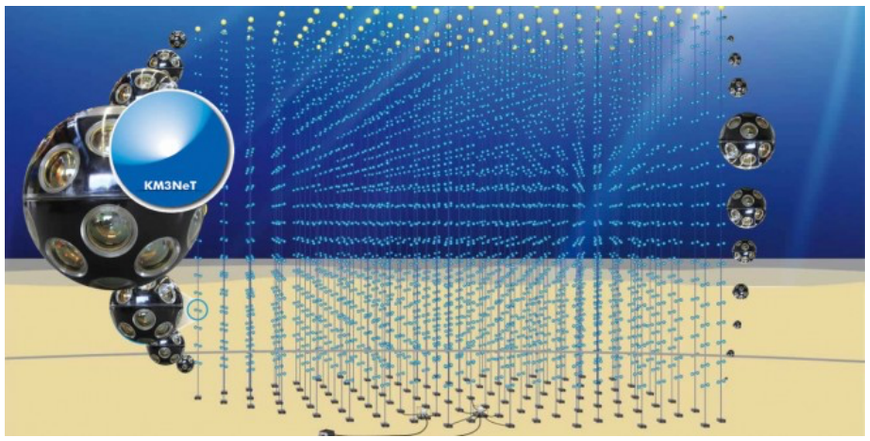
ASTRONOMIE NEUTRINO
ANTARES et KM3NeT

DAMIEN DORNIC (CPPM)

PNHE - Sept 14, 2021

Neutrino panorama

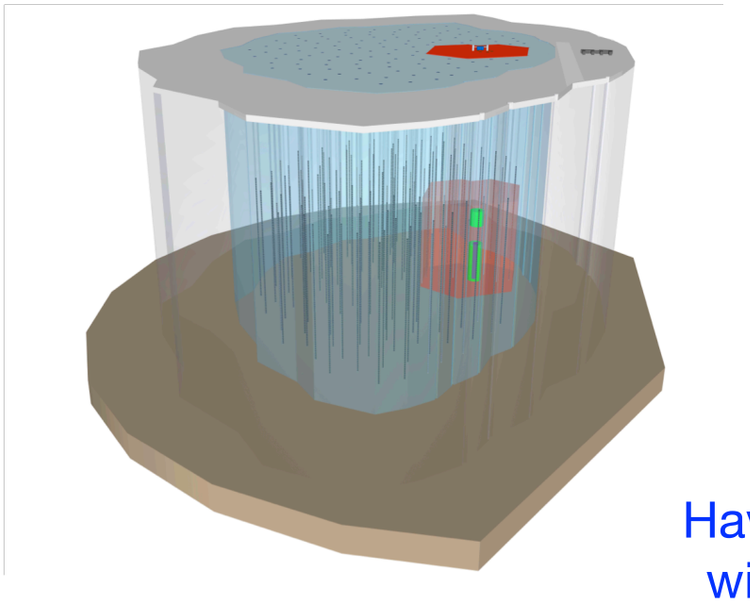
Precision Frontier



KM3NeT, GVD

Having the best angular resolution with a reasonable instrumented volume

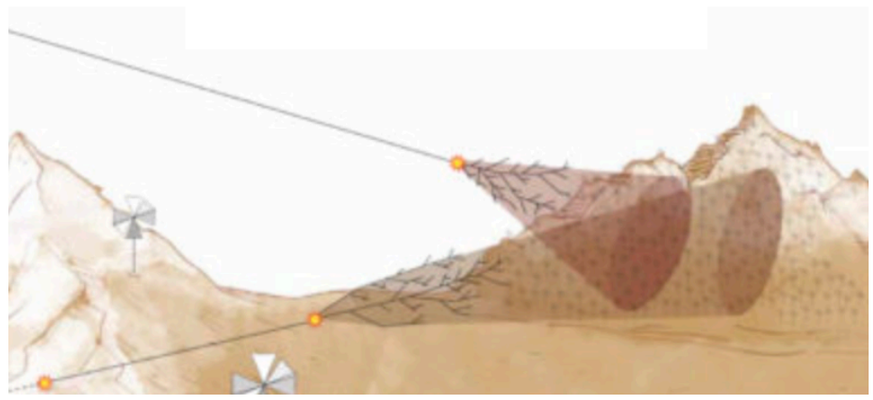
Intensity Frontier



IceCube Gen2

Having the largest statistics with reasonable precision

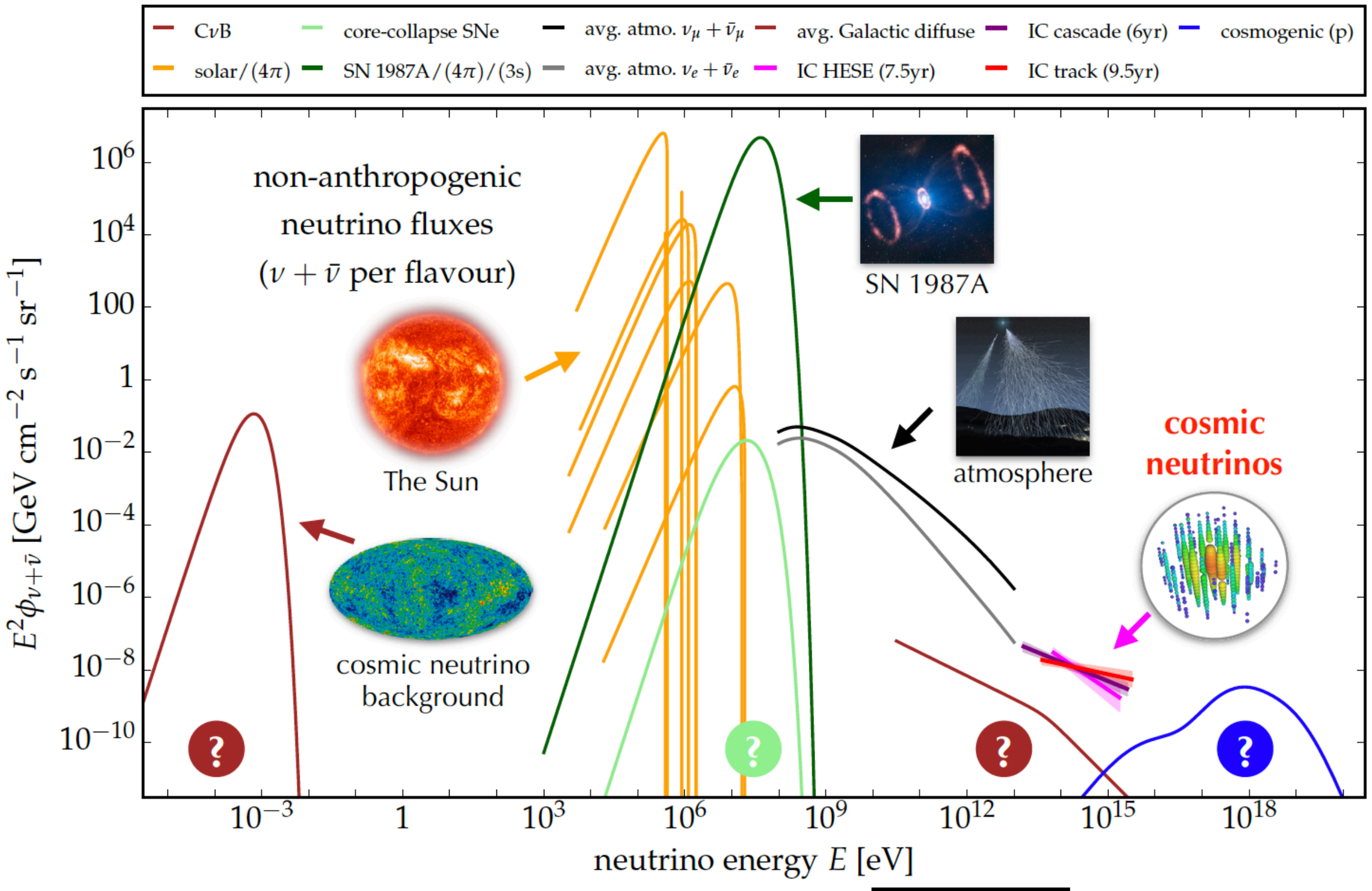
Energy Frontier



GRAND, ARA, ARIANNA, POEMMA

Tracking cosmogenic ν at UHE

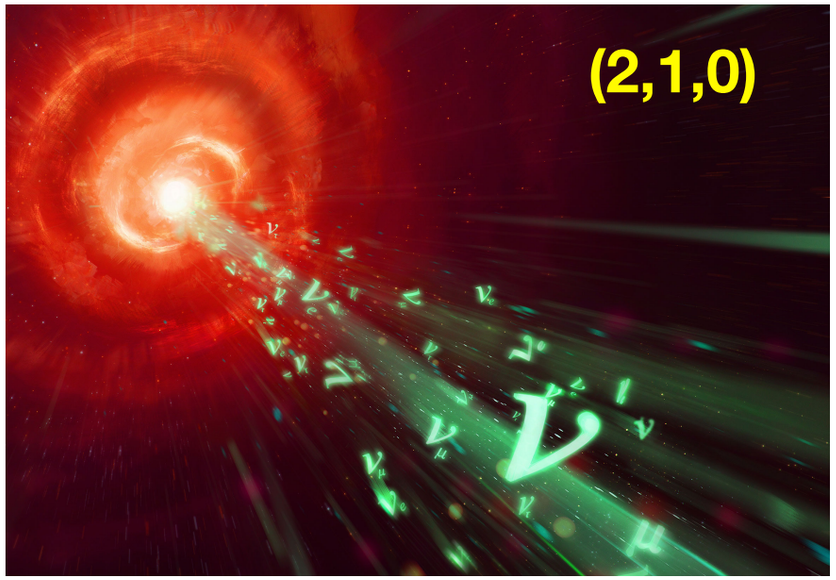
Astrophysical neutrino fluxes



ANTARES

KM3NeT

All-flavor neutrino detection



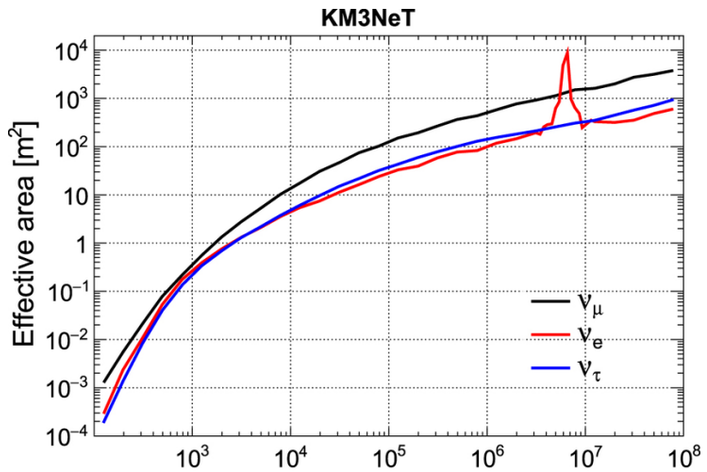
New physics ?

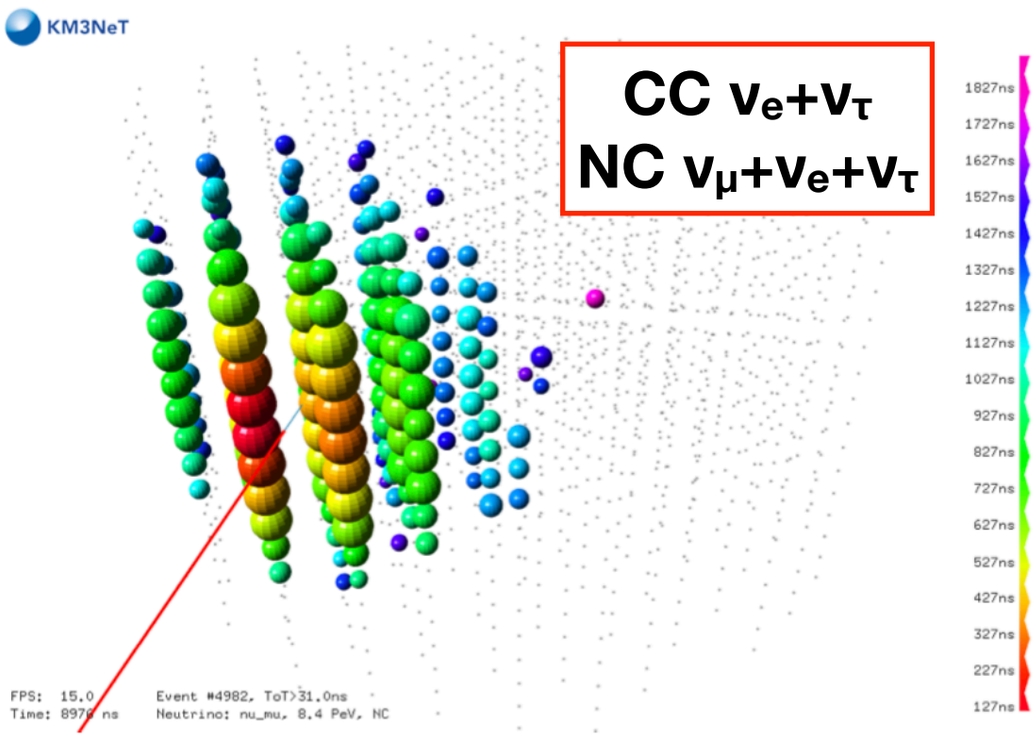
Oscillation

(1,1,1)

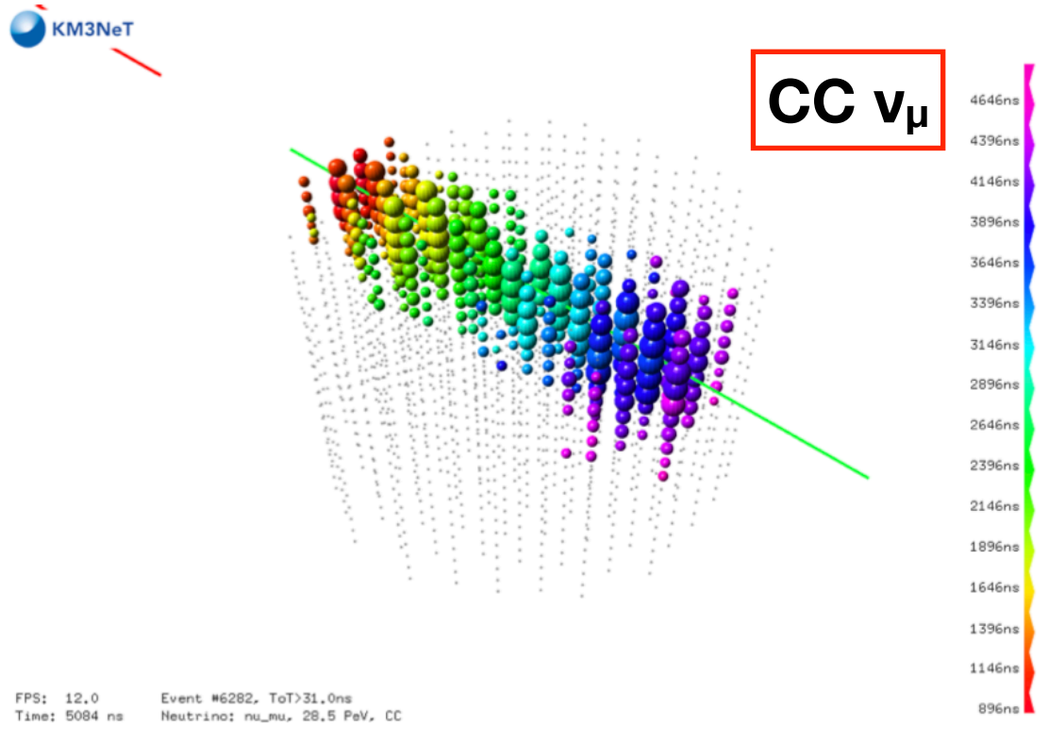
Each neutrino flavor brings information

$\Longrightarrow$ All-flavour astronomy





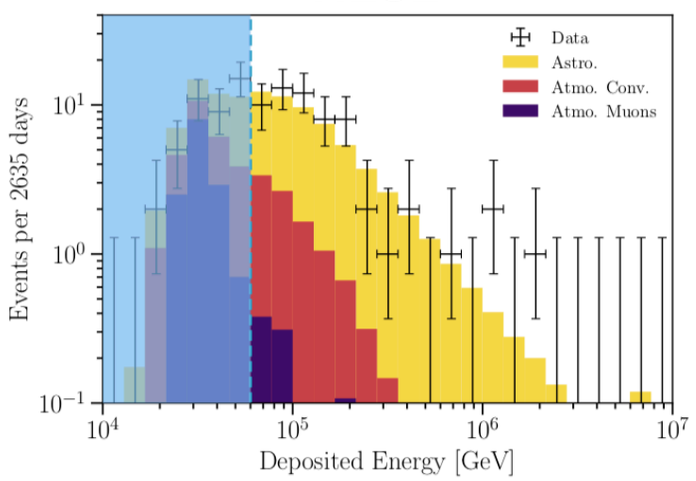
(double cascade for VHE ν_τ)



