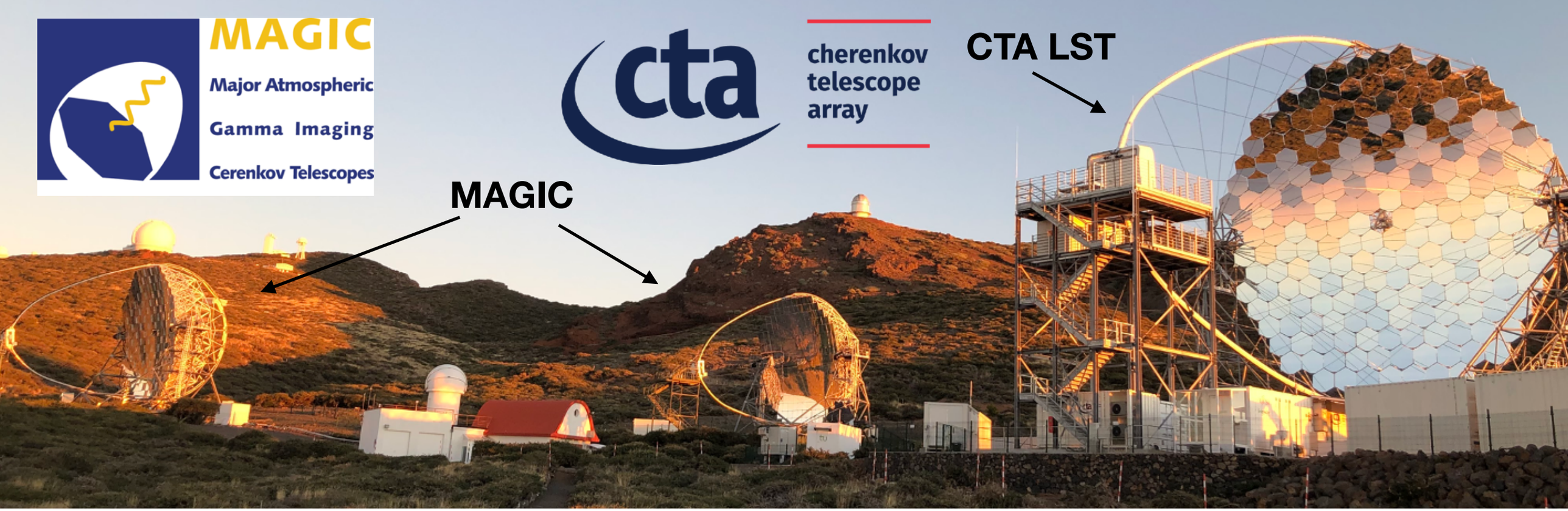


Multi-messenger γ-ray observations by MAGIC & CTA

Koji Noda (ICRR, U. Tokyo)

25 Mar 2022

Synergies at new frontiers at γ, ν, and GW

MAGIC · CTA LST

- MAGIC
  - 2x 17 m, FoV 3.5 deg, 1039 PMT (0.1 deg)
  - 1st tel. since 2004, 2nd tel. since 2009
    Camera upgrade in 2012. **Operational since 2013 with the current sensitivity**

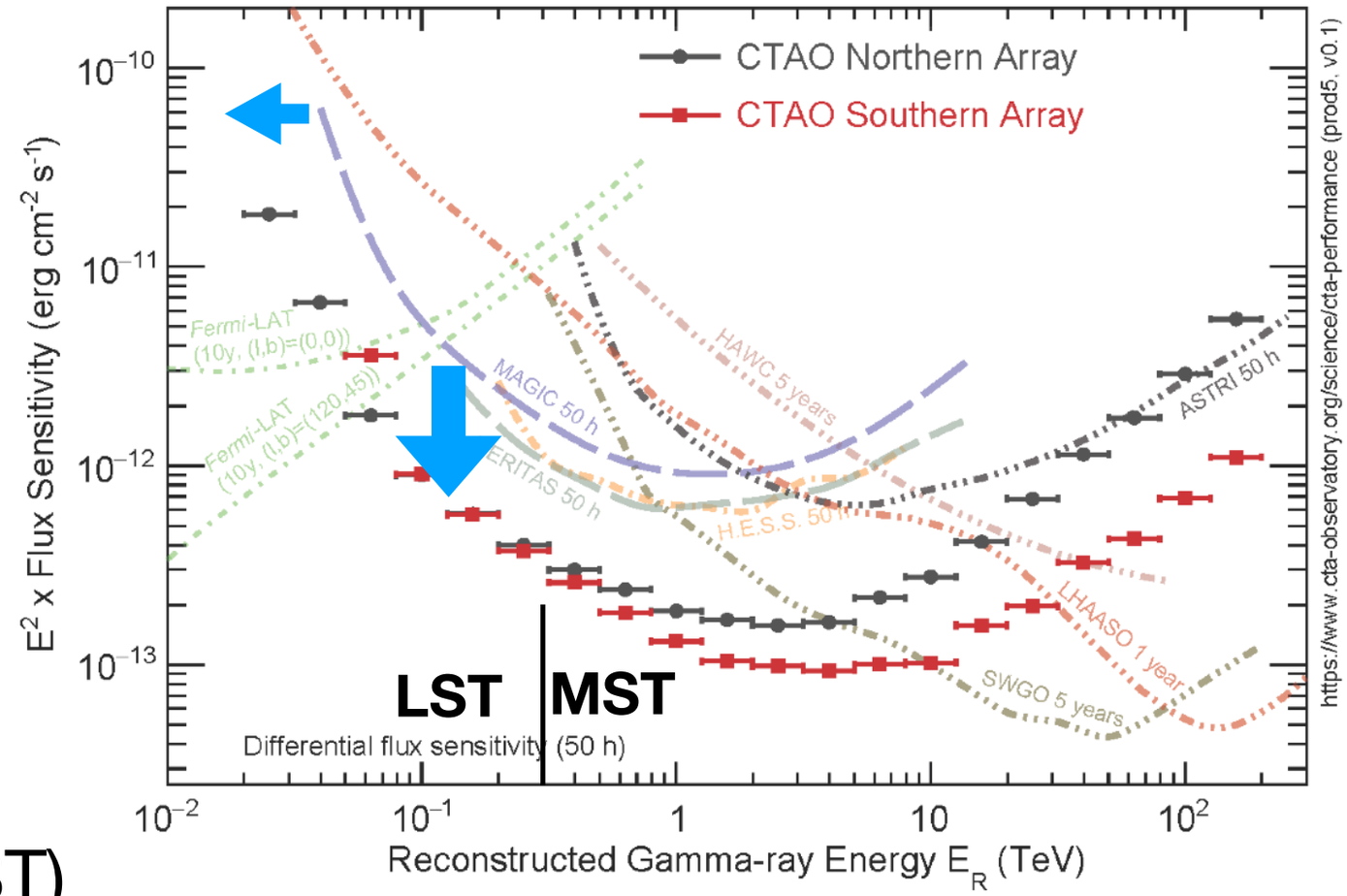
- Large Size Telescope (LST) of Cherenkov Telescope Array (CTA)

  - 1 of 3 types, array of tens IACTs
  - 4x 23 m, FoV 4.5 deg, 1855 PMT (0.1 deg)
  - North site: LST1 since 2018, operational now
    4 LSTs to be completed in 2024, obs. will start

- Both in ORM, La Palma, Spain. **Can follow the same sources**

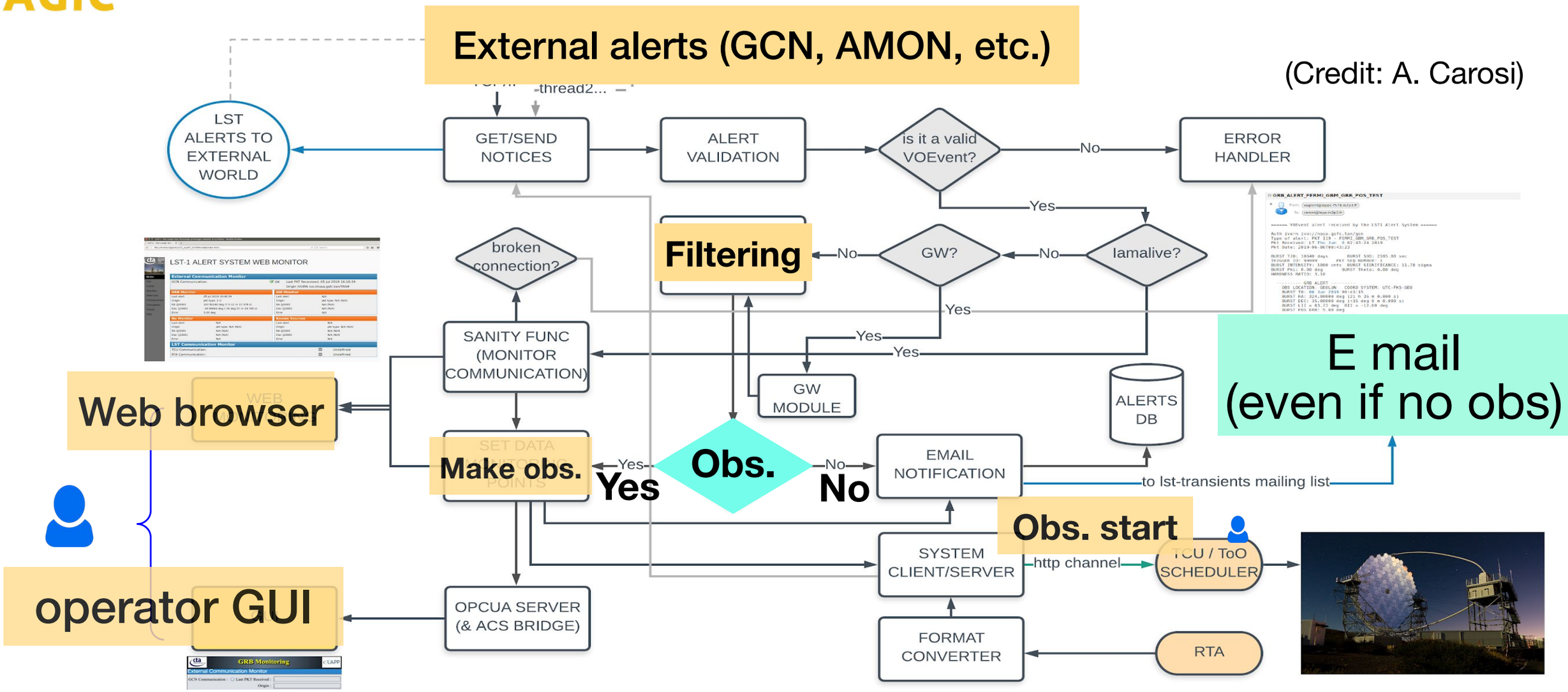
MAGIC => LST improvements

- **E threshold: 30-50 GeV (MAGIC) => 20 GeV (LST)**
  Less EBL absorption, farther objects can be detected
- **Sensitivity:** <0.7% Crab @ 220 GeV in 50 h (MAGIC)
  => **x10 improve with LST**
- Resolutions @ TeV:
  E 15% => 10% (LST)
  Angular 0.06 => 0.05 deg (LST)
- Weight: 70 t => 100 t
  Fast rotation: 7 deg/s => 9 deg/s (180 deg/ 20 s)
  LST can start to observe transients within 1 min



