tilepy: rapid tiling strategies in mid/small FoV observatories

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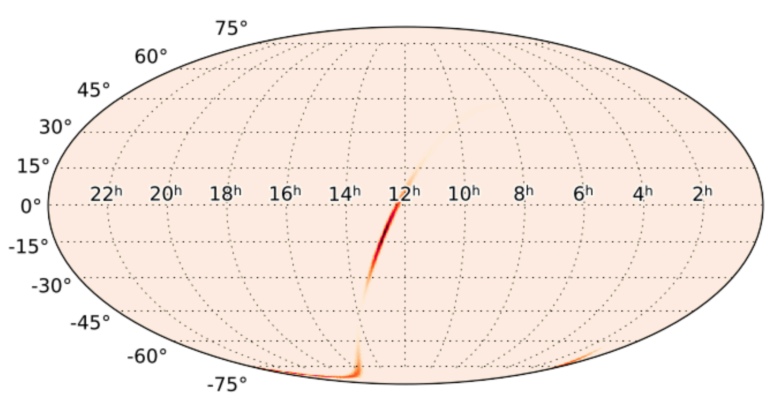
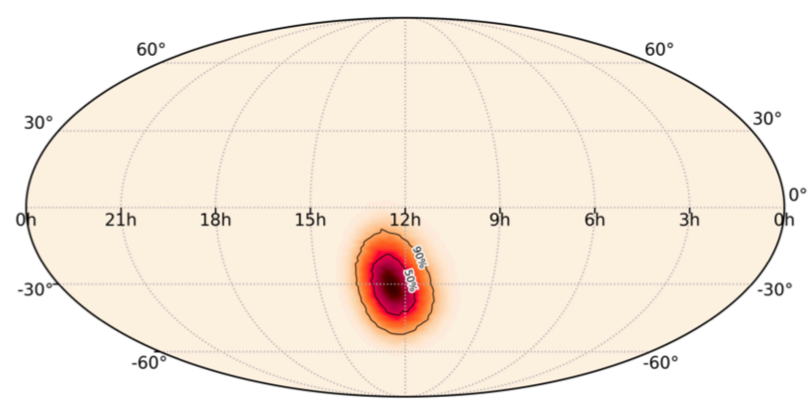
Science cases with *large uncertainty in the localisation*

- The localisation of various multi-messenger events presents very large uncertainties
- Range goes from from tens to thousands of squared degrees
- Examples are: Fermi-GBM gamma-ray bursts, LVK gravitational waves, cascade IceCube neutrinos



GW170817 (LH)



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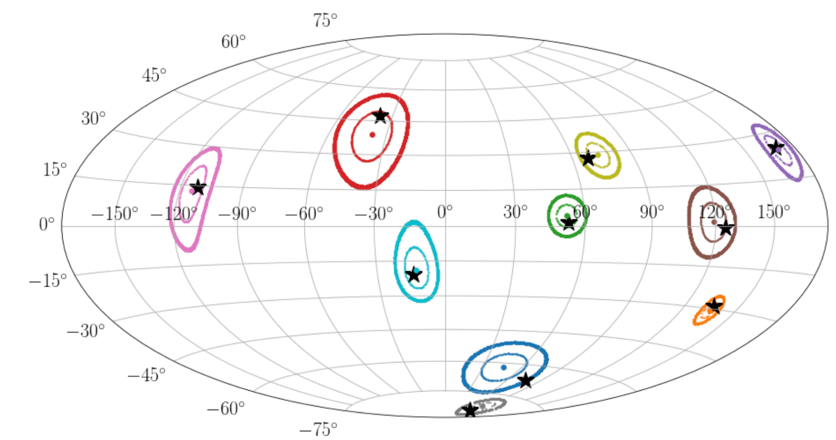


Cascade <u>simulated events</u>

- For mid/small-size telescope, this is a big challenge ➡ **Observation strategies**

tilepy

- Set of python algorithms providing an observation scheduler, in a fairly complex scenario
- Originally developed for the followup of gravitational waves with very high energy Cherenkov telescopes (H.E.S.S. experiment)

