MWL follow-up of neutrino alerts

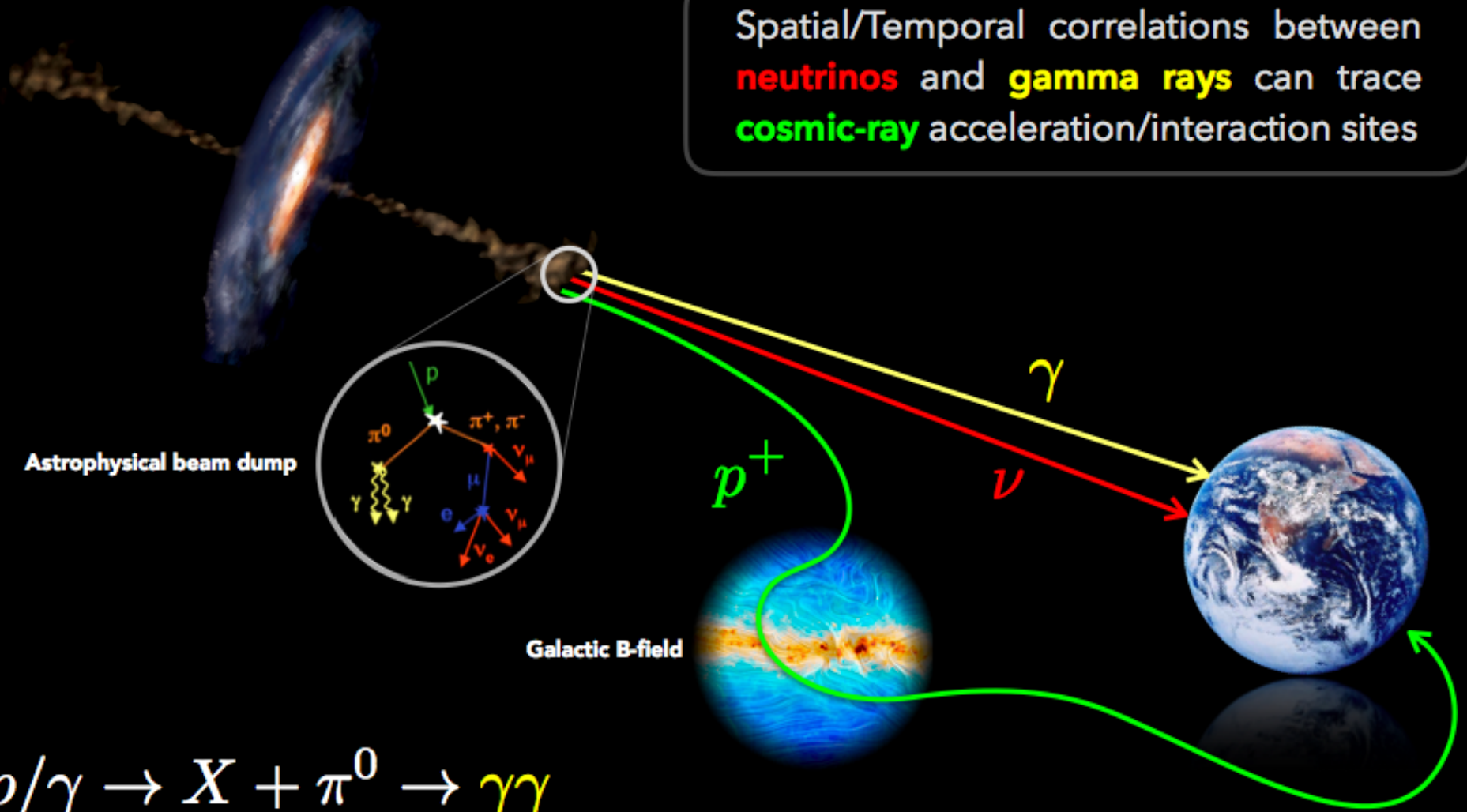
Challenges and perspectives

Konstancja Satalecka, DESY
TMEX 2020, Quy Nhon, Vietnam

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

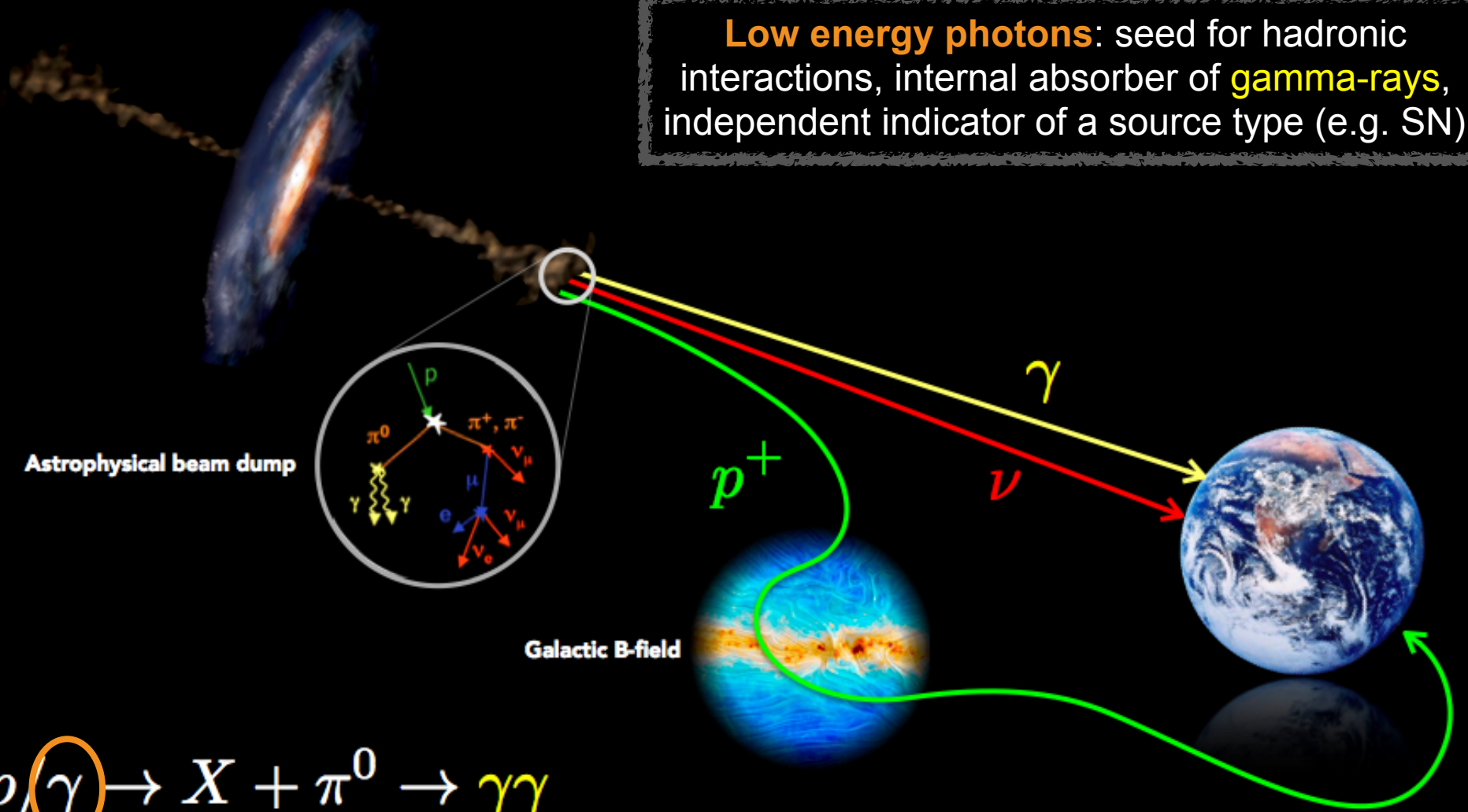
DESY.

Spatial/Temporal correlations between **neutrinos** and **gamma rays** can trace **cosmic-ray** acceleration/interaction sites



$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ **(oscillates to ~1:1:1)**

Low energy photons: seed for hadronic interactions, internal absorber of gamma-rays, independent indicator of a source type (e.g. SN)



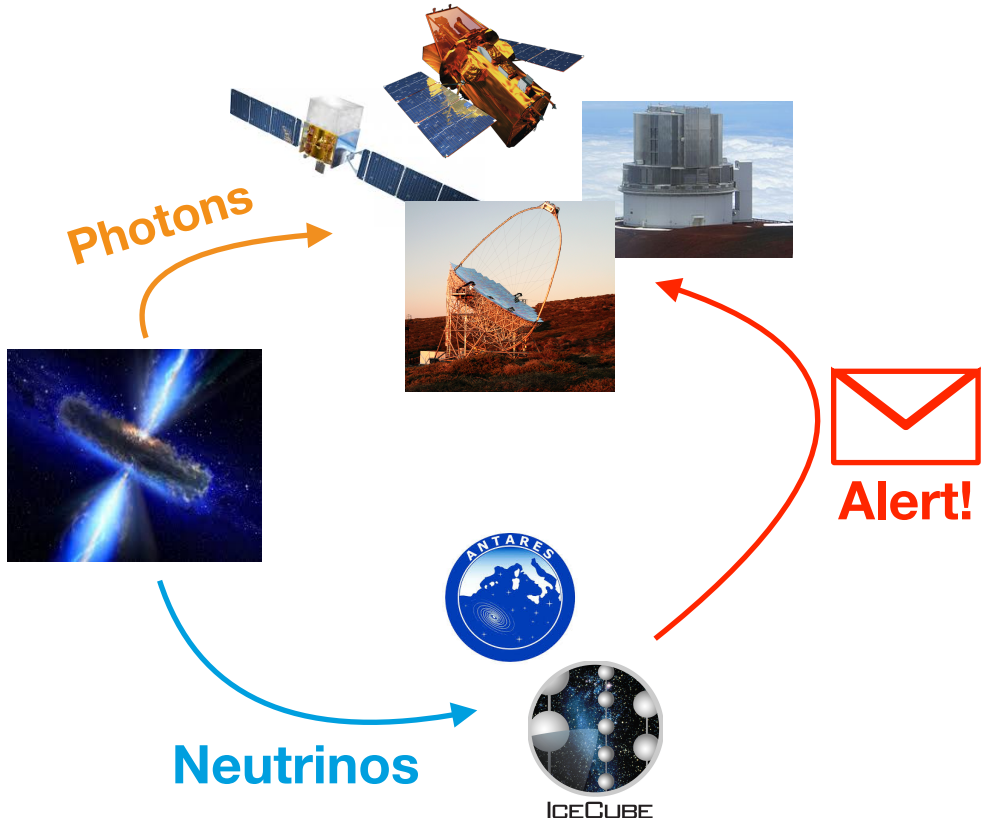
$$p + p/\gamma \rightarrow X + \pi^0 \rightarrow \gamma\gamma$$
$$\rightarrow X + \pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$ (oscillates to ~1:1:1)

Real-time neutrino alerts

Catch them in the act!

- Key for understanding neutrino source emission: **simultaneous MWL data**

- **IC alerts**:
  - Public: single high energy events > 60 TeV (via AMON, since 2016)
  - Private: event clusters, specific programs aimed at gamma-ray and optical telescopes (since 2012)
- **ANTARES alerts**:
  - Only private
  - Optical, X-ray, gamma-ray follow-up
  - Single events & doublets
- **AMON sub-threshold coincidence search:**
  - Public: HAWC/IC and Fermi-LAT/ANTARES

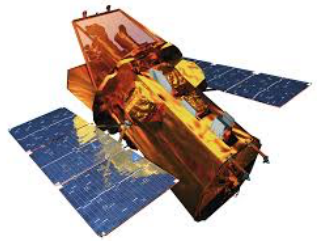


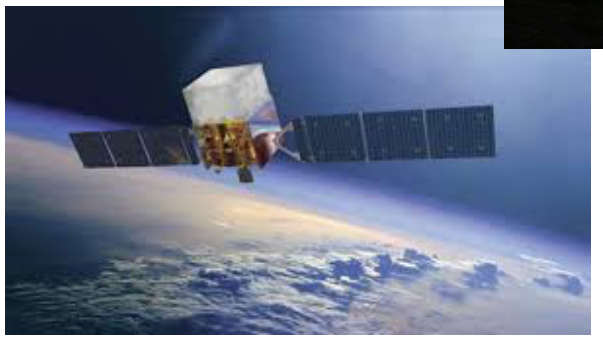
IceCube: M.G. Aartsen et al., Astropart. Phys. 92 (2017) 30-41s
ANTARES: S. Adrián-Martínez et al., JCAP 02 (2016) 062
AMON: H. Alaya et al., PoS(ICRC2019)841; H. Alaya et al., ApJ 886 (2019) 2

See the talk by **E. Blaufuss** for details on neutrino alerts

Neutrino alert follow-up…

…what happens next?





