Multi-messenger Transient Astrophysics with IACTs

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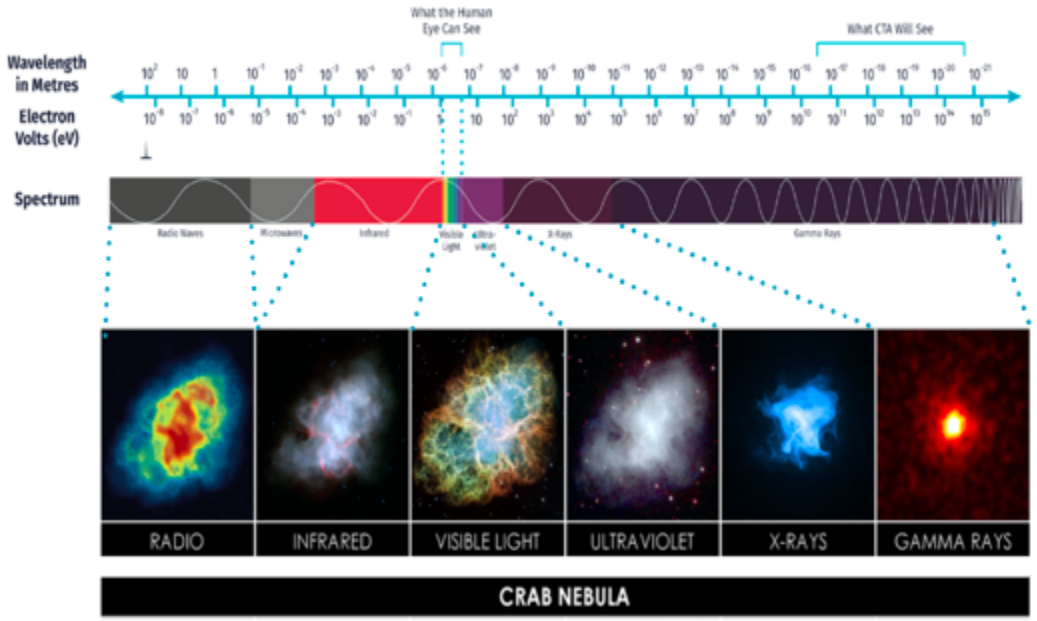
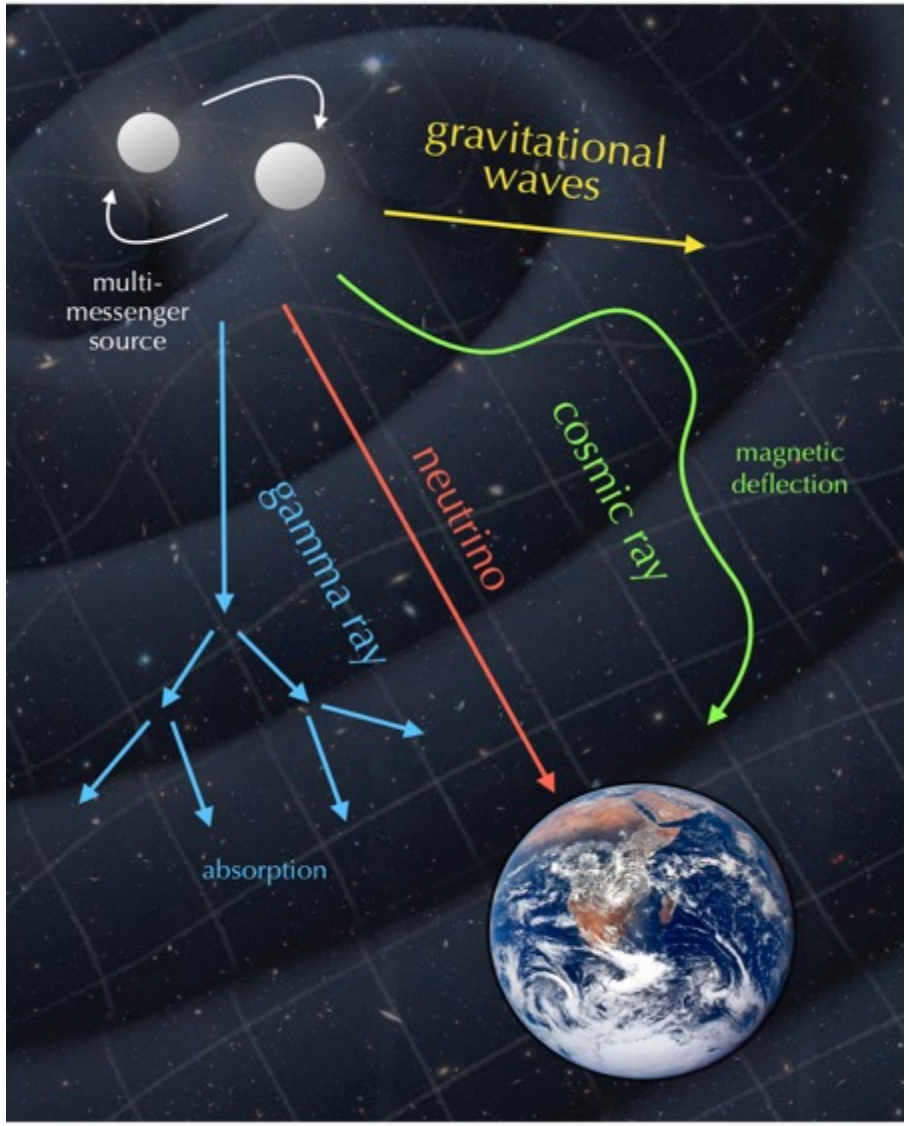
Multi-messengers: new information with every messenger

- Cosmic rays (CR)
- Neutrinos
- Gravitational Waves (GW)
- Electromagnetic (EM) radiation





Multi-messengers: cataclysmic cosmic events

	GW	Neutrino	Gamma-rays	FRB
BNS merger	yes	maybe	yes	maybe
BBH merger	yes	In extreme scenarios	In extreme scenarios	?
AGNs	no	yes	yes	maybe
Stellar core collapse	Yes if close	yes	yes	maybe
Magnetars	No / maybe	maybe	yes	yes

Binary Neutron Stars (BNS):
Mass, inclination from **GW**
Localisation from **optical**
GRB properties from **gamma**
Kilonovae propertie from **opt/IR**

Active Galactic Nuclei (AGN):
Neutrino + Gamma = hadronic emission processes

Will focus on Gravitational Waves **GW**
and Fast Radio Bursts **FRBs** in the scope of very-high energy astrophysics

Very-high energy gamma-rays

- Photon energy ranging from 10s GeV to 100s TeVs
- Can be detected indirectly by ground based instruments through their interaction with the atmosphere -> Cherenkov light
- Production processes – non-thermal :
  - Leptonic: Synchrotron, Inverse Compton
  - Hadronic: Pion decay

➢ **Probing the high energy non-thermal emission in GW, GRBs, FRBs and neutrino events**

