



ICRC2019

36th International Cosmic Ray Conference - Madison, WI, USA

THE ASTROPARTICLE PHYSICS CONFERENCE

RP6 — Rapporteur Talk on Neutrinos

Alexander Kappes

Madison, August 1, 2019



Institute for Nuclear Physics

living.knowledge

Neutrinos at ICRC 2019

- Overall about 180 contributions

- 2 review talks
- 3 highlight talks
- 75 parallel talks (given)
- O(100) posters

- Review talks

- A Brief History of Neutrino Astronomy (Francis Halzen)
- Physics and Astrophysics with UHE Cosmic Neutrinos (Abigail Vieregge)

- Highlight talks

- HE neutrinos from persistent and transient activities of compact objects (Ke Fang, **PoS(ICRC2019)008**)
- Results from IceCube (Dawn Williams, **PoS(ICRC2019)016**)
- Results from the Mediterranean neutrino detectors (Rosa Coniglione, **PoS(ICRC2019)006**)

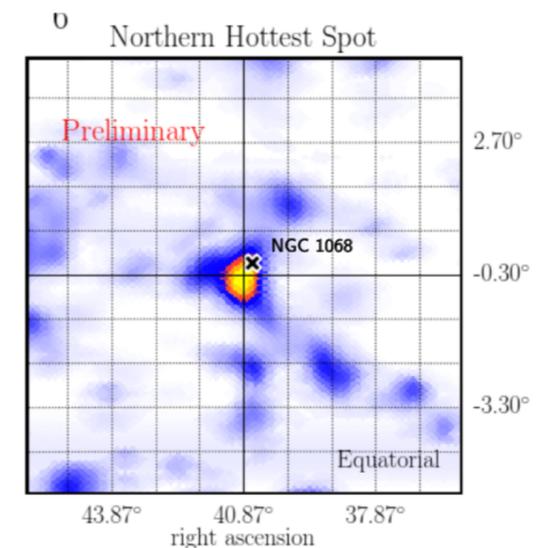
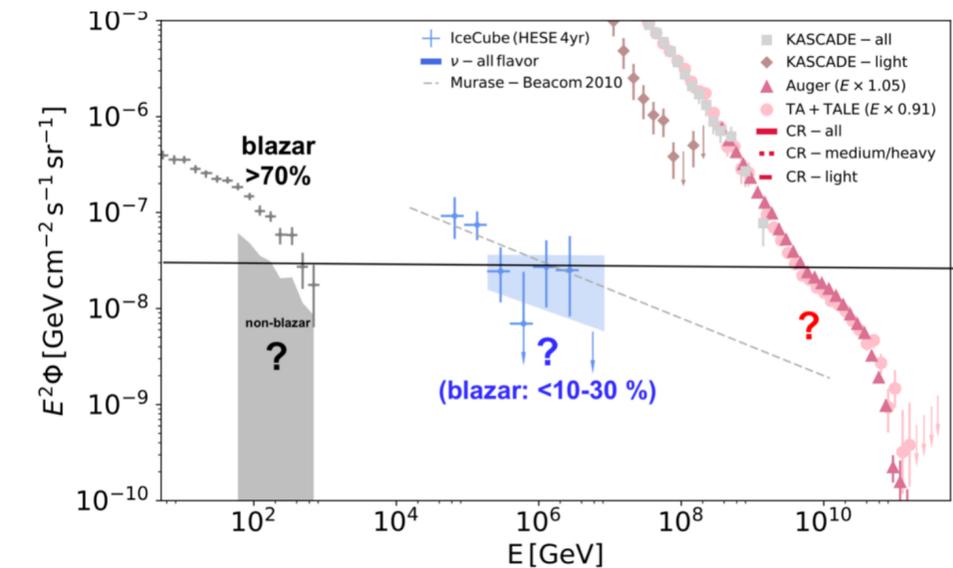
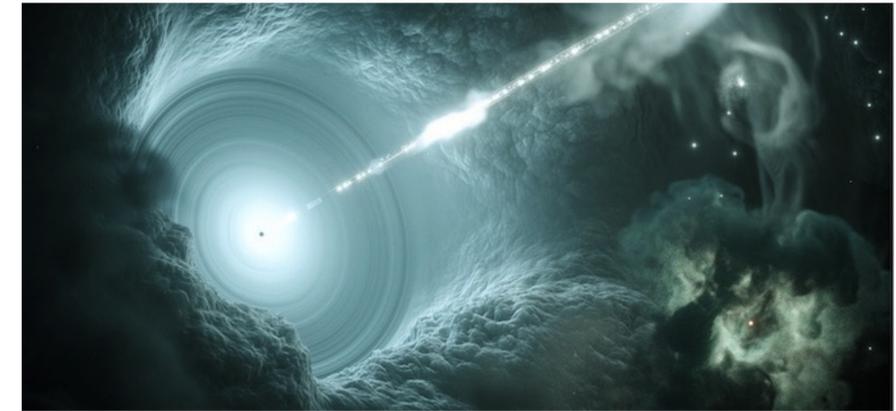
Thanks to all for the interesting talks and discussions !

And apologies to everyone not mentioned and for any mistakes



Hot topics

- Understanding neutrino emission from TXS 0506+056 (blazars)
- Understanding the astrophysical diffuse neutrino spectrum in the multi-messenger context
- Searching for point-like sources and multi-messenger activities
- The quest for UHE neutrinos

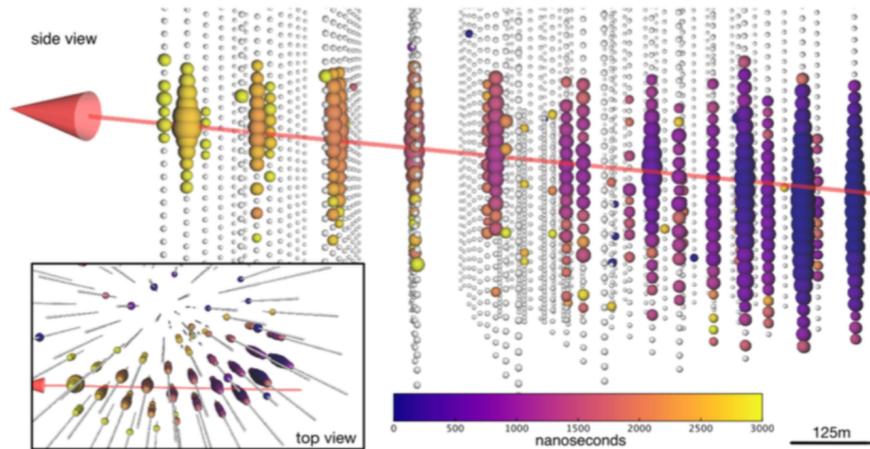


Understanding neutrinos from TXS 0506+056

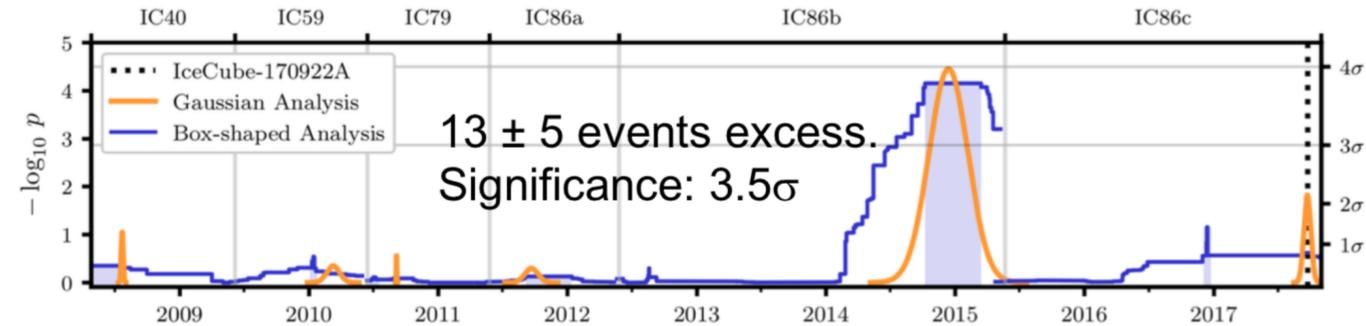
Neutrinos from the AGN blazar TXS 0506+056

Sept. 22, 2017:

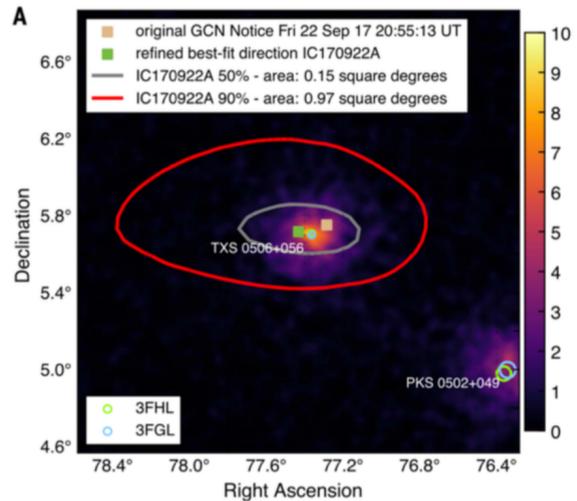
A neutrino in coincidence with a blazar flare



2014-2015: A (orphan) neutrino flare found from the same object in historical data



Science 361 (2018) no. 6398, eaat2890

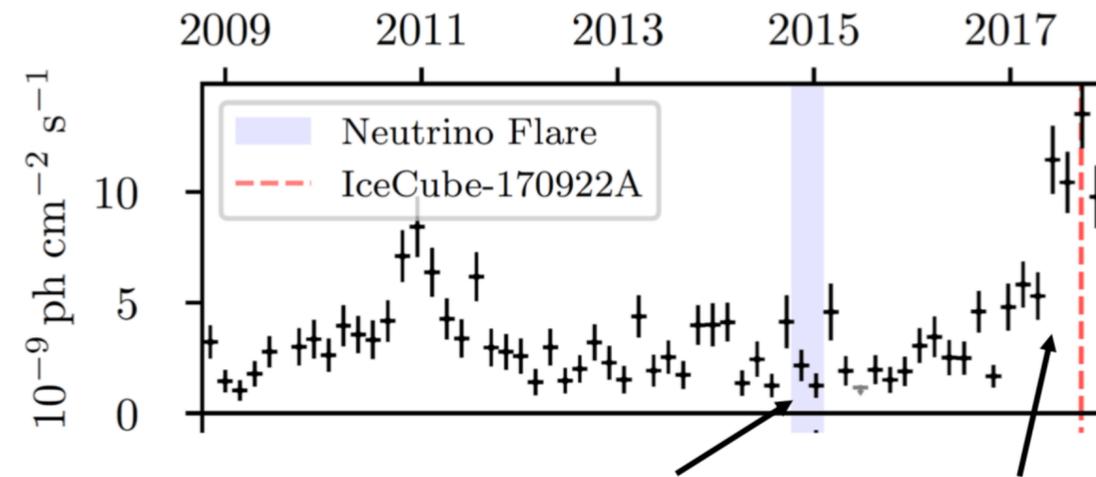


Observed by Fermi-LAT and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

Fermi-LAT data; Padovani et al, MNRAS 480 (2018) 192



At 2014-15 neutrino flare

The 2017 flare

Understanding neutrinos from TXS 0506+056

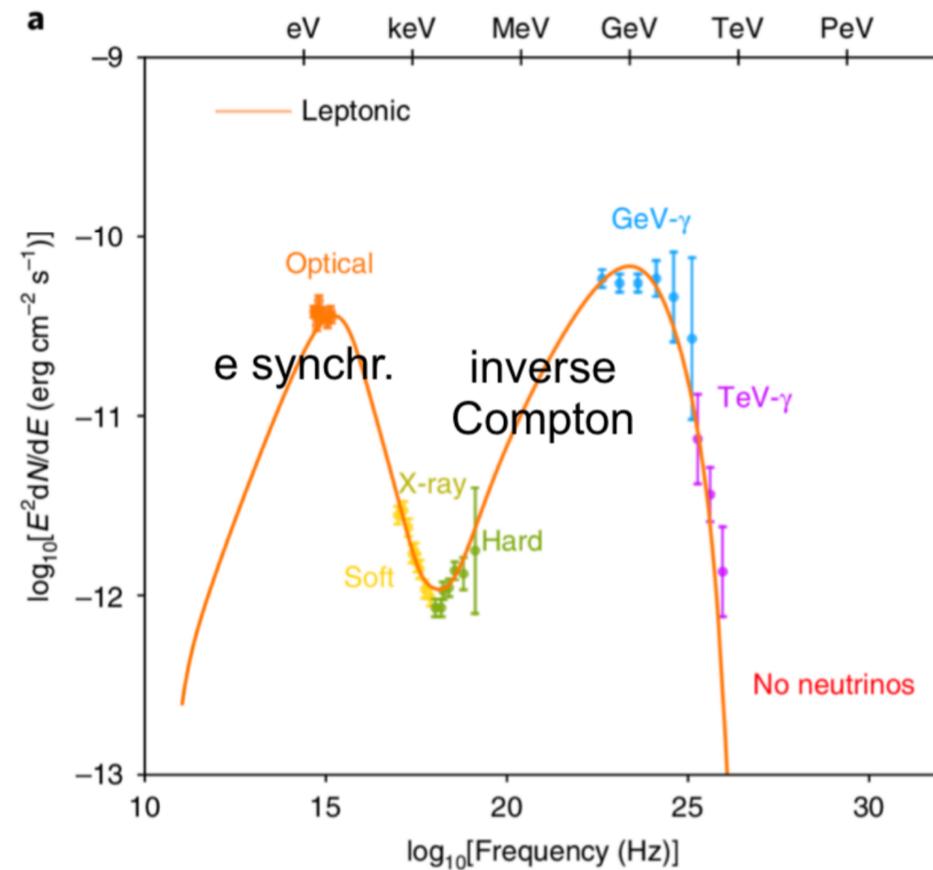
One zone model results (2017 flare)

PoS(ICRC2019)1032 (Walter Winter)

Fewest assumptions

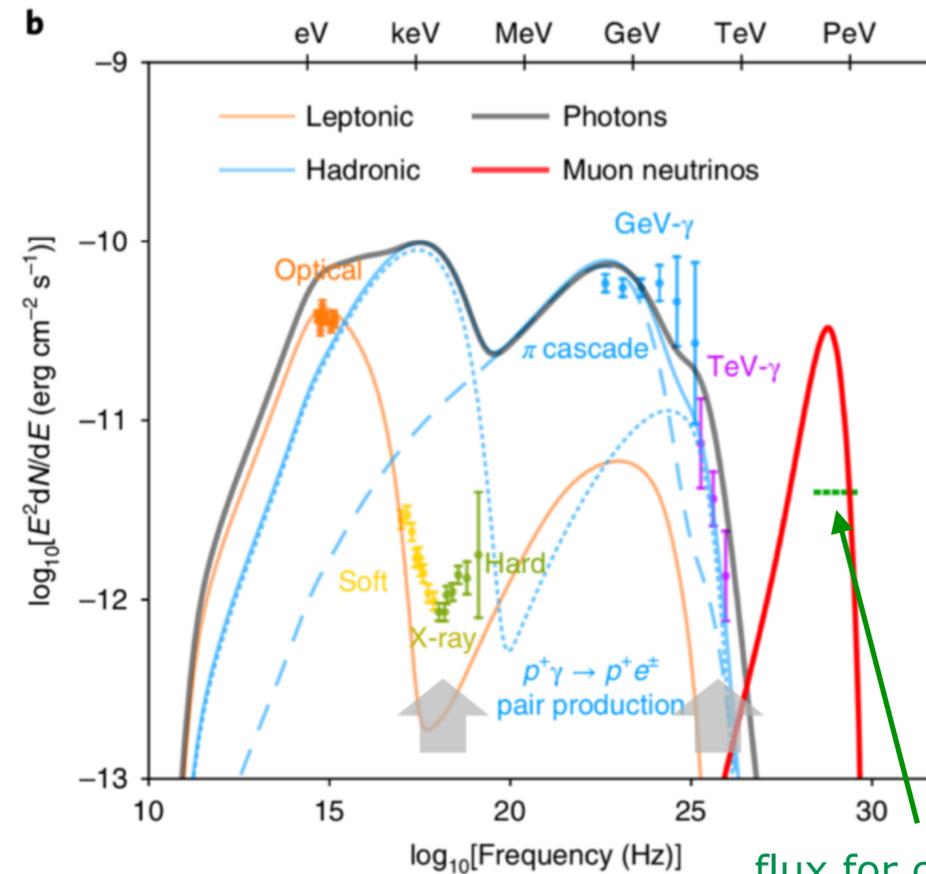


Leptonic models



- No neutrinos

Hadronic (π cascade) models

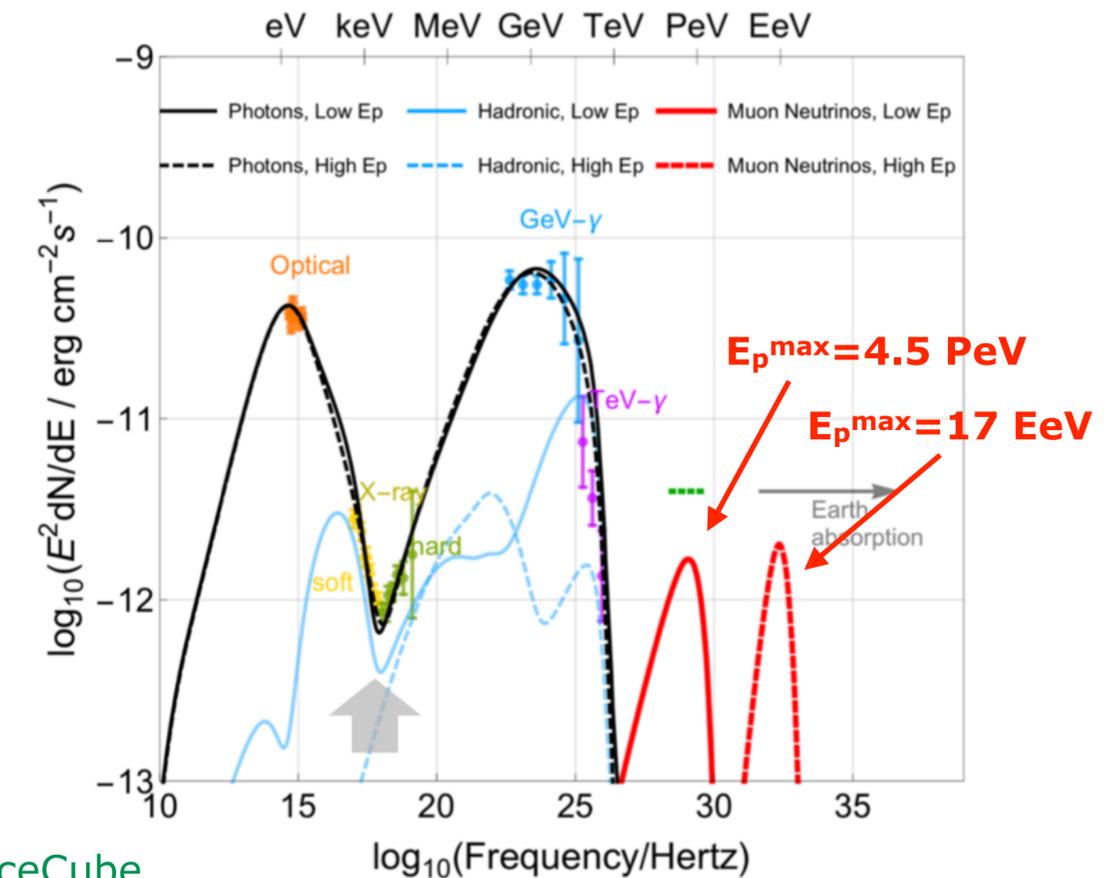


flux for one IceCube neutrino in 180 days

- Violate X-ray data

X-ray (and TeV γ -ray) data indicative for hadronic origin

Hybrid or p synchrotron models

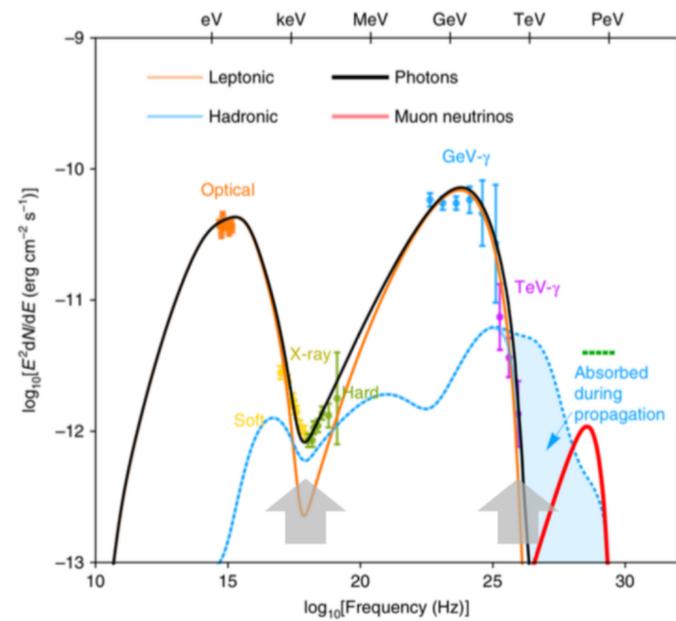
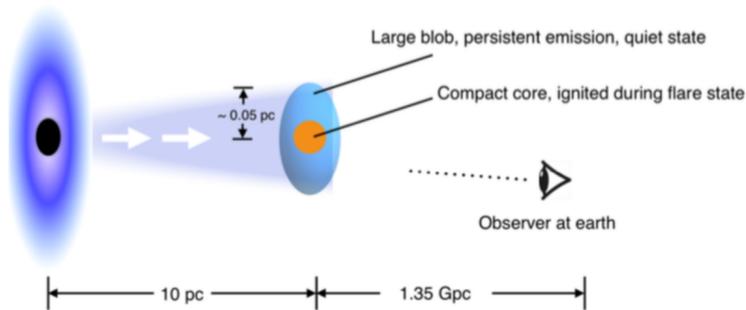


- Violate energetics (L_{edd}) by a factor of a few hundred or significantly exceed ν energy

More freedom through more sophisticated sources geometries

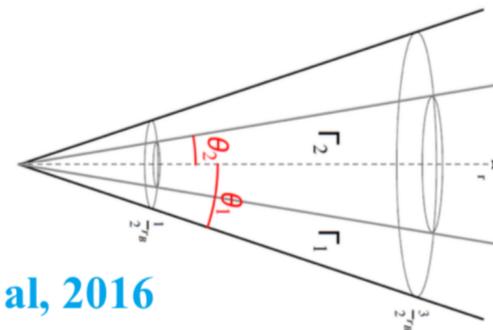
... to satisfy energetics problem. At the expense of more parameters.

Formation of a compact core

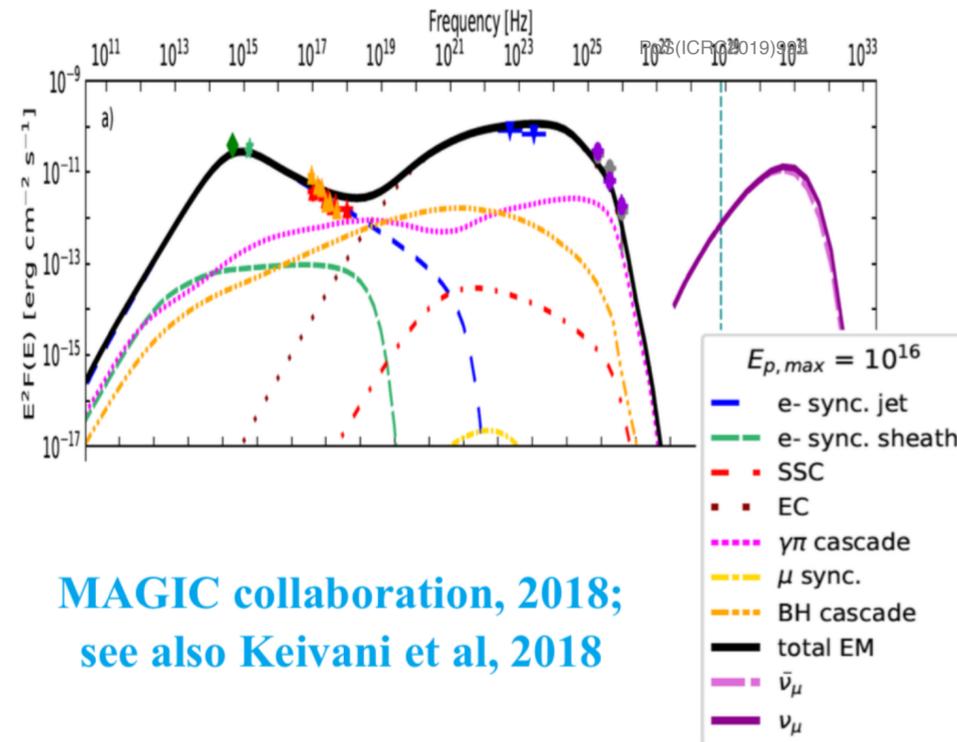


Gao et al, *Nature Astronomy* 3 (2019) 88

External radiation fields

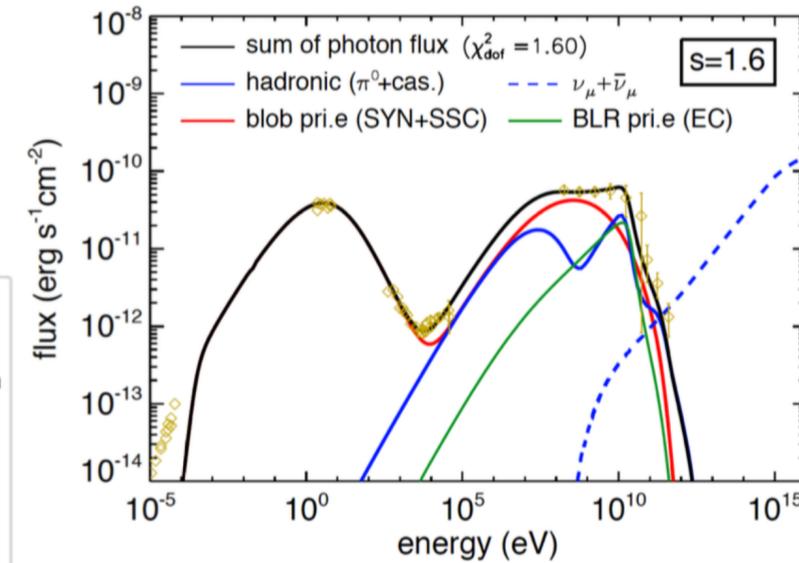
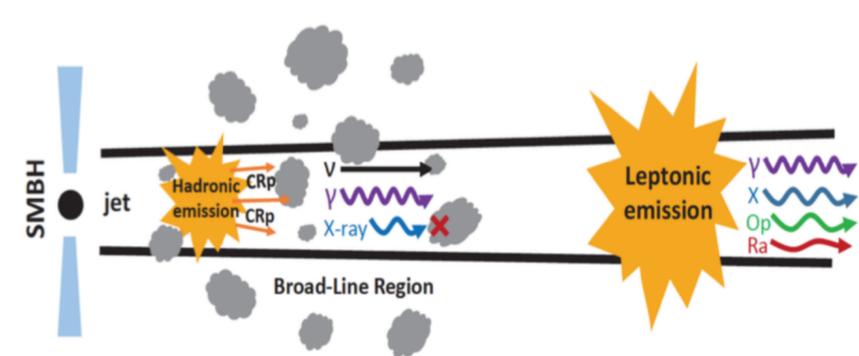


