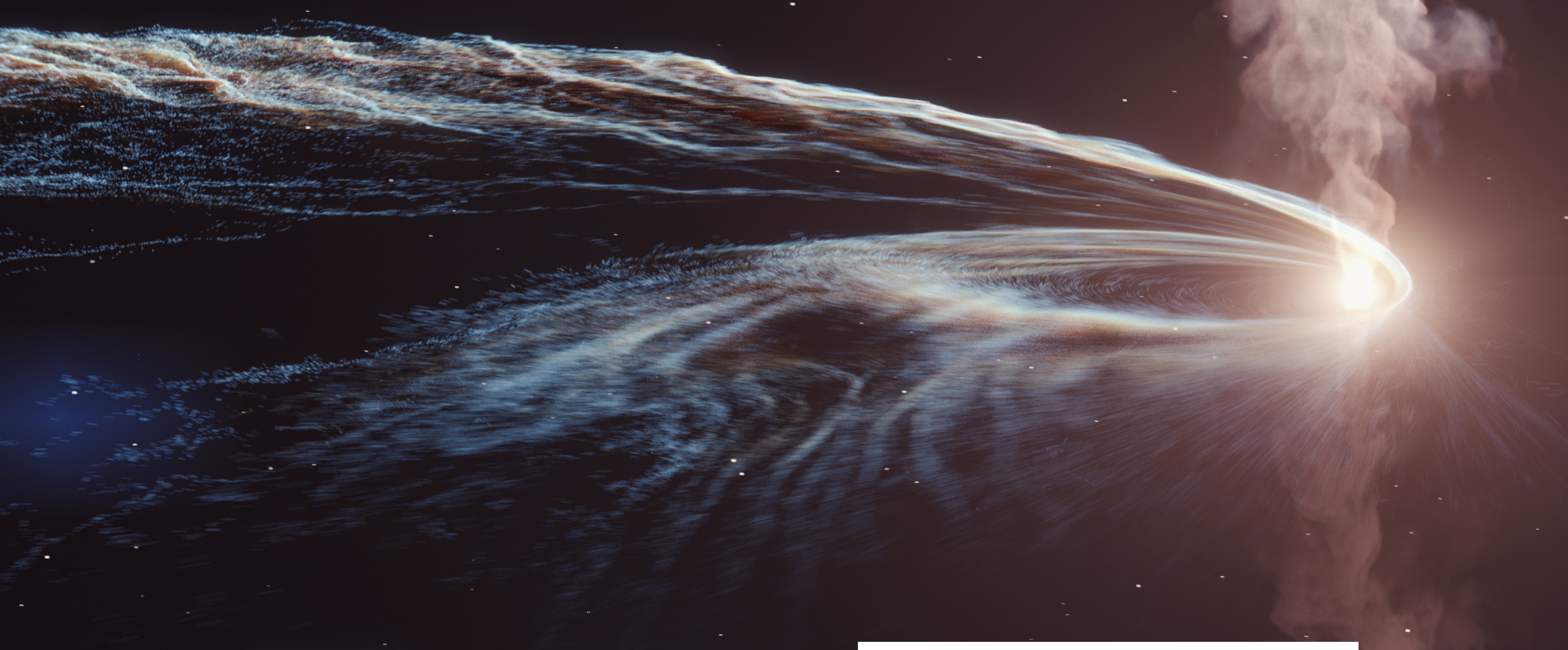
Astrophysics of cosmic-ray accelerators

Anna Franckowiak



UHECR 2022, L'Aquila, 3.10.2022

RUHR UNIVERSITÄT BOCHUM
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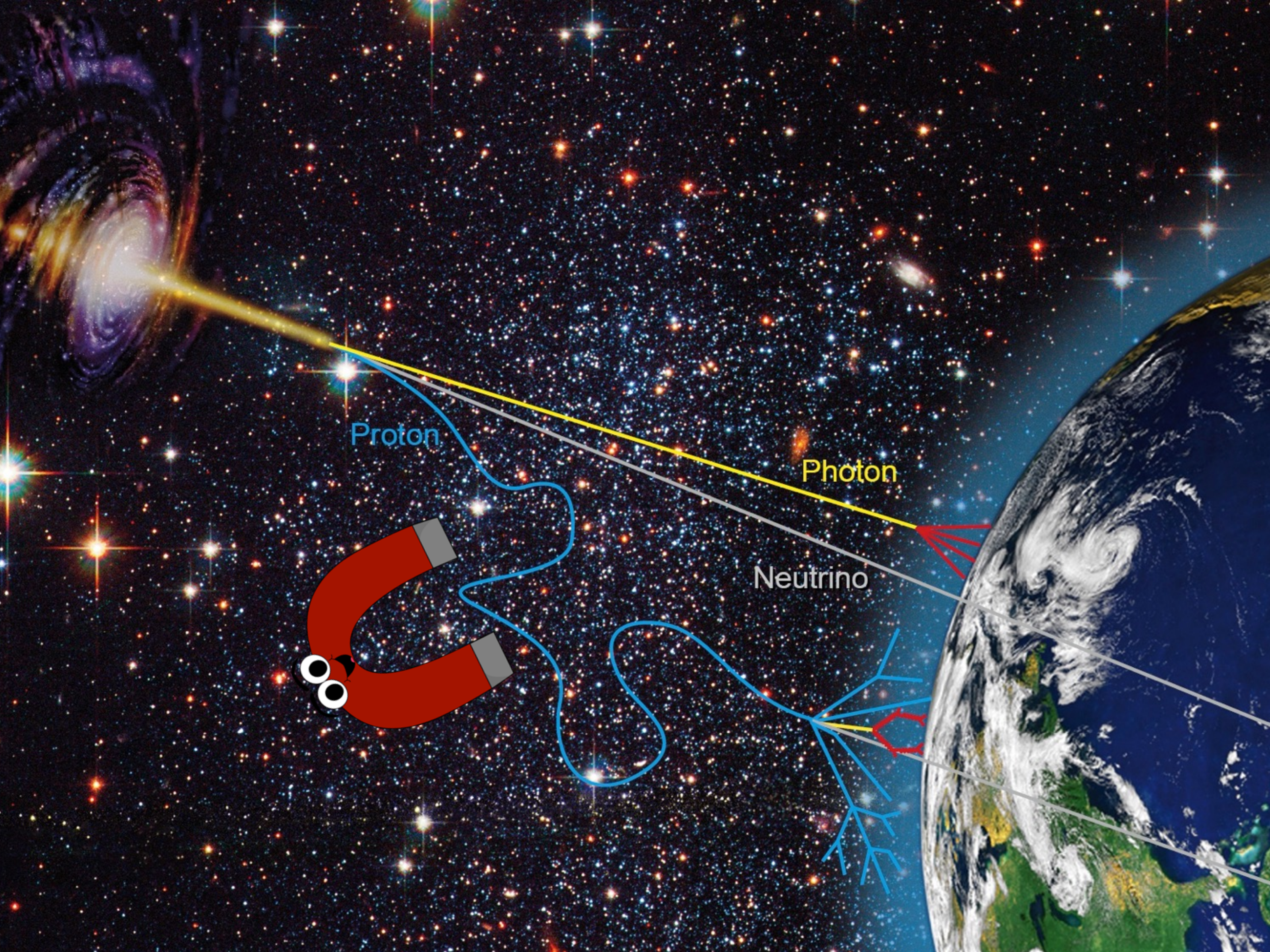

Proton
Photon
Neutrino

Neutrino Production Processes

Cosmic ray

pp

$p\gamma$

target

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

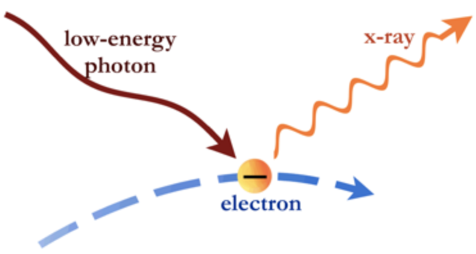
Neutrino Production Processes

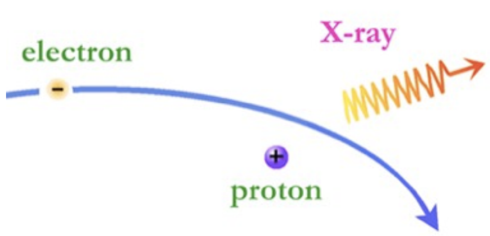
Cosmic ray

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

target

Gamma-rays are not exclusively produced in hadronic processes





Neutrino Production Processes

Cosmic ray

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$p\gamma$ $\rightarrow$

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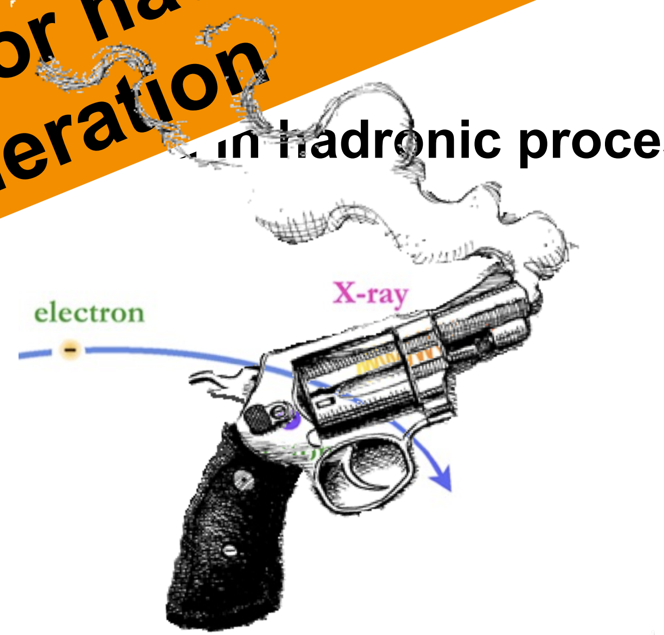
$$\ldots + \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$

$$\ldots + \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \ldots + \bar{\nu}_\mu$$

$$\ldots + \pi^0 \rightarrow \gamma\gamma$$

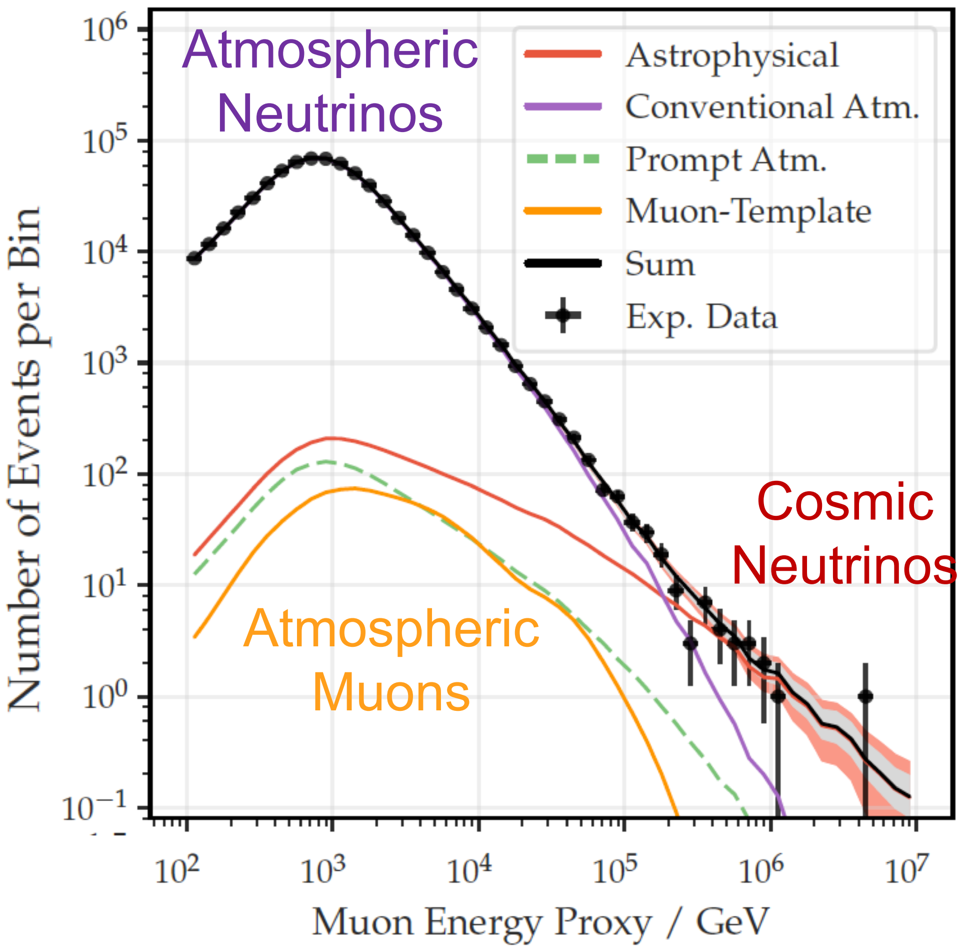
Neutrinos are the smoking gun signature for hadronic acceleration

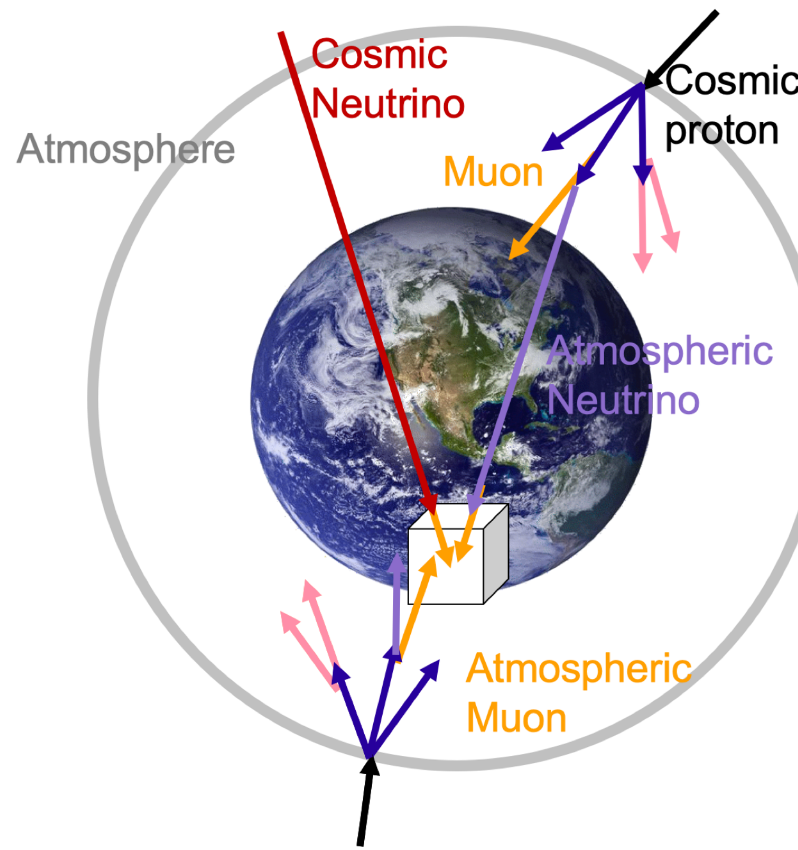
Gamma … in hadronic processes



Diffuse Flux discovered!

Northern Sky

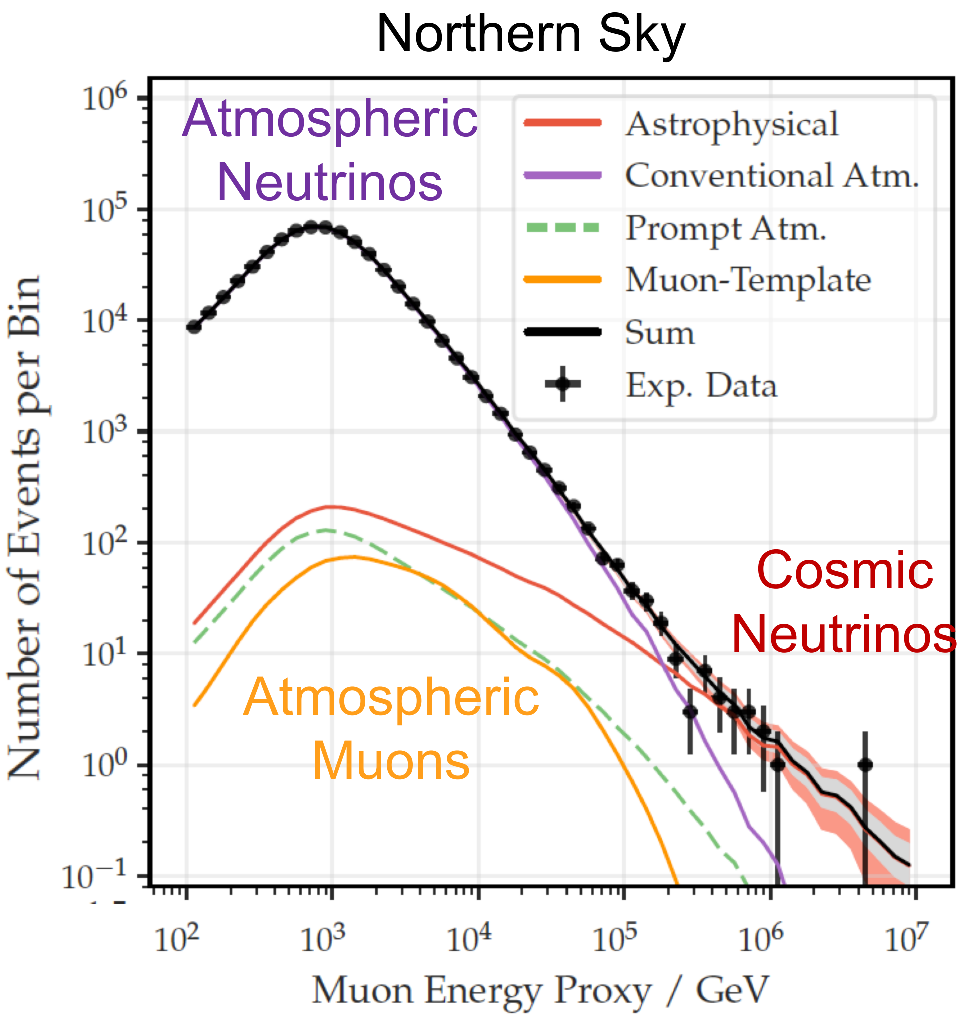




IceCube Coll. ApJ 928 (2022) 50

Where do the neutrinos come from?