HE ν diffuse fluxes detected

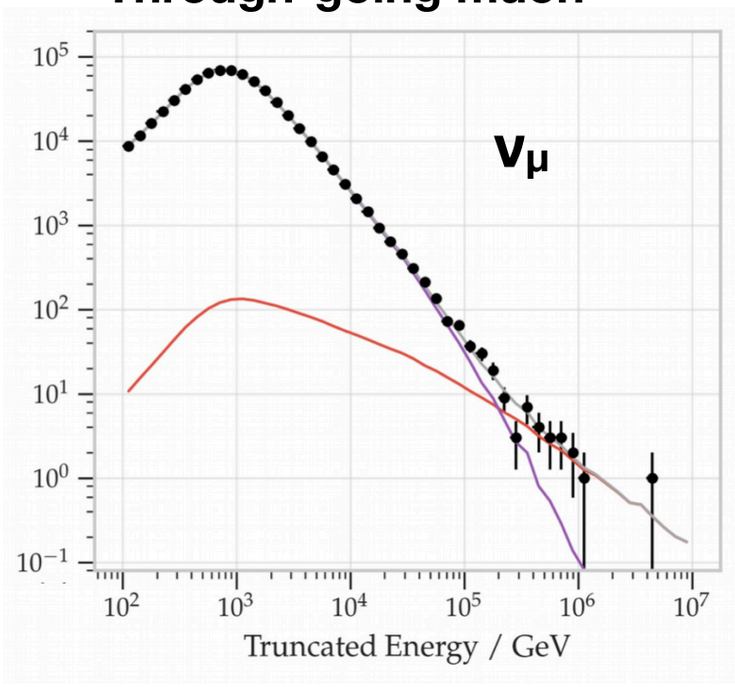
IceCube 7-10 yrs

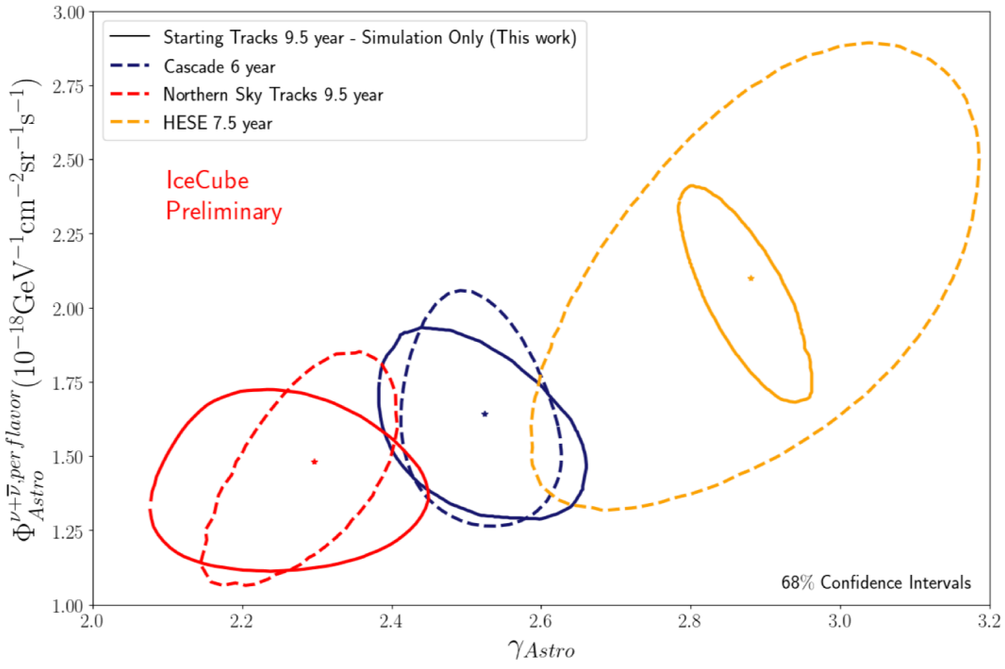
HESE



arXiv:2011.03545

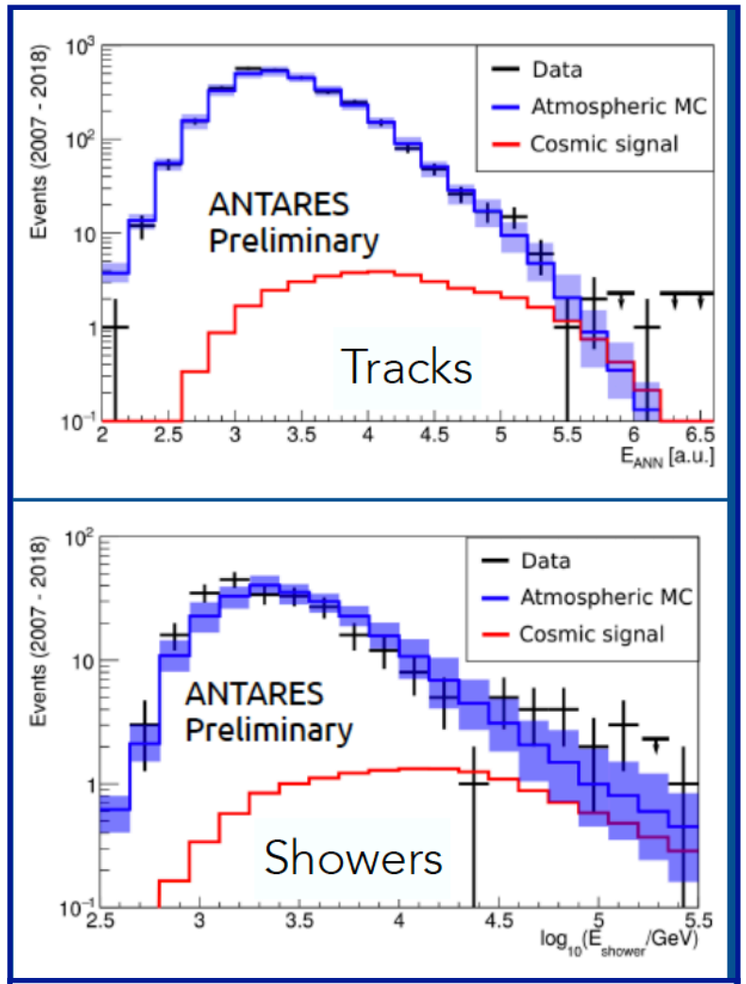
Through-going muon

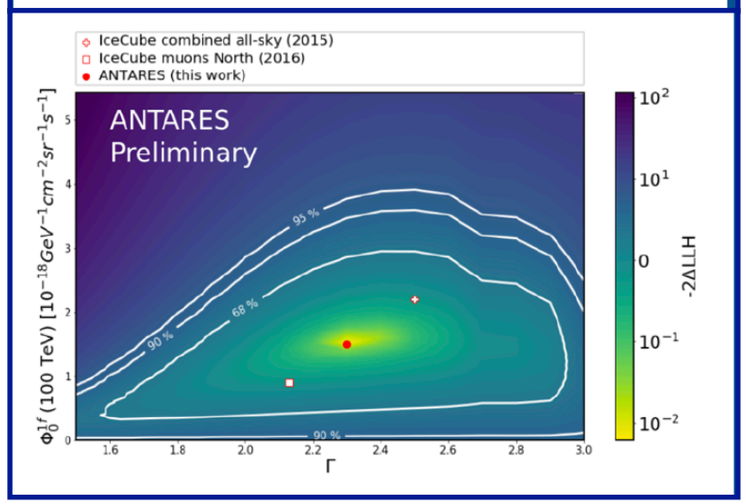




PoS(ICRC2021)1130

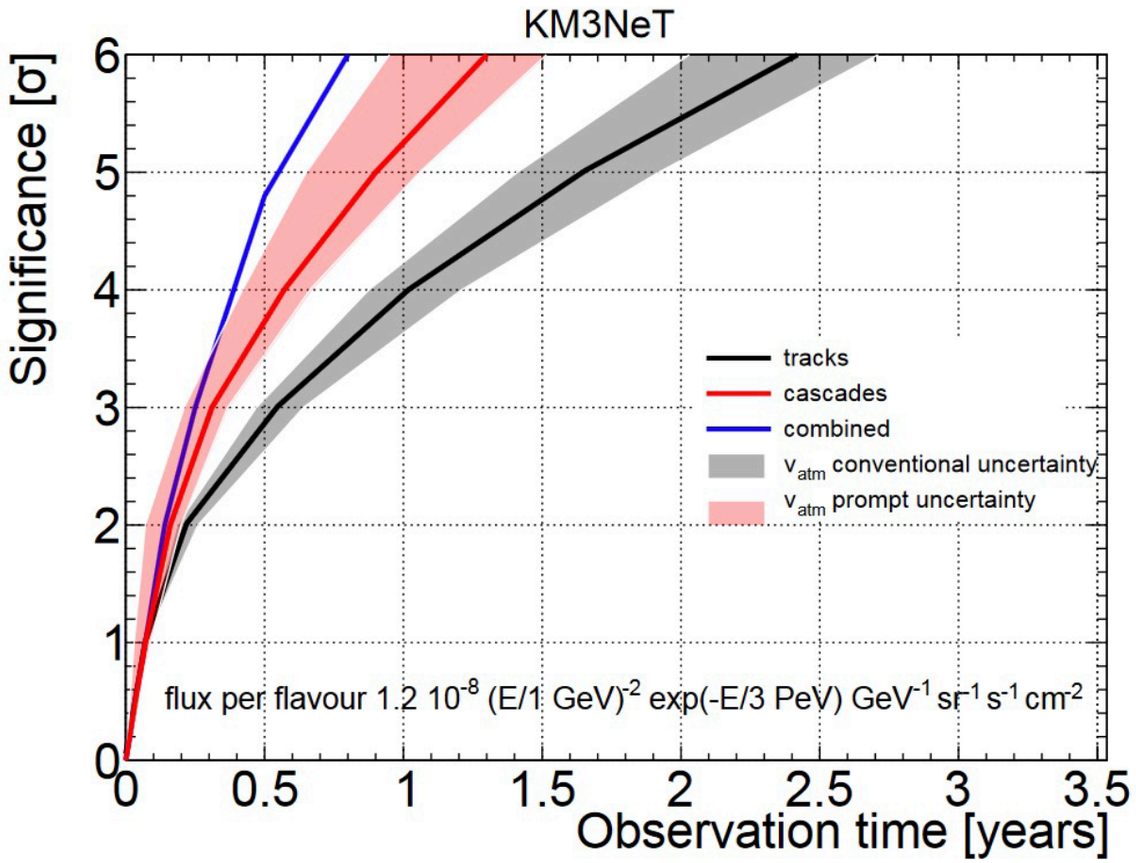
ANTARES 11 yrs





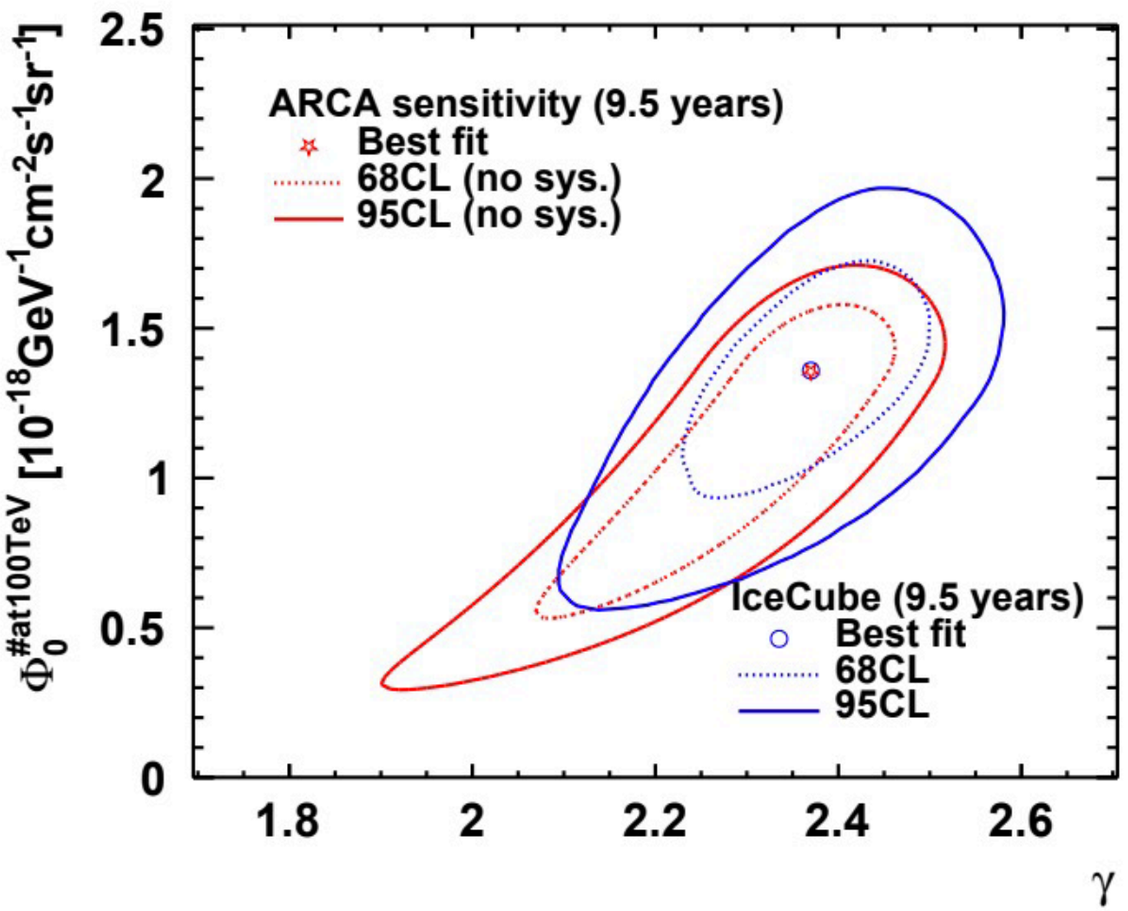
PoS(ICRC2021)1126

HE ν diffuse fluxes with KM3NeT



Measurement of the parameters of the flux (norm, spectrum, charm ?)

Detectability of the HE flux (benchmark IC flux)



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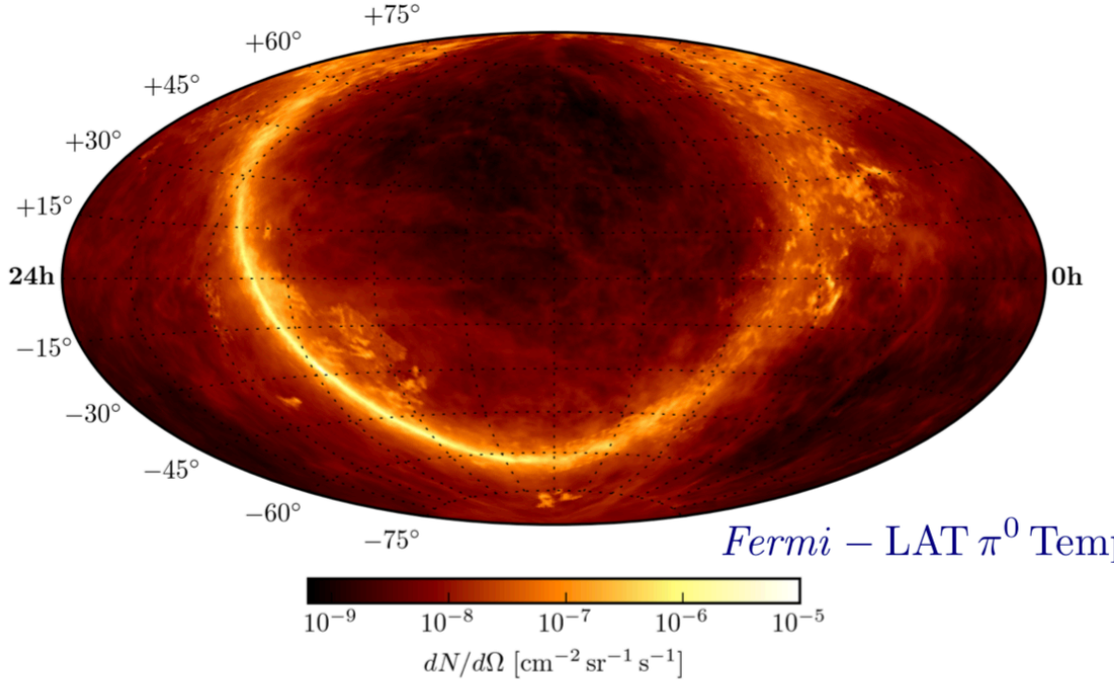
Where is the galactic diffuse component ?

