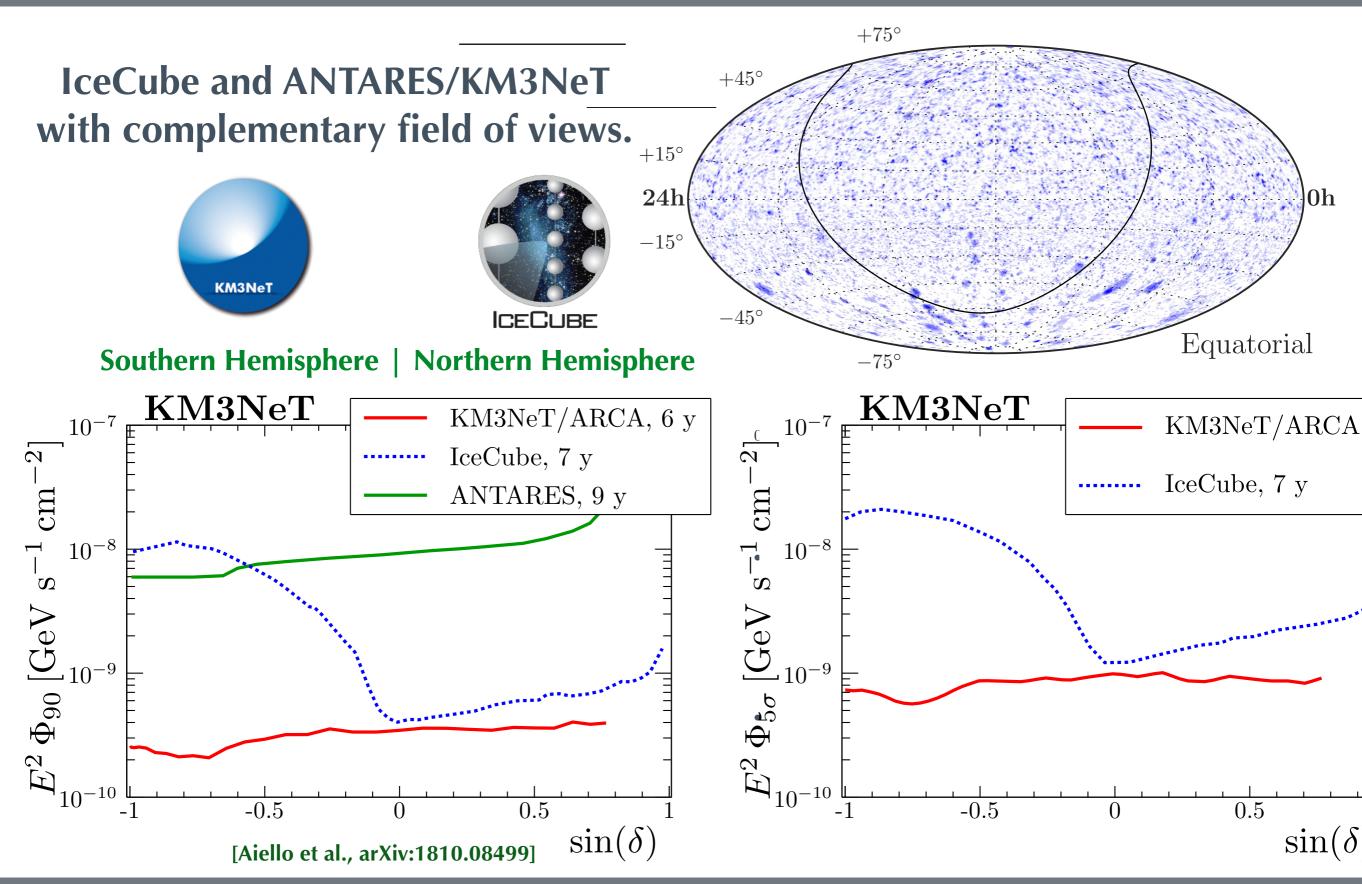




[Aartsen et al., Astrophys.J. 835 (2017) no.2, 151]

