Multi-Messenger Astronomy at ICRC 2021

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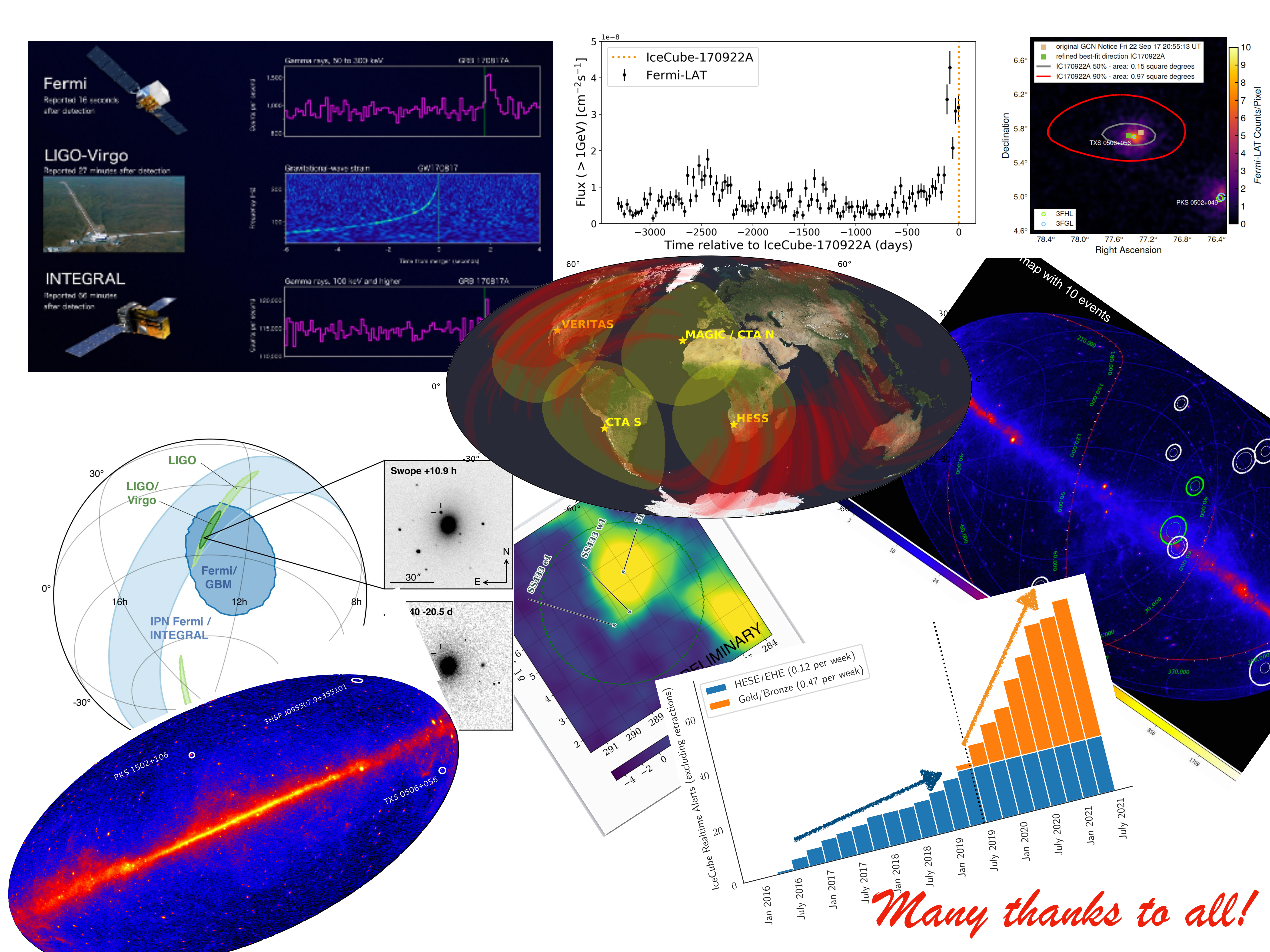
July 23, 2021

VILLUM FONDEN
Sapere Aude
CARLSBERG FOUNDATION
SFB 1258 Neutrinos Dark Matter Messengers



Many thanks to all!

Outline

- Real time alert systems and multi-messenger networks
- Blazars and active galactic nuclei
- Tidal disruption events
- Gravitational wave sources
- Galactic sources
- Conclusions

Bonus: Homework for ICRC 2023!

Disclaimer: This talk covers a selection of the most recent developments presented over the past two weeks. Not all suitable references are provided for each subject.

Real Time Astronomy

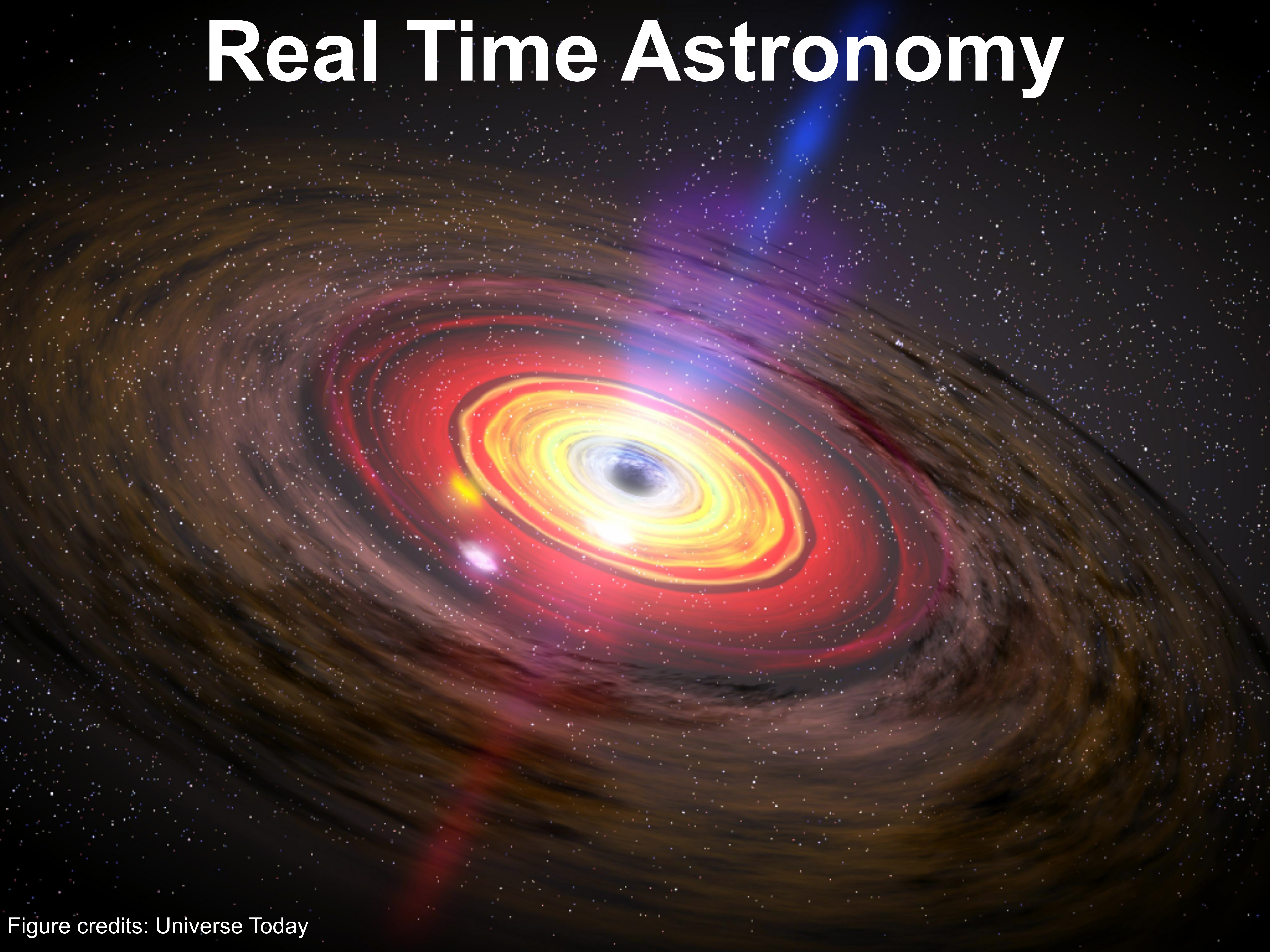
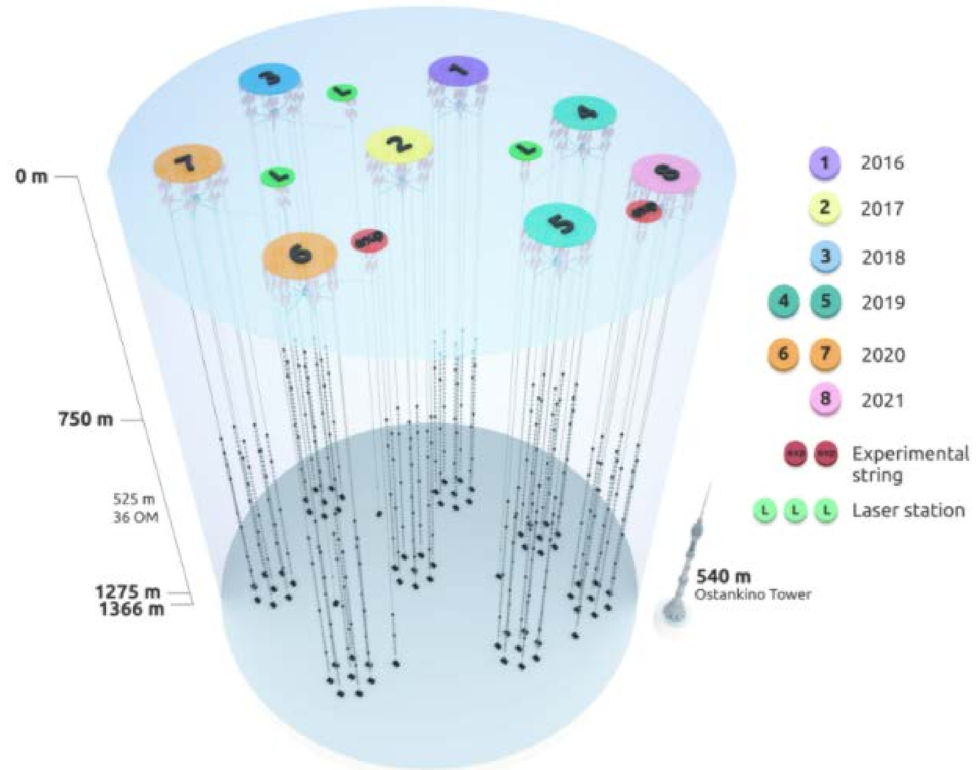
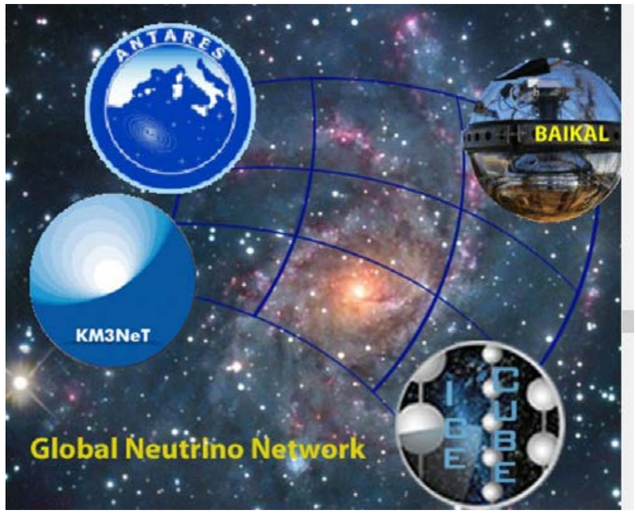


Figure credits: Universe Today

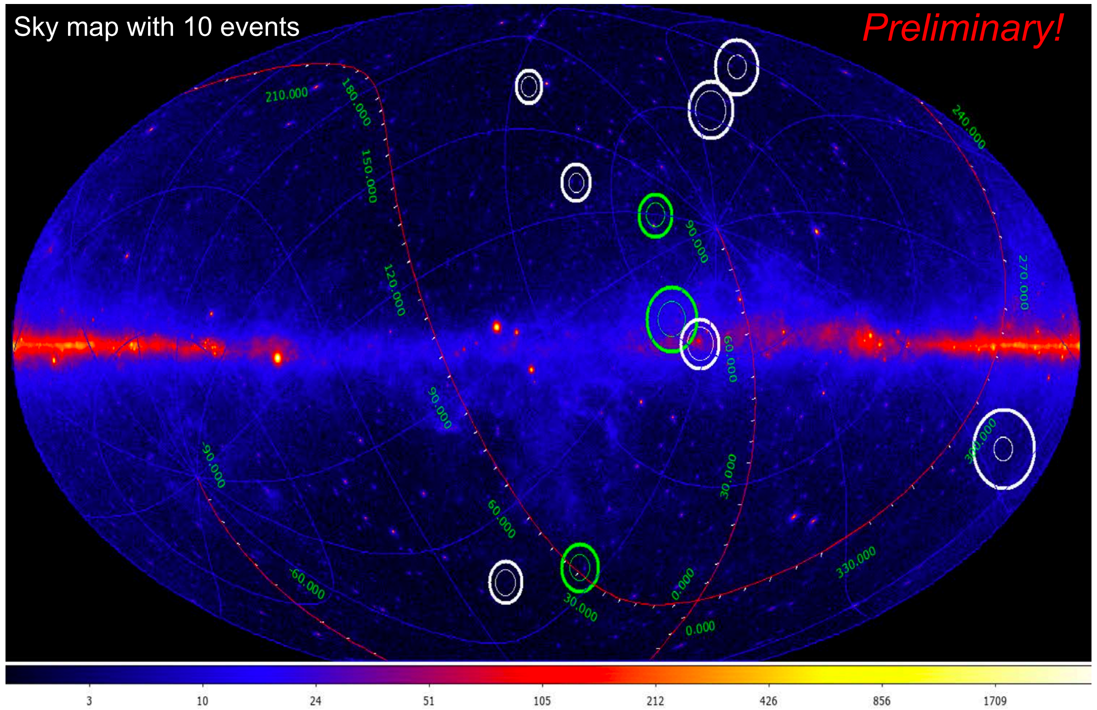
Real Time Astronomy with Baikal-GVD

Status 2021: 8 clusters, 3 laser stations, experimental





10 possible associations found!

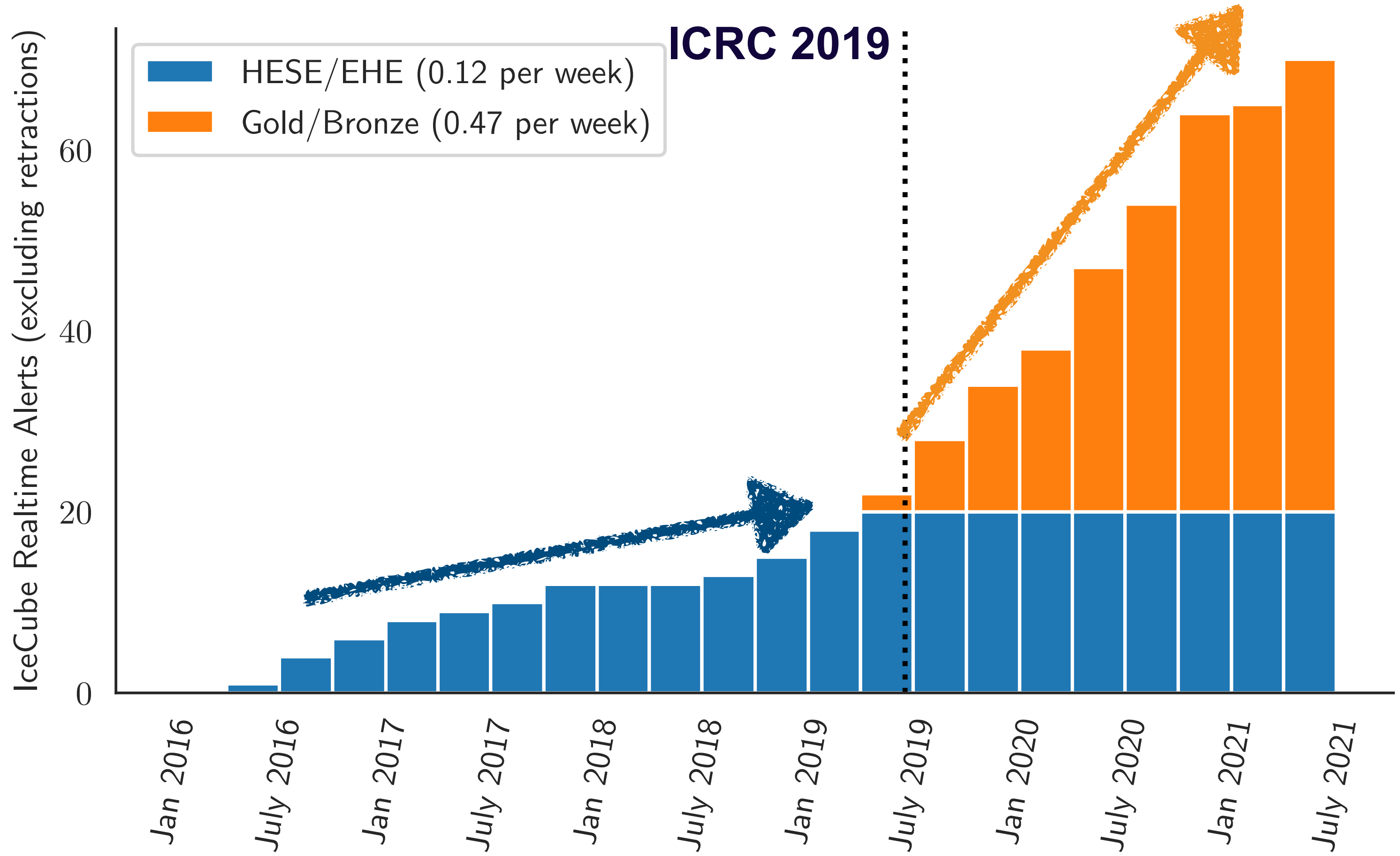


Effective volume 2021: 0.40 km^3 (cascade mode)

- Largest neutrino telescope in the Northern Hemisphere.
- Alarm system to monitor the sky in real time (in place since fall 2020, delay of few hours).
- Fast follow-up searches for coincidences of Baikal-GVD events with ANTARES and IceCube alerts.
- Off-line searches based on electromagnetic data.

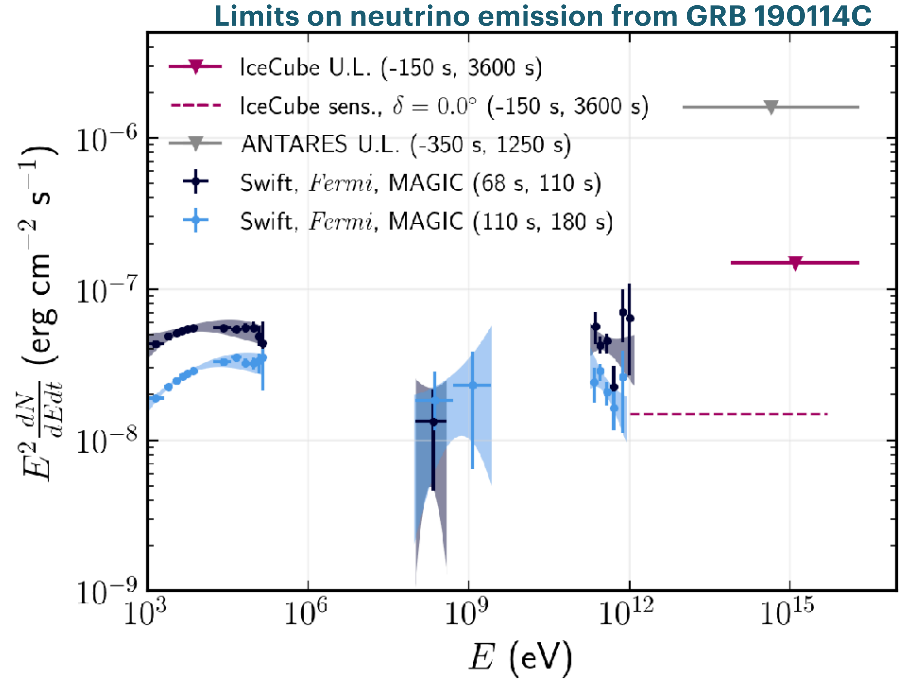
Zhan Dzhilkibaev, PoS 002, Olga Suvorova, PoS 946. See Feifei Huang, PoS 941 for real time alerts with Km3NeT.

IceCube Alerts & Real Time Follow-Up

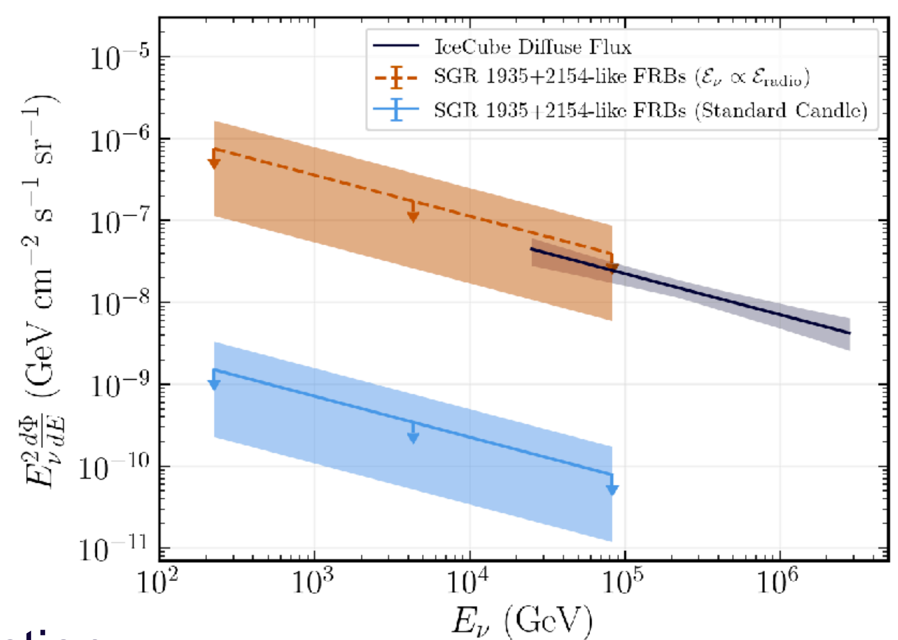


Targets: Gamma-Ray Bursts

Limits on neutrino emission from GRB 190114C



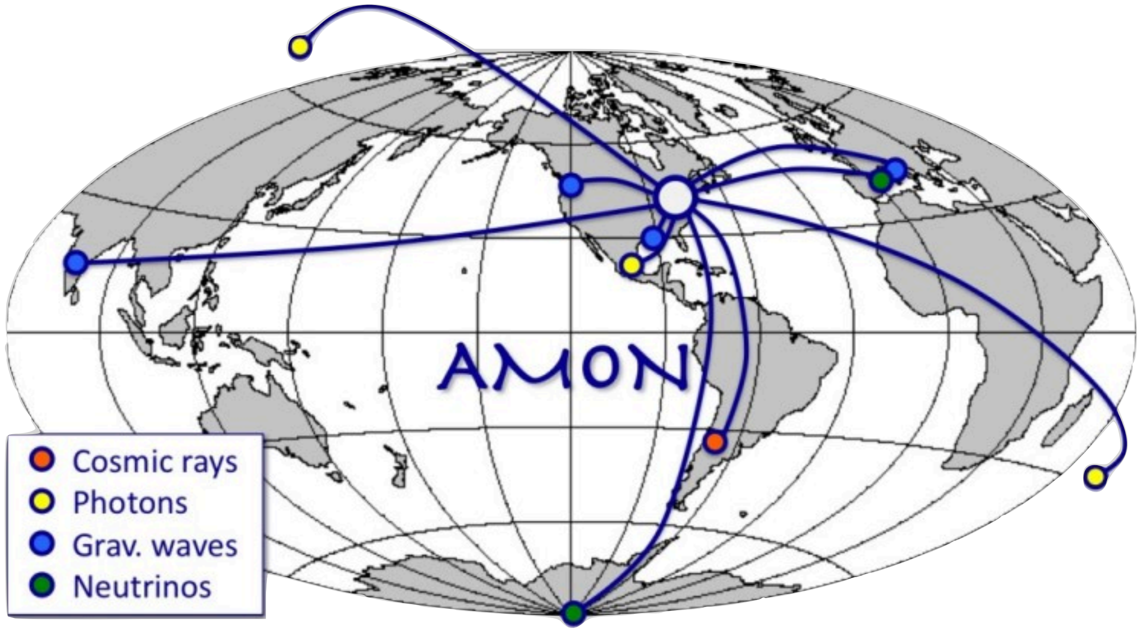
Targets: Fast Radio Bursts



- IceCube releases alerts & responds to transient searches in real time.
- Used over 50 times (GRBs, FRBs, blazar flares, …); no significant detection.
- Current limits constrain nearby bright transients and future ones aim to constrain populations of sources.

Marek Kowalski, PoS 022. Robert Stein, PoS 009. Alex Pizzuto, PoS 952. Martina Karl, PoS 940.

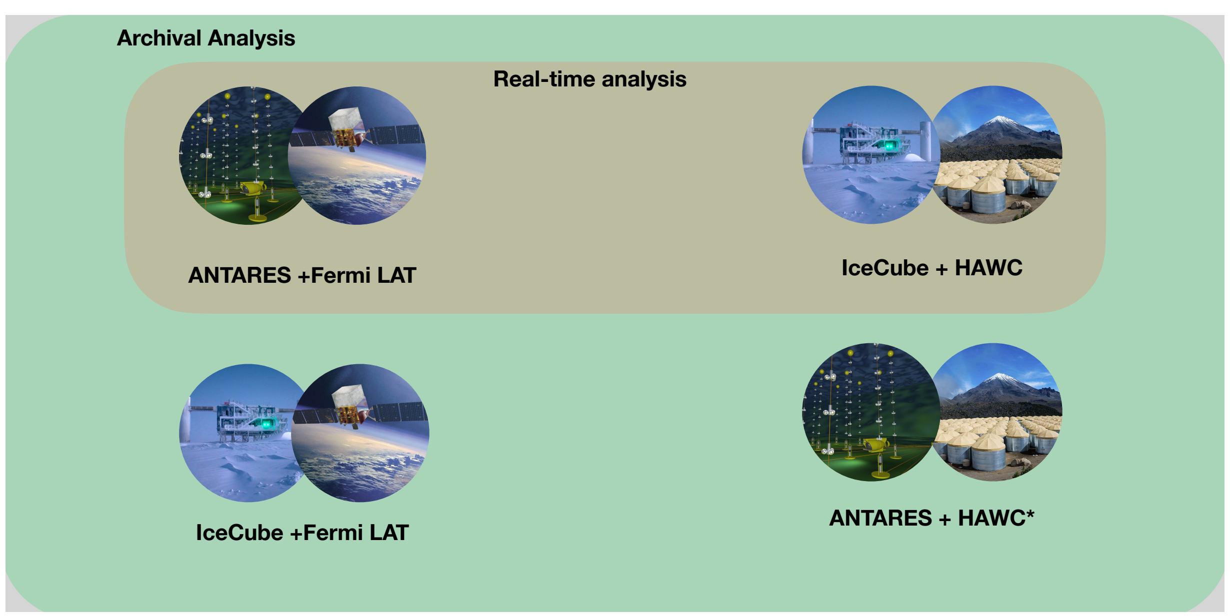
AMON: A Multi-Messenger Network



- Real time coincidences.
- Archival studies (coincidence analysis).
- Triggering and follow-up Observatories.
- Using sub-threshold data.
- Broadcast directly to GCN/TAN.

NuEM channel (active since 1 yr):

- Searching for HE gamma-ray and neutrino coincidences.
- No counterparts found in archival coincidences.



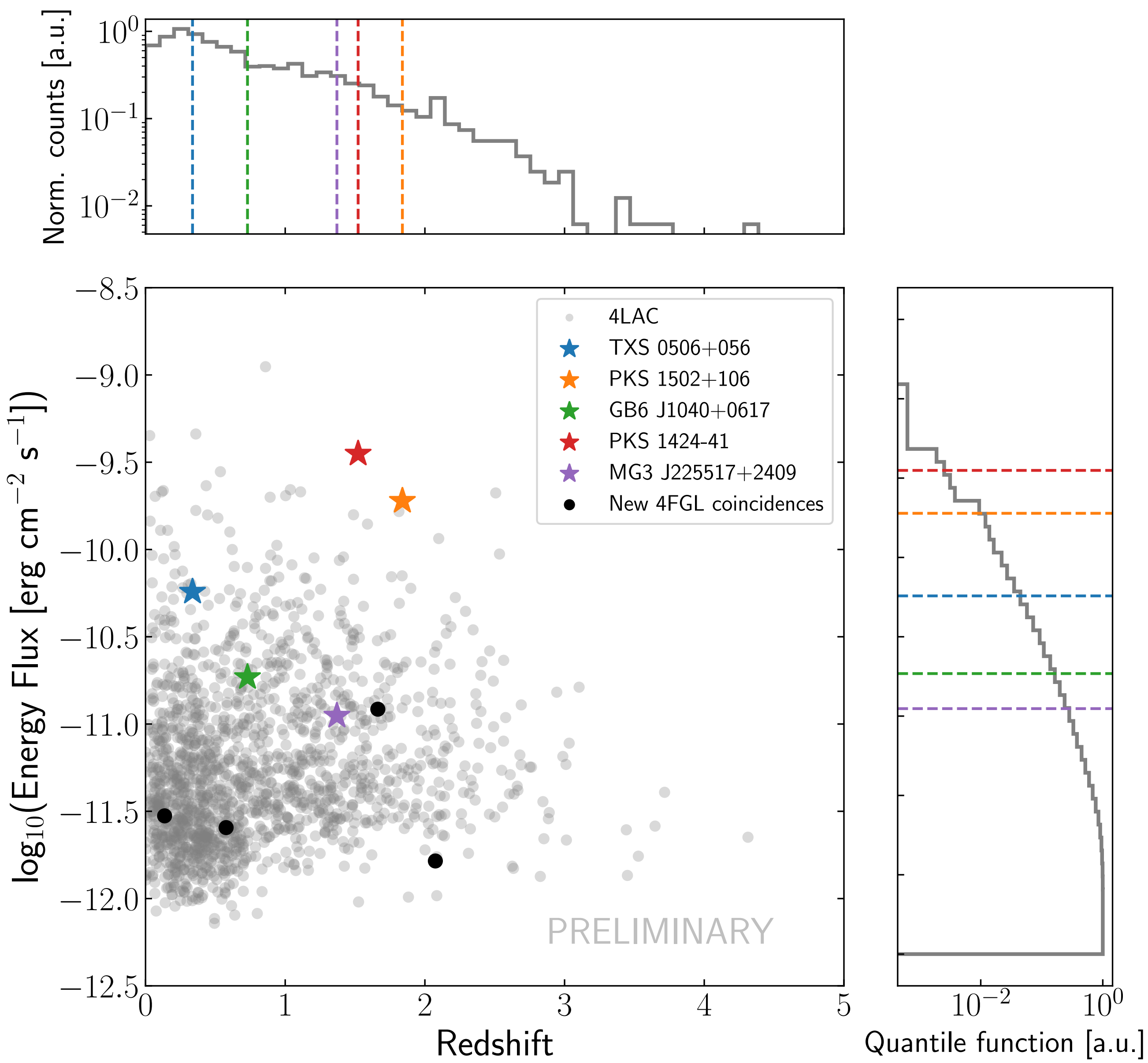
Coincidences in the NuEM channel

Name	R.A. [°]	Decl. [°]	$\delta\theta$ [°]	FAR [yr^{-1}]	Time UTC
Real-time alerts					
NuEM-210515A	93.64	14.66	0.15	3.93	2021-05-15 00:20:43
NuEM-210515B	93.93	12.51	0.20	1.90	2021-05-15 00:19:27
NuEM-210111A	162.34	19.46	0.37	3.85	2021-01-11 13:06:41
NuEM-201124A	134.99	7.74	0.23	2.96	2020-11-24 14:13:37
NuEM-201107A	140.20	29.76	0.15	3.49	2020-11-07 15:55:31
ANTARES-Fermi 200704A	255.42	-34.48	0.43	0.98	2020-07-04 15:53:48
NuEM-200202A	200.30	12.71	0.17	1.39	2020-02-02 14:07:52
ANTARES-Fermi 191011A	49.96	18.80	0.40	1.21	2019-10-11 15:54:32
Archival Coincidences					
ANTARES-Fermi	248.00	-7.7	0.07	0.09	2012-11-21 20:19:52
ANTARES-Fermi	279.68	-5.05	0.10	0.09	2014-08-05 11:13:33
HAWC-IceCube	4.93	2.96	0.16	0.99	2016-12-12 04:38:41
HAWC-IceCube	173.99	2.27	0.53	0.026	2018-04-12 07:54:51
HAWC-ANTARES	25.6	25.0	0.2	0.7	2016-01-08 04:39:38
HAWC-ANTARES	222.8	-0.8	0.2	0.87	2017-09-07 01:21:22
HAWC-ANTARES	85.4	3.4	0.2	0.41	2019-03-29 03:01:18

Hugo Ayala, PoS 958. Timothee Gregoire, PoS 934.
See Fabian Schuessler, PoS 935 for Astro-COLIBRI.

