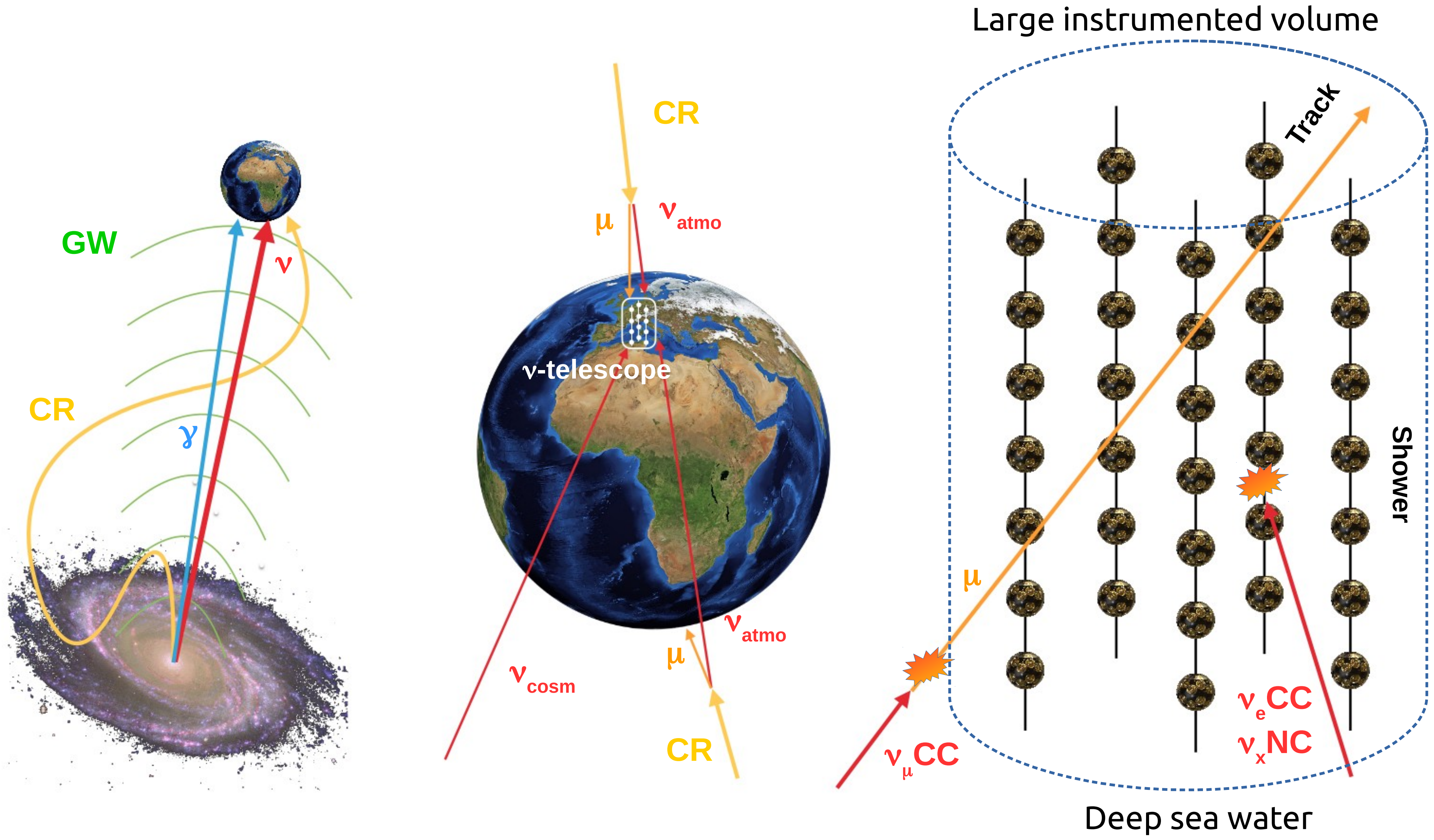
Recent results in high-energy neutrino astronomy

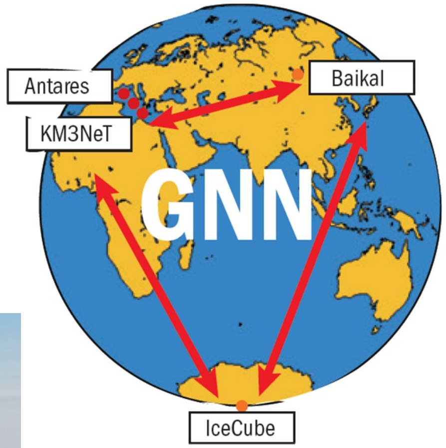
Luigi Antonio Fusco – Laboratoire APC, Paris

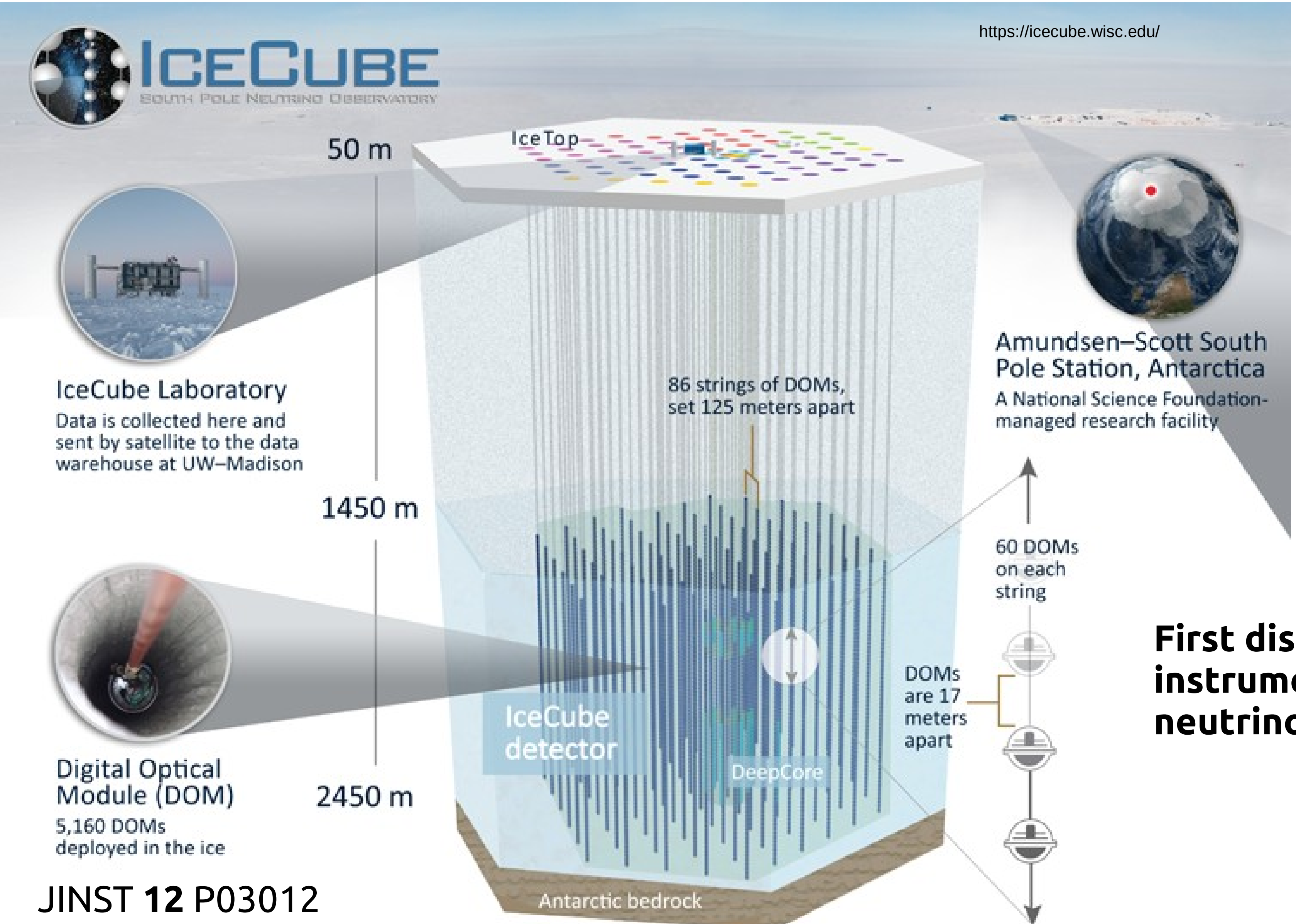
Neutrini, fotoni e onde gravitazionali: nuove prospettive per l'astrofisica di alte energie
Catania, 26 Novembre 2019

Neutrino astronomy in a nutshell



The current generation of neutrino telescopes





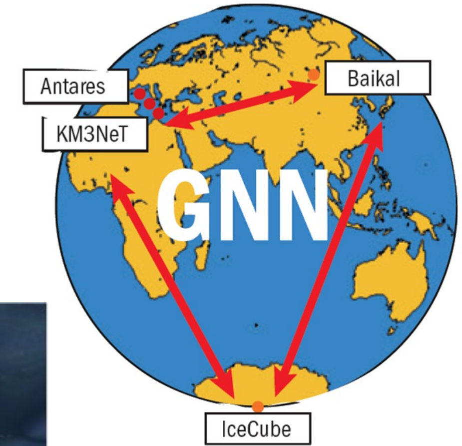
km³ neutrino telescope

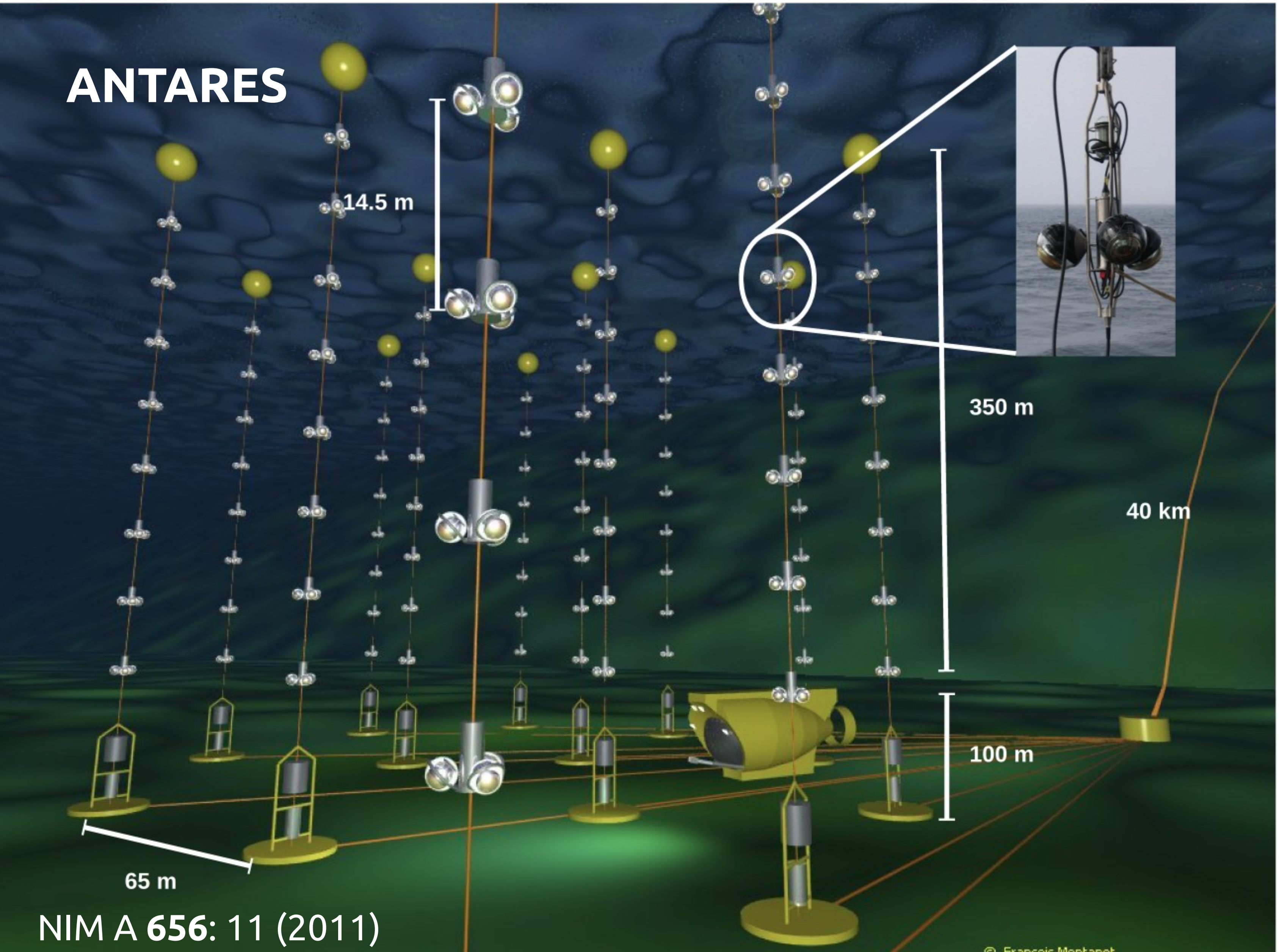
10+ years of data taking at the South Pole

First discovery instrument for HE neutrino astronomy

JINST **12** P03012 (2017)

The current generation of neutrino telescopes



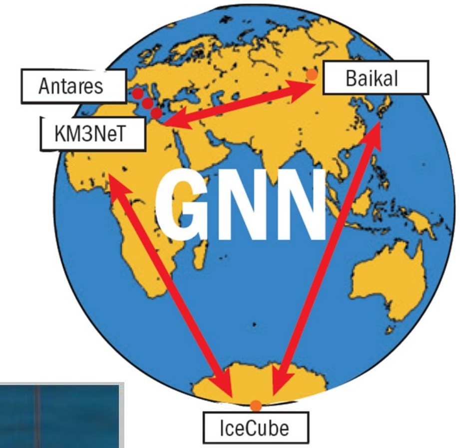


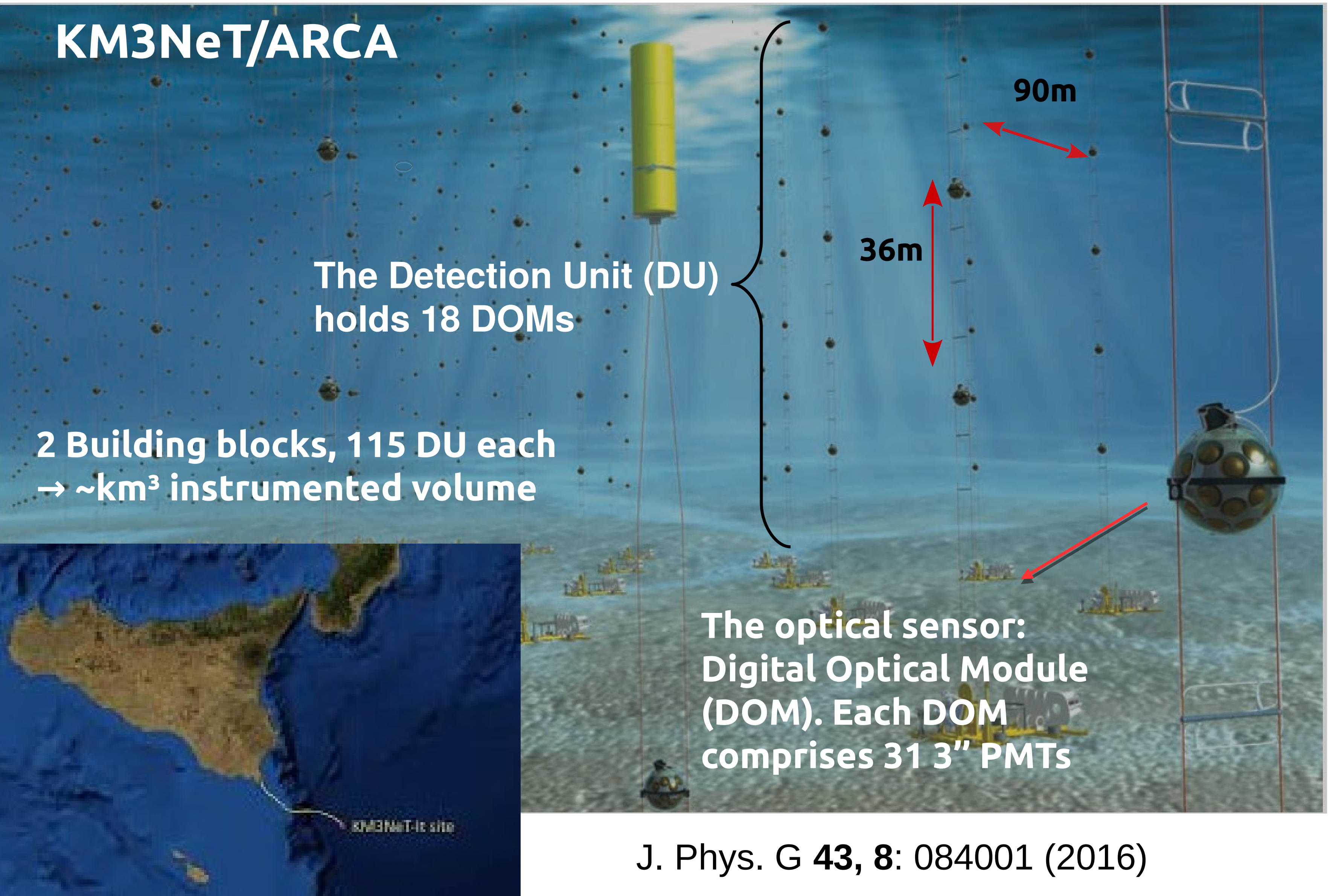
NIM A **656**: 11 (2011)

0.01 km³ neutrino telescope

11+ years of data taking in the Mediterranean Sea (France)

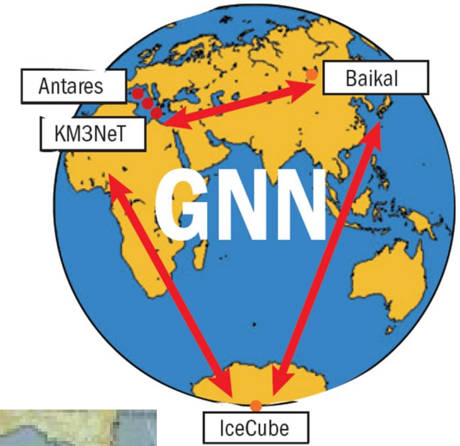
The current generation of neutrino telescopes



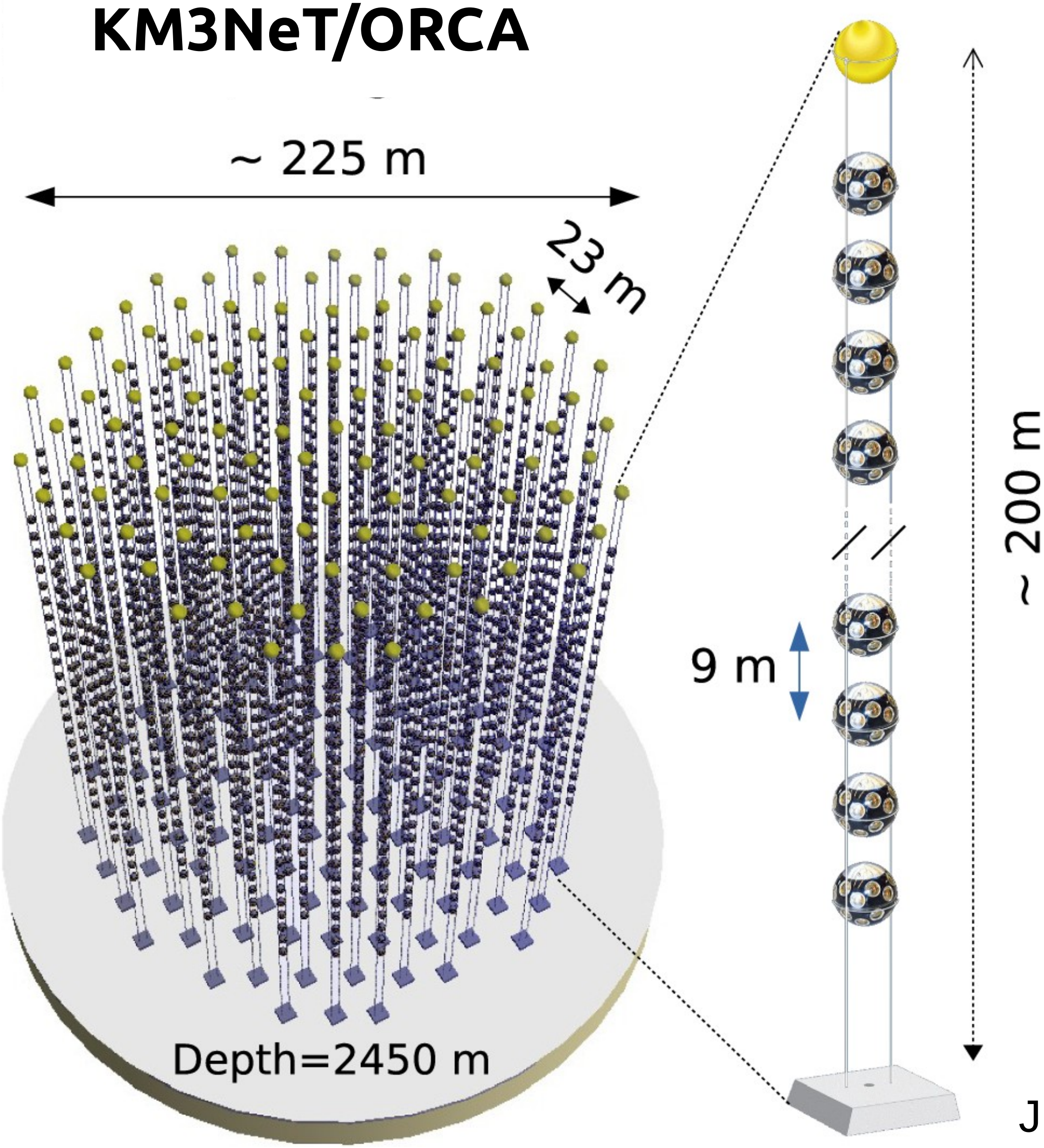


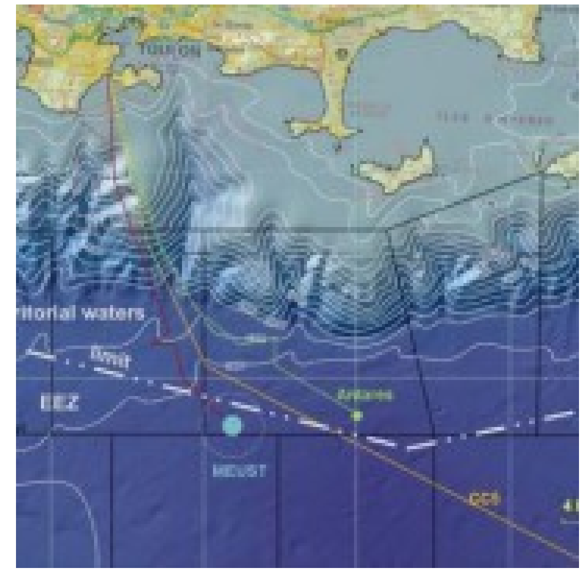
J. Phys. G **43, 8**: 084001 (2016)

The current generation of neutrino telescopes



KM3NeT/ORCA





Uniform KM3NeT detector design

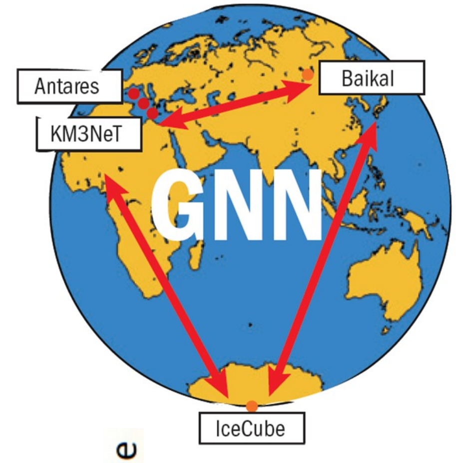
Designed to assess NMO, but Low-E Astrophysics also accessible

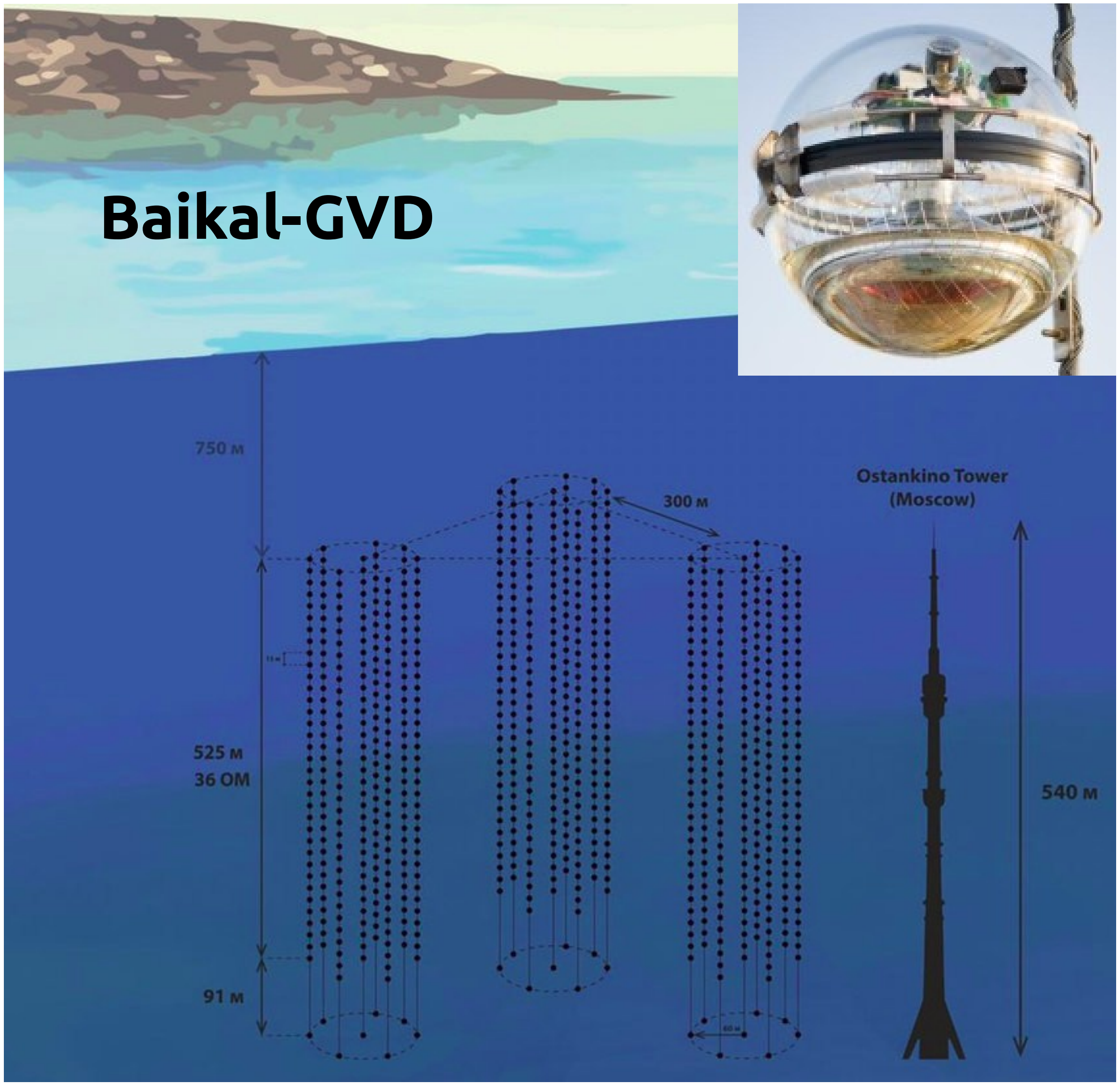
See e.g.
POS(ICRC2019)857
POS(ICRC2019)934

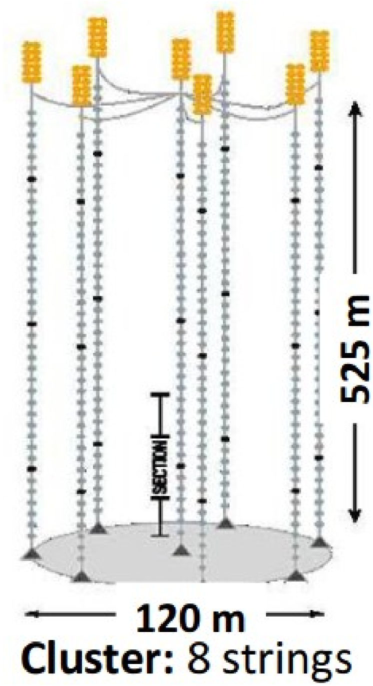
J. Phys. G **43, 8**: 084001 (2016)

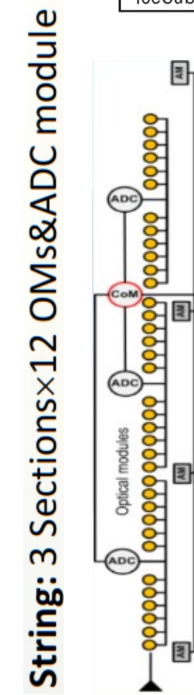
KM3NeT

The current generation of neutrino telescopes







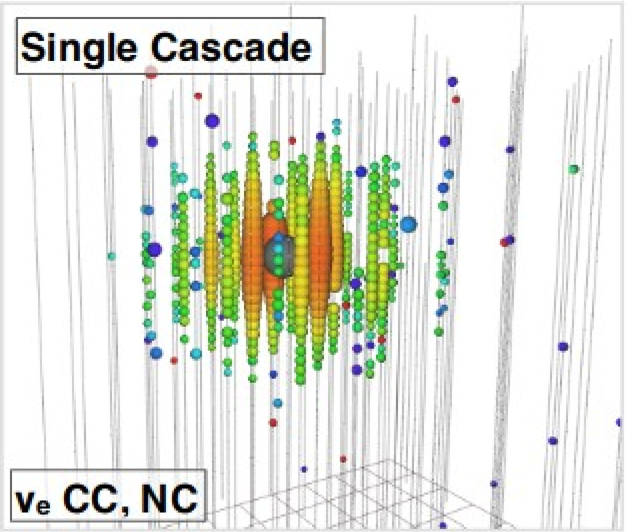


5 clusters working now, more to come
V_{inst}~0.3km³

EPJ WoC **207**: 01003 (2019)

