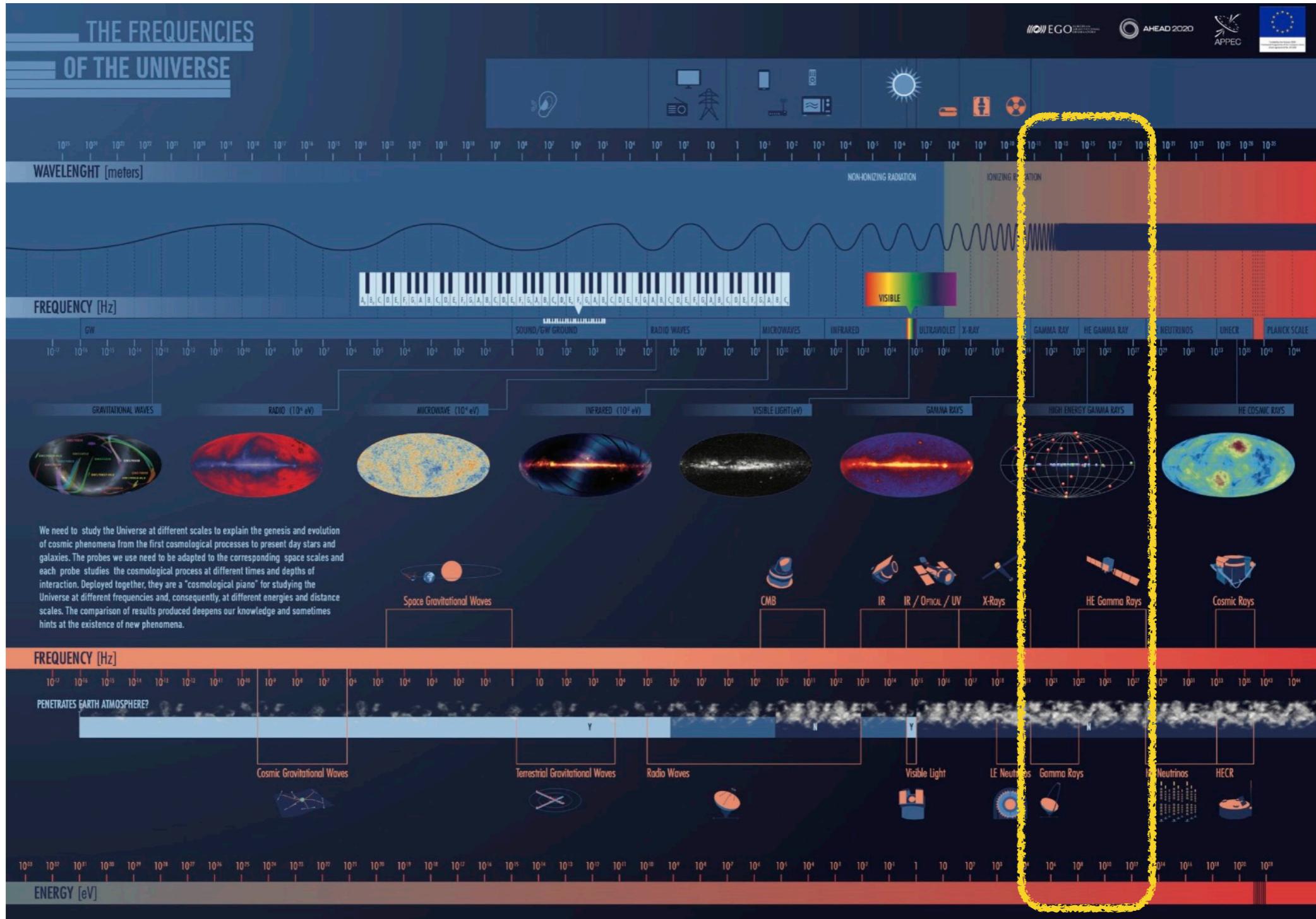


Multi-messenger astrophysics with current and future high-energy gamma-ray observatories

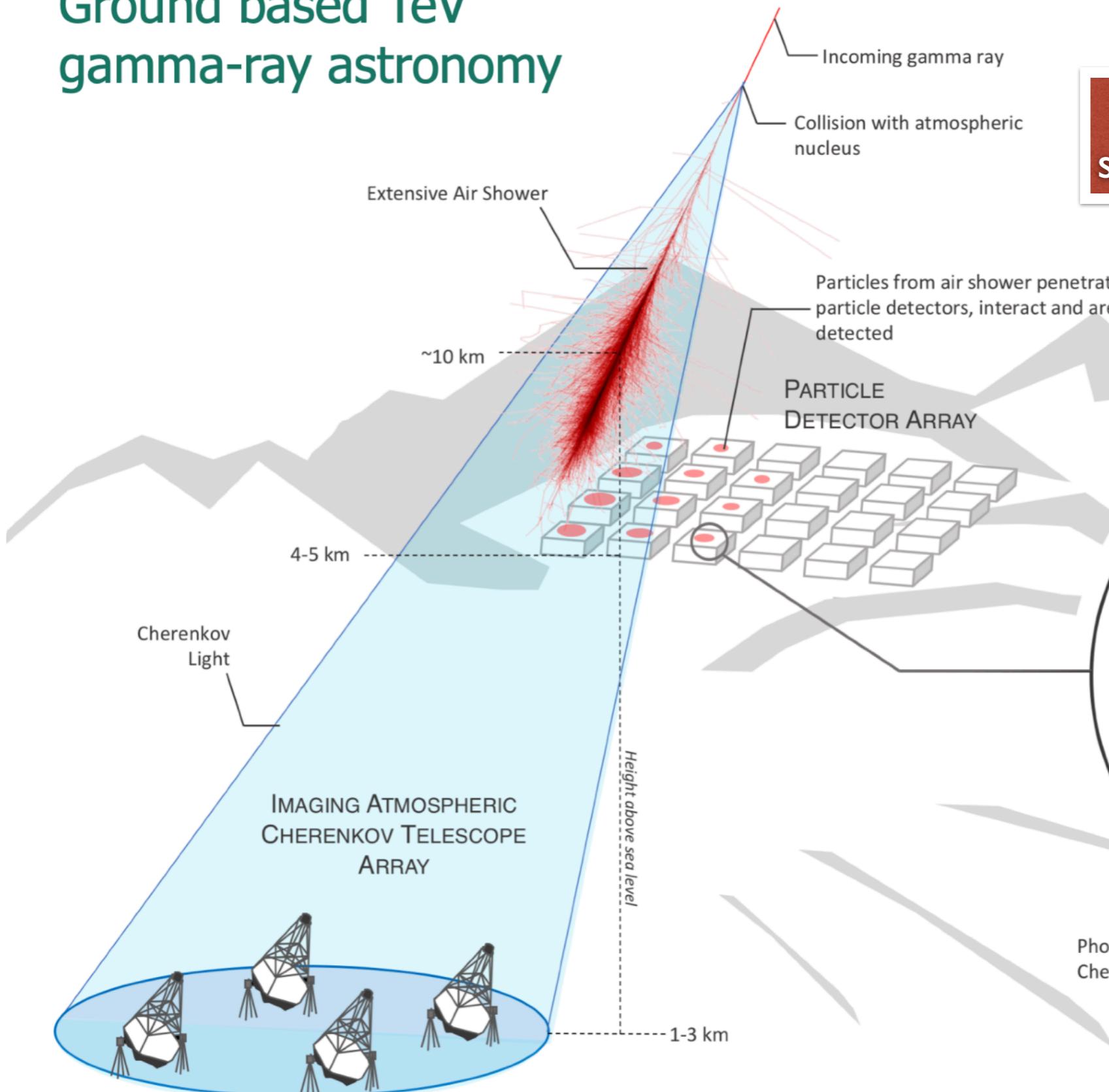


Monitoring vs follow-up observatories

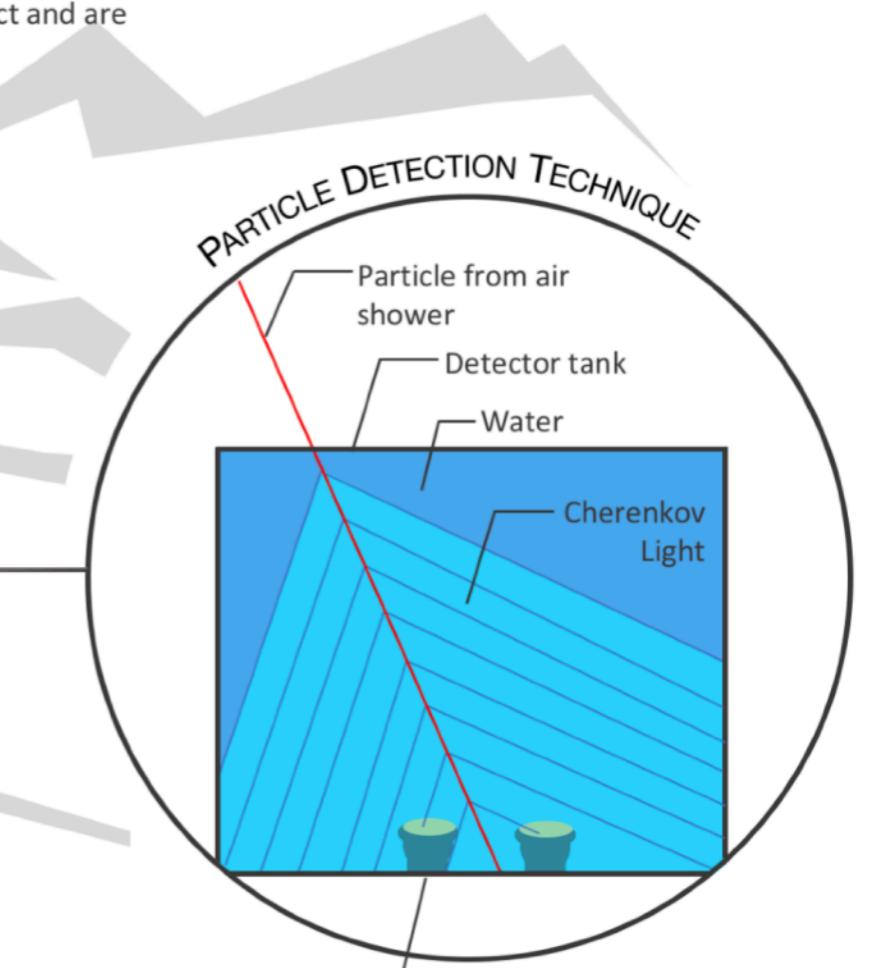
- Large field-of-view: monitor the sky + provide alerts
- Small field-of-view: high-sensitivity follow-up observations

	Fermi	HAWC	IceCube	CHIME	LSST /Vera Rubin	ASKAP	VLA	Keck	CTA
	Large FoV	Small FoV							
Monitoring (+ duty cycle)									
Sensitivity									
Resolution									
Energy threshold	High	Low							

Ground based TeV gamma-ray astronomy



FoV + duty-cycle vs sensitivity + $E_{\text{threshold}}$ + resolution

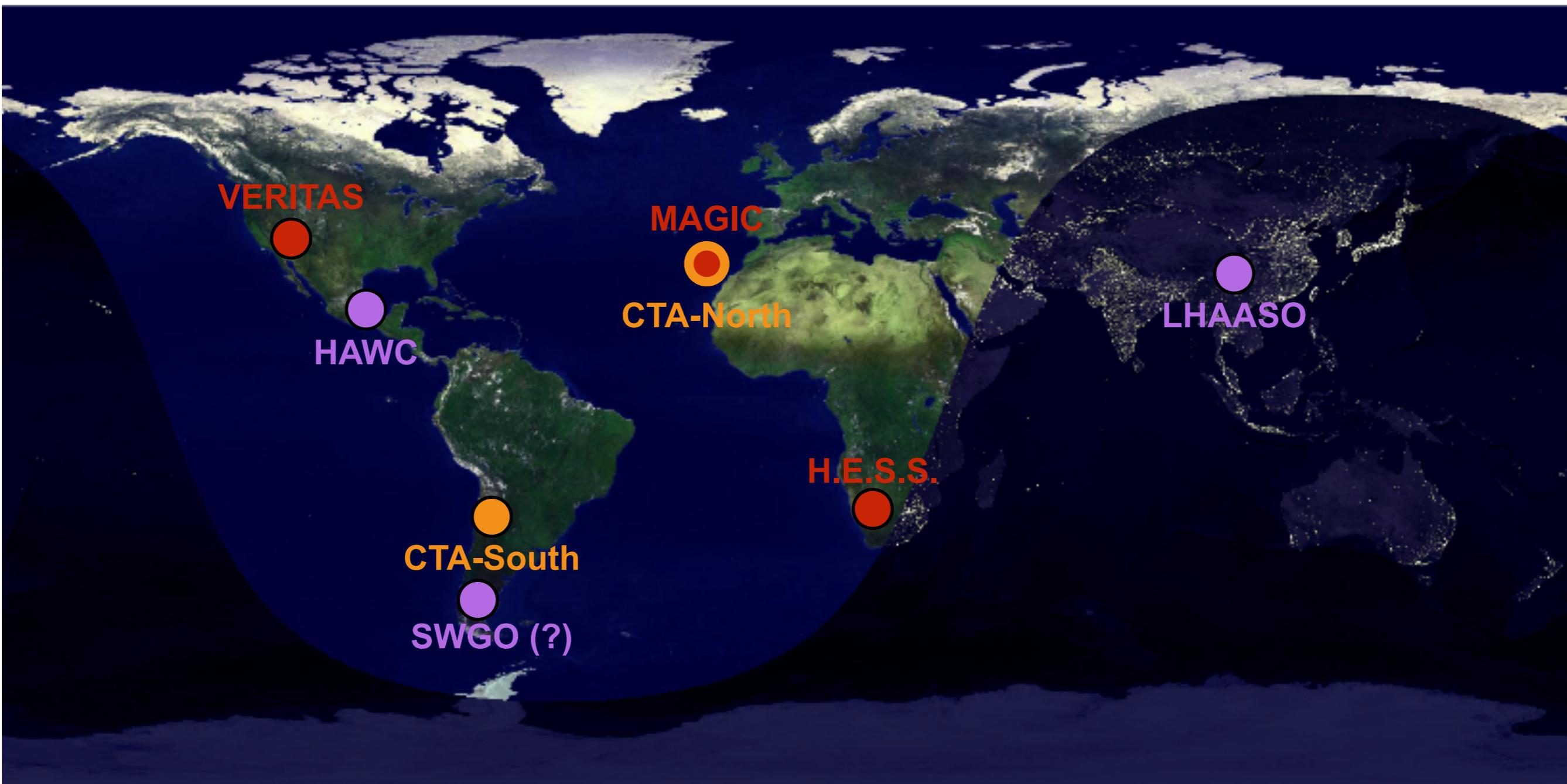


Shower image, 100 GeV γ -ray adapted from: F. Schmidt, J. Knapp, "CORSIKA Shower Images", 2005,
<https://www-zeuthen.desy.de/~jknapp/fs/showerimages.html>

Not to scale

H. Schoorlemmer

VHE gamma-ray astronomy

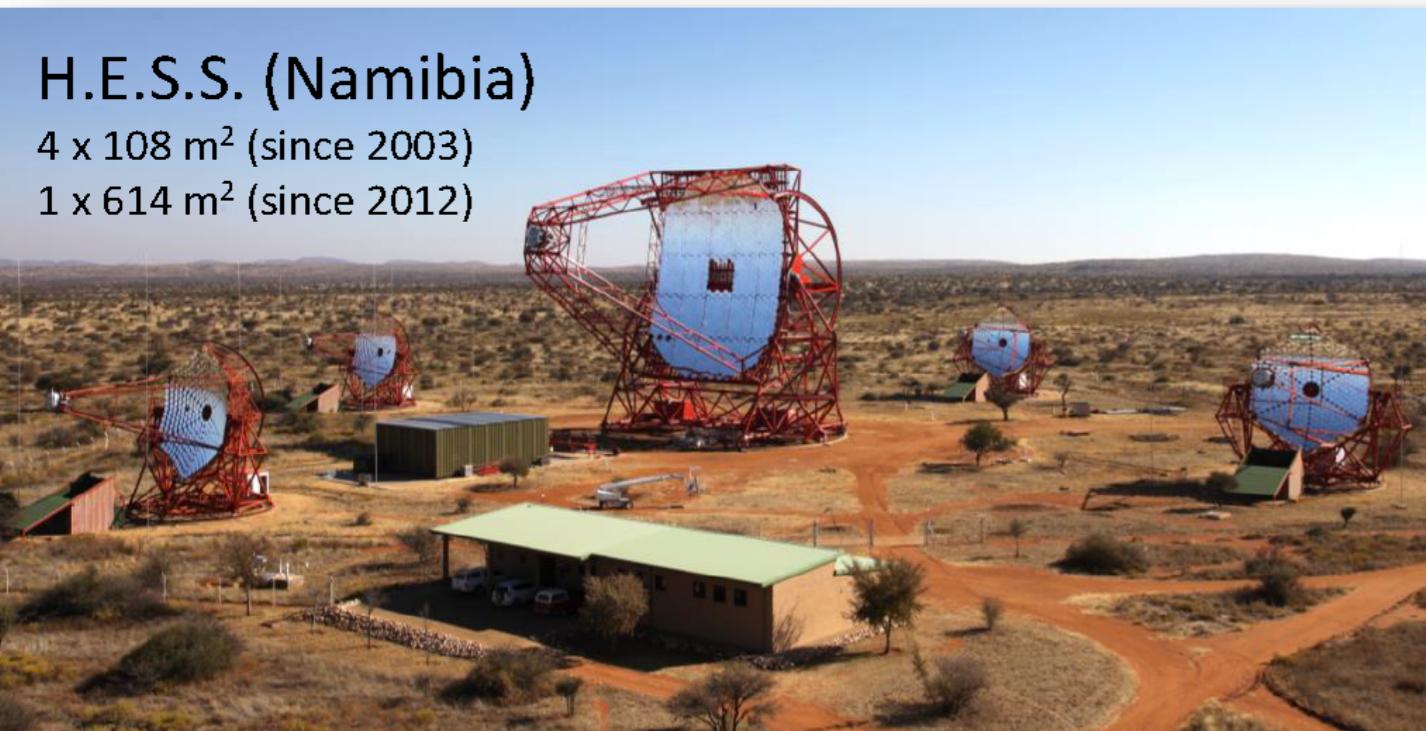


IACTs: high (spatial and energy) resolution follow-up observatories

H.E.S.S. (Namibia)

4 x 108 m² (since 2003)

1 x 614 m² (since 2012)



MAGIC (La Palma)

2 x 236 m² (since 2003 / 2009)



VERITAS (Arizona)

4 x 110 m² (since 2007)



Searches for transient phenomena

Flaring stars

CVs / Novae

Supernovae

Gamma-ray Bursts

Gravitational Waves

Active Galactic nuclei

Tidal Disruption Events

Neutrinos

Gamma-ray Binaries

Microquasars

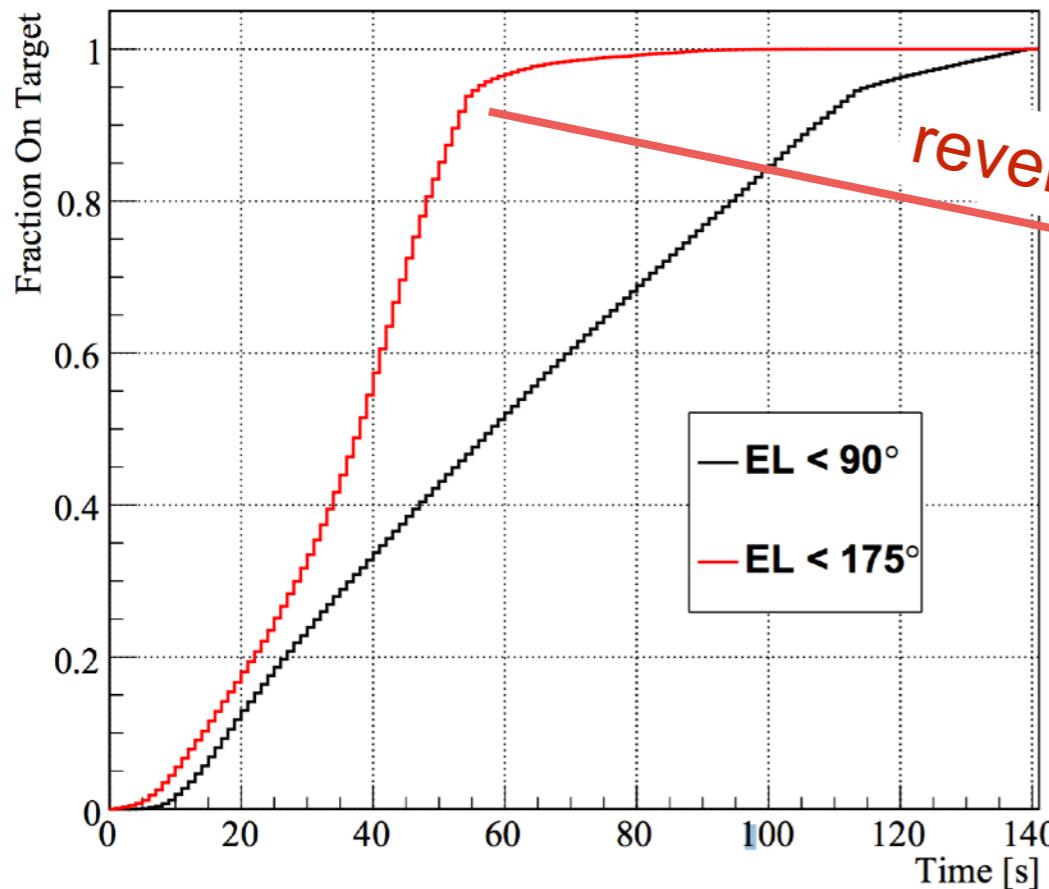
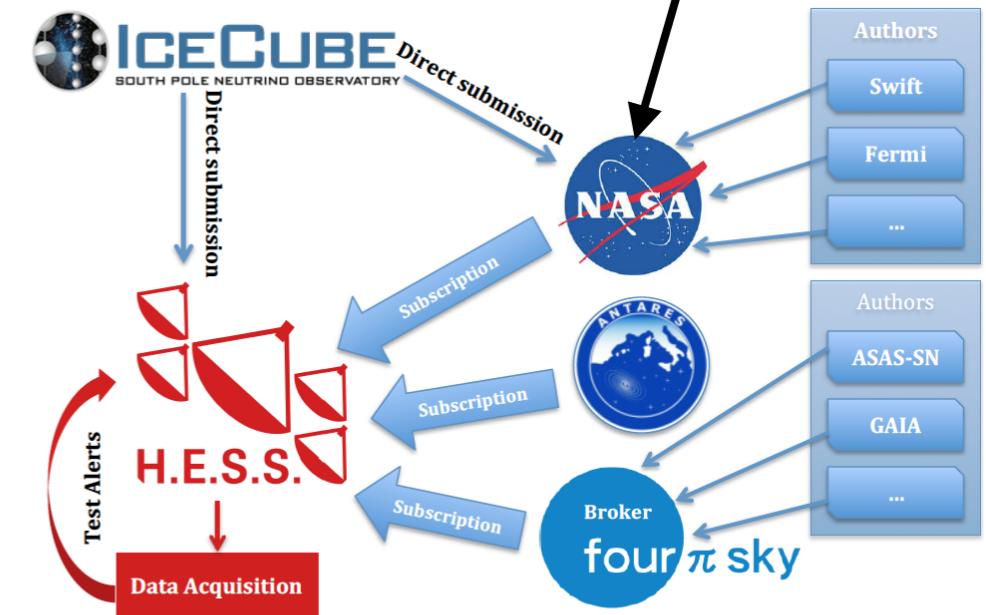
Unknowns

