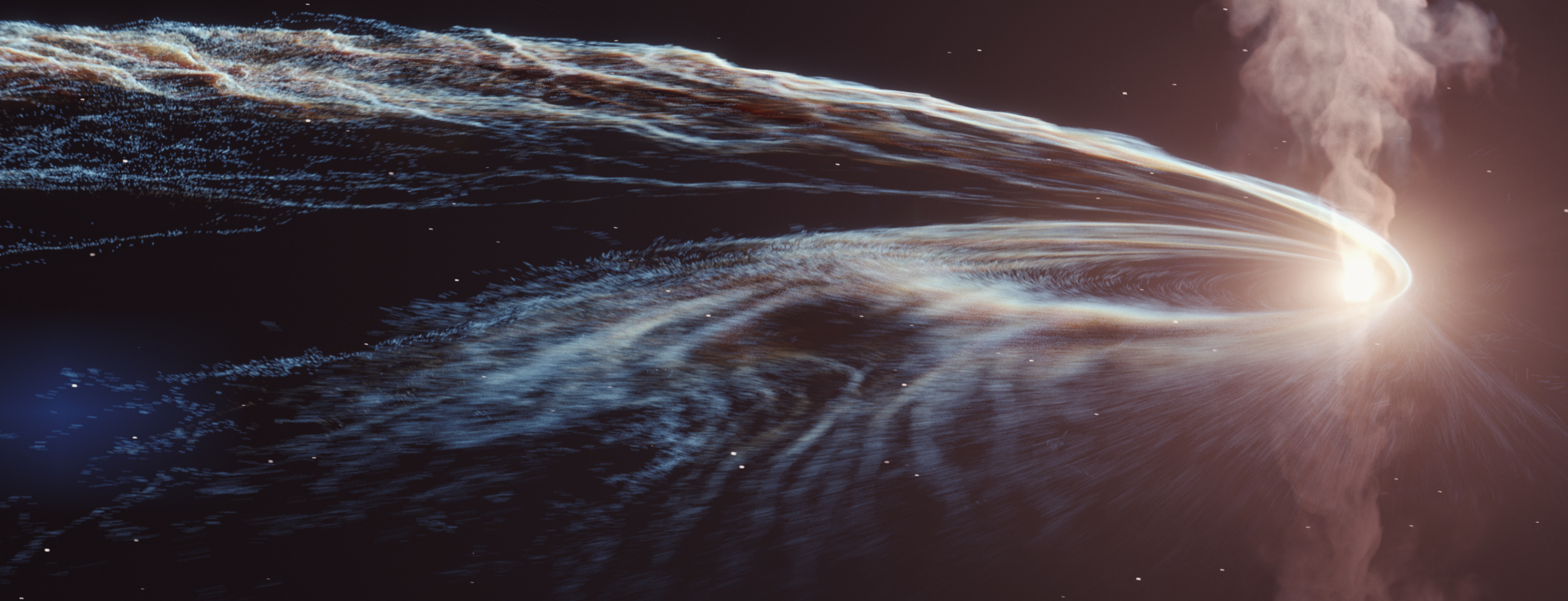
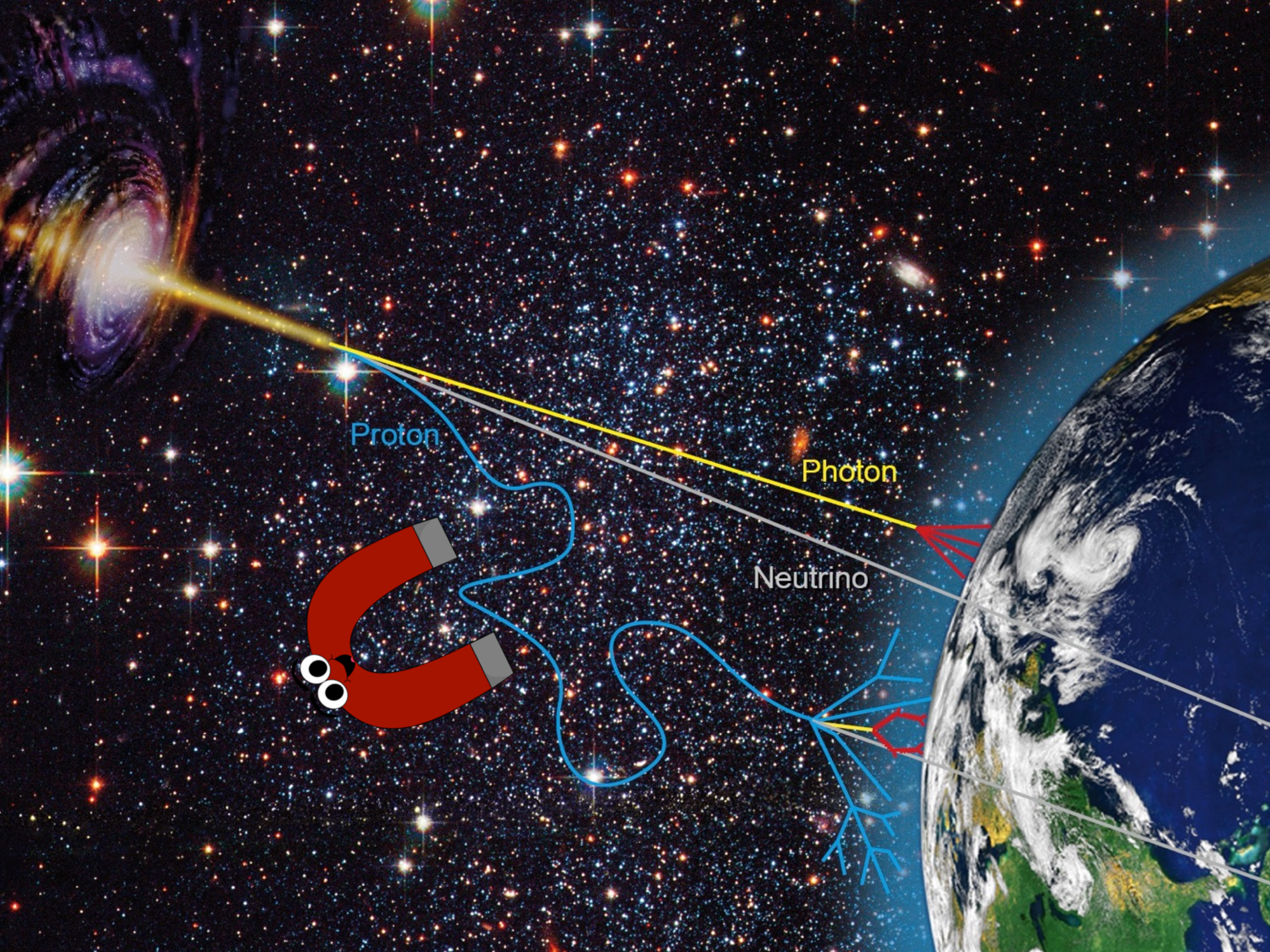
Counterparts of Neutrinos

Anna Franckowiak



RUHR UNIVERSITÄT BOCHUM RUB

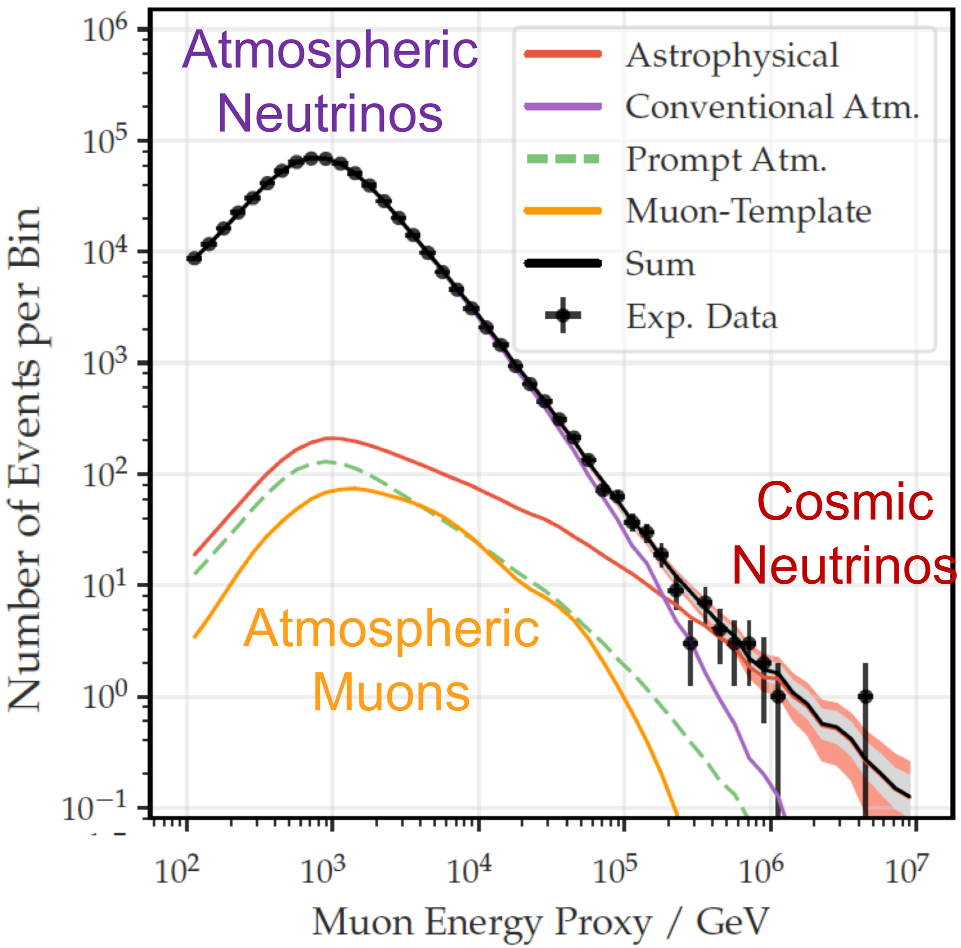
Astro-COLIBRI Workshop, 27.09.2022

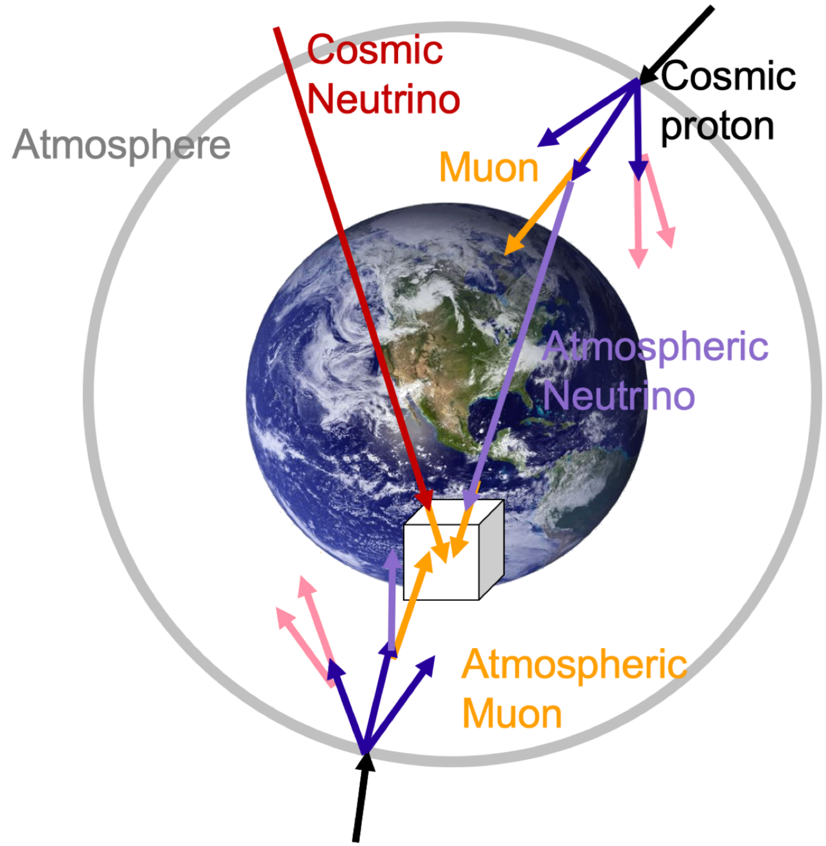


Proton
Photon
Neutrino

Diffuse Flux discovered!

Northern Sky

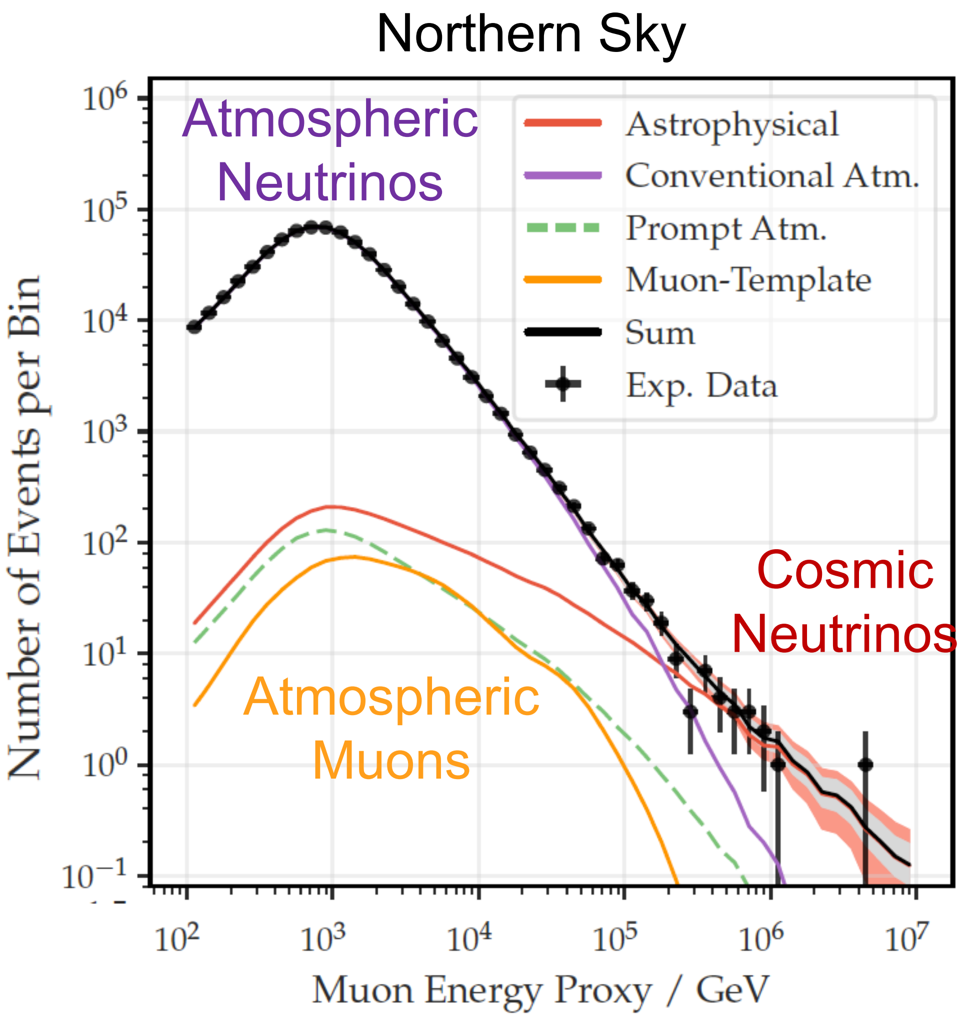




IceCube Coll. ApJ 928 (2022) 50

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)**

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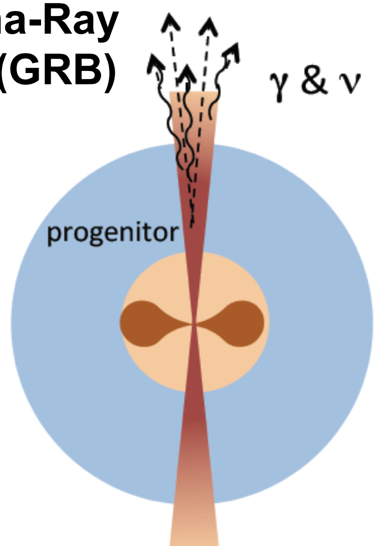
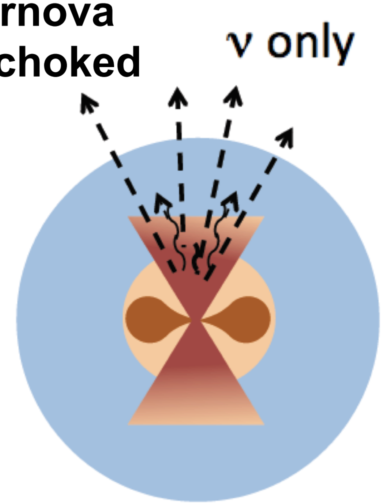
Source Candidates

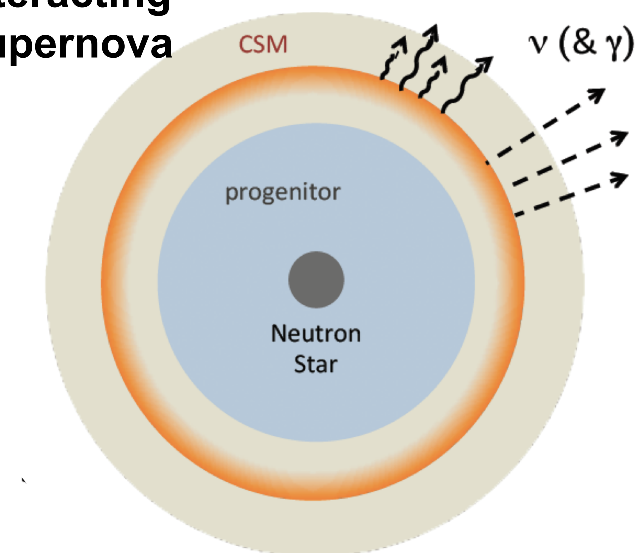
Gamma-Ray Burst (GRB)



