



**CBPF**

Centro Brasileiro  
de Pesquisas Físicas

UNIDADE DE PESQUISA DO MCTI

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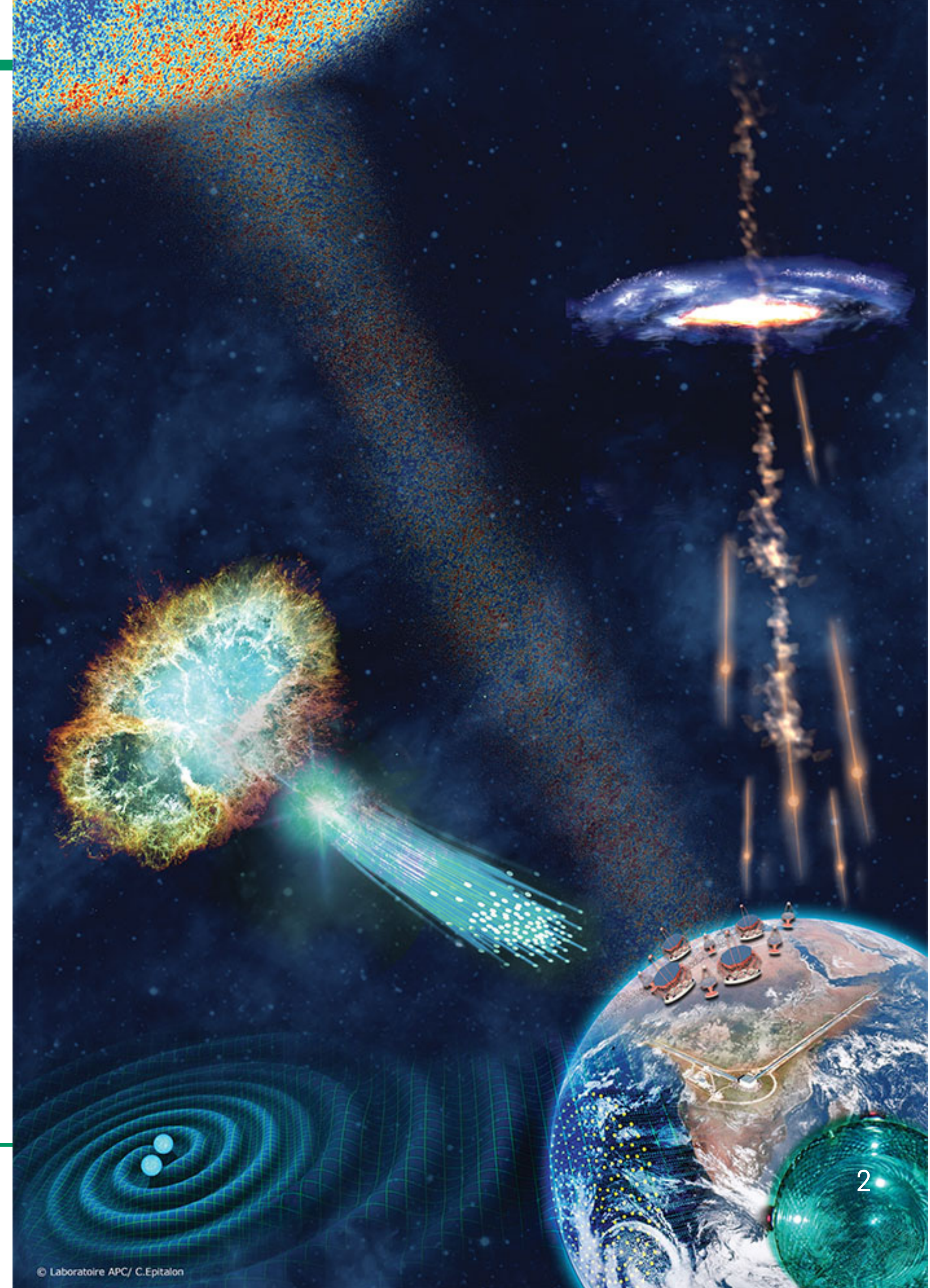
# CTA : Multi-wavelength and Multi-Messenger Activities and Perspectives

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ULISSES BARRES DE ALMEIDA - APRIL 2022 - INFN / UNIV. TRIESTE

# Content

- 1. Brief introduction**
- 2. Setting up the stage**
- 3. The CTA context**
- 4. CTA coordination activities**
- 5. Towards the UHE regime**

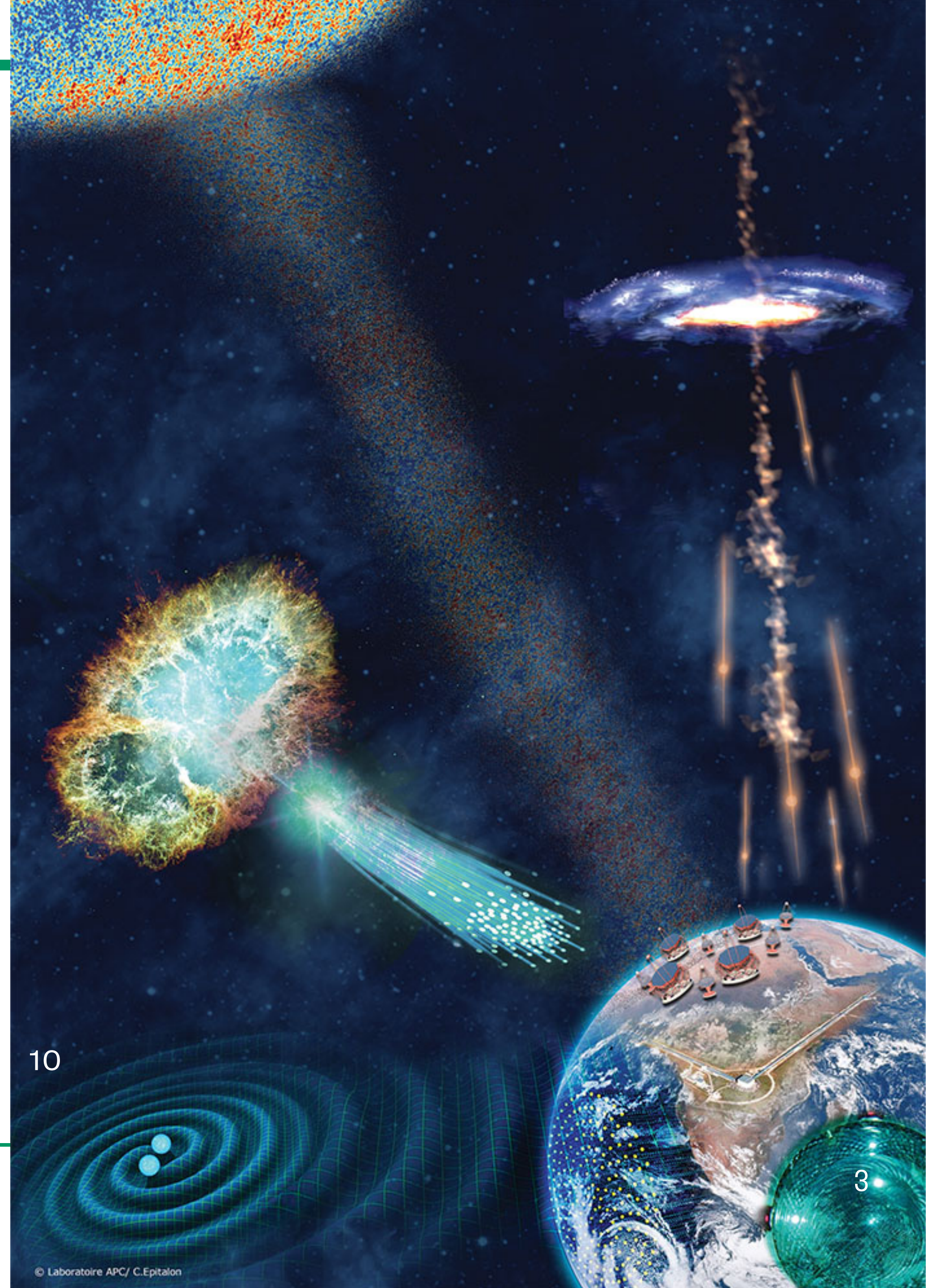


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# Brief Introduction

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ULISSES BARRES DE ALMEIDA - AVRIL 2022



10

3

# Astroparticle Physics : MM scenario



© adapted from a slide by Johannes Knapp



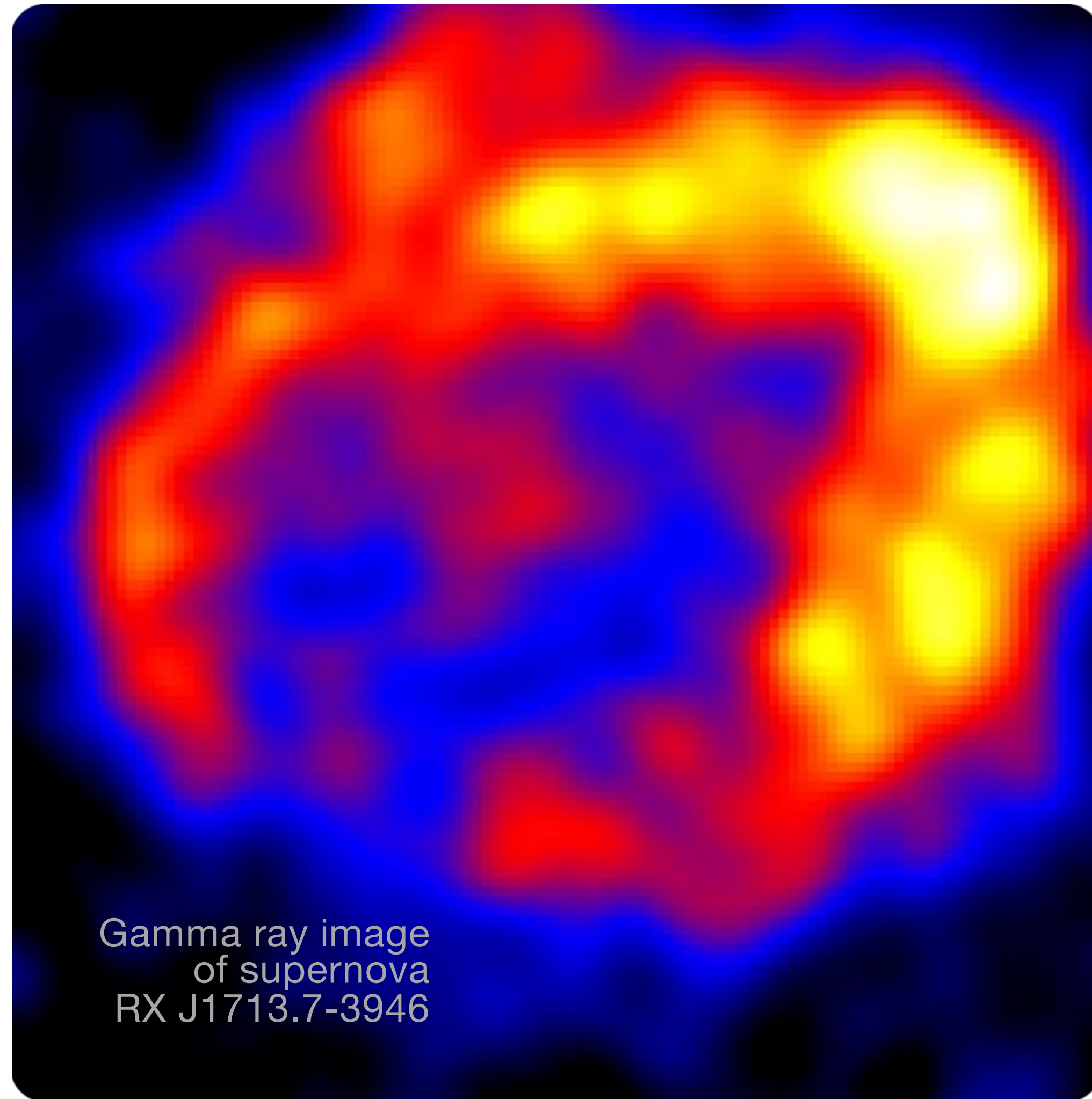
**Astronomy with photons**

**Charged cosmic-ray physics: p, e<sup>-</sup>, He, Fe, ...**

**Neutrino signals**

All messengers are interconnected and relate back to the same sources: multi-messenger astrophysics

# Status of ground-based gamma-ray astronomy



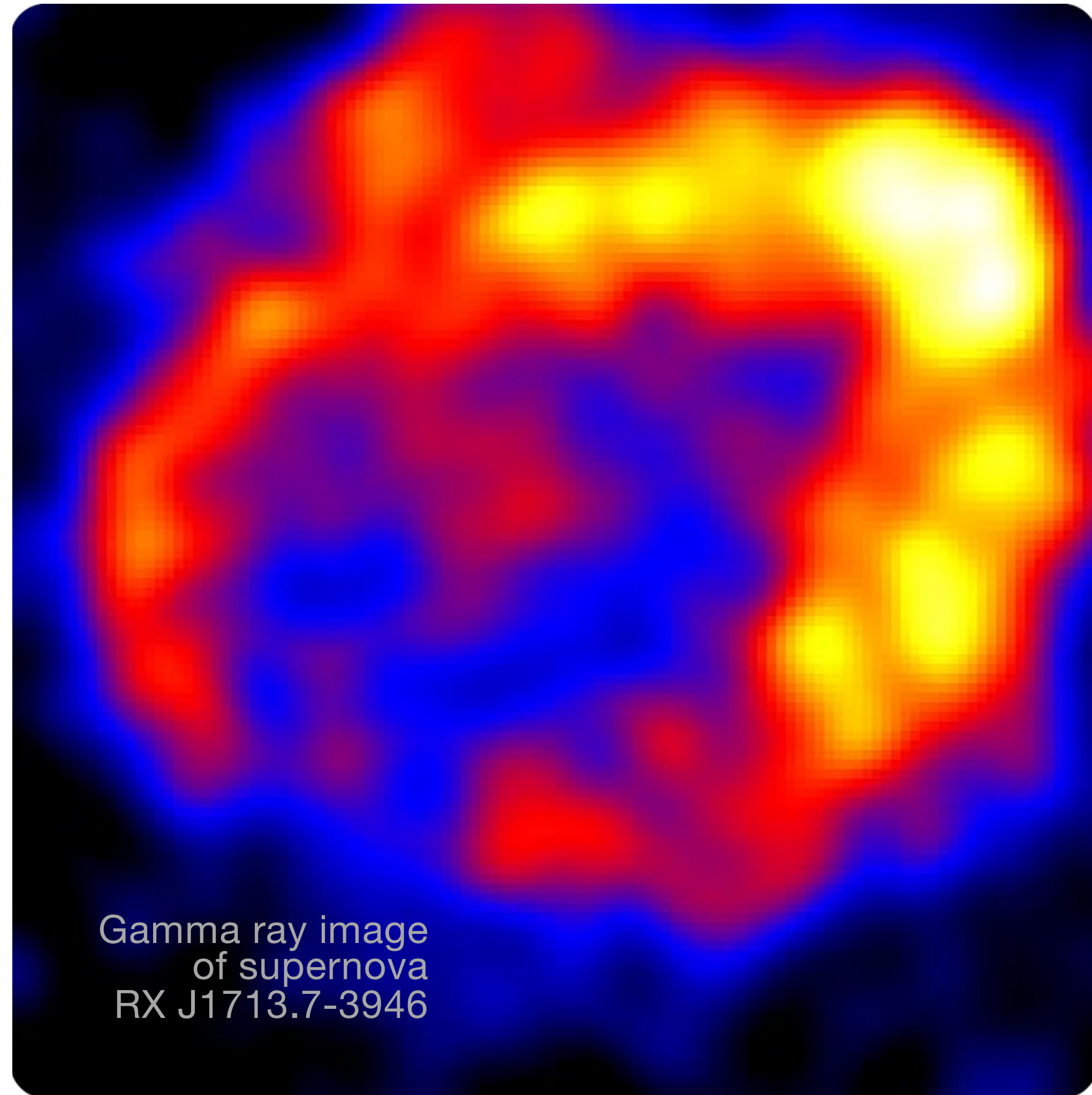
**Cherenkov Astronomy has reached the status of "real astronomy"**

- good-resolution skymaps,  $\sim 5'$
- 200+ sources detected
- spectra from c. 30 GeV to 30 TeV
- times resolved light curves down to minute timescales

**The recipe of the success?**

- efficient gamma-hadron separation + stereoscopy
- large light collection, mirror areas 100+ m<sup>2</sup>
- sensitive cameras, small-pixel sizes  $\sim 0.2^\circ$
- large field of view of several degrees

# Status of ground-based gamma-ray astronomy



**Cherenkov Astronomy has reached the status of "real astronomy"**

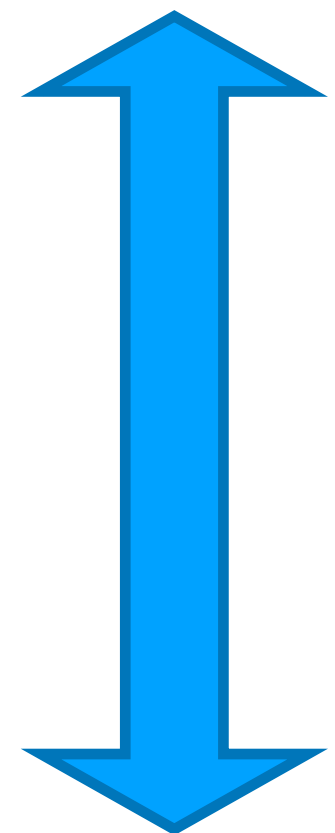
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**The recipe of the success?**

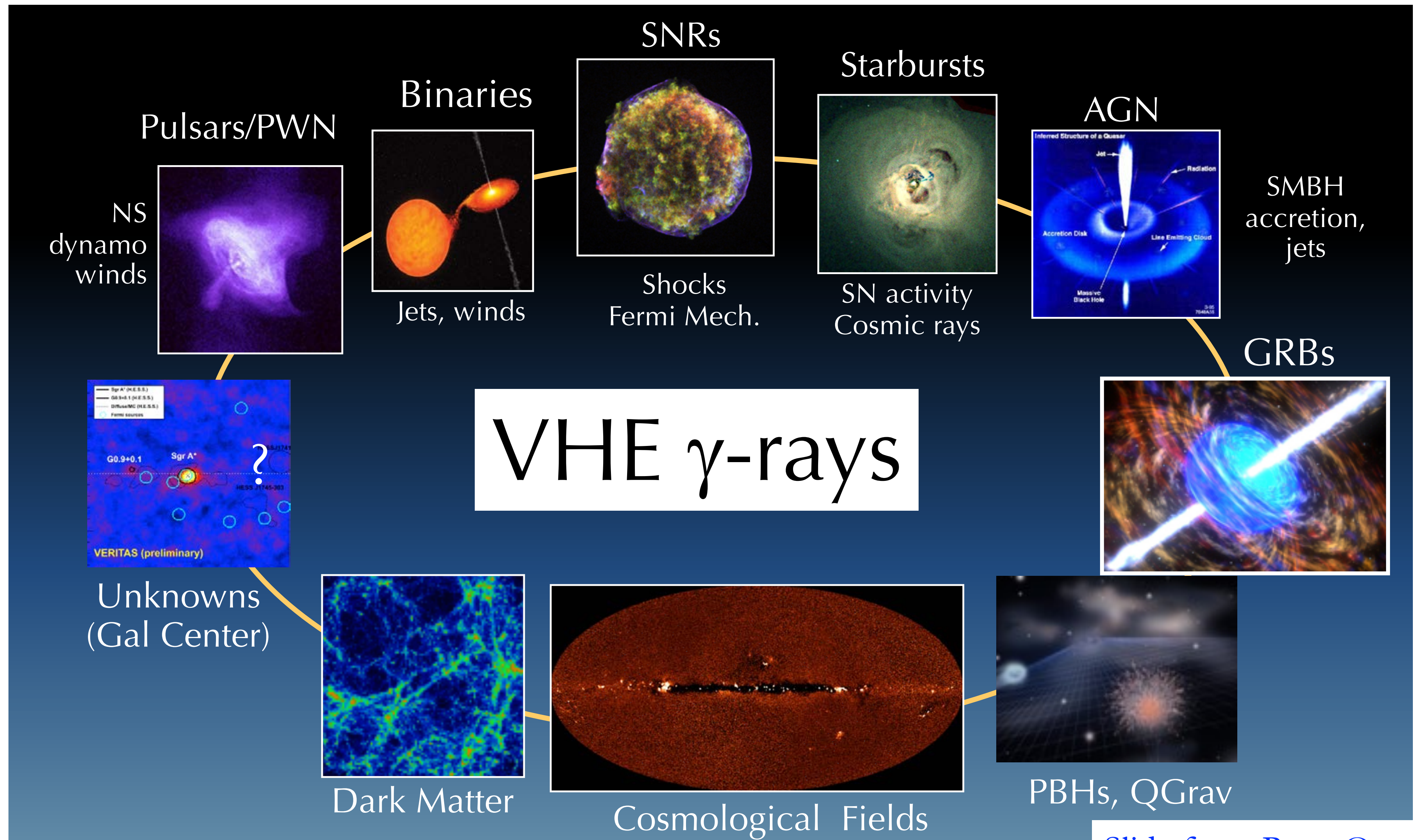
**Also for ground-particle arrays...**

- very-high altitude arrays,  $> 4$  km a.s.l.
- dense / calorimetric measurement of the EAS particles
- large array areas,  $\gg$  shower footprint
- large muon effective areas

# Non-thermal Astrophysics

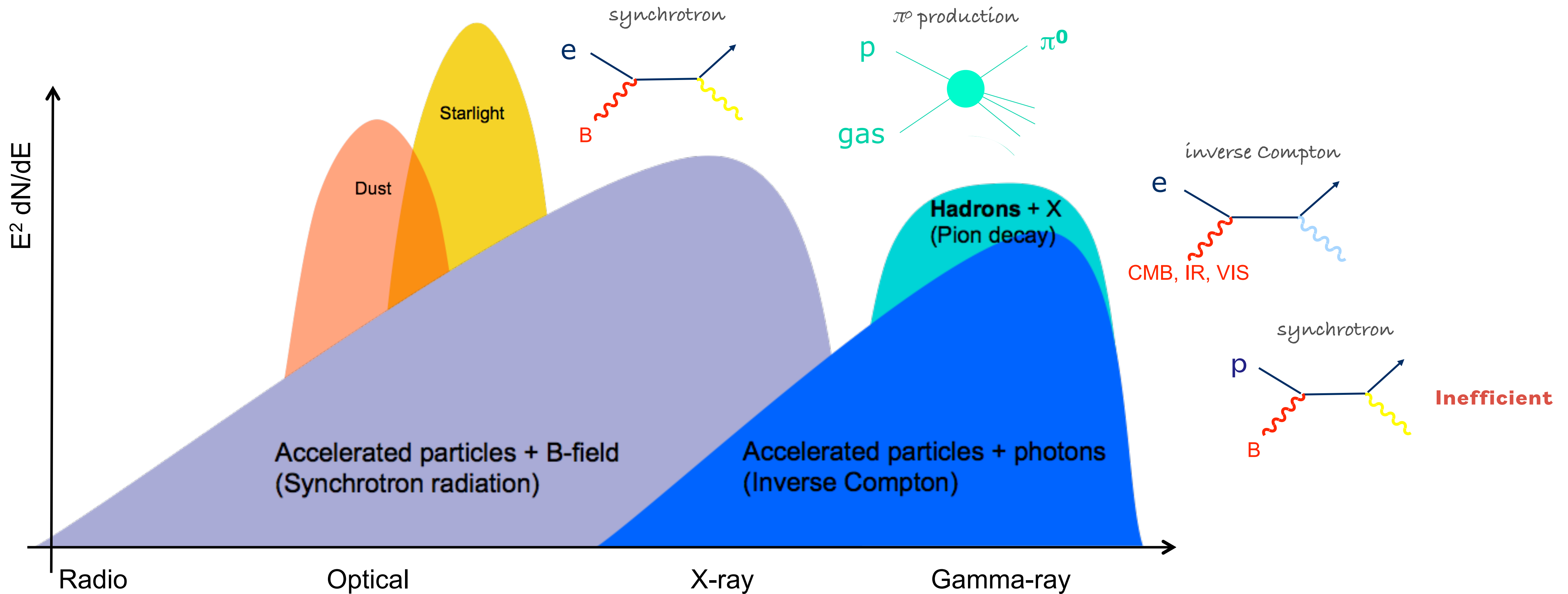


# Astro-particle Physics



Slide from Rene Ong

# Anatomy of a relativistic astrophysical source

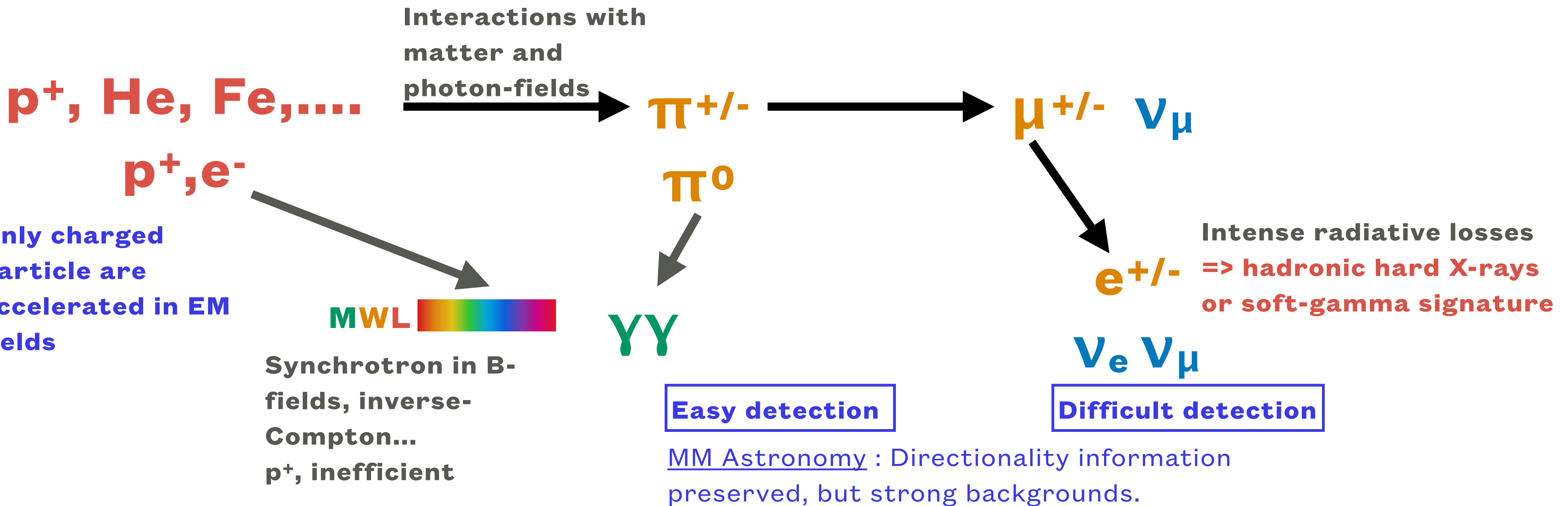


© plot by Christian Stegmann, DESY, MG XIV Meeting 2015 (modified)



# Connecting the puzzle

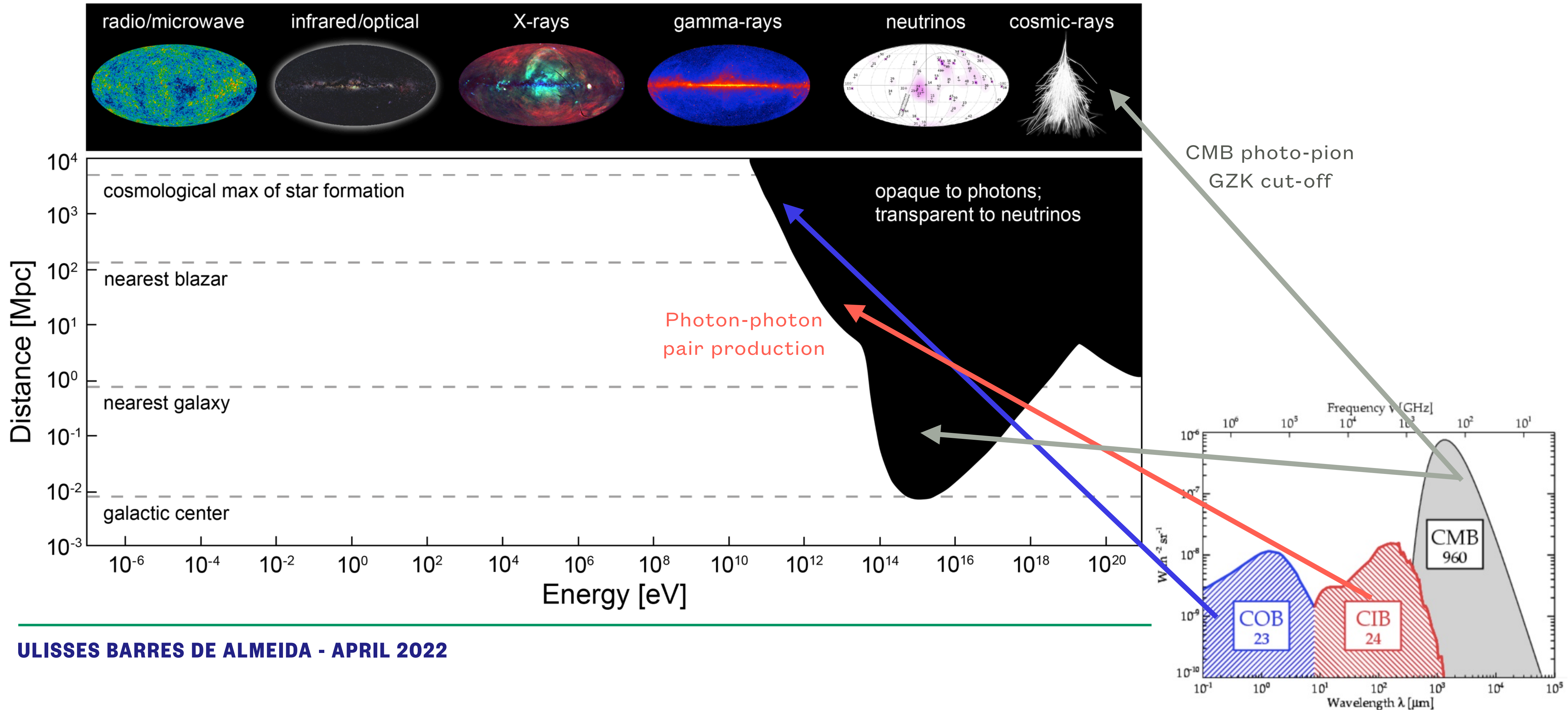
All messengers are connected and relate back to the same sources: logic behind the multi-messenger astrophysics



**Gamma-rays are the cornerstone of multi-messenger astrophysics**

© adapted from a slide by Johannes Knapp

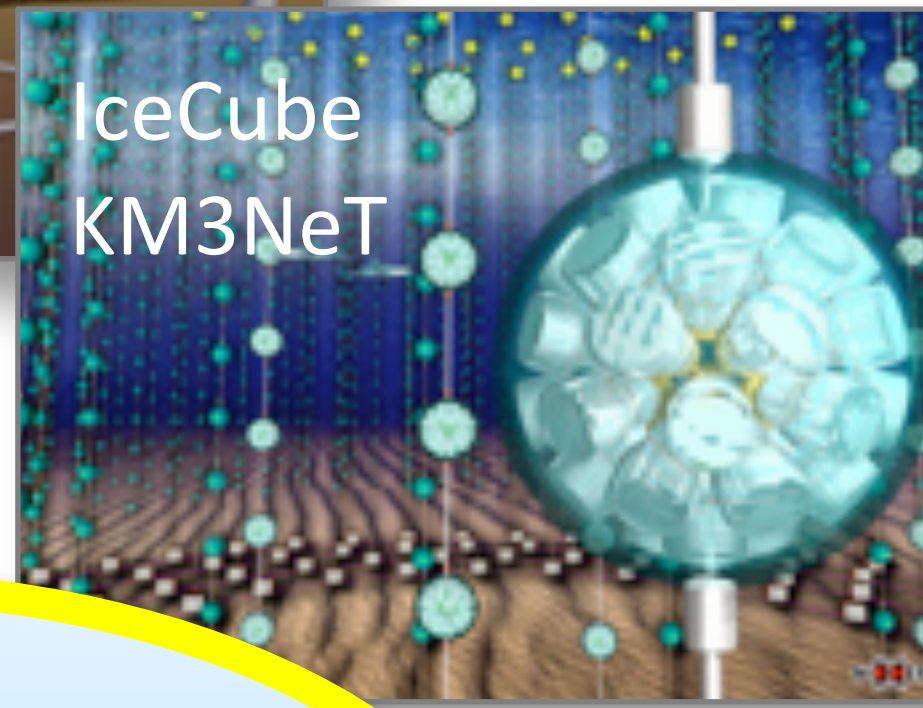
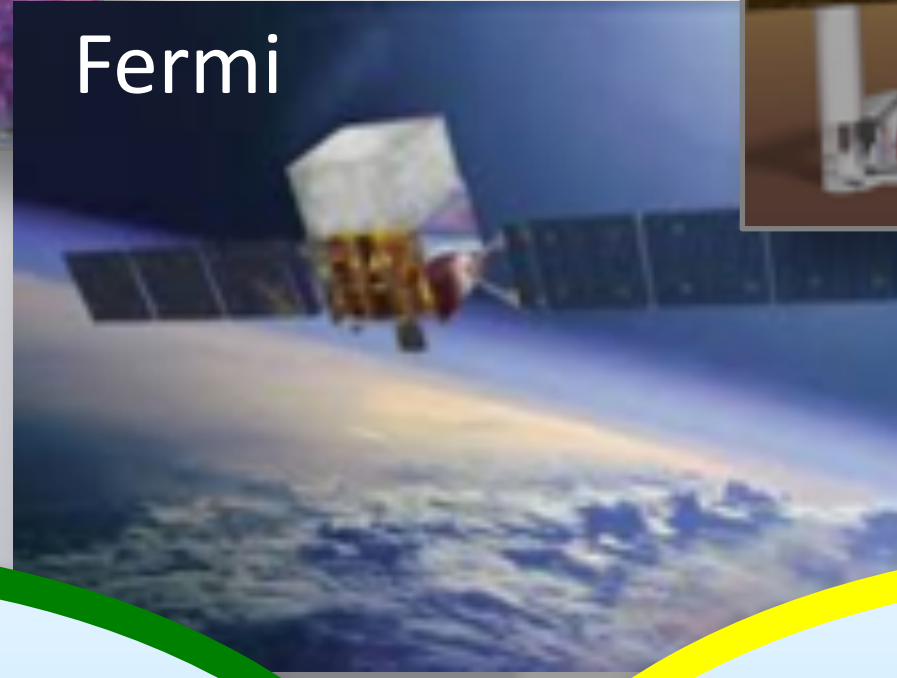
# Neutrinos : probe of deeper horizon, denser environments



# CTA SYNERGIES WITH MWL INSTRUMENTS



© slide by Werner Hofmann



Target selection & ToOs

Object characterization

Wide-band / MM SED



# CTA SYNERGIES WITH MWL INSTRUMENTS



© slide by Werner Hofmann, modified



- **Non-thermal emission in radio**
- **High-resolution VLBI to image emission zones**
- **Mapping of the diffuse gas (CR targets) to complement CTA view of diffuse emission around accelerators**

- **Detection of fast-variability signals from compact sources**
- **Optical polarimetry to isolate non-thermal component in mixed emission scenarios**

- **X-ray study of shock regions, accretion, high-speed outflows, which connect back to particle acceleration**
  - **Soft gamma-ray telescopes for detection of high-energy transients**

**MWL**

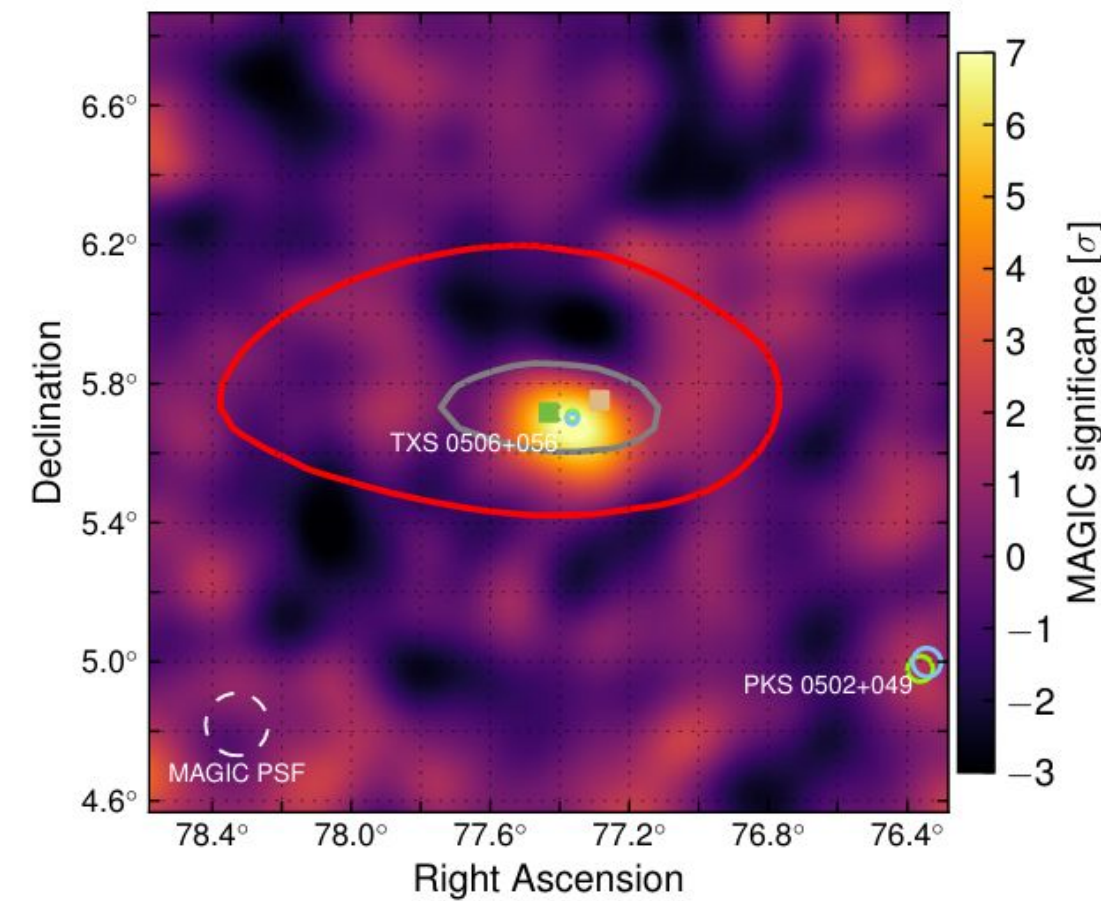


# Multi-messenger Phenomenology

Multi-messenger Astrophysics has emerged in the past decade, with gamma-ray astronomy at its very center.

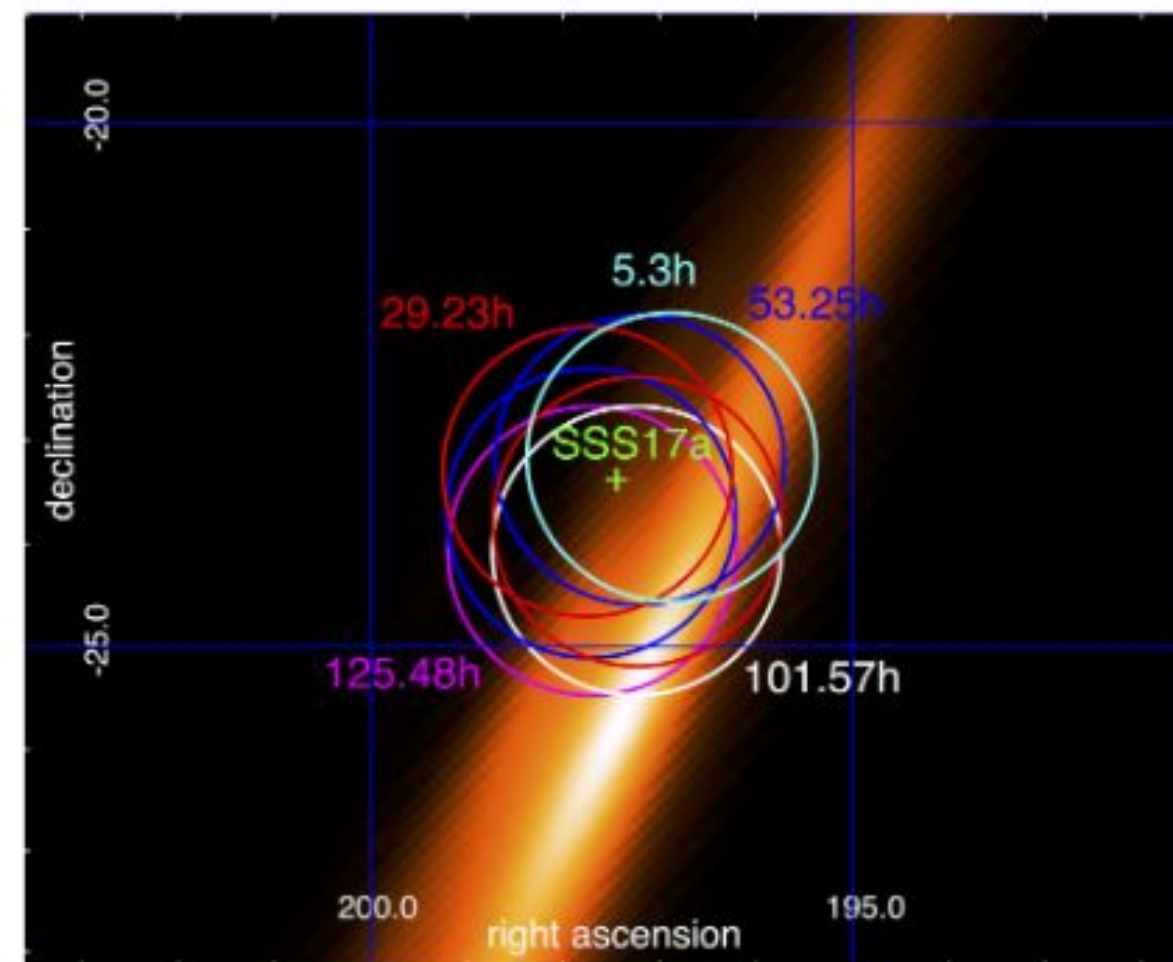
- Attempt at a neutrino / VHE connection for TXS 0506+056

IceCube / Fermi-LAT / MAGIC  
2018 - Science 361, 6398



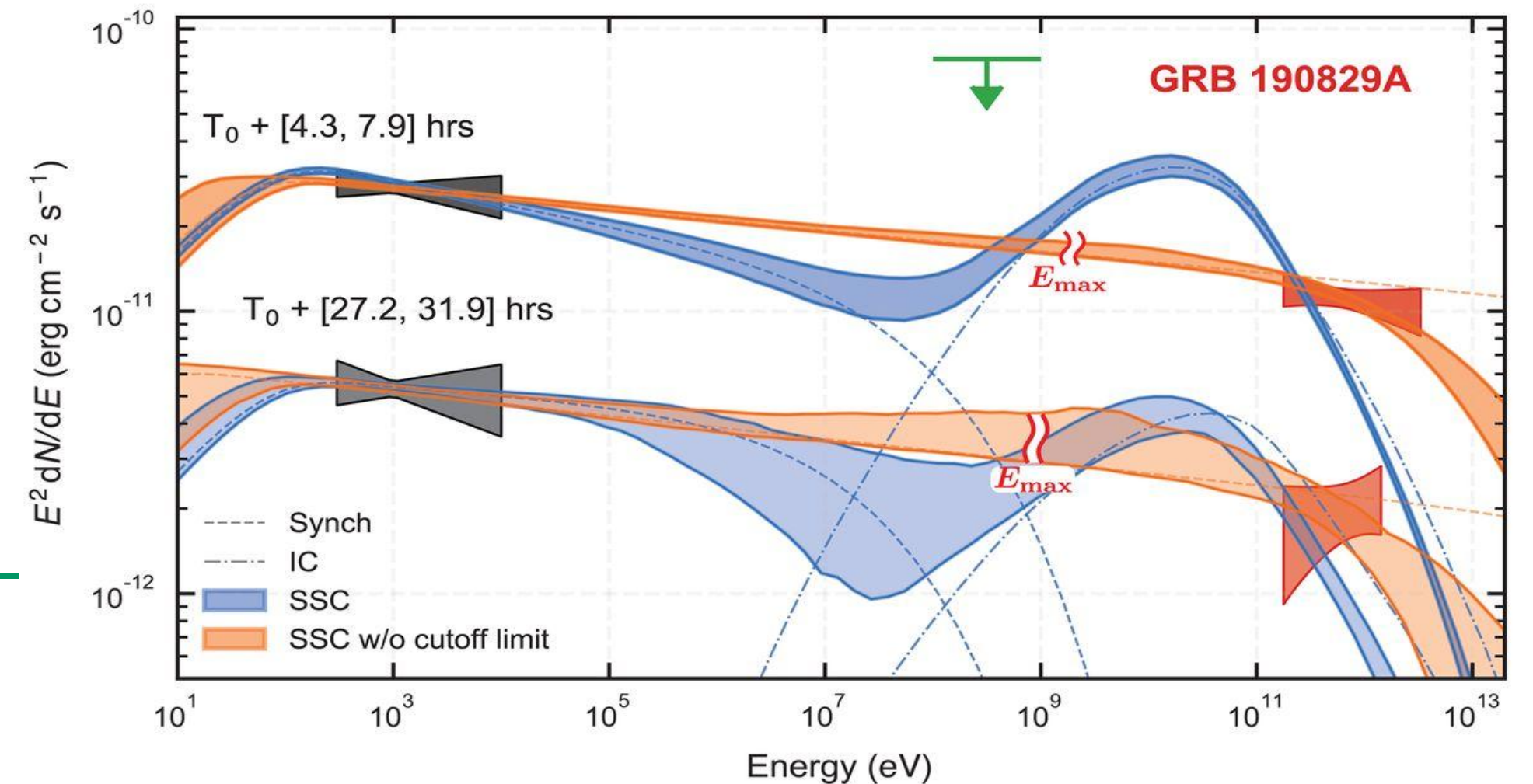
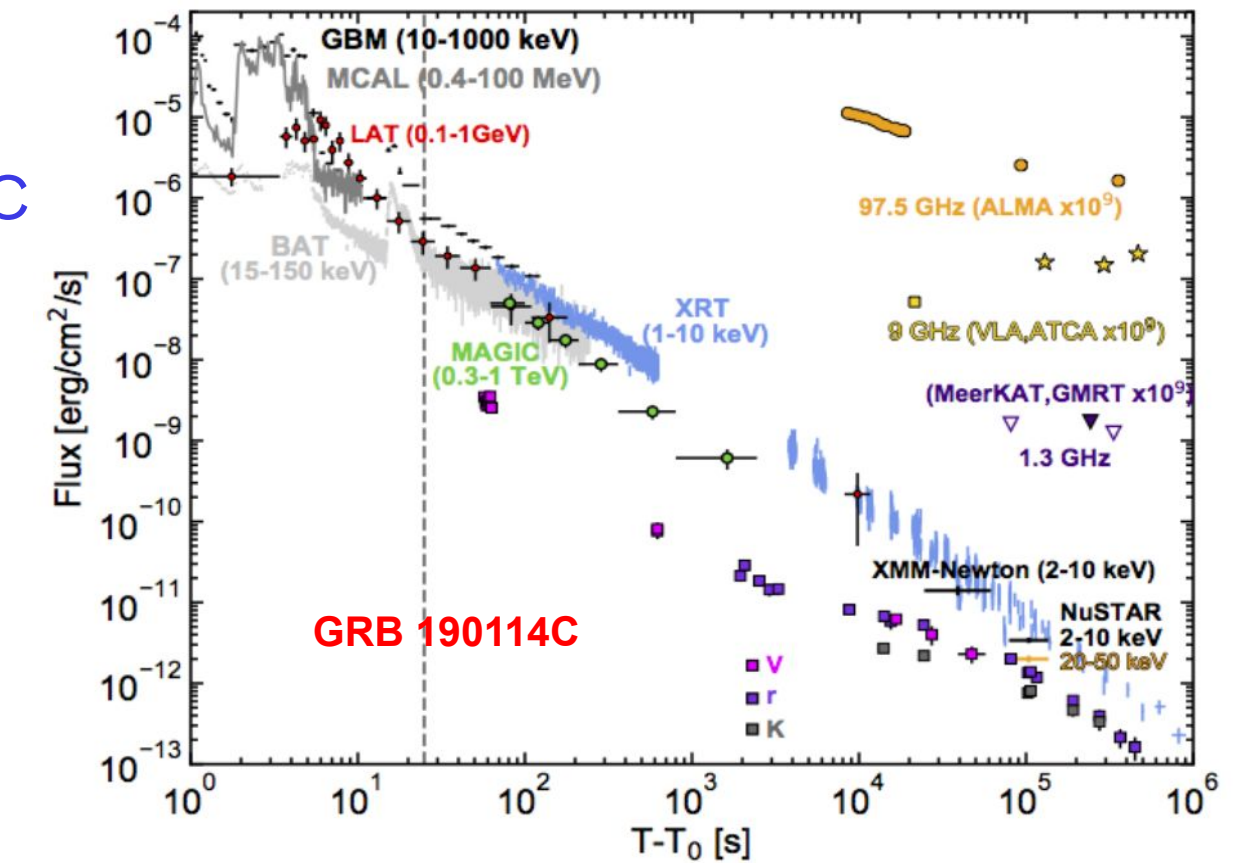
- TeV Observations of event GW 170817

