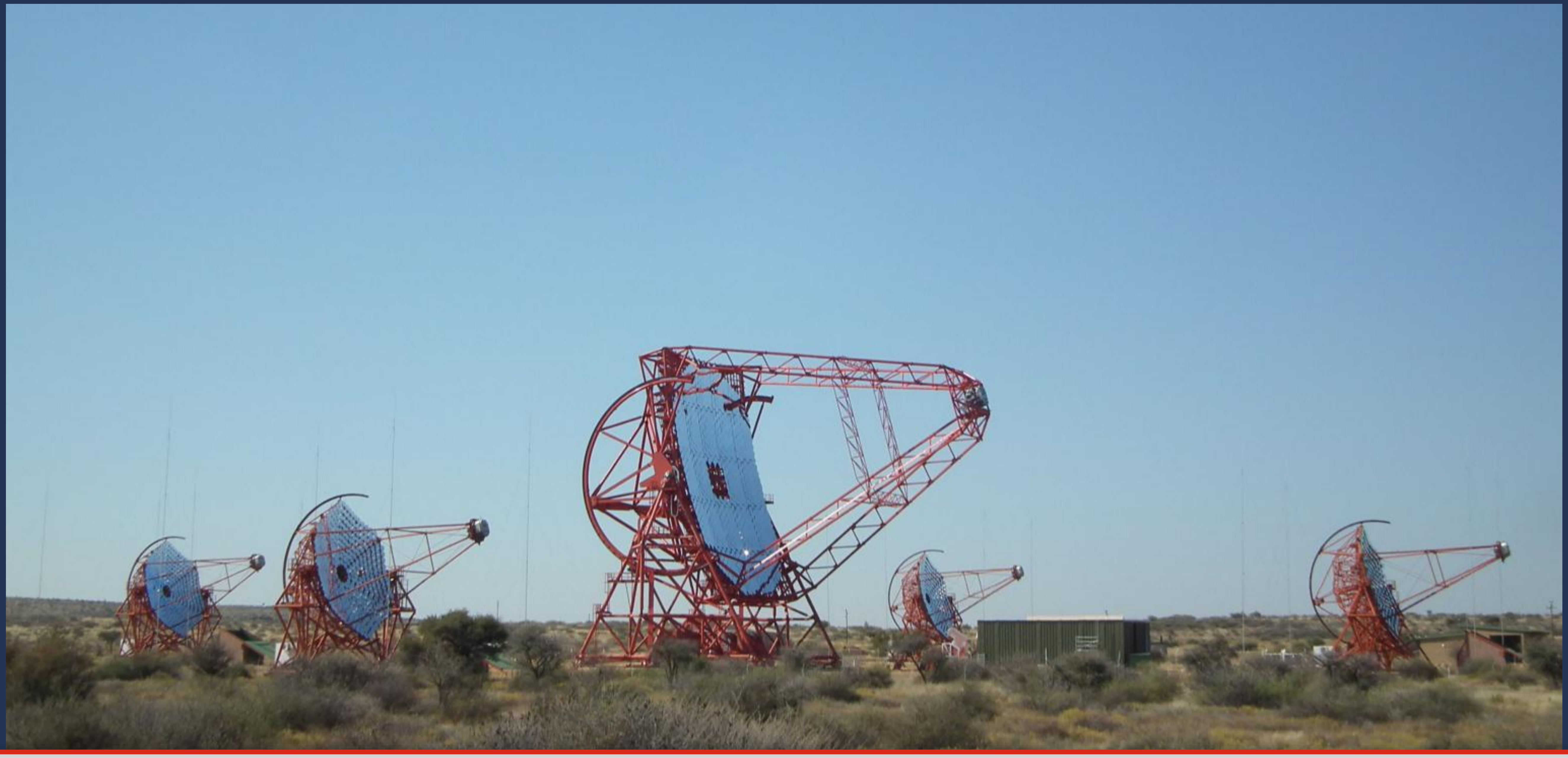
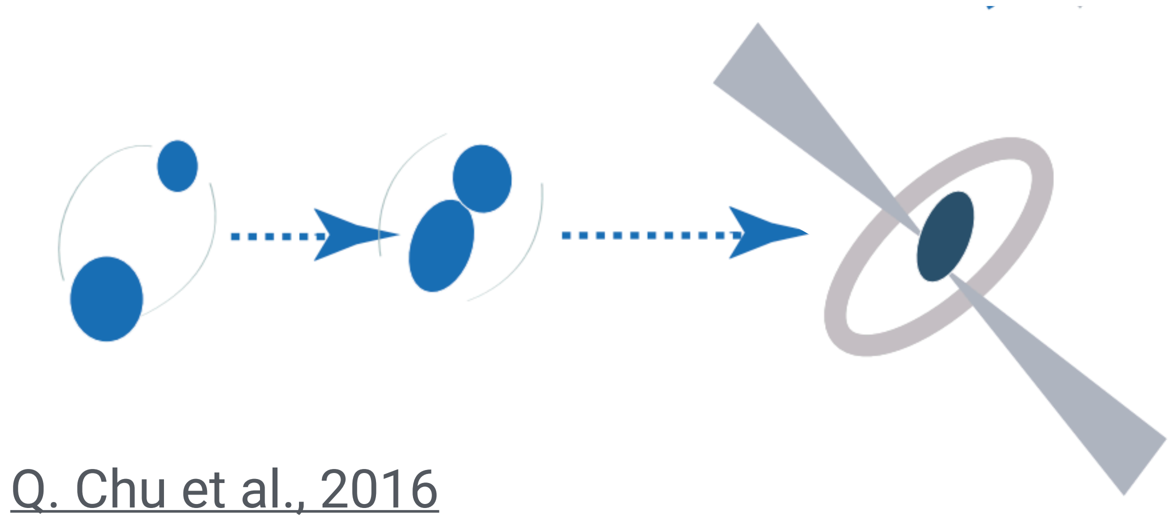
Gravitational-wave follow-up at Very High Energies with H.E.S.S.

Sylvia J. Zhu, DESY

Halim Ashkar (LLR), Ruslan Konno (DESY), Heike Prokoph (DESY), Fabian Schüssler (CEA)
and the H.E.S.S. GW group



H.E.S.S.



Q. Chu et al., 2016

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H.E.S.S.

“VHE”: >100 GeV

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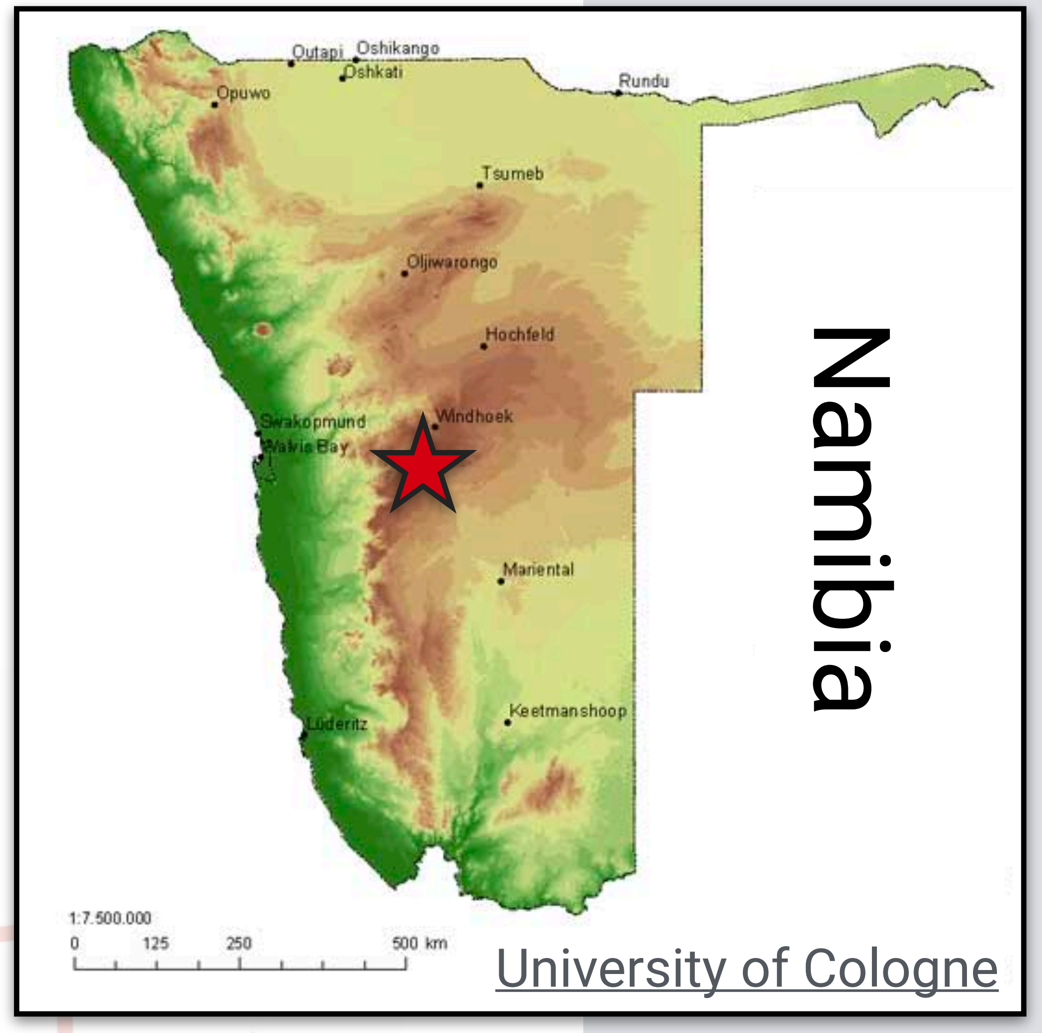
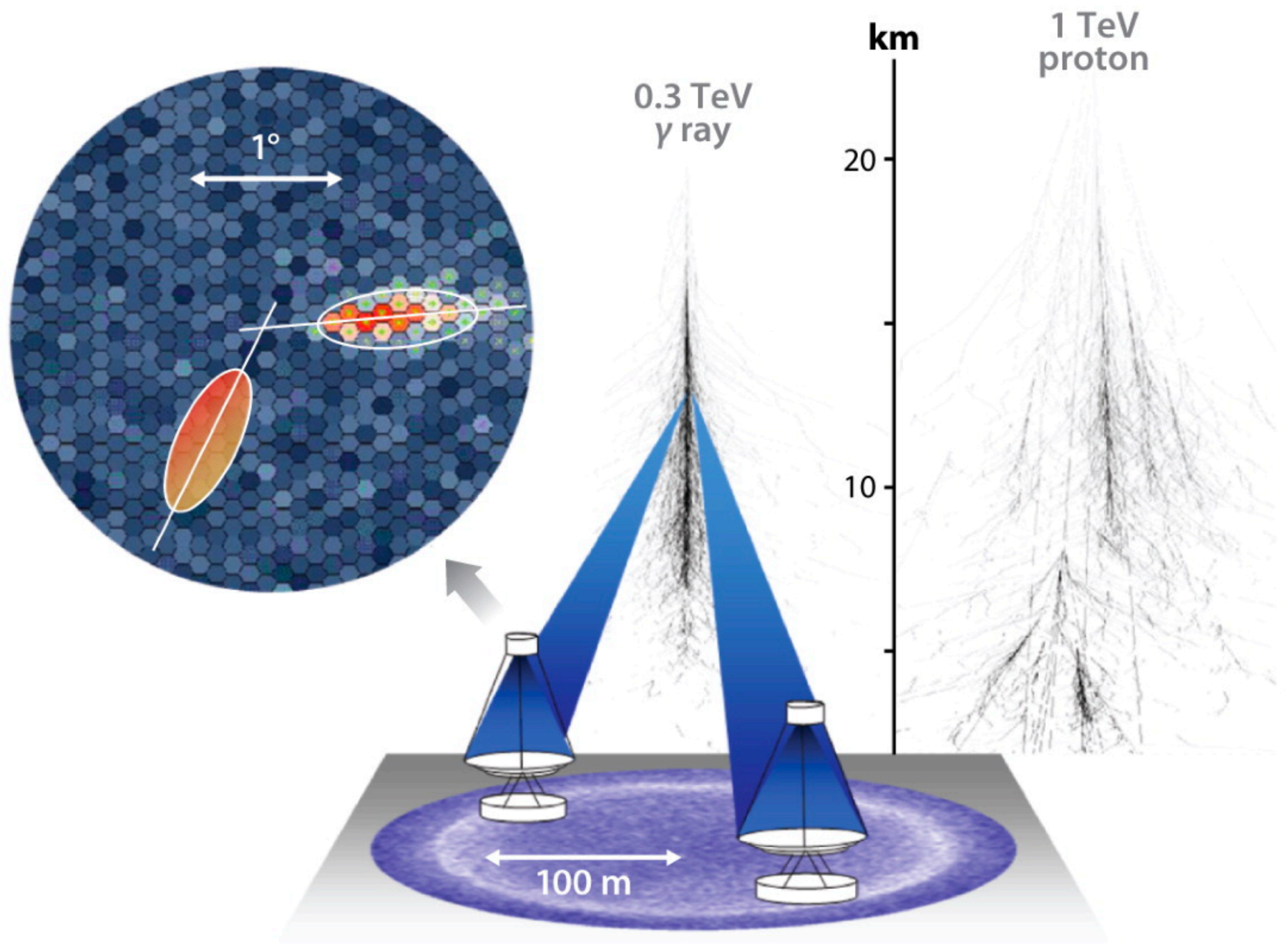


H.E.S.S.: High Energy Stereoscopic System

To detect VHE gamma rays, you have to use the atmosphere as part of your detector