- 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

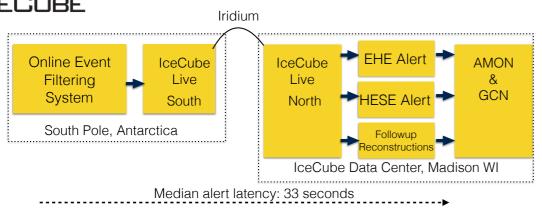


### Realtime Neutrino Alerts



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





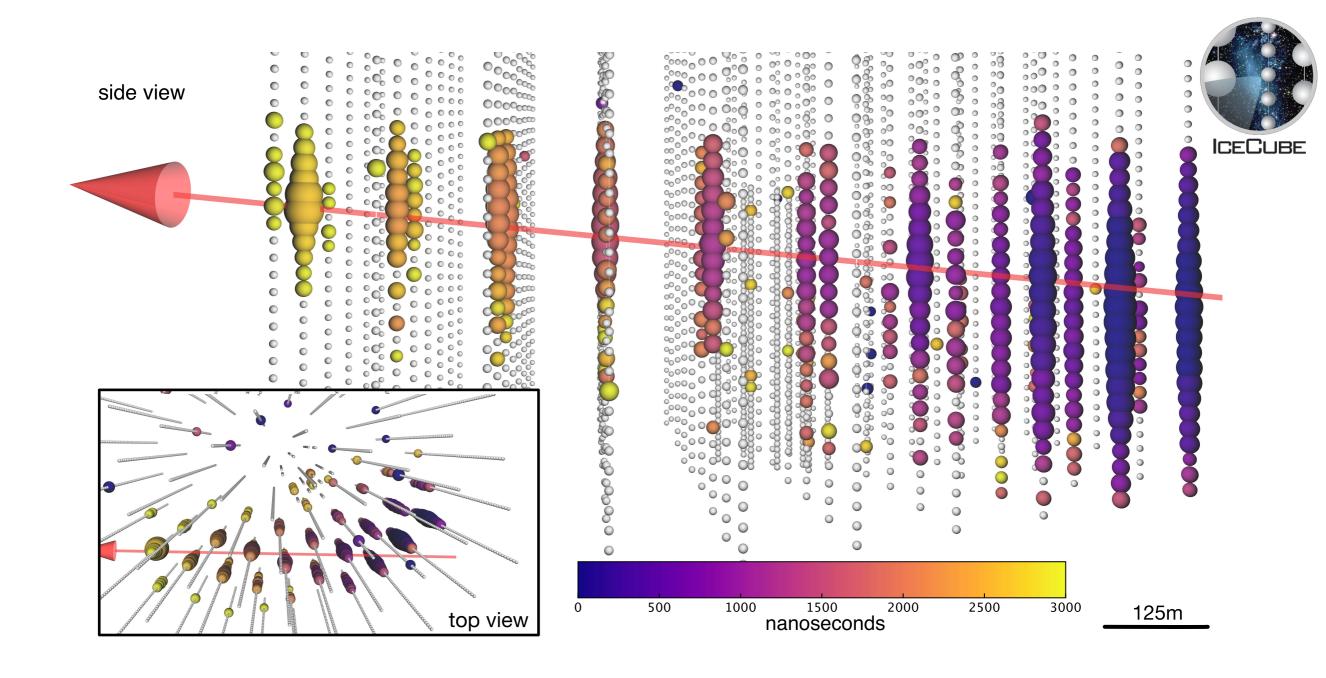
- 50% astrophysical neutrino fraction
- angular resolution 0.5-2deg
- high-energy starting tracks (>60TeV)
  - 4.8 alerts/year (1.1 signal/year)
- through-going muons (>100TeV)
  - 4-5 alerts/year (2.5-4 signal/year)

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

[Blaufuss et al., Proceedings of ICRC 2017]

[Dornic et al., Proceedings of ICRC 2017]

### Realtime Neutrino Alerts



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

Neutri

s and may Optical observations were performed by galactic sources, although the cinclividue of purcean informativity in the Galleran ste Fallow whip he EBIS Details on the gin. Highthe All-Sky Automated Survey for Supernovae remain as yet unidentified Continuously grow of servations by inaging atmospheric Clastenkow). The btained upper produced (ASAS-SN) (40), the Liverpool Telescope (41), the itoring the entire sky for astrophysical neu- telescopes, notably the Major Atmospheric o, optical, Gamma Imaging Cherenkov (MAGIC) log(Frequency [Hz]) Fig. 4. Broa nd spec telescopes, revealed periods where 18 20 28 30 the detected γ-ray flux from the blazar IceCube (50%) MAGIC (95%) TXS 0506+056 reached energies up to 400 GeV. Mea-IceCube (90%) Fermi (95%) surements of the source have also been completed at x-ray, optical, and 5.72 .sciencemag.org/ on July 12, 2018 radio wavelengths. We have investigated models associating neutrino 6.5 5.68 -and γ-ray production and find that correlation of the neutrino with the 5.64 Declination [º] flare of TXS 0506+056 is statistically 77.37 • 77.33 significant at the level of 3 standard 6.0  $\underline{\underline{\mathbf{dev}}}$  value of the basis of the #edshift of TXS 0506+056, we derive constraints for the muon-neutrino Ruminosity for this source and find them to be similar to the luminosity 90 85 80 75 70 observed in  $\gamma$ -rays. SARA/UA INTEGRAL (UL) VERITAS (UL) 5.0 Swift UVOT Fermi-LAT HAWC (UL) **CONCILUSION.** The energies of the 5.0 ASAS-SN **AGILE** Neutrino - 0.5yr γ-rays and the eutrino indicate that knata/HONIR PKS-0502+049 Swift XRT MAGIC Neutrino - 7.5yr blazar jets may accelerate cosmic rays kaso/KWFC NuSTAR H.E.S.S. (UL) to at least several PeV, The observed 10<sup>6</sup>  $10^{15}$ association of a high-energy neutrino Energy [eV] 78.5 78.0 Right Asc 5 nsion [° 177.0 76.5 with a blazar during a period of 0enlegend here quety can the optical-ultraviolet range and the second one in the GeV Right Ascension [°]