Search for the correlation of neutrinos with the template map of emission from Galactic plane based on spatial distribution from γ-ray data (Fermi/LAT - HAWC)

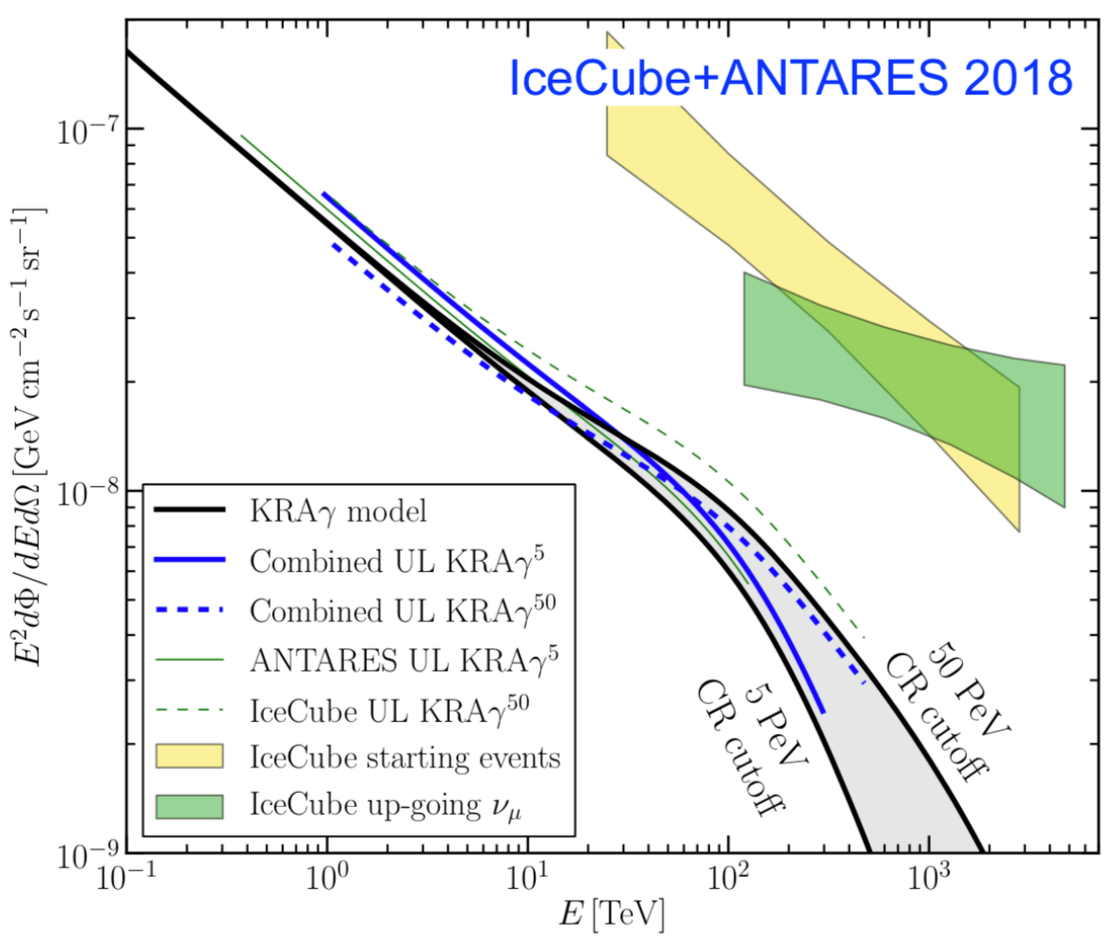
$\Longrightarrow$ **Galactic contribution constrained at the level of ~10% of the diffuse flux**

$\Longrightarrow$ **But models have large uncertainties above 10 TeV**

$\Longrightarrow$ **KM3NeT can test all the conventional models**

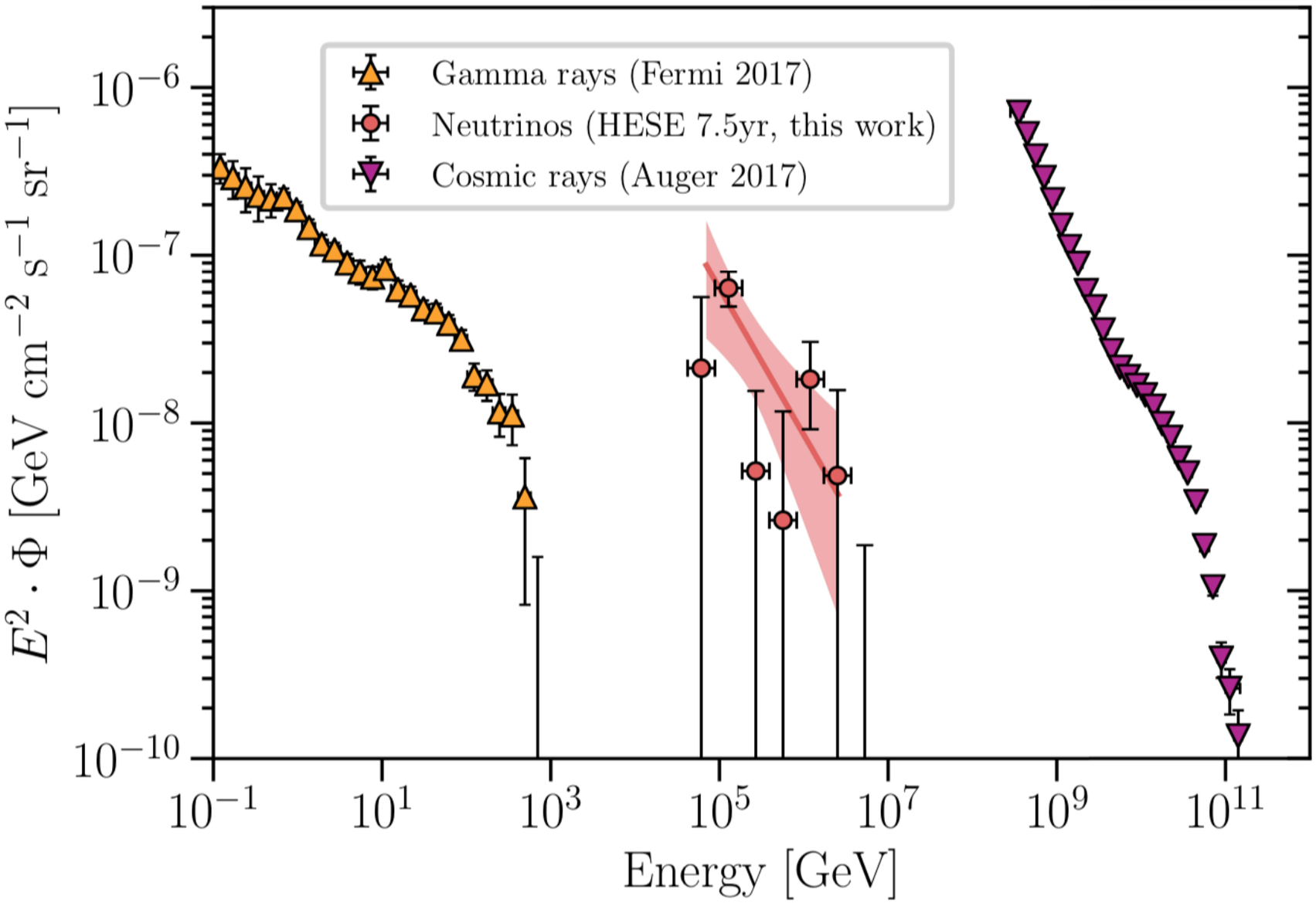


Energy cutoff	Sensitivity [$\Phi_{\mathrm{KRA}_\gamma}$]			Fitted flux	p-value	UL at 90% CL
	Combined	ANTARES	IceCube	[$\Phi_{\mathrm{KRA}_\gamma}$]	[%]	[$\Phi_{\mathrm{KRA}_\gamma}$]
5 PeV	0.81	1.21	1.14	0.47	29	1.19
50 PeV	0.57	0.94	0.82	0.37	26	0.90



Multi-messenger context

Diffuse high-energy fluxes of gamma rays, neutrinos, and cosmic rays

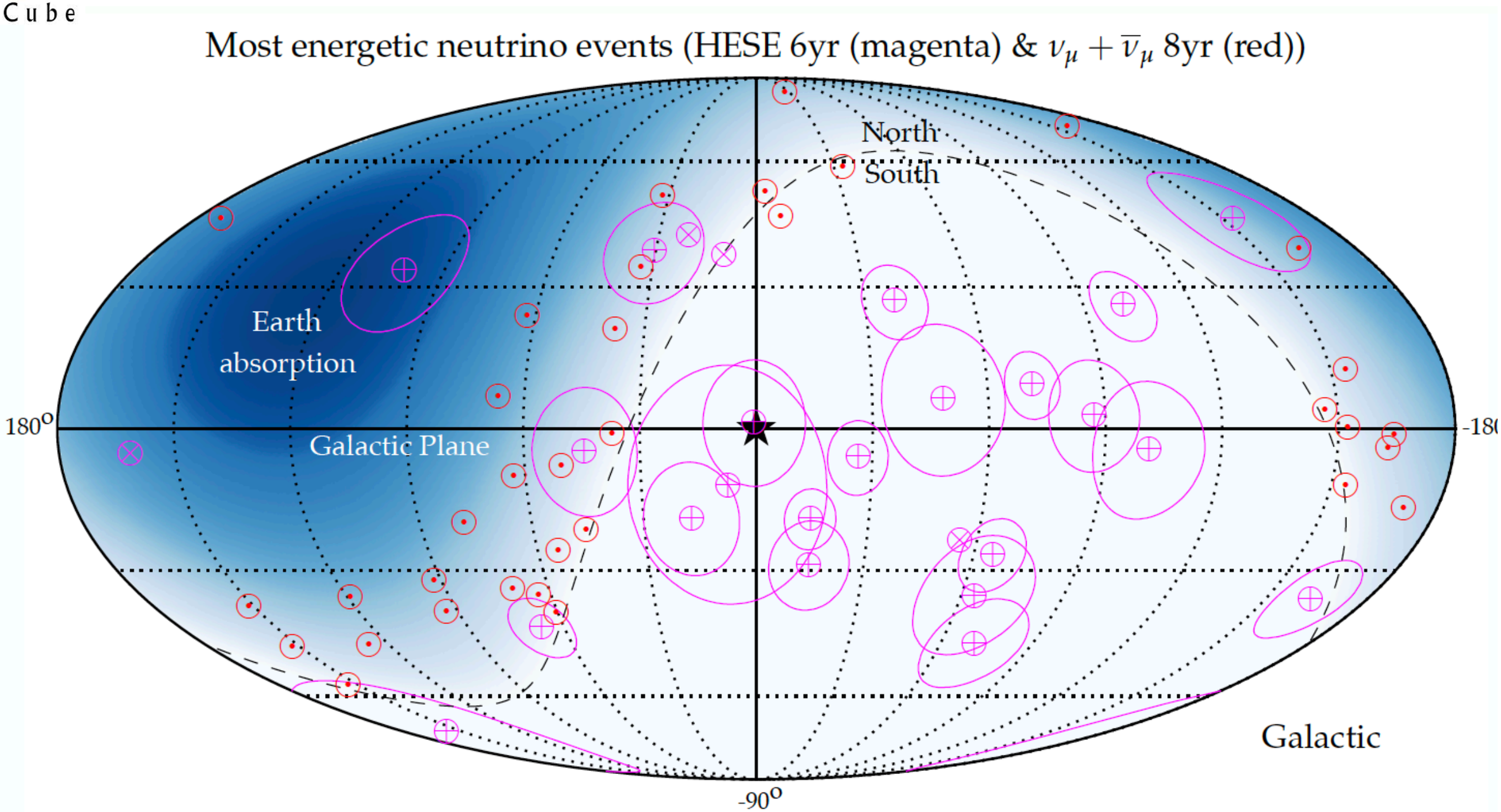


arXiv:2011.03545

$\Longrightarrow$ **The comparable energy content of these three fluxes is of particular interest in the investigation of cosmic-ray origin despite their different energy ranges**

$\Longrightarrow$ **Common sources ? Common production mechanism ?**

VHE neutrino sky (IceCube)

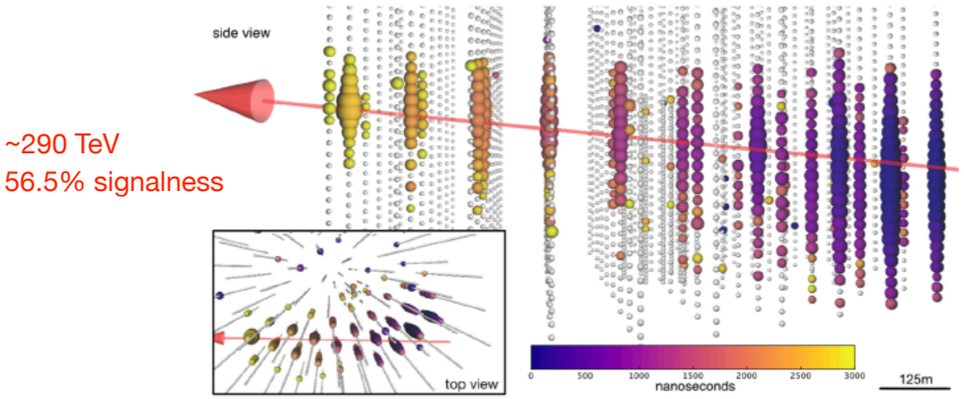


No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

(Maybe) one identified source

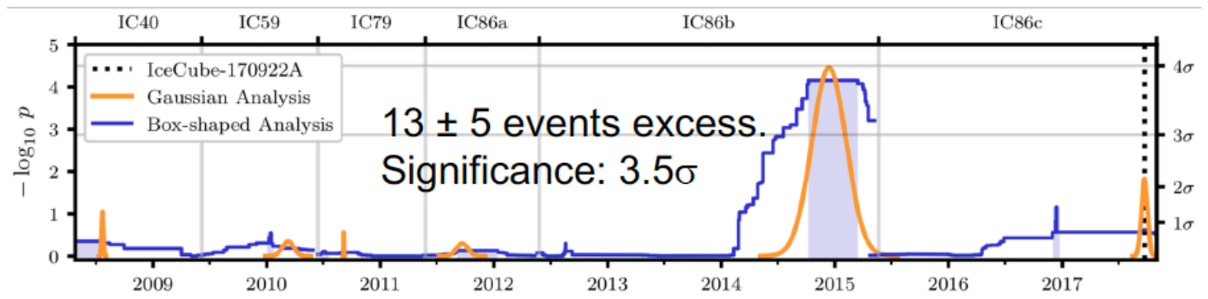
Neutrinos from the AGN blazar TXS 0506+056

Sept. 22, 2017:
A neutrino in coincidence with a blazar flare

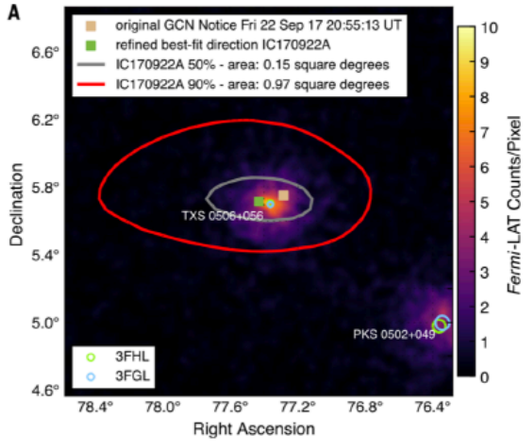


~290 TeV
56.5% signalness

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



Science 361 (2018) no. 6398, eaat2890

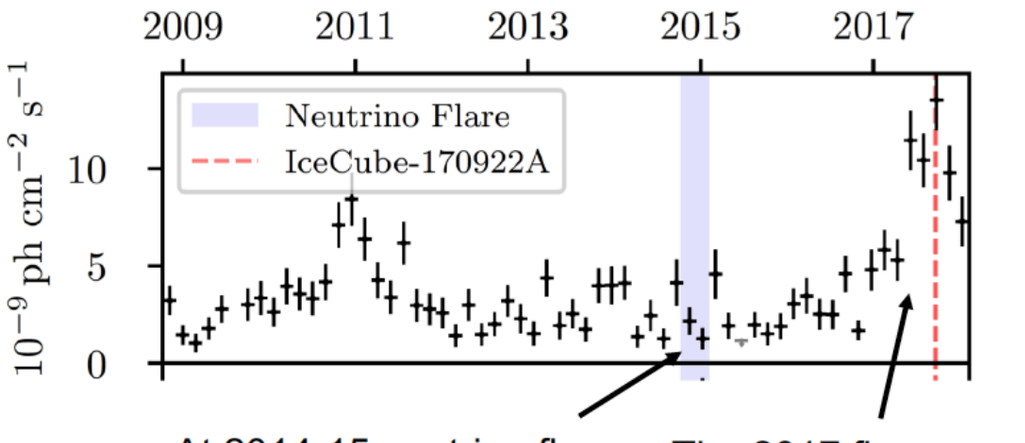


Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

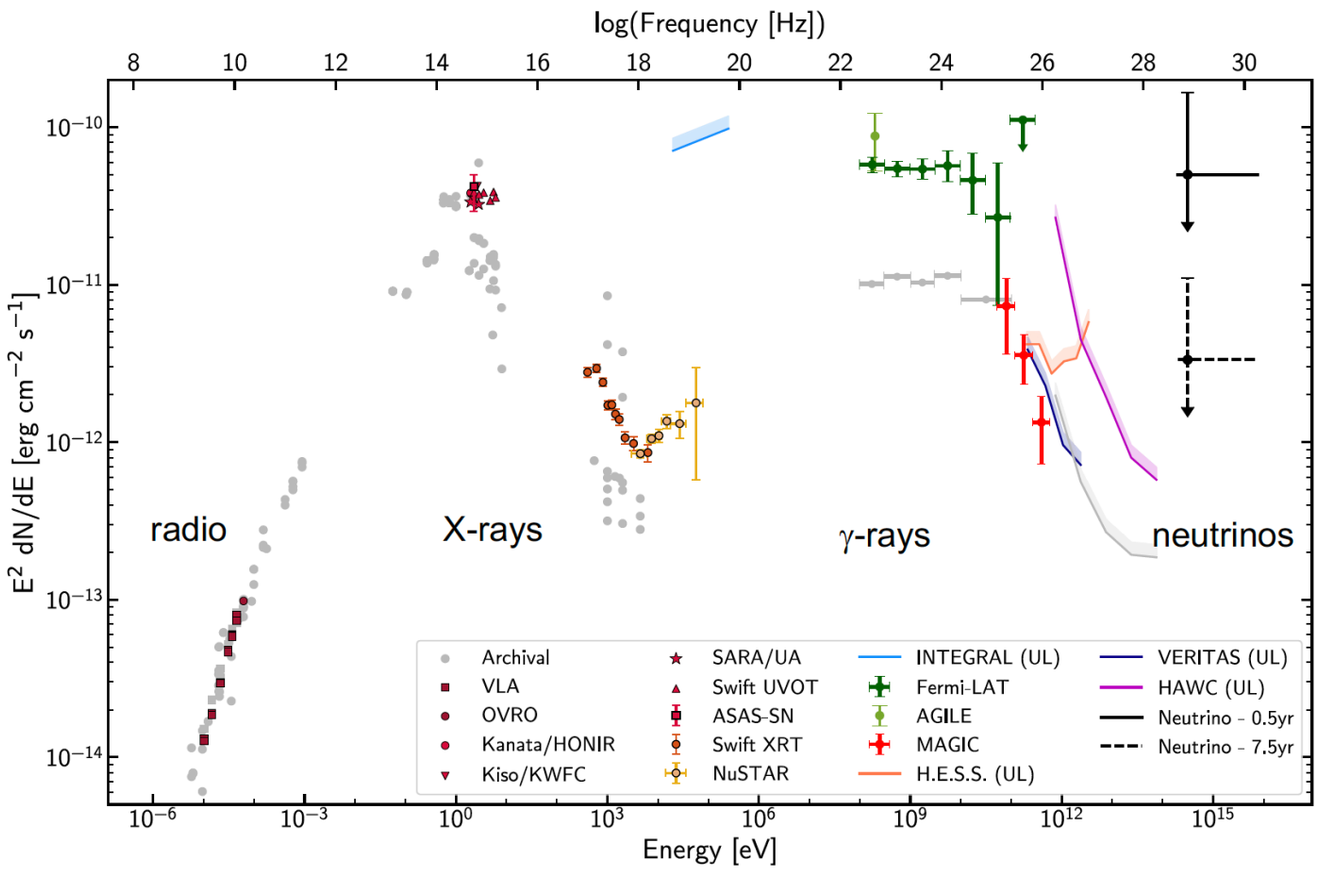
Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



