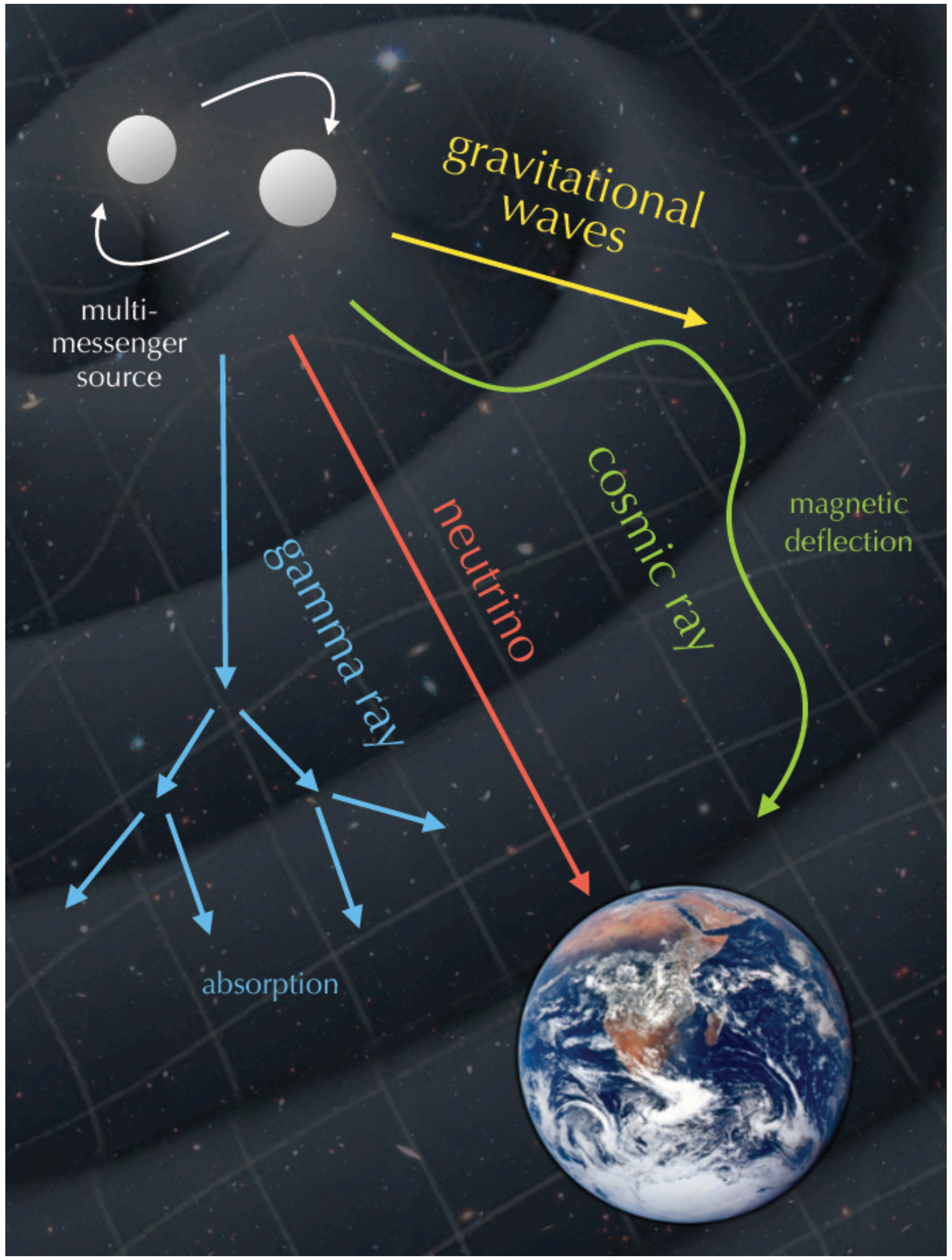
Multi-messenger observations with neutrinos

DAMIEN DORNIC (CPPM)

Cospa - April 22, 2022

Neutrinos as cosmic messenger

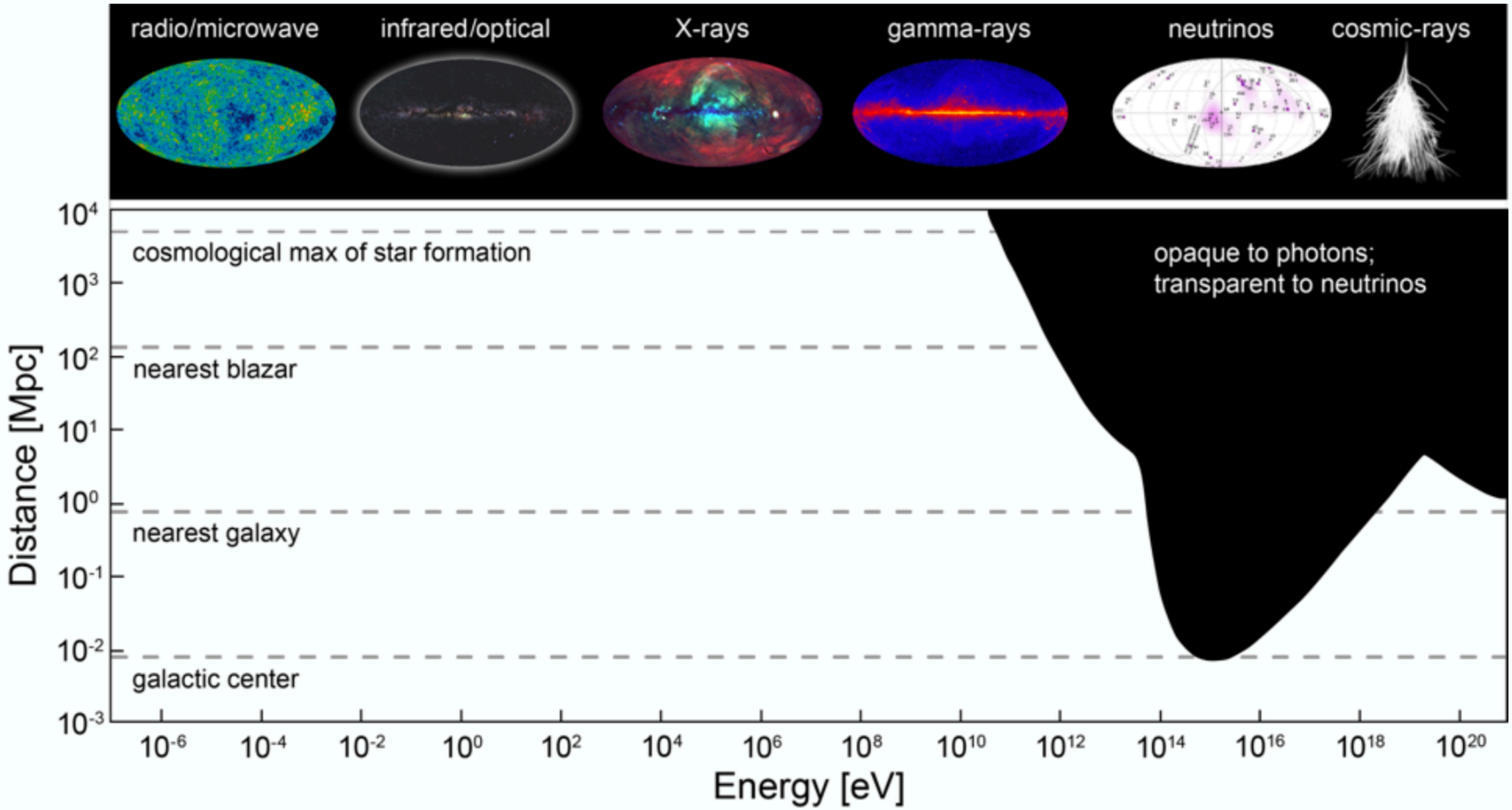


Multi-messenger: use of the 4 messengers to study extreme astrophysical phenomena. Each one bring one piece of the puzzle.

Neutrinos are neutral, weakly-interacting, elementary particles.

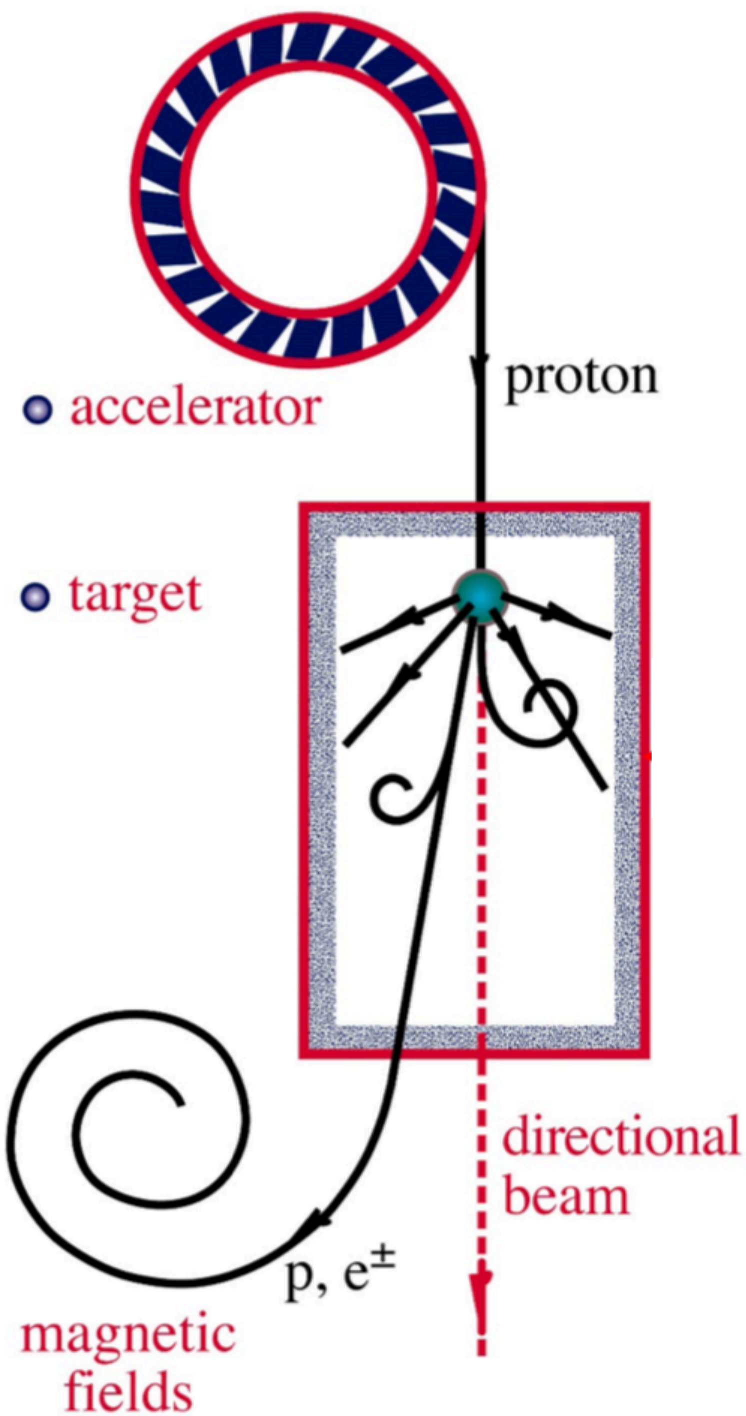
⟹ Smocking gun of the cosmic-ray sources.
⟹ However, finding neutrino sources is still challenging [large background contamination and tiny fluxes]

Promise land

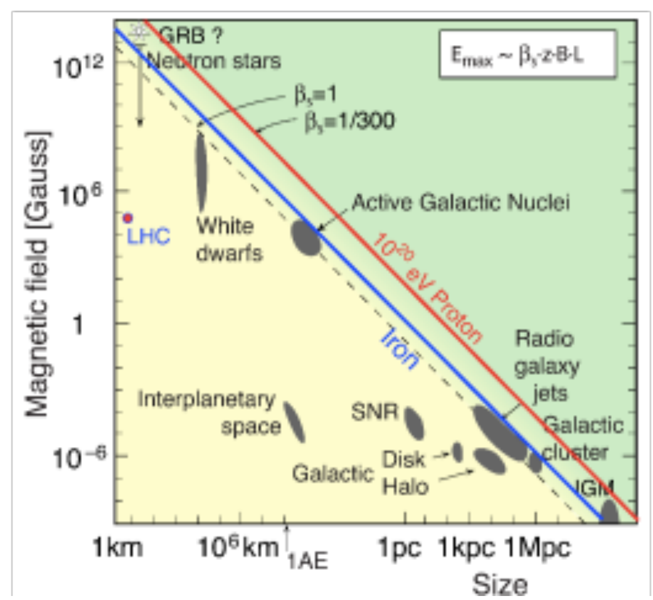


The Universe is opaque to EM radiation for ¼ of the spectrum, i.e. above 10-100 TeV where IceCube sees cosmic neutrinos.

Potential neutrino sources



To produce neutrino ⟹ CR accelerator & target



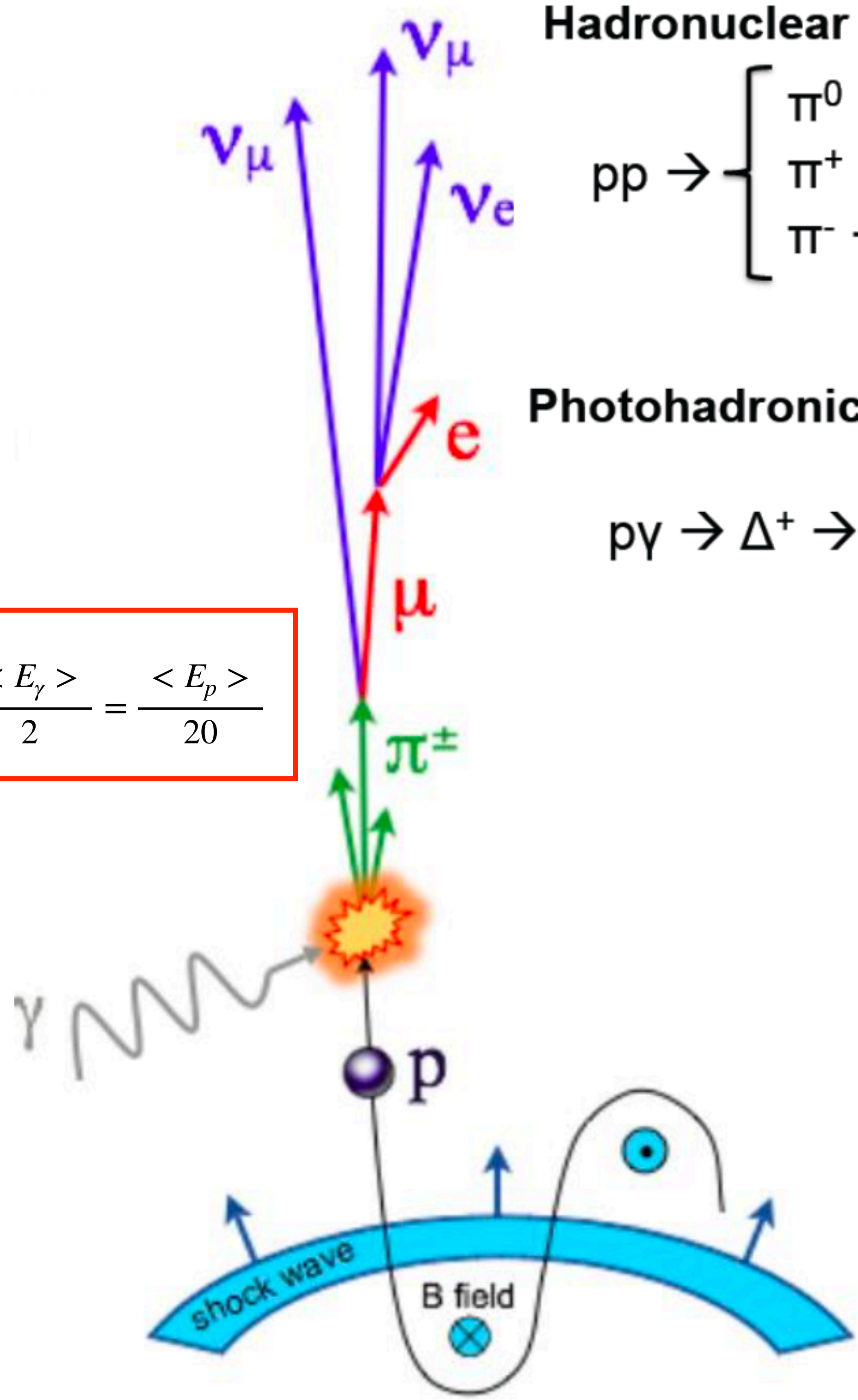
Hillas criteria

$p + \gamma \rightarrow \Delta^+$ (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

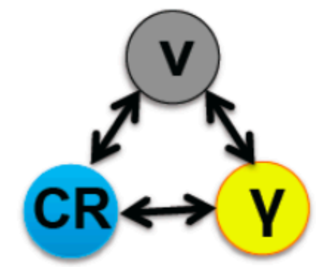
HE neutrino production



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

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

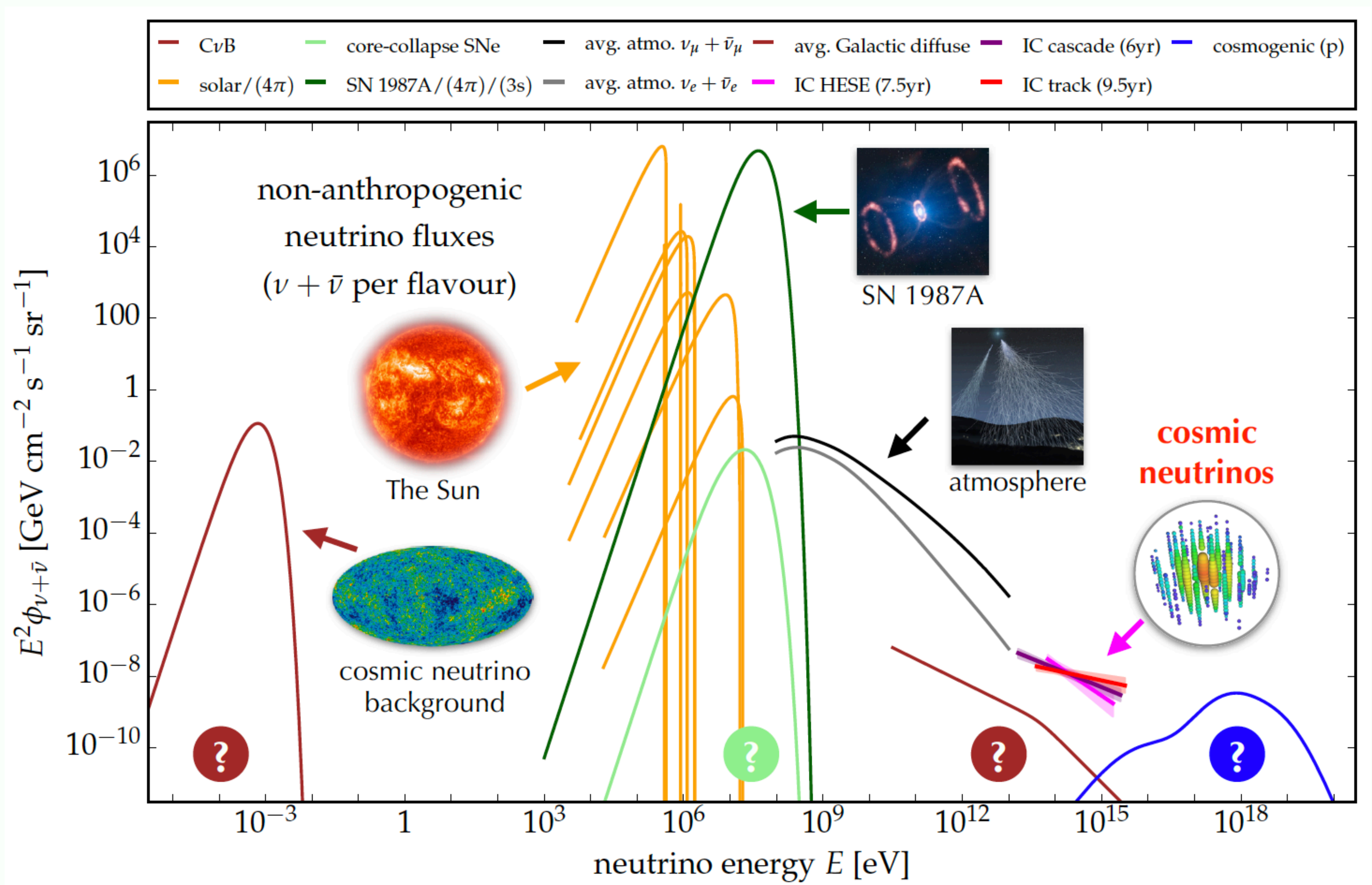
$$\nu_e : \nu_\mu : \nu_\tau \sim 1:2:0$$

Oscillations average out over cosmic baselines

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

Strong links between CR, γ-ray, ν ⟹ Multi-messenger astronomy

Astrophysical neutrino fluxes



ANTARES

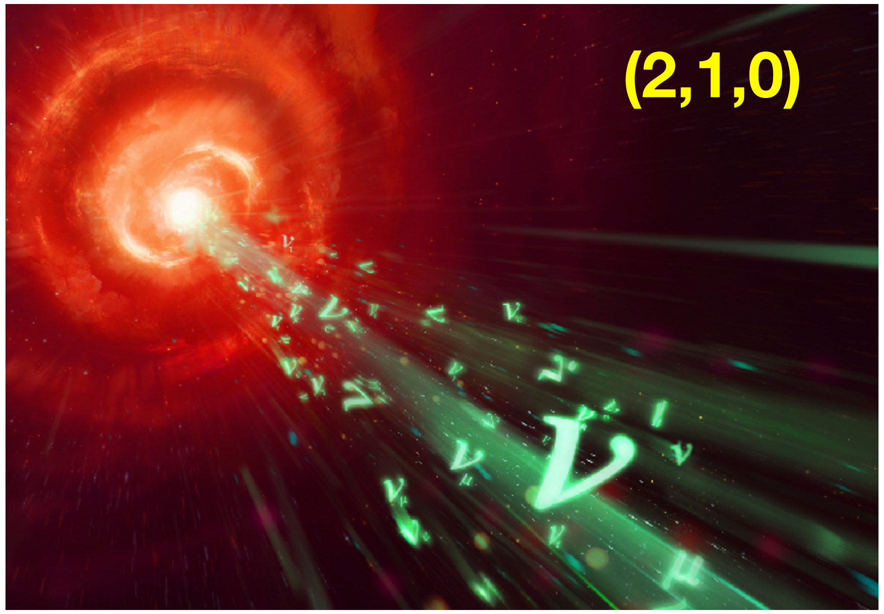
KM3NeT

IceCube

GVD

All-flavor neutrino detection

ν_e ν_μ ν_τ

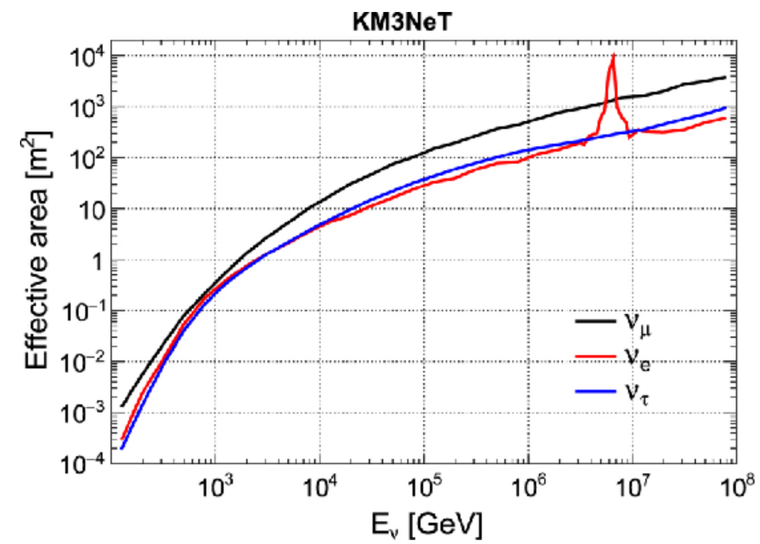


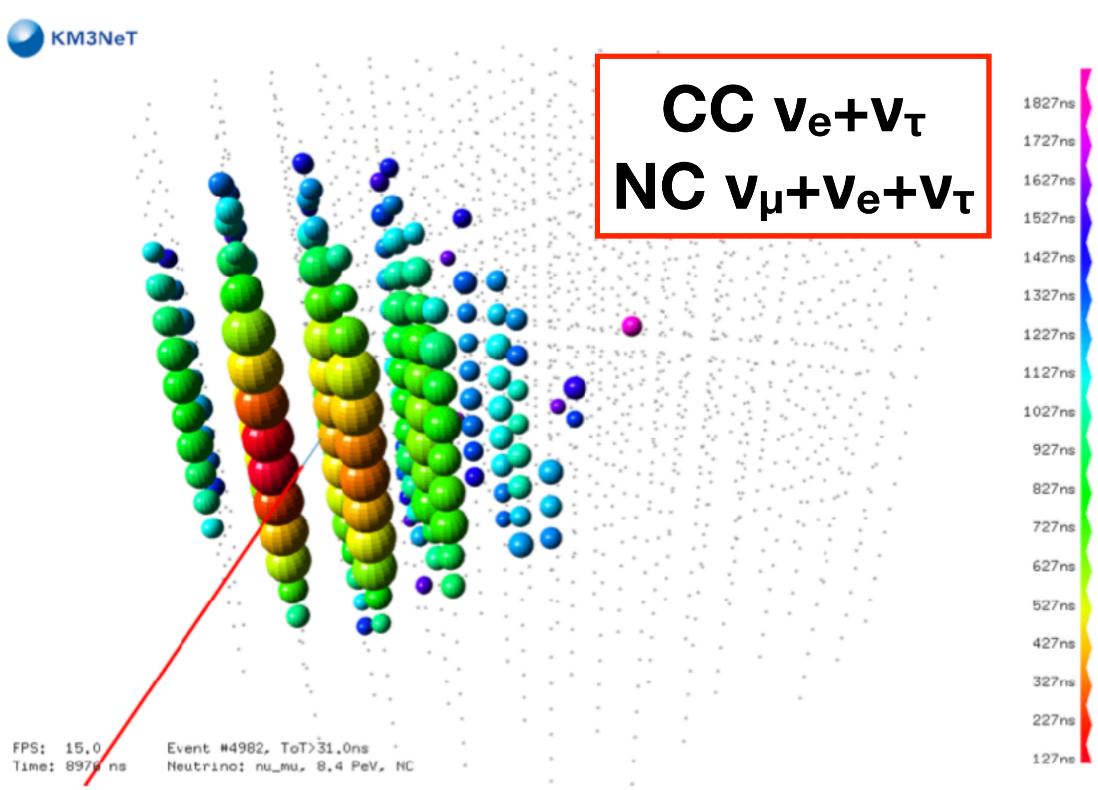
New physics ?

