High-energy neutrinos and multi-messenger astronomy

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PUMA - Sept 26, 2022

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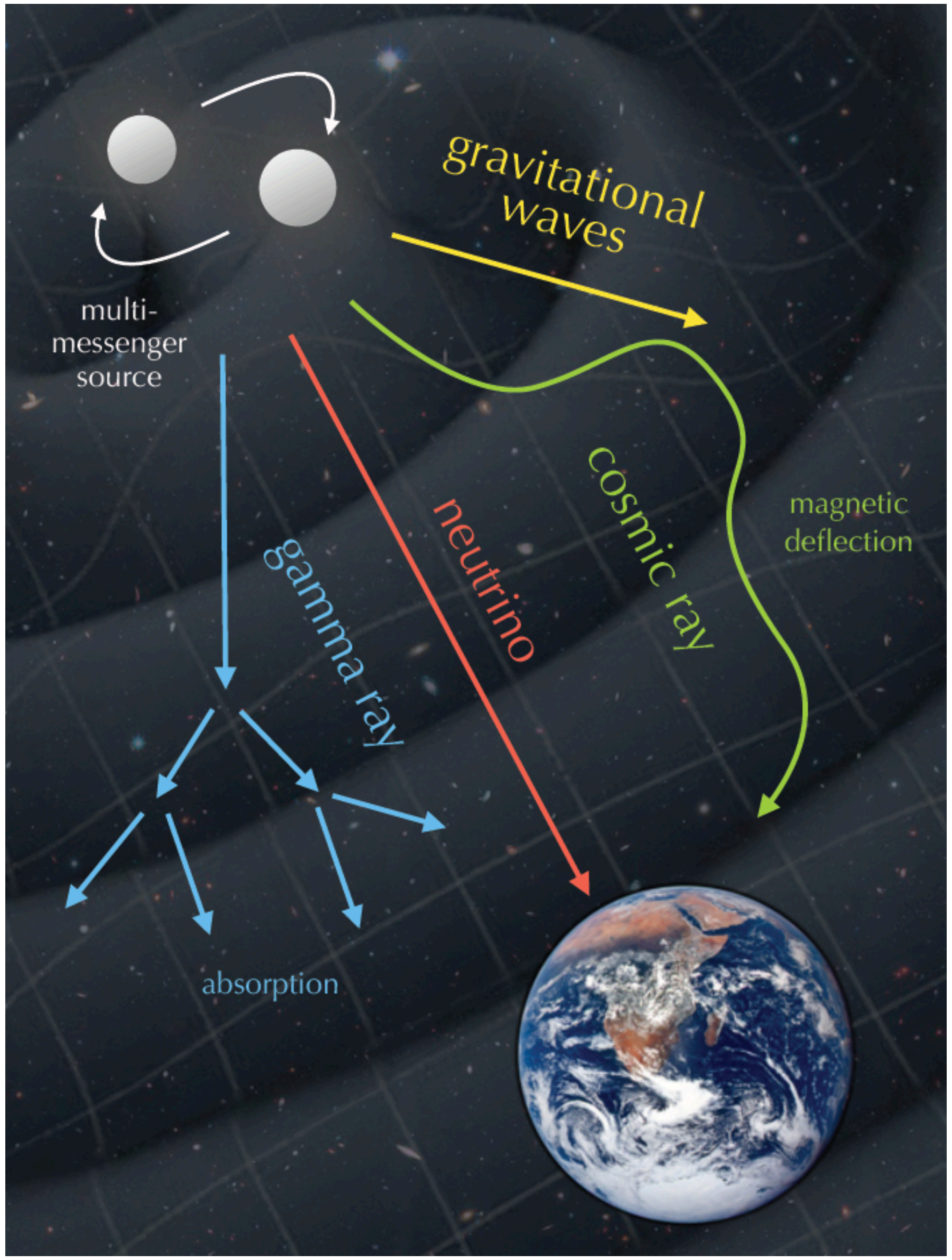
Multi-messenger astronomy

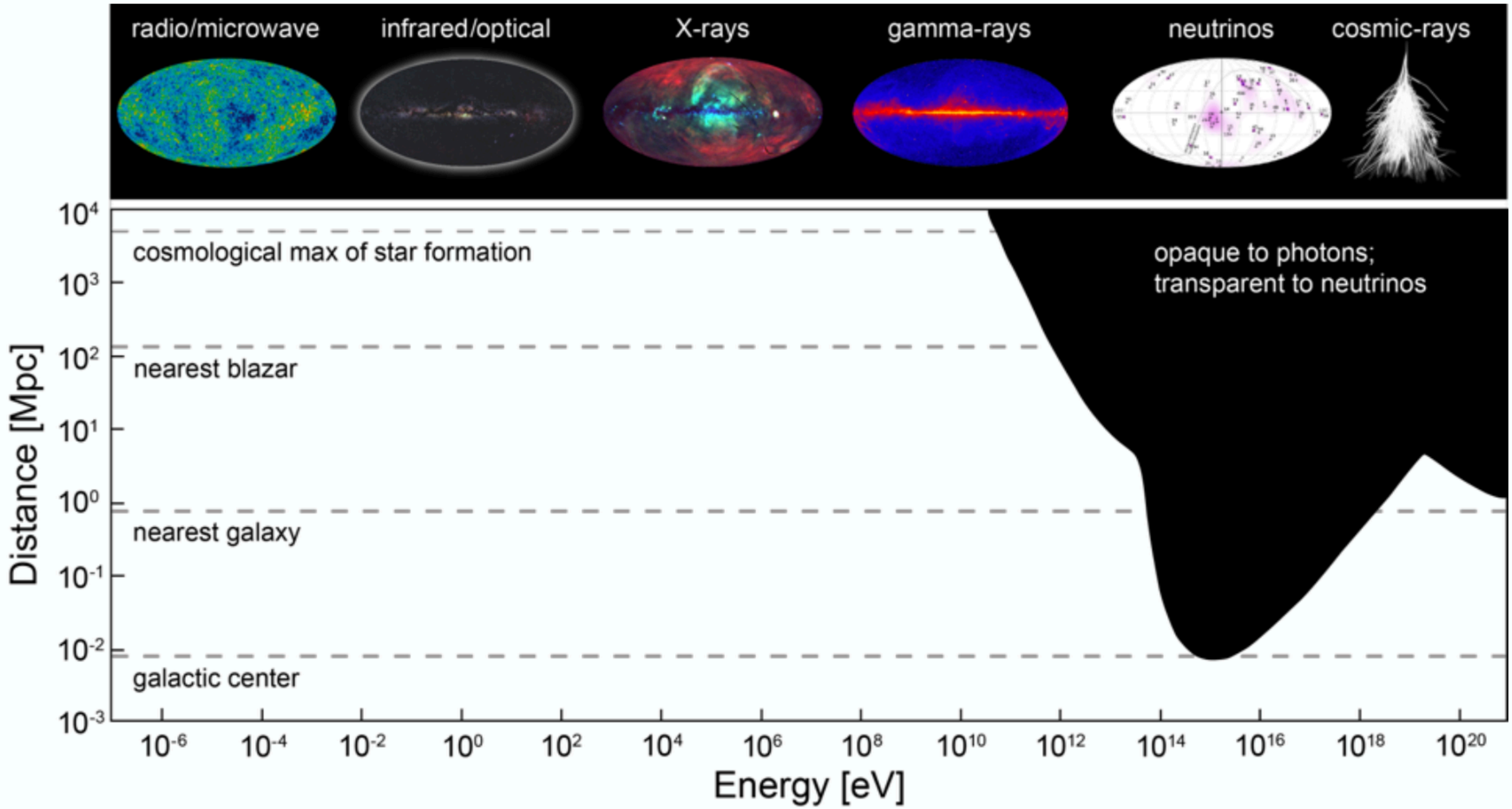


Multi-messenger: use of the 4 messengers to study extreme astrophysical phenomena. Each one bring one piece of the puzzle.

Neutrinos are neutral, weakly-interacting, elementary particles.

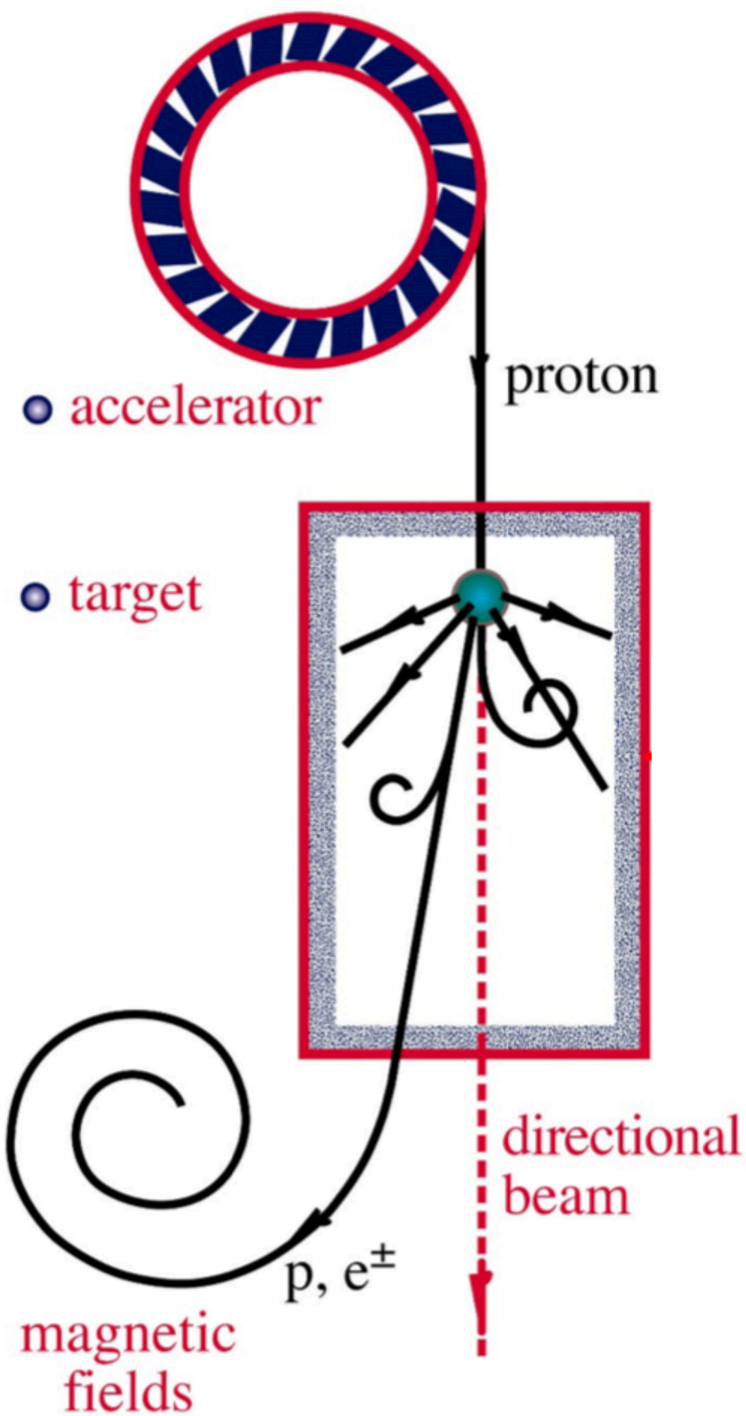
⟹ Smocking gun of the cosmic-ray sources.
⟹ However, finding neutrino sources is still challenging [large background contamination and tiny fluxes]

Promise land

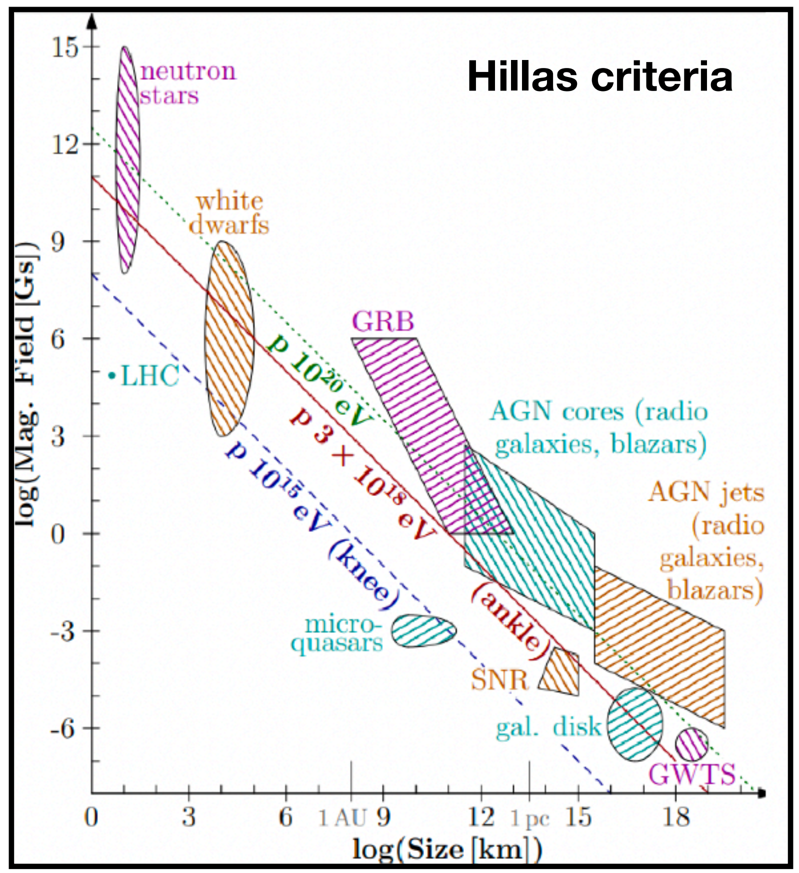


The Universe is opaque to EM radiation for ¼ of the spectrum,
i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

Potential neutrino sources



To produce neutrino ⟹ CR accelerator & target

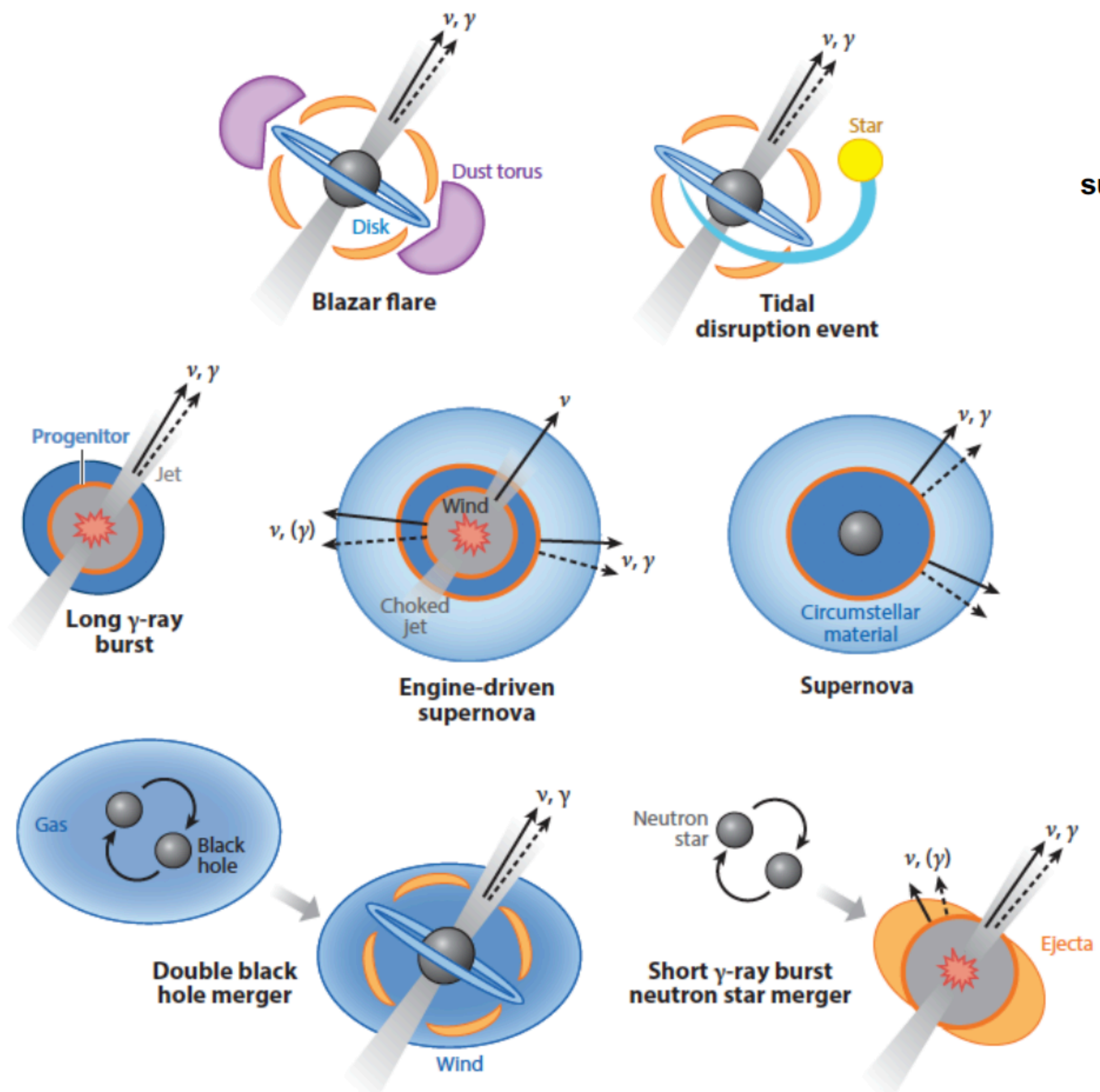


$p + \gamma \rightarrow \Delta^+$ (For 1-10 PeV → X-ray)

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

Potential transient neutrino sources



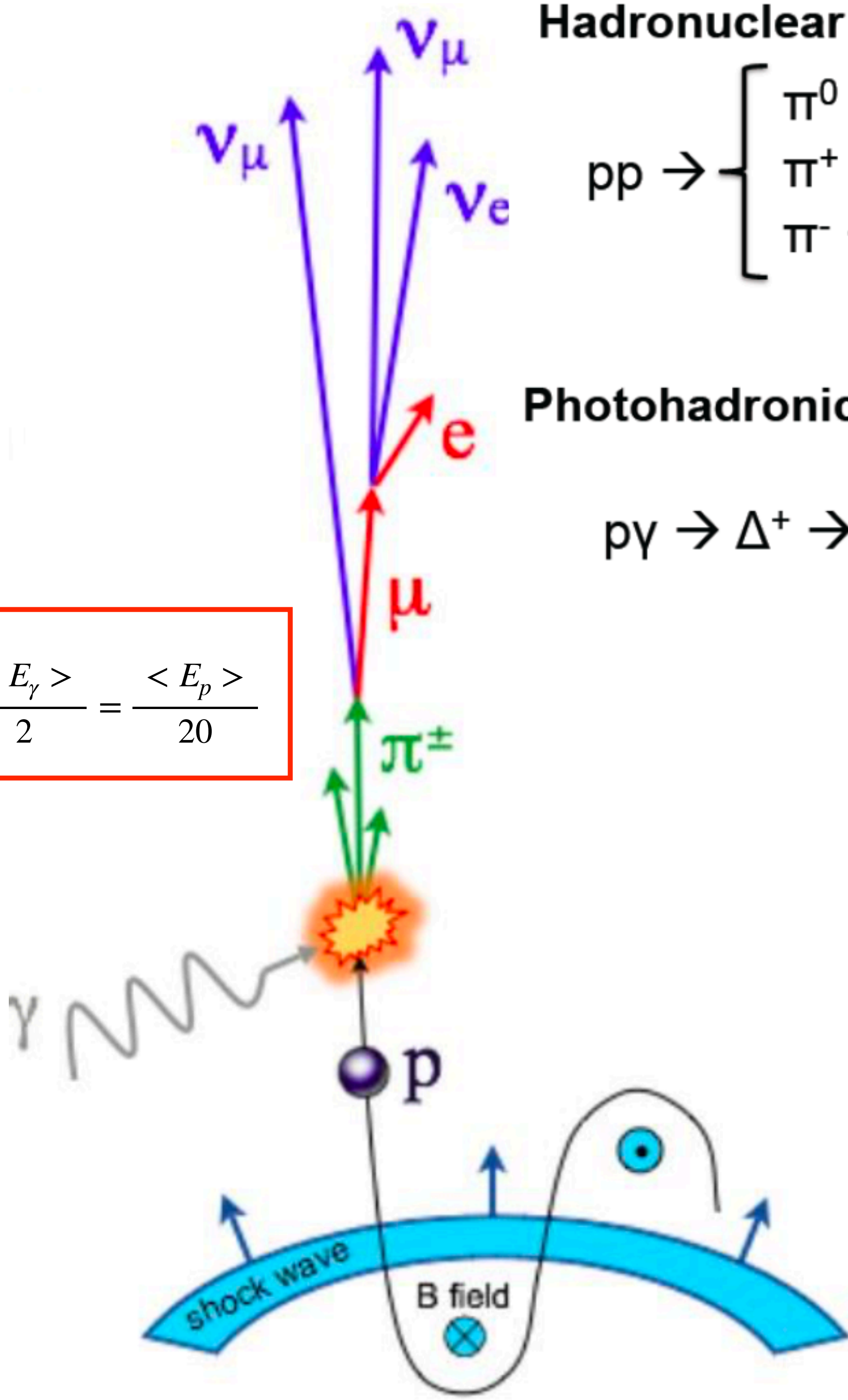
supermassive black holes

massive stellar deaths

compact mergers (promising GW sources)

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

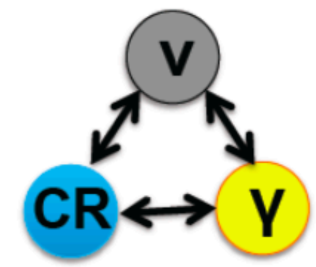
HE neutrino production



$$< E_\nu > = \frac{< E_\gamma >}{2} = \frac{< E_p >}{20}$$

Hadronuclear (e.g. star burst galaxies and galaxy clusters)

$$pp \rightarrow \begin{cases} \pi^0 \rightarrow \gamma\,\gamma \\ \pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \bar{\nu}_\mu \\ \pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \bar{\nu}_\mu \nu_\mu \end{cases}$$



Photohadronic (e.g. gamma-ray bursts, active galactic nuclei)

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\,\pi^0 \rightarrow p\,\gamma\,\gamma \\ n\,\pi^+ \rightarrow n\,\mu^+ \nu_\mu \rightarrow n\,e^+ \nu_e \bar{\nu}_\mu \nu_\mu \end{cases}$$

cosmic ray + gamma

cosmic ray + neutrinos

Neutrino flavour ratio at source:

pion-muon decay

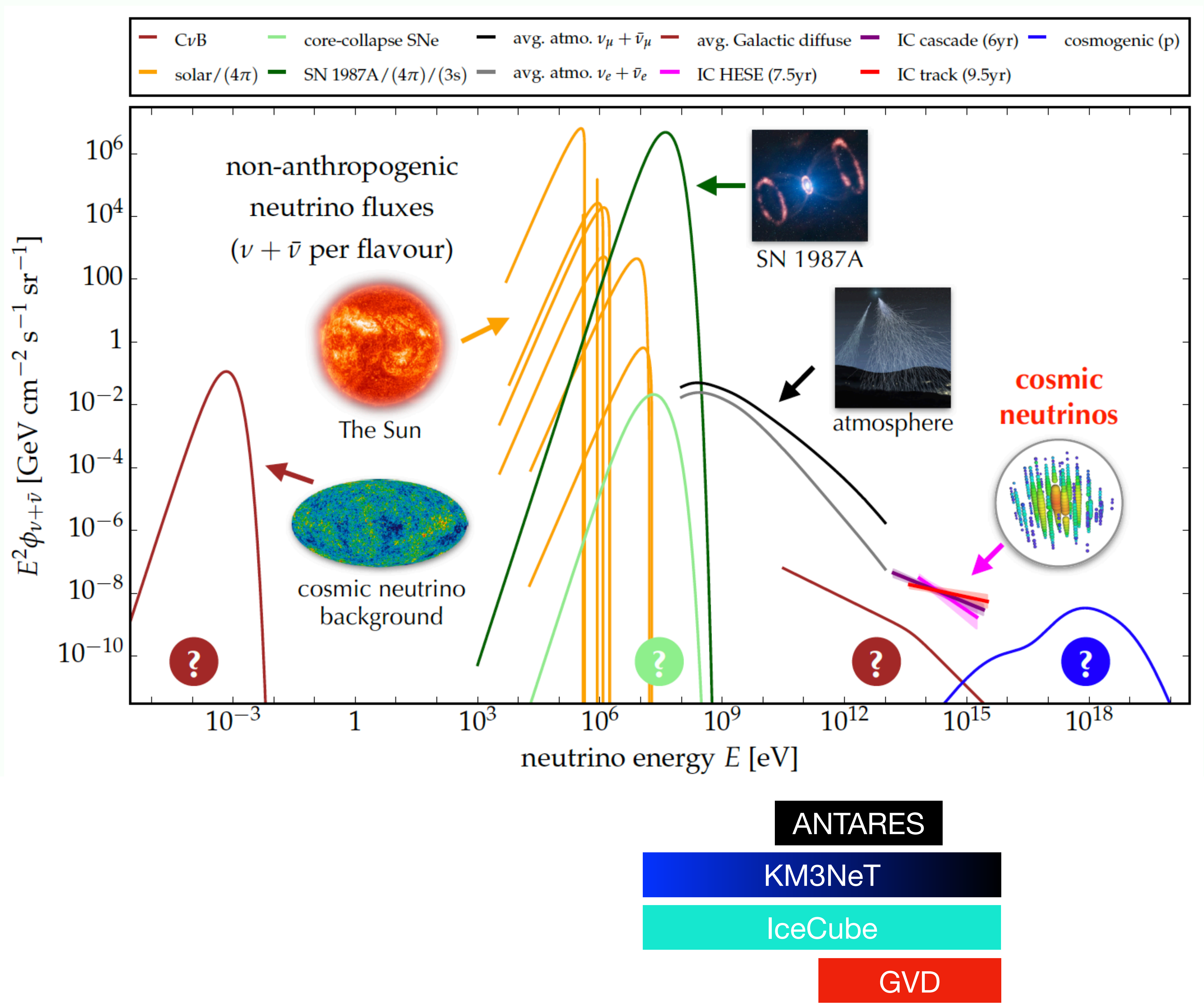
$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 2 : 0$$

Oscillations average out over cosmic baselines

$$\nu_e : \nu_\mu : \nu_\tau \sim 1 : 1 : 1$$

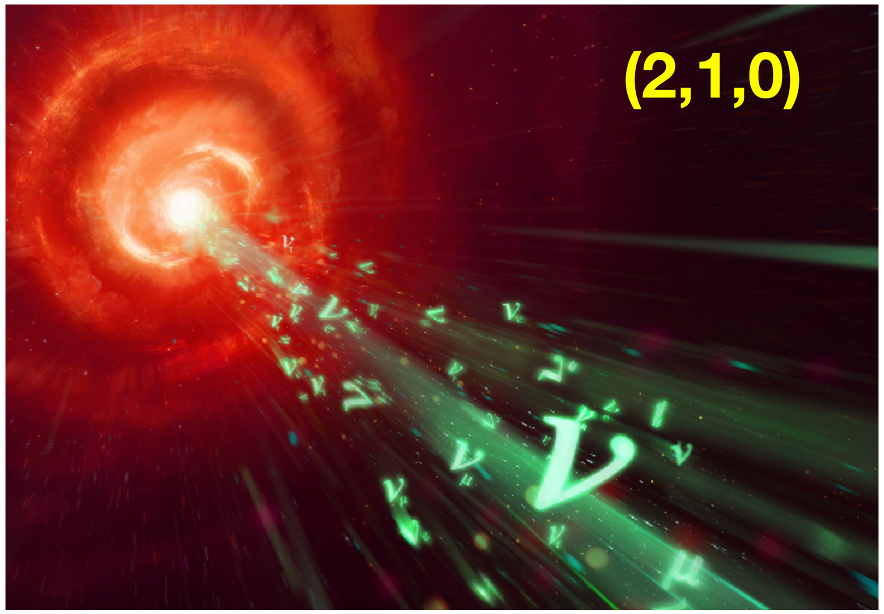
Strong links between CR, γ-ray, ν $\Longrightarrow$ Multi-messenger astronomy

Astrophysical neutrino fluxes



All-flavor neutrino detection

ν_e ν_μ ν_τ

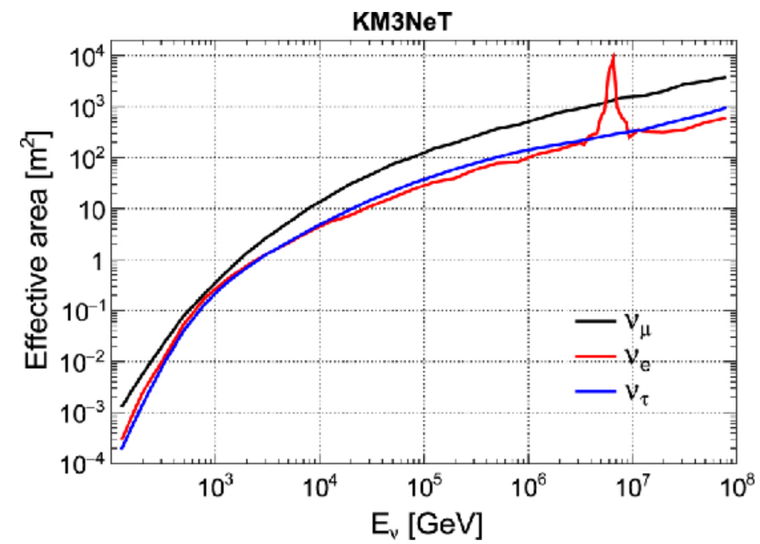


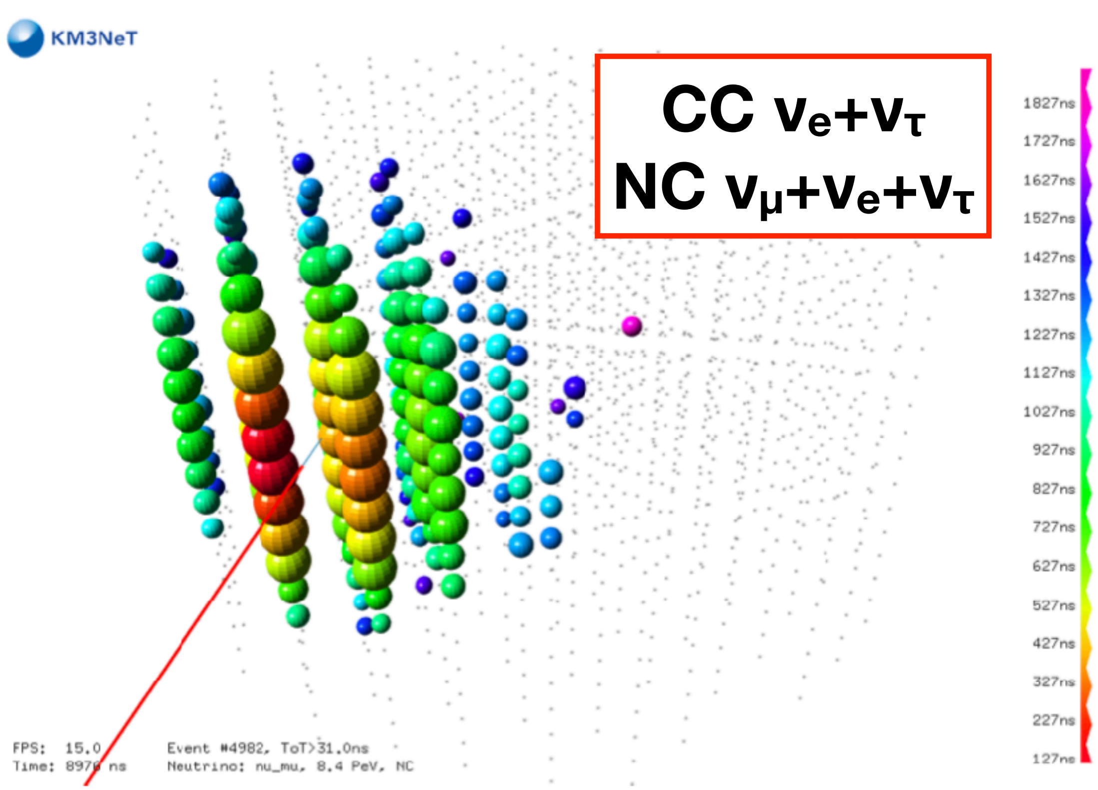
New physics ?