Follow-Up of Neutrino Alerts with Fermi-LAT

Fermi-LAT follow-up observations of real time high-energy neutrino detections have identified 7 candidate counterparts (since 2019; scanning the whole sky every 3 hrs).



Outstanding coincidences with a single candidate counterpart

IceCube-190730A and PKS 1502+106

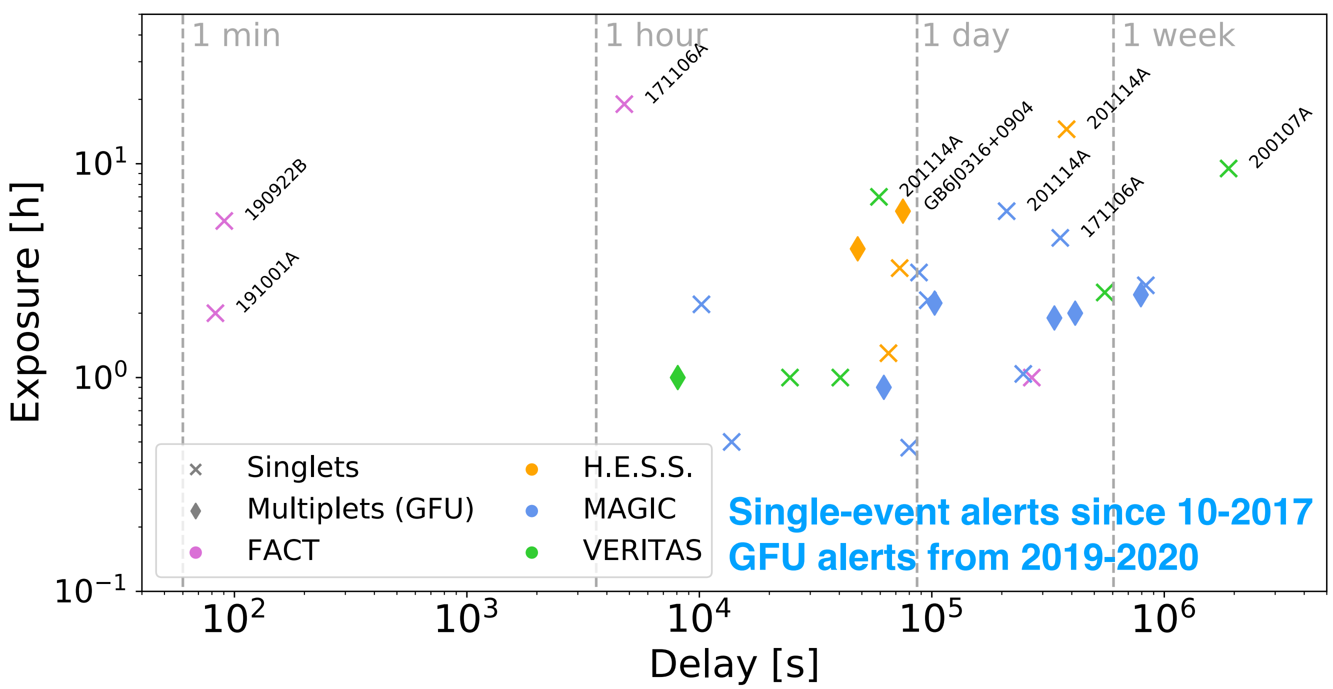
- Gold alert with 67% signalness, well-reconstructed
- PKS 1502+106 is a FSRQ with a large redshift of z = 1.84
  - It is the 15th brightest blazar in the 4LAC catalog
- Detected in low gamma-ray state at neutrino arrival
- Neutrino production supported by several works (Rodrigues+2021, Britzen+ 2021, Plavin+ 2021)

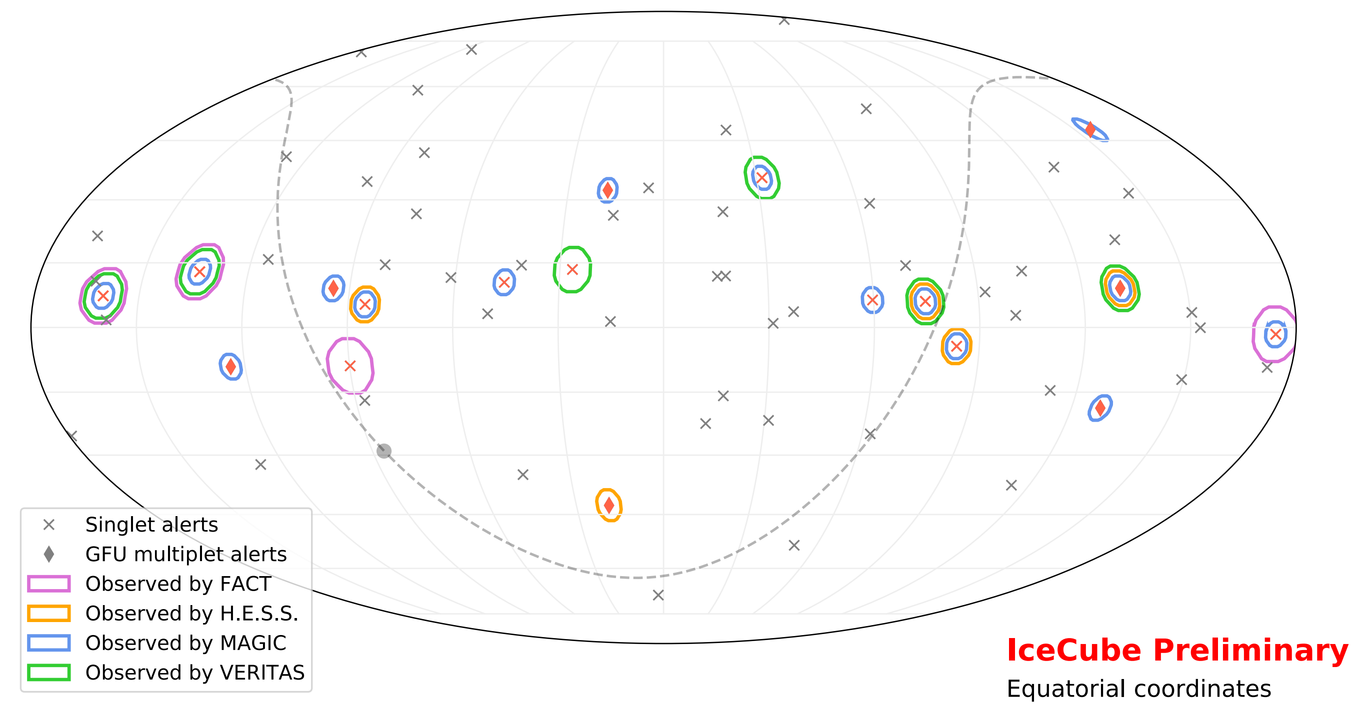
- Improvement of follow-up strategies foreseen.
- Active proposals for follow-up observations with the European VLBI Network (EVN), Nordic Optical Telescope (NOT), RoboPol at Skinakas Observatory, *Swift*-XRT, etc.

Simone Garrappa, PoS 956. See Francesca Capel, PoS 981 for a discussion on evaluation of cosmic coincidences.

Follow-Up of Neutrino Alerts with IACTs

Cherenkov telescope arrays (IACTs: FACT, H.E.S.S., MAGIC, VERITAS) operate a follow-up program of neutrino alerts sent by IceCube to identify VHE gamma-ray counterparts.

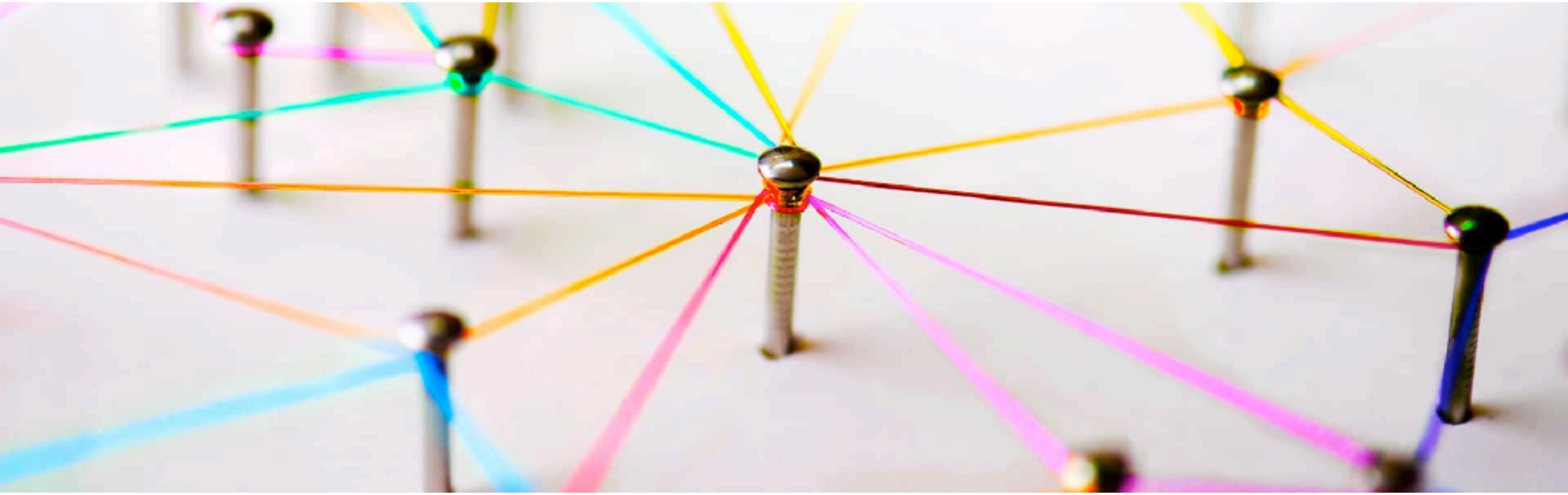




- Observations of gamma-ray sources around a *cluster of neutrino events* identified by IceCube (GFU).
- Follow-up of *single high-energy neutrino candidate event of astrophysical* origin (e.g. IC-170922A).
- Observational strategies: fast reaction (<1day); deep exposures (FACT, HESS, VERITAS) or follow-up of many alerts (MAGIC).
- No VHE gamma-ray counterpart detected since IC-170922A/TXS+056 (MAGIC & VERITAS).

Konstancja Satalecka, PoS 960.
See Olga Sergijenko, PoS 975, Andrea Bulgarelli, PoS 937, Roberta Zarin, PoS 005 for CTA alert & follow-up systems.

Homework for ICRC 2023



- Crucial to foster fruitful collaborations among different Observatories.
- Need to improve rapid alert systems and inclusive multi-messenger networks.
- Necessary to coordinate efforts to establish efficient multi-messenger platforms & infrastructure.
- Detection of single neutrinos limited by follow-up capacities. Think about the optimal strategies.

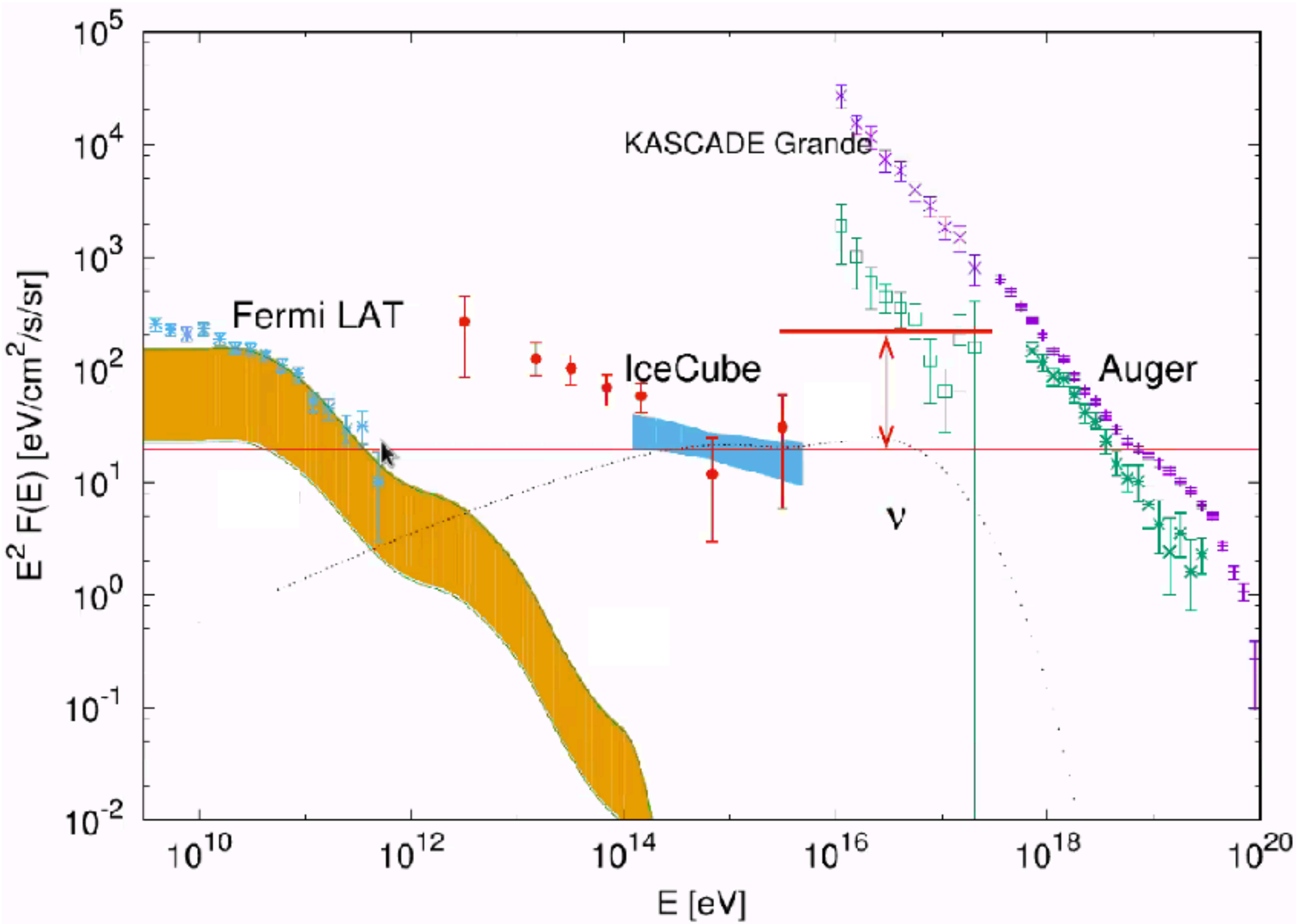
Sessions # 25, 27, 28, 47.

Blazars & Active Galactic Nuclei

Figure credit: theconversation.com

Emerging Picture

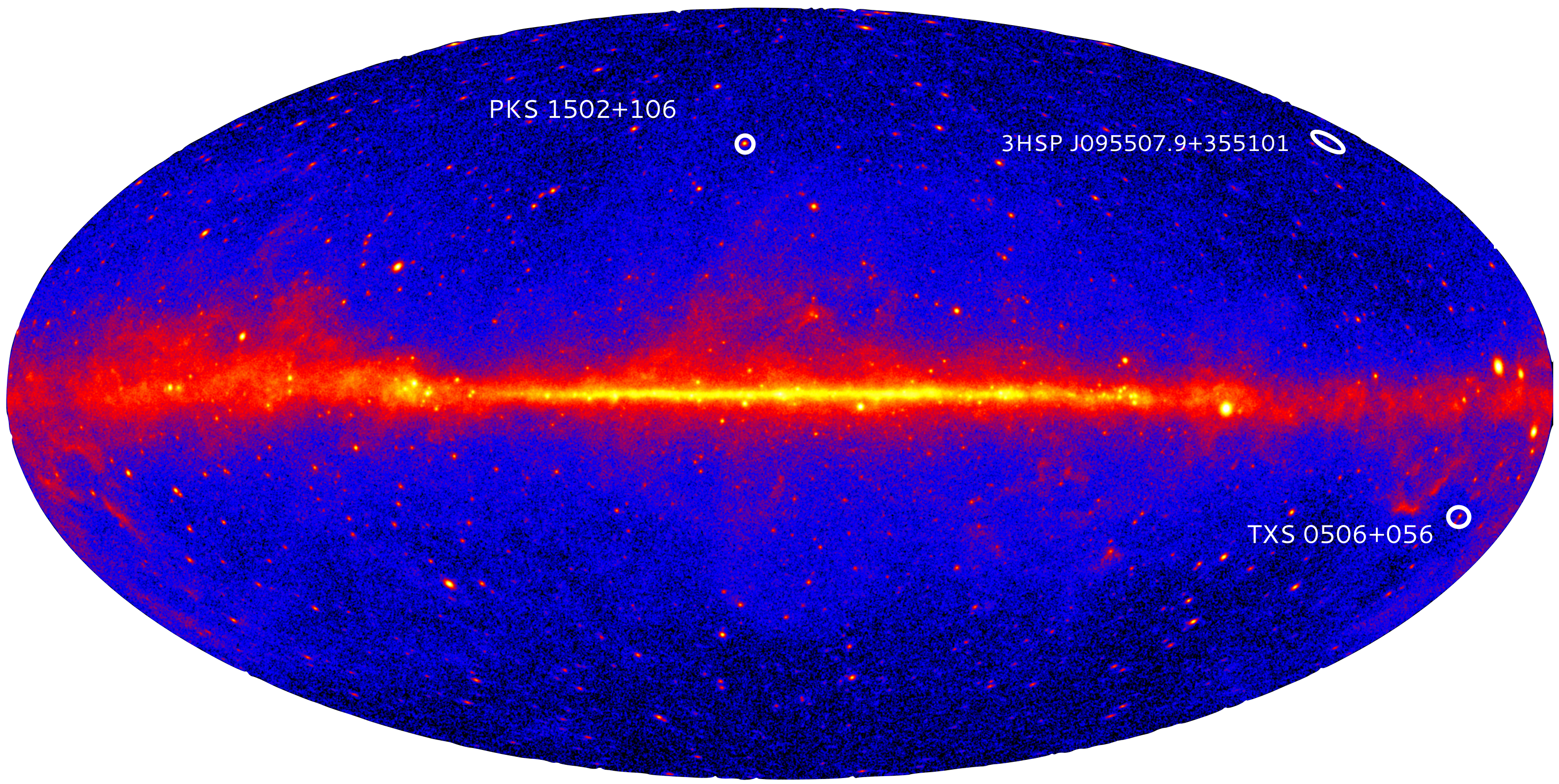
Connection among all messengers seems unlikely.

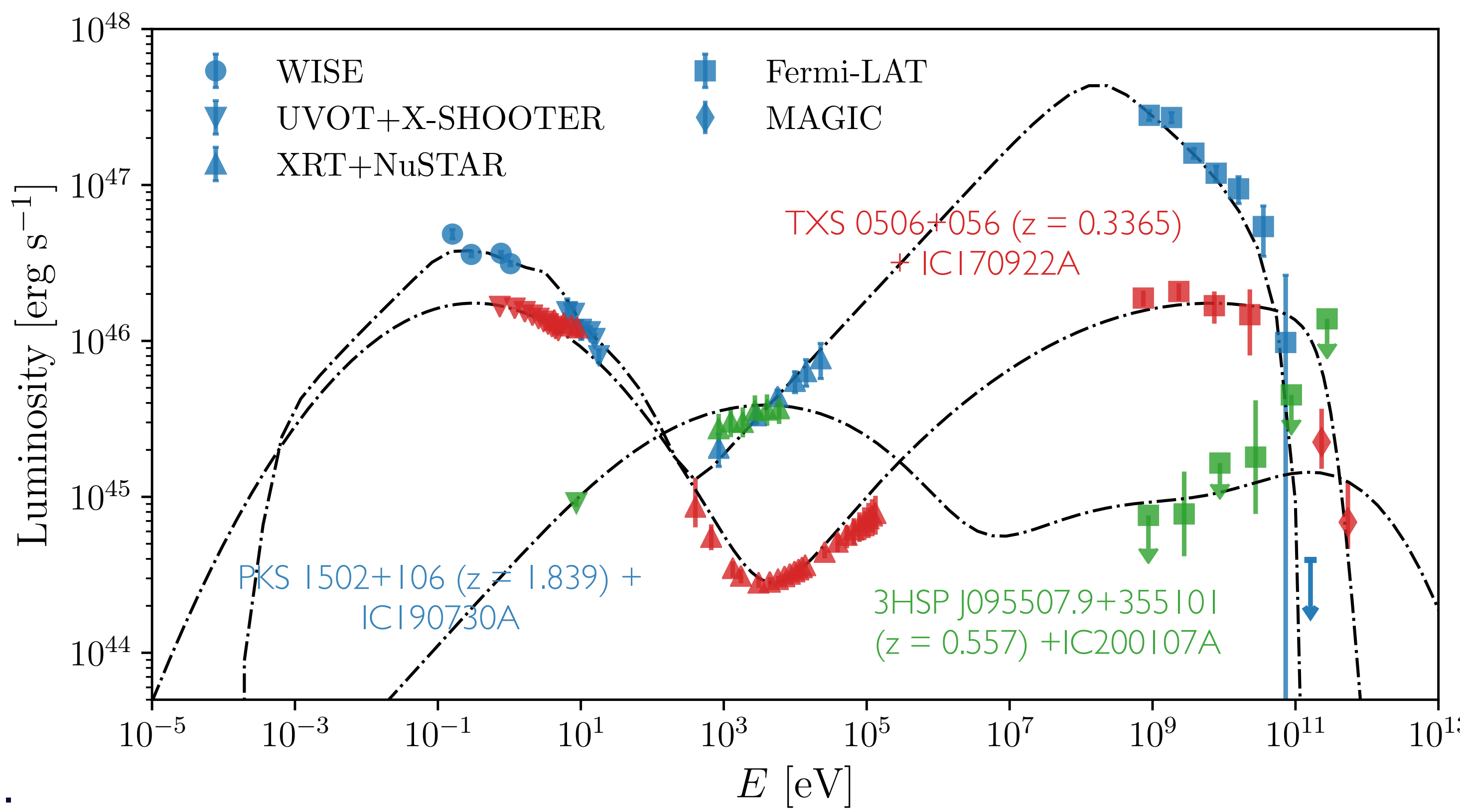


Marek Kowalski, PoS 022. Foteini Oikonomou, PoS 030. Michael Kachelriess, PoS 018.

IceCube Neutrino Events & Blazars

Blazars cannot explain the observed diffuse neutrino flux, but several IceCube neutrino events may be in coincidence with blazars.

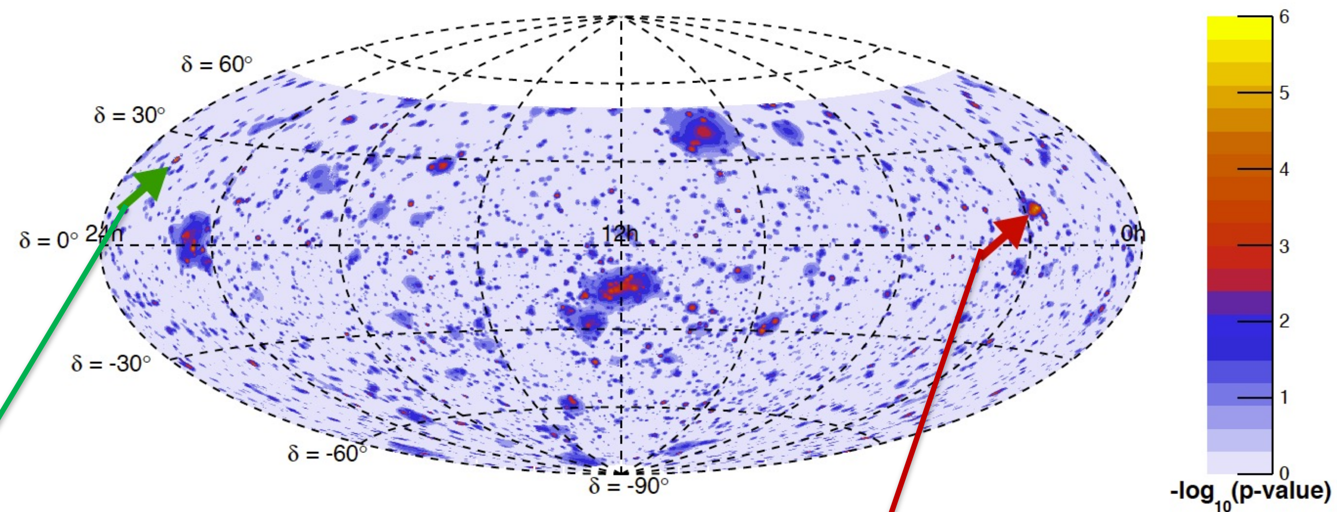




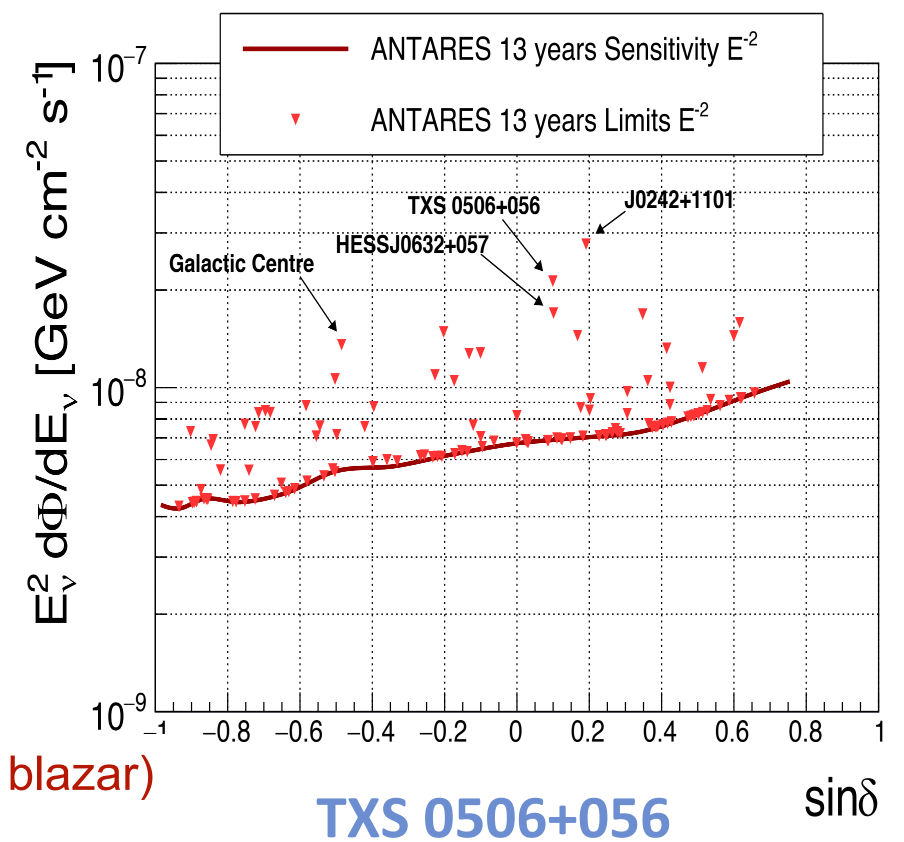
Foteini Oikonomou, PoS 030.

ANTARES Neutrino Events & Blazars

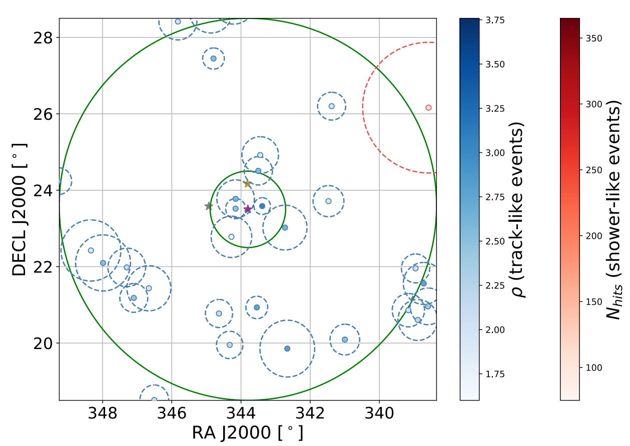
Updated: ANTARES 13 years (3845 days of live time): 10162 tracks and 225 showers



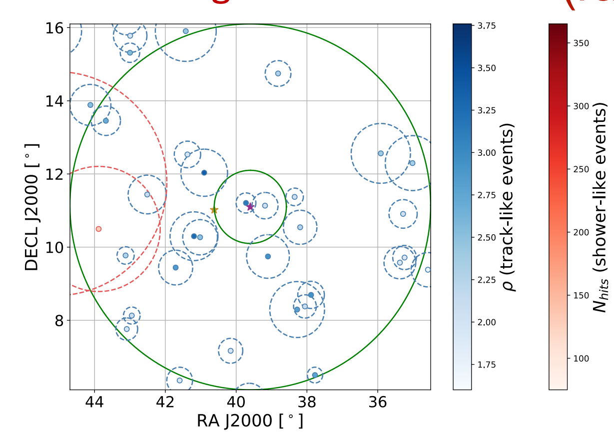
121 sources investigated



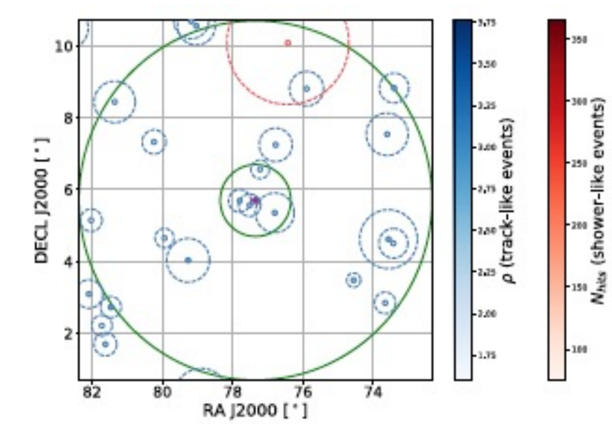
2nd most significant cluster:
RA=343.8° δ=+23.5°
pre trial: 4.2 σ
Close to blazar MG3 J225517+2409 (orange star)



The most significant cluster:
RA=39.6° δ=+11.1°
pre trial: 4.3 σ (48% post)
Within 1 degree of J0242+1101 (radio blazar)



TXS 0506+056



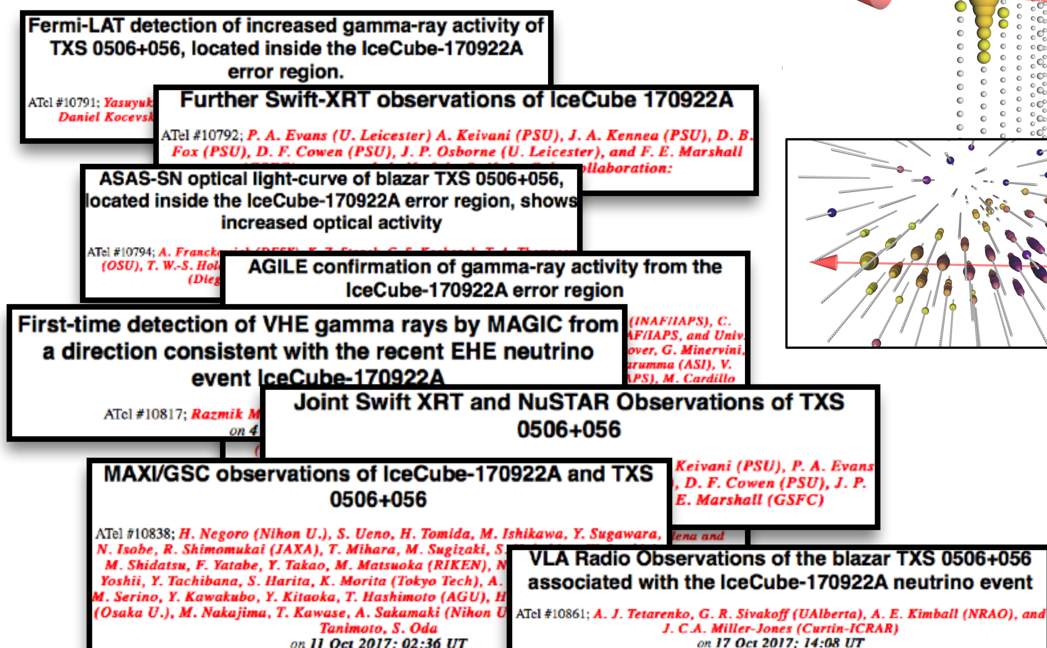
Pre (post) trial: 3.1σ (2.6σ)
4 muon events within 1°

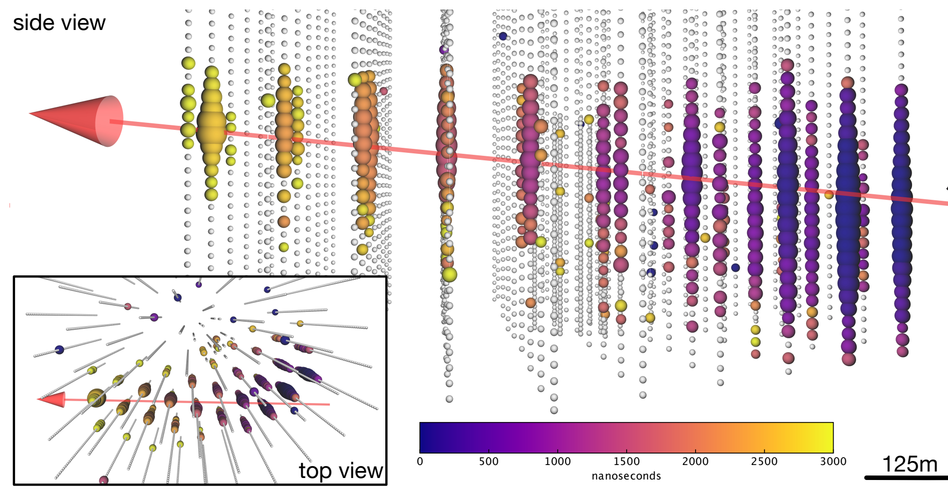
Paschal Coyle, PoS 042. Giulia Illuminati, PoS 1161.