Very-high energy gamma-rays

- Pho
  TeVs
- Can
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- Proc
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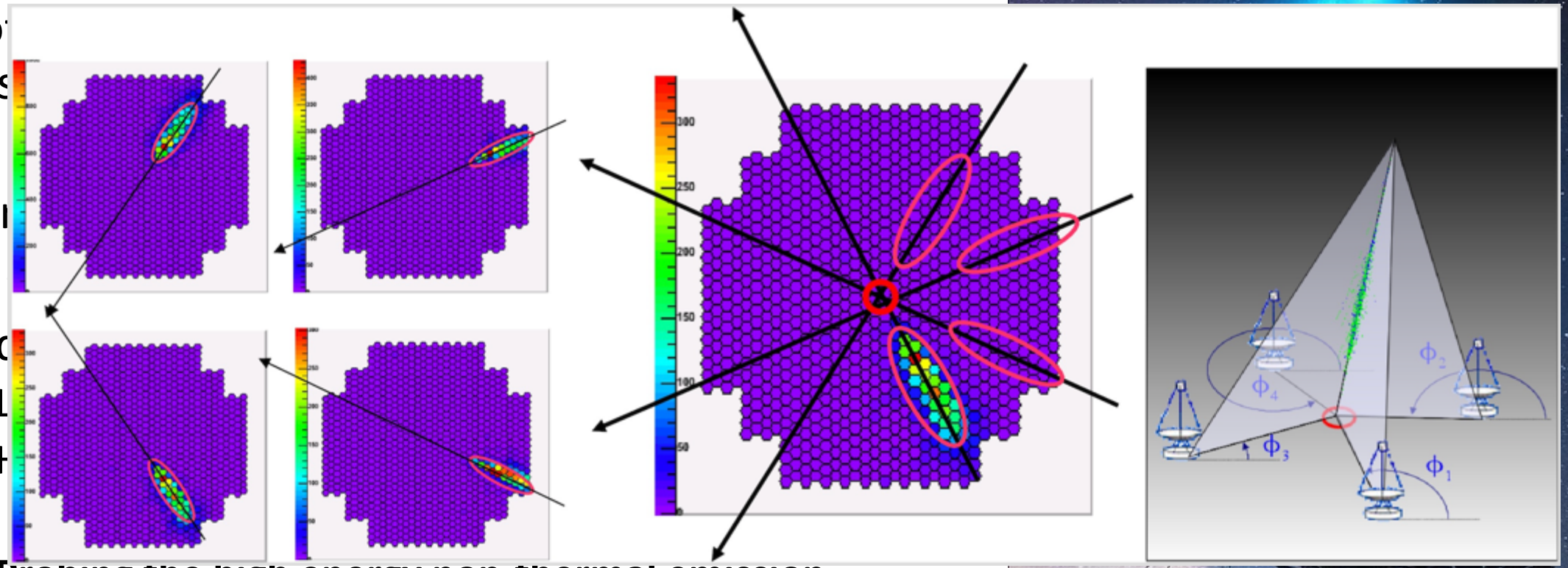
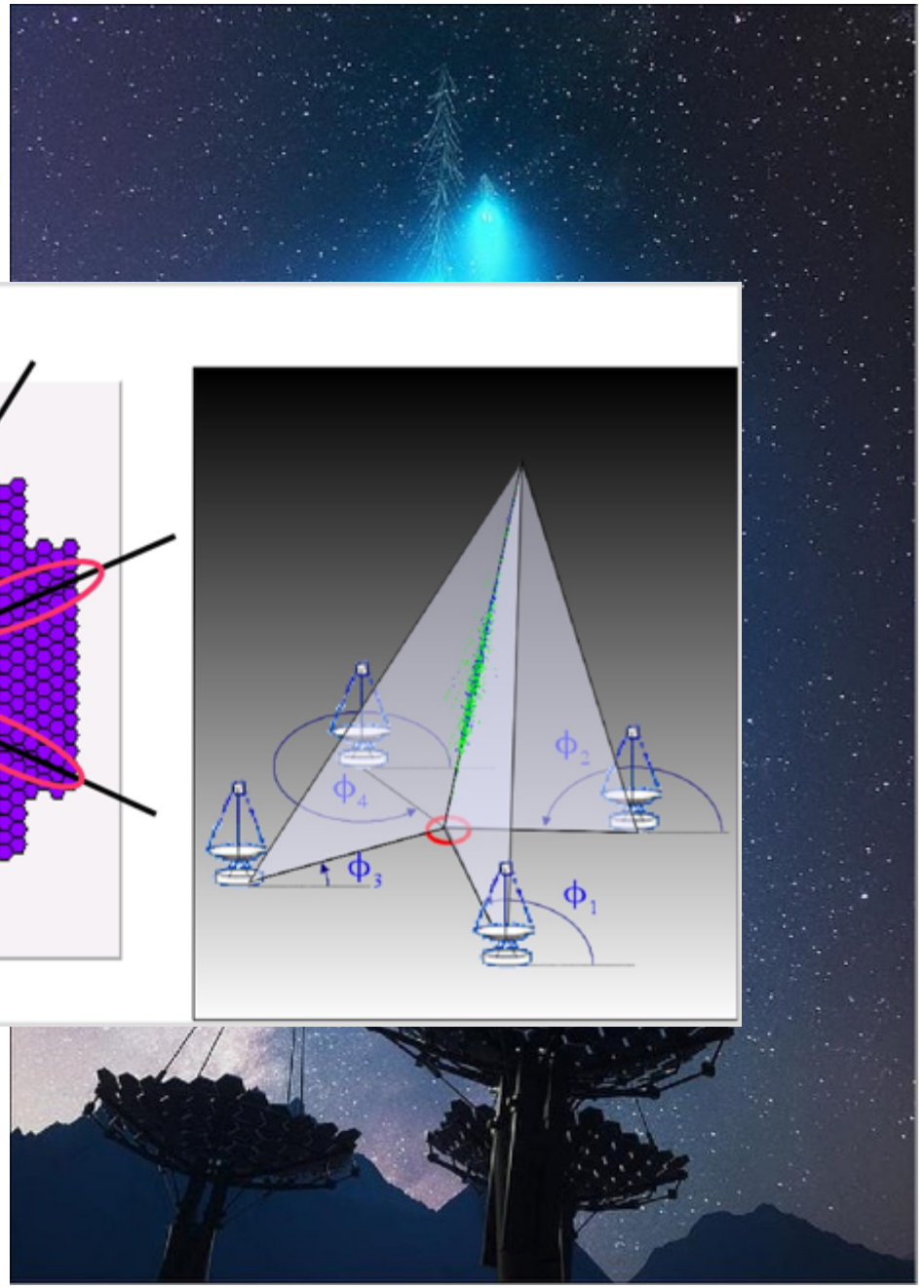
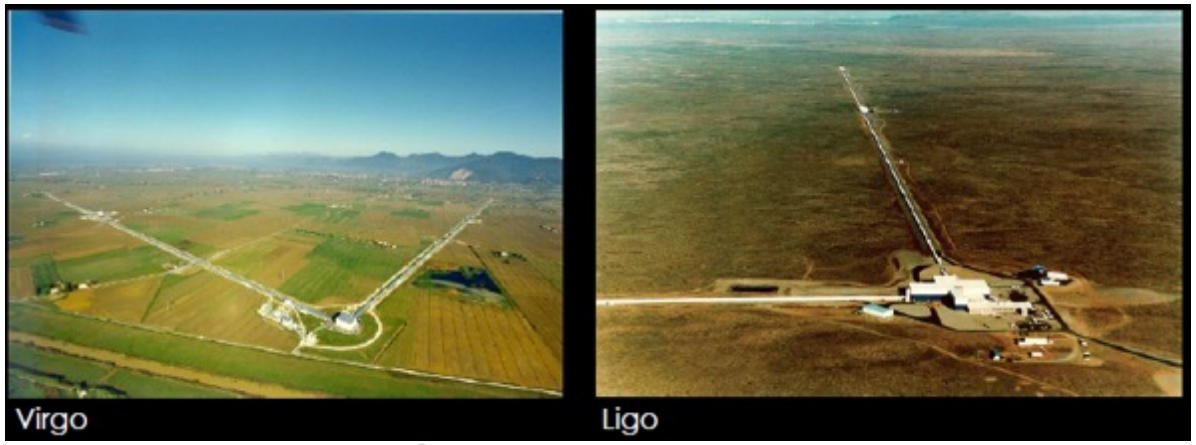
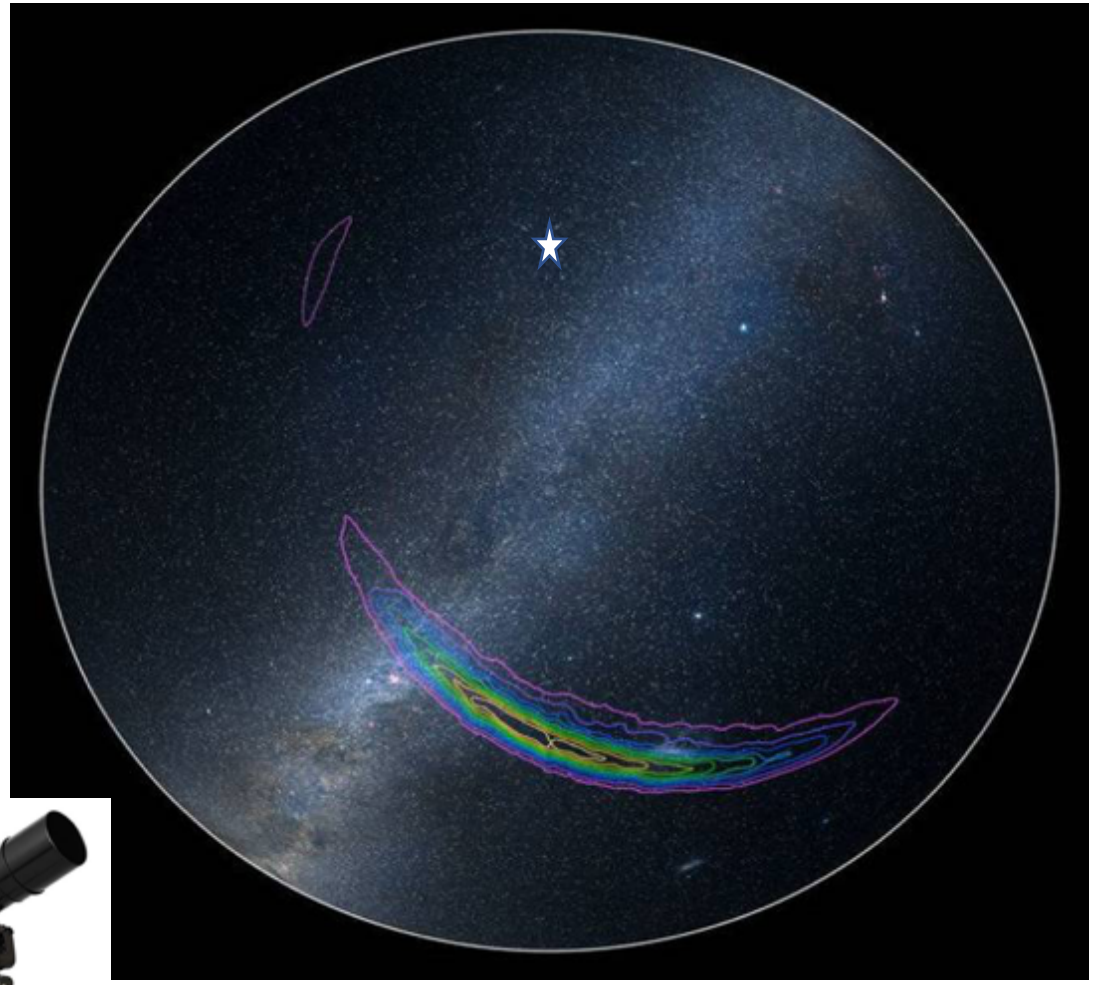