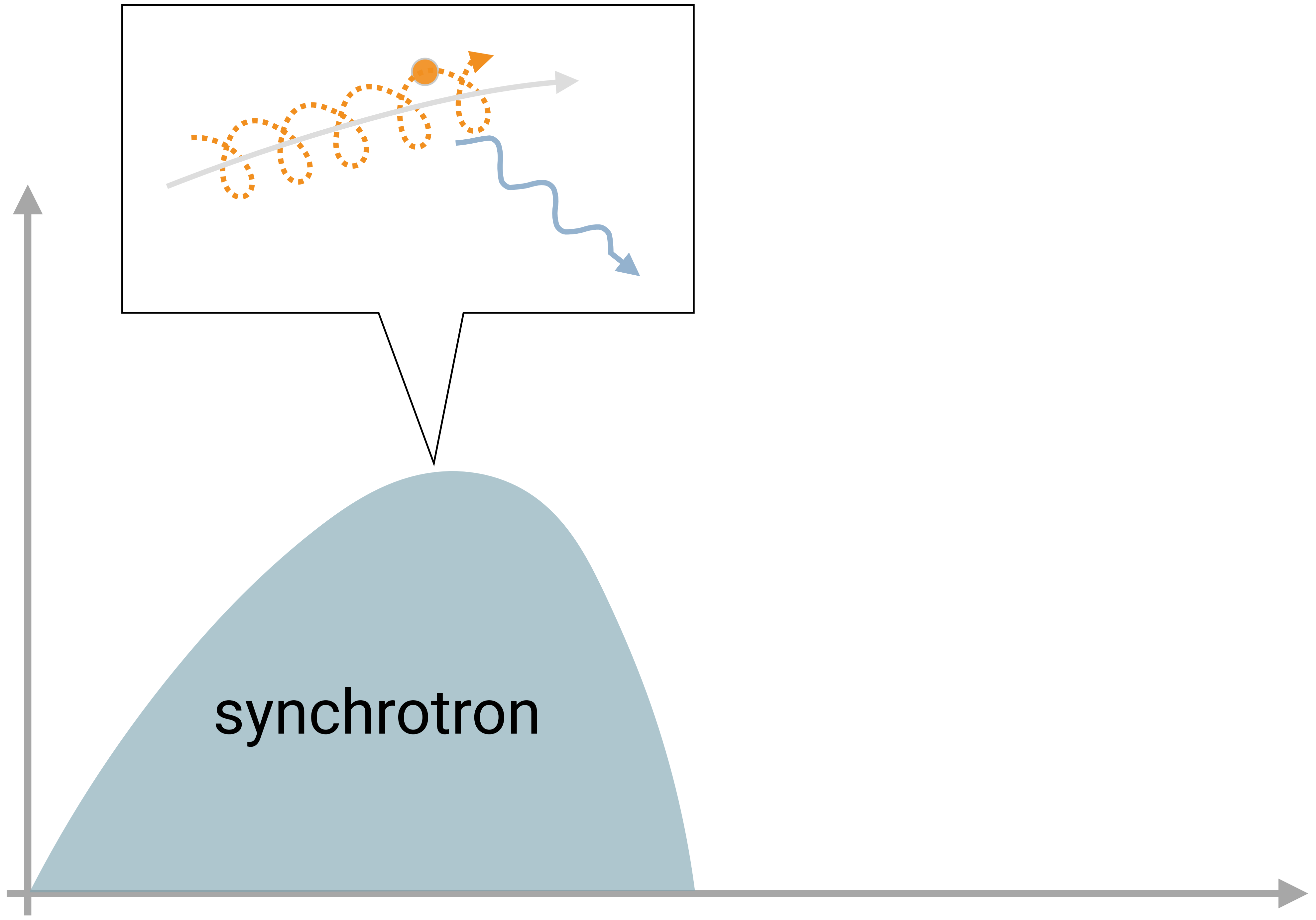
(or water)

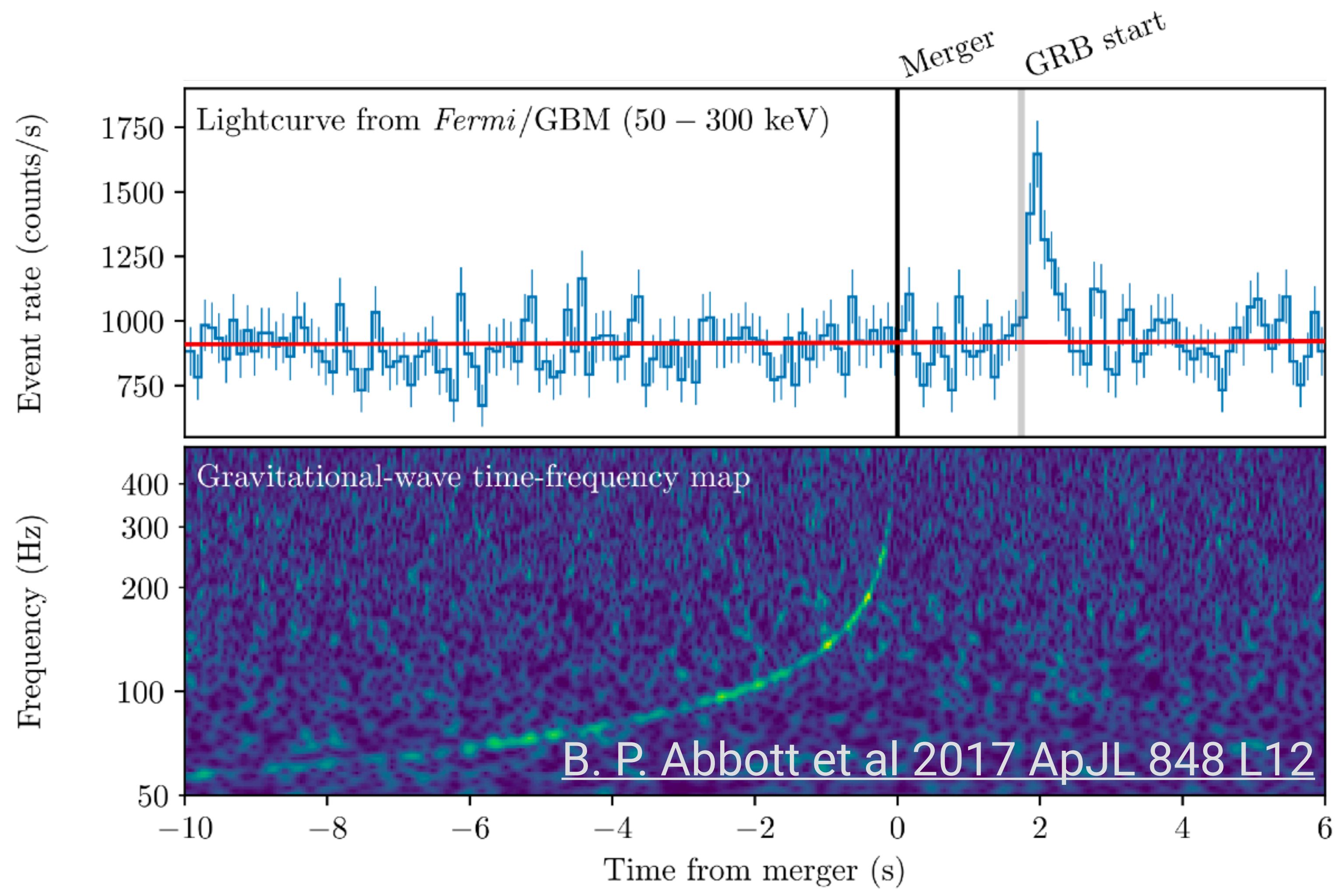
- Field of view ~ 20 deg^2 (a few deg radius)
- Energy range ~ tens of GeV to hundreds of TeV
- Can repoint 100° per minute
- One 28m + four 12m telescopes

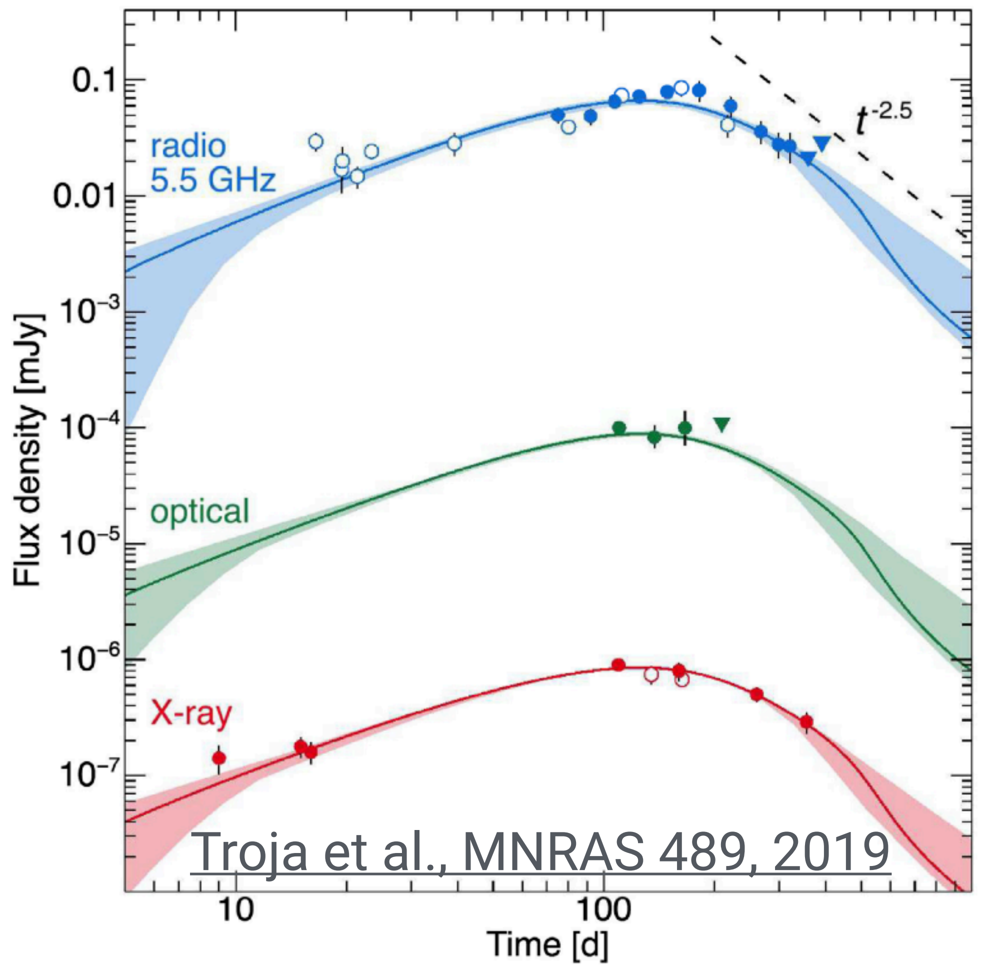


Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

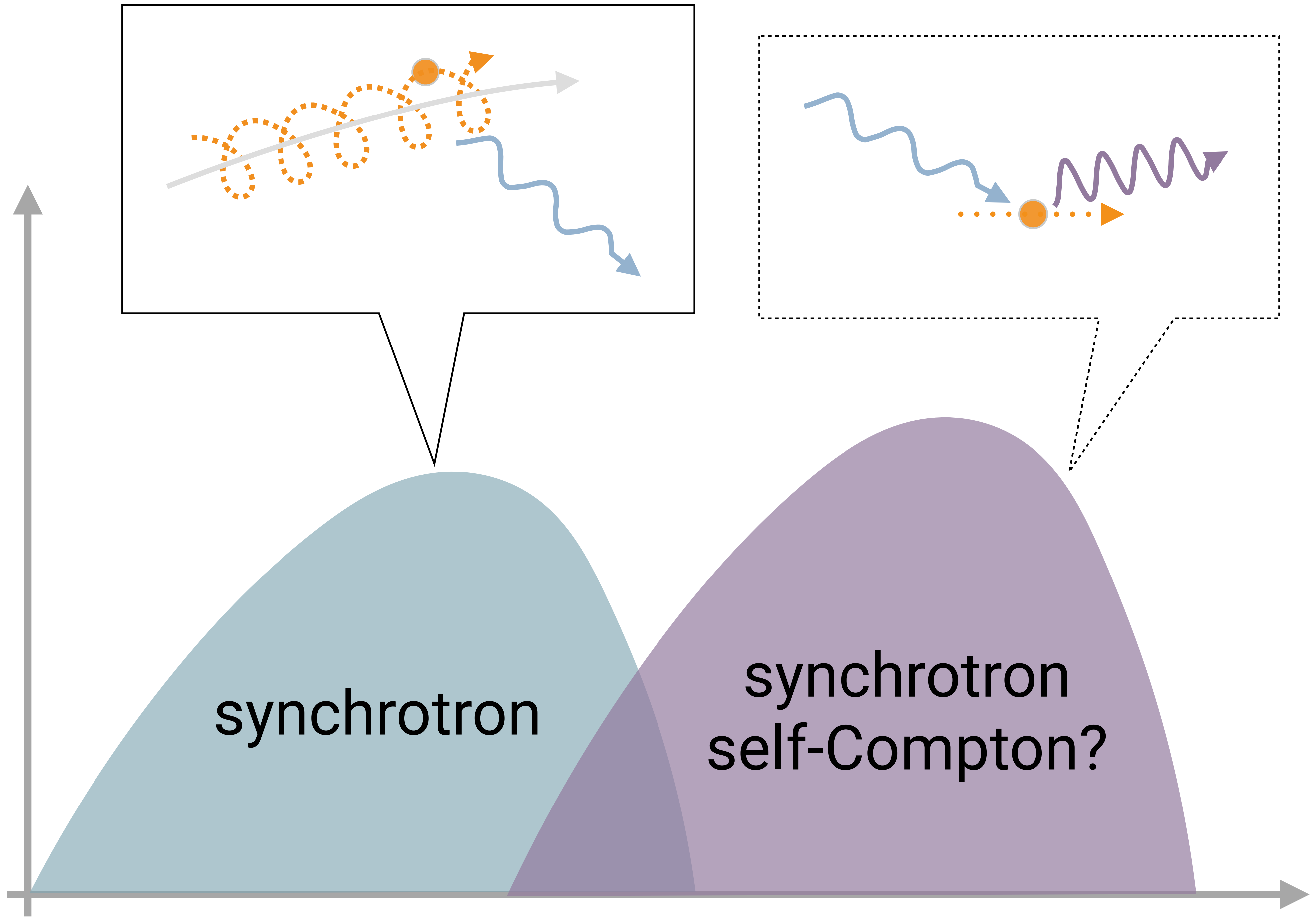
VHE follow-up of GW events: What are we looking for?

