The H.E.S.S. Gravitational Wave Rapid Follow-up Program

Transient Sky 2020

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https://arxiv.org/abs/1906.10426 **accepted for publication in JCAP**

H.E.S.S.

GW & GRBs

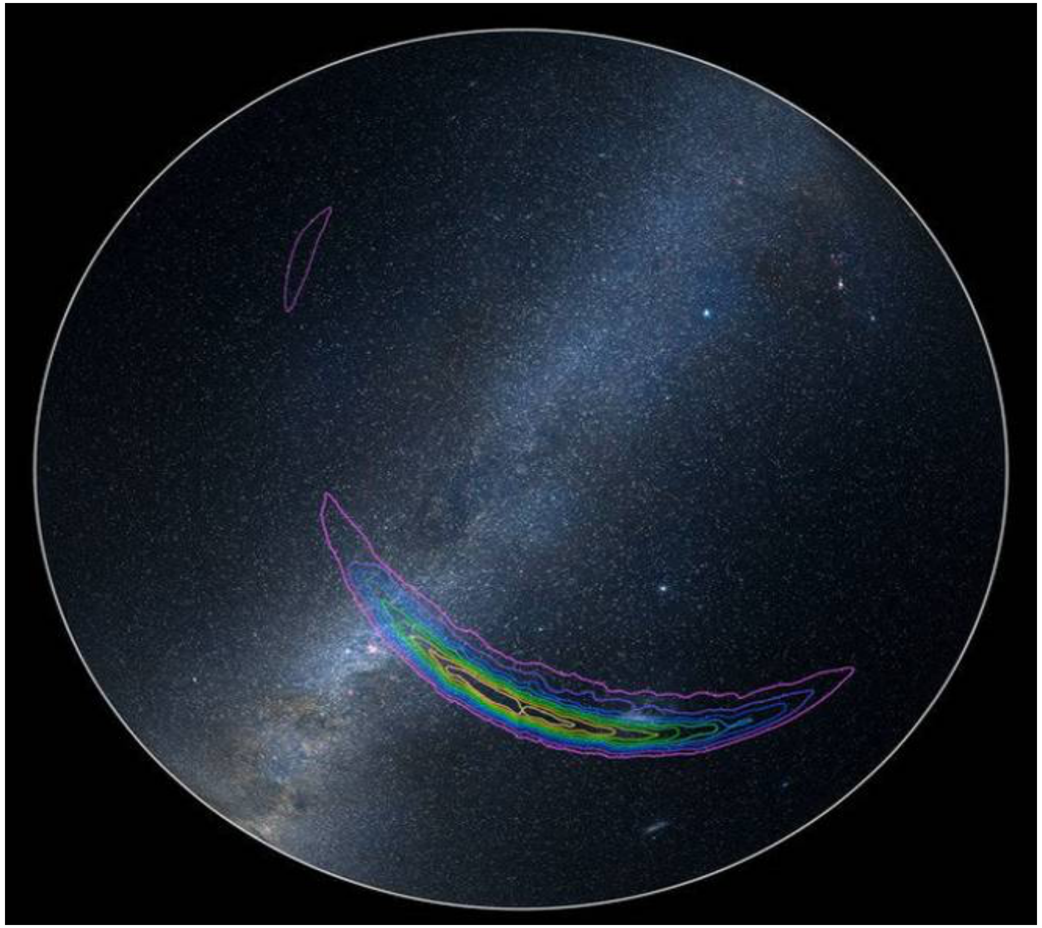
- GW170817 has established the link between the emission of GWs and short GRBs through BNS mergers.
- K. Murase, et al. and P. Veres and P. Mészáros predict short GRBs detectable by IACTs from CBC like in certain scenarios
- Short GRB at VHE energies: GRB 090510 up to 10s GeVs ----- GRB 160821B :evidence by MAGIC of gamma-ray emission above 0.5 TeV

- Recent VHE GRNS: H.E.S.S. GRB180702B and **GRB190829** GRB190114C.
  - ➢ Efficient particle acceleration, possibly via relativistic jets → VHE gamma-rays over an extended period of time from the very early (e.g. GRB190114C) to the late afterglow phase (e.g. GRB180720B and GRB190829A).
- There also seem to be striking similarities between the fading X-ray and VHE gamma-ray flux levels.
- X-ray behavior of short GRBs is similar to long GRBs (M. Nysewander, et al.)
  - With typically fainter flux levels → hopes for possible VHE emission of short GRBs.
  - Fainter fluxes make the afterglow detection of short GRBs in the VHE band even more challenging than for long GRBs.
  - \+ The fact that the emission in the afterglow phase is showing a steady decrease:
  - ➢ **The need for high sensitivity and rapid follow-up observations in order to detect electromagnetic (EM) counterpart of GWs at VHE energies in the early bright phase becomes clear.**

Note: Delayed emission cases not treated here… An example can be found in our previous paper on EM170817 long-term follow-up with H.E.S.S.

GW localization

- GW localization can span 10s to 1000s of degrees in the sky.
- Unlike most transients GW follow-up requires a strategy.
- Long time to cover.
- Therefore:
  - Focus on most probable position at first to have the best shot.
  - Fast computation time and telescope reaction.

