VHE gamma follow-up programs of HE neutrino alerts

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based on work with Manuel Artero, Armand Fiasson, et al.

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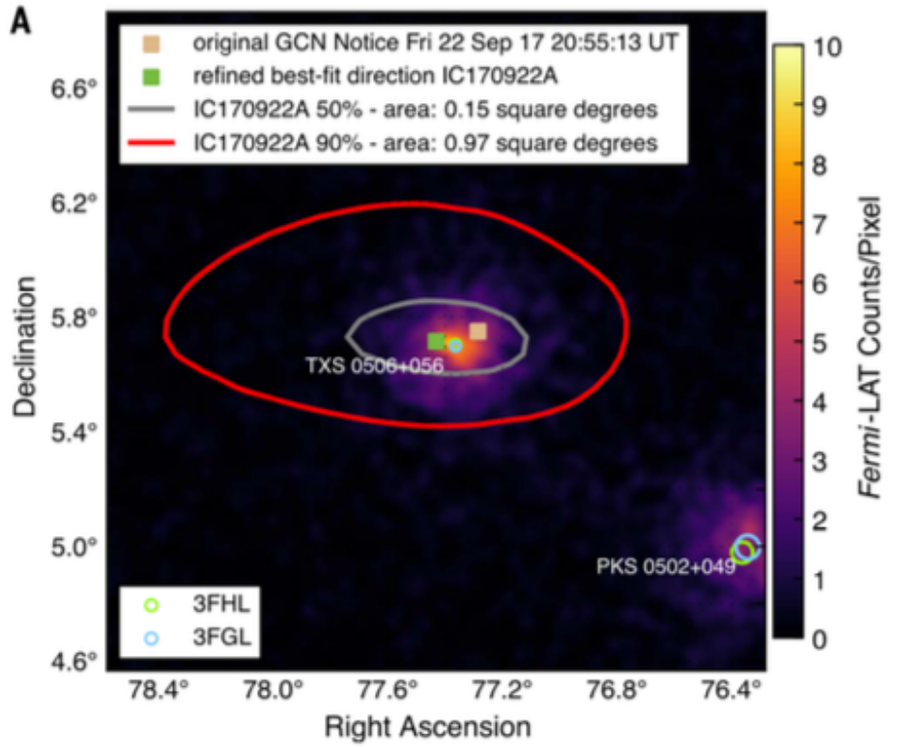
ICEHAP

CHIBA UNIVERSITY

Introduction

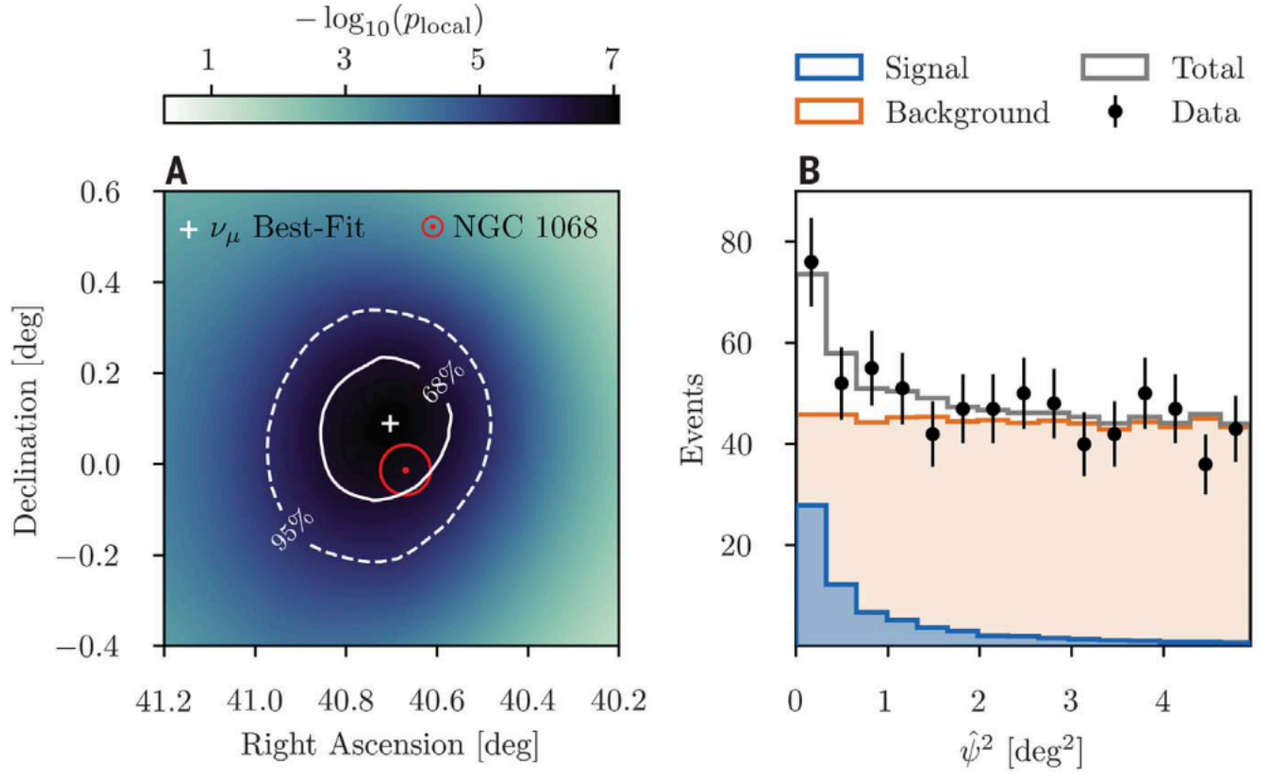
- There have been "very natural" suggestions to try to observe both VHE γ and HE ν from the same sources
  - as π's from pp or pγ emits γ if π0 while ν if π+/-
- Discovery of the astrophysical ν's by IceCube in 2013 (See Aya's talk for the efforts in the experiment side)
- ν source hunting with gamma-rays
  - Gamma Follow Up (GFU) program with IACTs since 2012
    - Long history. In IceCube, known as the name of the event selection
  - "Too" famous example of IC-170922A / TXS 0506+056
    - "only one example for long time
- The result of the long history **"The known γ-emitters are NOT the majority of the ν-emitters"**