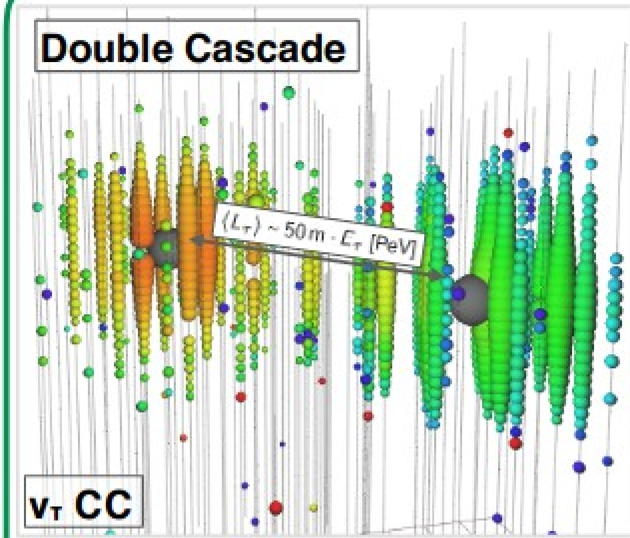
Event topologies in a neutrino telescope

early → late



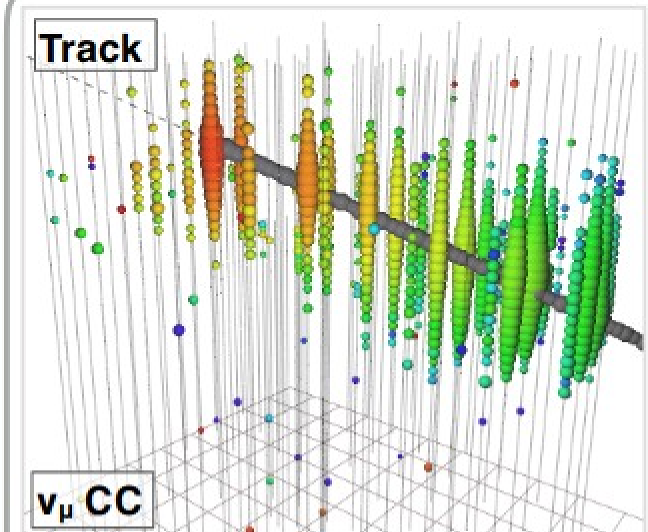
All NC interactions
ν_e CC interactions

Good energy resolution
Bad angular resolution



ν_τ CC interactions with hadronic / electronic tau decay

Good energy resolution
Angular resolution gets better with larger lengths

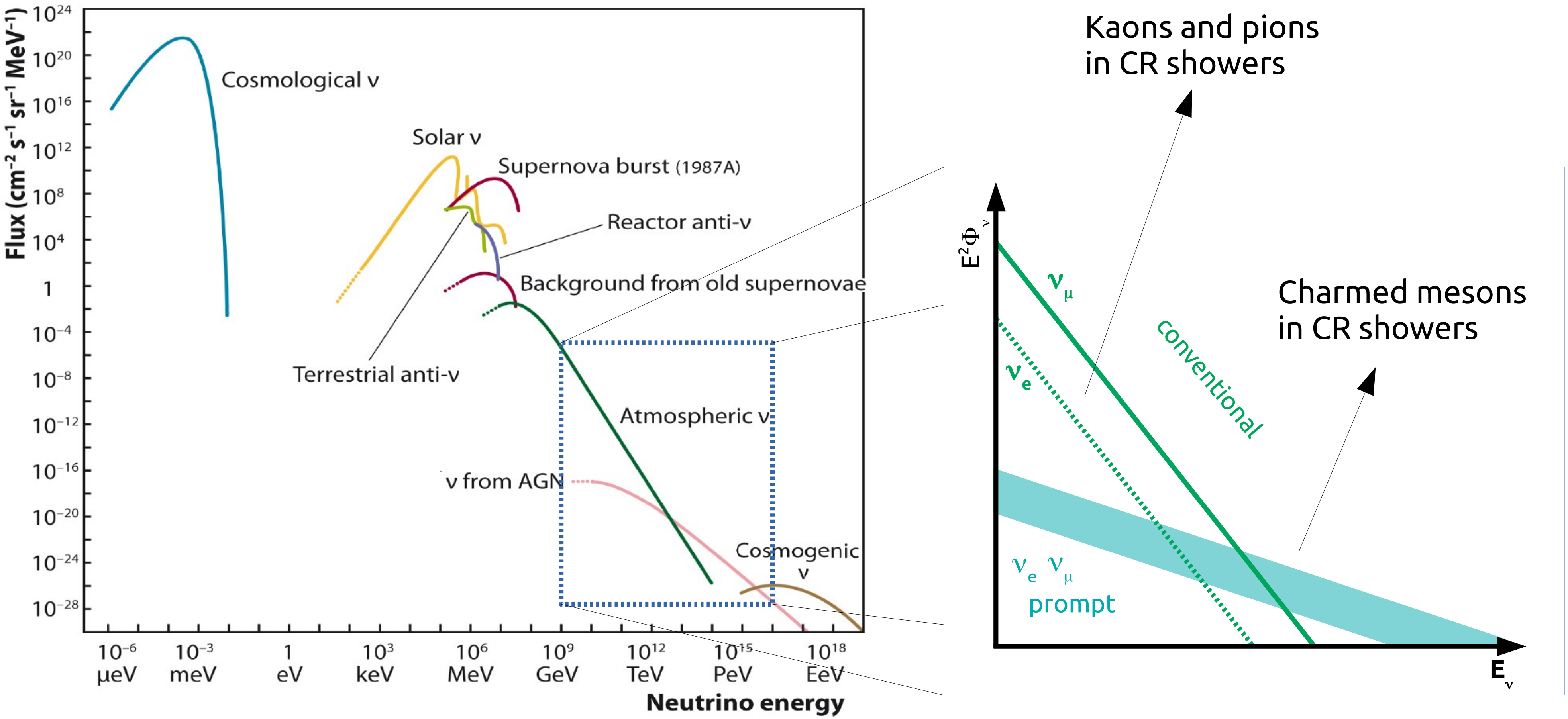


ν_μ CC interactions
Atmospheric μ
ν_τ CC interactions with muonic tau decay

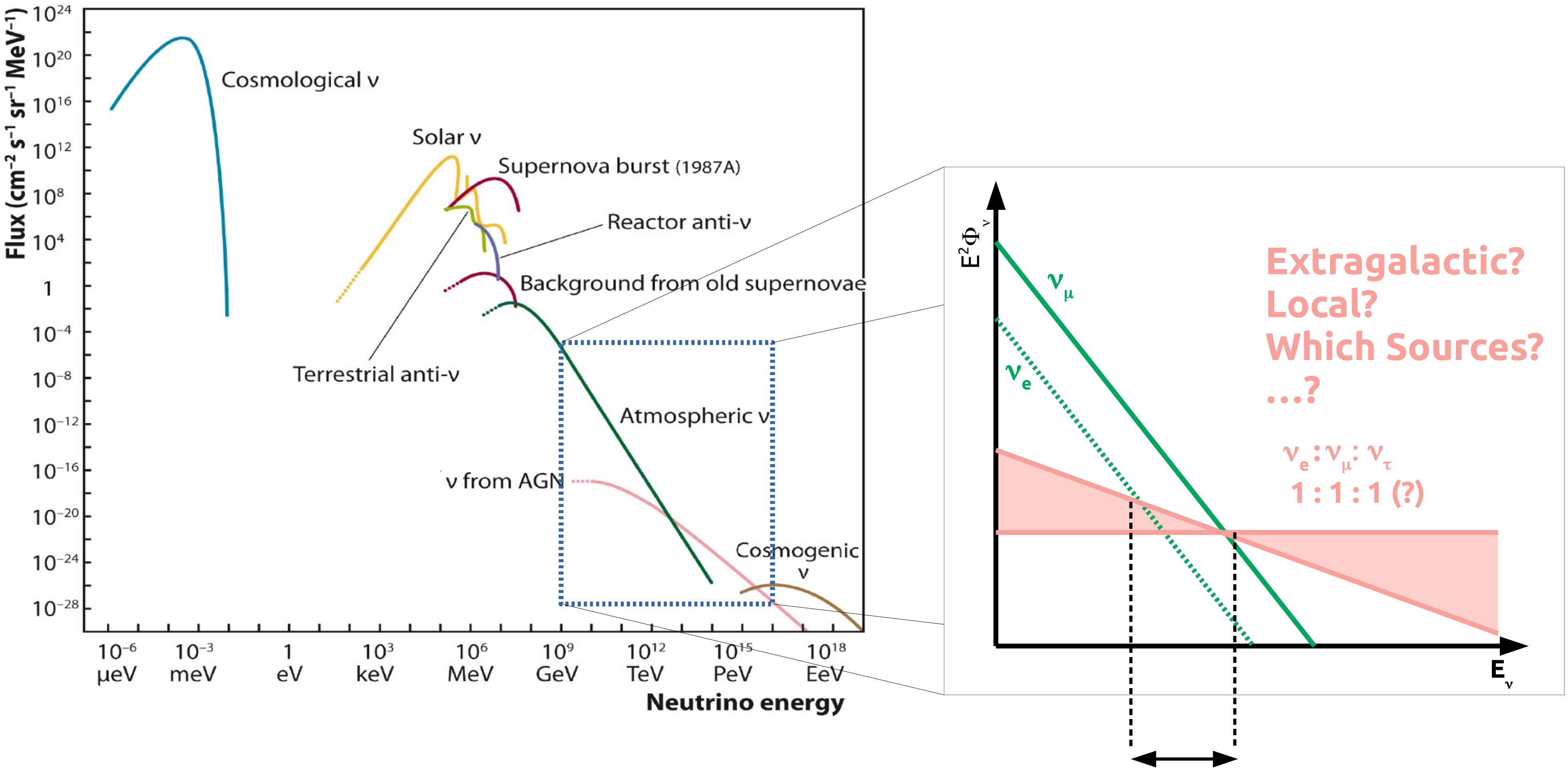
Bad energy resolution
Good angular resolution

Simulated event displays in the IceCube detector

High-energy diffuse neutrino fluxes

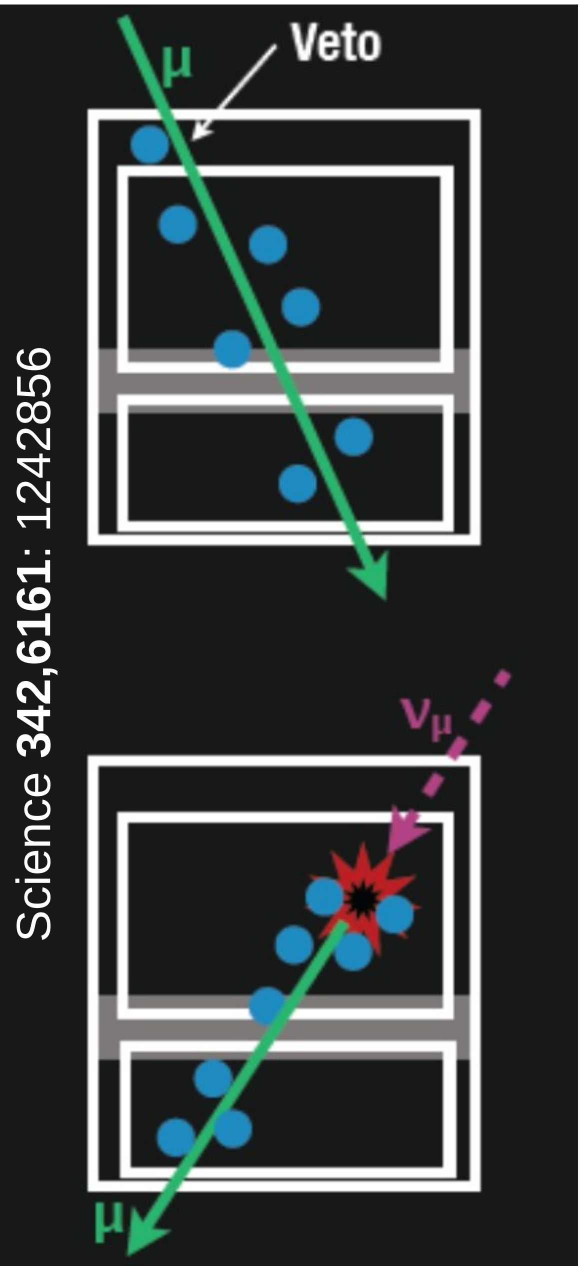


High-energy diffuse neutrino fluxes

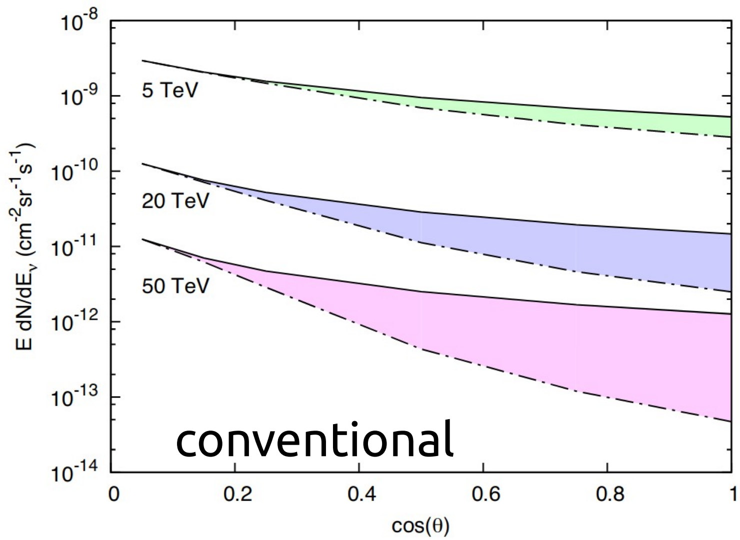


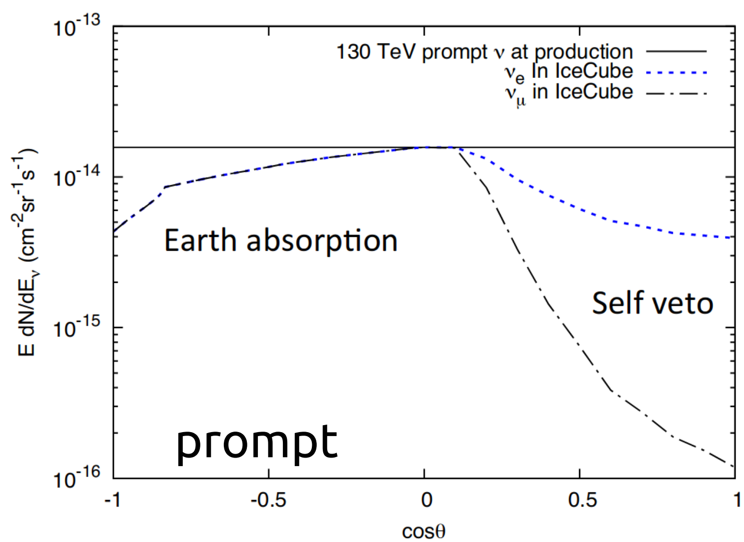
Atmos-to-Cosmic transition
30-200 TeV

The discovery of HE cosmic neutrinos



Vetoing downward-going passing-through events
→ **rejection of accompanied atmospheric neutrinos**





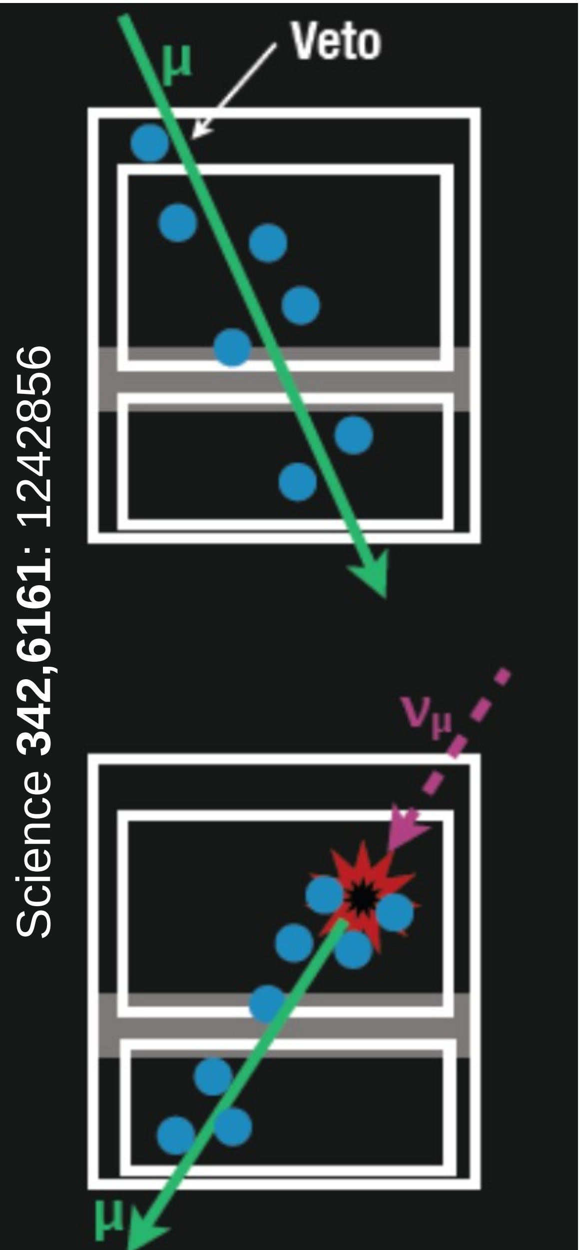
Opens the sky to downward-going neutrino events → **highest energies**

Dependent on the proper modelisation of:

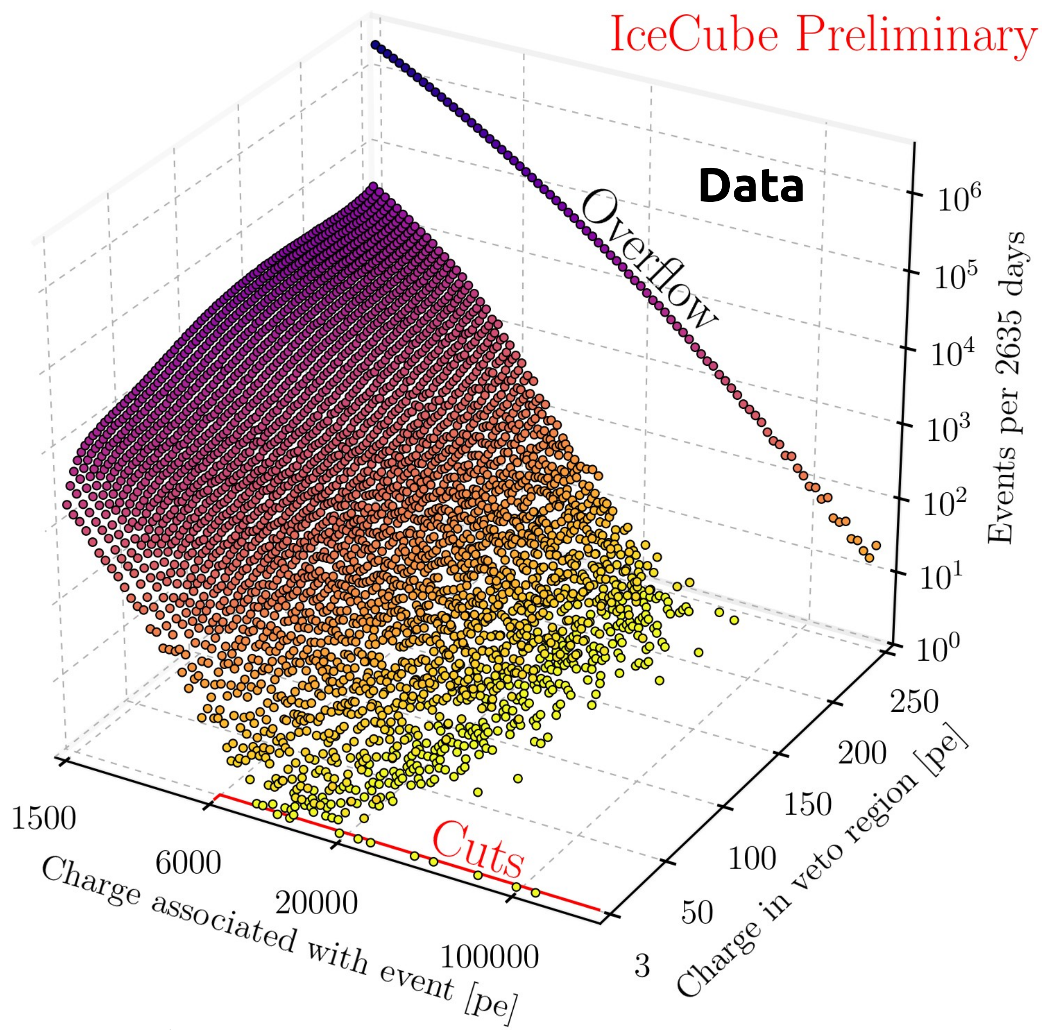
– CR muon flux at the detector
– CR muons in the detector

JCAP **1807** (2018) no.07, 047

The discovery of HE cosmic neutrinos



Vetoing downward-going passing-through events
→ **rejection of accompanied atmospheric neutrinos**



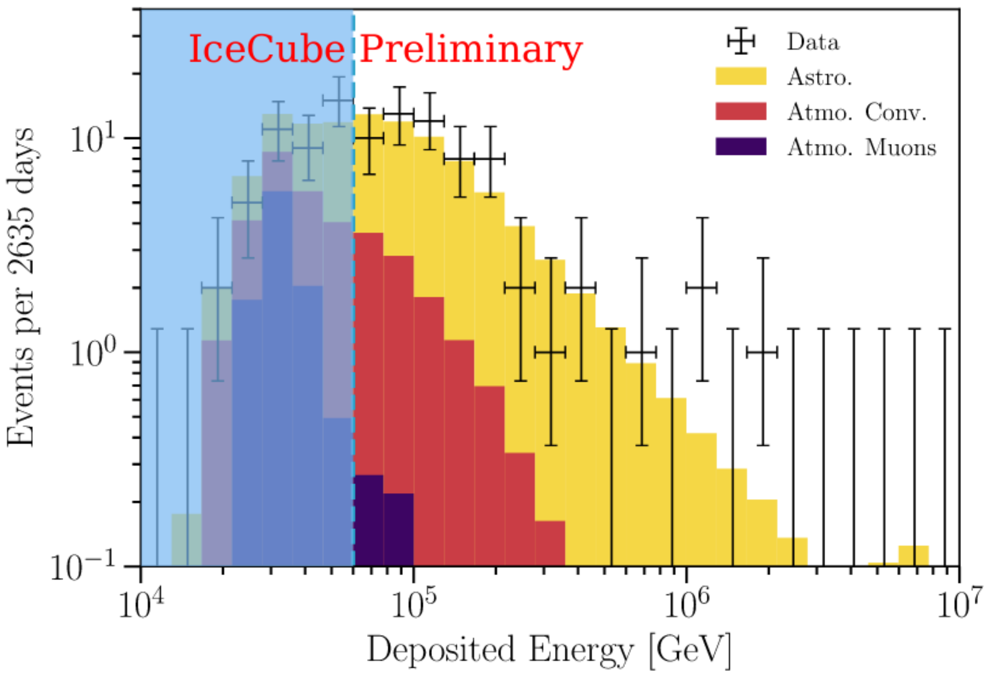
PoS(ICRC2019)1004

The HESE sample (7.5 years)

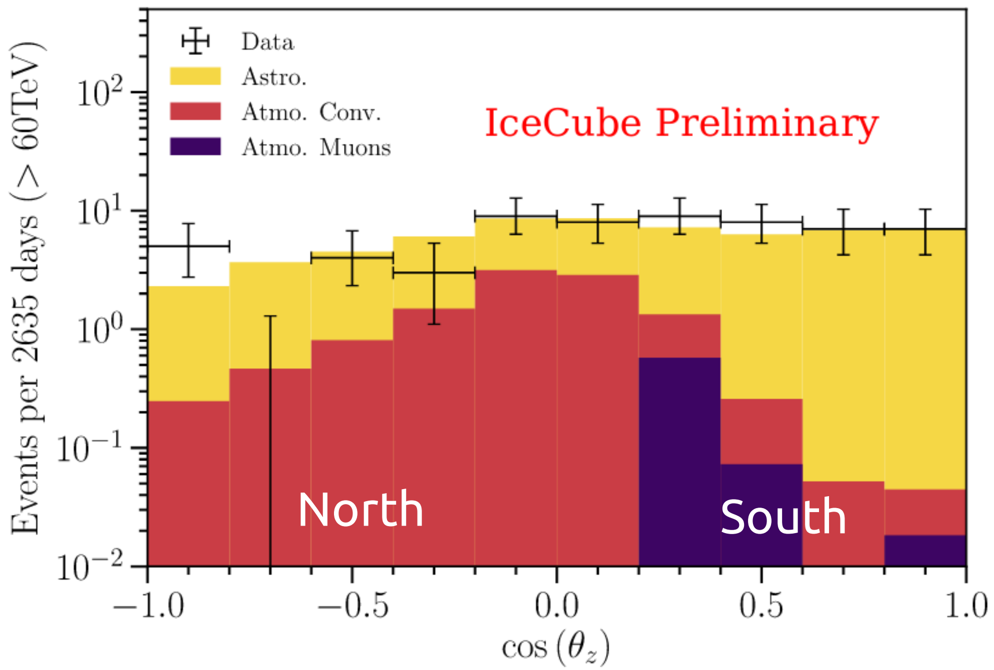
High-energy starting events above 60 TeV
– Southern sky accessible (veto)
– Northern sky more opaque (absorption)

$\Phi^{1f}(100\ \text{TeV}) = (2.15^{+0.5}_{-0.15})\ 10^{-18}\ (\text{GeV cm}^2\ \text{s sr})^{-1}$
$\Gamma = 2.9 \pm 0.2$

Too soft?



Compatible with isotropy



Not really compatible with any reasonable atmospheric assumption; however a null-prompt is fitted

PoS(ICRC2019)1004

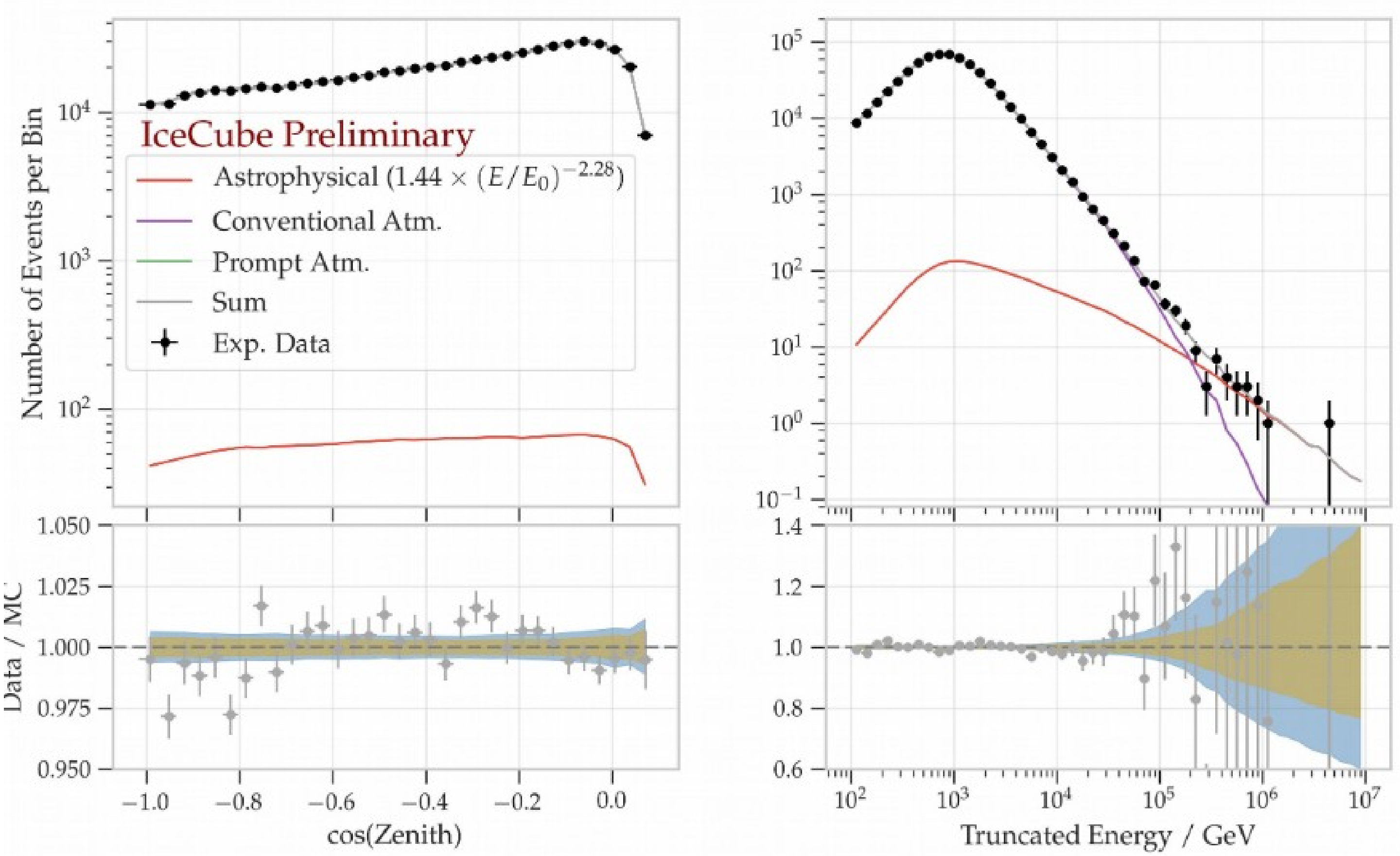
The track sample (9.5 years)

Earth used as a shield against CR muons
→ **cosmic excess at the highest energies (>100 TeV)**

$\Phi^{1f}(100\ \mathrm{TeV}) = (1.44 \pm 0.25)\ 10^{-18}\ (\mathrm{GeV\ cm^2\ s\ sr})^{-1}$
$\Gamma = 2.28 \pm 0.09$

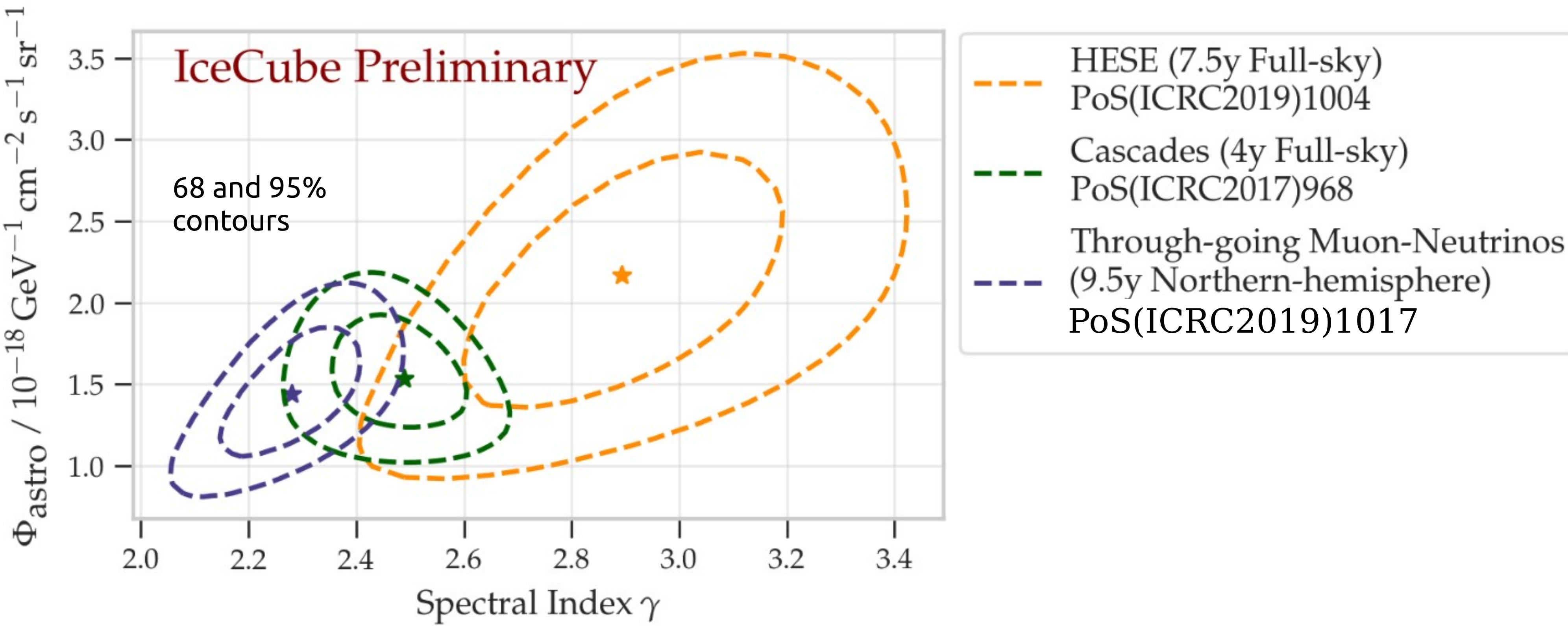
Extra-galactic sources should behave like that
Which ones?