Oscillation

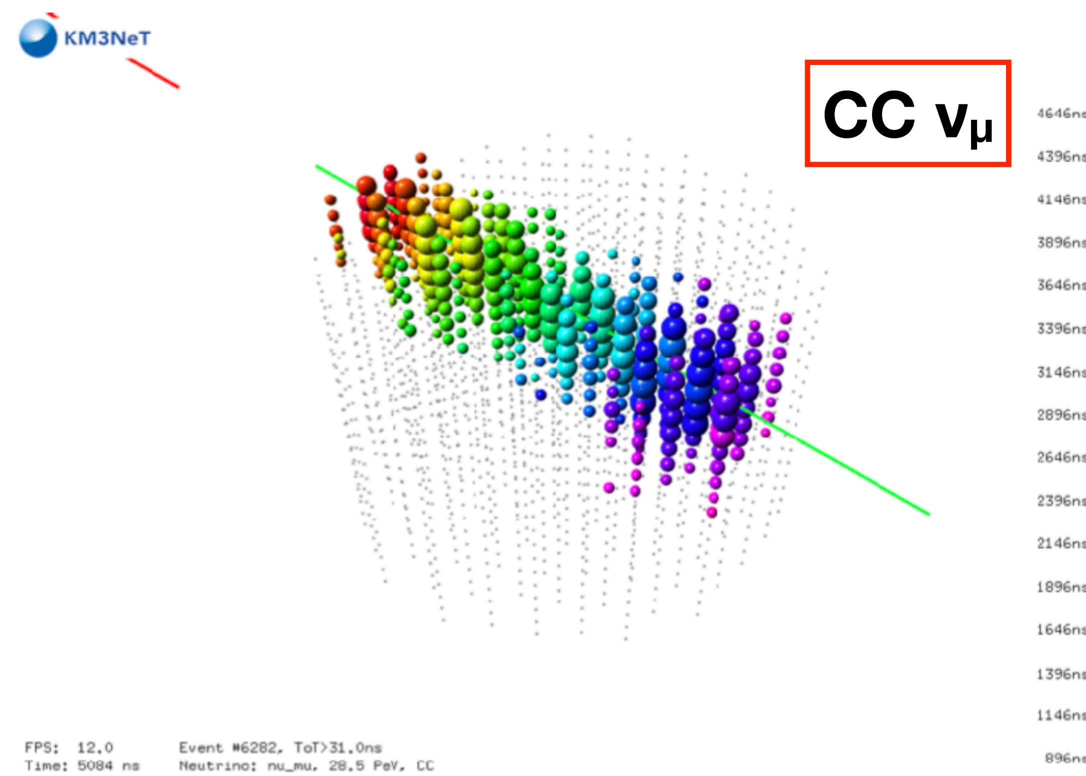
(1,1,1)

Each neutrino flavor brings information
⟹ All-flavour astronomy



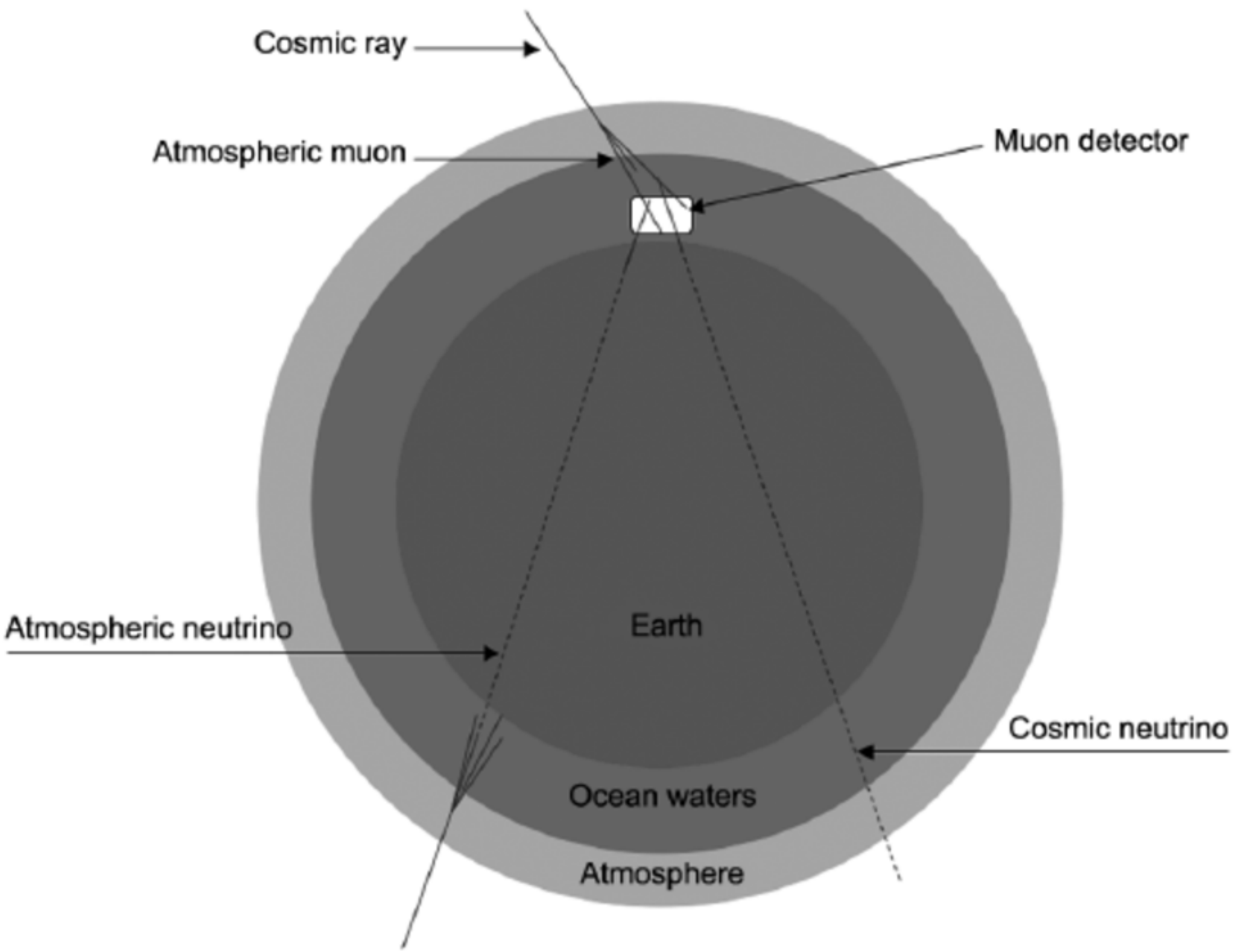


(double cascade for VHE ν_τ)