➢ **Probing the high energy non-thermal emission in GW, GRBs, FRBs and neutrino events**



GW: origin, detection and follow-up challenges





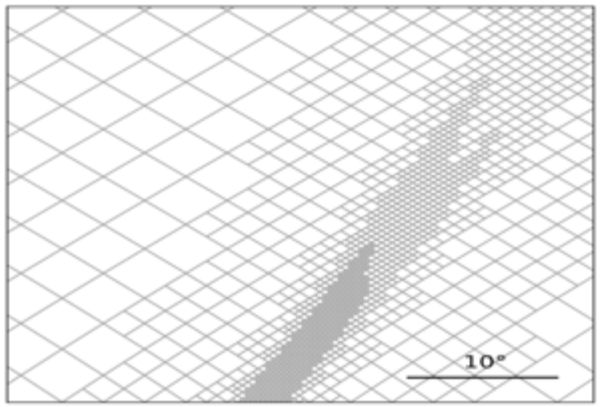
Poor localization -> large regions to inspect

GW: tackling the challenge: recipe

From GW detectors:

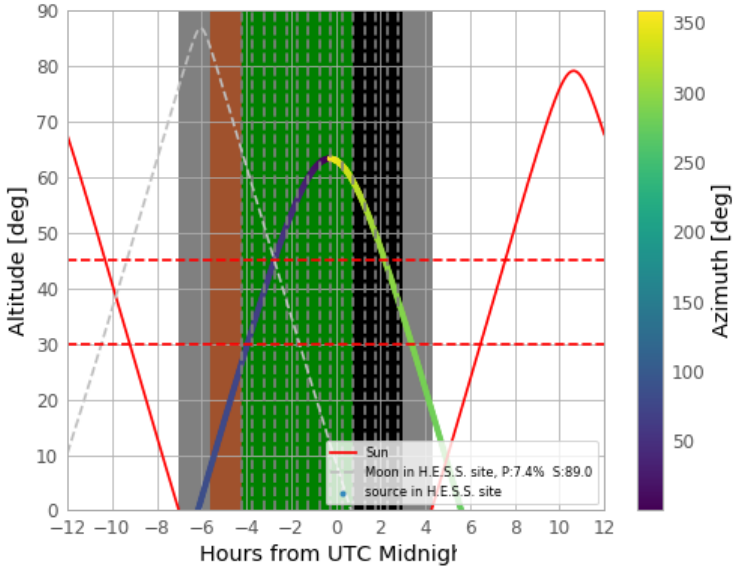
- GW localization map
  - HEALPix format
  - Pixel indices + 4 layers

1. Posterior Probability: ρ_i
   - Distance distribution info:
     2. Distmu: distance average: μ_i
     3. Distsigma: distance std deviation: σ_i
     4. Distnorm: normalization: N_i