Upper-limits from HESS.  
2017 - ApJL 850, L22  
Upper-limits from Fermi-LAT.  
2018 - ApJ 861, 85



- GRB detection at VHE: a breakthrough and a gateway to probing GW events at TeV energies

GRB 190114C / MAGIC  
early afterglow detection (< 100s)  
GRB 190829A / HESS  
late afterglow detection (> ks)



# Multi-messenger Phenomenology: Pillars



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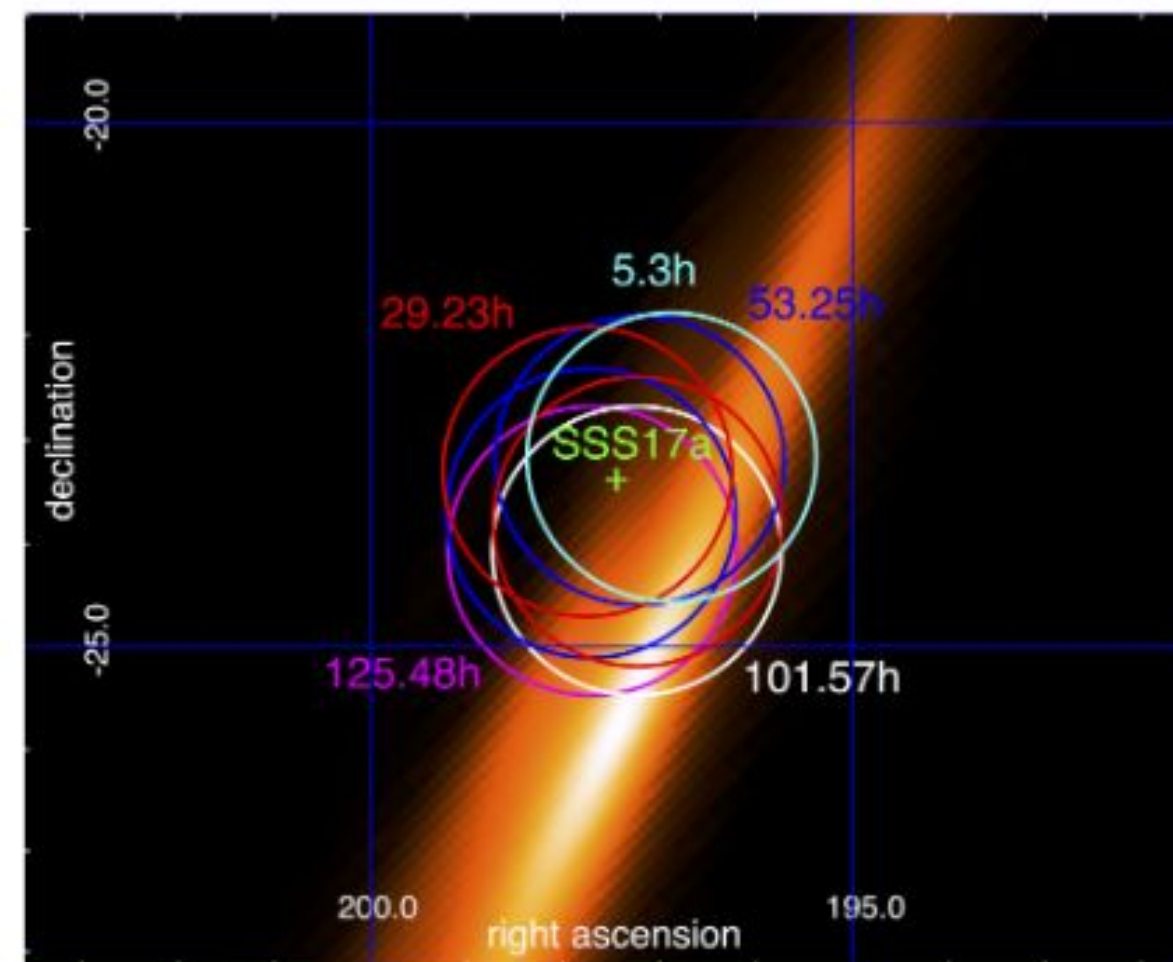
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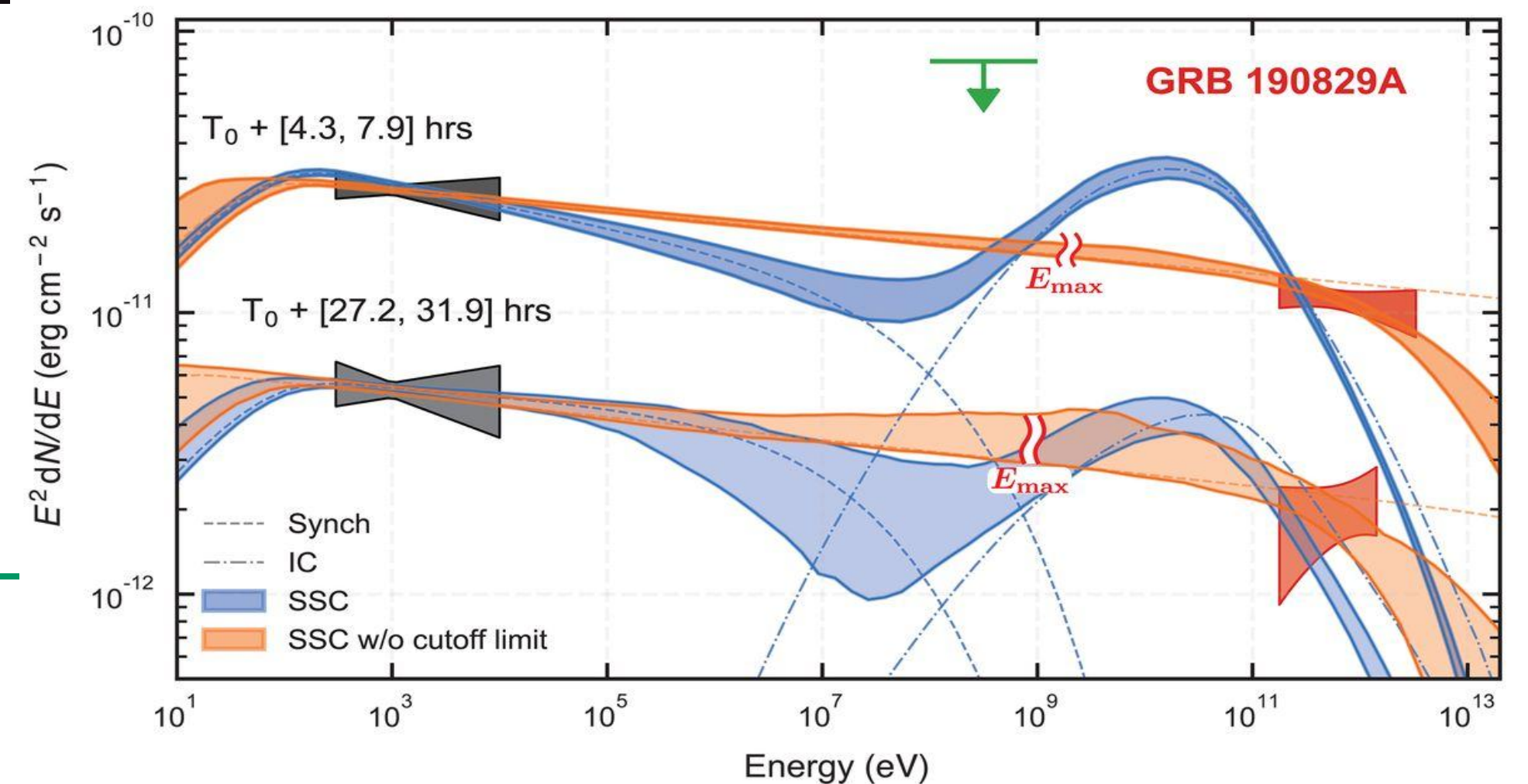
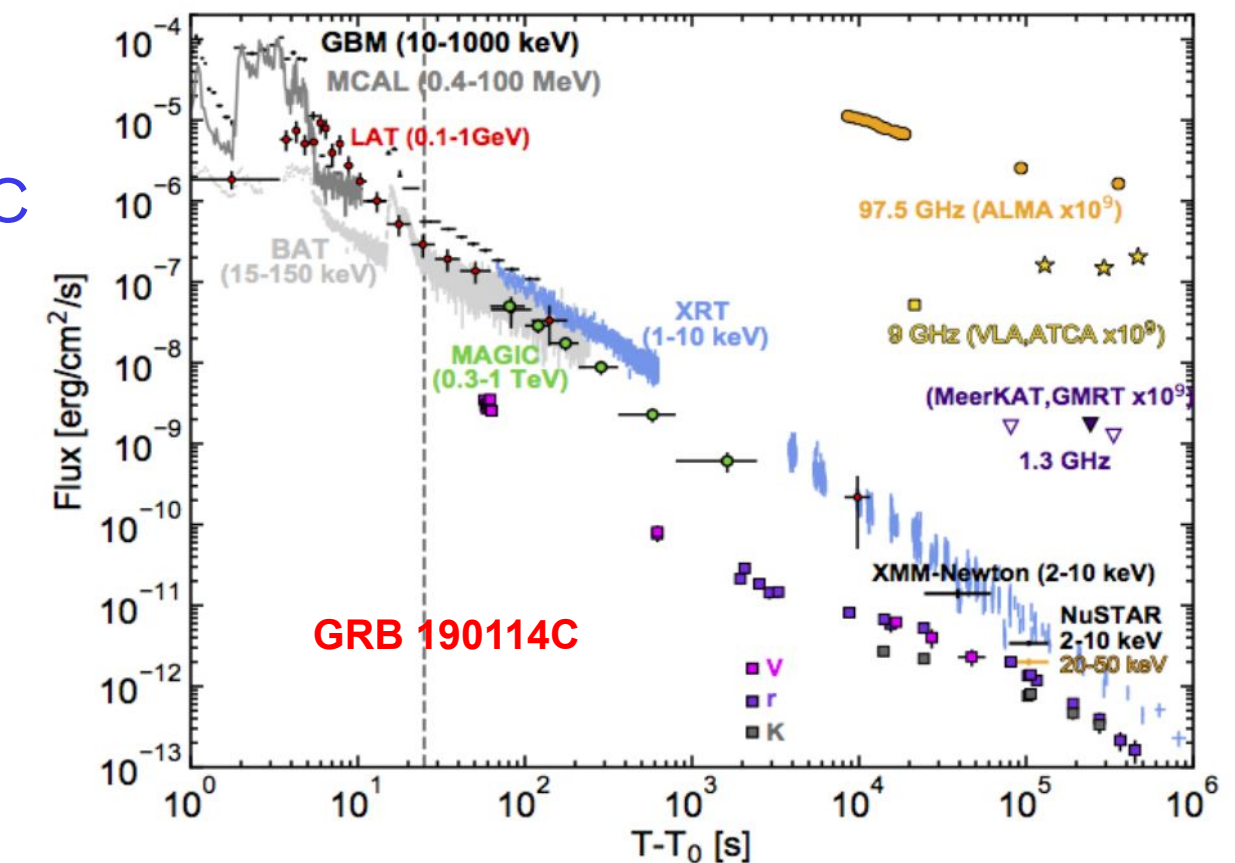
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- GRB detection at VHE: a breakthrough and a gateway to probing GW events at TeV energies

GRB 190114C / MAGIC early afterglow detection (< 100s)  
GRB 190829A / HESS late afterglow detection (> ks)



# WHAT DRIVES HIGH IMPACT SCIENCE?

Number of H.E.S.S Nature & Science papers

Year 

03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21
	1	2	3			2						1	1		1	2	1	1

**New instrument**

CT1  
operat

28 m telescope  
CT5 added

CT1-4 camera  
upgrade

CT5 camera  
upgrade

## MWL/MM:

- Multimessenger observations of a flaring blazar coincident with high-energy neutrino
- A very-high-energy component deep in the gamma-ray burst afterglow
- Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow

## Deep observations:

- The exceptionally powerful TeV gamma-ray emitters in the Large Magellanic Cloud
- Acceleration of petaelectronvolt protons in the Galactic Centre

## New analysis techniques

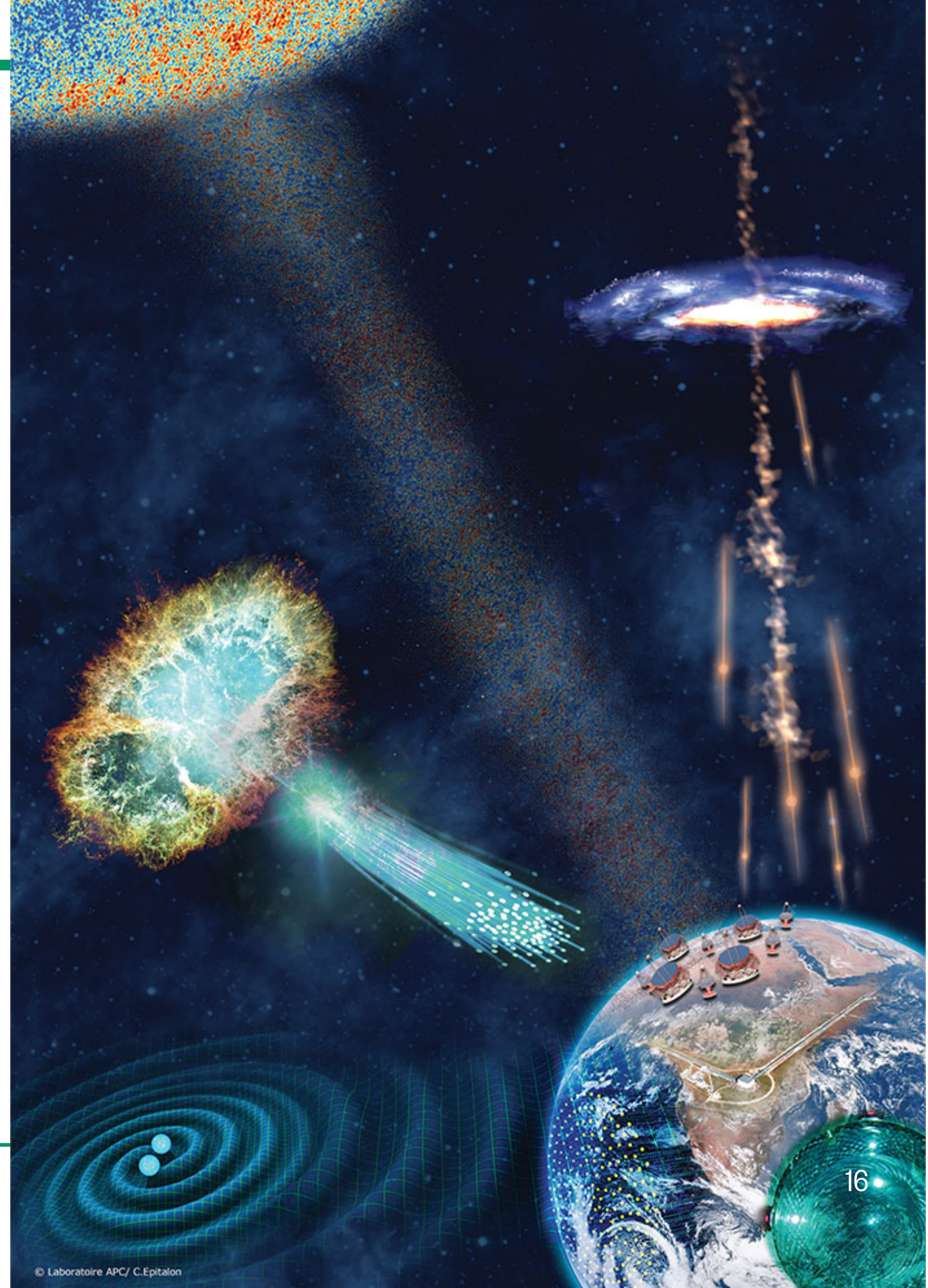
- Resolving the Crab pulsar wind nebula at teraelectronvolt energies
- Resolving acceleration to very high energies along the jet of Centaurus A

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# Setting up the stage

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Cost ~ 330 MEuro for construction (cash + in-kind)  
All construction funds available!

### CTA Observatory (CTAO)

- CTA-North La Palma (1<sup>st</sup> telescope operating!)
- CTA-South in Chile
- CTA HQ, Bologna
- CTA Data Centre, Berlin

### CTA Arrays "alpha" Configuration

- Northern Array: 4 LSTs + 9 MSTs
- Southern Array: 14 MSTs + 37 SSTs

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

Large Sized Telescope LST (23m)

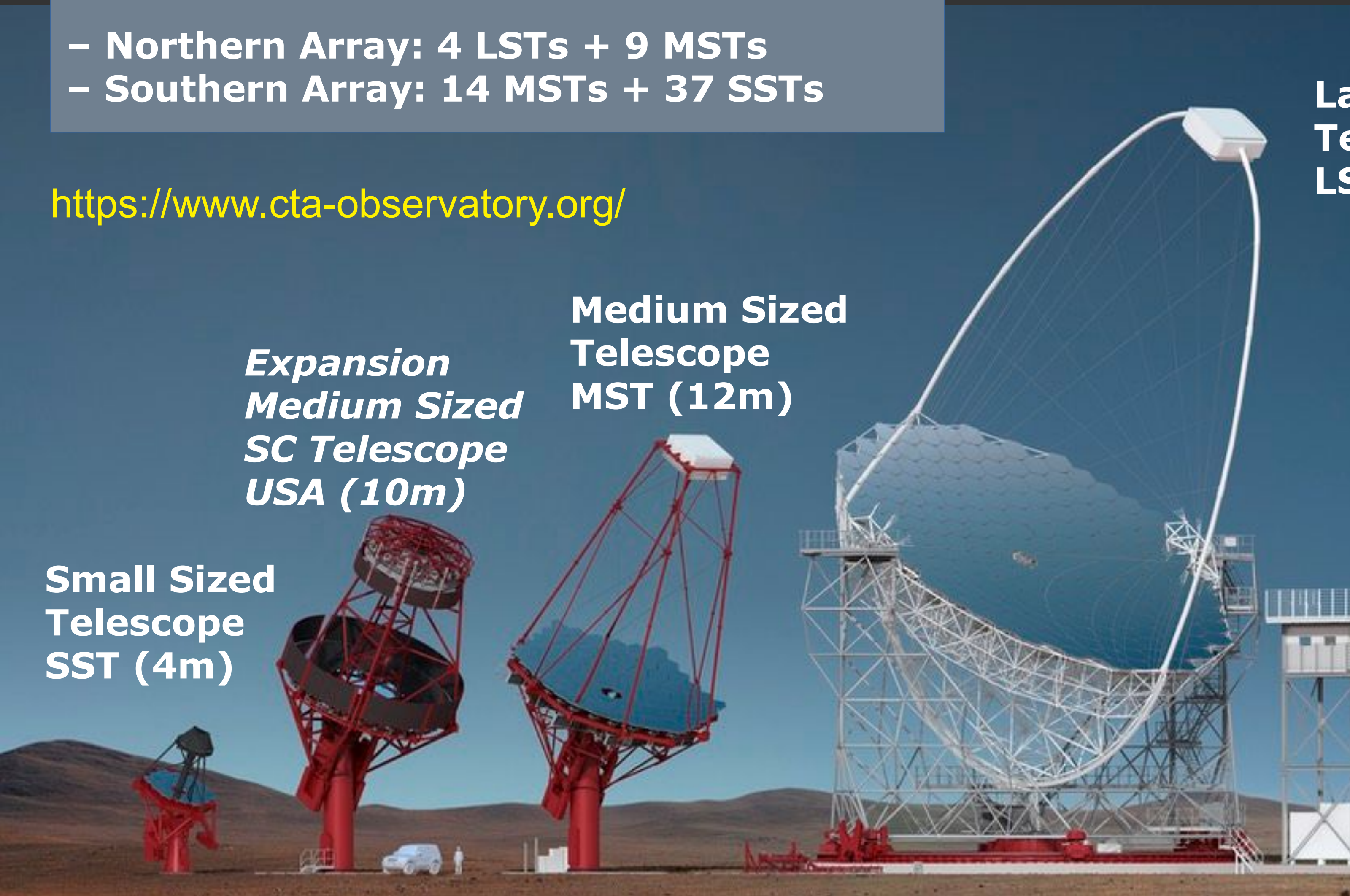


Expansion Medium Sized SC Telescope USA (10m)

Medium Sized Telescope MST (12m)

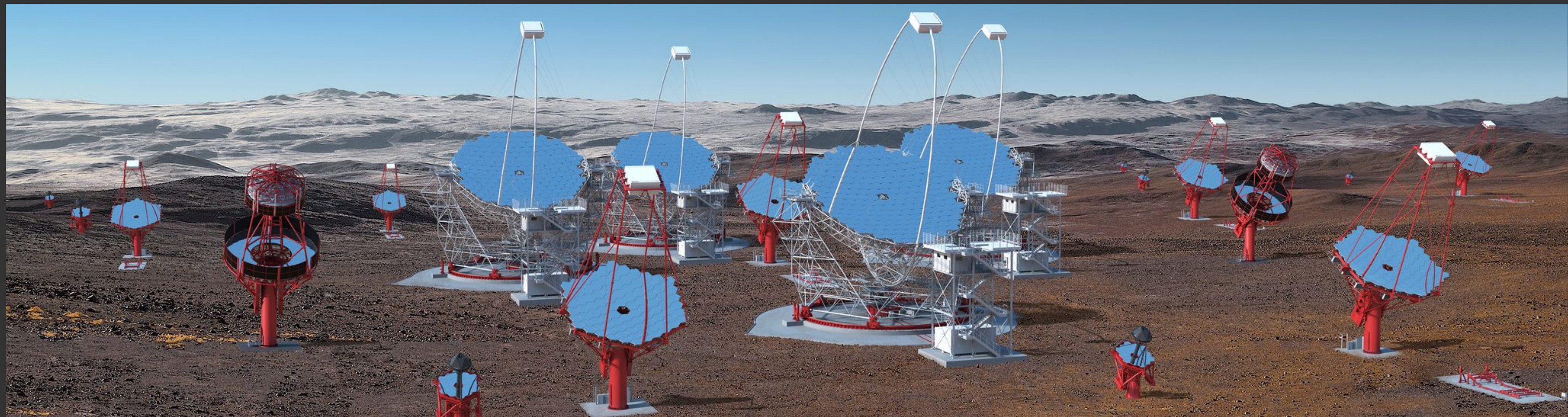
Small Sized Telescope SST (4m)

LST-1 (CTA-North)



# CTA – North & South

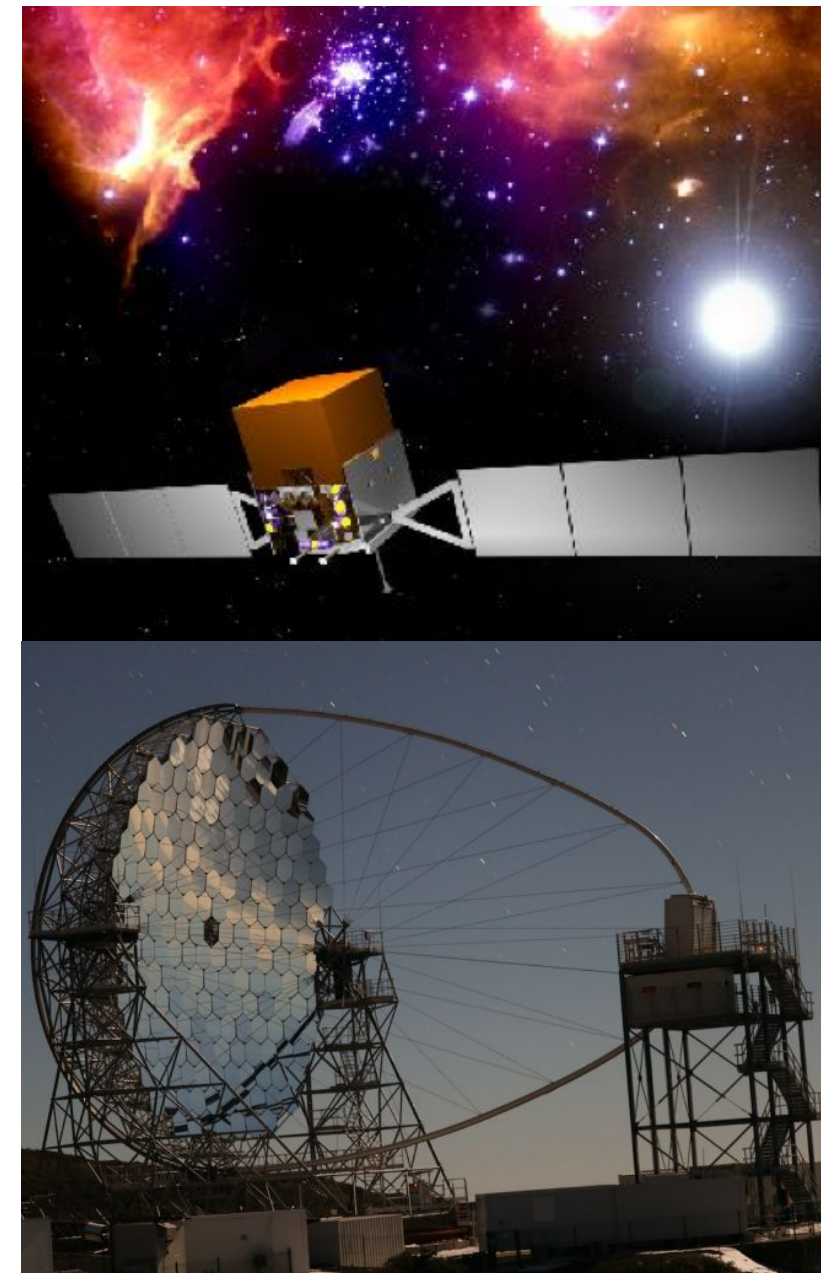
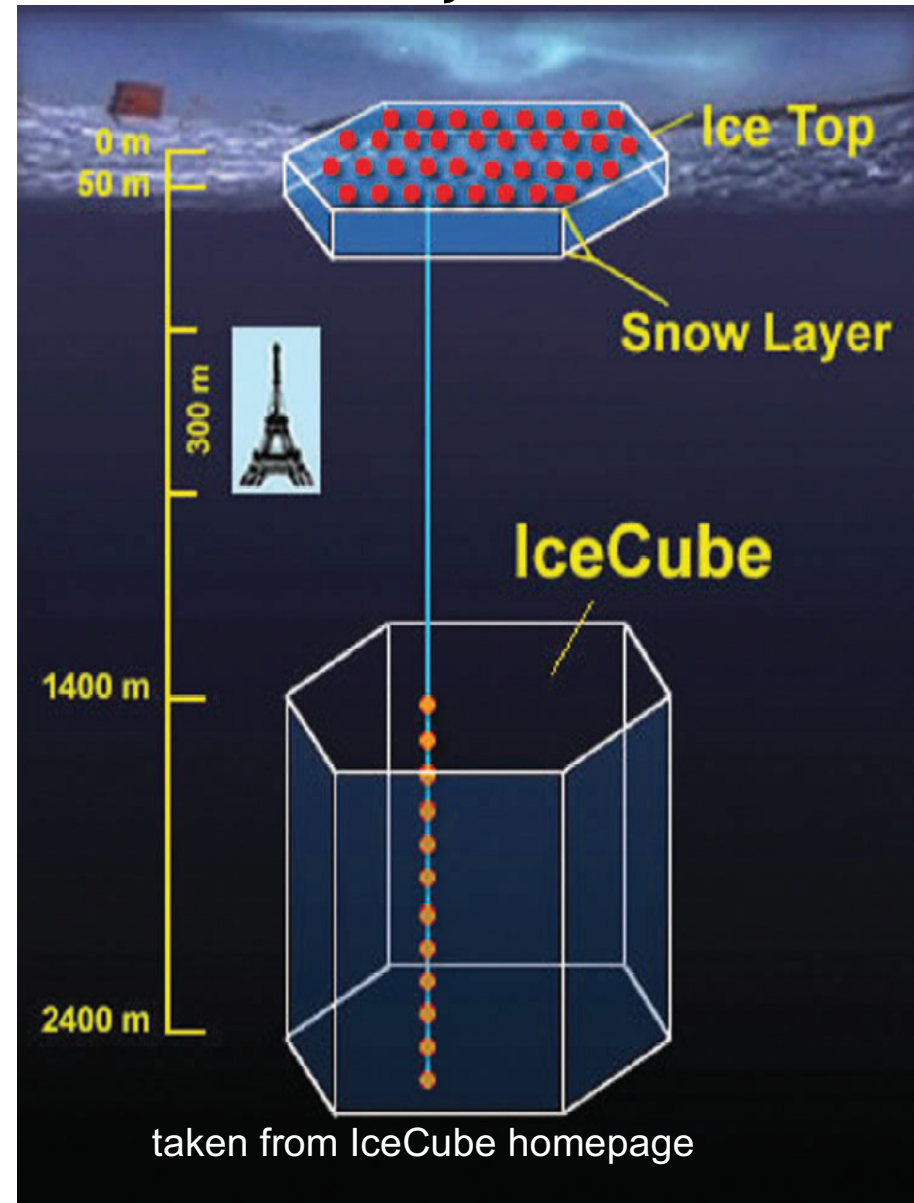
**Construction phase – from late  $\sim 2022$  for  $\sim 5$  years, incl. verification science**  
**Operations phase – Announcement of opp phase and full KSPs.**



# CTA as a player in the MWL+MM arena

## Neutrinos

IceCube, KM3Net



## Gamma-rays

Fermi, LHAASO, IACT...

## Cosmic rays

AMS-02, Auger,...



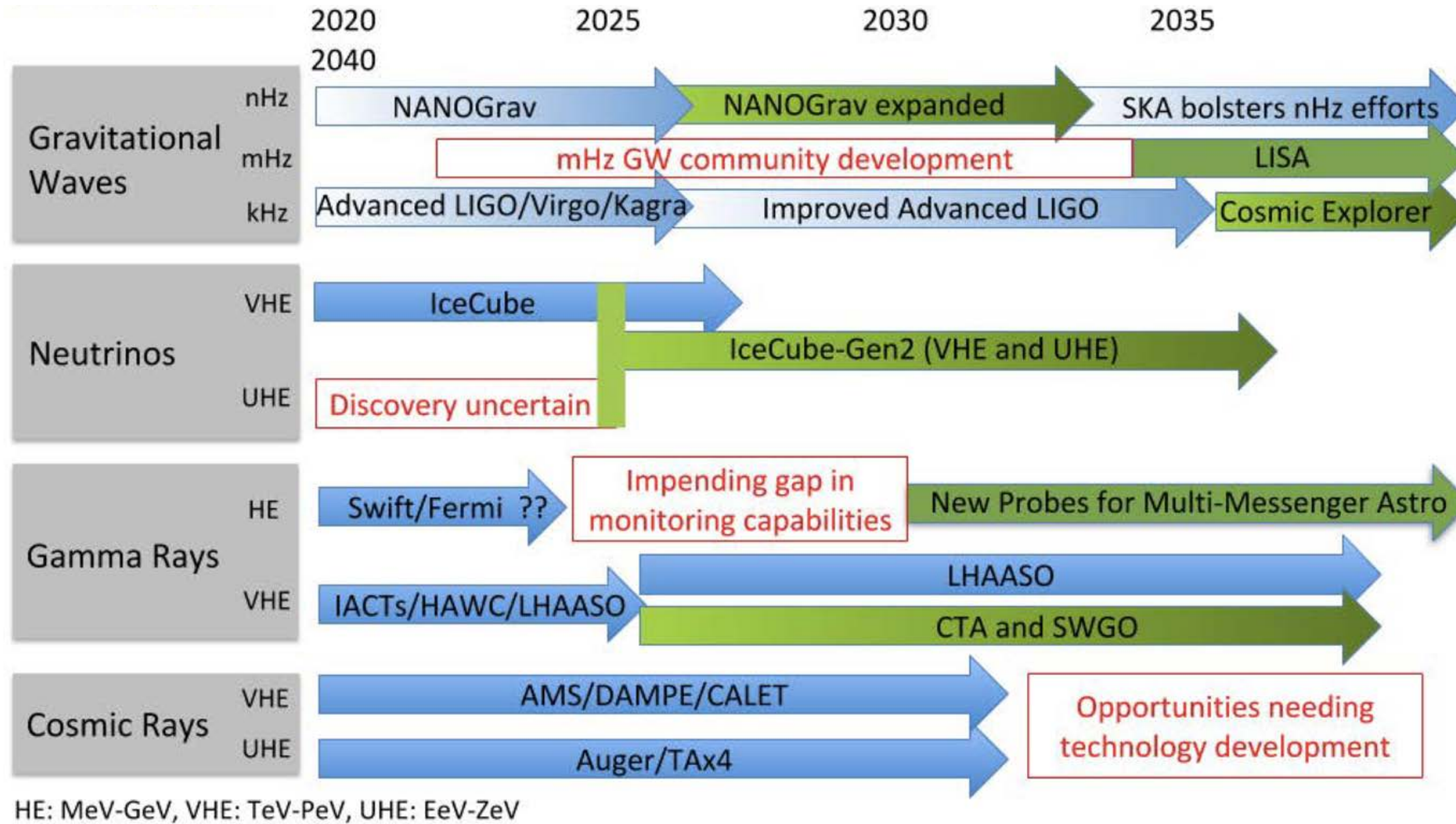
## MWL Facilities

## Gravitational Waves

LIGO, VIRGO, KAGRA



# MM Perspective from Astro 2020



Existing/planned projects  
Missing capabilities  
Endorsed projects

HE: MeV-GeV, VHE: TeV-PeV, UHE: EeV-ZeV

# CTA as a player in the MWL+MM arena



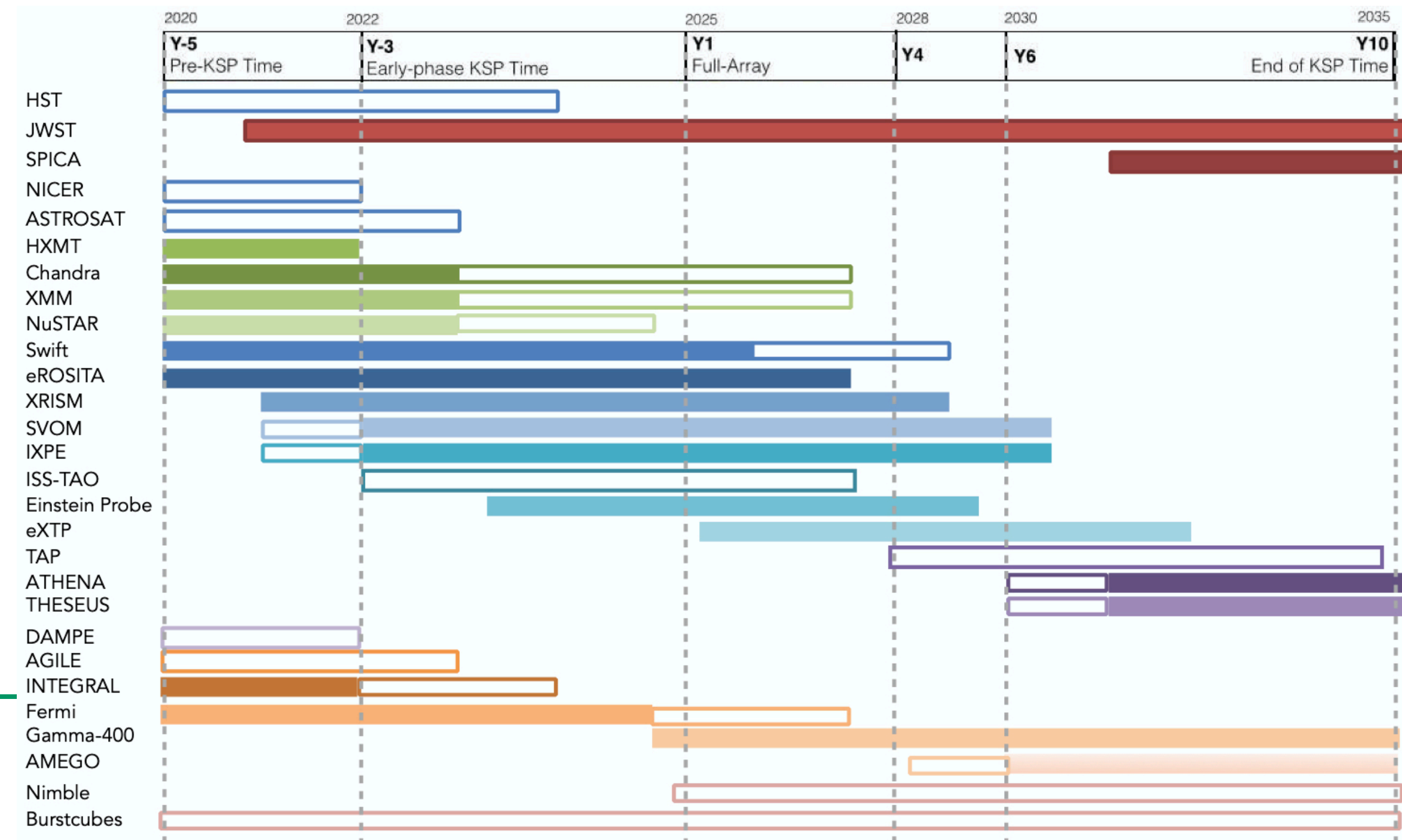
CTA will be the largest (open) observatory in the VHE range (20 GeV - 300 TeV), with two sites in both hemispheres for full sky access

- most sensitive in the range below < 10s TeV
- unique short timescale sensitivity ( $> 10^3 \times$  Fermi-LAT) < 300 GeV
- unique angular resolution  $< 0.01^\circ$  in entire energy range
- largest FoV in a pointing instrument ( $\sim 8^\circ$ ), ideal for surveys
- rapid response of LSTs (< 30 s)



A powerful and large precision instrument in the TeV range

Operations expected to start between 2025-27 : contemporaneous to a new generation of MWL and MM instruments



# CTA as a player in the MWL+MM arena

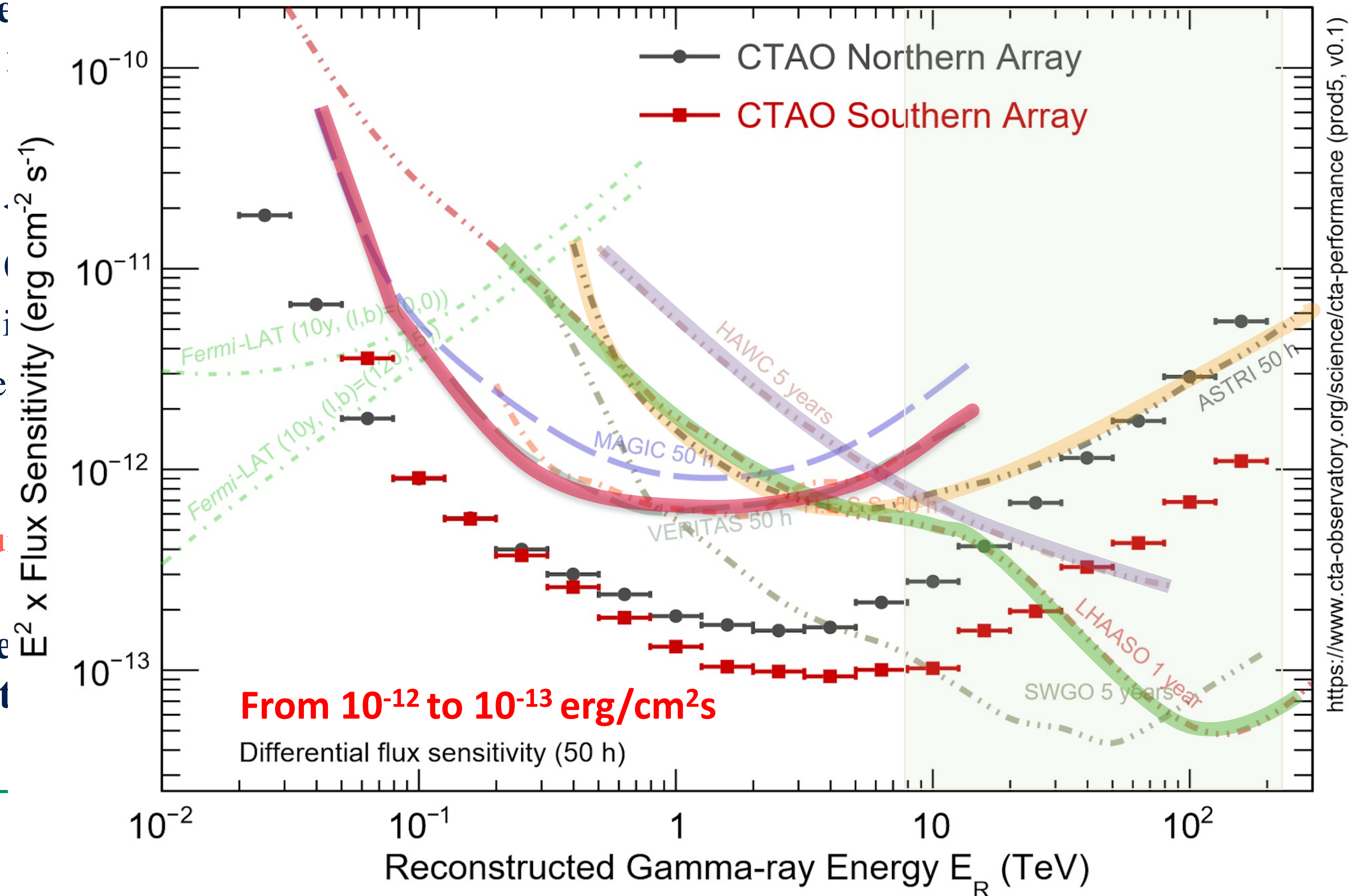


CTA will be the largest (open) observatory (20 GeV - 300 TeV), with two sites and full-sky access

- most sensitive in the range below 100 TeV
- unique short timescale sensitivity (minutes)
- unique angular resolution  $< 0.01^\circ$  in the MWL
- largest FoV in a pointing instrument
- rapid response of LSTs ( $< 30$  s)

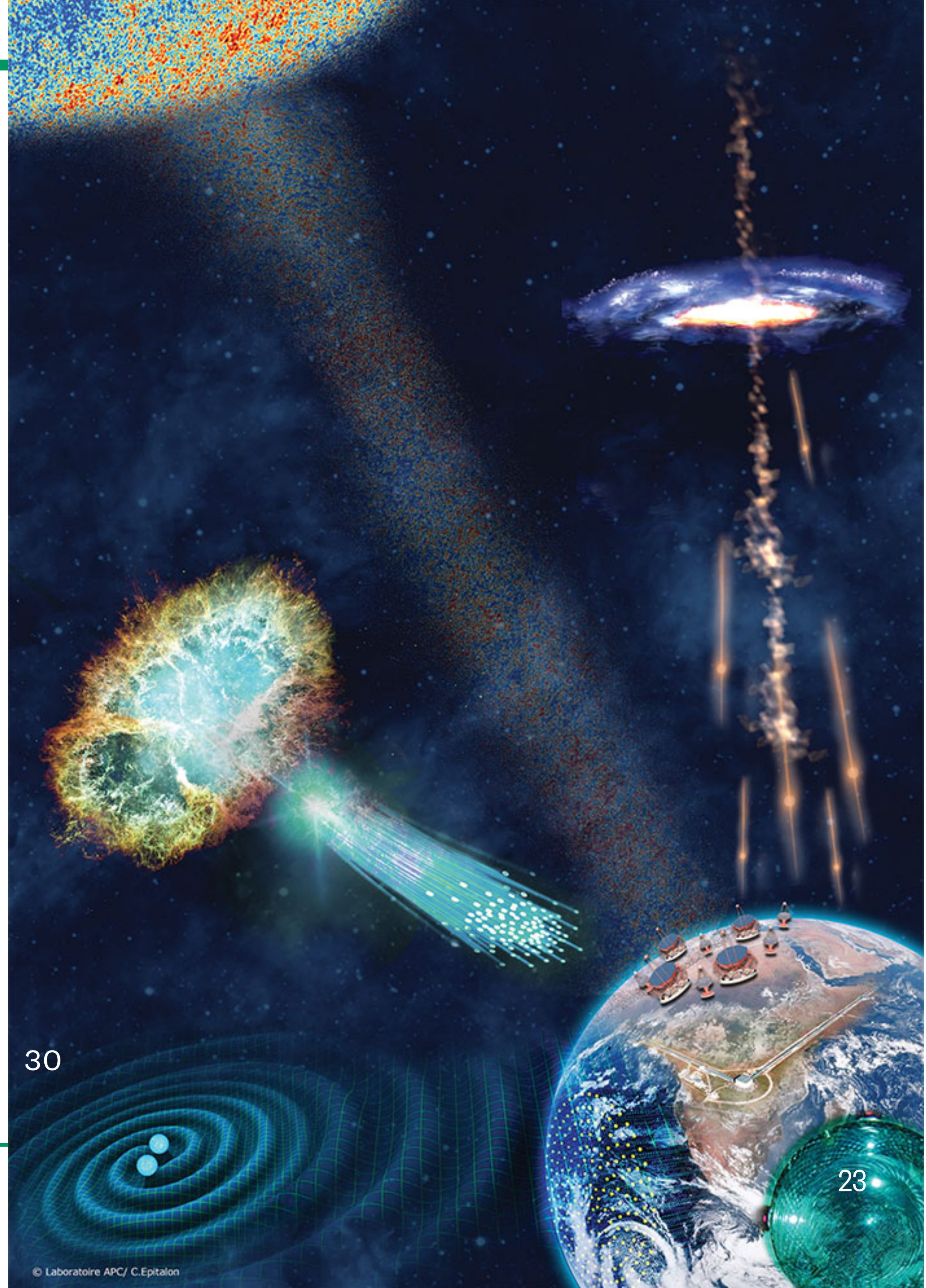
A powerful and large precision instrument