Oscillation

(1,1,1)

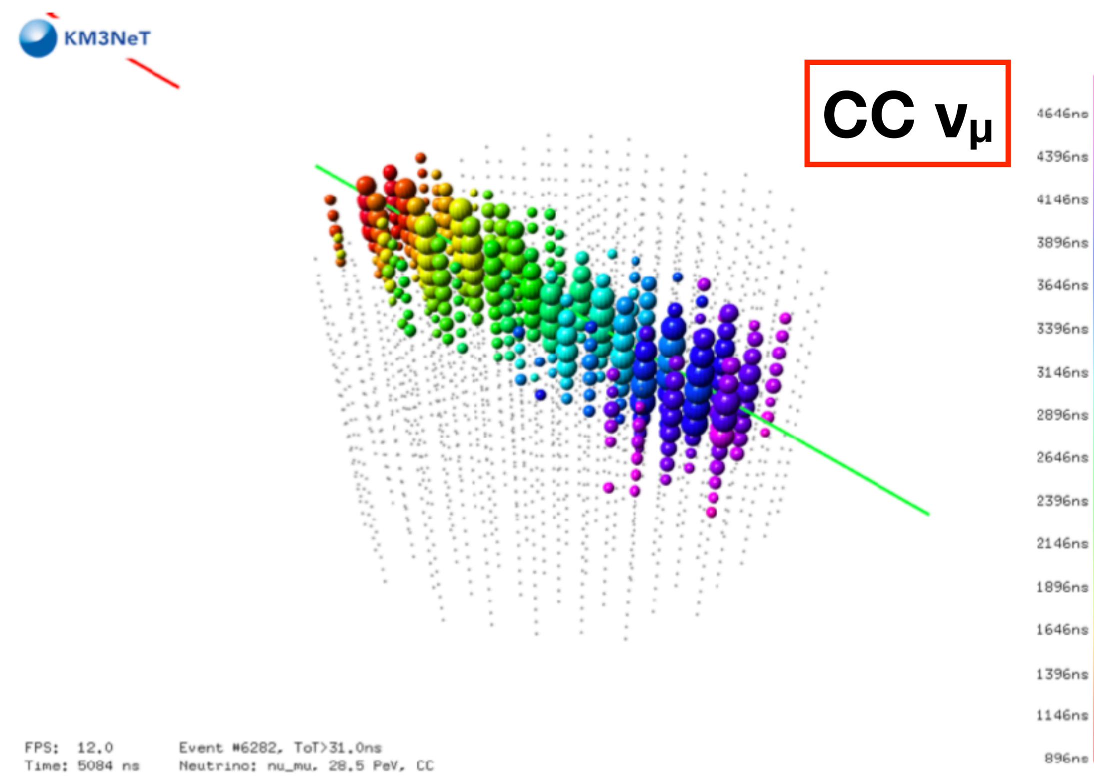
Each neutrino flavor brings information
⟹ All-flavour astronomy





CC $\nu_e+\nu_\tau$
NC $\nu_\mu+\nu_e+\nu_\tau$

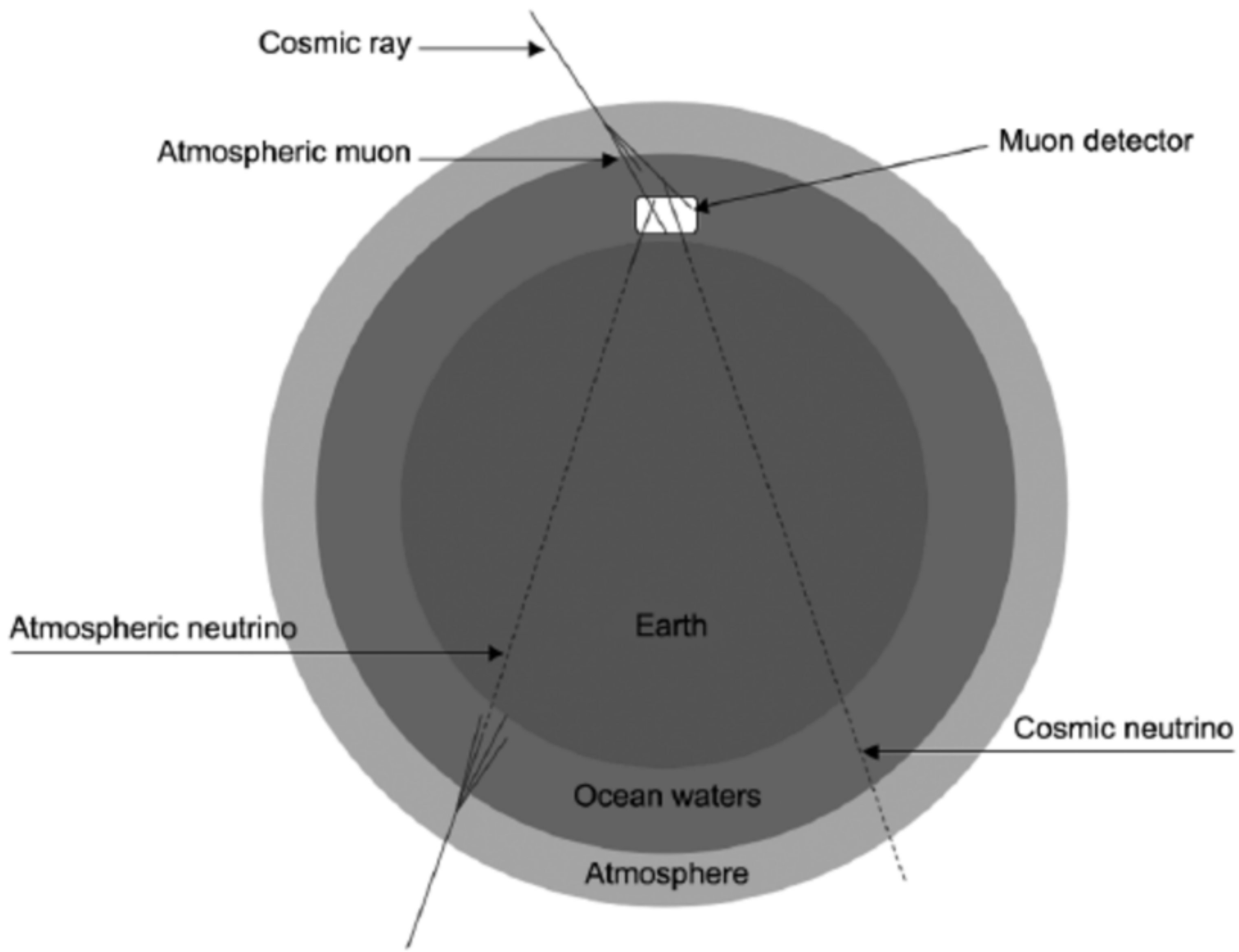
(double cascade for VHE ν_τ)



CC ν_μ

Background dominated @ neutrino Telescope

⟹ **The HE neutrino experiments are background dominated: atmospheric muons, atmospheric neutrinos, optical backgrounds**



In 1 km^3 detector:

μ_{atm} ~ 10^8 - 10^{10} /yr

ν_{atm} ~ 10^5 - 10^6 /yr

ν_{cosmic} ~ 100 - 500 /yr

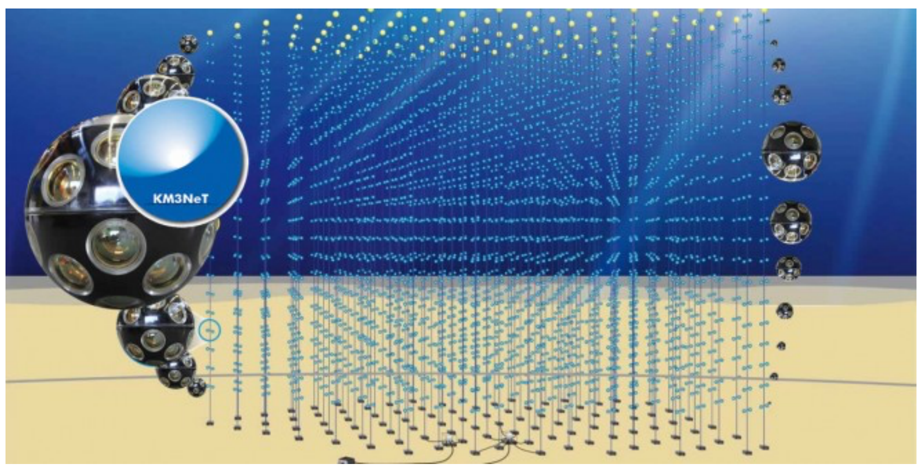
⟹ **Require efficient all-sky event reconstruction, VETO, drastic event selection**

Neutrino panorama

Precision Frontier

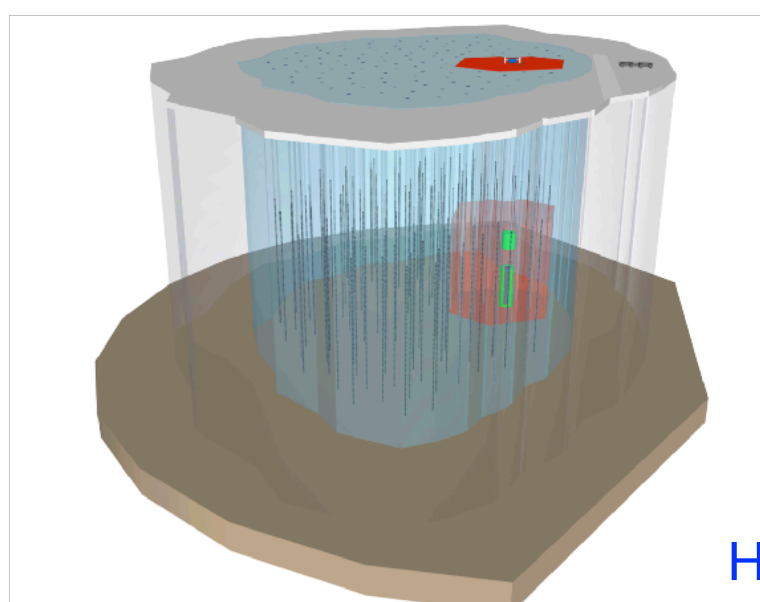
Intensity Frontier

Energy Frontier



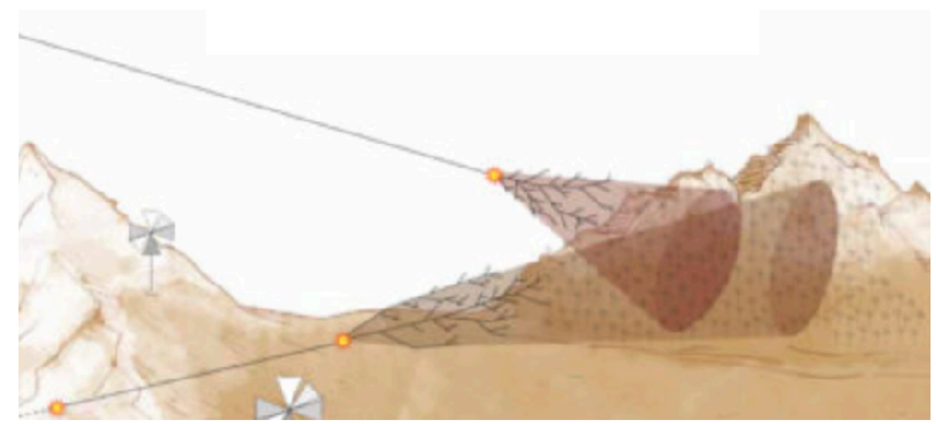
KM3NeT, GVD

Having the best angular resolution with a reasonable instrumented volume



IceCube Gen2

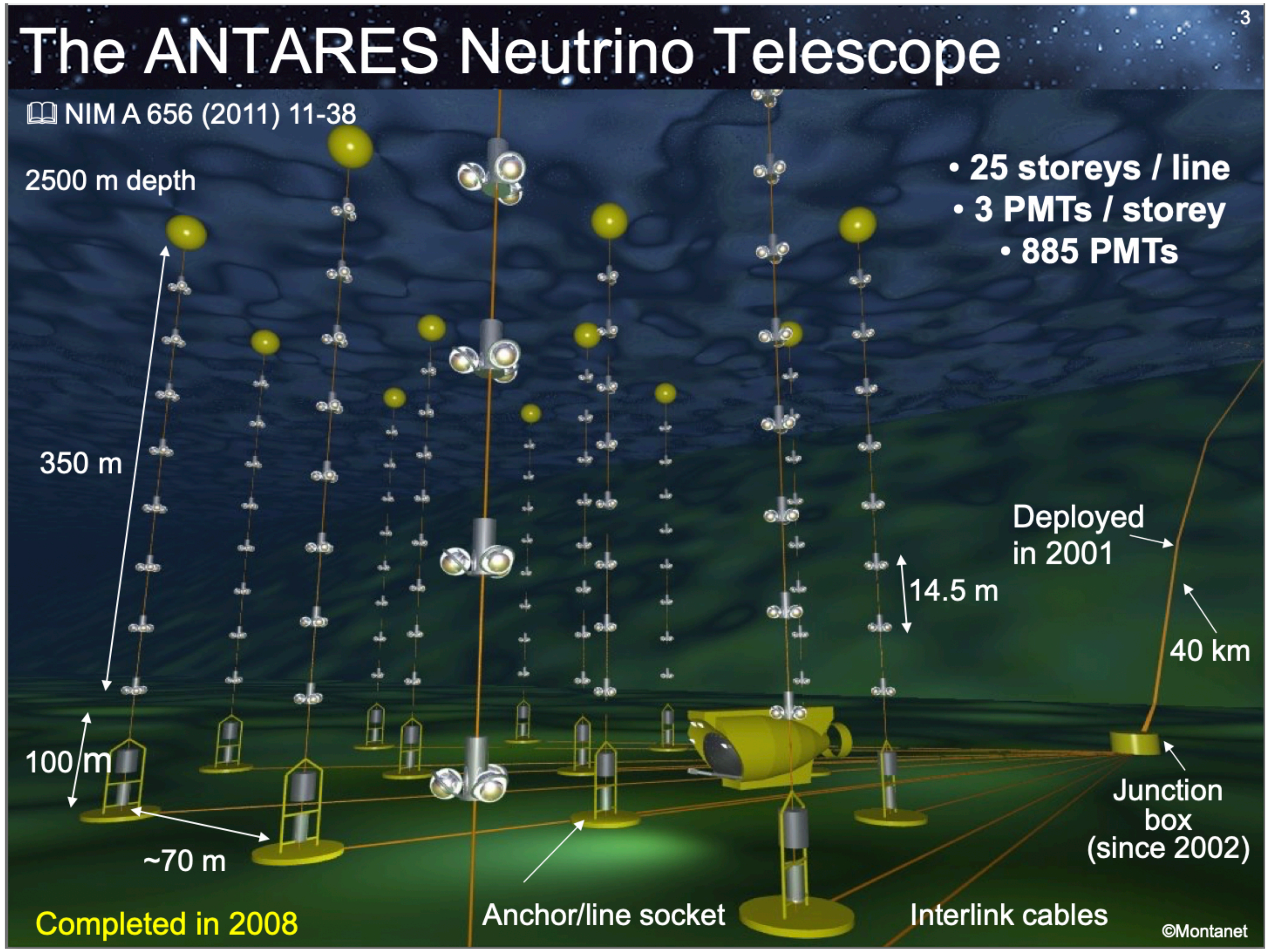
Having the largest statistics with reasonable precision



GRAND, ARA, ARIANNA, POEMMA

Tracking cosmogenic ν at UHE

End of the ANTARES adventure



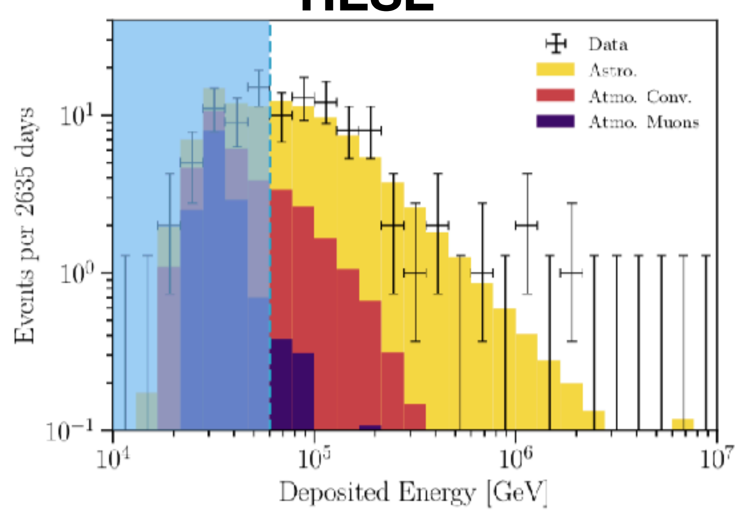
⟹ **ANTARES: continuous data-taking between 2007-2022 with very high efficiencies**
⟹ **ANTARES has been switch off in Feb 2022 and full recovery of the materials in June 2022.**
⟹ **Very competitive physics results. Legacy analyses still in progress. All the data will become public soon.**
⟹ **KM3NeT adventure**

HE ν diffuse fluxes detected

IceCube 7-10 yrs

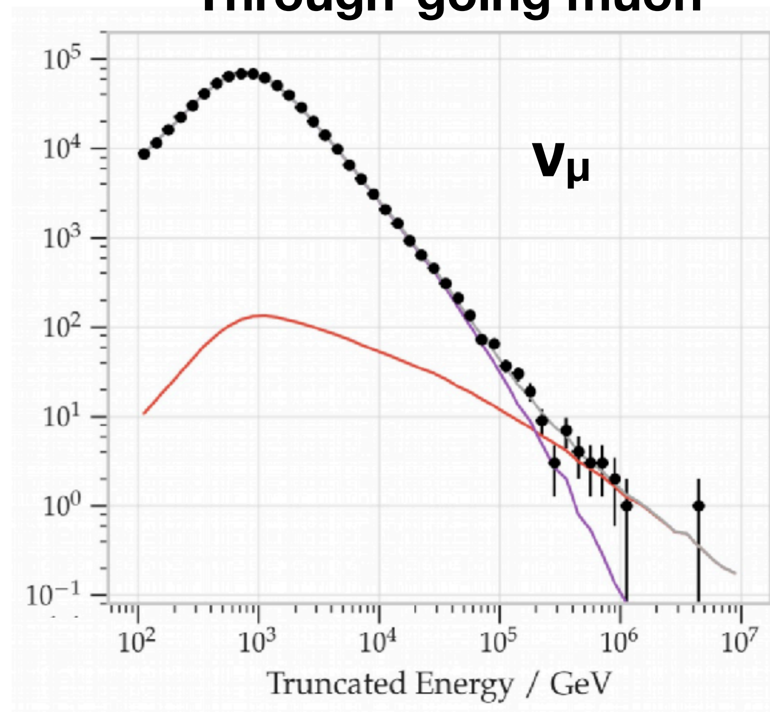
ANTARES 11 yrs

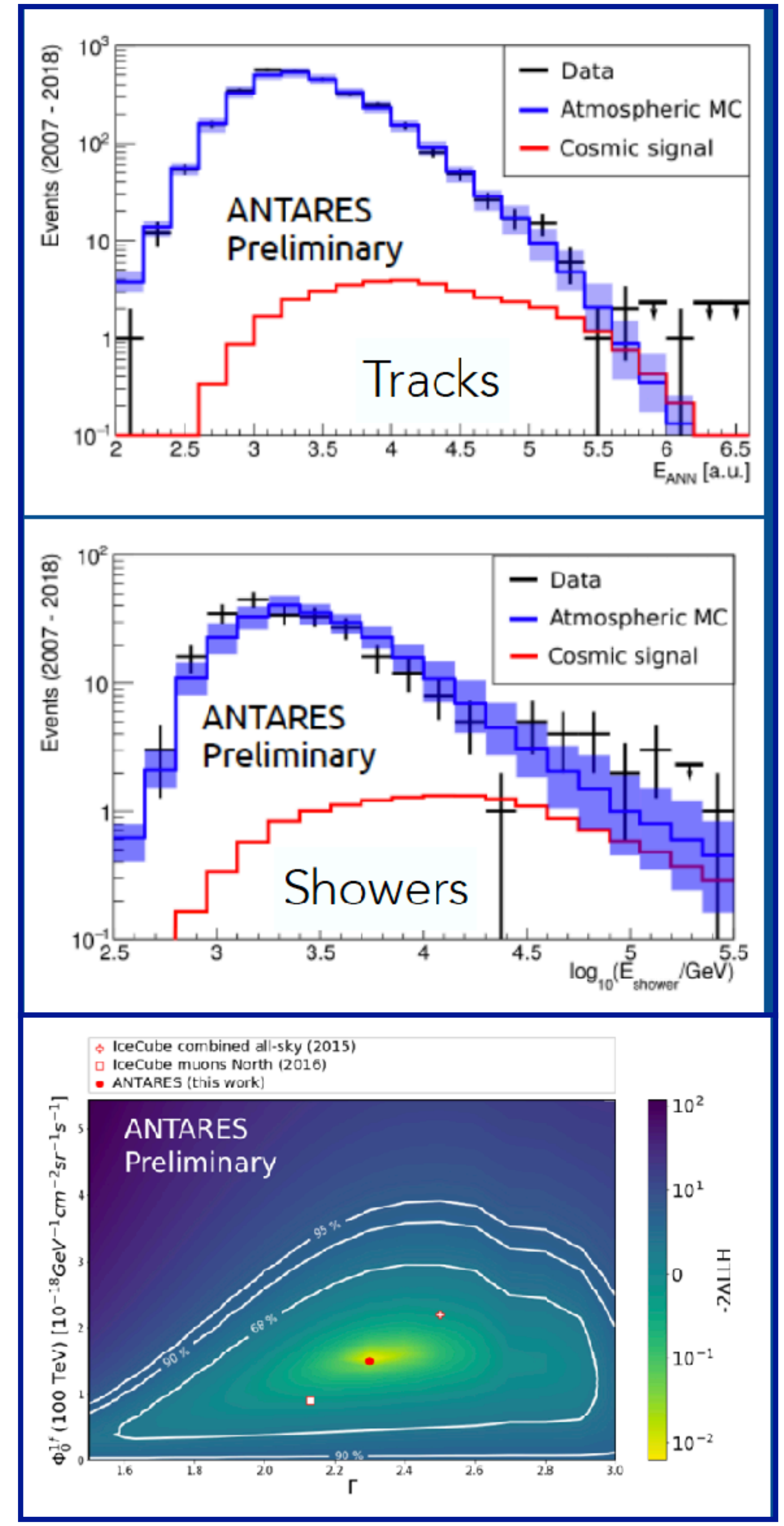
HESE



arXiv:2011.03545

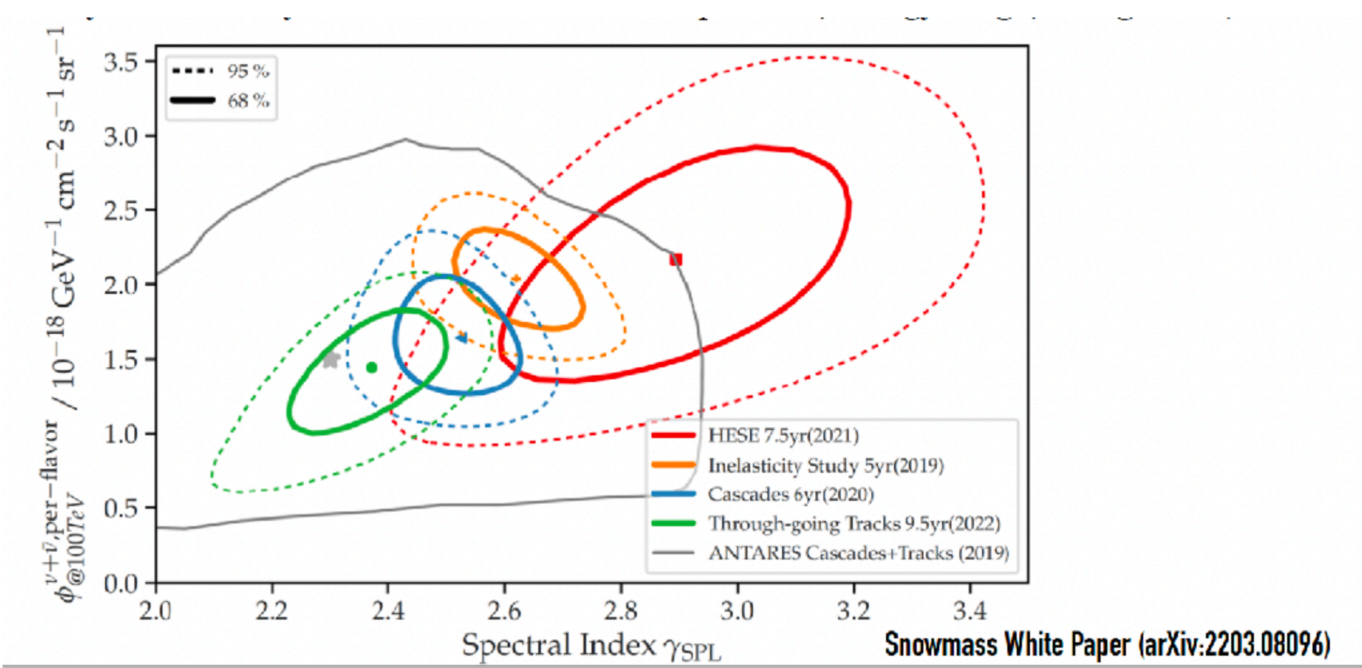
Through-going muon





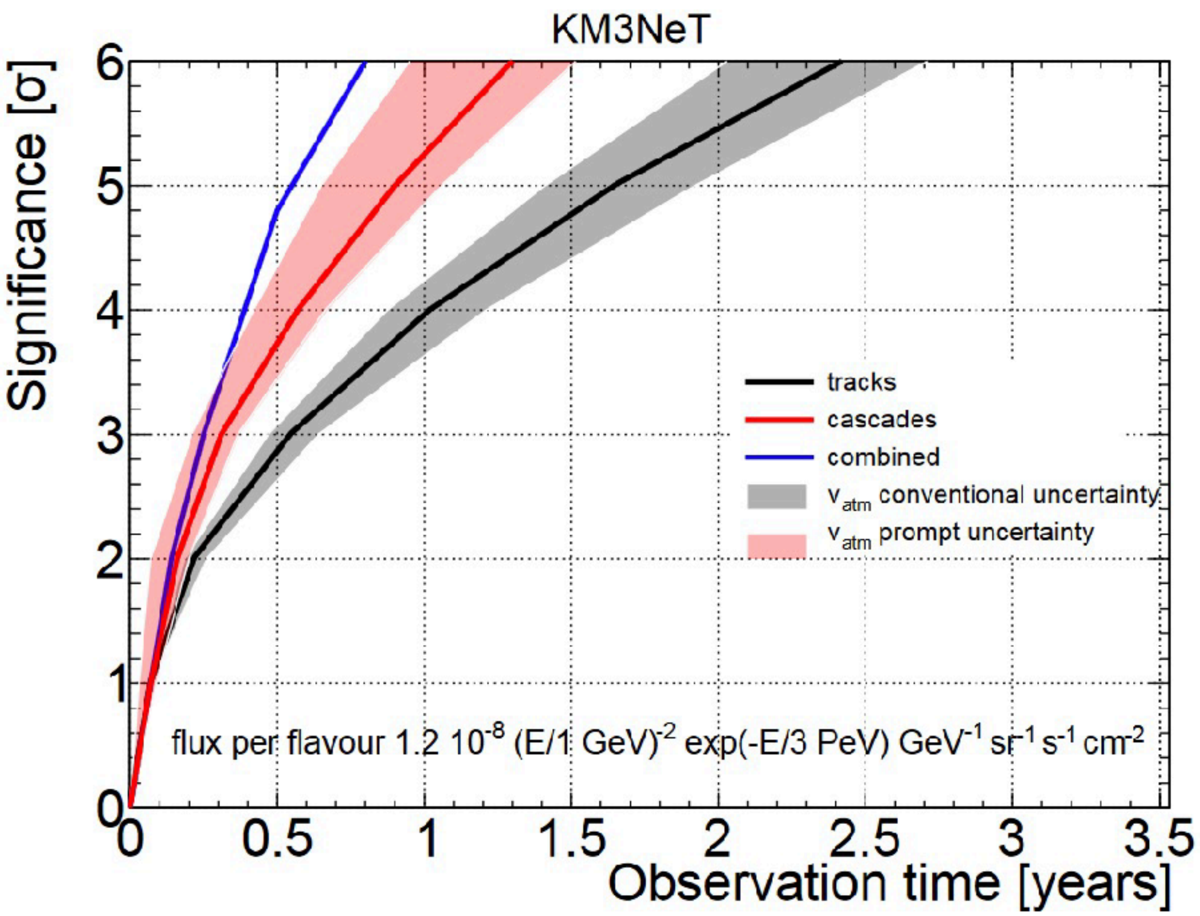
PoS(ICRC2021)1126

GVD is also seen this flux at 3σ



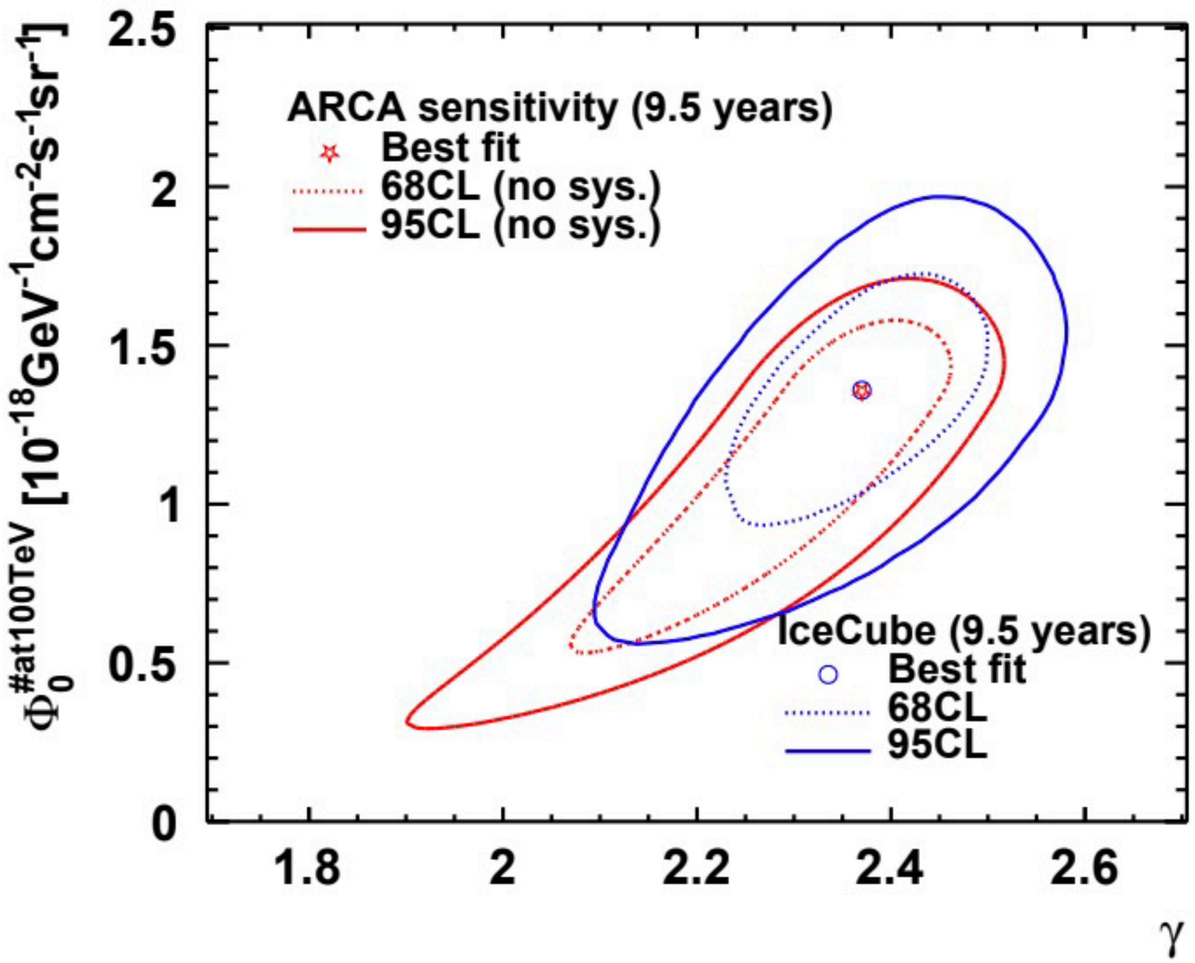
Snowmass White Paper (arXiv:2203.08096)