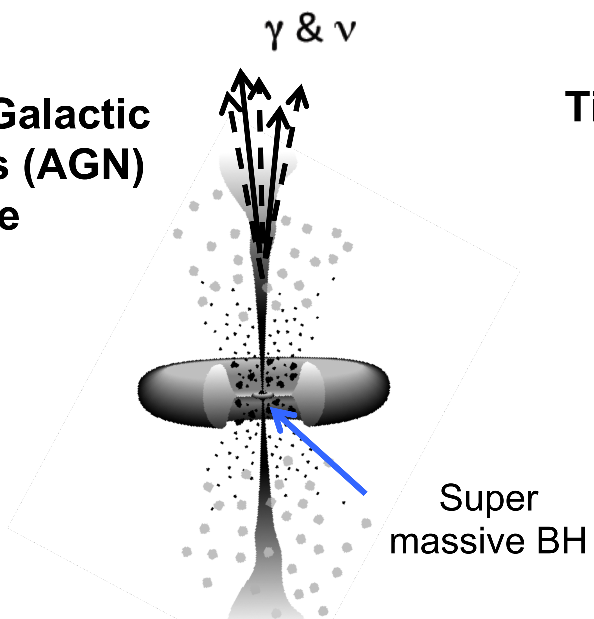
Supernova with choked jets



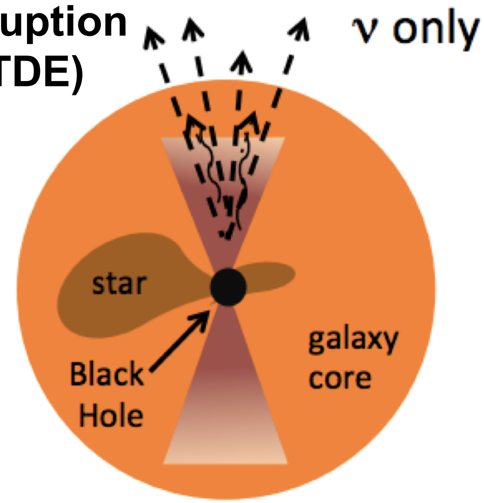
Interacting Supernova



Active Galactic Nucleus (AGN) jet / core



Tidal Disruption event (TDE)



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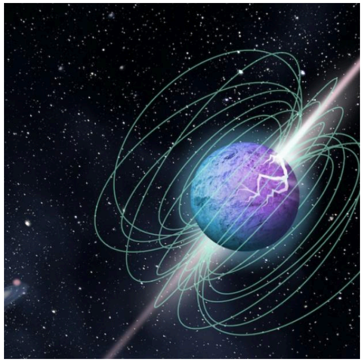
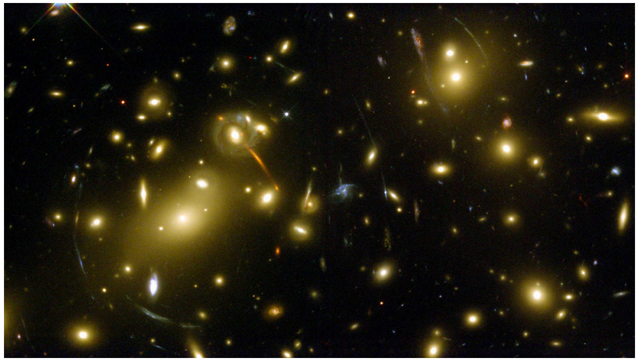
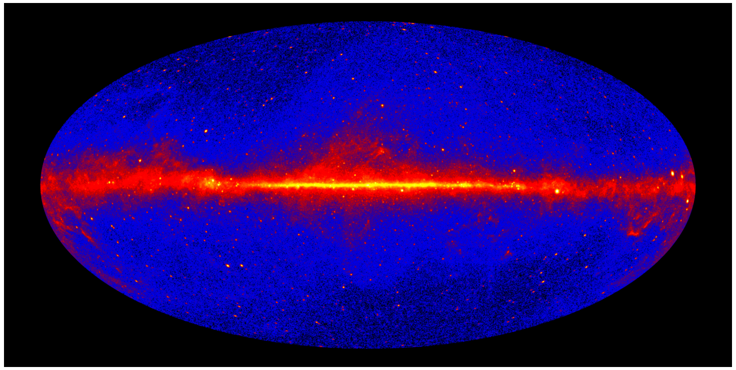
Source Candidates (continued)

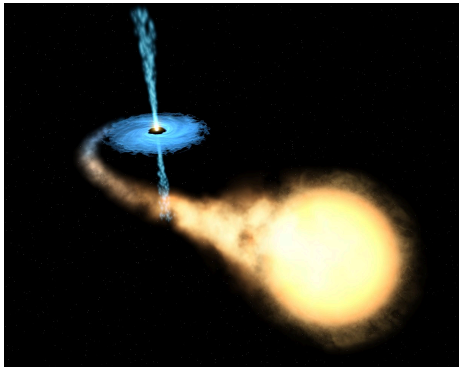
Extragalactic: Starforming galaxies, galaxy clusters, FRBs …





Galactic sources: SNR, PWN, Binaries, Novae, Galactic plane …





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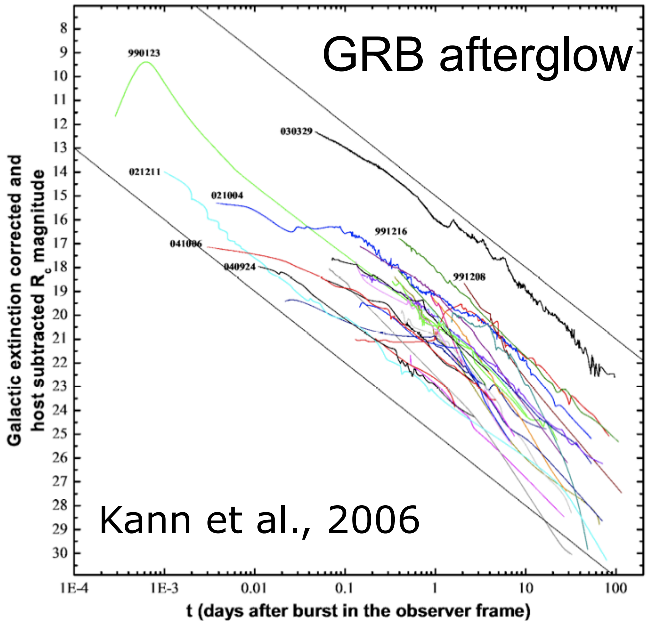
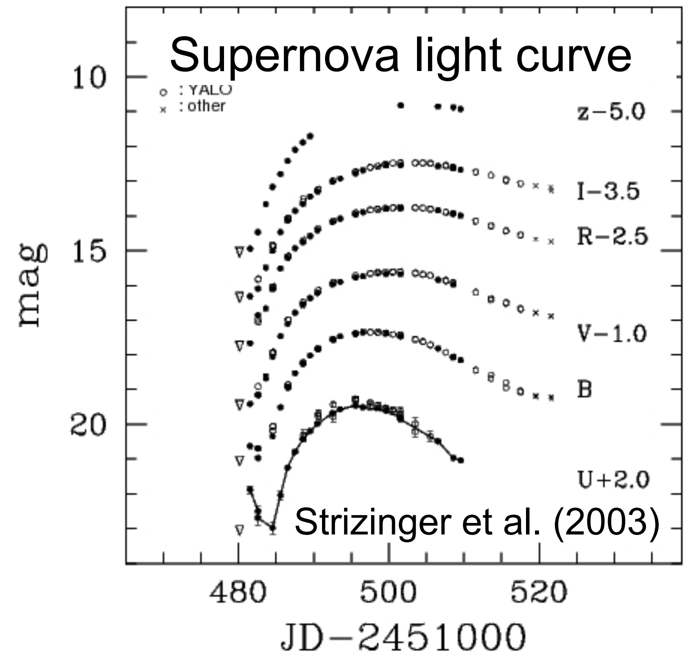
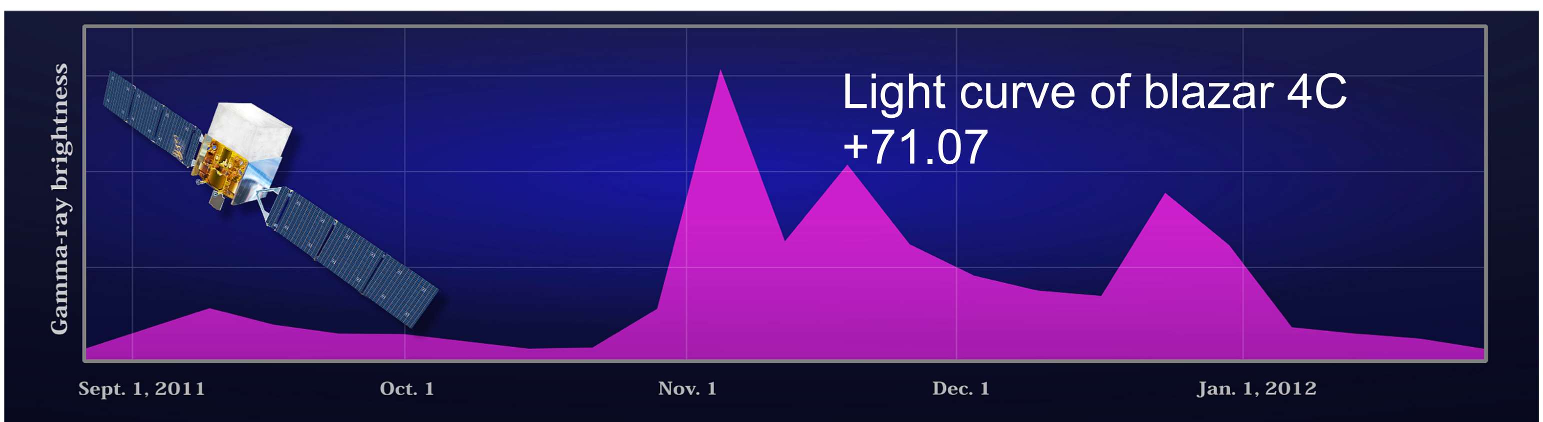
Counterpart Examples

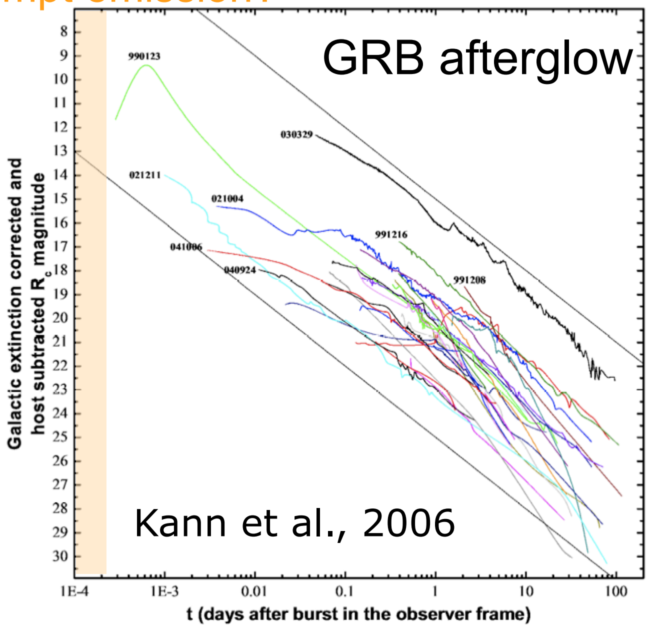




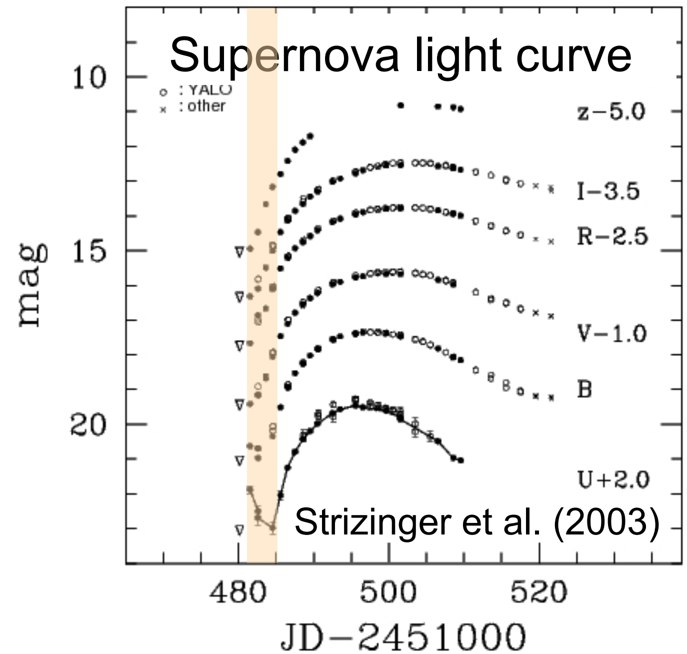


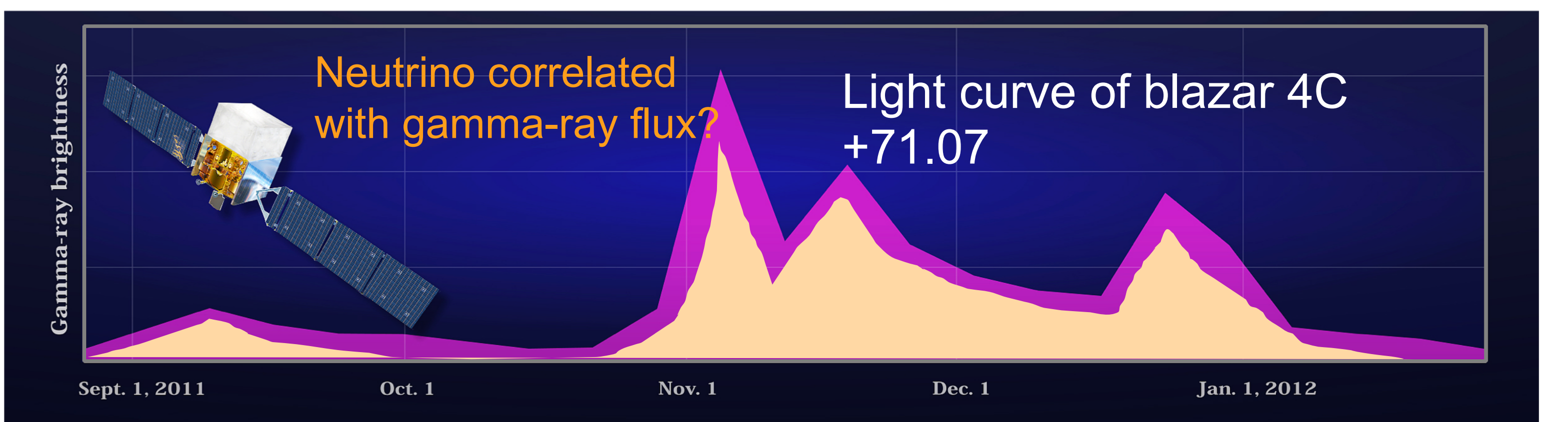
Counterpart Examples

Neutrino coincident with prompt emission?



Neutrino coincident start of explosion?





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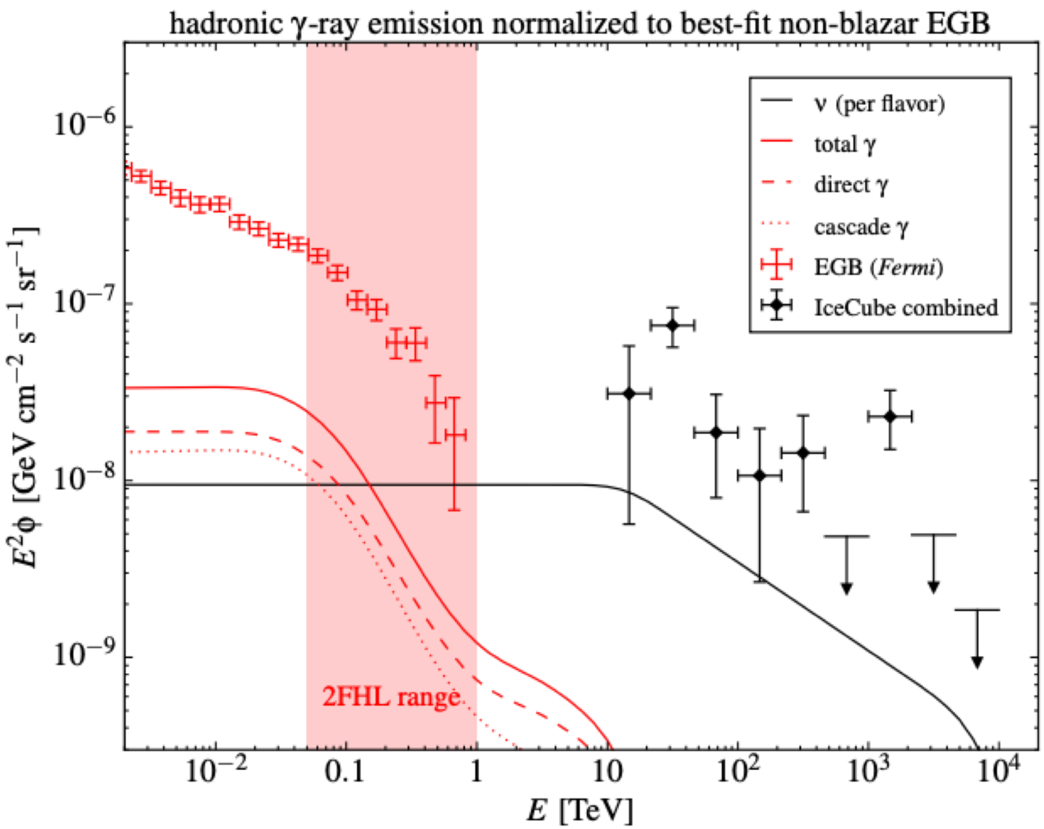
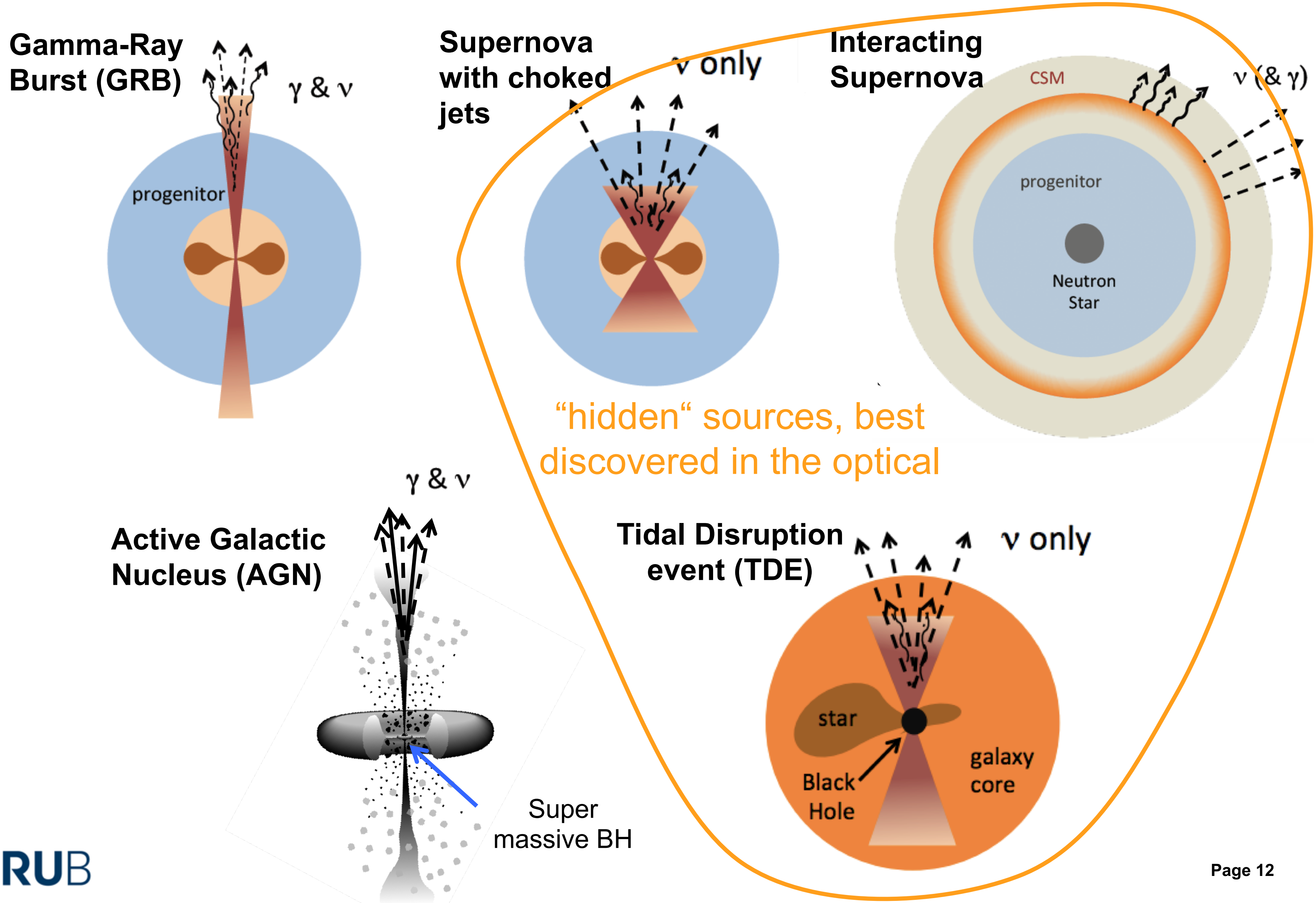
Gamma-ray emitters are obvious candidates, but …