Sikora et al, 2016



MAGIC collaboration, 2018; see also Keivani et al, 2018

Jet-cloud interactions

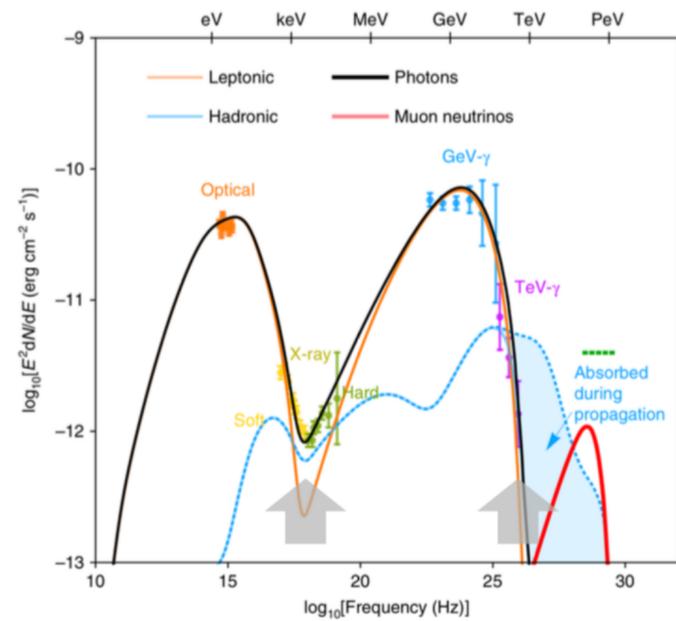
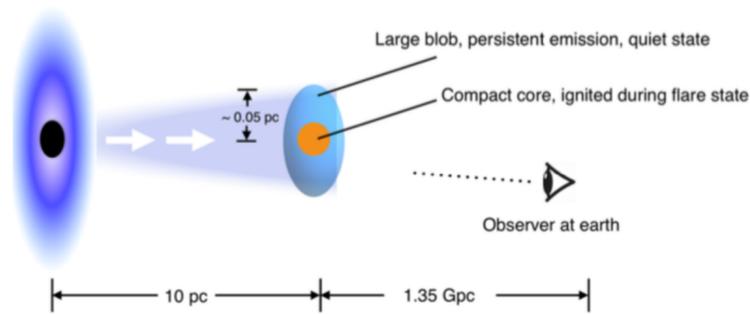


Liu et al, 2018

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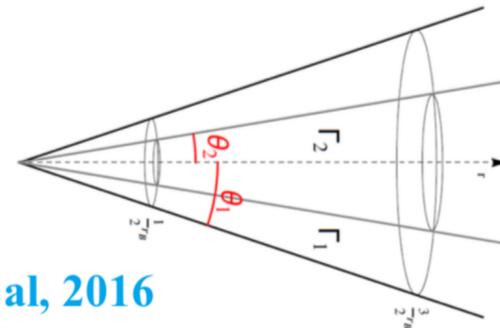
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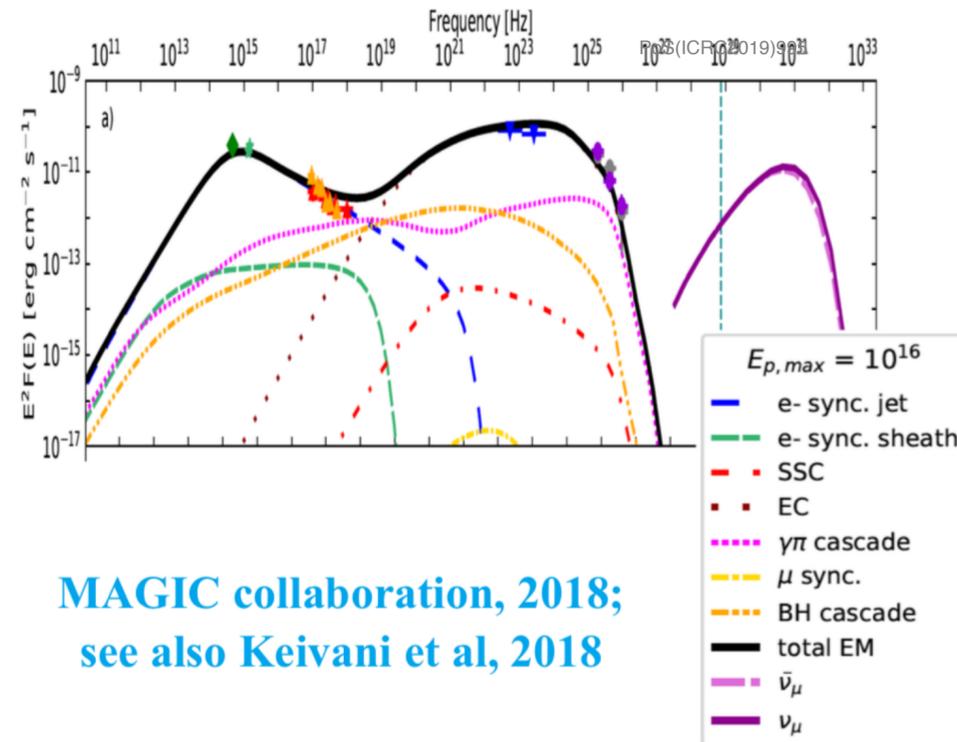


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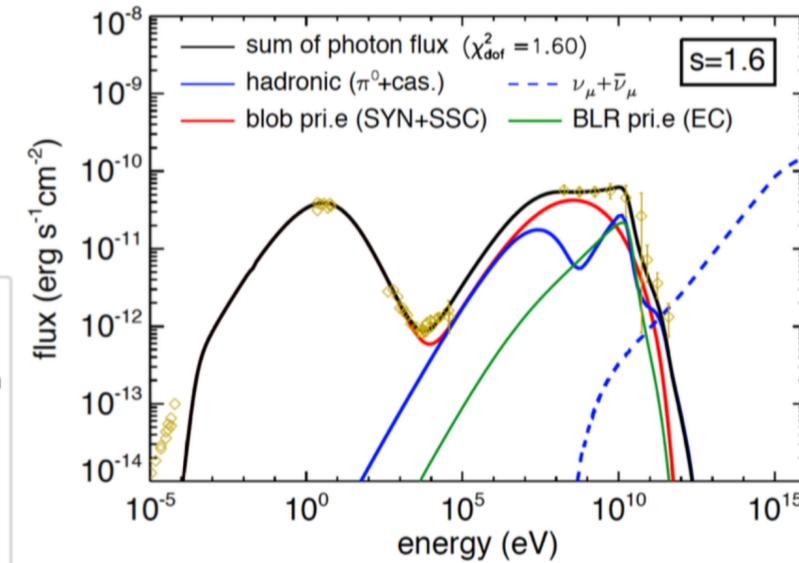
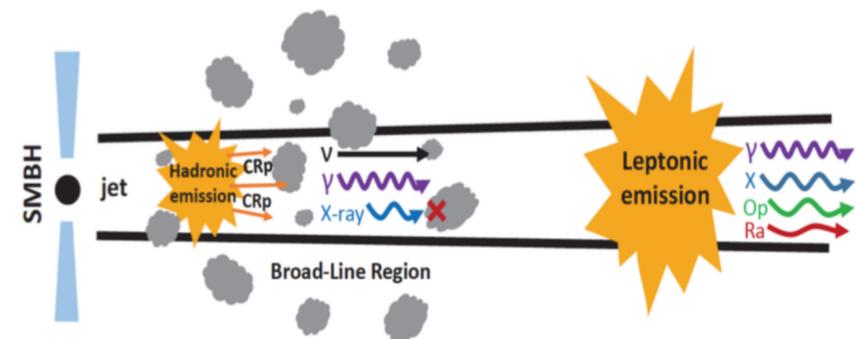


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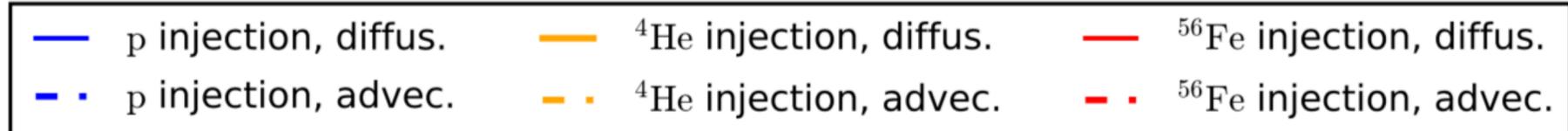
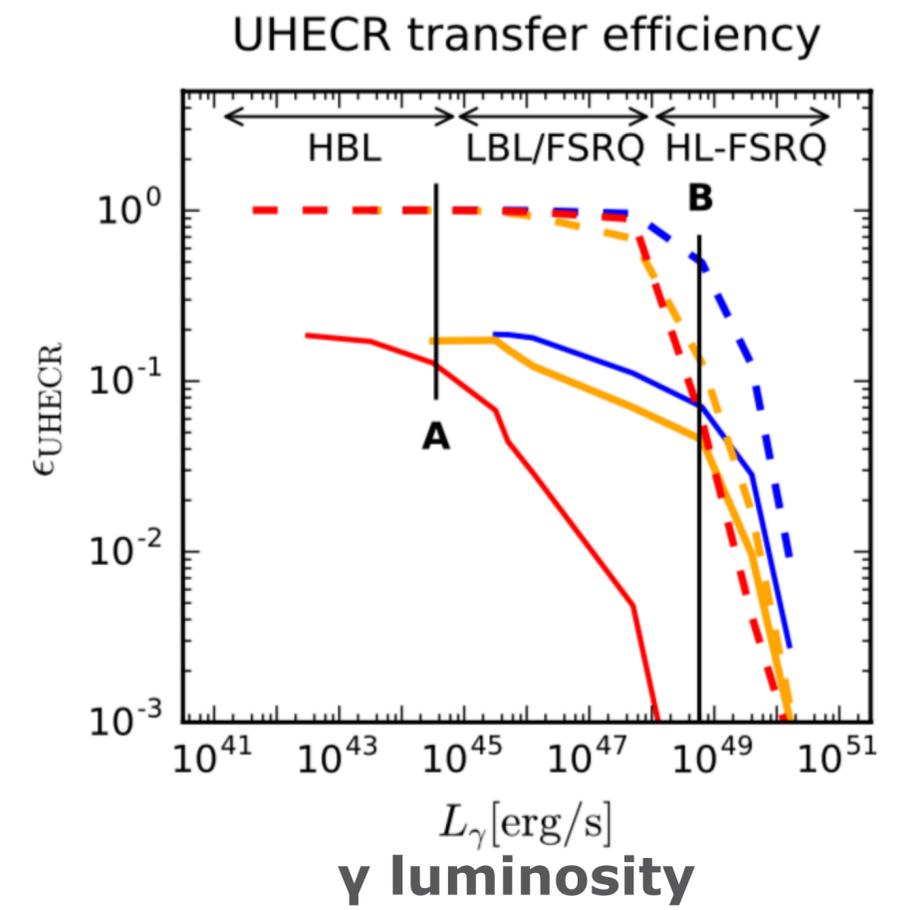
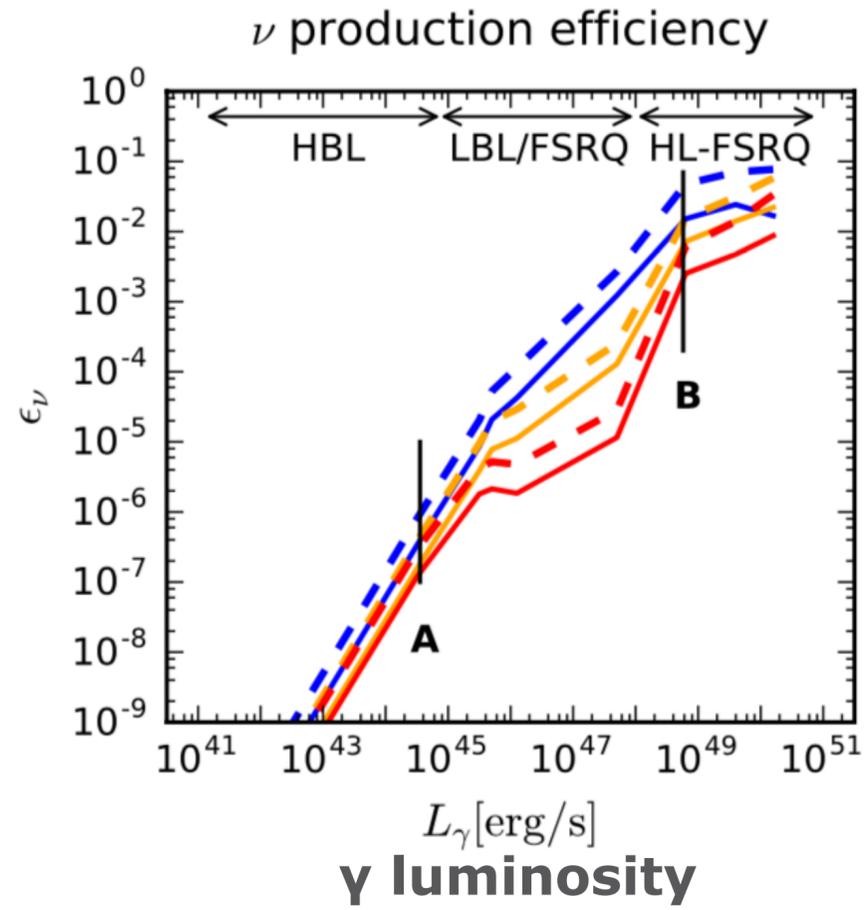
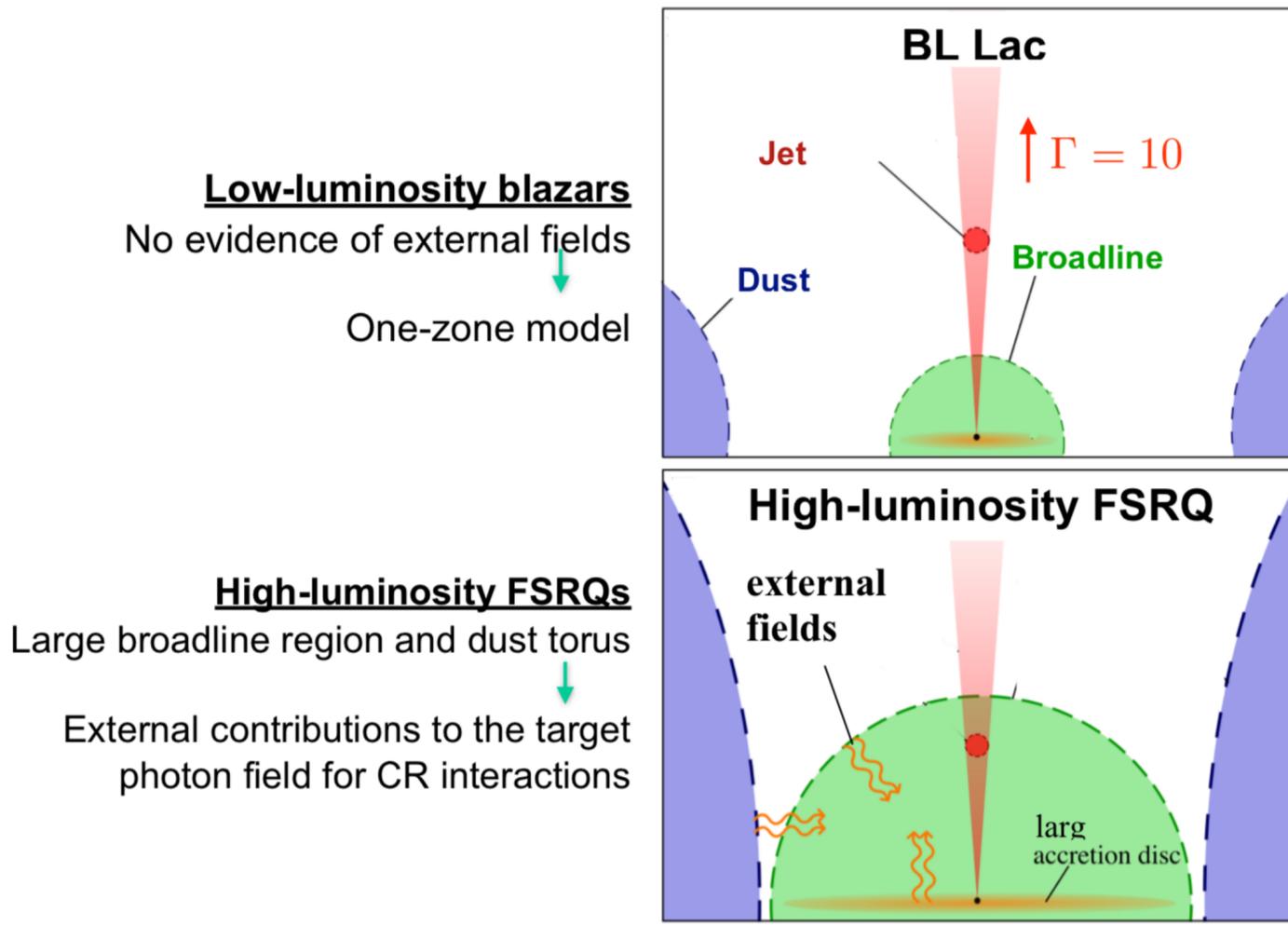


Liu et al, 2018

see also PoS(ICRC2019)971 (modeling of individual blazar flares)

Modeling of blazars

Neutrinos vs CRs: opposite trends



- Powerful blazars like FSRQs are good neutrino emitters with low UHECR efficiency
- HBL Lacs are good sources of UHECR, with low neutrino production efficiency
- Heavier chemical compositions lead to lower neutrino cutoff energies due to disintegration

Summary (long)

Interpretation in terms of one-zone models

- 😊 Simplest possible geometry, few parameters
- 😊 Describe SED and time response reasonably well (modulo some discussion of UV data)
- 🤔 Have to accept that either L_{edd} is significantly exceeded or that neutrino energies does not match
- 🤔 2014-15 neutrino flare: more than two neutrino events difficult to accommodate

Interpretation in terms of multi-zone models:

- 😊 External radiation fields (e.g. disk, sheath) or compact core models promising
- 😊 Can produce substantially larger neutrino event numbers with reasonable energetics
- 😊 Some models (compact core, jet-cloud) can produce a spectral hardening in gamma-rays (2014-15 flare)
- 🤔 Too early for solid conclusions, mostly because of sparseness of data

What did we learn qualitatively from 2017 event?

- Time-response of SED and X-ray data point towards leptonically dominated model
- X-ray/gamma-ray data need to be monitored (indicative for hadronic contribution)
- More such associations are needed for solid conclusions on predicted neutrino event rates

What did we learn qualitatively from 2014-15 flare?

- Description of 13 events requires high radiation density with imprints in the SED which seem to be *in contradiction to observations*
- Up to five events plausible in external radiation field model
- Expected (neutrino) spectral shape very different from IceCube analysis (power law). Consequences?
- Need multi-wavelength monitoring to exclude that signal shows up elsewhere

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- Up to ... model
- Expe ... from
- Need ... signa

Need better modeling but also more data

Two days ago ...

IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106

ATel #12967; *Ignacio Taboada (Georgia Institute of Technology), Robert Stein (DESY Zeuthen)*
on 30 Jul 2019; 23:58 UT
Credential Certification: Ignacio Taboada (itaboada@gatech.edu)

Subjects: Neutrinos, AGN



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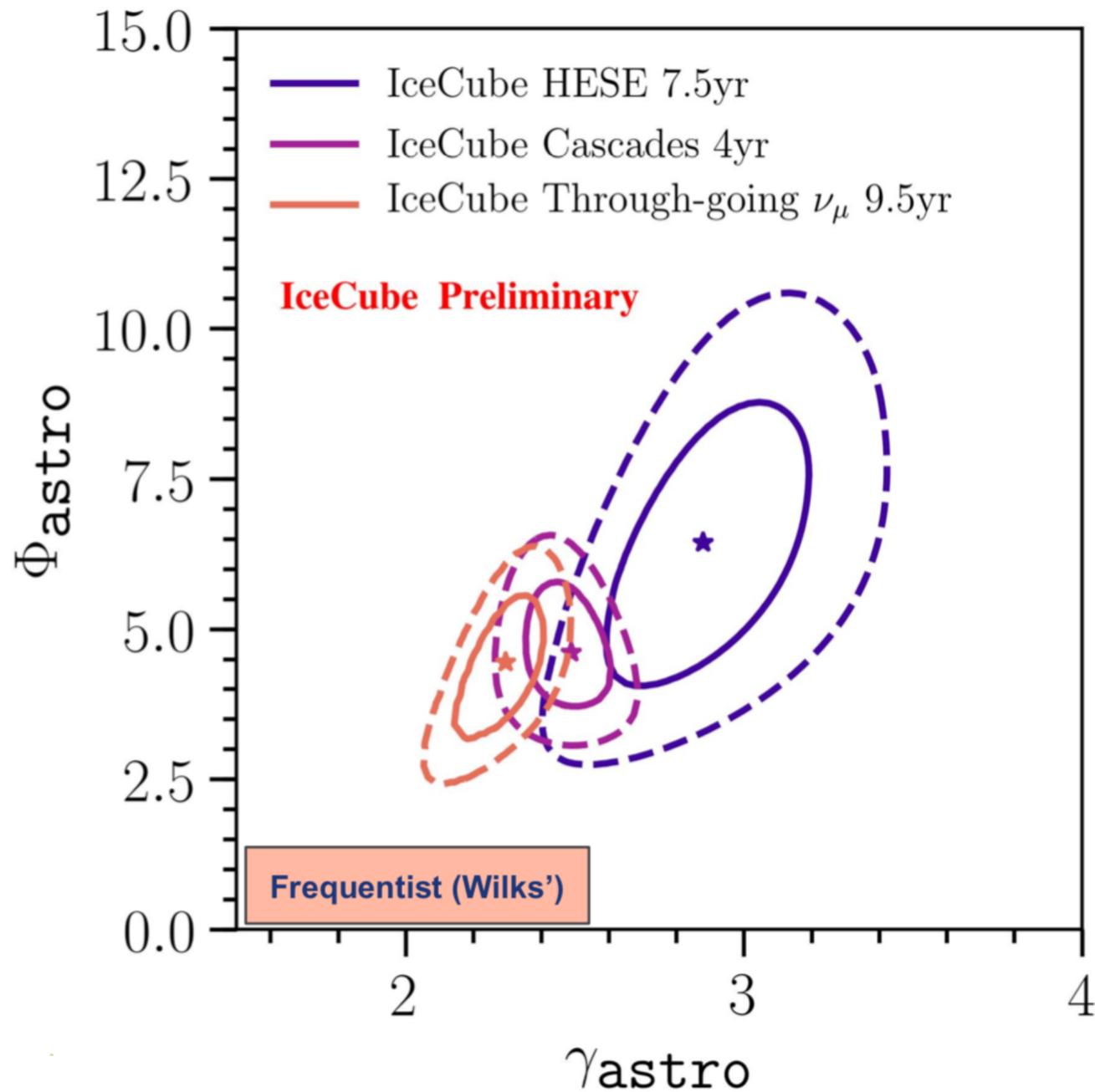
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**Understanding the Diffuse
Astrophysical Neutrino Flux**

IceCube: Updated neutrino samples

PoS(ICRC2019)1017 (Jöran Stettner)

PoS(ICRC2019)1004 (Austin Schneider)



$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} [\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$$

Name	Approx. Neutrino Energy	Direction	Dominant Flavor	Unbroken Spectral Index
HESE	50 TeV - 5 PeV	All-sky	e, μ , τ	2.89
Cascades	5 TeV - 5 PeV	All-sky	e, τ	2.48
NuMu	50 TeV - 10 PeV	Northern sky	μ	2.28

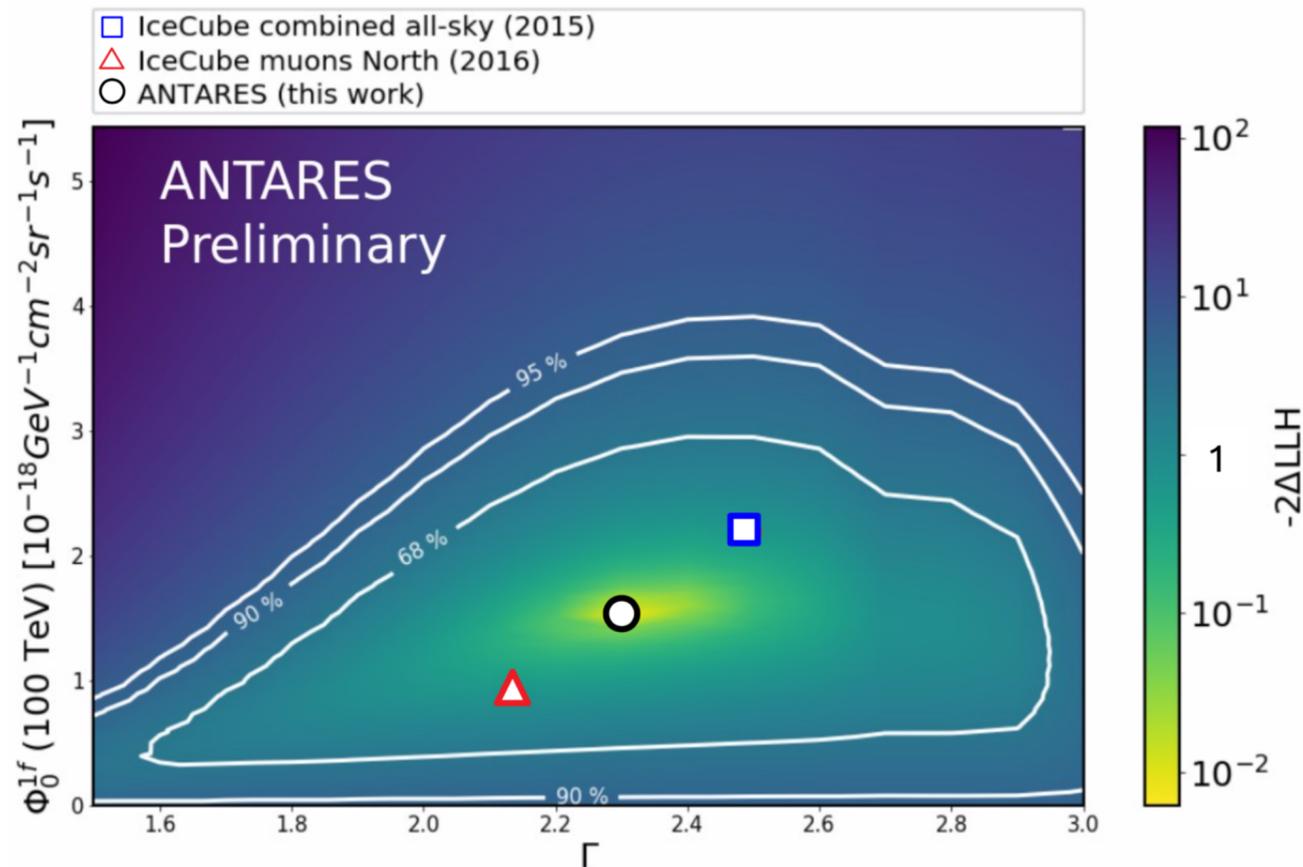
Differences in single power-law parameters not in tension with each other but may hint at an additional spectral structure

