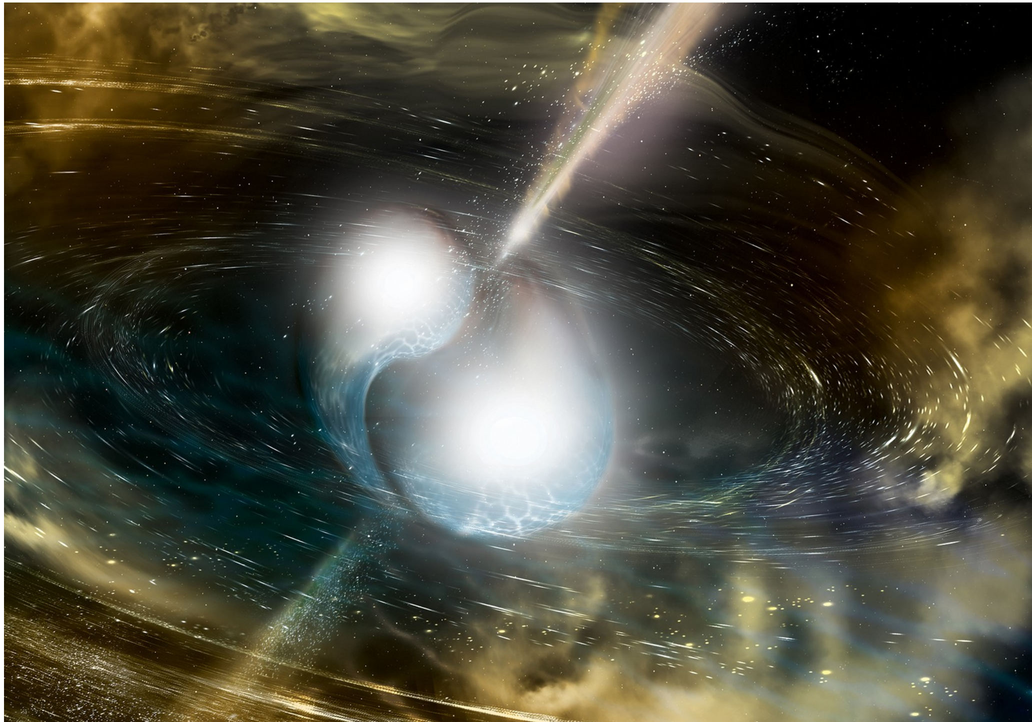
Fermi-LAT sensitivity
to the gravitational wave follow-up

Work done for the Masters Thesis
University of Turin, Department of Physics



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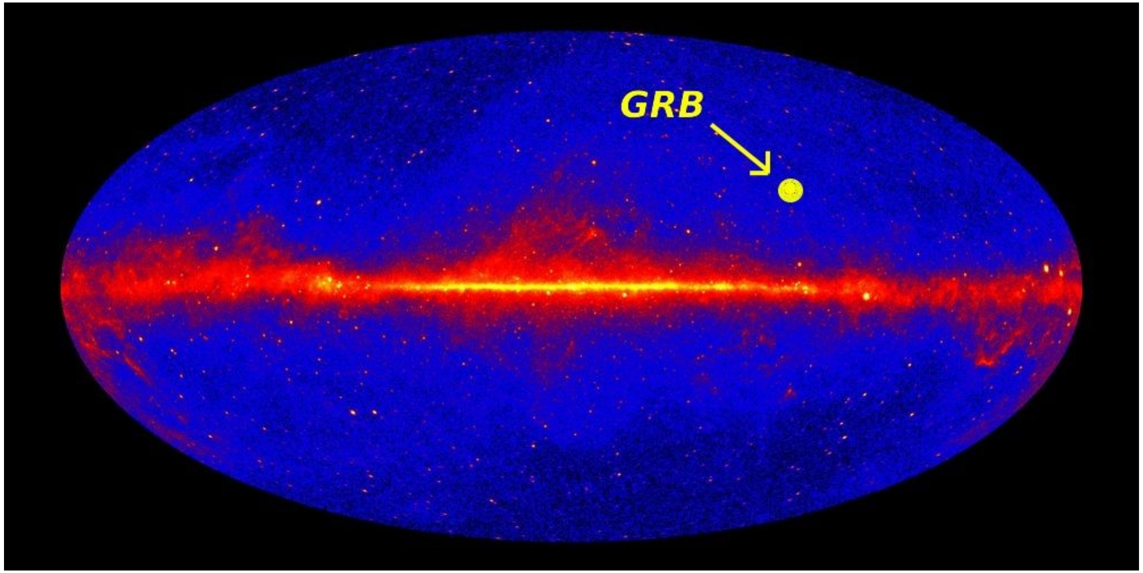
Thesis target

Determine the Fermi-LAT sensitivity to the follow-up of gravitational waves (GWs):

1) realize a **procedure that can be employed to any GW event** and that produces the sensitivity map of Fermi-LAT;

2) determine the **trial factor** involved in the search of the counterpart, motivating an **optimization of the search**.



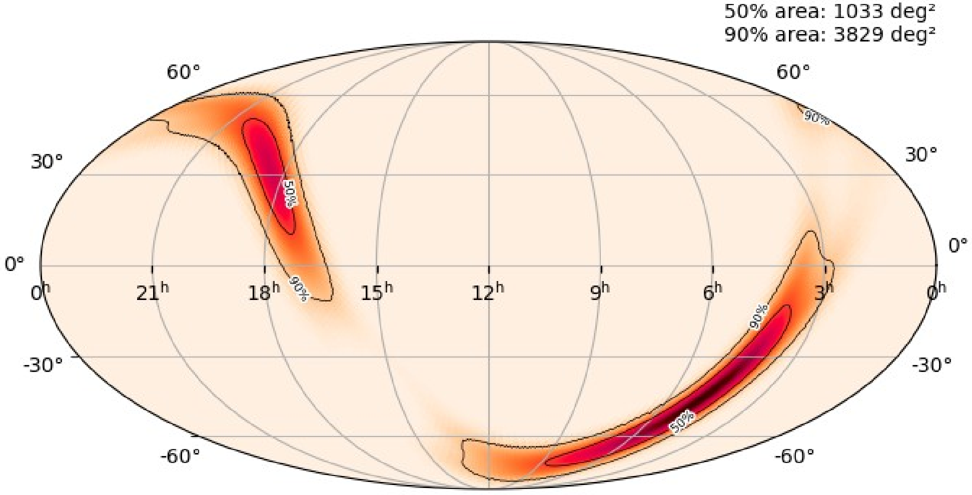
All-sky map produced by Fermi-LAT – galactic coordinates.