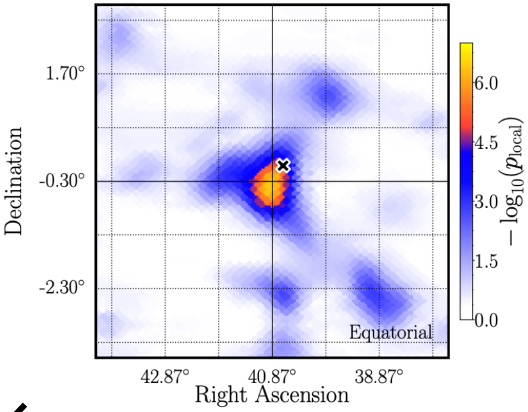
… in order not to overshoot the measured gamma-ray background a majority of the neutrino sources has to be dark in GeV gamma rays (“hidden sources”)

Bechtol et al. ApJ 836 (2017)

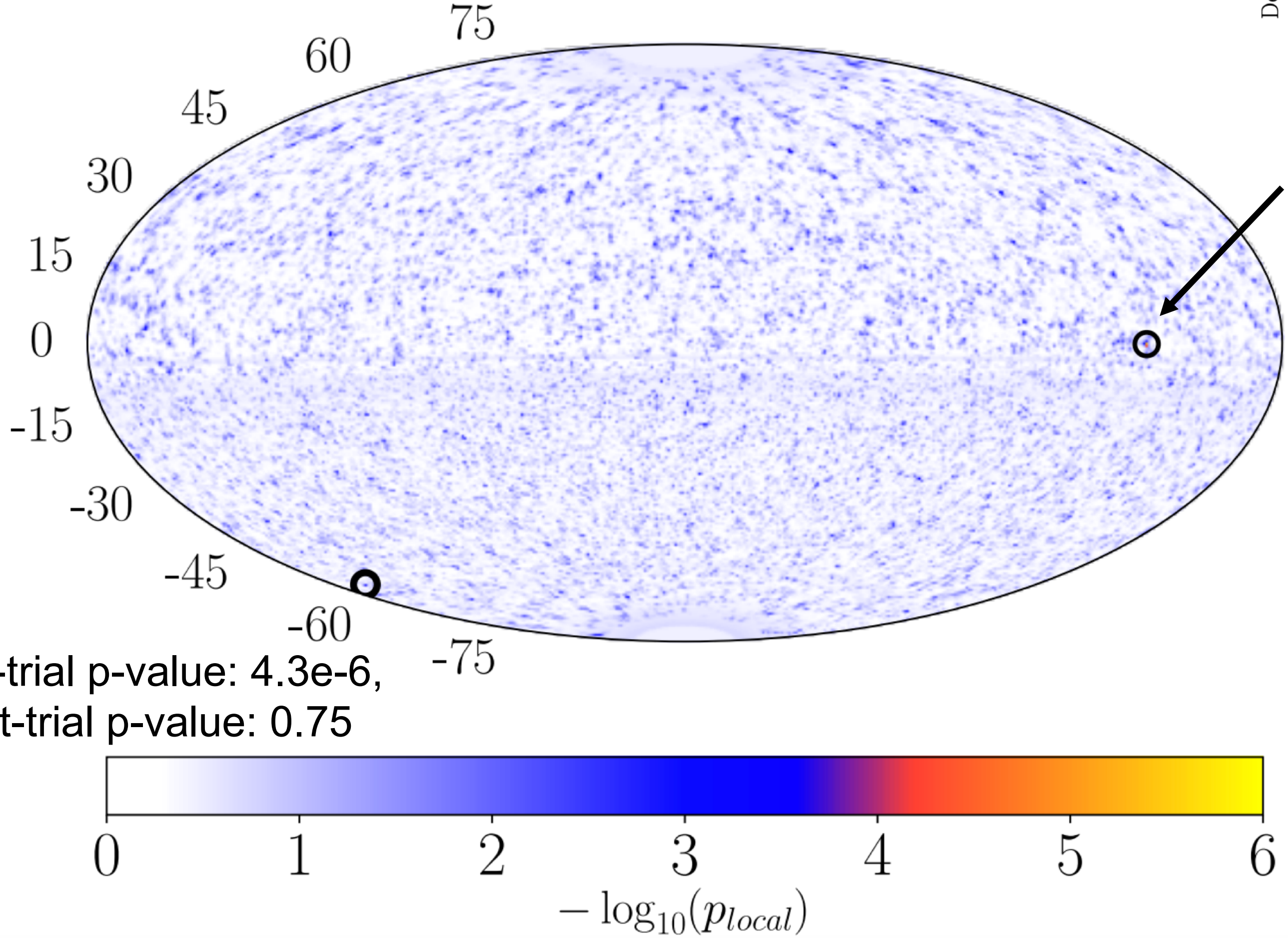
Selection of Source Candidates



Hotspot Search



Pre-trial p-value: 3.5e-7,
Post-trial p-value: 9.9e-2



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

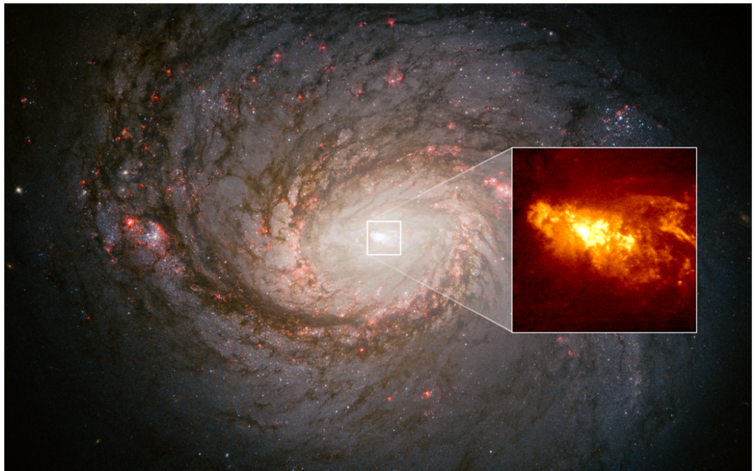
IceCube Coll. PRL 124 (2020)

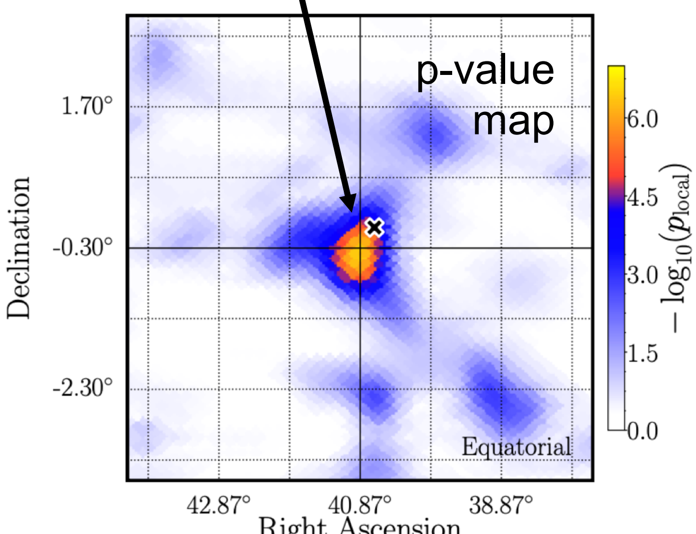
Search for neutrinos from pre-defined source list

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

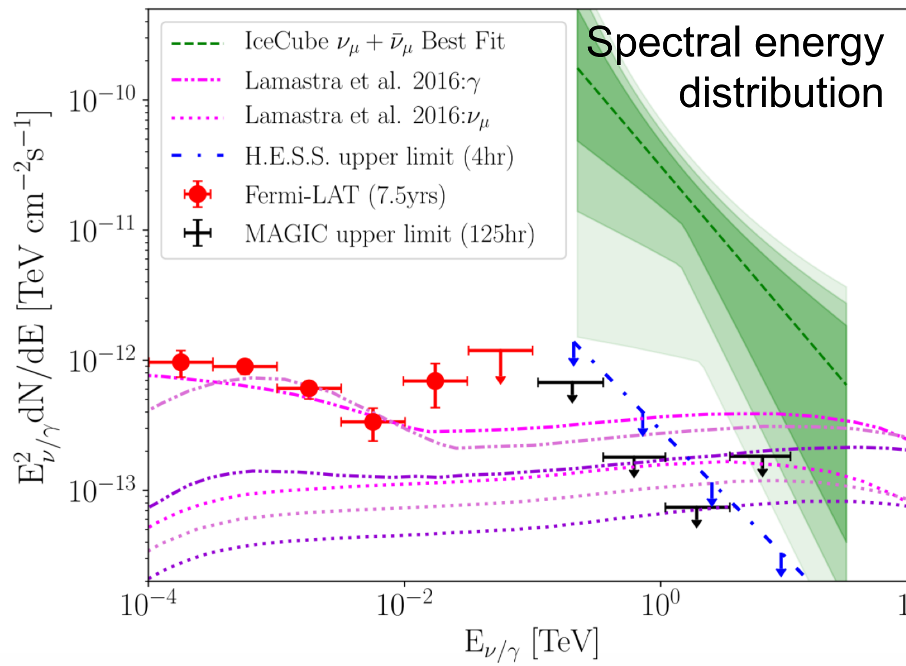
Most significant candidate: **NGC 1068**

Source Candidates – NGC 1068





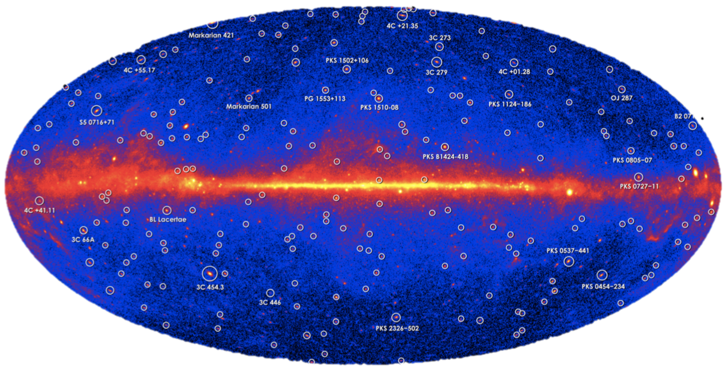
- 2.9 sigma excess in TeV neutrinos (~60 events) in 10 years of IceCube data
- Nearby (M=14Mpc) Seyfert 2 galaxy
- AGN and star-forming activity

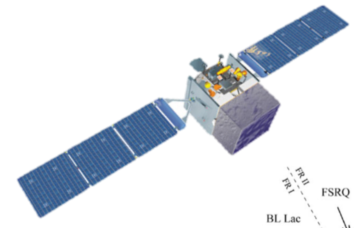


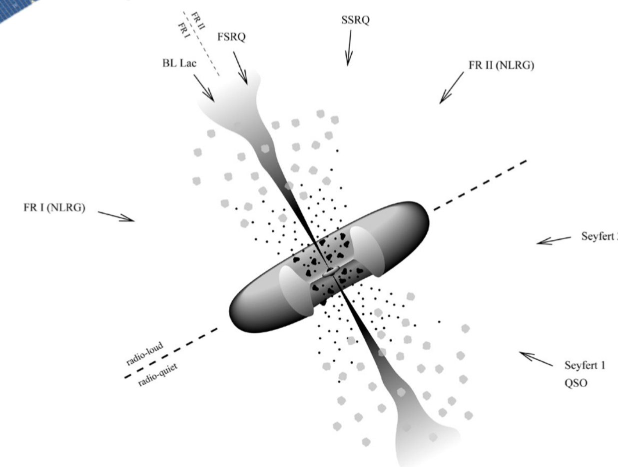
Gamma rays need to be absorbed

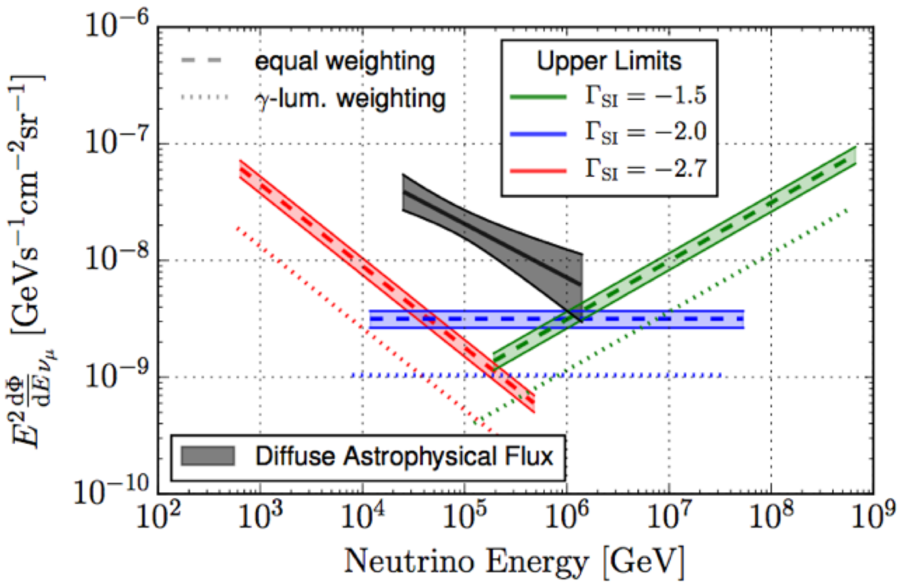
IceCube Coll. PRL 124 (2020)

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.

IceCube Coll. ApJ 835 (2017)

Other Stacking Analyses

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

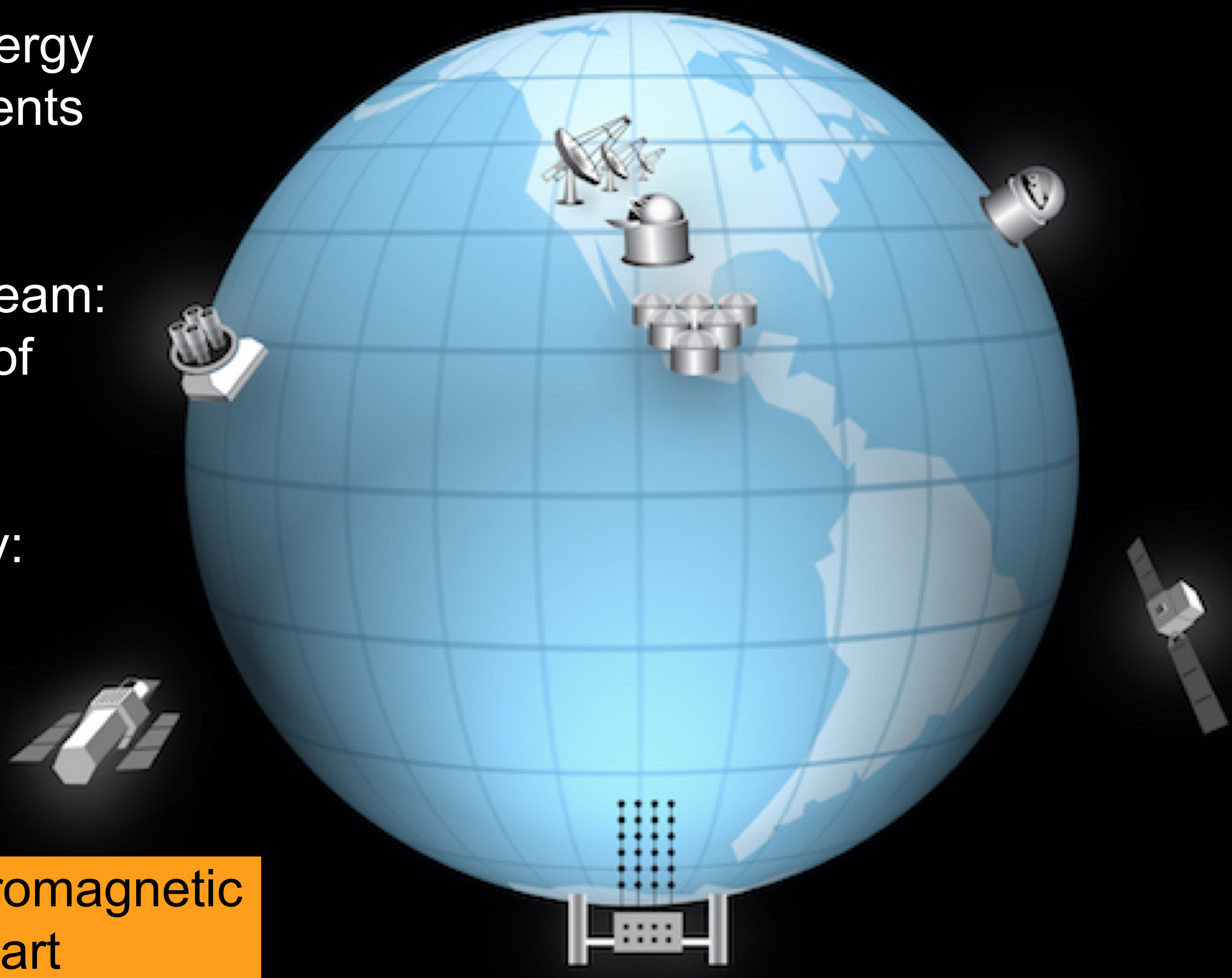
- Stacking of GRBs → GRBs contribute less than 1% to diffuse neutrino flux (IceCube Coll., ApJ 805 (2015), ApJ 824 (2016))
- Stacking of Fermi low-energy sources → contribute less than 1% (IceCube Coll. ApJ 2022)
- ….

