

The exciting (and imminent!) science of CTAO* and its connections to Dutch research

ANTON PANNEKOEK
INSTITUTE

GRAPPA
GRAVITATION ASTROPARTICLE PHYSICS AMSTERDAM

Event Horizon Telescope

AFRICA
MILLIMETRE
TELESCOPE

CTAO

erc
BlackHolic

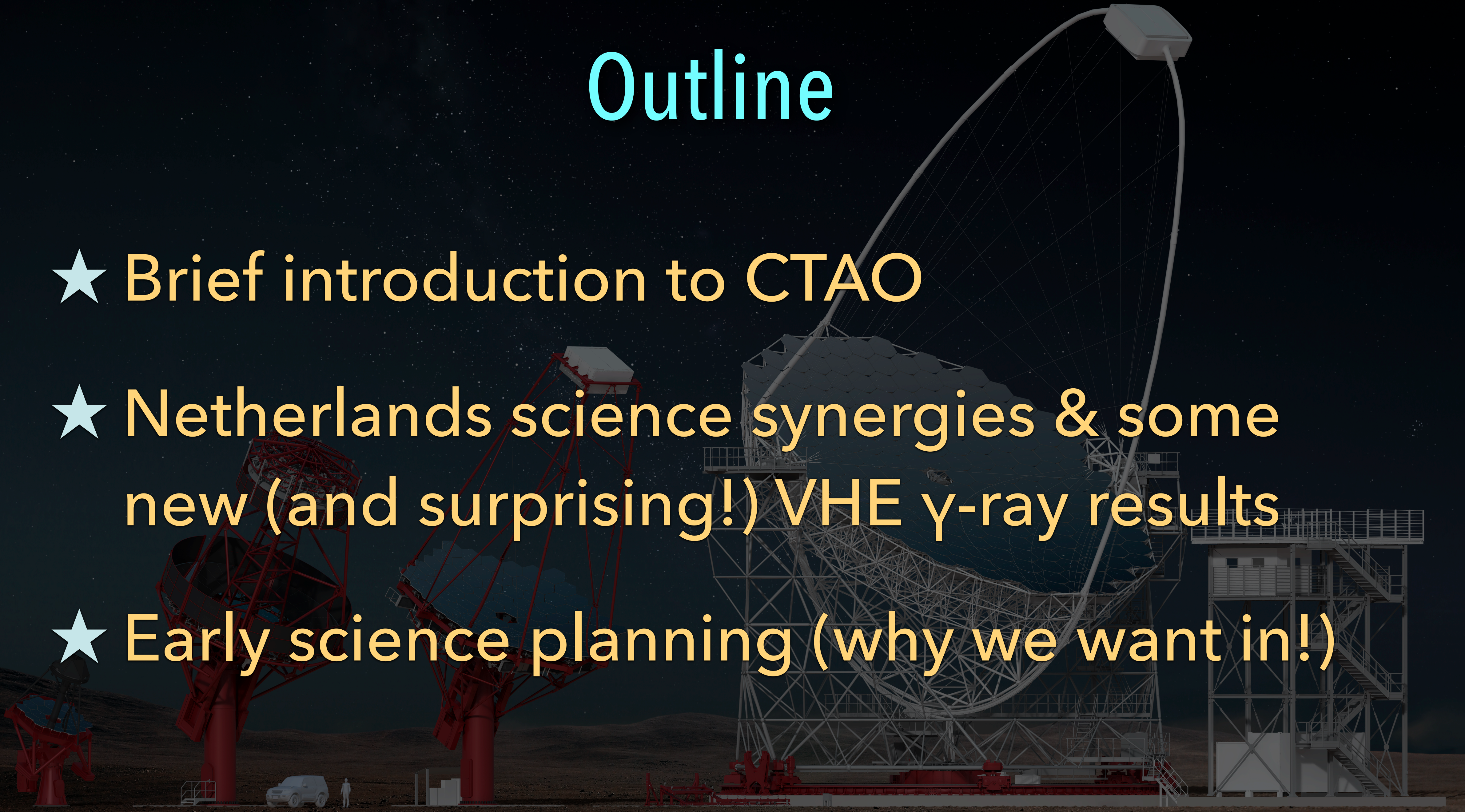
NWO

— 200 R_g

Sera Markoff (API/GRAPPA, University of Amsterdam) on behalf of the CTAO-NL team
*CTAO = Cherenkov Telescope Array Observatory

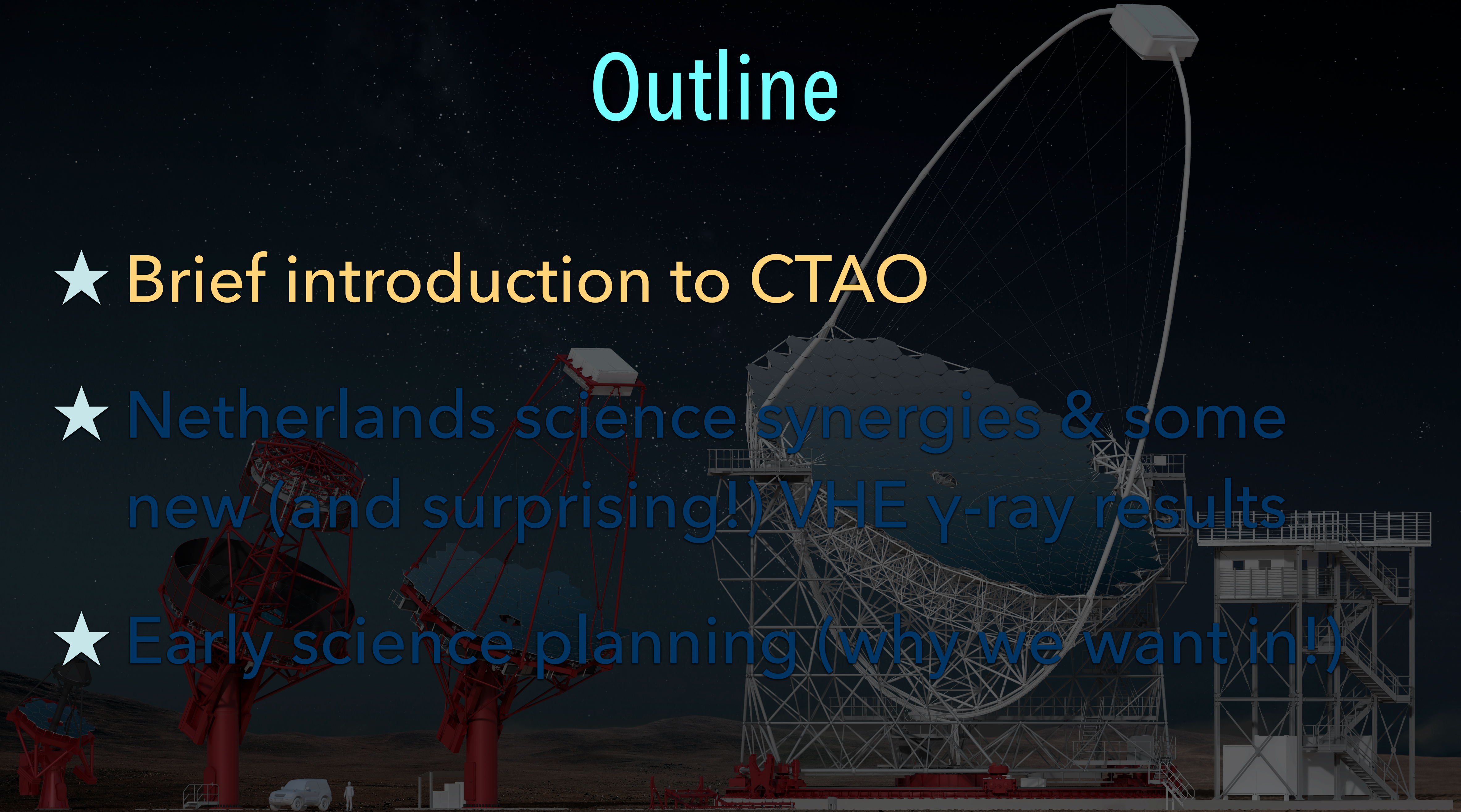
Outline

- ★ Brief introduction to CTAO
- ★ Netherlands science synergies & some new (and surprising!) VHE γ -ray results
- ★ Early science planning (why we want in!)



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Where do the highest energy cosmic rays come from?

Galactic = Supernova remnants

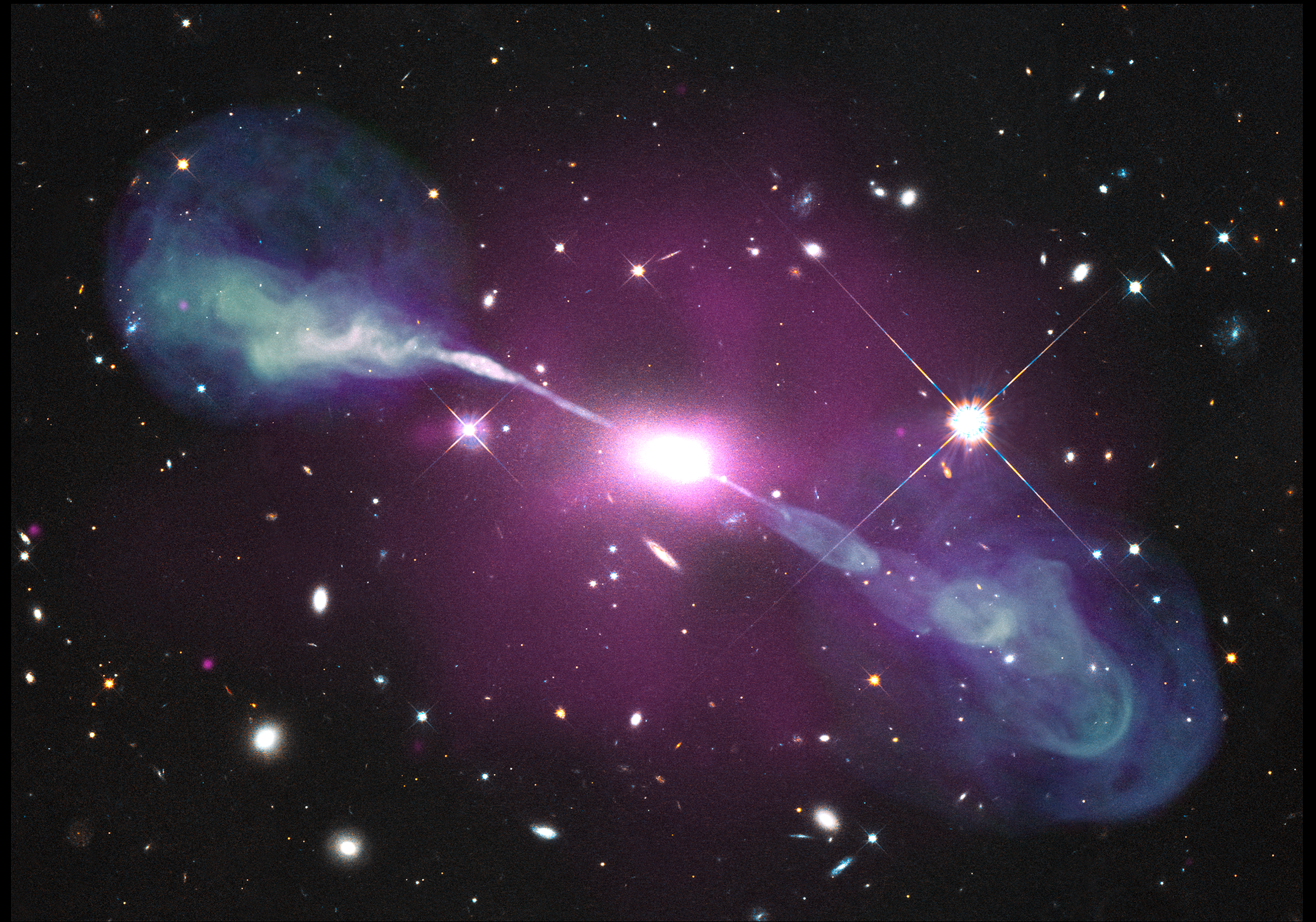
$E_{\text{max}} \sim 10^{15} \text{ eV (PeV)}$



Cas A, Credit: NASA/CXC/SAO

Extragalactic = AGN jets

$E_{\text{max}} \sim 10^{20} \text{ eV}$



Hercules A, Credit: Xray (NASA/CXC/SAO), Optical (NASA/HST), Radio (NSF/NRAO/VLA)

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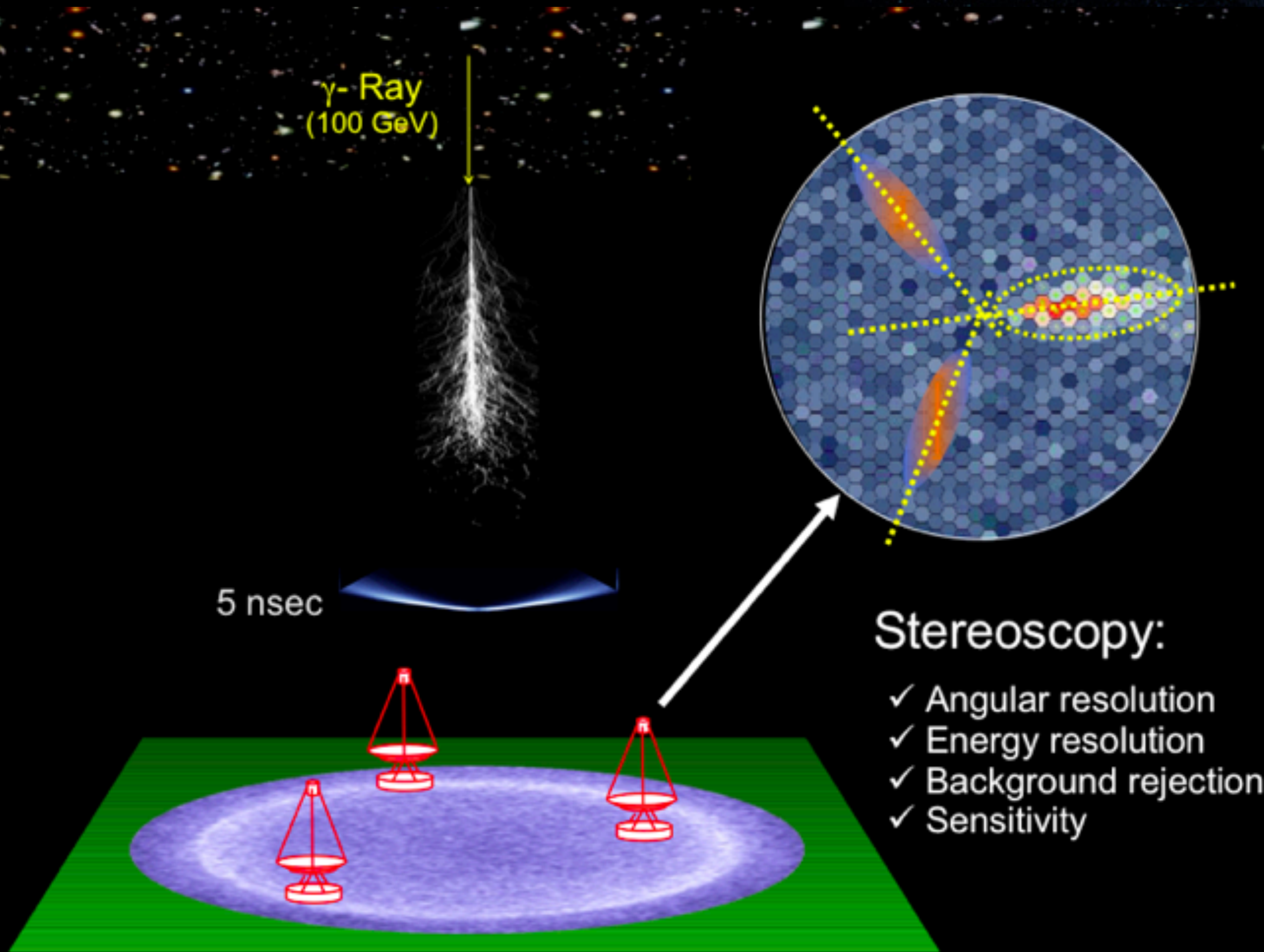
Extragalactic = AGN jets

$$E_{\text{max}} \sim 10^{20} \text{ eV}$$

If these sources accelerate HE CRs (p's, ions), they will interact to produce ~equal fluxes in HE γ 's and ν 's \Rightarrow MM

Inevitably you also accelerate or get (decays) HE e^-/e^+ s and thus *correlated* radio through X-ray emission \Rightarrow MWL

VHE γ -rays: Imaging Atmospheric Cherenkov Telescopes (IACTs)



Credits to W. Hoffmann

VHE γ -rays: Imaging Atmospheric Cherenkov Telescopes (IACTs)

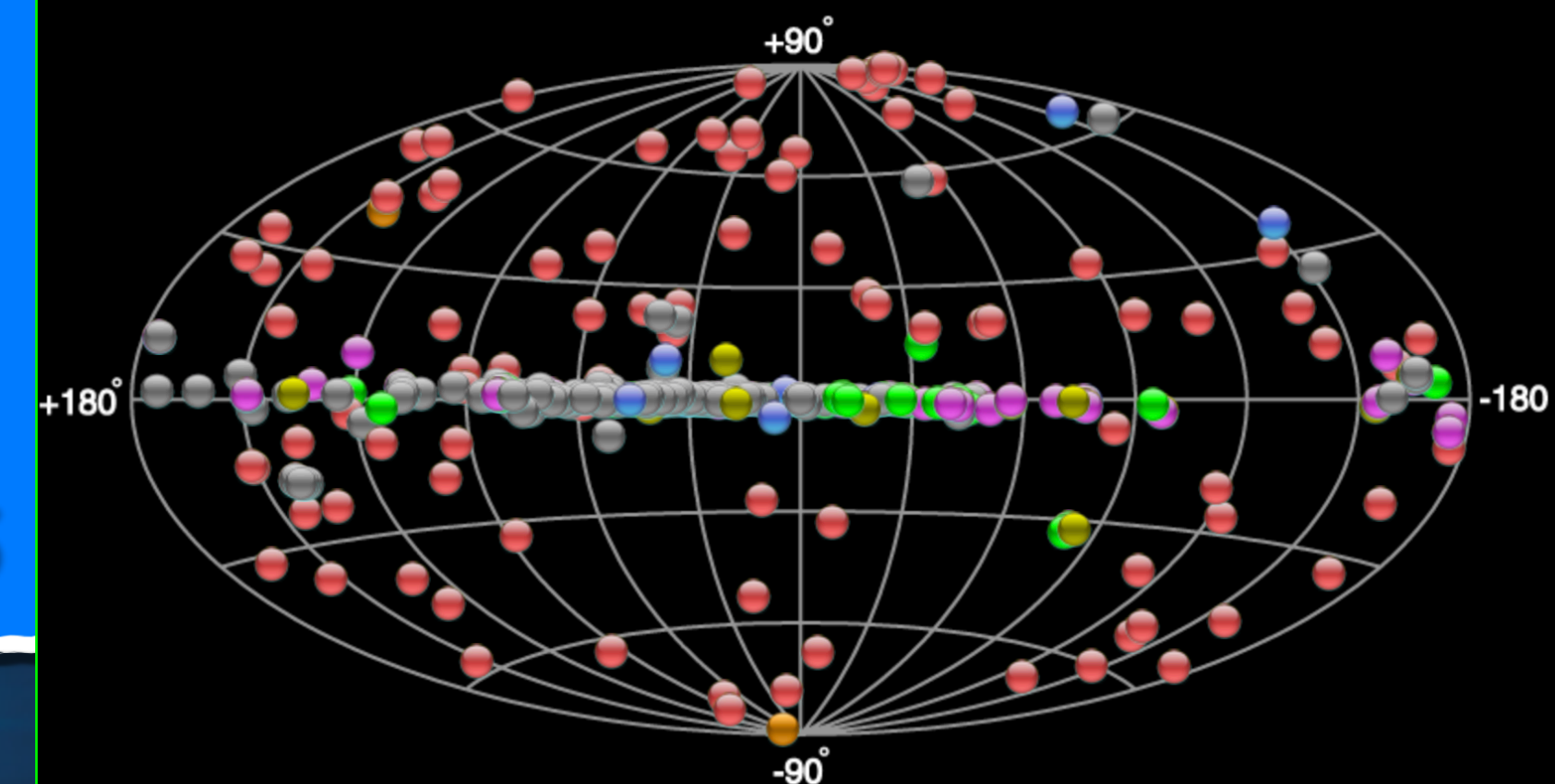
Result: VHE ($>100\text{GeV}$) γ -ray astronomy is now a "mature" field with:

- >315 detected sources in >15 different source classes
- $\mathcal{O}(\text{arcmin})$ resolution skymaps
- energy spectra from 30 GeV - PeV !
- time-resolved lightcurves down to mins

H E S S

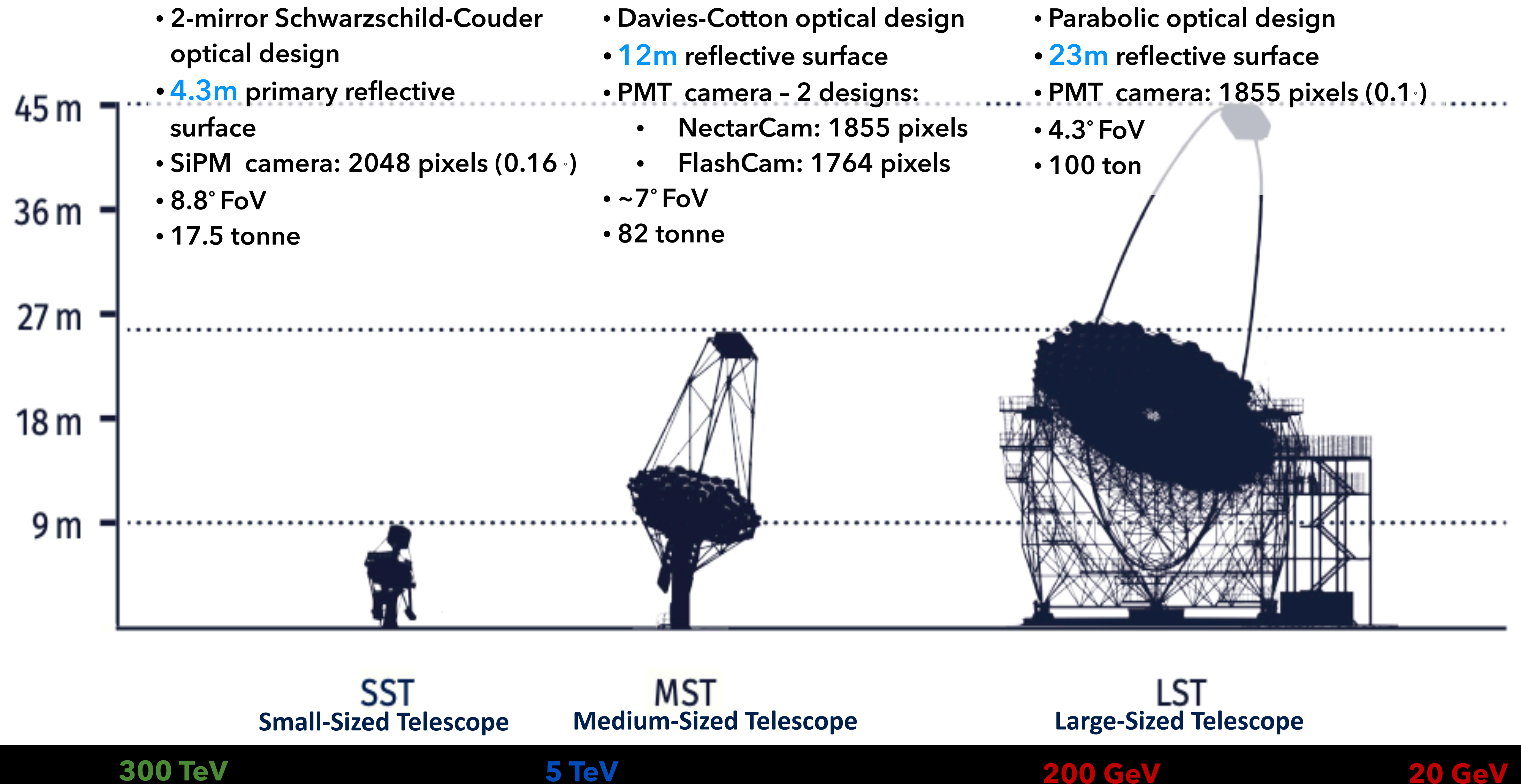


Welcome to TeVCat!



Credits to W. Hoffmann

CTAO will offer full N/S sky coverage with unprecedented sensitivity

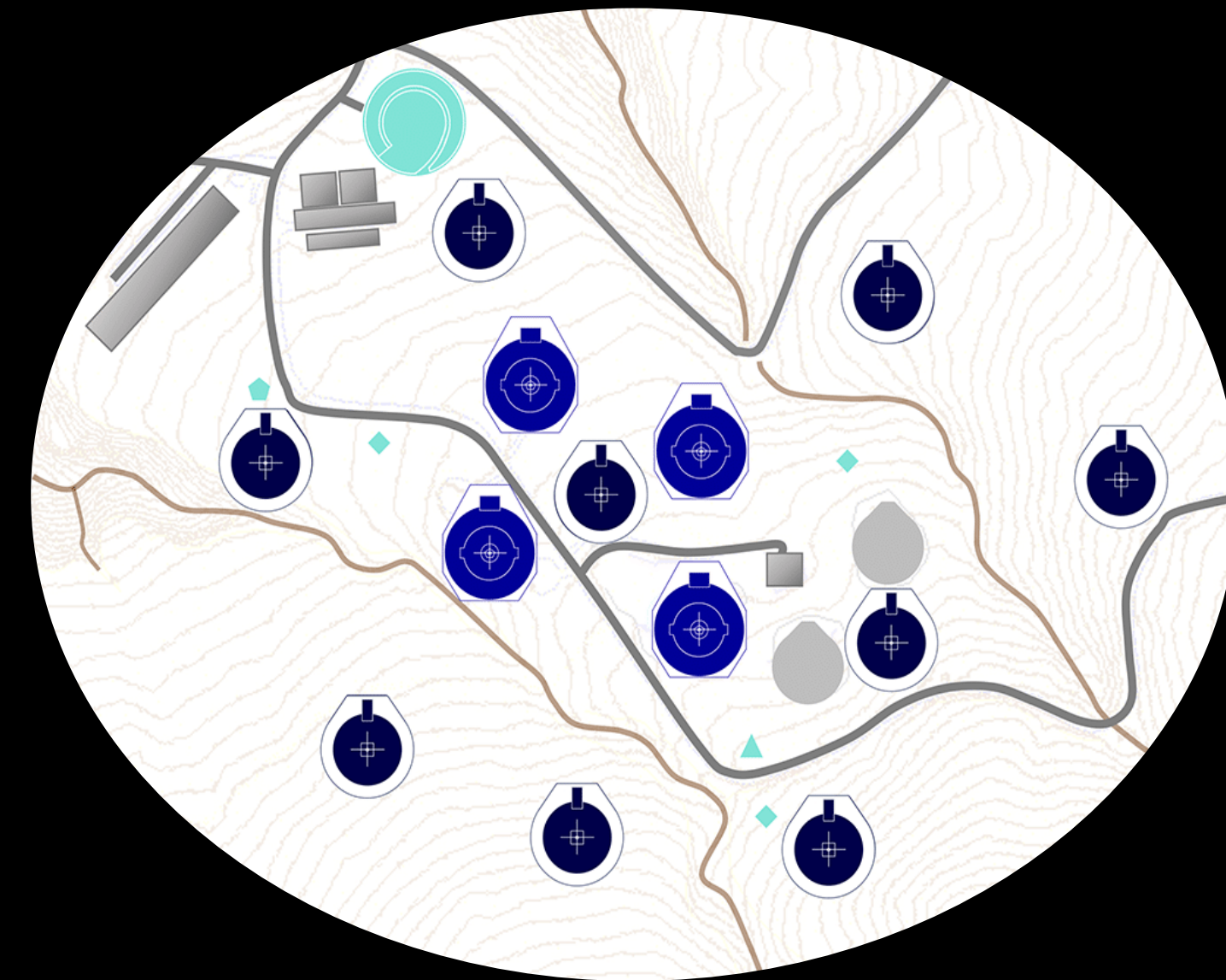


"Alpha" configuration currently under construction



CTAO Northern Array

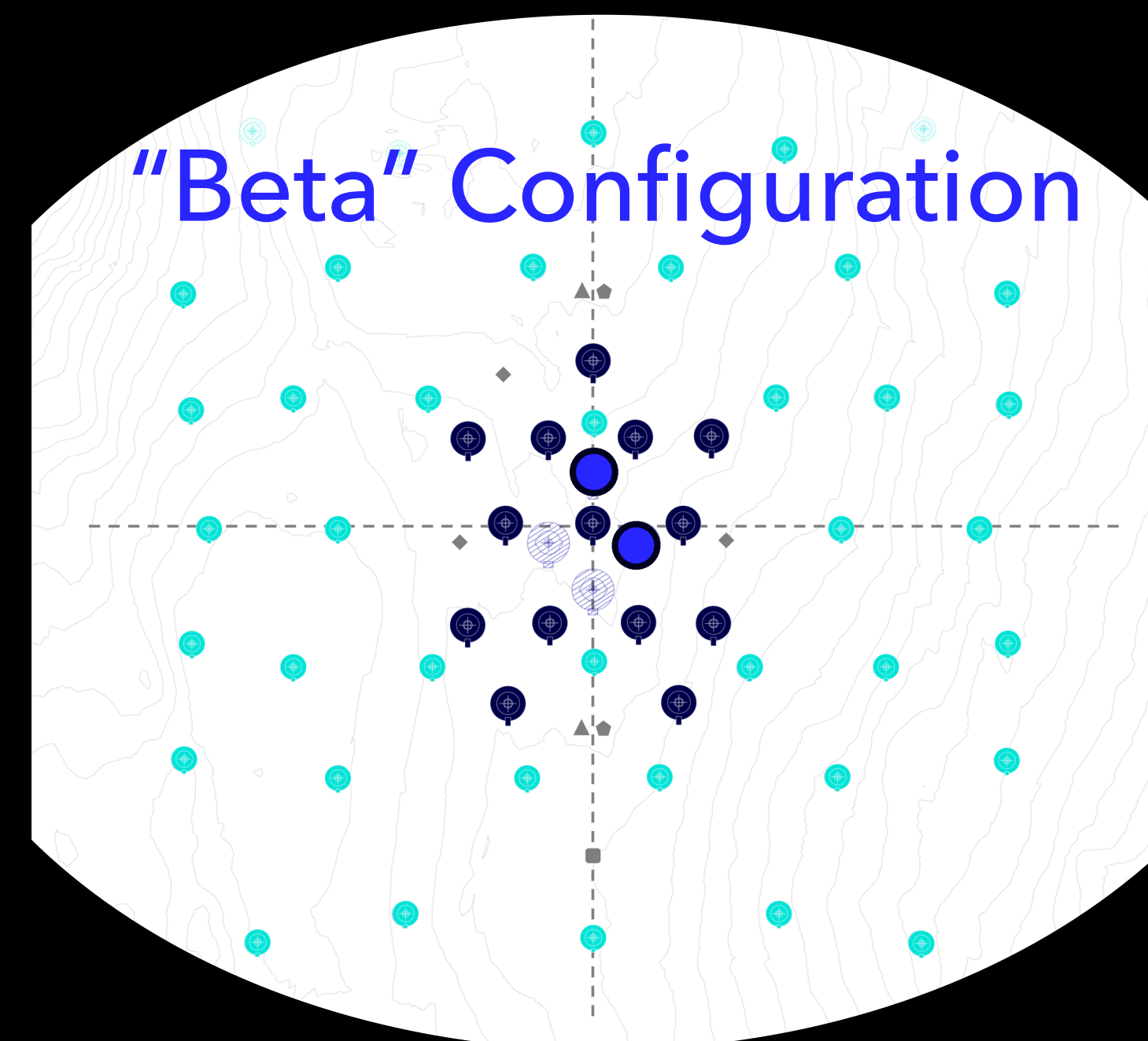
- **4 LSTs + 9 MSTs**
- 0.25 km² footprint
- focus on extragalactic science



CTAO Southern Array

- **14 MSTs + 37 SSTs**
- 3 km² footprint
- focus on Galactic science

PRELIMINARY



Plus for CTAO-N: two other nearby VHE facilities (MAGIC & ASTRI)

CTAO Northern Array

- **4 LSTs + 9 MSTs**
- 0.25 km² footprint
- focus on extragalactic science



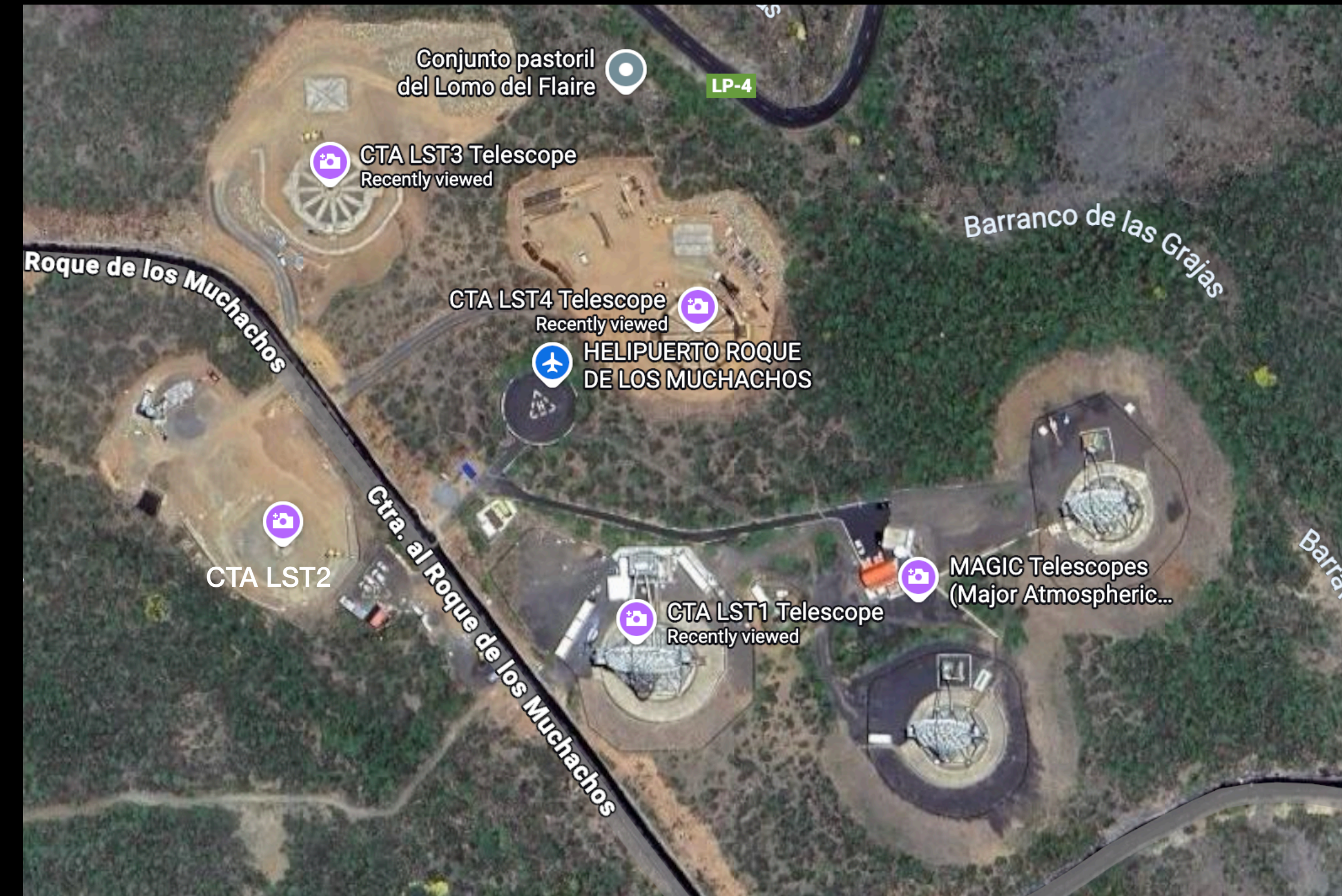
CTA North
ORM La Palma, Spain

CTA South
ESO, Chile

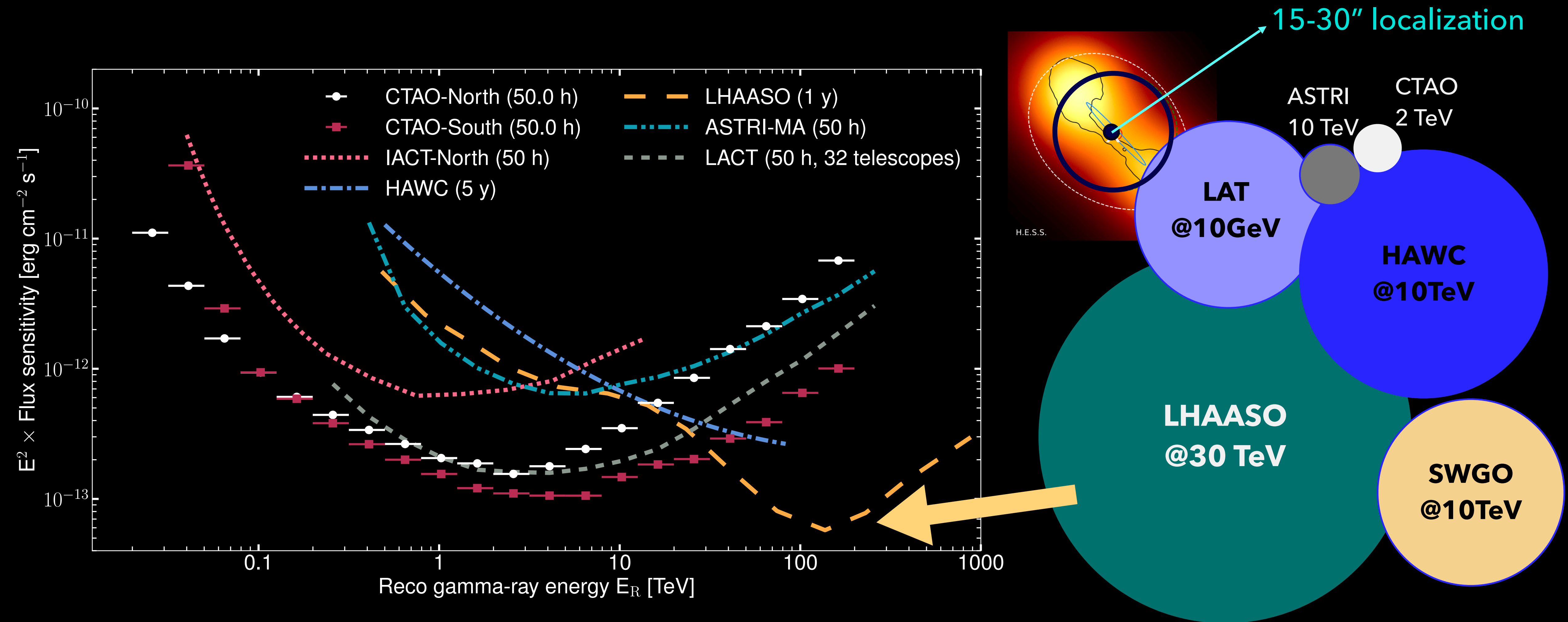
CTAO Southern Array

- **14 MSTs + 37 SSTs**
- 3 km² footprint
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PRELIMINARY