HE ν diffuse fluxes with KM3NeT



Detectability of the HE flux (benchmark IC flux)

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



PoS(ICRC2021)1077

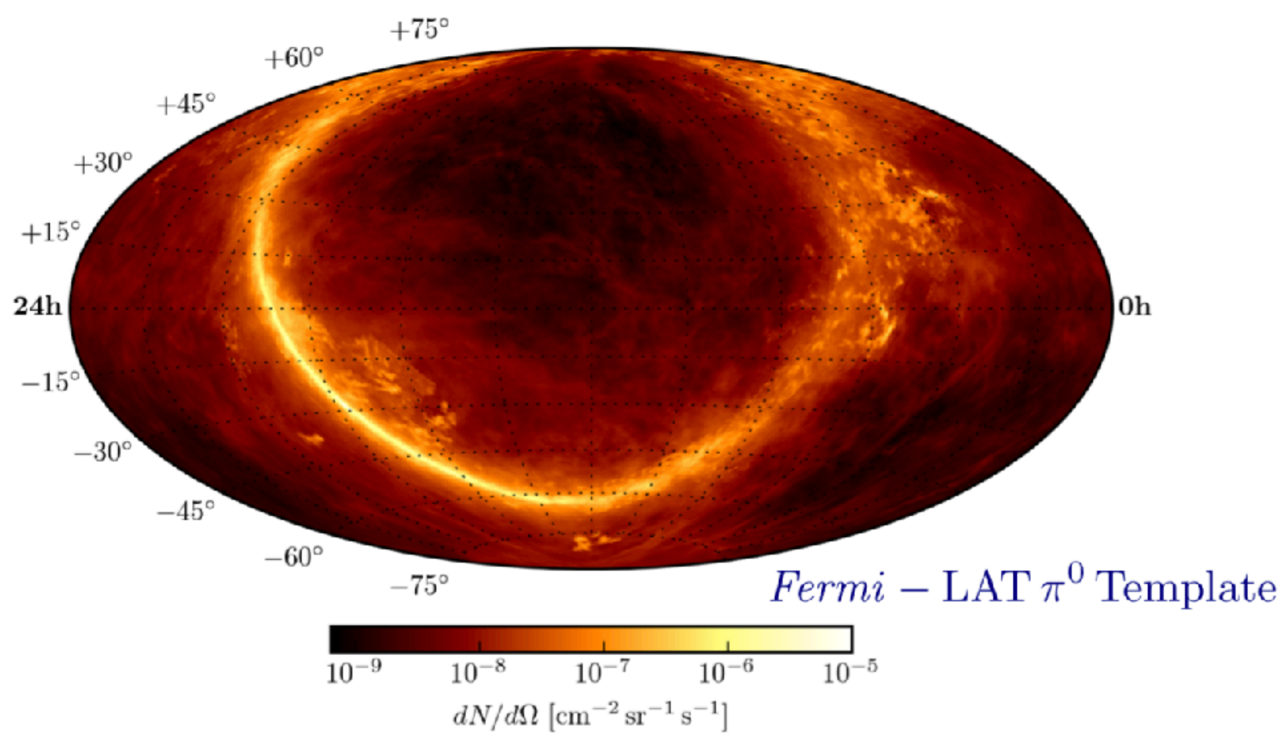
Where is the galactic diffuse component ?

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)

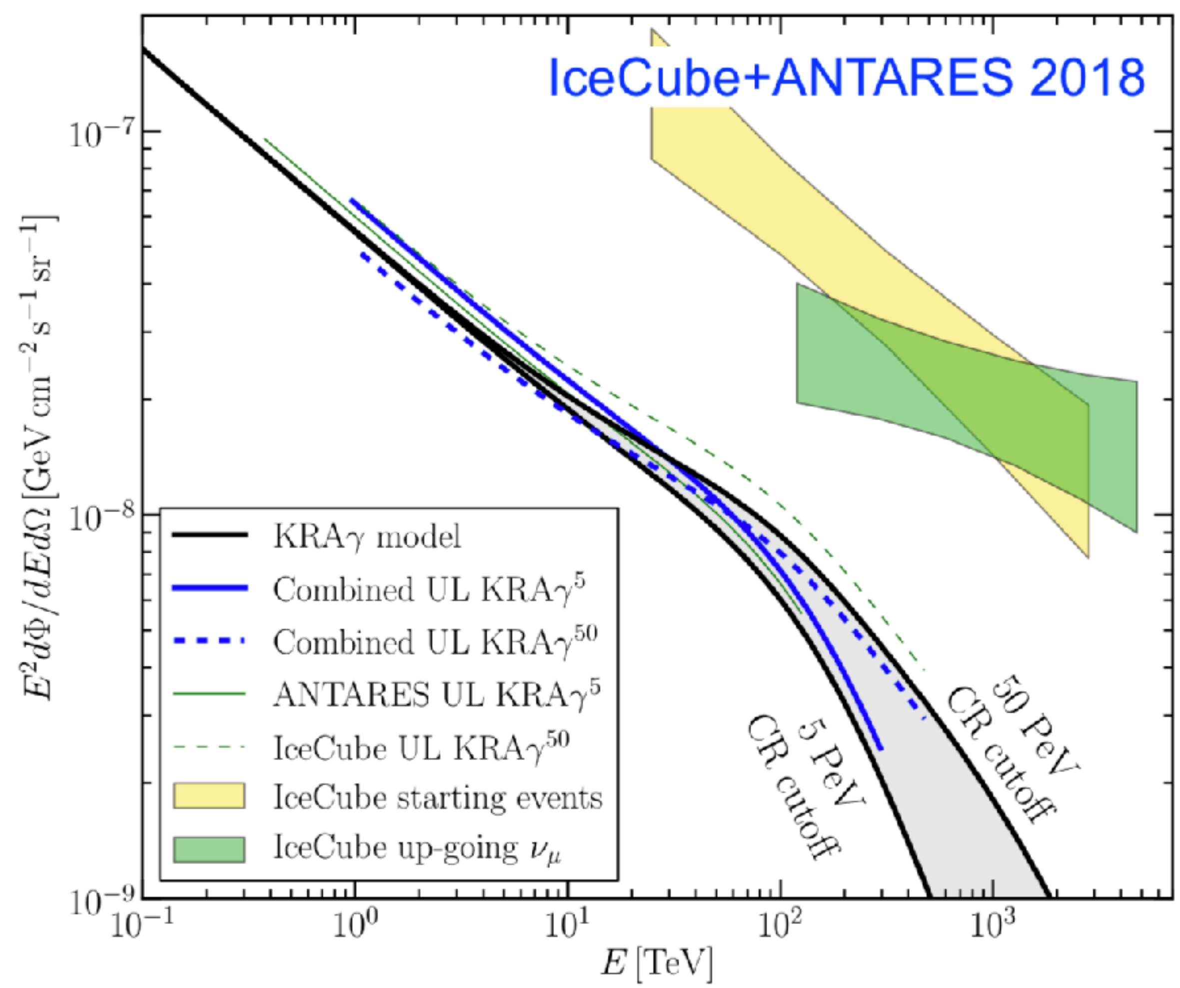
⟹ **Galactic contribution constrained at the level of ~10% of the diffuse flux**

⟹ **But models have large uncertainties above 10 TeV**

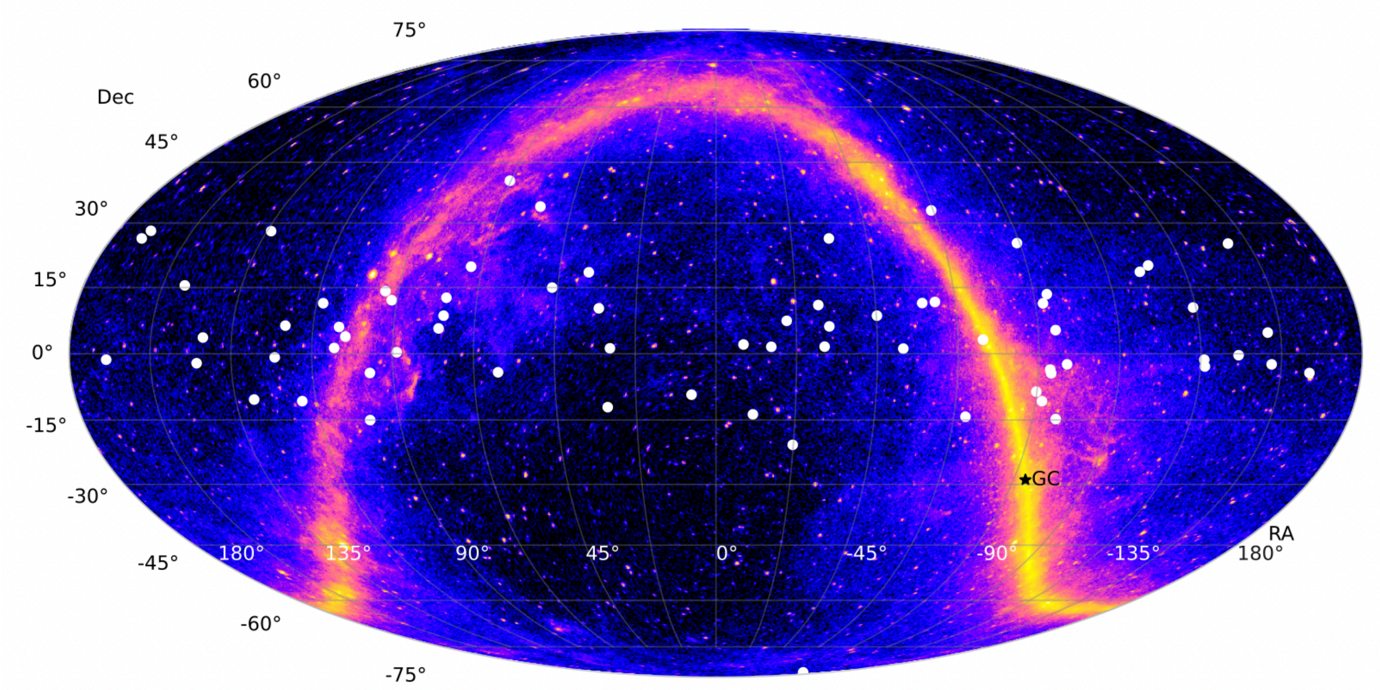
⟹ **KM3NeT can test all the conventional models**



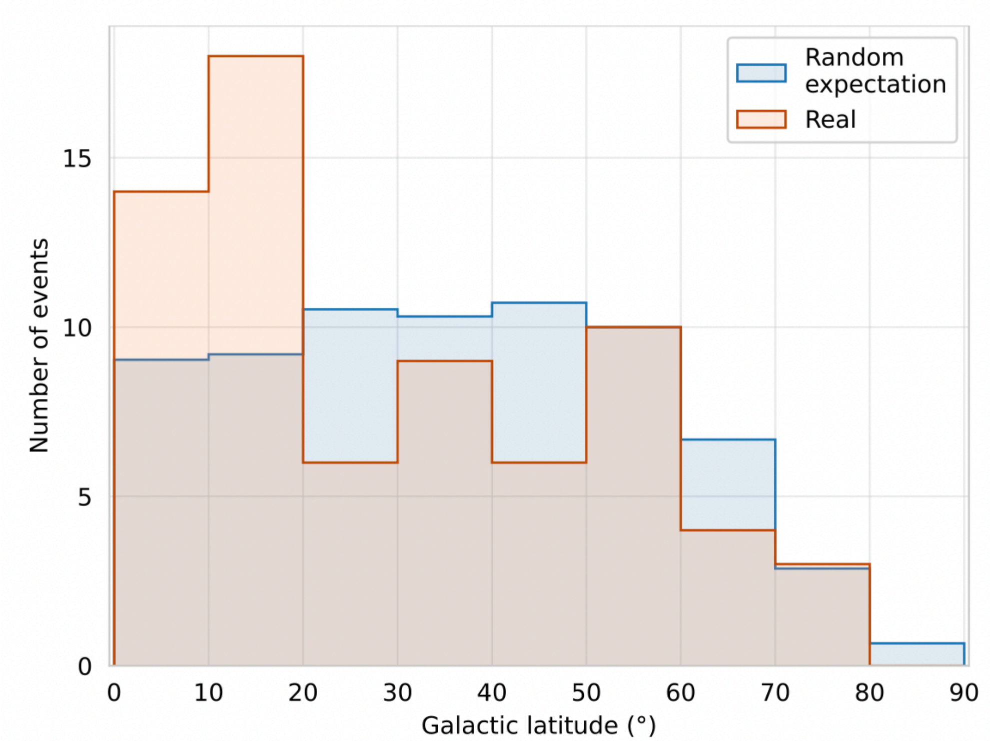
Energy cutoff	Sensitivity [Φ_{KRA_γ}]			Fitted flux	p-value	UL at 90% CL
	Combined	ANTARES	IceCube	[Φ_{KRA_γ}]	[%]	[Φ_{KRA_γ}]
5 PeV	0.81	1.21	1.14	0.47	29	1.19
50 PeV	0.57	0.94	0.82	0.37	26	0.90

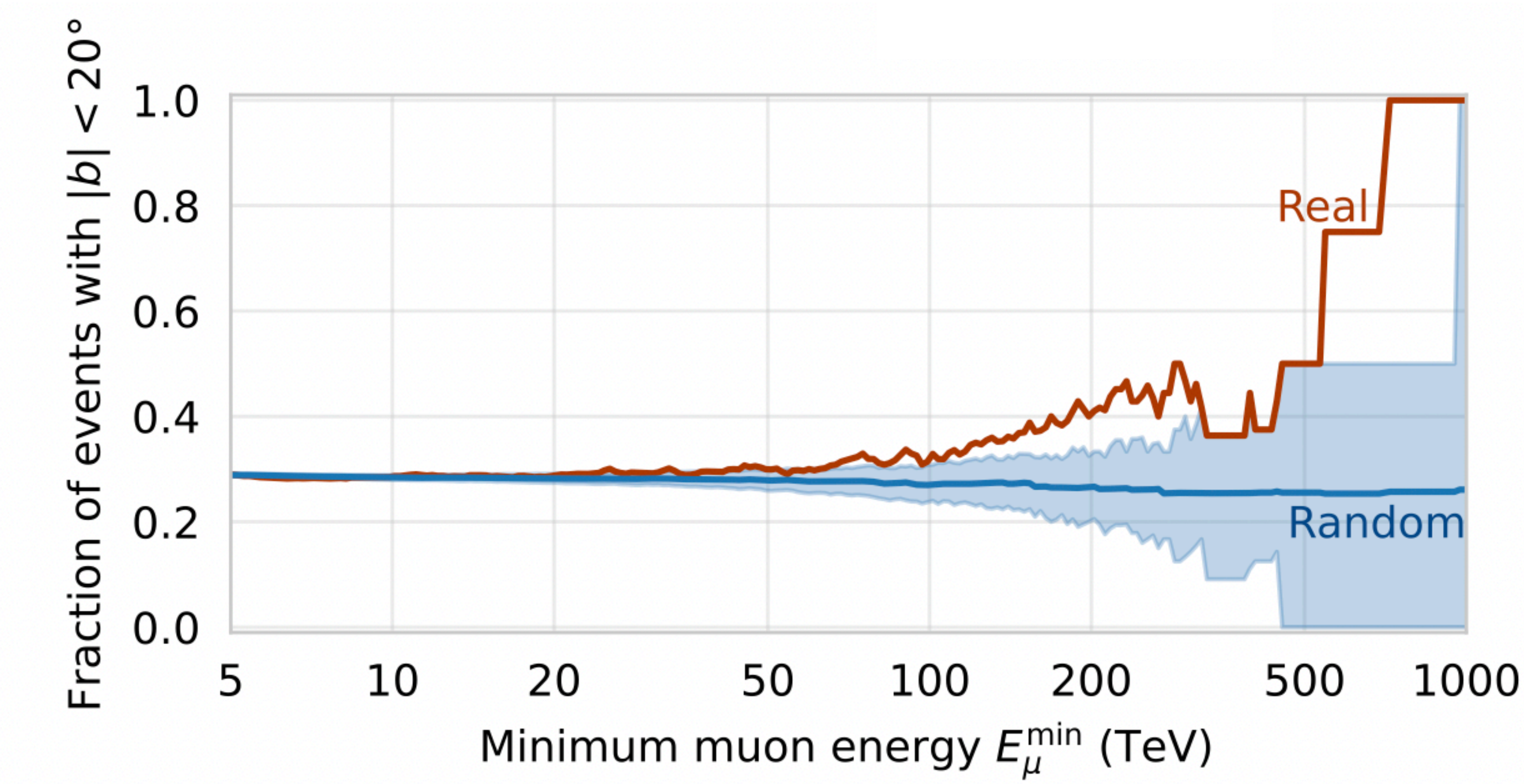


Where is the galactic diffuse component ?



Very interesting correlation between the Galactic plane and IceCube public events above 200 TeV (4.1 σ) and the normalisation of the flux consistent with the prediction of the gamma-ray flux detected by Tibet above 100 TeV





Kovalev, Plavin, Troitsky, arXiv:2208.08423 (2022)

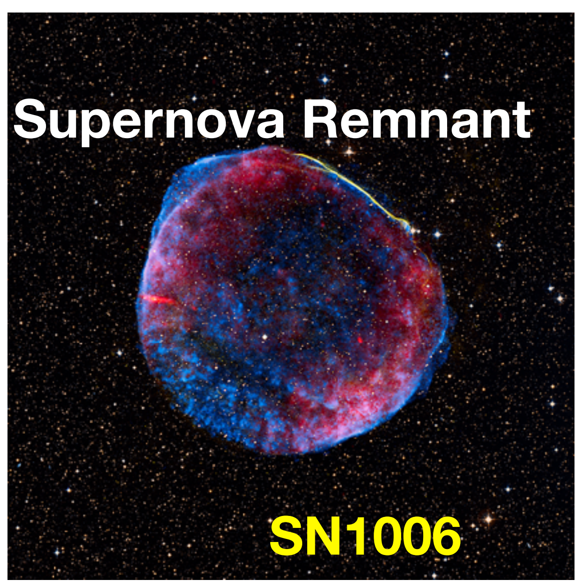
So far, no evidence for a galactic neutrino source

VHE γ-ray observations as a potential guide

- Supernova Remnants, Pulsar Wind Nebulae, Binaries, Nova, ….
- IACTs and ground arrays have reported more than hundreds of Galactic sources
- LHAASO report gamma rays with up to PeV range

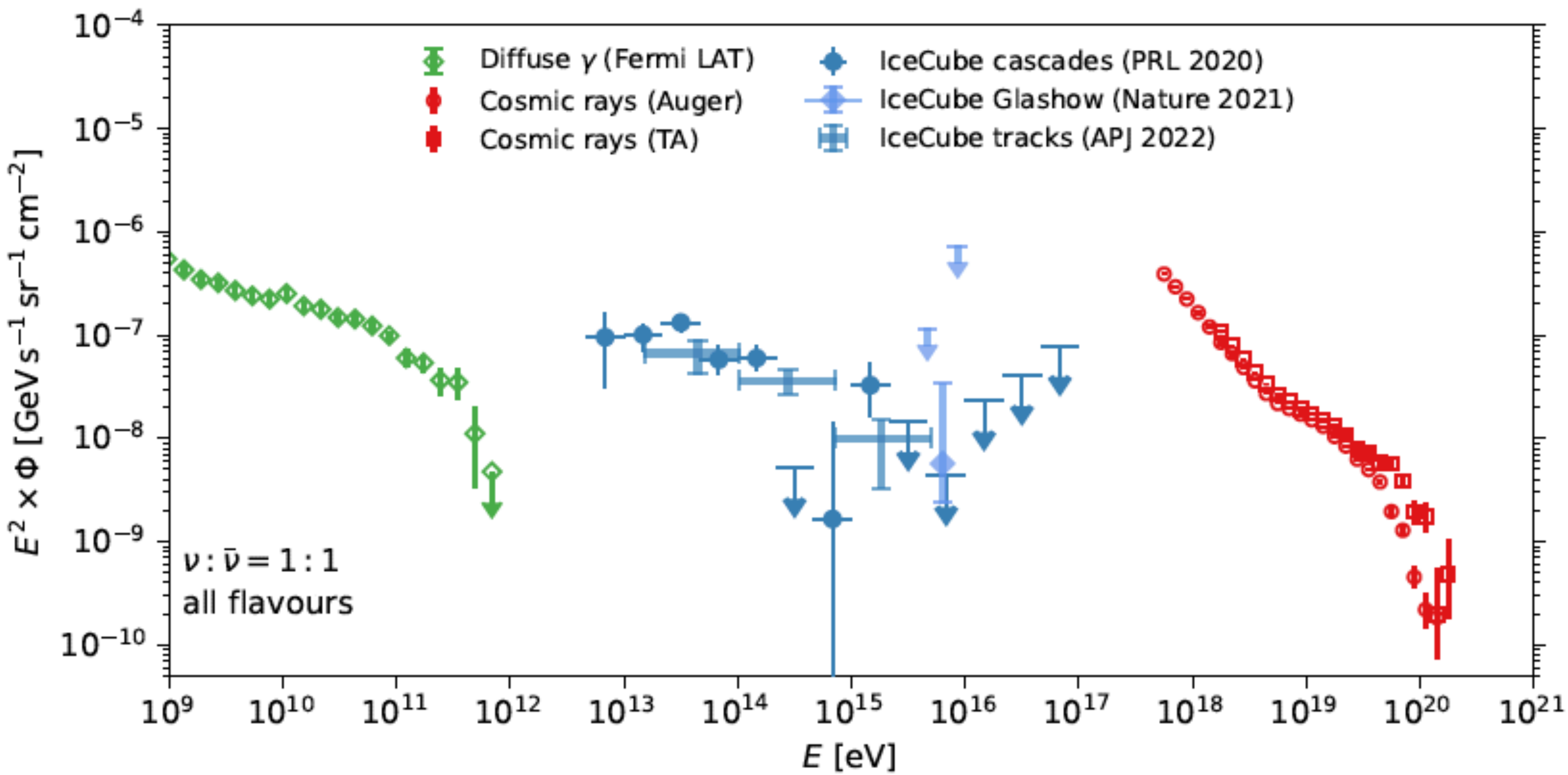
⟹ **Emission measured from many γ-ray sources is leptonic-dominated but there are hadronic components (IC443, W51, RXJ1713 (?)…)**

⟹ **Need to wait for 1st neutrino measurement. KM3NeT/GVD are well located to do so.**



Multi-messenger context

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

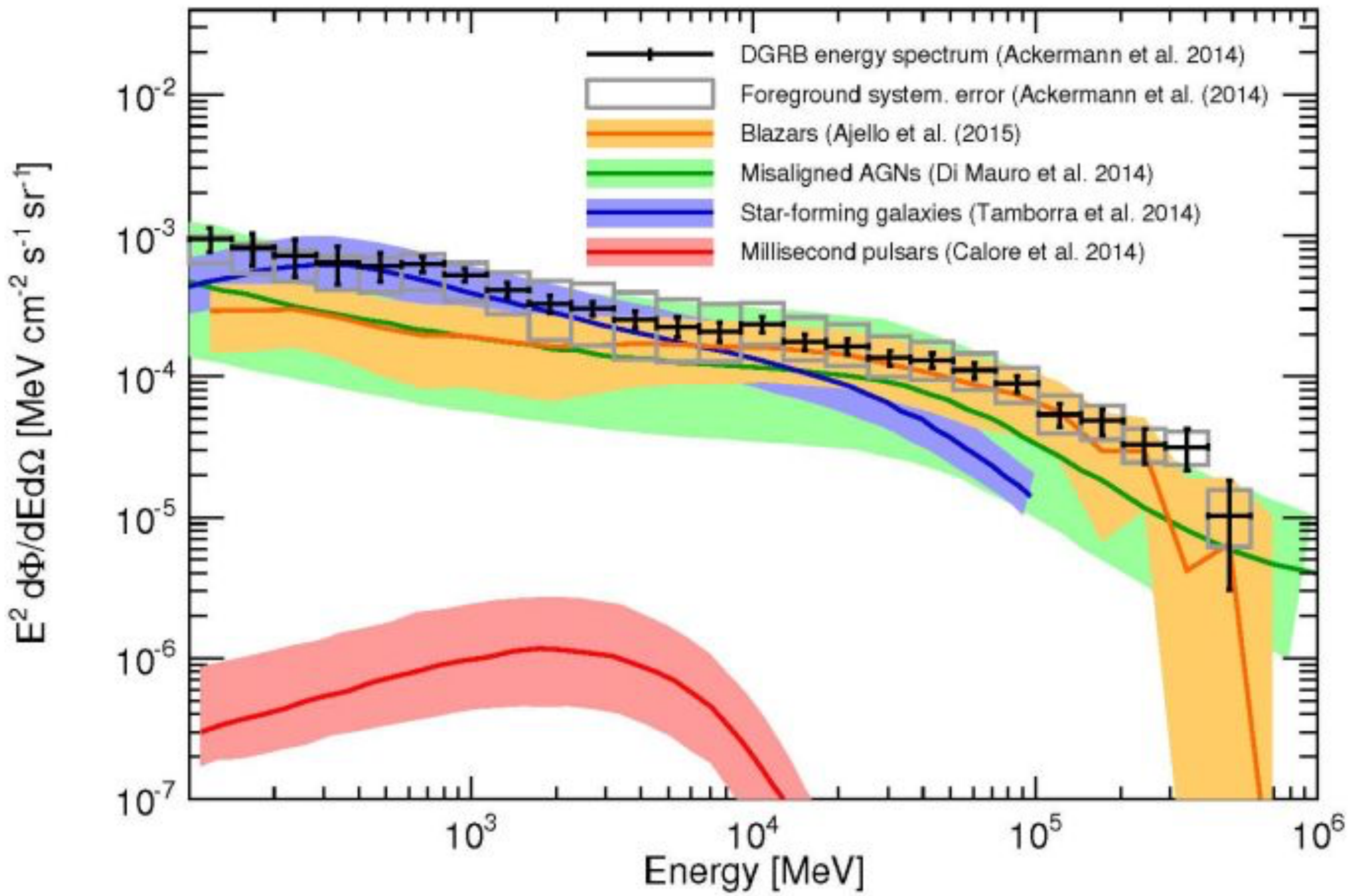


⟹ The comparable energy content of these three fluxes is of particular interest in the investigation of cosmic-ray origin despite their different energy ranges

⟹ Common sources ? Common production mechanism ?