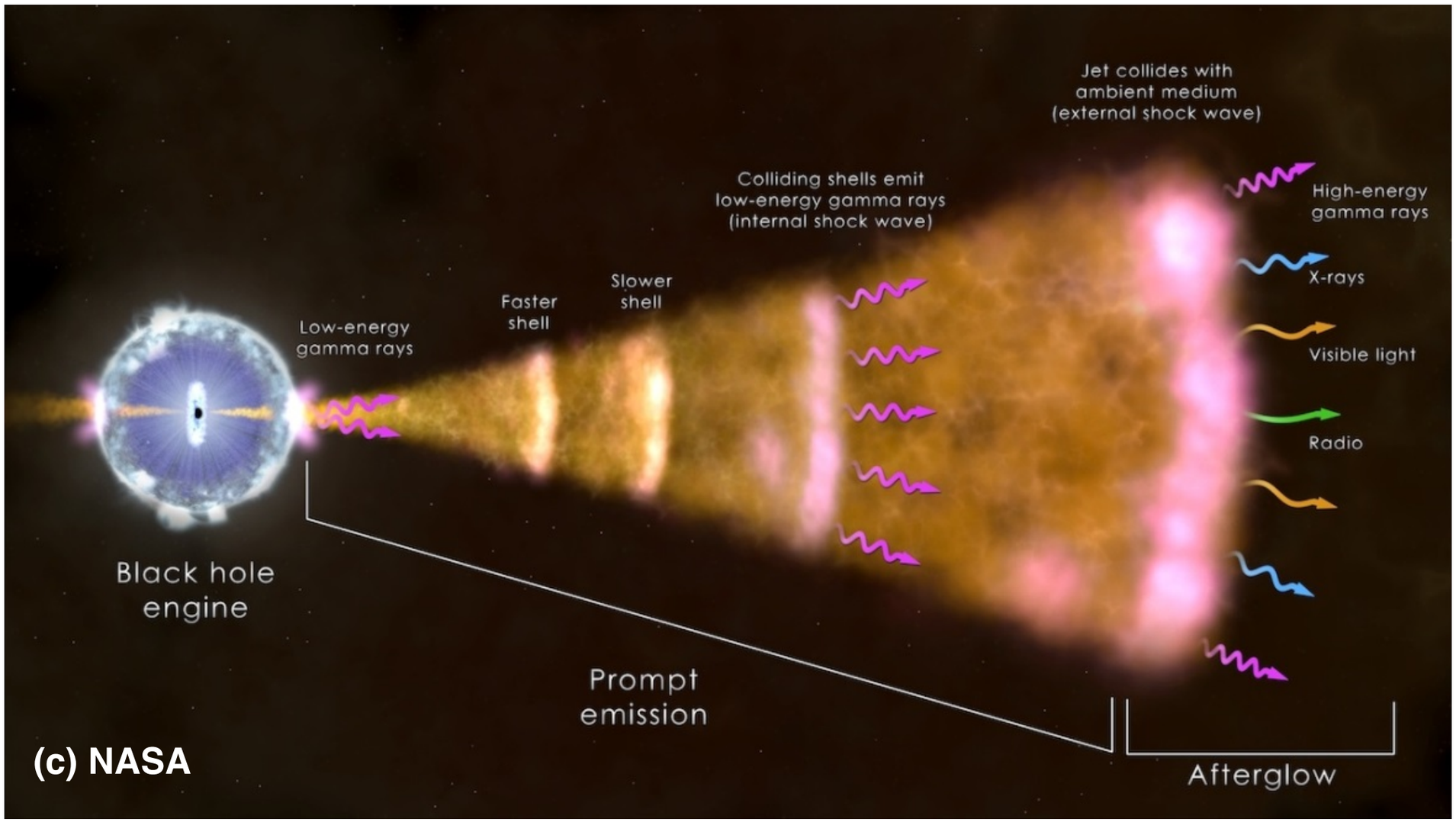
MAGIC/LST focus on (far) transients by design

AAS / Transient Handler

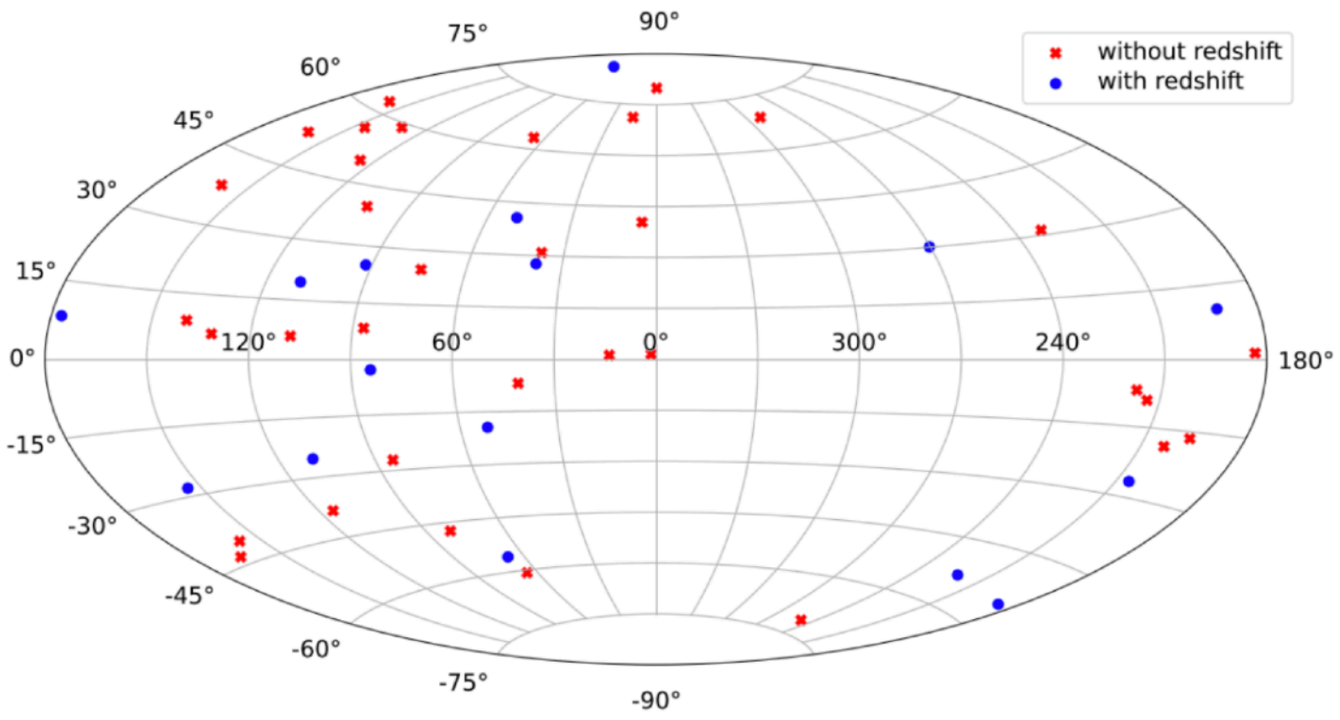


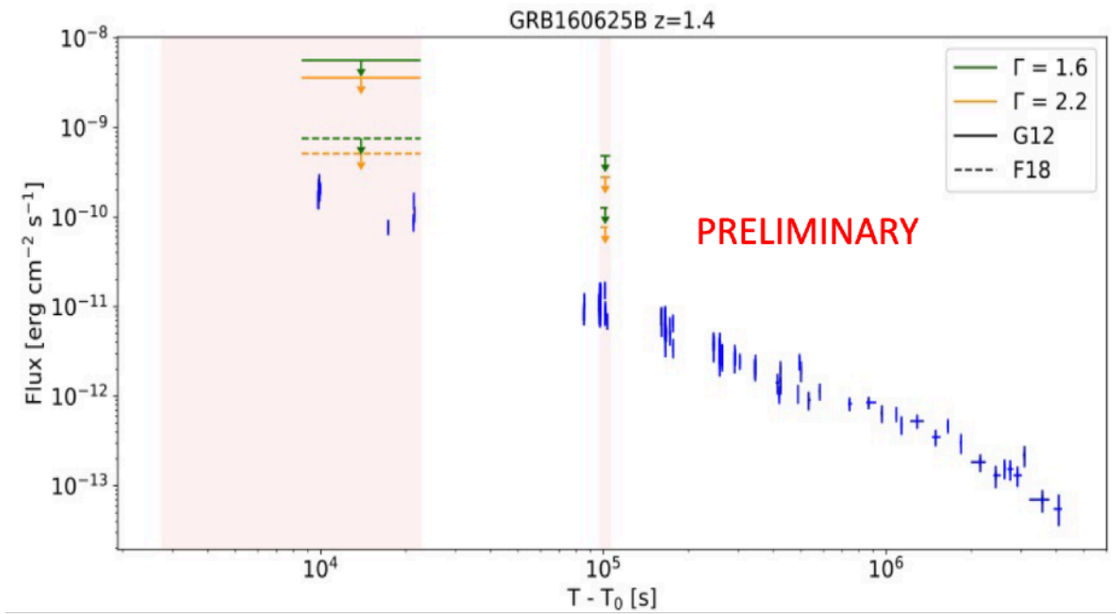
- Need a dedicated system to receive alerts, filter them, and start & control the special observation
- MAGIC: Automatic Alert System (AAS), LST: Transient Handler
- Developers of MAGIC AAS contribute to LST TH. Already operational

Gamma-ray burst (GRB) follow-up



MAGIC GRB obs.