CTAO steady source performance compared to other facilities



CTAO designed to be an incredibly powerful survey machine

SENSITIVITY 10x

**ARCMINUTE ANGULAR
RESOLUTION**

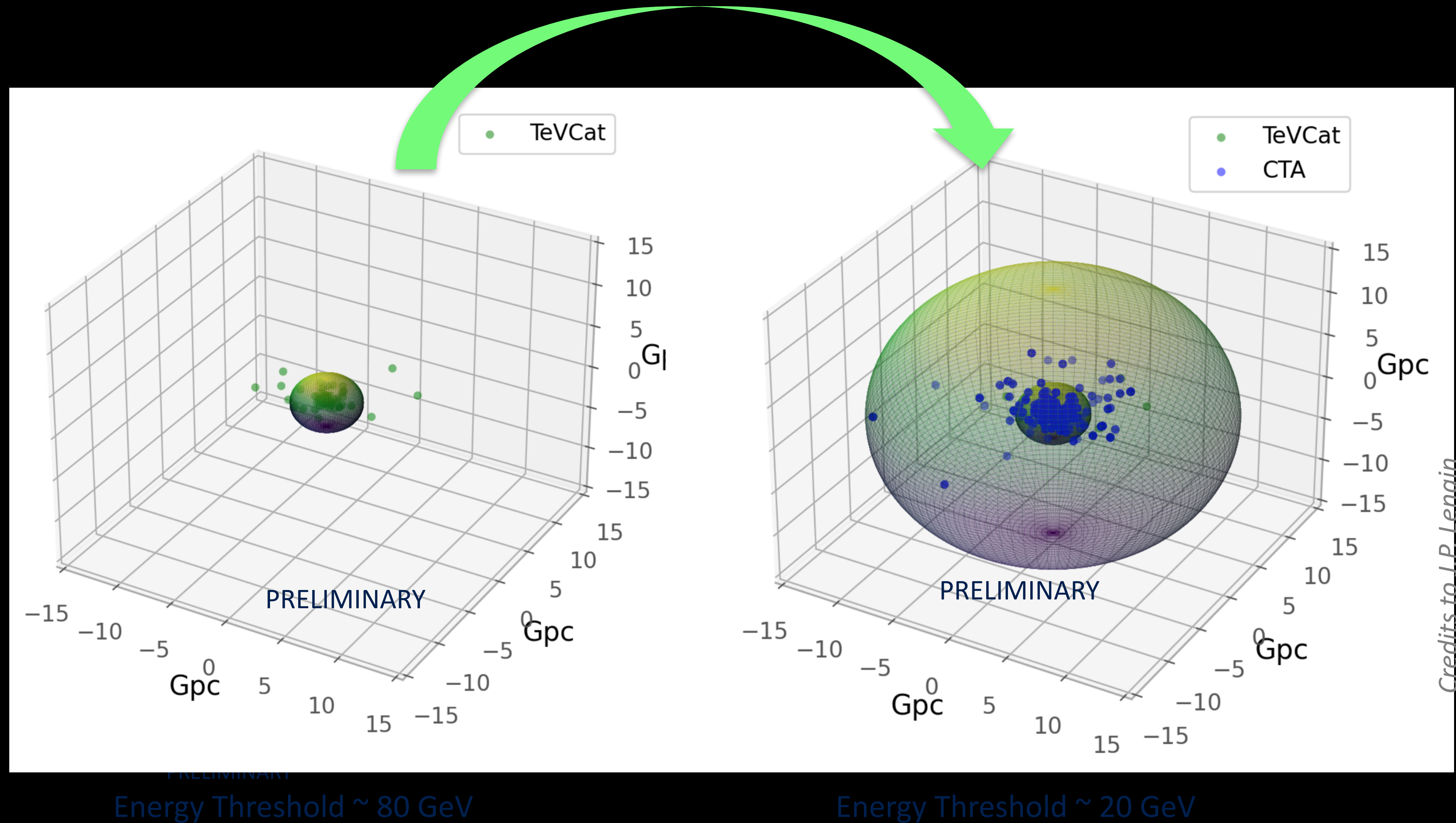
**<10% ENERGY
RESOLUTION**

**WIDE ENERGY RANGE
20 GeV - 300 TeV**

8° FoV (2x)

FULL SKY COVERAGE

**30s RESPONSE TO
ALERTS + RTA**



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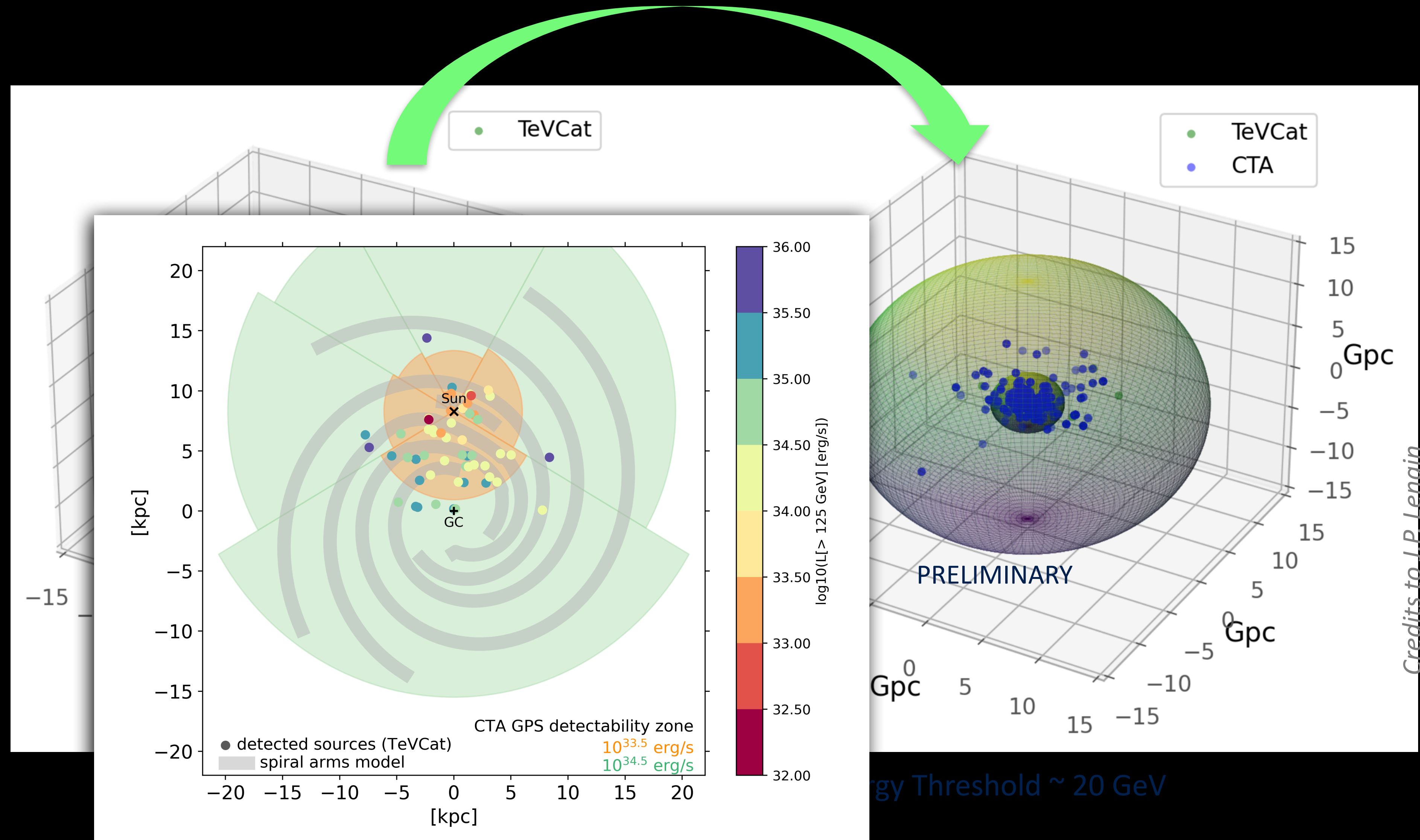
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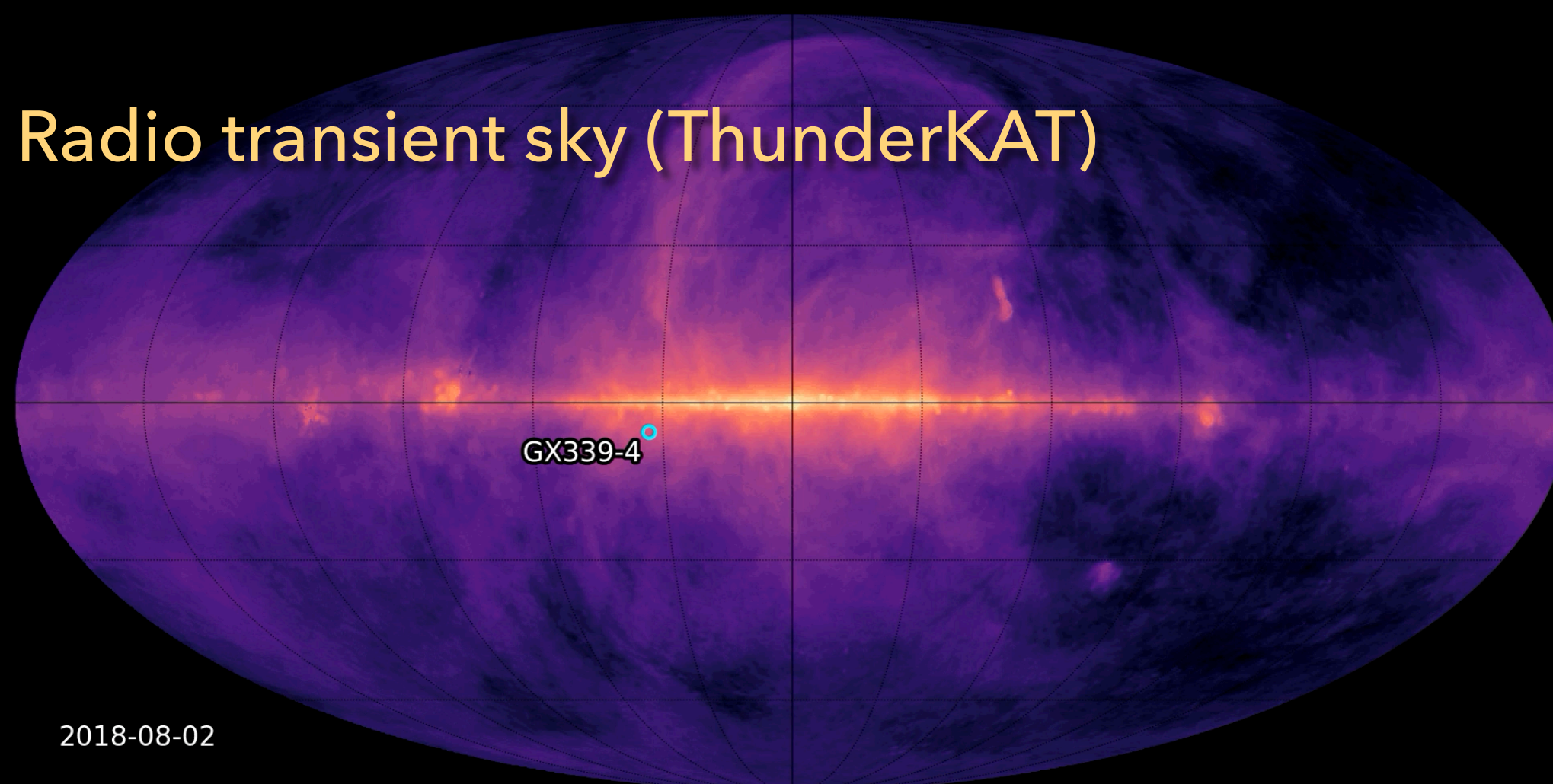
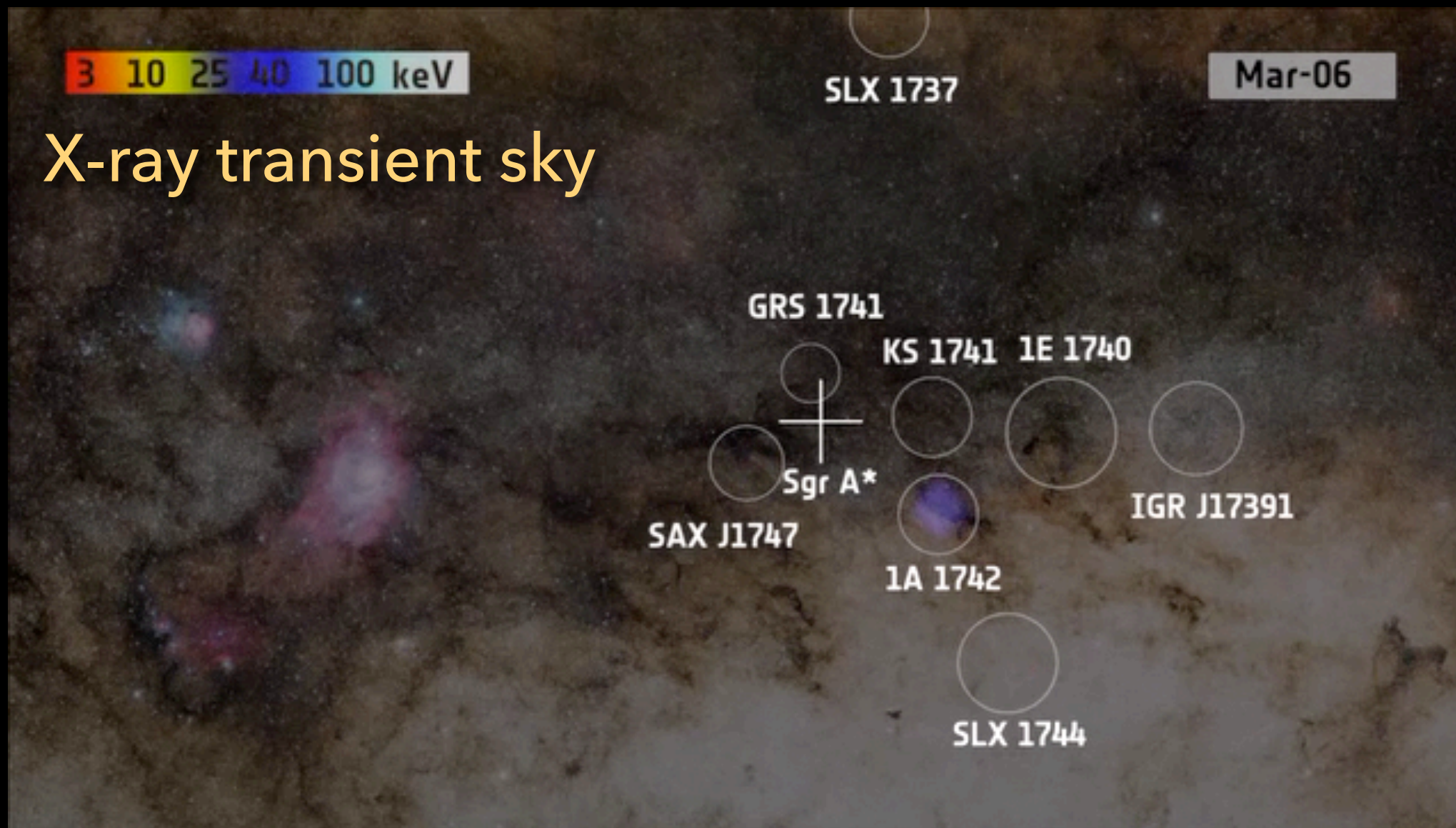
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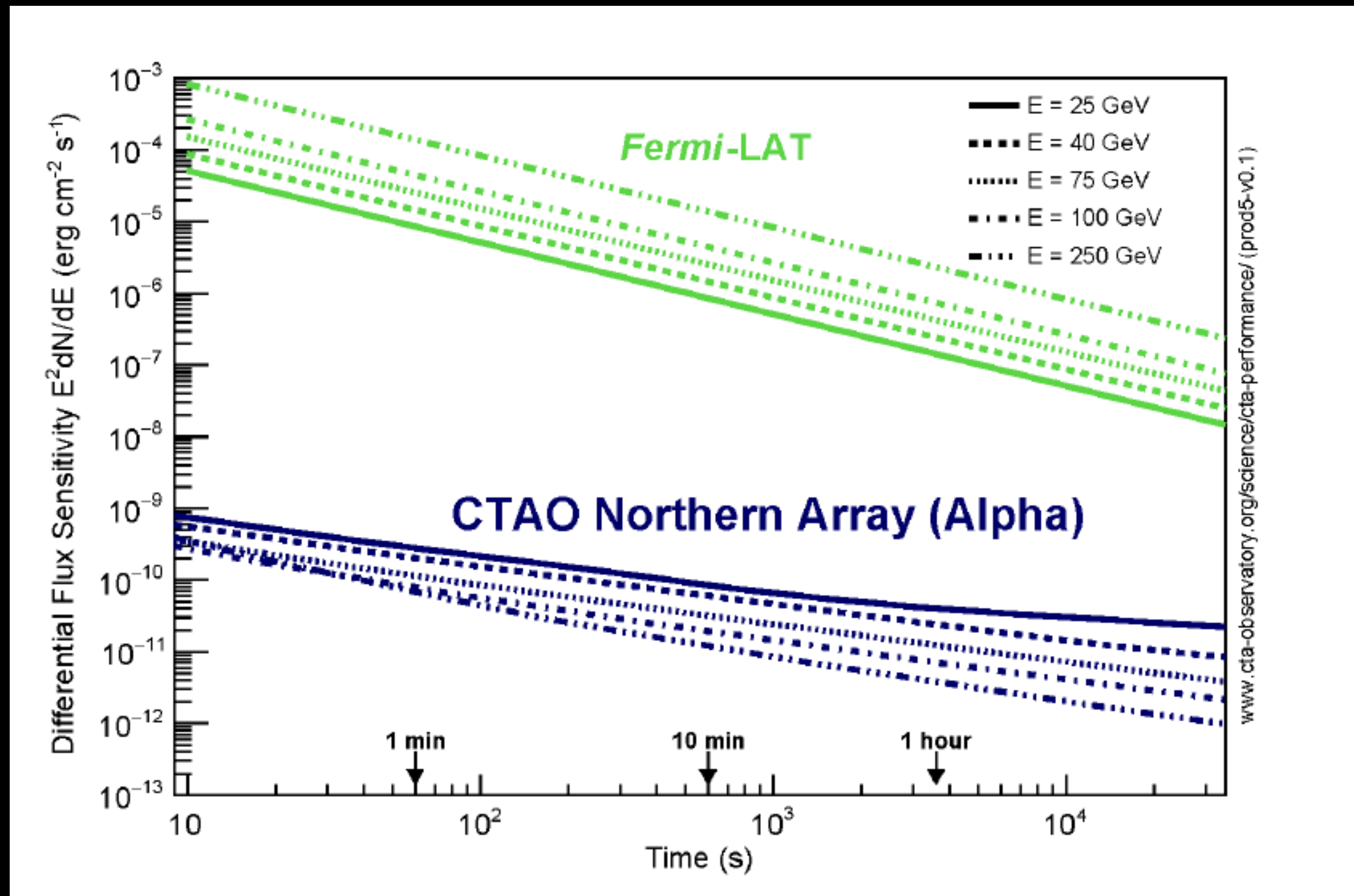
Remy++2021, ICRC/CTA GPS KSP

CTAO is a major advance in many areas, but *groundbreaking* for transients!



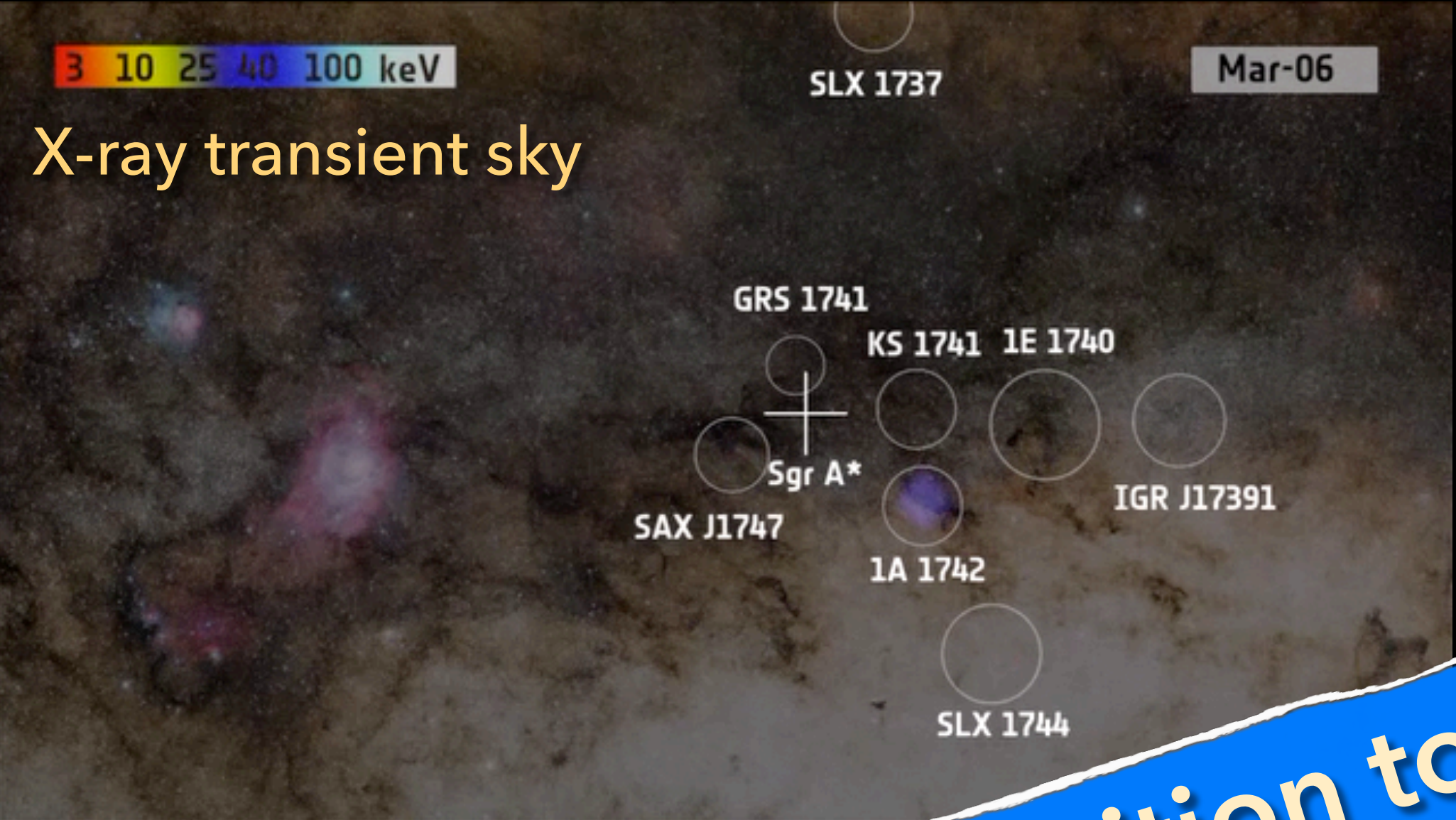
2018-08-02

VHE variability is the unique key CTAO offers to identify and characterise CR/v sources!



<https://www.cta-observatory.org>

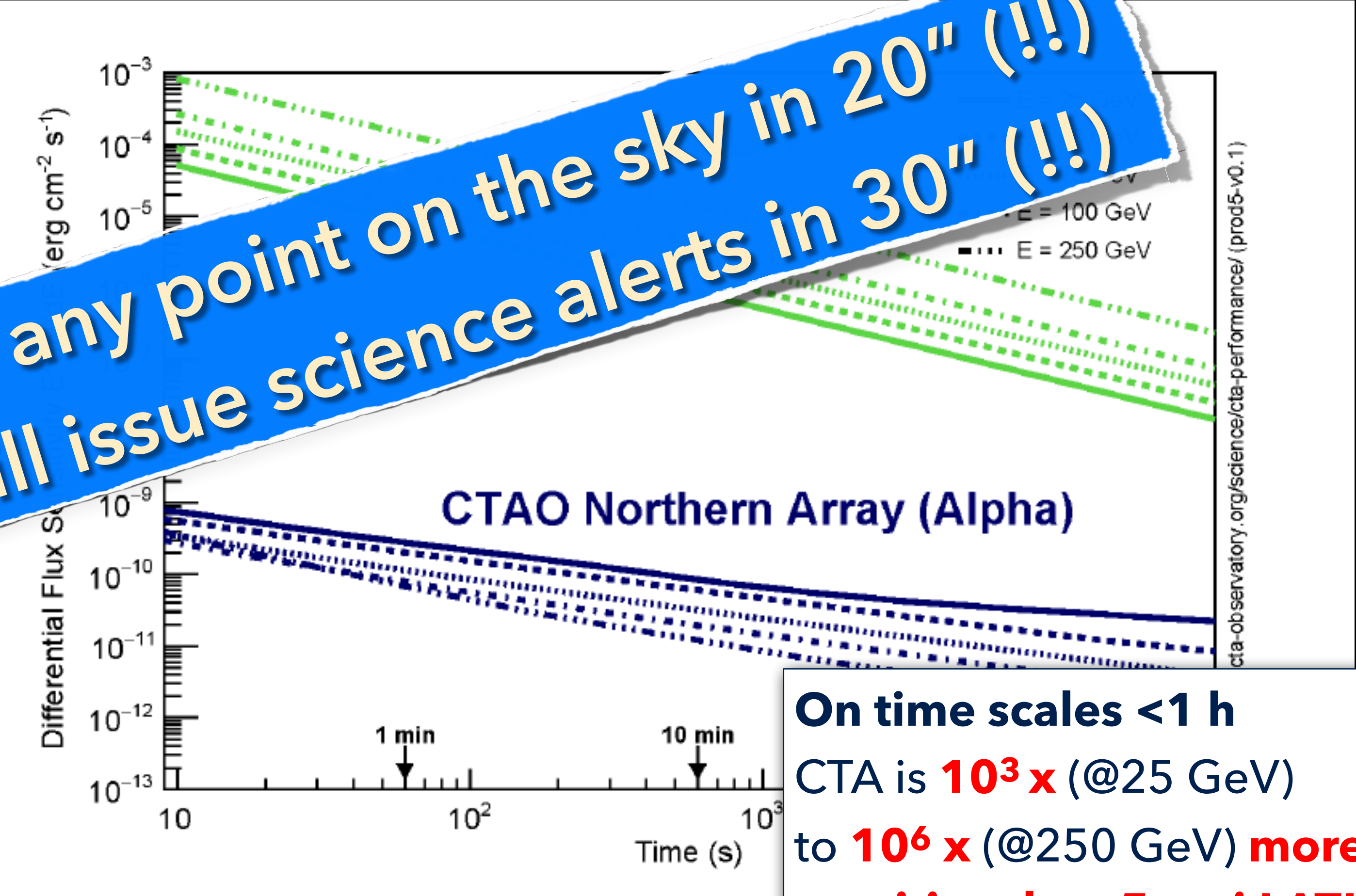
CTAO is a major advance in many areas, but *groundbreaking* for transients!



VHE variability is the unique key CTAO offers to identify and characterise CR/v sources!

LSTs can reposition to any point on the sky in 20" (!!)
Real-time analysis will issue science alerts in 30" (!!)

Radio tra

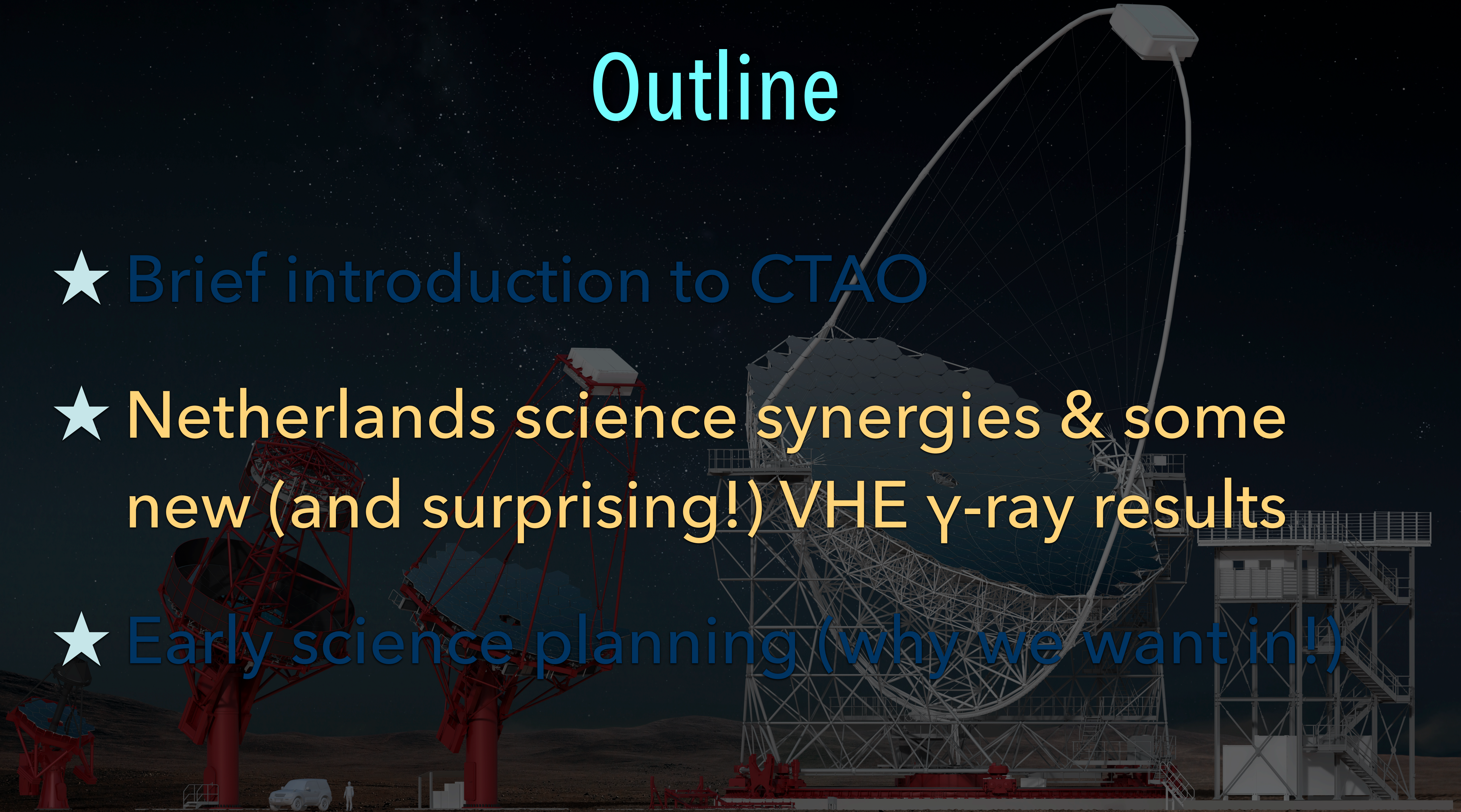


On time scales $< 1 \text{ h}$
CTA is **$10^3 \times$** (@25 GeV)
to **$10^6 \times$** (@250 GeV) **more sensitive than *Fermi-LAT*!!**

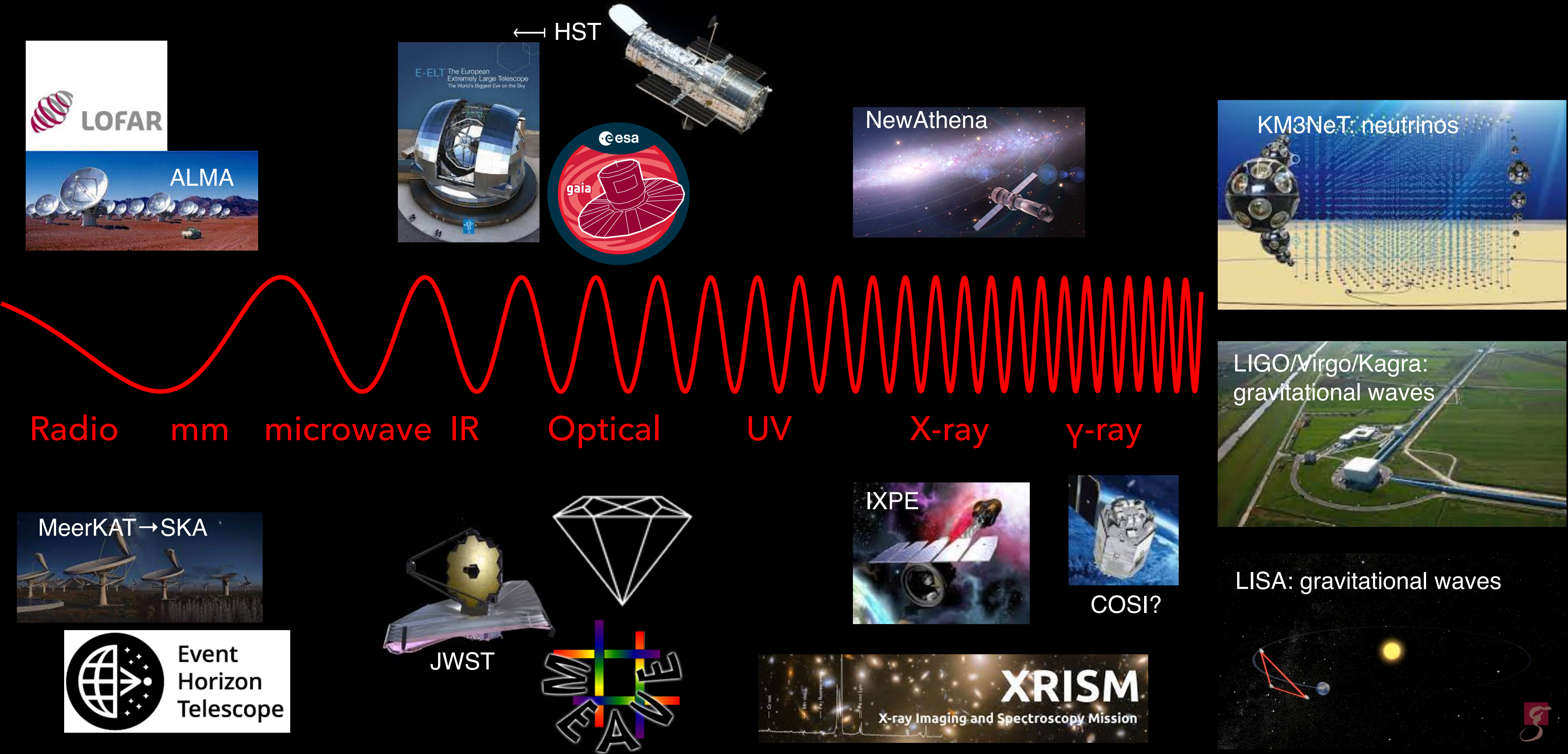
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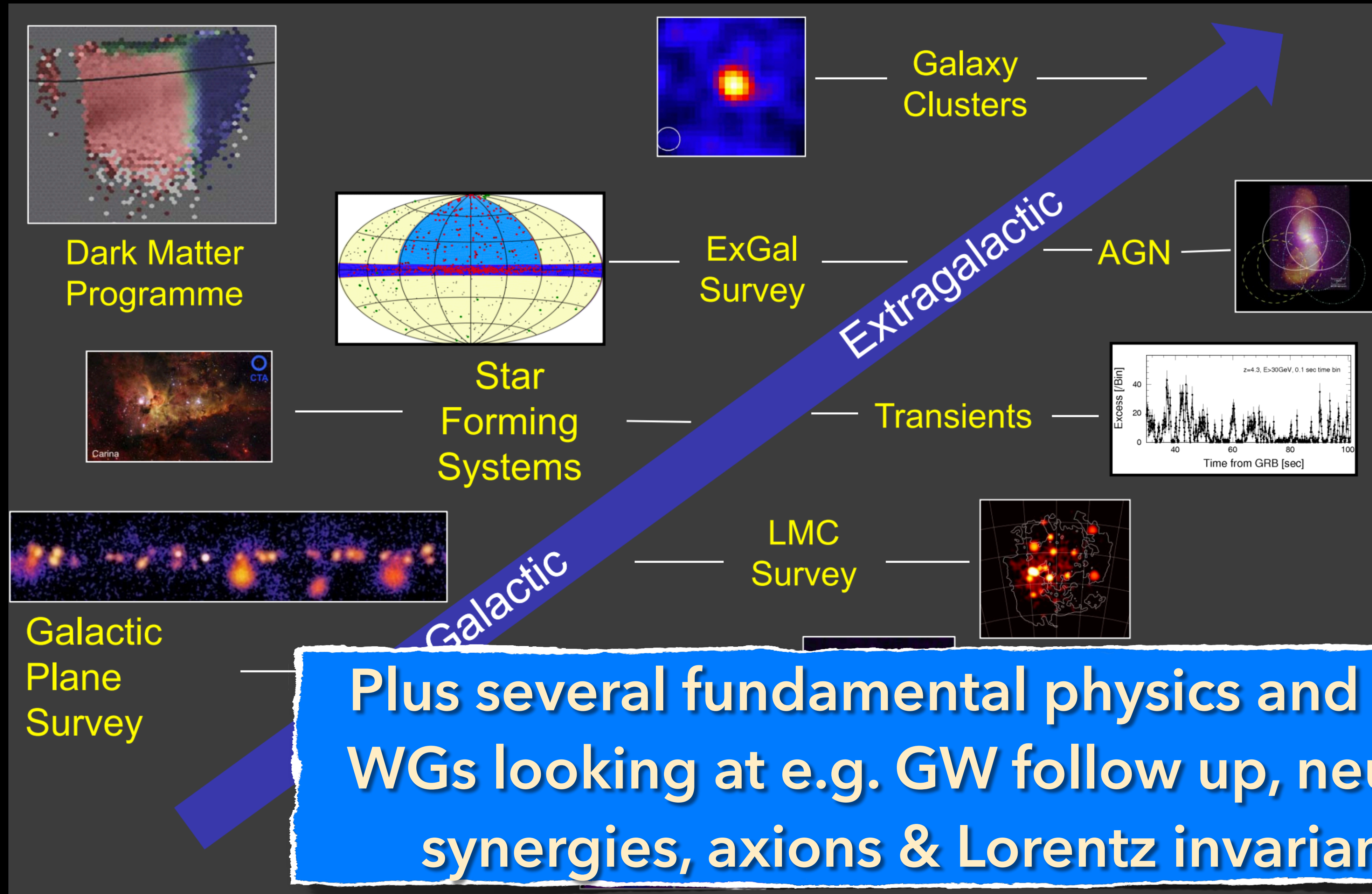
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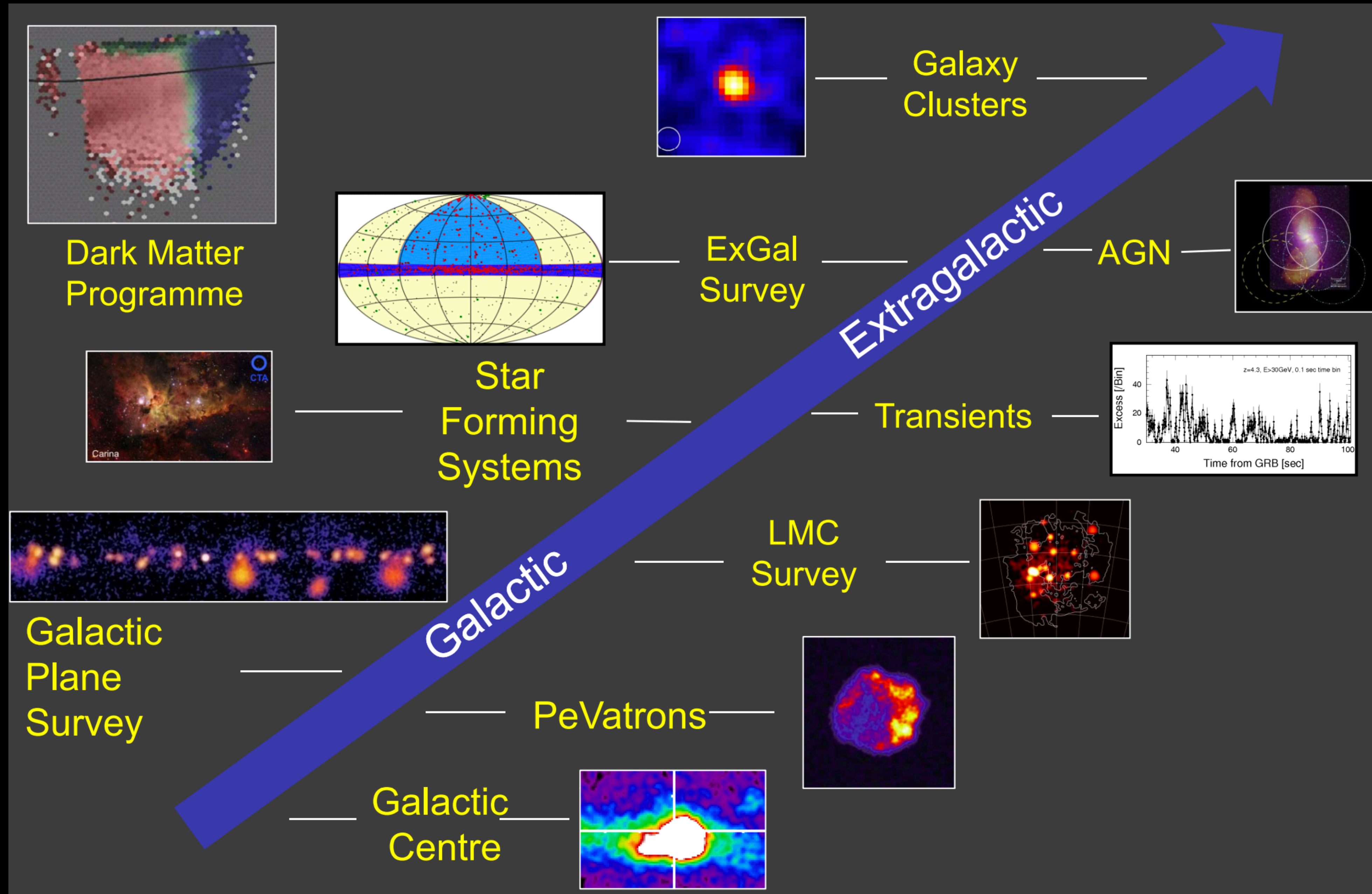
CTAO synergies with the Dutch MWL/MM community (through ~2030s)