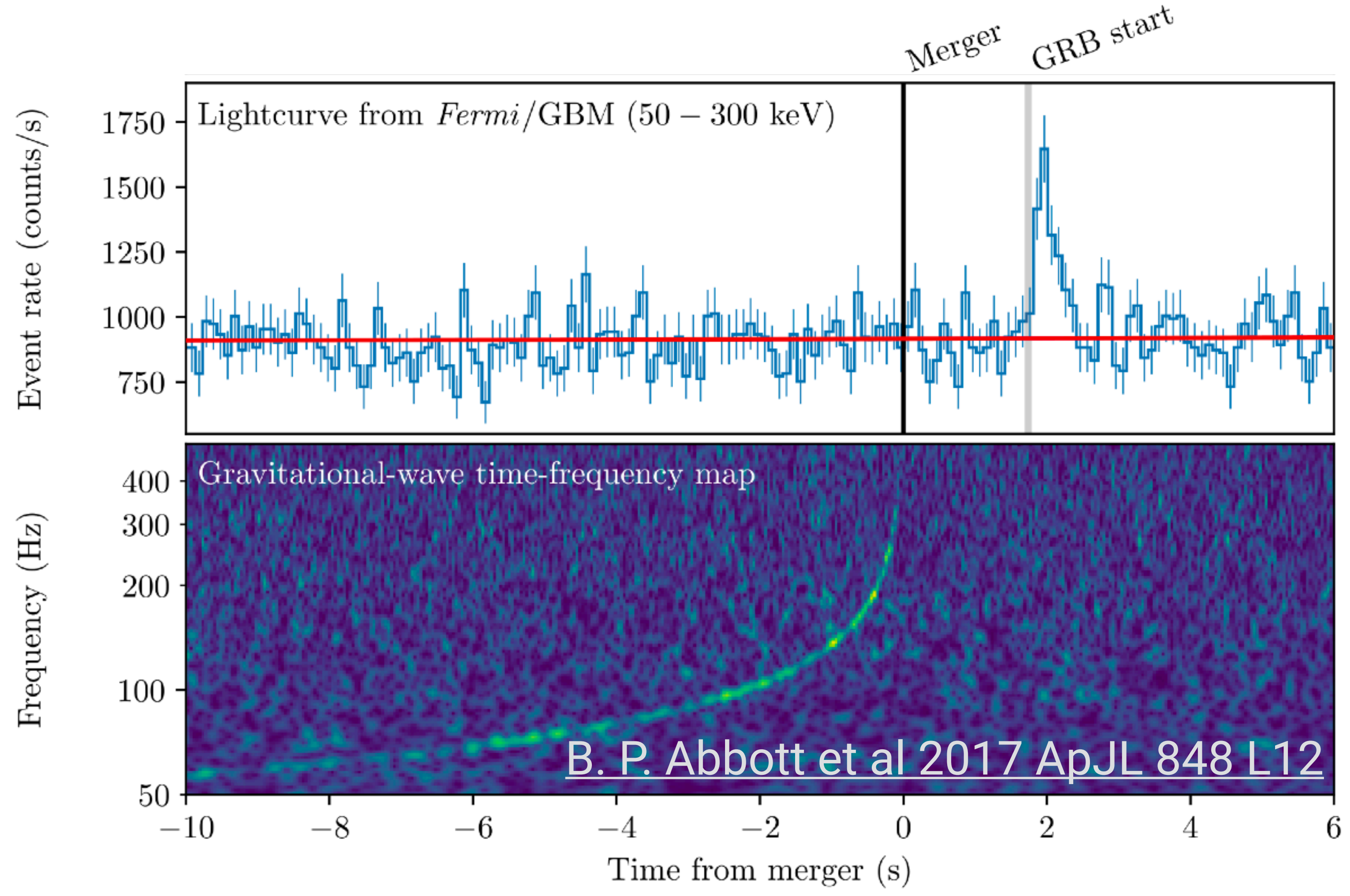


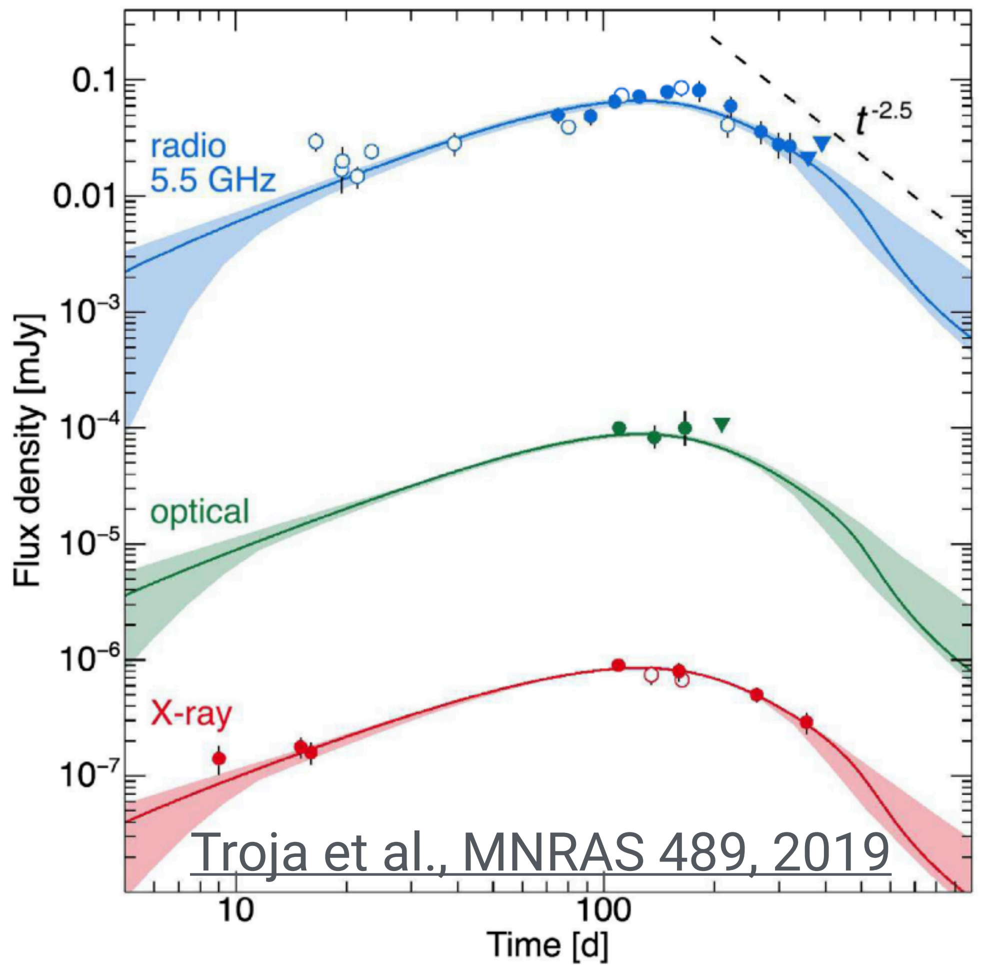




VHE follow-up of GW events: What are we looking for?