IceCube Coll., Science (2018)

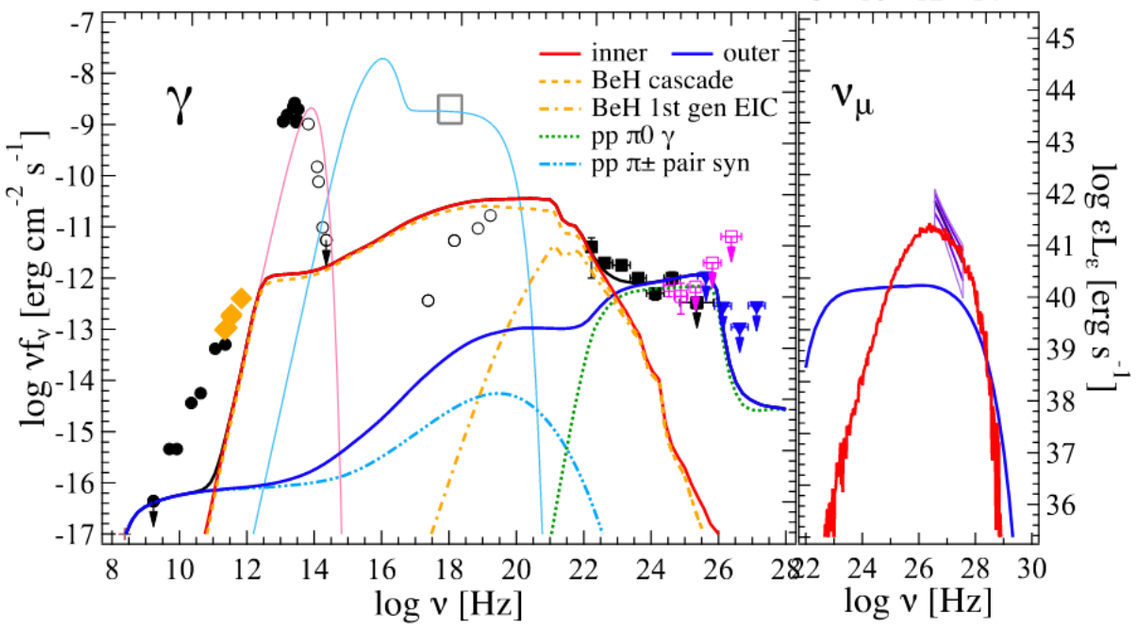
Mystery,,,

- Second ν-source published in 2022: NGC 1068
  - Seyfert galaxy (**not blazar**)
  - Detected by Fermi, but **not in VHE** (constrained by MAGIC)
  - Very weak, probably steady
    Much different from TXS 0506



IceCube Coll., Science, **378**, 538-543 (2022)

- Possible explanation: e.g., "Both pp & pγ are contributing and a part show pp feature while the other pγ feature"
  - Complex, somehow unnatural, as often the nature indeed is :)

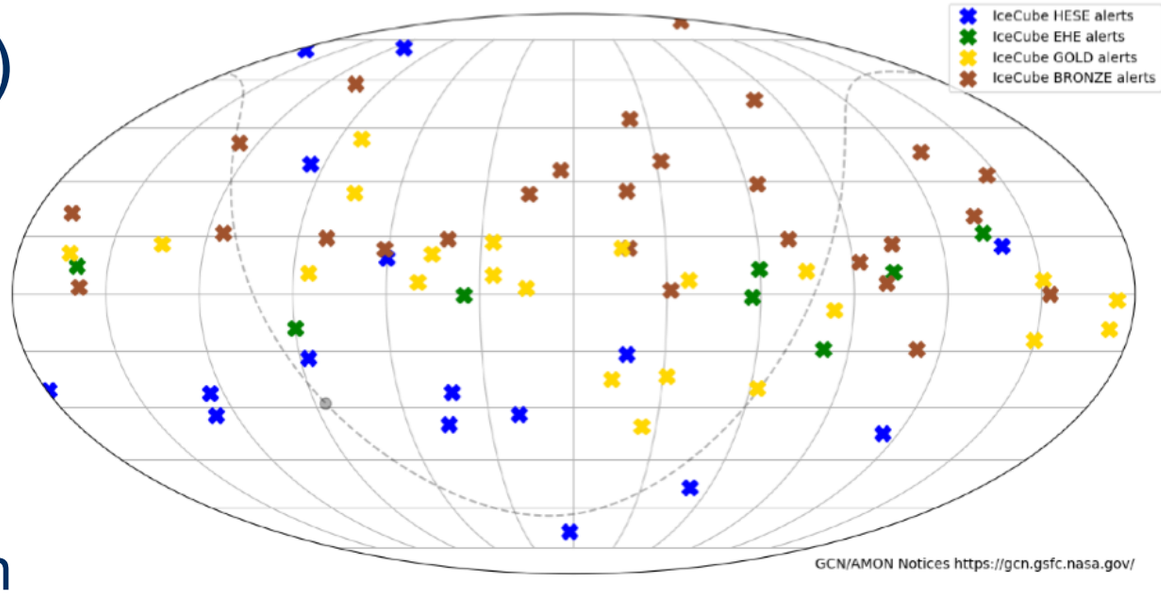


S. Inoue et al., arXiv:2207.02097

- So, 2 types? more? Let's solve this mystery with IACT,,, but **need to observe ν directions with "less bias" to γ-emitters**

