tilepy: rapid tiling strategies in mid/small FoV observatories

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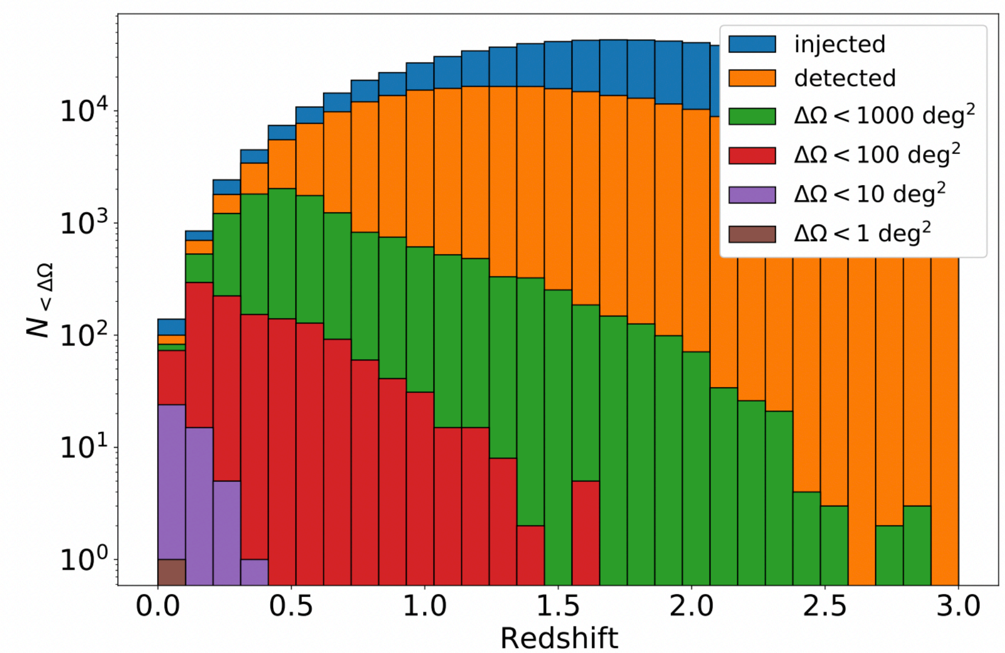
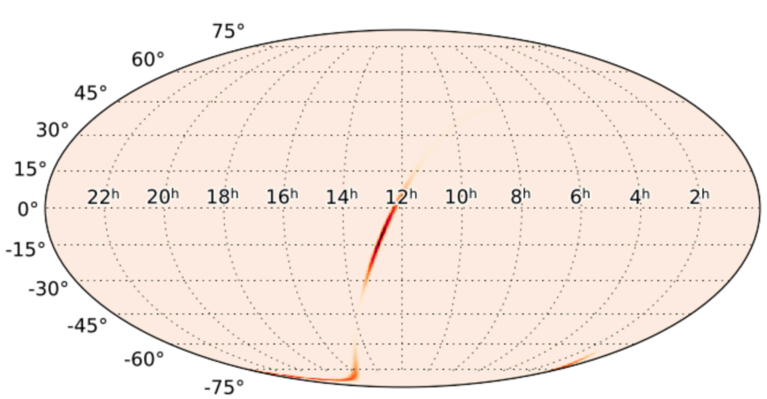
Science cases which are poorly localized

- The localisation of various multi-messenger events presents very large uncertainties
  - From tens to thousands of squared degrees!
- Although some localisation will get better, others will not!
- Examples: Fermi-GBM gamma-ray bursts, LVK gravitational waves, cascade IceCube neutrinos

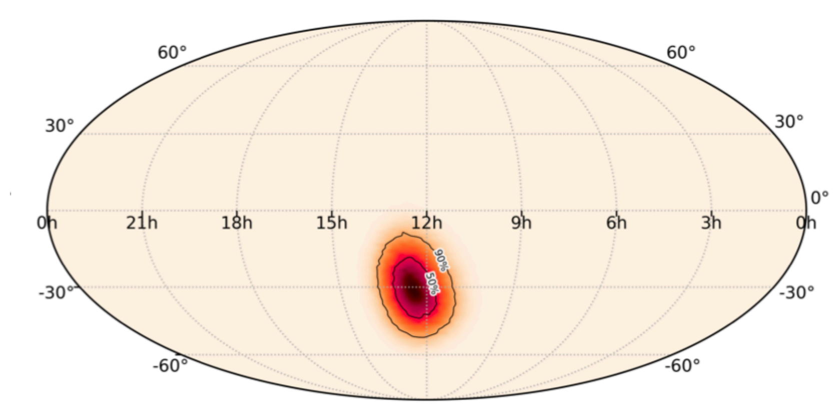
Branchesi et al JCAP07(2023)068

sky-localization (90% C,R.) of randomly oriented BNS systems by ET





GW170817 (LH)



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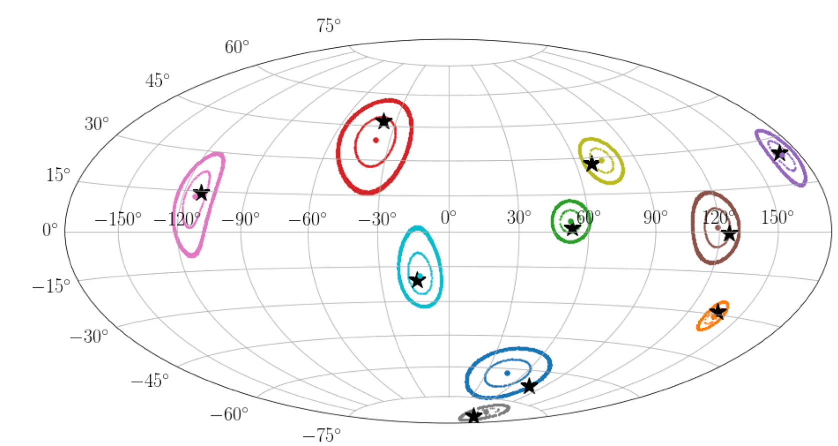
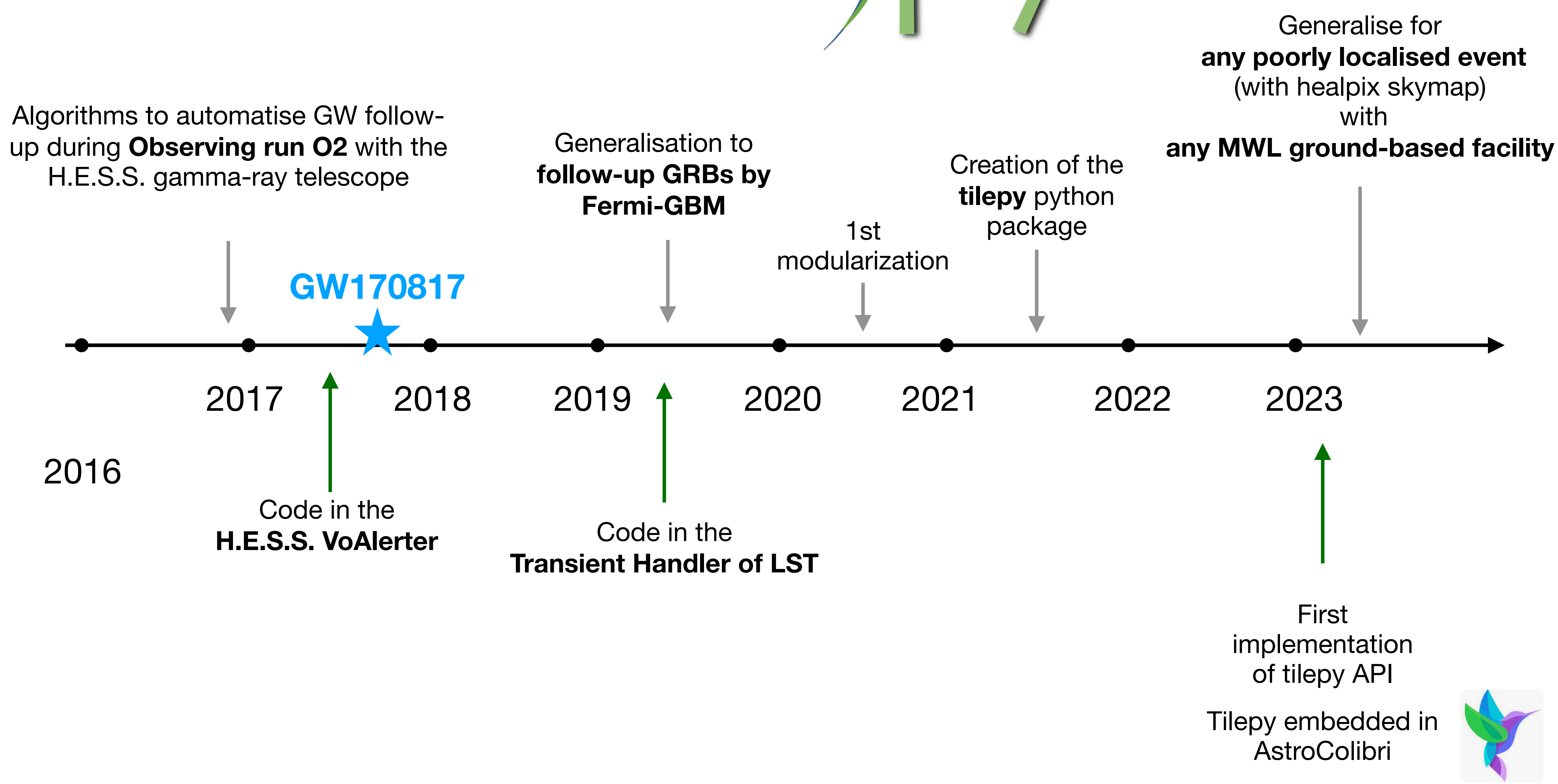