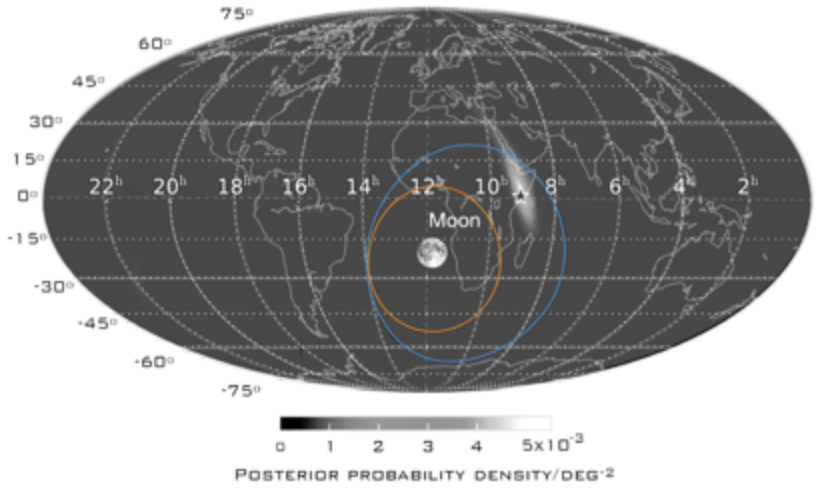


From our telescopes

- Observation time
- Observation conditions
- Visibility condition



Compute the best position to observe during each window – example in next slide

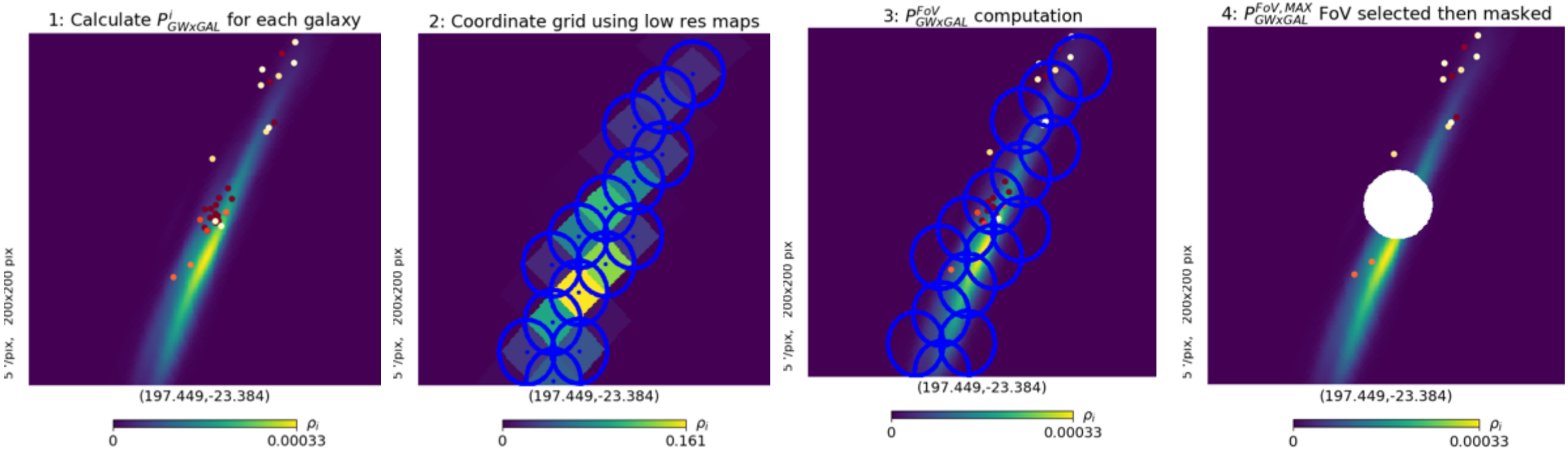


GW: follow-up algorithms and strategies

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

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

$$P^{\mathrm{FoV}}_{\mathrm{GWxGAL}} = \int_0^{2\pi} \int_0^{r_{\mathrm{FoV}}} P^i_{\mathrm{GWxGAL}}(r,\phi)\, \mathrm{d}r\mathrm{d}\phi.$$



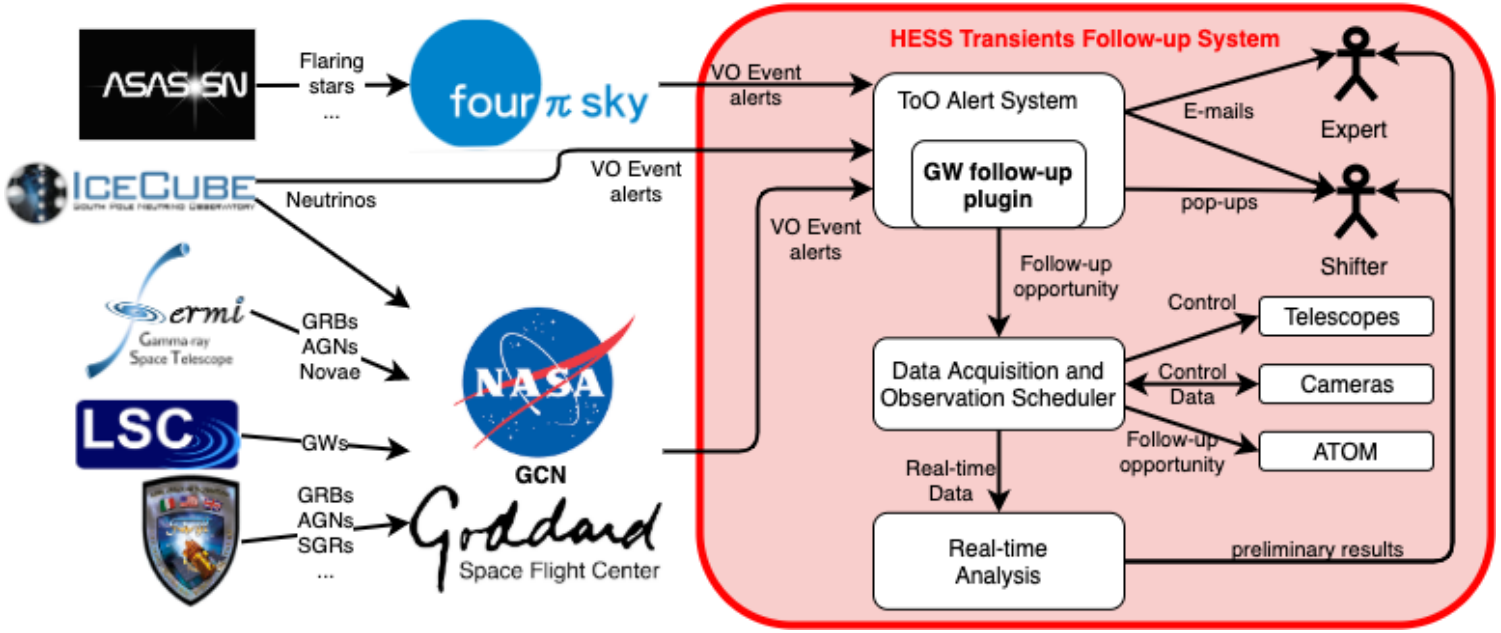
Re-do for next window

GW follow-up strategies

- 5 strategies in our arsenal (2D and 3D).
- Optimized, tested and assessed.
- I refer you to our paper for more info.

Ashkar et al., *JCAP,* JCAP03(2021), 45.

The H.E.S.S Transient ToO System.



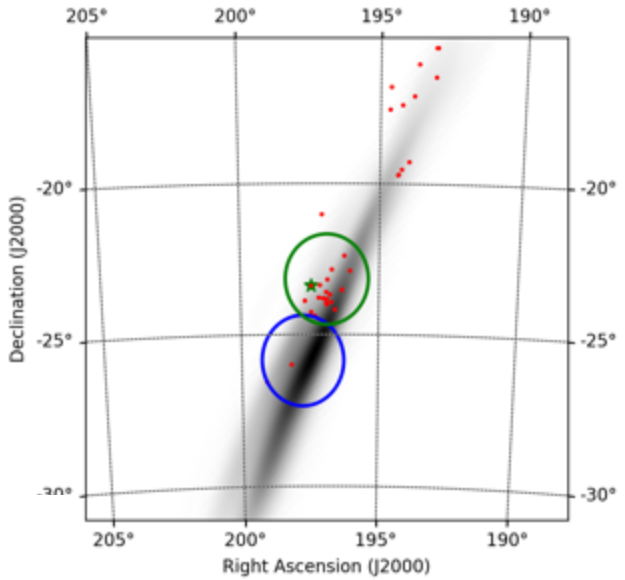
Observation results of VHE gamma-rays of GW170817

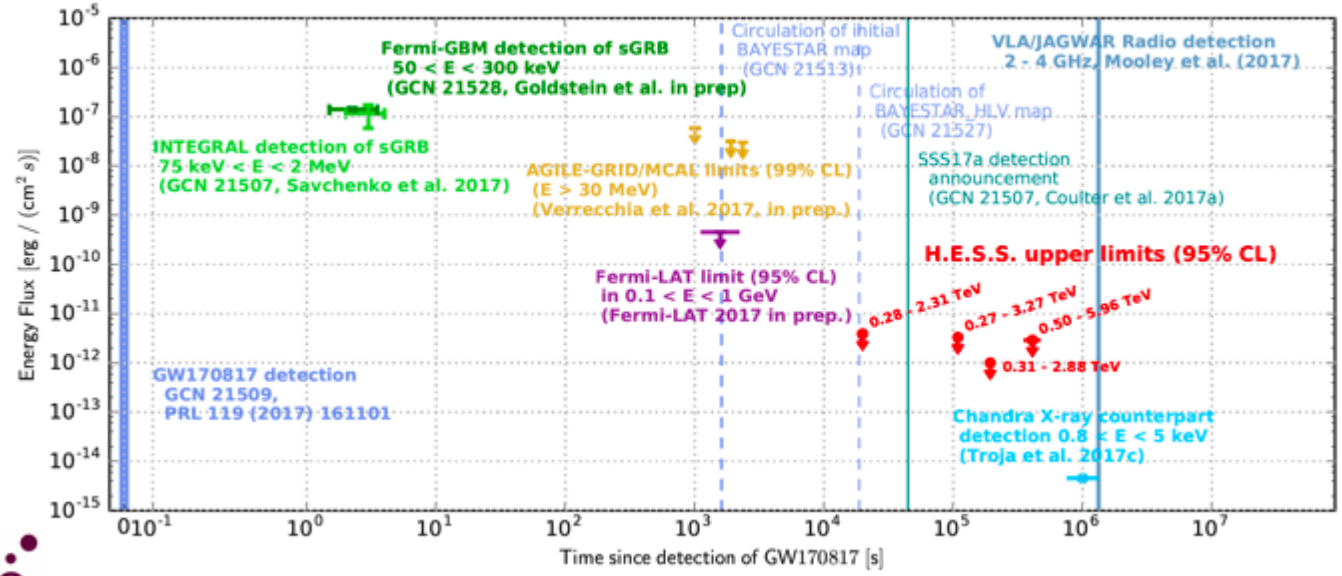
H.E.S.S. was the first ground based instrument on target!