CTAO Key Science Projects (KSPs)



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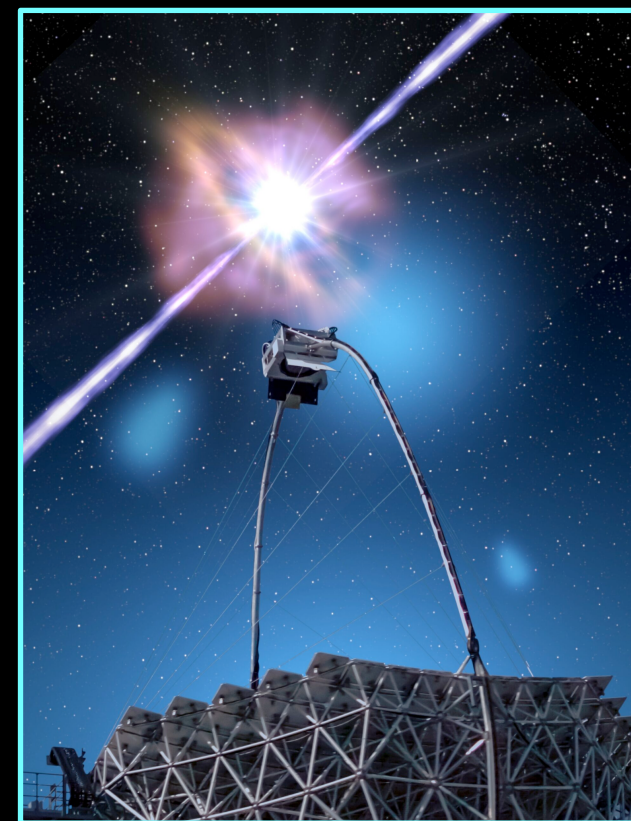
CTAO Key Science Projects (KSPs)



arXiv:1709.07997

- Defines key science questions and synergies, and the large observational programs (KSPs) meant to address them
- Since its writing, entirely new fields have opened up and the KSPs are being redefined as we speak:

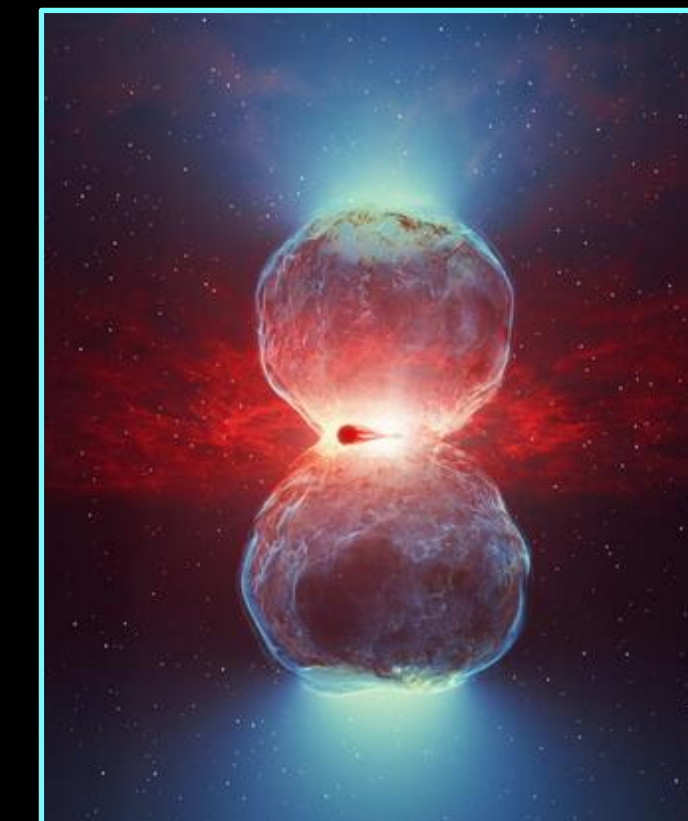
GRBs



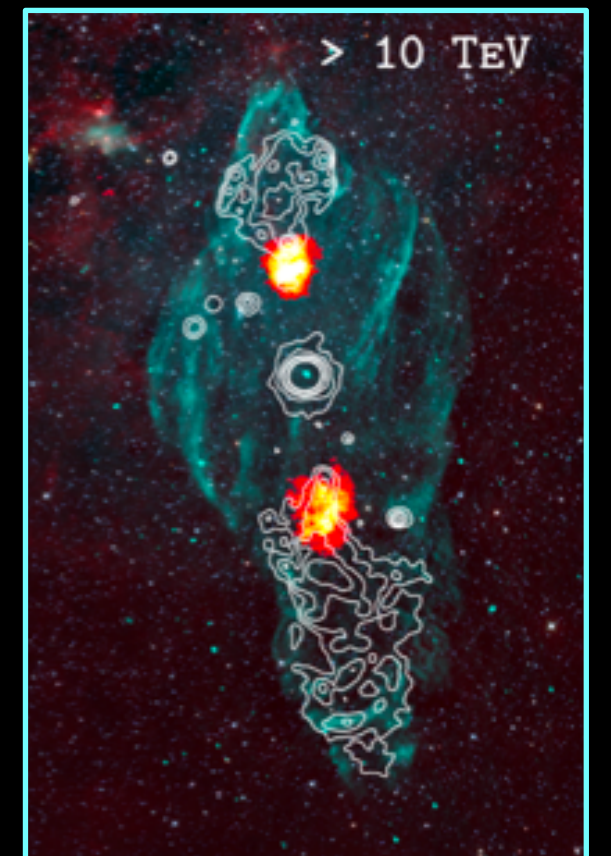
GWs from BNSs



Novae

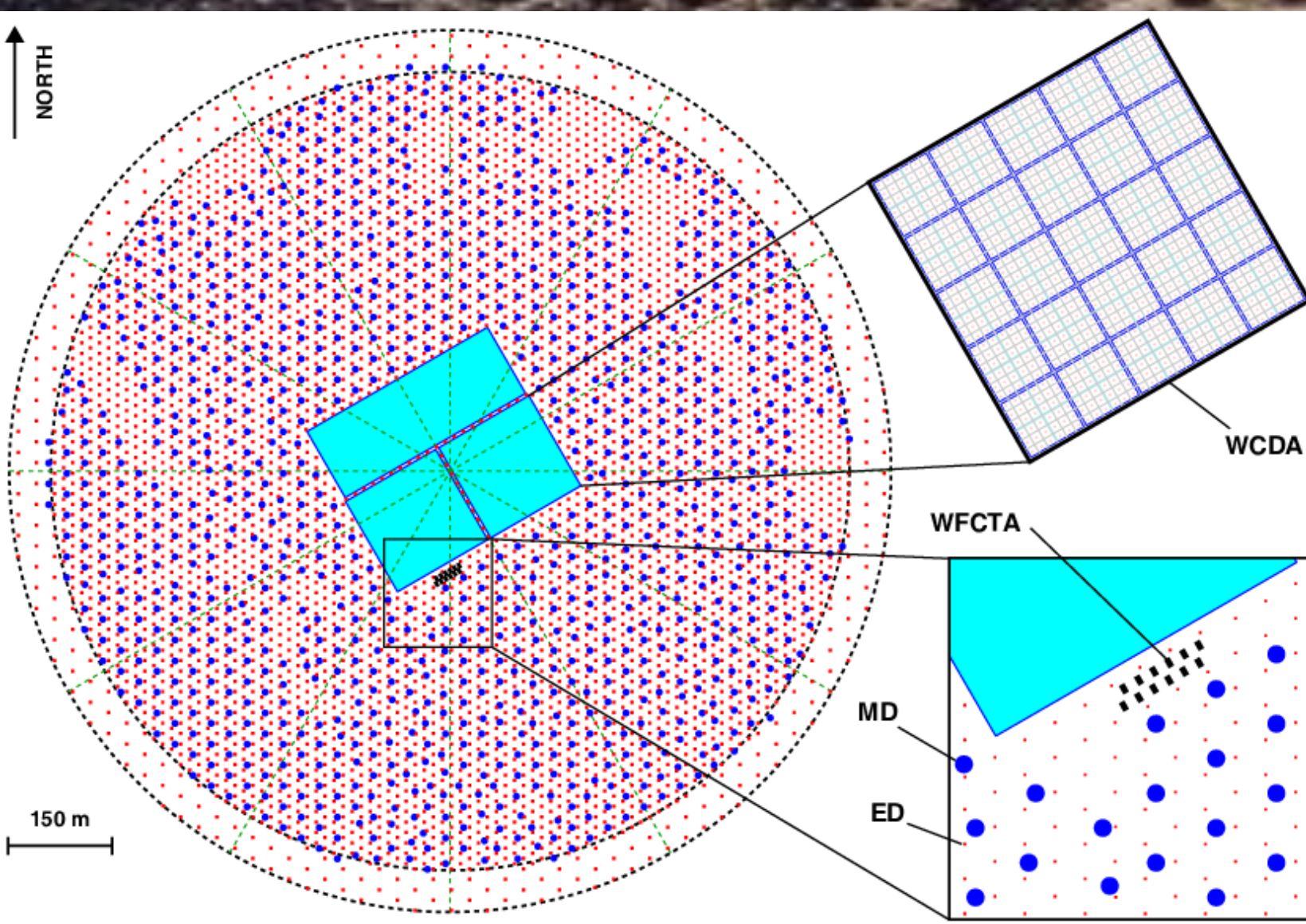


Microquasars



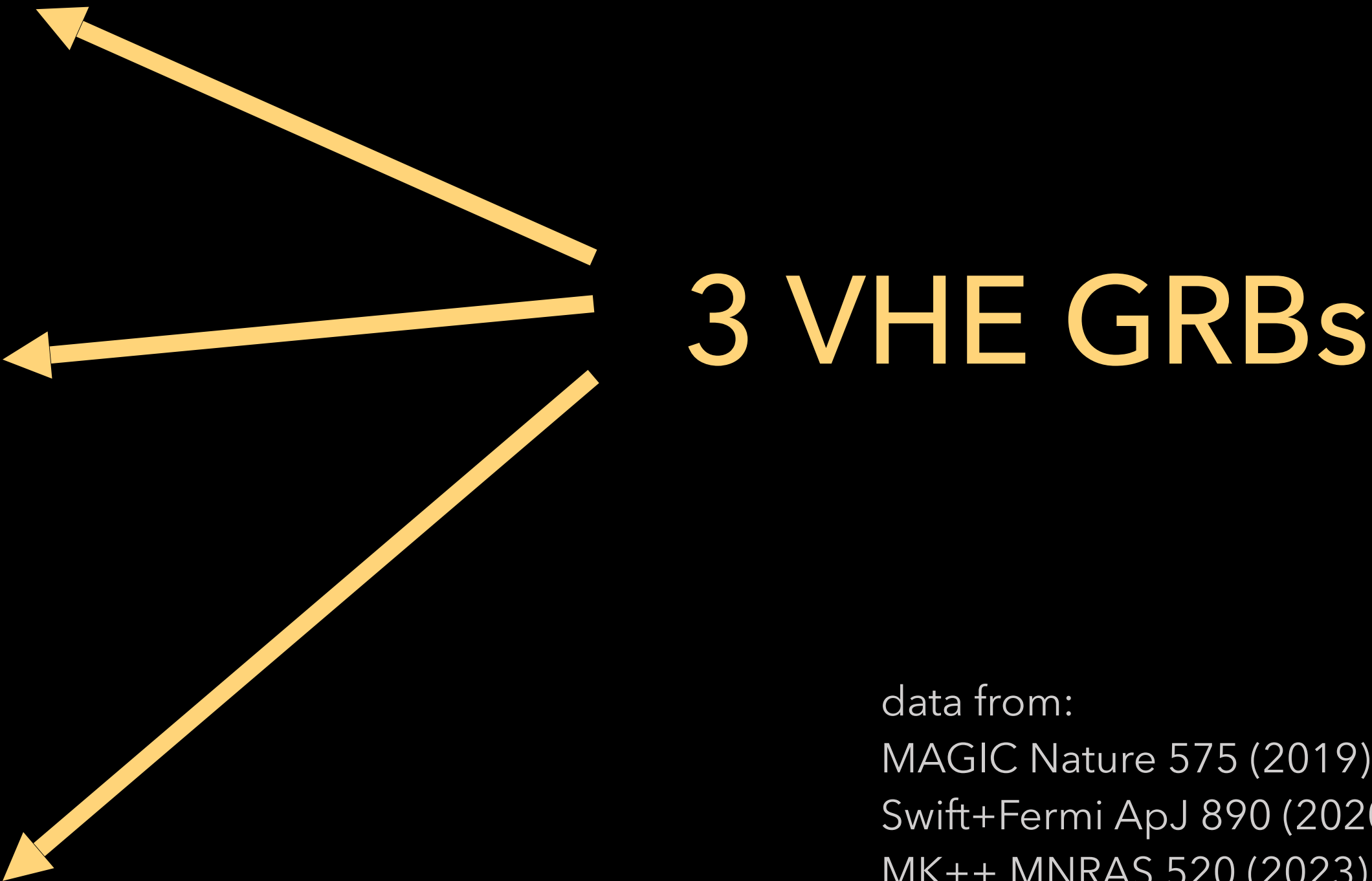
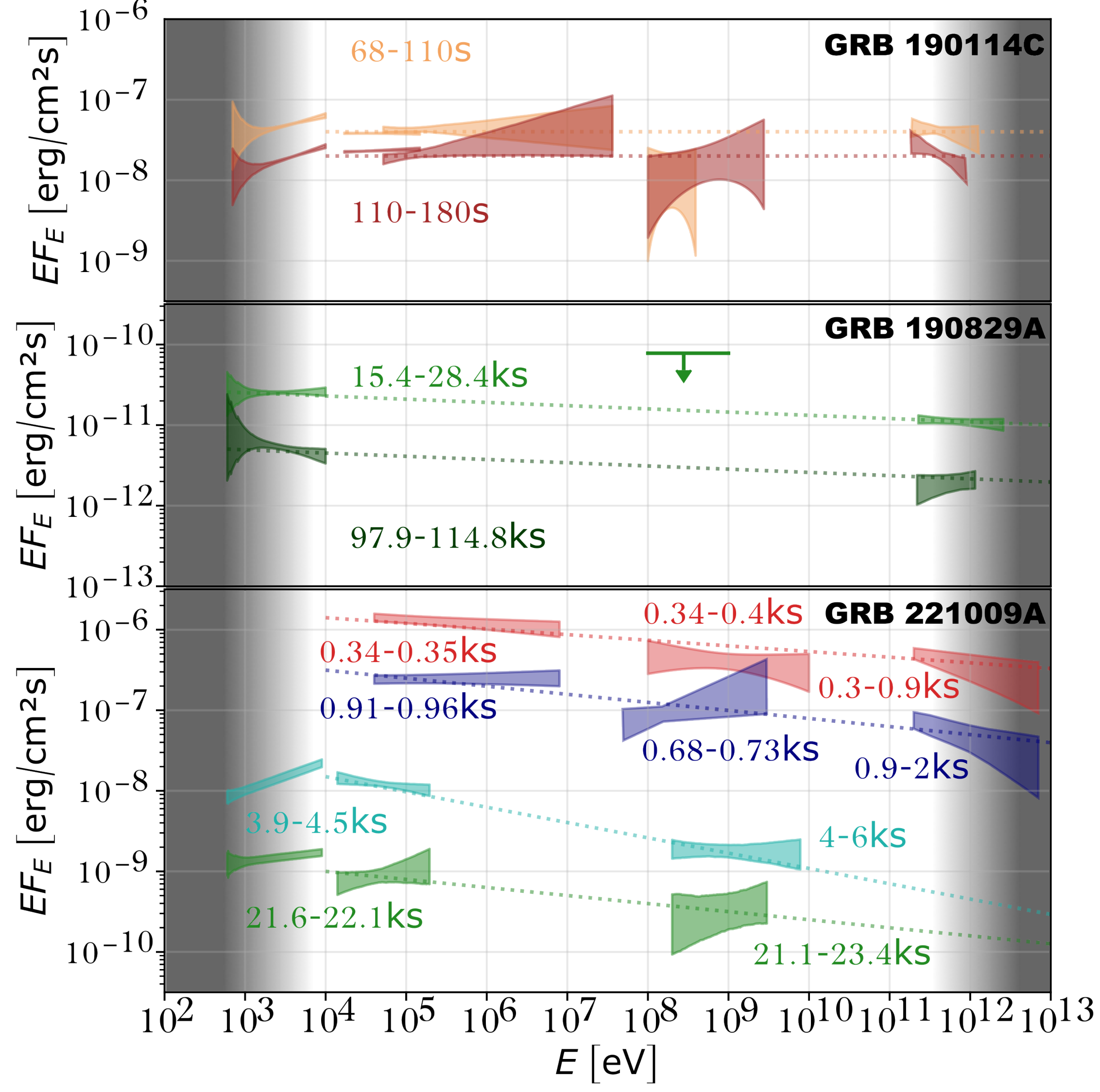
Large High Altitude Air Shower Observatory (LHAASO) in China

Consists of three arrays: 1.3 km² array (KM2A) electromagnetic particle and muon detectors, a water Cherenkov detector array (WCDA) with a total active area of 78,000 m², and 18 wide FoV air Cherenkov telescopes (WFCTA)



Surprise! Since 2017 already 6 GRBs detected in VHE (>100 GeV)!

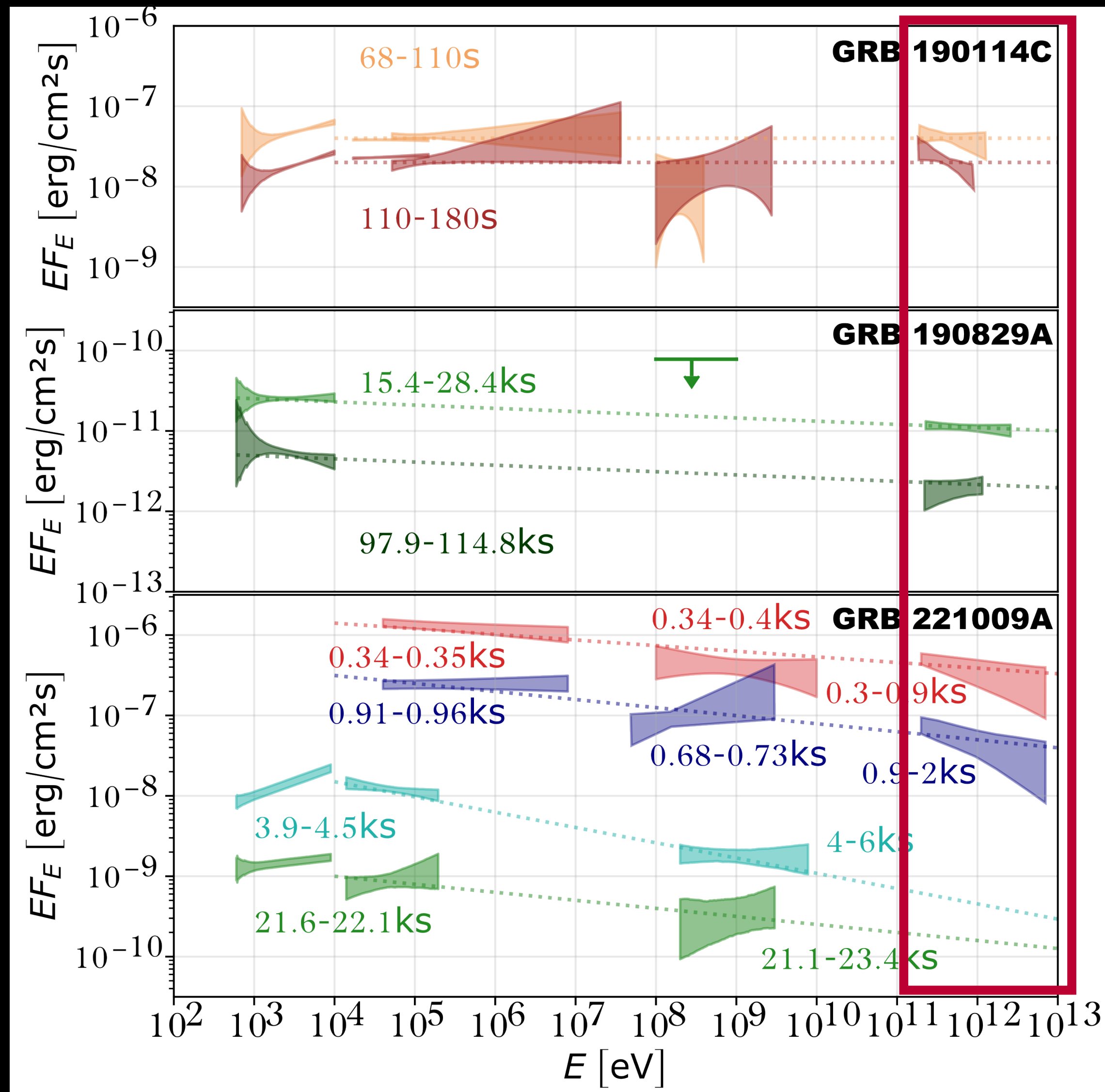
photoelectric abs. pair production (EBL= γ -ray cosmology)



3 VHE GRBs

data from:
MAGIC Nature 575 (2019)
Swift+Fermi ApJ 890 (2020)
MK++ MNRAS 520 (2023)
H.E.S.S. Science 372 (2021)
Zhang++ ApJL 956 (2023)
Liu++ APJL 943 (2023)
Tavani++ ApJL 956 (2023)
LHAASO Science 380 (2023)
MK++ MNRAS 529L (2024)

VHE GRBs show unprecedented/unanticipated hard spectra!



→ **MAGIC**



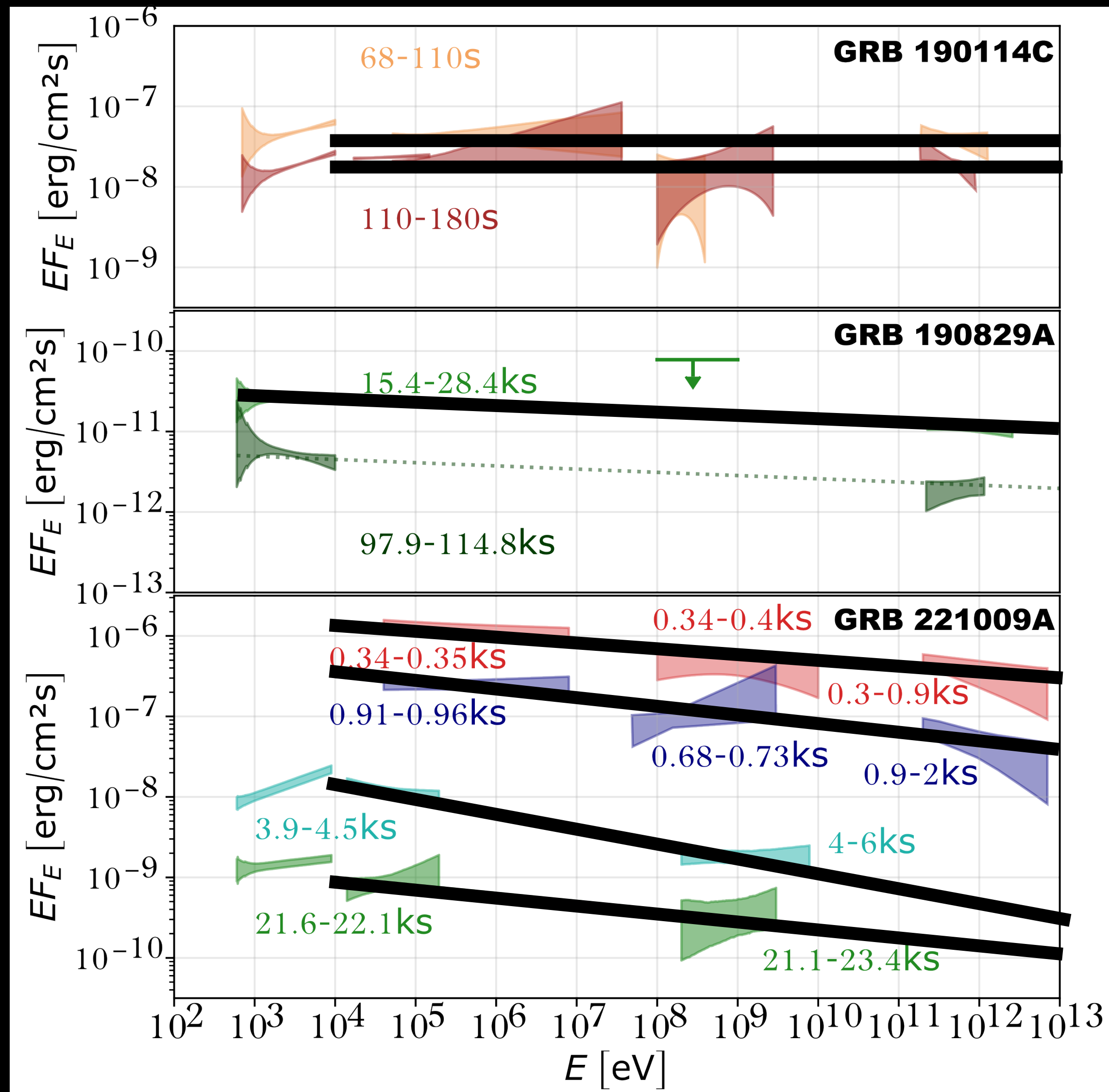
→ **H.E.S.S.**



→ **LHAASO**



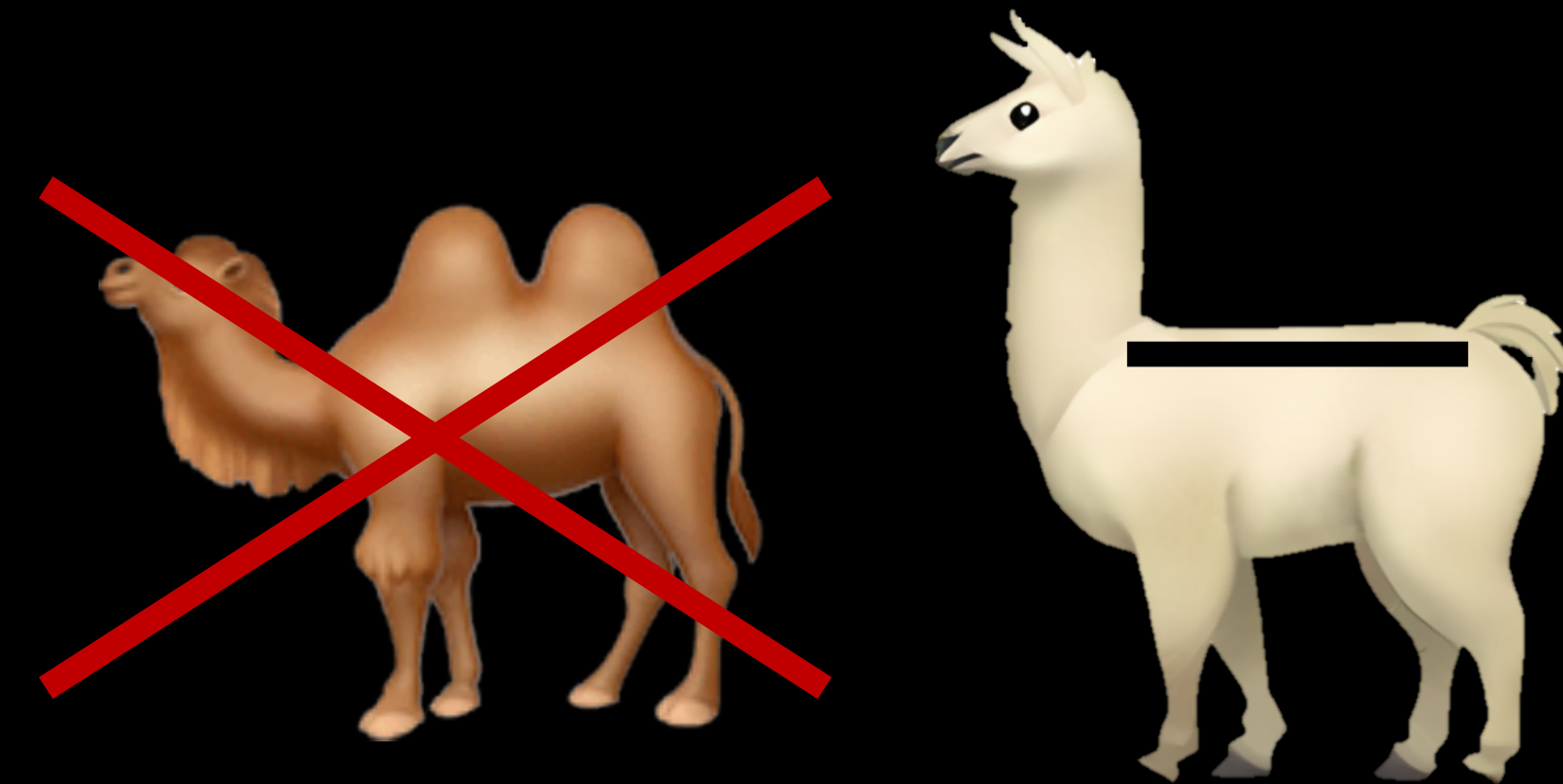
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→ **MAGIC**

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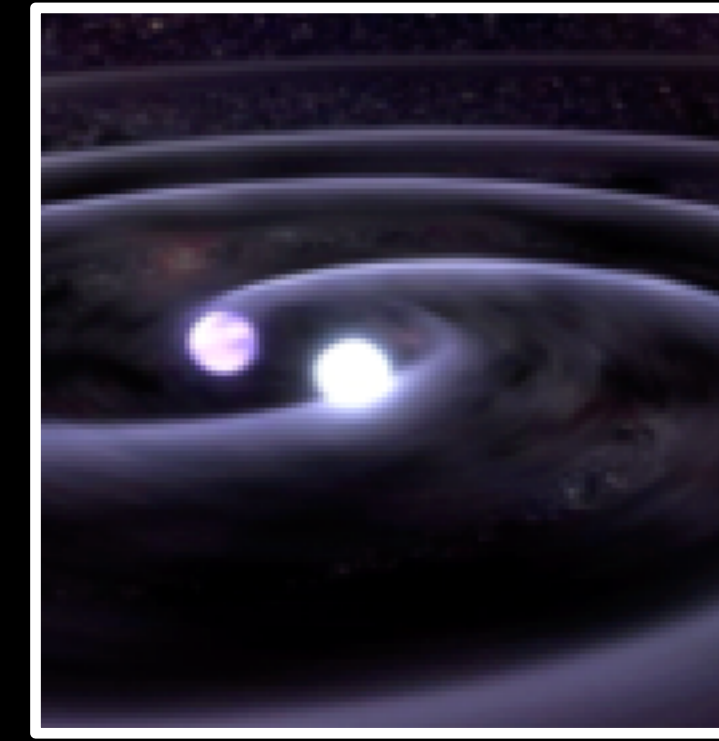
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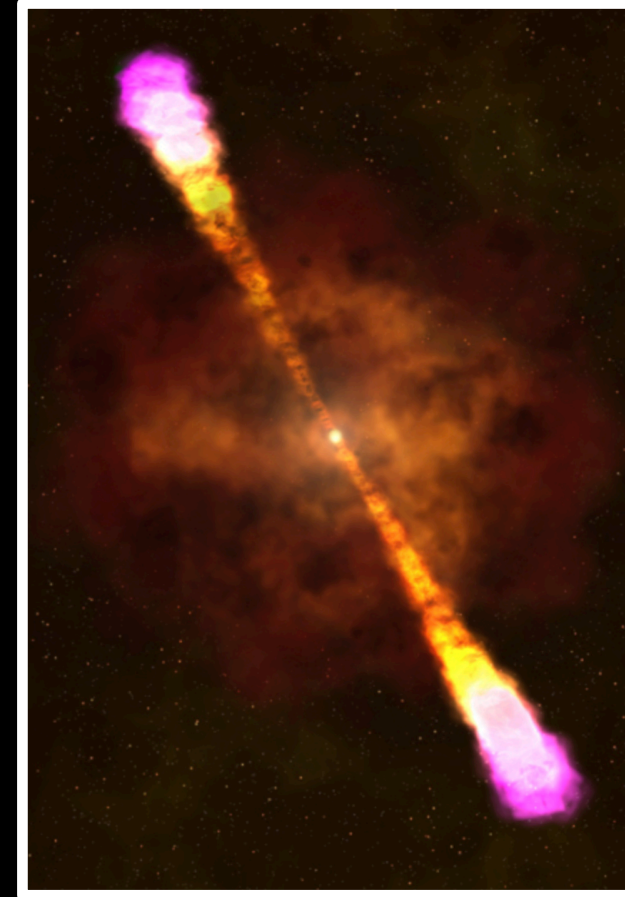
single power-law up
to TeV energies?!?