Cascade <u>simulated events</u>

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

The history of tilepy



Schussler, F. , MSA et al., (2023). ICRC 2023

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

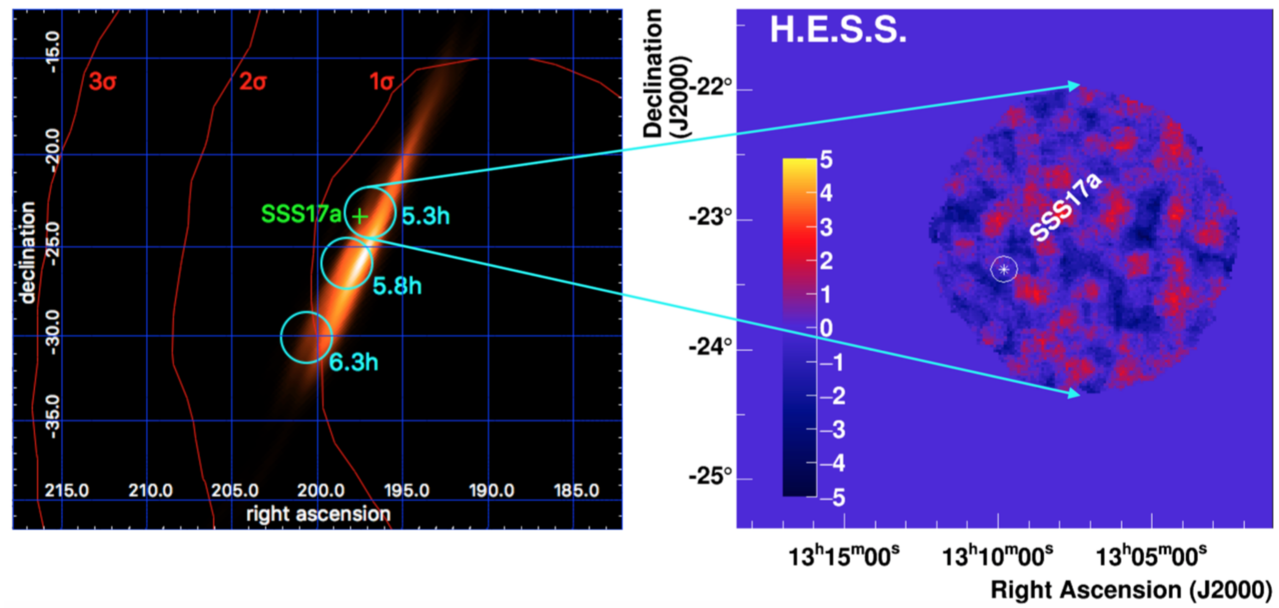
MSA, Schüssler, F. Moriond VHEPU 2017, PoS 167-174.

(Some) past scheduled observations with tilepy

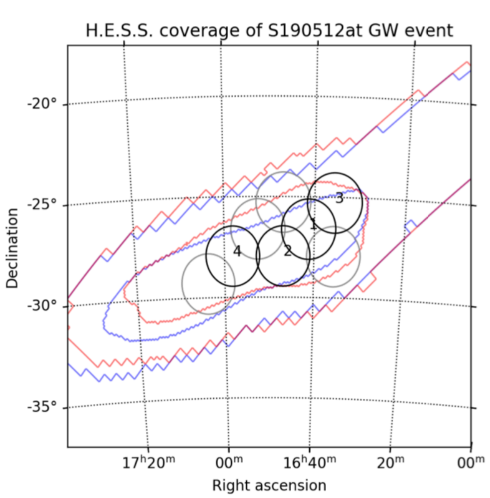
- Automatic response with scheduling algorithms which maximise the total probability covered with observations (use of galaxy catalogs)

- H.E.S.S. followup of observing run O2 :

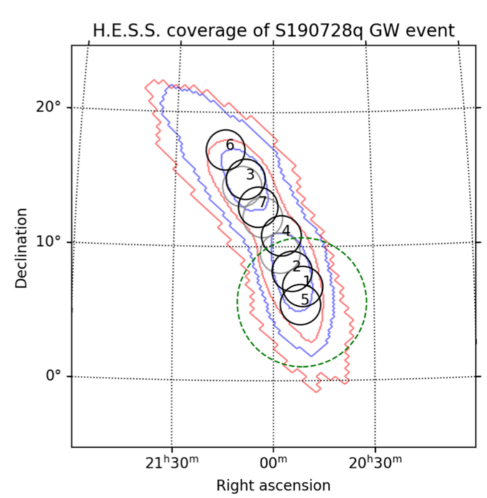
Abdalla, H, MSA, et al., The Astrophysical Journal Letters, 850(2), L22



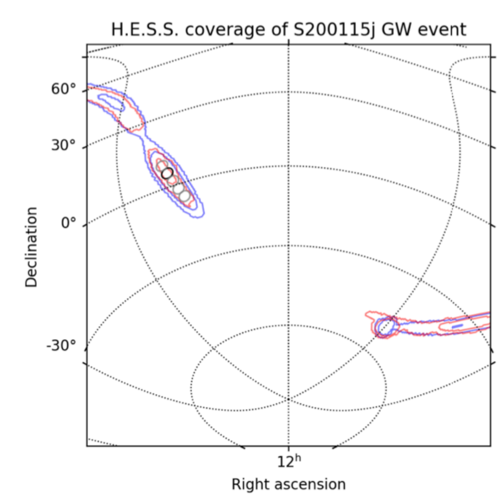
- H.E.S.S. followup of observing run O3



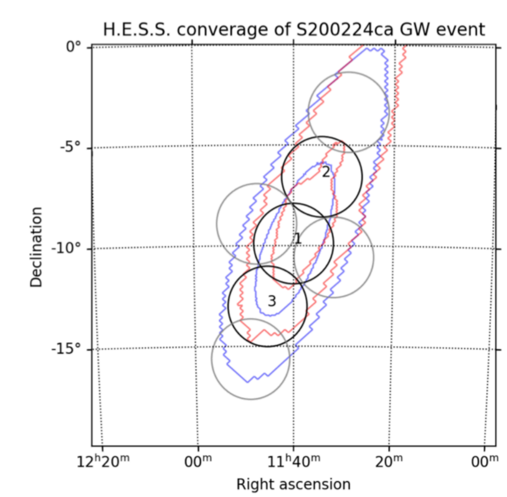
$P_{covered} \sim 21\%$



$P_{covered} \sim 64\%$



$P_{covered} \sim 25\%$



$P_{covered} \sim 70\%$

Ashkar, H., MSA et al., (2020), JCAP, 2021.03 (2021): 045.

tilepy

The architecture

- Modular, flexible python package to schedule observations of large sky regions from a localisation probability density sky map
- Multi-observatory, multi-telescope, multi-wavelength

Inputs

- Characteristics of the event
- Coordinates and main characteristics of the telescope

Favouritetelescope.cfg

Healpix skymap

Time

Core functions

Three stage architecture

ObservationScheduling.py

- Parsing and strategy selection

↓

TilingDetermination.py

- Effectively obtain tiles

↓

PointingTools.py

- Visibility conditions
- Probability computation
- Display results

Extra tools

RankingObservations.py

PointingPlotting.py

↓

Schedule for the night

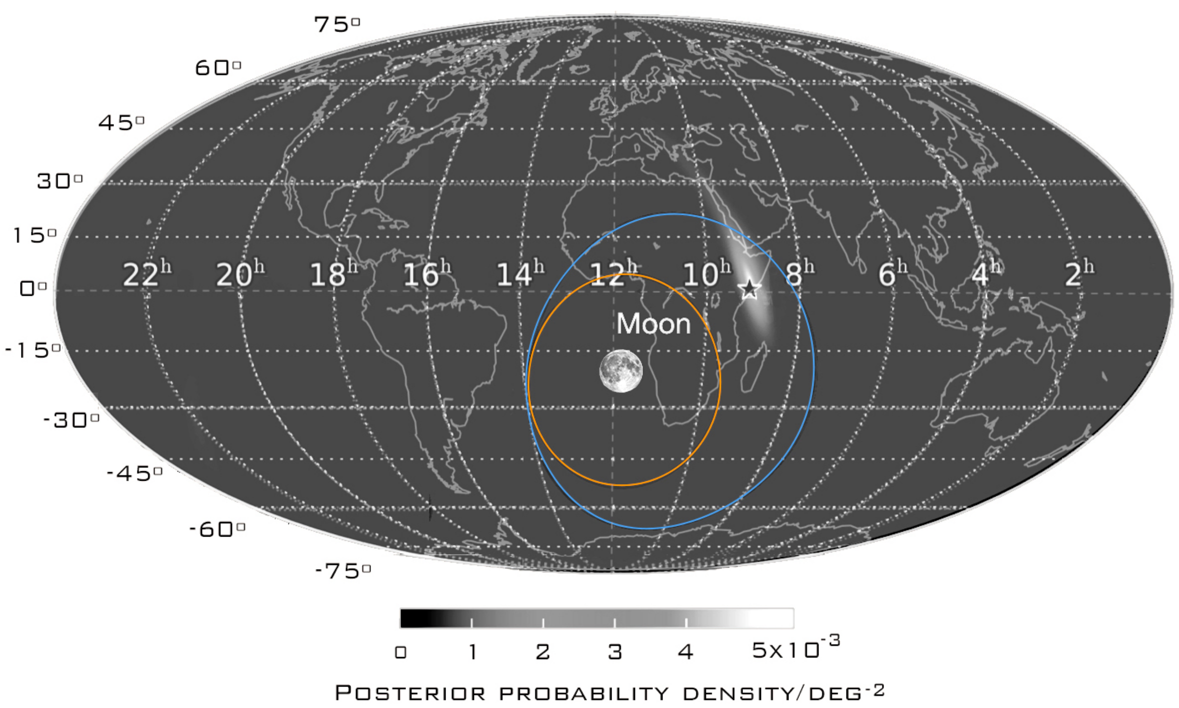
Observation constraints

- The consideration of the observation constraints of the telescope is used to schedule observations

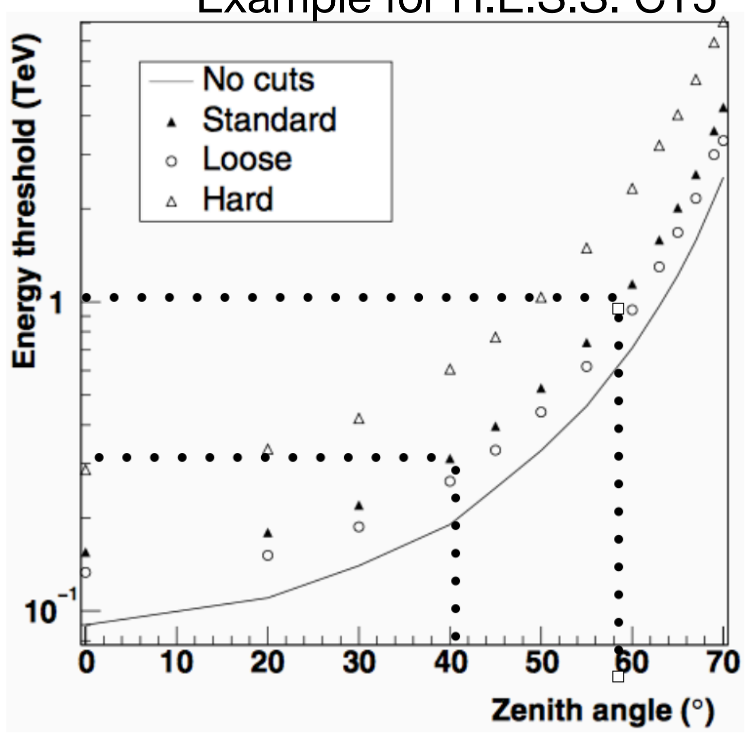
- The code supports **any type of observations contraints** (**daytime**, **moontime**, **darktime**)

  - Evolution of the Sun and the Moon (astronomical darkness, observations with moon (extra requirement to parametrise the separations skymap-moon, moon phase..)