Three Strategies

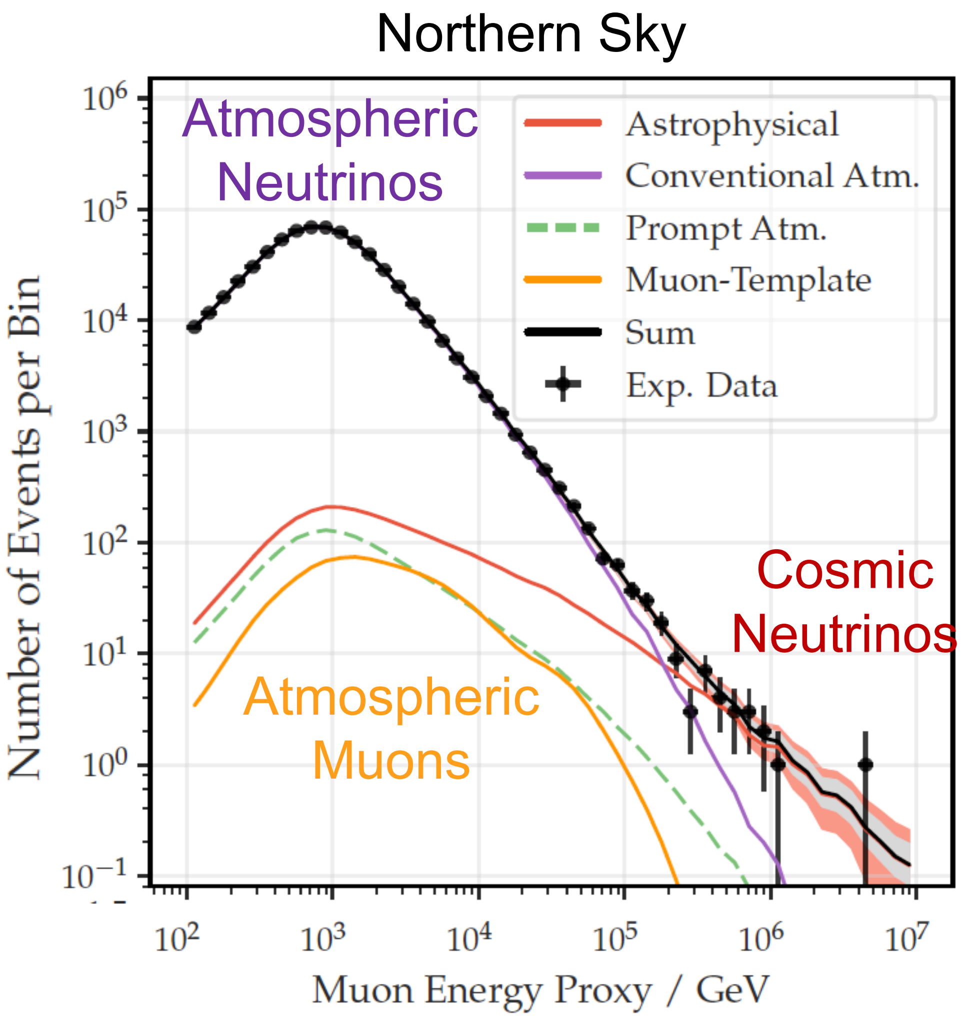


1. Look for hotspots in the neutrino sky → identify source candidates
2. Start from EM source catalog → look for neutrinos from source population ("stacking")
3. Focus on high-energy neutrinos with high signal probability → look for EM counterparts

Main Challenges

- Neutrino angular resolution poor compared to EM instruments
- Large background of atmospheric events
- **We don't know what to look for (many possible source candidates), what is the best wavelength to trace neutrino emission?**

Three Strategies



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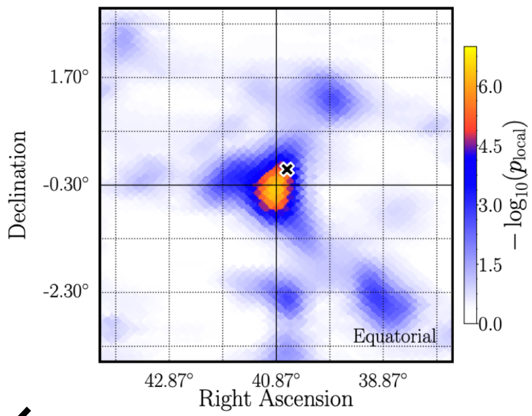
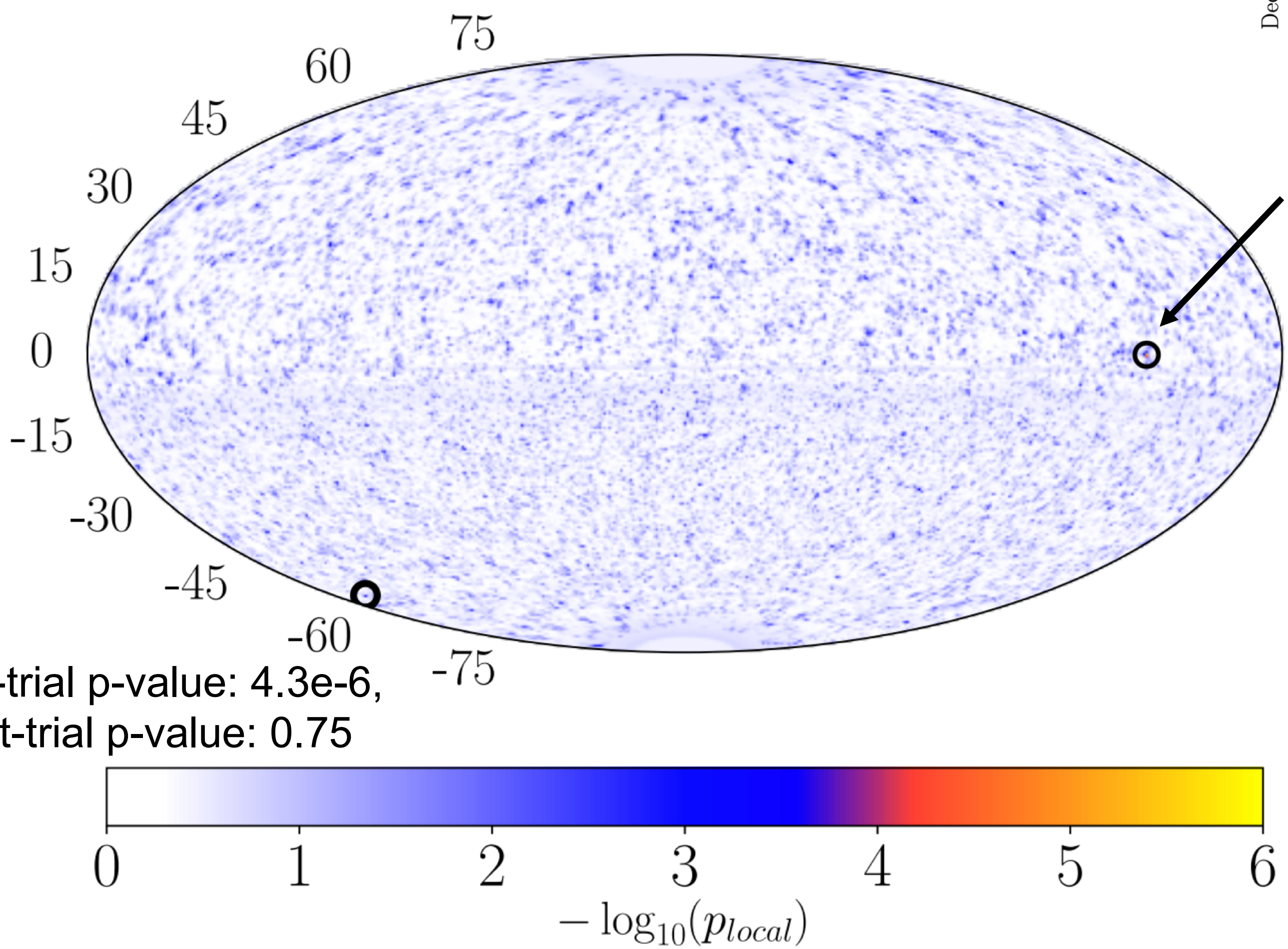
Hotspot Search



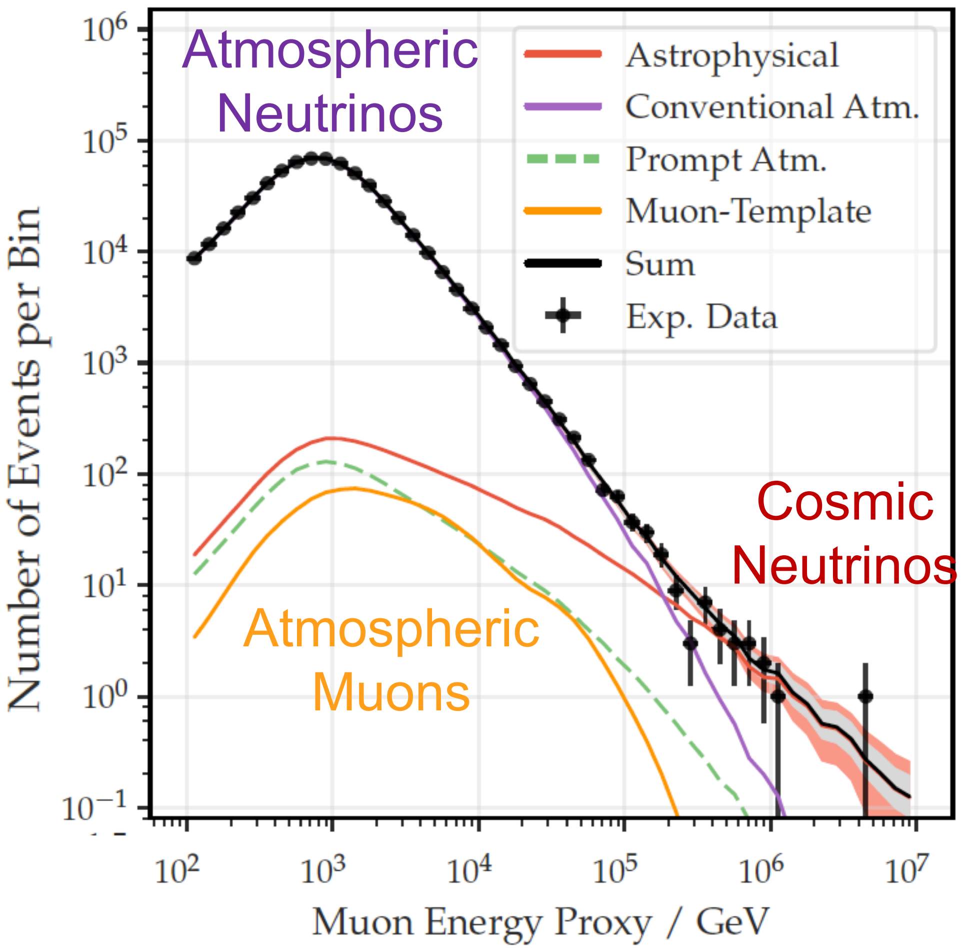
Pre-trial p-value: 3.5e-7,
Post-trial p-value: 0.1



Pre-trial p-value: 4.3e-6,
Post-trial p-value: 0.75

Three Strategies

Northern Sky



1. Look for hotspots in the neutrino sky → identify source candidates
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Gamma-rays emitters are obvious candidates

Cosmic ray

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Search for neutrinos from pre-defined source list

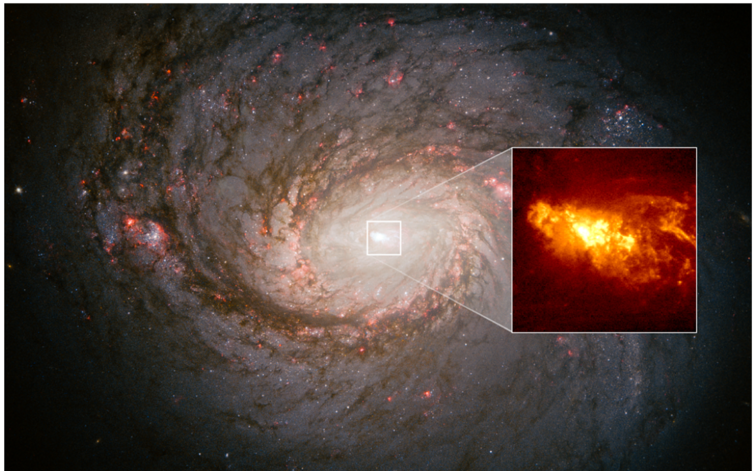
- 110 sources based on **gamma-ray properties** and weighted with neutrino search sensitivity
  - **8 starburst galaxies** detected by Fermi-LAT
  - **98** brightest Fermi-LAT **blazars** (above 1 GeV)
  - **12 galactic sources based on VHE gamma-ray** measurements

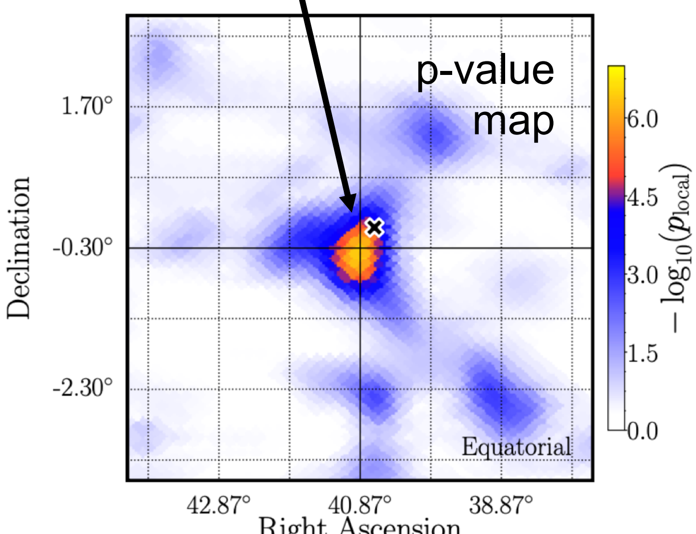
Most significant candidate: **NGC 1068**

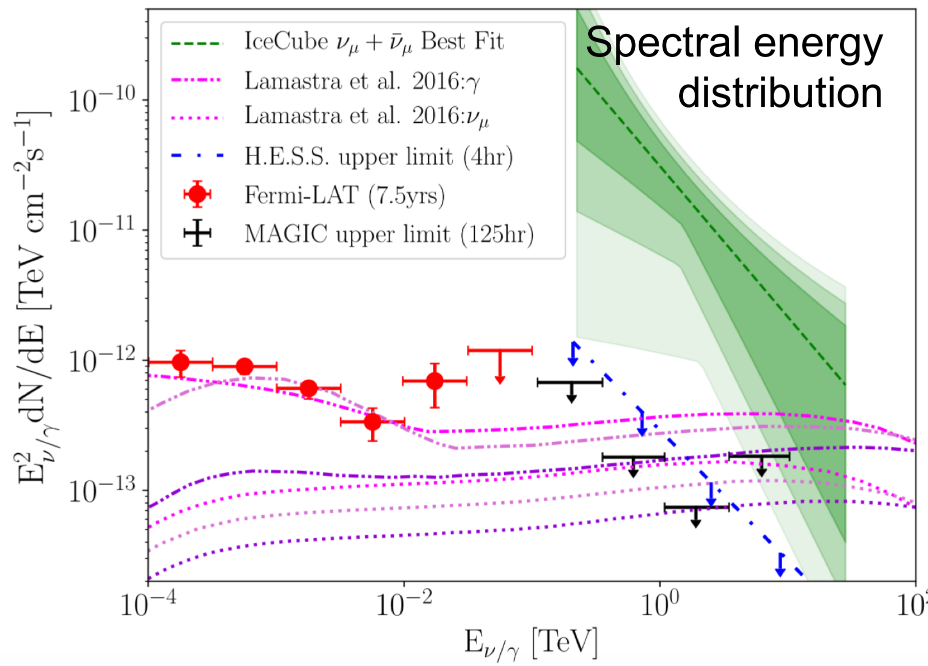
IceCube Coll. PRL 124 (2020)

Source Candidates – NGC 1068

- 2.9 sigma excess in TeV neutrinos (~60 events) in 10 years of IceCube data
- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity



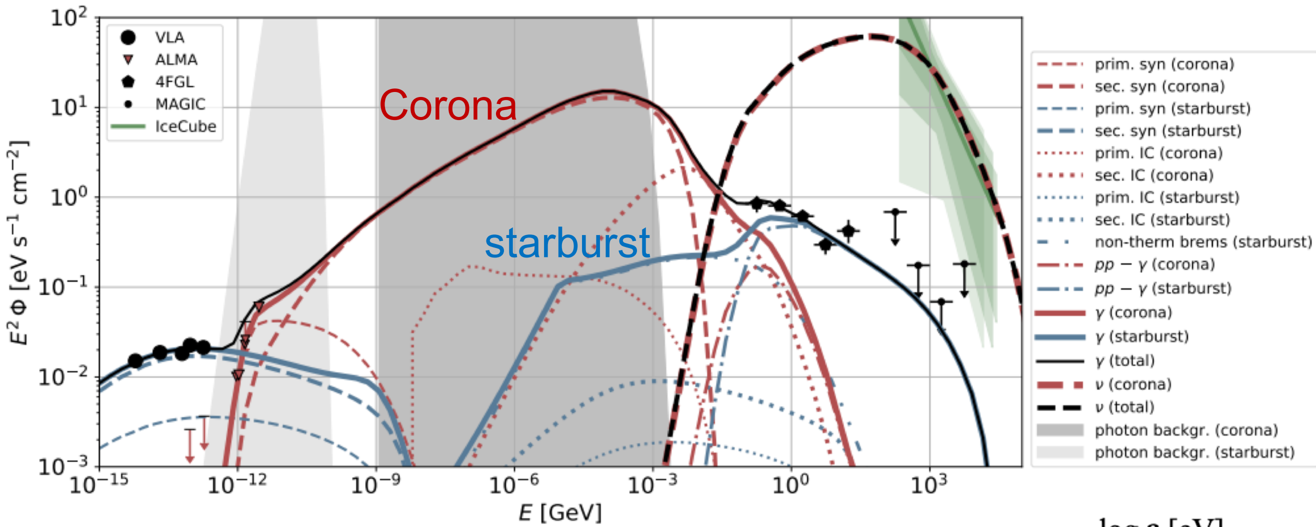




Gamma rays need to be absorbed

IceCube Coll. PRL 124 (2020)

Spectrum of NGC 1068 (M77)



Neutrinos from corona, gammas from starburst

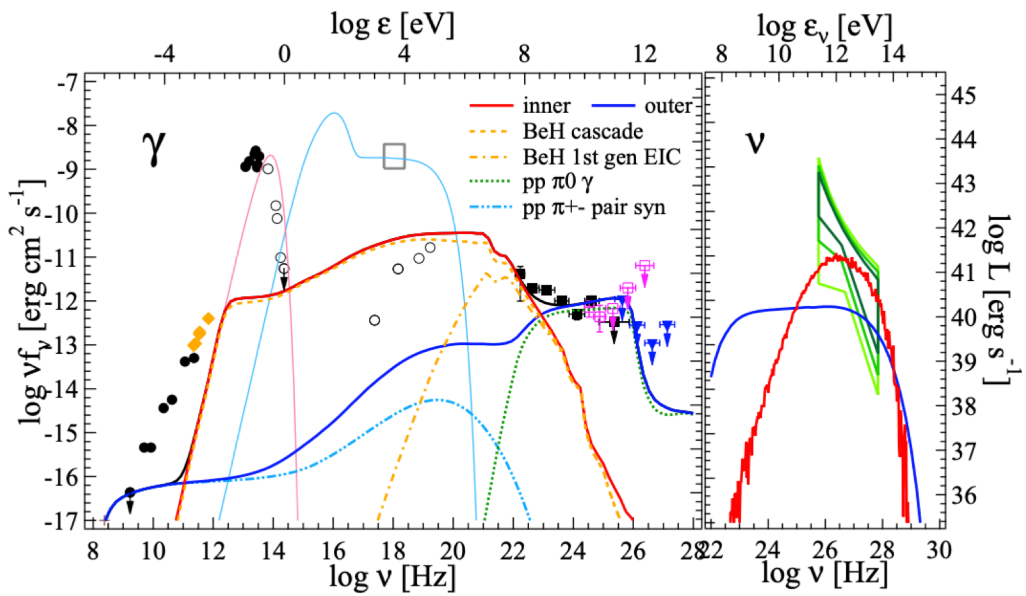
Eichmann et al. 2021

arXiv:2207.00102

Neutrinos from failed outflow, gammas from external shock

Inoue et al. 2022

arXiv:2207.02097



See also Inoue et al. ApJL 891 (2020)

