Follow-up γ-ray observations of neutrino events with the H.E.S.S. imaging atmospheric Cherenkov telescope

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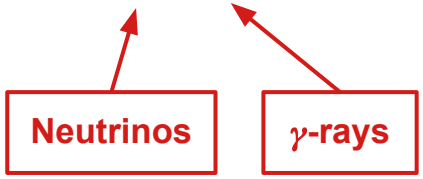
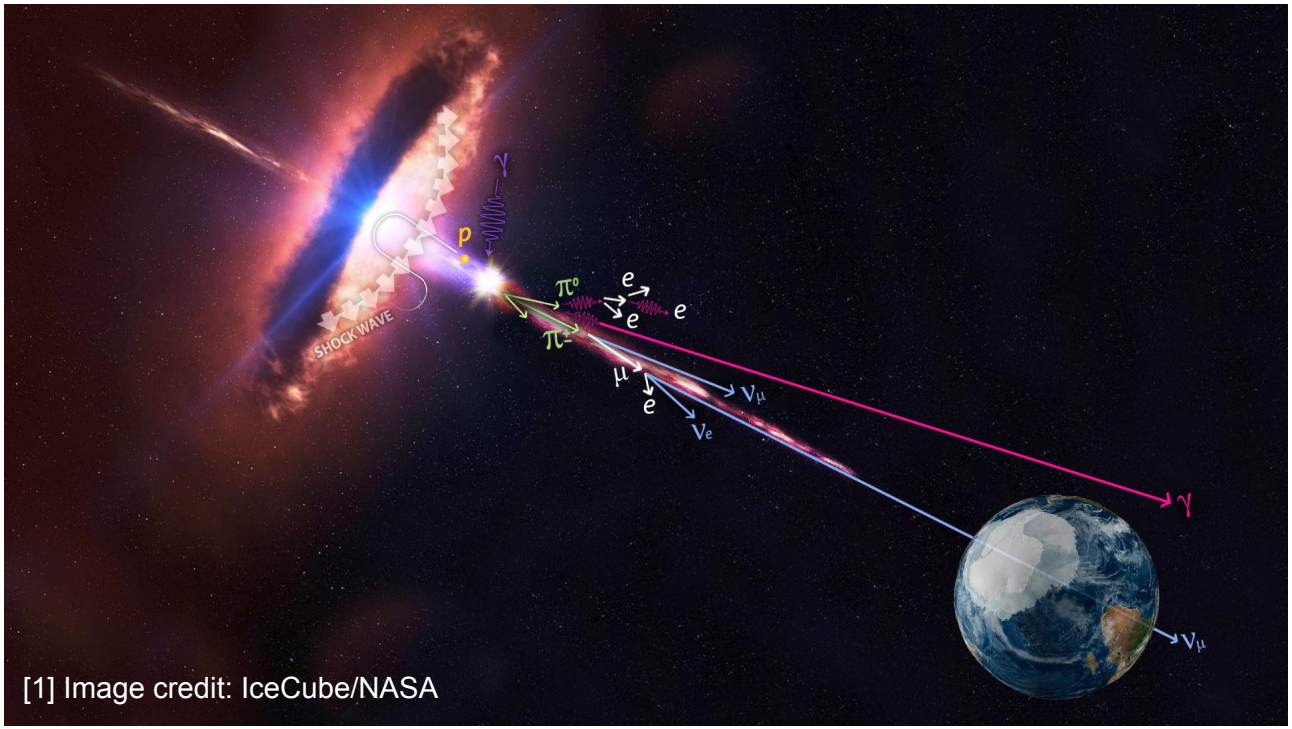
Astronomdagarna 2021: 21st Oct, 2021

H.E.S.S.