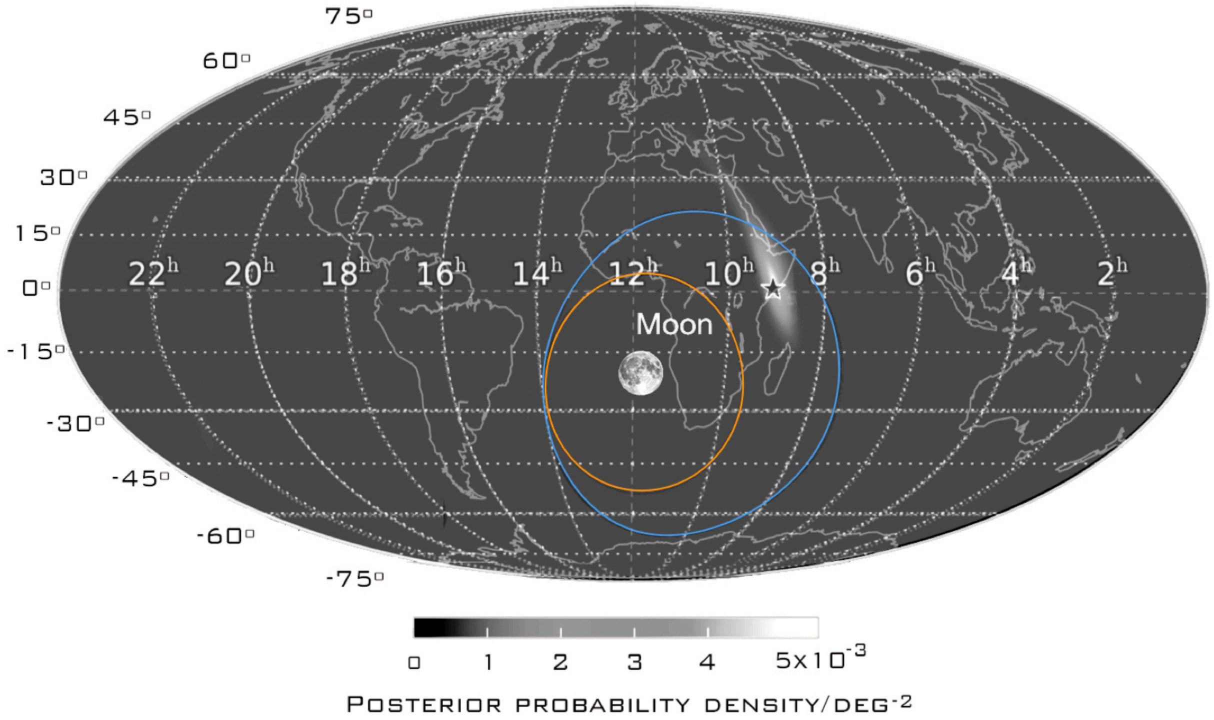


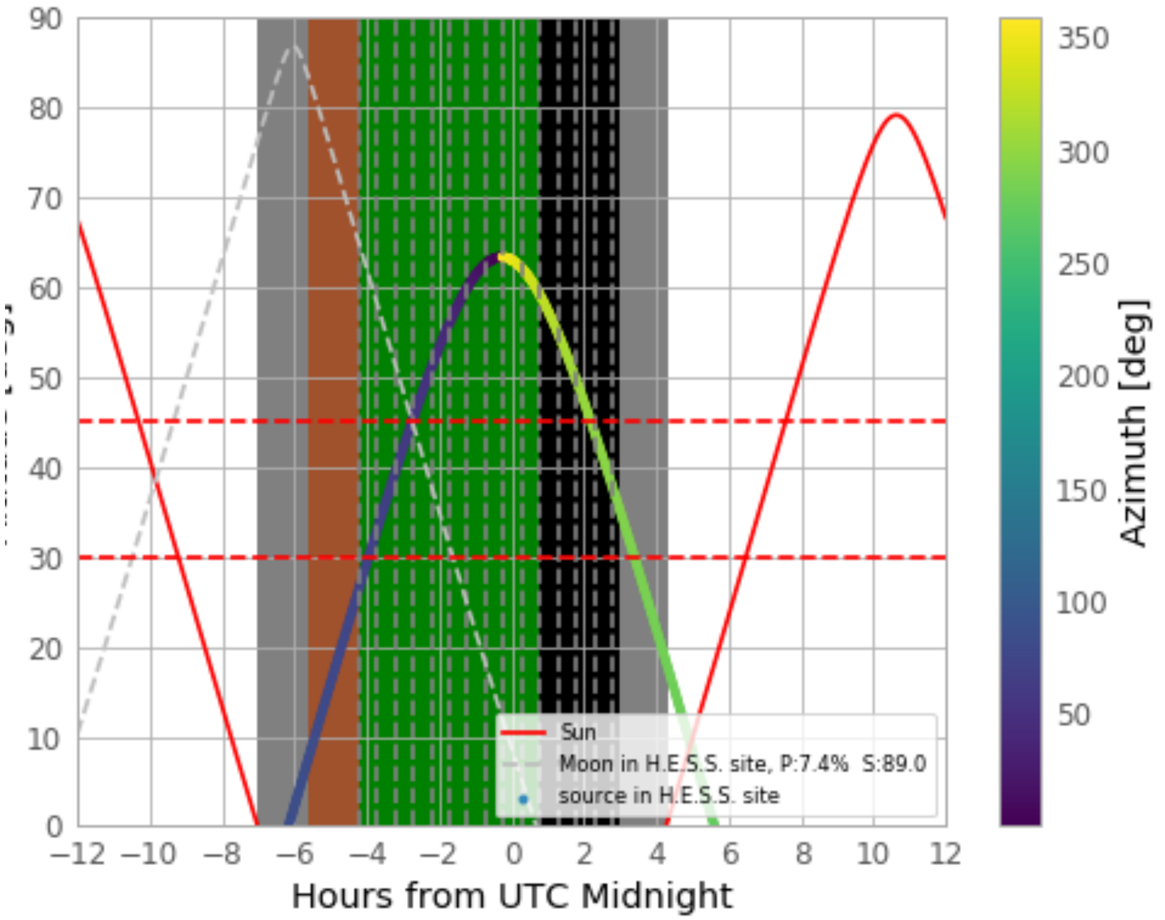
GW follow-up with IACTS: general considerations

- IACTs observation conditions:
  - Low light falling into the PMTs
  - Sun and moon altitude, moon-phase and moon and source separation are considered
  - Observation with moderate moonlight could extend the observation time by ~10 %
  - H.E.S.S. 28 mins standard observations

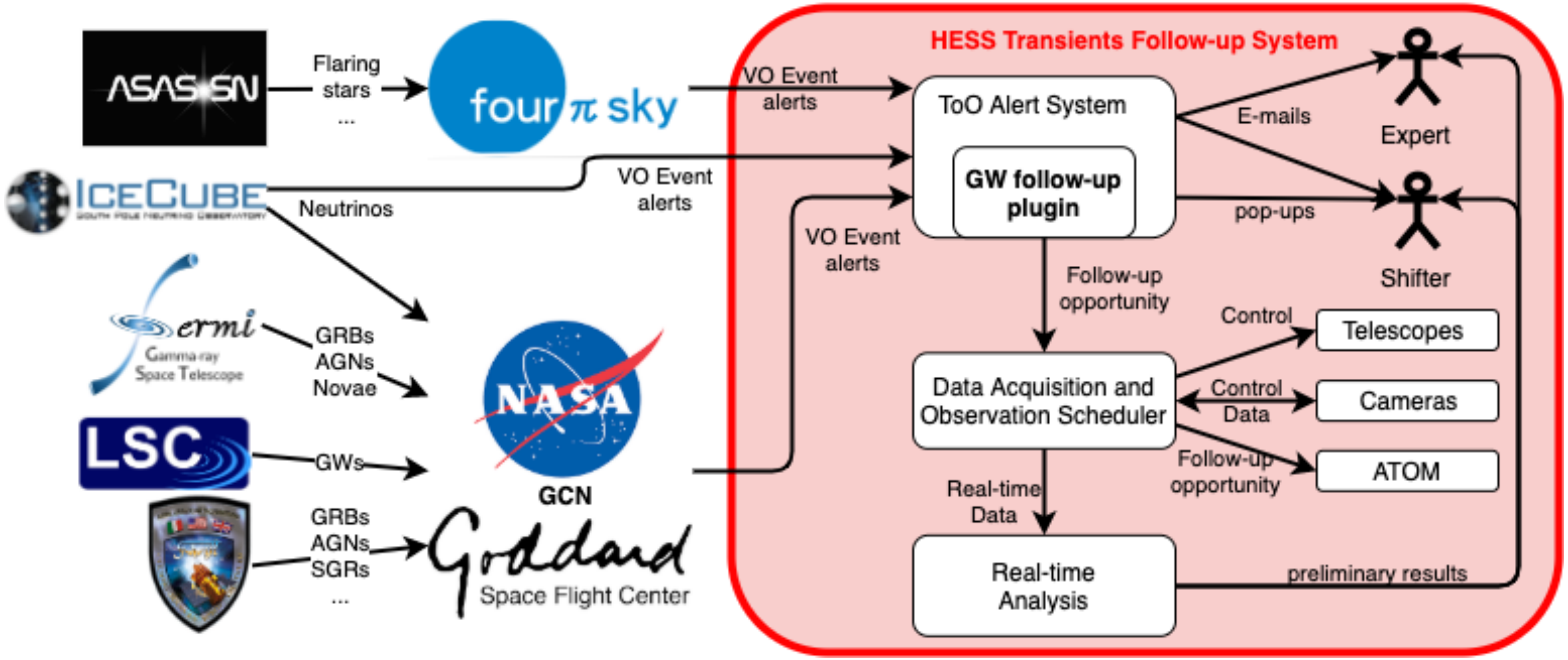
- IACTS visibility condition:
  - Determined by the location of the IACT on earth: H.E.S.S. southern hemisphere.
  - Observation zenith angle restrictions < 60 deg.
  - Favoring low zenith angle observations: Energy threshold increases with zenith angle.

GW follow-up with IACTS: general considerations





H.E.S.S. Transient Sytem



GW alert content

- Detection time
- Arrival time
- Name of the event
- Pipeline: Burst or CBC
- Nature of CBC: BBH, BNS, MassGap, NS-BH, Terrestrial
- Link to GW map

GW alert maps

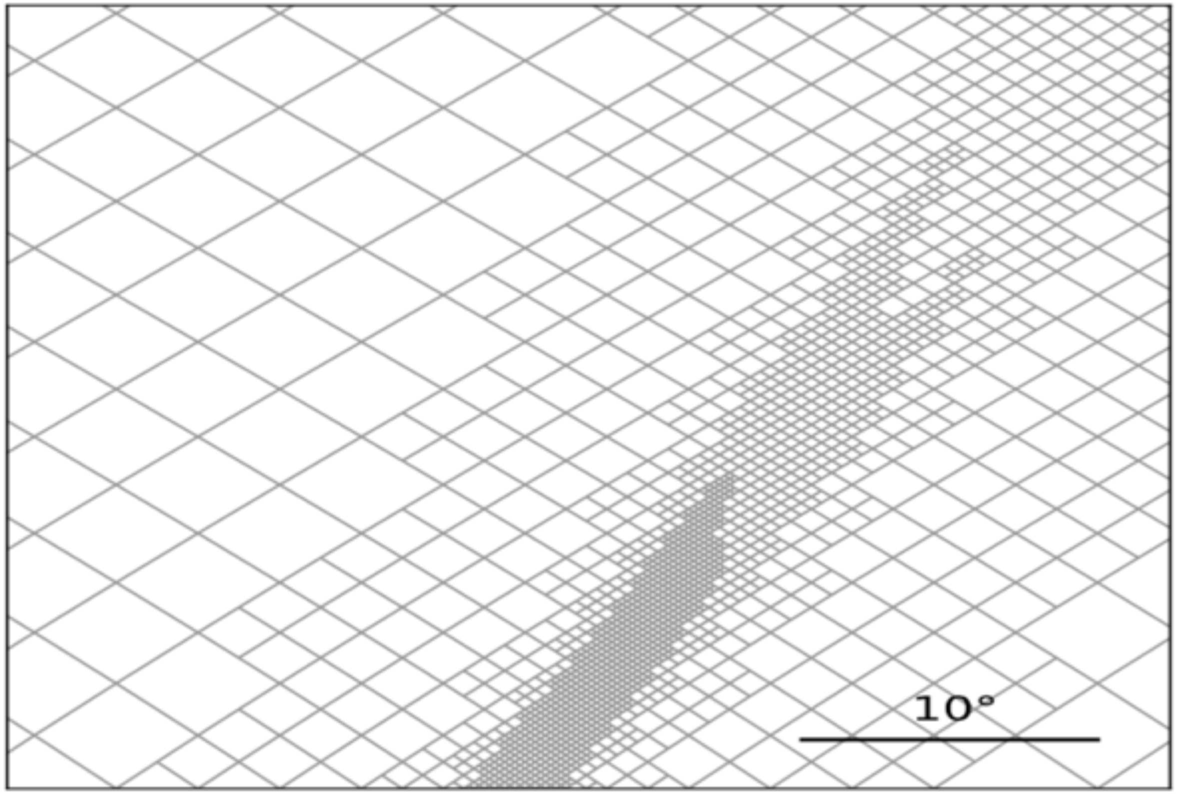
- HEALPix format
- Pixel indices + 4 layers