Current *known* situation @ ν⇒γ

- Now only IceCube publishes alerts in realtime
  - Upgoing events at South Pole are from northern sky, matching CTA-N
  - KM3Net and Baikal GVD would start to publish alerts in near future (?) Mostly in the southern sky (??)
- **Public alerts** (e.g. in GCN Notices)
  - Single tracks (singlet) since 2015
    - Gold / Bronze: former HESE/EHE, reorganized in 2019, only with the probability called "signalness"
      - Gold: horizontal long tracks
        Bronze: more upgoing = from north
    - **TXS 0506 was in fact triggered by EHE-170922A (not GFU). Need to continue with the CTA era**
  - Single cascade alerts since 2021
    - Localization error 3-30 deg **Similarity to GW. Collaborative work for source/galaxy selection and tiling needed in CTA & O4+ era**



K.Satalecka+, PoS(ICRC2021)960

More *unknown* part: private alerts

(Mostly from K.Satalecka+, PoS(ICRC2021)960)

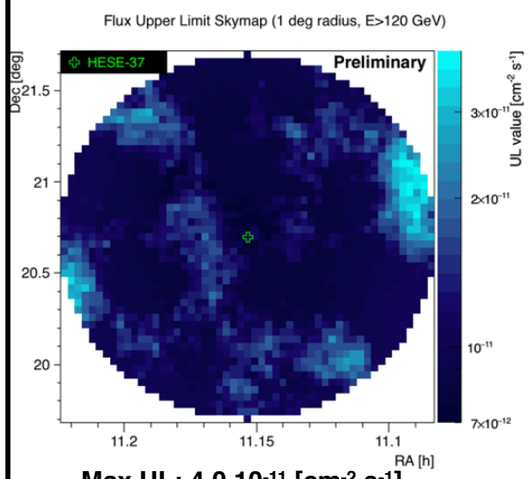
- Multiple event (multiplet) in time scale of sec - 180 days
- Correlation with preselected γ-sources = **strong bias to γ**
  - Fermi-LAT catalog (3FGL or 3FHL)

    - Extragalactic source with known redshift and $z \leq 1.0$
    - 3FGL: variability index > 77.2; 3FHL: variability based on Bayesian blocks > 1
    - Culmination at the IACT site within a chosen zenith angle limit (usually <45°)
    - Assuming that the source can produce a gamma-ray flare with a 10-fold increase over the average *Fermi*-LAT flux, the extrapolated flux above 100GeV has to exceed the IACT 5σ sensitivity for observation times between 2.5 h to 5 h.

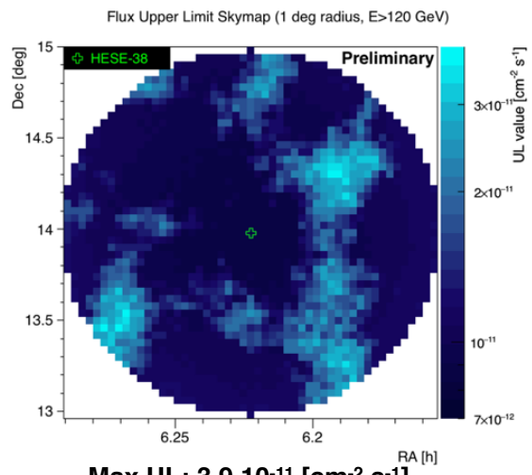
    - At least 2 arbitrary numbers (variability 77.2 and flare x10)
    - No EBL attn., so meaning of x10 is different source by source
  - TeVCat
    - Taken probably in 2017, so not fully clear from "all extragalactic sources detected by IACTs, GC, and Crab have been added"
- 120-180 sources per IACT (178 for MAGIC)
- Private automatic email, followed by another email with more detailed analysis by a person in charge (2-3 h later)

Efforts for many ULs...

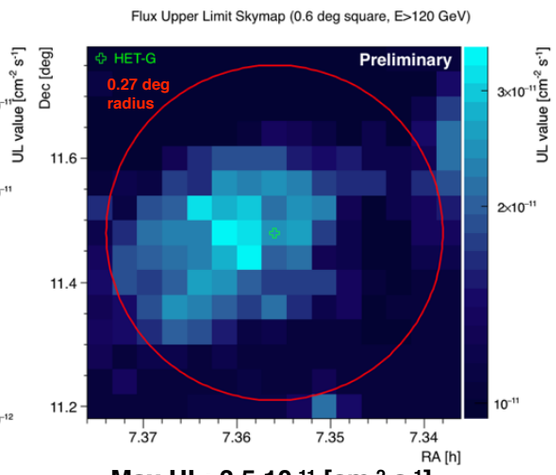
↓ **Upper-limit maps** UL (95% C.L.) estimated for E >120 GeV assuming a power-law spectrum with index -2.3. No. of excess is bound to >0, to obtain conservative flux ULs. Stay tuned for HESE-160427 UL map!



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



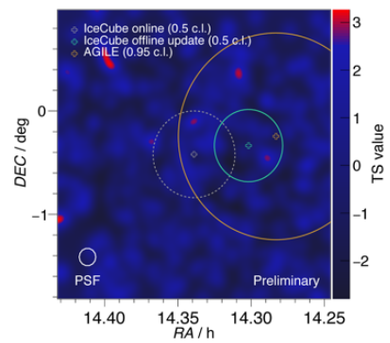
Max UL: 3.9 10^{-11} [cm^{-2} s^{-1}]



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

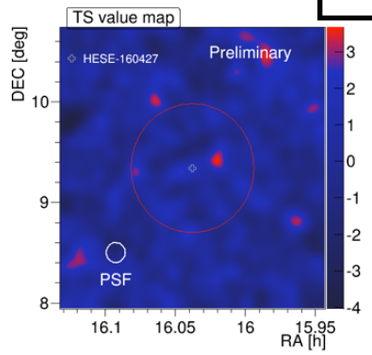
Archival HESE

Noda+ TeVPA 2016



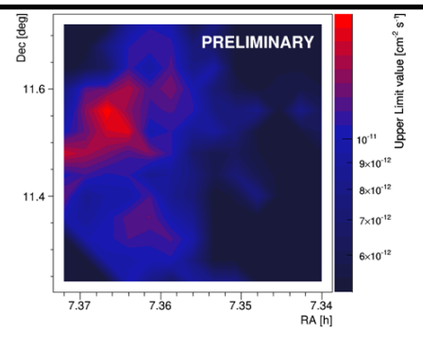
HESE/EHE-160731A (ATel #9315)

- 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.)

