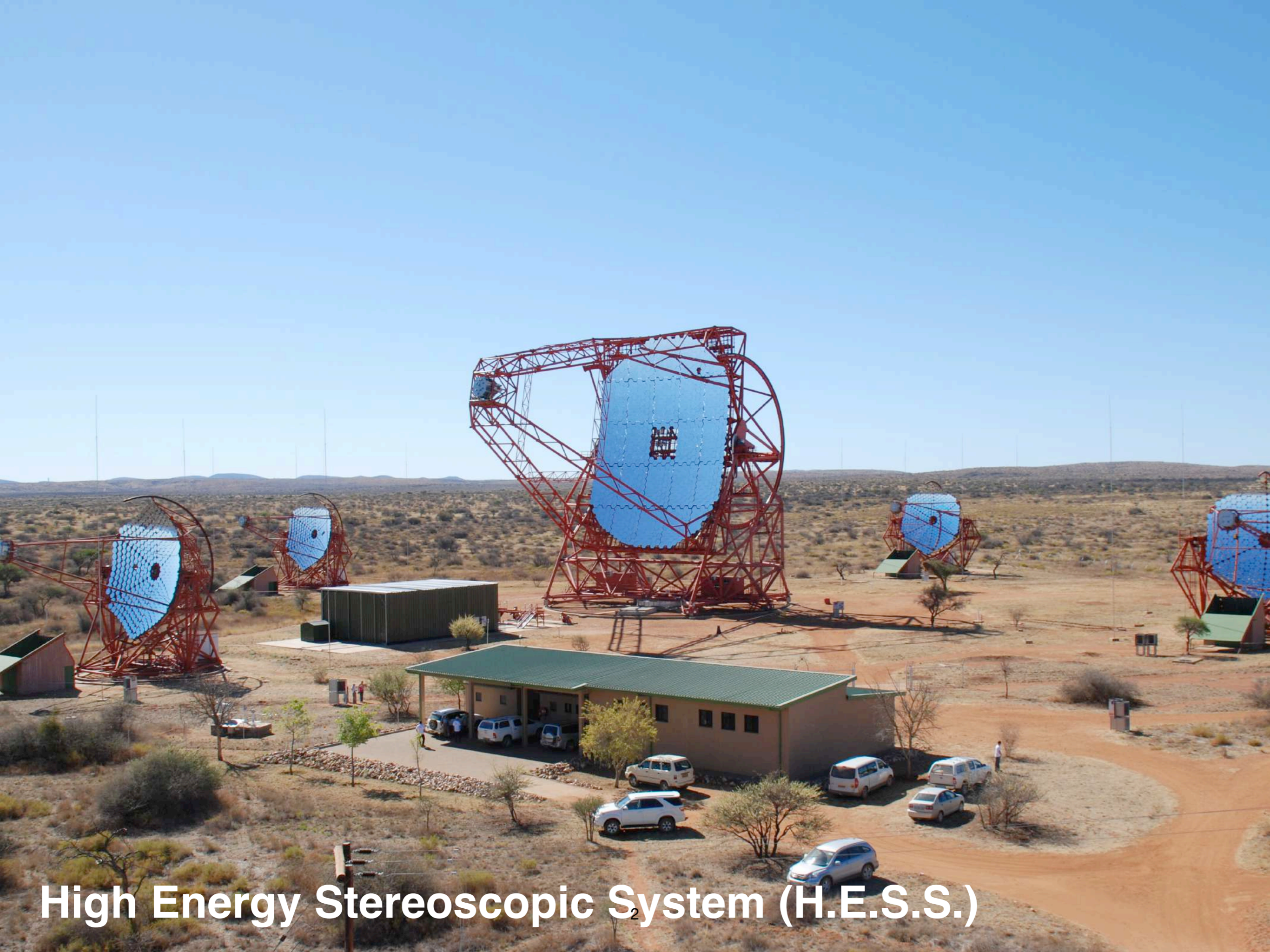


The Cherenkov Telescope Array (CTA) in the multi-messenger era

Pierre Cristofari
LUTH, Observatoire de Paris

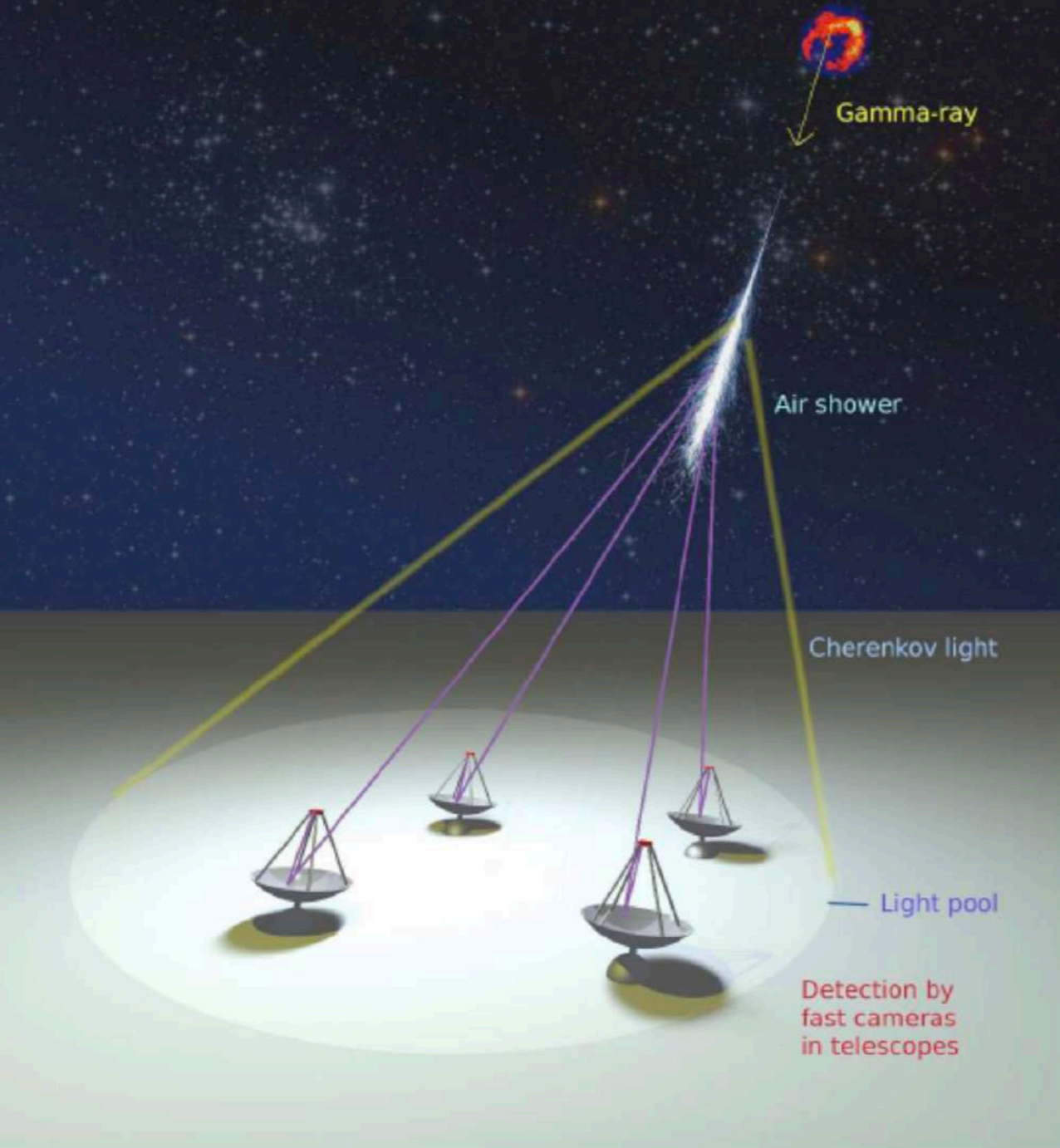




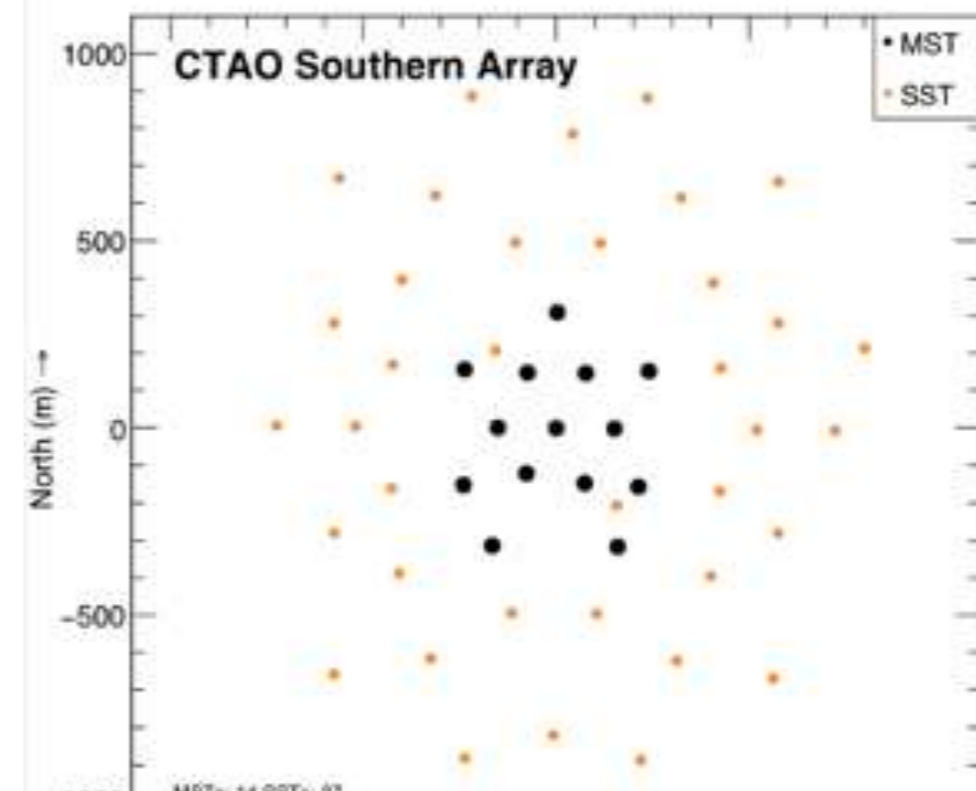
High Energy Stereoscopic System (H.E.S.S.)

Imaging Atmospheric Cherenkov Instruments

CTA, H.E.S.S., Veritas, MAGIC



CTA North site: 4 LST+ 9 MST



CTA South site: 14 MST + 37 SST

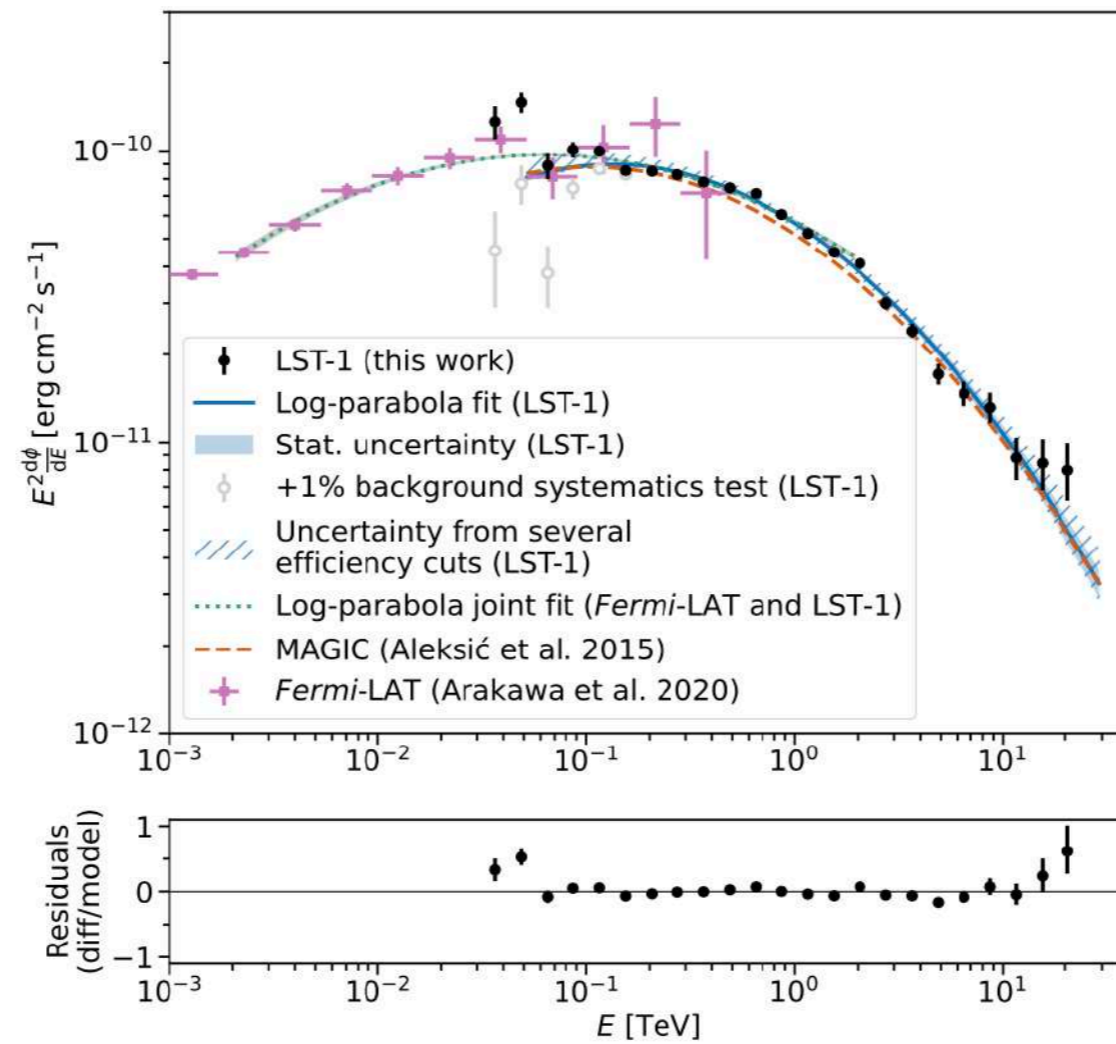


Large size telescope (LST) CTA (first light Dec. 2018)

