

***AGILE γ -ray sources coincident
with cosmic neutrino events***



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(INAF-OAR & ASI-SSDC)
on behalf of the AGILE Team

- IceCube results with single starting events (HESE)
- Cosmic neutrino source candidates and γ -rays
- AGILE search for γ -ray counterparts to IceCube HESE events
- Summary and conclusions

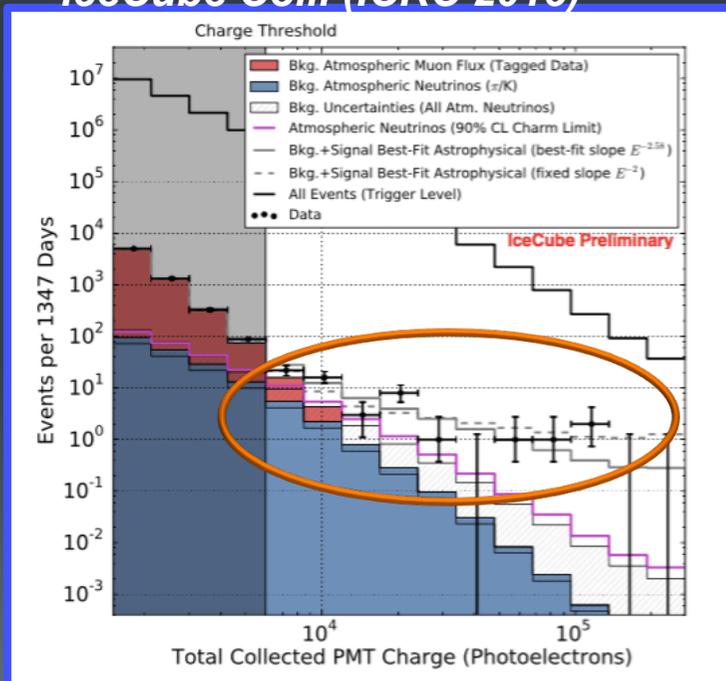


IceCube results with single starting events (HESE)

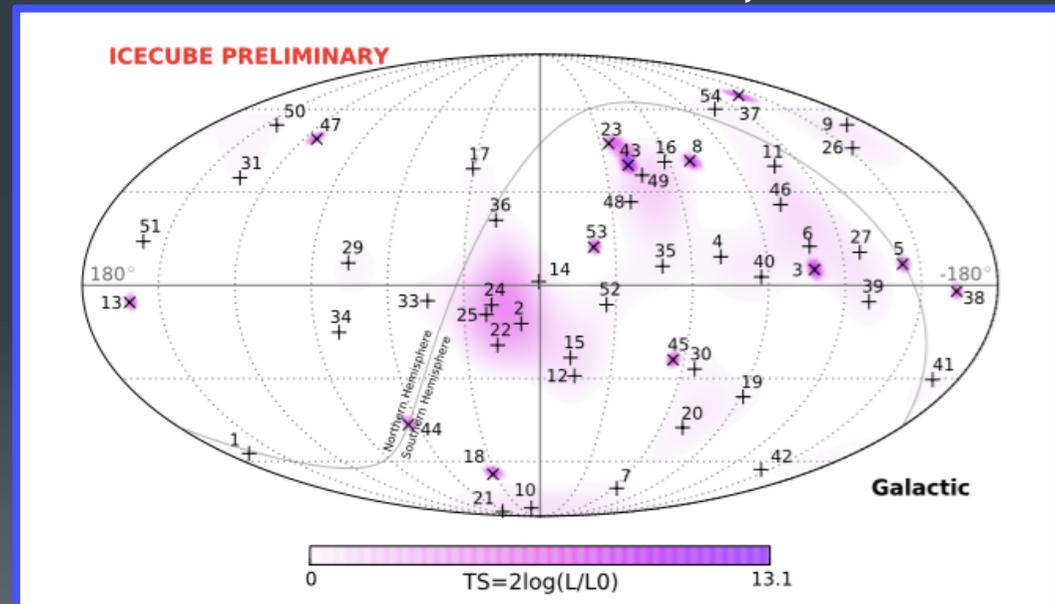
ICECUBE HESE ν -signal (all-sky)

- First evidence of a diffuse flux of astrophysical neutrinos provided by IceCube using 3 and 4 years of data (2010-2014).
- In total, 54 “high-energy starting events” (HESE) with interaction inside the detector: mostly *shower-like* events from ν_e and ν_τ with ang. resolution of ~ 10 deg.

IceCube Coll. (ICRC 2015)



Aartsen et al., Science 2013



Confirmed using a 8-year data sample (ICRC 2017)

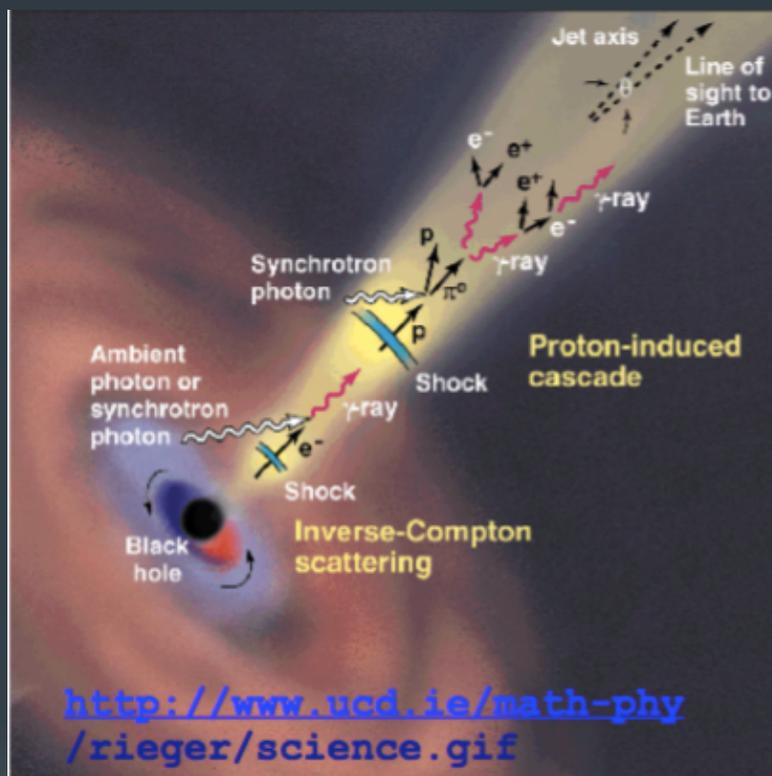


Cosmic neutrino source candidates

Blazar AGNs main source candidates

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Recently works (Resconi et al. 2017) provide hints that HBL subclass of blazars may be the sources of some of the IceCube HESE neutrinos as well as of UHECRs seen by Auger/TA.

- Blazar jet ideal sites of CRs acceleration
- Photomeson production against intense radiation fields.
- Gammas and neutrinos from neutral and charged meson decay
 - $p + \gamma \rightarrow \Delta^+ \rightarrow p + \pi^0 \rightarrow p + \gamma \gamma$
 - $p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \rightarrow n + \mu + \nu$
- Sources of target radiation:
 - Photons from the accretion disk
 - IR photons from a dust torus
 - Non-thermal photons inside the jet (SSC models)

Other possible candidates

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- Star forming galaxies (SFGs): can explained at most 10% of the IceCube diffuse flux.
- Gamma-ray bursts (GRBs): any spatial and temporal correlation with single IceCube neutrinos has been seen yet (<1% contribution to the diffuse ν -flux).
- Radio-galaxies
- Galactic sources

What else?

- Hidden blazars? 50% of (low luminosity) blazars might be not identified.
- E.M. hidden sources? γ -rays absorbed or degraded down to lower energies.
- Compact sources: AGN cores, white dwarf mergers, ...

- Sources of cosmic neutrinos may be identified by rapid **follow-up observations** from space- and ground-based observatories.
- Since April 2016, IceCube alerts the astronomical community through the GCN network whenever a clear detection of a cosmic neutrinos occurs.
- Only **HESE *track-like* events** with good angular resolution ($\sim < 2^\circ$) are published through the network.
- Two types of ν -events are announced:
 - **HESE events: 100 TeV - 1 PeV**
 - **EHE events: several hundreds of TeV**