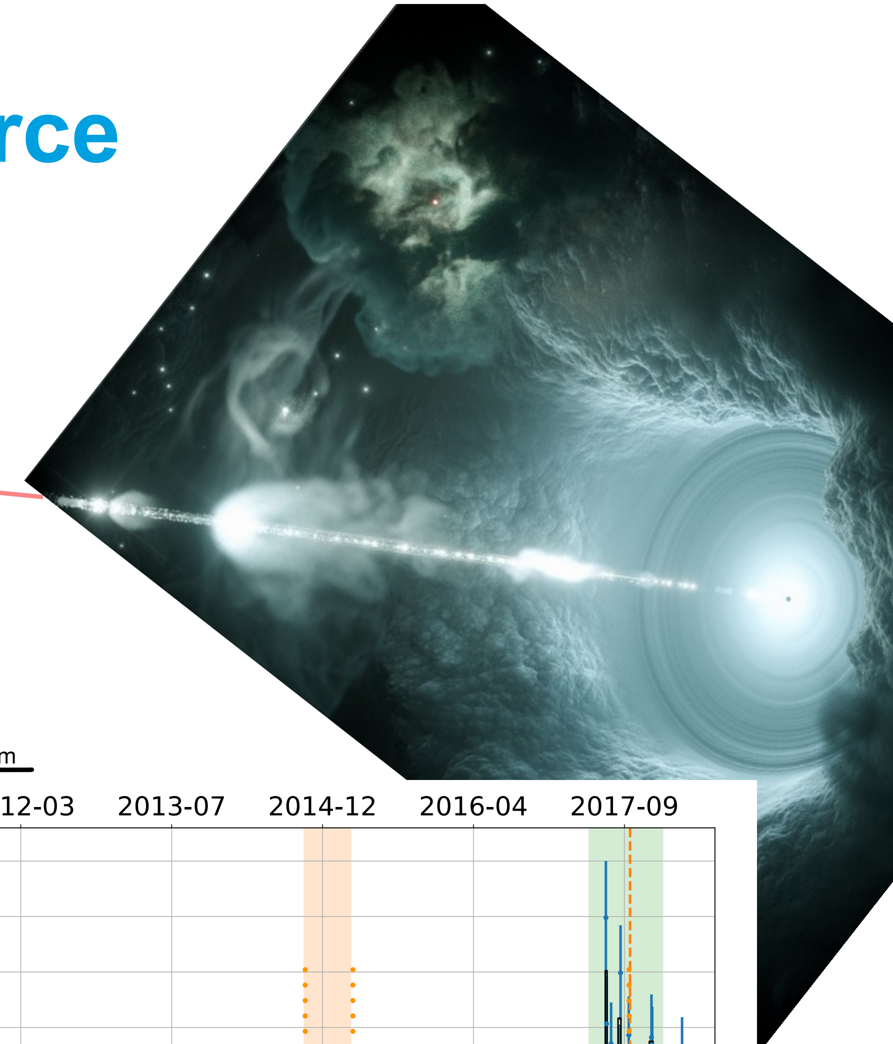
Possible Association #1: TXS 0506+056

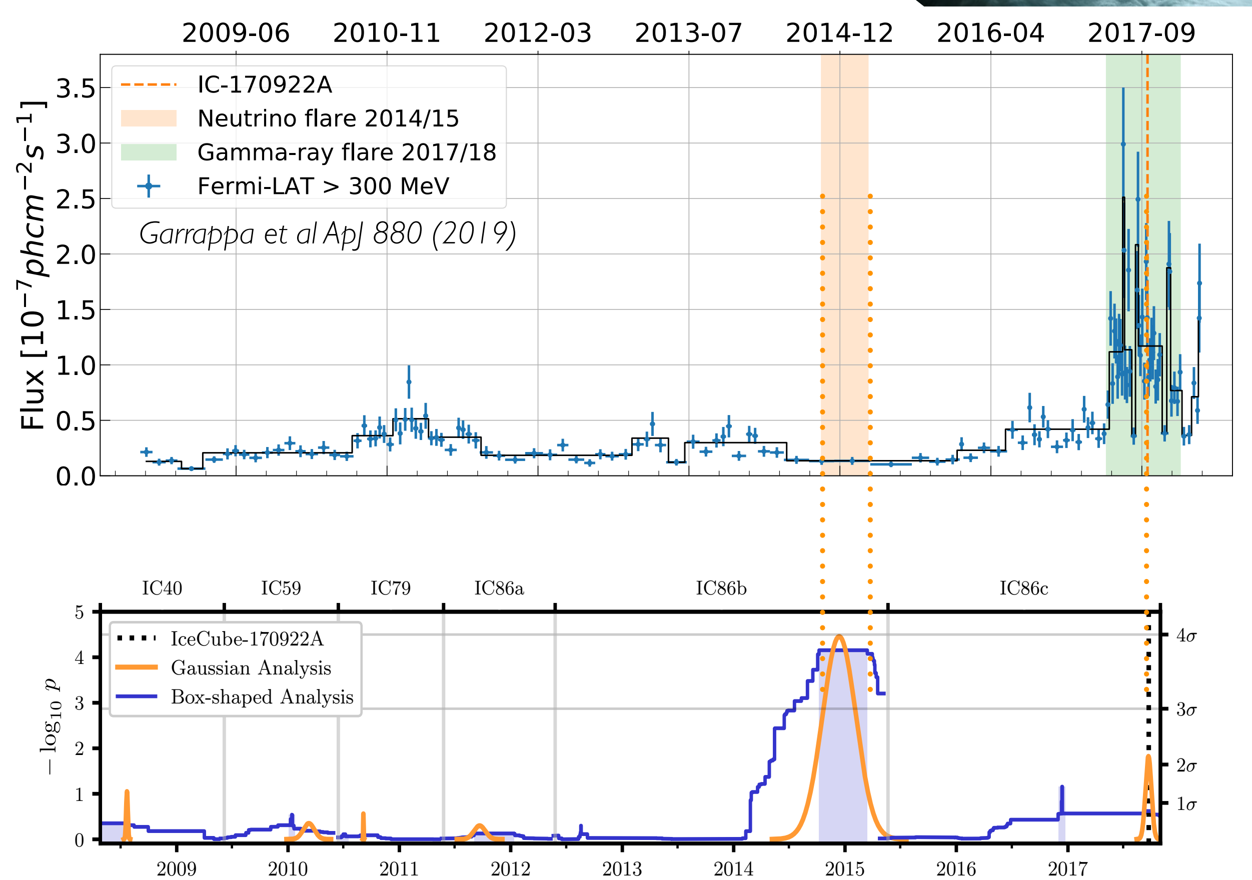
TXS 0506+056 - first neutrino point source

A flaring Blazar in spacial and temporal coincidence with IC170922A







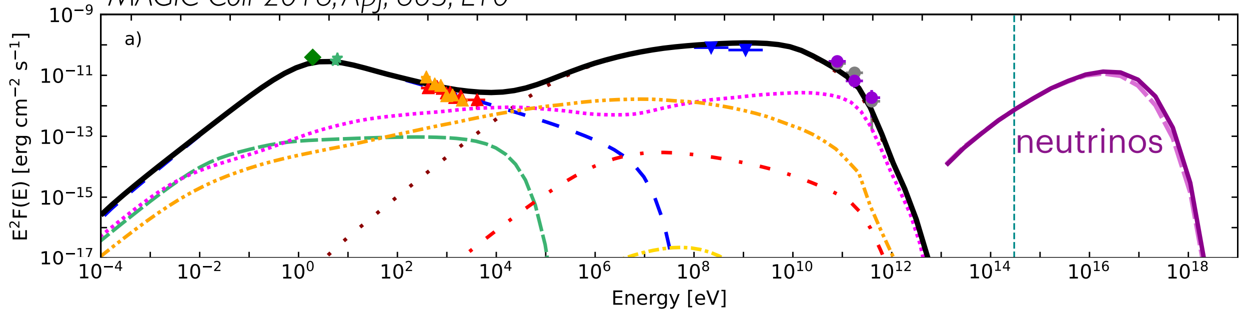


290 TeV muon neutrino coincident with bright flare of TXS 0506+056 (3σ)
signalness of neutrino 56.5%
13±5 more neutrinos from direction of TXS 0506+056 seen in 2014-15 (3.5σ)

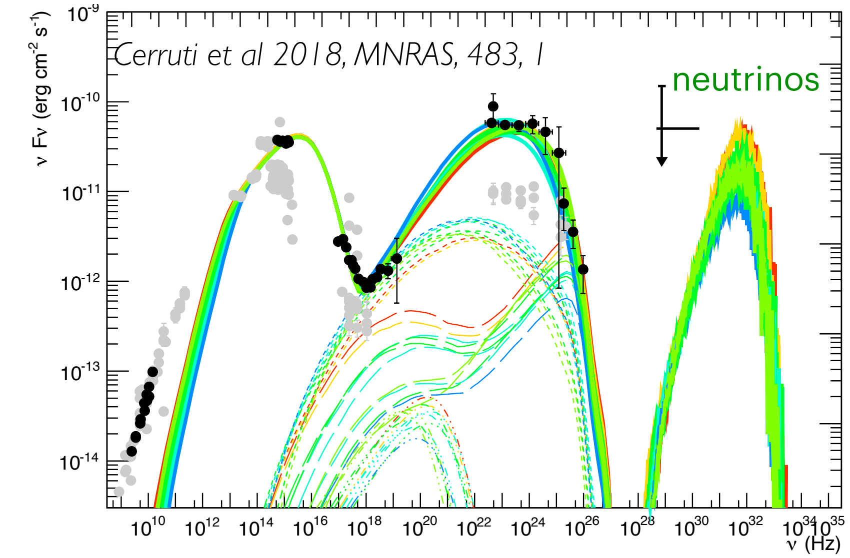
Marek Kowalski, PoS 022. Foteini Oikonomou, PoS 030.

Possible Association #1: TXS 0506+056

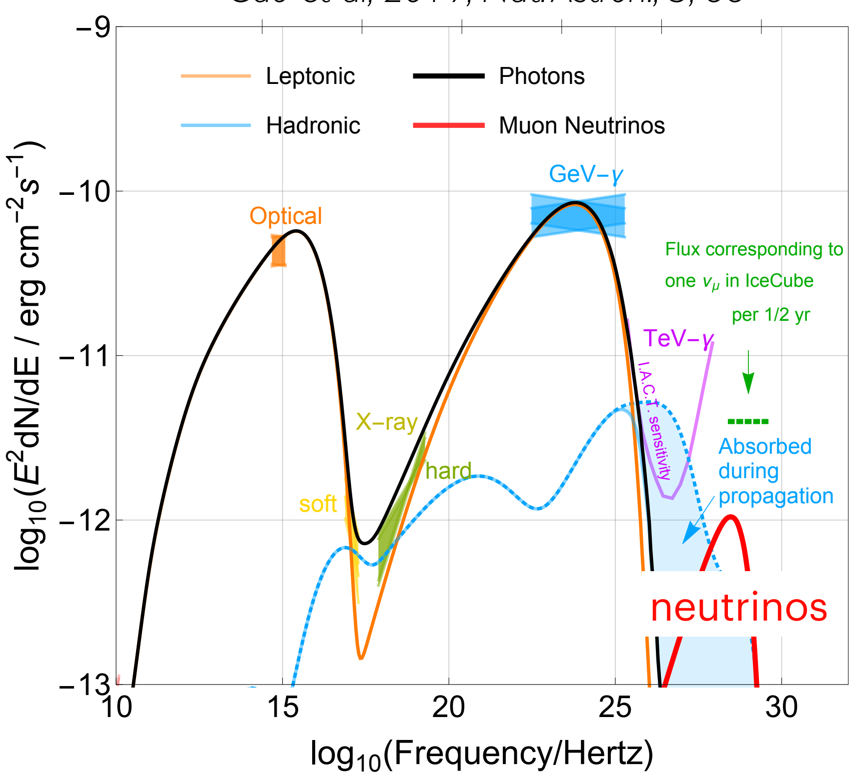
MAGIC Coll 2018, ApJ, 863, L10



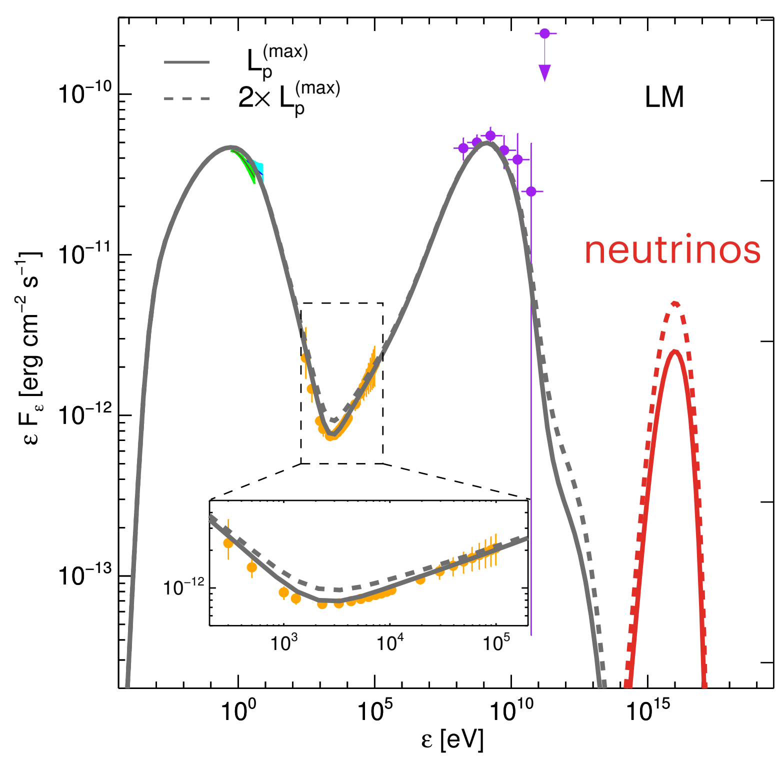
$N_{\nu_\mu} \lesssim 0.05/6$ months



Gao et al, 2019, Nat. Astron., 3, 88



Keivani et al. 2018, ApJ, 864, 84



Statistically consistent with the detection of one event

IceCube et al 2018, Strotjohann et al A&A 622(2019)

A misclassified FSRQ

Padovani, FO, Petropoulou et al MNRAS 484 (2019)

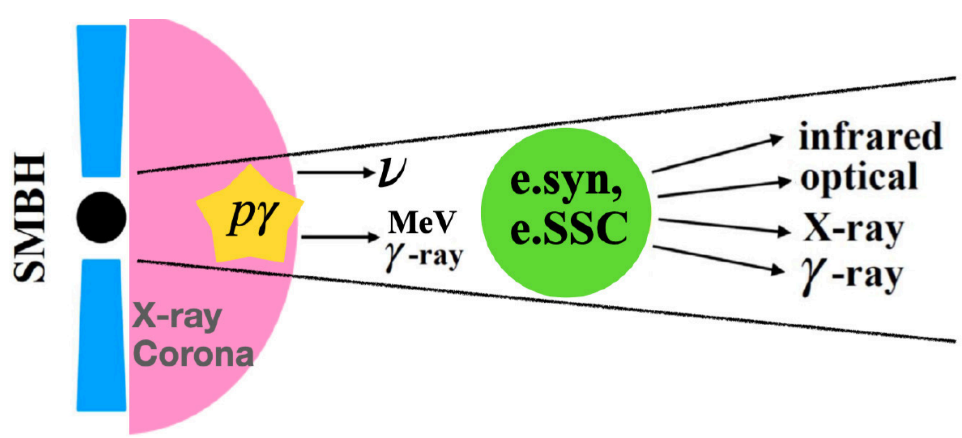
Requires **atypically large proton luminosity and photon fields** ***to have produced 0.05 neutrinos/6 months***

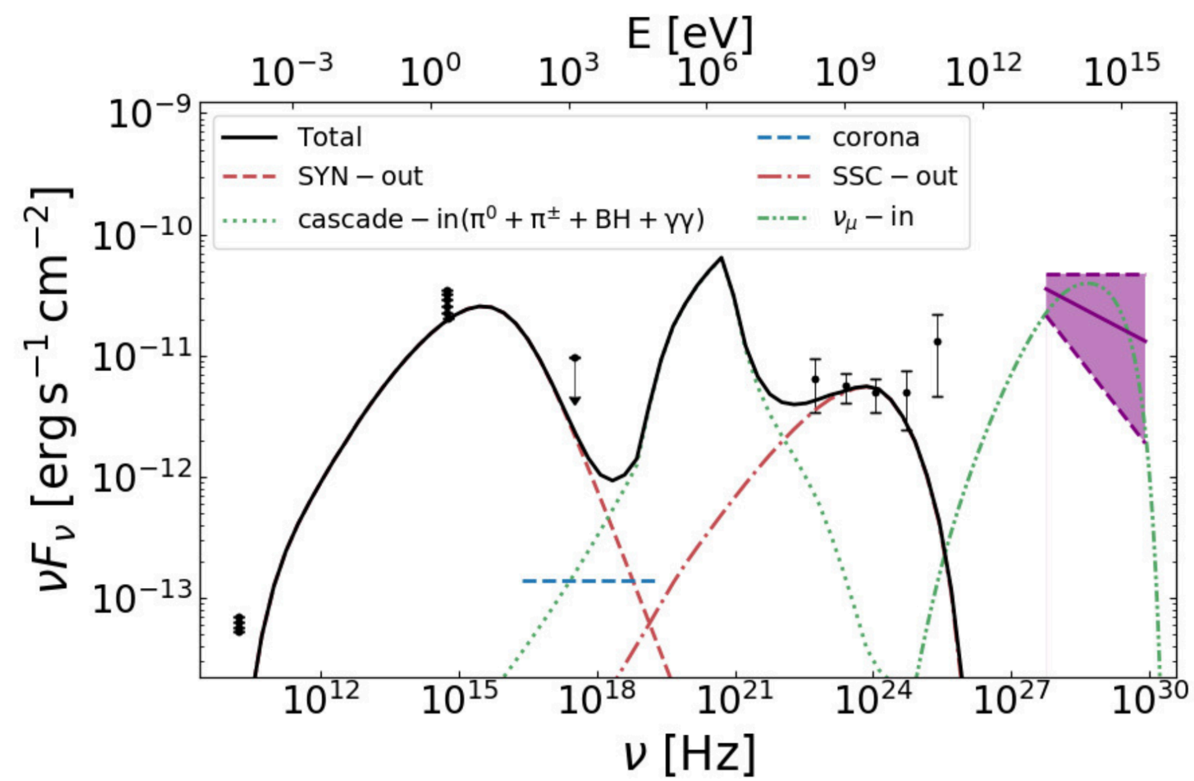
Foteini Oikonomou, PoS 030. See Matteo Cerruti, PoS 979 for code comparison of hadronic models.

TXS 0506+056: Alternative Models

Multi-Zone Models

- No GeV gamma-ray activity found during the neutrino detection period; possibly large opacity for gamma rays in the neutrino production region.
- Continuous particle acceleration/injection in the inner blob at the jet base (hot X-ray corona).
- The dissipation processes in outer blob are responsible for the multi-wavelength emission.





Model testable through a sensitive MeV gamma-ray instrument able to catch the MeV flare around the arrival time of a neutrino event from the blazar.

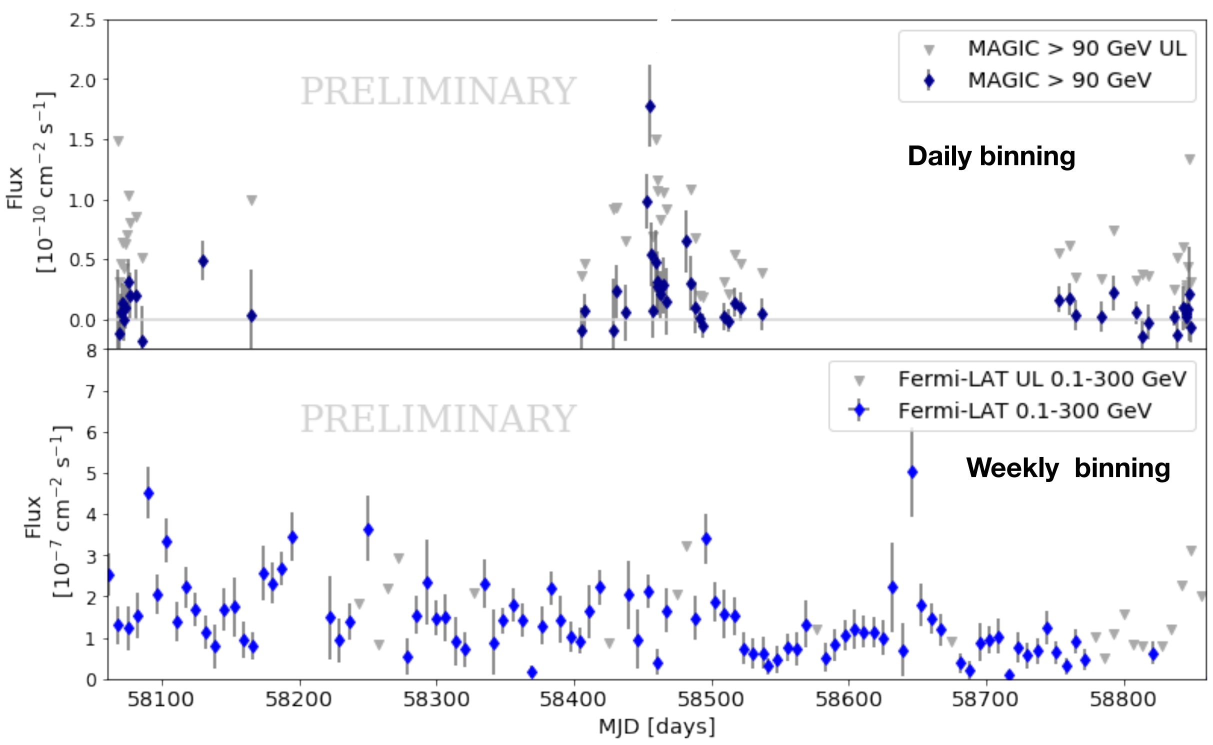
Alternative Scenarios

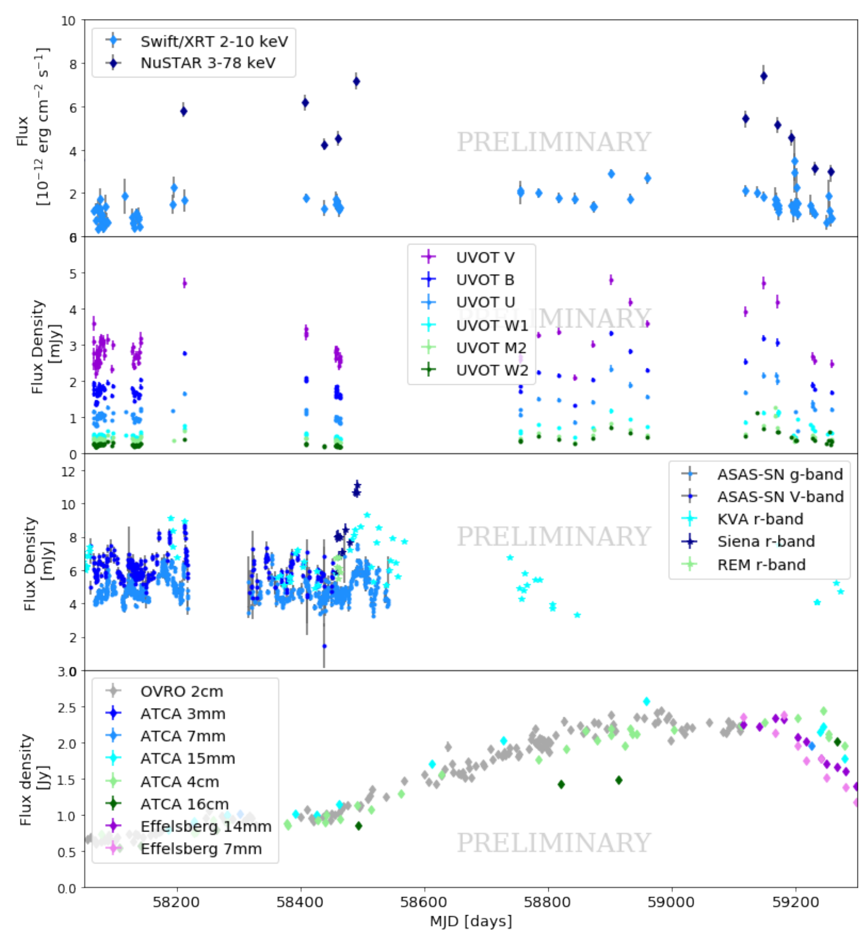
Neutrino emission from supermassive binary black hole merger (SMBBH). SMBBH merger accompanied by spin flip of the jet that would explain periodic emission. Testable with GW observations.

Rui Xue, PoS 985. Ze-Rui Wang, PoS 984. Ilija Jaroschewski, PoS 991.

Multi-Epoch Monitoring of TXS 0506+056

TXS 0506+056 was sparsely monitored before 2017. Dedicated monitoring program with MAGIC and MWL (ATCA, OVRO, TELEAMON) partners.





- Optical, UV and X-ray light curves show variability on a daily scale
- The X-ray flux changed by a factor of ~2-3 over the monitoring period in both the soft and hard X-ray energy ranges

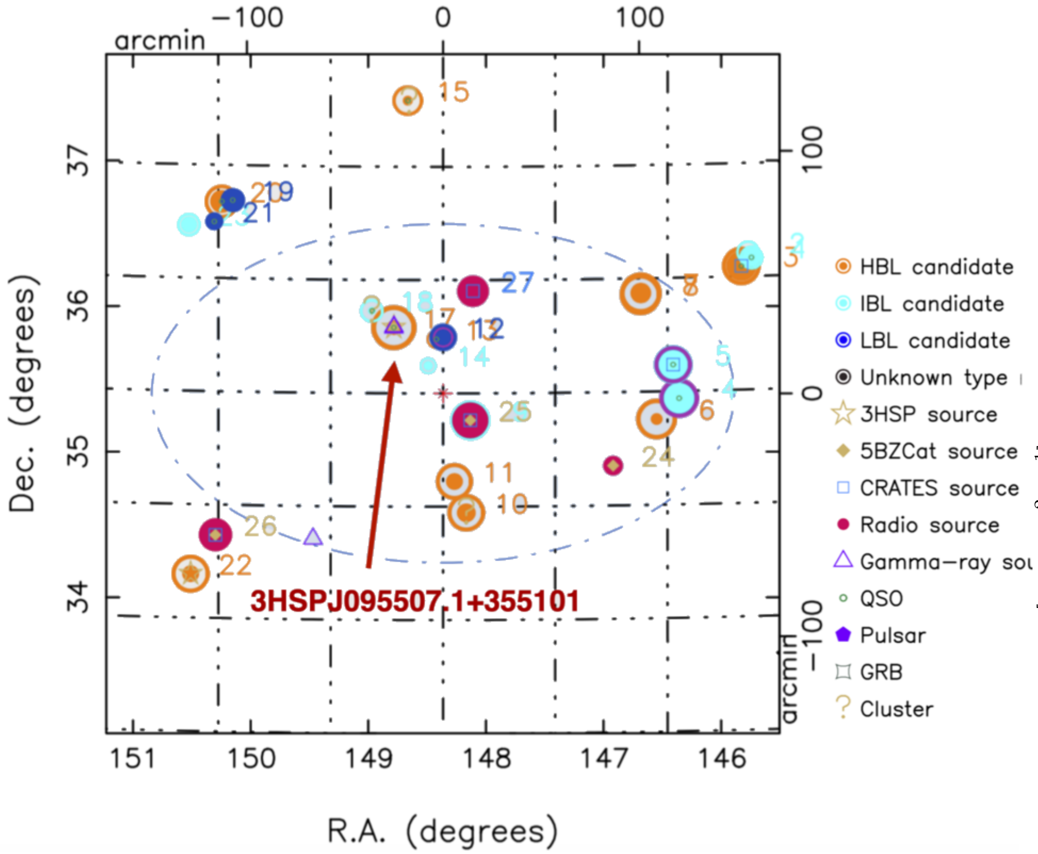
- Radio light curve shows an increasing trend with super-imposed episodes of relatively rapid variability
- Peak in the end of 2020 and then decay, which is still on-going

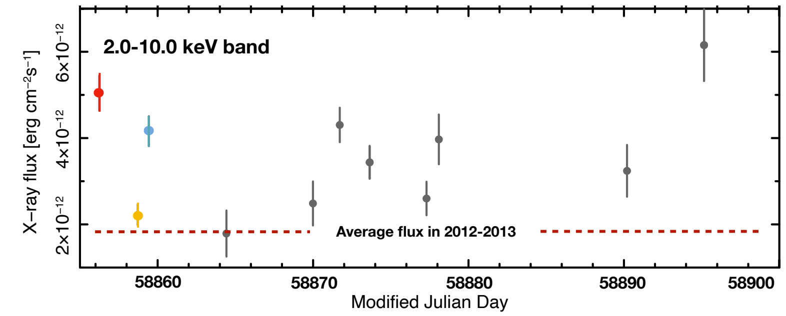
- Source not detected in VHE gamma-rays for most of the time.
- On Dec 1st and 3rd, 2018 a VHE gamma-ray flare observed by MAGIC with flux comparable to the one in 2017.
- SED modeled in the frame of lepto-hadronic model reveals a sub-dominant hadronic component; expected neutrino events rates compatible with IceCube and ANTARES observations.

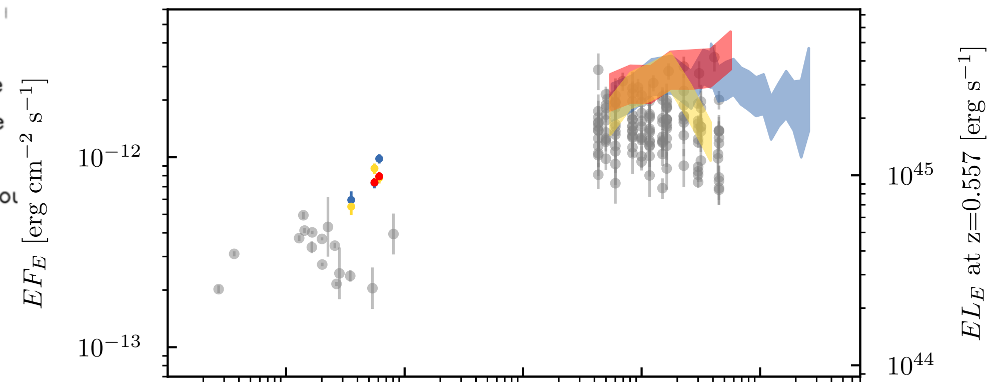
Konstancja Satalecka, PoS 875.