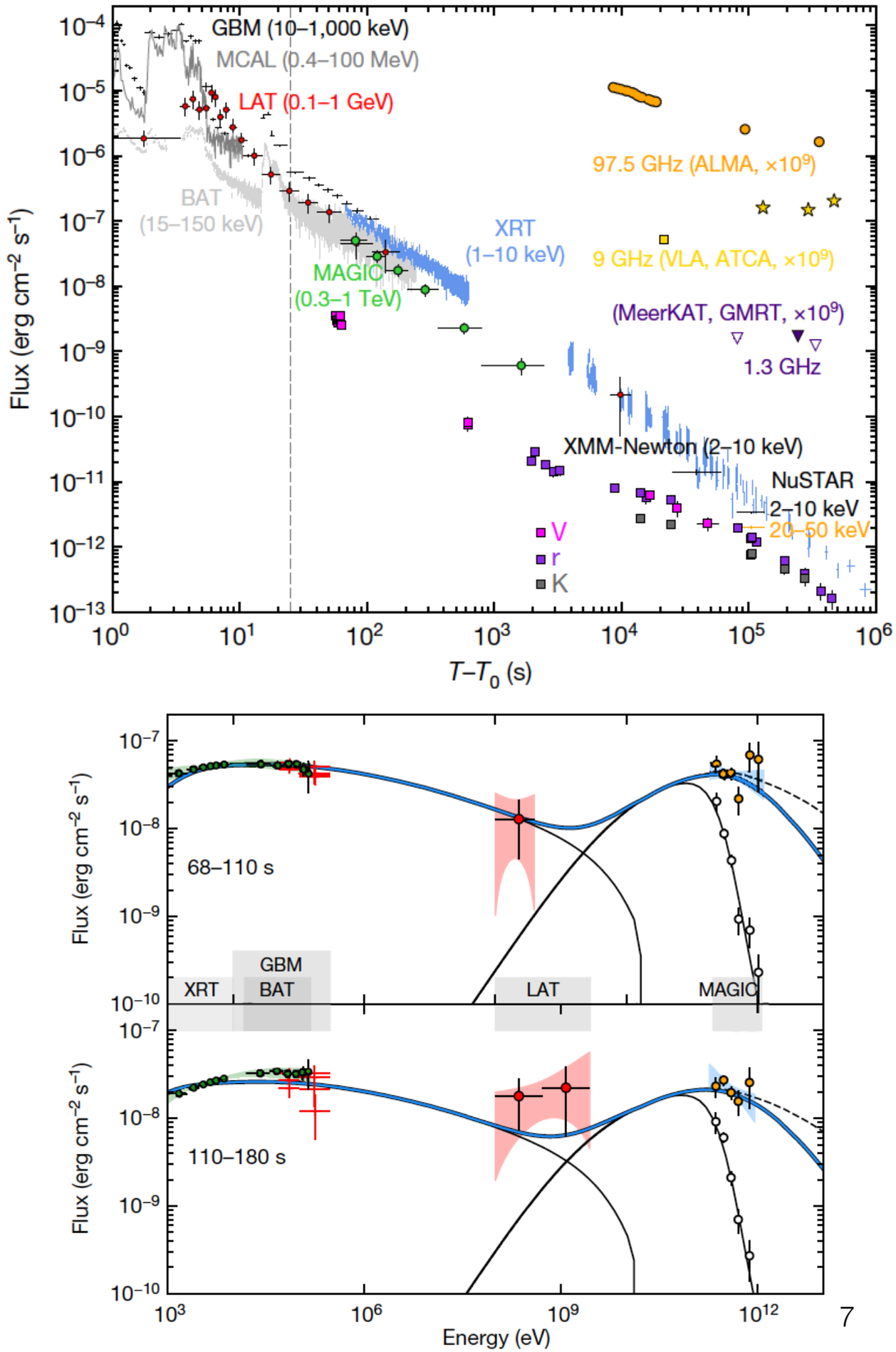




- 107 GRBs in total observed in 2005 - 2019
  - 2005-: mono, 2009-: stereo, 2013-: upgraded
- **50 in 2013 - 2019 (with the upgraded telescopes)**
  - Hints of detection already in 2014 & 2016
    Reported only upper limits (but 160821B)
  - 41 GRBs removing non-optimal conditions (Longo+ @ ICRC 2021)
- 2019: **190114C** detection in Jan, 2 papers in Nature in Nov
- 2020 Mar - May: covid19, 2021 Sep-Dec: eruption

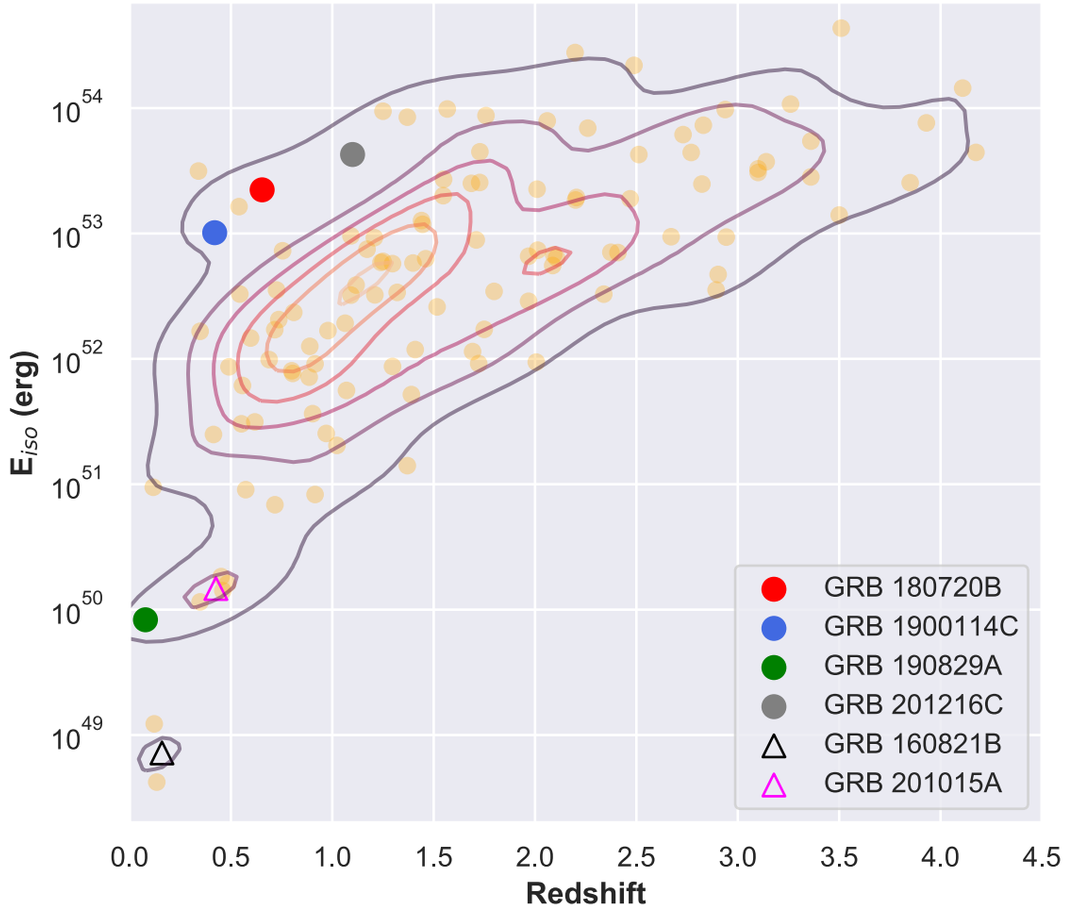
190114C

- Long GRB, T_{90} = 361s by Swift-BAT,"very bright"
- Alert received at 22 s after GRB onset, obs. start at 50 s, data acquisition started 57s +5 s to obtain analyzable data
- Zenith angle 55 deg, moderate moon, z = 0.42 (the 3rd closest in GRBs observed by MAGIC)
- First detection of TeV gamma-rays from a GRB
- MWL modeling (23 instruments): SSC is natural interpretation (No big need for different models)



Other VHE GRBs

- 180720B: HESS, clear (? marginal?)
- 190829A: HESS, low luminosity
  - Presented in ICRC2021 "hard to explain with SSC, better with a single Synchrotron component"
- 201015A: MAGIC, marginal detection (3.5 sigma), low luminosity?
- 201216C: MAGIC, clear detection with > 5 sigma. z=1.1, the farthest source detected by IACTs ever.
  Observed by LST (but cross analyses not possible)



Redshift - Eiso of VHE & GBM GRBs
(Noda & Parson, 2021 submitted)

2 groups in VHE (long) GRBs? but need more statistics, which is needed also to conclude on the "SSC discussion" => LST!

LST GRBs

First regular follow-up started at the beginning of 2021

- Only several events observed so far (partially due to swift malfunctioning)
- Fully automatic procedure is under development
- Started with MAGIC strategy.
  Expecting higher z (2-4) with the lower E threshold than MAGIC, increasing VHE GRB stat
- **Optimizations**: observations to later (from <4 hrs to, e.g., 24 hrs), more GBM GRBs with a large localization error (1 deg to ~2 deg)
  - but then need to reduce frequency, by selecting with brightness?
- Analysis need to be optimized as well
- **Detection / observation of the prompt emission !**

	T_0 [UTC]	T_{90} [s]	z	Start time [UTC]	Delay [s]	Trigger
GRB 201216C	23:07:31	48.0	1.1	20:57:03	79200	*Swift*
GRB 210511B	11:26:39	6	-	03:37:54	58200	*Fermi*-GBM
GRB 210704A	19:33:24	1	-	21:32:43	119	*Fermi*-GBM
GRB 210731A	22:21:07	25.9	1.25	23:22	3600	*Fermi*-GBM
GRB 210807A	10:03:40	156.3	-	03:55:17	1071	*Swift*
GRB 220302A	07:40:19	20	-	05:23:06	1302	*Swift*

From Carosi+, ICRC 2021 (updated in Mar 2022)