- Most pointing instruments try to perform observations asap:
  - ASAS-SN, MASTERS (optical), Swift (X-ray), MAGIC & HESS (VHE gamma-rays) point automatically (for all or chosen alert classes)

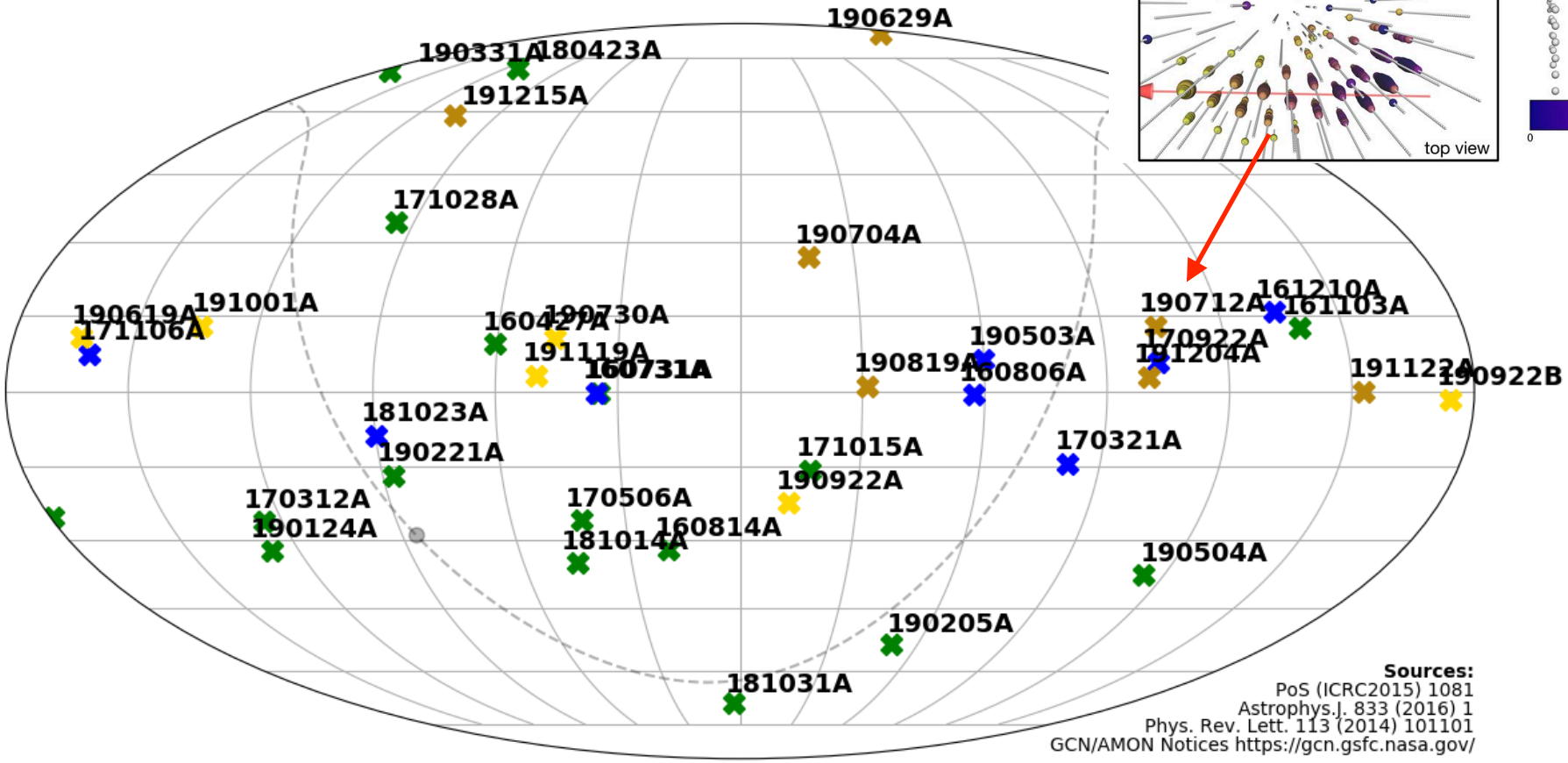
- Large FoV and monitoring instruments like ZTF (47 deg^2, optical), HAWC (VHE gamma-rays) and HE g-ray satellites provide:
  - Sky images before/after → possible counterpart variability, new transient objects in the IC event error circle on different time scales
  - Important input for statistical interpretation of the results

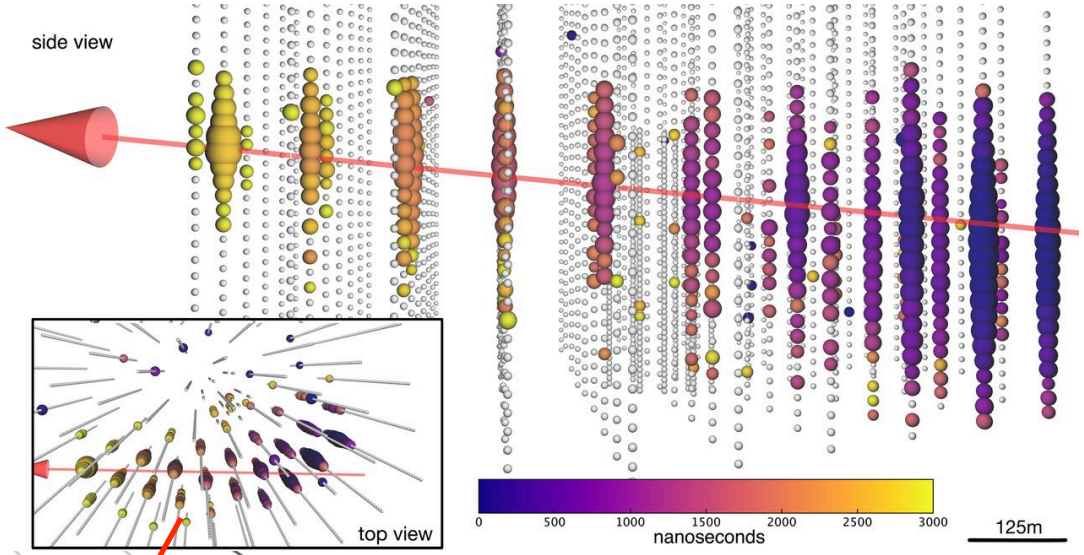
- Optical telescopes provide important information on source type and redshift estimation

Real-time MultiMessenger

First evidence for a neutrino source!

The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams.
***Science* 361, eaat1378 (2018)**





3σ correlation of IC-170922A (~300 TeV) with the flaring blazar TXS 0506+056

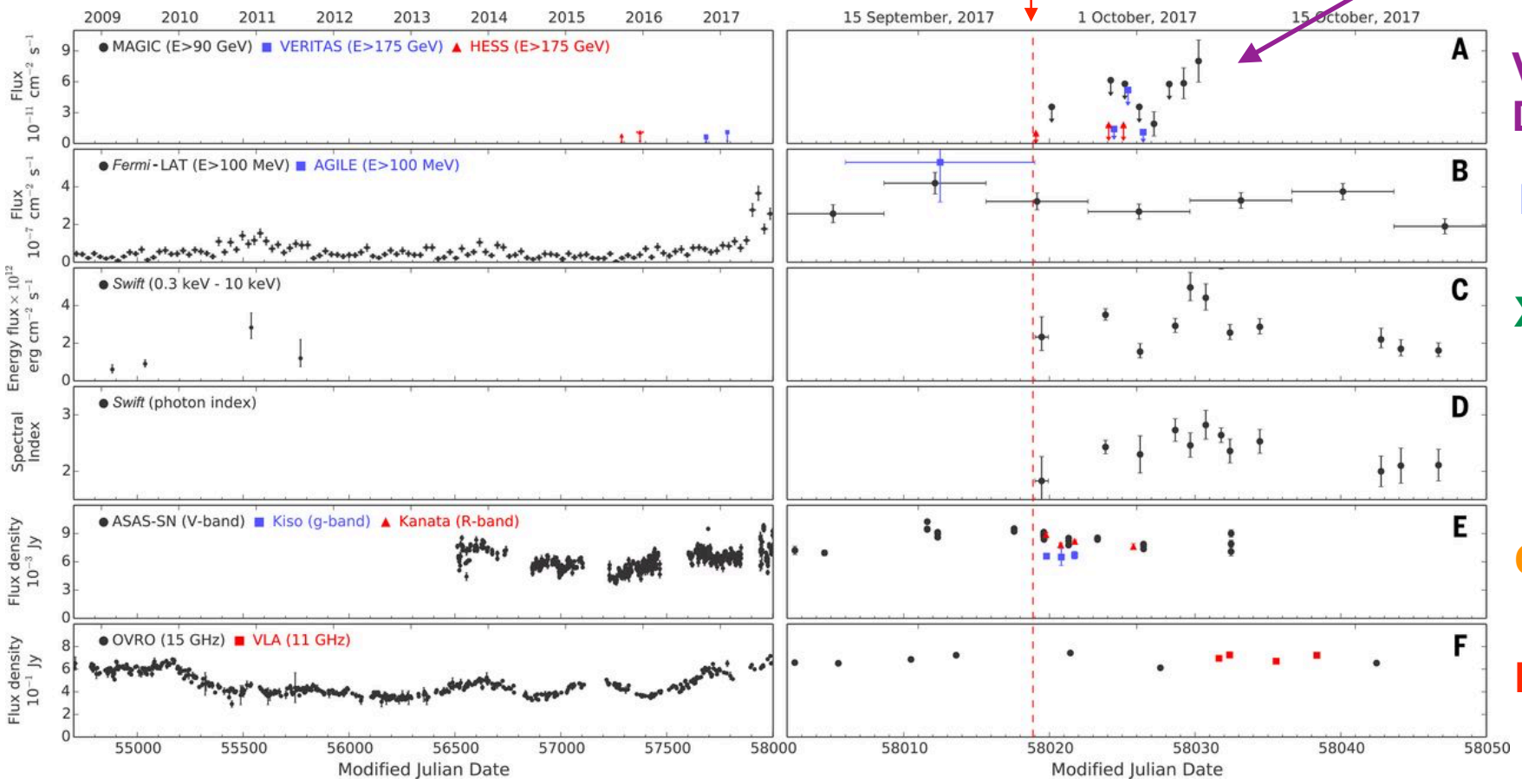
TXS 0506+056

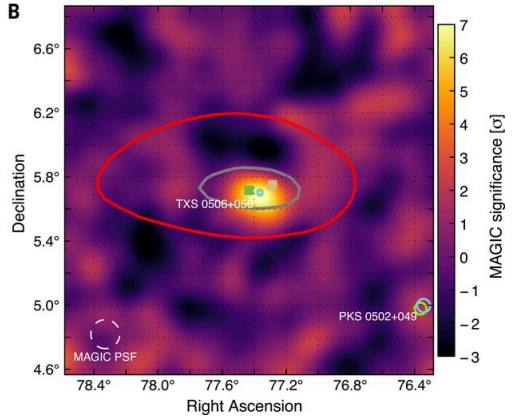
Multiwavelength light curve

The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, eaat1378 (2018)

Fast MWL response over all EM spectrum!