Characteristics of the event →

Characteristics of the telescope →

tilepy

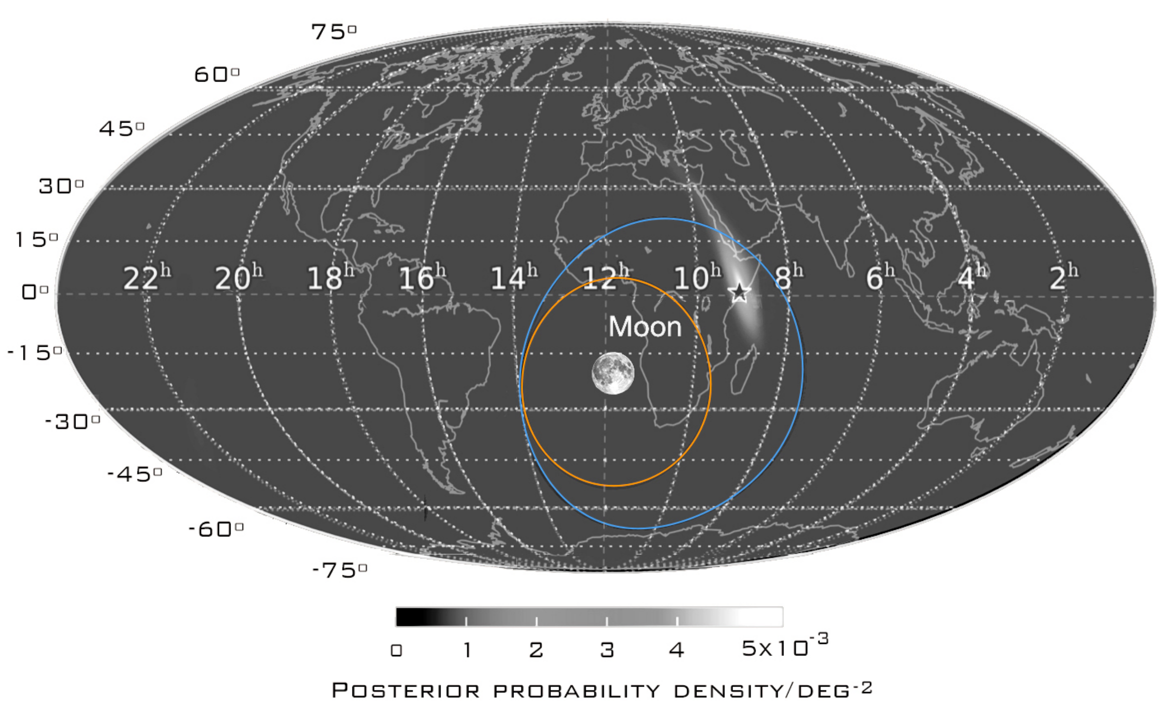
- Visibility conditions function: darkness and moonlight observations and airmass considerations
- Probability computation functions
- Plotting functions to display results

→ Schedule for the night

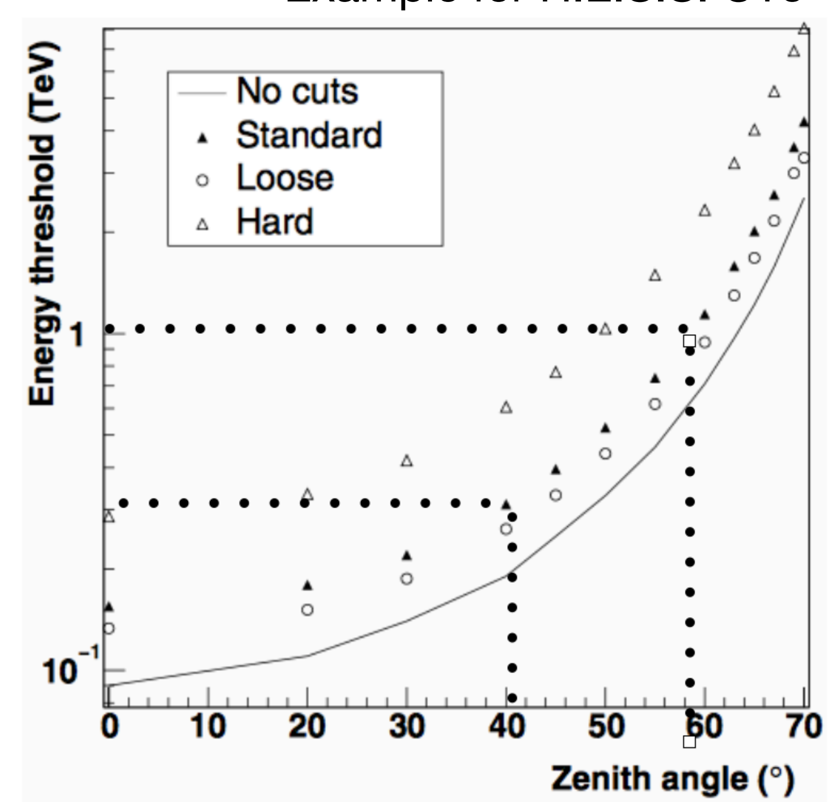
Ashkar, H., SA, M., et al., (2020). The HESS Gravitational Wave Rapid Follow-up Program. JCAP2021, 2021.03: 045
SA, M., Schüssler, F. Moriond VHEPU 2017, PoS 167-174.