Redshift: 0.33
Type: ISP / BL lac
Among 50 bright blazars

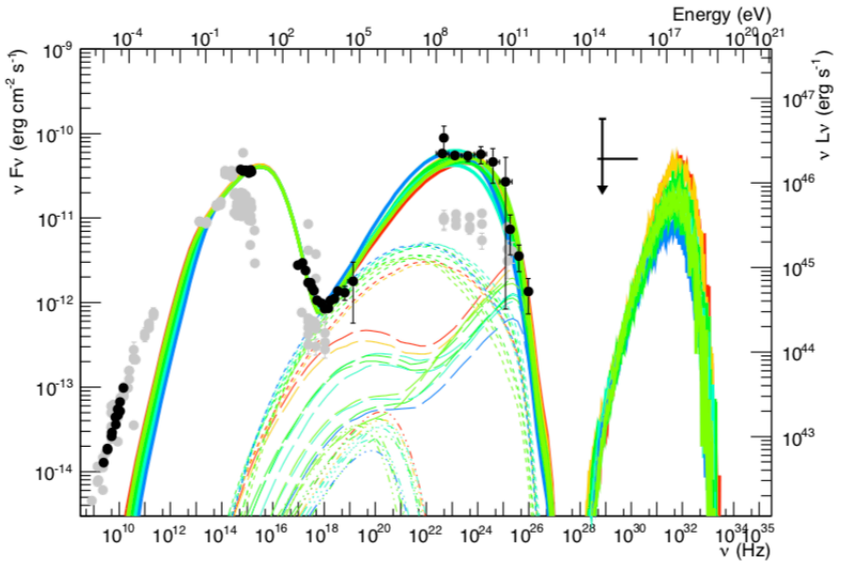
Neutrino luminosity is ~4 times higher than gamma-ray luminosity
⟹ challenge for models

A difficult parametrization

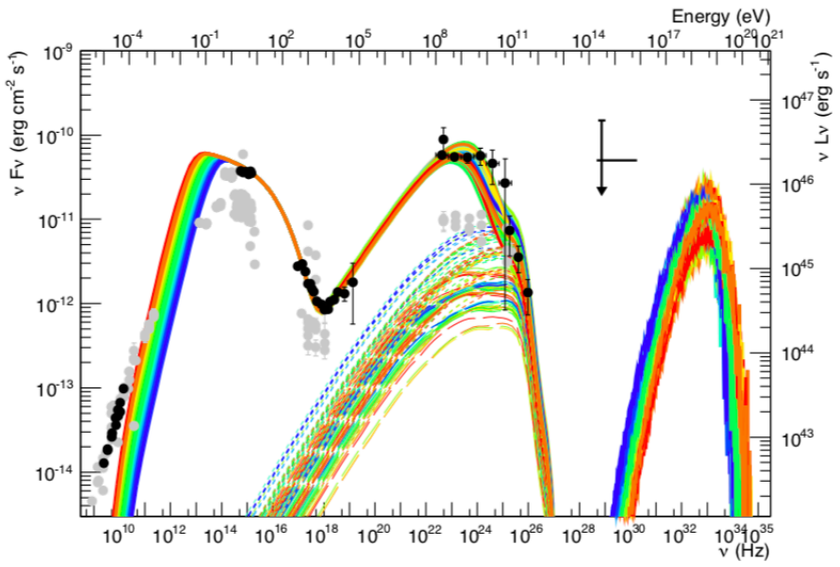


- Simple 1-zone models are not working properly
- More sophisticated multi-zone models on the market to satisfy the energetic problem: interaction with external field (Sikora 2016), jet-cloud interaction (Liu 2018), formation of a compact core (Gao 2019)…

⟹ Simultaneous X-ray data are extremely important for the modeling, even more important than the very high energy

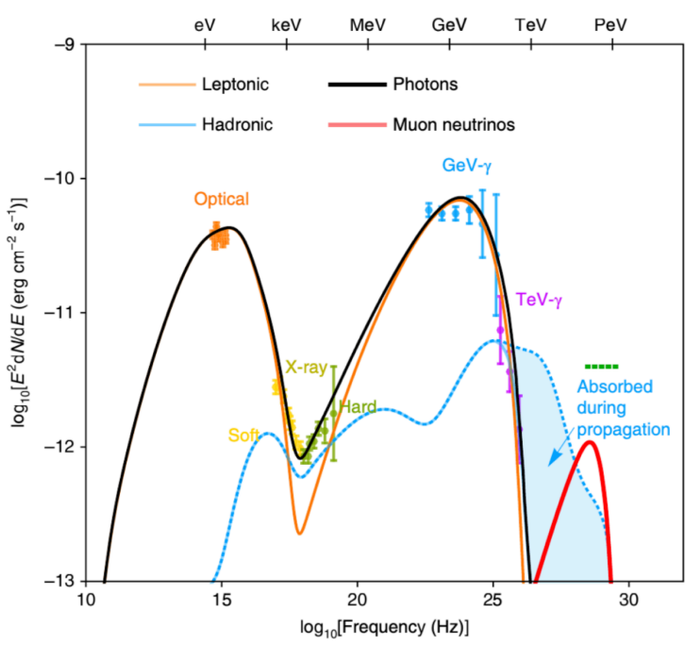


(b) Lepto-hadronic modeling of TXS 0506+056



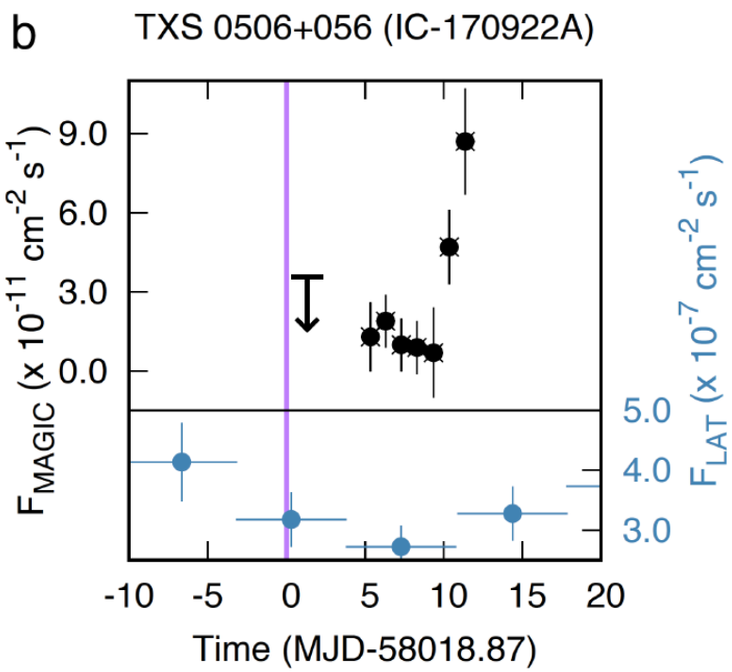
(a) Proton synchrotron modeling of TXS 0506+056

(Cerruti et al, 2018)



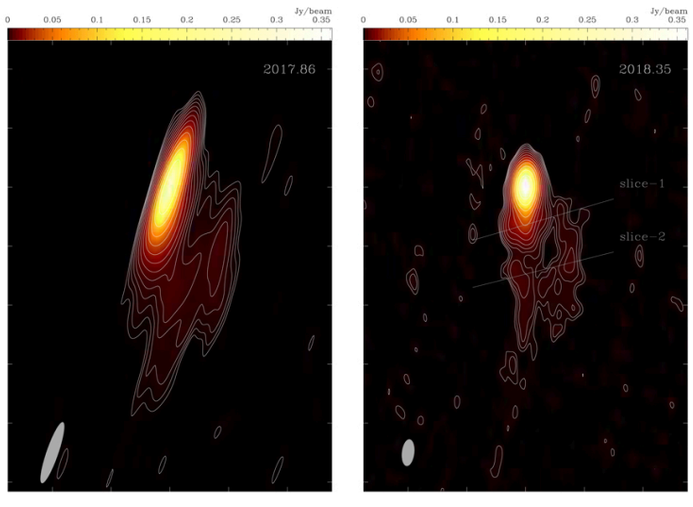
(Gao et al, 2018)

Refined multi-wavelength follow-up



- MAGIC, HESS and VERITAS: no TeV gamma rays at the time the neutrino was produced
- MAGIC: onset of the TeV flux 5 days after IC170922
- MASTER: the blazar switches from the “off” to “on” state 2 hours after the neutrino

Kun et al. 2020



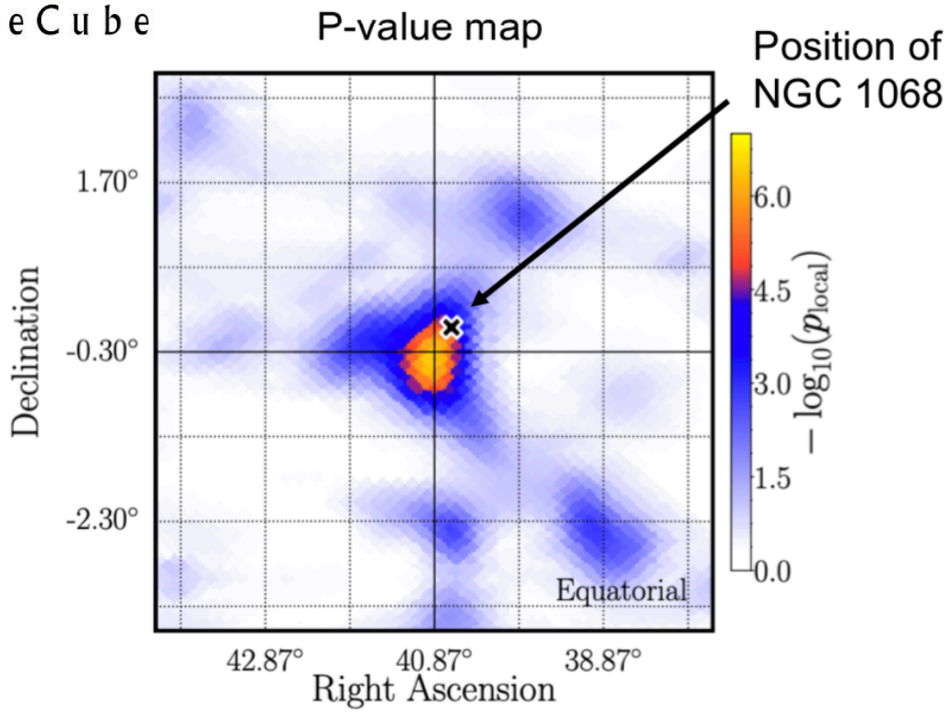
- Radio interferometry images show that the jet interacts with a target close to the base of the jet
- γ-rays accompanying the neutrinos lose their energy in the target that produces them

A&A 633, L1 (2020)

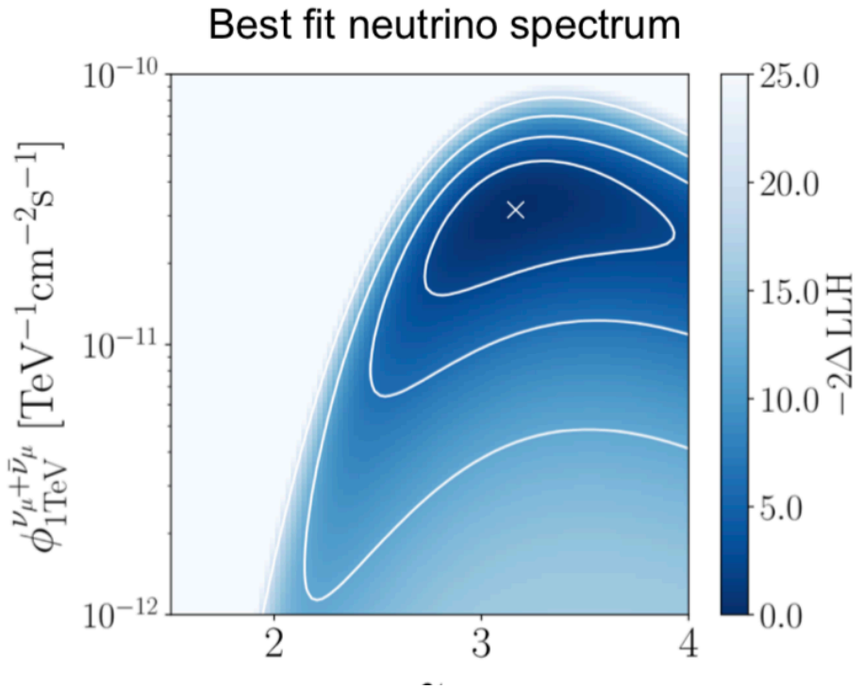
TXS is not a blazar at times that neutrinos are produced.

When a source is transparent to HE γ-rays there is an insufficient photon or matter target density to produce neutrinos.

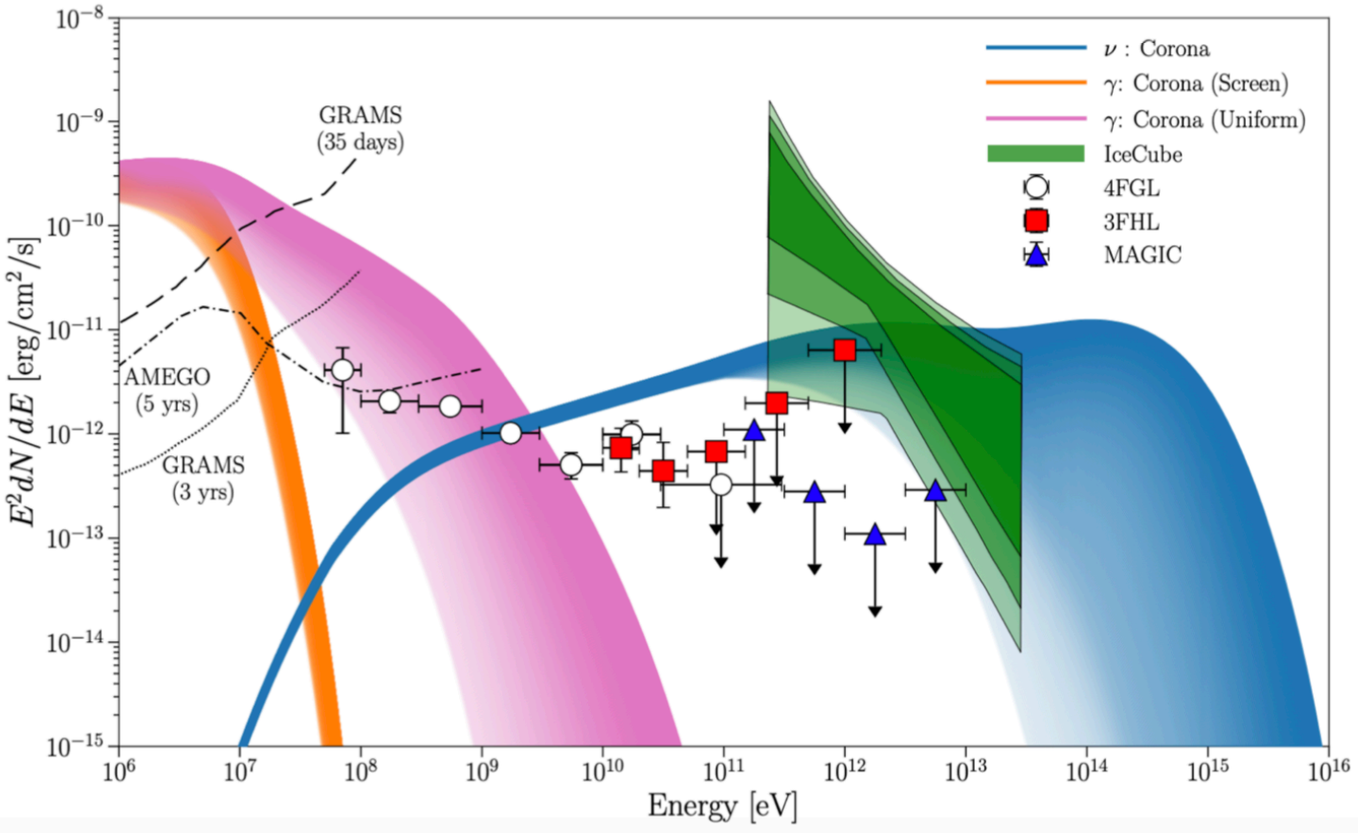
NGC1068



Hottest spot in Northern sky close to NGC 1068, most significant source in predefined list: Post-trial: 2e-3 (2.9σ)



IceCube Coll. PRL 124 (2020)