- 5.3 hours after merger
- 5 minutes after the update of the GW skymap

(LV reconstruction)

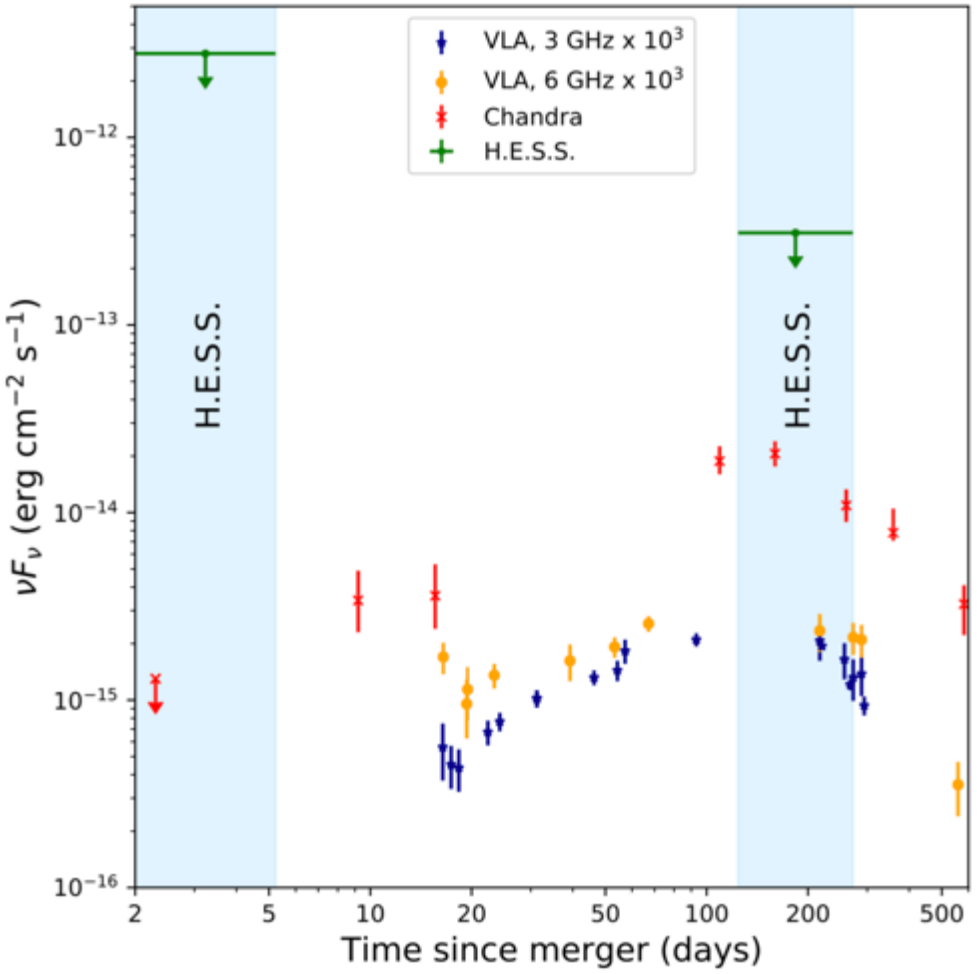
- The first ground-based observation was on the afterwards identified position of the NS-NS
- In subsequent nights, observations were modified according to the NS-NS location

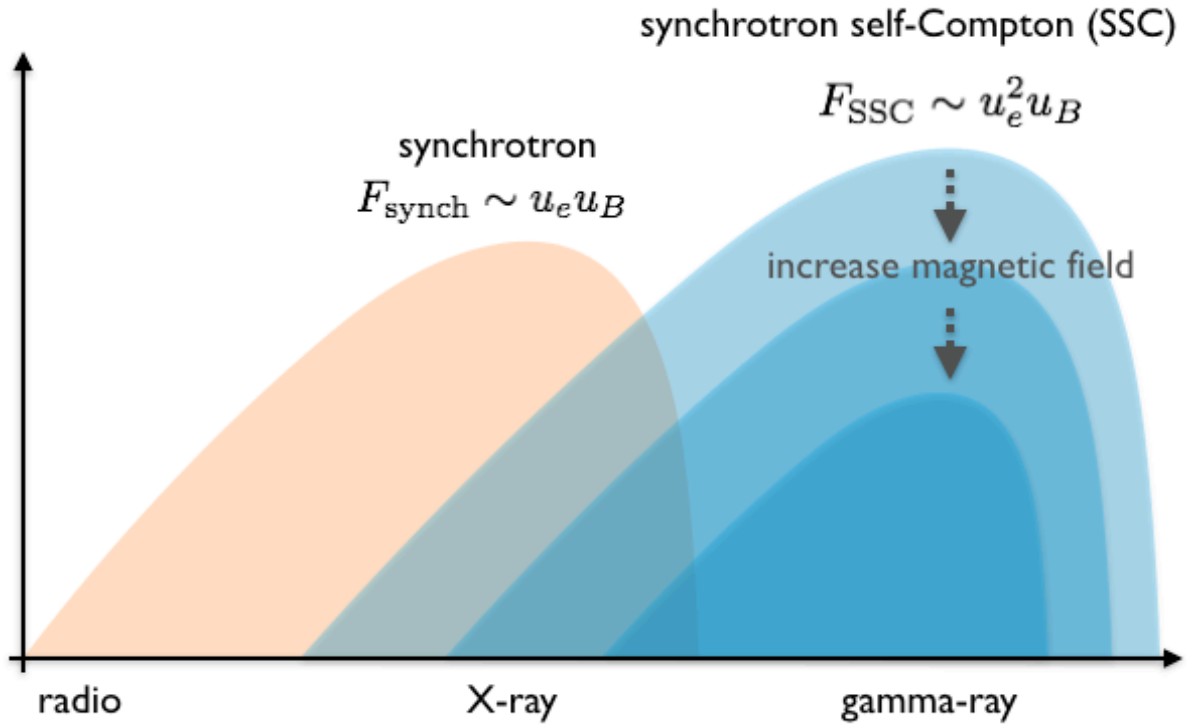




H.E.S.S. collaboration (2017). *ApJ.* 850. L22.