Expected occurrence rate: ~4-5/yr

Updated HESE/EHE event list

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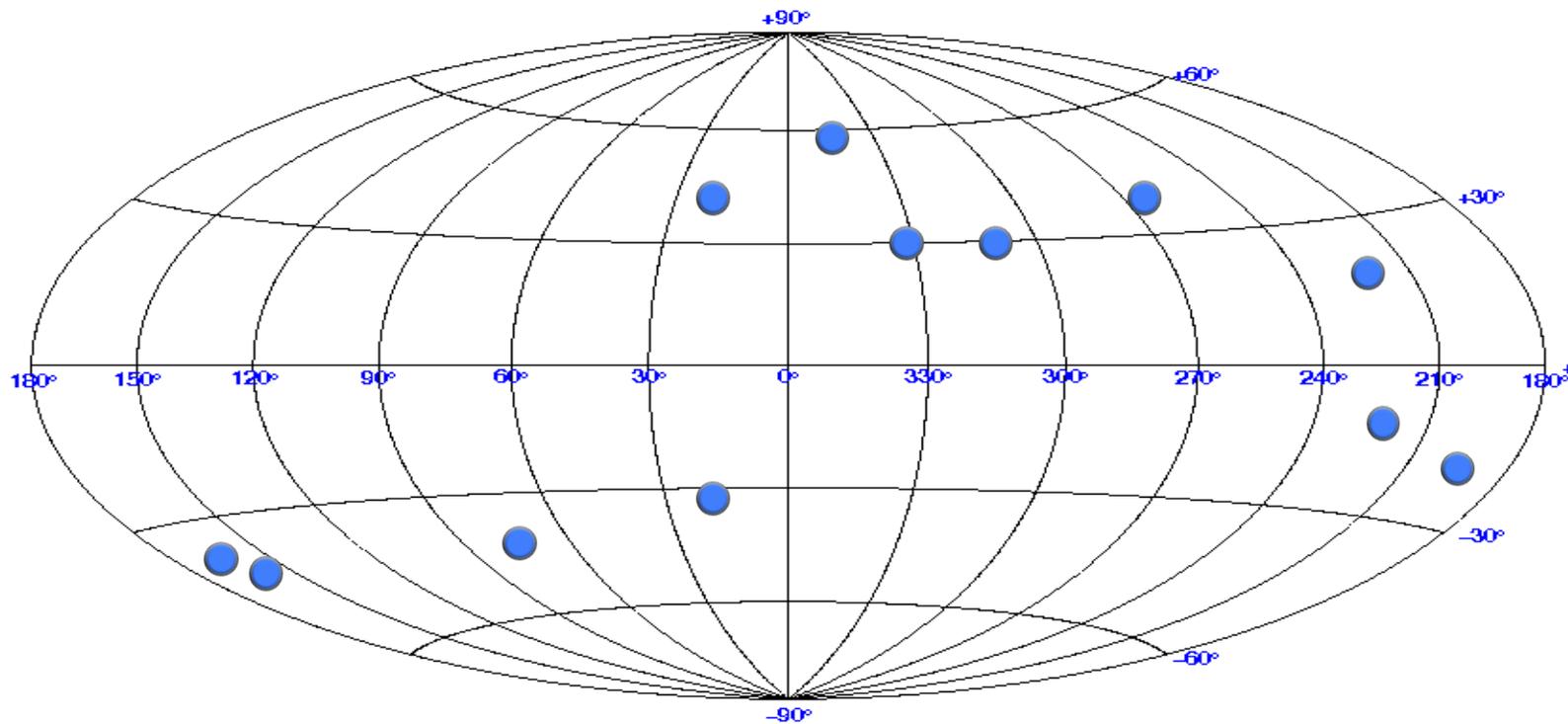
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ICECUBE Event ID	T0 (yy/mm/dd hh:mm:ss)	Category
<u>67093193</u>	16/04/27 05:52:32.00	HESE
<u>6888376</u>	16/07/31 01:55:04.00	HESE/EHE
<u>26552458</u>	16/08/06 12:21:33.00	EHE
<u>58537957</u>	16/08/14 21:45:54.00	HESE
<u>38561326</u>	16/11/03 09:07:31.12	HESE
<u>80127519</u>	16/12/10 20:06:40.31	EHE
<u>65274589</u>	17/03/12 13:49:39.83	HESE
<u>80305071</u>	17/03/21 07:32:20.69	EHE
<u>32674593</u>	17/05/06 12:36:55.80	HESE
<u>50579430</u>	17/09/22 20:54:30.43	EHE
<u>56068624</u>	17/10/15 01:34:30.06	HESE
<u>17569642</u>	17/11/06 18:39:39.21	EHE

HESE/EHE sky distribution

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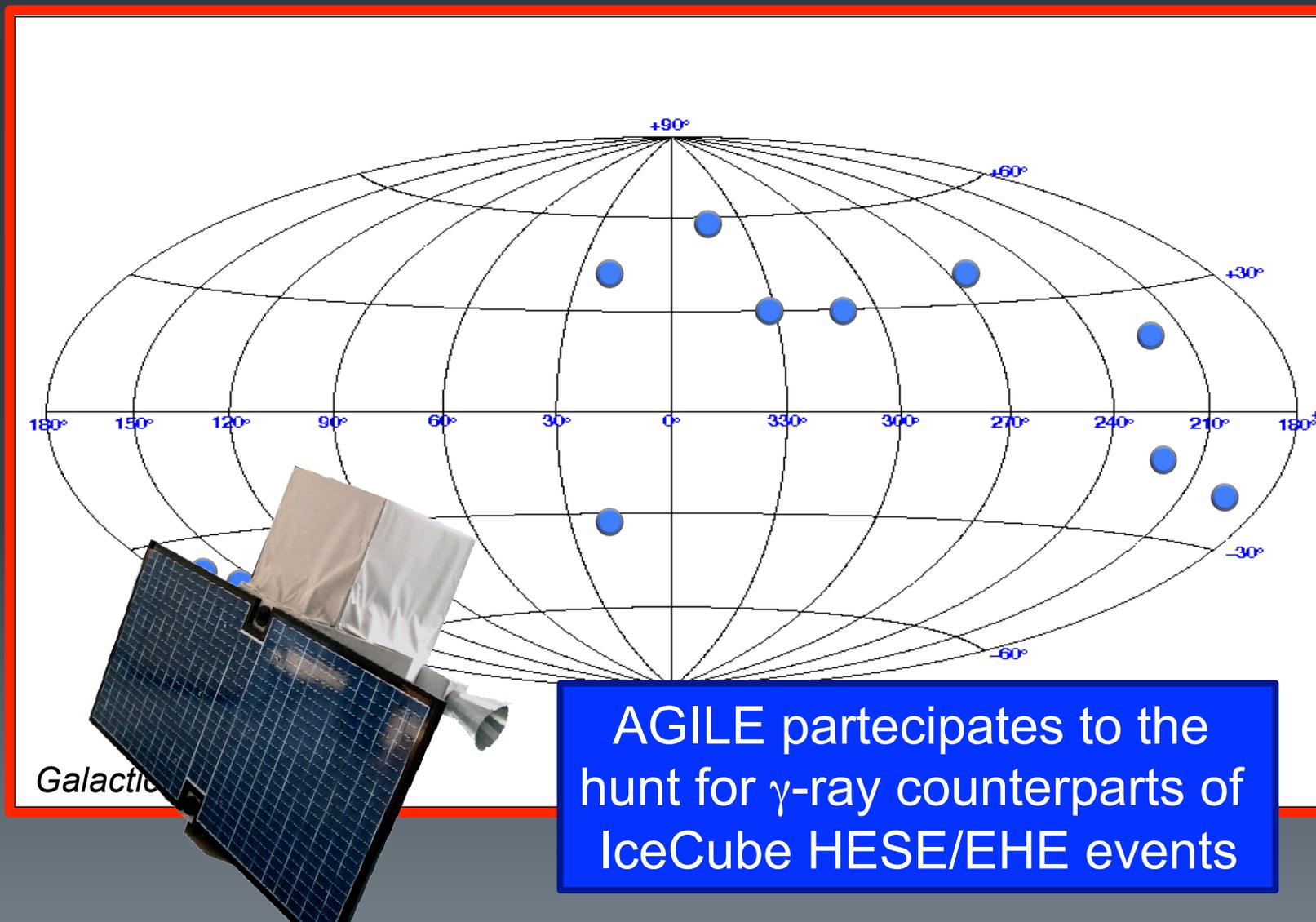


Galactic coordinates

HESE/EHE sky distribution

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AGILE search for γ -ray
counterparts to
IceCube HESE/EHE events



**The AGILE Payload:
the most compact instrument
for HE astrophysics**

only ~100 kg (~ 60 × 60 cm)

- **GRID gamma-ray imager (30 MeV - 30 GeV)**
- **SuperAGILE hard X-ray imager (18 - 60 keV)**
- **MCAL Minicalorimeter (0.3 - 100 MeV)**

ASI Mission with INFN and INAF participation

AGILE in spinning mode

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- Very large field of view (~ 2.5 sr).
- Coverage of 70% -- 80% of the whole sky every day.
- Very fast ground segment: first *Quick Look* analysis (on *contact* basis) available after ~ 30 min after telemetry download.

Very suitable instrument to perform all-sky searches for short transient γ -ray sources and γ -ray counterparts to multi-messenger transients (GW and neutrinos).

Automatic AGILE QL detections

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- AGILE *Quick Look* detection system searches for gamma-ray transients above 100 MeV over predefined 2-day maps.
- Blind search for count excesses above the background using standard detection method (XIMAGE, spotfinder).
- Each candidate transient is then evaluated using the standard AGILE maximum likelihood (ML) algorithm.