Operations expected to start between 2023 and 2025, contemporaneous to a new generation of instruments



# The CTA Context

BASED MOSTLY ON RESULTS  
AND PRESENTATIONS BY CTA  
AT ICRC 2021



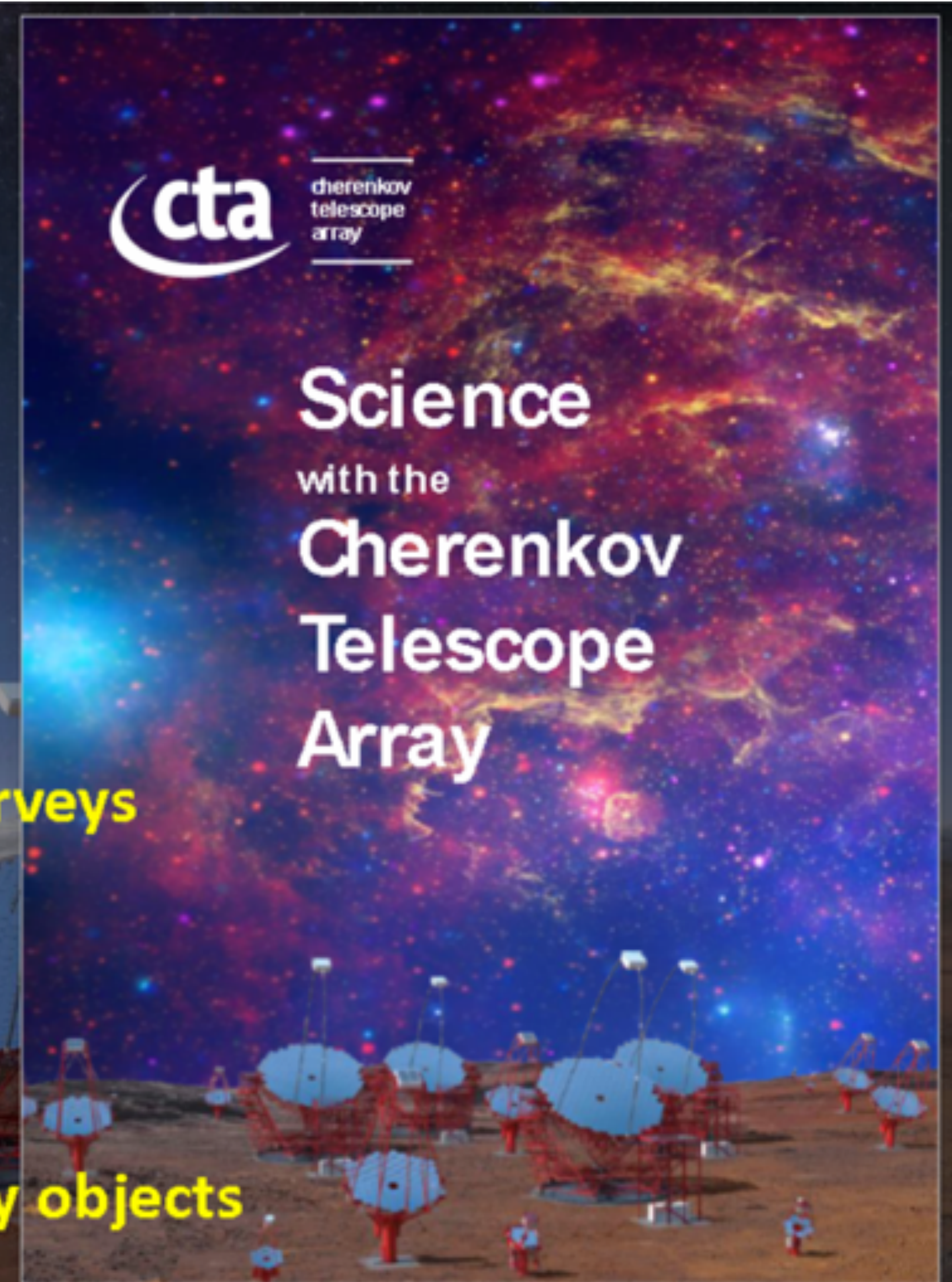
# KEY SCIENCE PROJECTS

provide legacy data sets and data products

1. Dark Matter Programme
2. Galactic Centre
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Beyond Gamma Rays

Surveys

Key objects



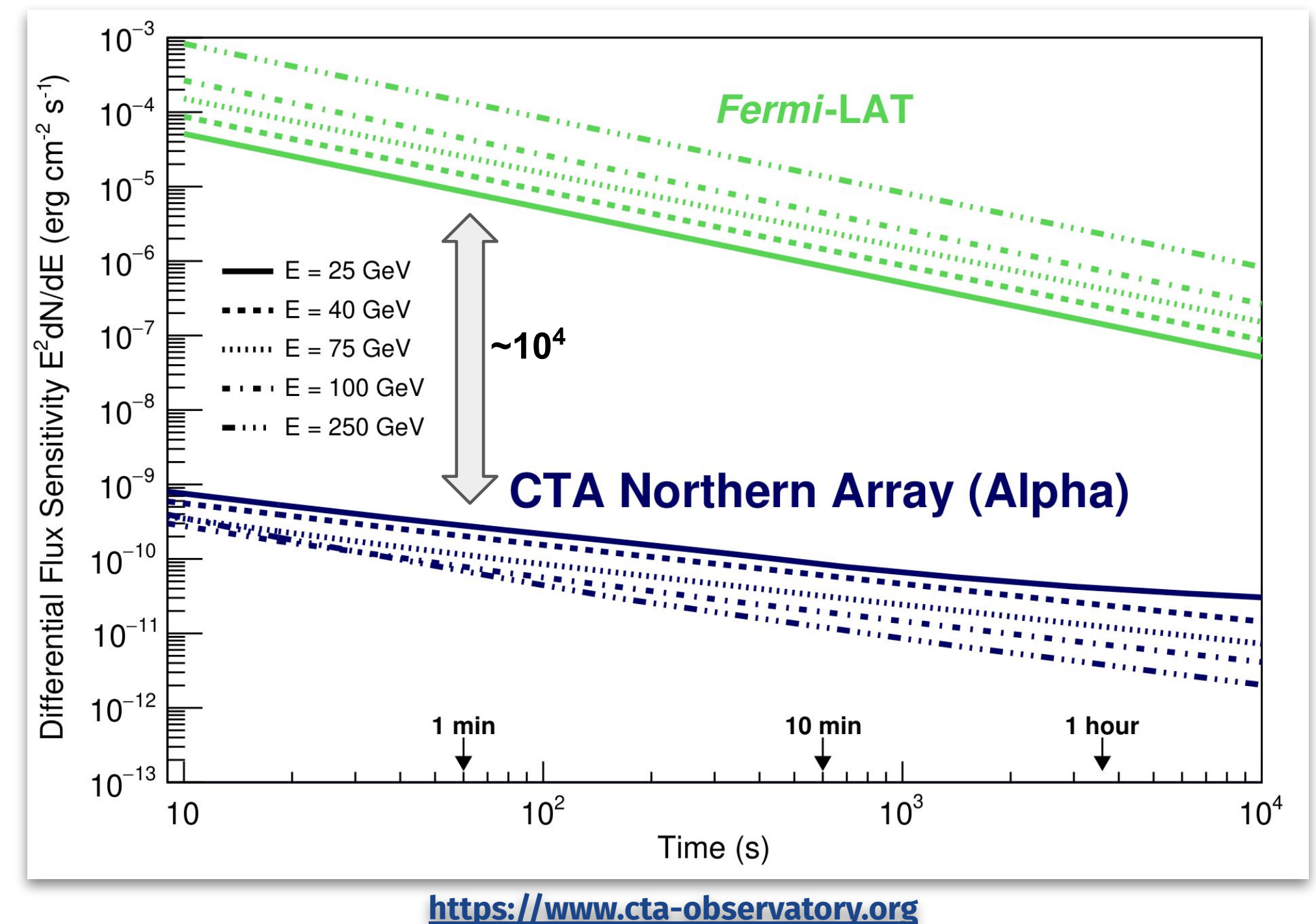


# CTA Transient and MM Programme



CTA will have a strong transient and multi-messenger programme, following its unique short-timescale sensitivity in the multi-GeV range,  $\sim 10^4$ x superior to Fermi-LAT for timescales up to several ks.

- **Gamma-ray bursts (GRBs)**, external alerts from monitoring facilities. Simulations of a realistic GRB populations estimate CTA detection prospects to few GRBs per year.
- **Galactic transients**, serendipitous detection of a wide range of galactic transients expected from CTA regular Galactic Plane Survey monitoring: flares from pulsar wind nebulae (PWN), X-ray binaries, novae, microquasars, magnetars, etc.
- **High-energy neutrino transients**, CTA strategy is to follow-up (golden) neutrino to maximize the chance of detecting a VHE counterpart.
- **GW transients**, follow-up by CTA can play a unique role to ID counterparts thanks to large FoV and divergent pointing strategy.
- **Core-collapse Supernovae**, investigation of CTA prospects in detecting a wide range of different types of CCSNe and their different signature in the VHE regime.



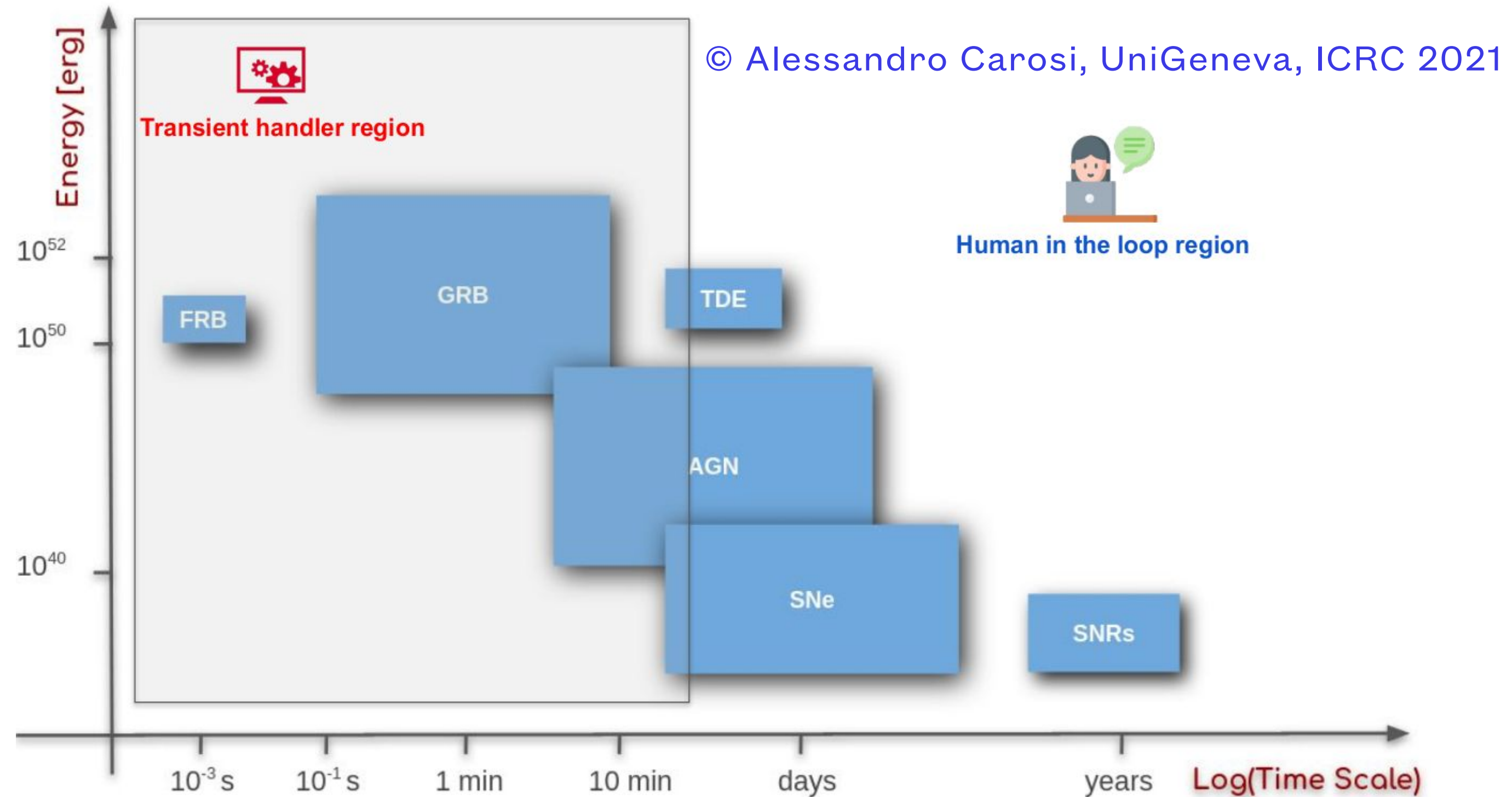
# CTA Transient and MM Programme



Multi-messenger research will require **large cooperation between CTA and other facilities**, operating at all bands of the EM and at different ‘messengers’.

## Key elements being

- Ability to receive alerts from many different sources, which will be implemented in CTA via a dedicated *‘transient handler’*
- Ability to deliver alerts in near real-time to the external astrophysical community for follow-up by other instruments



**PROTOCOLS FOR EXTERNAL COMMUNICATIONS HANDLING**

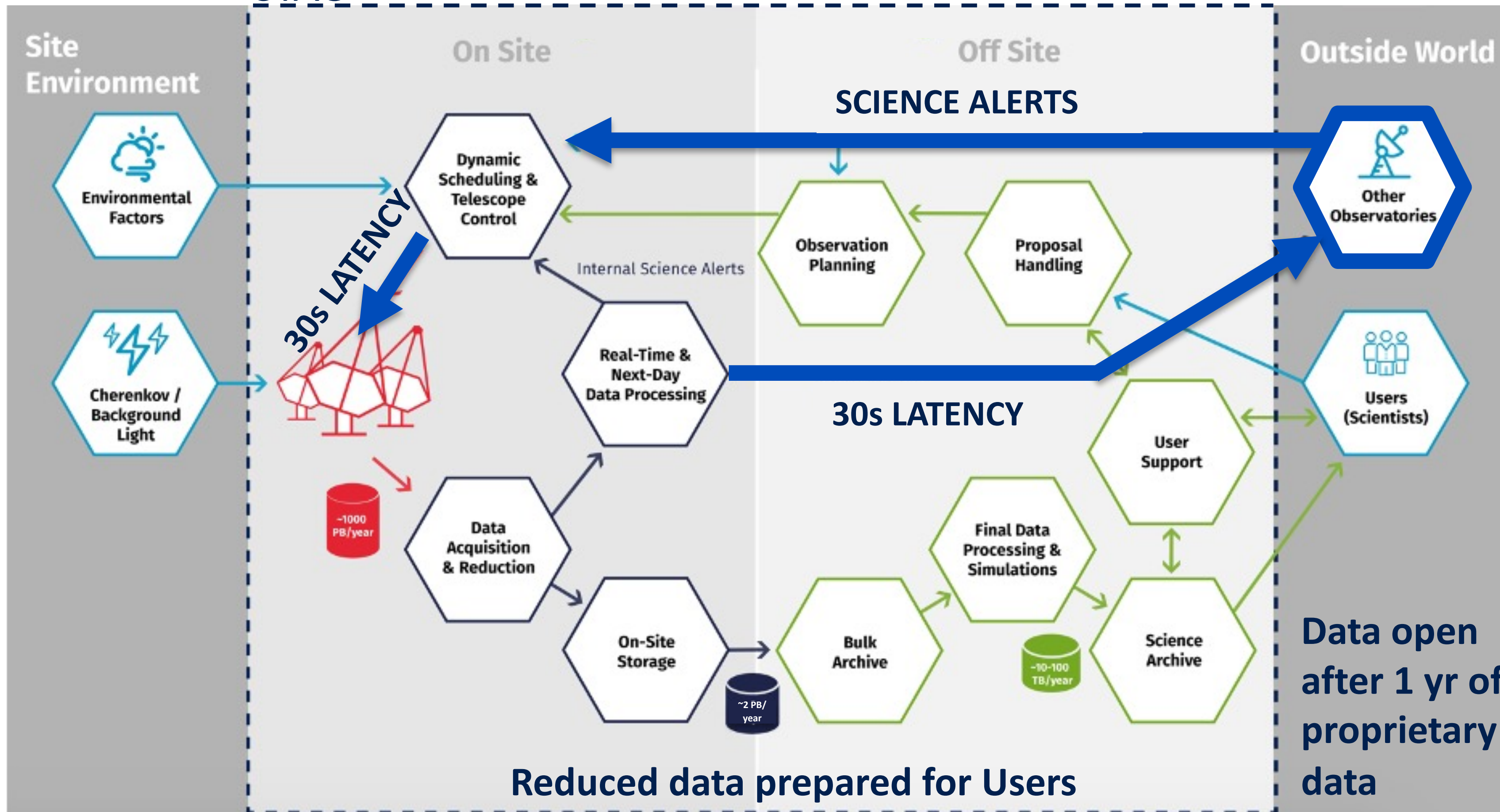
**ALERT FILTERING AND OBSERVABILITY ASSESSMENT**

**RECEIVING AND HANDLING OF ALERTS**

**INTERNAL COMMUNICATIONS HANDLING FOR SCHEDULING**

# CTA : alert and follow-up system

CTAO



**Online analysis** - On time scales from 10s to 30 min

**Efficient science alert generation** - Alerts will be generated with a latency of 30s

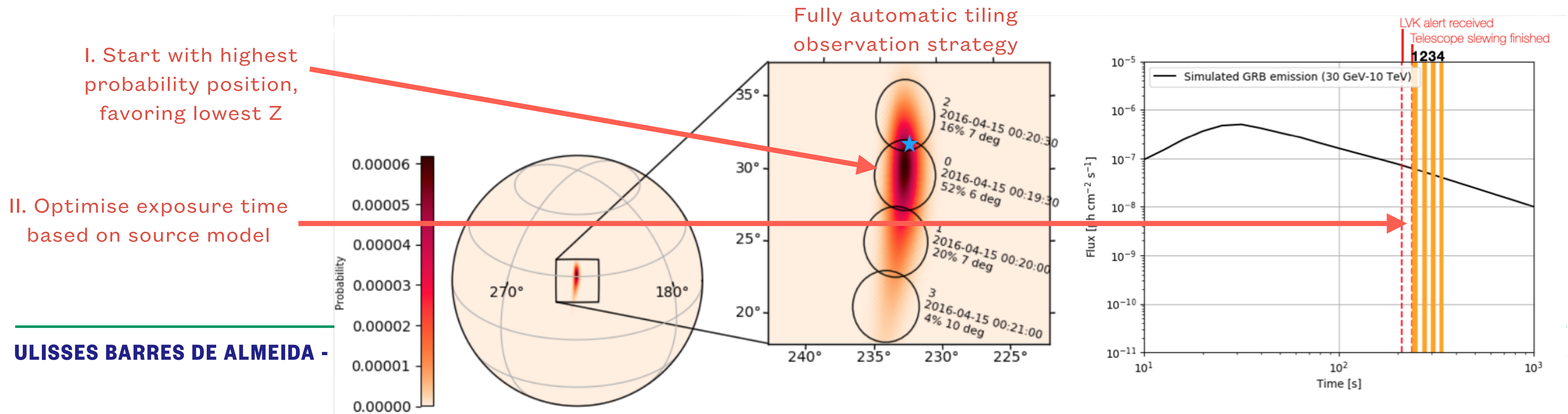
**Fast follow-up and short term detections** - CTA will quickly follow-up on external triggers (within 30s of alert received)

**DETAILED OPERATIONS REQUIREMENTS UNDER DEVELOPMENT**

# CTA follow-up observation strategy



- CTAO will perform regular (1-3x per week) follow-up observations of GW-GRB and (golden)  $\nu$  alerts
- The observational strategy is a key element for the success of the programme
  - Optimal pointing pattern to cover the largest total alert uncertainty region (10-1000 deg<sup>2</sup>) (Patricelli+2018, Bartos+2019)
  - Optimal pointing cadence: exposure time tailored to achieve  $5\sigma$  detection
  - Site coordination to prioritize best observational conditions (sky brightness and quality, zenith angle) and to guarantee lowest energy threshold
  - Divergent array pointing mode to increase the FoV



# CTA follow-up observation planning



CTAO is conducting different studies for the planning and optimization of its follow-up programme, based on tailor-made population studies

- GRB population study : POSyTIVE (*Ghirlanda+2019*)
- Neutrino source population : FIRESONG (*Tung+2021*)
- Neutron Star-Neutron Star mergers : GWCOSMoS (*Patricelli+2018*)

simulation of source population based on open-source theoretical codes

estimation of gamma-ray emission based on phenomenological assumptions

optimization of the CTAO observation strategy

simulation of CTA response

Estimation of the CTA detection rate

**ctools and  
gammapy  
pipelines**

© Roberta Zanin, CTAO, ICRC 2021 (adapted)

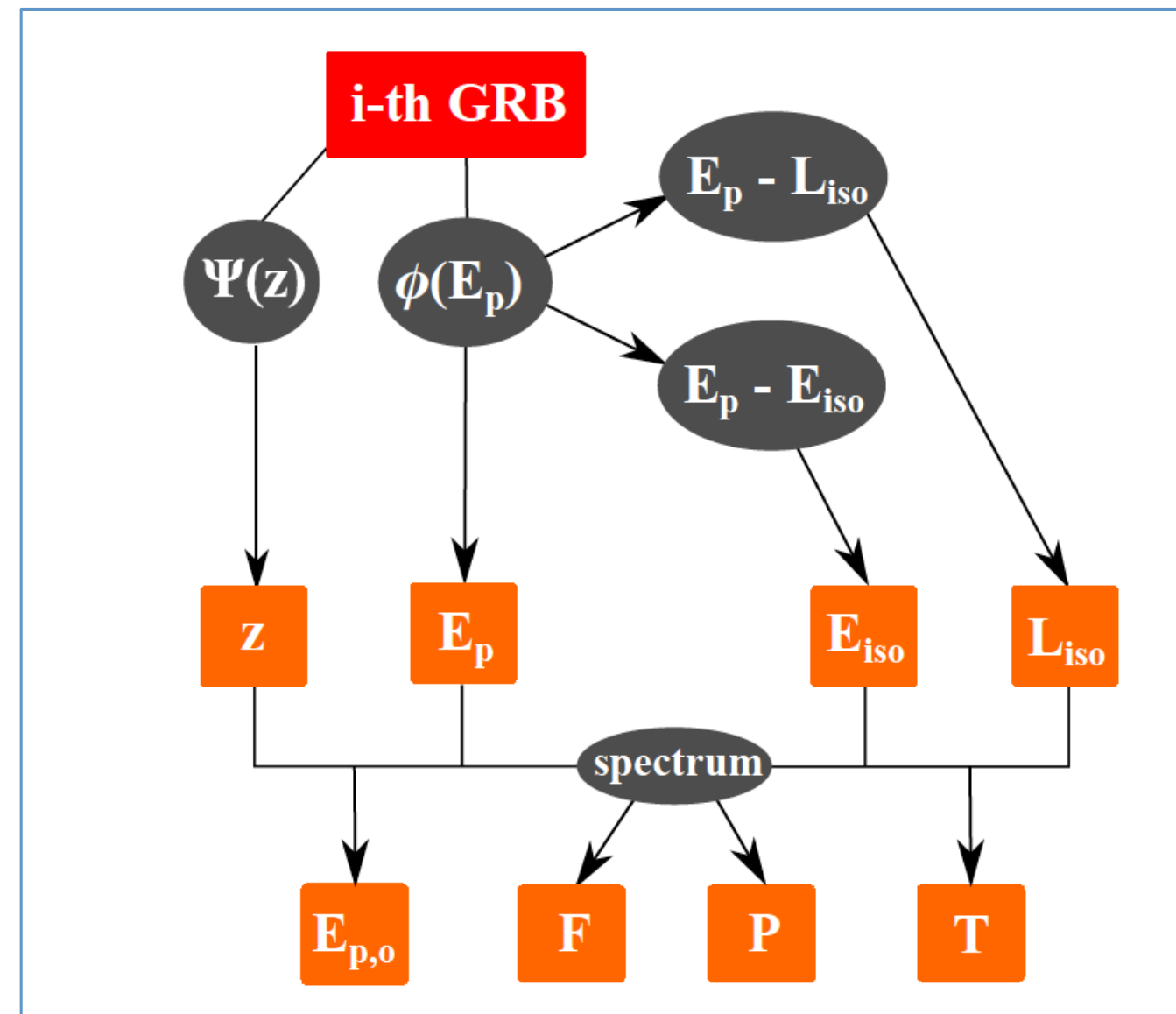
# GRB POSYTYVE (Ghirlanda et al. 201x)

POpulation SYnthesis Theory Integrated project for V<sub>HE</sub> Emission

## CTA strategy: External alerts and LSTs

- Fast repointing: prompt 0.01 - 1 ks; afterglow in  $\sim 1/t$
- Low Energy:  $\sim 100$  GeV to counter EBL absorption
- Present rates: a few GRB expected per year (Inoue+ 2013)

Name	Obs.	$\sigma_{\max}$	Delay	E range	T90 (s)	Eiso (erg)	z
180720B	H.E.S.S.	5.3	10 hr	100 - 400 GeV	49	$6 \times 10^{53}$	0.654
190114C	MAGIC	50	1'	0.2 - 1 TeV	25	$2.5 \times 10^{53}$	0.4245
190829A	H.E.S.S.	22	4h20'	0.2 - 3 TeV	63	$2 \times 10^{50}$	0.0785
201216C	MAGIC	>5	57"	100 GeV	30	$5 \times 10^{53}$	1.1



G. Ghirlanda et al. A&A 594 (2016), A84.

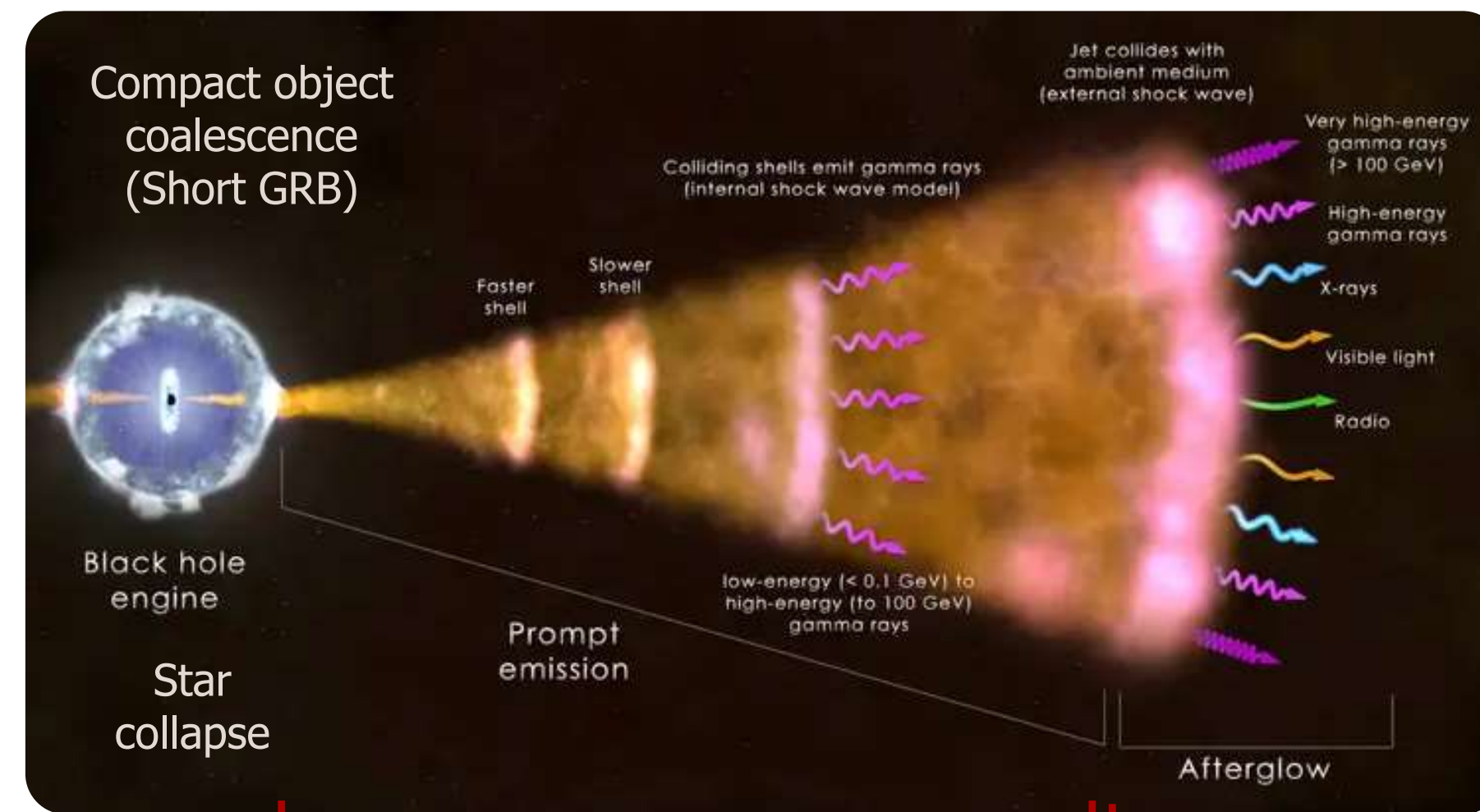
### Population

Monte Carlo  
Calibrated on Fermi-  
GBM & Swift data

1000 GRB - 44 yr

Swift bright GRBs,  
 $P(15-150 \text{ keV}) > 2.6 \text{ } \gamma \text{ cm}^{-2} \text{ s}^{-1}$

Giancarlo G.



Željka B.

Lara N.

### Detection Analysis



SoHAPPy  
with



Franz L. et al.  
Thierry S.

# GRB Detection rates, $\omega$

Th. Stolarczyk, November 2021



## Reference Simulations

- Over 1000 initial GRB, 45% visible
- Visible window (at prompt,  $t_{90} > \Delta t_0$ )
- Reported  $3\sigma$ ,  $5\sigma$  detections in 90% of trials

## Detection rates

- 50% detected at  $5\sigma$ , 90% CL < 10'
- max- $\sigma$  reached after 1.3 hours (median)

Rate		N	S	N only	S only	Both	Total
Vis.	Counts	446 ± 21	452 ± 21	159 ± 13	165 ± 13	287 ± 17	611 ± 25
	yr <sup>-1</sup>	10.1 ± 0.5	10.3 ± 0.5	3.6 ± 0.3	3.8 ± 0.3	6.5 ± 0.4	13.9 ± 0.6
	@trig	13%	11%	10%	10%		
3 $\sigma$	Counts	64 ± 8	53 ± 7	19 ± 4	13 ± 4	64 ± 8	96 ± 10
	yr <sup>-1</sup>	1.5 ± 0.2	1.2 ± 0.2	0.4 ± 0.1	0.3 ± 0.1	1.5 ± 0.2	2.2 ± 0.2
	@trig	48%	49%	58%	54%		
5 $\sigma$	Counts	57 ± 8	46 ± 7	17 ± 4	11 ± 3	53 ± 7	81 ± 9
	yr <sup>-1</sup>	1.3 ± 0.2	1.0 ± 0.2	0.4 ± 0.1	0.2 ± 0.1	1.2 ± 0.2	1.8 ± 0.2
	@trig	51%	50%	65%	64%		

# GRB Detection rates, $\omega$

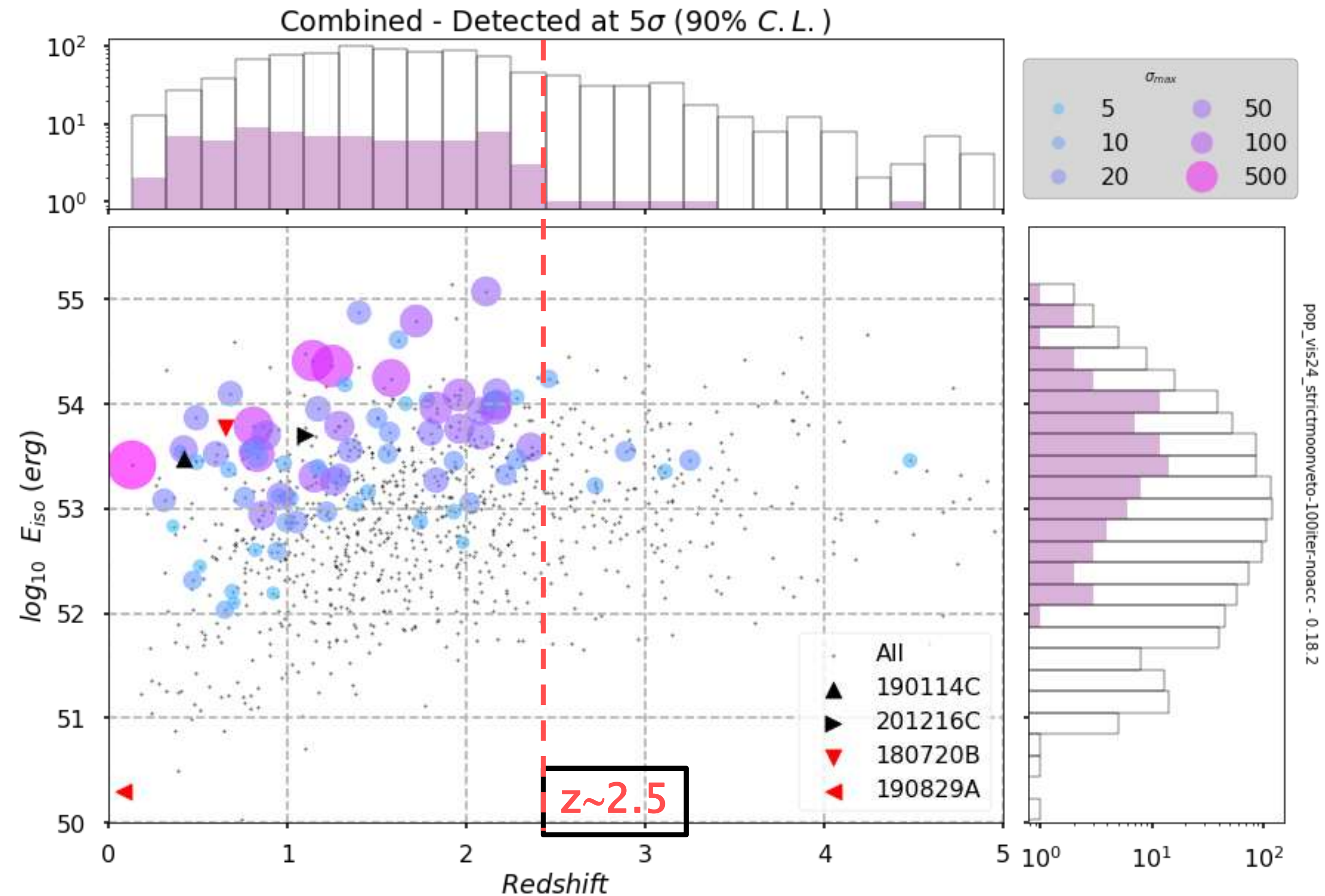
Th. Stolarczyk, November 2021

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# GRB Detection rates, $\omega$

Th. Stolarczyk, November 2021

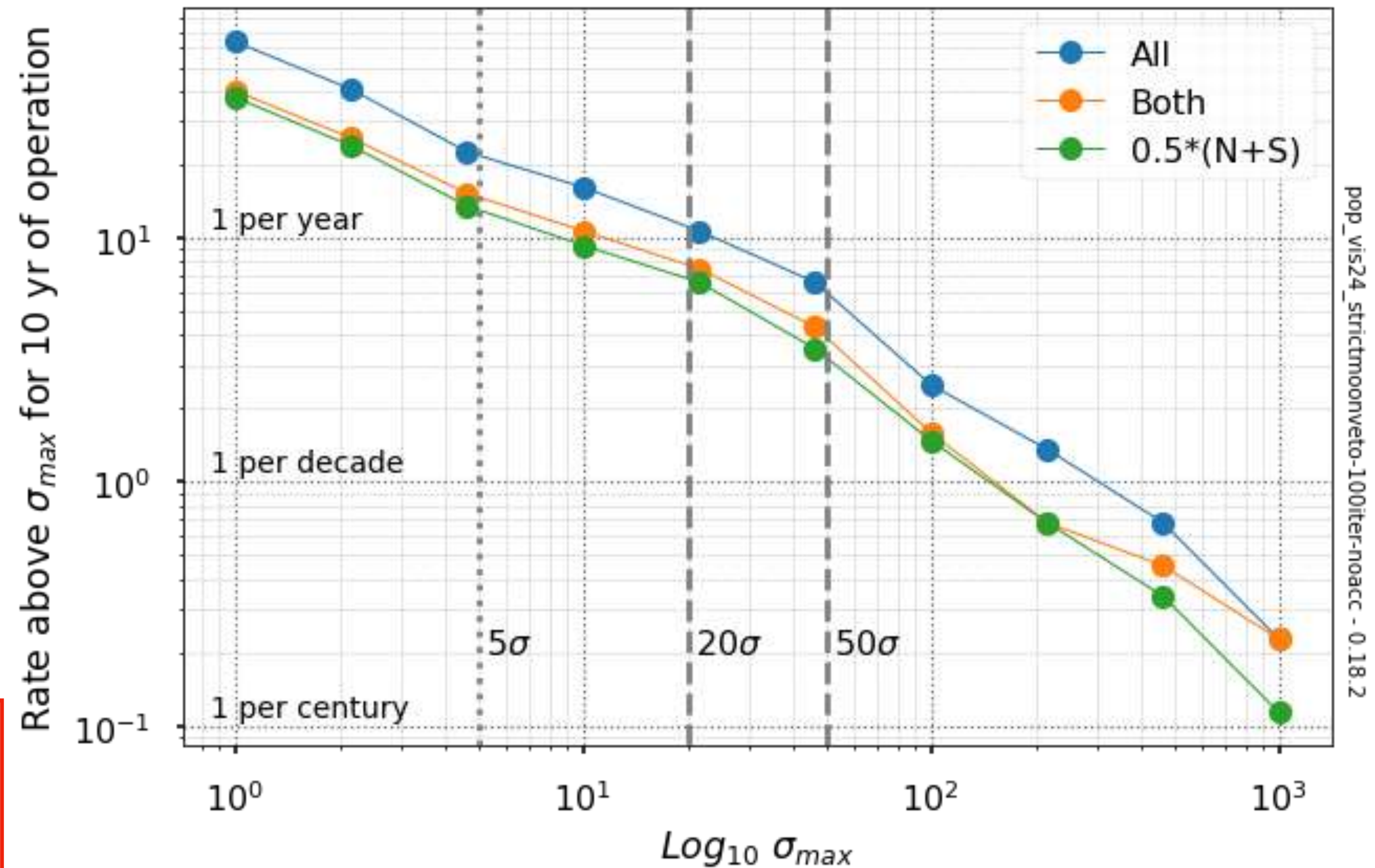
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## Detection rates

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$\geq 5\sigma$  : ~ 2 per year  
 $\geq 20\sigma$  : ~ 1 every year  
 $\geq 50\sigma$  : ~ 1 every 2 years



# GRB Detection rates, $\omega$

Th. Stolarczyk, November 2021



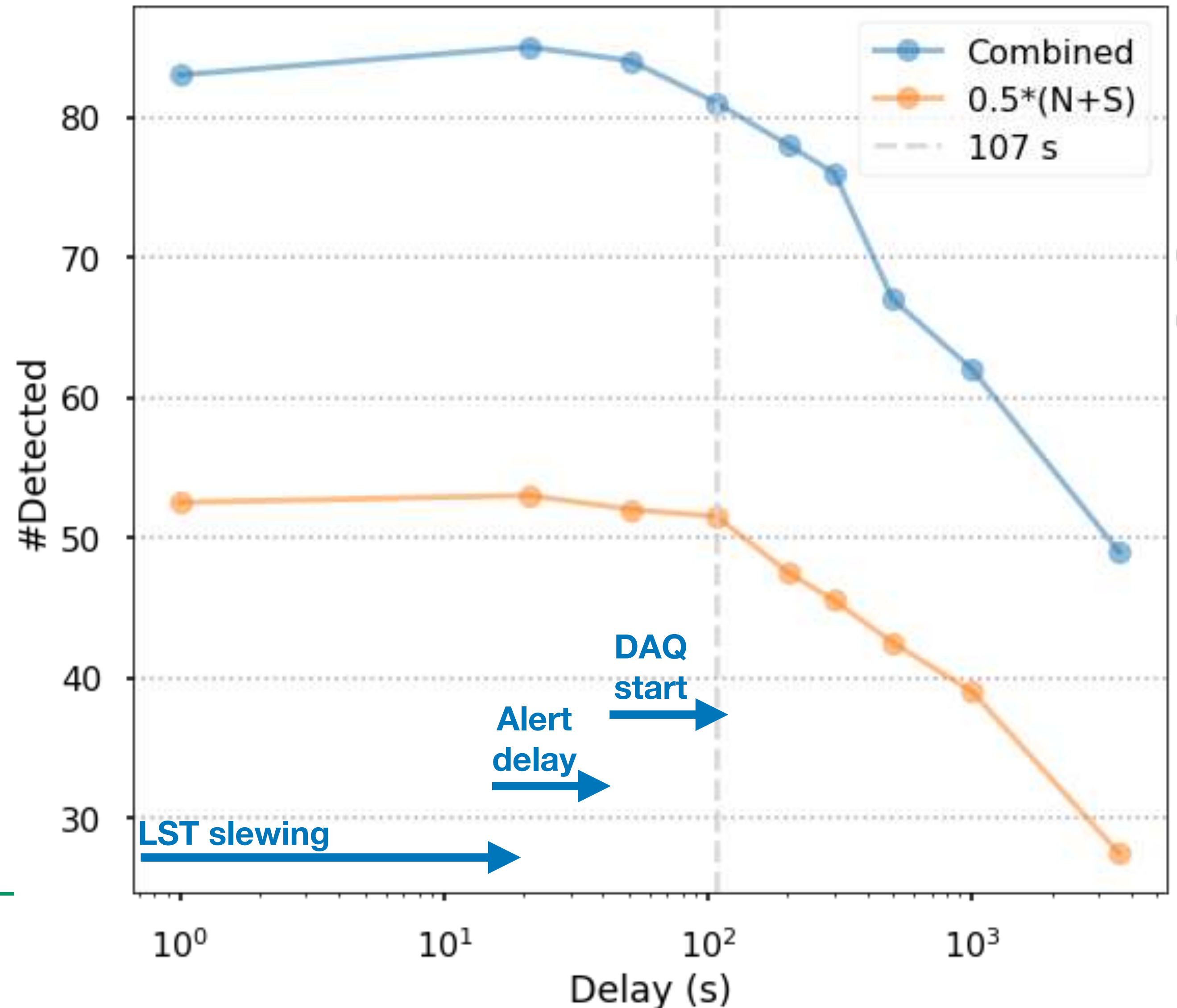
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**DETAILED OPERATIONS  
REQUIREMENTS UNDER  
DEVELOPMENT**



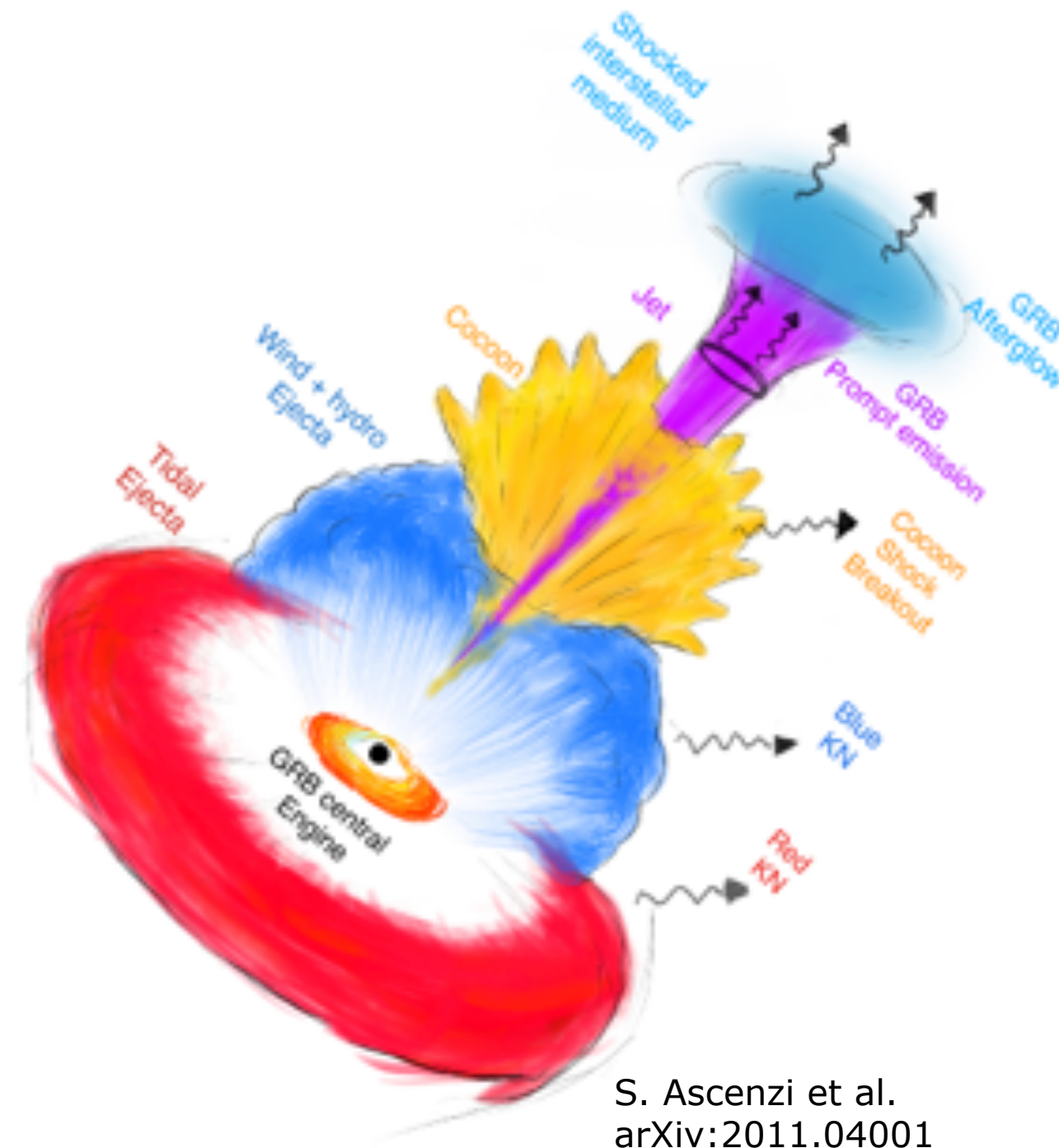
# The steep path towards GW-VHE connection

## FIRST TEV DETECTIONS OF GAMMA-RAY BURSTS



After two decades of attempts, **first long GRBs** were detected at VHE (early and late afterglow emission).