HE neutrinos from γ-ray sources

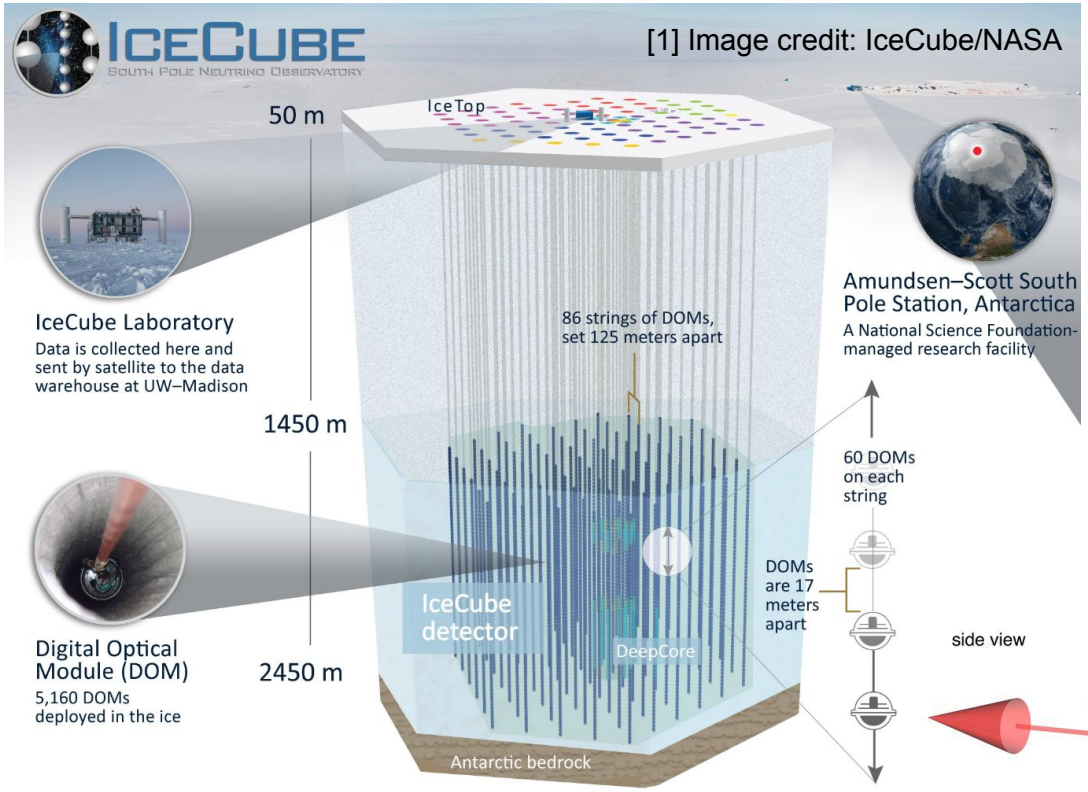
- Interaction of hadrons and radiation fields at source: $p + \gamma \rightarrow \pi^{\pm}/\pi^{0}$
- Indicators of UHE cosmic rays (energies above tens of PeV)
- Point directly back to the source
- Most likely extragalactic candidates: Blazars (AGN)