Automatic AGILE QL detections

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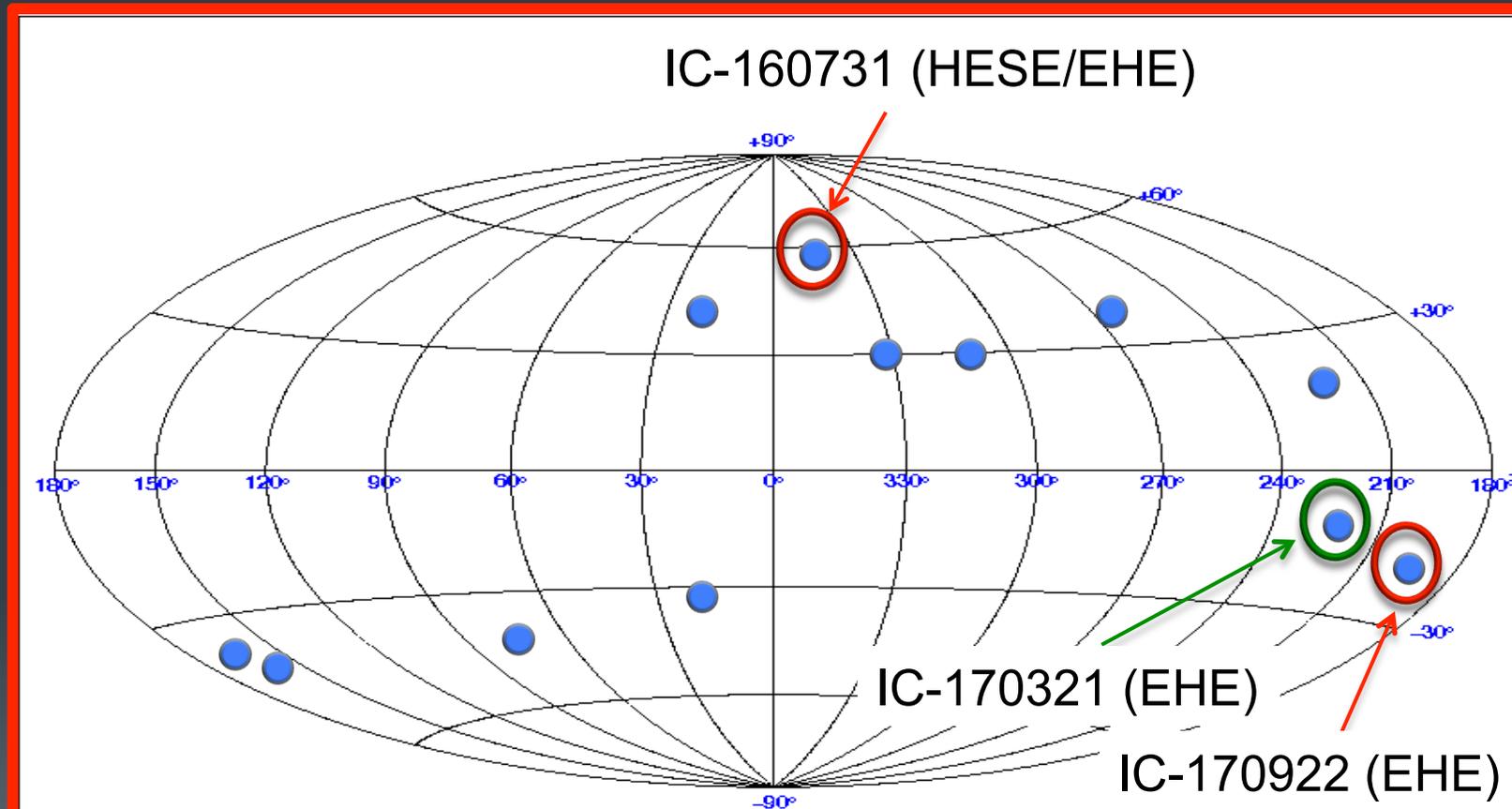
- AGILE *Quick Look* detection system searches for gamma-ray transients above 100 MeV over predefined 2-day maps.
- Blind search for count excesses above the background using standard detection method (XIMAGE, spotfinder).
- Each candidate transient is then evaluated using the standard AGILE maximum likelihood (ML) algorithm.

Systematically search in the AGILE QL database for transient gamma-ray detections *spatially and temporally* consistent with the IceCube neutrino events announced since 2016.

AGILE QL detections of IceCube events

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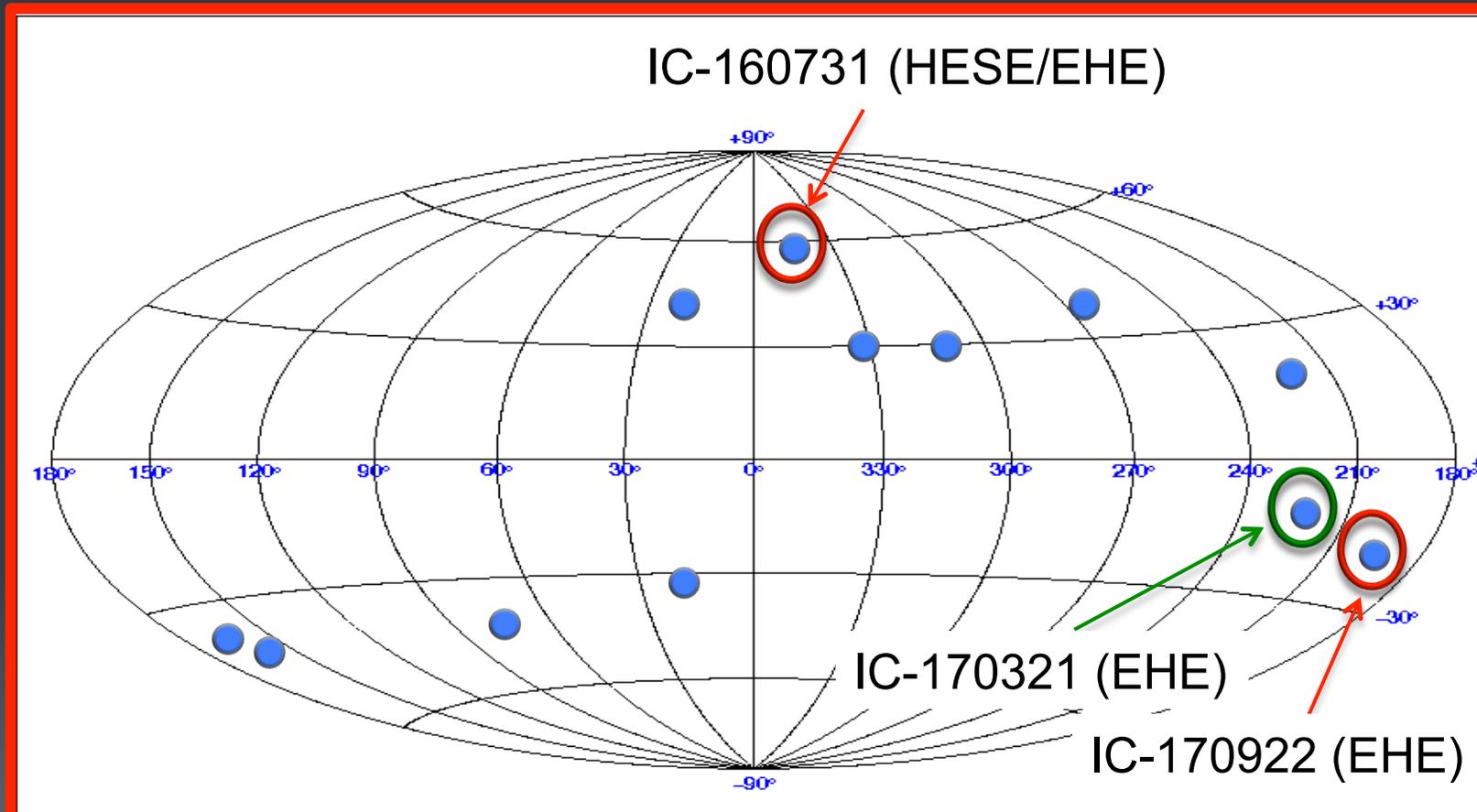


3 AGILE detections ($\sim 4\sigma$ each) from the automatic QL system (running over predefined 2-day maps) consistent with time/position of 3 IC events out of 10.

AGILE QL detections of IceCube events

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Search radius around the input neutrino positions
optimised according to the AGILE ang. resolution.

Summary of the 3 AGILE QL detections

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Lucarelli et al., submitted

PRELIMINARY

AGL src	ICECUBE Event	T0	Category	AGILE QL δt [days]	AGILE Flux $\times 10^{-6}$ [ph/cm ² /s]
A	<u>IC-160731</u>	16/07/31 01:55	HESE/EHE	-2.0	1.8 ± 0.7
B	<u>IC-170321</u>	17/03/21 07:32	EHE	-2.2	1.5 ± 0.6
C	<u>IC-170922</u>	17/09/22 20:54	EHE	-2.8	1.7 ± 0.7

- **AGL source A**: announced by AGILE in ATel. #9265 and further investigated in ApJ 846 (Lucarelli et al. 2017).
- **AGL source B**: **new from AGILE QL database search**, not previously announced in Atel.
- **AGL source C**: announced by AGILE in ATel. #10801. Confirm gamma-ray emission observed by Fermi-LAT (ATel. #10791) from the direction of the BL Lac blazar TXS 0506+056 (see paper on multi-messenger and MWL observations, **Science 361, 2018**).