IC-170922A





VHE γ rays: MAGIC discovery
Day-scale variability

HE γ rays: flare 0.5 yr

X-ray: day-scale variability

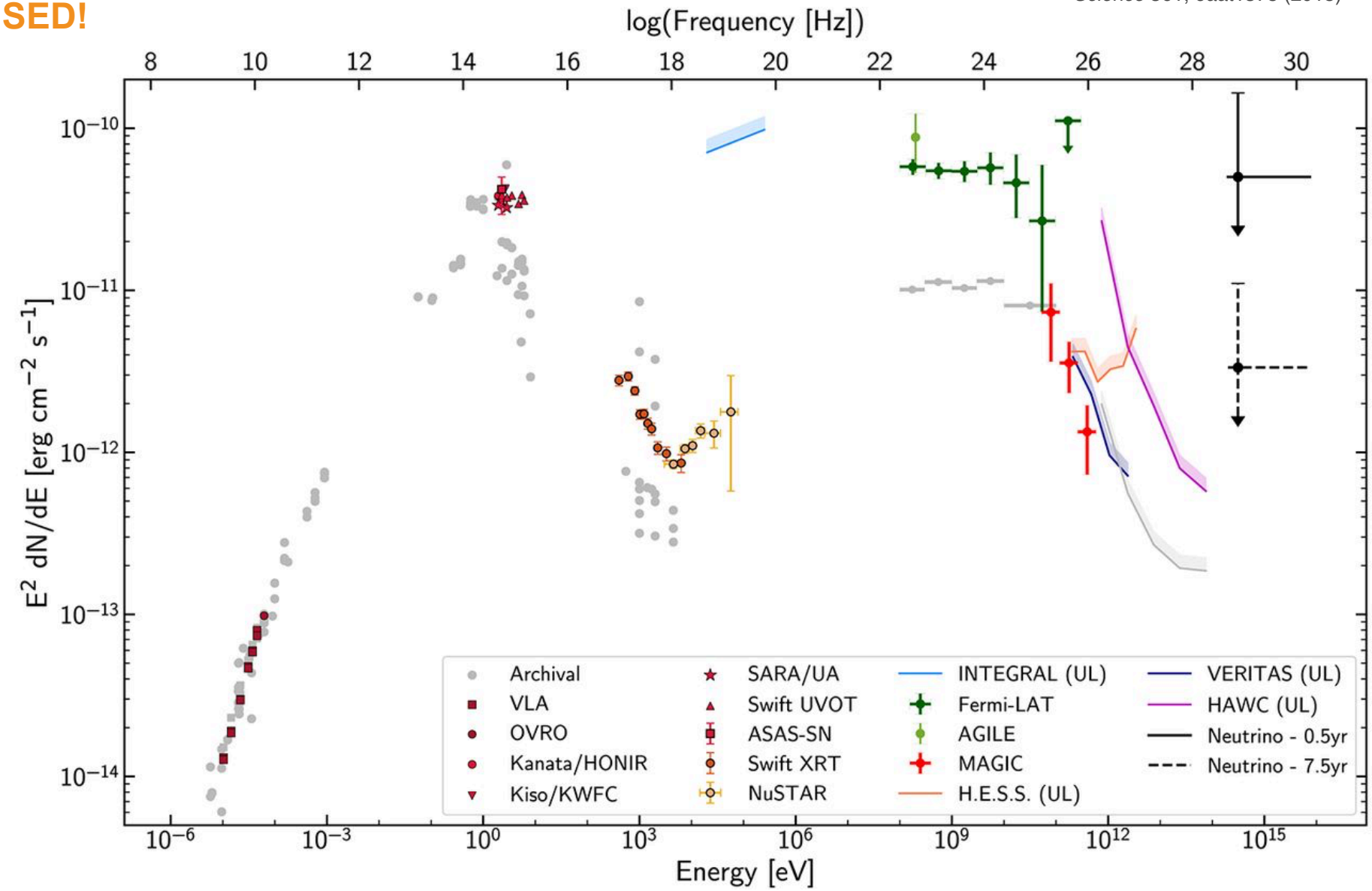
Optical: enhanced emission

Radio: enhanced emission

TXS 0506+056

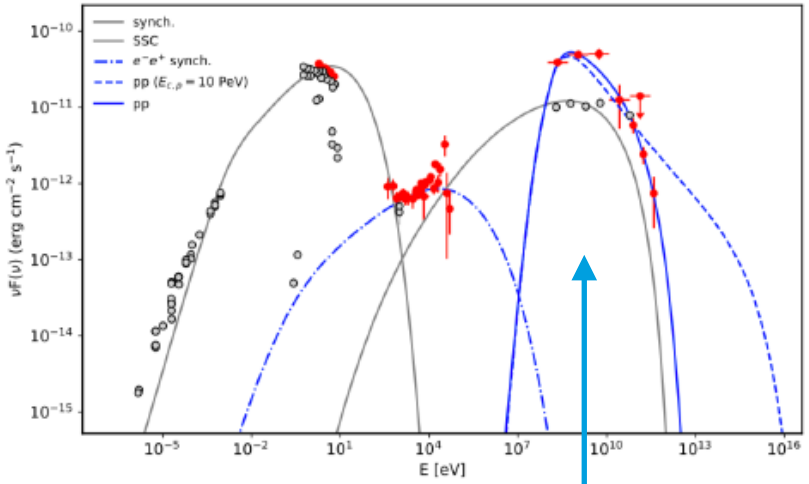
First MM SED!

The IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S, INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool telescope, Subaru, Swift/NuSTAR, VERITAS, and VLA/17B-403 teams. *Science* 361, eaat1378 (2018)

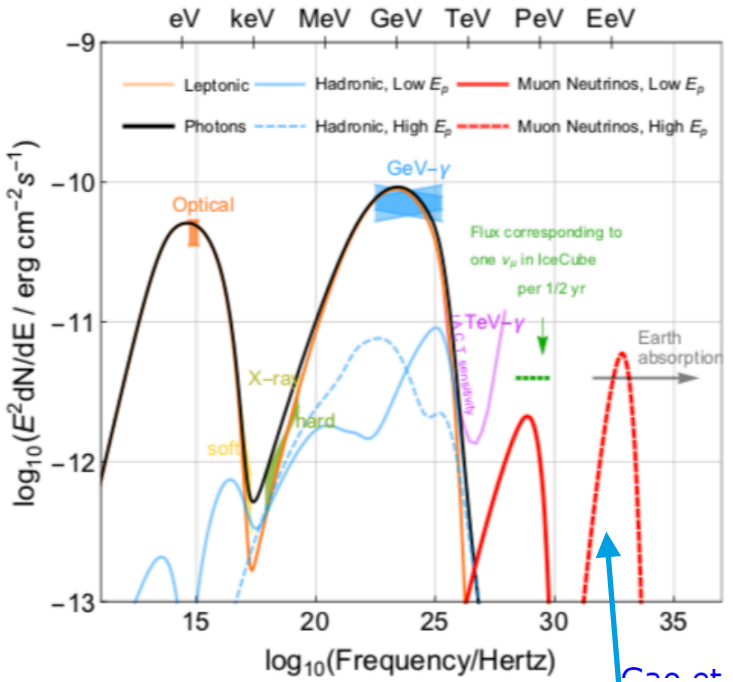


TXS 0506+056

Theoretical interpretations

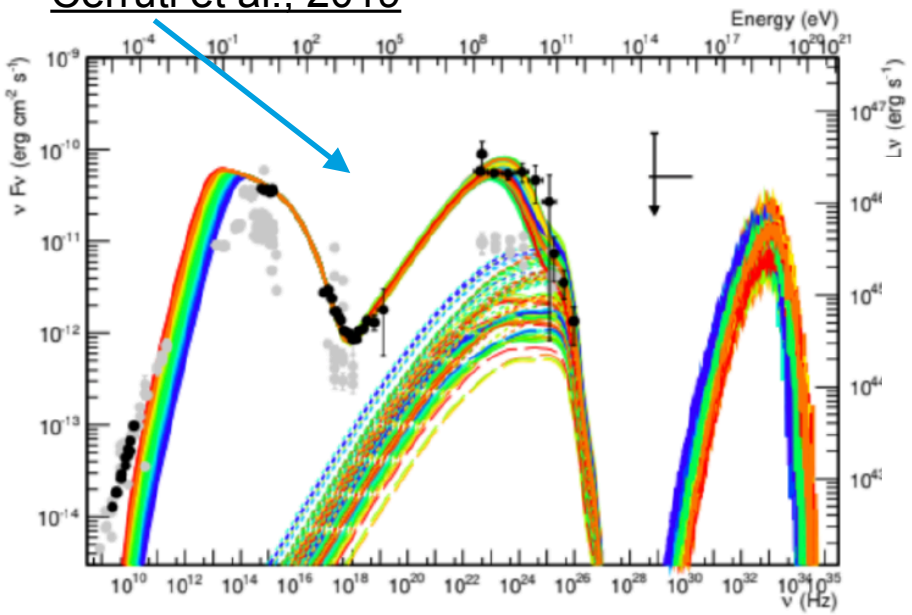


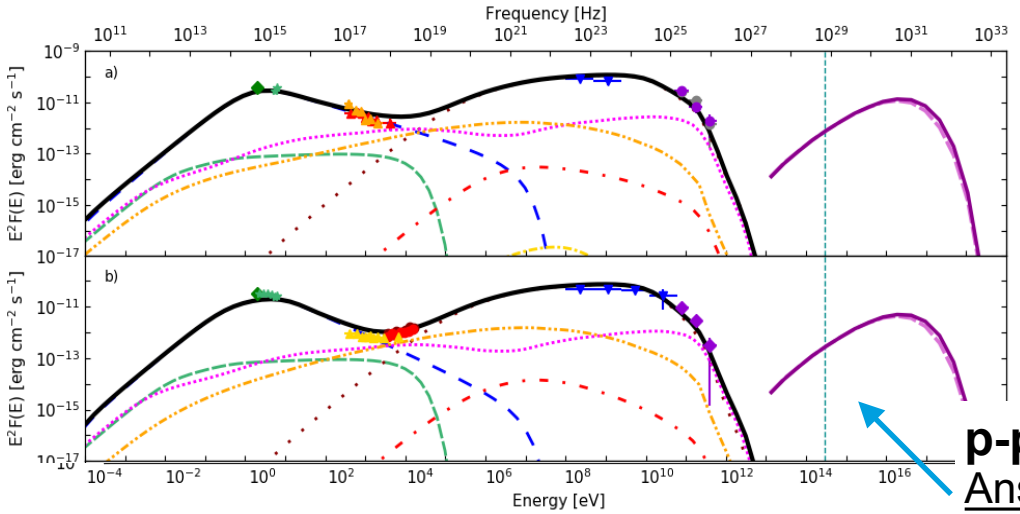
Jet+cloud (pp)
Sahakyan et al., 2018
Liu et al., 2019