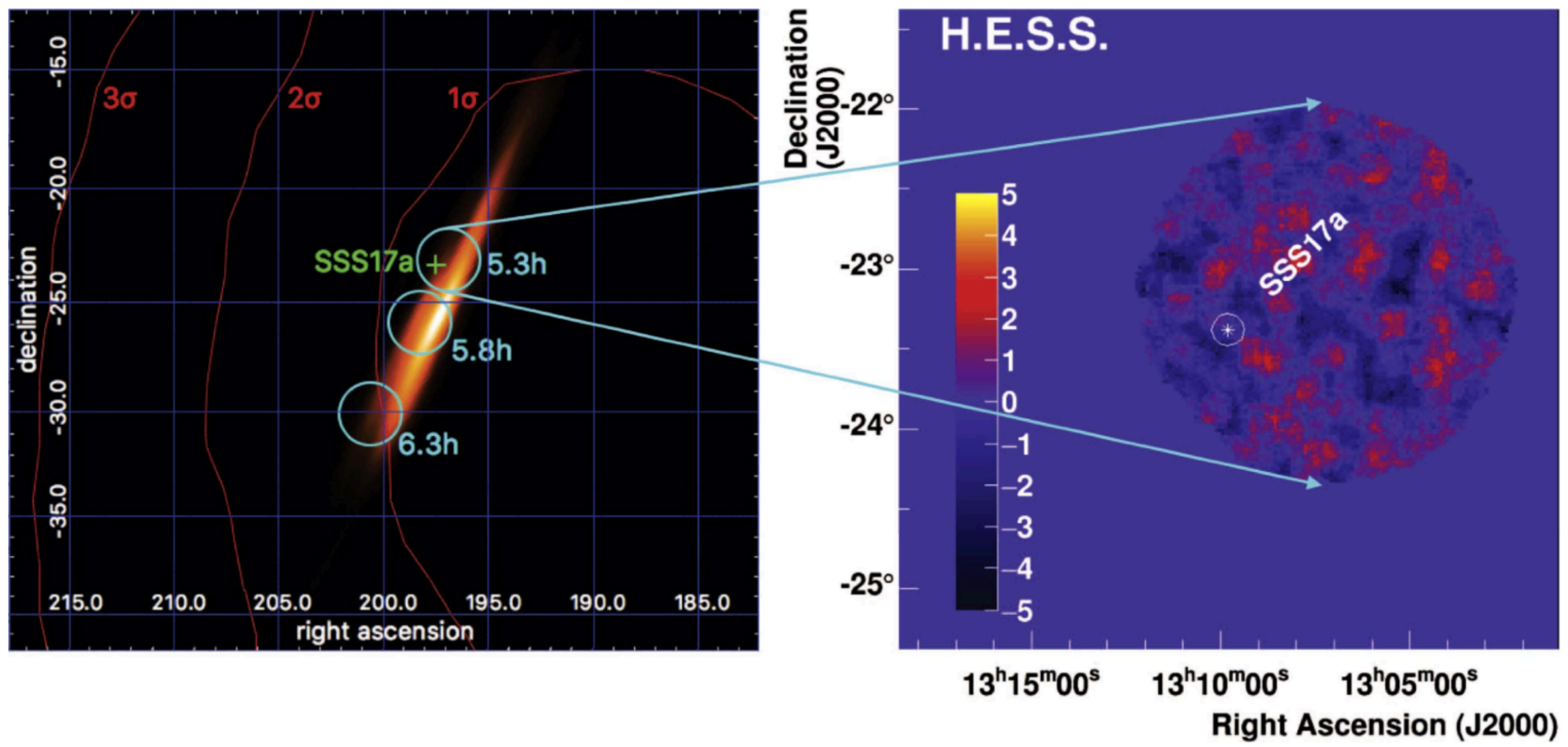




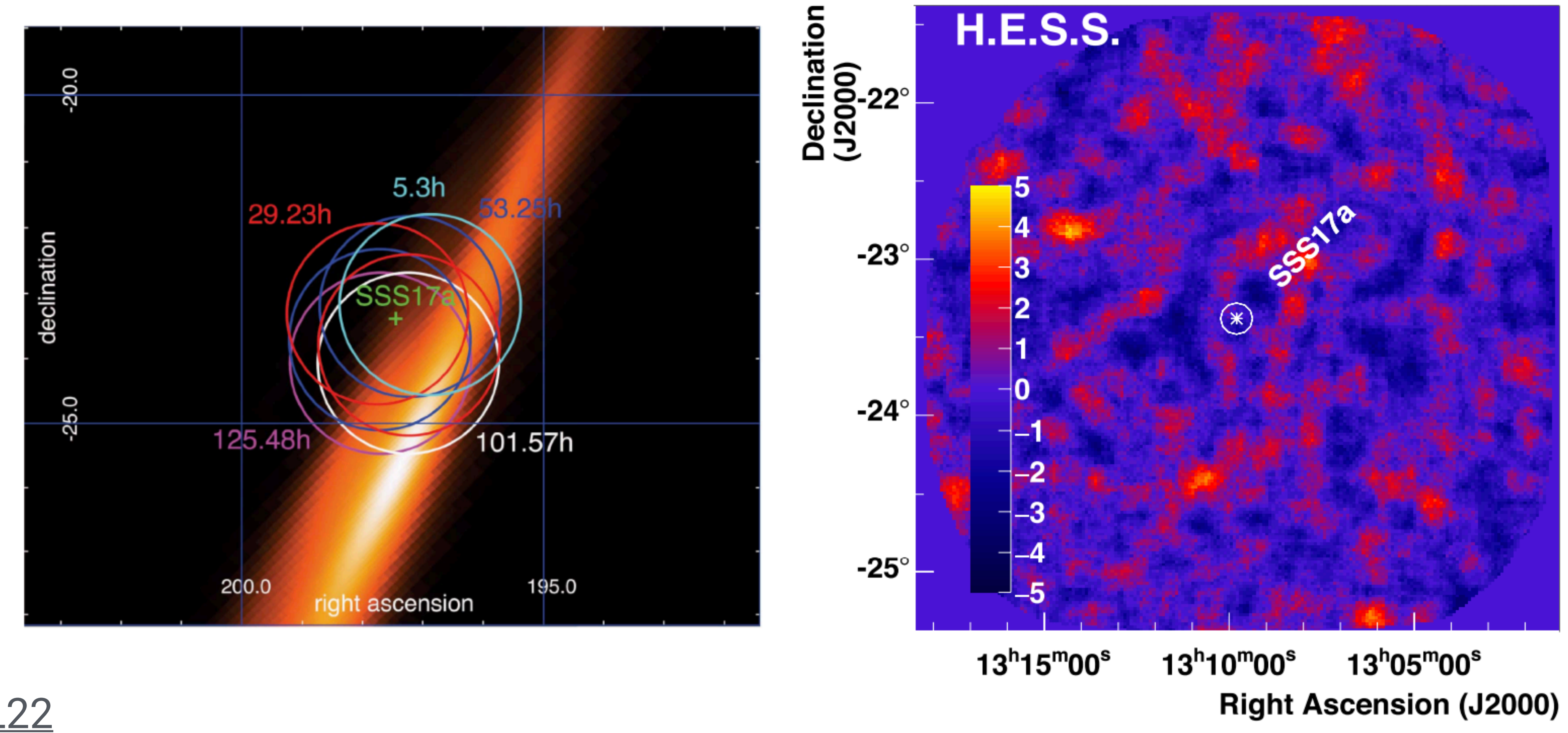
GRB 170817A: Rapid follow-up

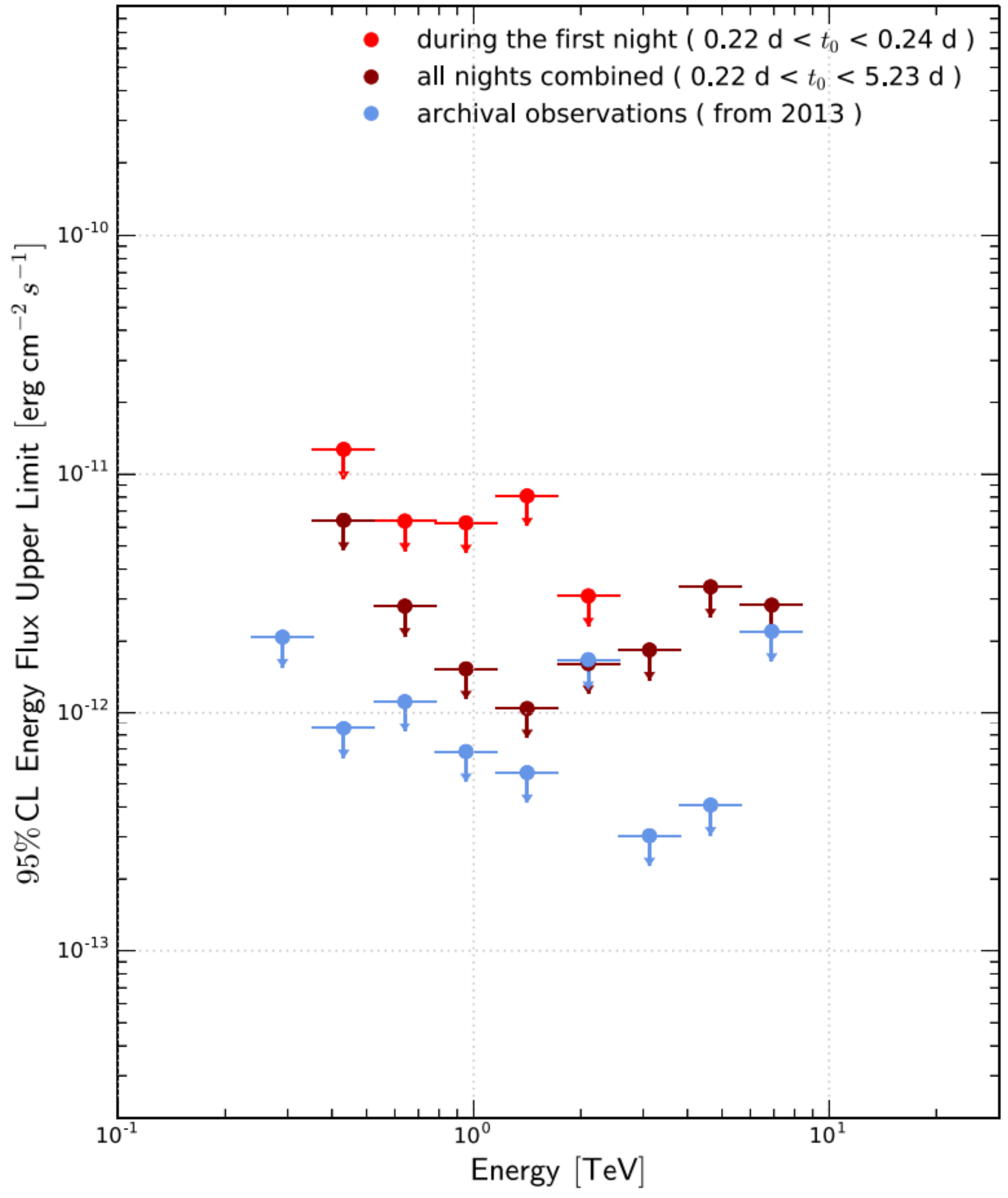
H.E.S.S. observed the true position within 5.3 hours of the merger, as well as on later nights

night 1



nights 2-6



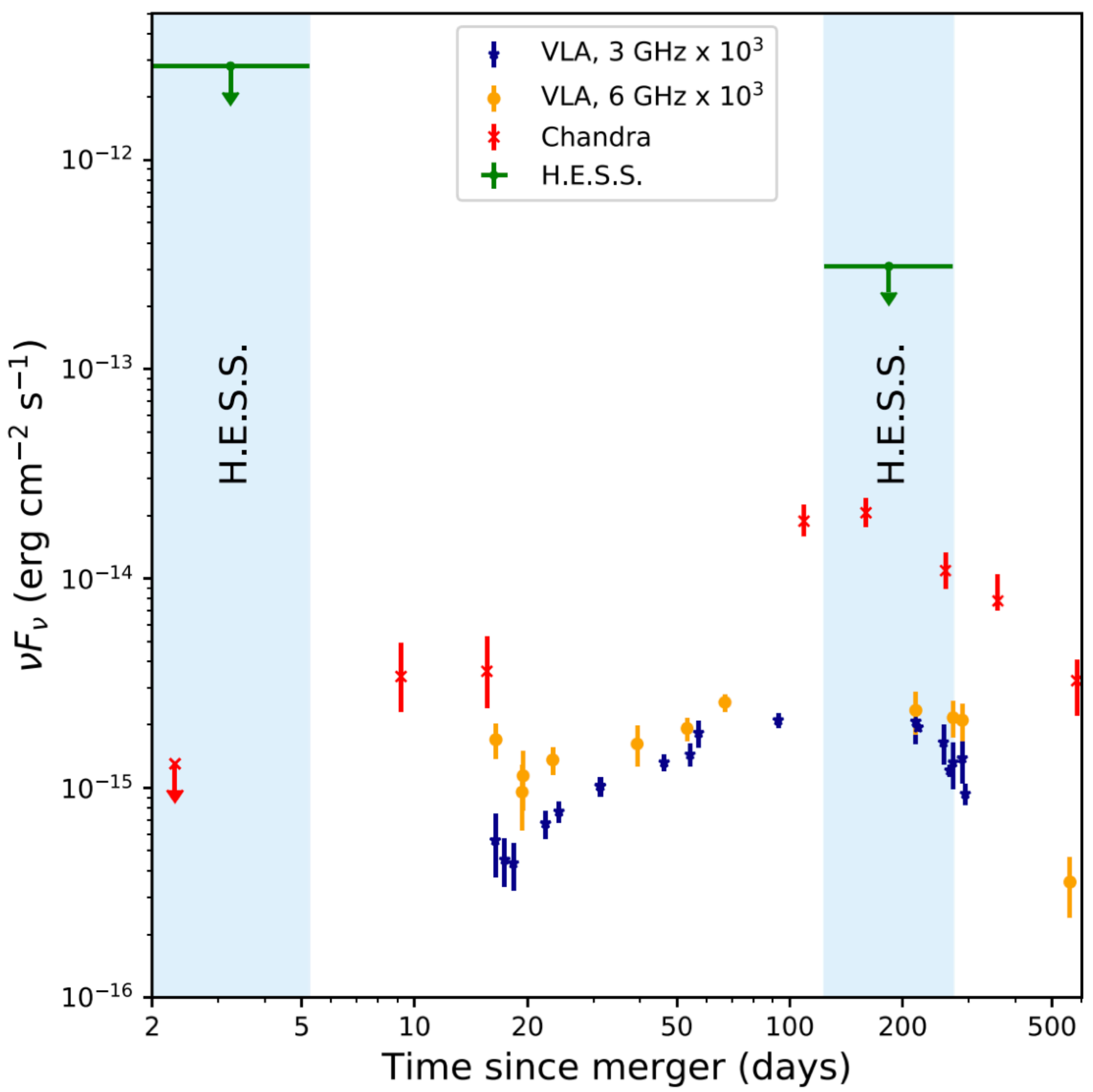


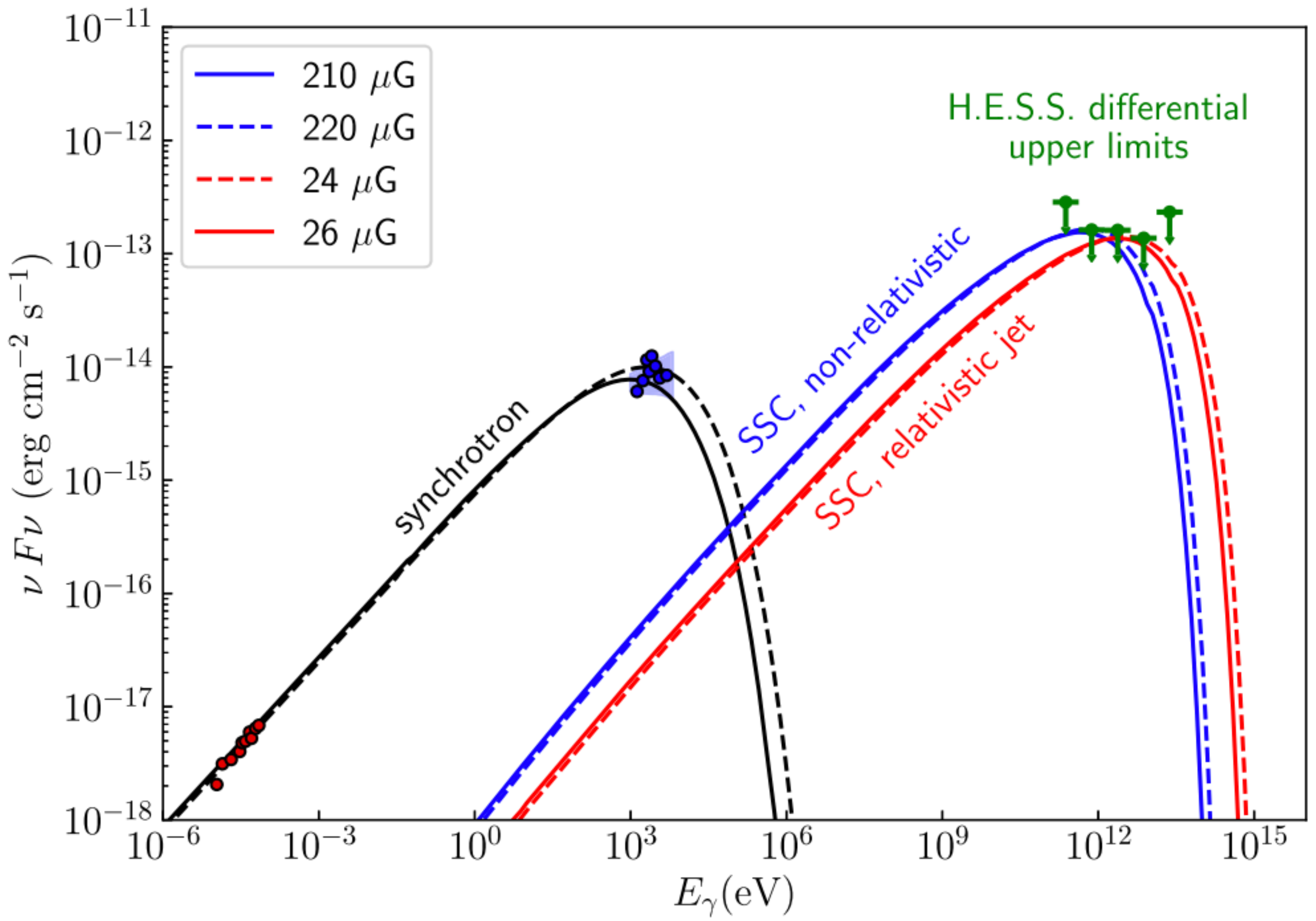
(a) SSS17a: H.E.S.S. limits

H. Abdalla et al 2017 ApJL 850 L22

GRB 170817A: Deep observations during the afterglow peak

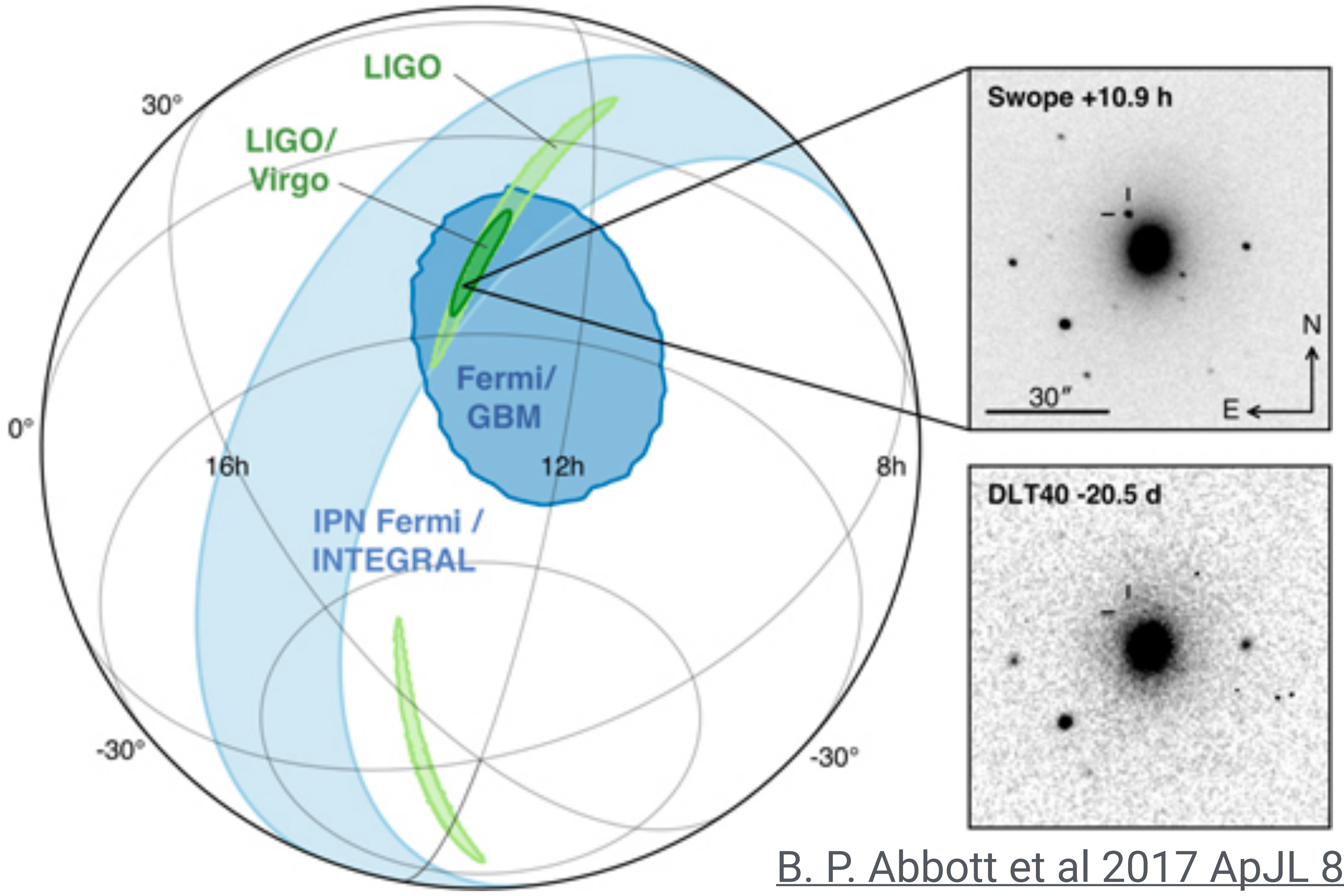
H.E.S.S. observations during the peak of the afterglow can constrain the magnetic field strength