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

IceCube Target of Opportunity Program

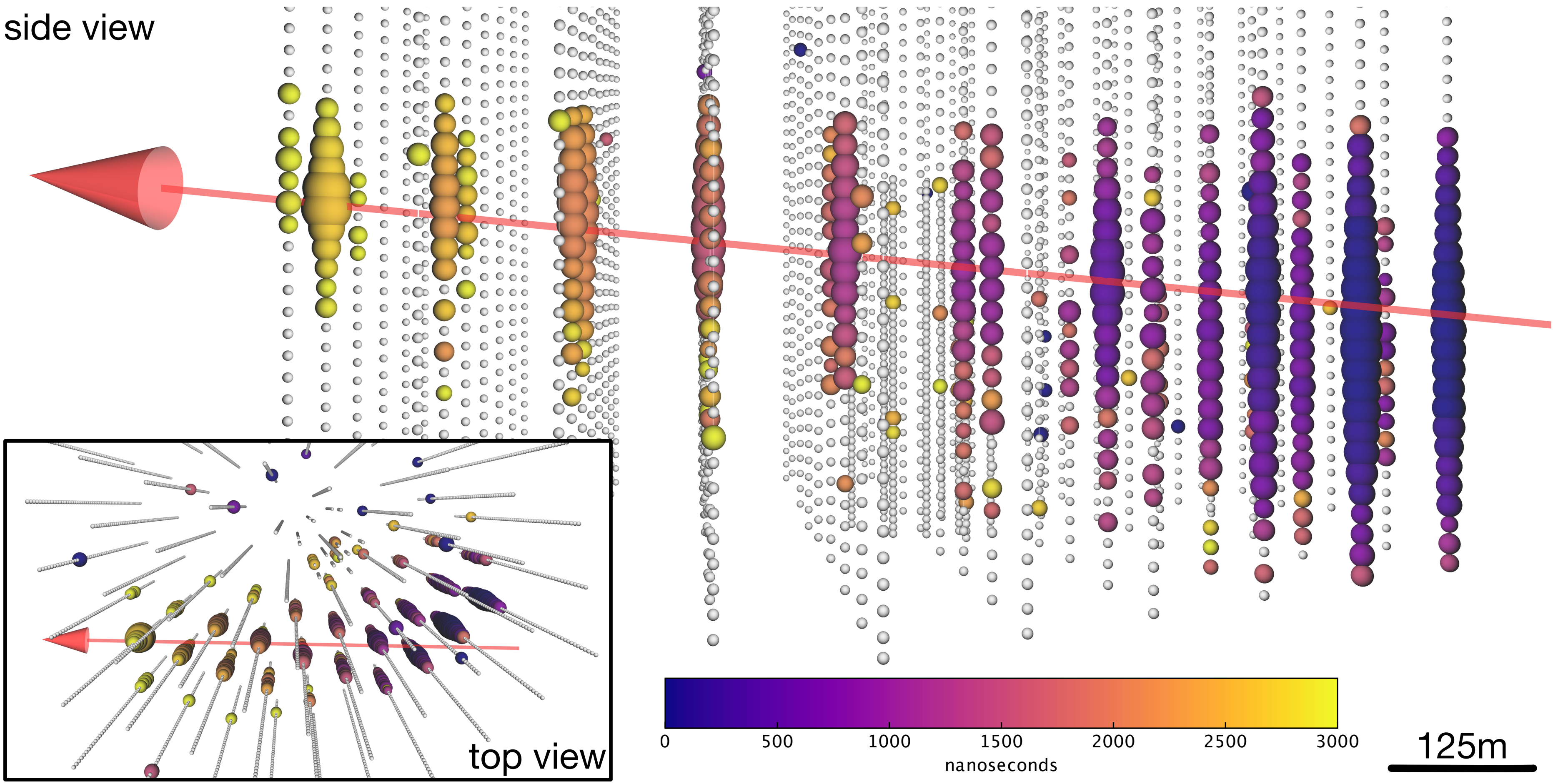
Public alerts since April 2016

- 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

IC-170922A – a 290 TeV Neutrino



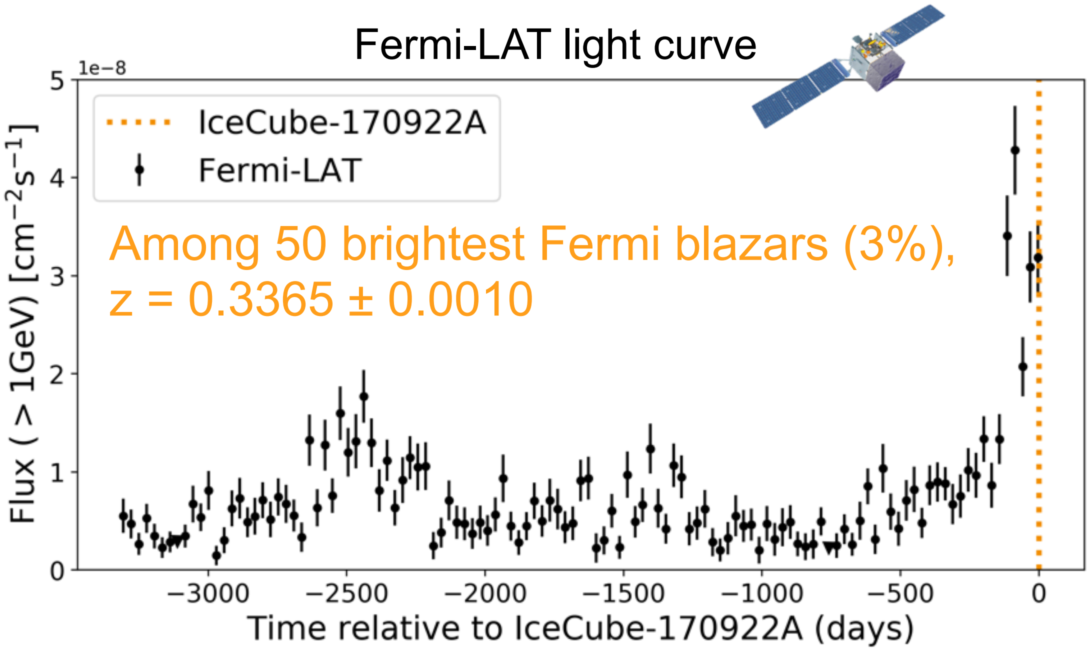
Signalness: 56.5%

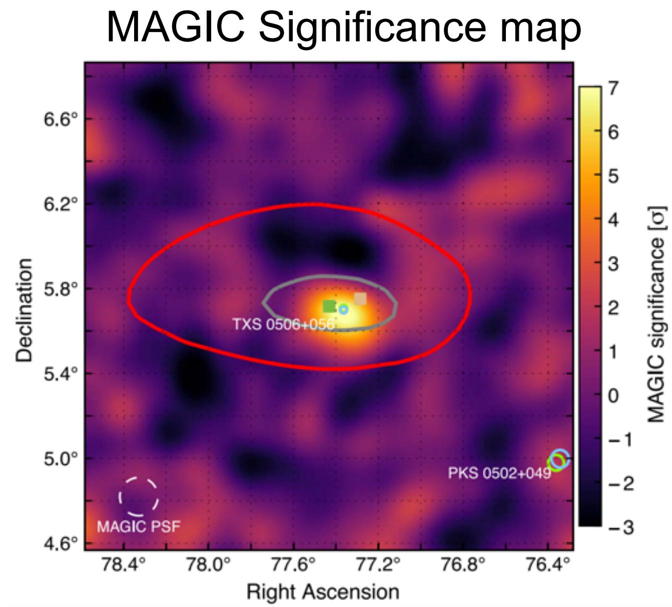
IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kapteyn, Kanata, Kiso, Liverpool, Subaru, Swift, VERITAS, VLA, Science 2018

Fermi-LAT finds Flaring Source

Fermi-LAT Coll., ApJ 846, 2017, Video credits: Matteo Giomi, Fermi-LAT Collaboration

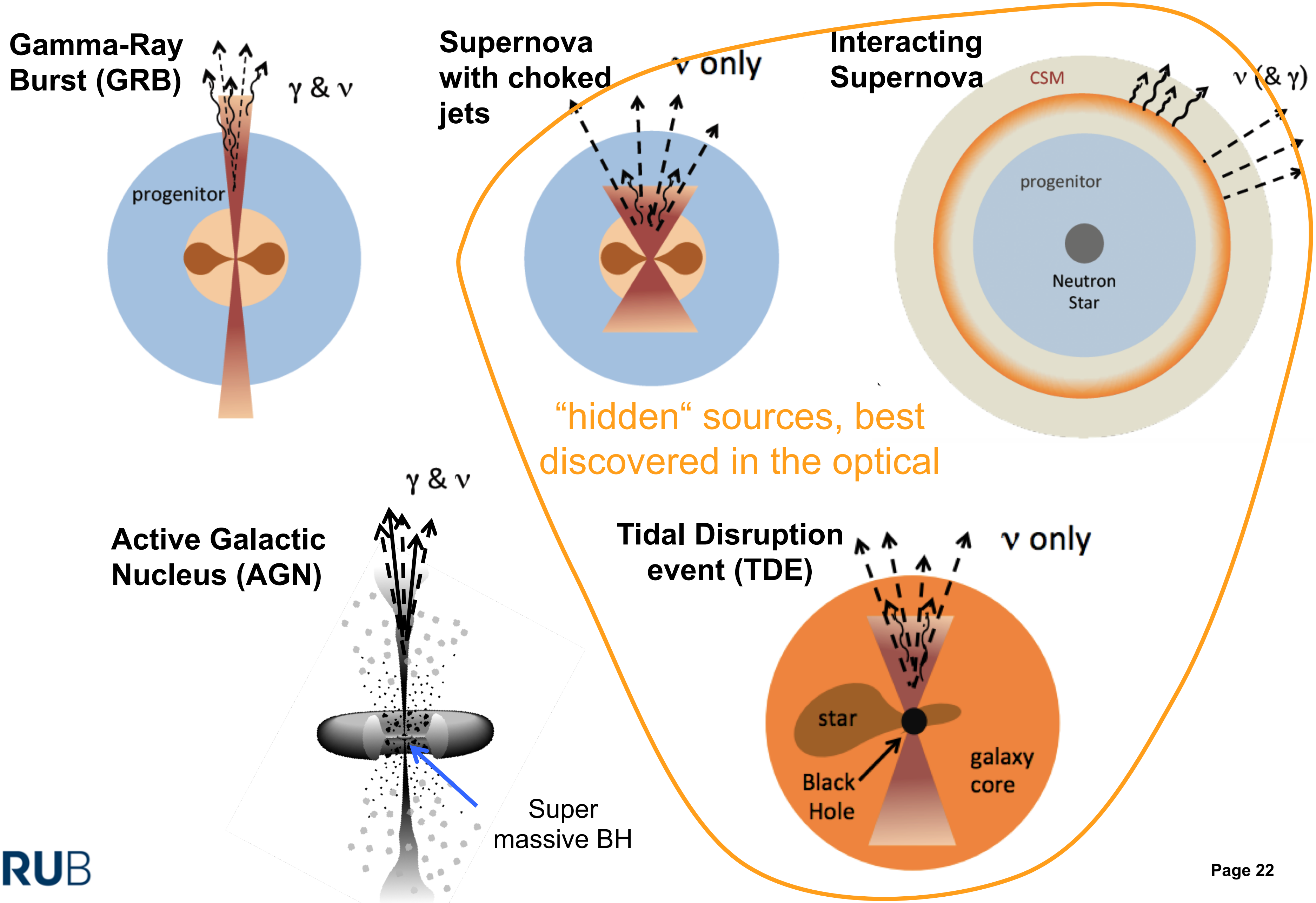
Source Candidates – TXS 0506+056





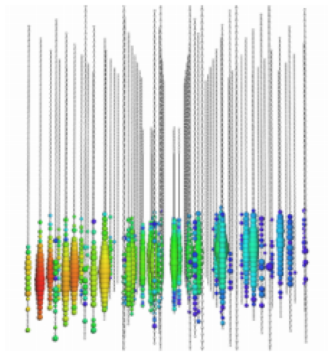
300 TeV neutrino coincident with gamma-ray flare (3sigma significance)

Selection of Source Candidates

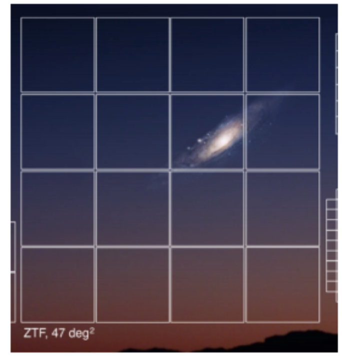


ZTF Follow-up Pipeline

Reject stars, planets, artifacts, asteroids



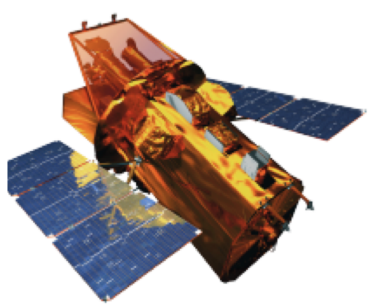
1. high-energy neutrino alert arrives



2. Observe with ZTF

3. Follow-up with AMPEL

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

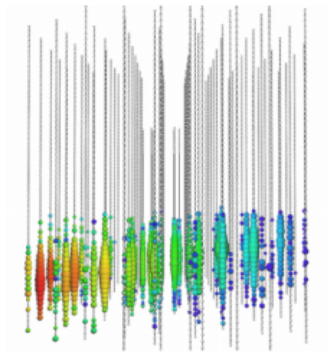


Reject unrelated transients (e.g. Type Ia SNe)

4. Trigger further follow-up observations

ZTF Follow-up Pipeline

Reject stars, planets, artifacts, asteroids



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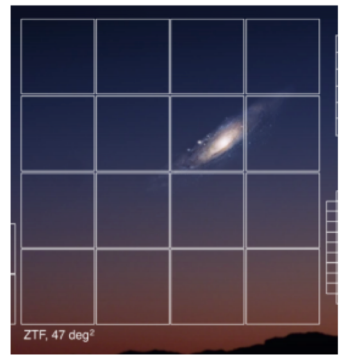
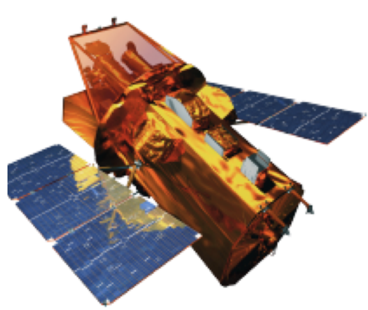


2. Obse
ZTF

3. Follow-up with AMPEL

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

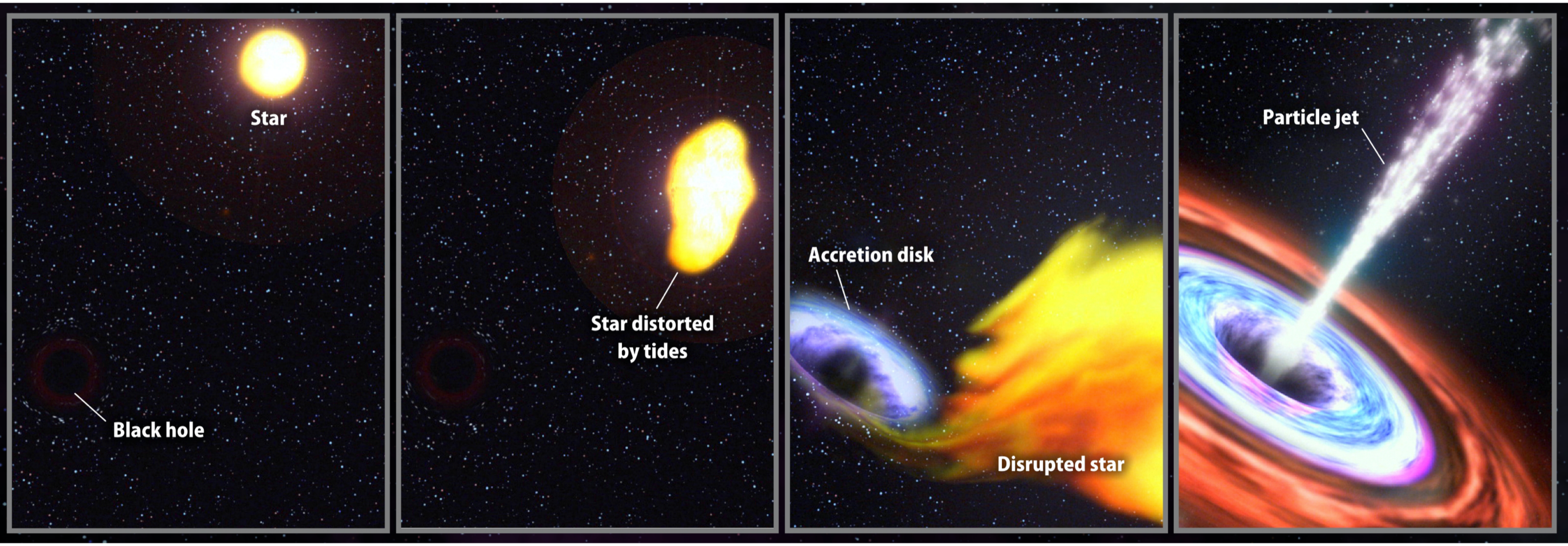


Reject unrelated transients (e.g. Type Ia SNe)