- Optimisation to compensate for atmosphere effects
  - Examples: dependency of the energy threshold with the zenith angle of the showers, airmass for optical telescopes



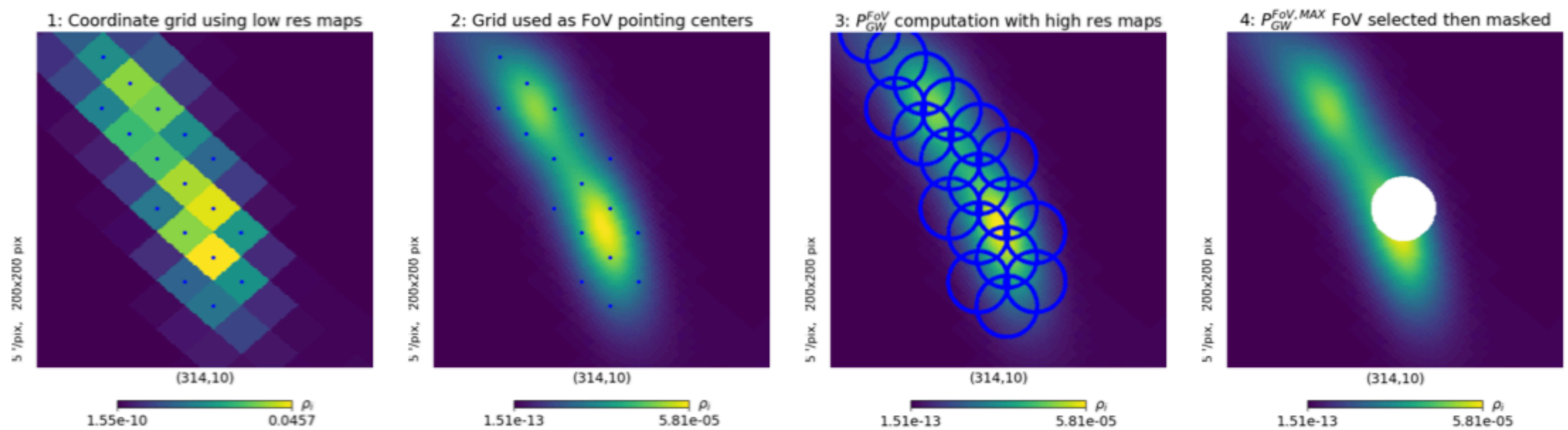
Example for H.E.S.S. CT5



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

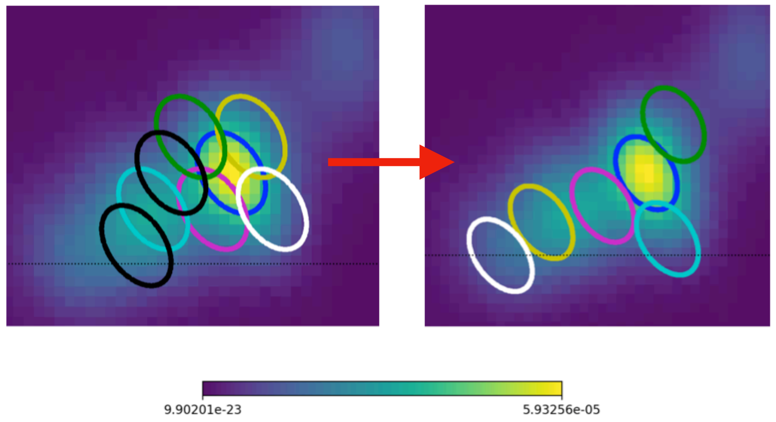
Probability Selection Algorithms

- **2D Algorithms:** from the probability distribution of the localisation



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

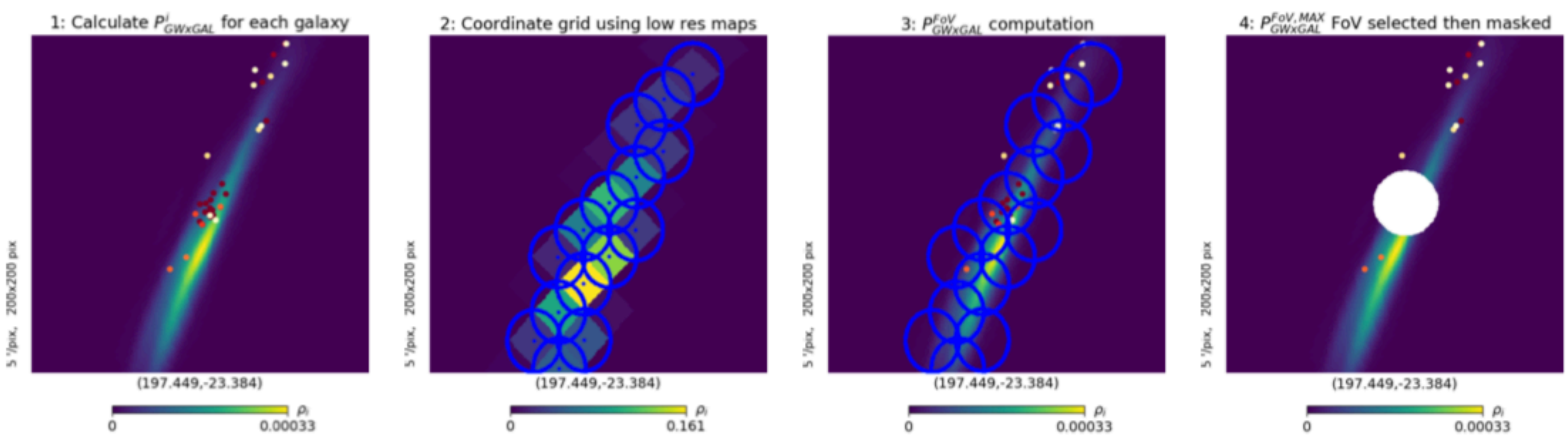
- Parallel use of a high-resolution and a low-resolution skymap
- Coverage optimisation by masking observed regions



Probability Selection Algorithms

- **3D Algorithms**: obtain 3D posterior 'probability x galaxy' distribution.
  - Most common example: GW skymap and galaxy catalogs (e.g. GLADE+)

  Two possibilities:
  - Use coordinates of the galaxies as coordinates of a grid
  - Use center of pixels as coordinates of a grid



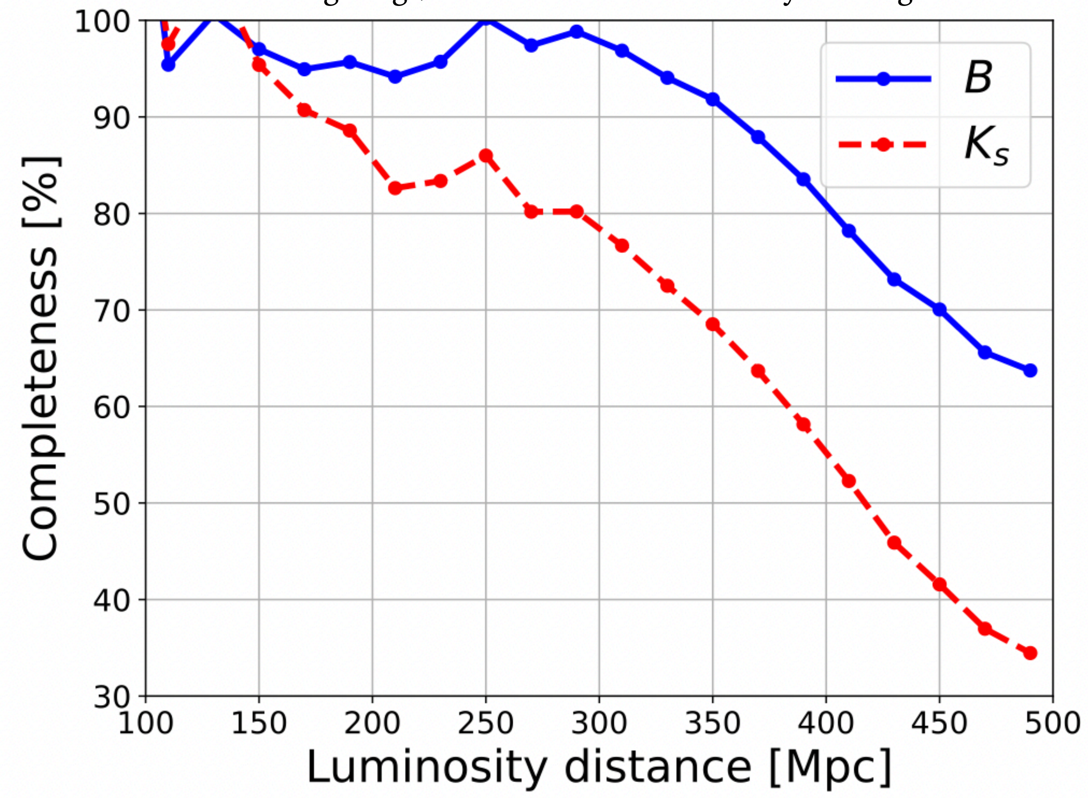
Types:
- **Galaxy targeted search** (small-FoV observatories): selection based on the largest galaxy
- ***Galaxy clustering* search** (mid-FoV observatories): integration of the probability in the FoV

Glade+ galaxy catalog

- Glade+ catalog (from PIC/CosmoHub): ~23 million of object
  - GWGC, 2MPZ, 2MASS XSC, HyperLEDA, WISExSCOSPZ, SDSS-DR16Q quasar catalog
- Completeness of the catalog.
  - Complete up to a luminosity distance of ~44 Mpc in terms of the cumulative B-band luminosity of galaxies, and contains all of the brightest galaxies giving half of the total B-band luminosity up to ~95 Mpc.