Follow-up with Fermi-LAT

- **Multi-messenger** observations: comprehensive description of **compact binary object mergers** and **GRBs;**

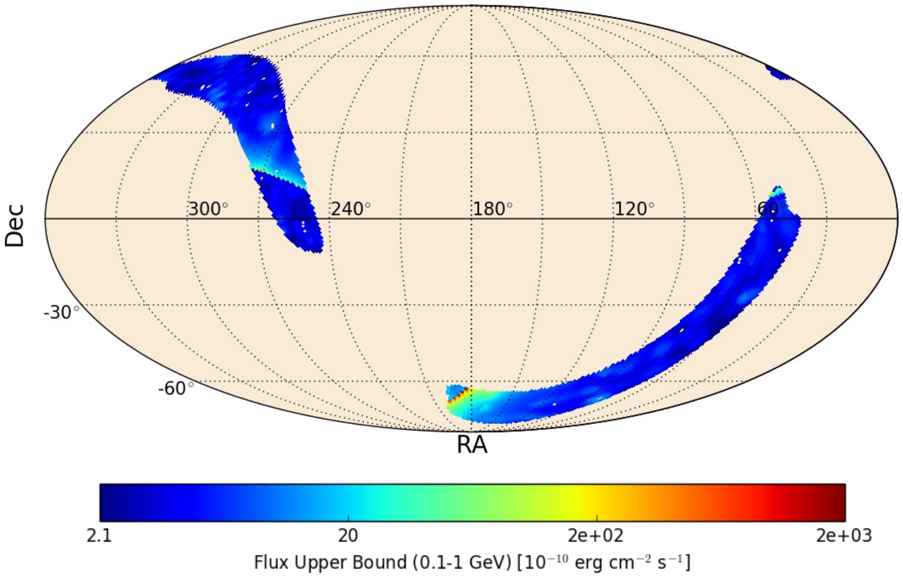
- **Pipeline** - follow-up of GW events:
    - **uniform scanning of all the localization region**;
    - in case of non-detection: **flux upper bounds**!

LIGO/Virgo event S190910d: NS-BH candidate



Credit LIGO/Virgo Collaboration.

Fermi-LAT upper bounds



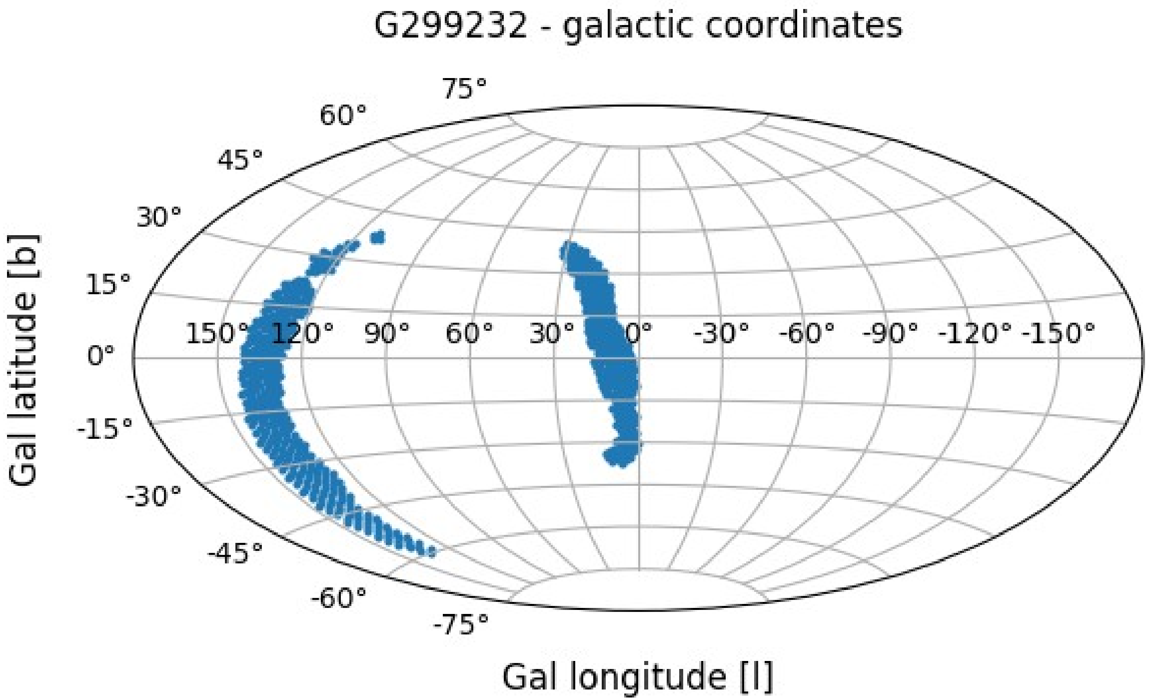
Credit Fermi-LAT Collaboration

Part 1: Fermi-LAT sensitivity to a GW event

I realized a **procedure** to determine the **Fermi-LAT sensitivity** to a **GW event**.

Case of study - LIGO/Virgo event G299232:

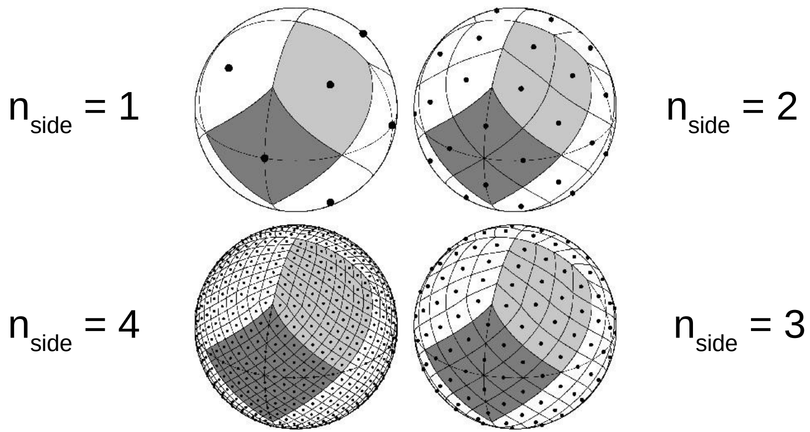
- time of trigger: t_{gw} = *2017-08-25, 13:13:37 UTC;*
- localization region (90% c.l.): *2363.451 deg*^{2} .