Best fit is a null-prompt also here (see backup)



PoS(ICRC2019)1017

A global view on IceCube HE cosmic neutrino measurements



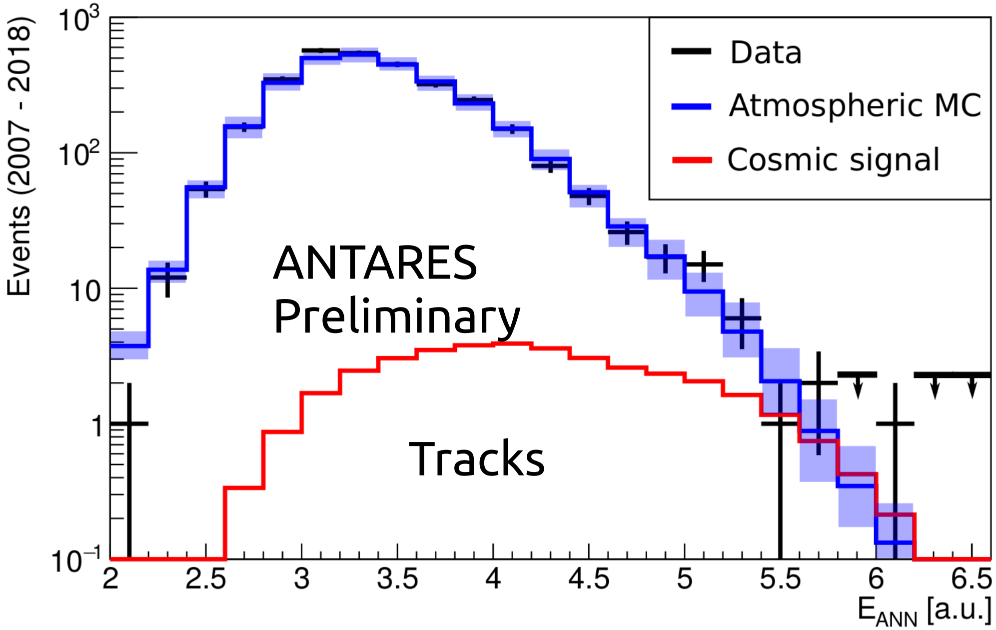
→ **test for deviation from single power-law description**

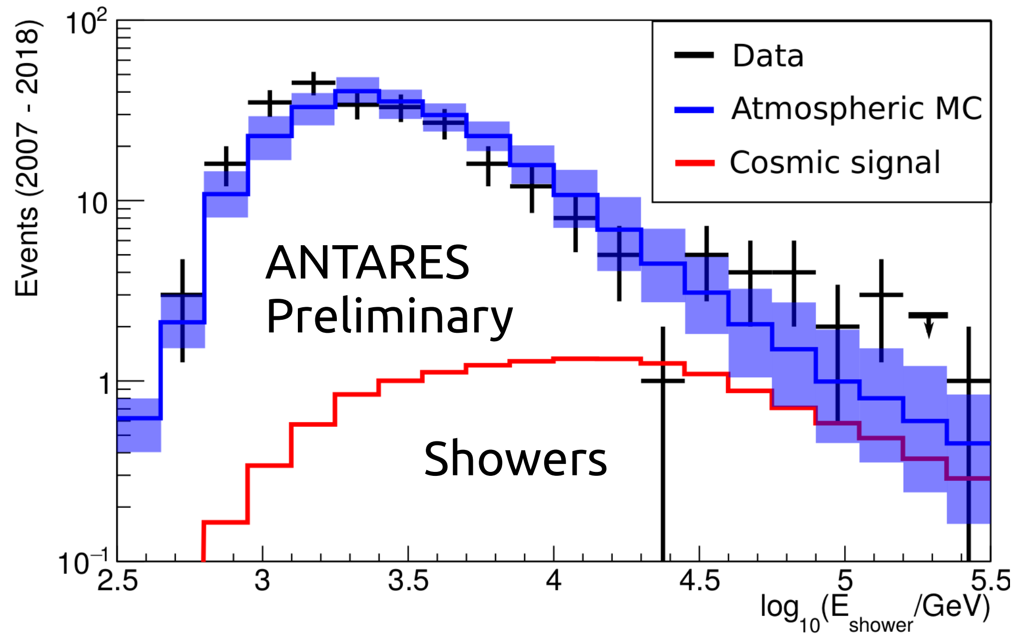
IceCube spectral analysis in the HESE shows that the difference between the 1- and 2-component model is ~1σ

Tracks and HESE still compatible at 95% CL

PoS(ICRC2019)1017 + PoS(ICRC2019)1004

The ANTARES search for HE neutrinos





3380 days of livetime

Considering the HE tail (~1% highest E)

→ **data: 50** events
(**27** tracks + **23** showers)

→ **bkg MC: 36.1 ± 8.7** (stat.+syst.)
(**19.9** tracks and **16.2** showers

→ **signal MC: ~10 events expected**
(**4.5** tracks and **5.5** showers)

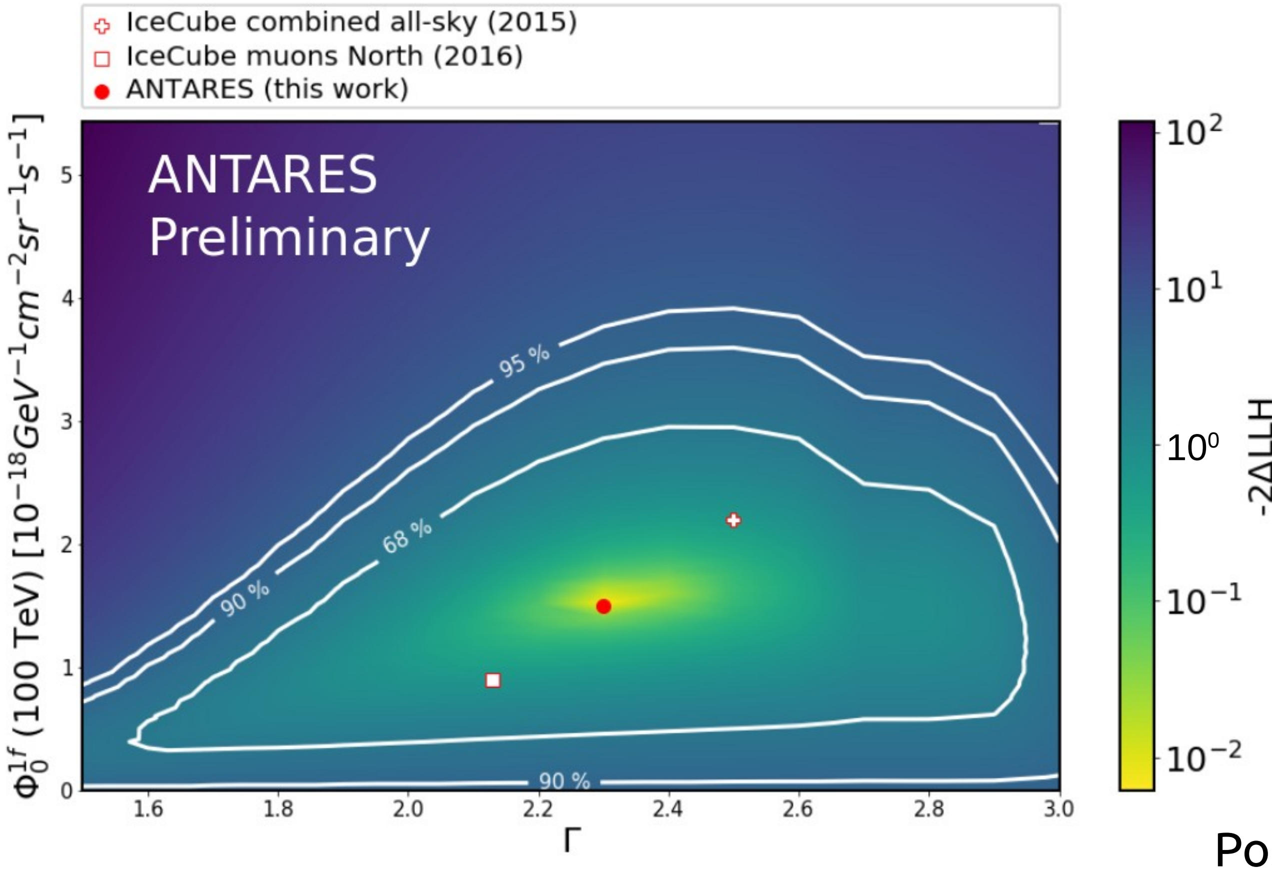
Null-cosmic excluded at 90% C.L.
1.8σ excess

PoS(ICRC2019)891

The ANTARES search for HE neutrinos

Upward-going events, simultaneous fit for the shower and track sample

Φ^{1f}(100 TeV) = (1.5±1.0) 10^{-18} (GeV cm^2 s sr)$^{-1}$
Γ = 2.3±0.4



When fitting individually the samples

Tracks

Φ^{1f}(100 TeV) = ($0.8^{+0.5}_{-0.4}$) 10^{-18}
$\Gamma = 2.0^{+0.8}_{-0.4}$

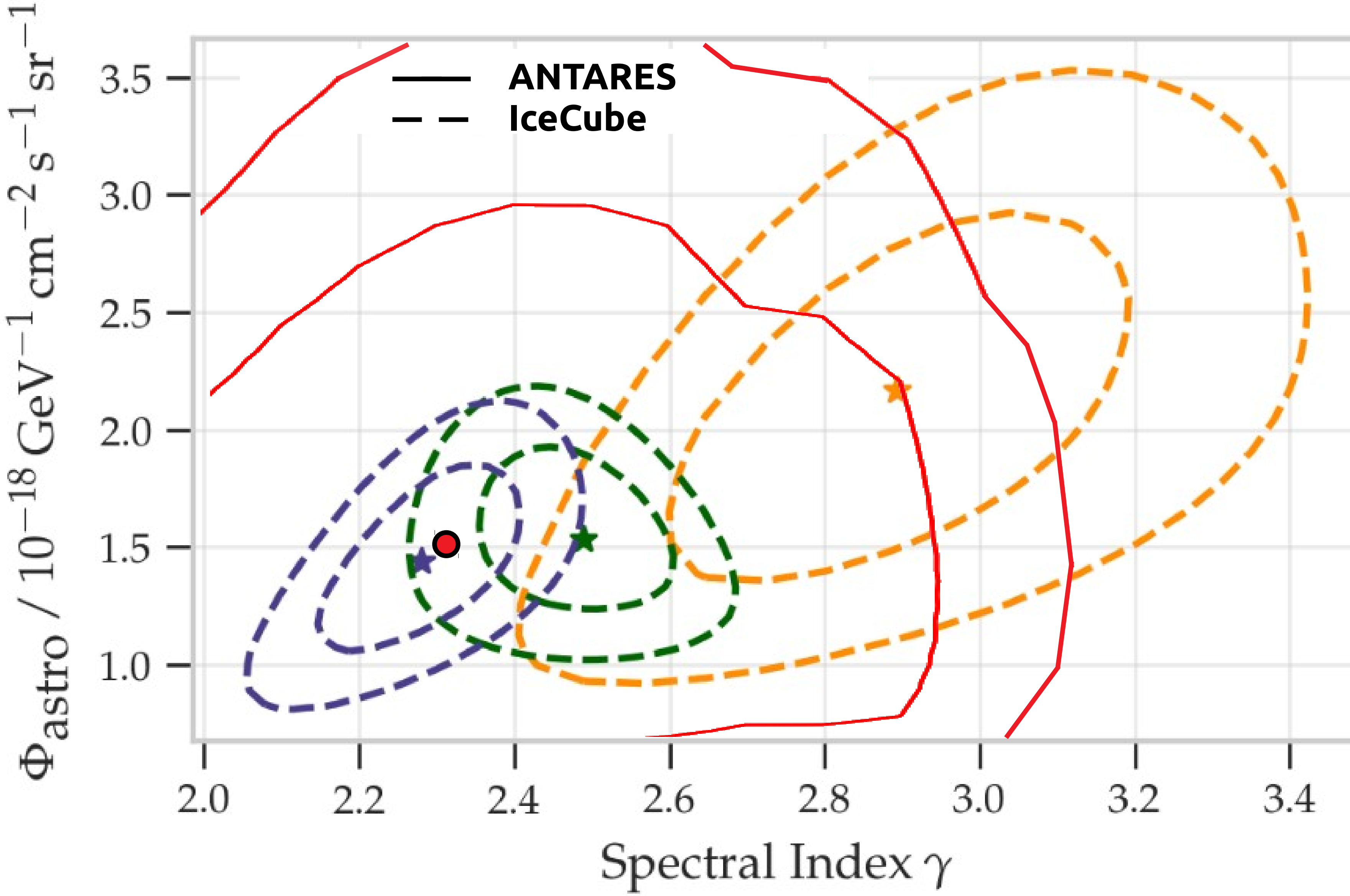
Showers

Φ^{1f}(100 TeV) = (2.1±0.8) 10^{-18}
Γ = 2.4±0.4

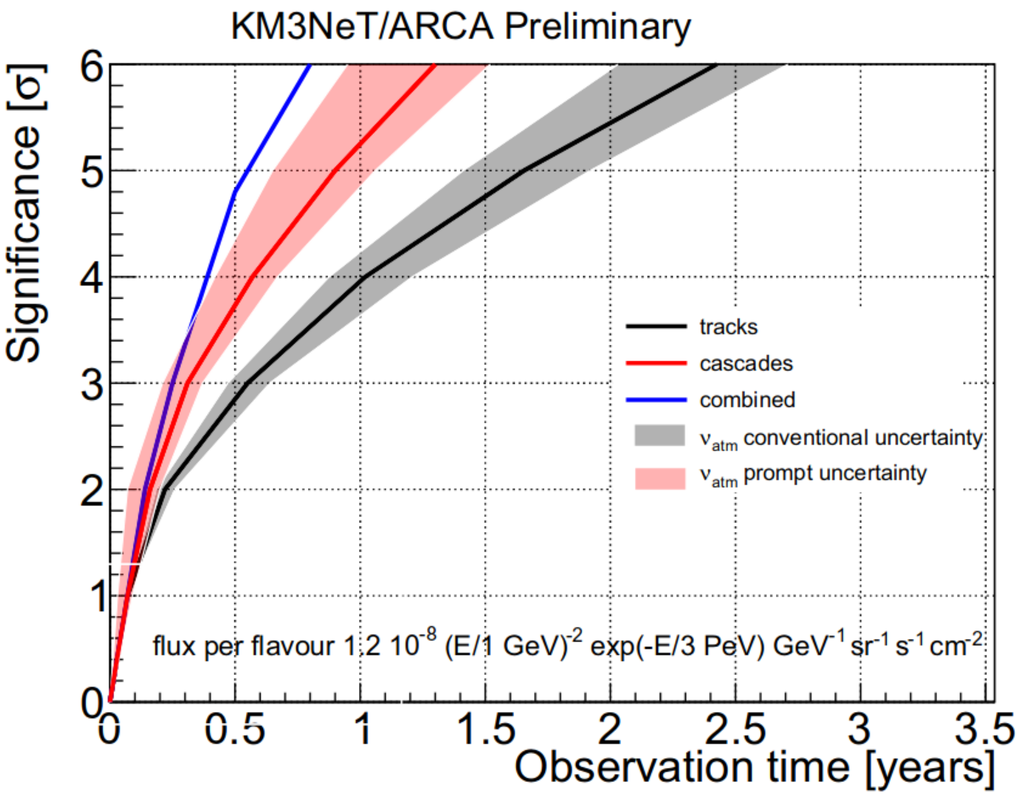
NB: Atmospheric flux is fitted as more intense than in the model; prompt is forced to exist in the fit

PoS(ICRC2019)891

Putting it into context



KM3NeT/ARCA diffuse flux sensitivity



High sensitivity to HE neutrino cosmic flux

Quick re-discovery of an IceCube-like signal and analysis with improved energy recostruction

Different systematics

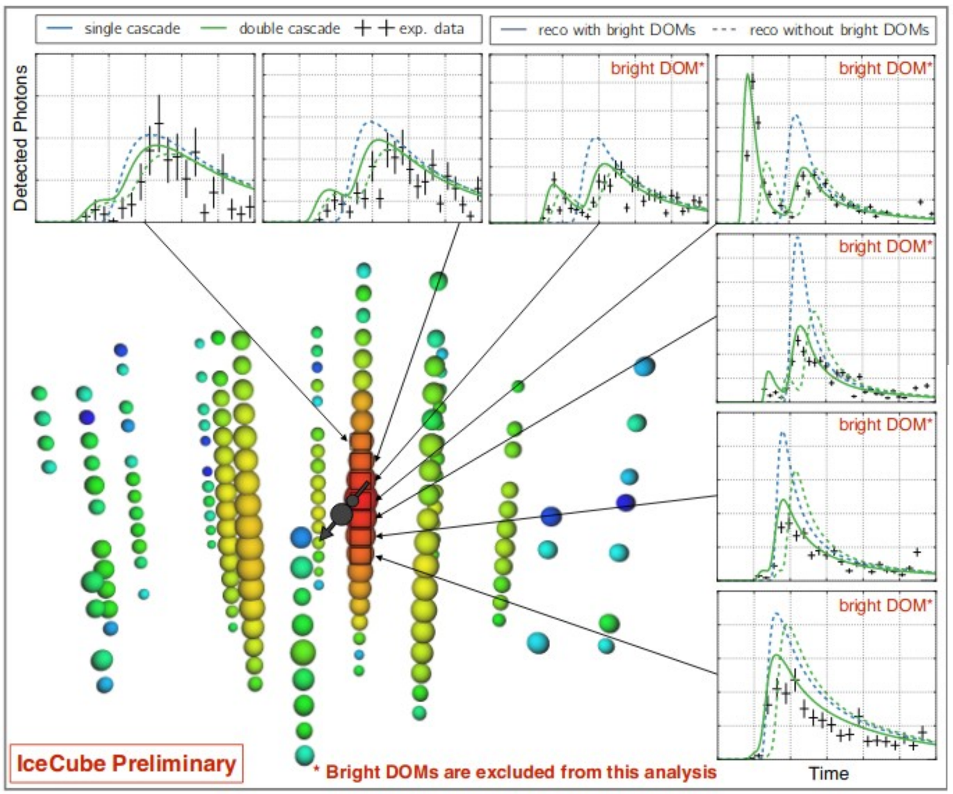
– detector
– background

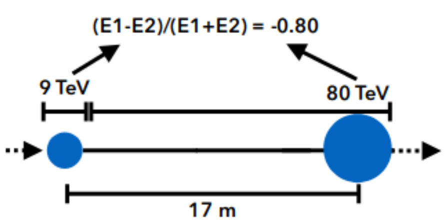
J. Phys. G **43, 8**: 084001 (2016)

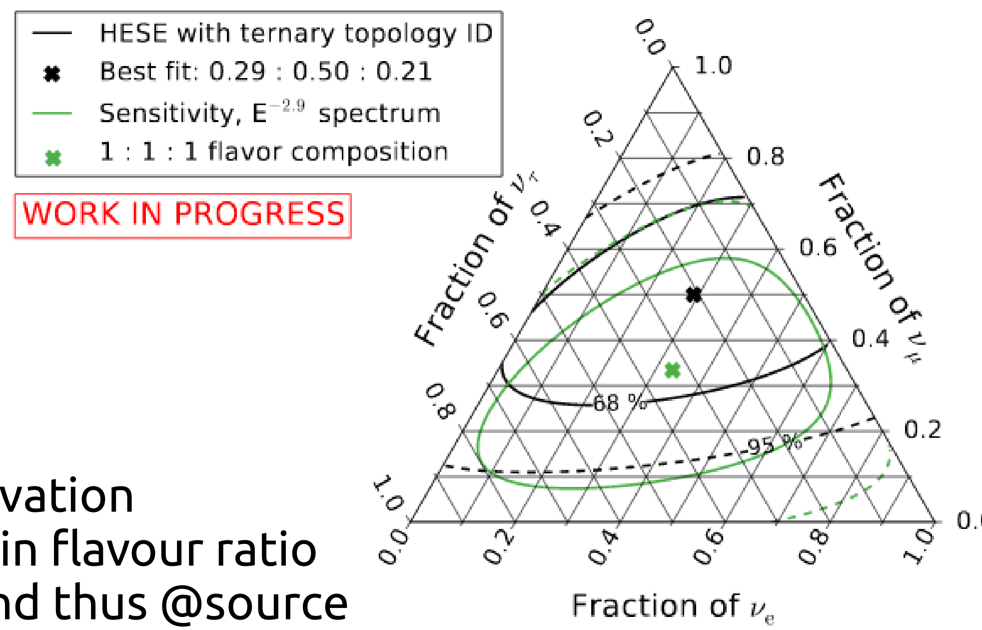
HE tau neutrinos in IceCube

No atmospheric background → tau flux can only be of cosmic origin

1 candidate events
(+ one which is a PeV HESE)



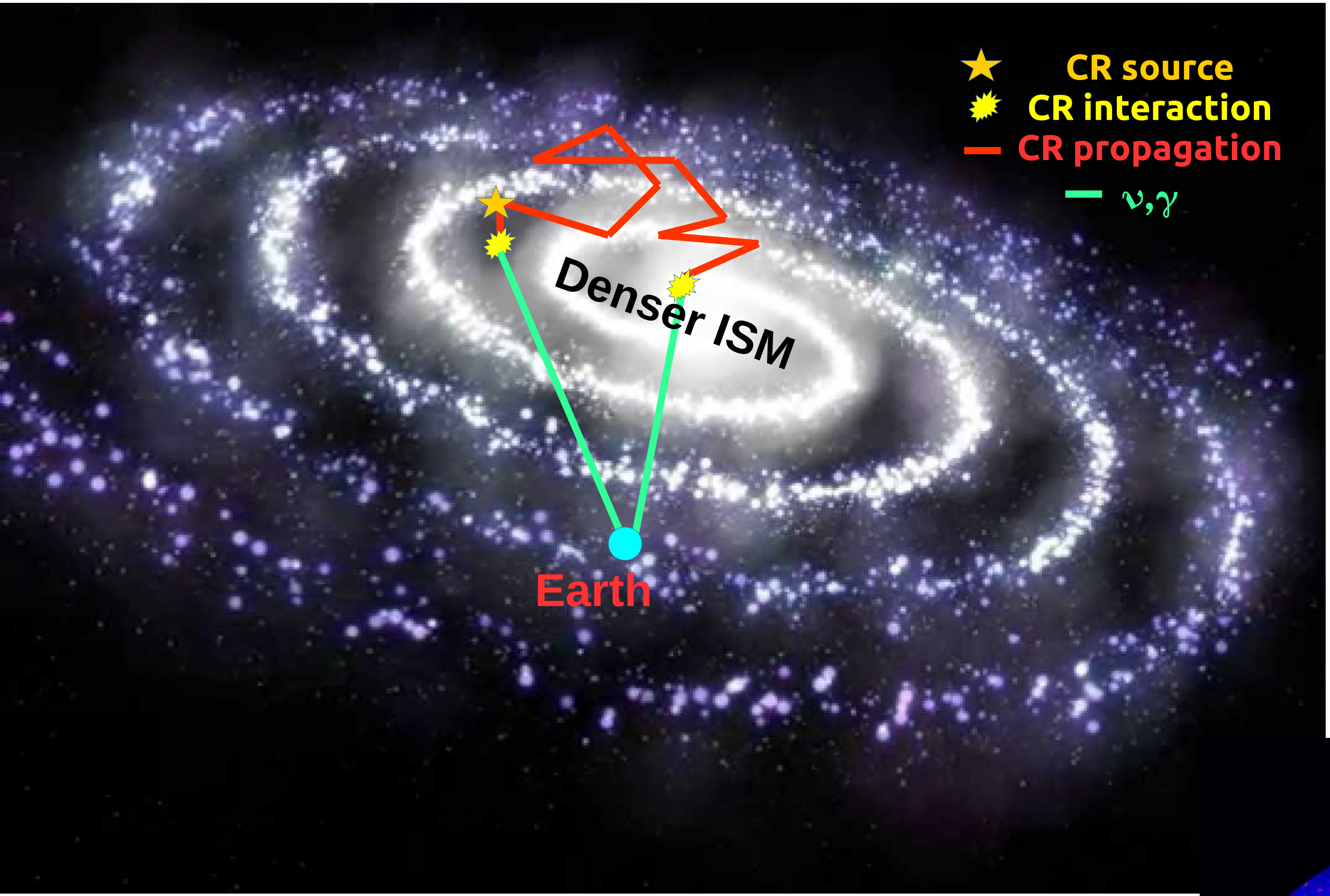




Tau observation
→ constrain flavour ratio
@Earth and thus @source

PoS(ICRC2019)1015

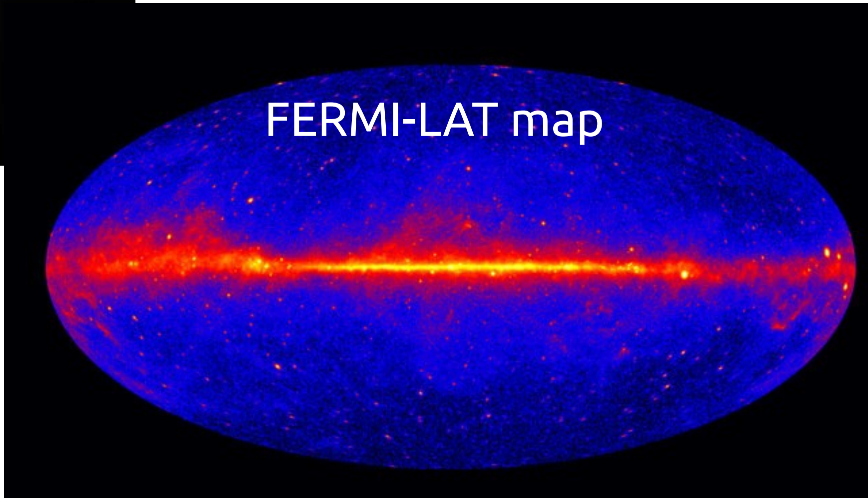
γ and ν: CR propagation in the Milky Way



Neutrinos carry direct information on CR propagation. e.g.:

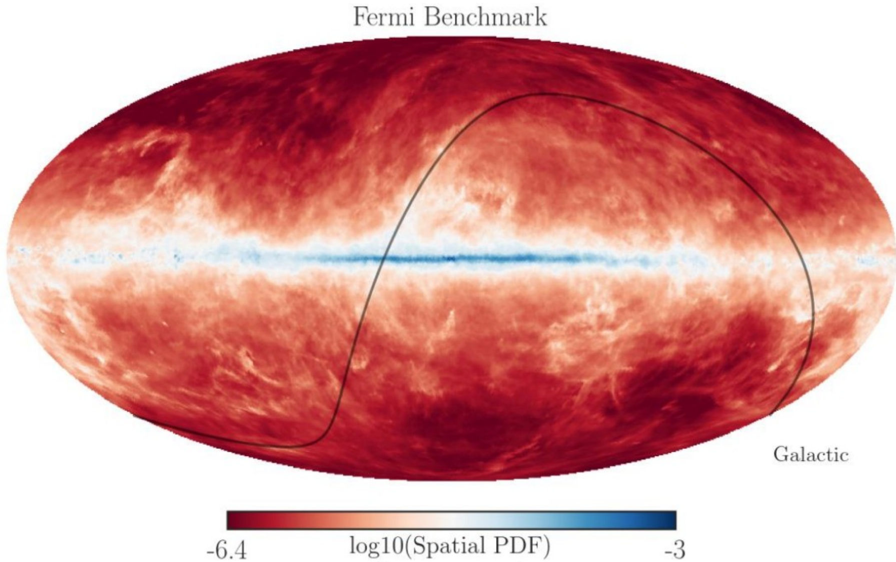
- Non-homogeneous diffusion can enhance γ and ν emission

- Molecular clouds/dense environments boost γ and ν fluxes

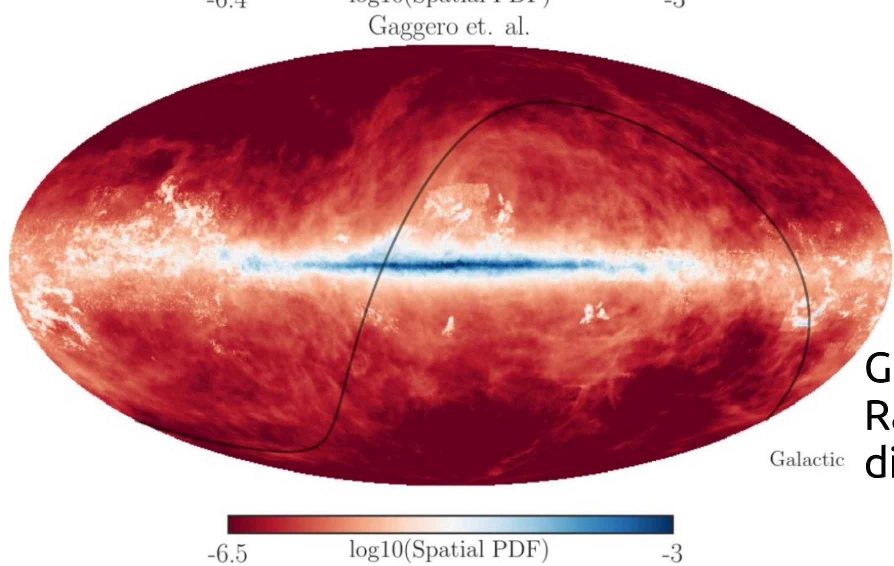


* ApJ. **750:** 3, 2012
** ApJ Lett. **815**: L25, 2015

ν models from GCR and γ

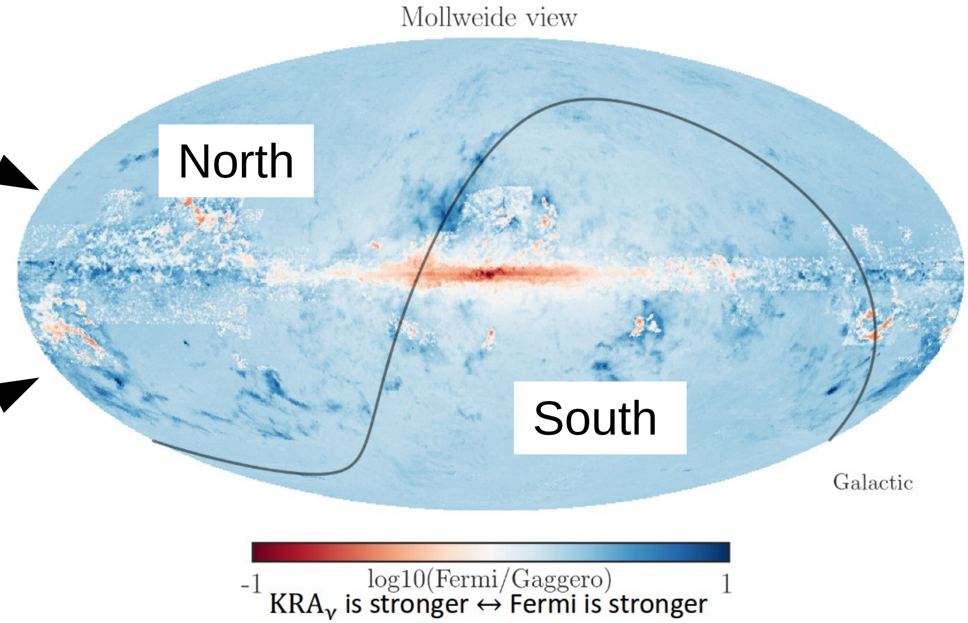


Standard model*



Gaggero et al.**
Radially dependent diffusion – data tuned

Ratio of the two

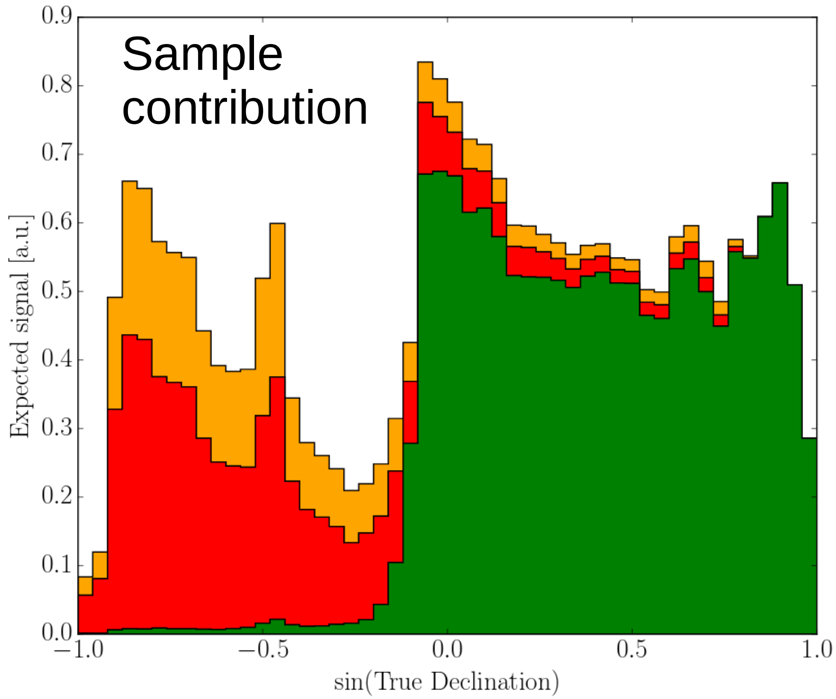


Harder/stronger in the centre
Softer/lower in the periphery
→ different fields of view can test differently the model