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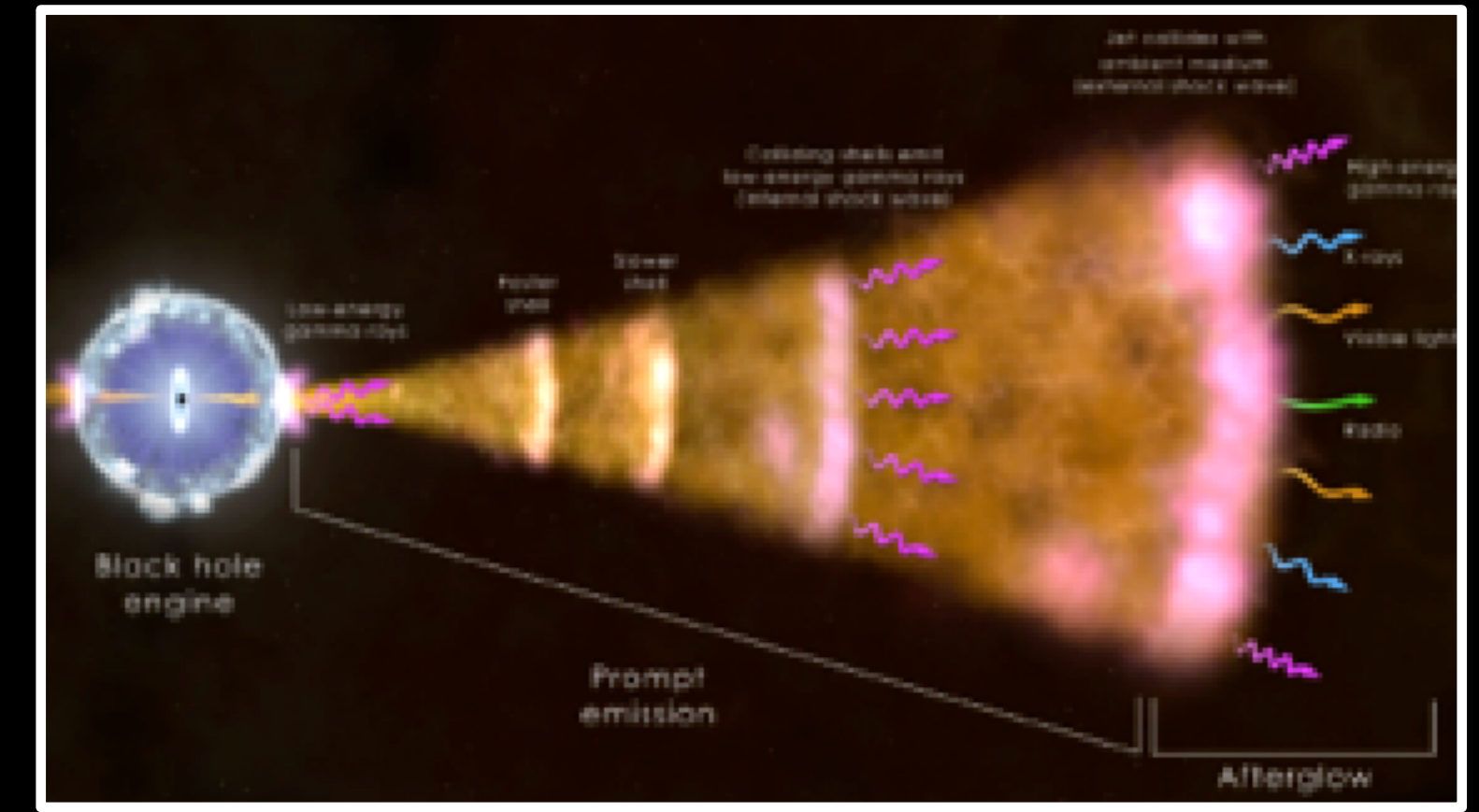
GW170817: first off-axis sGRB!



NS merger

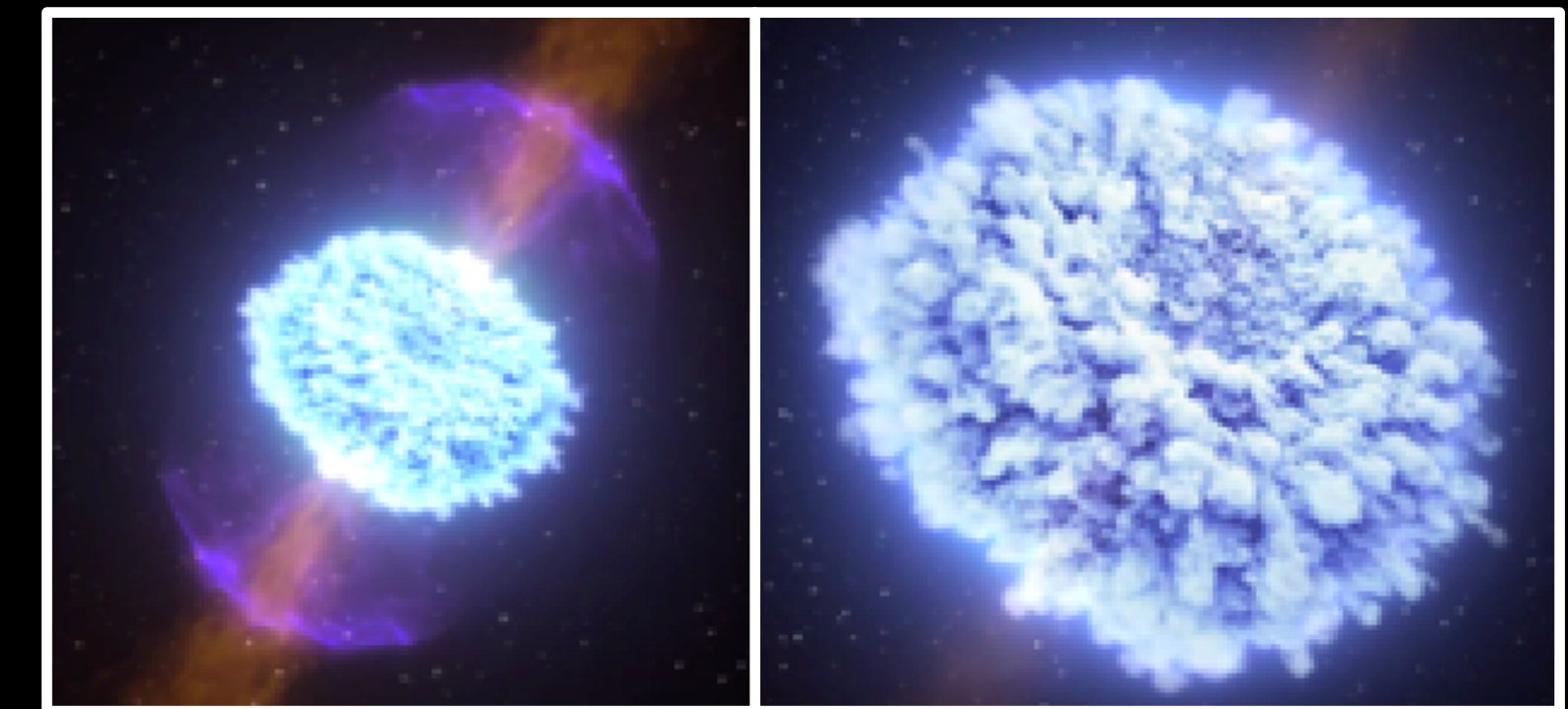
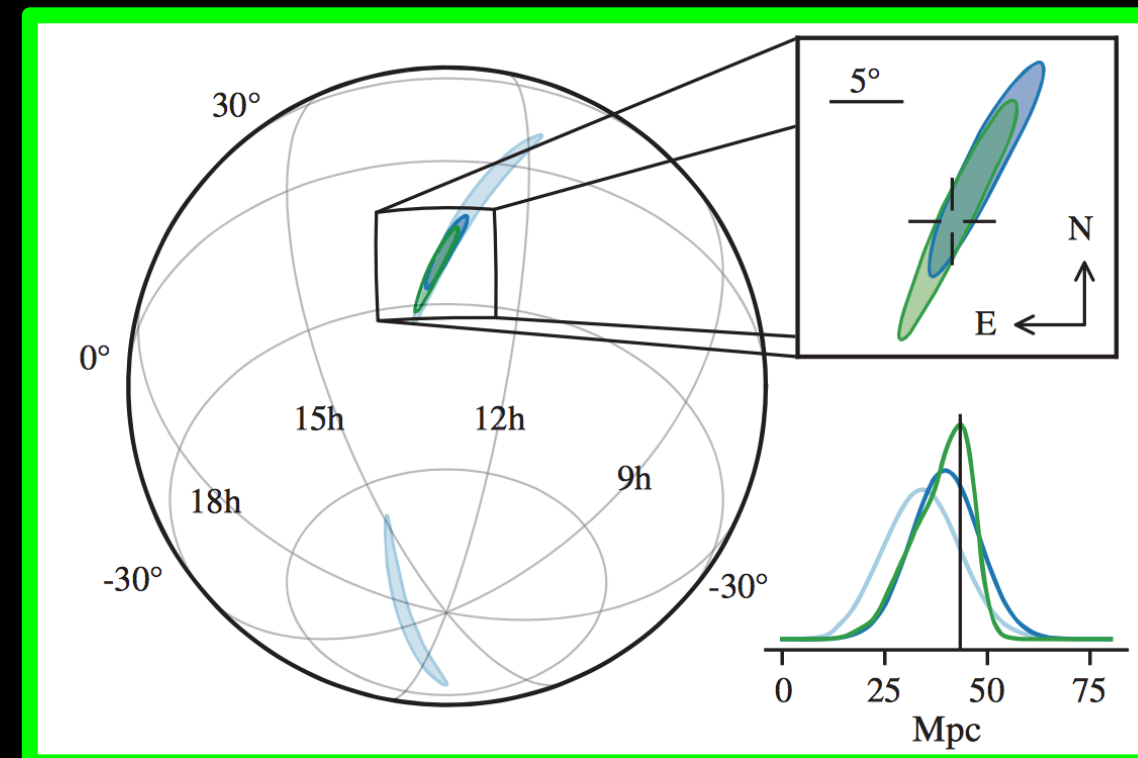
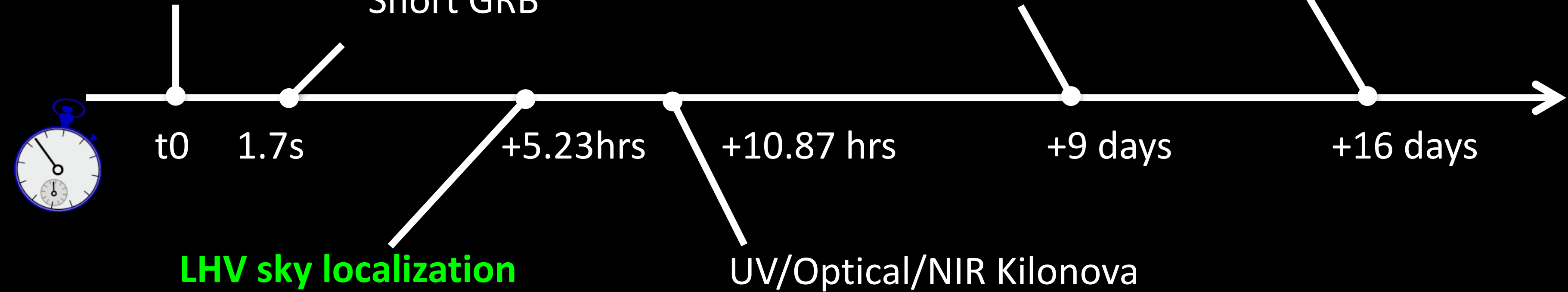


Short GRB



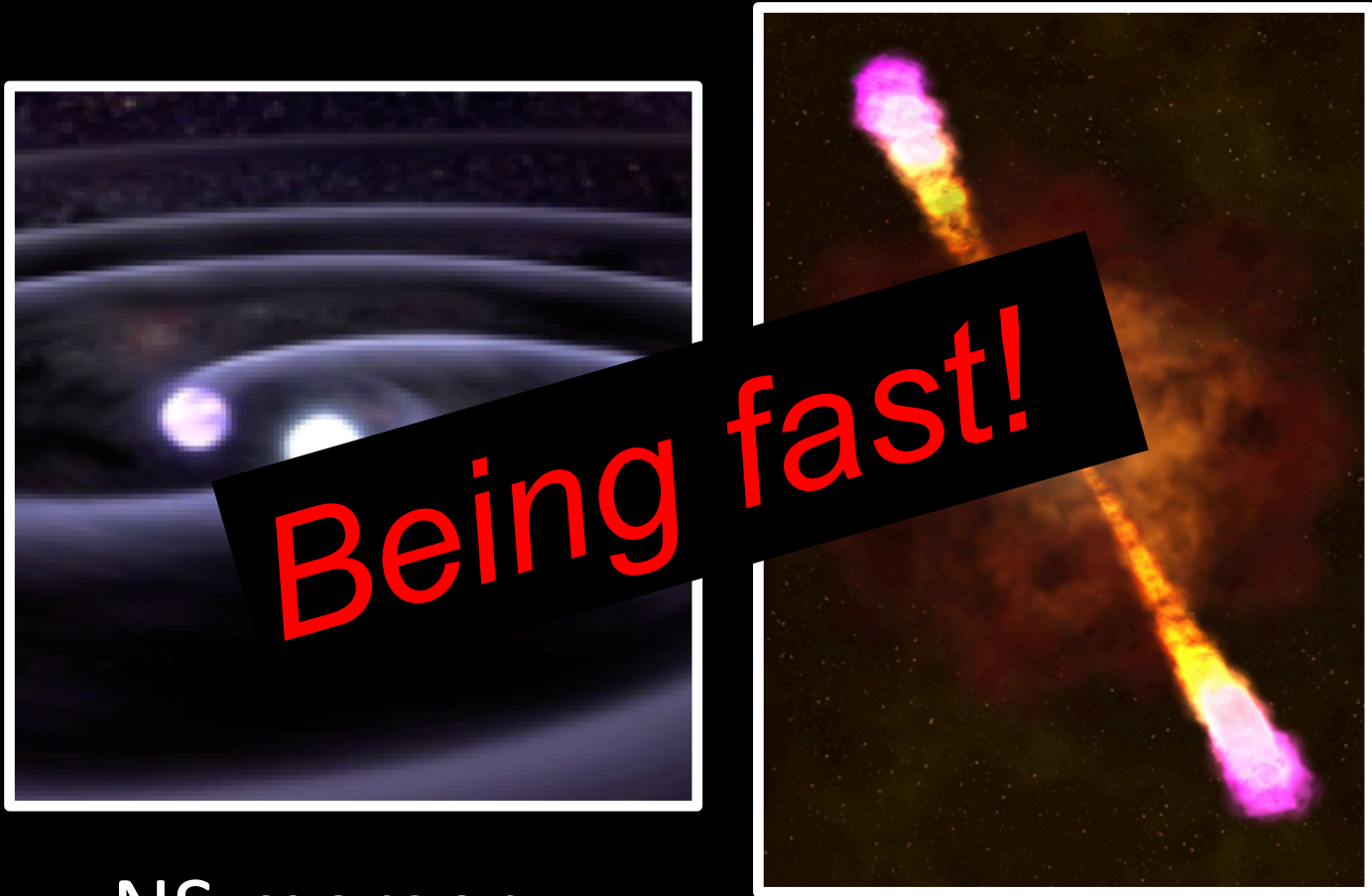
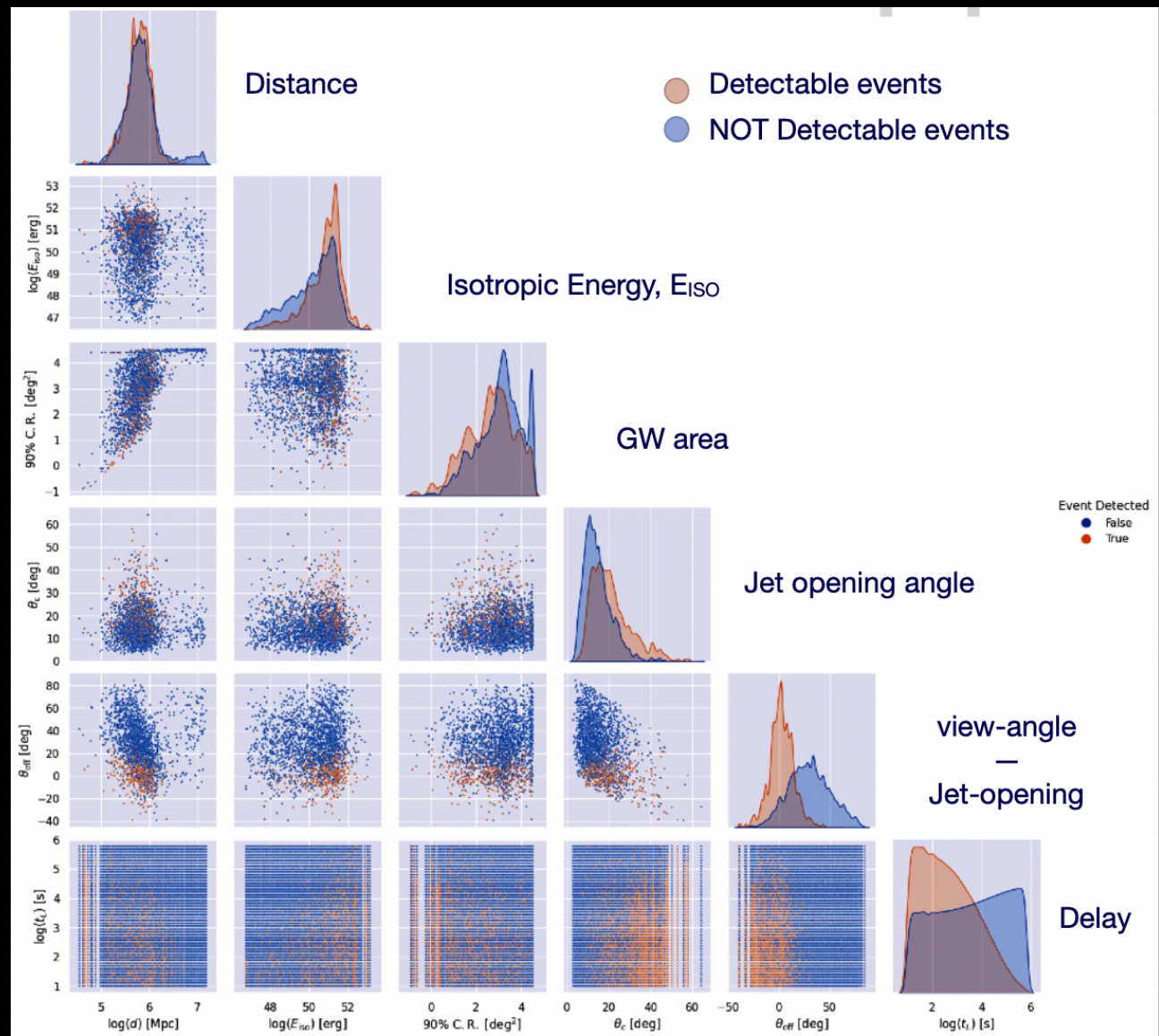
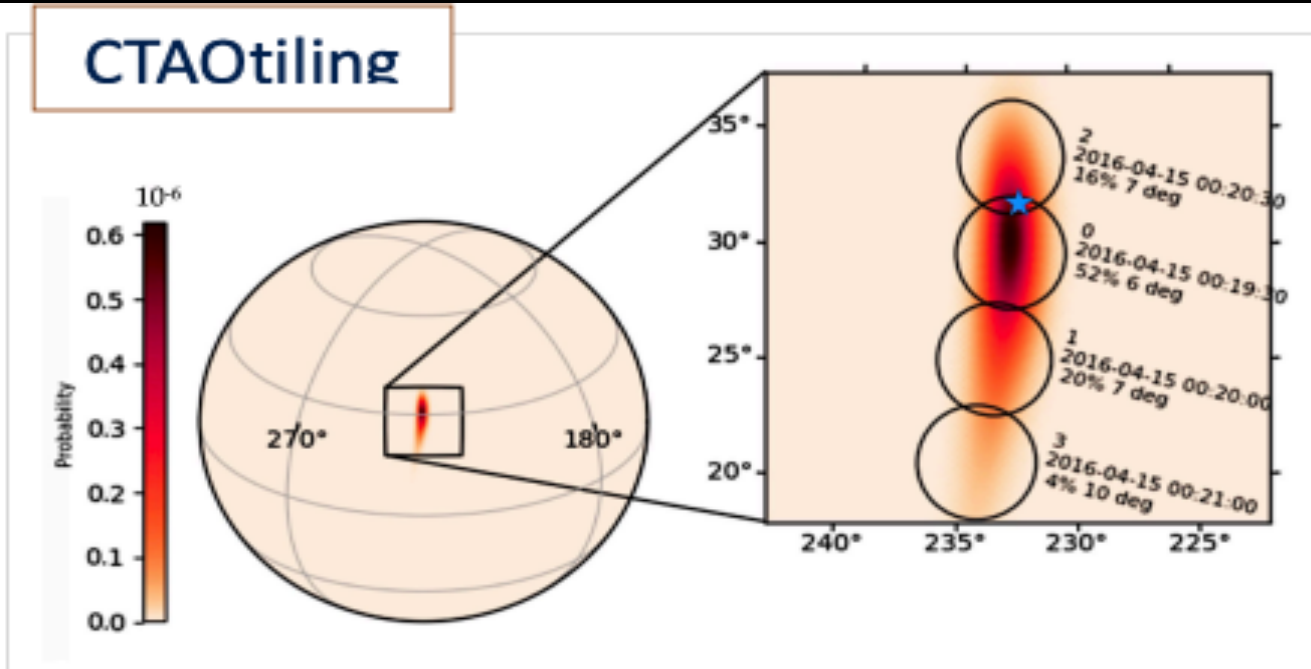
X-ray

Radio afterglow

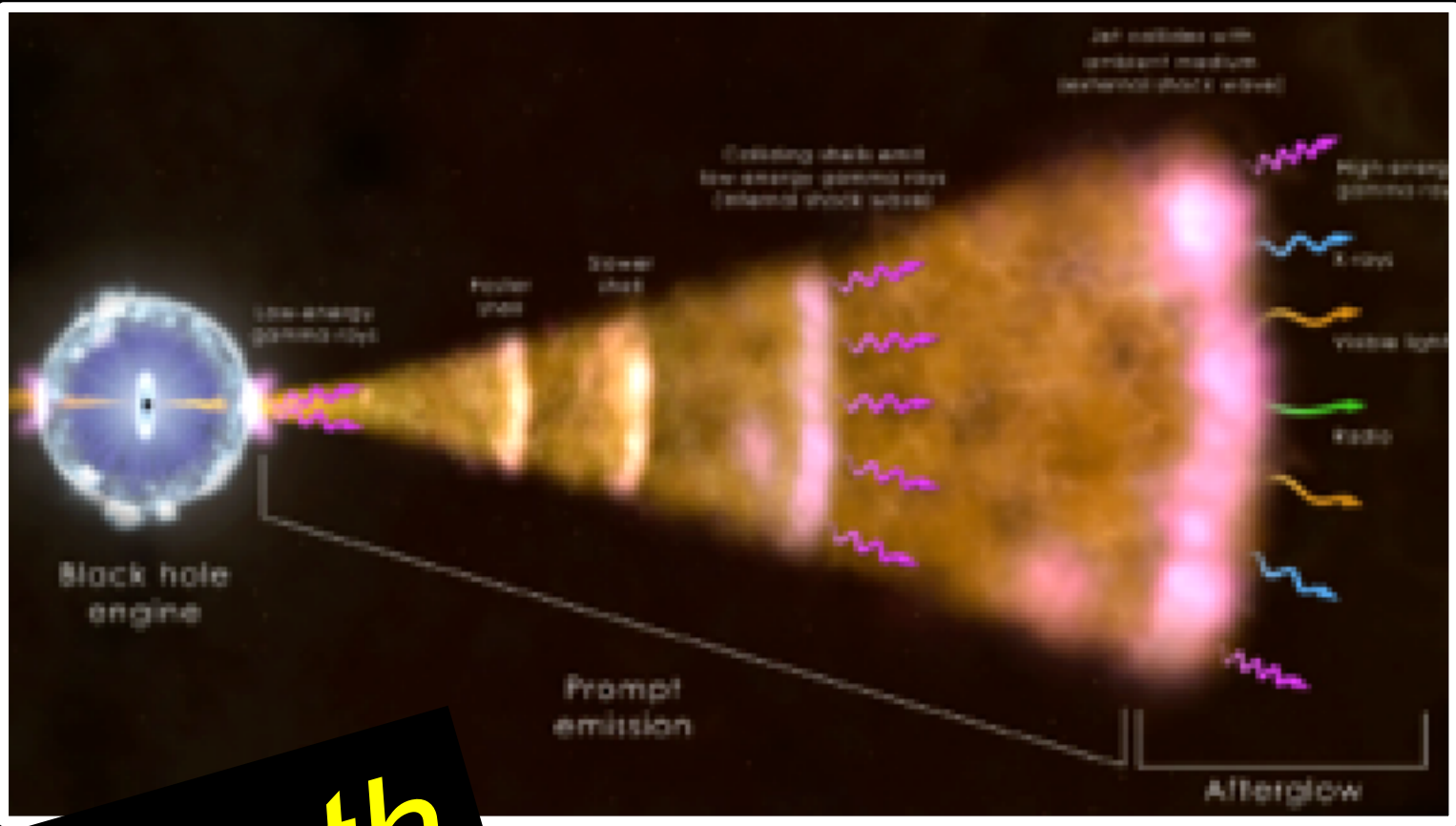


GW170817: first off-axis sGRB!

CTAO GW planning:



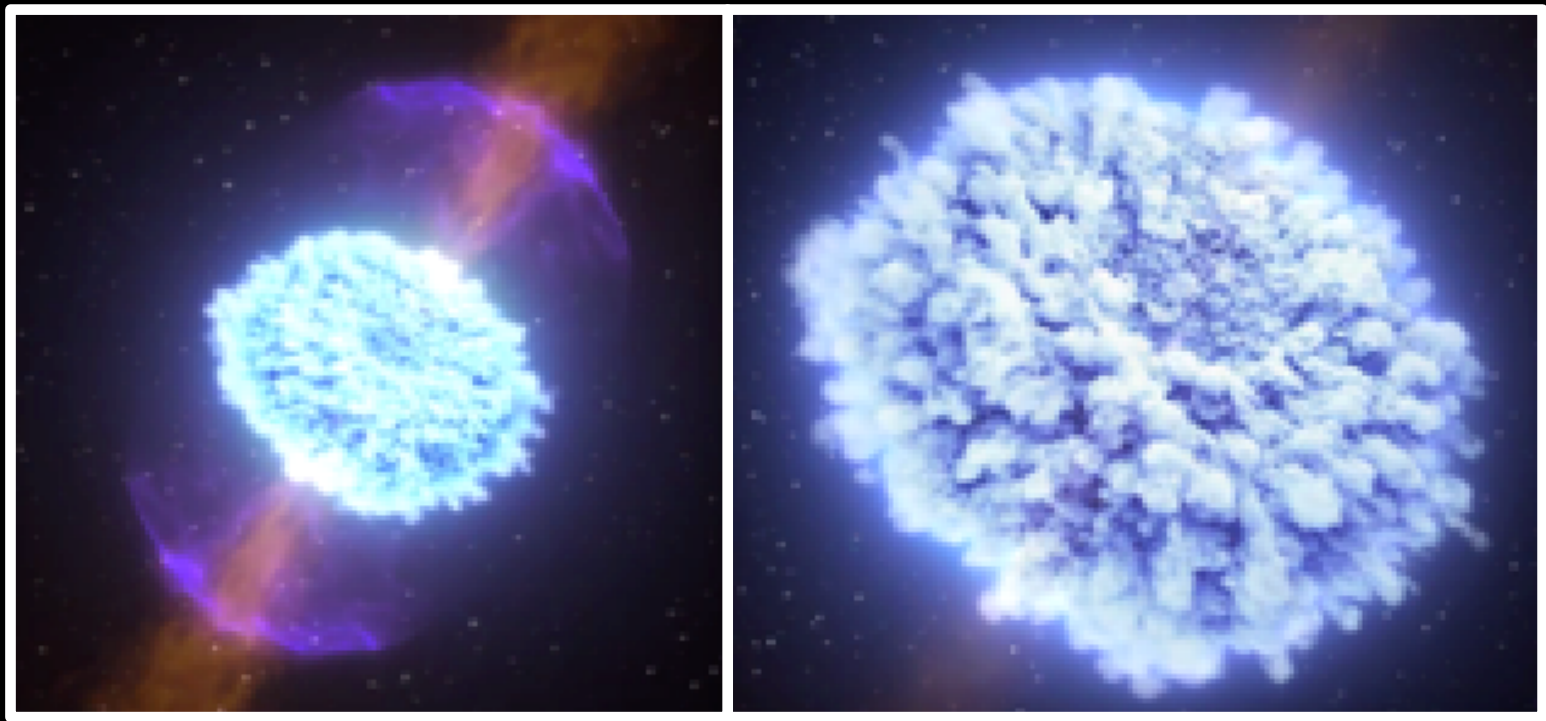
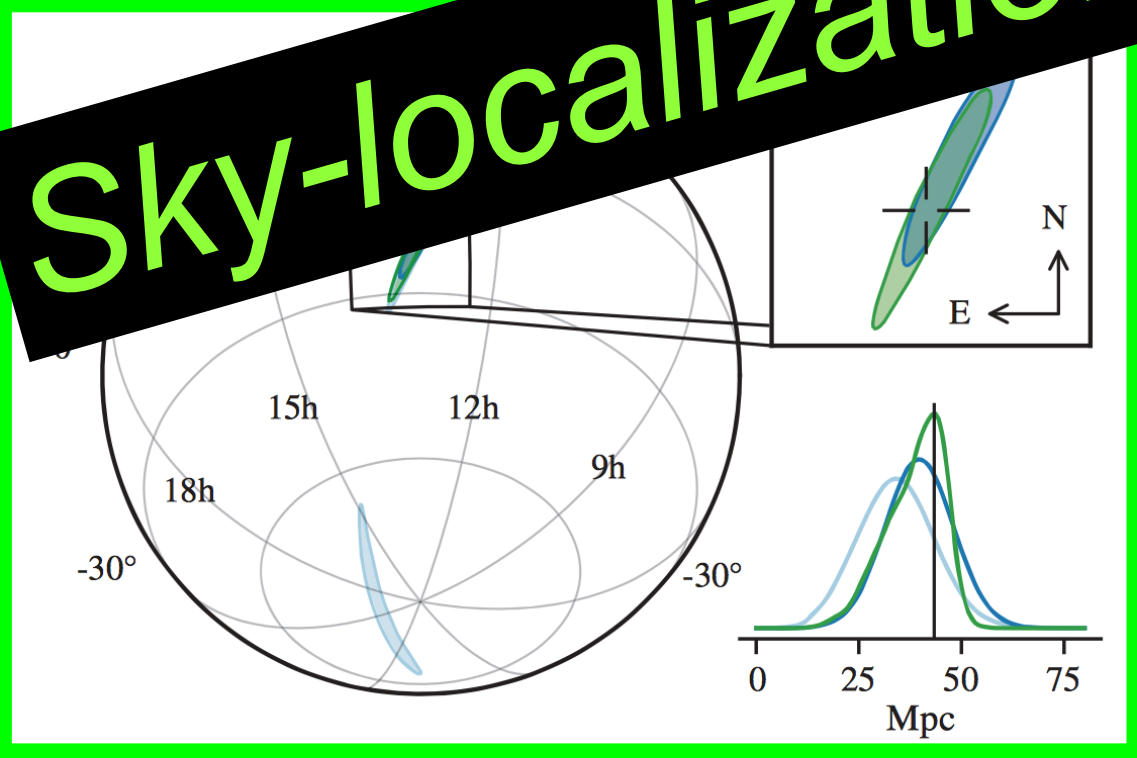
Being fast!



Multi-wavelength coverage!

LHV sky localization

Sky-localization!

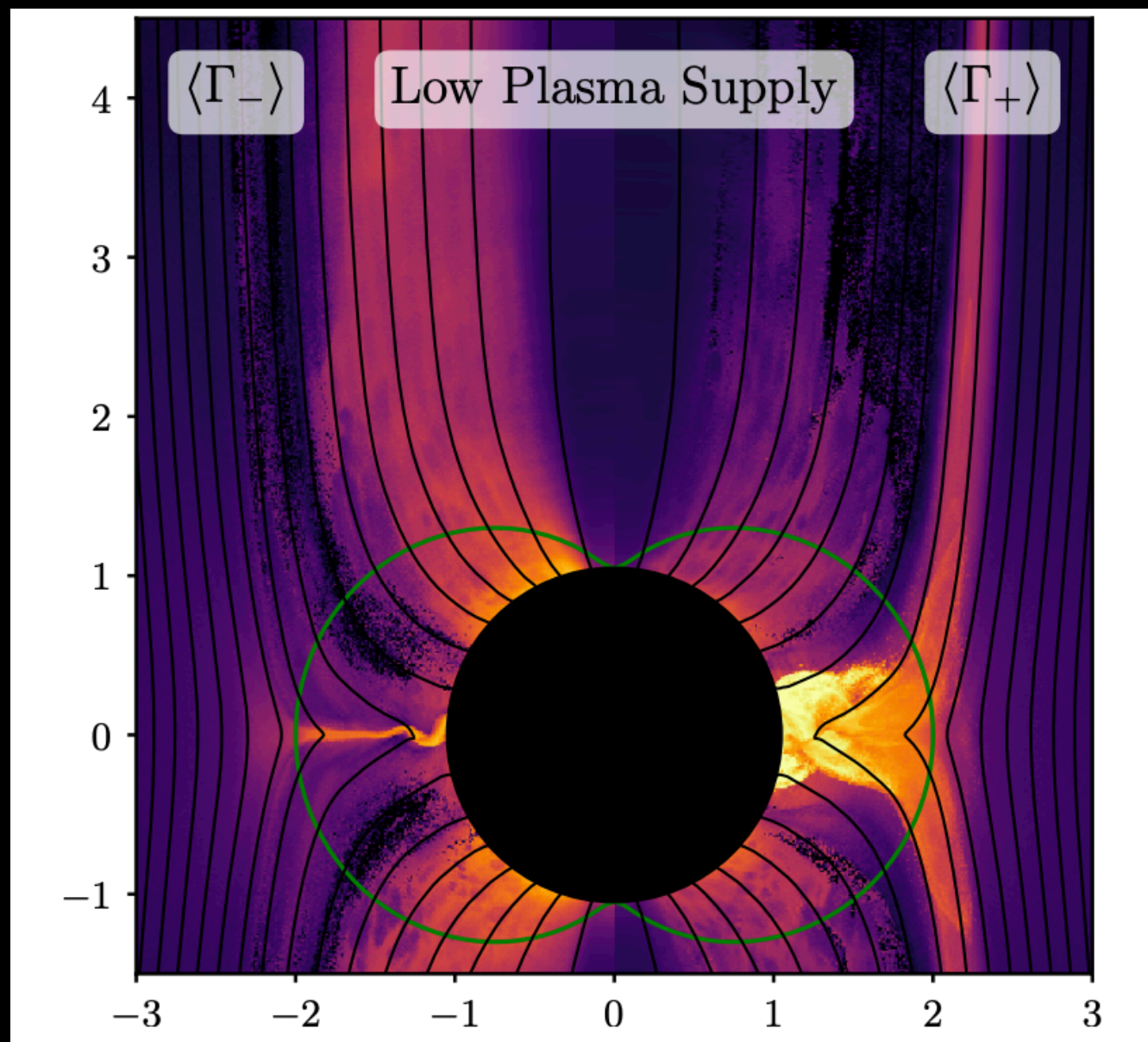


Understanding = localising: particle acceleration and VHE γ -rays

3C273 (Jester++2006), jet "colour" (wavelength) traces particle acceleration:

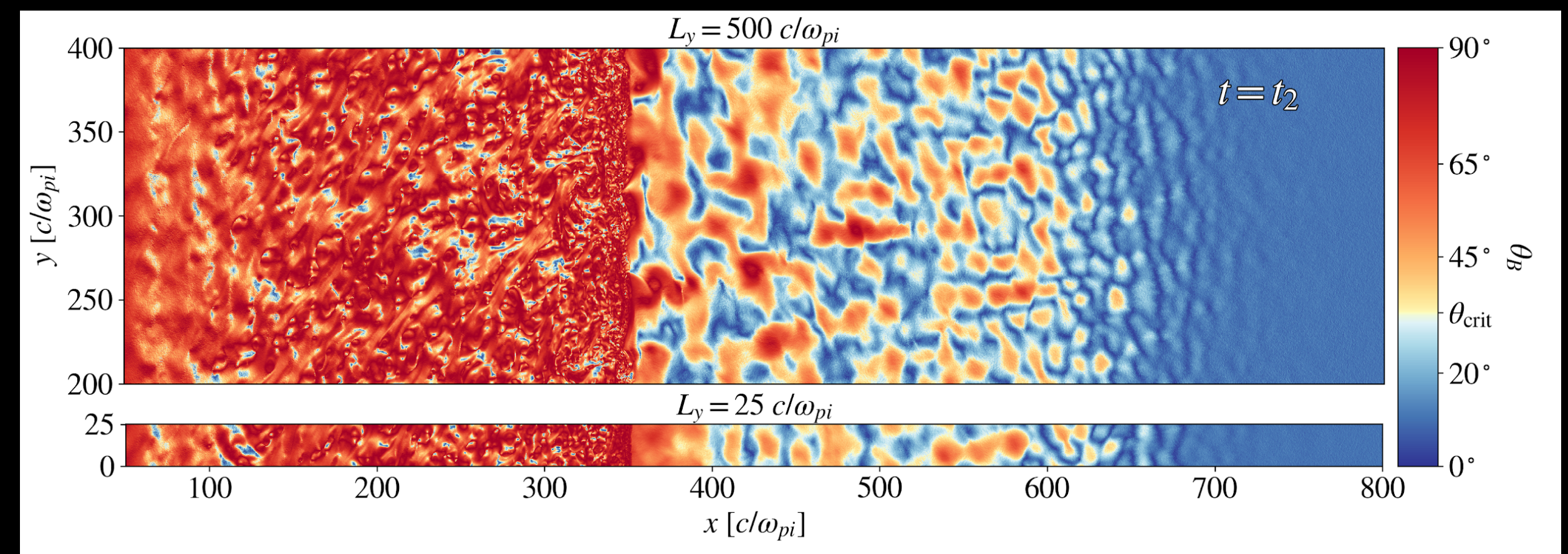
Blue: X-rays (Chandra), Green: Optical (HST), Yellow: Optical & Peak Radio, Red: Radio (VLA)