Data selection and grid preparation

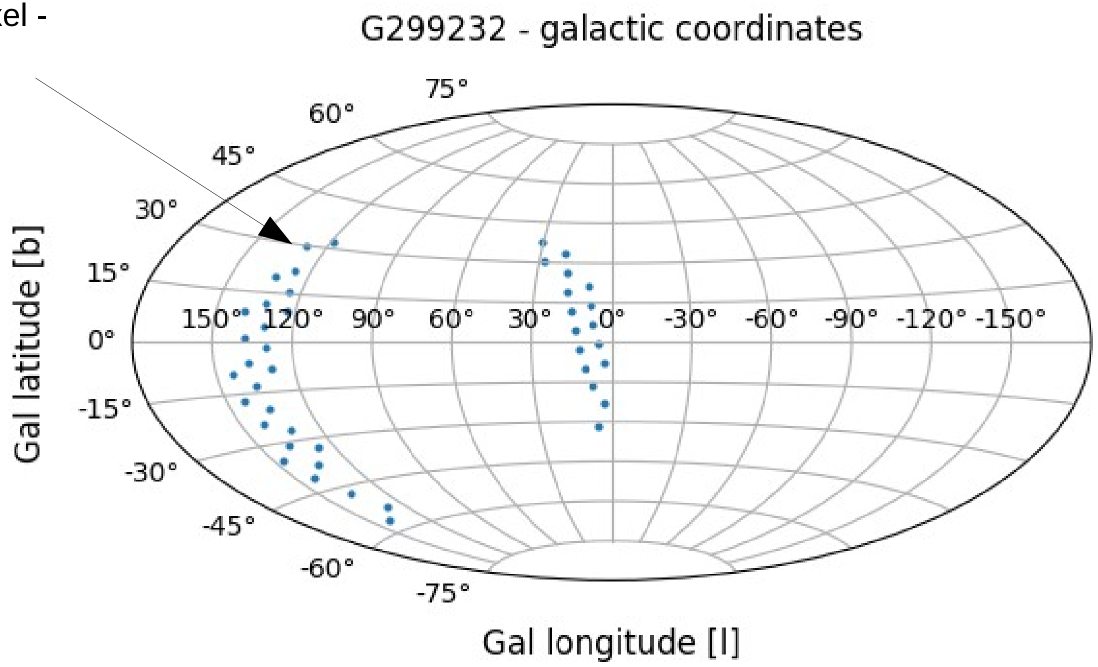
- Fermi-LAT data (photons and spacecraft files) in a time window of 10ks starting at t_{gw};
- Grid of 44 equispaced pixels - grid resolution $n_{side} = 8$ in the HEALPix format.

$$N_{pix} = 12 \times n_{side}^2$$



HEALPix map for different resolutions n_{side}.

Center of the pixel - HEALPix format



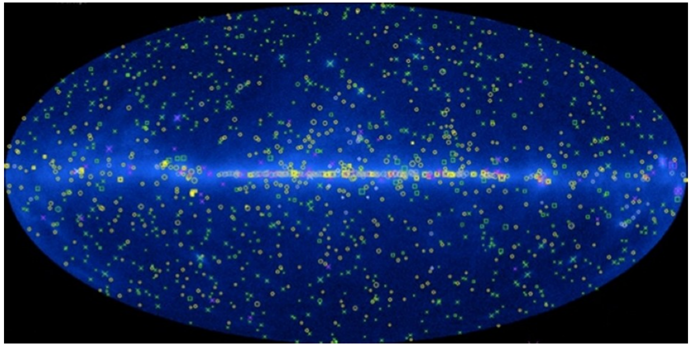
HEALPix map for the localization region, $n_{side} = 8$.

Simulations

Model – as in standard Fermi-LAT simulations.

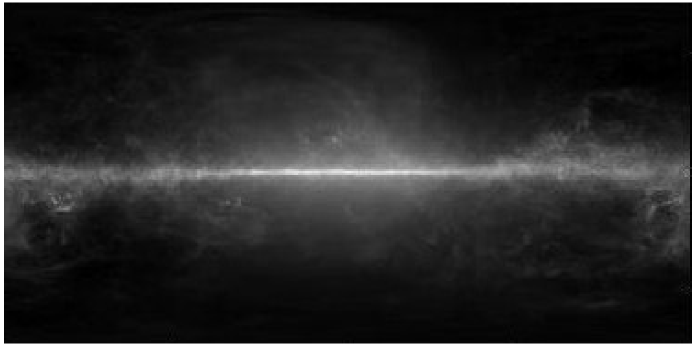
1. Point and **extended sources**:

e.g. Pulsars, Active Galactic Nuclei, Supernovae Remnants.



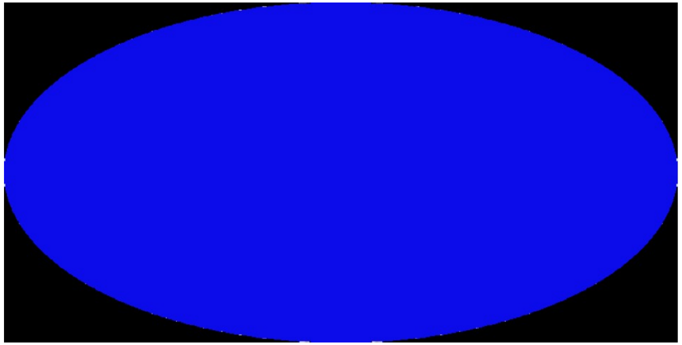
2. Galactic diffuse emission:

cosmic rays + dust / gas / radiation field → γ-rays.



3. Isotropic residual emission:

extra-galactic sources,
charged particles misclassified as γ rays;



4. GRB:

- spectrum $dN/dE \propto E^{-2}$;
- simulated into each point of the grid, for different fluxes and seeds:

→ 44 (**positions**) x 20 (**fluxes**) x 20 (**seeds**) = 17600 simulations

fluxes ↓ $[10^{-10}, 10^{-7}]$ erg/cm^{-2}/s^{-1}

seeds ↓ Probabilistic nature of the response of the LAT to an incoming photons flux.