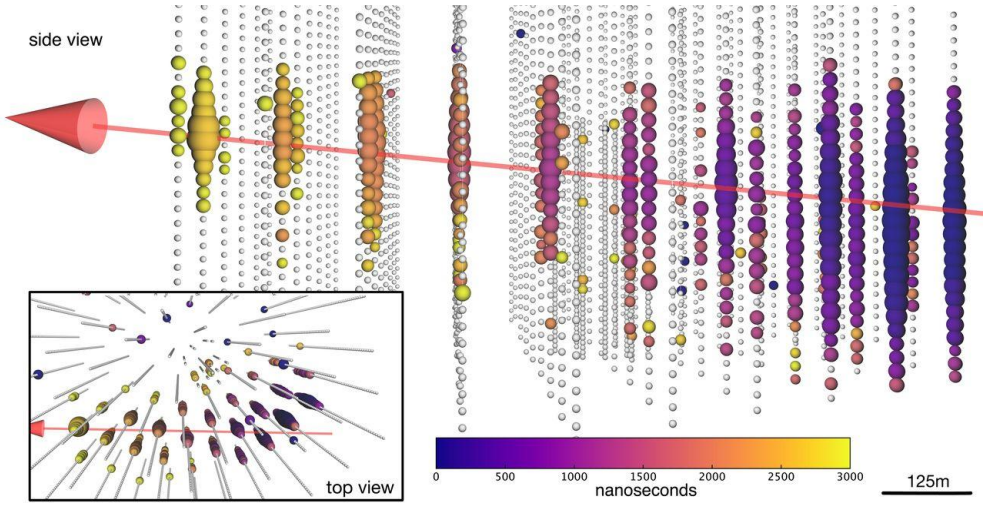
[1] Image credit: IceCube/NASA

Detection of HE neutrinos - IceCube



- Neutrinos interact with atoms to produce muons
- Resulting muons emit Cherenkov light in clear Antarctic ice
- Detected tracks in strings with 5160 optical modules

[2] doi:10.1126/science.aat1378



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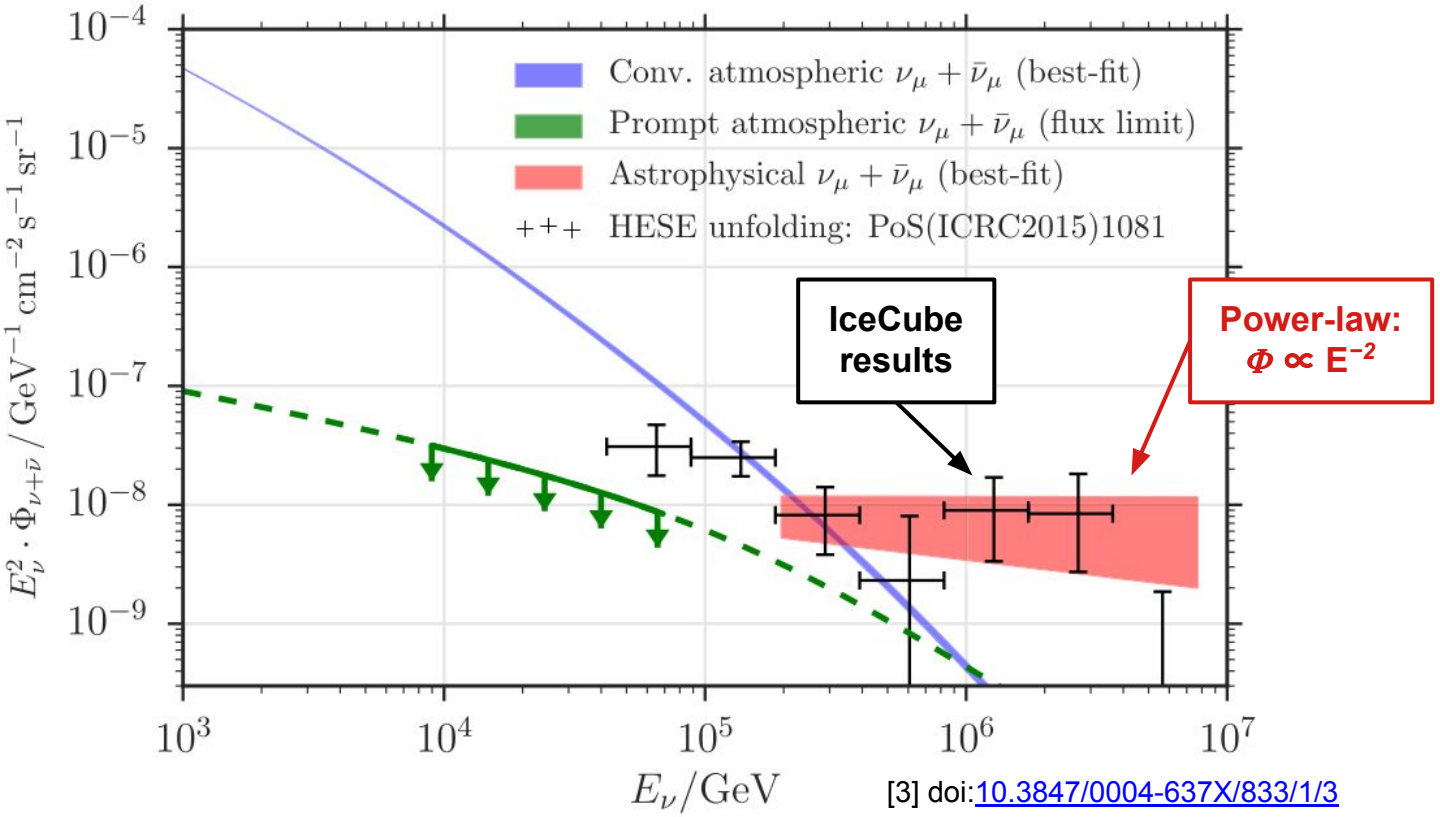
Astrophysical vs. atmospheric origin