Online HESE/EHE

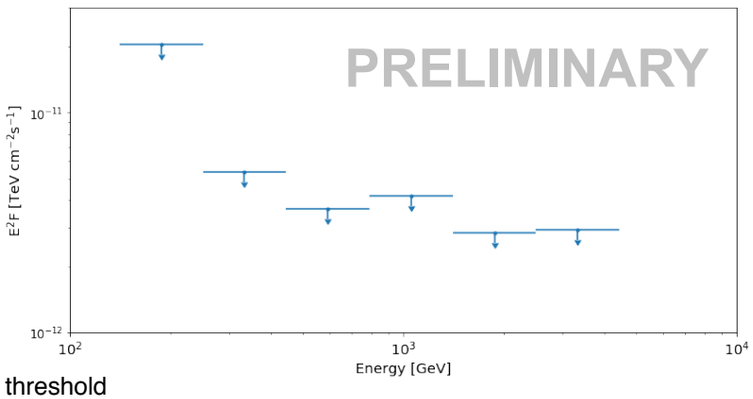
Berti+ Blois 2018

limits, limits, limits,,,,

GFU (PMN J035-1843)

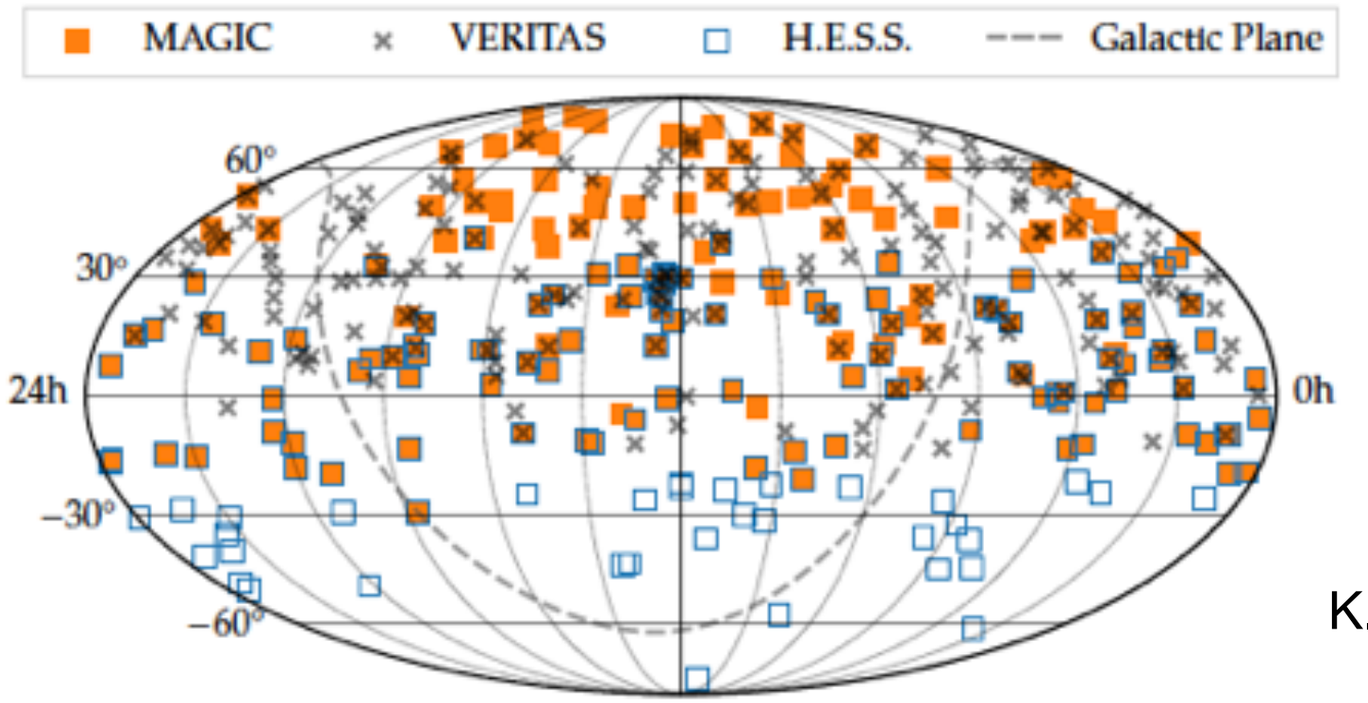
Satalecka+ ICRC 2021

- **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

LST proposal of improvements



different list of targets depending on IACTs

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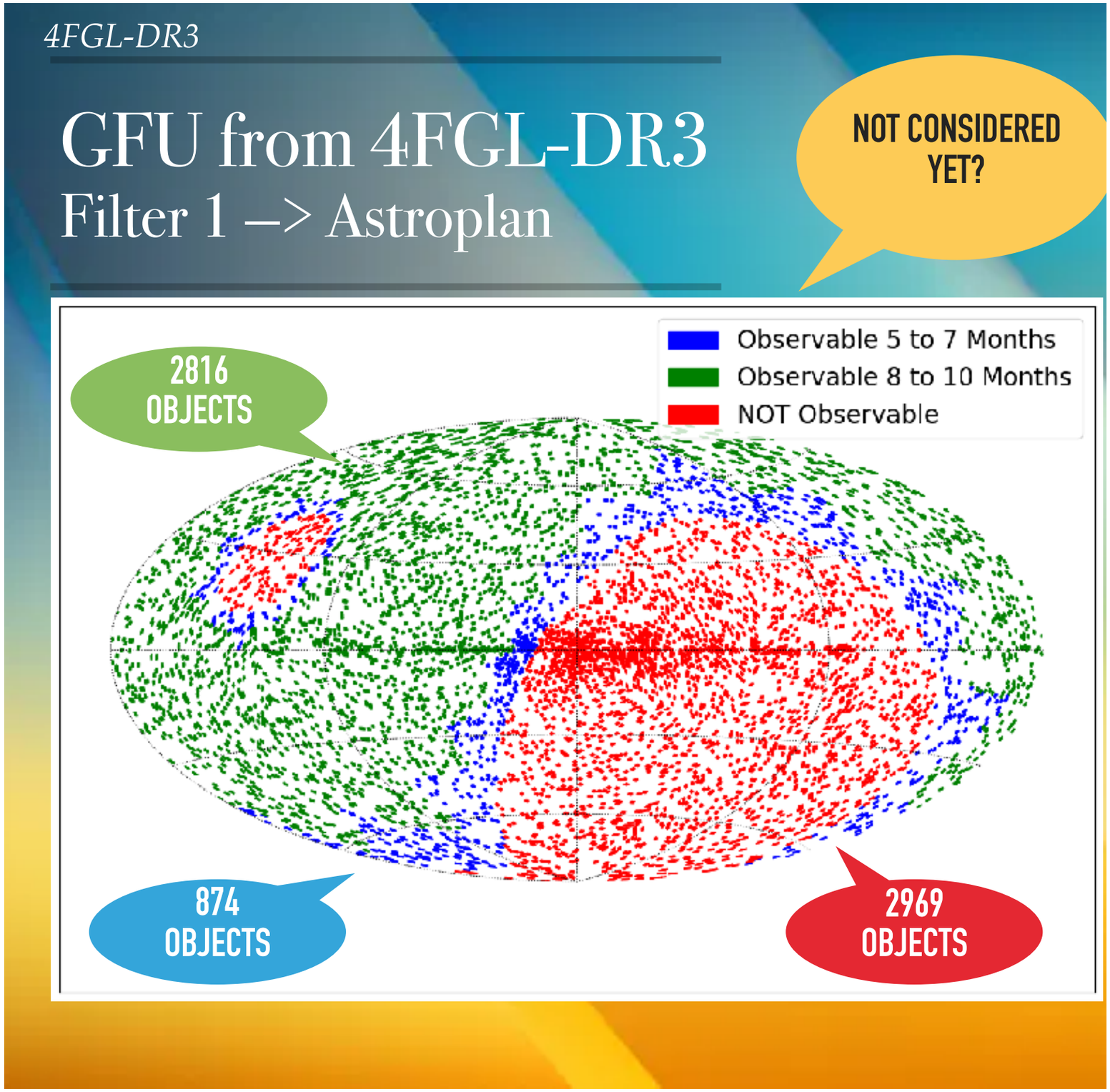