Observation constraints

- The consideration of the observation constraints of the telescope is needed to schedule observations
- Main constraints come from the Sun and the Moon
  - Example: astronomical darkness, observations with moon (extra requirement to parametrise the separations skymap-moon, moon phase..)
- Effects of the atmosphere.
  - Examples: dependency of the energy threshold with the zenith angle of the showers, airmass for optical telescopes



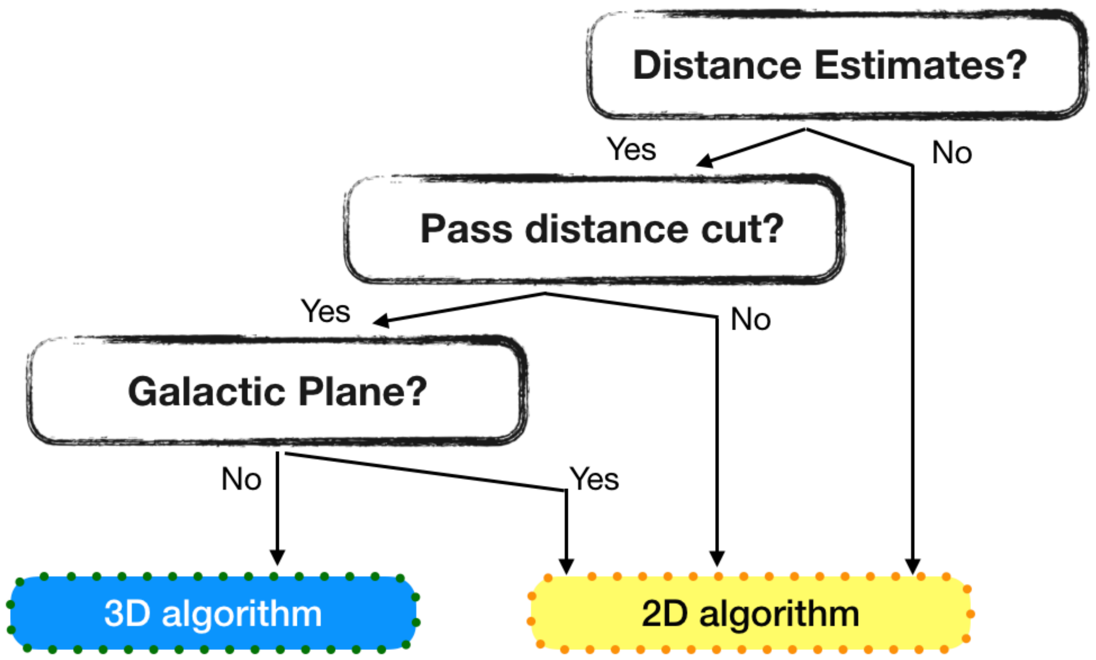
Example for H.E.S.S. CT5



Algorithm selection depending on the use case

- The selected algorithm will depend on:
  - Science case
  - Characteristics of the instrument

- Two main classes:
  - 2D algorithms use 2D probability distribution of the localisation
  - 3D algorithms use galaxy catalogs to associate a probability of a galaxy to be the host of the event