- Effective cut on the distance to 500 Mpc ~4 million galaxies
- **In GW follow-ups:**
  - **Distance cut to use the galaxy catalog defined as luminosity distance+2 standard deviation.**
  - Definition of a galactic plane region: the galaxy catalog is not used

*compared to Schechter functions for the galaxies giving 90% of the total luminosity in the given band



https://glade.elte.hu
https://cosmohub.pic.es/catalogs/305

Extra functionalities

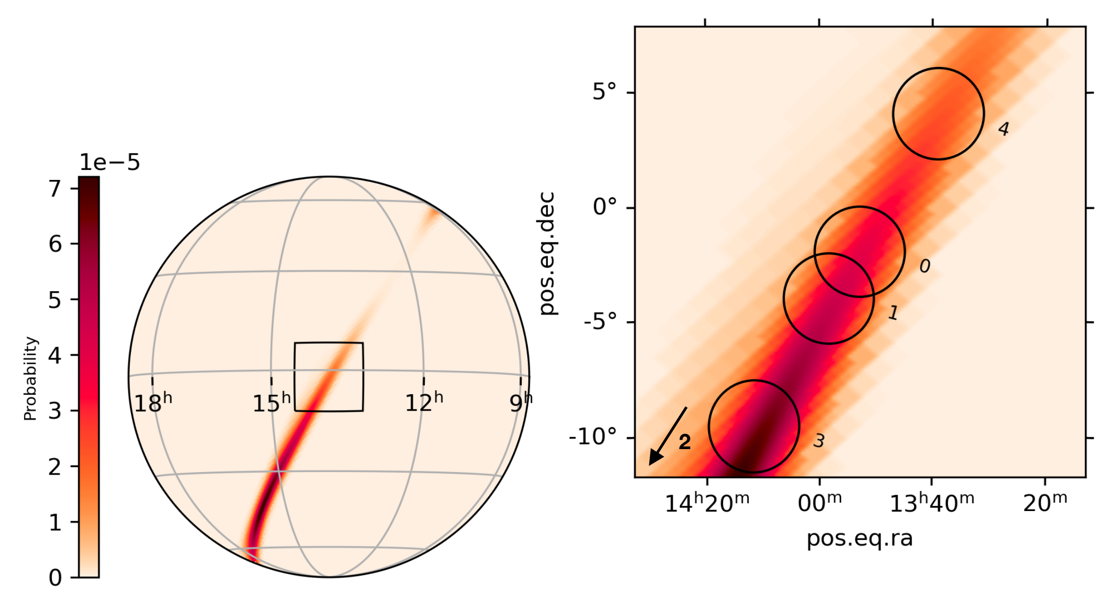
- **Physically-motivated weighting** using galaxy mass (BNS merger rate *ongoing*)
  - à la *mangrove* J-G Ducoin, *MNRAS*, 492,4, 2020, 4768–4779

- **Second round.** Once a large region of the localisation is scanned, option to restart scanning that zone back again
  - Specially in *well-localized* events where the probability density profile is steep.

- **Subtraction of the previous observation**, via an input file.
  - Observed regions are masked.
  - Allows to perform pointings of events from which we expect updated localisation (GW, GRB Fermi-GBM Ground/Final)

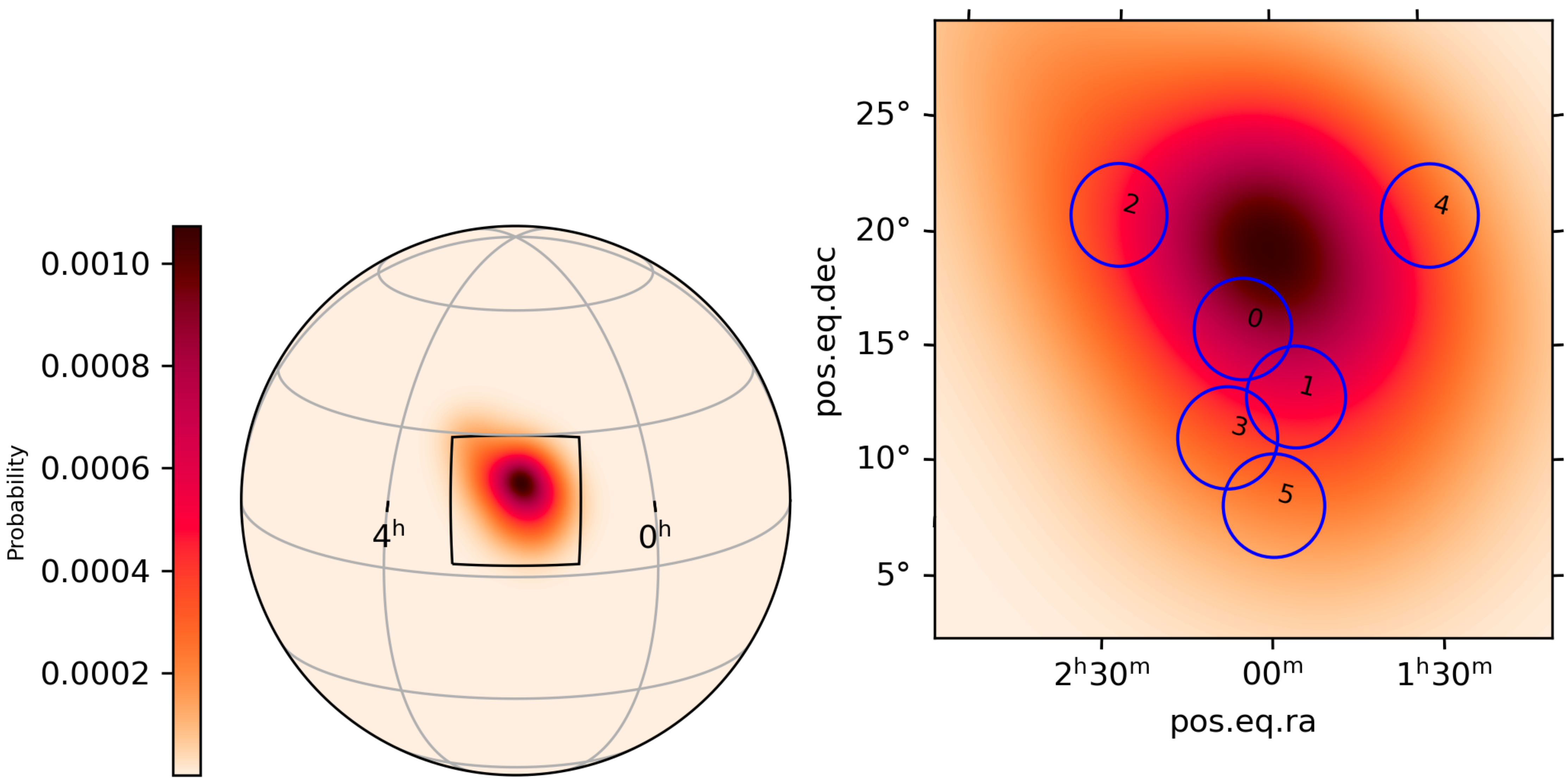
- **Ranking of observations:** the ordering at the beginning of observation campaign *might not be* the ones decided at the middle of the observation campaign
  - A way to account for the evolution of the accessible sky
  - Need to account for overlapping regions

Due to visibility evolution: 0-1-2-3-4-5
The real priority : 2-3-1-0-4



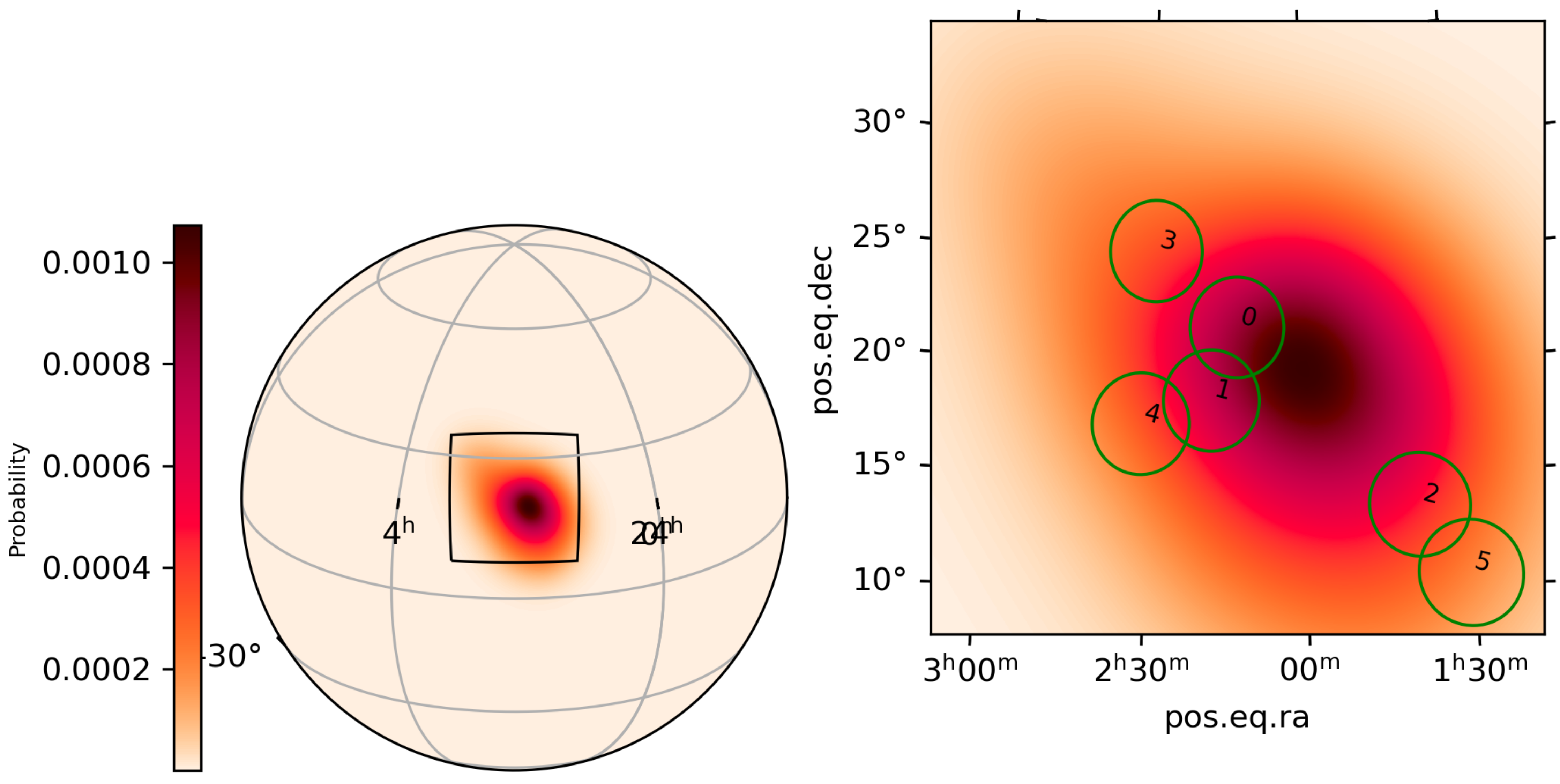
Multi-telescope coverage

- Four CTA/LST-telescope strategy tiling independently a Fermi-GBM alert
    - 1st LST (exposure=20m, FoVradius= 2.3deg, zenith cut = 70)