We need to provide the same for CTA/LST. **Let's improve for future**

- Update catalogs (4FGL, recent TeVCat)
- No variability cut (after NGC 1068), if possible
- Redshift info should be included only as the EBL attenuation
- Only one arbitrary number, then it can be tuned to have a practical number of sources (which decide false alarm rate)

Following studies by M. Artero, supervised by A. Fiasson and me

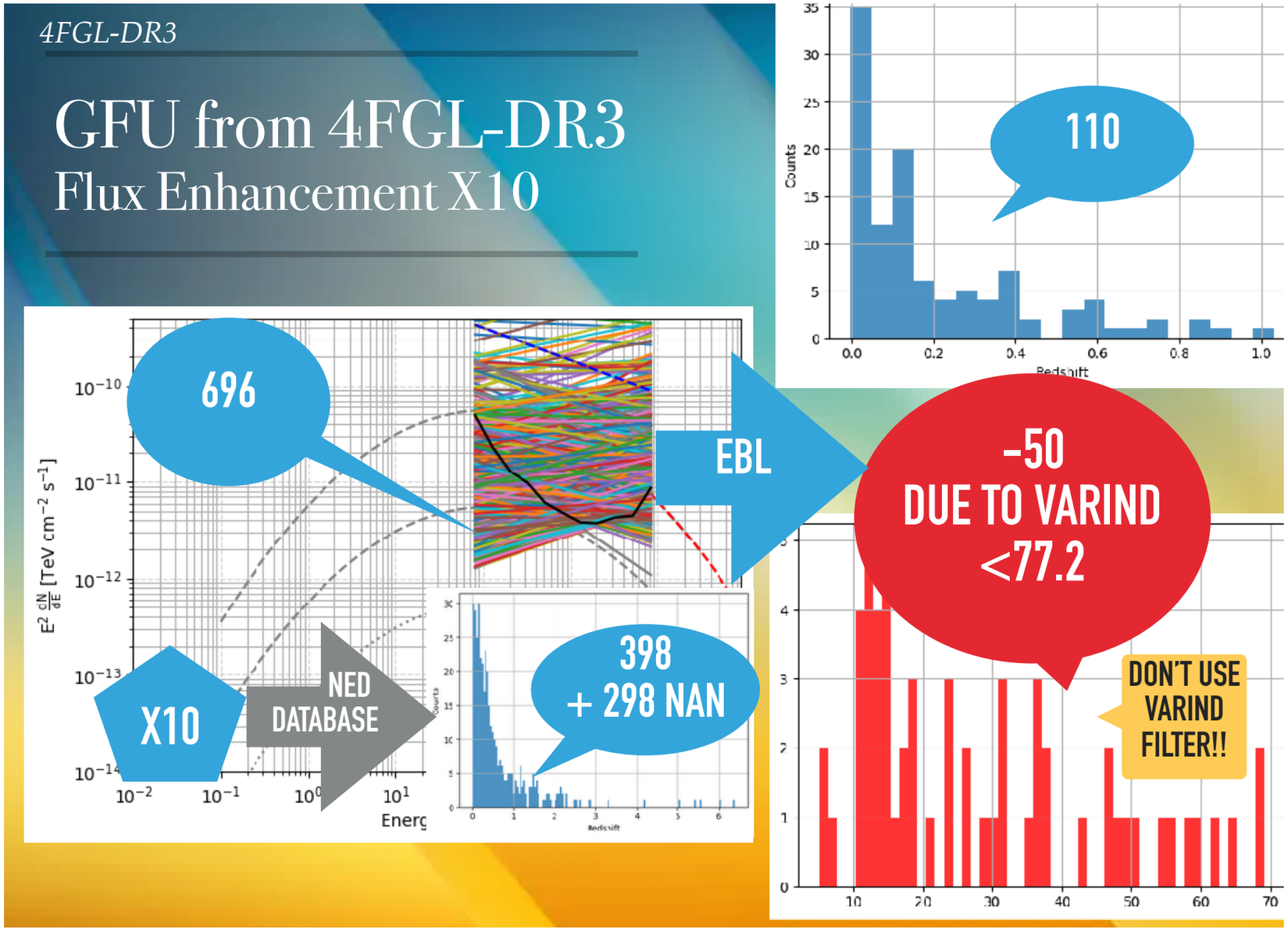
4FGL (instead of 3FGL/3FHL)