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

IceCube
South Pole Neutrino Observatory

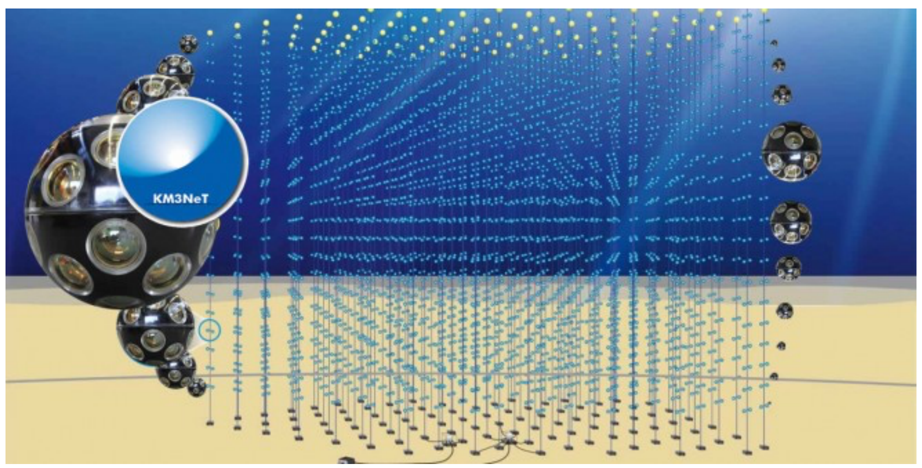
ANTARES

ANITA

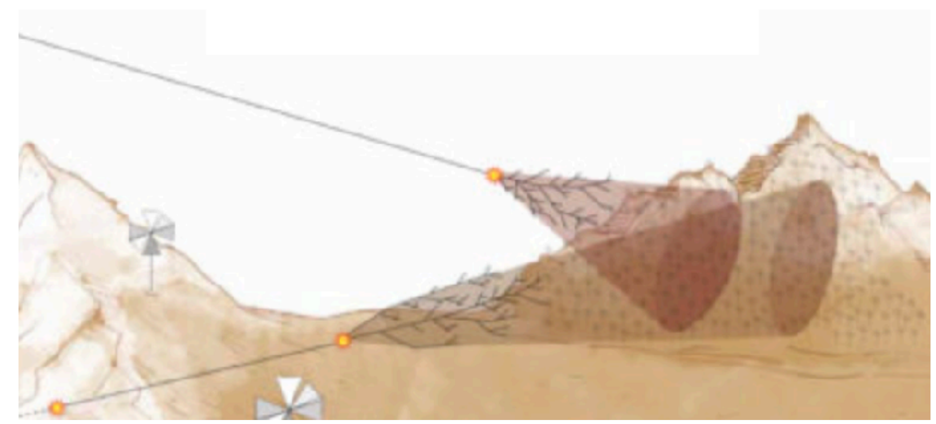
PIERRE AUGER OBSERVATORY

Precision Frontier

Energy Frontier



Intensity Frontier

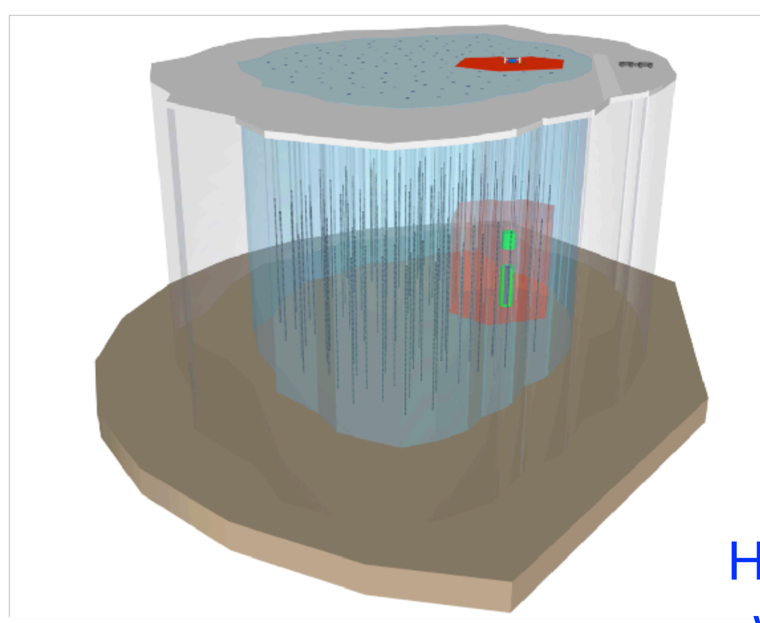


GRAND, ARA, ARIANNA, POEMMA

Tracking cosmogenic ν at UHE

KM3NeT, GVD

Having the best angular resolution with a reasonable instrumented volume



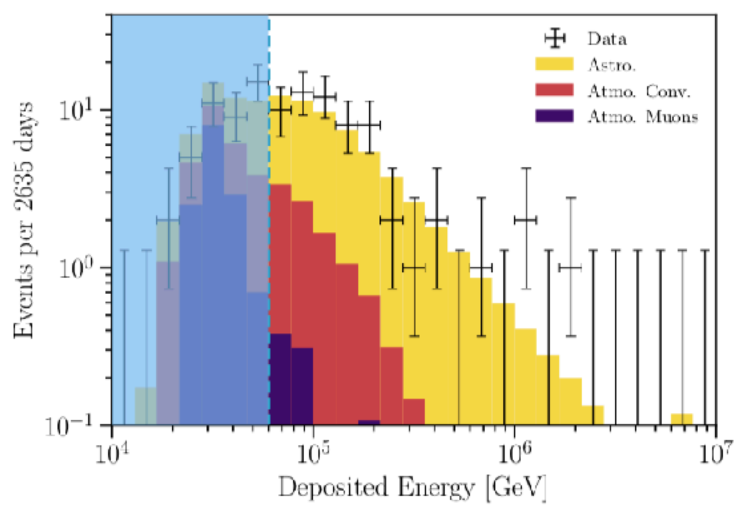
IceCube Gen2

Having the largest statistics with reasonable precision

HE ν diffuse fluxes detected

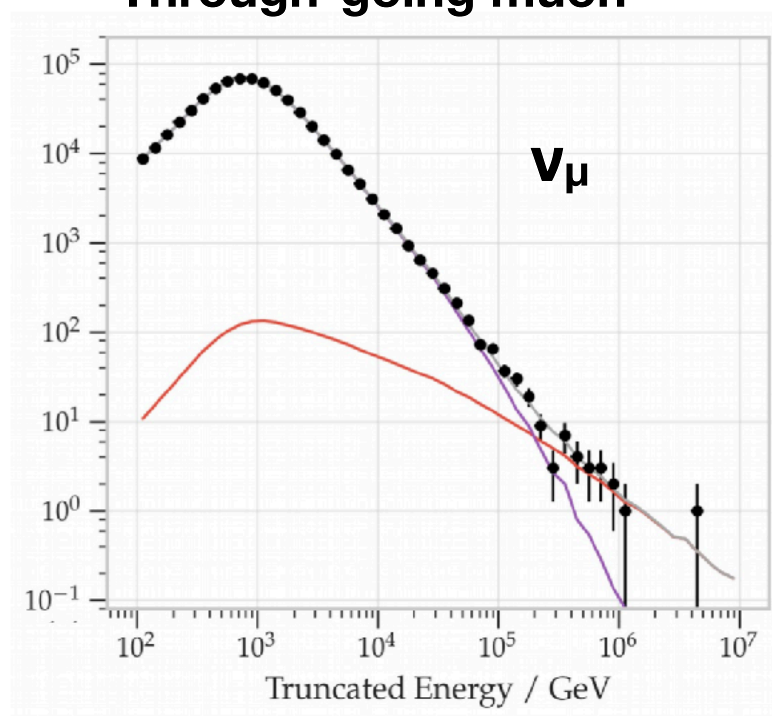
IceCube 7-10 yrs

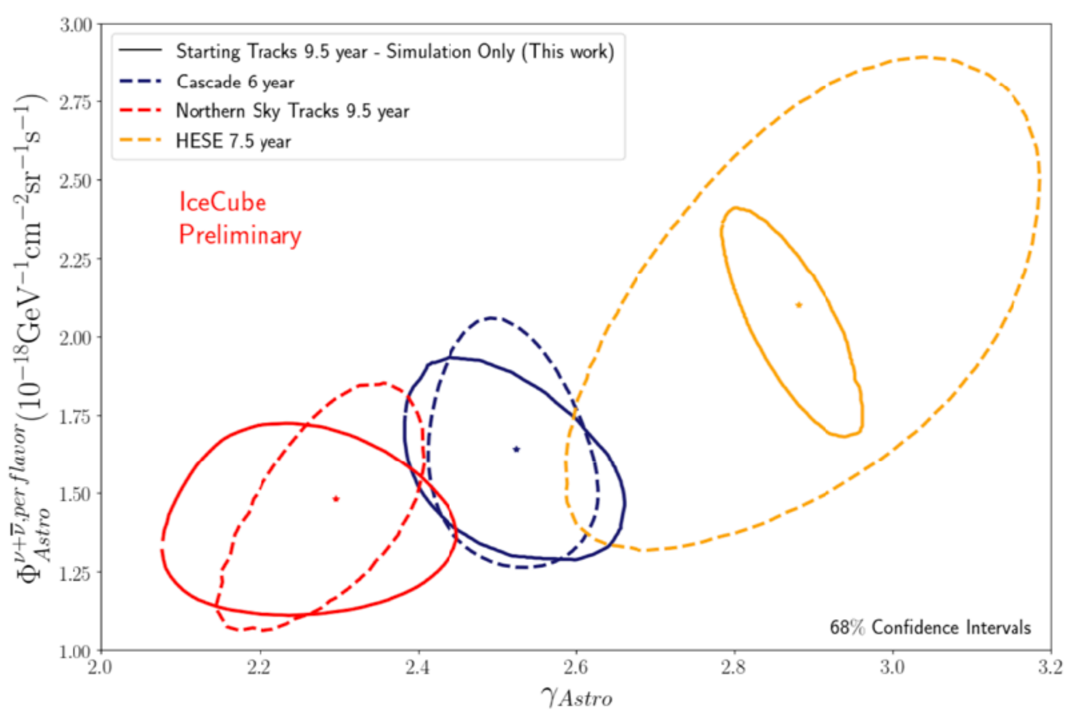
HESE



arXiv:2011.03545

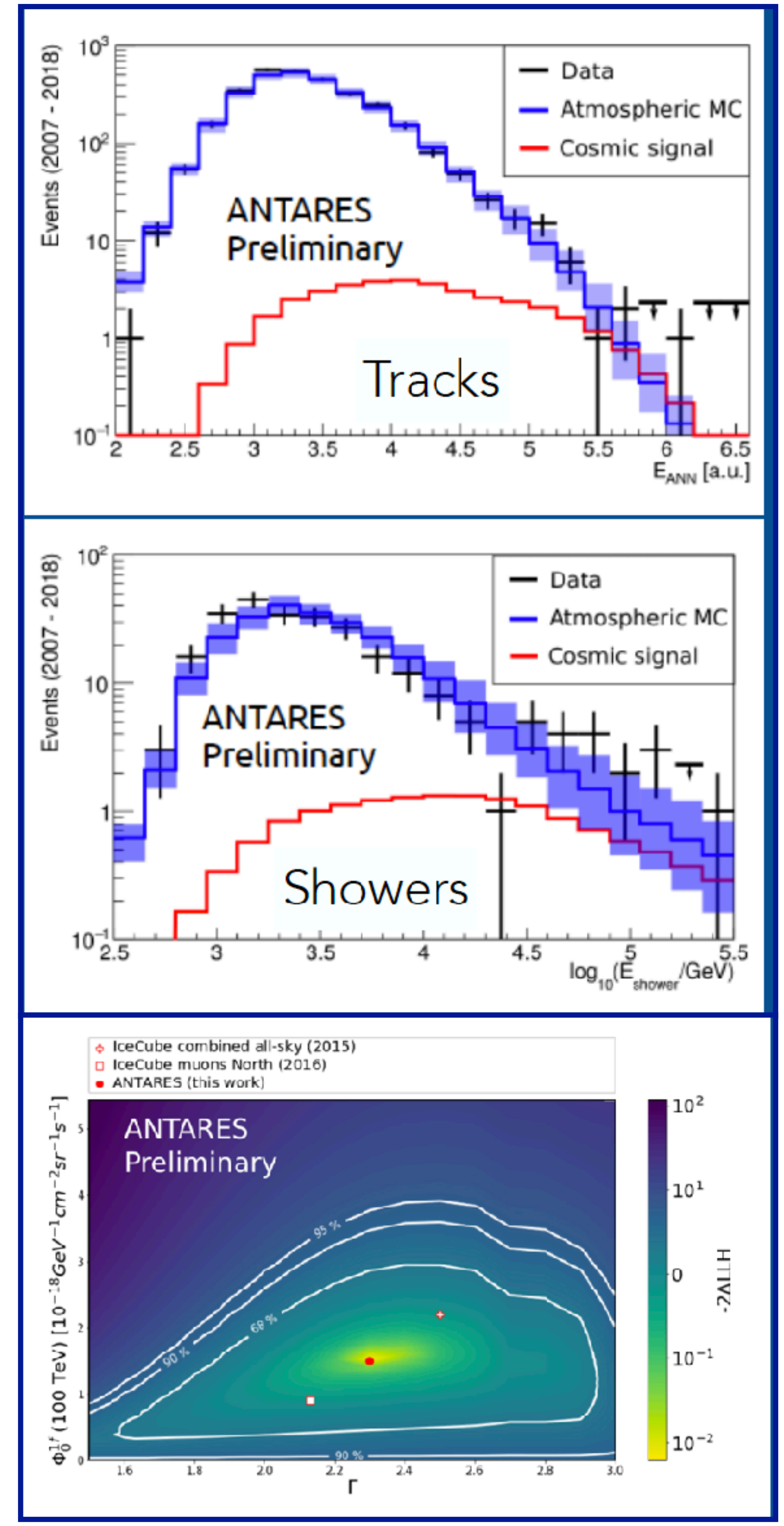
Through-going muon





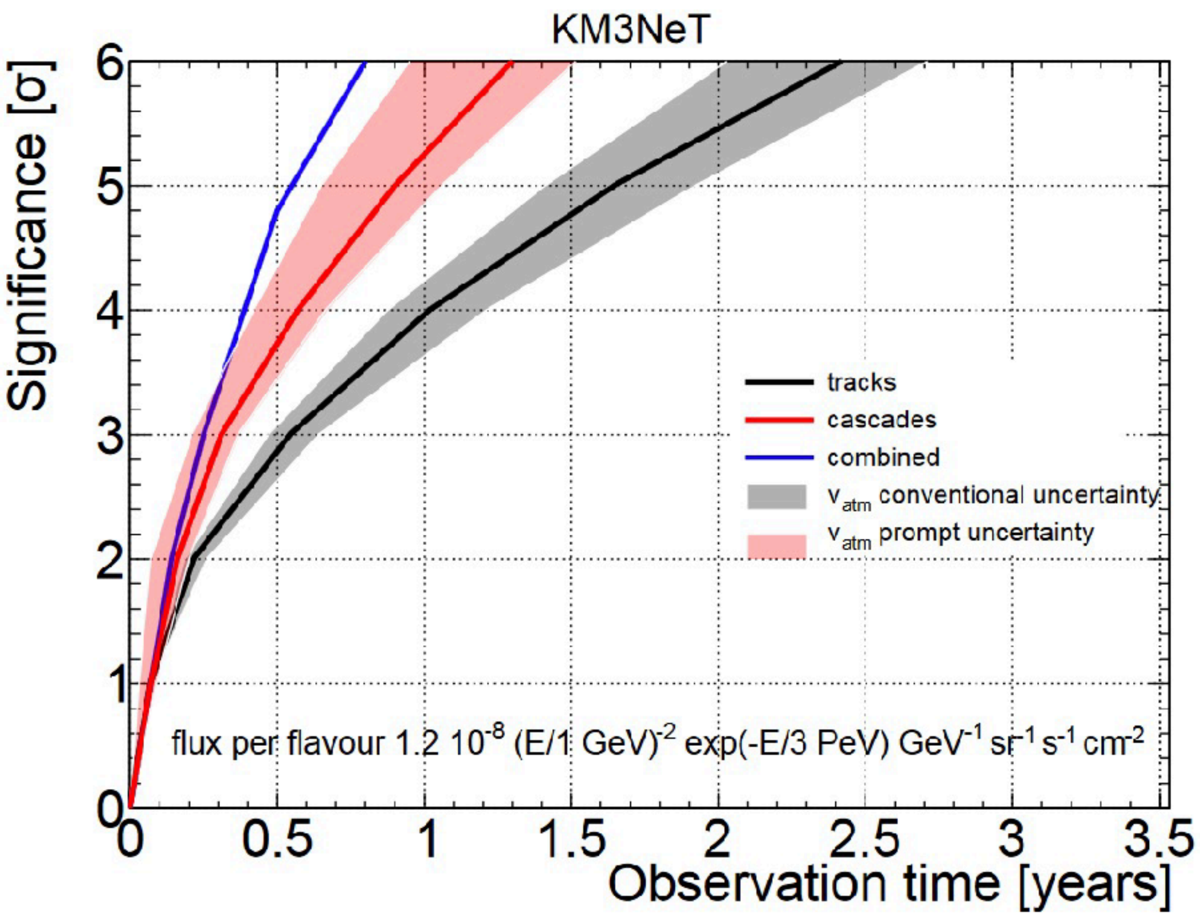
PoS(ICRC2021)1130

ANTARES 11 yrs



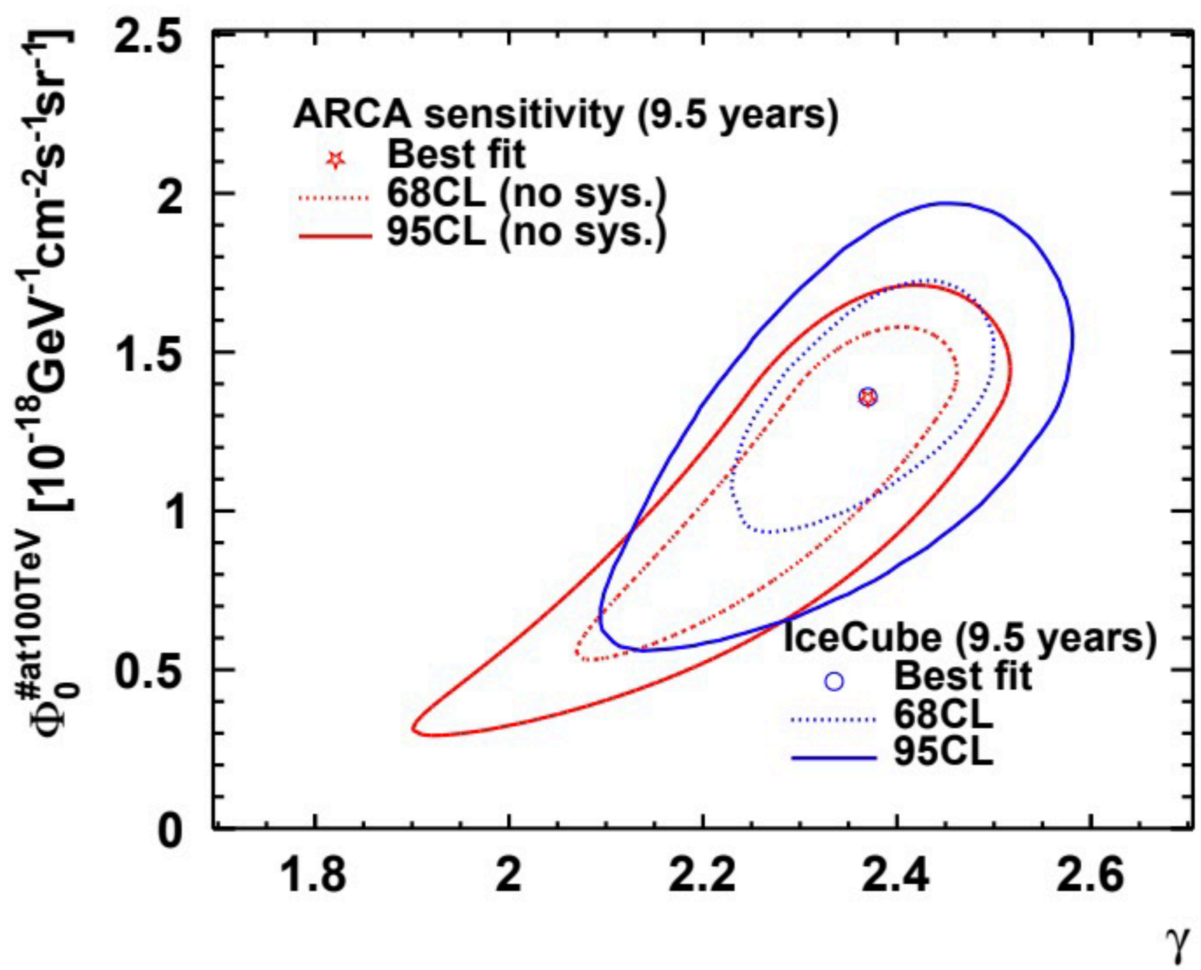
PoS(ICRC2021)1126

HE ν diffuse fluxes with KM3NeT



Detectability of the HE flux (benchmark IC flux)

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



PoS(ICRC2021)1077

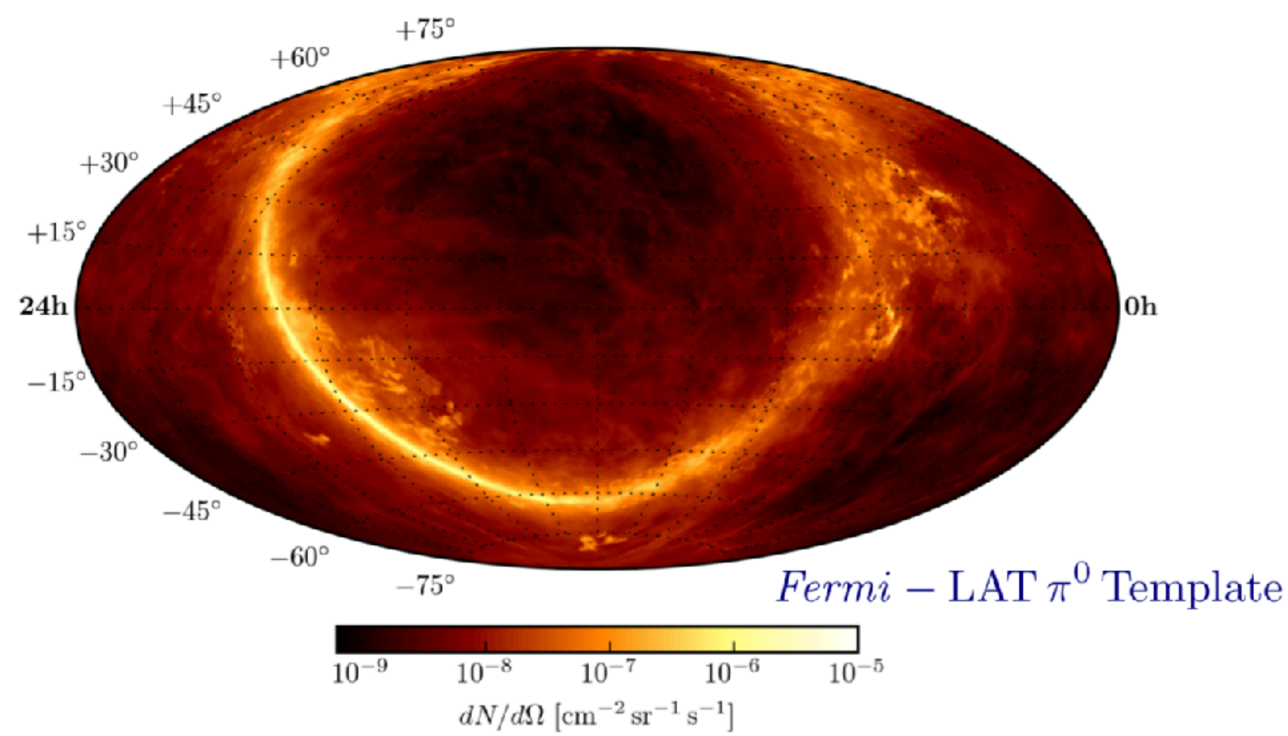
Where is the galactic diffuse component ?

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)

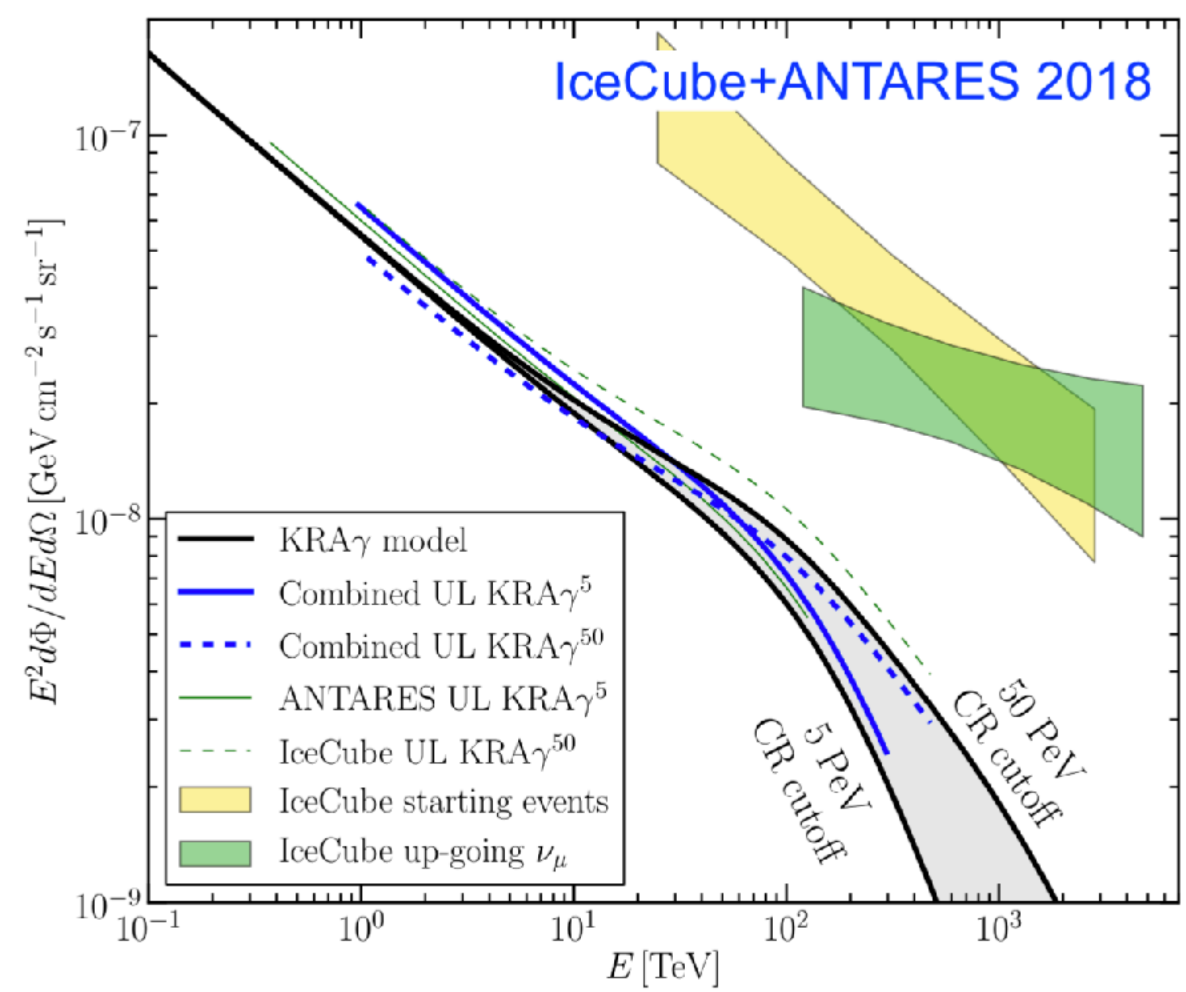
⟹ **Galactic contribution constrained at the level of ~10% of the diffuse flux**

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

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

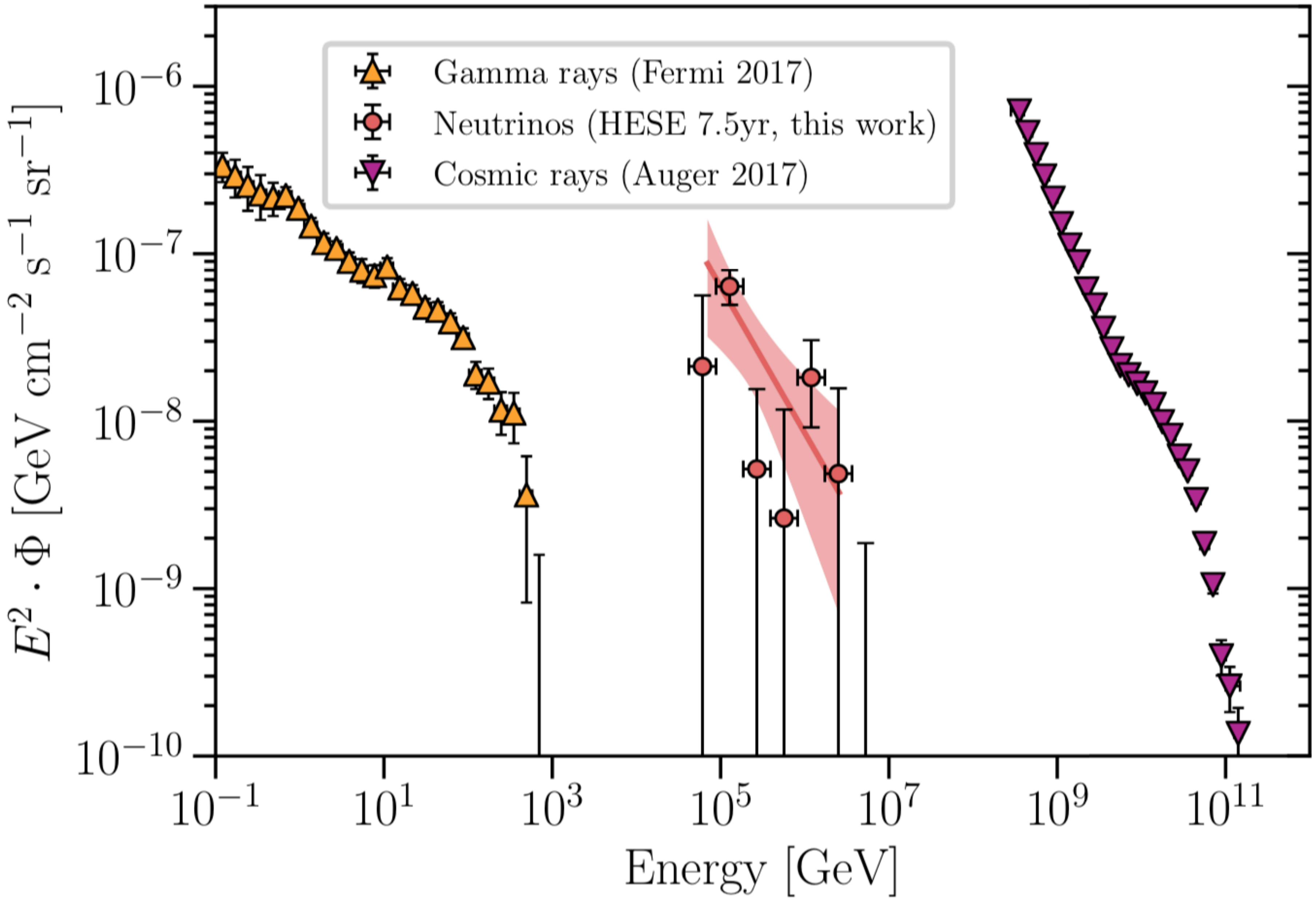


Energy cutoff	Sensitivity [Φ_{KRA_γ}]			Fitted flux	p-value	UL at 90% CL
	Combined	ANTARES	IceCube	[Φ_{KRA_γ}]	[%]	[Φ_{KRA_γ}]
5 PeV	0.81	1.21	1.14	0.47	29	1.19
50 PeV	0.57	0.94	0.82	0.37	26	0.90



Multi-messenger context

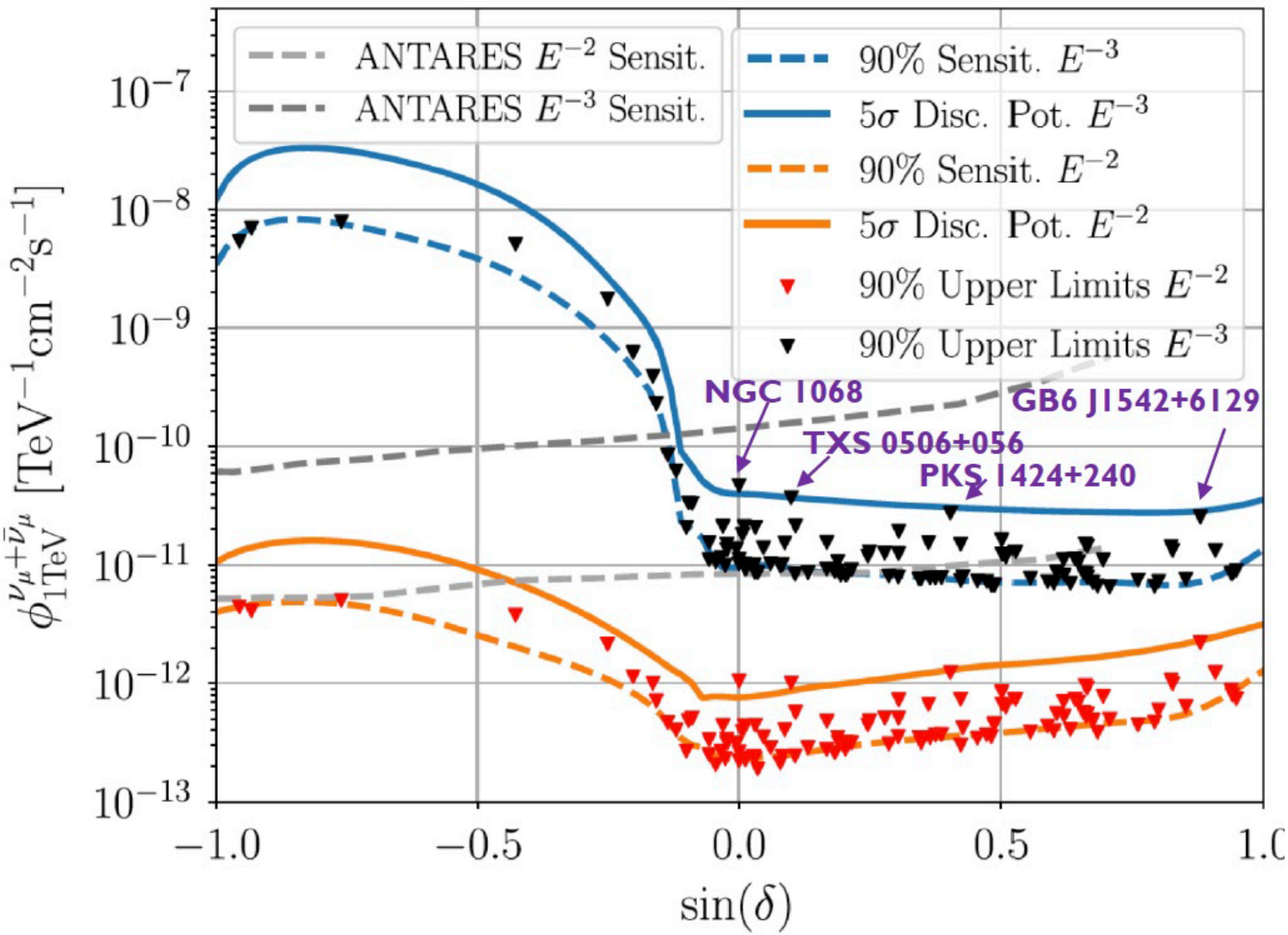
Diffuse high-energy fluxes of gamma rays, neutrinos, and cosmic rays



arXiv:2011.03545

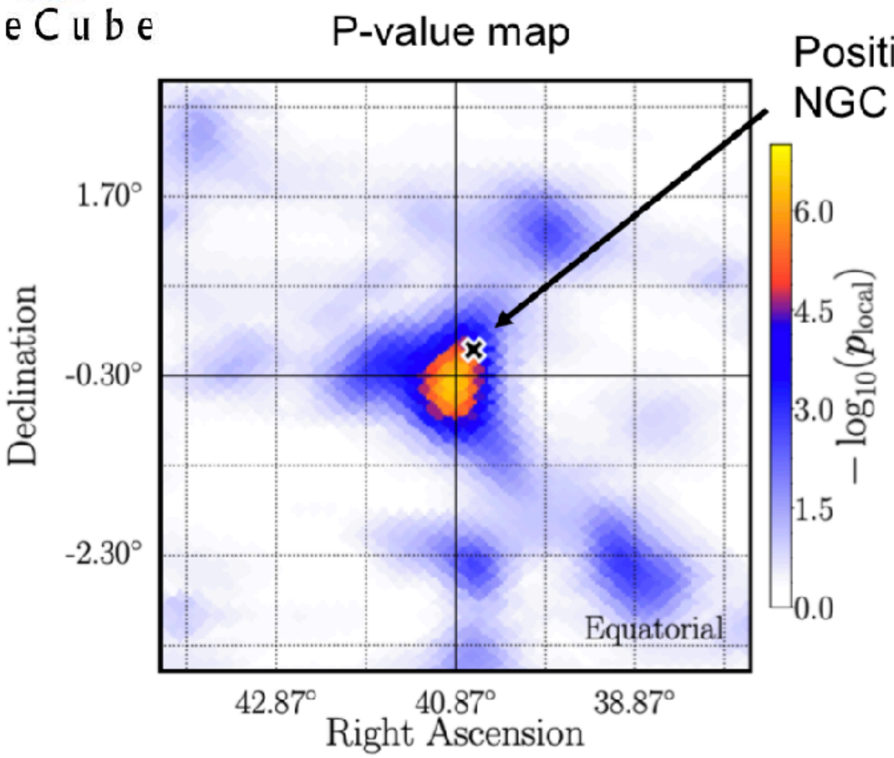
⟹ The comparable energy content of these three fluxes is of particular interest in the investigation of cosmic-ray origin despite their different energy ranges
⟹ Common sources ? Common production mechanism ?