Multimessenger observations of blazar TXS 0506+956-Thee Multimessenger observations of blazar TXS 0506 154 The steerions of blazar TXS 0506 154 The steerion of plazar TXS 0506 154 The steerion o shown as blue circles, with sizes representing their 95% positionalb as= as uming a spectrum of  $dN/dE \propto E^{-2}$  at the most probation = asThe list of author affiliations is available in the full energy (311 TeV). neutrino scolncident with the source names. The IceCube land neutrino scolncident with the blazar the Scolncident with the blazar the Scolncident with the blazar the source names. The IceCube land neutrino scolncident with the source names. The IceCube land neutrino scolncident with the source names. The IceCube land neutrino scolncident with the source names. \*The full lists of participating members for each optical position is shown by the pink square. The yellow circle team and their affiliations are provided in the

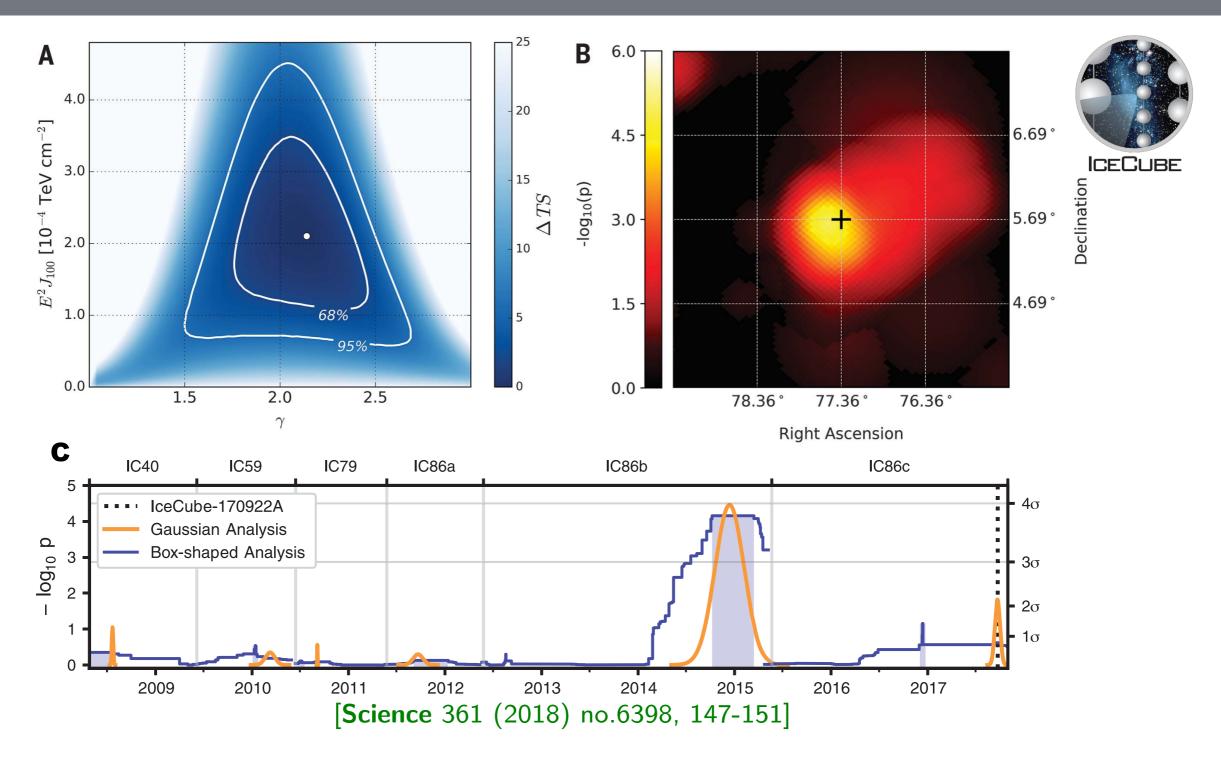
Supplemental interest Fermi-LEAT blazars and one of the most Cite this particle as IceCube Collaboration et al.,

on an R-band optical image of the sky.