Possible Association #2: 3HSP J095507.9+35510

An extreme blazar at z = 0.557 coincident with a 300 TeV neutrino

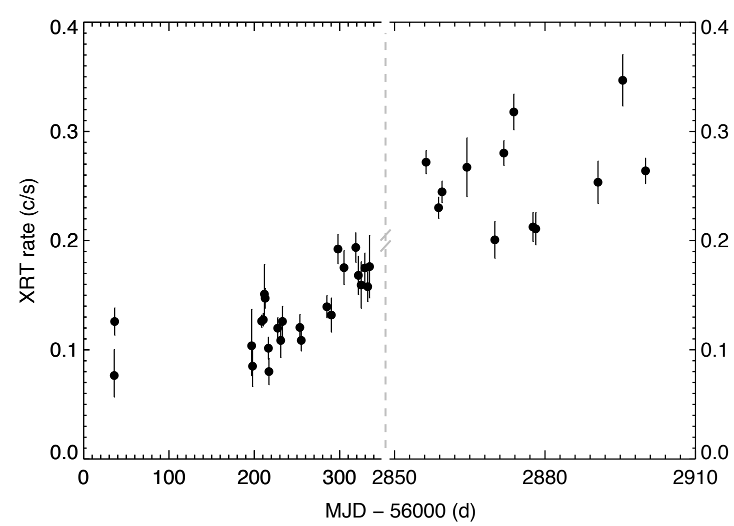


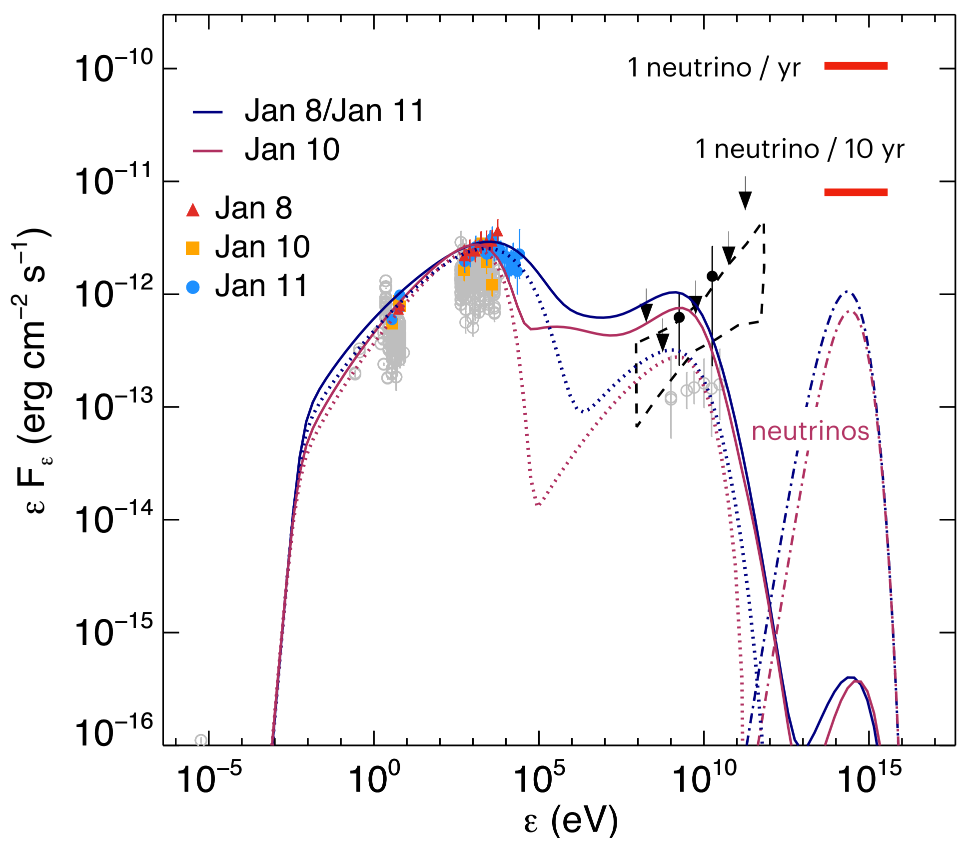




Detected in a high, very hard and variable X-ray state shortly after the neutrino arrival.

10year Swift-XRT Light curve





Maybe the neutrino detection was a coincidence?

Neutrino production in interactions with jet photons

Scaling the neutrino flux with the X-ray flux of the source we obtained:

$$N_{\nu_\mu}(E > 100\ \text{TeV}) \lesssim 0.1/10\ \text{years (IC Point Source)}$$
$$\lesssim 0.01/10\ \text{years (IceCube GFU)}$$

$$L_p \gtrsim 360$$

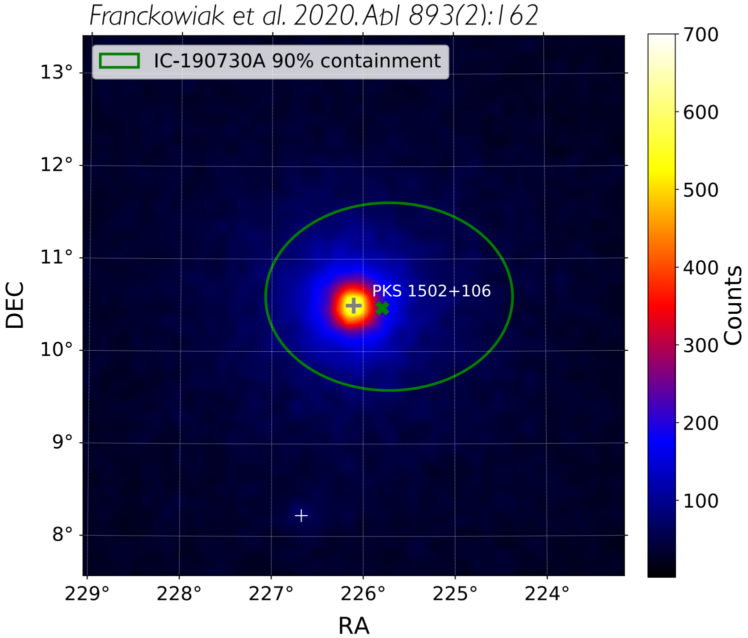
Foteini Oikonomou, PoS 030.

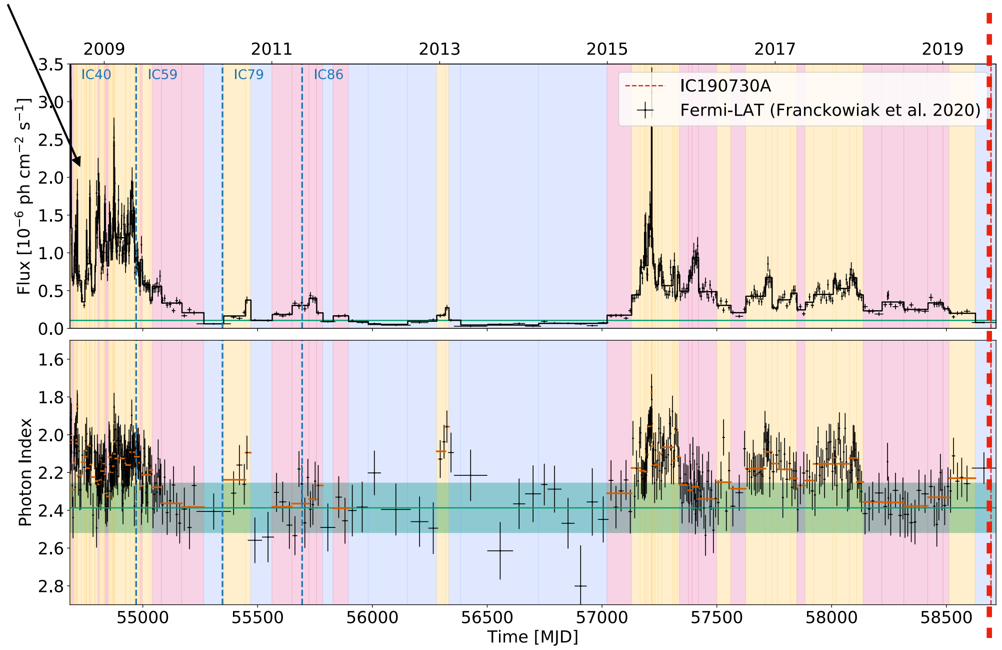
Possible Association #3: PKS 1502+106

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

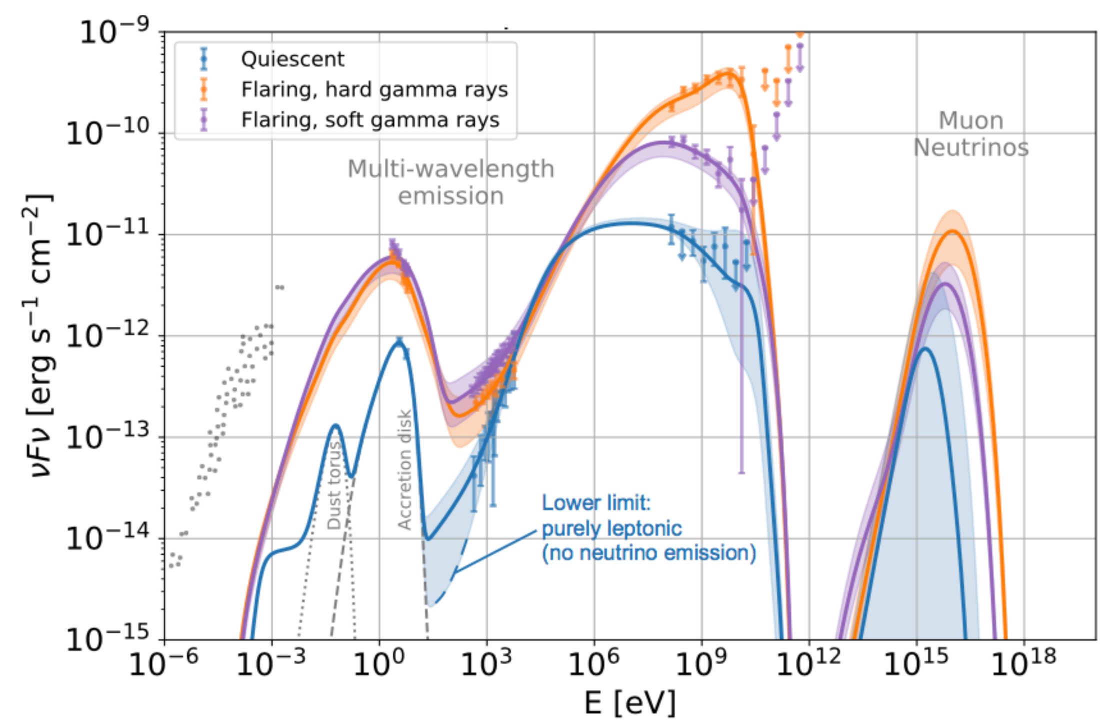
Second brightest extragalactic gamma-ray source

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?

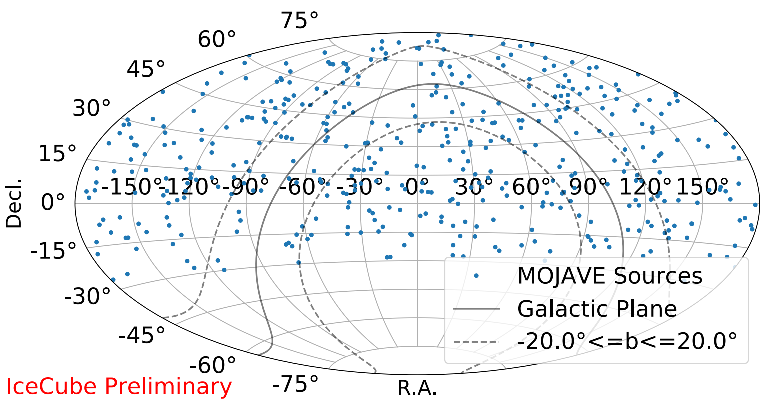
Model State	Quiescent	Leptohadronic Hard Flare	Soft Flare
N_{events} per year	$0.47^{+2.19}_{-0.47}$	$3.19^{+1.90}_{-1.71}$	$1.27^{+0.8}_{-0.55}$
N_{events} (total)	$1.77^{+8.23}_{-1.77}$	$10.94^{+6.56}_{-5.84}$	$4.32^{+2.71}_{-1.87}$

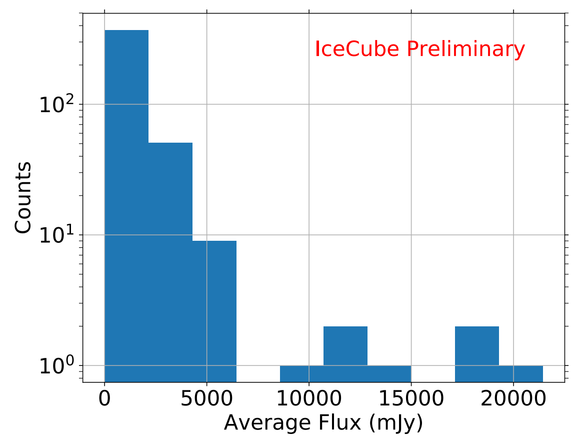
Foteini Oikonomou, PoS 030. Xavier Rodrigues, PoS 1018. Rui Xue, PoS 985.

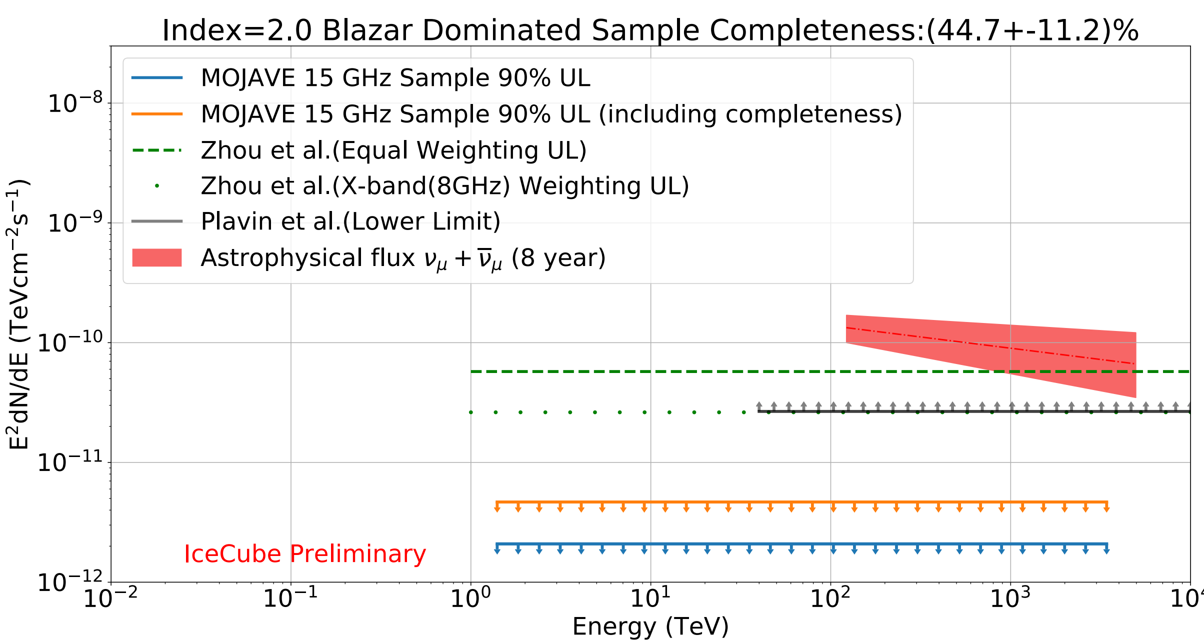
Radio and Neutrino Correlations?

Internal absorption of gamma rays may cause a lack of energetic gamma-rays.
Possible correlation between neutrinos and low-energy photons in the X-ray and radio bands.

Correlation analysis between AGN radio observations reported in the MOJAVE XV catalog and 10 years of **IceCube** data

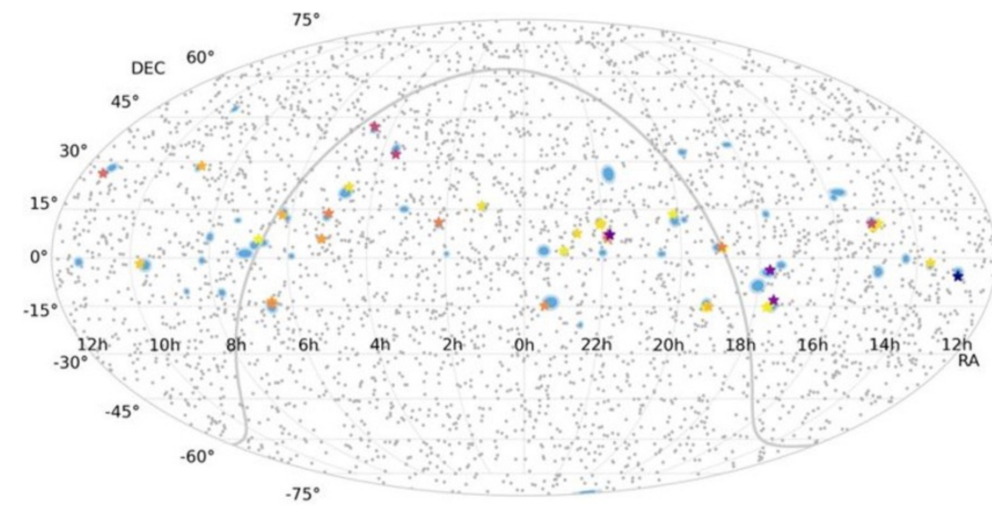


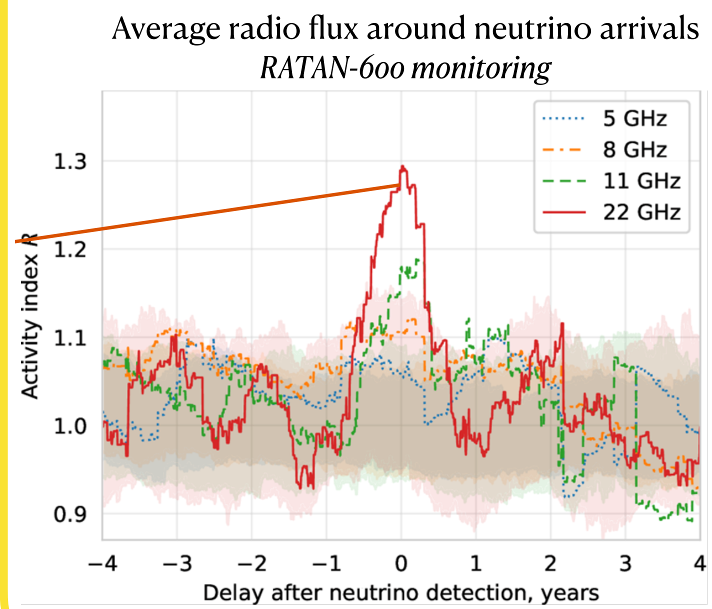




Radio loud AGN can not explain more than 6% of the diffuse neutrino flux.

Correlation analysis between VLBI sample with 10 years of **IceCube** data





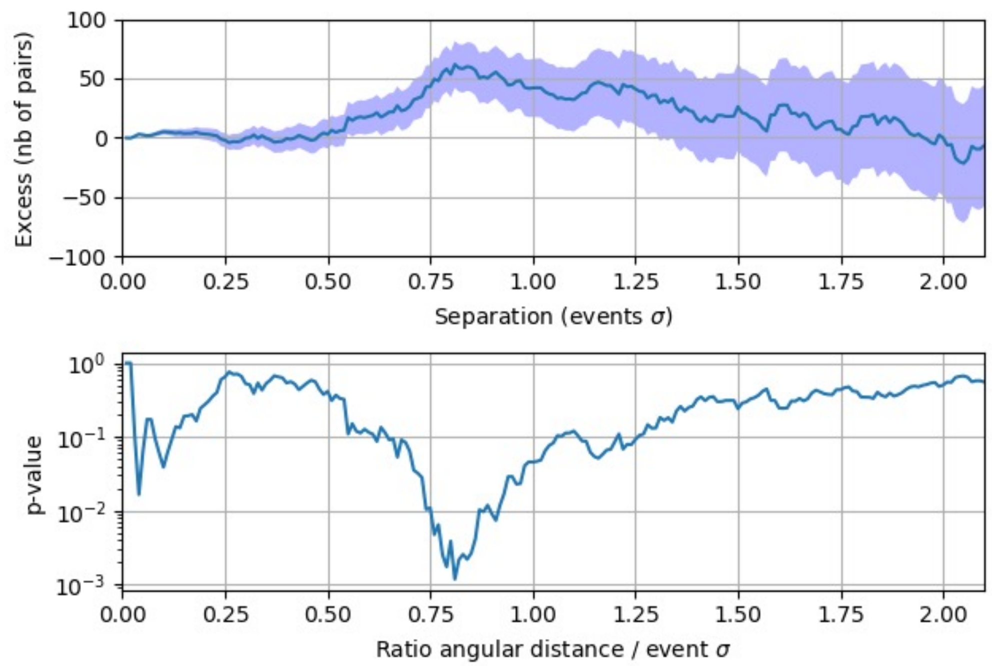
Neutrinos arrive when blazars are brighter in radio (strong effect for PKS 1502+106)

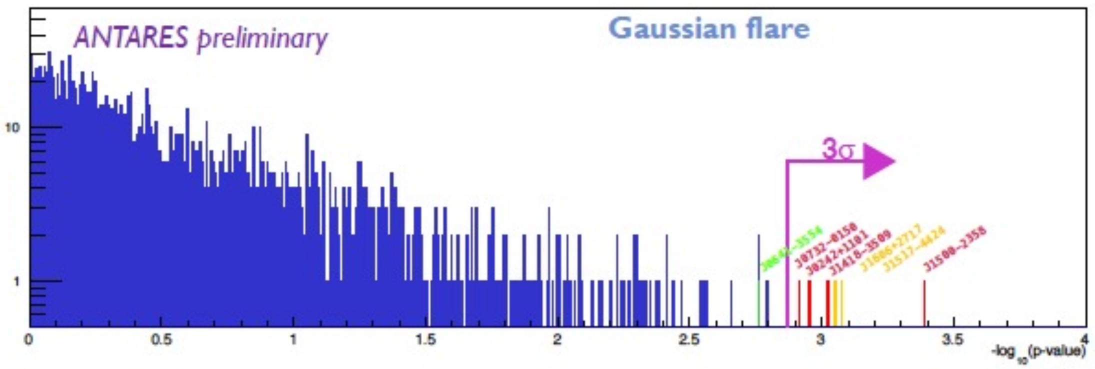
Hints that gamma-rays and neutrinos may be produced in different regions of blazars and are not directly related.

Abhishek Desai, PoS 949. Alexander Plavin, PoS 967. Matthias Kadler, PoS 974.

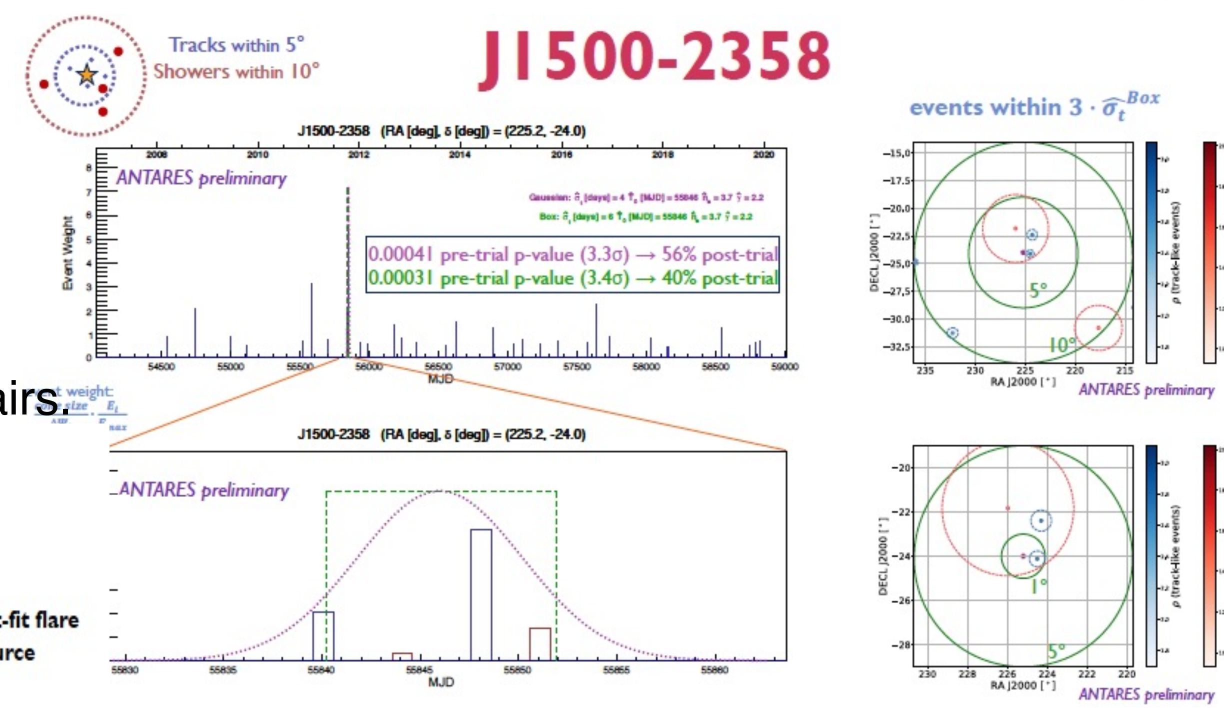
Radio and Neutrino Correlations?

Correlation analysis between VLBI sample with 13 years of **ANTARES** data.





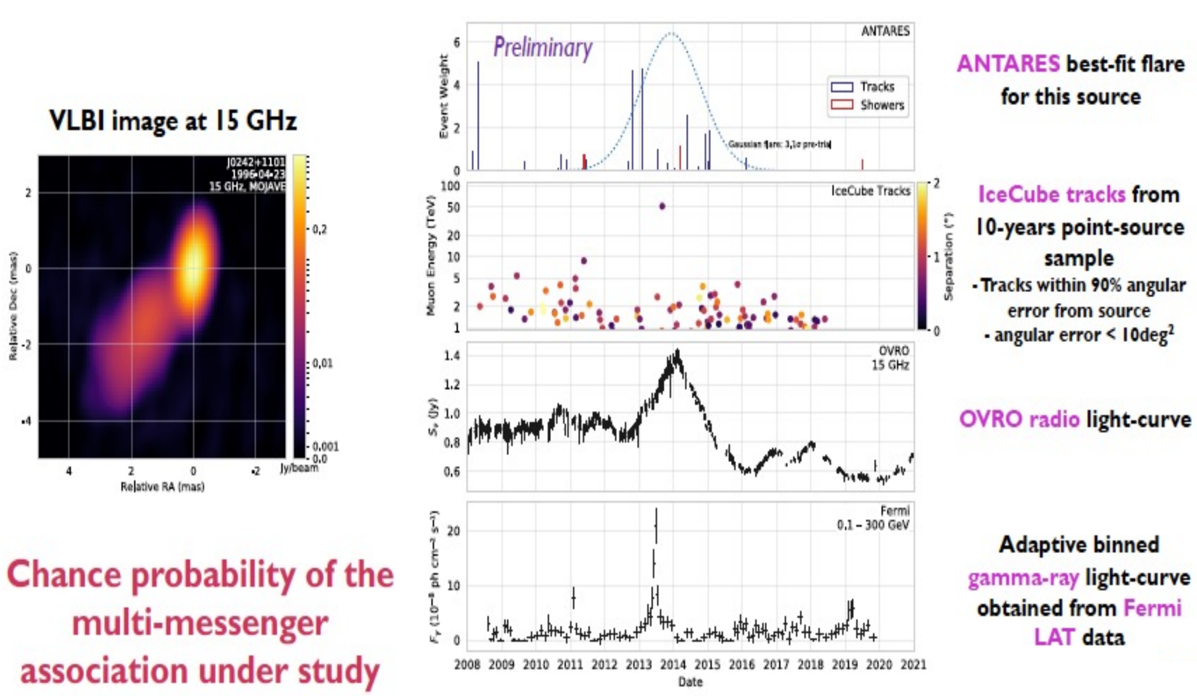
>3σ pre-trial
J1500-2358
J1517-4424
J1606+2717
J1418-3509
J0242+1101
J0732-0150
J0641-3554



2 tracks
2 showers

Indication for collective excess of neutrino-blazar pairs.

J0242+1101: potential radio-γ-ν association



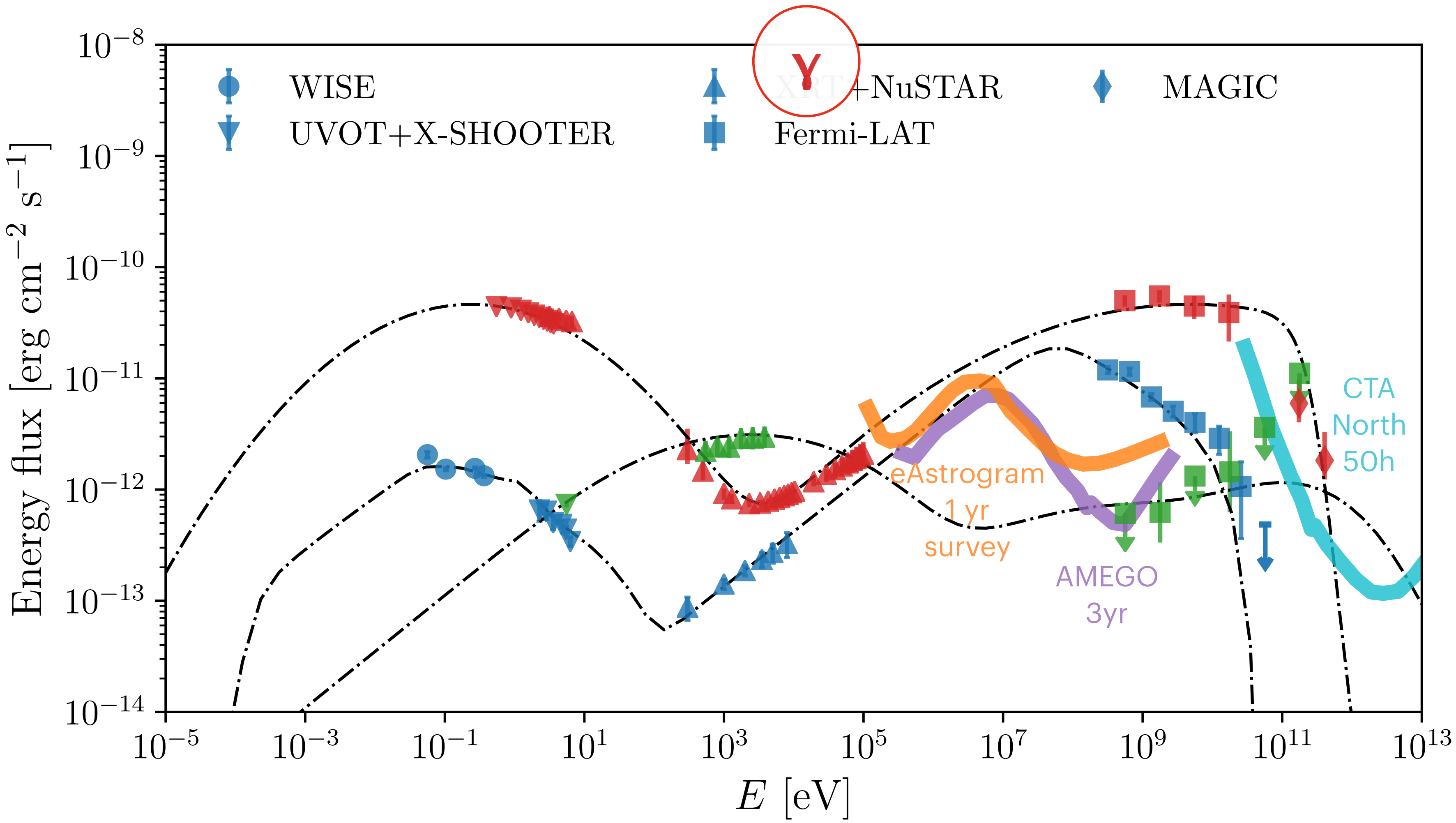
Chance probability of the multi-messenger association under study

See also Zhan Dzhilkibaev, PoS 002 for potential neutrino correlations with radio blazars observed by Baikal-GVD.

Julien Aublin, PoS 1164. Paschal Coyle, PoS 042. Giulia Illuminati, PoS 972.

Homework for ICRC 2023

- Models statistically consistent with the detection of neutrinos but require extreme parameters, atypical of the blazar population.
- Need to move beyond one-zone model as well as investigate time variability.
- Where are neutrinos and photons produced? Leptonic or lepto-hadronic models?
- Multi-wavelength long-term evolution needs to be explored.
- Emerging trend of possible correlation between neutrino and radio/X-ray data to be understood.



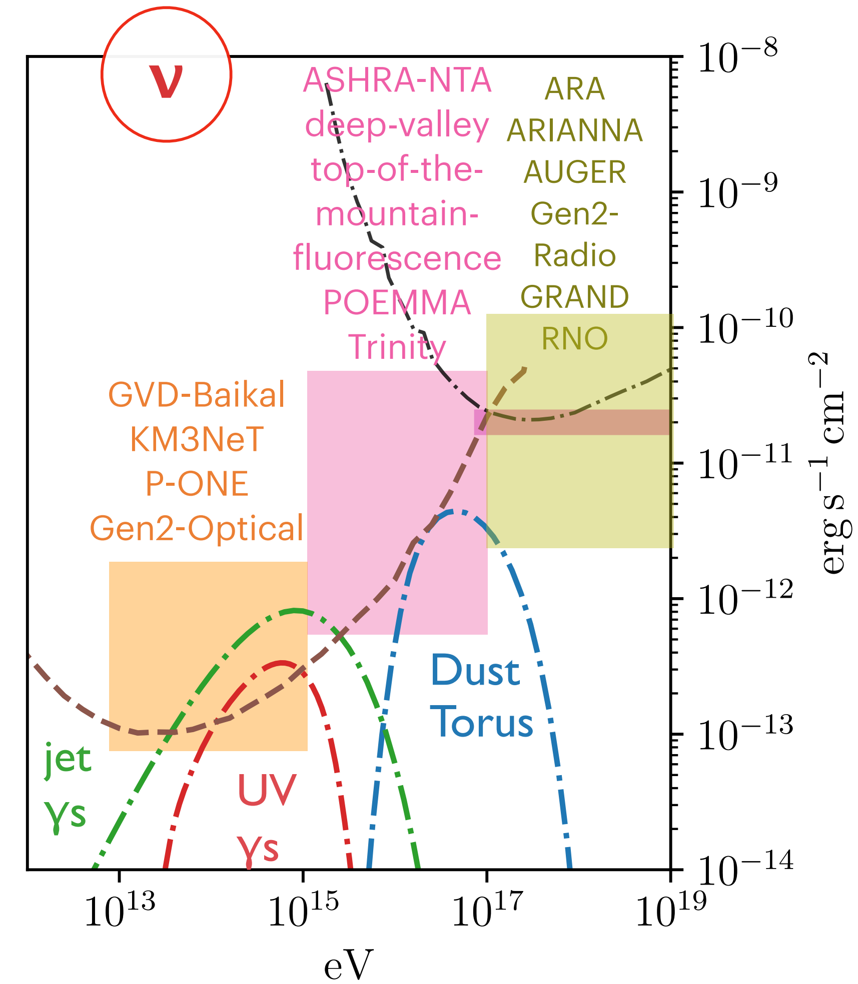


Figure credit: Foteini Oikonomou. Sessions # 25, 48, 49.