Fast Radio Bursts

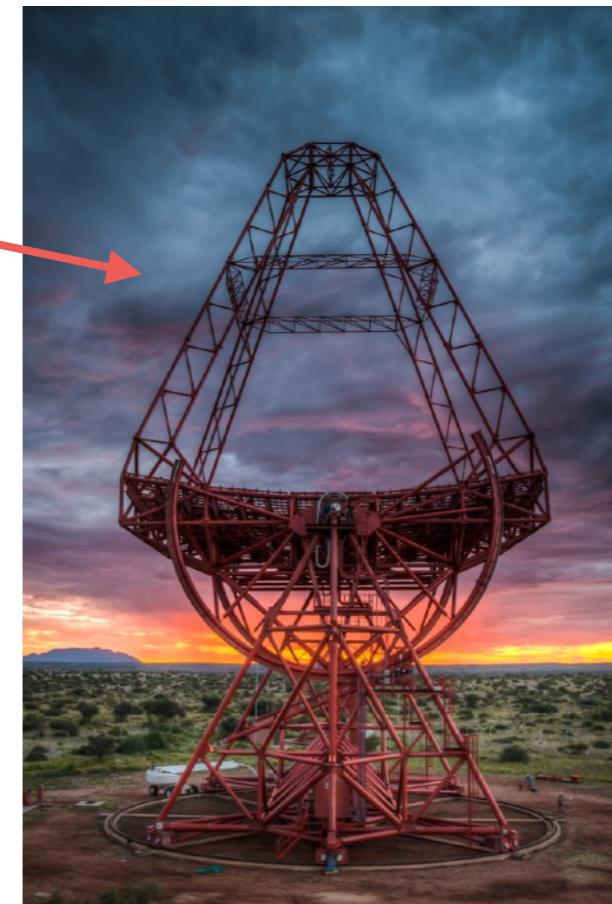
Soft Gamma-ray Repeaters

The H.E.S.S.-II response to ToOs

- main design principles of the H.E.S.S. 28m telescope
 - large photon collection area (614 m² mirror area; largest IACT worldwide)
 - **rapid response time**
 - **flexible + fully automatized alert system**



Hofverberg et al., ICRC 2013

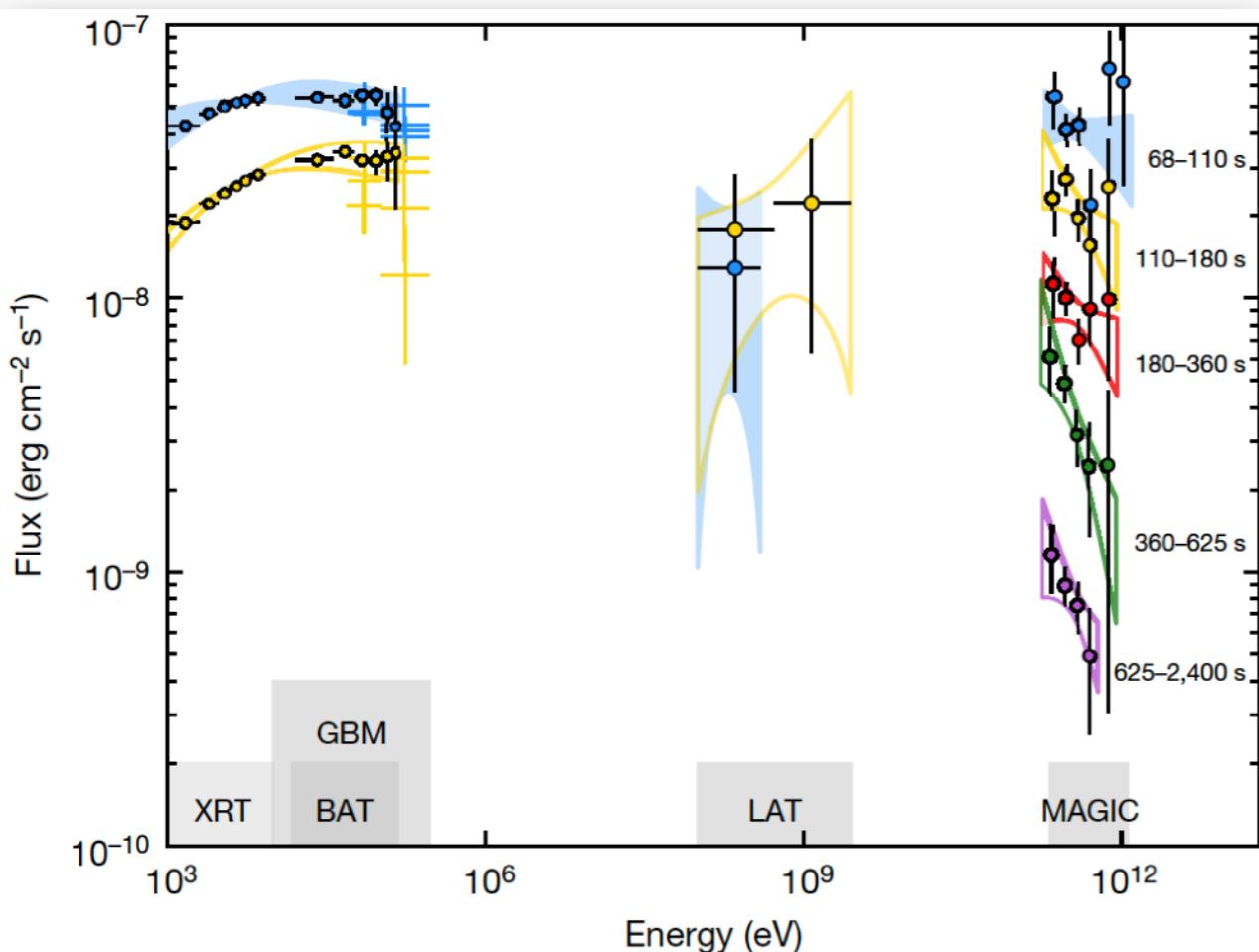




Gamma-ray bursts

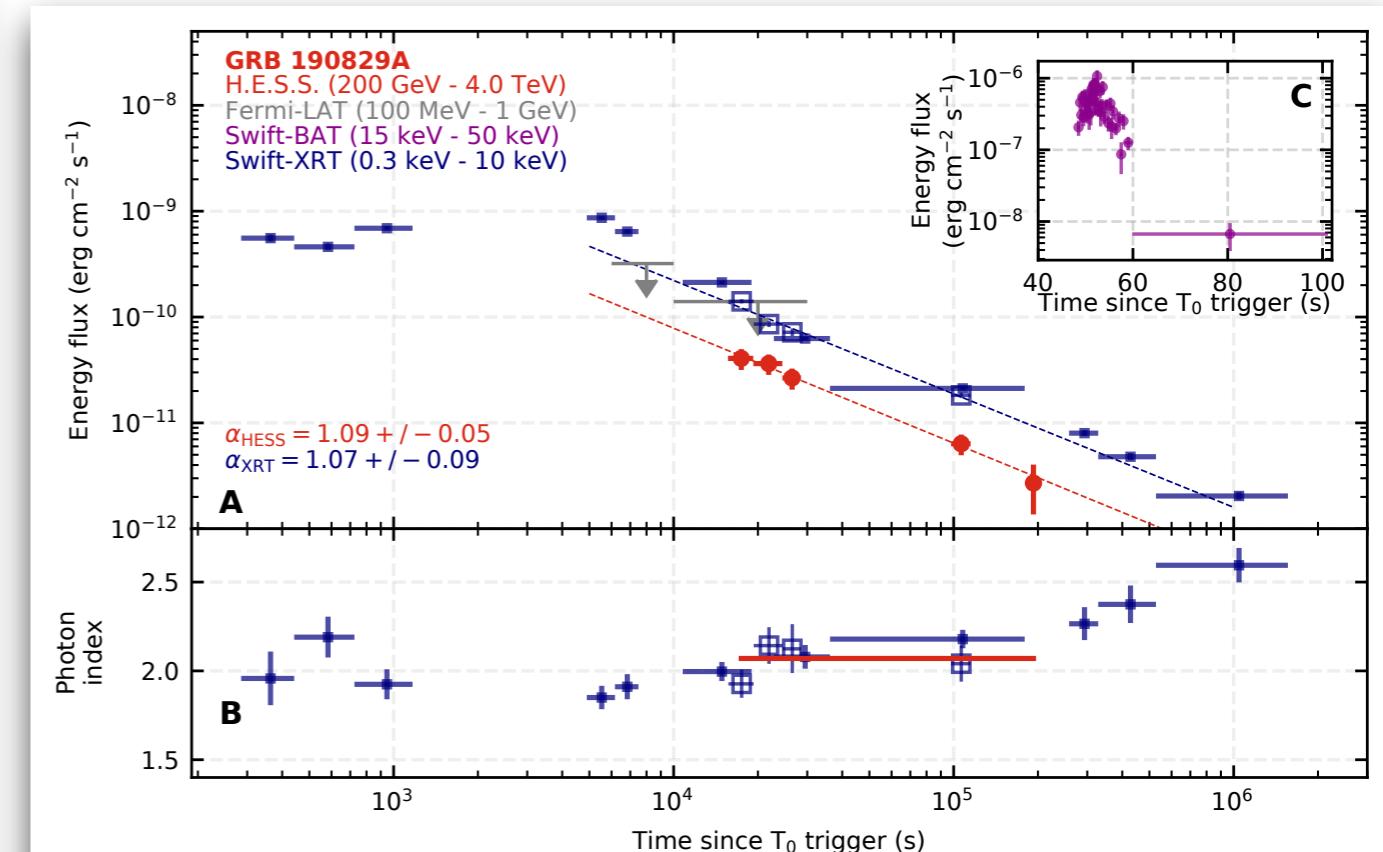
time evolution of flux and spectra at very-high energies

GRB 190114C



MAGIC Collaboration
Nature 575, 459 (2019)

GRB 190829A

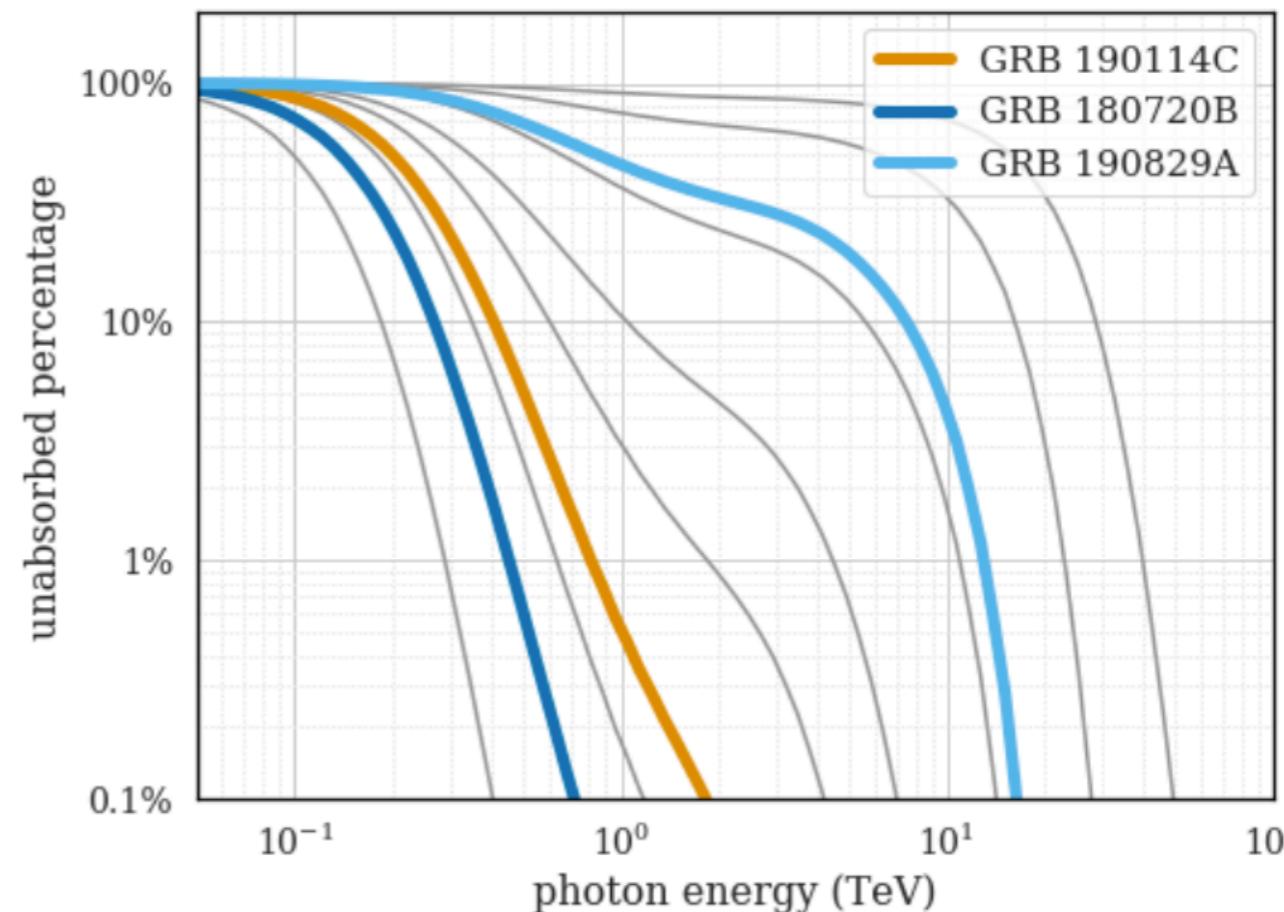
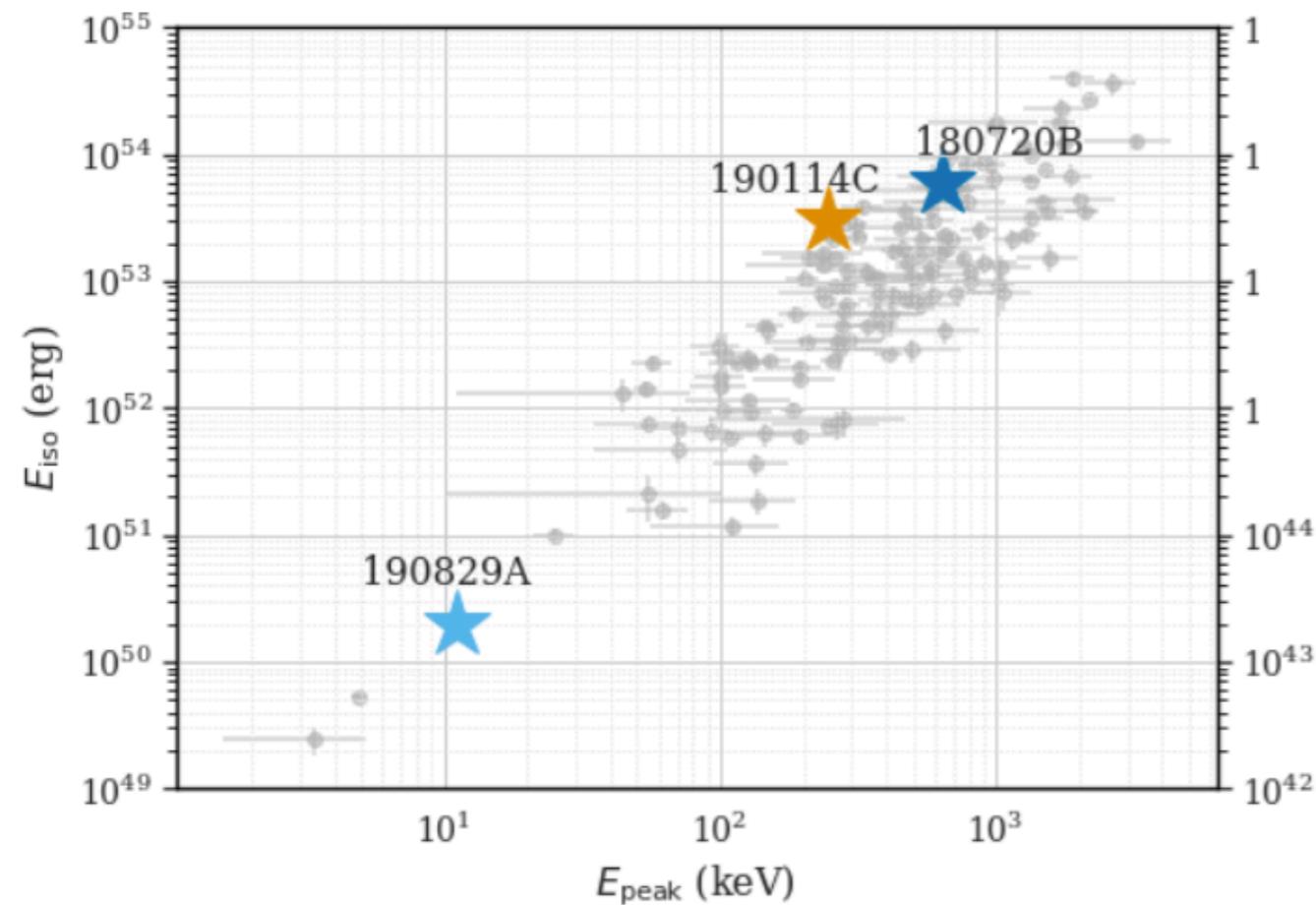


H.E.S.S. Collaboration
Science 372, 6546 (2021)



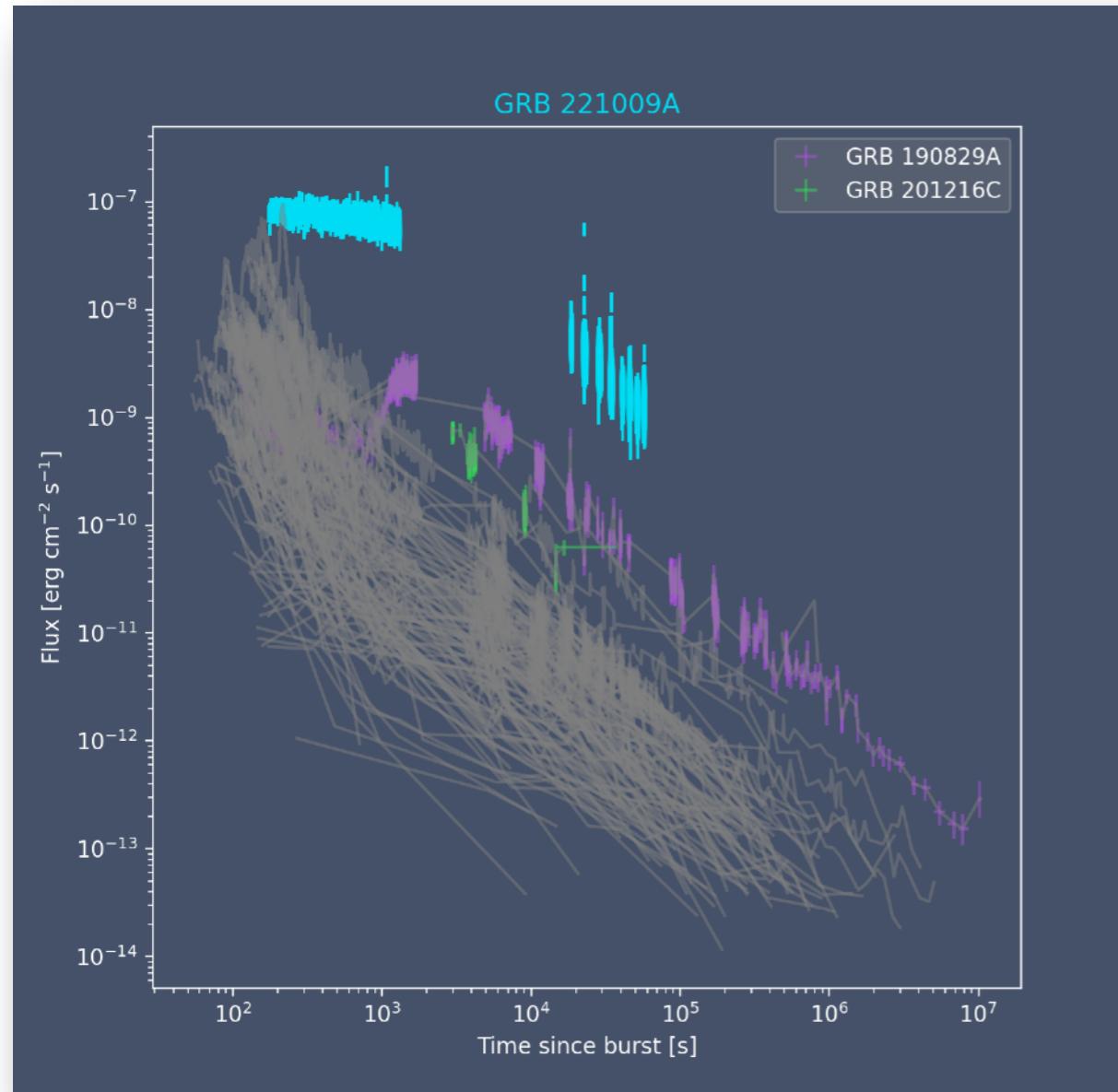
Gamma-ray bursts

Towards population studies at VHE energies

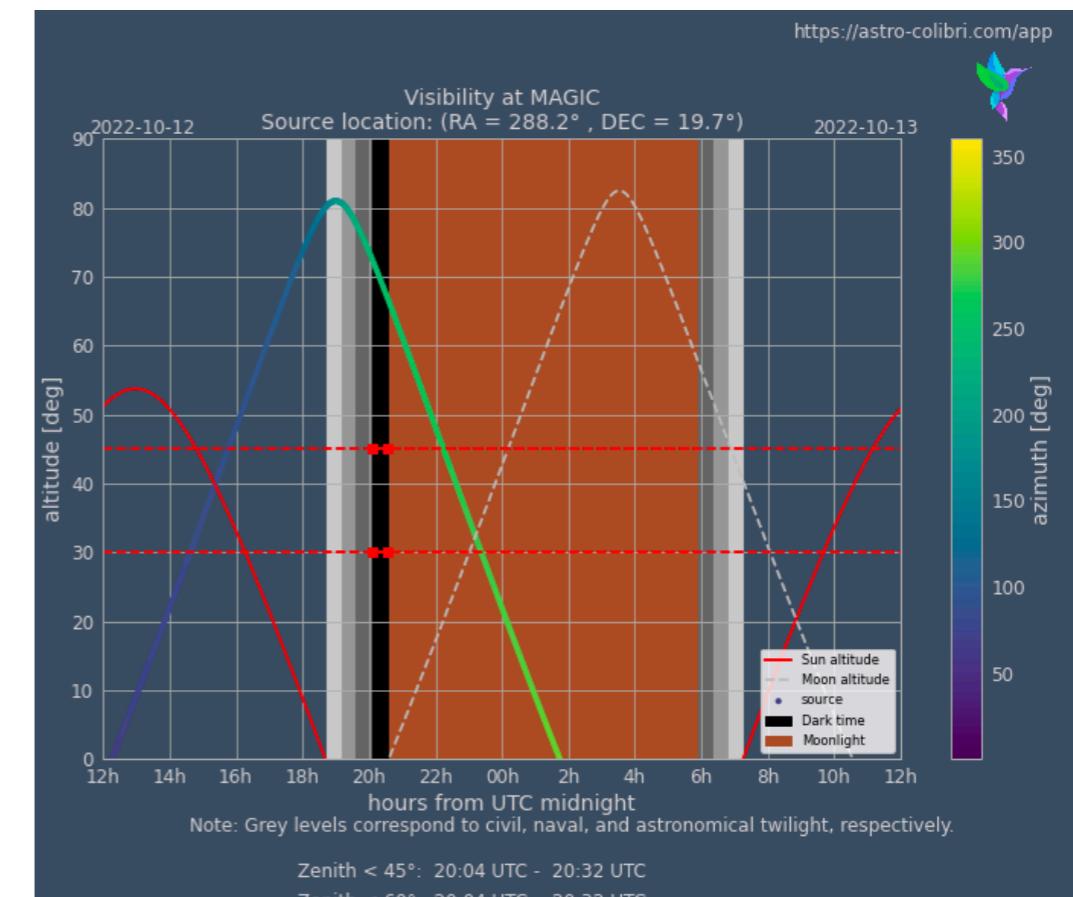


GRB 221009A

The brightest GRB ever detected



- Detected by Swift, Fermi-GBM, Fermi-LAT, optical, ...
- $z=0.151$, estimated $E_{iso}=2\times 10^{54}$ erg
- Burst left the LHAASO FoV
- IACTs blocked by the moon at the moment