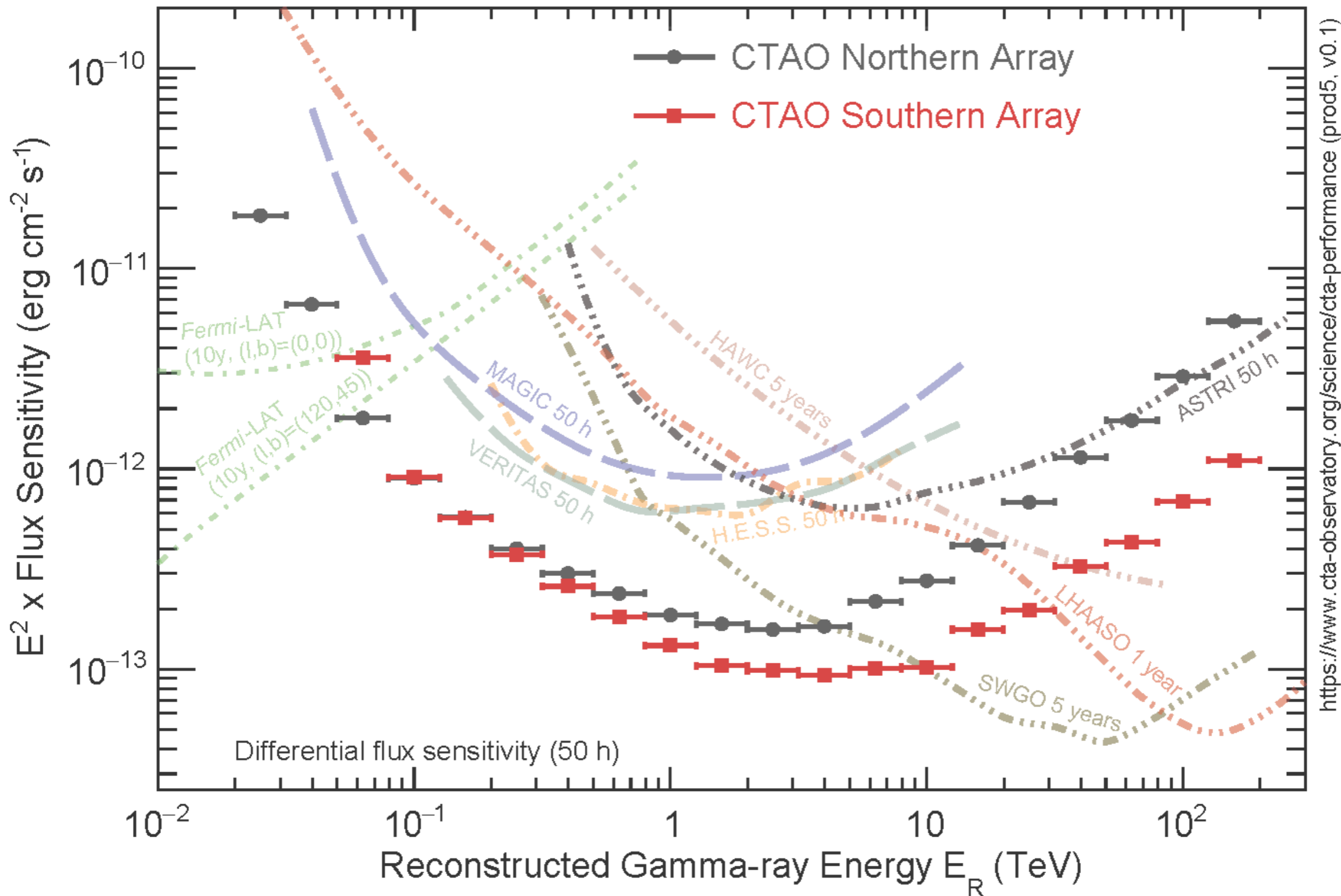
Observations of the Crab Nebula and Pulsar with the Large-Sized Telescope Prototype of the Cherenkov Telescope Array

H. ABE,¹ K. ABE,² S. ABE,¹ A. AGUASCA-CABOT,³ I. AGUDO,⁴ N. ALVAREZ CRESPO,⁵ L. A. ANTONELLI,⁶ C. ARAMO,⁷ A. ARBET-ENGELS,⁸ C. ARCARO,⁹ M. ARTERO,¹⁰ K. ASANO,¹ P. AUBERT,¹¹ A. BAKTASH,¹² A. BAMBA,¹³ A. BAQUERO LARRIVA,^{5,14} L. BARONCELLI,¹⁵ U. BARRES DE ALMEIDA,¹⁶ J. A. BARRIO,⁵ I. BATKOVIC,⁹ J. BAXTER,¹ J. BECERRA GONZÁLEZ,¹⁷ E. BERNARDINI,⁹ M. I. BERNARDOS,⁴ J. BERNETE MEDRANO,¹⁸ A. BERTI,⁸ P. BHATTACHARJEE,¹¹ N. BIEDERBECK,¹⁹ C. BIGONGIARI,⁶ E. BISSALDI,²⁰ O. BLANCH,¹⁰ G. BONNOLI,²¹ P. BORDAS,³ A. BORGHESE,²² A. BULGARELLI,¹⁵ I. BURELLI,²³ M. BUSCEMI,²⁴ M. CARDILLO,²⁵ S. CAROFF,¹¹ A. CAROSI,⁶ F. CASSOL,²⁶ D. CAUZ,²³ G. CERIBELLA,¹ Y. CHAI,⁸ K. CHENG,¹ A. CHIAVASSA,²⁷ M. CHIKAWA,¹ L. CHYTKA,²⁸ A. CIFUENTES,¹⁸ J. L. CONTRERAS,⁵ J. CORTINA,¹⁸ H. COSTANTINI,²⁶ G. D'AMICO,²⁹ M. DALCHENKO,³⁰ A. DE ANGELIS,⁹ M. DE BONY DE LAVERGNE,¹¹ B. DE LOTTO,²³ R. DE MENEZES,²⁷ G. DELEGLISE,¹¹ C. DELGADO,¹⁸ J. DELGADO MENGUAL,³¹ D. DELLA VOLPE,³⁰ M. DELLAIERA,¹¹ D. DEPAOLI,²⁷ A. DI PIANO,¹⁵ F. DI PIERRO,²⁷ R. DI TRIA,³² L. DI VENERE,³² C. DÍAZ,¹⁸ R. M. DOMINIK,¹⁹ D. DOMINIS PRESTER,³³ A. DONINI,¹⁰ D. DORNER,³⁴ M. DORO,⁹ D. ELSÄSSER,¹⁹ G. EMERY,³⁰ J. ESCUDERO,⁴ V. FALLAH RAMAZANI,³⁵ G. FERRARA,²⁴ F. FERRAROTTO,³⁶ A. FIASSON,^{11,37} L. FREIXAS COROMINA,¹⁸ S. FRÖSE,¹⁹ S. FUKAMI,¹ Y. FUKAZAWA,³⁸ E. GARCIA,¹¹ R. GARCIA LÓPEZ,¹⁷ C. GASPARRA,³⁹ D. GASPARRINI,³⁹ F. GEYER,¹⁹ J. GIESBRECHT PAIVA,¹⁶ N. GIGLIETTO,²⁰

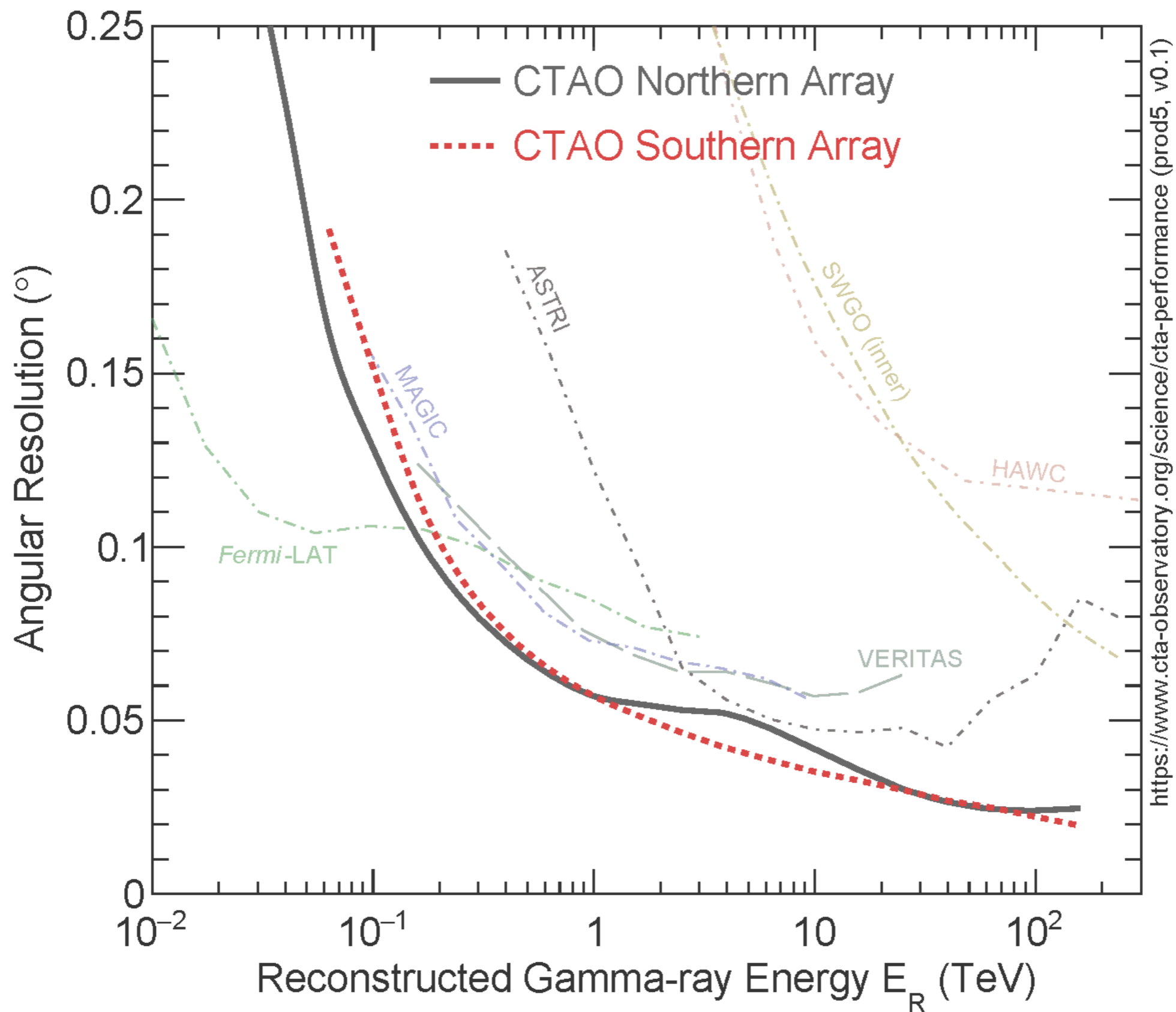
Et al.



Performance



Performance

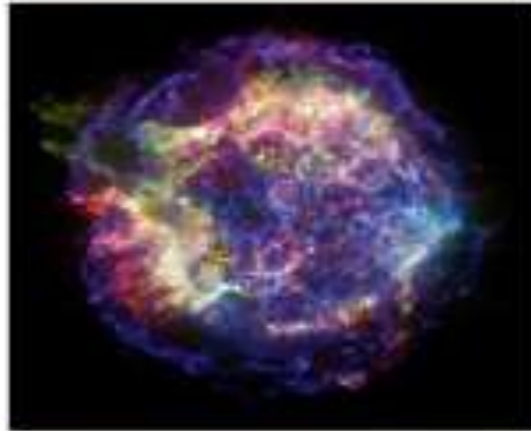


<https://www.cta-observatory.org/science/cta-performance> (prod5, v0.1)

Main scientific projects (CTA)

Origin and role of
relativistic particles

Sites and mechanisms
of CR acceleration



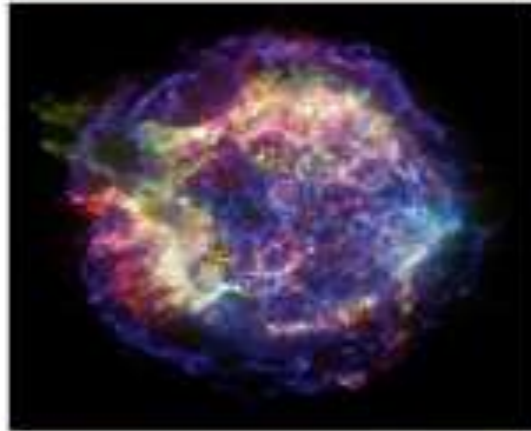
CR propagation/feedback
in star-forming systems



Main scientific projects (CTA)

Origin and role of relativistic particles

Sites and mechanisms of CR acceleration



CR propagation/feedback in star-forming systems



Probing extreme environments

Processes close to neutron stars and black holes



Relativistic jets, winds, and explosions



Main scientific projects (CTA)

Origin and role of relativistic particles

Sites and mechanisms of CR acceleration



CR propagation/feedback in star-forming systems



Probing extreme environments

Processes close to neutron stars and black holes

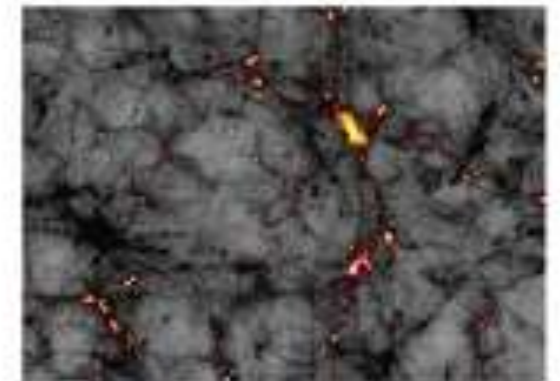


Relativistic jets, winds, and explosions

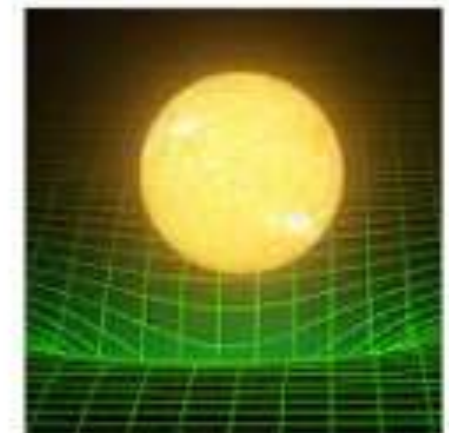


Frontiers of Physics

Nature and distribution of dark matter



Lorentz-invariance violation



CTA in the MWL & MM era

Photons

SKA

Vera-C.-Rubin

SVOM

Athena

CTA

LHAASO

CTA in the MWL & MM era

Photons

SKA

Vera-C.-Rubin

SVOM

Athena

CTA

LHAASO

Cosmic Rays

AMS-02

JEM-EUSO

CTA in the MWL & MM era

Photons

SKA

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Cosmic Rays

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Athena

JEM-EUSO

Neutrinos

KM3Net

IceCube

CTA

LHAASO

CTA in the MWL & MM era

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JEM-EUSO

SVOM

Athena

CTA

LHAASO

Neutrinos

KM3Net

IceCube

Gravitational waves

LIGO-Virgo

LISA

CTA in the MWL & MM era

Photons

Cosmic Rays

SKA

Vera-C.-Rubin

AMS-02

CTA: Largest OPEN observatory in the world in the VHE range (20 GeV-300 TeV), full sky

1. Short timescale sensitivity (<300 GeV, 3-4 orders of magnitude above Fermi-LAT)
2. Angular resolution (\sim arcmin $>$ 100 TeV)
3. Large FoV ($\sim 8^\circ$), adapted for surveys
4. Rapid response (<30 s for LSTs)
5. 2025-2027