NGC 1068 also contributes to the SBG excess found by Auger

Different interaction models

Table 2. Populations investigated

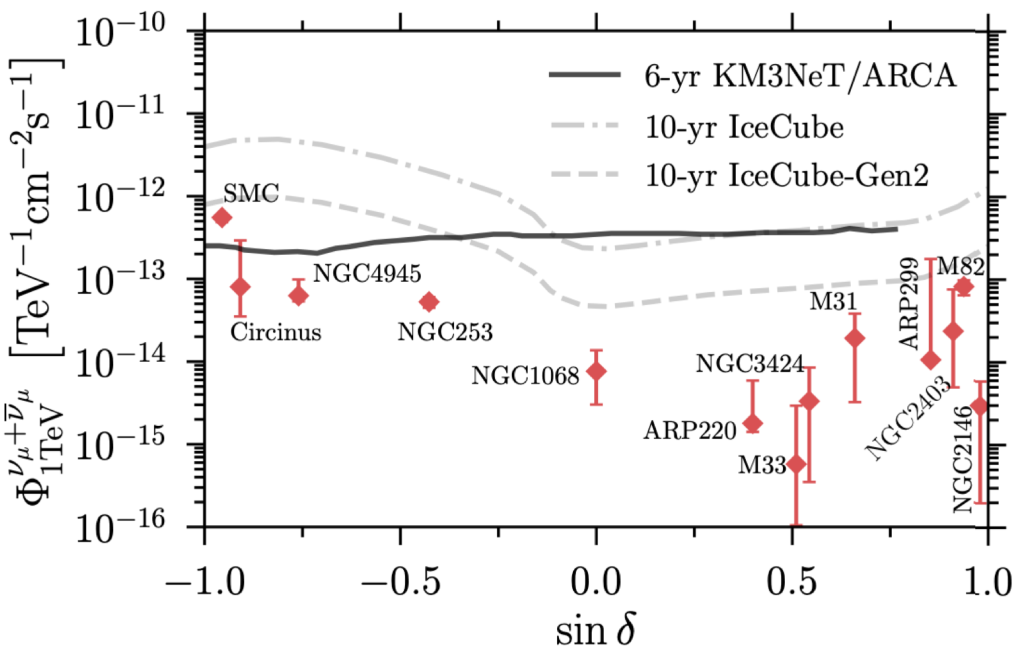
SBGs	l [°]	b [°]	Distance[a] [Mpc]	Flux weight [%]	Attenuated weight: A / B / C [%]	% contribution[b]: A / B / C [%]
NGC 253	97.4	-88	2.7	13.6	20.7 / 18.0 / 16.6	35.9 / 32.2 / 30.2
M82	141.4	40.6	3.6	18.6	24.0 / 22.3 / 21.4	0.2 / 0.1 / 0.1
NGC 4945	305.3	13.3	4	16	19.2 / 18.3 / 17.9	39.0 / 38.4 / 38.3
M83	314.6	32	4	6.3	7.6 / 7.2 / 7.1	13.1 / 12.9 / 12.9
IC 342	138.2	10.6	4	5.5	6.6 / 6.3 / 6.1	0.1 / 0.0 / 0.0
NGC 6946	95.7	11.7	5.9	3.4	3.2 / 3.3 / 3.5	0.1 / 0.1 / 0.1
NGC 2903	208.7	44.5	6.6	1.1	0.9 / 1.0 / 1.1	0.6 / 0.7 / 0.7
NGC 5055	106	74.3	7.8	0.9	0.7 / 0.8 / 0.9	0.2 / 0.2 / 0.2
NGC 3628	240.9	64.8	8.1	1.3	1.0 / 1.1 / 1.2	0.8 / 0.9 / 1.1
NGC 3627	242	64.4	8.1	1.1	0.8 / 0.9 / 1.1	0.7 / 0.8 / 0.9
NGC 4631	142.8	84.2	8.7	2.9	2.1 / 2.4 / 2.7	0.8 / 0.9 / 1.1
M51	104.9	68.6	10.3	3.6	2.3 / 2.8 / 3.3	0.3 / 0.4 / 0.5
NGC 891	140.4	-17.4	11	1.7	1.1 / 1.3 / 1.5	0.2 / 0.3 / 0.3
NGC 3556	148.3	56.3	11.4	0.7	0.4 / 0.6 / 0.6	0.0 / 0.0 / 0.0
NGC 660	141.6	-47.4	15	0.9	0.5 / 0.6 / 0.8	0.4 / 0.5 / 0.6
NGC 2146	135.7	24.9	16.3	2.6	1.3 / 1.7 / 2.0	0.0 / 0.0 / 0.0
NGC 3079	157.8	48.4	17.4	2.1	1.0 / 1.4 / 1.5	0.1 / 0.1 / 0.1
NGC 1068	172.1	-51.9	17.9	12.1	5.6 / 7.9 / 9.0	6.4 / 9.4 / 10.9
NGC 1365	238	-54.6	22.3	1.3	0.5 / 0.8 / 0.8	0.9 / 1.5 / 1.6
Arp 299	141.9	55.4	46	1.6	0.4 / 0.7 / 0.6	0.0 / 0.0 / 0.0
Arp 220	36.6	53	80	0.8	0.1 / 0.3 / 0.2	0.0 / 0.2 / 0.1
NGC 6240	20.7	27.3	105	1	0.1 / 0.3 / 0.1	0.1 / 0.3 / 0.1
Mkn 231	121.6	60.2	183	0.8	0.0 / 0.1 / 0.0	0.0 / 0.0 / 0.0

A. Aab *et al* (Auger Collaboration) 2018 *ApJL* **853** L29

Other Seyfert Galaxies

Source	p-value Stochastic (High CR pressure)	Stochastic (Modest CR pressure)	Magnetic reconnection
NGC 1068	10^{-6}	0.09	1.8×10^{-4}
NGC 1275	0.03	0.3	0.1
CGCG 164-019	0.04	0.3	0.1
UGC 11910	0.1	0.4	0.09
Cen A	0.5	0.2	0.2
Circinus Galaxy	0.5	0.3	0.3
NGC 7582	0.5		
ESO 138-1	0.5		
NGC 424	0.5		
NGC 4945	0.5		

Prospects for observations of bright nearby Seyfert galaxies in 10 years of IceCube



Stacking analysis in progress with IceCube data

Kheirandish et al. ApJ 2021, Ambrosone ApJL 2021, Condorelli 2022

A. Ambrosone's and A. Condorelli's talks on Thursday

Stacking Analyses (uncomplete list)

Hints / evidence

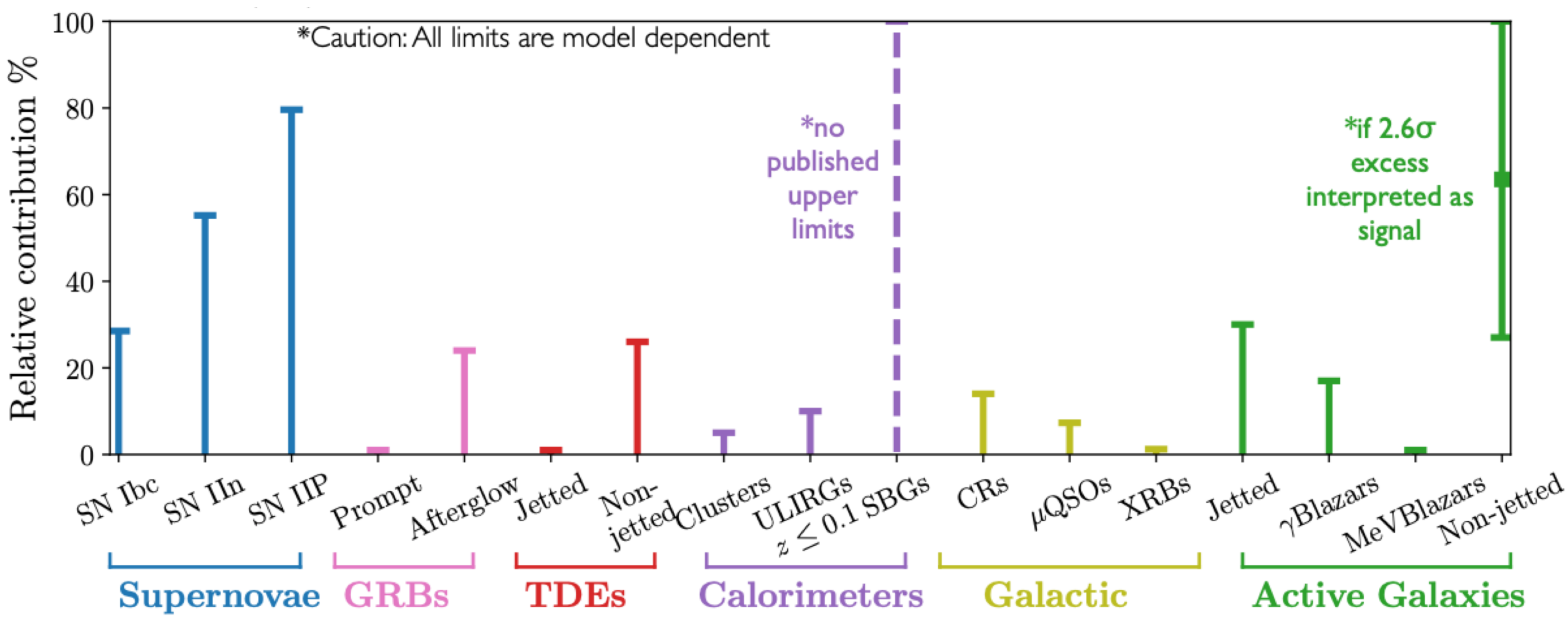
- Stacking of blazars from BZCat ~ 6×10^{-7} p-value (Buson et al. ApJL 2022)
- Stacking of radio-loud AGN ~ 0.2% p-value (Plavin et al. ApJ 894 (2020))
- Stacking of AGN cores: ~ 0.5% p-value (IceCube Coll. PRD 2022)

Upper limits

- Fermi-LAT blazars: <10% of diffuse flux (IceCube Coll. ApJ 835 (2017))
- Stacking of GRBs → GRBs contribute less than 1% to diffuse neutrino flux (IceCube Coll., ApJ 805 (2015), ApJ 824 (2016))
- Stacking of Fermi low-energy sources → contribute less than 1% (IceCube Coll. ApJ 2022)
- ….

Challenge: Weighting scheme needed. What is the right tracer for neutrino emission? → Input from theory!?

Summary of Stacking Limits



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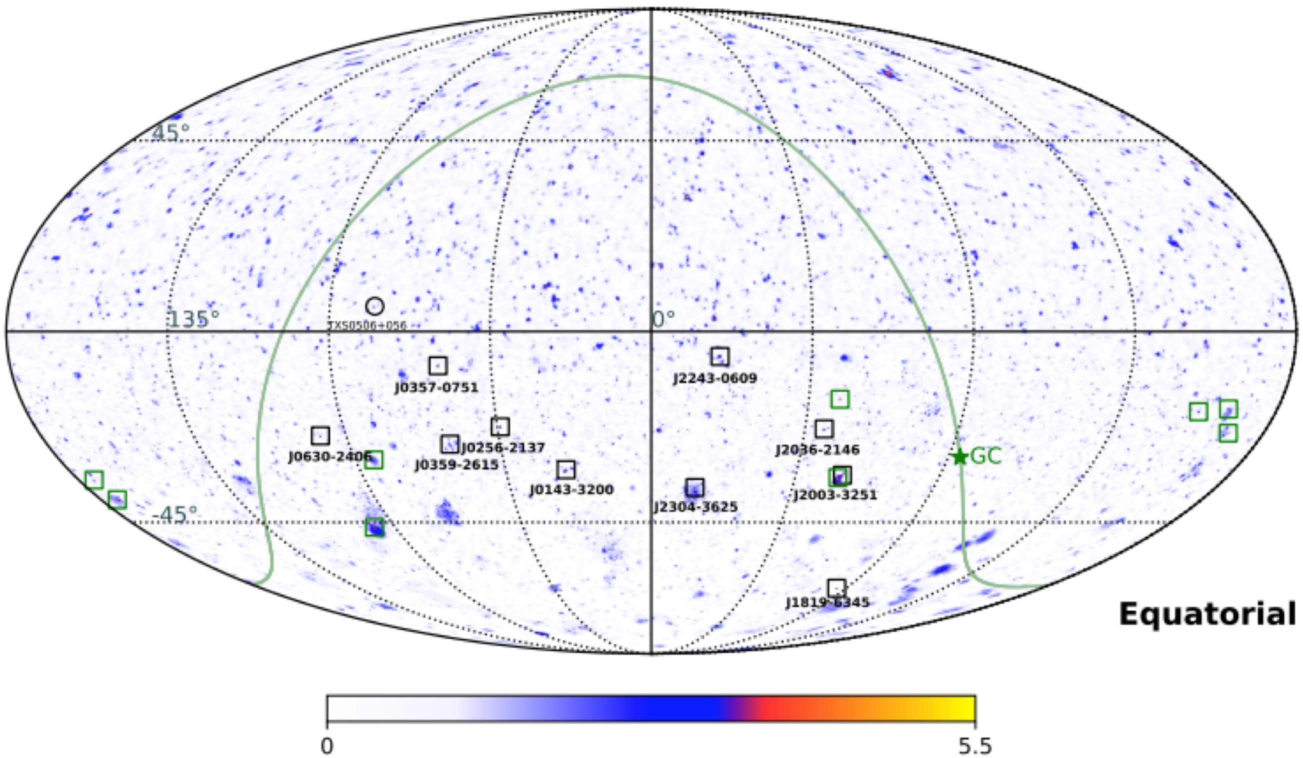
F. Oikonomou PoS ICRC2021 (2022) 030, arXiv:2201.05623

Stacking with BZCat

IceCube 7-year hotspot map

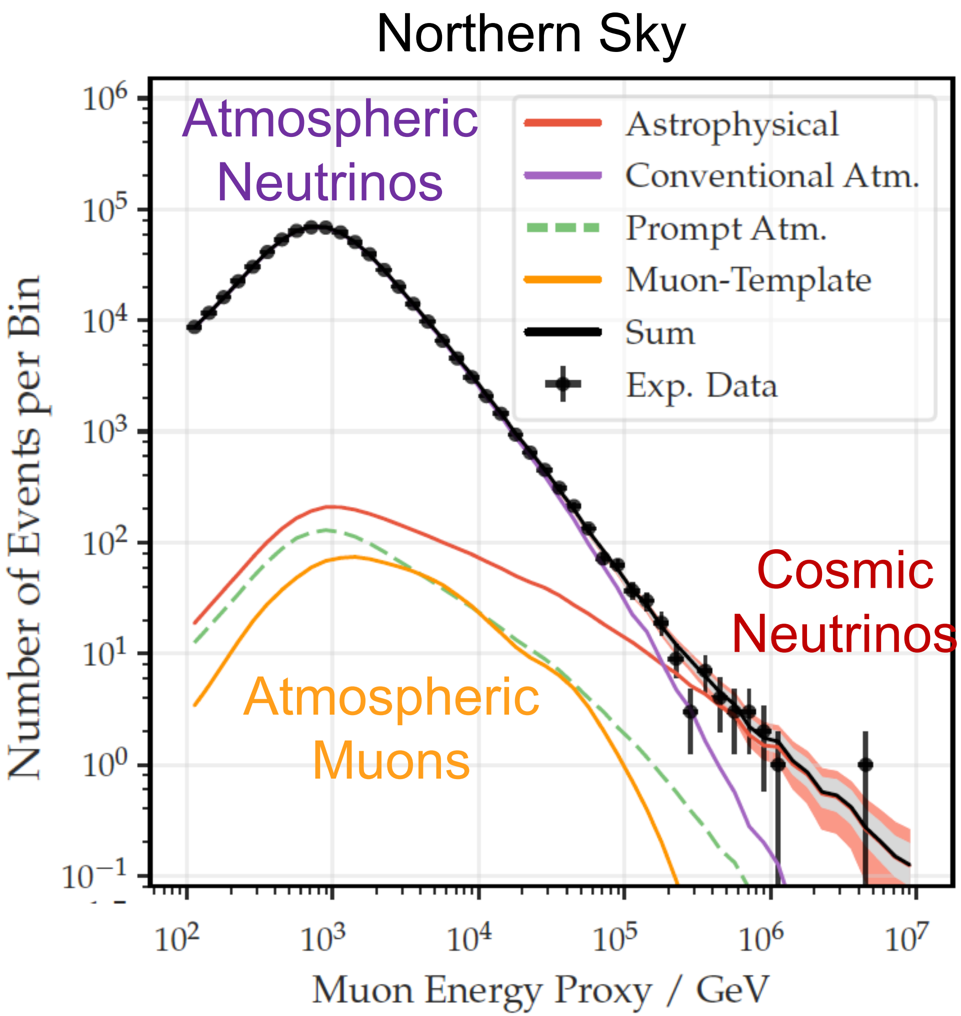


Analysis reduced to Southern sky (dec < 85 deg)

Correlation of blazars with IceCube neutrino alerts at chance coincidence of 6×10^{-7}

Buson et al. ApJL 2022

Three Strategies



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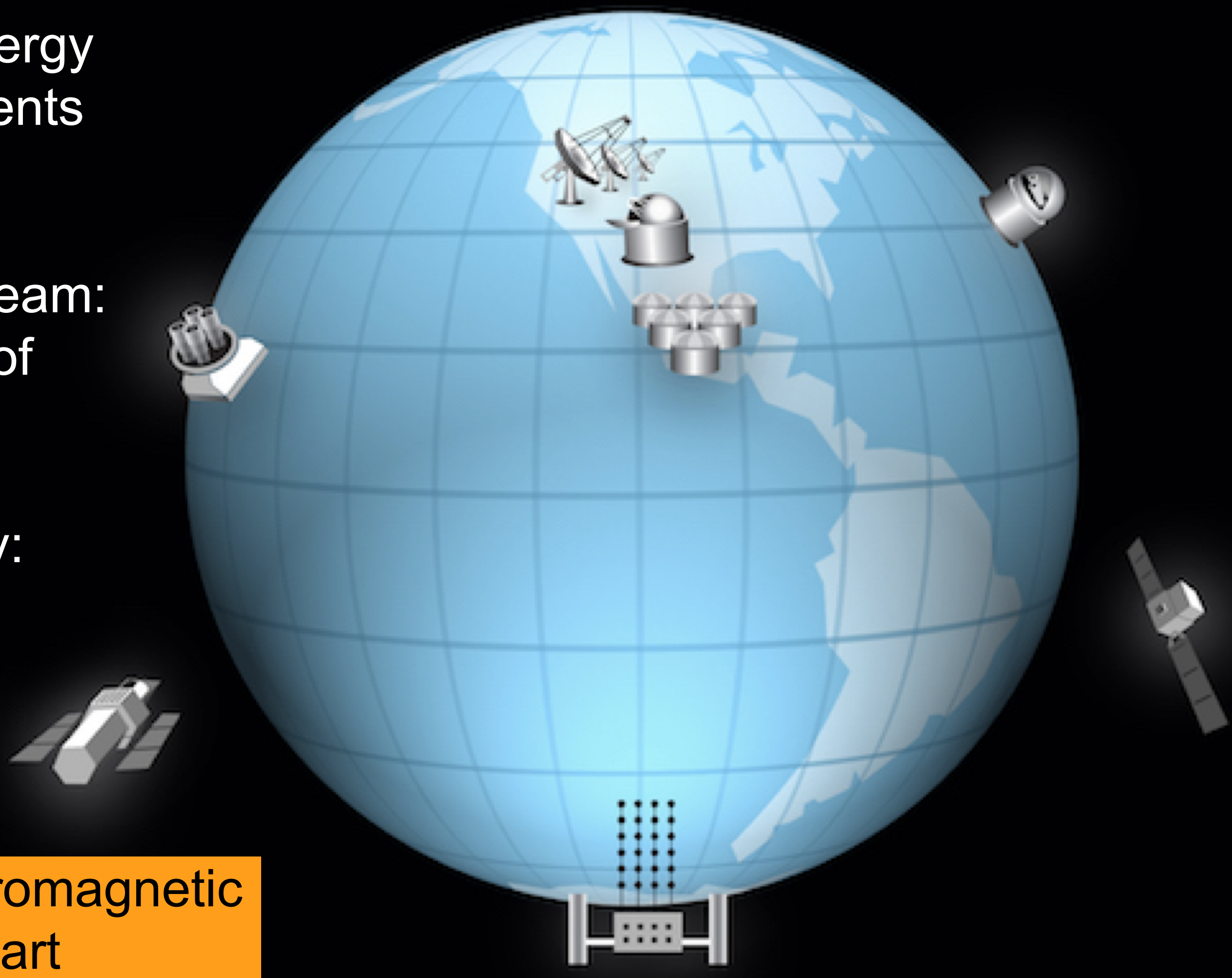
IceCube Target of Opportunity Program