Analysis

Standard Fermi-LAT analysis: **unbinned likelihood, log-ratio test** to determine the significance of the GRBs.

1. **Likelihood *L*** that the model *M* realizes the data:

binned $$L = e^{-N_{\exp}} \prod_i \frac{m_i^{n_i}}{n_i!}$$ → **unbinned** $$L = e^{-N_{\exp}} \prod_i m_i$$

- n_i : number of events measured in the bin *i* ;
- m_i : number of events expected in the bin *i* from *M*;
- $N_{exp} = \Sigma m_i$: total number of events expected from *M*.

2. **Test Statistic TS** :

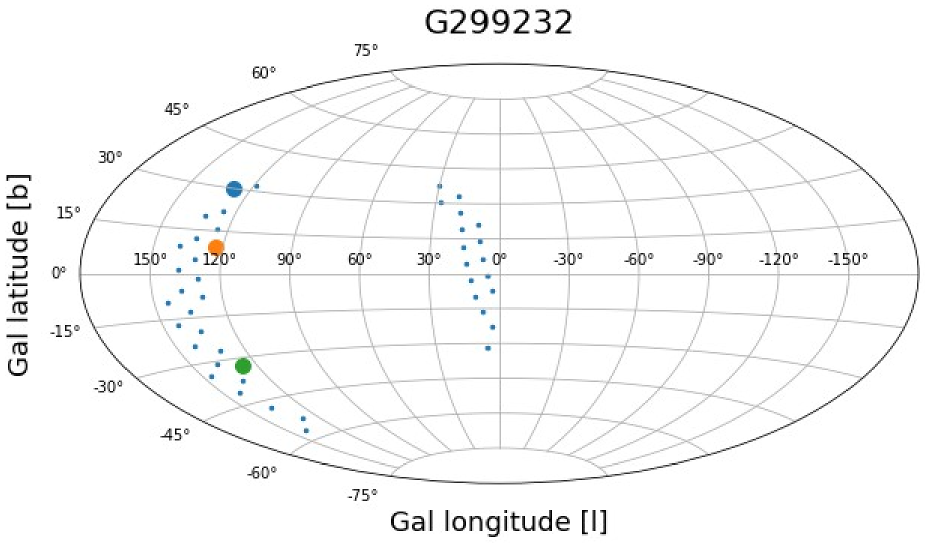
$$TS = -2 \ln \frac{L_0}{L_1}$$

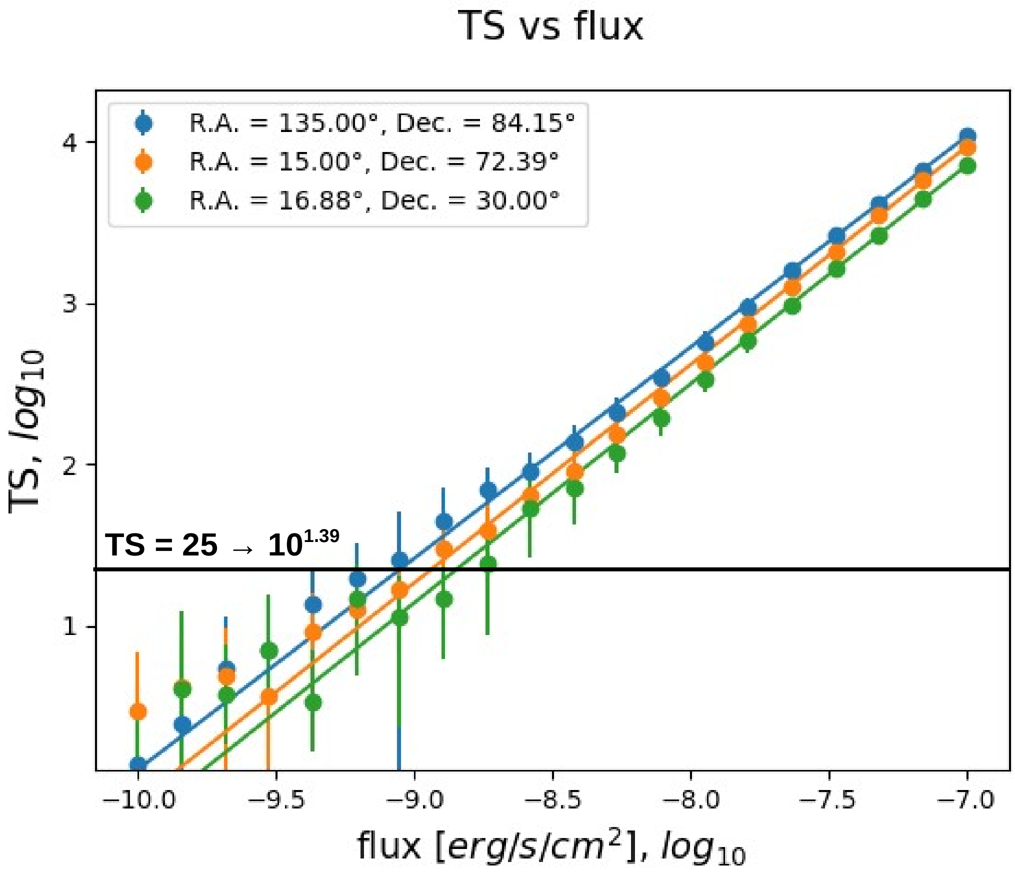
- L_0 : likelihood of the null-hypothesis (model: only background);
- L_1 : likelihood of the alternative hypothesis (model: background plus GRB).

TS = 25 corresponds roughly to the detection (5σ criterion).

For each pixel of the grid:

- TS is an **increasing function** of the GRB flux;
- TS is averaged over the seeds: error bars;
- **flux so that the GRB is detected with TS = 25**.