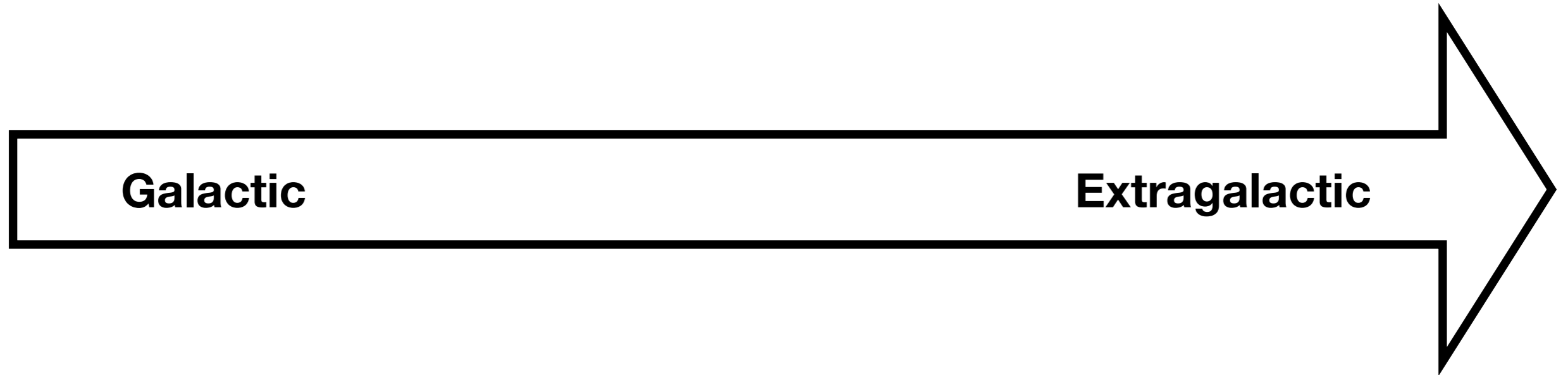
KM3Net

IceCube

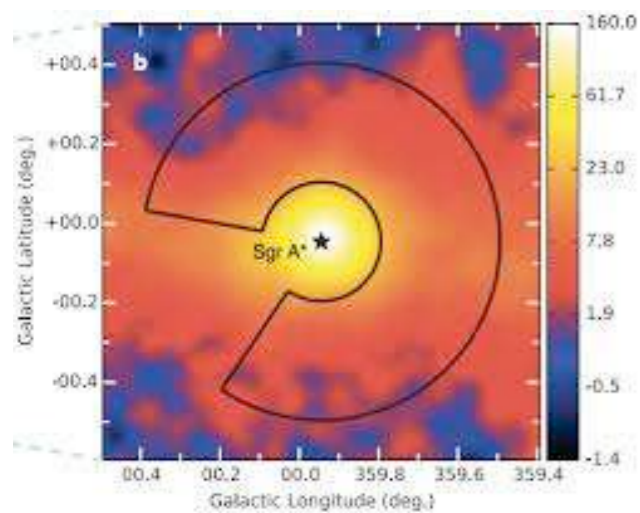
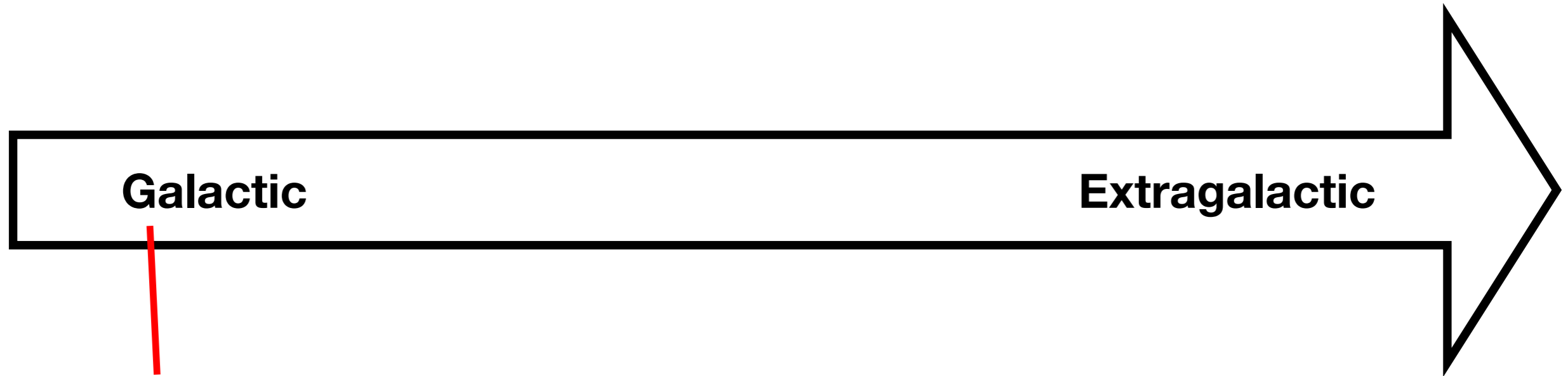
LIGO-Virgo

LISA

The TeV sky: what are we looking at?

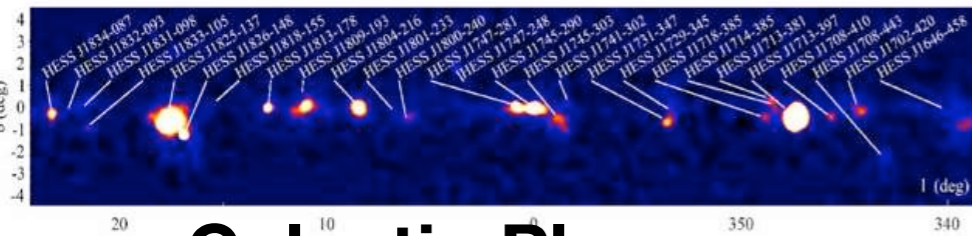


The TeV sky: what are we looking at?

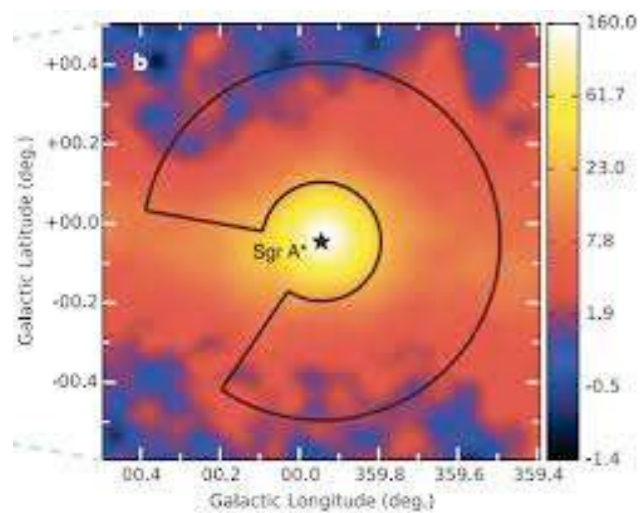
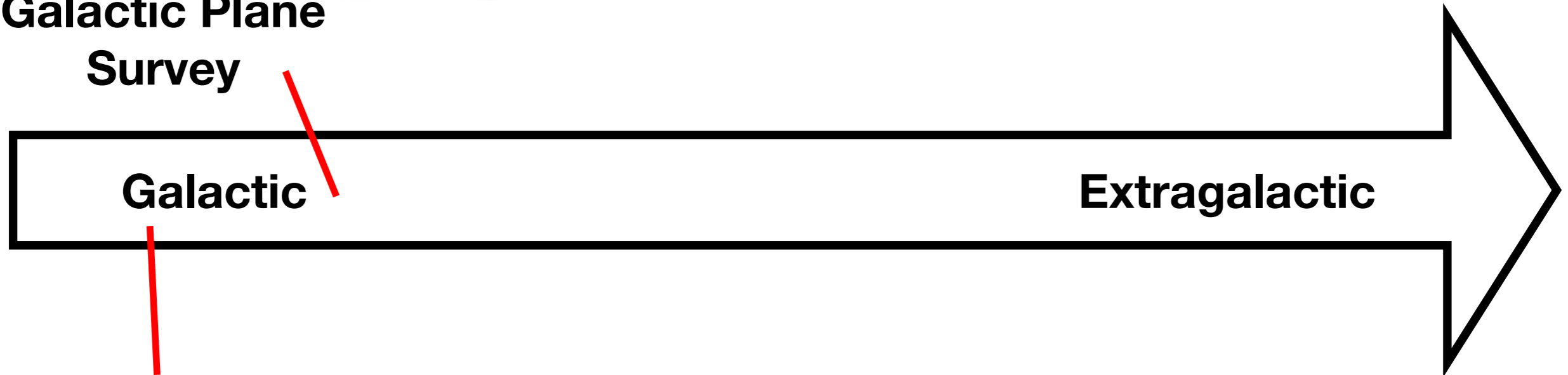


Galactic center

The TeV sky: what are we looking at?

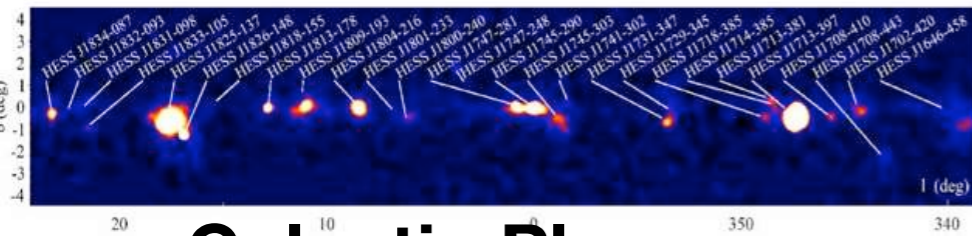


**Galactic Plane
Survey**

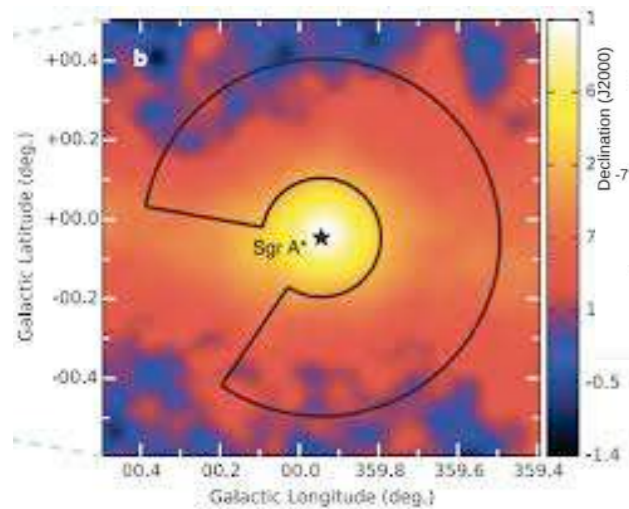
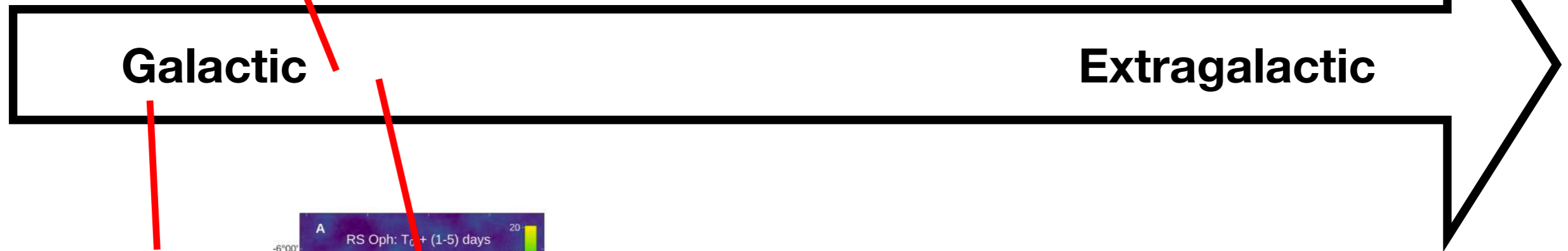


Galactic center

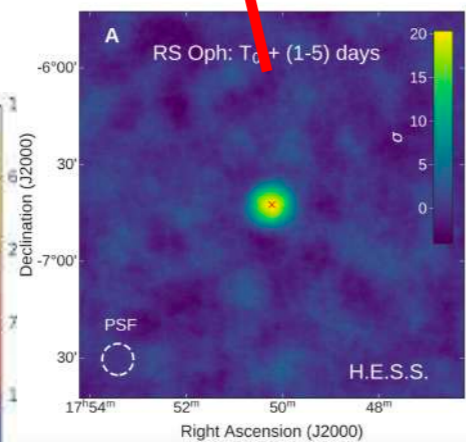
The TeV sky: what are we looking at?



Galactic Plane Survey

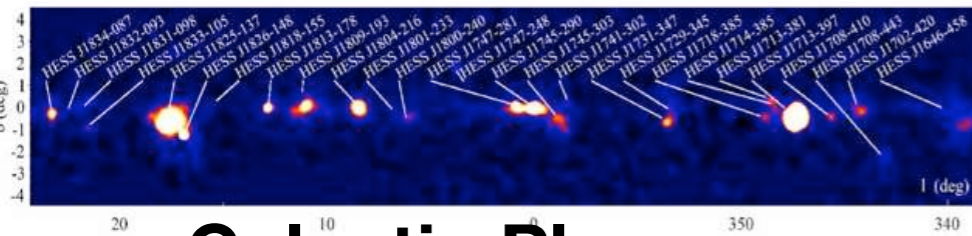


Galactic center

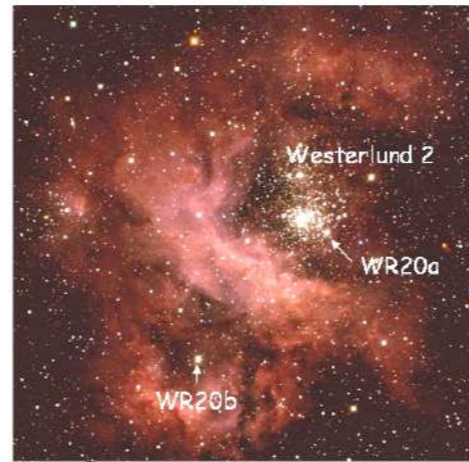


Novae

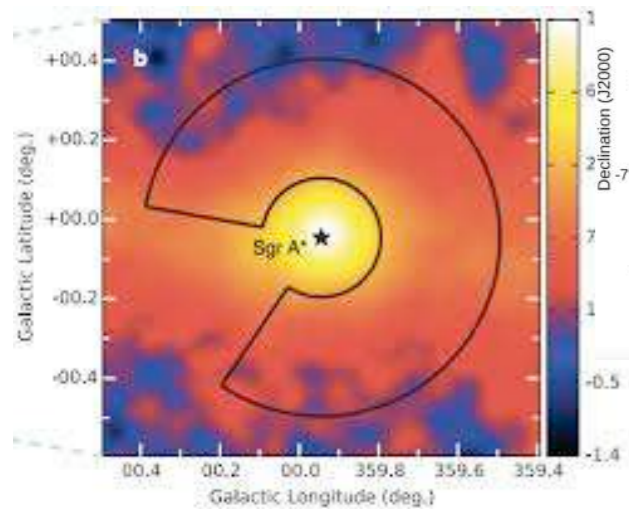
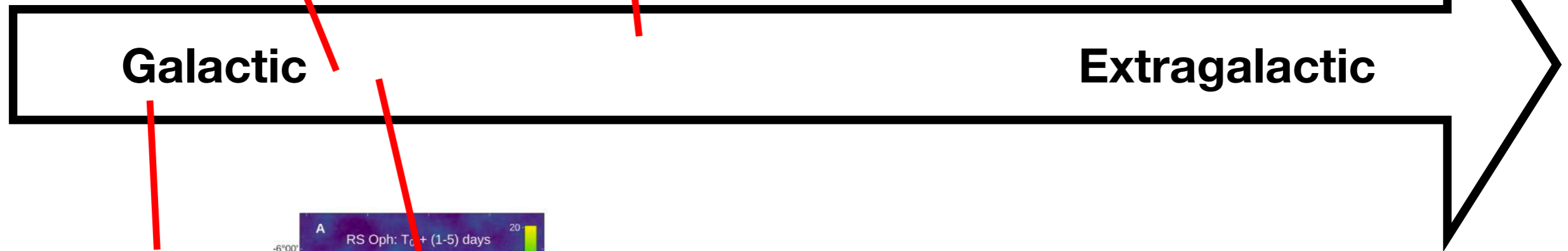
The TeV sky: what are we looking at?