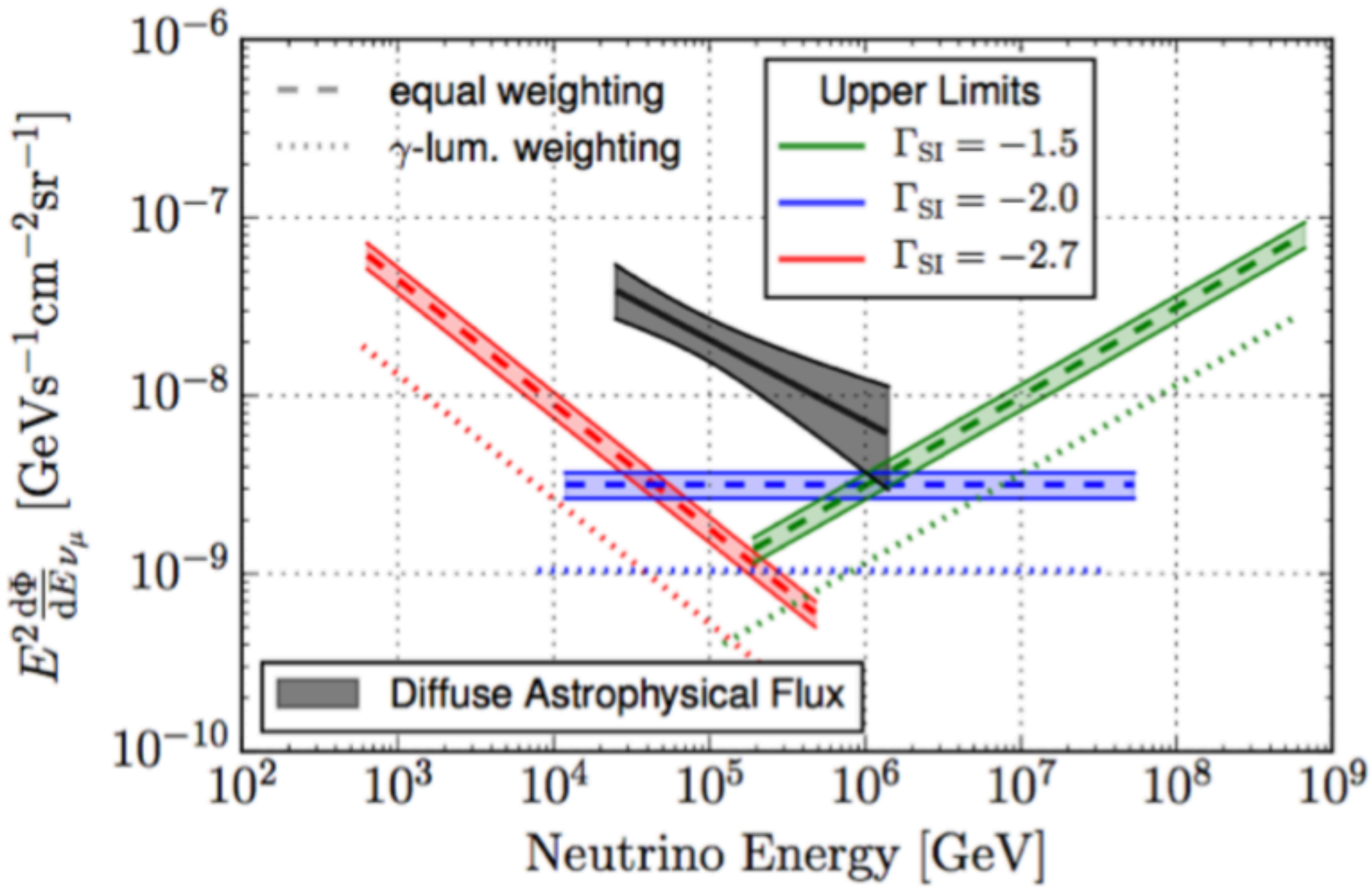
Isotropic Gamma-ray background

⟹ **The extragalactic HE sky is largely dominated by the AGN emission that are among the most powerful emitters of electromagnetic radiation in the Universe.**



⟹ **That's why AGNs have been always proposed as candidate sources of CRs. In particular, blazars account for ~80-85%**

Source population studies



IceCube Coll. ApJ 835 (2017)

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

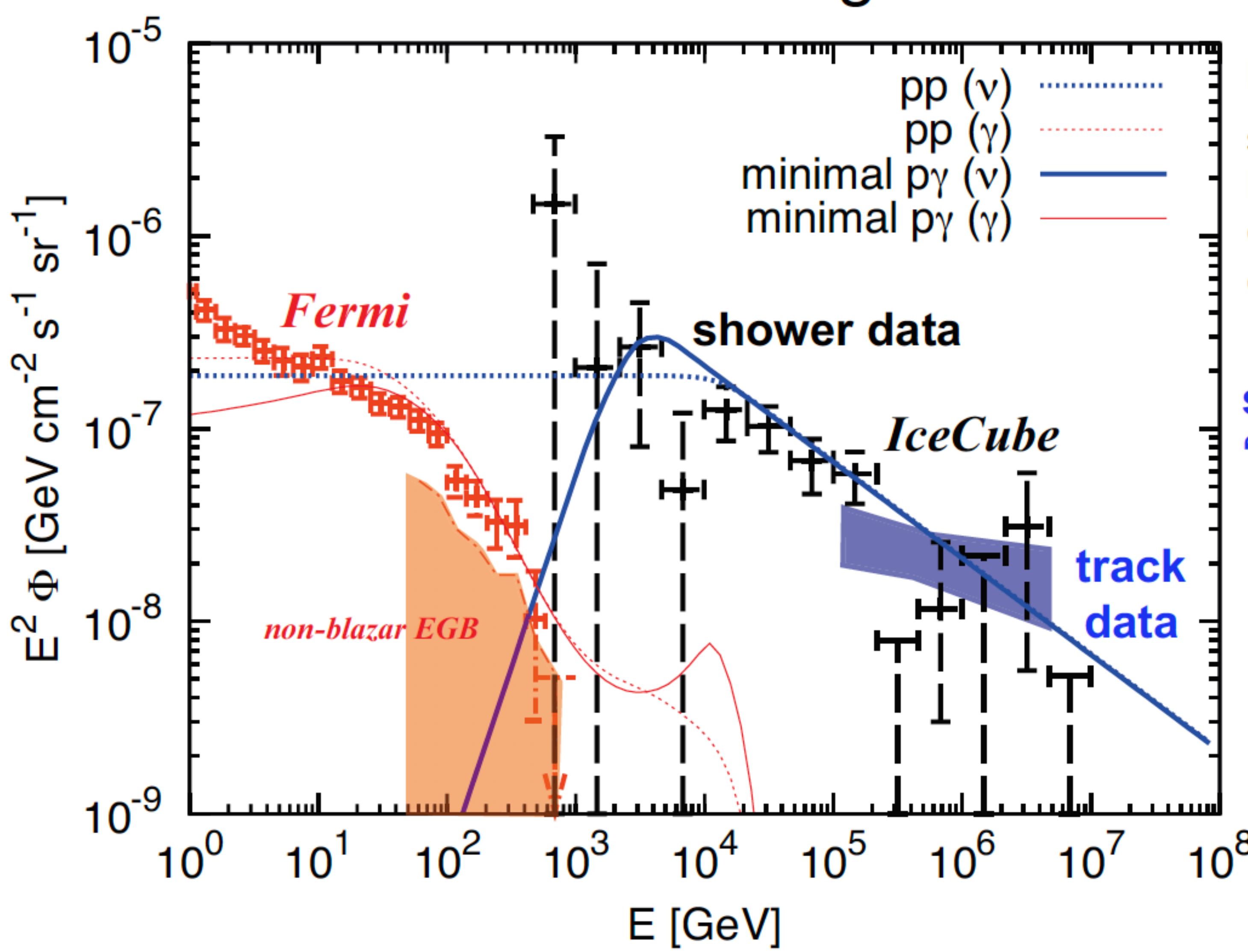
⟹ ***Fermi*-LAT blazars** can only be responsible for a **small fraction** of the observed neutrinos.

⟹ Multiple populations

+ similar limit for TDE contribution (~26 %)

Neutrino sources should be mainly opaque to gamma-rays

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



KM, Guetta & Ahlers 16 PRL

see also
KM, Ahlers & Lacki 13 PRDR
Capanema, Esmaili & KM 20 PRD
Capanema, Esmaili & Sepico 20

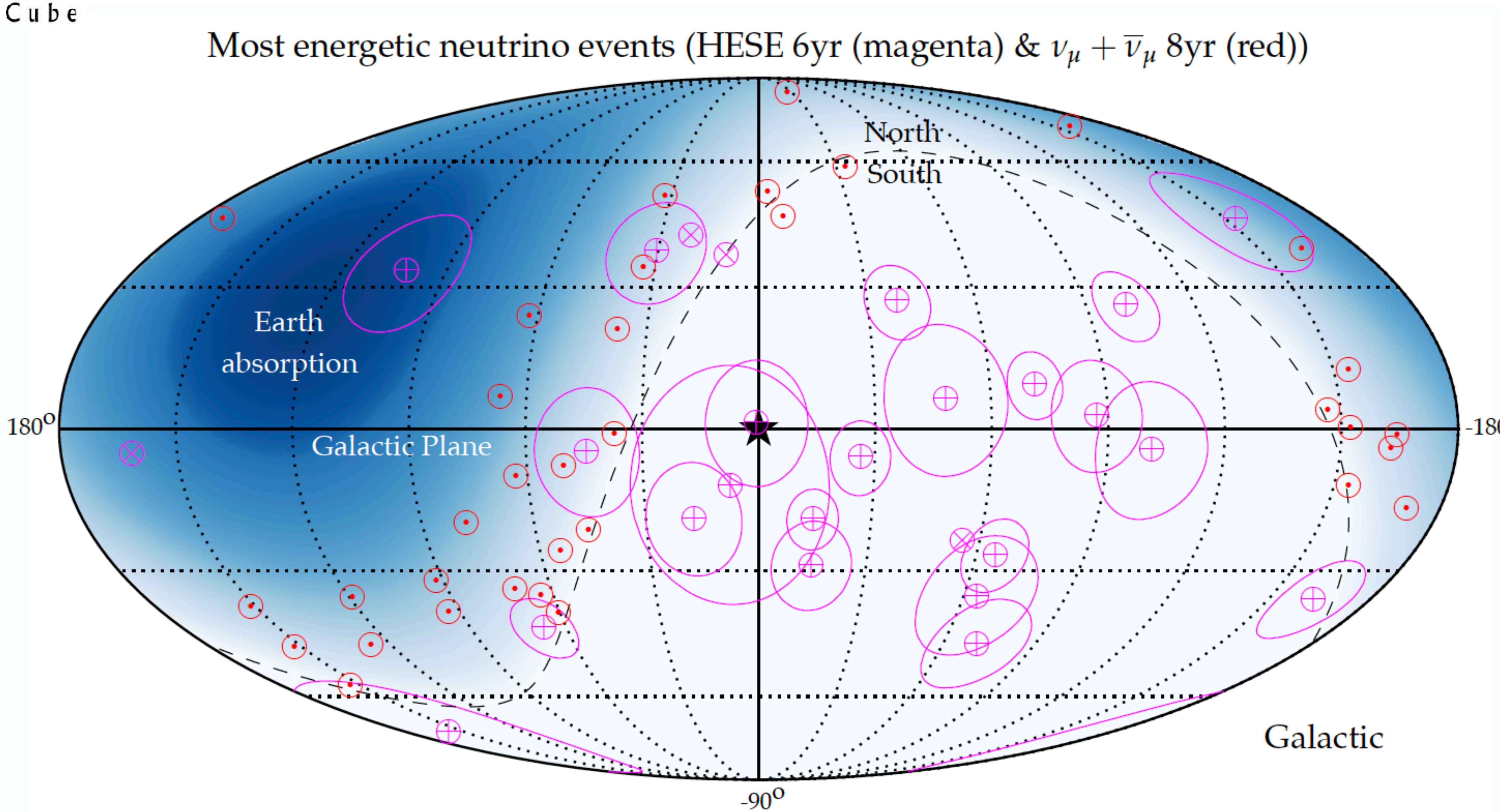
source-independent "generic" ν spectra considered

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

→ existence of "hidden (i.e., γ-ray opaque) neutrino sources"

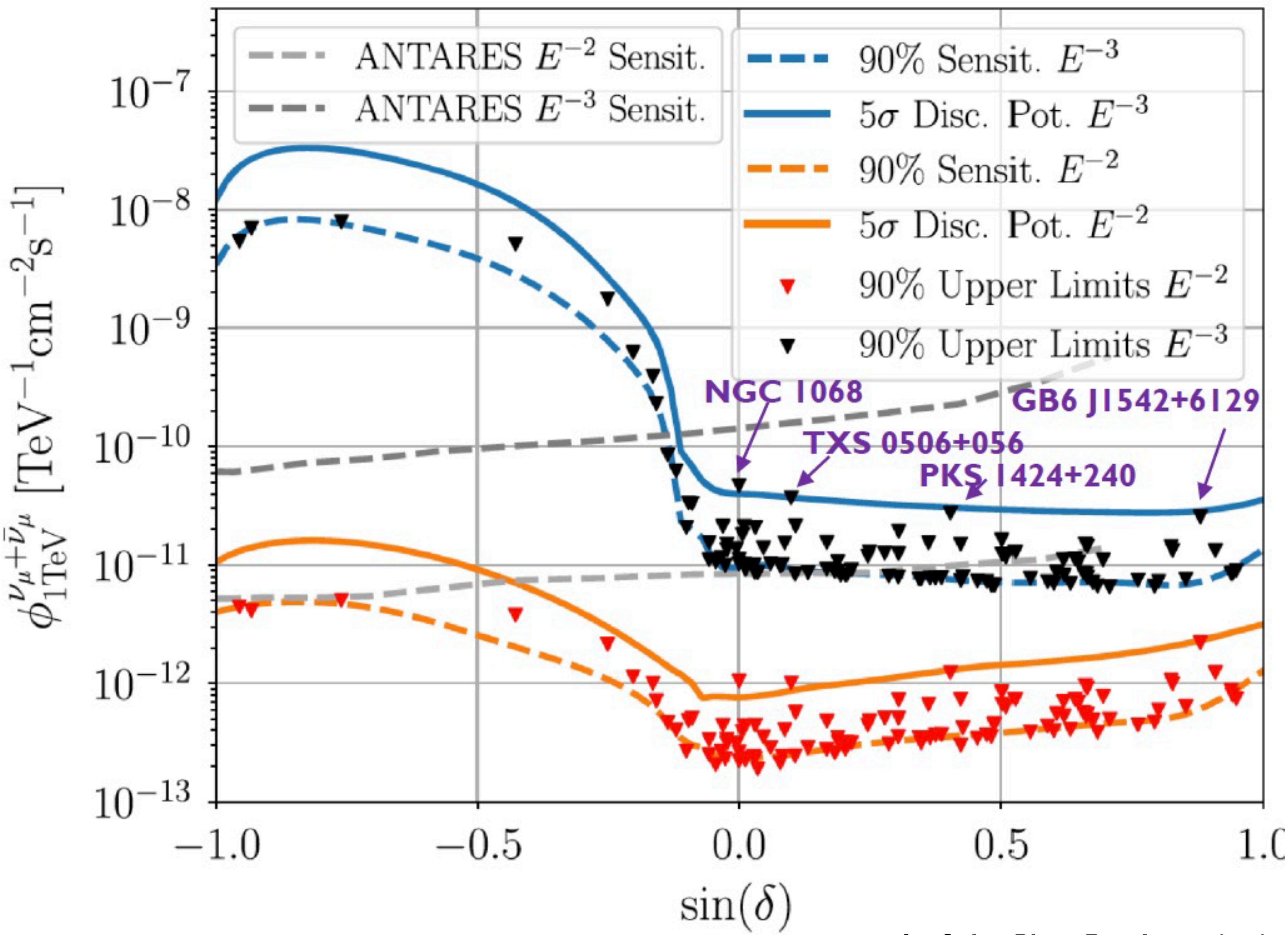
(ν data above 100 TeV can be explained by γ-ray transparent sources)

VHE neutrino sky (IceCube)



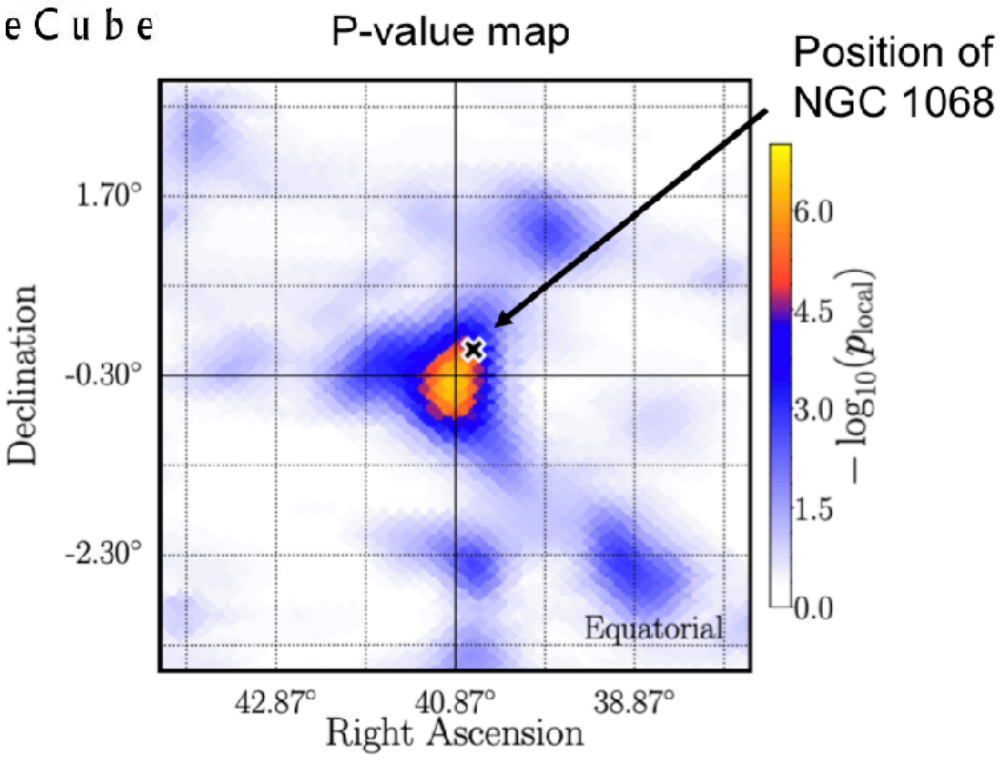
No significant steady or transient emission from known Galactic or extragalactic high-energy sources, but **several interesting candidates.**

Time integrated10-yr point-like source searches



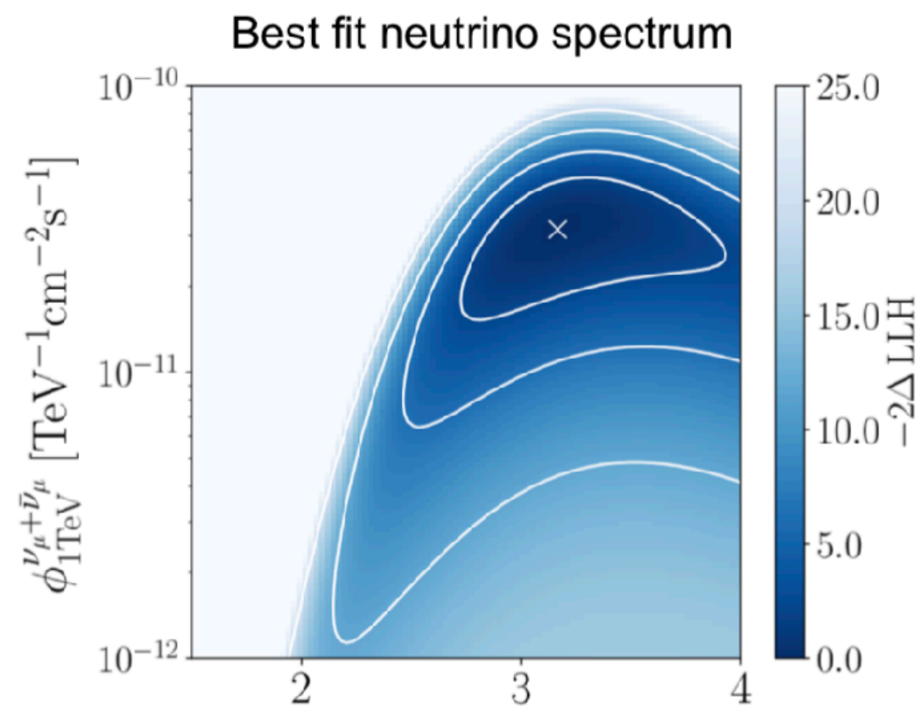
IceCube, Phys. Rev. Lett. 124, 051103 (2020)

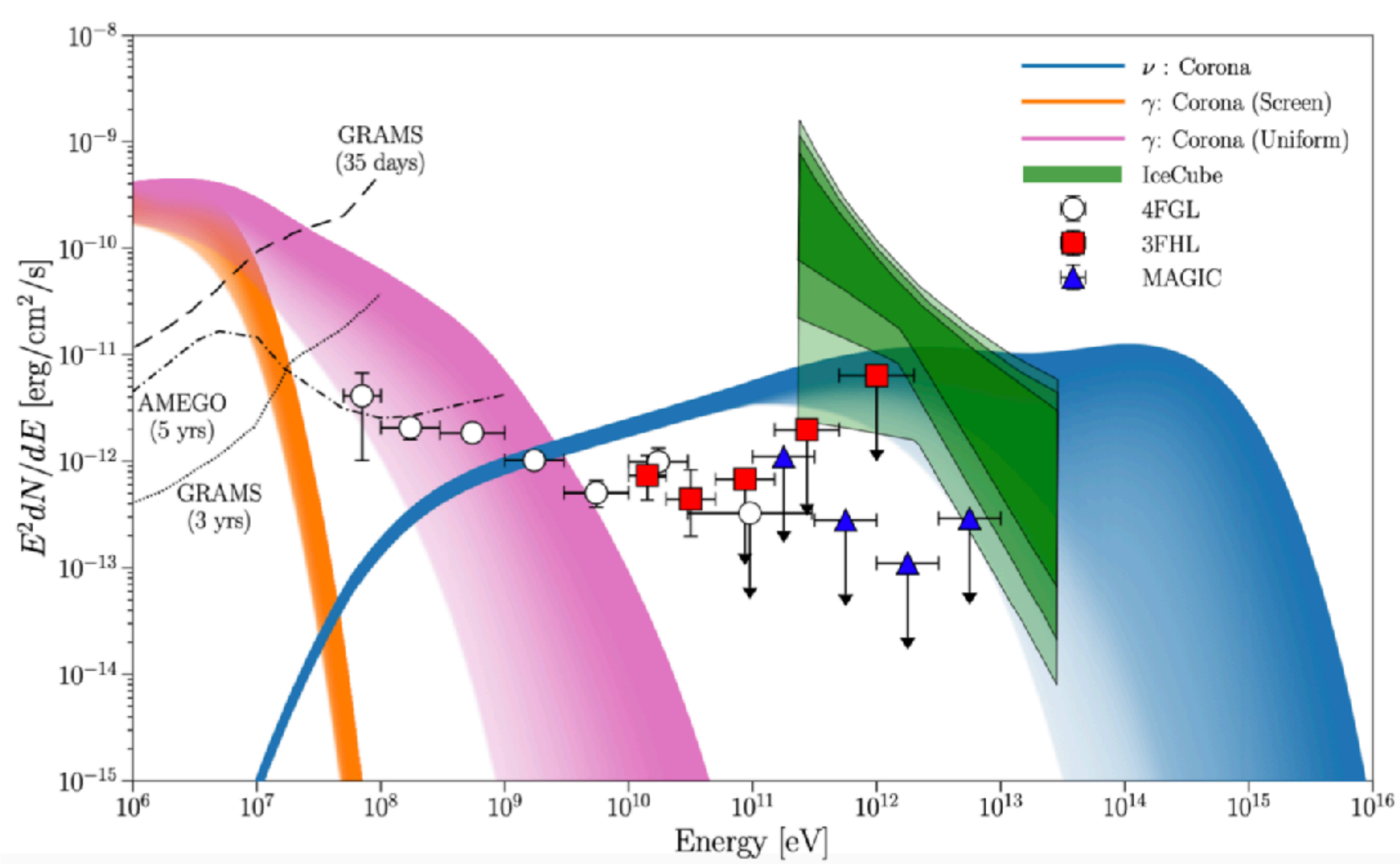
NGC1068



IceCube Coll. PRL 124 (2020)

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





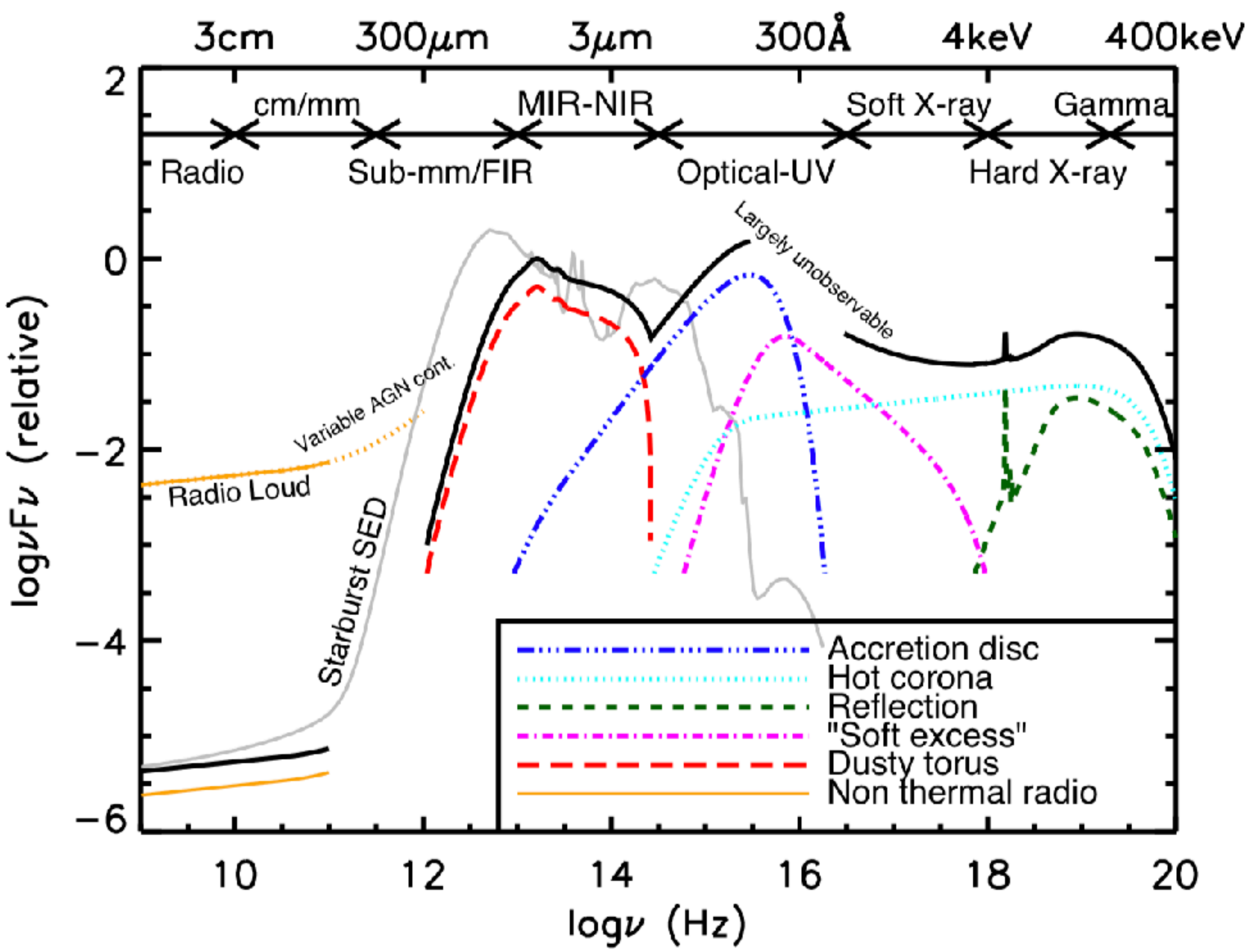
- **Seyfert 2 galaxy (M77) at 14 Mpc (star forming region)**
- **Neutrino production only at the vicinity of the SMBH (intense X-ray target): reported neutrino flux is higher than the GeV gamma-ray flux**

⟹ significant γ-rays absorption

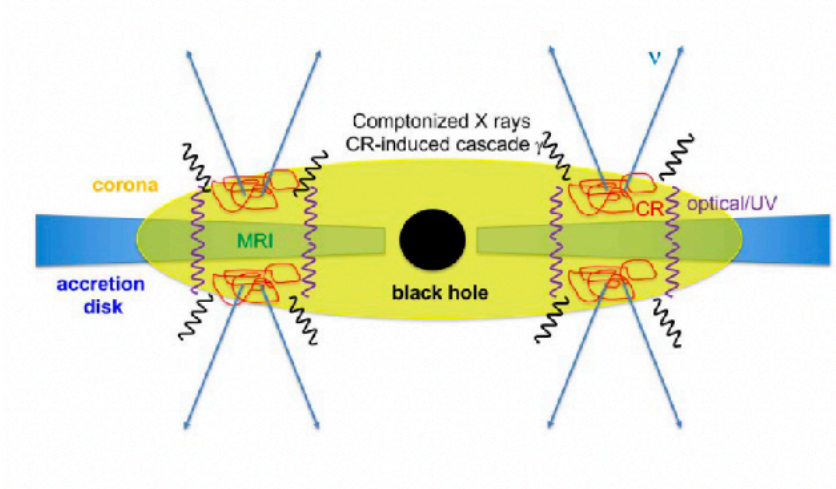
Inoue et al. ApJL 891 (2020)

Seyfert model

X-ray spectra (2-100 keV) are dominated by the thermal emission of the accretion disc hot corona. Confirmation of weak non-thermal activity in the corona (~3%). This non-thermal coronal activity was pinpointed through millimeter (mm) excess .
=> This can generate significant HE particles (pair-cascade scenario).
=> Seyfert galaxies are about four orders of magnitude more numerous than blazars and then might dominate the cosmic neutrino sky.



