CBPF
Centro Brasileiro de Pesquisas Físicas
UNIDADE DE PESQUISA DO MCTI

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

ULISSES BARRES DE ALMEIDA - APRIL 2024 - IFSC/USP

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2. Setting up the stage
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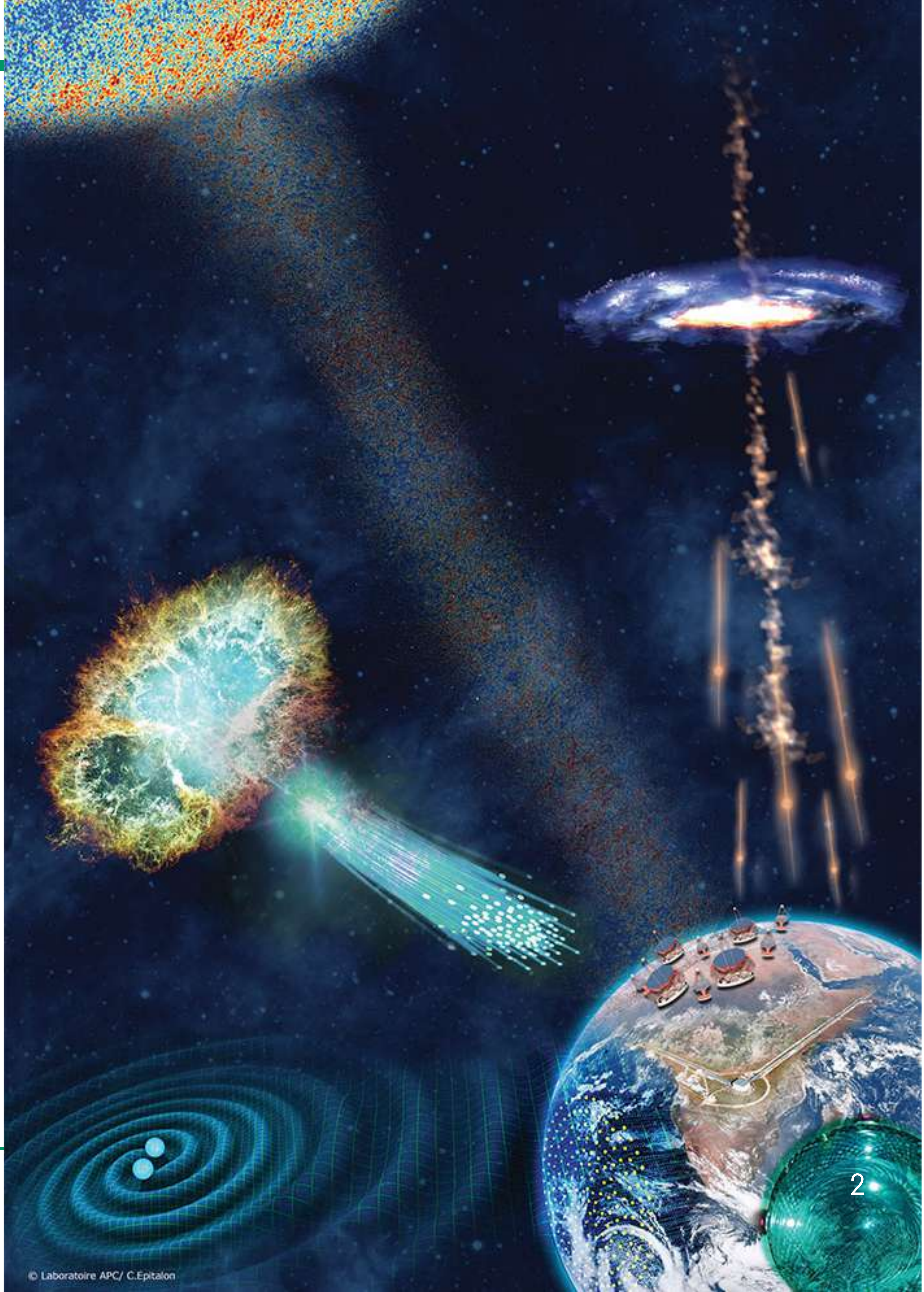
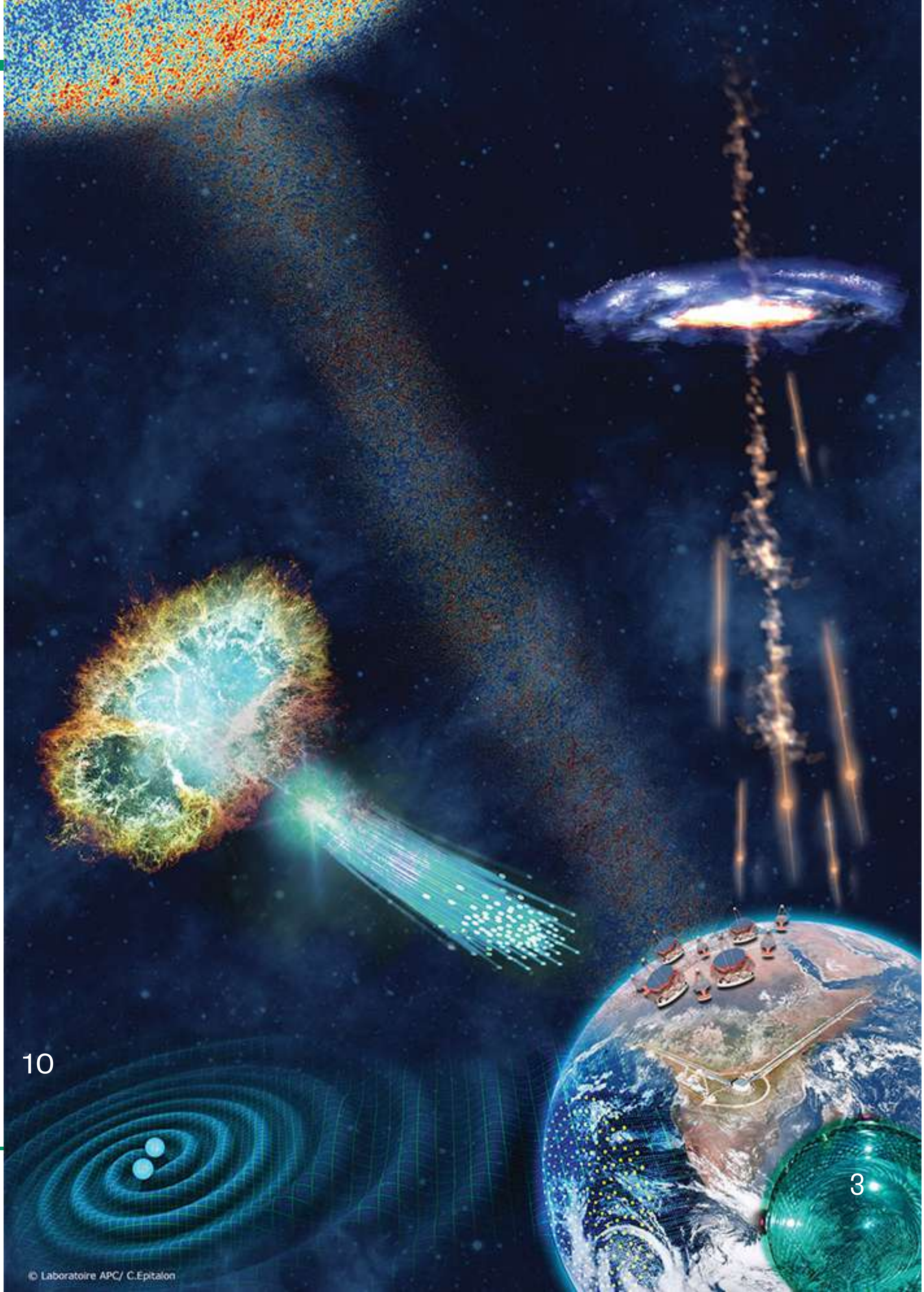
5. Towards the UHE regime



Brief Introduction



Astroparticle Physics : MM scenario

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sub-mm IR-UV X-rays Gamma-rays →

meV … eV … keV … MeV … GeV … TeV … PeV … EeV … ZeV

Realm of Astroparticle Physics

Astronomy with photons

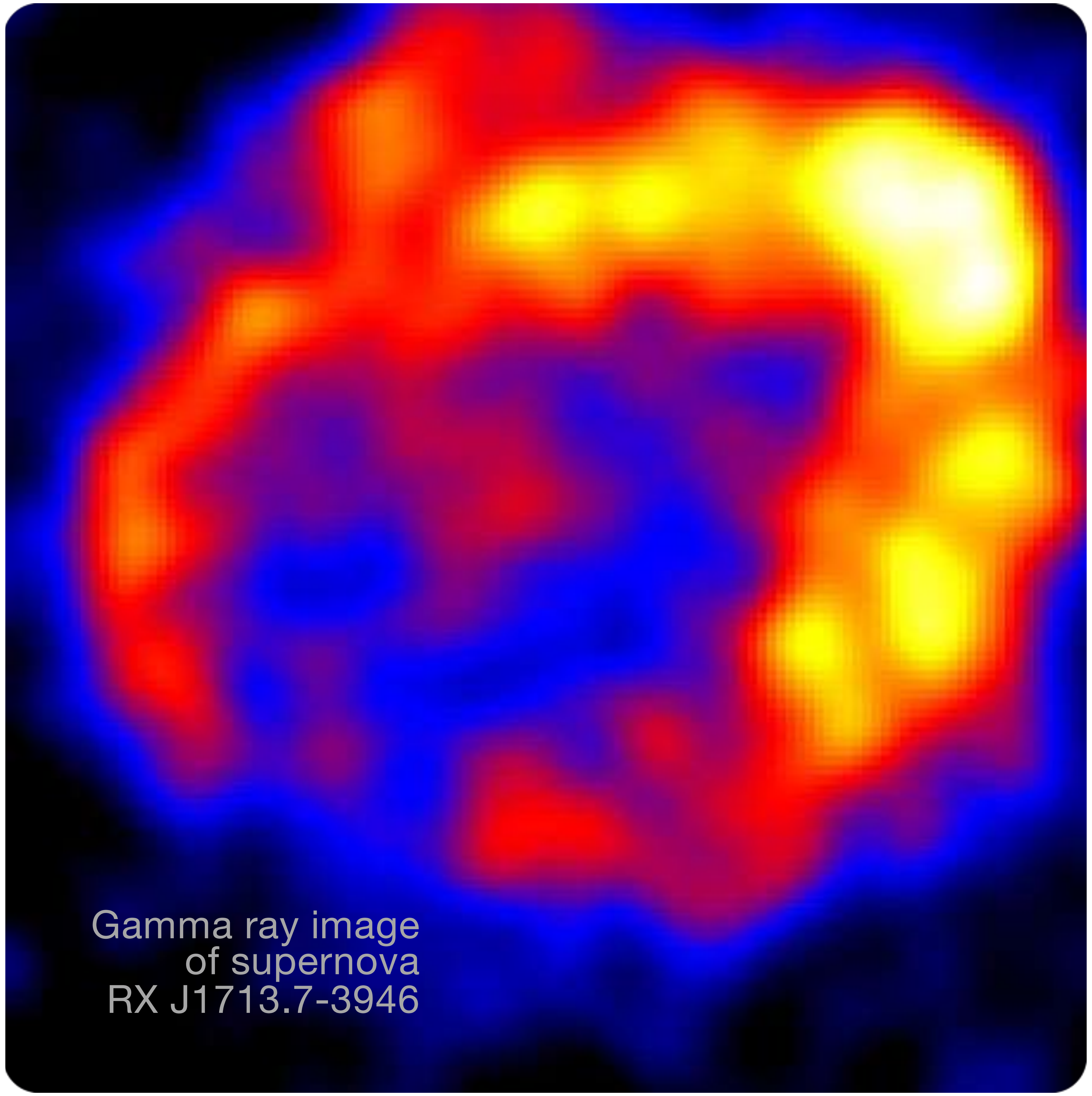
Charged cosmic-ray physics: p, e-, He, Fe, …

Neutrino signals

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

GRAVITATIONAL WAVES? PROBES OF COMPACT SOURCES

Status of ground-based gamma-ray astronomy



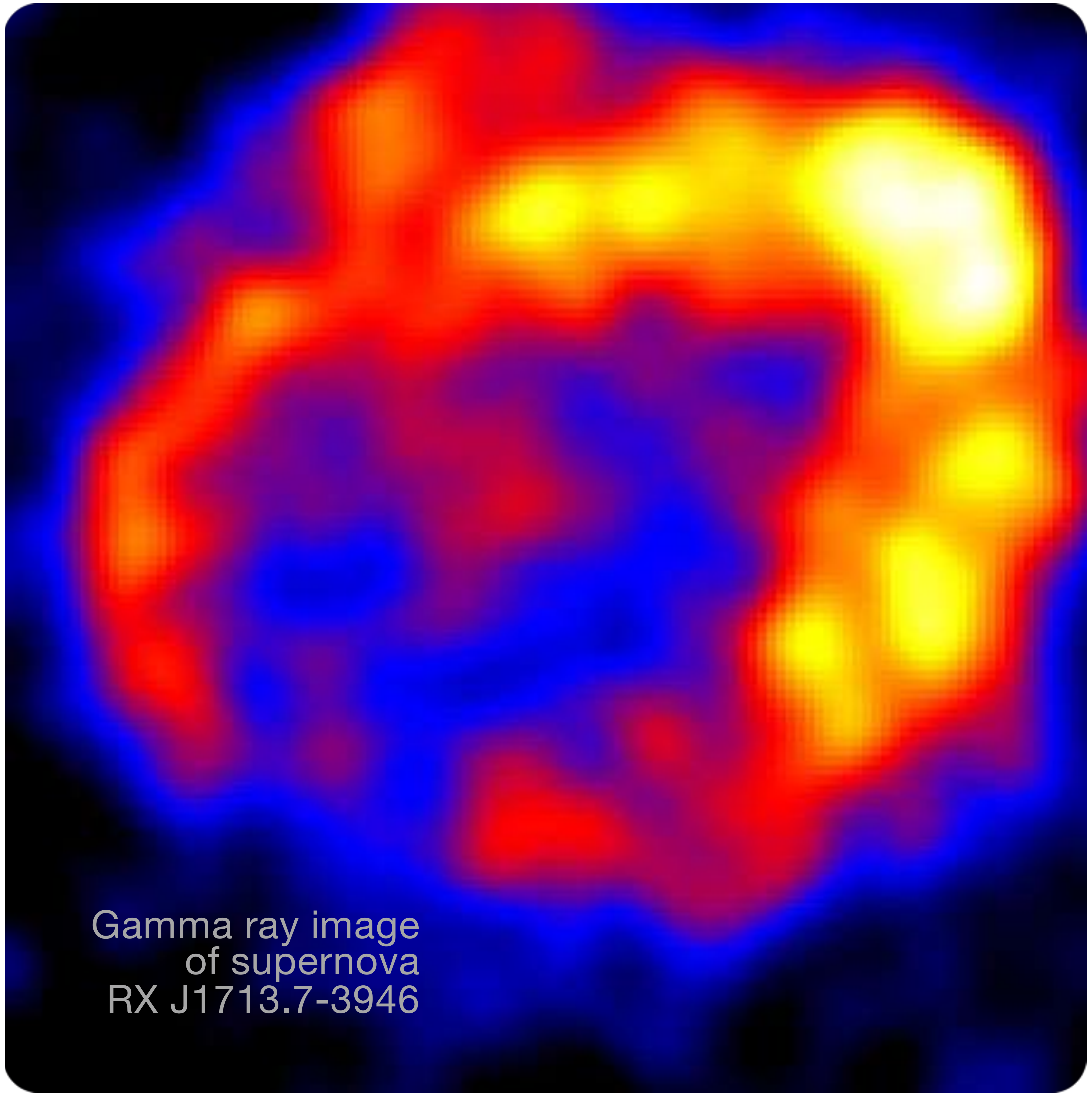
Cherenkov Astronomy has reached the status of "real astronomy"

- good-resolution skymaps, ~ 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^2
- sensitive cameras, small-pixel sizes ~ 0.2°
- large field of view of several degrees

Status of ground-based gamma-ray astronomy



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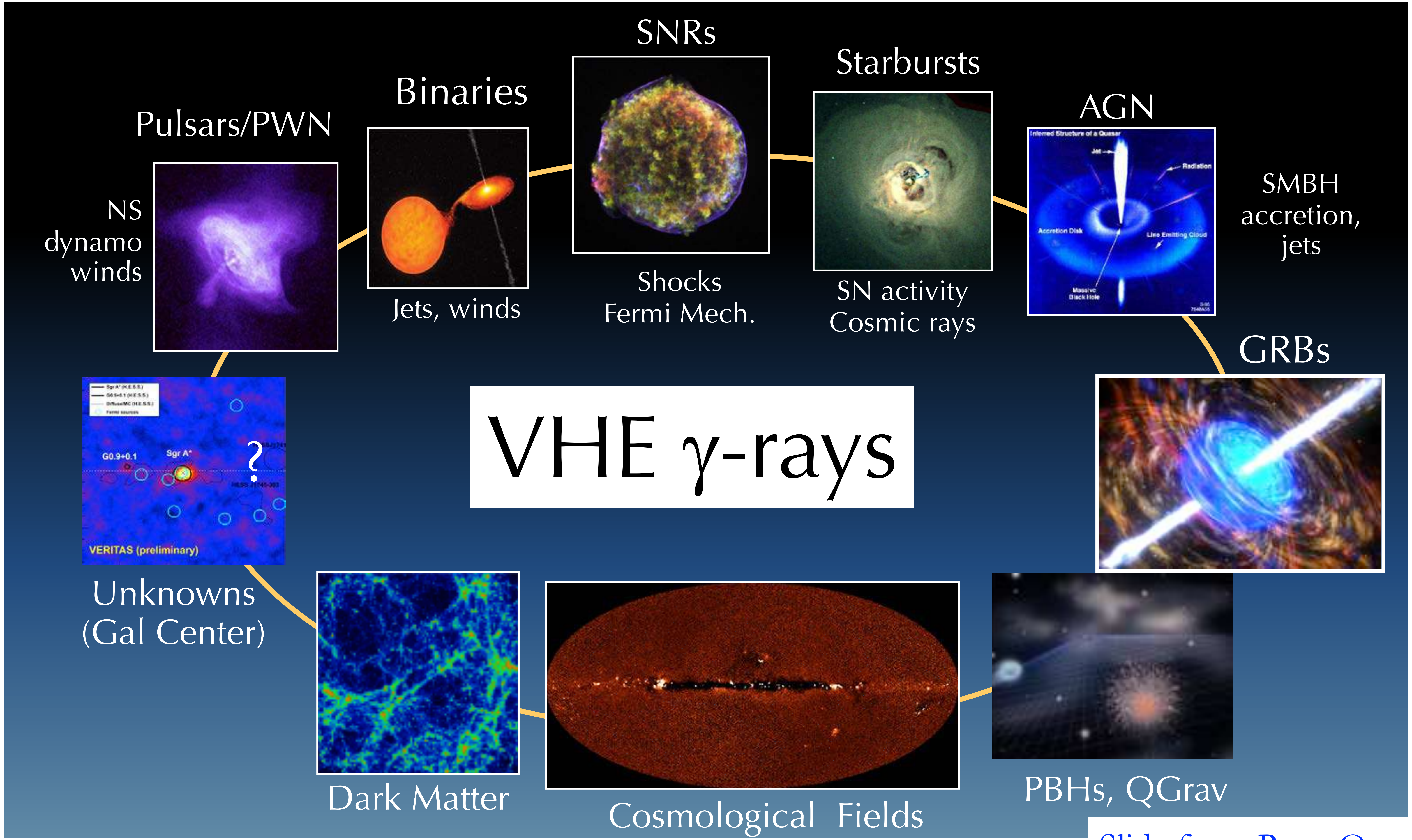
The recipe of the success?

Also for ground-particle arrays…

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

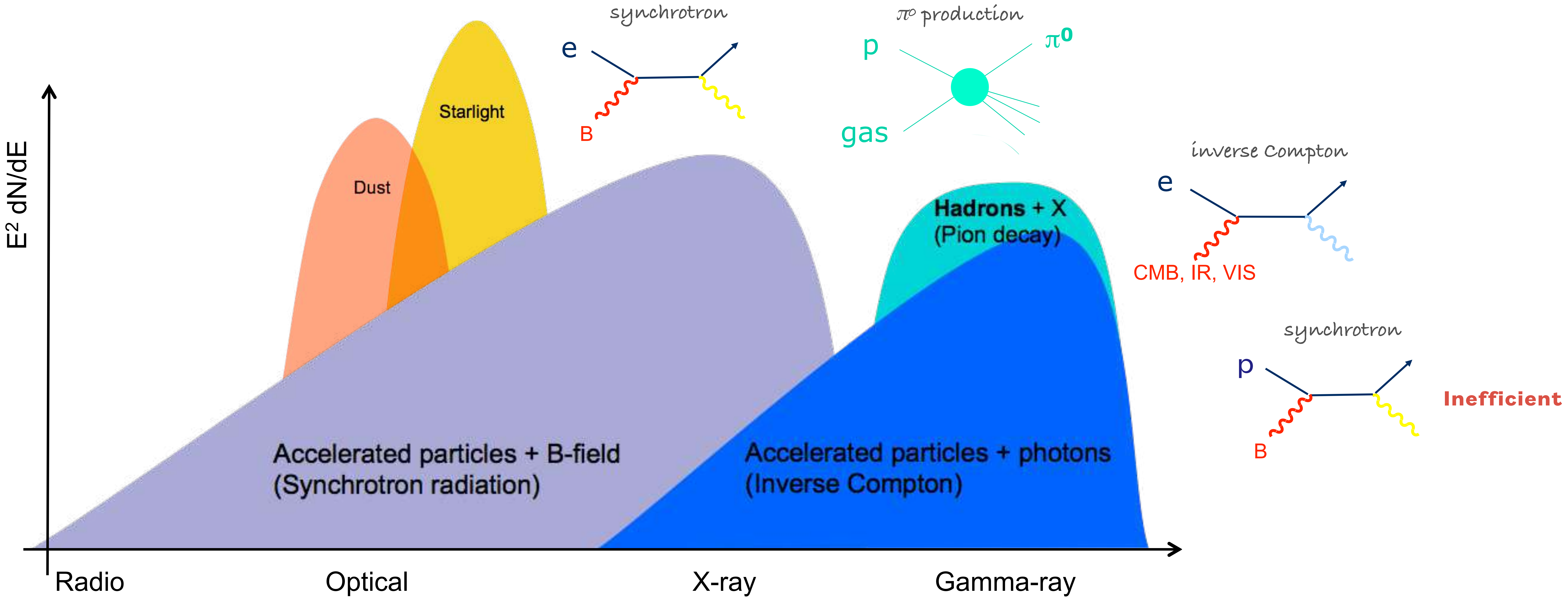
Non-thermal Astrophysics

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

serrapilheira CBPF

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

p^+, He, Fe,....