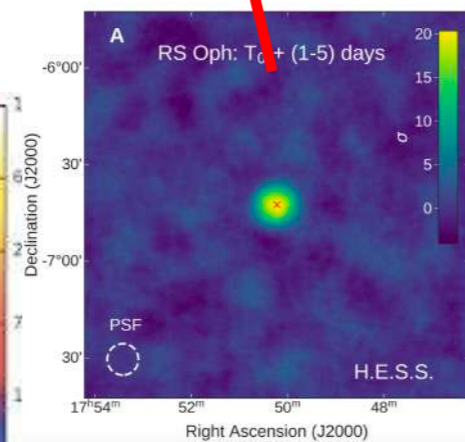
Galactic Plane Survey



Star forming regions

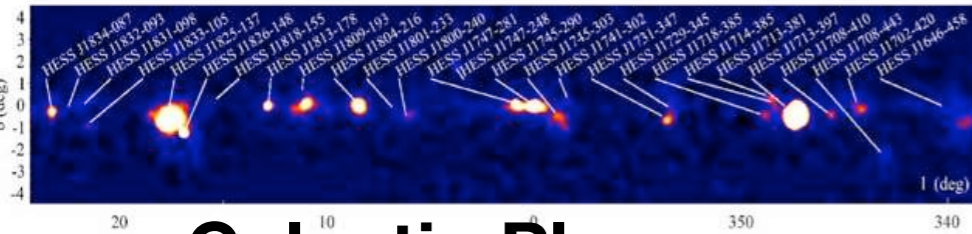


Galactic center

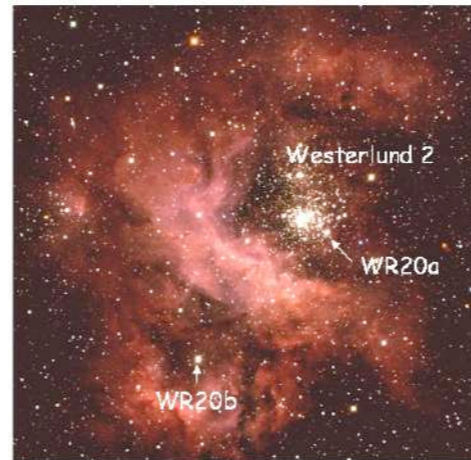


Novae

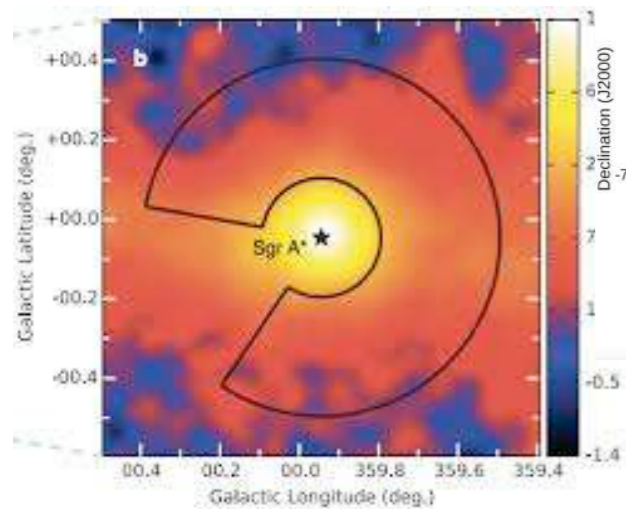
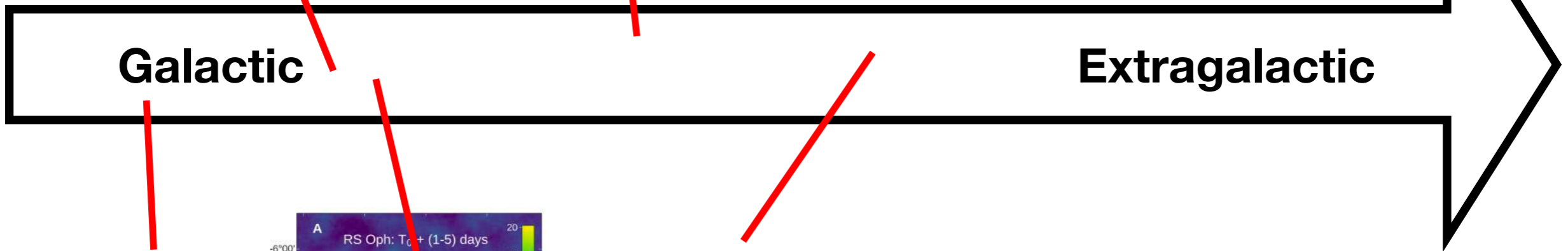
The TeV sky: what are we looking at?



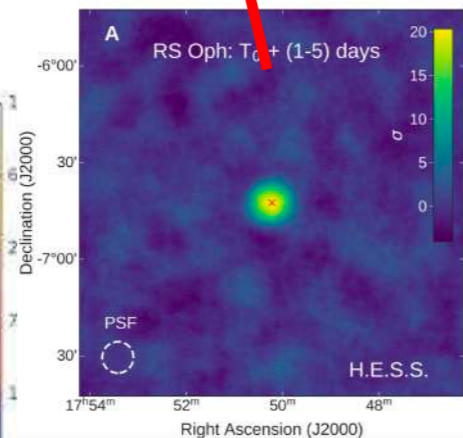
Galactic Plane Survey



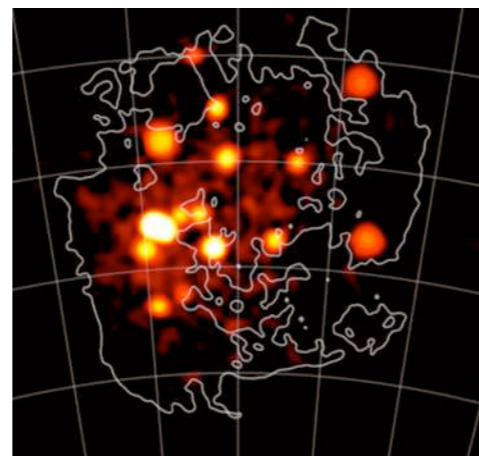
Star forming regions



Galactic center

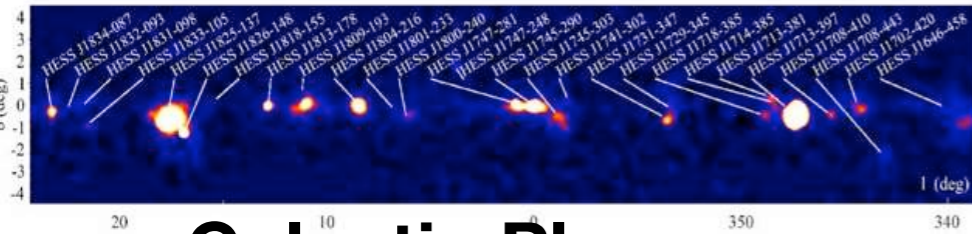


Novae

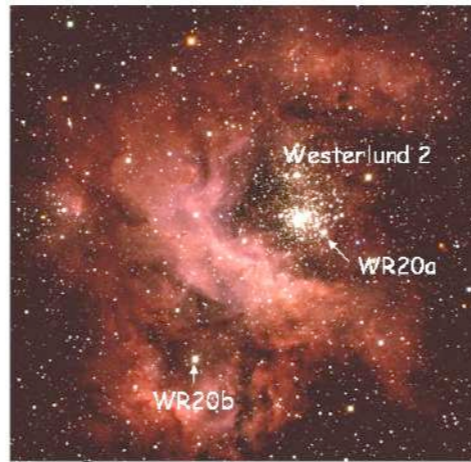


LMC survey

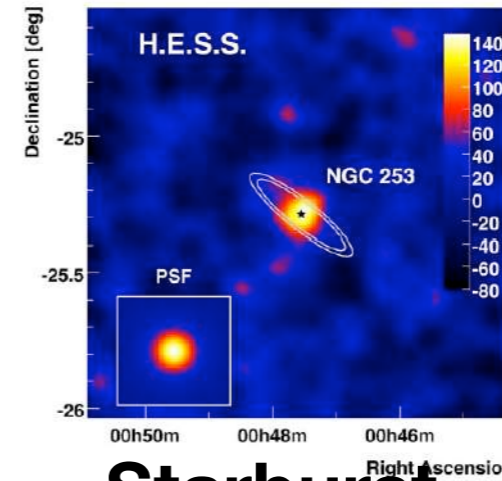
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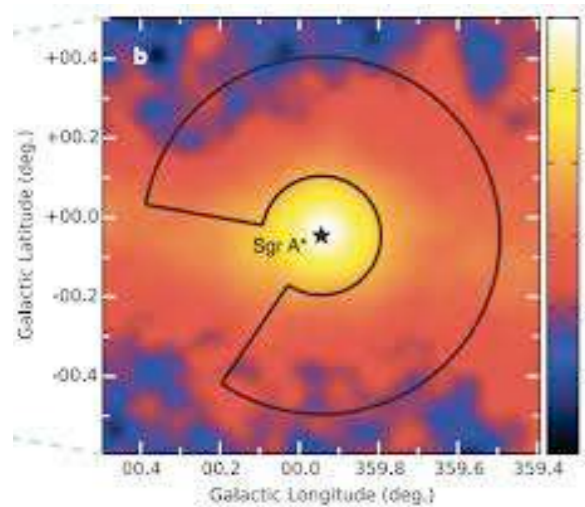
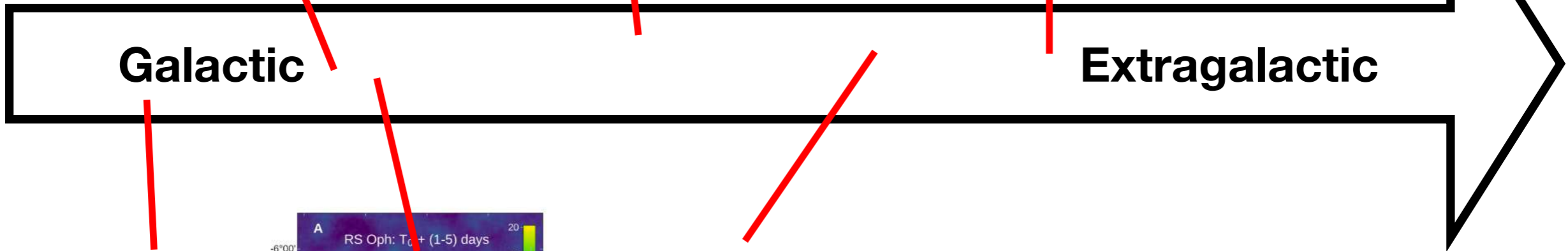
Galactic Plane Survey



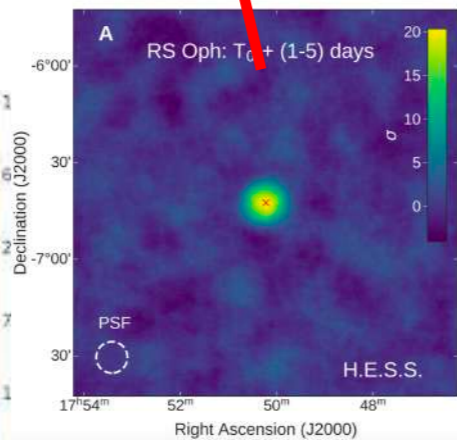
Star forming regions



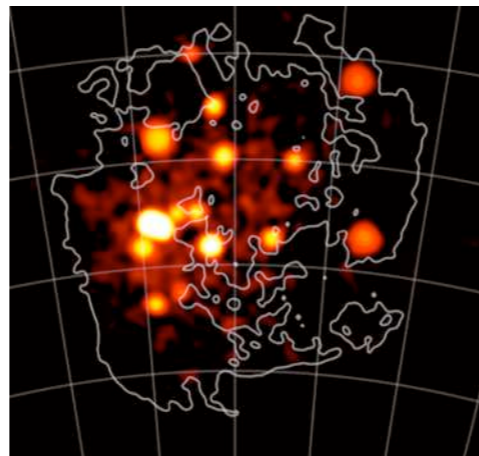
Starburst galaxies



Galactic center

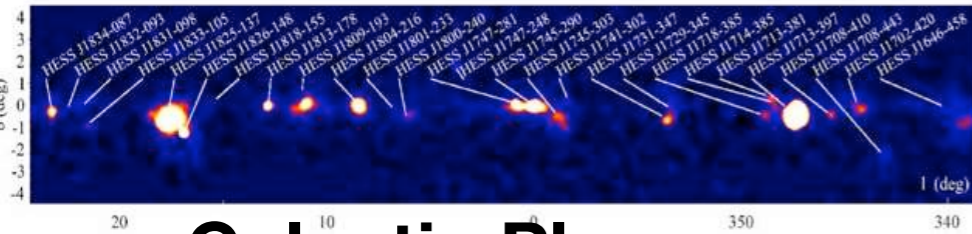


Novae

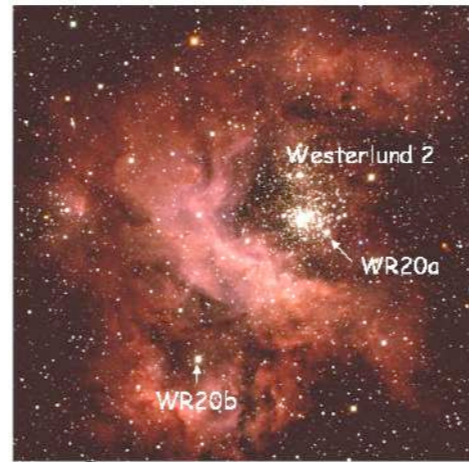


LMC survey

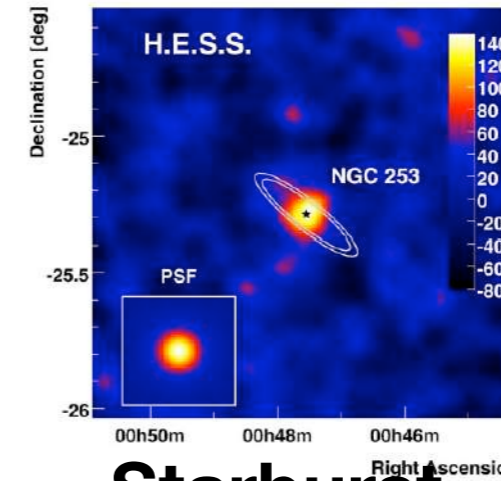
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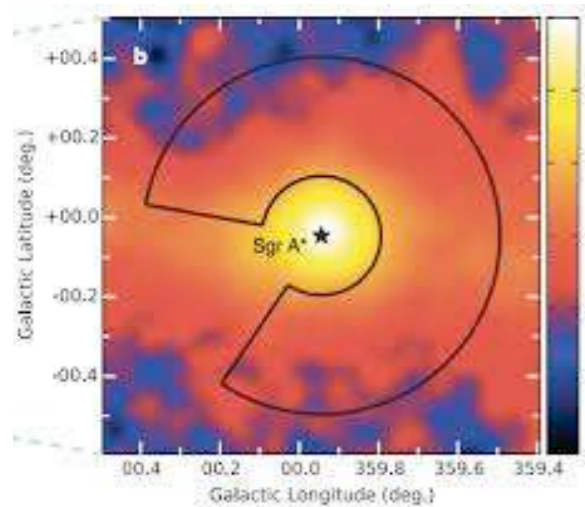
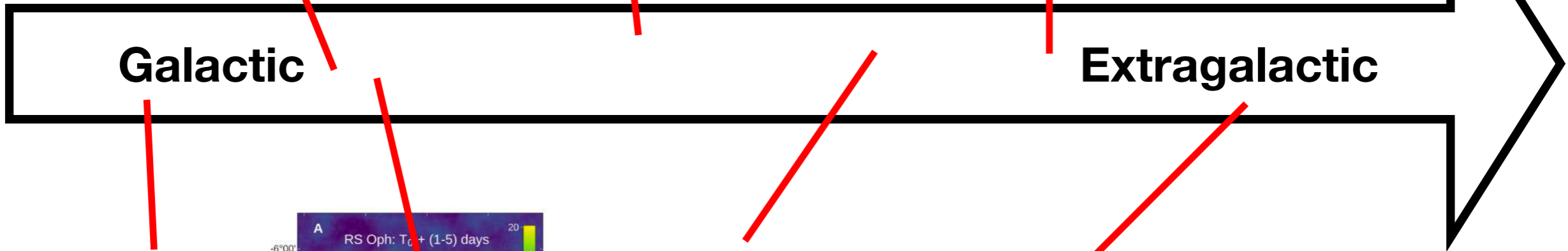
Galactic Plane Survey