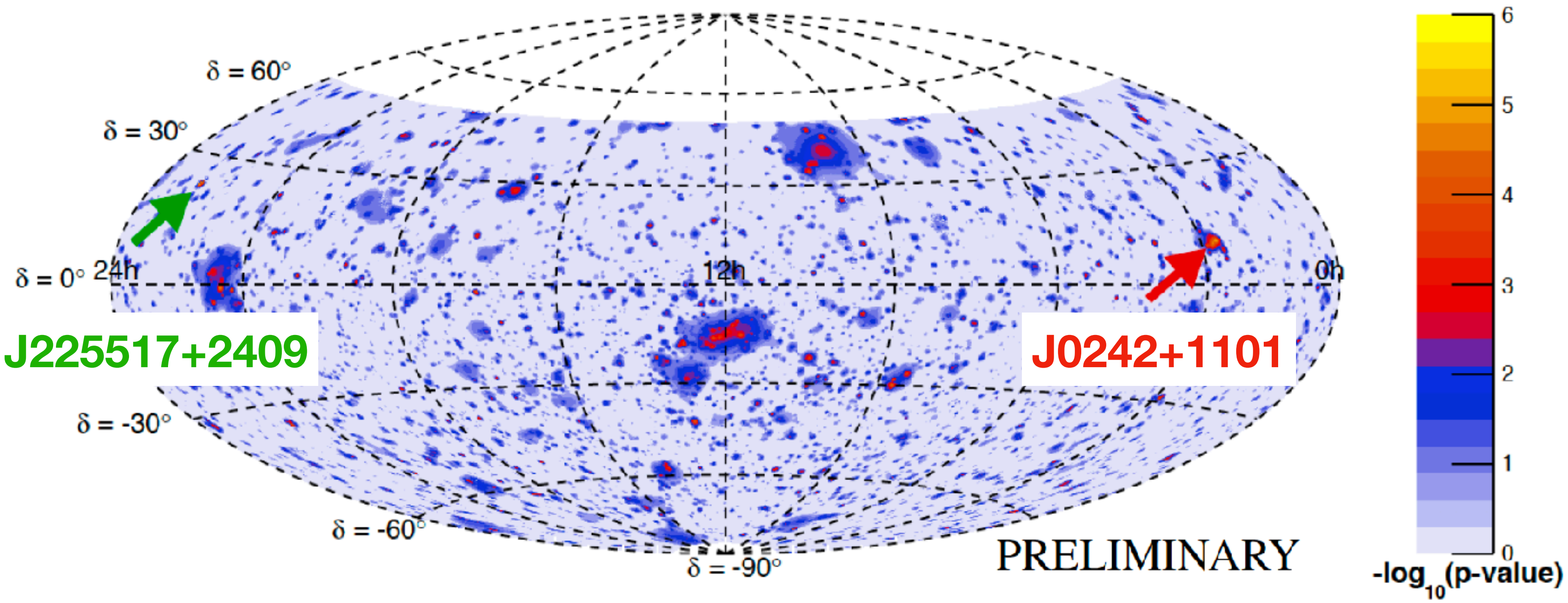
(Inoue + 2021)

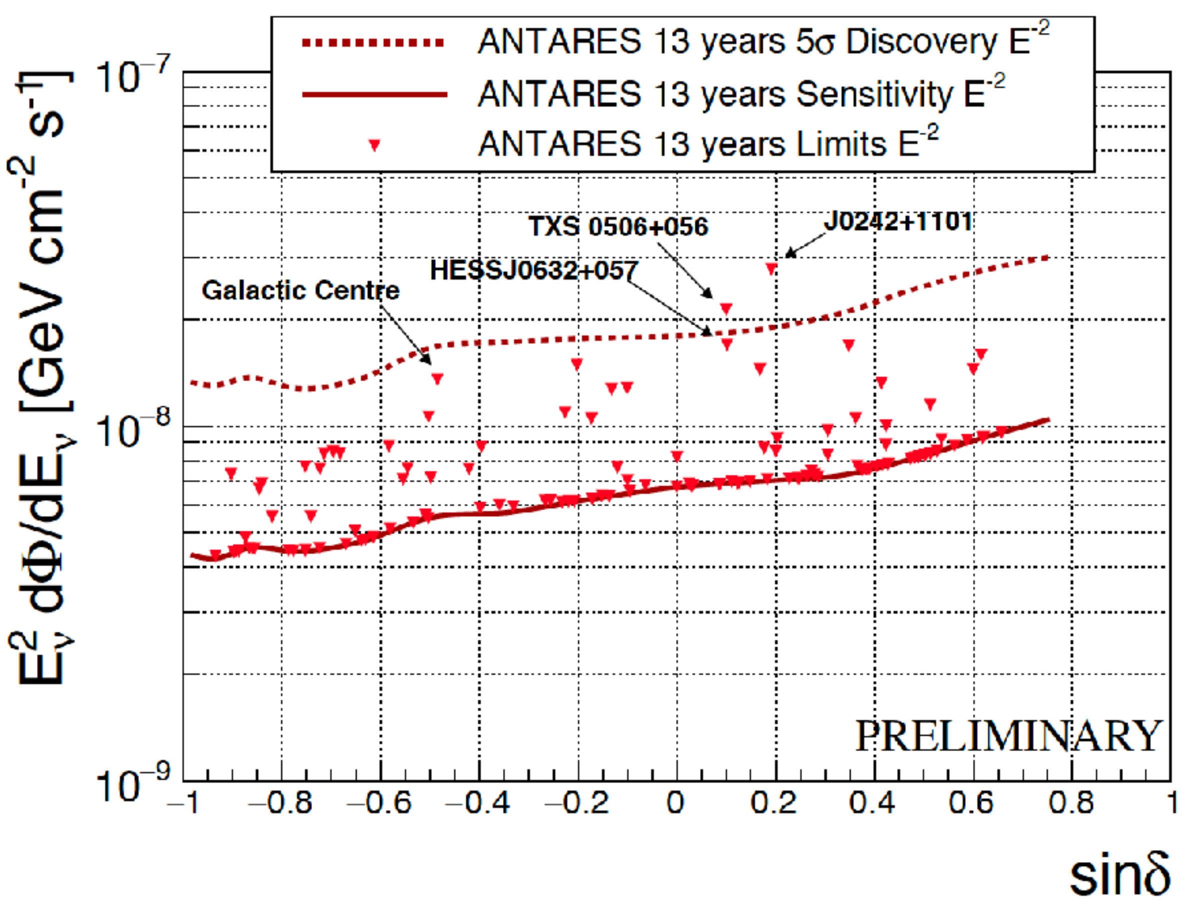


NGC 1068 is one of the intrinsically brightest X-ray Seyfert galaxy, i.e. after correcting the attenuation effects due to the molecular torus located in the line-of-sight.
=> Coherent with the assumption that the neutrino production is proportional to the accretion disc luminosity.

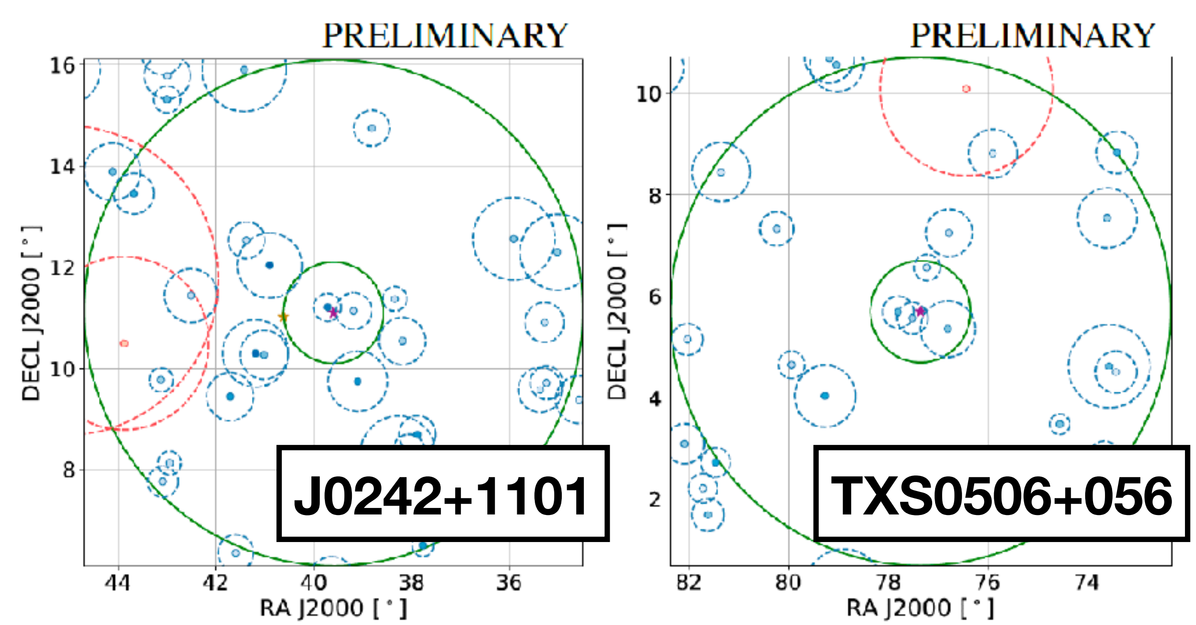
Next potential discovery: Centaurus A and Circinus galaxy with KM3NeT (but extended)

Last ANTARES PS results 2007-2020





Radio-bright blazars



3.8σ pre-trial

2.4σ post-trial

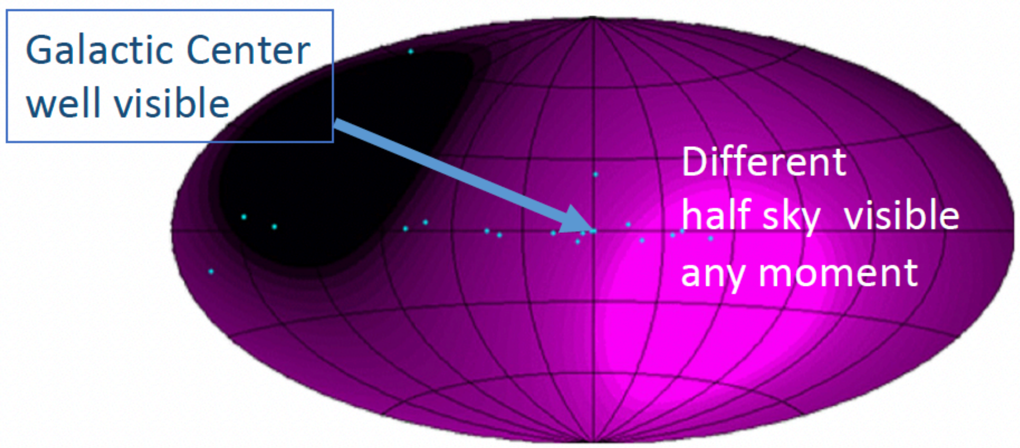
2.8σ pre-trial

(increasing significance compare to the last search)

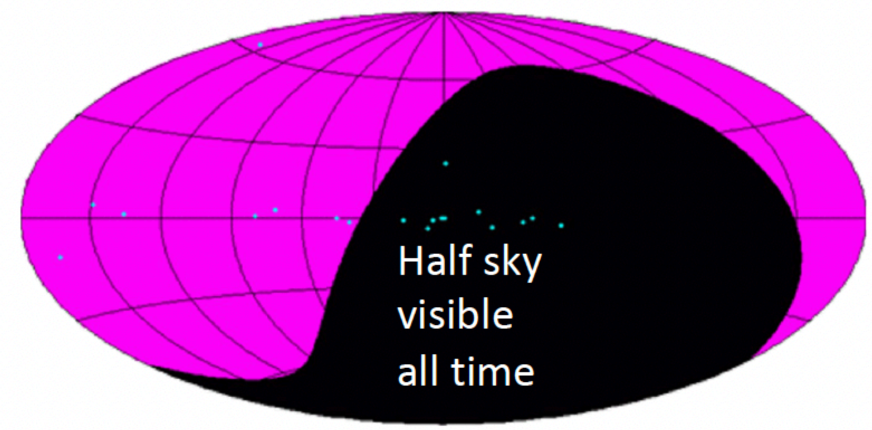
PoS(ICRC2021)1161

KM3NeT will be an important player

Complementary FoV, the very good angular precision of the neutrino direction
(See C. Di Stefano talk)

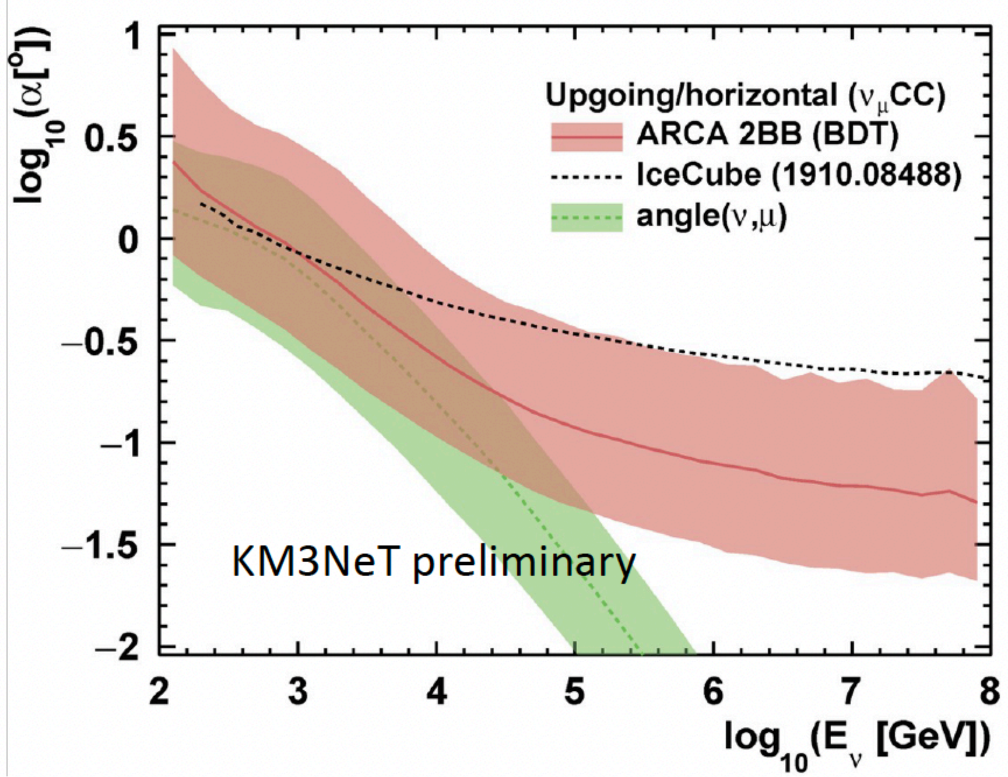


Mediterranean Sea (~43deg North)

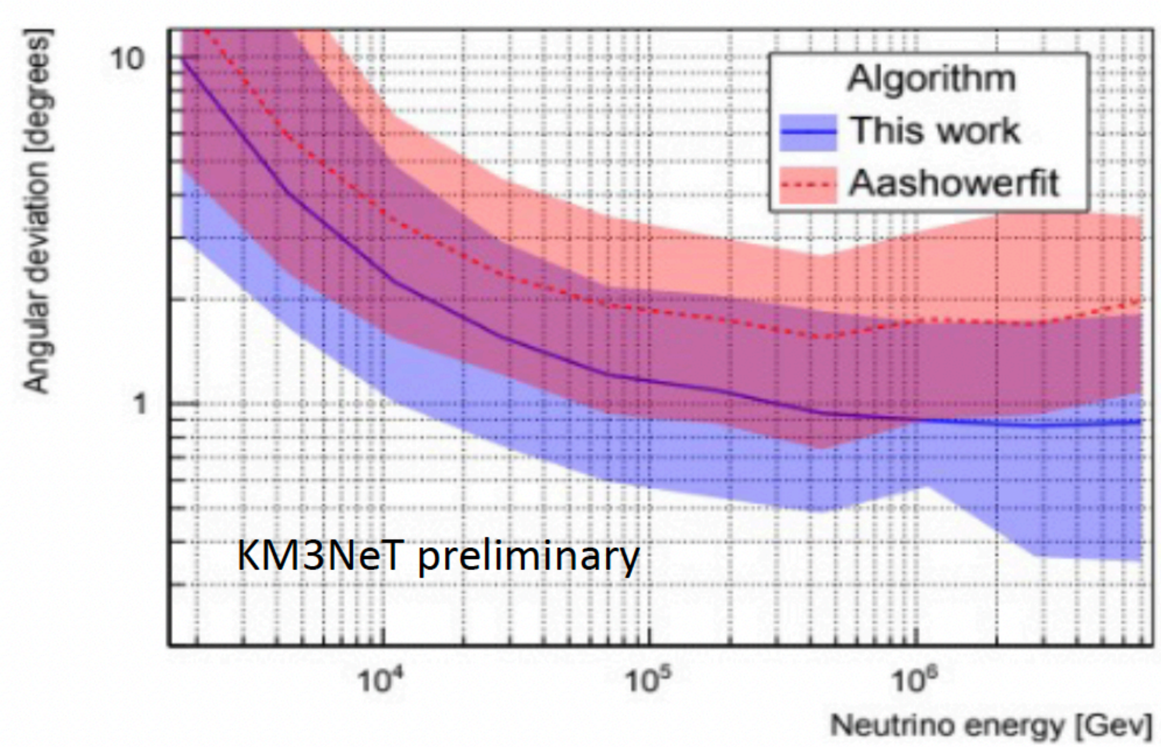


South Pole

Tracks



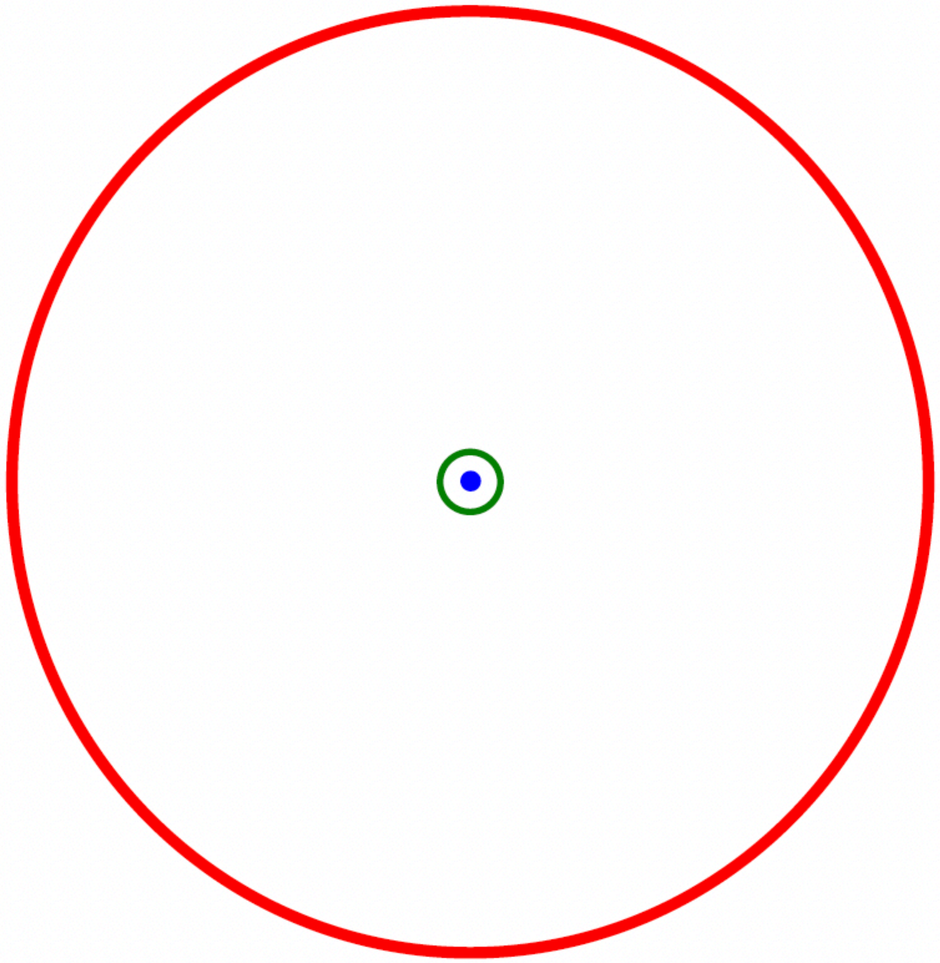
Cascades



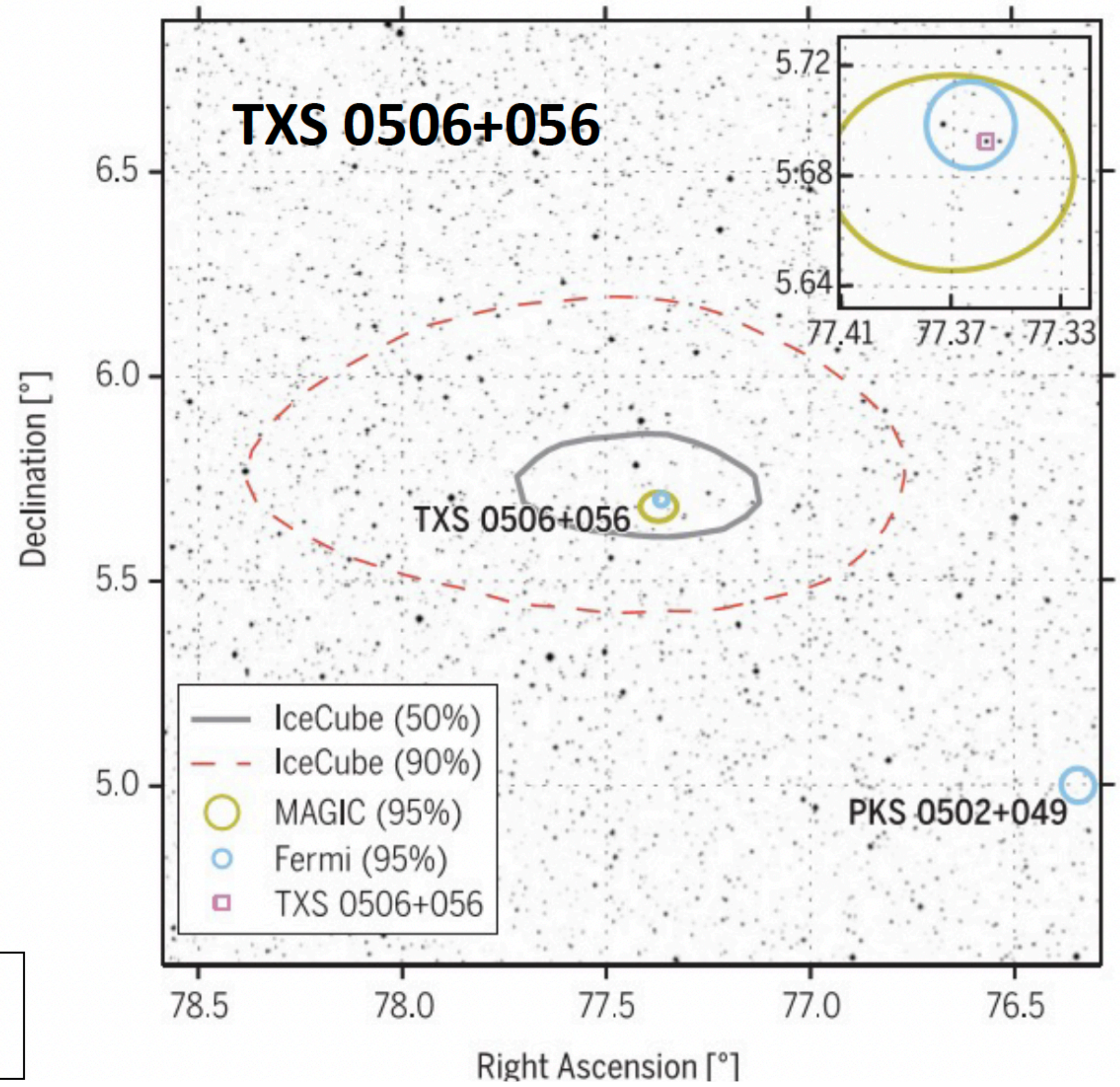
KM3NeT will be an important player

KM3NeT resolution

KM3NeT/ARCA expected intrinsic resolution for high energy (>=PeV) tracks/cascades



Morphology of extended sources can be explored (track events)



Multi-messenger alerts

Given the current statistics-limited samples of astrophysical neutrinos, one of the most optimum analysis strategies is to:

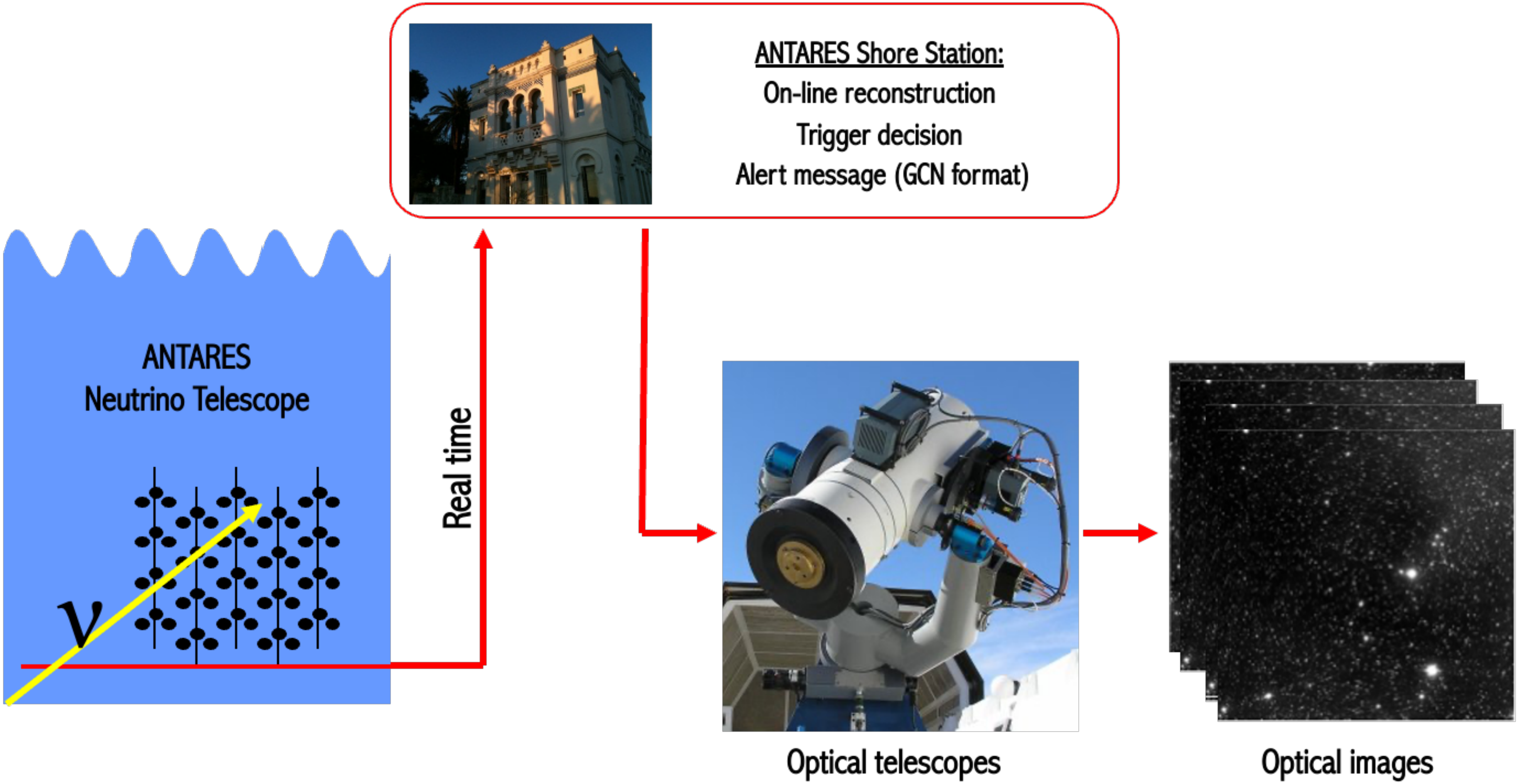
- **Alerts to community upon detection of likely « astrophysical » neutrinos for rapid follow-ups**
- **Real-time searches for neutrino signals in response to transient events observed in other messengers**

These observations can:

- **Strengthen or refine detections made in single messenger**
- **Probe source dynamics and populations, even in the absence of signal**
- **Identify the sources of the observed high-energy astrophysical neutrinos**

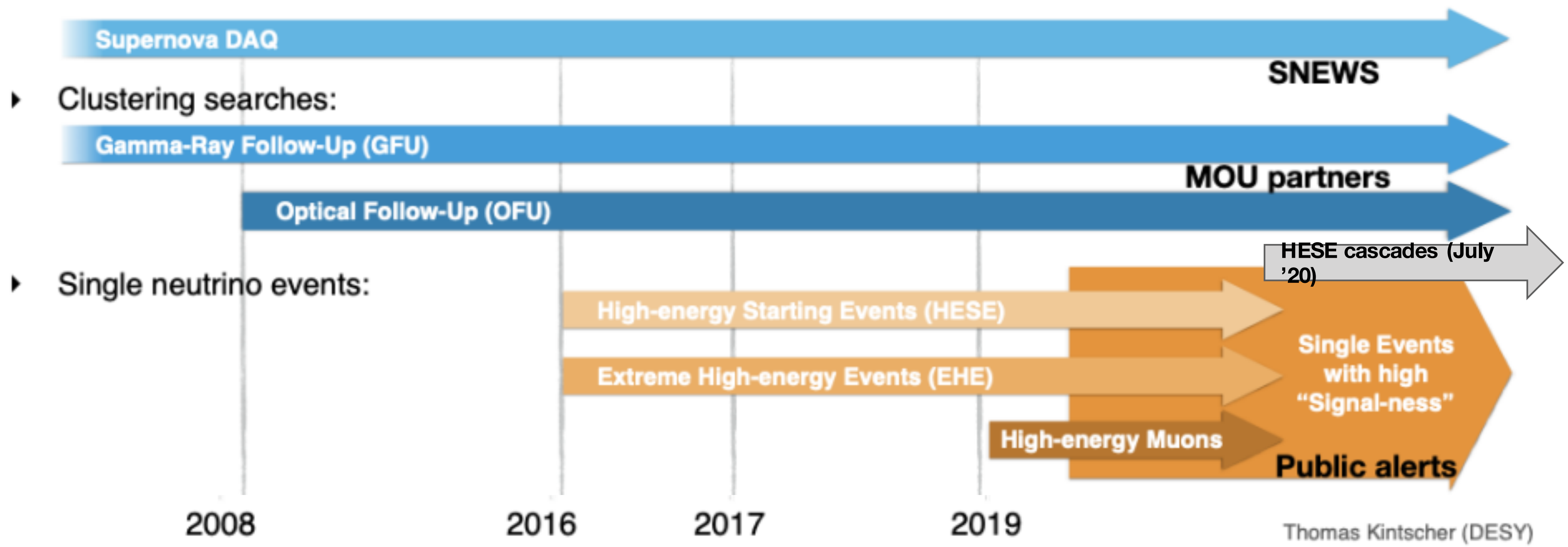
Multi-messenger alerts

IceCube and ANTARES have implemented in 2008-9, a neutrino alert sending program



IceCube neutrino alerts

IceCube is sending a broad list of alerts mainly centered in muon neutrino tracks



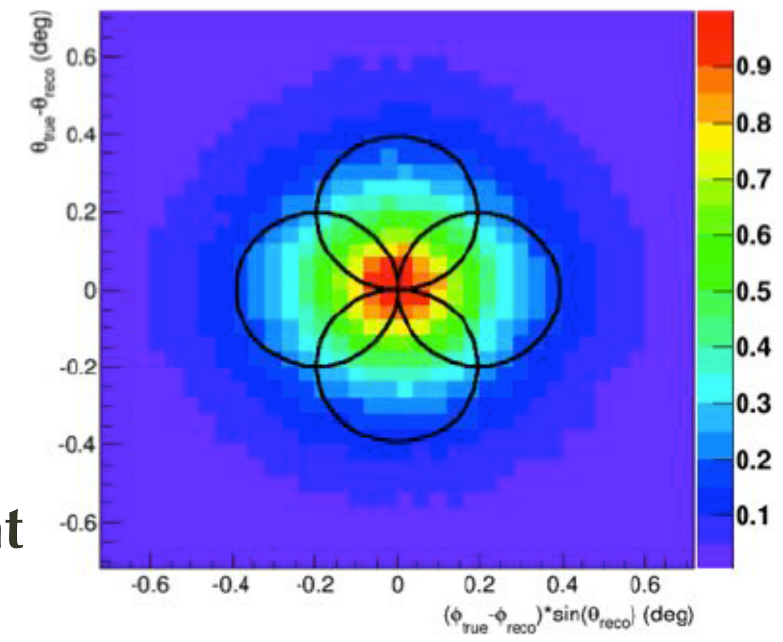
Updated selection: GOLD / BRONZE single events

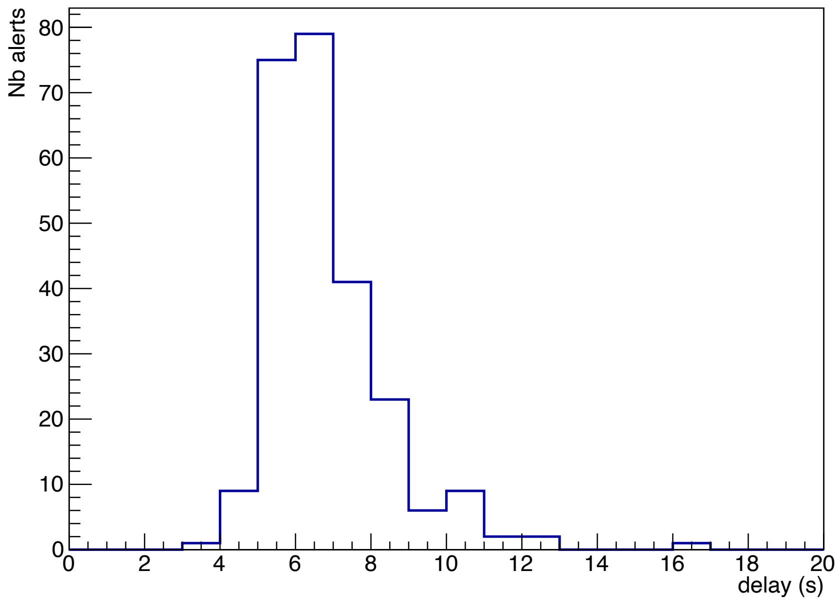
- Improved background rejections
- Added through-going track selections
- "Signalness" $= N_{Signal} / (N_{Signal} + N_{Background})$
- 2 classifications:
  - GOLD : > 50% signalness
  - BRONZE : > 30% signalness

ANTARES neutrino alerts

Triggers:
* Doublet of neutrinos: ~0.04 event / yr.
* Single neutrino with direction close to local galaxies: ~1 TeV, ~10 events / yr.
* Single HE neutrinos: ~7 TeV, ~15 event / yr
  => Sub-sample HE neutrinos: ~5 TeV, 20 events / yr
  => Sub-sample VHE neutrinos: ~30 TeV, ~3-4 events / yr.