Interactions with matter and photon-fields → $\pi^{+/-}$ → $\mu^{+/-}$ ν_μ

π^0 → $\gamma\gamma$

$\mu^{+/-}$ → $e^{+/-}$ ν_e ν_μ

p^+,e^- → MWL

Only charged particle are accelerated in EM fields

Synchrotron in B-fields, inverse-Compton...
p^+, inefficient

Intense radiative losses
=> hadronic hard X-rays or soft-gamma signature

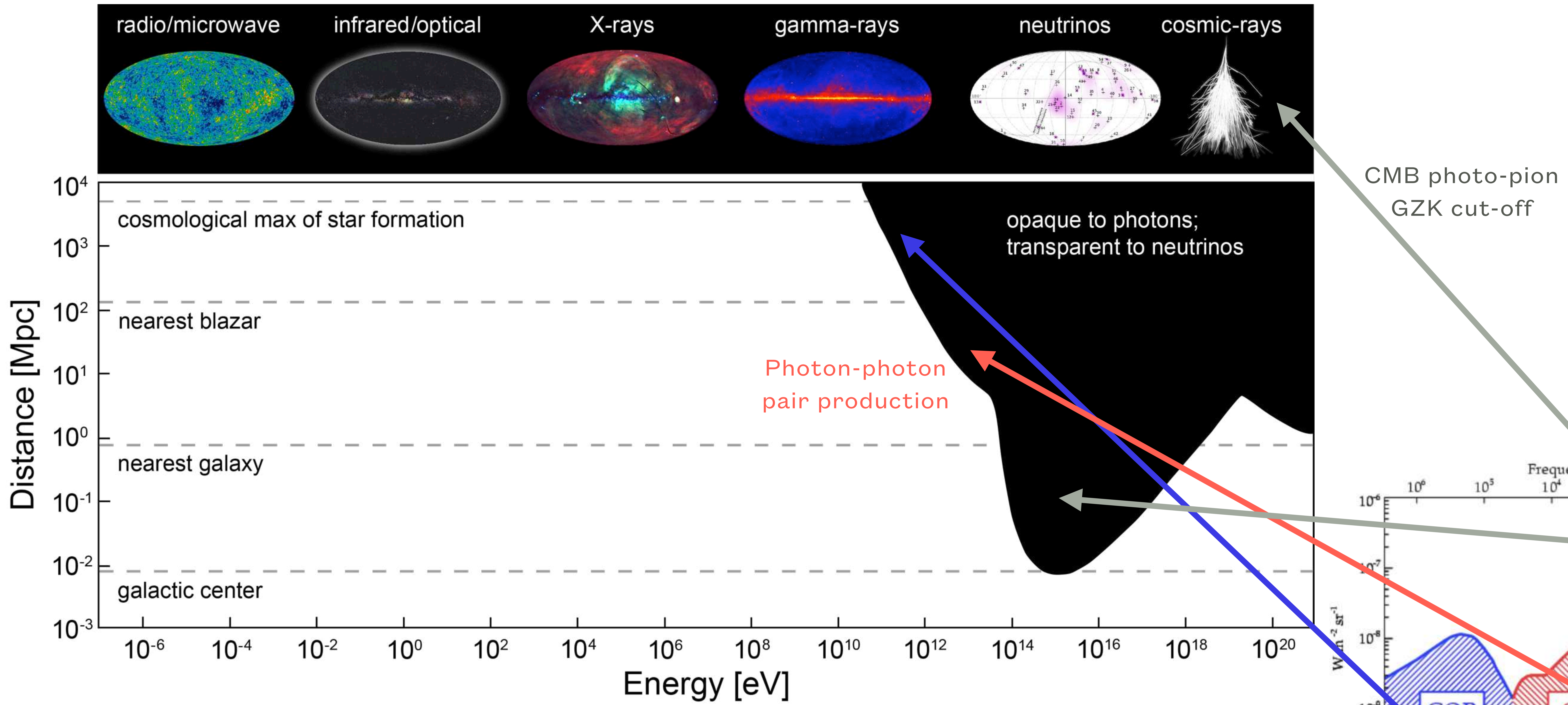
Easy detection

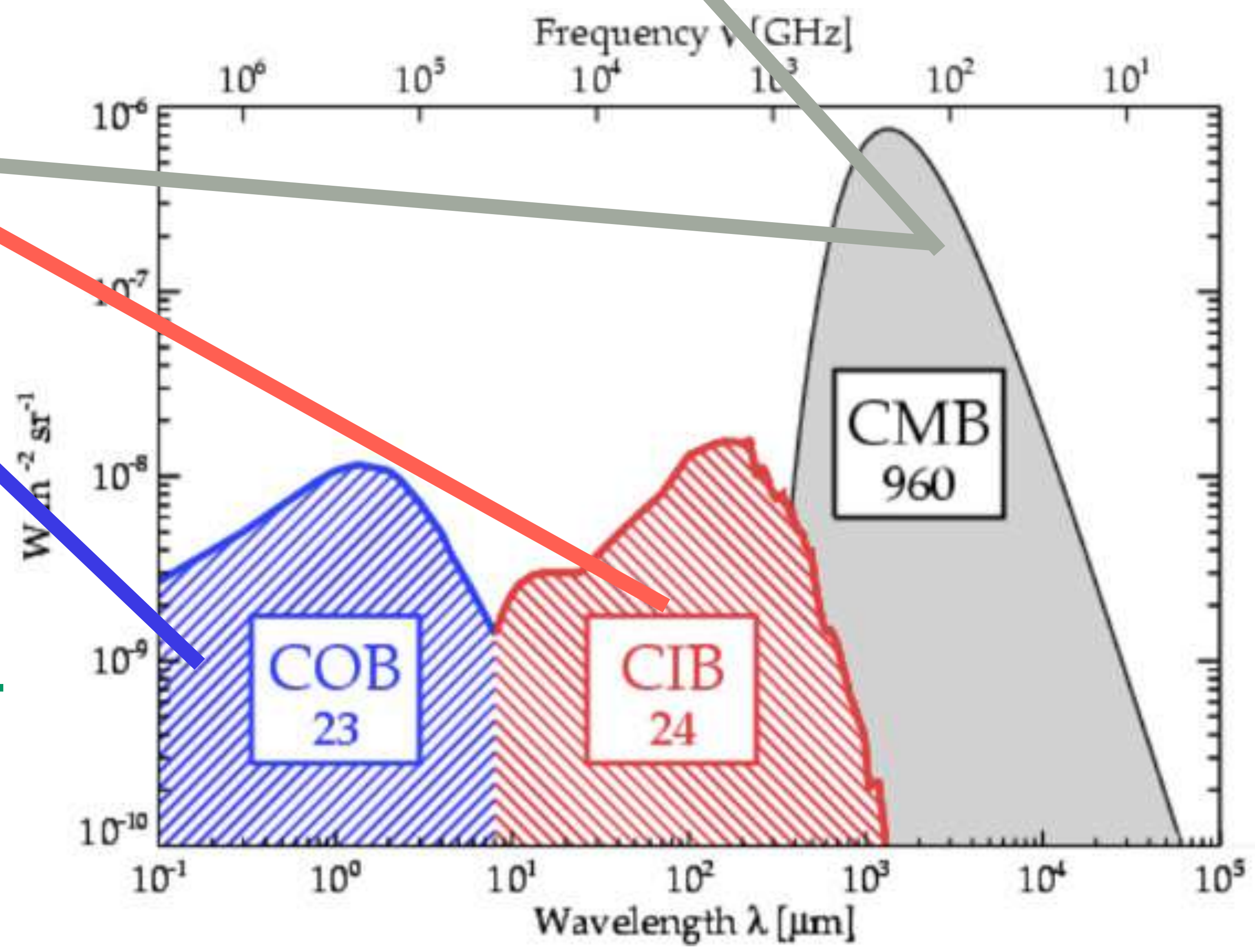
Difficult detection

MM Astronomy : Directionality information preserved, but strong backgrounds.

Gamma-rays are the cornerstone of multi-messenger astrophysics

Neutrinos : probe of deeper horizon, denser environments





CTA SYNERGIES WITH MWL INSTRUMENTS

CTA SYNERGIES WITH MWL INSTRUMENTS

- 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: Pillars

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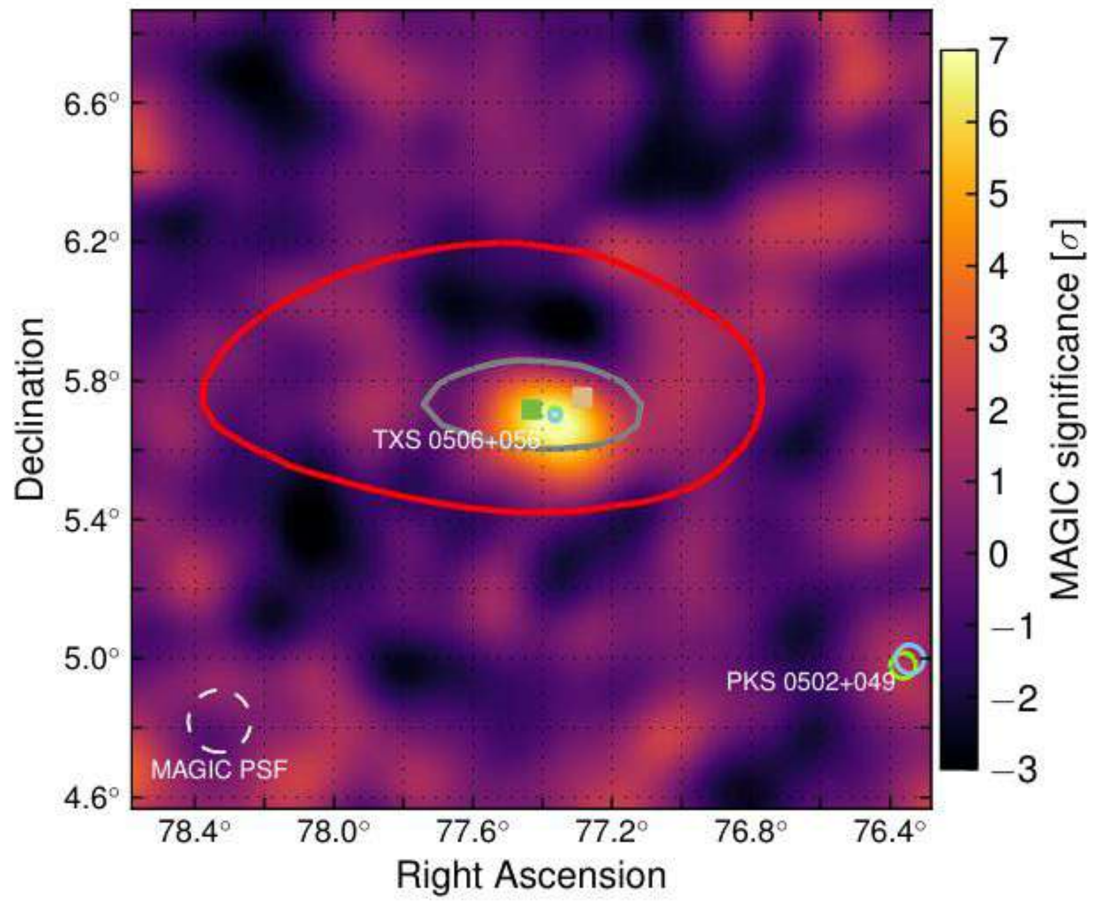
Multi-messenger Astrophysics has emerged in the past decade, with gamma-ray astronomy at its very center.

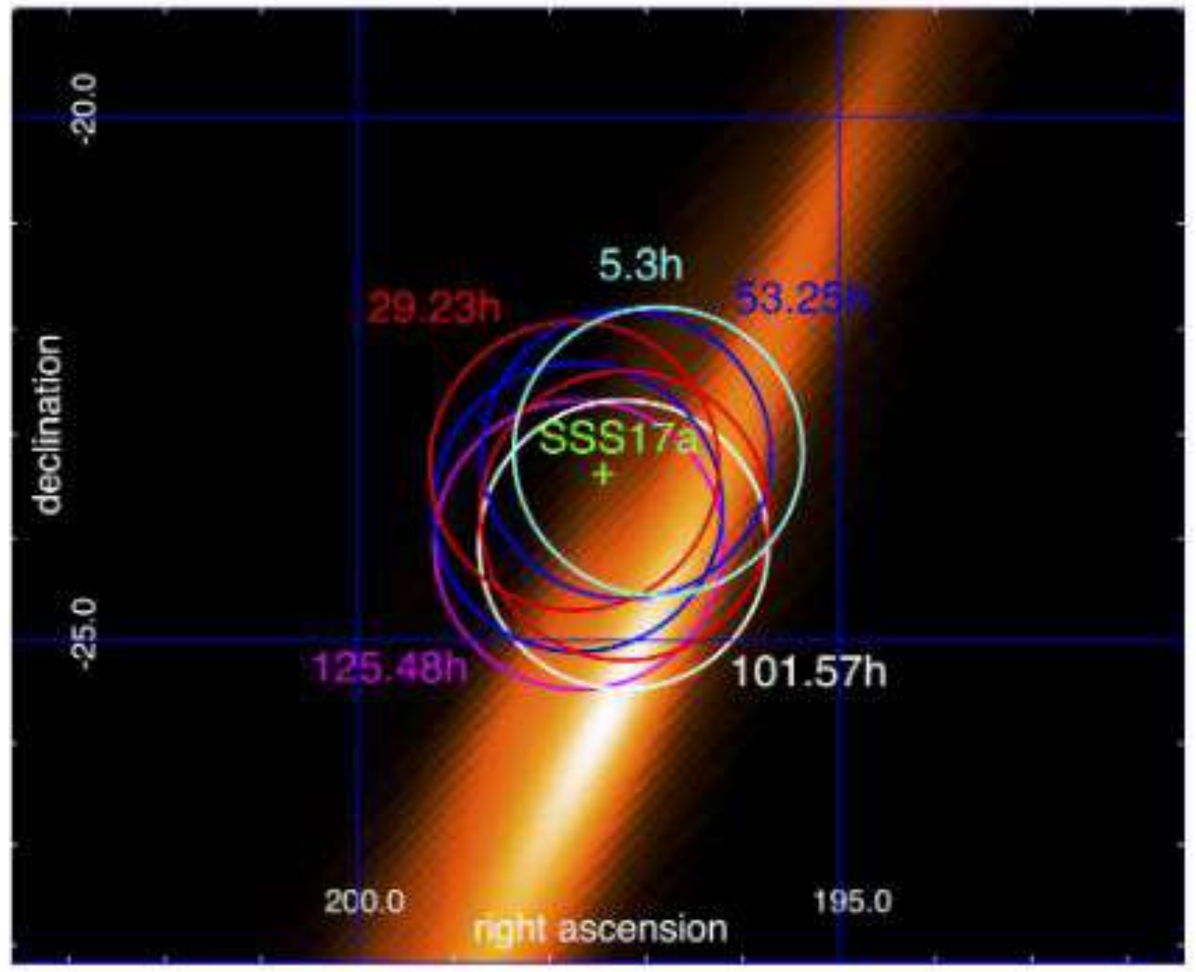
- **Attempt at a neutrino / VHE connection for TXS 0506+056**

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



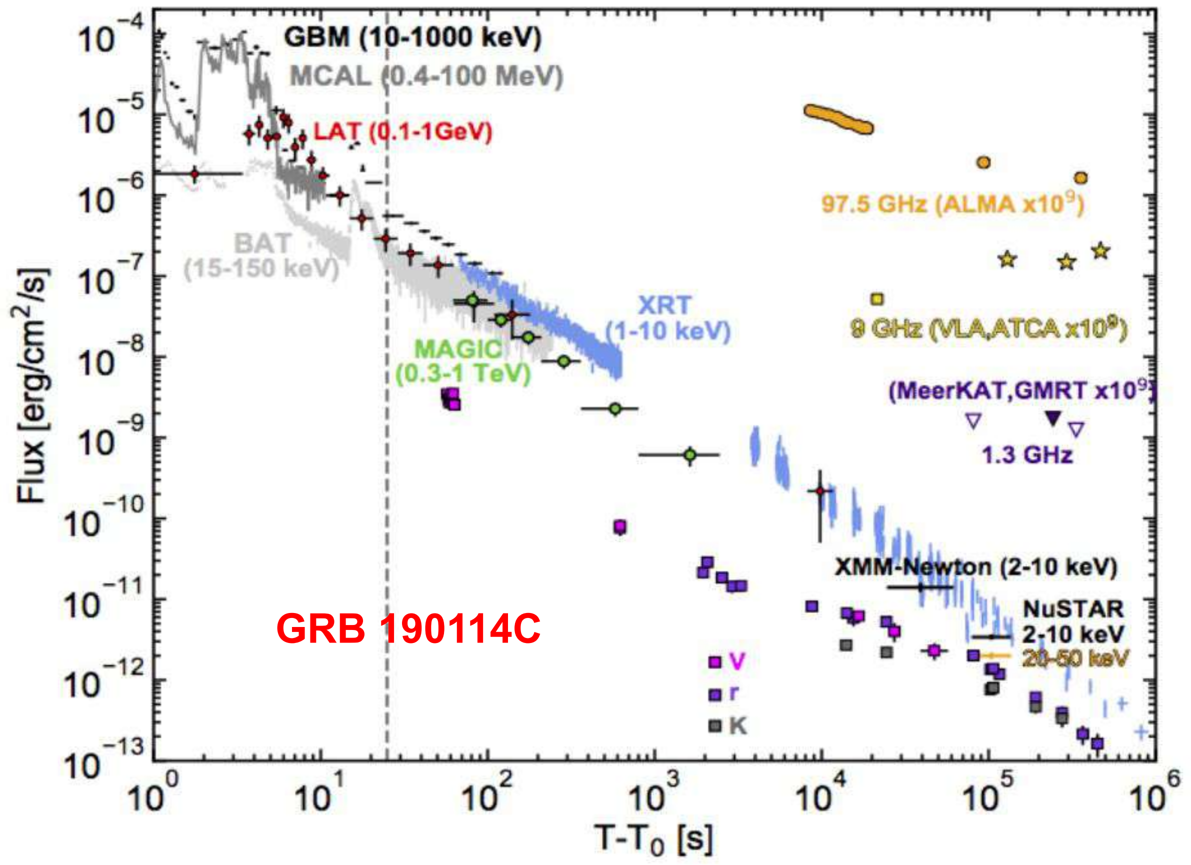
- **TeV Observations of event GW 170817**

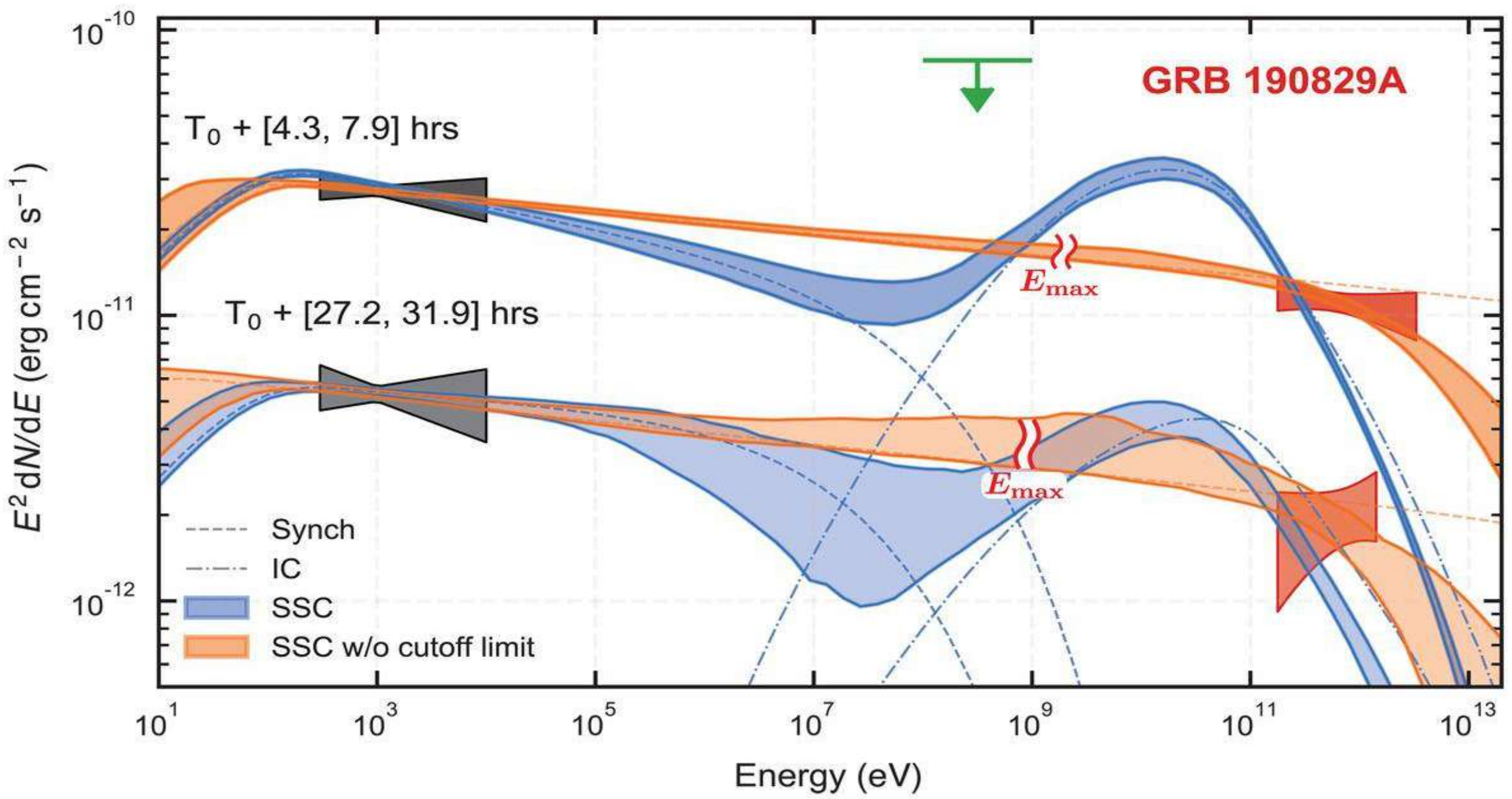
  Upper-limits from HESS.
  2017 - ApJL 850, L22
  Upper-limits from Fermi-LAT.
  2018 - ApJ 861, 85



- **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)





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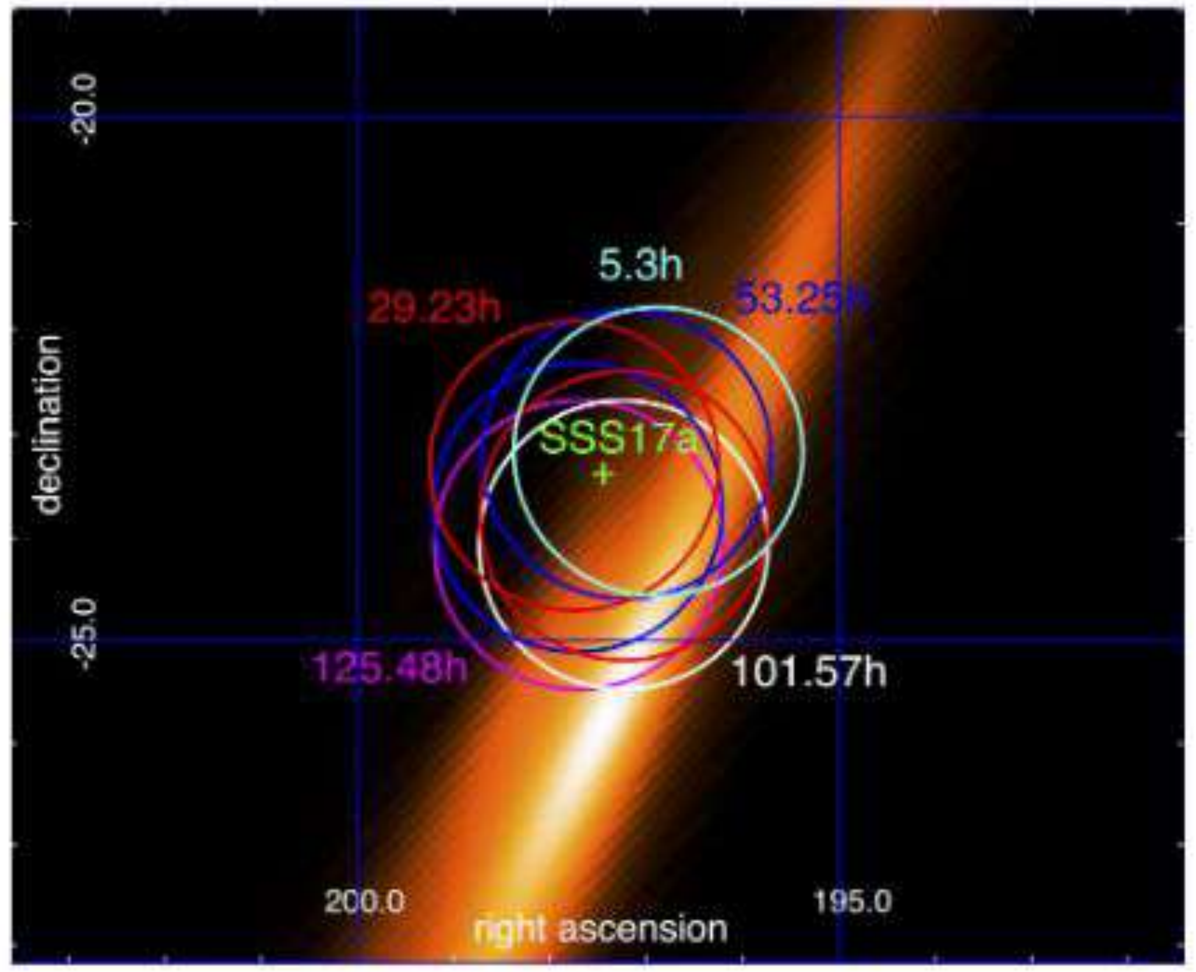