- Neutrinos also produced in atmospheric air showers (background)
- Above ~100 TeV astrophysical neutrinos are dominant
- Probability of neutrino to be astrophysical → **signalness**



[3] doi:10.3847/0004-637X/833/1/3

Real-time alert system

- IceCube distributes a notice to AMON (Astrophysical Multimessenger Observatory Network) and a GCN (Gamma-ray Coordinates Network) alert for follow-up observations

```
////////////////////////////////////////////////////////////
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Fri 22 Sep 17 20:55:13 UT
NOTICE_TYPE:      AMON ICECUBE EHE
RUN_NUM:          130033
EVENT_NUM:        50579430
SRC_RA:            77.2853d {+05h 09m 08s} (J2000),
                   77.5221d {+05h 10m 05s} (current),
                   76.6176d {+05h 06m 28s} (1950)
SRC_DEC:           +5.7517d {+05d 45' 06"} (J2000),
                   +5.7732d {+05d 46' 24"} (current),
                   +5.6888d {+05d 41' 20"} (1950)
SRC_ERROR:        14.99 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   18018 TJD;   265 DOY;   17/09/22 (yy/mm/dd)
DISCOVERY_TIME:   75270 SOD {20:54:30.43} UT
REVISION:         0
N_EVENTS:         1 [number of neutrinos]
STREAM:           2
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000e+00 [dn]
ENERGY :          1.1998e+02 [TeV]
SIGNALNESS:       5.6507e-01 [dn]
CHARGE:           5784.9552 [pe]
SUN_POSTN:        180.03d {+12h 00m 08s}   -0.01d {-00d 00' 53"}
SUN_DIST:         102.45 [deg]   Sun_angle= 6.8 [hr] (West of Sun)
MOON_POSTN:       211.24d {+14h 04m 58s}   -7.56d {-07d 33' 33"}
MOON_DIST:        134.02 [deg]
GAL_COORDS:       195.31,-19.67 [deg] galactic lon,lat of the event
ECL_COORDS:        76.75,-17.10 [deg] ecliptic lon,lat of the event
COMMENTS:         AMON_ICECUBE_EHE.
```

```
TITLE:   GCN CIRCULAR
NUMBER:  21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy
neutrino candidate event

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg  90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000
```

Alert reference number

Initial arrival direction

Refined arrival direction

Neutrino energy (120 TeV)

Astrophysical origin probability (56.5%)

[4] https://gcn.gsfc.nasa.gov/amon.html, https://gcn.gsfc.nasa.gov/gcn3_archive.html