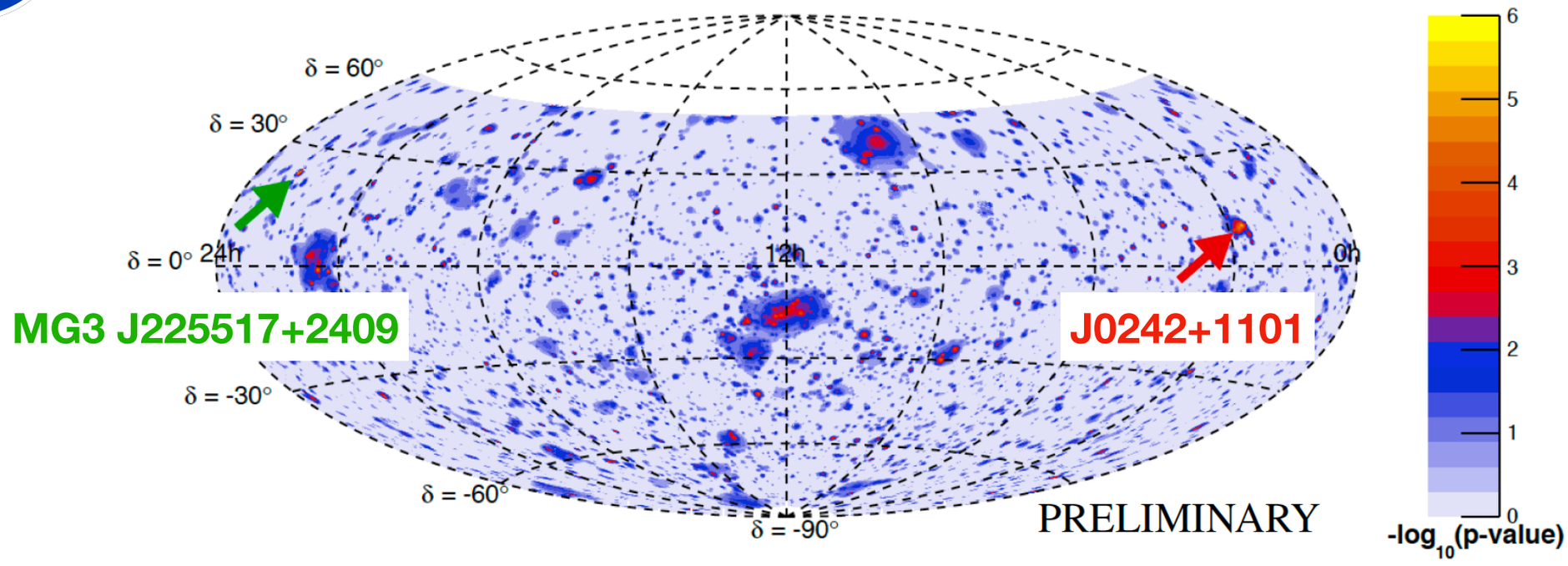


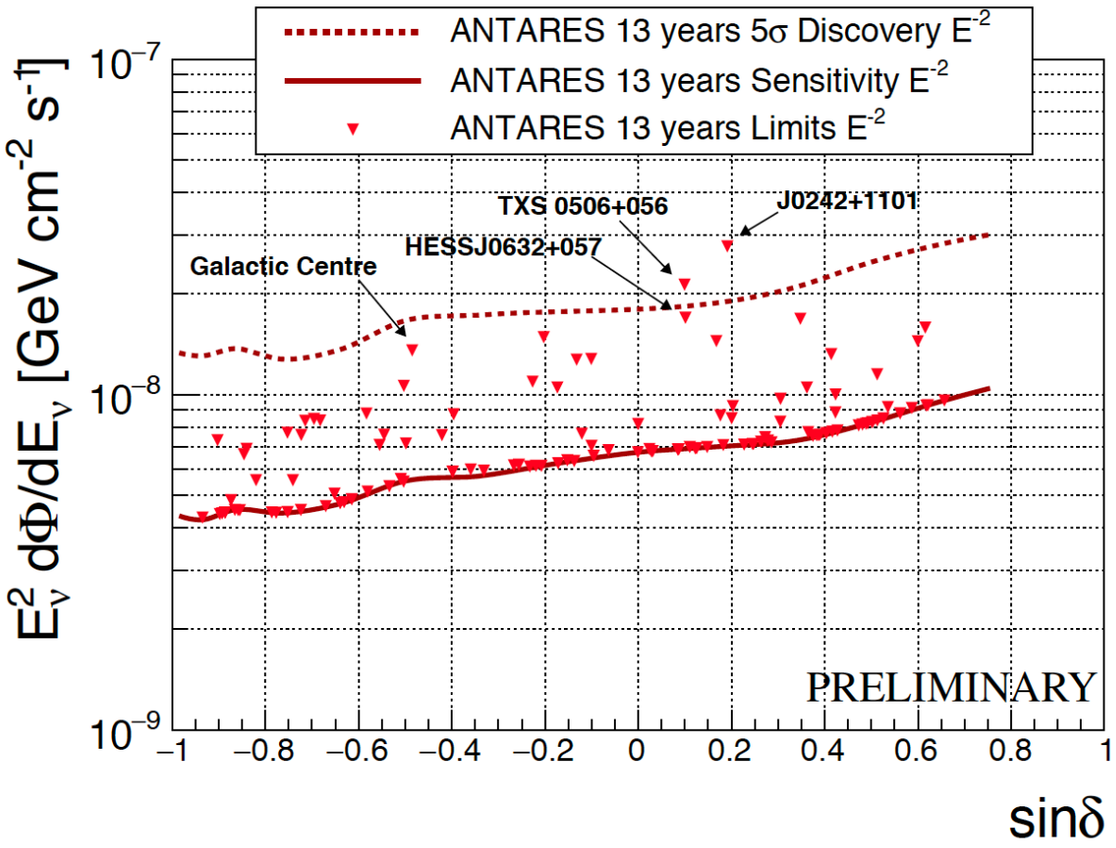
- **Seyfert 2 galaxy (M77) at 14 Mpc (star forming region)**
- **Neutrino production only at the vicinity of the SMBH (intense X-ray target): reported neutrino flux is higher than the GeV gamma-ray flux**

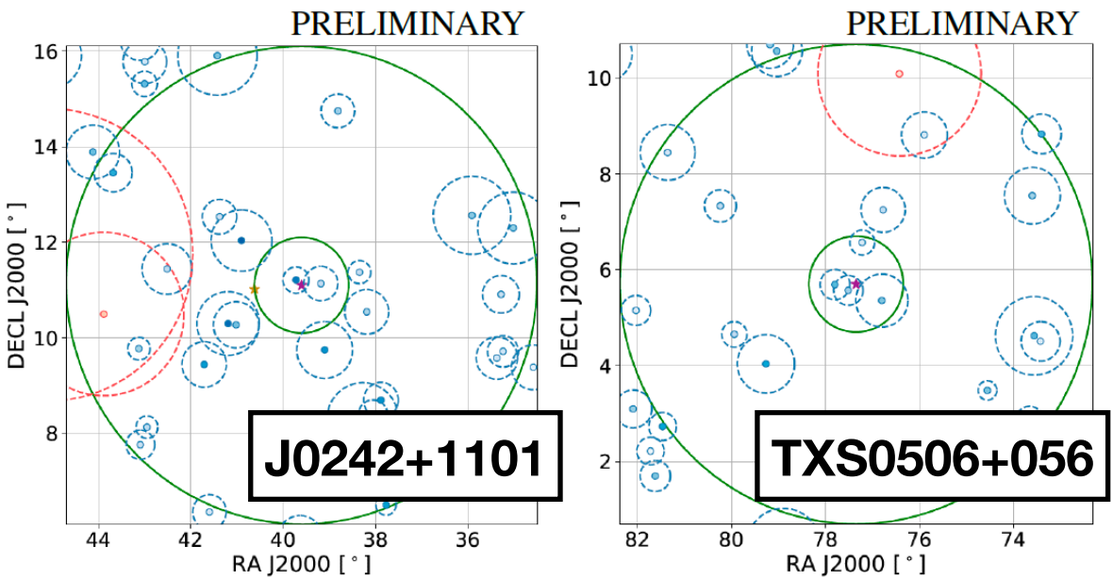
$\Longrightarrow$ significant γ-rays absorption

Inoue et al. ApJL 891 (2020)

Last ANTARES PS results 2007-2020







3.8σ pre-trial

2.4σ post-trial

2.8σ pre-trial

(increasing significance compare to the last search)

PoS(ICRC2021)1161

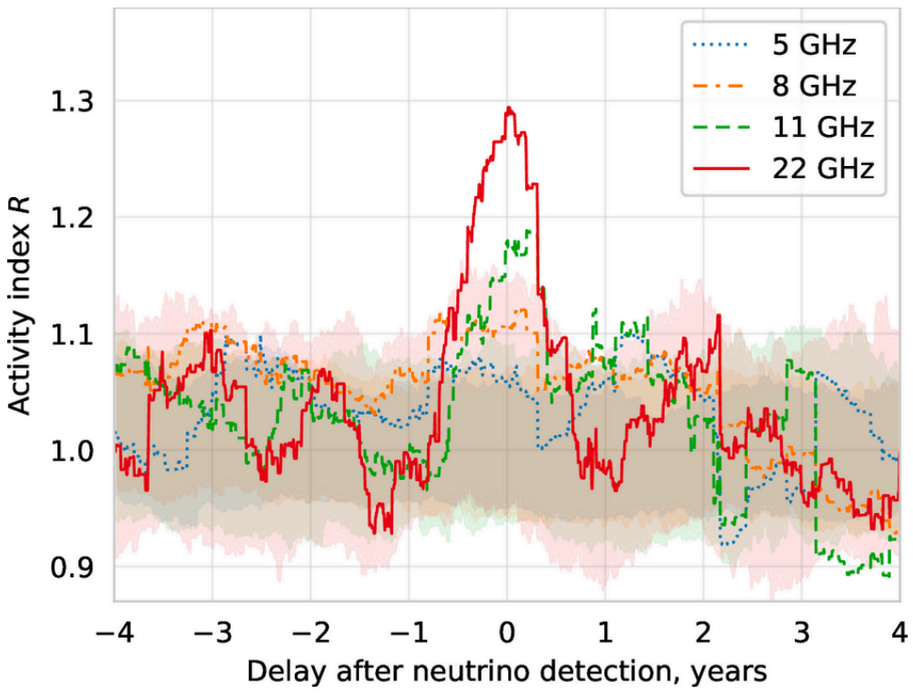
Correlation with radio blazars

In 2020/21, Platvin and co looked at the association of blazars with released IceCube neutrino detections

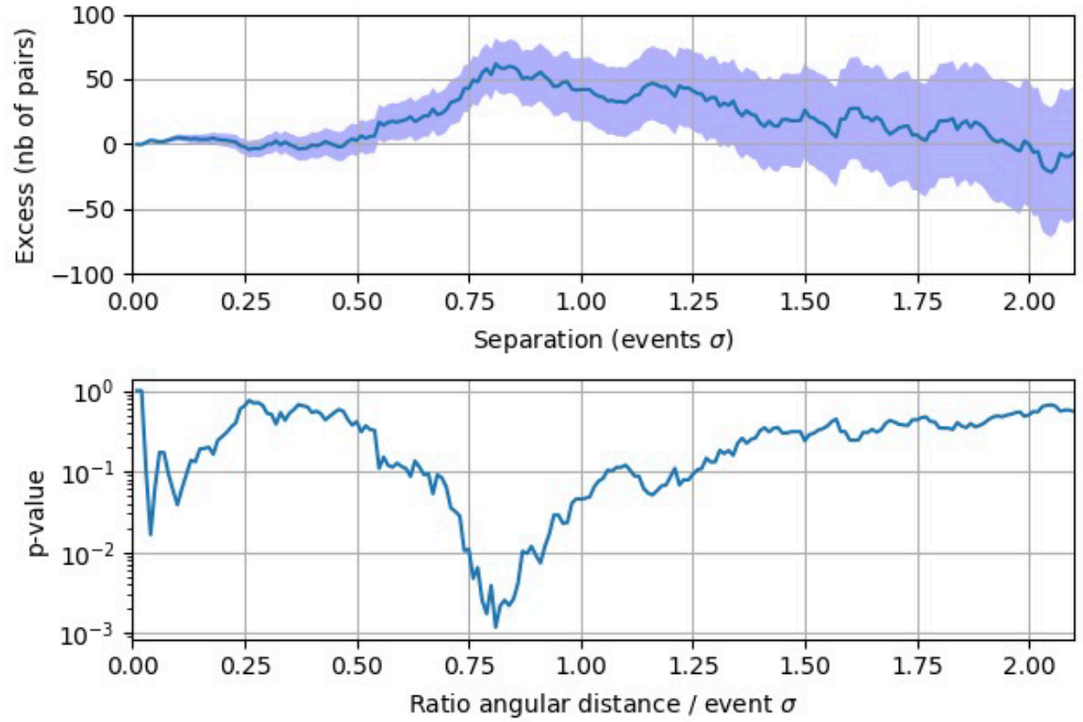
$\Longrightarrow$ **Neutrinos from TeVs to PeV are produced in central parsecs of radio bright blazars. They correlate with major flares in jets.**

$\Longrightarrow$ Radio interferometry is key to this discovery

$\Longrightarrow$ Analysis with ANTARES data in progress



Plavin, Kovalev, Kovalev, Troitsky
2020: ApJ, 894, 101
2021: ApJ in press, arXiv:2009.08914



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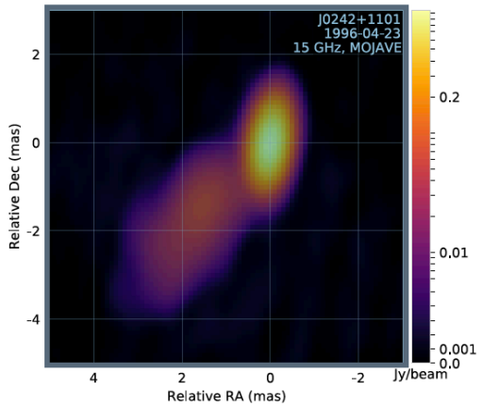
Search for correlation radio blazars in VLBI data (2774 objects) and ANTARES PS sample 2007-2020 (10162 tracks) $\Longrightarrow$ post-trial p-value of 0.022 ($\sim 2.3\,\sigma$). **Analysis still in progress**

Neutrino flares from radio sources

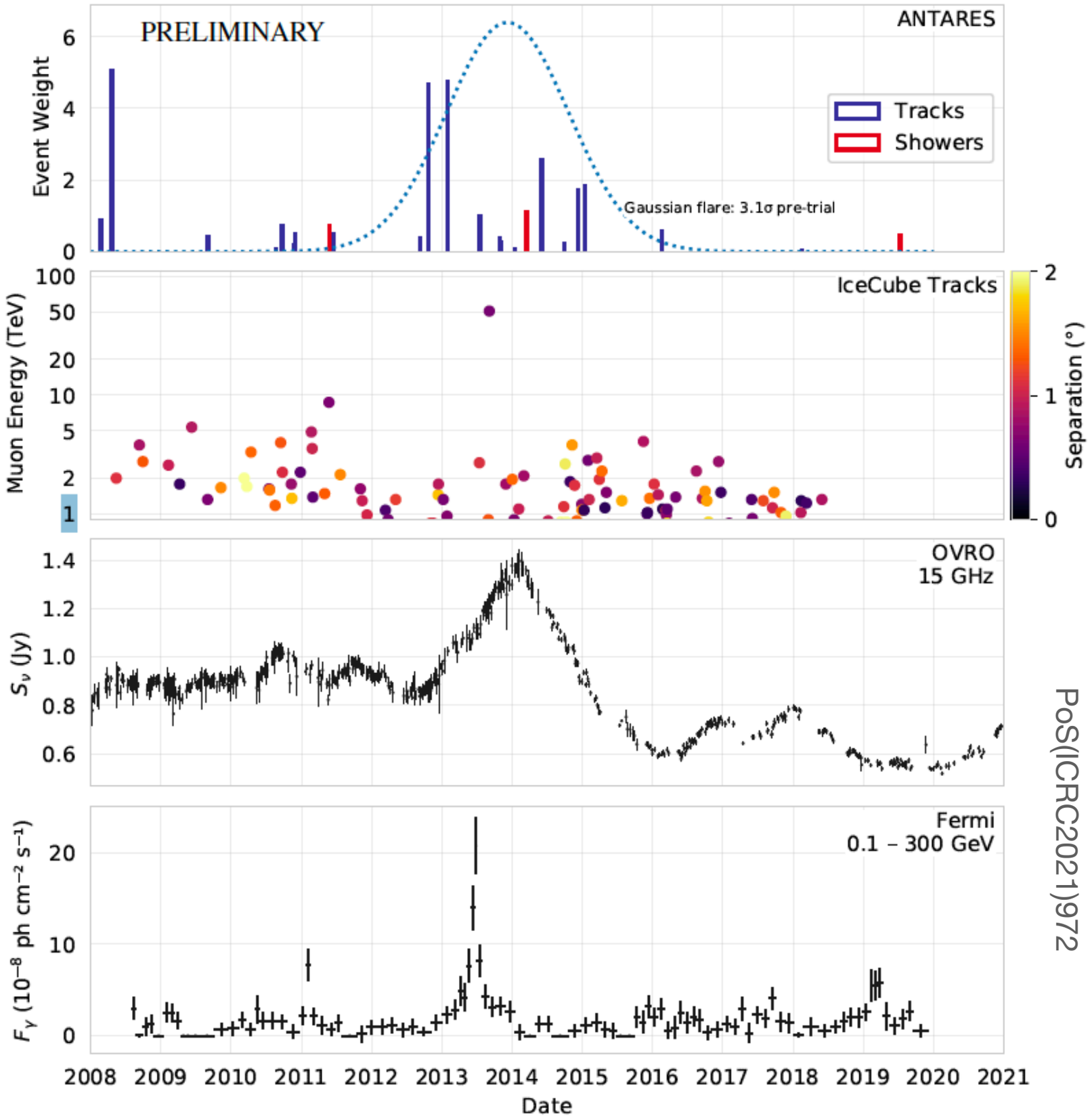
Looking for neutrino flares from the 2774 VLBI radio-selected blazars
Best association: J1500-2358