Time integrated10-yr point-like source searches



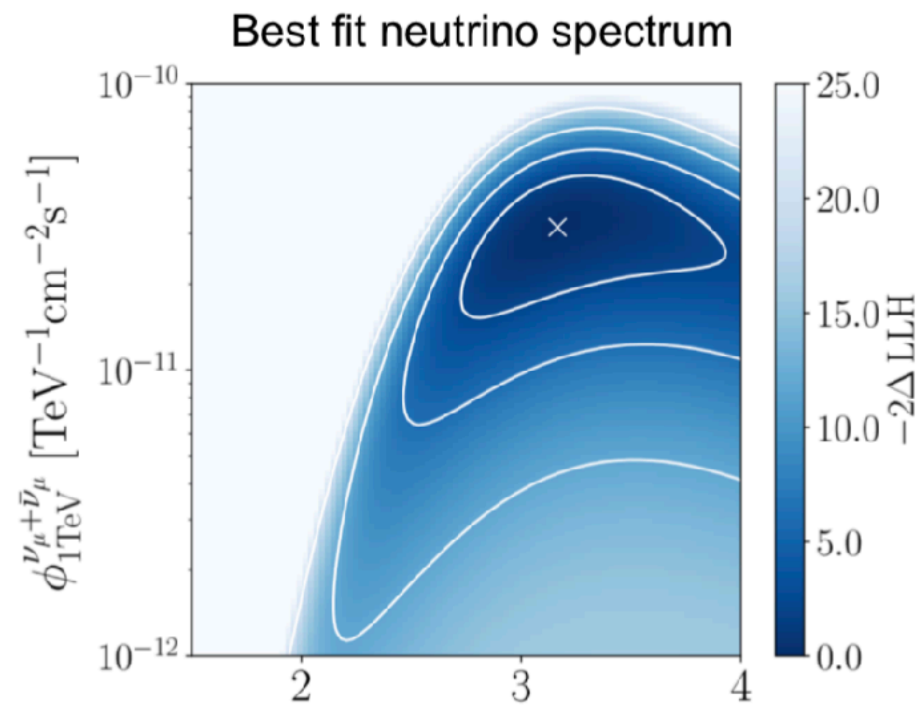
IceCube

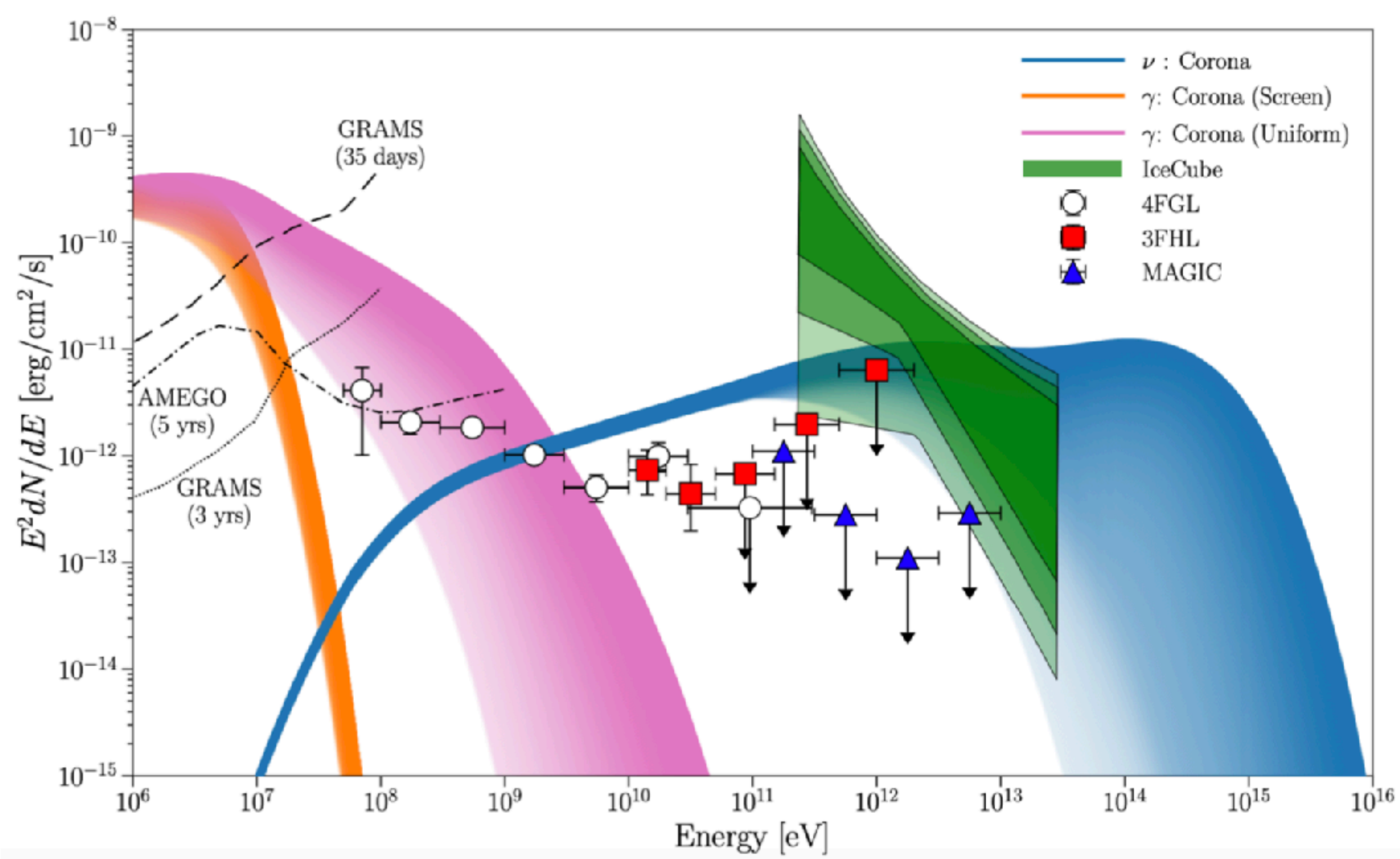
NGC1068



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)





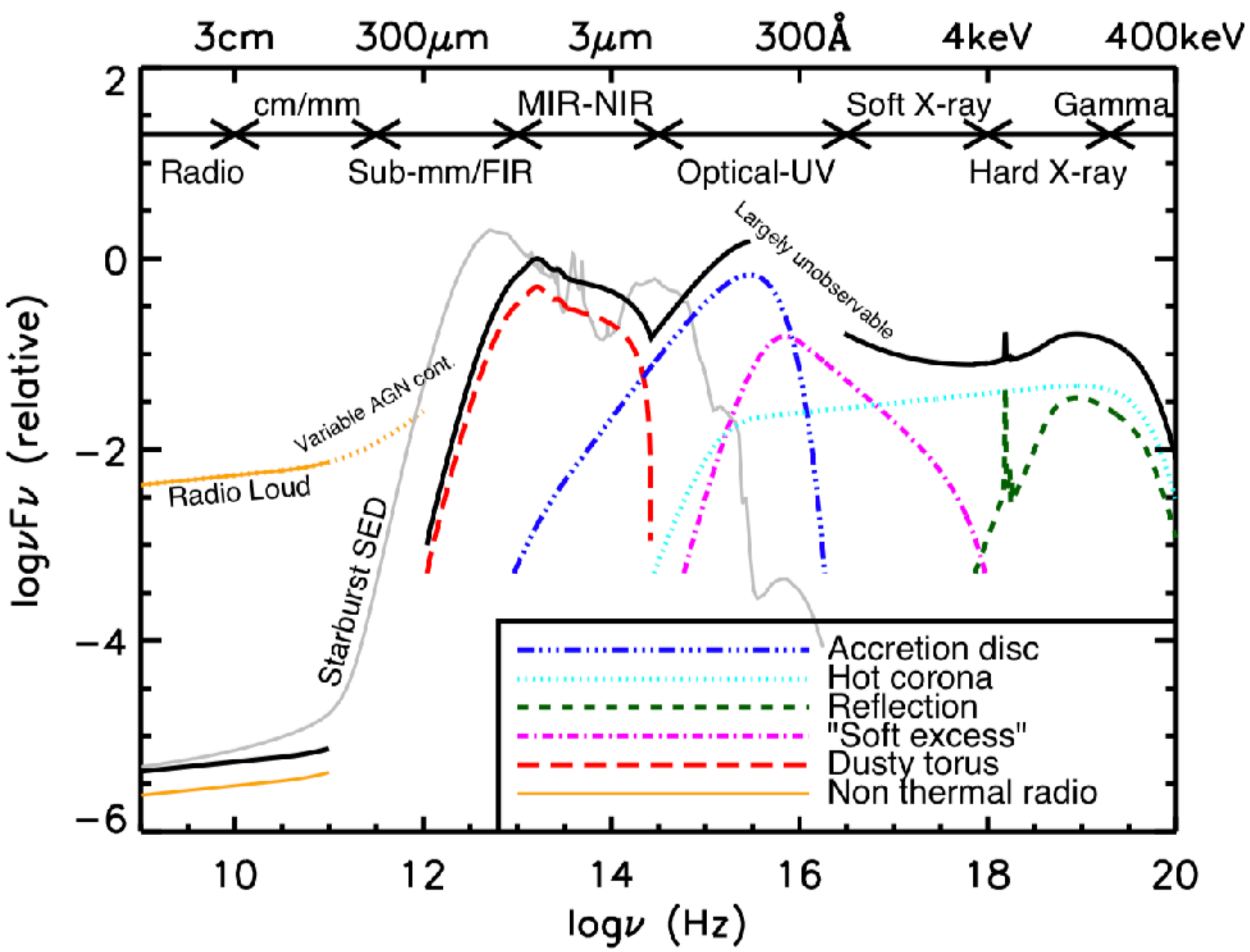
- Seyfert 2 galaxy (M77) at 14 Mpc (star forming region)
- Neutrino production only at the vicinity of the SMBH (intense X-ray target): reported neutrino flux is higher than the GeV gamma-ray flux

⟹ 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. Even weak non-thermal activity in the corona (~3%) can generate significant HE particles (pair-cascade scenario).
=> Non-thermal coronal activity can be also be pinpointed through millimeter (mm) excess .
=> Seyfert galaxies are about four orders of magnitude more numerous than blazars and then might dominate the cosmic neutrino sky.

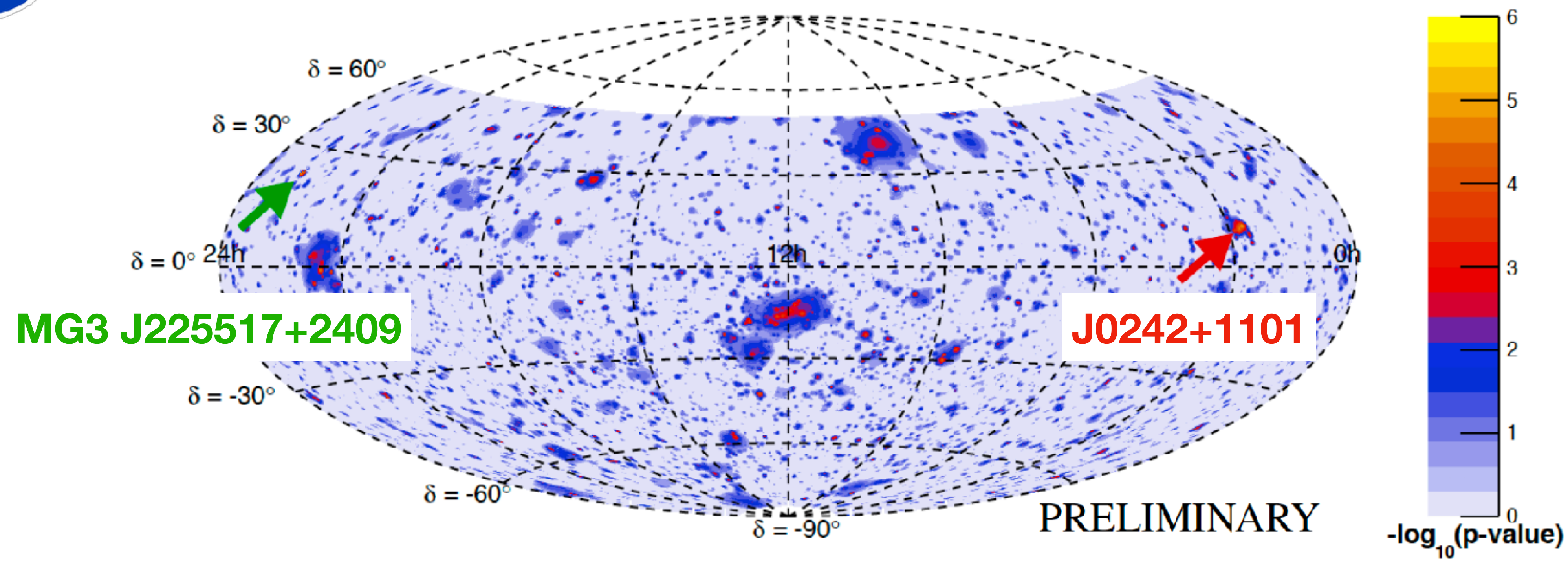


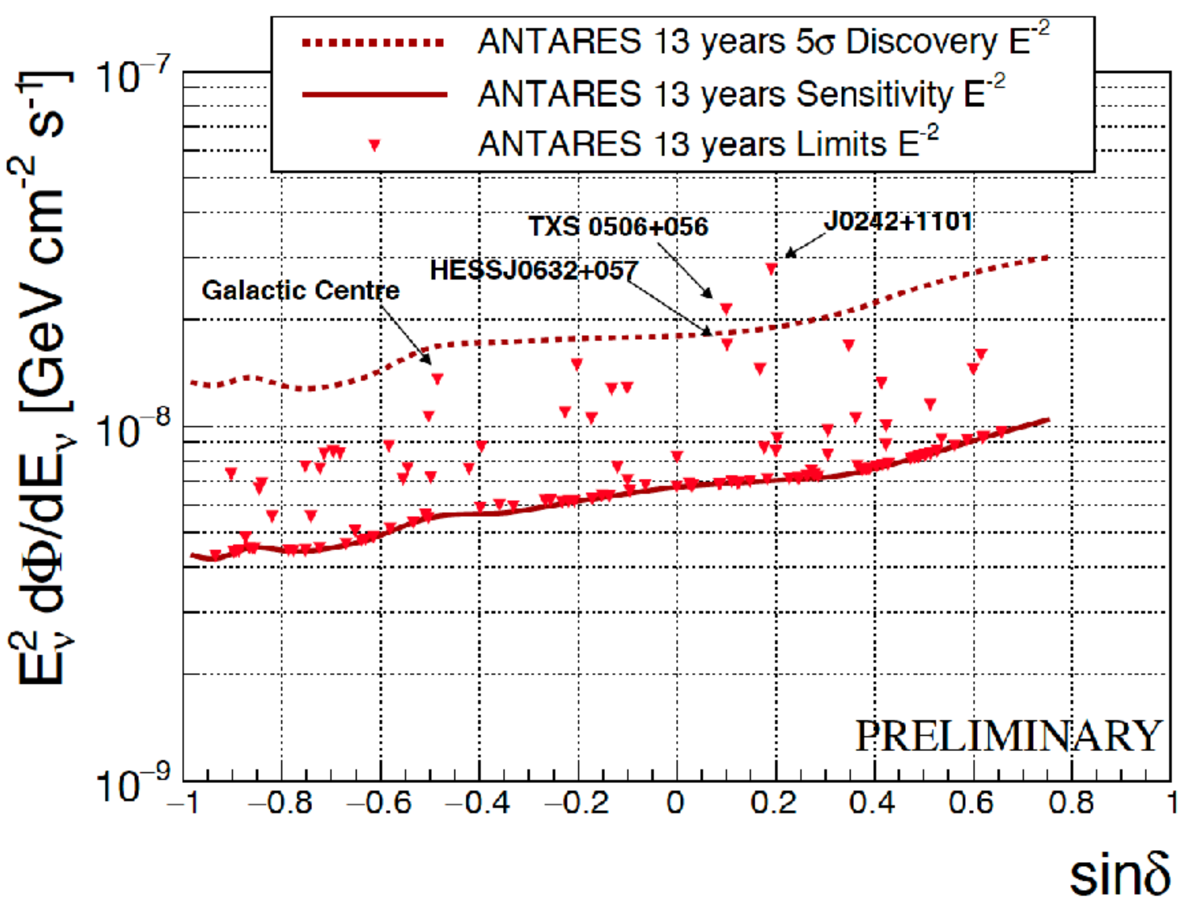
(Inoue + 2021)

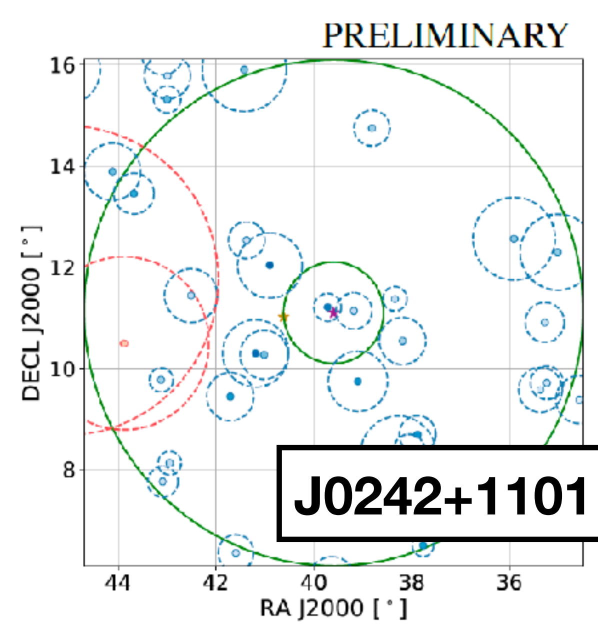
NGC 1068 is one of the intrinsically brightest X-ray Seyfert galaxy, i.e. after correcting the attenuation effects due to the molecular torus located in the line-of-sight.
=> Coherent with the assumption that the neutrino production is proportional to the accretion disc luminosity.

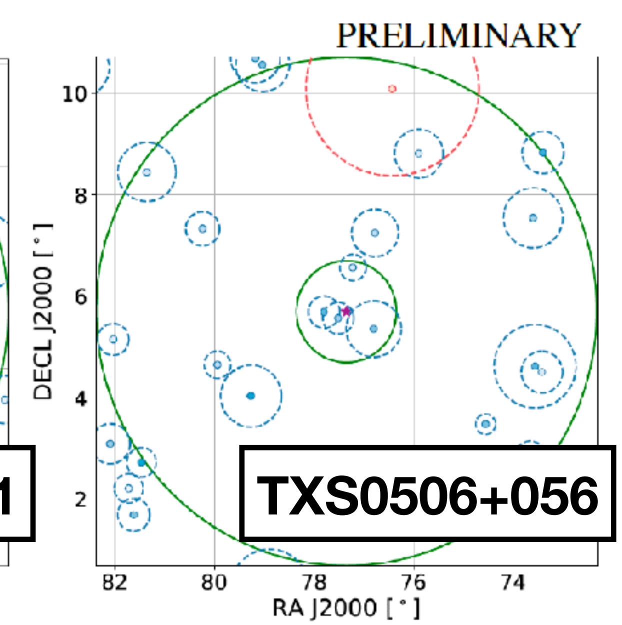
Next potential discovery: Centaurus A and Circinus galaxy (but extended)

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

Multi-messenger alerts

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

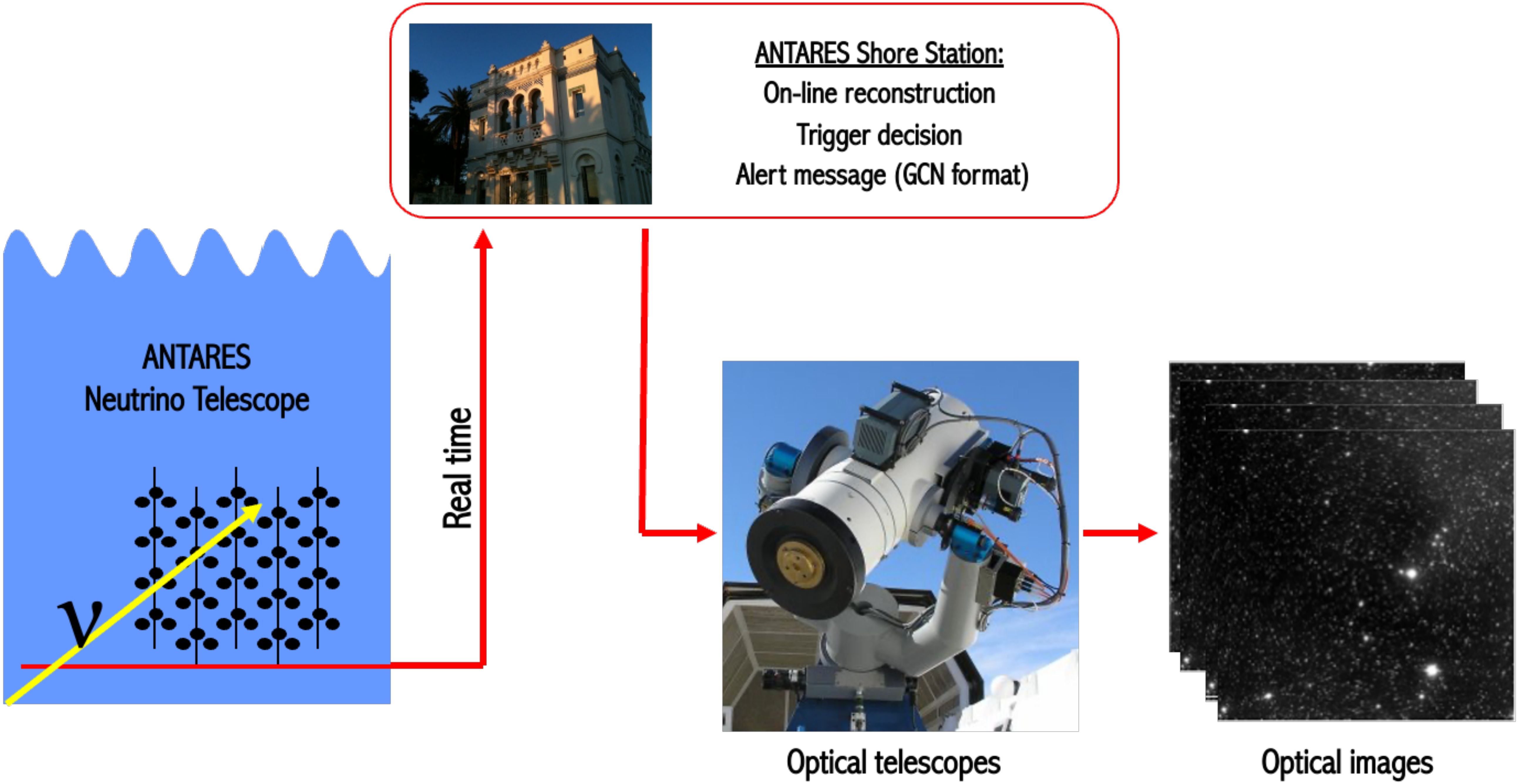
- **Alerts to community upon detection of likely « astrophysical » neutrinos for rapid follow-ups**
- **Real-time searches for neutrino signals in response to transient events observed in other messengers**