Single post-trial probability

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- Post-trial false alarm probability (i.e. chance coincidence probability in time (Blackburn 2015)):

$$\rightarrow P_i = 2 * FAR * \delta t * (1 + \ln(\Delta t/t_{bin}))$$

where:

- ✧ FAR is the *False Alarm Rate* per 2-day map per pixel for detections above 4σ on single 2-day integration maps (estimated using the whole database of QL detections in spinning).
- ✧ δt = distance in time (in terms of # of QL maps) from T_0
- ✧ Δt = window of interest around $T_0 \rightarrow \pm 4$ days (== 2 QL maps)

$$\rightarrow P_i \text{ (post-trial)} \sim (2 \div 5) \times 10^{-3}$$

PRELIMINARY

Joint post-trial probability

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- *Joint* post-trial probability to observe 3 gamma-ray/neutrino associations out of 10 neutrino alerts analysed since the beginning of the IceCube alert system:

$$\rightarrow P_{\text{joint}}(\text{post-trial}) = 1 - (1 - P_A * P_B * P_C)^N \sim 10^{-6} (\sim 5\sigma)$$

PRELIMINARY

where:

- ✧ N (# global trials) = 10 (# of alerts) * 3 (# of search radius optimizations)

The probability of a random association between the 3 AGILE detections and the 3 neutrino events (out of 10) is quite low → significantly hints towards an astrophysical connection between gamma-ray/neutrino.



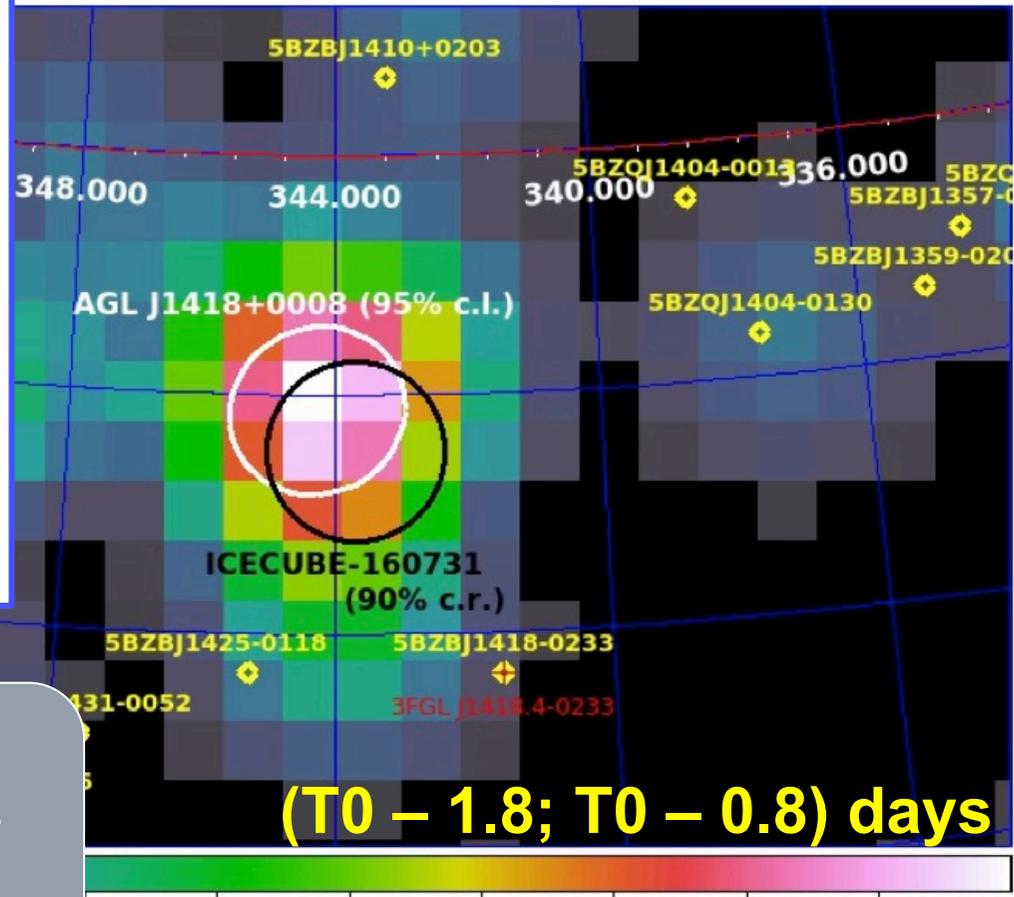
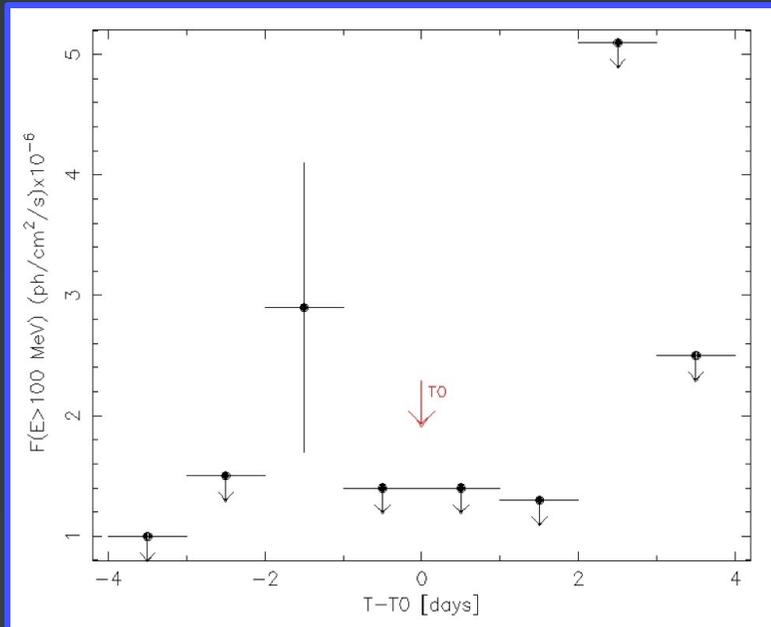
AGILE and IC-160731 (src A)

IC-160731/AGL J1418+0008 transient

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Lucarelli et al., ApJ 846 (2017)



(T0 - 1.8; T0 - 0.8) days

- 4.9 σ peak significance on the 24-hour integration T0 - 1.8; T0 - 0.8.
- Not seen by Fermi due to a very poor source visibility during this period.

No clear known counterpart seen within the AGILE/ICECUBE err. circl.

Targeted SWIFT data on 1RXS J141658

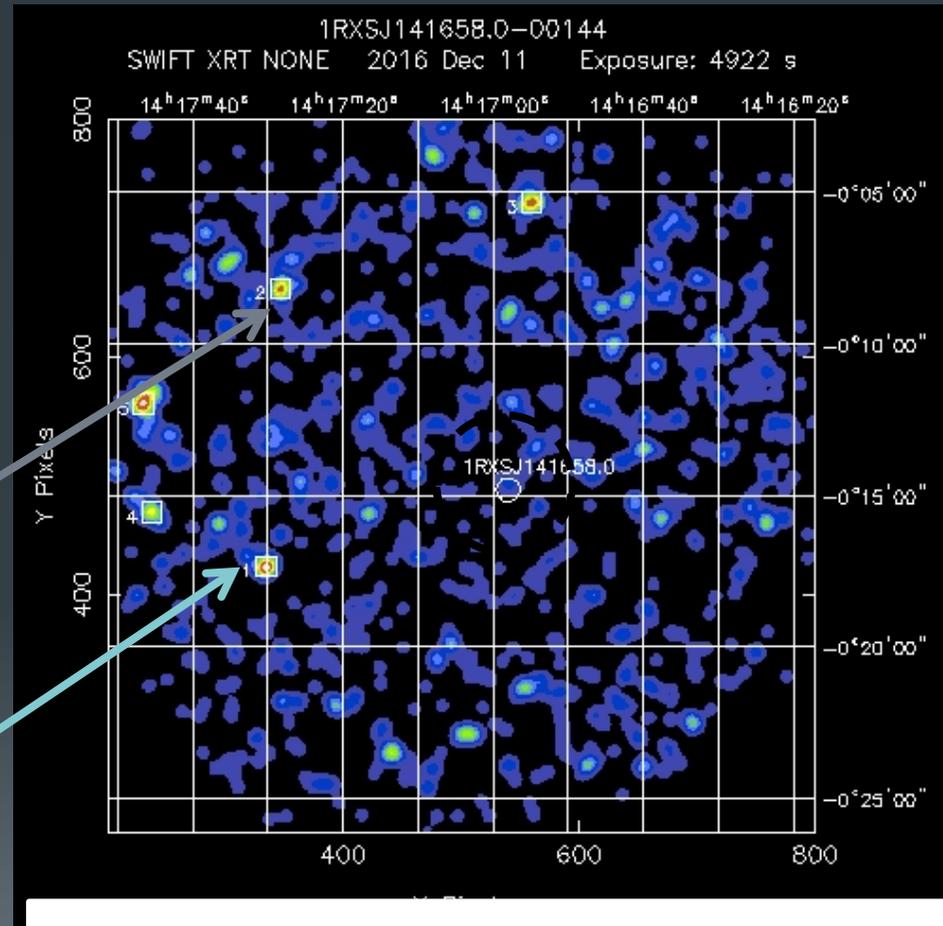
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Lucarelli et al., ApJ 846 (2017)

- 5 ks ToO observation performed ~6 months later than T0.
- No X-ray emission on the 1RXS J141658 position
→ HBL nature of this AGN candidate not confirmed.

5 un-catalogued X-rays sources detected during the ToO.