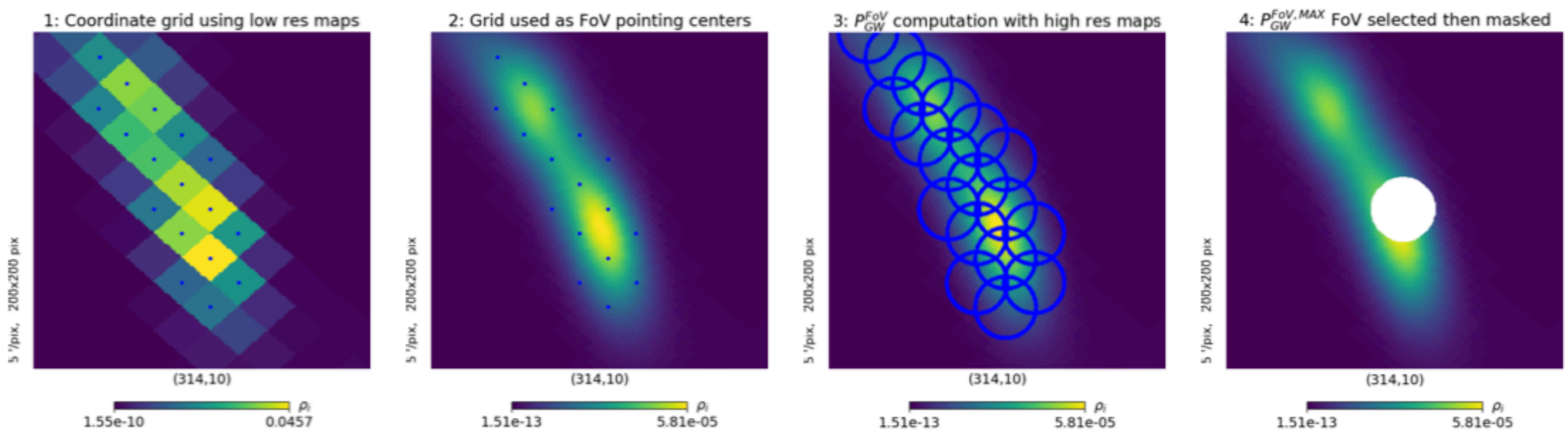
- Use of information from a galaxy catalog to obtained a weighted probability per galaxy of hosting the event.
  - Parameters to use: stellar mass, BNS merger rate, B-luminosity, K- luminosity…

- Depending on the telescope FoV: galaxy-targeted strategy or FoV-integrated probability

Ashkar, H., SA, M., et al., (2020). The HESS Gravitational Wave Rapid Follow-up Program. JCAP2021, 2021.03: 045

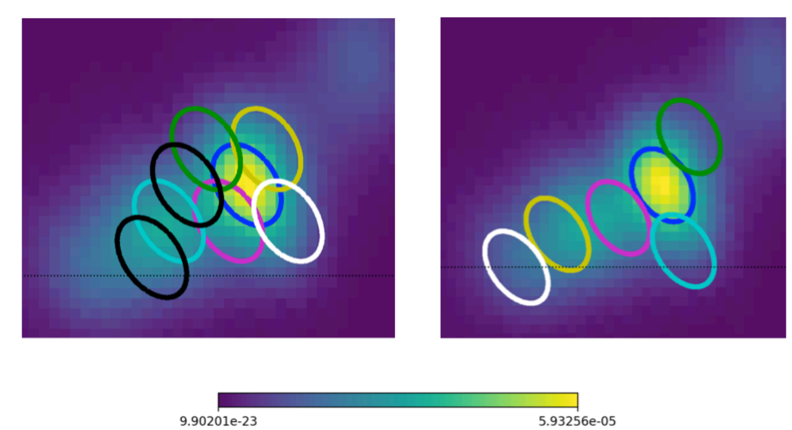
Probability Selection Algorithms

- Definition of probabilities:
  - 2D Algorithms: 2D localisation uncertainty region of GW sky map



<u>Optimisation in the skymap treatment:</u>

- Parallel use of a high-resolution and a low-resolution skymap
- Coverage optimisation by masking observed regions



Ashkar, H., MSA, et al., (2020). The HESS Gravitational Wave Rapid Follow-up Program. JCAP2021, 2021.03: 045