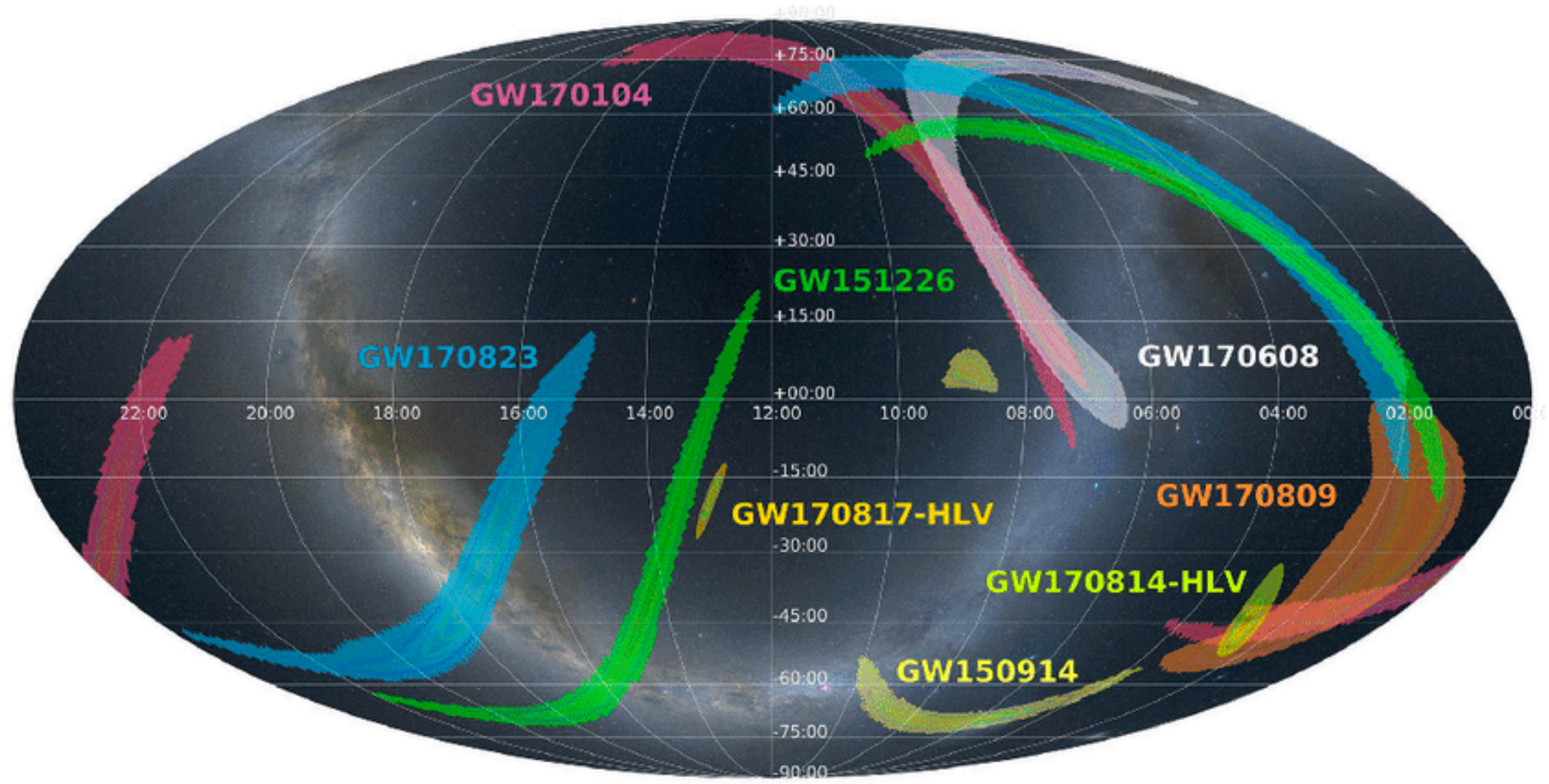


H. Abdalla et al 2020 ApJL 894 L16

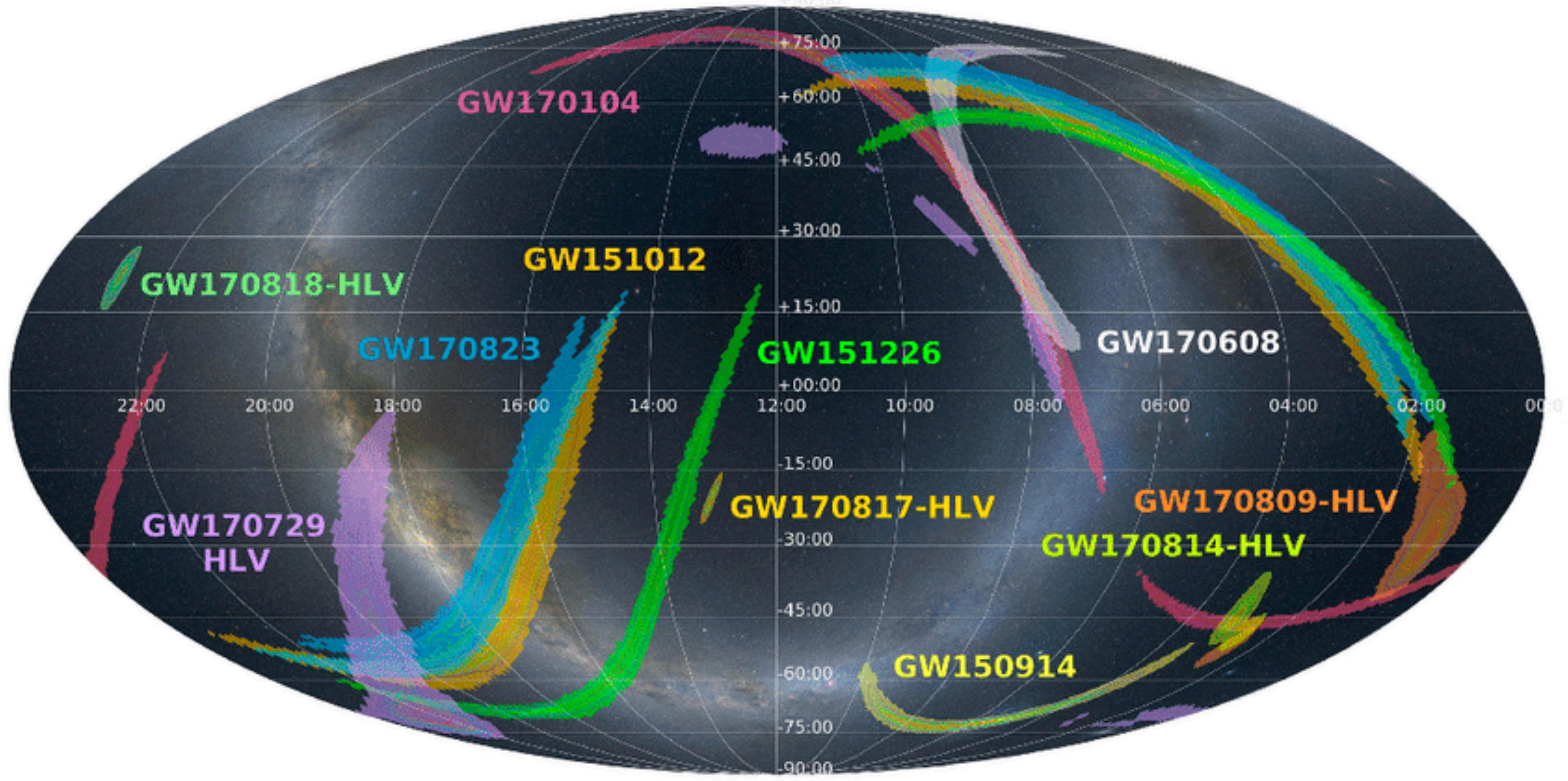
What about less well-localized GW events?