4. Trigger further follow-up observations

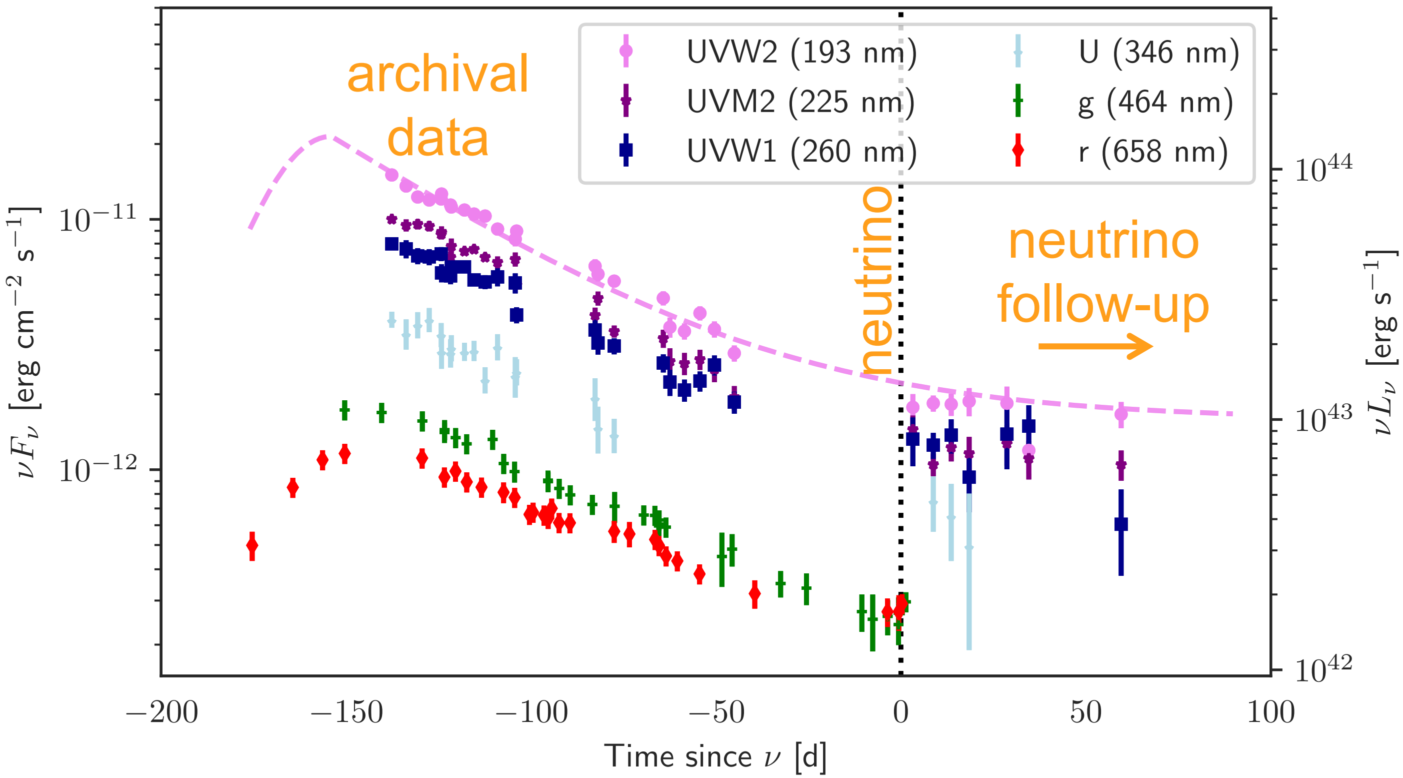
Source Candidates – AT 2019dsg

Tidal Disruption Event (TDE)

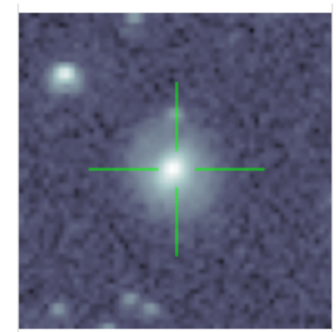


~50 TDEs identified, 3 jetted TDEs

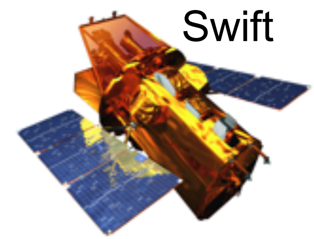
Source Candidates – AT 2019dsg



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

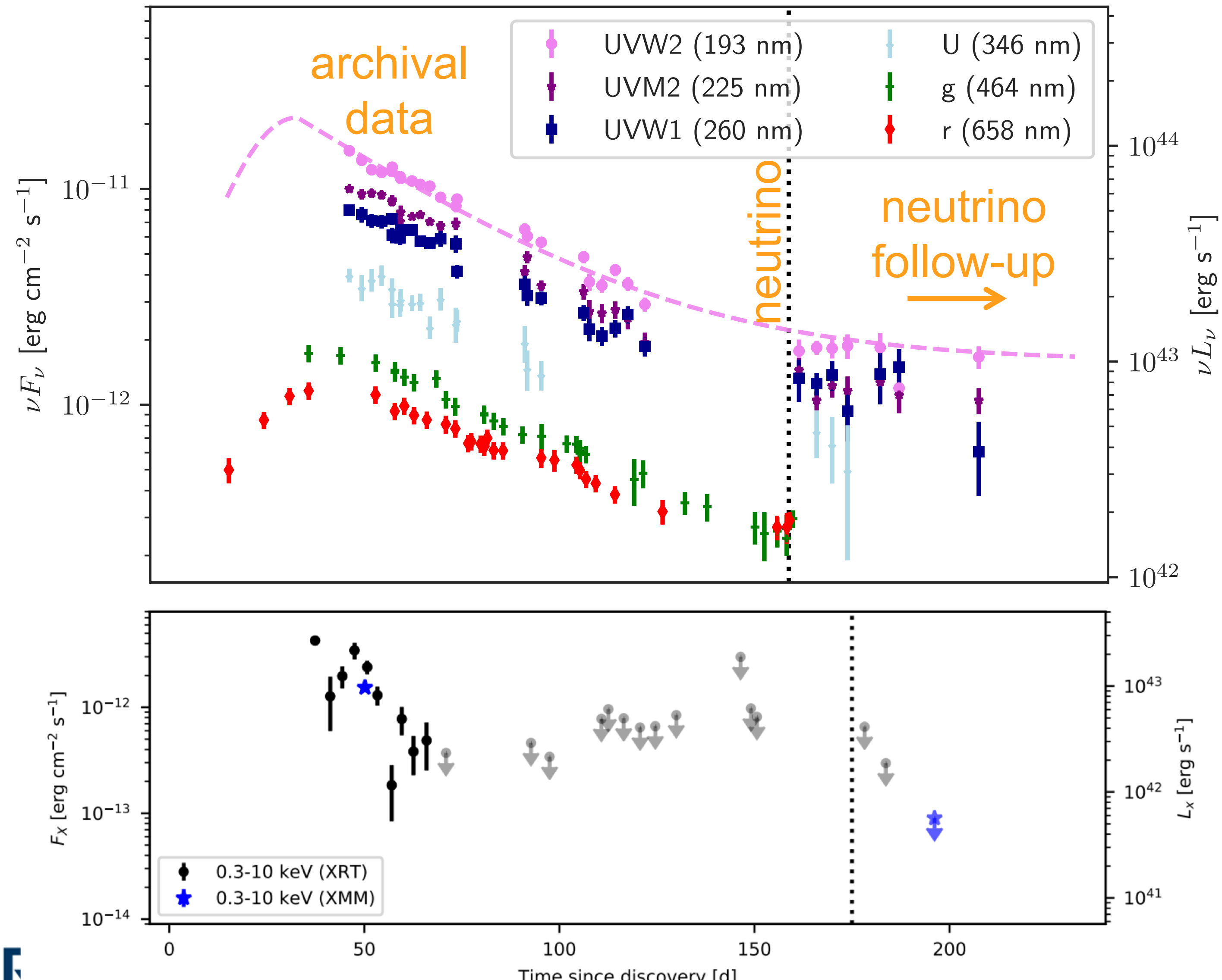


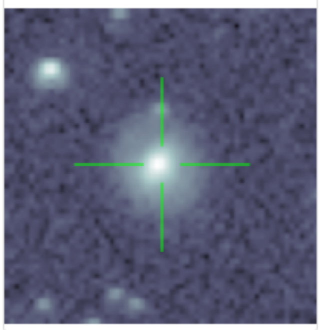
Swift



Fermi

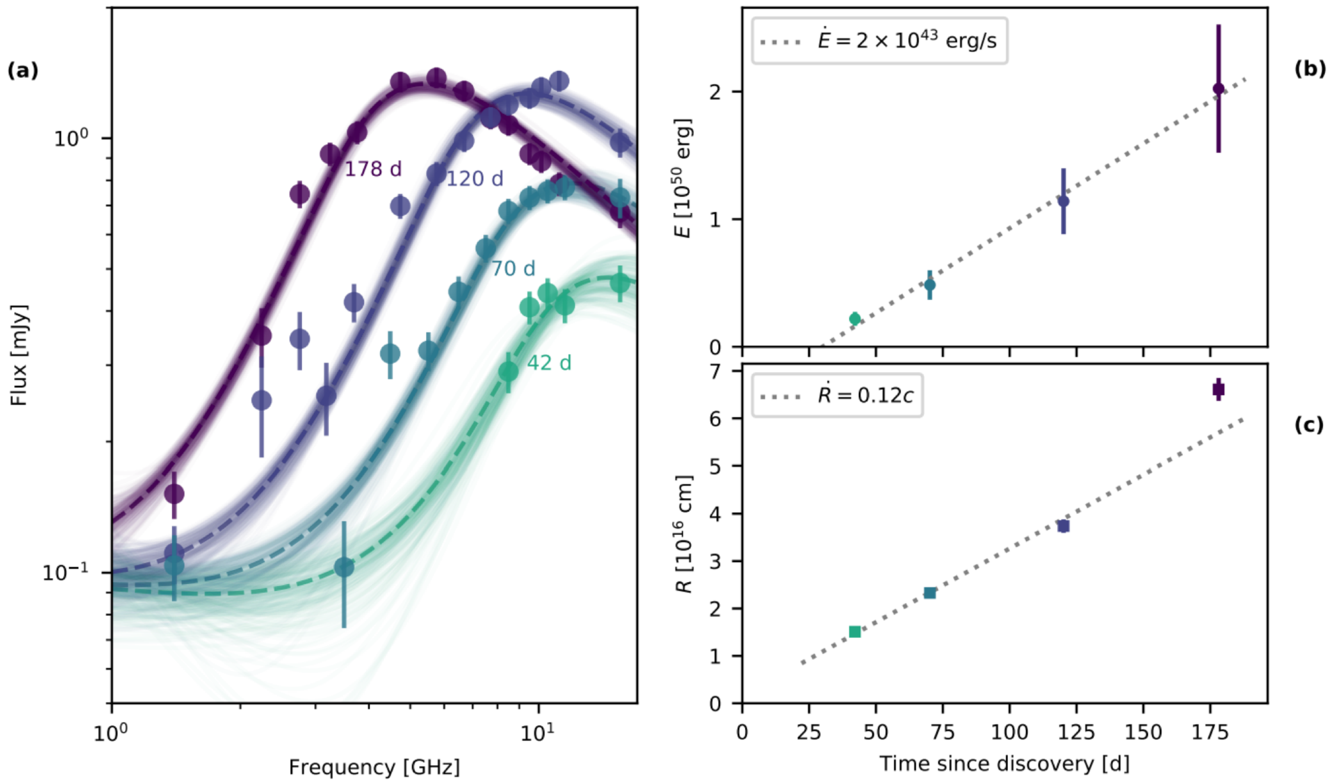
Source Candidates – AT 2019dsg





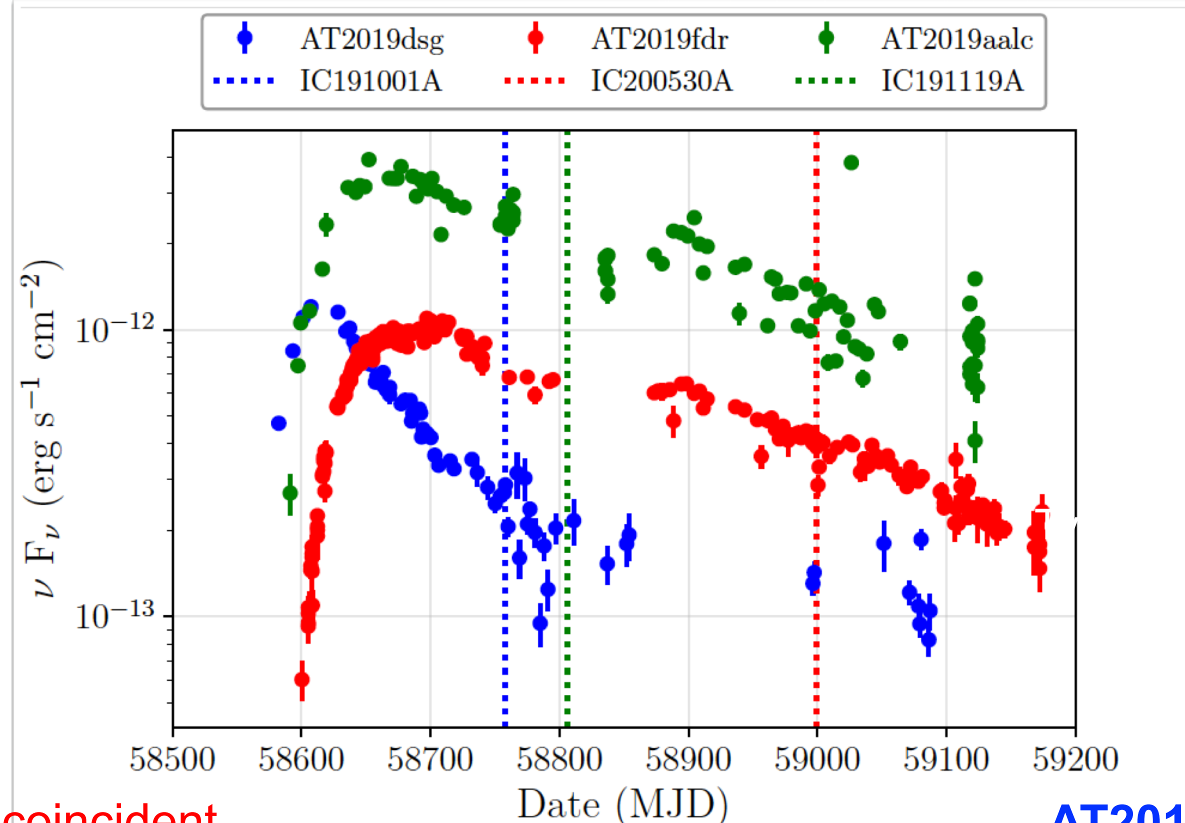
Source Candidates – AT 2019dsg

Radio observations



Radio data reveals long-lasting activity of central engine

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

What have we learned?

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

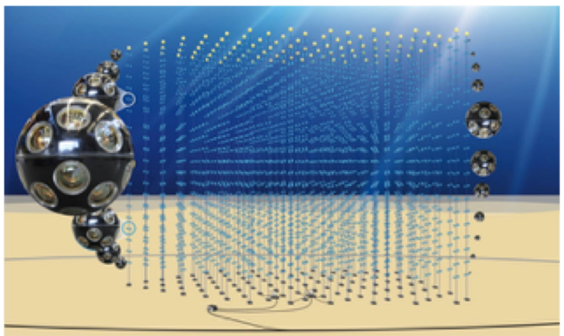
Next Generation Neutrino Telescopes

ICECUBE SOUTH POLE NEUTRINO OBSERVATORY

ANTARES

Today's neutrino telescopes

Neutrino sources on the southern sky

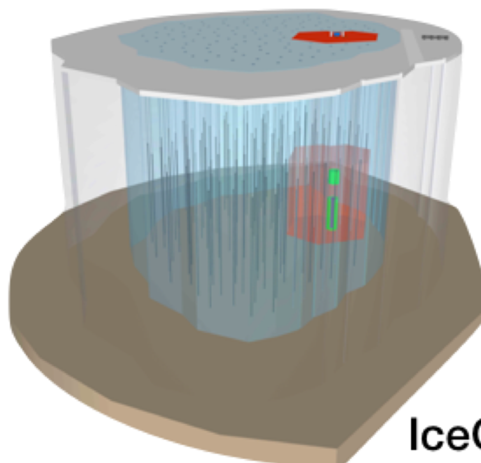


KM3NeT / Baikal-GVD
(construction started)

P-ONE Pacific ocean

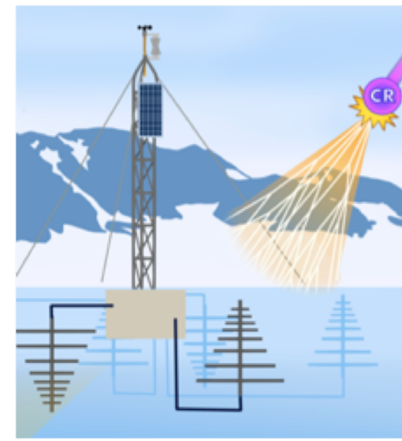
TRIDENT South Chinese Sea

5x better sensitivity in the TeV-PeV energy range



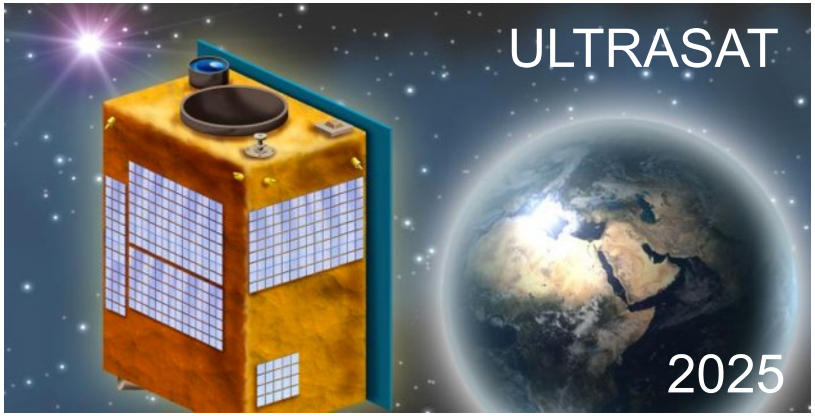
IceCube-Gen2
(Phase 1 started)

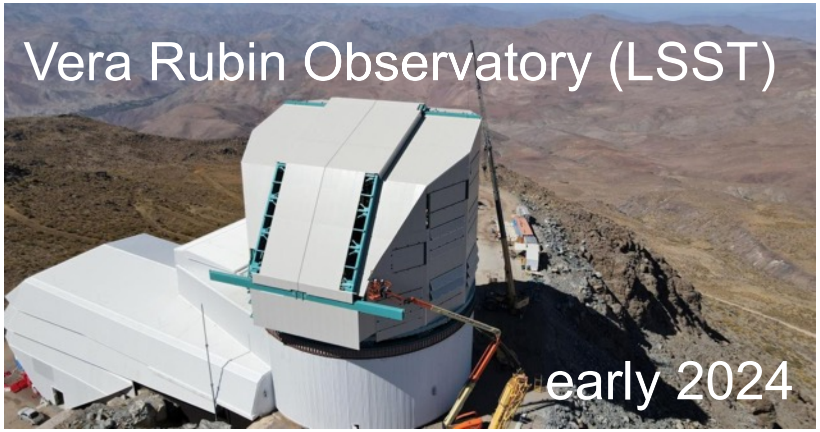
Neutrinos at EeV energies

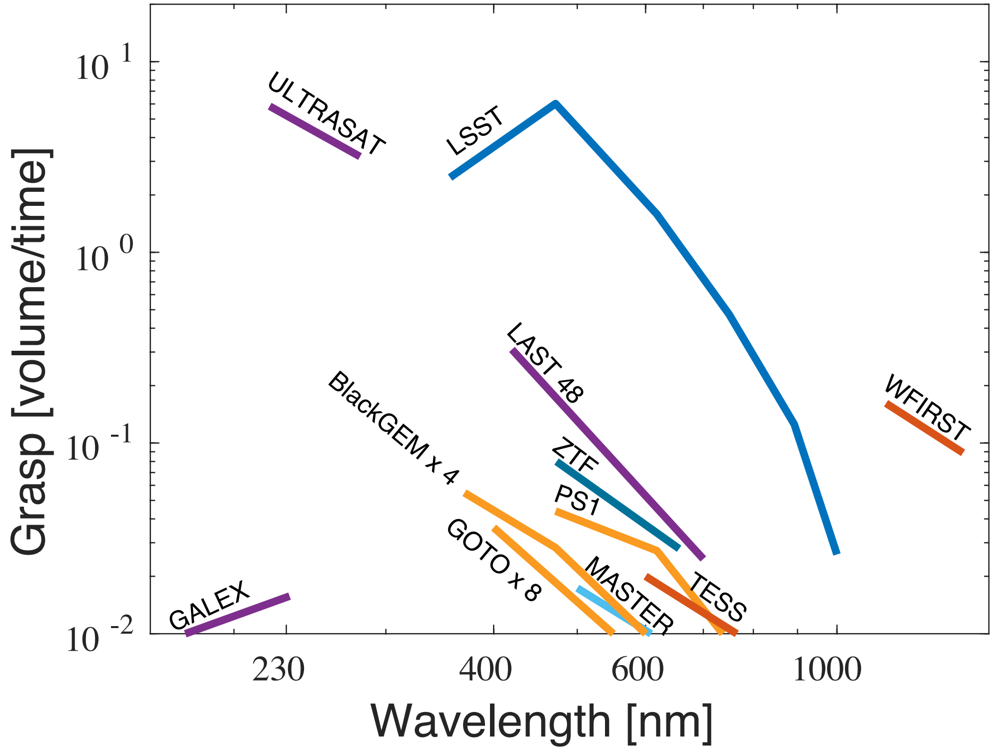


ARA/ARIANNA, RNO, Gen2-Radio
(proposals in)