- Start from the original **6659** => **3690** survived the visibility cut at La Palma
- Possible further improvement: seasonal lists?
  - 2816 (874) visible for > (<) 8 months
  - Might be tricky with variable time window (s -180 d)



4FGL: Flux with EBL

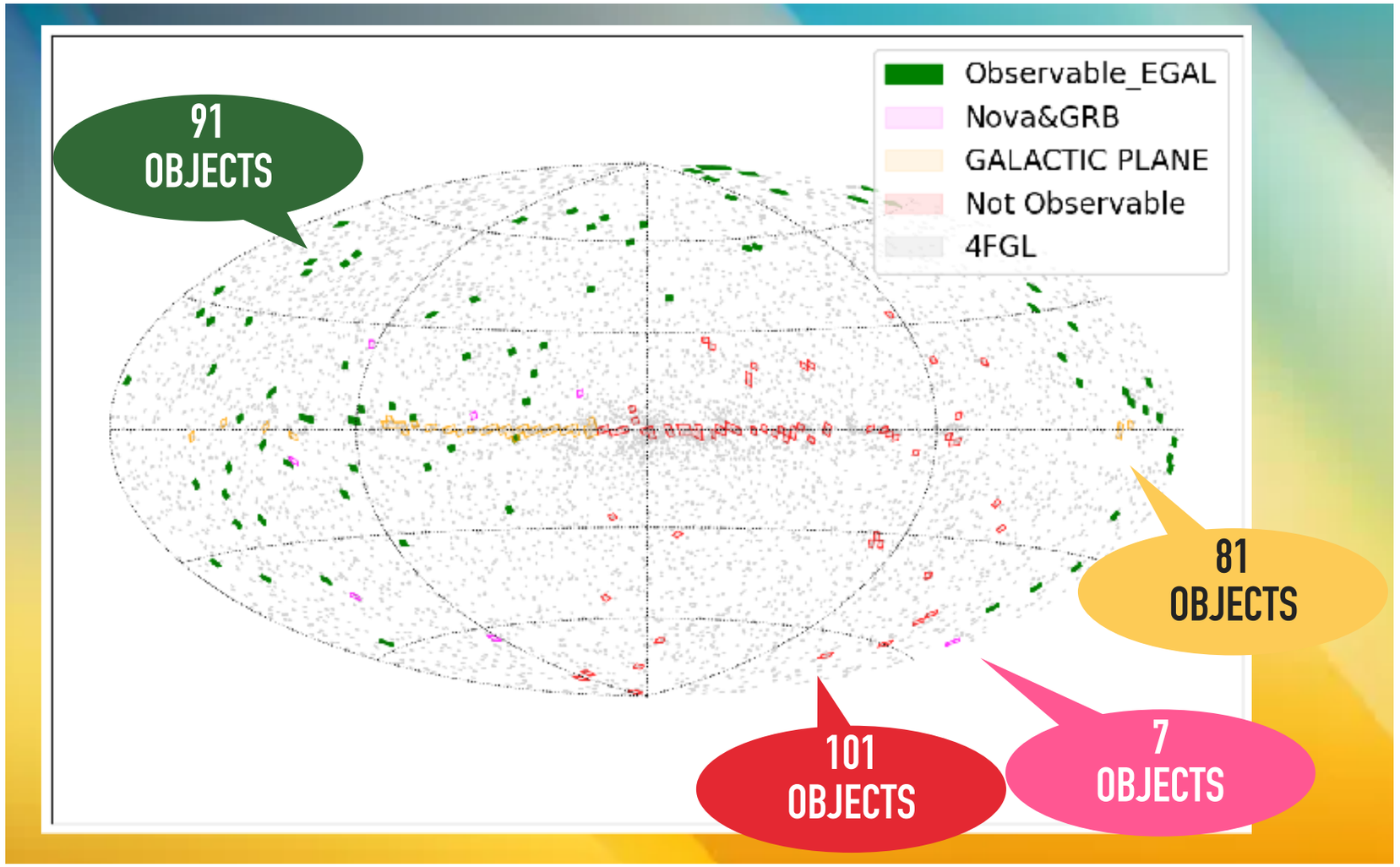
- Flux: extrapolation with PL to VHE range, and flux enhanced by x10
- Compared with IACT sensitivity
  => **696** survived
  => **398** known z
- EBL attenuated, compared again with the sensitivity
  => **110 in the end**
  - Tried flux x1, x2, x5, but the same x10 is the optimal
  - No need for z<1



- ***Fully cutting sources without z, which are probably far γ emitters***
- ***Variability is not used any more***

Adding TeVCat sources

- **280** in the original (as of Oct 2022. TeVCat is updated very frequently!) => **179** by visibility => **98** extragalactic (|b| >2.5 deg)
- -7 non-repeating transients (GRB and Nova) => **91**
- -46 double-counts with 4FGL, -6 duplication (e.g., pulsar & nebula) => **39**
- Finally removed (by hand) unIDs, galactic SNR/PWN => **29**