2nd best: J0242+1101 (PKS 0239+108) with interesting MWL/MM counterparts

VLBI image at 15 GHz

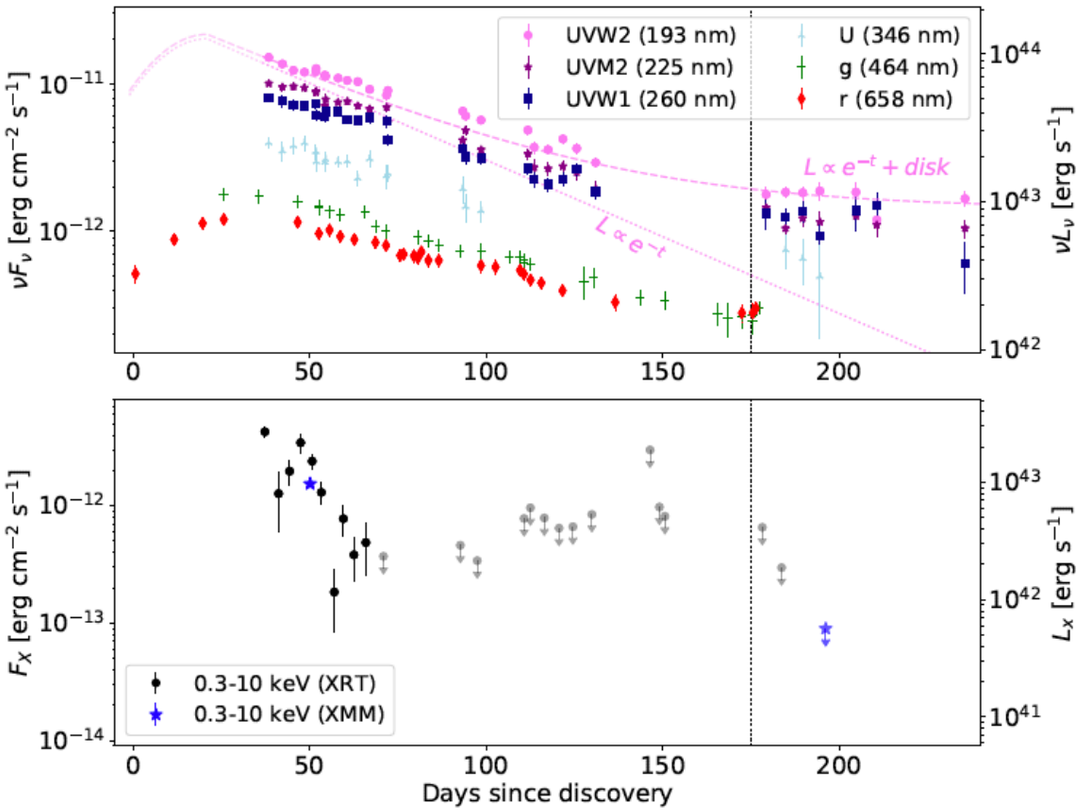


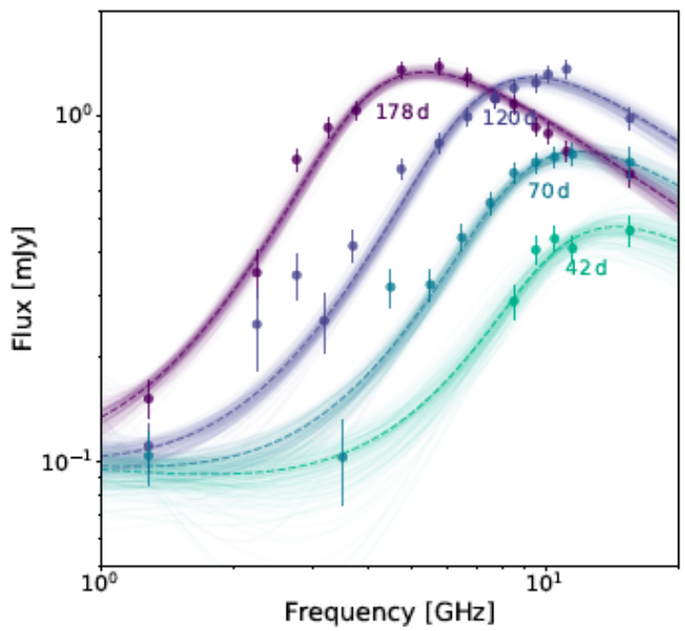
Computation of the chance probability of the association between radio, γ-ray and neutrino observations in progress



PoS(ICRC2021)972

TDEs as new potential neutrino sources





R. Stein et al., arXiv:2005.05340

Tidal Disruption Events (TDE)

- A star is torn into pieces by the gravitational force of a SuperMassive Black Hole (SMBH)
- Part of the debris are accreted
- Extreme cases can host a relativistic hadronic jet
- 100 candidate TDEs observed, 3 with evidence of jets (hard X-ray spectrum)

IC191001A - AT2019dsg:

- Follow-up of the neutrino alert by ZTF
- Identification of of the TDE AT2019dsg with p-value of 0.2% to 0.5% of random association; ~3σ
- AT2019dsg was already 150 days post-peak: large delay of the neutrino arrival (z~0.05)

- Possible other association: IC200530A - AT2019fdr (delay of ~300 days)
- Analyses by ANTARES: no association

KM3NeT point-source capabilities

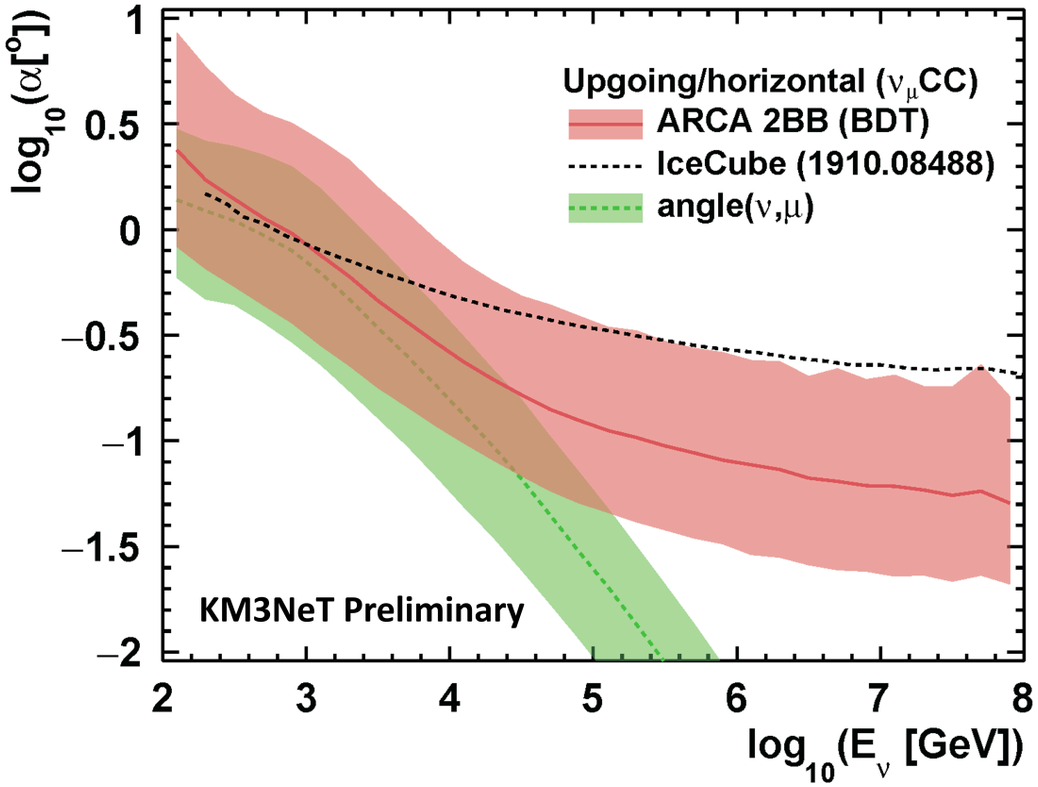
⟹ Thanks to the improved angular resolution, large energy coverage, KM3NeT will have interesting performances on the search for PS

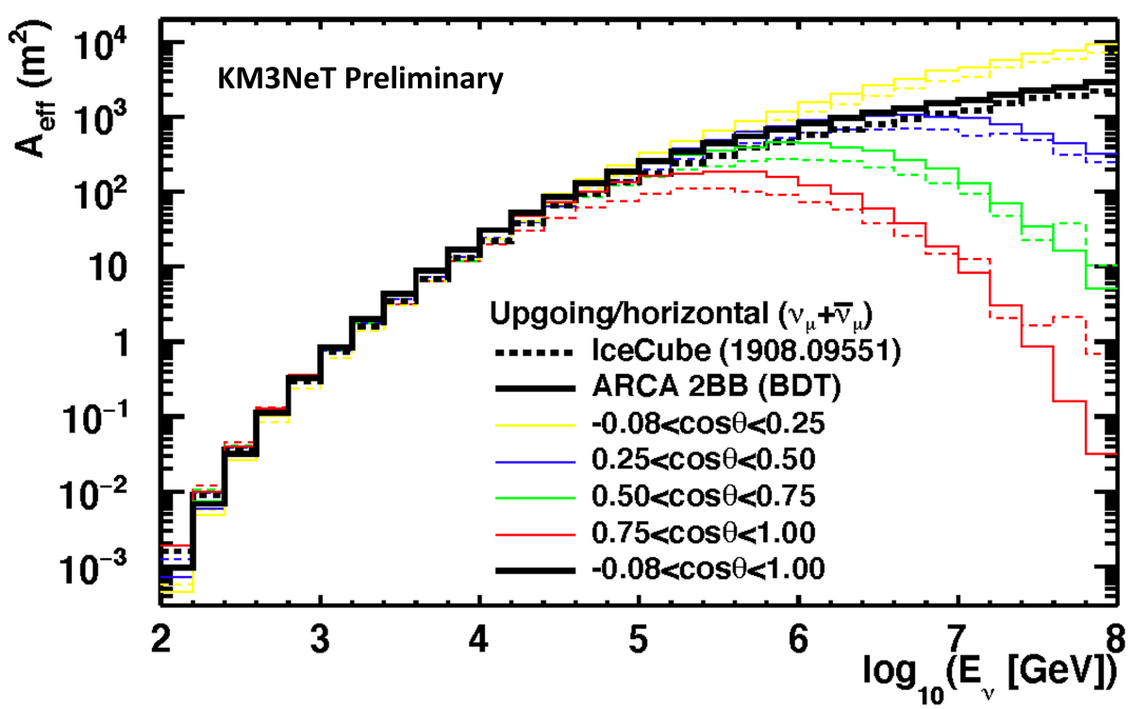
For ARCA tracks:

- ➡ Gal. sources: 0.2° at 10 TeV
- ➡ Extra-gal. sources: 0.1° at 100 TeV
- ➡ VHE: 0.06° at 10 PeV
- ➡ But poor energy resol. ~2-3

For ORCA tracks:

- ➡ 7° at 10 GeV, 2° at 100 GeV, <1° at 1 TeV
- ➡ Energy resolution ~20-30%





(Only track neutrino)

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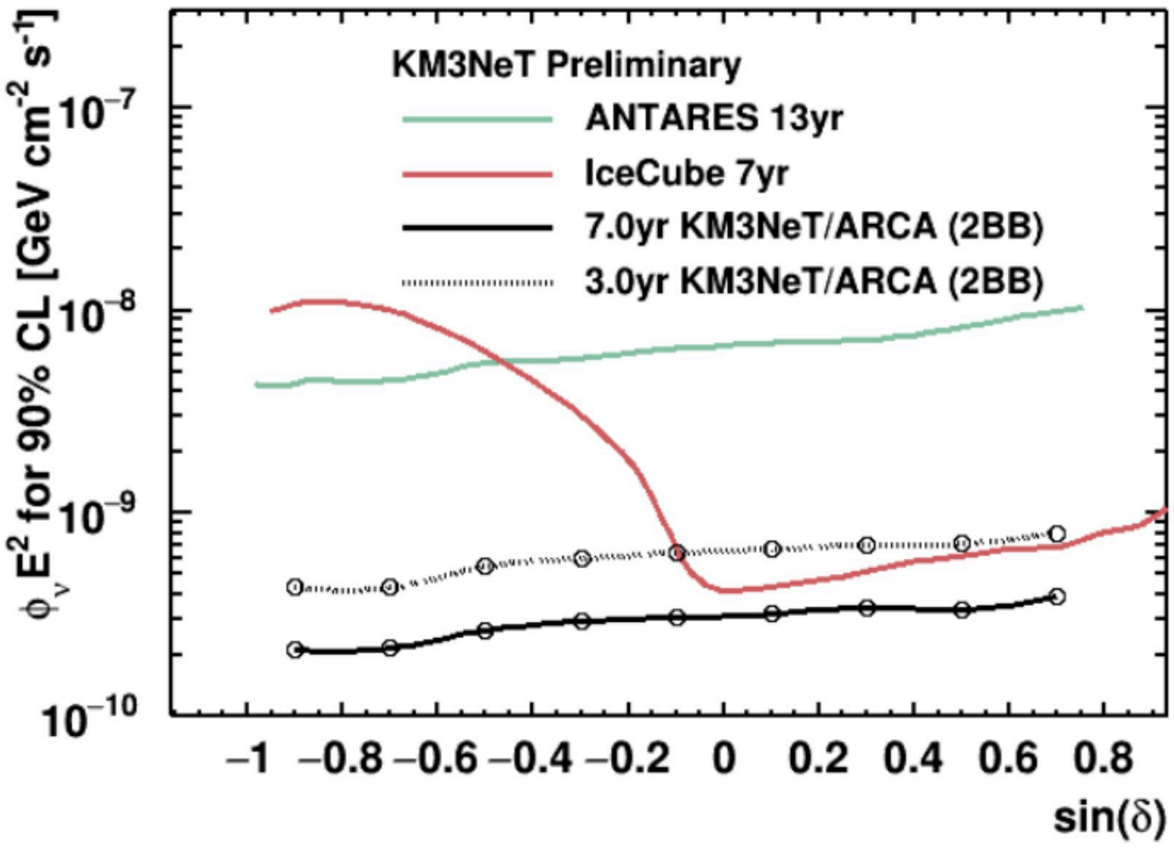
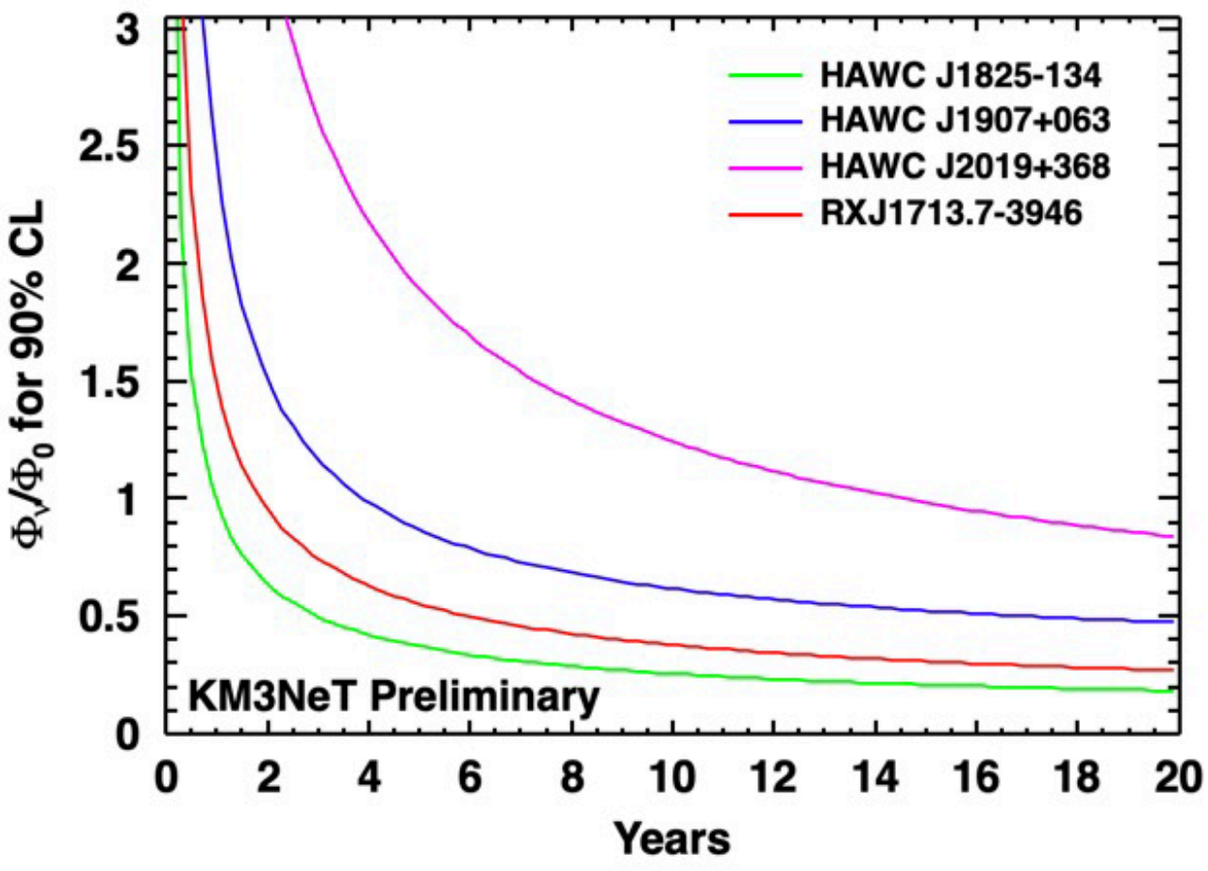
KM3NeT point-source capabilities