Magnetospheres



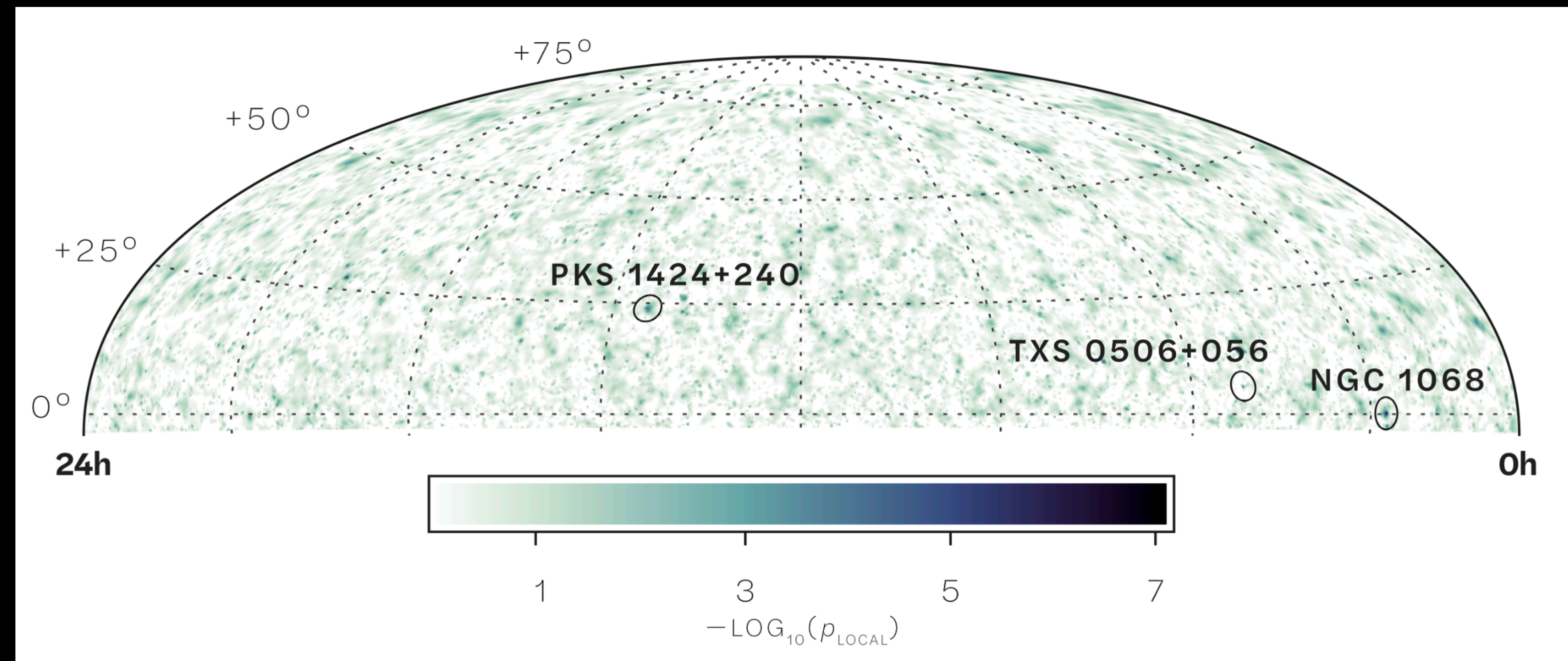
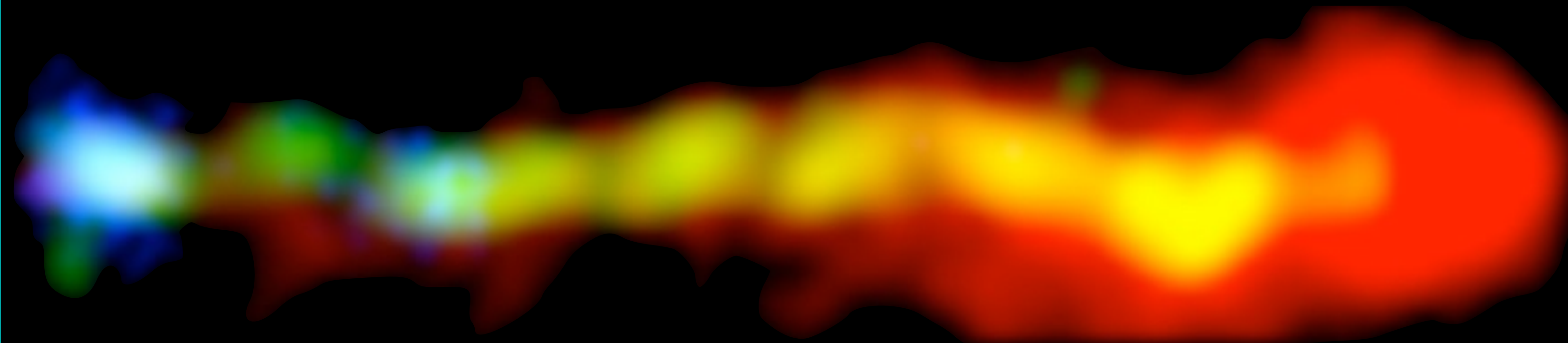
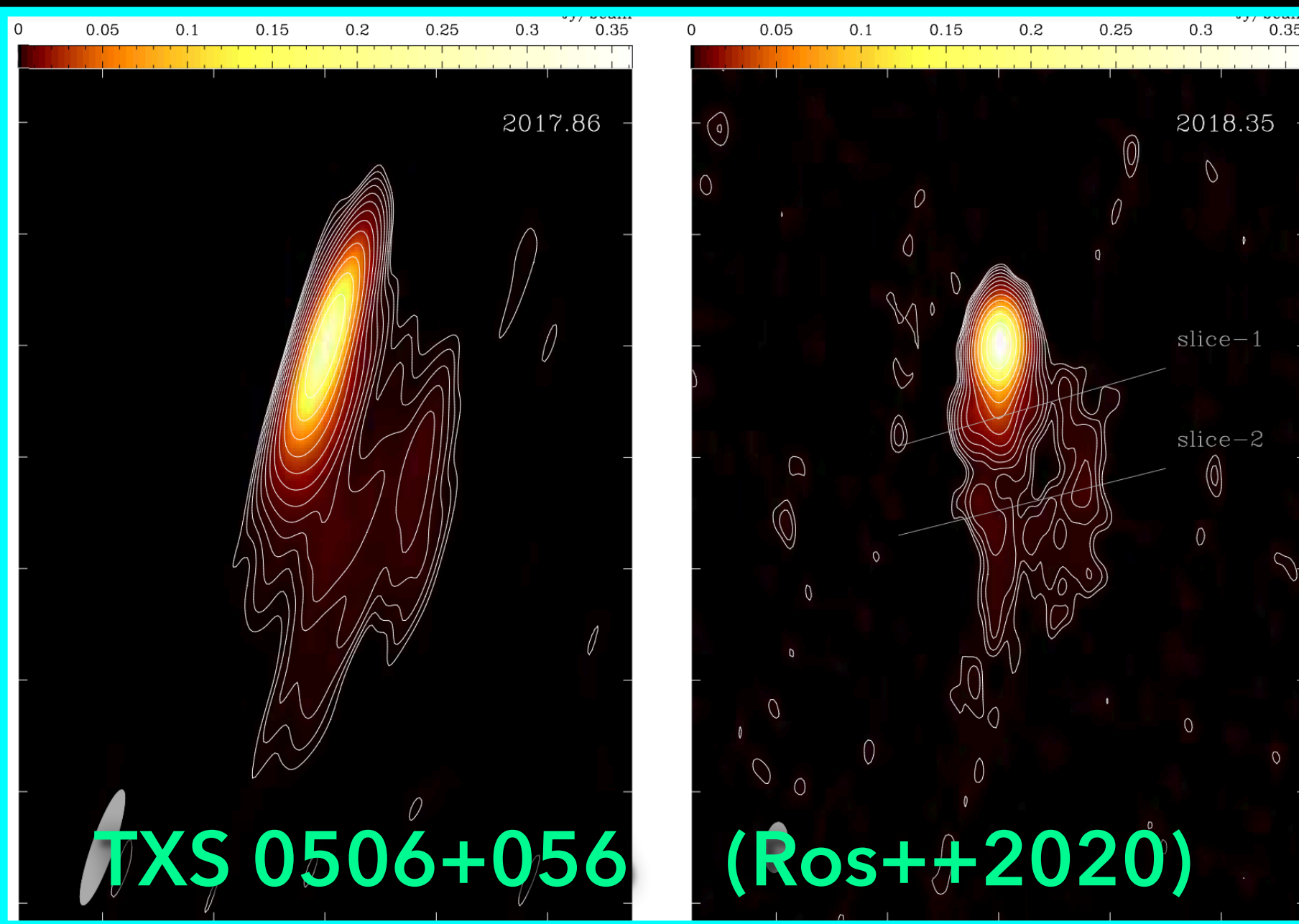
e.g. Rieger & Mannheim 2000; Rieger & Aharonian 2008; ... Parfrey, Philippov & Cerutti 2019; Bransgrove, Ripperda & Philippov 2021; Hakobyan, Ripperda & Philippov 2023; + work by many others...

Shocks/shear/turbulence (umbrella terms for many mechanisms)

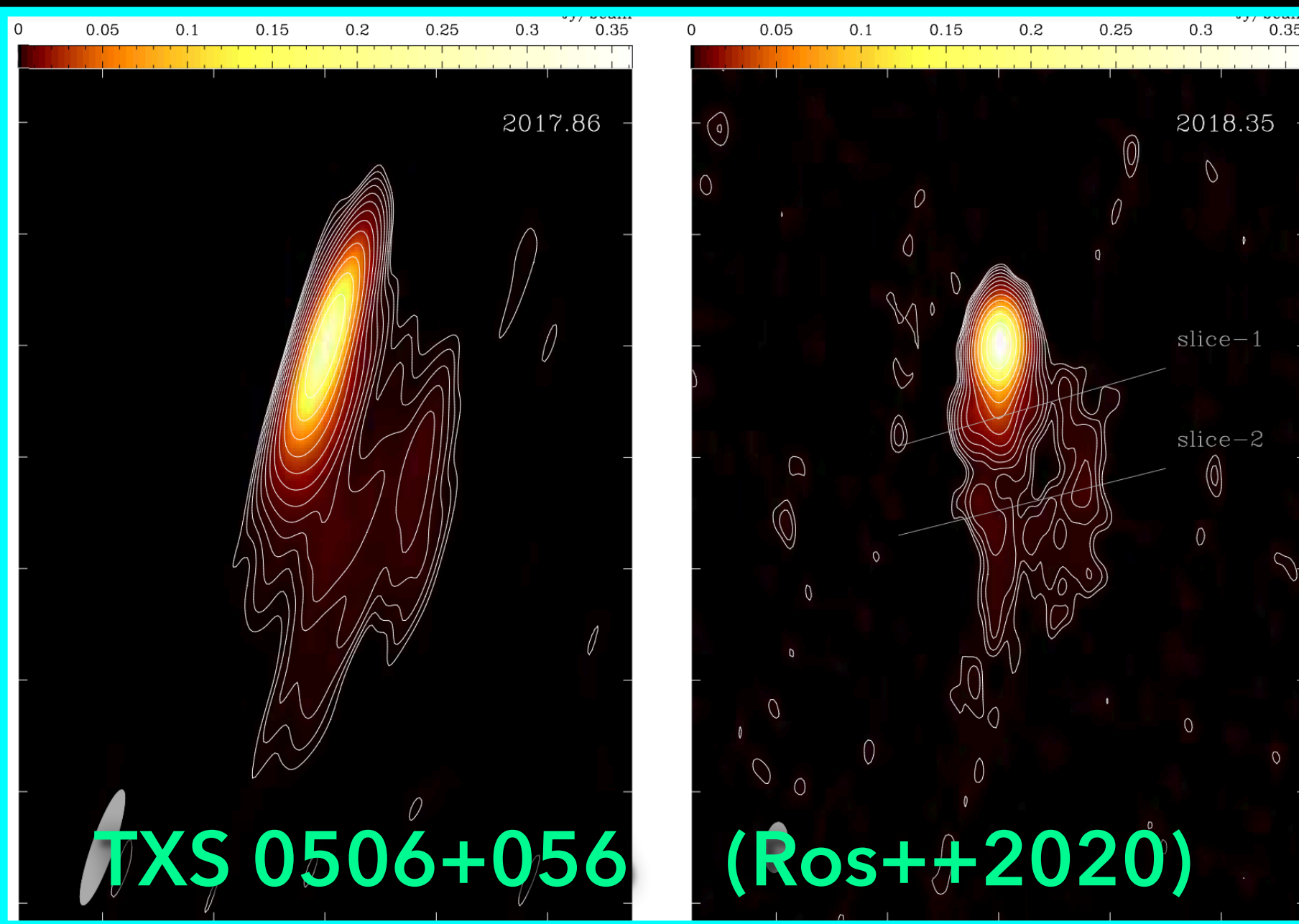


eg. Crumley++2019, Sironi++2021; and see numerical/semi-analytical work by eg, Aharonian; Bai; Bell; Böttcher; de Gouveia Dal Pino; Drury; Giannios; Jokipii; Kirk; Lazarian; Marscher; Oikonomou; Petropoulou; Reimer; Reville; Winter; ++ many many others...

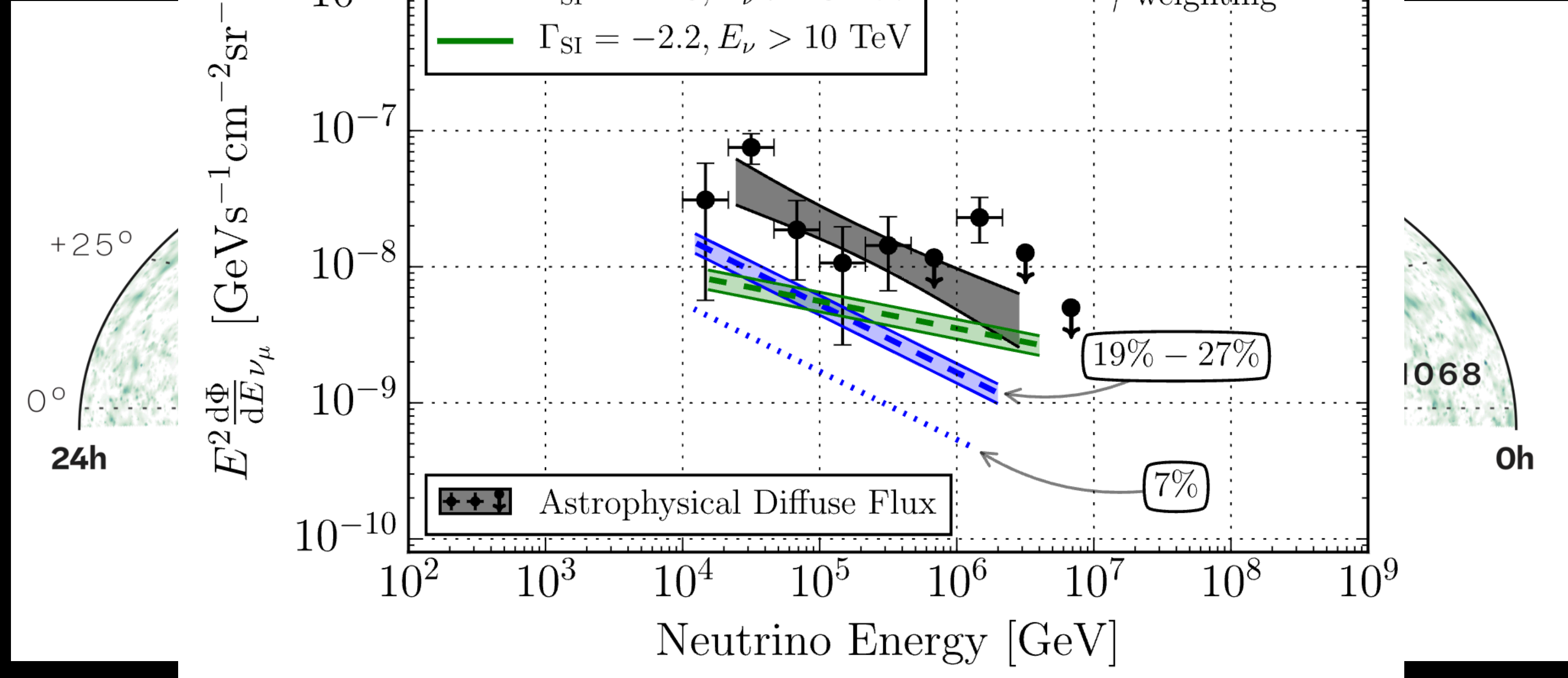
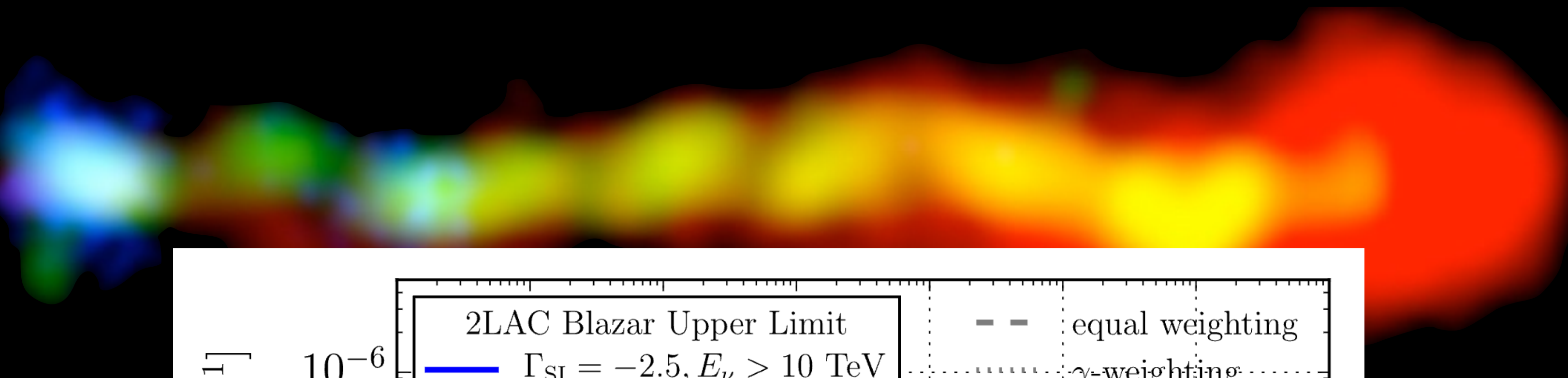
Neutrinos challenging the "classic" blazar picture



Neutrinos challenging the "classic" blazar picture

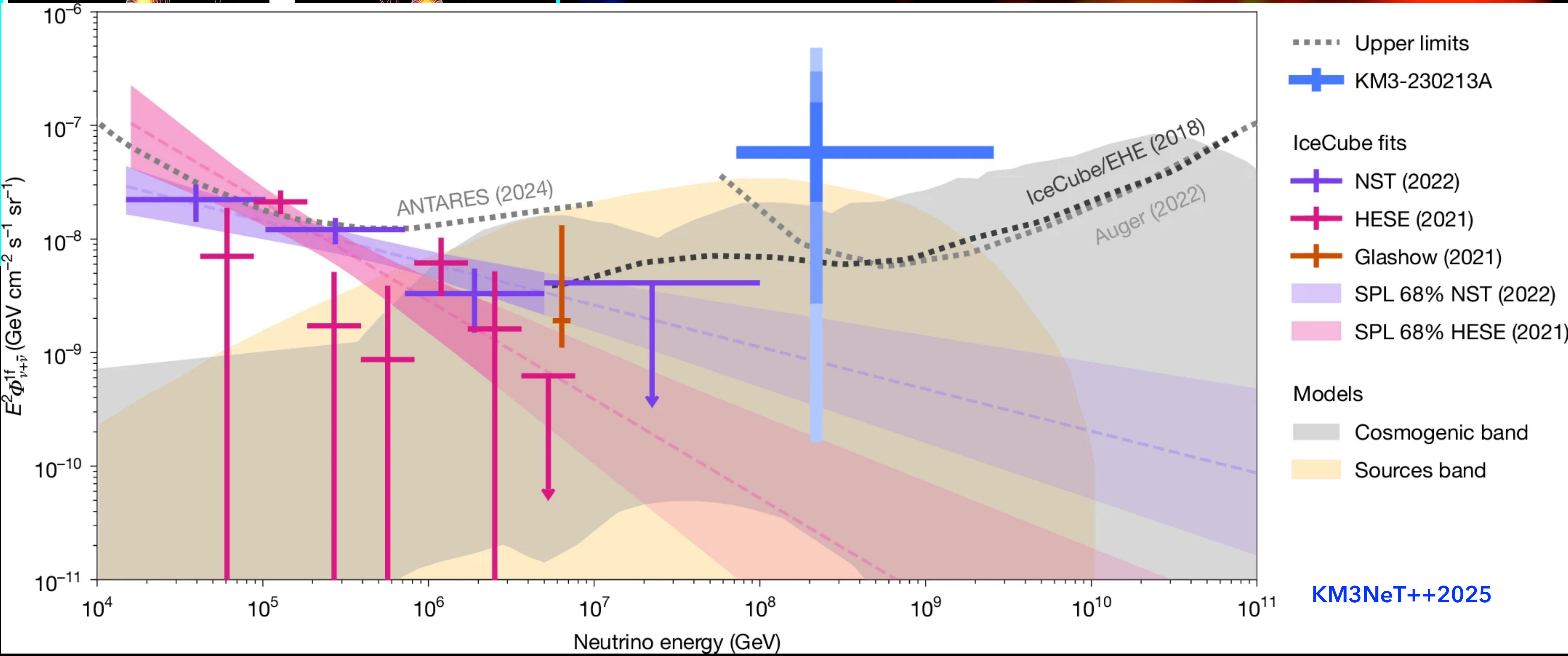
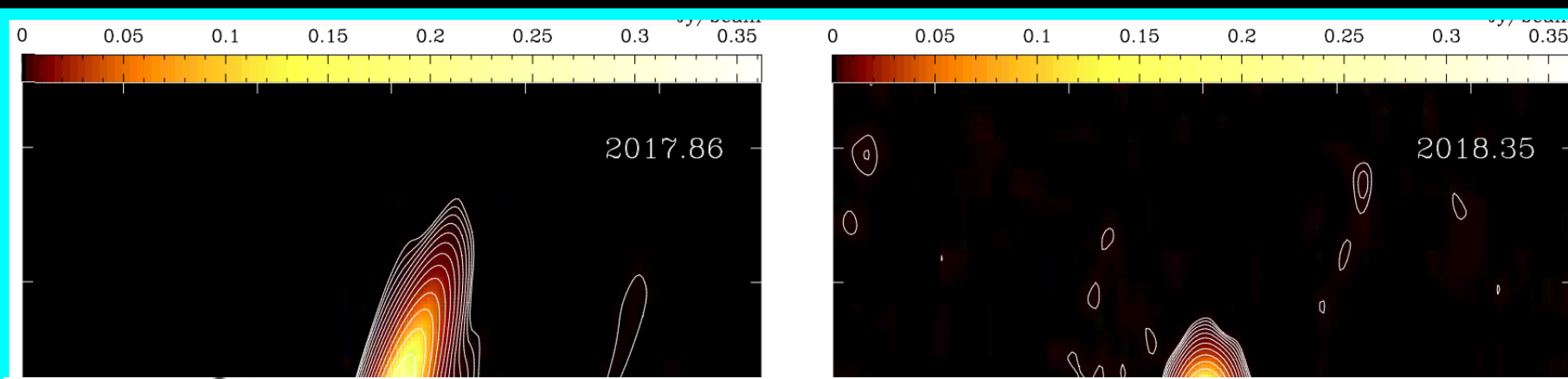


IceCube Collaboration 2018; 2022, Science



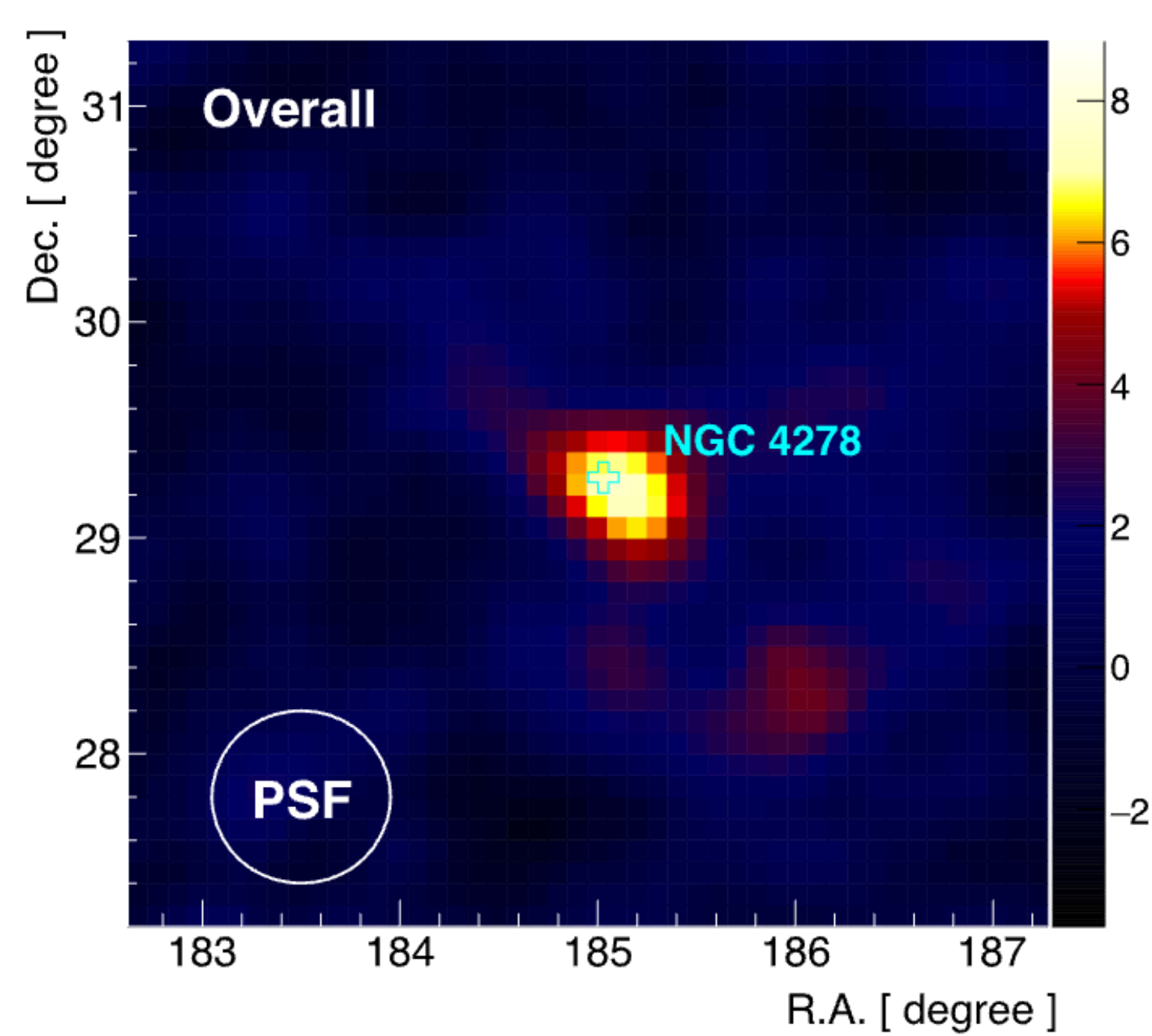
IceCube Collaboration 2017

Neutrinos challenging the "classic" blazar picture

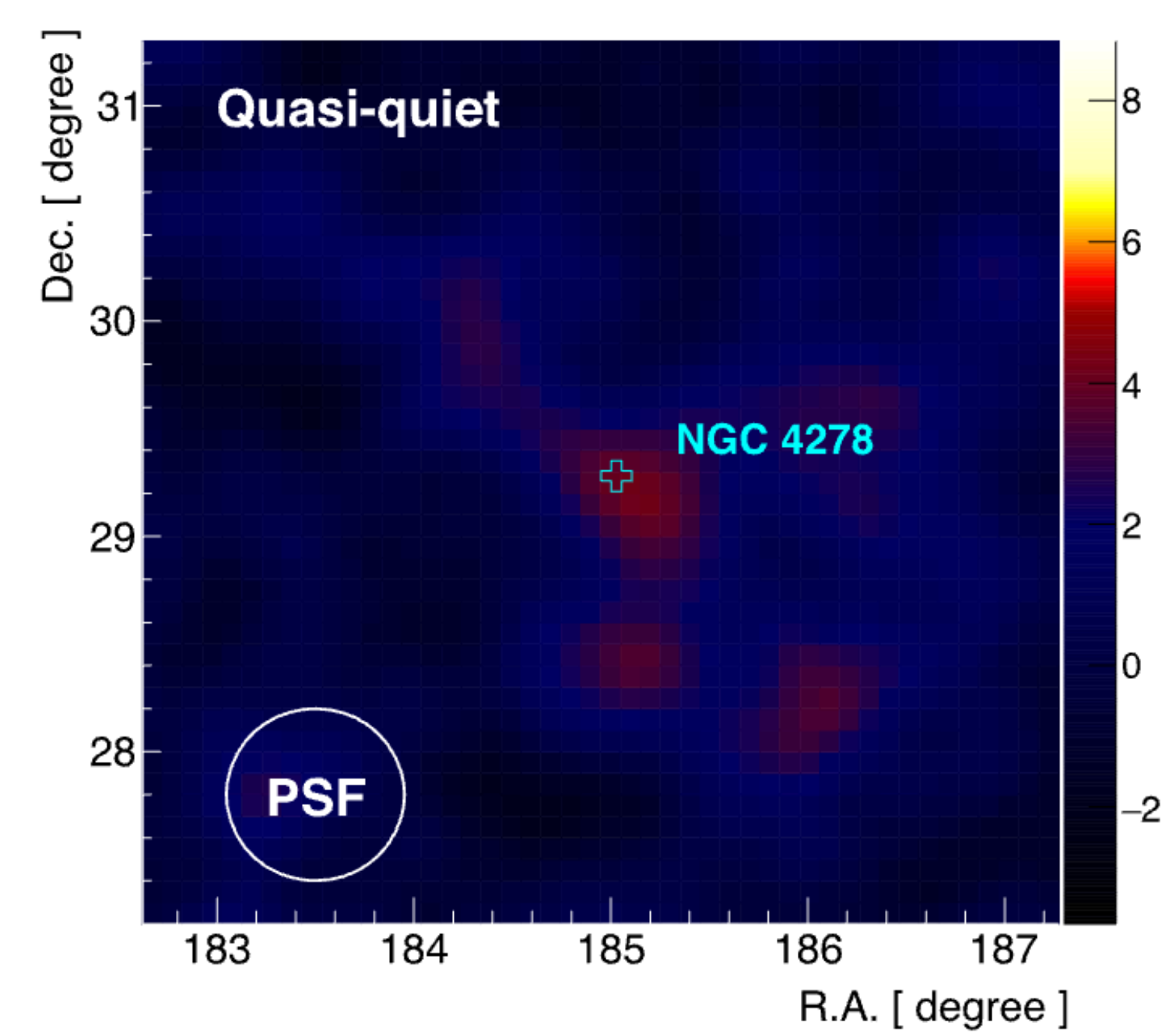


LHAASO revolution!

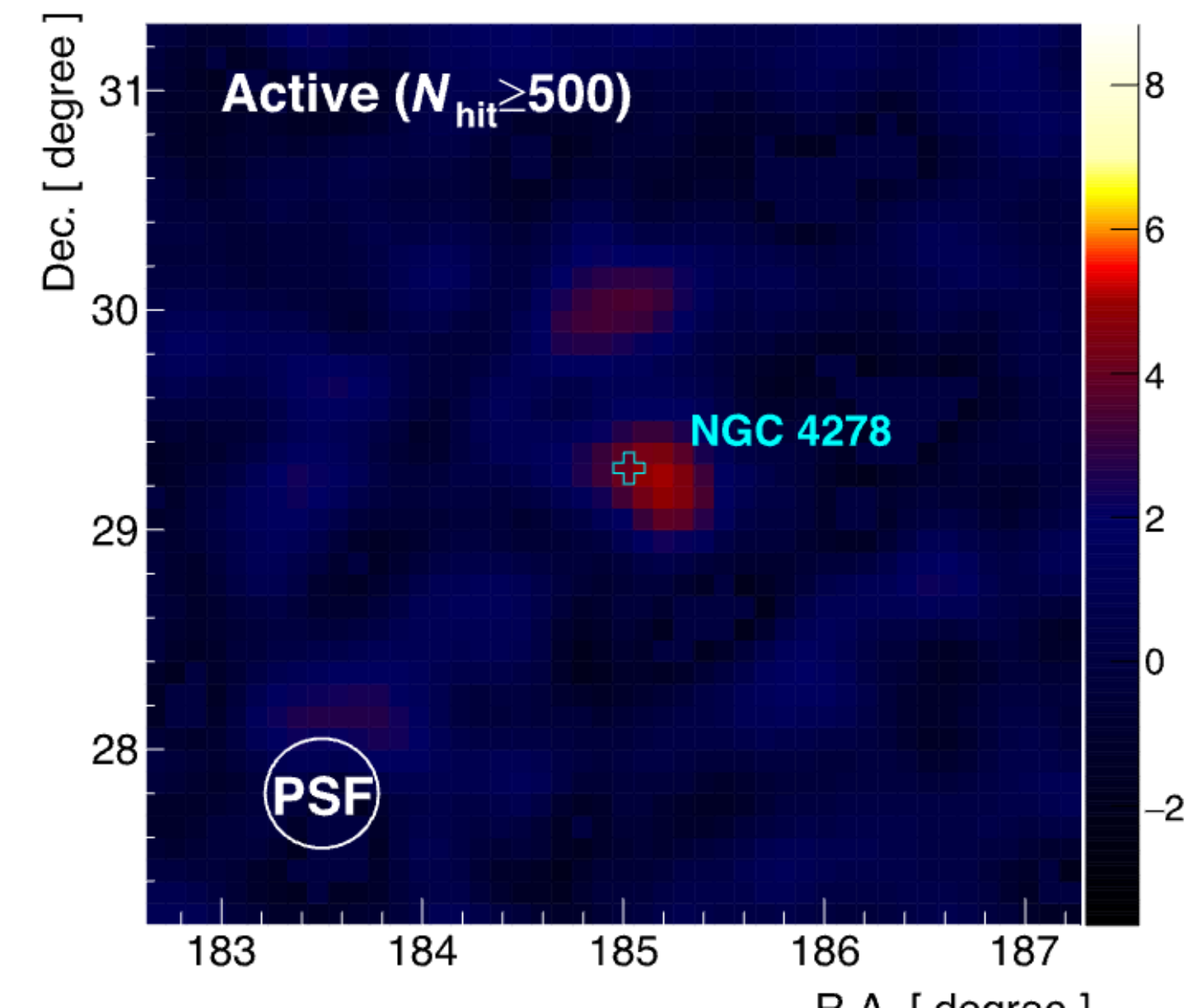
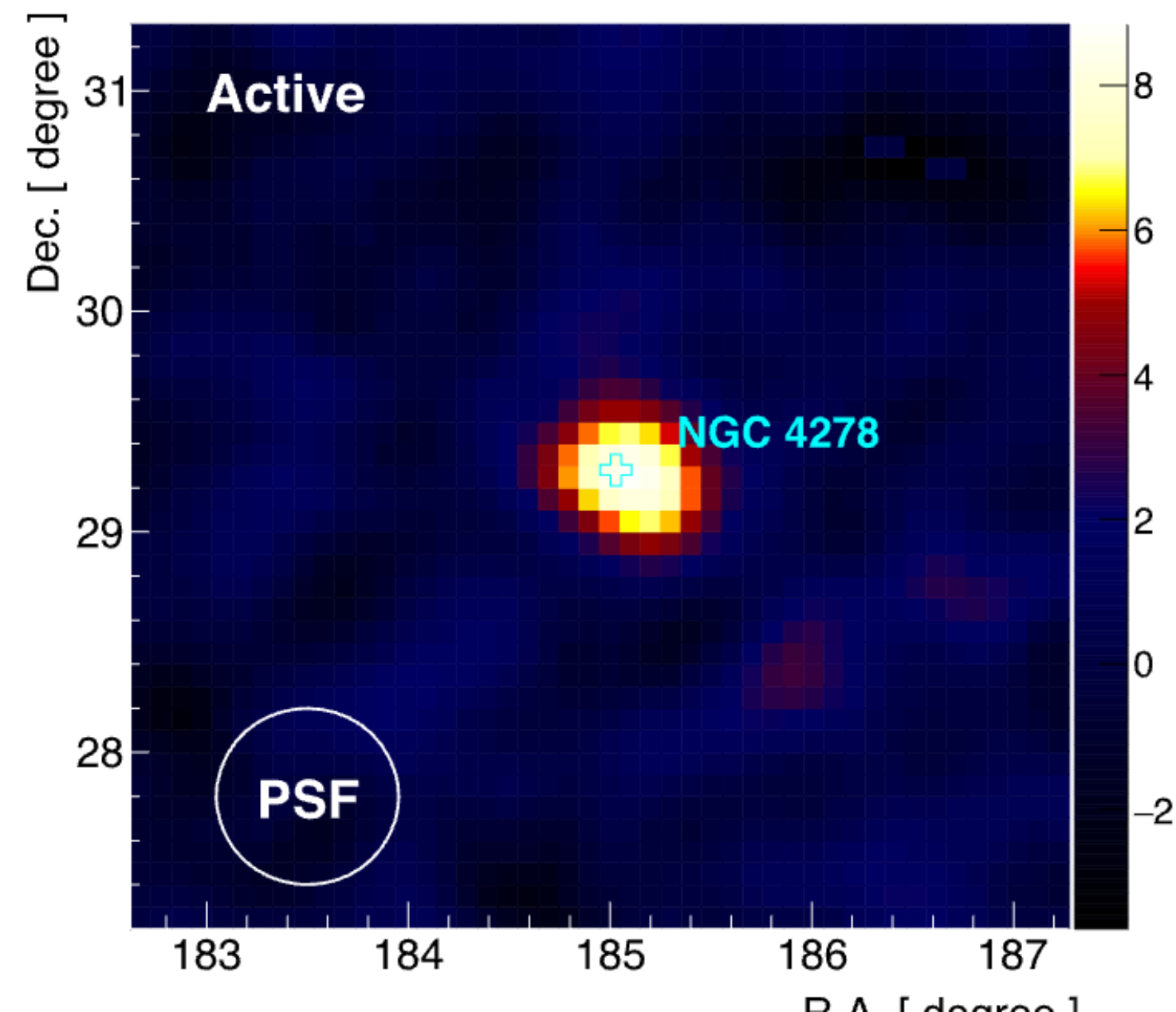
- Now detecting VHE (> 10 TeV) γ -ray emission from non-blazar, LLAGN!