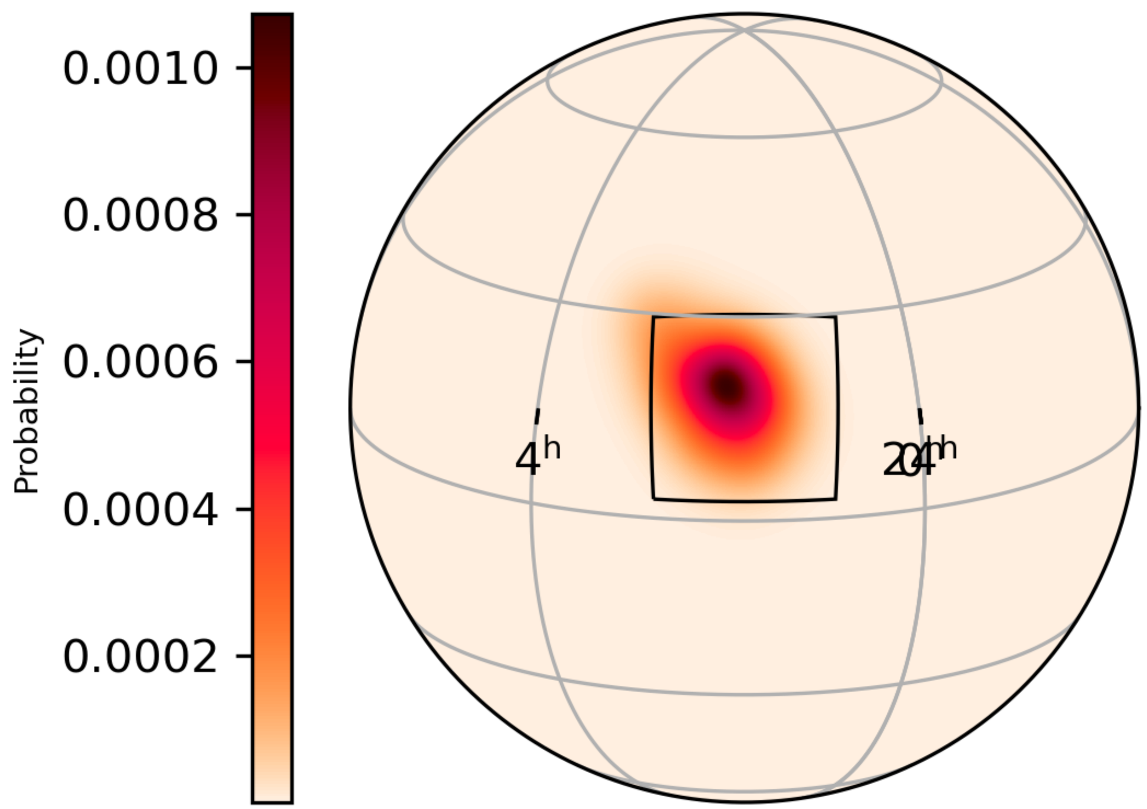
Multi-telescope coverage

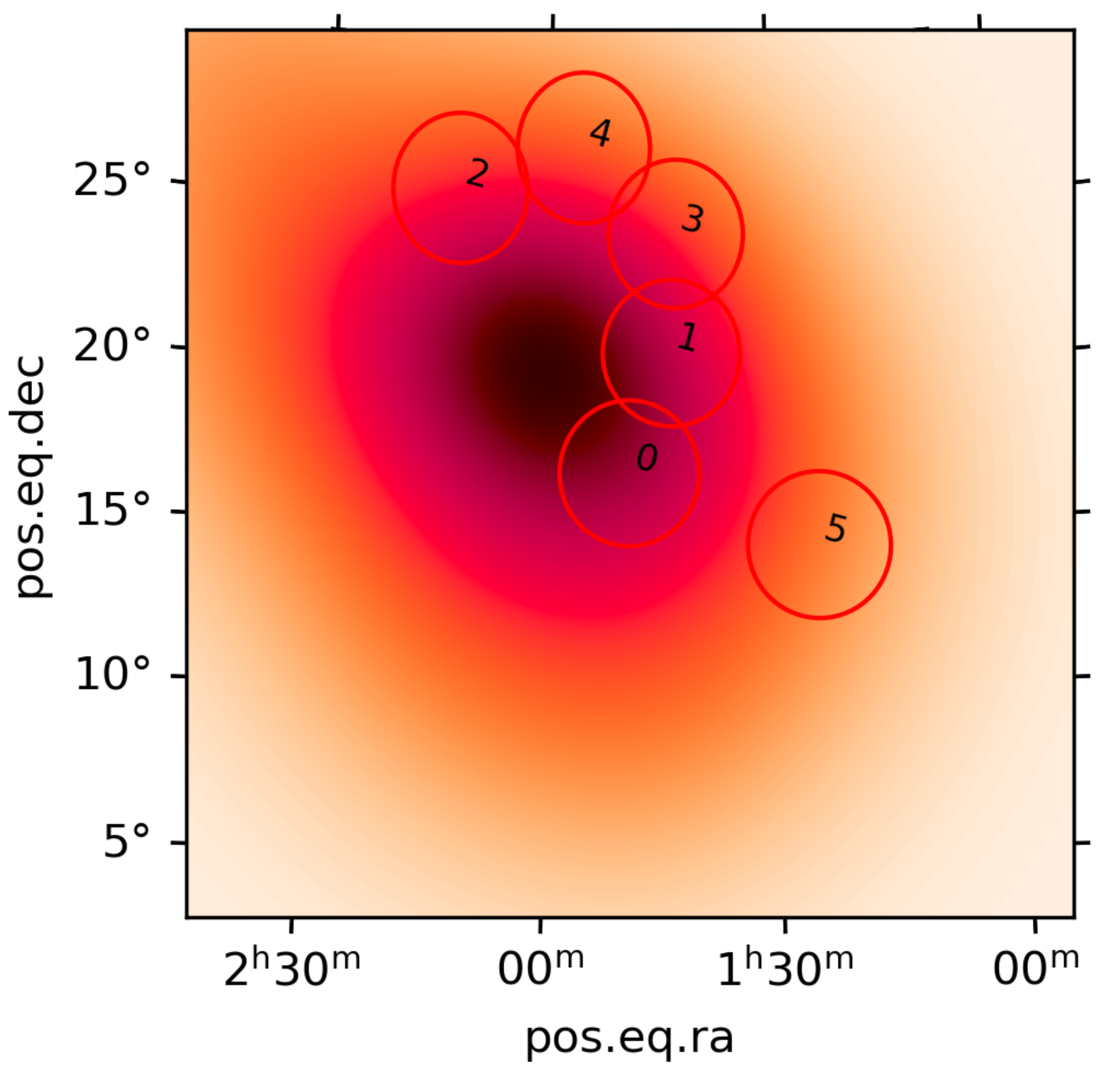
- Four CTA/LST-telescope strategy tiling independently a Fermi-GBM alert
  - 2nd LST (exposure=20m, FoVradius= 2.3deg, zenith cut = 70)



Multi-telescope coverage

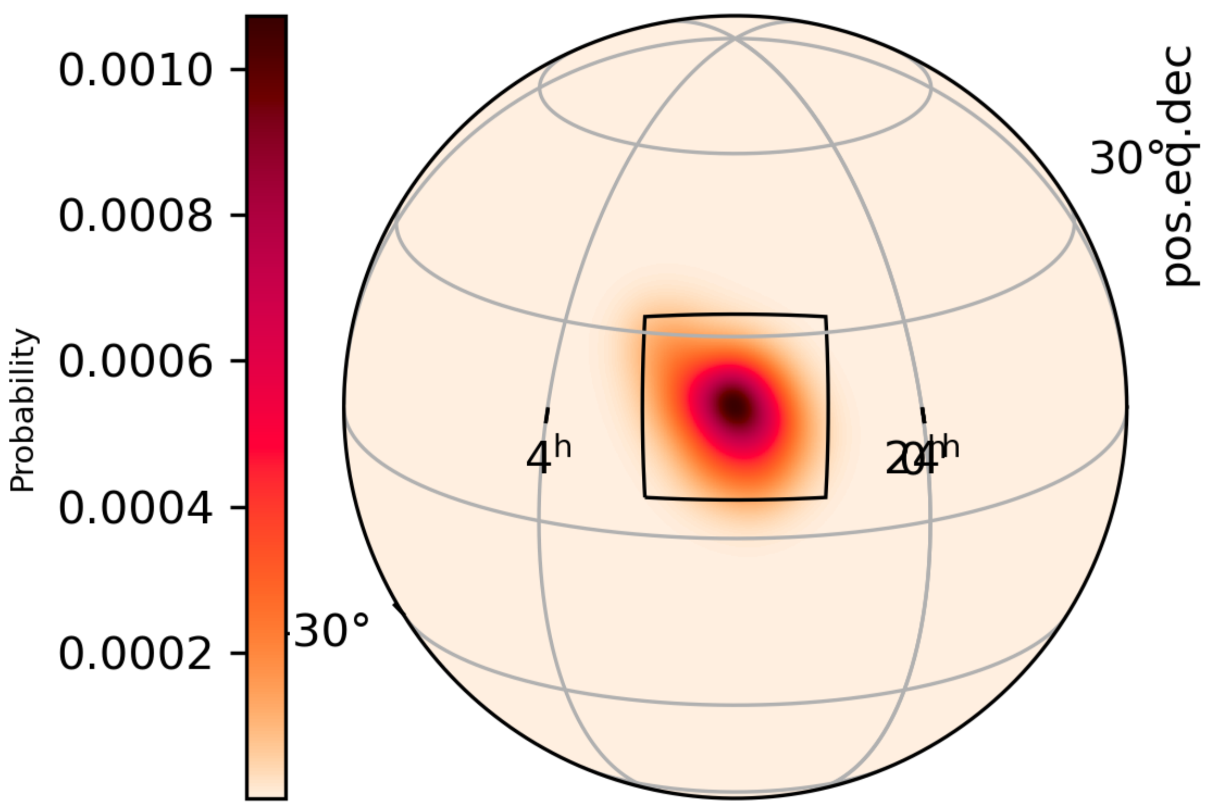
- Four CTA/LST-telescope strategy tiling independently a Fermi-GBM alert
  - 3rd LST (exposure=20m, FoVradius= 2.3deg, zenith cut = 70)