Public alerts since April 2016

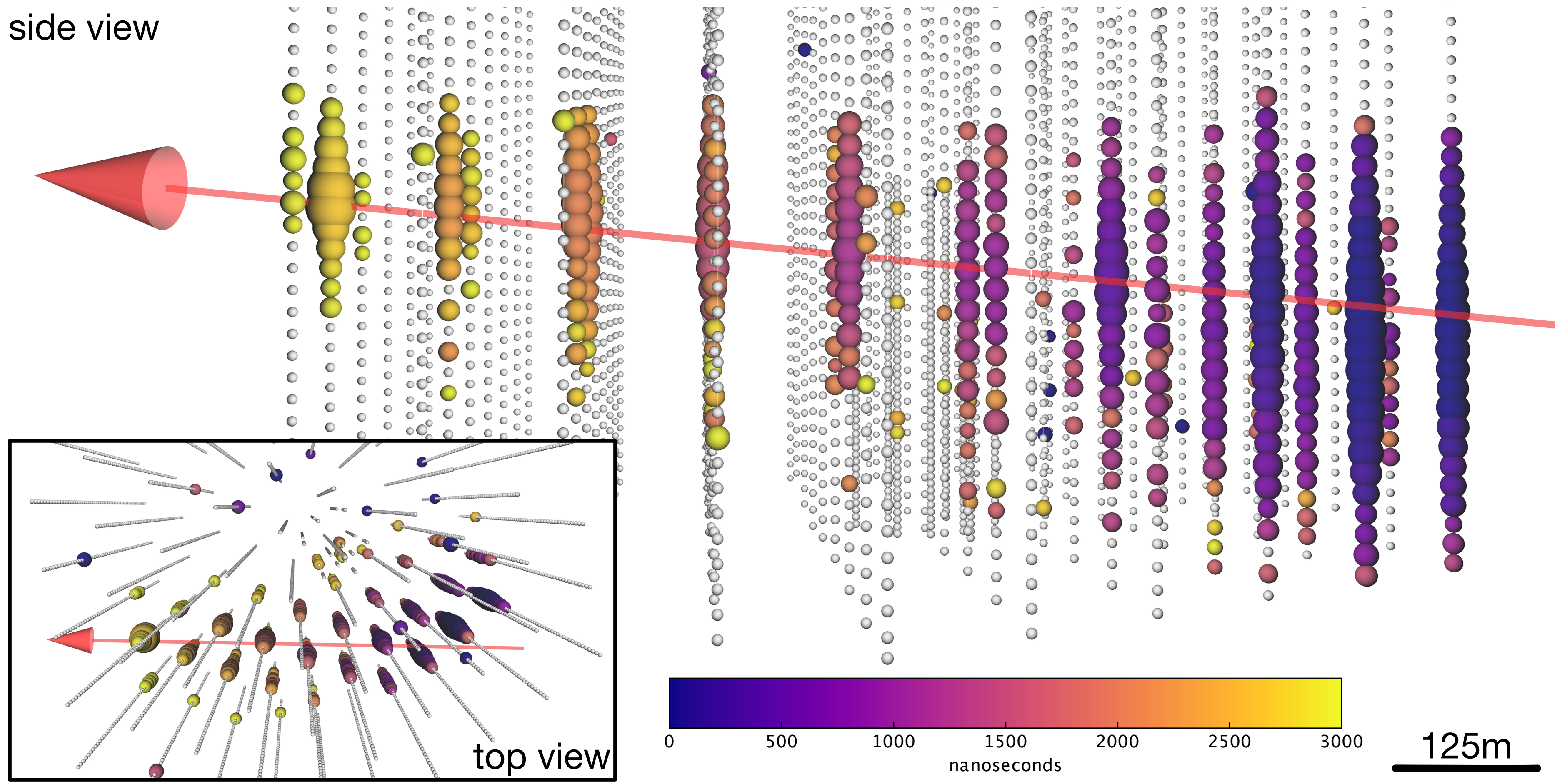
- Single high-energy muon track events (> ~100TeV)
- “Gold” alert stream: 10 / yr, ~5 / yr of cosmic origin
- Median latency: 30 sec



Goal: Find electromagnetic counterpart

Astropart. Phys., 92, 30 (2017)

IC-170922A – a 290 TeV Neutrino

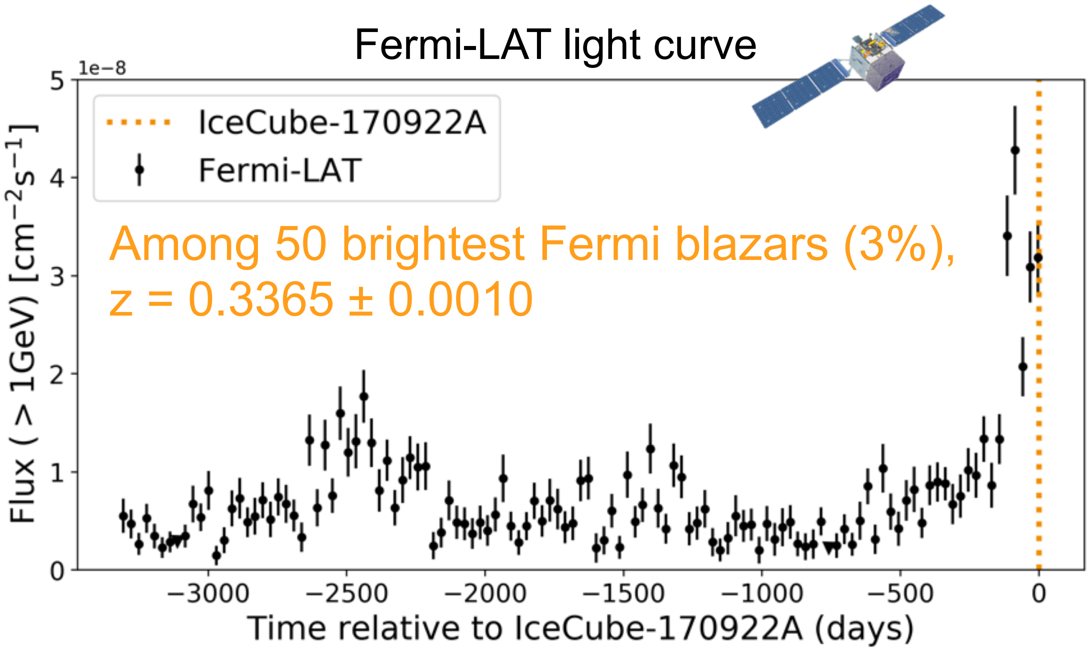


Signalness: 56.5%

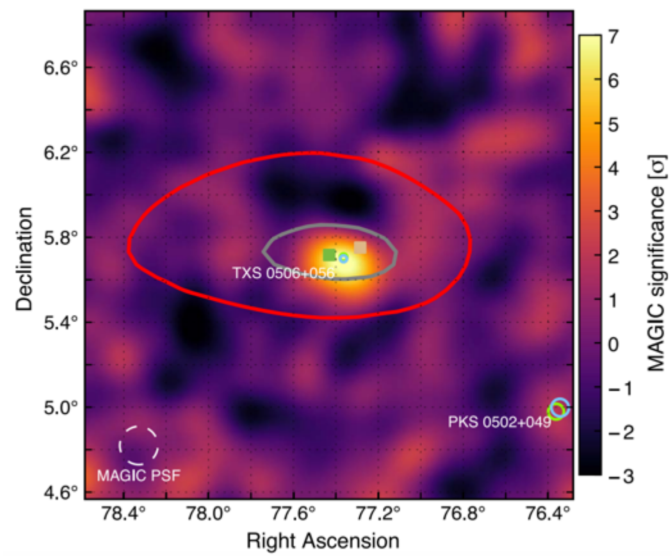
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Source Candidates – TXS 0506+056

Fermi-LAT light curve



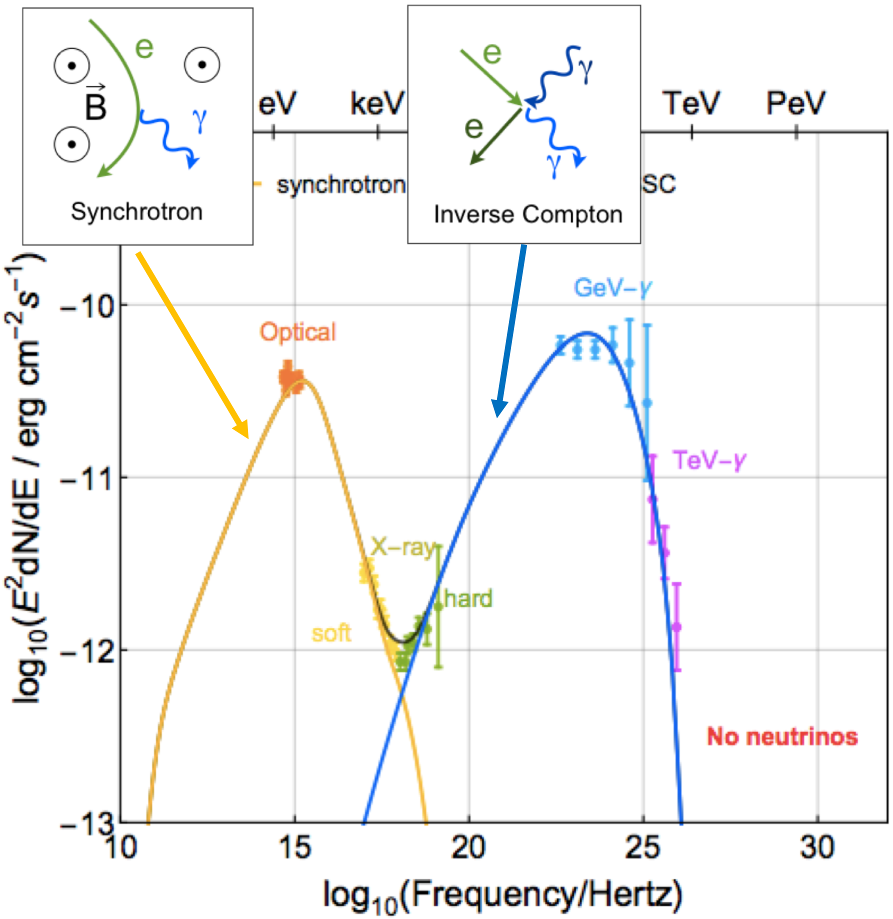
MAGIC Significance map

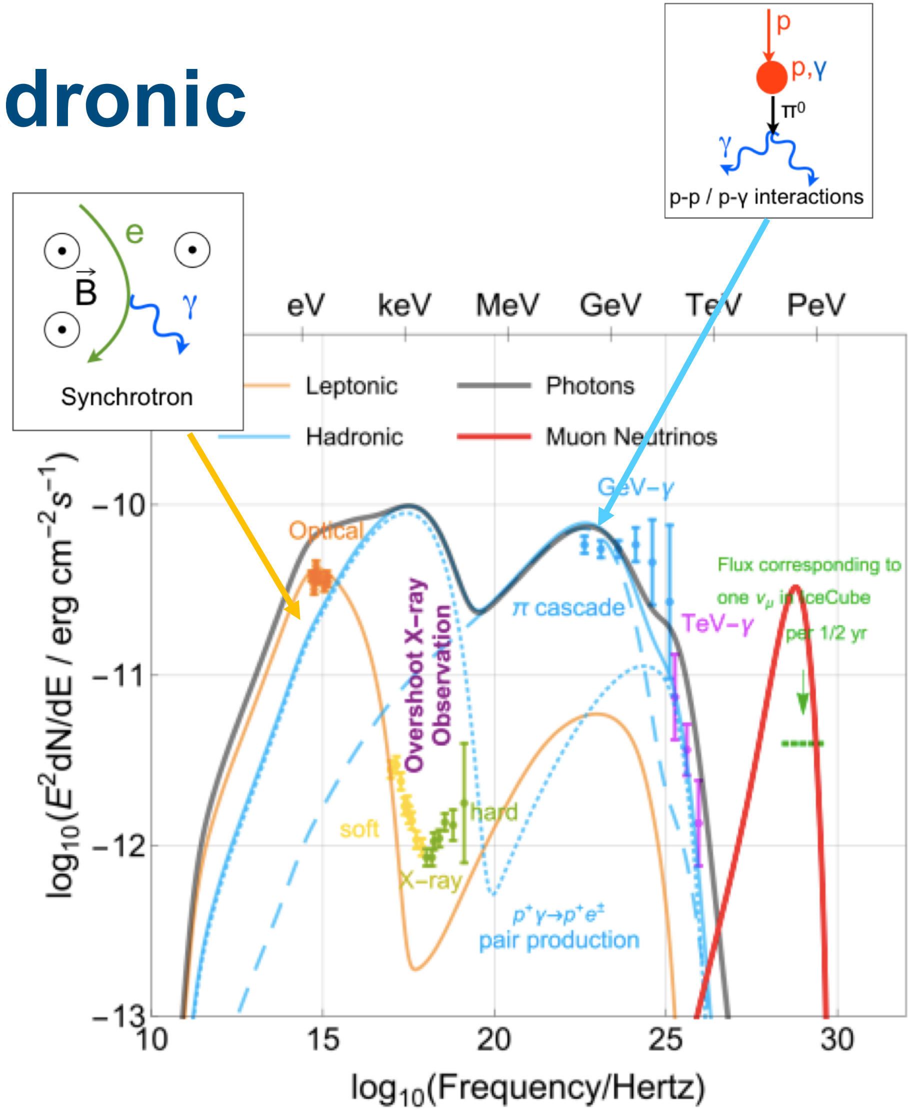


300 TeV neutrino coincident with gamma-ray flare (3sigma significance)

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Modeling – leptonic, hadronic





Simple one-zone hadronic models violate X-ray constraints
→ More complex models needed

Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

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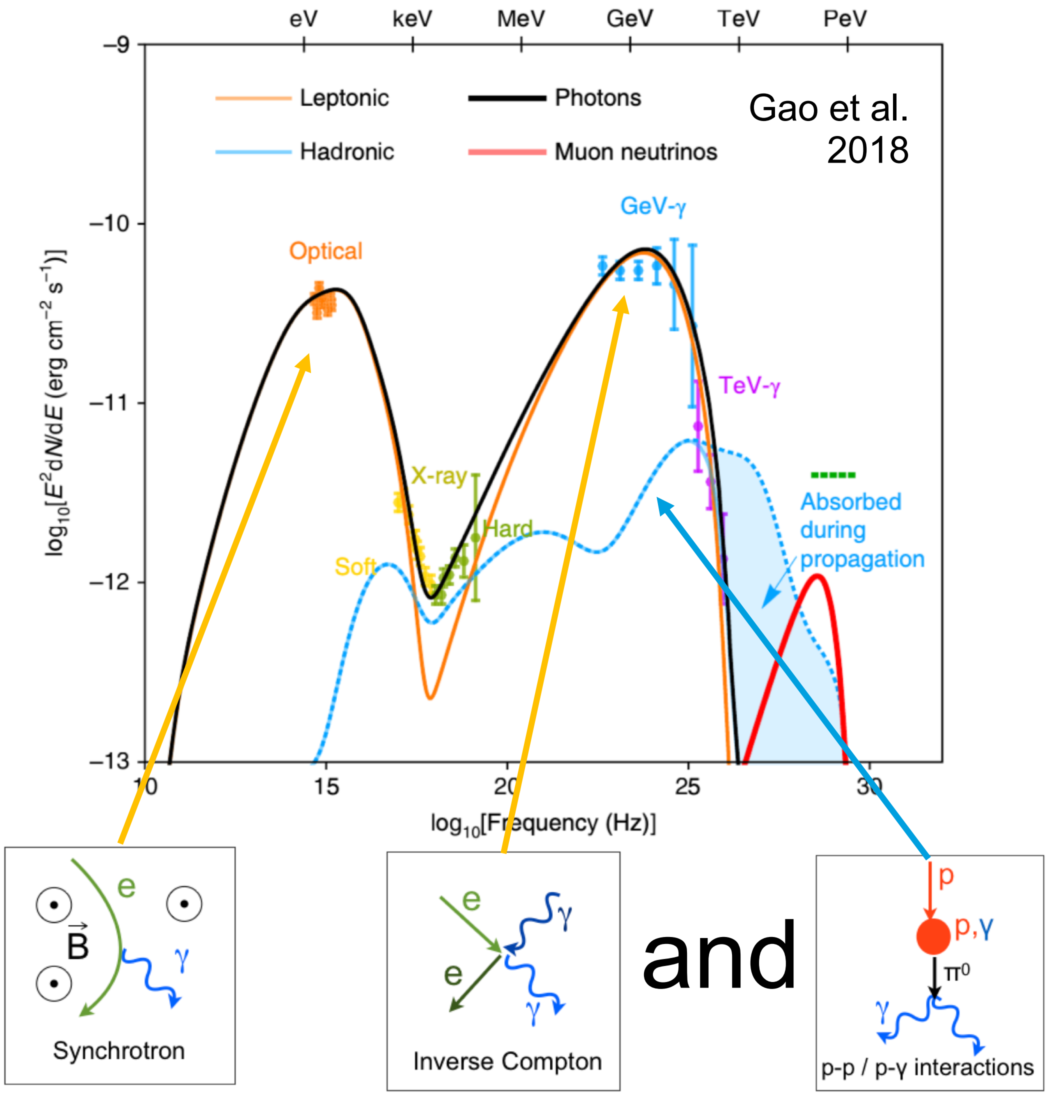
Modeling – lepto-hadronic



Gao et al., Nature Astronomy 2018,
Keivani et al., ApJ, 2018, MAGIC Coll., ApJ, 2018, Cerruti et al. MNRAS 2018, …

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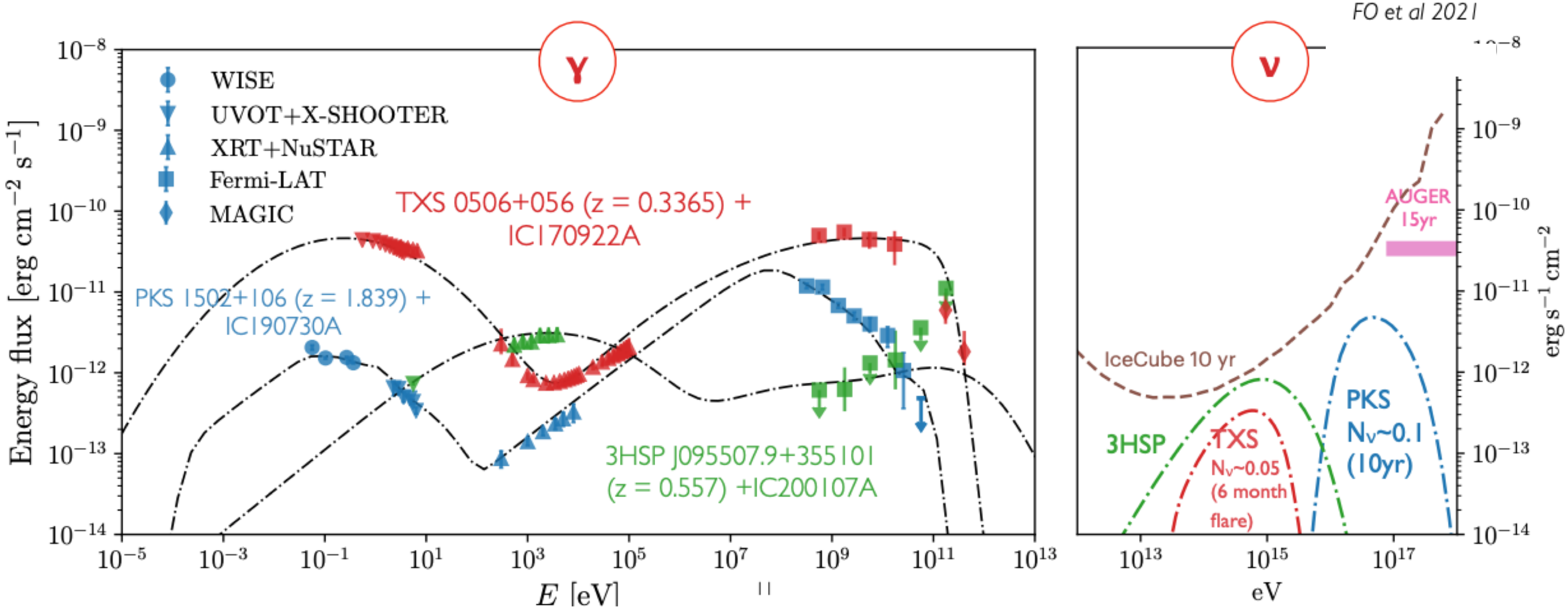
Other blazar-neutrino alert coincidences