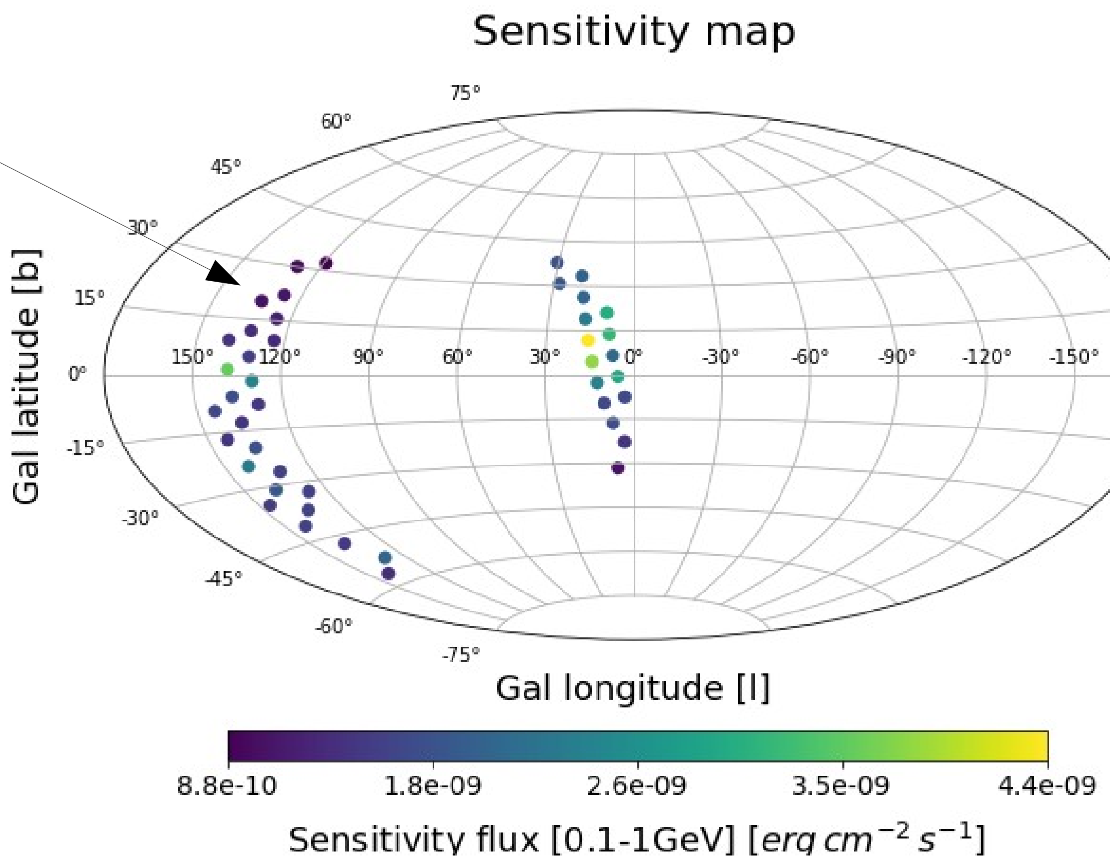


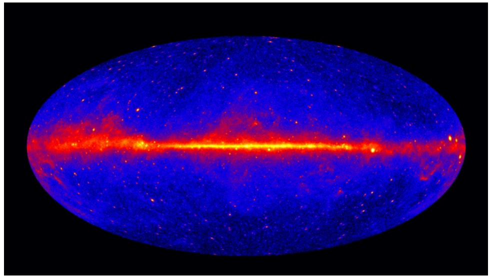


3 different positions on the grid.

Results

Flux at TS = 25



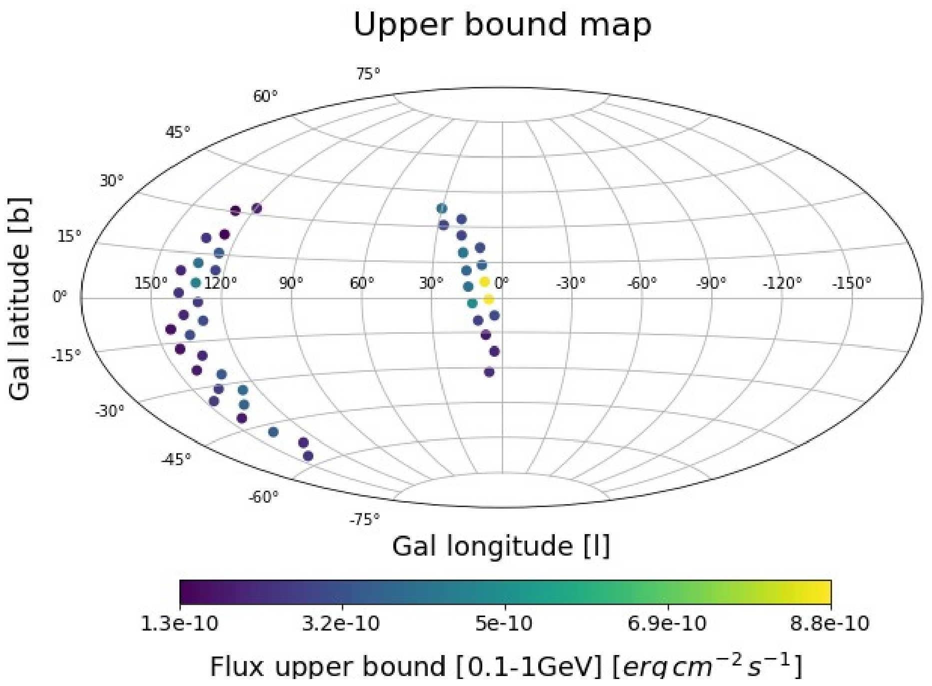


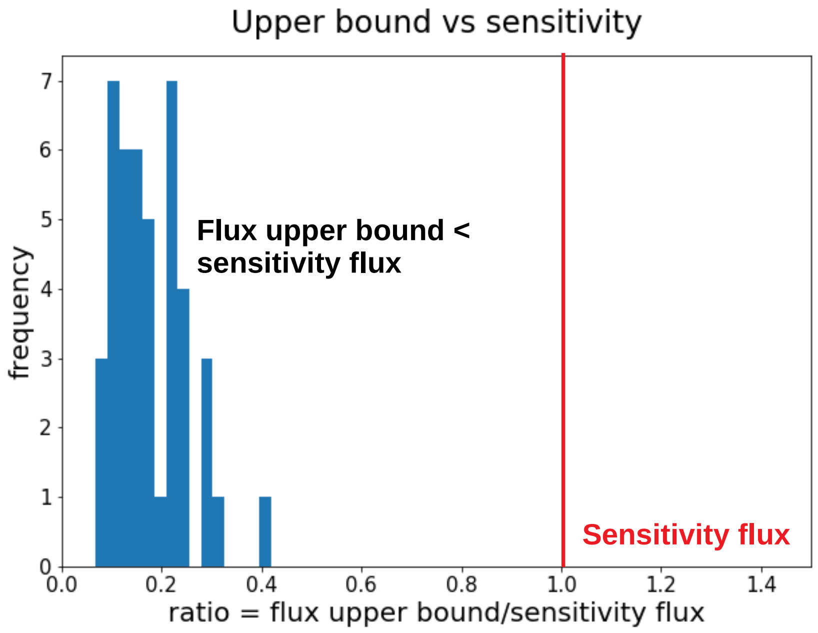
Gamma-ray sky

Check:

- the sensitivity decreases near the galactic disk → consistent with higher galactic background.