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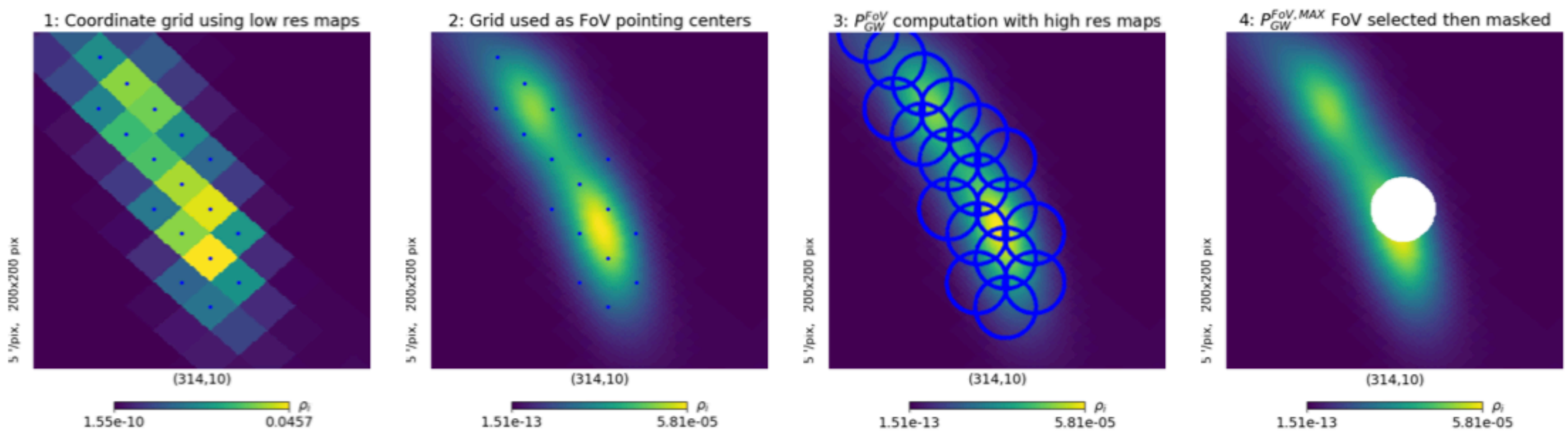
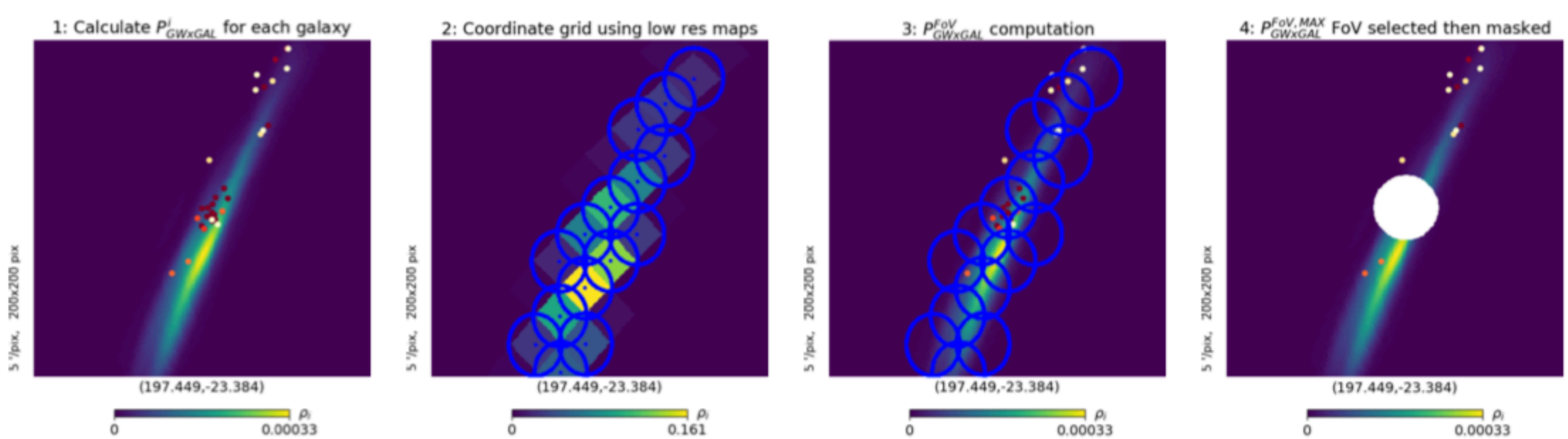


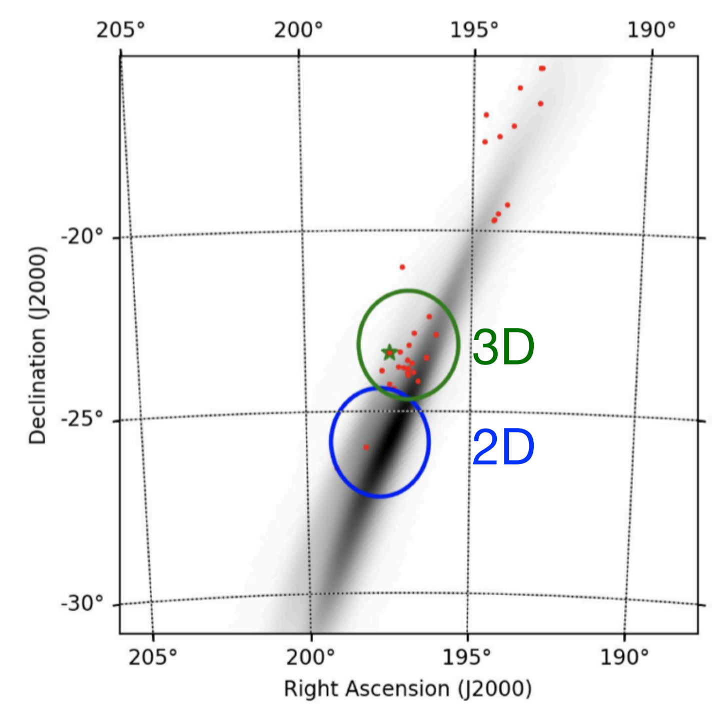
  - 3D Algorithms: obtain 3D posterior ‘GW x galaxy’ probability distribution using GW skymap and galaxy catalogs (e.g. GLADE+)