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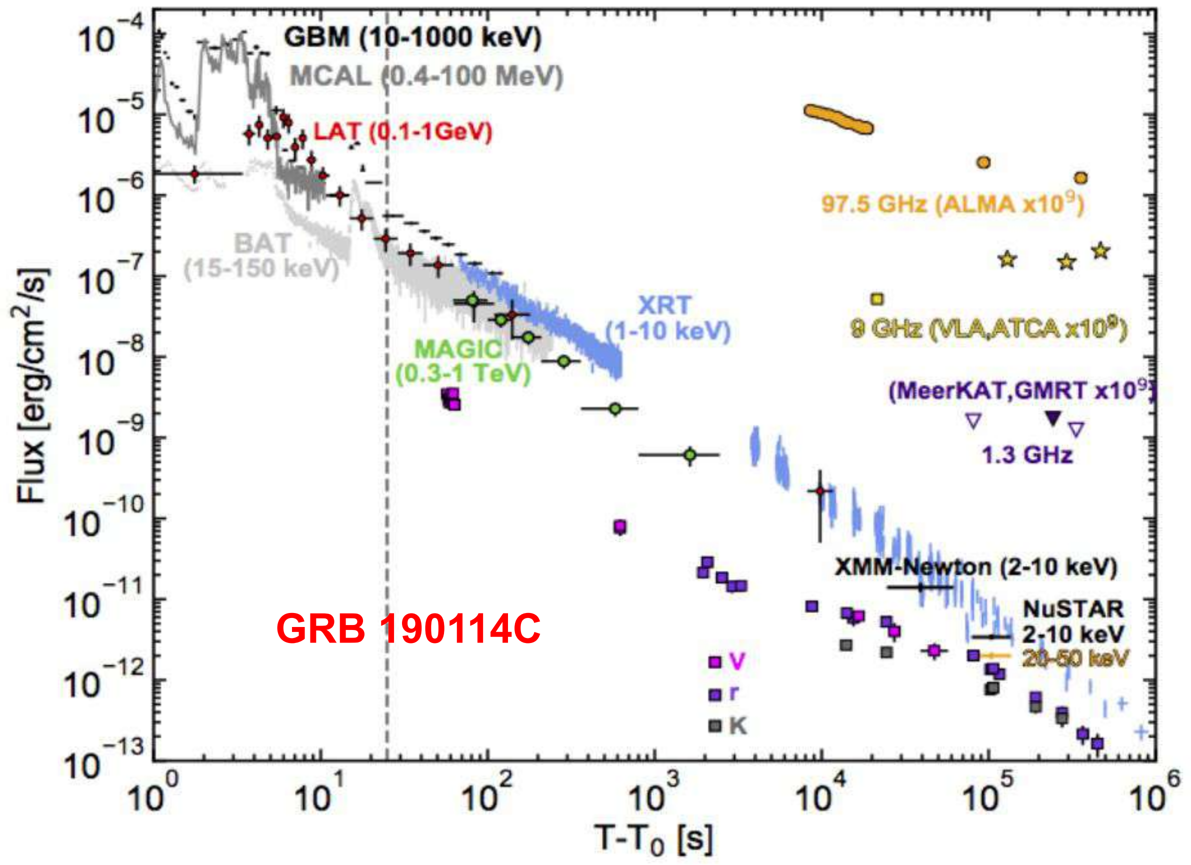
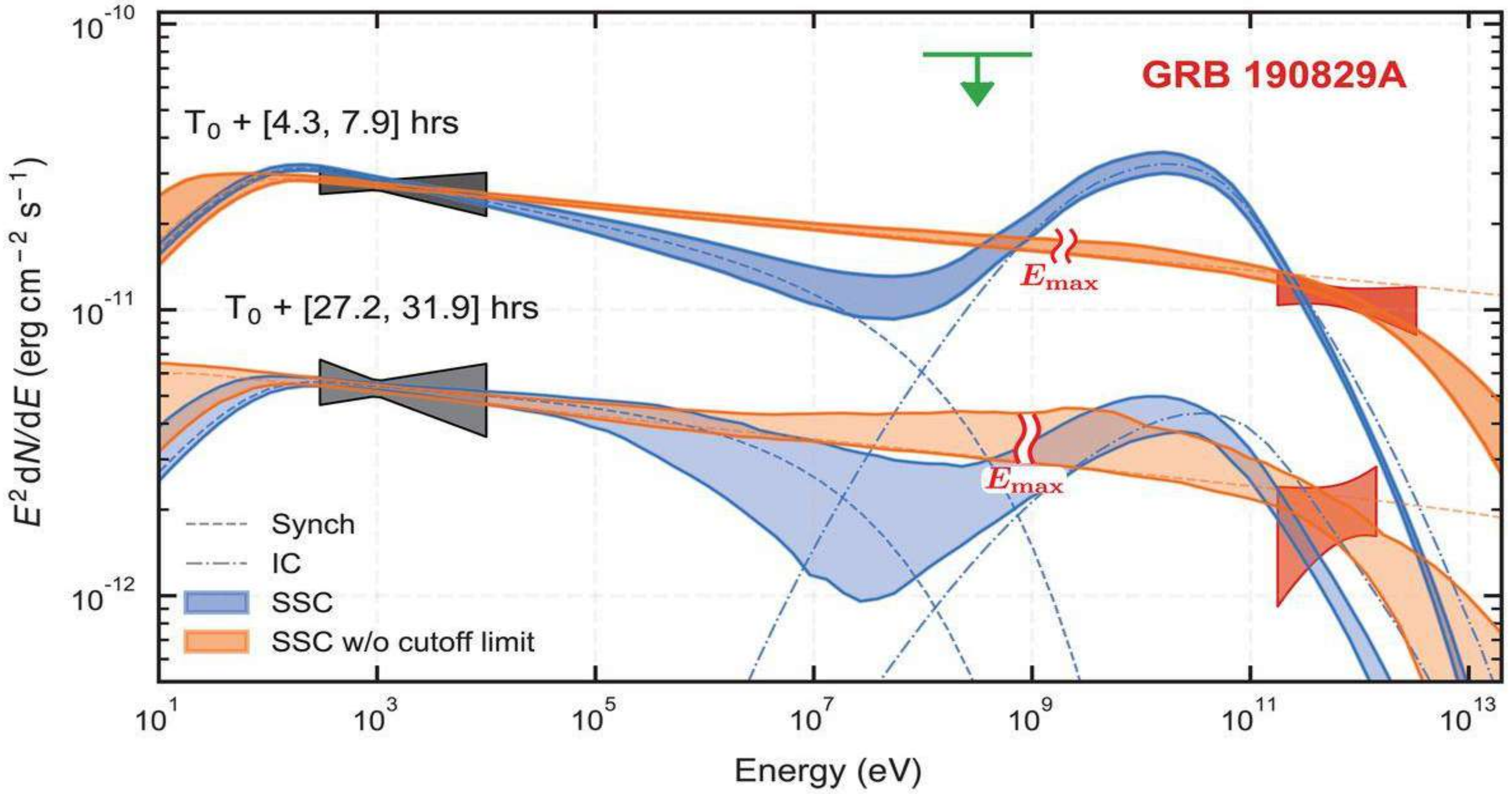
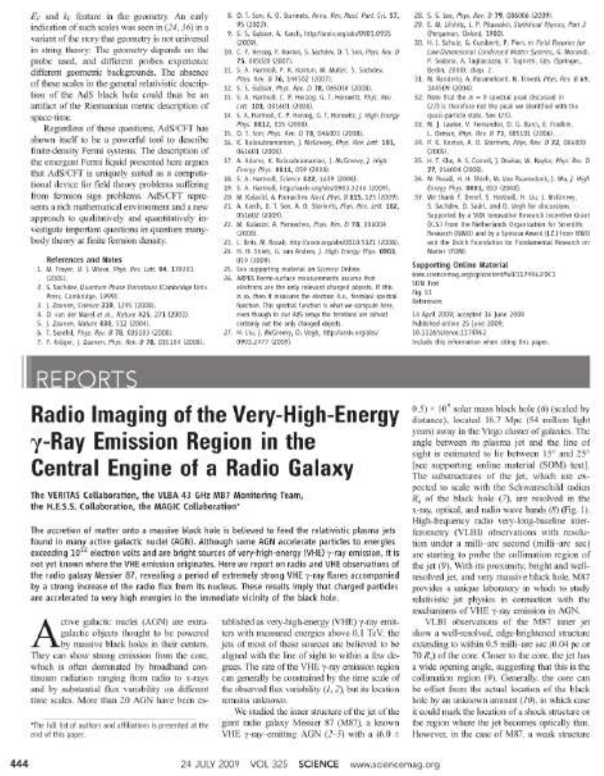




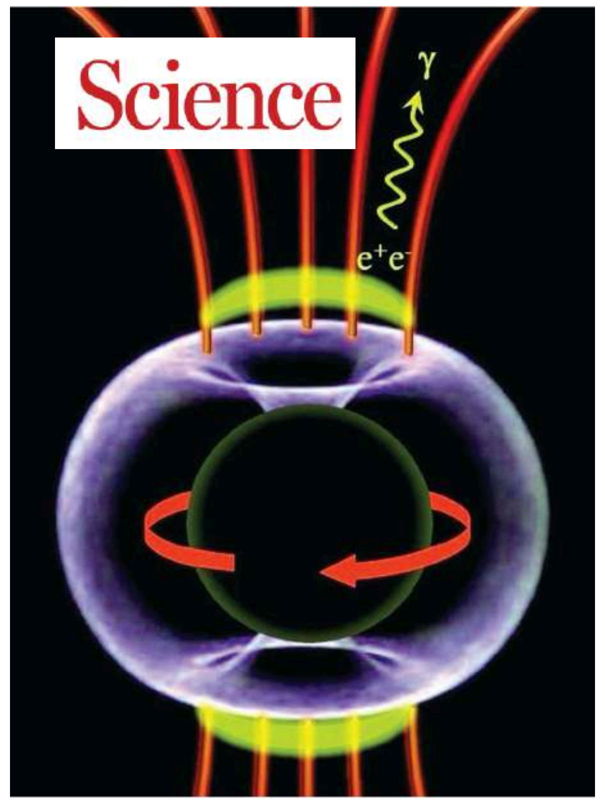
The impact of MWL/MM Science

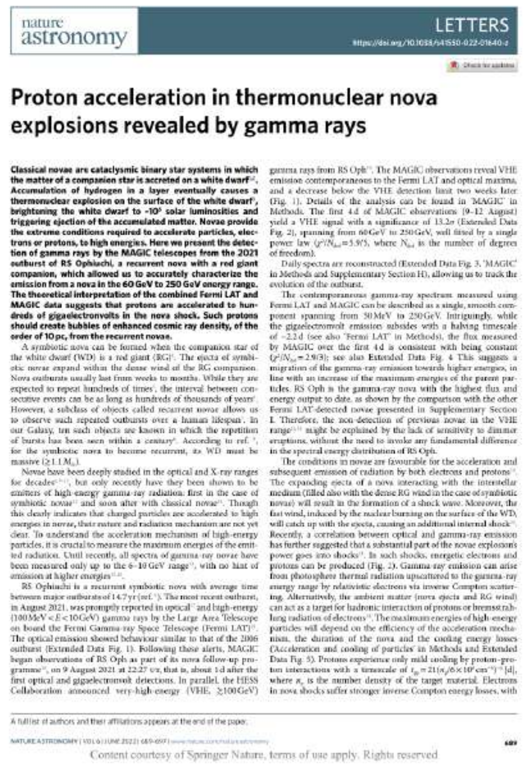
Principais publicações do MAGIC: PRL, Nature, Science

2005	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	1	2	2	1			1		1	1			1	2	1		1	1


REPORTS

Radio Imaging of the Very-High-Energy γ-Ray Emission Region in the Central Engine of a Radio Galaxy




nature astronomy LETTERS

Proton acceleration in thermonuclear nova explosions revealed by gamma rays

MWL/MM

- The Location of the Particle Acceleration in Messier 87 Radiogalaxy Revealed
- Observation of inverse Compton emission from a long γ-ray burst
- Cosmic rays from the blazar TXS 0506+056 associated with PeV high-energy neutrino

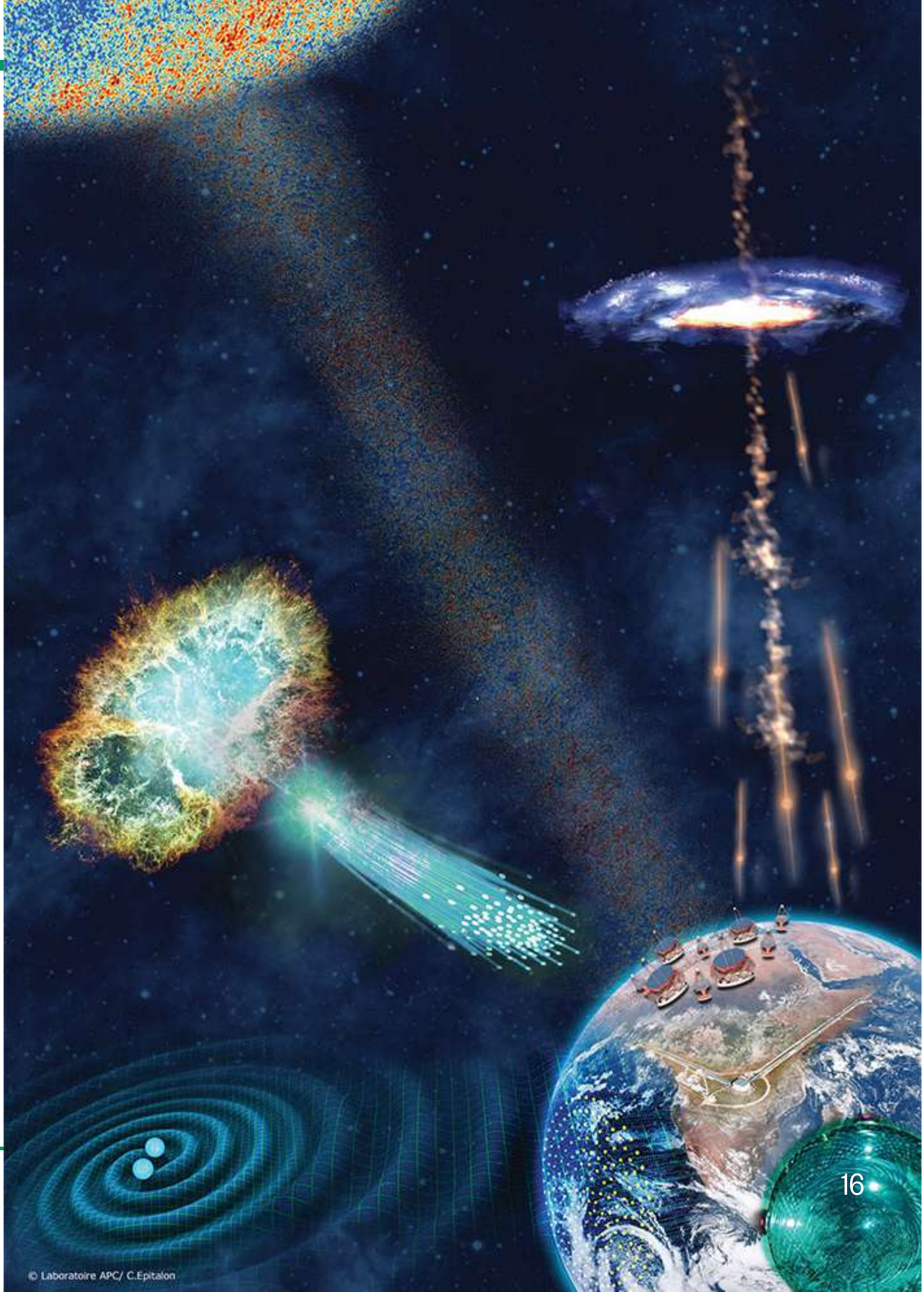
New Techniques

- Teraelectronvolt emission from the γ-ray burst GRB 190114C
- MAGIC very large zenith angle observations of the Crab Nebula up to 100 TeV

Observational frontiers

- Measurement of the EBL using MAGIC VHE observations of blazars up to z = 1
- New hard-TeV extreme blazars detected with the MAGIC telescopes

Setting up the stage



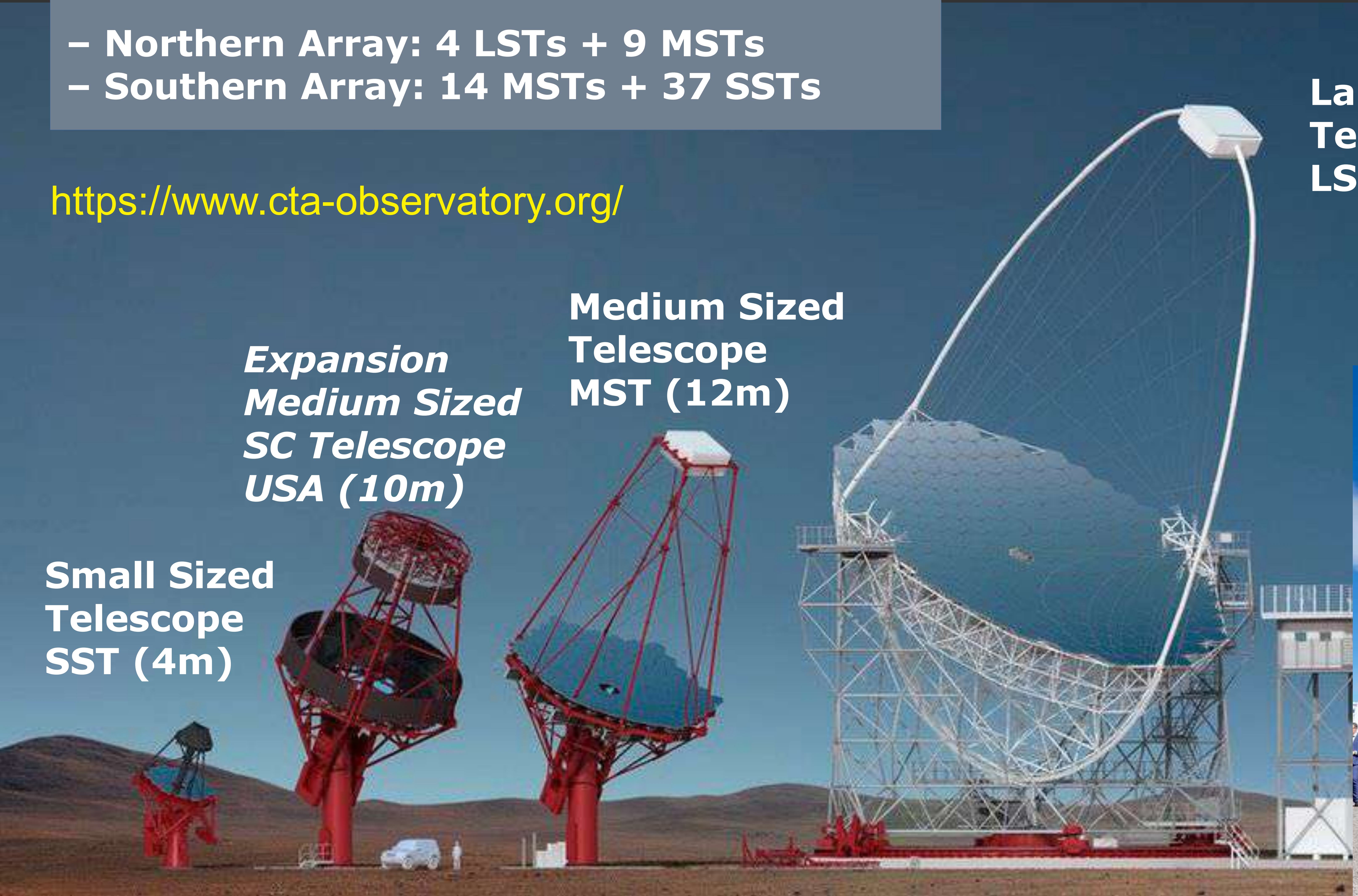
Cost ~ 330 MEuro for construction (cash + in-kind)
All construction funds available!

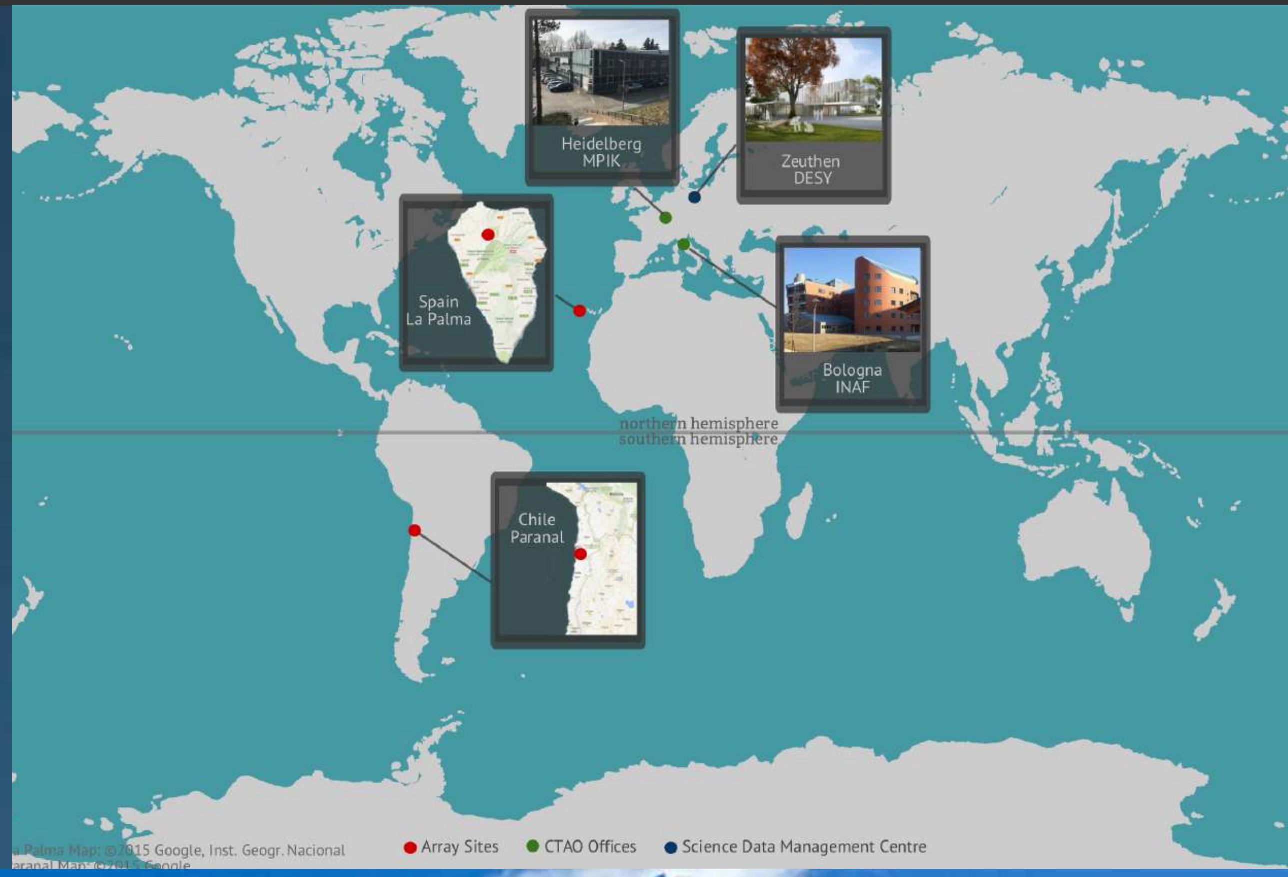
CTA Observatory (CTAO)
- CTA-North La Palma
  (1st telescope operating!)
- CTA-South in Chile
- CTA HQ, Bologna
- CTA Data Centre, Berlin

CTA Arrays "alpha" Configuration

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

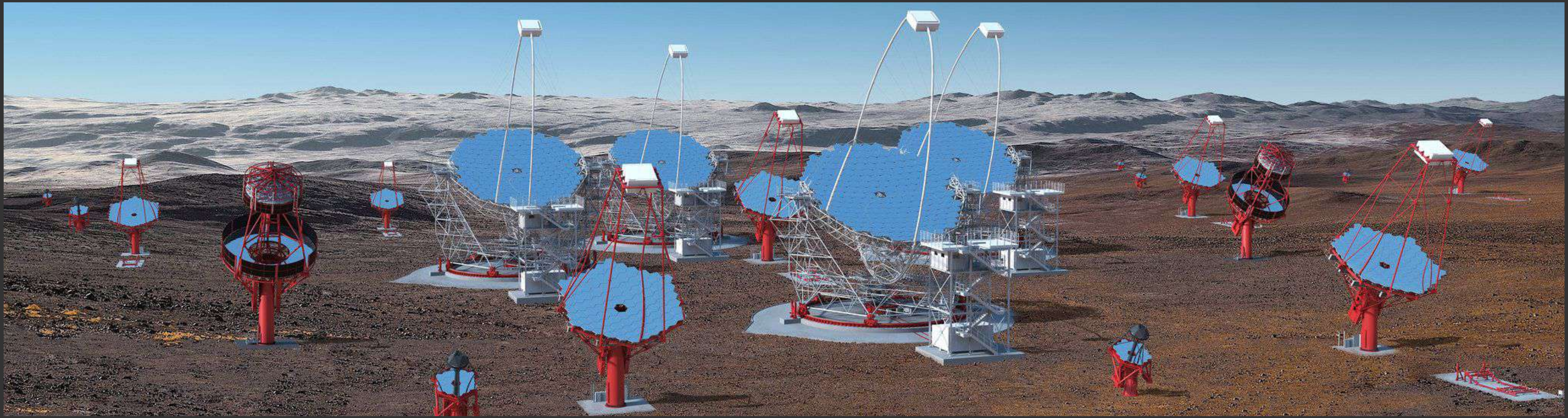
https://www.cta-observatory.org/





CTA – North & South

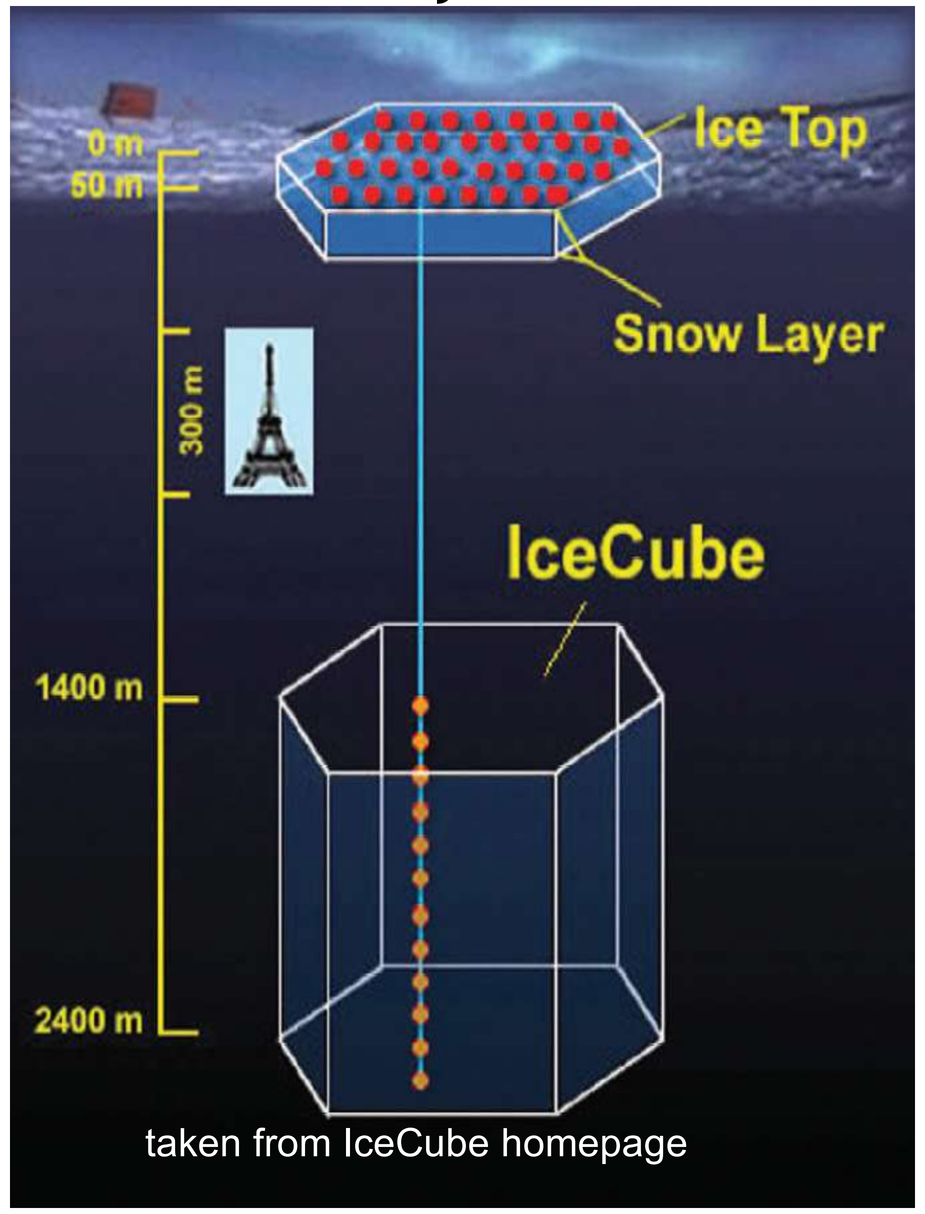
Construction phase – from late ~2022 for ~5 years, incl. verification science
Operations phase – Announcement of opp phase and full KSPs.