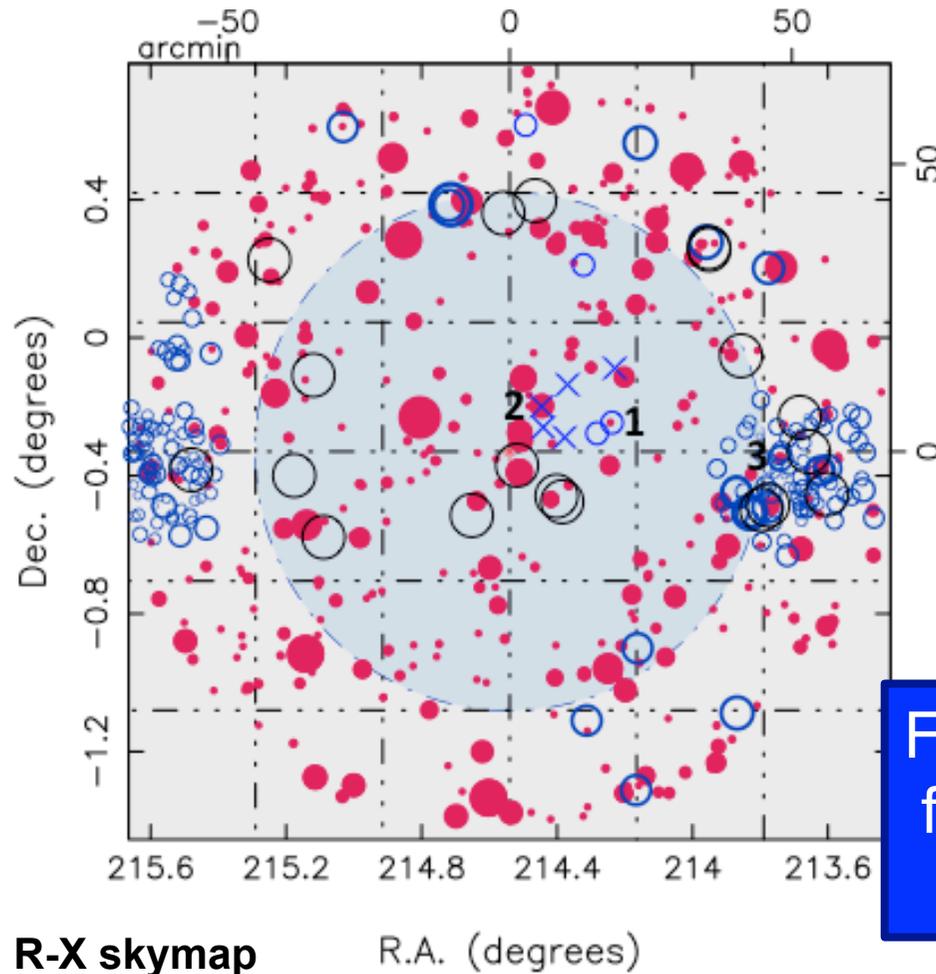
1RXS J141658-00144:
possible HBL blazar candidate

Update on e.m. counterpart search

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Lucarelli et al., submitted



New search around
ICECUBE-160731/AGL
J1418 using SSDC
SkyExplorer tool and
the ASI *OpenUniverse*
web portal (Giommi,
Chang).

Further HBL/HSP candidate
found within this sky region
(under evaluation).



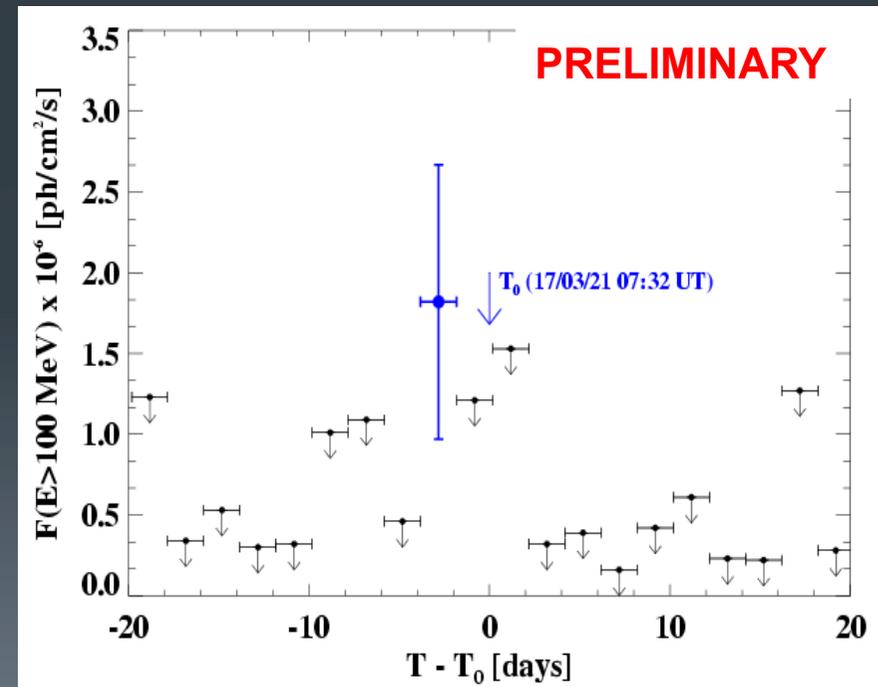
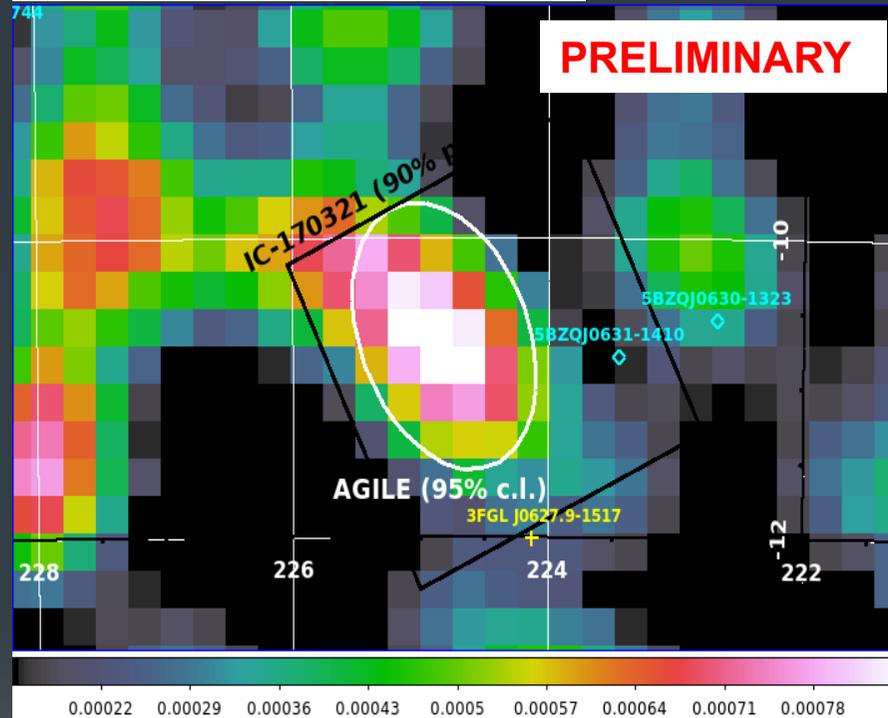
AGILE and IC-170321 (src B)

- IceCube EHE event announced on Mar. 21, 2017.
- R.A., Decl. (J2000): **(98.3, -15.02) deg, i.e. (l,b)=(224.42,-10.75) deg**, not far from the Galactic plane. Higher diffuse gamma-ray emission.
- Very poor e.m. follow-up (no optical follow-up available).
- Fermi-LAT ULs on emission above 100 MeV around T_0 and in the days before T_0 (GCN #20971).

AGILE QL detection on short 2-day time interval 28

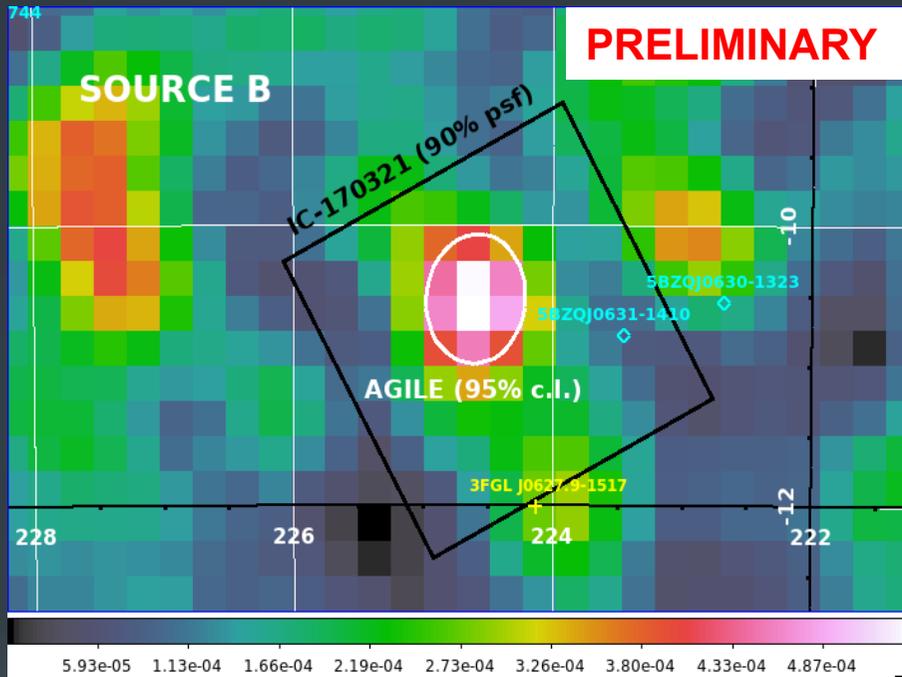
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Lucarelli et al., submitted