The interpretation of the second of the seco

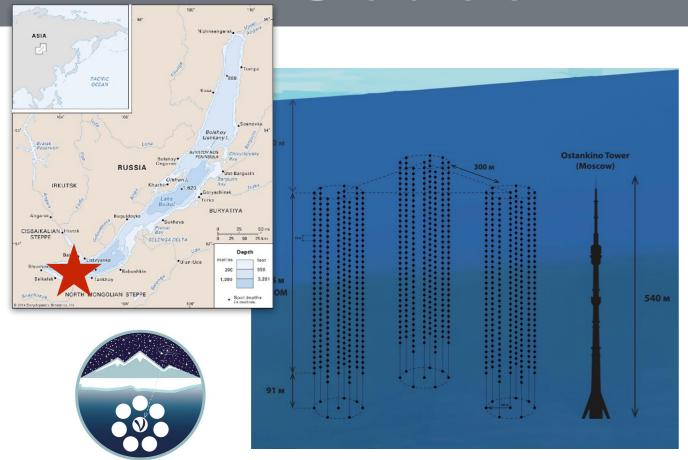
Science 31, eaat1378 (2018). DOI: 10.1126/ science.aat1378

#### TXS 0506+056



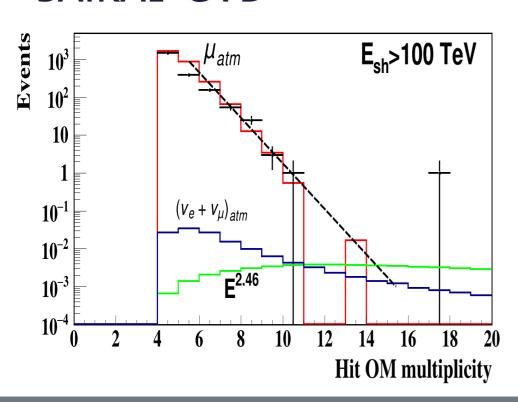
- Independent  $3.5\sigma$  evidence for neutrino flare  $(13\pm 5 \text{ events})$  in 2014/15.
- ullet Implies neutrino luminosity of  $1.2 imes10^{47}$  erg/s over 158 days ( $\simeq4 imes L_{
  m Fermi}$ ).

## Outlook: Baikal-GVD

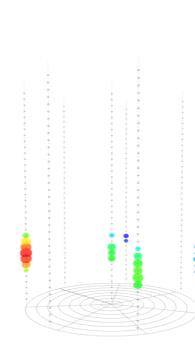


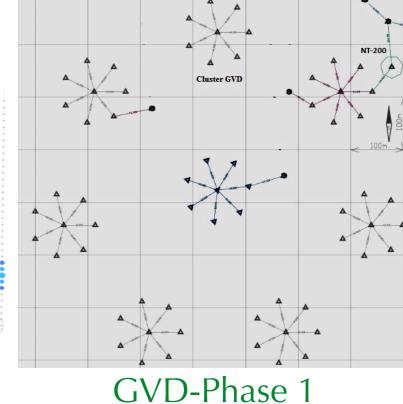
- **GVD Phase 1:** 8 clusters with 8 strings expected to be completed by 2020/21 (~0.4 km<sup>3</sup>)
- cluster depth: 735–1260 m
- 3 clusters deployed 2016–18
- final goal: 27 clusters (~1.4 km<sup>3</sup>)

**BAIKAL-GVD** present detector outline (2018)



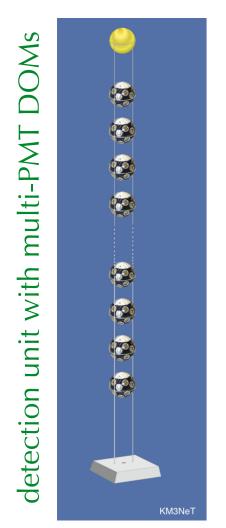
first physics results: cascade spectrum / cascade event in 2015 data