ANTARES: Study of HE diffuse ν flux

PoS(ICRC2019)891 (Luigi A. Fusco)

Likelihood fitting of the high-energy sample

Atmospheric (Honda + Enberg together) fitted simultaneously with the cosmic flux normalisation and spectral index of the **track and shower samples together**

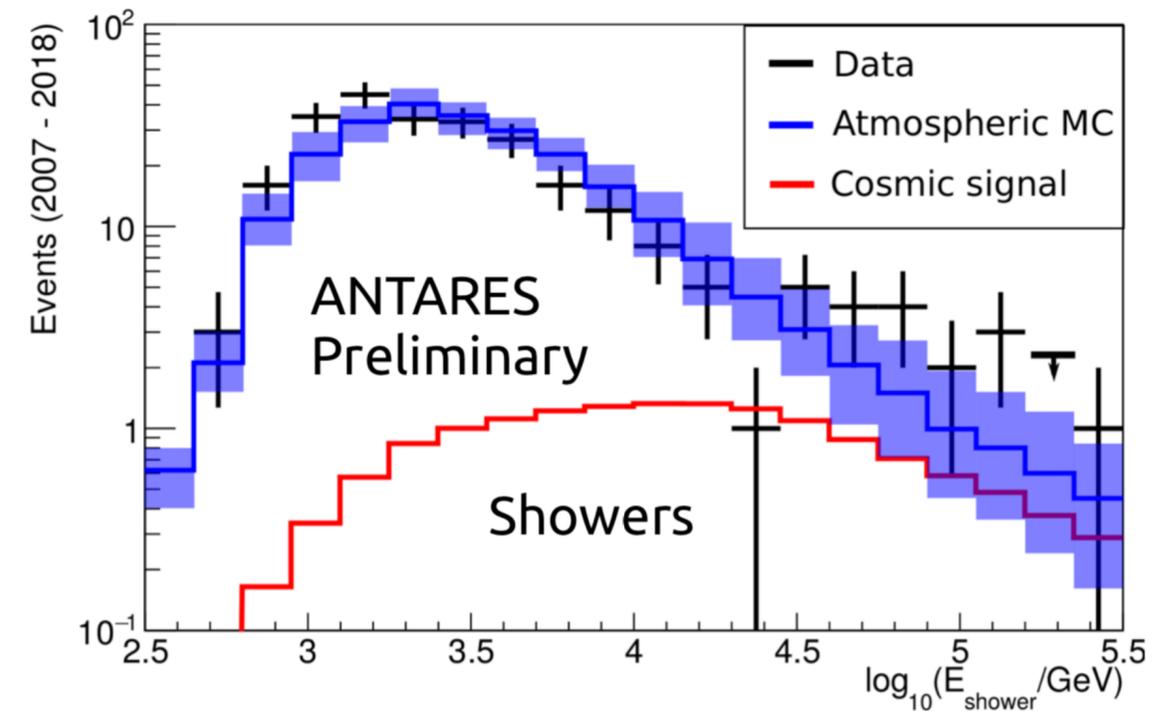


$$\Phi^{1f}(100 \text{ TeV}) = (1.5 \pm 1.0) \cdot 10^{-18} \text{ (GeV cm}^2 \text{ s sr)}^{-1}$$
$$\Gamma = 2.3 \pm 0.4$$

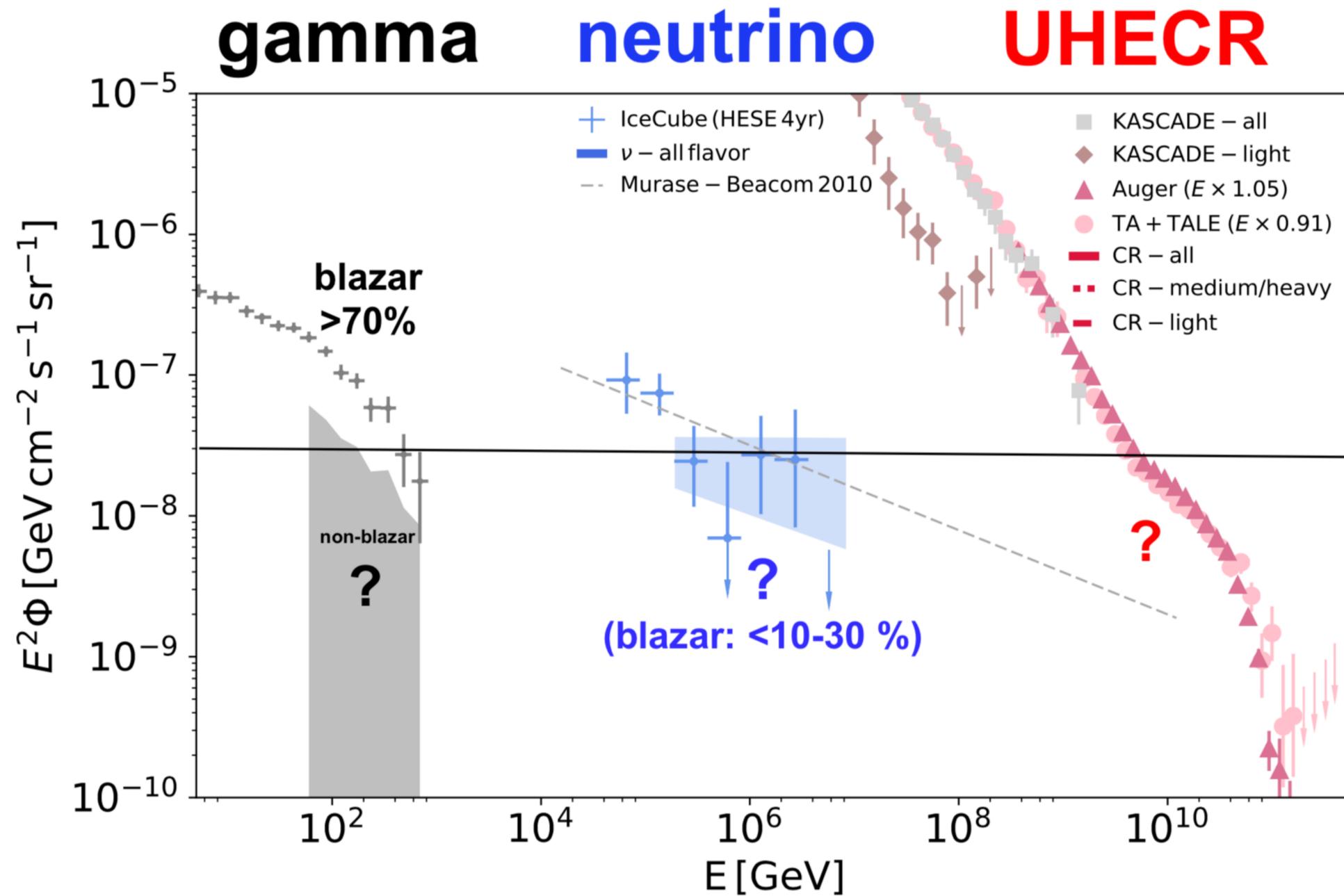
Atmospheric flux
 $1.25 \times$ (Honda + Enberg)

From the fit
 1.8σ excess
0-cosmic excluded c.l. >90%

**Compatible with IceCube measurement
but still low significance**



The multimessenger picture



- Connection between gammas, neutrinos and UHECR?
- How to connect them?

Particle energy budgets are roughly comparable (10^{43} - 10^{44} erg Mpc⁻³ yr⁻¹)

Neutrino – Gamma – UHECR Connection

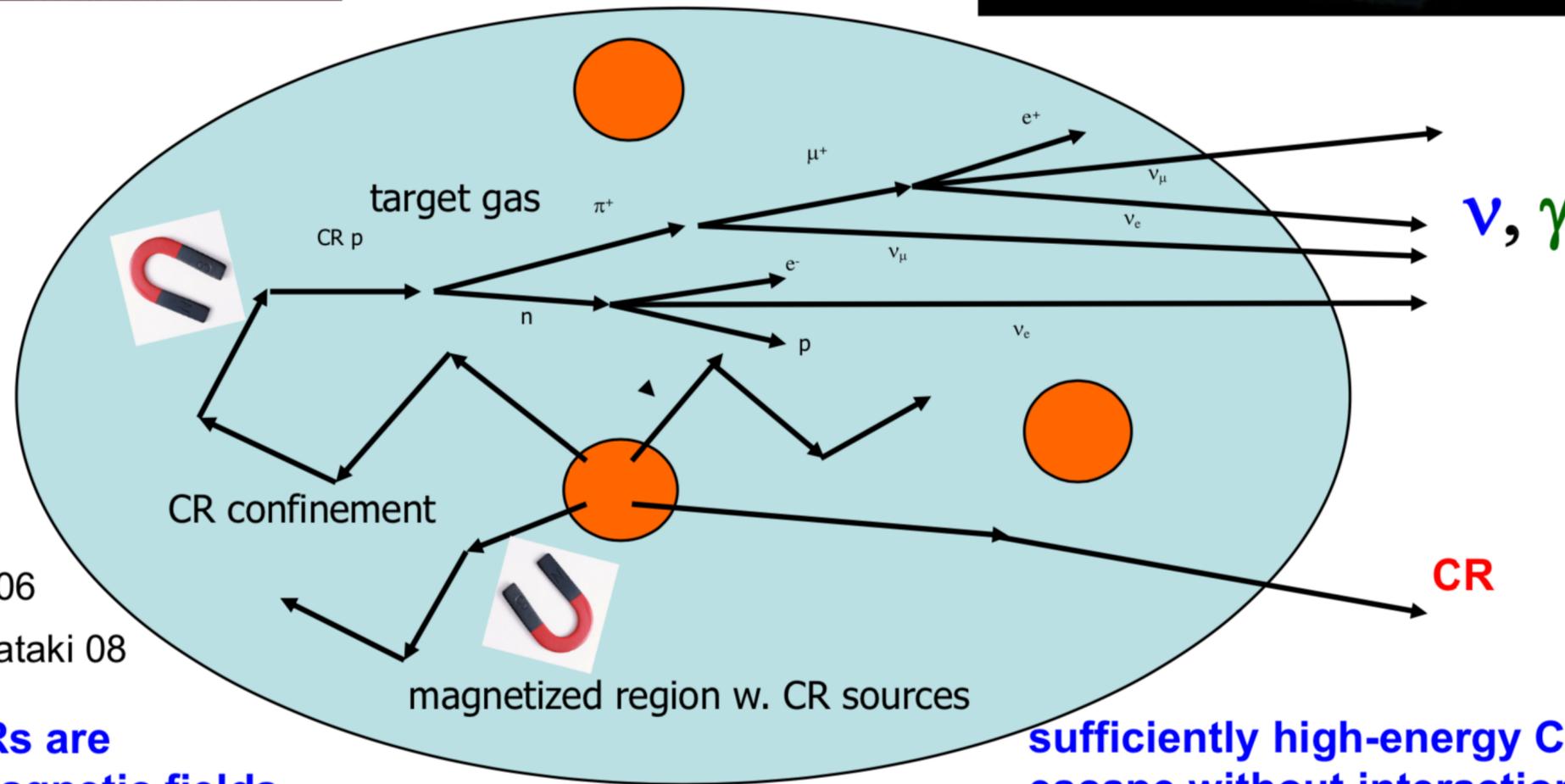
PoS(ICRC2019)965 (Kohta Murase)

Starburst galaxies



“cosmic-ray reservoirs”

Galaxy clusters/groups



Loeb & Waxman 06
KM, Inoue & Nagataki 08

low-energy CRs are confined by magnetic fields

sufficiently high-energy CRs escape without interactions

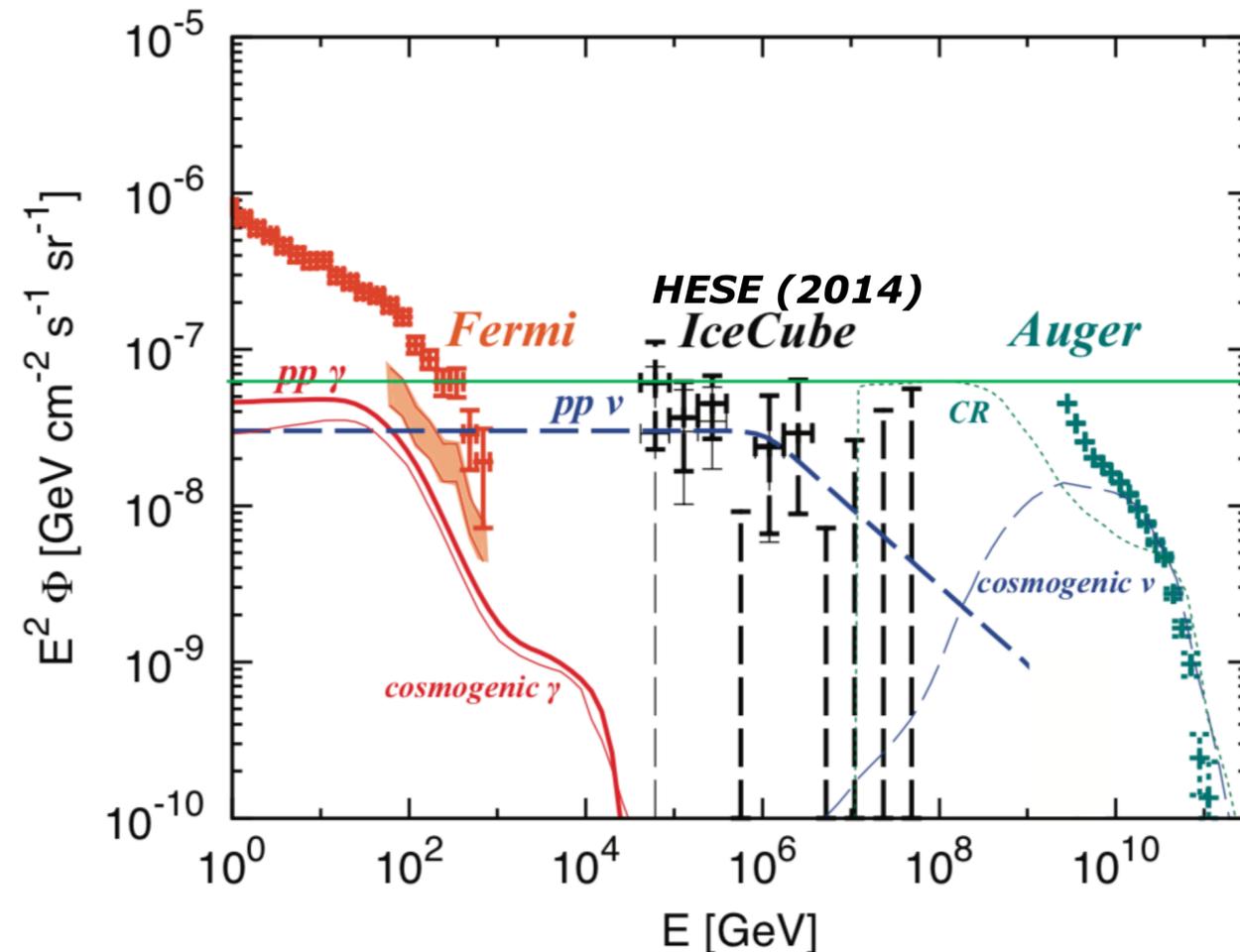
Neutrino – Gamma – UHECR Connection

Cosmic-ray reservoir:

(grand-)unification of neutrinos, gamma rays & UHECRs

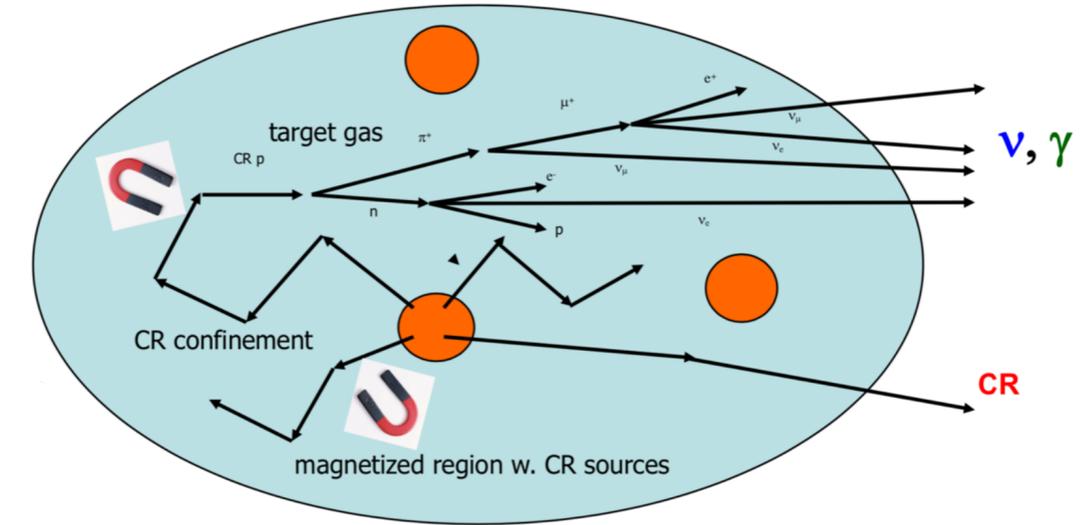
simple flat energy spectrum w. $s \sim 2$ can fit all diffuse fluxes

- Explain >0.1 PeV ν data with a few PeV break (theoretically expected)
- Escaping CRs may contribute to the observed UHECR flux

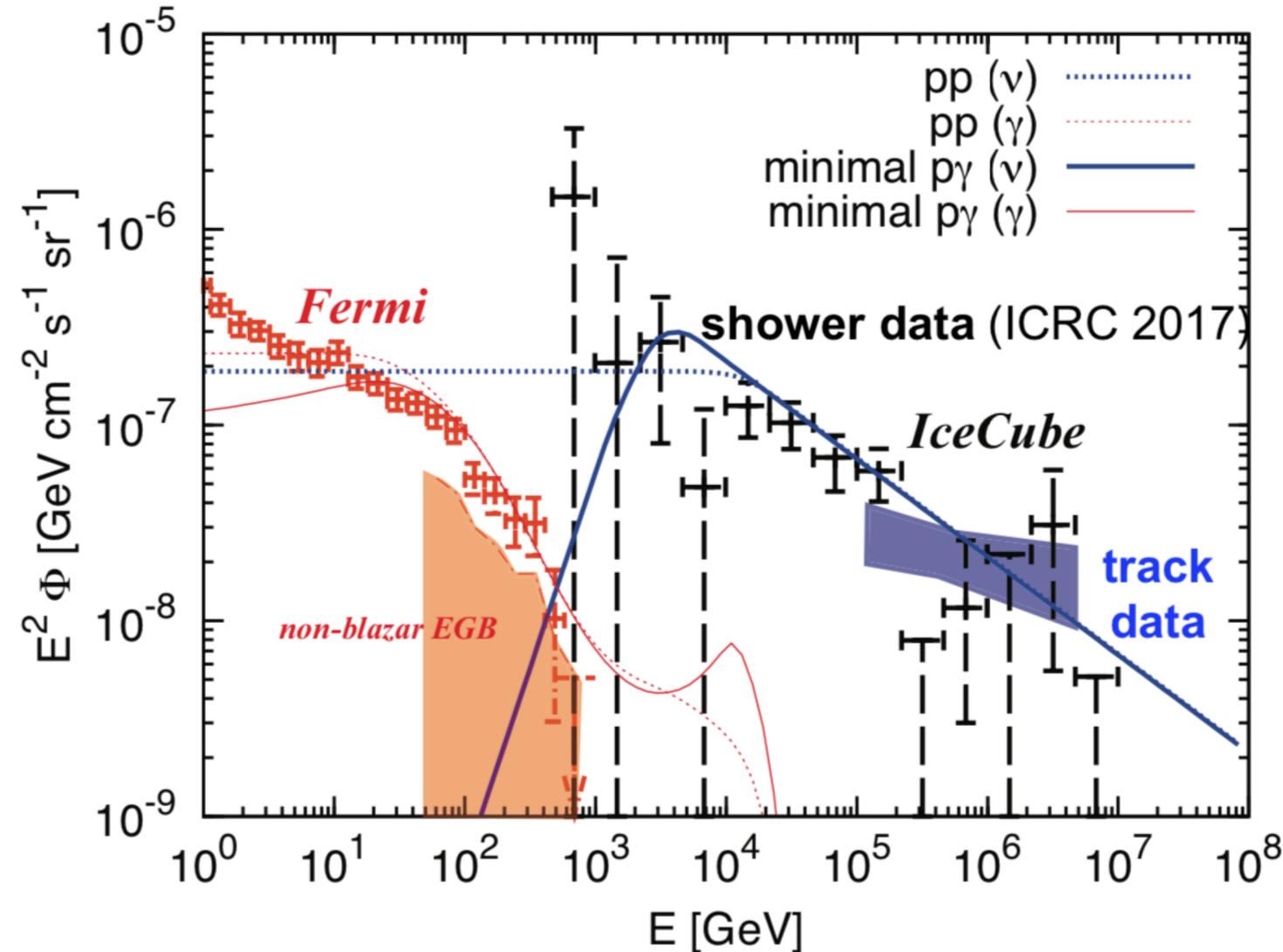


KM & Waxman 16 PRD

PeV ν – confined CR
 UHECR – escaping CR
 sub-TeV γ – “sum”



- 10-100 TeV shower data: large fluxes of $\sim 10^{-7}$ GeV cm⁻² s⁻¹ sr⁻¹



KM, Guetta & Ahlers 16 PRL

Potential deviation from single power law could be explained by two different source populations

- $\gtrsim 100$ TeV: gamma-ray transparent cosmic-ray reservoirs
- $\lesssim 100$ TeV: gamma-ray dark sources

Fermi diffuse γ -ray bkg. is violated ($>3\sigma$) if ν sources are γ -ray transparent

→ **existence of “hidden (γ -ray dark) sources”**

(ν data above 100 TeV can be explained by γ -ray transparent sources)



ICRC2019

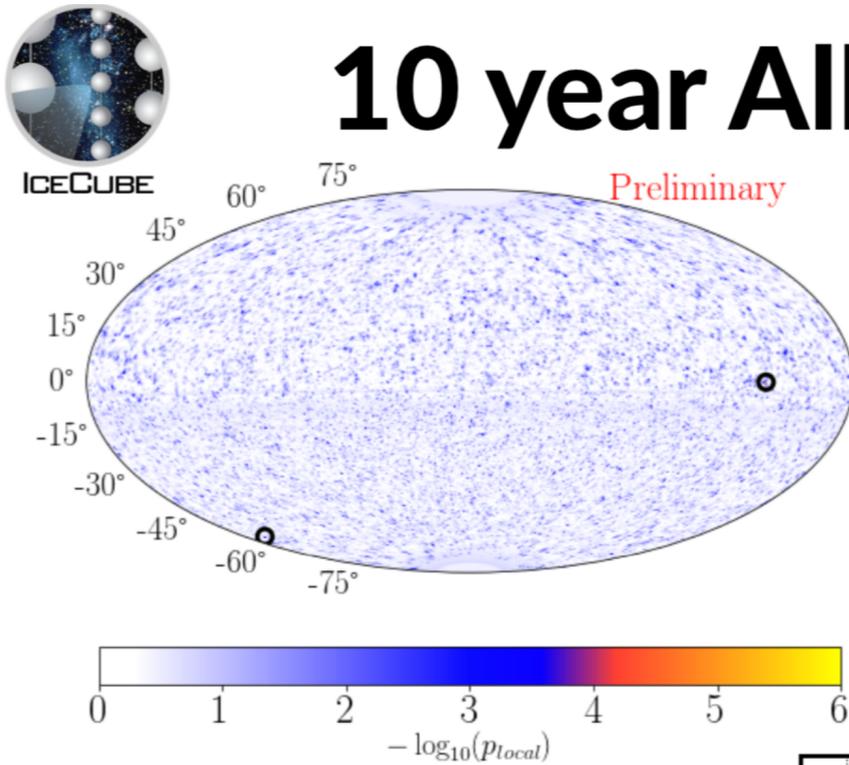
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**Searching for Point-like Source
and Multi-Messenger Activities**

Point-like sources – IceCube

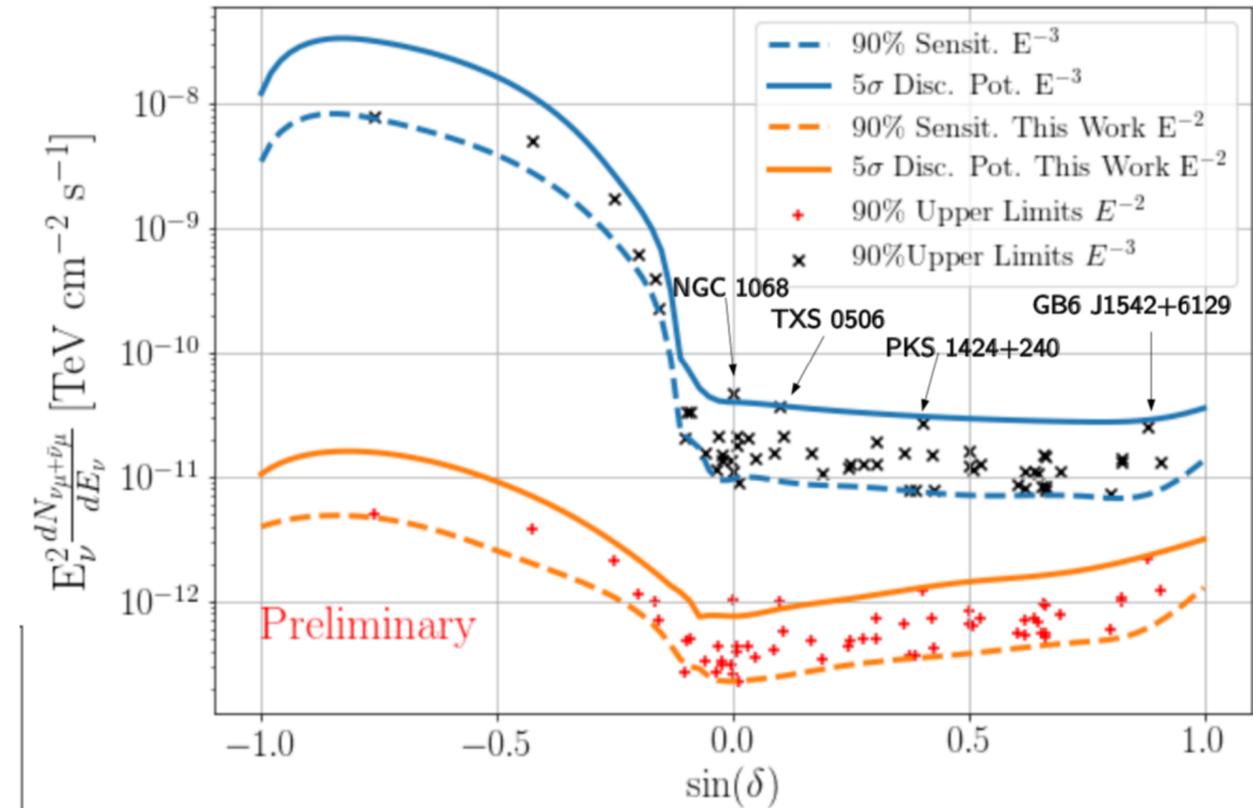
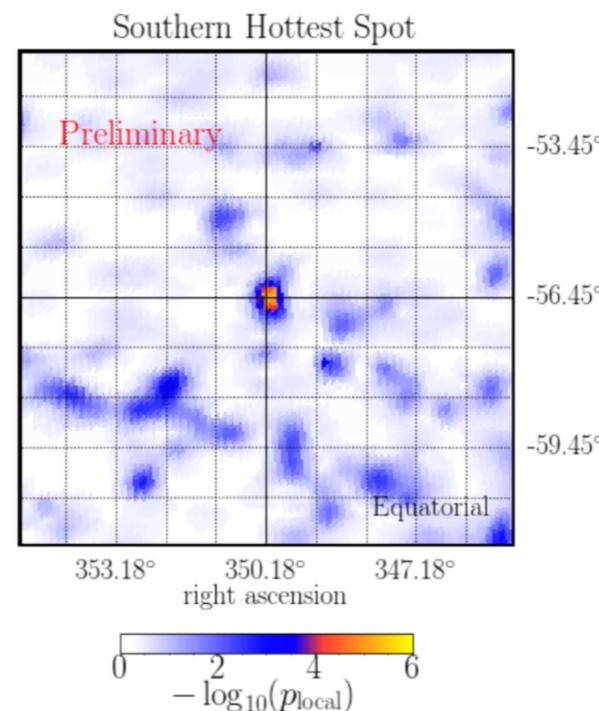
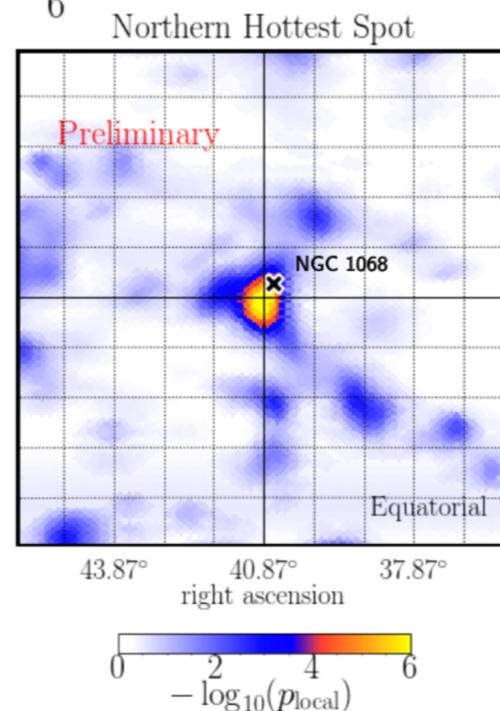
10 year All-Sky Scan Results



- Evaluate likelihood of signal over background for grid over entire sky.
- **Hottest point** = position with smallest p-value in each hemisphere.