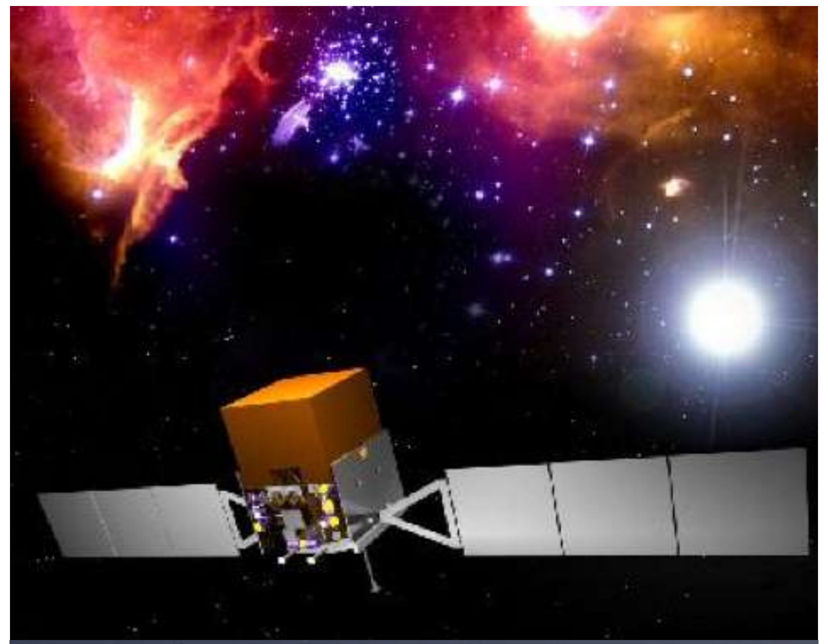


CTA as a player in the MWL+MM arena

Neutrinos

IceCube, KM3Net





Gamma-rays

Fermi, LHAASO, IACT…

Cosmic rays

AMS-02, Auger,…

Gravitational Waves

LIGO, VIRGO, KAGRA

MWL Facilities

MM Perspective from Astro 2020

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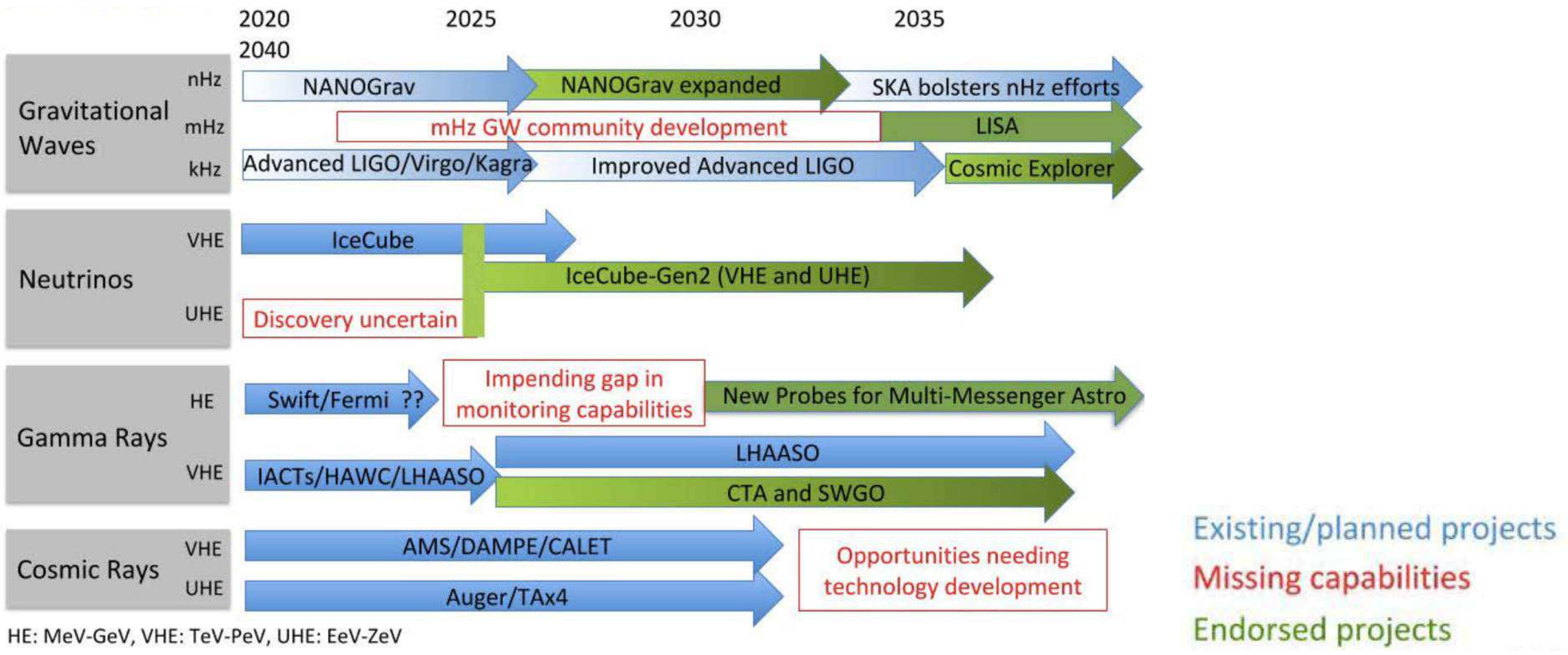


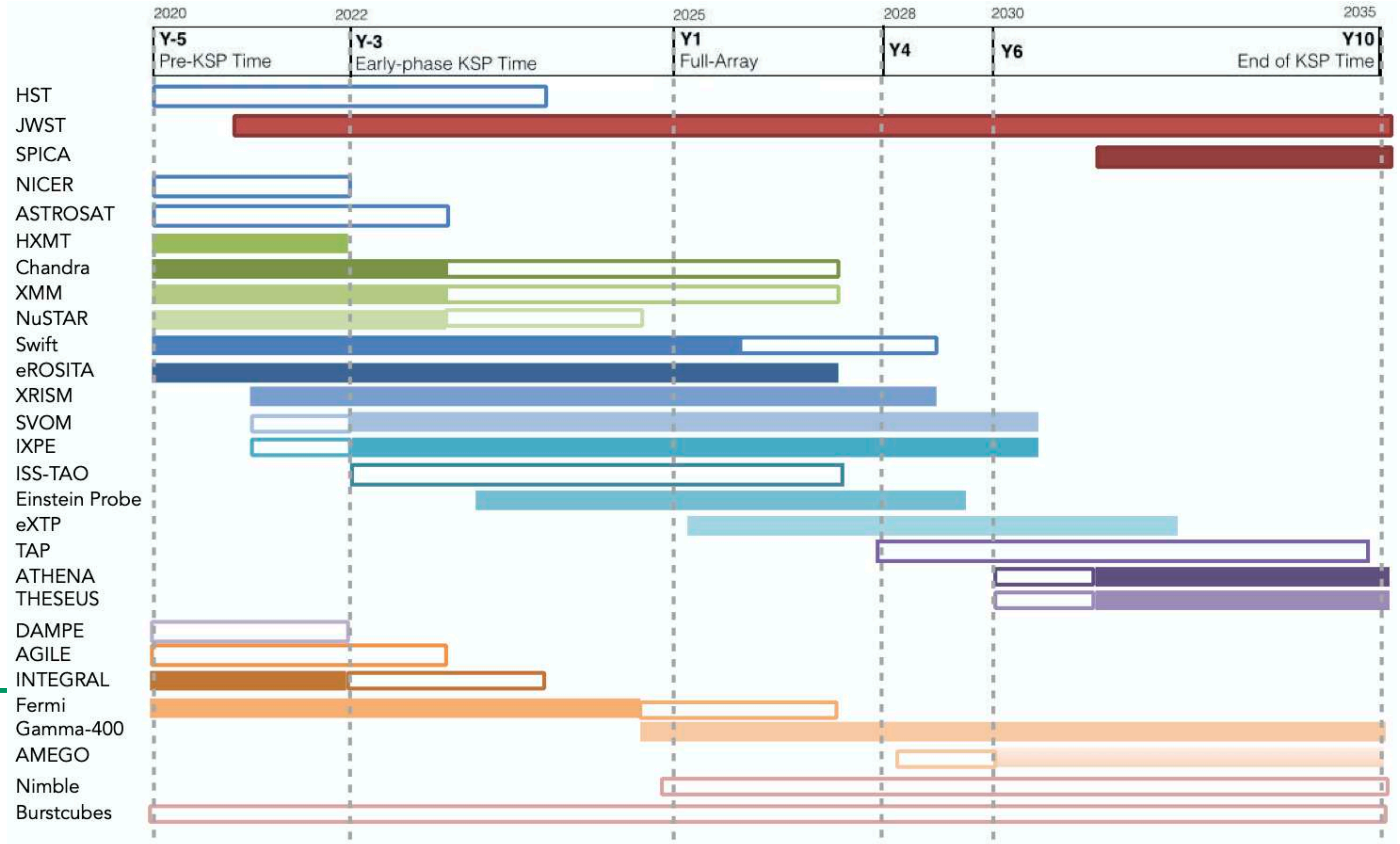
CTA as a player in the MWL+MM arena

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 x Fermi-LAT) < 300 GeV
- unique angular resolution < 0.01° in entire energy range
- largest FoV in a pointing instrument (~ 8°), ideal for surveys
- rapid response of LSTs (< 30 s)

A powerful and large precision instrument in the TeV range

Operations expected to start beyond 2027 : contemporaneous to a new generation of MWL and MM instruments



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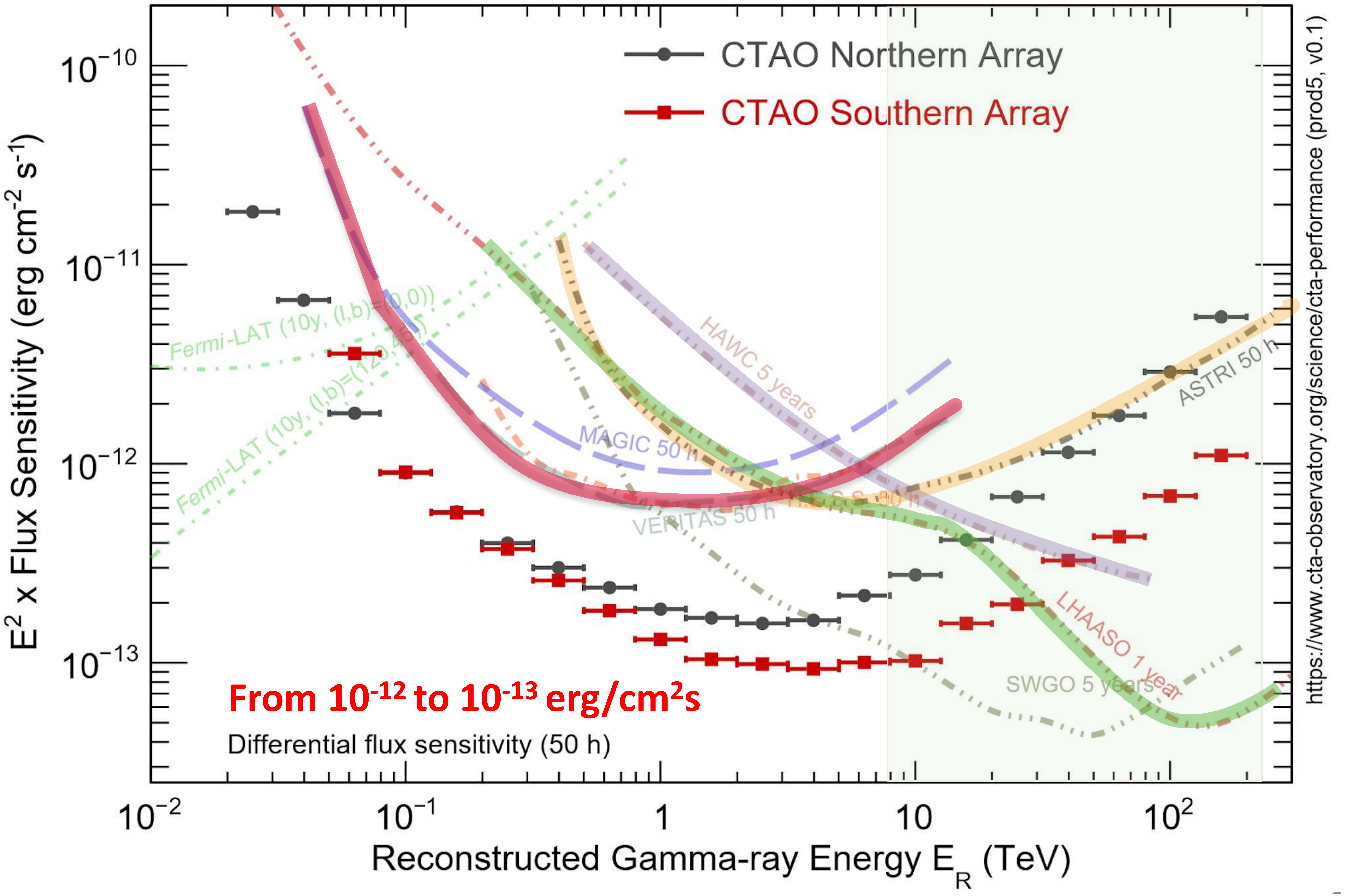
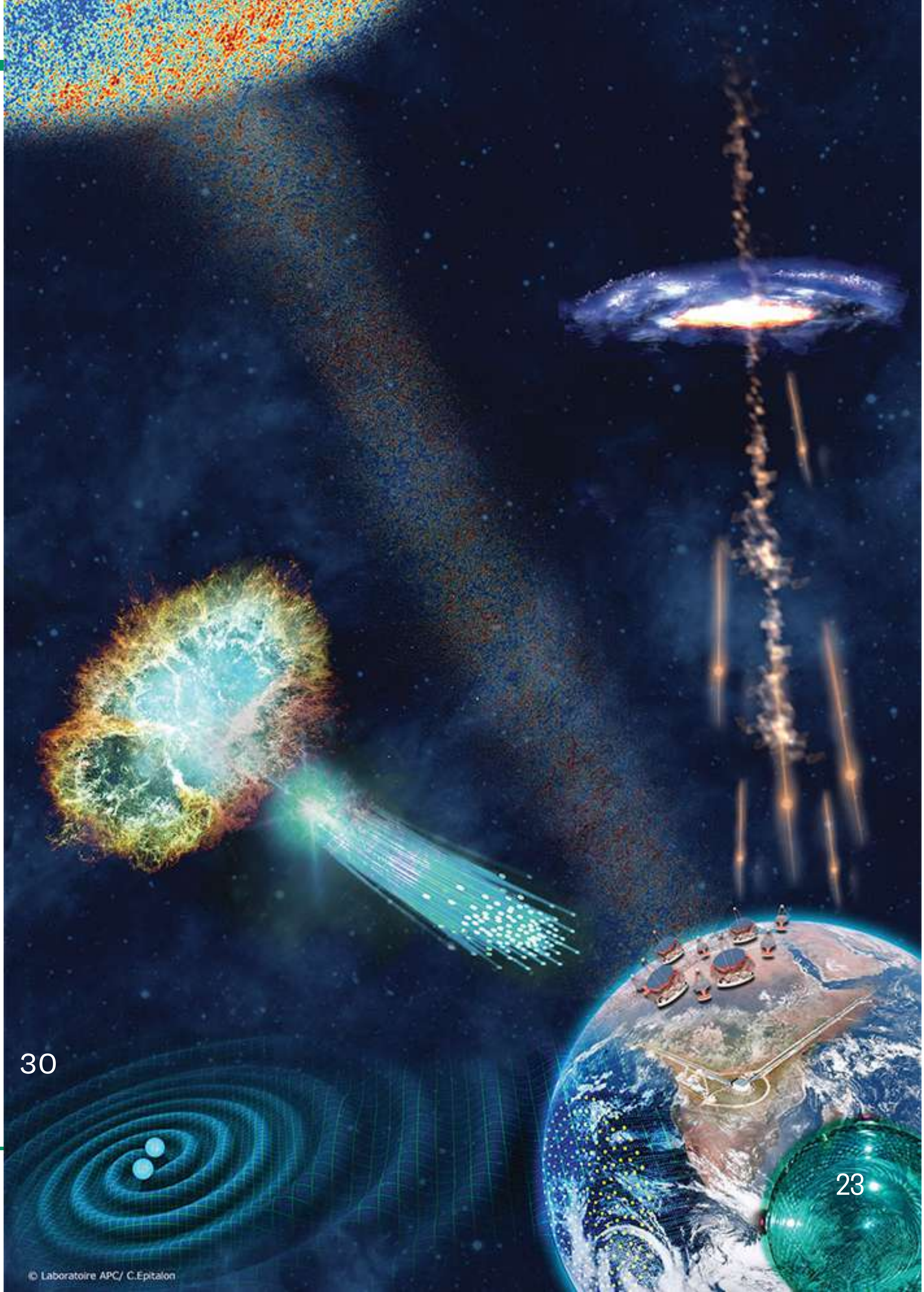


The CTA Context

BASED MOSTLY ON RESULTS
AND PRESENTATIONS BY CTA
AT ICRC 2023



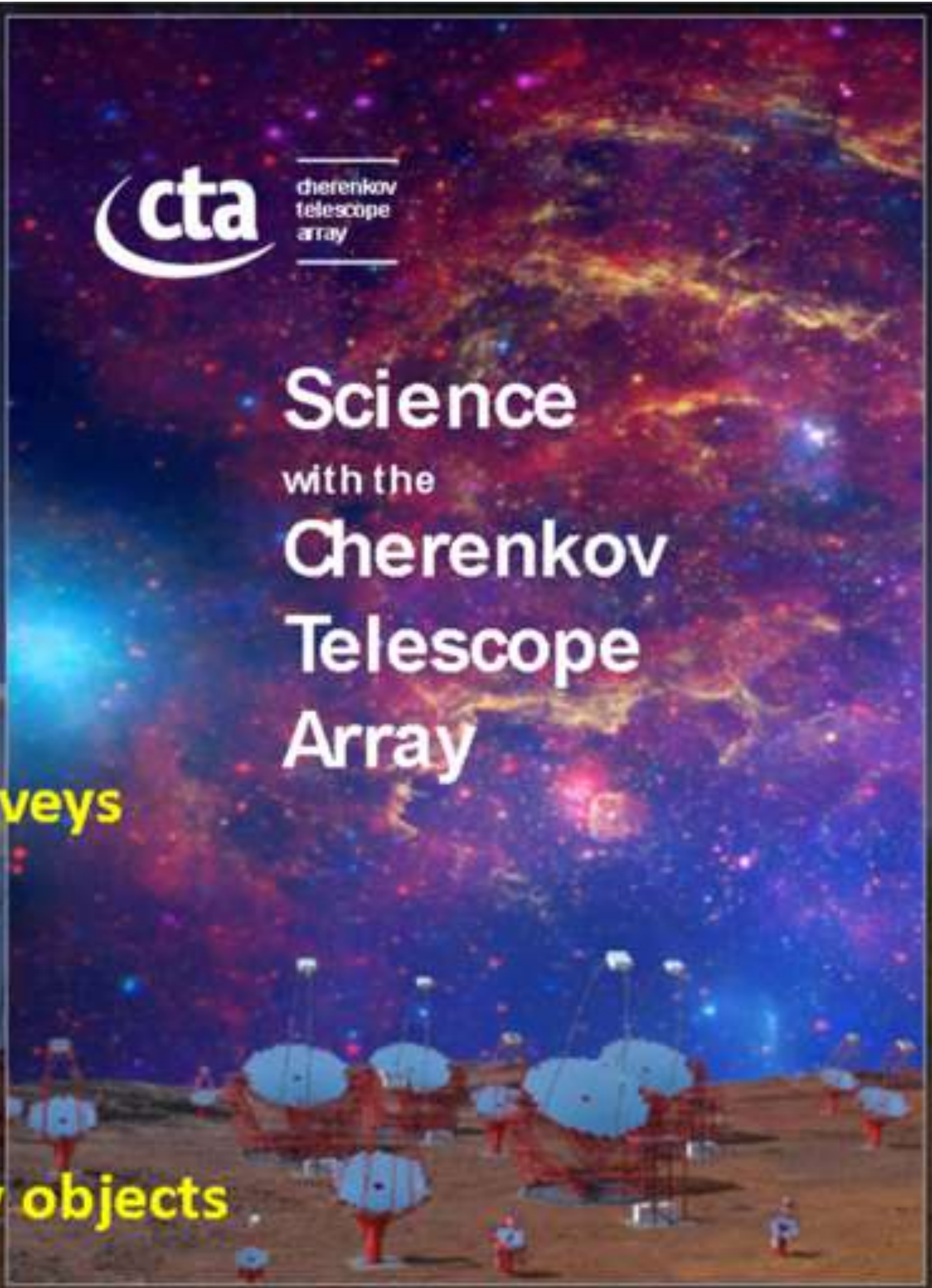
KEY SCIENCE PROJECTS

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



www.worldscientific.com/worldscibooks/10.1142/10986

Thanks to Franz Longo

CTA Transient and MM Programme

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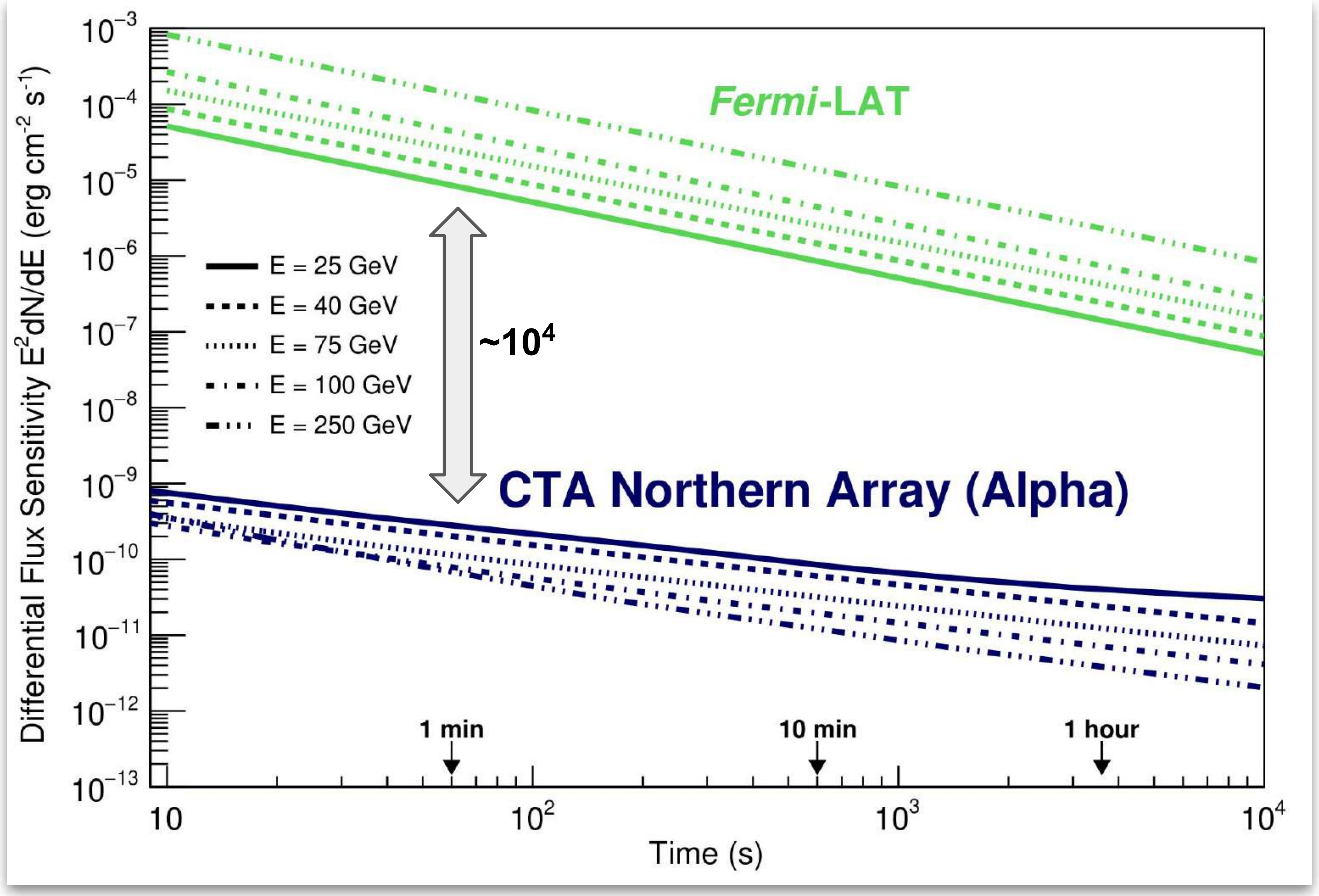
CTA will have a strong transient and multi-messenger programme, following its unique short-timescale sensitivity in the multi-GeV range, ~10^4x superior to Fermi-LAT for timescales up to several ks.