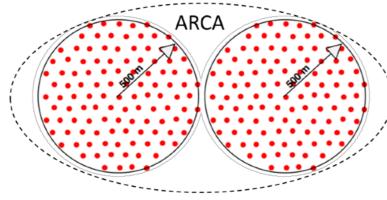




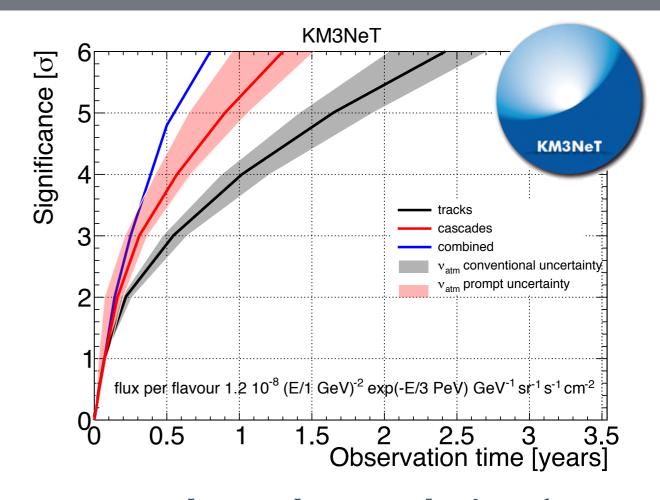
### Outlook: KM3NeT/ARCA

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





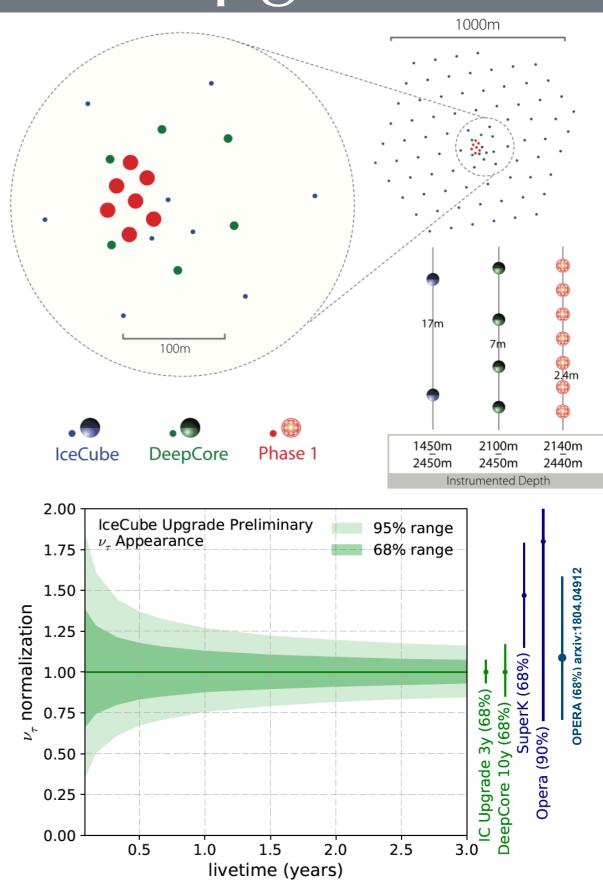




- Improved angular resolution for water Cherenkov emission.
- 5σ discovery of **diffuse flux** with full ARCA within one year
- Complementary field of view ideal for the study of point sources.

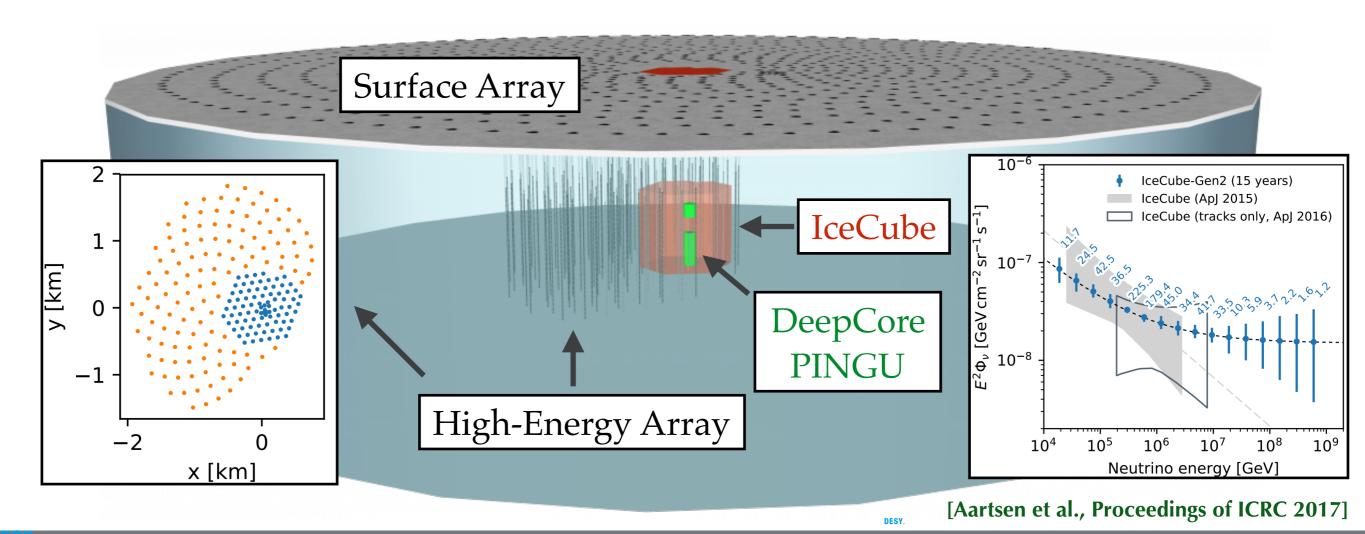
## Outlook: IceCube Upgrade

- 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



#### Vision: IceCube-Gen2

- · Multi-component facility (low- and high-energy & multi-messenger).
- In-ice high-energy Cherenkov array with 6-10 km<sup>3</sup> volume.
- Under investigation: Surface arrays for in-ice radio Askarayan and cosmic ray veto (air Cherenkov and/or scintillator panels).