Where can you find tilepy

- A good schedule strategy will make the difference.
- Tilepy is currently being used in H.E.S.S., LST and CTA-C
- Early release is available in Github: **astro-transients/tilepy**
- API: **tilepy.com**. Cloud-based computing of GW follow-up schedules using tilepy is provided by the Astro-COLIBRI platform.
- User interface via **astro-colibri.science** now available!

GW170817 with tilepy

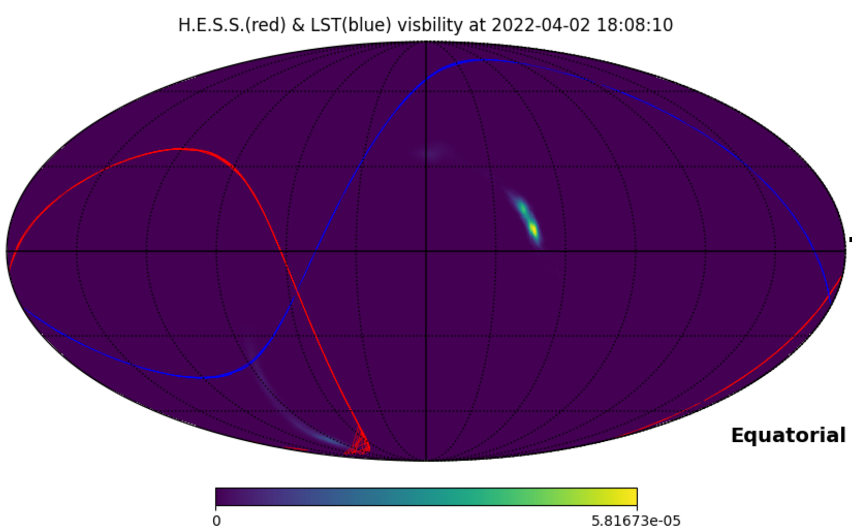


Ashkar, H., SA, M., et al., (2020). JCAP2021, 2021.03: 045

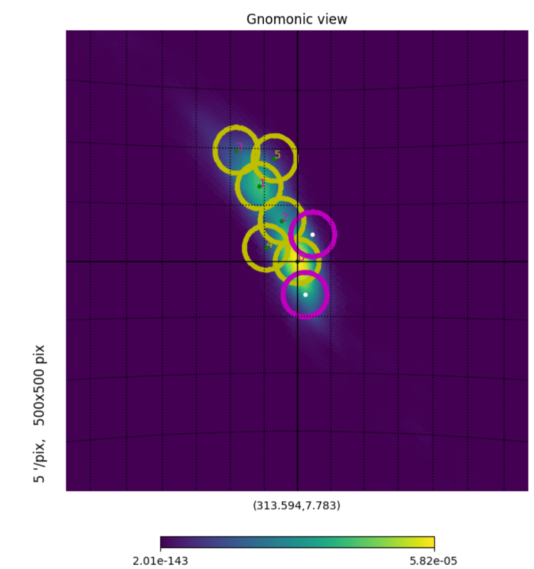
Reichherzer et al. ApJS (2021)