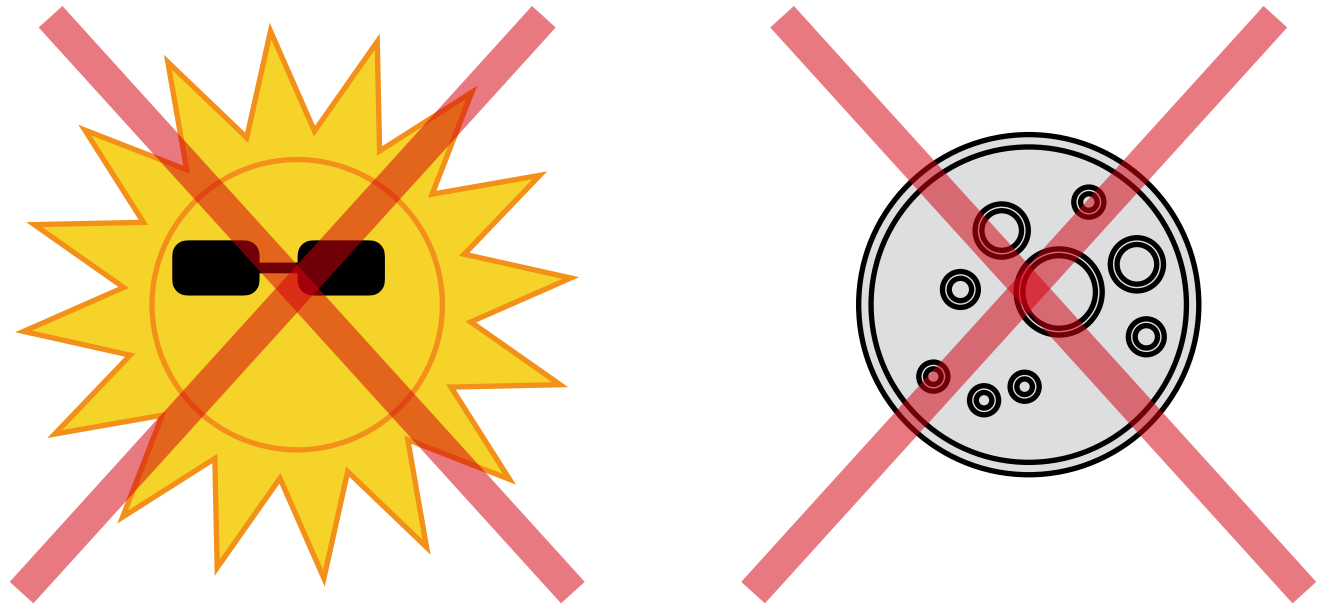
B. P. Abbott et al 2017 ApJL 848 L12



B.P. Abbott et al., Liv Rev Rel 23, 2020

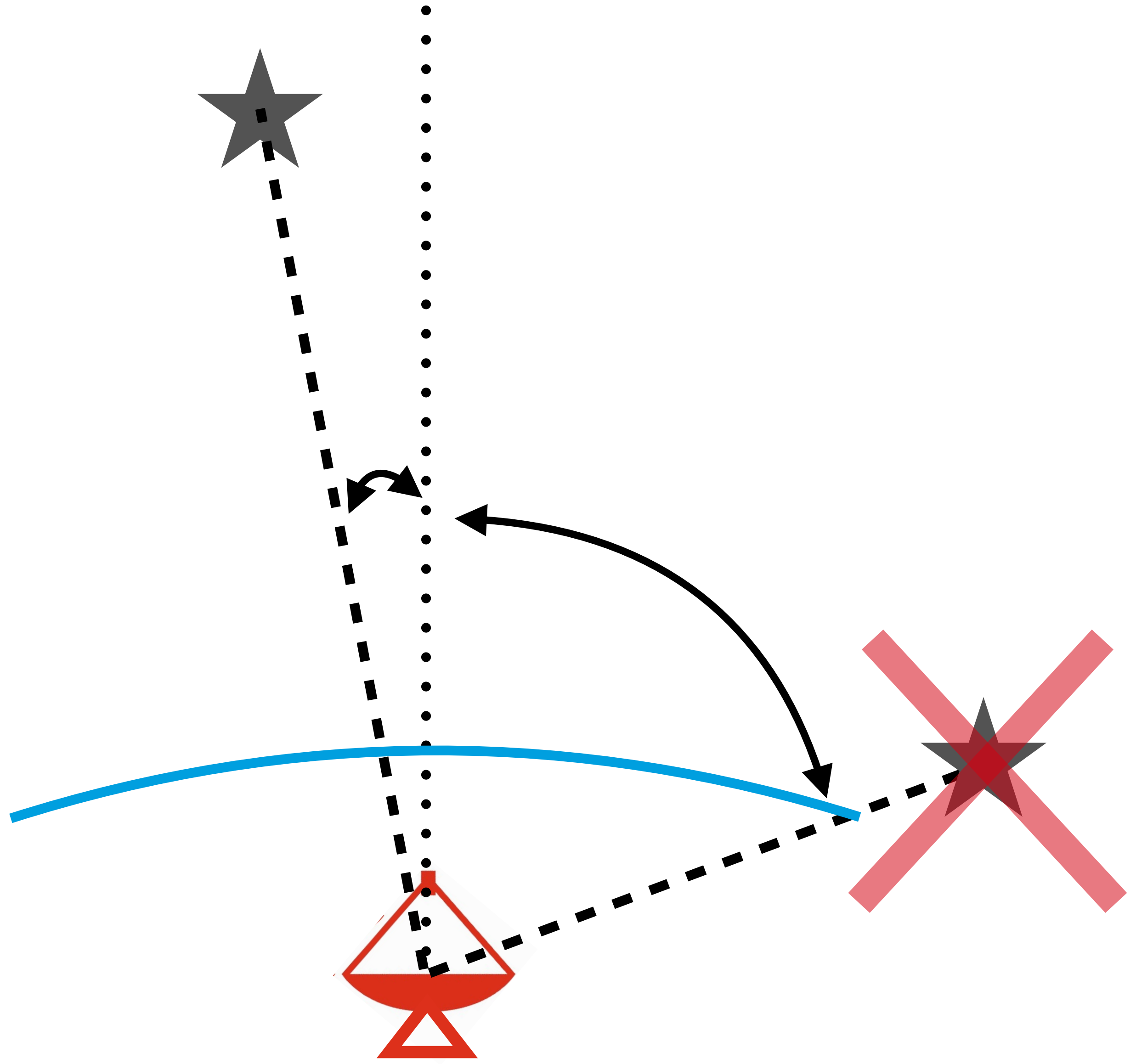


So you want to observe with your air Cherenkov telescope



Too much ambient light
is bad for your cameras

Cloudy nights mean
fewer photons get through

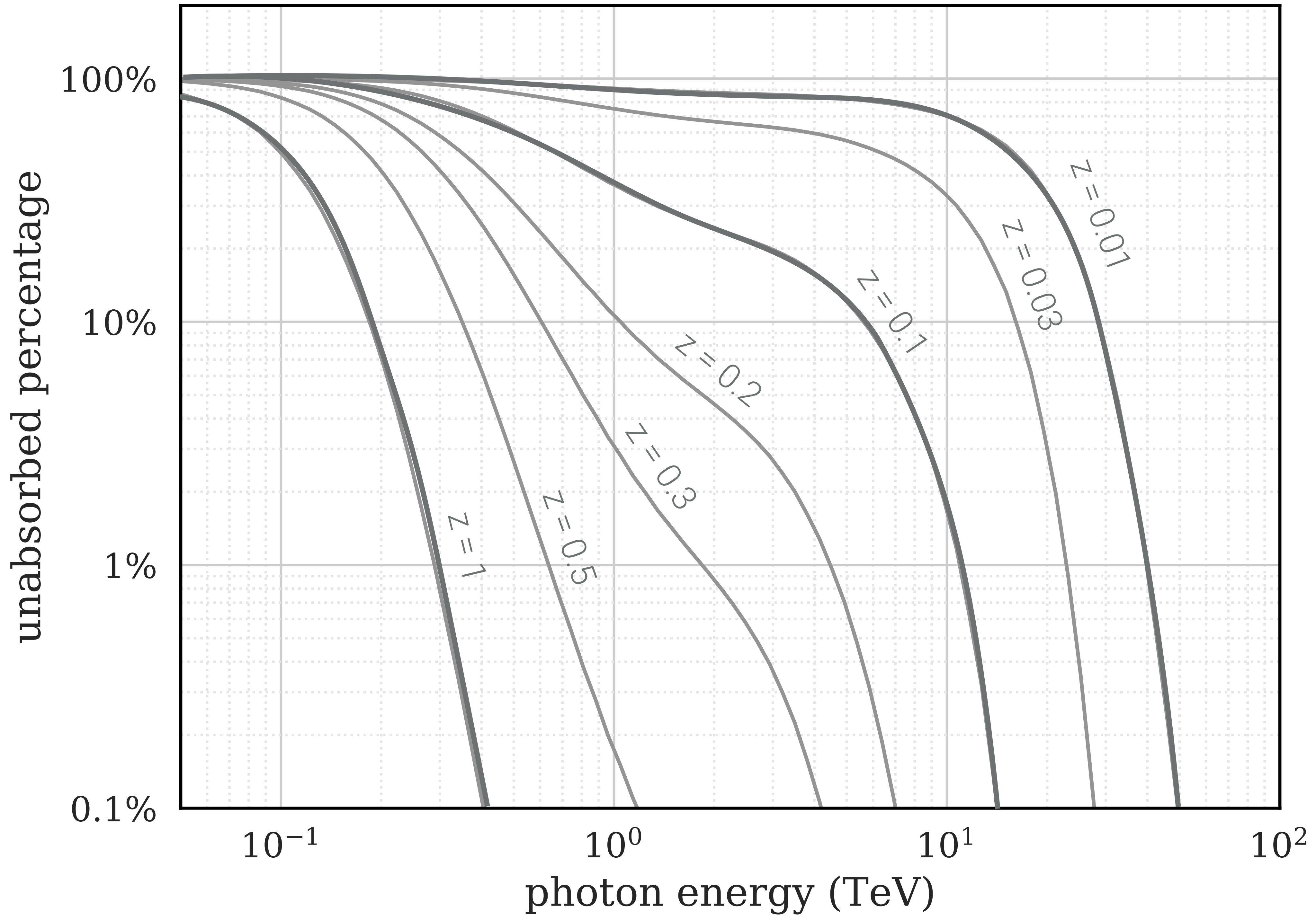


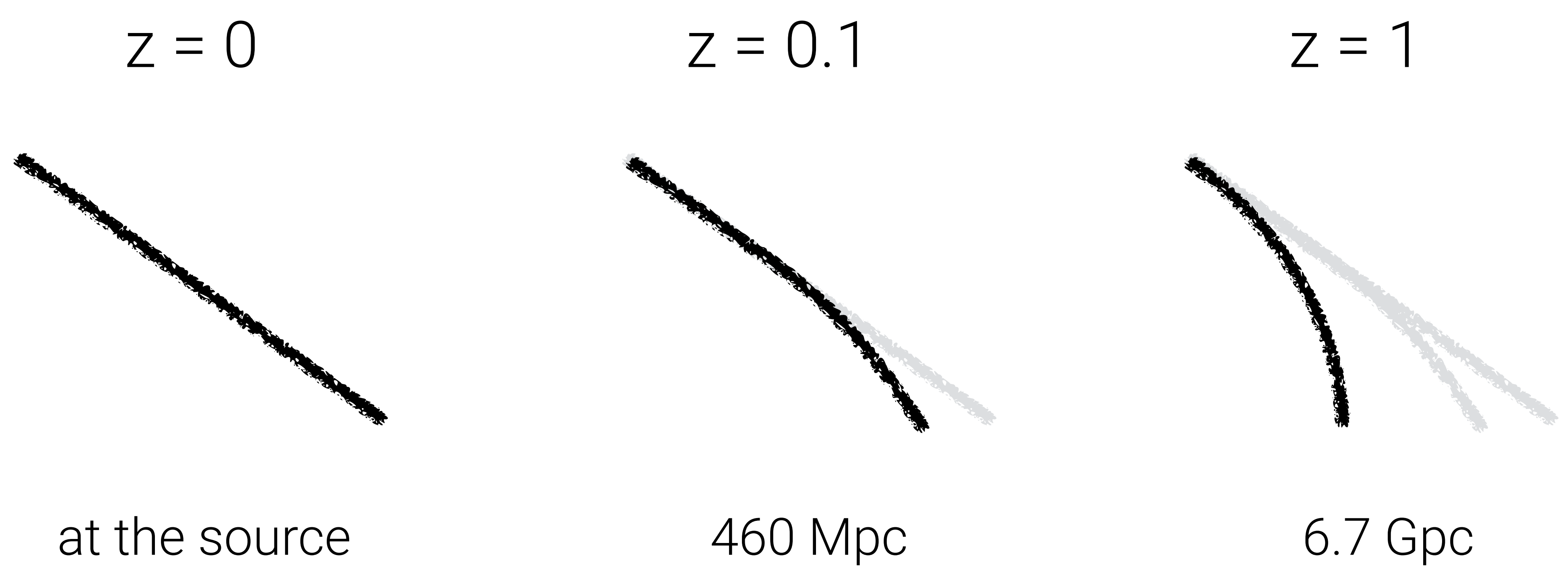
Large zenith angles result in
poorer statistics, and you
lose low energy photons

Effect of the Extragalactic Background Light (EBL)

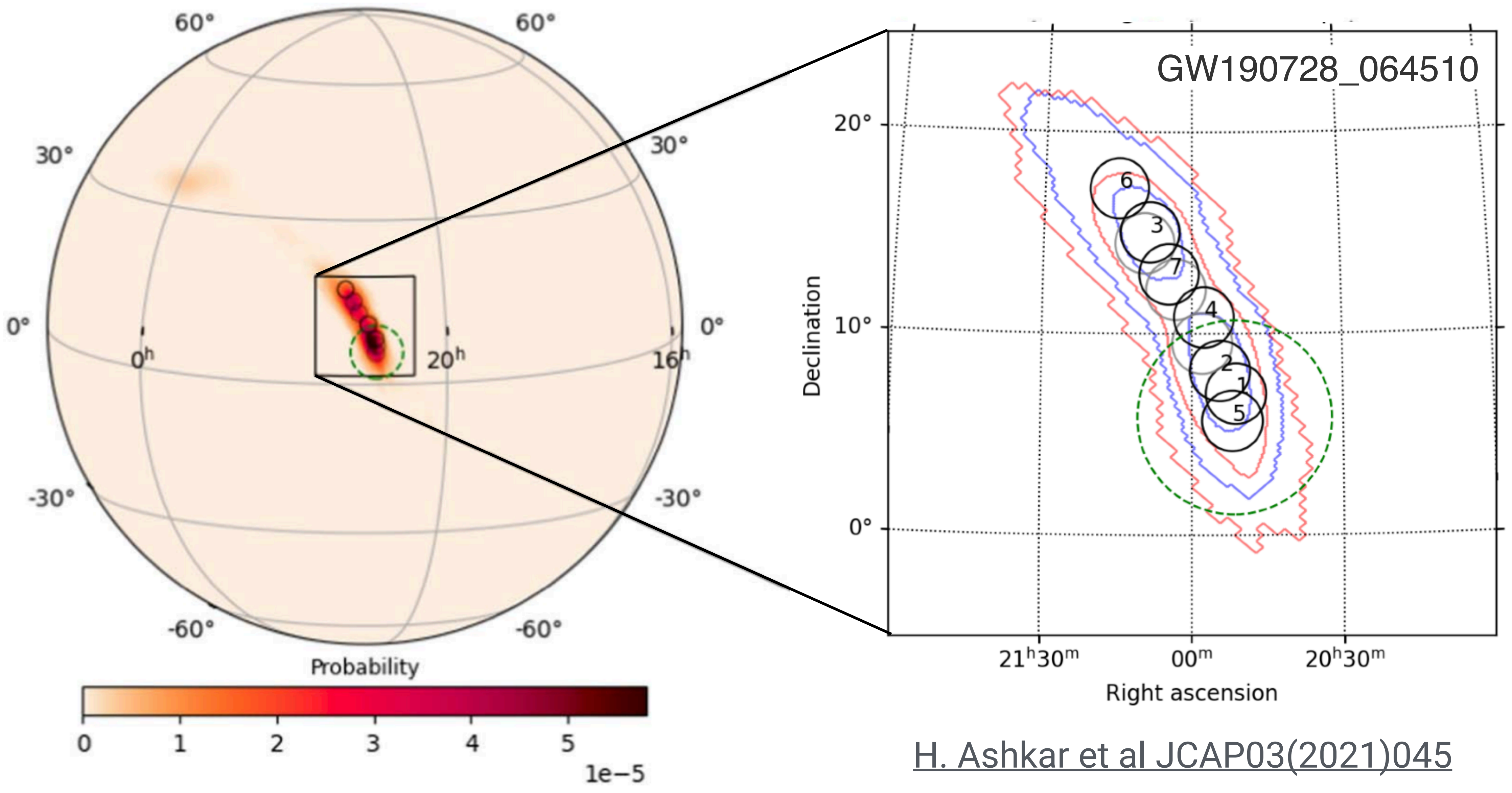
Higher energy gamma rays are preferentially absorbed by the EBL on their way to Earth

e.g., model of Franceschini et al. 2008





H.E.S.S. tiled observations of GW alerts



H. Ashkar et al JCAP03(2021)045

Field of view ~ 20 deg² (a few deg radius)

H.E.S.S. requirements for observing mergers with …

… two black holes:

>50% localiation probability could be covered in one night

… at least one neutron star:

>10% localization probability could be covered in one night

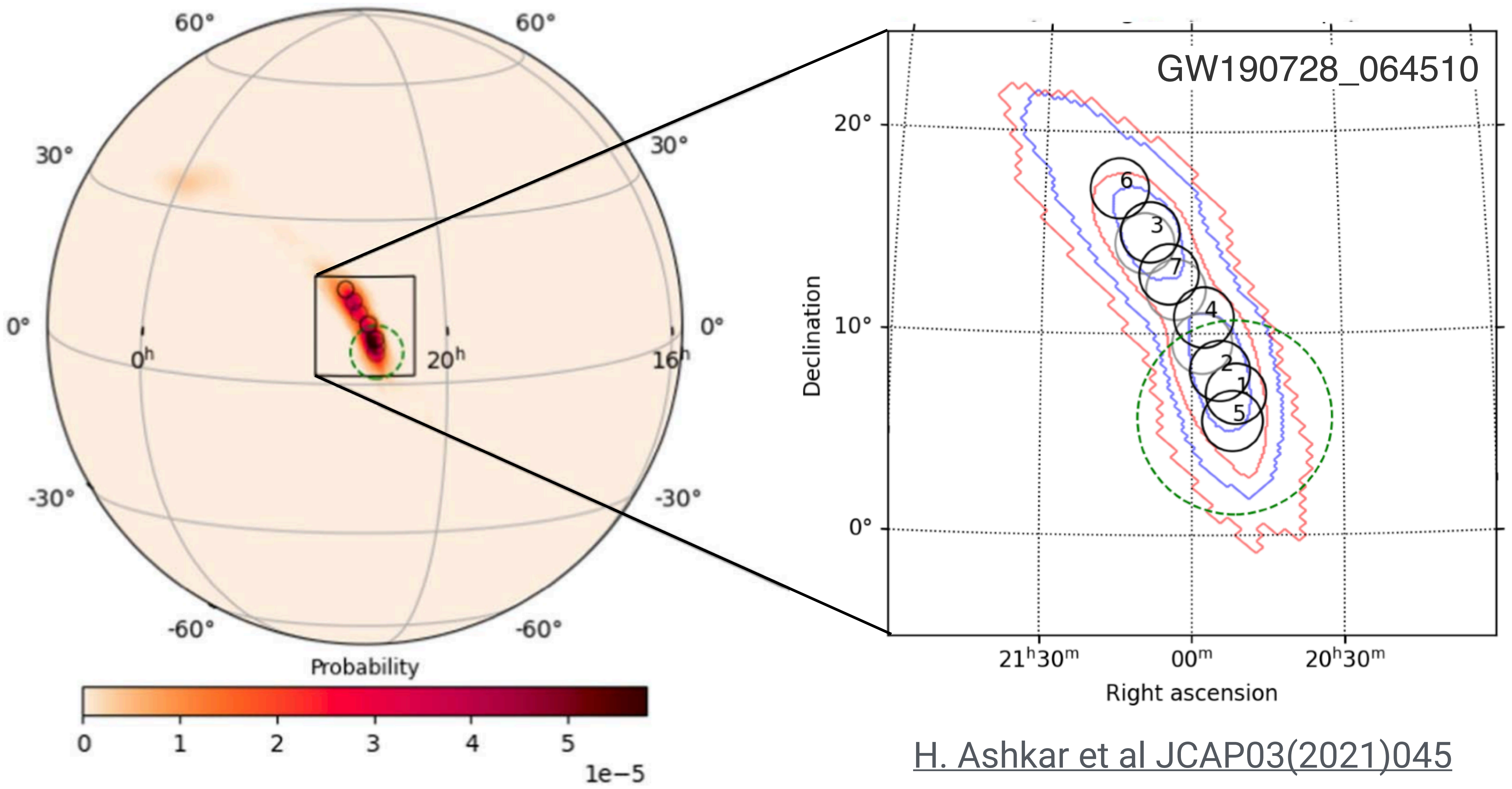
In O2/O3, we observed …

… one NS-NS merger: GW170817

… one NS-BH merger: GW200105 (but, bad weather conditions)