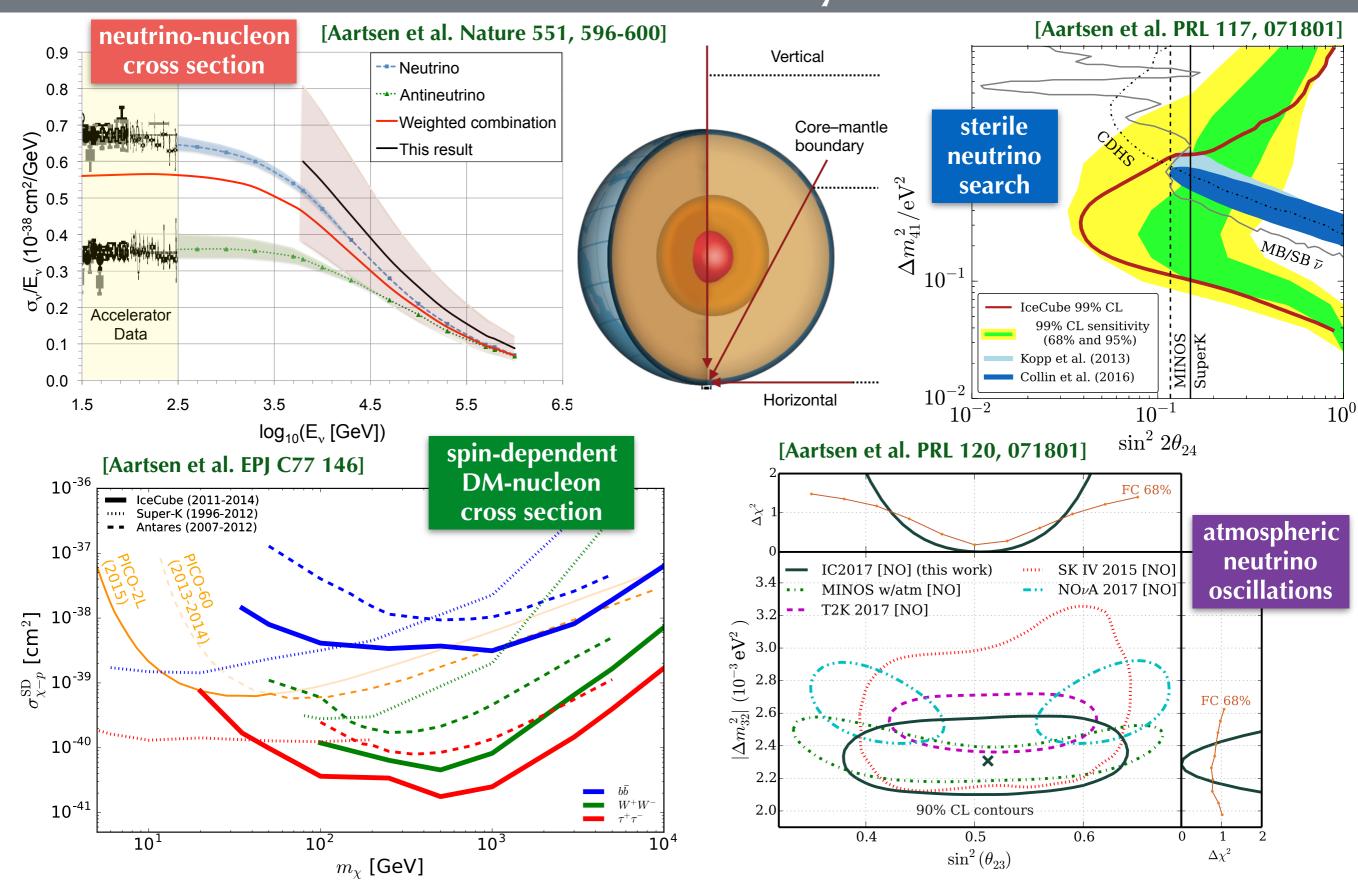
## Summary

- 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, ...