The future: Generalising the methods

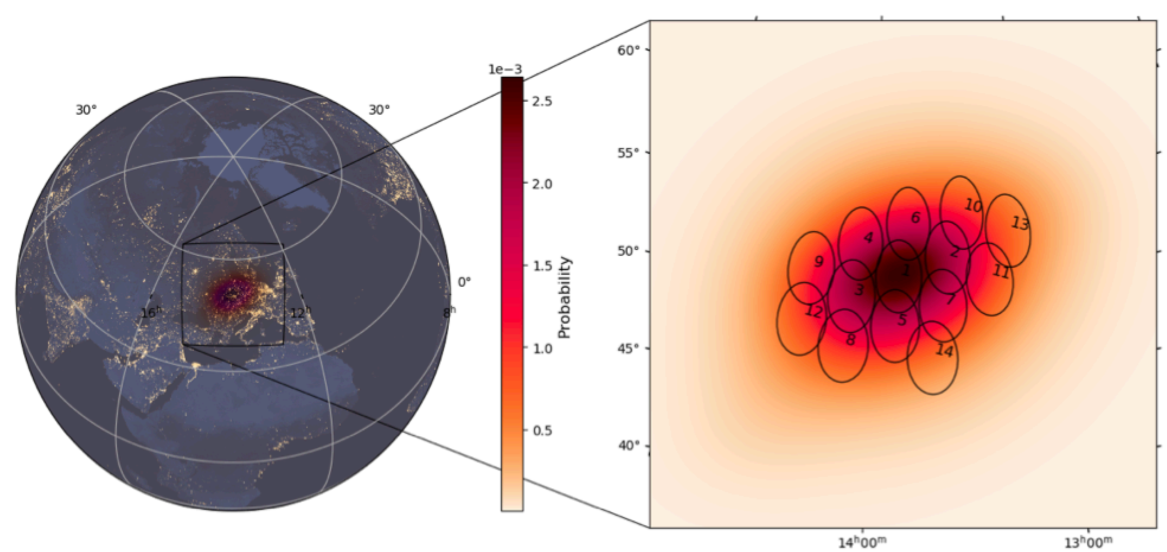
- Generalisation to N-small/mid FoV observatories
  - Number of observatories: 2 observatories that follow-up the same event already included
  - Type of observatory




```
"Observation Time UTC" RA(deg) DEC(deg) PGW Round ObsName
"2022-04-02 18:08:07.080256" 96.4286 -74.6034 0.0405 1 'Hess'
"2022-04-02 18:38:07.080256" 98.6538 -70.9067 0.0233 1 'Hess'
"2022-04-03 02:29:34.942246" 313.5938 7.7827 0.1485 1 'North'
"2022-04-03 02:29:34.942246" 317.1094 14.4775 0.1063 1 'North'
"2022-04-03 02:38:07.080256" 312.8906 4.7802 0.0684 1 'Hess'
"2022-04-03 02:59:34.942246" 315.0 11.4152 0.0895 1 'North'
"2022-04-03 02:59:34.942246" 319.2188 17.5828 0.0505 1 'North'
"2022-04-03 03:08:07.080256" 312.1875 10.1999 0.0251 1 'Hess'
"2022-04-03 03:29:34.942246" 316.4062 8.9893 0.0223 1 'North'
"2022-04-03 03:29:34.942246" 315.7031 16.9578 0.0208 1 'North'
```



- Other science cases:
  - Fermi-GBM GRB follow-up observations: 2D treatment of the uncertainty regions
  - IceCube neutrinos in the near future!



Carosi, A., SA, M. et al., ICRC2021, PoS838, 2021

Thanks for your attention!

Back up

Uncertainty regions: GW sky maps and galaxy catalogs

- 3D GW sky maps: posterior probability distribution
  - Gaussian likelihood and a uniform-in-volume prior

$$p(r|\mathbf{n}) = \frac{\hat{N}(\mathbf{n})}{\sqrt{2\pi}\hat{\sigma}(\mathbf{n})}\exp\left[-\frac{(r-\hat{\mu}(\mathbf{n}))^2}{2\hat{\sigma}(\mathbf{n})^2}\right]r^2$$

$$\frac{dP}{dV} = \rho_i \frac{N_{pix}}{4\pi}\frac{\hat{N}_i}{\sqrt{2\pi}\hat{\sigma}_i}\exp\left[-\frac{(r-\hat{\mu}_i)^2}{2\hat{\sigma}_i^2}\right]$$