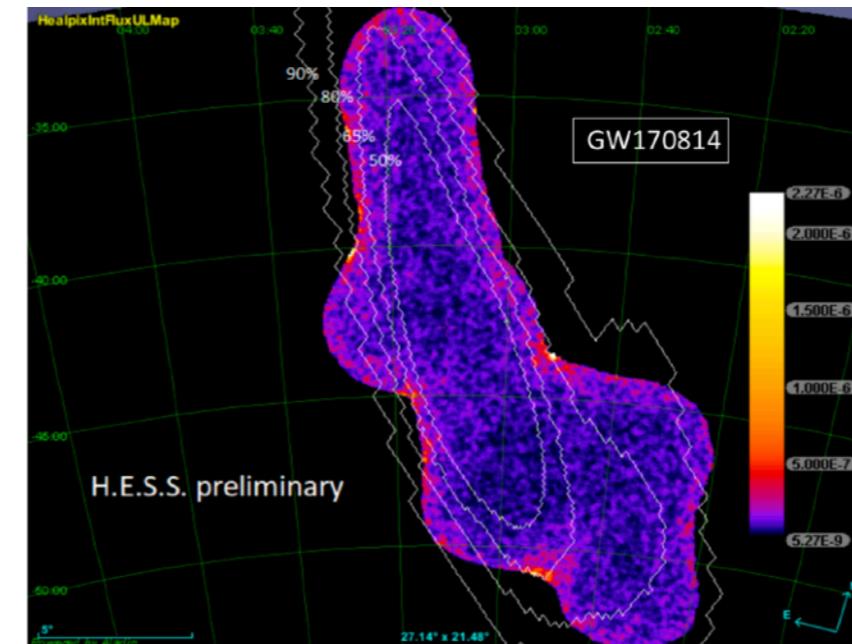
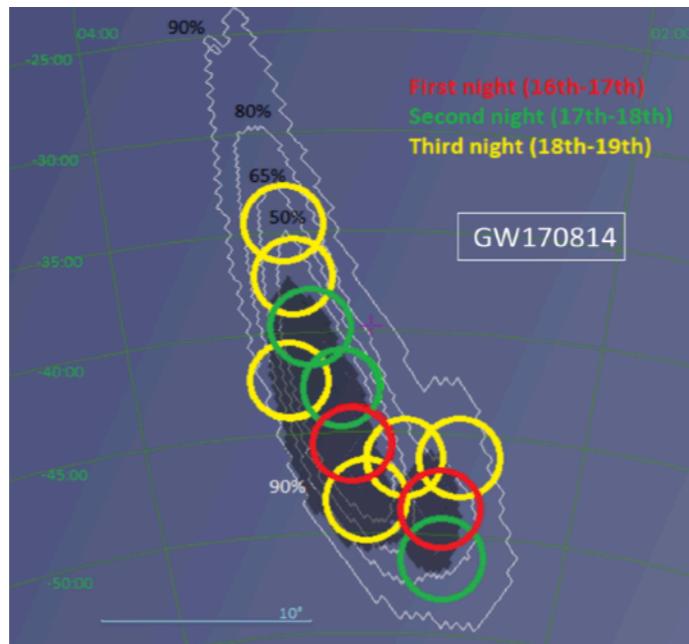


Nice use case for our workshop

VHE searches for GW counterparts



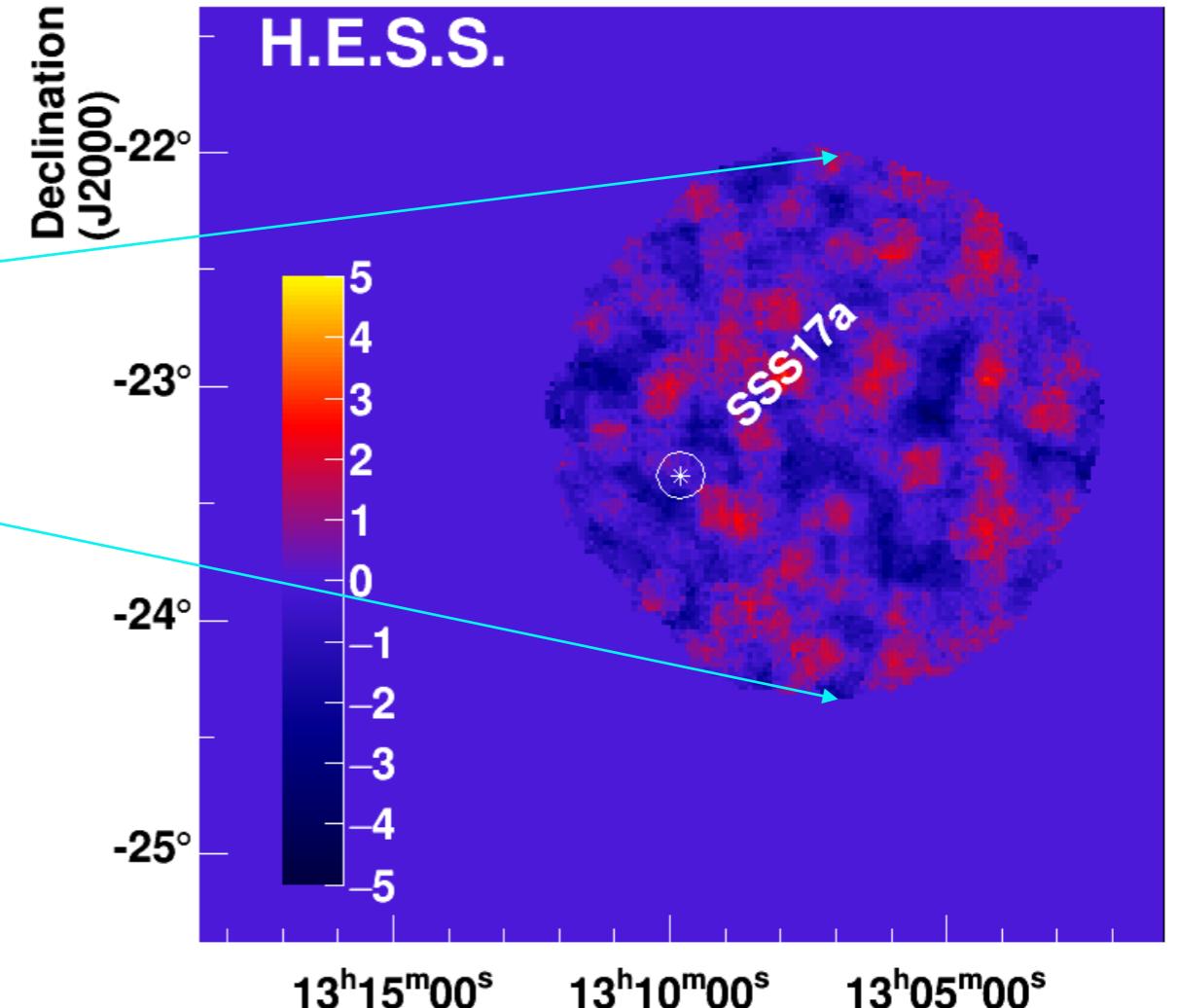
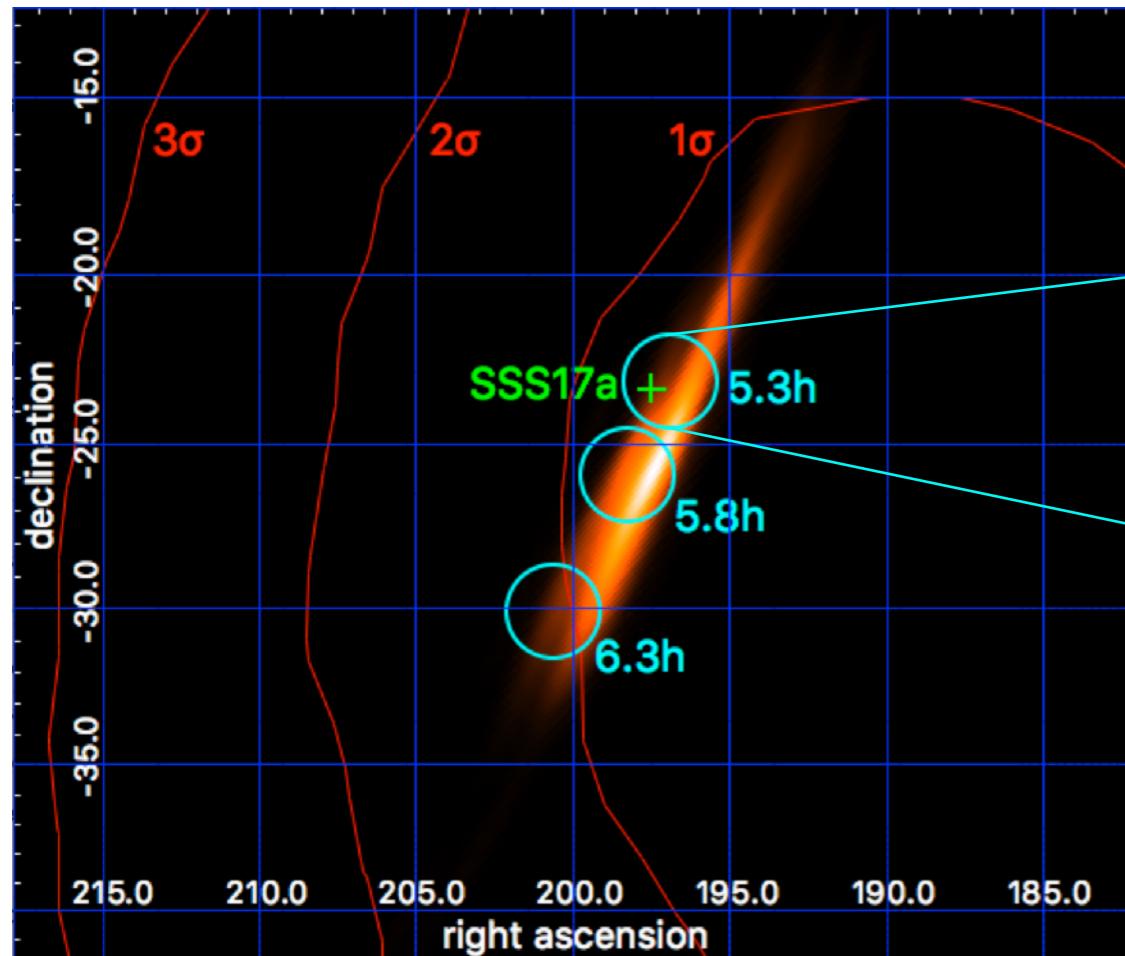
- GW151226 (MAGIC): the second BBH merger
 - Exploratory searches with a few pointings mirroring optical observations
 - De Lotto et al. (MAGIC Collaboration), IAU Symposium 324 (2017)
- GW170104 (VERITAS):
 - 39 pointings (5min each) covering ~27% of the localization region
 - GCN #21153
- GW170814 (H.E.S.S.): the first GW event detected by 3 interferometers
 - First complete coverage of the localization region
 - H.E.S.S. Collaboration, ApJ 923, 109 (2021)



H. Ashkar et al. (H.E.S.S.), 12th INTEGRAL conference, arXiv:1906.10426

Gravitational waves

H.E.S.S. rapid follow-up of GW170817

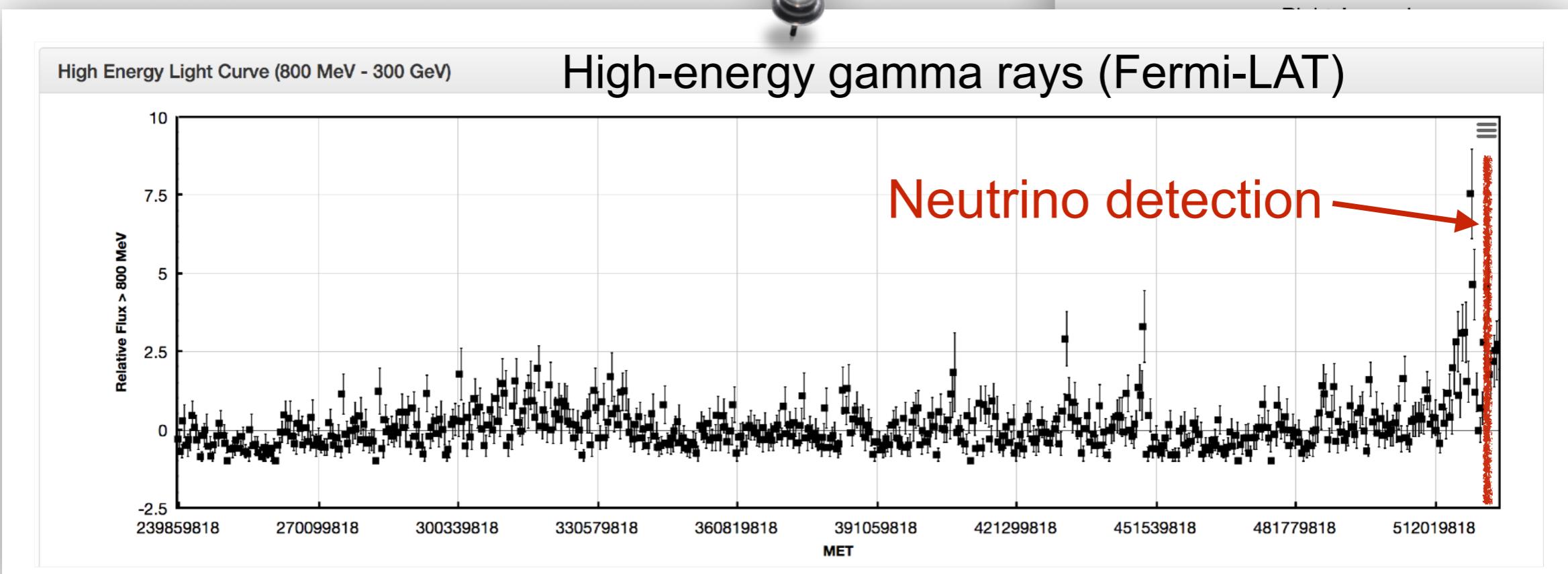
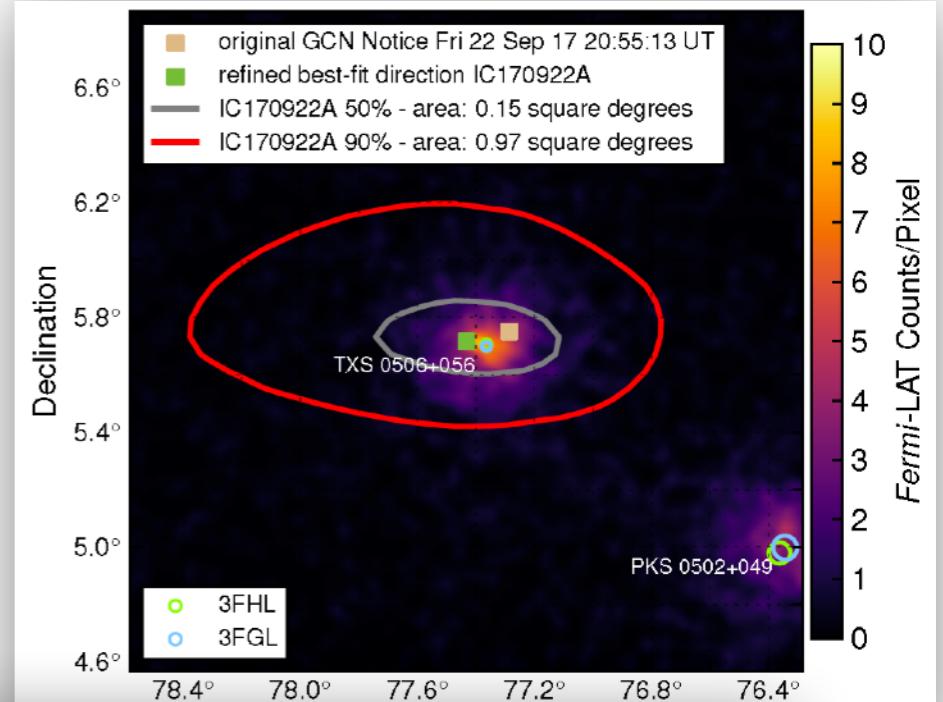


- First observations of a ground-based pointing instrument
 - 5.3 hours after GW170817 (5 minutes after the joint Ligo+Virgo analysis)
- Extensive monitoring of the remnant => limits on the magnetic field
- Complex scheme to optimize the tiling => ready for O4

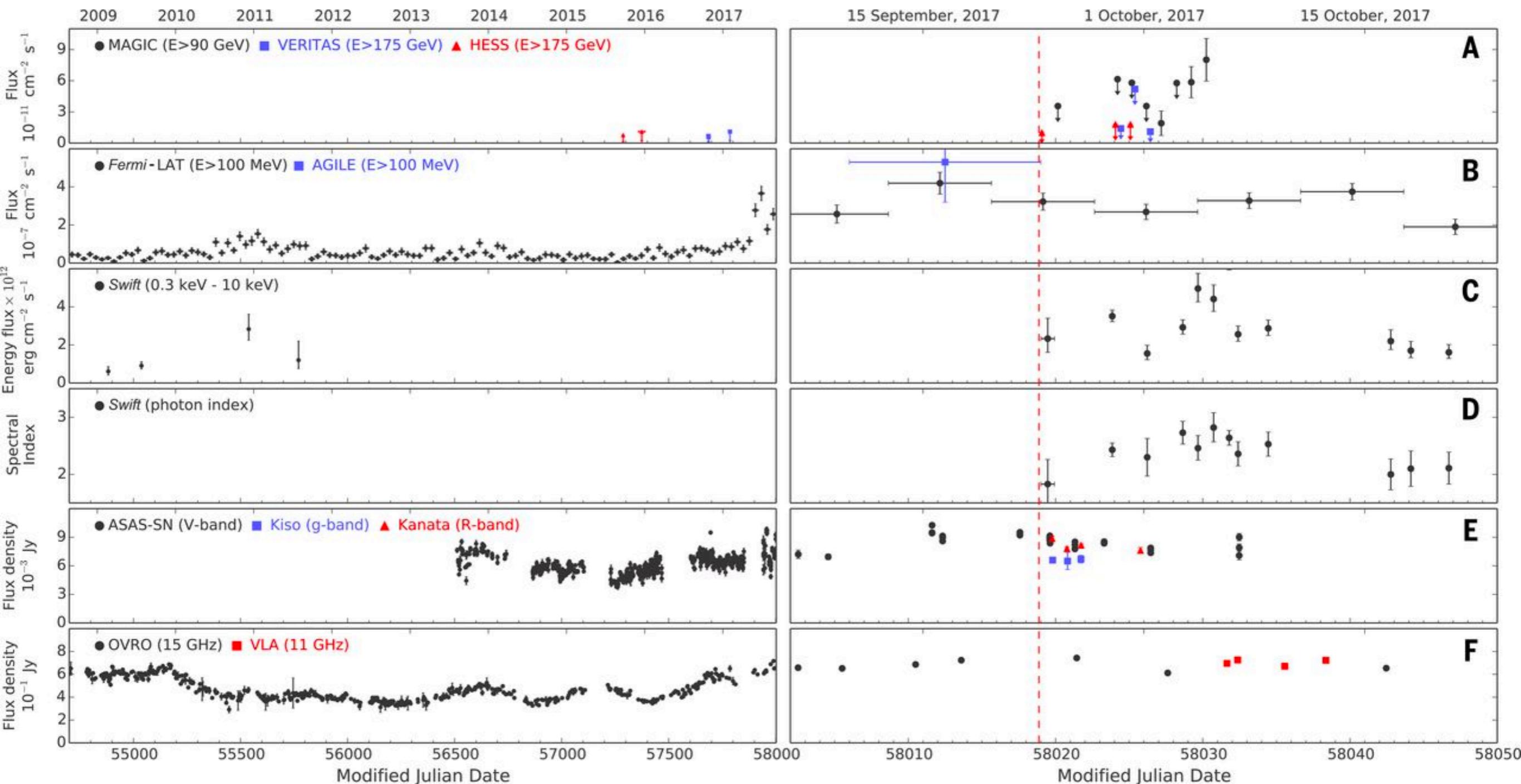
IceCube-170922A and TXS 0506+056



- 28/09/2017 Fermi-LAT: Detection of an active blazar (active galactic nuclei with the jet pointing towards Earth) within the neutrino uncertainty region [ATEL #10791](#)
- activity in all wavelengths (optical - X-rays - gamma rays) with unprecedented flux levels