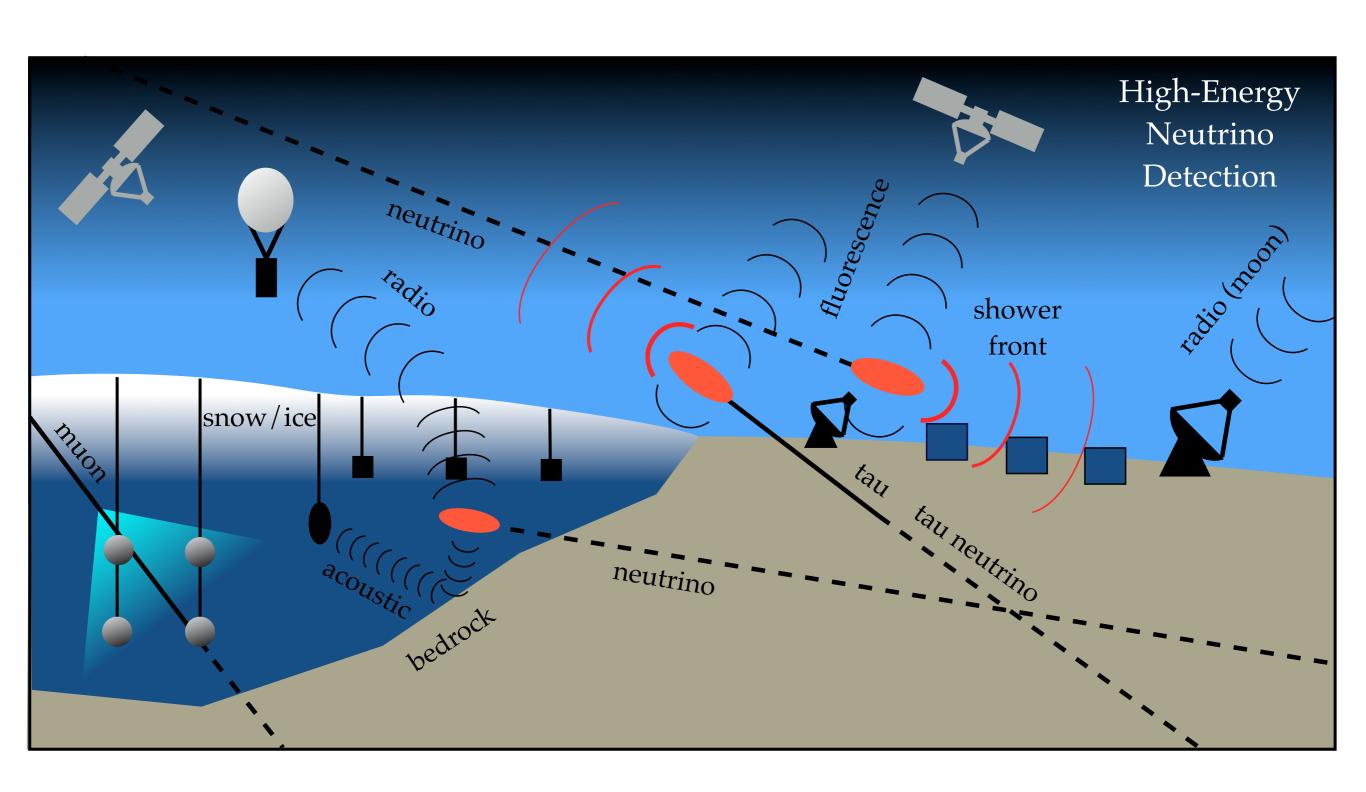
#### Thank you for your attention!