The next step lies in the detection of **short GRBs** and perhaps (maybe with EAS arrays), the **prompt emission!**



S. Ascenzi et al.  
arXiv:2011.04001

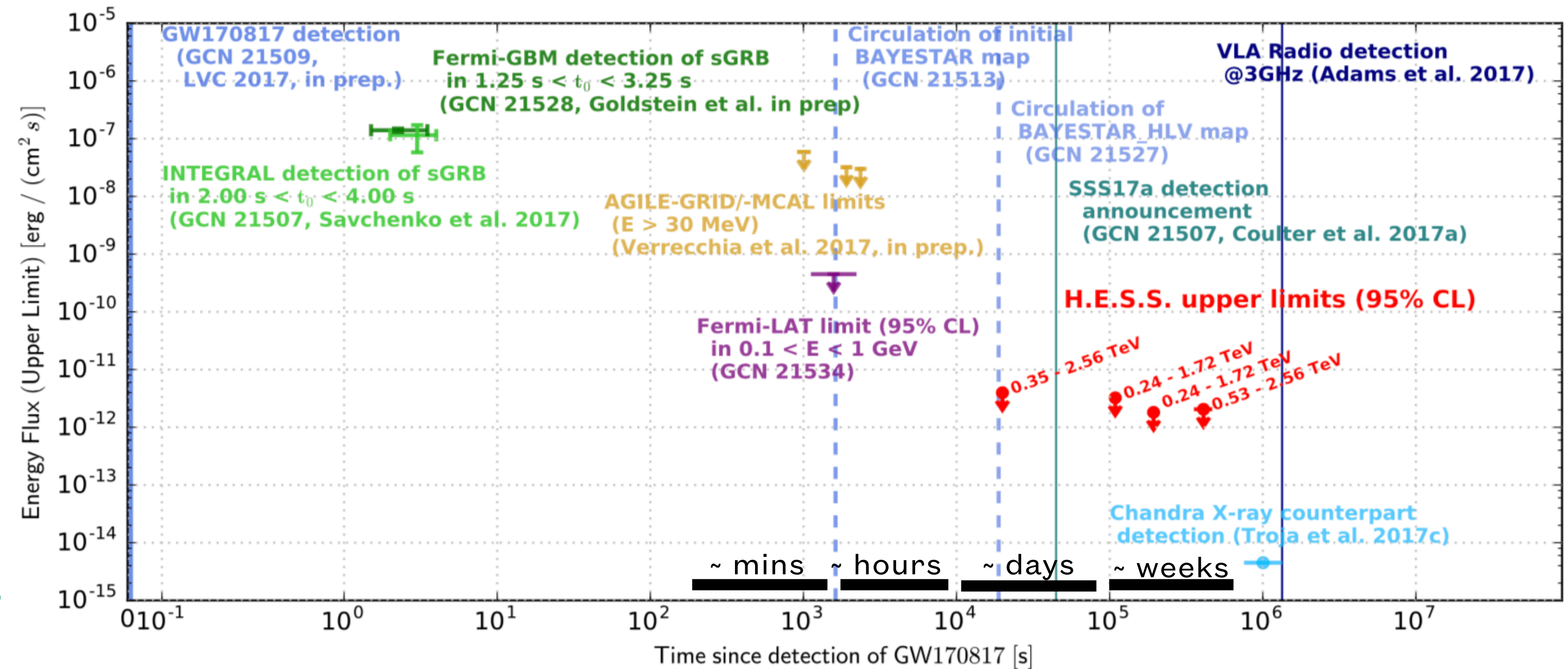
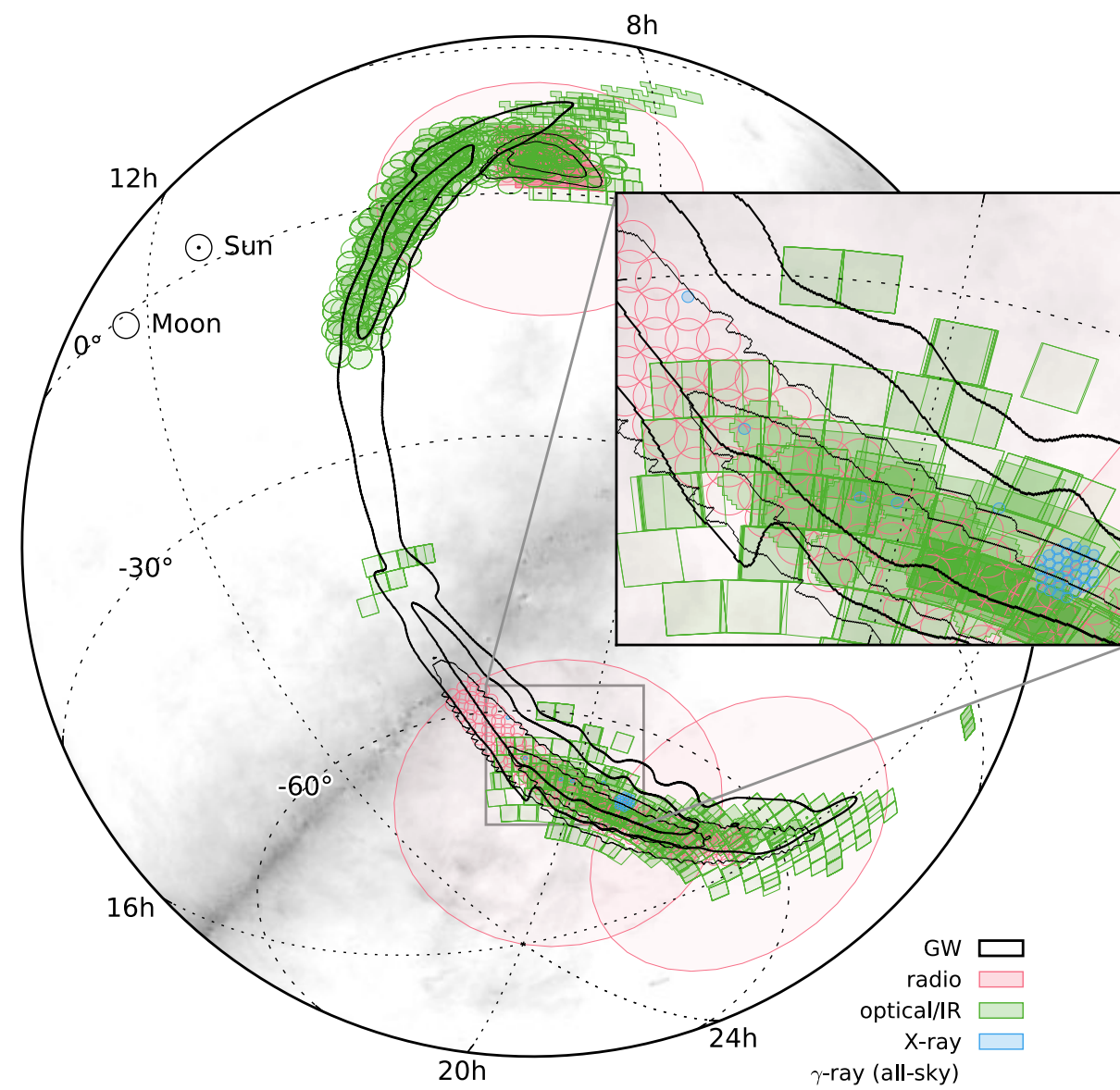
- **GRB 190114C** (*MAGIC Coll., Nature, 2020*)
  - long GRB at  $z = 0.42$
  - early detection at  $T_0 + 60s$  (2 ks),
  - $E = [0.2, 1]$  TeV
- **GRB 180720B** (*H.E.S.S. Coll., Nature, 2020*)
  - long GRB at  $z = 0.65$
  - late detection after  $T_0 + 10h$
- **GRB 190829A** (*H.E.S.S. Coll., Science, 2020*)
  - long GRB at  $z = 0.078$  (very close!)
  - for 3 nights, after  $T_0 + 4h$
  - $E = [0.2, 3.3]$  TeV
- **GRB 160821B** (*MAGIC Coll. ApJL, 2021*)
  - **short GRB** at  $z = 0.162$
  - data taking starting at  $T_0 + 24s$ , for 4h
  - $3\sigma$  hint,  $E > 500$  GeV
- **GRB 201015A** (*ICRC 2021, PoS ID 305, Y.Suda*)
  - long GRB at  $z = 0.42$
  - early detection at  $T_0 + 40s$
  - $3\sigma$  hint,  $E > 500$  GeV
- • **GRB 201216C** (*ICRC 2021, PoS ID 395, S.Fukami*)
  - long GRB at  $z = 1.1$
  - early detection after  $T_0 + 56s$
  - $E < 100$  GeV

# GW source localization

Arrival direction of GW is estimated from time delays (and amplitude modulation) of the signal.

Triangulation with VIRGO has allowed for a better sky localisation (down to  $\sim$  few  $\text{deg}^2$ )

Challenge for EM counterpart ID : time vs. space localisation



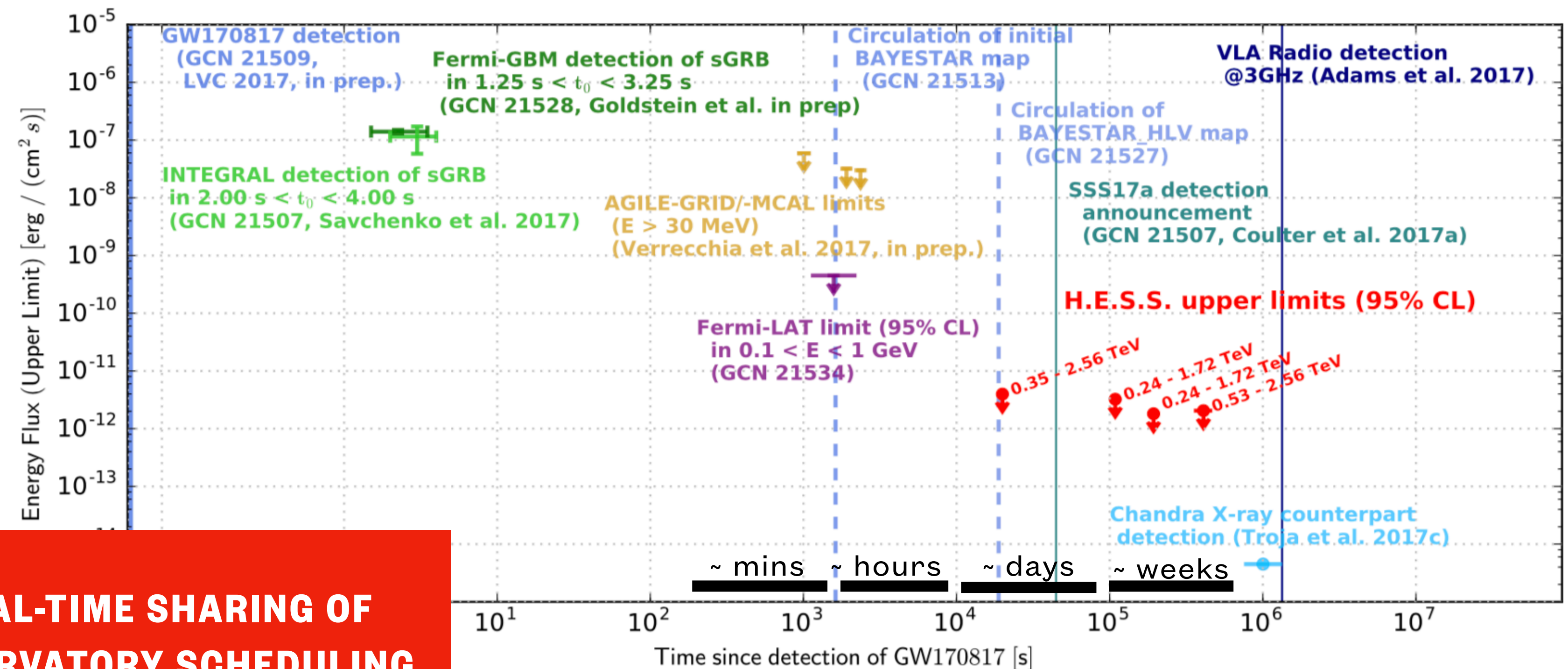
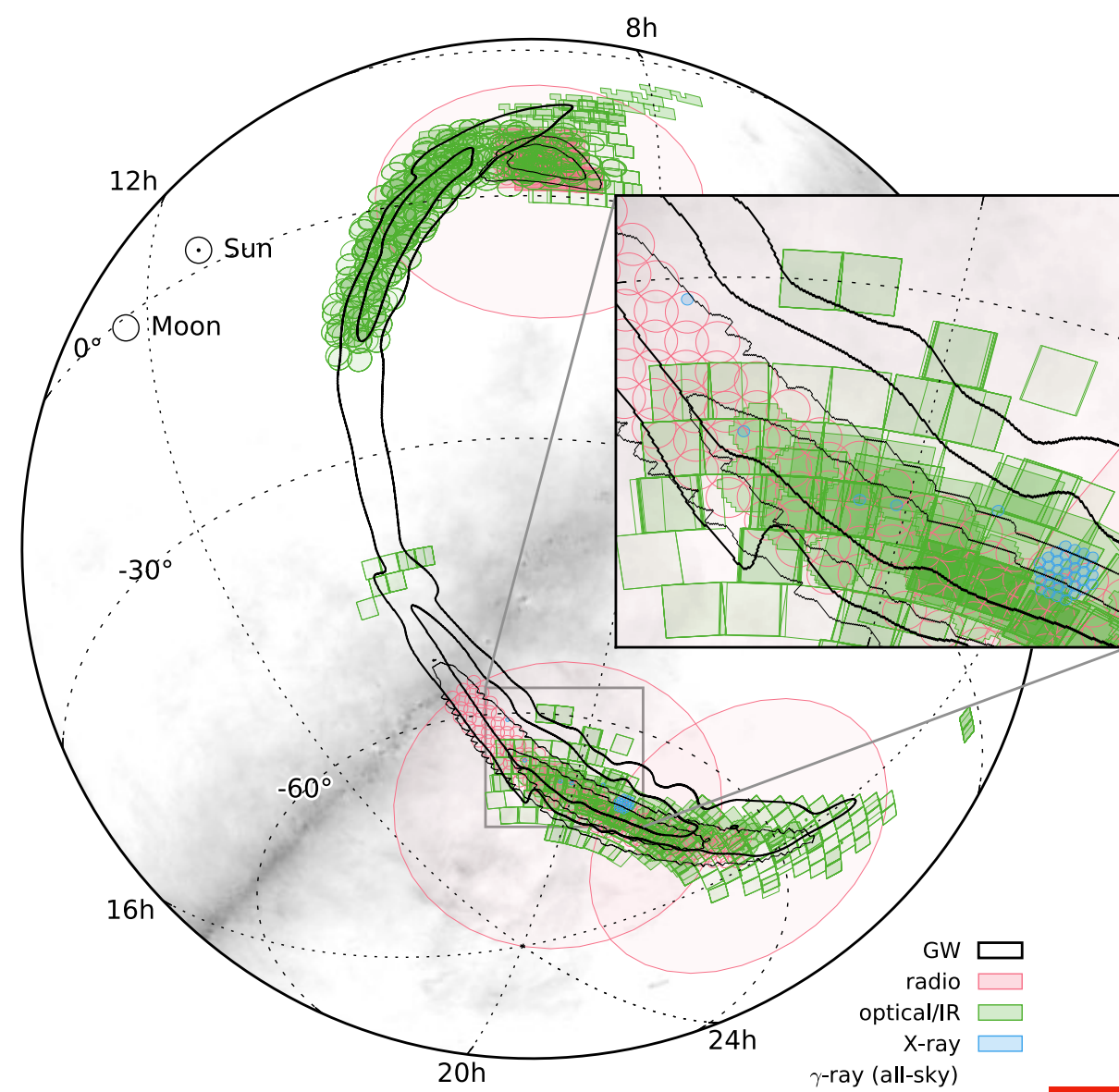
Tiling by EM observatories :  
coordinated scheduling and  
follow-up of observations.

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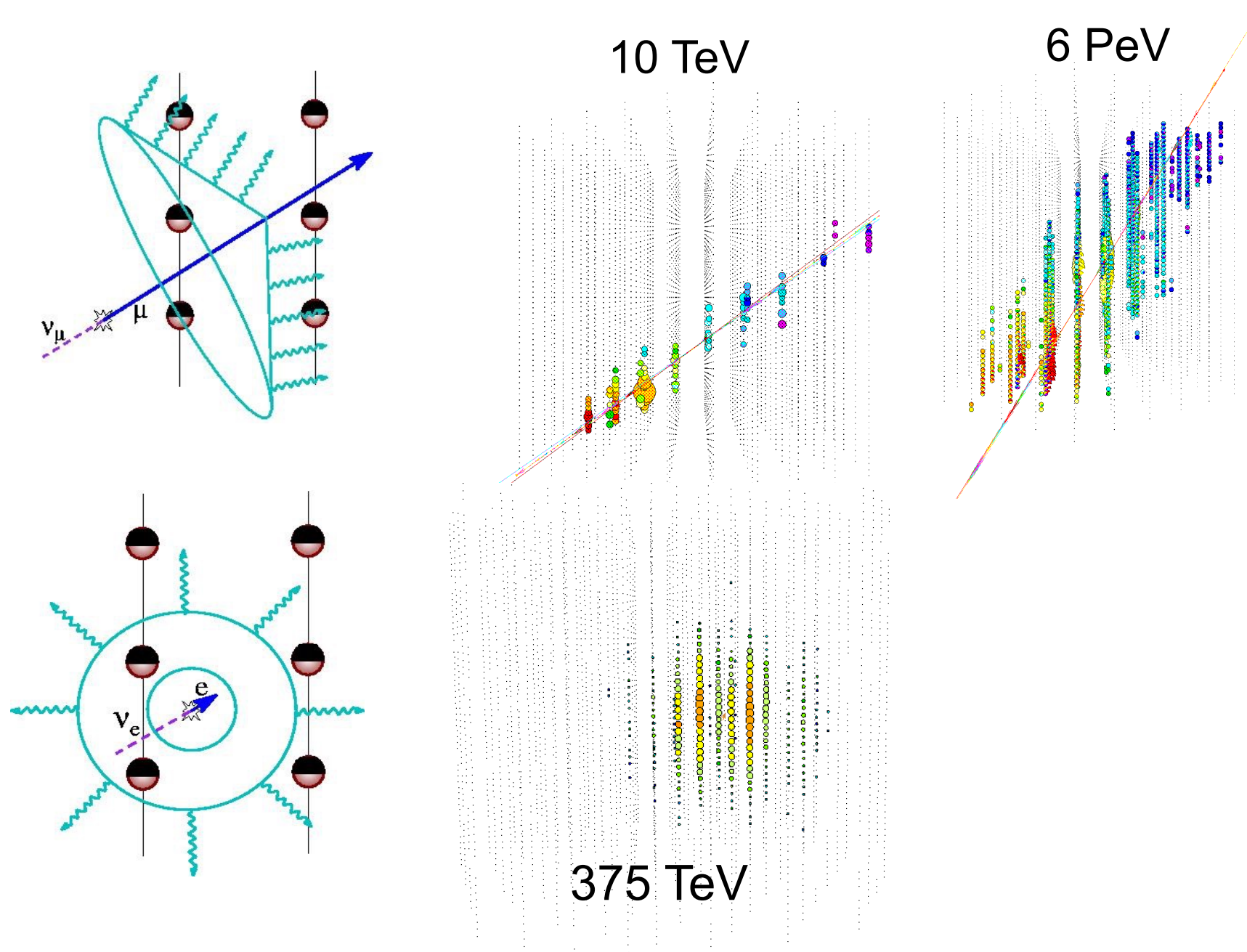
**REAL-TIME SHARING OF  
OBSERVATORY SCHEDULING**

# Neutrino FIRESONG (Tung et al. 2021)

<https://github.com/ChrisCFTung/FIRESONG>

**VHE (IceCube) neutrinos originate in decay process from mesons produced in hadronic interactions:**

- $\pi^+ \rightarrow \mu^+ + \nu_\mu$  or  $\pi^- \rightarrow \mu^- + \nu_\mu$  from pion decay.
- $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$  or  $\mu^- \rightarrow e^- + \nu_\mu + \nu_e$  from muon decay.



**Neutrinos create charged particles in interactions, which then produce the Cherenkov radiation detected.**

## Muon-tracks

better type of event for astronomy, with good localization ( $< 1^\circ$ )  
most common type of event, thanks to the long trajectories which cross the detector.

## Cascade events

results from electron and tau neutrino interactions

Event has poor localization but good energy resolution and lower background

# Neutrino FIRESONG (Tung et al. 2021)

<https://github.com/ChrisCFTung/FIRESONG>

## CTA strategy: Neutrino Target of Opportunity (NToO):

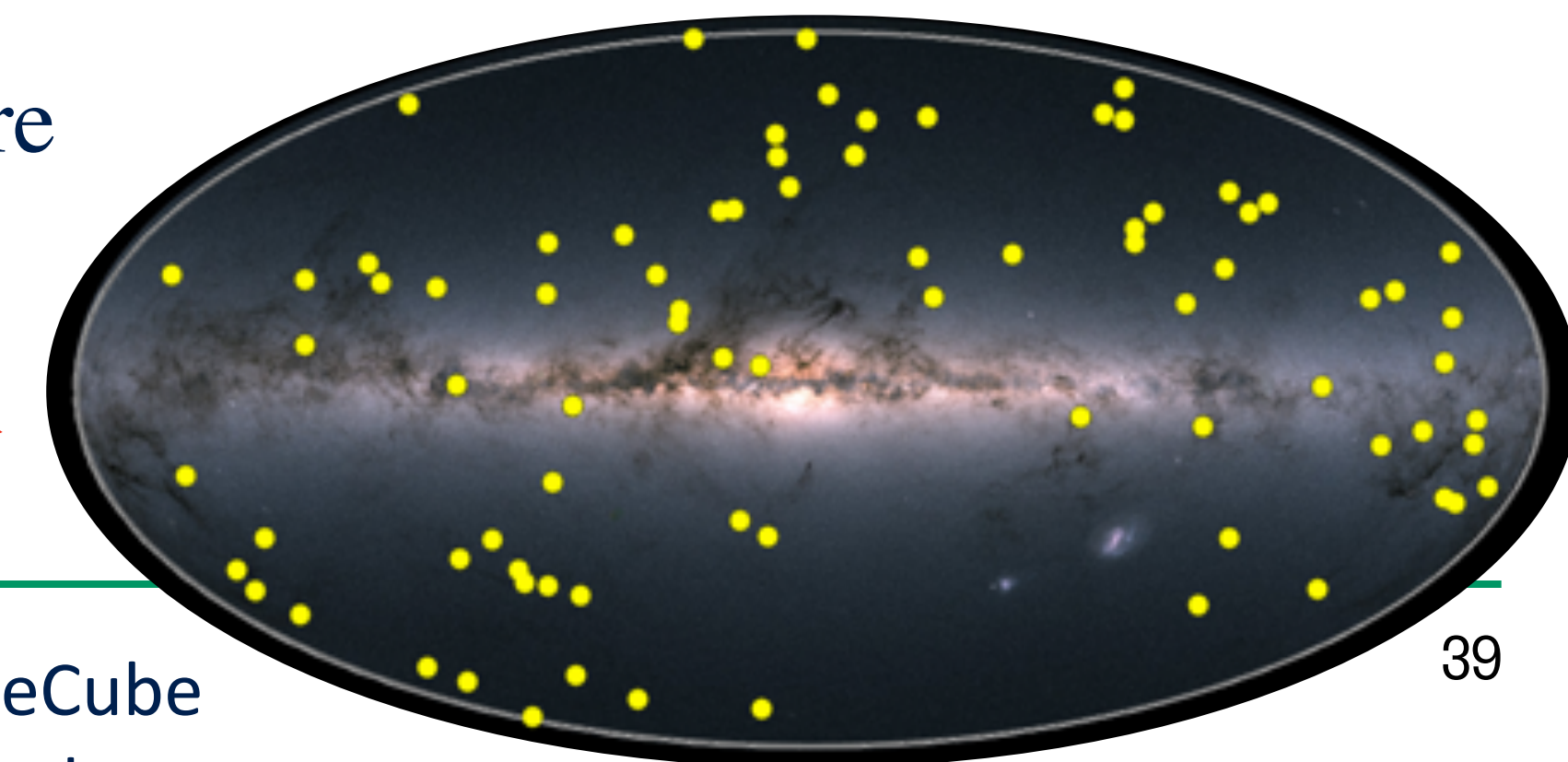
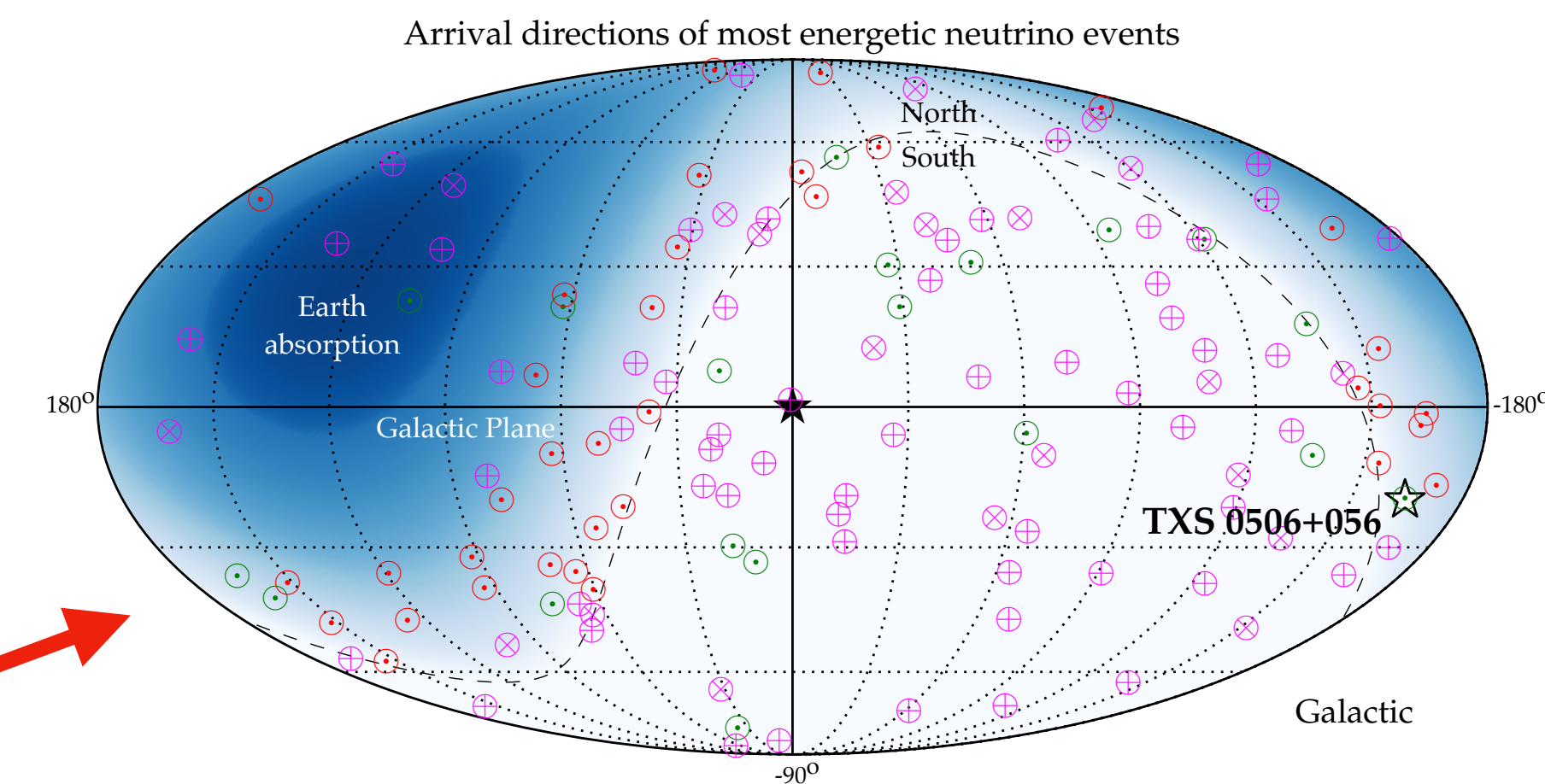
- Transients: CTA search for gamma-ray counterpart from a neutrino alert
- Steady sources: monitor hotspots exceeding IceCube sensitivity

## FIRESONG

- Simulate a neutrino population according to source evolution and luminosity function

## Density vs. Luminosity plot

- **Steady sources**: sources/Mpc<sup>3</sup> vs. neutrino luminosity
- **Transient sources**: burst rates/Mpc<sup>3</sup> (%flaring blazars) vs. neutrino flare luminosity



- |   |                             |
|---|-----------------------------|
| • <b>IC-170922A</b> : TXS 0506+056 ( $z = 0.3365$ )         | <i>IceCube Collab. 2018</i> |
| • <b>IC-190730A</b> : PKS 1502+106 ( $z = 1.84$ )           | <i>IceCube Collab. 2019</i> |
| • <b>IC-200107A</b> : 3HSP J095507.9+355101 ( $z = 0.557$ ) | <i>IceCube Collab. 2020</i> |
| • <b>IC-141209A</b> : GB6 J1040+0617 ( $z = 0.7351$ )       | <i>Garappa et al. 2019</i>  |

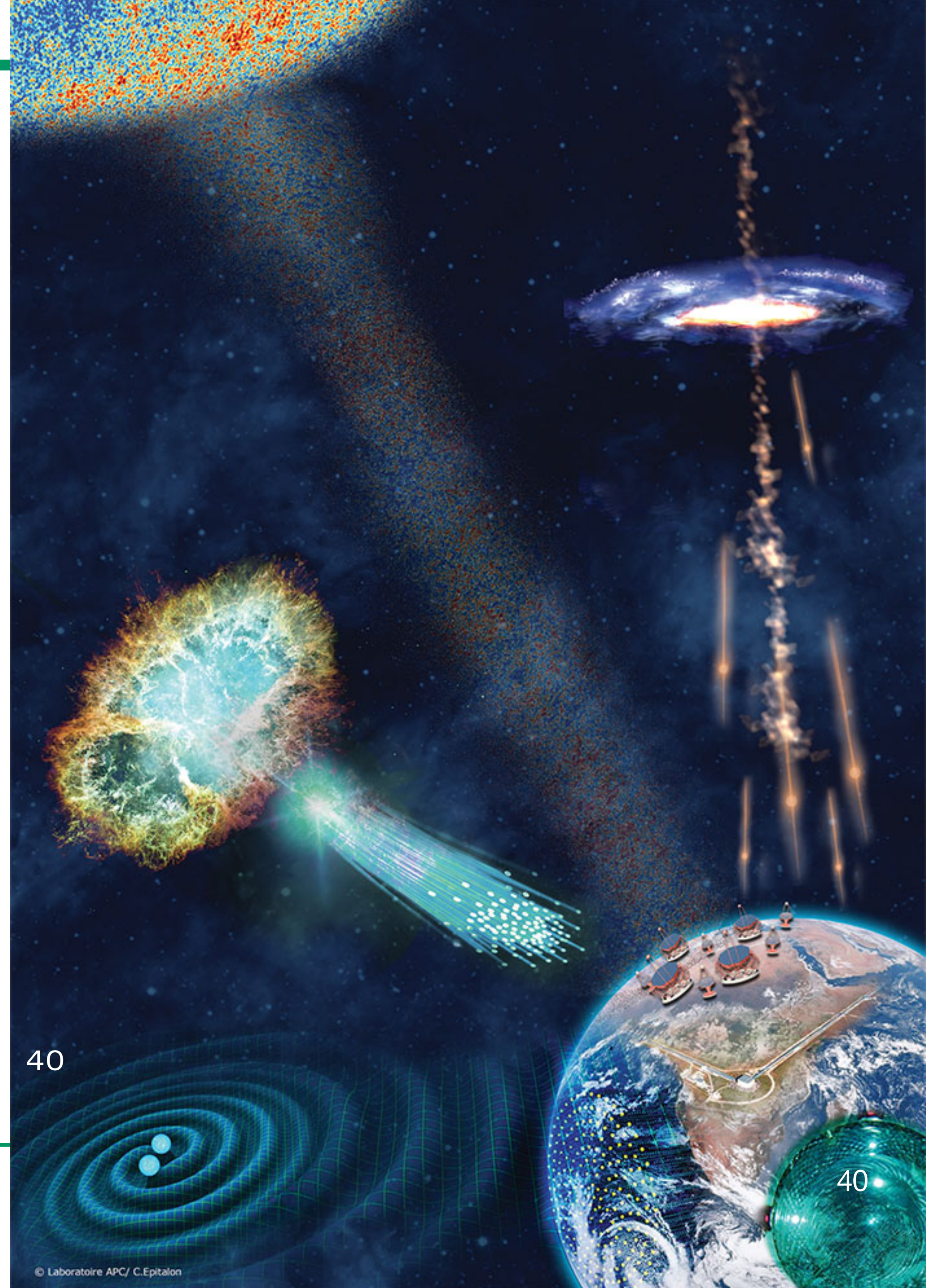
IceCube  
neutrino alerts

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# CTA Coordination Activities

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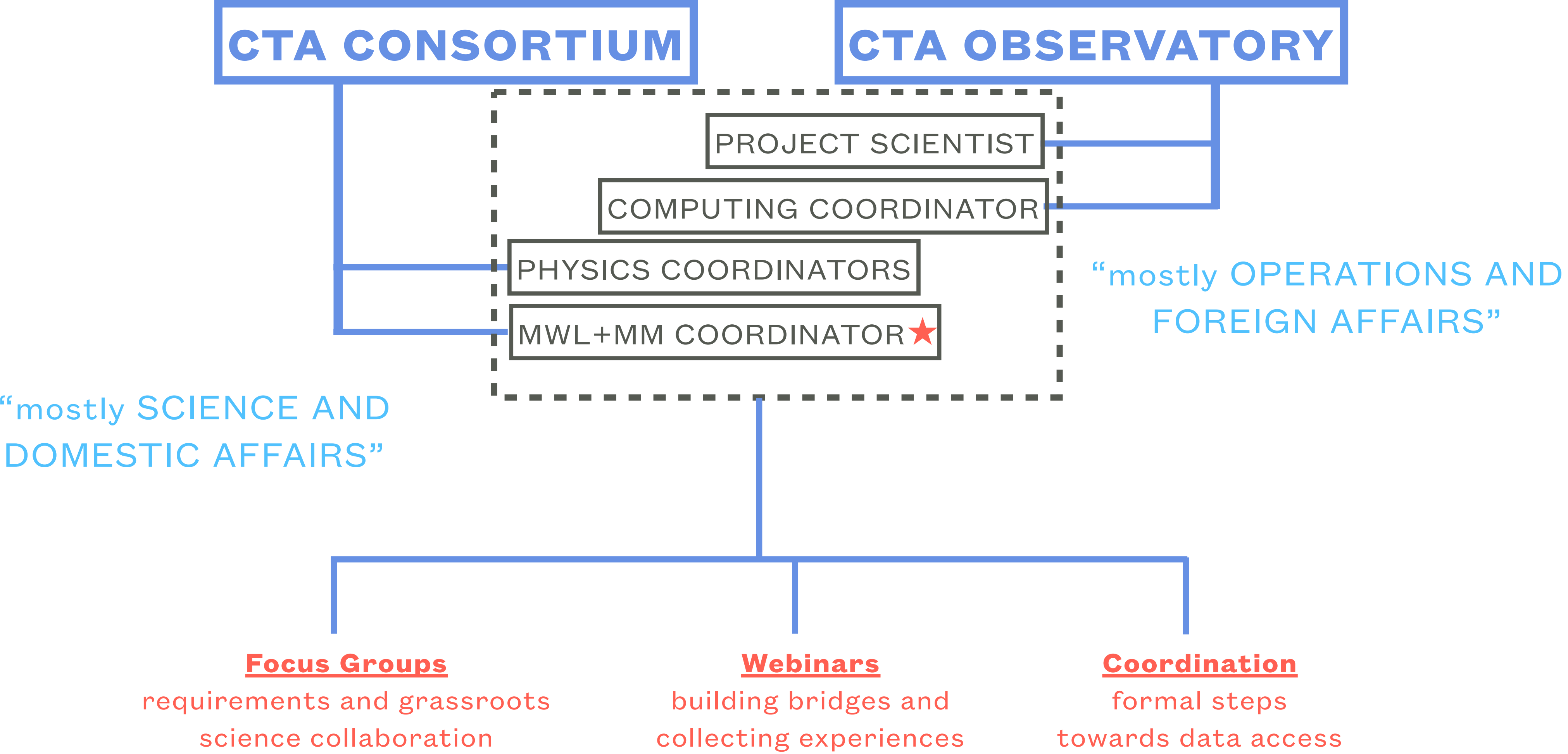


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# CTA MWL & MM Coordination Structure



# CTA MWL & MM Coordination Task Force



The achievement of the **CTA core Science Goals** depends on a wealth of MWL and MM data (often involving intense coordination between facilities), and the purpose of the MWL&MM Coordination Task Force is to identify, plan and secure those.

**Spatial  
Coordination  
for Surveys**

**Extension of  
Spectral  
Coverage**

**Catalogue cross-matching  
for resolving counterparts  
and source ID**

**Temporal  
coordination for  
variable sources**

**Alerts for Transient  
Phenomena**

Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	●	●	●	●	●	●	●			●
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	●	●		●	●	●	●	●		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	●	●		●	●	●	●	●	●	●
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.				●		●	●			●
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	●	●	●	●	●	●	●	●		●
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	●	●		●	●	●	●	●		●
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	●	●		●	●	●	●			●
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.	●	●	●		●	●	●			●
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						●				●

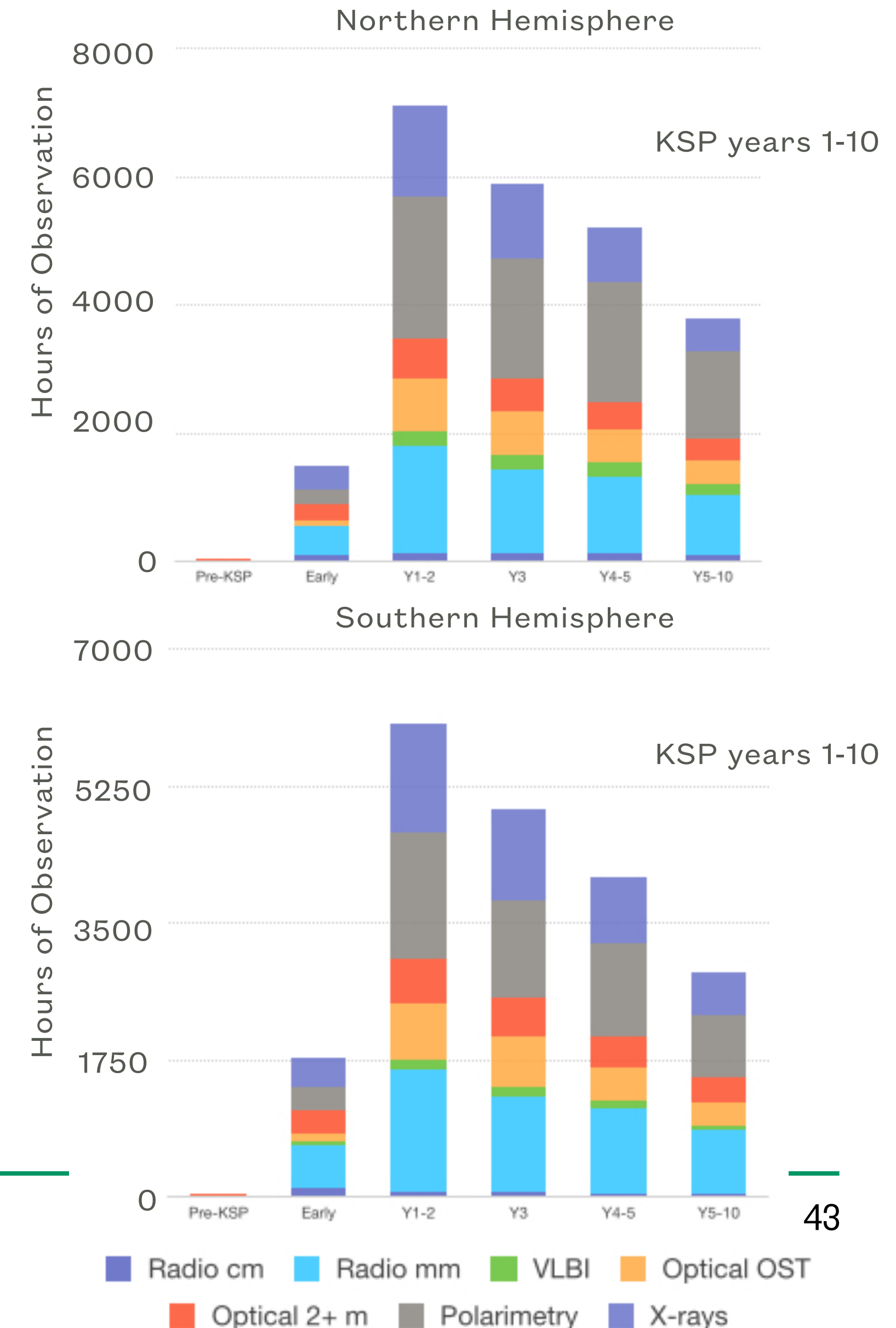
- Essential
- Important
- Useful

# CTA MWL & MM Coordination Task Force

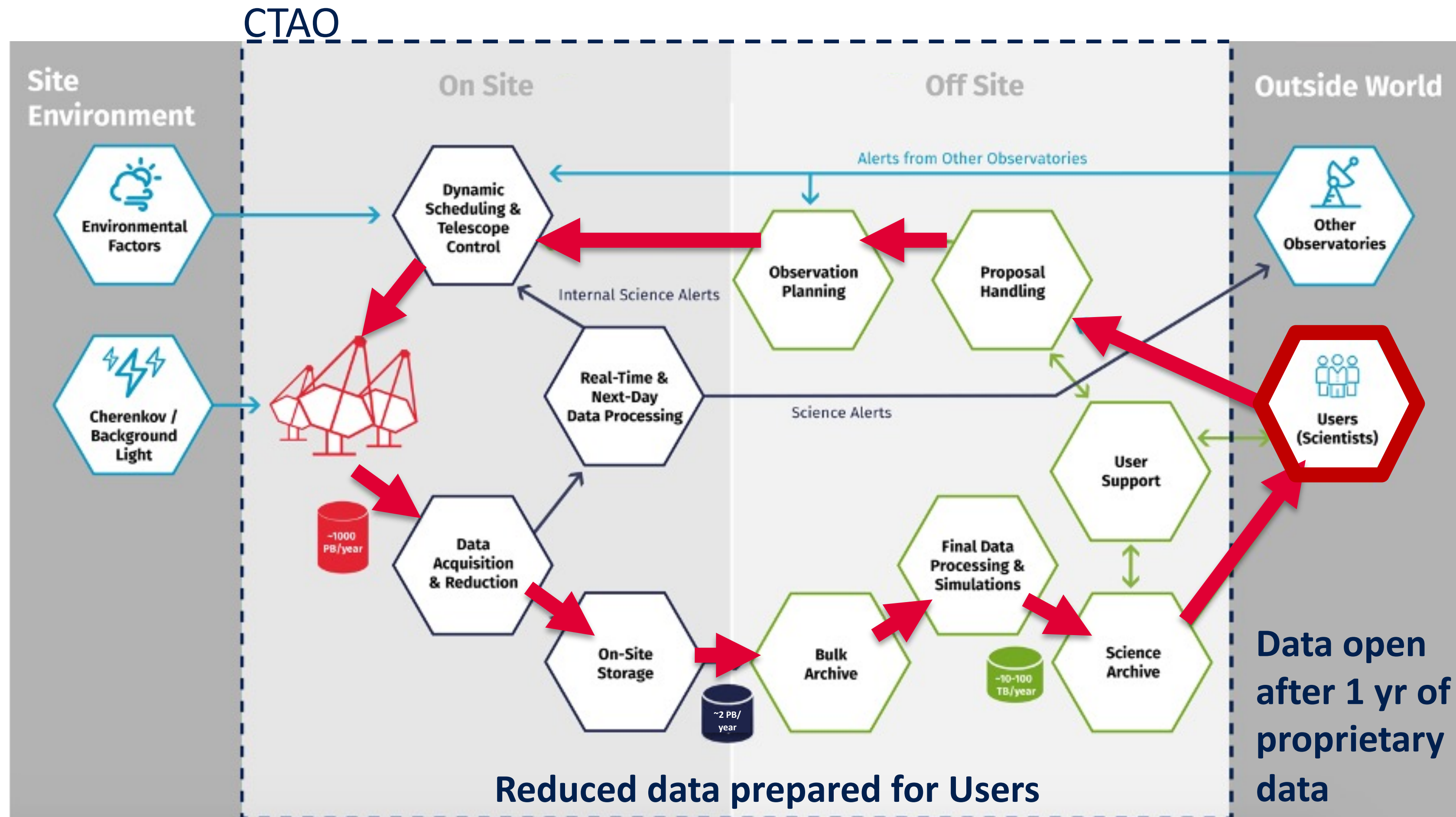


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<b>Transient Factories</b>	Wide-field monitoring & transients detection. Multi-messenger follow-ups.				●		●	●			●
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<b>MeV-GeV Gamma-rays</b>	High-energy transients. Pion-decay signature. Inverse-Compton process	●	●		●	●	●	●	●		●
<b>Other VHE</b>	Particle detectors for 100% duty cycle monitoring of TeV sky.	●	●		●	●	●	●			●
<b>Neutrinos</b>	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.	●	●	●		●	●	●			●
<b>Gravitational Waves</b>	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						●				●



# CTA : an open observatory



**Open Observatory** - Allows external teams to propose observational programs to CTA, adding flexibility and multiplying its science potential

**Open Data** - A fundamental ingredient for MM science, not only from the point of view of alerts, but data archives which are necessary for pursuing MWL & multi-messenger science programme.