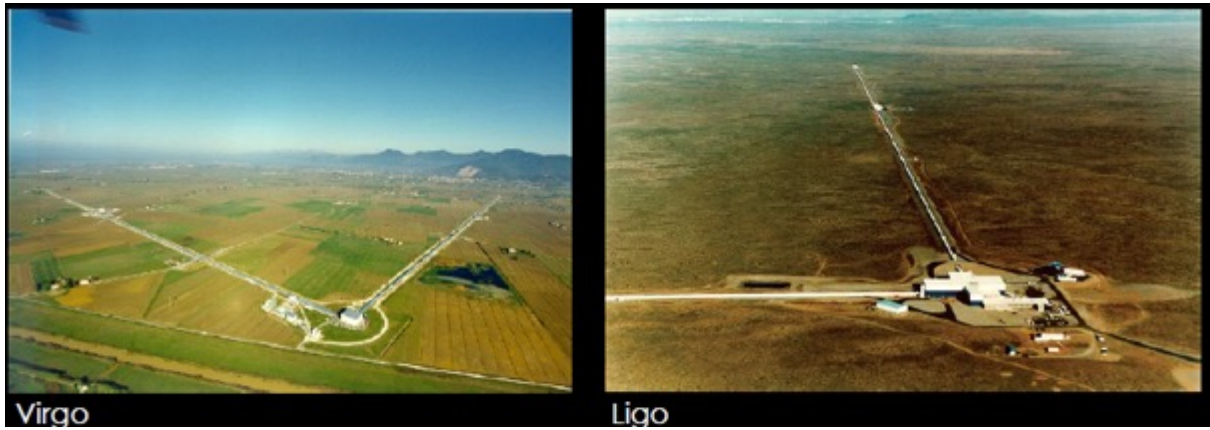
1. Prob: Posterior Probability

- If has3D info:

    2. Distmu: distance average
    3. Distsigma: distance error
    4. Distnorm: normalization

Singer, L. P. et al. 2016, *The Astrophysical Journal Letters*, 829L, 15S





GW follow-up algorithms:

All implemented algorithms follow the same general procedure:

- 1. Select the most probable sky location fulfilling the IACT observation conditions (e.g. zenith angle range, dark time, etc.).
- 2. Schedule observation for this direction at T0 with a duration t.
- 3. Mask a circular sky region representing the effective IACT field-of-view around that region. Note that this condition allows for the overlap of observing region whenever it is beneficial for the total probability coverage maximization.
- 4. Using the modified visibility window Ti = T0 + i t, where i is the observation number and the iteratively masked skymap, steps 1-3 are repeated until gamma-ray emission is detected by the real-time analysis, the covered probability for the next observations is insignificant or the allocated observation time is used.

GW follow-up algorithms: 2D

- Exploits the 2D posterior probability without taking distance info in consideration.
- Best-pixel algorithm:
  - Pointing observations according to the selection of individual high probability pixels $P_{GW_i} = \rho_i$
- PGW-in-FoV algorithm:
  - Exploit full probability in the FoV $P_{\rm GW}^{\rm FoV} = \int_0^{2\pi} \int_0^{r_{\rm FoV}} \rho(r, \phi) \, {\rm d}r{\rm d}\phi,$
  - For a given observation window choose $P_{\rm GW}^{{\rm FoV},i} = P_{\rm GW}^{{\rm FoV},MAX}$
  - How it's done in next slide:

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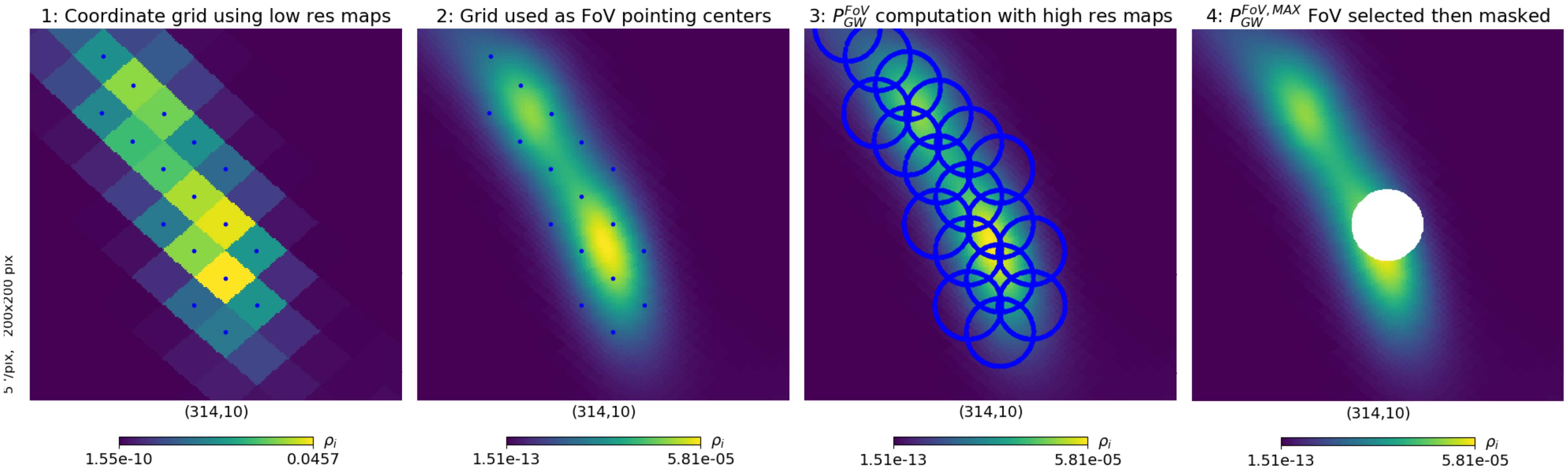
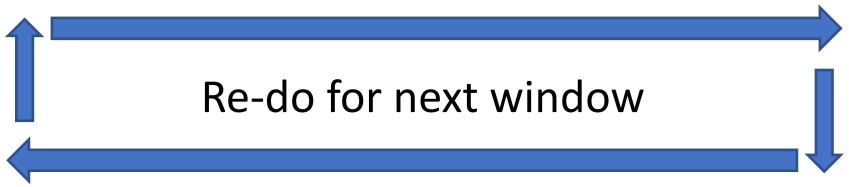
GW follow-up algorithms: 2D

PGW-in-FoV algorithm:



Note: - Optimized Nside = 64
- Here Nside = 32 for presentation purposes



GW follow-up algorithms: 3D

- Exploits the 2D posterior probability + 3D distance information
- Correlation of GW maps and Galaxy catalogs:
  - Posterior probability volume defined by:
  - New normalized probability P_{GWxGAL}:

$$\frac{\mathrm{d}P}{\mathrm{d}V} = \rho_i \frac{N_{\mathrm{pix}}}{4\pi} \frac{\hat{N}_i}{\sqrt{2\pi}\hat{\sigma}_i} \exp\left[-\frac{(z-\hat{\mu}_i)^2}{2\hat{\sigma}_i^2} \right]$$

$$P^i_{\mathrm{GWxGAL}} = \frac{\mathrm{d}P^i/\mathrm{d}V}{\sum_j \mathrm{d}P^j/\mathrm{d}V}$$

with

$$\sum_i P^i_{\mathrm{GWxGAL}} = 1.$$

- <u>Best-galaxy algorithm: </u> choosing for each window the highest P^i_{GWxGAL}

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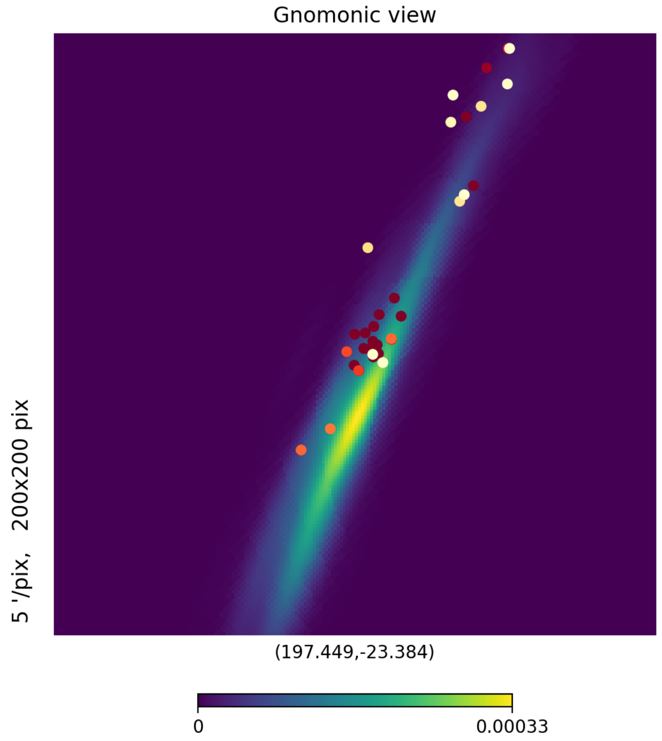
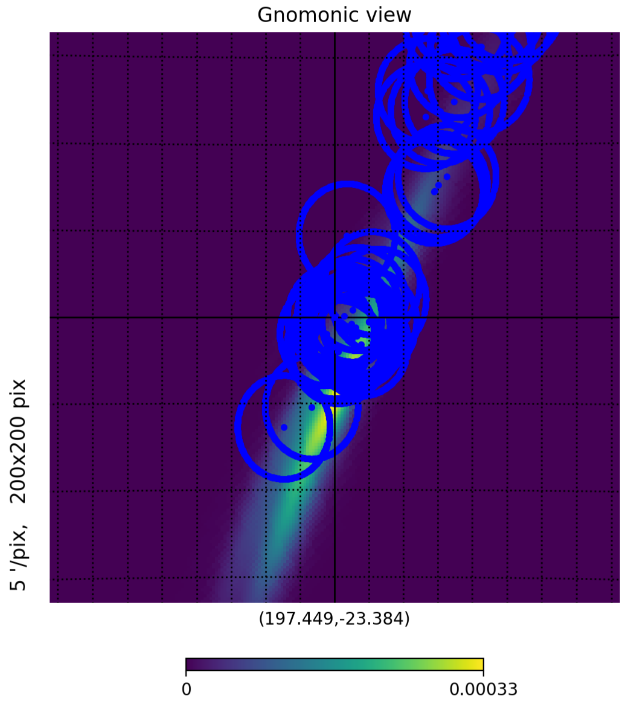
GW follow-up algorithms: 3D

- <u>Galaxies-in-FoV algorithm</u>:
  - Exploiting the 3D probability in the FoV: $$P^{\rm FoV}_{\rm GWxGAL} = \int_0^{2\pi} \int_0^{r_{\rm FoV}} P^{i}_{\rm GWxGAL}(r,\phi)\,{\rm d}r{\rm d}\phi.$$
  - Choosing the galaxies as seeds for the pointings.