Plots by C.Haack, for the IceCube Collaboration

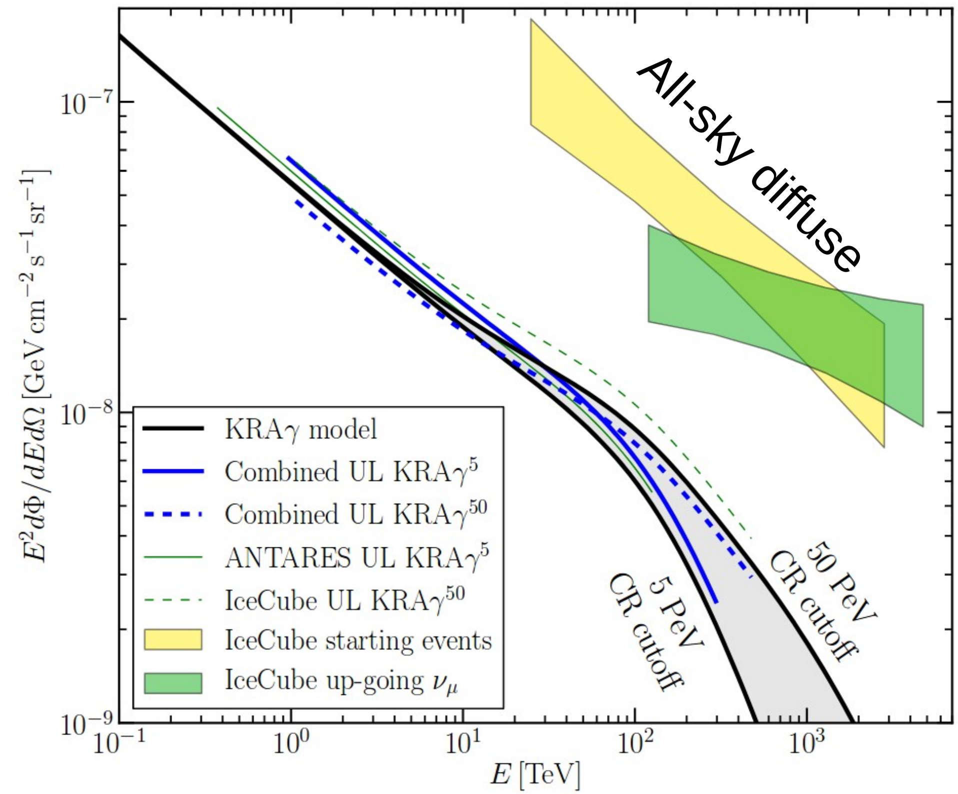
νs from the GP

Joint analysis ANTARES (tracks + cascades) and IceCube (tracks)



+ spectral energy distributions are different in the model

No significant excess observed

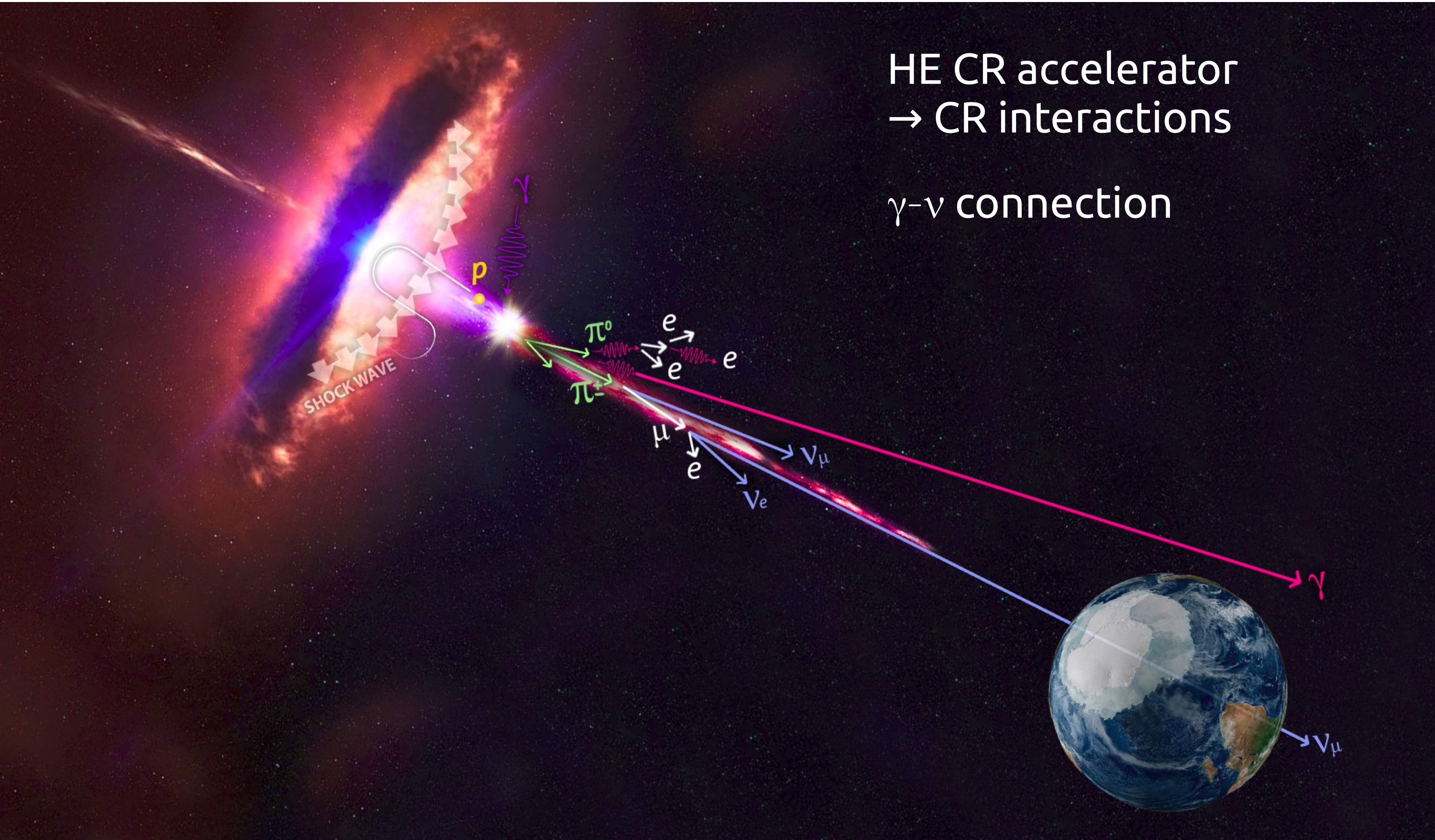


Low latitude Galactic contribution constrained to 8% of the all-sky flux

ApJ Lett **868**: L20 (2018)

New IC cascade analysis:
ApJ **886**: 1, 2019 (see backup)

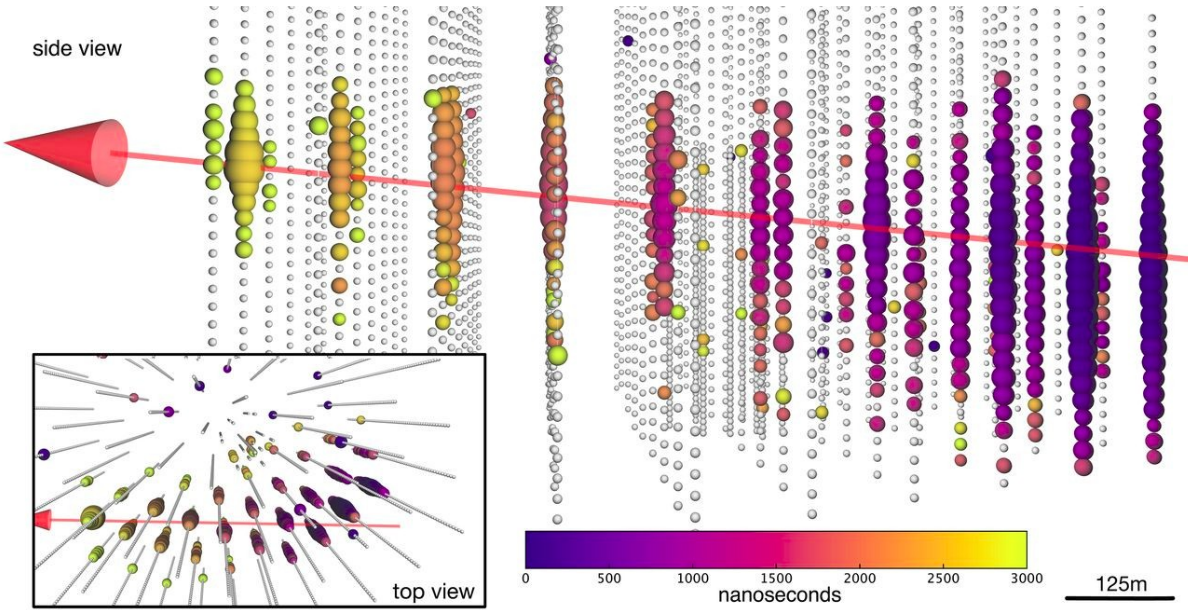
Individual sources of neutrinos



HE CR accelerator
→ CR interactions

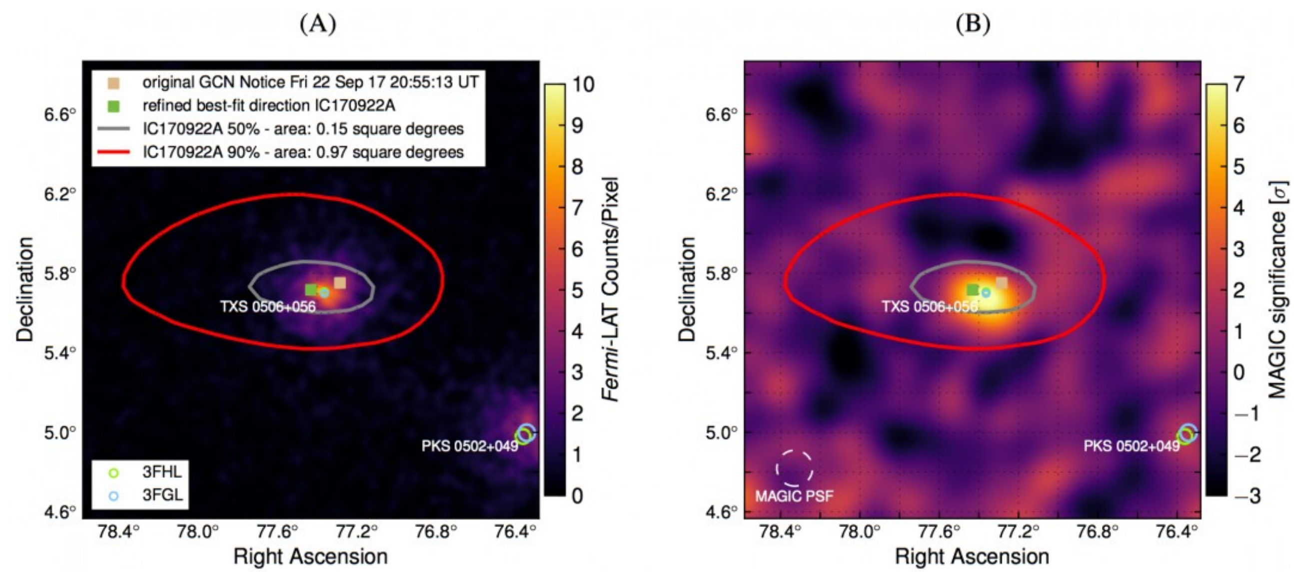
γ-ν connection

IC170922A and TXS 0506+056



270 TeV muon
On 22 September 2017 at 20:54:30.43 UTC

RA 77.4° and Dec +5.7°

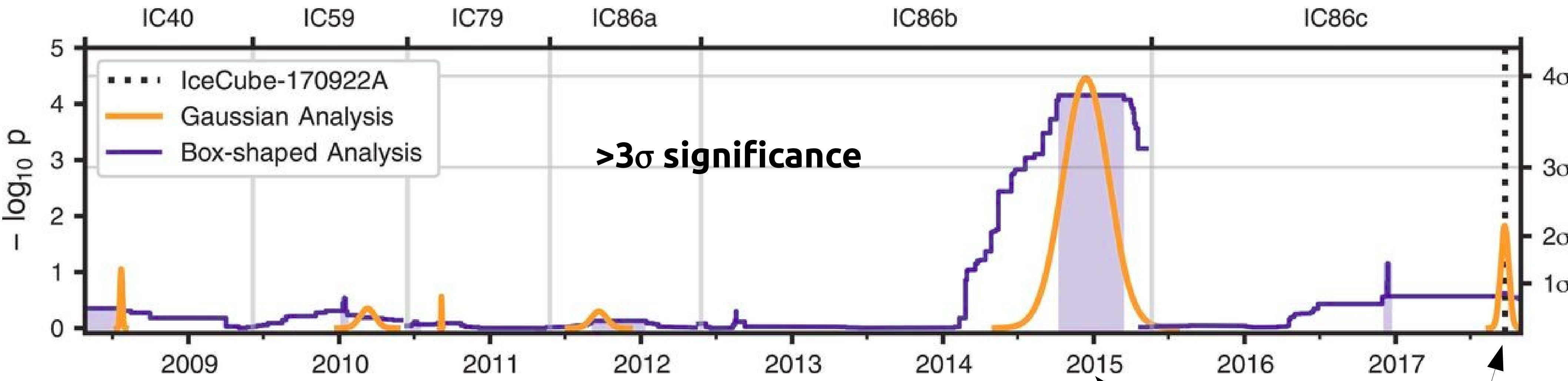


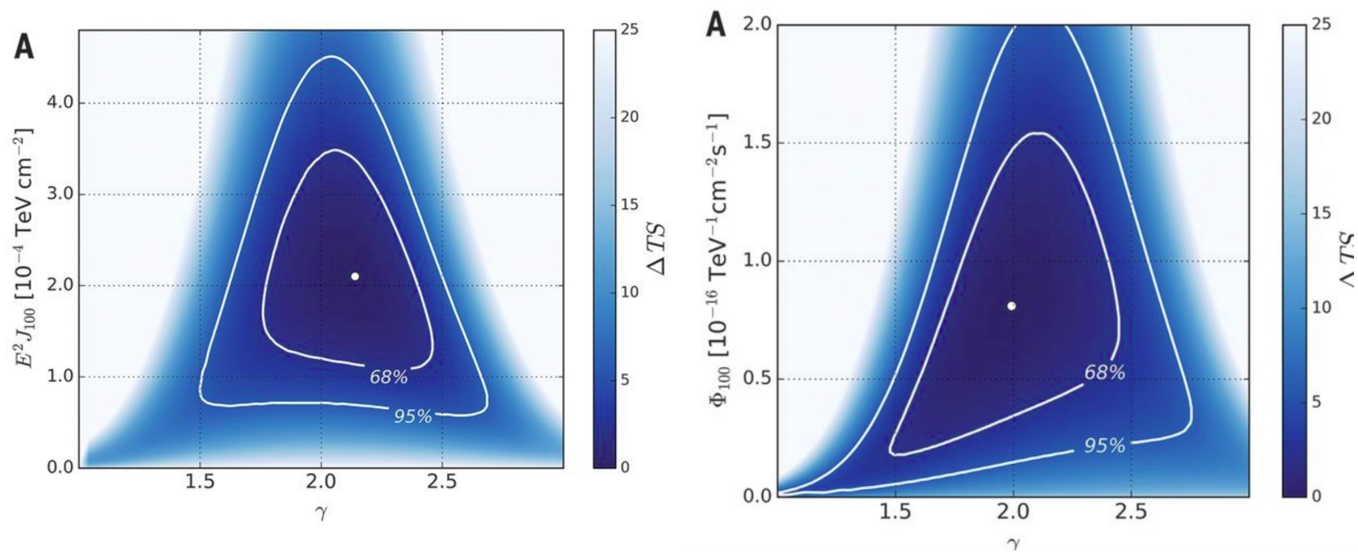
Fermi-LAT and MAGIC prompt follow-up
>3σ significance

Not really compatible with other close-by emitters

Science **361, 6398**, eaat1378
DOI: 10.1126/science.aat1378

TXS 0506+056





13 neutrinos
in excess
No gammas

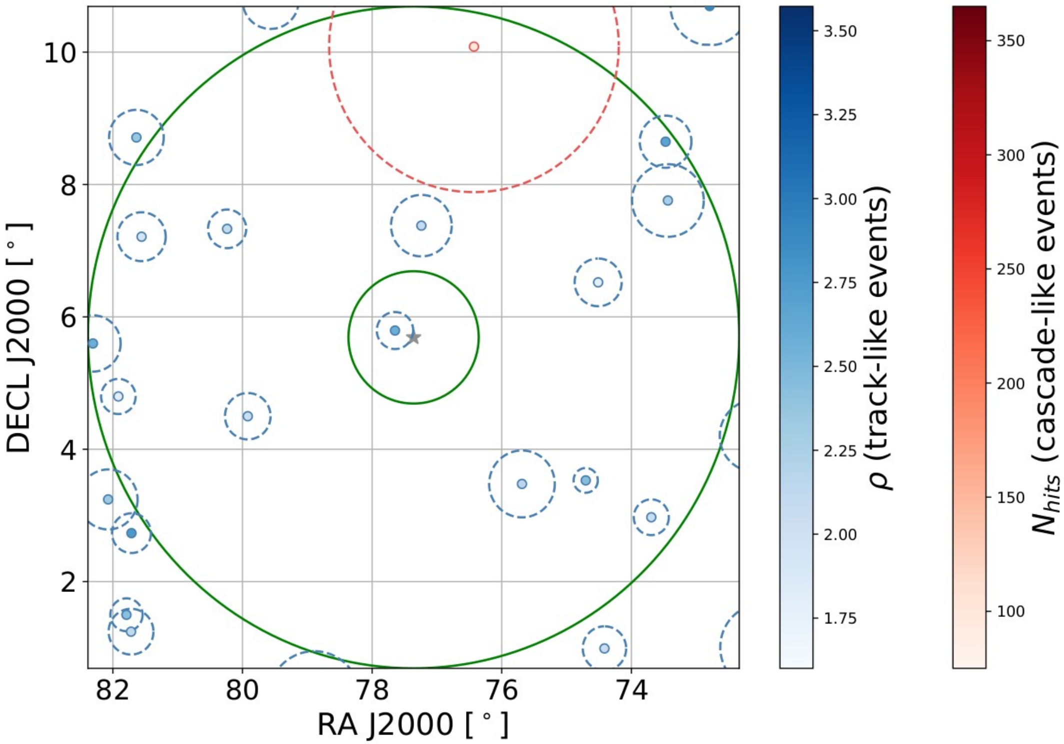
gamma flare
+ IC170922A

Some ambiguities in the interpretation are still there (no flare in 2015? is it a peculiar source? ...)

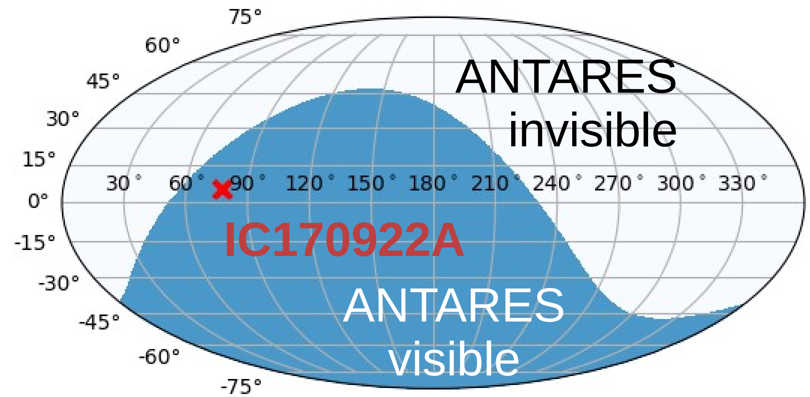
Science **361, 6398**, pp. 147-151
DOI: 10.1126/science.aat2890

TXS 0506+056

Offline analysis (2007-2017)



1.03 signal-like events fitted → p-value = 3.4% (pre-trial)
3rd most significant candidate out of 107*



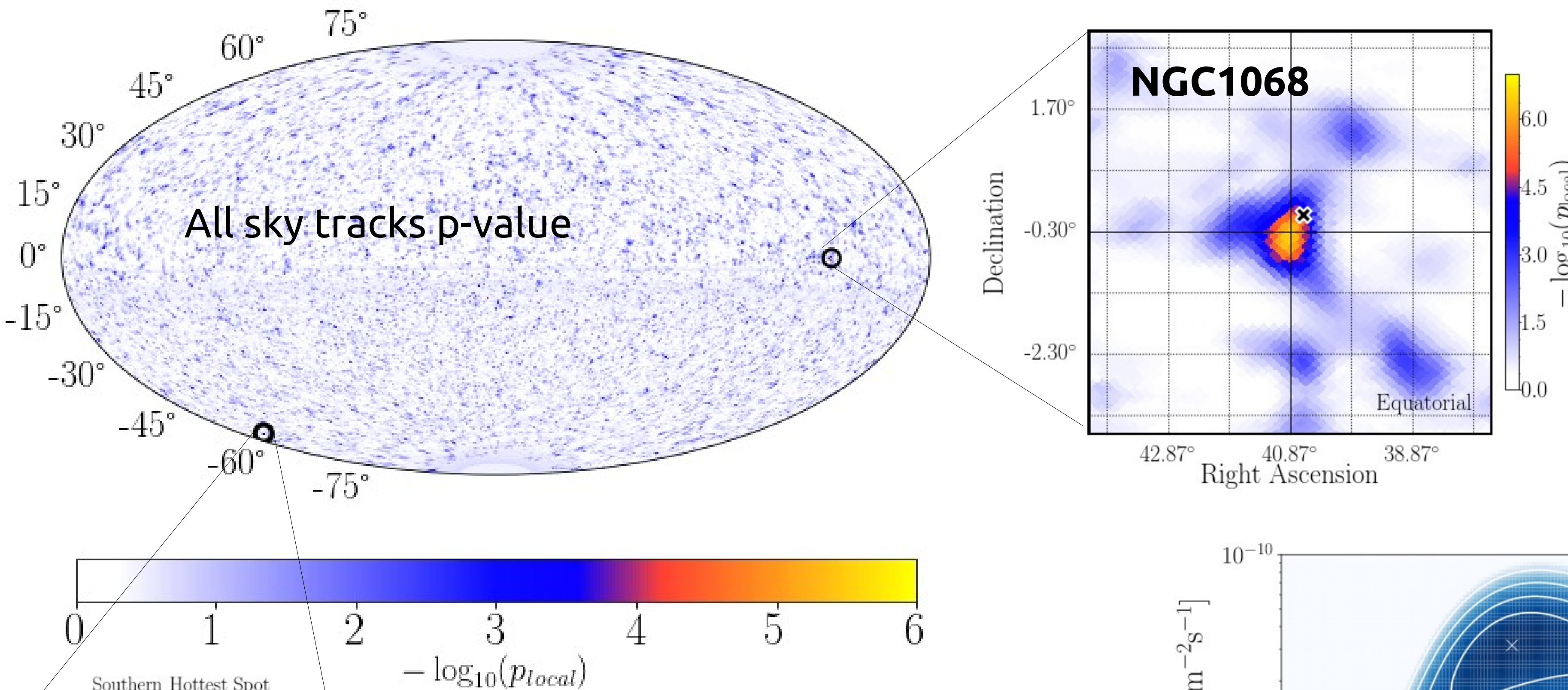
Online data-stream analysis
→ no coincident event
ATEL #10773 released by ANTARES the following day

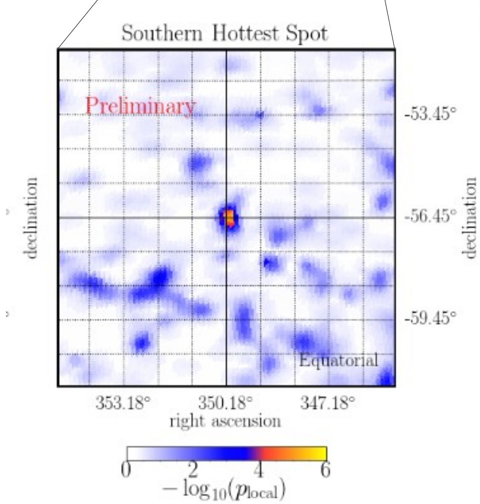
+ time dependent search for space-time clustering with the IC neutrino flare – no excess observed

* off the published 2007-2015 analysis; 87% post-trial

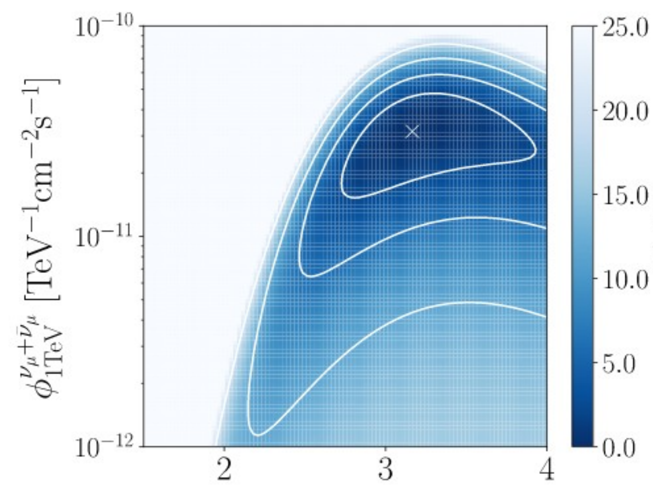
ApJ Lett **863** no.2: L30, 2018

Point source searches results



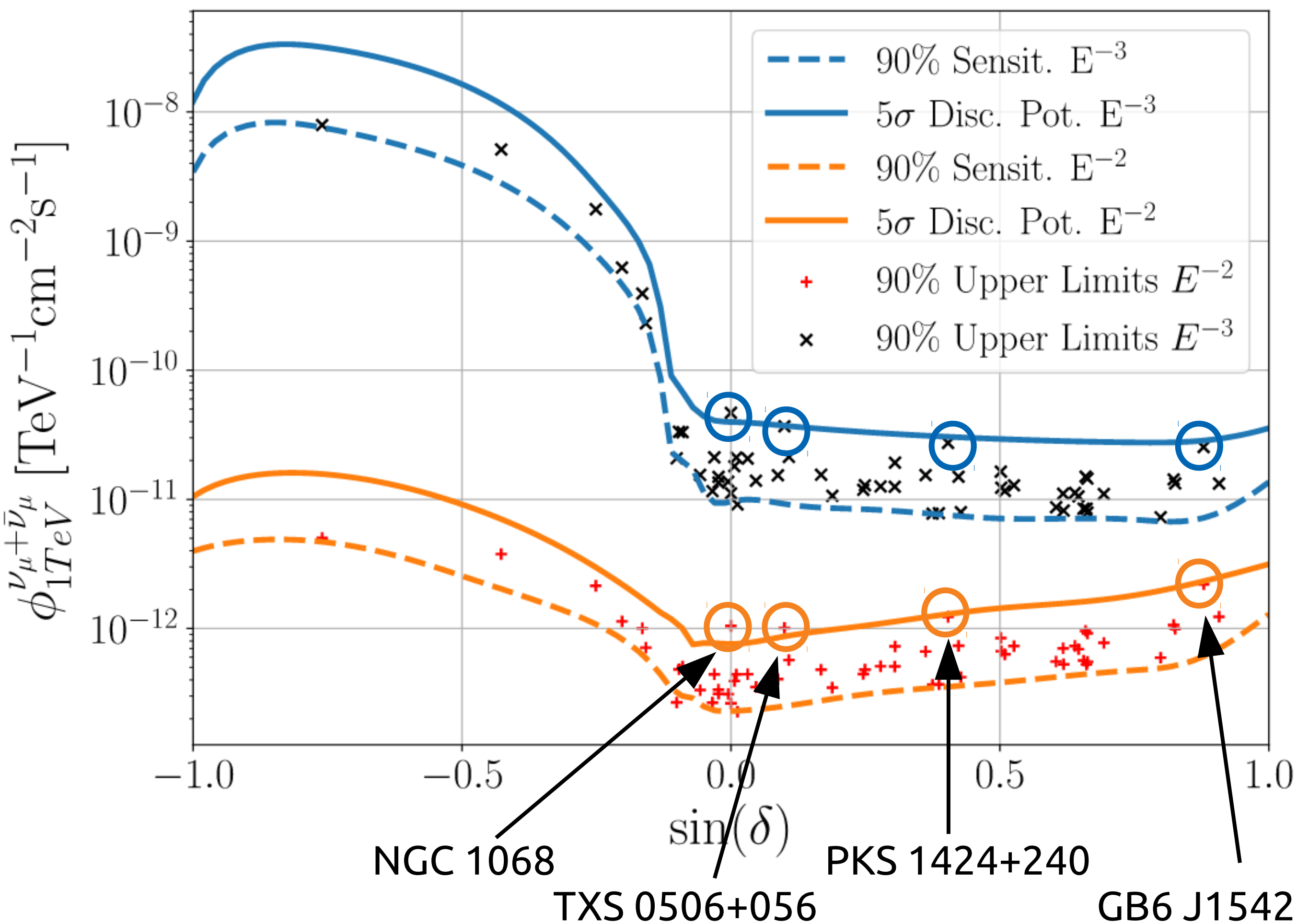


pre-trial p-values
Still not that significant,
but some hints for
clustering



PoS(ICRC2019)851 + arxiv:1910.08488

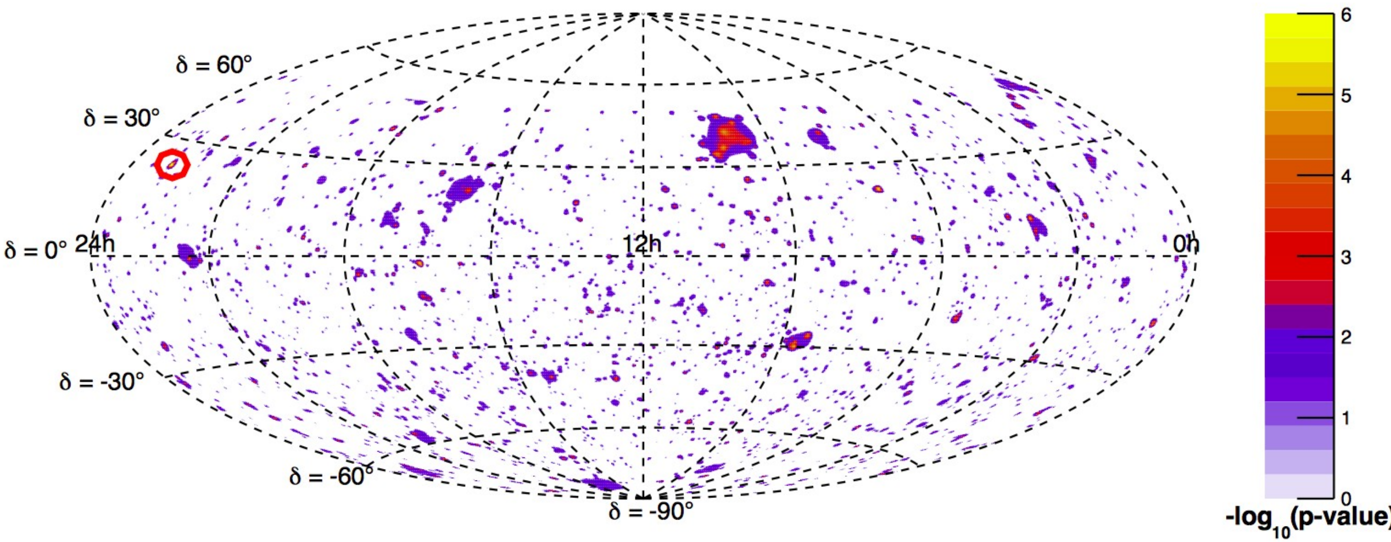
Point source searches results



Somewhere between 2-3σ excess

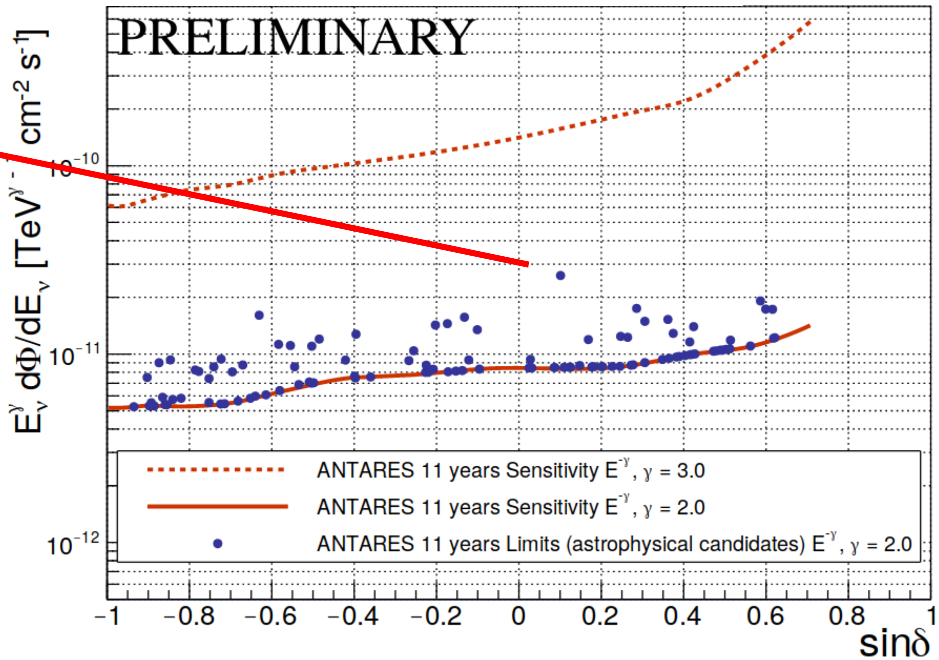
PoS(ICRC2019)851 + arxiv:1910.08488

Point source searches results



Combined tracks + showers

HESSJ0632+057
(α,δ) =(98.24°,5.81°)
1.4σ



Still more sensitive than IceCube for soft spectra in the Southern Sky

PoS(ICRC2019)920

Point source searches results

Astrophysical catalogs

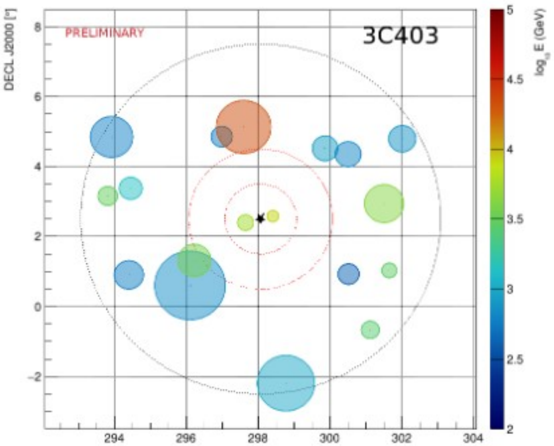
- Fermi 3LAC Blazars (1255 sources in FoV)
  [Ackermann et al. ApJ 2015]
- Star Forming Galaxy catalog observed in γ by Fermi (54 in FoV)
  [Ackermann et al. ApJ 2012]
- Giant radiogalaxies catalog selected in soft γ ray (53 in FoV)
  [Bassani et al. MNRAS 2016]
- Dust obscured AGN selected in X rays (10 in FoV)
  [Maggi et al. PhysRevD 2016]