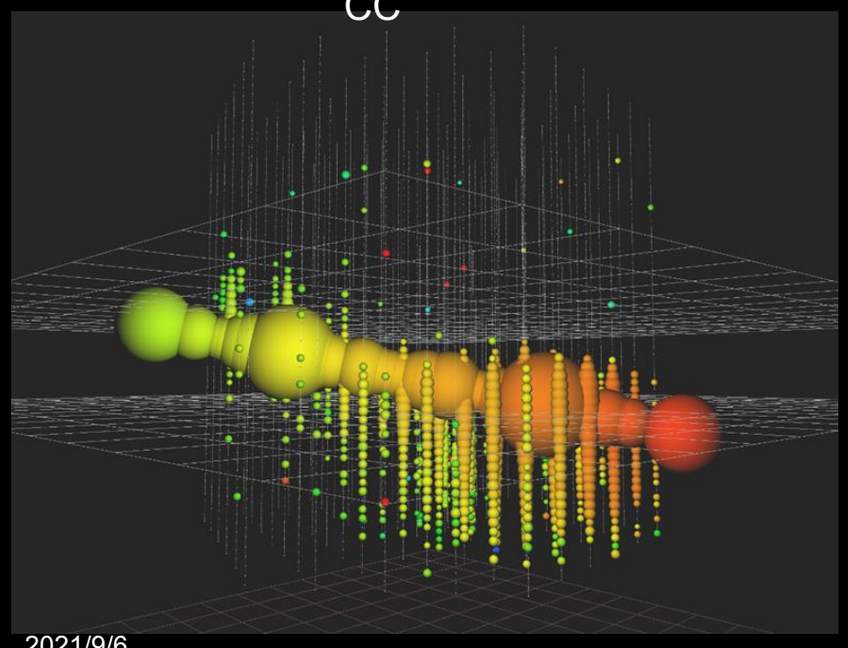
Neutrino follow-up

IceCube Event Topology

Track

$\nu_\mu \xrightarrow[CC]{} \mu$

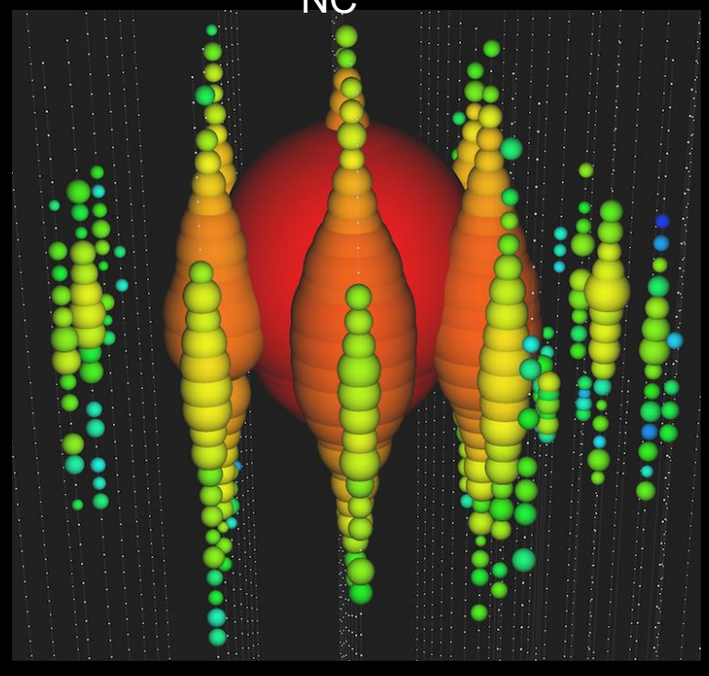
$\nu_\tau \xrightarrow[CC]{} \tau$ (only at ultra-high energies)



Cascade (shower)

$\nu_e \xrightarrow[CC]{} e + X$

$\nu_x \xrightarrow[NC]{} x + X$ x=e, μ, τ

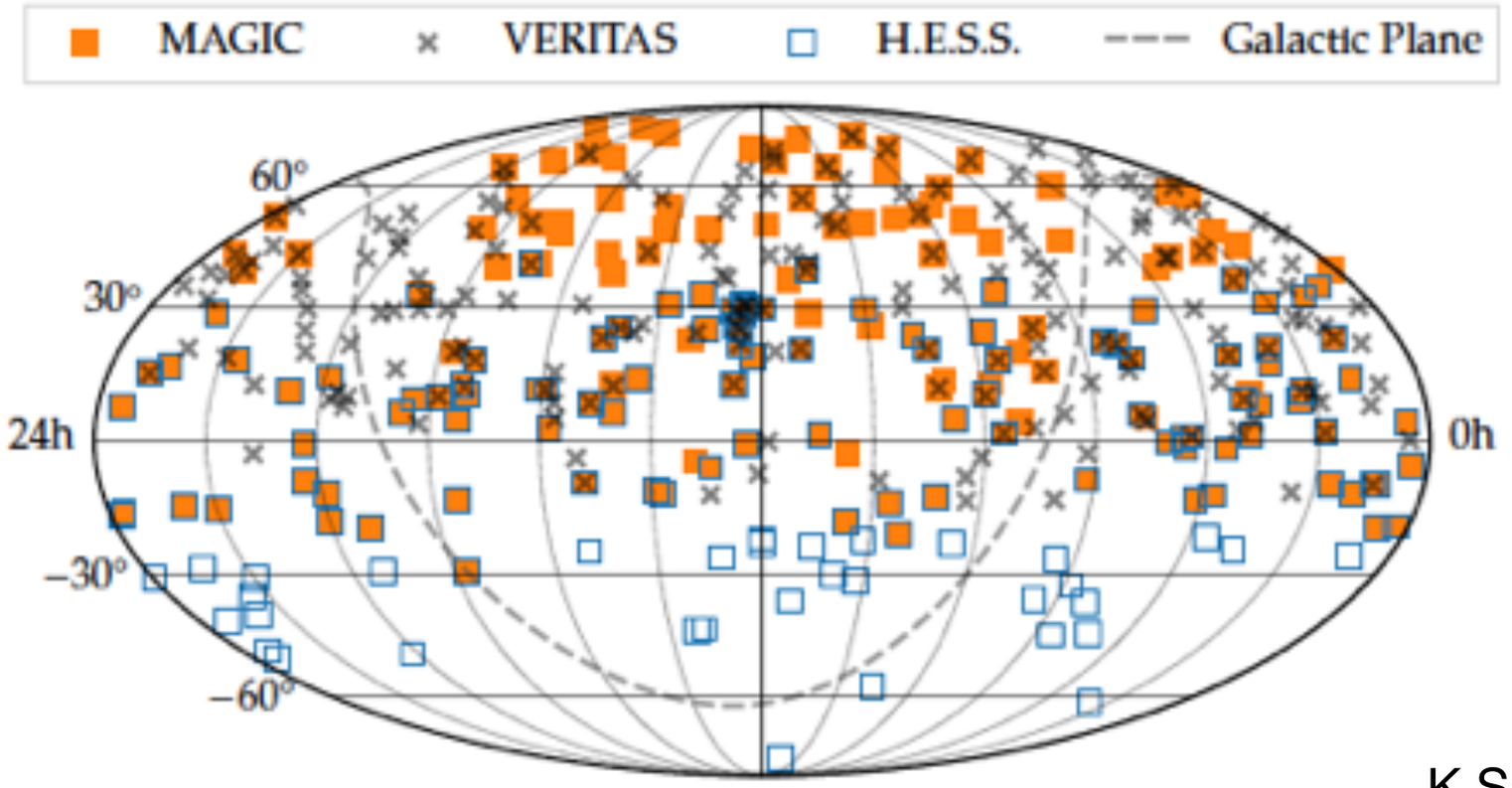


2021/9/6

18

Slide by Yoshida (Chiba)

γ follow up (2012-)

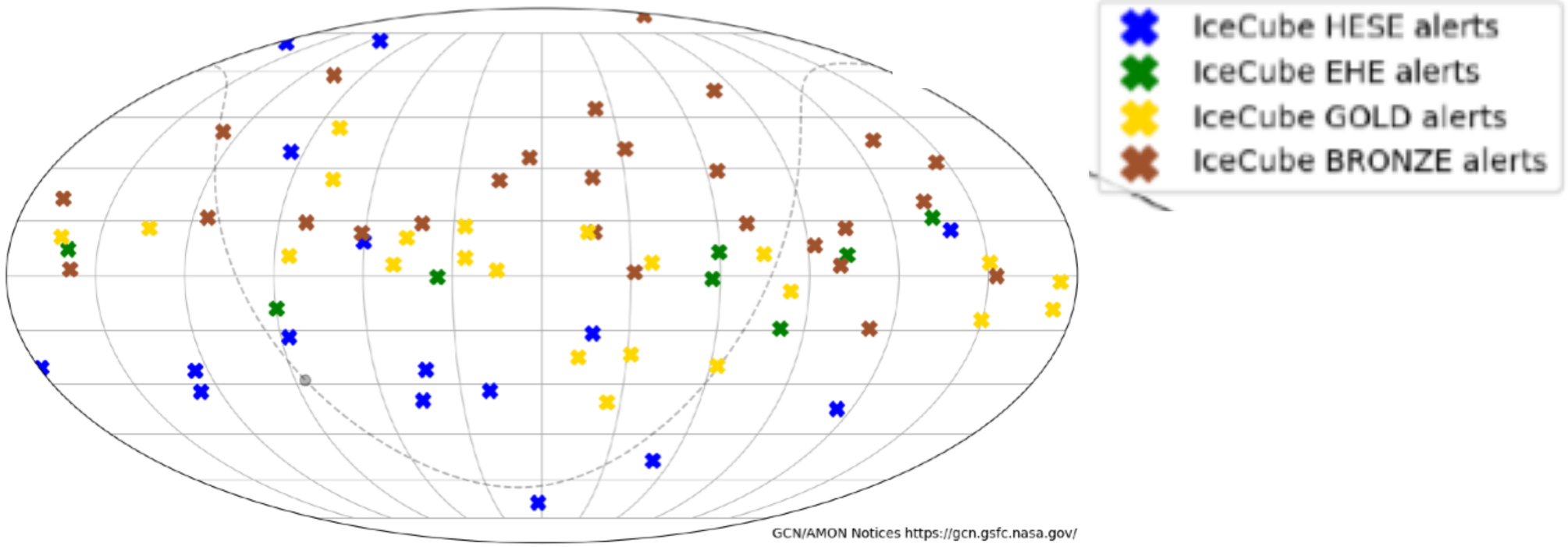


different list of targets depending on IACTs

K.Satalecka+, PoS(ICRC2021)960

- **Gamma Follow Up (GFU):** multiplet in time scale from s to 180 days, **correlation with gamma sources** in TeVCat & Fermi LAT && distance (z<1) && variability in γ && IACT-dependent conditions (observability and extrapolated flux > 100 GeV) ***Strong bias to γ-rays***
- MAGIC & VERITAS since 2012, HESS since 2019. >10 observed in MAGIC. Private alert by email, triggering ToO obs. (not automatic)