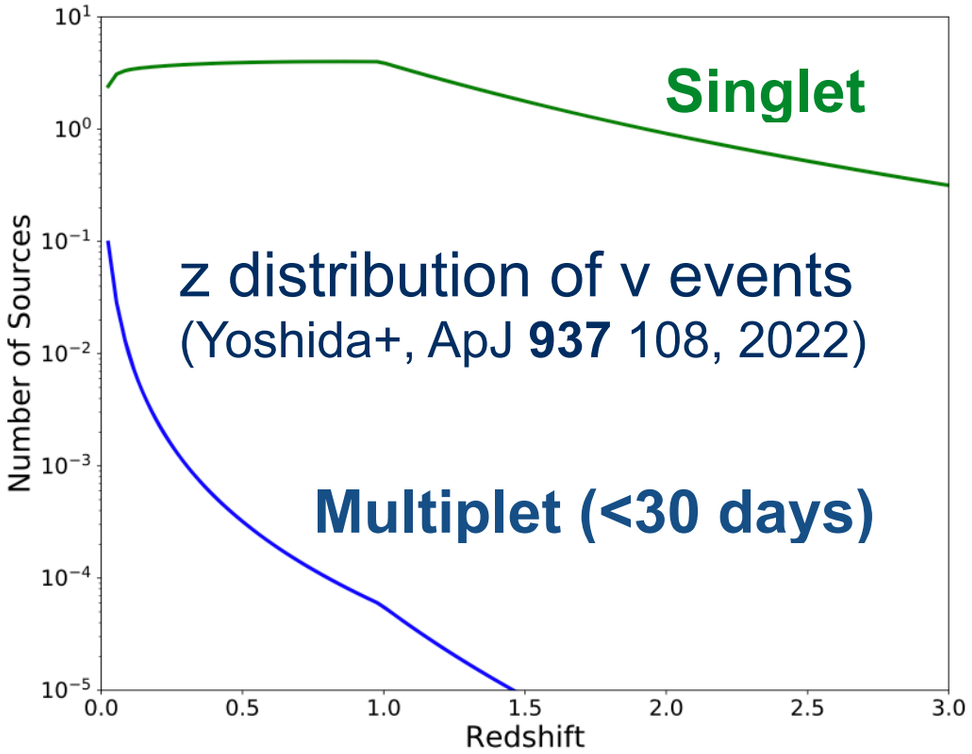


LST proposal for γ emitters 110+29 = 139

reduced from MAGIC 163+15 = 178

New list of nearby galaxies

- If (some of) ν is not from known GeV/VHE γ emitters, what can be done with VHE γ is ONLY to find new (probably dim) γ sources
- "multiplet" mostly from z<0.5, while singlet can be from z~1-3
  => **search over nearby galaxies**
- Situation is common. E.g., optical telescopes also want to observe as nearby sources as possible.
  But, **particularly important for IACT** to get involved, **due to EBL**