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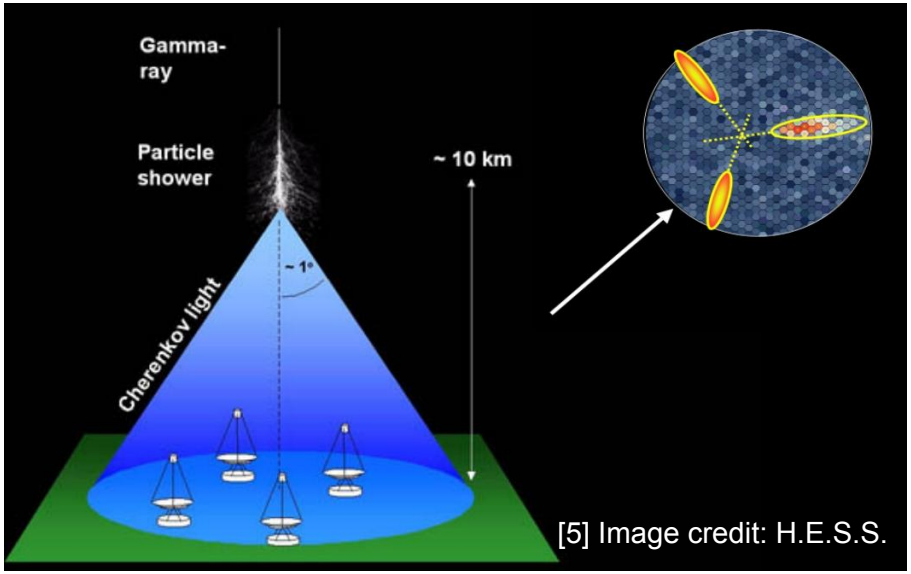
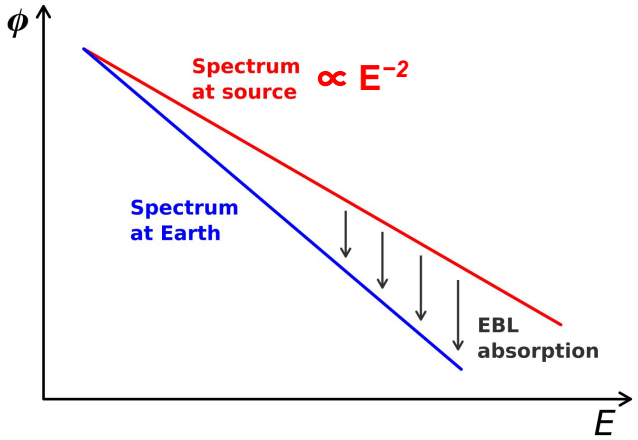
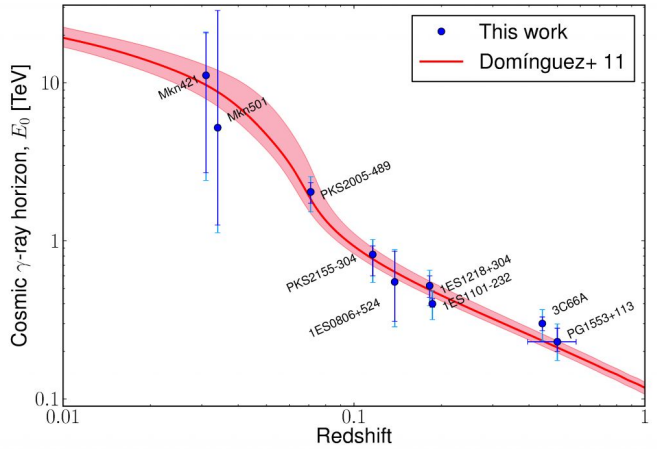
Follow-up VHE γ-ray observations with H.E.S.S.

- Remember: HE neutrinos and VHE γ-rays produced at the same source
- VHE γ-ray absorption due to EBL (Extragalactic Background Light)
- H.E.S.S.:
  - Operational since 2002
  - Four 12 m (5° FOV) and one 28 m (3.2° FOV) telescope
  - Energy range ~ [30 GeV, 100 TeV]



[5] Image credit: H.E.S.S.