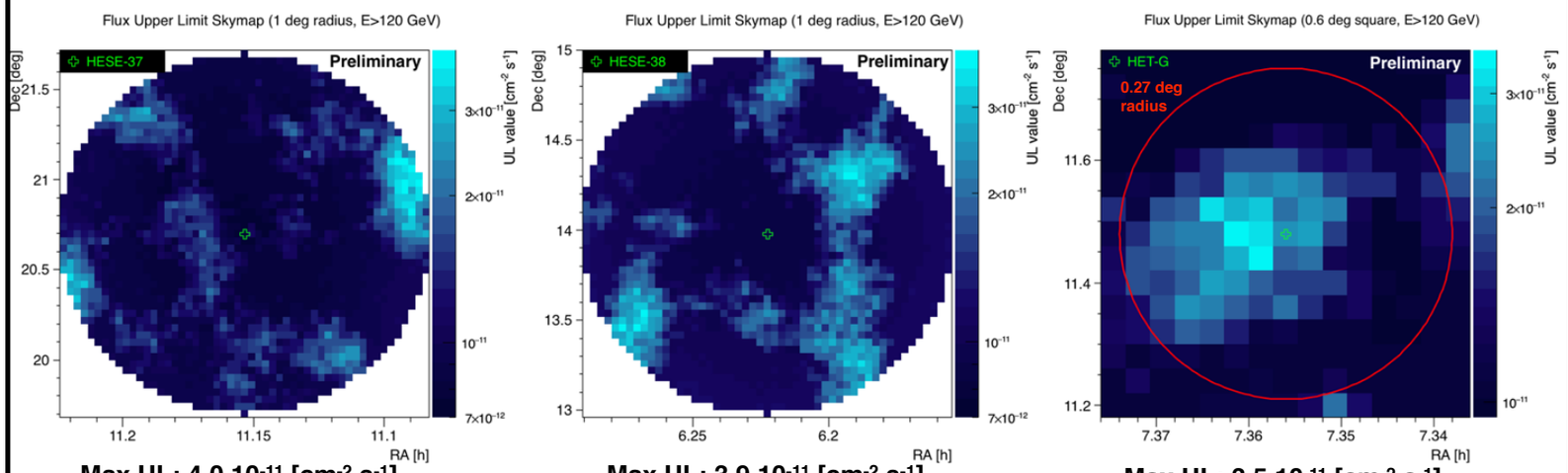
ν alert follow-up (2015-)



- **HESE/EHE:** single neutrinos (singlet), 2015-, no corr. condition, public
  - MAGIC observed in 2016 archival HESE & track events in 2015
  - Since mid 2016, the automatic observation system for neutrinos (GCN/AMON) has started to operate as for GRBs. Since then, MAGIC has observed 6 online alert events over 3 years
- **GOLD/BRONZE:** HESE/EHE was re-organized in 2019, only with the probability "signalness". 10 events over ~2 years observed by MAGIC
  - Bronze alerts tend to be upward in the south pole = northern sky

Efforts for many ULs...

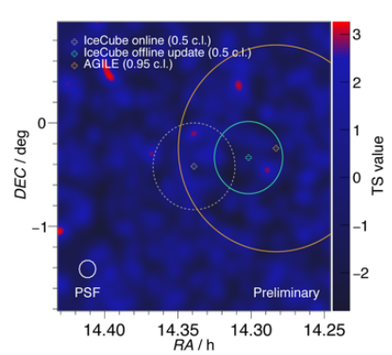
↓ **Upper-limit maps** UL (95% C.L.) estimated for E >120 GeV assuming a power-law spectrum with index -2.3. No. of excess is bound to >0, to obtain conservative flux ULs. Stay tuned for HESE-160427 UL map!



Max UL: 4.0 10^{-11} [cm^{-2} s^{-1}] **Max UL: 3.9 10^{-11} [cm^{-2} s^{-1}]** **Max UL: 3.5 10^{-11} [cm^{-2} s^{-1}]**

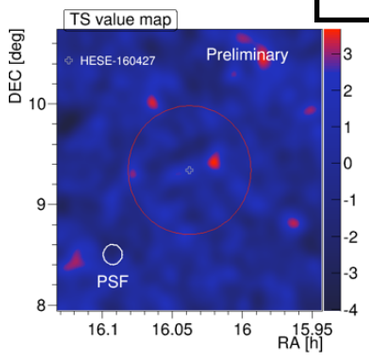
Archival HESE

Noda+ TeVPA 2016



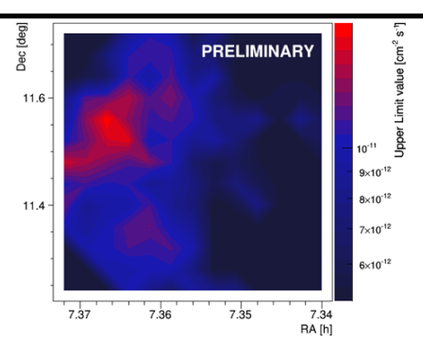
HESE/EHE-160731A (ATel #9315)

- 1.3 h data starting at $\sim t_0 + 16$ h
- zd $45° \div 65°$
- $E_{thr} \sim 800$ GeV (due to calima)
- No signal found (no excess at AGL J1418+0008 position)



HESE-160427A

- 2 h data starting at $\sim t_0 + 42$ h
- zd $18° \div 26°$
- $E_{thr} \sim 120$ GeV (due to moon)
- Hotspot (3.6σ, 2.1σ after trials) 0.3° away from center



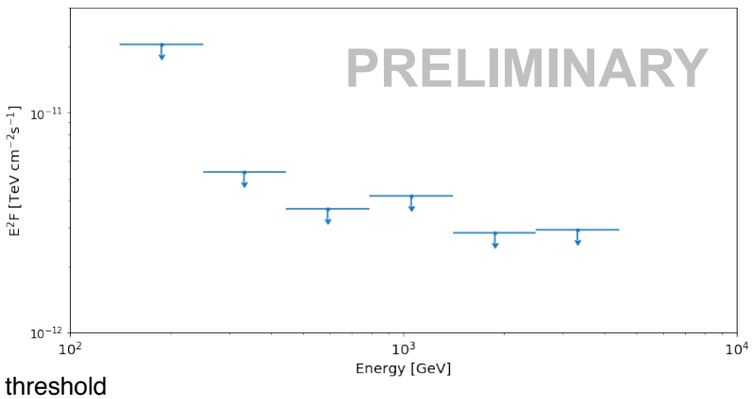
2 PeV track (ATel #7856)

- 11.6 h in March/December 2016
- zd $16° \div 38°$
- $E_{thr} \sim 120$ GeV
- Flux UL at 95% C.L.: $(0.6 \div 2) \times 10^{-11}$ cm^{-1} s^{-2} ($\sim 2 \div 7\%$ C.U.)

GFU (PMN J035-1843)

Satalecka+ ICRC 2021

- **Neutrino flare:**
  - Found using the **all-sky multiplet** search algorithm
  - FAR for this alert channel < 1/yr
  - Duration: ~3.7 days
  - **Significance: 5.1σ (pre-trial)**
  - Alert issued with delay of 1 day, channel was in test phase



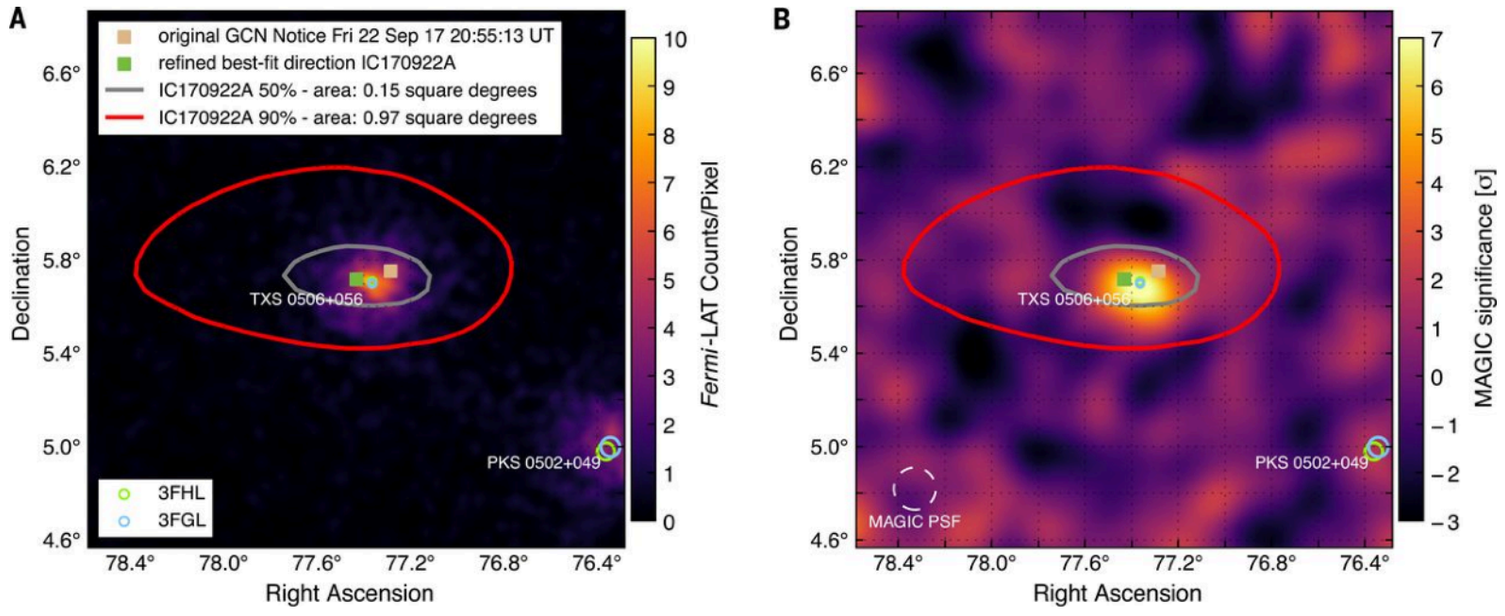
- **MAGIC observations:**
  - Delay: ~5 days after passing the alert threshold
  - Exposure of 2h, with zenith angle 47-52 deg
  - Pointed to the **nearest (~0.35 deg away) source PMN J035-1843**, a blazar with unknown redshift
  - **No detection**, integral flux upper limit: F_{UL} (> 250 GeV) = 5.16 x 10^{-11} cm^{-2} s^{-1}
  - Differential flux ULs calculated using the Rolke method at 95% C.L. and assuming a spectral index of 2.5