(a)

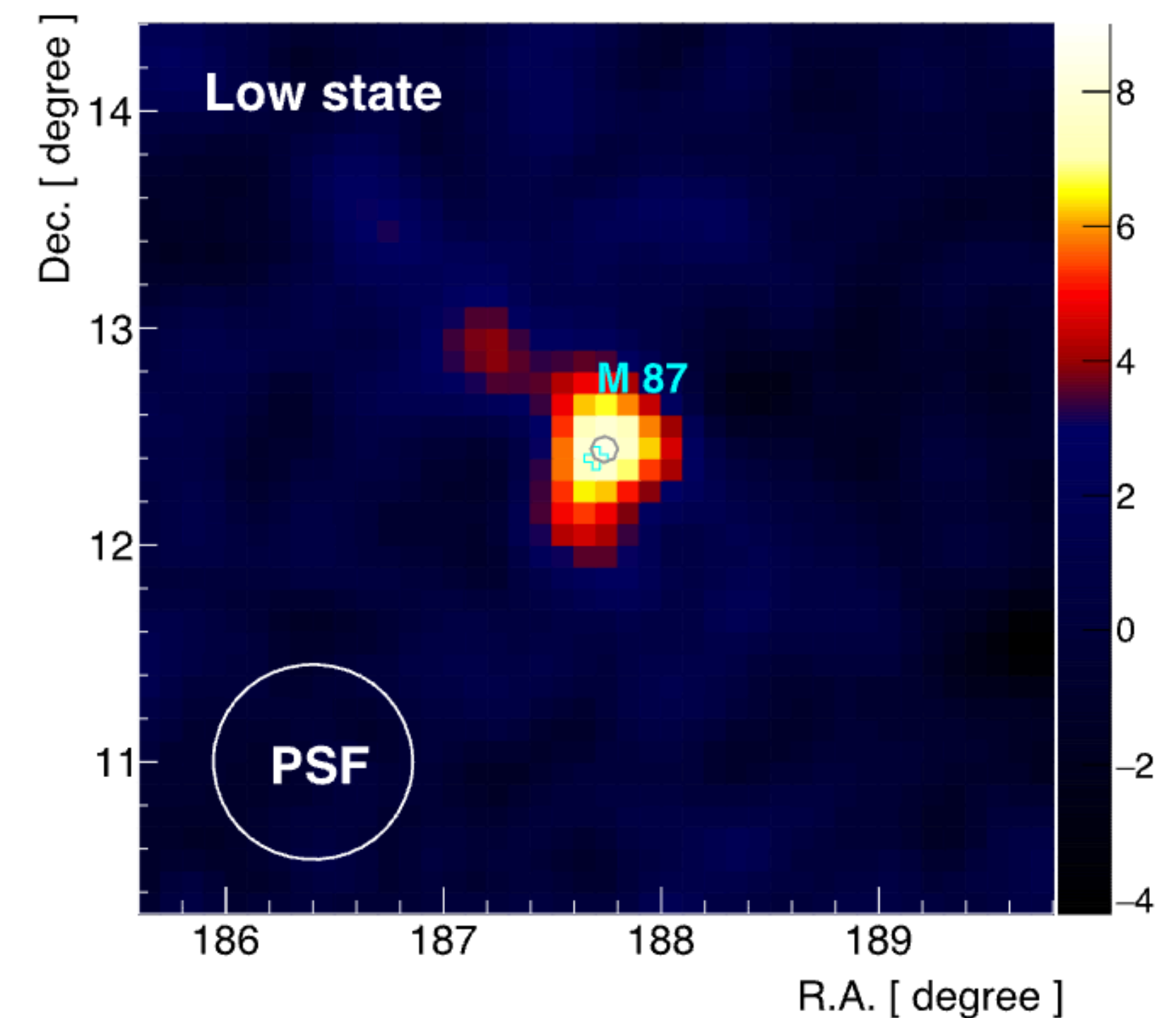
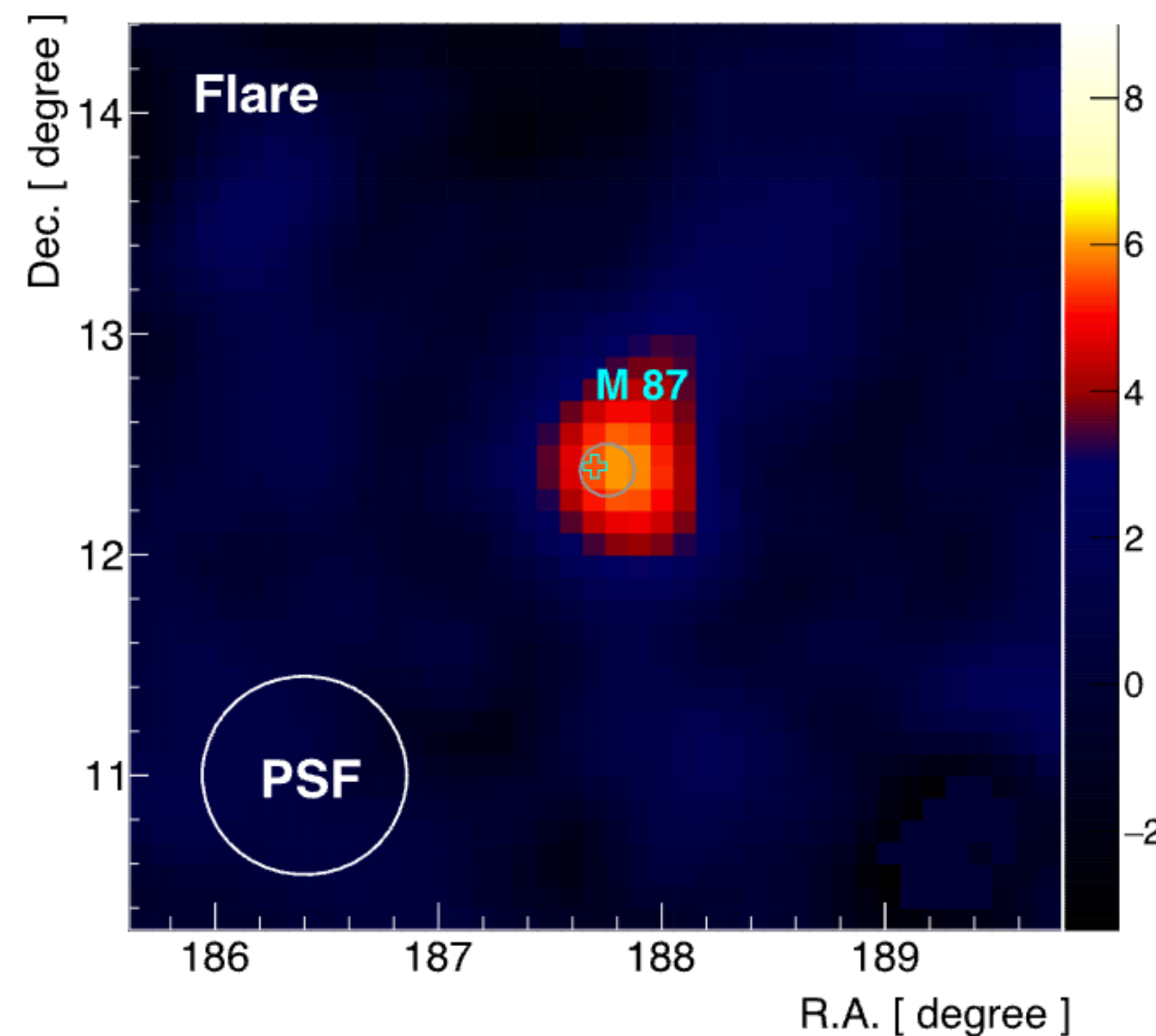
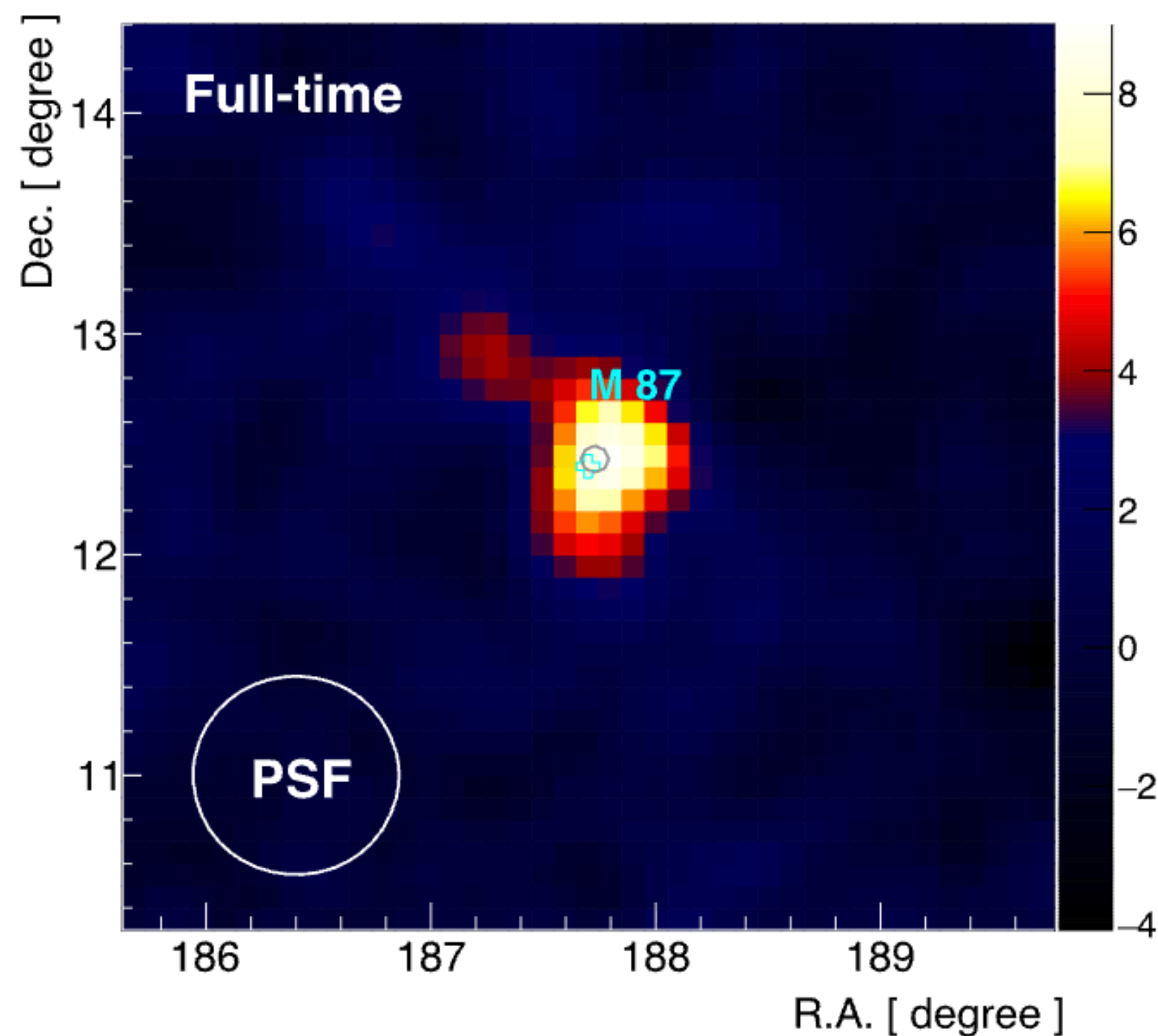
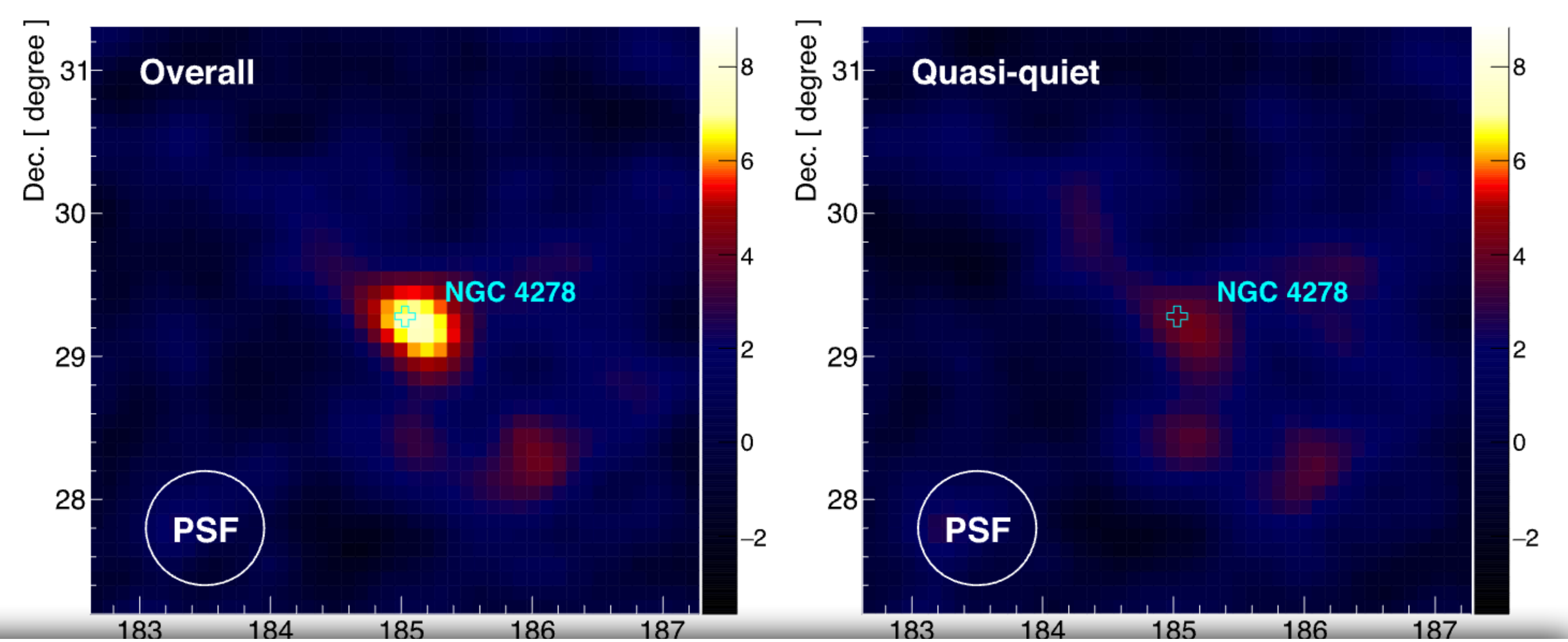


(b)



LHAASO revolution!

- Now detecting VHE (> 10 TeV) γ -ray emission from non-blazar, LLAGN!



Opens up an amazing synergy with global mm-VLBI (EHT/GMVA)

4/2019 & 5/2022: first images supermassive black hole in the heart of a galaxy (then)

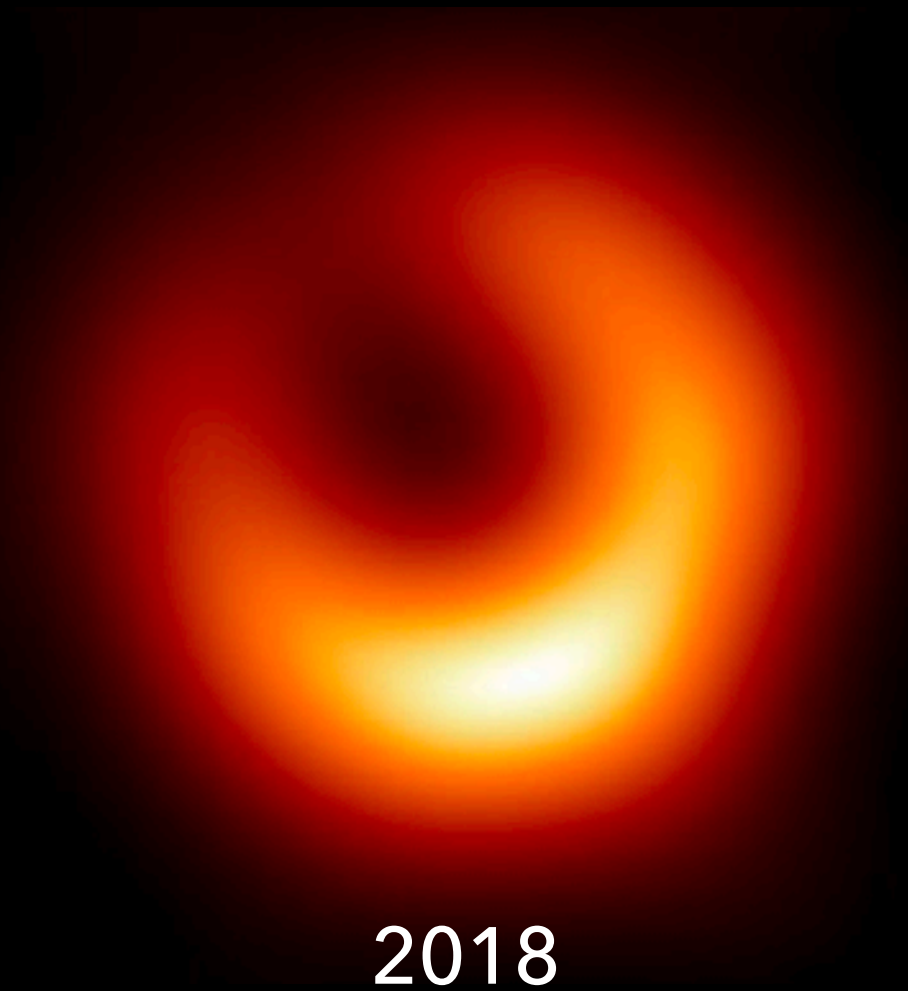
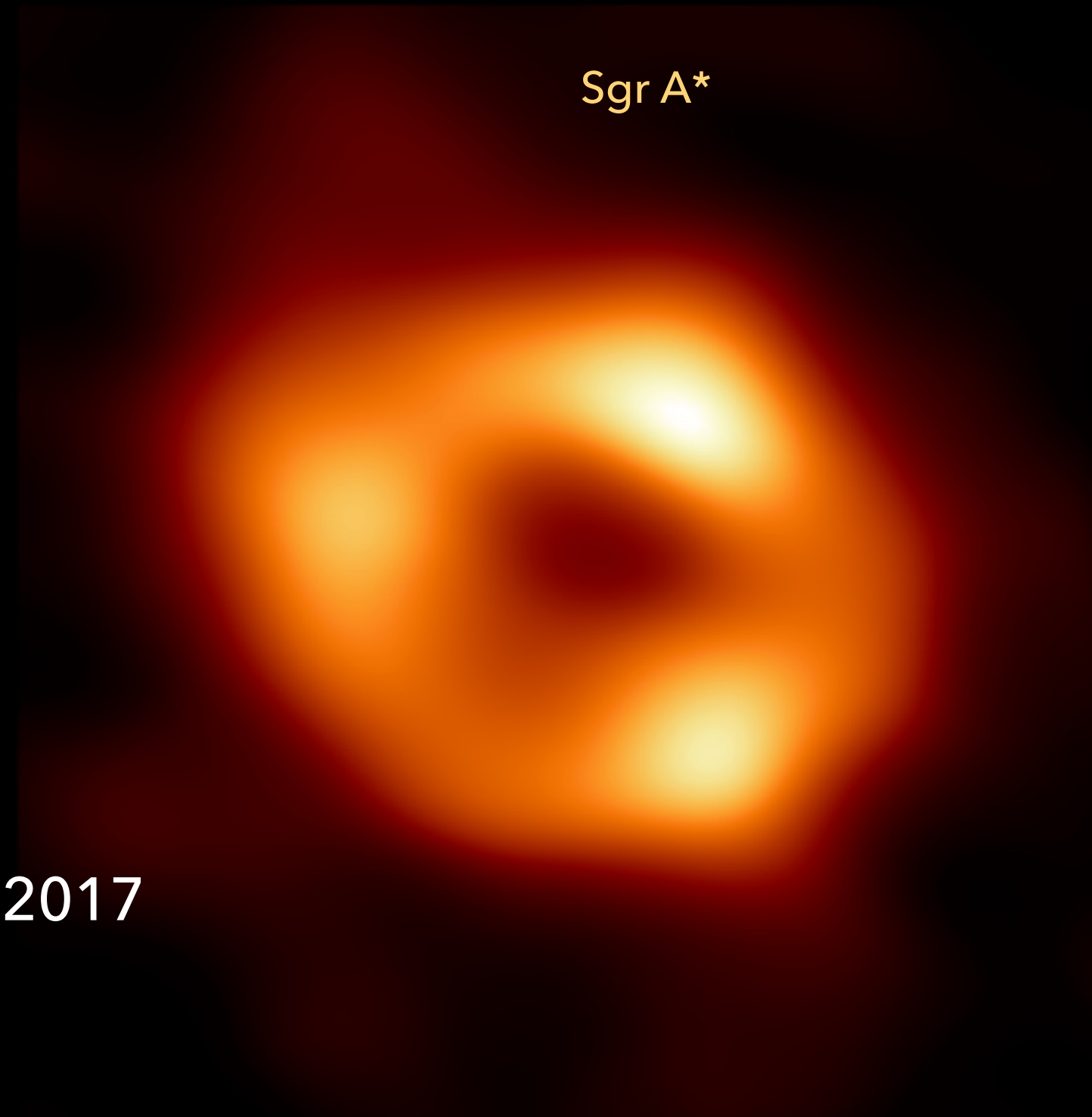
Now!!

M87*

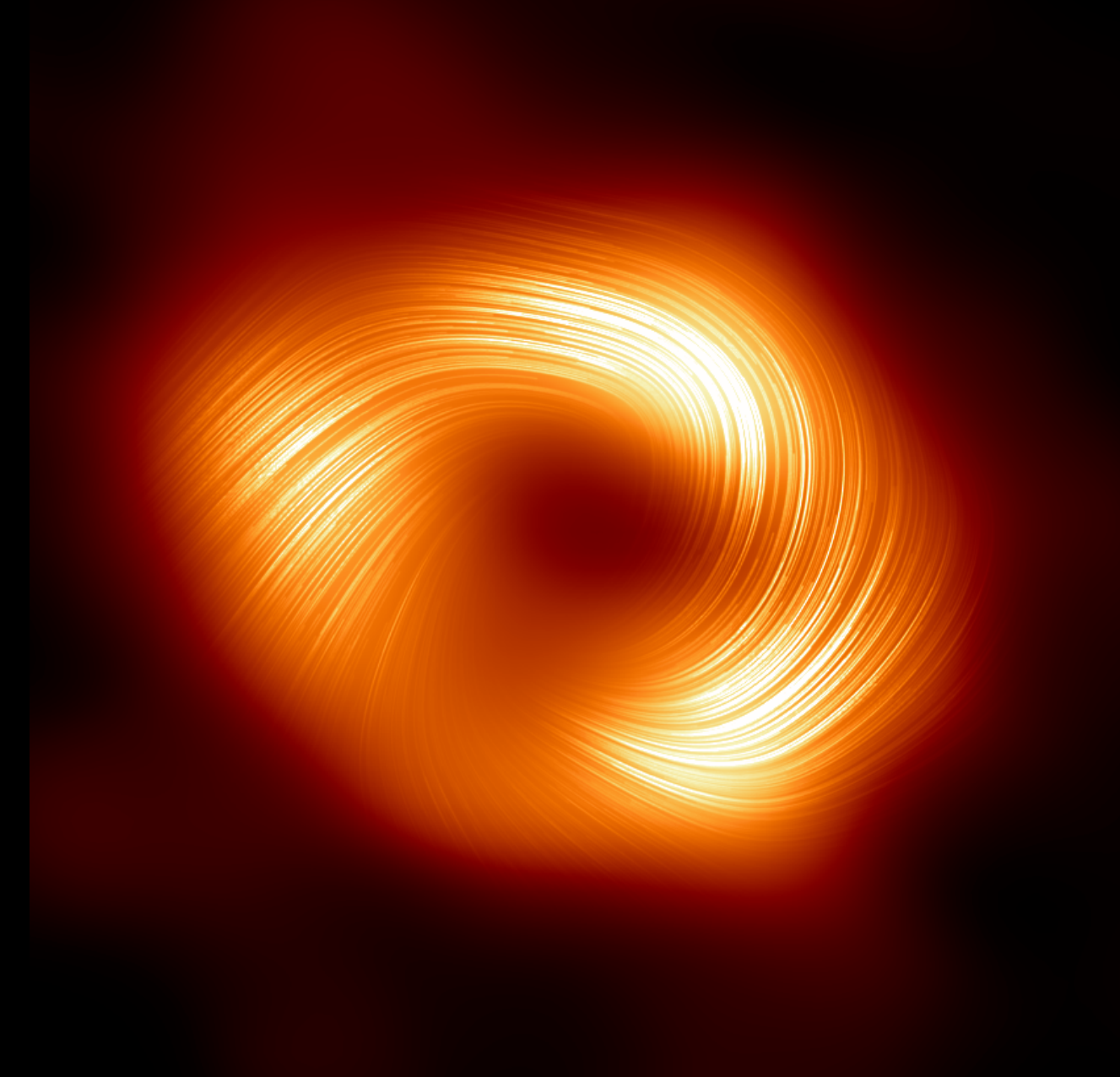


2017

Sgr A*

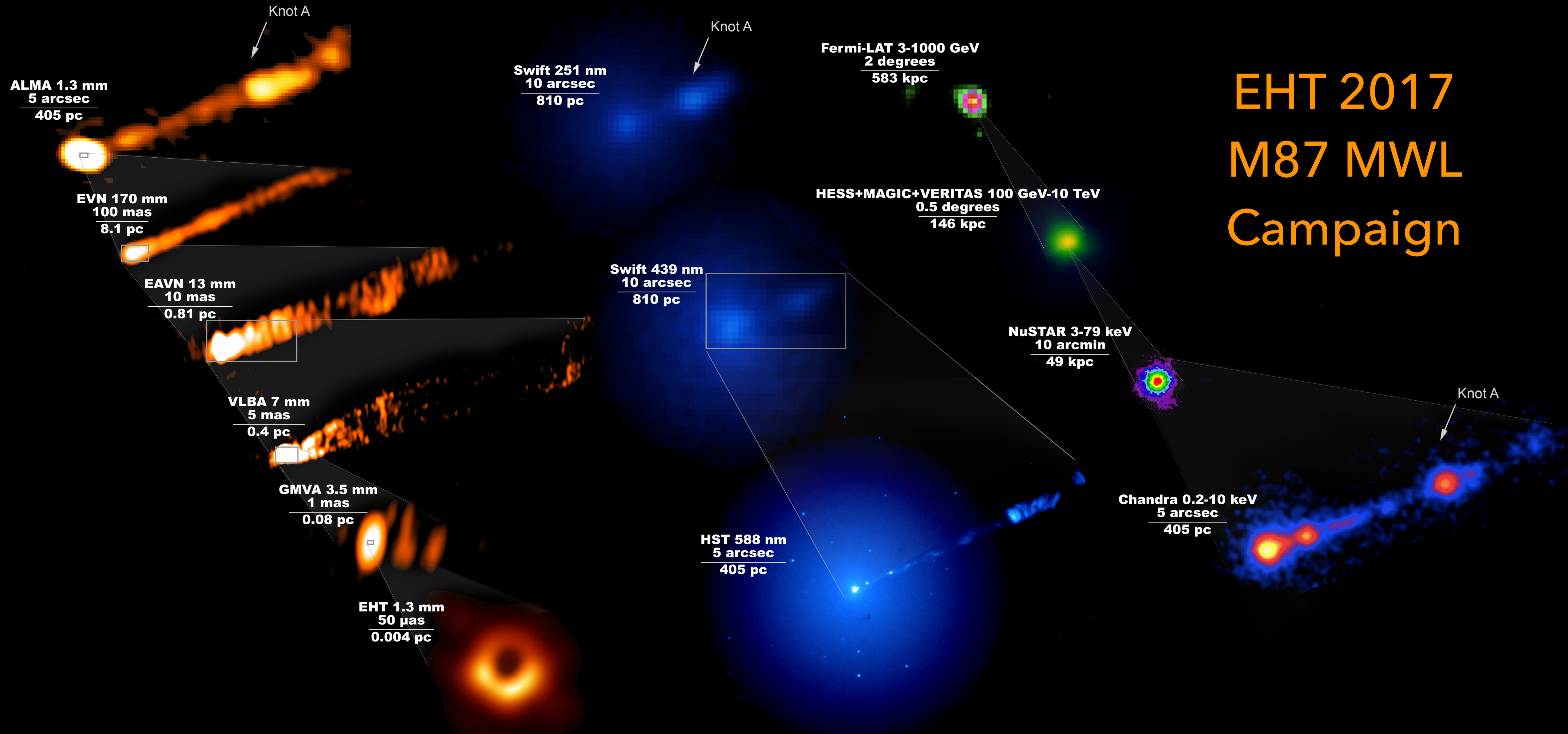


2018

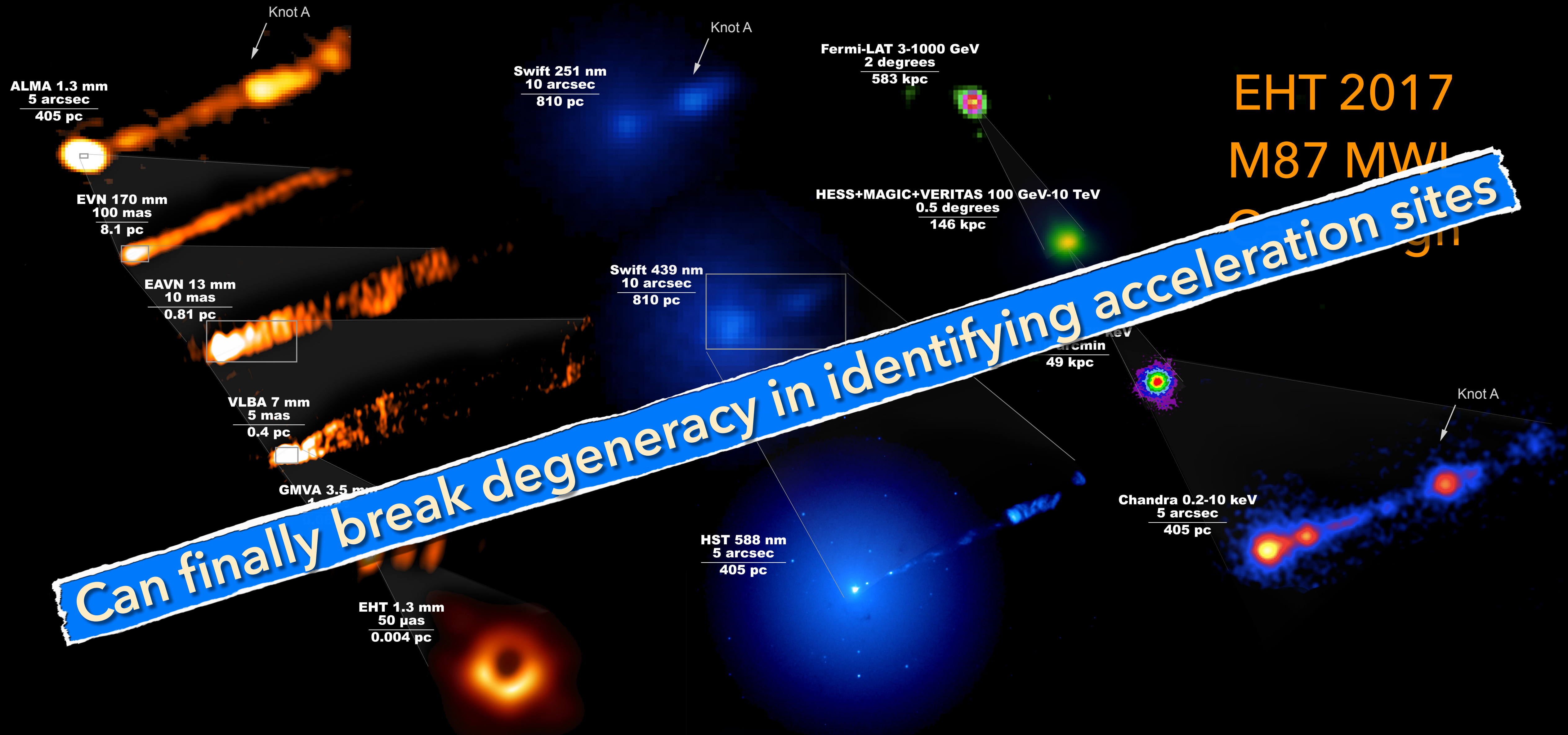


Models need to explain not only images but also MWL spectra

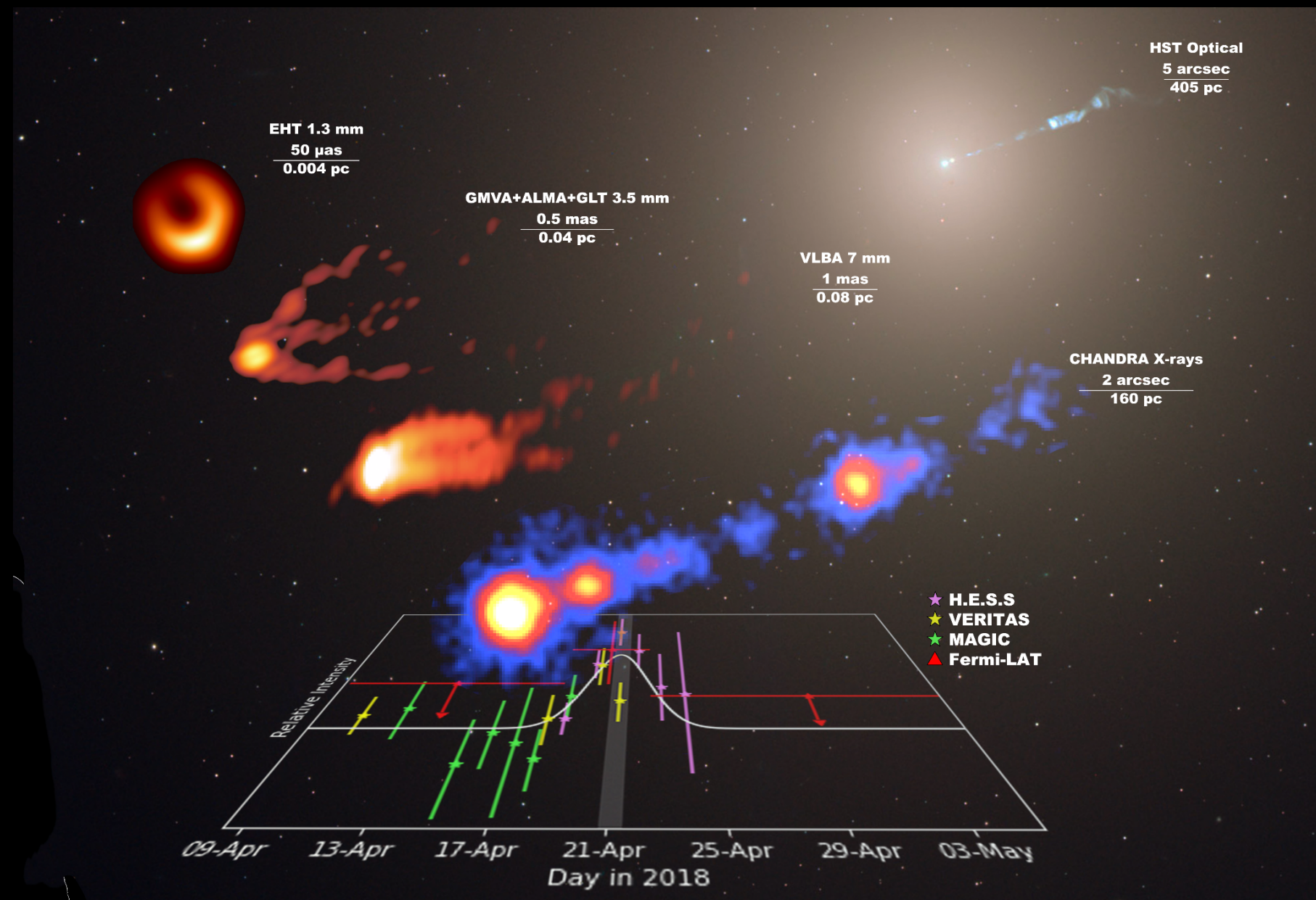
EHT 2017 M87 MWL Campaign



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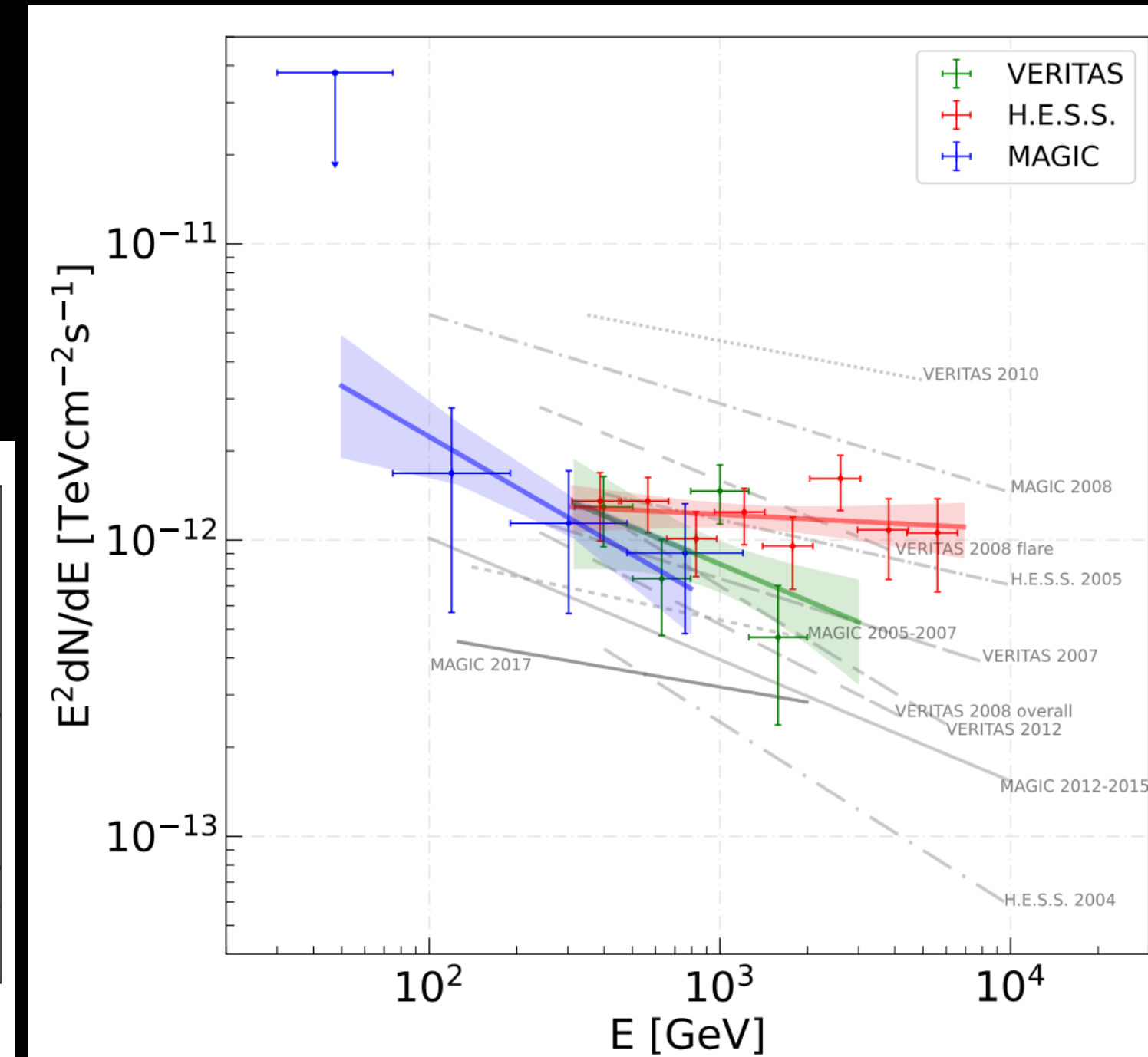
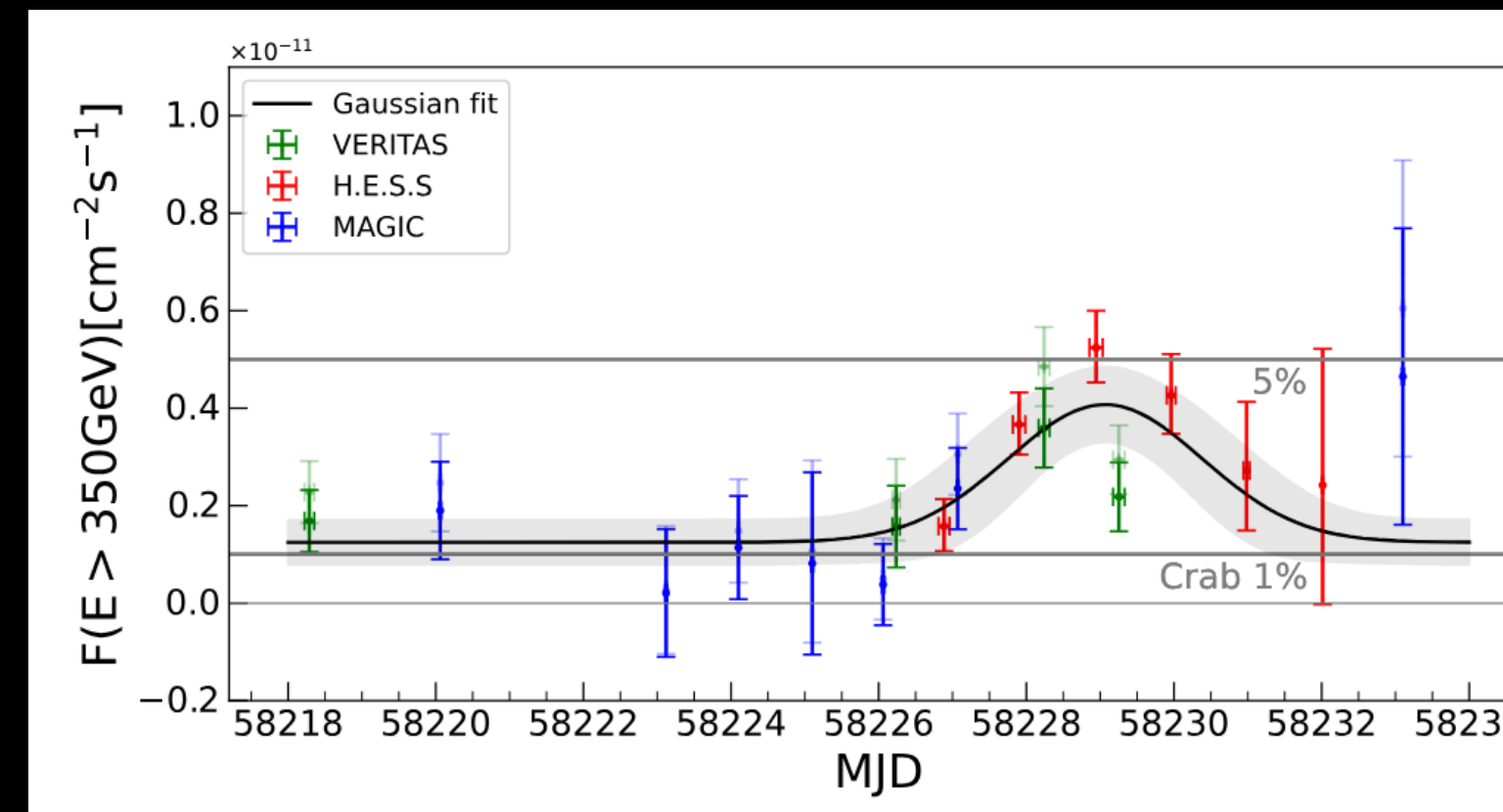


EHT M87 2018 MWL campaign: first VHE γ -ray flare!