Hottest Point in North : $\delta \geq -5^\circ$
 RA = 40.87° , Dec = -0.30°
 $n_{\text{signal}} = 61.5$, $\gamma = 3.4$, TS = 25.3
 $-\log_{10}(\text{pval}) = 6.45 \Rightarrow 9.9\%$ post-trial

Hottest Point in South : $\delta < -5^\circ$
 RA = 350.18° , Dec -56.45°
 $n_{\text{signal}} = 17.8$, $\gamma = 3.3$, TS = 20.0
 $-\log_{10}(\text{pval}) = 5.37 \Rightarrow 75\%$ post-trial

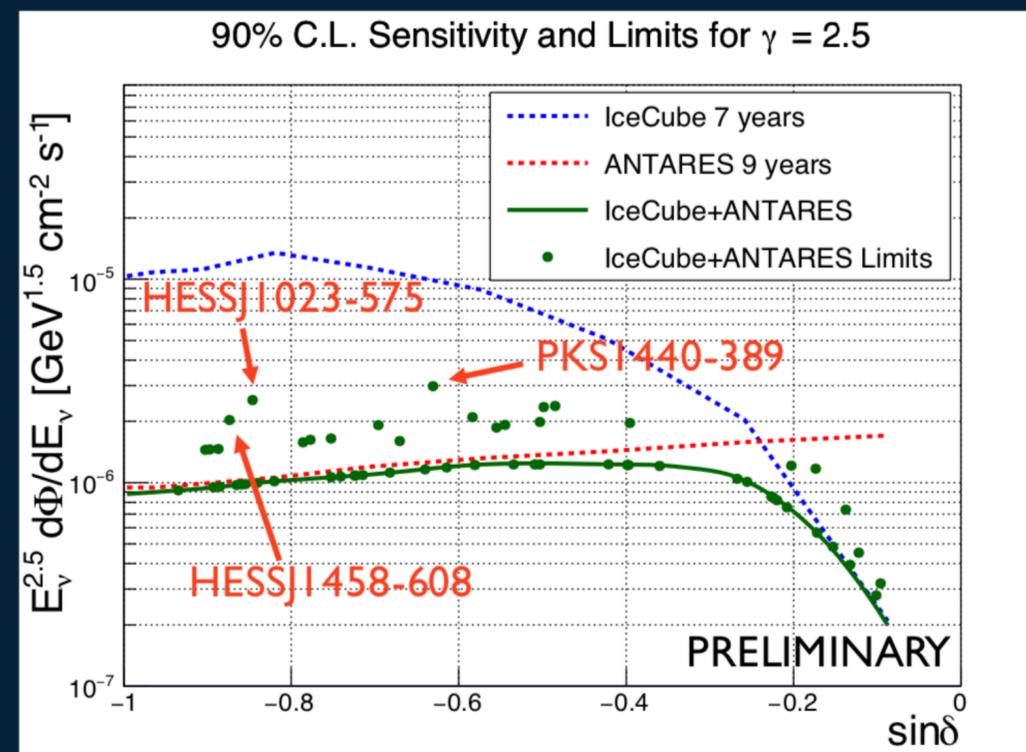
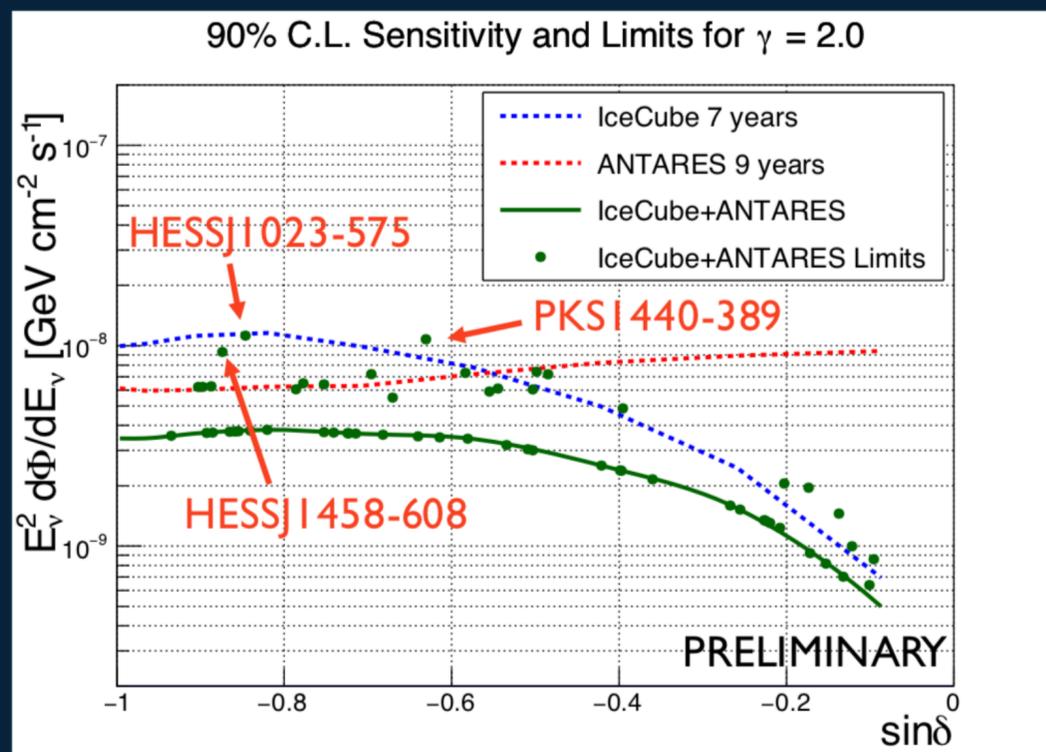


- Most significant source from list NGC1068 (2.9σ post trial)
- 4 most significant sources 3.3σ post trial (2.2σ without TXS 0506)

Point-like sources – combined ANTARES/IceCube analysis

PoS(ICRC2019)919 (Giulia Illuminati)

Source name	δ	\hat{n}_s	$\hat{\gamma}$	pre-trial p-value	$\Phi_{E^{-2.0}}^{90\%C.L.}$ [$10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1}$]	$\Phi_{E^{-2.5}}^{90\%C.L.}$ [$10^{-6} \text{ GeV}^{1.5} \text{ cm}^{-2} \text{ s}^{-1}$]
HESSJ1023-575	-57.76°	6.4	3.5	0.0079	11.2	2.5
PKS1440-389	-39.14°	3.0	2.4	0.0085	10.8	3.0
HESSJ1458-608	-60.88°	3.7	3.6	0.036	9.3	2.0



Highest excess:
HESSJ1023-575
0.2 σ post-trial
significance

Improvement up to a factor 2 achieved in the sensitivity to point sources compared to individual analyses

Multi-messenger activities

- **IceCube**

- New low-energy real-time stream for events starting in the detector
- Improved real-time neutrino alert system
- A catalogue of astrophysical neutrino candidates for IceCube

PoS(ICRC2019)954
PoS(ICRC2019)1021
PoS(ICRC2019)852

- **ANTARES**

- Overview alert system

PoS(ICRC2019)871

- **Astrophysical Multimessenger Observatory Network (AMON)**

- Real-time coincidences, sub-threshold data analyses

PoS(ICRC2019)841

New neutrino telescopes coming online — Baikal GVD first results

Stages of the deployment of the GVD-1

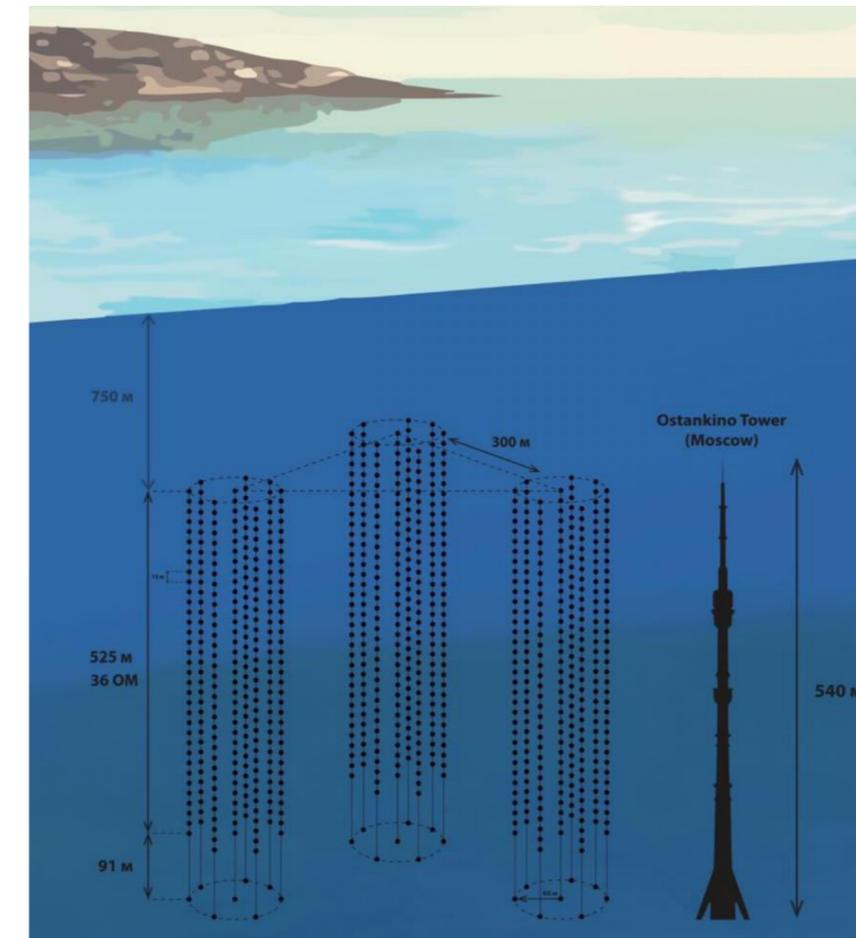
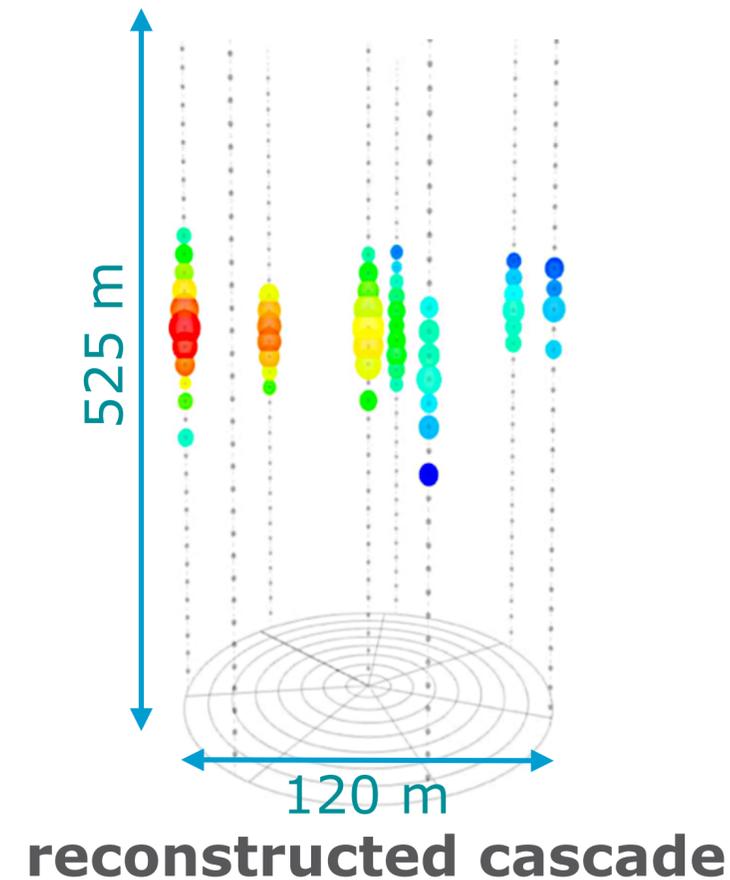
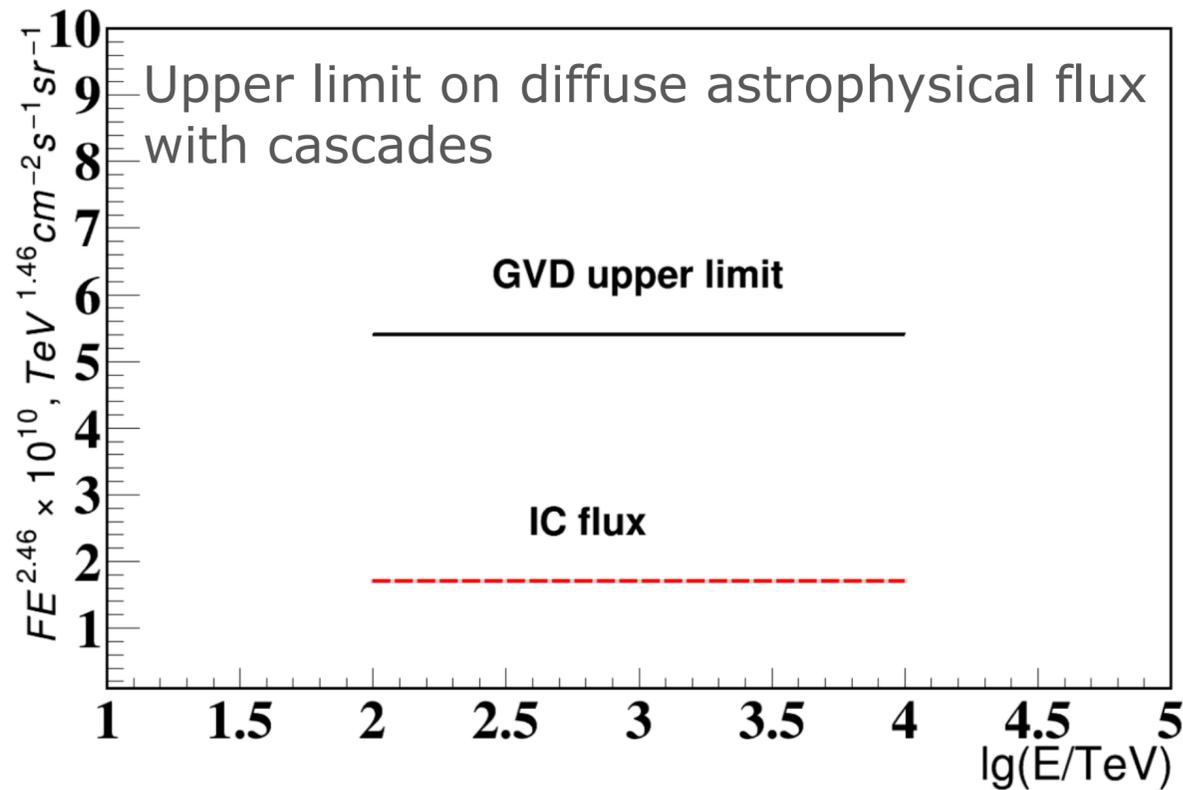
Configuration	2016	2017	2018	2019
The number of OMs	288 (8str×36)	576	864	1 440
Geometric sizes	∅120m×525m	2×∅120m×525m	3×∅120m×525m	5×∅120m×525m
Eff. Vol. (E > 100TeV)	0.05 km ³	0.1 km ³	0.15 km ³	0.25 km ³

PoS(ICRC2019)873 (Rastislav Dvornick)

PoS(ICRC2019)1011 (F. Smikovic)

PoS(ICRC2019)876 (L. Fajt)

**Goal GVD-1:
8 clusters by 2021**



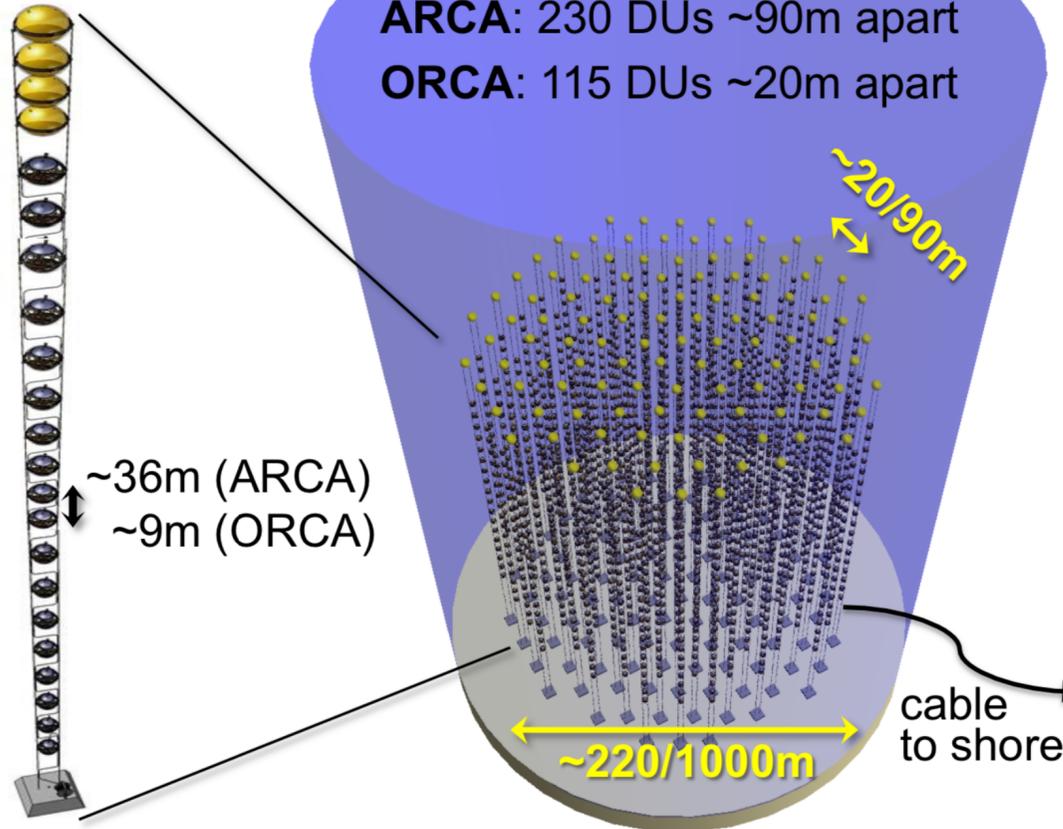
New neutrino telescopes coming online — KM3NeT ARCA/ORCA first results

Digital Optical
Module (DOM)

Detection
Unit (DU)



31 x 3"-PMTs
(19↓, 12↑)



Jannik Hofestädt, ICRC2019, Madison, 26.07.2019

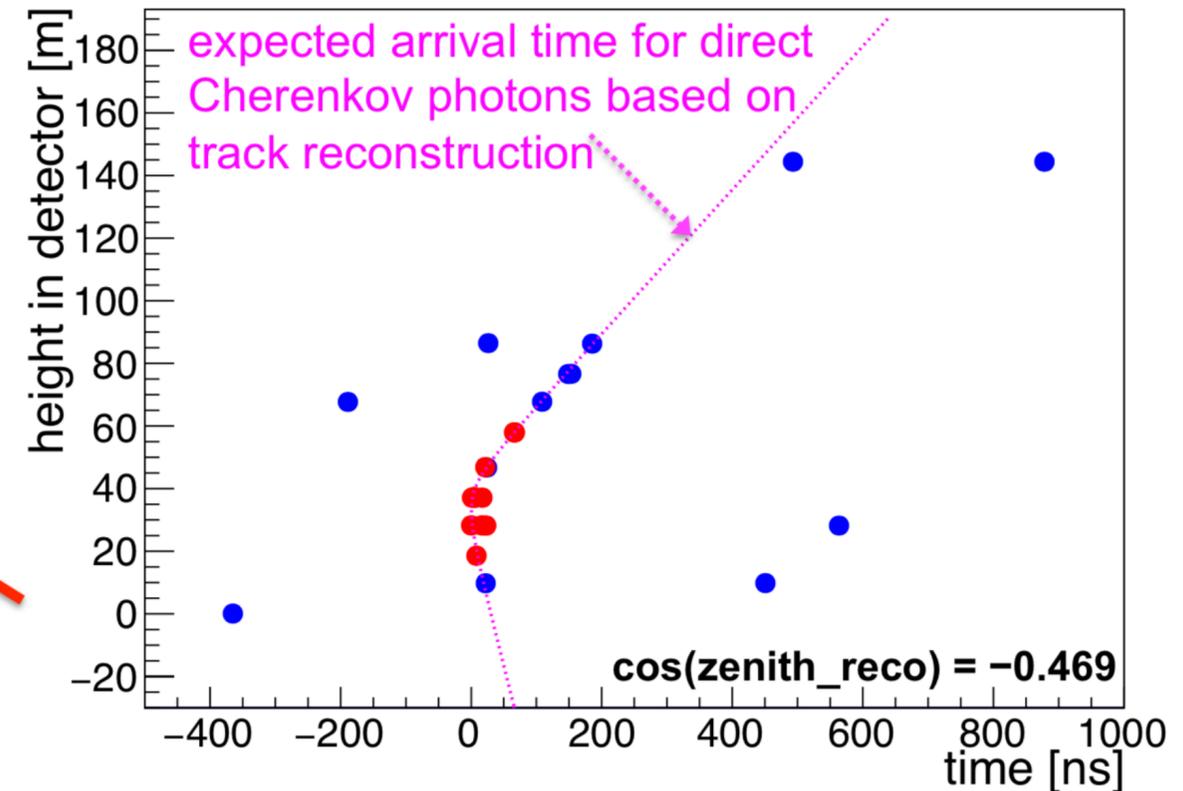
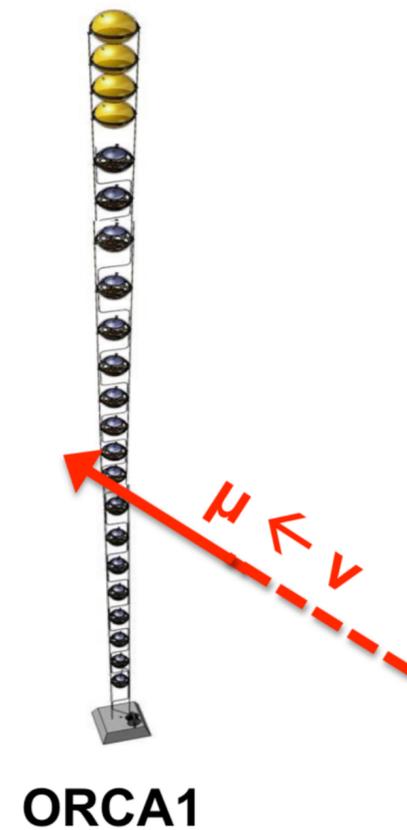
3

Status:

- KM3NeT-ARCA 1 line
- KM3NeT-ORCA 4 lines

• Example: up-going neutrino candidate

event=1668, run=2974, #hits=26, $\cos(\text{zenith_reco})=-0.469$
DU 2



- Most detected photons arrive 'on-time' due to the large scattering length in deep-sea water