Results





Check:

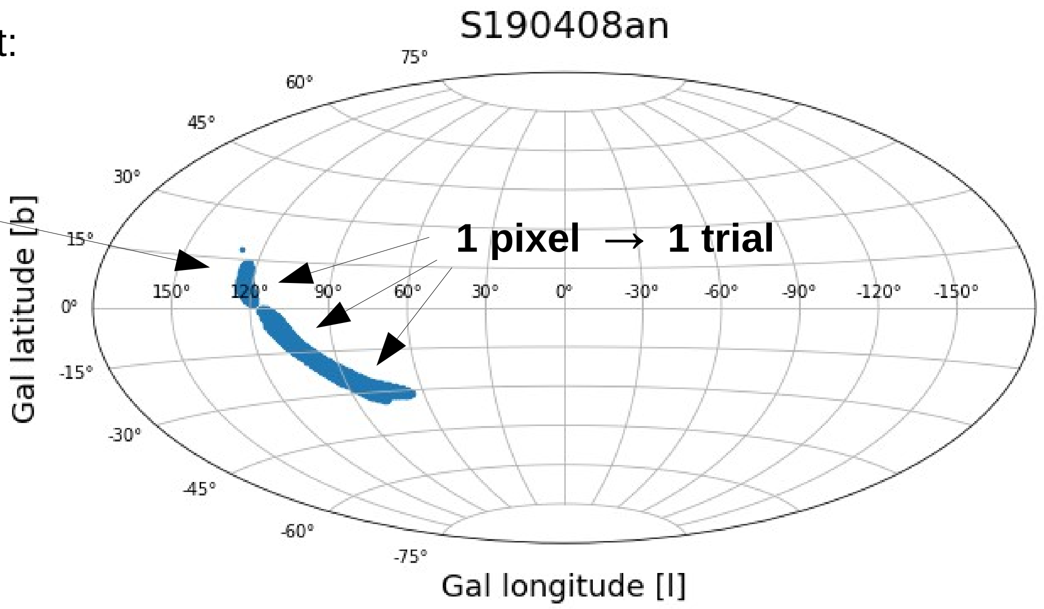
- the sensitivity flux is always greater than the flux upper bound → consistent with Fermi-LAT non-detection.

This procedure was **successfully tested** also for the LIGO/Virgo event S190426c.

Part 2: Trial Factor

1. Scanning the entire localization region of the GW event:

→ **typically several hundreds of trials** (1871 trials for S190408an, n_{side}= 128).



2. More likely a large excess due to statistical fluctuations of the background:

→ **threshold TS_{thr} @ detection has to be recalibrated**;

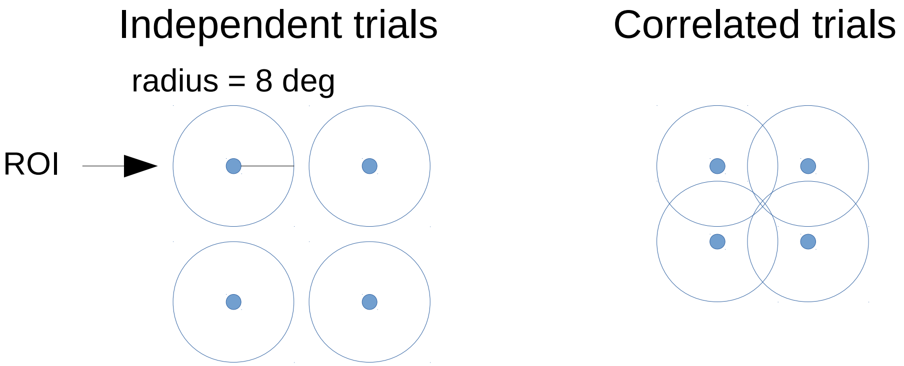
→ *the more you look, the less you find* .

3. Near ROIs are overlapped:

→ the **trials are not independent** ;

→ **number of *effective* trials n_{eff}**;

→ no theoretical expectation for TS_{thr} .



Strategy

I determined the TS_{thr} following this strategy:

1. **LIGO/Virgo event** S190408an (BBH);
2. 10k **simulations** of the photons file, only background;
3. **likelihood analysis** in two grids (grid resolution n_{side} = 64, 128);
4. number of *effective* trials $\mathbf{n_{eff}}$:

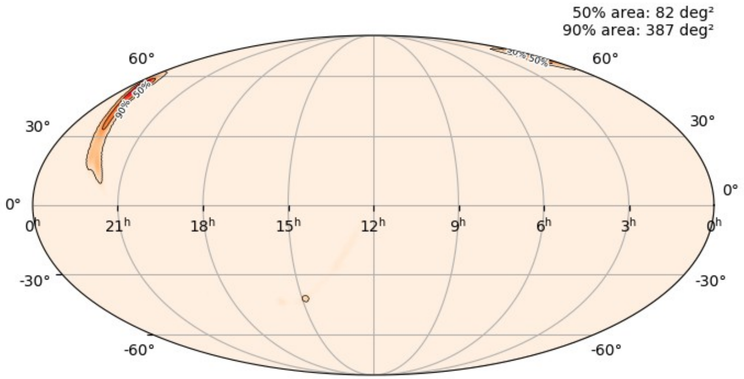
$$p' = 1 - (1-p)^{n_{eff}}$$

← Bonferroni/Šidák correction for multiple tests

where:

- *p* : probability density function (pdf) of the *TS* for one trial;
- *p'* is the pdf of the TS_{max} for n_{eff} trials;

↓ List of the maximum TS in the localization region, over all the simulations.