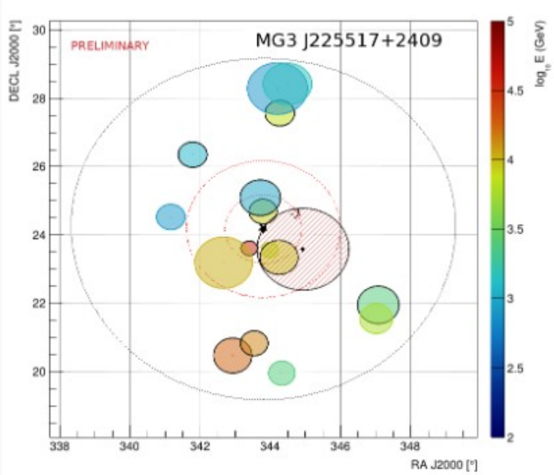
HE Neutrino sample

- IceCube high energy tracks (55 sources in FoV)
  (35 tracks from 8 yr up-going muons + 21 HESE 6 yr)
  [IceCube collaboration, ICRC 2017]

Catalog stacking

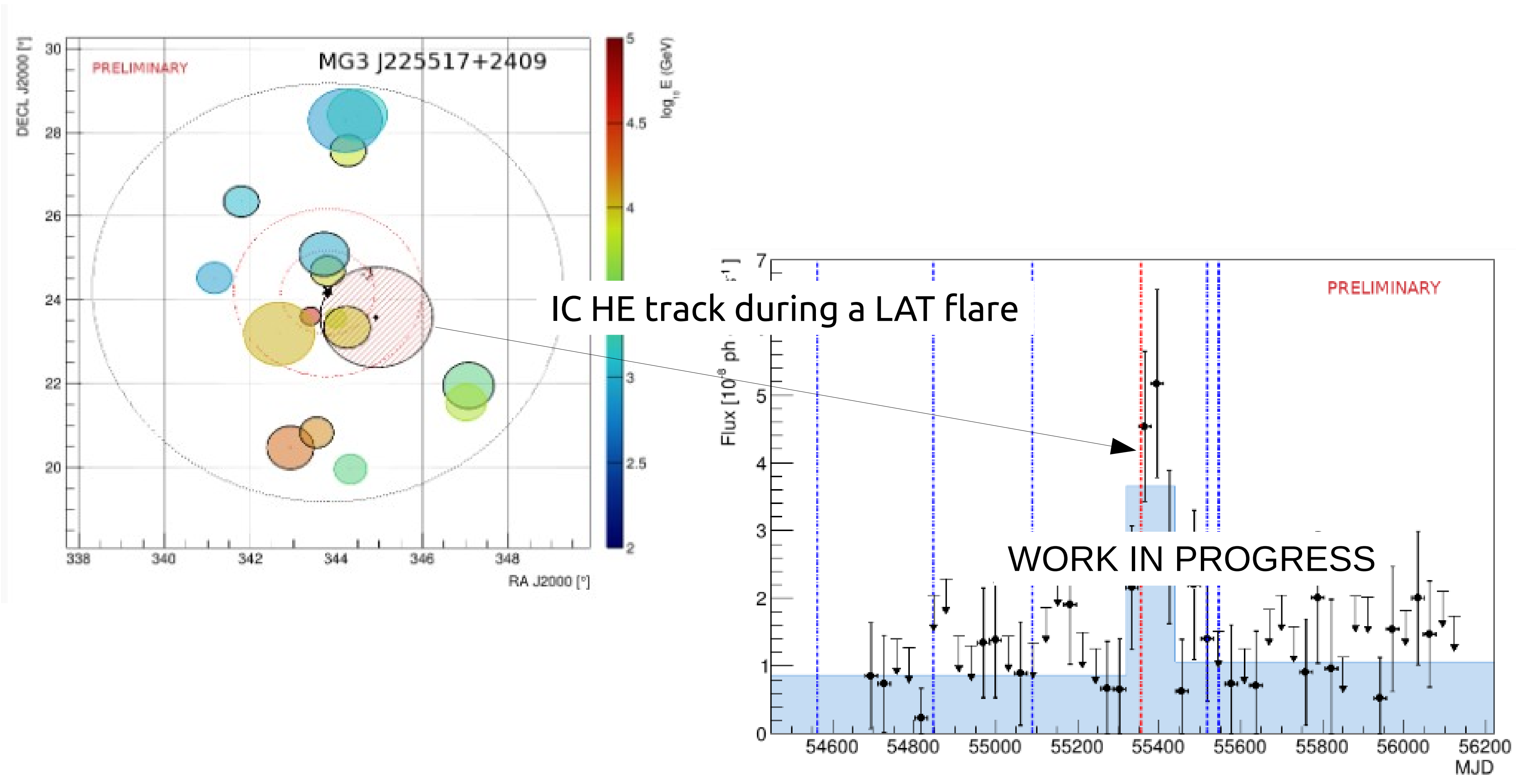
→ non significant excess with radio galaxies and 3LAC



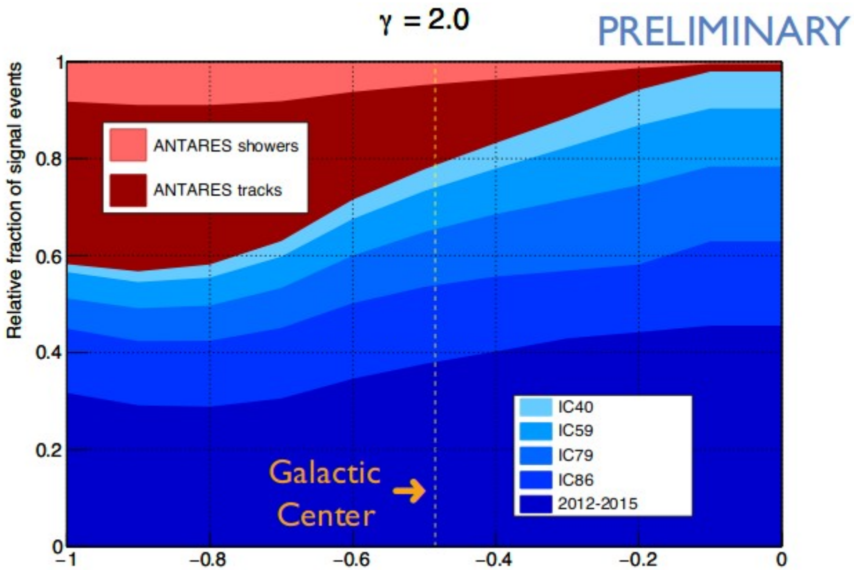


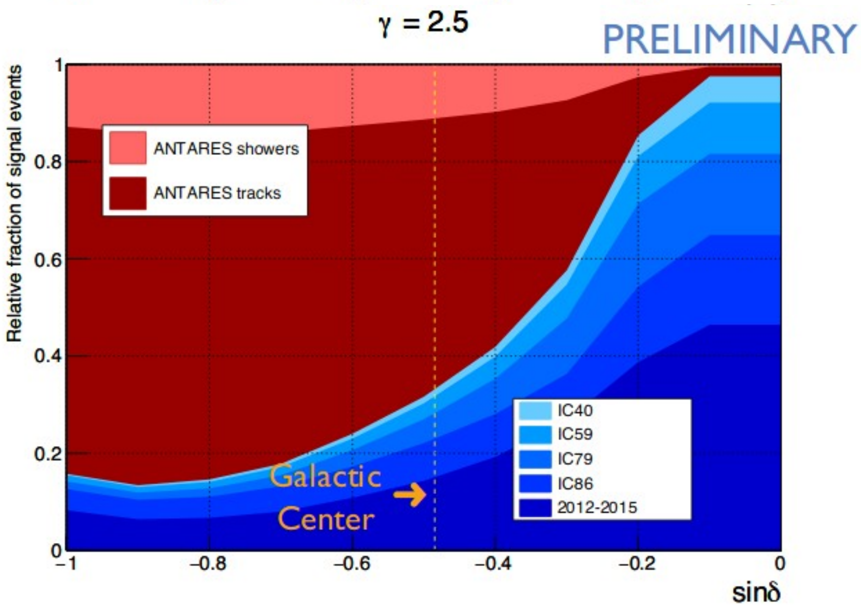
PoS(ICRC2019)840

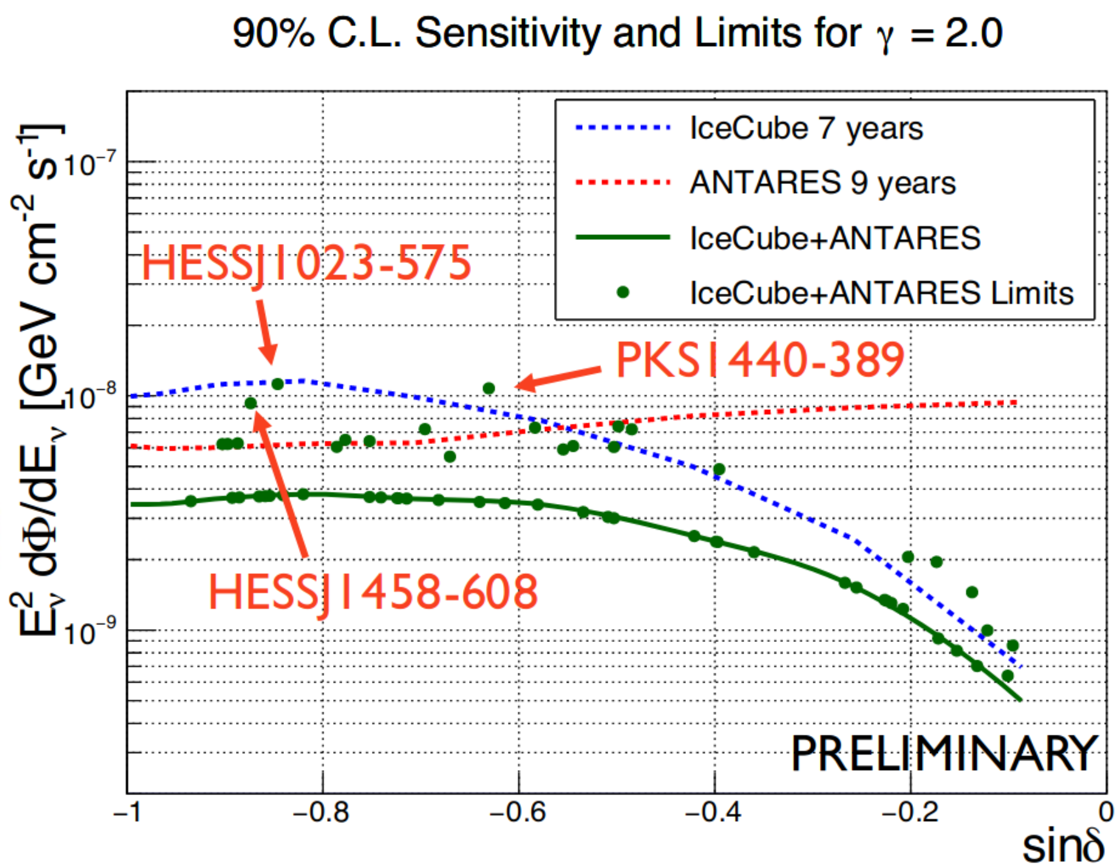
Point source searches results



Joint point source search results







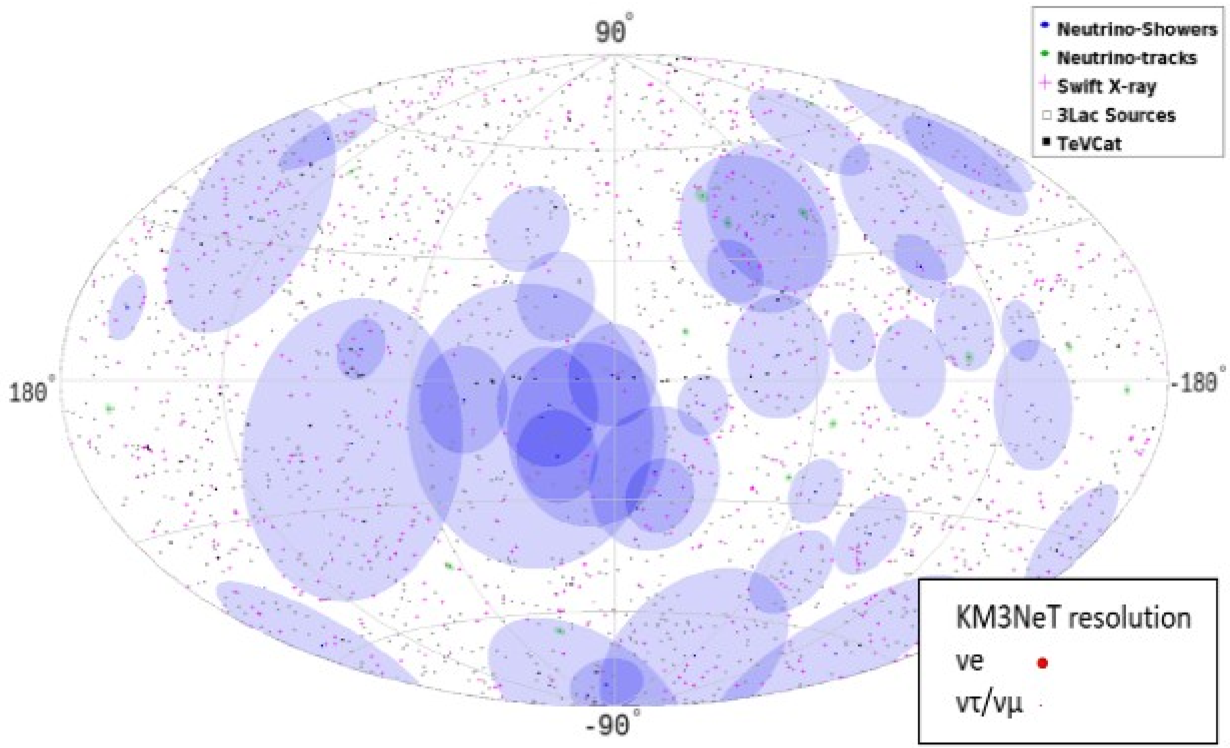
+ constraints on SgrA* in the backup

PoS(ICRC2019)919

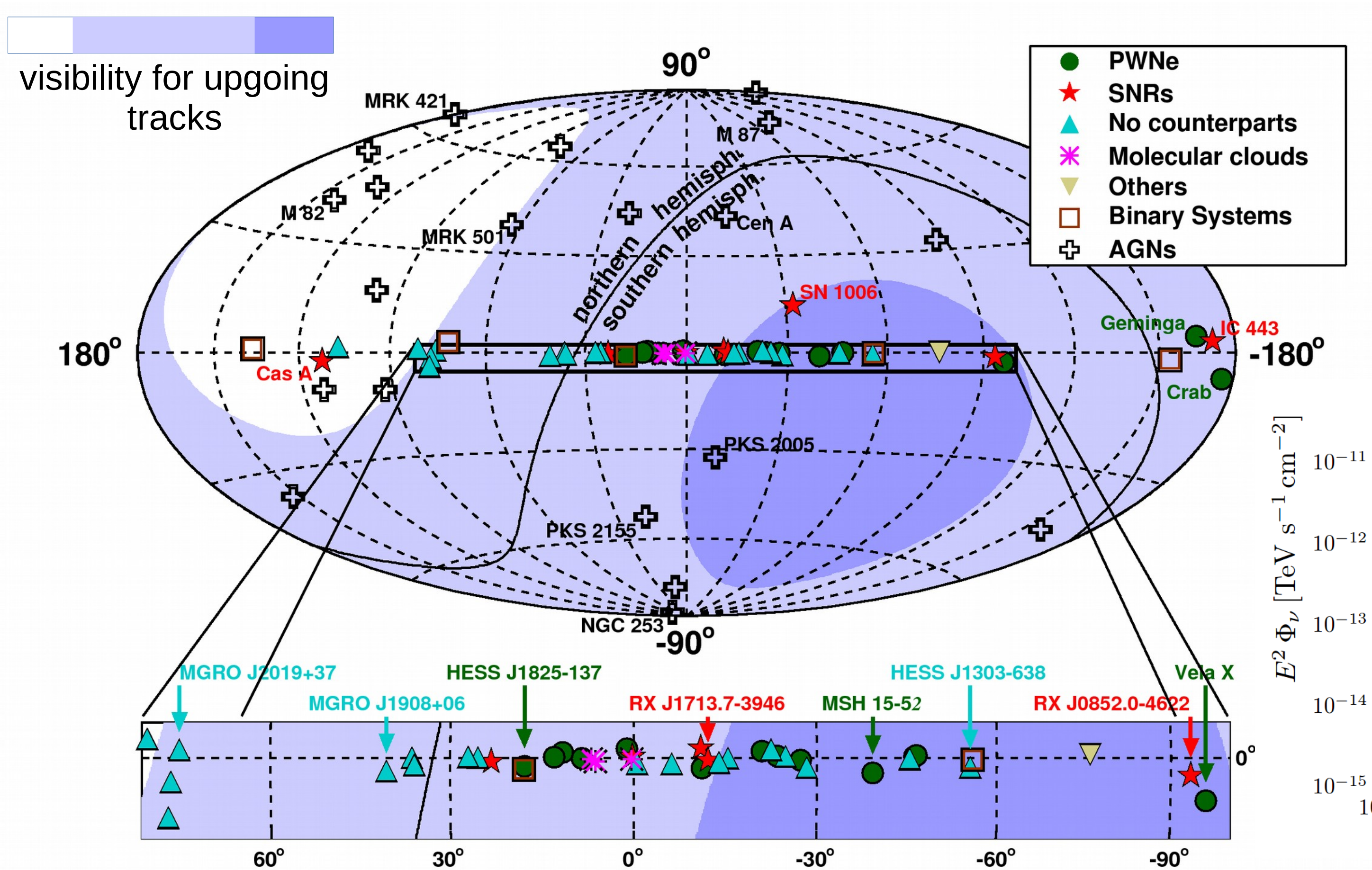
Why a km³ neutrino telescope in the sea/underwater?

- Water is optimal for light
  - Limited scattering → direct photons
  - Homogeneous medium → easy to simulate, less systematics

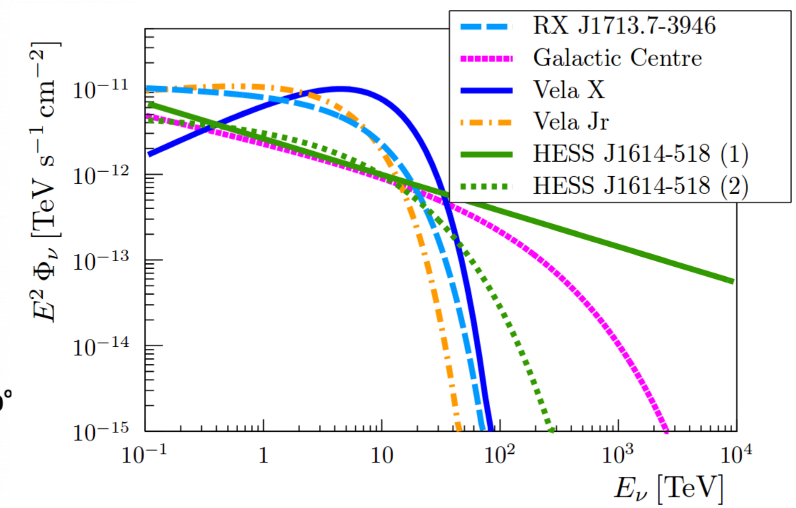
→ 0.1 degree angular reconstruction accuracy



Why a km³ neutrino telescope in the Mediterranean Sea/North?

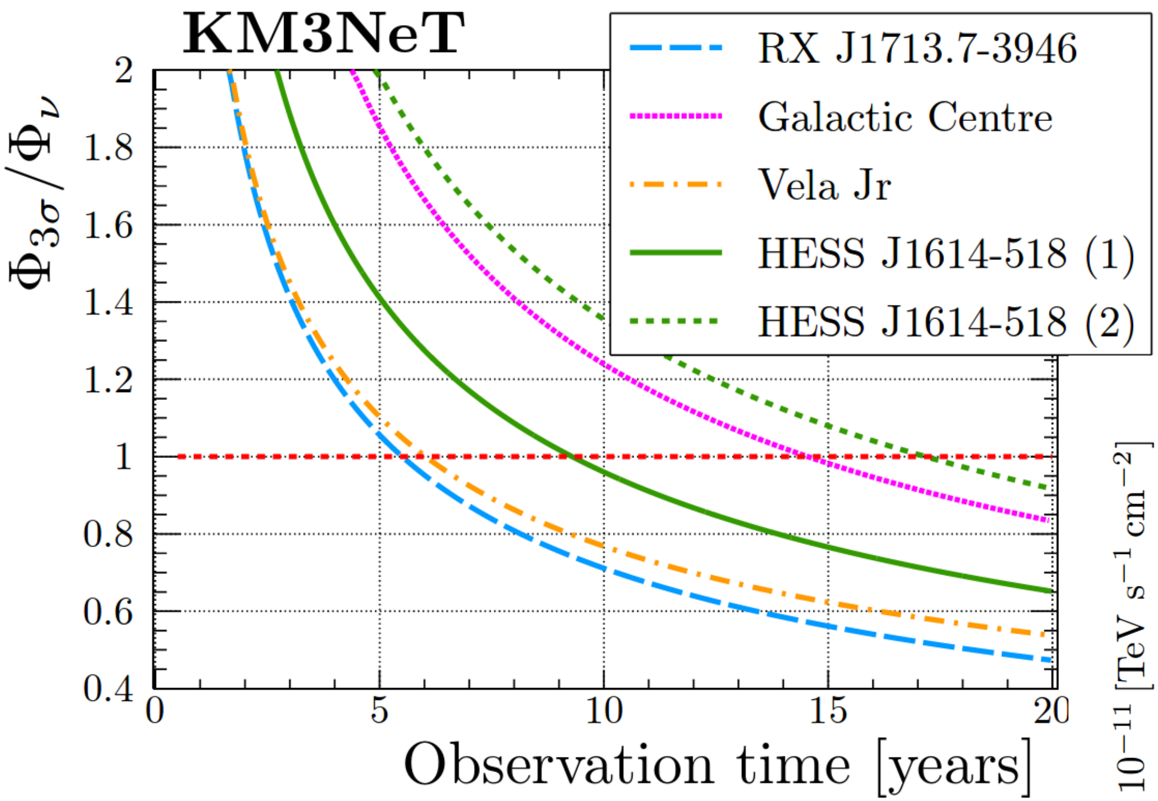


High visibility with 0.1° angular resolution



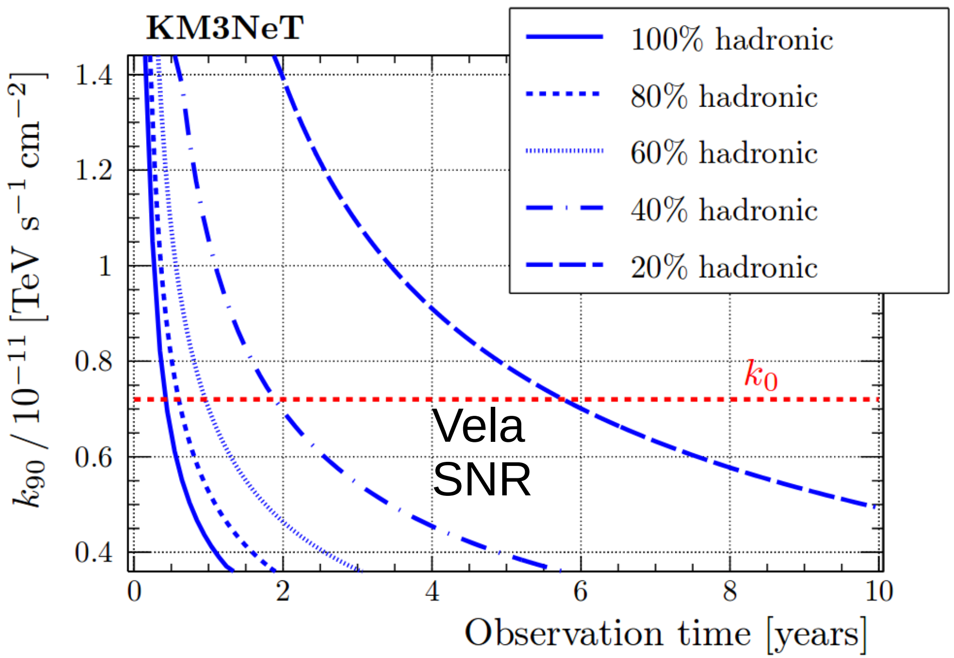
Soft spectra from γ obs.
→ lowE threshold analysis

KM3NeT/ARCA and galactic sources



Discovery potential for potential Galactic targets

If no neutrino observation → constrain the hadronic component

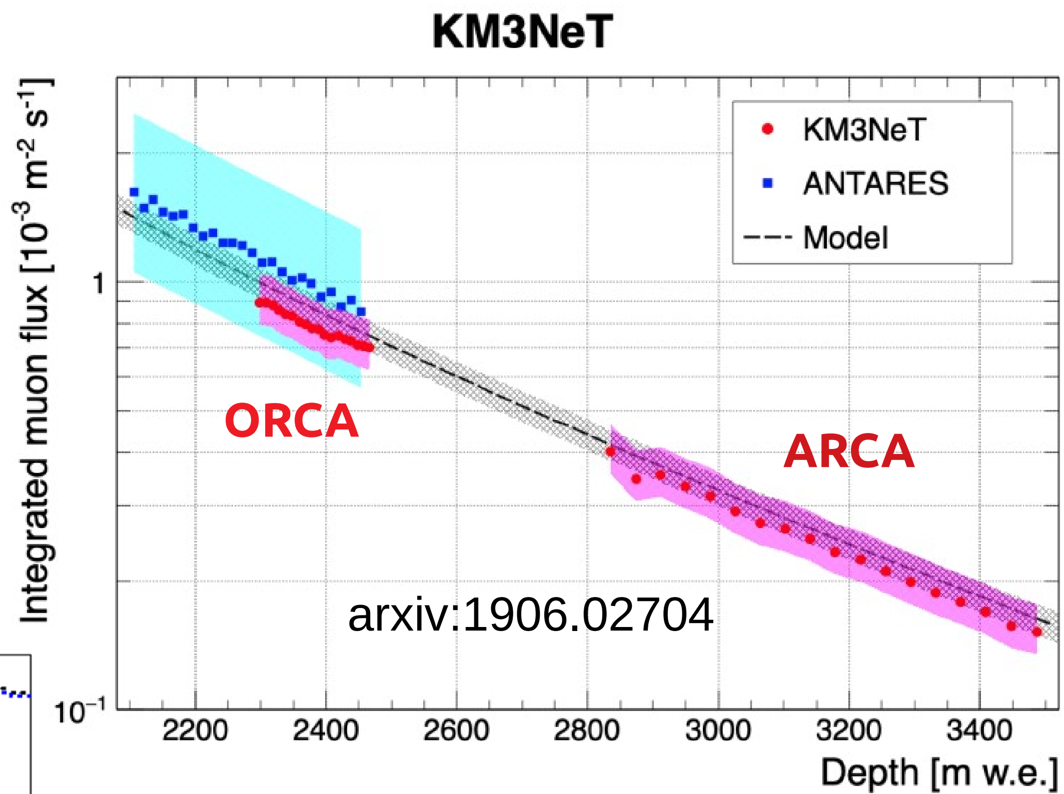


Astrop. Phys. **111**: 100, 2019

KM3NeT current status

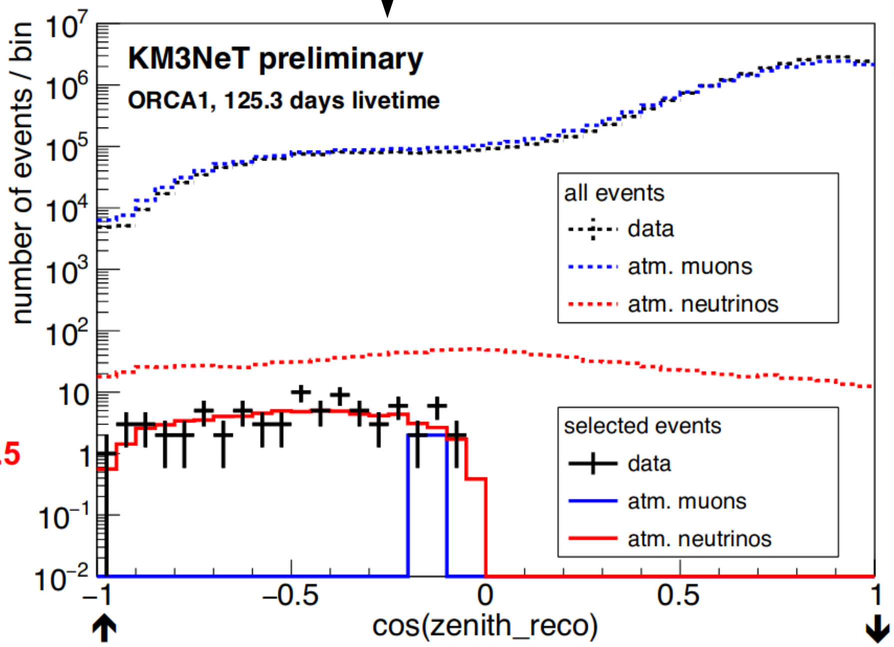
4 DUs at the French site
1 DU at the Italian site
Currently working