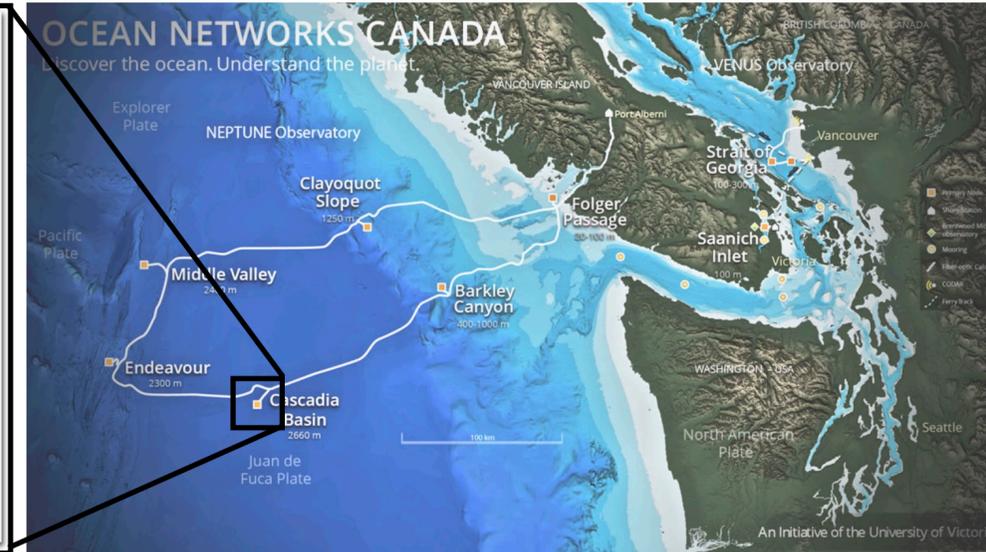
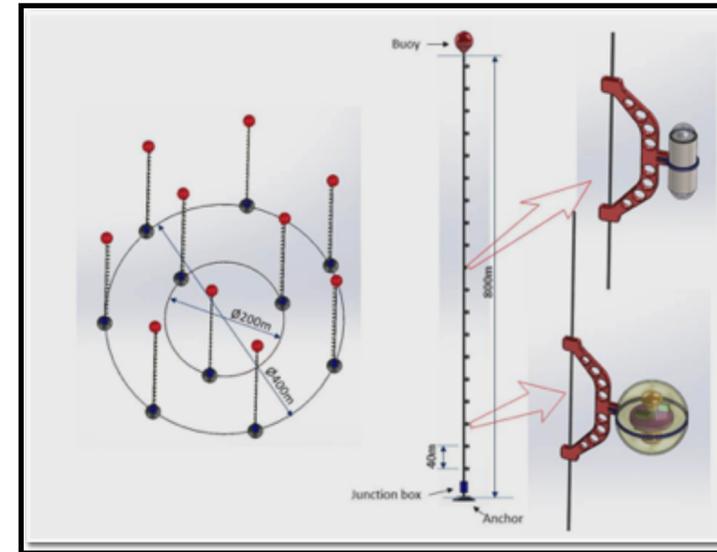
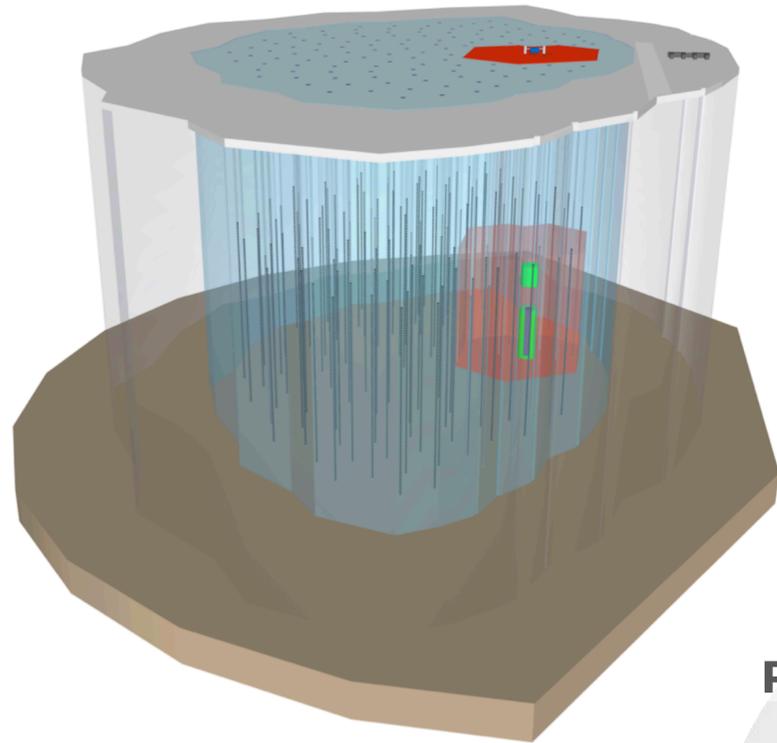
Jannik Hofestädt, ICRC2019, Madison, 26.07.2019

Neutrino reconstruction with single line !

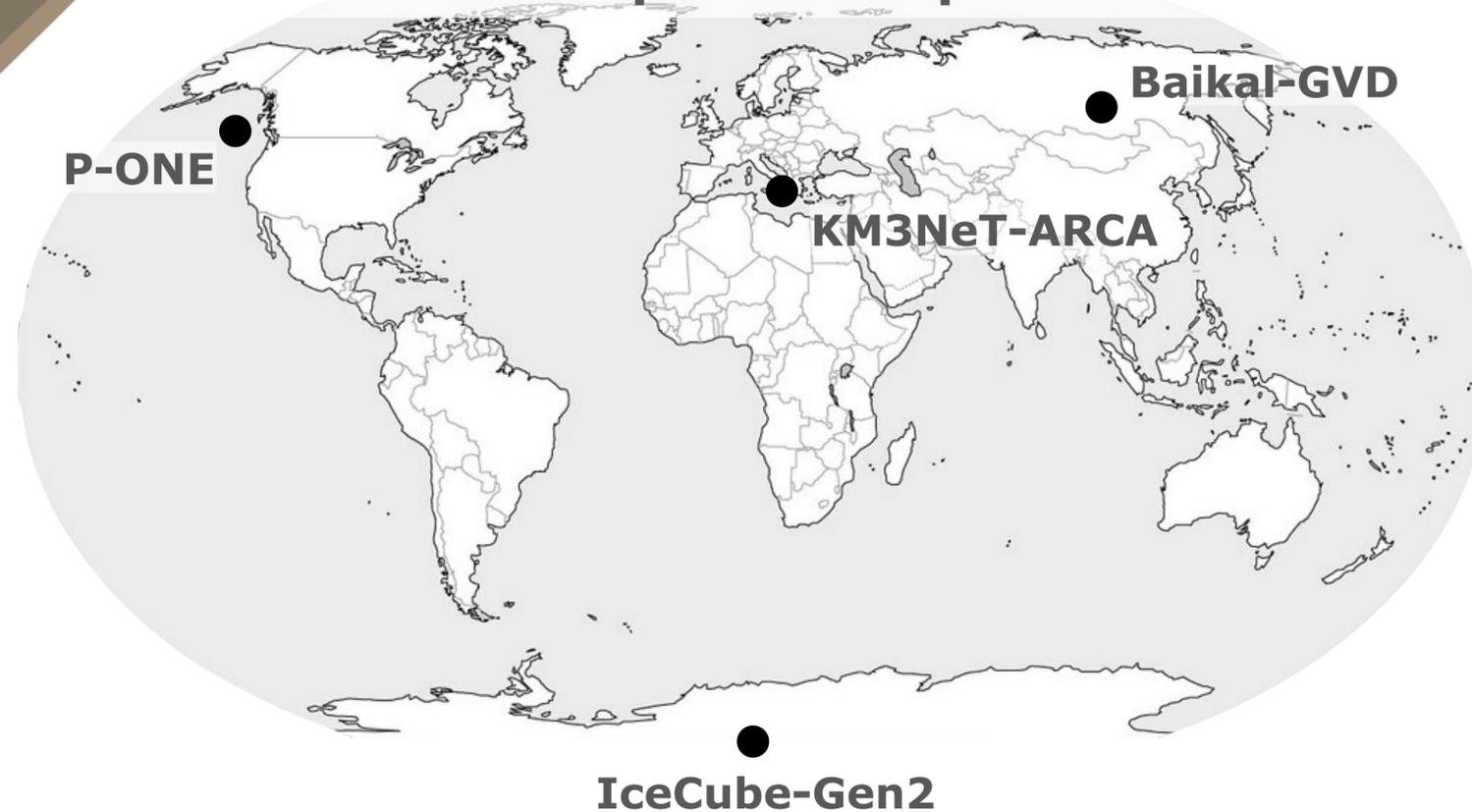
Future neutrino telescopes

P-ONE (E. Resconi) — New kid on the block

IceCube-Gen2



Neutrino telescope landscape in 2025–30



- In conceptual phase
- Up to 500 strings optimized for horizontal HE muon tracks
- STRAW pathfinder mission successfully operating (PoS(ICRC2019)890)



ICRC2019

36th International Cosmic Ray Conference - Madison, WI, USA

THE ASTROPARTICLE PHYSICS CONFERENCE

The Quest for UHE Neutrinos

Finding UHEv – Current/planned experiments, and new ideas

Air showers

- Radio (*interferometric*)

- **ANITA** PoS(ICRC2019)867
- **TAROGÉ** PoS(ICRC2019)967
- **BEACON** PoS(ICRC2019)1033
- **GRAND** PoS(ICRC2019)233

- Particles

- **Auger** PoS(ICRC2019)979

- Cherenkov

- **Ashra-1**, NTA PoS(ICRC2019)976
(also fluorescence)
- **TRINITY** PoS(ICRC2019)970
- **POEMMA** PoS(ICRC2019)378

In-ice showers

- Radio

- **ARA**, ARA5 PoS(ICRC2019)858
- **ARIANNA**, ARIA PoS(ICRC2019)980
- **RNO** PoS(ICRC2019)913

- Radar

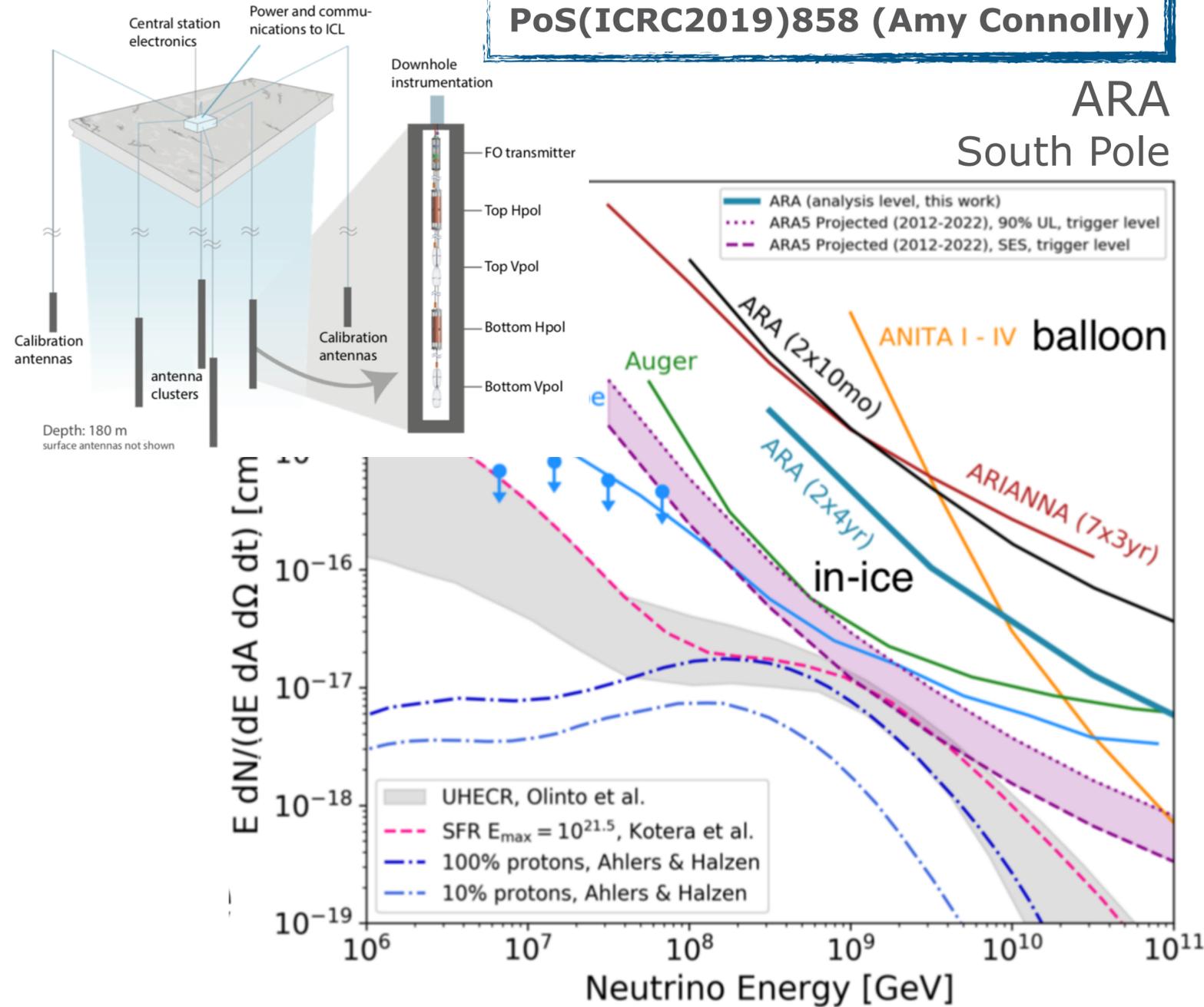
running, planned

PoS(ICRC2019)986

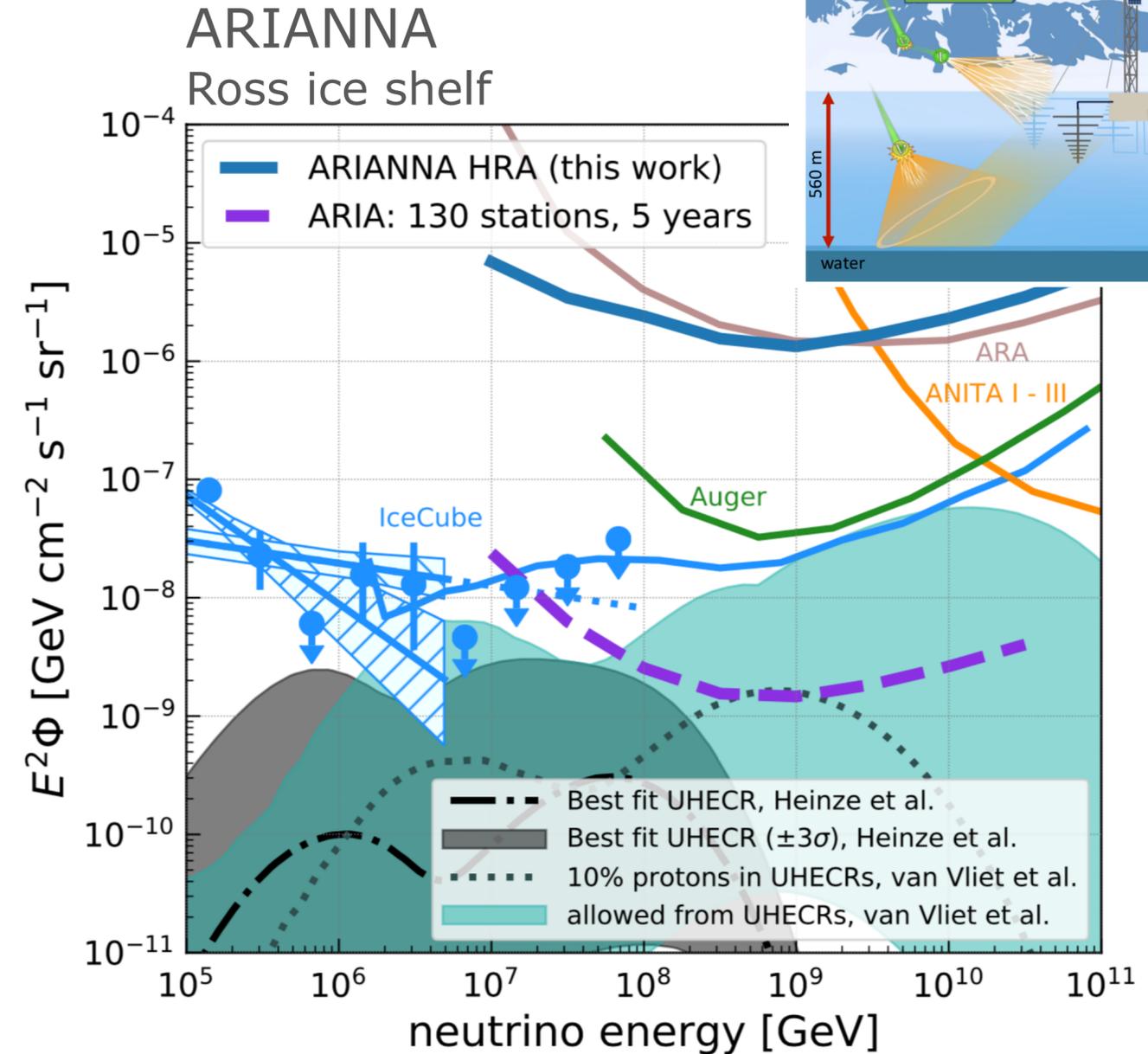
UHE ν — Why radio?

Large attenuation lengths (~ 1 km) enable observation of large volumes > 100 's km^3

PoS(ICRC2019)858 (Amy Connolly)

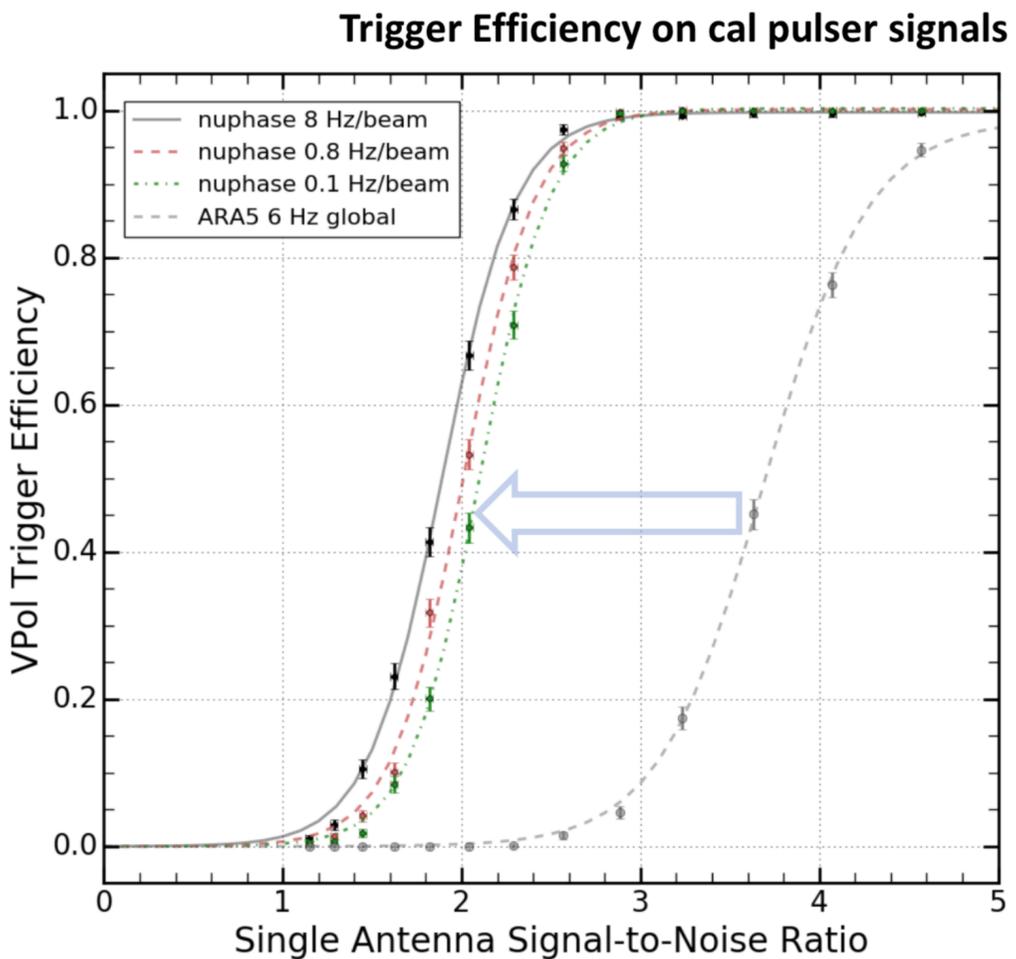


PoS(ICRC2019)980 (Christian Glaser)



Lowering the energy threshold with interferometry – Test setup in ARA

- Phased array (10-antenna) installed in A5 station
- In-situ measurements using A5 station calibration pulser, in the near field

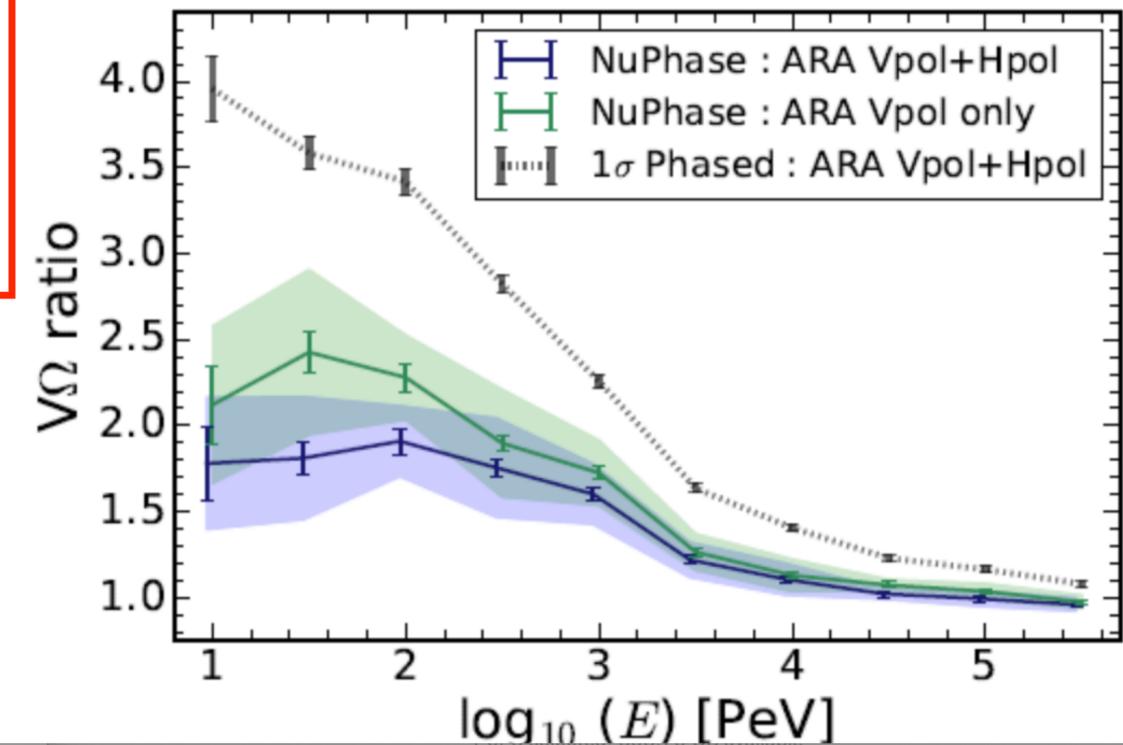
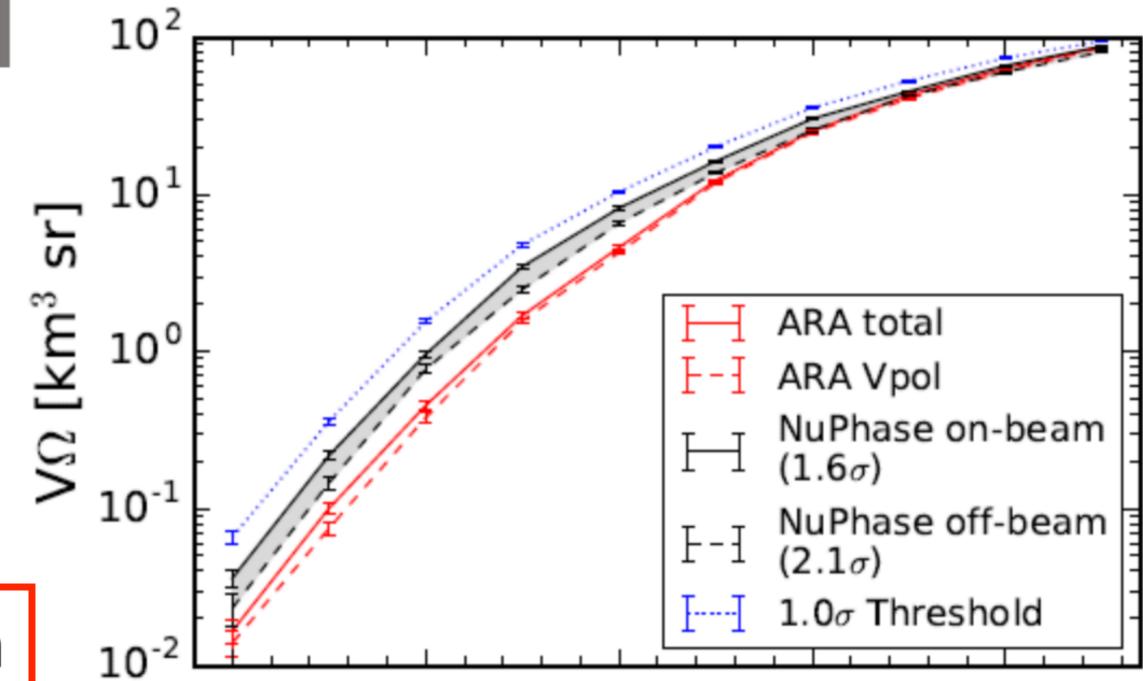


Effective Volume

Measured performance of the ARA NuPhase trigger added to the ARASim detector simulation package

Demonstrated ~2x increase in per-station trigger-level effective volume at 10-300 PeV

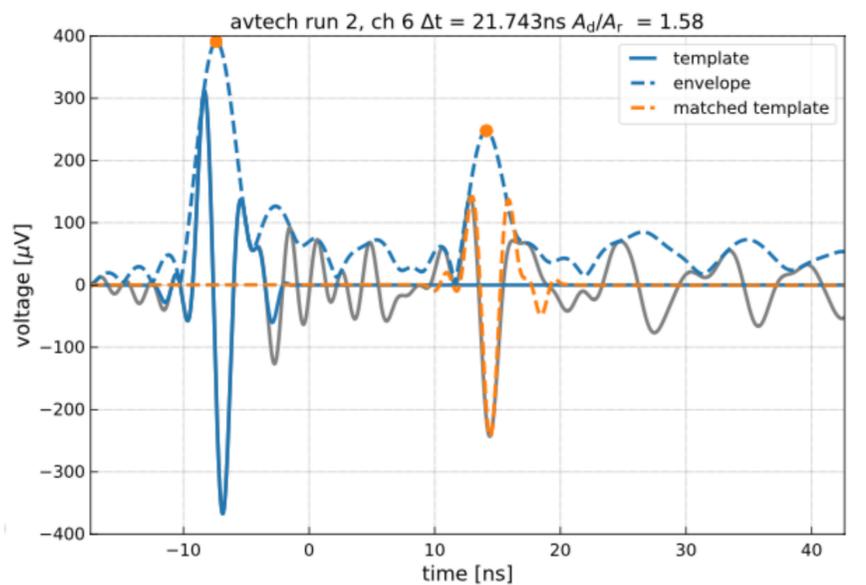
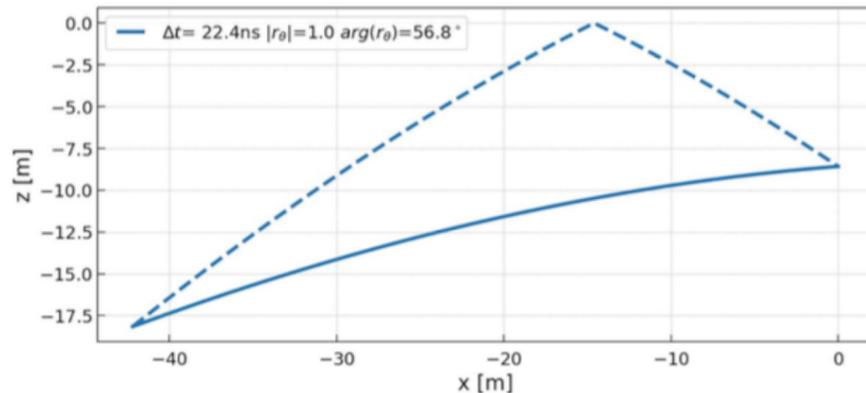
Also studied an enhanced trigger system with lower threshold at VSNR=1.