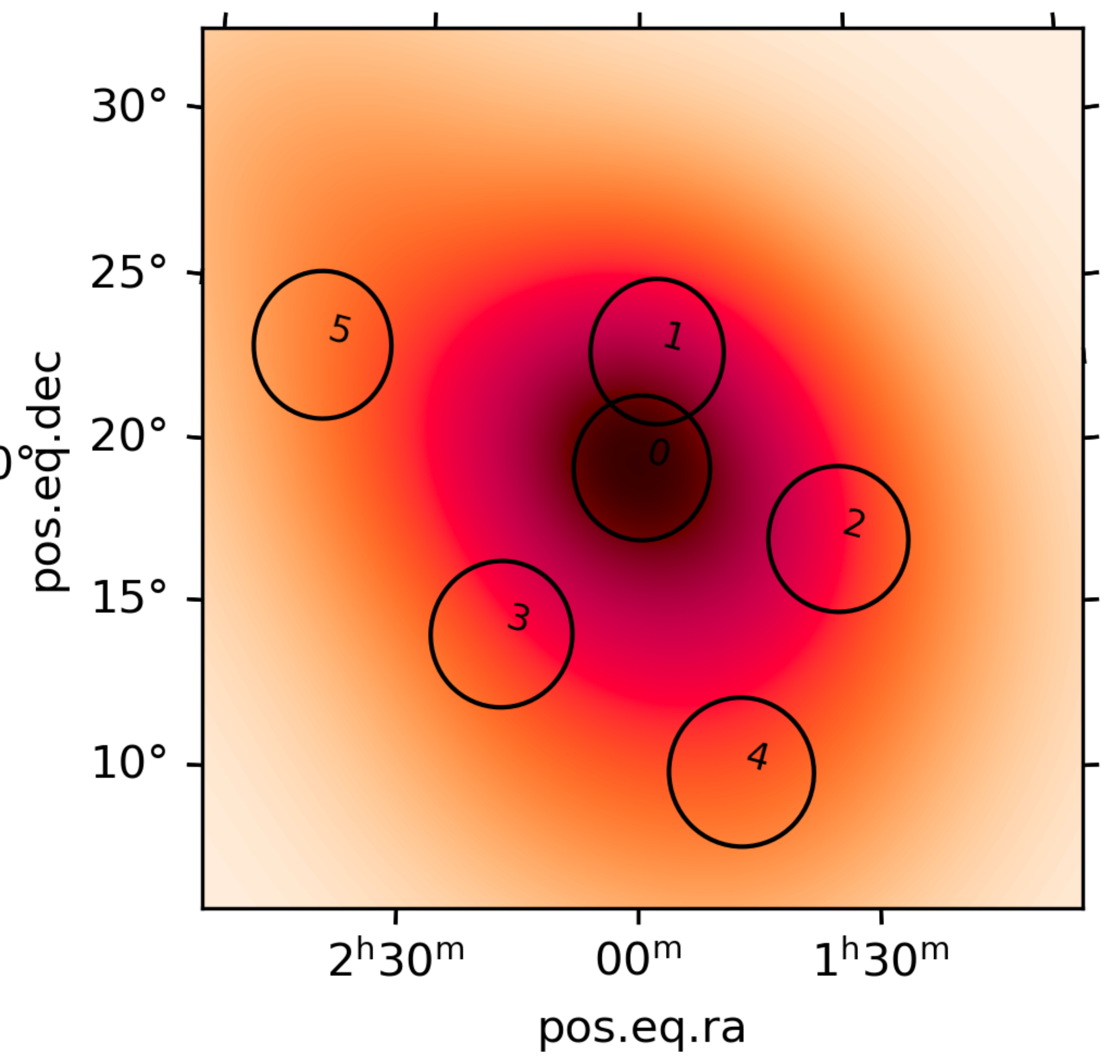




Multi-telescope coverage

- Four CTA/LST-telescope strategy tiling independently a Fermi-GBM alert
  - 4th LST (exposure=20m, FoVradius= 2.3deg, zenith cut = 70)

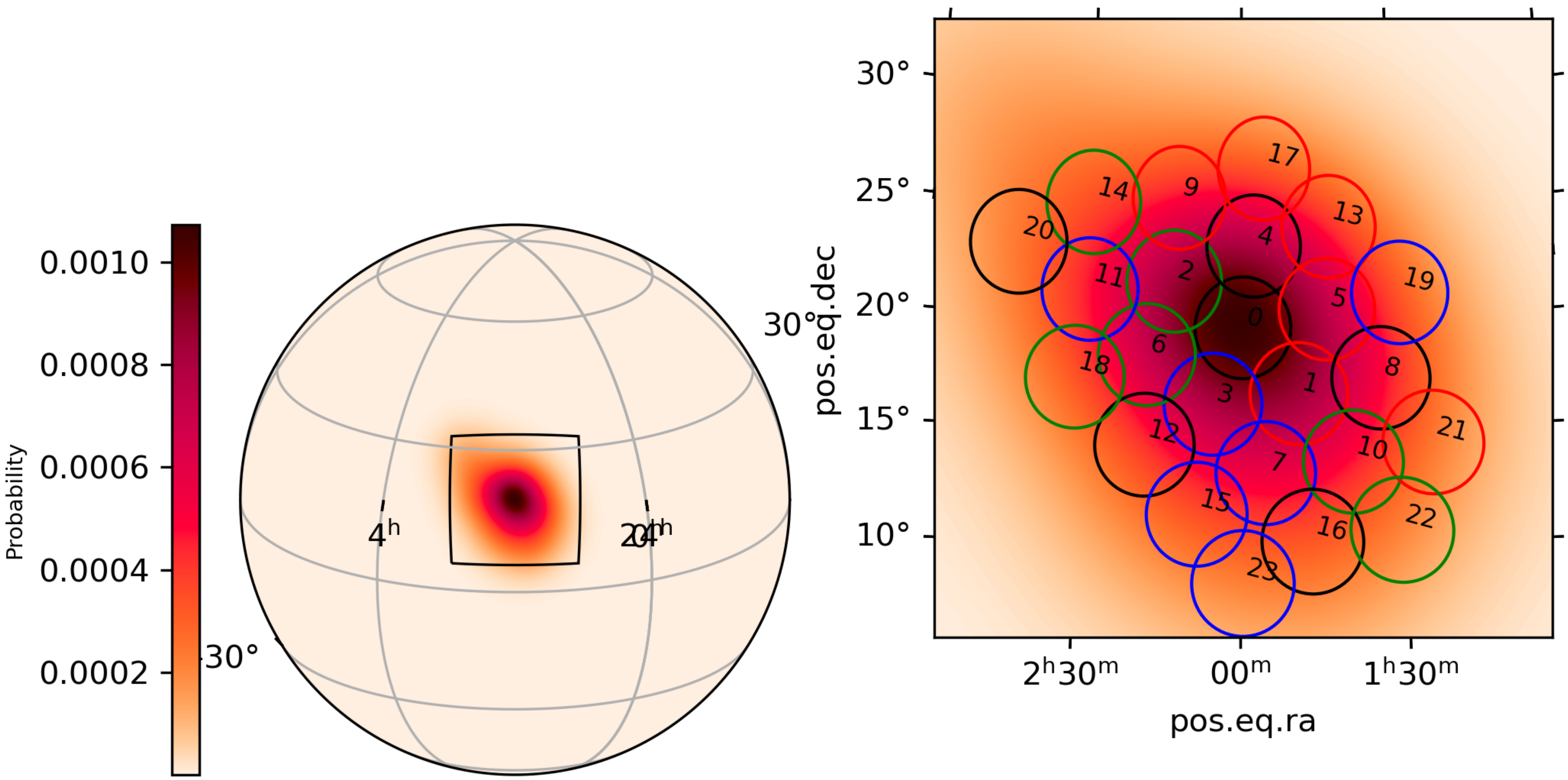




Multi-telescope coverage

- Four CTA/LST-telescope strategy tiling independently a Fermi-GBM alert

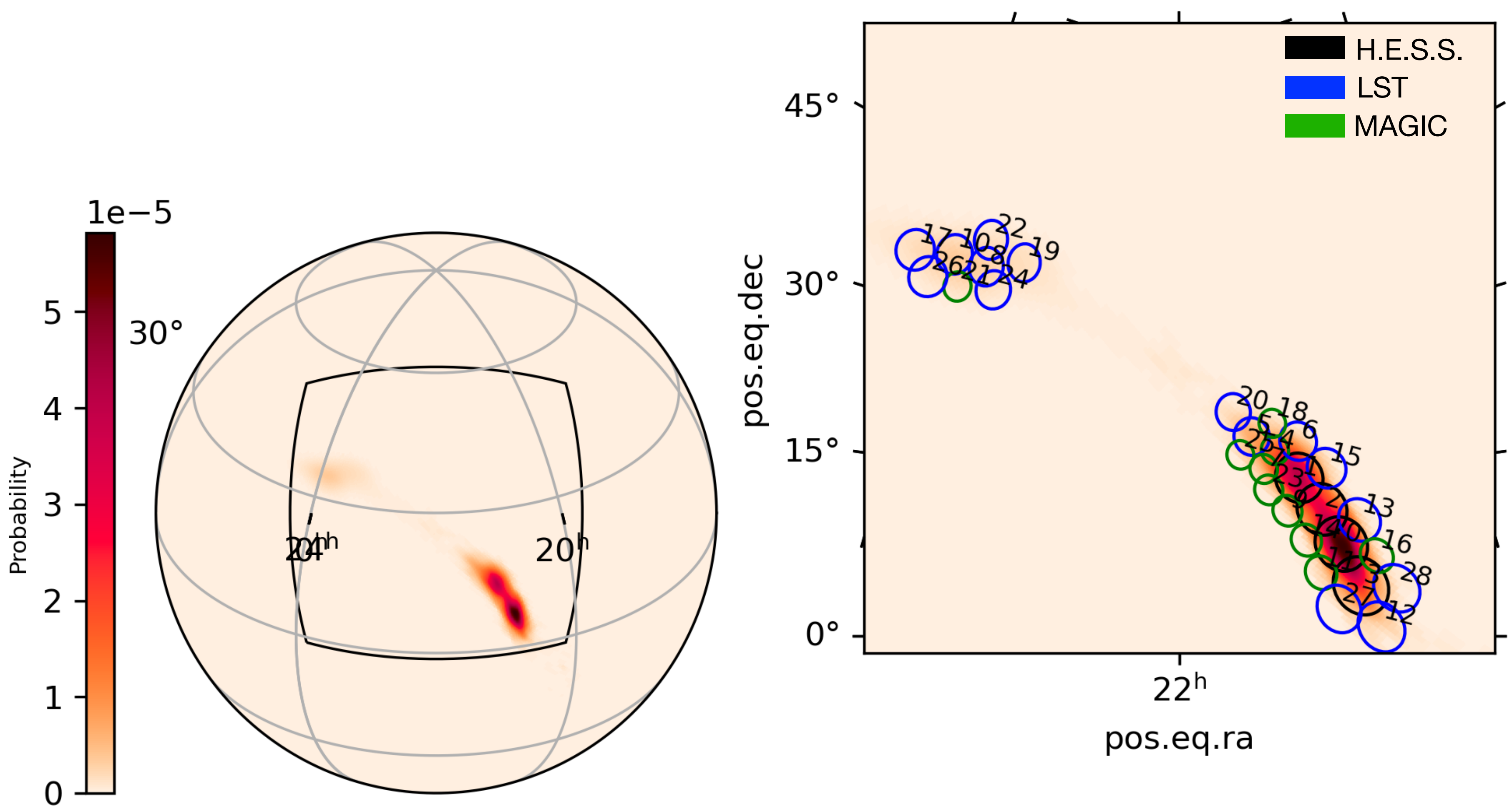
4 identical telescopes (FoVradius = 2.3deg)
Coverage in 1h40m (vs. 6h20)
(Each pointing duration 20 minutes, as typically in IACTs)