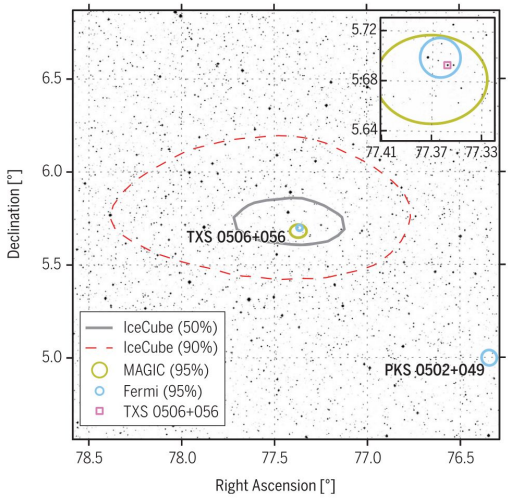


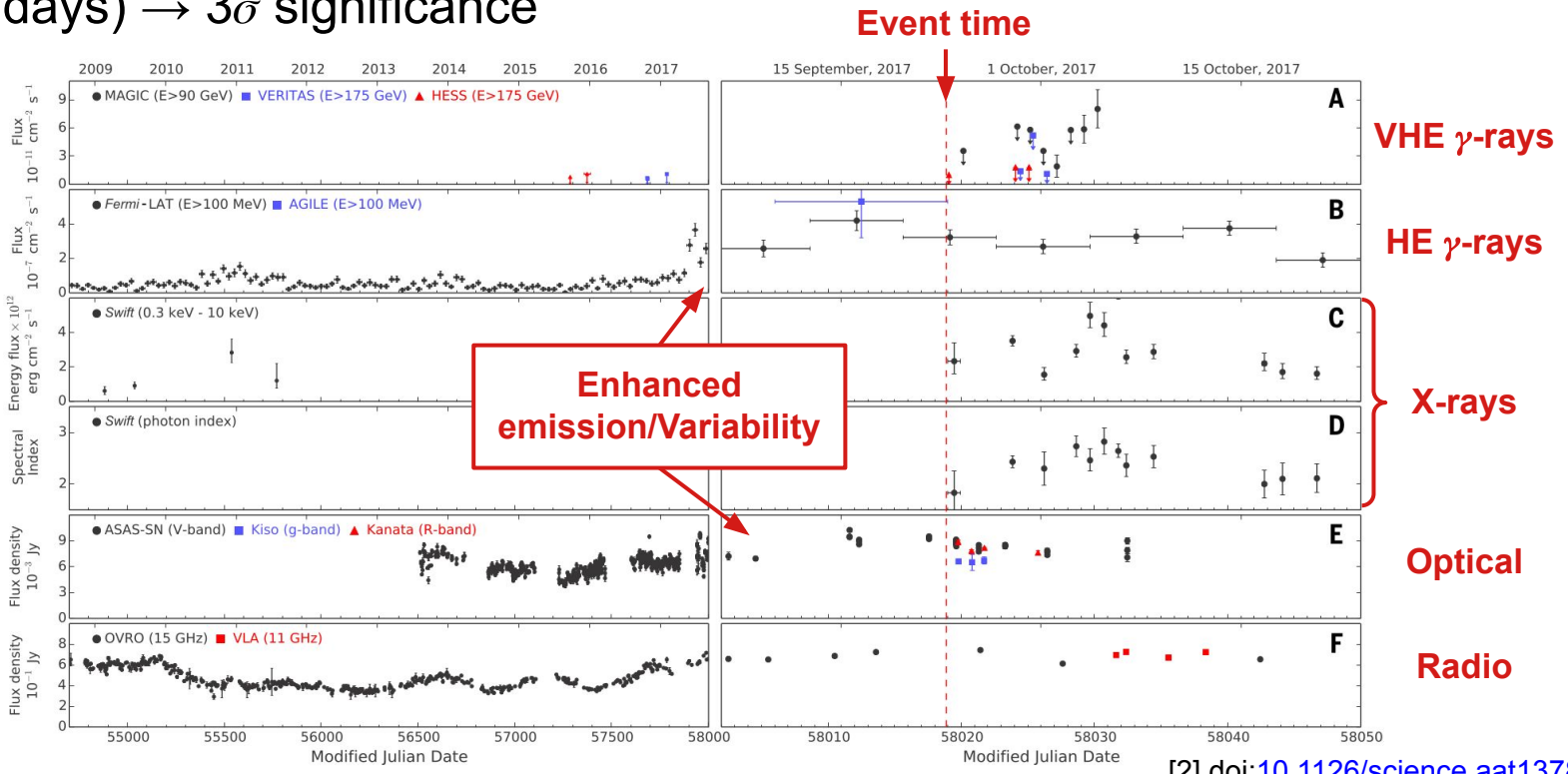


[6] doi:10.1088/0004-637X/770/1/77

IceCube-170922A from direction of TXS 0506+056

- Neutrino detected on 22.9.2017 with energy 120 TeV
- Coincident with γ-ray source (within 0.1°, z = 0.3365)
- Multiwavelength observation campaign of the source (14 days) → 3σ significance