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**

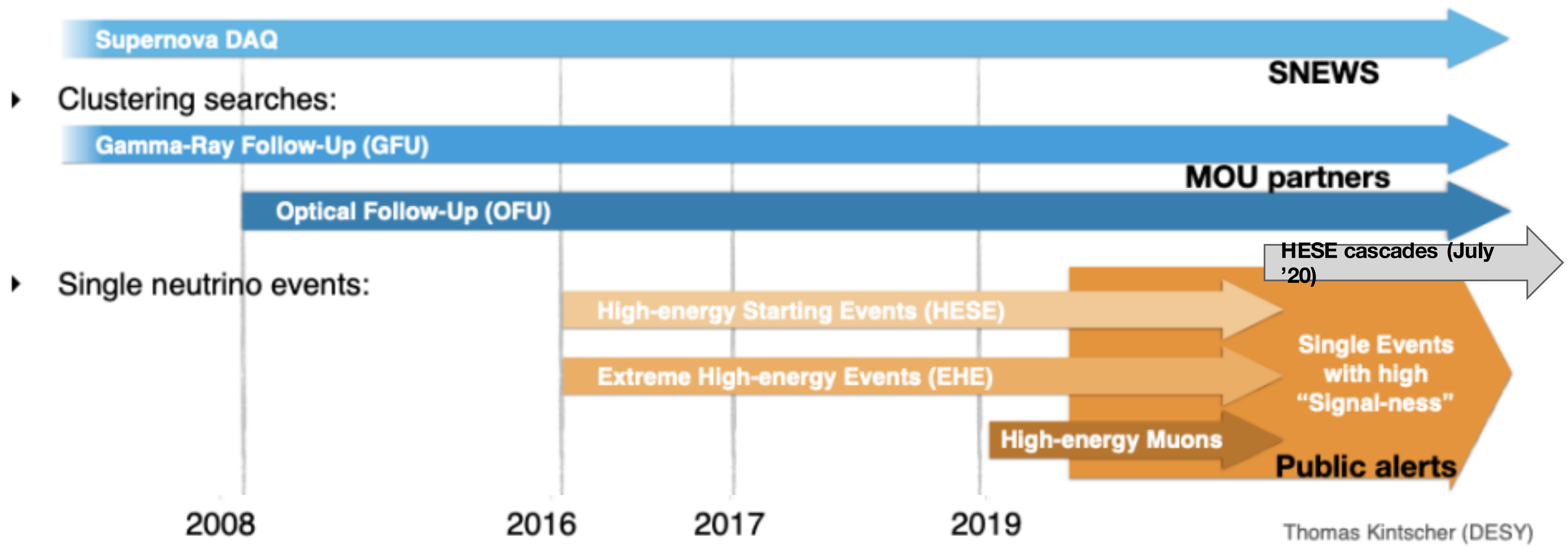
Multi-messenger alerts

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



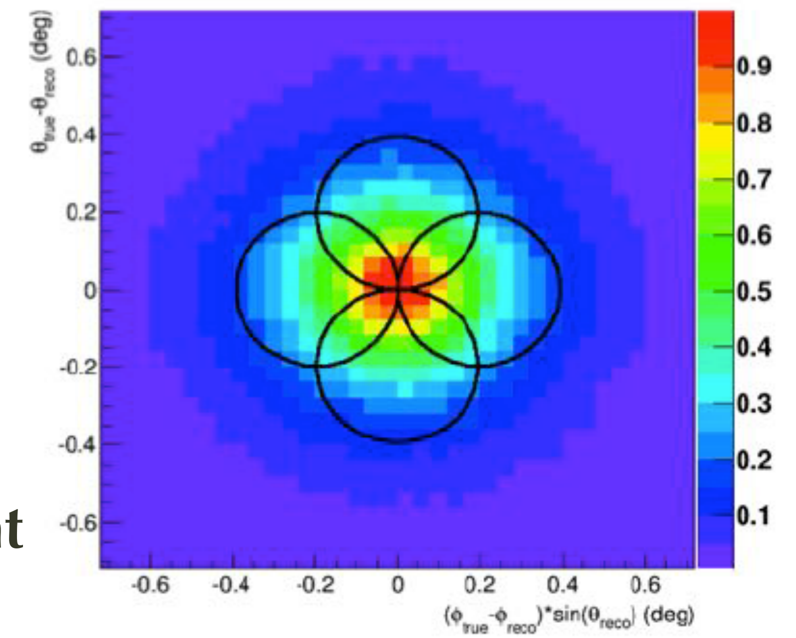
Updated selection: GOLD / BRONZE single events

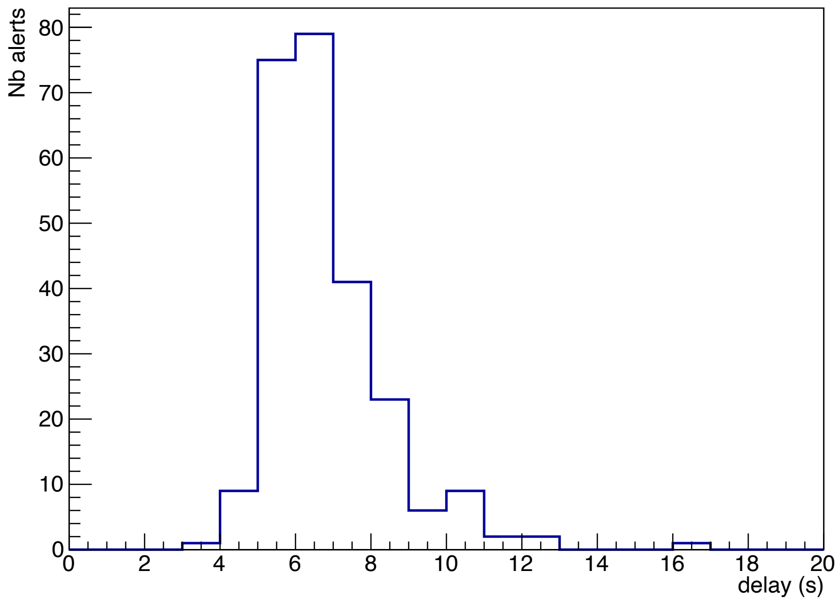
- Improved background rejections
- Added through-going track selections
- "Signalness" = $N_{Signal} / (N_{Signal} + N_{Background})$
- 2 classifications:
  - GOLD : > 50% signalness
  - BRONZE : > 30% signalness

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.

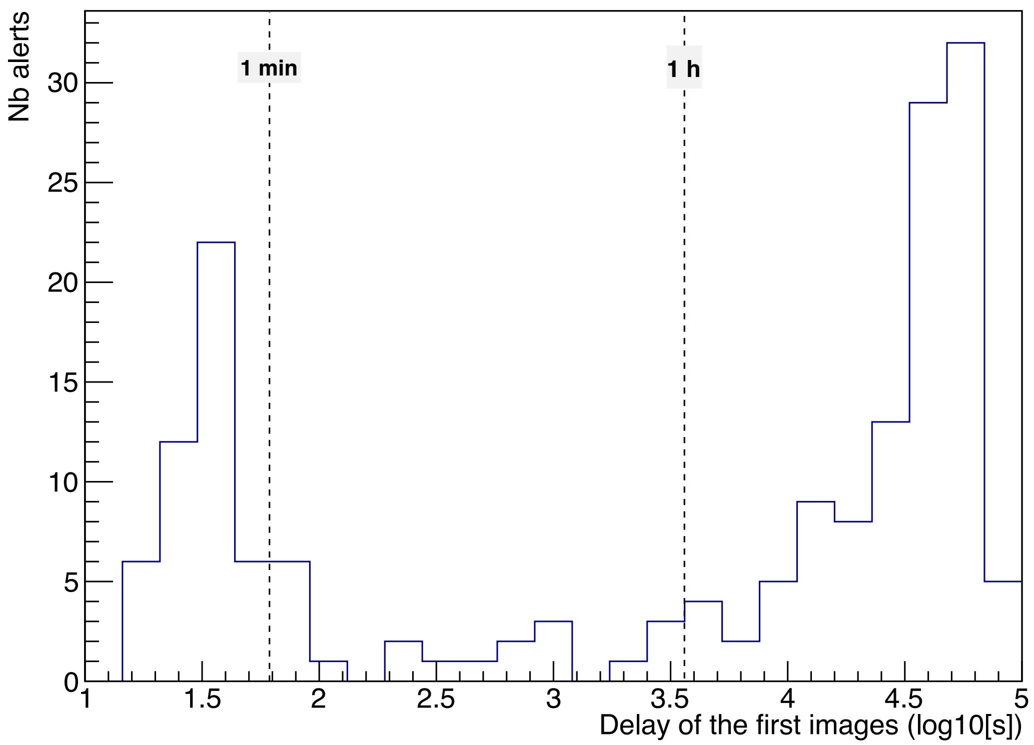
ANTARES PSF : ~0.4º (median)





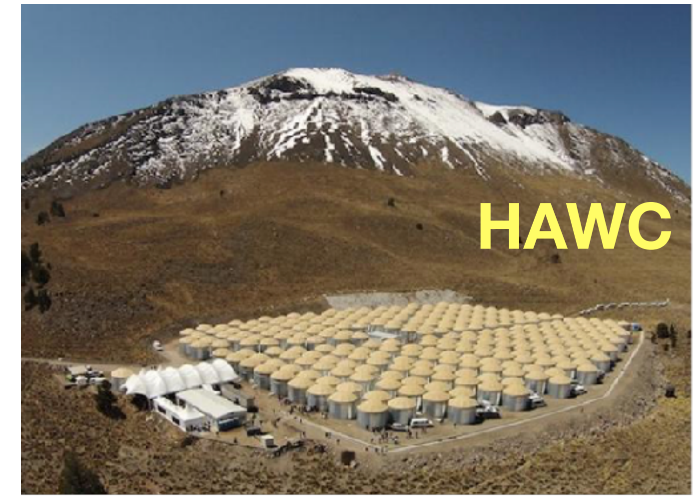
Alert message sent via the GCN using either GCN socket / VO Event
⟹ Average delay: ~6-7 s

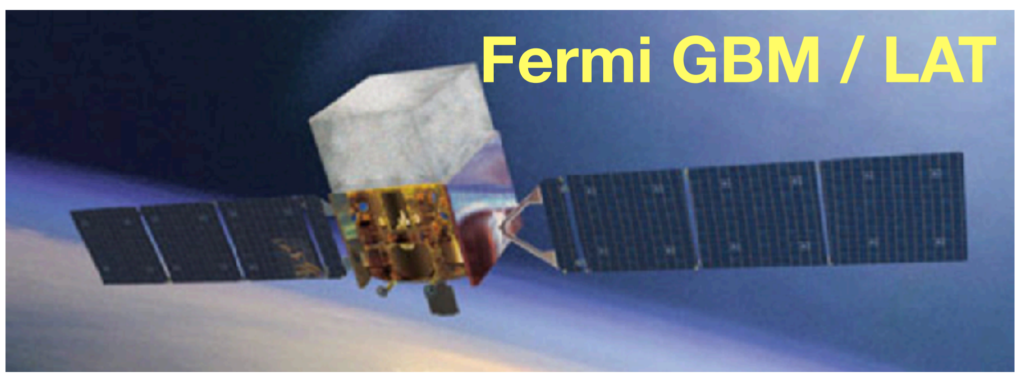
Private alert except if a potential counterpart is founded



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)

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…)

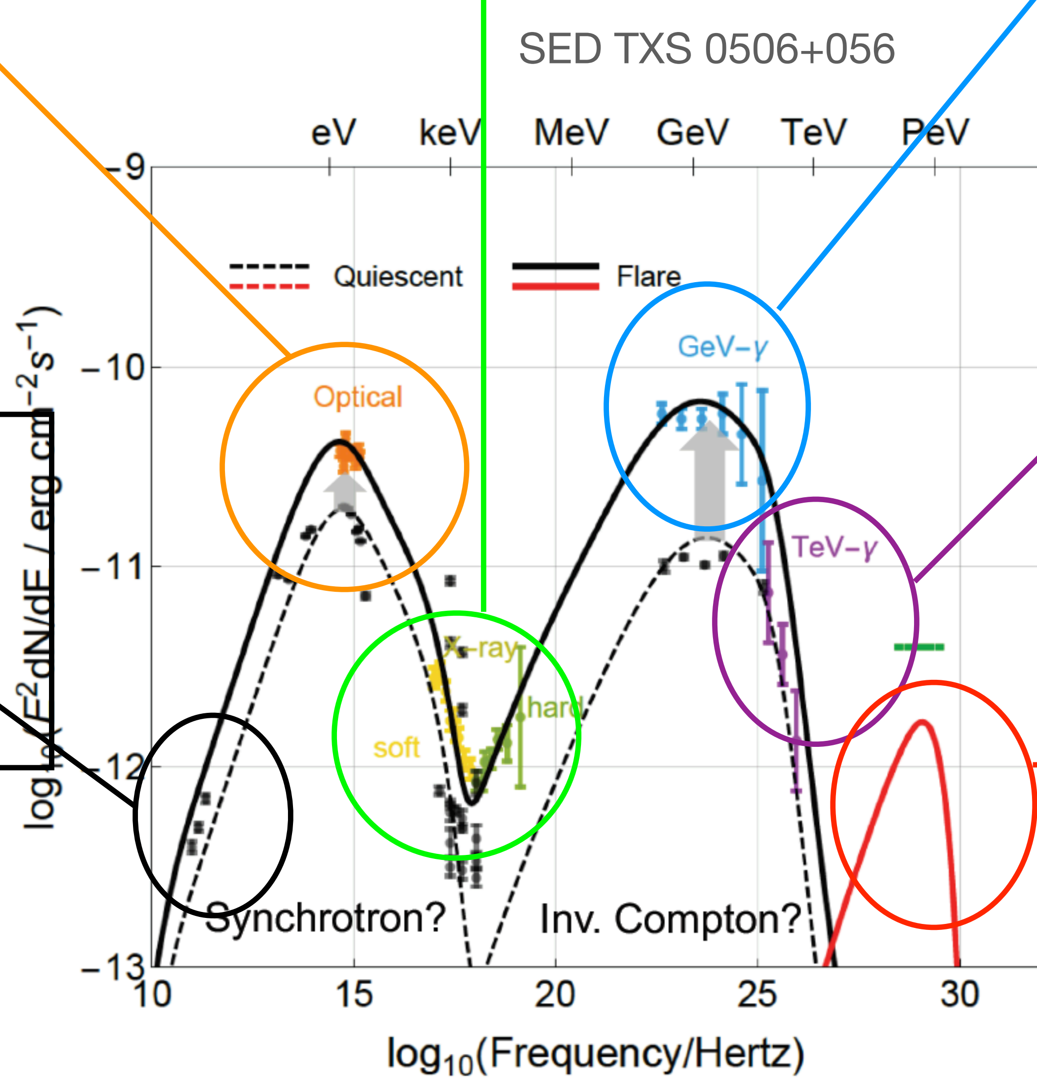
X-ray telescopes: Swift, INTEGRAL, SVOM, ATHENA…
- Very clean sky
- Provide transient triggers (GRB, AGN, Novae…)
- ToO program (not so easy access)

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

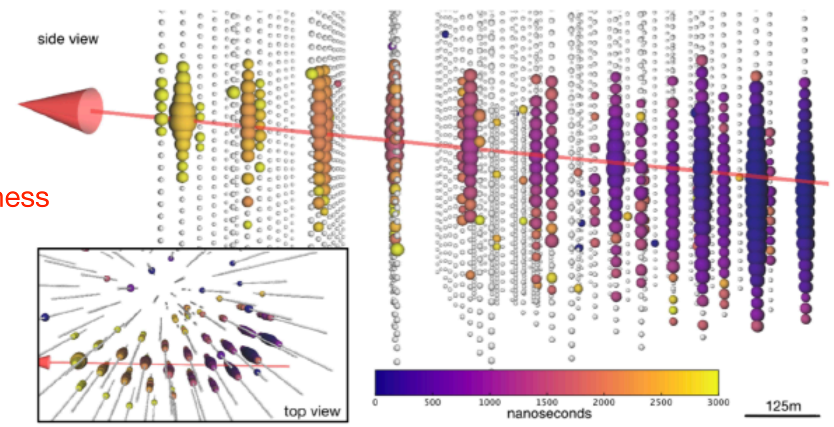
+ link with LIGO/VIRGO
+ SK, SNEWS

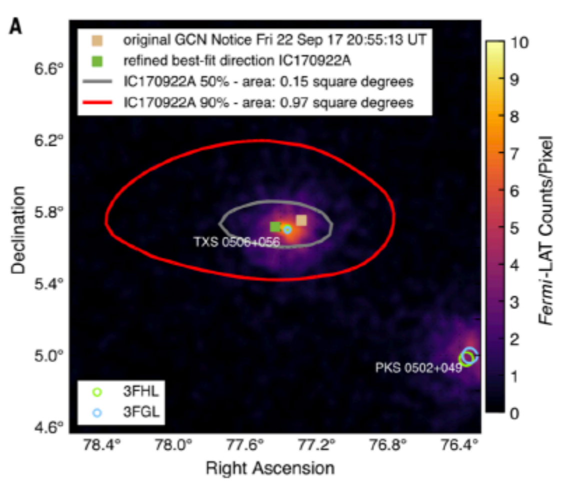
(Probably) one identified source

Neutrinos from the AGN blazar TXS 0506+056

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

~290 TeV
56.5% signalness





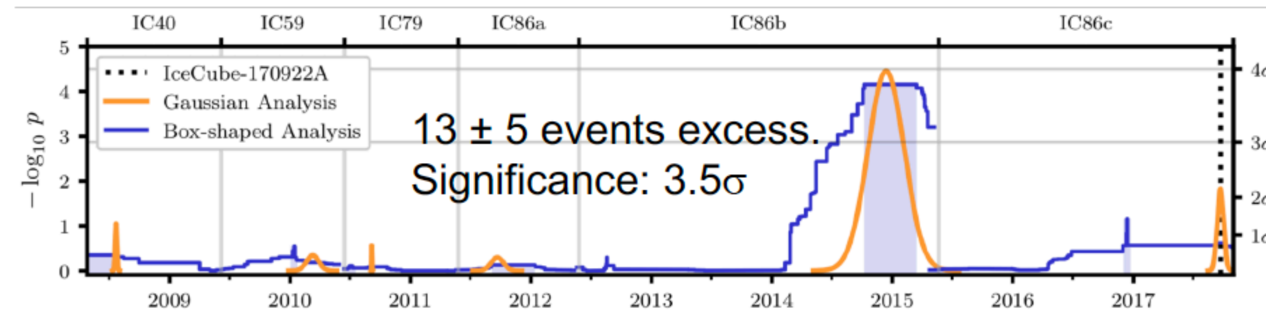
Observed by Fermi-*LAT* and MAGIC

Significance for correlation: 3σ

Science 361 (2018) no. 6398, eaat1378

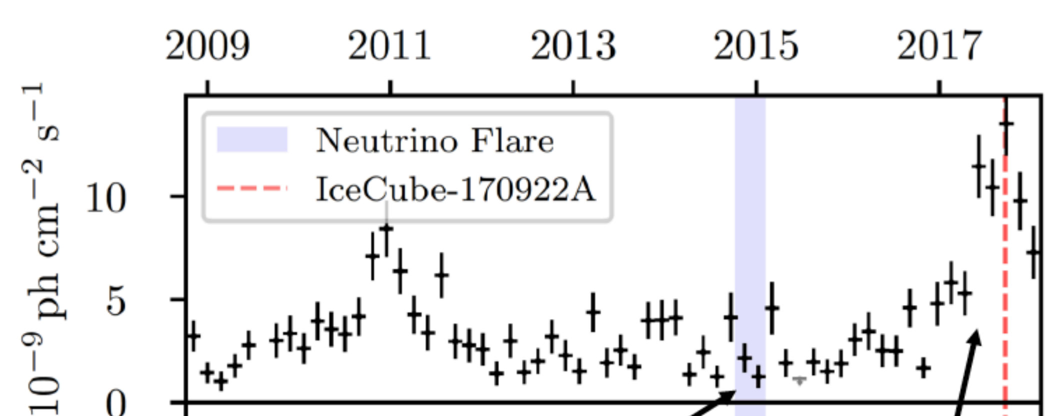
Redshift: 0.33
Type: ISP / BL lac
Among 50 bright blazars

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



Science 361 (2018) no. 6398, eaat2890

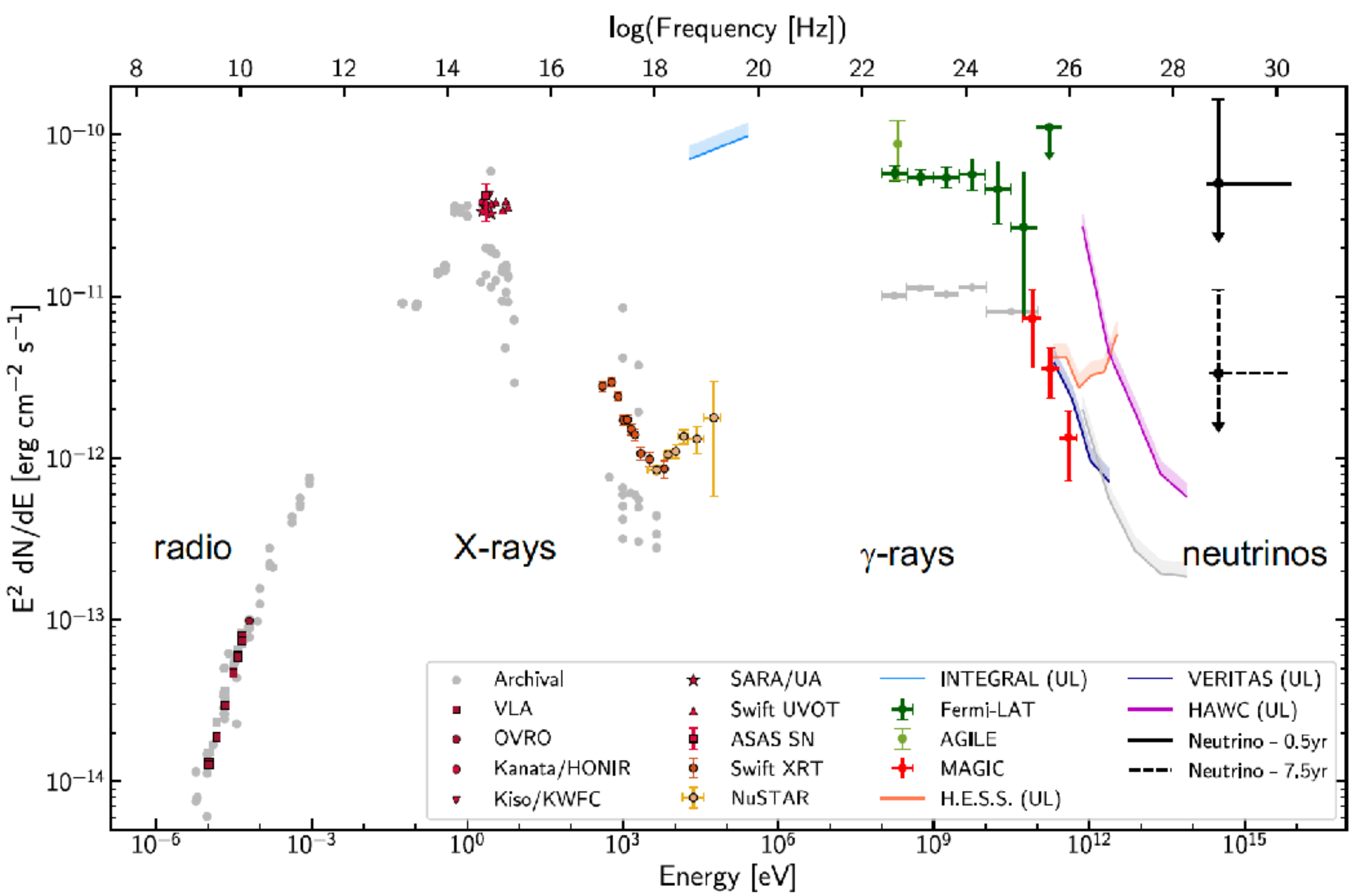
Fermi-*LAT* data; Padovani et al, MNRAS 480 (2018) 192



At 2014-15 neutrino flare — The 2017 flare

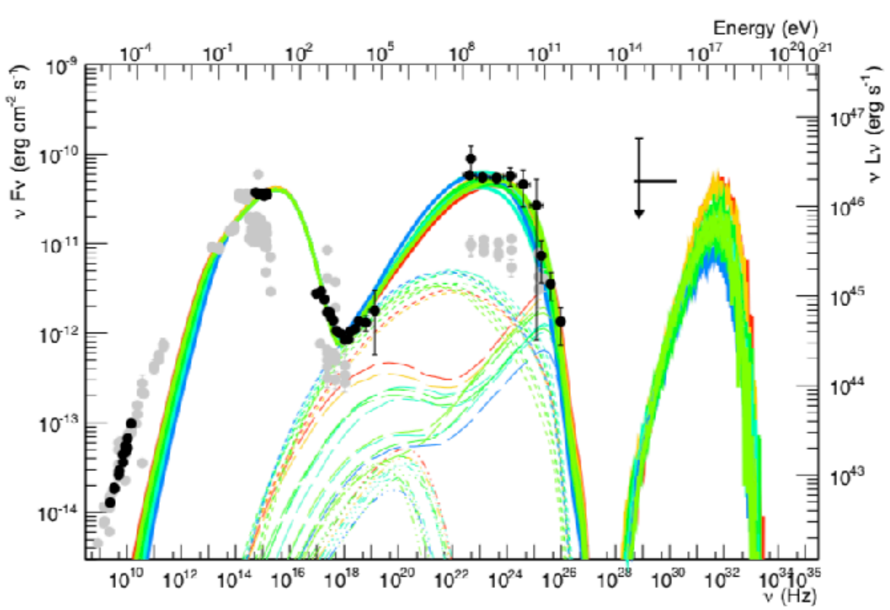
Neutrino luminosity is ~4 times higher than gamma-ray luminosity
⟹ challenge for models