Multi-observatory coverage

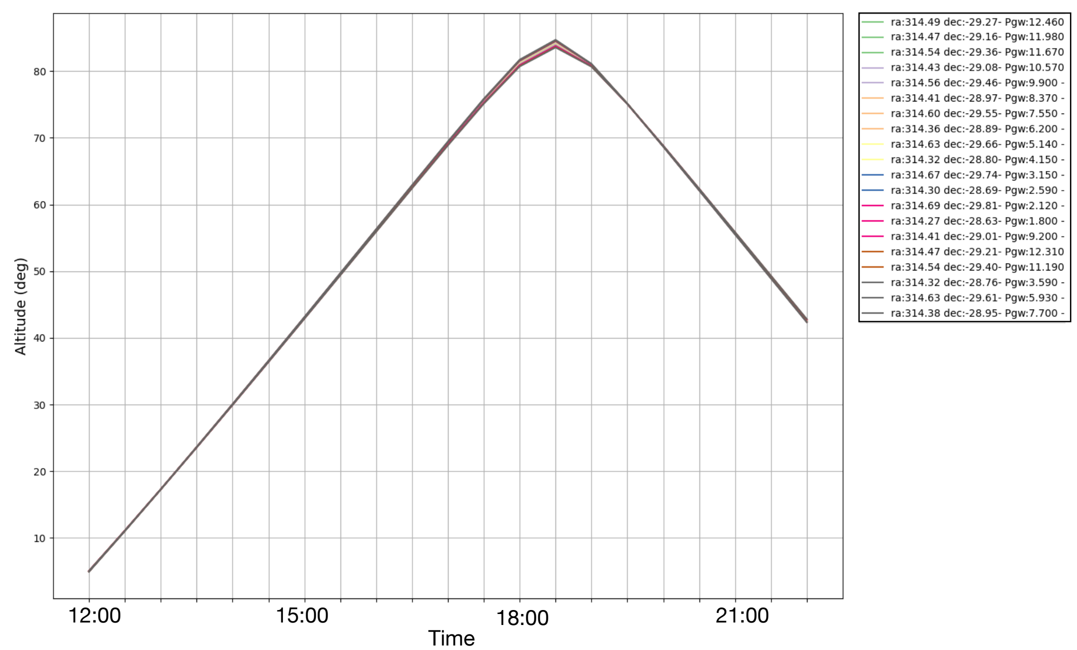
- Three gamma-ray telescope strategy for gravitational waves
  - MAGIC (30m, 1.5, zenith cut = 60°): observations from 18:58-21:58
  - LST (15m,2deg, zenith cut = 70°): observations from 18:58-22:28
  - HESS (30m, 2.5deg, zenith cut = 60°)observations from 00:30-02:00

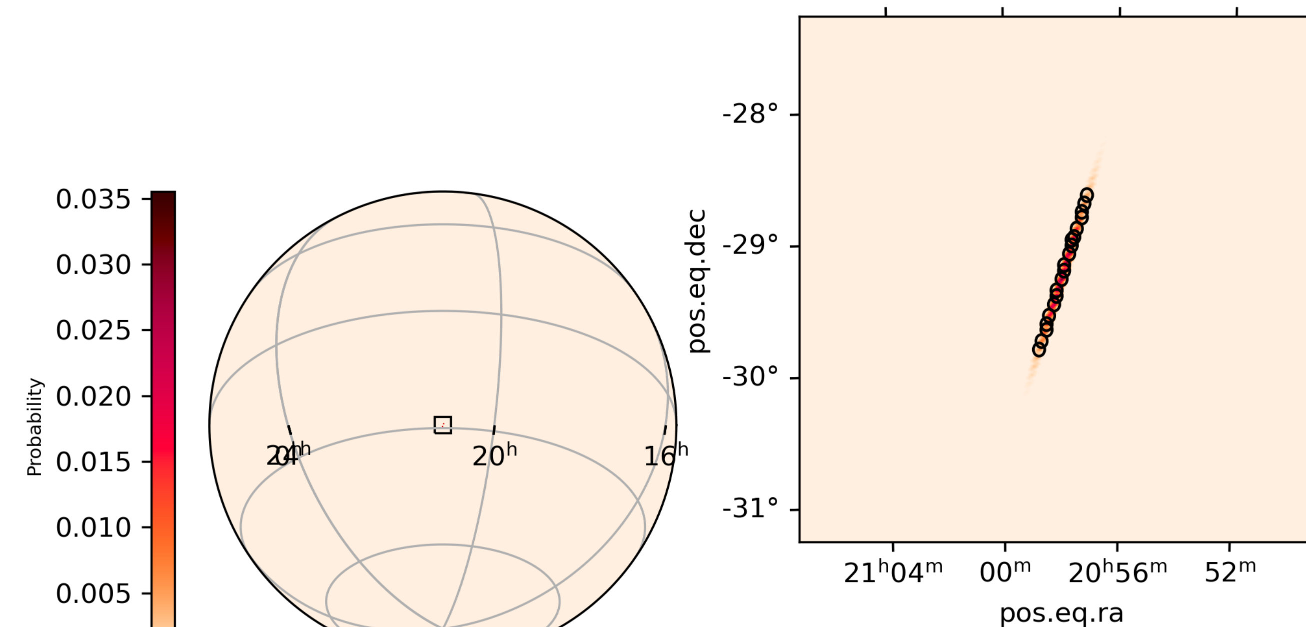
- Very large probability coverage of ~95%
- Regions unreachable by H.E.S.S. are covered by MAGIC and LST



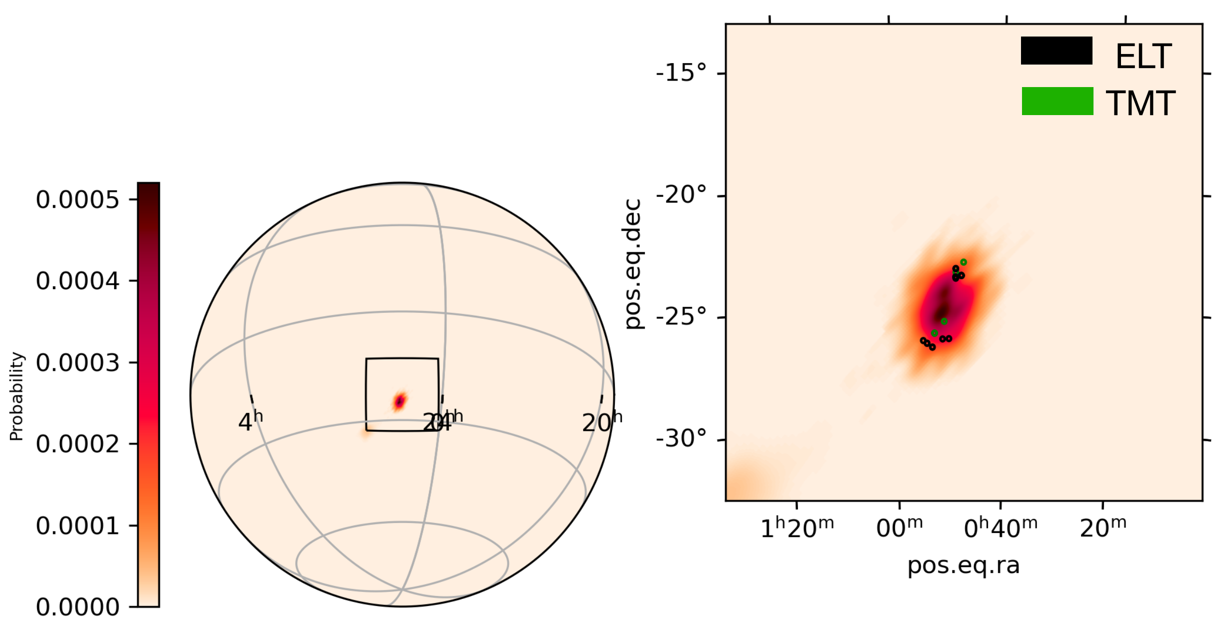
Multi-wavelength coverage with small FoV