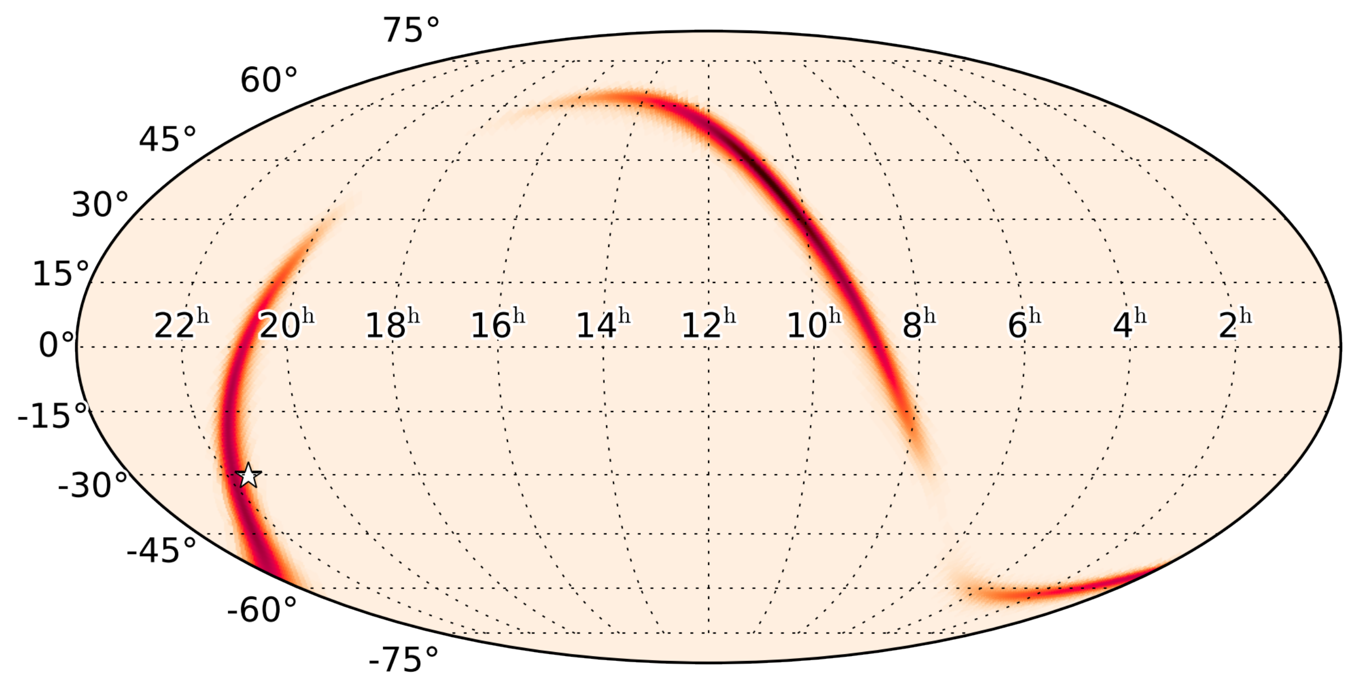
$\hat{\mu}_i$: mean

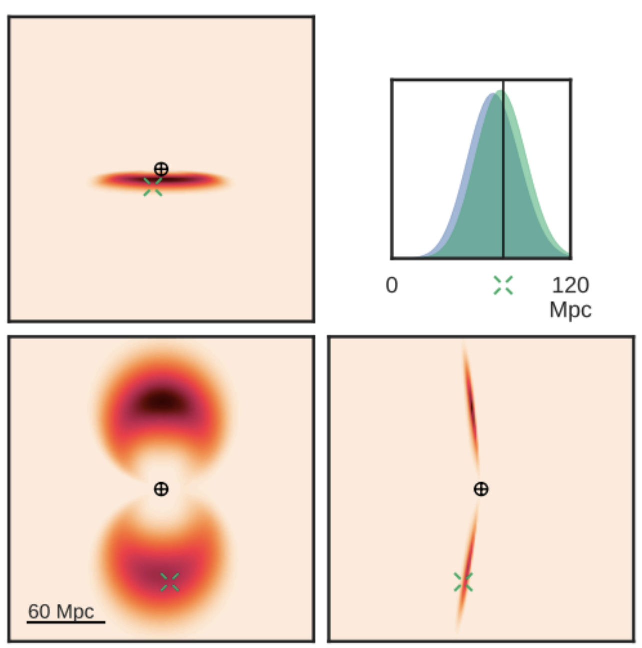
$\hat{\sigma}_i$: scale

$\hat{N}_i$: normalization

Singer, LP., et al., *APJ Letters* 829.1 (2016): L15 arXiv: 1603.07333

- Combine the posterior probability distribution with the local distribution of sources (r)





=> We have a probability per pixel $\rho(r,\phi)$ and we can obtain a probability of the galaxy to host the event $P^i_{GW\times GAL}$