ANTARES PSF : ~0.4º (median)

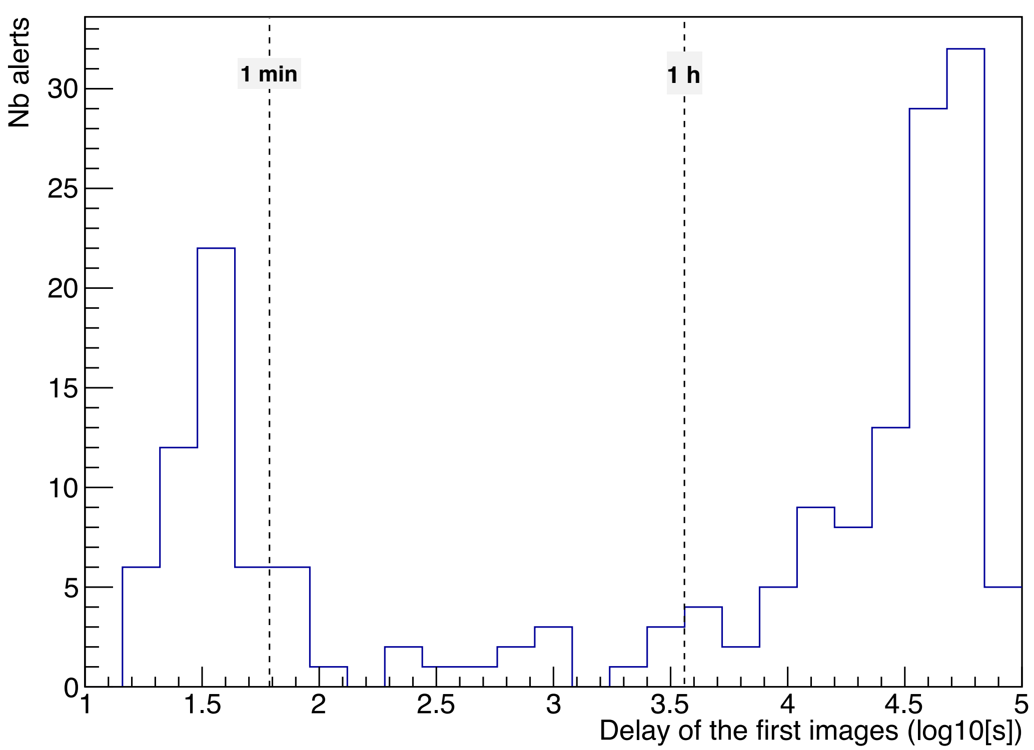




Alert message sent via the GCN using either GCN socket / VO Event
⟹ Average delay: ~6-7 s

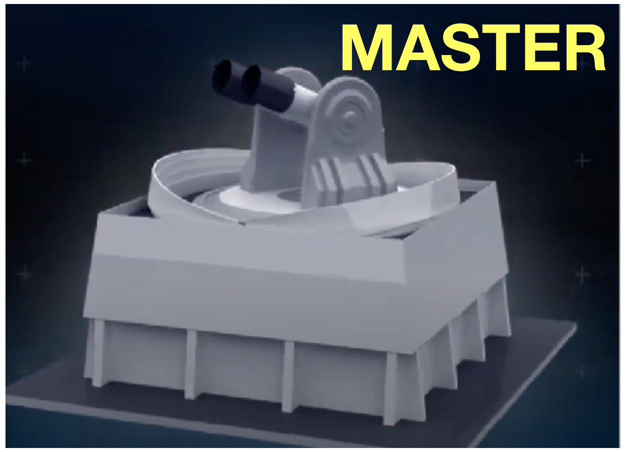
Private alert except if a potential counterpart is founded

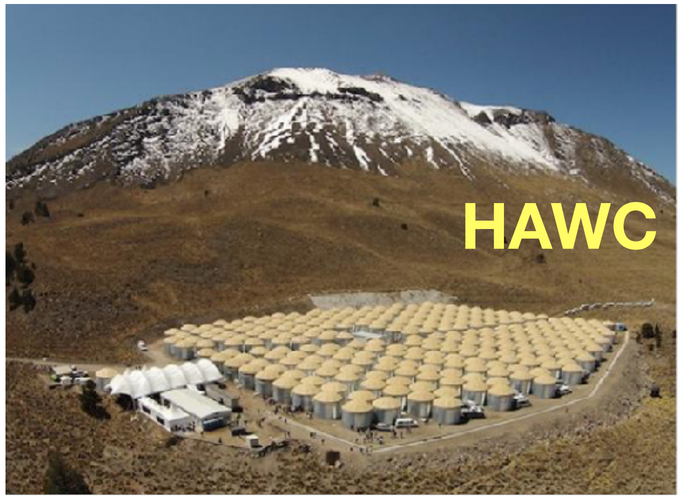
Delays between the time of 1st image and the neutrino trigger
⟹ 218 alerts < 1 day
⟹ 55 alerts < 1 min
(wait for the alert visibility, stop previous acquisition, point the telescope, start the acquisition)

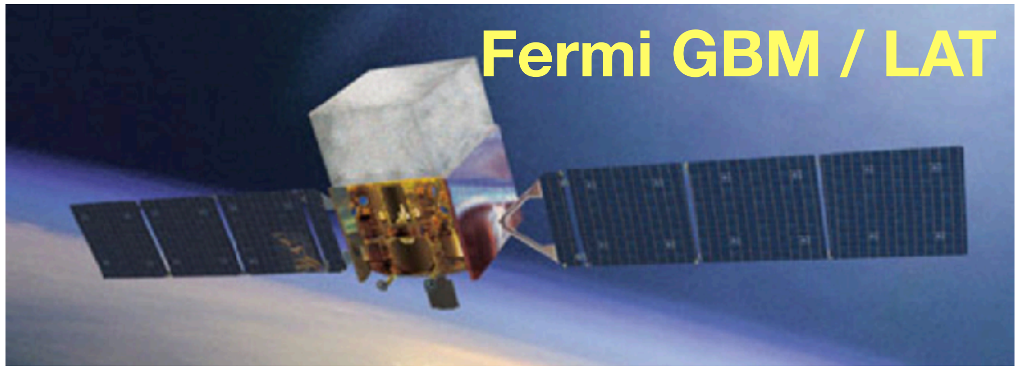


ANTARES, Astroparticle Physics, 2012, 35 (8)

Main followers







Multi-messenger synergies

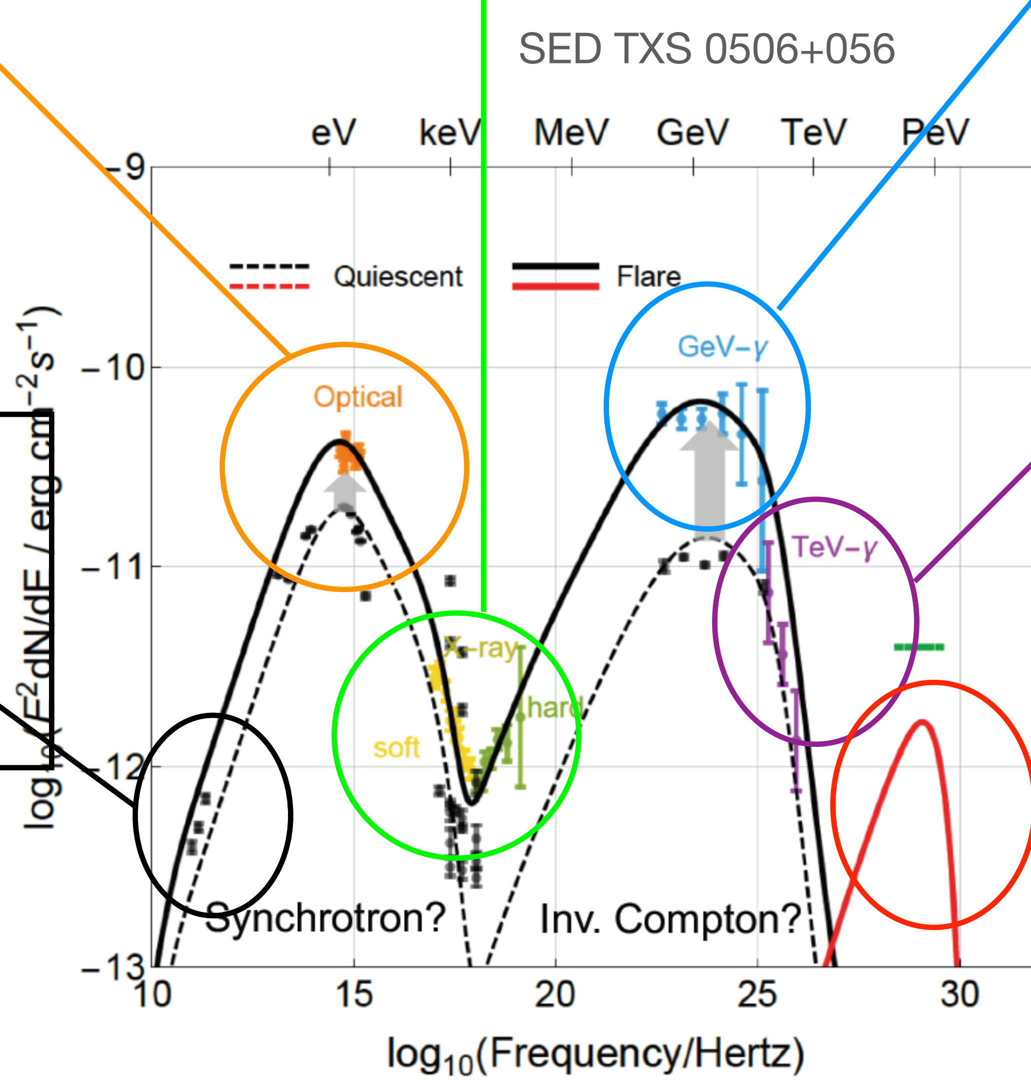
Optical telescopes: TAROT, MASTER, LCOGT, ZTF, LSST…
- Easy access follow-up of large error box
- Characteristation of the potential counterpart with spectroscopy (nature, redshift…)

X-ray telescopes: Swift, INTEGRAL, SVOM, 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, VLBI…
- Provide triggers (FRB…)
- Follow-up

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

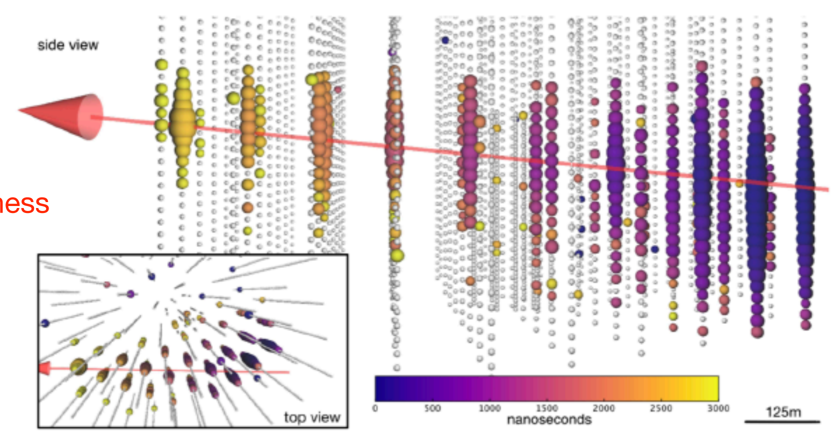
+ link with LIGO/VIRGO
+ SK, SNEWS

(Probably) one identified source

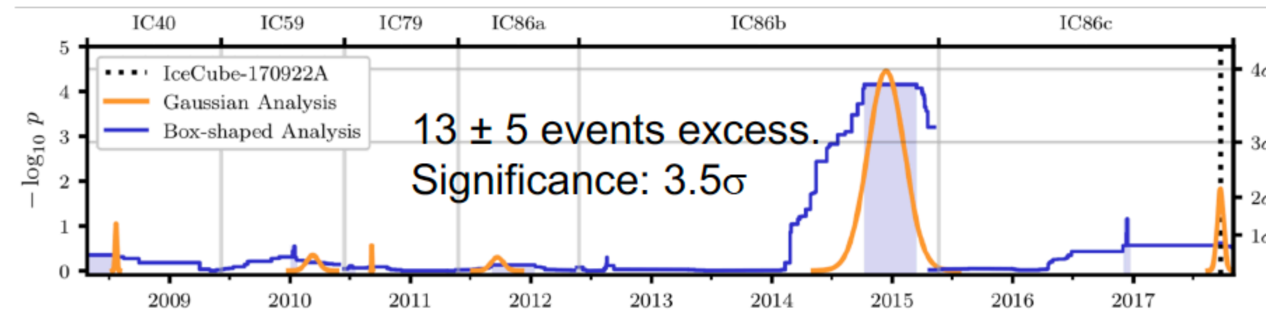
Neutrinos from the AGN blazar TXS 0506+056

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

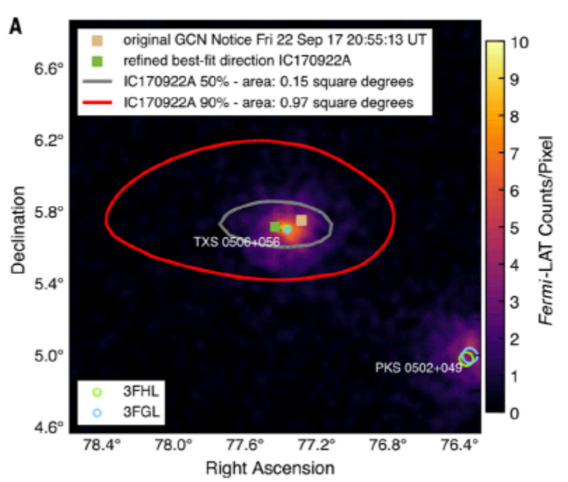
~290 TeV
56.5% signalness



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



Science 361 (2018) no. 6398, eaat2890



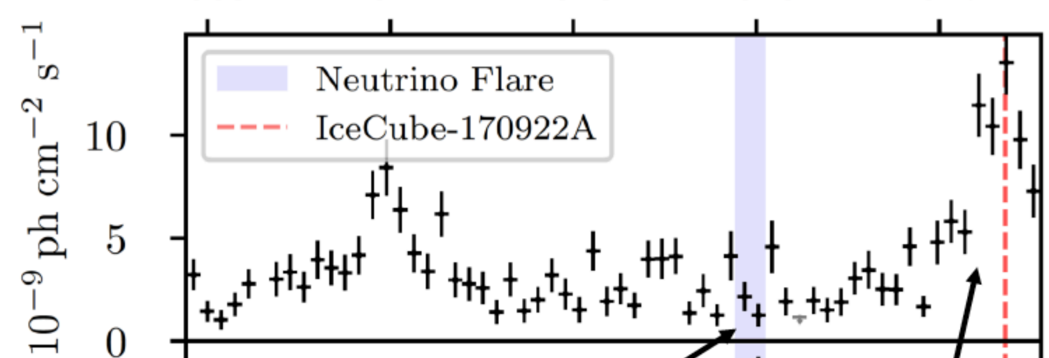
Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

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

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

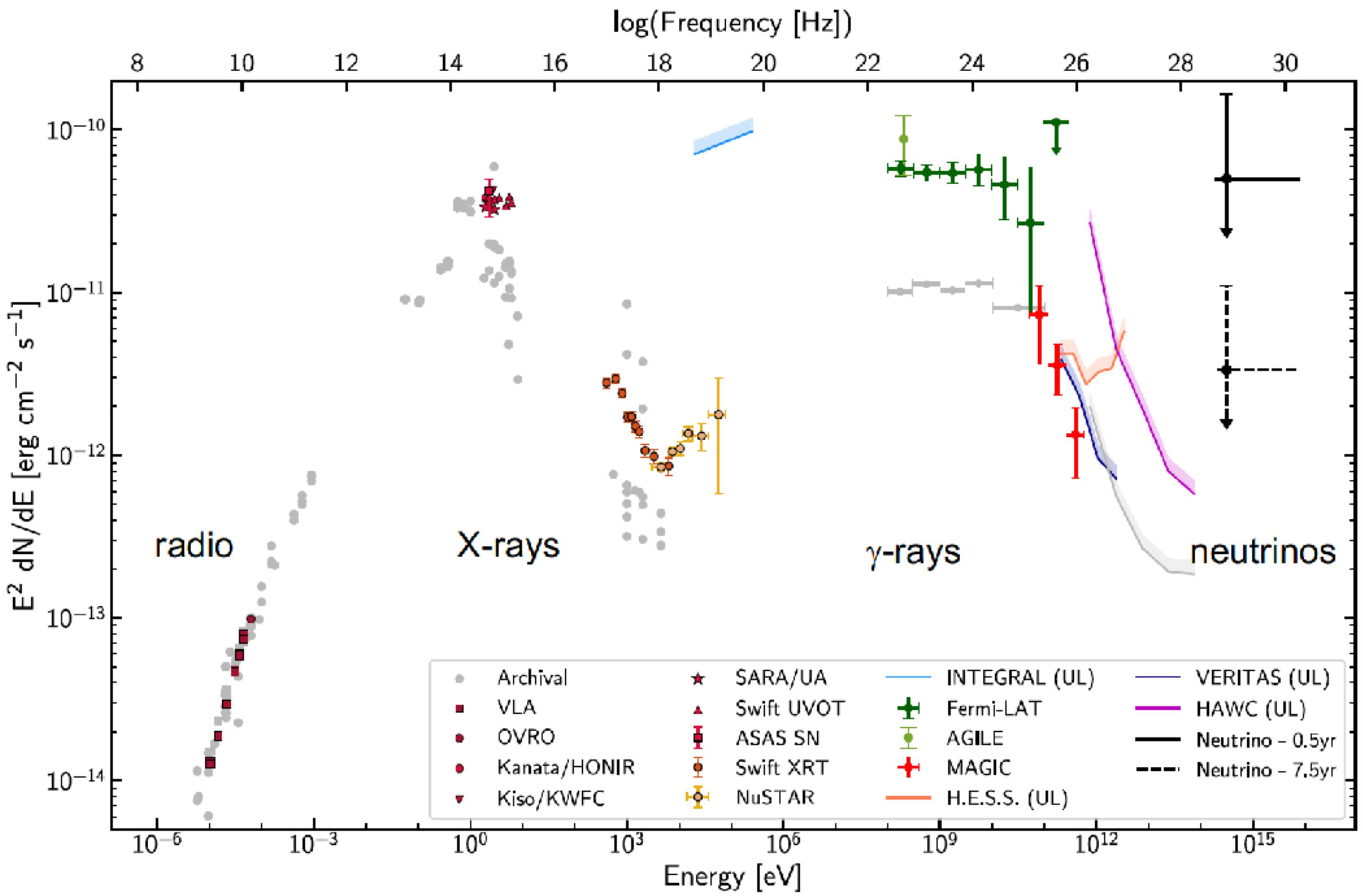


At 2014-15 neutrino flare

The 2017 flare

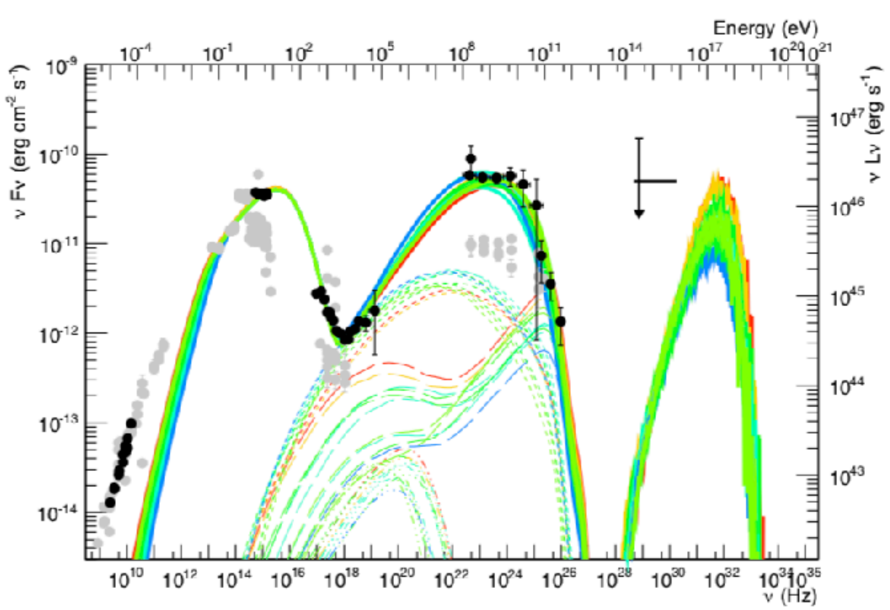
Neutrino luminosity is ~4 times higher than gamma-ray luminosity
⟹ challenge for models

A difficult parametrization

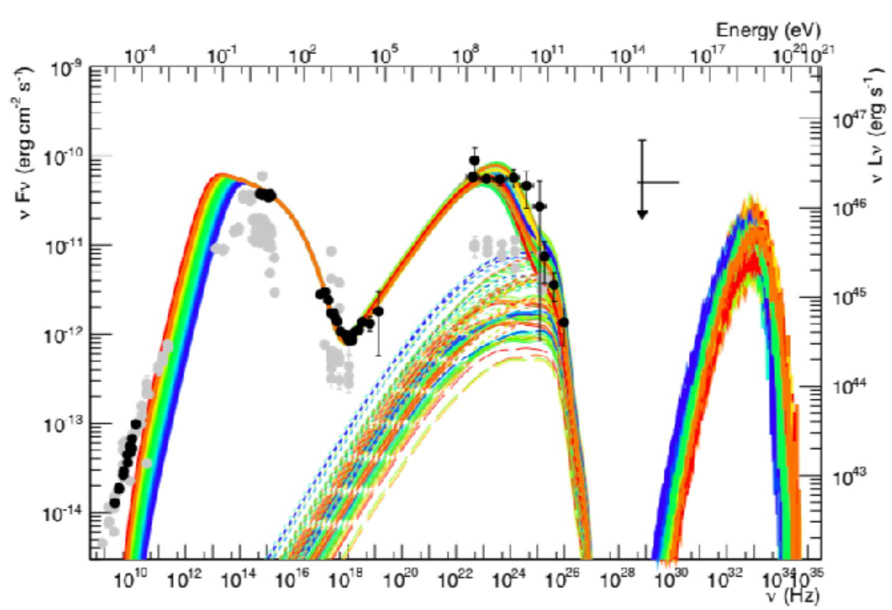


- Simple 1-zone models are not working properly
- More sophisticated multi-zone models on the market to satisfy the energetic problem: interaction with external field (Sikora 2016), jet-cloud interaction (Liu 2018), formation of a compact core (Gao 2019)…

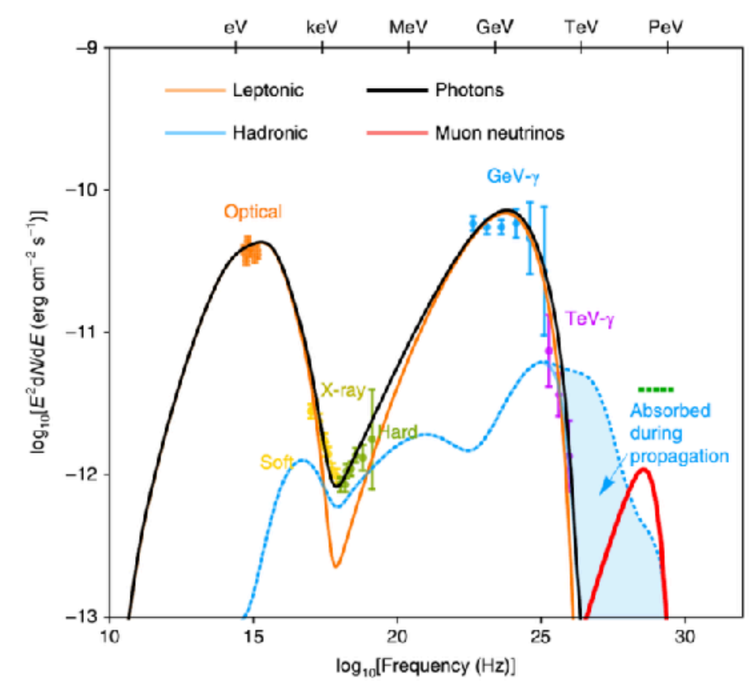
⟹ Simultaneous X-ray data are extremely important for the modeling, even more important than the very high energy



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



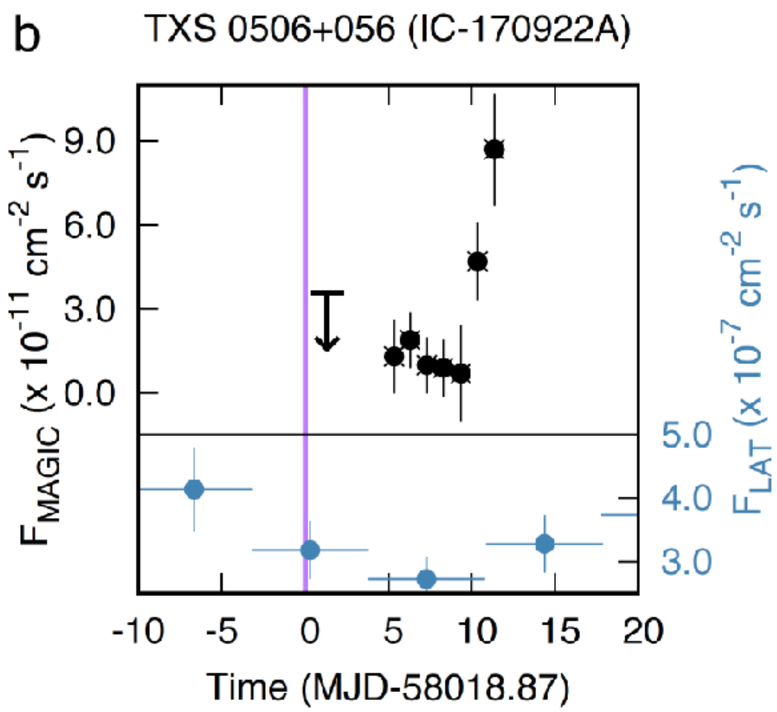
(a) Proton synchrotron modeling of TXS 0506+056



(Cerruti et al, 2018)

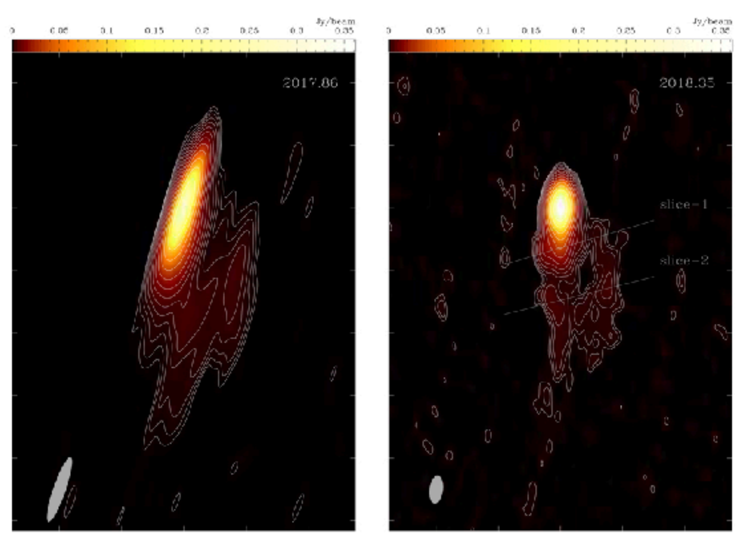
(Gao et al, 2018)

Refined multi-wavelength follow-up



Kun et al. 2020

- 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



A&A 633, L1 (2020)

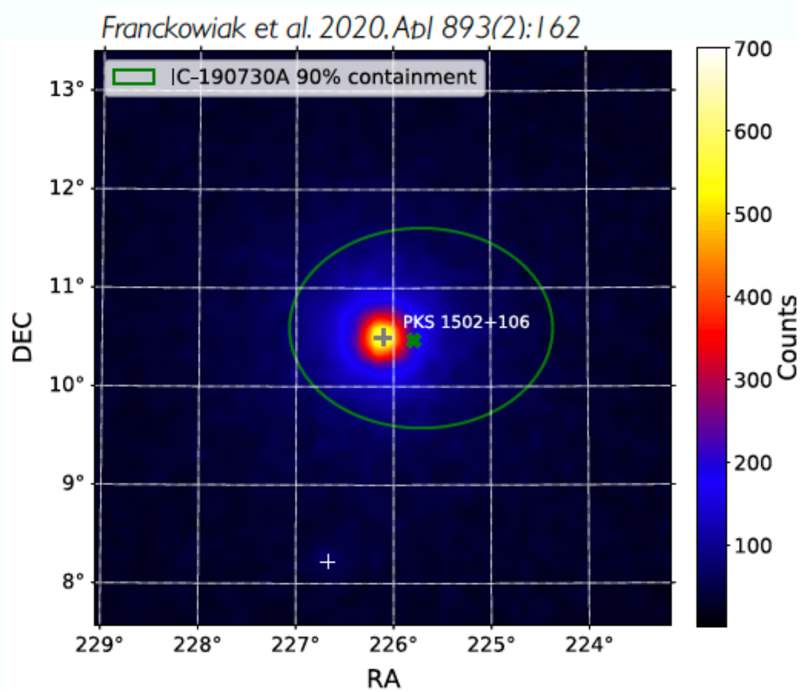
- Radio interferometry images show that the jet interacts with a target close to the base of the jet
- γ-rays accompanying the neutrinos lose their energy in the target that produces them

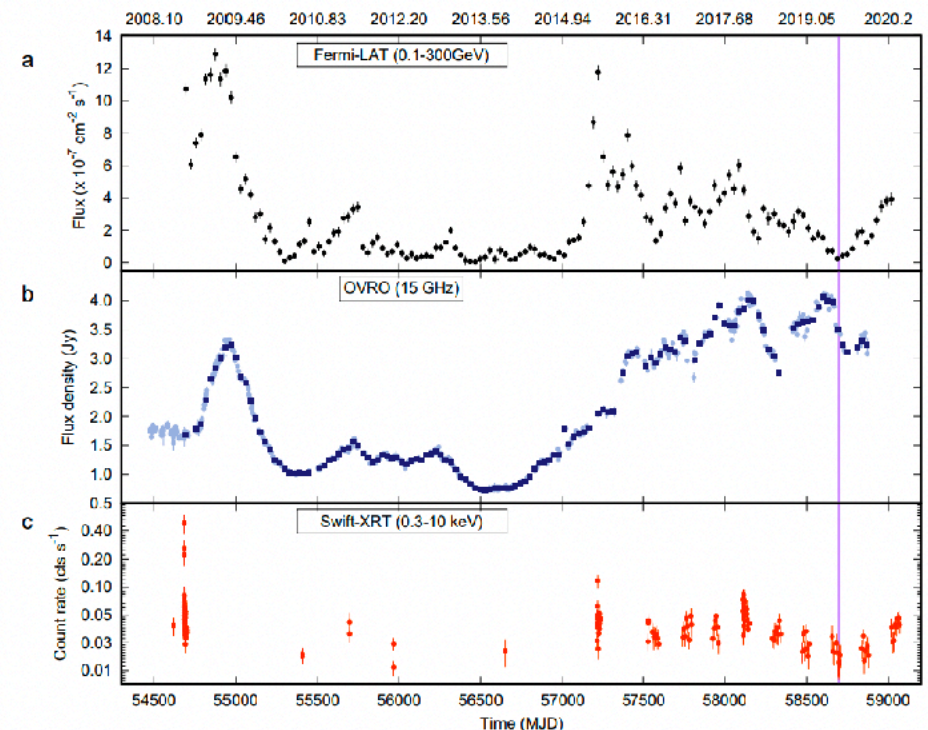
TXS is not a blazar at times that neutrinos are produced.