⟹ **Thanks to the improved angular resolution, large energy coverage, KM3NeT will have interesting performances on the search for PS**

Sensibilities



Galactic extended source



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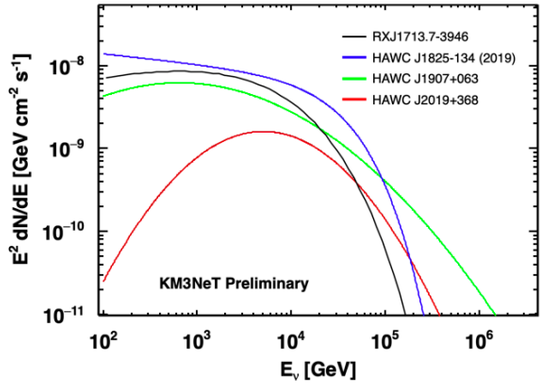
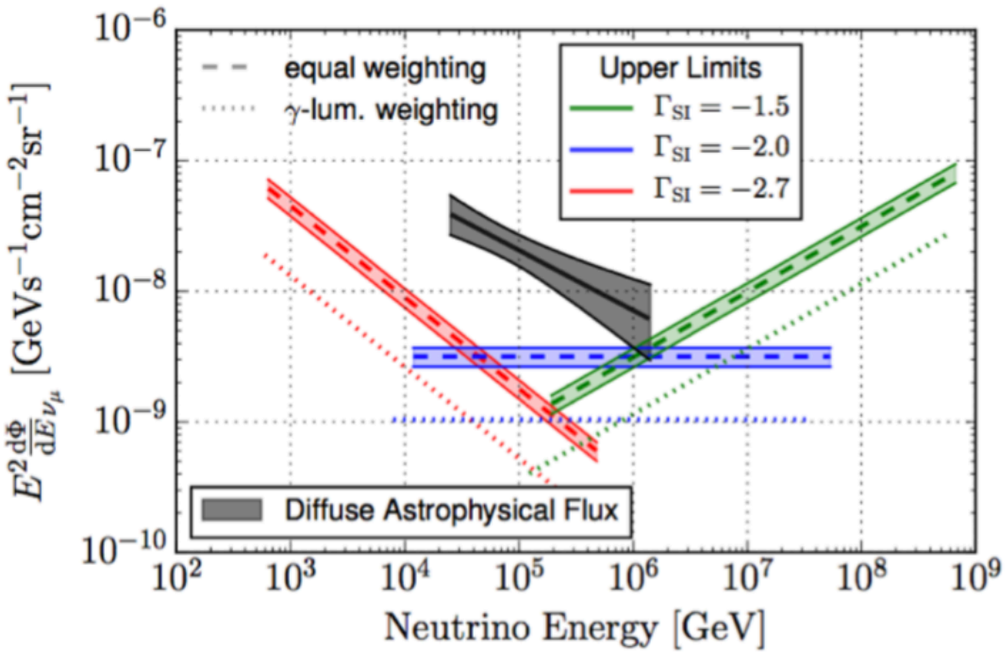
(Can gain ~30% adding cascade events)



Source	Decl, RA [°]	Ext [°]
RXJ 713.7-3946	-39.77, 258.8	0.6 (disk)
HAWC J1825-134	-13.37, 276.4	0.53 (Gauss)
HAWC J2019+368	36.76, 304.92	0.356 (Gauss)
HAWC J1907+063	6.32, 286.91	0.67 (Gauss)

Source population studies



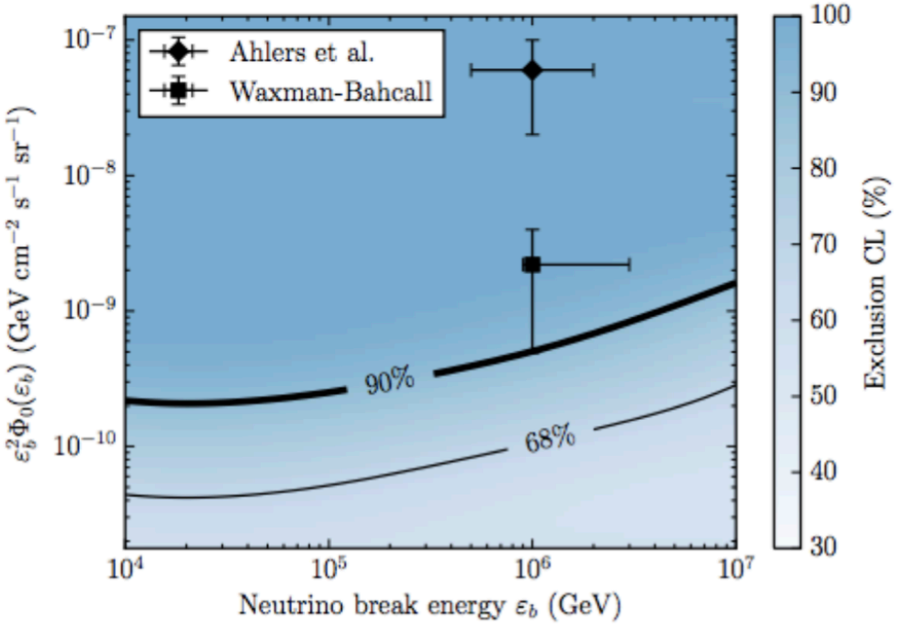
IceCube Coll. ApJ 835 (2017)

Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

$\Longrightarrow$ ***Fermi*-LAT blazars** can only be responsible for a **small fraction** of the observed neutrinos.

$\Longrightarrow$ Multiple populations

+ similar limit for TDE contribution (~26 %)



IceCube Coll., ApJ 805 (2015), ApJ 824 (2016)

Prompt emission of > 800 GRBs correlated with IceCube data

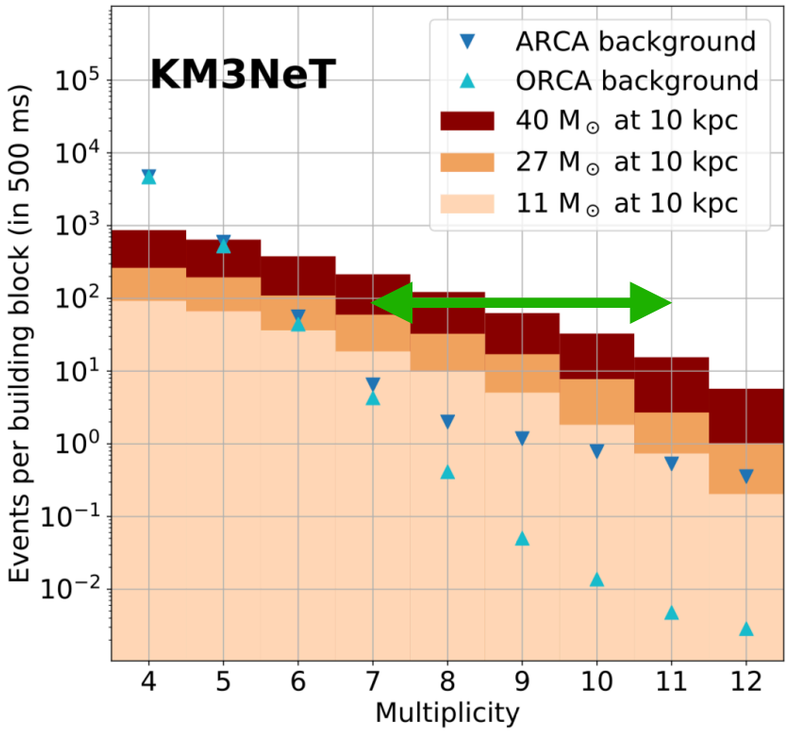
$\Longrightarrow$ no excess found (Try others precursor, afterglow and absorbed GRB searches)

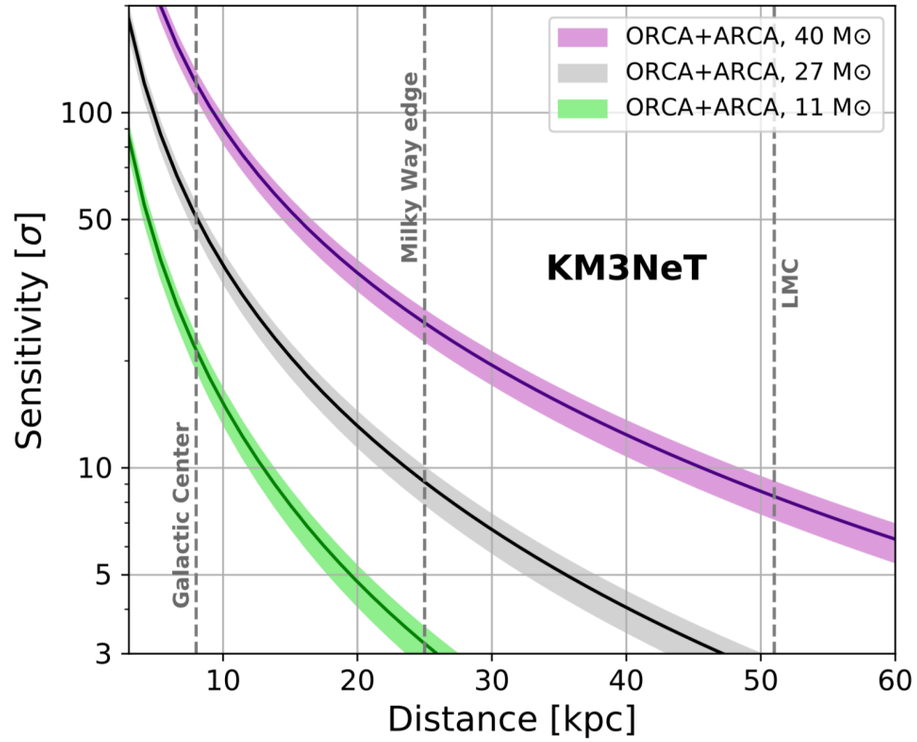
$\Longrightarrow$ **GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained**

Core-Collapse supernovae with KM3NeT

CCSN → 99% of the energy in neutrinos o(10 MeV)

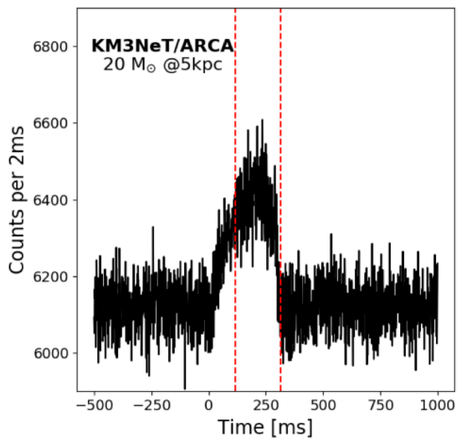
No event-by-event reconstruction ⟹ collective increase of the multiplicity rate on the DOMs of the detector



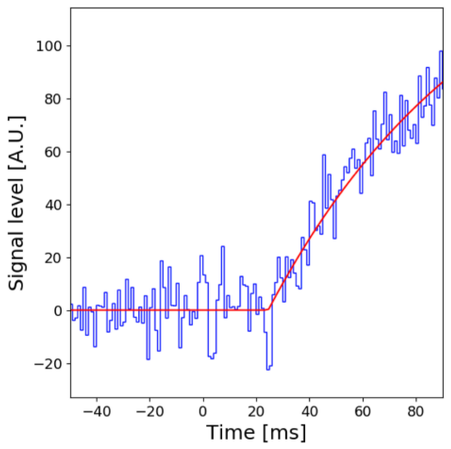


Astrophysical analyses:

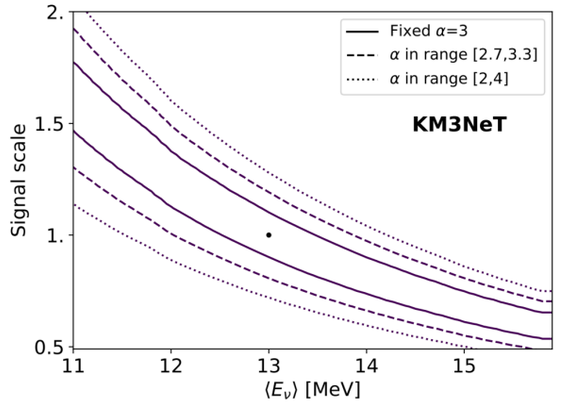
+ connected to SNEWS (2.0)



Time profile



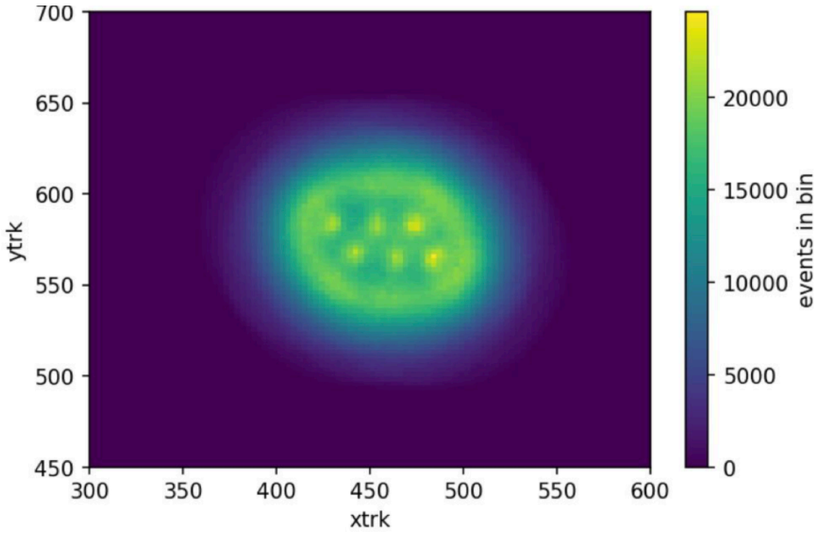
T_0 estimate



Neutrino spectrum

PoS(ICRC2021)1102

Last news of KM3NeT

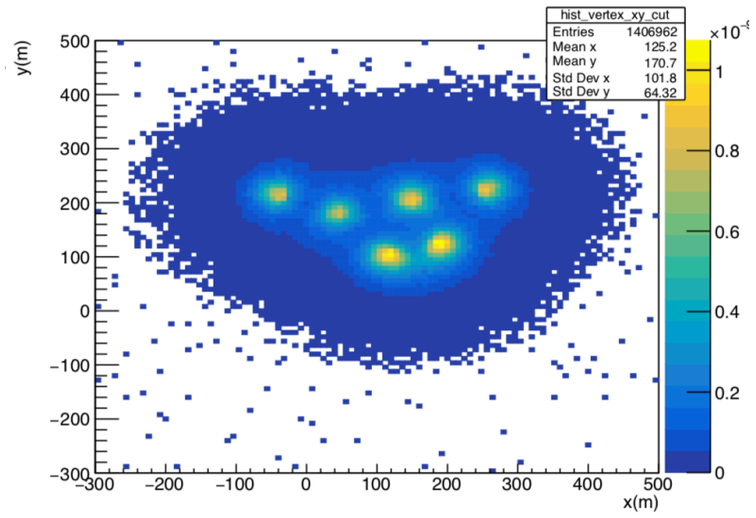


ORCA: 1 GeV - few TeV

6 strings in operation since 18 months

$\Longrightarrow$ Already better performances than ANTARES and IceCube

$\Longrightarrow$ Continuous construction: +7 in October, +~6 in April



ARCA: 100 GeV - few PeV

6 strings in operation since 3 months

$\Longrightarrow$ Almost similar performances than ANTARES

$\Longrightarrow$ Continuous construction: +5 in September, +12 in April


ORCA, ready to be deployed


ARCA, ready to be deployed

Summary

Solid measurements of the diffuse high-energy neutrino flux by IceCube and ANTARES. We are touching the top of the iceberg of the neutrino sources.