### Backup Slides

## Neutrino Physics

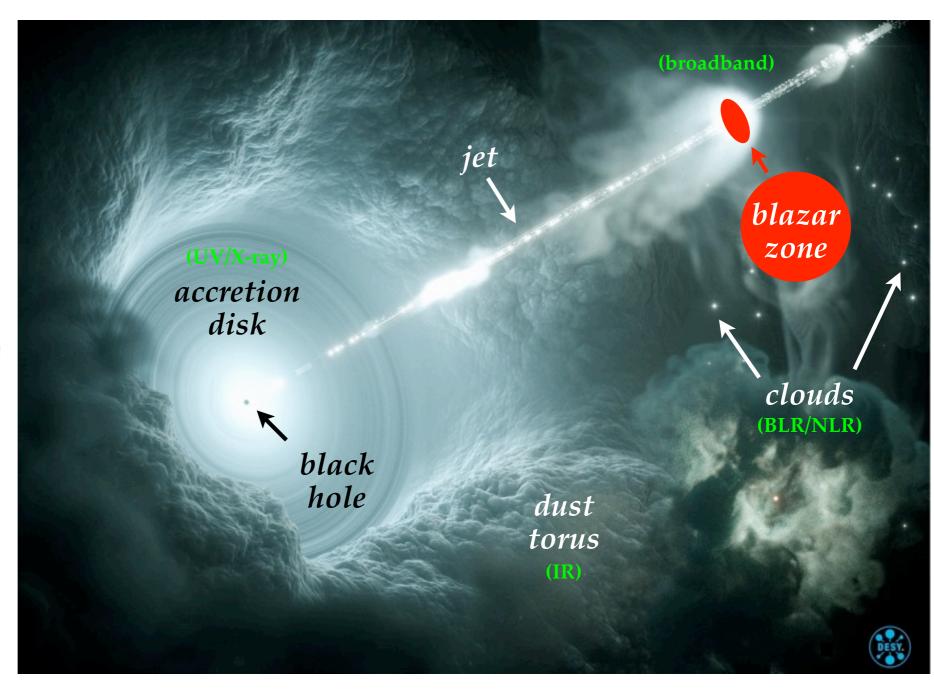


## Detection Principles



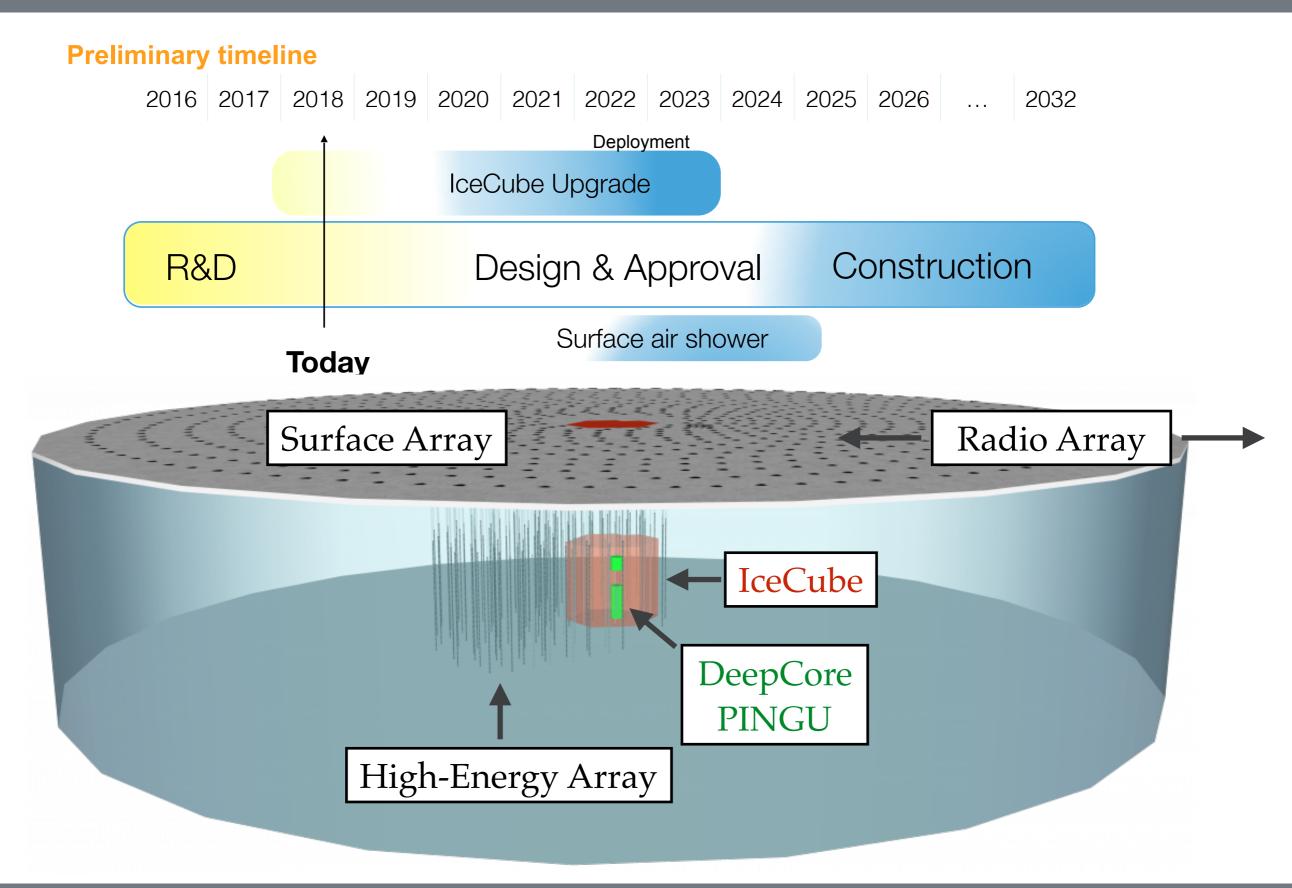
#### Blazars as Neutrino Factories

- 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

			11011111.0011010016, 3.1111/0 0 10.2017		
Detector	Туре	Mass (kt)	Location	Events [10 kpc]	
IceCube	long string	600	<b>South Pole</b>	1,000,000	
Hyper-K*	H <sub>2</sub> O	374	Japan	75,000	
DUNE*	Ar	40	USA	3,000	
Super-K	H <sub>2</sub> O	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	

9/26/18