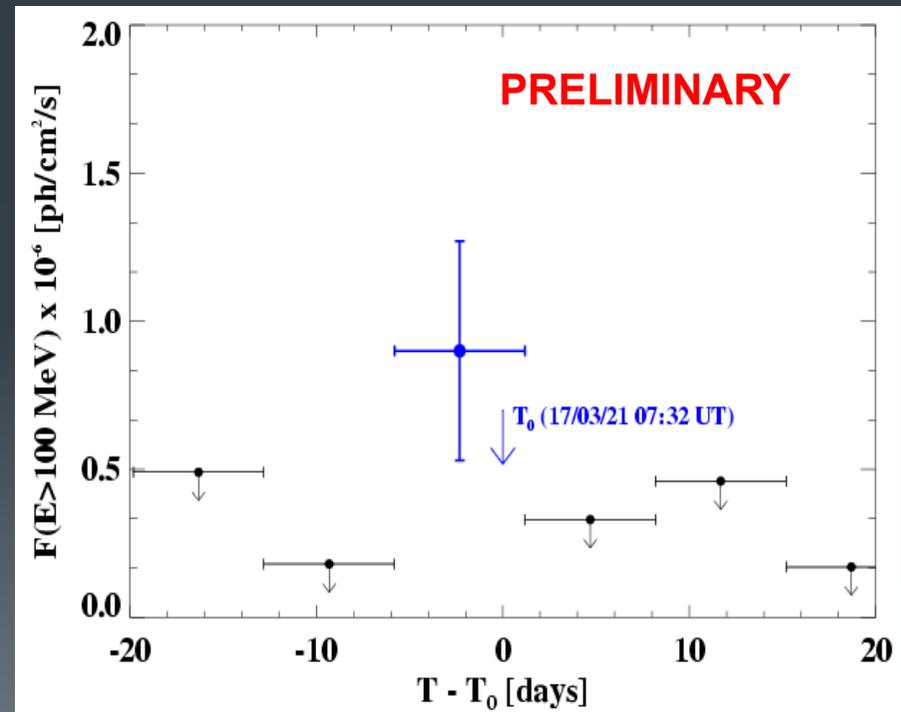


... and on longer interval around T_0

Lucarelli et al., submitted



7-day timebin lightcurve



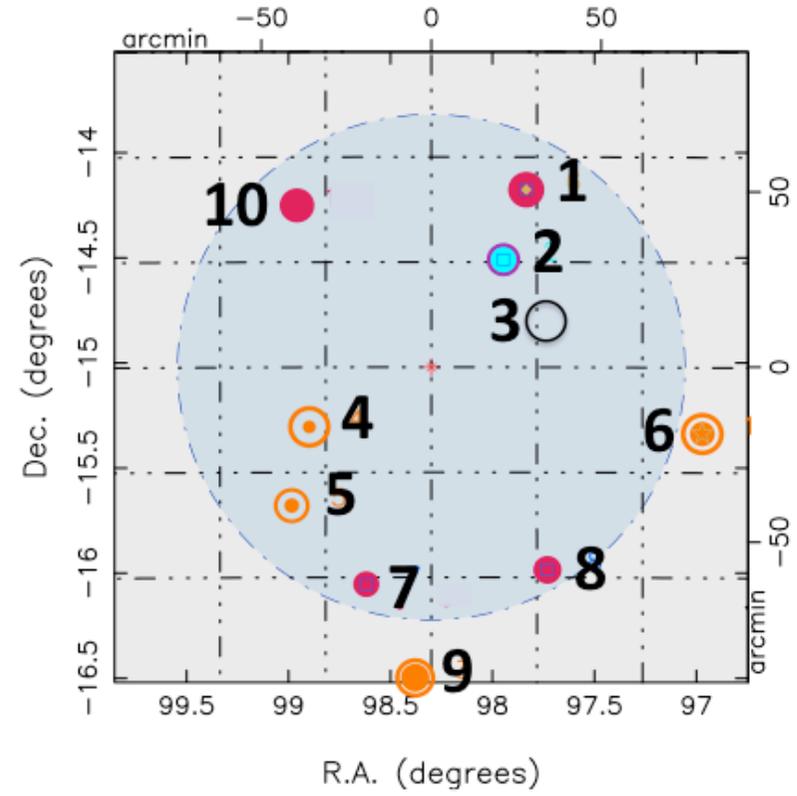
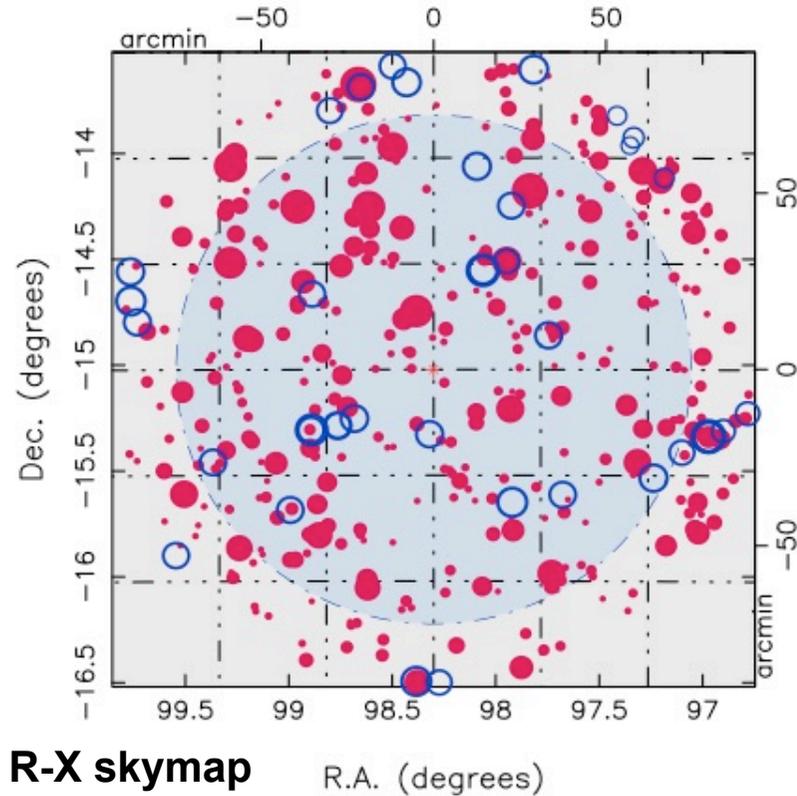
Counterpart search for IC-170321

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Produced with SkyExplorer & OpenUniverse