Observation results of VHE gamma-rays of GW170817

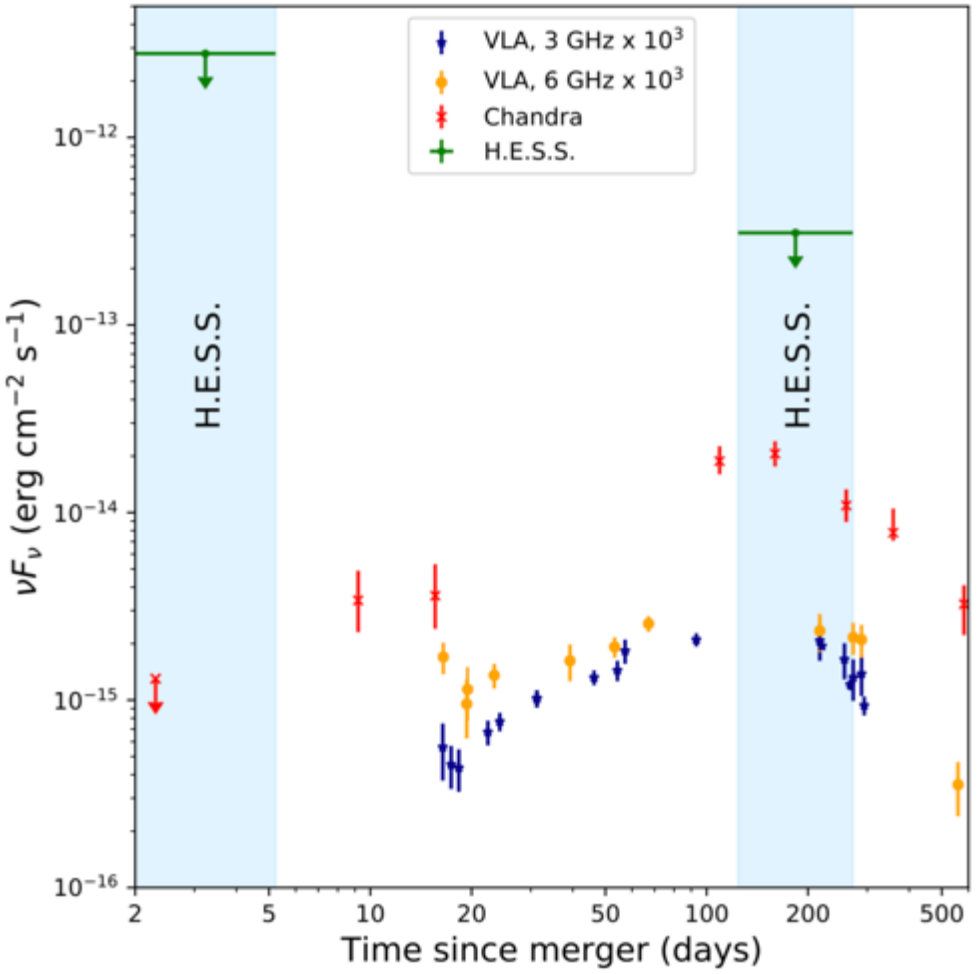


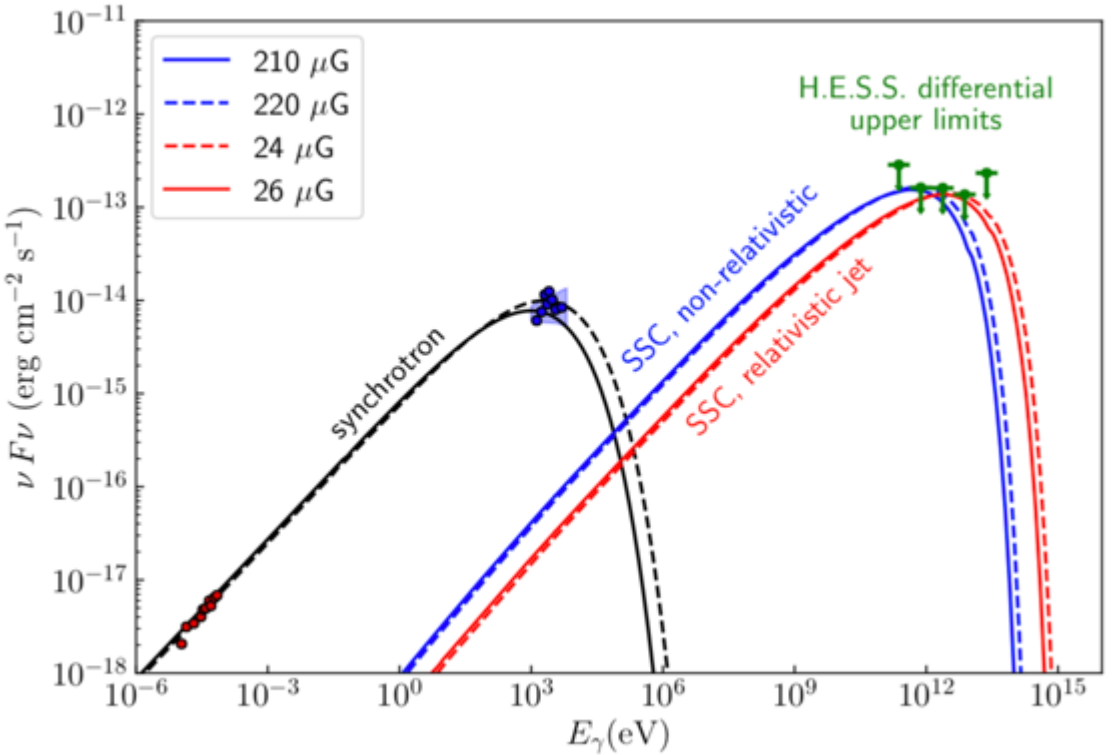


2 scenarios:
Spherical outflow: $\gtrsim$ 200 uG
Off-axis jet: $\gtrsim$ 50 uG

H.E.S.S. collaboration et al., *APJ*, **894,** L16

Observation results of VHE gamma-rays of GW170817



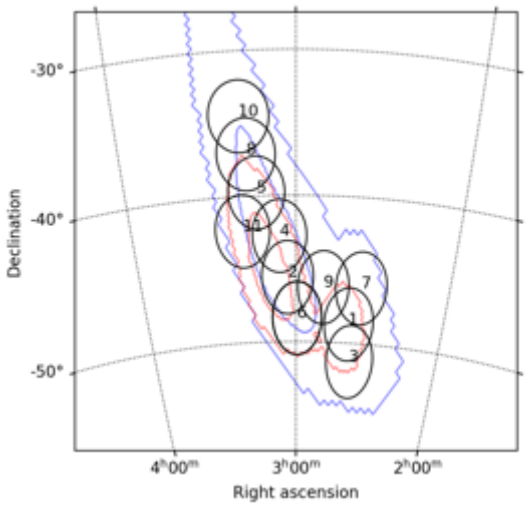


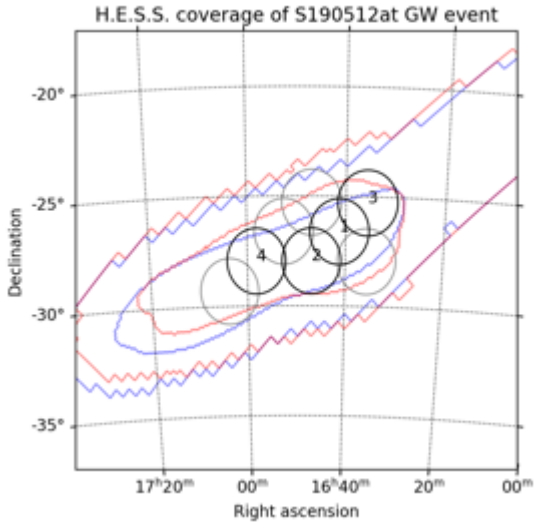
2 scenarios:
Spherical outflow: ≳ 200 uG
Off-axis jet: ≳ 50 uG

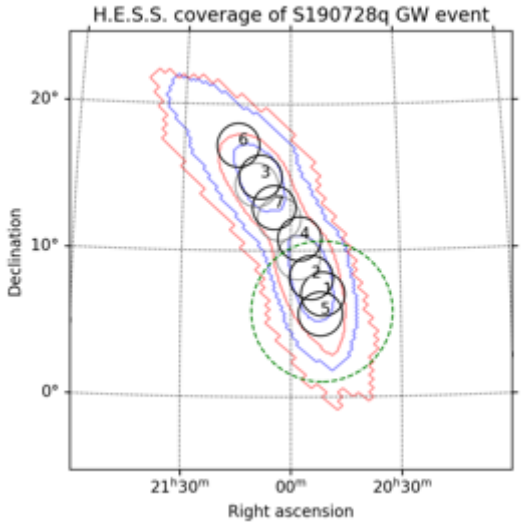
H.E.S.S. collaboration et al., APJ, 894, L16

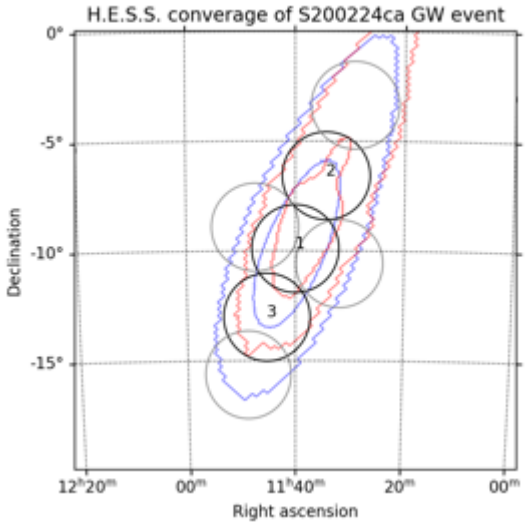
Observation results of Black Hole mergers