**LEARN THE LESSONS FROM FERMI:**

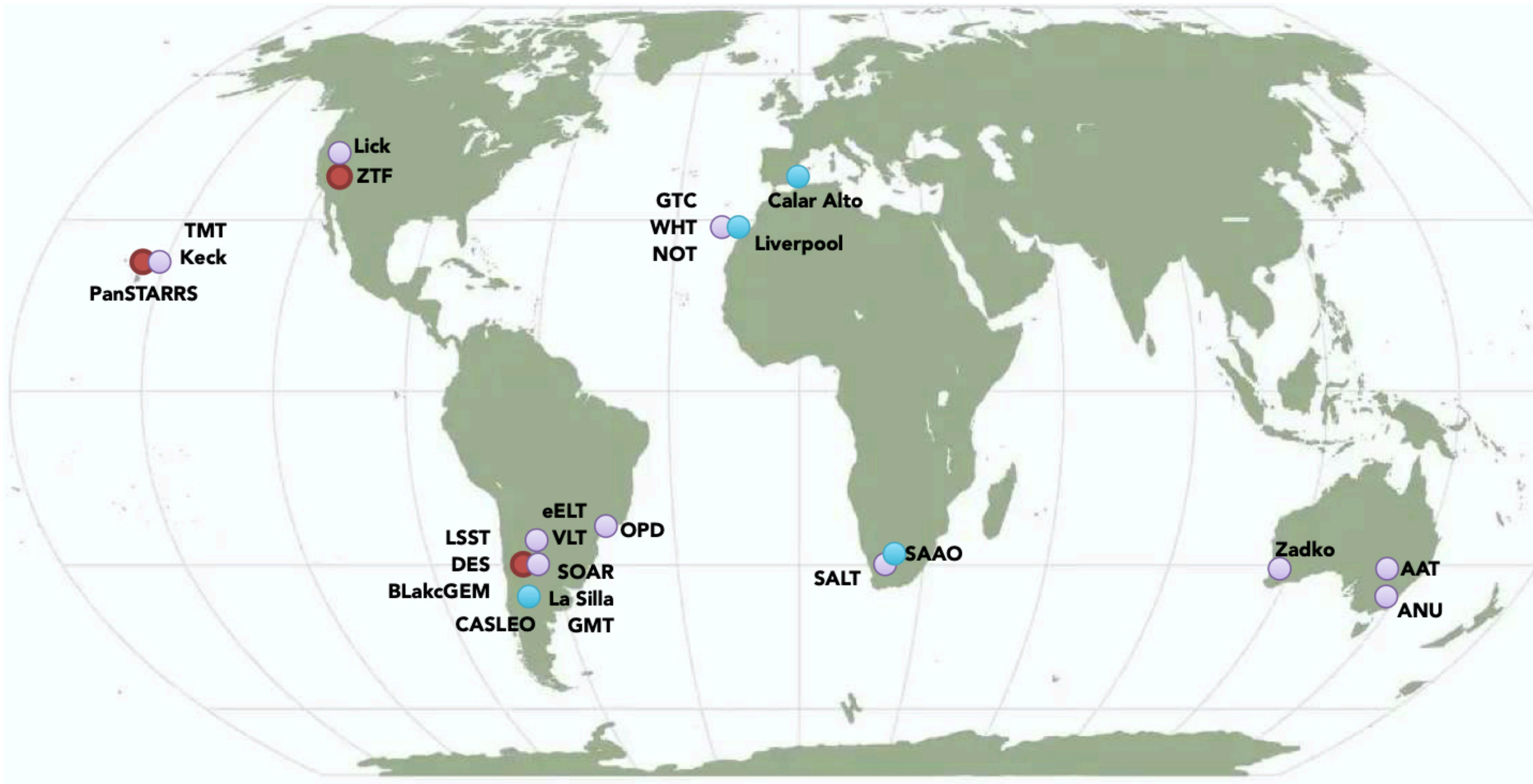
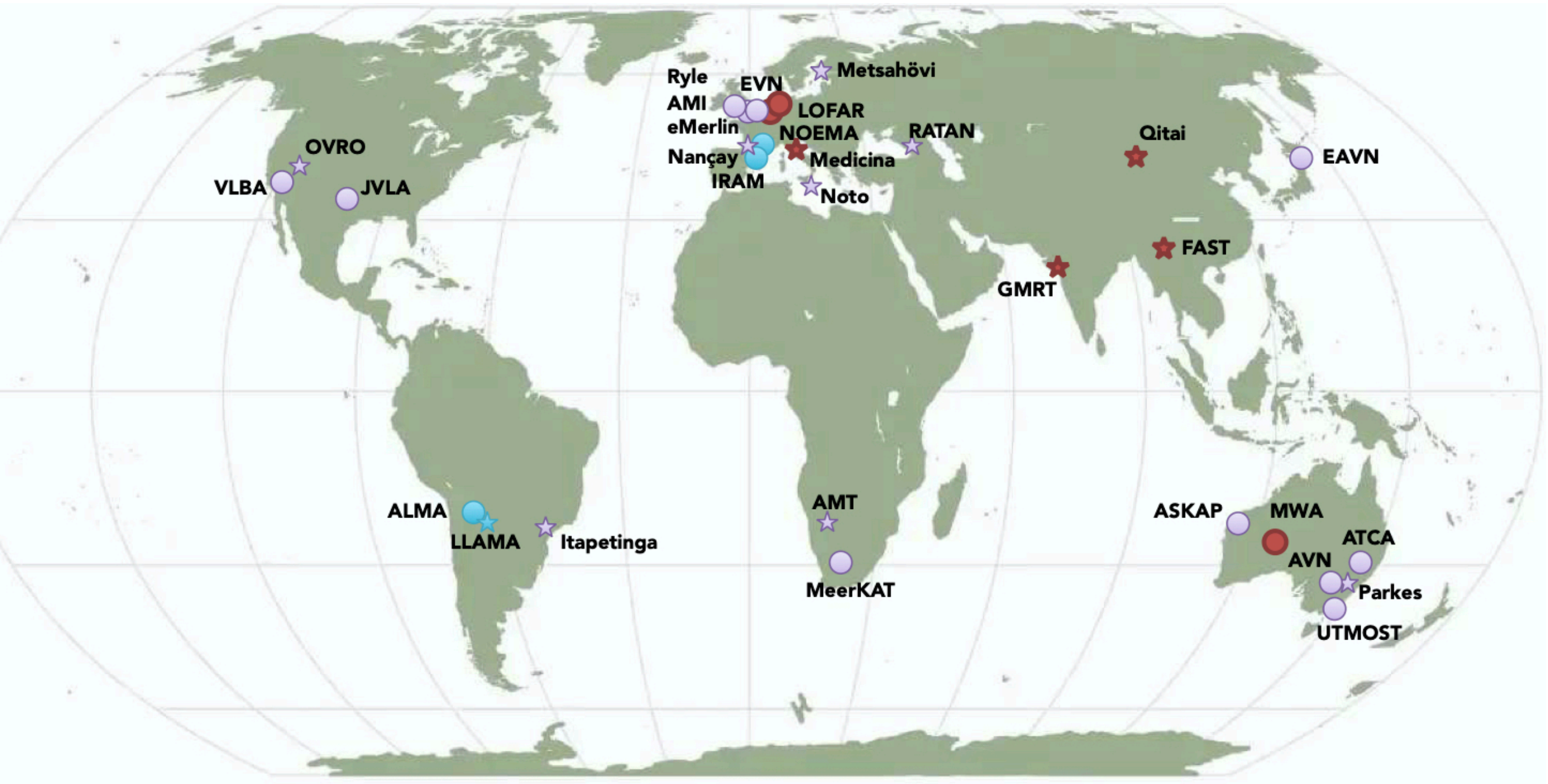
- FAST SHARING OF KEY DATA PRODUCTS
- BUILD UP EARLY YOUR NETWORK OF FRIENDS

# An ecosystem of ground-based facilities



## Radio Facilities Map

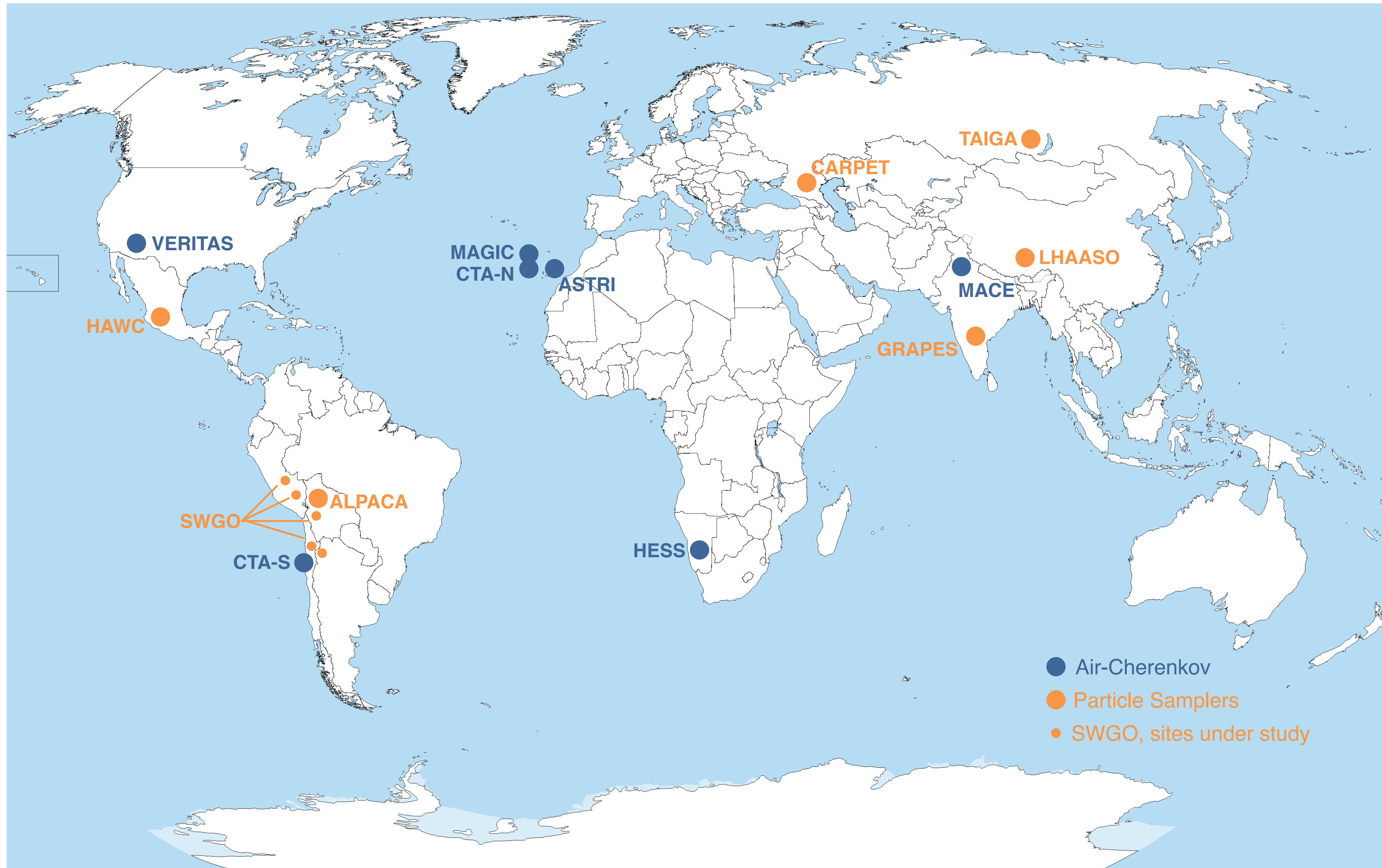
## Optical Facilities Map



- Low Frequency Radio
- Mid-Hi Frequency Radio
- mm /sub-mm Radio
- ★ ☆ ★ monitoring / follow-up?

- Transient Factories
- Major OIR Facilities
- Polarimetric Capability

# Gamma-ray ground-based facilities



**IACTS** - ASTRI and MACE = extended longitude coverage capabilities, with low-E threshold and deep source observations towards high energies

**Particle arrays** - LHAASO & SWGO = unprecedented all-sky coverage at VHE-UHE for alert and monitoring, as well as all-sky surveys.

# CTA Synergies Webinar Series



“AGN Multiwavelength Research Strategies: the Fermi Large Area Telescope Experience”

**David Thompson**

All available from the CTA YouTube channel:

<https://www.youtube.com/c/CherenkovTelescopeArrayObservatory>

The series continues in September, monthly, open to all.

**Register @** <https://www.cta-observatory.org/outreach-education/events/webinars-researchers/>

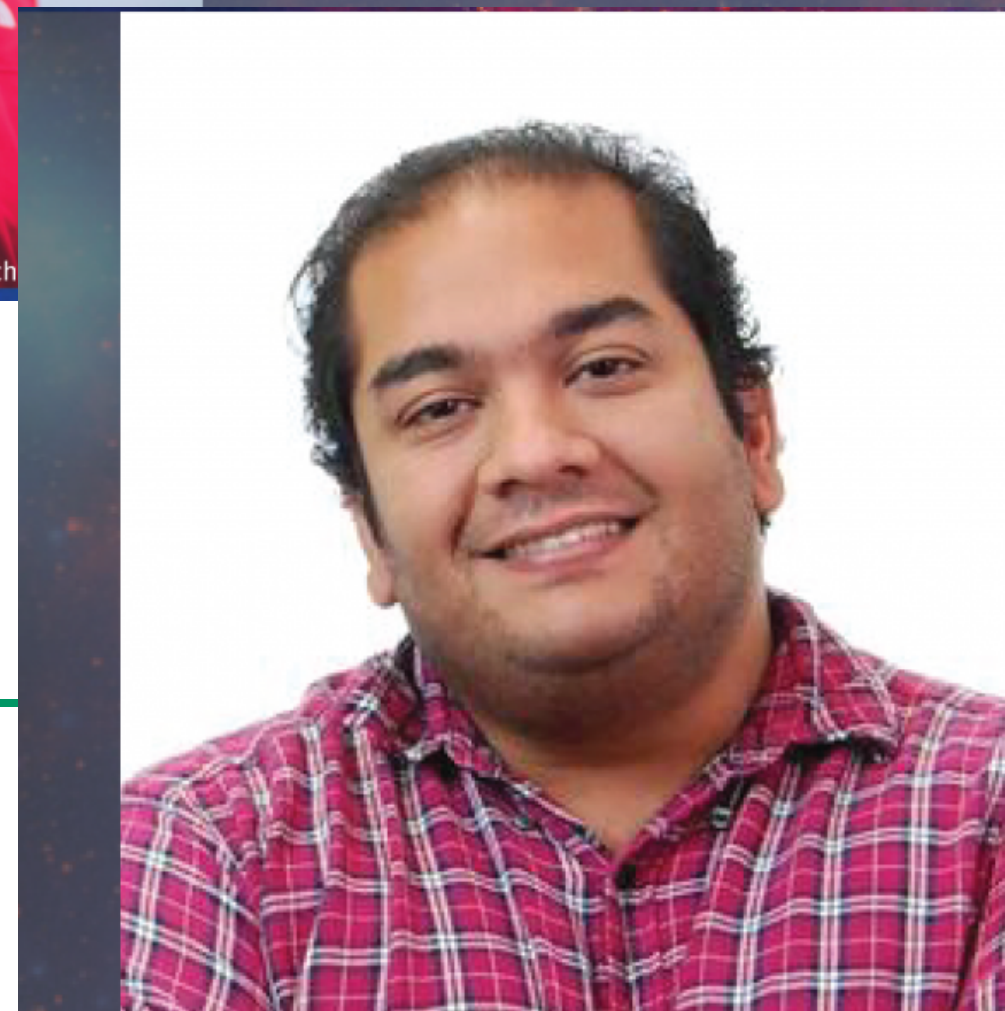
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“Multi-Messenger (MM) Data Networks: The potential and impact on the CTA science”

**Anna Franckowiak**

*Full professor at Ruhr-Universität Bochum & MM Group  
Leader at DESY*



“Alert Brokers for Astrophysical Surveys: What is in it for CTA and how to engage”

**Gautham Narayan**

*Assistant Professor at the University of Illinois at Urbana-Champaign  
Deputy Analysis Coordinator of the Rubin Observatory's Dark Energy Science Collaboration*



# Building operational requirements for CTAO, e.g. Workshop for MWL-MM Coordination

<https://arxiv.org/pdf/2007.05546.pdf>

**Transients and Alert Communications** - **(a)** Development of automate name servers to correlate events found by different facilities or wavebands; **(b)** expand GCN experience into other wavebands such as X-rays and radio; **(c)** keep alert / communication standards and protocols homogeneous across wavebands and in coordination with the IVOA; **(d)** enforce broad and timely accessibility to data.

**Data Policies** - **(a)** Limit as much as possible data proprietary limits for enabling time-critical science; **(b)** incorporate the FAIR principles within open astronomy data; **(c)** large projects should lead open data and data sharing policies.

**Follow-up spectroscopy** - **(a)** Increase the capacity of spectroscopic follow-up, critical fro transient ID; **(b)** invest in integrating medium-to-small observatories and observation capabilities around the globe; **(c)** avoid duplication of efforts by means of improved communication protocols; **(d)** train machine-learning models for event / source ID an classification.

**Telescope Coordination** - **(a)** Adoption of common formats for all observatories to report previous or planned observations; **(b)** offer joint MWL proposal opportunities to avoid “double jeopardy and logistic difficulties in coordination challenges.

**ToO Implementation** - **(a)** Treat ToOs as part of the requirements definition process in the early stages of new facilities planning; **(b)** implement science-driven rather than “programatic considerations” on location and availability of ToO time whenever possible; **(c)** make choice allocation process of ToO time transparent; **(d)** limit data proprietary time for ToOs; **(d)** rapid availability of data products provision and software products needed for publication-quality results.

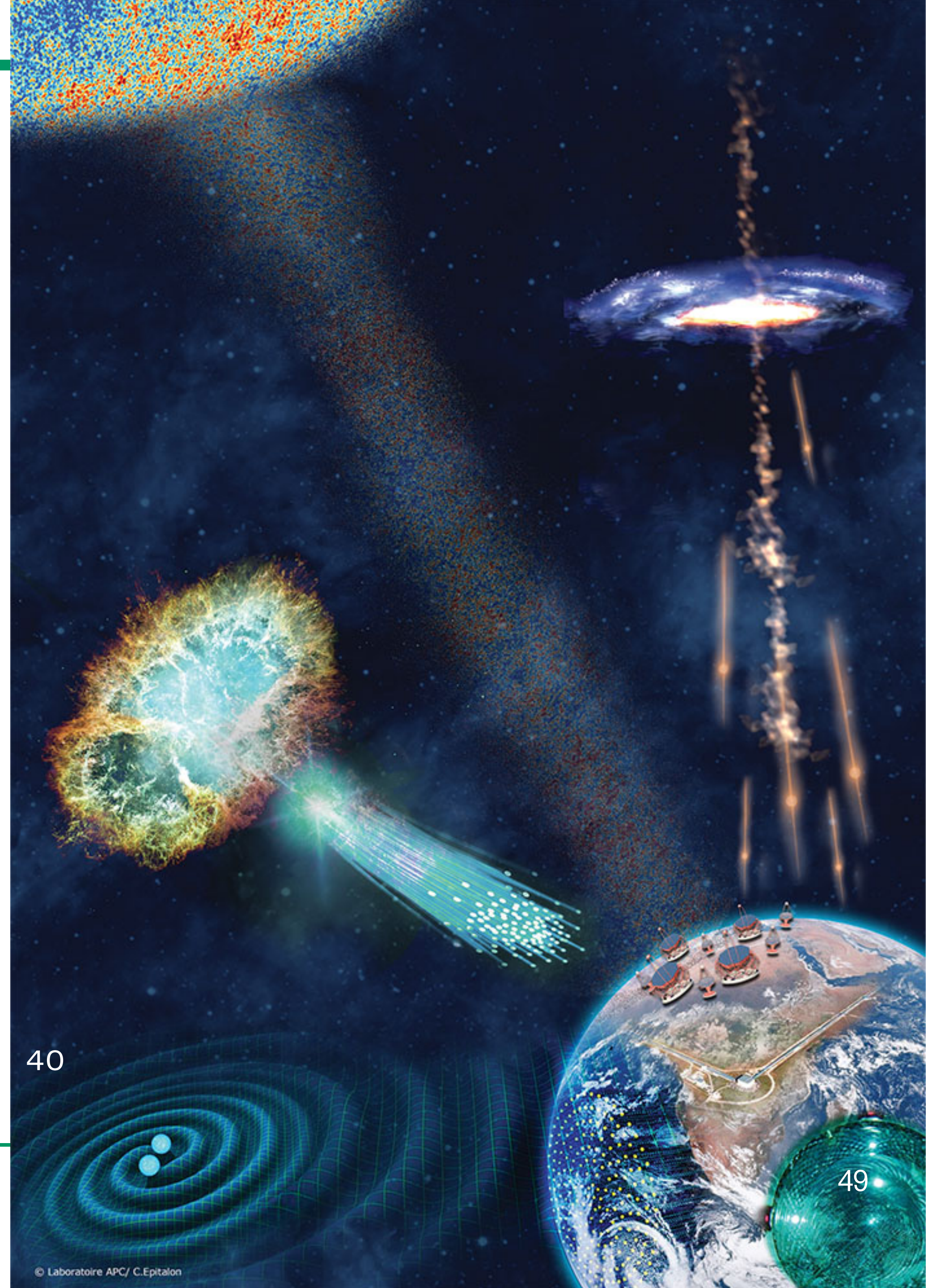


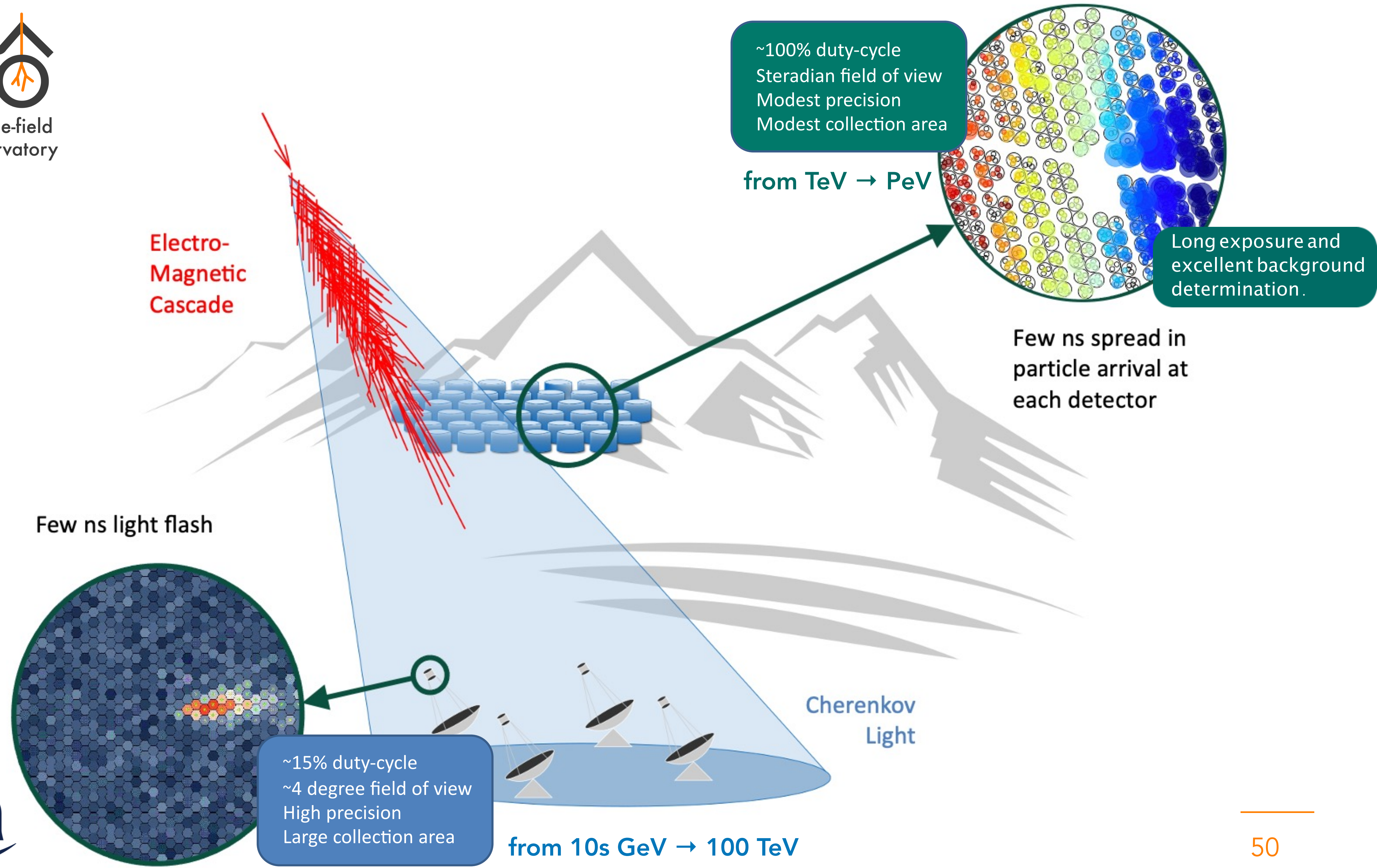
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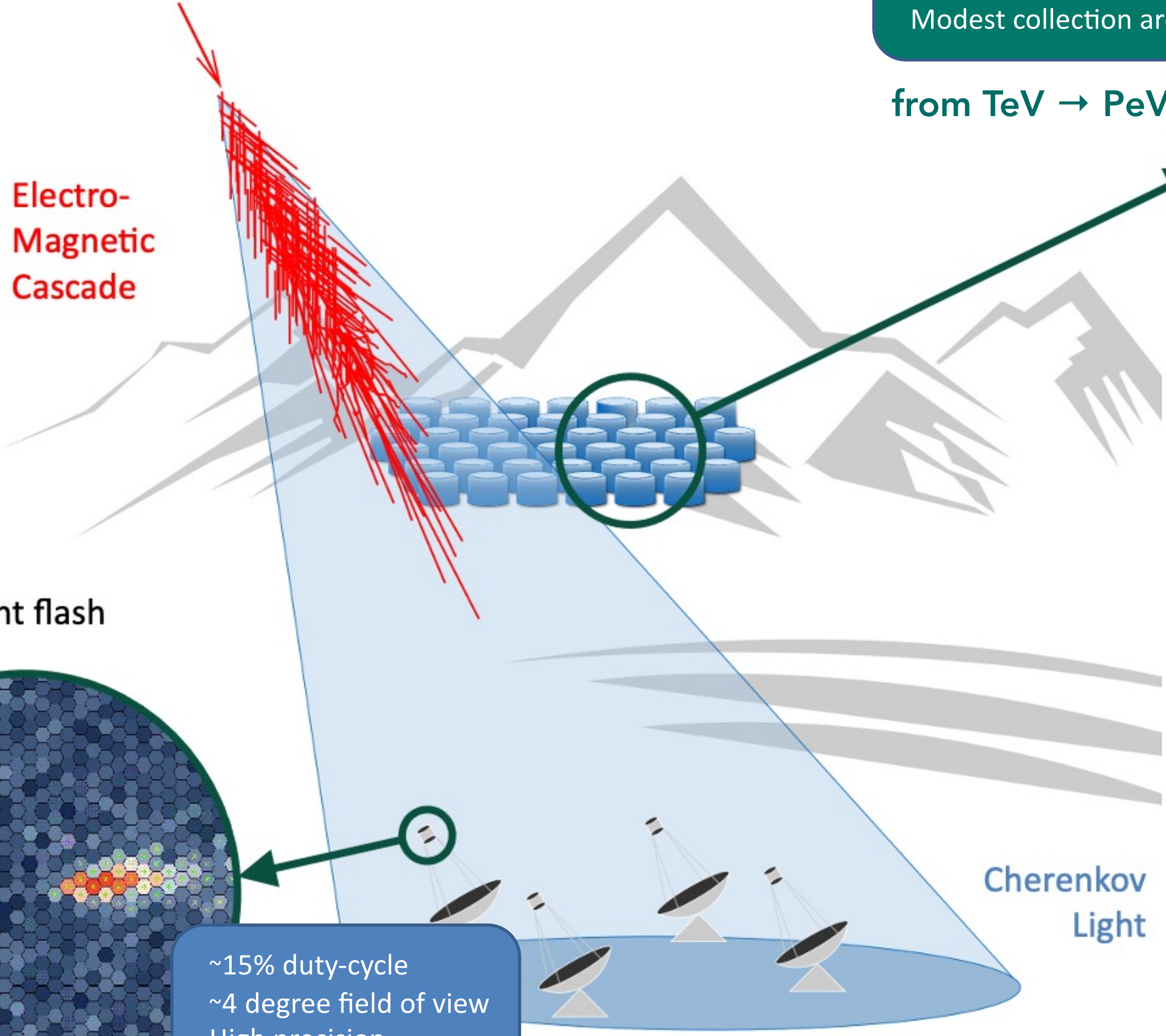
# Towards the UHE Regime

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~100% duty-cycle  
Steradian field of view  
Modest precision  
Modest collection area

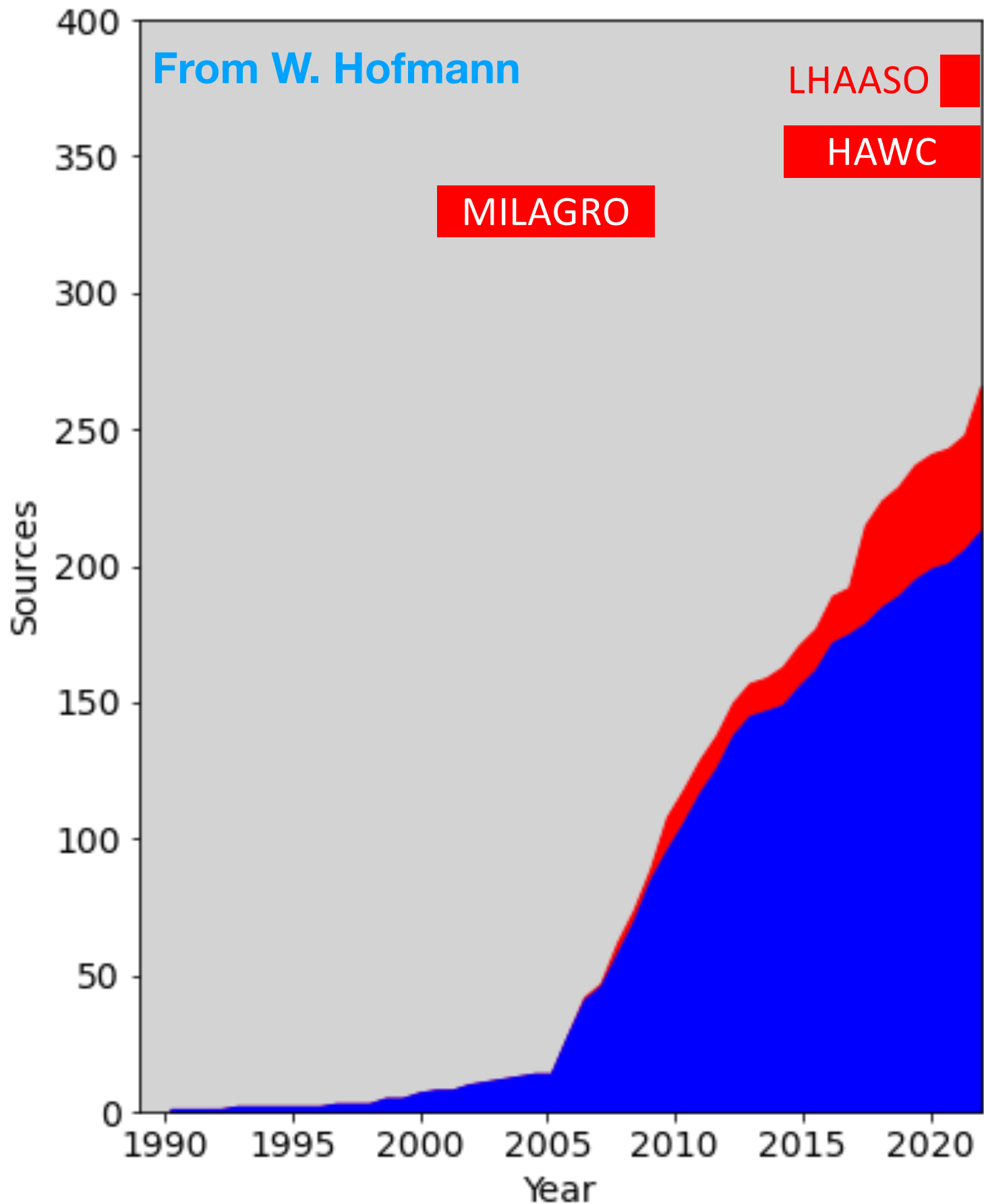
from TeV → PeV

Long exposure and  
excellent background  
determination.

Few ns light flash

~15% duty-cycle  
~4 degree field of view  
High precision  
Large collection area

from 10s GeV → 100 TeV



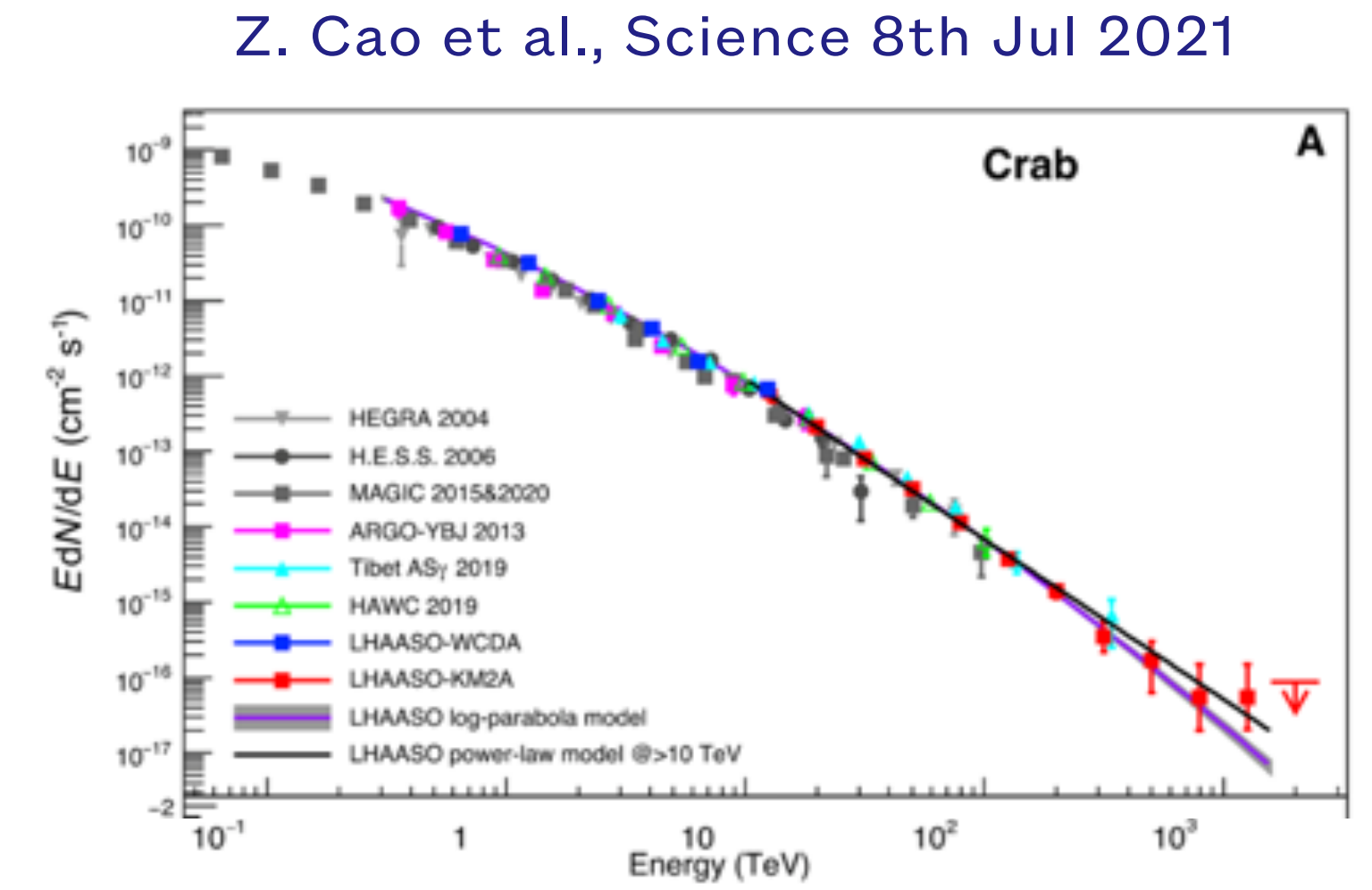
# A new piece in the MM board

LHAASO

EAS WCD+km<sup>2</sup> array

Sichuan (China)

@ 4410 m a.s.l.



PeV gamma-rays from the Crab.

**Wide-Field** - circa 1 sr of the sky, with 100% duty cycle.

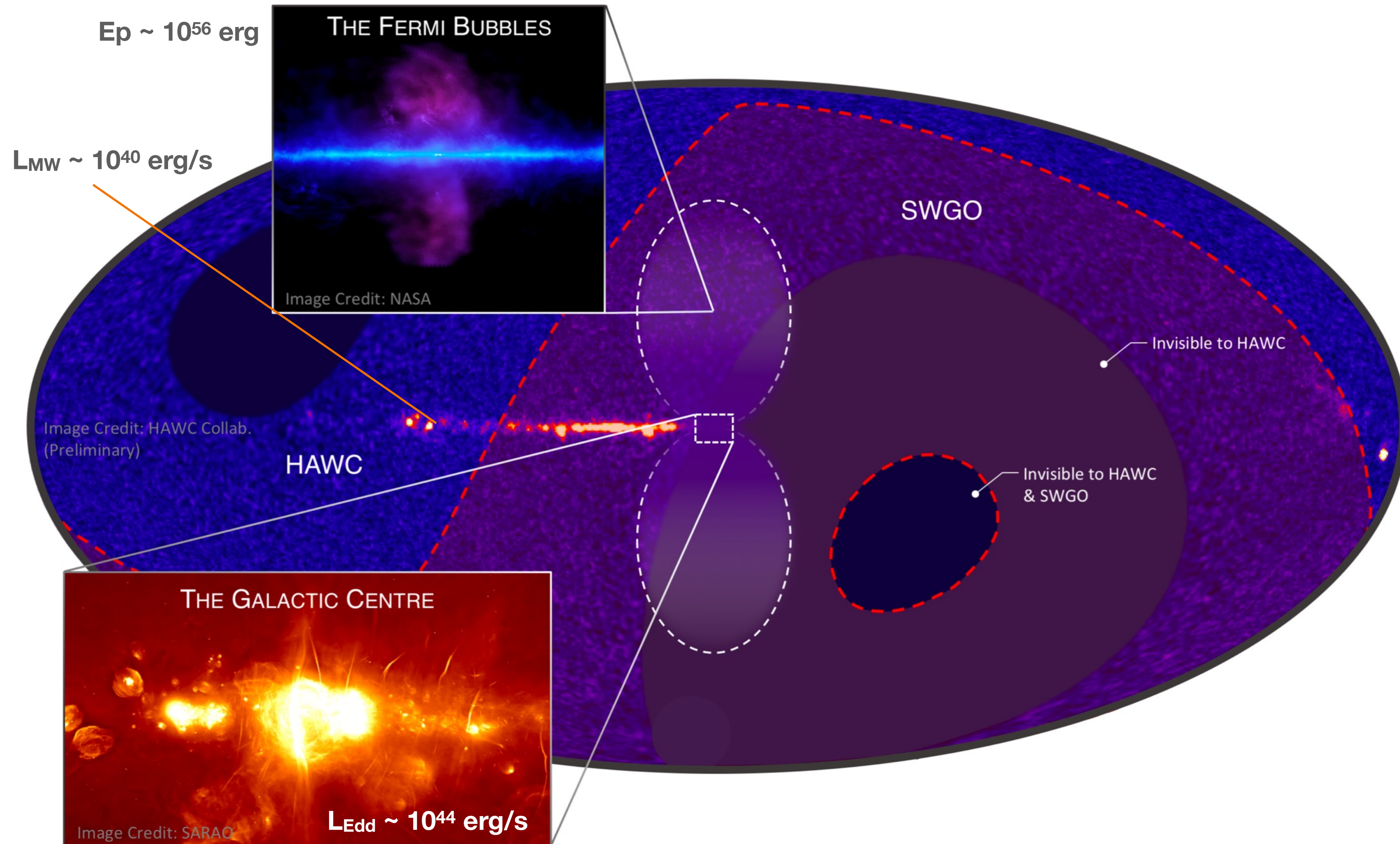
**UHE energies & muon array** - Nearly background free above 100 TeV, unique view to PeV gamma-rays