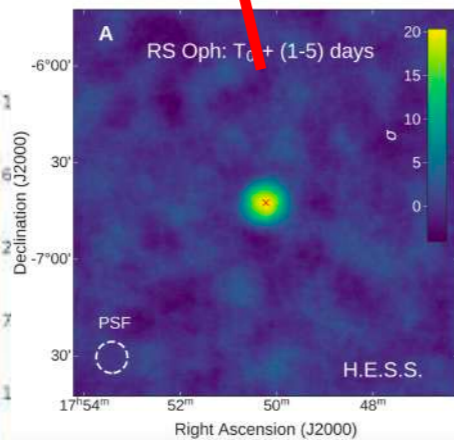
Star forming regions



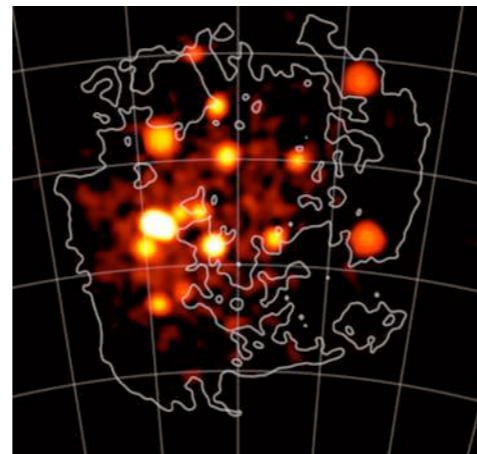
Starburst galaxies



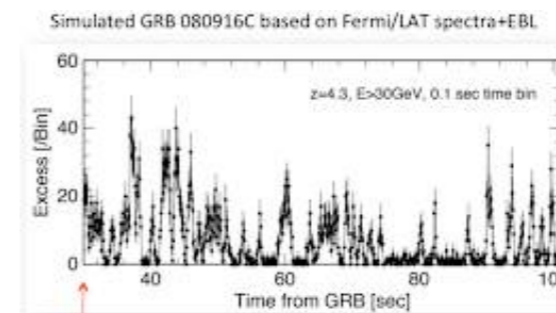
Galactic center



Novae



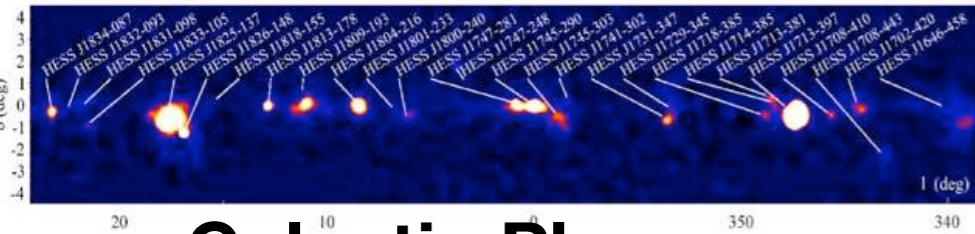
LMC survey



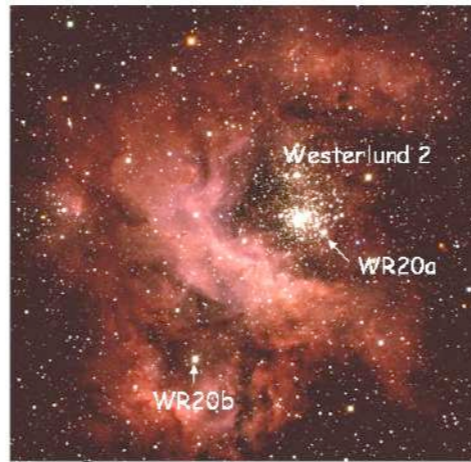
Transients (GRBs/ supernovae)

CTA Consortium paper Acharya+2019, World Scientific, 10.1142/10986, arxiv:1709.07997

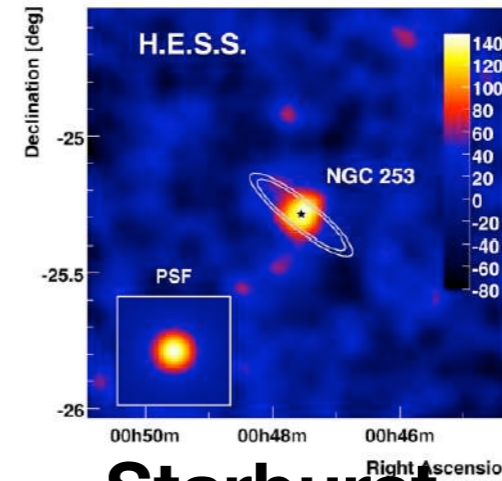
The TeV sky: what are we looking at?



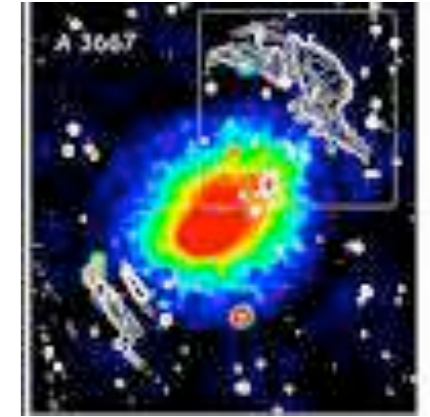
Galactic Plane Survey



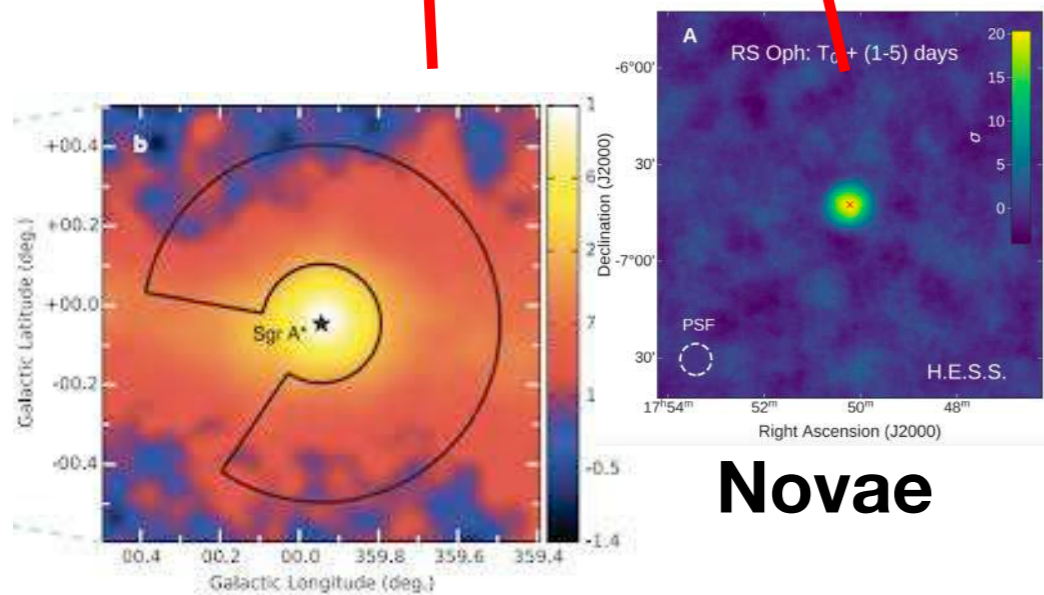
Star forming regions



Starburst galaxies

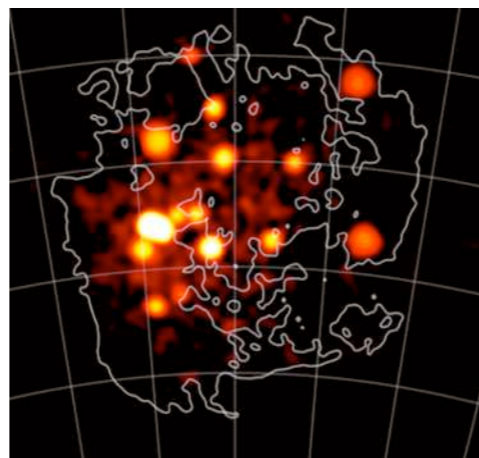


Clusters of galaxies

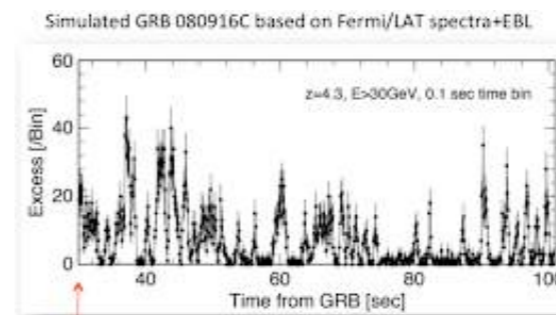


Novae

Galactic center



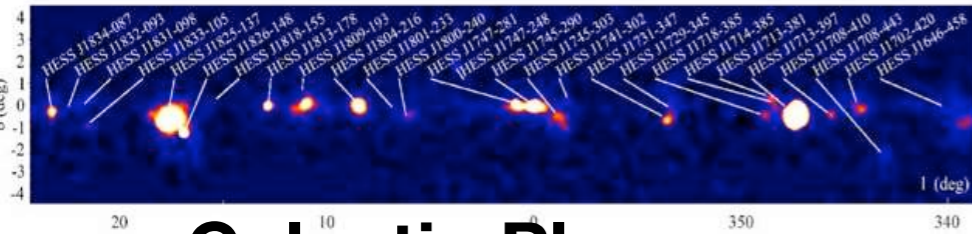
LMC survey



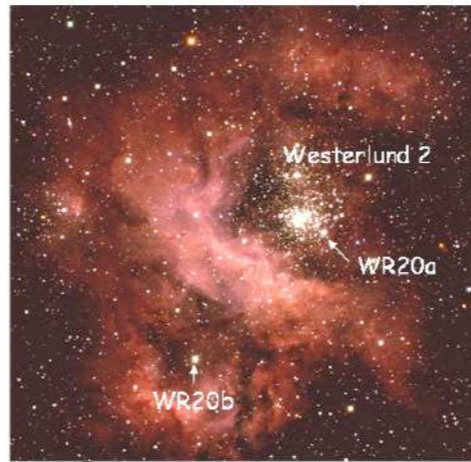
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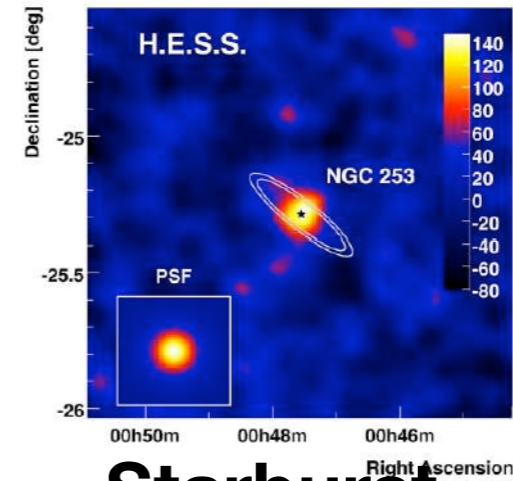
The TeV sky: what are we looking at?



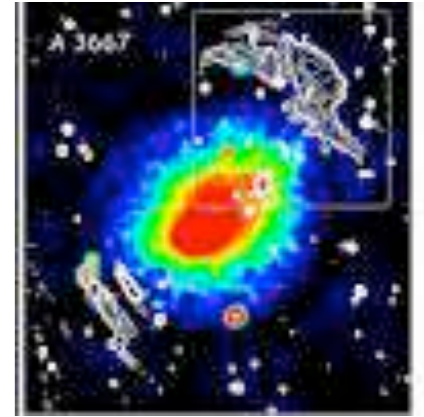
Galactic Plane Survey



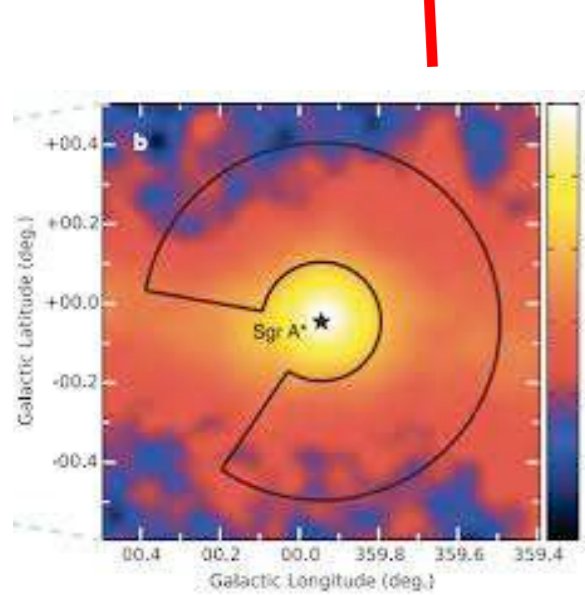
Star forming regions



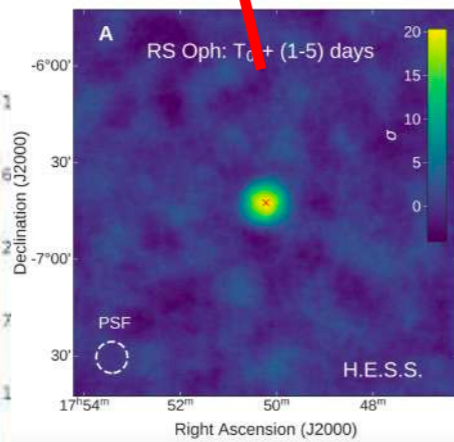
Starburst galaxies



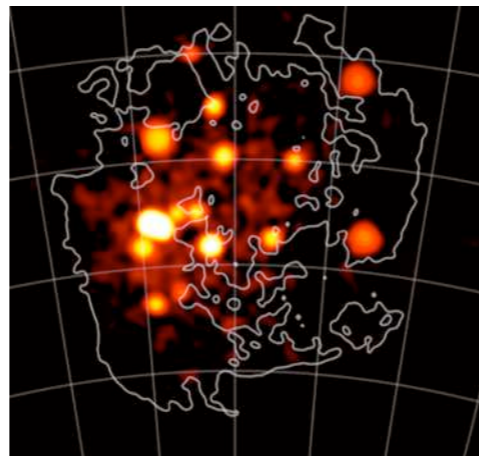
Clusters of galaxies



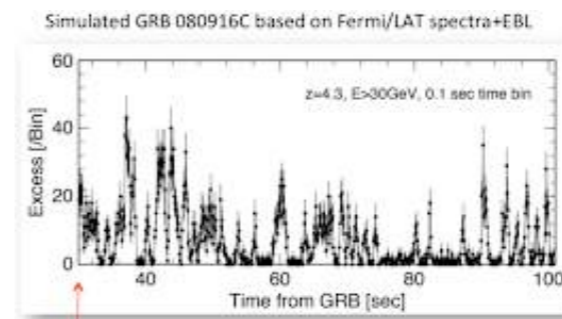
Galactic center



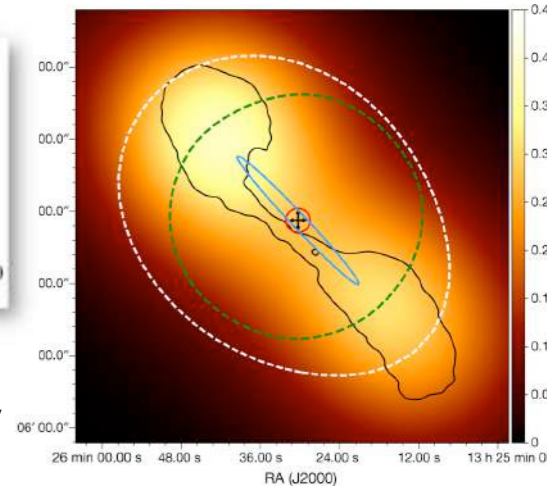
Novae



LMC survey

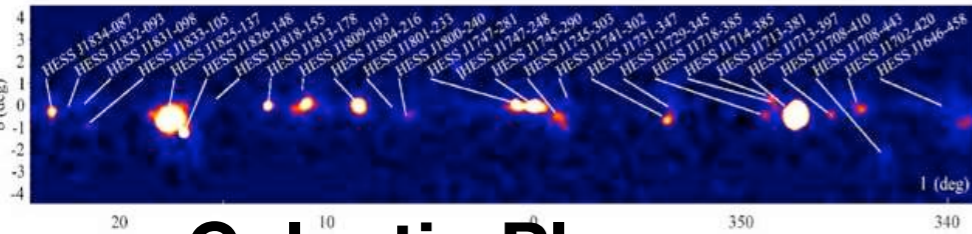


Transients (GRBs/ supernovae)