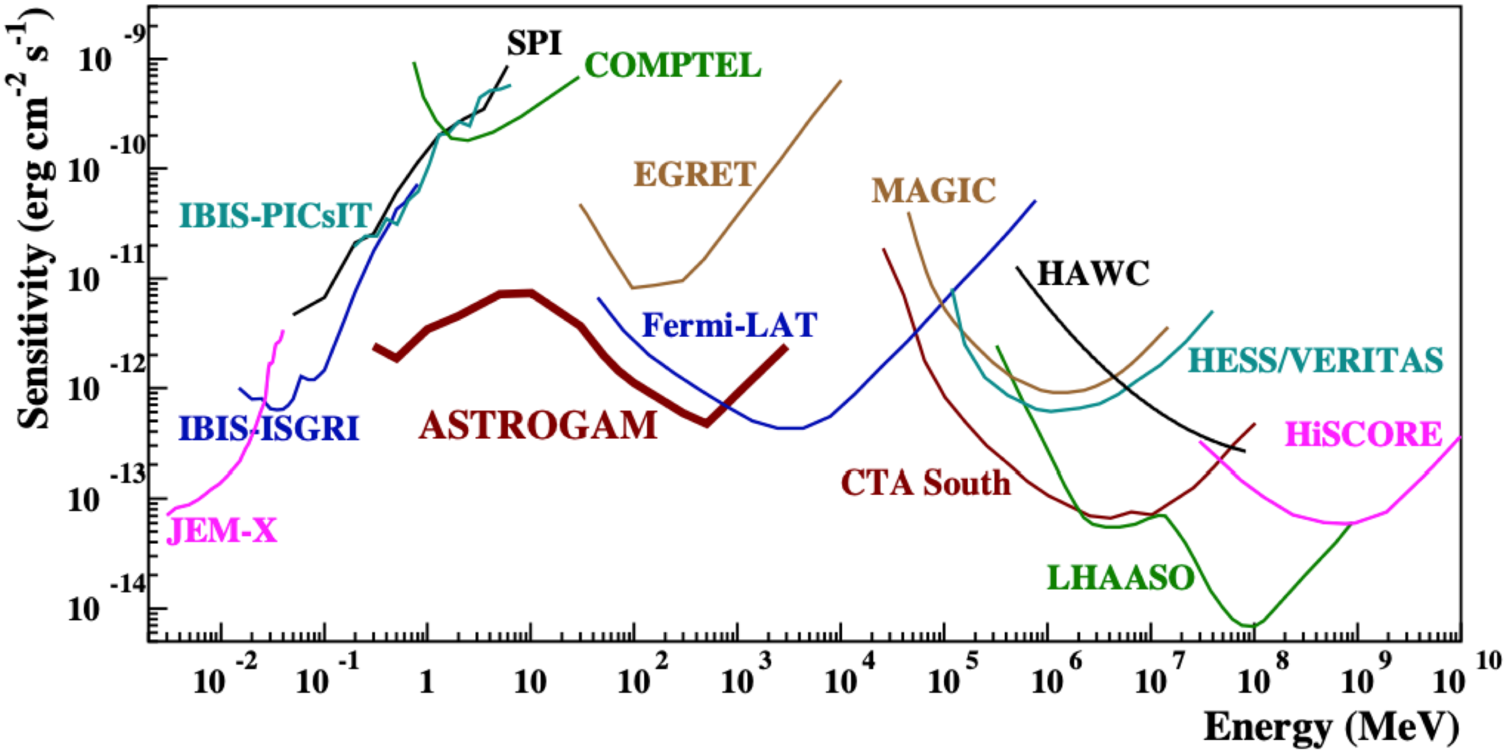
New Instrument to identify Counterparts

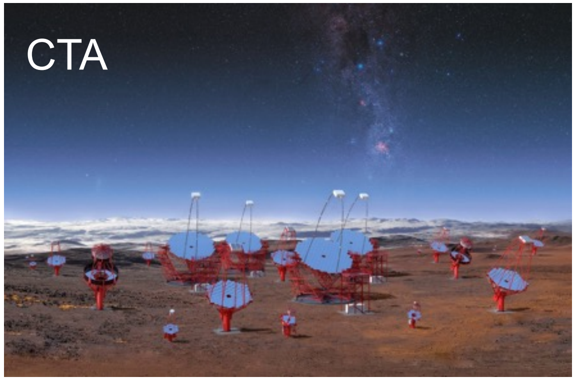






Closing the Gap in the MeV Range

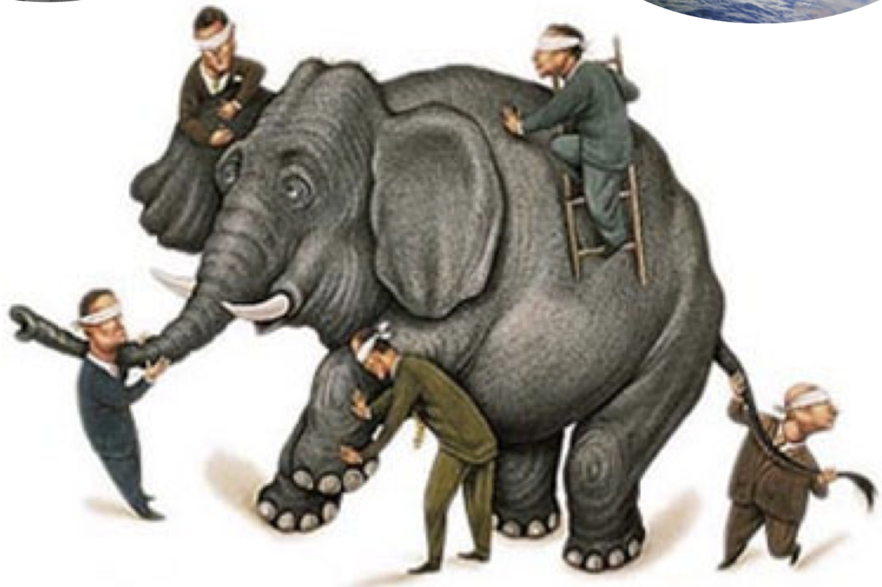


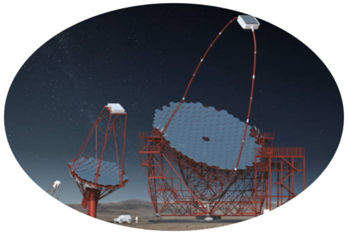


RUB

Summary

Neutrinos are unique messengers from the **high-energy Universe**





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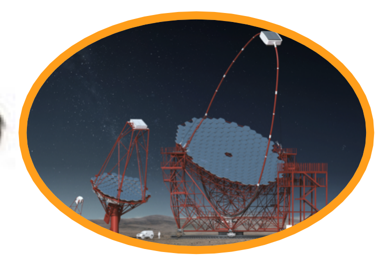
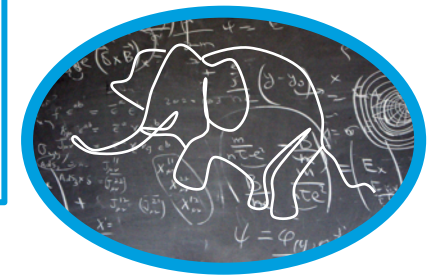
Summary

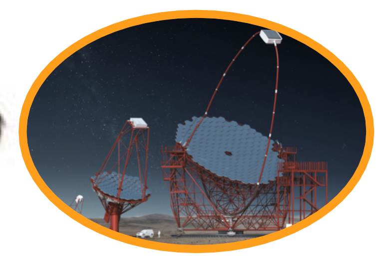
Multi-wavelength observations are key to identify neutrino (and cosmic-ray) sources



Summary

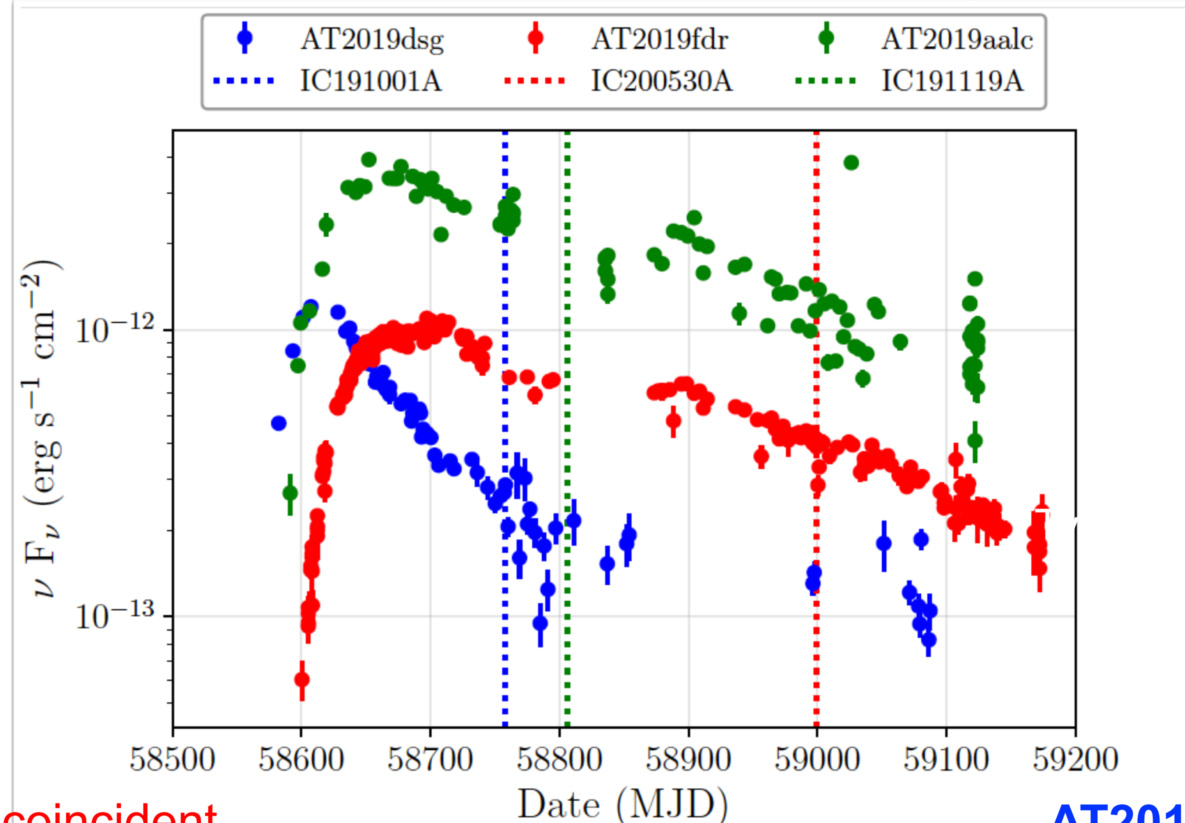
Theory plays a crucial role to **interpret the multi-messenger data**





Stay tuned!

Two more TDE candidates!



AT2019fdr coincident with IC200530A

AT2019aalc coincident with IC191119A

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

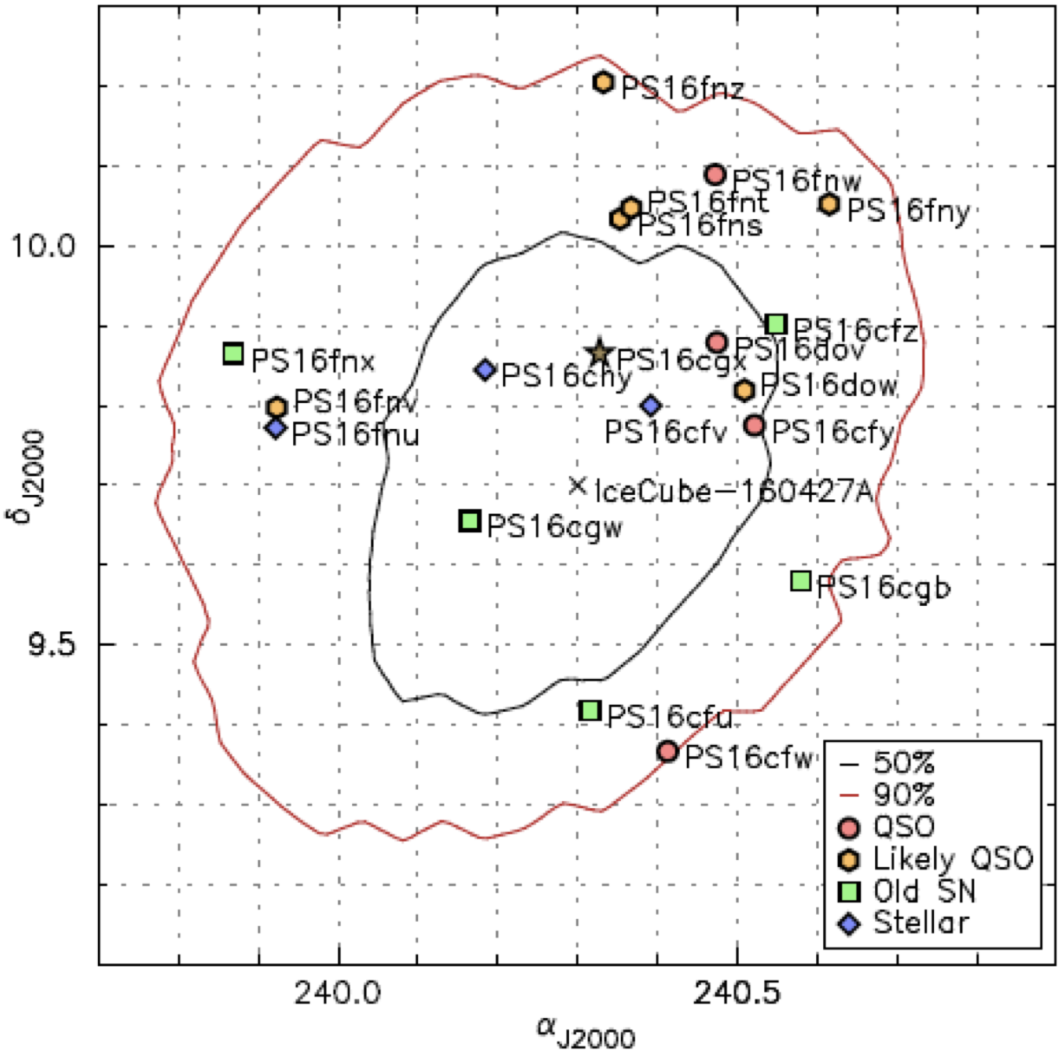
TDE population as new neutrino source class?

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

S. Reusch et al. PRL 2022

S. Van Velzen et al. arXiv:2111.09391

Pan-STARRS follow-up of IC-160427A



Type	Number
QSO	10
Stellar	3
Old SNe	5
Young SN	1
Total	**19**

Young SN found:
PS 16cgx
at z=0.29

Chance probability:

- if **type Ic** (associated with GRBs): **~2%**
- if **type Ia** (no HE neutrinos exp.): **~15%**