**VHE monitor** - Unprecedented monitoring potential below 10 TeV for transient discoveries.

# Gamma-ray Observatories Worldwide



# A Wide-Field Experiment in the South

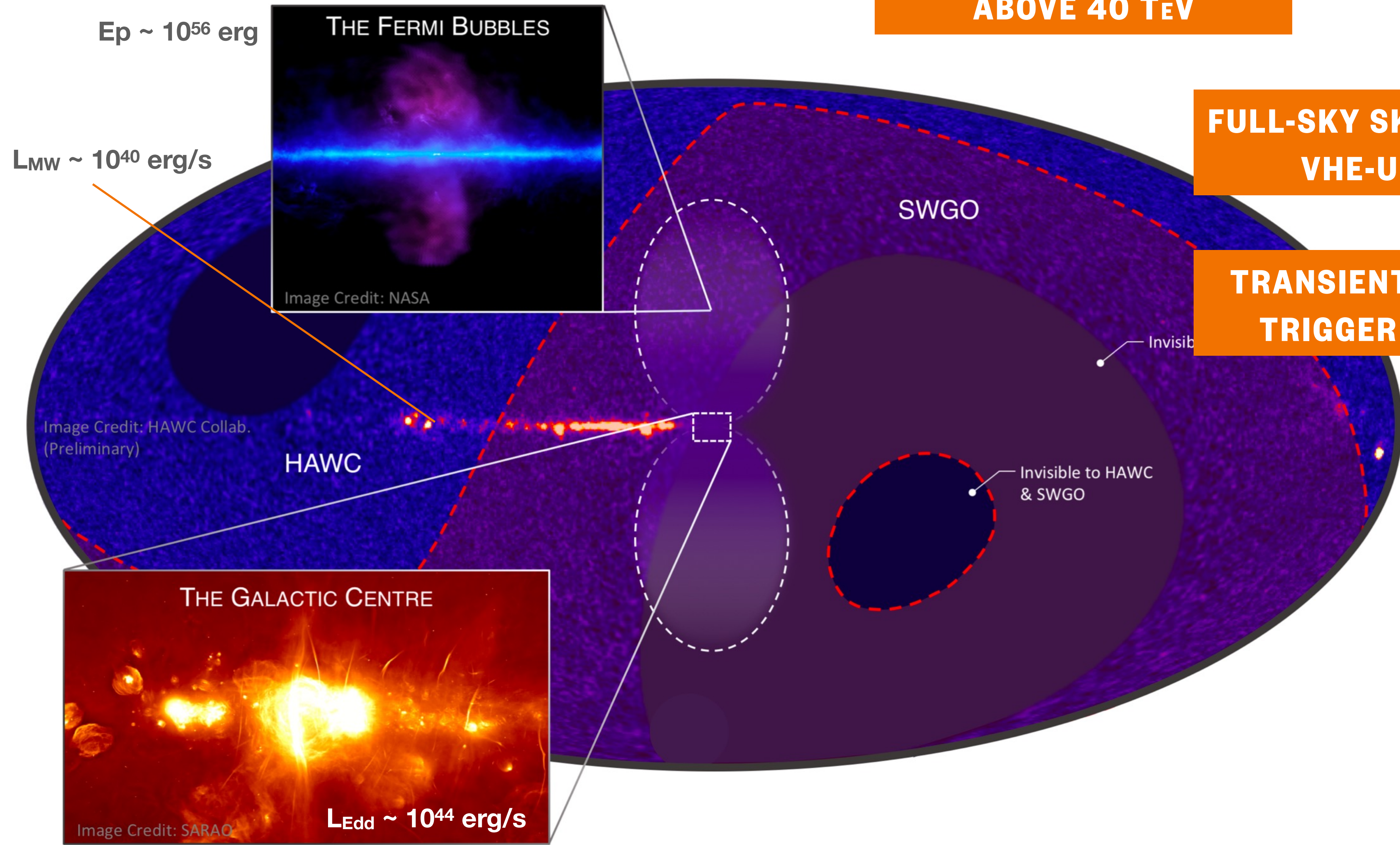


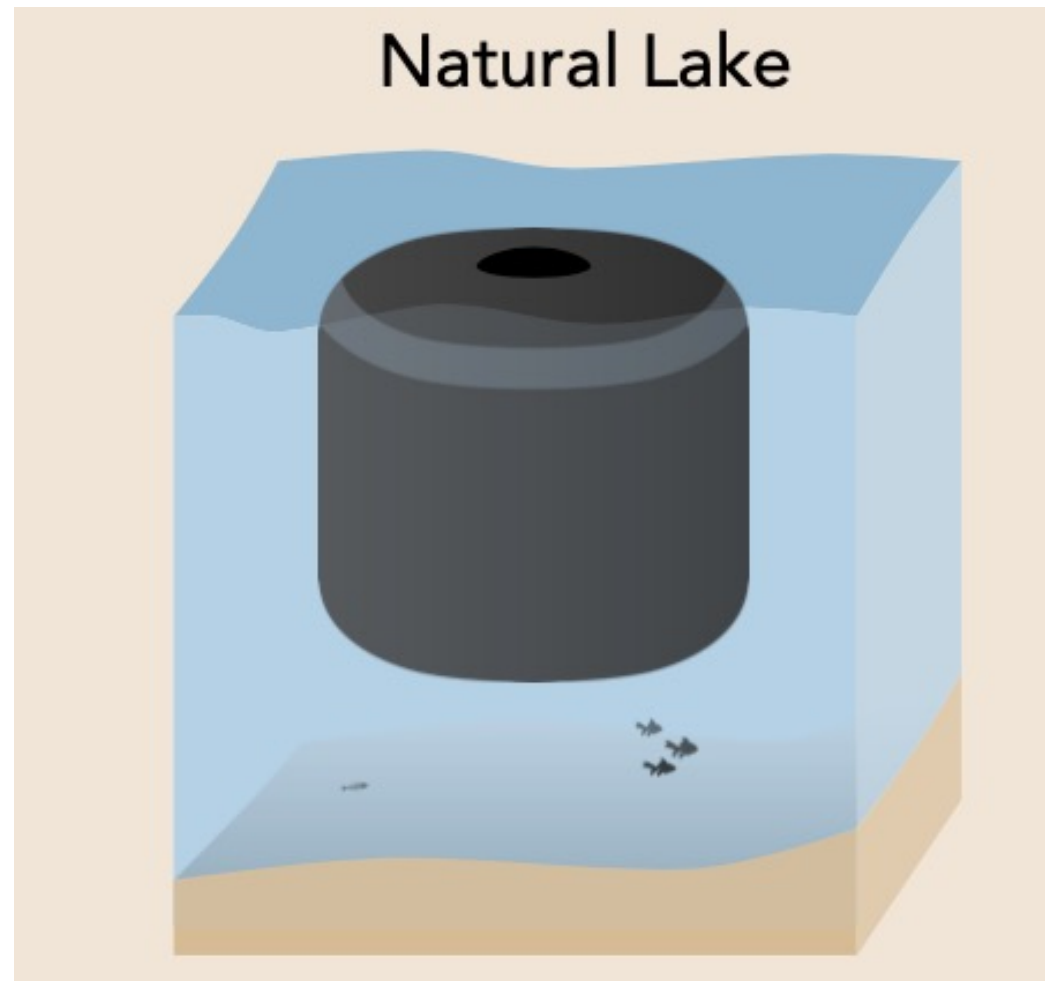
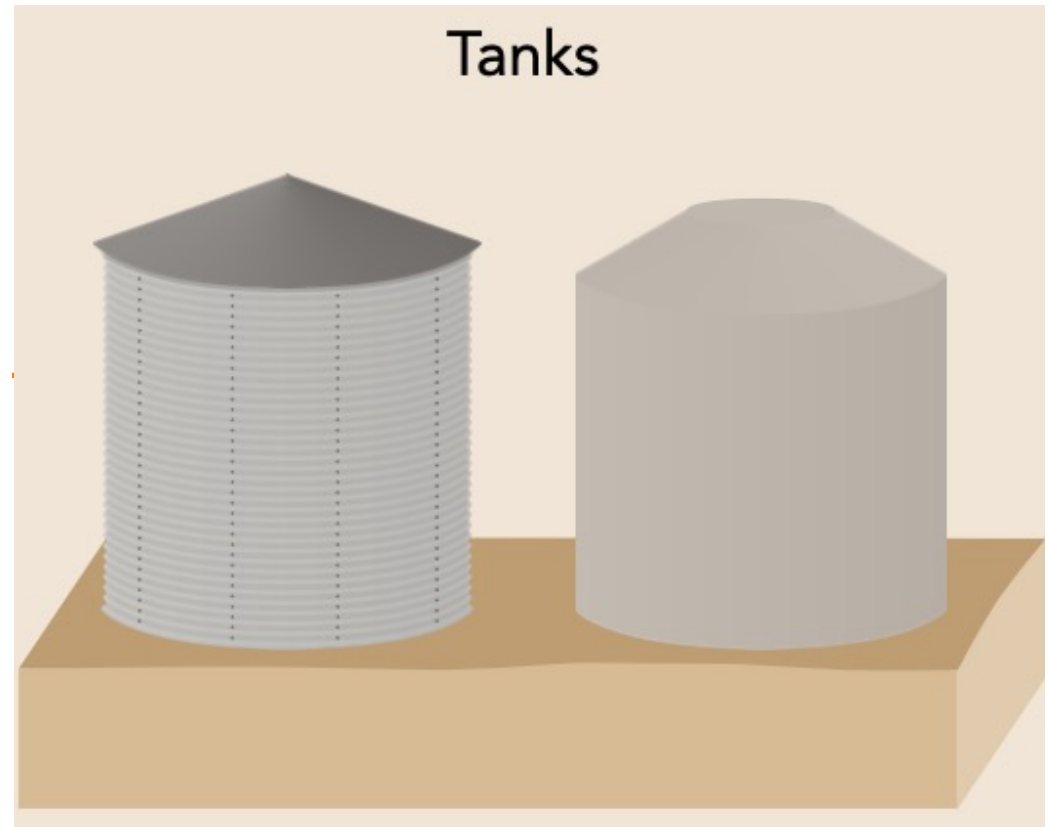
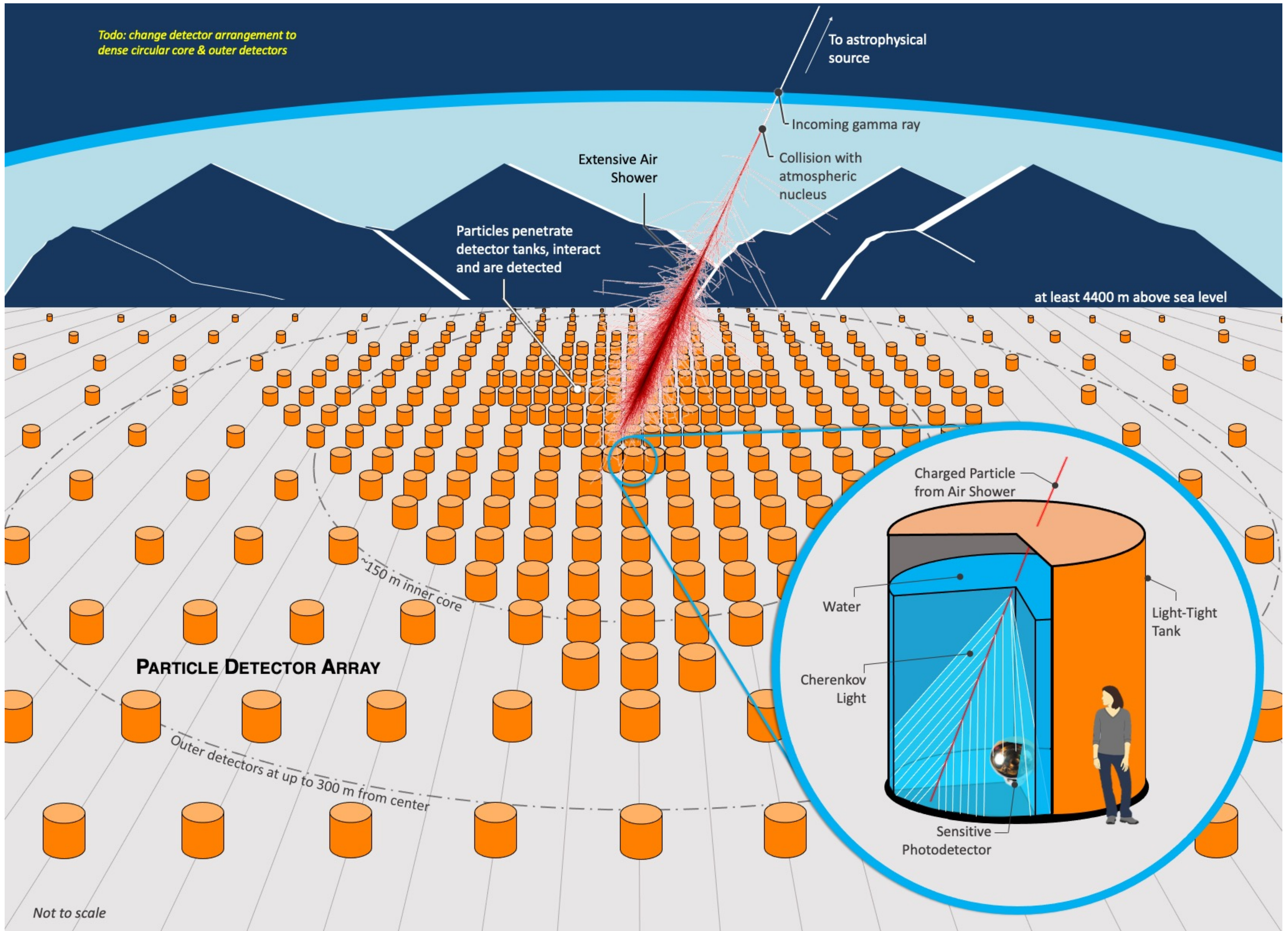
# A Wide-Field Experiment in the South

**LEADING TECHNIQUE  
ABOVE 40 TeV**

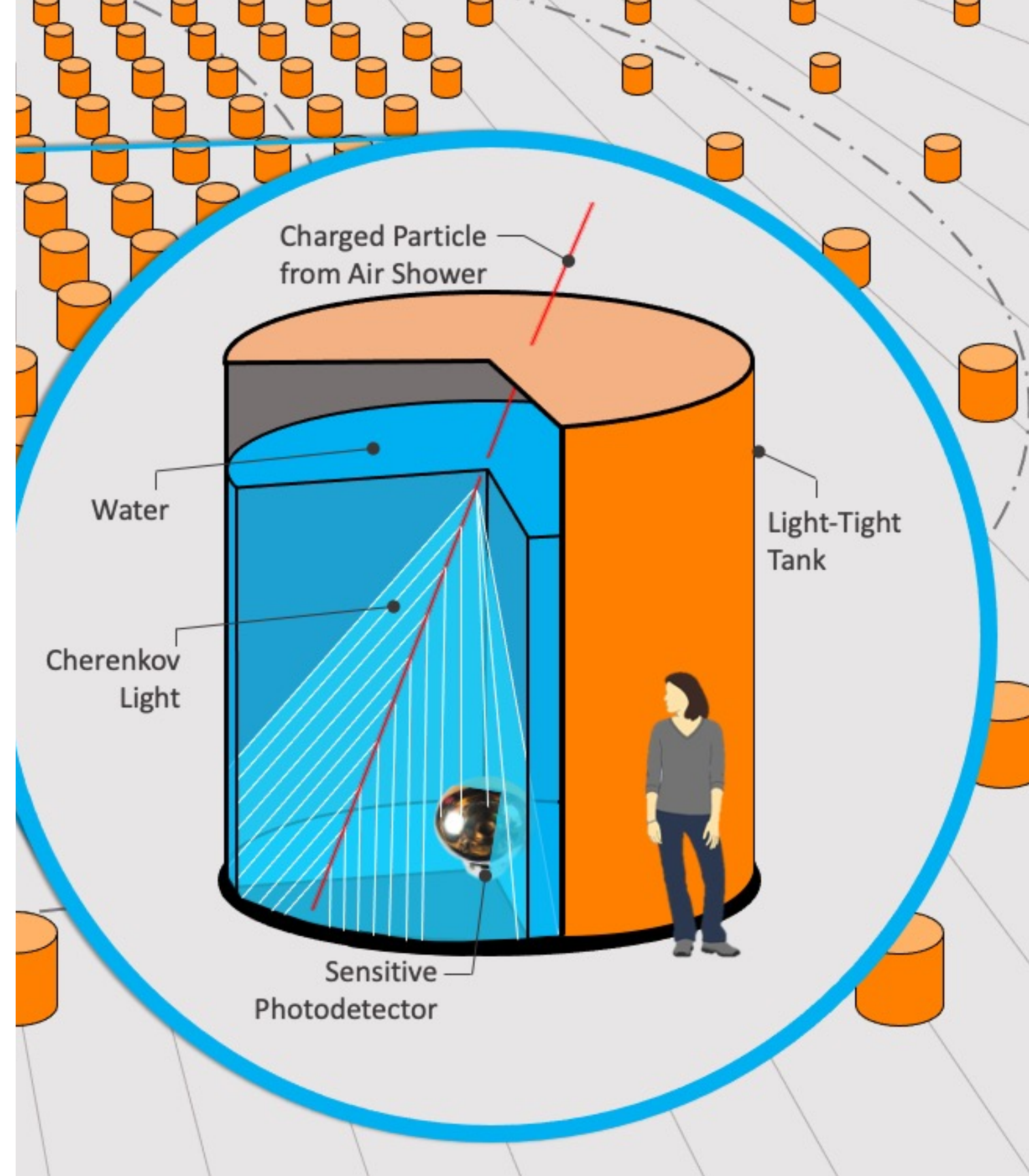
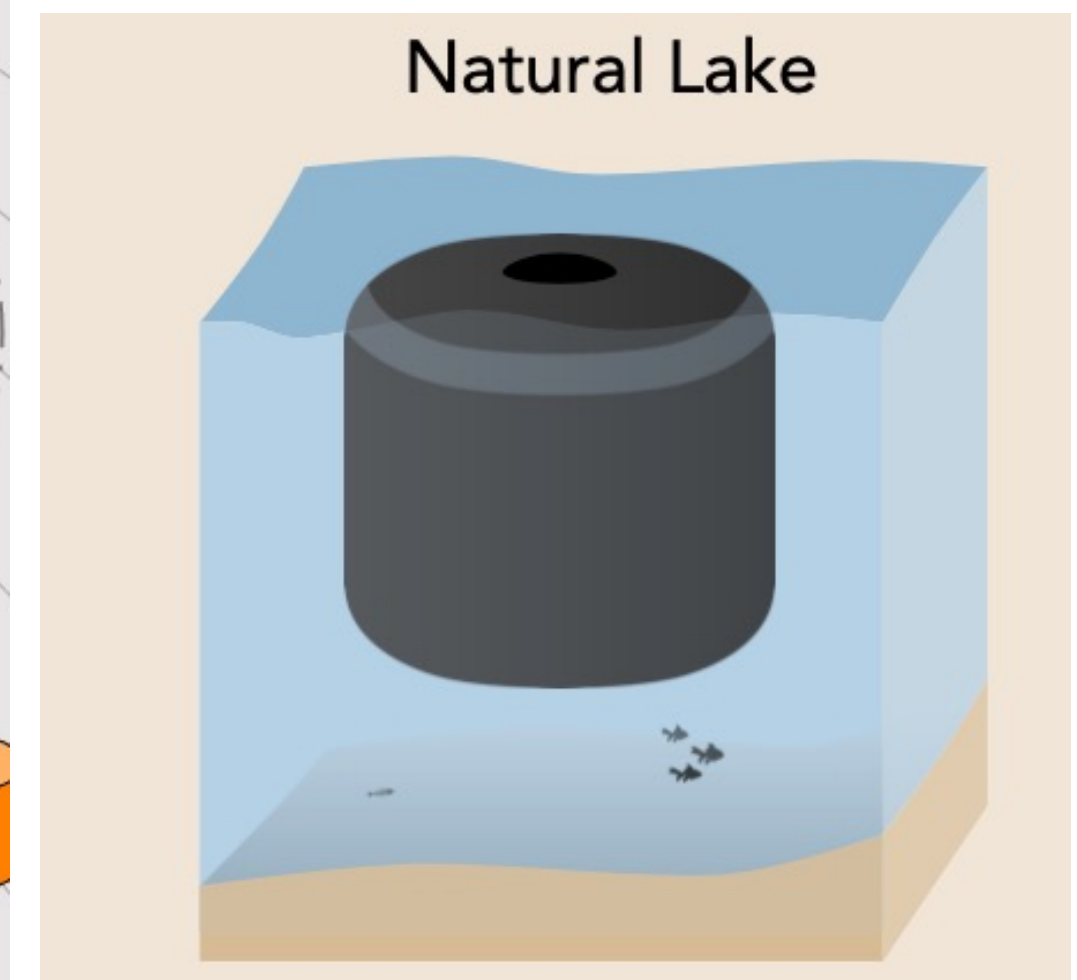
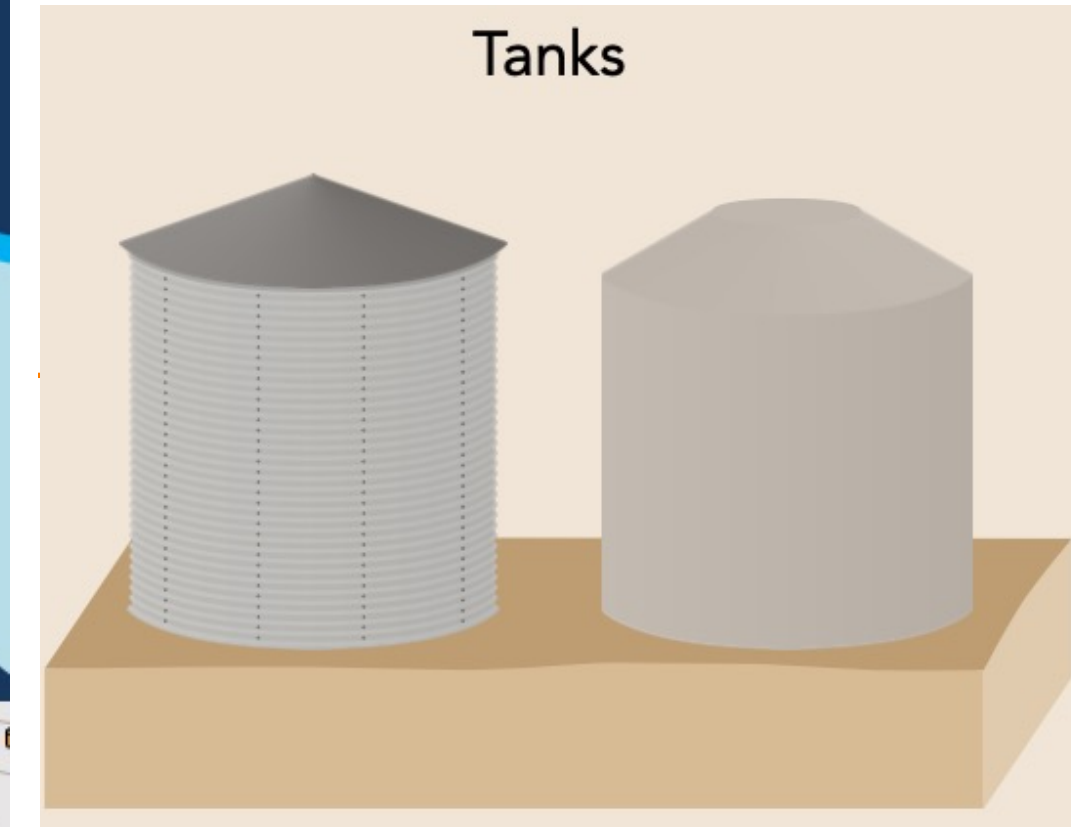
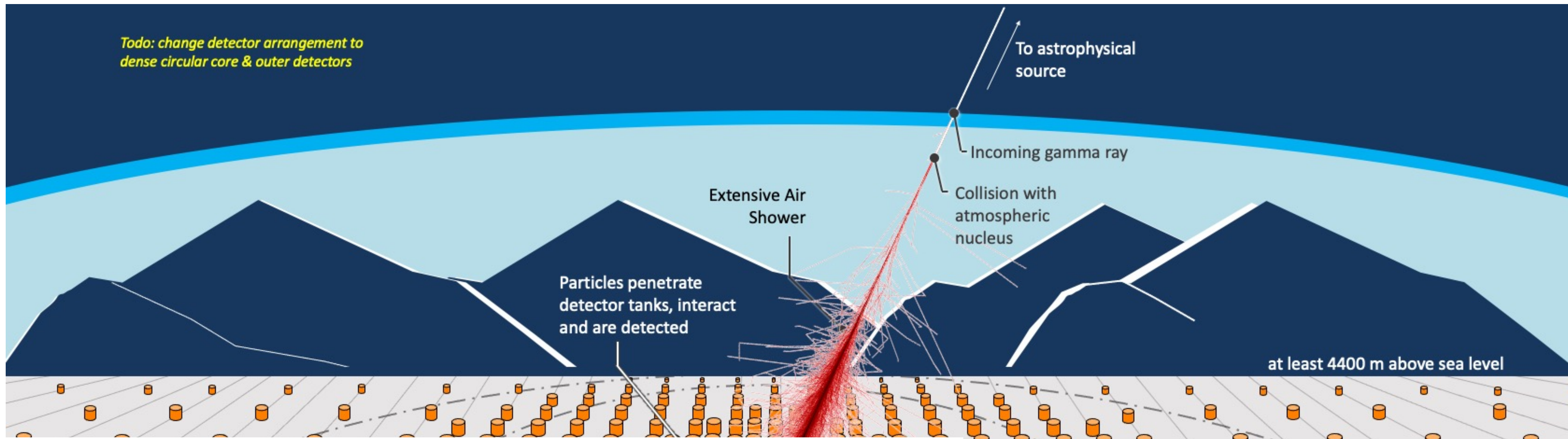
**FULL-SKY SURVEY IN THE  
VHE-UHE REGIMES**

**TRANSIENT SCIENCE & VHE  
TRIGGER / MONITORING**









Science Case	Design Drivers	Benchmark Description
Transient Sources: Gamma-ray Bursts	Low-energy sensitivity & Site altitude <sup>a</sup>	Min. time for 5 $\sigma$ detection: F(100 GeV) = 10 <sup>-8</sup> erg/cm <sup>2</sup> .s, PWL index = -2., F(t) $\propto$ t <sup>-1.2</sup>
Galactic Accelerators: PeVatron Sources	High-energy sensitivity & Energy resolution <sup>b</sup>	Maximum exp-cutoff energy de- tectable 95% CL in 5 years for: F(1TeV) = 5 mCrab, index = -2.3
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity & Angular resolution <sup>c</sup>	Max. angular extension detected at 5 $\sigma$ in 5-yr integration for: F(>1TeV) = 5 $\times$ 10 <sup>-13</sup> TeV/cm <sup>-2</sup> .s
Diffuse Emission: Fermi Bubbles	Background rejection	Minimum diffuse cosmic-ray residual background level. Threshold: < 10 <sup>-4</sup> level at 1 TeV.
Fundamental Physics: Dark Matter from GC Halo	Mid-range energy sensitivity Site latitude <sup>d</sup>	Max. energy for $b\bar{b}$ thermal relic cross-section limit at 95% CL in 5-years, for Einasto profile.
Cosmic-rays: Mass-resolved dipole / multipole anisotropy	Muon counting capability <sup>e</sup>	Max. dipole energy at 10 <sup>-3</sup> level; Log-mass resolution at 1 PeV – goal is A={1, 4, 14, 56}; Maxi- mum multipole scale > 0.1 PeV

# Potential sites for installation, above 4.4 km altitude in the Andes

lat. 15 S



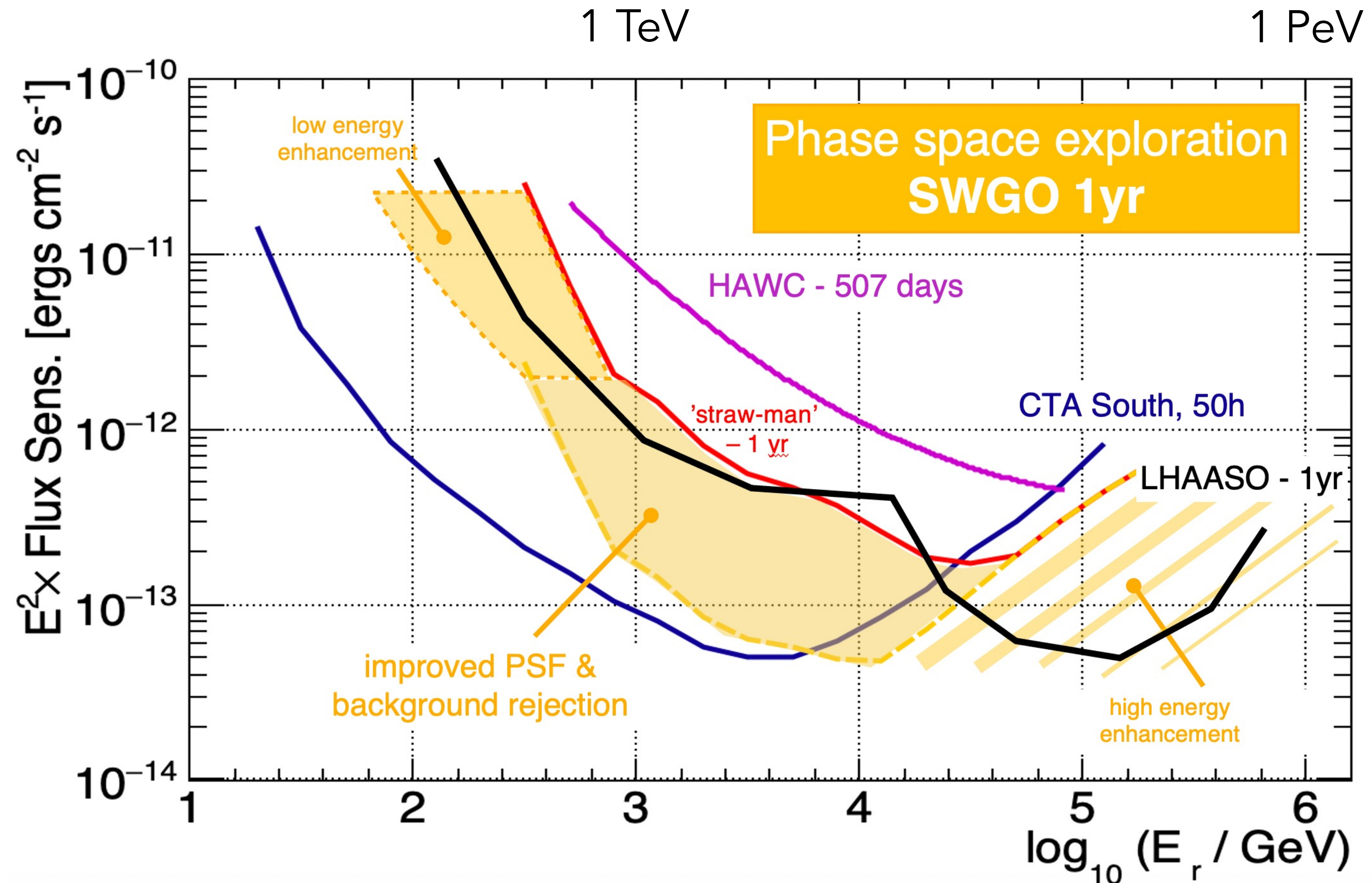
lat. 23 S

- 📍 Alto Tocomar (Argentina)
- 📍 Cerro Vecar (Argentina)
- 📍 Chacaltaya (Bolivia)
- 📍 AAP Pajonal (Chile)
- 📍 AAP Pampa La Bola (Chile)
- 📍 Lake Sibinacocha (Peru)
- 📍 Imata (Peru)
- 📍 Yanque (Peru)

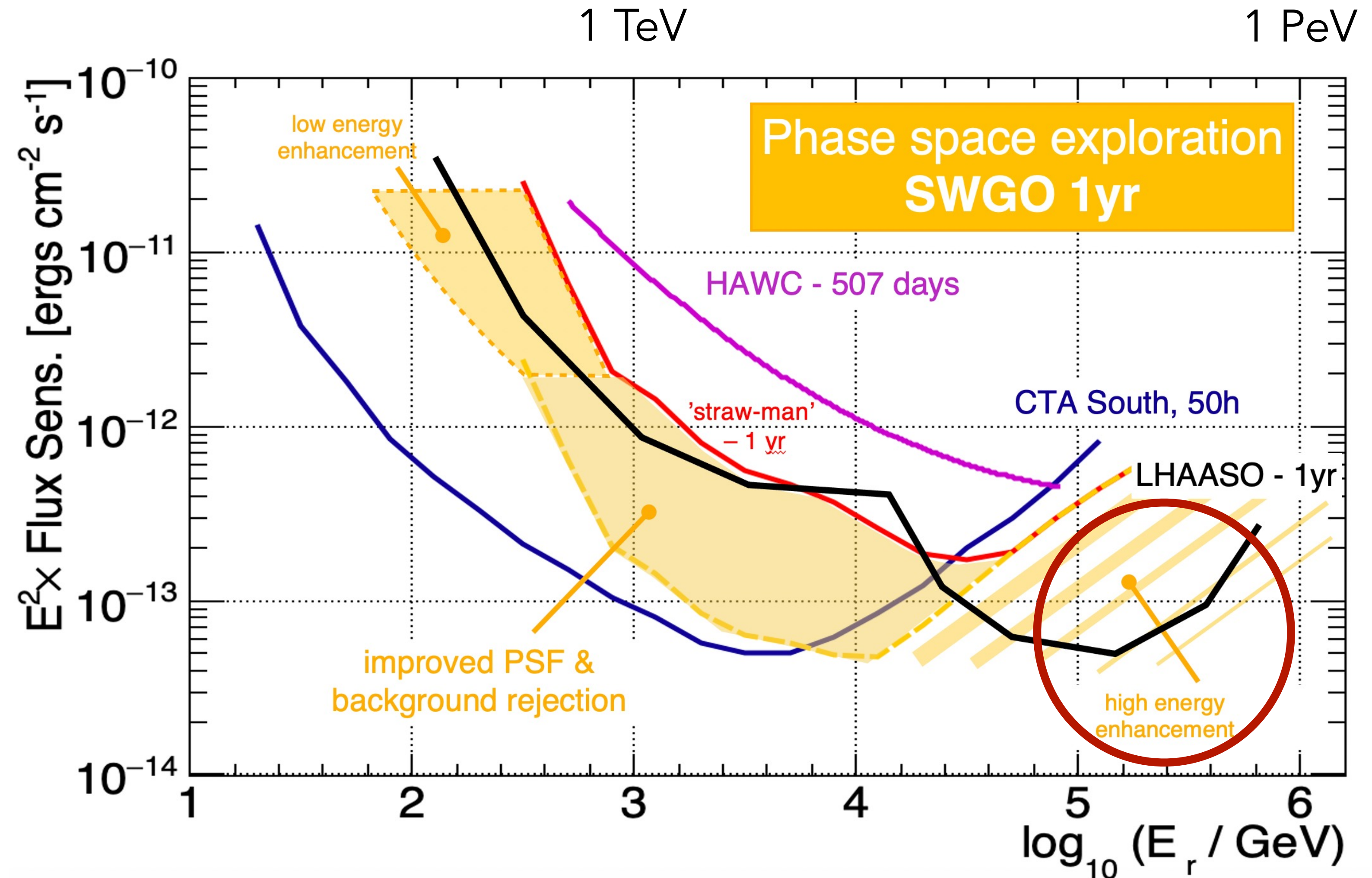
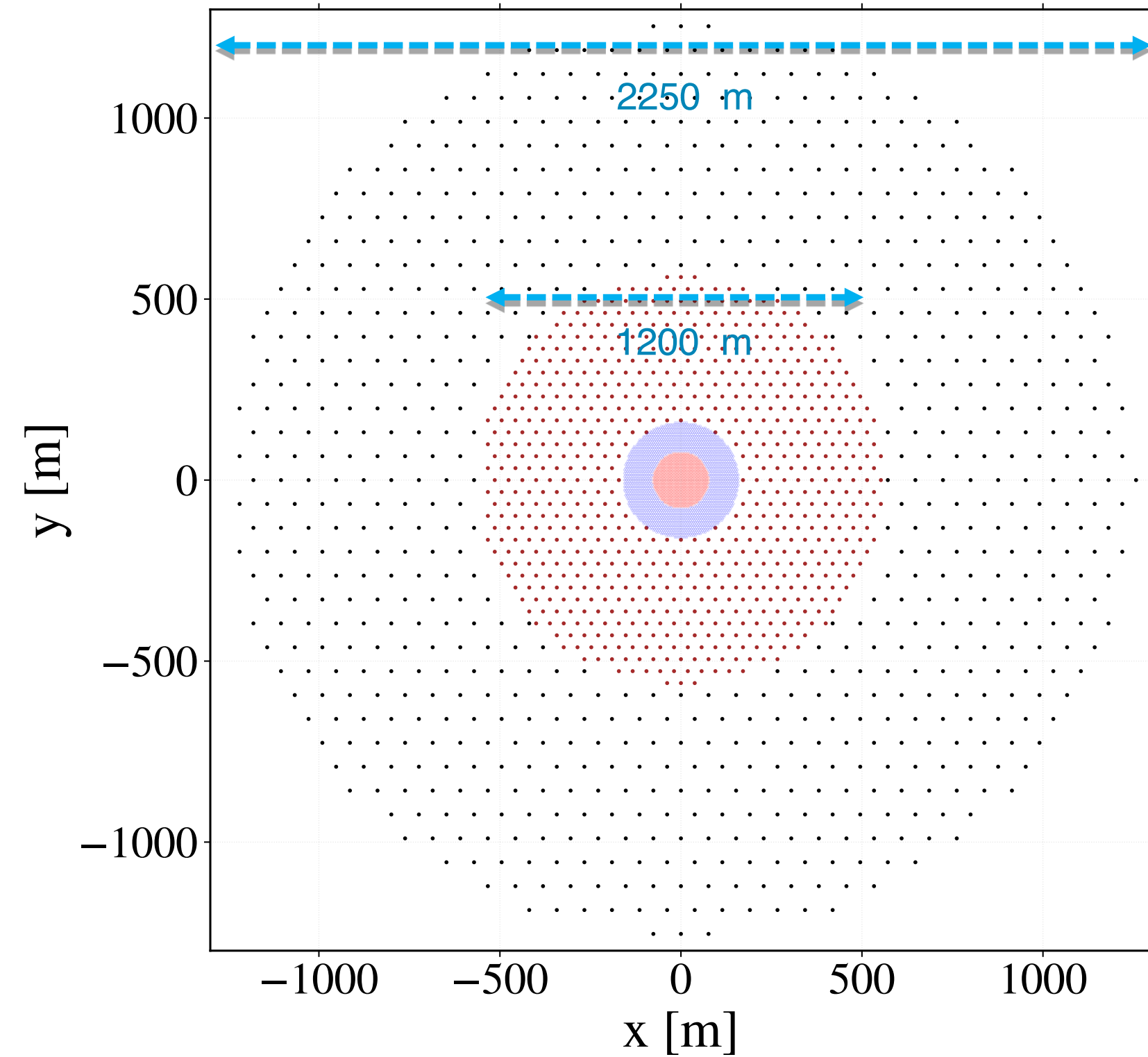
**SITE VISITS CURRENT UNDER  
PLANNING FOR THE SECOND  
SEMESTRE**

Country	Elevation	Location:
Peru	4900	Laguna Sibinacocha
Peru	4450	Imata lake
Peru	4450	Imata
Peru	4450	Yanque
Argentina	4800	Cerro Vecar
Argentina	4450	Alto Tocomar
Chile	4700	ALMA Pampa La Bola
Chile	4400	AAP Pajonales
Bolivia	4700	ALPACA area

# Phase Space Exploration



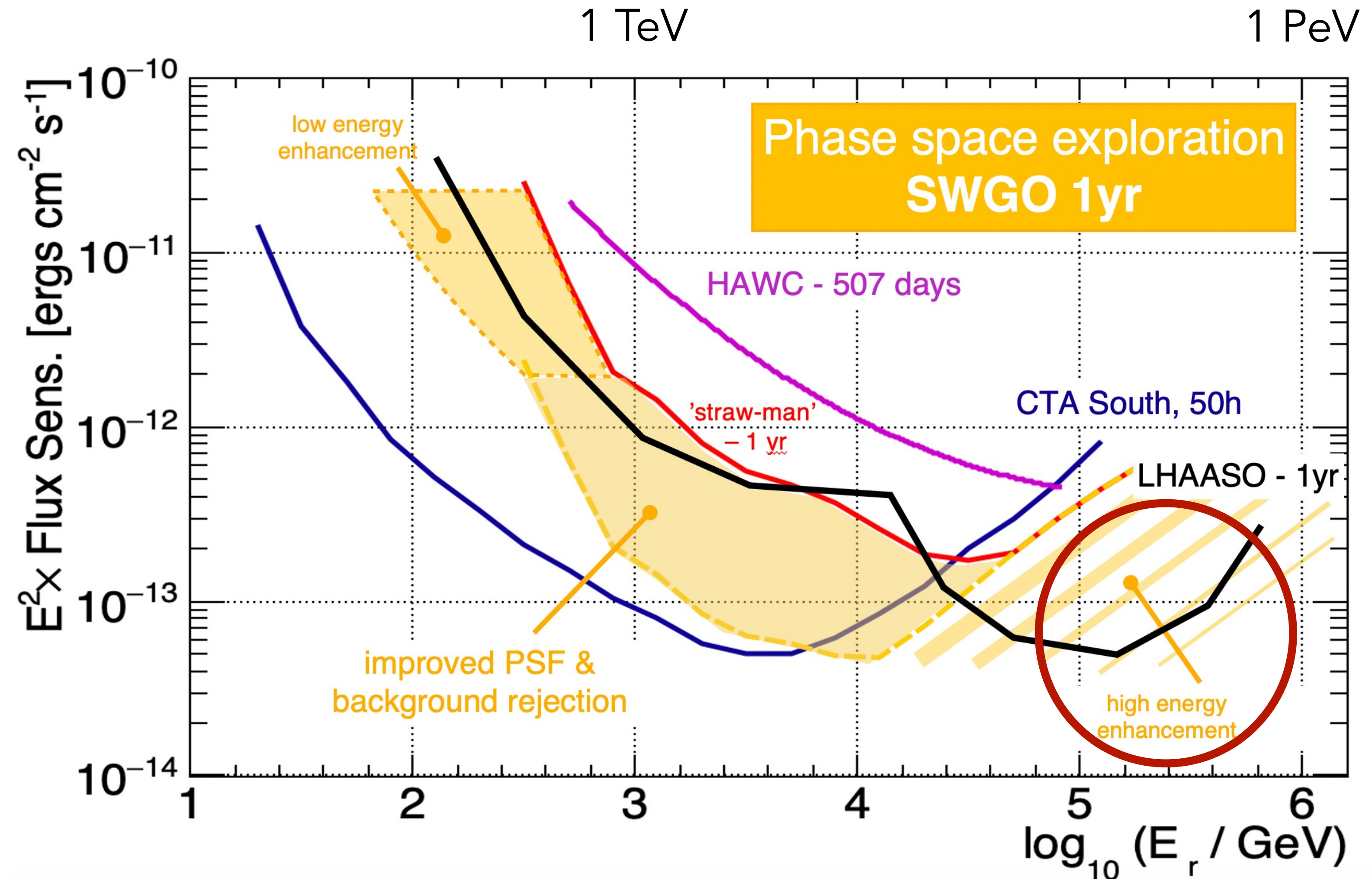
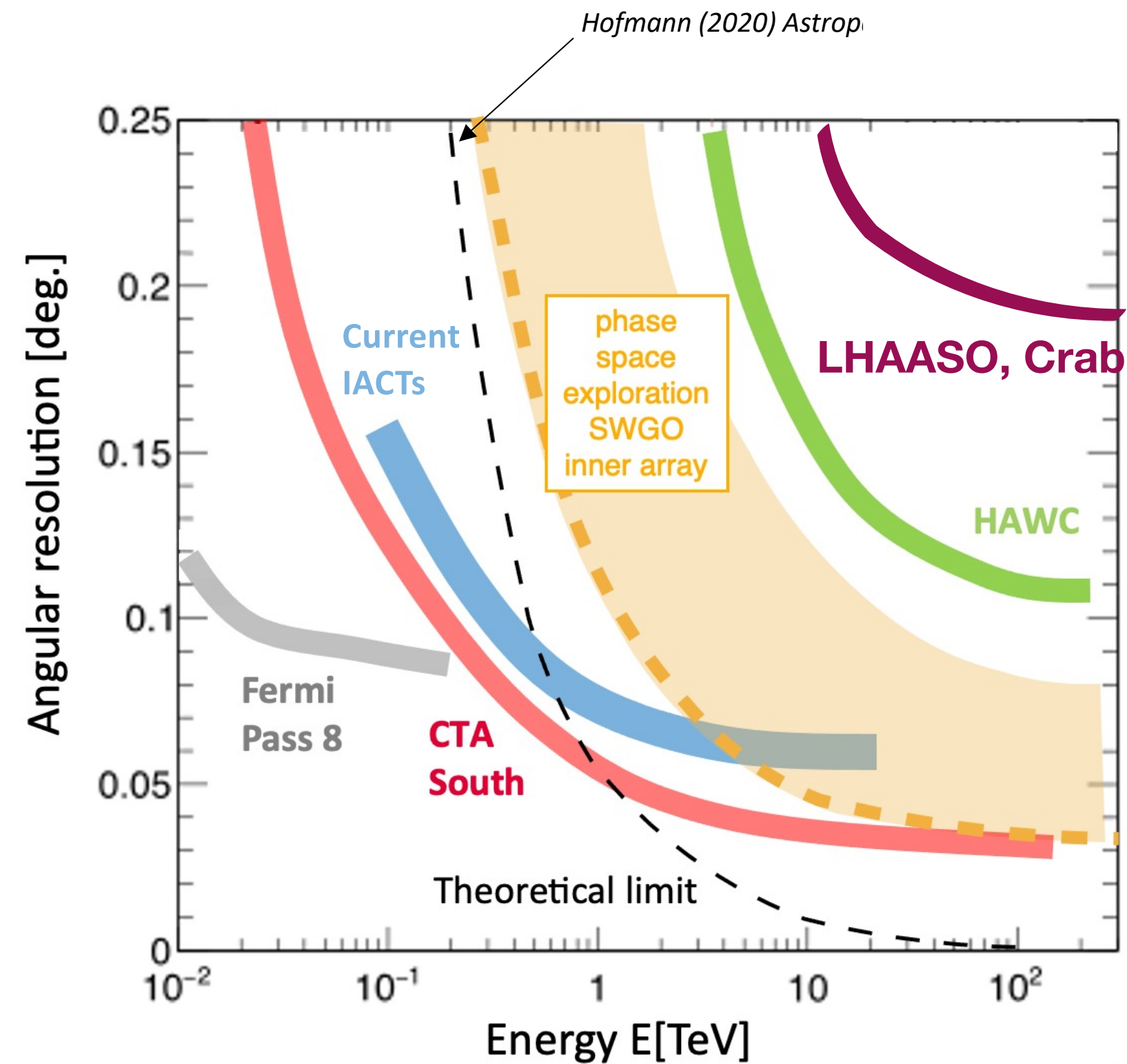
# Phase Space Exploration