Lucarelli et al., submitted



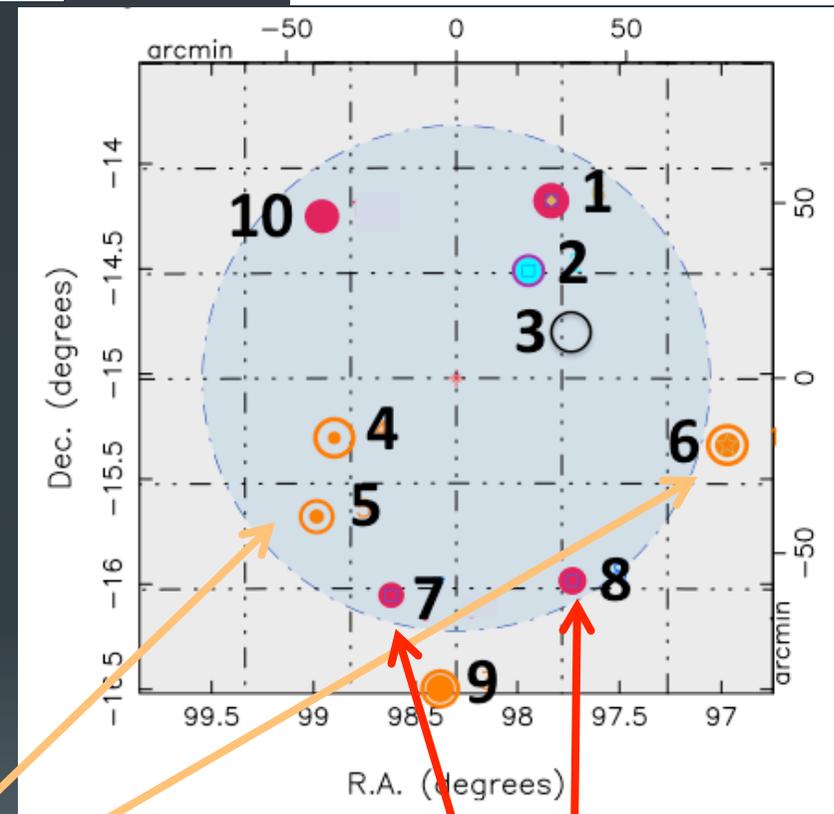
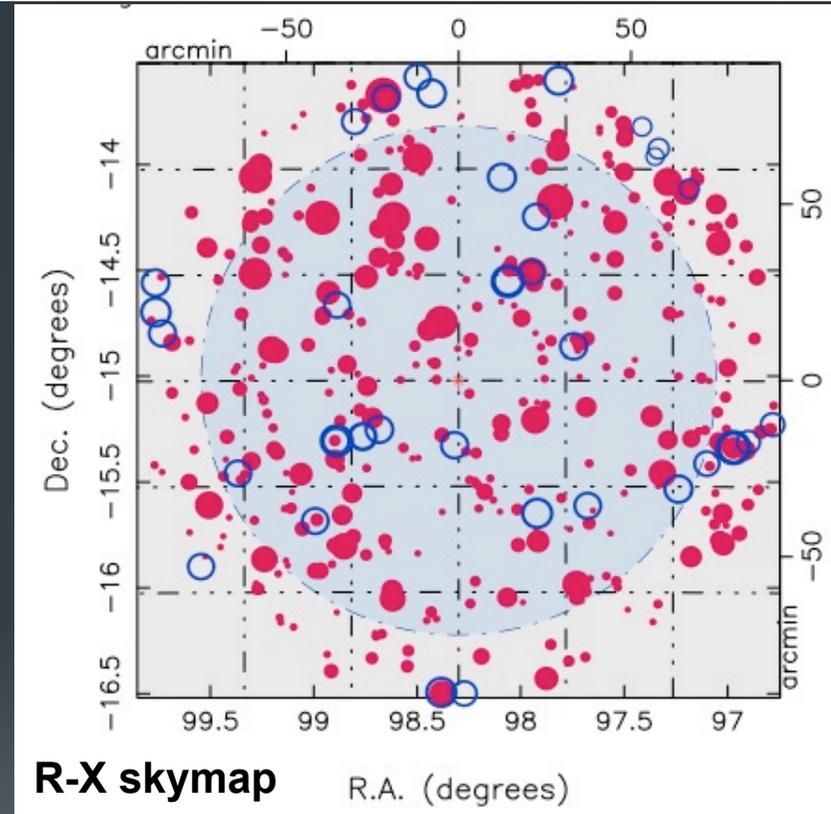
Counterpart search for IC-170321

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Produced with SkyExplorer & OpenUniverse

Lucarelli et al., submitted



HBL/HSP candidates

Flat spectrum r-sources



AGILE and IC-170922 (src C)

- EHE IceCube event announced on Sept. 22, 2017.
- R.A., Decl. (J2000): (77.43, 5.72) deg.
- HE γ -rays observed both by AGILE and Fermi-LAT consistent with the IceCube error box (ATel's #10791 and #10801).
- Also VHE γ -rays observed by MAGIC a few days after the neutrino event T0 (ATel #10817).

The blazar TXS 0506+056 (also known as a 3FGL and 3FHL source) located inside the IceCube error region
→ Identification as the IC-170922 neutrino emitter
(Science 361, 2018)

AGILE observation of IC-170922

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AGILE detection over 2-days maps
appeared again near event time T₀
from the automatic QL detection systems.

AGILE 18-21 Sept. 2017 (21:00 UTC)

ICECUBE-170922A (90% PSF)

TXS 0506+056
+

PKS 0502+049

PKS 0459+060
+

MG1 J050533+0415
+

AGILE 95% c.l.

4C +06.21
+

PRELIMINARY

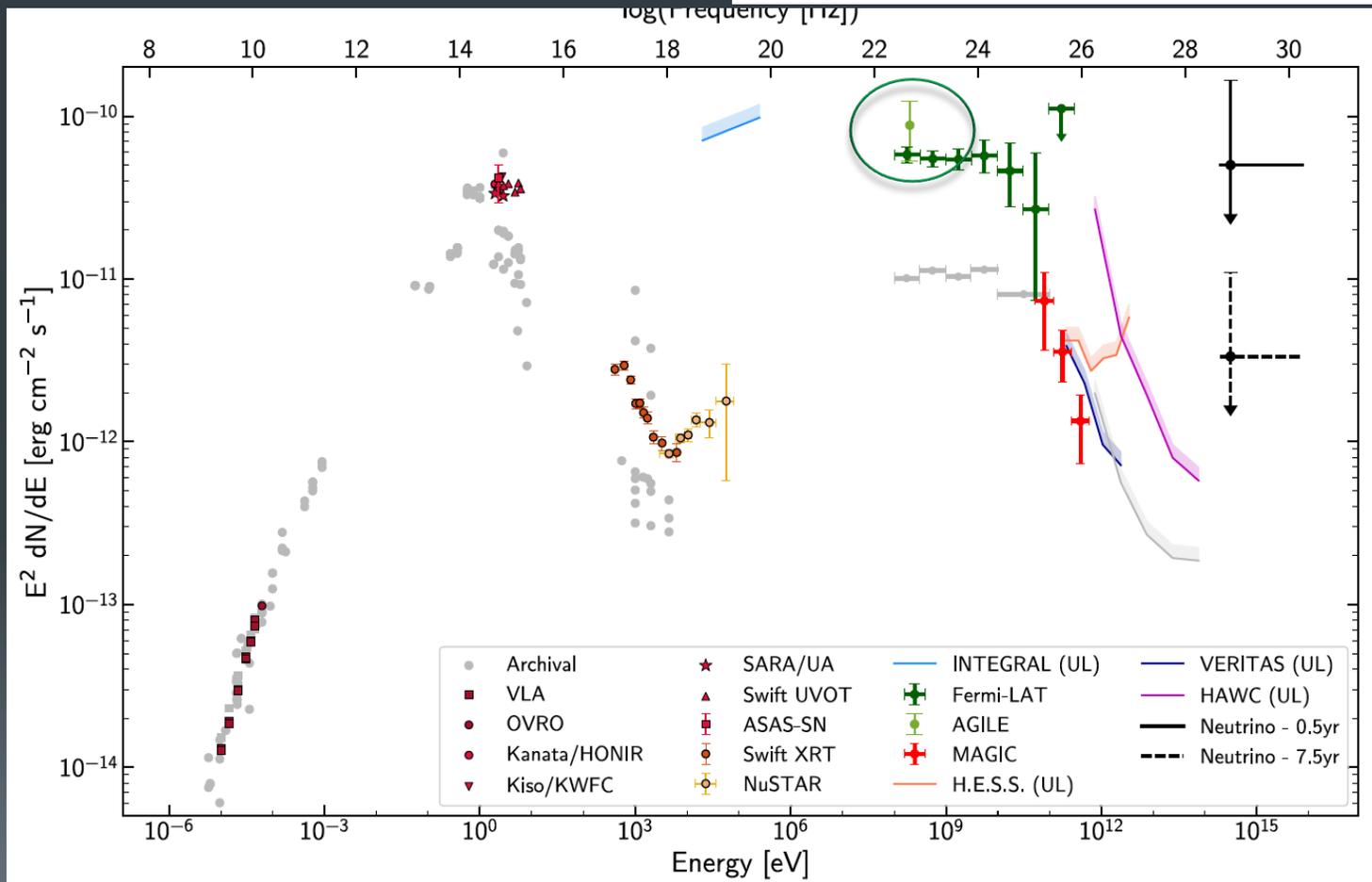
Consistent with the position of the BL Lac source TXS 0506+056, seen also at VHE gammas near T₀ (Atel #10817). TXS 0506 as the first cosmic neutrino source ever detected!

1.12e-04 1.39e-04 1.65e-04 1.91e-04 2.18e-04 2.44e-04

Broadband (SED) for the blazar TXS 0506+056

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IceCube Coll. et al., Sci 361 (2018)



(observations within 14 days from T₀)

- **AGILE src A and IC-160731:** no obvious e.m. counterpart found. Swift ToO six months after T0, Fermi low source visibility (Lucarelli et al., ApJ 846, 2017). **New possible candidates** using MW Tools (Lucarelli et al. 2018, submitted).
- **AGILE src B and IC-1703121:** no obvious e.m. counterpart found. Low Galactic latitude, very poor e.m. follow-up, possible candidates using MW Tools (Lucarelli et al. 2018, submitted).
- **AGILE src C and IC-170922:** AGILE contribution to the MWL identification of the BL Lac TXS 0506+056 as the likely neutrino emitter (Science 361, 2018).
- Estimated γ /neutrino luminosities consistent with extra-gal compact objects ($10^{46} \div 10^{47}$ erg s⁻¹) in all three cases.