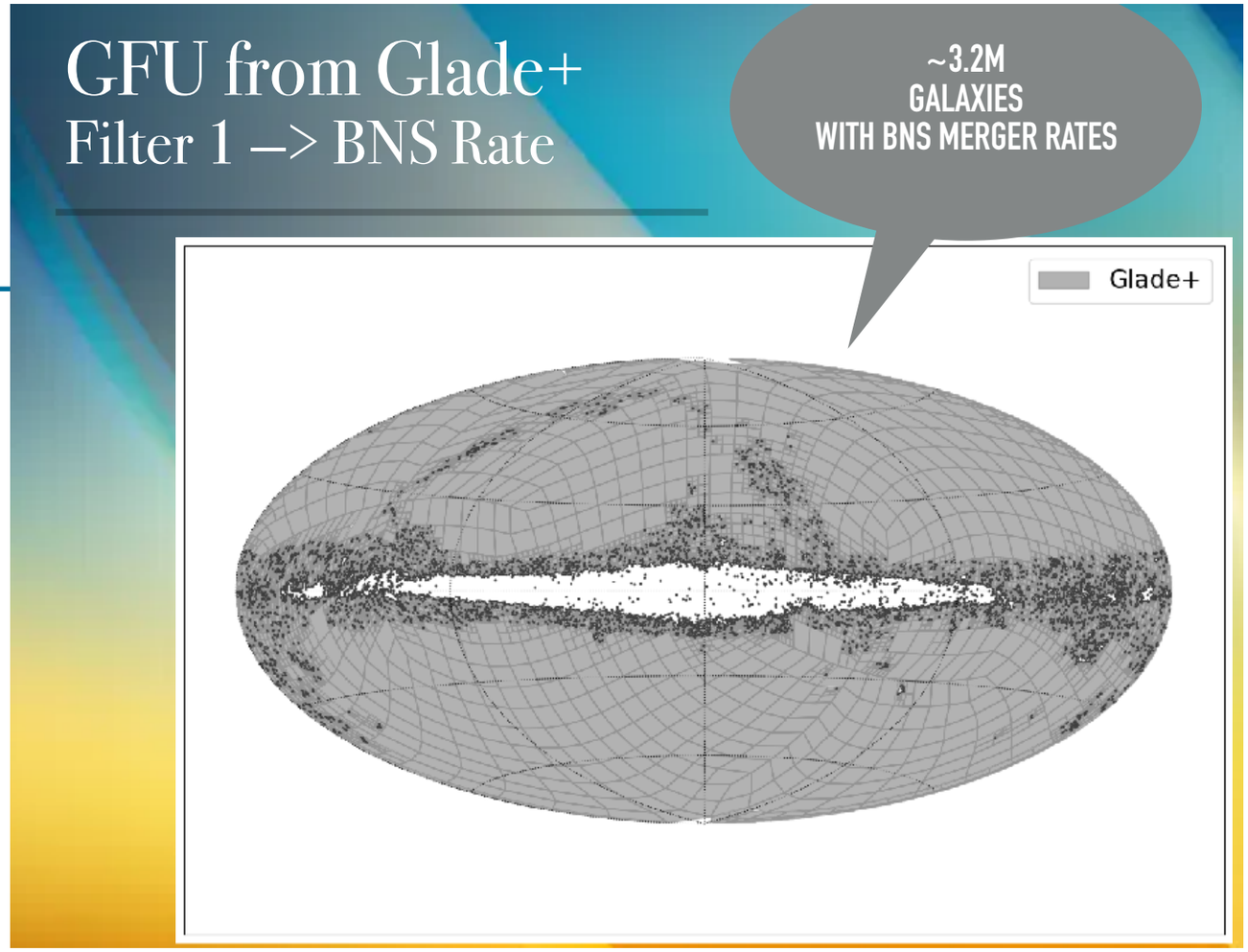


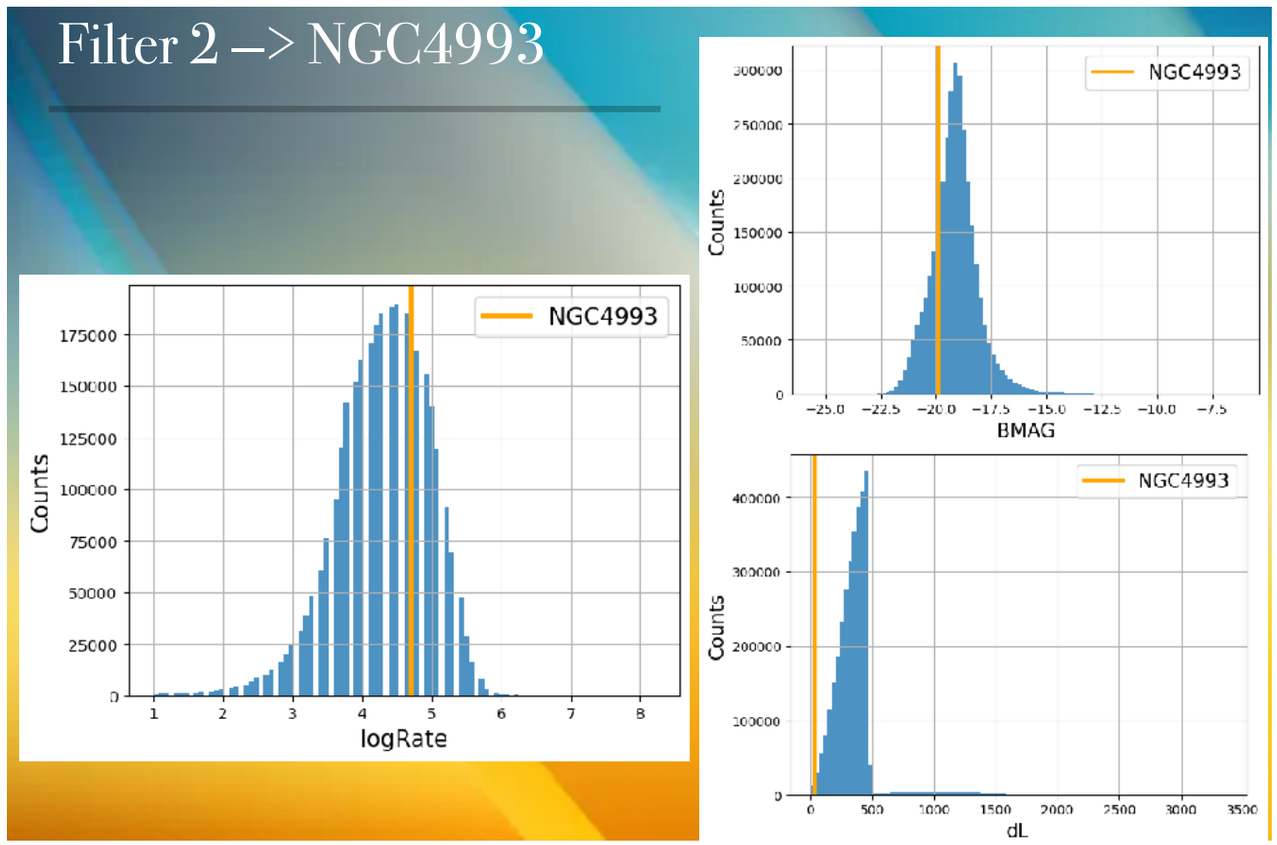
- Situations around multiplet are similar to GW signal
  => List of galaxies for GW = **GLADE+** catalog
  - It has an entry of BNS rate estimated with the stellar mass
  - Synergies / collaboration with GW-optical astronomers

GLADE+

- **3.2M** with the BNS entry
- Distance is not enough to get a reasonable number. Used BNS rate and Bmag, to select those with a high probability of BNS
  - As a typical value, we use NGC 4993 where GW170817 was located (44 Mpc)

  => **224** galaxies
- => **94** by visibility in La Palma
- => **73** by removing one of two too-close galaxies in the sky





Thoughts in the LST side

- Surely a room for improvements for the GLADE+ list
  - Cutting too much? Better to search for a factor farther distant sources (44 Mpc ~= z@0.01,,, at least up to 200 Mpc ~= z@0.05?)
    - Need a higher threshold in multiplet search only for this channel?...
  - Better to observe alerts from this list for a **longer time than the γ-based list**, as we somehow know that it is probably dim in γ
    - Need to revise also the followup observation strategy, but a bit tricky to do so within a single alert channel?...

- Anyway, we LST proposed **212 sources** to IceCube
  - 110 from 4FGL with revised methods, for GeV γ emitters
  - 29 from TeVCat, for known (bright) VHE γ emitters
  - 73 from GLADE+, nearby galaxies with a high BNS rate
- Compared with MAGIC, -22% for γ, while +19% with GLADE+
  - At least, no practical problem for the work load of analyses by human

Summary

- Let's solve the mystery of HE neutrino emitters by IACTs
- The current follow-up has only 1 success (?) of ν-γ correlation
  - but by a public alert of a single event. NOT by the private alert of correlation between ν multiple events and preselected γ-source list.
  - Too low number to conclude what is the main ν-emitters...
- Can be due to the private alert construction. We should improve it for CTA/LST, so proposed a revised list to IceCube
  - Improving the selection criteria of γ-sources, reducing the bias to γ
  - Adding another list of nearby galaxies
- Discussions started in IceCube. ***Let's see how long it will take for me to be an IceCuber :)***