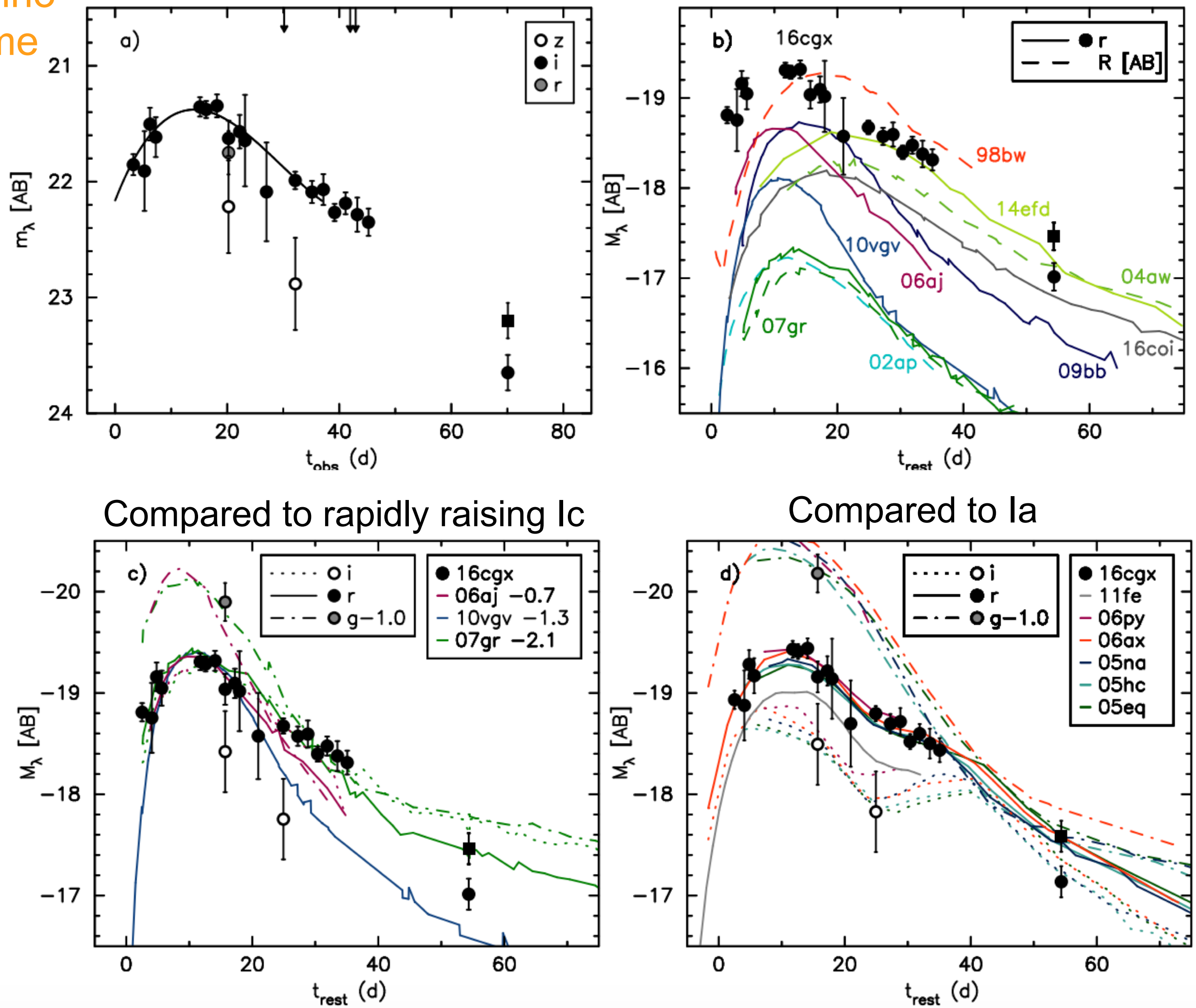
Neutrino should arrive at explosion time

t=0 neutrino arrival time

Compared to nearby Ic-BL

Compared to rapidly raising Ic

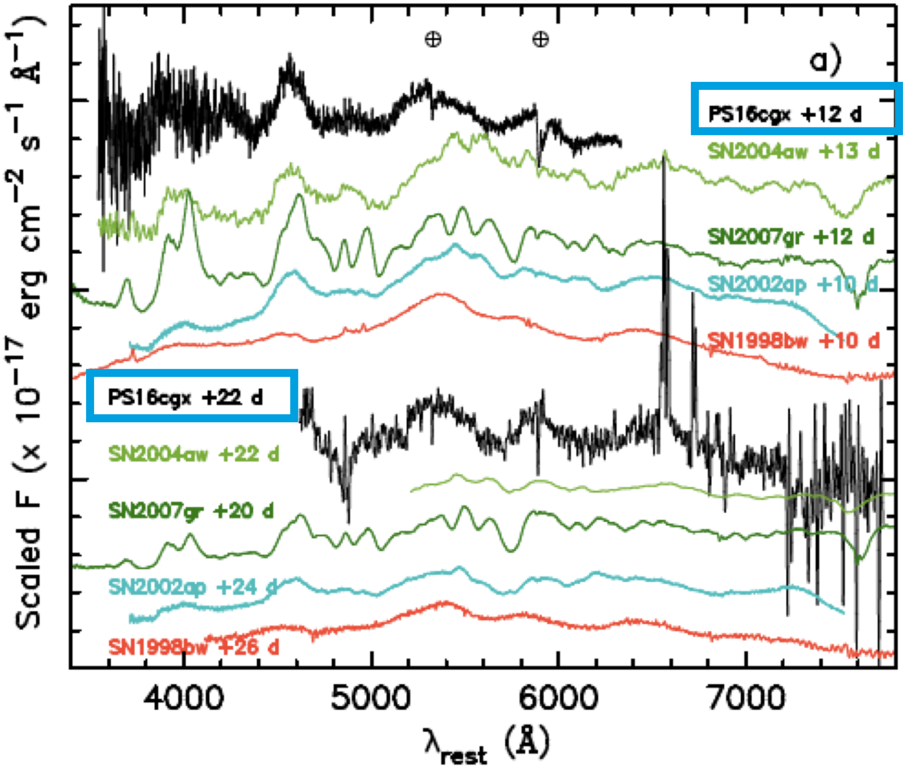
Compared to Ia



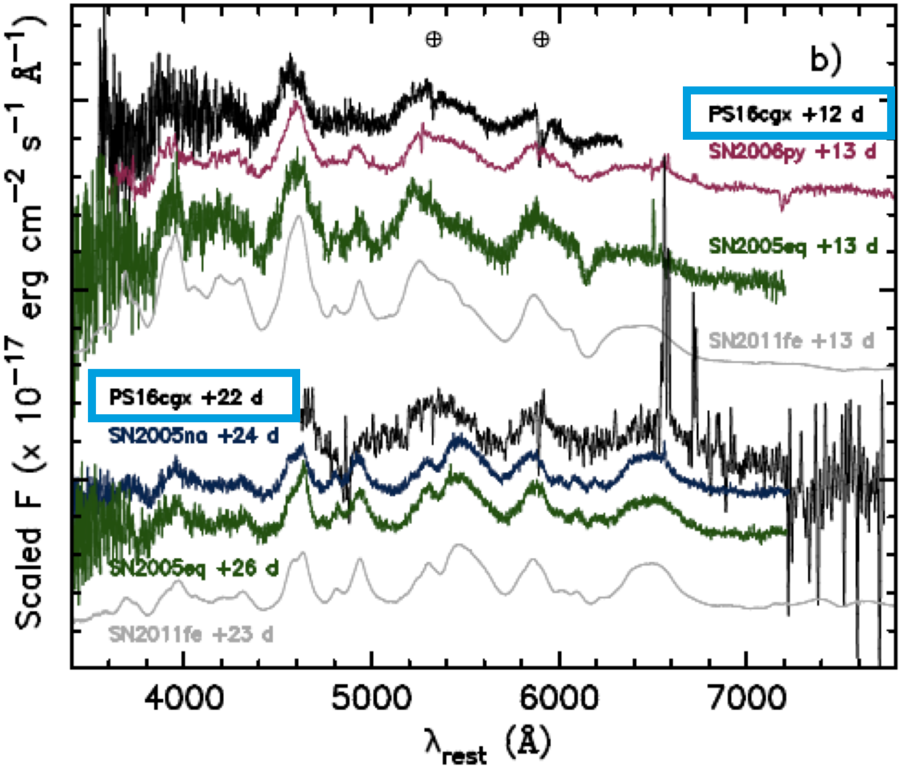
What type of SN is PS 16cgx?

Spectra

Comparison with core-collapse (type Ic), candidates for choked jets and neutrino emitters



Comparison with thermonuclear explosions (type Ia), no neutrino emitters

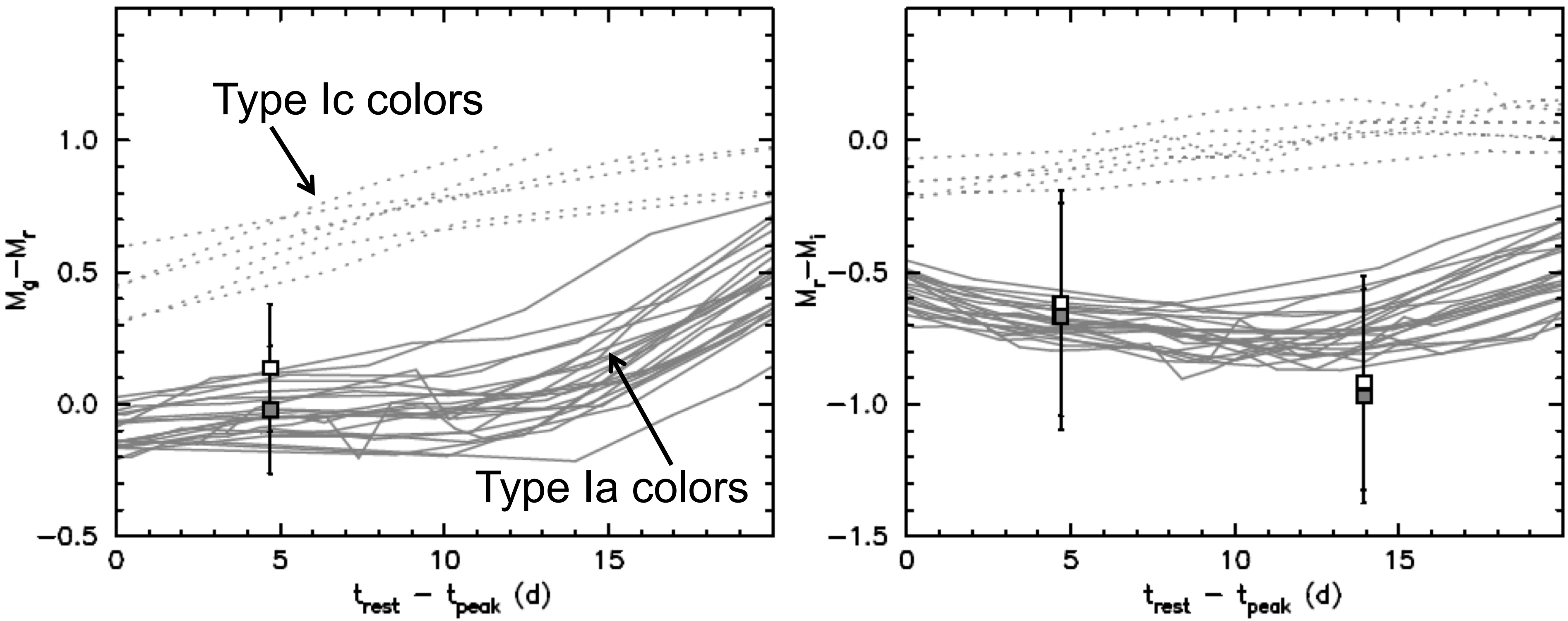


RUB E. Kankare et al. (IceCube and Pan-STARRS), A&A 626, A117, 2019

What type of SN is PS 16cgx?

Colors

PS 16cgx is more likely of type Ia → not a high-energy neutrino emitter

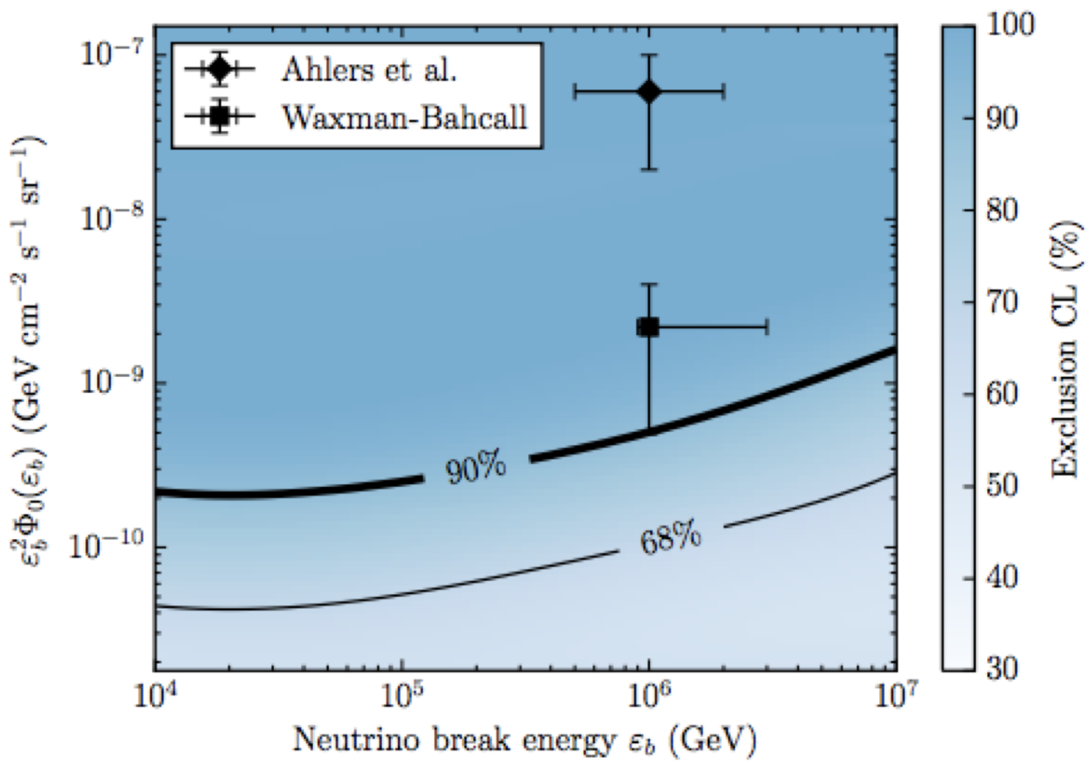


Gamma-Ray Bursts (GRBs)

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

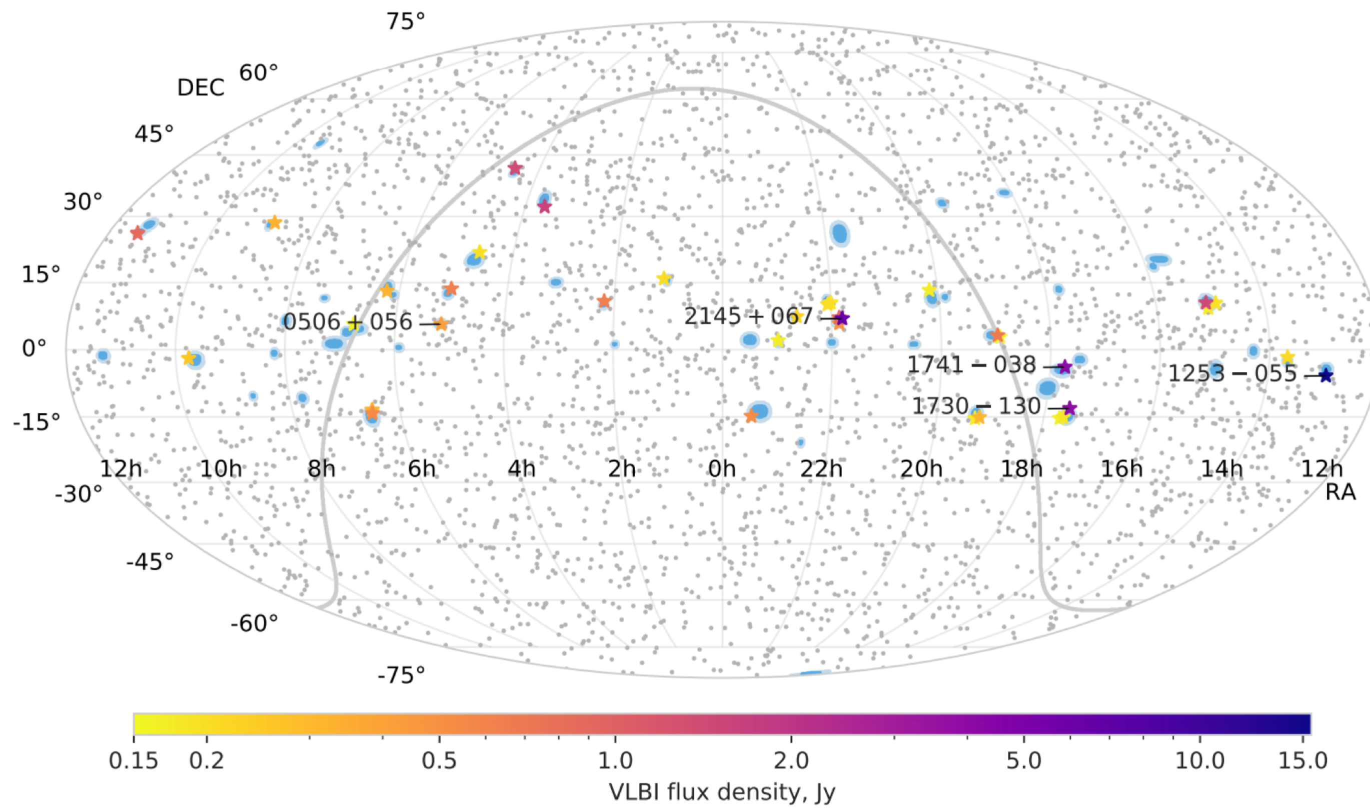


GRBs contribute less than 1% to observed diffuse neutrino flux. Potential large population of nearby low-luminosity GRBs not constrained

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

Stacking with radio-loud AGN

Correlation with VLBI-flux-density limited sample of AGN



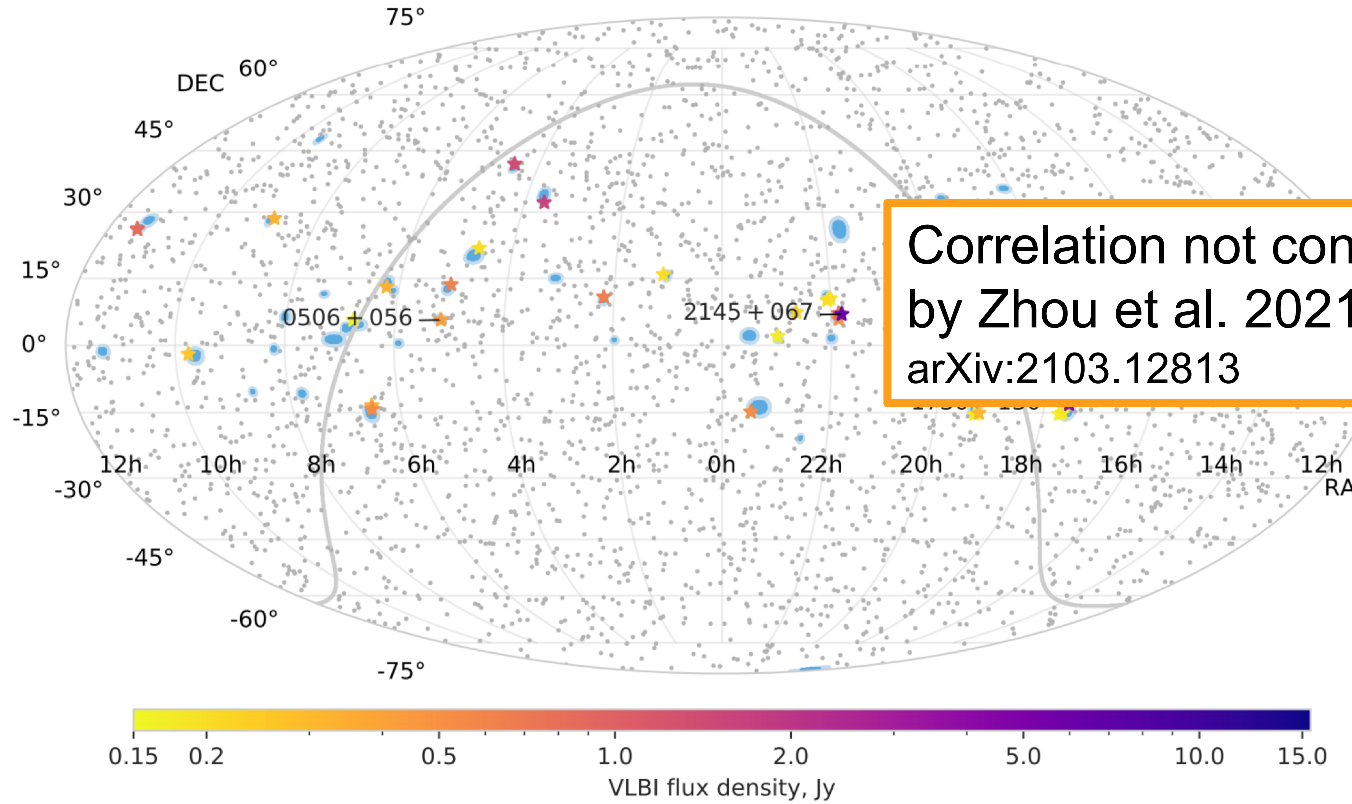
Correlation of radio-bright AGN with IceCube neutrino alerts at chance coincidence of 0.2%