⊙ **Potential Expansion towards the PeV energy scale**

✓ achieved with  $O(\text{km}^2)$  area array

# Phase Space Exploration

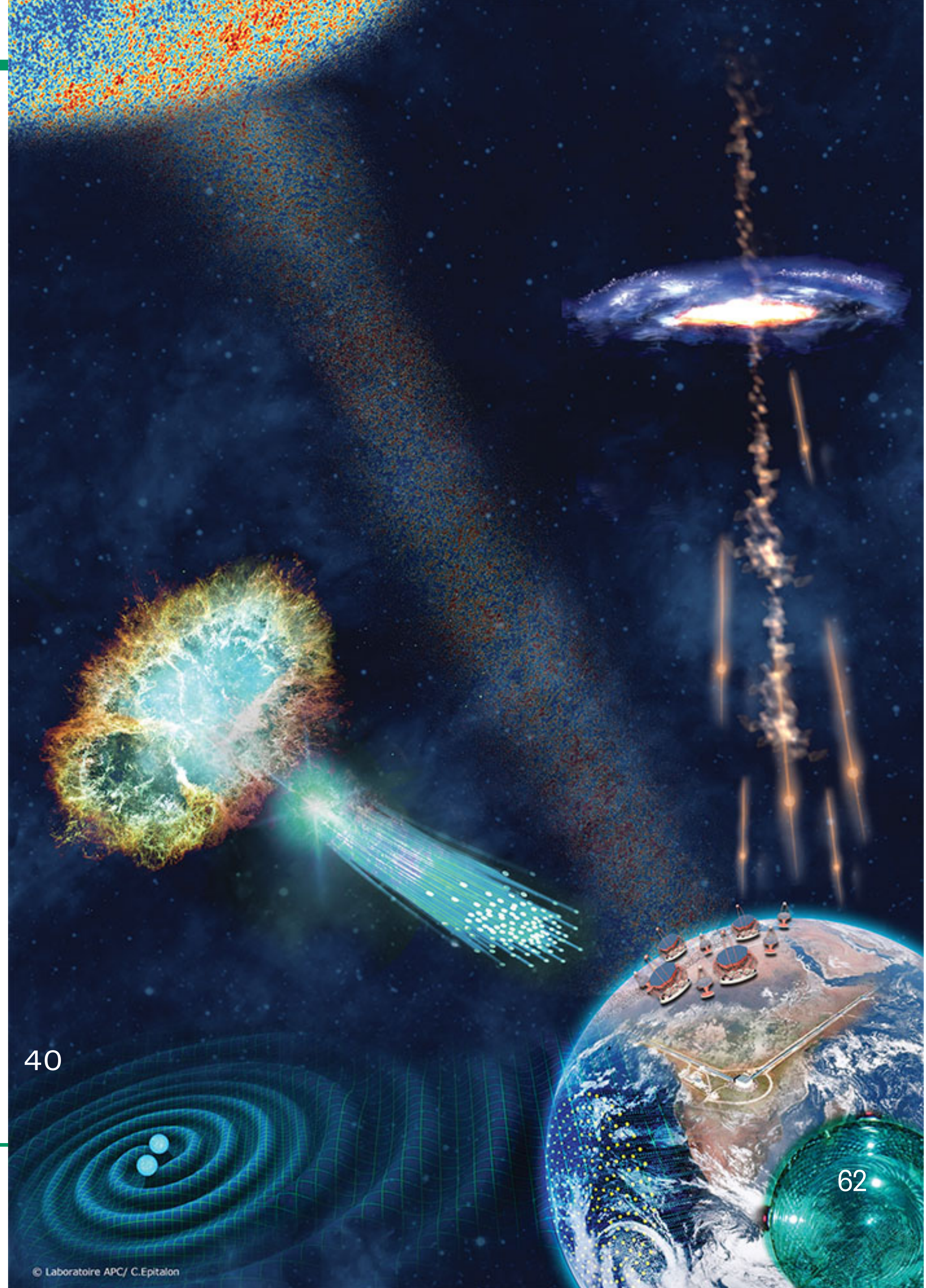


## Angular Resolution?

- ✓ Goal is to achieve unprecedented resolution at UHE regime

# Extra Slides

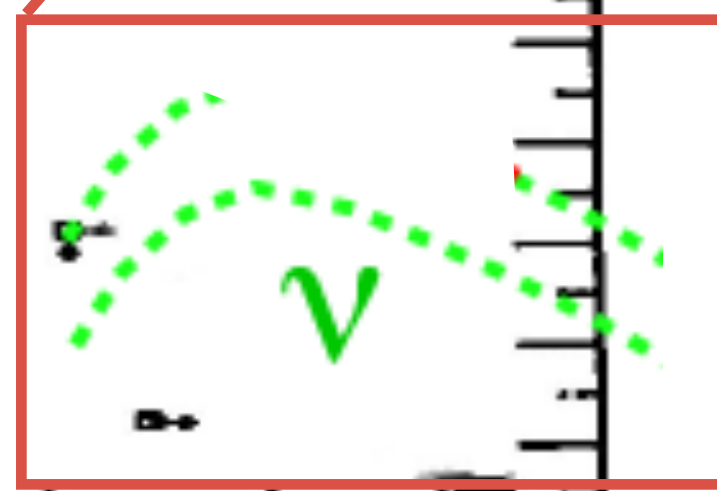
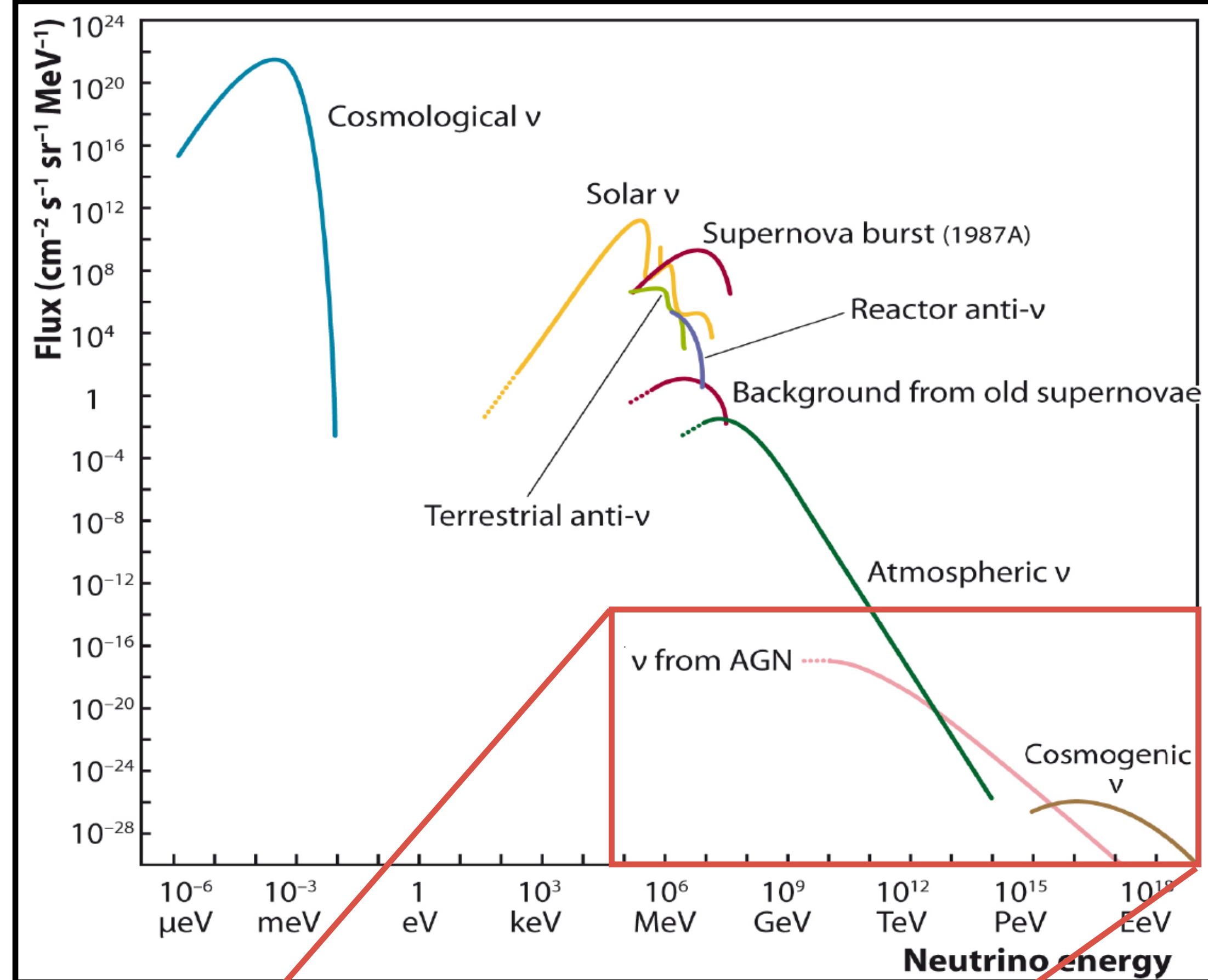
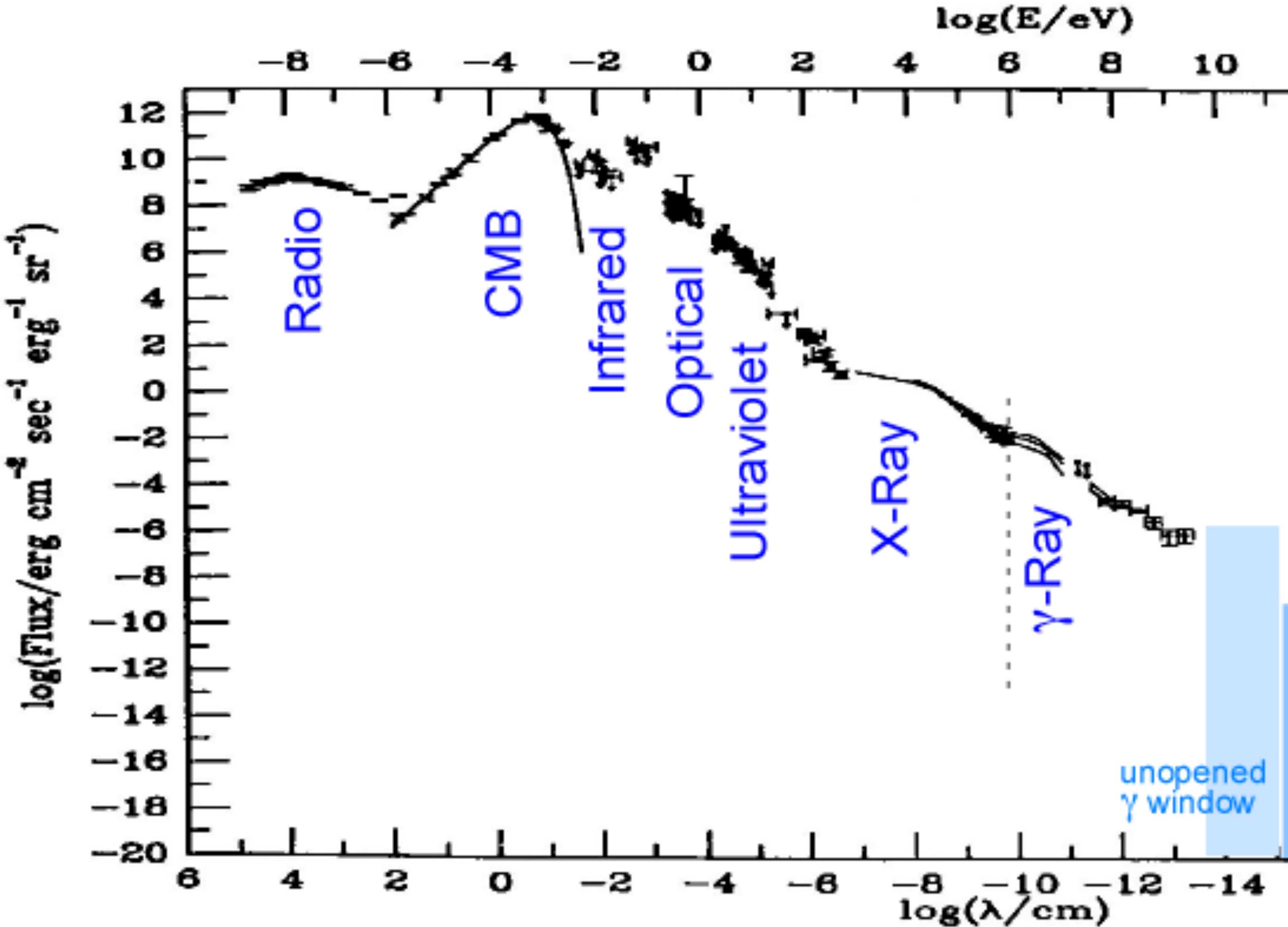
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# Astroparticle Physics



# The Status of CTA arrays



## Omega Configuration

### The Definitive CTA array configuration

- North: 4 LSTs, 15 MSTs
- South: 4 LSTs, 25 MSTs, 70 SSTs

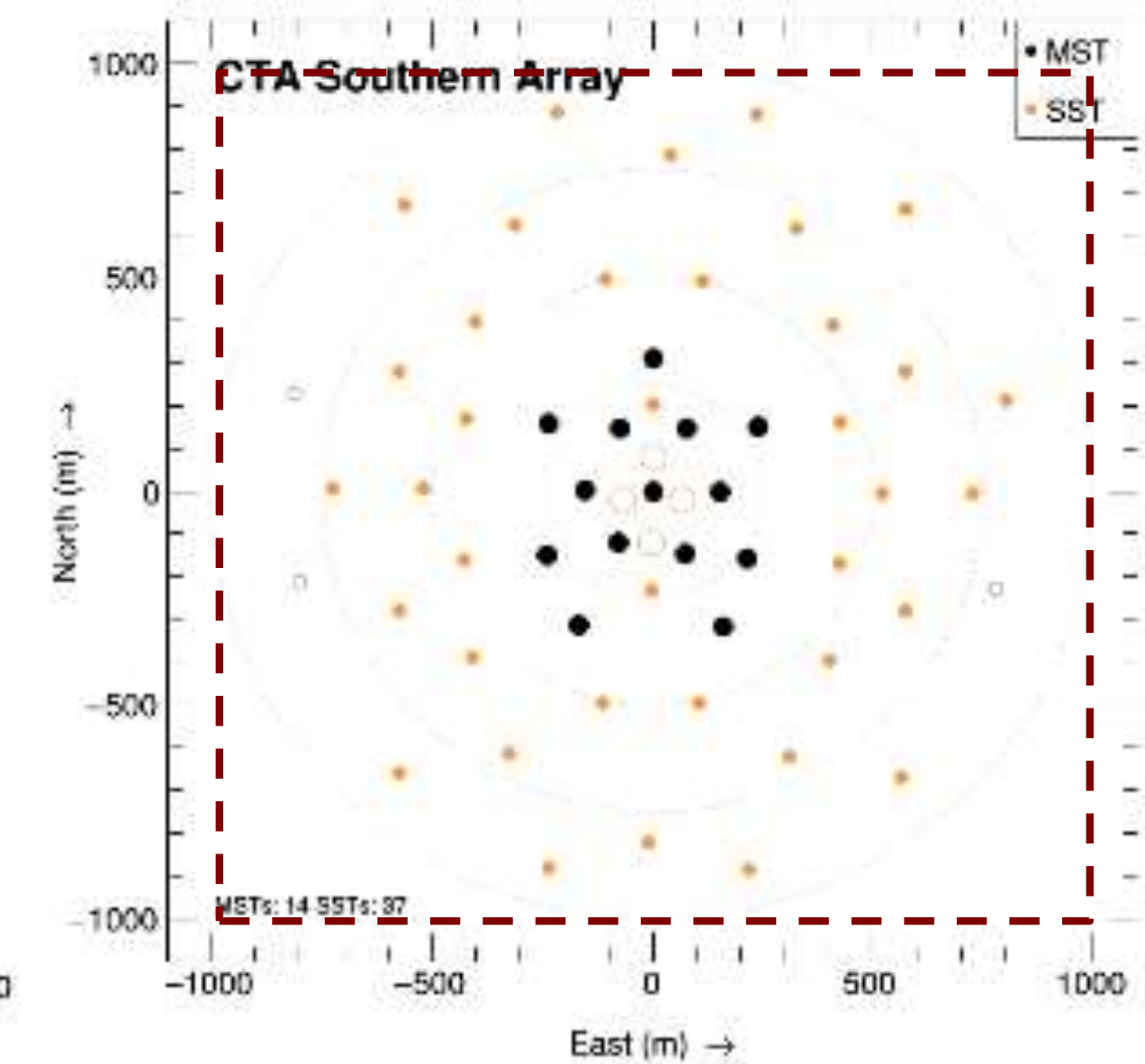
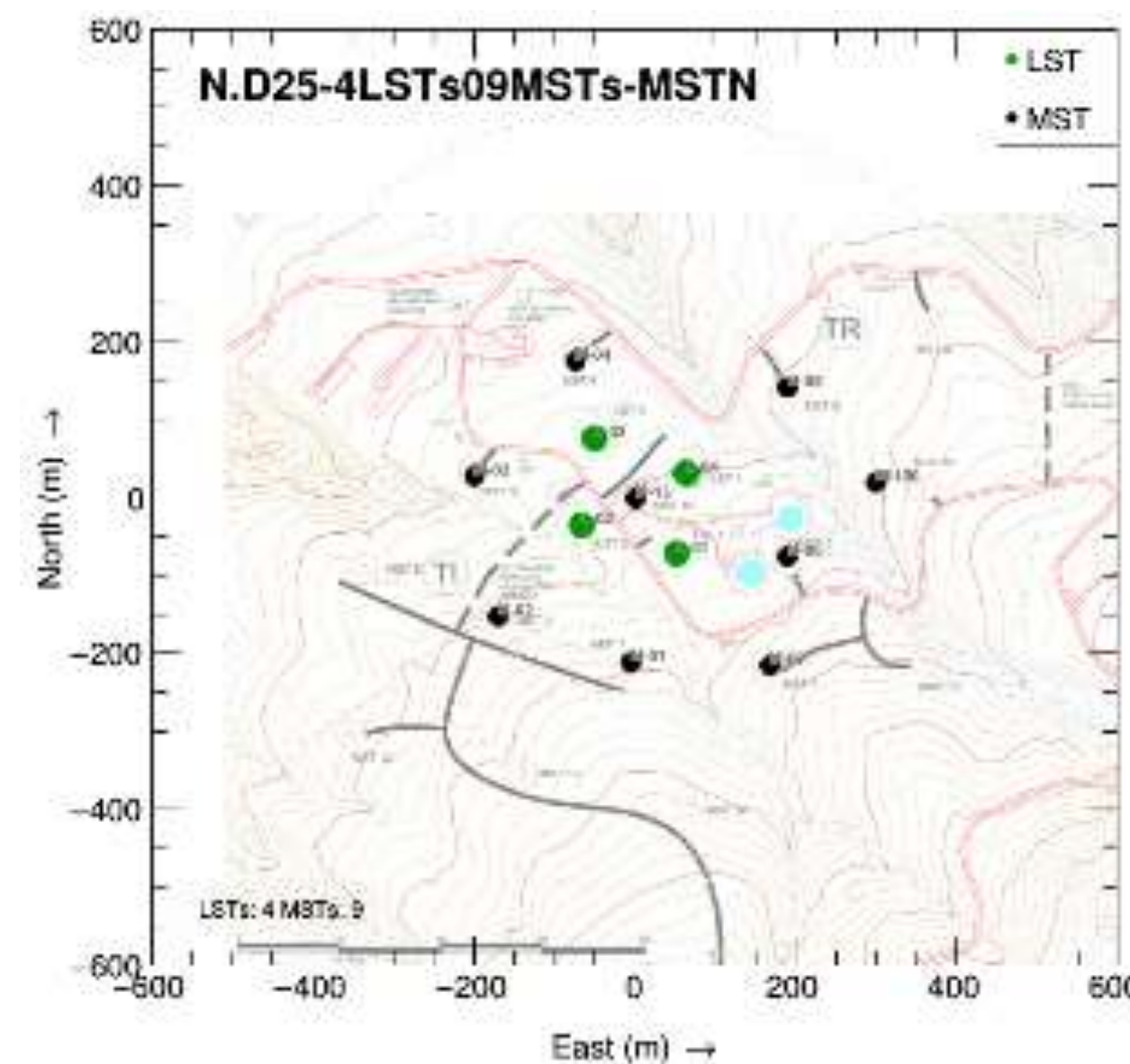
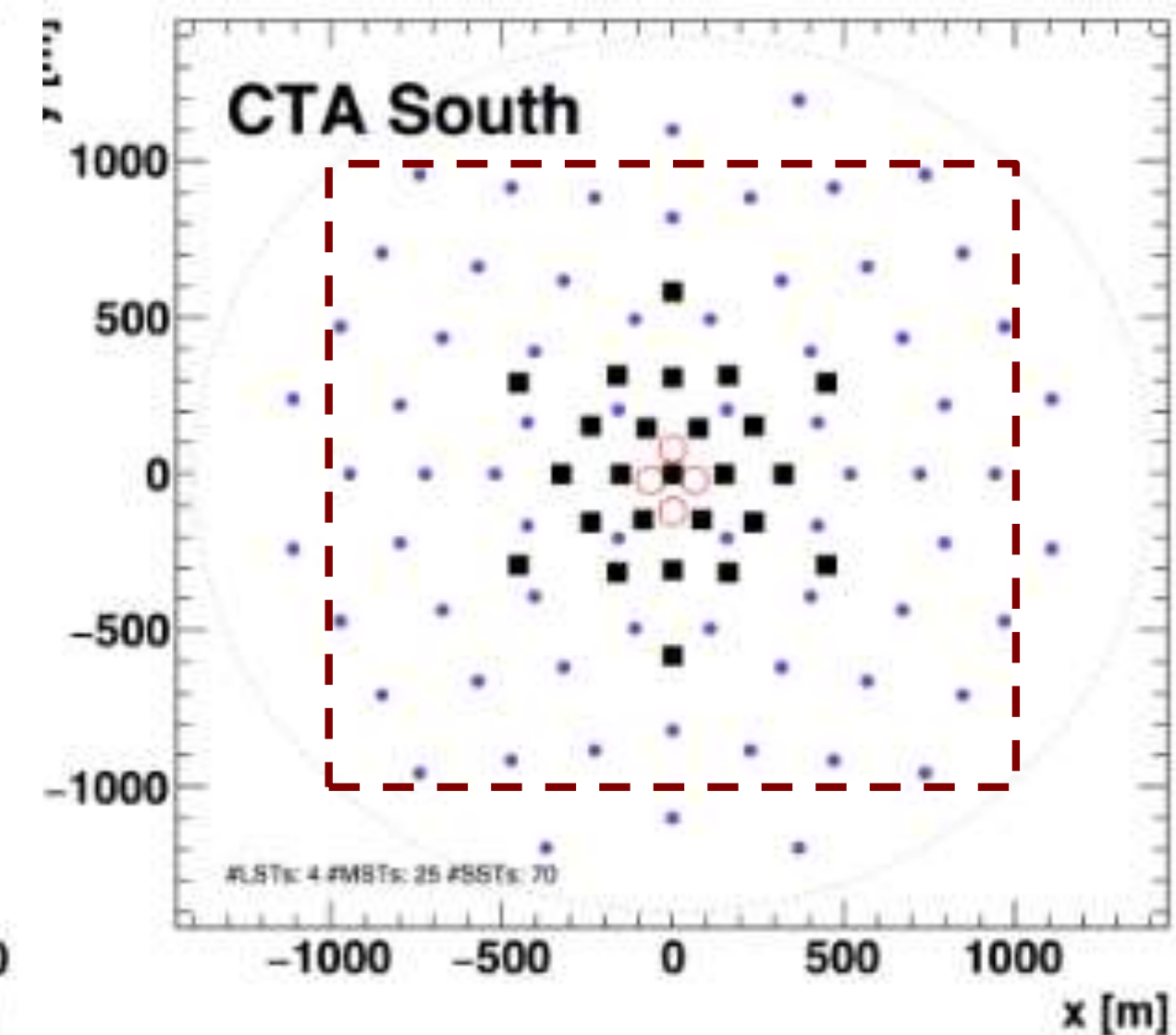
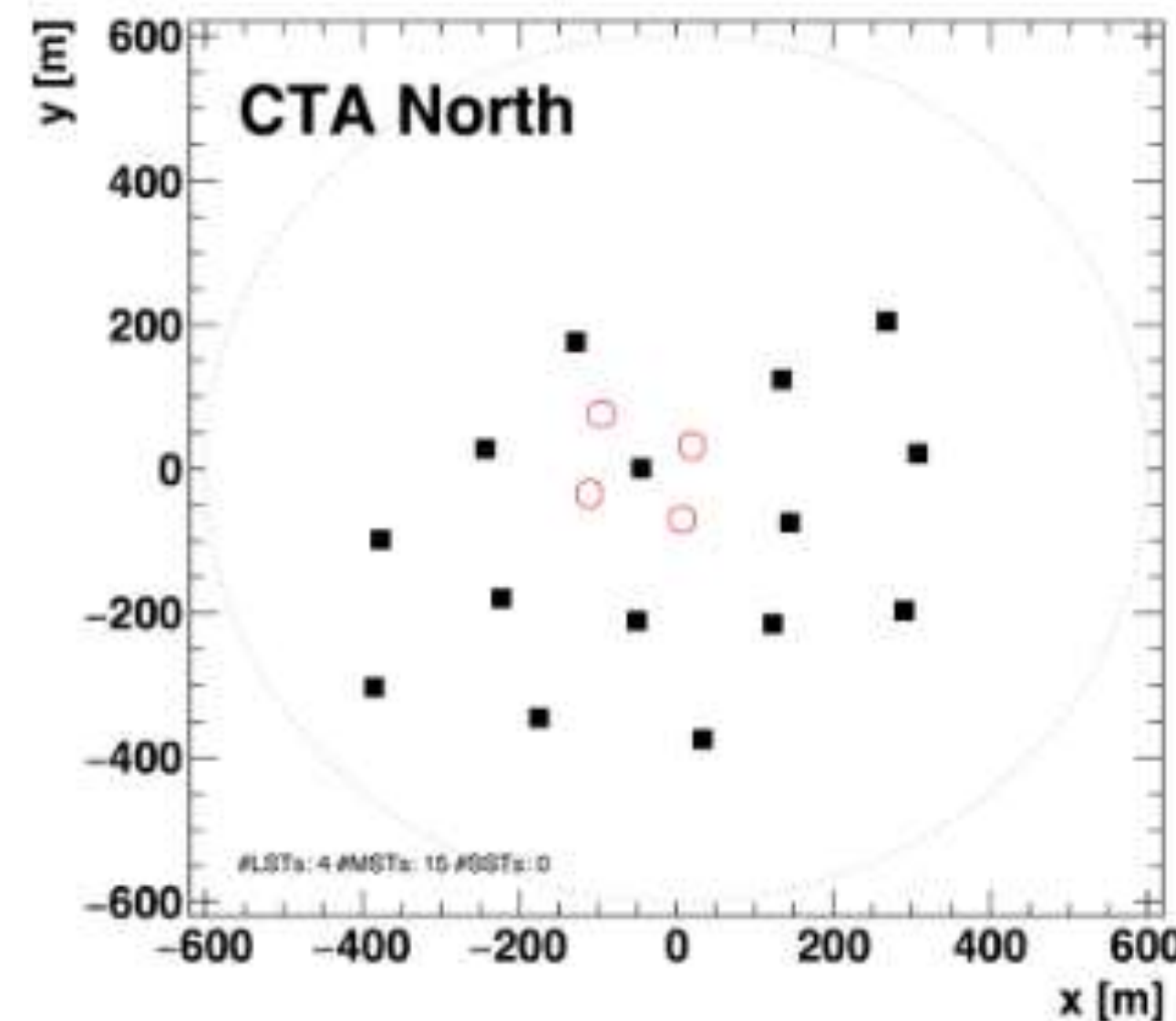
## Alpha Configuration

### The starting (funding-secured) point

- North: 4 LSTs, 9 MSTs
- South: 0 LSTs, 14 MSTs, 37 SSTs

(For transients, slewing times and E threshold increased)

Beware of possible beta configuration with LSTs in South!





# GW COSMoS (Patricelli et al. 2018)

<https://doi.org/10.6084/m9.figshare>

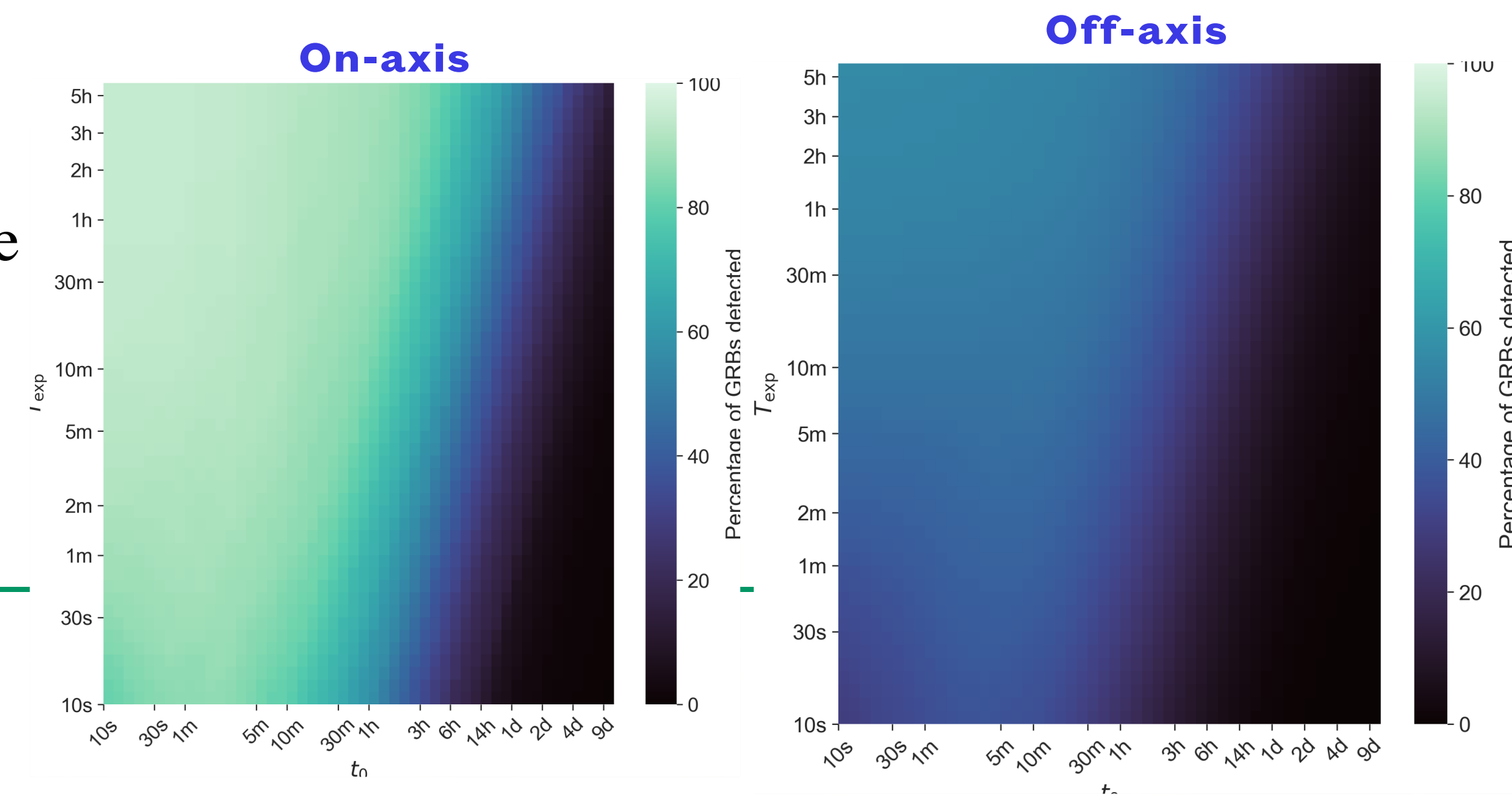


**Investigate the capability of CTA to detect EM counterparts to GW events, using detailed simulations of BNS mergers accompanied by short GRBs.**

- Based on GW detection expectations for (next) run O4
- Populations synthesis: assumes that all BNS associated with short GRBs (Ghirlanda et al. 2016)
  - Light-curve modeled according to X-ray afterglow for short GRBs
  - Spectrum: power-law with photon index  $\sim -2.2$  (GRB 190114C)
- **Principal GRB detectability factors:** GW alert latency ( $\sim$  mins) + CTA alert response ( $\sim 30$  s), positional uncertainty of GW.

## Prospects for detection are overall promising:

- For  $t \sim T_0 + 30s$ ; c. 90% (on-axis) / 50% (off-axis) GRBs detectable with exposure  $< 30$  min
- For  $t_0 \sim T_0 + 10$  min; c. 90% (on-axis) / 50% (off-axis) GRBs detectable with exposure  $\sim$  few hours



# Neutrino FIRESONG (Tung et al. 2021)



<https://github.com/ChrisCFTung/FIRESONG>

## Steady Sources

Standard candles, follow the SFR evolution model of Madau & Dickinson (2014)

Local density  $\rho = 10^{-12}$  to  $10^{-5}$  Mpc<sup>-3</sup>

Luminosities:  $L_\nu = 5 \times 10^{47}$  to  $10^{57}$  erg/year

Gamma-ray flux parametrised assuming  $p\gamma$  interactions Ahlers & Halzen (2018)

Sources exceeding the IceCube sensitivity (Aartsen et al., IceCube Collaboration, (2019)) are used as seeds of the NToO for CTA

Assuming all the sources are always observable by CTA

## Transient Sources

Standard candles and the flat cosmological evolution

Based on the neutrino flare model of TXS 0506+056 in 2014-2015 Halzen et al., ApJ 874 (2019)

Only a fraction **F** (1%, 5% and 10%) of all blazars is responsible for the astrophysical neutrino flux

All the sources are assumed to have the same flare duration in their reference frame (110 days @z TXS)

Assuming IC Gold alerts and events always observable by CTA

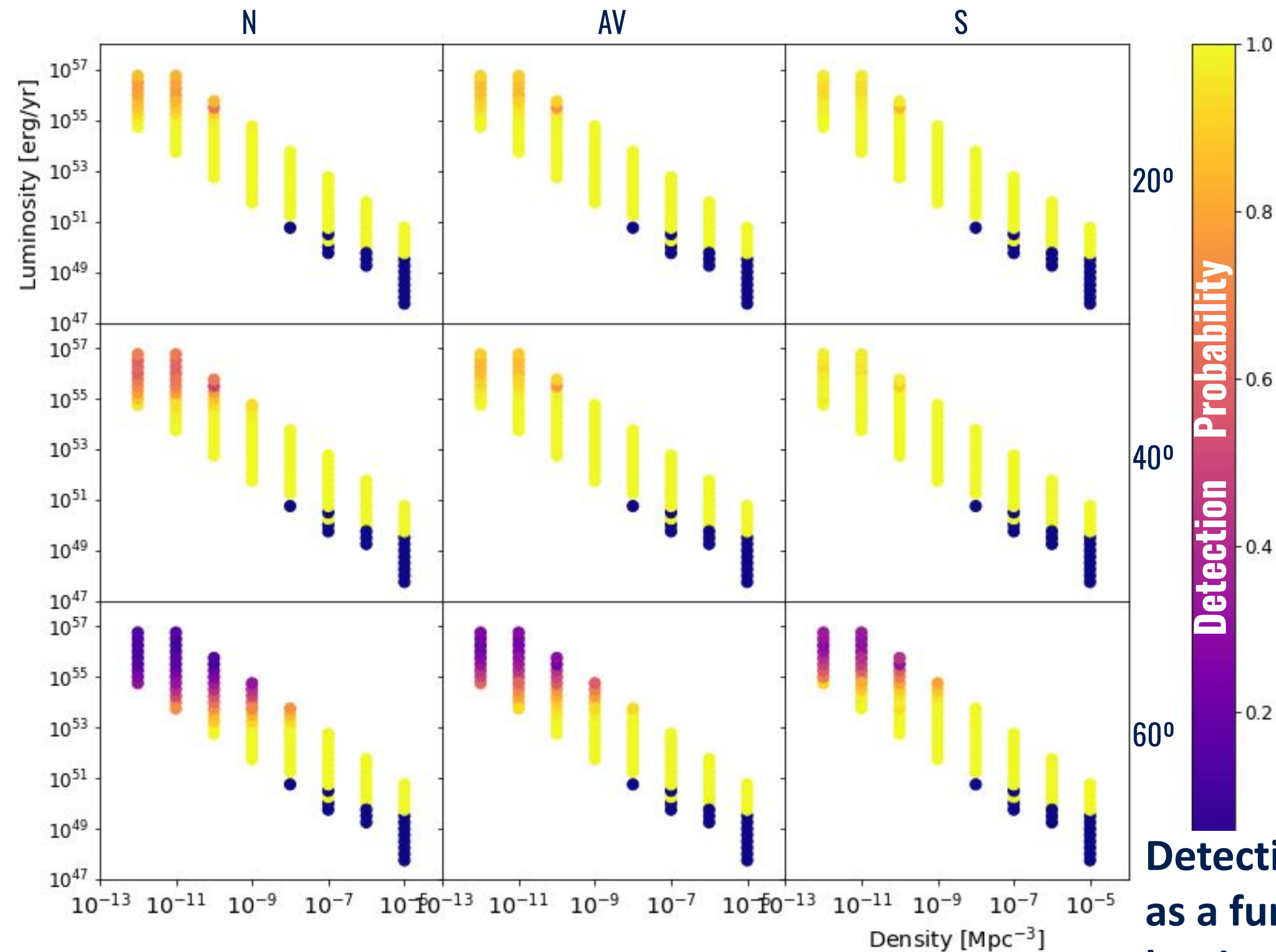
O. Sergijenko

# Neutrino FIRESONG (Tung et al. 2021)



<https://github.com/ChrisCFTung/FIRESONG>

CTA-N; 30 min obs; SFR evolution



## Steady Sources

Assuming these sources will be always observable by CTA:

At low-mid zeniths ( $20^\circ$ - $40^\circ$ ) CTA-N detects all sources up to  $\rho = 10^{-9} \text{ Mpc}^{-3}$

Drastic performance loss, up to 65%, at high zeniths ( $60^\circ$ )

Magnetic field effect: 10-30% difference for low to high zeniths

For sources with flat redshift evolution the trends are similar, but less pronounced

Detection probability as a function of source luminosity and local density of sources, for 30 exposure  
PoS(ICRC2021)975

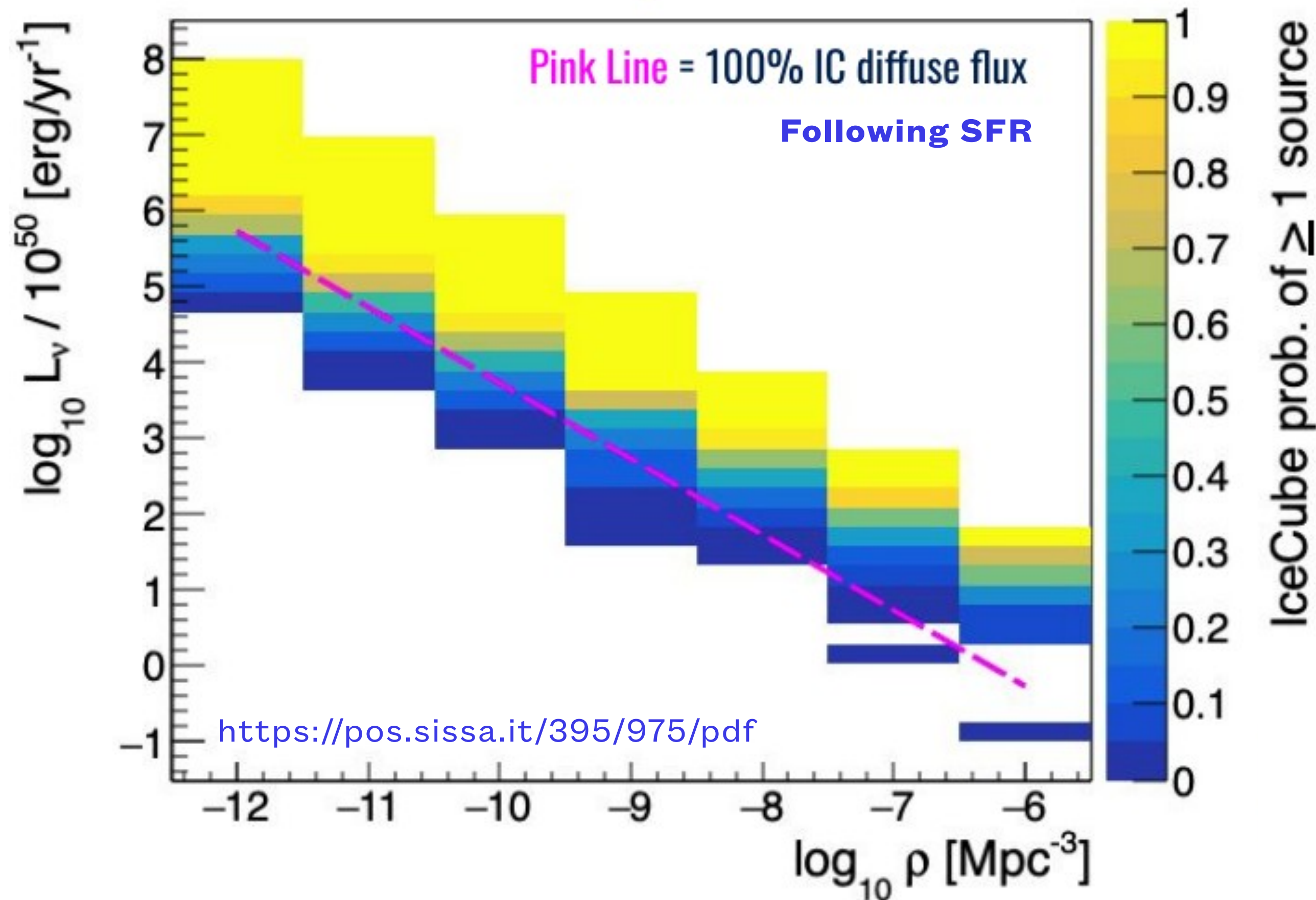
O. Sergijenko

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<https://github.com/ChrisCFTung/FIRESONG>

## Steady Sources



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O. Sergijenko

# Neutrino FIRESONG (Tung et al. 2021)

<https://github.com/ChrisCFTung/FIRESONG>

CTA 30 mins obs; Flaring blazars

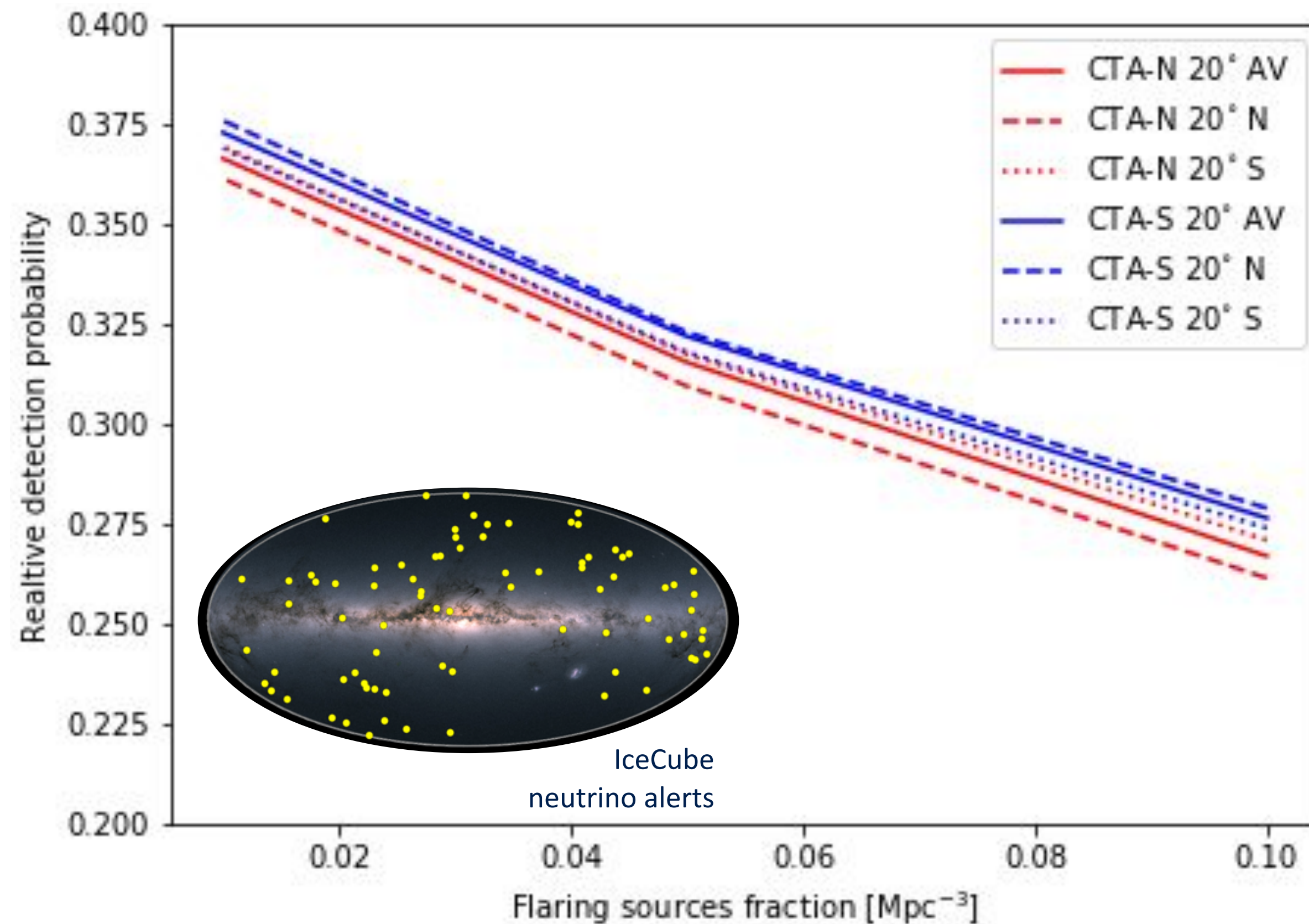
## Transient Sources (Flaring blazars)

Selecting IC Gold alerts (>50 %) and assuming observable conditions by CTA:

CTA detection probability grows while  $F$  decreases (as expected: flux of each flare is increasing)

Detection probability is almost identical for  $20^\circ$  and  $40^\circ$  zenith IRFs (difference < 1%), decreases by 4% for  $60^\circ$

Influence of magnetic field is minimal: <0.5% for CTA-S and up to 2% for CTA-N



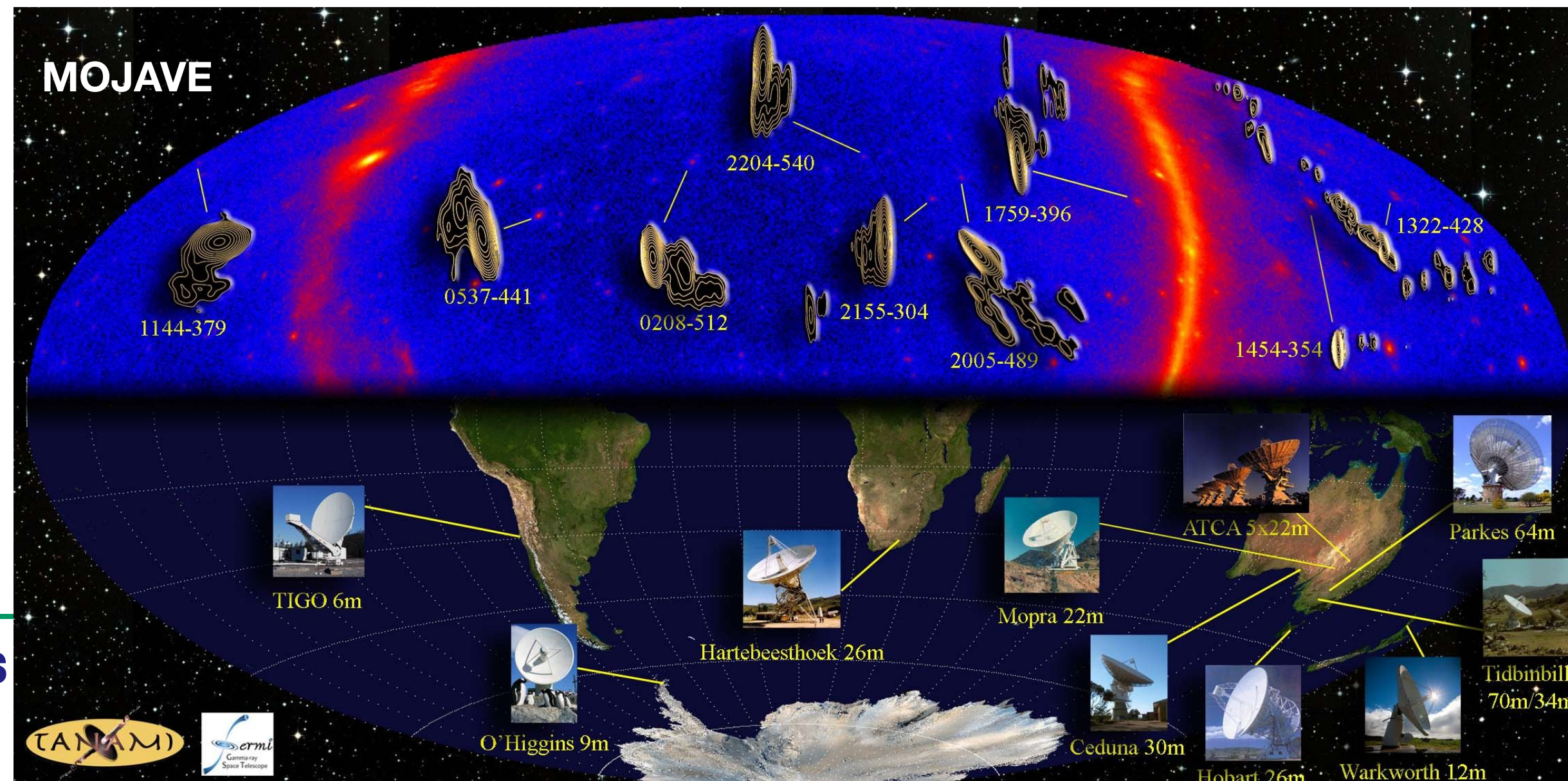
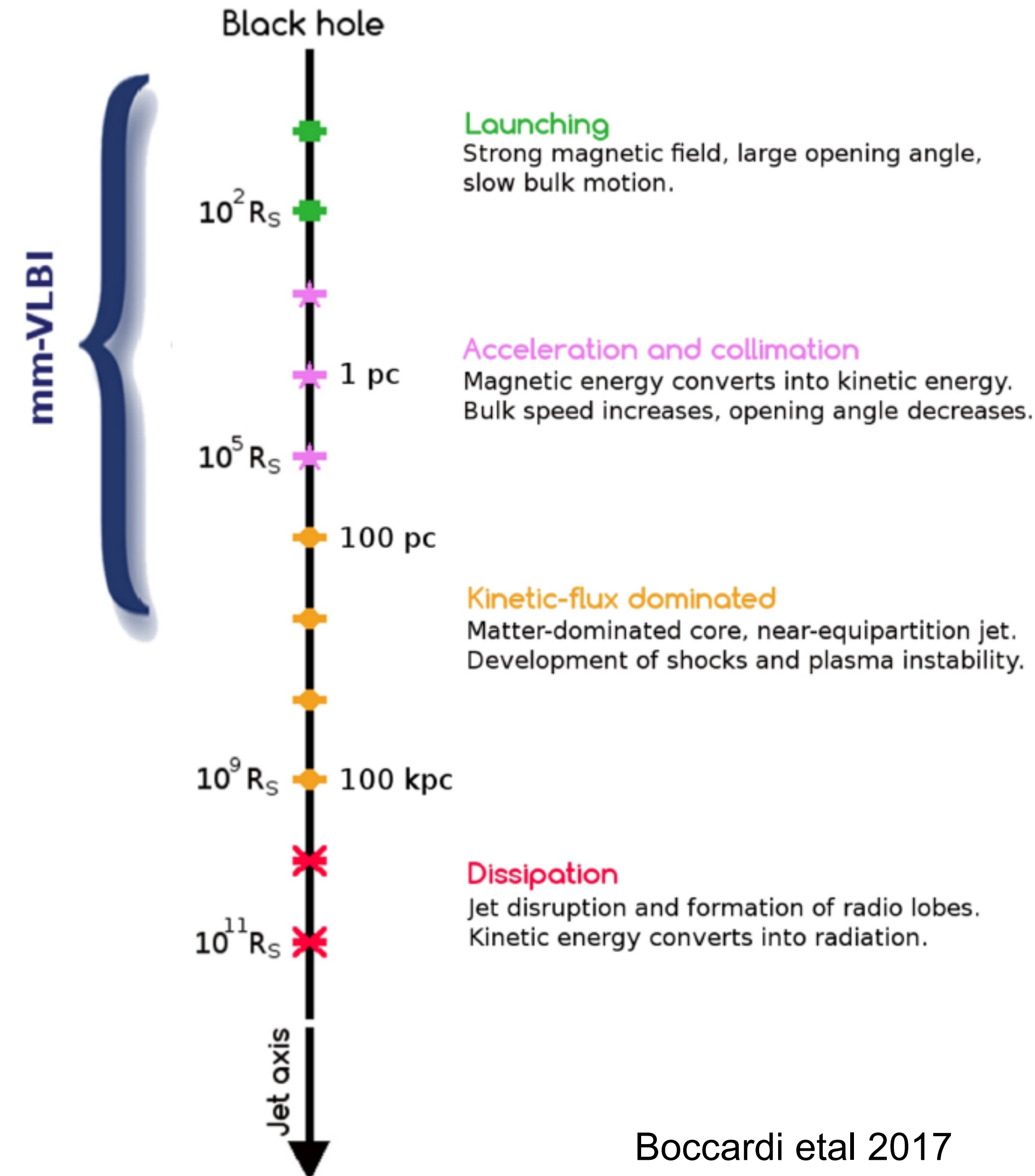
O. Sergijenko

# CTA Synergies with VLBI

Radio and Gamma-rays are two windows into the **non-thermal universe**.