Hadro-leptonic
Gao et al., 2018
Cerruti et al., 2019

Proton-synchrotron
Keivani et al., 2018
Gao et al., 2018
Cerruti et al., 2019



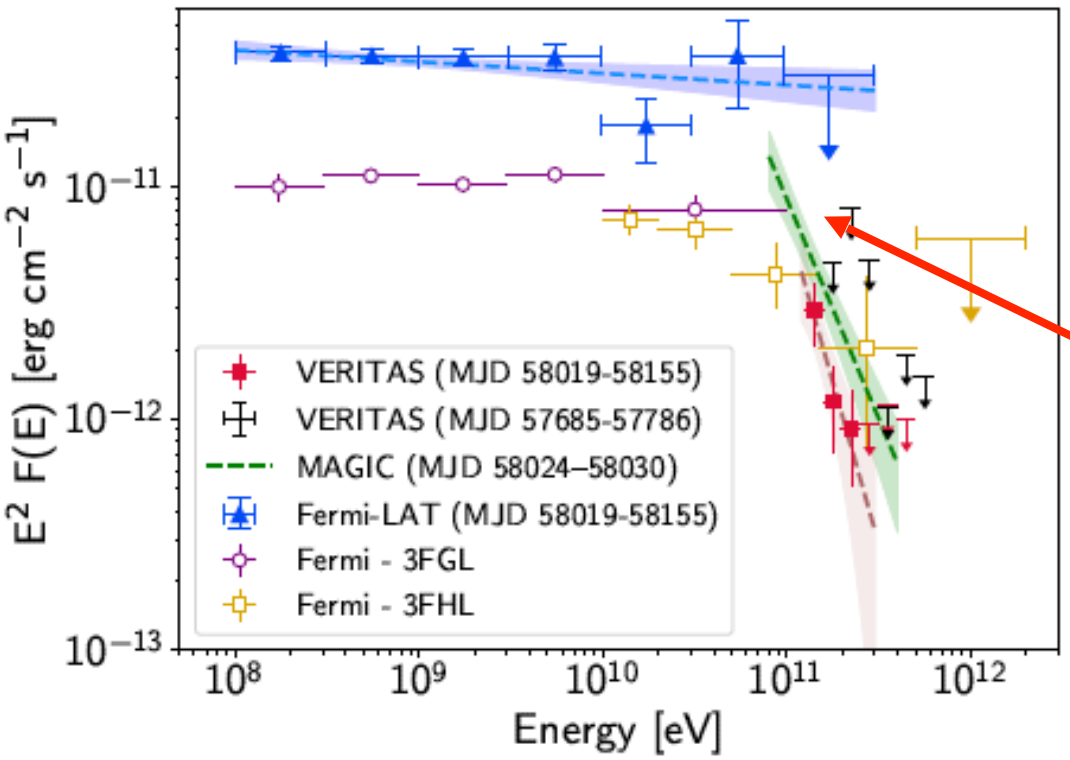


p-ph on external ph field
Ansoldi et al., 2018 (jet layer)
Keivani et al, 2018 (BB)
Righi et al., 2019 (RIAF)

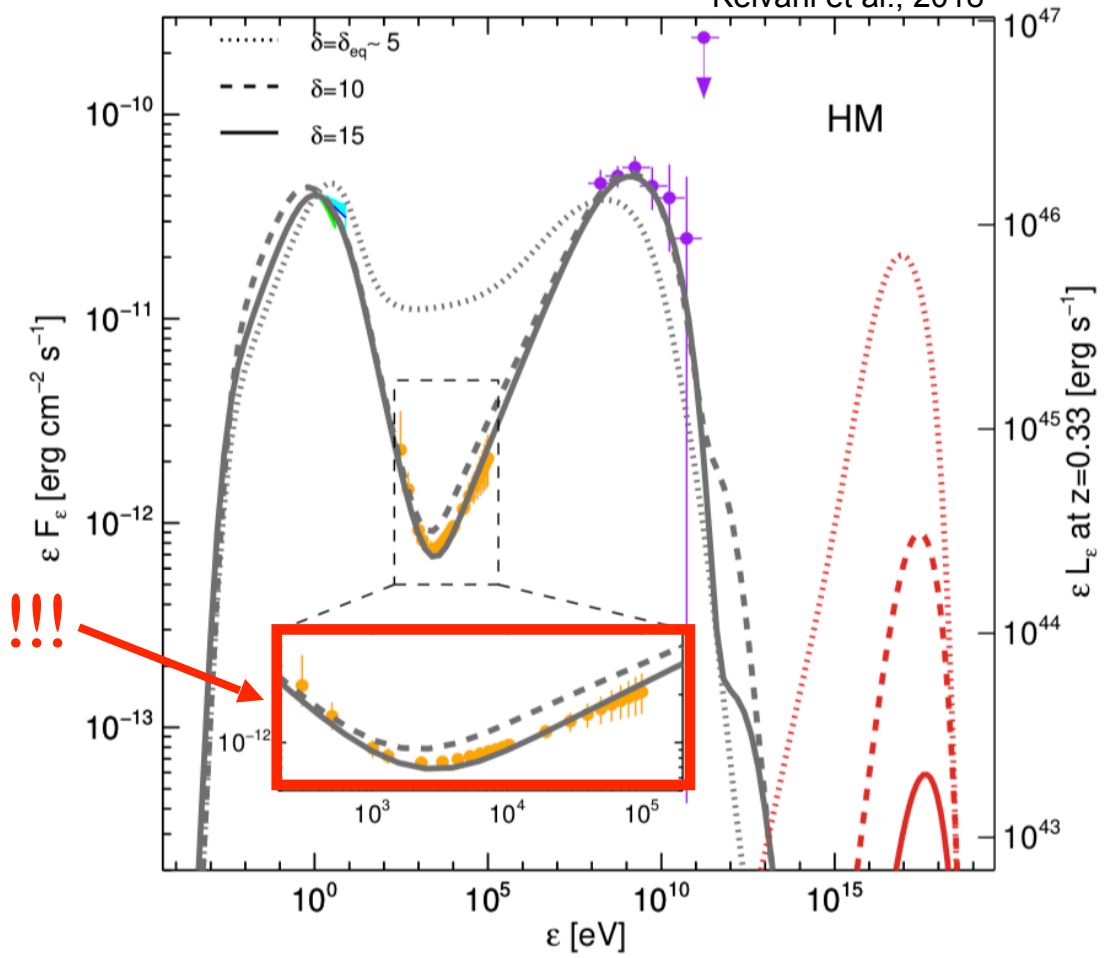
TXS 0506+056

What did we learn?

M. Santander, PoS(ICRC2019)782



Keivani et al., 2018



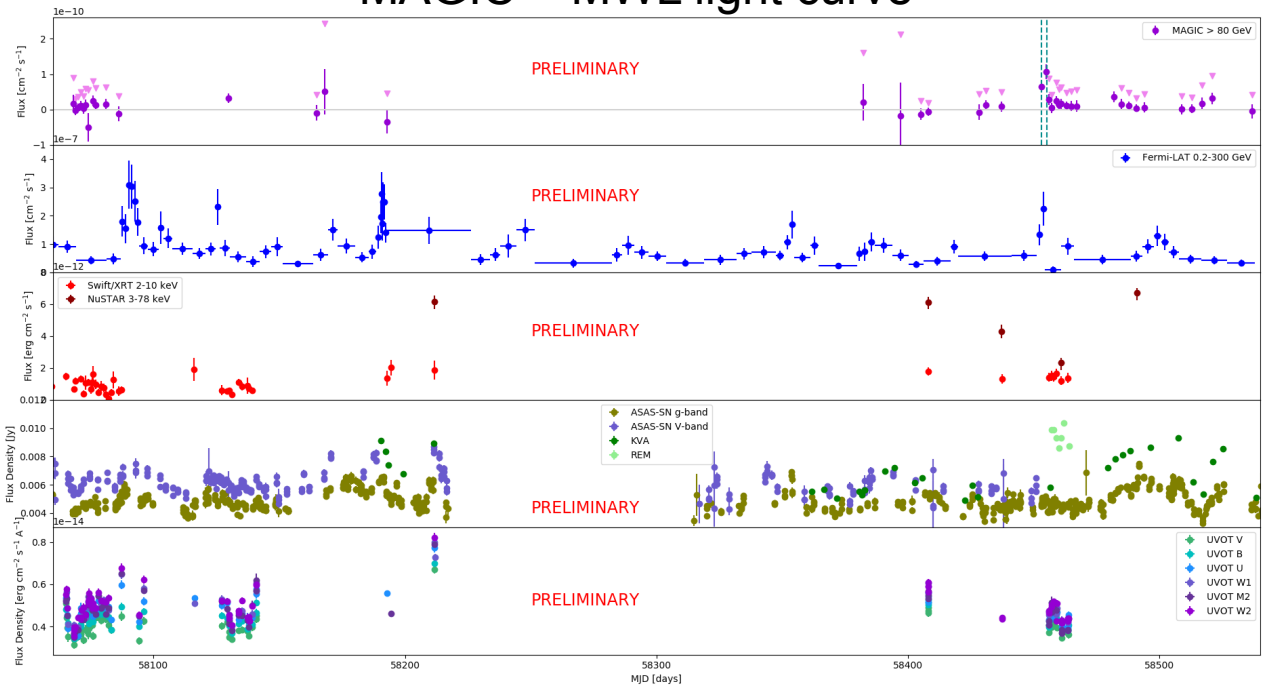
!!!

- Hard-X-rays / VHE gamma-rays proved to be extremely important to constrain the models
- Clear spectral curvature in VHE g-rays, apart from EBL effect: internal absorption, primary particle spectral break, production inefficiency…?
- Favoured scenario: leptonic + subdominant hadronic component → pure hadronic solutions are excluded!
- Simple one-zone models result in a very high proton luminosity → two-zone or external fields help a lot

TXS 0506+056

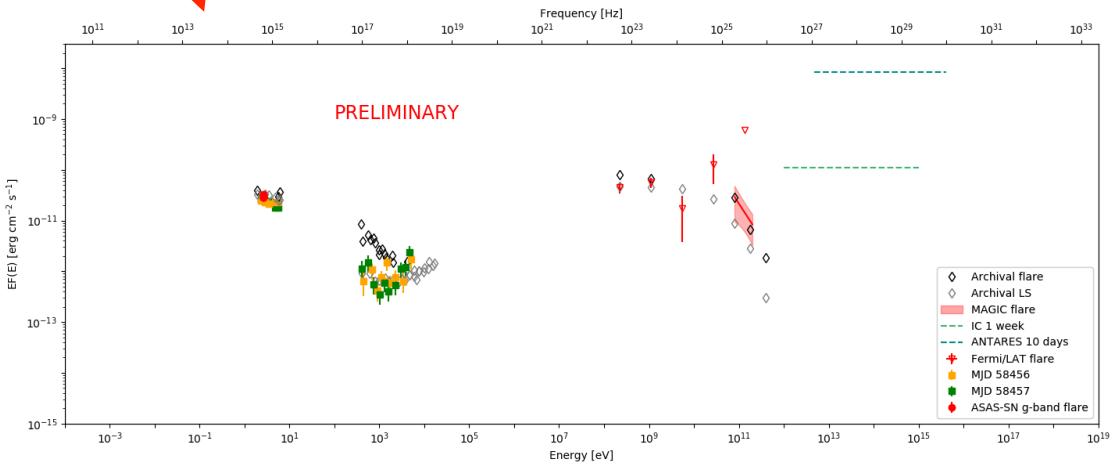
The story continues…

MAGIC + MWL light curve



Flare!