Tidal Distruption Events

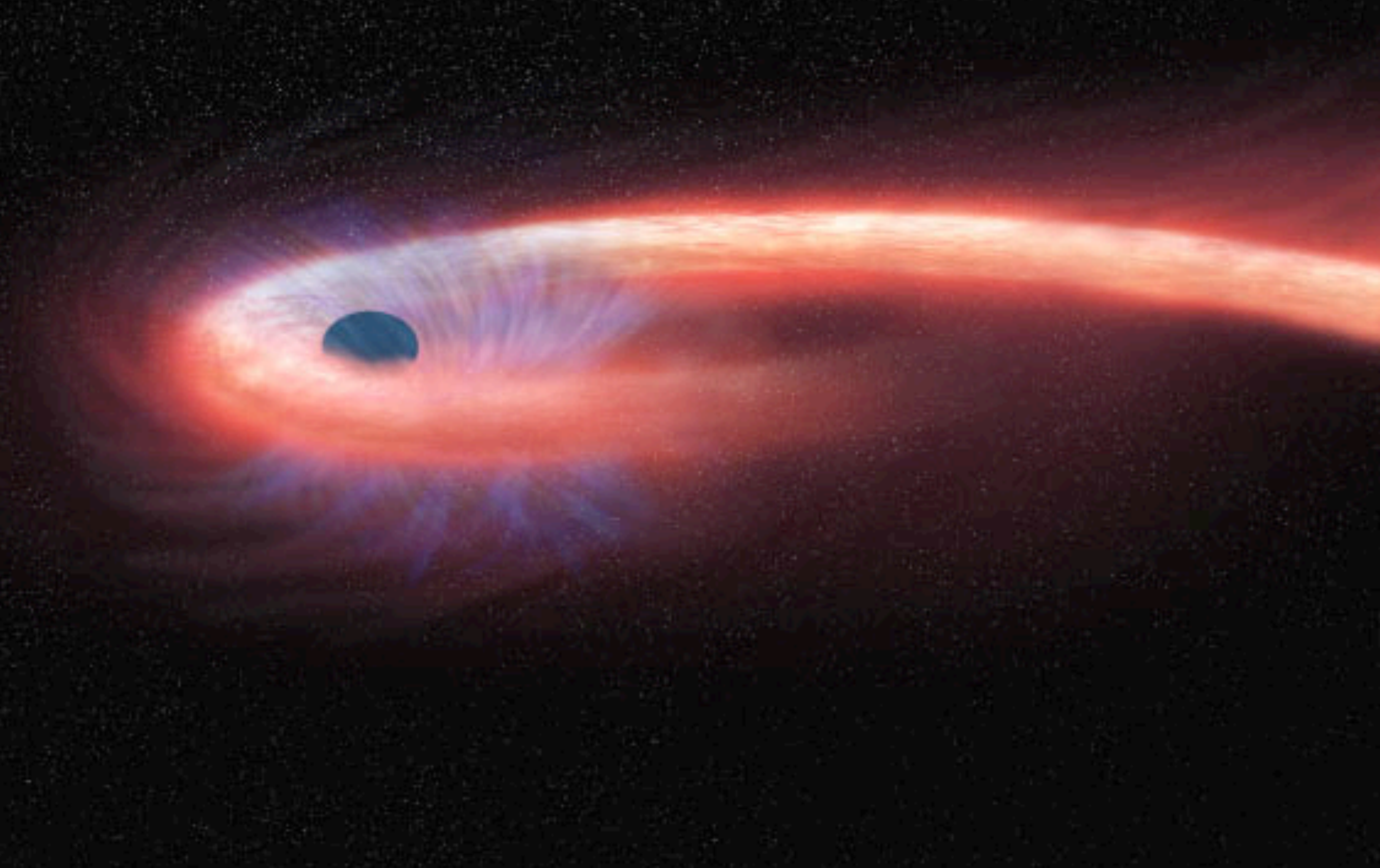
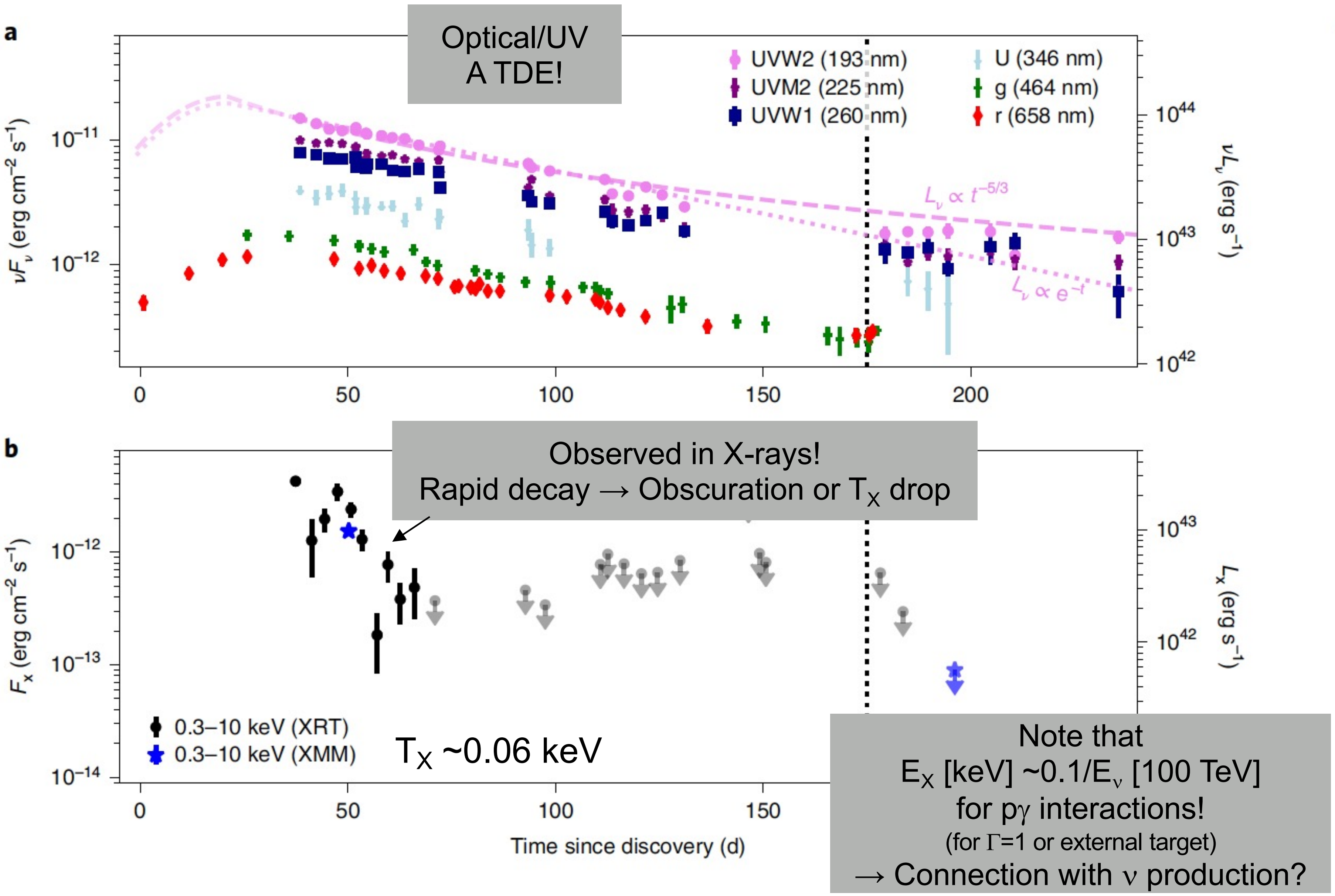
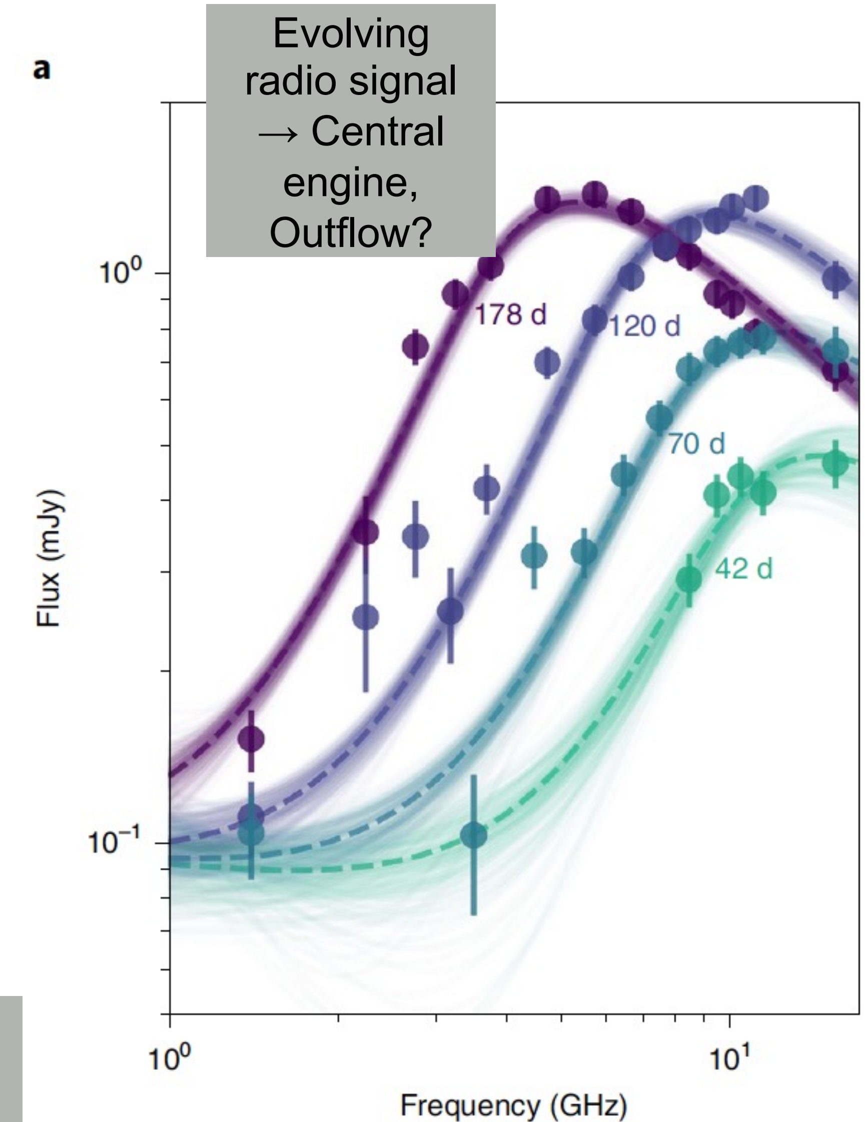


Figure credit: NASA/CXC/M. Weiss

Multi-Wavelength Observations of AT2019dsg

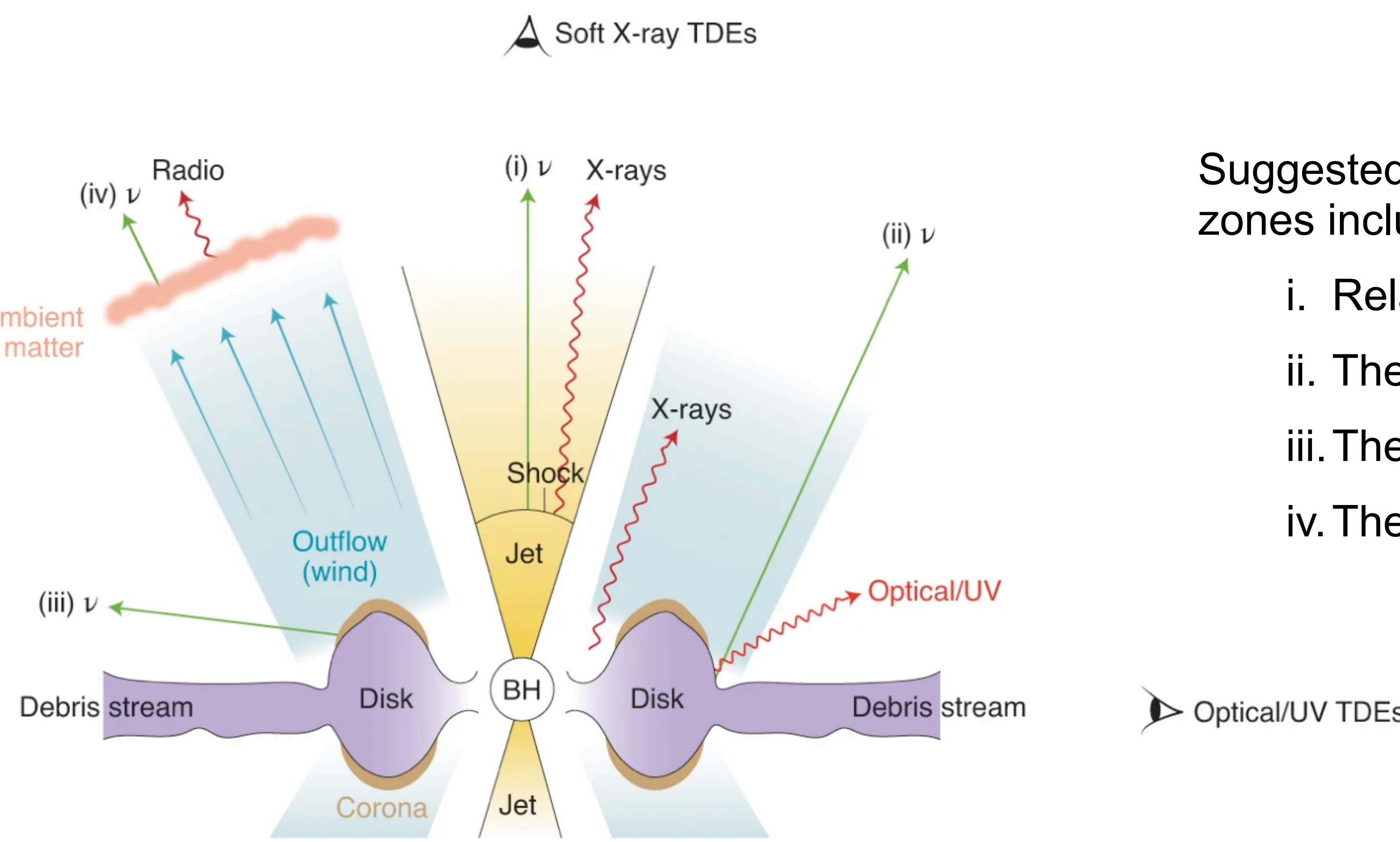




- Discovered by ZTF in April 2019. Second brightest ZTF TDE.
- Copious UV emission, rapid decay in X-rays, very large bolometric flux.
- Extended synchrotron emitting outflow emerging from radio analysis.
- Neutrino detected 175 days after discovery (0.2 PeV).

Robert Stein, PoS 009.

Neutrinos from AT2019dsg



Nat Astron **5** 436–437 (2021)
Hayasaki

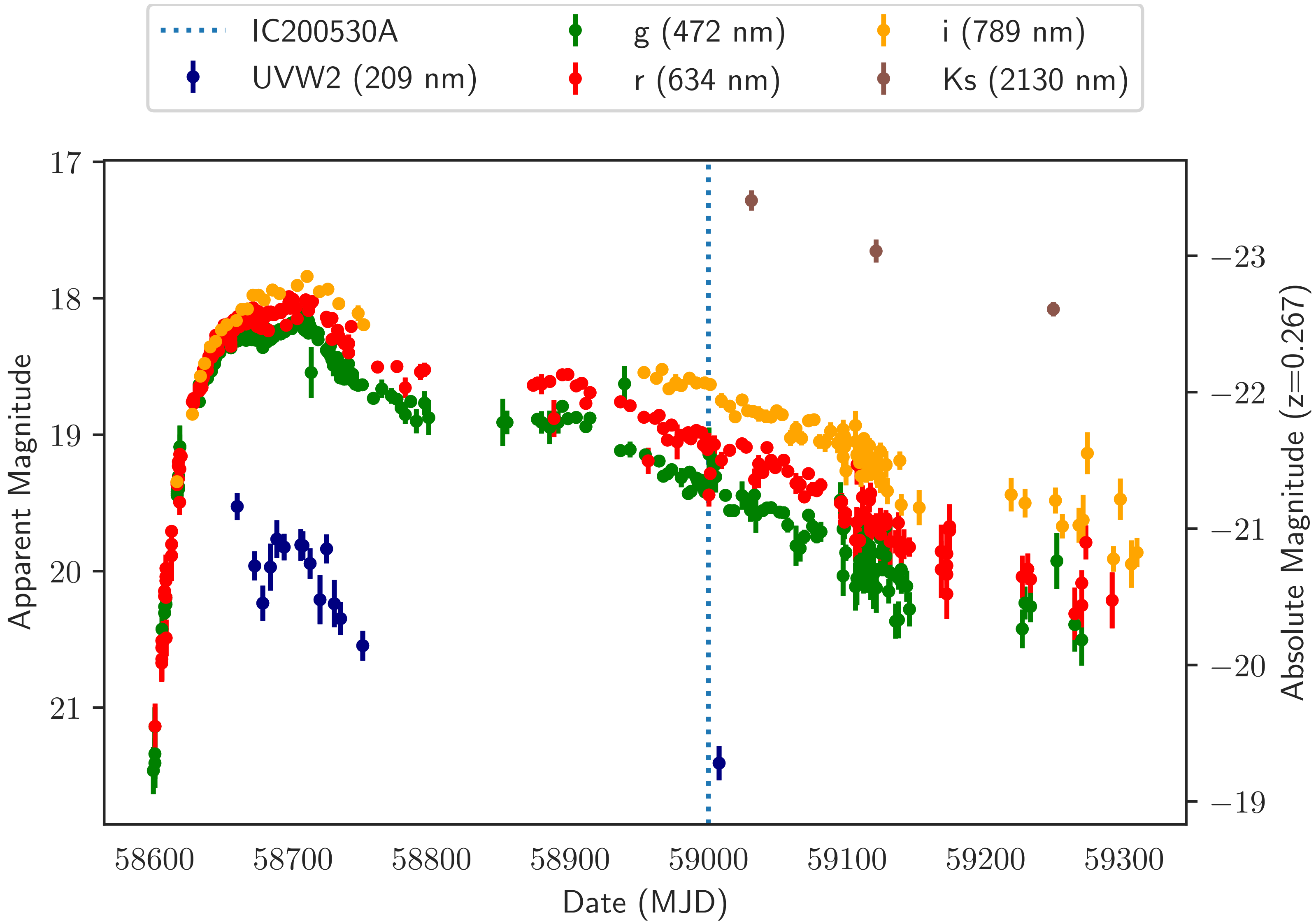
Suggested neutrino production zones include:

i. Relativistic Jets
ii. The accretion disk
iii. The disk corona
iv. The wind/outflow

- Conditions appear consistent with production/detection of one PeV neutrino.
- Various theoretical scenarios currently under debate.
- Is this TDE special? See Strotjohann et al., A&A (2019).
- Neutrinos from TDEs could contribute up to 26% to diffuse neutrino flux.

Robert Stein, PoS 009. Winter & Lunardini, PoS 997.

Another TDE-Neutrino Association?



Second event, AT 2019fdr, coincident with another neutrino event (IC200530A, 80 TeV).

- Is AT2019fdr a TDE in a narrow-line Seyfert Galaxy?
- Classified as probably TDE, but AGN flare origin cannot excluded.

Robert Stein, PoS 009.

Neutrino Searches with ANTARES and Baikal-GVD

No significant neutrino excess reported by ANTARES in the TeV-PeV range, but neutrino predictions lie below the ANTARES sensitivity.

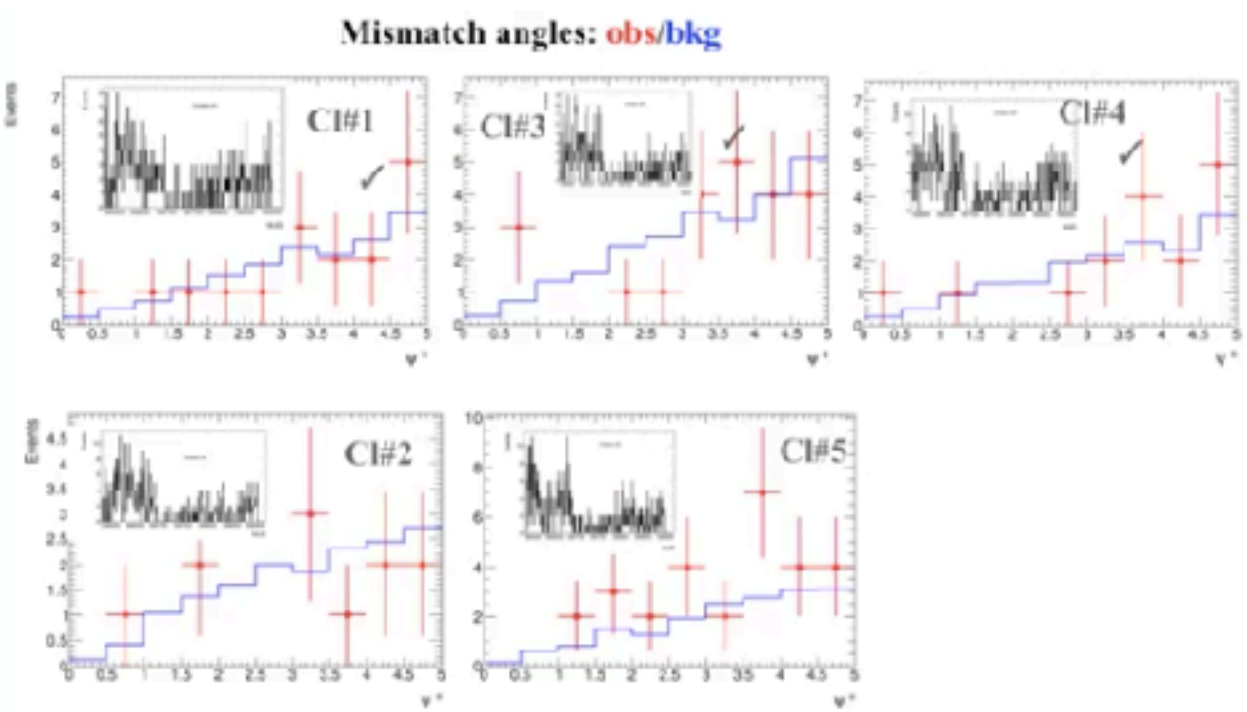
Baikal-GVD reported preliminary indications of a possible excess, but analysis still ongoing.

Within 5 deg from the declination of both TDEs, ANTARES finds 1 event only.

Upper limits on one-flavour neutrino flux.

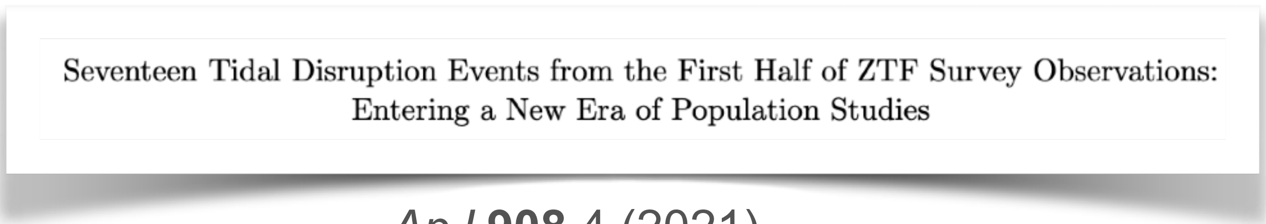
Source		Results						
Name	γ	$\hat{\mu}_{sig}$	p-value	$\Phi_0^{90\%C.L.}$ sensitivity	$\Phi_0^{90\%C.L.}$ limit	$\mathcal{F}^{90\%C.L.}$ sensitivity	$\mathcal{F}^{90\%C.L.}$ limit	$\log(\frac{E_{min}}{GeV})$ - $\log(\frac{E_{max}}{GeV})$
AT2019dsg	2.0	< 0.1	12.4%	7.3×10^{-8}	1.0×10^{-7}	14	19	3.6 - 6.6
	2.5	0.2	10.2%	1.5×10^{-5}	2.2×10^{-5}	29	43	2.8 - 5.5
	3.0	0.7	8.9%	1.2×10^{-3}	2.0×10^{-3}	230	380	2.1 - 4.7
AT2019fdr	2.0	0.5	6.7%	8.5×10^{-8}	1.3×10^{-7}	15	23	3.6 - 6.6
	2.5	0.5	7.9%	2.1×10^{-5}	3.0×10^{-5}	39	55	2.8 - 5.5
	3.0	0.6	9.1%	2.0×10^{-3}	3.0×10^{-3}	360	540	2.1 - 4.7

Within 5 deg from the declination of AT2019, Baikal-GVD finds 5 cluster of events currently under investigation.



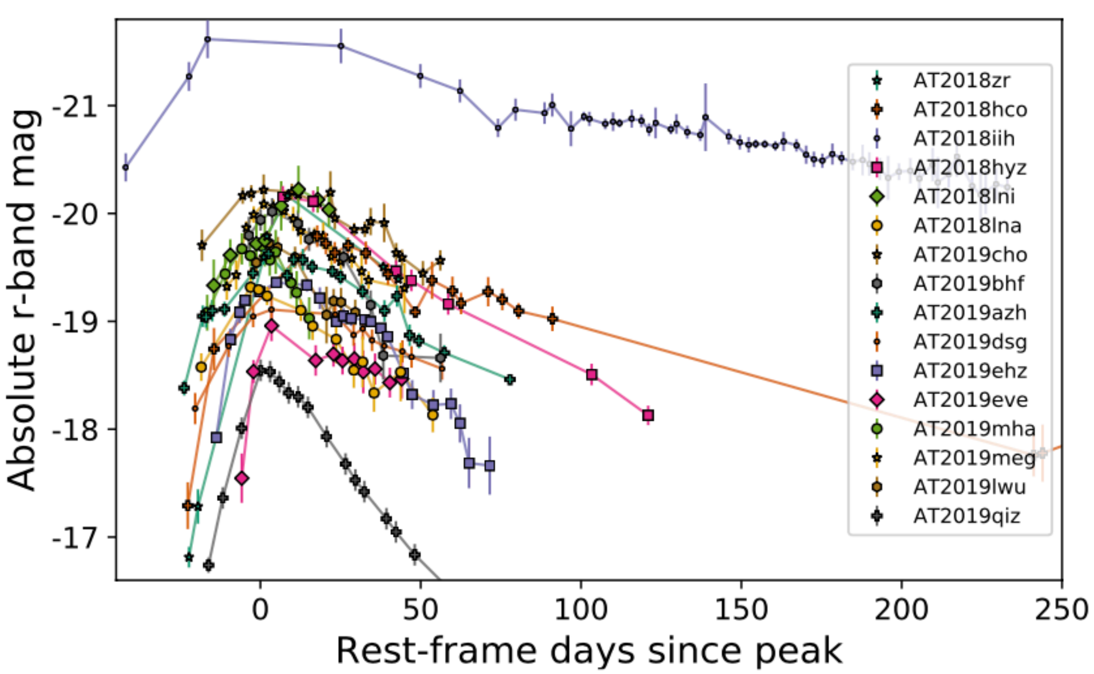
Olga Suvorova, PoS 946. Zhan Dzhilkibaev, PoS 002. Giulia Illuminati, PoS 1161. Robert Stein, PoS 009.

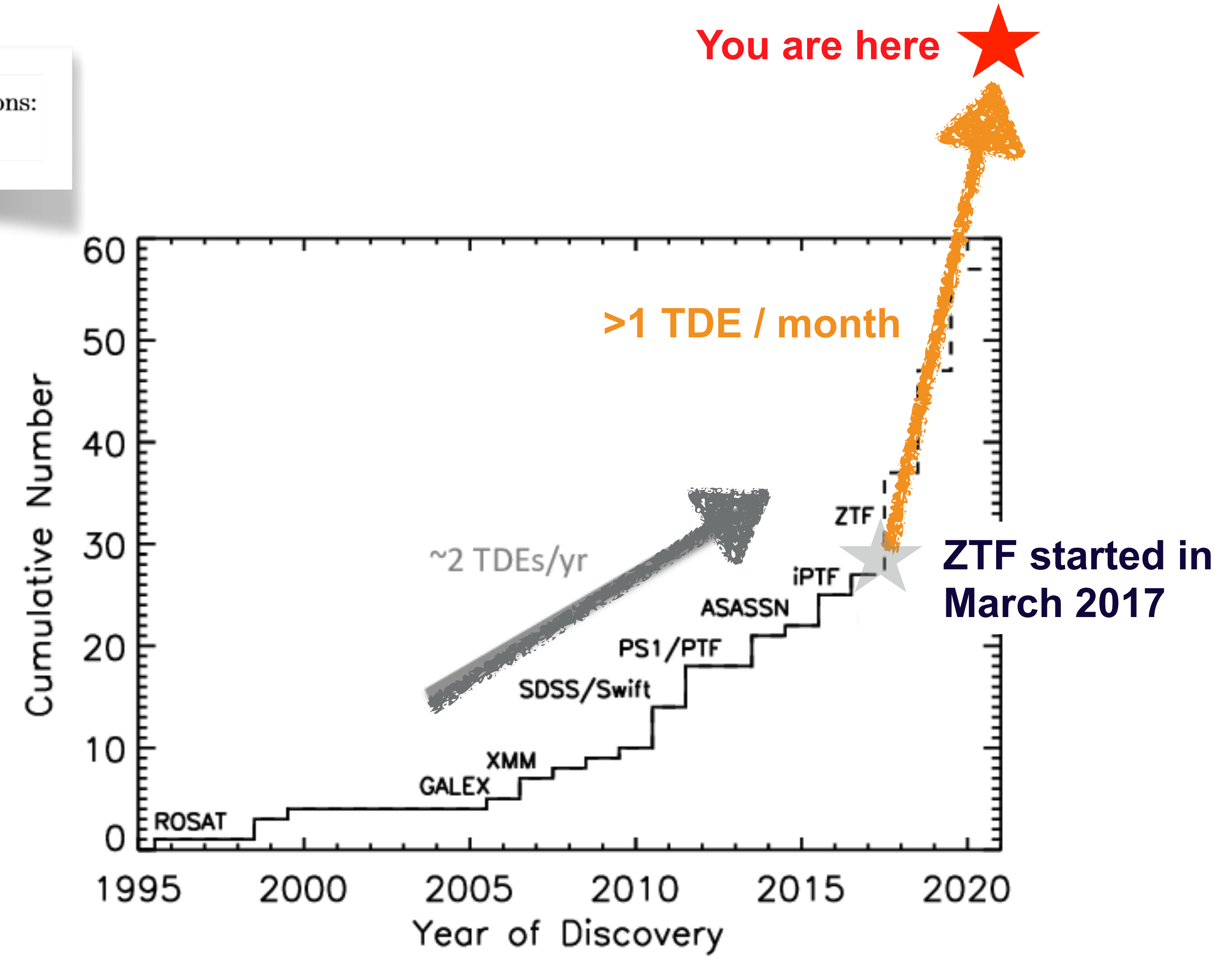
Homework for ICRC 2023


Seventeen Tidal Disruption Events from the First Half of ZTF Survey Observations: Entering a New Era of Population Studies

ApJ **908** 4 (2021)
van Velzen et al.

The view from ~~2019~~ 2021:





PASP **131** 078001 (2019)
Graham et al.

- We are entering a new era for the detection of TDEs, does this have implications on neutrino detection?
- Where are the neutrinos produced?
- Need to improve on our understanding of the TDE population.

Figure credit: Robert Stein. Session # 28.