Reconstruction of energy and direction in ARIANNA

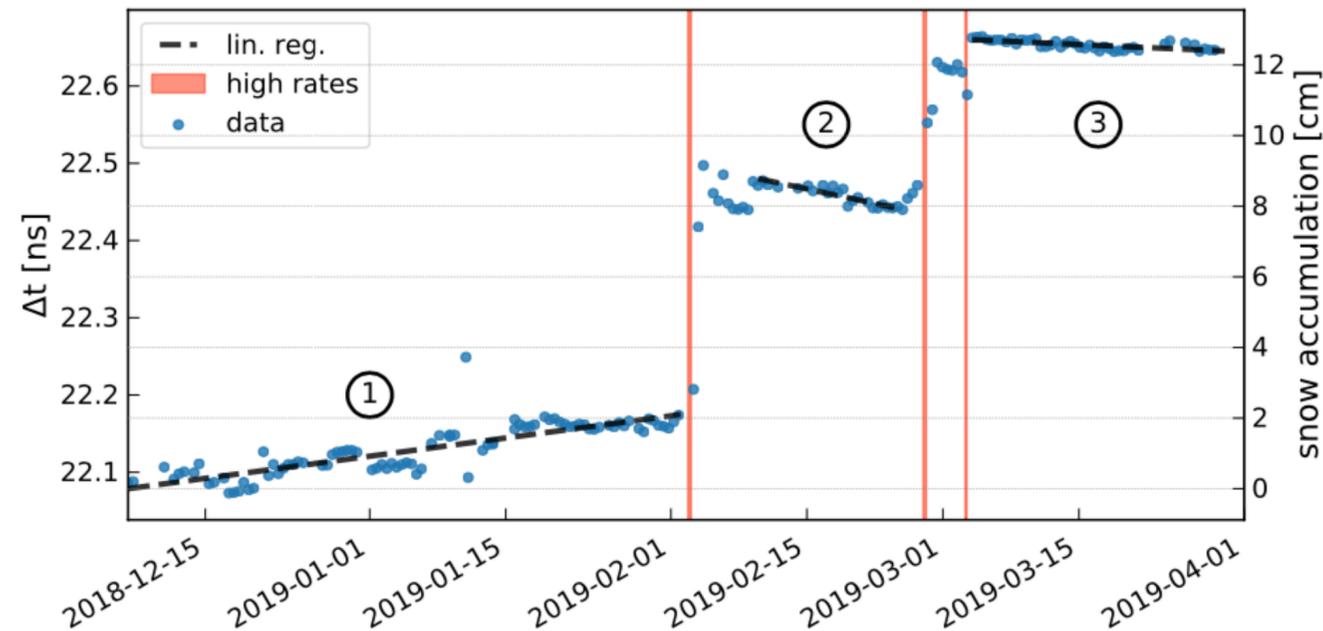
Reconstruction of Neutrino Direction and Energy

- A shallow detector has good sensitivity to the neutrino
 - **direction** (2° dominated by signal polarization, 7° already demonstrated via CRs)
 - **energy** (factor of two, limited by inelasticity fluctuations)
- Precise vertex distance reconstruction (15%) via **direct** and **reflected** signal detection



Also need to take snow accumulation into account

Proof of concept: Snow accumulation measurement



Neutrino reconstruction
PoS(ICRC19)899
PS1-108

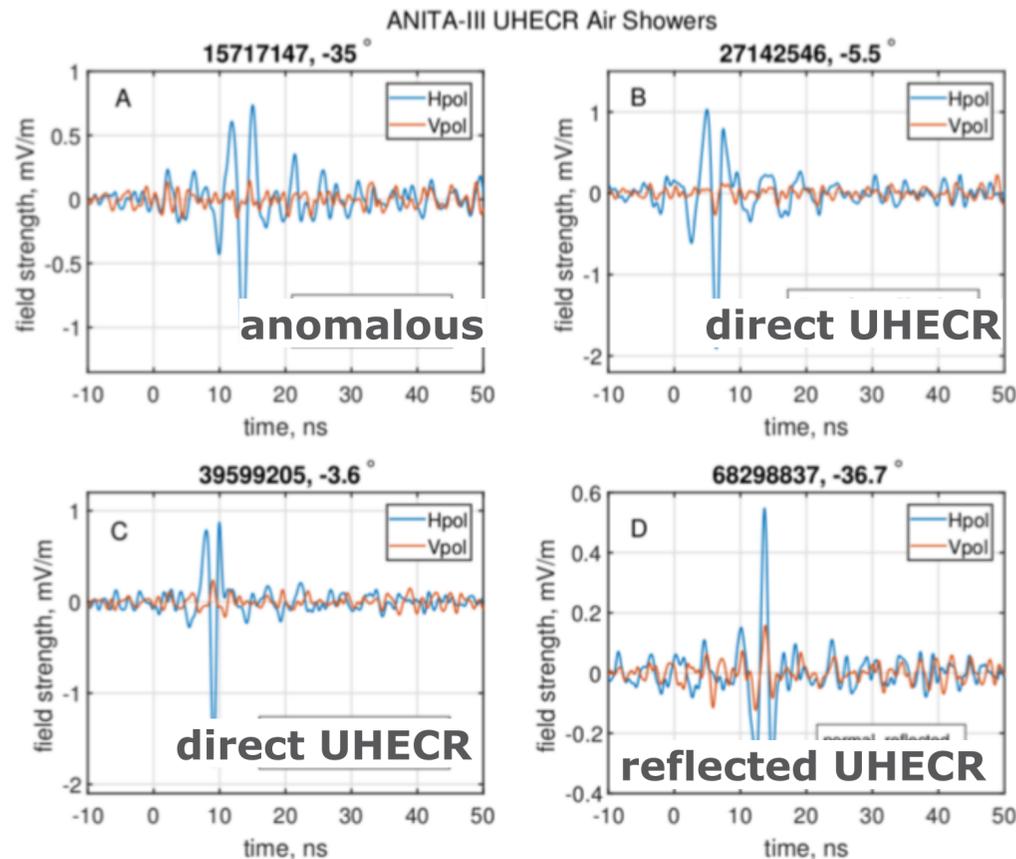
Cosmic rays
PoS(ICRC19)366
A. Nelles
Talk Saturday

NuRadioReco software
PoS(ICRC19)900
PS3-110

NuRadioMC software
PoS(ICRC19)896
PS3-107

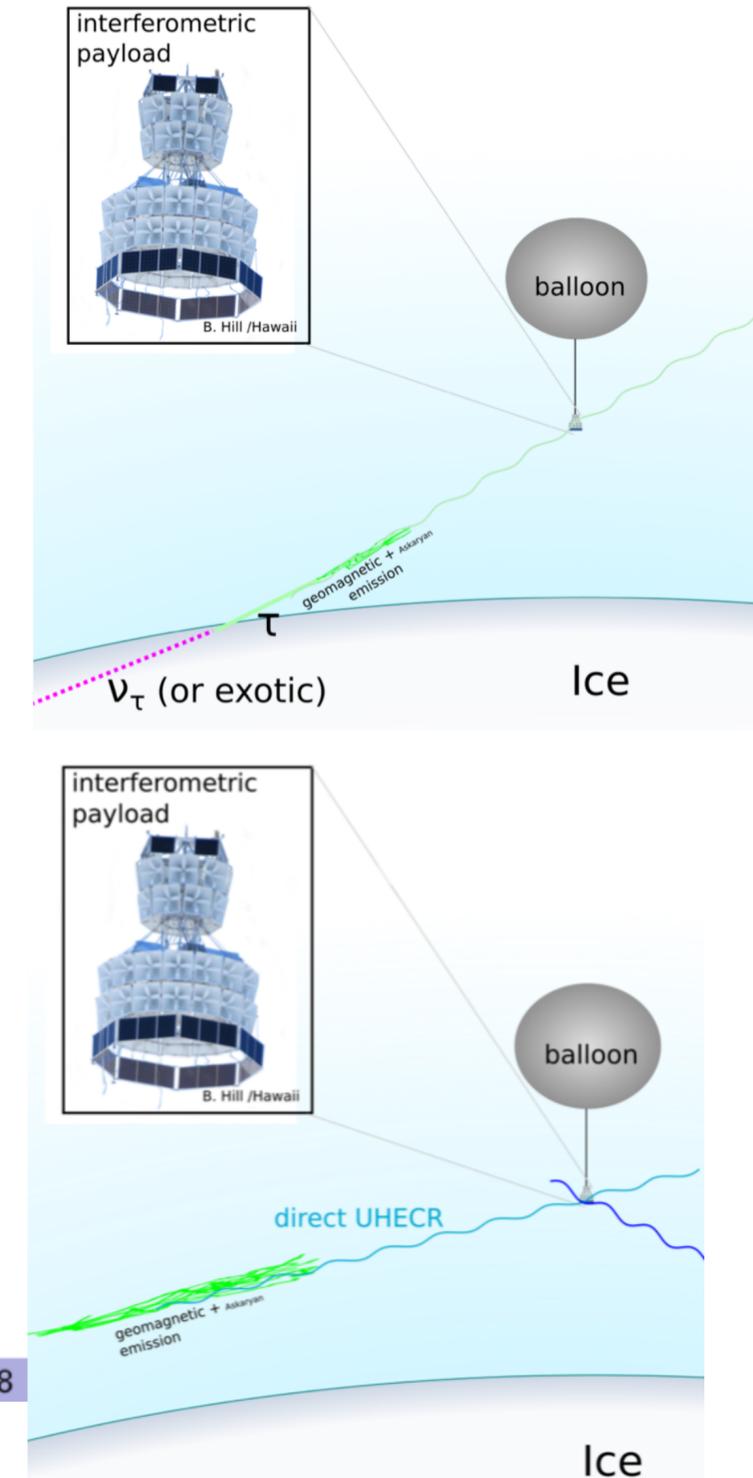
ANITA mystery events

Upward Shower Searches



Top-Left: Anomalous A-III event
 Top-Right, Bottom-Left: Direct UHECR candidates
 Bottom-Right: A reflected UHECR candidate

- An anomalous event found in ANITA-III (Phys.Rev.Lett. 121 (2018) no.16, 161102), similar to event found in ANITA-I.
- Mostly HPol, matches UHECR template, polarity consistent with direct cosmic ray event, but clearly points to ice, so consistent with an upward going air shower.
- “Looks like” a $\nu_\tau \rightarrow \tau$ candidate, but chord length through Earth in tension with SM cross-section and flux in tension with Auger and IceCube limits; a number of other explanations have been proposed.
- **ANITA-IV unblinded polarity not ready yet (sorry!).**



IceCube follow up on anomalous ANITA events

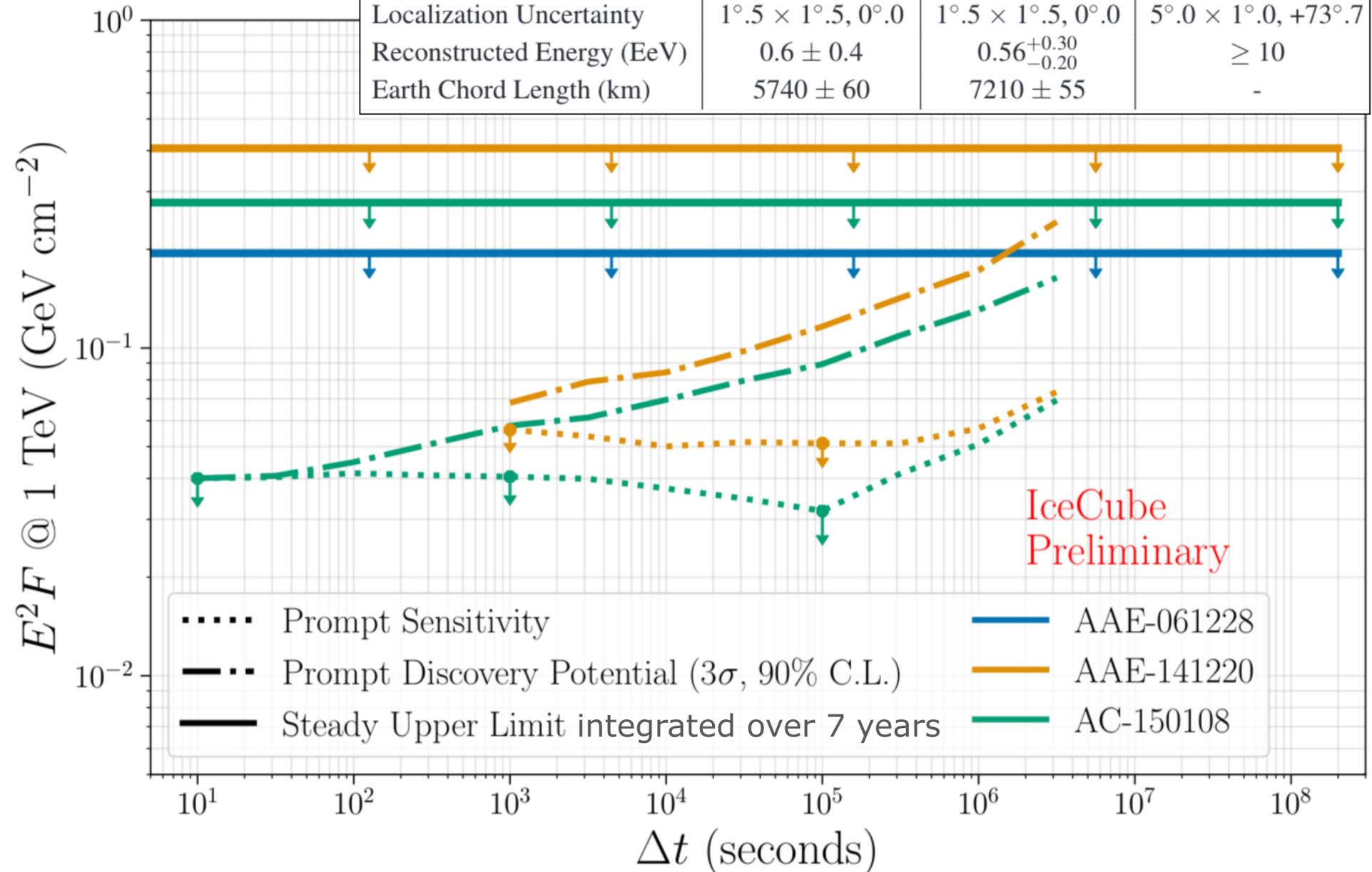
Diffuse flux interpretation exceeds bounds of many experiments

→ individual cosmic accelerator (with short emission timescale)

Search for counterparts in direction of ANITA events in IceCube data

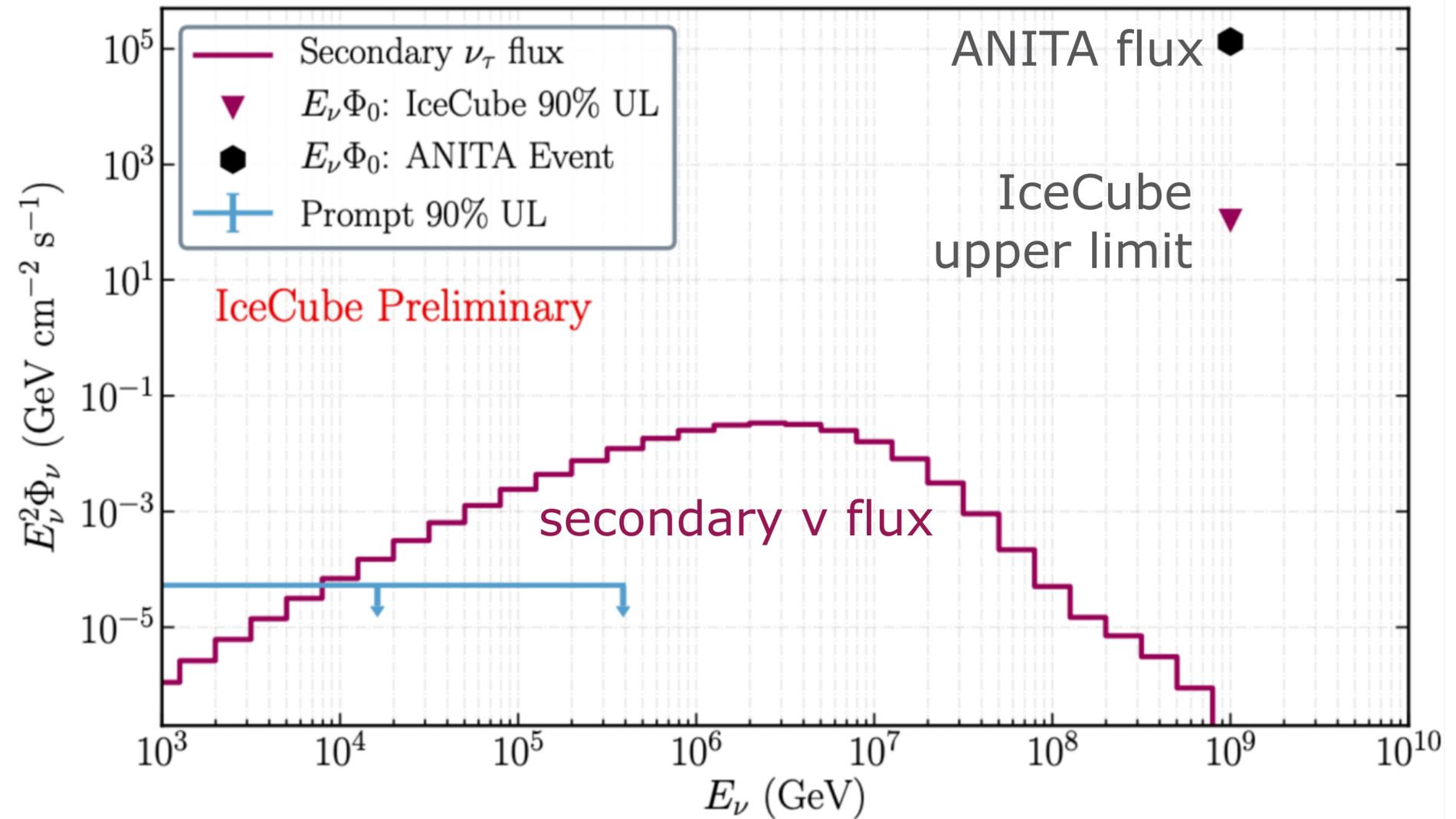
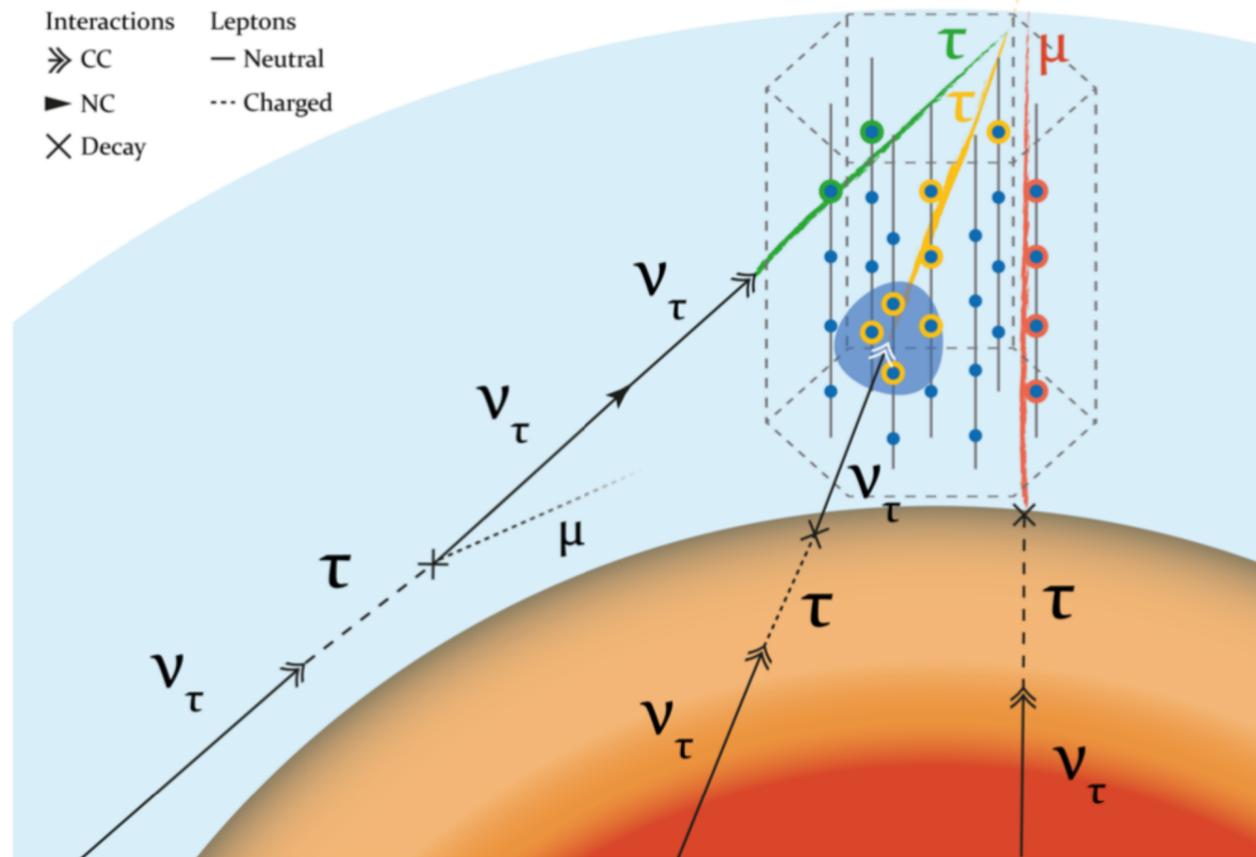
- Prompt: Search for coincident signal on short timescales ($\leq 10^5$ seconds)
- Steady: Time-integrated search for spatial clustering
- Results compatible with background → upper limits

	AAE-061228	AAE-141220	AC-150108
Detection Channel	Geomagnetic	Geomagnetic	Askaryan
Date (UTC)	2006-12-28	2014-12-20	2015-01-08
Time (UTC)	00:33:20.0	08:33:22.5	19:04:24.2
RA, Dec (J2000)	282°.14, +20°.33	50°.78, +38°.65	171°.45, +16°.30
Localization Uncertainty	1°.5 × 1°.5, 0°.0	1°.5 × 1°.5, 0°.0	5°.0 × 1°.0, +73°.7
Reconstructed Energy (EeV)	0.6 ± 0.4	0.56 ^{+0.30} _{-0.20}	≥ 10
Earth Chord Length (km)	5740 ± 60	7210 ± 55	-



IceCube follow up on anomalous ANITA events

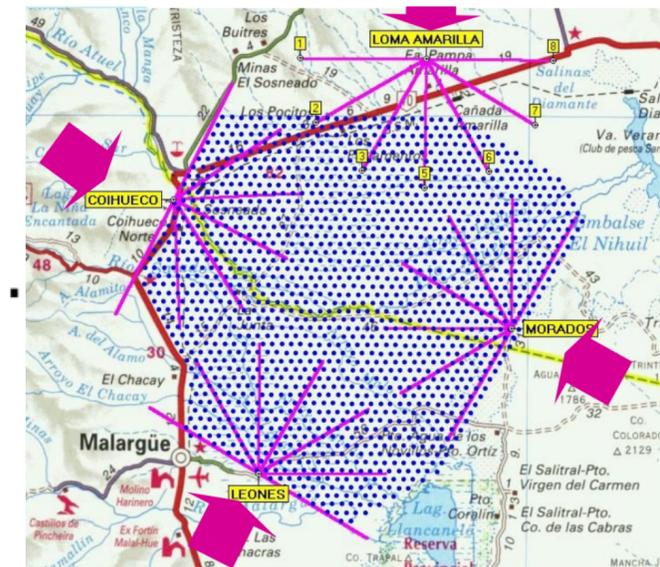
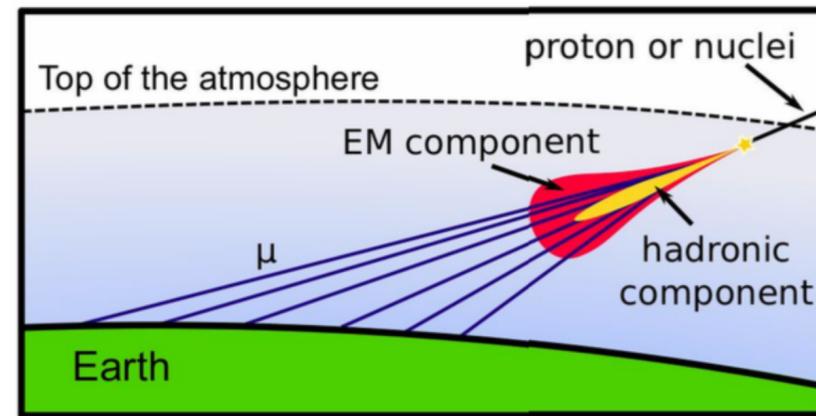
- Flux of EeV ν_τ traversing Earth will produce a secondary neutrino flux at lower energies via ν_τ regeneration
 - Set upper limit on EeV ν_τ flux from non observation in prompt analysis (1000 s time window)
- ANITA mystery event requires over-fluctuation at the 10^3 level !