Online HESE/EHE

Berti+ Blois 2018

limits, limits, limits,,,,

TXS 0506+056



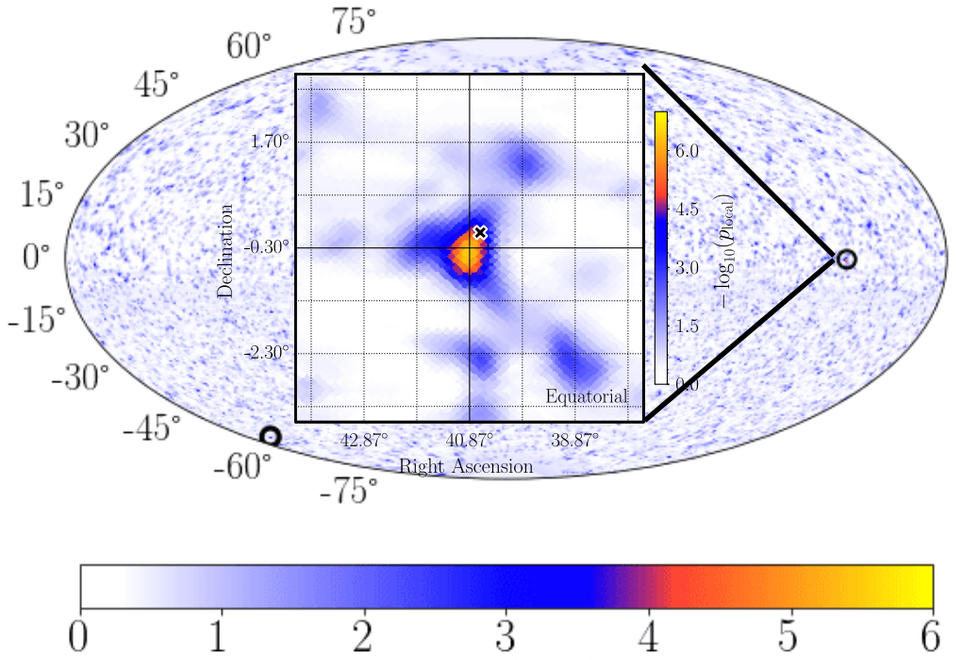
- Online alert EHE 170922A (Singlet, 290 TeV, ~1 deg error)
  Blazar TXS 0506+056 at 0.1 deg flared in optical and GeV (LAT)
  - MAGIC: bad weather in the day of the alert, ToO (normal) observation a few days later => detection of >100 GeV γ
  - Details in Science paper
- However,,, it is hard to explain the ν emission with a simple model. No other similar detection... It would be difficult to explain IceCube diffuse ν even if we sum up all such ν emissions from blazars

The consensus is "not yet clear"

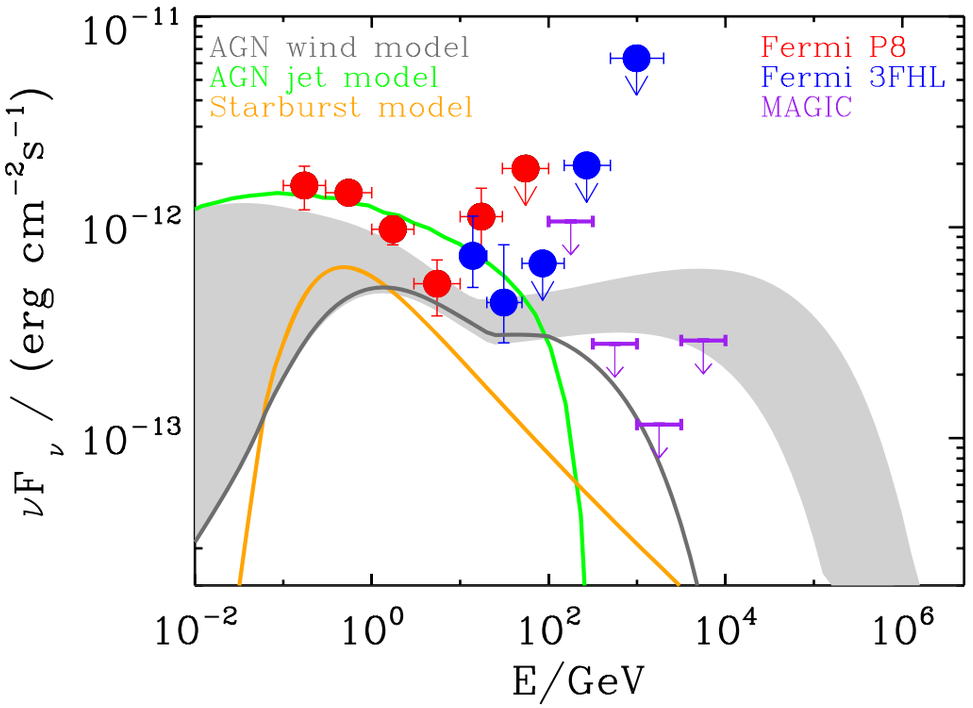
Non-blazar ν?

- IceCube point source search: 7-yr until 2015 max. significance among γ sources was a blazar 1ES1959+650, but BG prob. 54%
- 10-yr search <u>not depending on γ-ray sources</u> revealed **2.9 σ hotspot** 0.35 deg away from **NGC 1068 (M77) => became 4 σ**
- **not detected at VHE γ** (while 2nd & 3rd highest are TeV sources)
- nearby Sayfert 2 gal., detected by LAT
- MAGIC has observed it but **outside GFU proposal**, for <u>125 hr from 2016 to 2019</u>
  - Strong constraint in particular on the AGN wind models, but no clear alternative

Better to observe irrespective of known VHE/TeV γ source or not



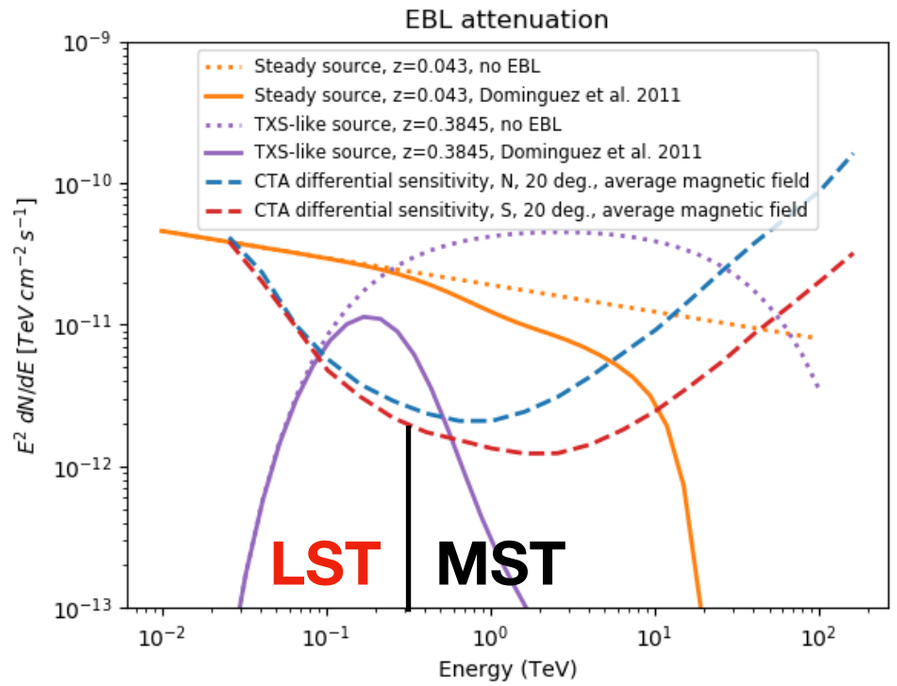
IceCube 10-yr data Aartsen+ (2020)



MAGIC Coll.+, ApJ 883 135 (2019)

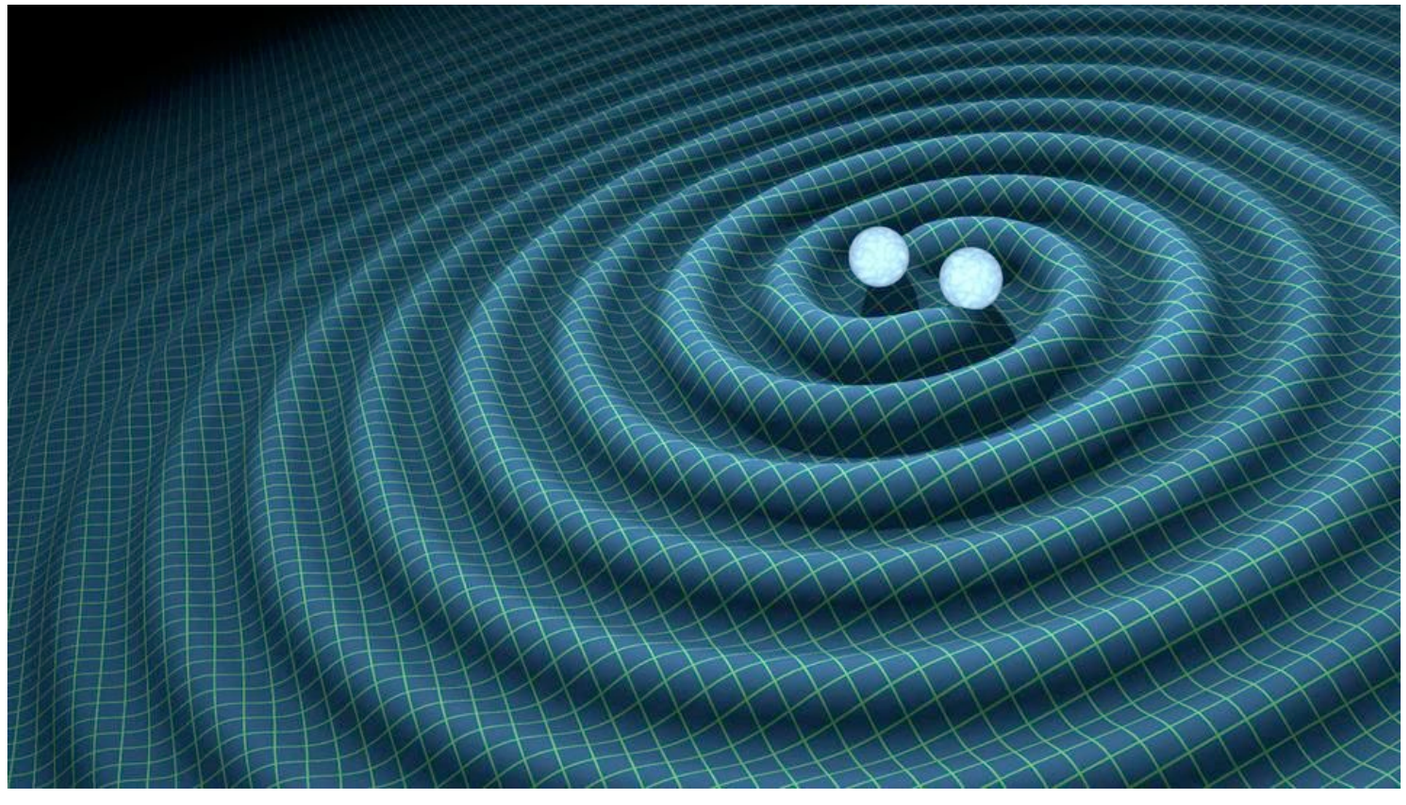
ν follow-up by CTA/LST

- Continue to observe GOLD / BRONZE (singlet). Official says ">11 astrophysical evts / yr" and MAGIC observed 5 evts / year. Expecting the same with **LST (~once per 2 months)**
- γ-ray followup (multiplet GFU) by LST
  - MAGIC ~2/year => need to revise for **LST (lower E, farther), more alerts**
  - private alert, MoU with IceCube: done
- **More obs. not biased to TeV γ**
  - more non-blazar AGN (but how?)
  - nearby SN (multiplet)
  - NS mergers (Galaxies? Technically the same as GRB & GW)
- Aug 2020-: Cascade activated, ~8/yr, large localization (3-30 deg) Source selection and/or tiling obs. = **tasks shared with GW**