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

Possible association IC190730A with PKS1502

PKS1502+106, a powerful flat spectrum radio quasar (FSRQ) at z=1.835 in direction coincidence with IC190730A (~300 TeV)

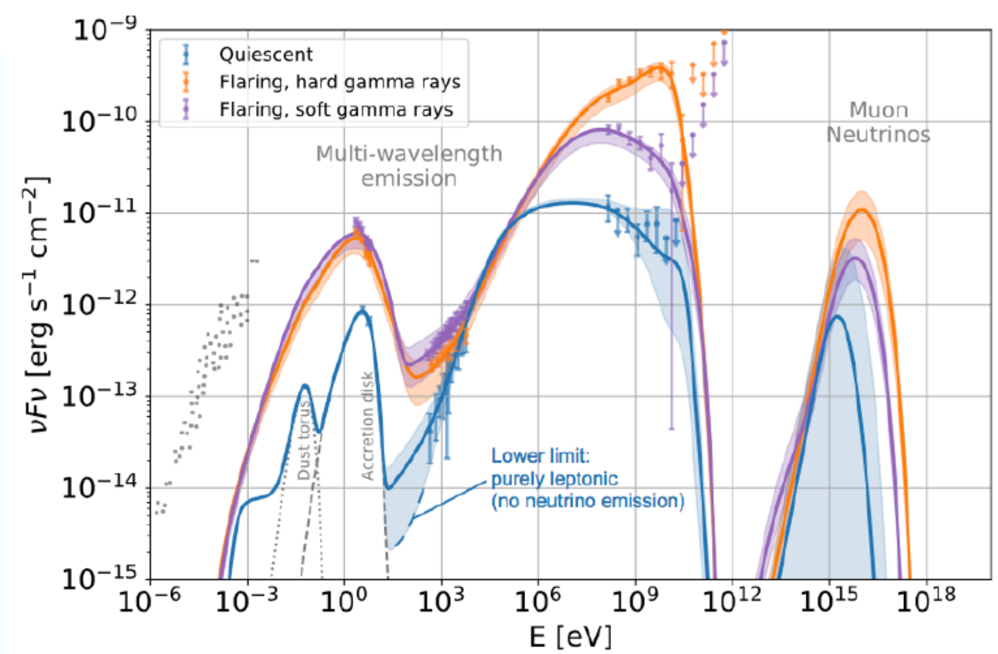




Kun, Bartos, JBT, Biermann, Halzen, Mez´´o ApJL (2021)

Neutrino detected in quiescent state of weak γ-ray activity

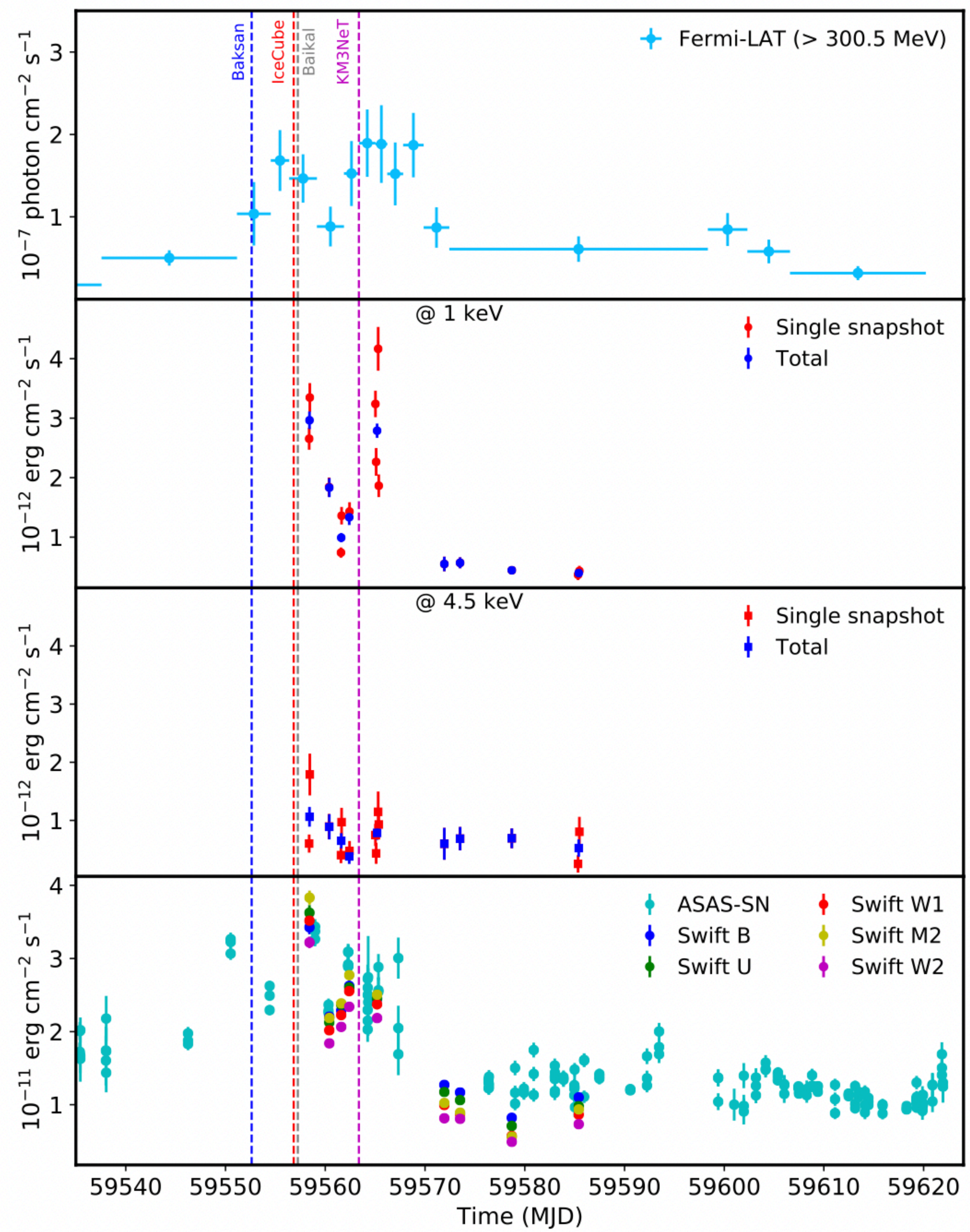
No more neutrinos observed during flaring period?



Model State	Quiescent	Leptohadronic Hard Flare	Soft Flare
$N_{\rm events}$ per year	$0.47^{+2.19}_{-0.47}$	$3.19^{+1.90}_{-1.71}$	$1.27^{+0.8}_{-0.55}$
$N_{\rm events}$ (total)	$1.77^{+8.23}_{-1.77}$	$10.94^{+6.56}_{-5.84}$	$4.32^{+2.71}_{-1.87}$

Foteini Oikonomou, PoS 030. Xavier Rodrigues, PoS 1018. Rui Xue, PoS 985.

Intriguing association with PKS0735+178



Sahakyan et al (arXiv:2204.05060)

IceCube: 1 bronze alert (~172 TeV) [GCN #31191]

ANTARES: no coincidence [ATel #15106]

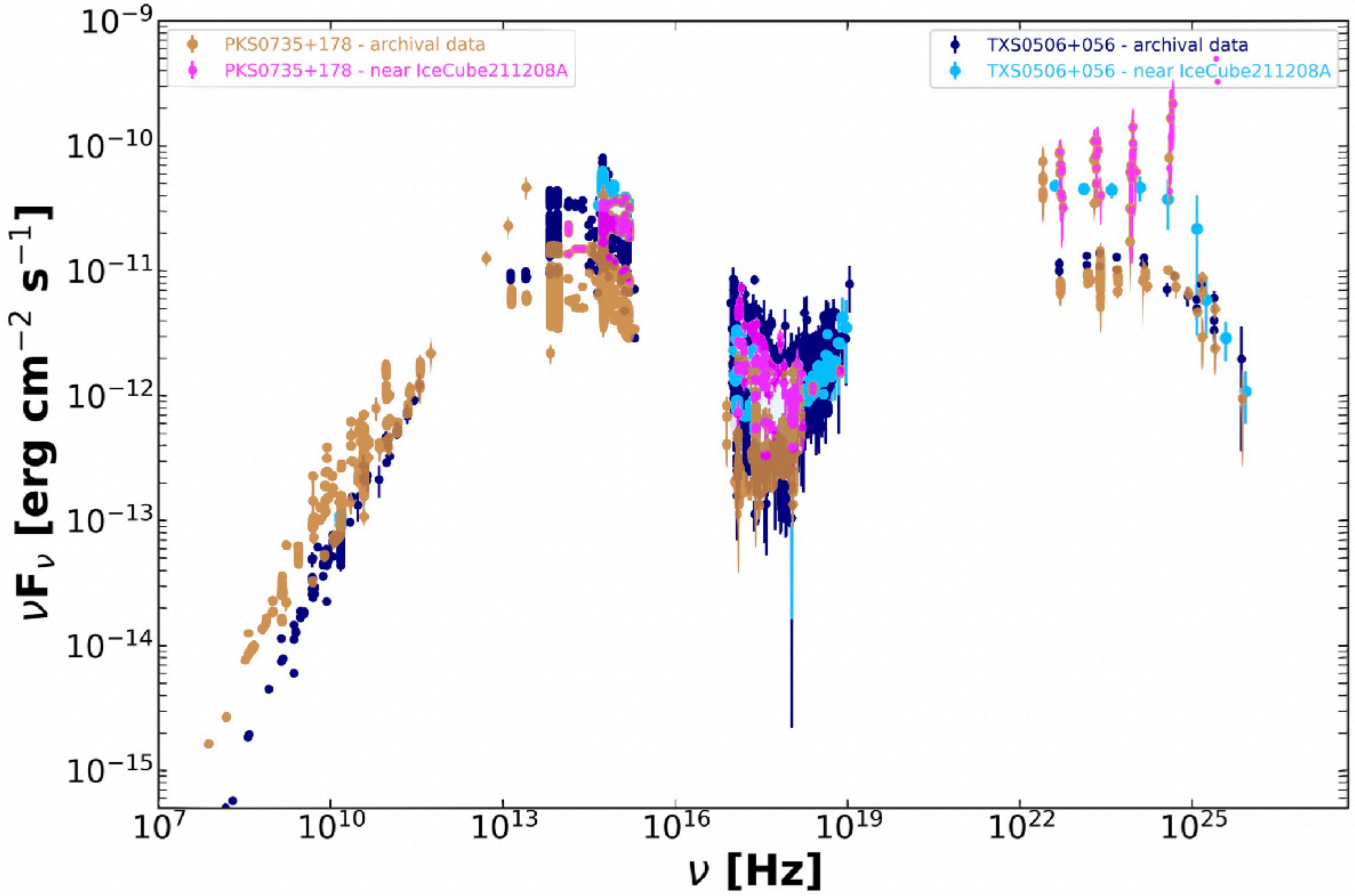
GVD-Baikal: 1 cascade event (~43 TeV), ~4h after the IC neutrino, ~5deg from the blazar direction (2.85 σ) [ATel #15112]

KM3NeT: 1 track neutrino candidate (~18 TeV) in ARCA, 1.8 deg from the blazar (p=0.14). No coincidence in ORCA [ATel #15290]

Baksan: 1 track neutrino (1 GeV), 2.2 deg from the blazar (~3 σ) [ATel #15143]

The blazar was found to experience a strong flare in gamma rays (ATel #15099, ATel #15129), X-rays (ATel #15102, ATel #15108, ATel #15109, ATel #15113, ATel #15130), optical (ATel #15098, ATel #15100, ATel #15132, ATel #15136, ATel #15148) and radio (ATel #15105) bands.

Intriguing association with PKS0735



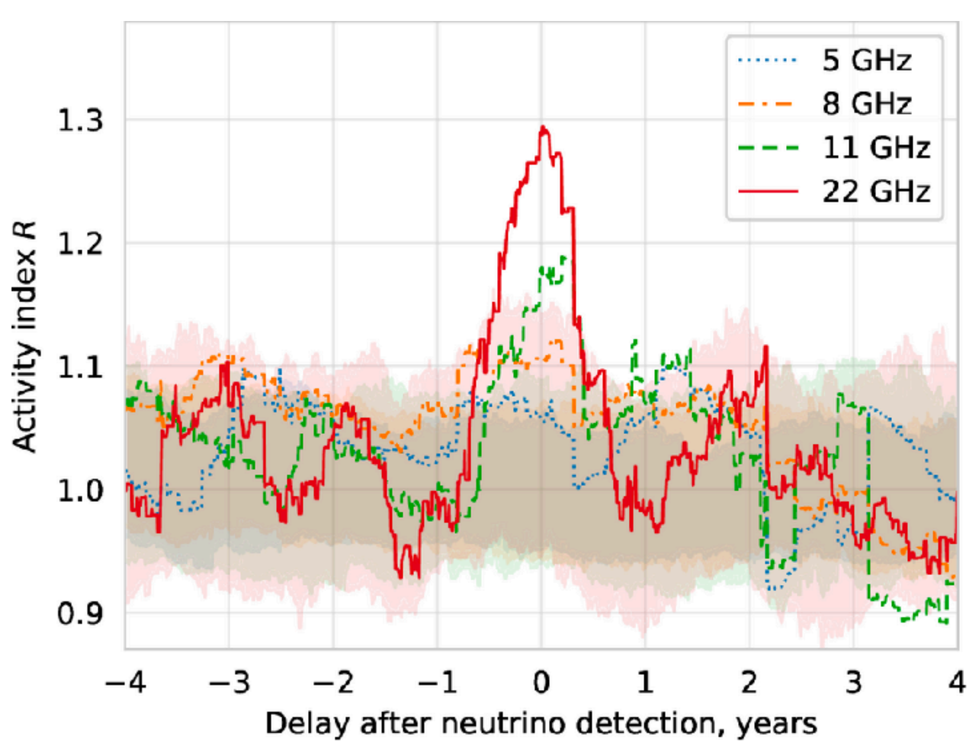
Sahakyan et al (arXiv:2204.05060)

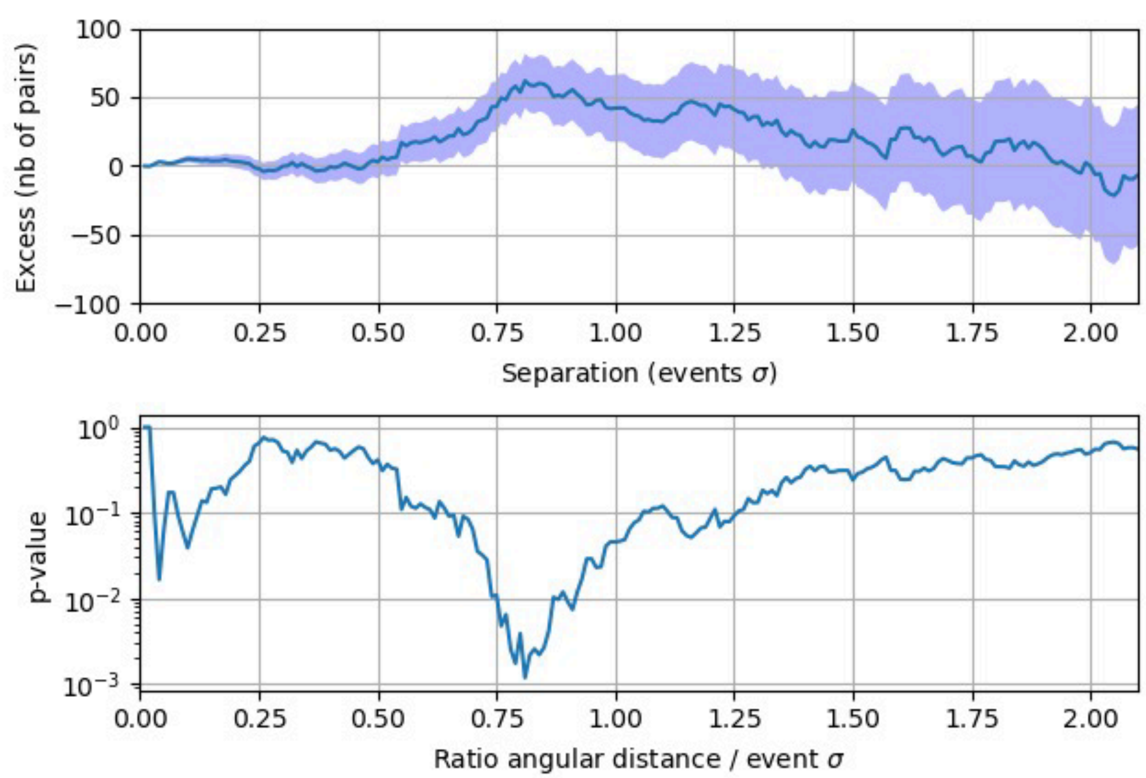
- **PKS 0735+178 (IHBL object) is one of the brightest BL Lac objects in the sky both in radio and gamma**
- **Similar spectral energy distributions, very high radio and γ-ray powers, and parsec scale jet properties as TXS0506**
- **Redshift unknown z ≥ 0.424**

Correlation with radio blazars

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

⟹ **Neutrinos from TeVs to PeV are produced in central parsecs of radio bright blazars. They correlate with major flares in jets.**
⟹ Radio interferometry is key to this discovery
⟹ Analysis with ANTARES data in progress





PoS(ICRC2021)1164

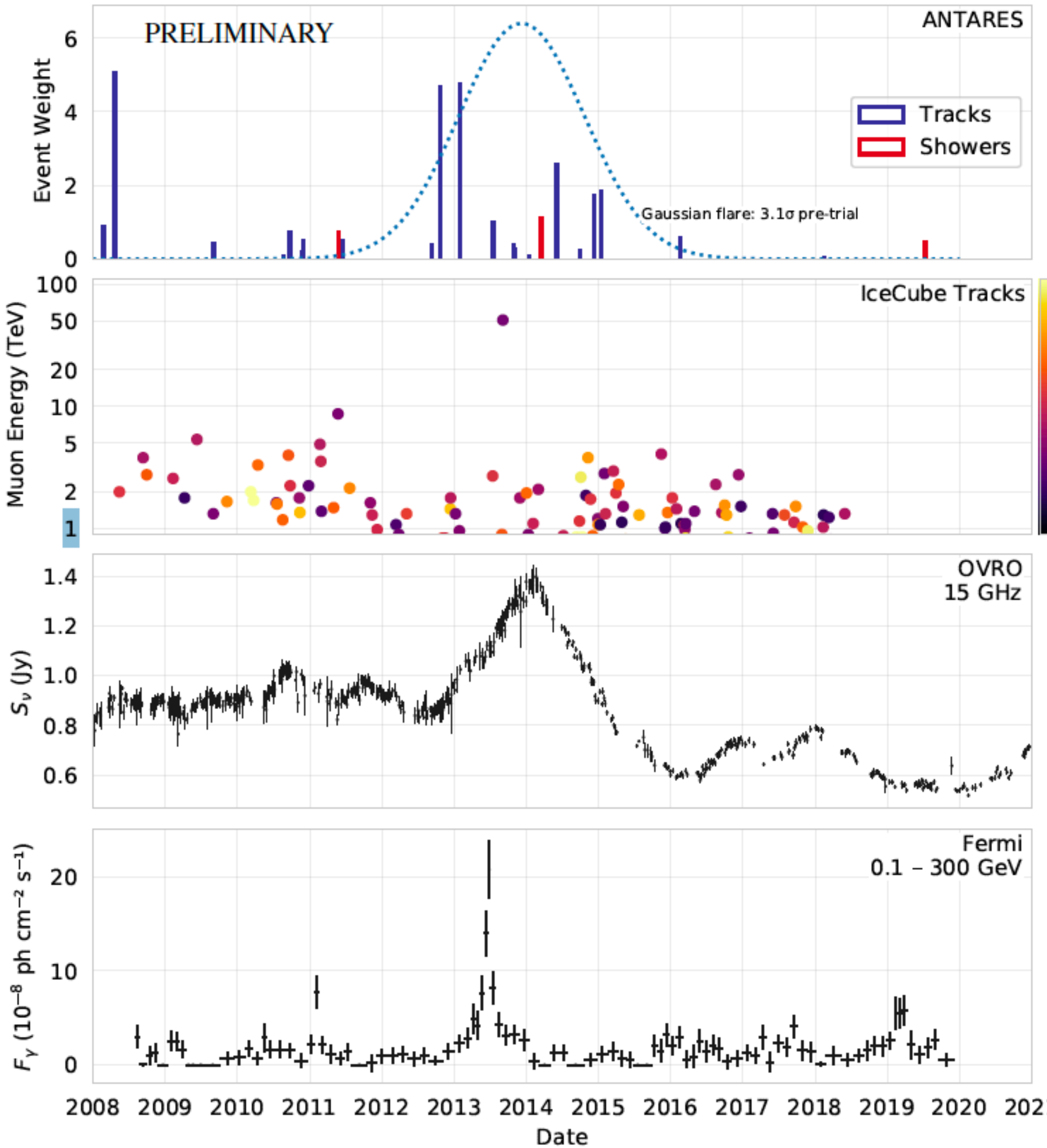
Plavin, Kovalev, Kovalev, Troitsky
2020: ApJ, 894, 101
2021: arXiv:2009.08914

Search for correlation radio blazars in VLBI data (2774 objects) and ANTARES PS sample 2007-2020 (10162 tracks) ⟹ post-trial p-value of 0.022 (~ 2.3 σ). **Analysis still in progress**

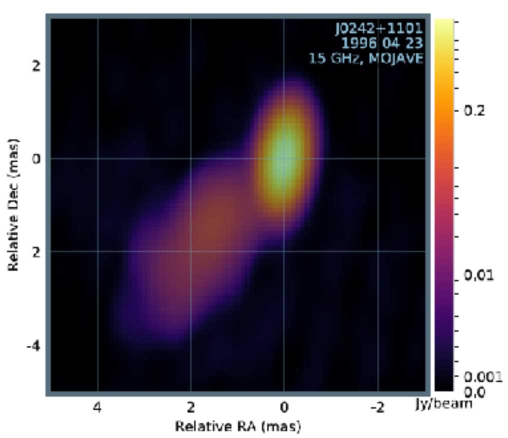
Neutrino flares from radio sources

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



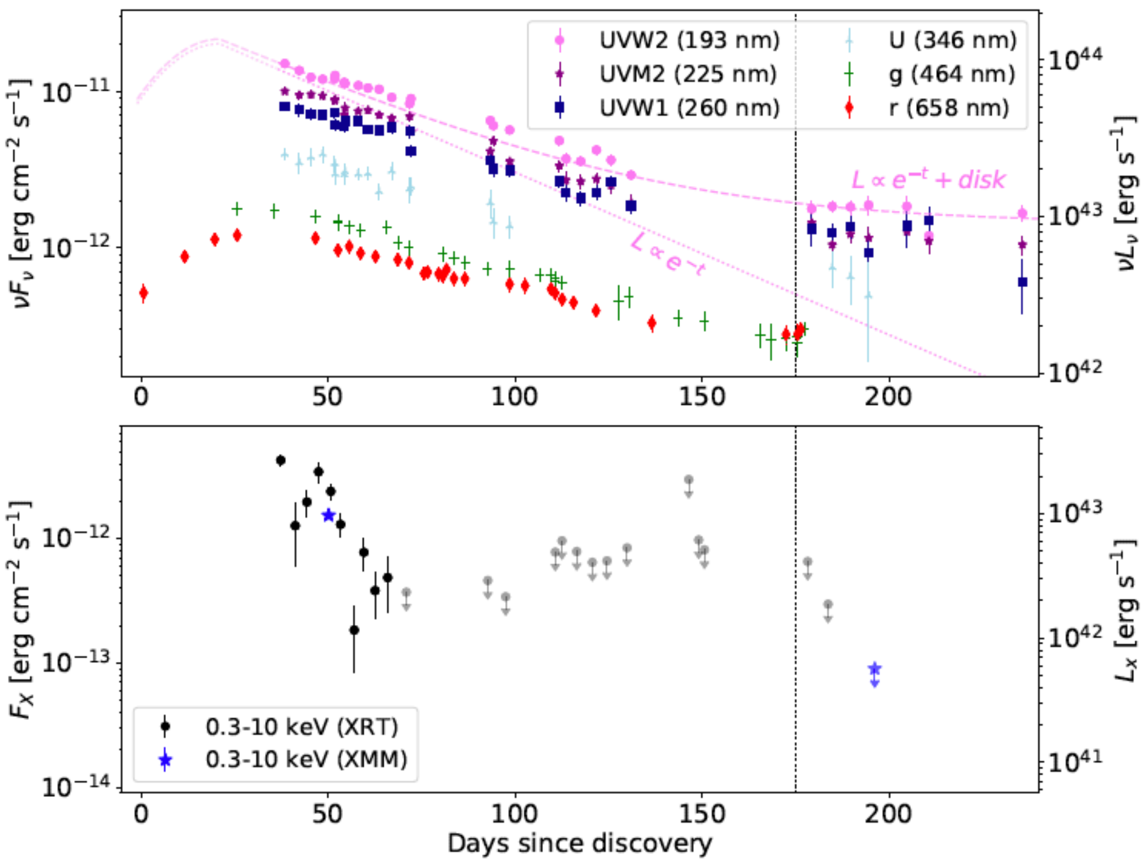
VLBI image at 15 GHz



PoS(ICRC2021)972

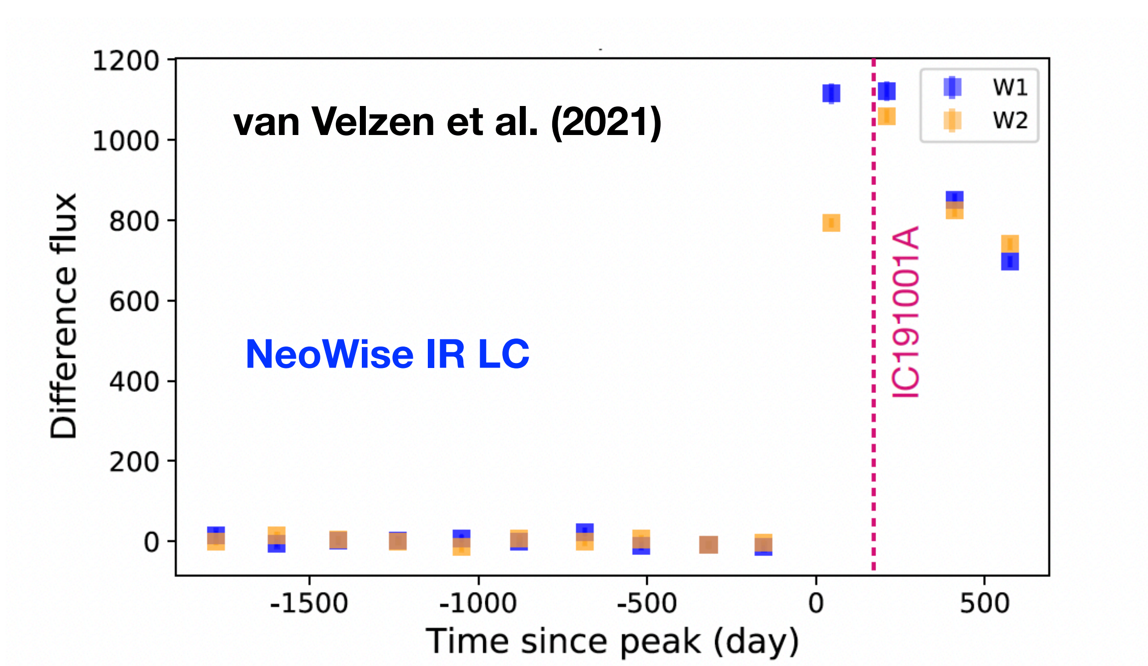
Computation of the chance probability of the association between radio, γ-ray and neutrino observations in progress

TDEs as new potential neutrino sources



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)