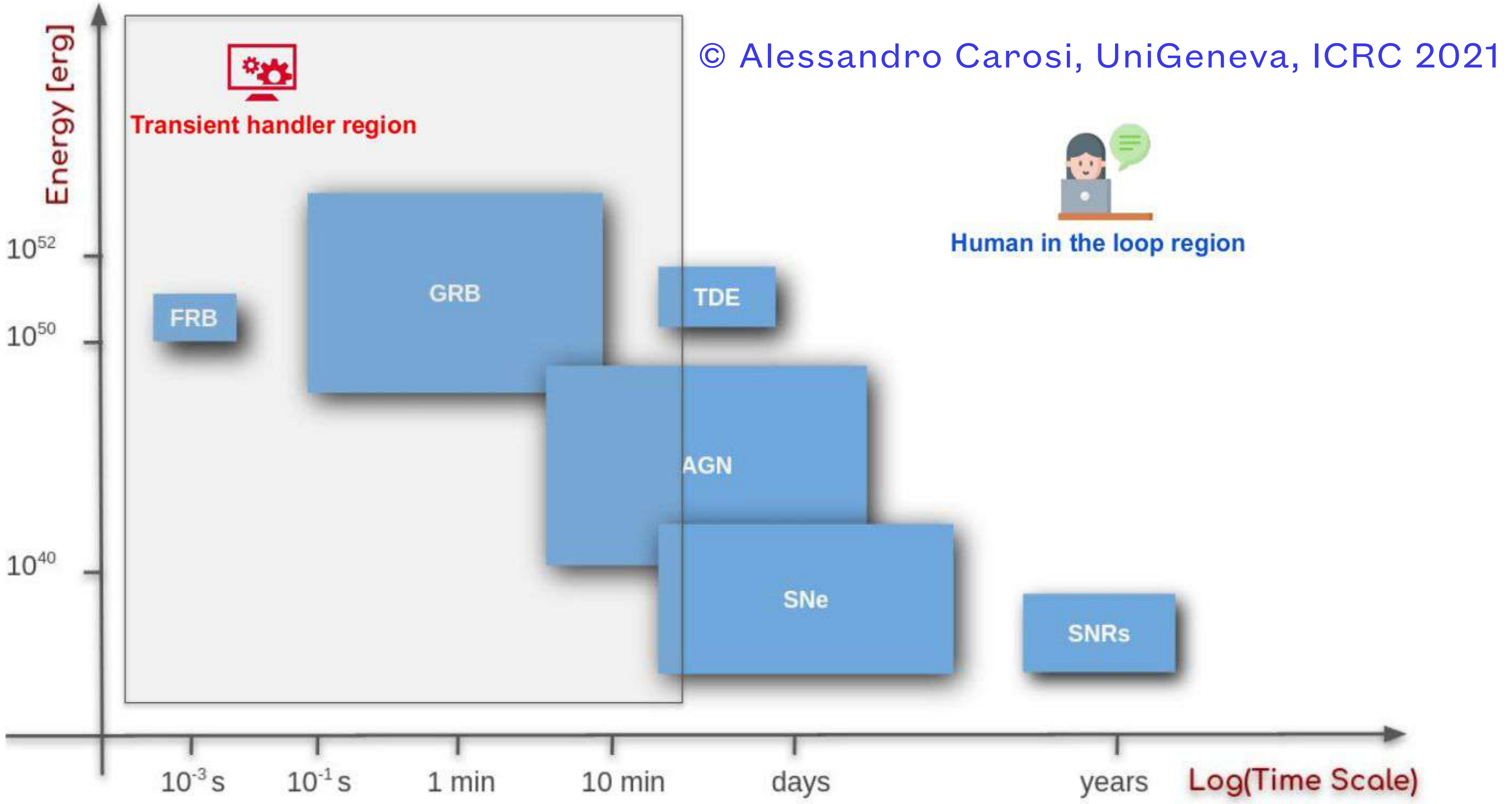
- **Gamma-ray bursts (GRBs)**, external alerts from monitoring facilities. Simulations of a realistic GRB populations estimate CTA detection prospects to few GRBs per year.
- **Galactic transients**, serendipitous detection of a wide range of galactic transients expected from CTA regular Galactic Plane 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.



https://www.cta-observatory.org

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

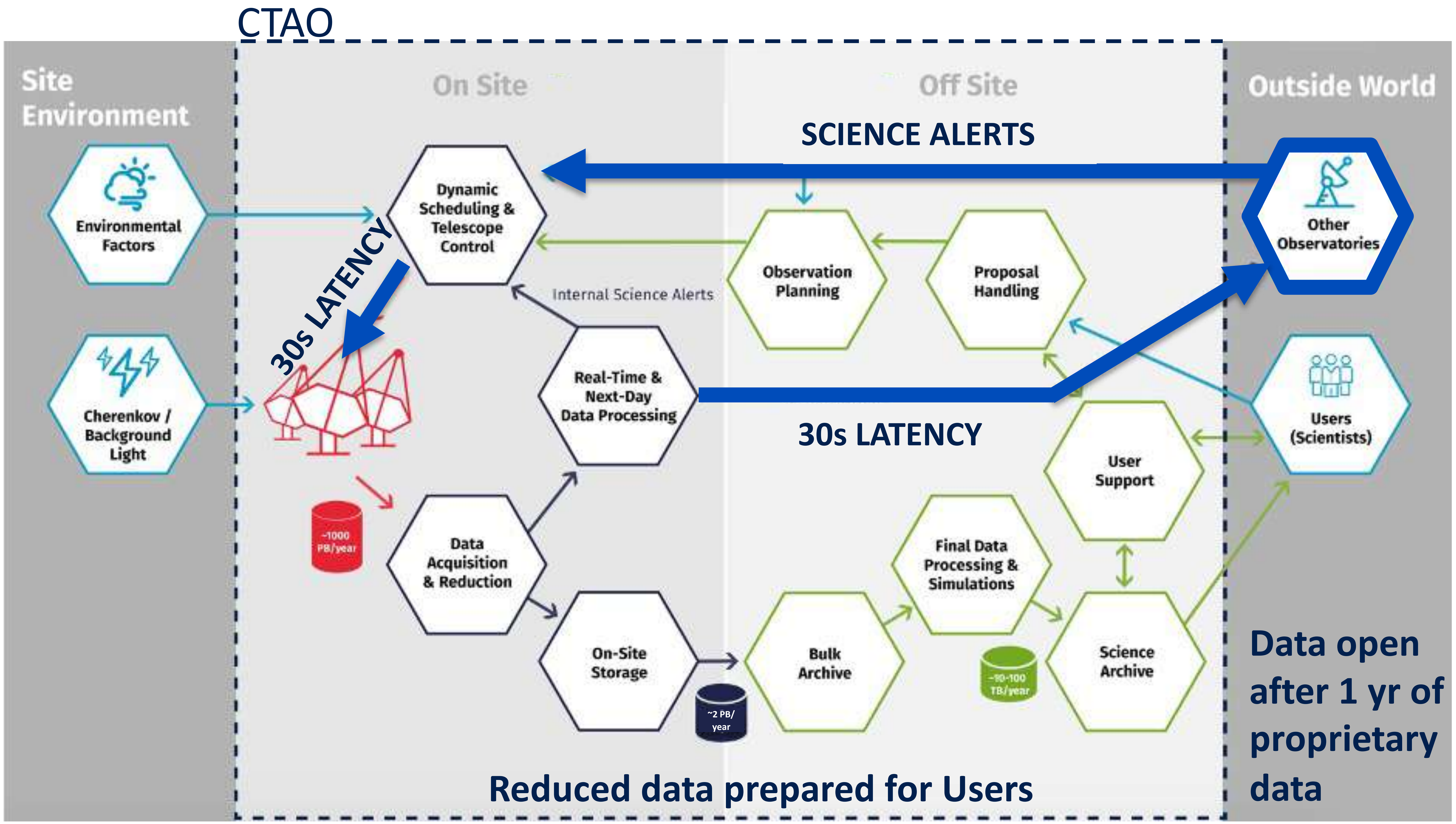
PROTOCOLS FOR EXTERNAL COMMUNICATIONS HANDLING

ALERT FILTERING AND OBSERVABILITY ASSESSMENT

RECEIVING AND HANDLING OF ALERTS

INTERNAL COMMUNICATIONS HANDLING FOR SCHEDULING

CTA : alert and follow-up system



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)

STUDY OF DETAILED OPERATIONS REQUIREMENTS RECENTLY CONCLUDED

CTA follow-up observation strategy

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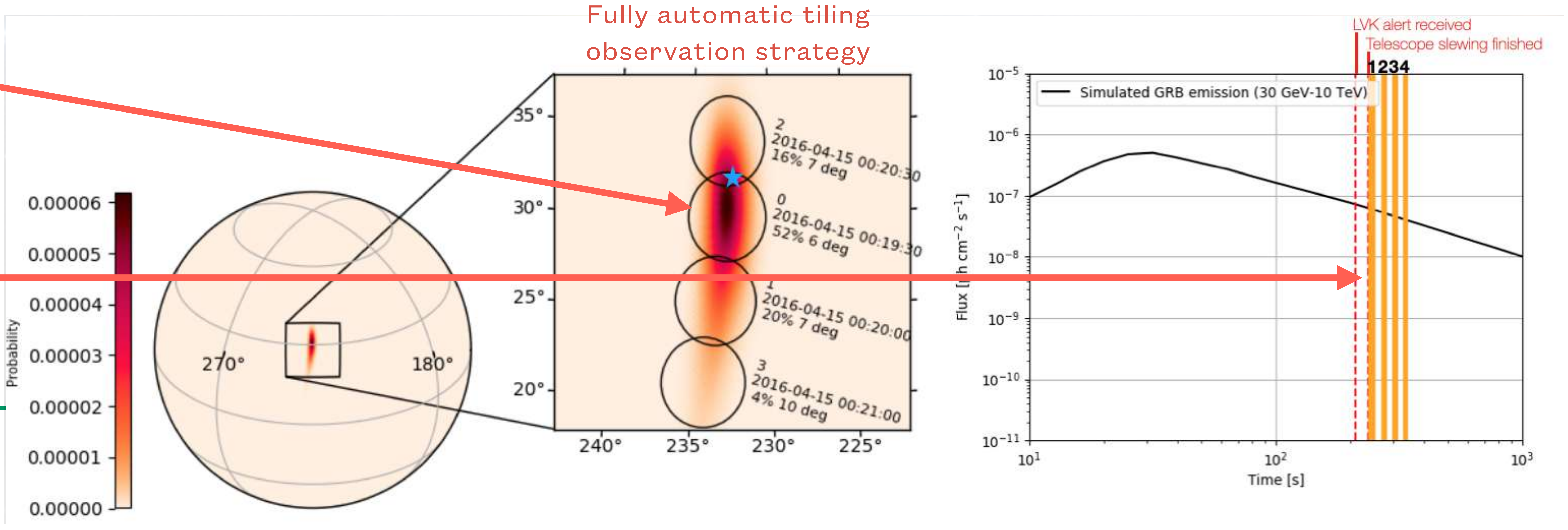
- **CTAO will perform regular (1-3x per week) follow-up observations of GW-GRB and (golden) ν alerts**
- **The observational strategy** is a key element for the success of the programme
  - Optimal pointing pattern to cover the largest total alert uncertainty region (10-1000 deg²) *(Patricelli+2018, Bartos+2019)*
  - Optimal pointing cadence: exposure time tailored to achieve 5σ 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

I. Start with highest probability position, favoring lowest Z

II. Optimise exposure time based on source model



CTA follow-up observation planning

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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

GRB POSYTIVE (Ghirlanda et al. 201x)

POpulation SYnthesis Theory Integrated project for VHE Emission

serrapilheira

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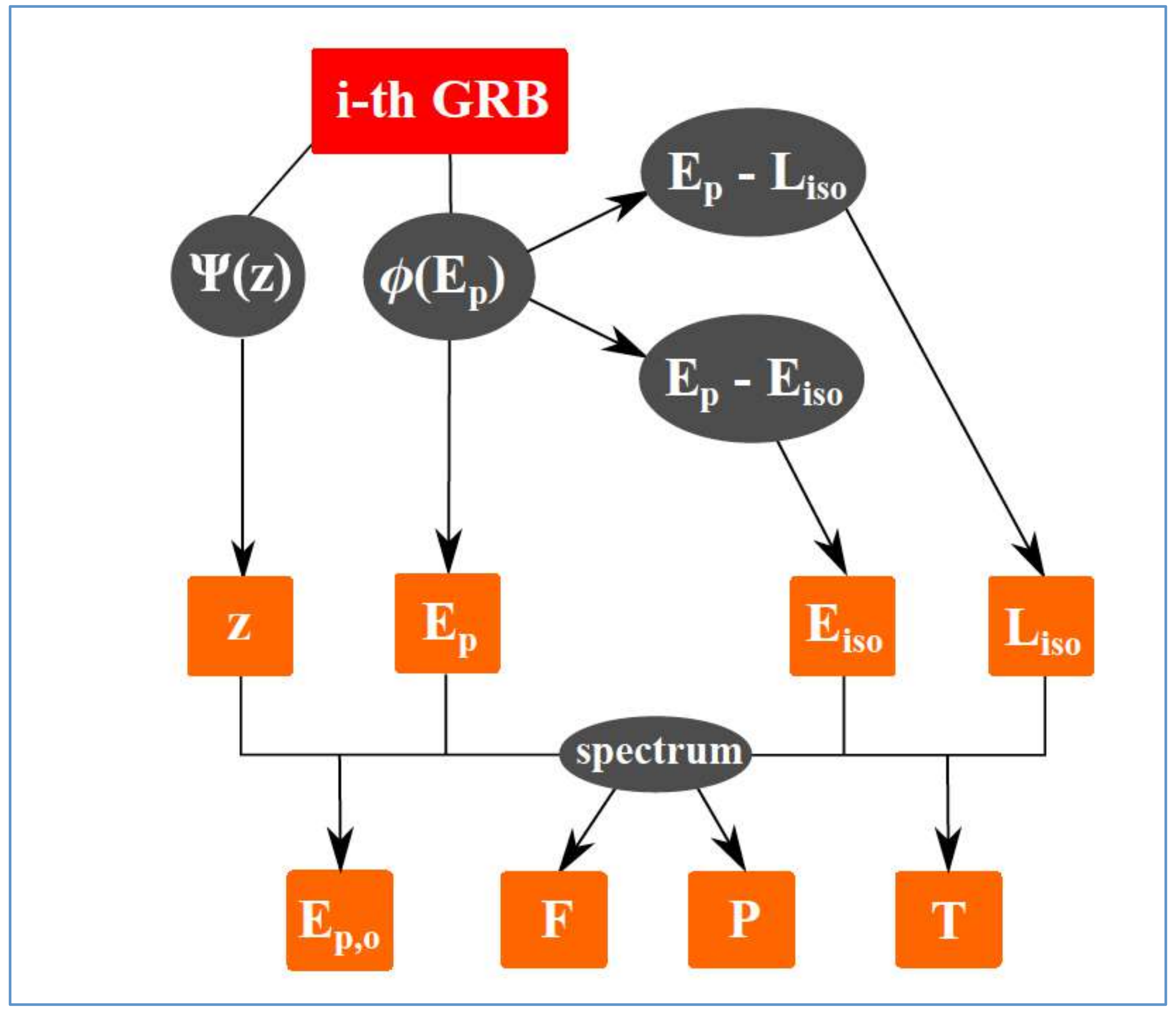
CTA strategy: External alerts and LSTs

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

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



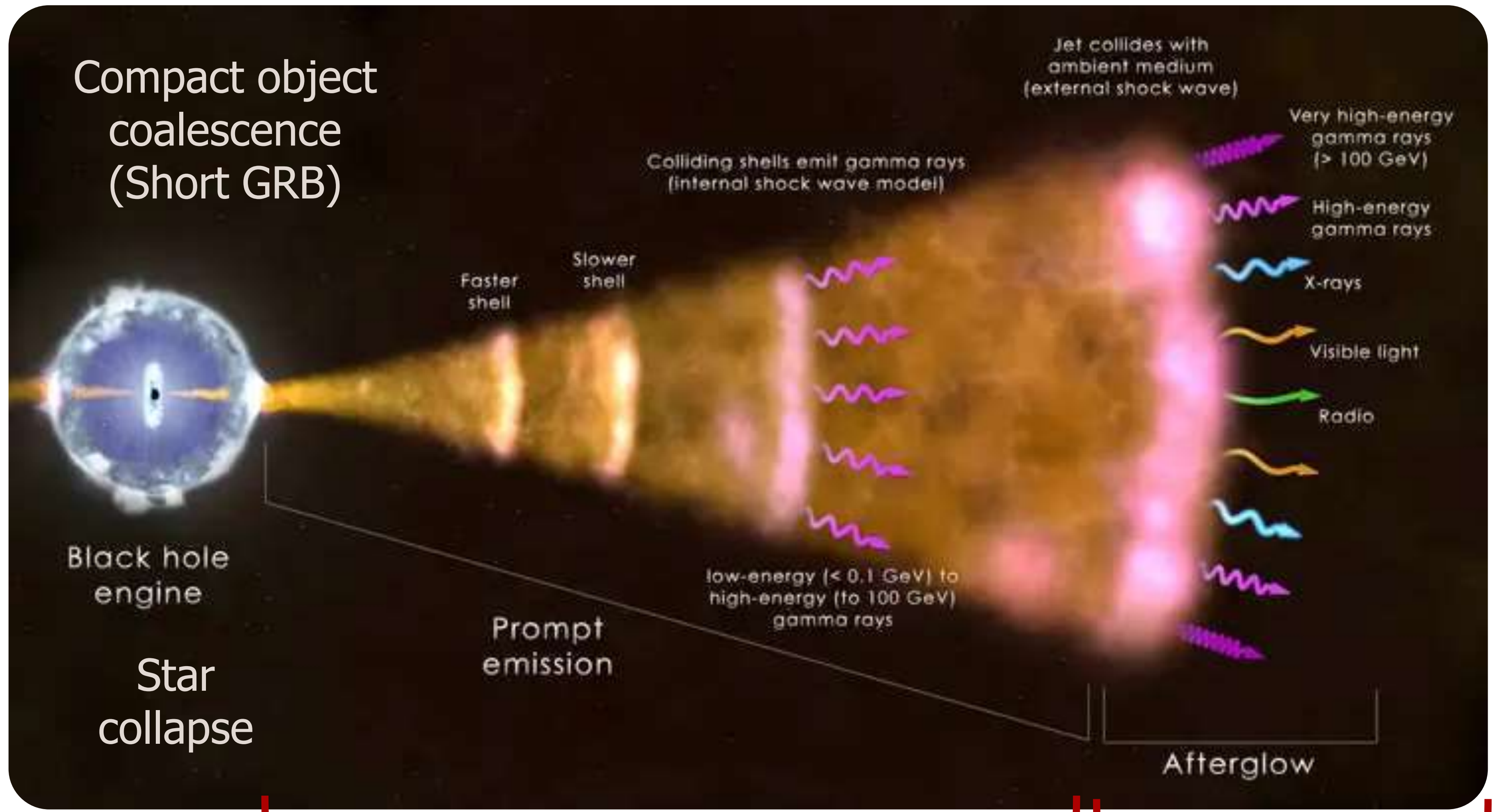
G. Ghirlanda et al. A&A 594 (2016), A84.

Population

Monte Carlo
Calibrated on Fermi-GBM & Swift data

1000 GRB – 44 yr

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



Detection Analysis

ctools

SoHAPPy with

A Python package for gamma-ray astronomy

Giancarlo G.

Željka B.

Lara N.

Franz L. et al.
Thierry S.

GRB Detection rates, ω

Th. Stolarczyk, November 2021

Reference Simulations

- Over 1000 initial GRB, 45% visible
- Visible window (at prompt, t90 > Δt_0)
- Reported 3σ, 5σ detections in 90% of trials

Detection rates

- 50% detected at 5σ, 90% CL < 10'
- max-σ 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^{-1}	**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%		
3σ	Counts	*64 ± 8*	*53 ± 7*	*19 ± 4*	*13 ± 4*	*64 ± 8*	*96 ± 10*
	yr^{-1}	**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%		
5σ	Counts	*57 ± 8*	*46 ± 7*	*17 ± 4*	*11 ± 3*	*53 ± 7*	*81 ± 9*
	yr^{-1}	**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, ω

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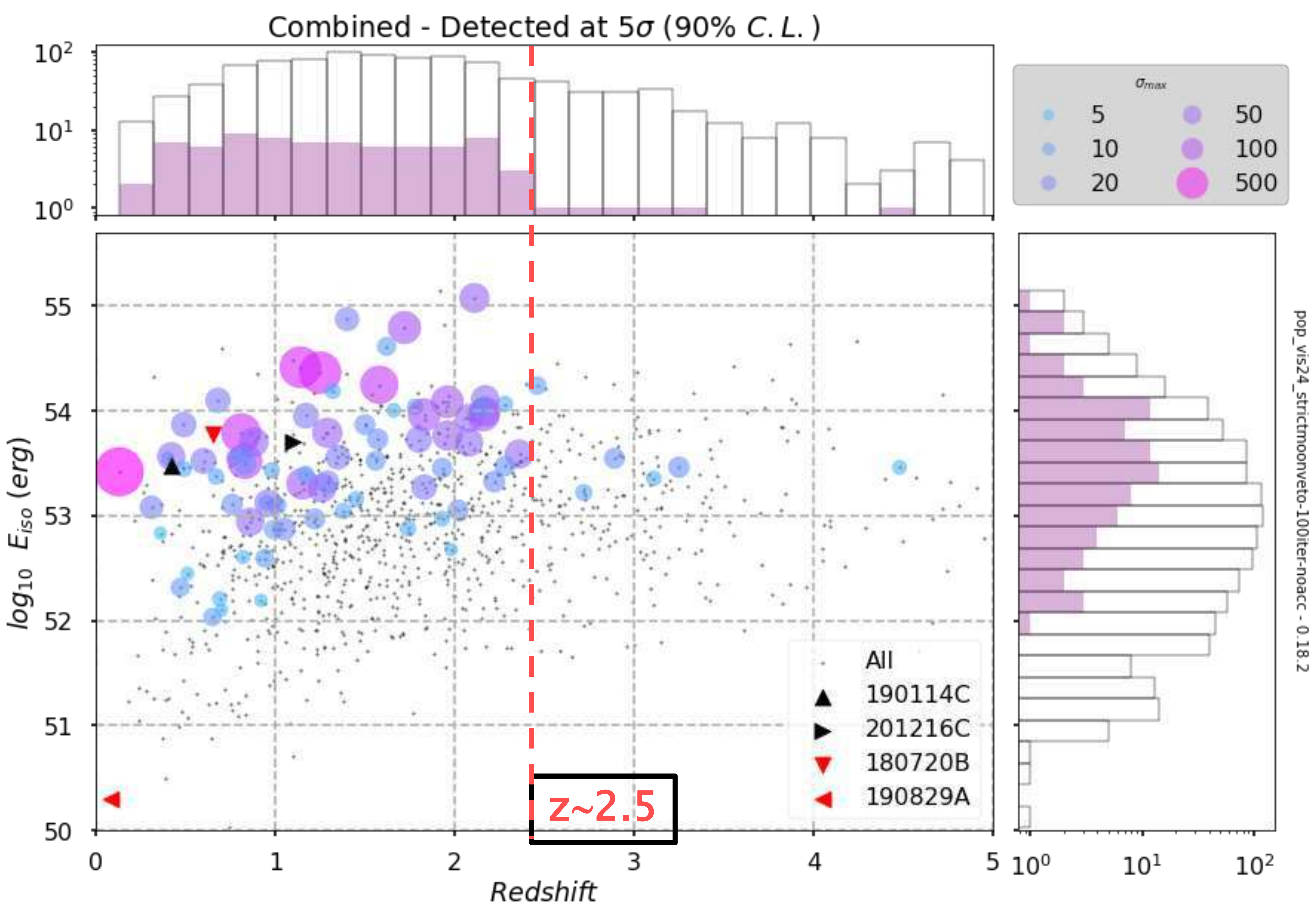