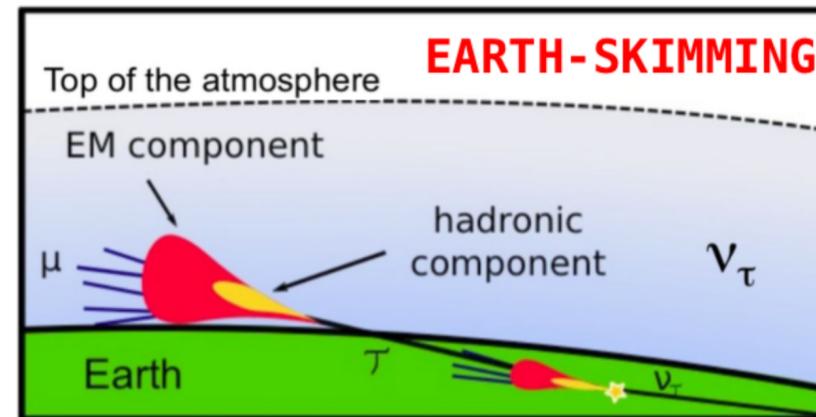
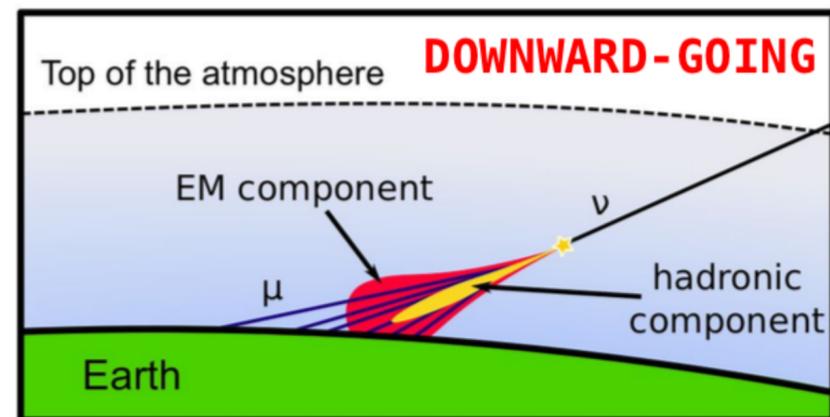
Detecting UHE ν with air showers

Neutrino identification in inclined showers

- **Protons & nuclei** initiate inclined showers high in the atmosphere.
Shower front at ground: mainly muons (small electromagnetic component).



- **Neutrinos** can initiate “deep” showers close to ground.
Shower front at ground: electromagnetic + muonic components.

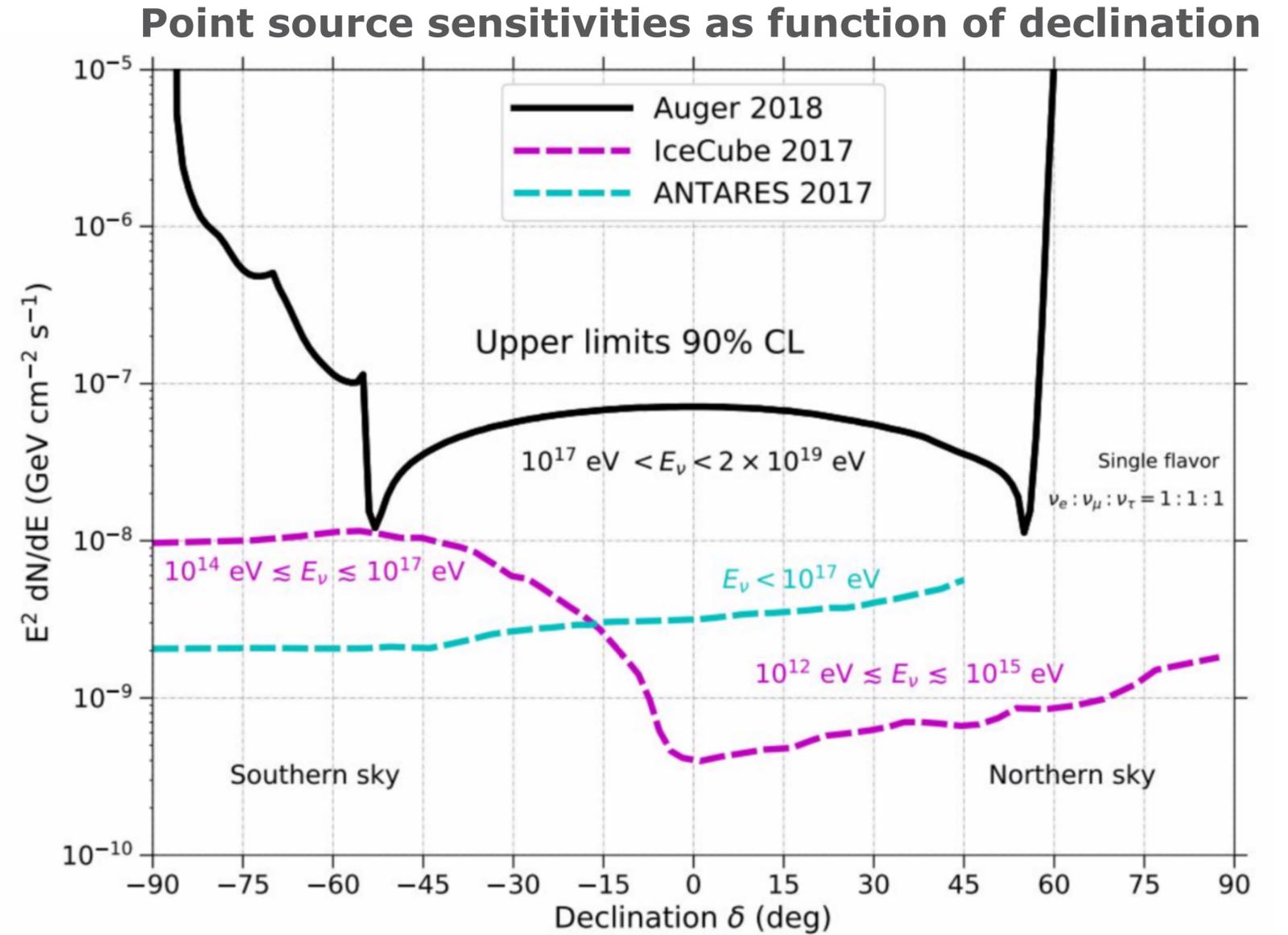
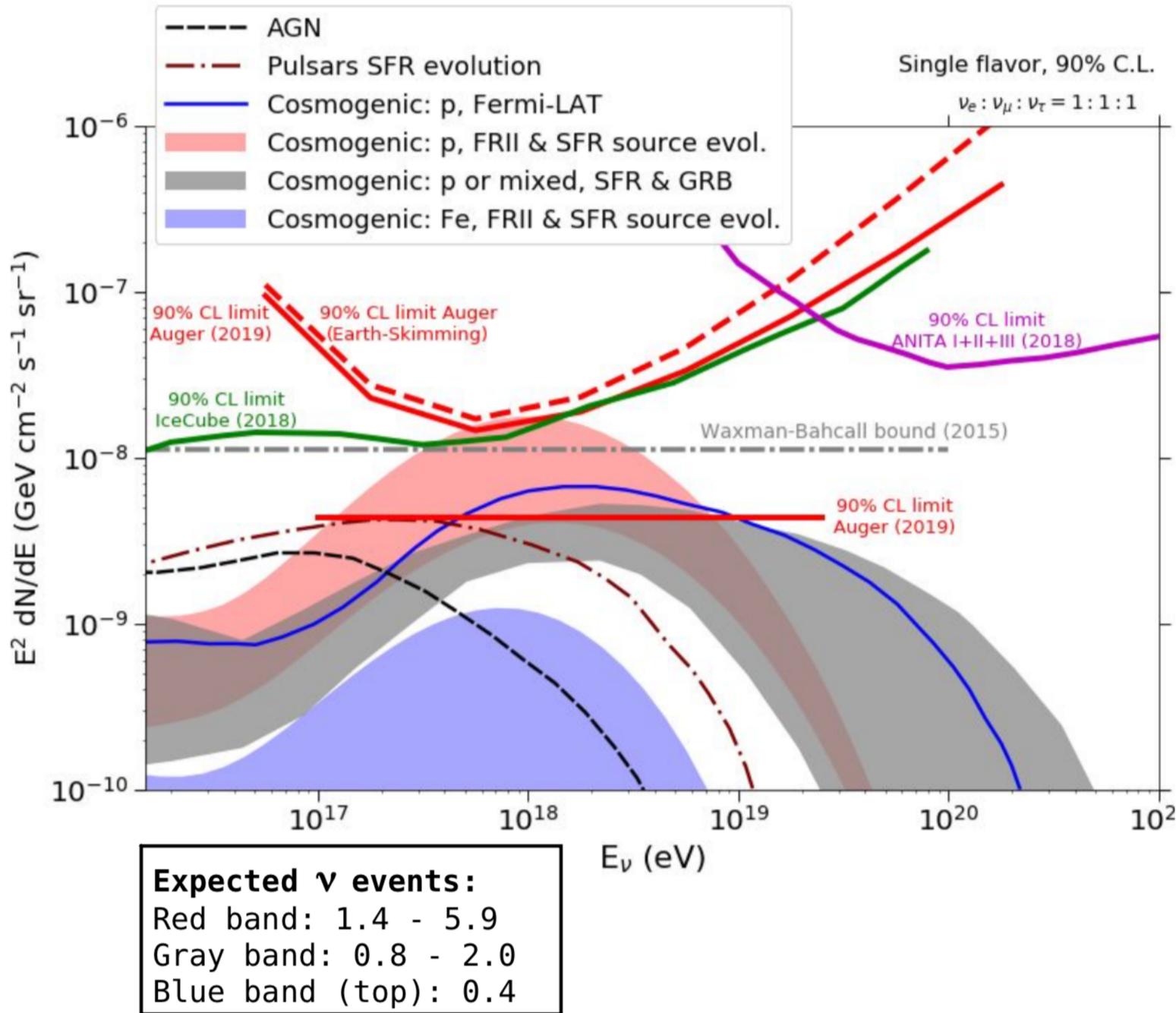


Earth-skimming most sensitive channel

VISIBLE SKY:
Earth-skimming ~ 5%
Downward-going ~ 25%

AUGER – Sensitivities

Limits to the diffuse flux of UHE ν

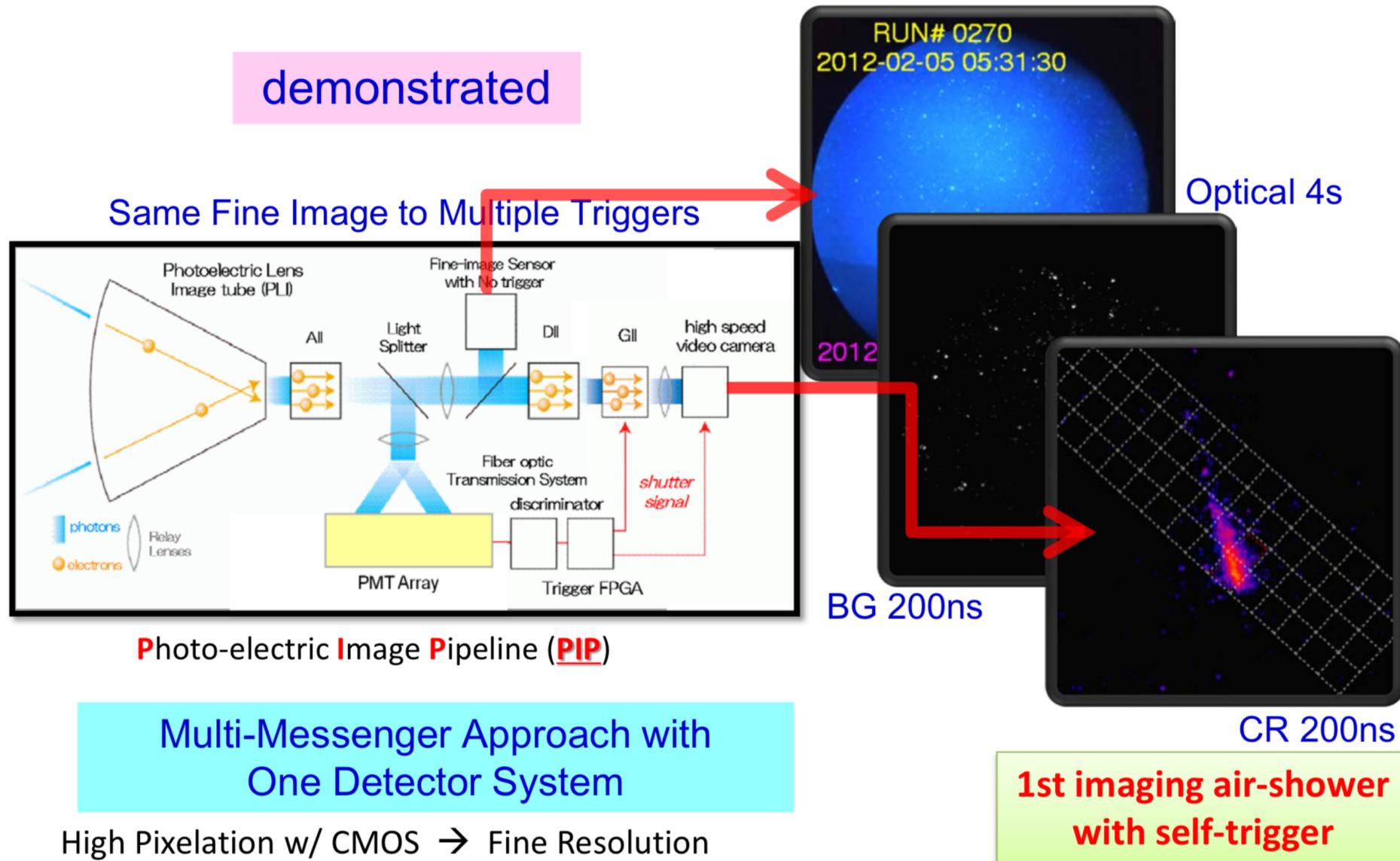


UHE ν with Cherenkov and fluorescence — Astra and NTA

PoS(ICRC2019)970 (Satoru Ogawa)

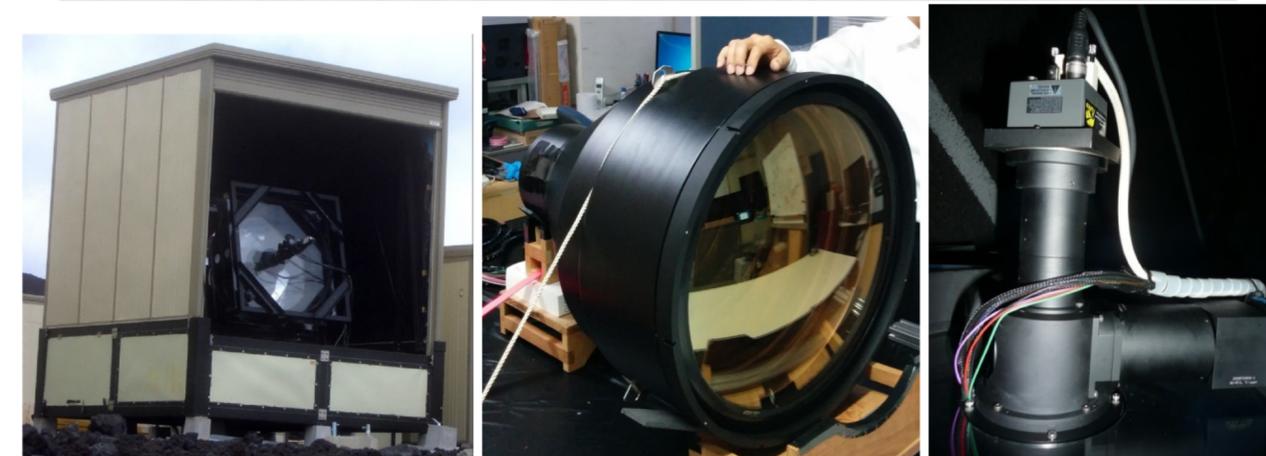
Ashra-1 Pipeline Trigger & Readout

demonstrated



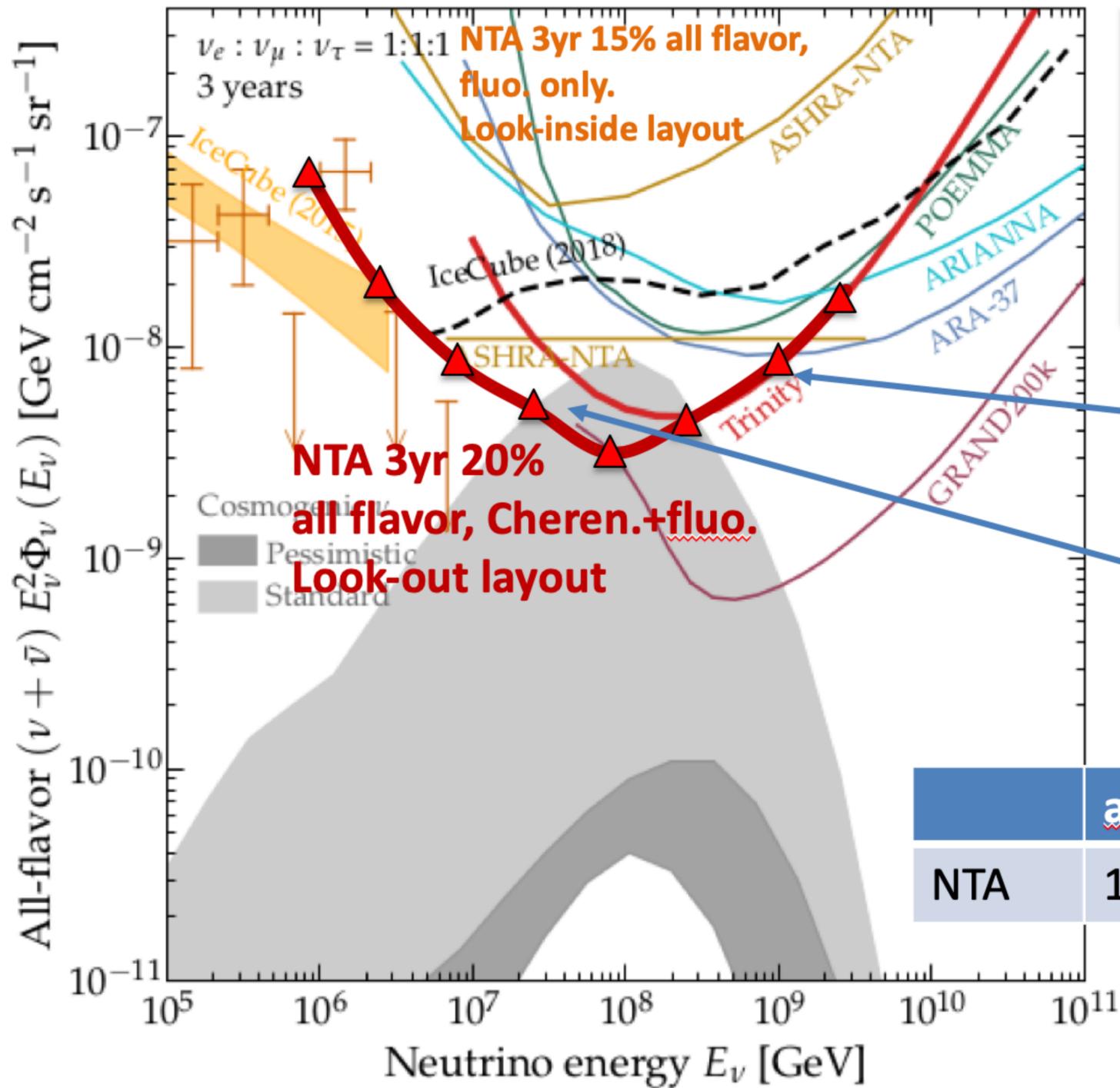
- Looking for Earth skimming tau neutrinos (also optical transients)
- Large field of view: 42°
- High resolution images of air showers

NTA LoI: arXiv:1408.6244



UHE ν with Cherenkov and fluorescence — Ashra and NTA

PoS(ICRC2019)970 (Saturo Ogawa)



NTA most sensitive for 1PeV-100PeV ν

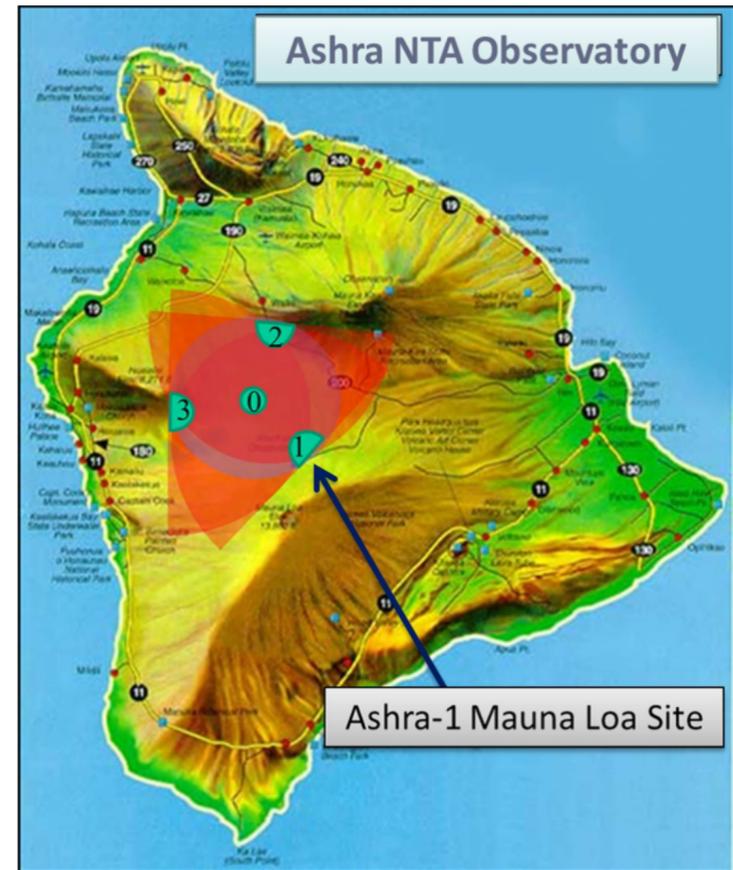
Clear test:
IceCube PeV ν extension
Cosmogenic ν

Far ES tau neutrino
Cherenkov observation

Near ES tau neutrino
fluorescence observation

Thanks to look-out layout

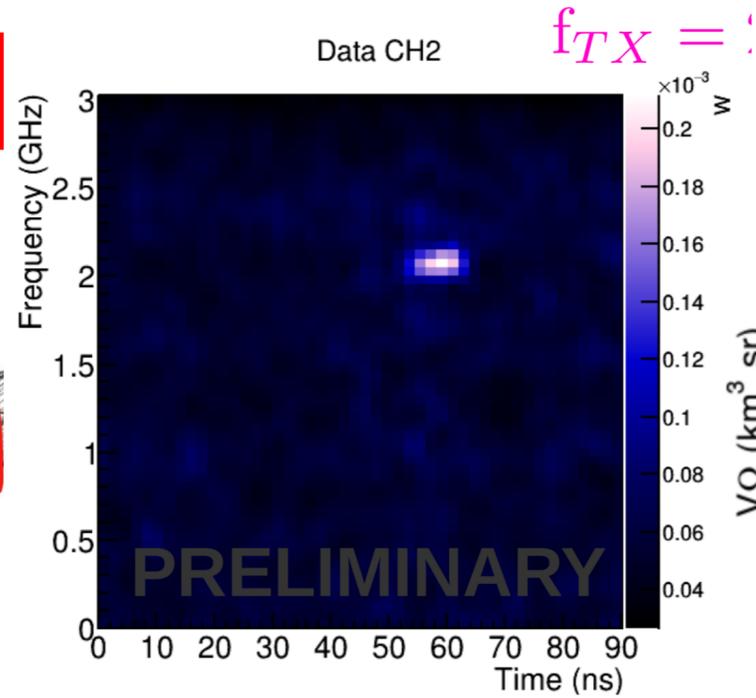
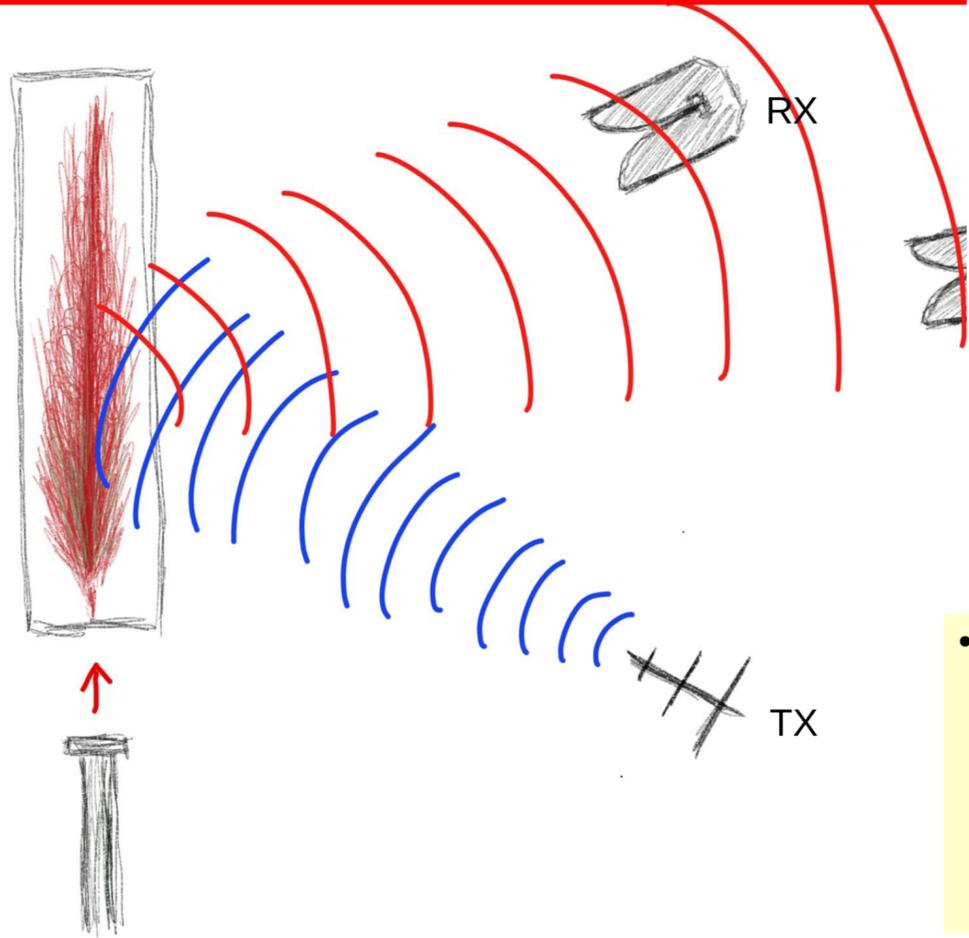
	<u>aper.</u>	height	<u>Fov</u>	<u>Resol.</u>
NTA	10 m ²	3 km	360° x 30°	0.125°