MM SED



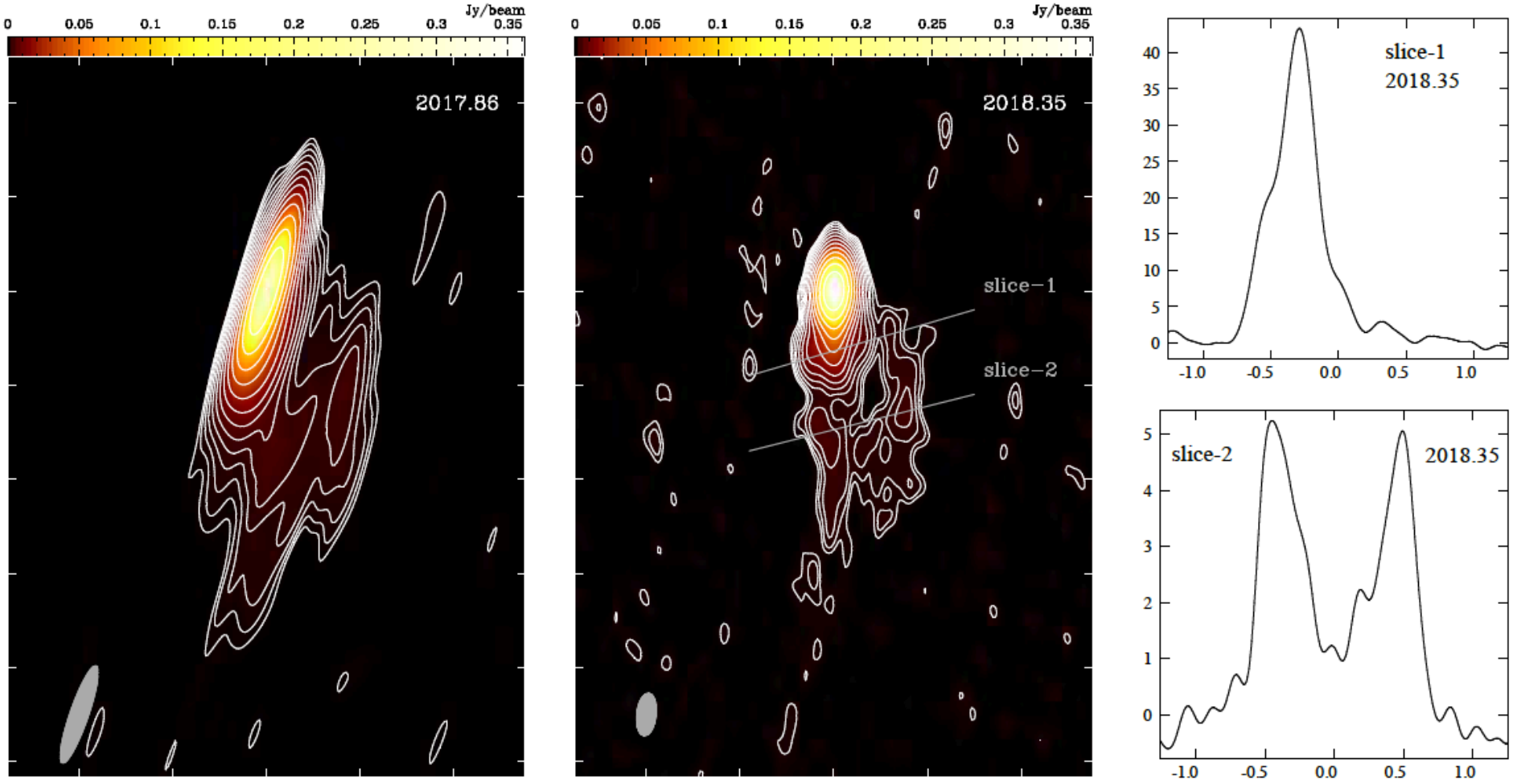
MAGIC monitoring:
PoS(ICRC 2019)783
PoS(ICRC 2019)645
HESS ToO:
PoS(ICRC2019)787
VERITAS monitoring:
PoS(ICRC2019)782

- **Dedicated MWL monitoring program**: collect a long-term data sample of TXS 0506+056
- Nov 2017 to Feb 2019: **~90h** collected (80h good quality); program on-going
- **Lowest VHE gamma-ray emission level** observed from this source so far
- MJD 58453 and MJD 58455: **enhanced emission** observed (ATel #12260), comparable to the 2017 flare
- Dedicated analysis with lower cleaning threshold planned → go < 80 GeV

TXS 0506+056

The story continues…

E. Ros et al., A&A 633, L1 (2020)



Radio measurements (VLBI) confirm the structured jet layer proposed in Ansoldi et al., 2018!

Public IceCube alerts…

…optical follow-up

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A candidate supernova coincident with IceCube-190922B from ZTF

ATel #13125; *Robert Stein (DESY), Anna Franckowiak (DESY), Marek Kowalski (DESY), Mansi Kasliwal (Caltech)*
on 23 Sep 2019; 20:34 UT
Credential Certification: Anna Franckowiak (anna.franckowiak@desy.de)

Subjects: Optical, Neutrinos, Request for Observations, Supernovae, Tra

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Candidate Counterparts to IceCube-191001A with ZTF

ATel #13160; *Robert Stein (DESY), Anna Franckowiak (DESY), Jannis Necker (DESY), Suvi Gezari (UMd), Sjoert van Velzen (UMd/NYU)*
on 2 Oct 2019; 22:00 UT
Distributed as an Instant Email Notice Transients
Credential Certification: Anna Franckowiak (anna.franckowiak@desy.de)

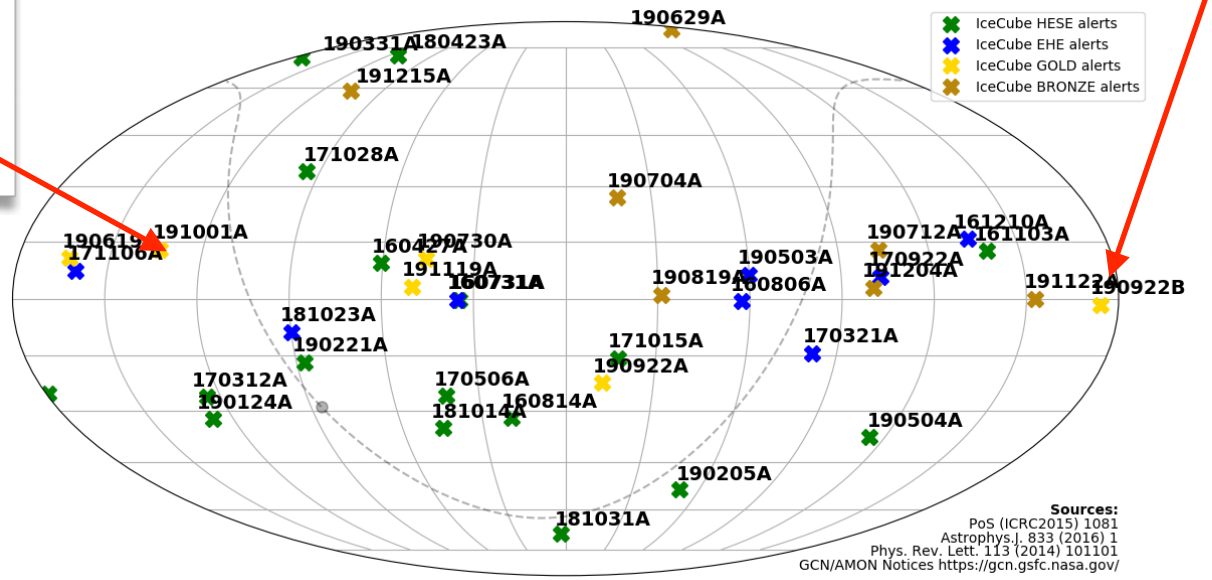
Subjects: Radio, Optical, X-ray, Neutrinos, Supernovae, Transient, Tidal Disruption Event

[Previous | Next | ADS]

Spectroscopic classification of SN 2019pqh by NUTS2, and implications for the claimed association with IceCube-190922B

ATel #13133; *A. Reguitti (Univ. Andres Bello), A. Pastorello, S. Benetti, Y.-Z. Cai, E. Cappellaro, A. Fiore, N. Elias-Rosa, L. Tomasella (INAF-OAPd), G. Valerin, P. Ochner (Padova University), A. Morales-Garoffolo (UCA), M. Stritzinger, S. Holmbo (Univ. of Aarhus), S. Moran (NOT), S. Brennan, E. Callis, M. Fraser (UCD), E. Kankare, R. Kotak, H. Kuncarayakti, T. Heikkila, S. Mattila, T. Reynolds (Univ. of Turku), P. Lundqvist (Stockholm Univ.), S. Dong, P. Chen, S. Bose (KIAA-PKU)*
on 26 Sep 2019; 13:51 UT
Distributed as an Instant Email Notice Supernovae
Credential Certification: Andrea Pastorello (andrea.pastorello@oapd.inaf.it)

Subjects: Optical, Neutrinos, Supernovae, Transient



- IC-190922B: ZTF (ATel #13125) SN 2019pqh, type confirmation SNII/IIb by NUTS2 (ATel #13133)
- IC-191001A: ZTF found a coincident TDE (ATel #13160)

Public IceCube alerts…

…HE gamma-rays follow-up

IceCube-190730A an astrophysical neutrino candidate in spatial coincidence with FSRQ PKS 1502+106

ATel #12967; *Ignacio Taboada (Georgia Institute of Technology), Robert Stein (DESY Zeuthen) on 30 Jul 2019; 23:58 UT*
Credential Certification: Ignacio Taboada (itaboada@gatech.edu)

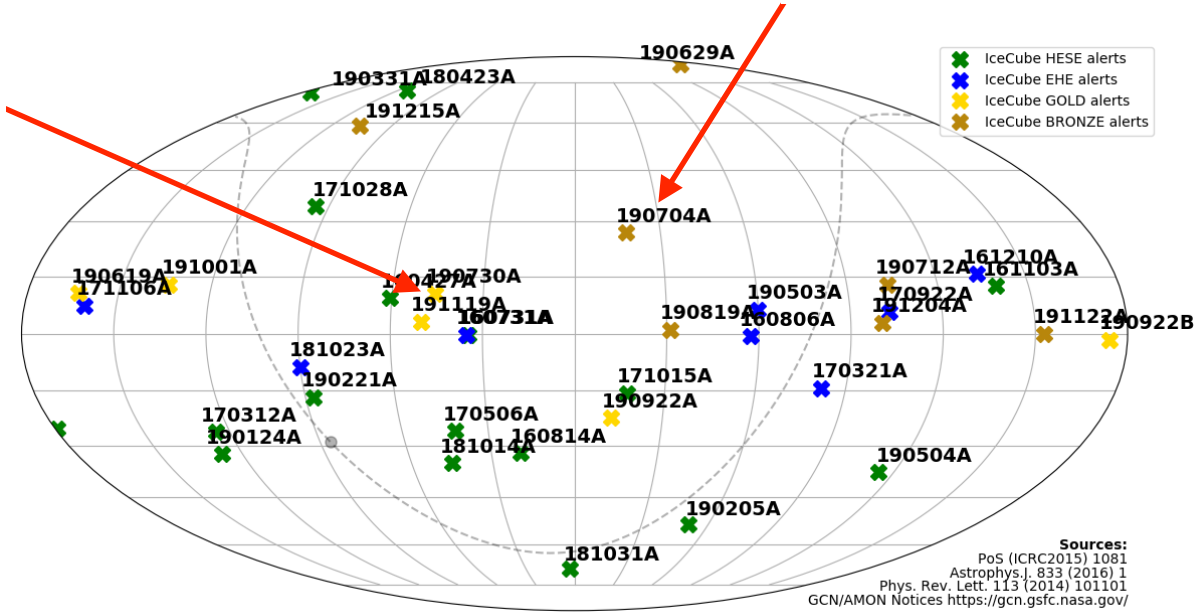
Subjects: Neutrinos, AGN

Referred to by ATel #: 12971, 12981, 12983, 12985, 12996

Fermi-LAT Gamma-ray Observations of IceCube-190704A and detection of the new gamma-ray source 1WHSP J104516.2+275133

ATel #12906; *S. Garrappa (DESY-Zeuthen, DE), S. Buson (Univ. of Wuerzburg, DE; UMBC, USA) and T. Venters (NASA-GSFC, USA) on behalf of the Fermi-LAT collaboration on 5 Jul 2019; 23:57 UT*
Credential Certification: Sara Buson (sara.buson@gmail.com)

Subjects: Gamma Ray, >GeV, TeV, VHE, Neutrinos, Request for Observations, AGN, Blazar