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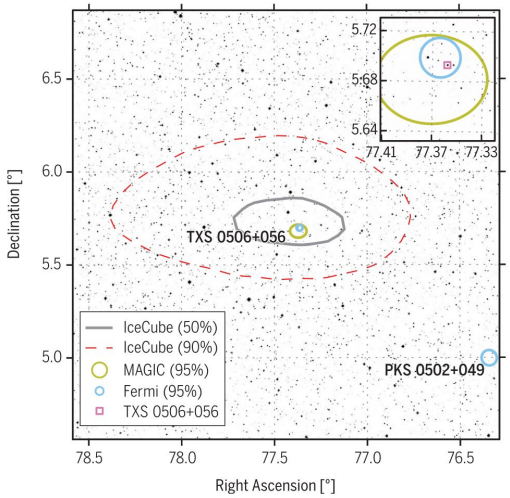
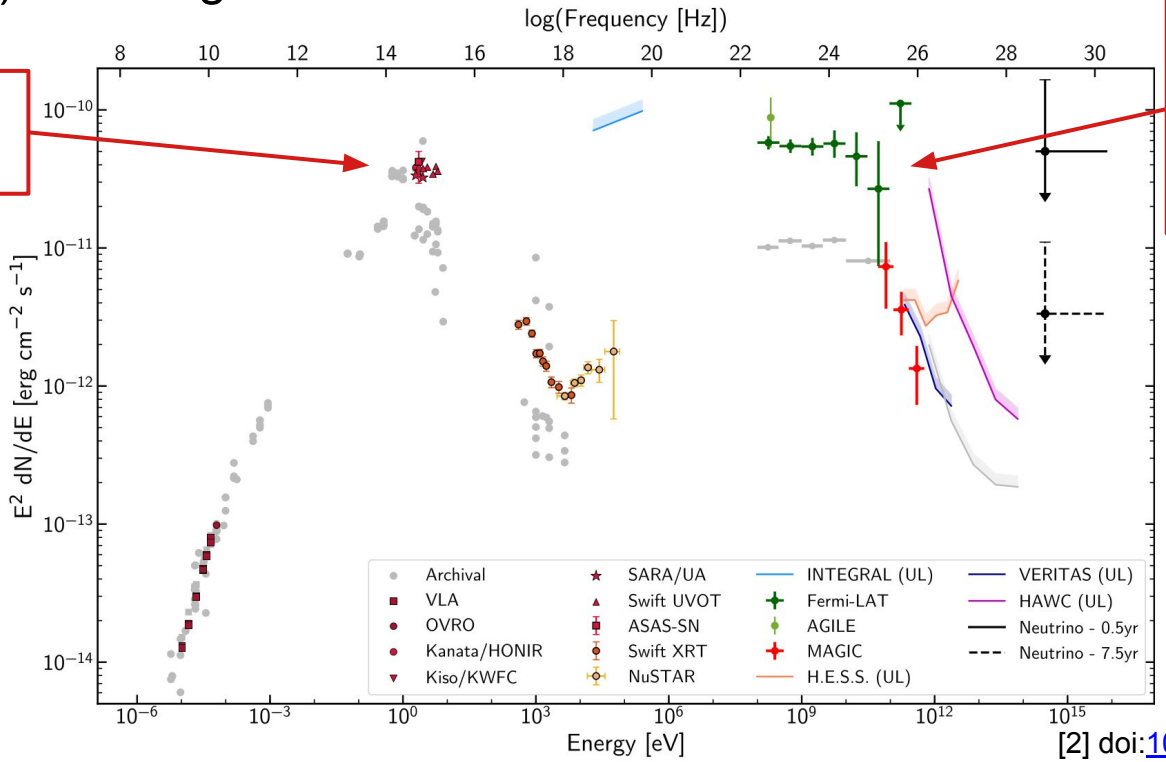