A difficult parametrization

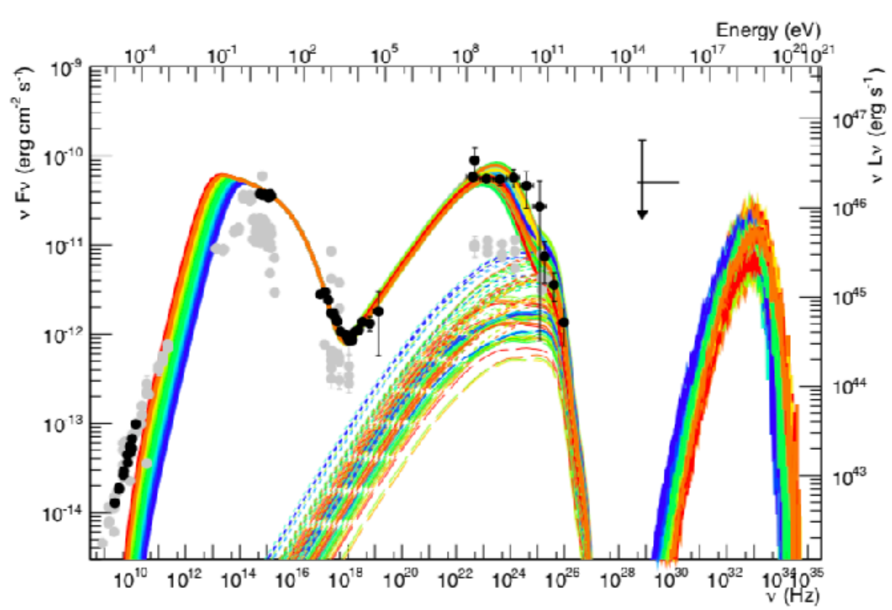


- Simple 1-zone models are not working properly
- More sophisticated multi-zone models on the market to satisfy the energetic problem: interaction with external field (Sikora 2016), jet-cloud interaction (Liu 2018), formation of a compact core (Gao 2019)…

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

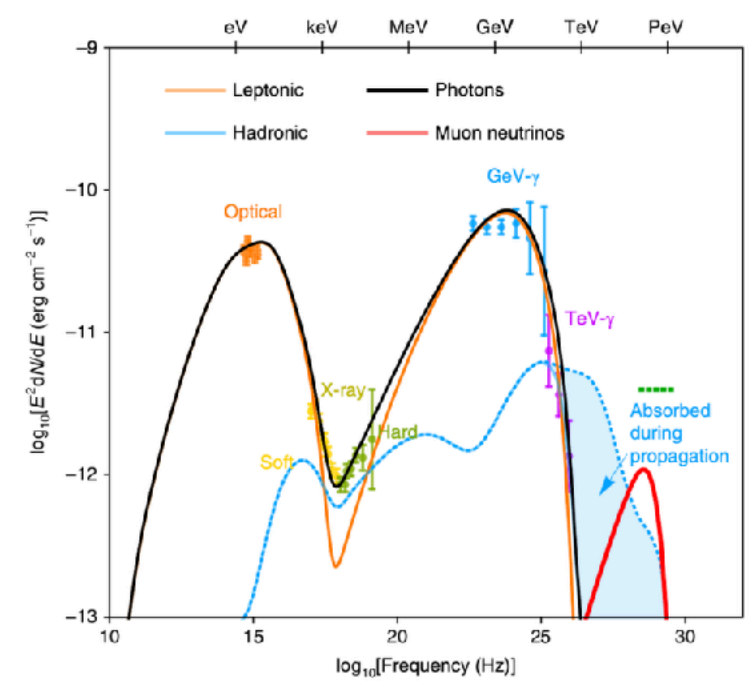


(b) Lepto-hadronic modeling of TXS 0506+056



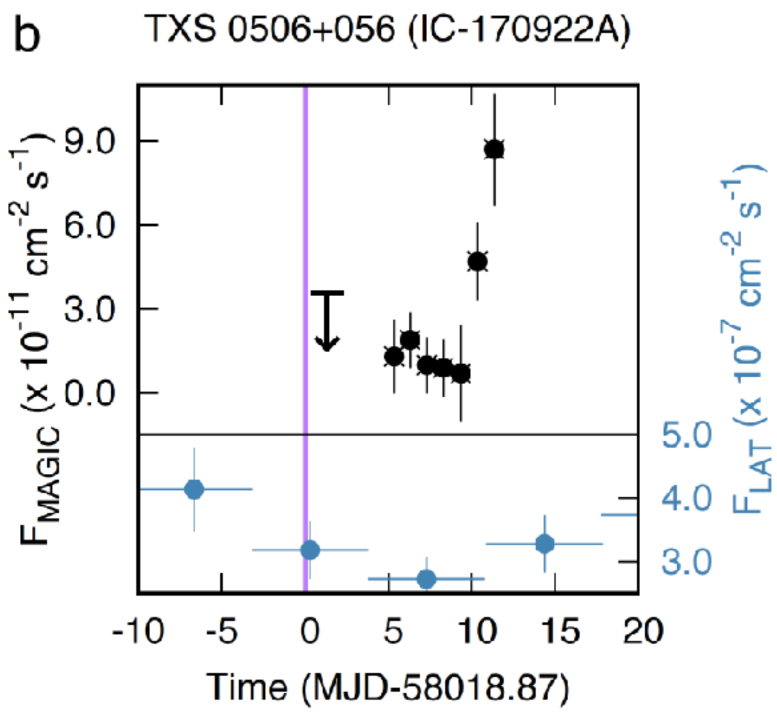
(a) Proton synchrotron modeling of TXS 0506+056

(Cerruti et al, 2018)



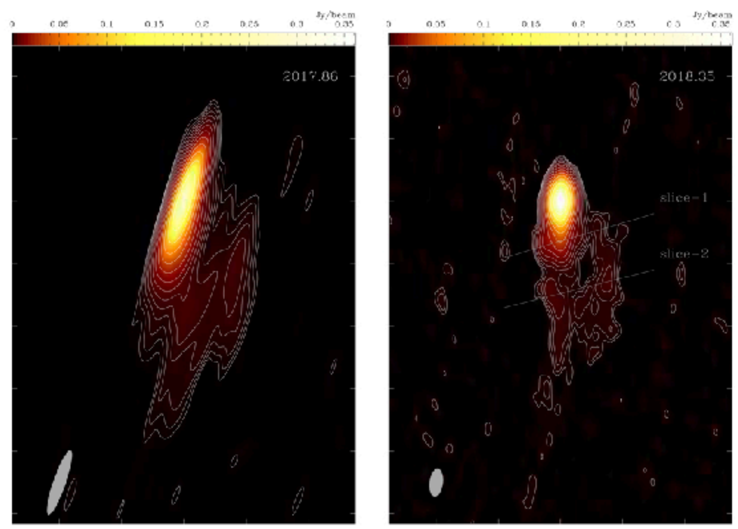
(Gao et al, 2018)

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.

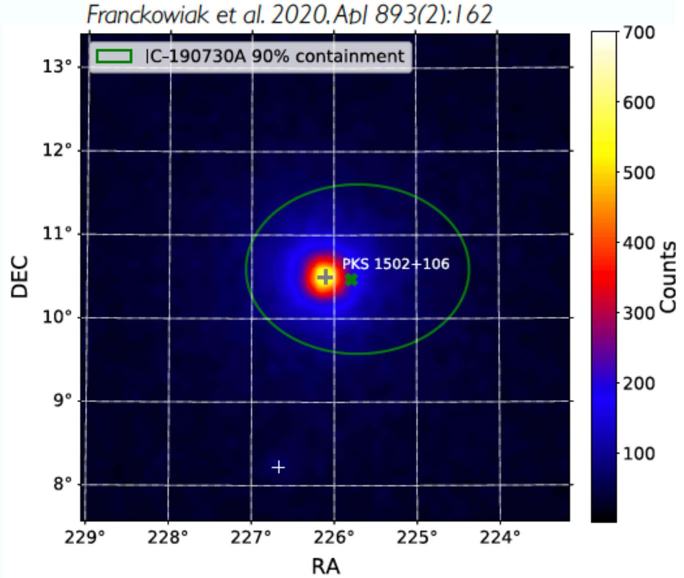
When a source is transparent to HE γ-rays there is an insufficient photon or matter target density to produce neutrinos.

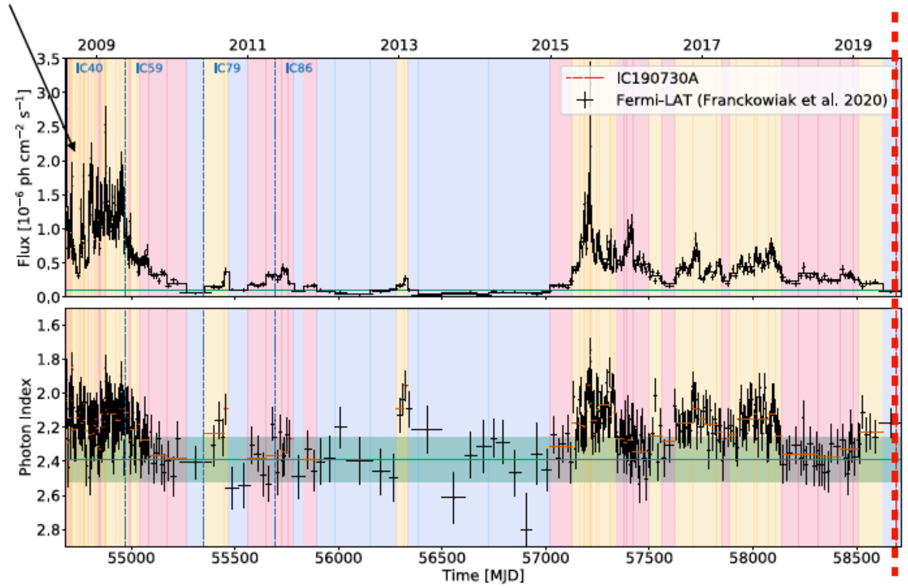
Possible association with PKS1502

A powerful flat spectrum radio quasar at z = 1.835 coincident with a 300 TeV neutrino

Second brightest extragalactic gamma-ray source

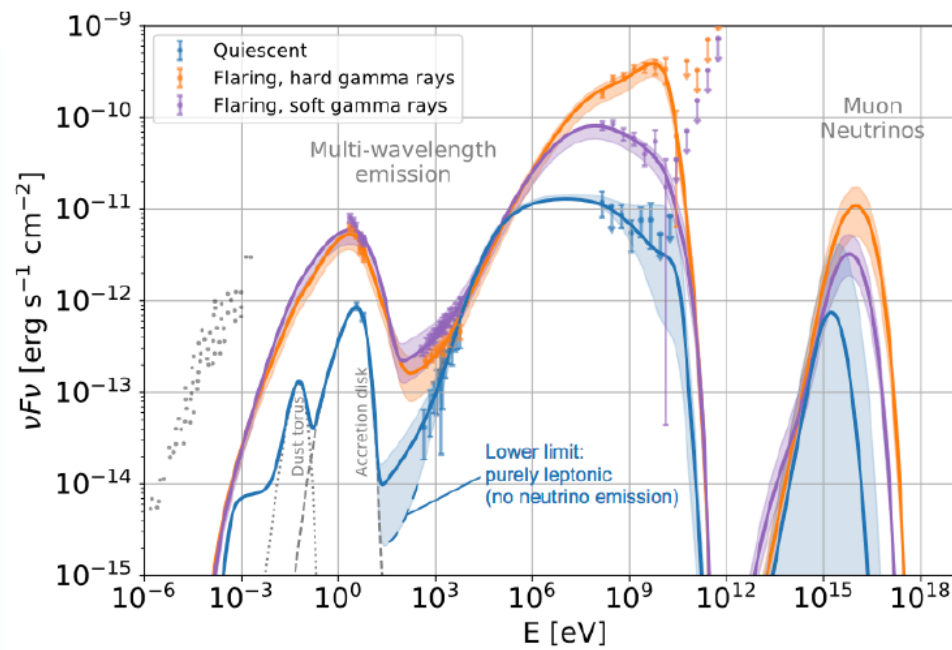
Franckowiak et al. 2020, ApJ 893(2):162





Detected in a quiescent state of weak gamma-ray activity at the time of neutrino arrival.

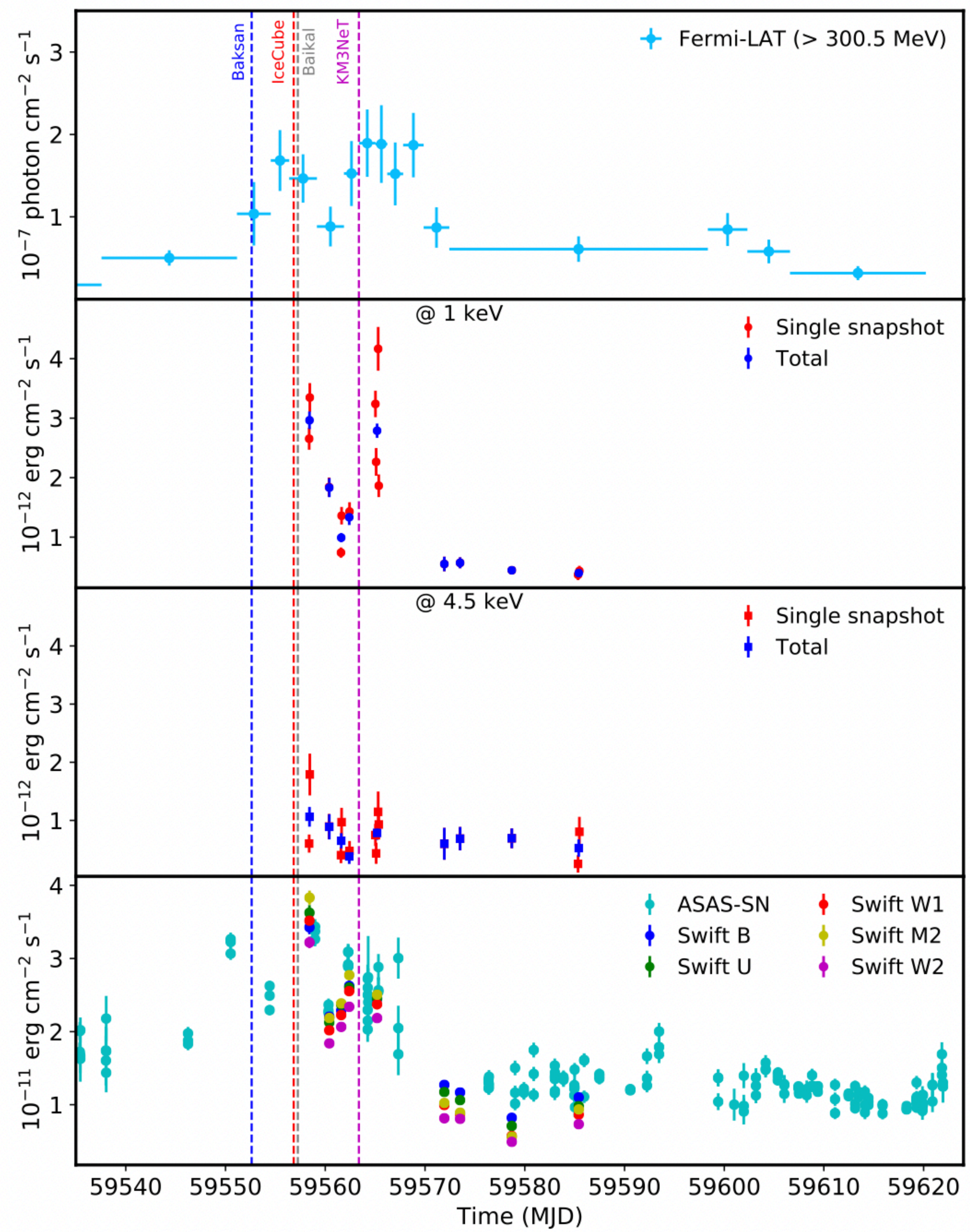
No more neutrinos observed during flaring period?



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



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]

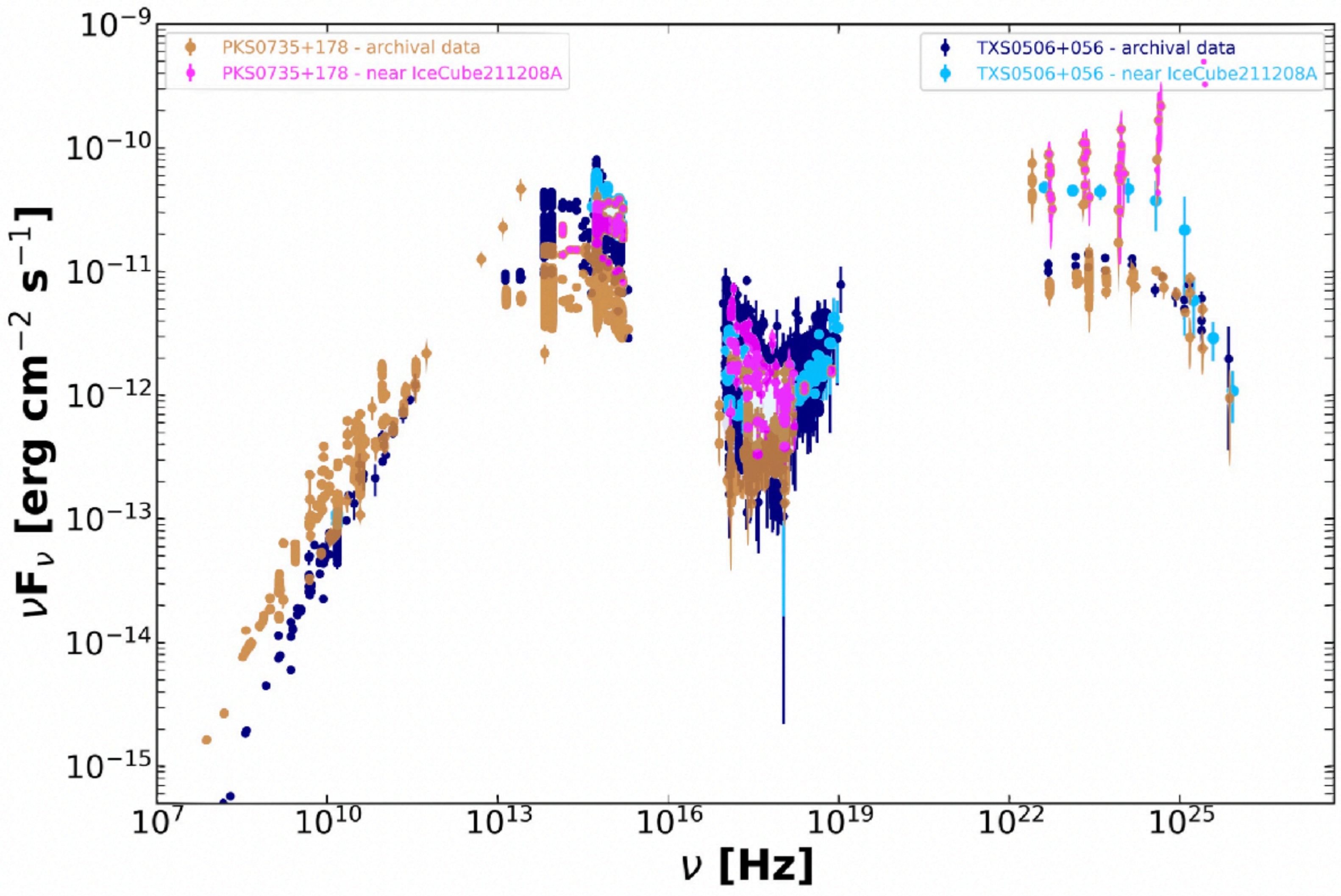
KM3NeT: 1 track neutrino candidate (~18 TeV) in ARCA, 1.8 deg from the blazar (p=0.14). No coincidence in ORCA [ATel #15290]

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.

Sahakyan et al (arXiv:2204.05060)

Intriguing association with PKS0735



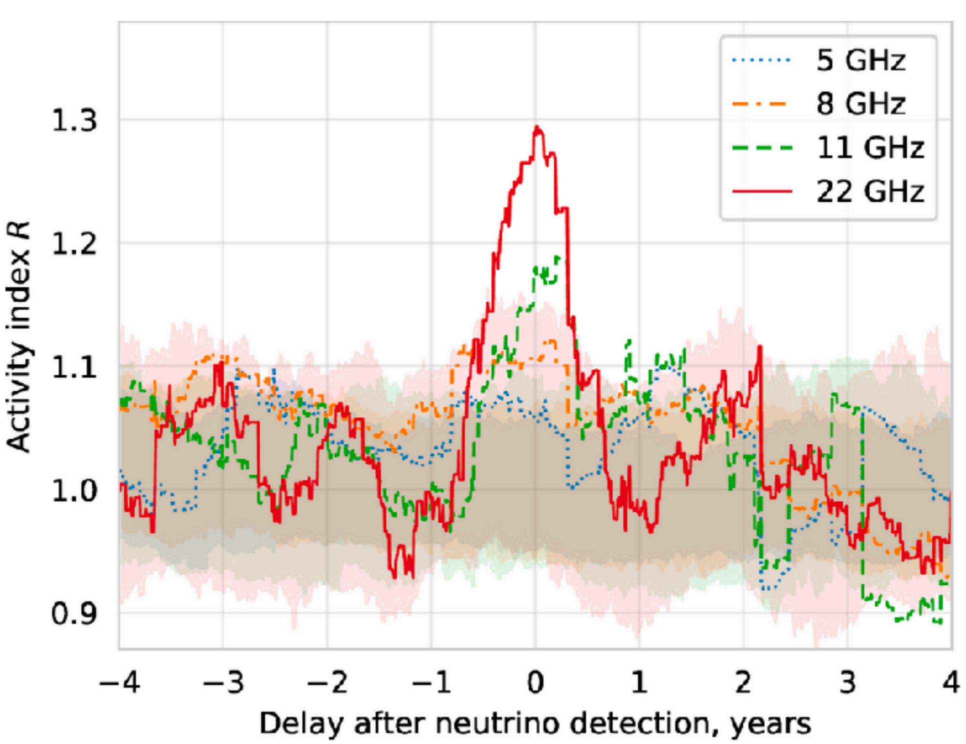
Sahakyan et al (arXiv:2204.05060)

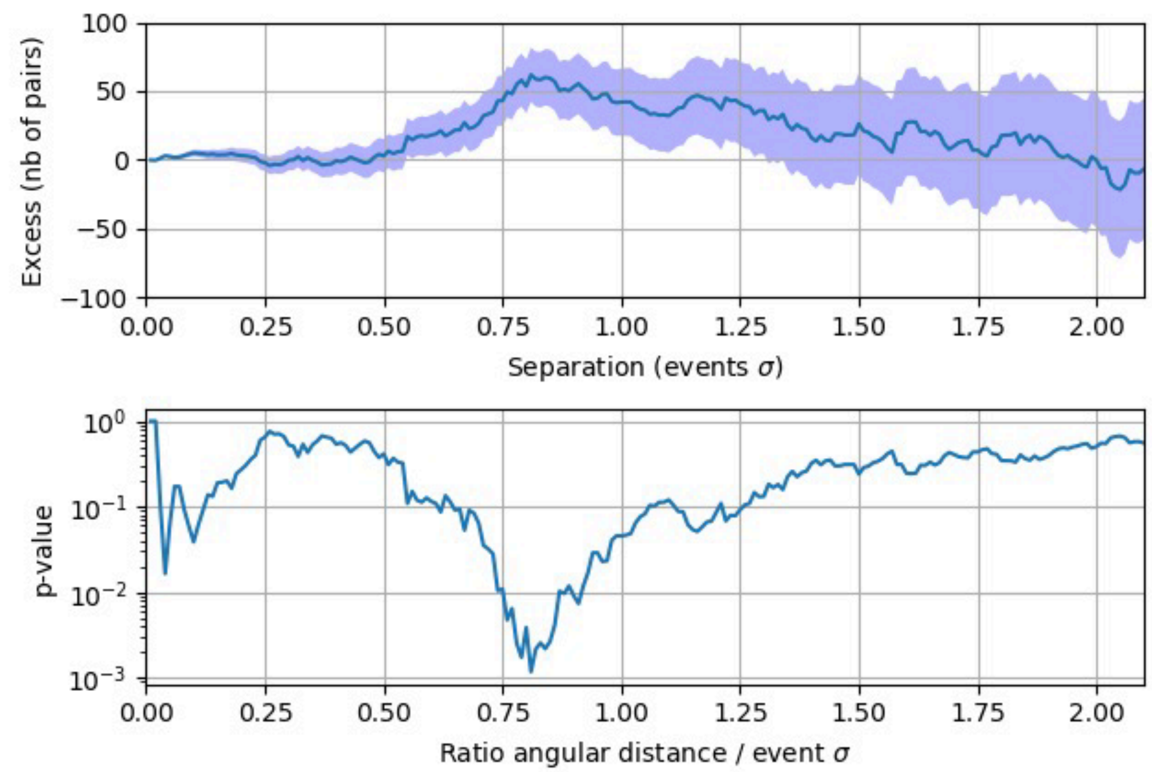
- PKS 0735+178 (IHBL object) is one of the brightest BL Lac objects in the sky both in radio and gamma
- Similar spectral energy distributions, very high radio and γ-ray powers, and parsec scale jet properties as TXS0506
- Redshift unknown z ≥ 0.424