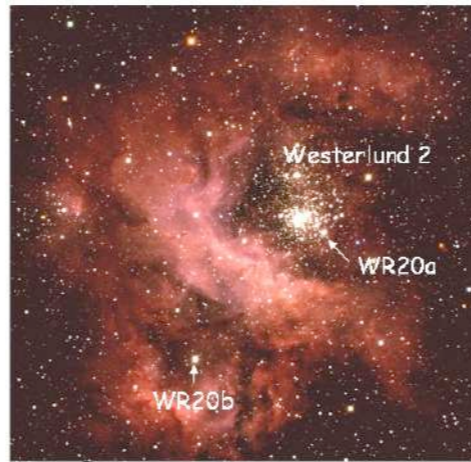


AGN + jets

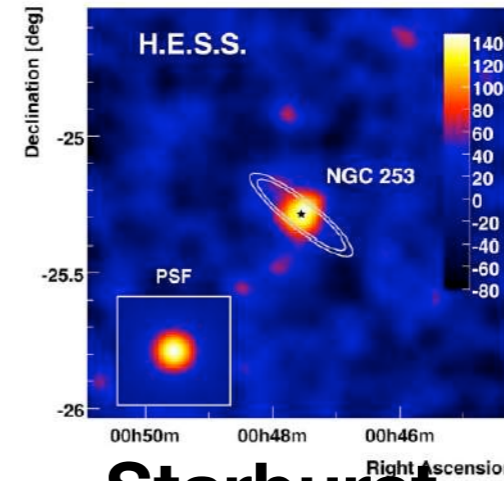
The TeV sky: what are we looking at?



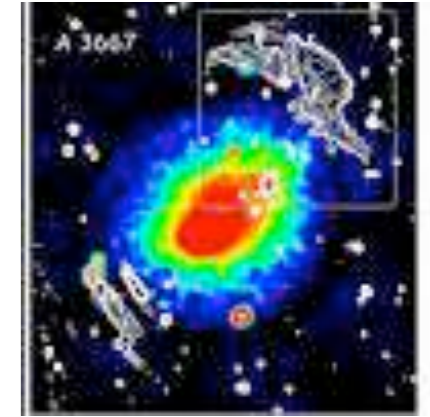
Galactic Plane Survey



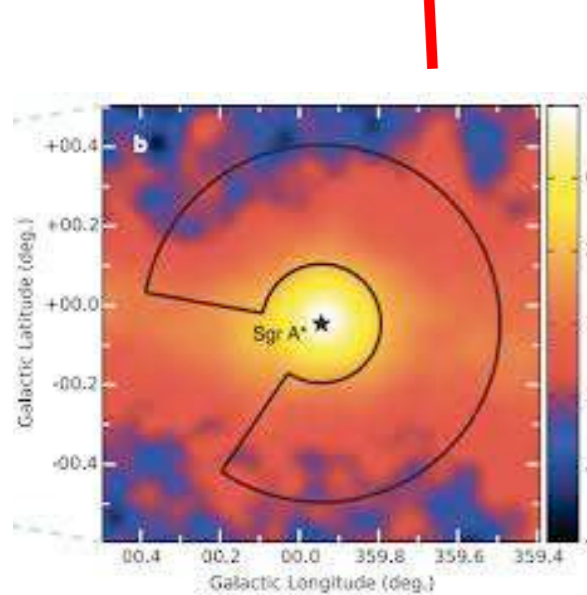
Star forming regions



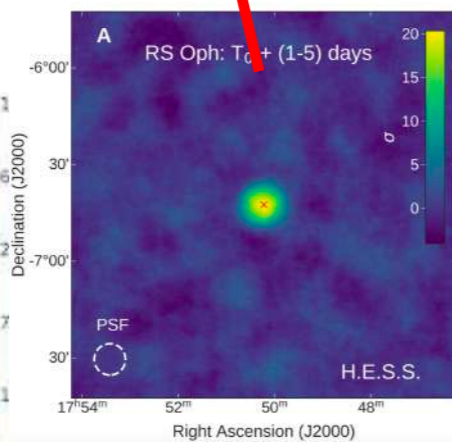
Starburst galaxies



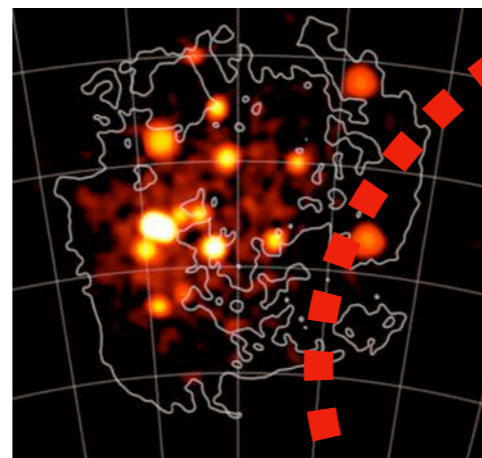
Clusters of galaxies



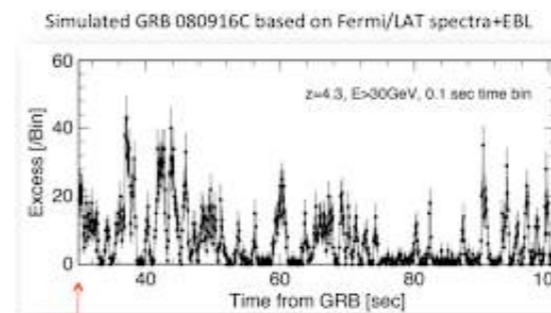
Galactic center



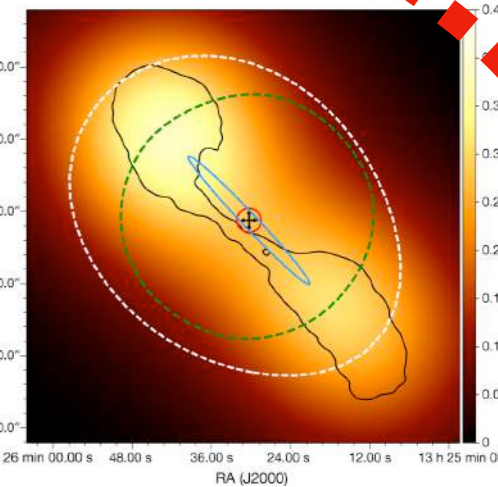
Novae



LMC survey

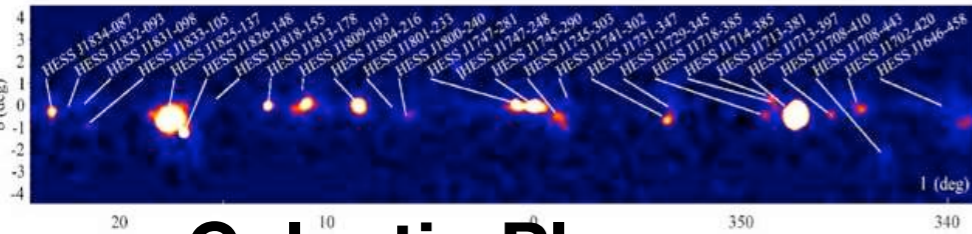


Transients (GRBs/supernovae)

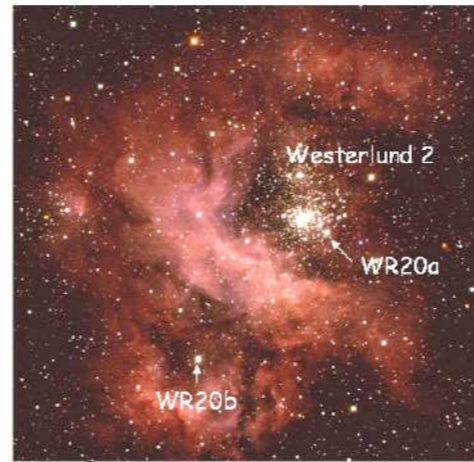


AGN + jets

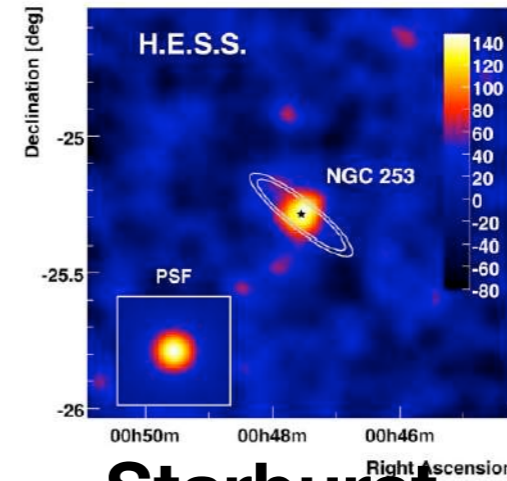
The TeV sky: what are we looking at?



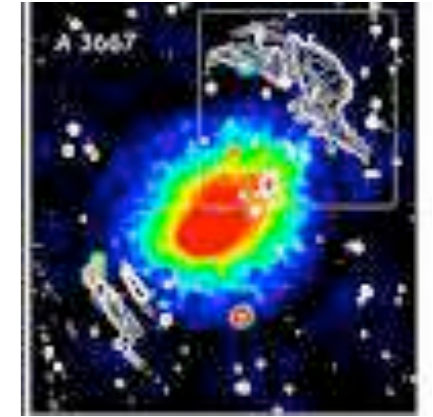
Galactic Plane Survey



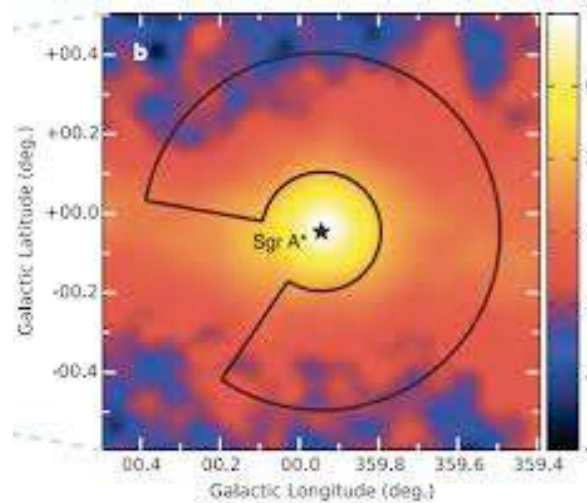
Star forming regions



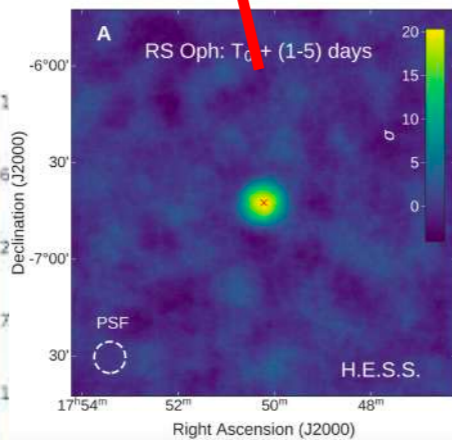
Starburst galaxies



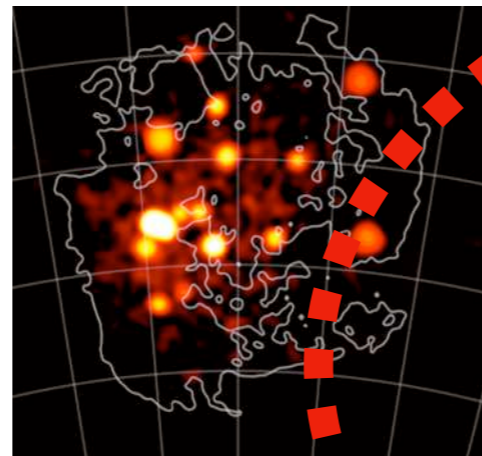
Clusters of galaxies



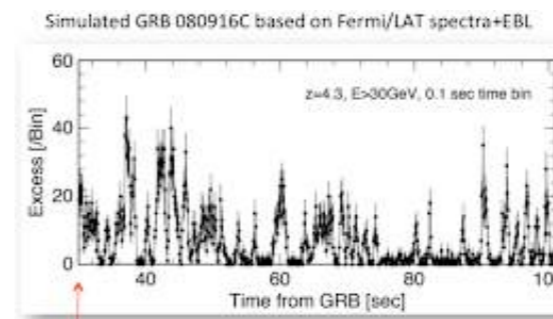
Galactic center



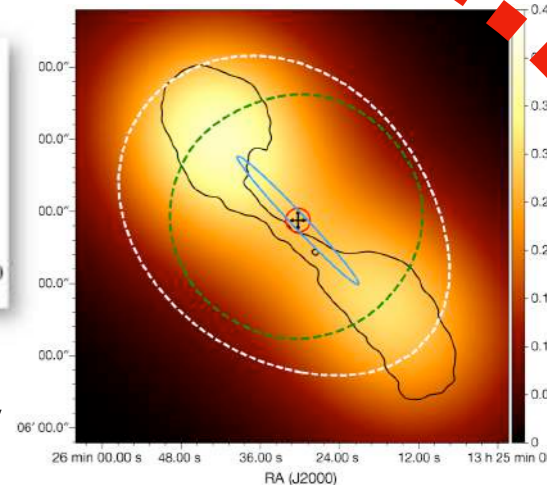
Novae



LMC survey



Transients (GRBs/supernovae)



AGN + jets

CTA: multi–messenger program (transients!)

1. **Gamma ray bursts:** external alerts from various facilities. Few GRBs/year expected
2. **Galactic transients:** PWNe, X-ray binaries, Novae expected from regular GPS monitoring
3. **High energy neutrino transients:** follow-up interesting events to maximize chance of counterpart
4. **GW transients:** follow-up with large FoV (divergent pointing strategy)
5. **Core-collapse Supernovae:** not detected yet

CTA: multi–messenger program (transients!)