M87* MULTIWAVELENGTH CAMPAIGN 2018

- Most significant γ -ray flare since 2010!



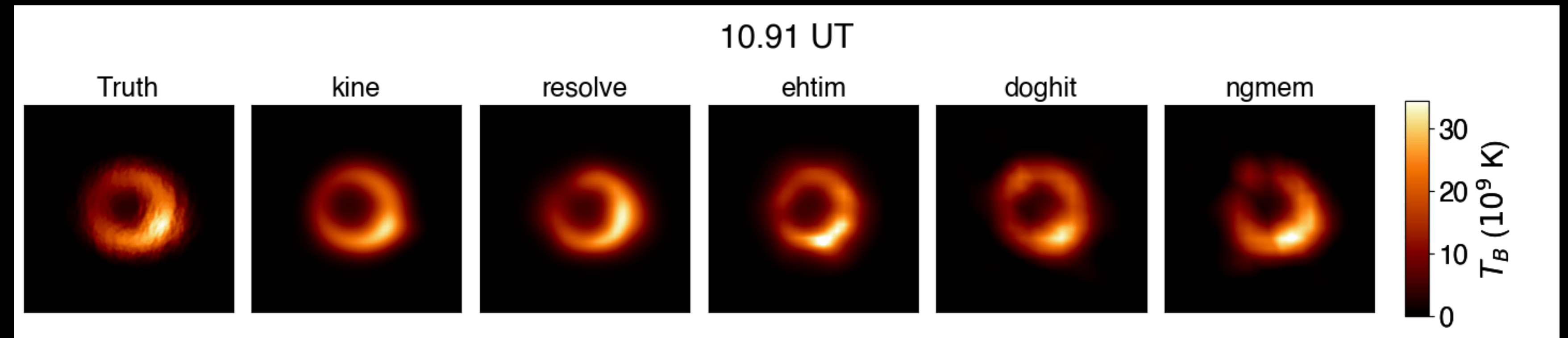
- Offers chance to test particle acceleration scenarios via an unprecedented set of constraints \Rightarrow value of monitoring, link to neutrino results & puzzle over UHECRs



Pilot for CTA AGN KSP: 2026 EHT M87 "movie" campaign!

- ▶ We (EHTC) are conducting a groundbreaking ~2 month VLBI campaign in March/April 2026, on M87* (plus calibrators: 3C273, 3C279)!!
- ▶ Baseline schedule is every 3-4 days for 4 hours w/ALMA, some days longer with the rest of the array not including ALMA
- ▶ We have significant cm-radio VLBI through VHE γ -ray multi-wavelength coverage lined up, including Chandra, NuSTAR, Fermi, HESS, MAGIC, VERITAS and hopefully LST-1!!

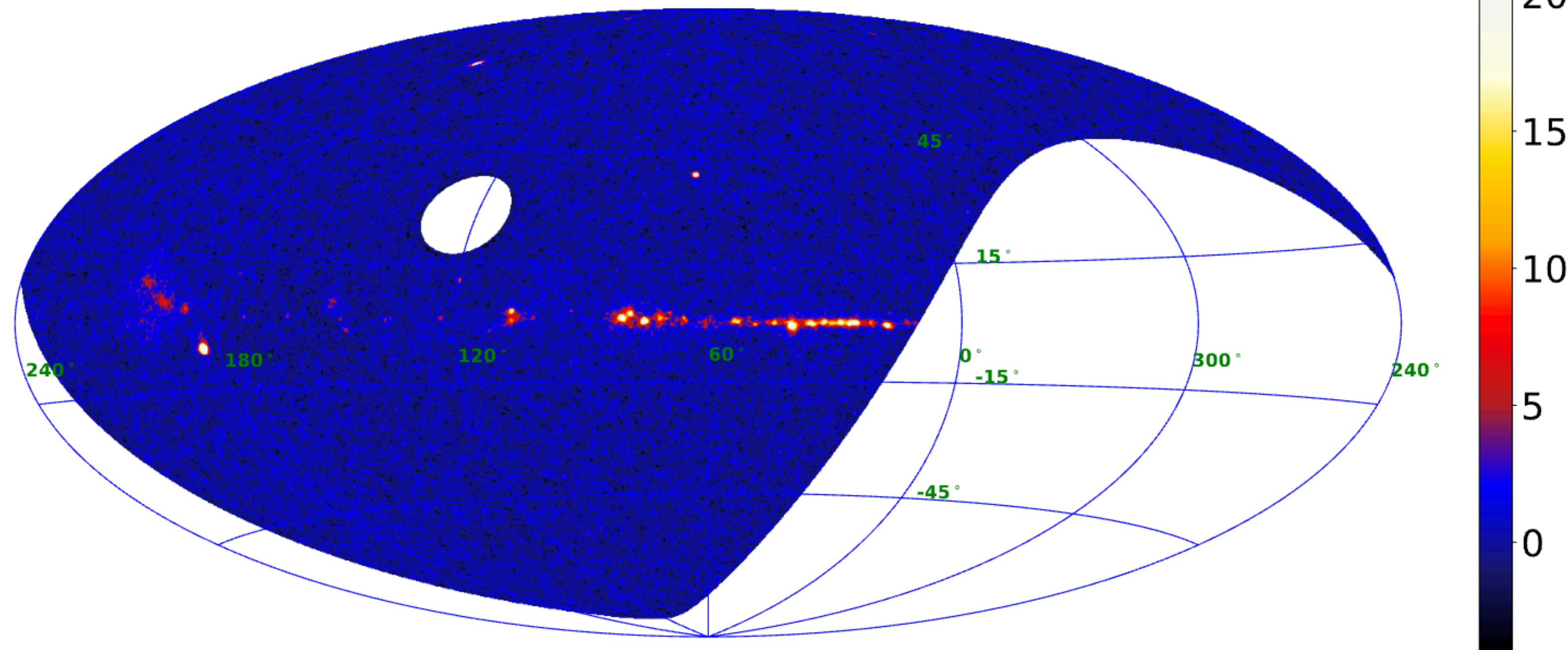
- ▶ Sgr A* gives us some idea what to expect!



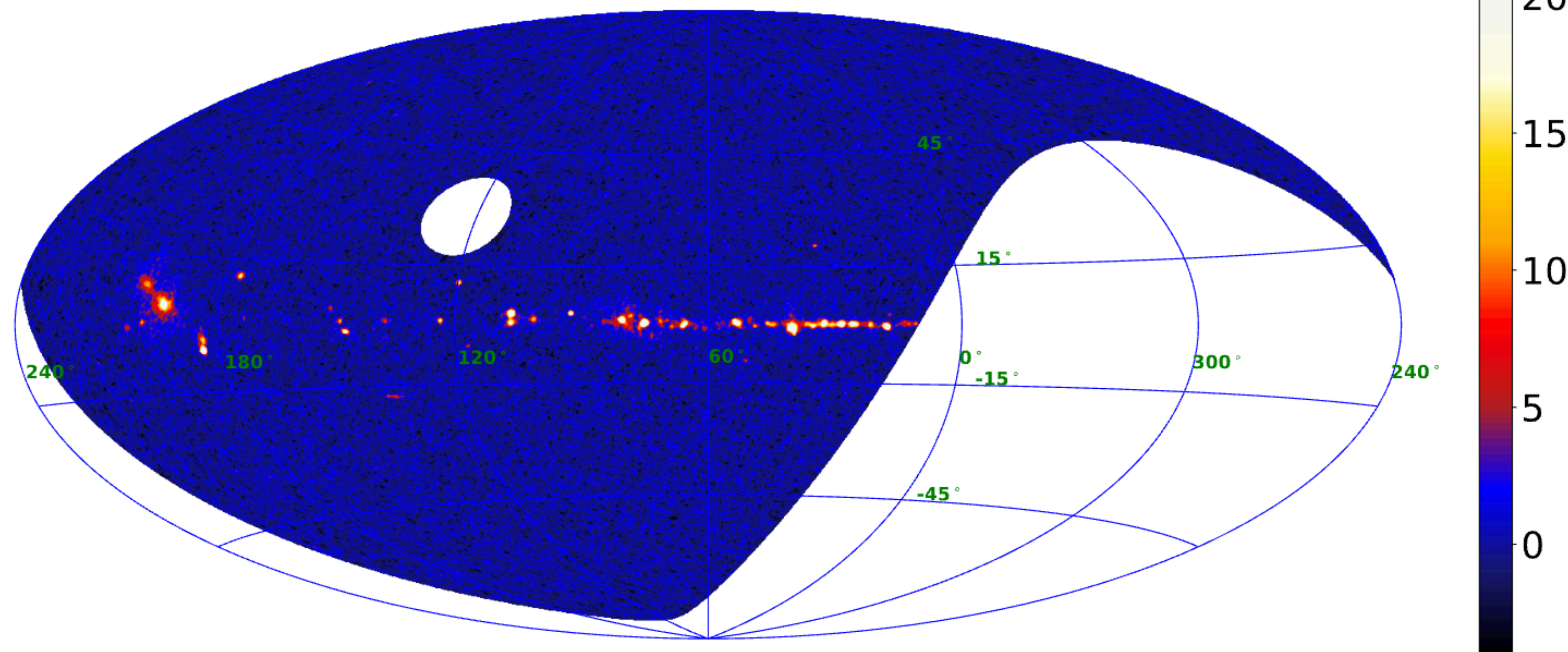
LHAASO revolution II

- ▶ >100 galactic sources so far
- ▶ ~30% never seen by any other instrument!
- ▶ ~50% have $E > 100$ TeV
- ▶ Milky Way is full of (non-SNR but non-ID'd) PeVatrons!

WCDA ($1 \text{ TeV} < E < 25 \text{ TeV}$) Significance Map

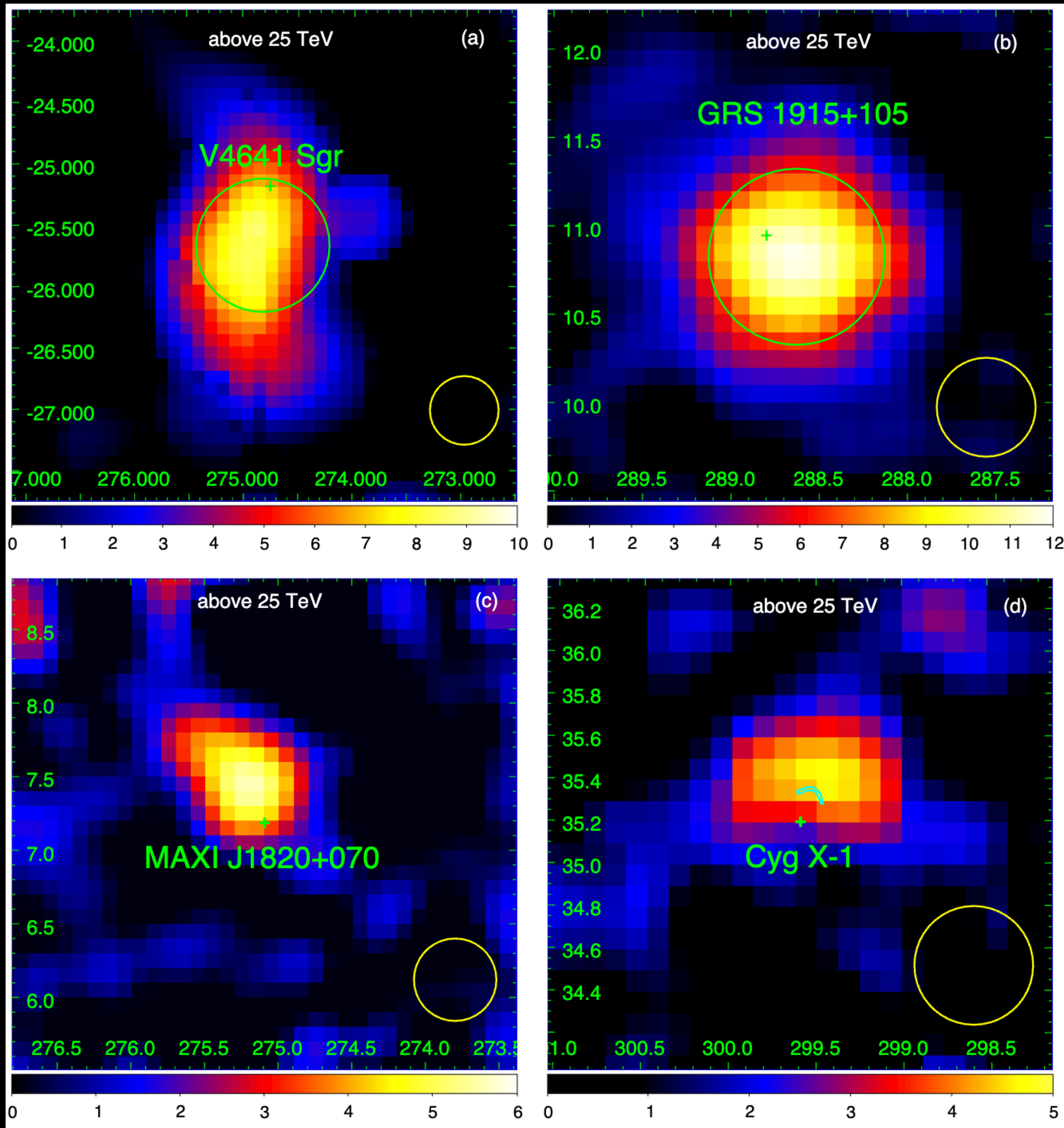


KM2A ($E > 25 \text{ TeV}$) Significance Map



LHAASO revolution II

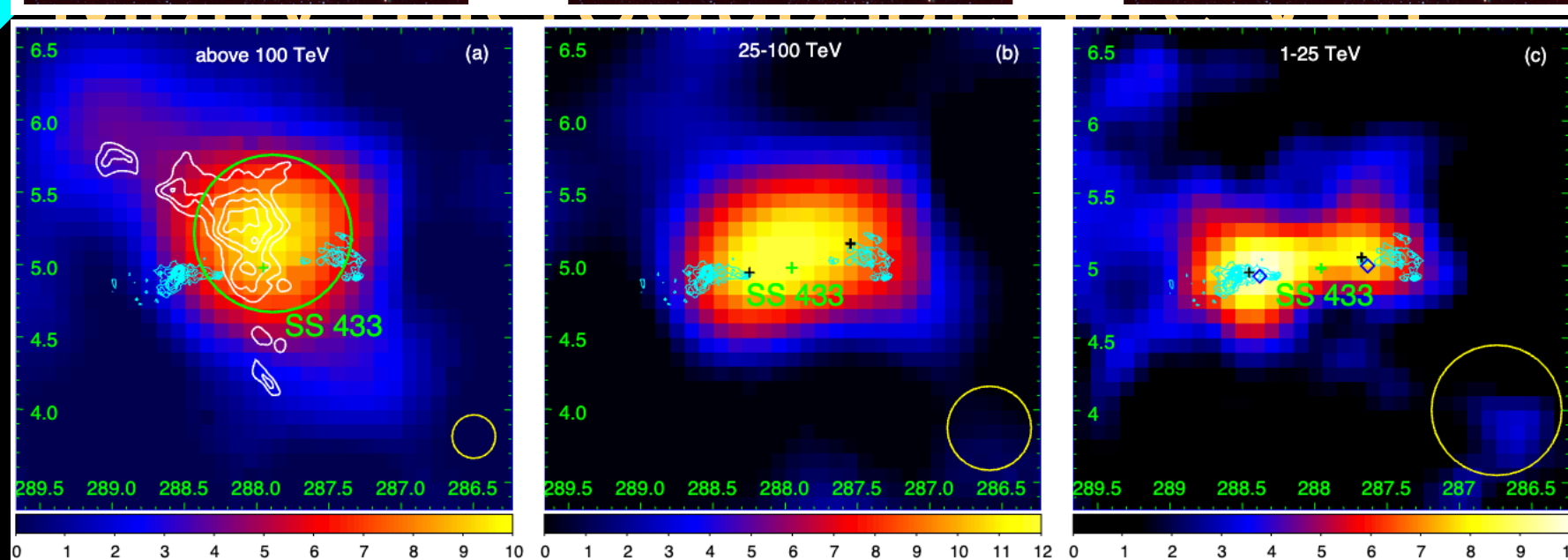
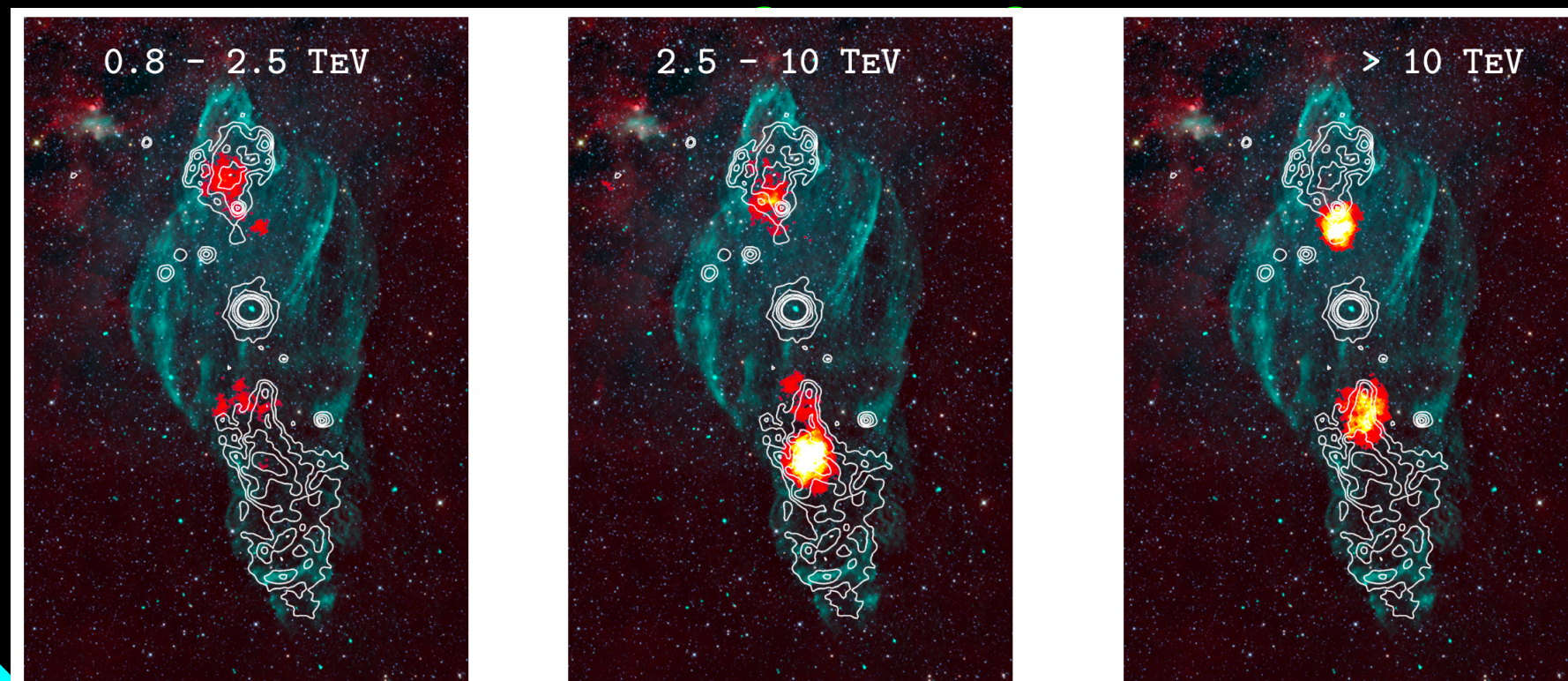
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- ▶ Many microquasars are VHE emitters, and could contribute to the GC CR population (Pevatrons?)!!



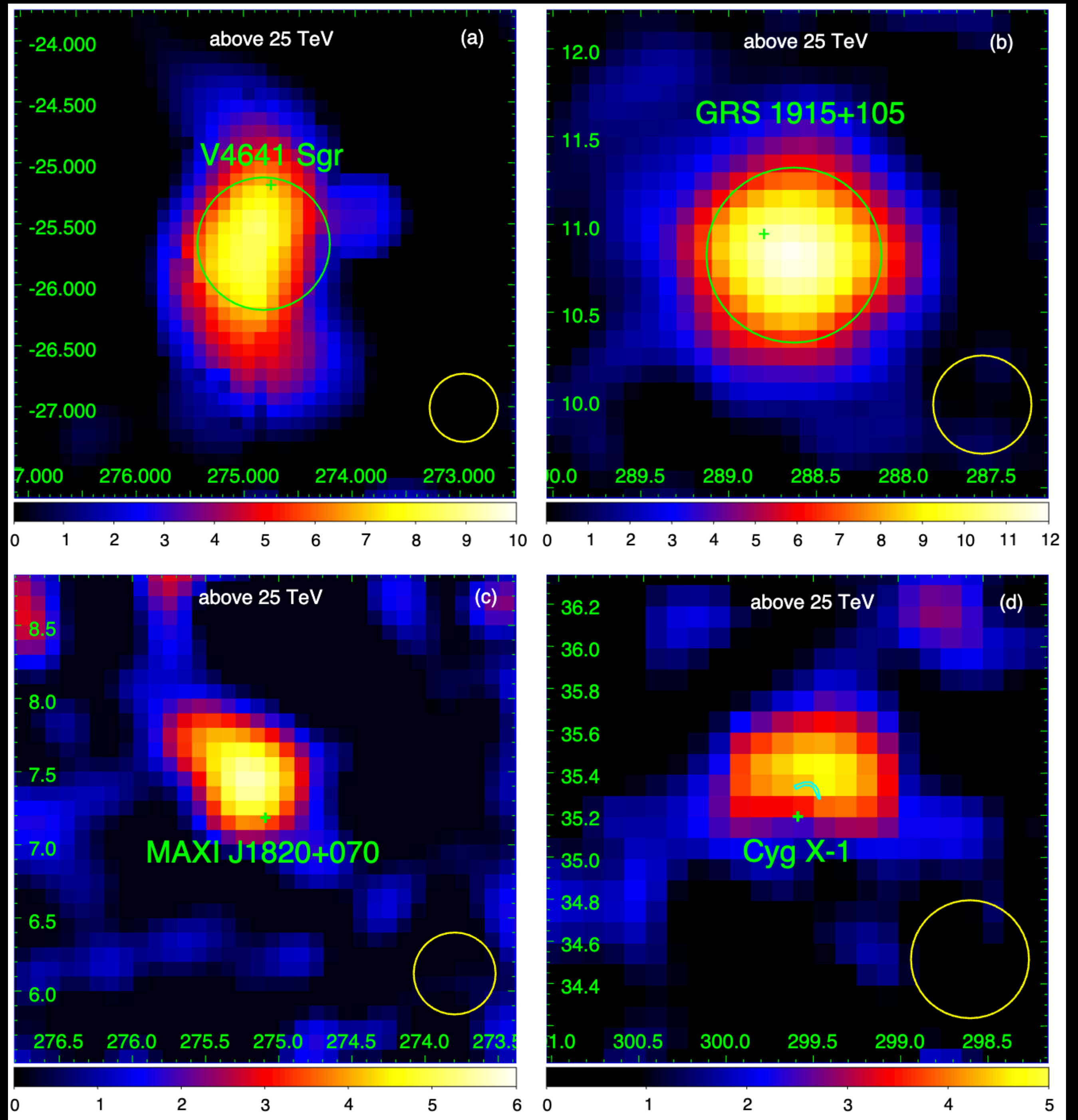
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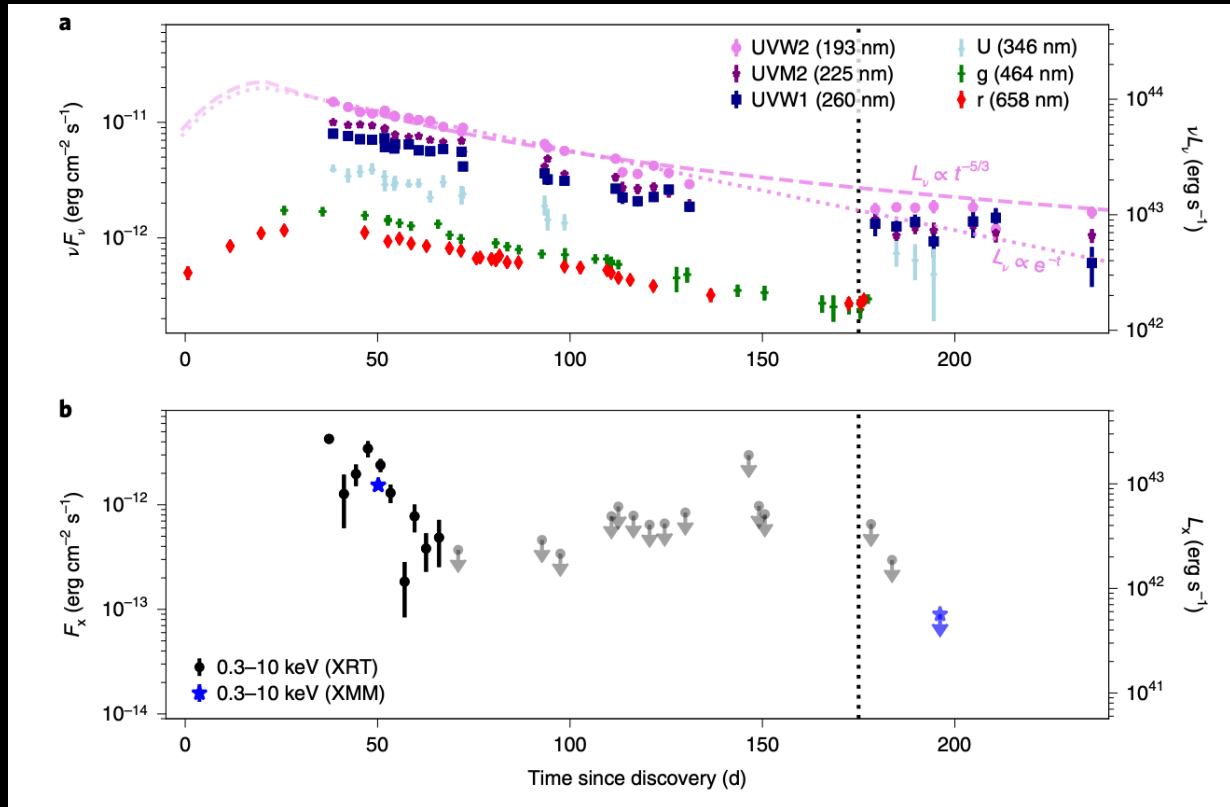
SS 433: **L.Olivera-Nieto++** 2021, 2022; HESS Collab, 2023