Correlation with radio blazars

In 2020/21, Platvin 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: ApJ in press, arXiv:2009.08914

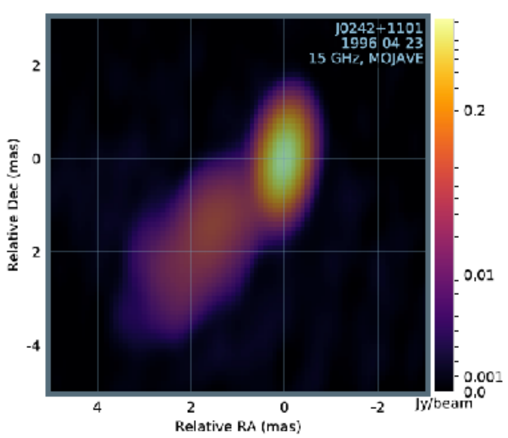
Search for correlation radio blazars in VLBI data (2774 objects) and ANTARES PS sample 2007-2020 (10162 tracks) ⟹ post-trial p-value of 0.022 (~ 2.3 σ). **Analysis still in progress**

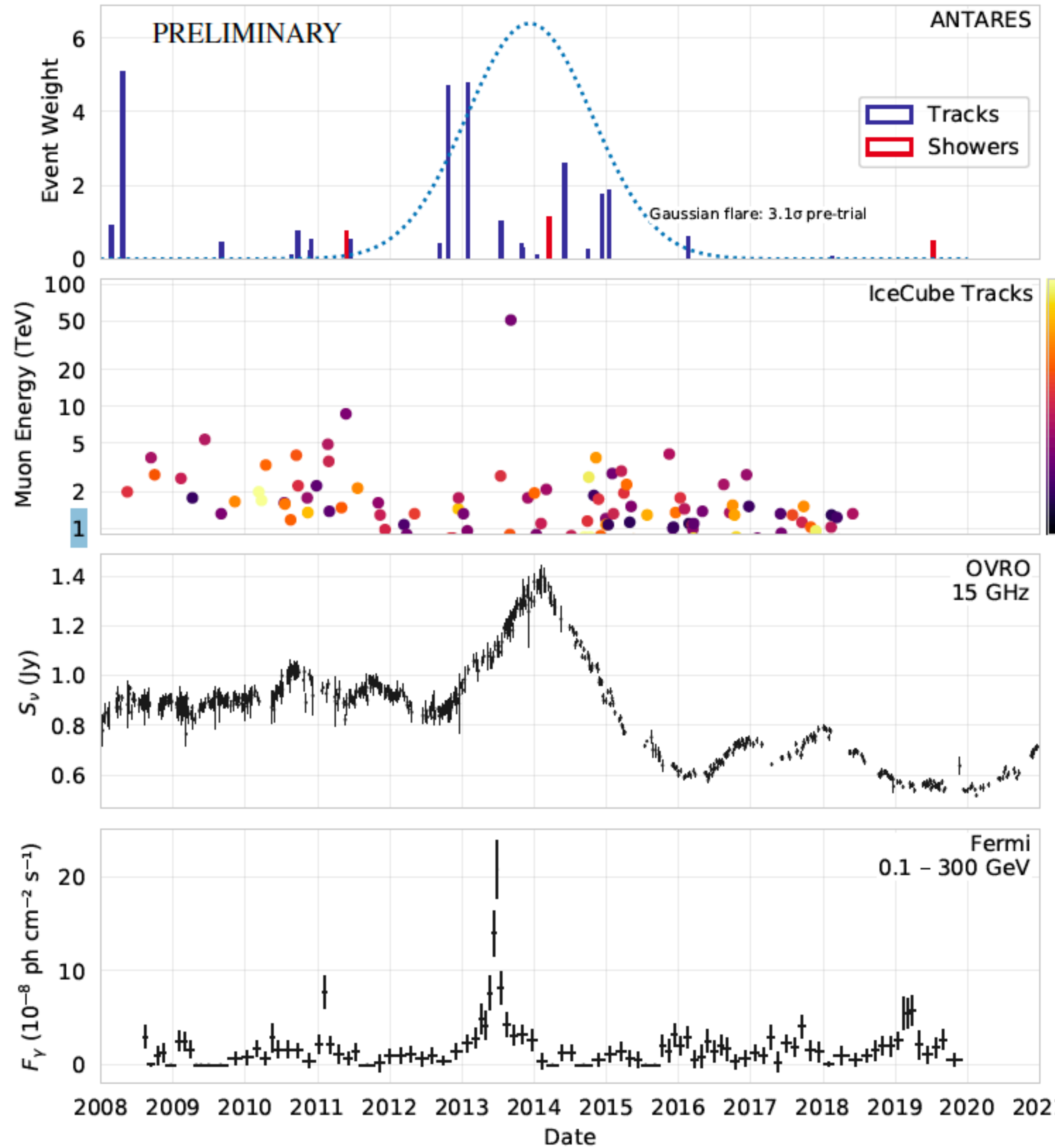
Neutrino flares from radio sources

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

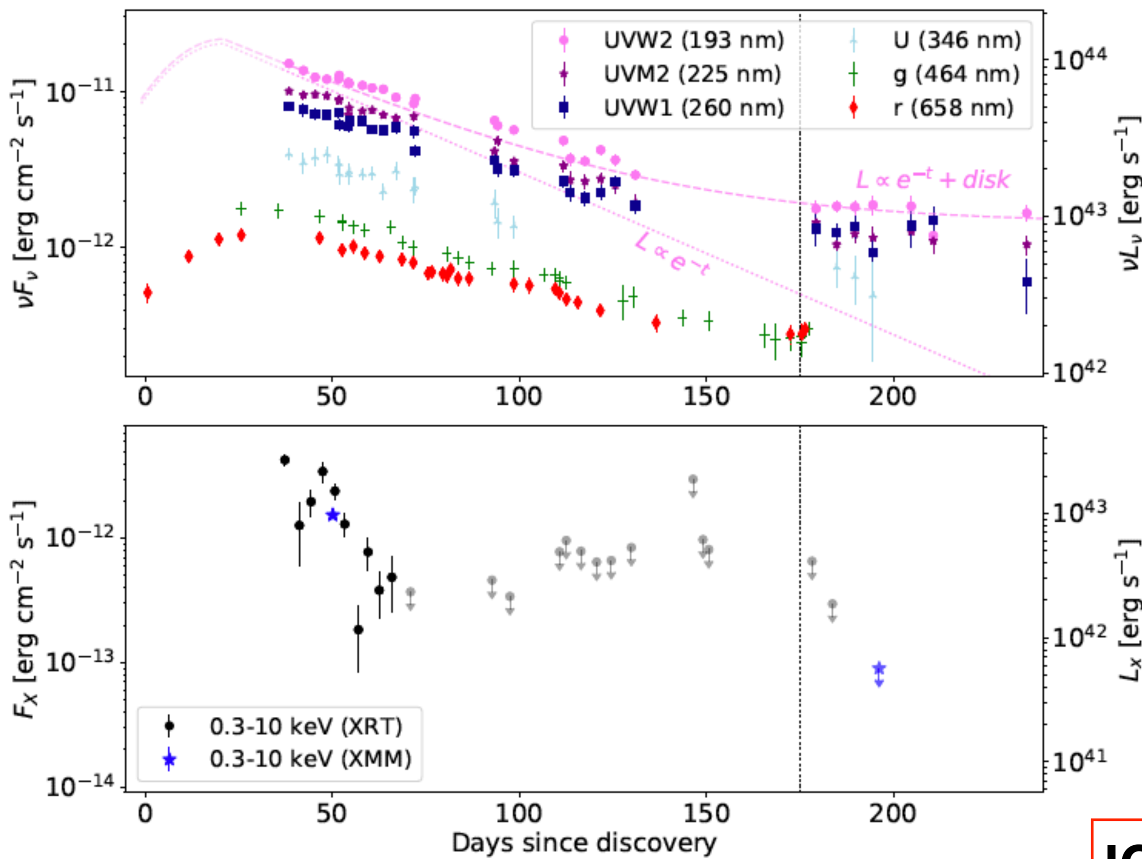


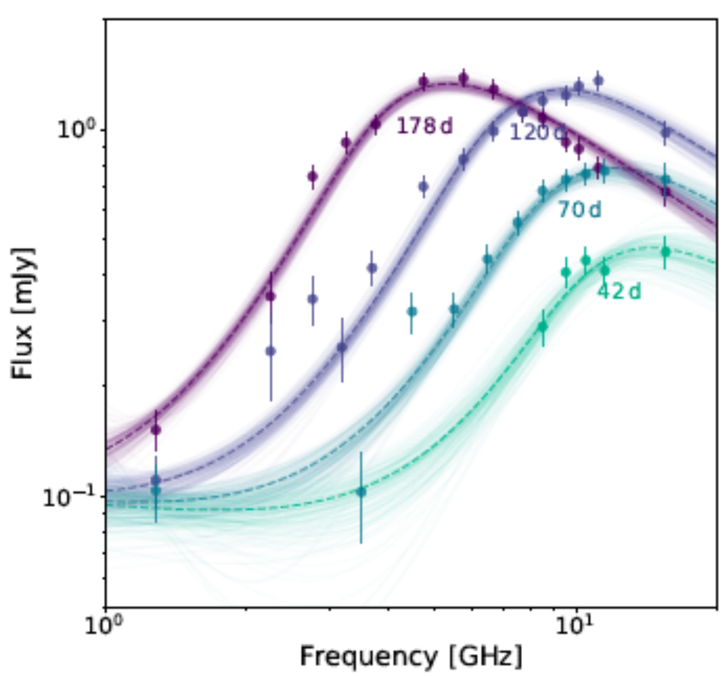


PoS(ICRC2021)972

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

TDEs as new potential neutrino sources





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)

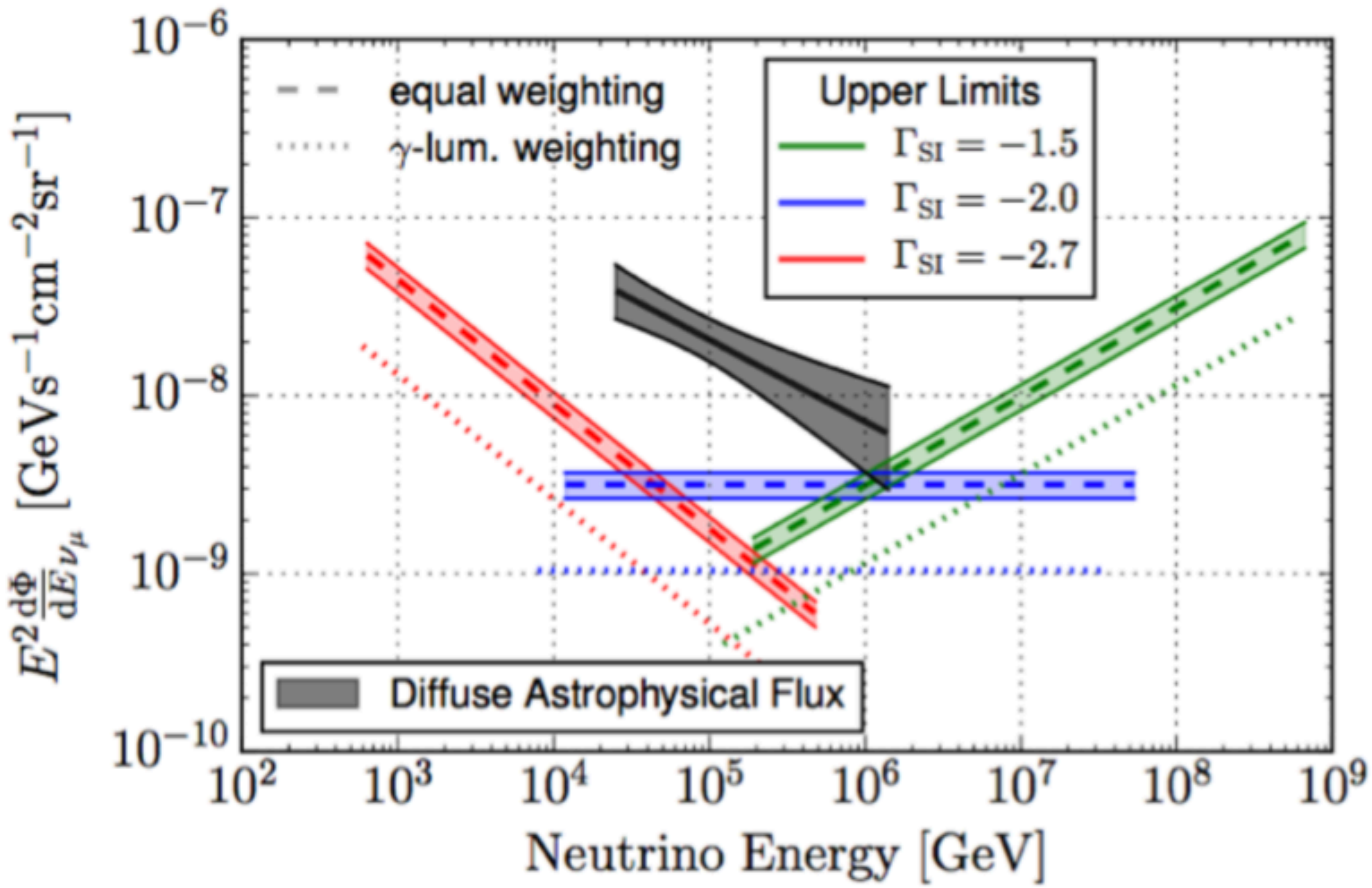
IC191001A - AT2019dsg:

- 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 for both TDEs

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

Source population studies



IceCube Coll. ApJ 835 (2017)

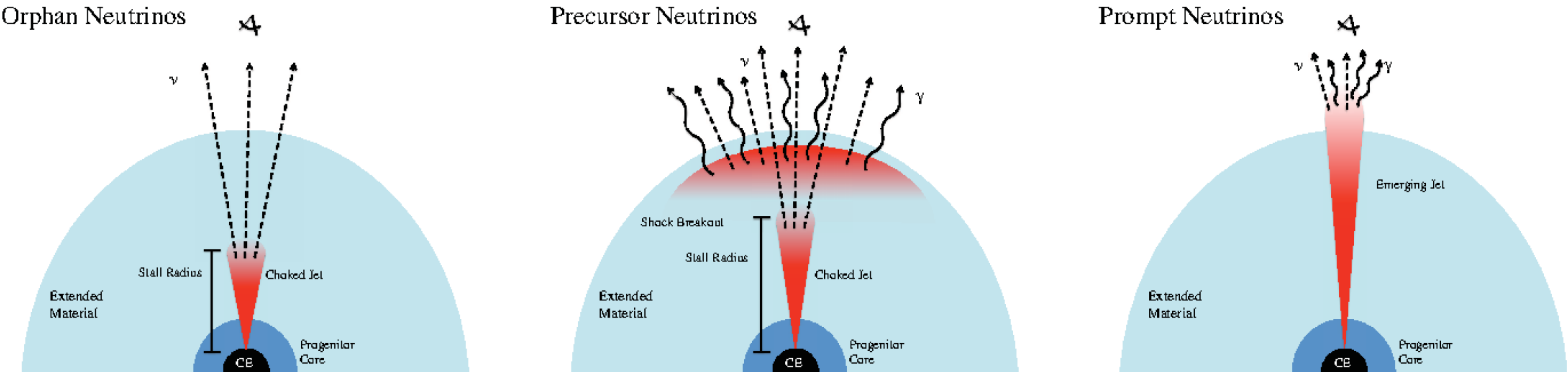
Correlation study of 3 years of IceCube data and 862 Fermi-LAT blazars

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

⟹ Multiple populations

+ similar limit for TDE contribution (~26 %)

Gamma-ray bursts

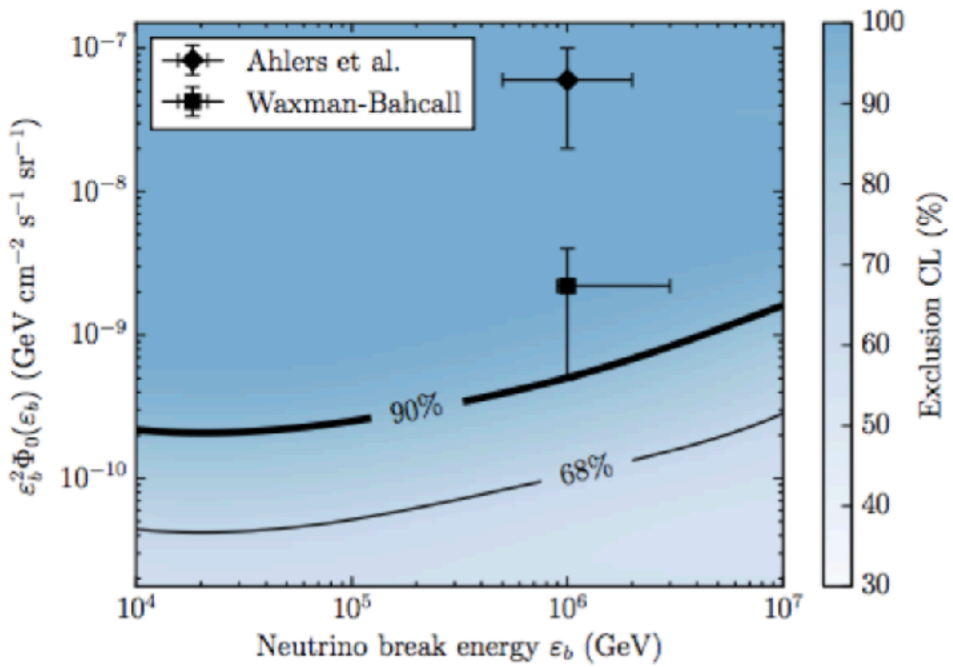


Despite intensive searches by IceCube and ANTARES >2000 bursts

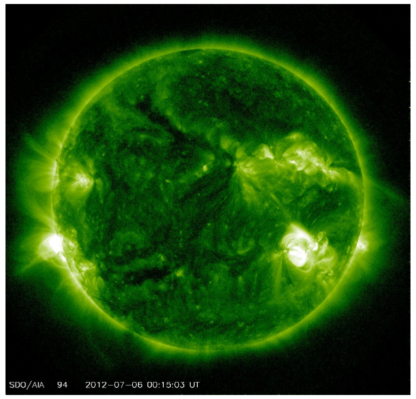
⟹ no excess found with the prompt emission

⟹ **GRBs contribute less than 1% to observed diffuse neutrino flux (<10% for ANTARES). Potential large population of nearby low-luminosity GRBs not constrained**

⟹ Try others precursor, afterglow and absorbed GRB searches

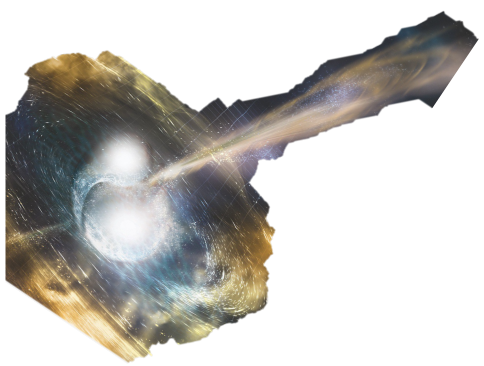


At low energy, possible neutrino astronomy



<u>Solar flare neutrinos</u>: up to 5 GeV neutrinos

- Produced by proton accelerated towards the solar atmosphere via magnetic reconnection
- Constraints on hadronic acceleration in solar flares (e.g., upper cutoff of the proton spectrum)
- Complementary to gamma rays and solar energetic particles



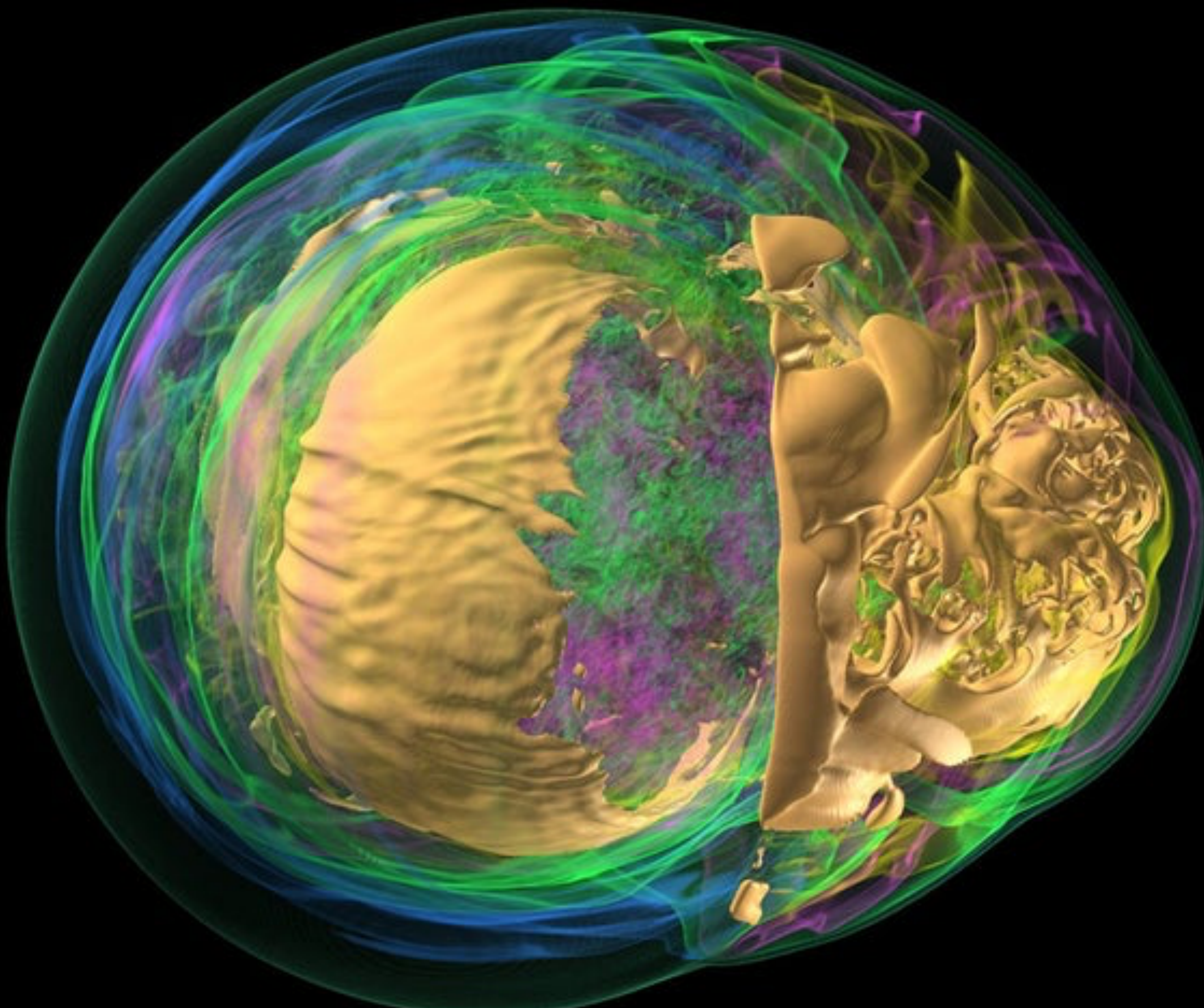
<u>Gamma Ray Bursts</u>: 1–100 GeV neutrinos