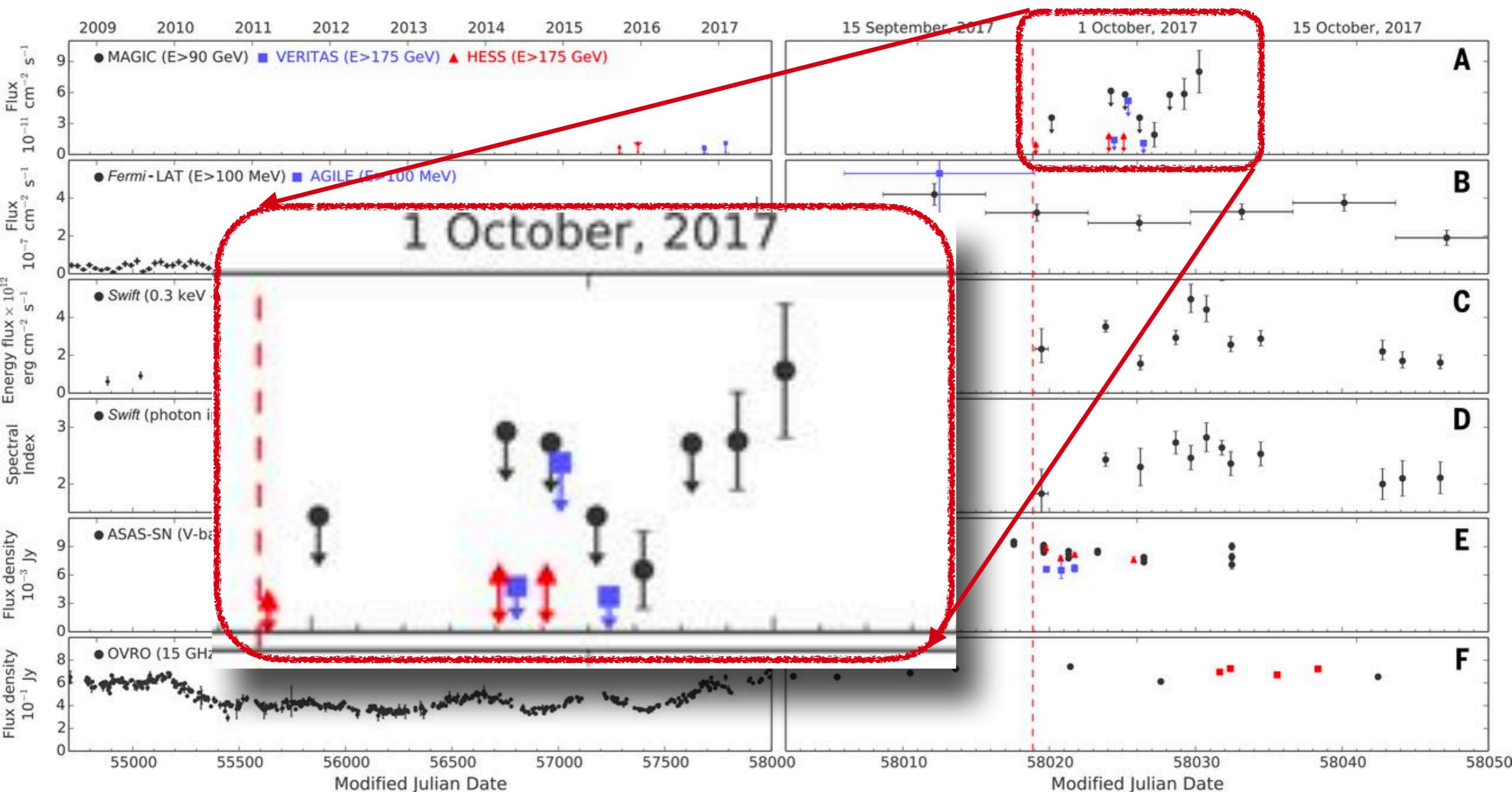


TXS0506+056



SCIENCE, Vol 361, Issue 6398

TXS0506+056

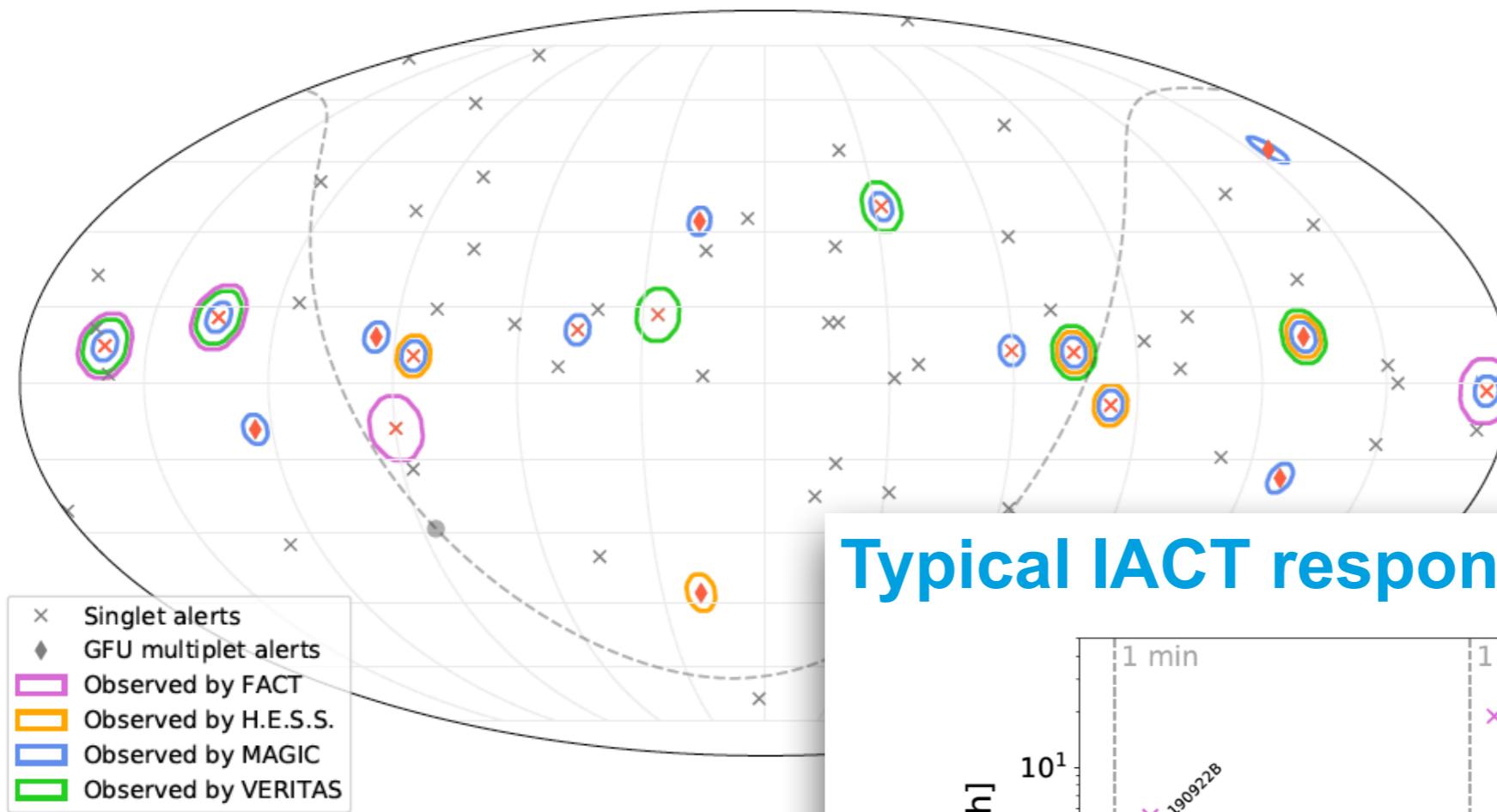


SCIENCE, Vol 361, Issue 6398

VHE emission associated to high-energy neutrinos



Alerts observed since October 2017



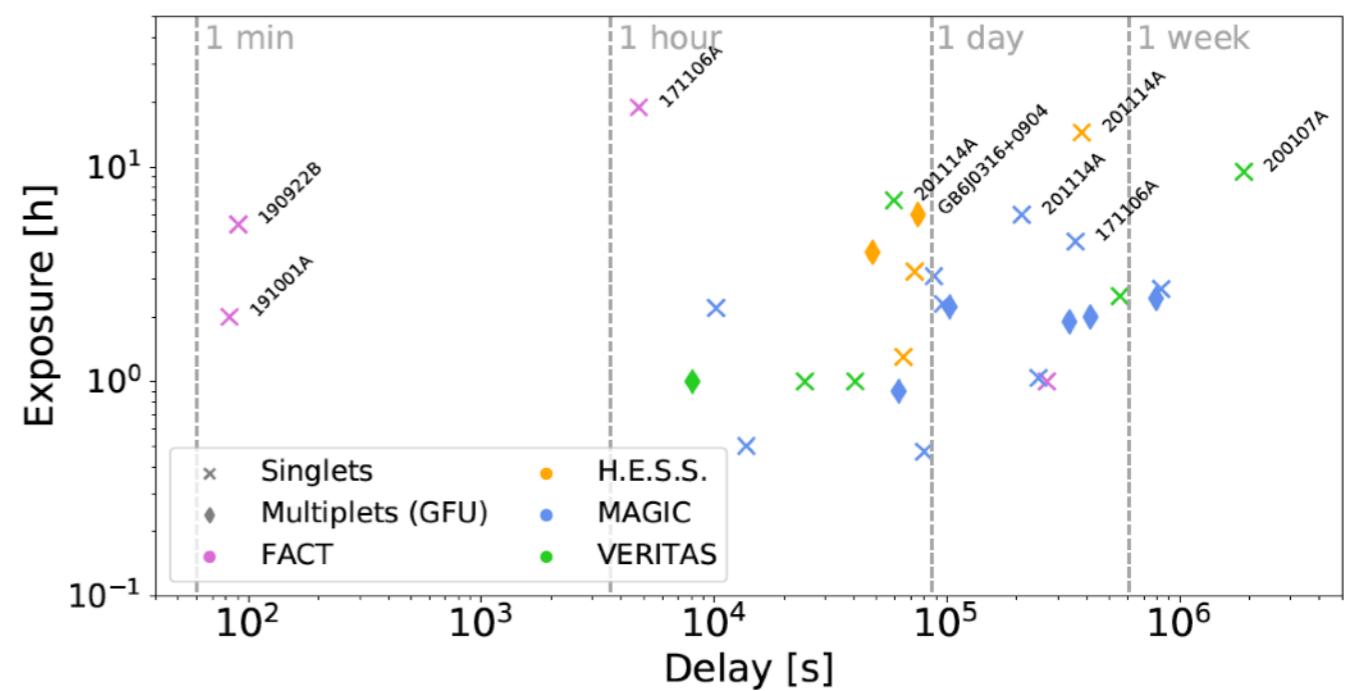
Joint effort by all IACTs

Santander et al. ICRC 2017
Satalecka et al., ICRC 2021

Alerts (Oct 2017 - Dec 2020):
62 singlets,
27 GFUs from 17 sources

Observed:
11 singlets,
GFUs from 7 sources

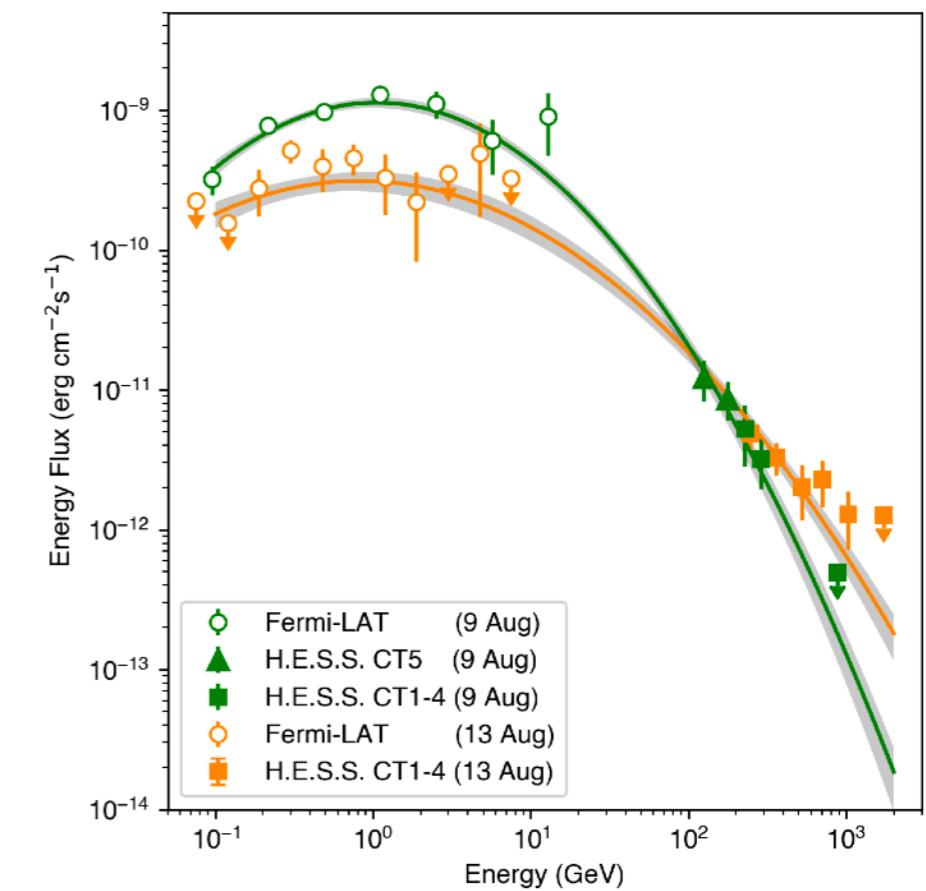
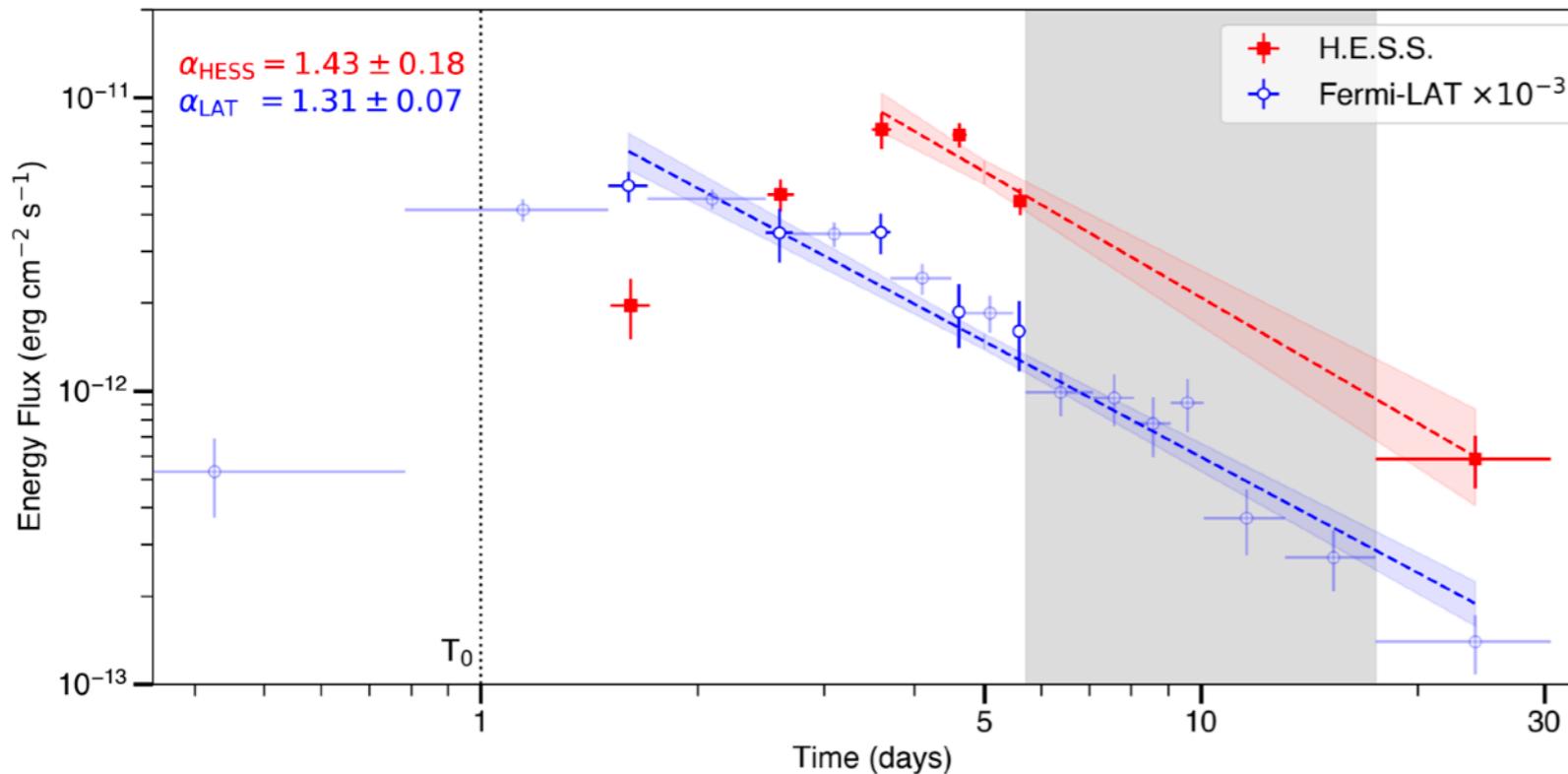
Typical IACT response



(Recurrent) novae

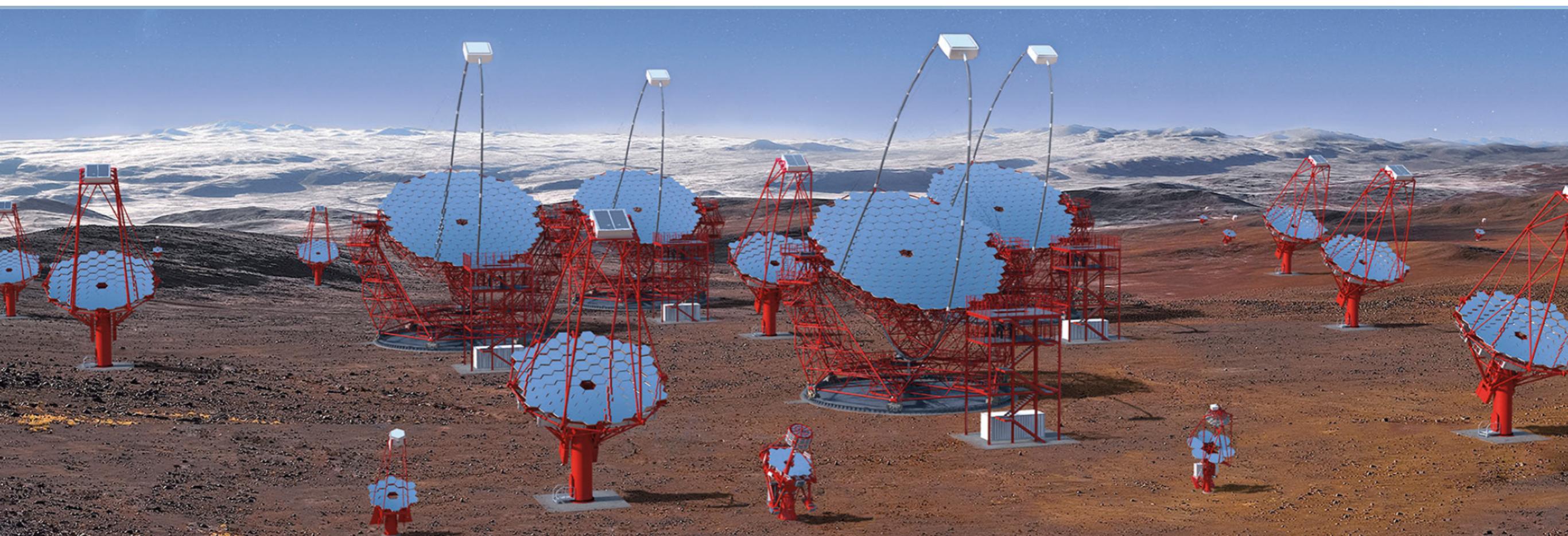
Efficient hadronic acceleration in RS Ophiuchi

- 1st Galactic transient
- Well-known recurrent nova; 2021 outburst detected by amateur astronomers
 - 2006 outburst in February restricted observation time for VHE follow-up
- H.E.S.S. VHE detection over \sim 20 days! Also detected by MAGIC + LST-1
- VHE peak flux 2 days after Fermi-LAT (3 days after optical); comparable decay slope
- Conclusion: hadronic scenario preferred; reaching theoretical limit of Emax via diffusive shock acceleration; SNe as CR accelerators...