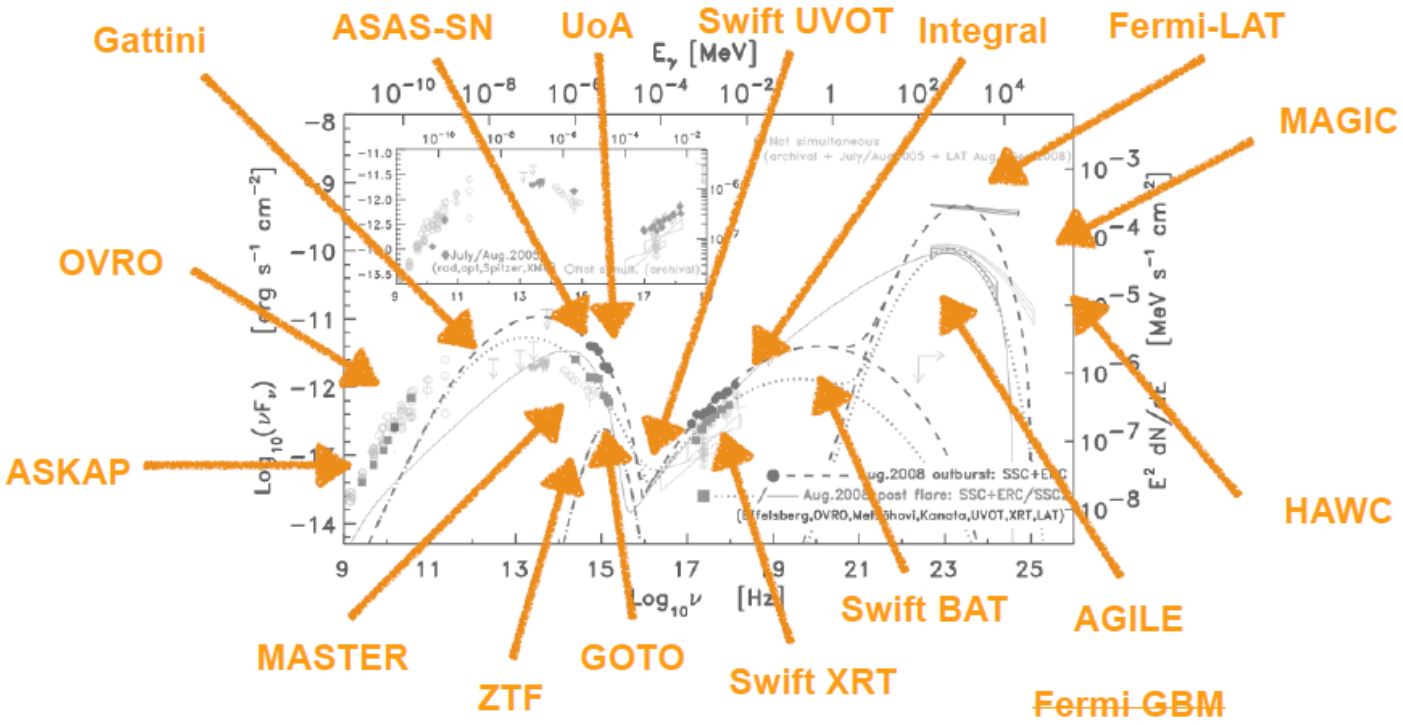


- **IC-190704A**: blazar 1WSP J104516.2+275133, redshift unknown, Fermi/LAT reports hard spectrum
- **IC-190730A**: PKS1502+106 (#ATel12697), FSRQ at z = 1.84

PKS 1502+106

Extensive MWL camapaign

Credit: R.Stein, TEXAS 2019



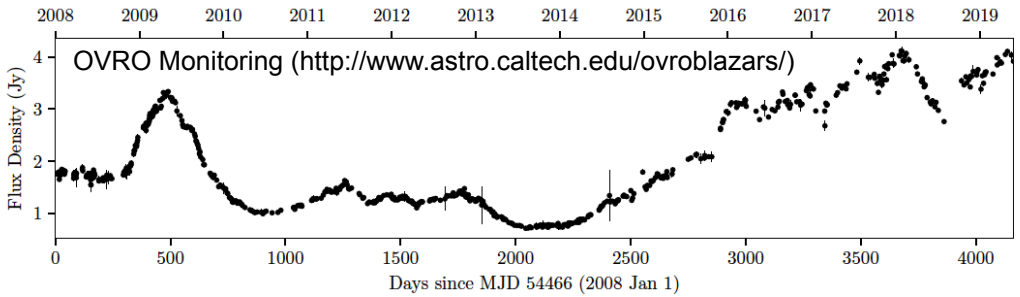
Neutrino candidate source FSRQ PKS 1502+106 at highest flux density at 15 GHz

ATel #12996; *S. Kiehlmann (IoA FORTH, OVRO), T. Hovatta (FINCA), M. Kadler (Univ. WÃ¼rzburg), W. Max-Moerbeck (Univ. de Chile), A. C.S. Readhead (OVRO)*
on 7 Aug 2019; 12:31 UT
Credential Certification: Sebastian Kiehlmann (skiehlmann@mail.de)

Subjects: Radio, Neutrinos, AGN, Blazar, Quasar

Tweet

On 2019/07/30.86853 UT IceCube detected a high-energy astrophysical neutrino candidate (Atel #12967). The FSRQ PKS 1502+106 is located within the 50% uncertainty region of the event. We report that the flux density at 15 GHz measured with the OVRO 40m Telescope shows a long-term outburst that started in 2014, which is currently reaching an all-time high of about 4 Jy, since the beginning of the OVRO measurements in 2008. A similar 15 GHz long-term outburst was seen in TXS 0506+056 during the neutrino event IceCube-170922A.

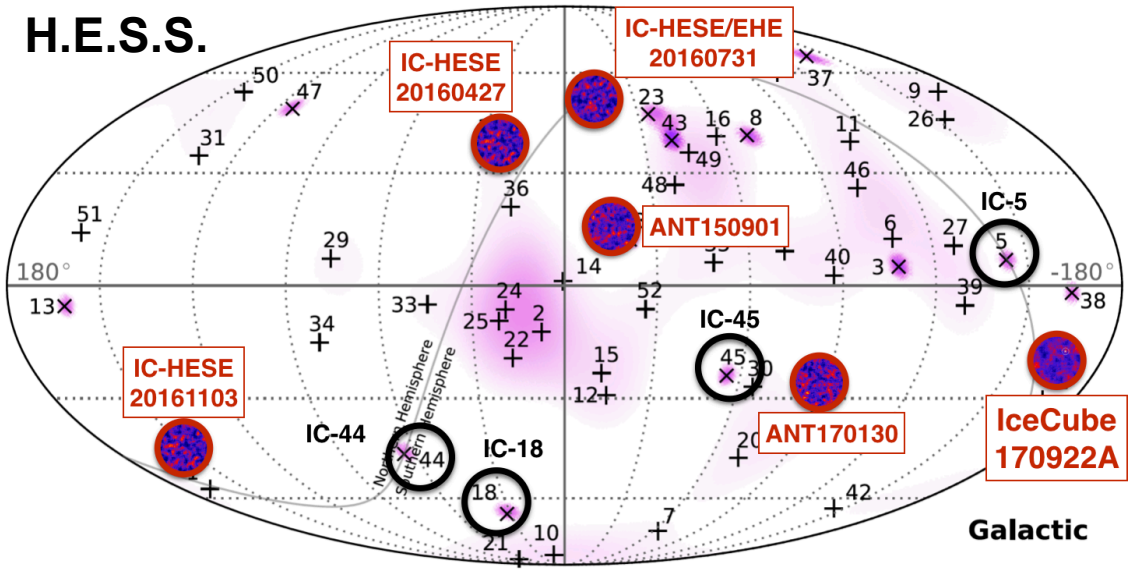


No evidence of short-term flaring activity in any wavelength…

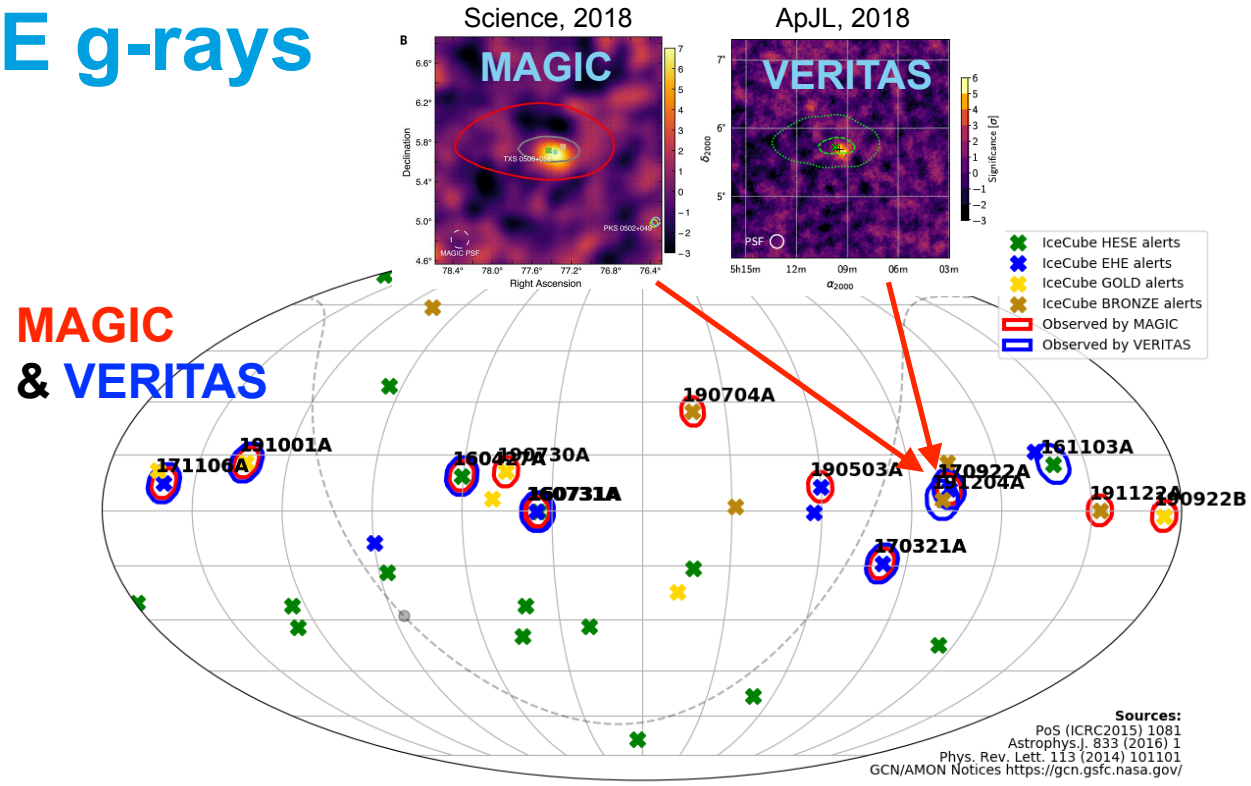
Long-term radio flare reported by OVRO, similar to TXS 0506+056…
Trend? Coincidence?

Neutrino alerts follow up in VHE g-rays

PoS(ICRC2019)787



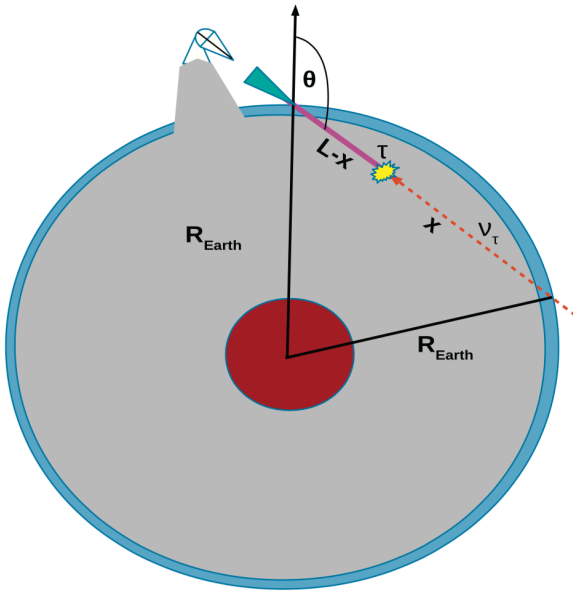
Science, 2018 ApJL, 2018

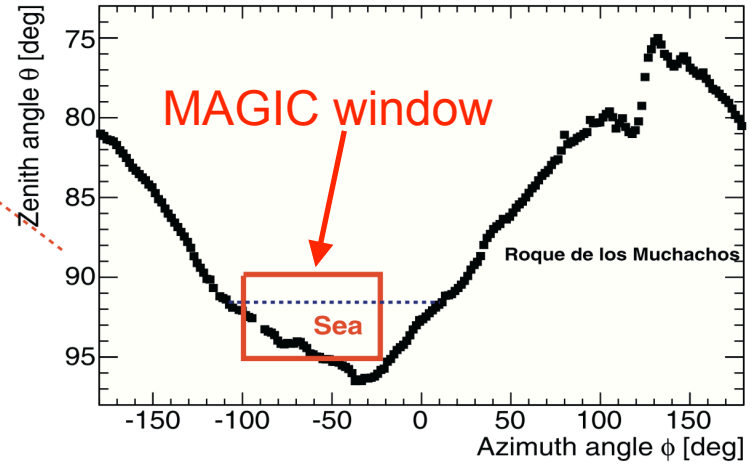


- H.E.S.S, MAGIC, VERITAS (>50 GeV) - up to 15% of their time spent on neutrino alerts follow-up
- **So far the only VHE g-ray source detected in coincidence with neutrino alert is TXS 0506+056**
- Challenges:
  - IACTs have small FoV → Need repointing (automatic for H.E.S.S. and MAGIC for GOLD alerts)
  - Limited by EBL (redshift up to ~1)
  - Dependence on source visibility, Moon, weather…
  - Large IC event localization error → how to interpret the non-detection?