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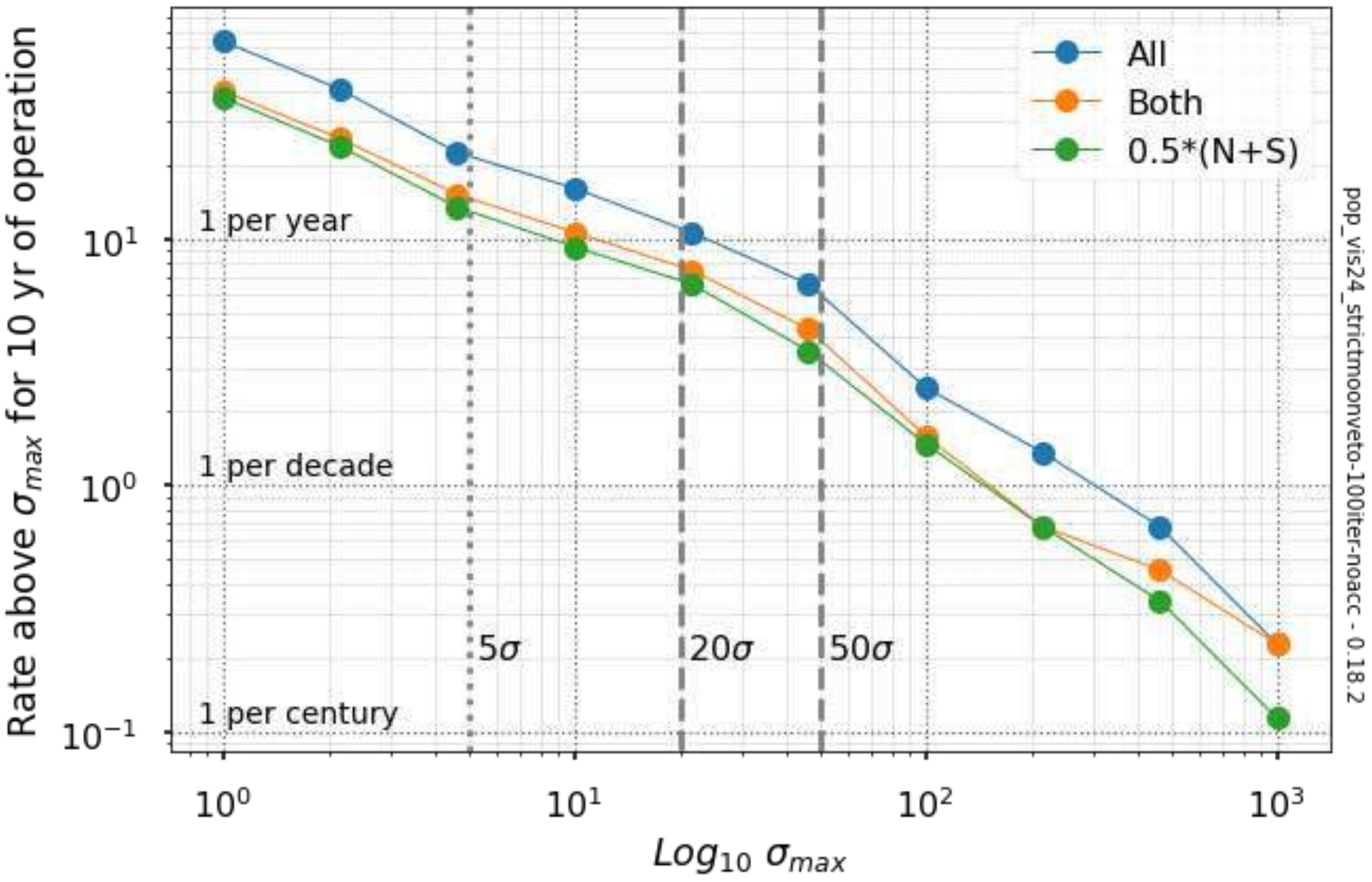
Detection rates

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

≥ 5σ : ~ 2 per year
≥ 20σ : ~ 1 every year
≥ 50σ : ~ 1 every 2 years



GRB Detection rates, ω

Th. Stolarczyk, November 2021

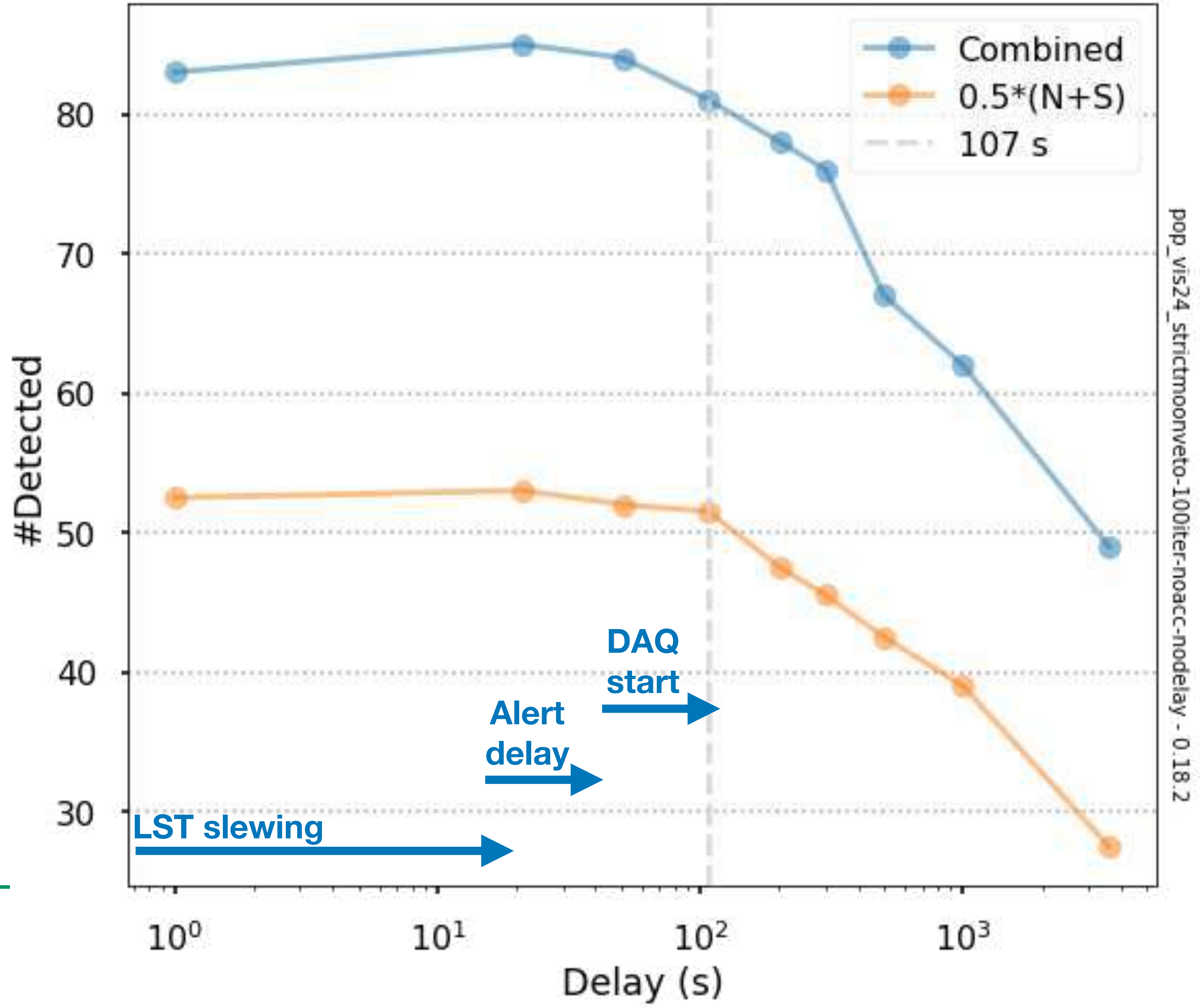
Reference Simulations

- Over 1000 initial GRB, 45% visible
- Visible window (at prompt, t90 > Δt_0)
- Reported 3σ, 5σ detections in 90% of trials

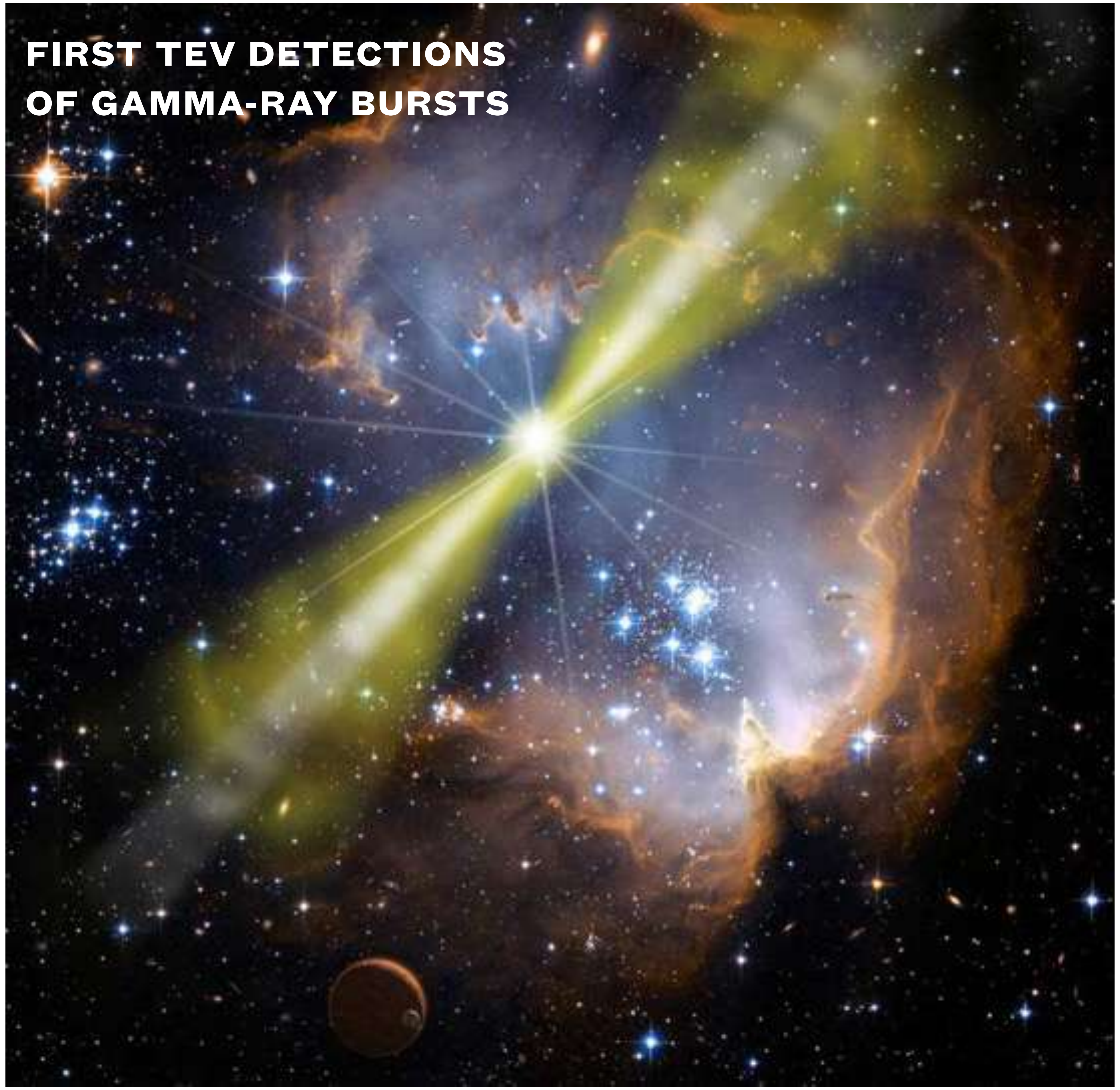
Detection rates

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

DETAILED OPERATIONS REQUIREMENTS UNDER DEVELOPMENT

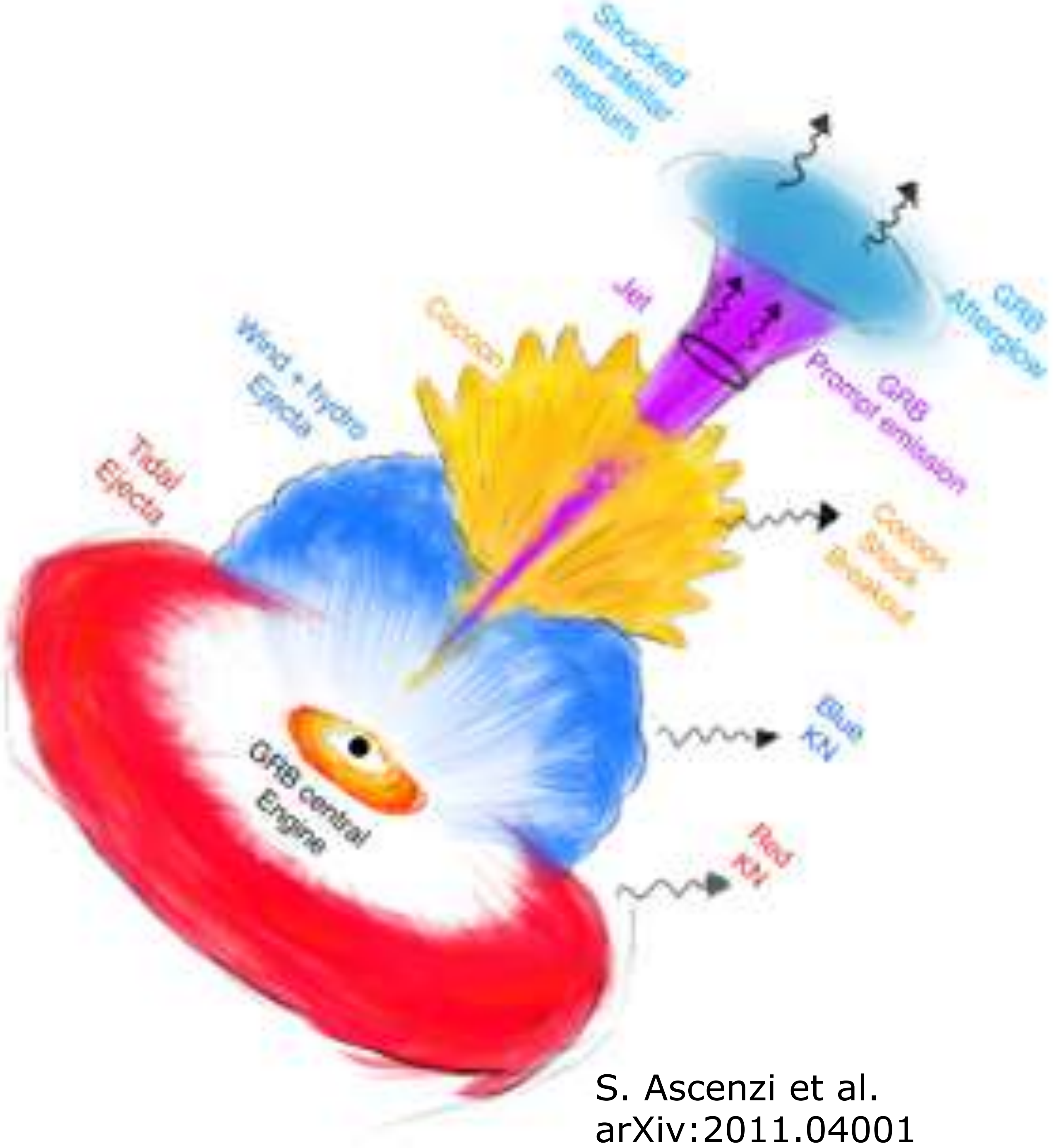


The steep path towards GW-VHE connection



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

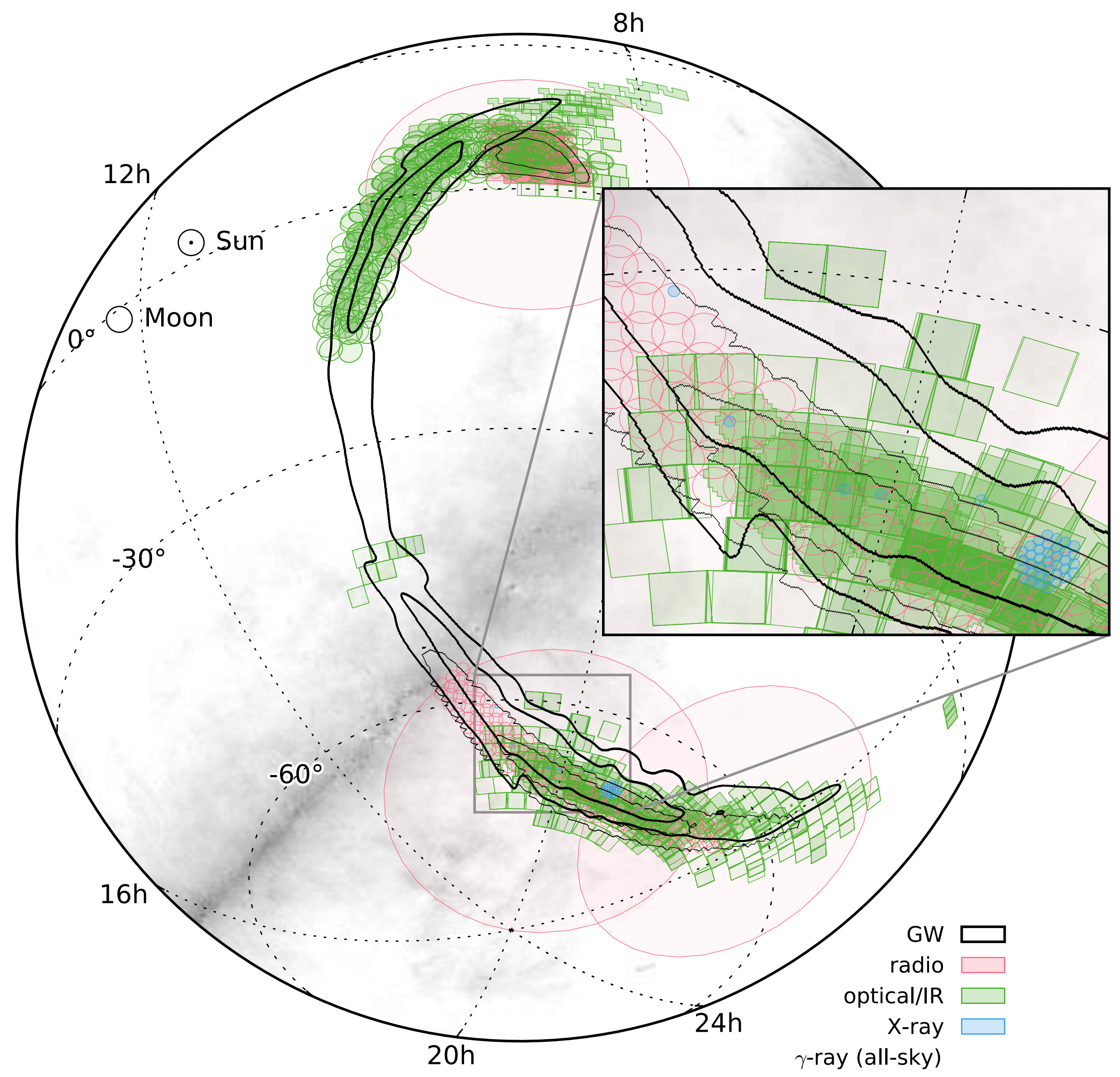
- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB at z = 0.42
  - early detection at T0 + 60s (2 ks),
  - E = [0.2, 1] TeV
- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB at z = 0.65
  - late detection after T0 + 10h
- **GRB 190829A** *(H.E.S.S. Coll., Science, 2020)*
  - long GRB at z = 0.078 (very close!)
  - for 3 nights, after T0 + 4h
  - E = [0.2, 3.3] TeV
- **GRB 160821B** *(MAGIC Coll. ApJL, 2021)*
  - **short GRB** at z = 0.162
  - data taking starting at T0 + 24s, for 4h
  - 3σ hint, E > 500 GeV
- **GRB 201015A** *(ICRC 2021, PoS ID 305, Y.Suda)*
  - long GRB at z = 0.42
  - early detection at T0 + 40s
  - 3σ hint, E > 500 GeV
- **GRB 201216C** *(ICRC 2021, PoS ID 395, S.Fukami)*
  - long GRB at z = 1.1
  - early detection after T0 + 56s
  - E < 100 GeV

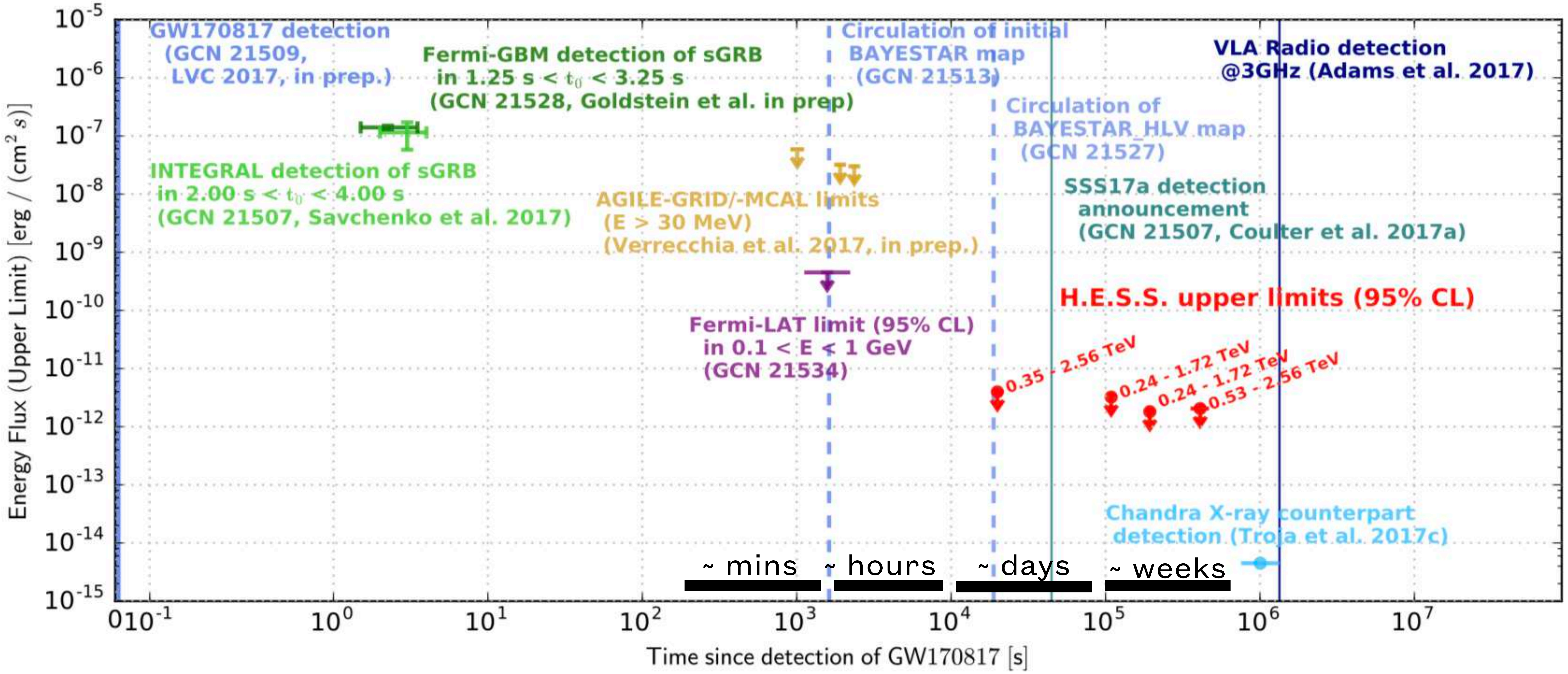
GW source localization

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

<u>Triangulation</u> with VIRGO has allowed for a better sky localisation (down to ~ few deg^2)

<u>Challenge for EM counterpart ID</u> : time vs. space localisation





Tilling by EM observatories :

coordinated scheduling and follow-up of observations.