Analysis of atmospheric muons →



Selection of atmospheric neutrinos ↓

Data: 77
ν MC: 67.5
μ MC: 4

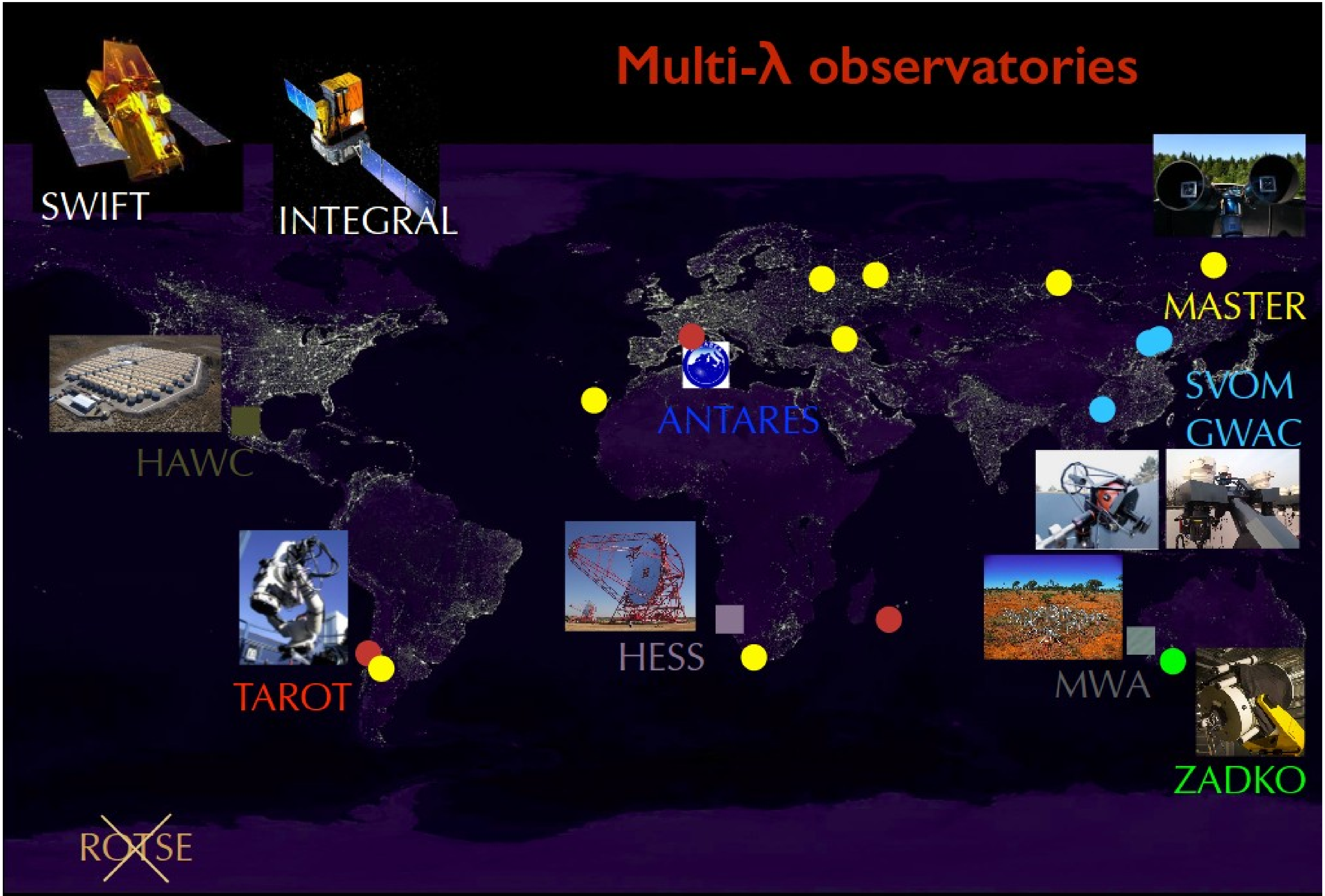


1 DU is already enough
to select atmospheric neutrinos

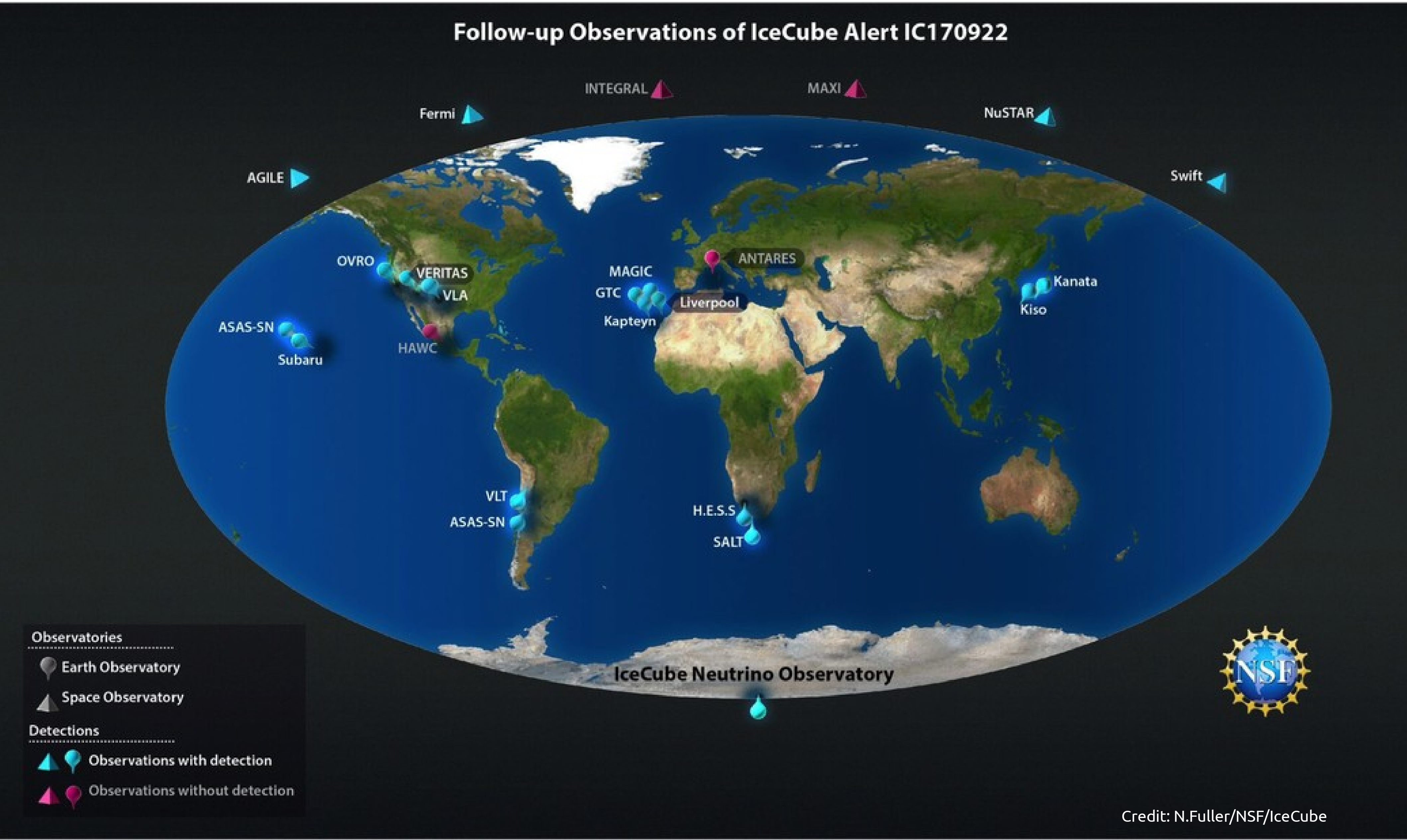
Same for ARCA and analysis with
4 DUs already in place

POS(ICRC2019)910

Multi-messenger follow-up program

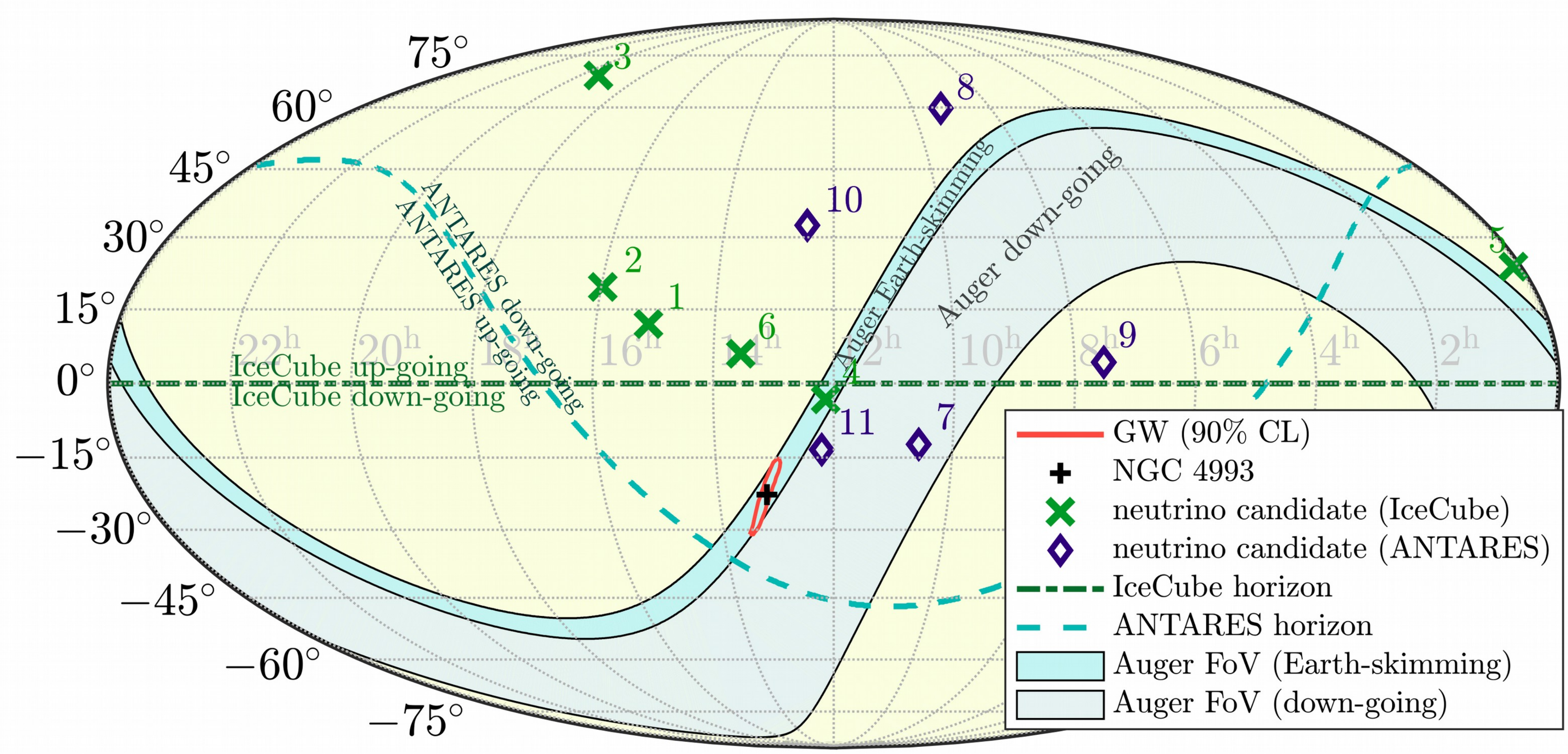


Multi-messenger follow-up program



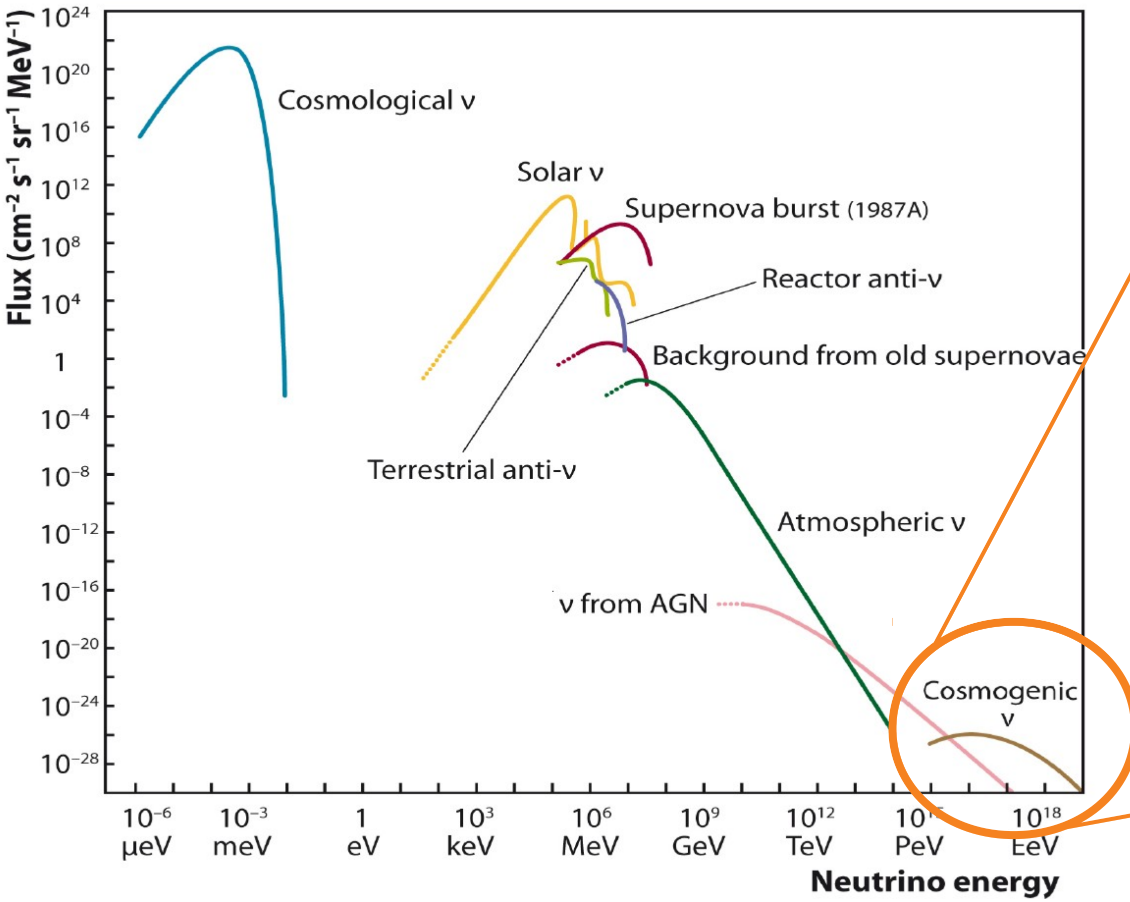
Neutrino searches from GW170817

i.e. neutrino telescopes also follow-up external triggers

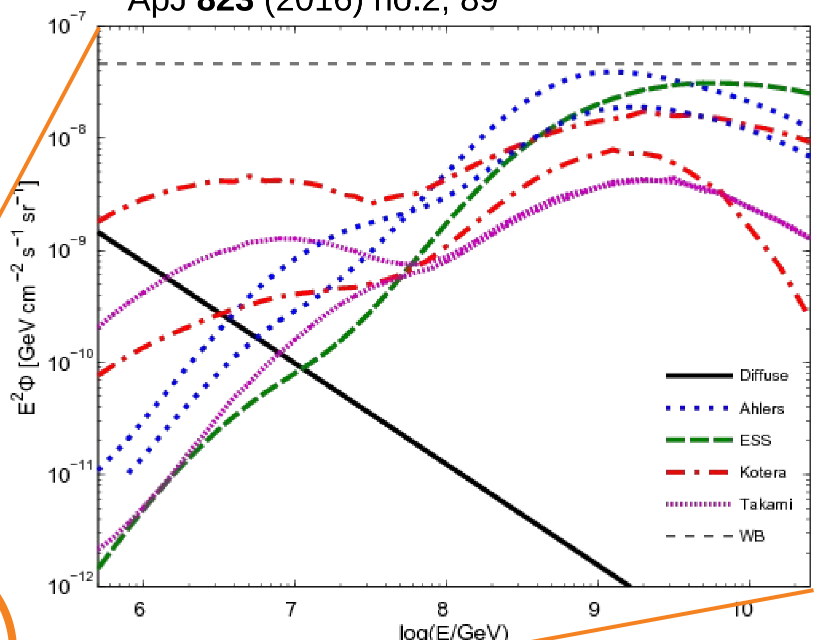


ApJLett **850**: L35 (2017)

Ultra HE diffuse neutrino fluxes

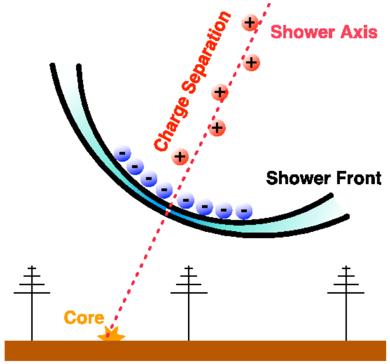


ApJ **823** (2016) no.2, 89



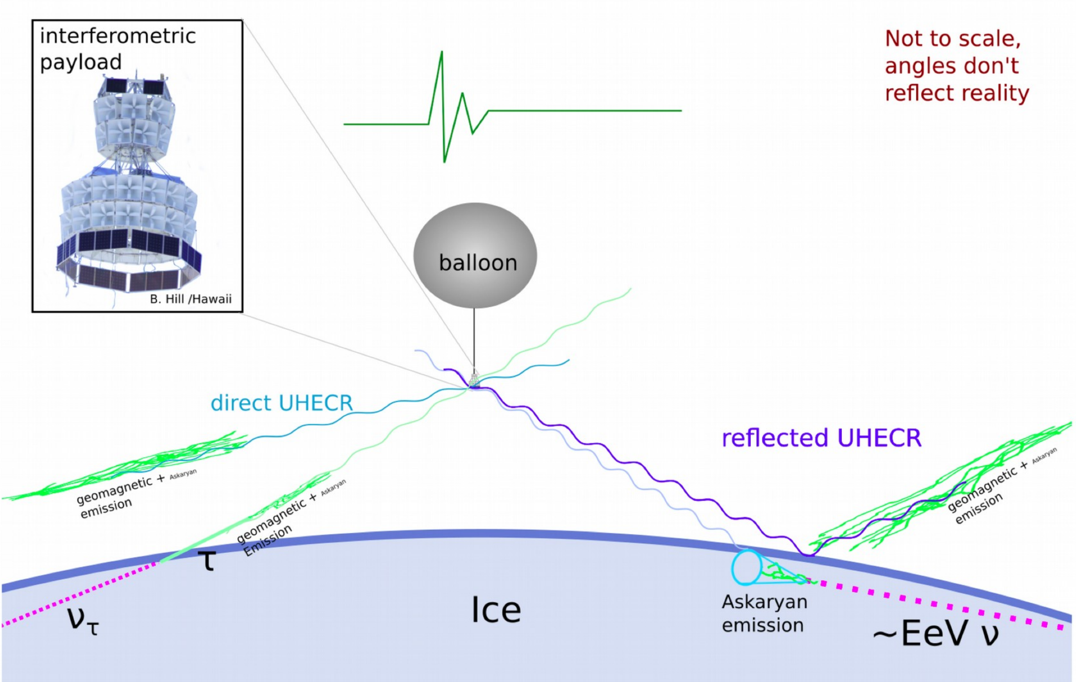
Neutrinos from photoproduction (UHECR with CMB)
Spectrum strictly related to UHECR physics

Radio neutrino detection – ANITA, ARA and ARIANNA

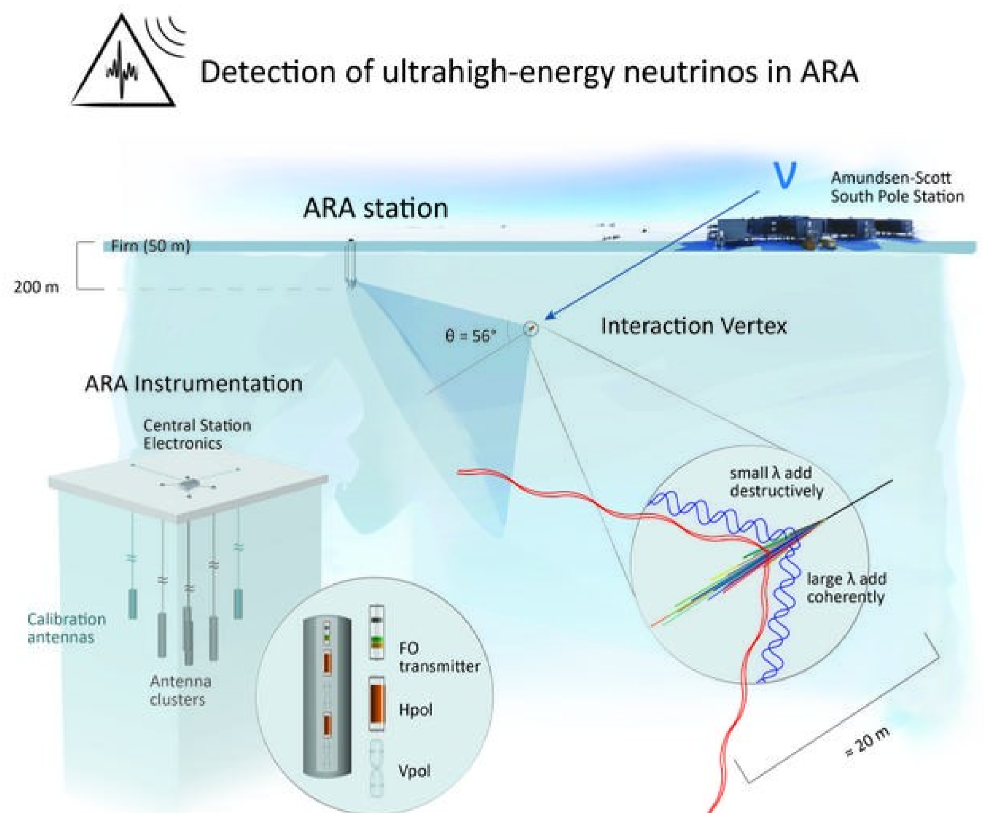


Circumpolar Antarctic flights on balloon of radio-antennas
→ ANITA

In-ice antennas
→ ARA and ARIANNA



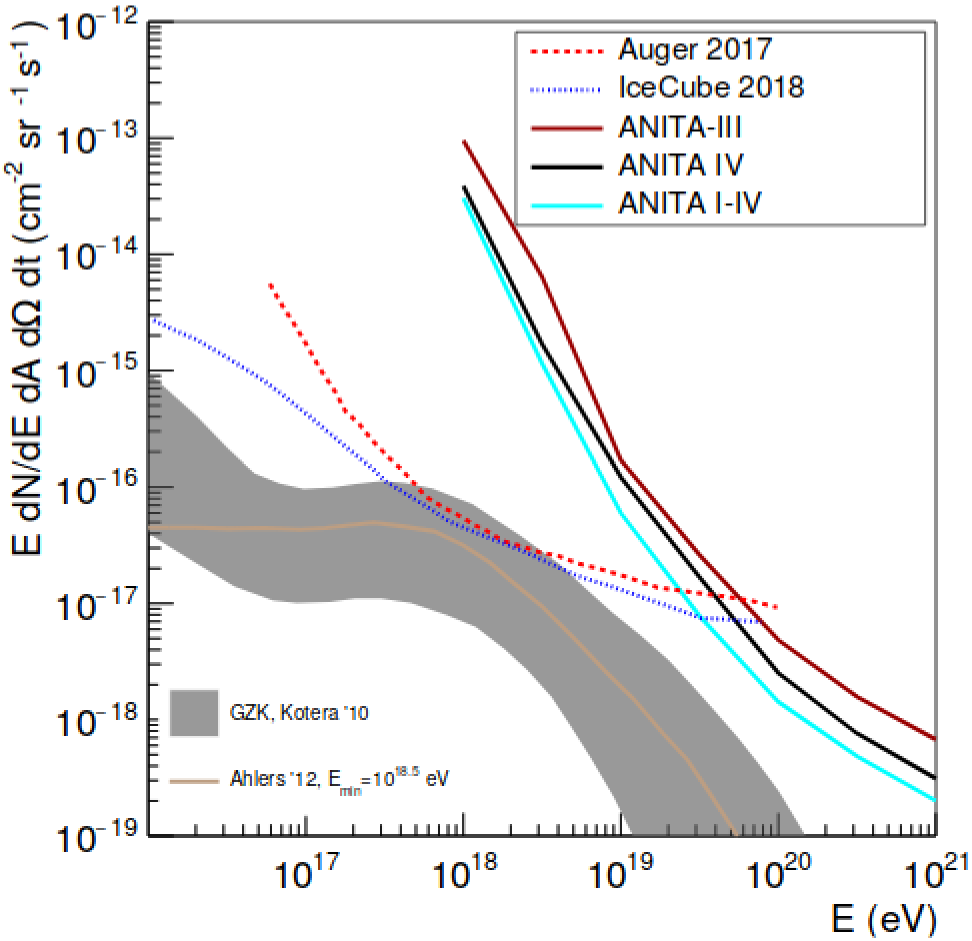
The ANITA detection concepts, figure from Cosmin Deaconu.



https://ara.wipac.wisc.edu

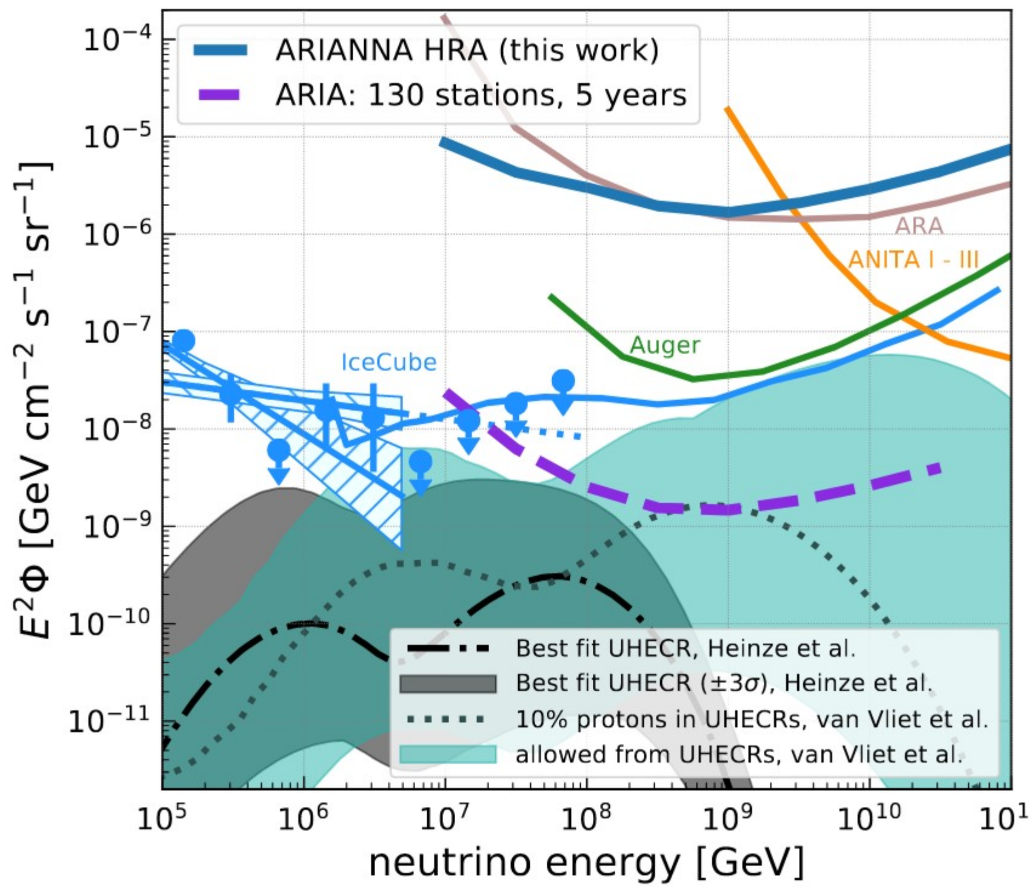
Radio neutrino detection – ANITA, ARA and ARIANNA

A few circumpolar Antarctic flights →not too far from models, need exposure increase



POS(ICRC2019)867

In-ice allows for cost-effective instrumentation of huge volumes → almost at discovery level



POS(ICRC2019)980

2 ANITA events

e.g. arxiv:1809.09615

TABLE I. Properties of the ANITA Anomalous Events

Property	AAE 061228	AAE 141220
Flight & Event	ANITA-I #3985267	ANITA-III #15717147
Date & Time (UTC)	2006-12-28 00:33:20	2014-12-20 08:33:22.5
Equatorial coordinates (J2000)	R.A. $282\overset{\circ}{.}14064$, Dec. $+20\overset{\circ}{.}33043$	R.A. $50\overset{\circ}{.}78203$, Dec. $+38\overset{\circ}{.}65498$
Energy $\varepsilon_{\rm cr}$	$0.6 \pm 0.4\,{\rm EeV}$	$0.56^{+0.30}_{-0.20}\,{\rm EeV}$
Zenith angle z'/z	$117\overset{\circ}{.}4$ / $116\overset{\circ}{.}8 \pm 0\overset{\circ}{.}3$	$125\overset{\circ}{.}0$ / $124\overset{\circ}{.}5 \pm 0\overset{\circ}{.}3$
Earth chord length ℓ	$5740 \pm 60\,{\rm km}$	$7210 \pm 55\,{\rm km}$
Mean interaction length for $\varepsilon_\nu = 1\,{\rm EeV}$	290 km	265 km
$p_{\rm SM}(\varepsilon_\tau > 0.1\,{\rm EeV})$ for $\varepsilon_\nu = 1\,{\rm EeV}$	4.4×10^{-7}	3.2×10^{-8}
$p_{\rm SM}(z > z_{\rm obs})$ for $\varepsilon_\nu = 1\,{\rm EeV}$, $\varepsilon_\tau > 0.1\,{\rm EeV}$	6.7×10^{-5}	3.8×10^{-6}
$n_\tau(1\text{–}10\,{\rm PeV}) : n_\tau(10\text{–}100\,{\rm PeV}) : n_\tau(> 0.1\,{\rm EeV})$	34 : 35 : 1	270 : 120 : 1

2 "anomalous" events were observed in ANITA-I and III in searches for upward going showers (ANITA-IV analysis not ready yet) over a bkg of 10^{-2}

Polarisation signature compatible with neutrino-induced/Earth-skimming events, but

– no real counterpart in the IceCube signal
– in some tension with predictions
– some possible human-related background could have produced them

Still, intriguing… and radio could be the way to go for EeV

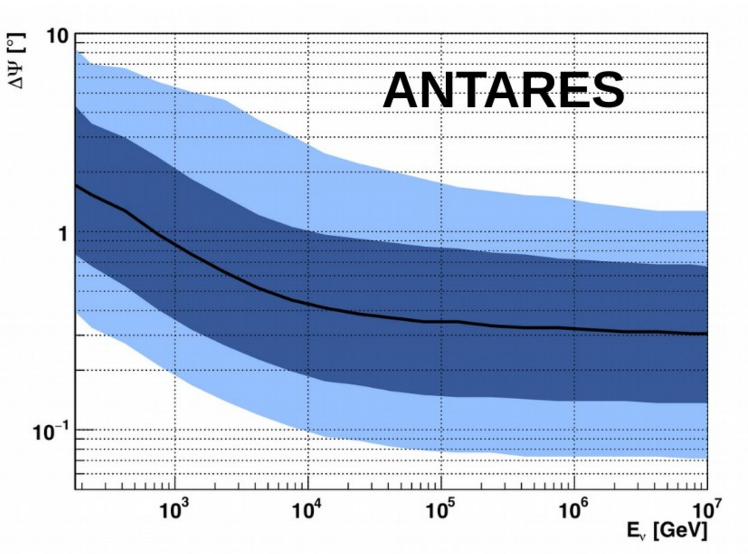
What was not covered (in full) here

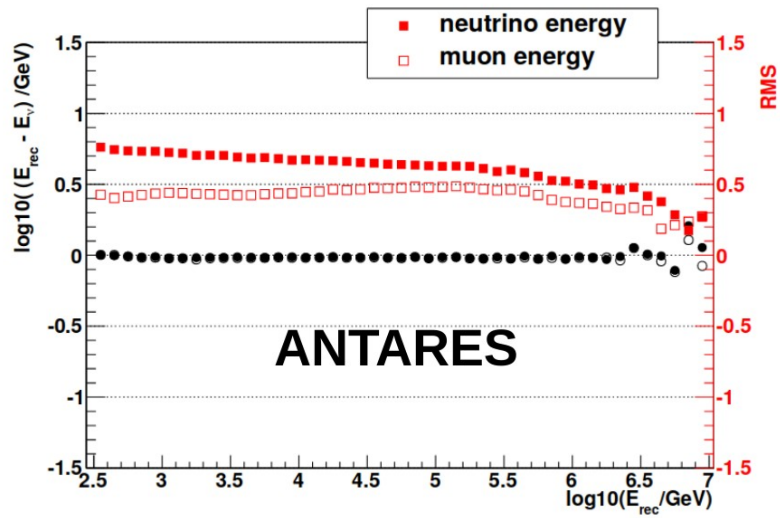
- Transient events (GRBs, FRBs, ...)
- Indirect searches for dark matter
- Neutrino oscillations
- Atmospheric neutrinos
- Particle physics (and BSM)
- Cosmic ray air shower physics
- Low energy astrophysics

Thanks for your attention!