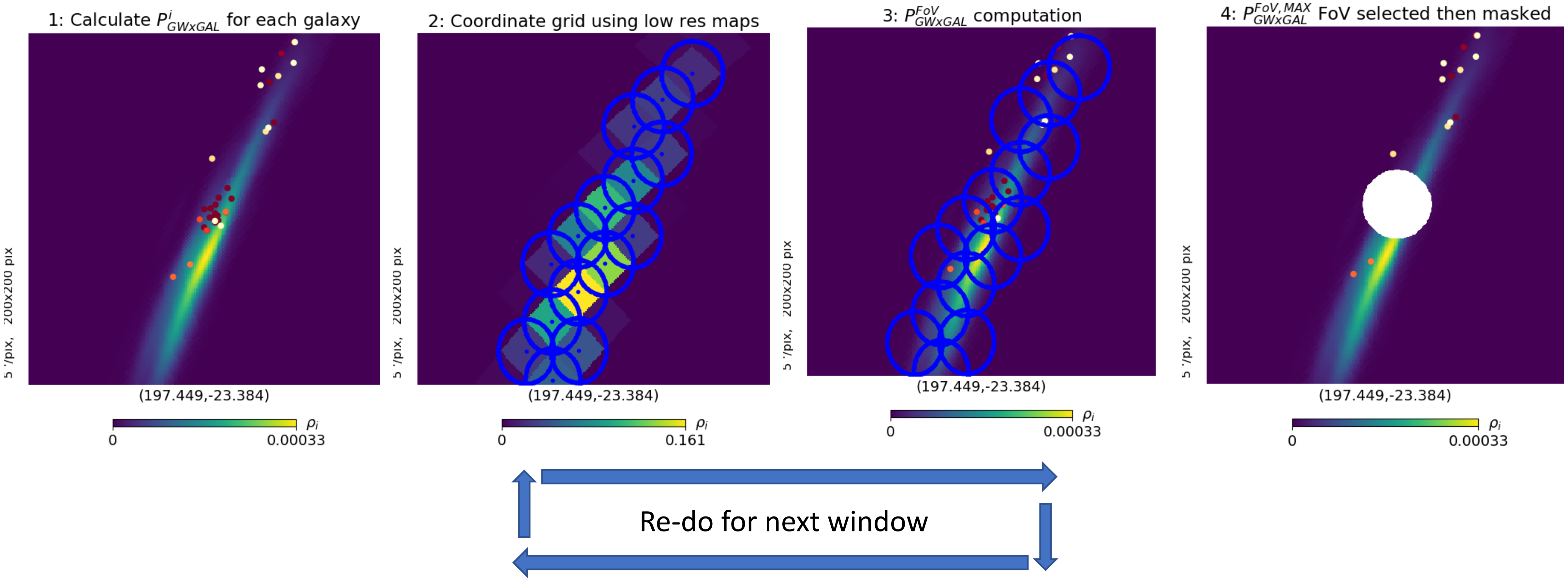




The number of galaxies could increase drastically with large GW volume localization: **Computation time will increase drastically**

GW follow-up algorithms: 3D

- PGalinFoV-PixRegion algorithm: mixing PGW-in-FoV & Galaxies-in-FoV
- The number of galaxies in the 3D space grows faster than the number of pixels in the 2D plan
- The regions explored are inside the x% of the localization region. We usually choose x > 90%.



Testing pipeline

- 250 simulated BAYESTAR GW maps from: L.P. Singer et al.
- 10 random times during 1 year: Total of 2500 MC simulations per algorithm.
- Test performed several times on different servers.
- Similar results where obtained.
- Results shown in this presentation are obtained with the currently running version.

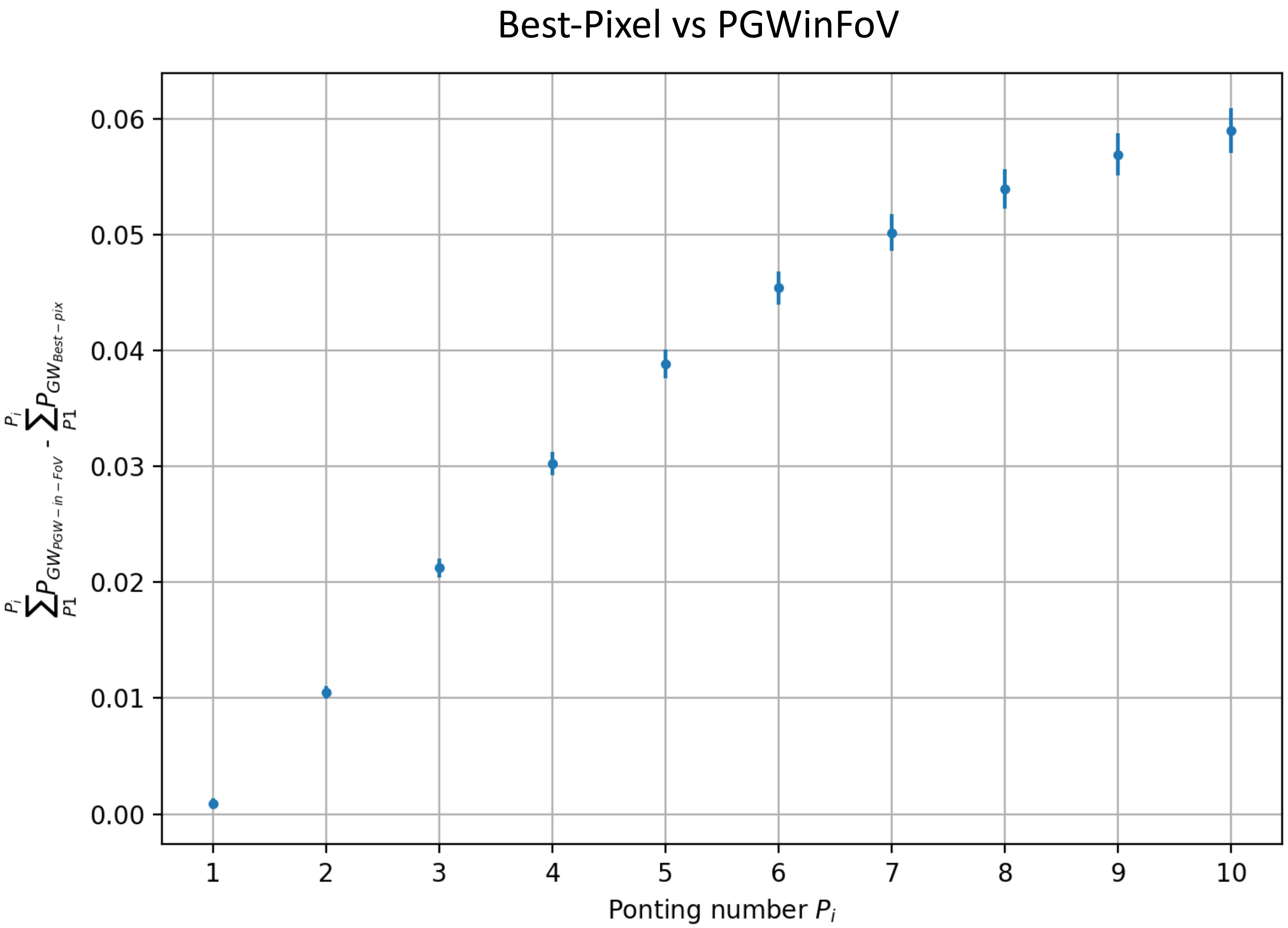
Performance assessment and comparison: 2D

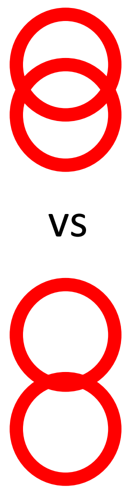
Slang:

- P_{GW}: 2D Probability inside of FoV

Method:

- Calculate the sum of P_{GW} up to i pointings
- Calculate the mean for all simulations
- Difference between the 2 algorithms





Increasing the pixel size might solve the overlap issue but will harm the accuracy of the probability computation

Exploiting the integrated probability inside the FoV of medium to large FoV telescopes is clearly profitable (more details in backup slides)

Performance assessment and comparison: 3D

Slang:
- P_{GW}: 2D Probability inside of FoV
- P_{Gal}: 3D Probability inside of FoV

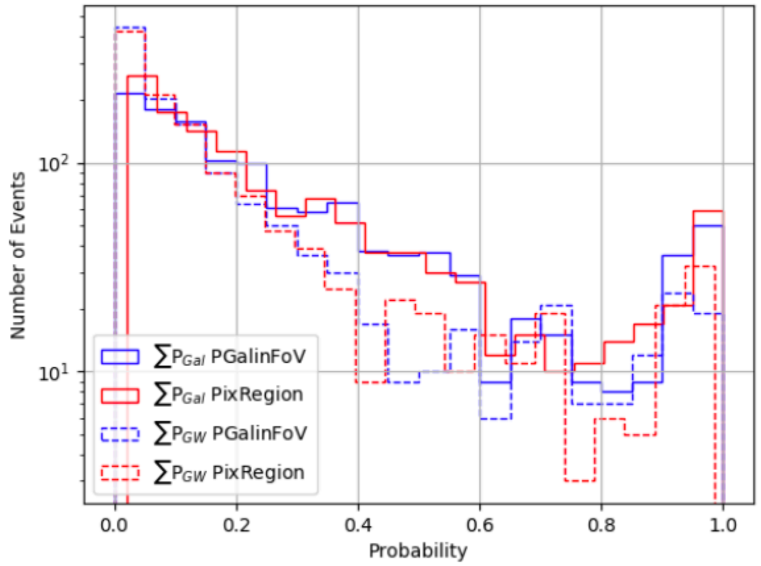


Figure 6. Total P_{GAL} and P_{GW} simulated coverage distributions for `PGalinFoV` and `PGalinFoV-PixRegion`.