Compact Binary Mergers

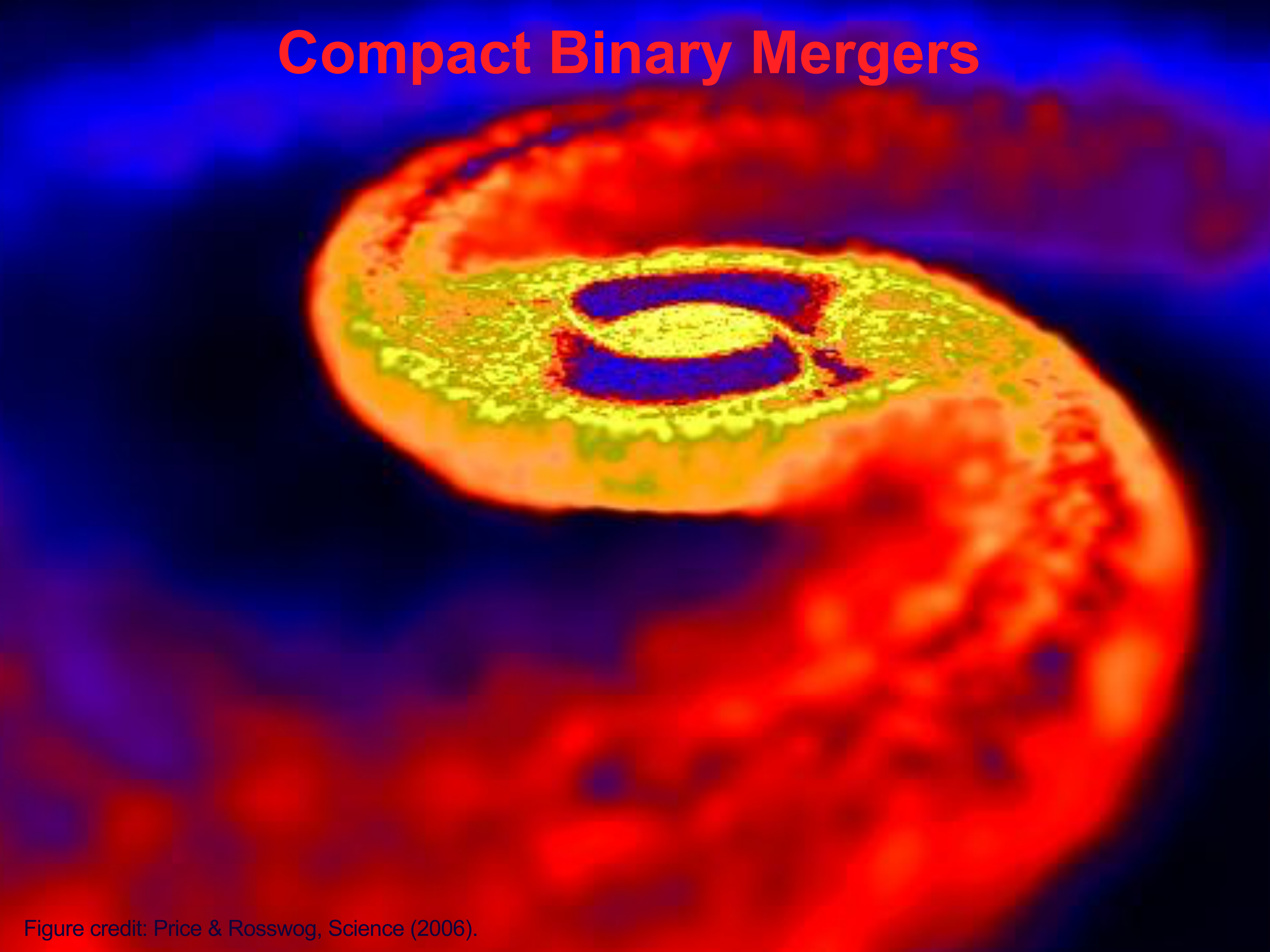


Figure credit: Price & Rosswog, Science (2006).

Compact Binary Mergers

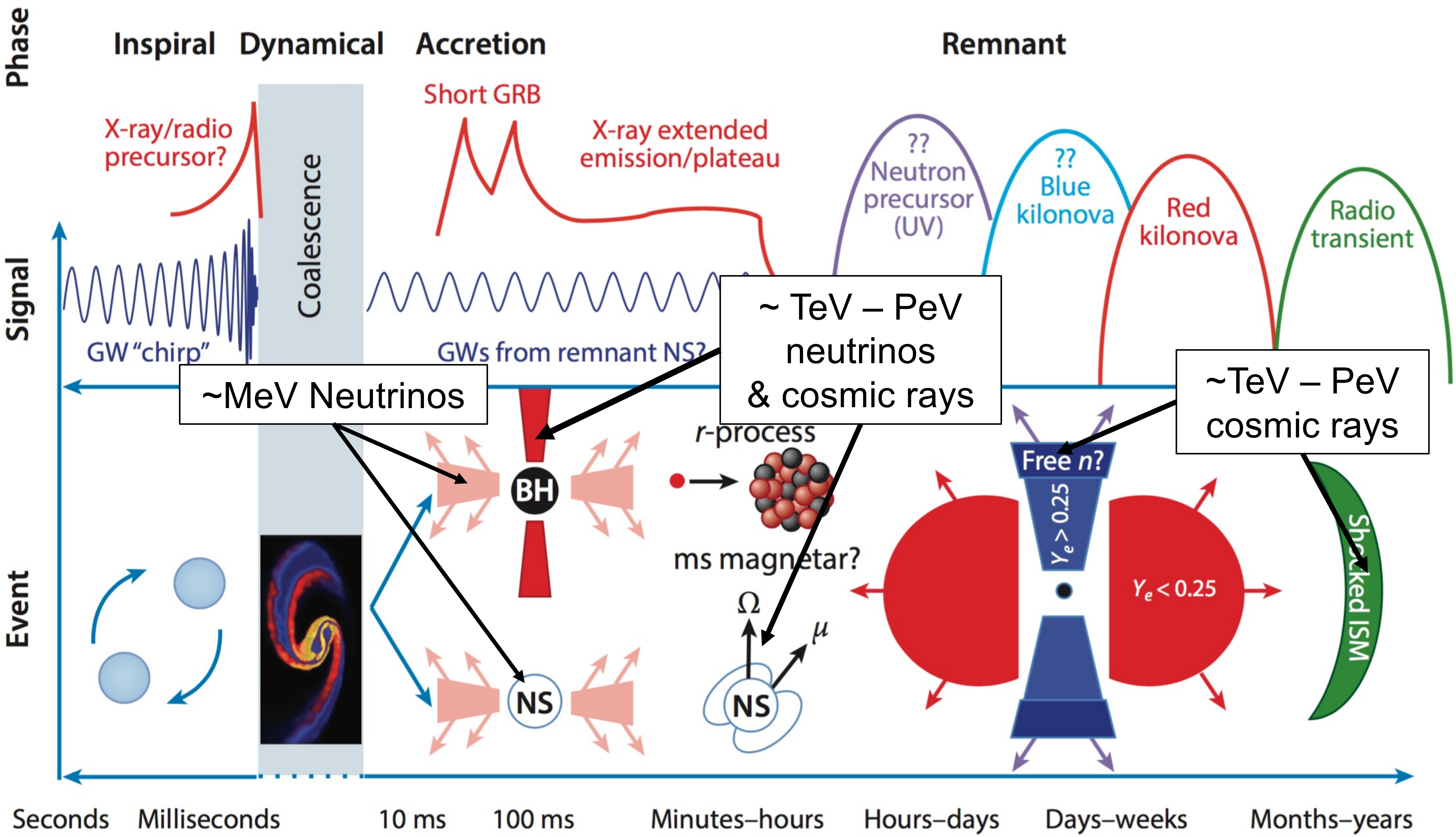
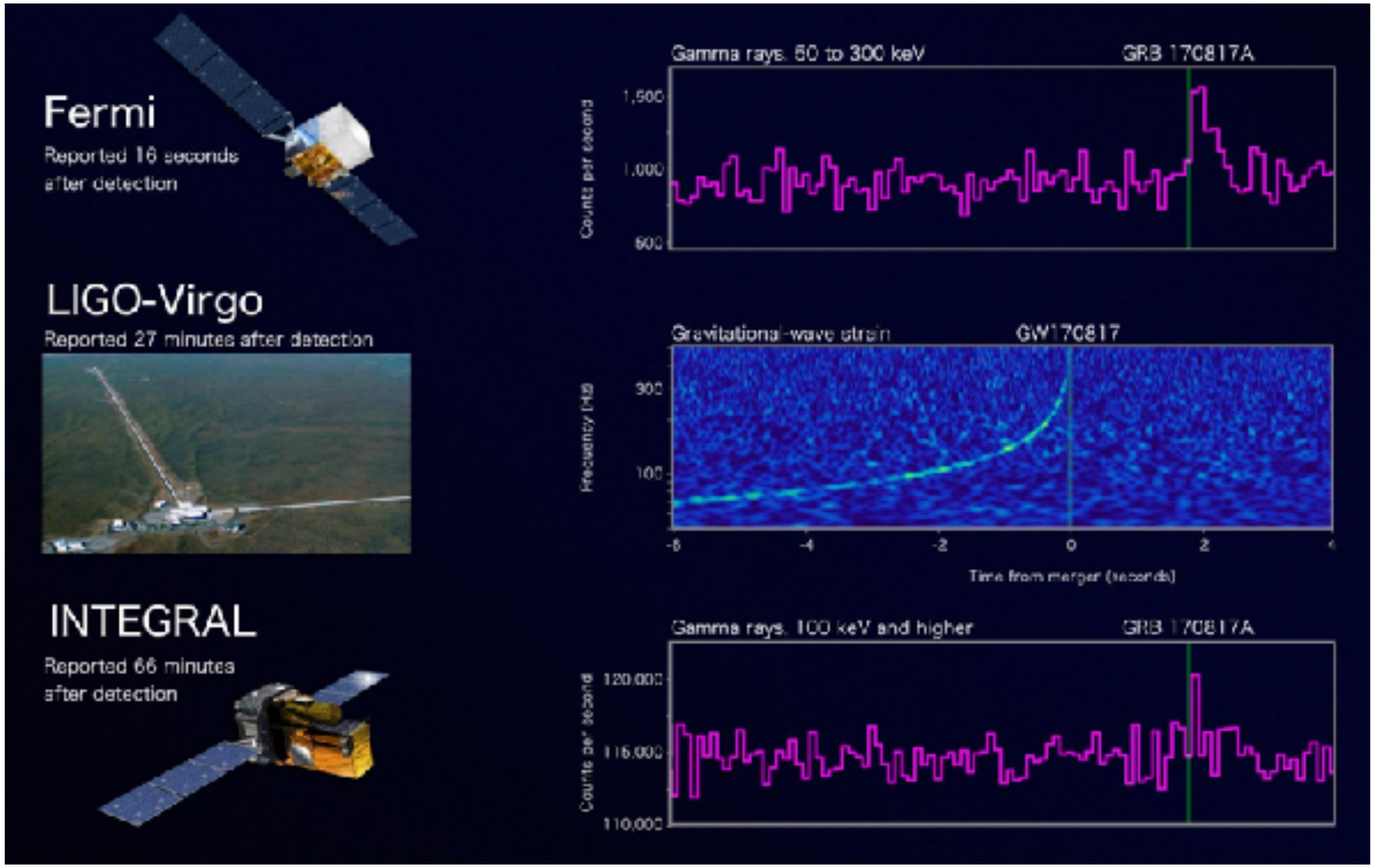
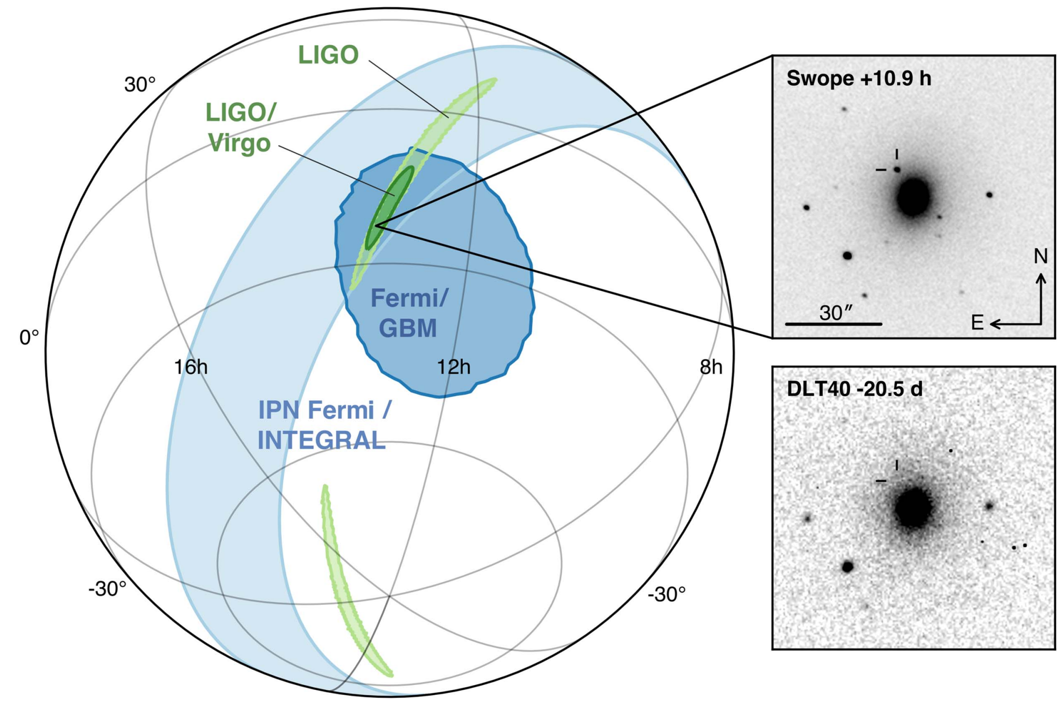


Figure credit: Brian Metzger.

GW 170817

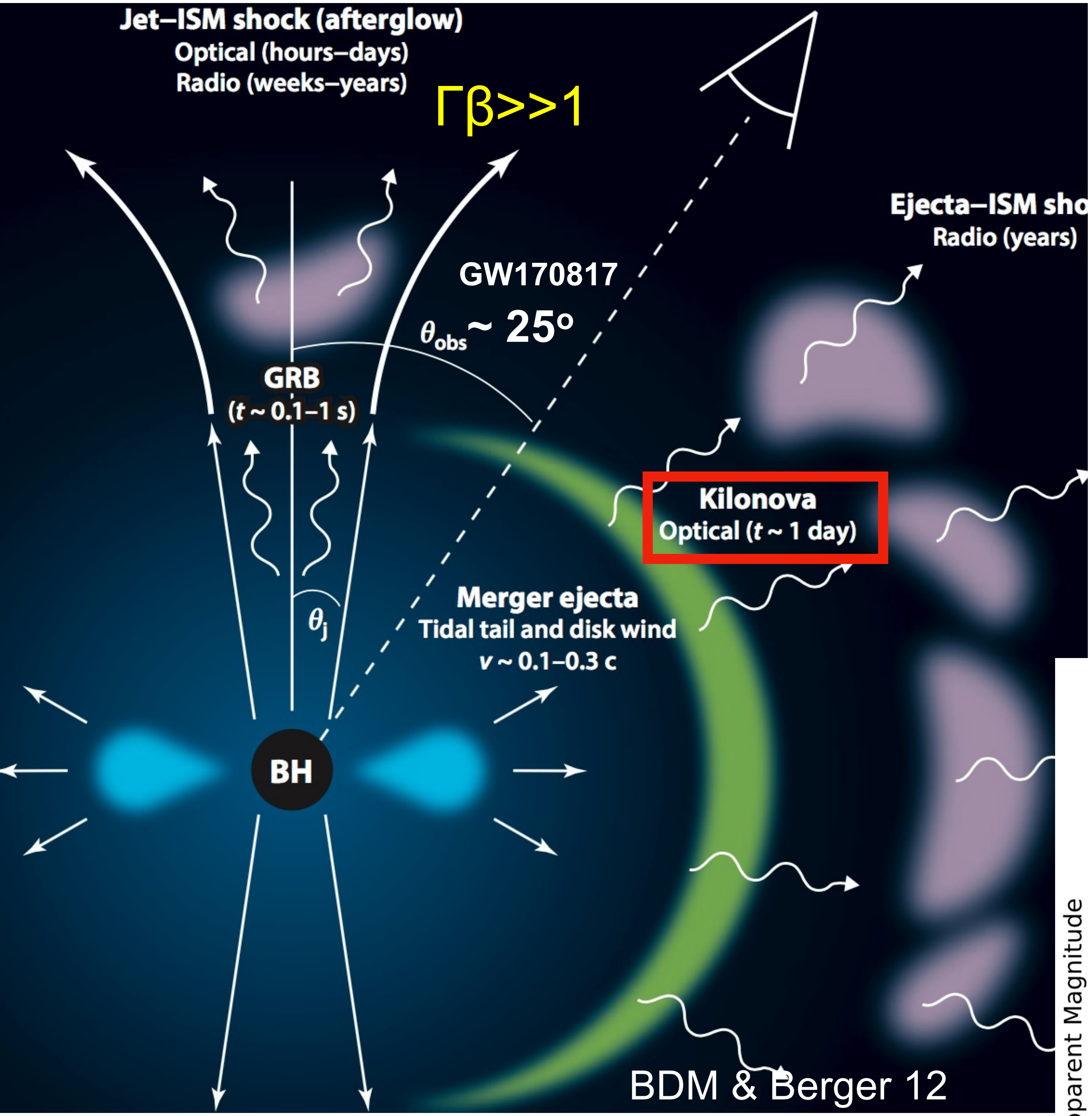


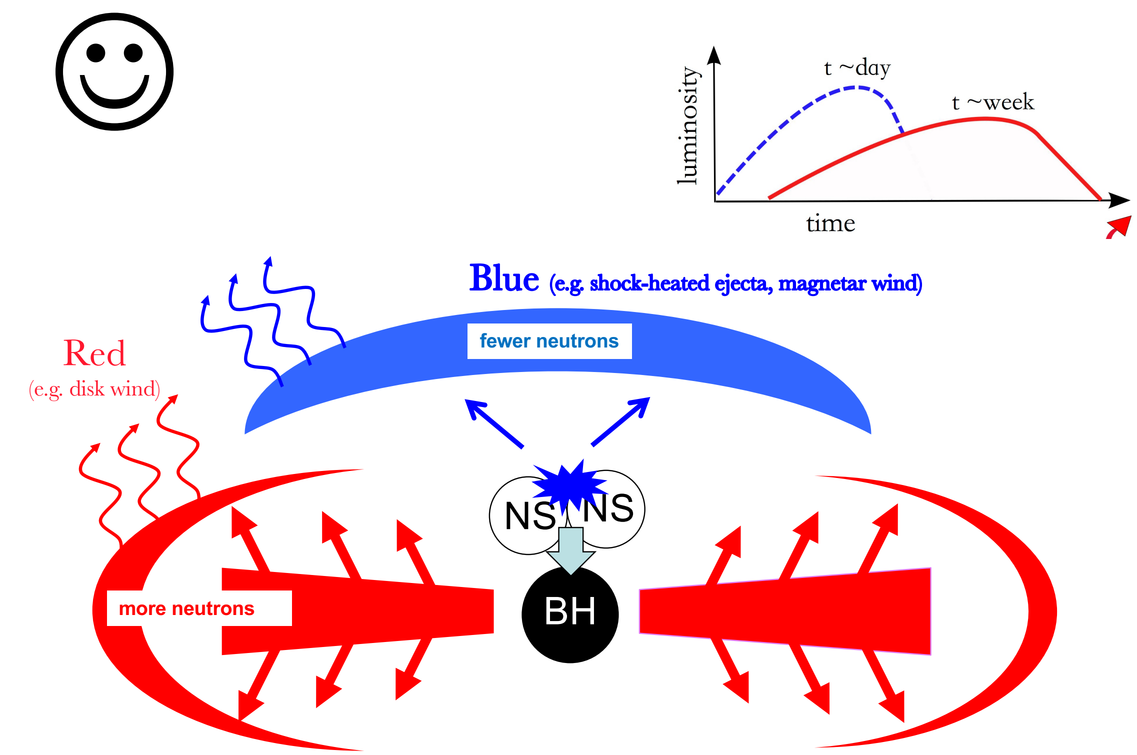


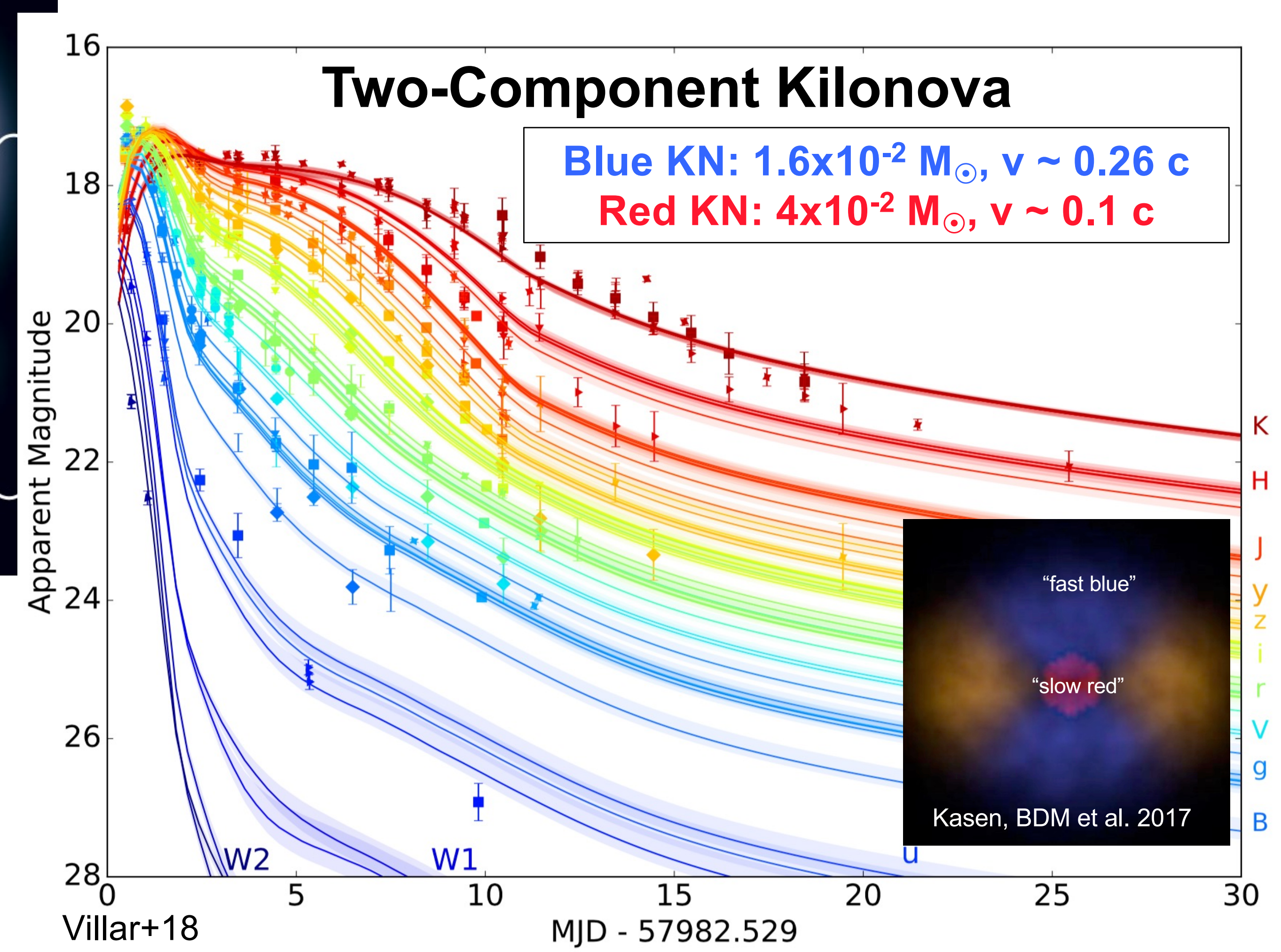
First joint detection of gravitational and electromagnetic radiation (GW170817 & GRB170817A).

Figure credit: Abbott et al., ApJ (2017), ESA.

Electromagnetic Counterparts: AT2017gfo



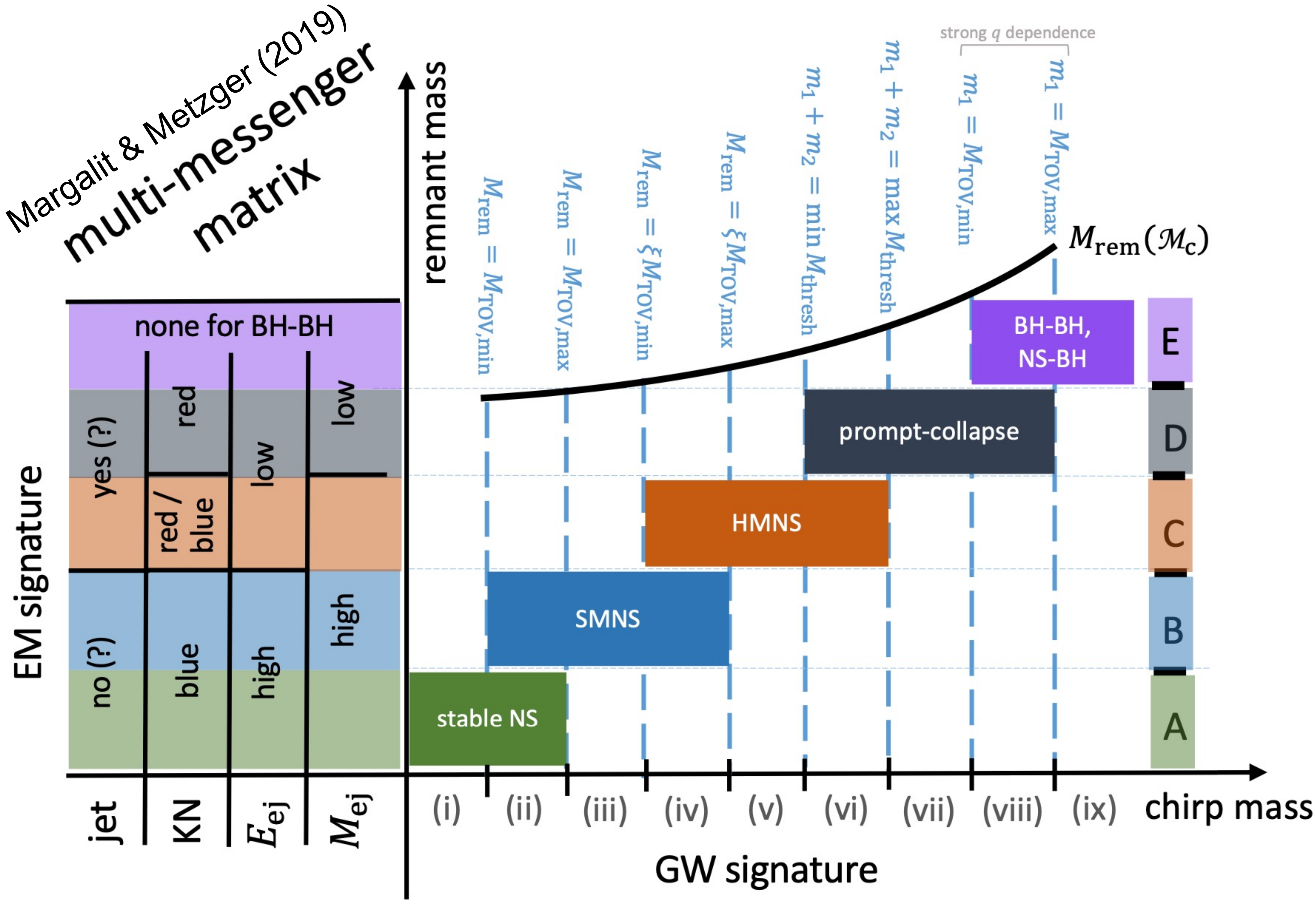




Kilonova colors reveal ejecta composition and provide information on ejecta source.

Brian Metzger, PoS 035. Antonio Stamerra, PoS 944.

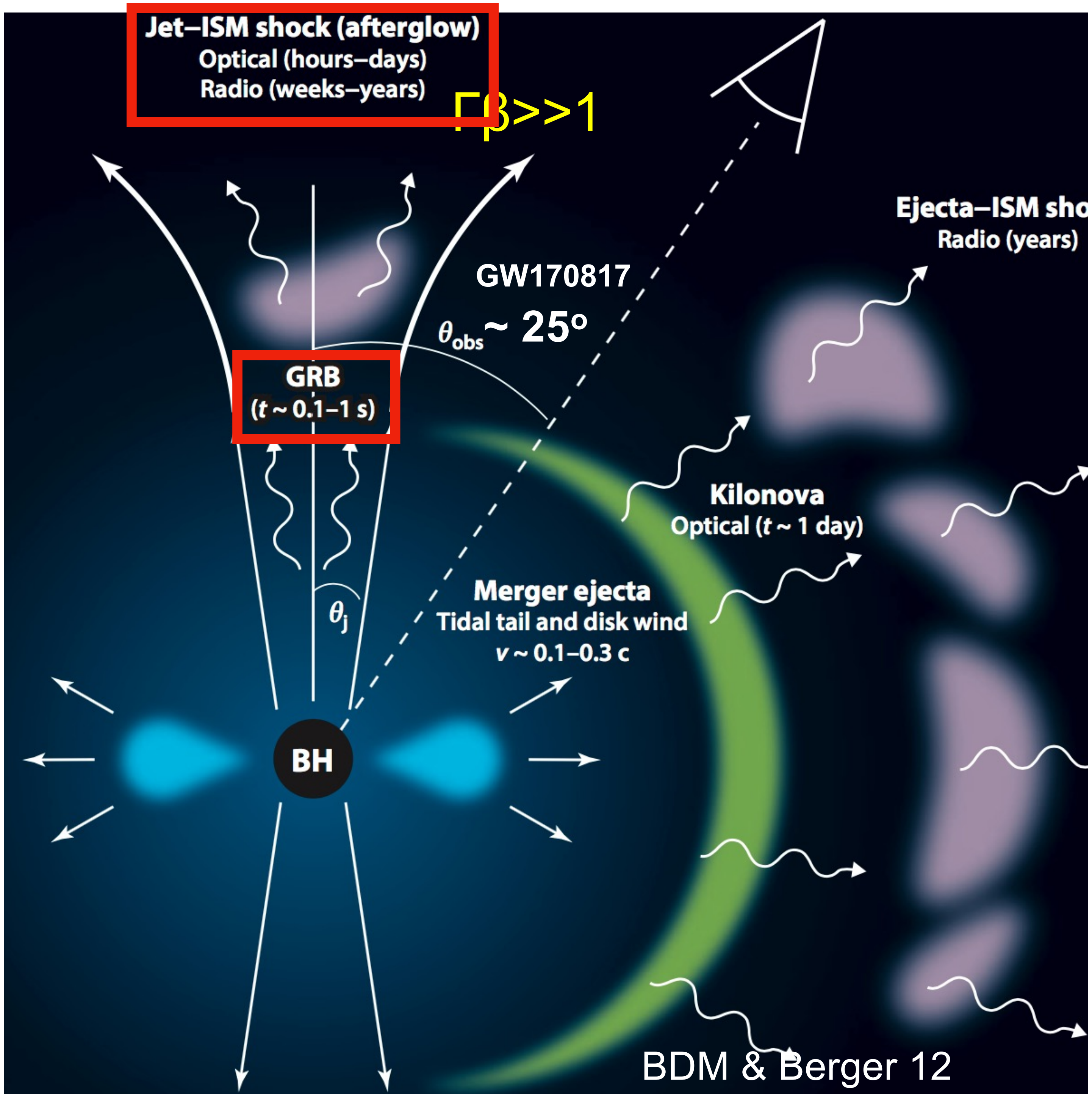
Multi-Messenger Measurements



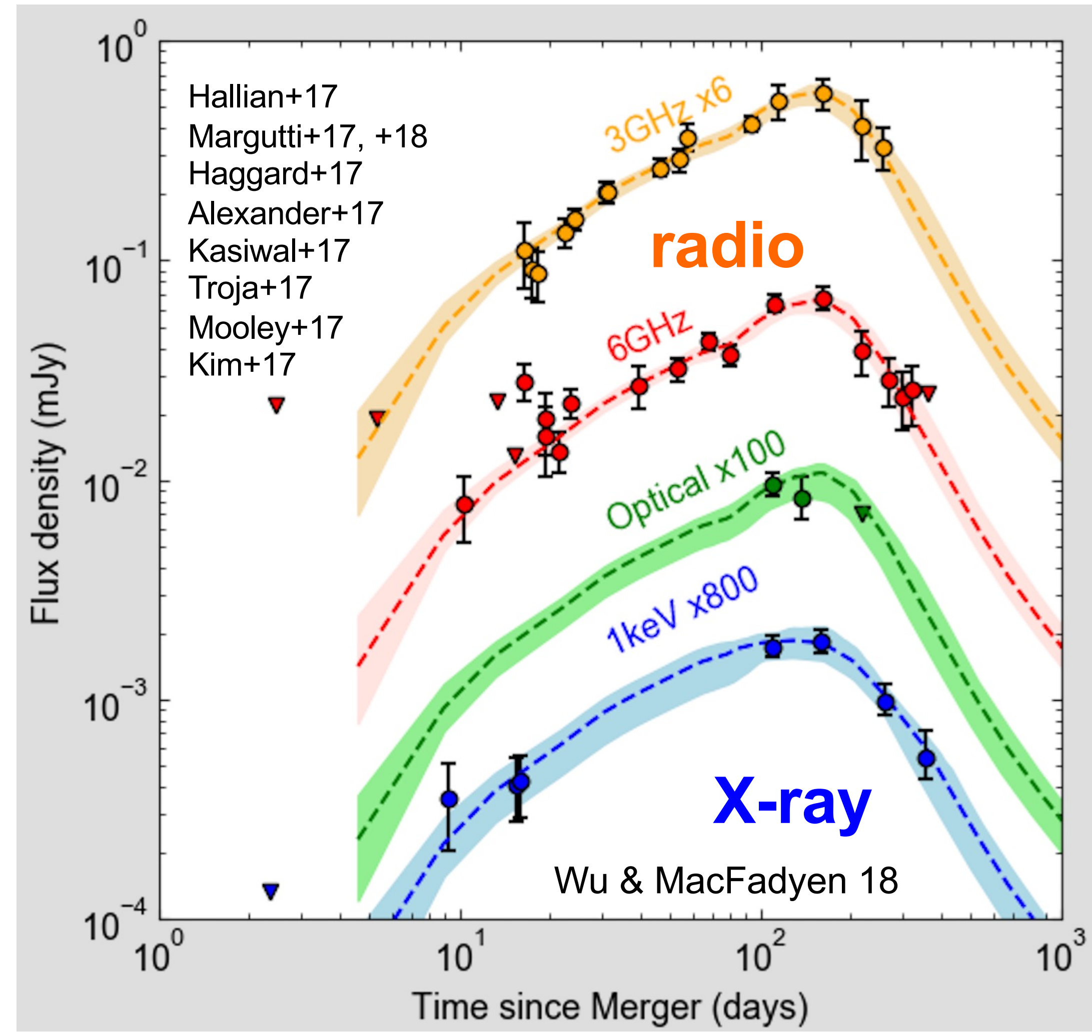
By using EM observations to ascertain the outcomes of a large population of future GW-detected mergers, we could assess the diversity of their r-process contributions and probe the NS EoS.