… four BH-BH mergers

H.E.S.S. tiled observations of GW alerts



H. Ashkar et al JCAP03(2021)045

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In O2/O3, we observed …

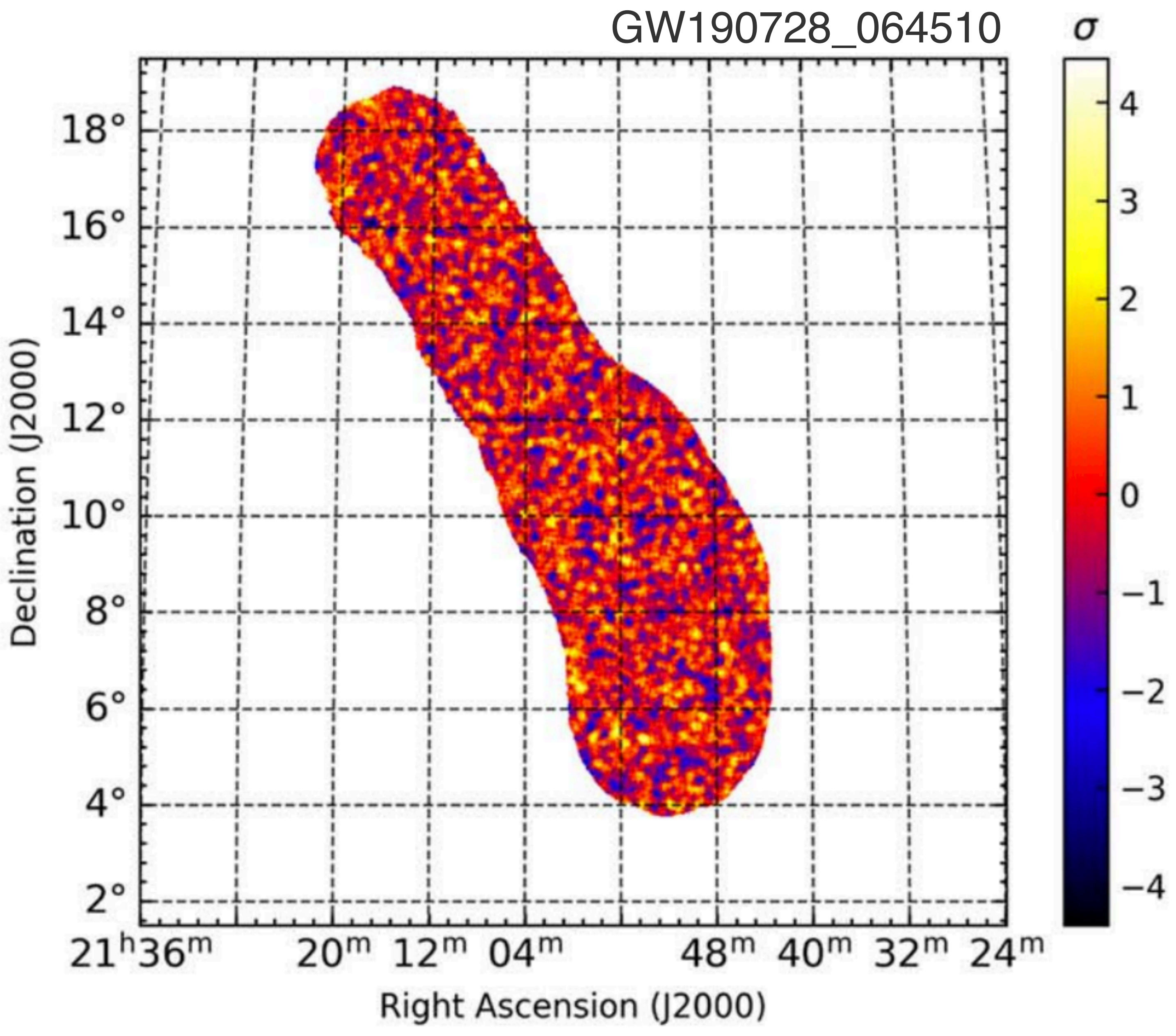
… one NS-NS merger: GW170817

… one NS-BH merger: GW200105 (but, bad weather conditions)

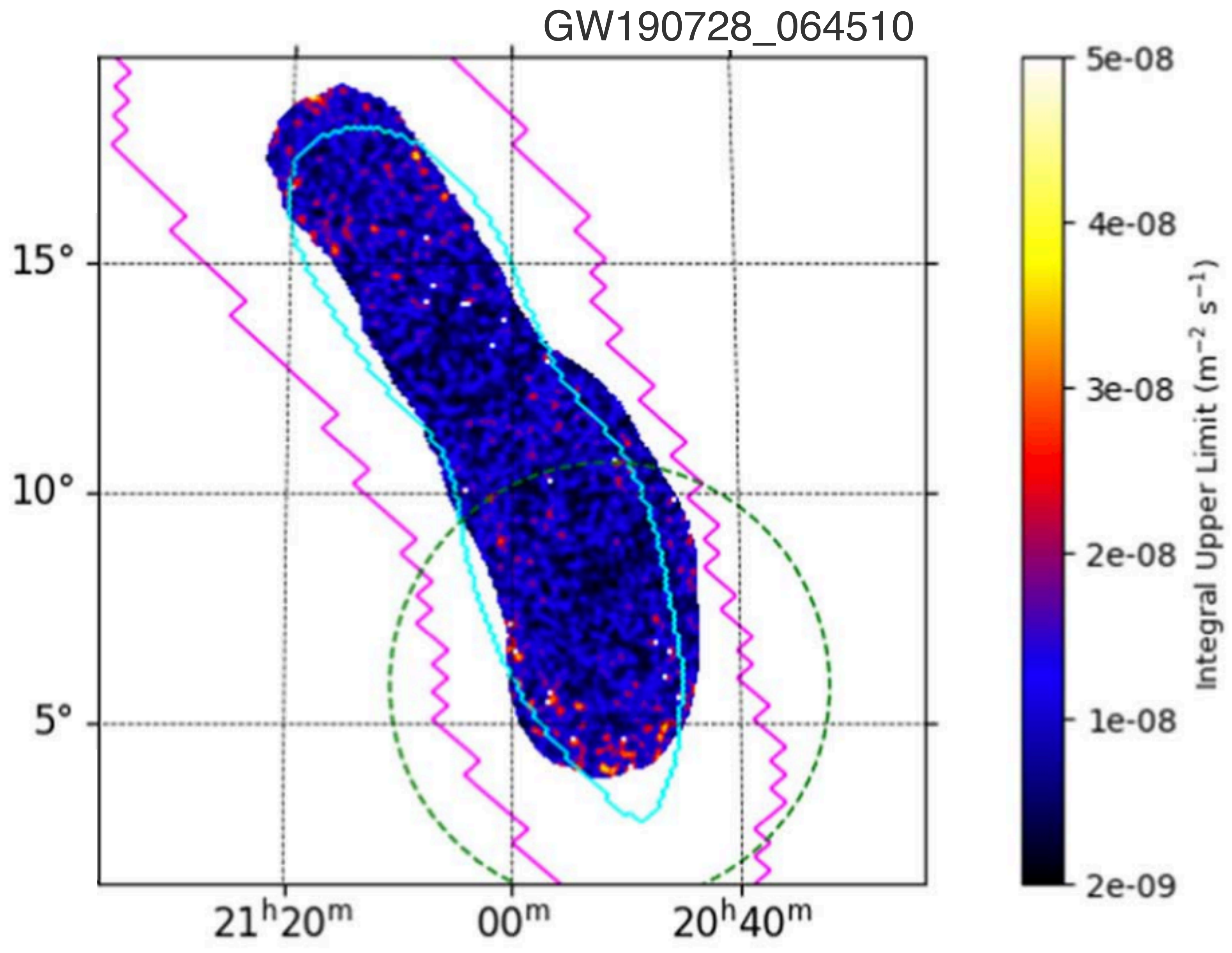
… four BH-BH mergers

Yes, we're discussing mergers with only black holes, but this is a proof of concept for GW events in general, and anyway you never know!

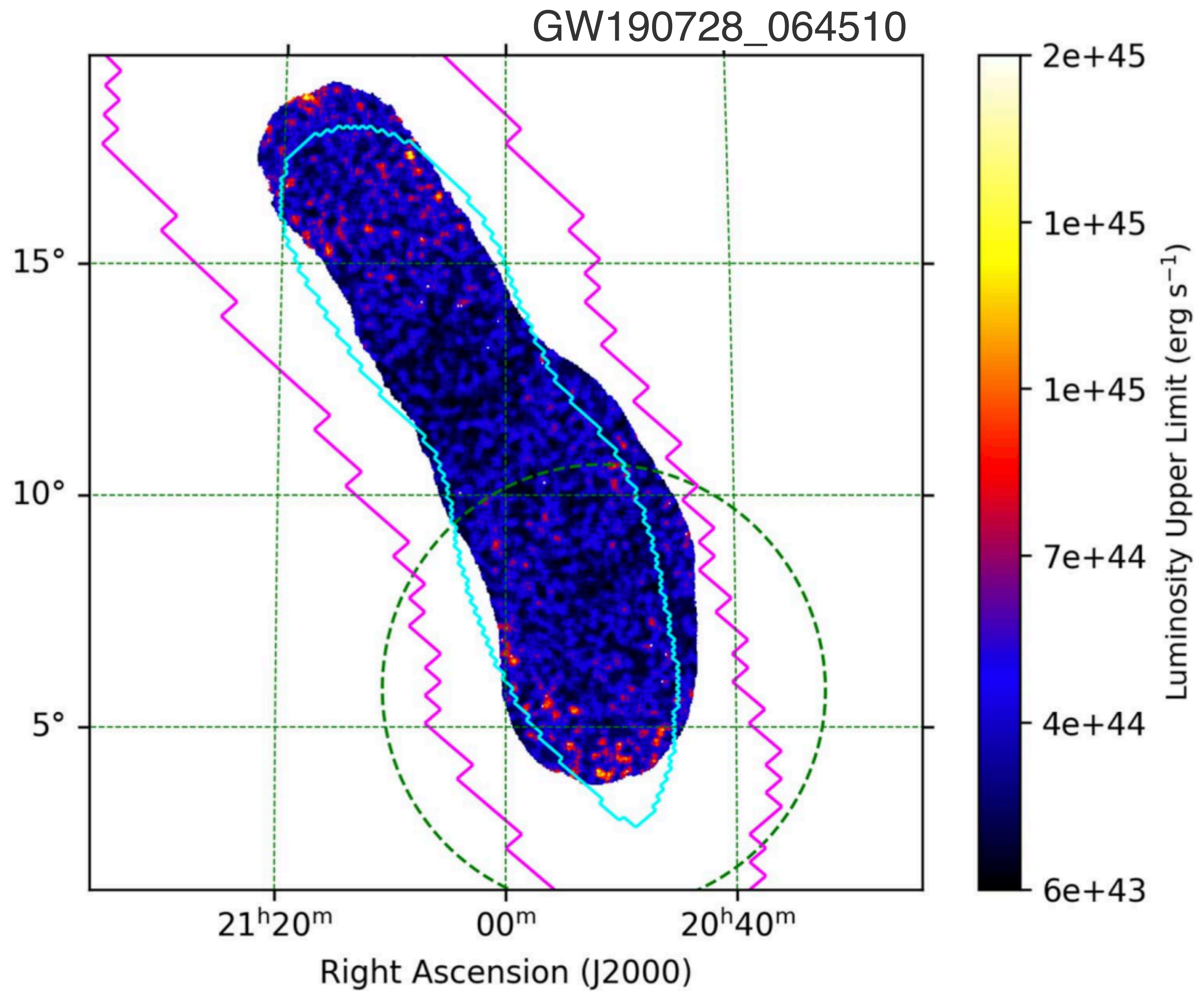
From observations to upper limits



significances
following Li & Ma (1983)



integral counts flux upper limits
assuming an E^{-2} intrinsic spectrum (EBL-corrected)



luminosity upper limits
using per-pixel GW distance estimates
and the E^{-2} intrinsic spectrum