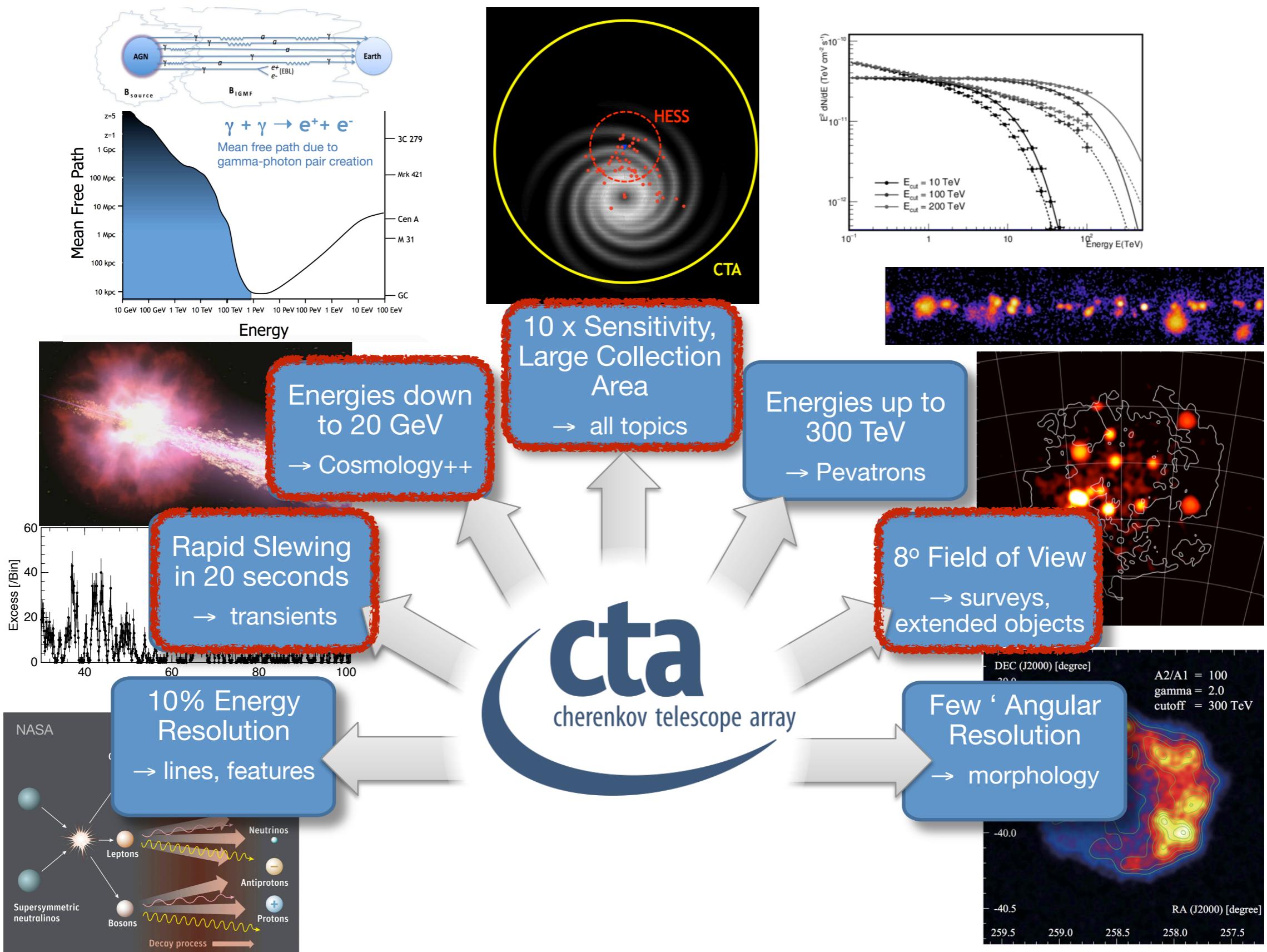
The Cherenkov Telescope Array





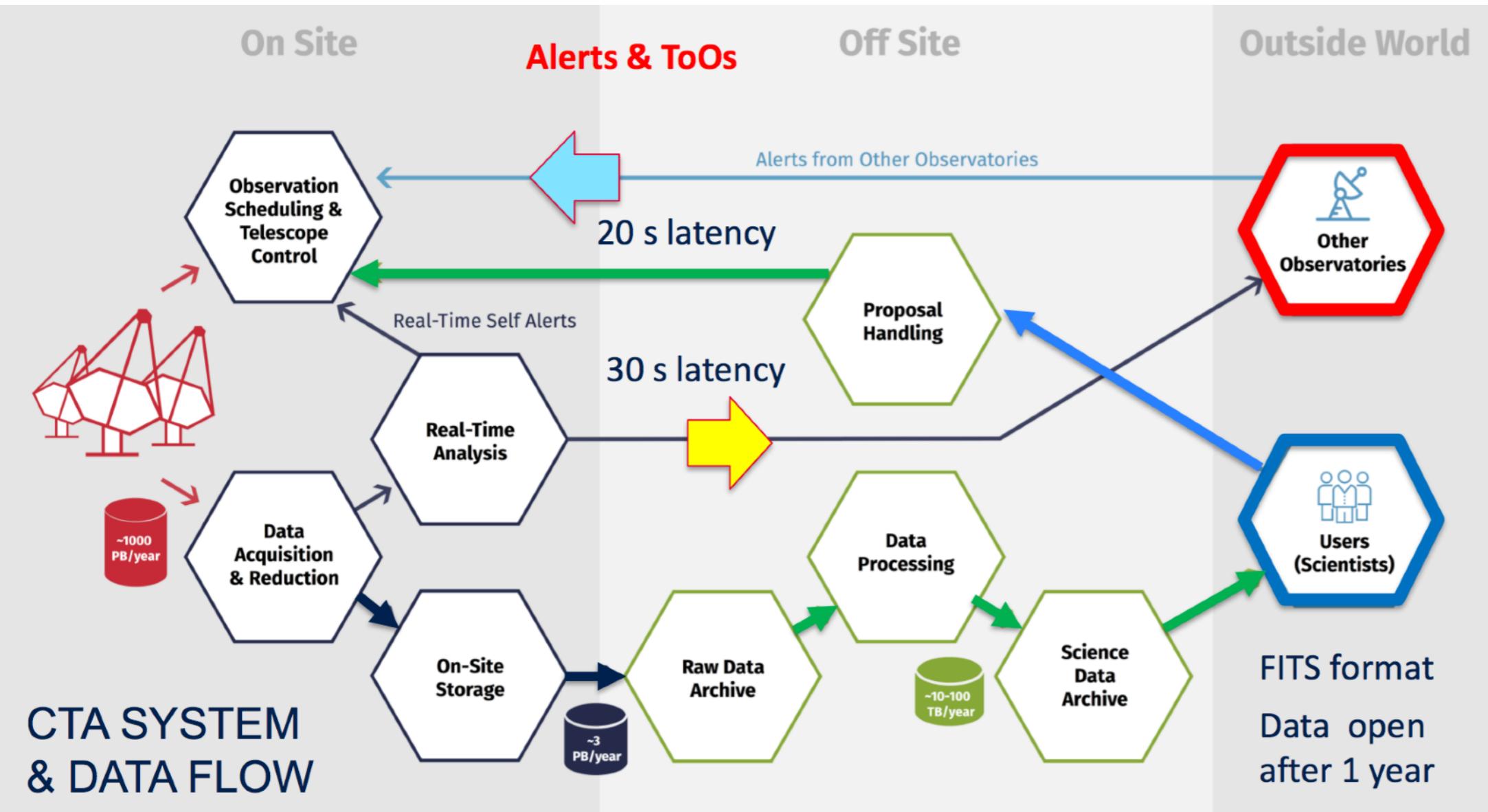
The Cherenkov Telescope Array



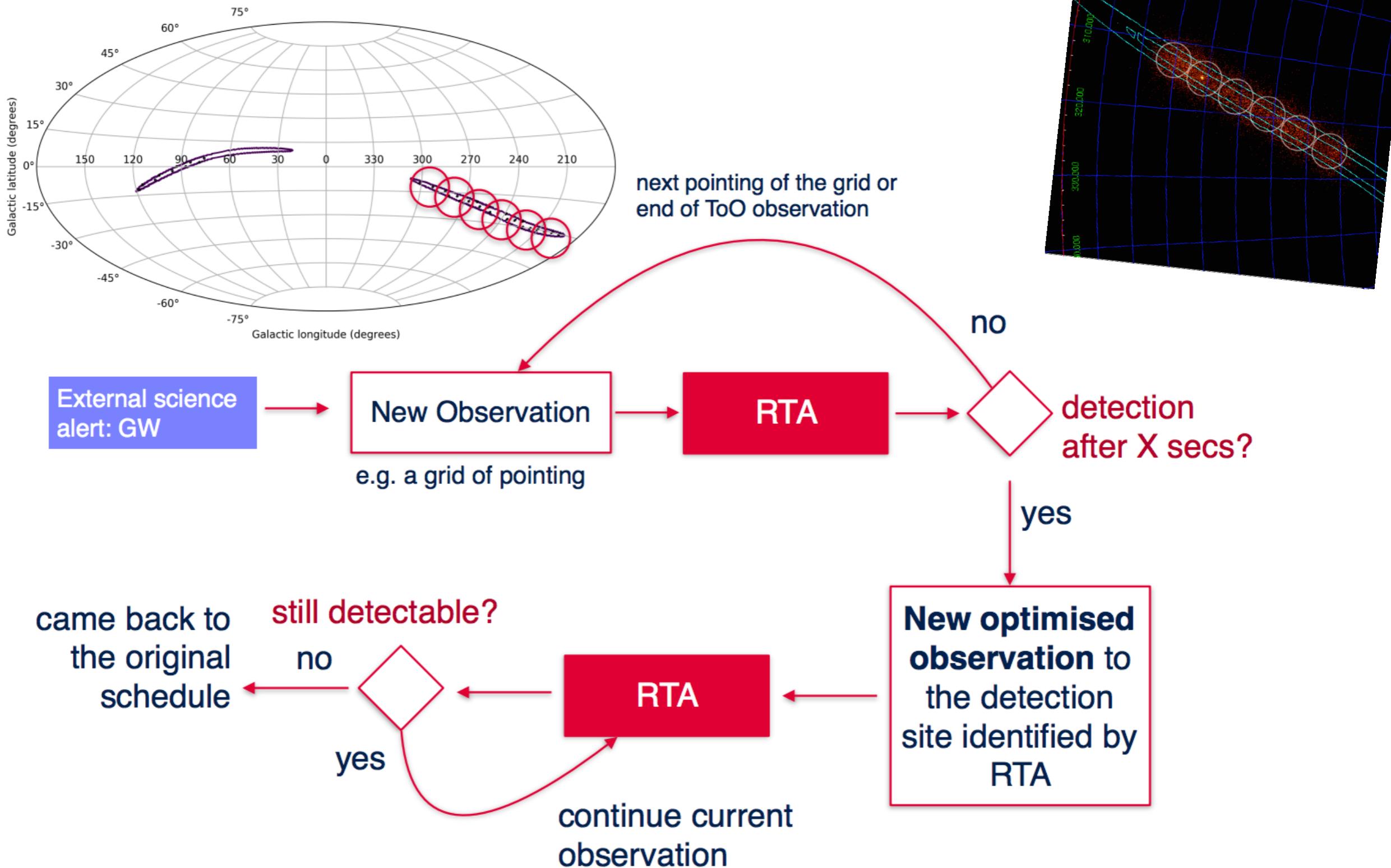


The CTA Transient program

- Transients are integral part of the CTA "Key Science Projects"
 - Observation time allocated to the CTA consortium
- dedicated Science Working Group "Transients and MWL"



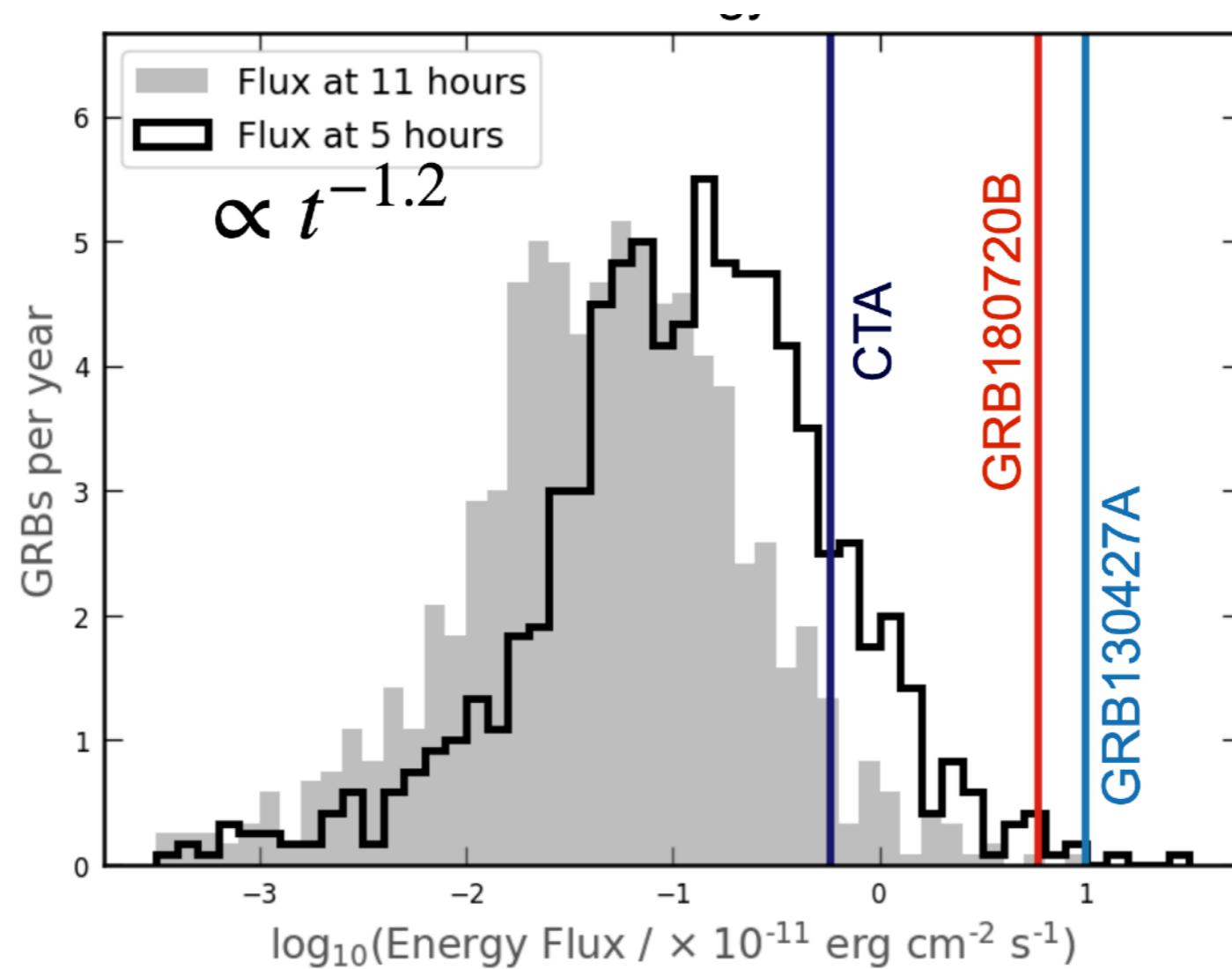
GW follow-up with CTA: real-time analysis



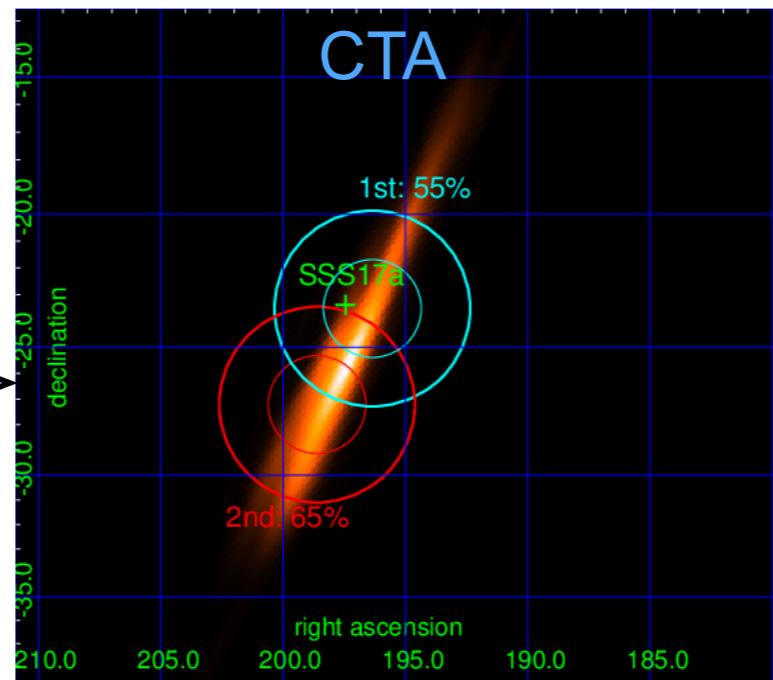
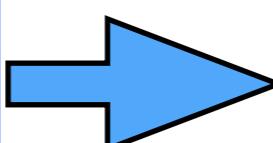
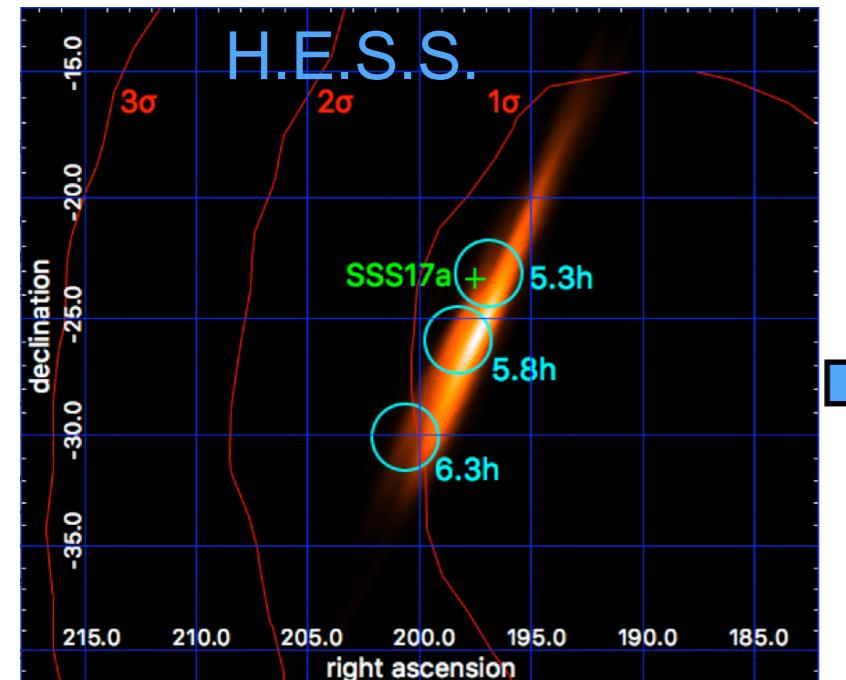
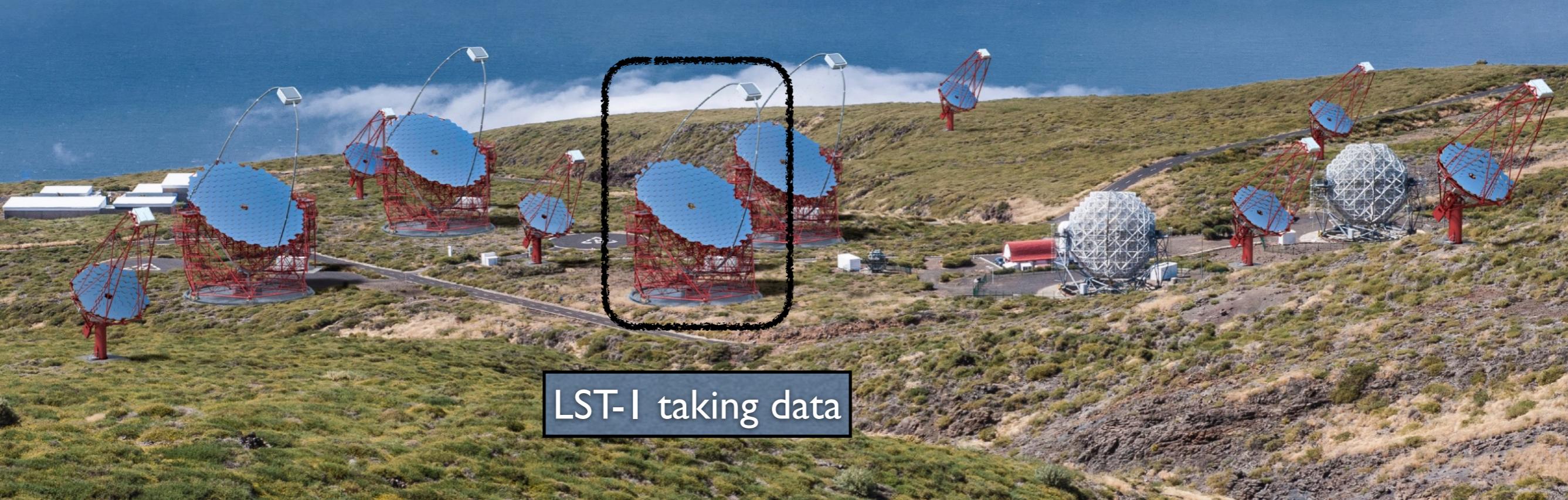
M. Seglar-Arroyo et al. (CTA), ICRC2019, [arXiv: 1908.08393](#)

Outlook: GRB detections with CTA

- ~10 times better sensitivity => increase detections + probe deeper into the afterglow
- Rapid slewing of the LSTs => catch parts of the prompt phase (?)



GW follow-up with CTA



H. Abdalla et al. (H.E.S.S.), ApJL 855:L22 (2017)

FS (CTA consortium), preliminary

- detailed studies ongoing
- extending work from
 - all current IACTs
 - I.Bartos et al., MNRAS 477 (2018) 639-647
 - B. Patricelli et al., JCAP 05 (2018) 056

High Altitude particle detector arrays



Milagro



ARGO-YBJ



HAWC



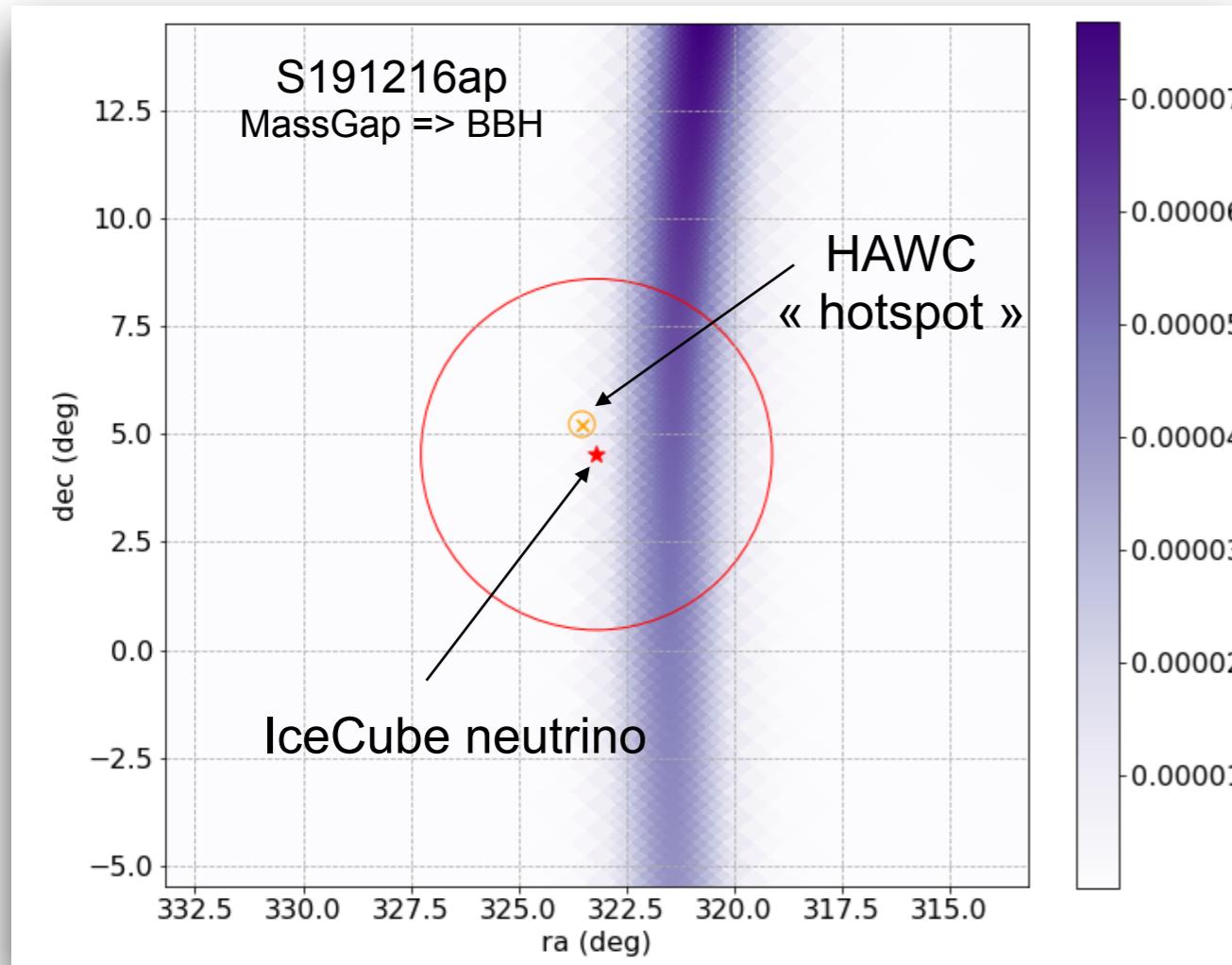
LHAASO



SWGO

MM searches with air shower arrays

- Large FoV + high duty-cycle
 - Smaller instantaneous sensitivity + higher $E_{\text{threshold}}$
- HAWC: automatized searches for excess at several timescales (0.3s - 100s)



GCN #26455
GCN #26463
GCN #26472
...