Conclusions

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- AGILE fully involved in the MWL follow-up of IceCube alerts published through the GCN network.
- **Systematic search in the AGILE QL database: 3 AGILE detections spatially and almost temporally coincident with 3 IceCube events out of 10.**
- Joint post-trial **chance** probability of the 3 AGILE γ /neutrino associations out of 10: **excluded at a level of $\sim 5\sigma$**



Thank you



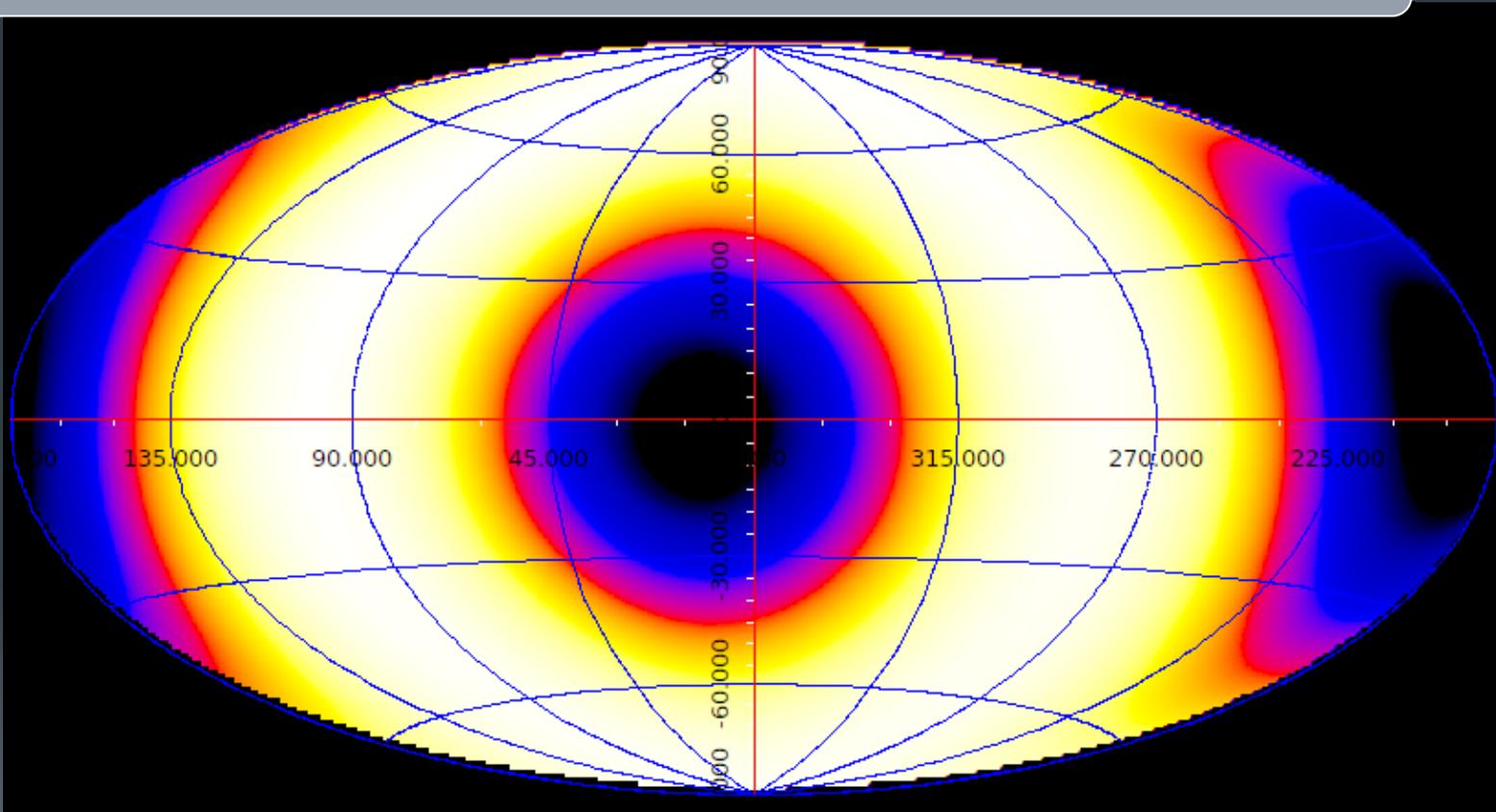
Backup Slides

AGILE in spinning mode

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Typical AGILE *all-sky* exposure over 1÷2 days of observation



Sensitivity over 2-day time integration ($E > 100$ MeV, 5σ): $3 \div 5 \times 10^{-10}$ erg/cm²/s

Angular resolution (100 MeV $< E < 1$ GeV): $1.2 \div 2.5$ deg

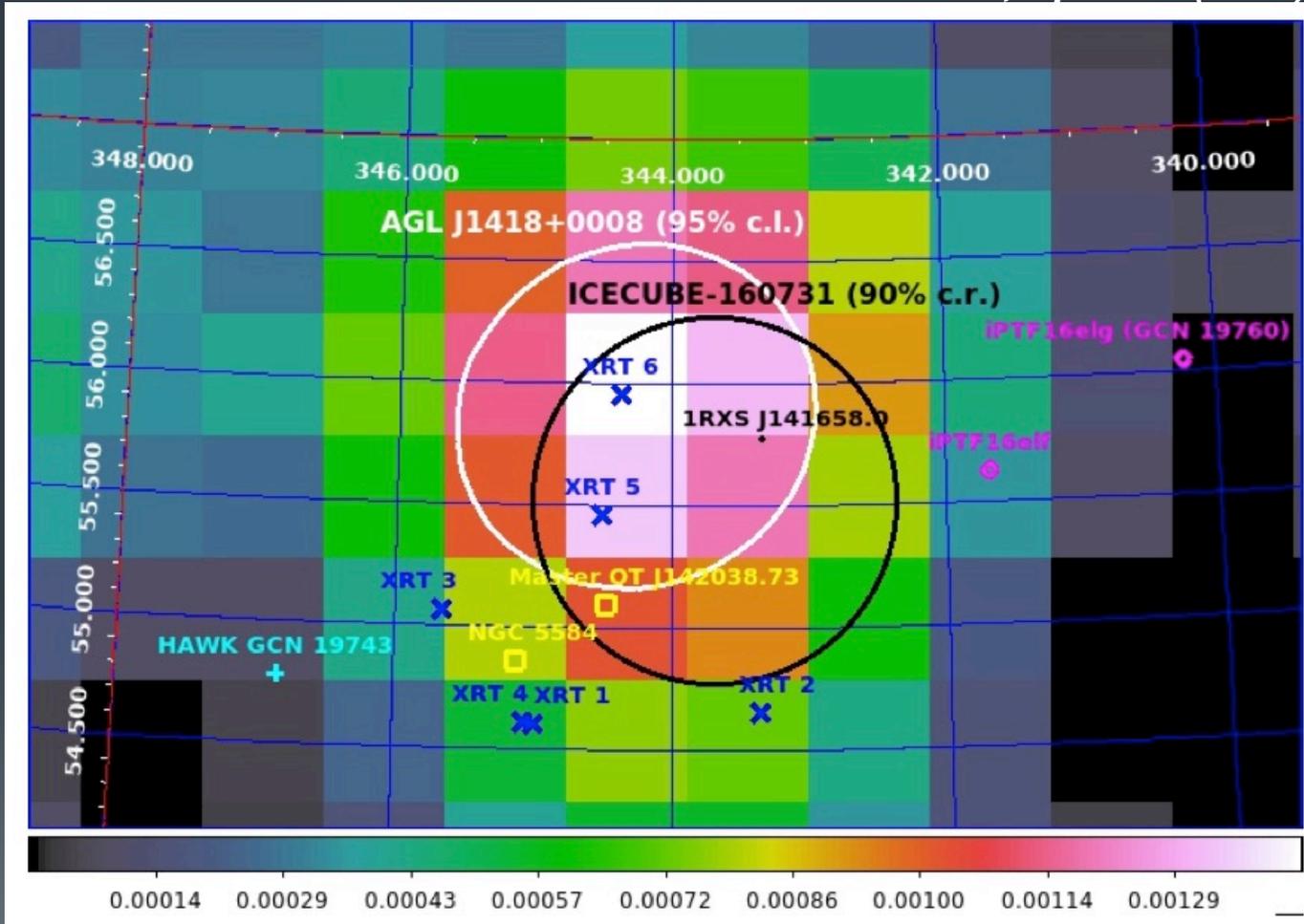
MWL follow-up of IC-160731

- Follow-up observations from other observatories (FERMI-LAT, MAGIC, SWIFT, HAWK, MASTER, FACT, etc.) have been reported.
- No detections of transients/steady e.m. emission consistent with the ICECUBE-160731 position has been reported so far from other wavelengths.

Mission/Observatory	ATel	GCN	Observation Time	Results
HAWK (TeV)	-	19743	30/07/16 21:28 – 31/07/16 02:59	No detection.
SWIFT (X-ray, Optical)	#9294	19747	31/07/16 03:00:46 - 14:51:52 UTC	Six known X-ray sources detected: no transients.
MASTER net (optical)	#9298	19748	2016-07-31 19:23:17 UT	No detection.
FERMI-GBM	-	19758	-	Position occulted by Earth at T0
FERMI-LAT	#9303	-	2.25 days from 2016 July 31.	No detection above 100 MeV
MAGIC	#9315	...	1.5 hrs starting from July 31 st , 21:25 UT	No detection above 600 GeV

e.m. counterpart candidates found during the IC-160731 MWL follow-up

Lucarelli et al., ApJ 846 (2017)



Lucairelli et al., ApJ 846 (2017)

- FERMI-LAT ULs of $\sim 10^{-7}$ ph/cm²/s on 2.25 days and 8 days from T_0 backward.
- Poor LAT visibility during the AGILE best-interval detection: LAT exposure up to 10 GeV comparable to the AGILE one.