GW source localization

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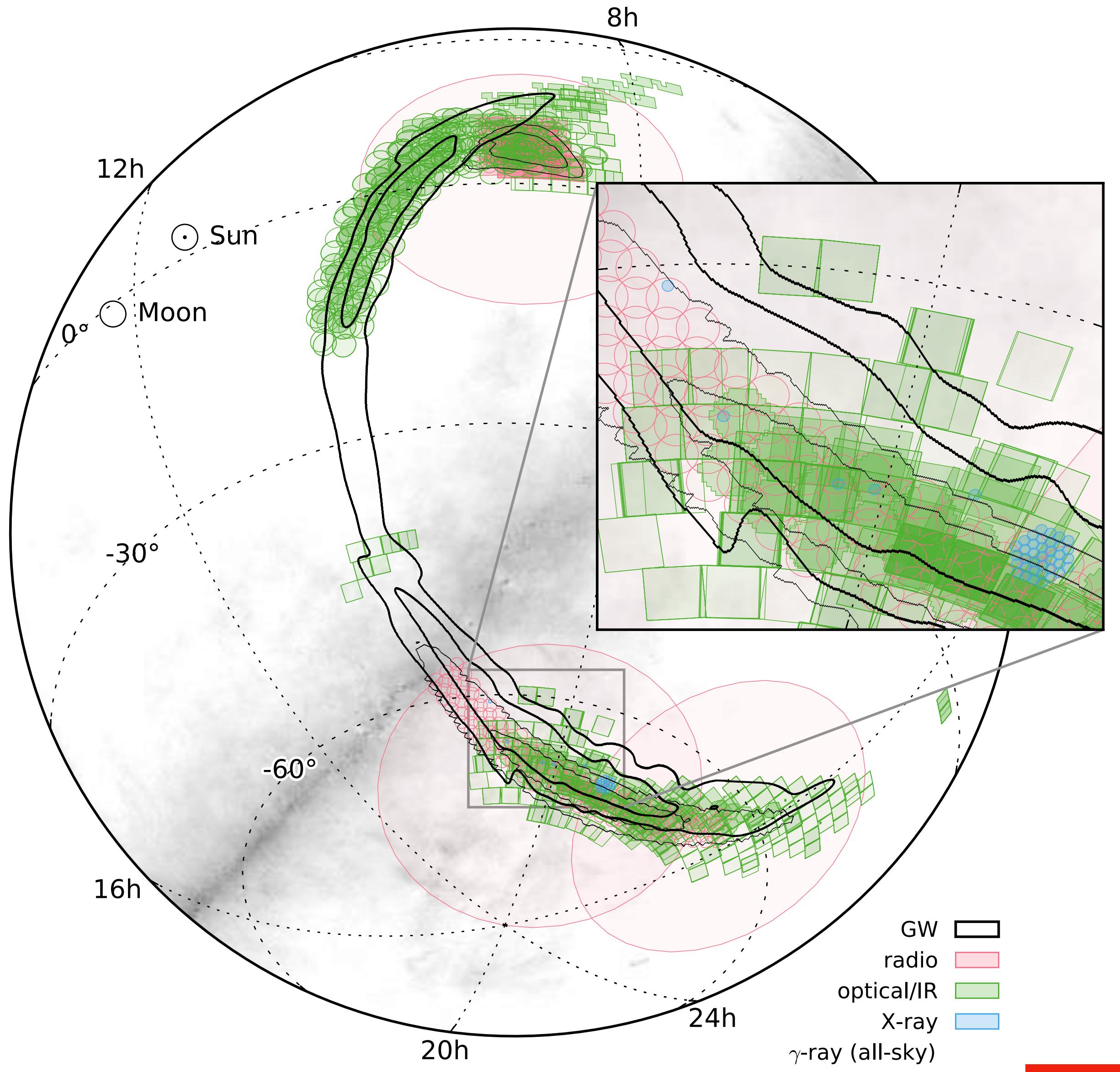
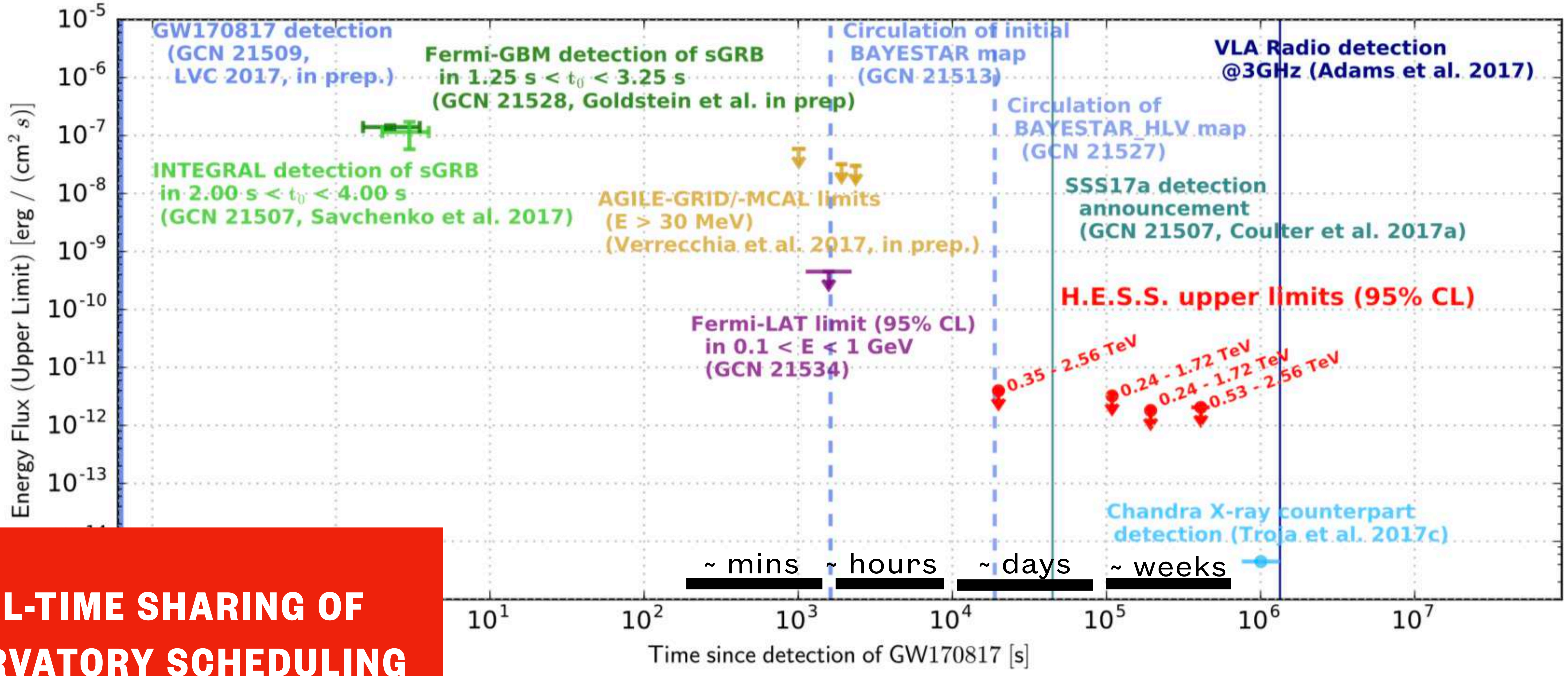




Tilling by EM observatories : coordinated scheduling and follow-up of observations.

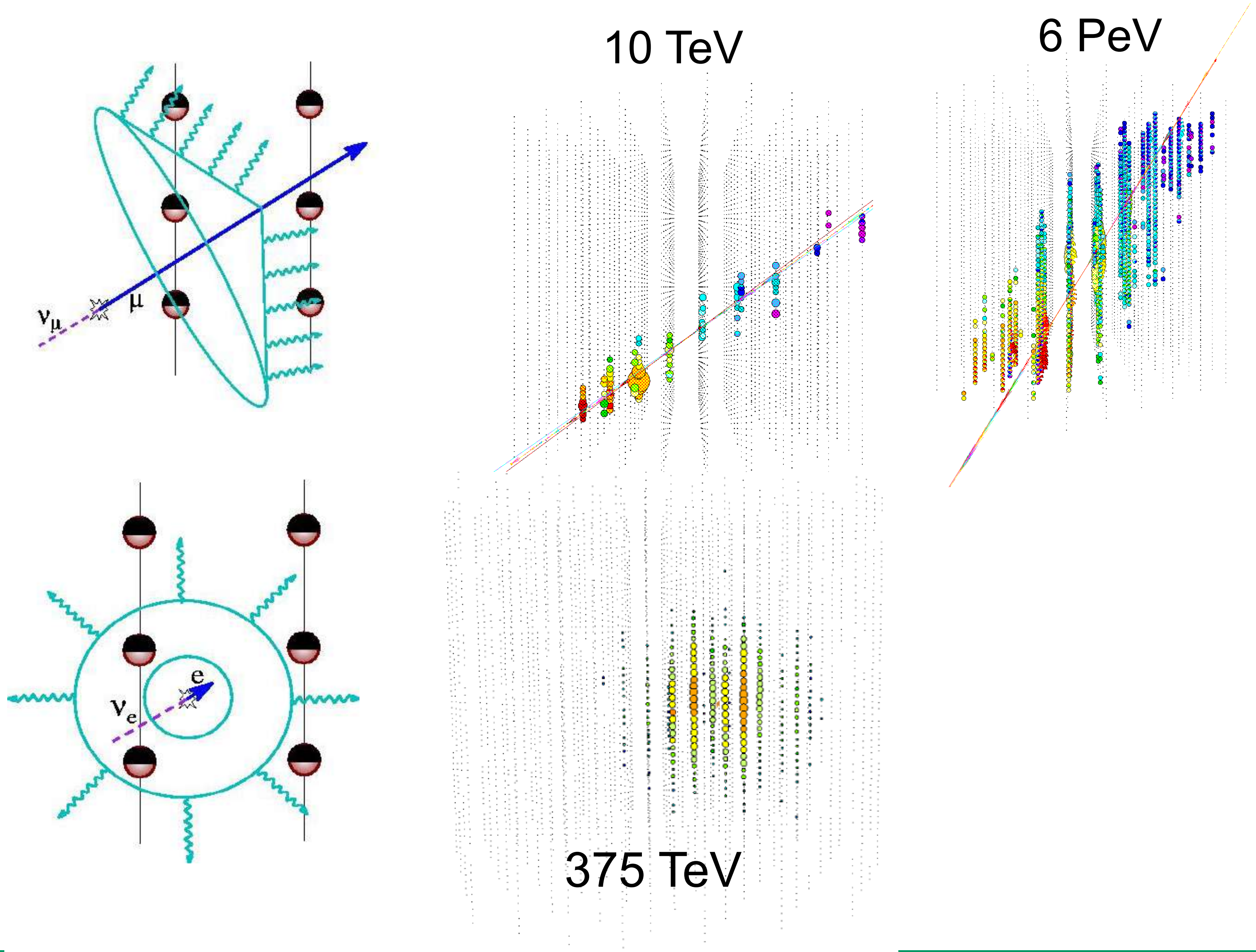
REAL-TIME SHARING OF OBSERVATORY SCHEDULING

Neutrino FIRESONG (Tung et al. 2021)

https://github.com/ChrisCFTung/FIRESONG

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

- $\pi^+ \longrightarrow \mu^+ + \nu_\mu$ or $\pi^- \longrightarrow \mu^- + \nu_\mu$ from pion decay.
- $\mu^+ \longrightarrow e^- + \nu_\mu + \nu_e$ or $\mu^- \longrightarrow e^- + \nu_e + \nu_\mu$ 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°)
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):

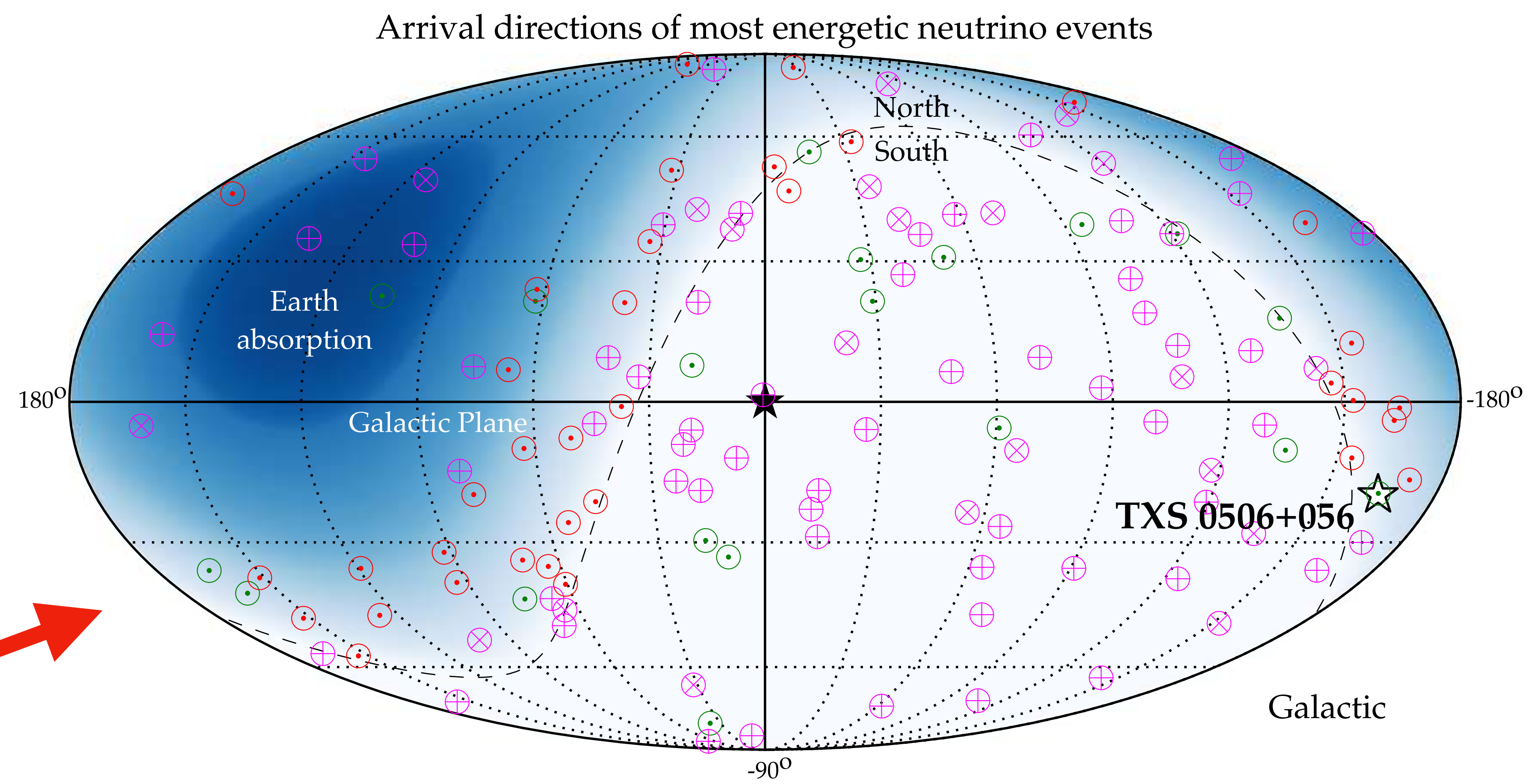
- Transients: CTA search for gamma-ray counterpart from a neutrino alert
- Steady sources: monitor hotspots exceeding IceCube sensitivity

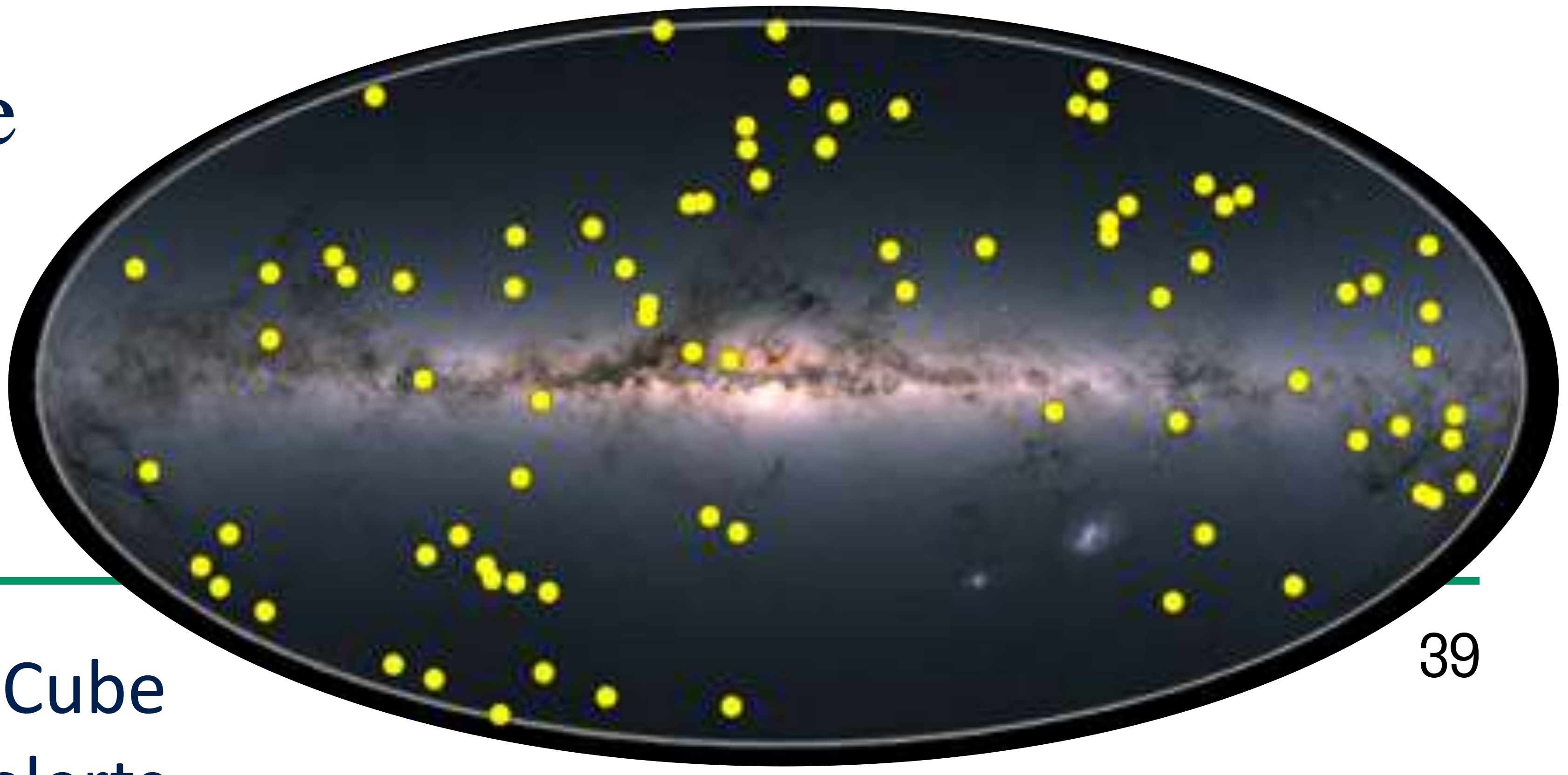
FIRESONG

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

Density vs. Luminosity plot

- Steady sources: sources/Mpc³ vs. neutrino luminosity
- Transient sources: burst rates/Mpc³ (%flaring blazars) vs. neutrino flare luminosity

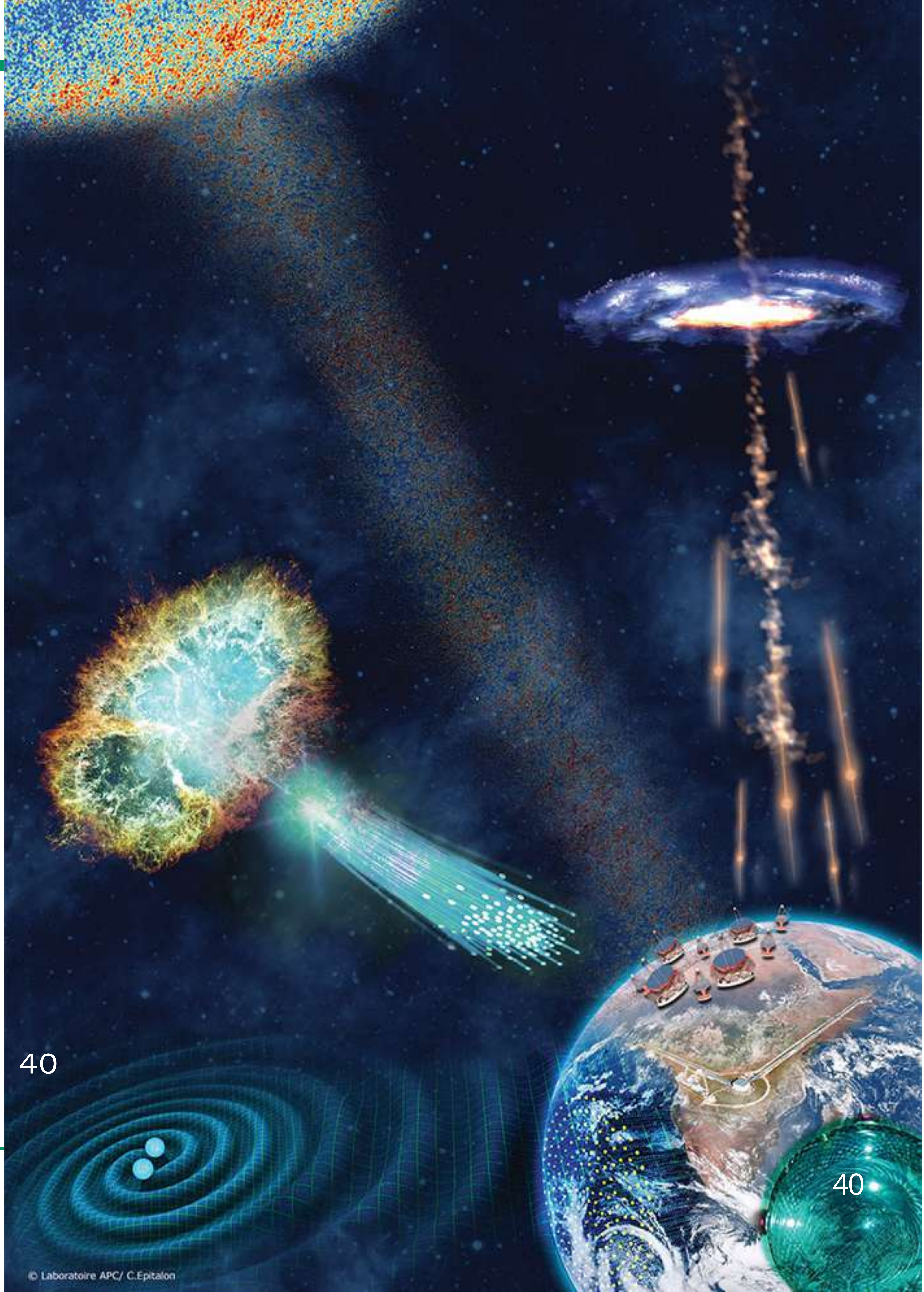




IceCube neutrino alerts

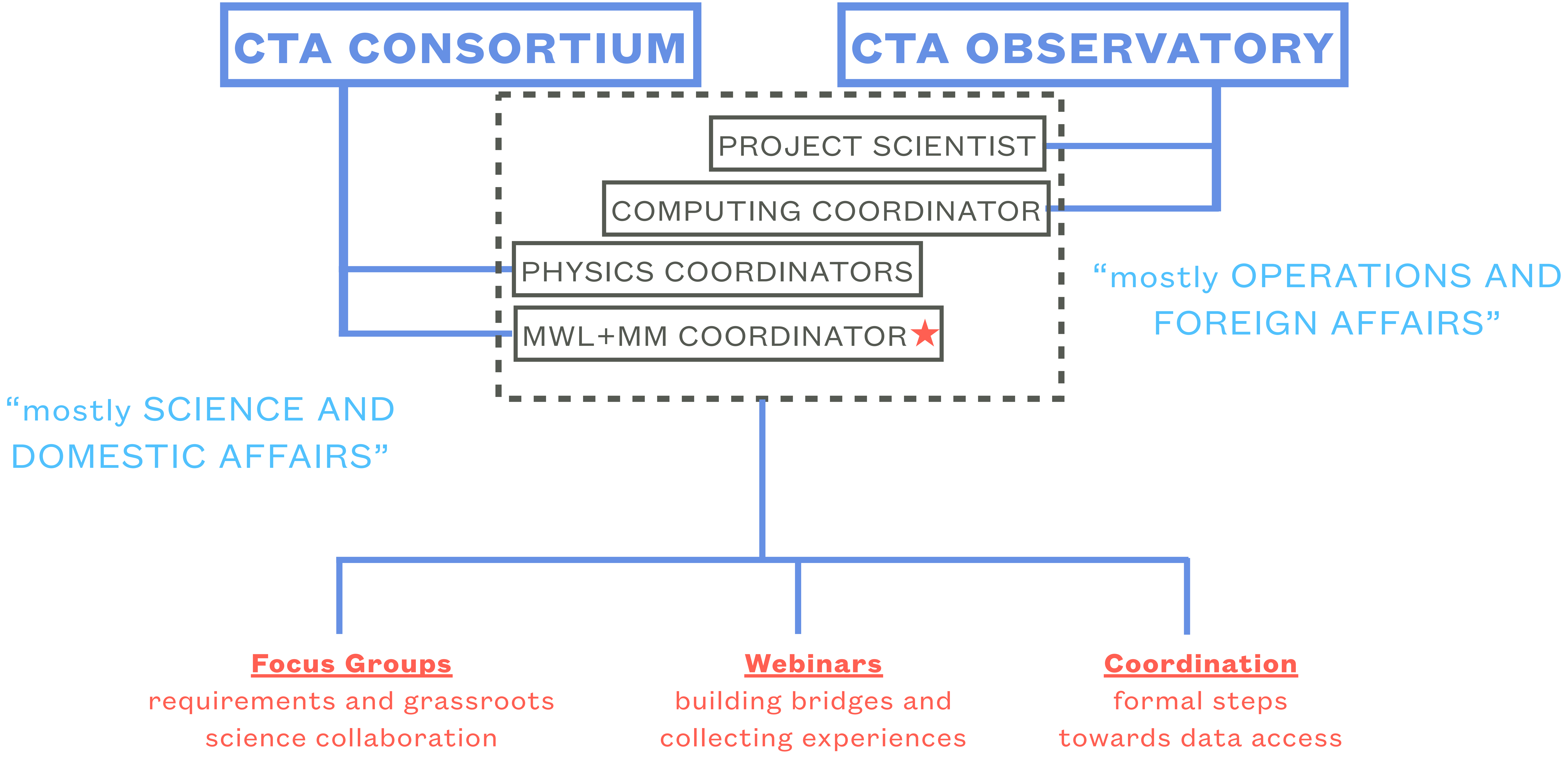
- **IC-170922A:** TXS 0506+056 (z = 0.3365) *IceCube Collab. 2018*
- **IC-190730A:** PKS 1502+106 (z = 1.84) *IceCube Collab. 2019*
- **IC-200107A:** 3HSP J095507.9+355101 (z = 0.557) *IceCube Collab. 2020*
- **IC-141209A:** GB6 J1040+0617 (z = 0.7351) *Garappa et al. 2019*

CTA Coordination Activities



ULISSES BARRES DE ALMEIDA - APRIL 2024

CTA MWL & MM Coordination Structure



CTA MWL & MM Coordination Task Force

CBPF

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.