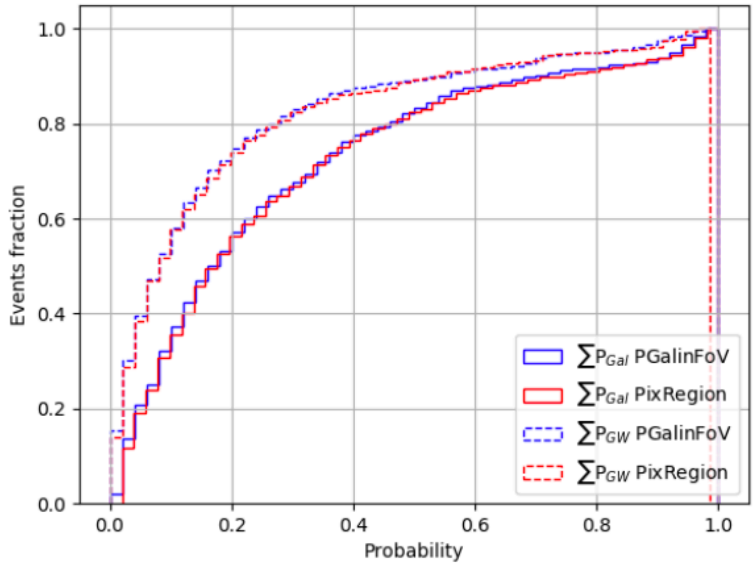


Figure 7. Total P_{GAL} and P_{GW} simulated coverage cumulative distributions for `PGalinFoV` and `PGalinFoV-PixRegion`.

Similar coverage with PGalinFoV and PGalinFoV-PixRegion. What about computation time ?

Performance assessment and comparison: 3D

Step by step computation time until scheduling

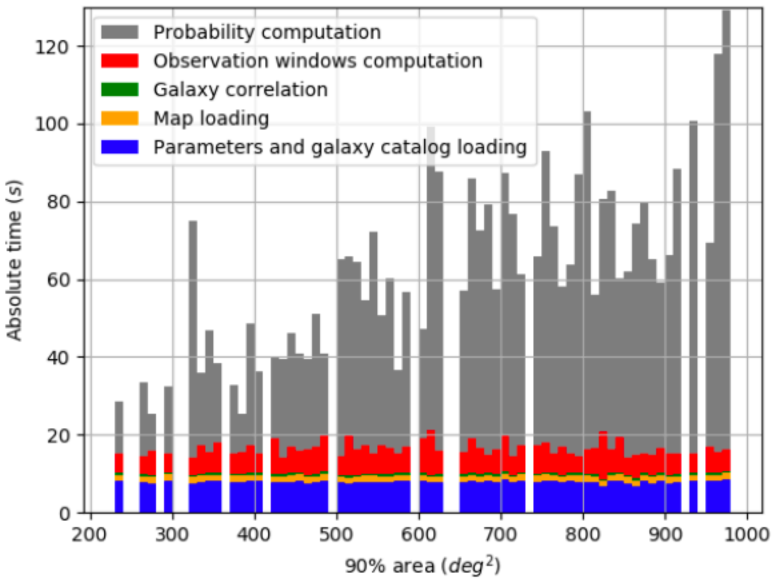


Figure 8. Absolute time for the computation of each step of the PGalinFov algorithm for N_{side} = 512 maps up to an area of 1000 deg^2.

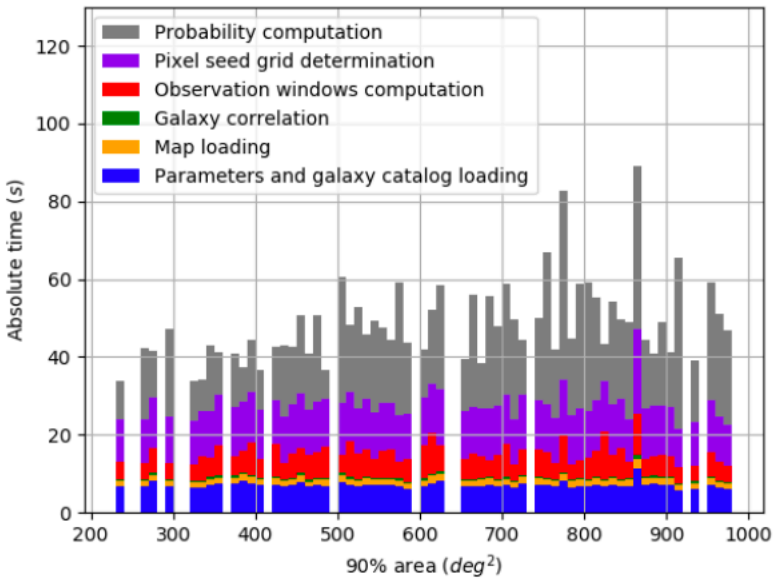


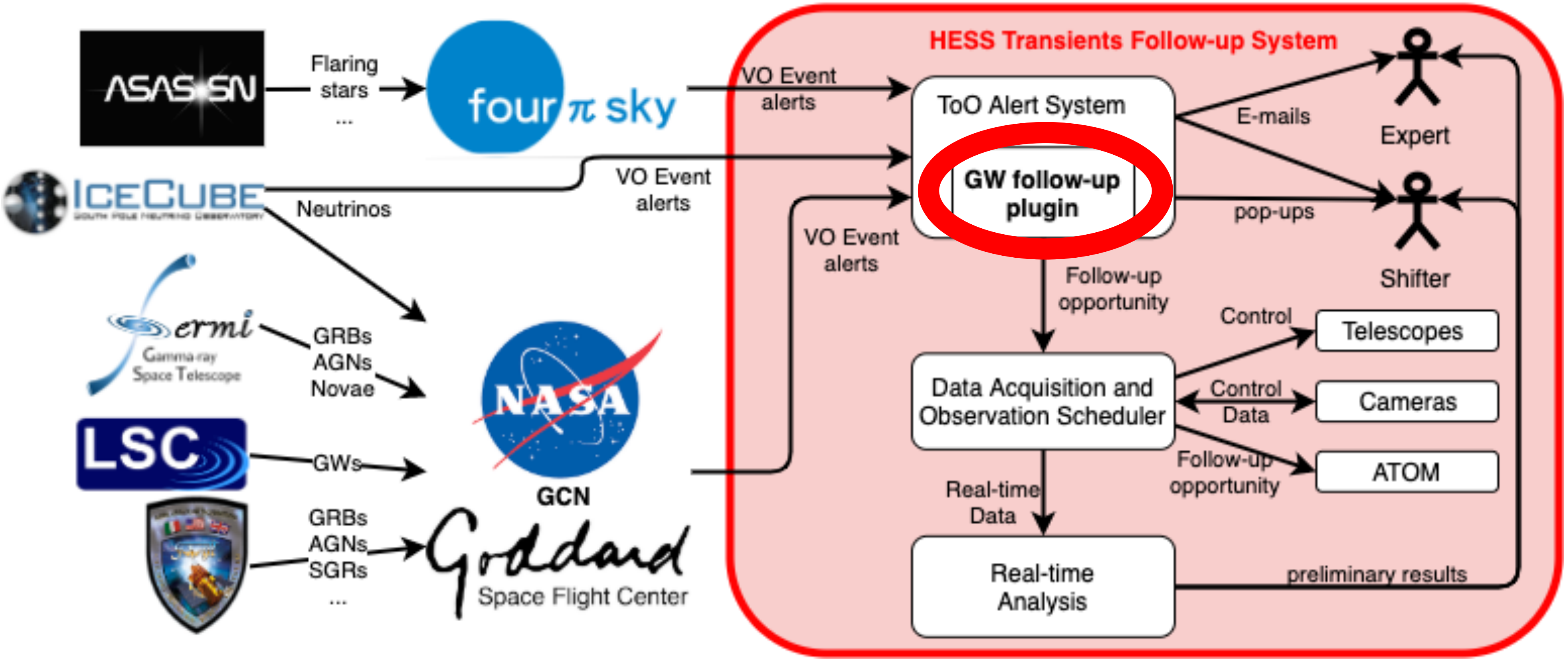
Figure 9. Absolute time for the computation of each step of the PGalinFov-PixRegion algorithm for N_{side} = 512 maps up to an area of 1000 deg^2.