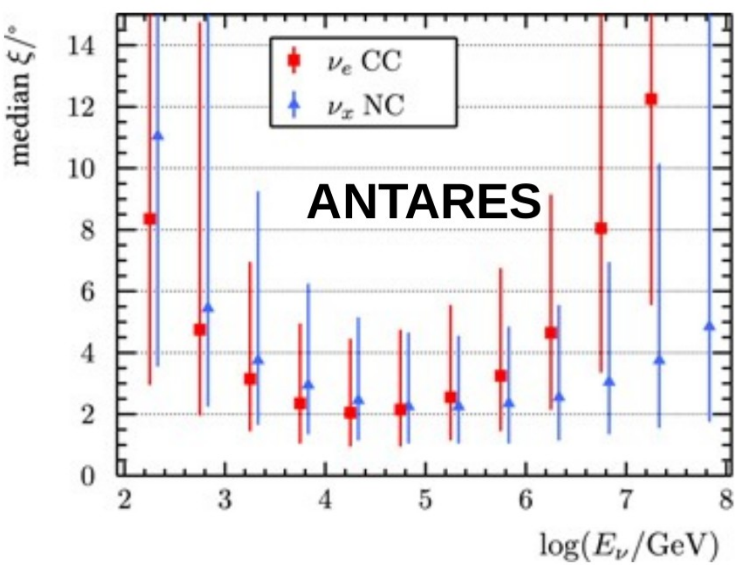
Backup

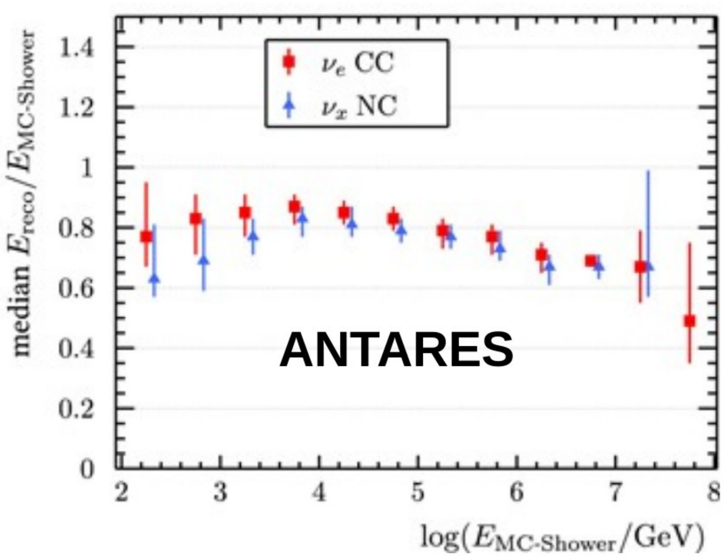
ANTARES event reconstruction





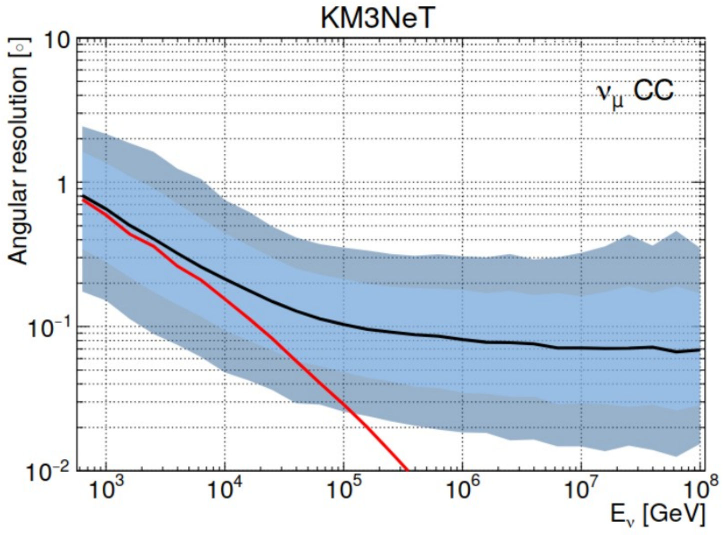
tracks

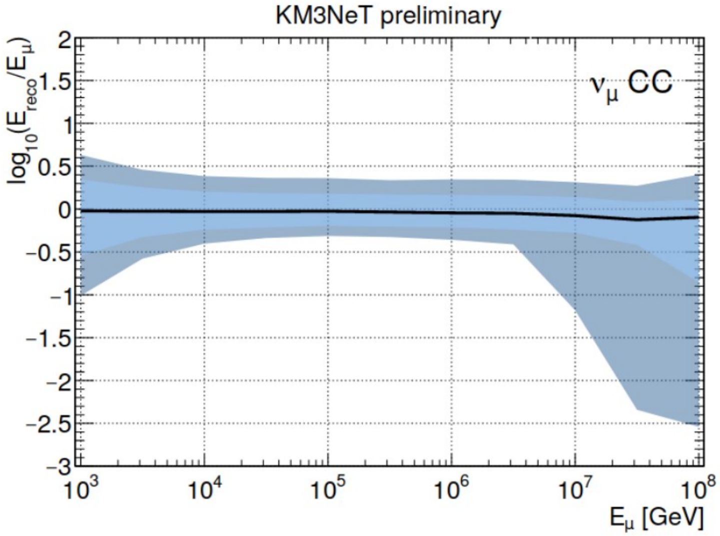




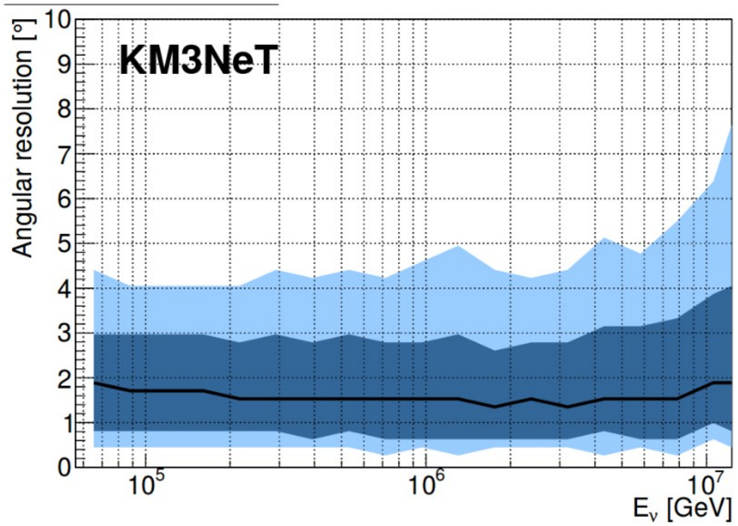
showers

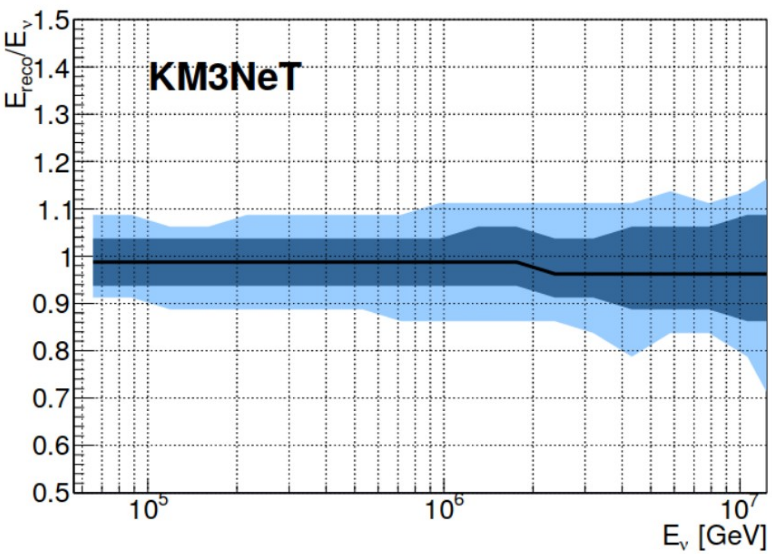
KM3NeT/ARCA event reconstruction





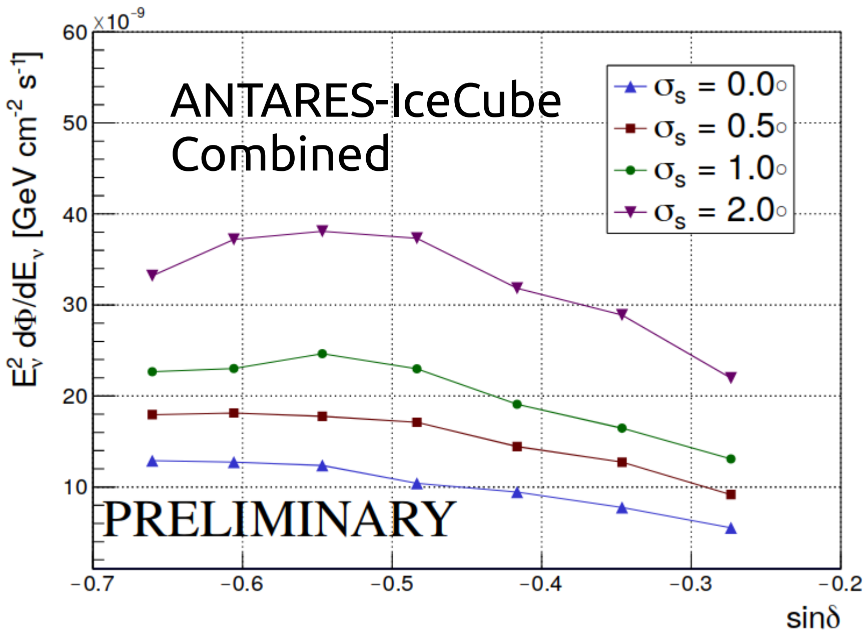
tracks

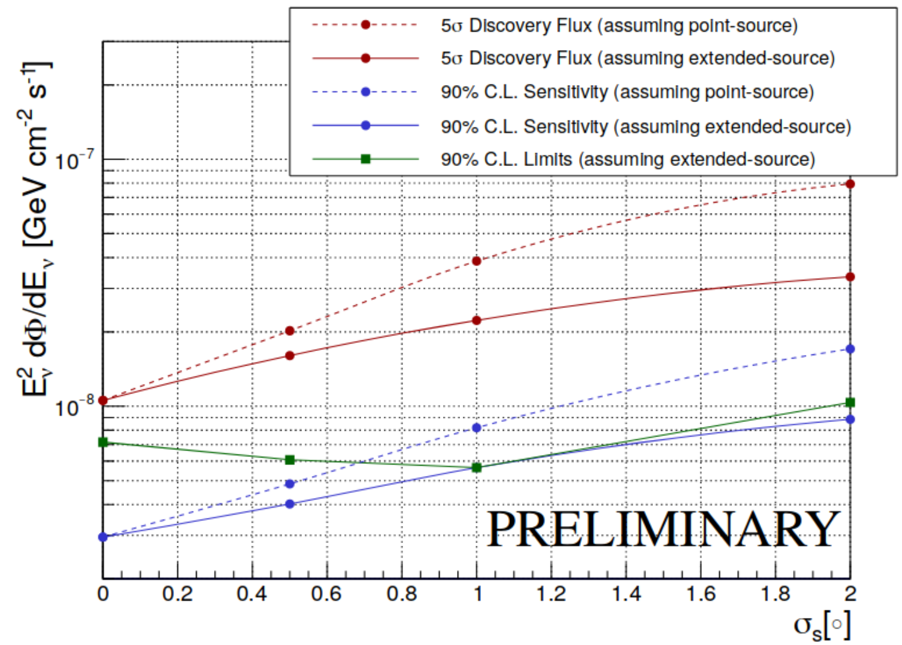


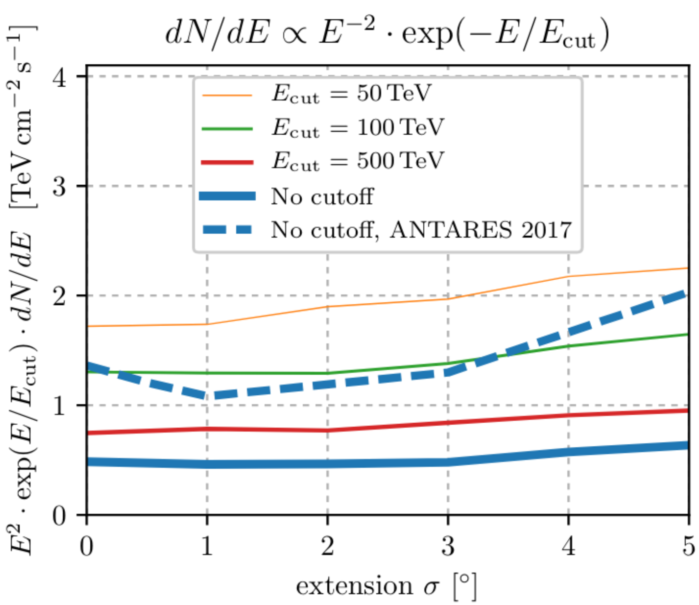


showers

SgrA*



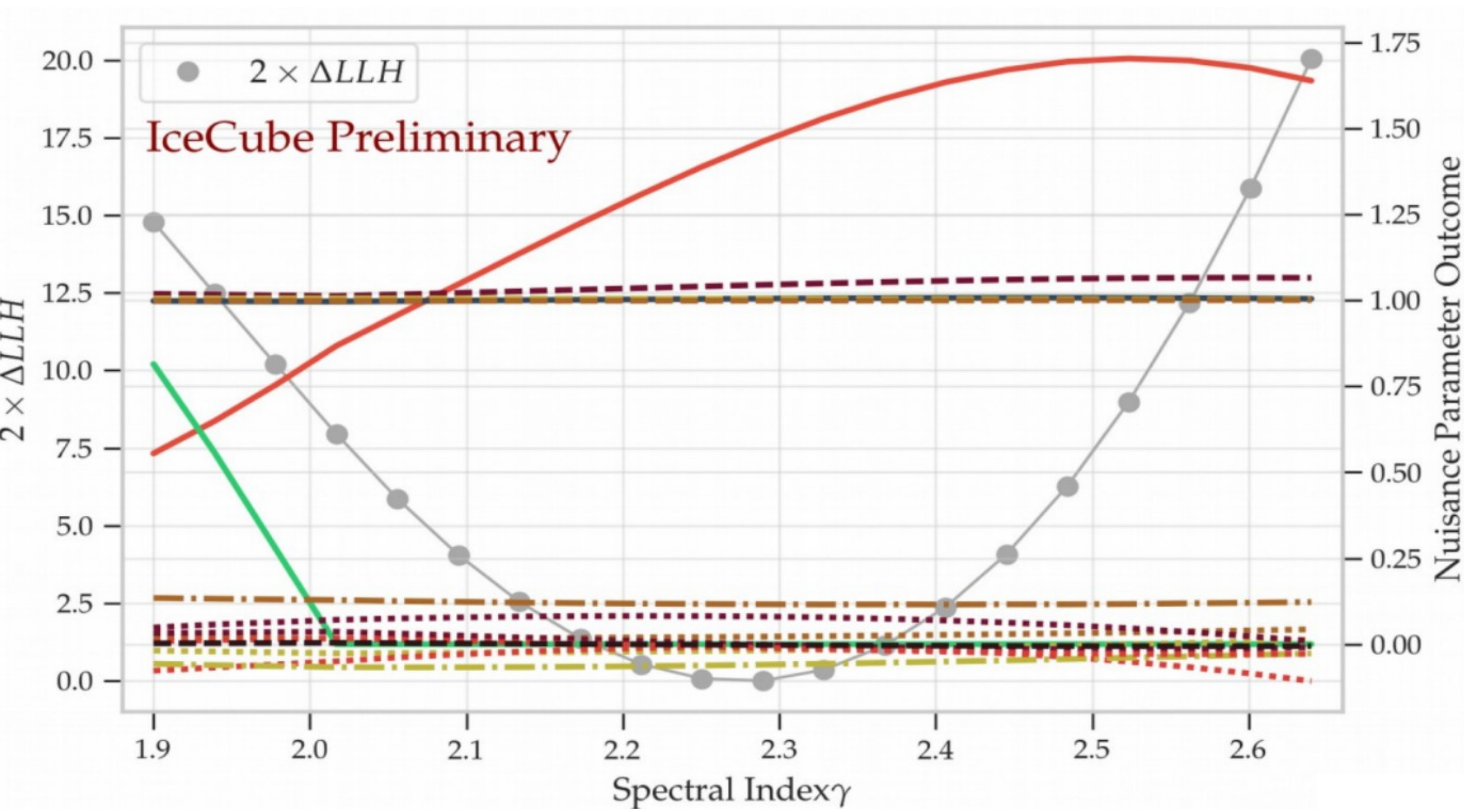


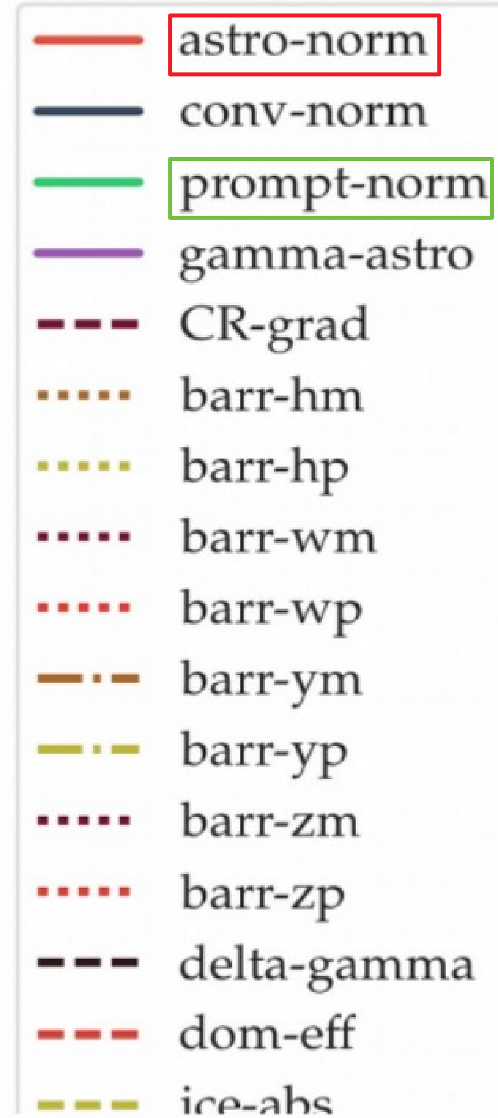


IceCube Cascade

The track sample

Influence of nuisance parameters in the fit

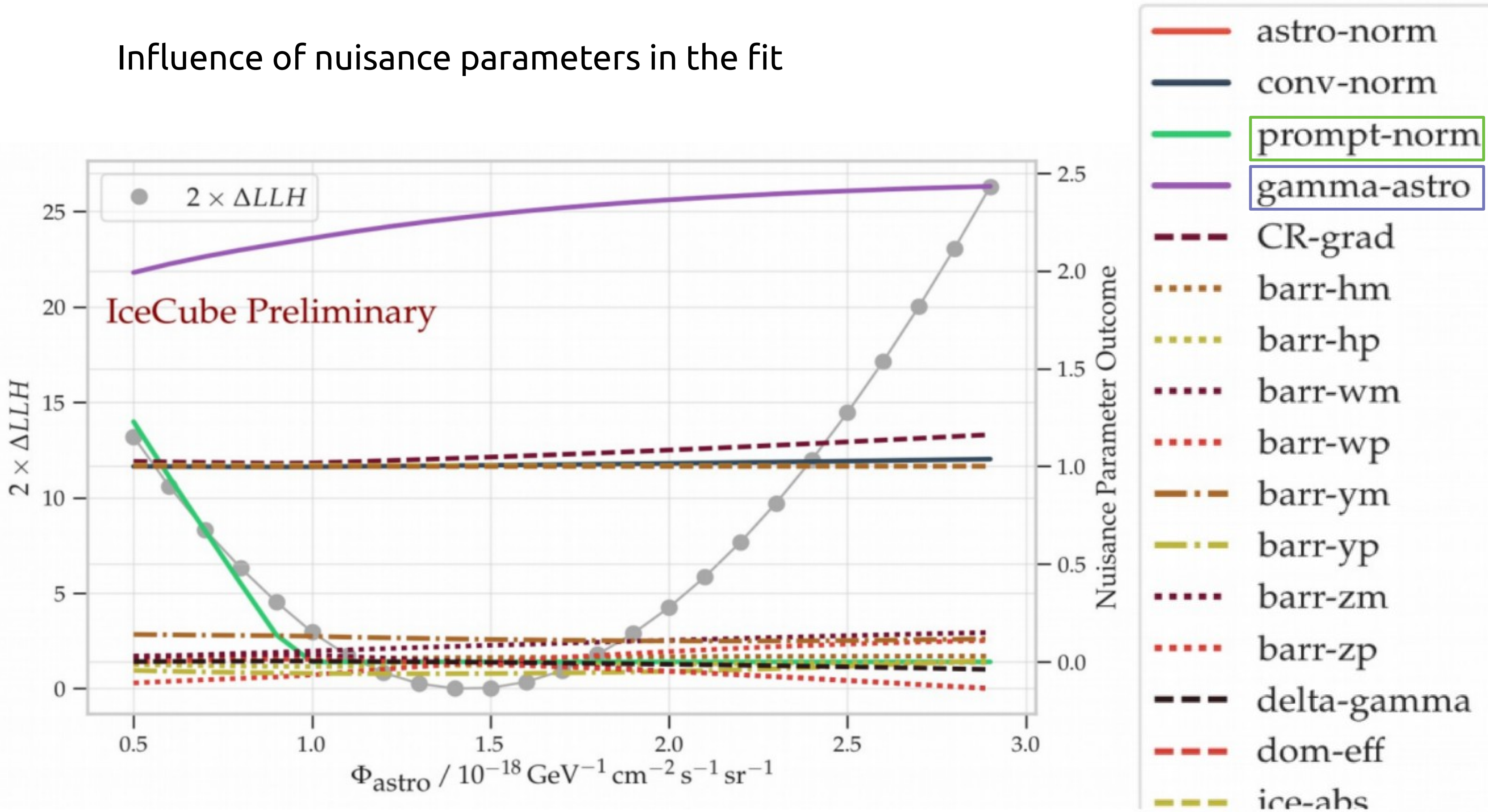




PoS(ICRC2019)1017

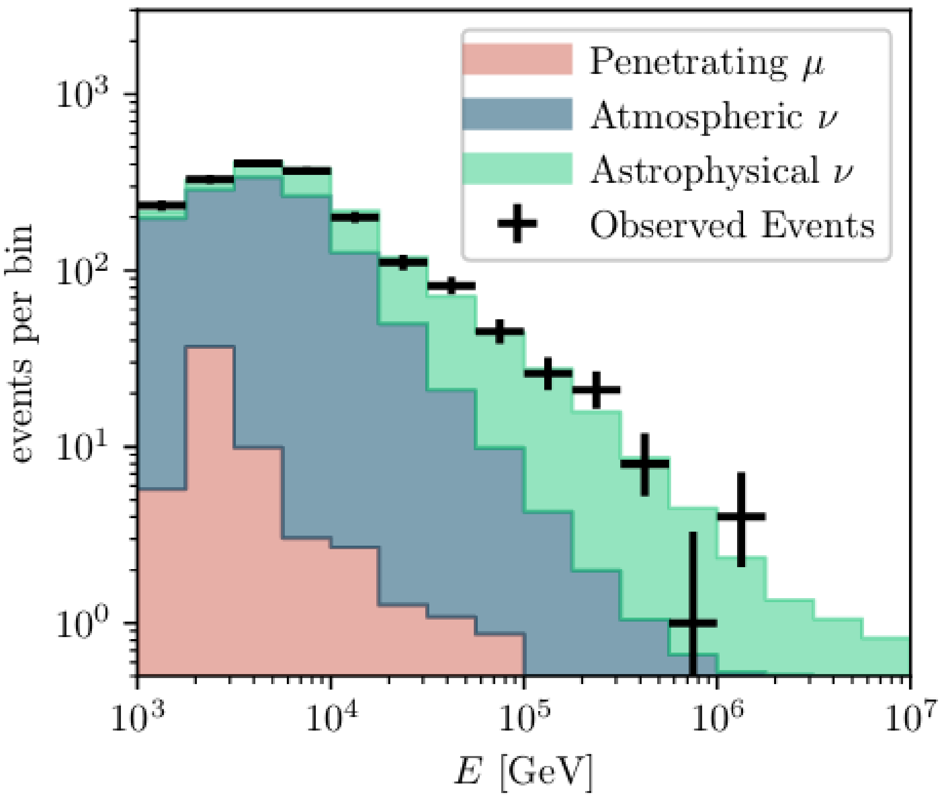
The track sample

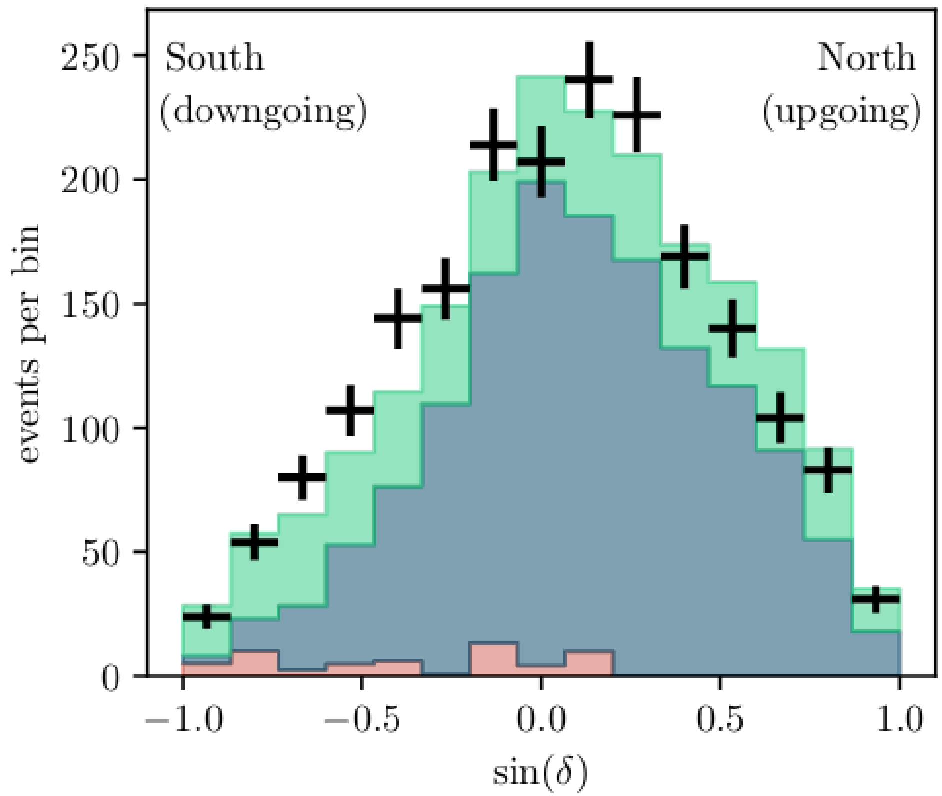
Influence of nuisance parameters in the fit



PoS(ICRC2019)1017

New cascade analysis

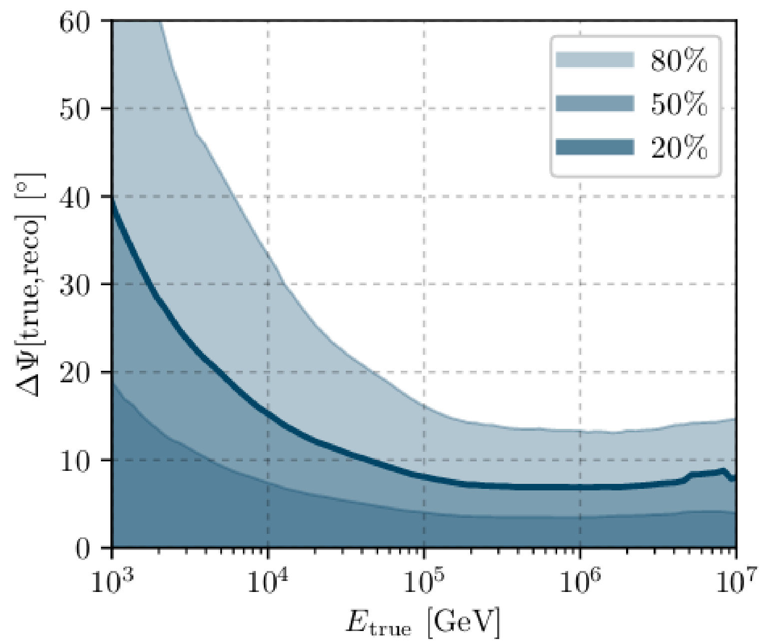




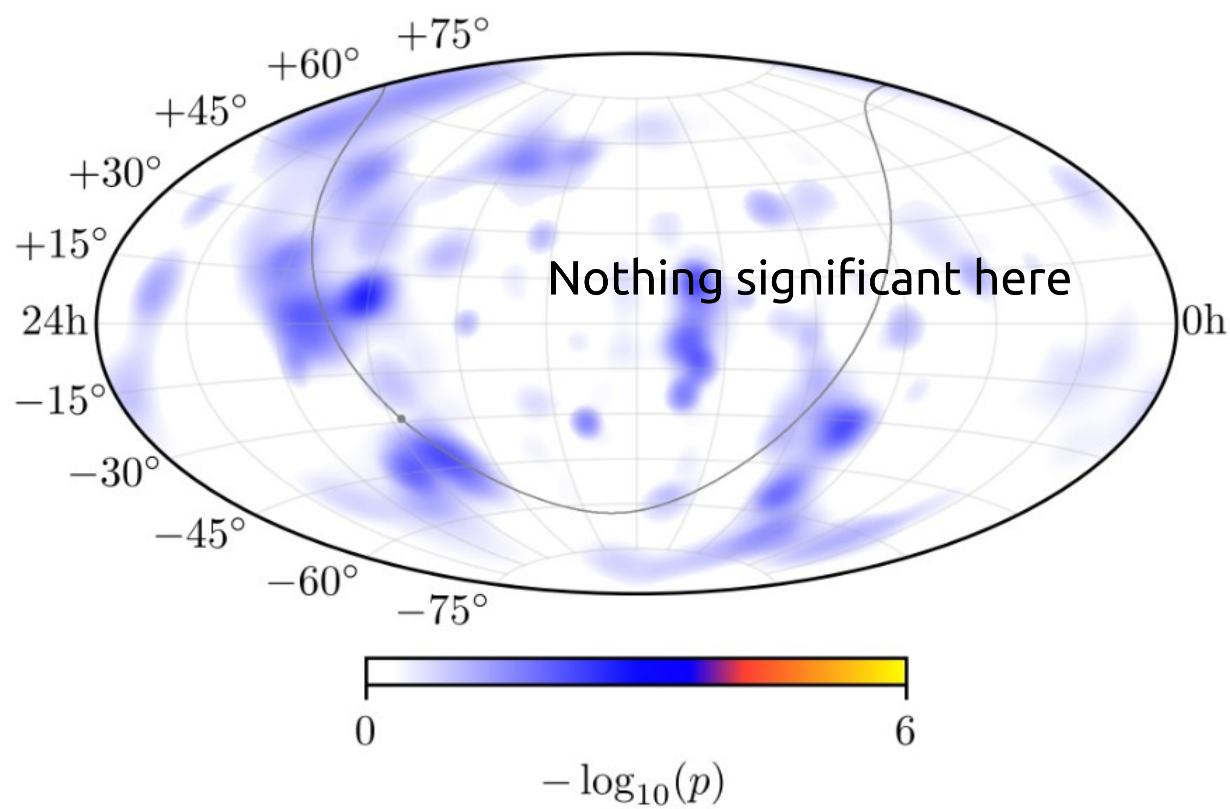
Φ^{1f}(100 TeV) ~ 1.5 10^{-18} (GeV cm^2 s sr)$^{-1}$
Γ ~ 2.5

ApJ **886**: 1 (2019)