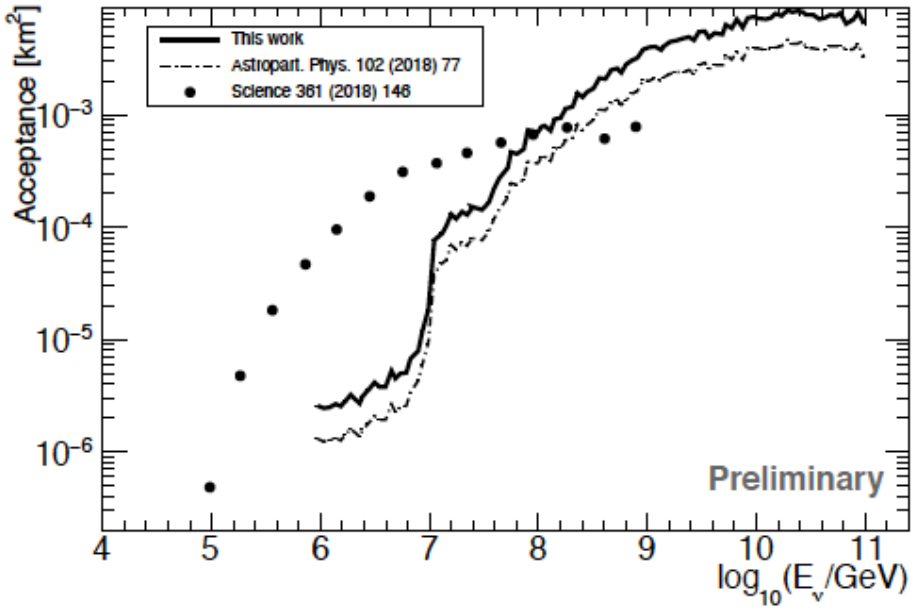
And now for something completely different…

…IACT follow-up in Earth-skimming mode





M.Mallamaci et al., PoS(ICRC2019)953



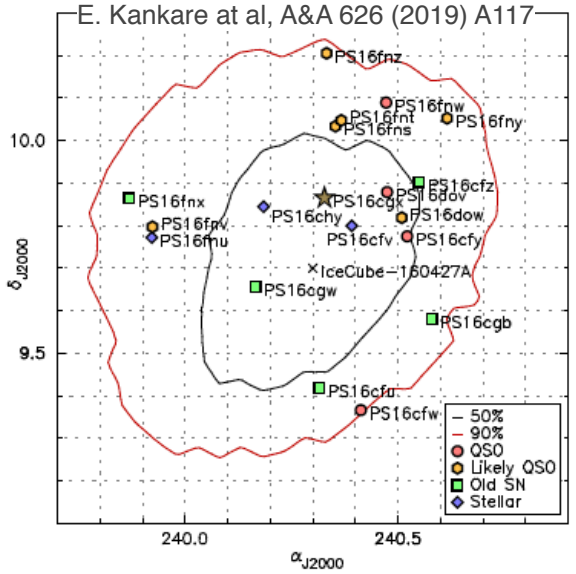
- Thanks to “tau-regeneration” we can look for tau induced showers from the sea/rock
- Sensitive to tau of PeV-EeV energies
- So far only implemented by MAGIC (Astropart. Phys. 102 (2018) 77 - diffuse flux limits)
- Since 2019: automatic check for each IC alert, if visible in the Sea window in the next 7 days
- Event selection optimised for short flares (M.Mallamaci et al., PoS(ICRC2019)953)

Neutrino alert follow-up

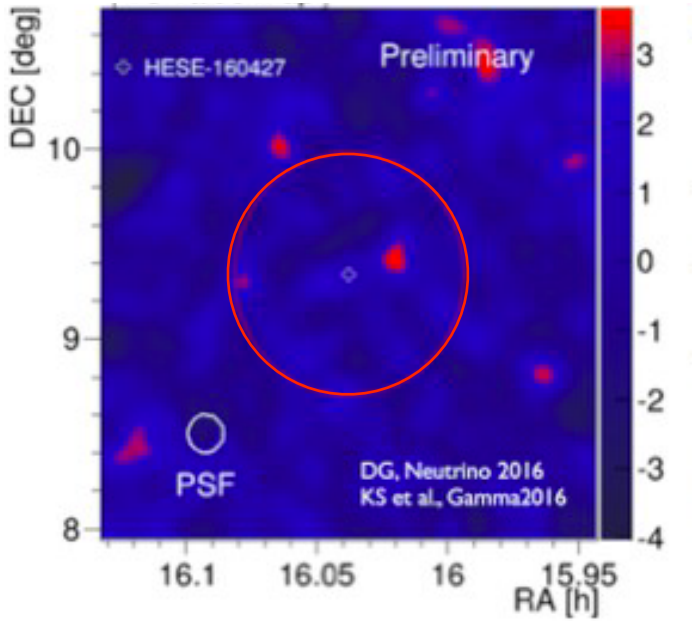
The challenges

- Source visibility, atmospheric conditions & Moon (optical & IACTs) → large delays in follow-up (if possible at all)
- Reach of the instruments (e.g. EBL absorption for IACTs & HAWC → sources only up to z=1 / z=0.3)
- Large IC event localisation error (few 10s arcmin - few degs) + small FoV (Swift, optical) → tiling needed
- Large IC event localisation error + high sensitivity (mostly optical tels. & Swift) → large number of possible counterparts → how to choose the most interesting one?
- Results reported through GCN notices and ATels in few hours up to days after observation, often in a non-machine readable format
- Analysis & interpretation:
  - How to asses the statistical significance of a possible counterpart detection?
  - How to interpret the non-detection?

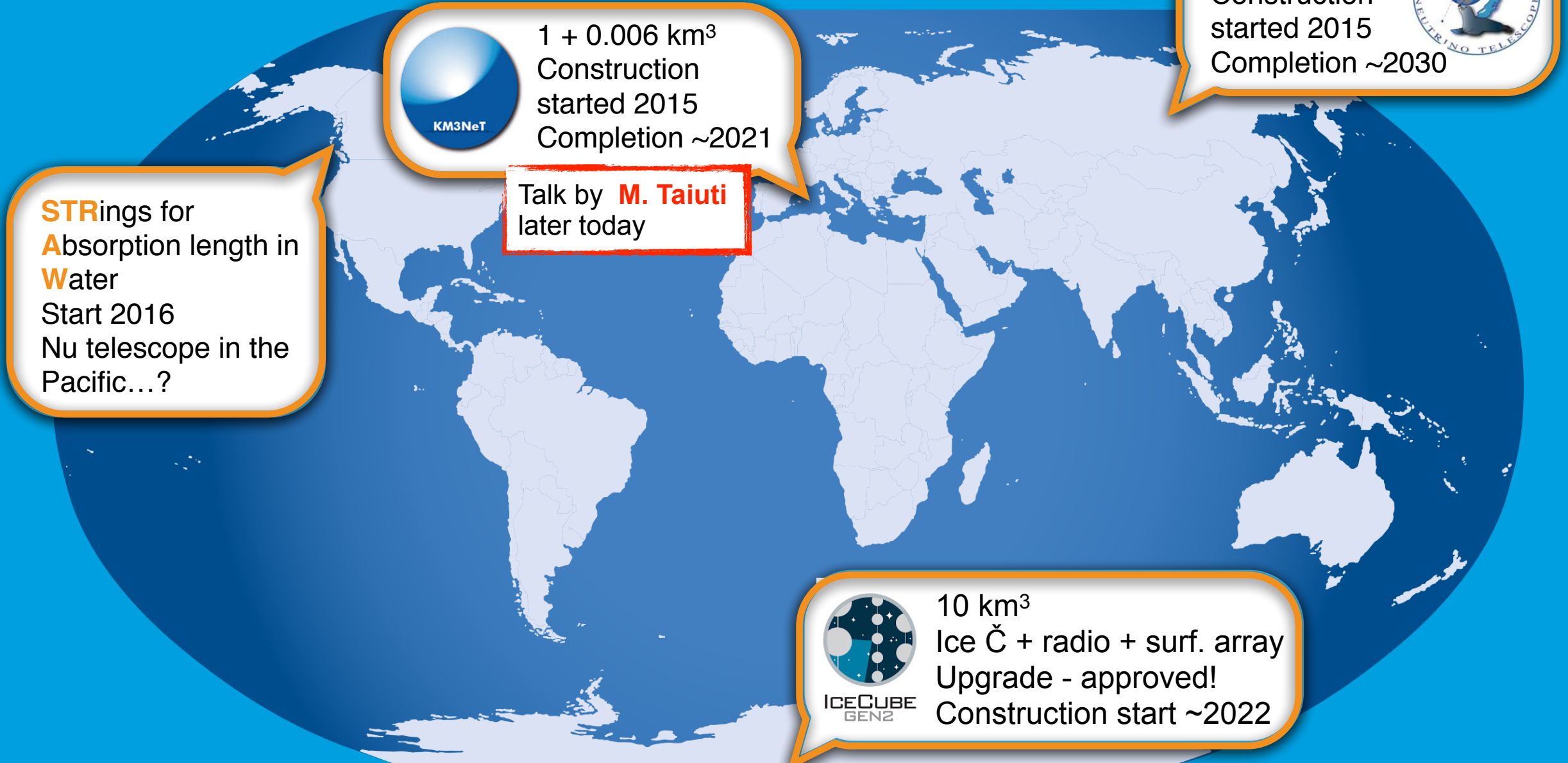
Pan-STARSS view of IC-160427A



MAGIC TS sky map of IC-160427A region



Instruments: future



1 + 0.006 km³
Construction
started 2015
Completion ~2021

Talk by **M. Taiuti**
later today

>1 km³
Construction
started 2015
Completion ~2030

STRings for
Absorption length in
Water
Start 2016
Nu telescope in the
Pacific…?