Localization region of S190408an – equatorial coordinates (credit LIGO/Virgo Collaboration).

5. threshold $\mathbf{TS_{thr}}$ corresponds to **p-value = 2.86 x 10**$^{-7}$ (5σ criterion) :

$$\int_{TS_{thr}}^{\infty} p' dx = 2.86 \times 10^{-7}$$

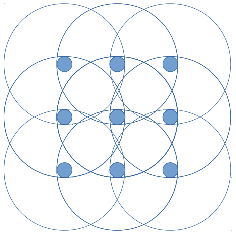
Results

I determined the **number of effective trials n_{eff}** for circular **areas with different radius**.

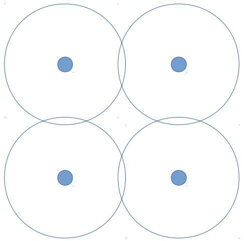
The number of effective trials is greater for n_{side} =128 than for n_{side} =64.

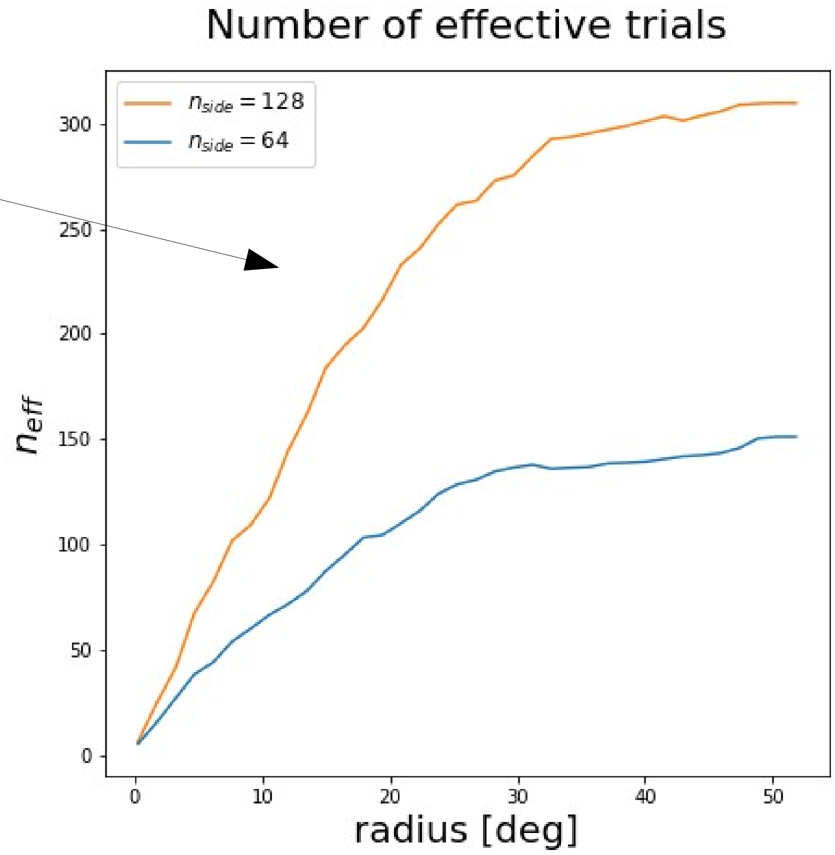
Consistent: more pixels in the same region!

n_{side} = 128



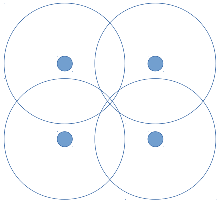
n_{side} = 64





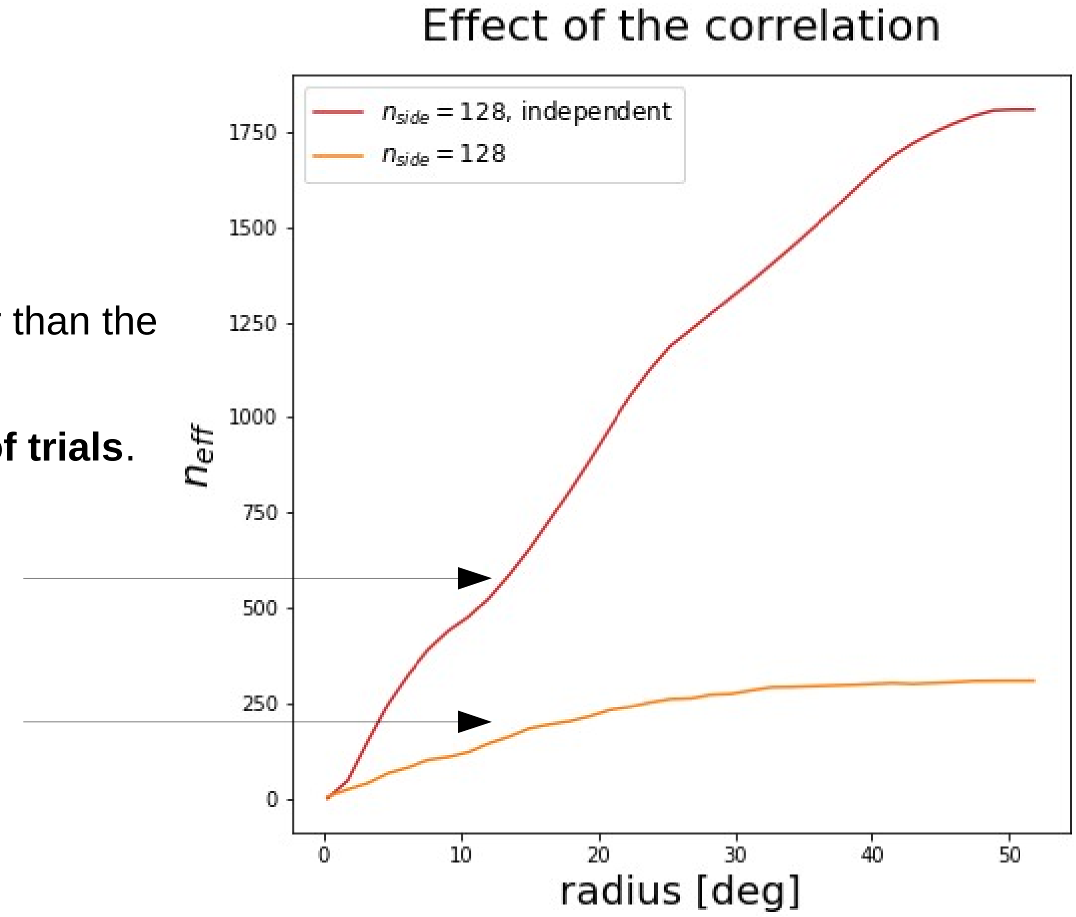
Results

ROIs overlapped → **trials correlated**.