RUB

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

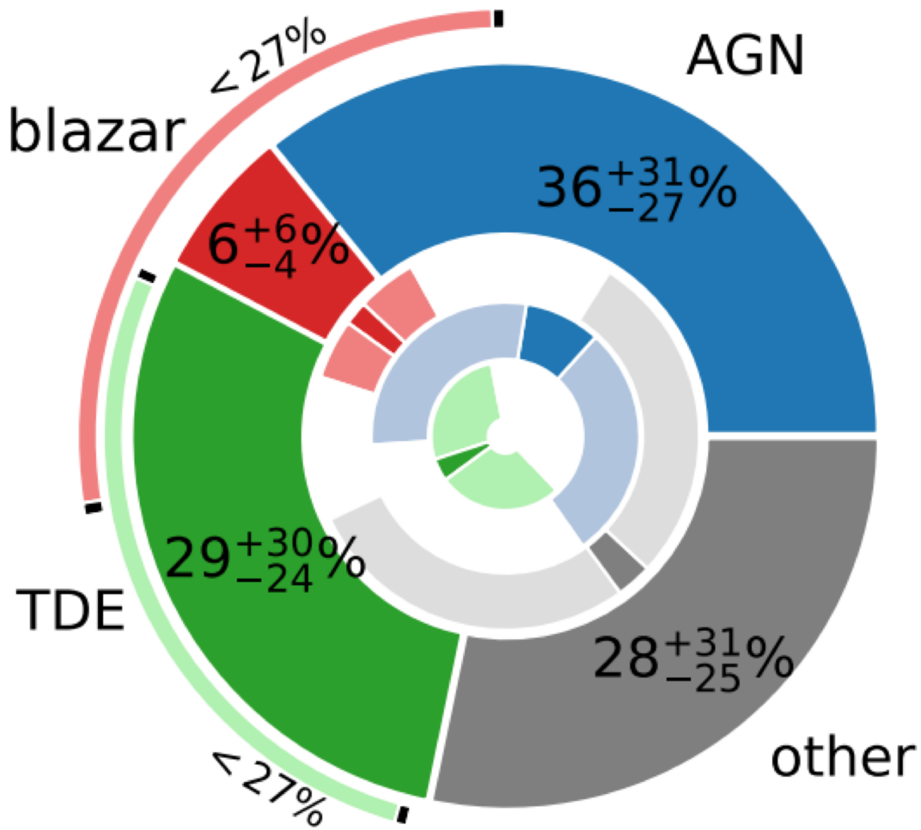


Correlation not confirmed by Zhou et al. 2021
arXiv:2103.12813

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

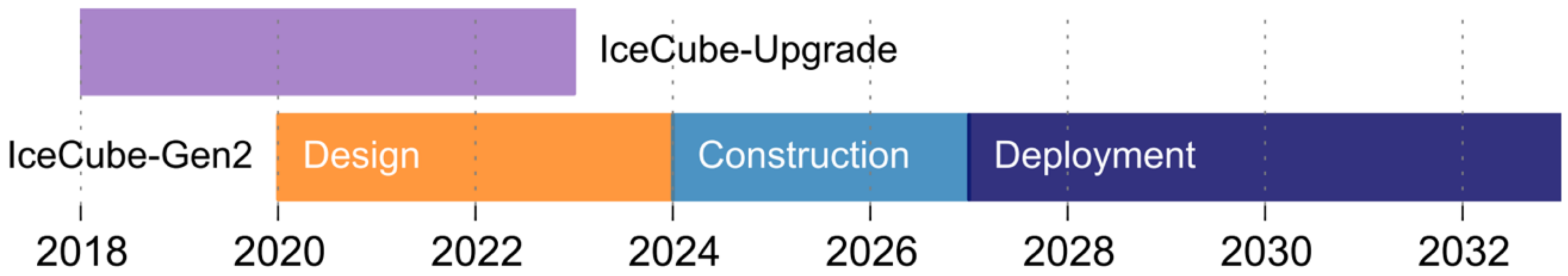
Plavin et al., ApJ 894 (2020), Plavin et al. 2020 arXiv:2009.08914

The Cosmic Neutrino Pi Chart

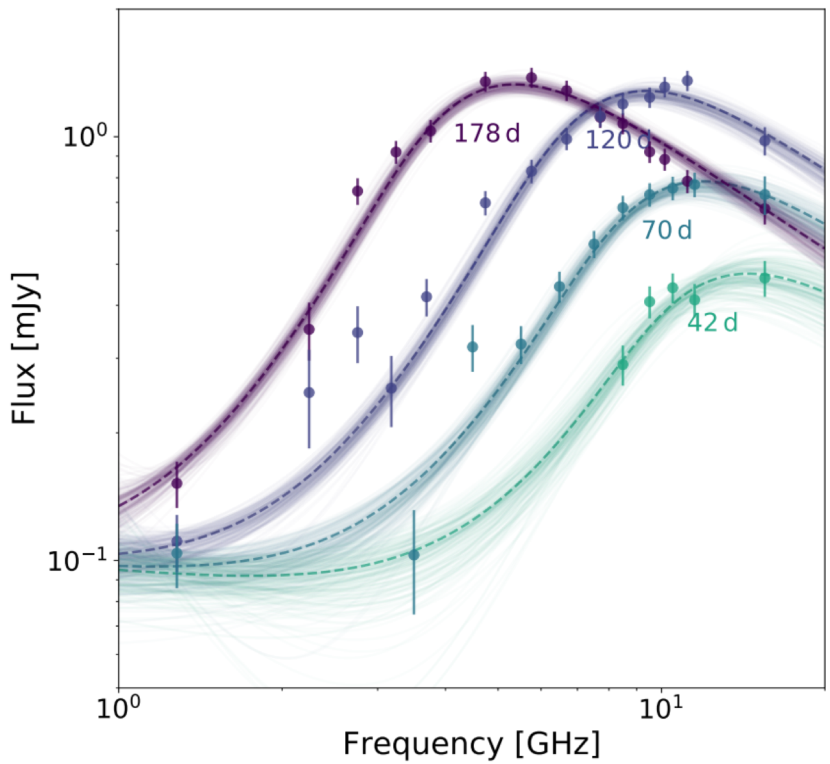


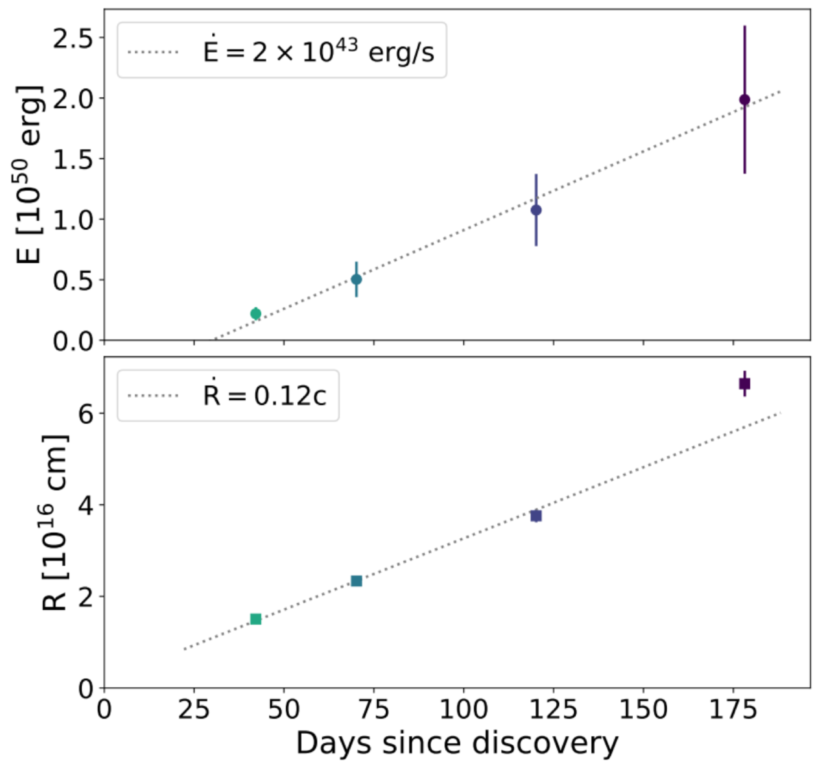
Bartos et al. Astrophys.J. 921 (2021)

IceCube-Gen2 time line



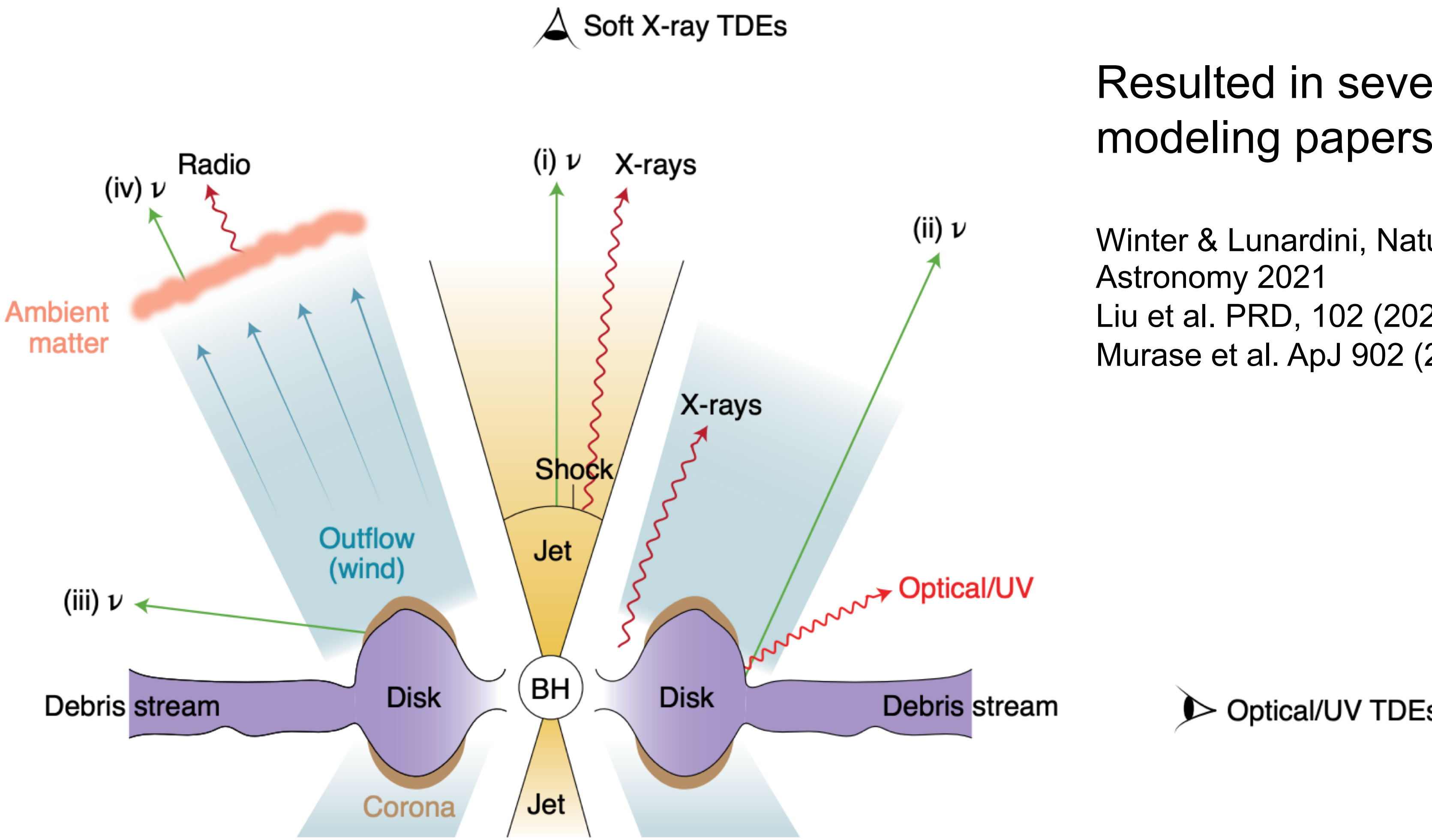
TDE AT2019dsg / “Bran Stark” coincident with 200 TeV Neutrino IC191001A





R. Stein et al., Nature Astronomy 2021

Neutrino Production in TDEs



Resulted in several modeling papers:

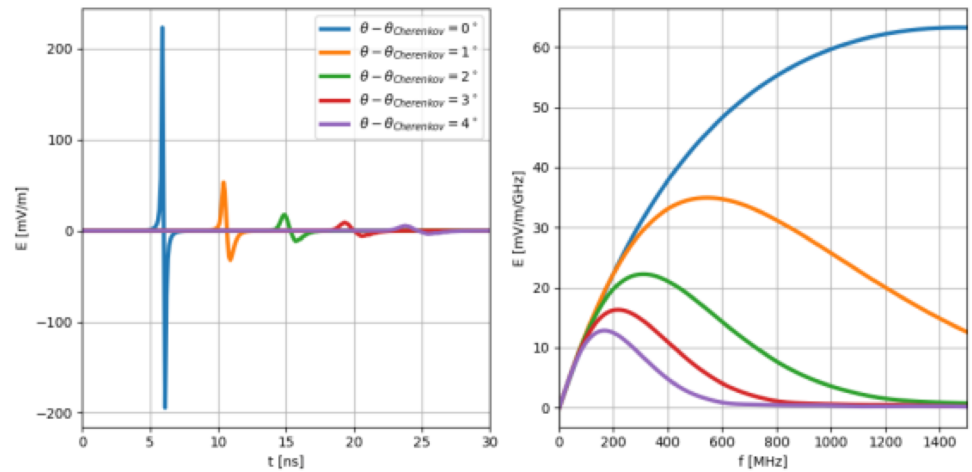
Winter & Lunardini, Nature Astronomy 2021
Liu et al. PRD, 102 (2020)
Murase et al. ApJ 902 (2020)

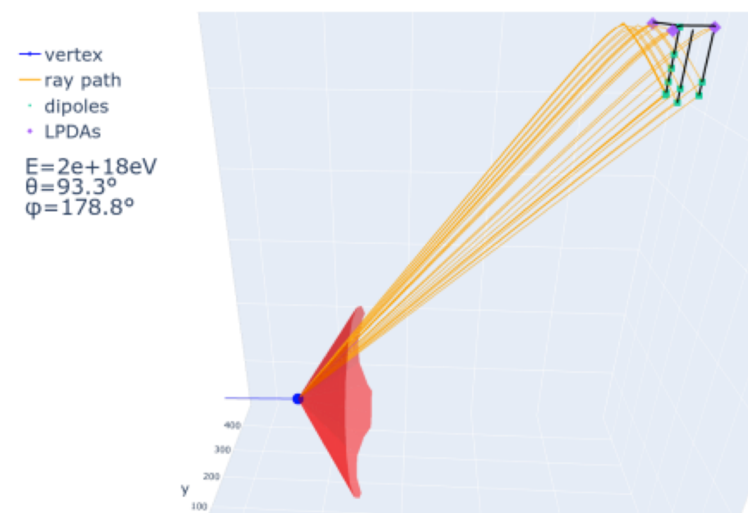
Hayasaki, Nature Astronomy 2021

Radio emission of showers in dense media

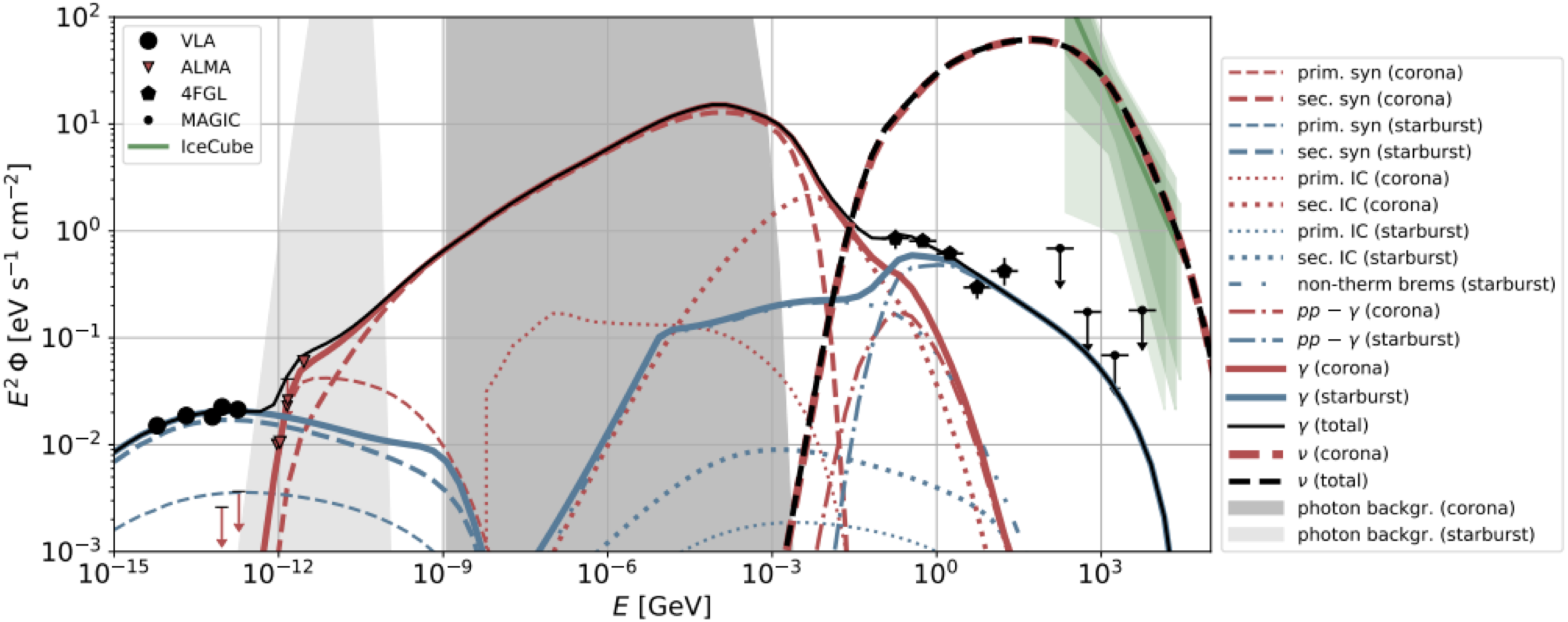
What are we looking for?

- **Askaryan effect**: Charge accumulation in the shower front gives rise to a changing current, which gives rise to radio emission
- Emission is coherent at frequencies corresponding to the size of the shower
- Index of refraction >> 1, emission strong on the Cherenkov cone, travel on non-straight lines with changing n
- Signals contain information in amplitude, frequency and polarisation





Spectrum of NGC 1068 (M77)



Eichmann et al. 2021