We note that Maps with Nside:
2048 → 30 s
1024 → 8 s
512 → < 2 s
256 → < 1 s

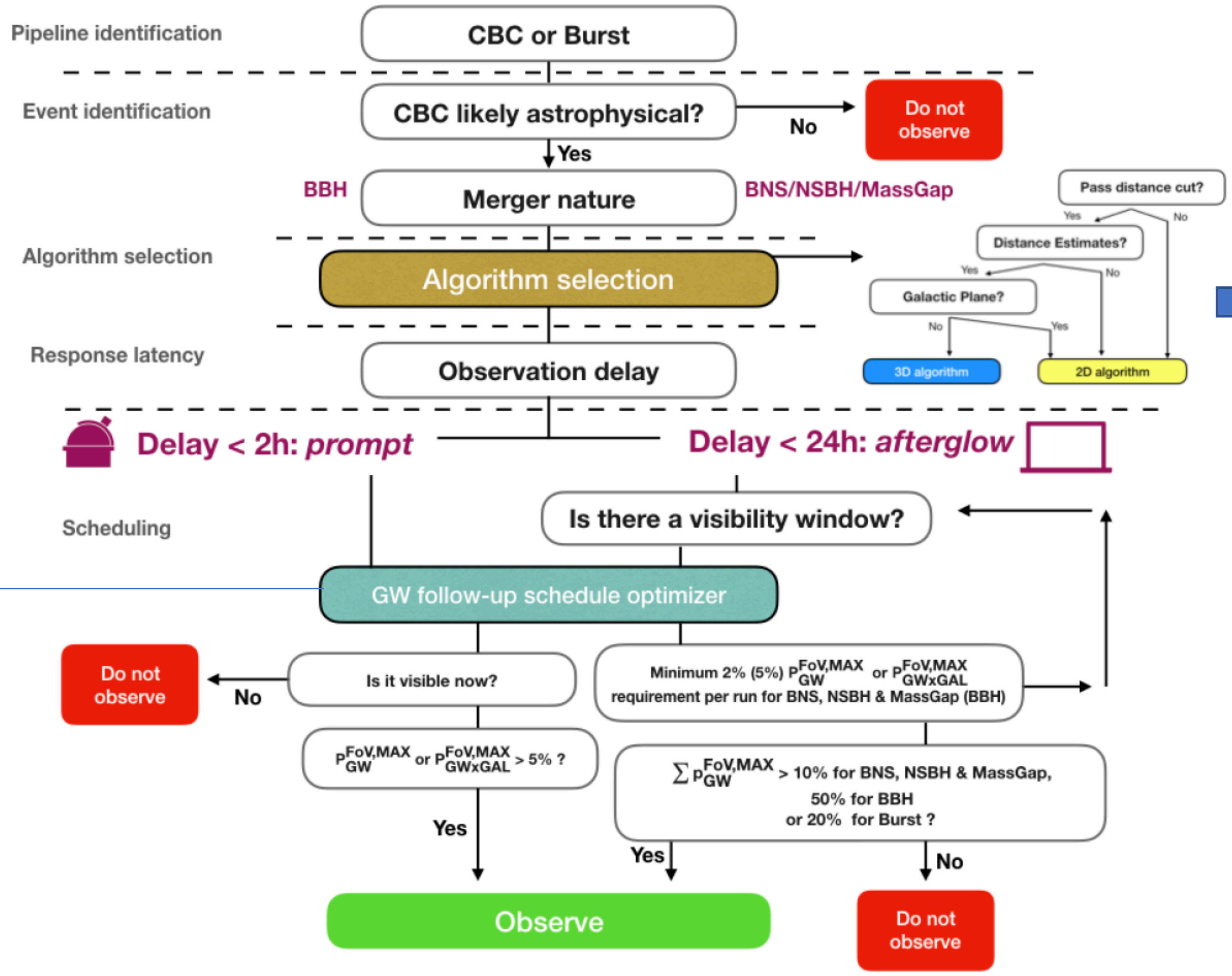
PGalinFoV will be used due to prompt observations requiring quick response and not loosing time while determining the pixel grid. Also H.E.S.S will be focusing on well localized events only.

PGalinFoV-PixRegion better suited for large maps.

H.E.S.S rapid follow-up program



H.E.S.S rapid follow-up program

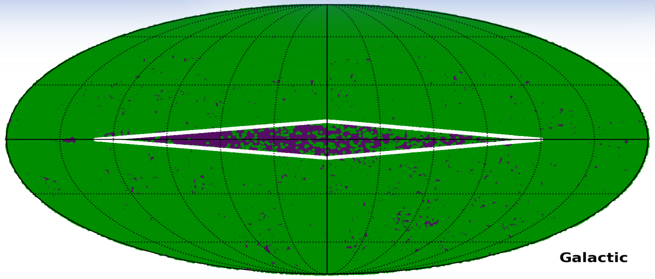


PGalinFov
PGWinFoV

Figure 10. Schematic overview of the decision tree used in the automatic response of H.E.S.S to GW events.

3D information?

Distance < 150 Mpc



Some selection cuts for H.E.S.S.:

- Terrestrial < 50%
- Follow-up delay < 24h
- Burst -> Total PGW > 20%
- BBH < 50% -> Total PGW > 10%
- BBH > 50% -> Total PGW > 50%
- PGW / run > 2% for BNS and > 5% for BBH and Bursts

H.E.S.S rapid follow-up program: output

For weather and technical issues

Start time	Ra	Dec	PGAL	Observation window	Priority
2017-08-17 17:59	196.88	-23.17	0.72	2017-08-17 17:55 → 2017-08-17 18:39	0
2017-08-17 18:27	198.19	-25.98	0.16	2017-08-17 17:55 → 2017-08-17 18:48	1
2017-08-17 18:56	200.57	-30.15	0.05	2017-08-17 17:55 → 2017-08-17 19:01	2

Table 1. Example of the observation schedule of the GW170817 follow-up. The priority of the pointings is higher in ascending order.

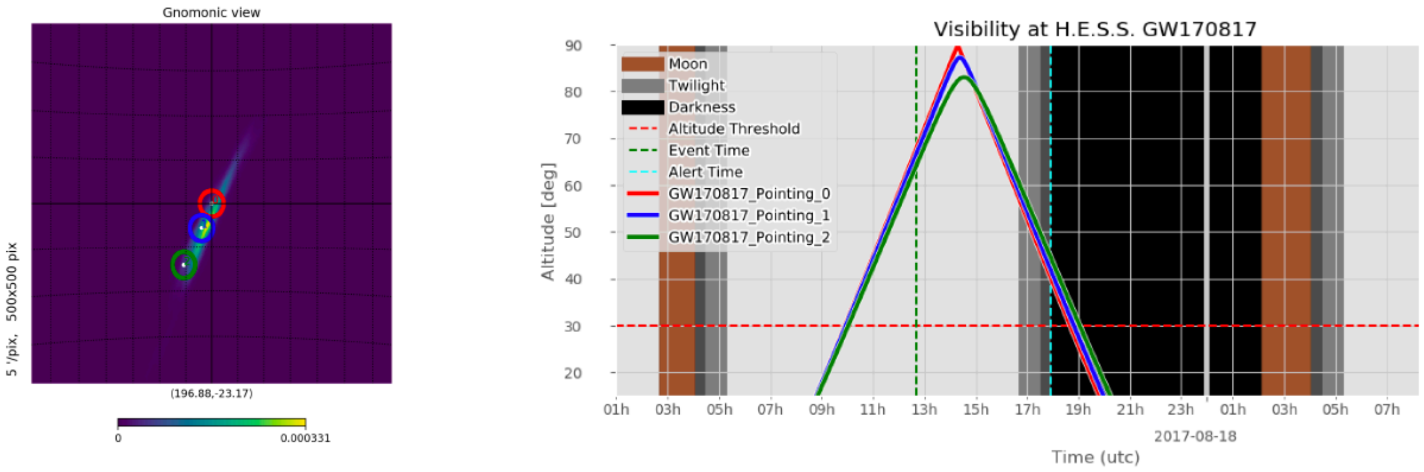
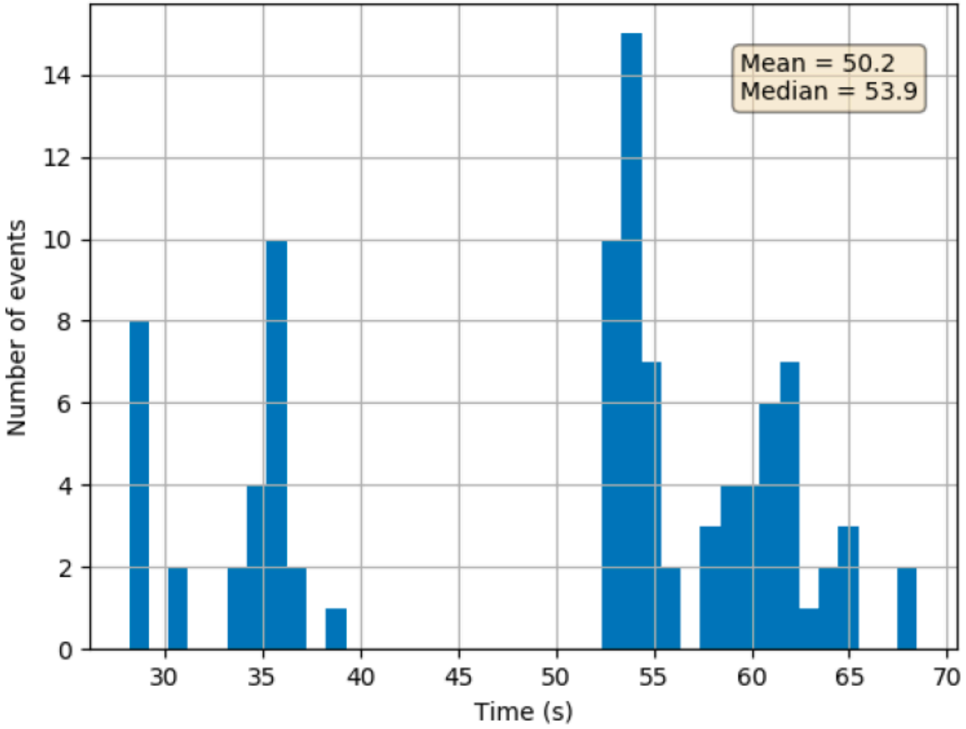


Figure 11. Example of the visual aid provided by the GW follow-up framework for the case of GW170817. On the **right** the scheduled pointings are superimposed on the GW map with their respective number and on the **left** the zenith angle evolution of their corresponding position throughout the night is shown.