High-energy multi-messenger astrophysics in real-time

- Many years of preparation coming to fruition
 - automatic alert systems + dedicated data analysis tools + MoUs + ...
- Gravitational waves + Gamma Ray Bursts
 - major breakthroughs over the last years (GW170817, GRB180720B, GRB190114C, etc.)
- High-energy neutrinos
 - transient sources promising (no point-source in IceCube + reduced chance prob.)
 - IceCube-170922A and TXS 0506+056: a first hint
- Galactic Novae: new class of VHE transients !
- ...
- Current instruments going strong; transition/synergies to CTA coming up
- Open yearly calls for observation proposals (e.g. MAGIC, H.E.S.S. + ToOs)
- First public data archives (e.g. H.E.S.S. data release)

Lessons learned

- Success of rapid, fully automatic systems to trigger observations
- Increasingly fast in reporting detections (currently: <1day; CTA: <1min)
- Increasing fraction of observation time dedicated to MWL/MM transients
- Increasingly open (observations + data release)

- Remain open minded and search for the unexpected
 - TXS 0506+056: VHE flare 10days after a neutrino detection
 - GRB 190829A: VHE emission 3days into the GRB afterglow
 - RS Ophiuchi: VHE emission detectable for several weeks
- MWL/MM information crucial: triggers + interpretation
- Substantial increase in MWL/MM information and opportunities
 - Automatized systems (using ML) for filtering/categorization
 - Modern centralized platforms and services for scientists

ACME

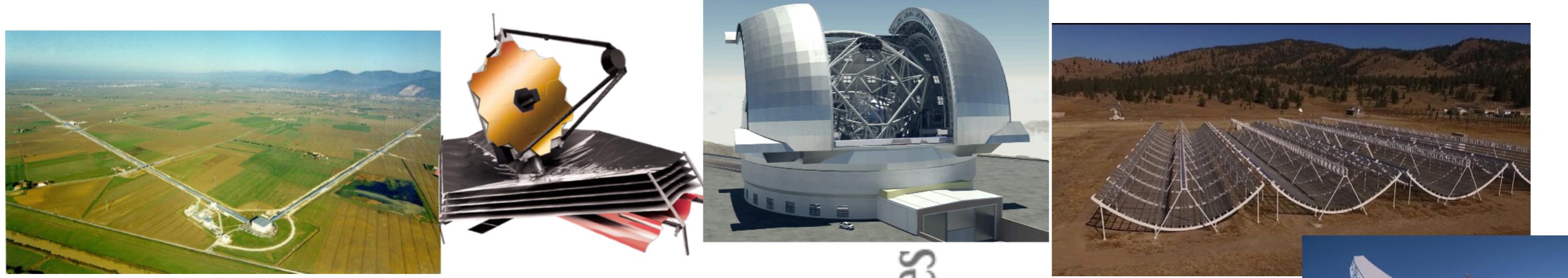
Gravitational Waves

SGRs
Supernovae
Neutrinos

Microquasars
Novae
AGN flares
Flaring stars

Fast Radio Bursts

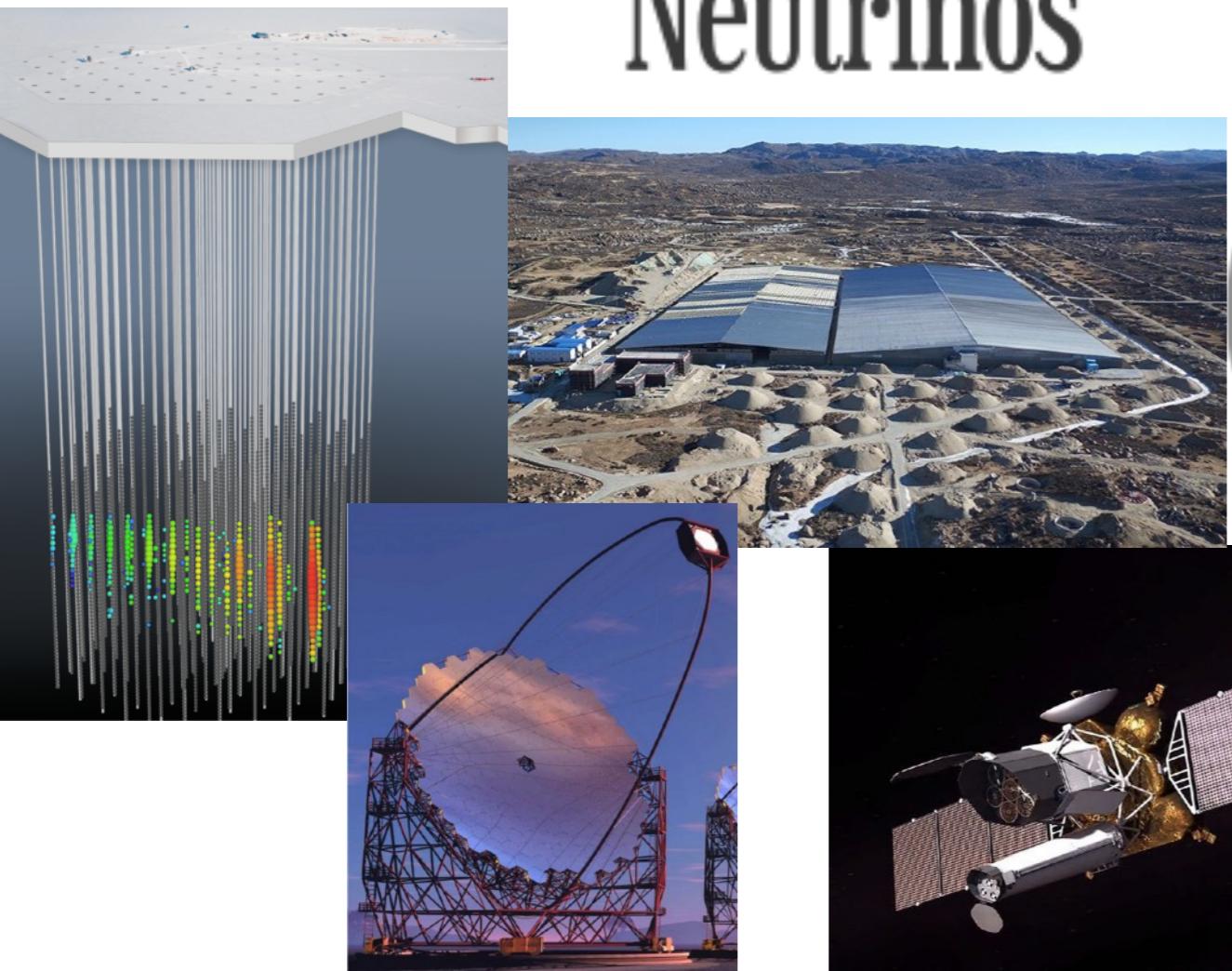
Gamma-ray Bursts



Gravitational Waves Neutrinos

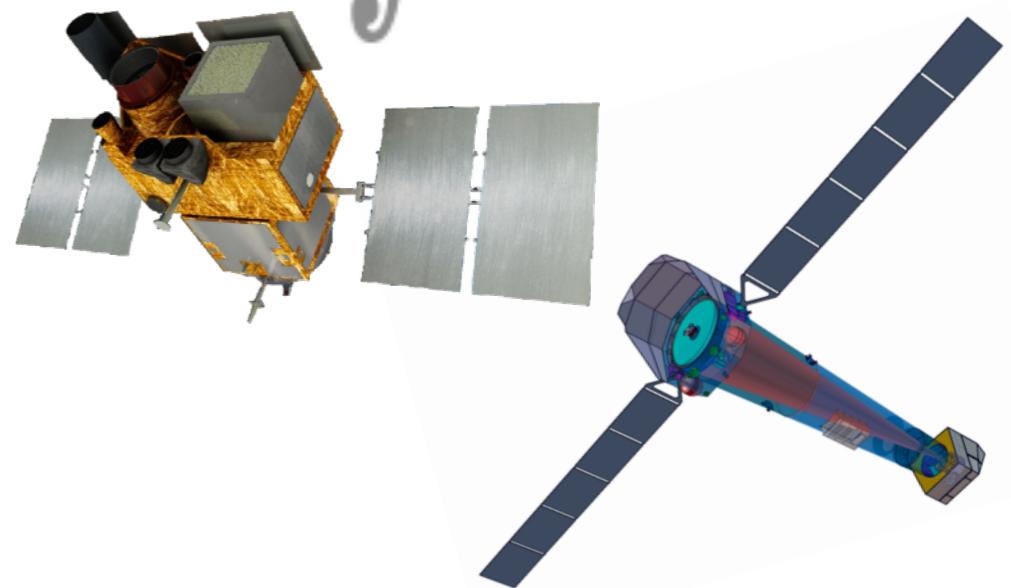
SGRs
Supernovae

Microquasars
Novae
AGN flares
Flaring stars

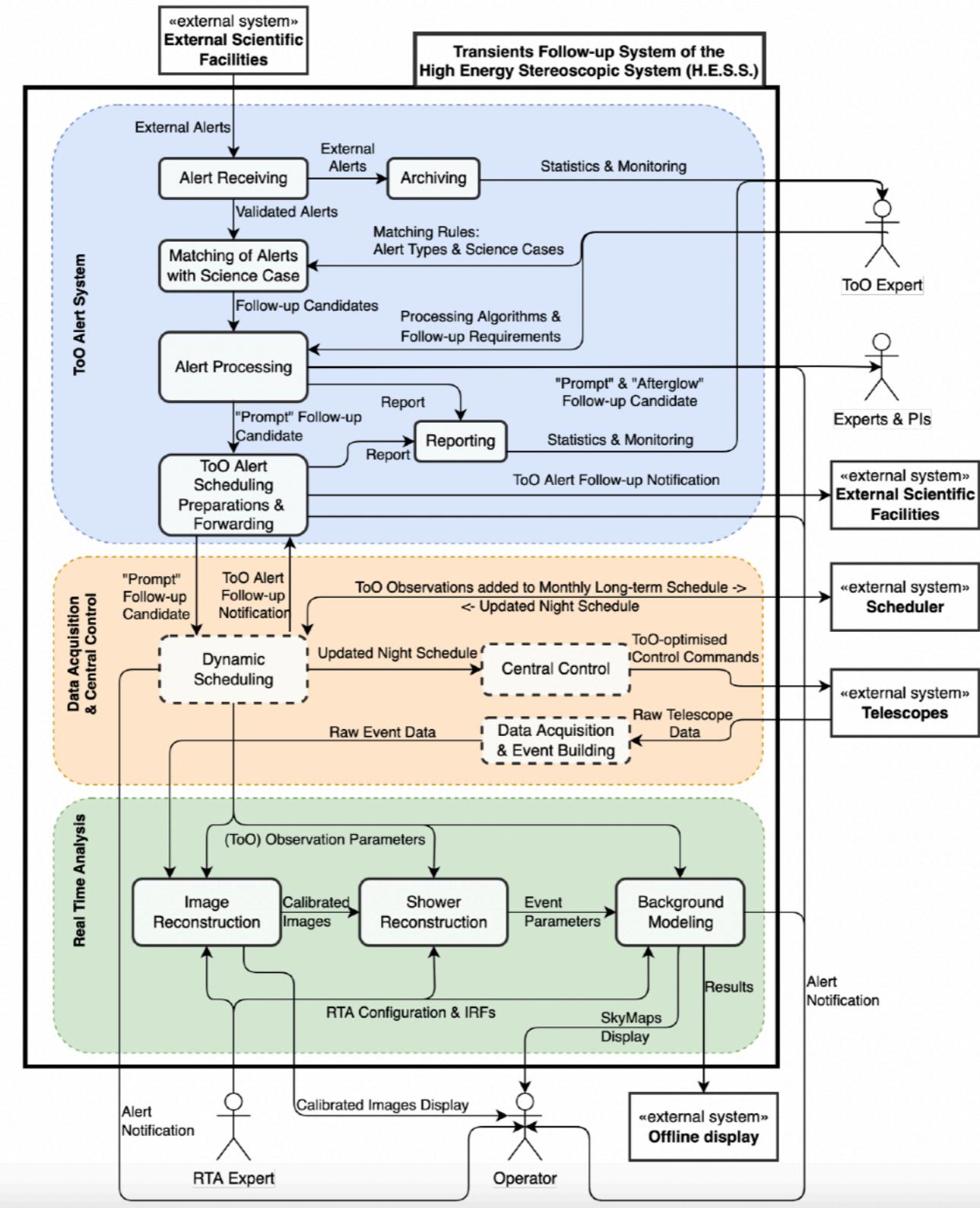


Fast Radio Bursts

Gamma-ray Bursts



The H.E.S.S. VoAlert system



C. Hoischen et al., arXiv:2203.05458; accepted by A&A

Astro-COLIBRI

- Increasing number of multi-messenger transients + a large variety sources of information (alerts, catalogs, monitoring, etc.)
- Need for novel tools and platforms to keep track and make informed decisions



<https://astro-colibri.com>

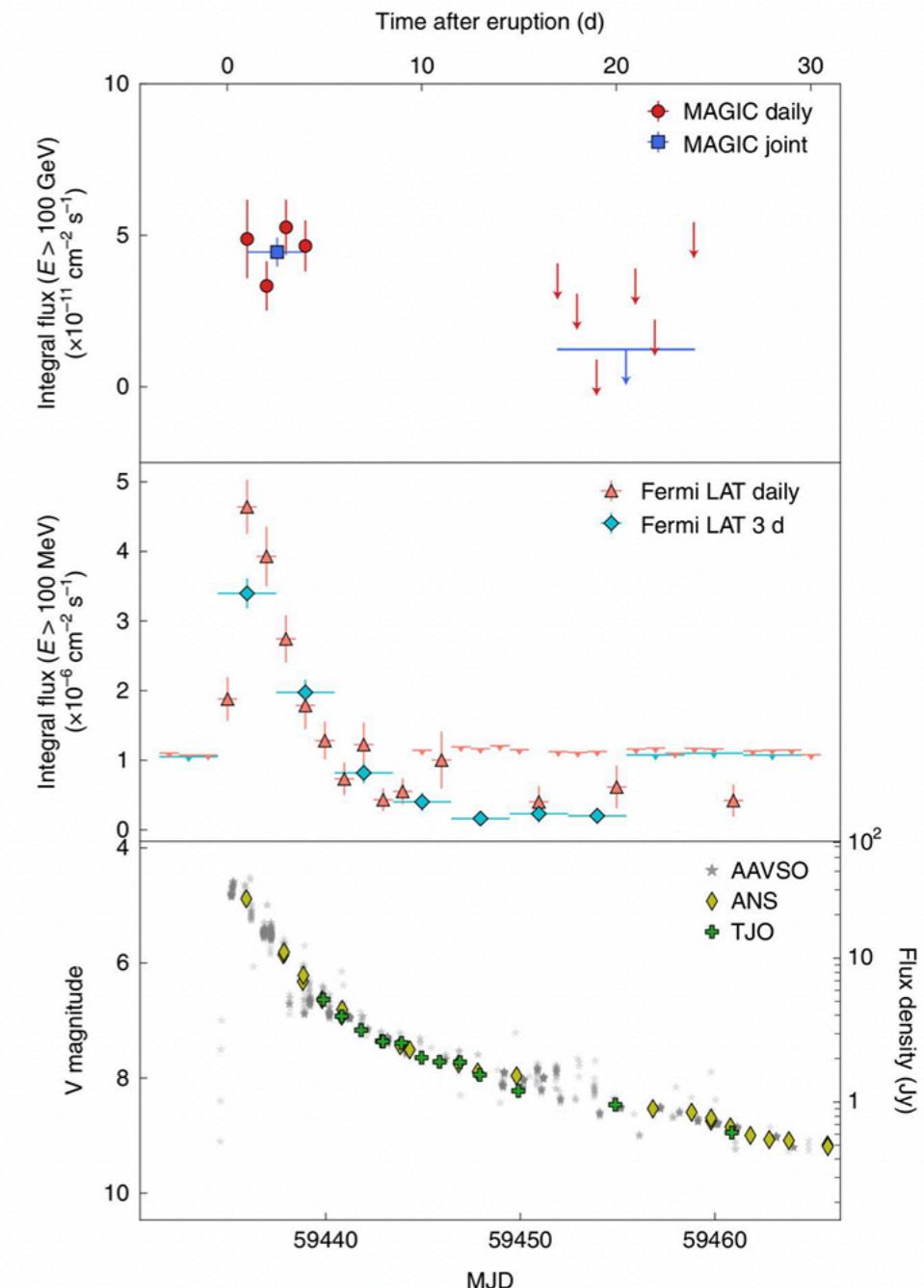


RS Ophiuchi

MAGIC detection of VHE gamma rays from Ophiuchi

Acciari et al., Nature Astronomy, 6, 760 (2022)

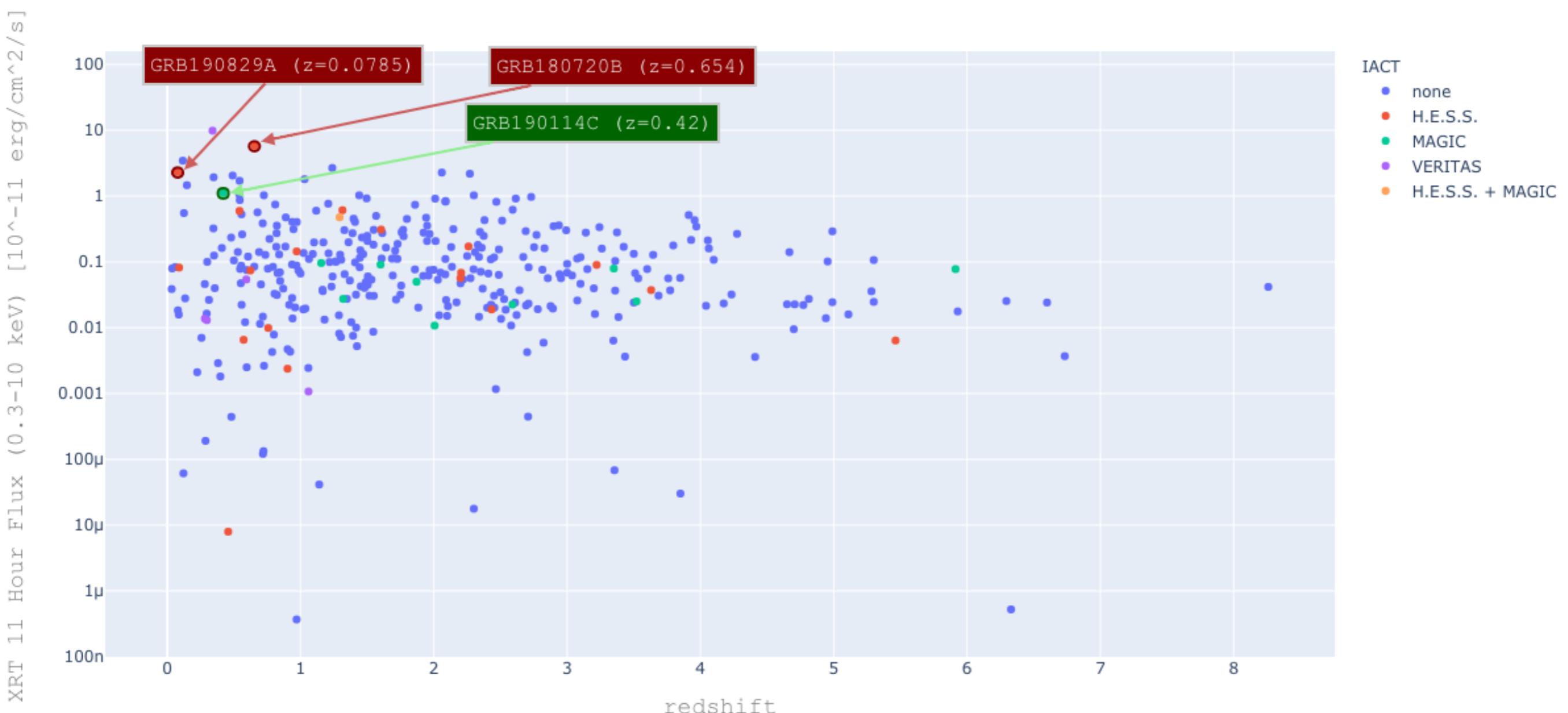
- Multiwavelength light curve of RS Oph
- VHE (MAGIC, top)
- high-energy (Fermi LAT, middle)
- optical (Joan Oró Telescope (TJO), Asiago Novae and Symbiotic Stars Collaboration (ANS) and American Association of Variable Star Observers International Database (AAVSO), bottom) bands.
- The lack of MAGIC data between MJD 59440 and MJD 59454 is due to the presence of bad weather conditions and strong moonlight.
- Error bars represent 1σ statistical uncertainties in the data points, and arrows are 95% confidence level upper limits.