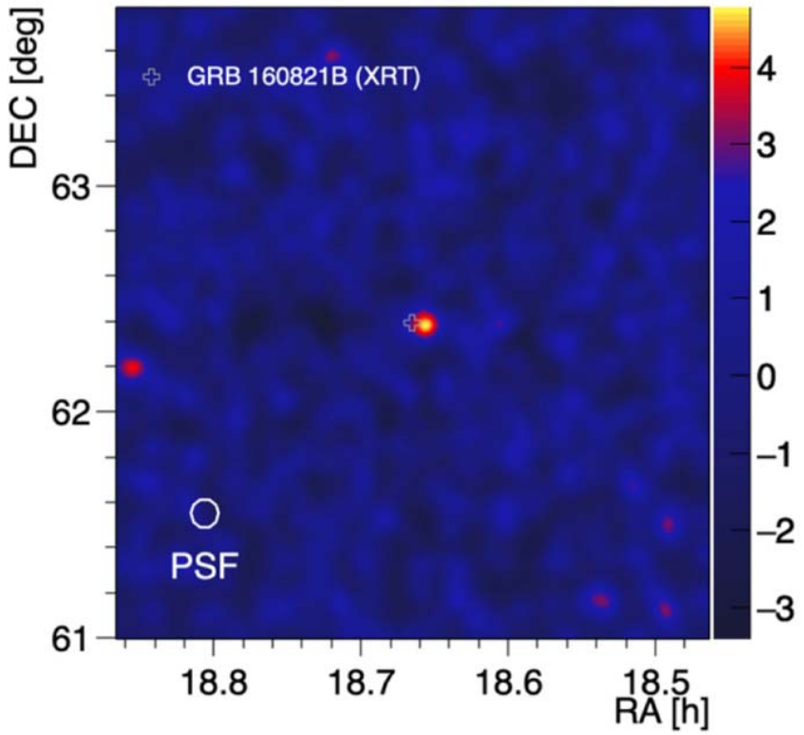
(Bošnjak+ 2021)

Gravitational wave (GW) follow-up

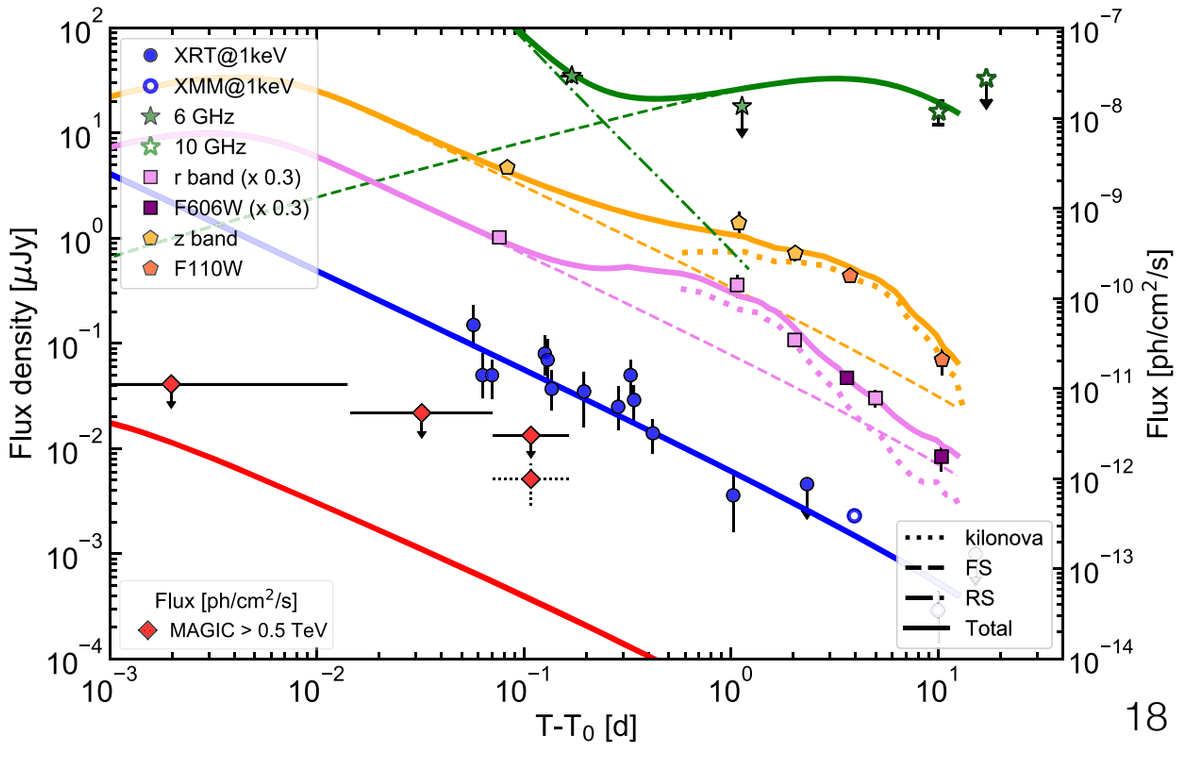


GW follow-up by IACT?

- No TeVγ from BBH/BHNS/BNS?
- BNS: non detection from GRB 170817A / GW170817 by HESS nor MAGIC, but > 5 hr
- **Short GRB 160821B** @ z = 0.16
  - MAGIC observed from 24 s after the onset under non-optimal conditions
    Hint of detection (3.1 sigma) >0.5 TeV
  - Reported a kilonova in 2019 "Most sampled after 170817" TeV gamma from **BNS/sGRB?**
  - Detailed model (4 emissions): TeV from SSC ~order beyond a rough estimation by the obs. External Compton?
- **BNS is hot topic also in IACT**

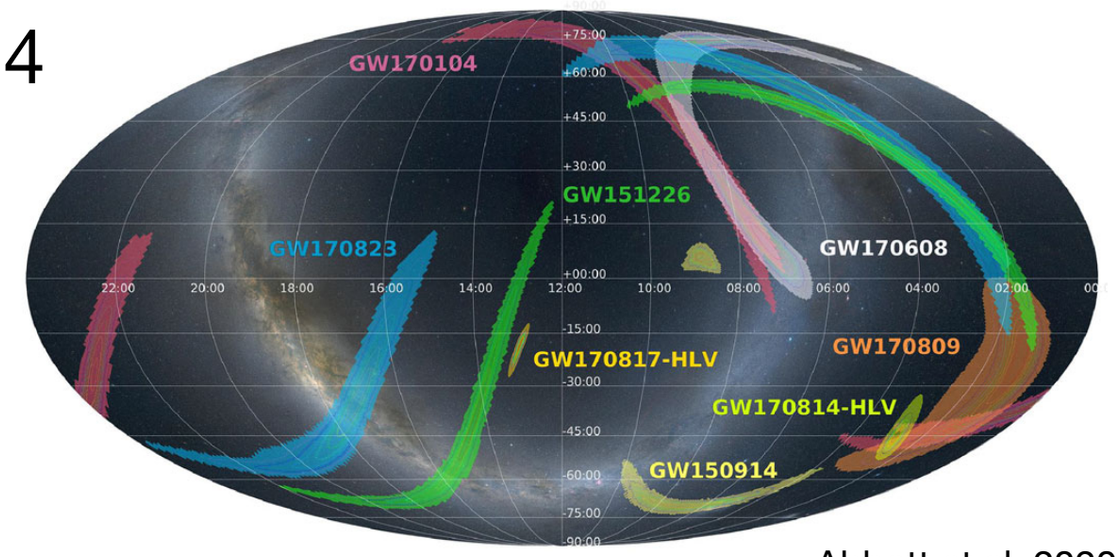


Acciari+ (MAGIC Coll.), ApJ 908 90 (2021)

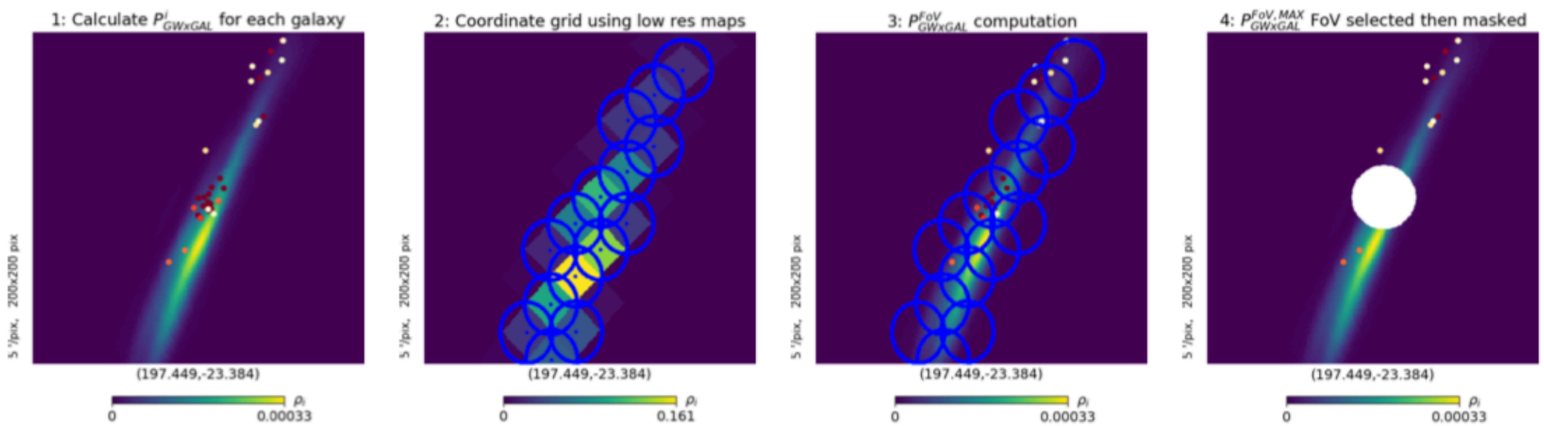


GW follow-up by MAGIC

- Participated in follow-ups since 2014
  - O1: GW151226, O2: GW170817 (still) under analysis
- Technically the same as GRB/ν but the larger localization errors
  - Selection of "interesting sources"
    - On-call shift in O3, 2 evts observed (under analysis)
    - Semi-automatic tool prepared for O4
- **Tiling observation** (implemented by HESS, Ashkar+ 2020) ?
  3D Algorithms: ‘GW x galaxy’ prob. using catalogs (e.g., GLADE)