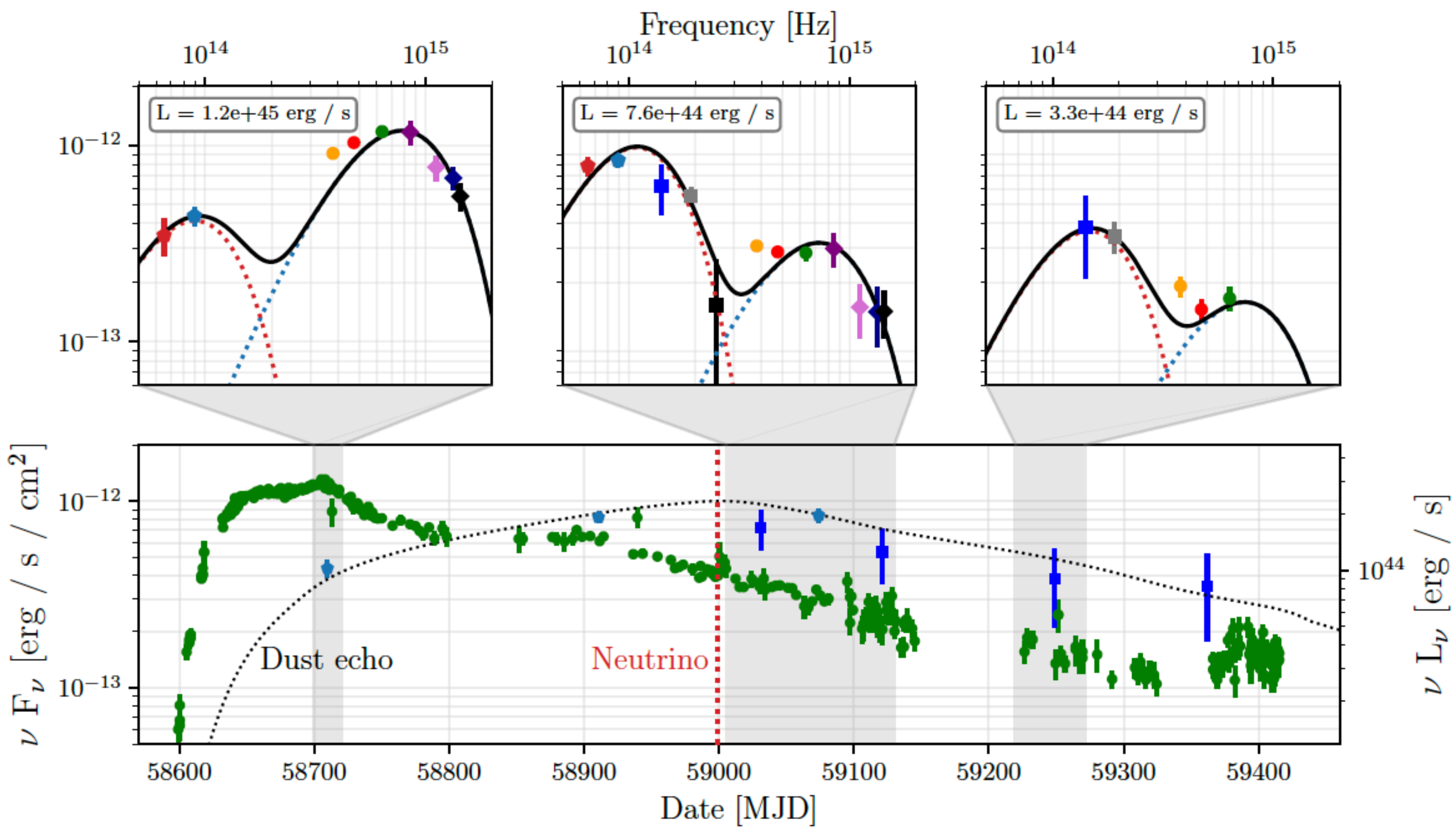
IC191001A - AT2019dsg:

- 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)

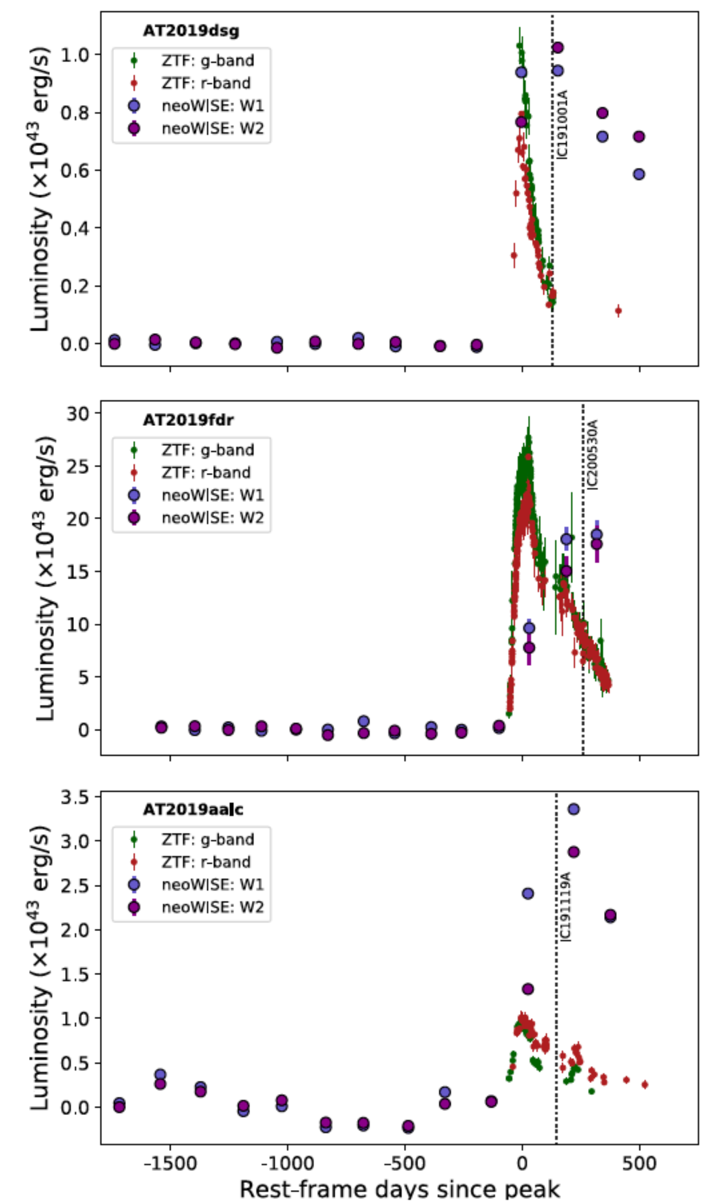
R. Stein et al., arXiv:2005.05340

TDEs as new potential neutrino sources

- **Possible other association: IC200530A - AT2019fdr (delay of ~300 days)**



Reusch et al. (2022 PRL)



van Velzen, Stein, et al. (2021)

- **A possible 3rd association: AT2019aajc / IC191119A**

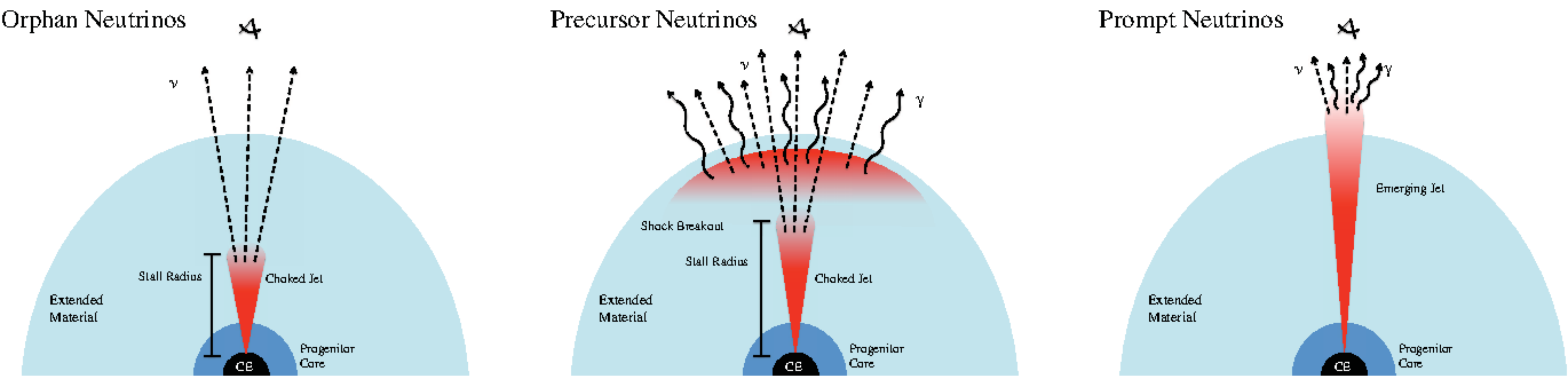
⇒ Quite common features: large dust echo (visible in IR LC), low mass BH

⇒ Stacking: 3.6 σ

Analyses by ANTARES: no association for both TDEs

A. Albert et al., ApJ 920 (2021) 50

Gamma-ray bursts

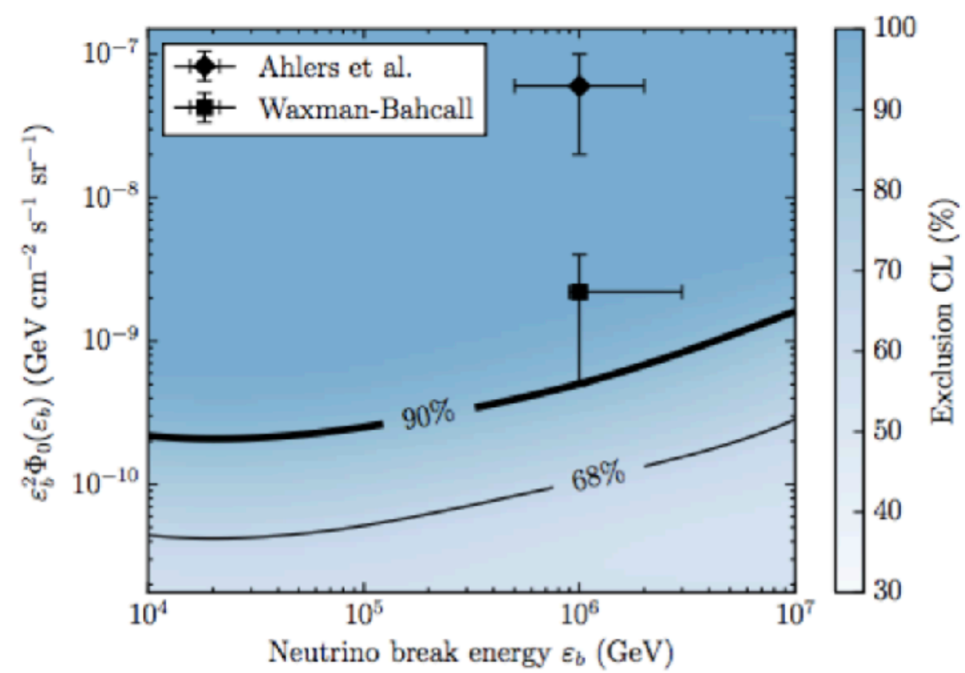


Despite intensive searches by IceCube and ANTARES >2000 bursts

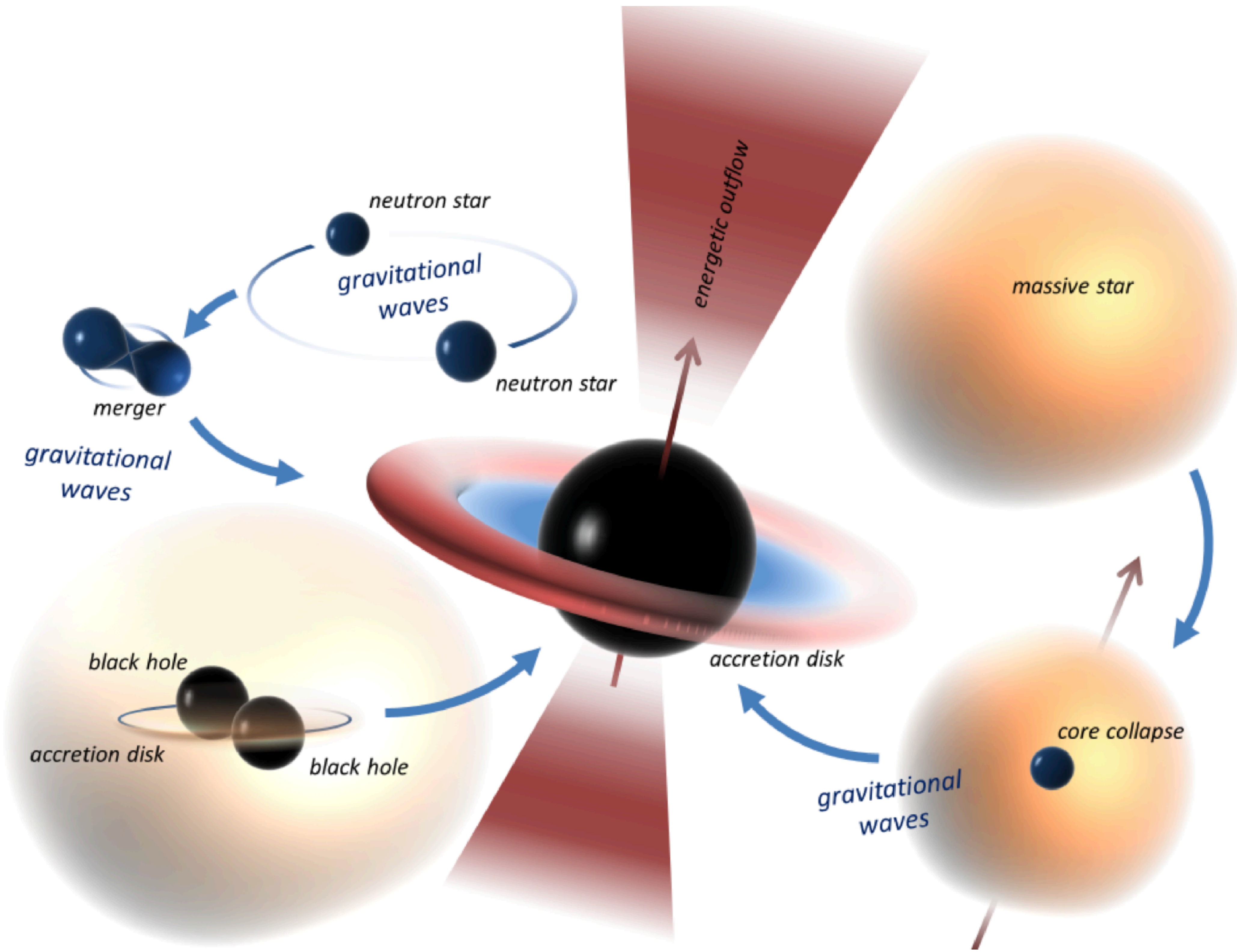
⟹ no excess found with the prompt emission

⟹ **GRBs contribute less than 1% to observed diffuse neutrino flux (<10% for ANTARES) if looking at the prompt window. Potential large population of nearby low-luminosity GRBs not constrained, larger time windows**

⟹ Try others precursor, afterglow and absorbed GRB searches



Compact binary mergers



Neutrinos @ Compact binary mergers

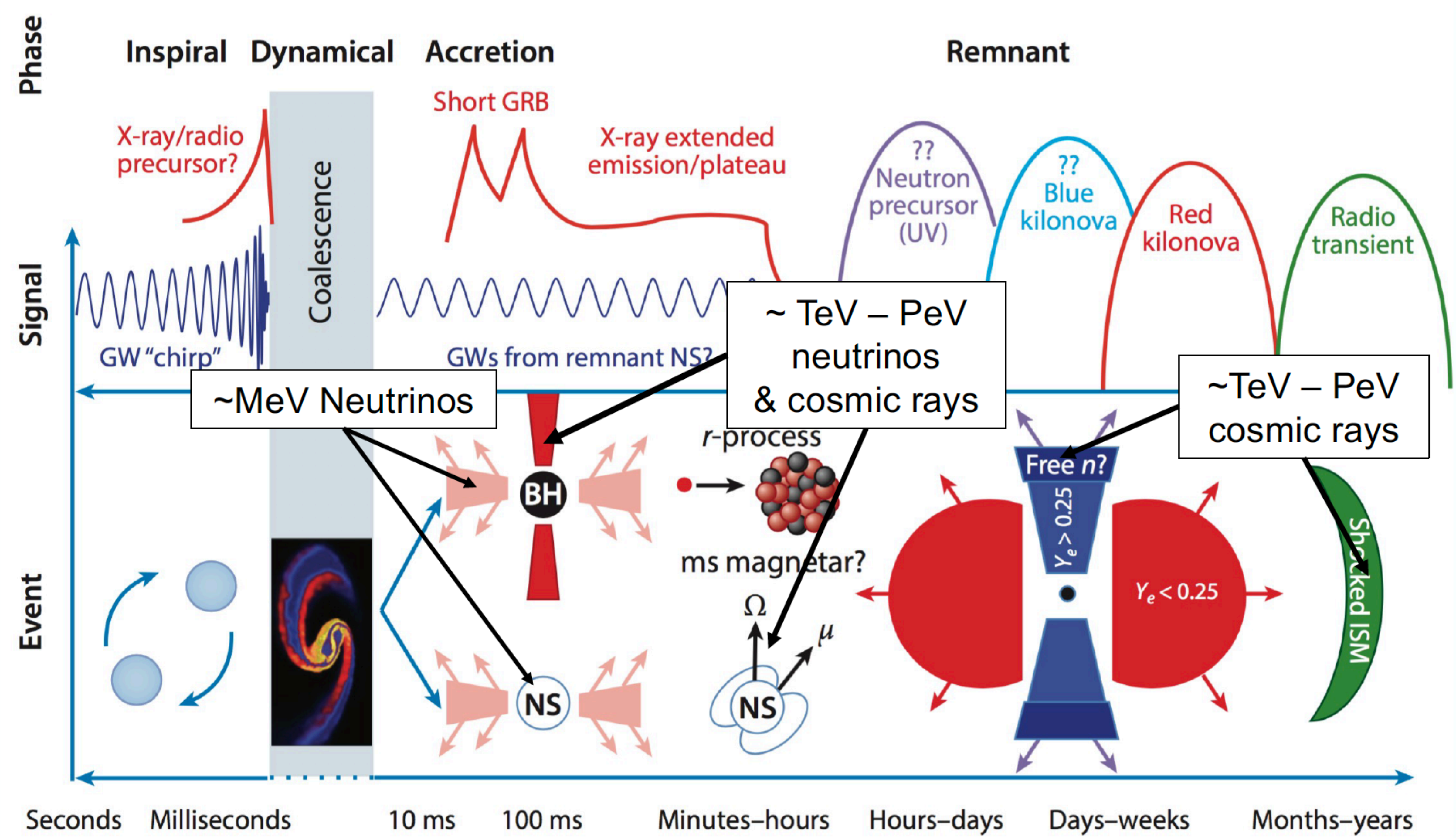
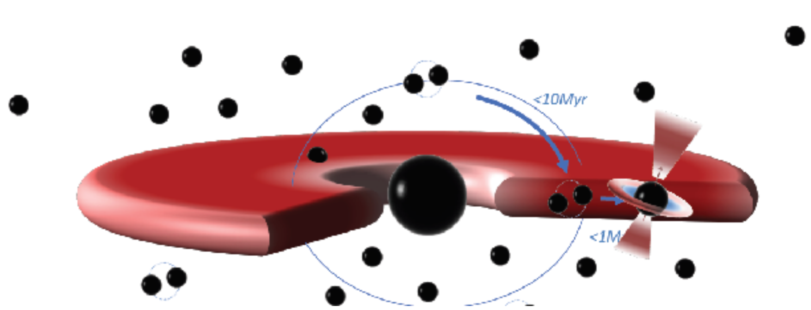


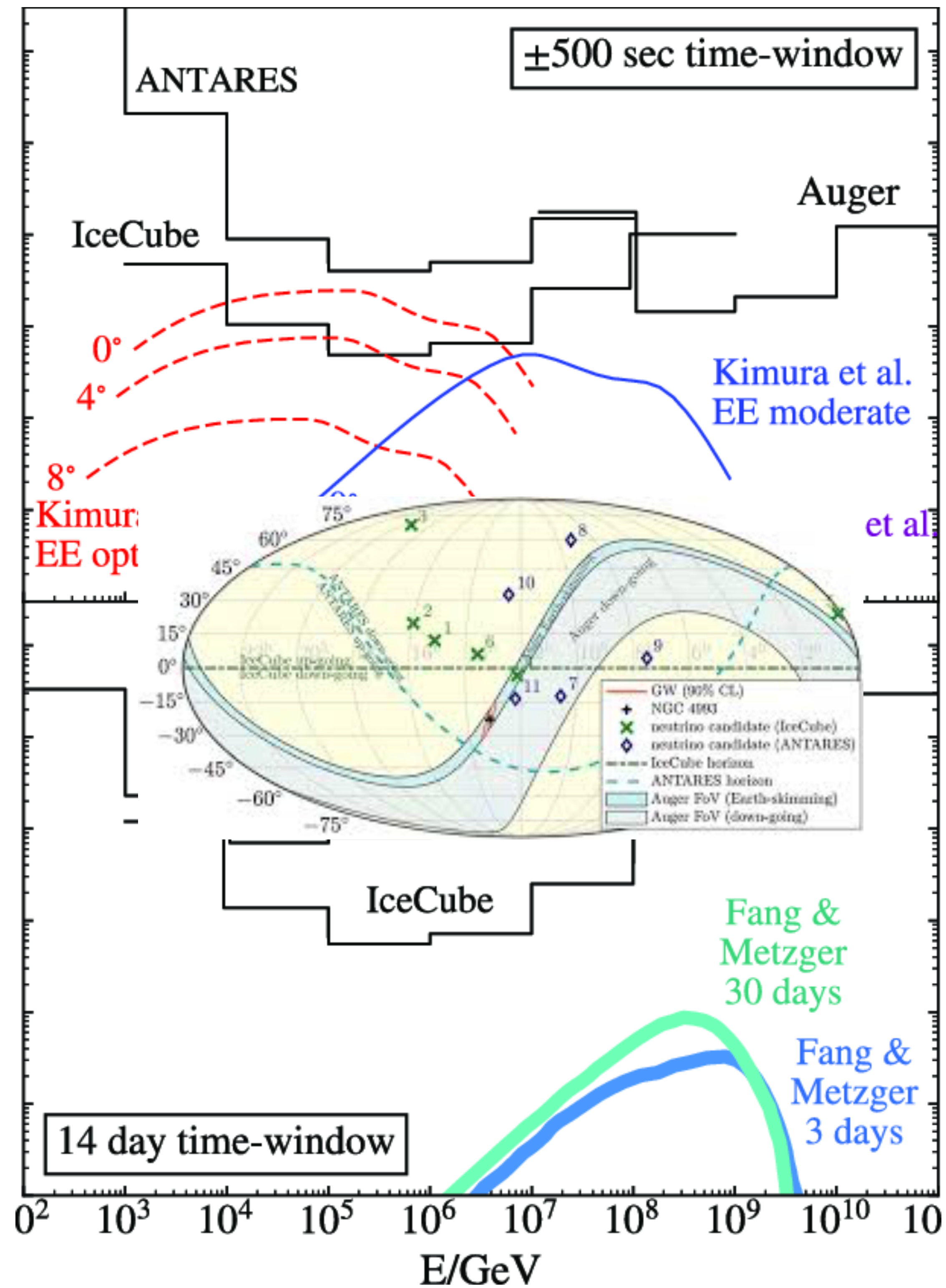
Figure credit: Brian Metzger.

Results of the neutrino searches

BNS merger or NS-BH: looking for a short GRB signal (kilonova produced too low energy neutrinos) or the remaining potential magnetar

BBH merger: either looking for BBH happening in dense environment or with large mass difference between the 2 progenitors (remaining accretion disk)





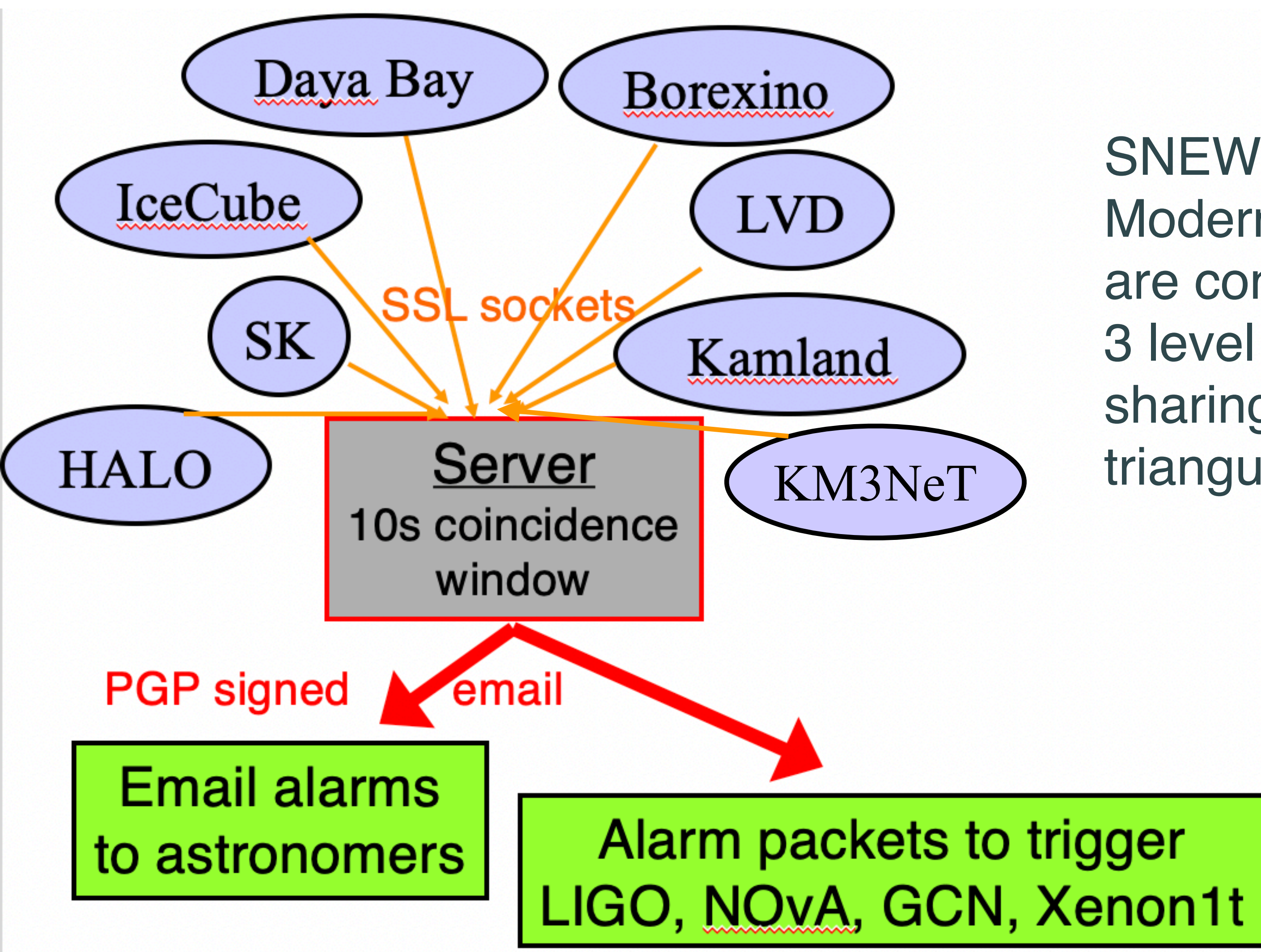
ANTARES + Auger + IceCube, *Astrophys.J.Lett.* 850 (2017) 2, L35

SNEWS

- SNEWS: Supernova Neutrino Early Warning System (started in 1998, fully operational in 2005)
- Neutrino detectors send alerts with FAR < 1 / week.
- 10 second coincidence time window.

=> A public alert is produced if coincidence is found. Prompt and positive alerts. Less than one false alert per century.

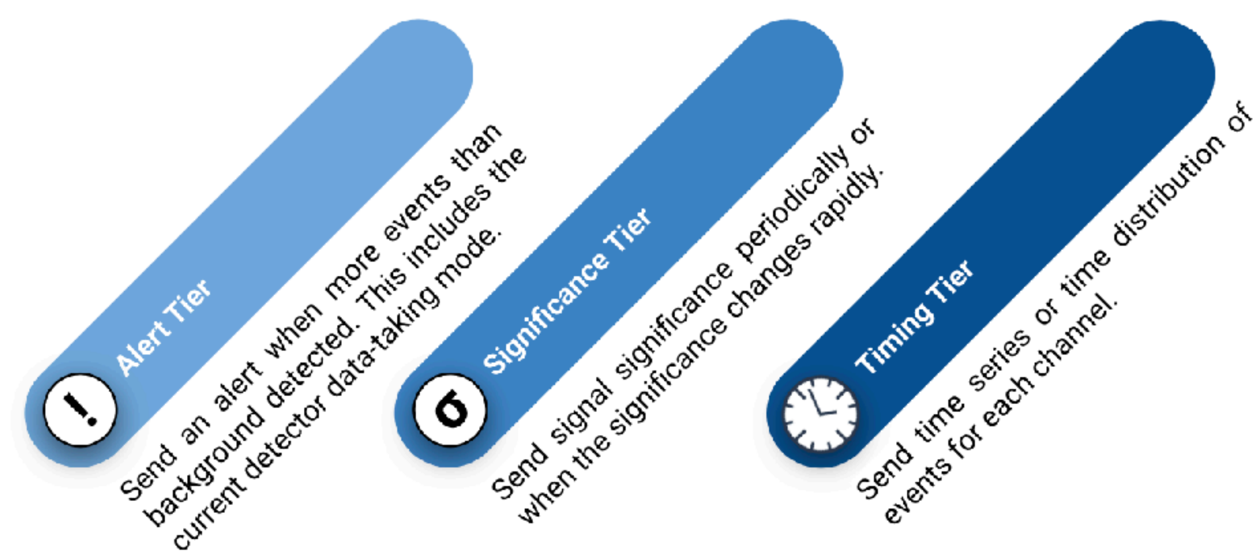
=> No SNEWS alert has been ever sent



SNEWS 2.0 (in development)

Modern multi-messenger scenario, low-threshold alerts are common => Richer multi-messenger program.

3 level of alerts: Significance-based alerts, time-series sharing, real-time analysis capabilities (e.g. triangulation).



Summary

→ **Solid measurements of the diffuse high-energy neutrino flux by IceCube, GVD and ANTARES. We are touching the top of the iceberg of the neutrino sources (blazars, TDE, Seyfert).**

- TXS 0506+056, PKS B1424-418, PKS1502+106, PKS0735+178
- MG3 J225517+2409, J0242+1101, J0538-4405…
- 3 TDEs

→ **In the Northern hemisphere, new neutrino detectors, GVD and KM3NeT are having competitive sensitivities, largely better than ANTARES effective area.**

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