integral energy flux upper limits
with the EBL-attenuated spectrum

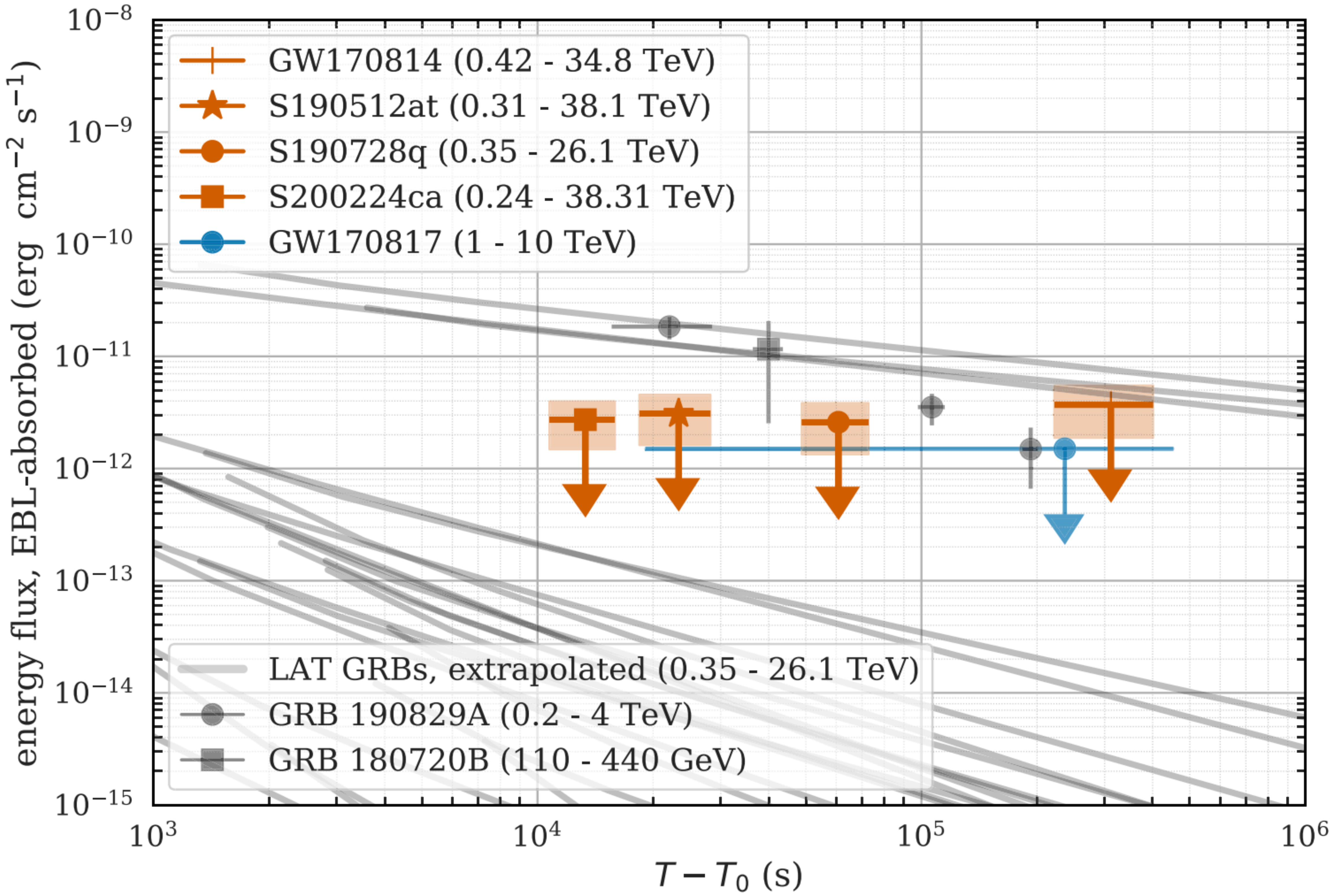
H. Abdalla et al 2021 ApJ 923 109

Putting these into context

The energy flux upper limits are much higher than the majority of the extrapolations of *Fermi*-LAT GRBs.

How to do better in the future?

-> Observe more deeply, and/or
observe earlier

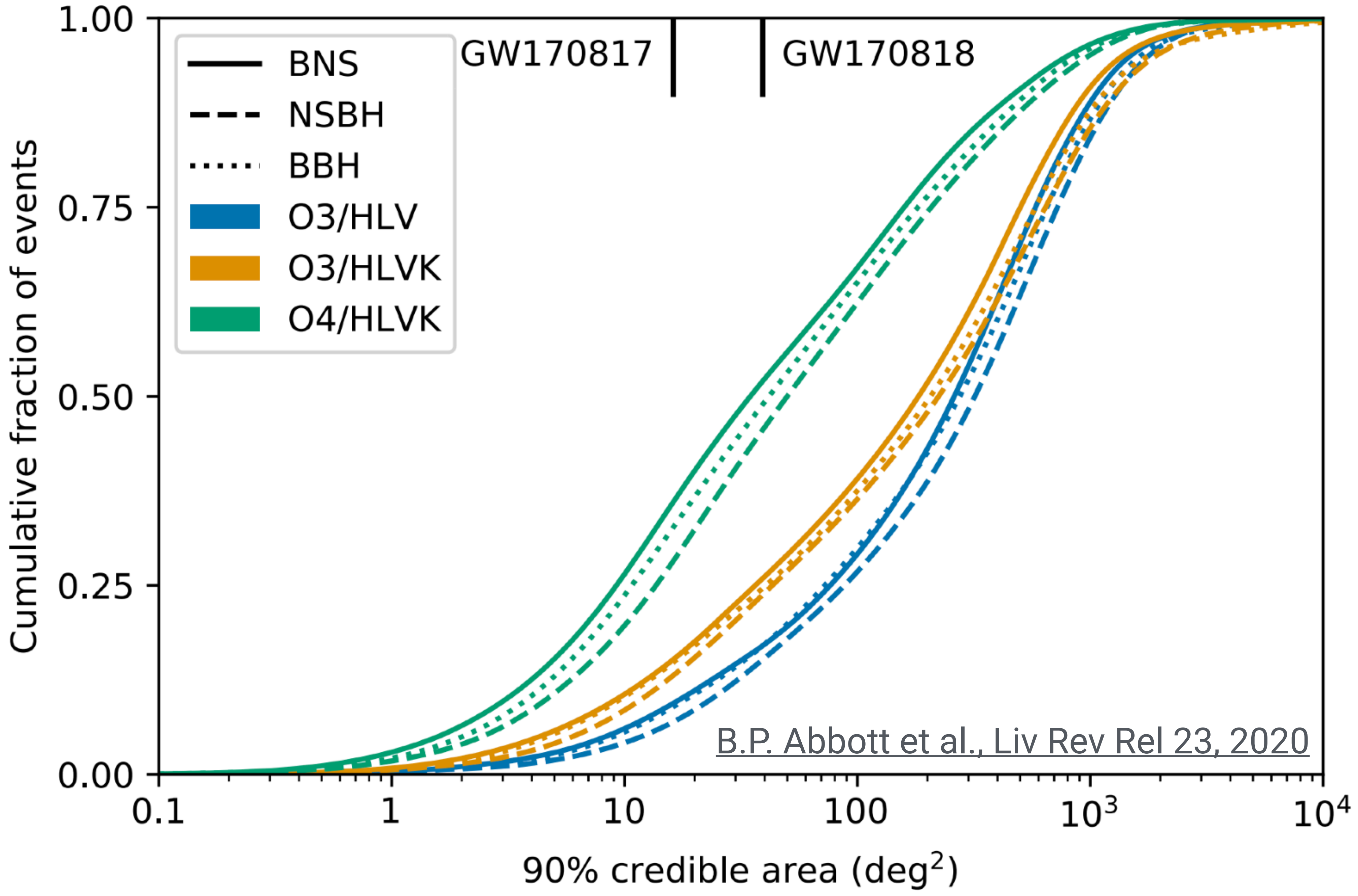


H. Abdalla et al 2021 ApJ 923 109

Prospects for O4 and beyond

In O4, there will be many more well localized GW events
=> H.E.S.S. can spend more time per sky position.

The rate of detections will increase
=> more events will be observable by H.E.S.S. at early times.



All of our sky maps are publicly available on the H.E.S.S. webpage.

backup

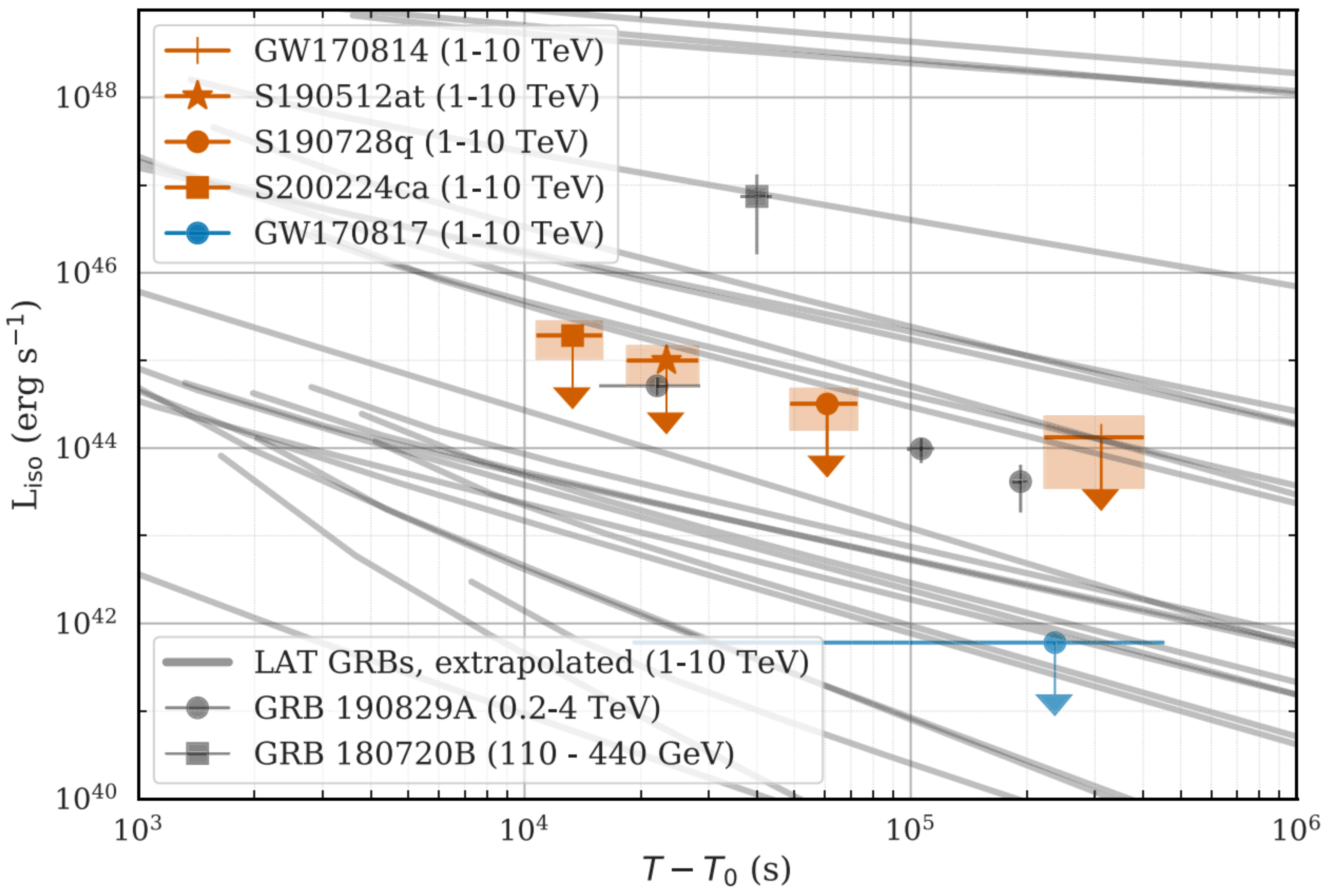
Table 2
Spectral Indices (γ) at a GW Event's Corresponding Redshift (Abbott et al. 2019, 2021a) and at $E_{\rm th}$ Assuming an Intrinsic E^{-2} Spectrum

GW Event	Redshift	$\gamma(E = E_{\rm th}, z = z_{\rm GW})$	Energy Range (TeV)	Coverage	$T_{\rm start}$, $T_{\rm stop}$ (s)
GW170814	$0.12^{+0.03}_{-0.04}$	2.73	0.42–34.80	75.4%	2.22×10^5, 4.10×10^5
GW190512_180714	$0.27^{+0.09}_{-0.10}$	3.50	0.31–38.31	34.5%	1.84×10^4, 2.82×10^4
GW190728_064510	$0.18^{+0.05}_{-0.07}$	2.98	0.35–26.10	50.8%	4.88×10^4, 7.28×10^4
S200224ca	0.29	3.08	0.24–38.31	62.13%	1.07×10^4, 1.59×10^4

Note. The redshift for S200224ca was estimated from the distance in LIGO Scientific Collaboration & Virgo Collaboration (2020b) using the cosmological parameters from Ade et al. (2016). The energy range used to derive the specific integral upper-limit maps and the corresponding coverage are presented in the fourth and fifth columns, respectively, and the sixth column lists the start and end of the H.E.S.S. observations of the GW event, as calculated from the reported GW merger time.

GW Event	Energy Flux, Event-specific (erg cm^{-2} s^{-1})		Luminosity, Standard (erg s^{-1})	
	Mean	Standard Dev.	Mean	Standard Dev.
GW170814	3.7×10^{-12}	1.8×10^{-12}	1.3×10^{44}	9.8×10^{43}
GW190512_180714	3.1×10^{-12}	1.5×10^{-12}	9.9×10^{44}	4.7×10^{44}
GW190728_064510	2.6×10^{-12}	1.3×10^{-12}	3.2×10^{44}	1.6×10^{44}
S200224ca	2.7×10^{-12}	1.2×10^{-12}	1.9×10^{45}	8.8×10^{44}

Note. The first column lists the GW event discussed in this paper. The second and third columns list the mean and standard deviation of the GW event-specific energy flux upper limits, not corrected for EBL absorption and calculated with the event-specific energy ranges and indices (Table 2). The fourth and fifth columns list the mean and standard deviation of the upper limits on isotropic luminosity, calculated from the EBL-corrected energy fluxes assuming an E^{-2} source spectrum over a 1–10 TeV energy range and using the per-pixel luminosity distances. These values are plotted in Figures 4 and 5.


GW170814 (1-10 TeV)
S190512at (1-10 TeV)
S190728q (1-10 TeV)
S200224ca (1-10 TeV)
GW170817 (1-10 TeV)
LAT GRBs, extrapolated (1-10 TeV)
GRB 190829A (0.2-4 TeV)
GRB 180720B (110 - 440 GeV)
L_{iso} (erg s^{-1})
10^{48}
10^{46}
10^{44}
10^{42}
10^{40}
10^{3}
10^{4}
10^{5}
10^{6}
$T - T_0$ (s)