The number of effective trials n_{eff} is smaller than the number of trials in absence of correlation:

→ the **correlation reduces the number of trials**.



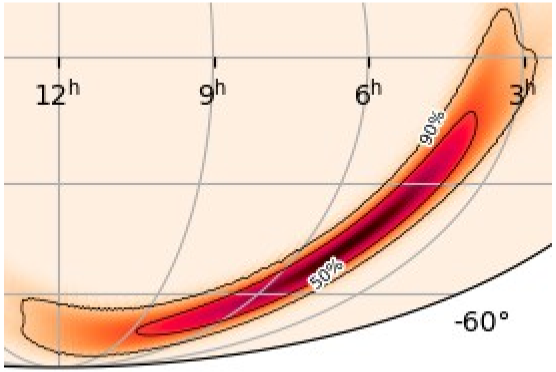
Results

Threshold of the detection TS_{thr}:

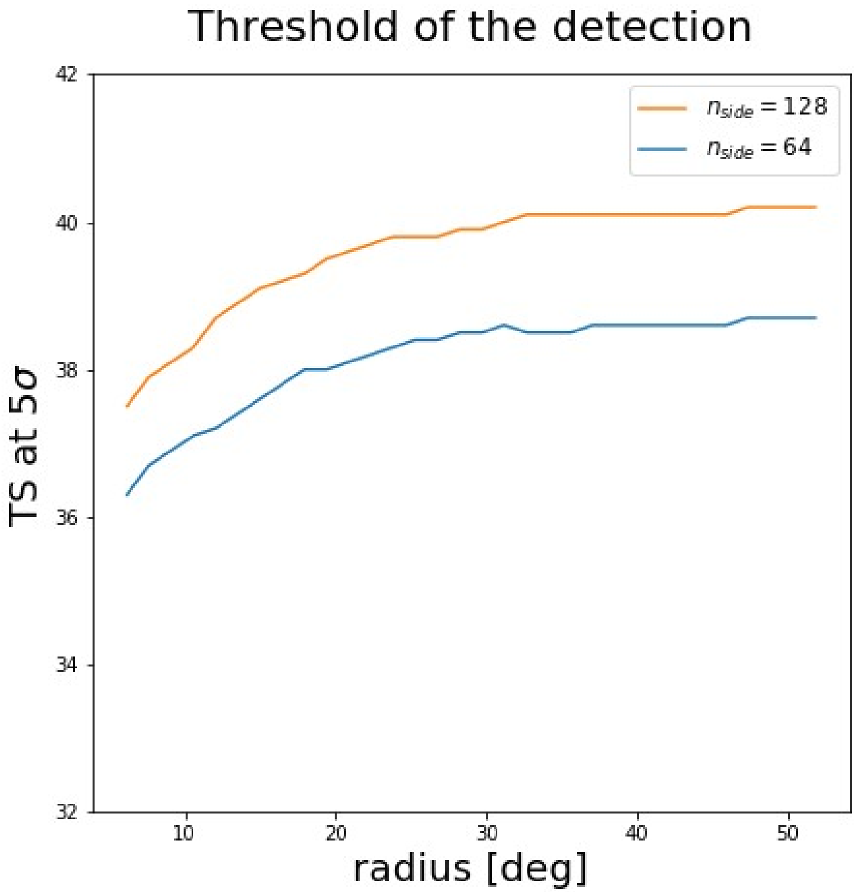
- TS_{thr} scales with the dimension of the area – until a plateau;
- **limit the search to small areas** in order to have the lowest TS_{thr} :

  → determine a quantitative criterion to define the optimal region of the search;

  → in case of non-detection, increase the area.



Intensity of the color proportional to the **probability to localize the GW event**



Conclusion

I determined the sensitivity of Fermi-LAT to the follow-up of gravitational waves.

1. Procedure to map the sensitivity flux to any GW event.

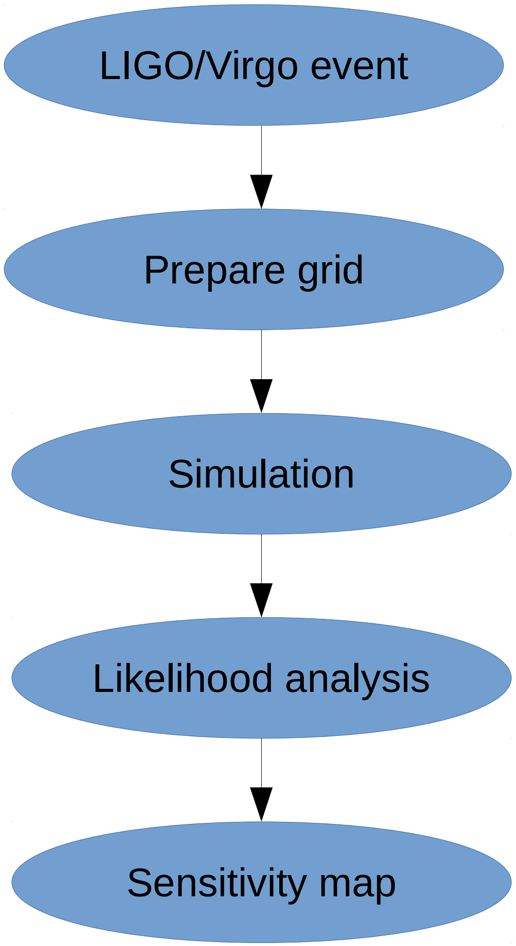
   → *Future prospect* : automate the procedure into a **pipeline triggered by LIGO/Virgo alerts**.

2. Threshold of detection TS_{thr} scales with the area of the search.

   → *Future prospect* :

   → **prioritize the search**: limited to LIGO/Virgo hot spots (see Nicola's contribution to the Fermi-LAT Collaboration Meeting at Santa Cruz, fall 2019);

   → determine a quantitative criterion to define the hot spots.



Acknowledgment

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