Brian Metzger, PoS 035.

Electromagnetic Counterparts: GRB 170817



Non-Thermal Synchrotron Radiation



Consistent with a powerful GRB viewed off-axis.

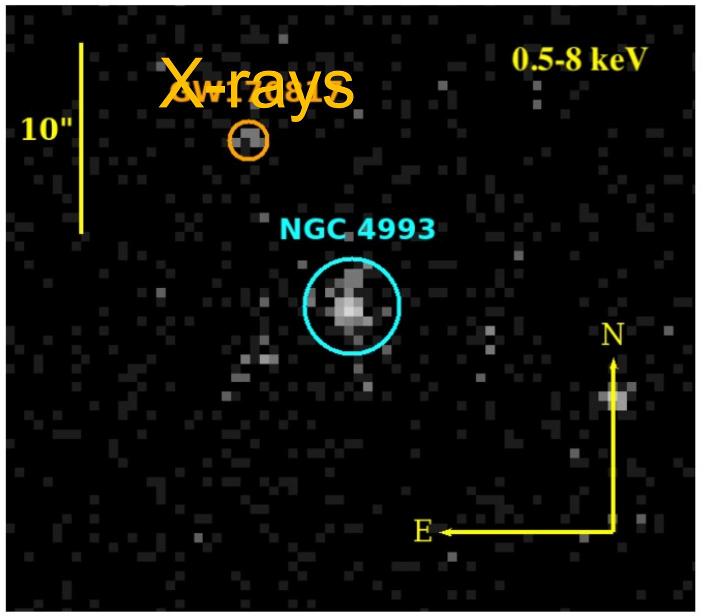
The time evolution of the electron power-law index can be observable in future off-axis GRB afterglows and provide constraints on particle acceleration across trans-relativistic shocks.

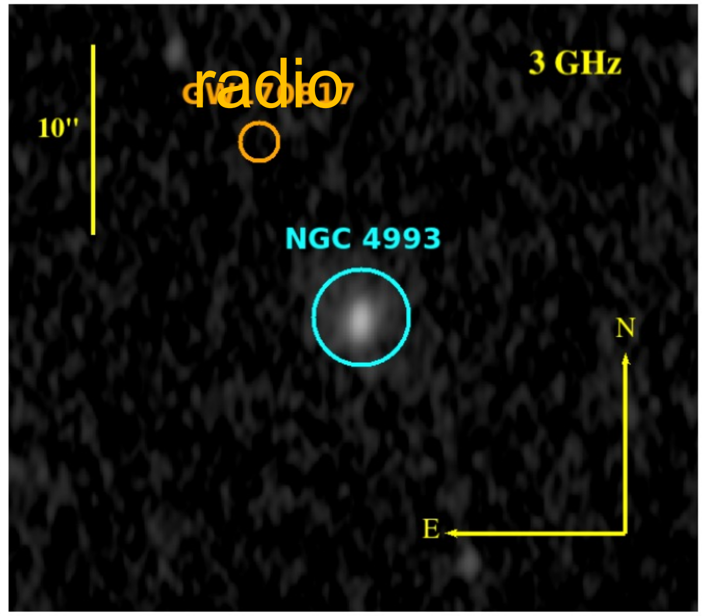
Brian Metzger, PoS 035. Kazuya Takahashi, PoS 1010.

GRB 170817 or AT2017gfo?

3.4 years later: X-rays are still there!

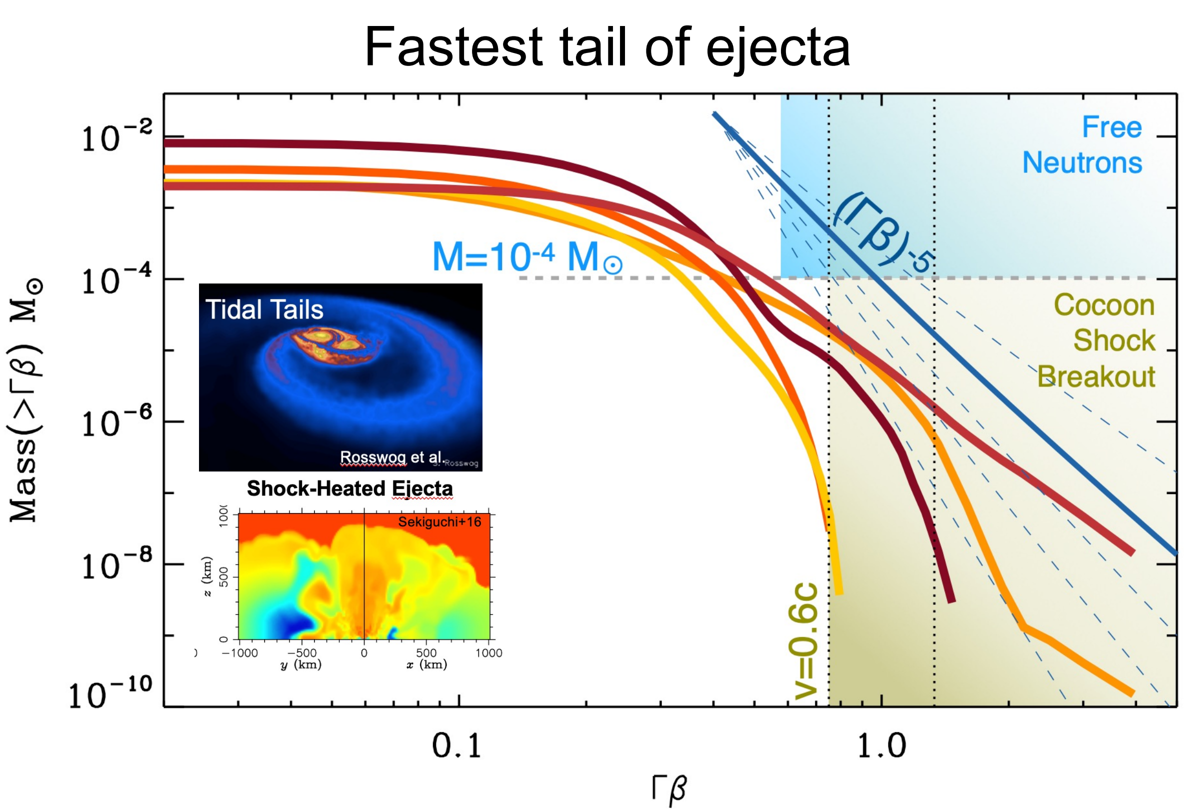
Haleja+21; see also Balasubramanian+21 Troja+21

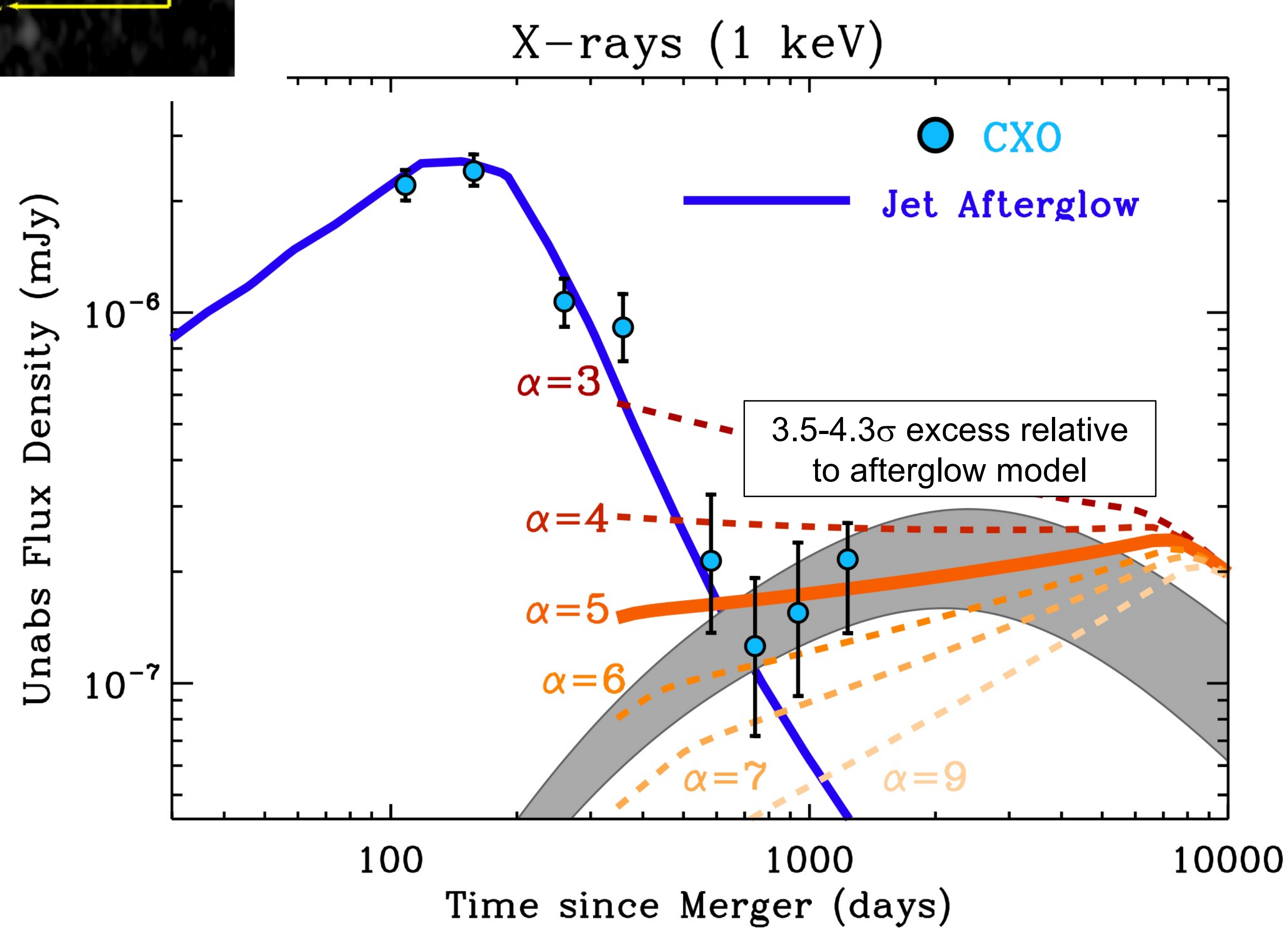




…but radio has continued to fade
=> change in spectral slope or new emission component

Fastest tail of ejecta

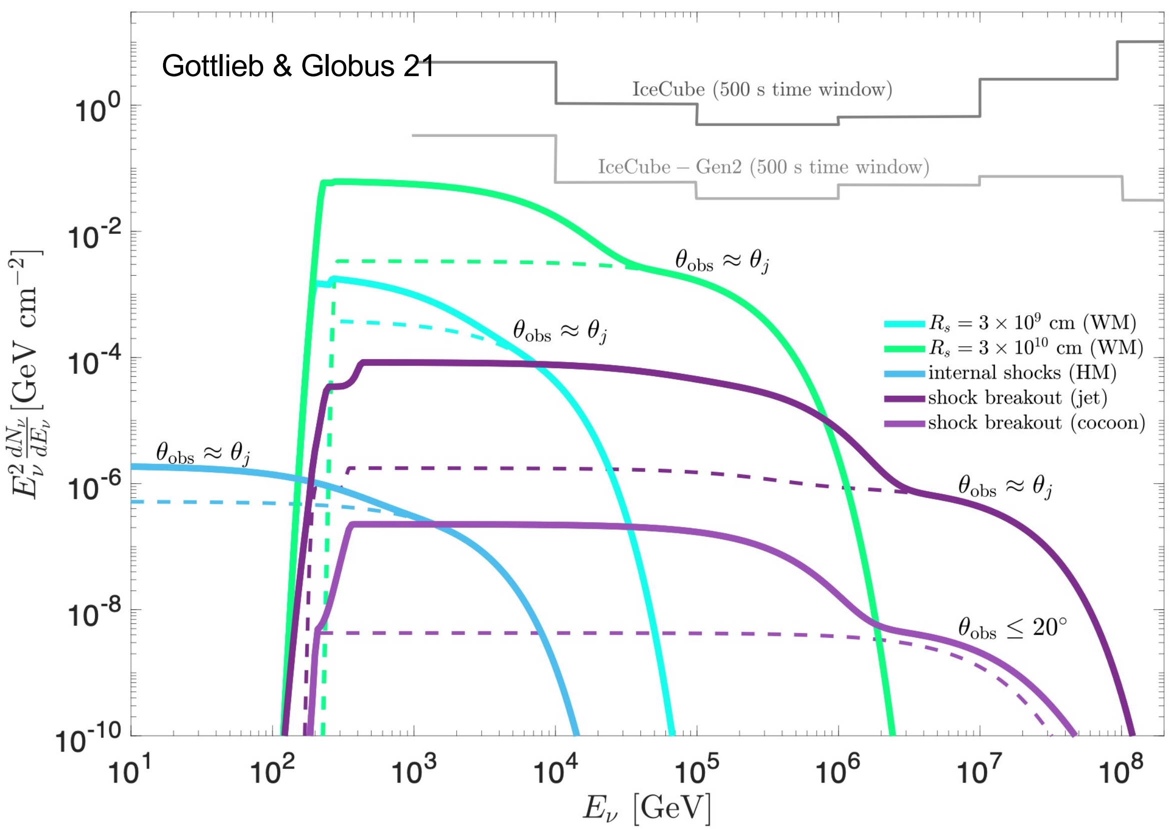




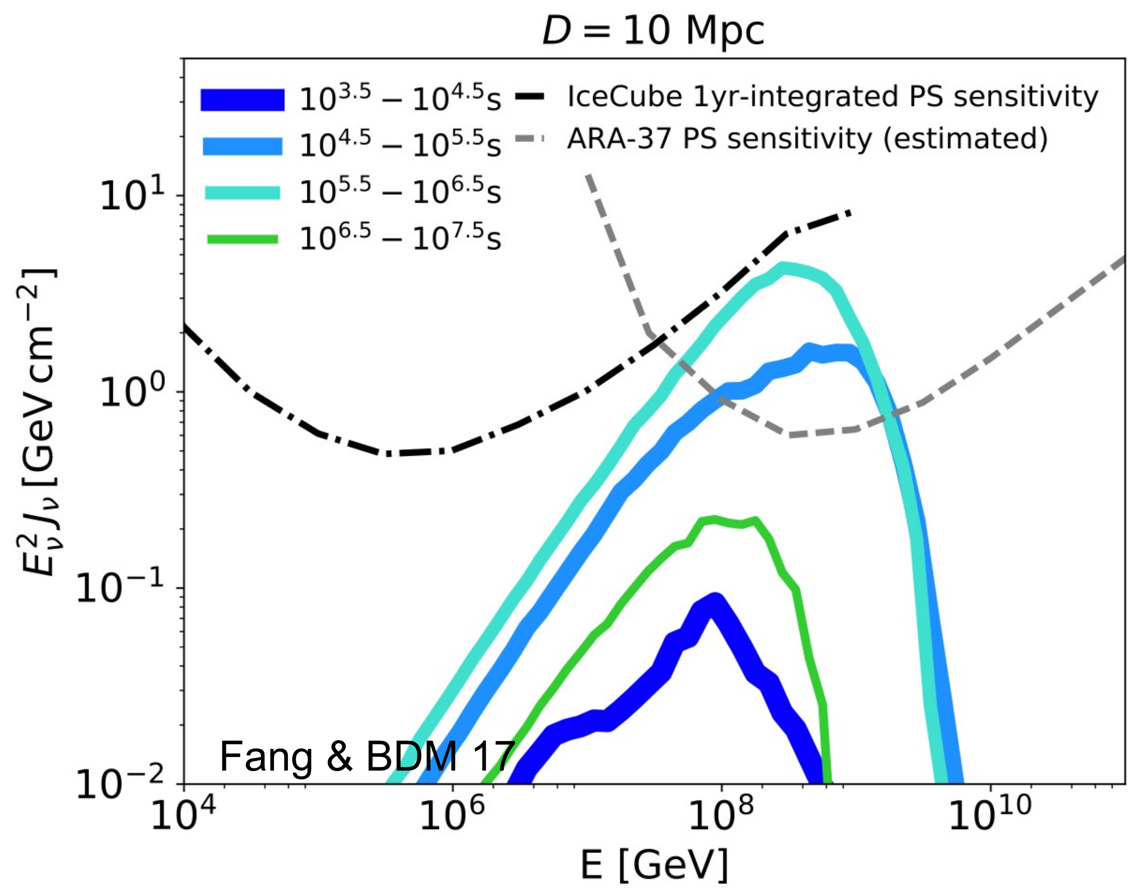
Brian Metzger, PoS 035.

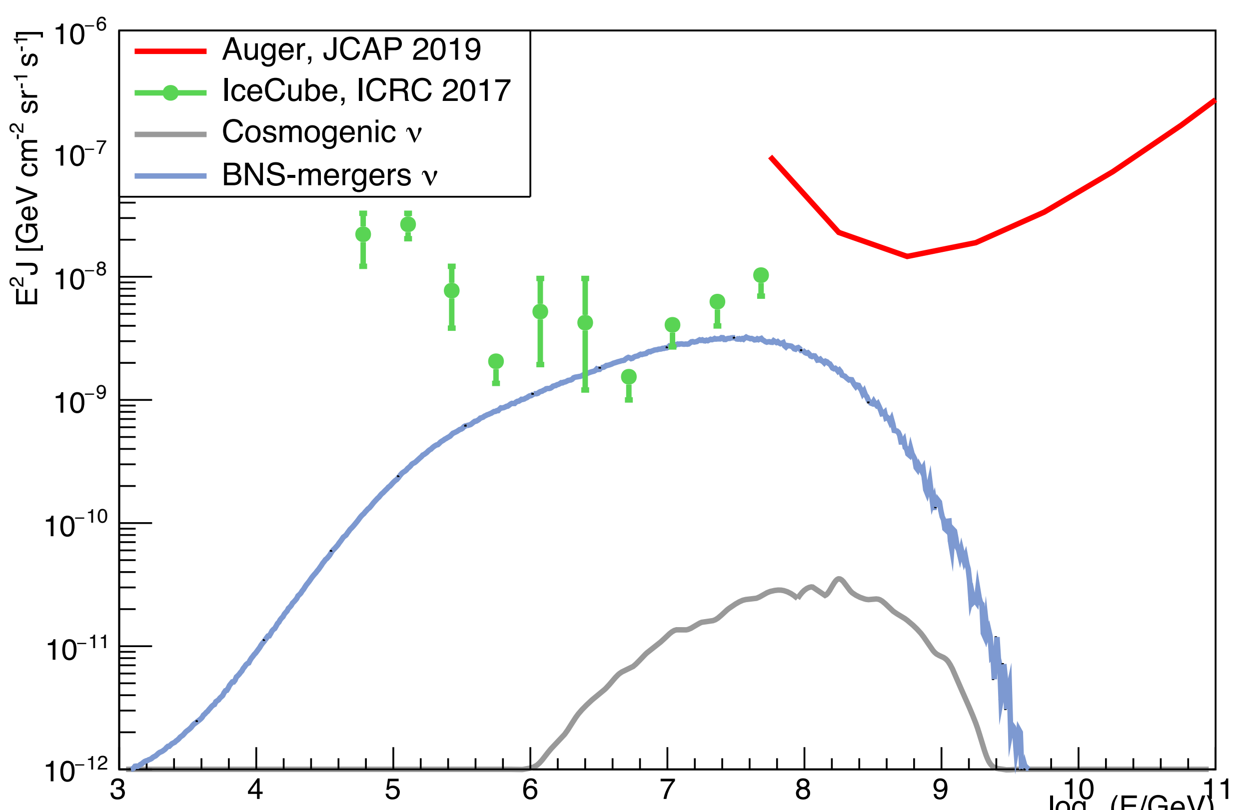
Neutrinos from Compact Binary Mergers?

Neutrinos from shock breakout.



Neutrinos from magnetar nebula.

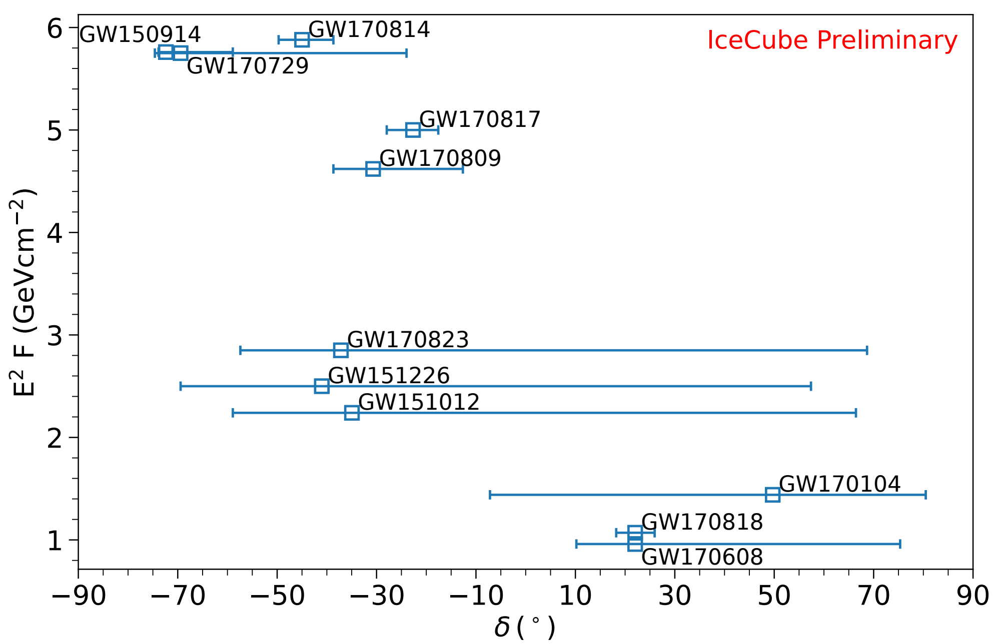




Neutrinos from interactions of confined UHECRs with the thermal and not-thermal radiation fields originated by the ejected material.

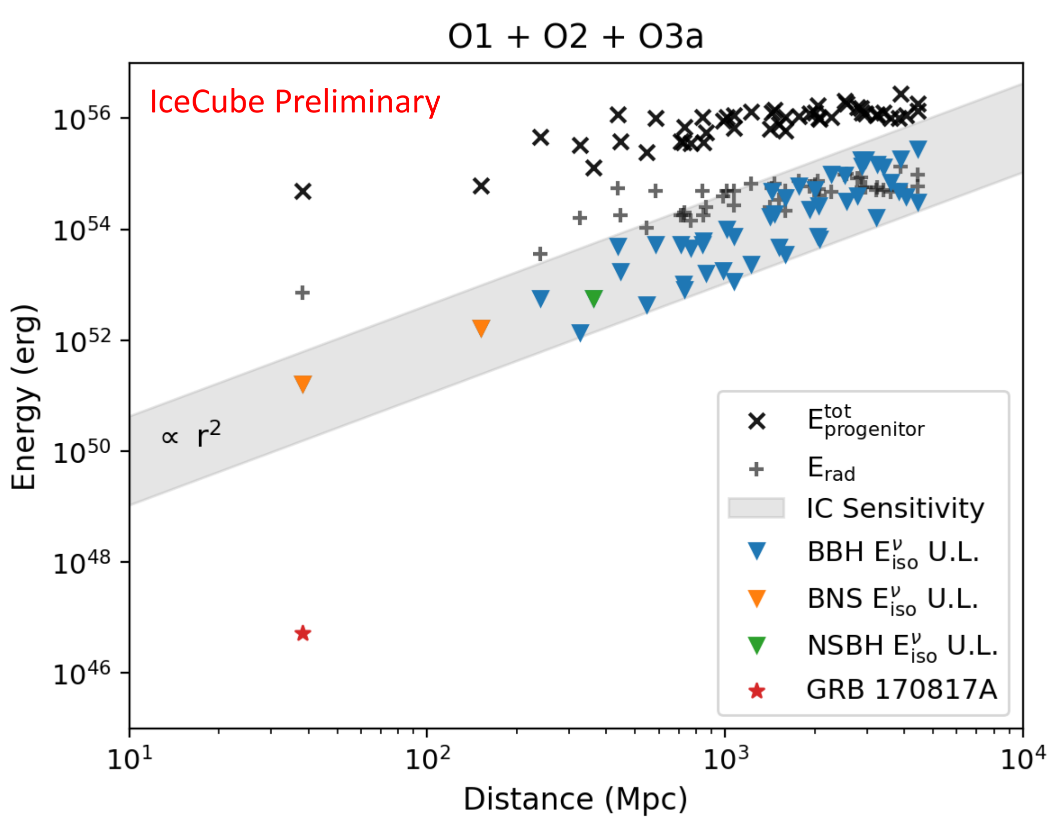
Brian Metzger, PoS 035. Simone Rossoni, PoS 1004.

IceCube Follow-Up of GW Sources



Low energy searches with IceCube Deep Core

Searches for neutrino counterparts (10-100s GeV). Similar exposure for north and south hemispheres.



Real time & offline searches of high-energy neutrinos

Two analyses for the HE neutrino follow-up:

- Low-Latency Algorithm for Multi-messenger Astrophysics (LLAMA)
  - Test statistic calculates odds ratio for a common source by including astrophysical emission priors in order to use the distance information from the GW detection
- Unbinned Maximum Likelihood (UML)
  - Test statistic uses the best fit for the signal neutrino count and spectral index

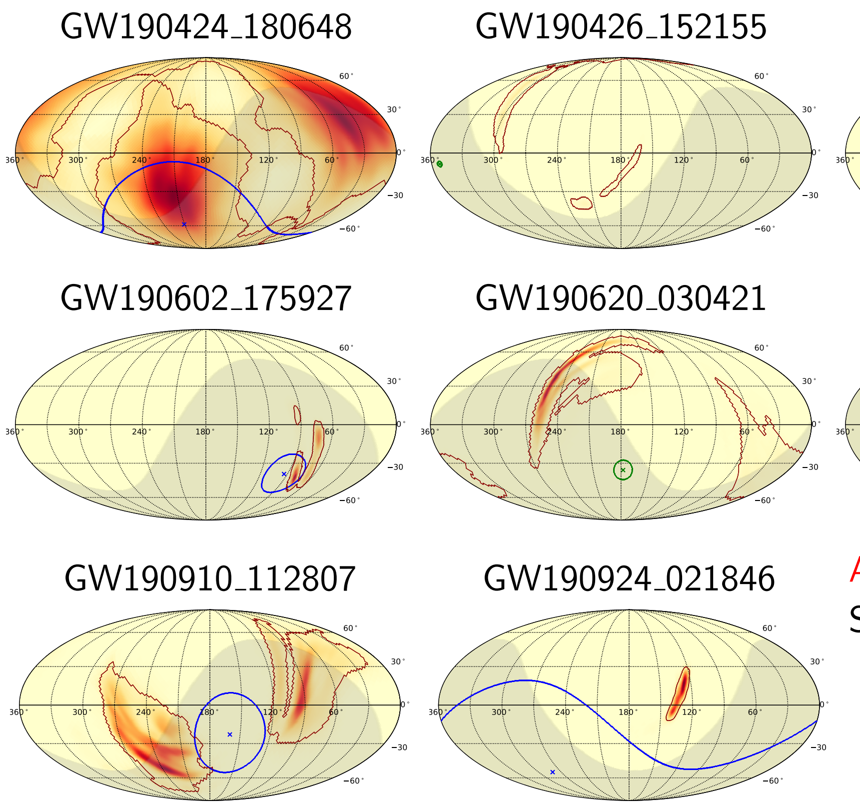
- Both analyses look for neutrinos ±500s around the GW event.
- Extended search (until 14 days after the merger) for binaries containing neutron stars.

No significant neutrino counterpart found yet.

Aswathi Balagopal, PoS 939. Doga Veske, PoS 950.
See Michael Schimp, PoS 968 for searches of UHE neutrino counterparts with AUGER.

Super-Kamiokande Follow-Up of GW Sources

Ten SK high-energy events in time coincidence

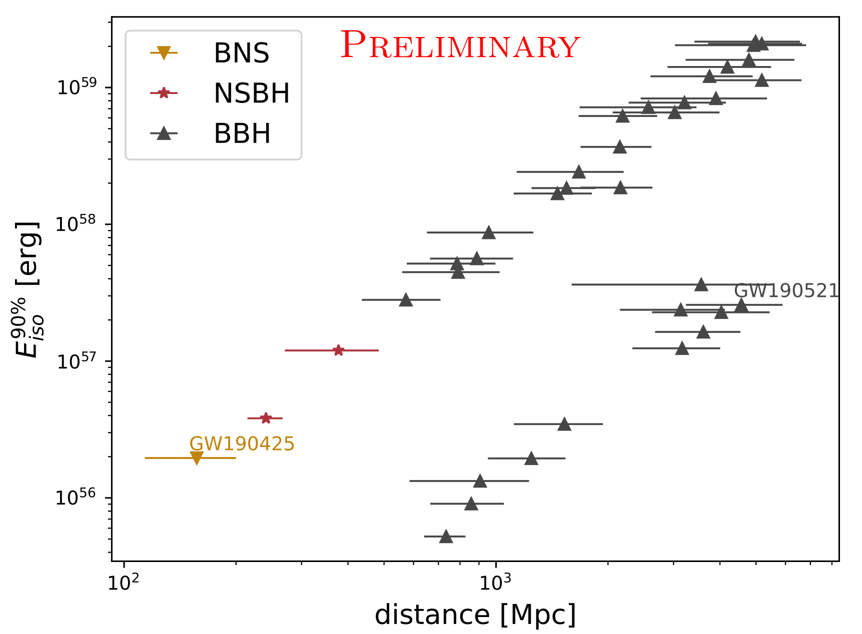


All plots are PRELIMINARY

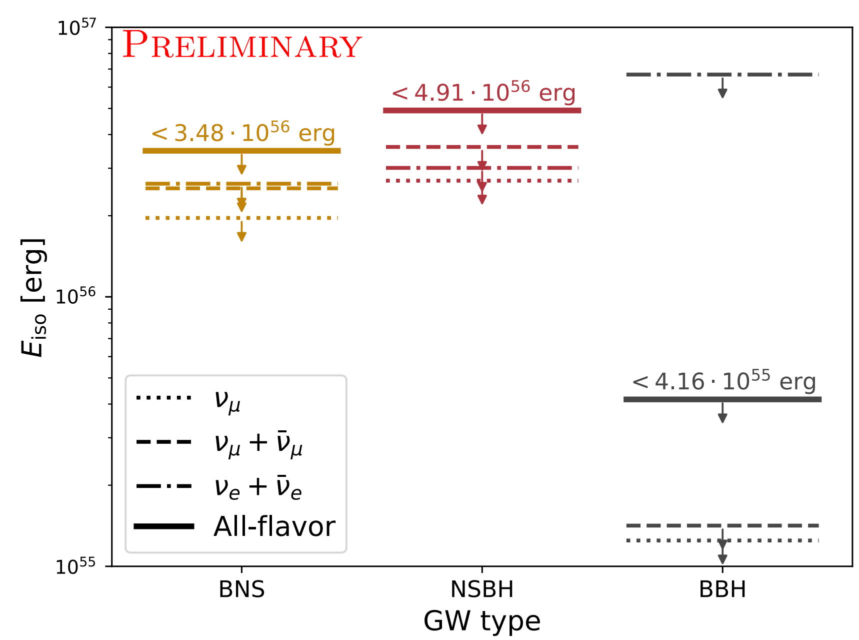
Skymaps in equatorial coordinates

- **Red:** GW localisation and 90% contour
- **Blue:** SK FC events with 1σ angular uncertainty
- **Green:** SK UPMU events.
- **Shaded area:** SK upgoing sky.