- TXS 0506+056, PKS B1424-418, PKS1502+106
- MG3 J225517+2409, J0242+1101, J0538-4405…

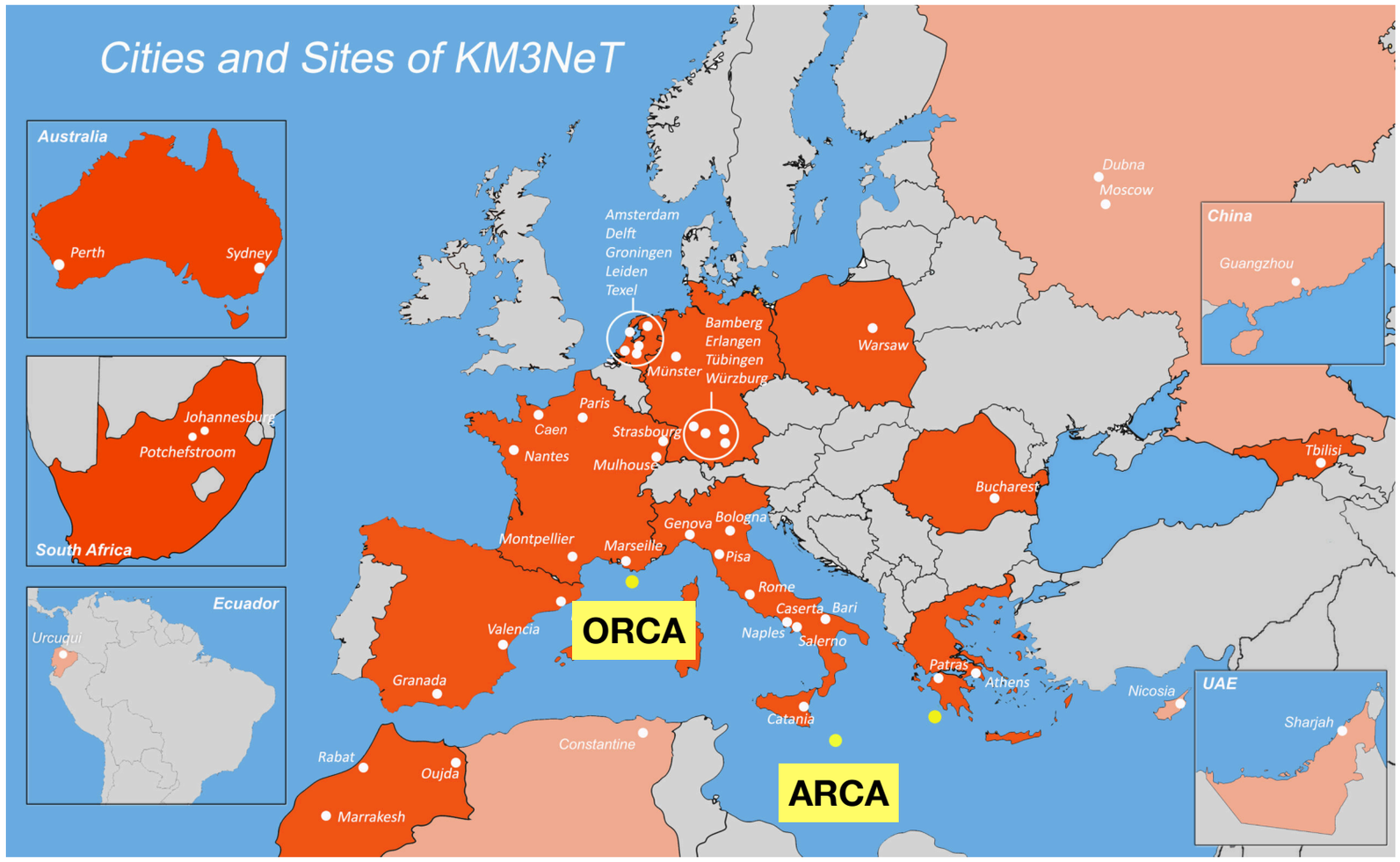
New neutrino detectors are arriving GVD, the largest neutrino telescope in the northern hemisphere and KM3NeT, which just arrives at the same or better effective area compared to ANTARES.

Simultaneous MWL/MM follow-up is the key to resolve the neutrino sources (too few statistic in the neutrino side)

Astronomy with the future generation neutrino detectors:

- Understand the diffuse neutrino flux (spectral features, galactic component, UHE tail…)
- Identify individual **sources** responsible for high energy neutrinos diffuse flux
- Neutrino **flavour ratio** and its indication of the source properties
- Constrain the production mechanisms of high-energy cosmic particles
- Link with UHECR - detection of c**osmogenic** neutrinos

KM3NeT in France



APC

CPPM

LPC

LUPM

IPHC

Subatech

Main thematics:

- Real-time analysis (alerts, correlation with external triggers…)
- CCSN detection
- Point-like sources
- Transient sources
- Multi-messenger analysis (GW, CR)
- VHE neutrino diffuse fluxes
- LE neutrino astronomy

Multi-messenger synergies

Optical telescopes: TAROT, MASTER, LCOGT, ZTF, LSST…
- Easy access follow-up of large error box
- Characteristation of the potential counterpart with spectroscopy (nature, redshift…)

X-ray telescopes: Swift, INTEGRAL, SVOM, THESEUS, ATHENA…
- Very clean sky
- Provide transient triggers (GRB, AGN, Novae…)
- ToO program (not so easy access)

γ-ray telescopes: Fermi-LAT
- All-sky complete monitoring
- Provide transient triggers (GRB, AGN…)

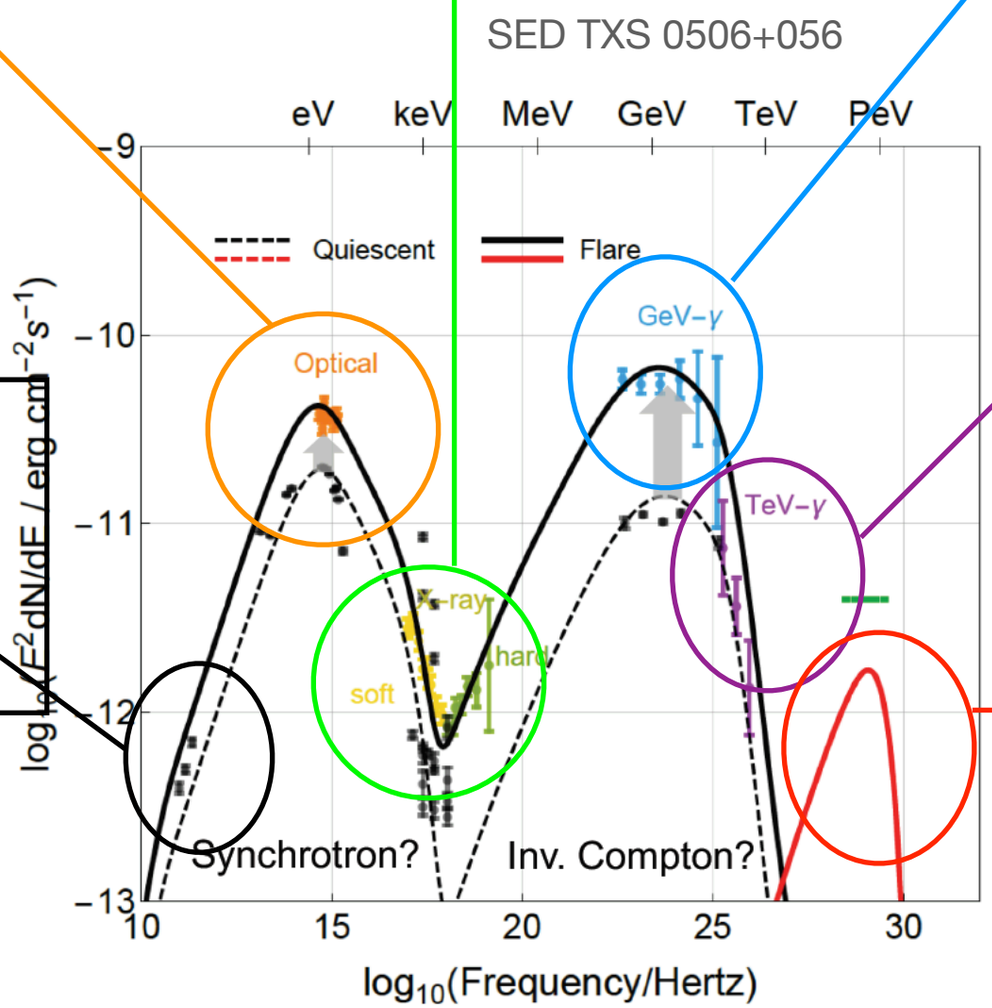
VHE γ-ray telescopes: HESS, MAGIC, CTA…
- Most natural common science case
- Follow-up (not easy access)

VHE γ-ray telescopes: HAWC, LHAASO…
- All-sky monitoring
- Provide triggers

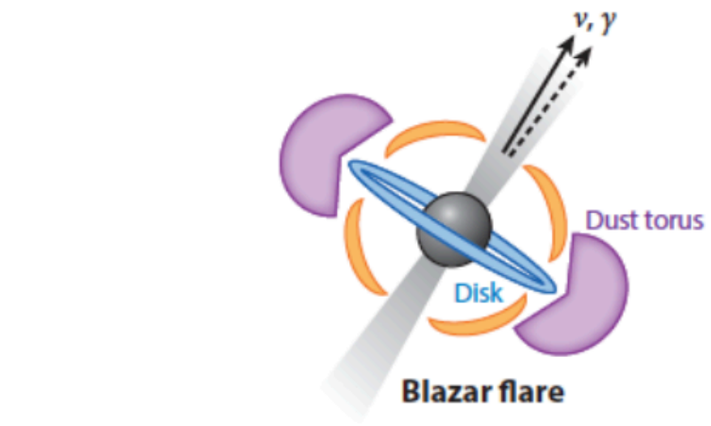
Radio telescopes: Parkes, MWA, Lofar, Nenufar, ASKAP, SKA…
- Provide triggers (FRB…)
- Follow-up

Neutrino telescopes: ANTARES, IceCube, KM3NeT, GVD…
- Mutual follow-up
- Confirmation of sources, improve significance

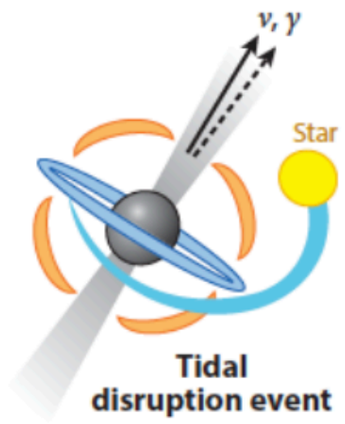
+ link with LIGO/VIRGO
+ SK, SNEWS



Potential transient neutrino sources

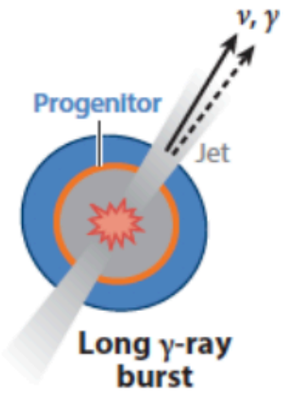


Blazar flare

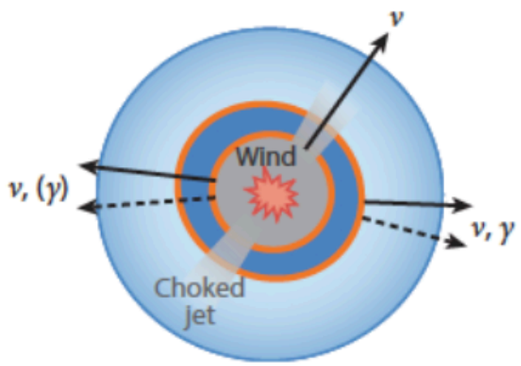


Tidal disruption event

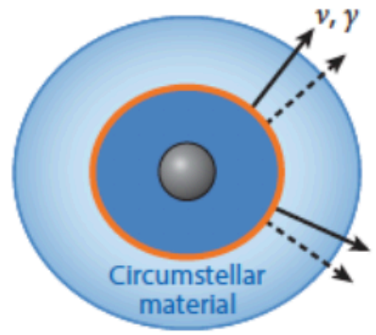
supermassive black holes



Long γ-ray burst

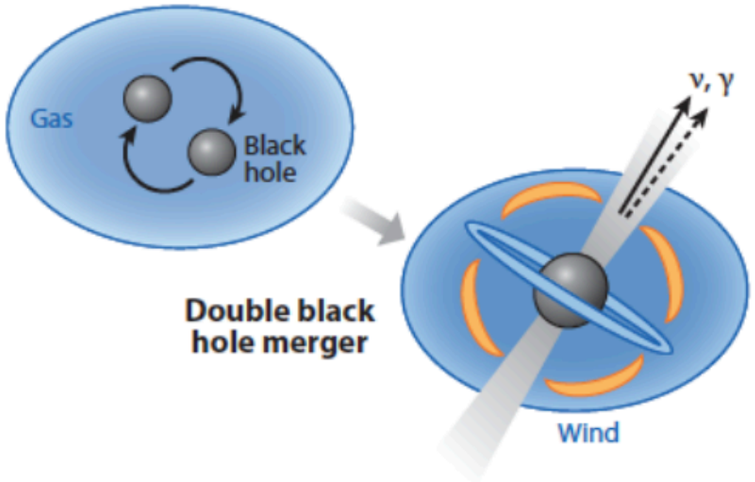


Engine-driven supernova

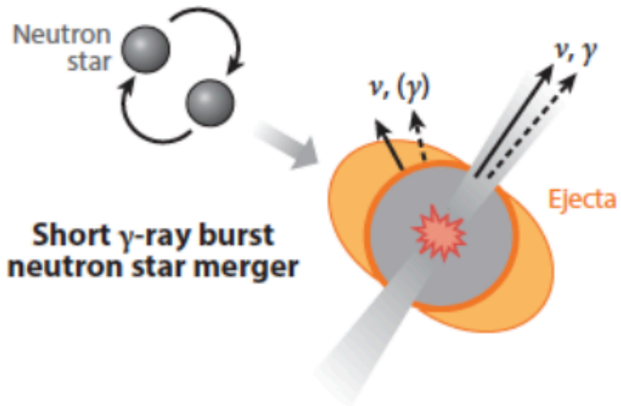


Supernova

massive stellar deaths



Double black hole merger

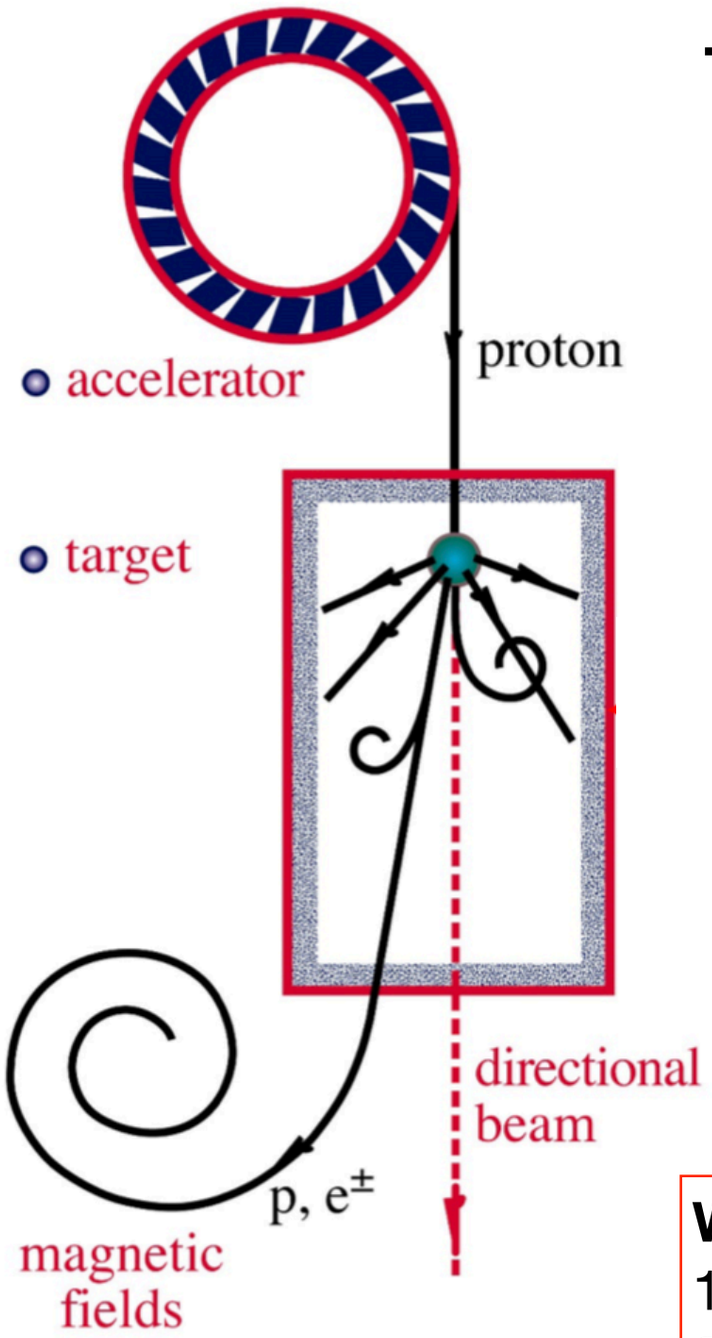


Short γ-ray burst neutron star merger

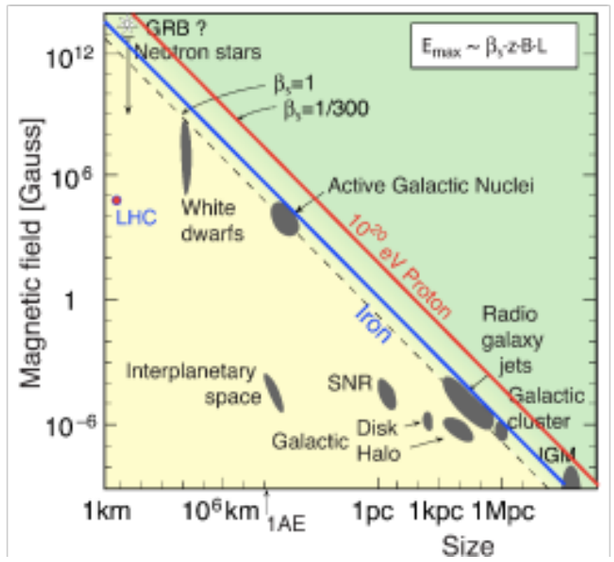
compact mergers (promising GW sources)

(As I am mainly working on transient/variable sources, I will not talk about SNR, PWN, SBG, SFG…)

Potential neutrino sources



To produce neutrino ⟹ CR accelerator & target



Hillas criteria

$p + \gamma \rightarrow \Delta^+$ (For 1-10 PeV → X-ray)

Radiation density (source luminosity, size, geometry)
⟹ But, likely opaque to γ-rays

Natural link: ν / TeV γ-ray / X-ray
But opacity…
Radio: good tracer of jet activity

Why transient sources ?
1. Pointing & timing → reducing atmospheric backgrounds
2. Dominant sources ≠ brightest sources
3. Flares/bursts → more target γ-rays → enhanced ν production

⟹ Good opportunities to find rare bright transients even now

(only need a few neutrinos to get a discovery !)