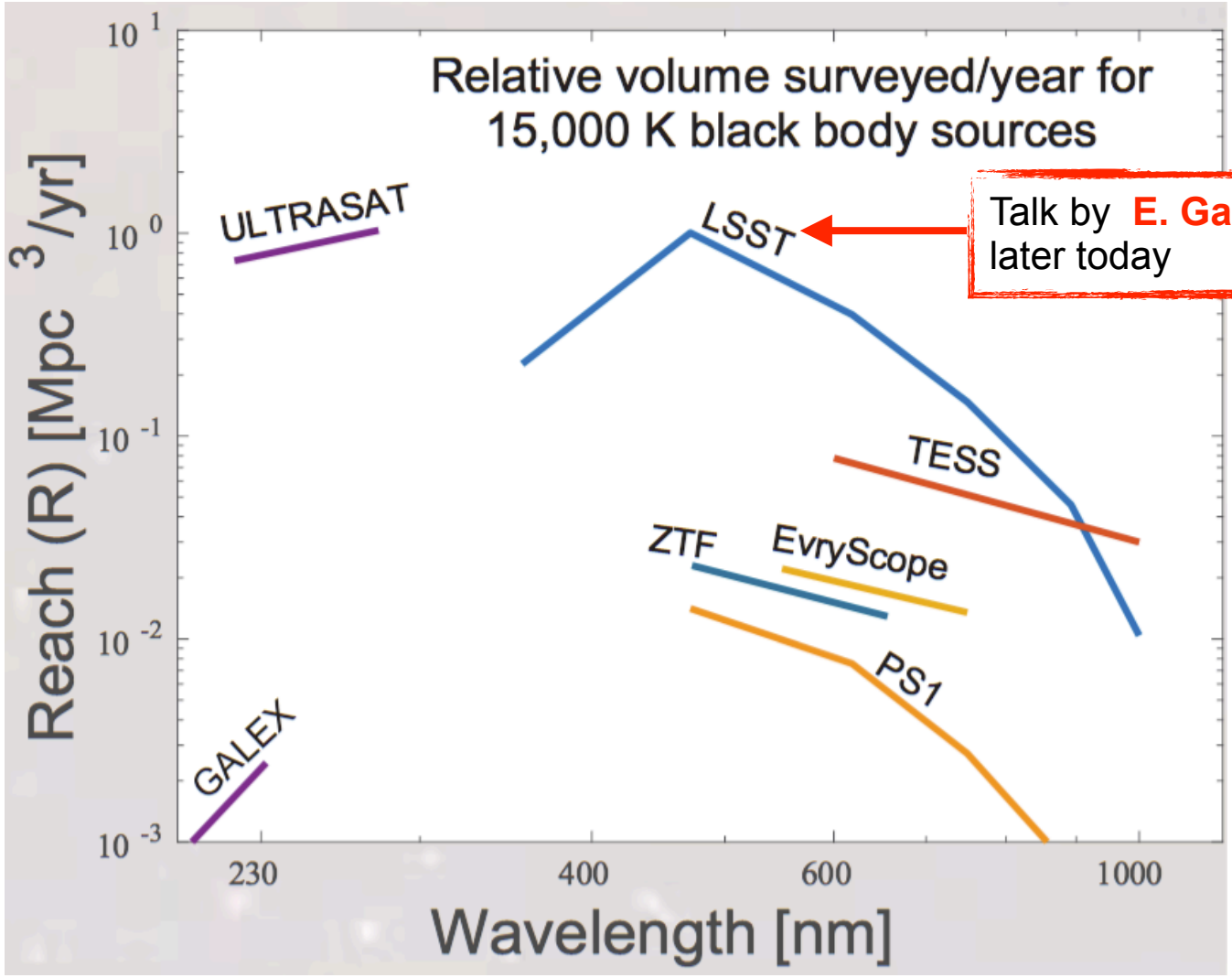
10 km³
Ice Č + radio + surf. array
Upgrade - approved!
Construction start ~2022

Optical follow-up

New instruments

- New instruments coming soon, e.g. LSST and ULTRASAT ~2023/24
- Reach increase of 2 orders of magnitude wrt present instruments
- LSST: 8m telescope w. 3 billion pixel camera 800 images & 30 TB/ night, 15s exposure in six bands, reach depth ~24.5 mag
- ULTRASAT: UV satellite, 15 deg FoV, 5 min cadence

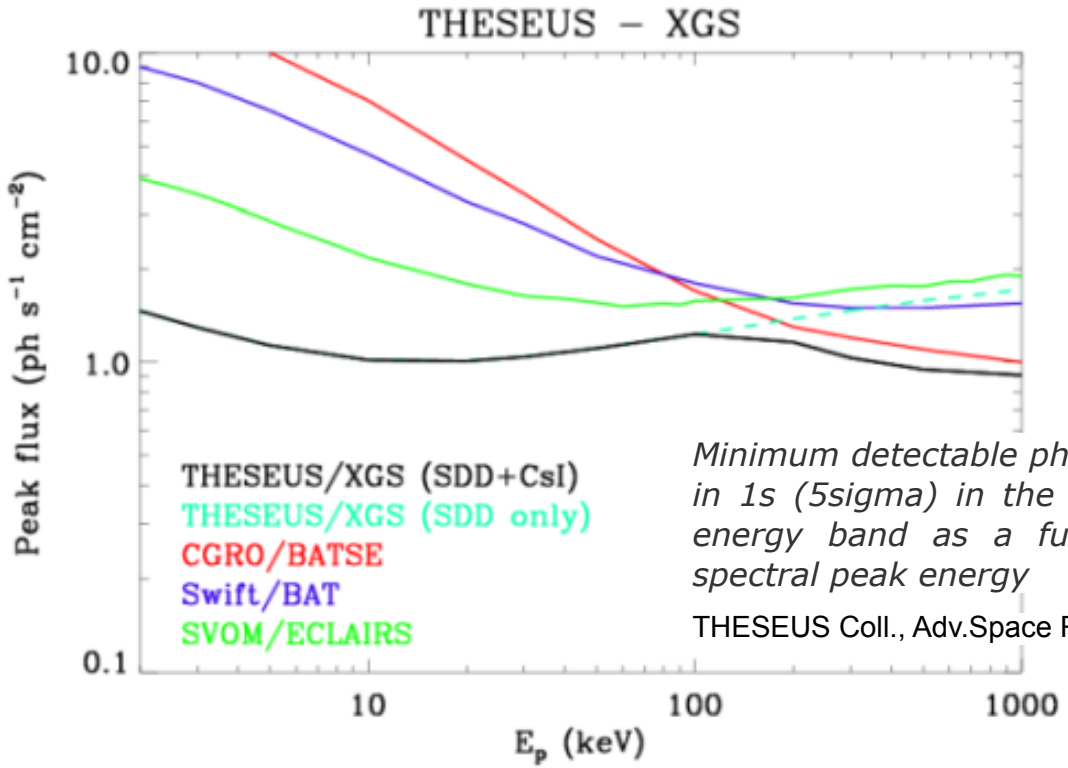
Source: https://www.weizmann.ac.il/ultrasat/science/science-goals



X-ray follow-up

New instruments

Talk by
C. Lachaud, SVOM
later today.



Minimum detectable photon peak flux in 1s (5sigma) in the 1 - 1000 keV energy band as a function of the spectral peak energy

THESEUS Coll., Adv.Space Res. 62 (2018) 191-244

SVOM (launch early 2020s):

- **ECLAIRs (4–120 keV)**: to detect and localize transients, FoV 2 sr
- **GRM (50 keV – 5 MeV):** γ-ray burst monitor to promptly alert the community
- **VT (400–950 nm):** near-IR to visible light telescope, FOV of 21×21 arcmin, up to 23 mag
- Ground support of optical telescopes

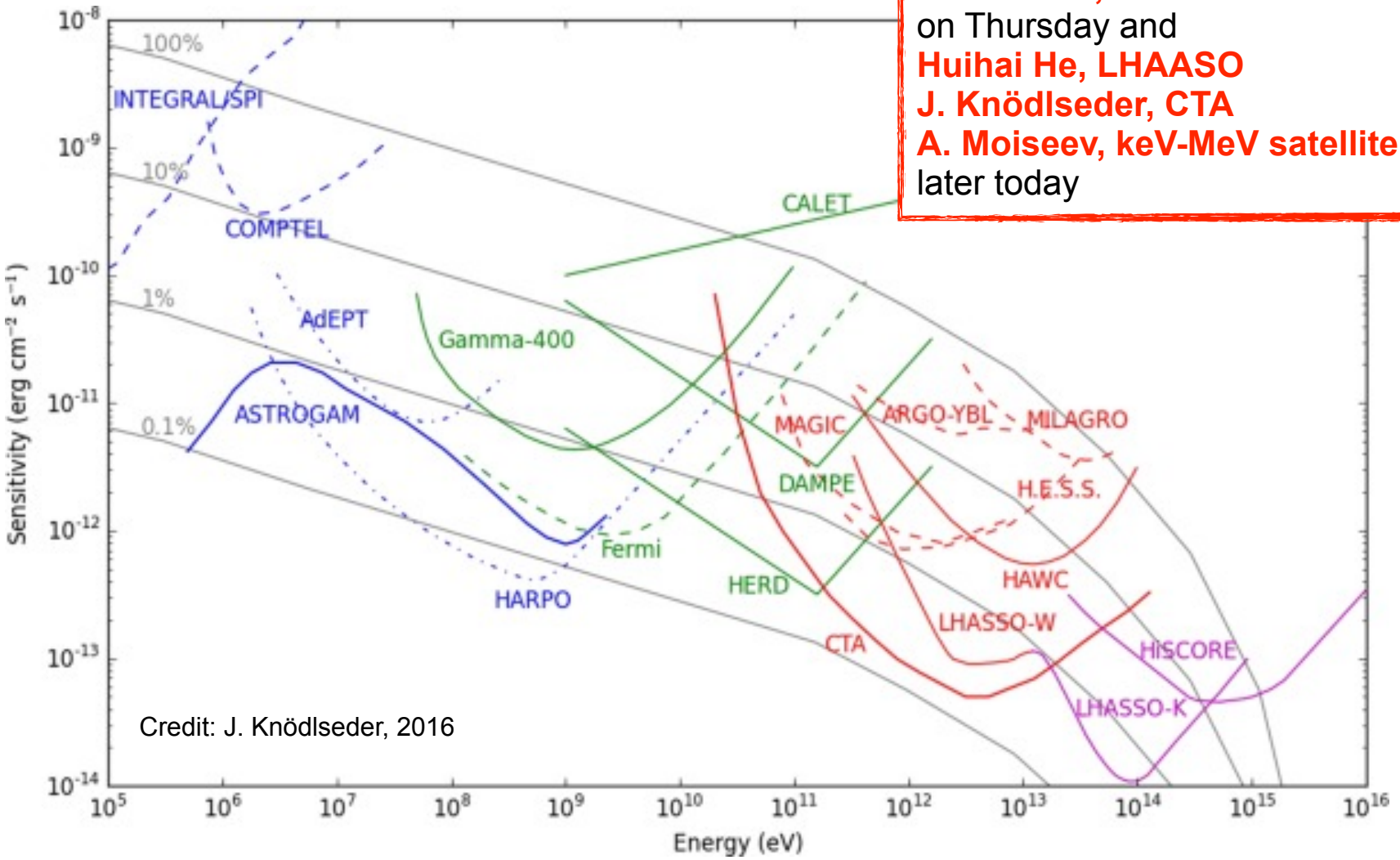
THESEUS (launch ~2032):

- **Soft X-ray Imager (SXI, 0.3 – 6 keV):** FOV ~1sr, source location accuracy < 1-2’
- **InfraRed Telescope (IRT, 0.7 – 1.8 μm**): 10’x10’ FOV, fast response, imaging and spectroscopy
- **X-Gamma rays Imaging Spectrometer (XGIS, 2 keV – 20 MeV**): ~1.5sr FOV, source location accuracy ~5 arcmin in 2-30 keV

Gamma-rays follow-up

New instruments

- Clear need for a MeV satellite
- HERD on board China's space station - high sensitivity monitoring of the GeV-TeV sky launch planned in early 2020s
- CTA and LHAASO coming soon
- Planned large FoV water-Cherenkov experiment SWGO



Talks by:
Ke Fang, SWGO
on Monday
A. Morselli, eASTROGRAM
on Thursday and
Huihai He, LHAASO
J. Knödlseder, CTA
A. Moiseev, keV-MeV satellite
later today

Summary

- TXS 0506+056 - first (and only…) compelling evidence of a neutrino source
- Several intriguing candidates: PKS 1502+106, SN 2019pqh, …

- Real-time alerts and MultiMessenger approach of high interest to the whole astro-community
- Large FoV facilities can provide multiple counterpart candidates
- High sensitivity pointing instruments narrow down the details
- Monitoring facilities extremely helpful in statistical interpretation of the results

"Vicious circle" of open questions:

- What are the sources of cosmic neutrinos?
- How to optimise our follow-up? How fast to react? Where to look? For how long?

New facilities to come in the nearest future - great chance, but also many challenges…
Higher sensitivity, larger FoV → more counterpart candidates!
More efforts needed to collect and process the MWL information efficiently