FO et al 2021



Models consistent (statistically) with neutrino detection for > month long flares but require atypically high proton content

No excess found in alert stacking using GeV gamma-rays as weights Lagunas Gualda ICRC 2021

Gamma-rays emitters are obvious candidates

Cosmic ray

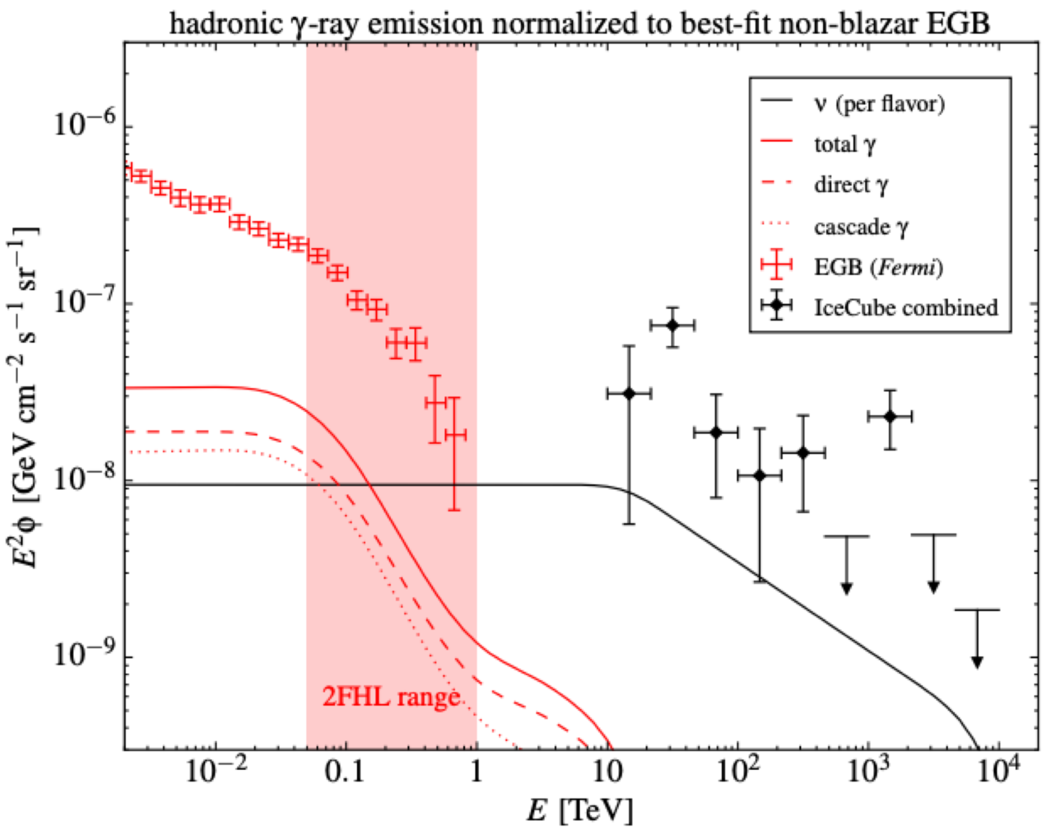
pp

$p\gamma$ $\rightarrow$

target

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

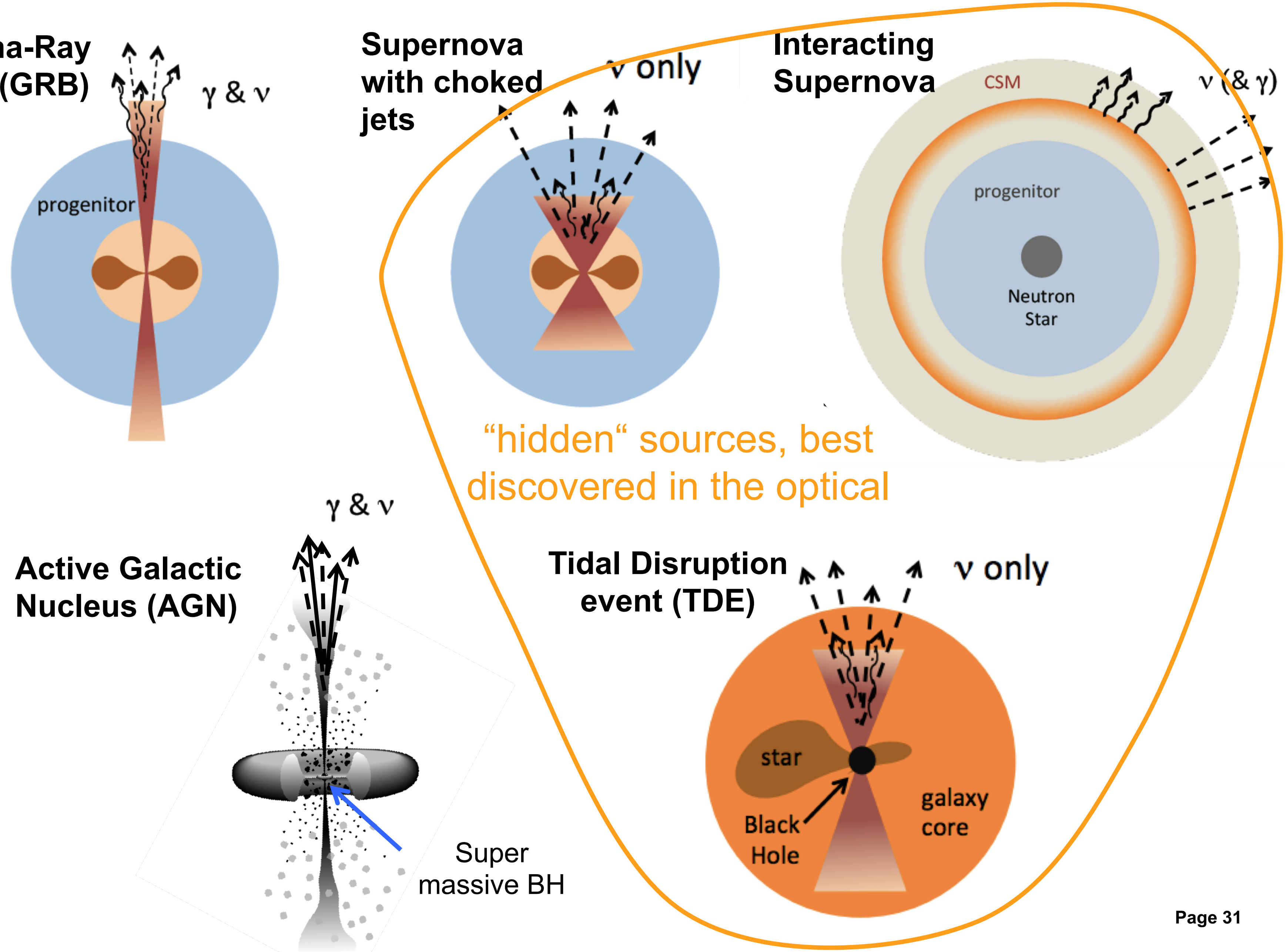
Gamma-ray emitters are obvious candidates, but …



… in order not to overshoot the measured gamma-ray background a majority of the neutrino sources has to be dark in GeV gamma rays ("hidden sources")

Bechtol et al. ApJ 836 (2017)

Selection of Source Candidates



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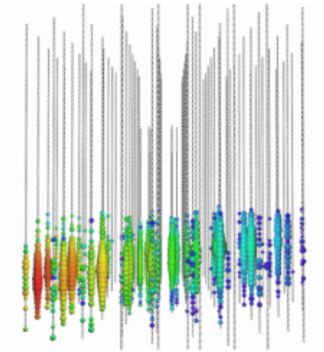
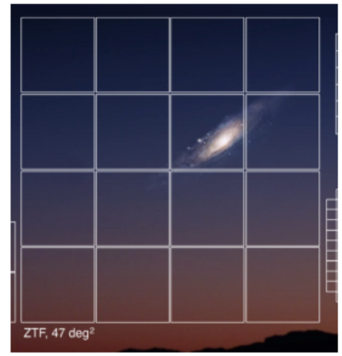
ZTF Follow-up Pipeline



1. high-energy neutrino alert arrives

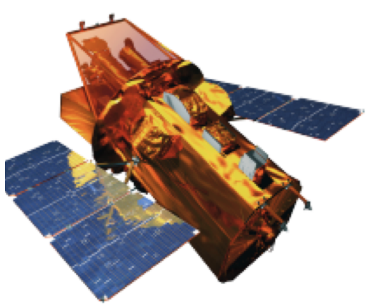


2. Observe with ZTF

3. Follow-up with AMPEL

Reject stars, planets, artifacts, asteroids

Nordin et al., A&A 631, A147 (2019)



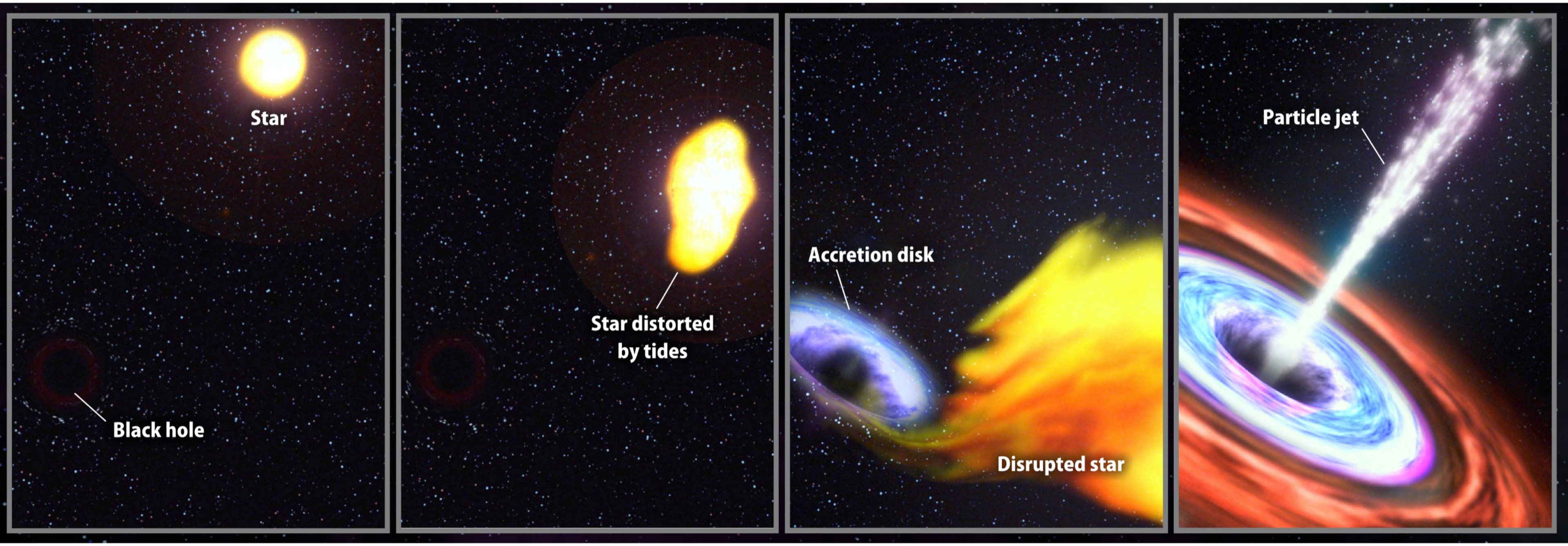
4. Trigger further follow-up observations

Reject unrelated transients (e.g. Type Ia SNe)

R. Stein et al. 2022

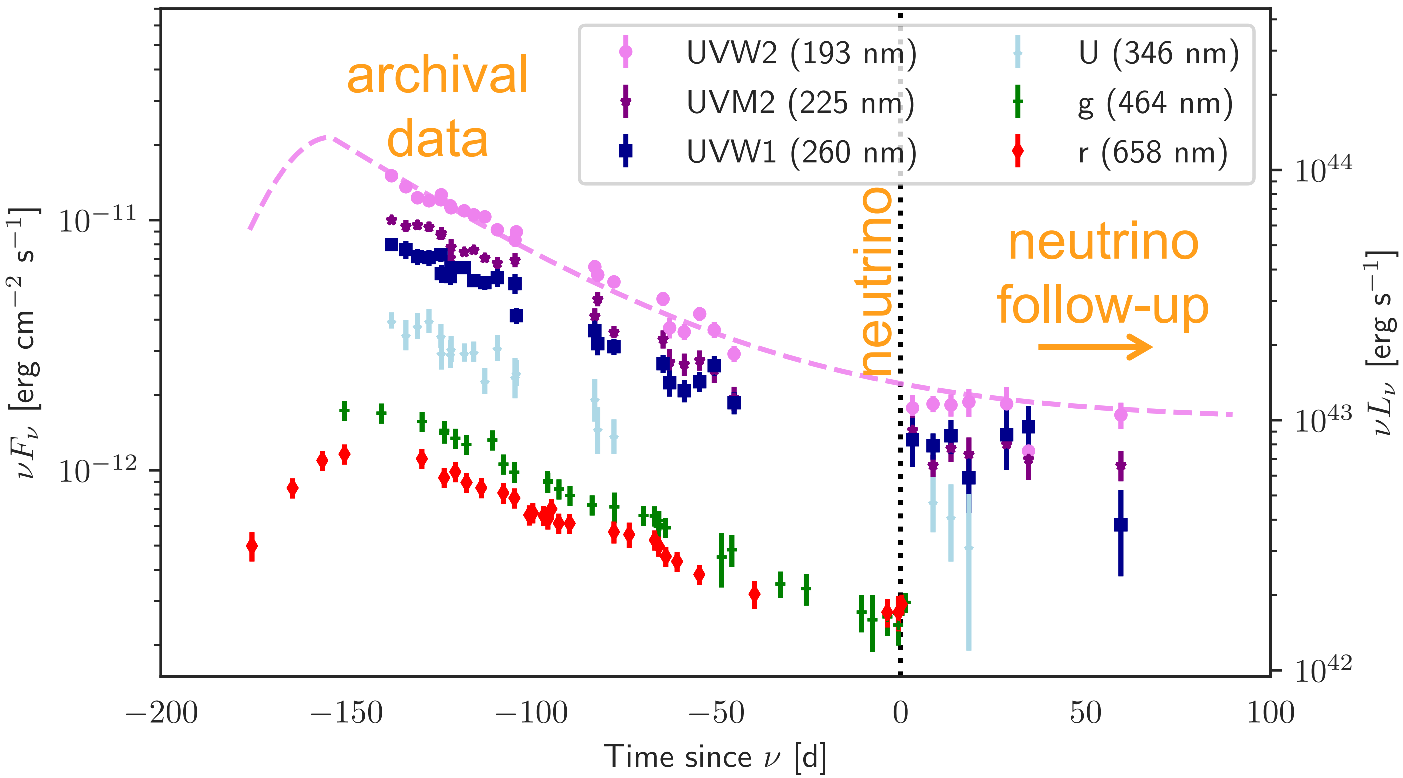
Source Candidates – AT 2019dsg

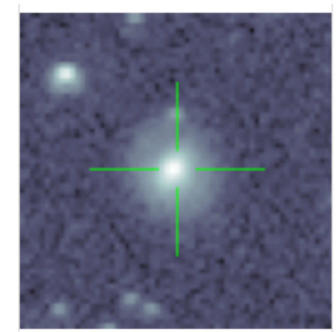
Tidal Disruption Event (TDE)

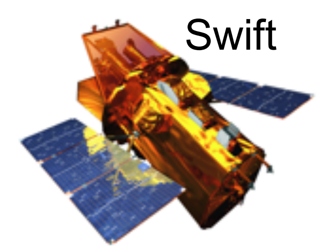


~50 TDEs identified, 4 jetted TDEs

Source Candidates – AT 2019dsg





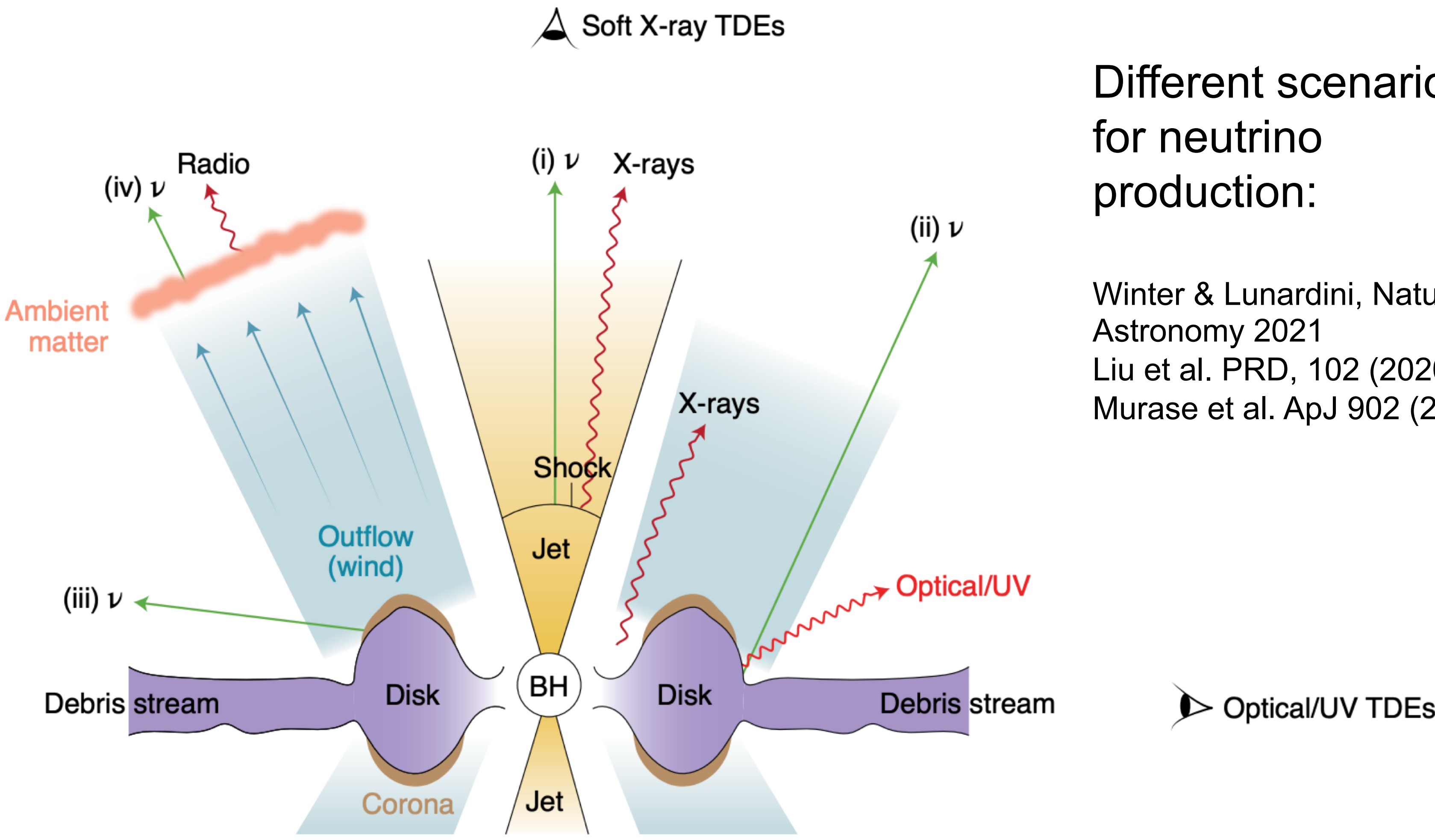


Distance: z = 0.05 (d = 230 Mpc), no gamma rays

- First hint of neutrino production in TDEs
- Two more candidates identified (3.7 sigma)

RUB R. Stein et al., Nature Astronomy 2021, S. Reusch et al. PRL 2022, S. Van Velzen et al. arXiv:2111.09391

Neutrino Production in TDEs



Different scenarios for neutrino production:

Winter & Lunardini, Nature Astronomy 2021
Liu et al. PRD, 102 (2020)
Murase et al. ApJ 902 (2020)

W. Winter's talk on Thursday

Hayasaki, Nature Astronomy 2021

What have we learned?