- Results are still not public
- They will be published in: **H.E.S.S. collaboration et al. in preparation for *ApJ.***





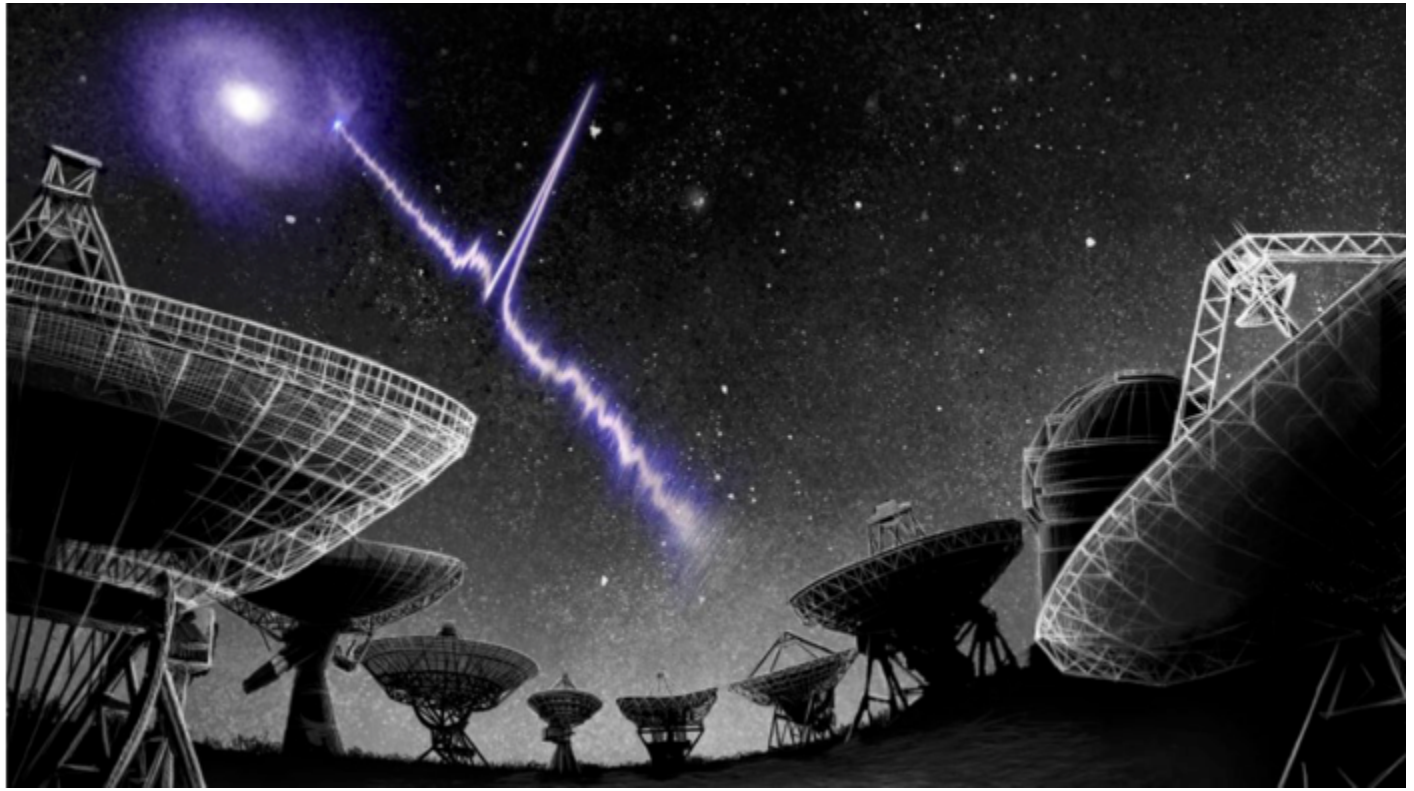




Fast Radio Bursts

- Bright ms flashed of radio emission
- Mysterious origin
- Mysterious process
- **Extragalactic origin**

FRB theory wiki



- Potential sites:
  - Magnetars
  - Pulsar and neutron stars
  - Neutron star mergers
  - AGNs
  - Cosmic strings
  - Alien spaceships

Fast Radio Bursts: the search for counterparts

By implementing ToO follow-up of FRBs

VoEvent protocol

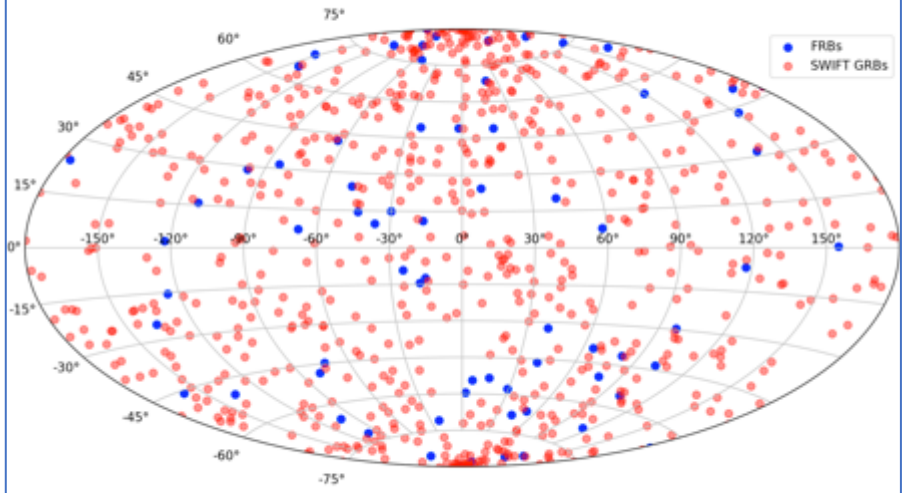
Joint observational campaigns with radio telescopes

FRB171019. joint campaign with MeerKAT, H.E.S.S. ans Swift.