Radar measurements of in-ice showers

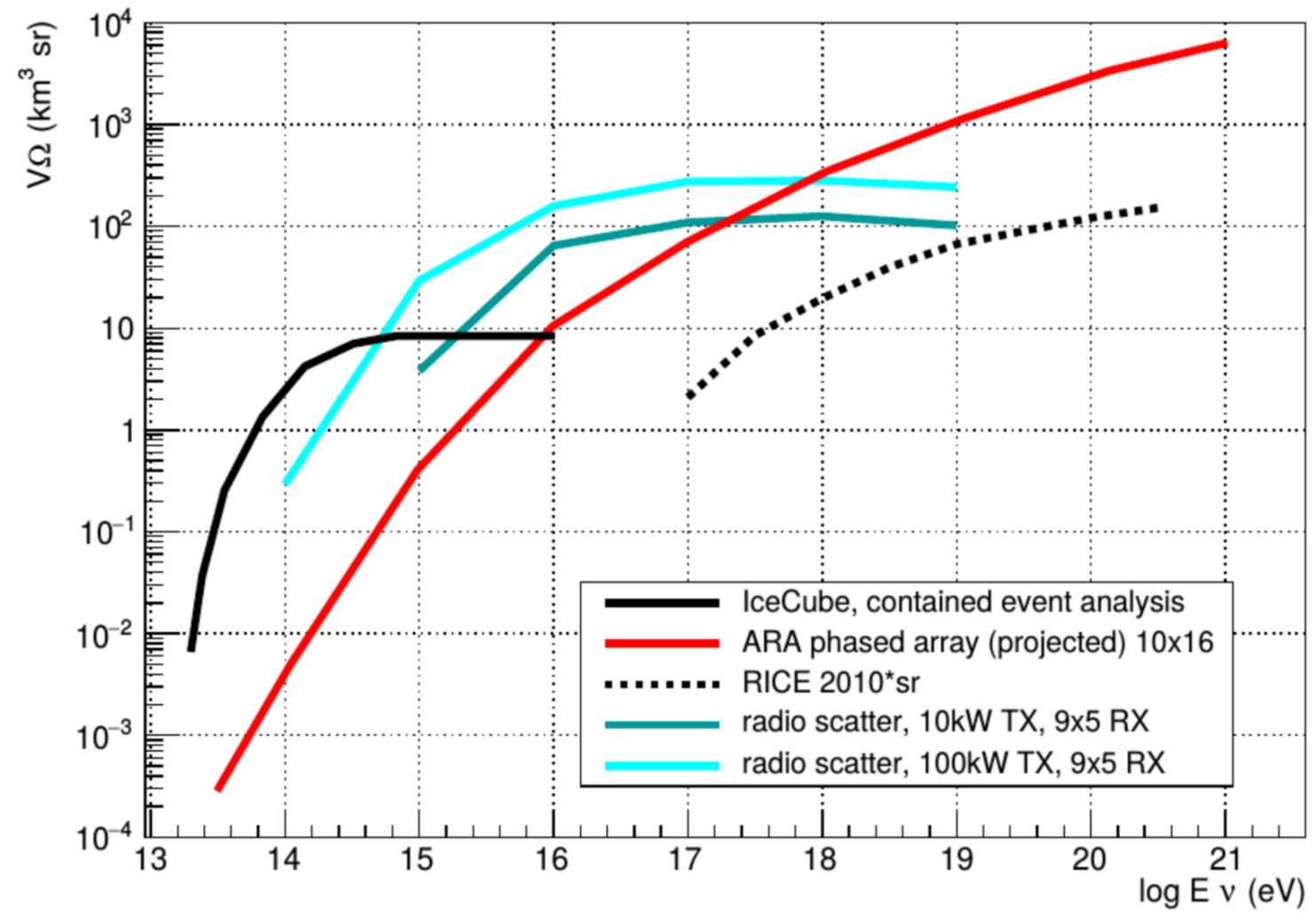
PoS(ICRC2019)986 (Steven Prohira)

SLAC T-576



- the ionization cloud of the shower reflects the transmitted signal to the receivers

- After analysis, observation of signal when beam and radar is on; no signal otherwise





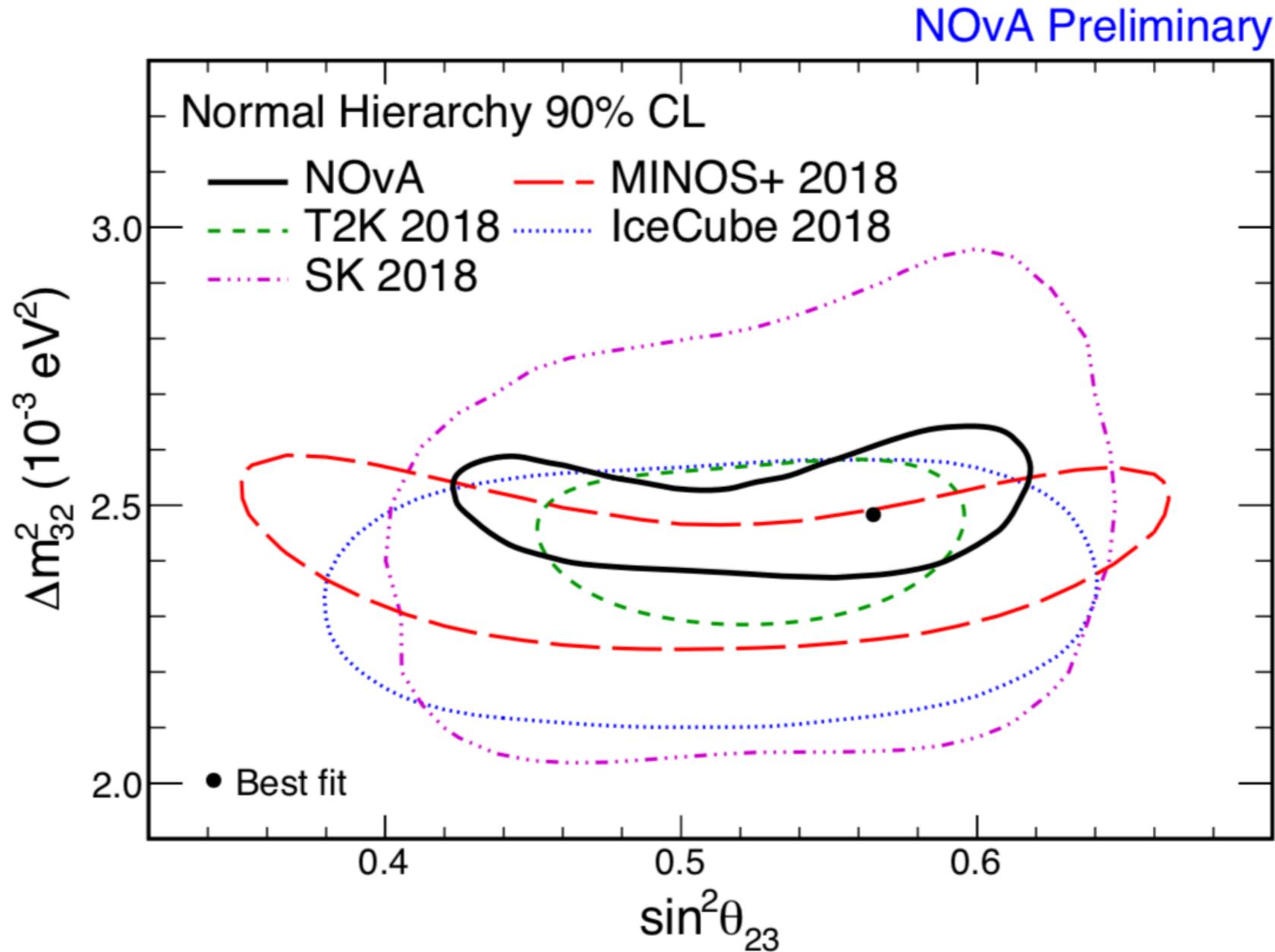
ICRC2019

36th International Cosmic Ray Conference - Madison, WI, USA

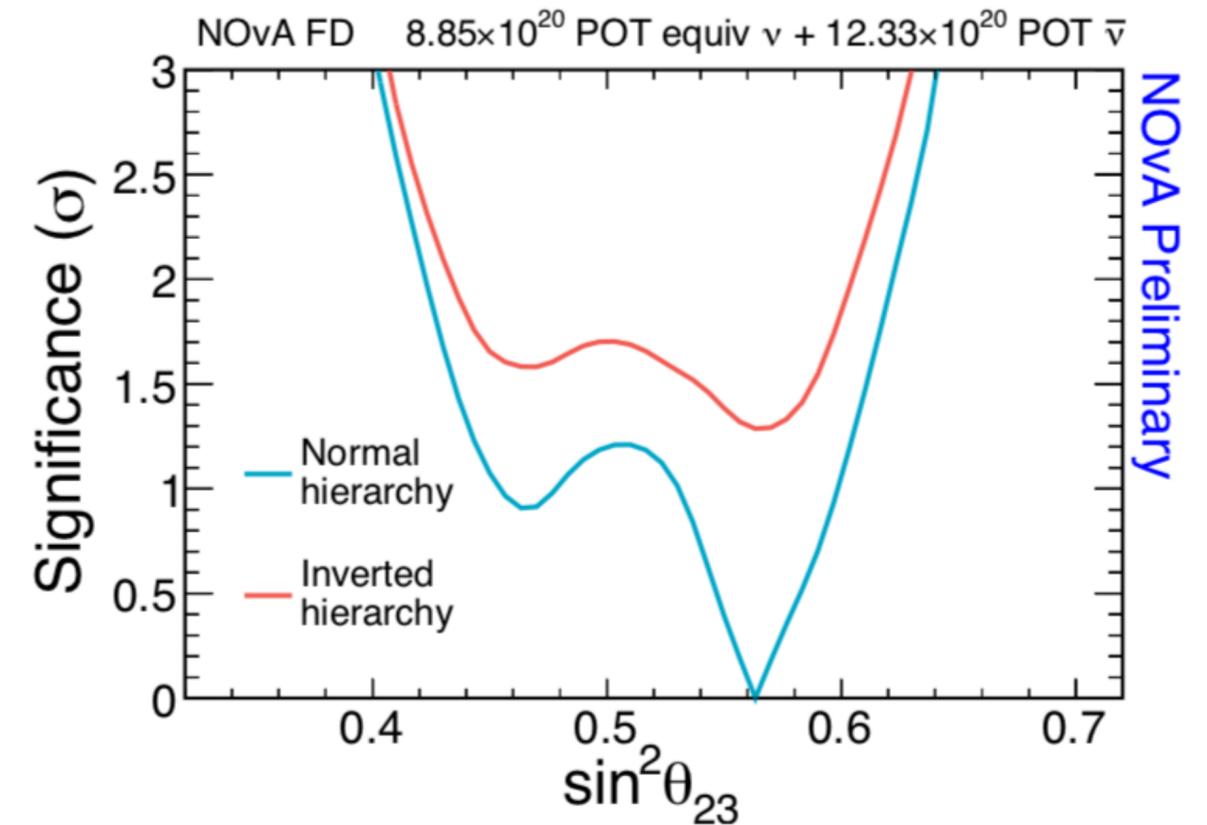
THE ASTROPARTICLE PHYSICS CONFERENCE

**Other Exciting Things
to Do with Neutrinos**

Neutrino oscillation



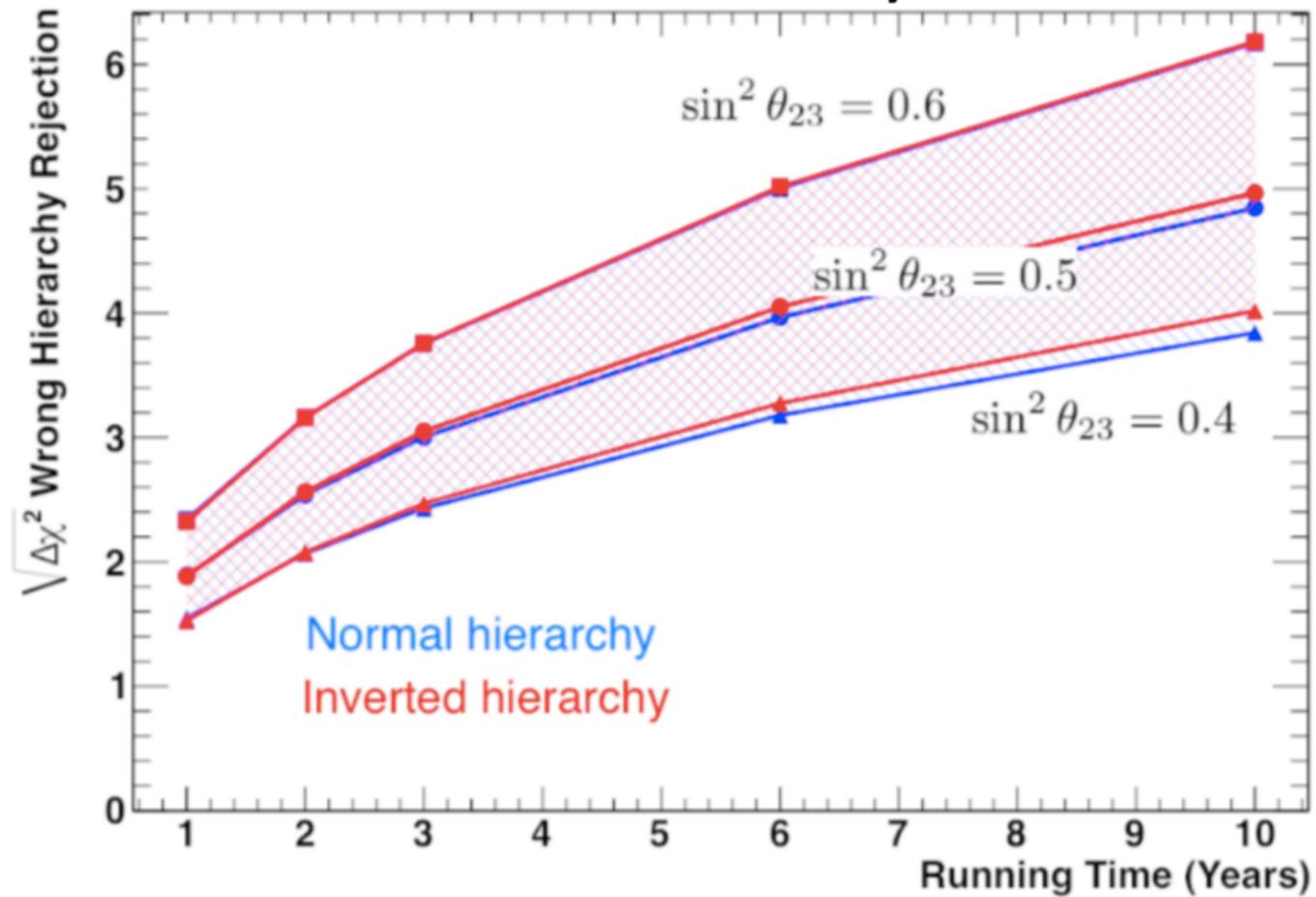
- $\Delta m_{32}^2 = (2.48^{+0.10}_{-0.06}) \times 10^{-3}$ eV 2 (NH)
- $\sin^2 \theta_{23} = 0.56^{+0.04}_{-0.03}$ (upper octant)



Other exciting things – Neutrino physics

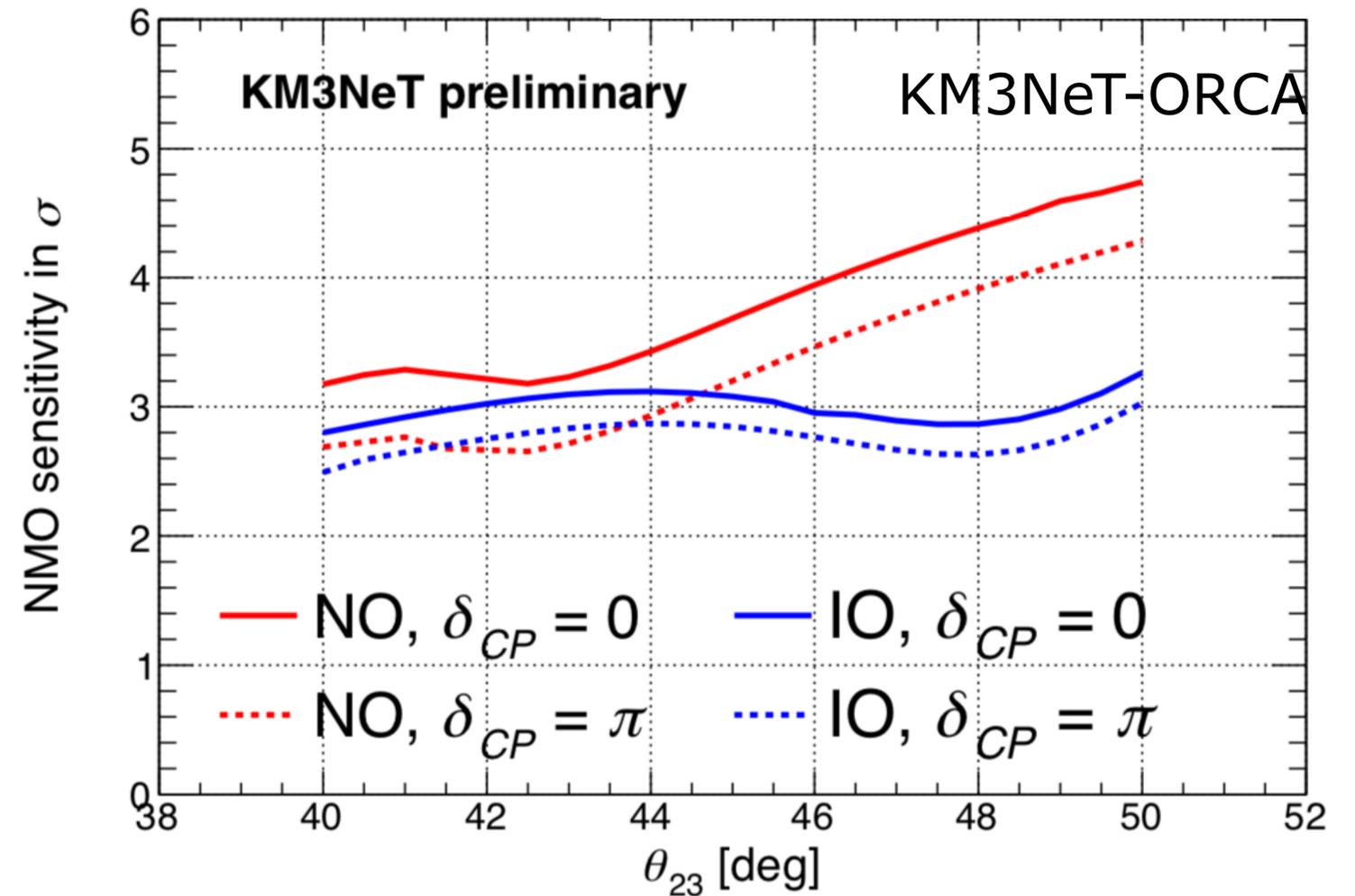
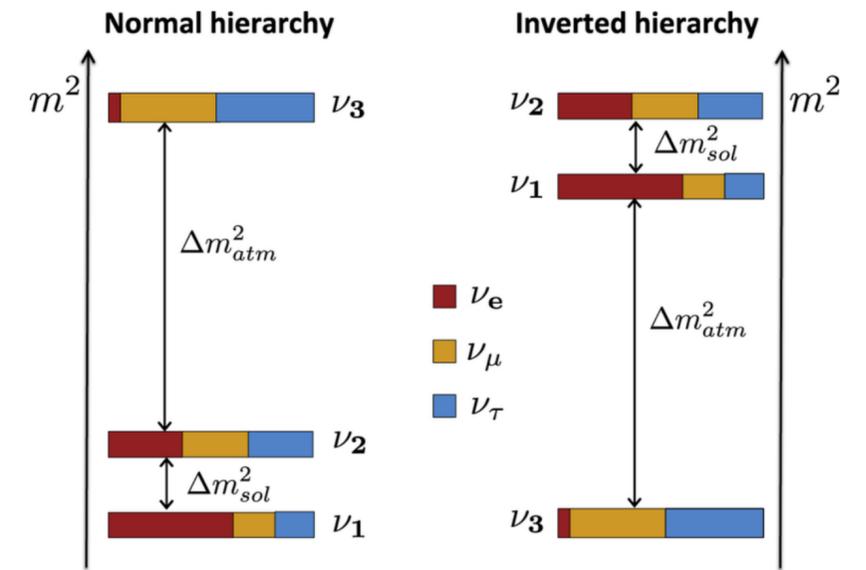
Neutrino Mass Ordering

T2HK+atm ν 10 yrs:



3-5 σ by Hyper-K 10 yrs w/ T2HK

PoS(ICRC2019)924 (Yoshitaka Itow)



PoS(ICRC2019)1019 (Bruno Strandberg)

Other exciting things to do with neutrinos

Physics at the Planck scale
PoS(ICRC2019)849

QUEST FOR NEW PHYSICS with Astro neutrino flavour @IceCube

Our Aims
Search for new physics using neutrinos
Spacetime effects can induce anomalous flavor mixing
Astrophysical neutrinos can inform us about physics near the Planck regime $E_{\text{Planck}} = \hbar c / G_p \sim 10^{27}$ GeV
Flavour sensitive to small effects via neutrino interferometry

Methodology
Effective Hamiltonian treatment
$$H_d = \frac{1}{2E} U M^2 U^\dagger + \frac{E^{d-3}}{\Lambda_d} \tilde{U} O_d \tilde{U}^\dagger$$

Goal is to search for scale of new physics Λ_d through flavour composition

Flavour Triangle
New Physics Scenario
Standard Model

High Energy Starting Events (HESE)
HESE events use fully contained interaction vertex
Outer layer acts as background veto region
Sensitive for neutrinos above 60 TeV
102 Events, 60 events above 60 TeV

Take Away
Given source flavor ratios of (1, 0, 0) and (0, 1, 0), we set limit on new physics scale
 $\Lambda_d \gtrsim 10^{22}$ GeV
Higher statistics anticipated to probe pion production (1, 2, 0) region
Stay tuned!

IceCube reaches first flavour constraints on New Physics below Planck scale

Excluded regions
 - O_p texture
 - O_{ν} texture
 - Planck Scale Expectation
 - IceCube, Nature Phys. 14, 961 (2018)

Quantum Gravity Frontier

New Physics Scale $[\log_{10}(\Lambda_d / M_{\text{Planck}})]$

Source Flavour Ratio $[f_\beta^s = (x : 1-x : 0)]$

Southampton, Queen Mary University of London, NEXt, Kareem Farrag, Contact: k.r.farrag@qmul.ac.uk

Earth tomography
PoS(ICRC2019)1024

Probing the Earth core composition with neutrino oscillation tomography

S. Bourret^a, J. A. B. Coelho^b, E. Kaminski^c and V. Van Elewyck^{a,d}

The elusive composition of the Earth's core
The Earth's core is believed to be mostly formed of Fe-Ni alloy. The combination of seismic data with constraints on the radius, total mass and momentum of inertia can be used to infer the radial matter density profile of the Earth. Current geophysical data require the presence of a few wt% of light elements inside the iron core, whose nature and amount remain controversial.

Neutrino oscillation tomography: principle
Atmospheric neutrinos:
 - isotropic fluxes of known flavour composition (ν_μ, ν_τ)
 - usually interacting \rightarrow can cross the entire Earth
 - wide range of energies (GeV \rightarrow TeV)
 - wide range of flavour oscillation pathlengths through the Earth (50 \rightarrow 12000 km)
 ν_μ (not ν_τ) interact with electrons in matter:
 - \rightarrow each potential proportional to electron density N_e
 - Matter effects modify the $\nu_\mu \rightarrow \nu_\tau$ oscillation probability along neutrino path; maximal effect at resonance energy:

$$E_{\text{res}} = \frac{2m^2 \cos 2\theta}{2E \sin 2\theta} = 7 \text{ GeV} \left(\frac{4.5 \text{ g/cm}^3}{\rho} \right) \left(\frac{\Delta m^2}{2.5 \times 10^{-3} \text{ eV}^2} \right) \cos 2\theta \approx 3 \text{ GeV}$$
 for core density
 \rightarrow Differential rate of interacting (anti)neutrinos of flavour β :

$$\frac{dN^\beta(E, \theta)}{dE d\Omega} = \sigma_\beta(E) \sum_{\alpha} \nu_{\alpha \rightarrow \beta}(E, \theta) \frac{d\nu_\alpha(E, \theta)}{dE d\Omega}$$

Detector response modelization

Water[ice]-based Cherenkov detectors: Option 1 (Water-based) vs Option 2 (Ice-based)

Detector	M_{det} (Mton)	E_{th} (GeV)	E_{res} (GeV)	$\sigma(E)/E$	$\sigma_{\text{had}}(E)/E$	$\sigma_{\text{had}}^{\text{had}}(E)/E$	$\sigma_{\text{had}}^{\text{had}}(E)/E$	$\sigma_{\text{had}}^{\text{had}}(E)/E$
ORCA-like [8]	2.5	30	30	10%	10%	0.1	0.2	99%
HyperKamiokande-like [10]	0.40	0.1	0.2	10%	10%	0.1	0.2	99%
DUNE-like [11]	0.04	0.1	0.2	10%	10%	0.1	0.2	99%
Next-generation	30	0.5	1.0	5%	5%	0.1	0.2	99%

Results and perspectives

Upcoming detectors: ORCA-like, HyperKamiokande-like, DUNE-like

The next generation: Super-ORCA-like

Detectors currently under construction (ORCA, DUNE, Hyper-K) only have the capability of measuring the amount of μ in the core with a precision of a few wt%. To achieve 1 wt% precision level, a next-generation detector would be needed, combining a large detection volume with good energy and angular resolutions. Lowering the detection threshold to the 1 GeV level with reasonably good flavour identification performance in the low-Gev region is critical. The Liquid Argon technology being initially available in the ~ 10 Mton scale, is a most promising alternative right inside a large-scale densified water Cherenkov detector (Super-ORCA [12]).

Summary and conclusions

- Picture of TXS 0506+056 and diffuse HE neutrino flux still unclear (need better models and more data).
- Neutrino telescopes in the northern hemisphere will complement IceCube in the next years.
- No UHE neutrinos detected so far but high dynamic in field. What about ANITA mystery events? Several instruments with significant increased sensitivity in the pipeline.
- Multi-messenger physics is key in understanding neutrino observations and the high-energy universe.

Summary and conclusions

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- Multi-messenger physics is key in understanding neutrino observations and the high-energy universe.

Exciting times lie ahead ...