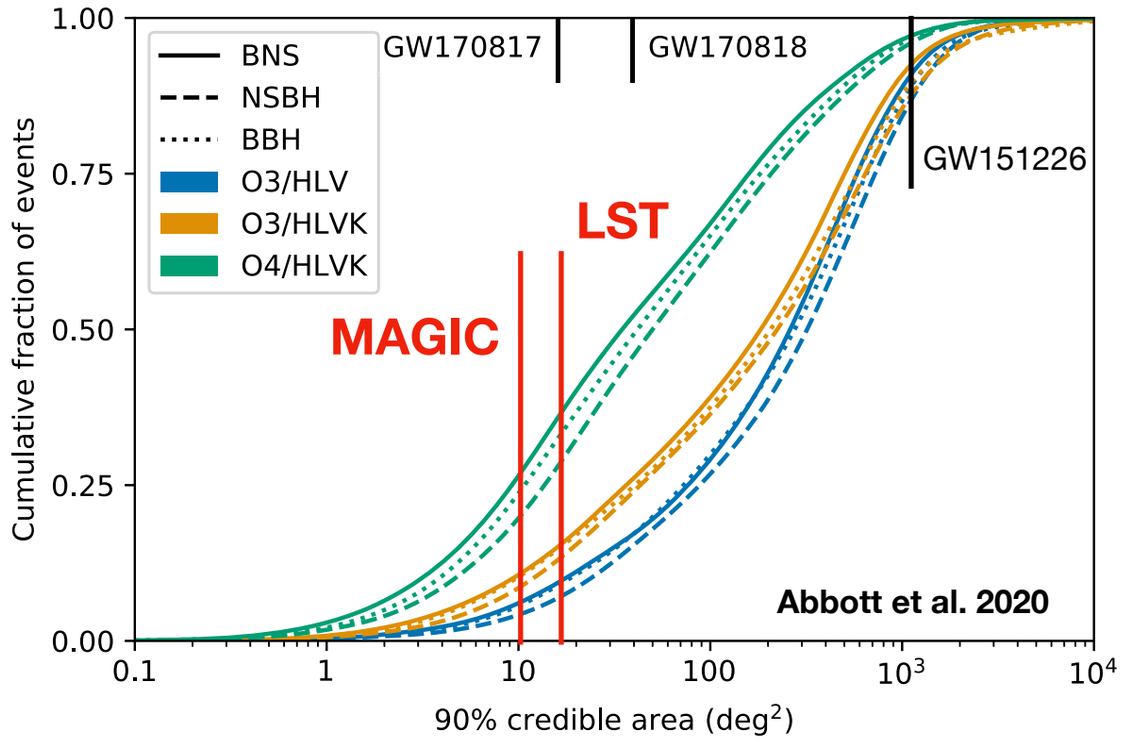


Abbott et al. 2020



GW follow-up by CTA/LST

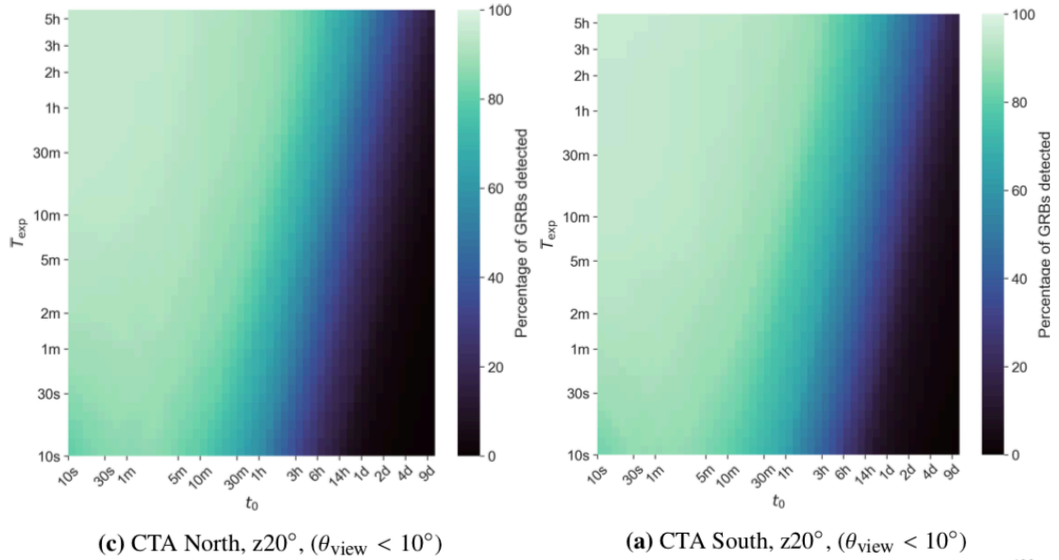
- O4 (from 2023?): KAGRA with a high sensitivity (in the latter half) = essential improvement, more alerts with a small error
  - **~30%: No need for selection or tiling, ~2-3 BNS/year**
  - **> a half: LST FoV (~16 deg2) can cover with the tiling**
    but need an optimized strategy (share experiences of ν cascades)
- Simulation of "If observed?": **BNS-GRB >90% (CTA Cons., in prep.)**
- MoU with LVK in near future (?)



On-axis GRBs ($\theta_{view} < 10^\circ$):

$t_0 \sim 30$ s, ~ 94 % detections with $T_{exp} \leq 30$ minutes.

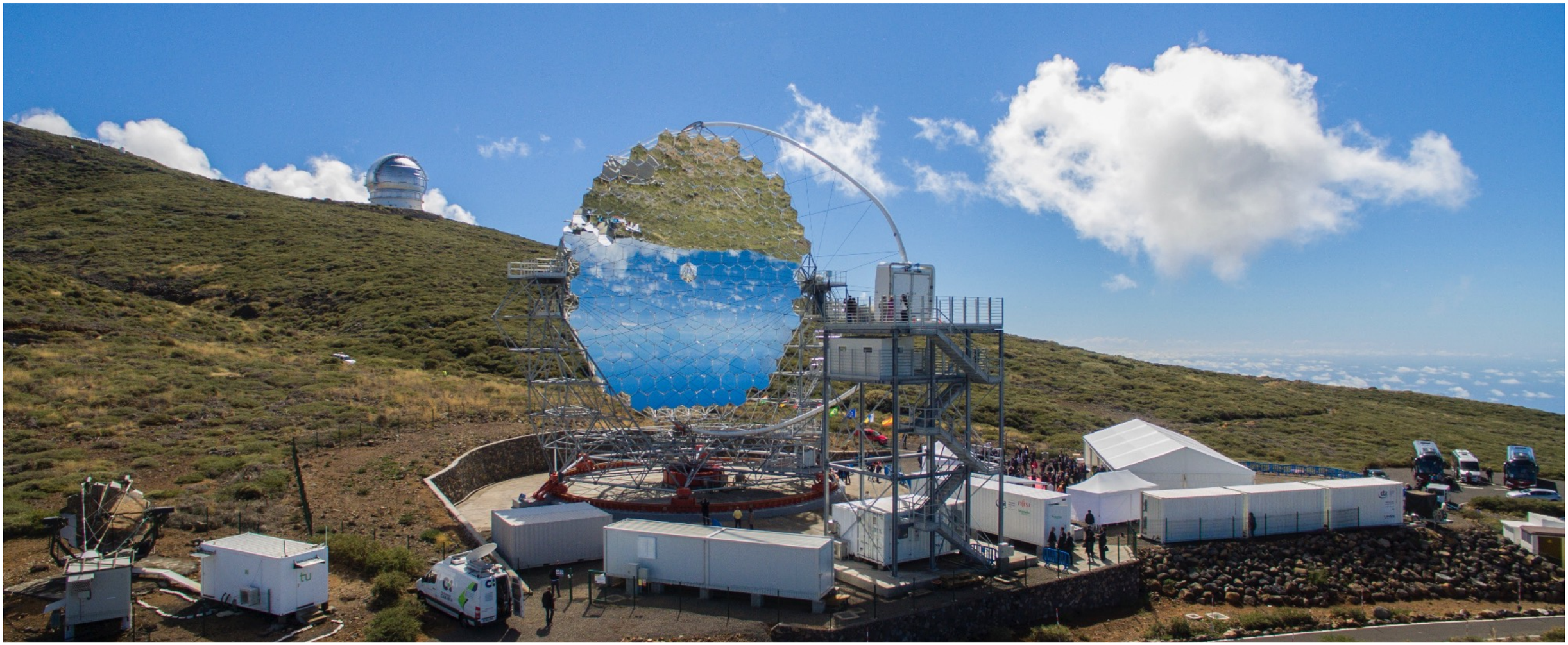
$t_0 \sim 10$ min ~ 92 % detections with $T_{exp} \sim$ hours



(c) CTA North, z20°, ($\theta_{view} < 10^\circ$)

(a) CTA South, z20°, ($\theta_{view} < 10^\circ$)

Outlook



Follow-up strategies

- **GRB**
  - Public alerts (Swift, Fermi,,, through GCN. SVOM?)
  - MWL? MAGIC has a strong connection to INAF, but unclear for LST. I always wait for z & host info in GCN. Please contact me as Deputy MWL coordinator in LST and one of Transient conveners in MAGIC
- **Neutrinos**
  - by IceCube: MoU signed for private alerts
    - Strong optical follow-up team in Japan, aiming at nearby SNe
  - Other exp.? Water (KM3Net, B-GVD) has a better localization
- **GW**
  - MAGIC has MoU with LVK. CTA/LST also needs one by O4.
  - Before KAGRA comes with a high sensitivity, we still need inputs from other follow-ups, even if nice tiling tools are being prepared
- Alerts from CTA? Yes in the future. Real Time Analysis to trigger obs.

Summary

- MAGIC under operation and CTA LST under construction:
  optimal for MWL/MM transients followup in a few tens GeV - TeV γ
- GRB: expand MAGIC strategy/results to farther GRBs and aim for the prompt emission, ~ 10 events / yr
- Neutrinos: continue AGN blazar follow-ups, improving for LST, but not only known (TeV) γ sources. ~10 events / yr
- GW: Short GRB / GW is a hot topic in coming years. To essentially overcome a large localization error, we need KAGRA. A few events / yr
- **More observations by LST, expecting detections in coming years**