Sources accelerate *protons* to at least *PeV* energies

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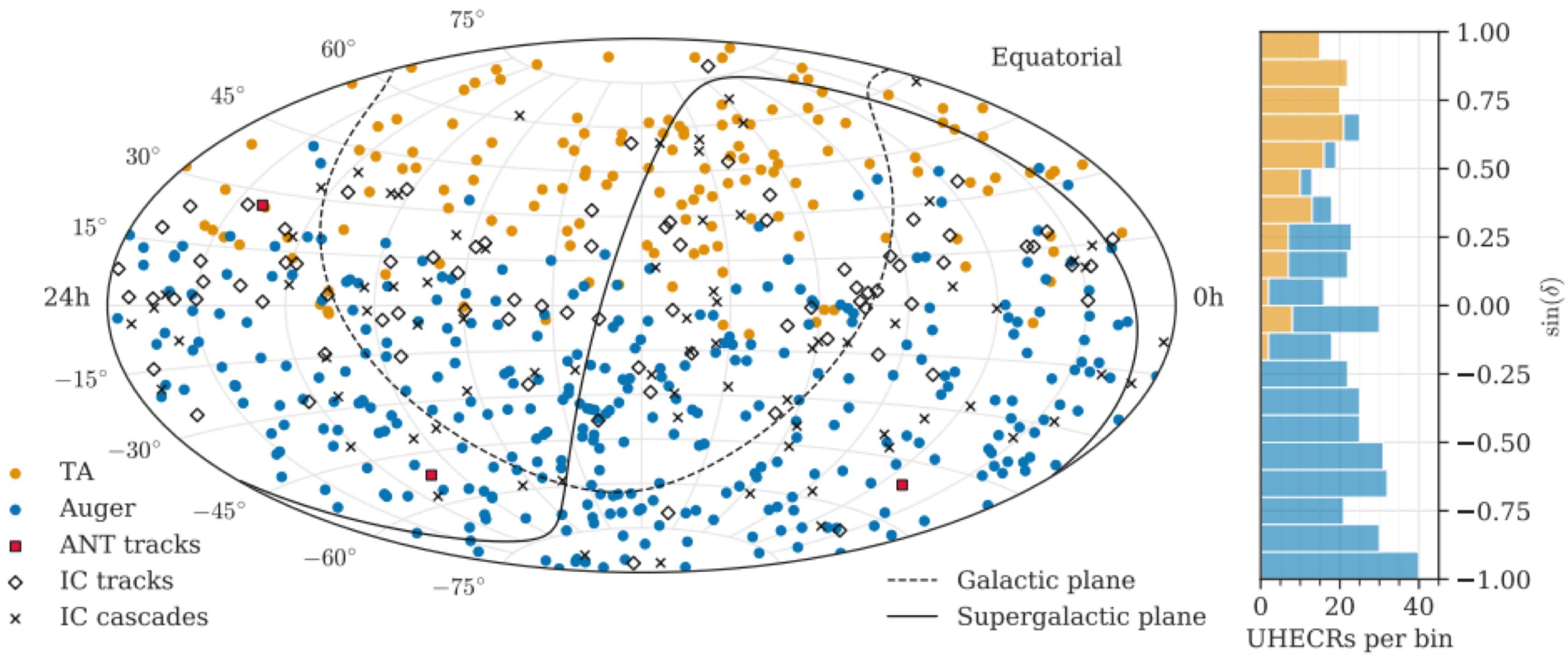
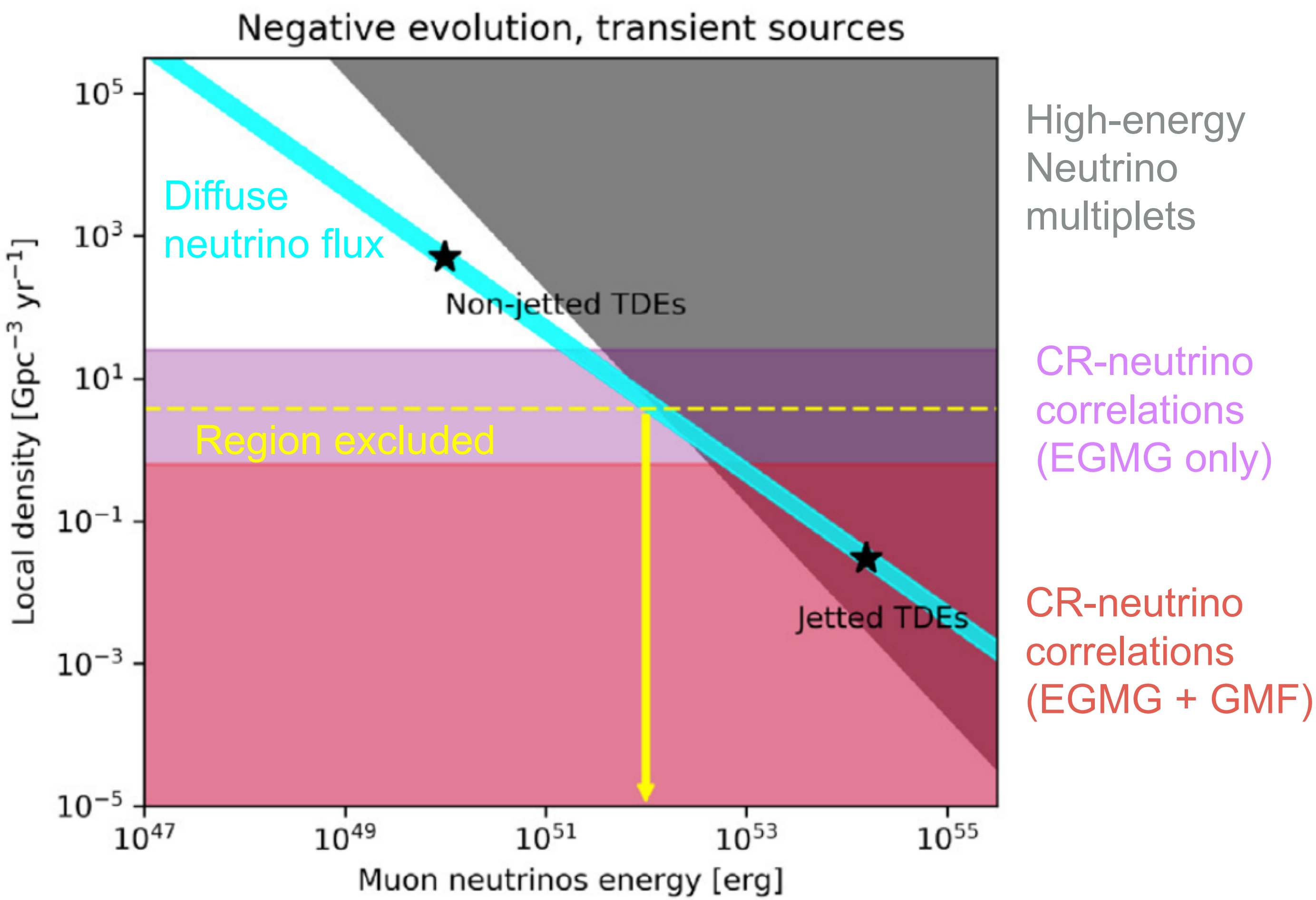
Correlation of arrival directions of neutrinos and UHECRs



No significant correlation found.
Neutrinos and UHECR have very different horizon.

ANTARES, IceCube, PAO, TA, ApJ 934 164 (2022)

Do we expect neutrinos to trace UHECRs?



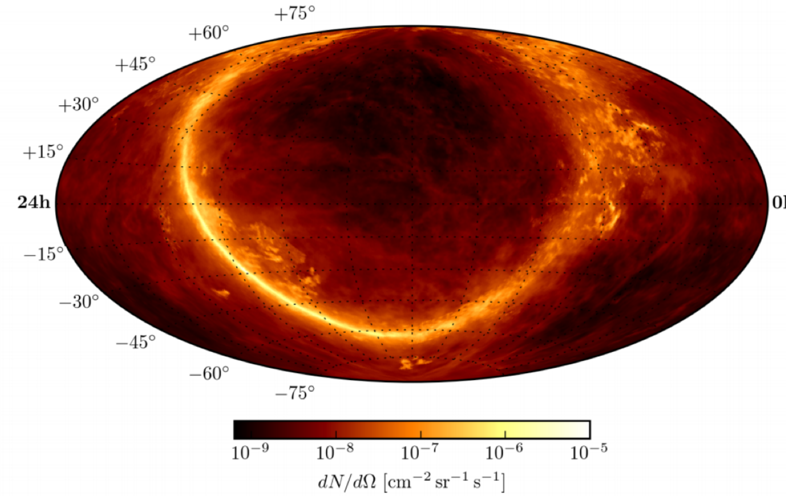
Non-observation of neutrino multiplets limits UHECR-neutrino correlation. Best chance for negative source evolution.

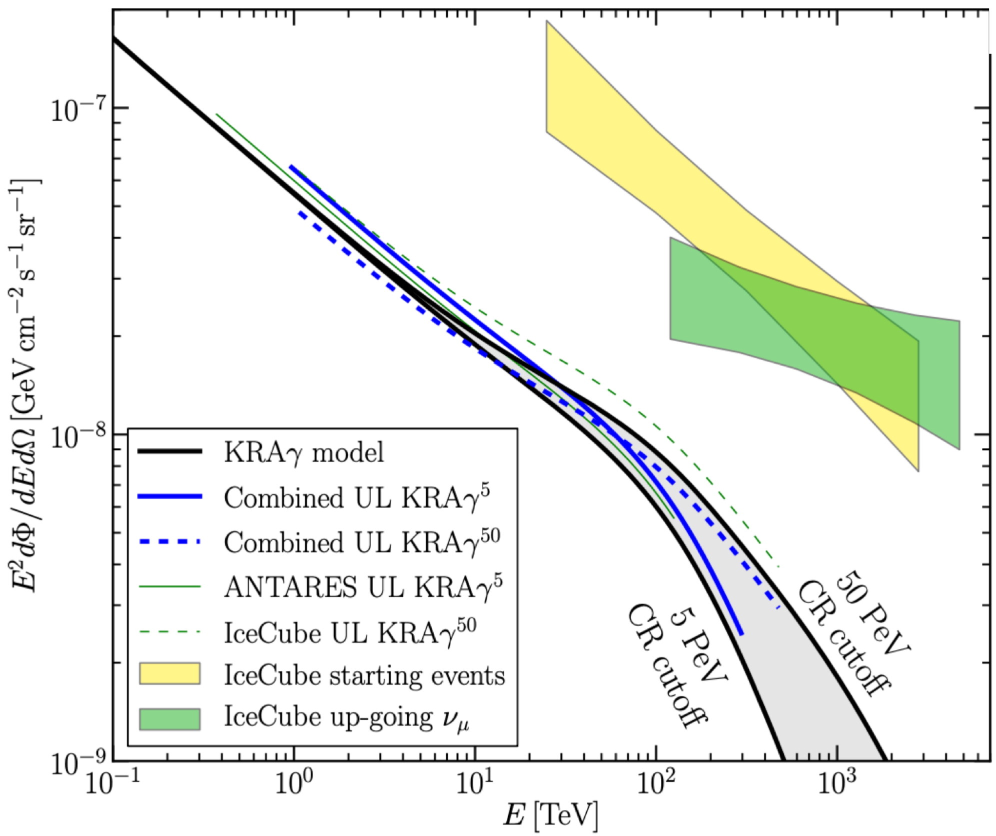
Palladino et al. MNRAS, 494 (2020)

Galactic Sources

Galactic Sources

Neutrino flux modeled by Galactic propagation code constraint by gamma-ray and cosmic-ray measurements





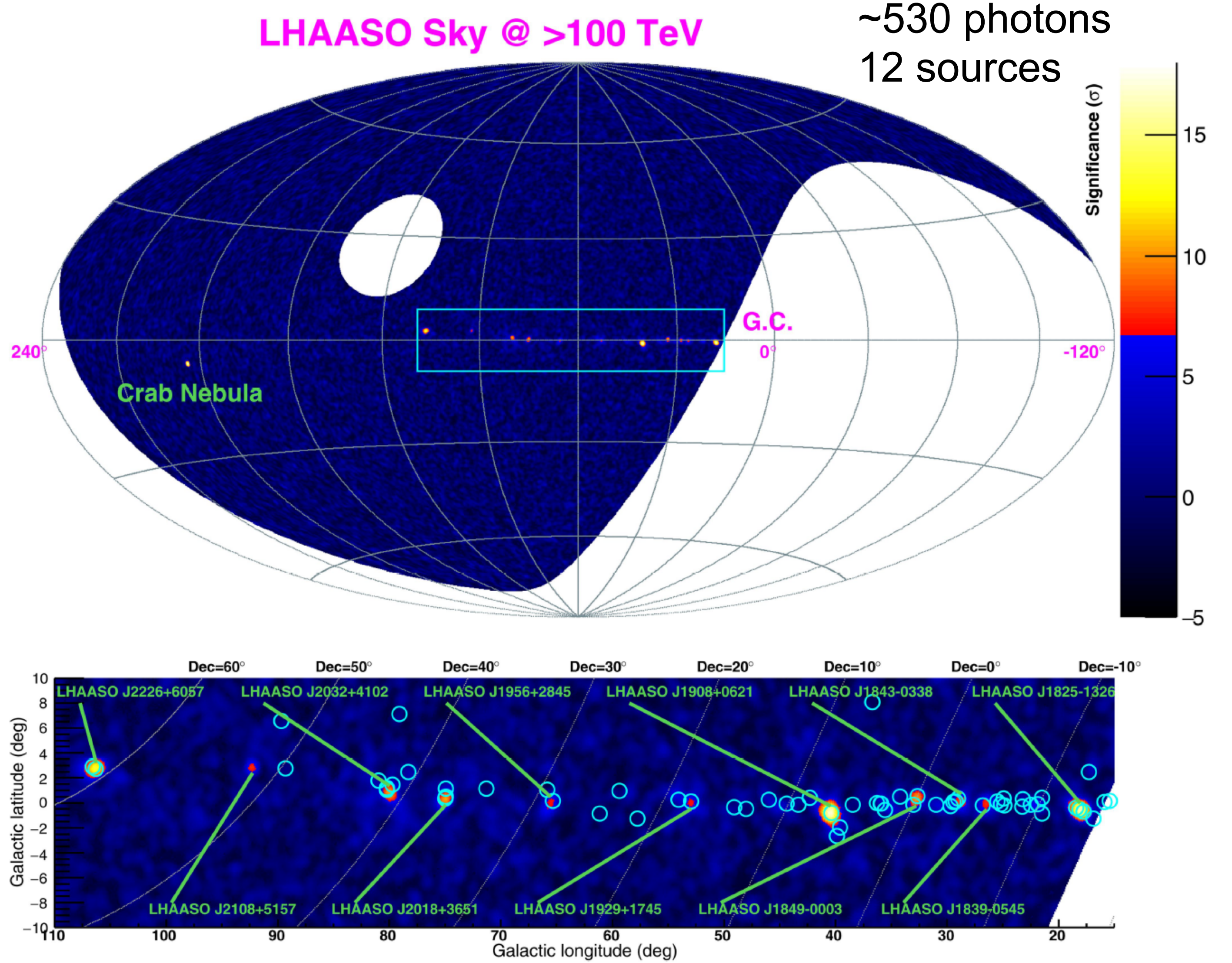
No significant neutrino excess found from Galactic plane yet

Contribution to diffuse flux <8.5%

ANTARES & IceCube, ApJ 868 (2018) no.2, L20

Gamma rays at highest energies

~530 photons
12 sources

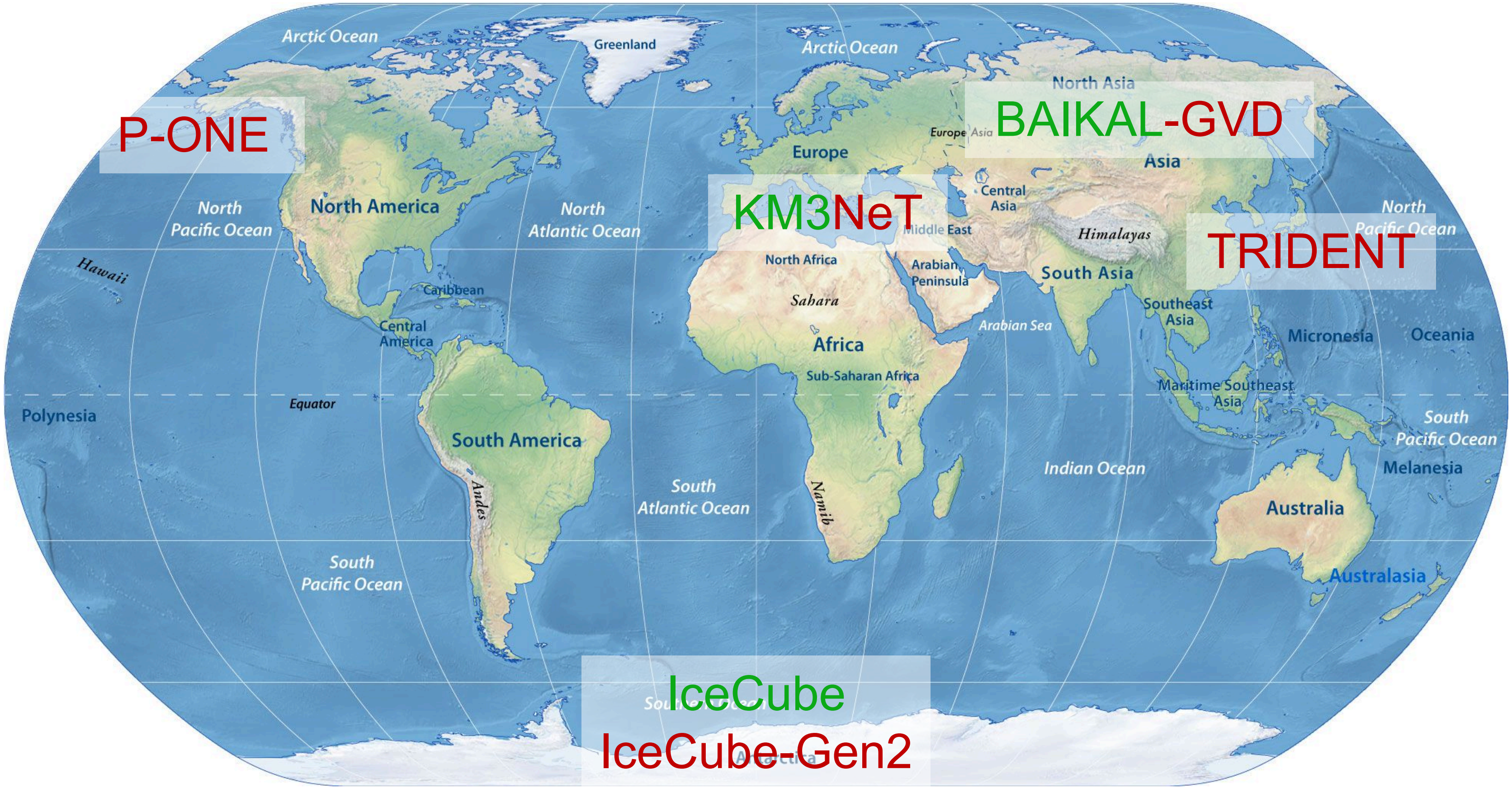


Existence of PeVatrons confirmed. Hadronic origin favored.