- IPN alert followup by (radio) telescope observing **during the day**

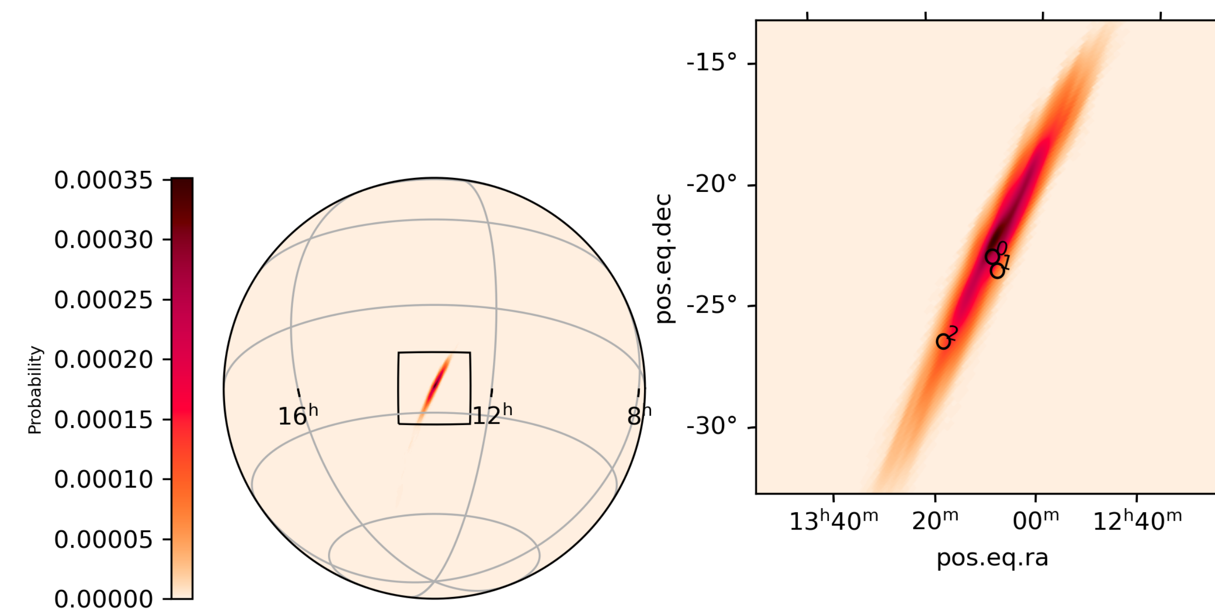




- GW190814 **galaxy-targeted**

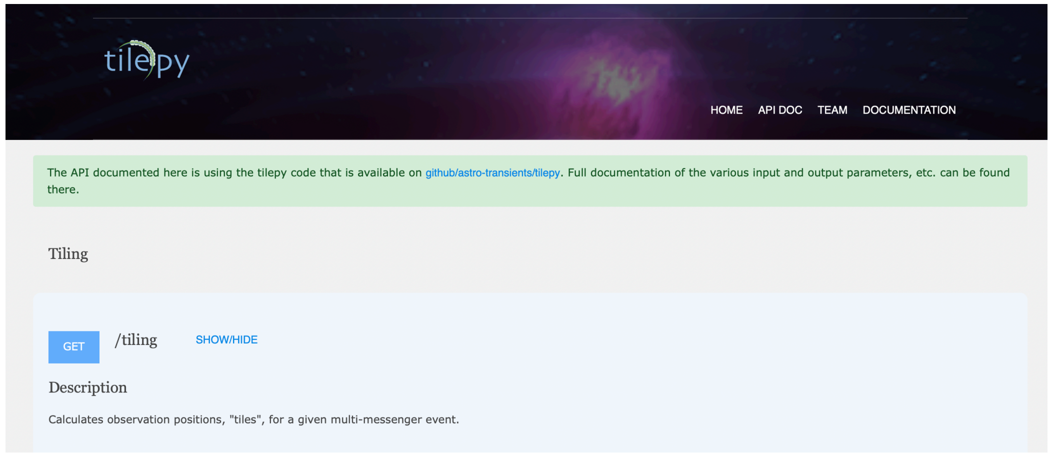


- GW170817 **galaxy-targeted with ATOM**



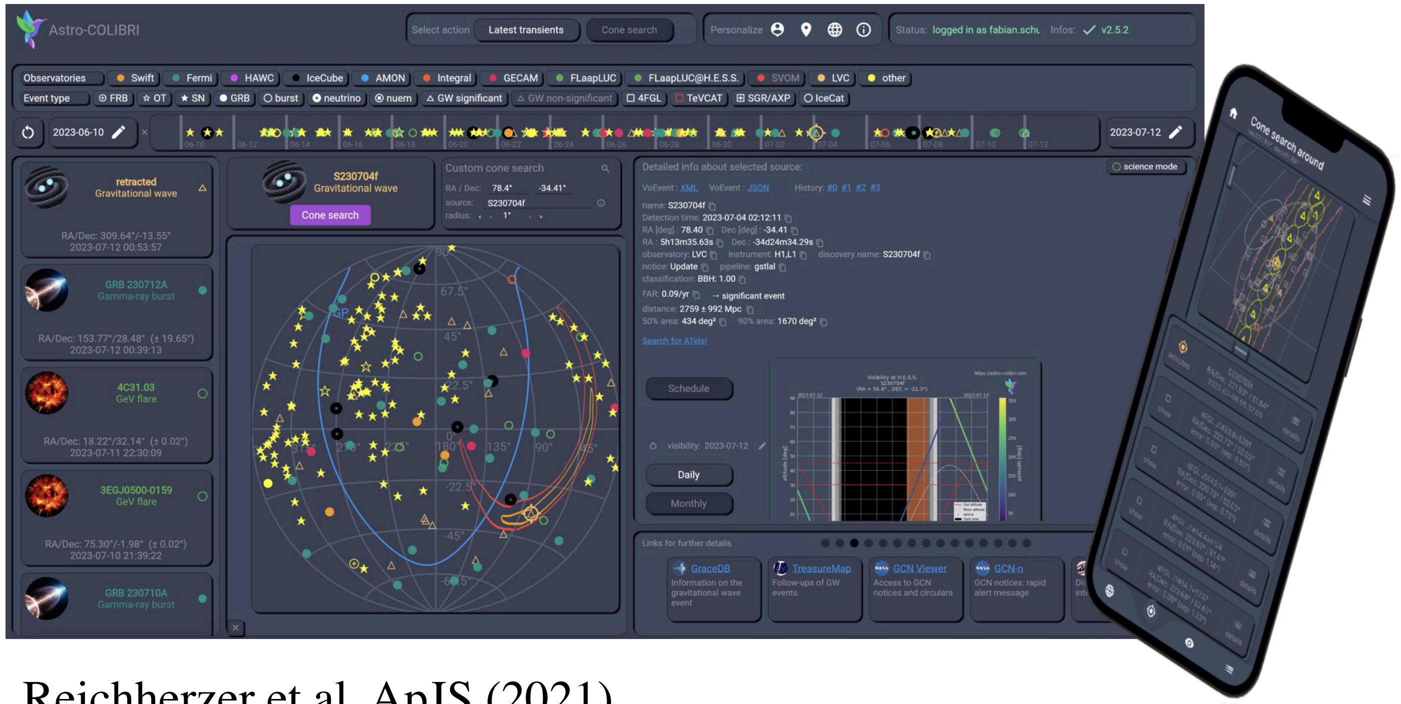
Where to find tilepy?

- GitHub repository of *demo* tilepy (v1.0 and documentation soon!)
  - github/astro-transients/tilepy



- API: **tilepy.com.** Cloud-based computing of GW follow-up schedules using tilepy is provided by the Astro-COLIBRI platform.
  - Example: https://tilepy.com/tiling?url_map=https%3A%2F%2Fgracedb.ligo.org%2Fapi%2Fsuperevents%2FS230528ay%2Ffiles%2Folib.multiorder.fits%2C1&start_obs_time=2023-05-28&latitude_obs=-23.27&longitude_obs=16.5&altitude_obs=1835

- User interface via **astro-colibri.science** available!



Reichherzer et al. ApJS (2021)

Keeping up with future changes in the community

- We are going to expand it to further poorly localised events:
  - neutrino: IceCube, KM3NET
  - GRBs: SVOM-GRM, cubesats…

- Make it faster. The speed is very dependent of the case (resolution, FoV, # pointings, method)

- Make it more modular.
  - Easier to implement new algorithms/science cases
  - Enable further contributions from the community

- Suggestions?

"*tilepy: a python package to detect the counterpart in follow-ups of transients with large uncertainties in the location*", in preparation

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

$\hat{\mu}_i$: mean

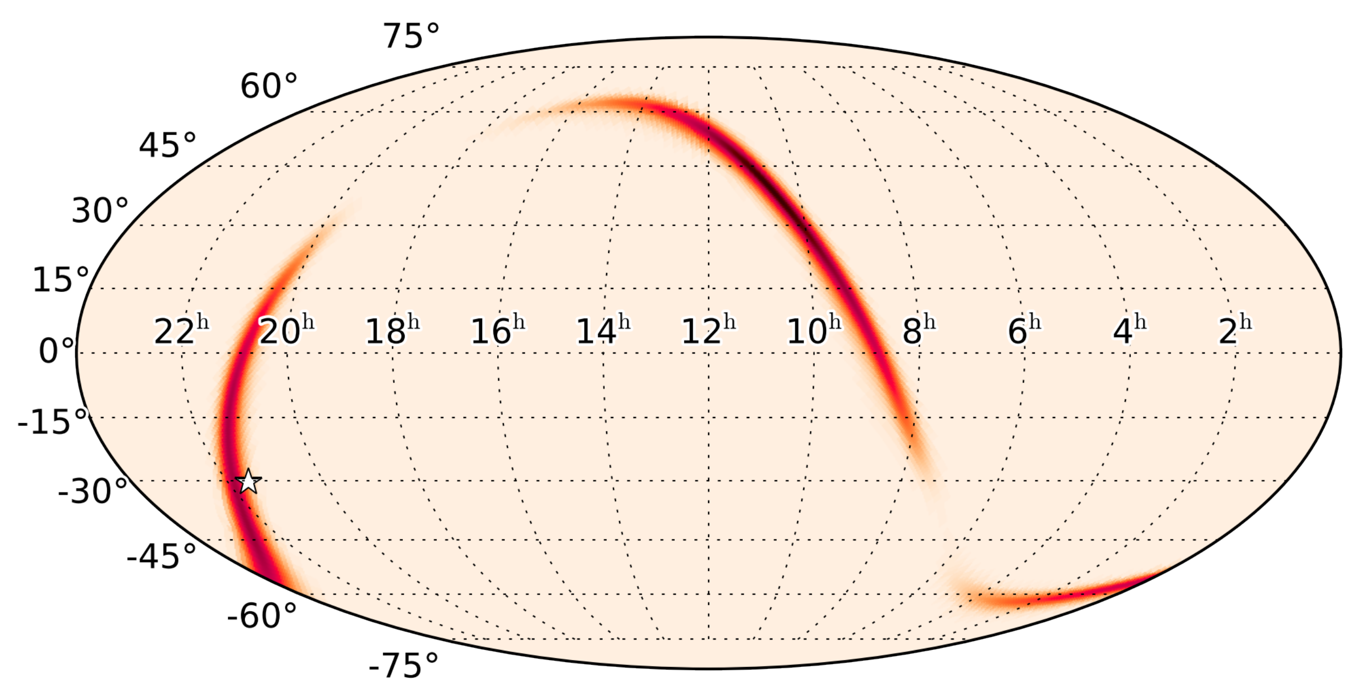
$\hat{\sigma}_i$: scale

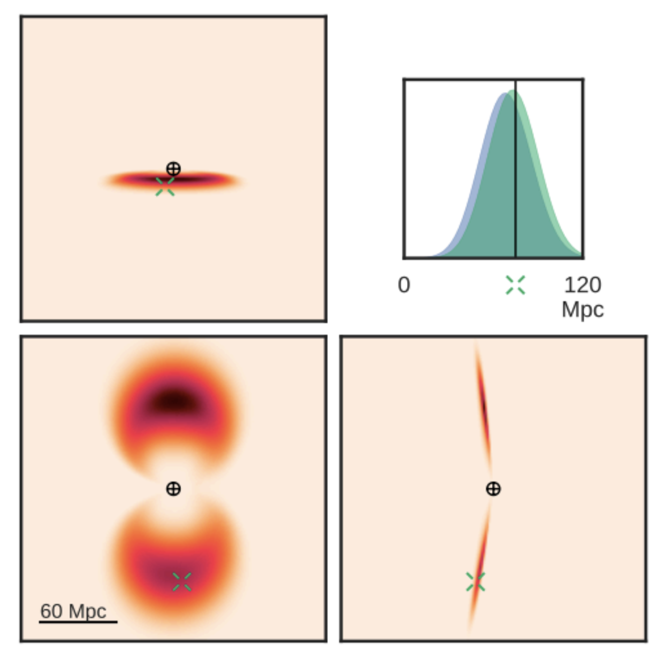
$\hat{N}_i$: normalization

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

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 $P^i_{GW \times GAL}$