H.E.S..S rapid follow-up program performance

Tested the H.E.S.S. response latency to prompt GW mock alerts. Only alerts passing all the cuts have been considered.

We note that
Maps with Nside:
2048 → 30 s
1024 → 8 s
512 (most cases) → < 2 s
256 → < 1 s



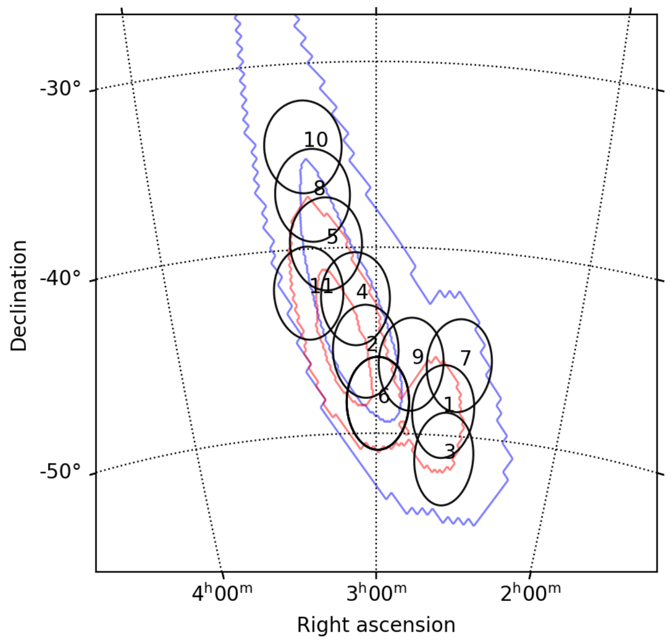
- Computation time + H.E.S.S. slewing time (max 1min)
- Response time estimated to be **<1min** for most cases and **<2mins** for all cases.

Figure 12. The H.E.S.S. *prompt* 3D response time to GW Mock alerts from July to October 2019 excluding telescope slewing time. Only alerts passing all filtering requirements are considered.

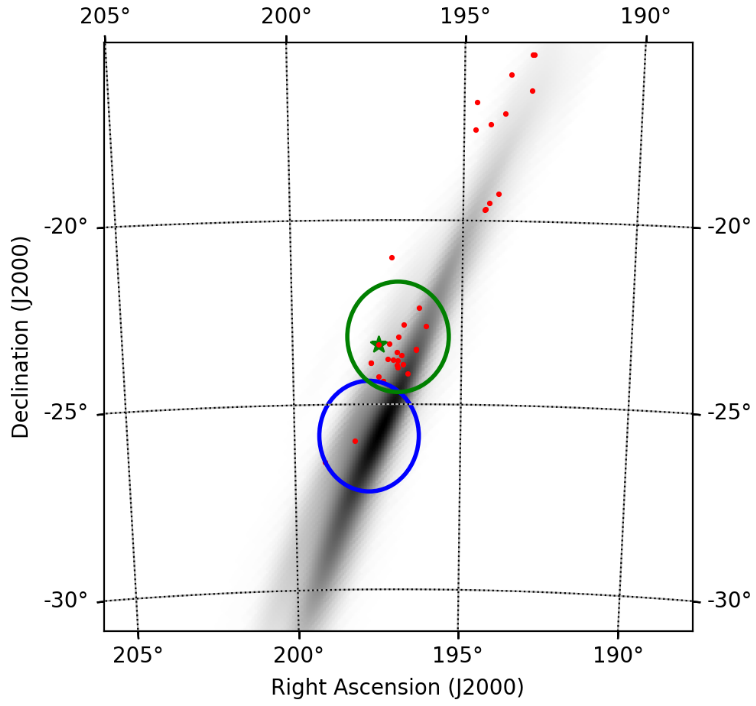
Testing with actual observations: O2

GW170814:

- First BBH events detected by 3 interferometers during O2
- performed over 3 First well localized event + visible for H.E.S.S.
- Observations nights
- First H.E.S.S. attempt for GW coverage and observations.
- Published in Ashkar H. et al.



Black circles: H.E.S.S. observed Fields
Red and Blue: 50% and 90% localization uncertainty



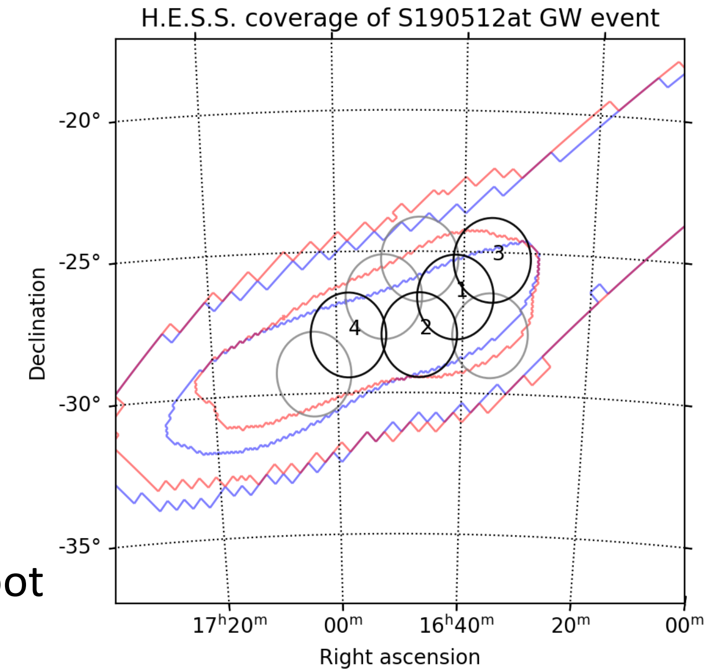
GW170817 (Golden Event)

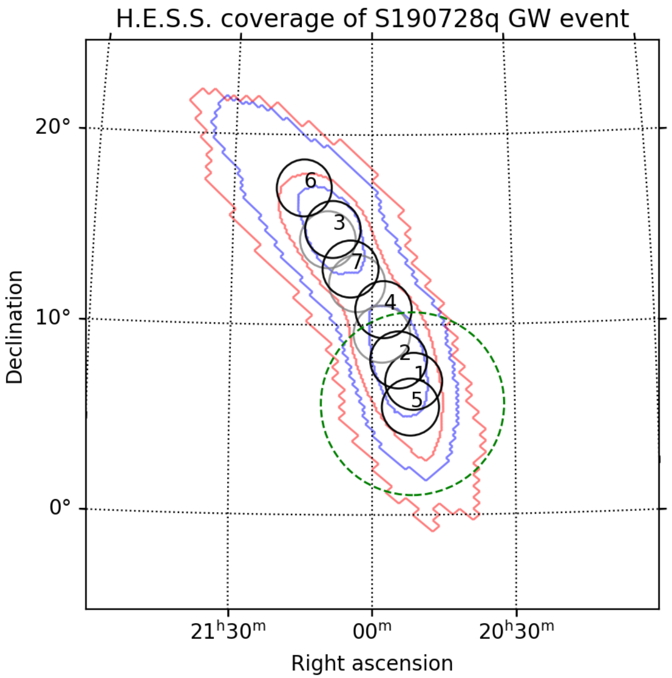
- Green circle obtained with 3D strategy
- Blue circle obtained with 2D strategy
- H.E.S.S. first ground based telescope to be on target after 5 mins of update.

H.E.S.S.

Testing with actual observations: O3a

S190512at:
- First well localized O3 event
- Favorable zenith angle
- Testing of the new GW follow-up strategy
- Observed during the following night
- Delay ~ 7h
- First run showed hotspot in the RTA





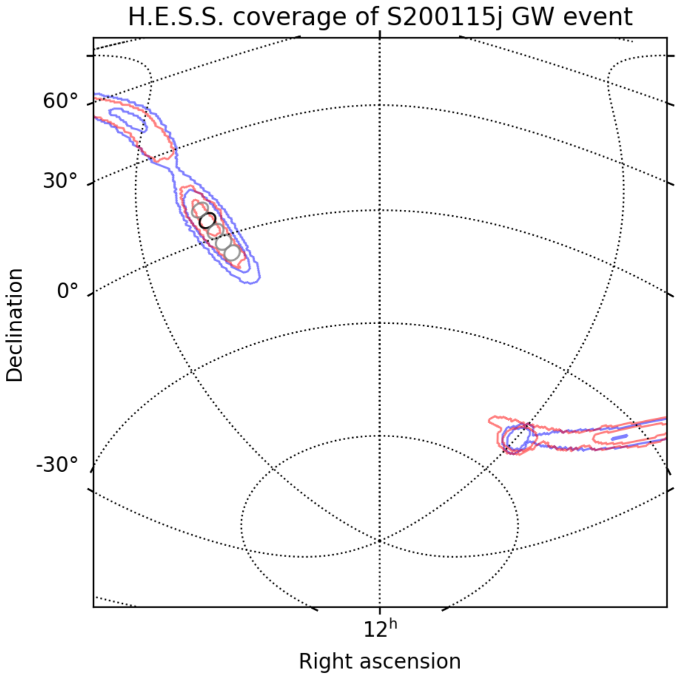
S190728q:
- Initially classified as NS-BH merger
- First alert triggered by H.E.S.S. Transient system
- Update during the night successfully triggered response system again (re-classified as BBH)
- Delay ~ 11h
- ZRF19abjethn + neutrino
- Sent GCN circular