Synchrotron emission peak

Inverse-Compton emission peak + Possible hadronic pion production



Higher flux compared to archival data

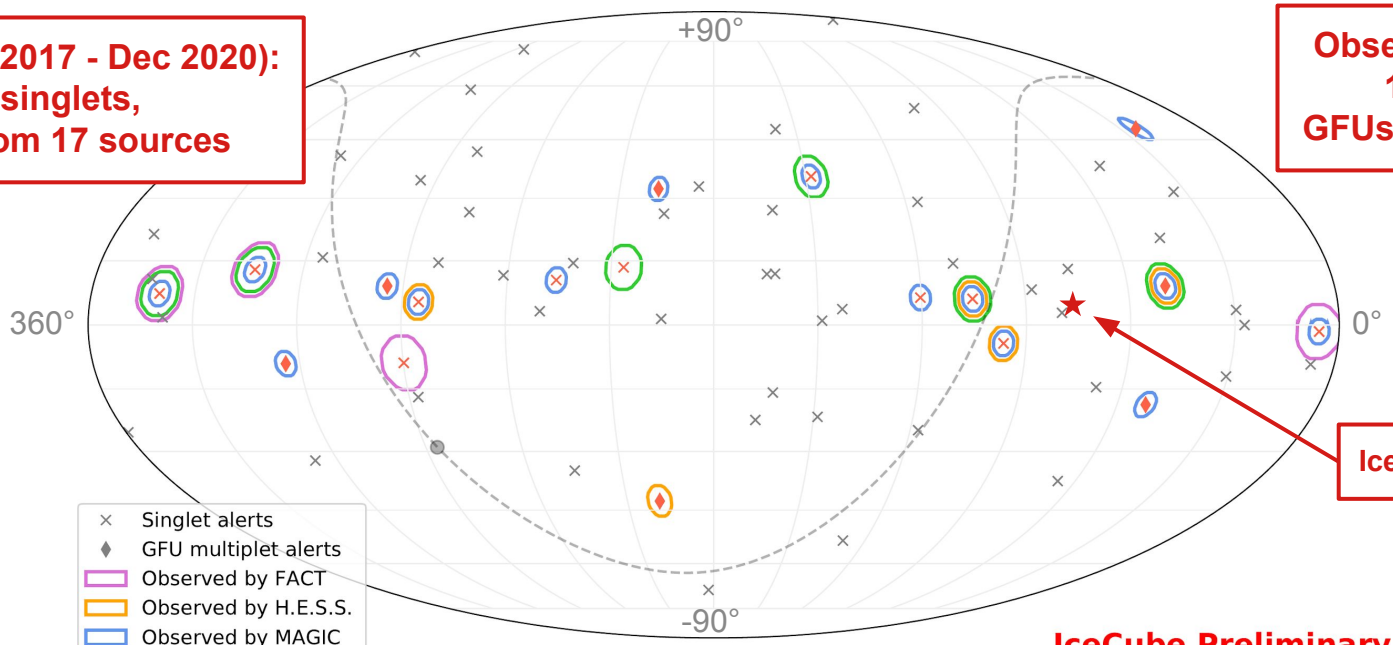
[2] doi:10.1126/science.aat1378

Observation campaign since IceCube-170922A

- In addition to singlet alerts, Gamma-ray Follow Up (GFU) alerts with multiple neutrinos from direction of a known source
- General observation strategy:
  1. Check for coincidence between neutrino and source
  2. Determine the state of the source + Compare with archival data
  3. Enhanced emission (significance?) or no variability (upper limits)

Alerts (Oct 2017 - Dec 2020):
62 singlets,
GFUs from 17 sources

Observed by IACTs:
11 singlets,
GFUs from 7 sources



[7] arXiv:2109.04350 [astro-ph.HE]

IceCube Preliminary
Equatorial coordinates

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Conclusions

- **Why observe HE neutrinos from extragalactic sources?**
  Confirmation of UHE cosmic ray production at sources, nature of cosmic ray acceleration, confirmation of hadronic pion production models
- **What can follow-up observation of VHE γ-rays tell us?**
  If source is highly active (statistically significant detection) or has no variability (upper limit constraints)
- **What is still needed?**
  Increased statistics of HE neutrinos from the same source/direction

Thank you!

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