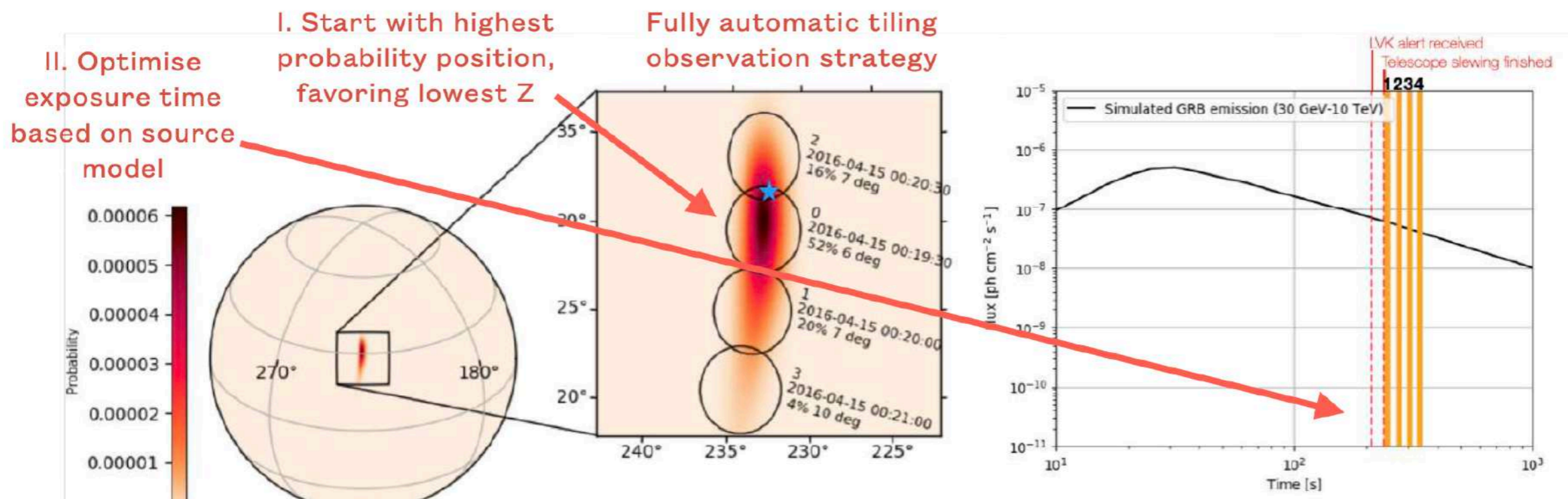
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Ability to receive alerts from many facilities: « *transient handler* »
Ability to deliver alerts to the external community in near-real-time

CTA: multi-messenger program (transients!)

Regular (1-3 per week) follow-up observations of GW-GRBs and neutrino alerts

1. **Optimal pointing pattern:** to cover the largest total uncertainty region (10-1000 deg²)
2. **Optimal pointing cadence:** exposure time to reach 5-sigma
3. **Site coordination:** to prioritize best observational conditions
4. **Divergent pointing mode:** to increase FoV



CTA: multi–messenger program (transients!)

Preparation of observations, study of strategies of detection and follow-up programs, using synthetic populations:

GRB population study: POSyTIVE (Bernardini et al. 2019)

NS-NS mergers: GWCOSMoS (Patricelli et al 2018)

Neutrino source population: FIRESONG (Tung et al. 2021)

CTA: multi-messenger program (transients!)

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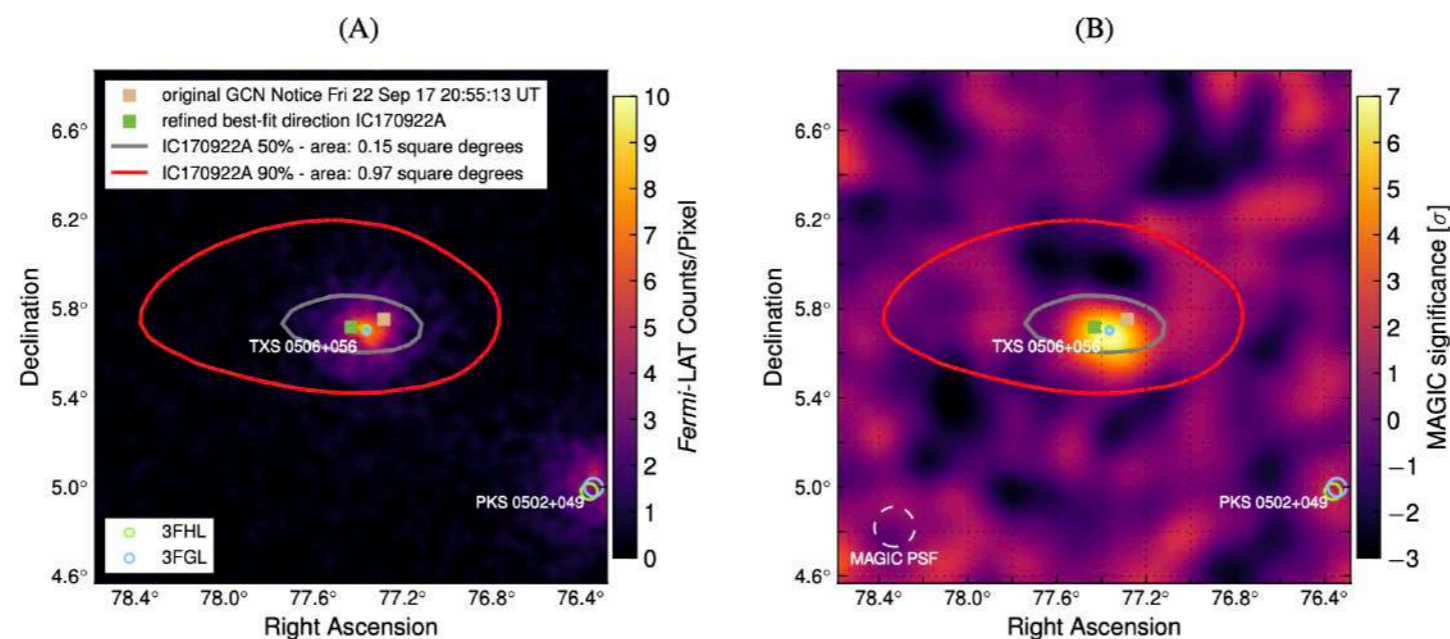
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Example: Neutrinos!

IceCube IC-170922A associated to flaring gamma-ray blazar TXS 0506+056



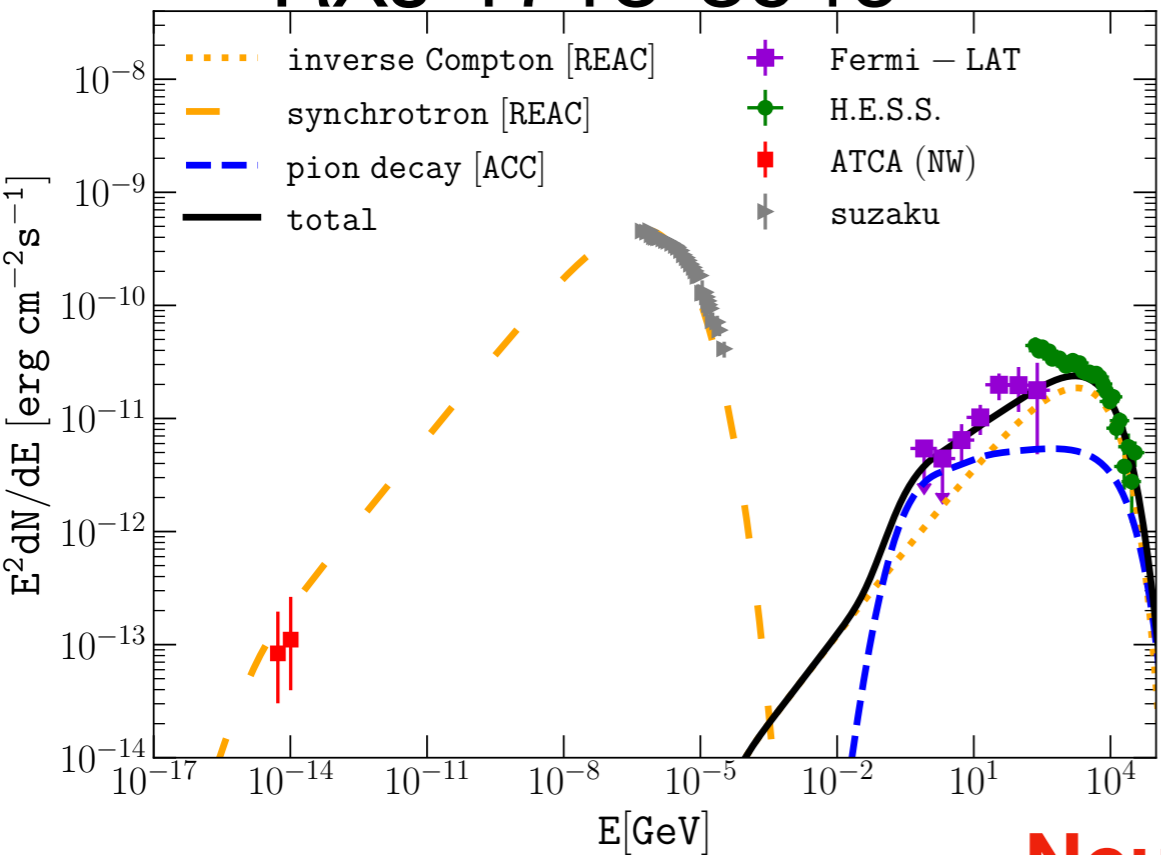
Neutrinos accompanied by VHE gamma rays from pp and py : **in 1/3 of cases, detection with CTA in 10 minutes** (Satalecka 2019, Bosnjak 2021)

CTA NToO : Neutrino target of opportunity program

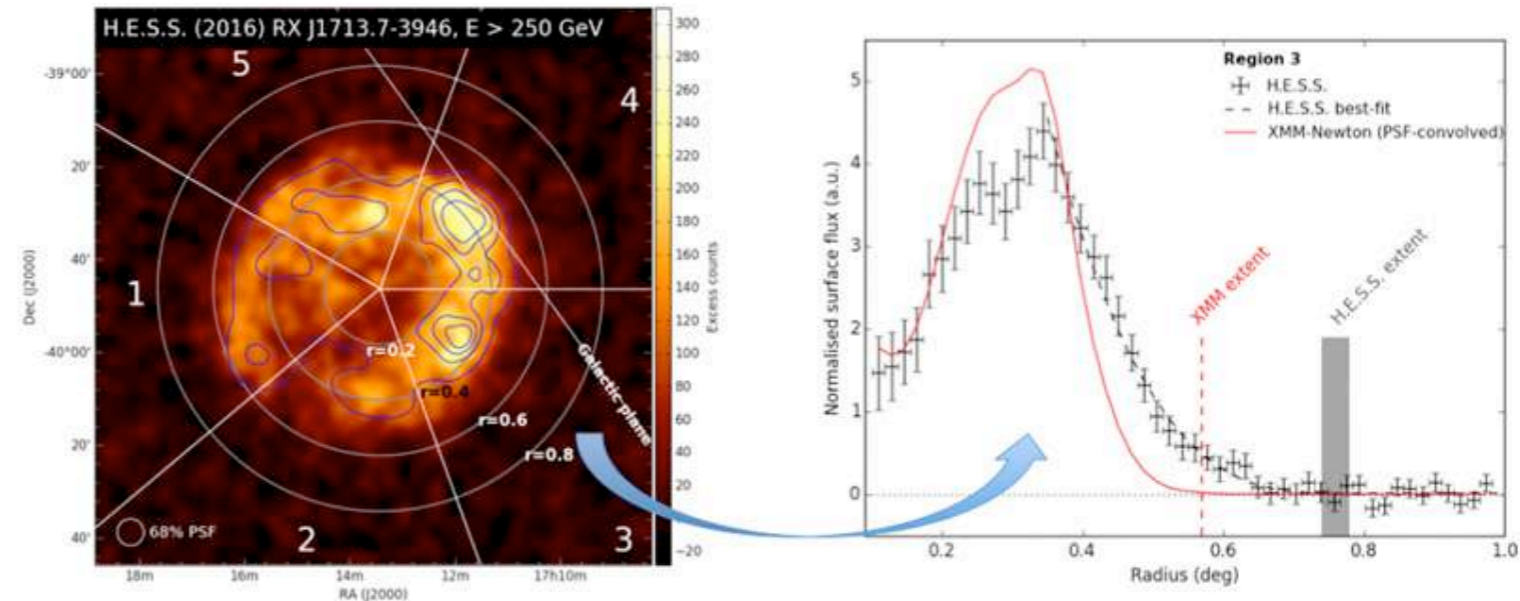
CTA: multi-messenger program, not only transients!

Supernova remnants: MWL + neutrinos

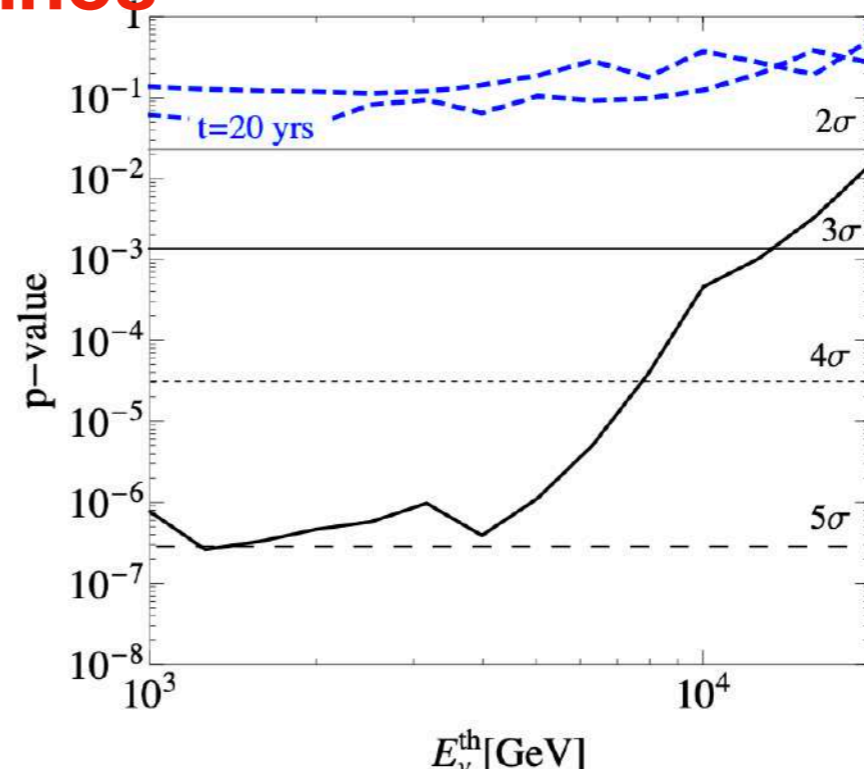
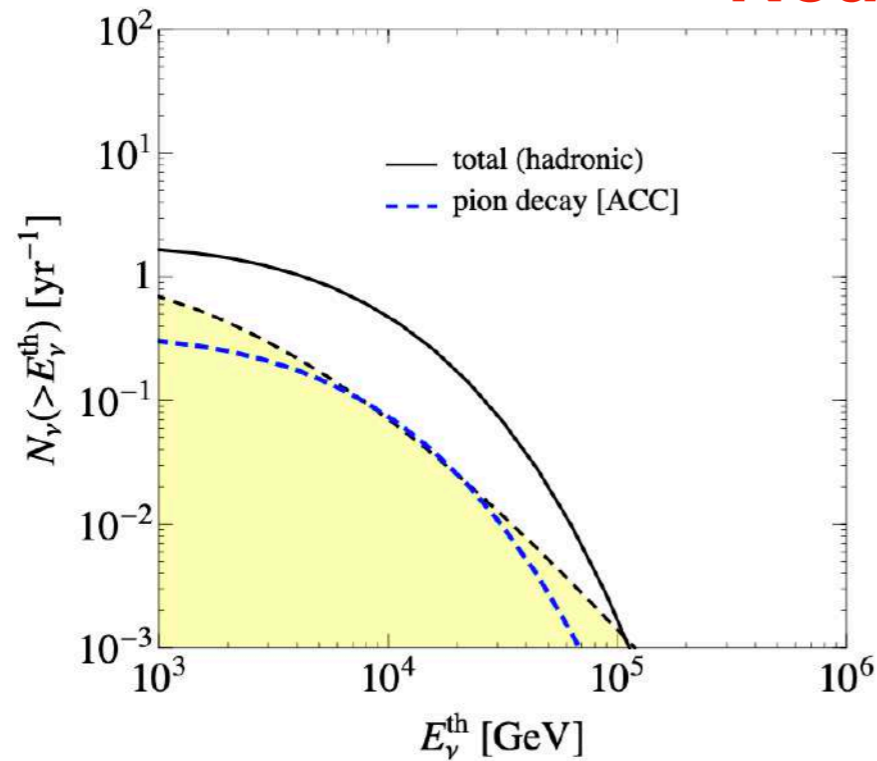
RXJ 1713-3946