Cao, Aharonian et al. Nature 594, 2021

In the Future

Next Generation Neutrino Telescopes



Operating

Planned / under construction

At very-high energies:

PAO, RNO-G, GRAND, POEMMA, …

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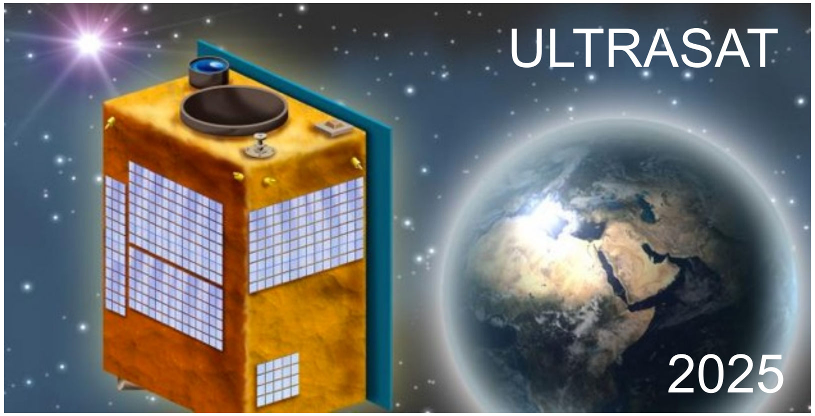
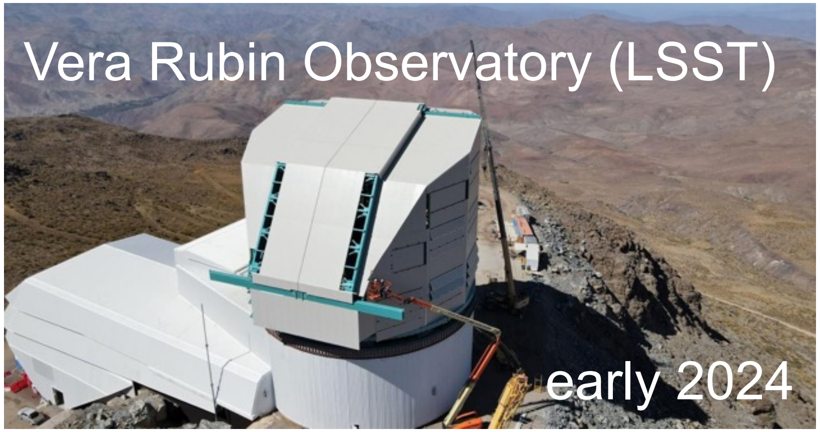
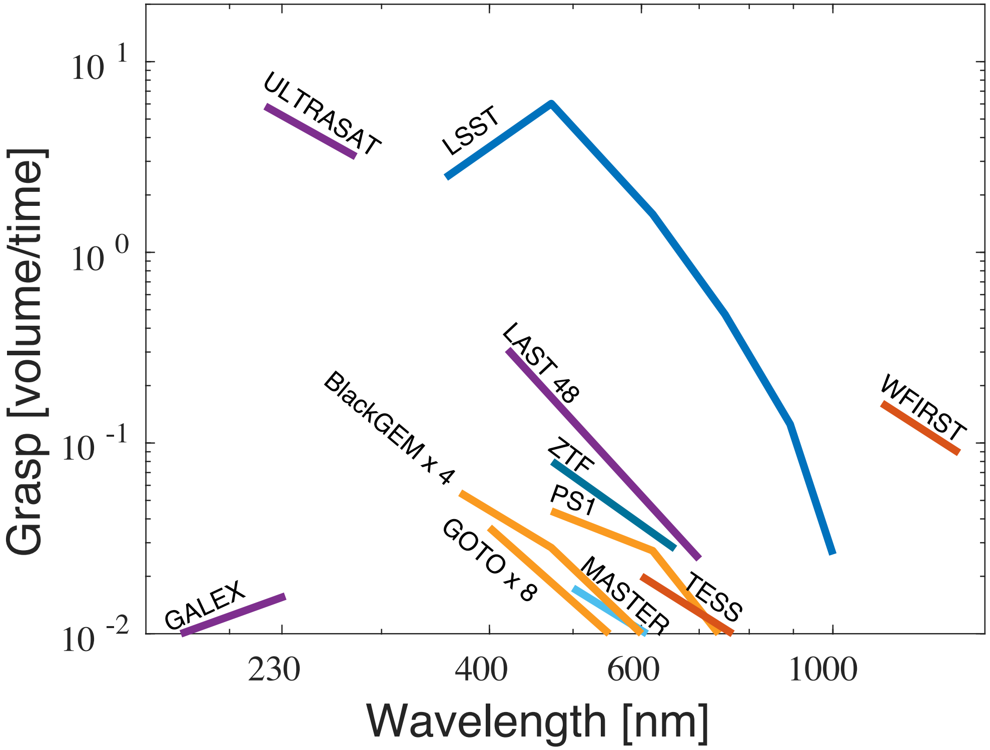
T. Chiarusi's talk on Thursday

New Instrument to identify Counterparts







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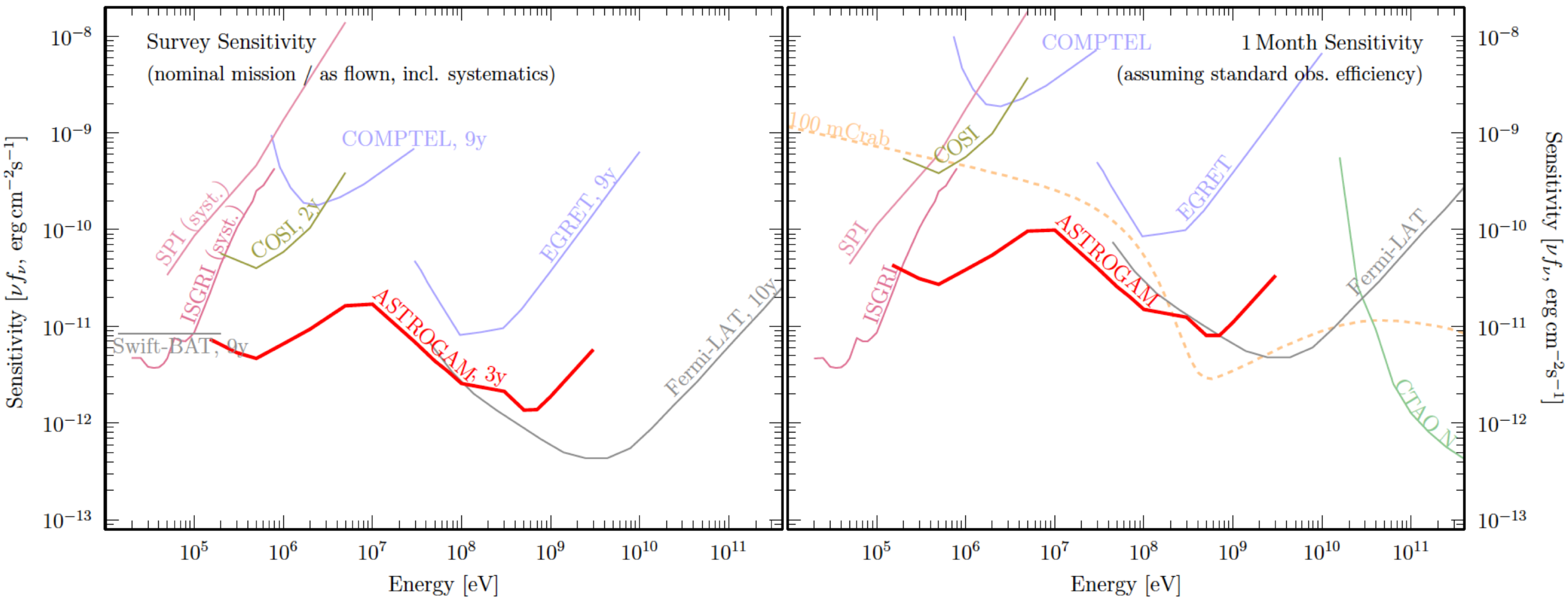
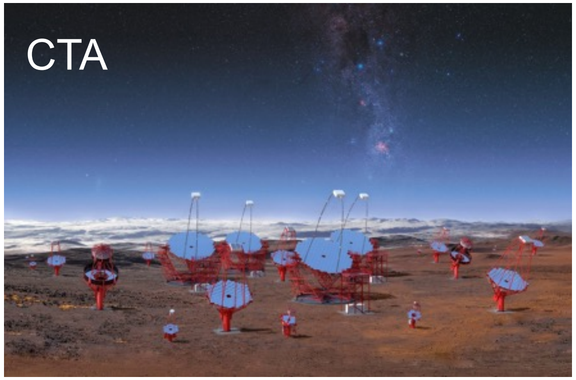
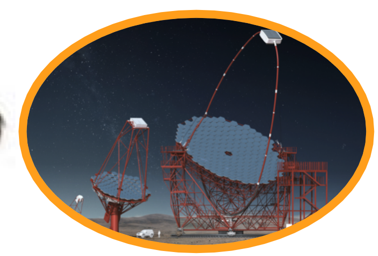
Closing the Gap in the MeV Range





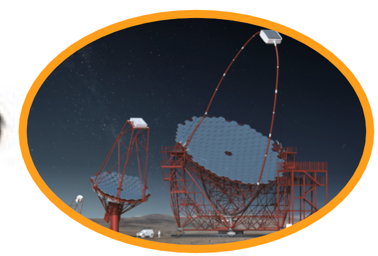
Summary

Neutrinos and gamma-rays are unique messengers from the **high-energy Universe**



Summary

Multi-wavelength observations are key to identify neutrino and cosmic-ray sources



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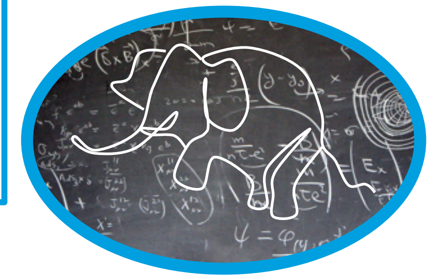
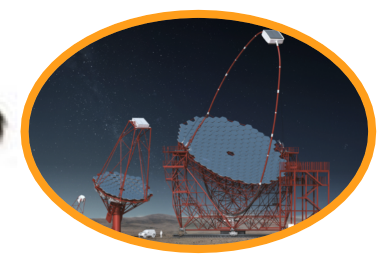
Summary

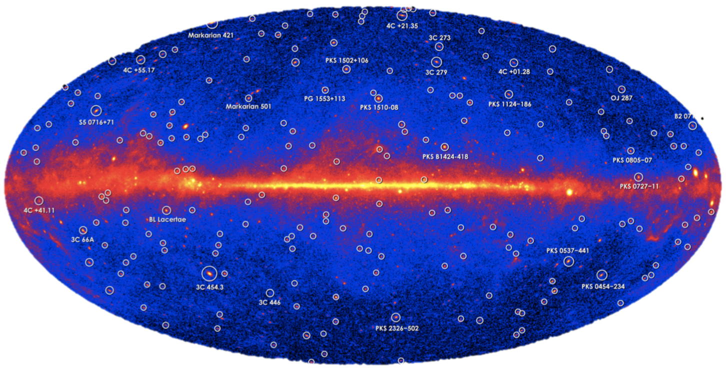
Theory plays a crucial role to **interpret the multi-messenger data**

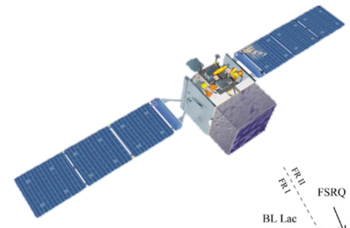


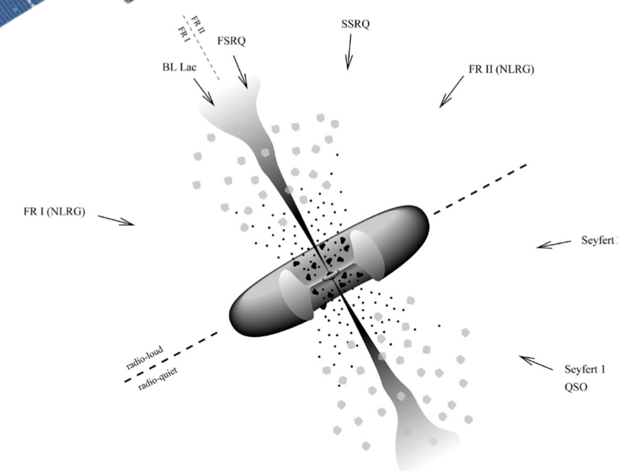


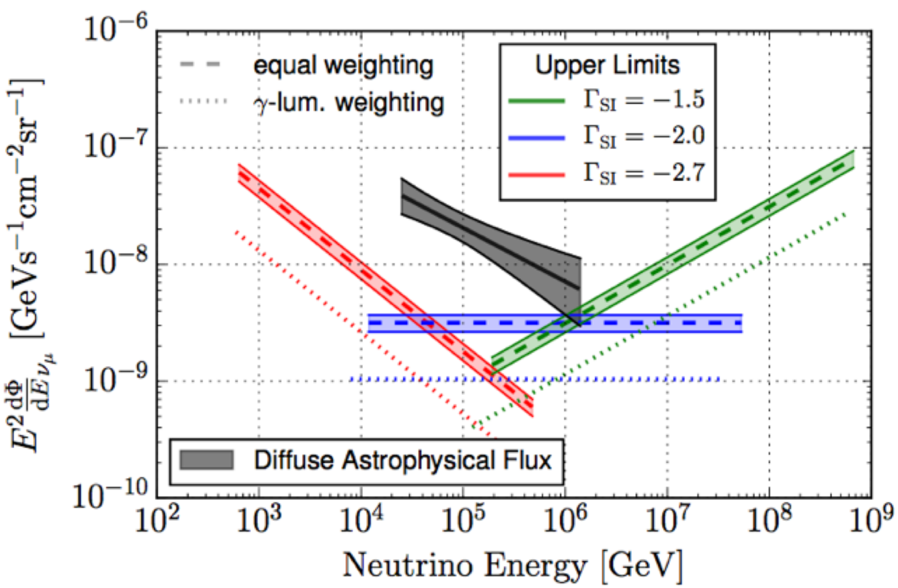
Stay tuned!

Stacking Analysis using Fermi-LAT blazar catalog









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 ν's.

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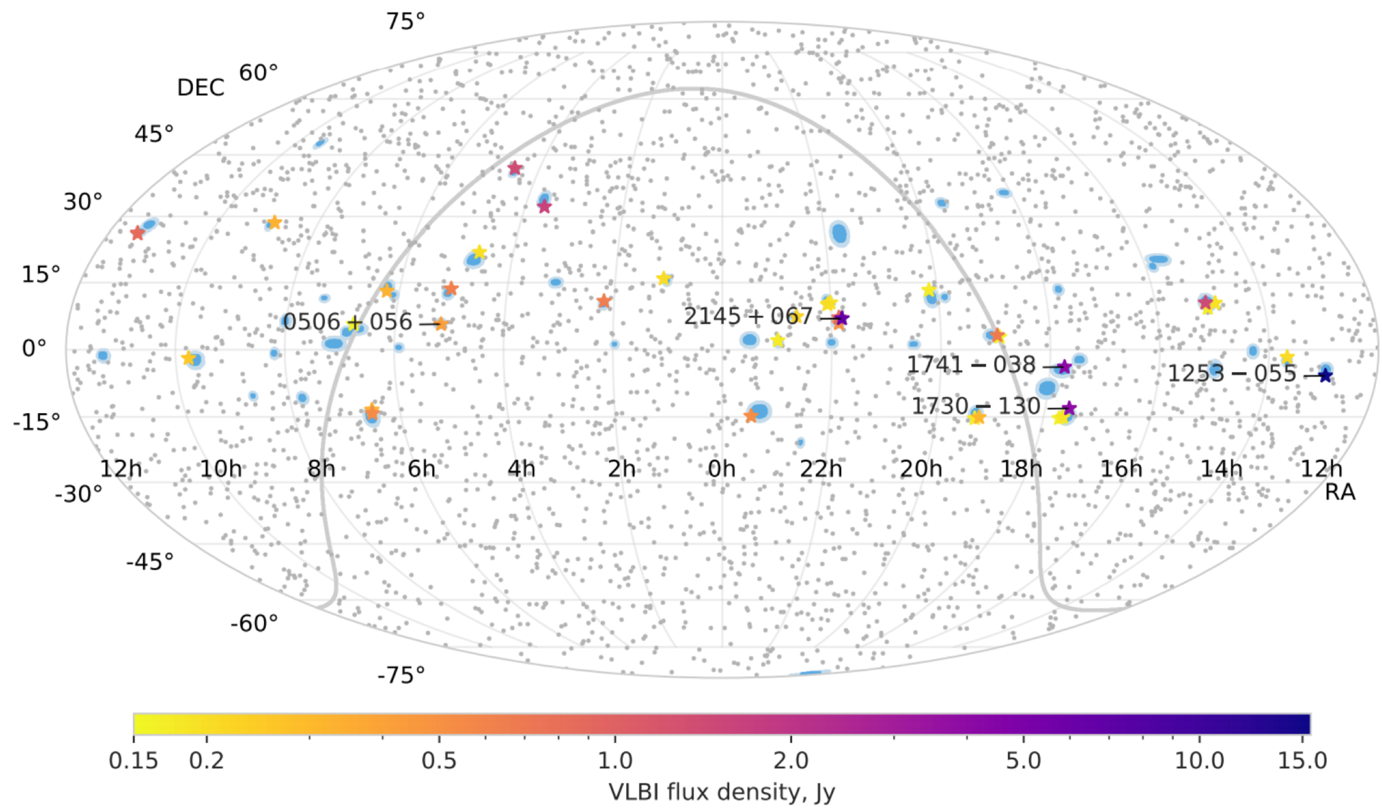
IceCube Coll. ApJ 835 (2017)

Stacking with radio-loud AGN

Correlation with VLBI-flux-density limited sample of AGN



Correlation of radio-bright AGN with IceCube neutrino alerts at chance coincidence of 0.2%