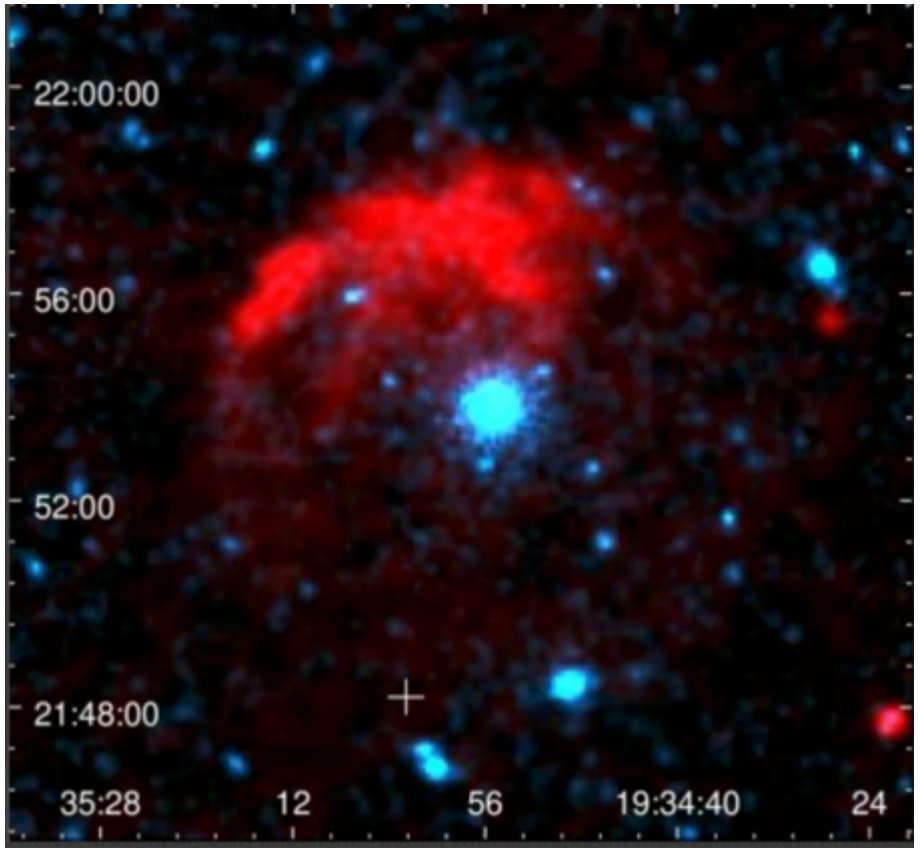
Caleb et al. in preparation for *MNRAS*

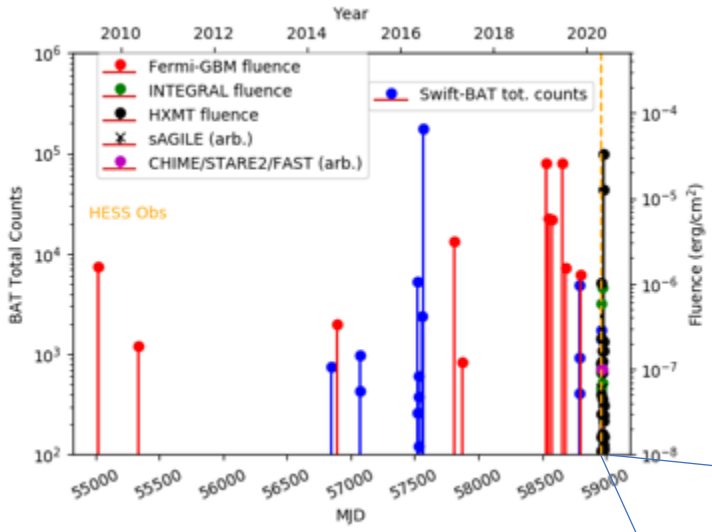
DWF: radio, optical, X-ray and gamma telescopes looking at the same sky together

Search the archival data for coincidence

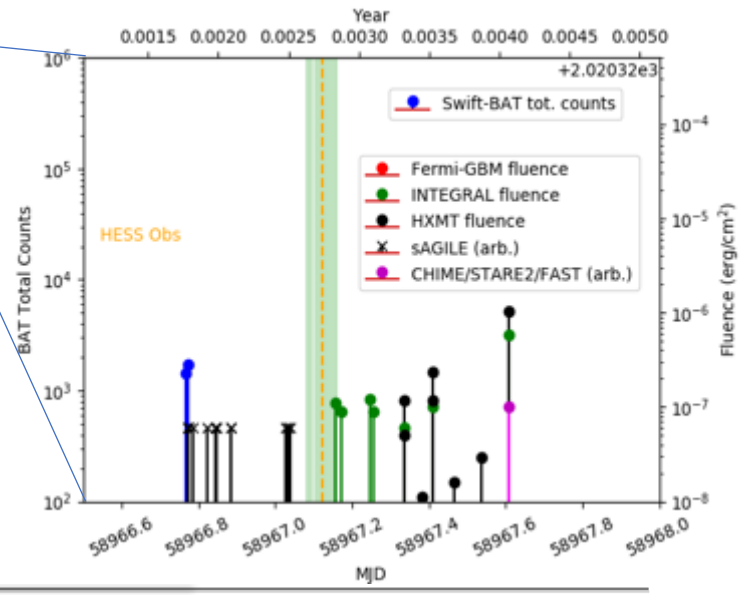


FRBs and Soft Gamma-ray Repeaters: SGR1935+2154 and FRB200428





Search for variability down to the ms scale



H.E.S.S. collaboration et al. in preparation for *MNRAS*

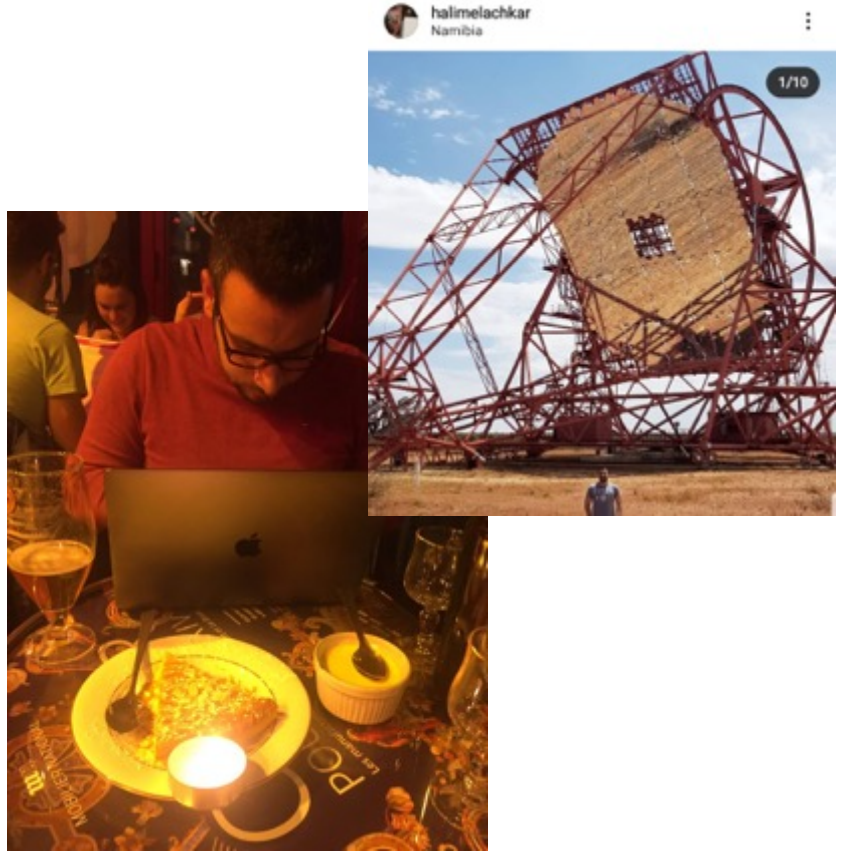
Summary

5 ToO sources - 4 messengers - 3 challenges
GW, GRB, **FRB**, SGR, Neutrino
GW, EM, CR, Neutrinos

Pre-observation:

- Optimization of follow-up
- Efficient scheduling
- Fast telescope response
- Network and bridges between facilities

Observation:



Post-Observation:

- New analysis methods
- Search for variability
- MWL and MM context
- Interpretation
- Discrimination or approval of models

Publications

Corresponding author:

- H.E.S.S. collaboration et al. (2019). Probing the magnetic field in the GW170817 outflow using H.E.S.S. observations, *ApJ*, 894, L16.
- Ashkar, H. et al. (2021). The H.E.S.S. Gravitational Wave Rapid Follow-up Program, *JCAP*, JCAP03(2021), 45.
- H.E.S.S. collaboration et al. (2021). H.E.S.S. follow-up of Binary Black Hole Coalescence events during the second and third Gravitational Waves observing runs, in preparation for *ApJ*.
- H.E.S.S. collaboration et al. (2021). Observation of burst activity from SGR1935+2153 associated to first galactic FRB with H.E.S.S, in preparation for *MNRAS*.
- Manisha, K. et al. (2021). MeerKAT search for persistent radio emission associated with localised FRBs, in preparation for *MNRAS*.

Contributor:

- H.E.S.S. collaboration et al. (2021). Paper on GRB190829A (title soon to be public), accepted for publication.

Previous publications:

- F. Durret, Y. Tarricq, I. Márquez, H. Ashkar, C. Adami (2019). The link between brightest cluster galaxy properties and large-scale extensions of 38 DAFT/FADA and CLASH clusters in the redshift range $0.2 < z < 0.9$, *A&A*, 622, A78.

Proceedings:

- H. Ashkar, F. Schüssler, M. Seglar-Arroy (2019). Searches for TeV gamma-ray counterparts to gravitational wave events with H.E.S.S., *Memorie della Società Astronomica Italiana*, 90, 49.
- H. Ashkar (2020). The hunt for VHE gamma-rays in the Gravitational Waves era, JRJC 2019. Book of Proceedings. 2020. hal-02971995v2, 11.

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