- Emitted below the photosphere after proton-neutron decoupling or in dense environment
- Potentially precursor to the EM signal
- Searches based on EM and/or GW detection

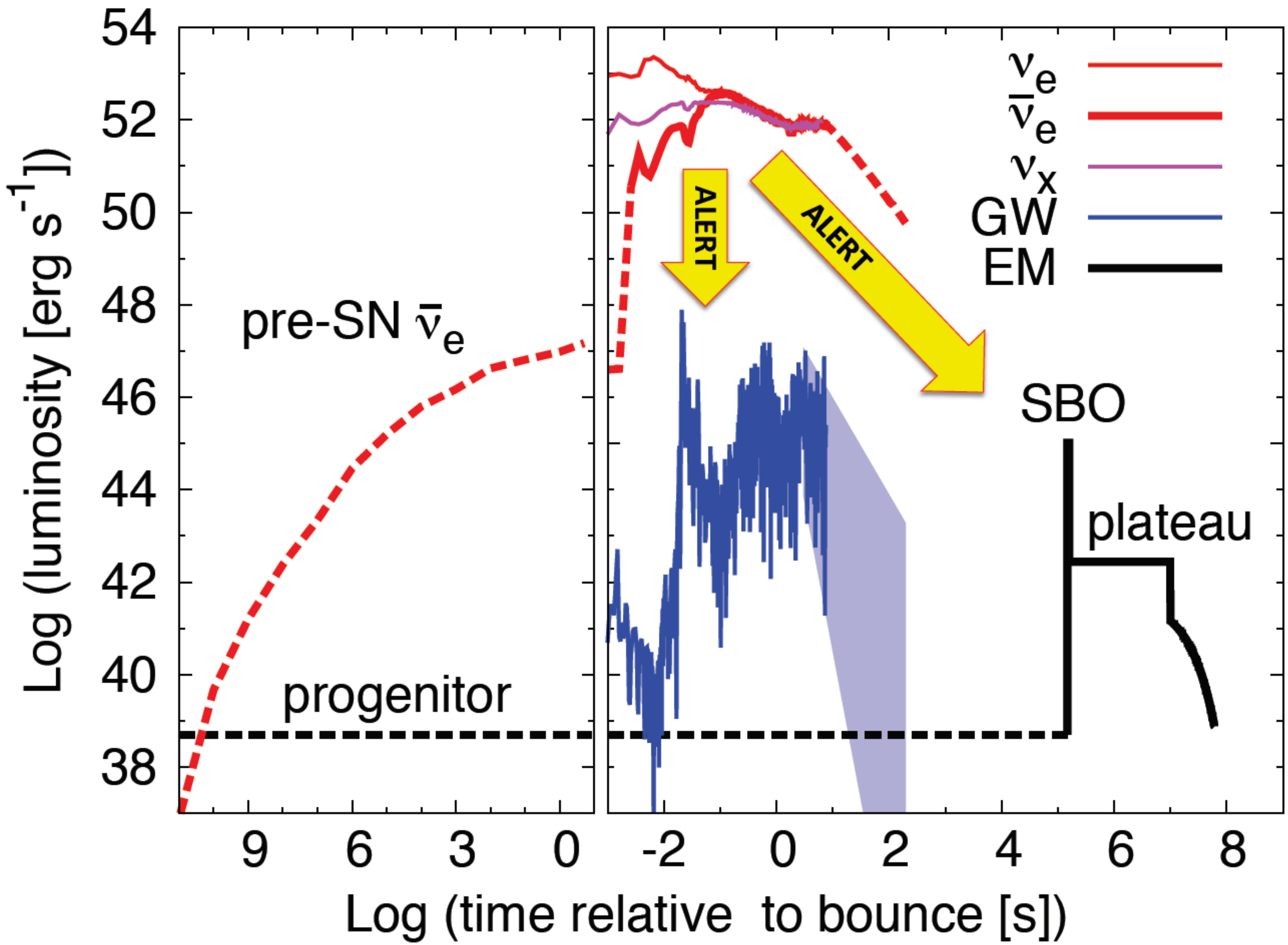
<u>Many other transients</u>: MeV-GeV range?

- Fast Radio bursts
- Novae
- Unknown transients based on LE neutrino monitoring

Neutrinos from core-collapse supernovae

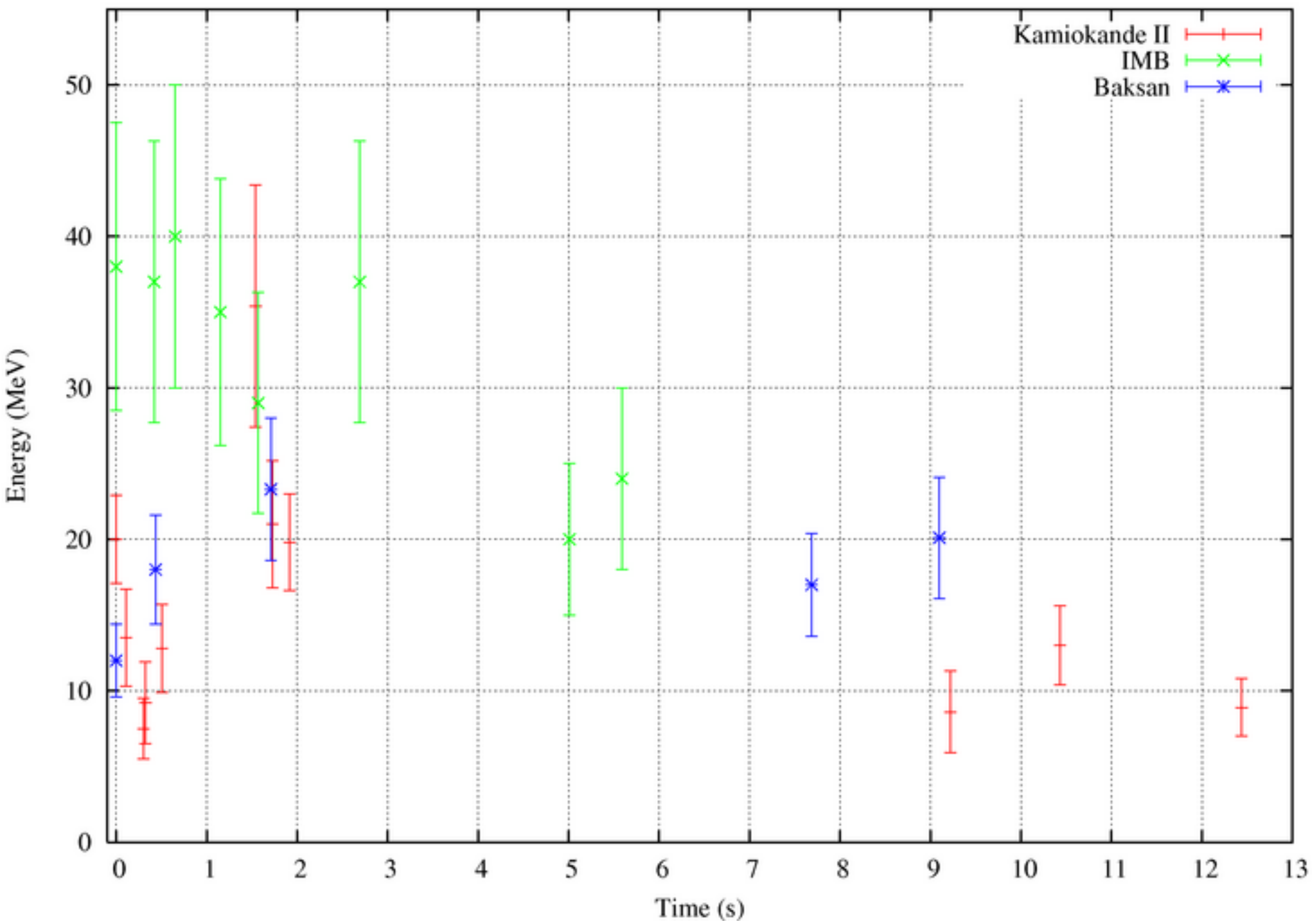


Multi-messenger light curve



SN1987a

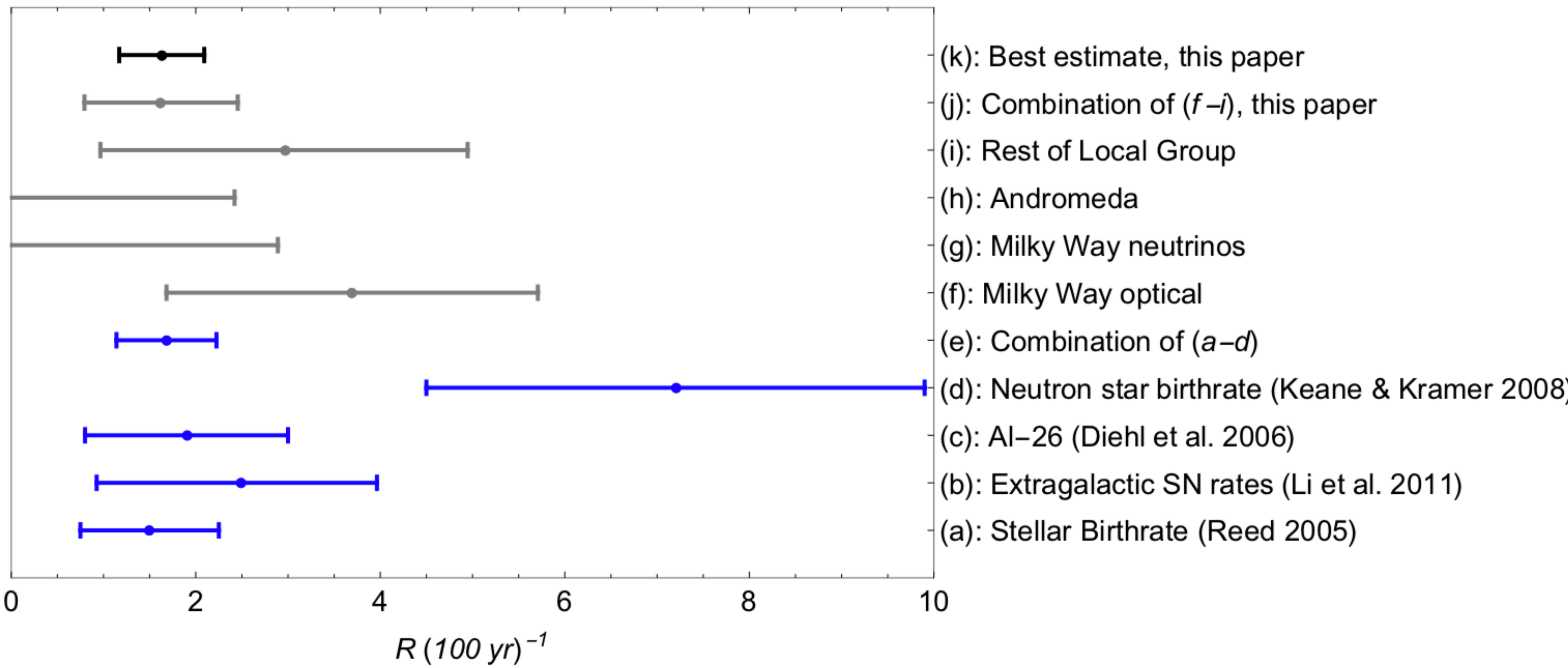
Only ~25 neutrinos detected (~10^{58} emitted)



- Kamiokande
  E_{th} = 8.5 MeV
  M = 2.9kt
  => 11 neutrinos
- IMB
  E_{th} = 29 MeV
  M = 6kt
  => 8 neutrinos
- Baksan
  E_{th} = 10 MeV
  M=130t
  => 3-5 neutrinos
- Mont Blanc
  E_{th} = 7 MeV
  M = 90t
  => 5 neutrinos (???)
  (delay -3h)

Expected rate of CCSN

- Humans haven't seen a galactic SN since Kepler
- Expected rate is very low ~1.6±0.5 per century !!!

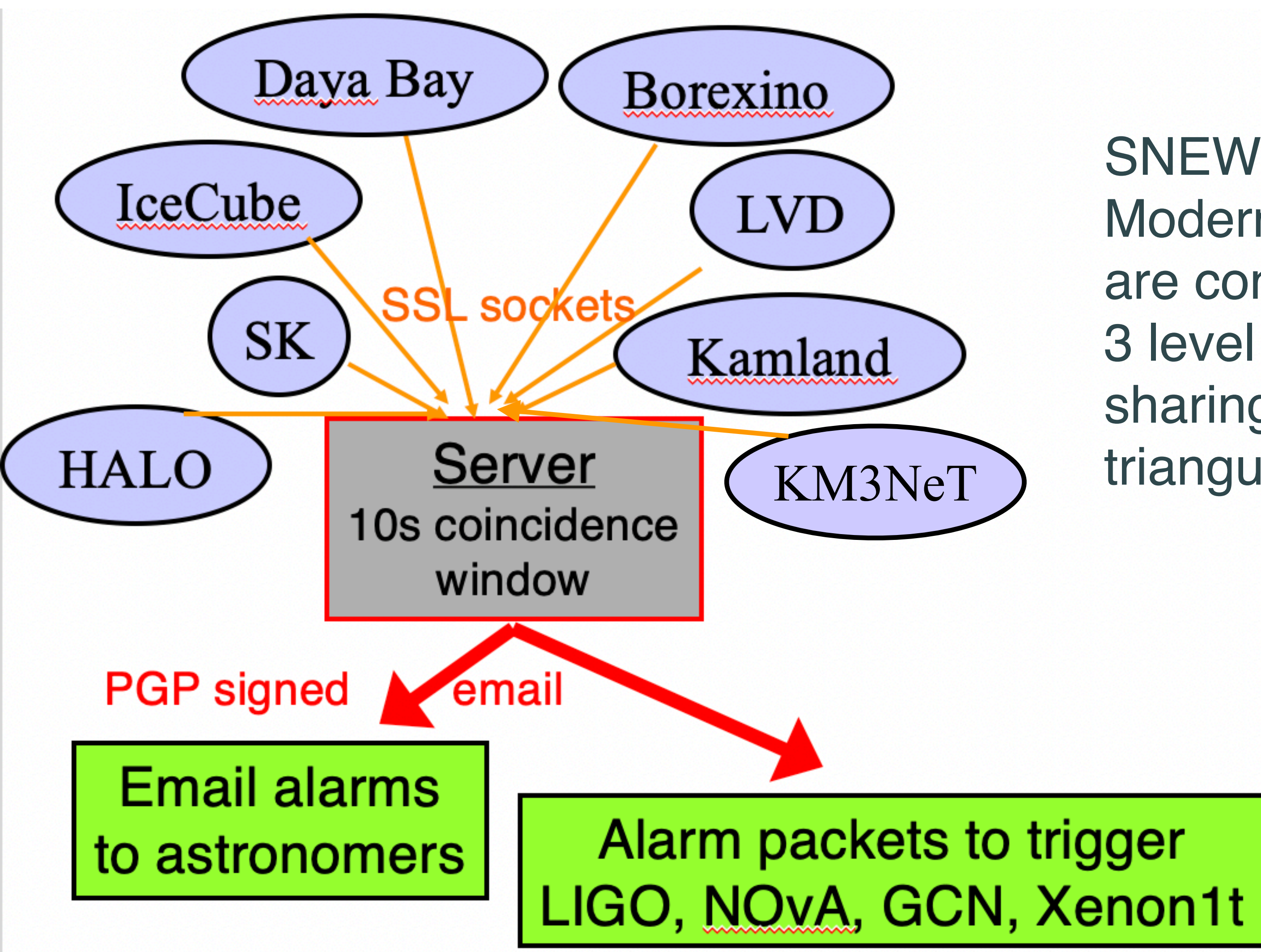


https://arxiv.org/pdf/2009.03438.pdf

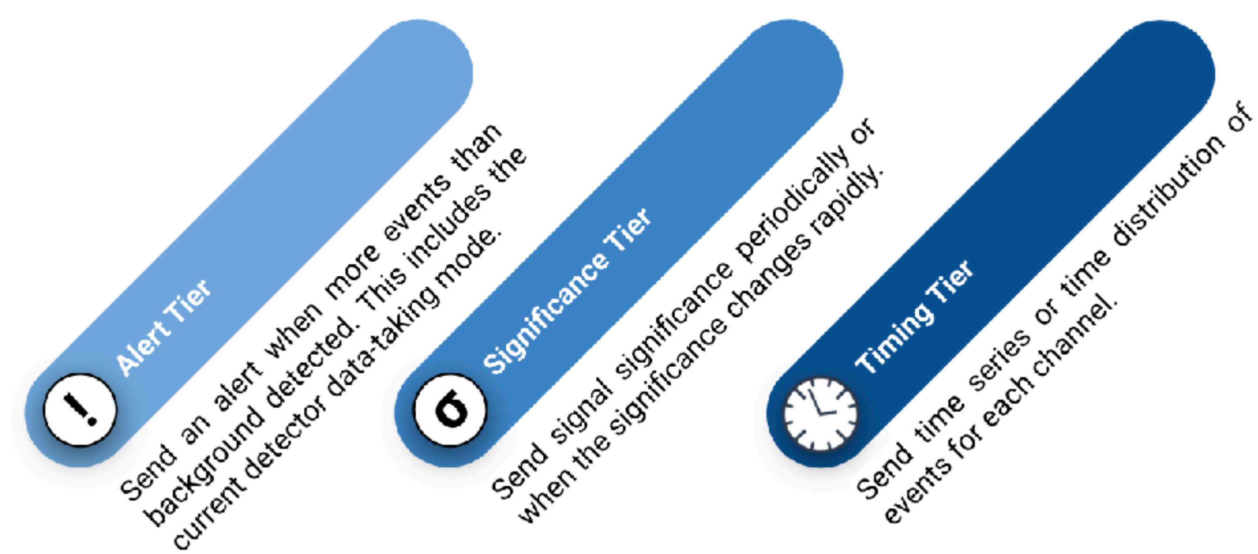
SNEWS

- 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).

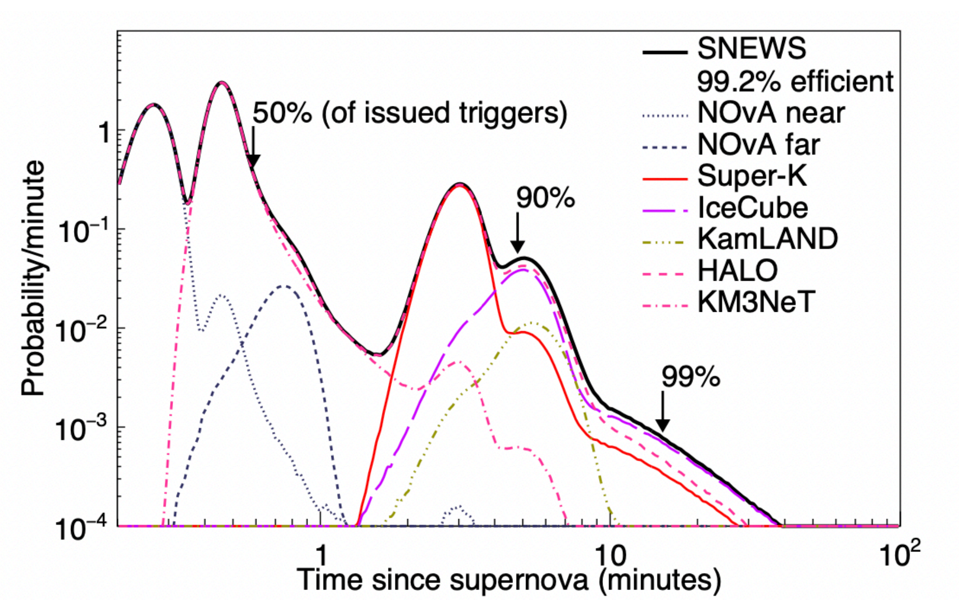


SNEWS2.0

Huge event rate

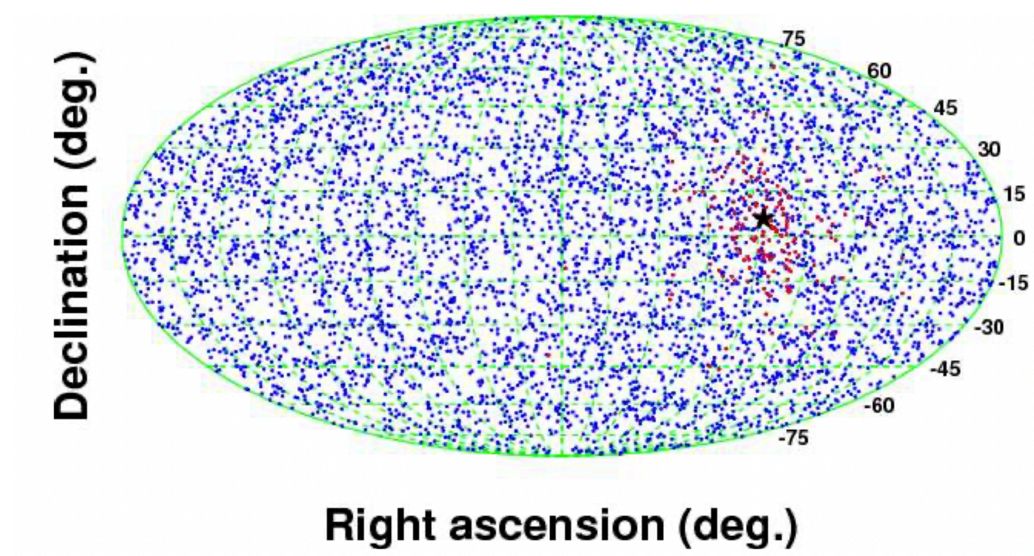
Experiment	Type	Mass [kt]	Location	11.2 $M_\odot$	27.0 $M_\odot$	40.0 $M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K	37K/38K	47K/38K
LVD	$C_nH_{2n}/\bar{\nu}_e$	1	Italy	190/190	360/350	340/240
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	-	250	-
XENONnT	Xe/any ν	0.006	Italy	56	106	-
LZ	Xe/any ν	0.007	USA	65	123	-
PandaX-4T	Xe/any ν	0.004	China	37	70	-

Alert latency

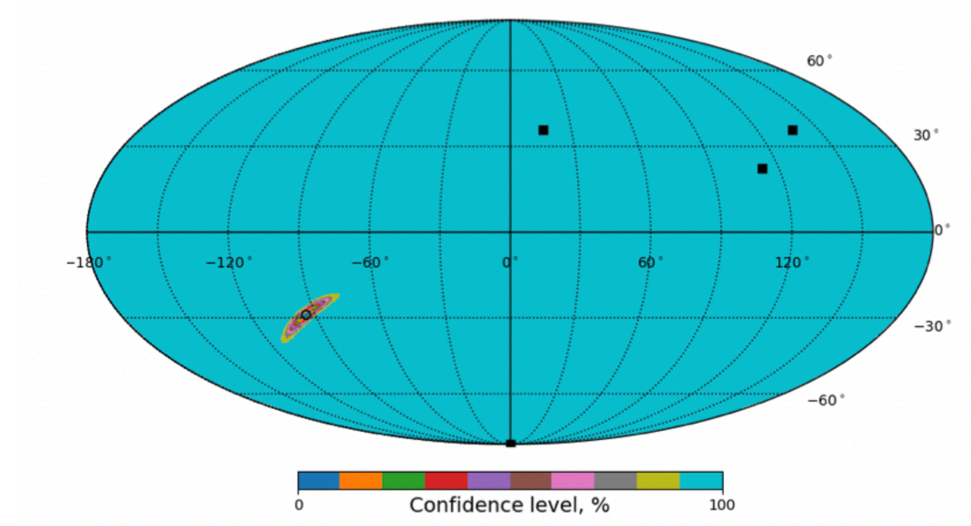


Pointing

SK



Triangulation



https://arxiv.org/pdf/2011.00035.pdf

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