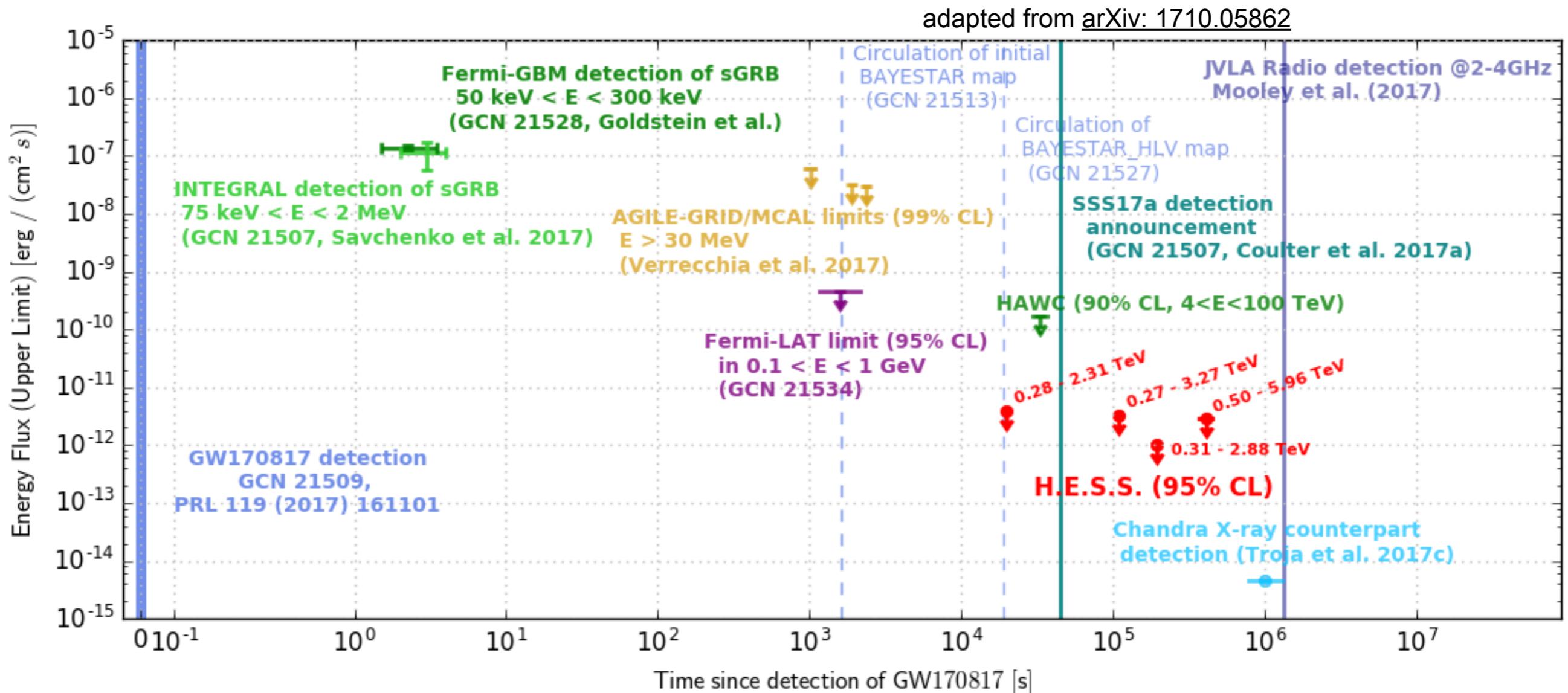
13.09.2022 -- CRIS 2022--

23

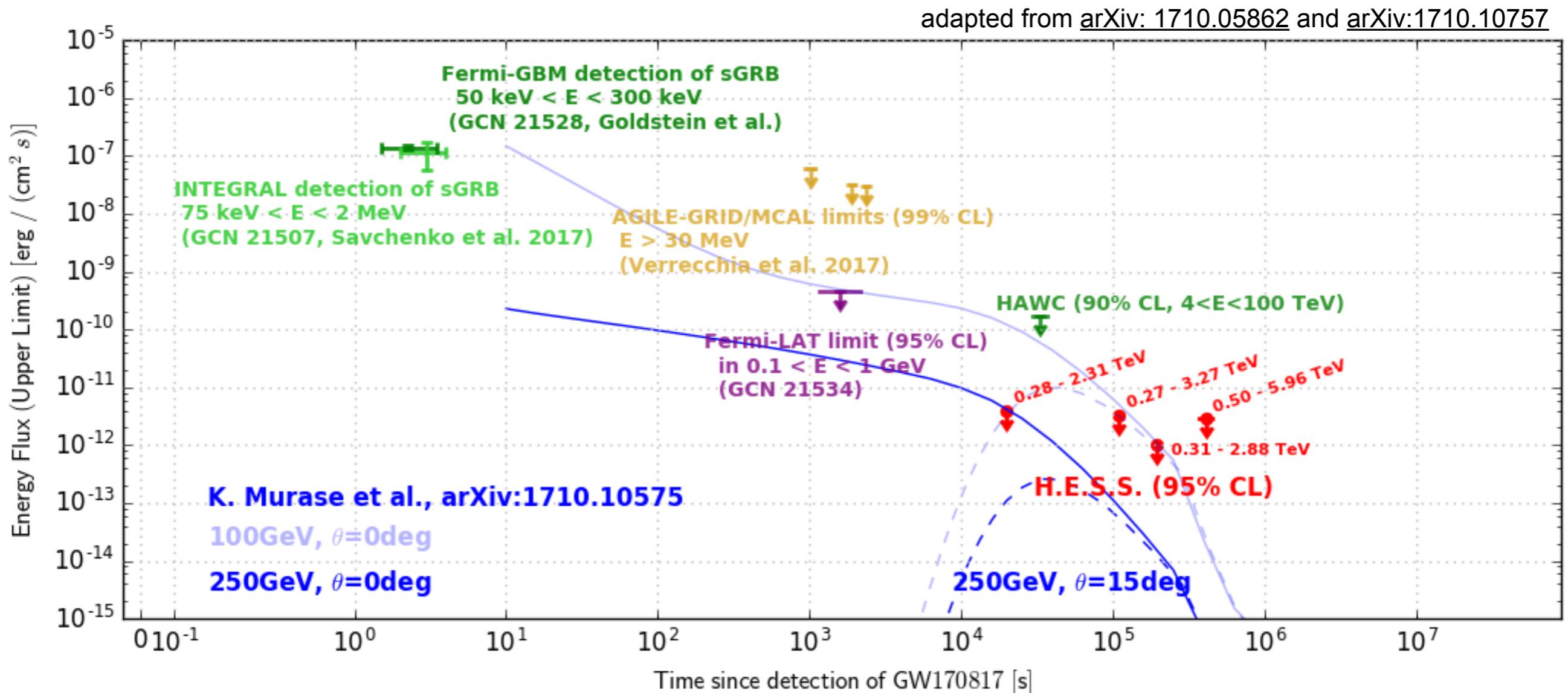
GRB observations with IACTs



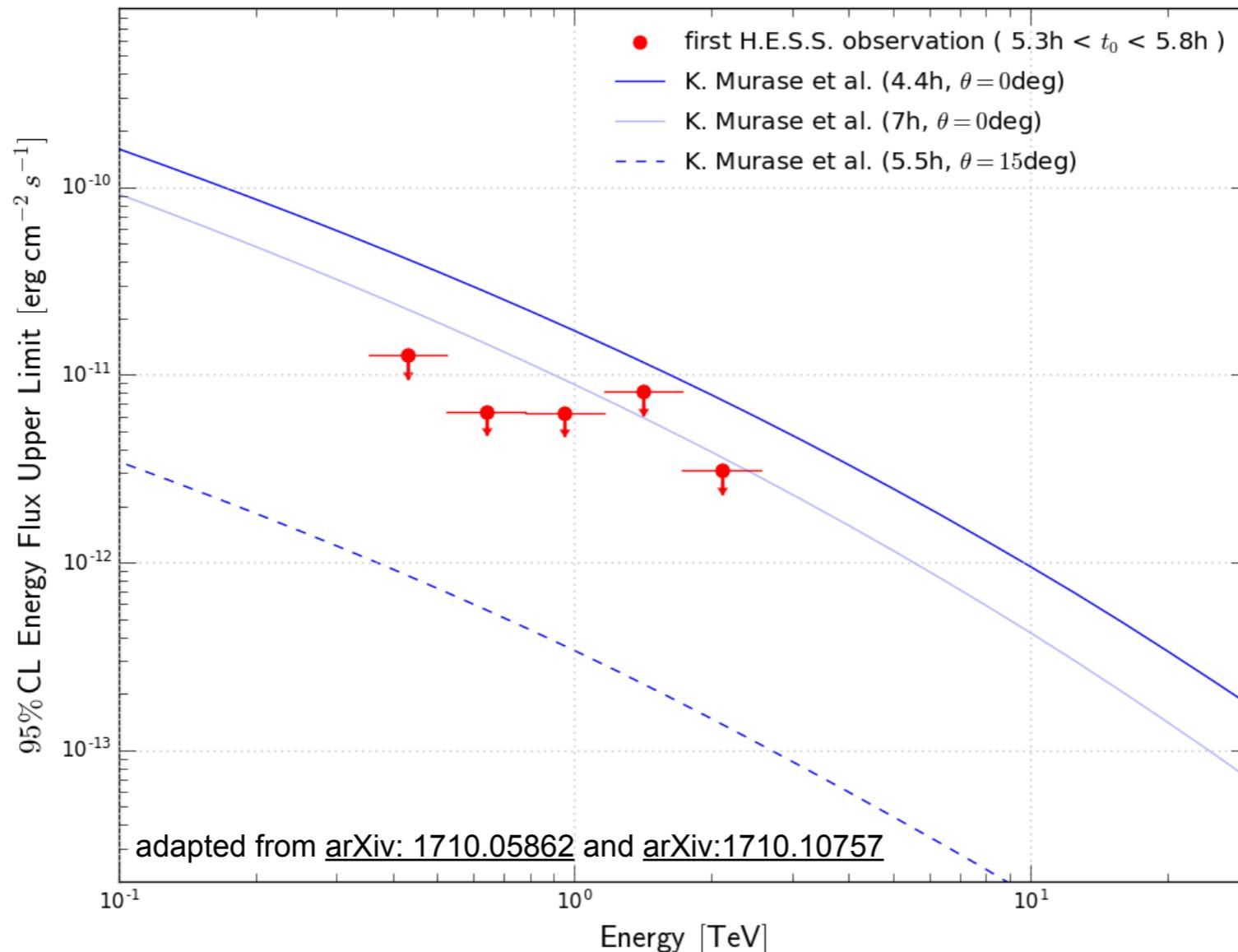
VHE observations of GW170817: prompt observations



VHE observations of GW170817: prompt observations

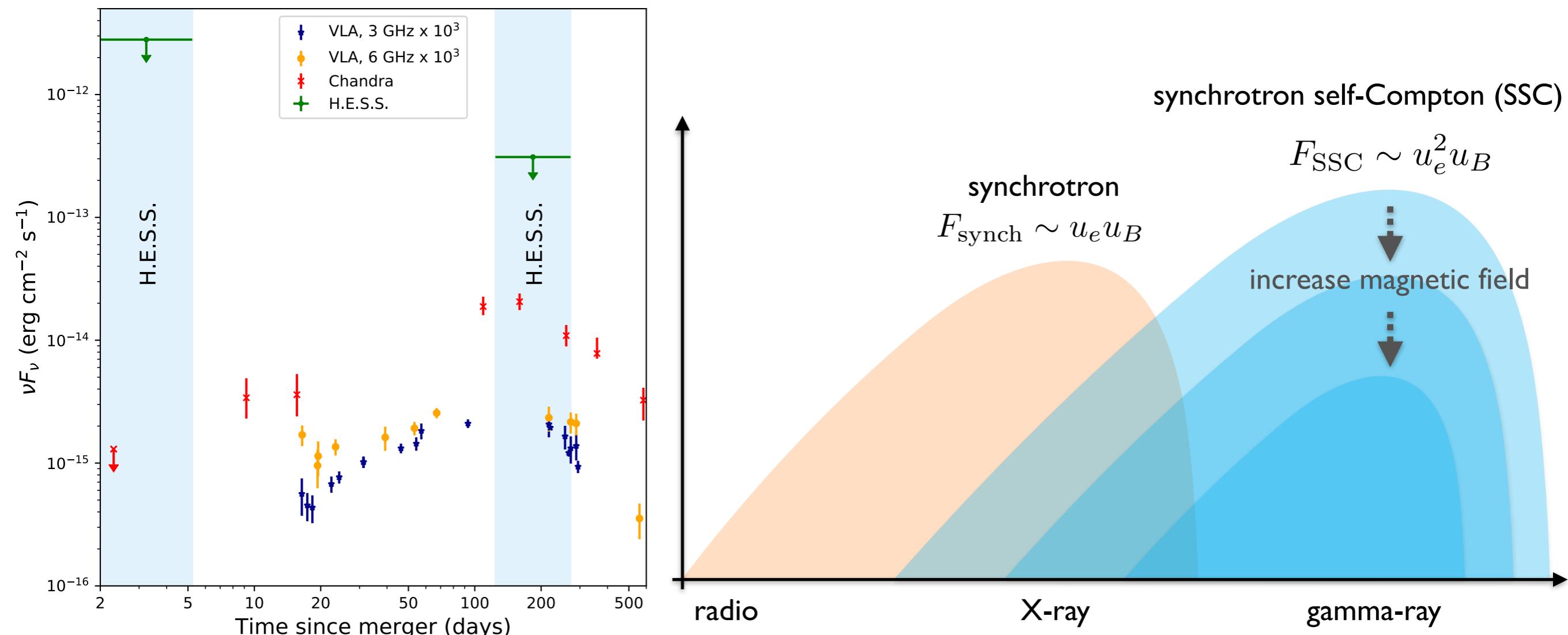


H.E.S.S. observations of GW170817: prompt observations



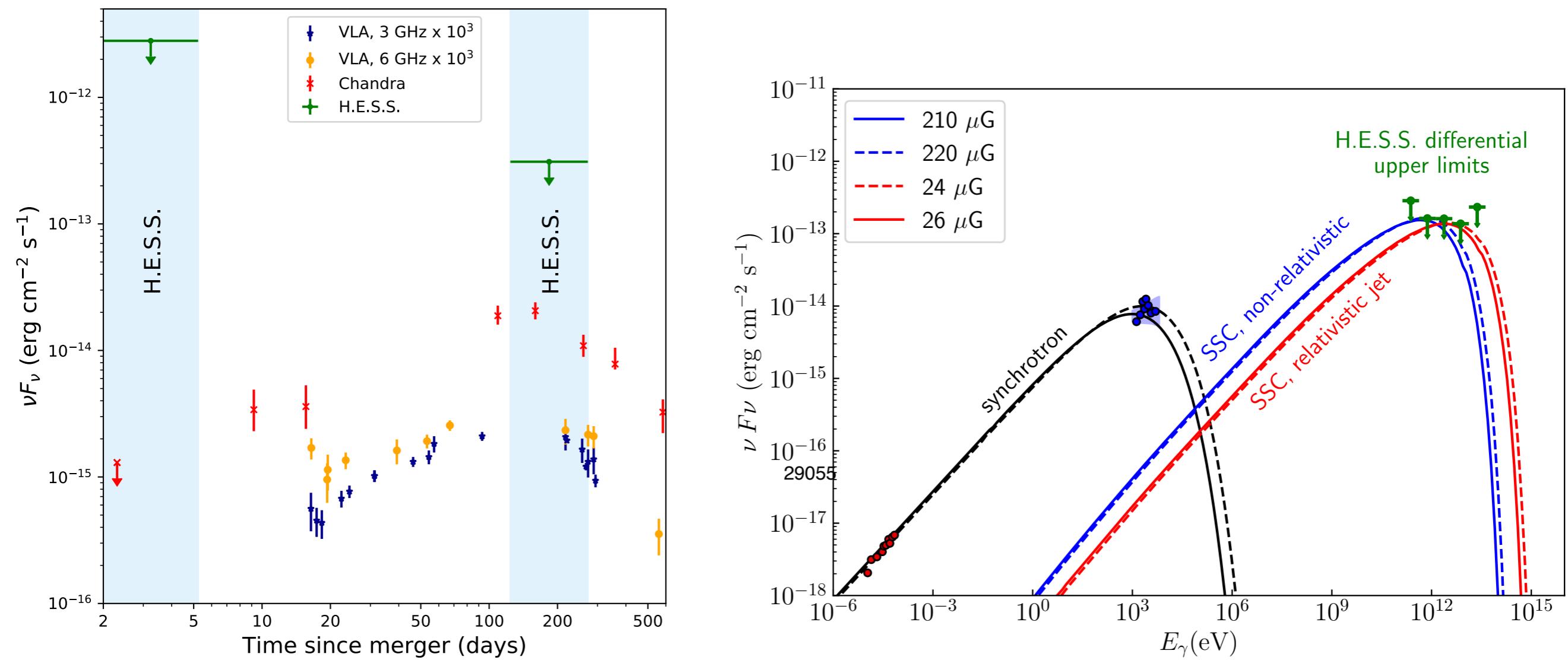
- e.g. K. Murase et al. (arXiv:1710.10575)
 - high-energy signatures from long-lasting central engines
 - inverse Compton: X-ray up-scattering by electrons in the jet
 - H.E.S.S. observations constrain on-axis emission
 - CTA will have access to off-axis emission

Longterm H.E.S.S. observations of GW170817



- Extensive H.E.S.S. follow-up during the peak of the X-ray+ radio emission
 - exploiting the link between synchrotron + SSC peaks to put limits on the B-field

Longterm H.E.S.S. observations of GW170817

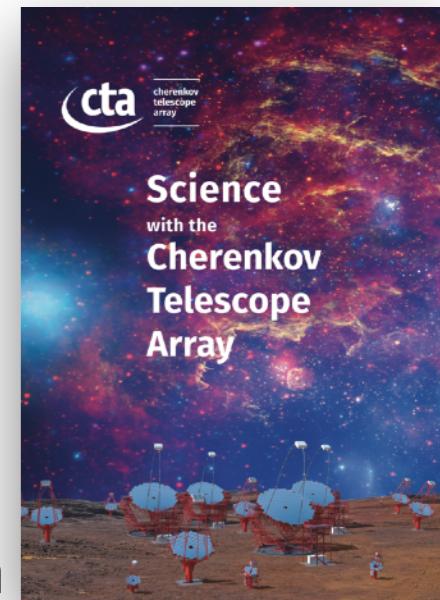


- Extensive H.E.S.S. follow-up during the peak of the X-ray+ radio emission
 - exploiting the link between synchrotron + SSC peaks to put limits on the B-field
 - isotropic, non-relativistic outflow: $B \gtrsim 210\mu\text{G}$
 - relativistic jet: $B \gtrsim 24\mu\text{G}$

H. Abdalla et al. (H.E.S.S. Collaboration), ApJL 894 (2020), 2

The CTA Transient program

- Transients are integral part of the CTA "Key Science Projects"
 - Observation time allocated to the CTA consortium
- dedicated Science Working Group "Transients and MWL"
 - Preparation of the first observations (reaction to external ToOs, definition observation program, preparation of science analysis, etc.)
 - Setup of multi-wavelength/messenger connections
 - Main topics: gamma-ray bursts, gravitational waves, high-energy neutrinos, FRBs, Galactic transients (e.g. microquasars, novae, magnetars, etc.)
 - Real-time analysis of the data => emission of notifications/alerts (internal + external)
- Also: AGN monitoring program + survey of the extragalactic sky + ...



The CTA Transient program

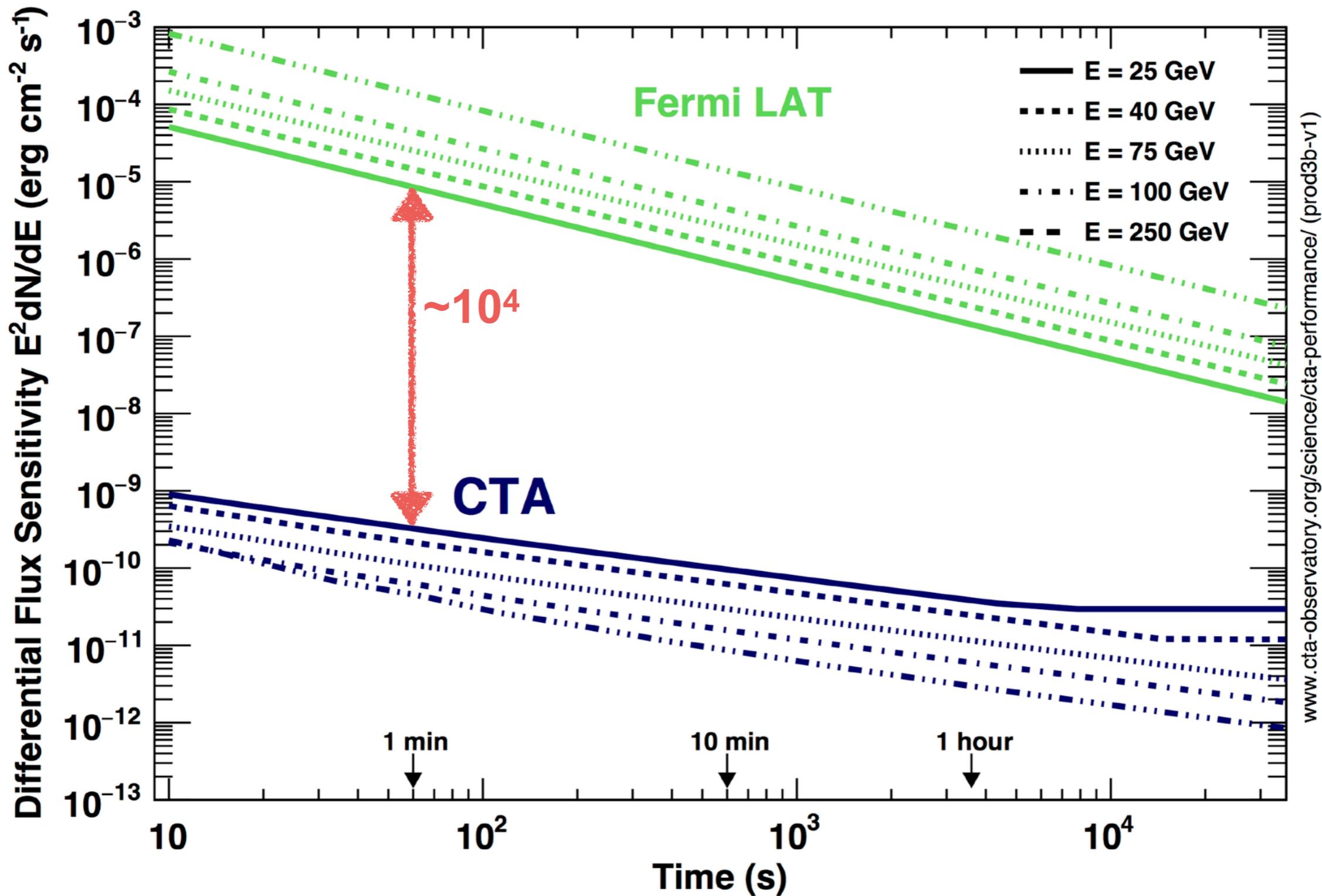
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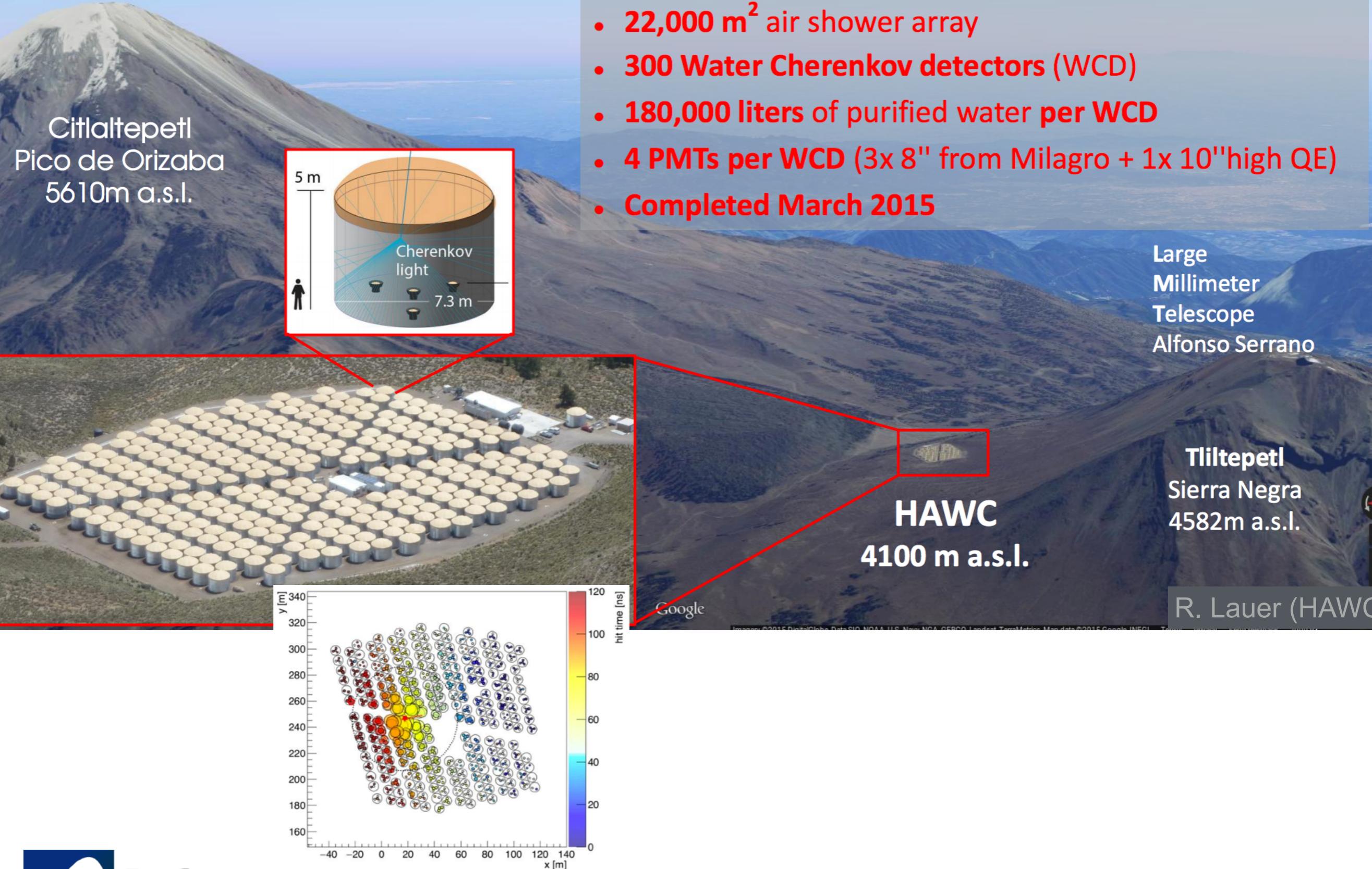
current status of proposed observation program