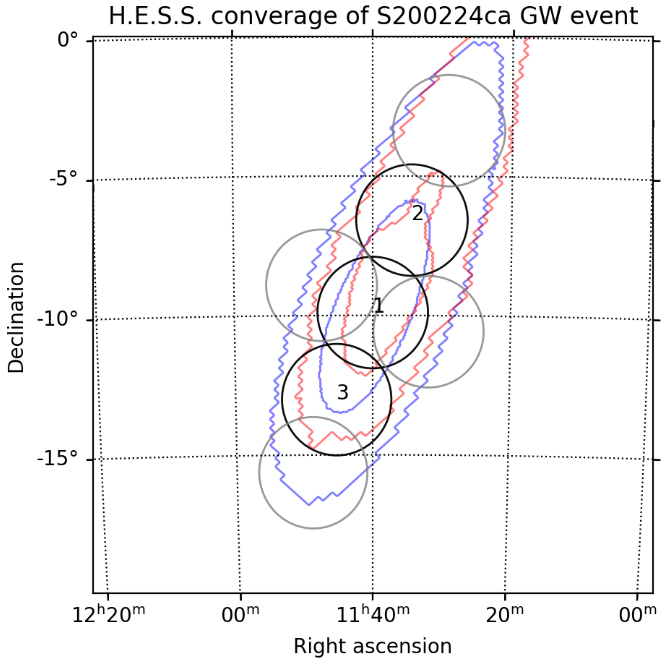
Grey circles: H.E.S.S. scheduled observations
Black circles: H.E.S.S. observed Fields
Red and Blue: 50% and 90% localization uncertainty

H.E.S.S.

Testing with actual observations: O3b

- **S200115j**: MassGap
- Observed with 1 run due to weather conditions





S200224ca:
- Very well localised BBH
- One of the most covered BBH
- Prompt alert
- Delay ~3 hours delay due to weather

- S190814bv (NS-BH)could not be observed due to moon light.
- Several scheduled observations could not be performed due to bad weather like on: S191204r (BBH) and S200114f (Burst).

Summary

- Golden Events like GW170817 are rare: optimization is a must for when it arrives.
- Rapidity is useful when *early warnings* alerts are implemented (successfully tested).
- Additional flag (True/False) that allows to use other variables like galaxy stellar masses (MANGROVE catalog).
- Flexible tools developed: configuration files containing telescope parameters (FoV, max zenith angle, desired selection cuts etc…)
- Flexibility of the tools (algorithms) allows them to be implemented on all kind of observatories: for now H.E.S.S., LST and CTA.
- GW scheduling testing pipeline was also useful for GBM tiling testing strategies.
- In H.E.S.S. For the arrival of several events at the same time: priority scheme determines which is observed first. Other transients are monitored by Astro-COLIBRI.

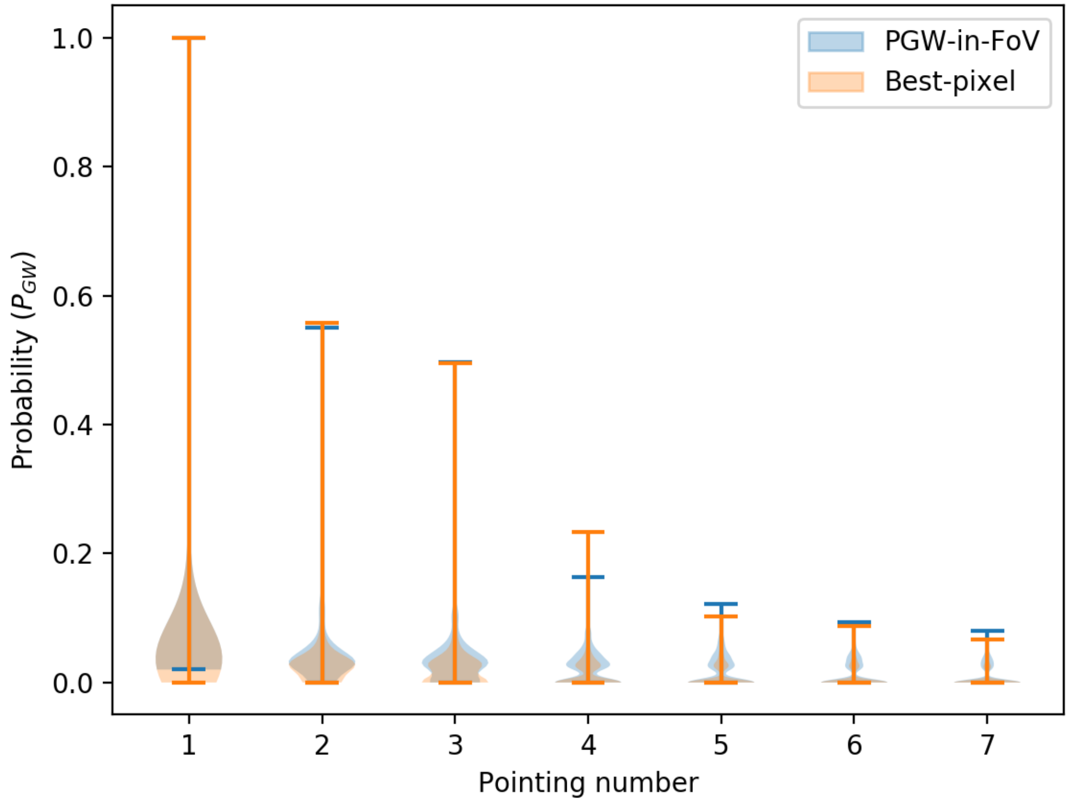
Prospects

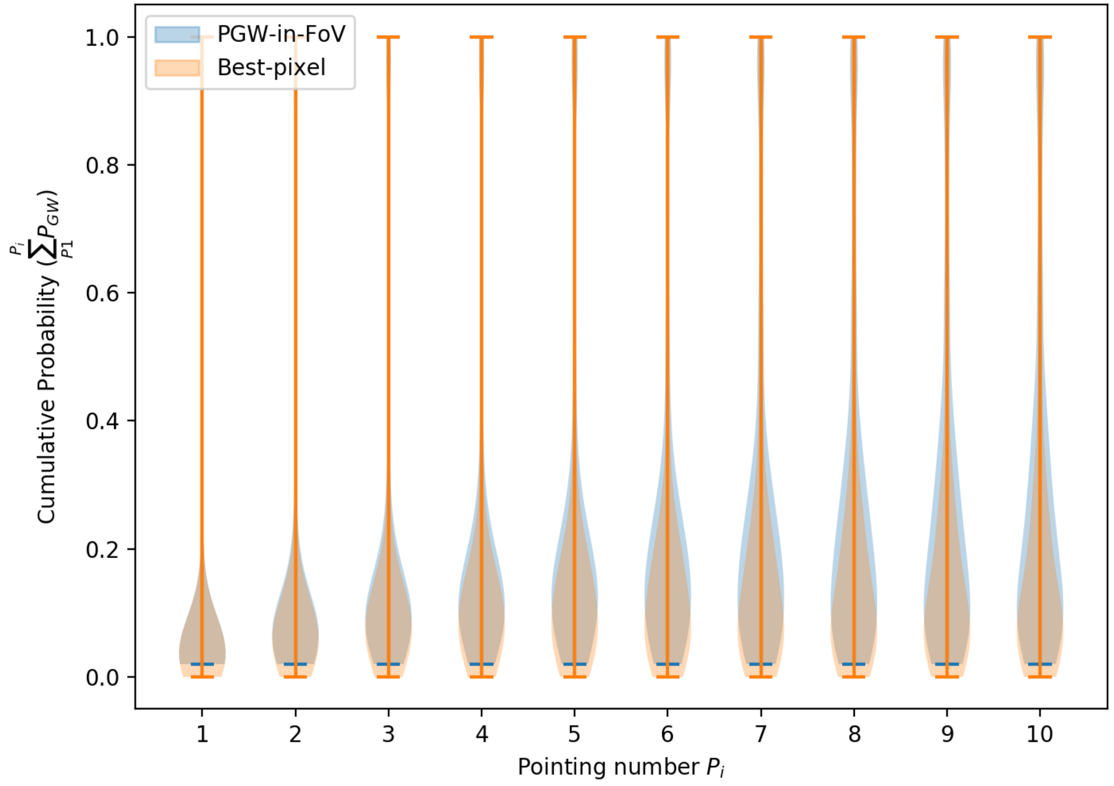
- Future improvements: Correlating Burst event with Galactic plane potential sources.
- Schedule observations with **n** telescopes/sites.
- Implementing 2 x 3D scheduling.
- GW follow-up analysis results in upcoming publication: H.E.S.S. collaboration et al. (in preparation).

- These tools are tested and approved: **https://arxiv.org/abs/1906.10426**

Backup

PGWinFoV vs BestPix





GW offline scheduler – testing pipeline

Launching scripts

Input:
- GW map
- Time (default now)
- Gal catalog (default GLADE)
- Configuration file
- Previously observed cords (opt)

Config

- FoV
- Max zenith angle
- Obs duration standard
- Min obs duration
- Location
- Zenith angle weight
- Use moon time (T/F)
- MANGROVE (T/F)
- Other…

Includes

Scheduler:
Parse config files
Read GW map and gal cat
Subtract observed positions
Obs windows
Coordinate grid
Correlation Gal X GW
Loop over window:
- Visibility
- zenith angle opt
- Best position
- PGW and Pgal
- Subtraction

Visibility windows
Priority
Visual aids

Tools:
Classes
Functions

Tools

MWL visualization
Schedule comparison

Output

Schedule + Windows + priority
Visual aids