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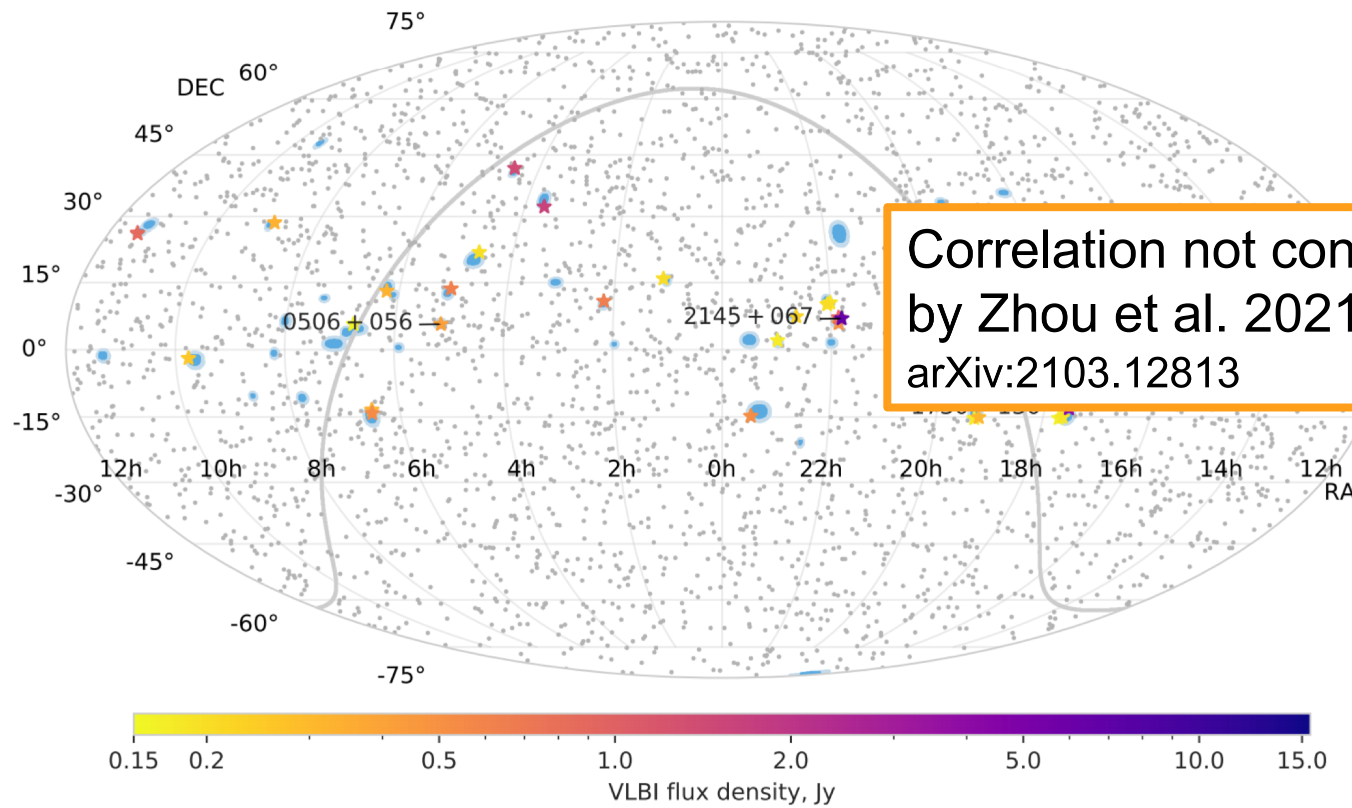
Plavin et al., ApJ 894 (2020), Plavin et al. 2020 arXiv:2009.08914

Stacking with radio-loud AGN

Correlation with VLBI-flux-density limited sample of AGN



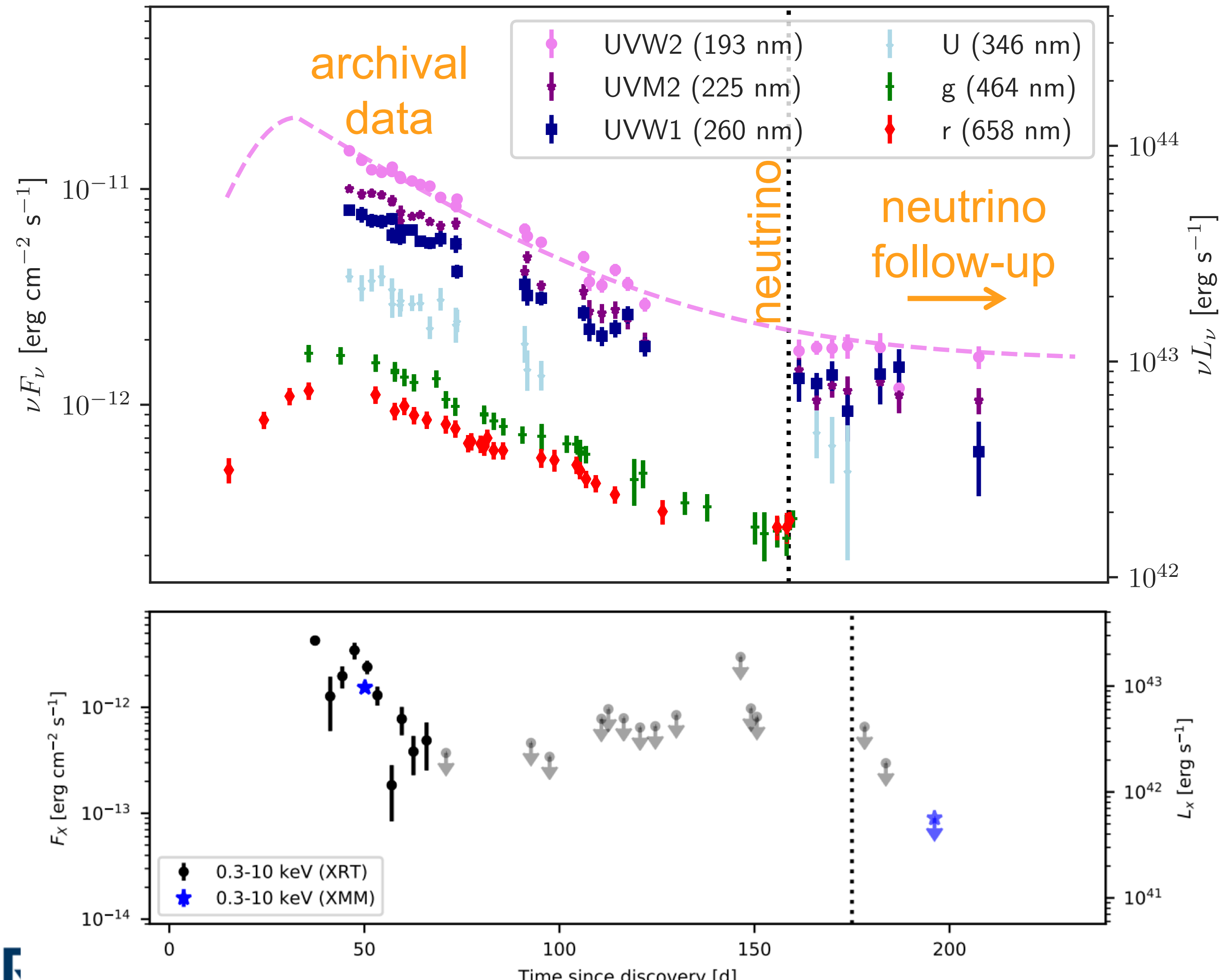
Correlation not confirmed by Zhou et al. 2021
arXiv:2103.12813

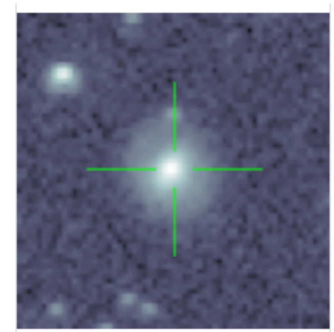
Correlation of radio-bright AGN with IceCube neutrino alerts at chance coincidence of 0.2%

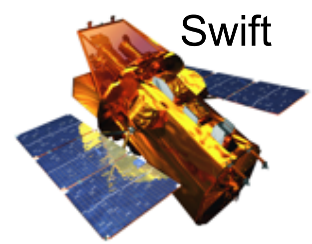
RUB

Plavin et al., ApJ 894 (2020), Plavin et al. 2020 arXiv:2009.08914

Source Candidates – AT 2019dsg

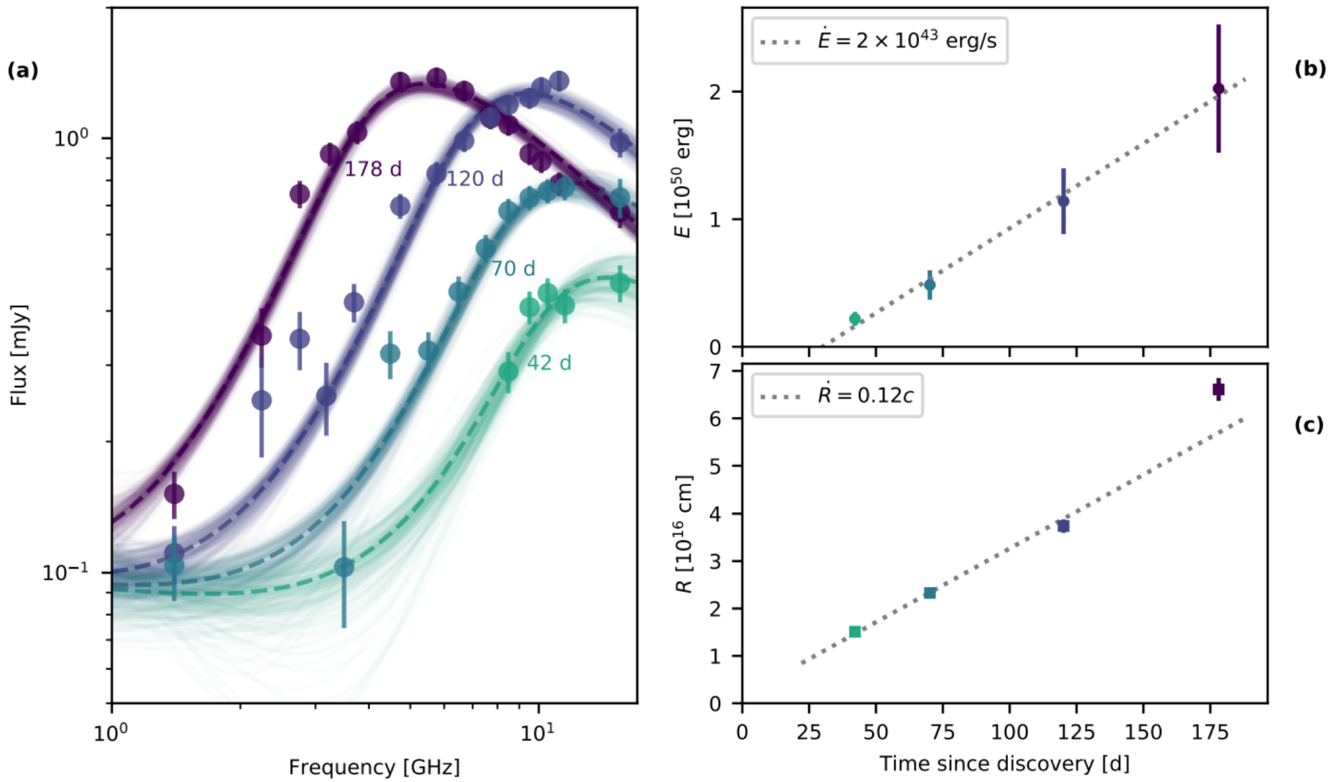






Source Candidates – AT 2019dsg

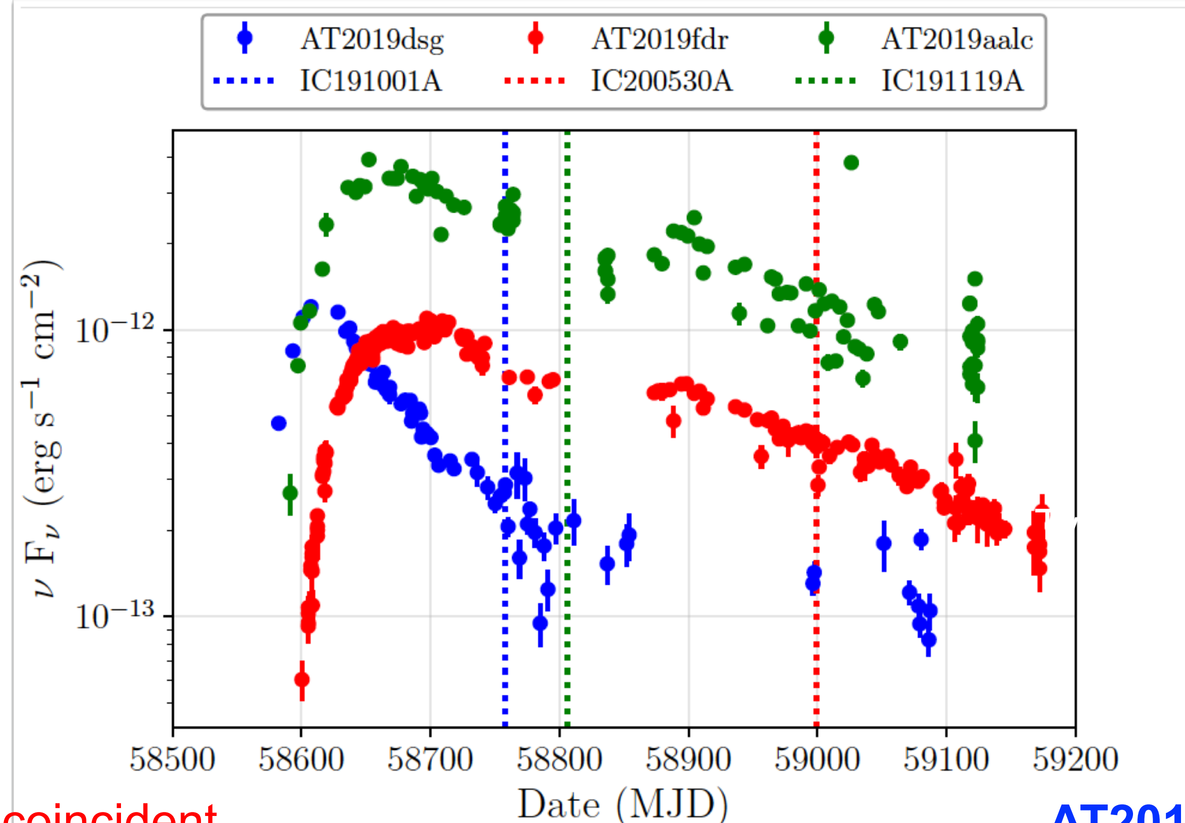
Radio observations



Radio data reveals long-lasting activity of central engine

RUB R. Stein et al., Nature Astronomy 2021

Two more TDE candidates!



AT2019fdr coincident with IC200530A

AT2019aalc coincident with IC191119A

$$p = 2 \times 10^{-4} \ (3.7\,\sigma)$$

First hint of neutrino production in TDEs
→ **Very efficient neutrino production in TDEs compared to AGN?**

S. Reusch et al. PRL 2022

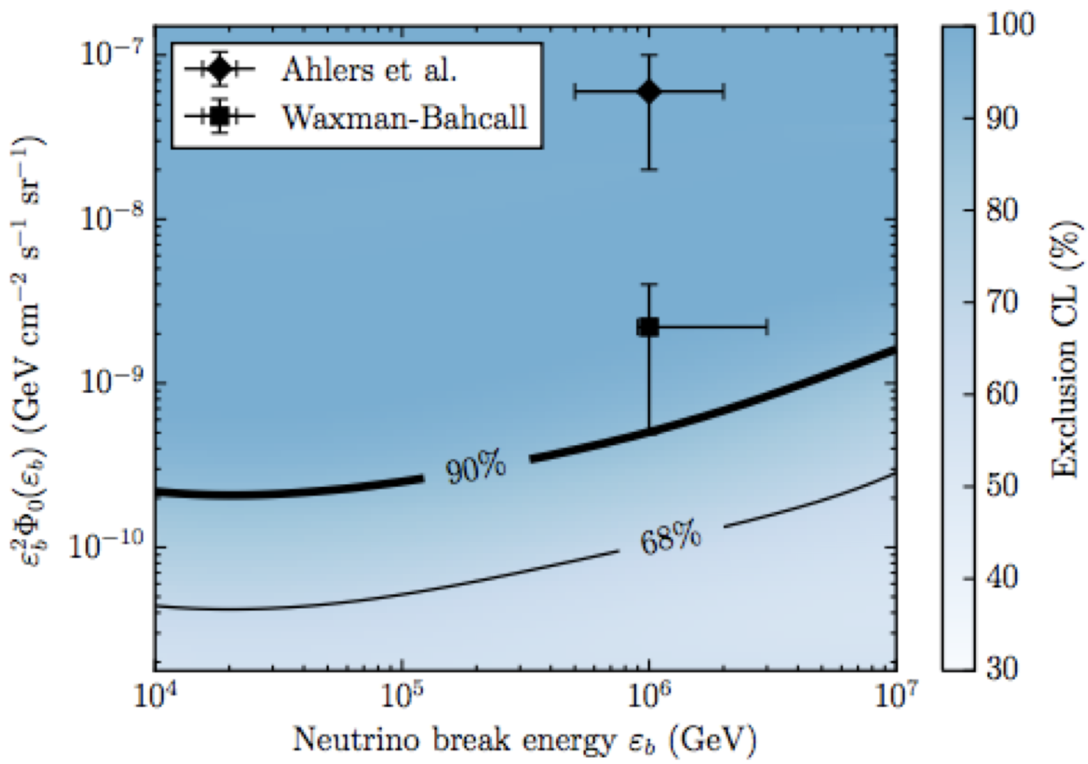
S. Van Velzen et al. arXiv:2111.09391

Gamma-Ray Bursts (GRBs)

Gamma rays and X-rays tell us **where** and **when** to look for neutrinos

Prompt emission of
> 800 GRBs correlated
with IceCube data
→ **no excess found**

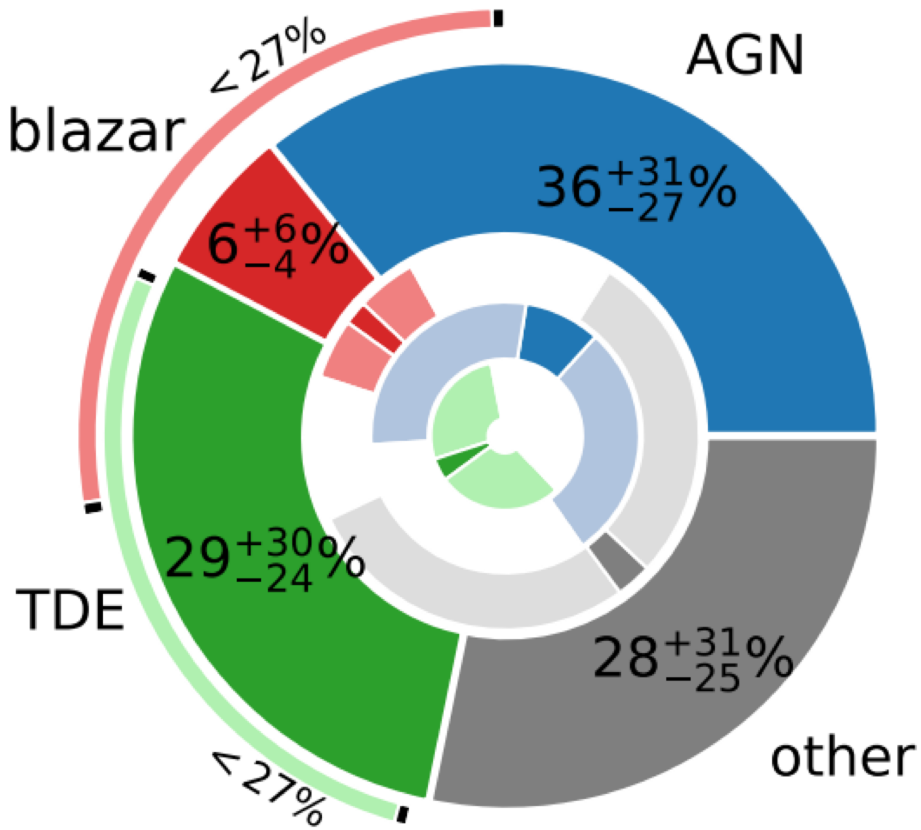
Precursor and
afterglow searches in
preparation



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

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

The Cosmic Neutrino Pi Chart



Bartos et al. Astrophys.J. 921 (2021)

IceCube-Gen2 time line