**Radio VLBI** : provides a deep and unique look into the innermost regions of relativistic jets and outflows, and allows to gather direct information on magnetic field structure and shock propagation.

**VHE Observations** : provide direct probes of particle acceleration, seed photons for IC scattering, hadronic processes as well as the EBL.

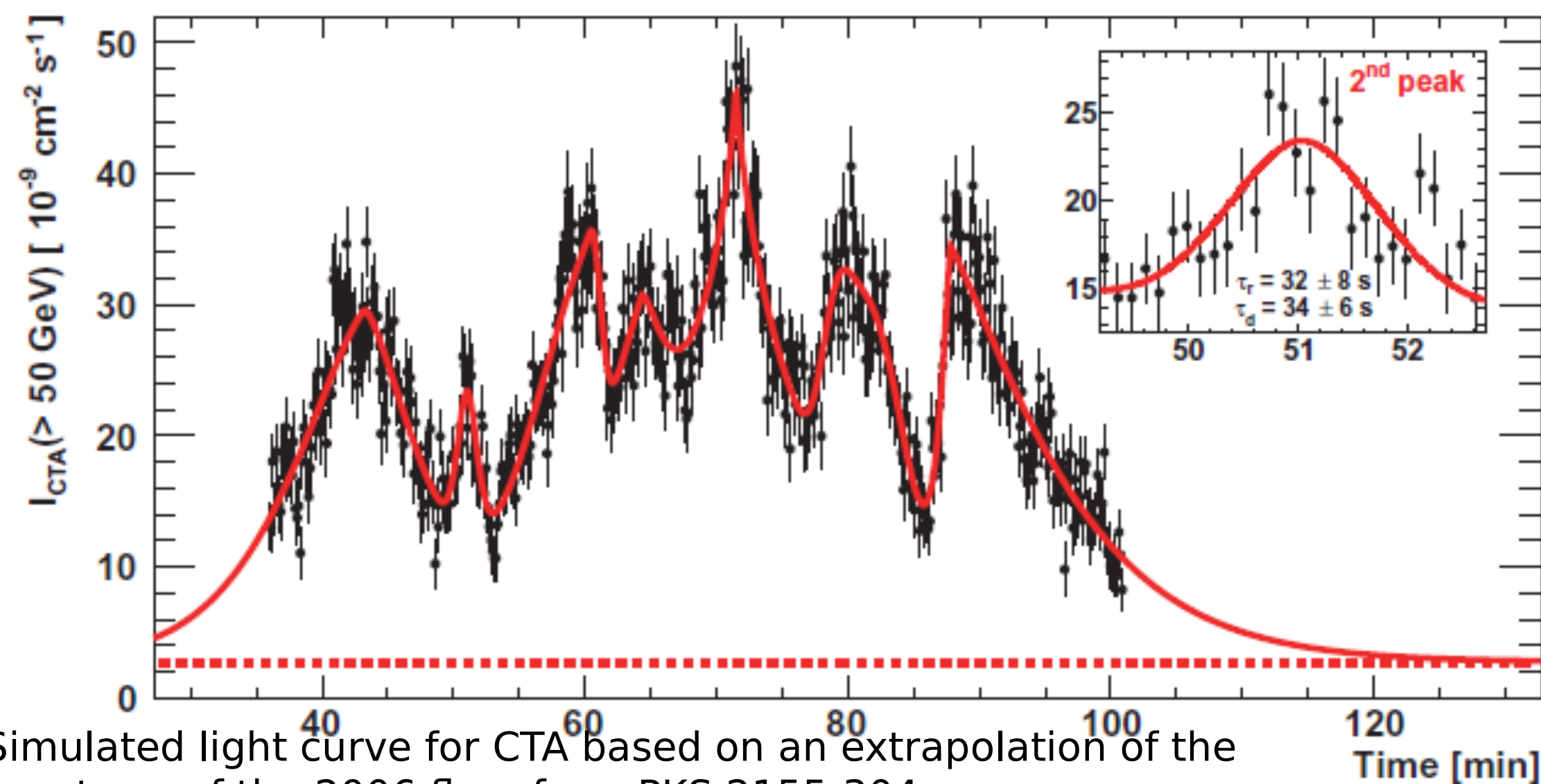


# CTA Synergies with VLBI

## Some Synergies within the CTA Science Programme

**Joint long-term monitoring:** use joint, long-term observations in VLBI and gamma-rays to locate the high-energy emitting regions in AGN (unresolved in VHE).

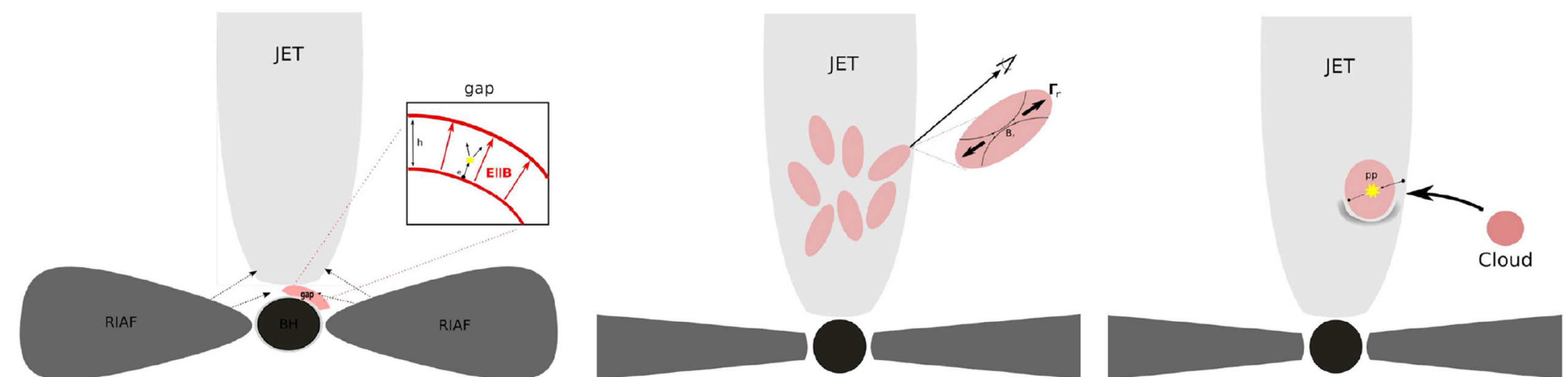
**Detailed spectra of emitting regions:** combine resolved VLBI spectral data and gamma-ray spectra to provide a deeper look into the gamma-ray emitting process in AGN.



Simulated light curve for CTA based on an extrapolation of the spectrum of the 2006 flare from PKS 2155-304

Variability seen in  $\gamma$ -rays implies a variety of possible models for the (compact) origin of HE radiation which need high-resolution radio-imaging to probe.

F. Rieger 2019



# CTA Synergies with SKA

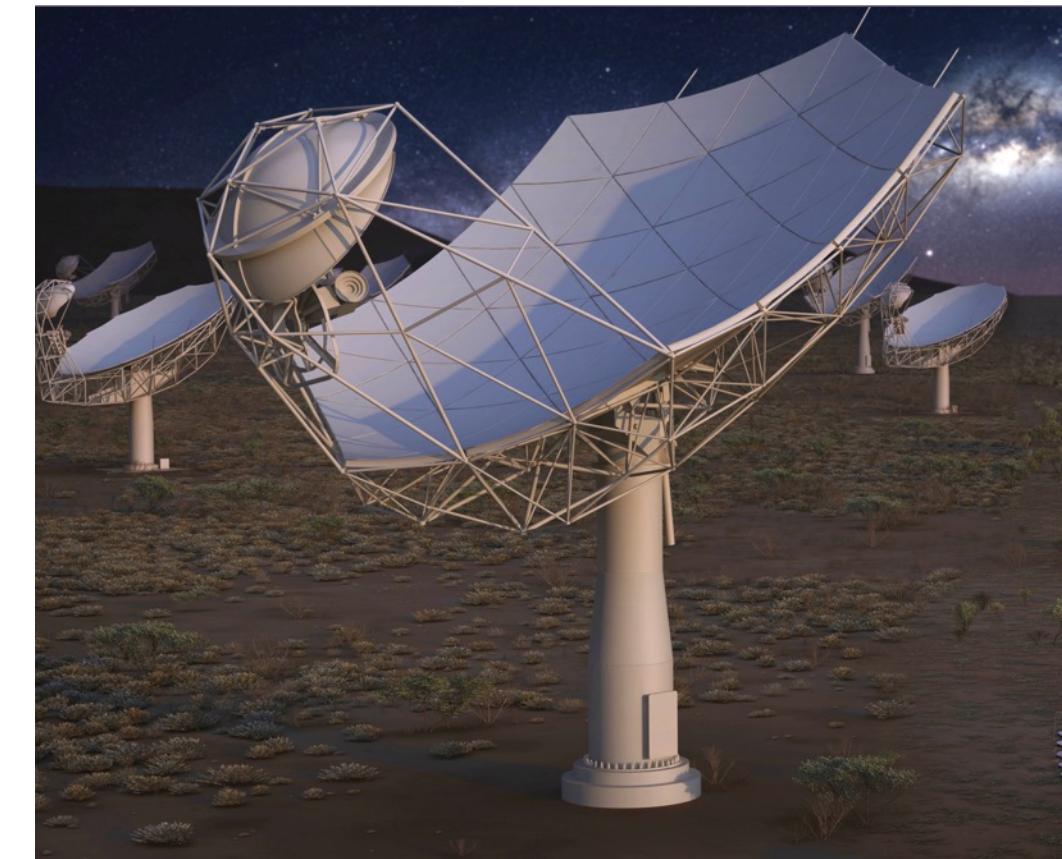
SKA will be the principal radio-telescope of the coming decades, and will have great impact in transients science:

**Transients localization :** SKA can provide precise (arc second or less) localization of transients and proper motions characterization for the study of TDEs, FRBs, GRBs, neutrinos...)

**High-resolution view of the Galactic Center :** fundamental for resolving sources and identify acceleration mechanisms associated to TeV emission and the GC PeVatron.

**Resolving emission regions in AGN jets :** SKA will expand the number of sources for which resolved jets will be accessible, expanding the possibilities for joint investigations with CTA.

**Study of AGN jets along cosmic time :** SKA will expand the horizon for AGN jet studies, seeing radio-loud AGN up to  $z \sim 8$ , providing a view at AGN and IGM evolution.





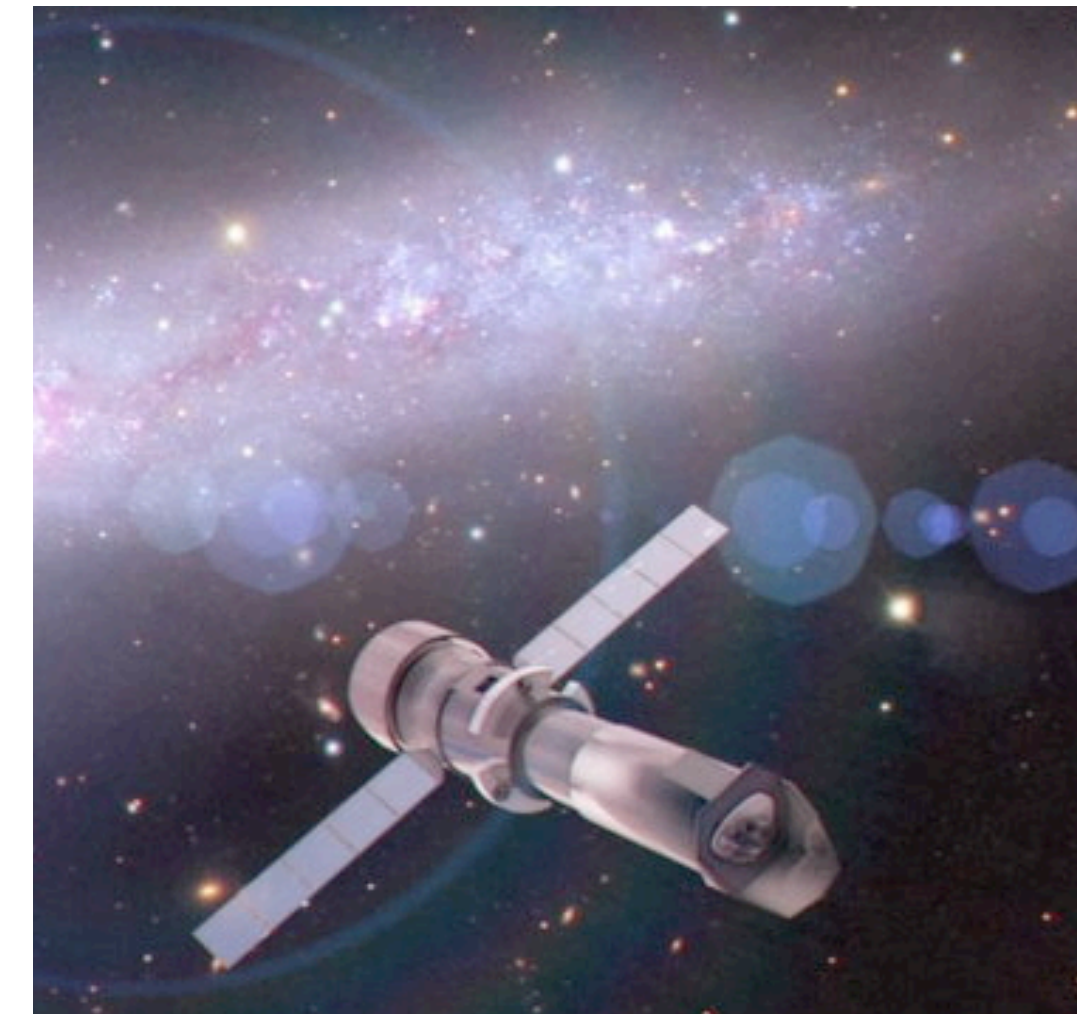
# CTA Synergies with X-rays

**ATHENA** will be a major X-ray Mission (planned, 2028) with wide-field / high-spectral and imaging capability at  $\sim$  keV energies.

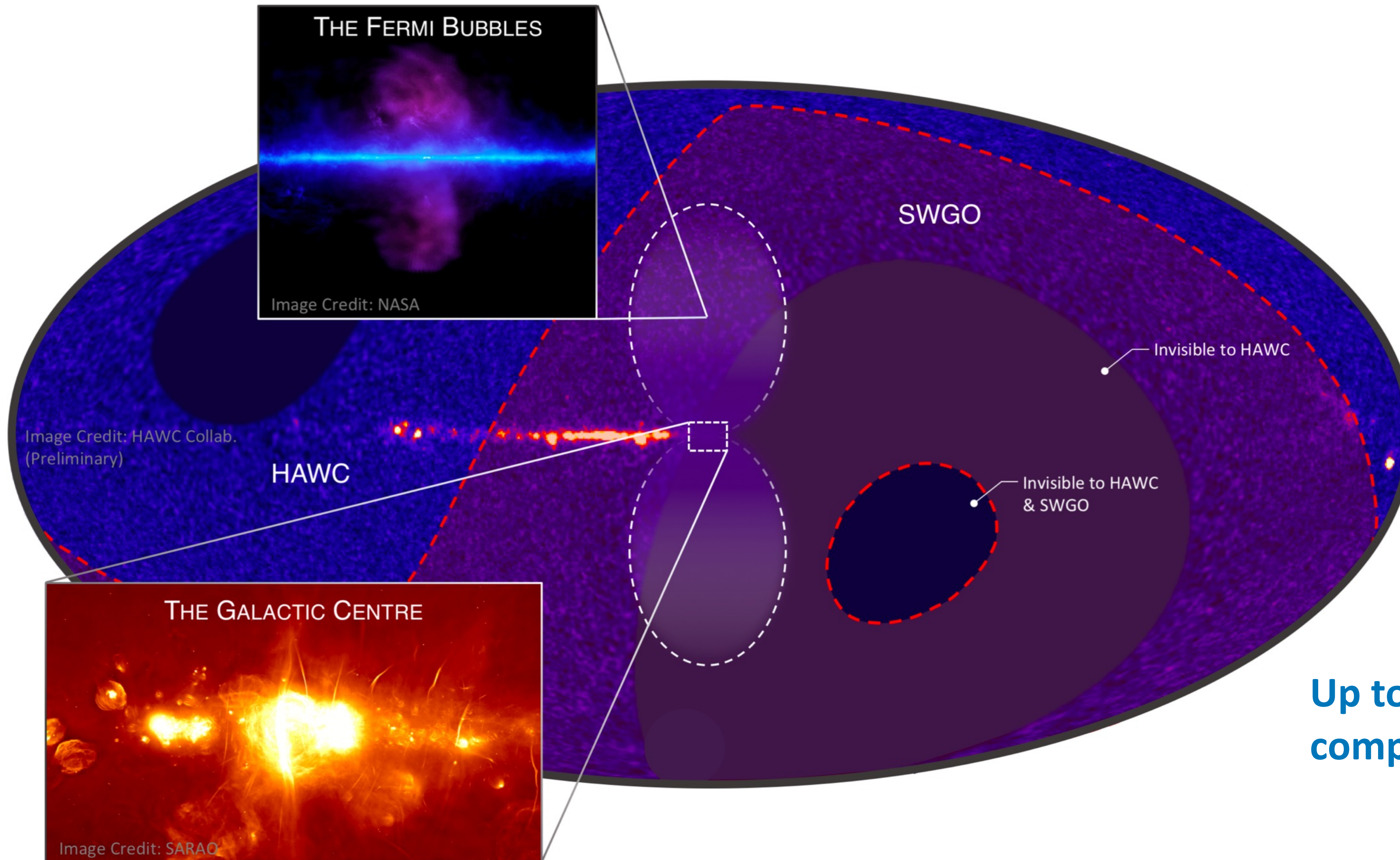
**Cluster of Galaxies:** CTA hopes to finally detected TeV emission from Galaxy Clusters, associated to their non-thermal emission component, with enormous synergy potential to joint studies with ATHENA, such as in cluster energetics and AGN feedback in the intra-cluster medium.

**THESEUS** will serve as a future GRB trigger provider to the world

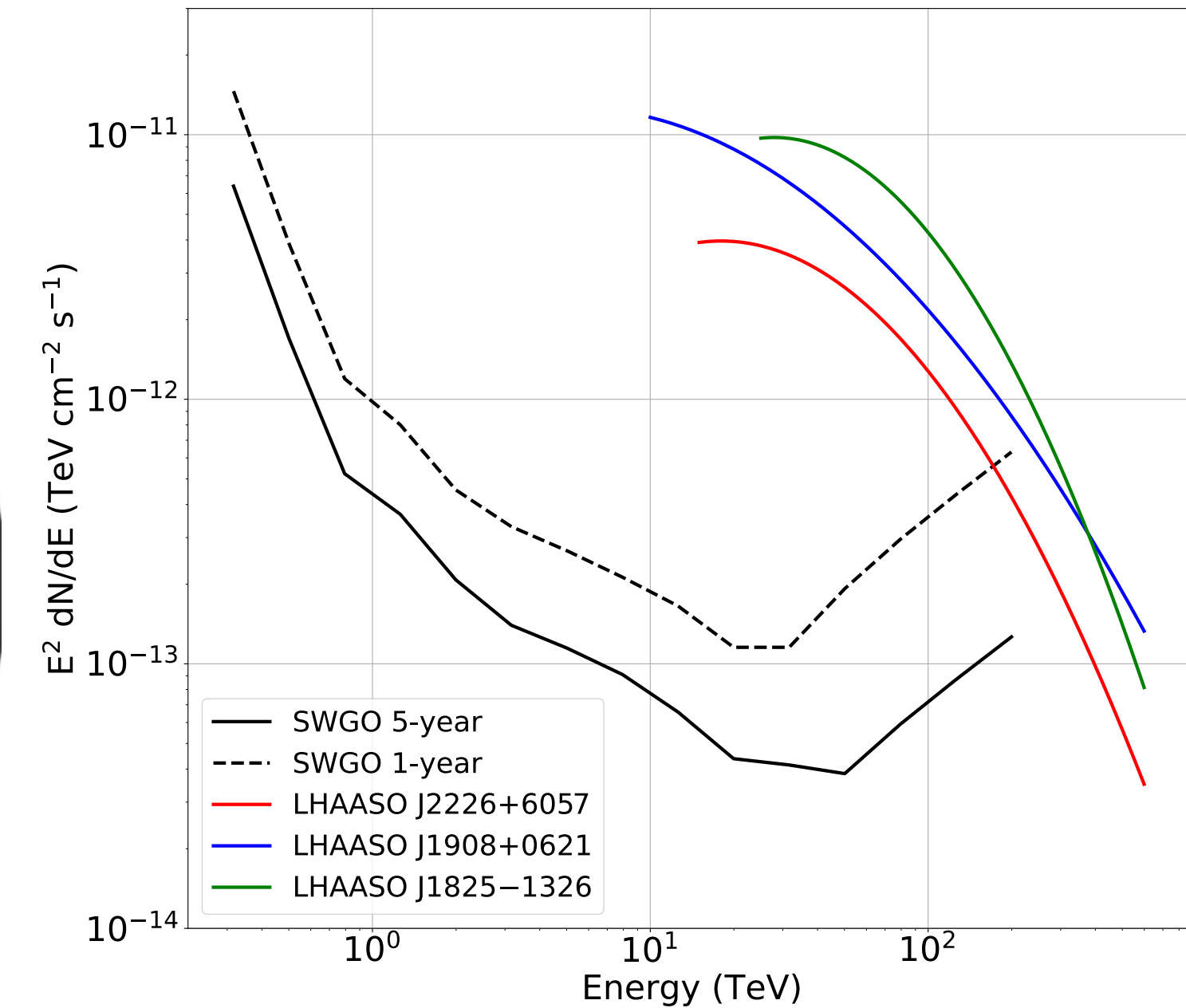
**Gamma-ray burst science:** As Swift has demonstrated, there is great potential for synergies in GRB science between THESEUS and CTA, in the provision and follow-up of triggers — **critically important here is also the future availability of a GeV gamma-ray mission (such as Fermi-LAT today) to help select most promising follow-ups for CTA.**



# A Wide-Field Experiment in the South

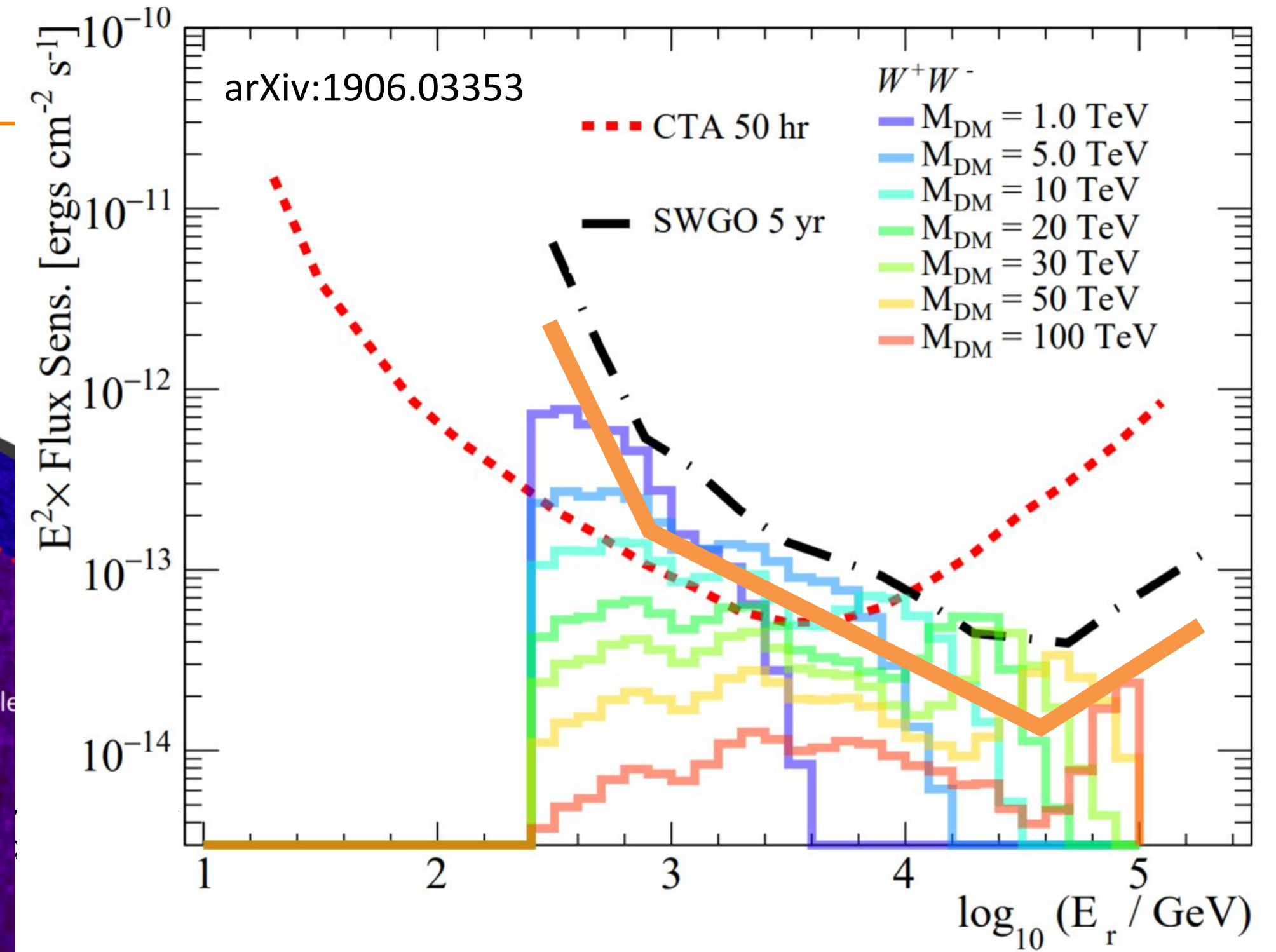
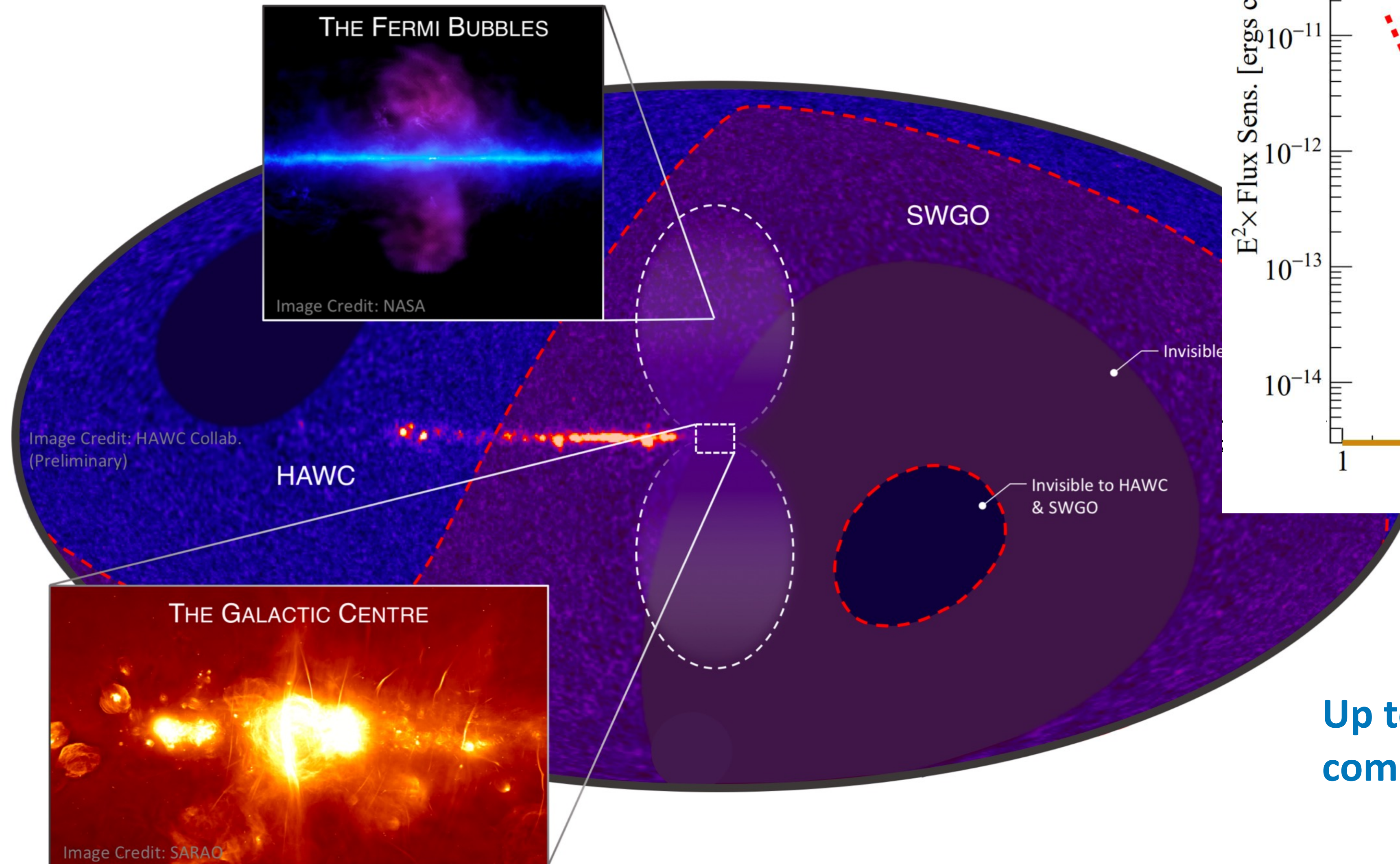


## Galactic Accelerators: PeVatron Sources



**Up to ultra-high energies, > 100 TeV,  
complementary to CTA measurements**

# A Wide-Field Experiment in the South



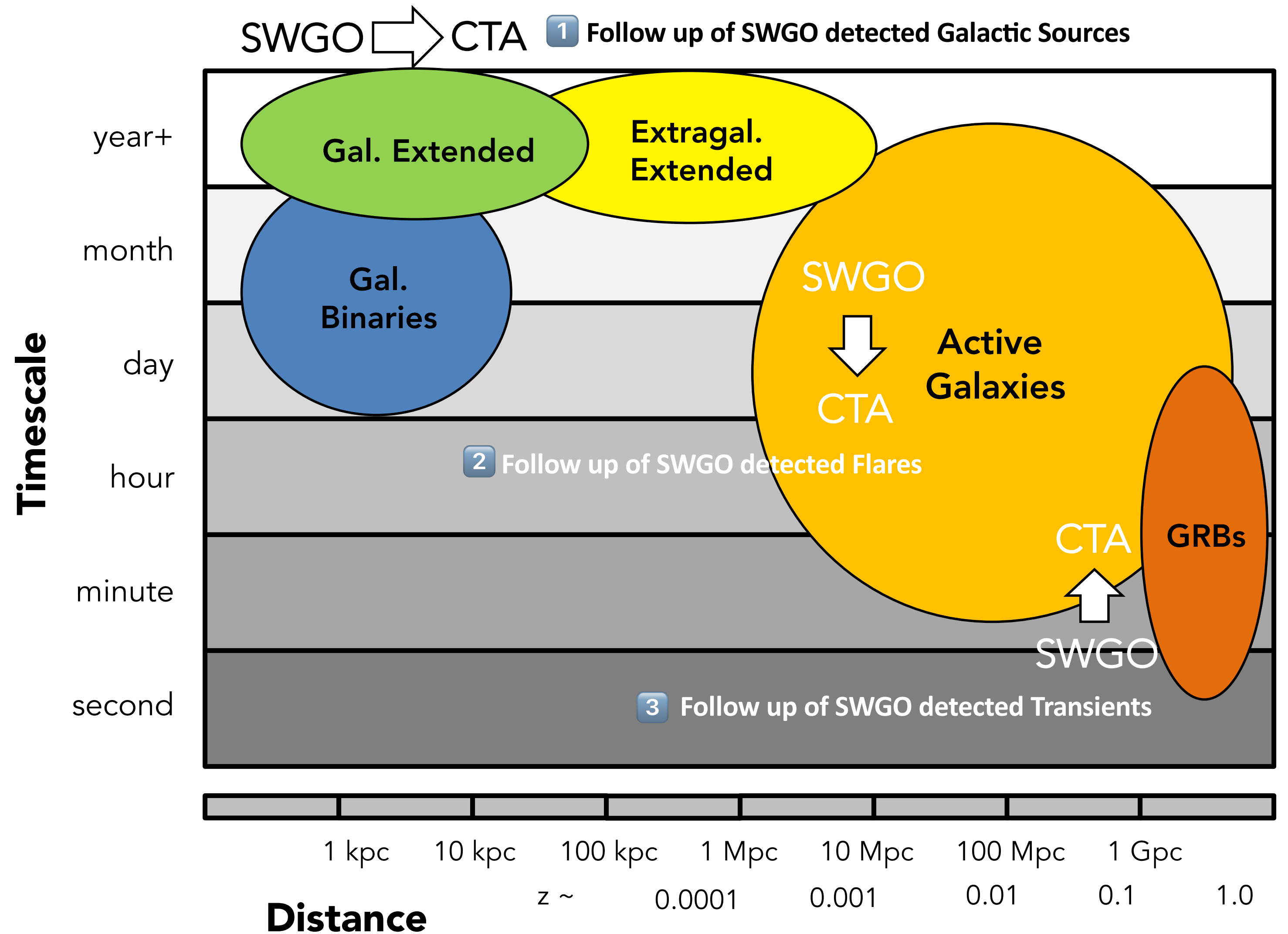
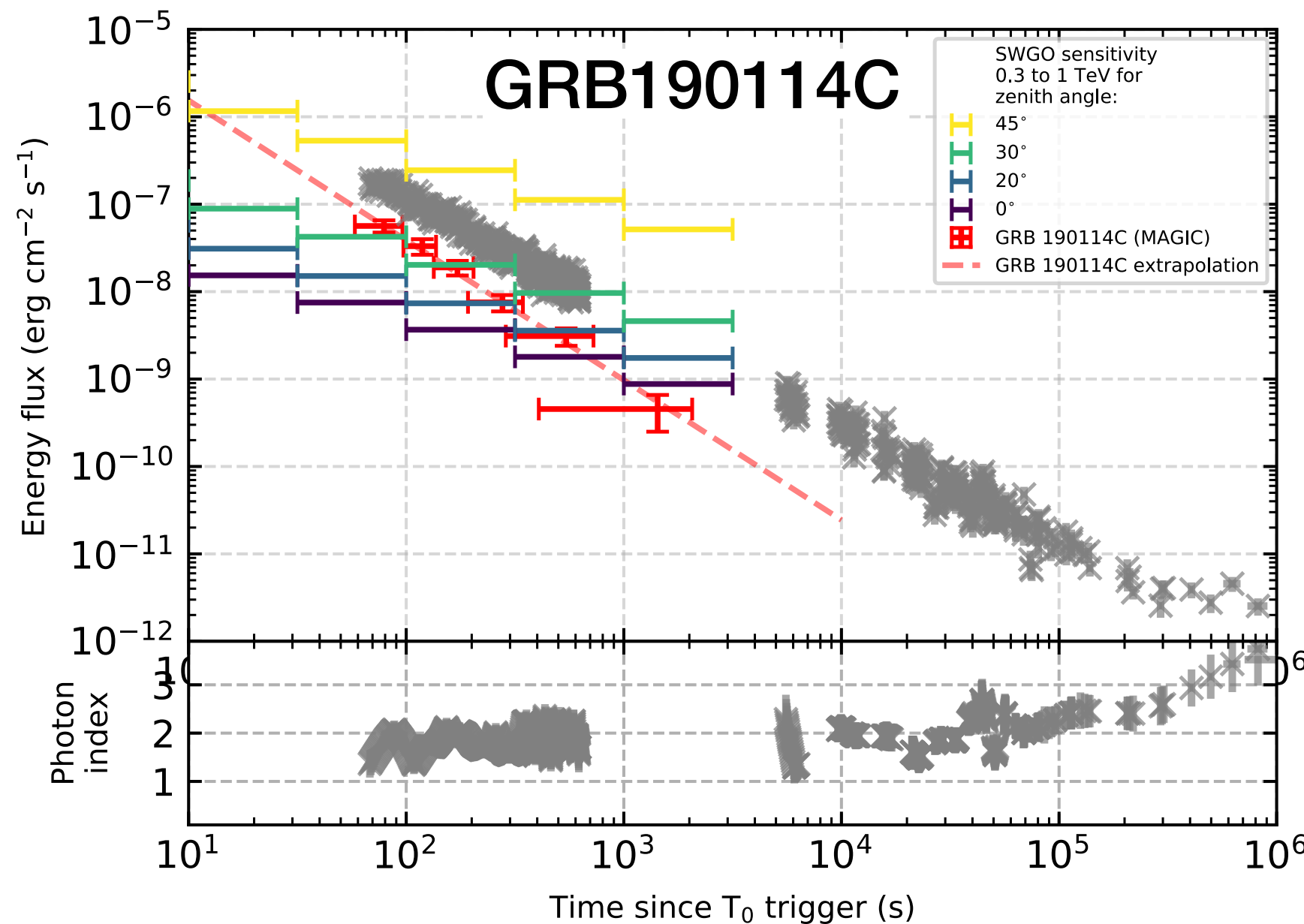
Fundamental Physics:  
Dark Matter from GC Halo  
+ other DSphs in the Southern Sky

**Up to ultra-high energies, > 100 TeV,  
complementary to CTA measurements.**

# A Wide-Field Experiment in the South

## Transient Synergies with CTA-S

- ✓ relevant piece in the multi-messenger scenario



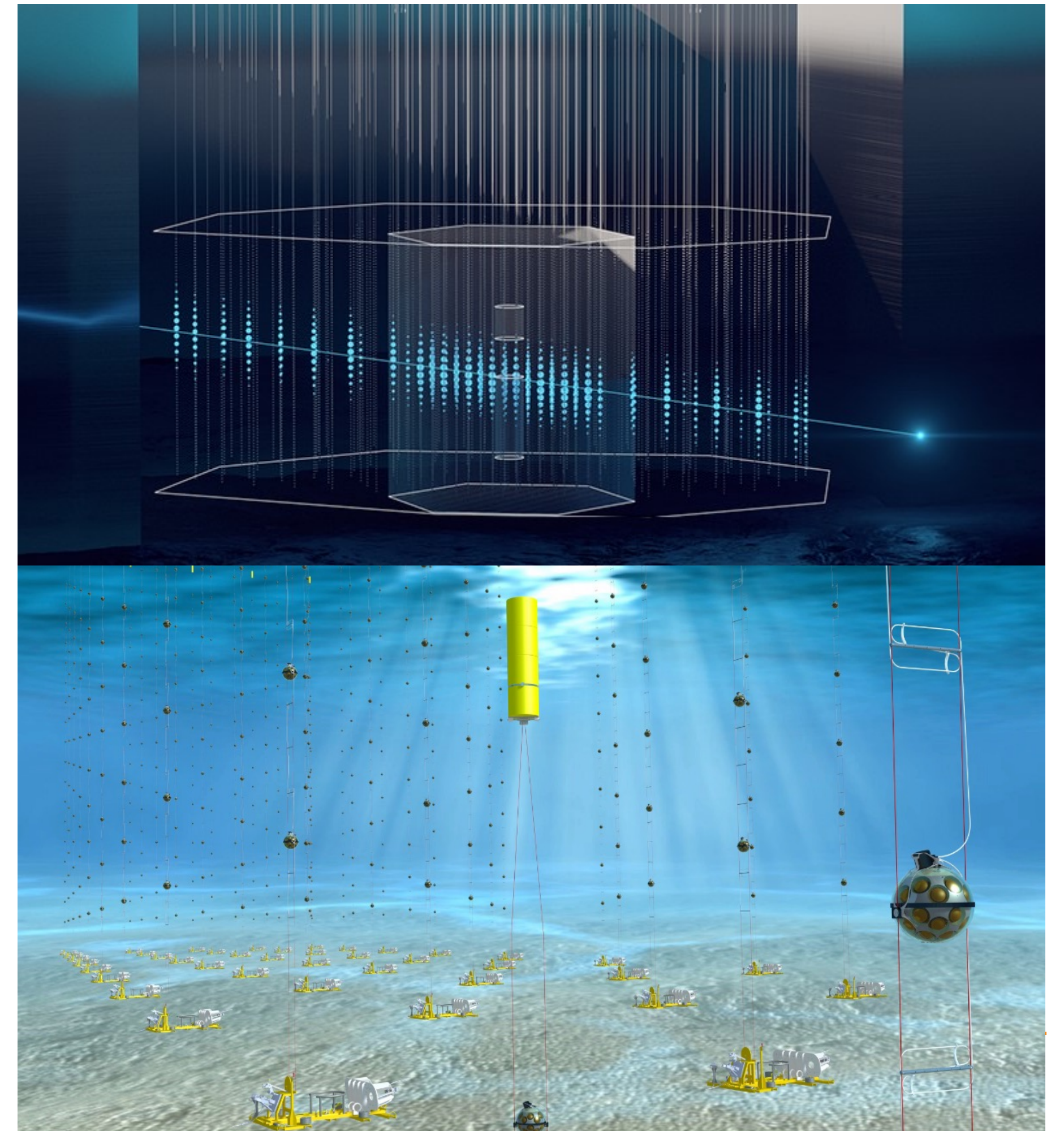
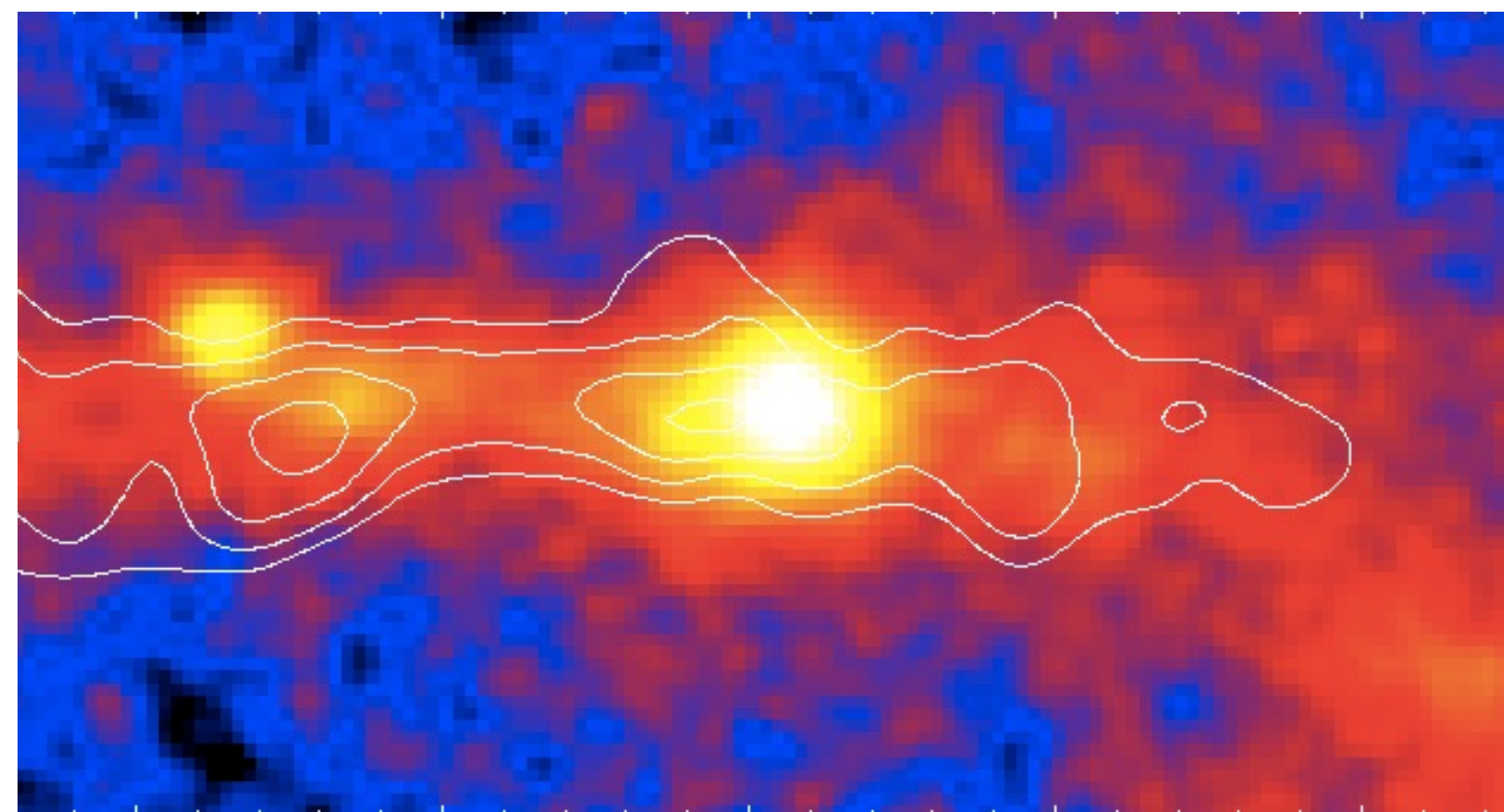
# A Wide-Field Experiment in the South

## ⊙ Neutrino Synergies

- ✓ complementary to new generation of experiments
- ✓ mapping diffuse emission and separating IC / pion-decay components

## ⊙ Together with LHAASO

- ✓ full sky-map of TeV-PeV emission sources



**Science Case:**

<https://arxiv.org/abs/1902.08429>

**+ updates in ICRC 2021**

<https://pos.sissa.it/395/>