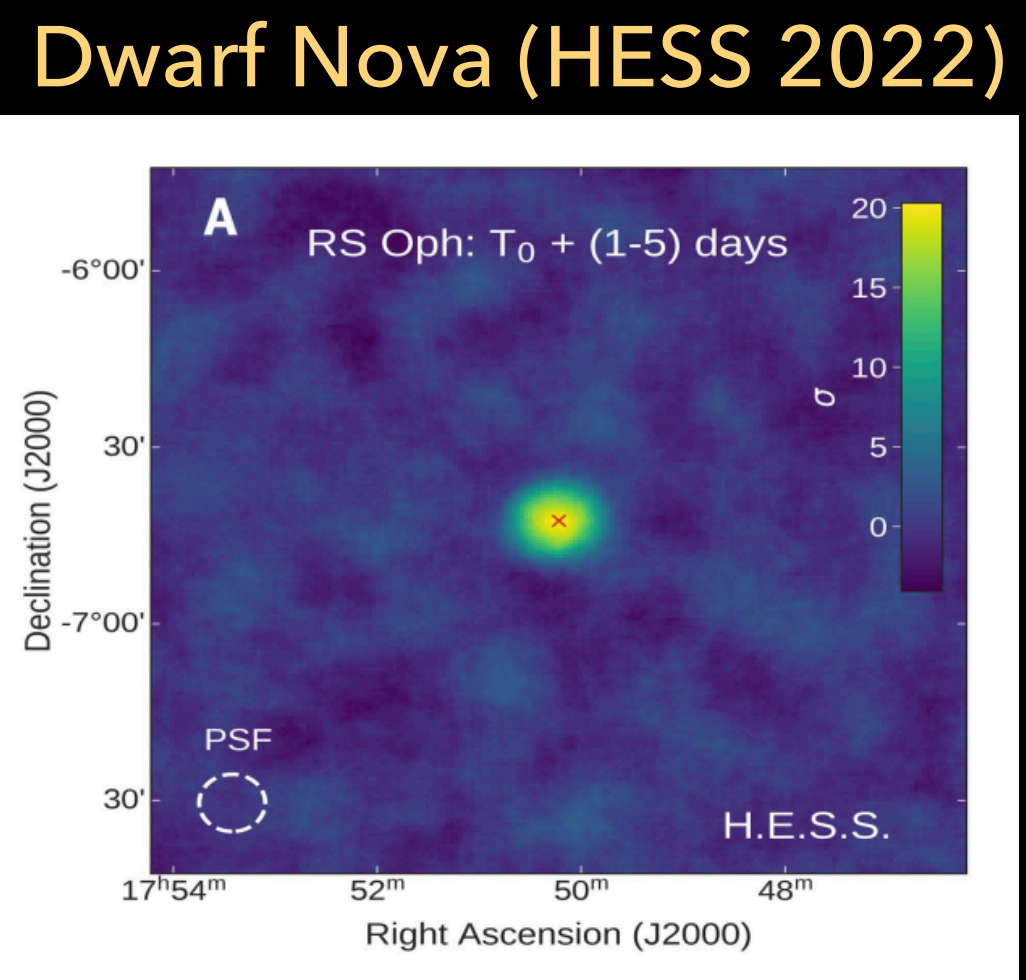
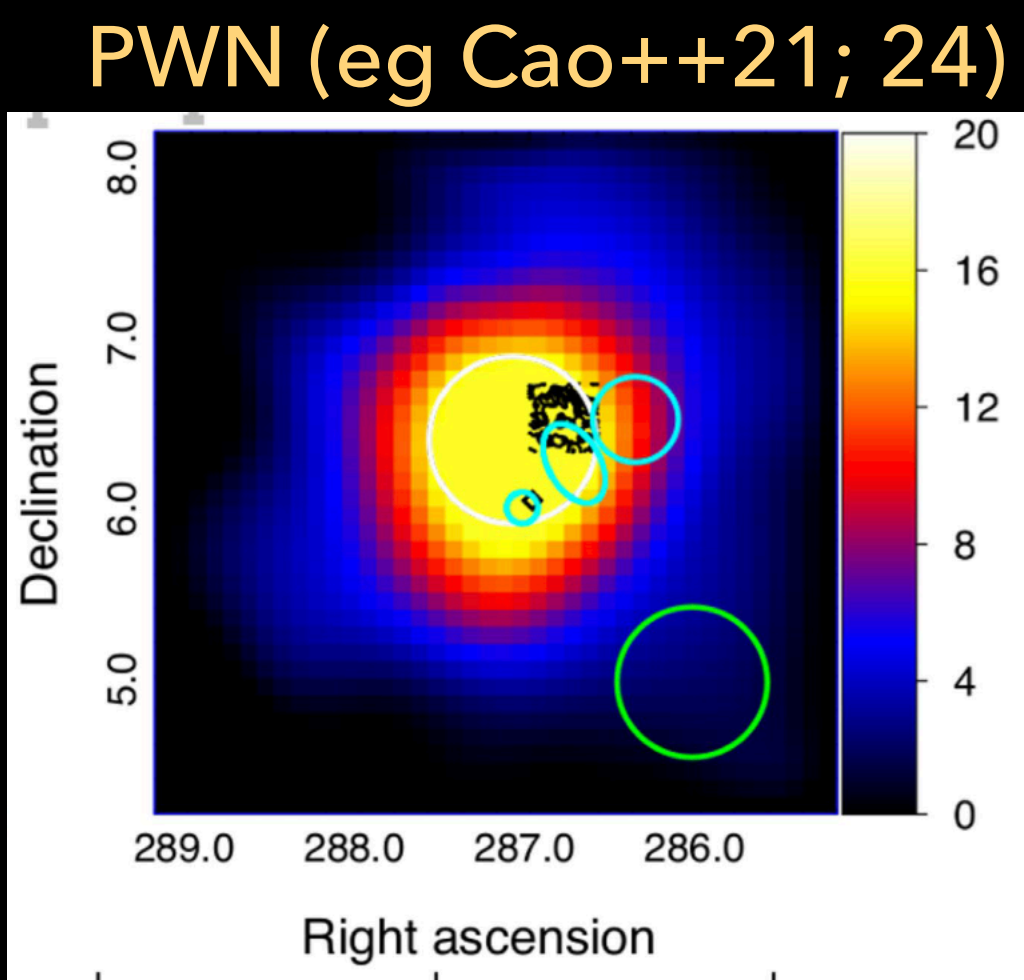
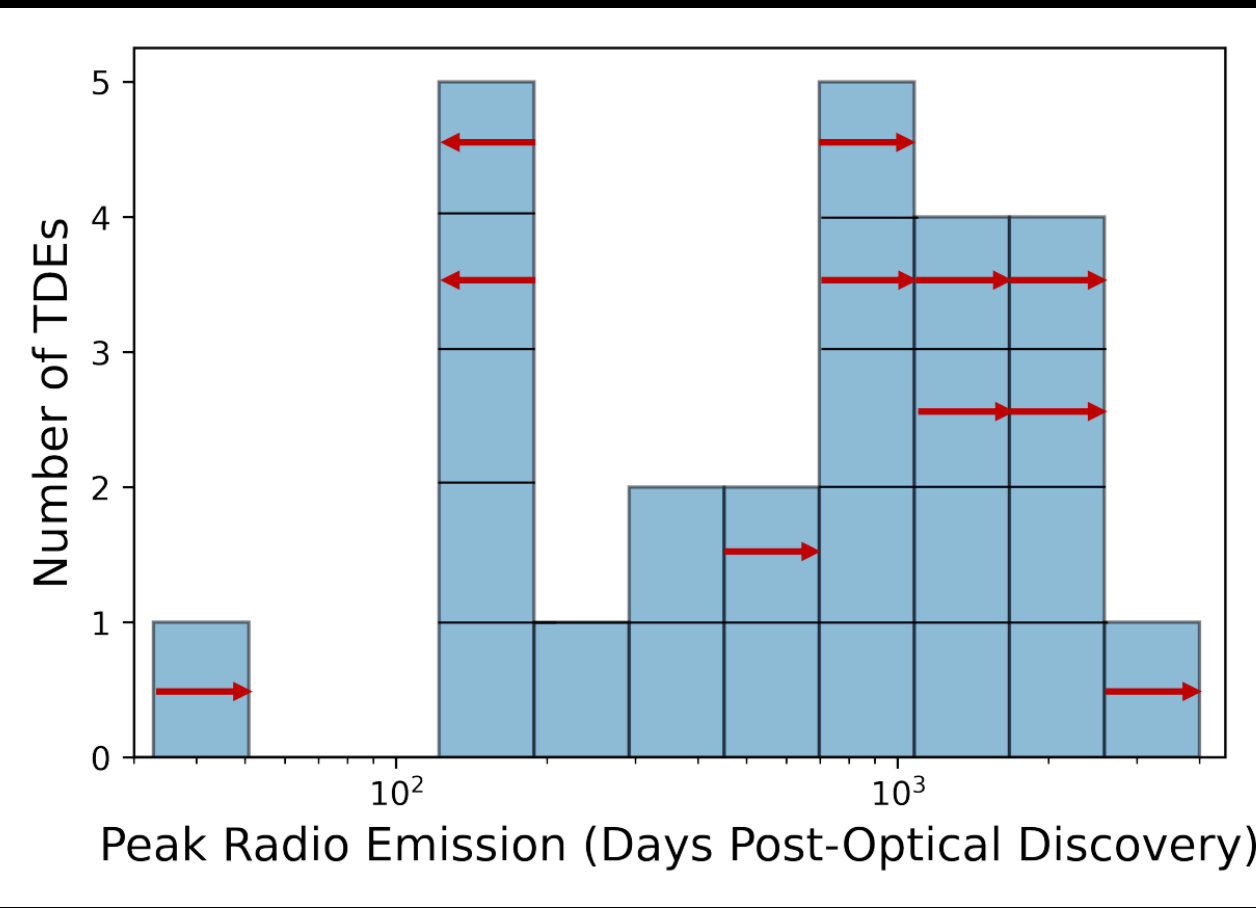
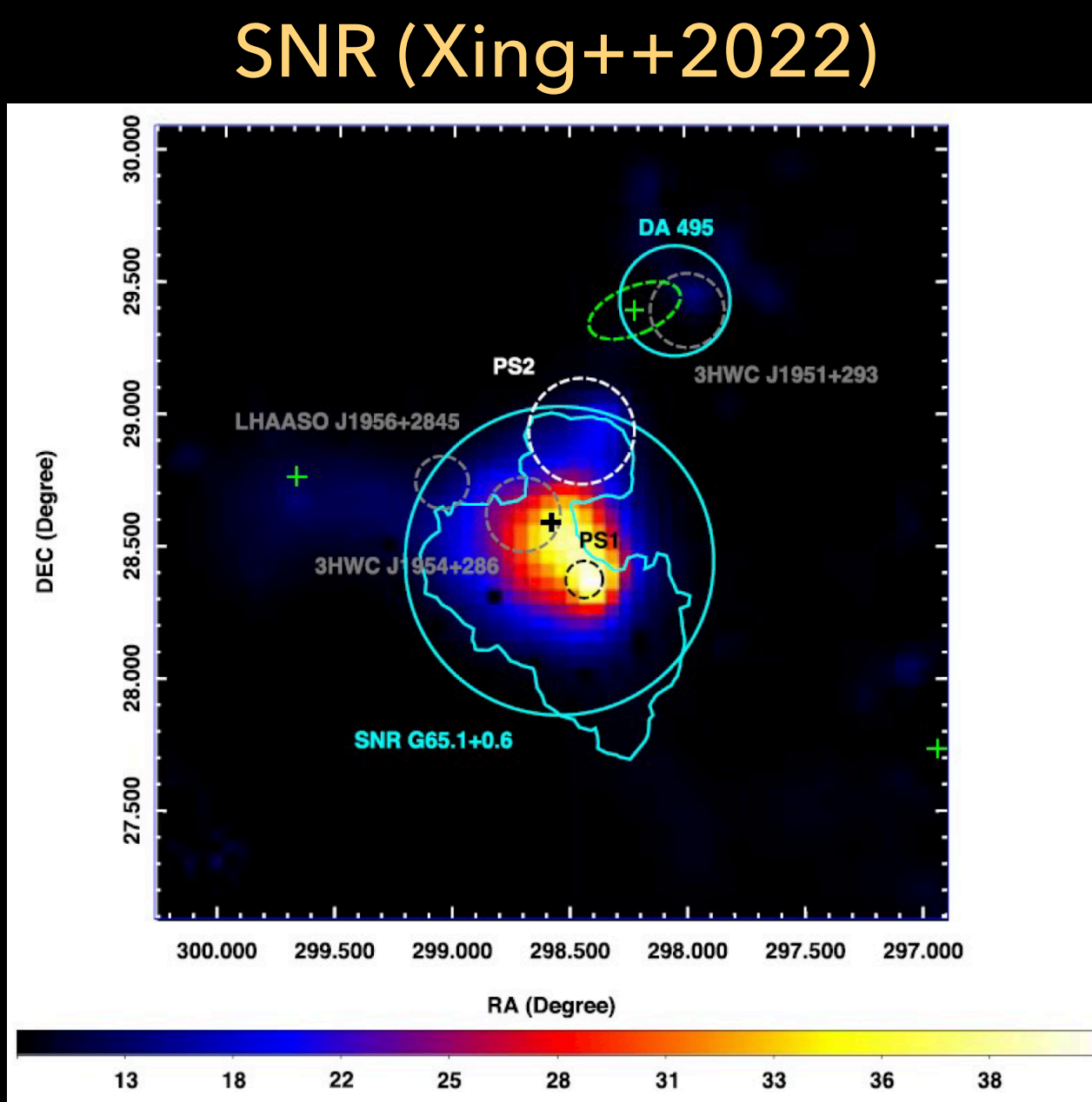
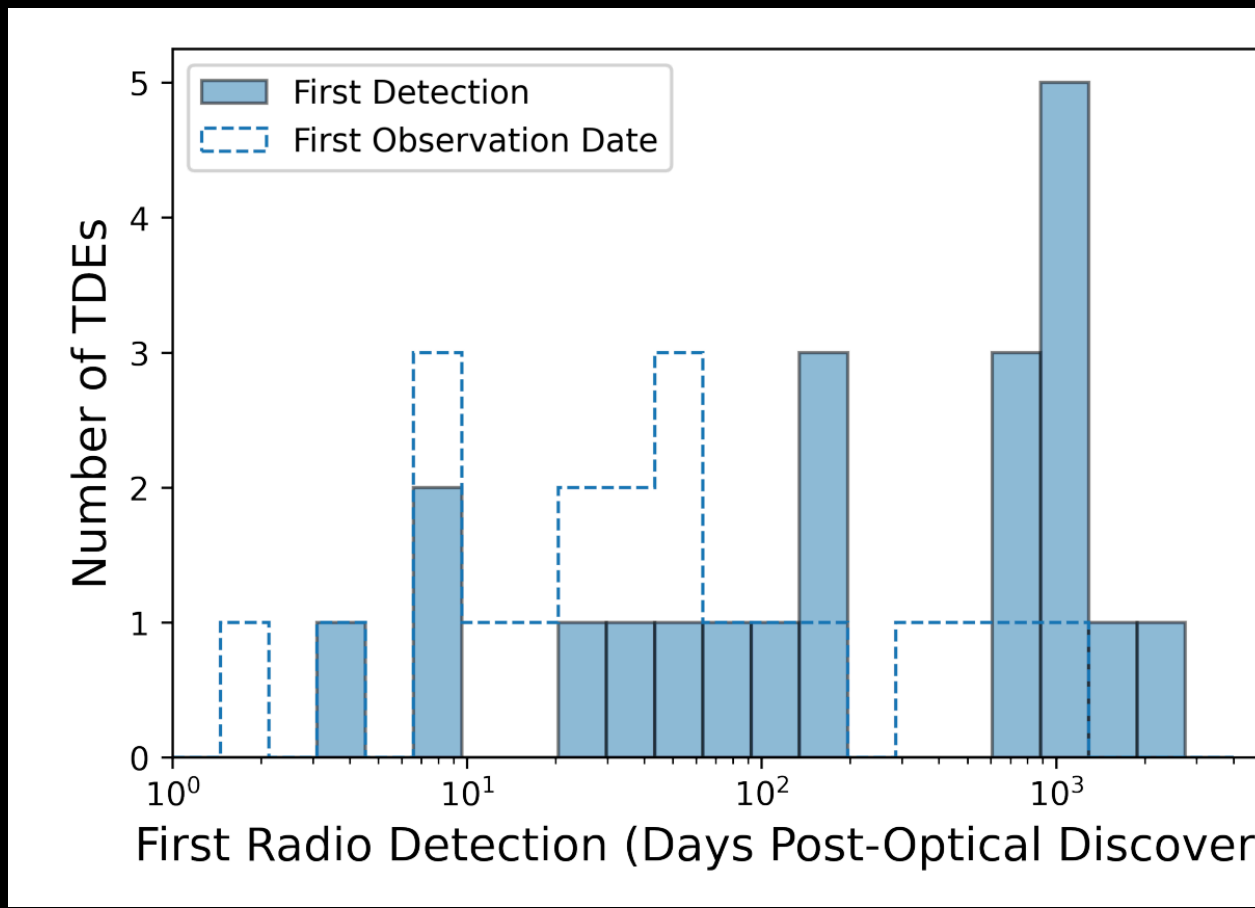
(LHAASO Collaboration; Cao++23; Cao++24 x2)



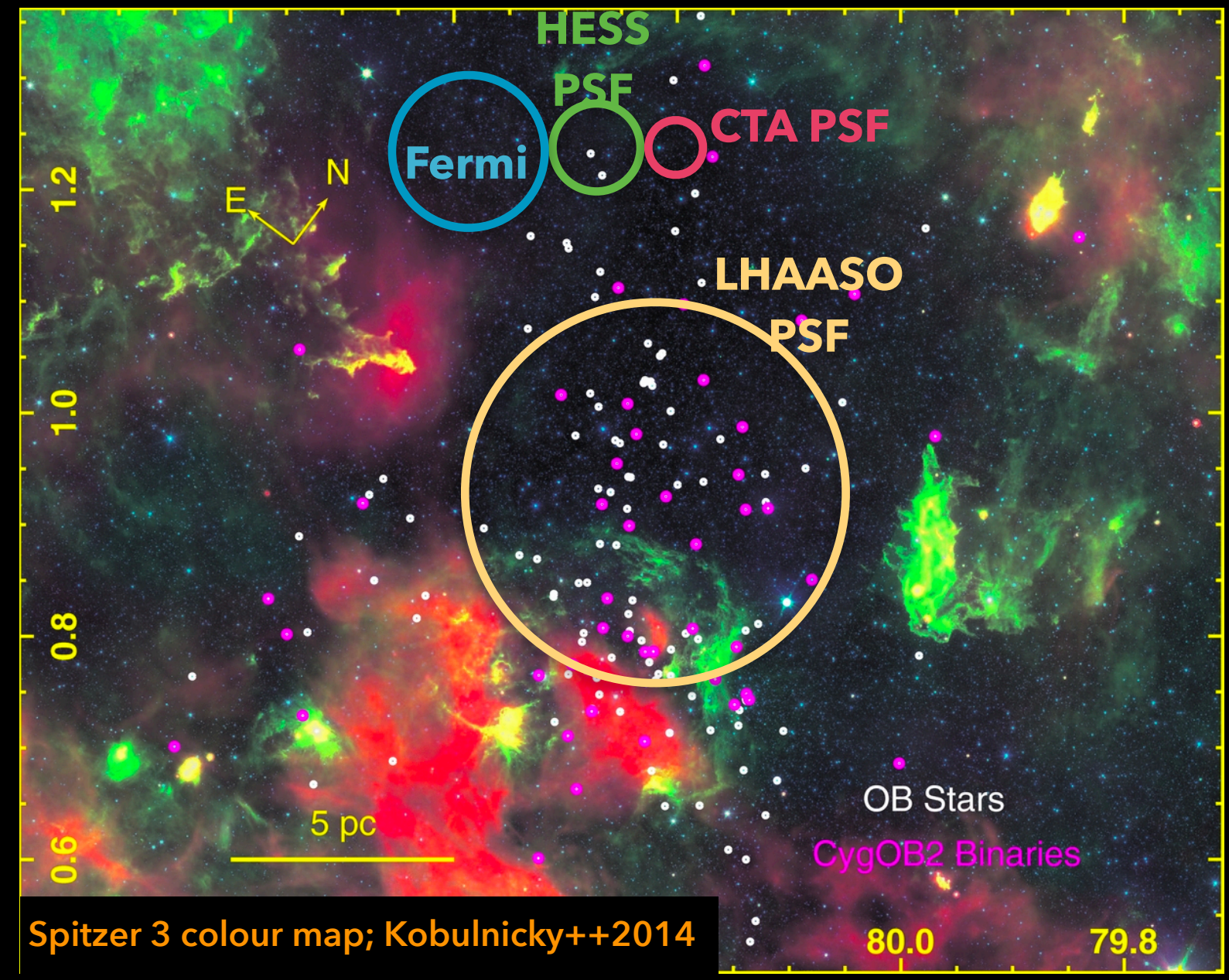
Rapidly evolving picture: many even previously unsuspected objects are now potential CTAO and IceCube/KM3NeT targets



TDEs (eg. Stein, v. Velzen++21; Cendes++24)

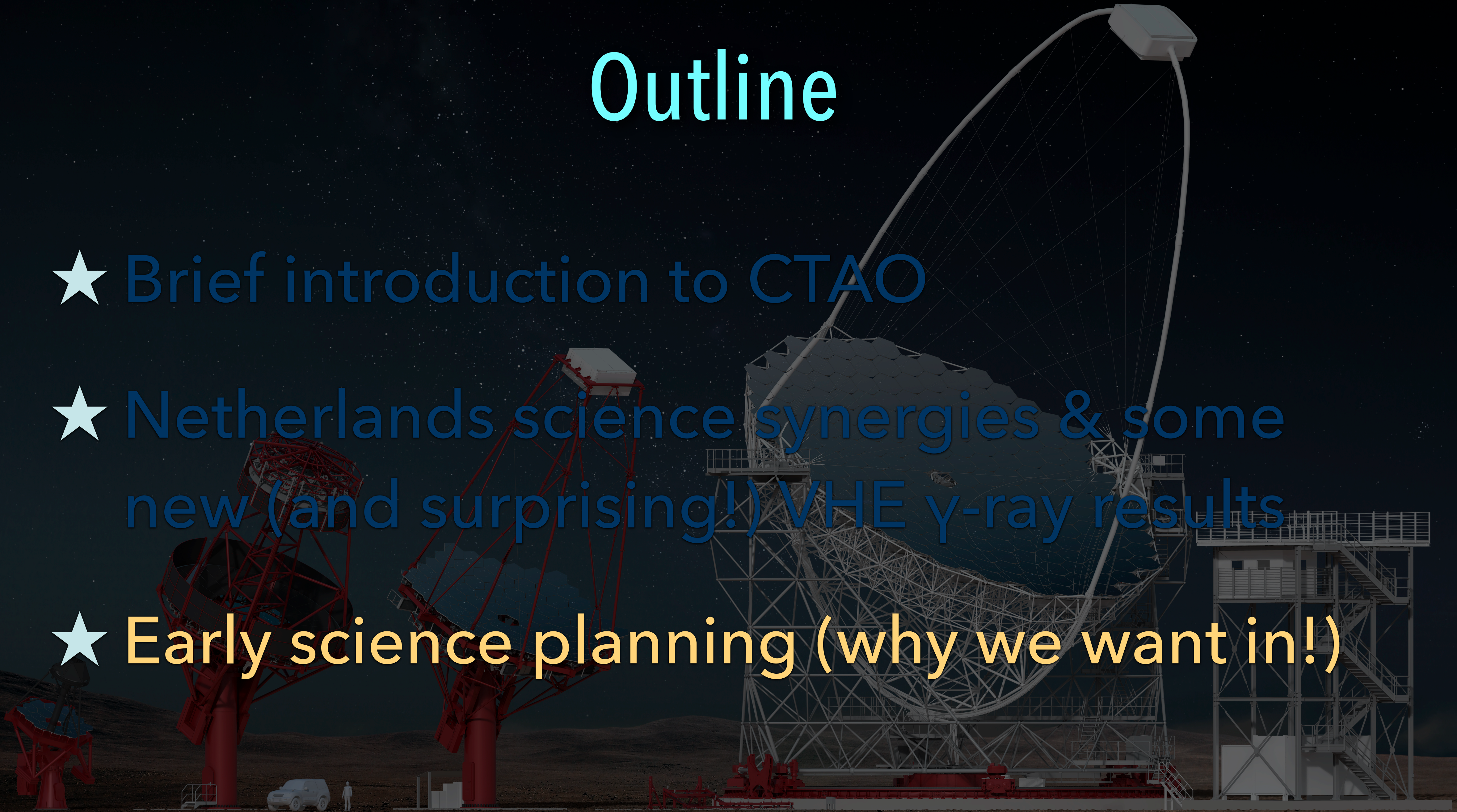


OB associations/young stellar clusters (Cao++21;24)

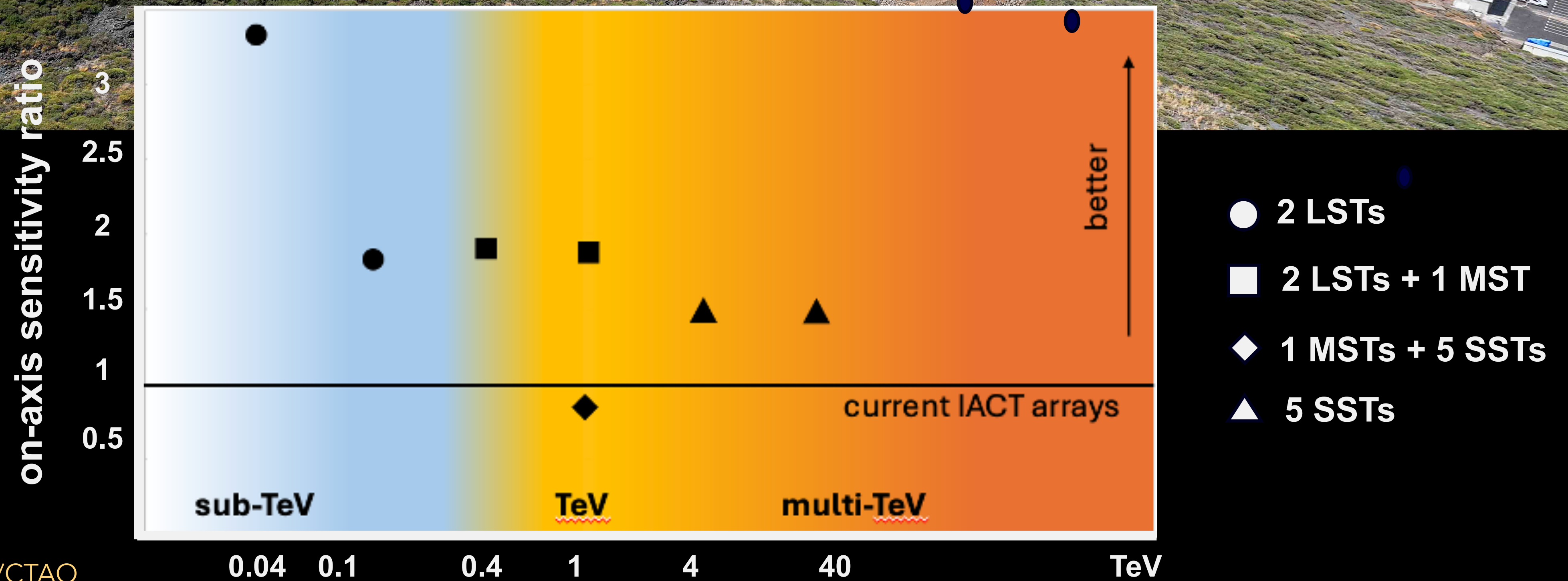
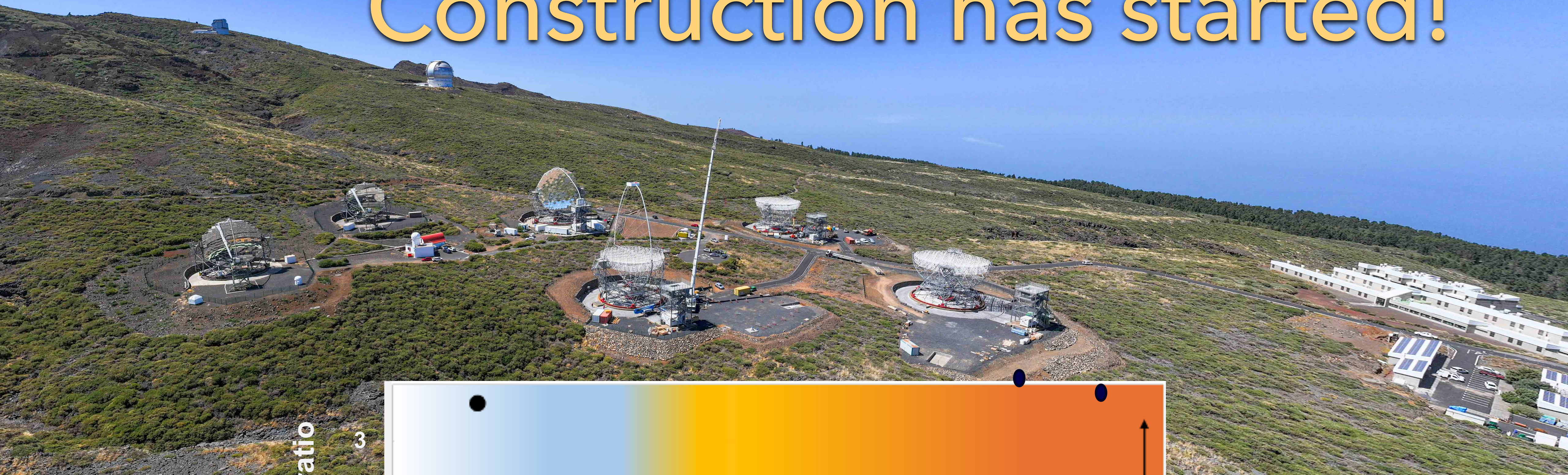


Outline

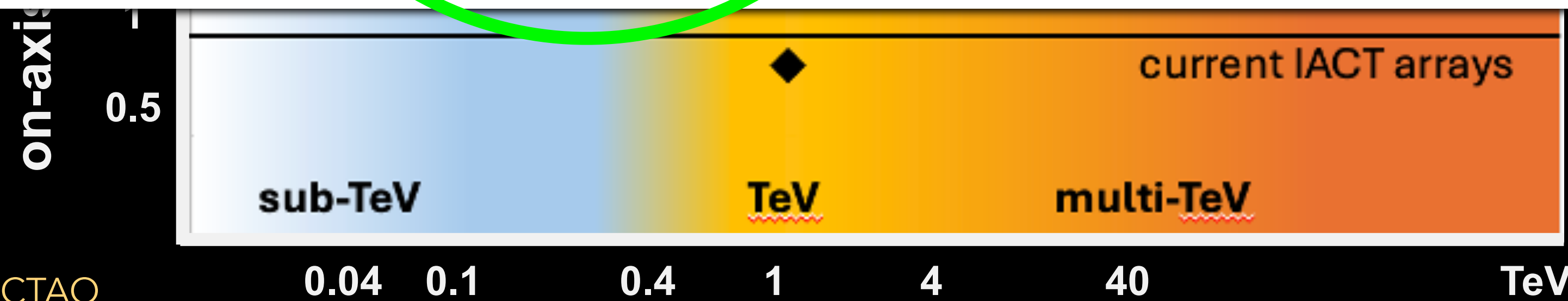
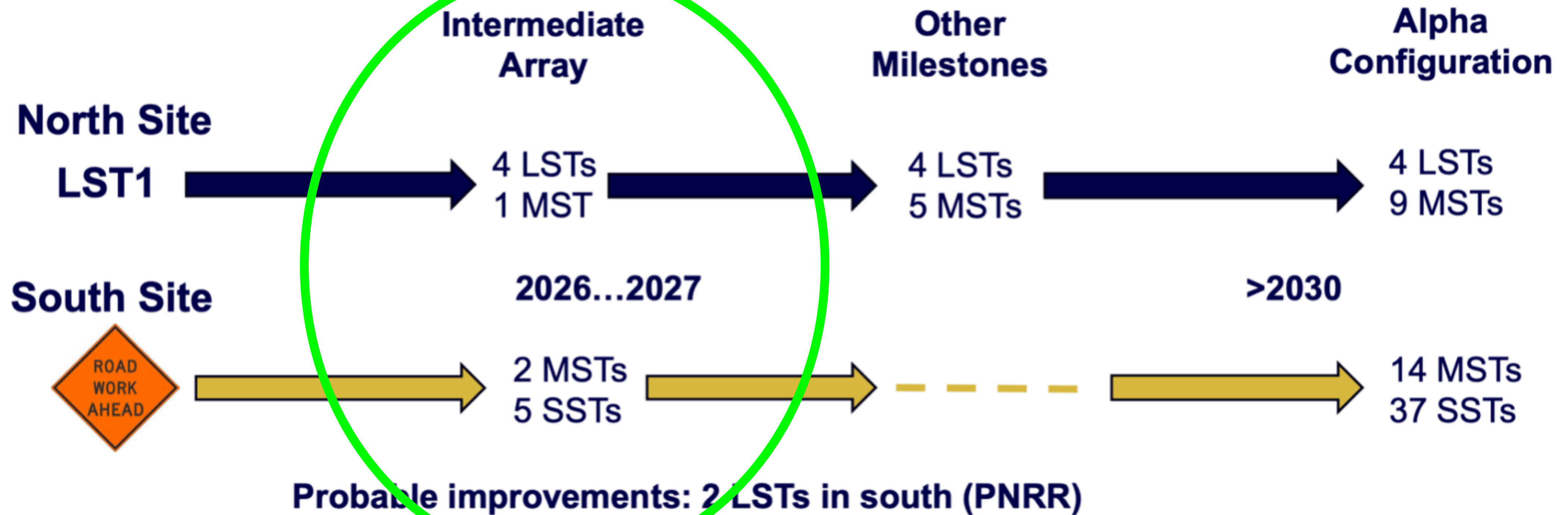
- ★ Brief introduction to CTAO
- ★ Netherlands science synergies & some new (and surprising!) VHE γ -ray results
- ★ Early science planning (why we want in!)



Construction has started!



Construction has started!



▲ 5 SSTs

Access policy

- Guaranteed Time Observations (GTOs = KSPs) as reward to the Contributing Parties (CPs) for the contribution to the construction project
- KSP Time is ~40% of the observing time over the first 10 years
- KSP Time profile is not flat: ~70% of the available time the first 2 yrs, then decreasing (i.e. the key discovery time!)
- Leadership positions of the KSP proposals proportional to the construction share

CTAO ERIC

10 – 13 partners

1 intergovernmental organization: ESO

9 Members/Observer:

Austria – Czech Rep – France – Germany – Italy
– Poland – Spain – Slovenia – Switzerland

1 strategic partner: Japan

3 Third Parties under negotiation

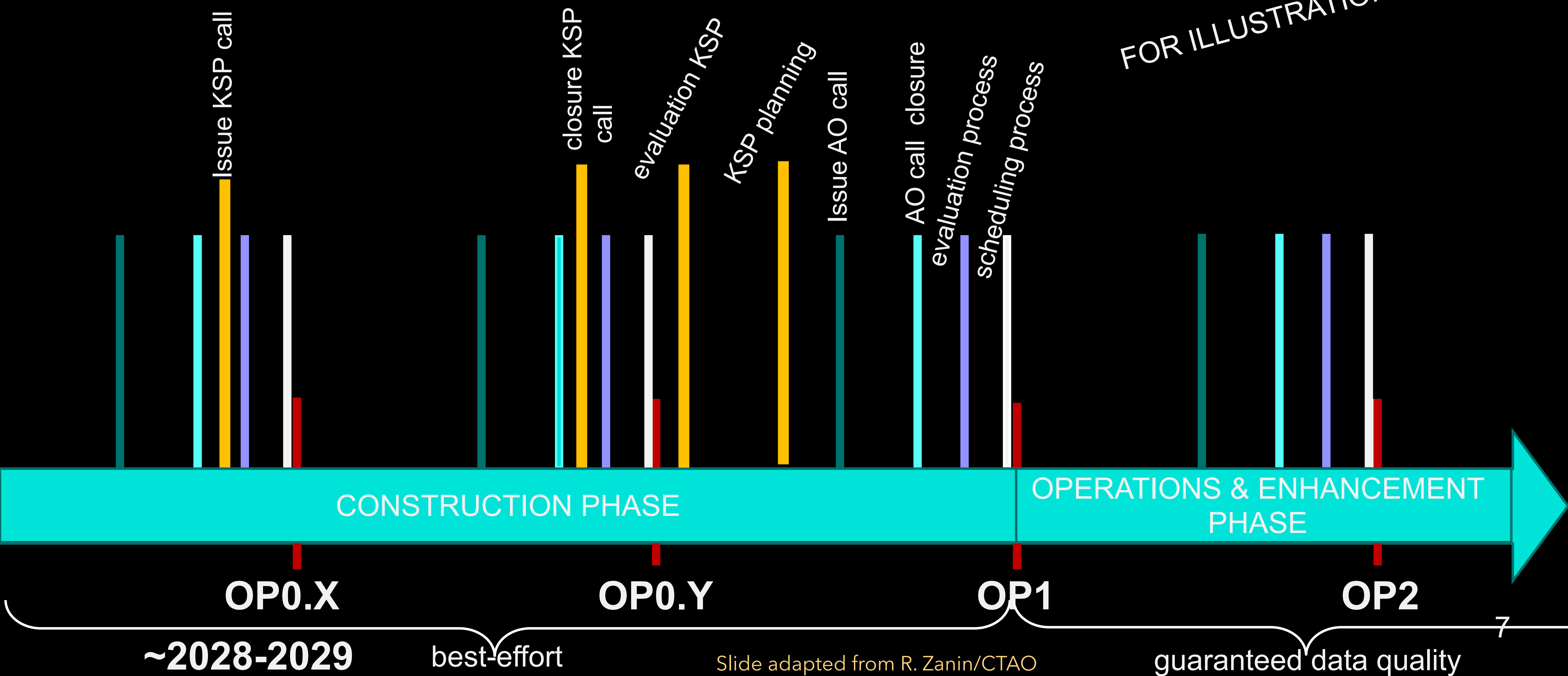
CTAO ERIC partners are contributing parties (CP)

All CPs are equivalent w/r/t the access policy!

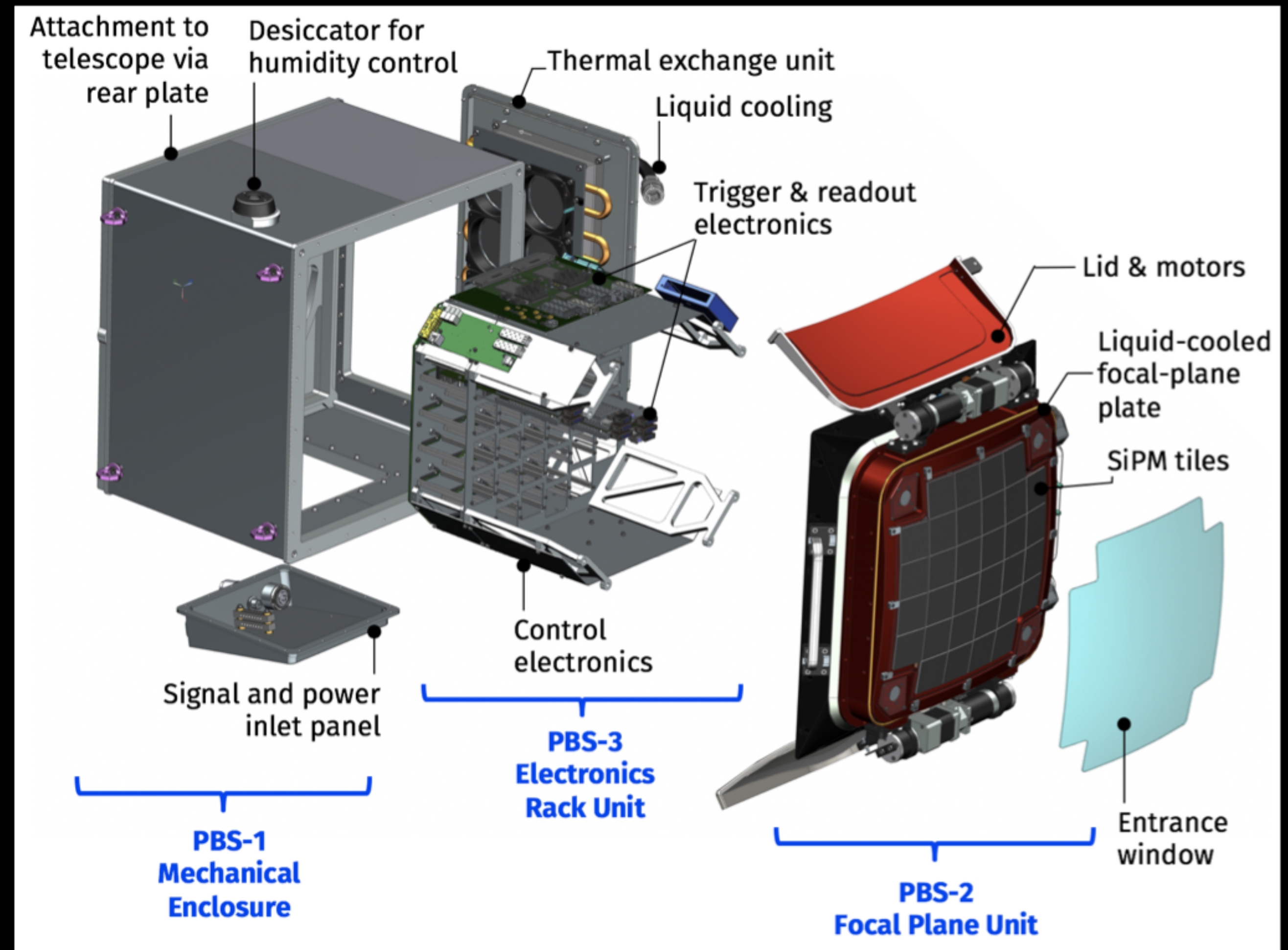
All KSP data public after 1 year (long time from now...)

Mid-term observatory plan

FOR ILLUSTRATION PURPOSES



CTAO: a national and international priority

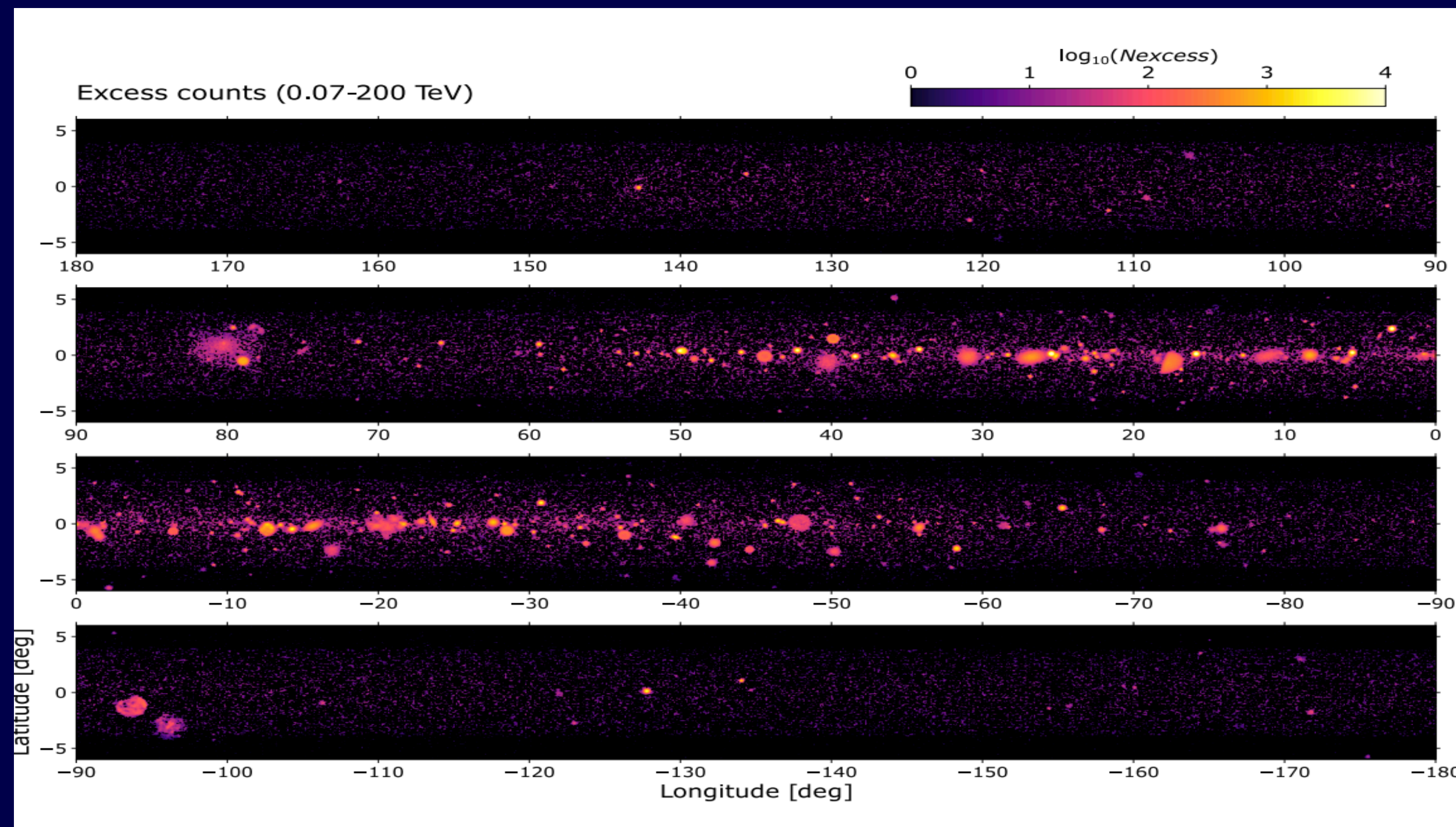


NWO-M, NOVA, NWO-G: ~4M€ in hardware/software investments
Enough to be counted towards ERIC membership!

Science Data Challenge

fully open and blind!

several yr of simulated CTAO observations provided as science-ready data sets



Goals:



- #1: allow the gamma-ray community as well as the broad astronomical community to explore the CTAO scientific capabilities
- #2: allow the users to familiarize with the technicalities of the analysis as well as with the CTAO science analysis tools

coming soon!



CTAO School

2nd Edition | 14-25 June 2025

-  Bertinoro, Italy
-  La Palma, Spain

Two weeks, two locations

Real observations, data analysis and science
The full astronomer experience

<https://school.ctao.org/>



Summary

- ★ CTAO will be revolutionary, and the first γ -ray ground-based observatory to allow open, proposal-driven science and RT analysis
- ★ The CR 'paradigm' is radically shifting and CTAO + MWL/MM observations are essential for advancing our physical understanding
- ★ CTAO really offers something for everyone, from astronomy to astroparticle to cosmology, and from GWs to fundamental physics!
- ★ First data are coming in a few years. For our significant investments over the last ~20 years we should be onboard and getting ready! This includes planning science collaboration across messengers!!