Cascade analysis for point-like emissions



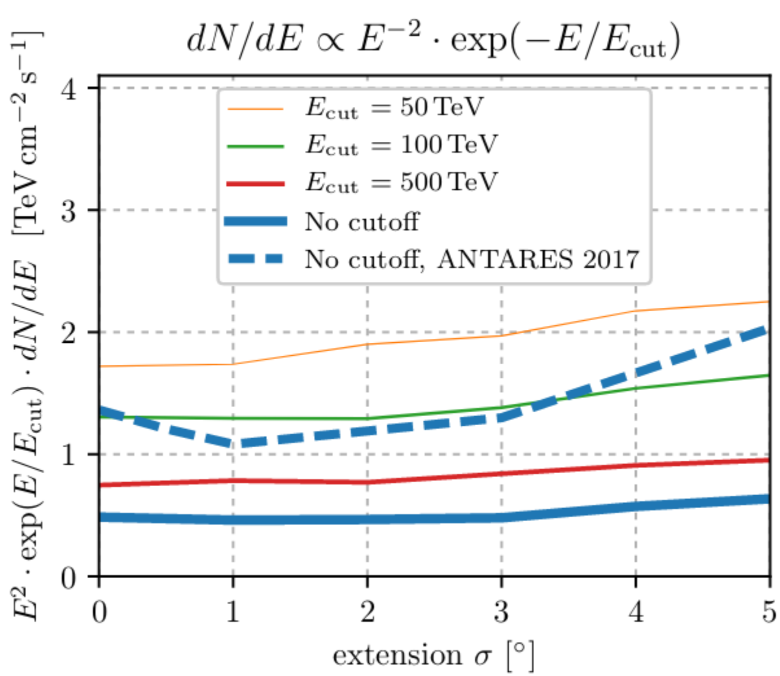
~10 degree median angular resolution, but low bkg and high statistics

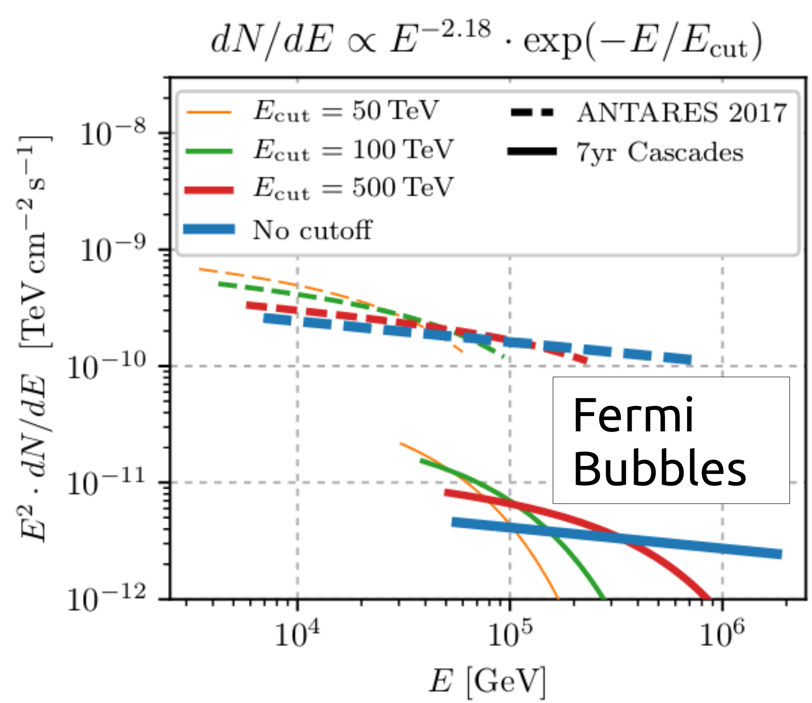


ApJ **886**: 1 (2019)

Cascade analysis for extended emissions

Galactic Plane	7yr Cascades				Previous Work			
Template	p-value	Sensitivity	Fitted Flux	UL	p-value	Sensitivity	Fitted Flux	UL
KRA_γ^5	0.021	0.58	0.85	1.7	0.29	0.81	0.47	1.19
KRA_γ^{50}	0.022	0.35	0.65	0.97	0.26	0.57	0.37	0.90
Fermi-LAT π^0	0.030	2.5	3.3	6.6	0.37	2.97	1.28	3.83



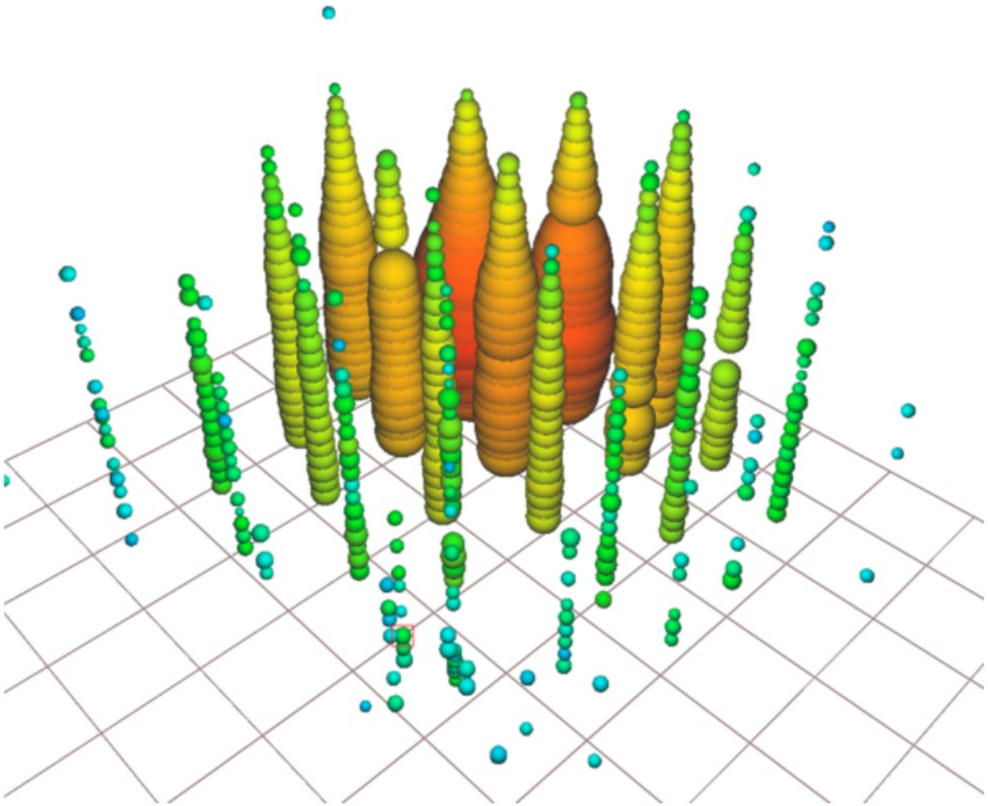


ApJ **886**: 1 (2019)

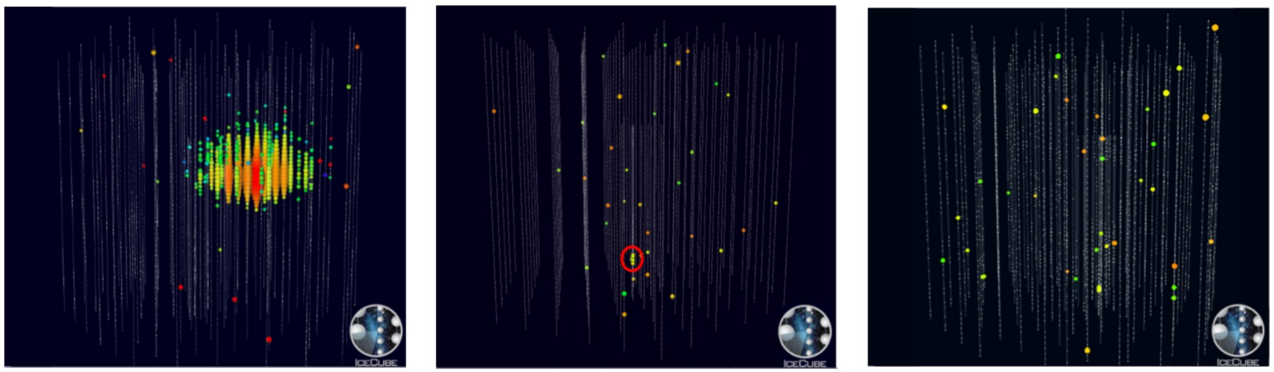
The highest-energy cascade event

Partially contained events
→ allow for higher energies
→ need more sophisticated analysis
to reject backgrounds

6 PeV cascade: candidate found in data
→ candidate Glashow-resonance event
(work is still ongoing)



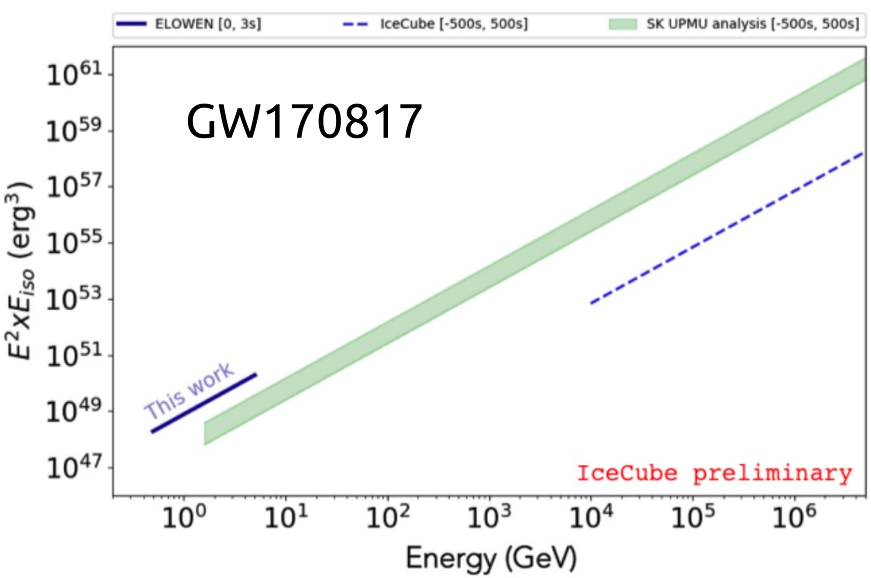
Low-energy astrophysics



(a) PeV neutrino interaction (b) GeV neutrino interaction (c) Detector noise event

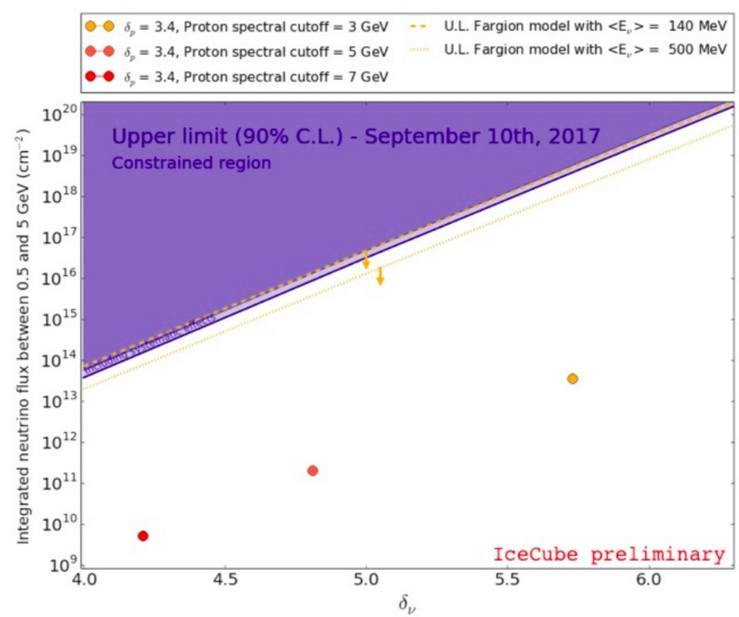
– Properly select event topology

– Search for event in a short time window corresponding to transient sources



PoS(ICRC2019)865

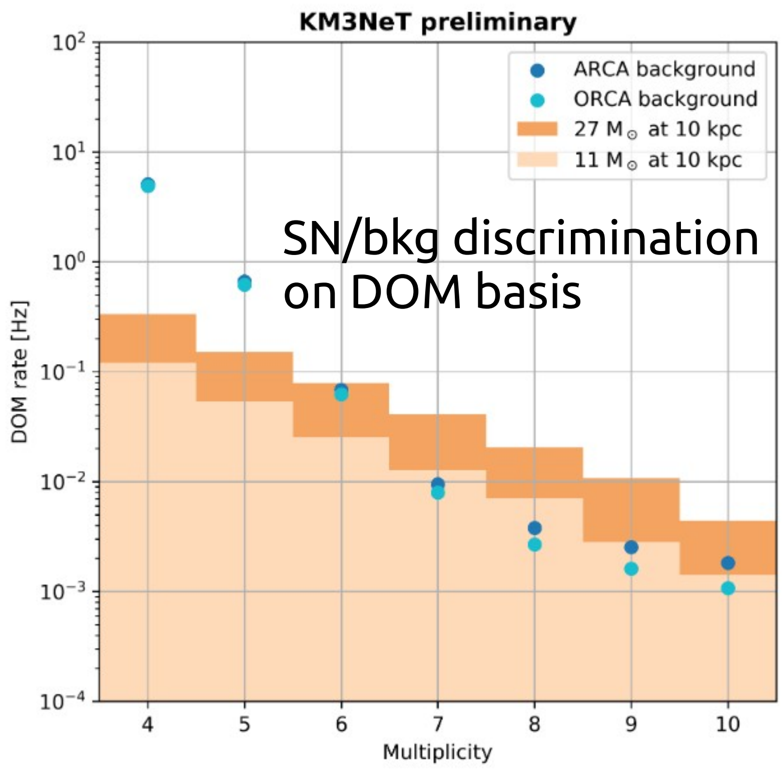
Solar flare

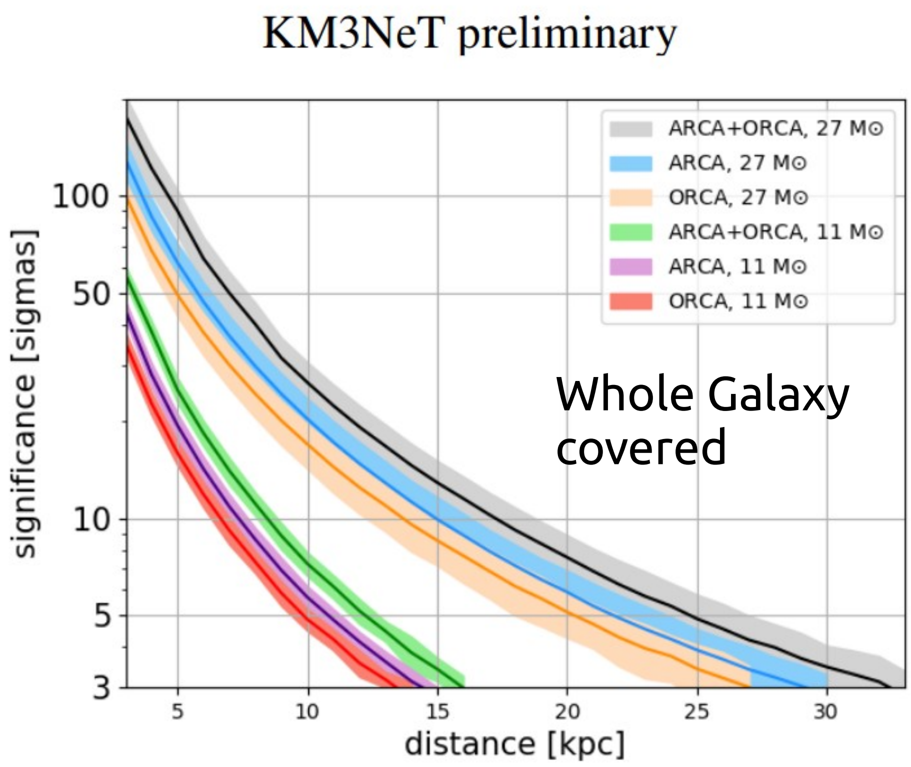


PoS(ICRC2019)1075

Low-energy astrophysics

Supernovae bursts would produce a large amount of MeV interaction close to the OMs
→ visible as an increase over the optical background rate



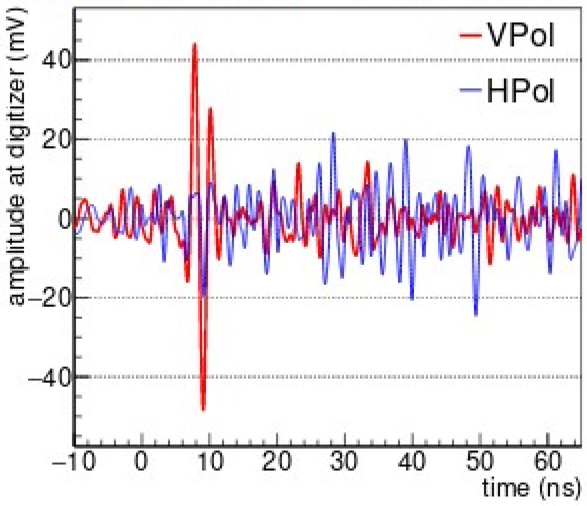


PoS(ICRC2019)857

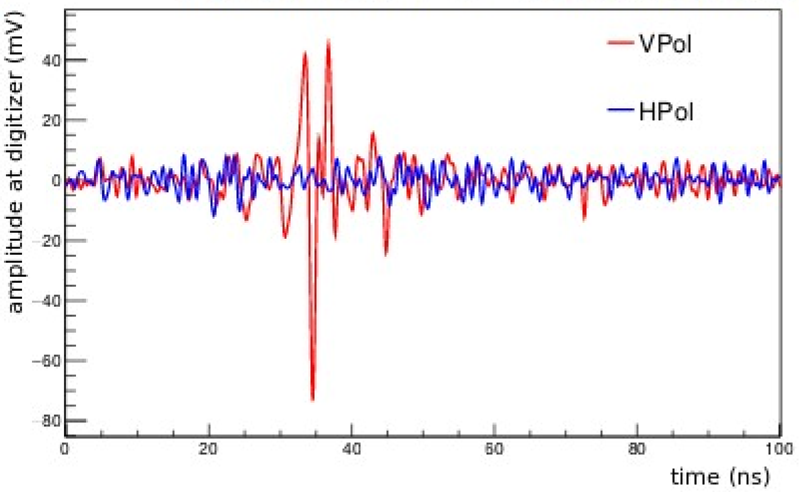
also ANTARES and IceCube do perform the same kind of searches

2 more ANITA events (in the standard diffuse search)

ANITA-III candidate:



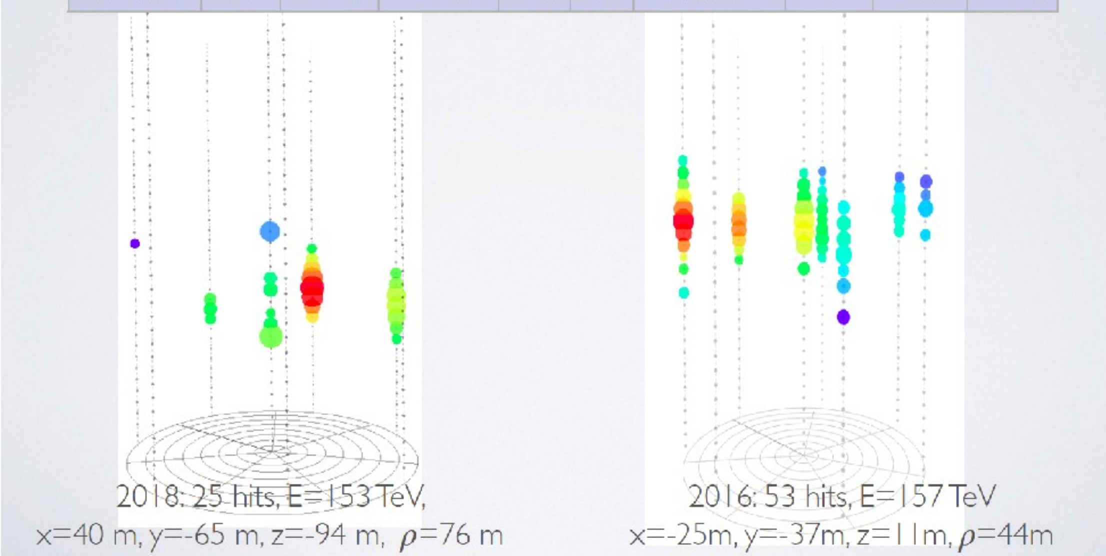
ANITA-IV candidate:

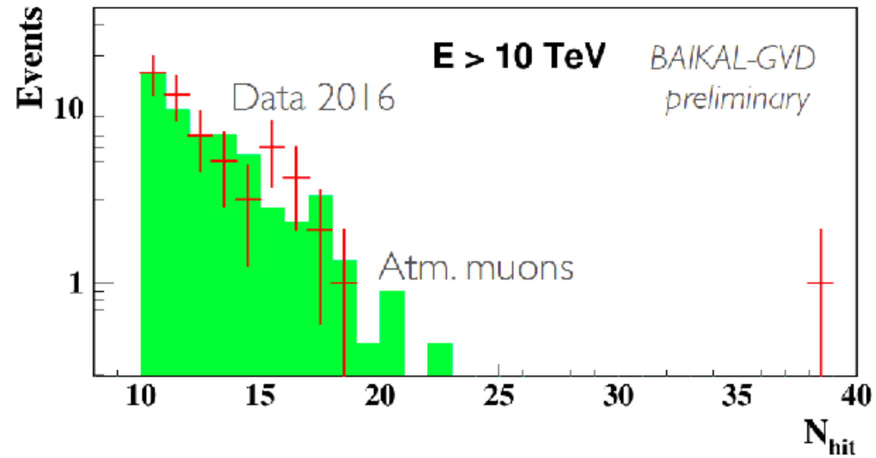


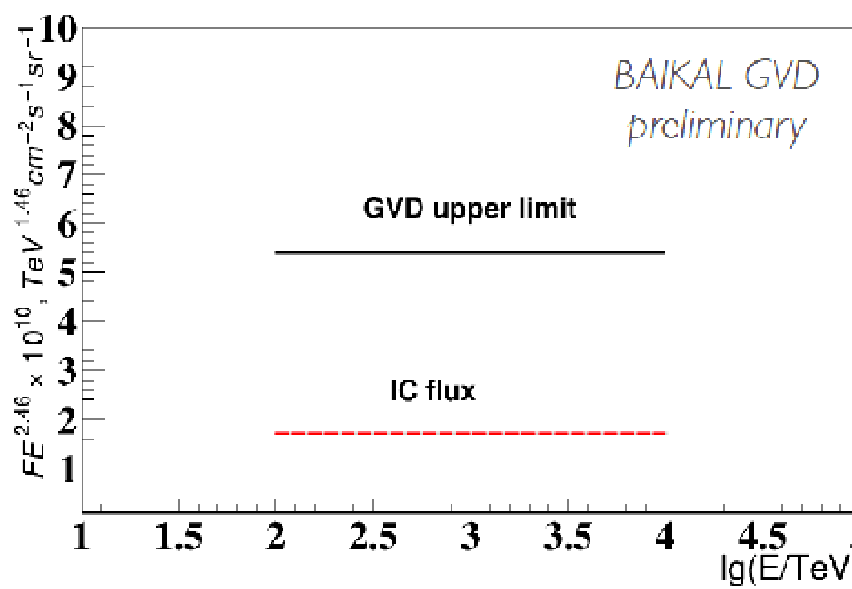
POS(ICRC2019)867

Baikal-GVD recent results

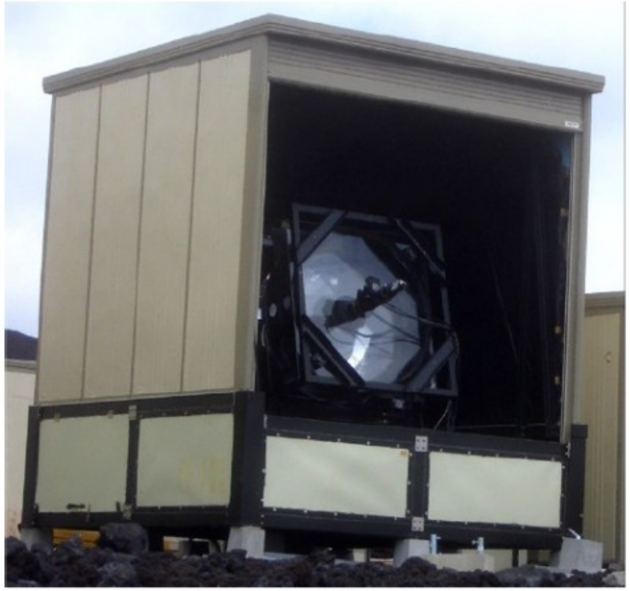
Date	E,TeV	Zenith degree	Azimuth degree	RA	Dec	T_{UNIX}	x, m	y, m	z, m
16.11.2015	107	56	131	139.5	5.6	1447637711	-50.2	49.7	-60.7
29.04.2016	157	57	249	173.4	14.0	1461925647	-25.1	-37.0	11.4
21.08.2018	153	49	57	231.7	49.1	1534868736	40.4	-65.7	-93.8
24.10.2018	107	69	112	41.3	0.7	1540416000	79.8	61.6	151.0
15.02.2019	339	67	350	68.4	61.9	1550278144	-48.0	75.7	4.3



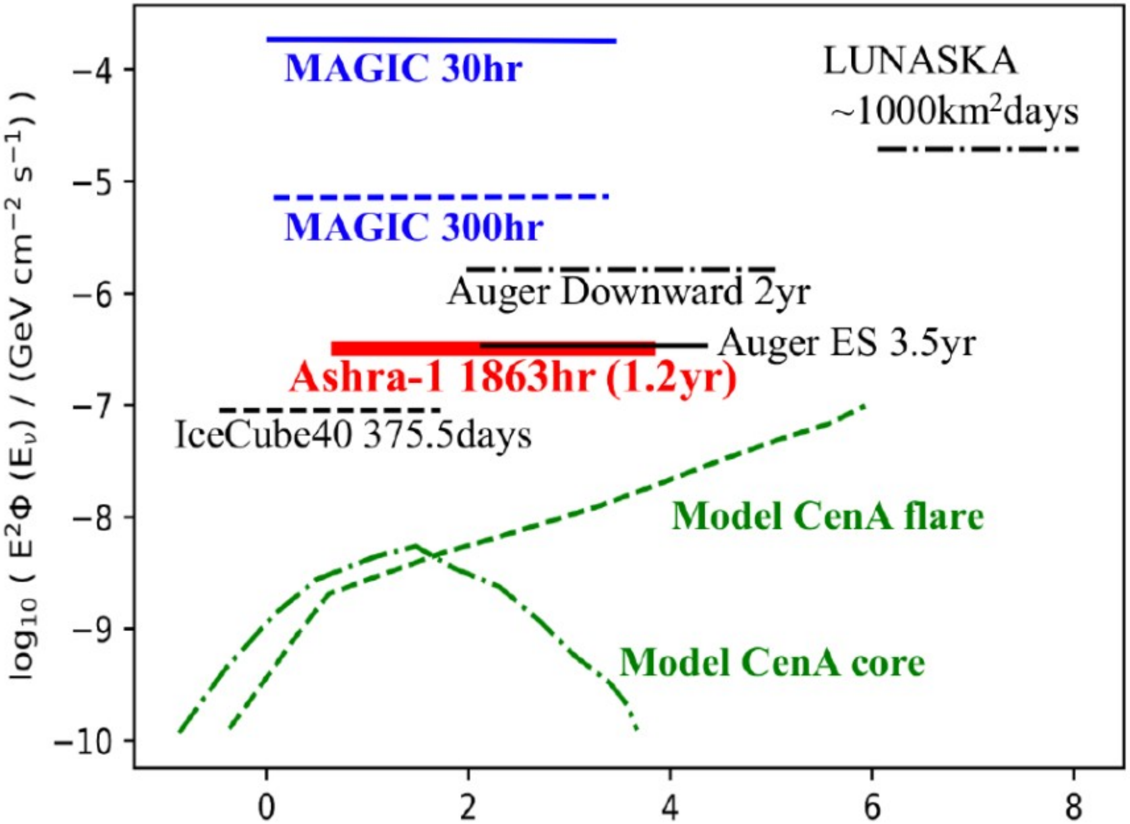




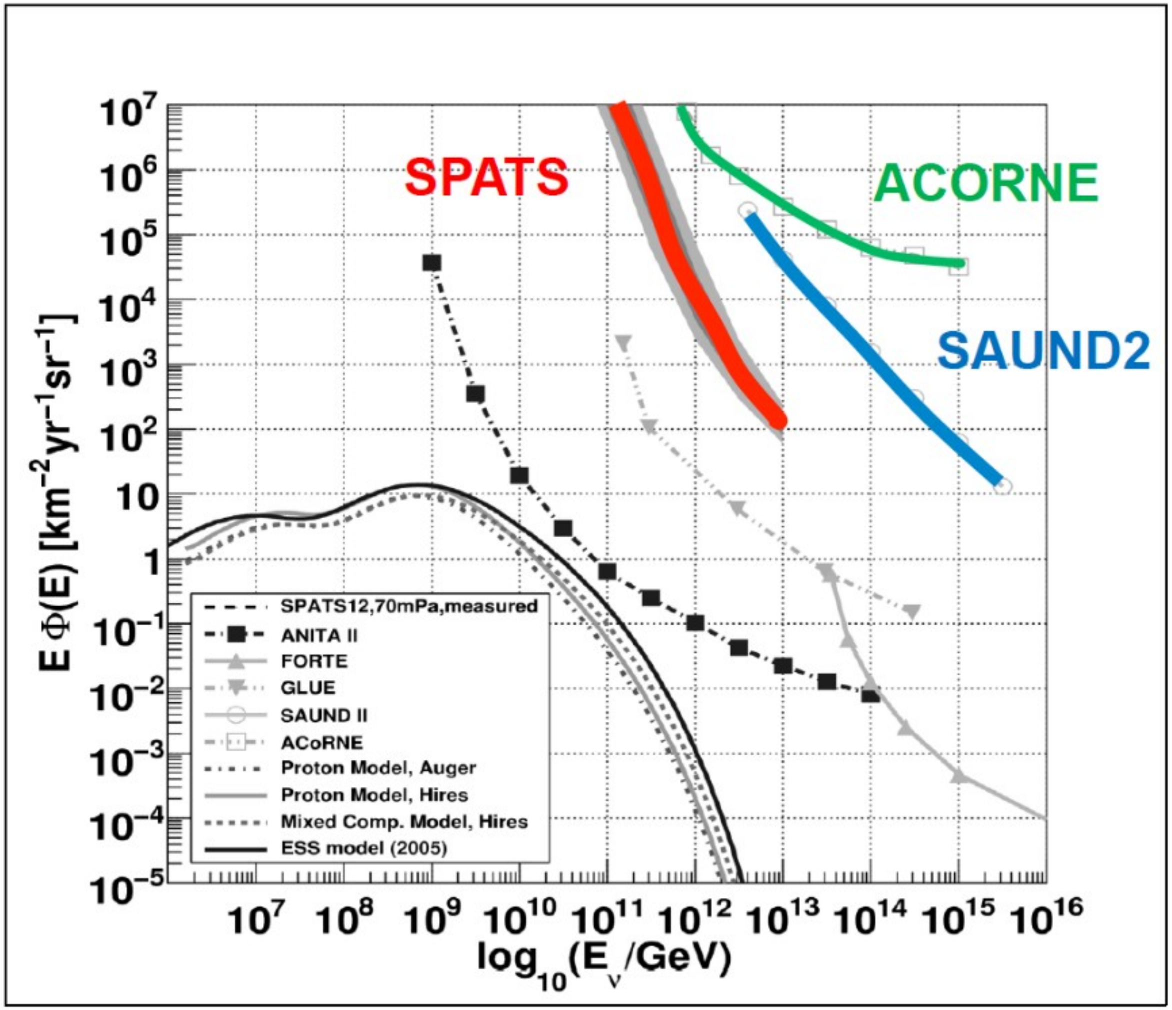
Air-shower imaging detection of neutrinos

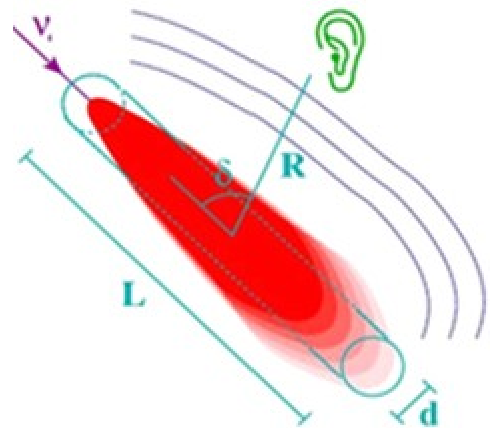


Ashra-1 PoS(ICRC2019)970



Acoustic detection of UHE neutrinos





R. Abbasi et al.,arXiv:astro-ph/1103.1216; adapded from R. Nahnhauer, Ricap 2011 by R. Lahman at ARENA2018