Priority	Target class	Observation times ($\text{h yr}^{-1} \text{ site}^{-1}$)			
		Early phase	Years 1–2	Years 3–10	Years 1–10
1	GW transients	20	5	5	
2	HE neutrino transients	20	5	5	
3	Serendipitous VHE transients	100	25	25	
4	GRBs	50	50	50	
5	X-ray/optical/radio transients	50	10	10	
6	Galactic transients	150	30	0(?)	
Total per site ($\text{h yr}^{-1} \text{ site}^{-1}$)		390	125	95	
Total both sites (h yr^{-1})		780	250	190	
Total in different CTA phases (h)		1560	500	1520	2020

Sensitivity to transient emission



High Altitude Water Cherenkov Observatory (HAWC)

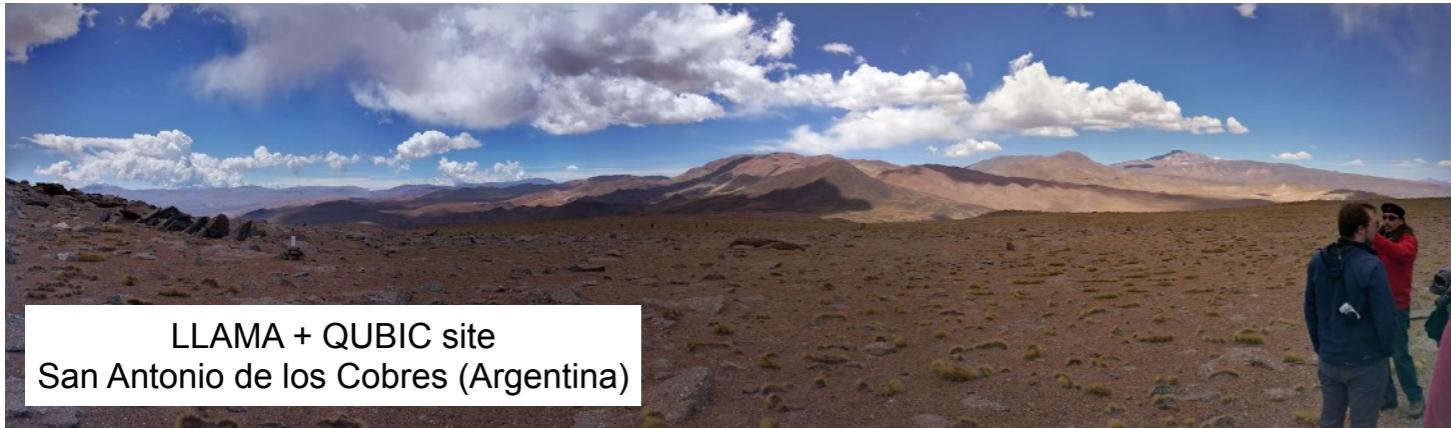


The Southern sky

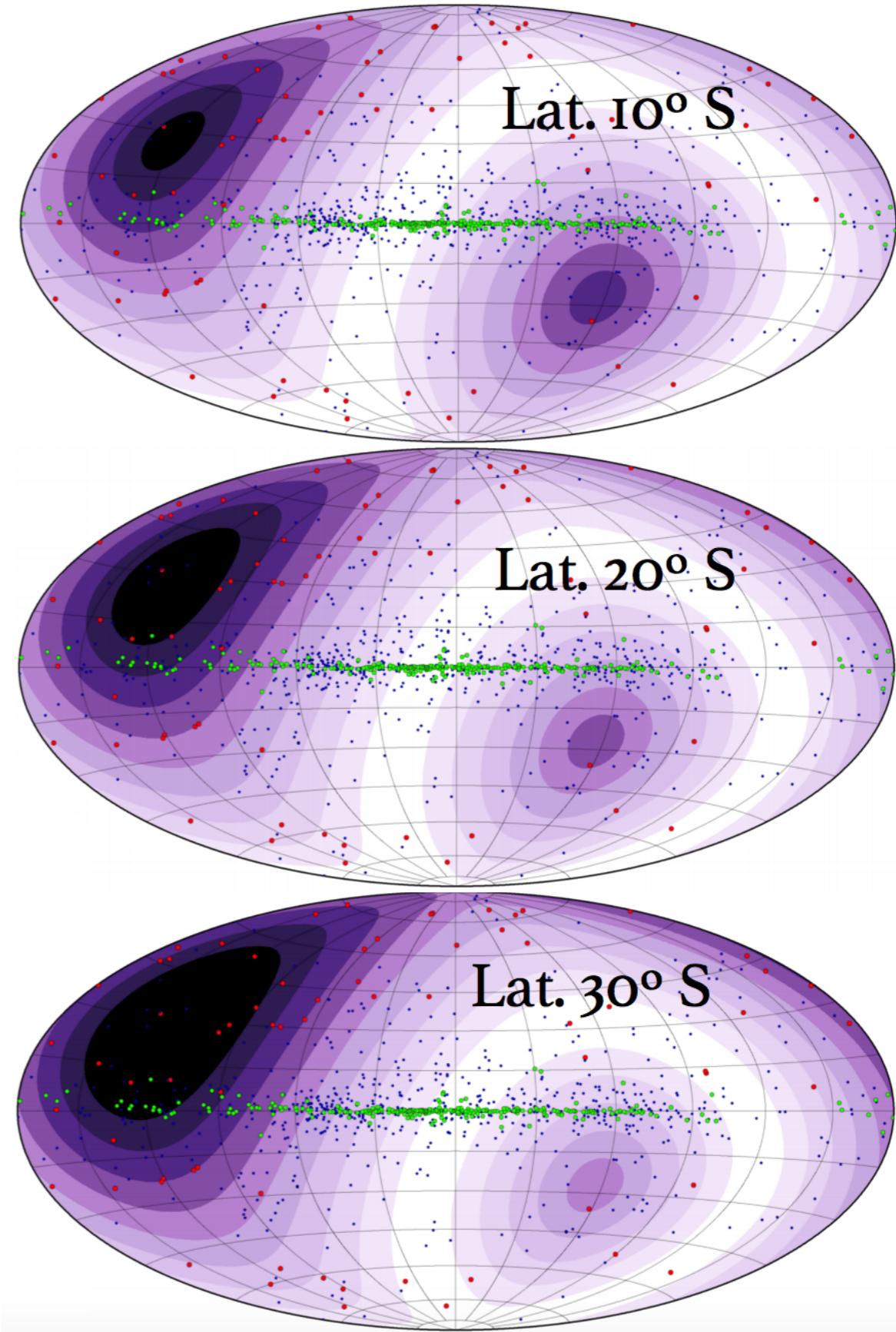


Potential SGSO/SWGO sites

- altitude ~4xxx m
- reasonably flat area
- latitude around 30°S
- infrastructure (incl. access to water)



other potential sites in Bolivia, Peru, etc.

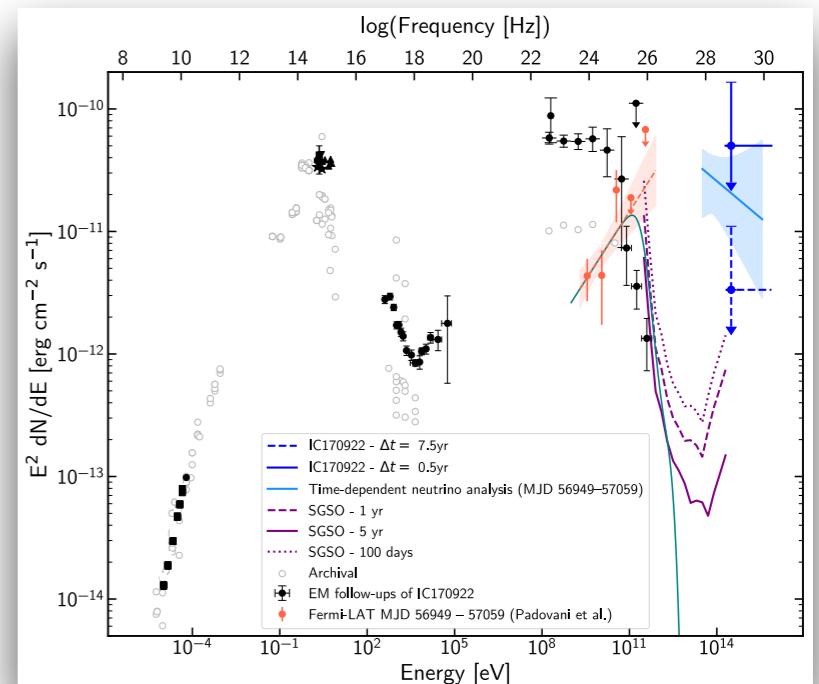
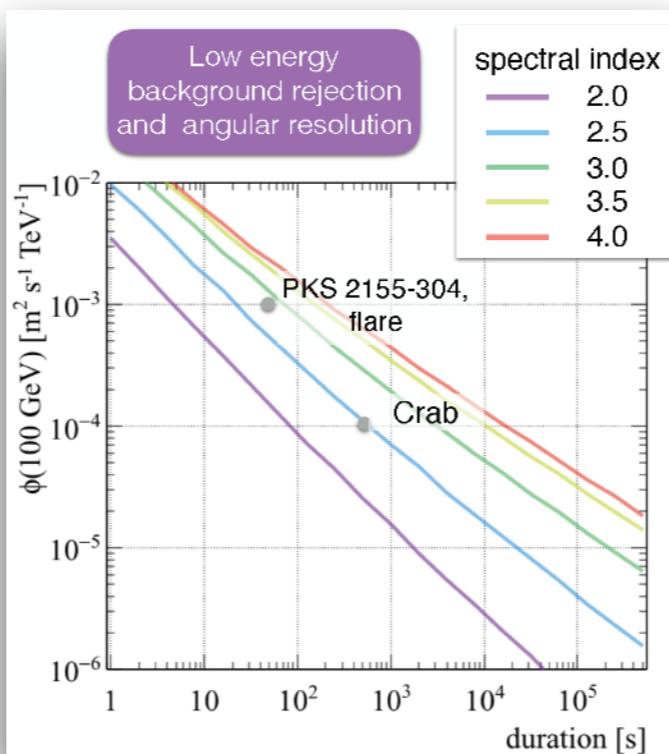
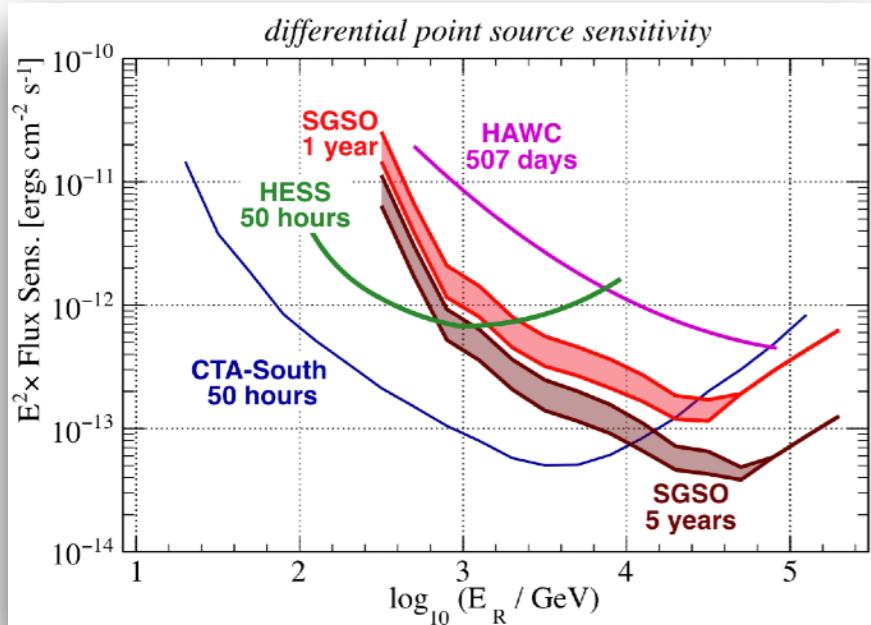


J. Hinton/H. Schoorlemmer

The main science drivers of SGSO/SWGO

- Cosmic ray acceleration and transport
- Monitoring the high-energy transient sky
- Physics beyond the Standard Model of particle physics
- Cosmic ray observations

Complementarity with CTA



Science Case for a Wide Field-of-View
Very-High-Energy Gamma-Ray Observatory
in the Southern Hemisphere

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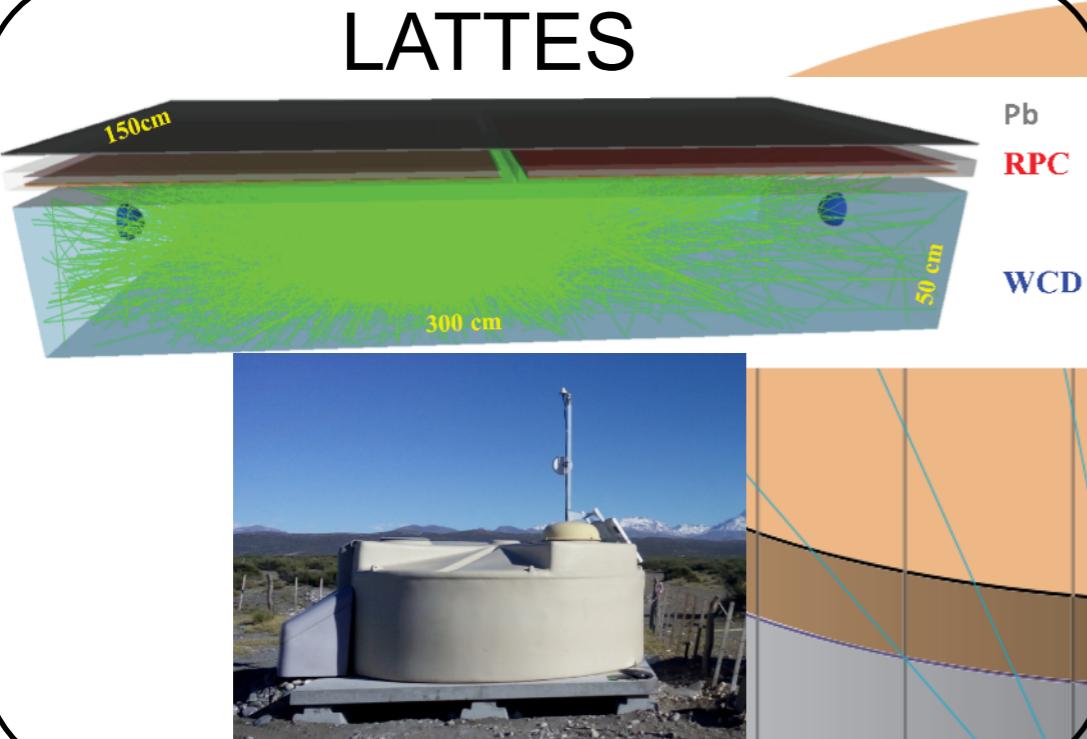
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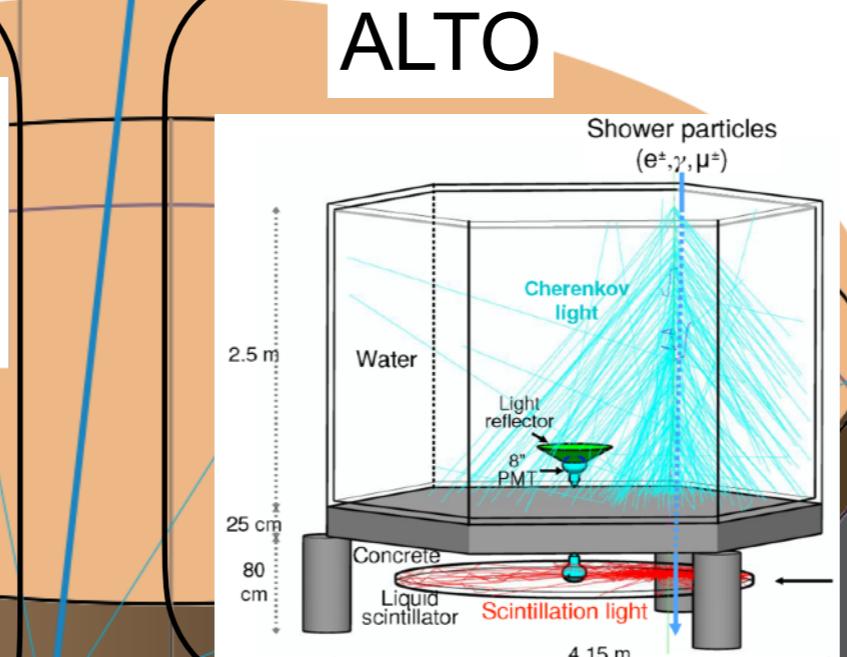
White paper:
arXiv: 1902.08429

Different novel design ideas + prototypes

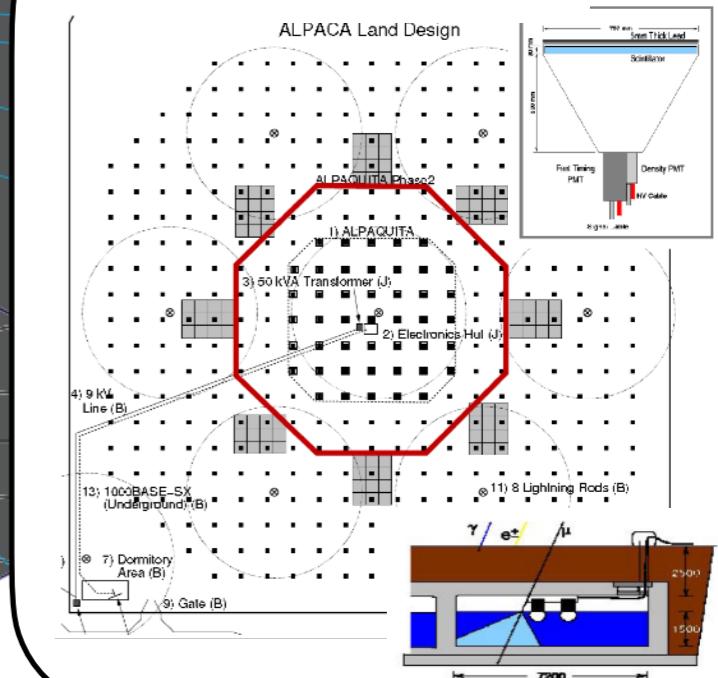
LATTES



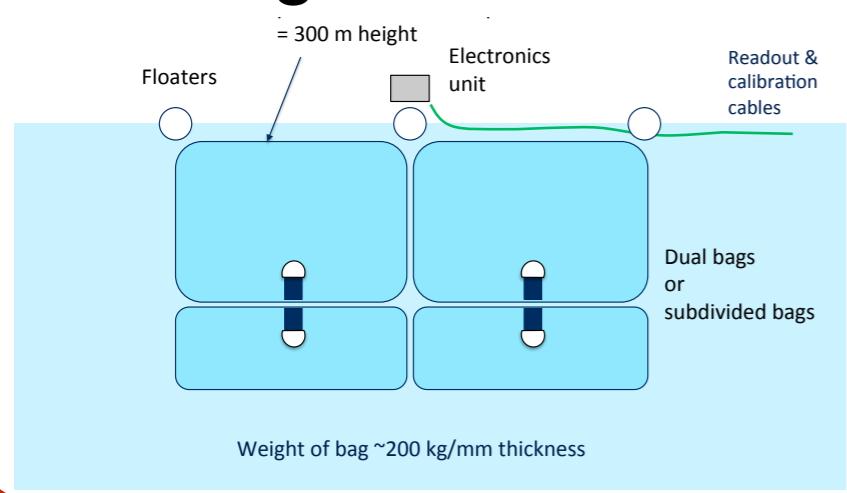
ALTO



ALPACA



"bags in a lake"



"layered WCD"