Individual limits on $E_{\text{iso}}^{\nu_\mu}$



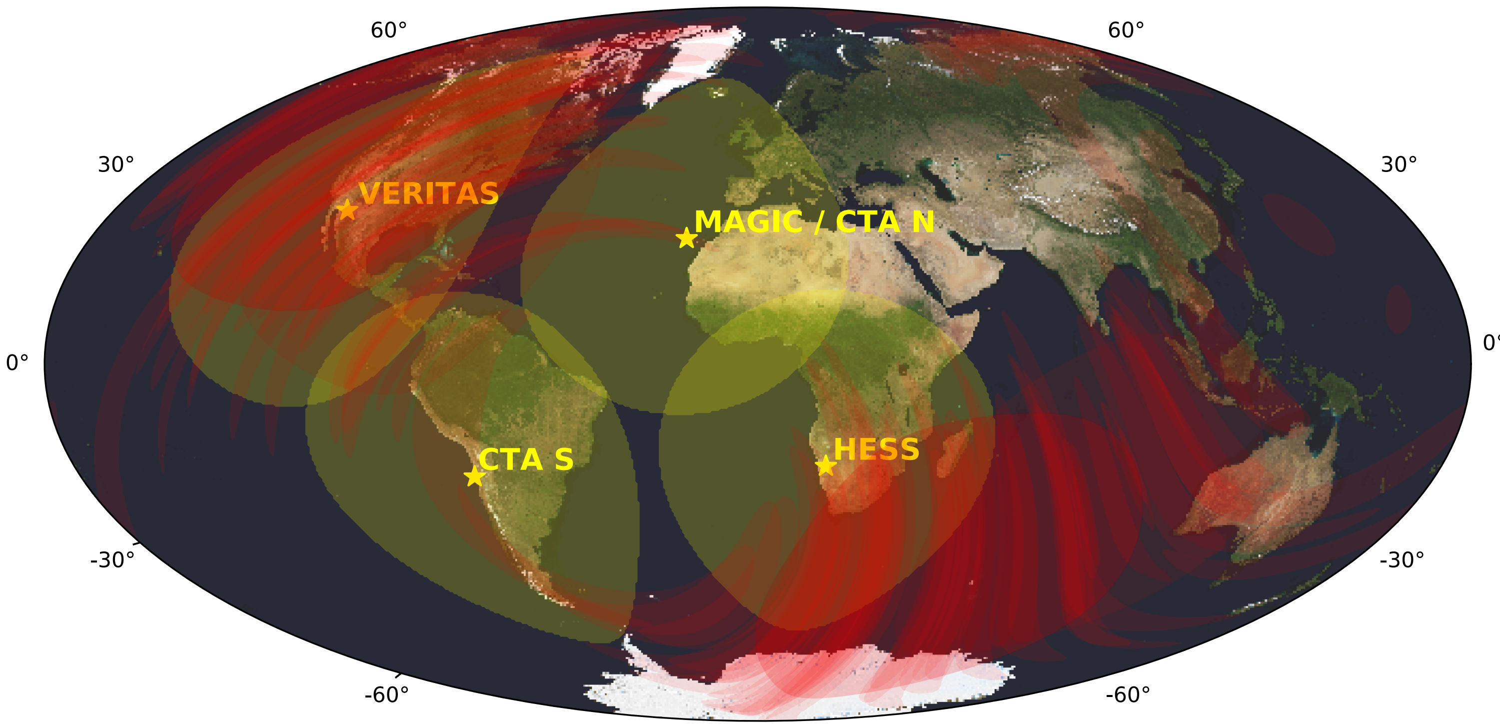
Stacked limits on $E_{\text{iso}}^{\text{all-flavours}*}$



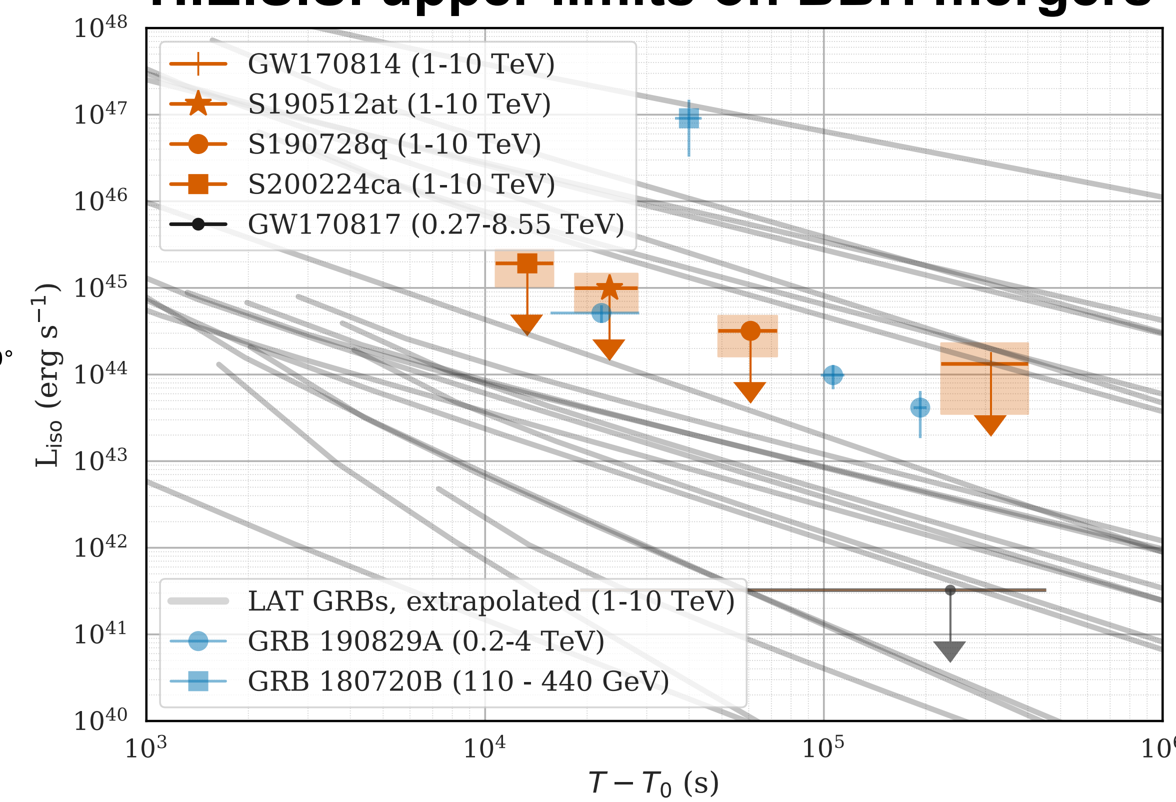
Future real-time public release of follow-ups for the LIGO/Virgo's O4 run.

Mathieu Lamoureux, PoS 947

VHE Gamma-Ray Counterparts of GW Sources



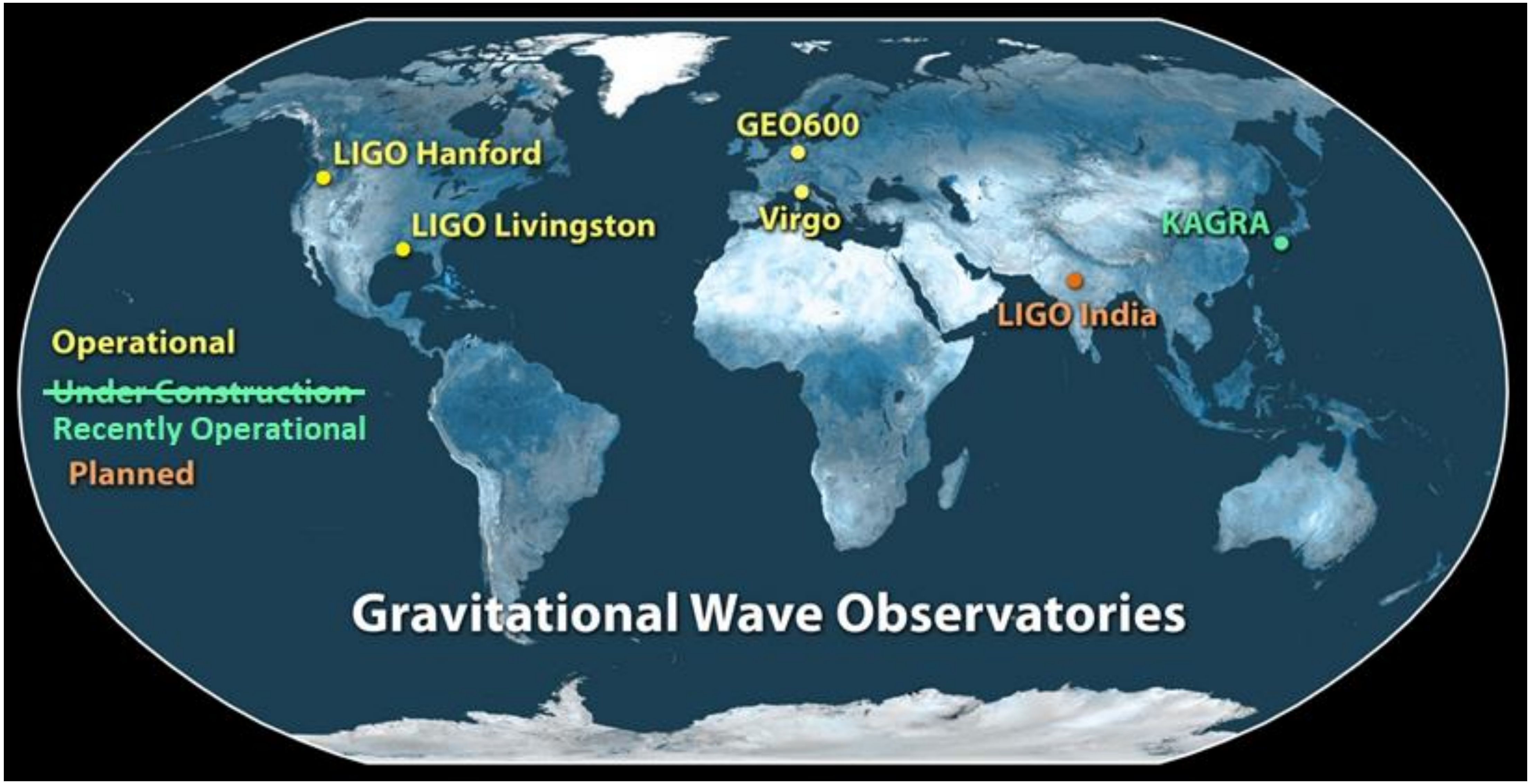
H.E.S.S. upper limits on BBH mergers



- Short GRBs may emit VHE radiation as proven by MAGIC and H.E.S.S. observations.
- No VHE counterpart to GWs has been observed so far (sub-threshold merger candidates identified in LIGO's O1 used to search in archival observations from VERITAS; upper limits on the integral flux).
- Follow-up observations of 4 BBH events performed by H.E.S.S. during O2 and O3 LIGO/Virgo runs and rapid follow-up strategy developed. Deeper observations expected for LIGO/Virgo's O4 run.
- CTA will be key (unprecedented sensitivity, rapid slewing capabilities, large field-of-view). Simulations predict CTA N and CTA S will be sensitive to detect on axis and off-axis GRBs with a delay up to 10 mins.

Colin Adams, PoS 950. Barbara Patricelli, PoS 998. Halim Ashkar, PoS 943, PoS 936. Roberta Zarin, PoS 005.

Homework for ICRC 2023



- Network of detectors with different sensitivities and locations crucial for future event characterizations.
- Need to get ready for expected larger number of multi-messenger detections.
- Mapping of the ingoing binary properties on the diverse outcomes through population studies.
- Crucial to gain insight and better understand neutron star physics and merger properties.

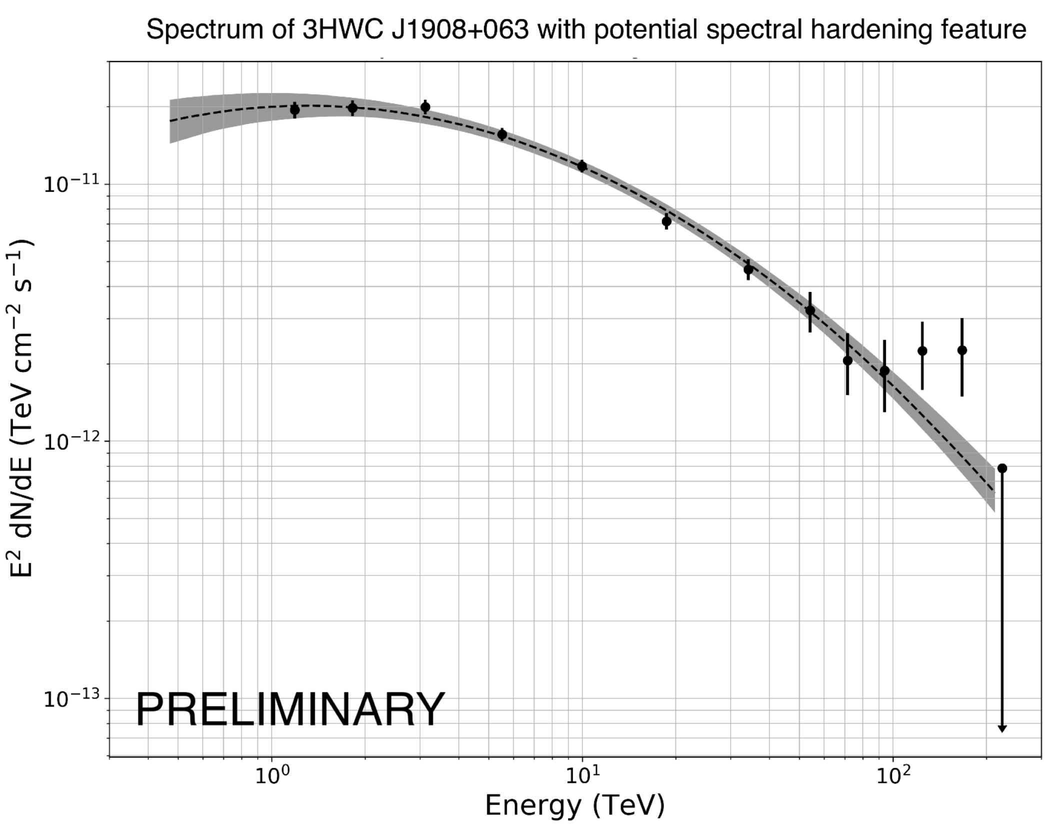
Figure credit: Doga Veske. Sessions # 27, 28.

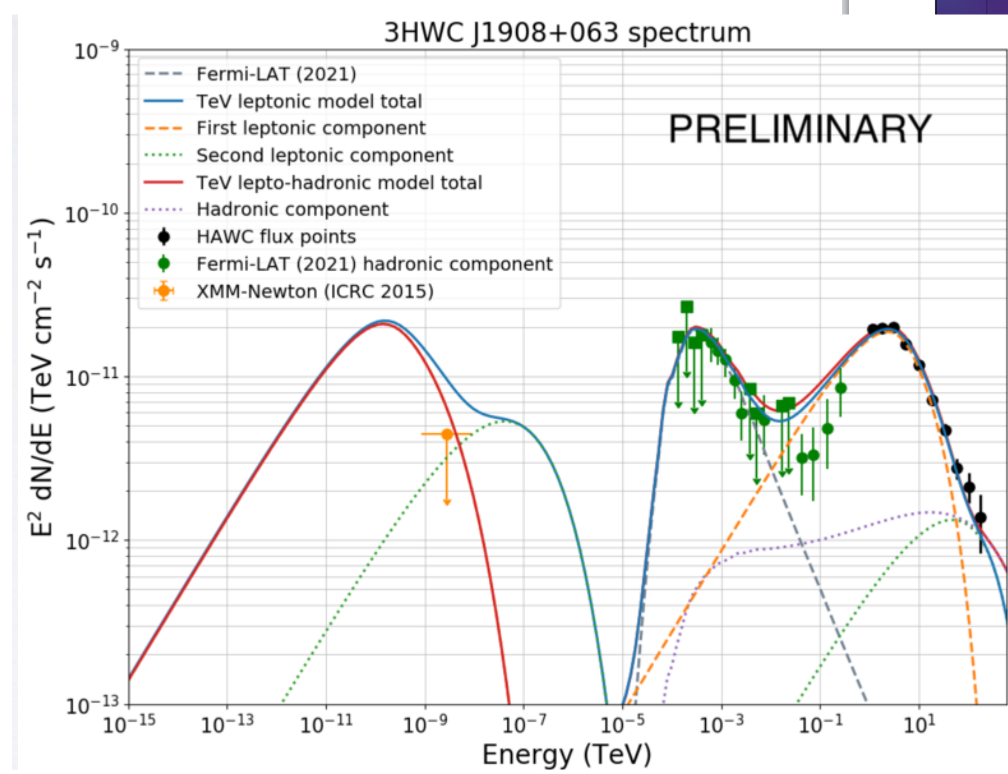
Galactic Sources and Starbursts

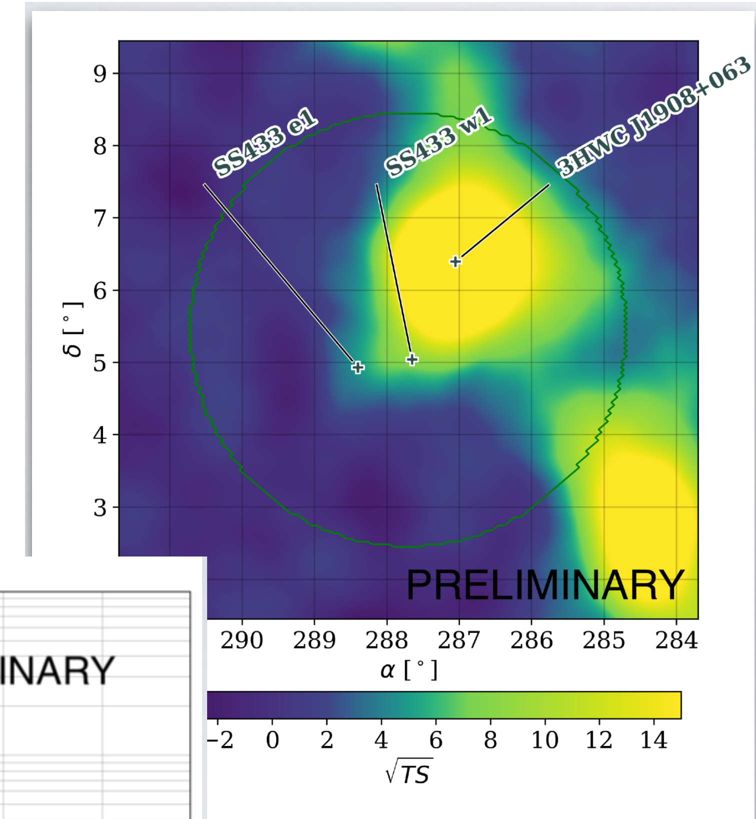
Figure credit: ESO

PeVatron Candidate: MGRO J1908+06

- Source detected beyond 100 TeV, implications for acceleration of cosmic rays?
- Hints for related neutrino emission from IceCube.
- 2 SNRs, 3 pulsars and other objects in the proximity of the source.
- Leptonic or hadronic scenario?







- **HAWC:** potential hardening feature > 100 TeV. Does this hint towards a second population of particles at the highest energies?
- **H.E.S.S.:** no hardening feature (lower statistics), but multiple components may exist in the nebula.

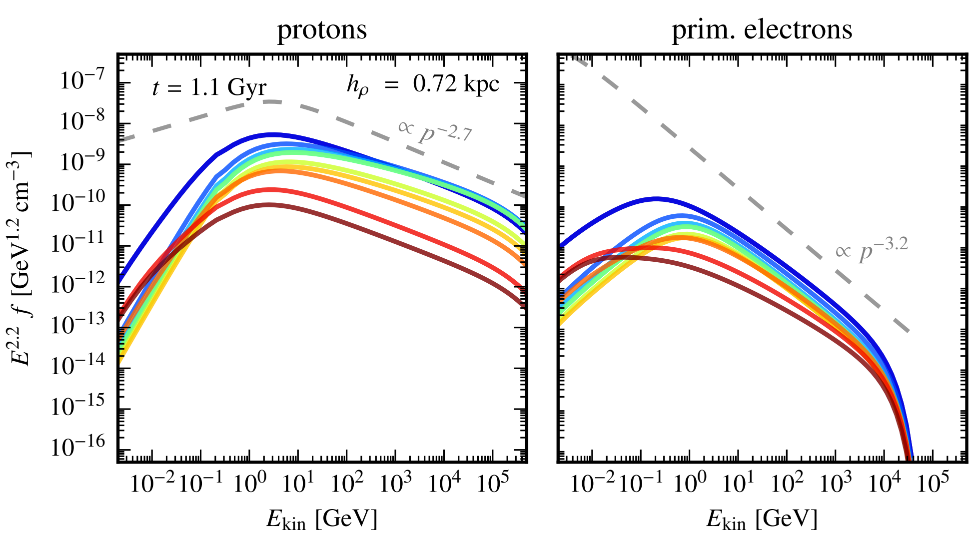
Kelly Malone, PoS 810. Dmitriy Kostunin, PoS 779.

See Kaya Mori, PoS 963 for NuSTAR observation campaign of pulsars wind nebulae.

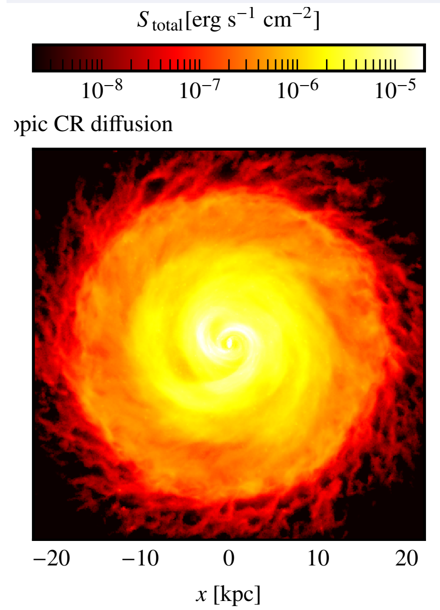
Starbursts and Galactic Winds

Starburst Galaxies: Cosmic ray spectra in 3D MHD simulations and multi-messenger predictions.

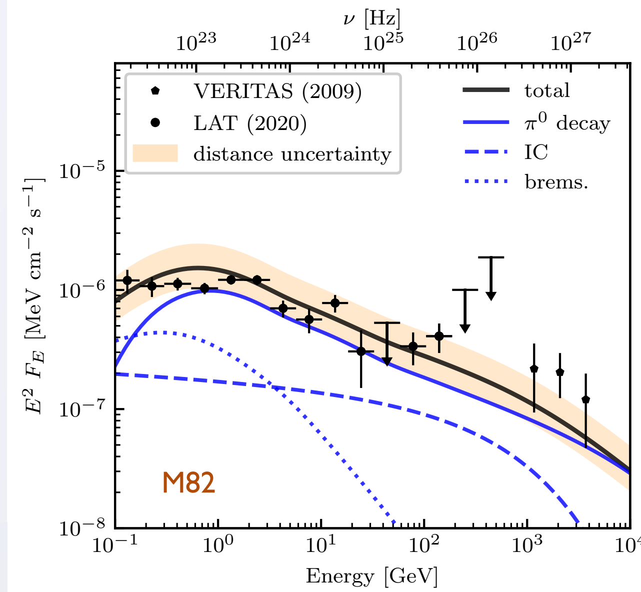
CR spectra & maps

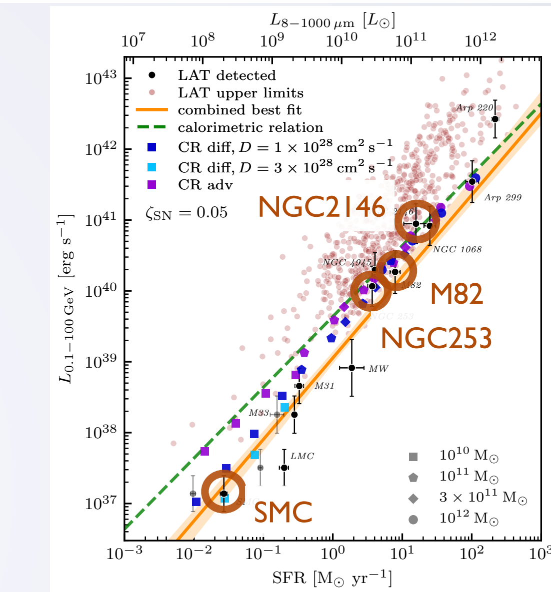


γ-ray emission

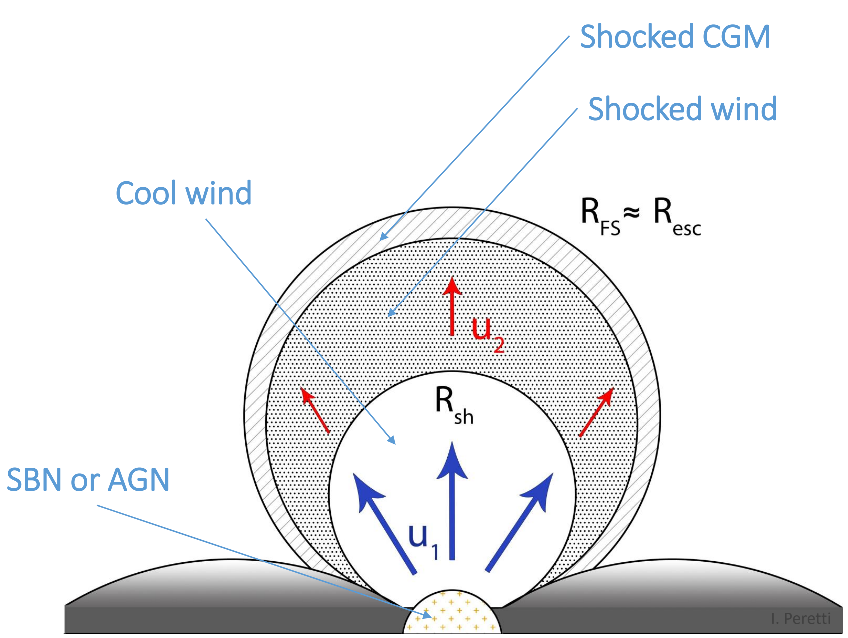


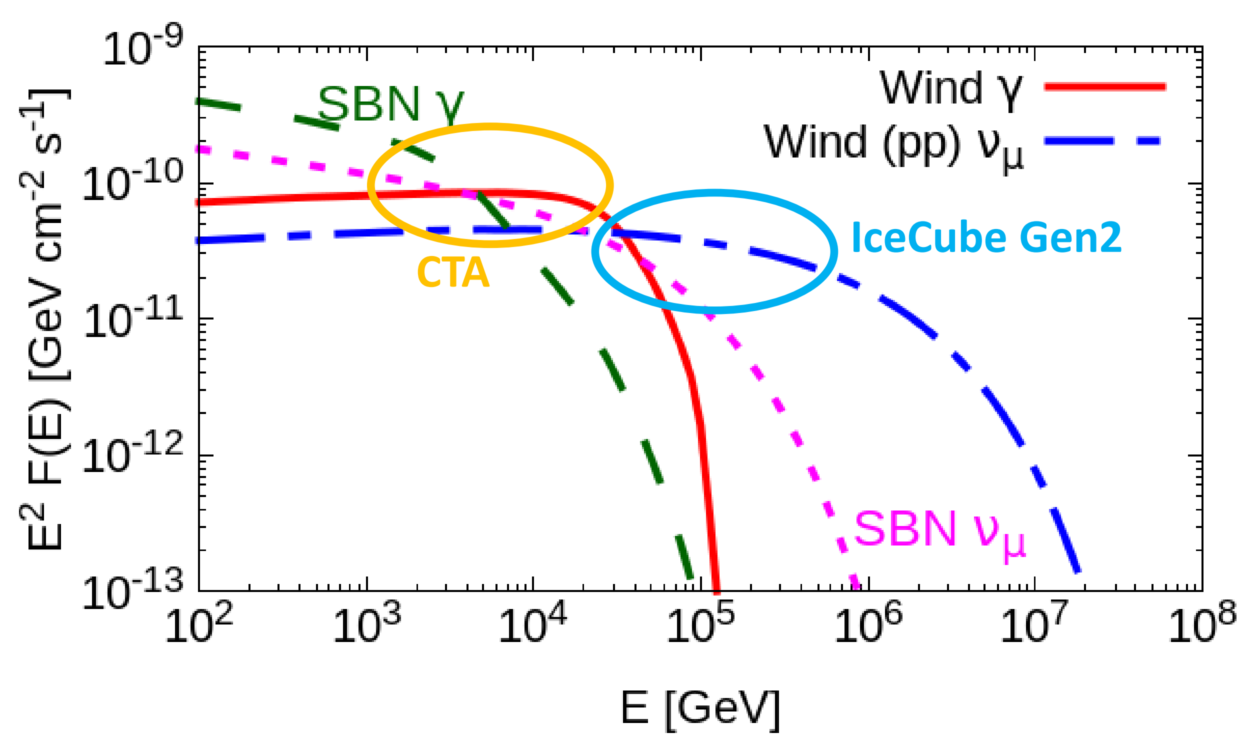
FIR - γ-ray relation and γ-ray spectra





Galactic Wind Super Bubbles: Protons accelerated up to 100s PeV at termination shock.

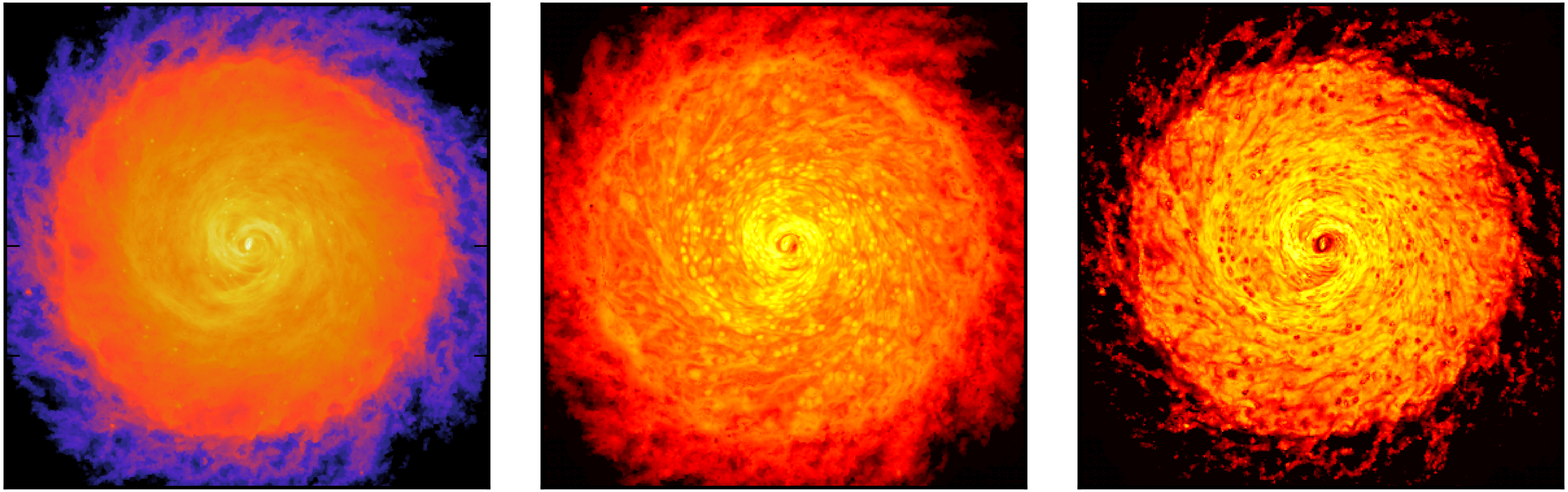




Gamma rays and neutrinos are copiously produced.
The escaping flux of protons and nuclei could contribute to the flux of cosmic rays observed at Earth.

Maria Werhahn, PoS 665 & Paula Kornecki, PoS 456. Enrico Peretti, PoS 995 & Giovanni Morlino, PoS 444.

Homework for ICRC 2023



- What is powering the galactic Pevatrons? What are the conditions for efficient particle acceleration?
- Are pulsars with nebulae (PWNe) efficient PeVatrons? What are the conditions which make acceleration very efficient? Crucial to observe more PWNe at various ages and environments.
- Hadronic or leptonic origin for these extreme TeV sources? Multi-messenger observations will be crucial.
- Need to progress in the modelling of starbursts and super bubbles.

Figure credit: Maria Werhahn. Sessions # 26, 55.

Conclusions

- Tremendous progress in multi-messenger searches of astrophysical sources.
- Scientific breakthroughs made possible by cooperation among different collaborations.
- We need to get ready for the growing number of neutrino events possibly associated to astrophysical sources as well as gravitational wave detections.
- Interpretation of multi-messenger data requires a major step forward in source modeling.

Very exciting times ahed!!

Thank you!