Morphology + X/TeV correlation



Neutrinos

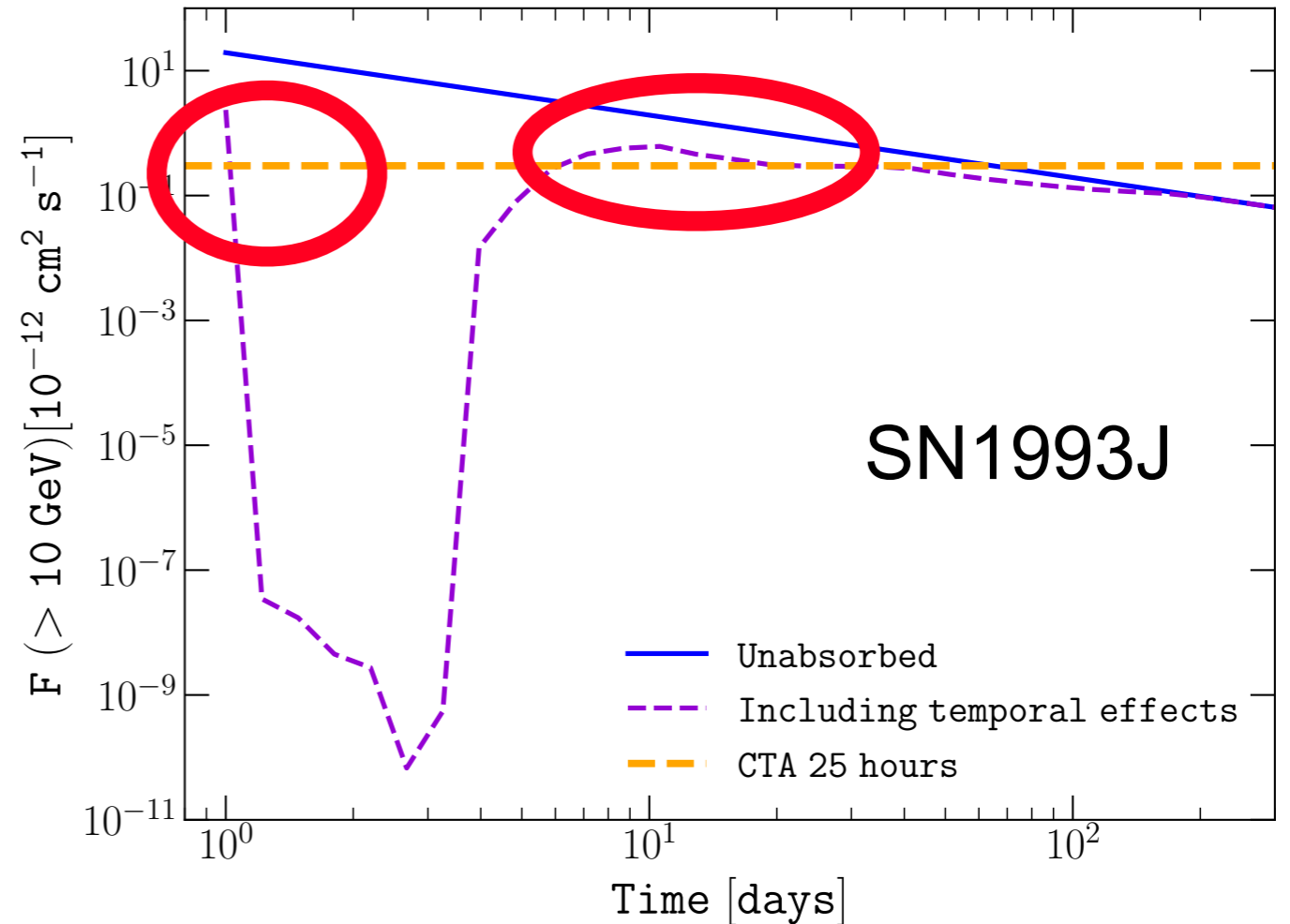
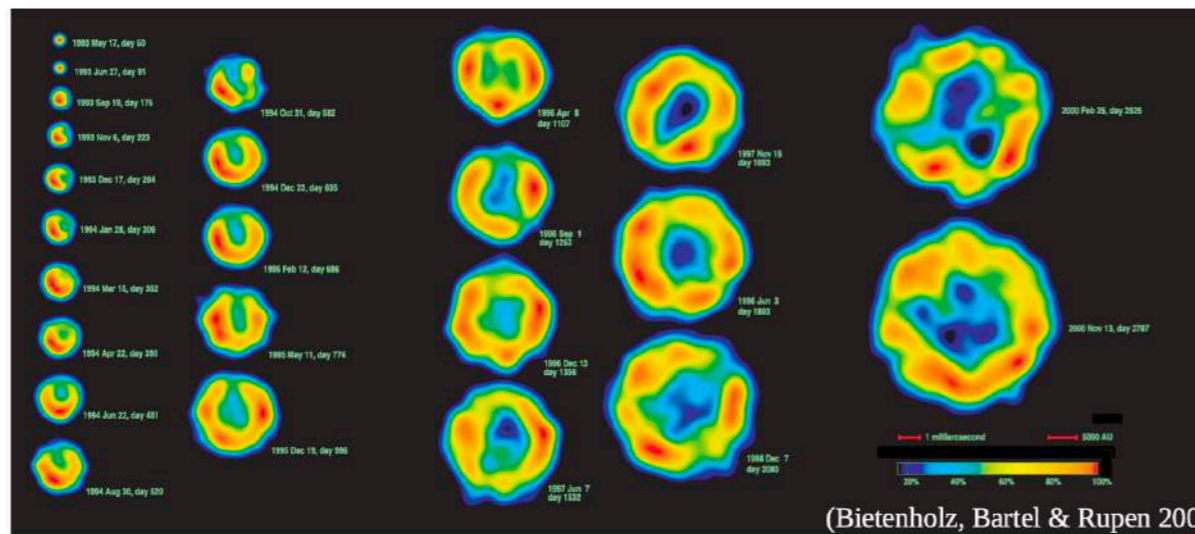


H.E.S.S./XMM

Core-collapse supernovae (extragalactic), not yet detected in the VHE domain

Modeling particle acceleration and gamma rays

$$\gamma\gamma \rightarrow e^+e^-$$



Detectability and strategy of detection with CTA

(Article CTA consortium)

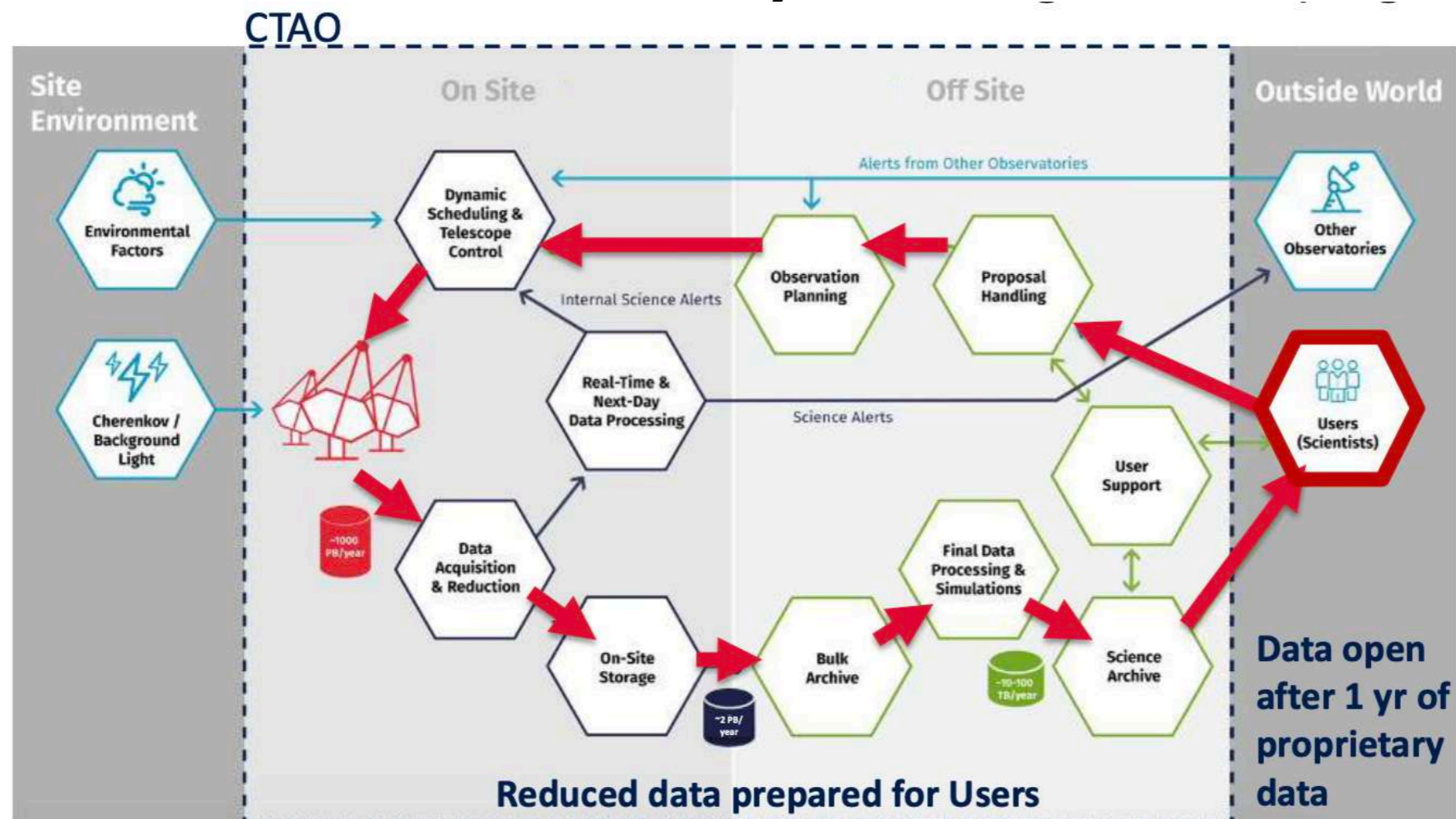
Observations triggered from other observatories (case of SN2023ixf)
MWL + neutrino follow-up

CTA: an open observatory

Data + analysis software available to everyone (after 1 year proprietary period)

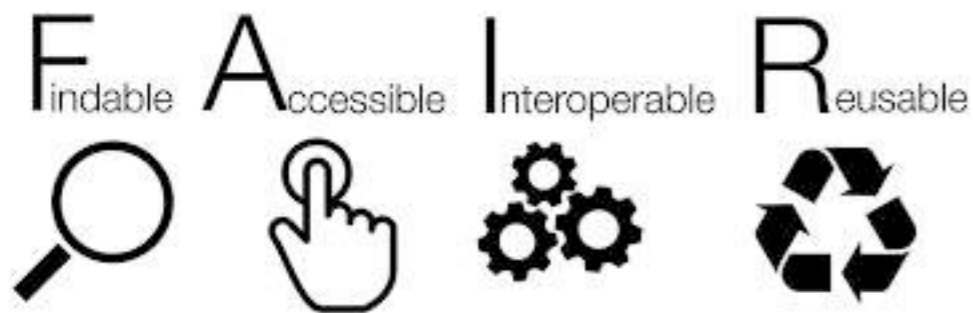
Open observatory: allows external teams to propose observational programs

Open data: essential for MM science, data archives accessible to everyone



CTA: an open observatory

**Data + analysis software available to everyone (after
1 year proprietary period)**



Donath, Terrier et al. 2023

**Work on Data model,
format, access portal,
Data challenge 2024**

Servillat, Boisson et al. 2022

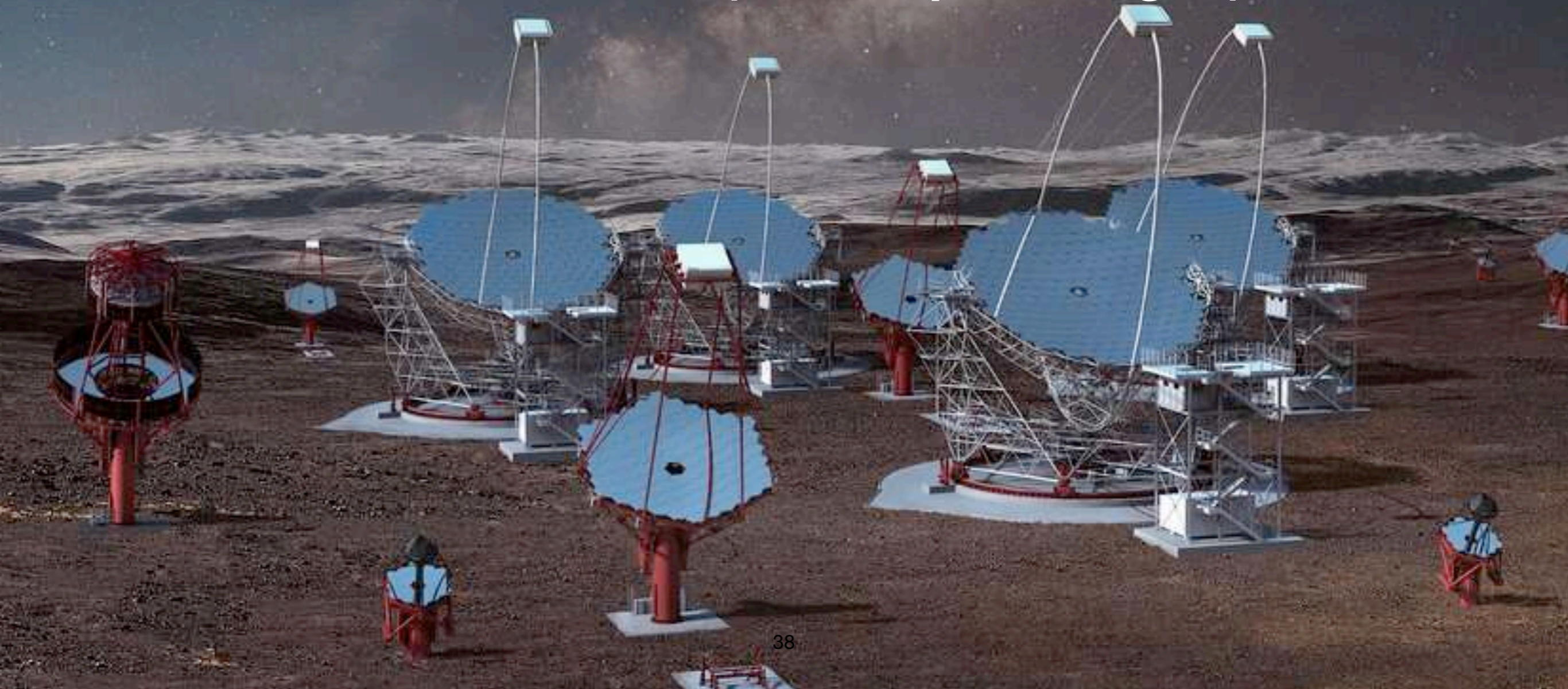
Take away

LST-1 already taking data

More LSTs+ SSTs by 2025

VHE follow-up + alerts for various candidates (blazars, neutrino sources, supernovae, Galactic transients + many more)

« CTA France » (talk Stephen Fegan)



CTA in the MWL & MM era