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.	Essential	Essential	Essential	Essential	Essential	Important	Important			Useful
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	Essential	Essential		Essential	Essential	Useful	Important	Essential		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	Essential	Essential		Important	Useful	Important	Essential	Essential	Essential	Useful
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.				Important		Essential	Important			Important
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	Essential	Important	Important	Essential	Important	Essential	Essential	Essential		Important
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	Essential	Important		Essential	Important	Essential	Essential	Essential		Essential
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	Essential	Important		Essential	Important	Important	Essential			Essential
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.	Useful	Useful	Important		Useful	Important	Important			Essential
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						Important				Essential

Essential
Important
Useful

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

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.

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.	🟢	🟠		🟢	🟠	🟠	🟢			🟢
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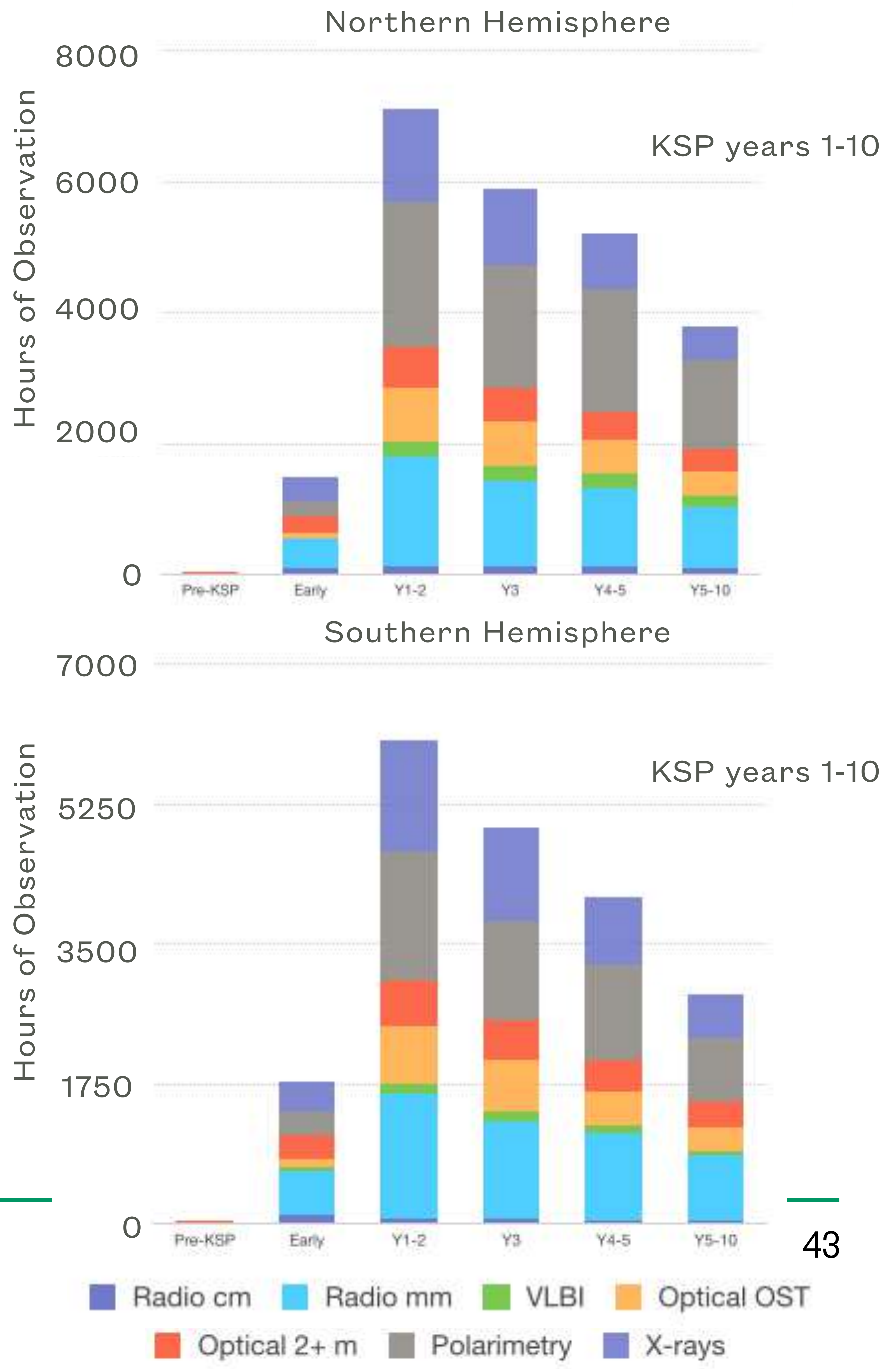
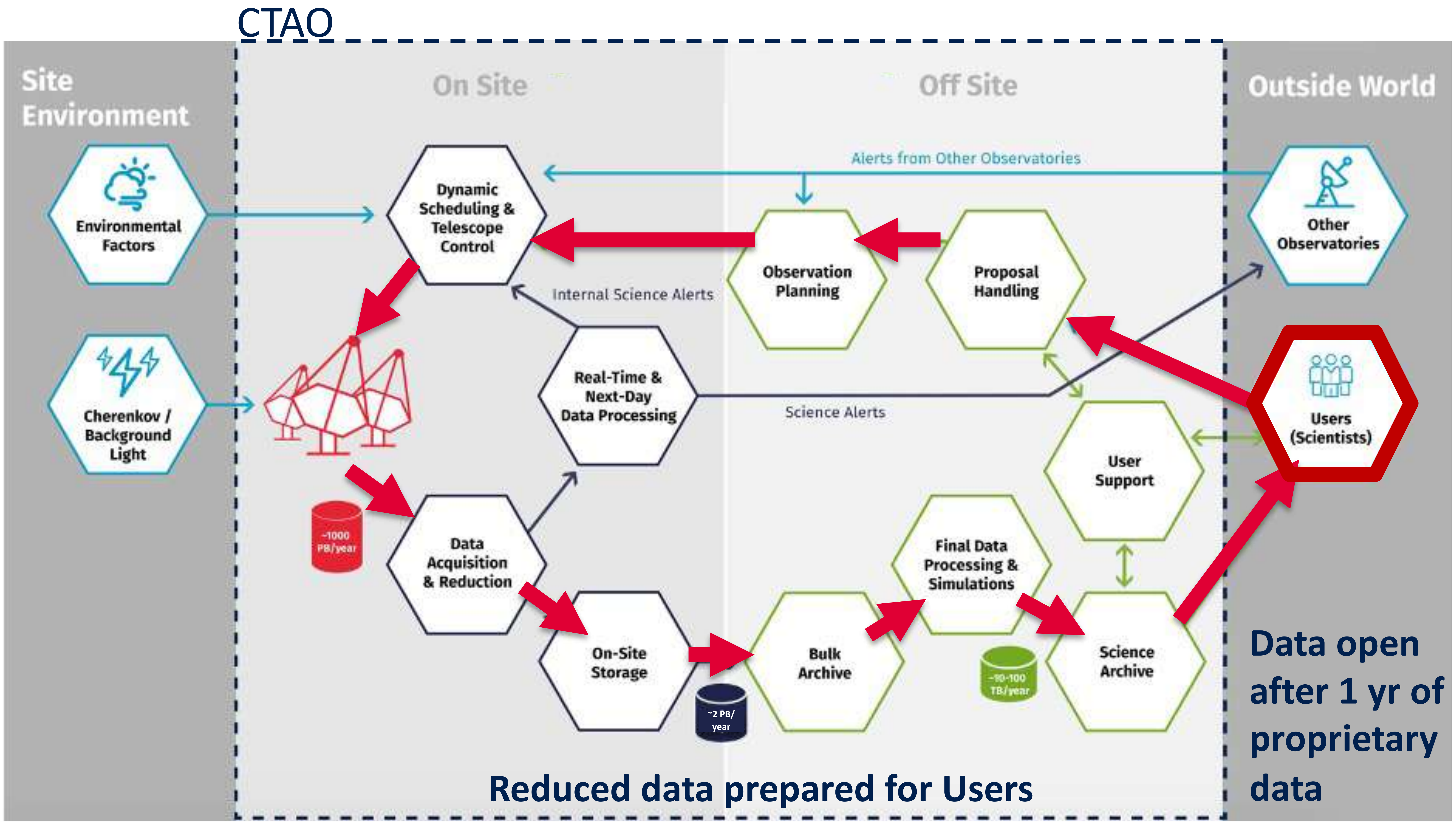
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						🟠				🟢



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.

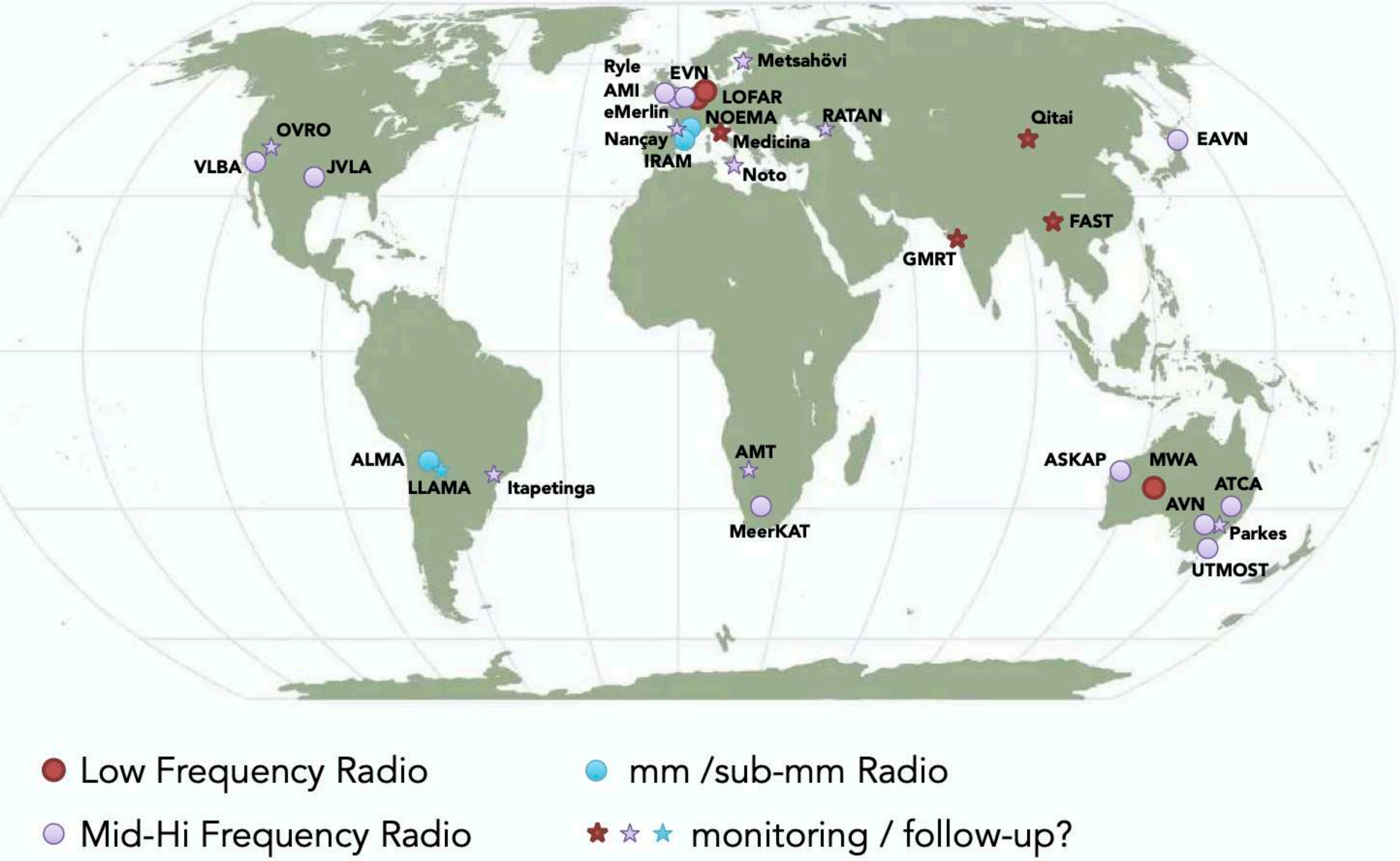
LEARN THE LESSONS FROM FERMI:

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

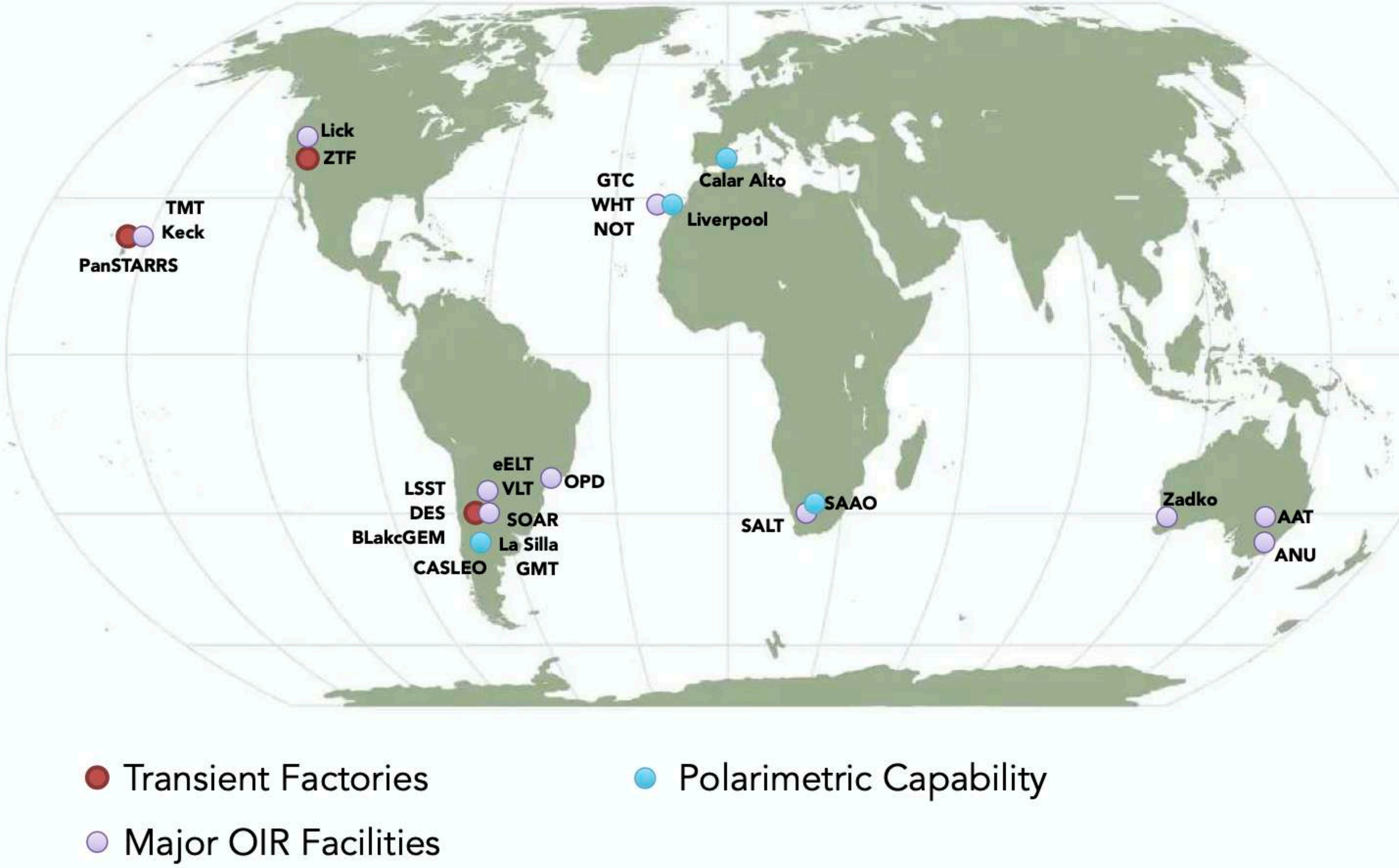
An ecosystem of ground-based facilities

CBPF

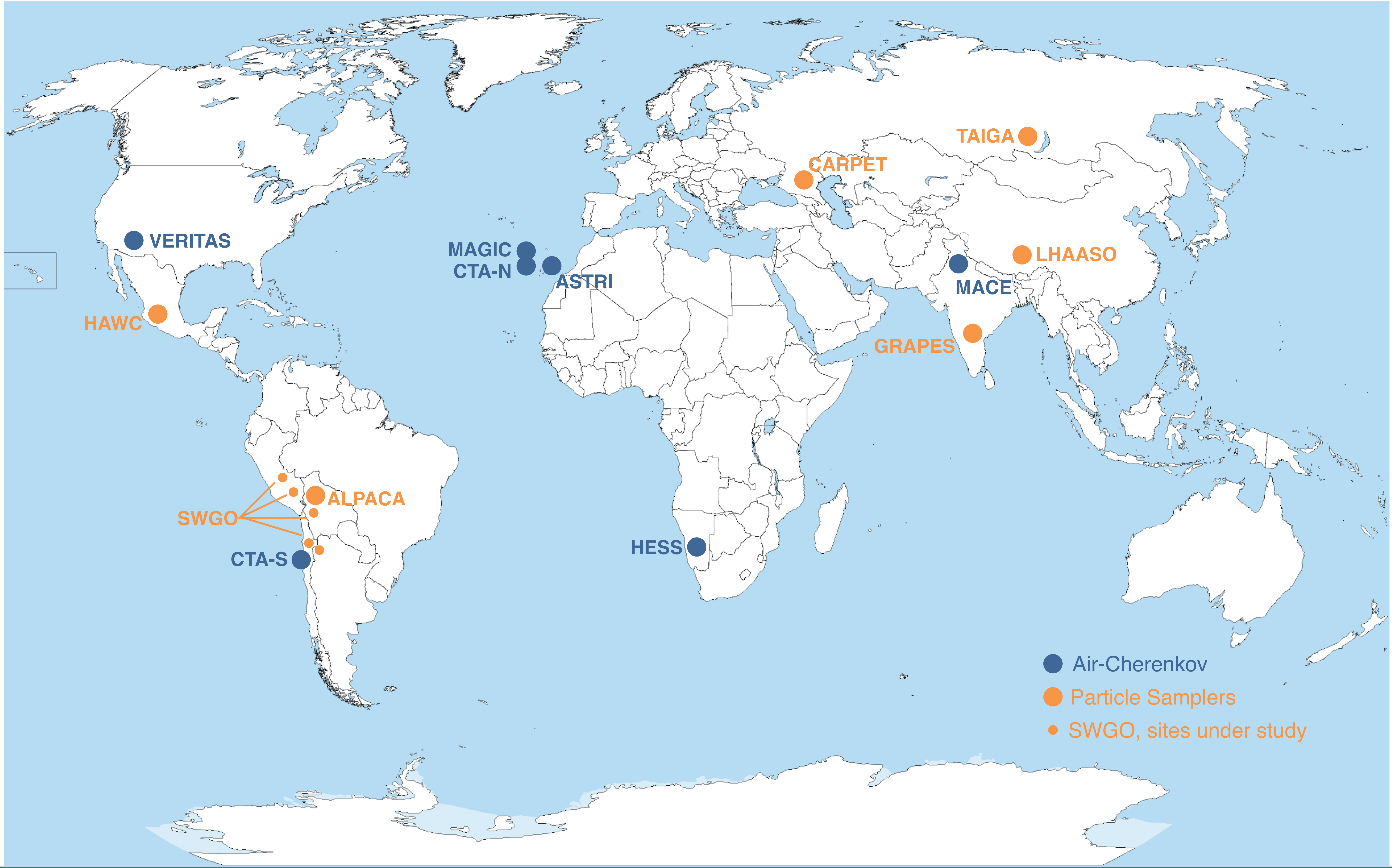
Radio Facilities Map



Optical Facilities Map



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

serrapilheira CBPF

“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

“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

The series is full of MWL/MM resources — have a look!

https://www.cta-observatory.org/outreach-education/events/webinars-researchers/

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.

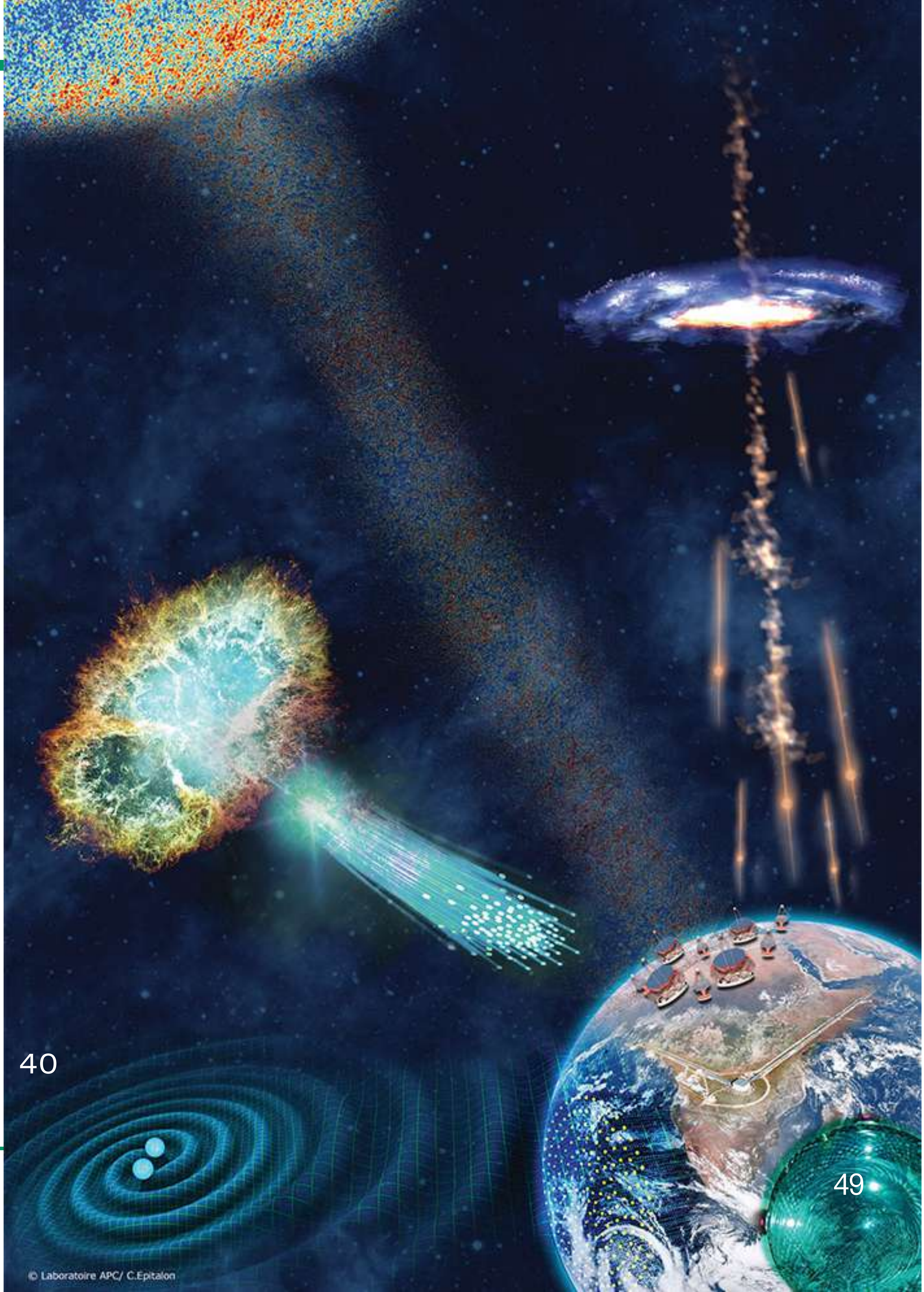
Data Policies - (a) Limit as much as possible data proprietary limits for enabling time-critical science; **(b)** incorporate the FAIR principles within open astronomy data; **(c)** large projects should lead open data and data sharing policies.

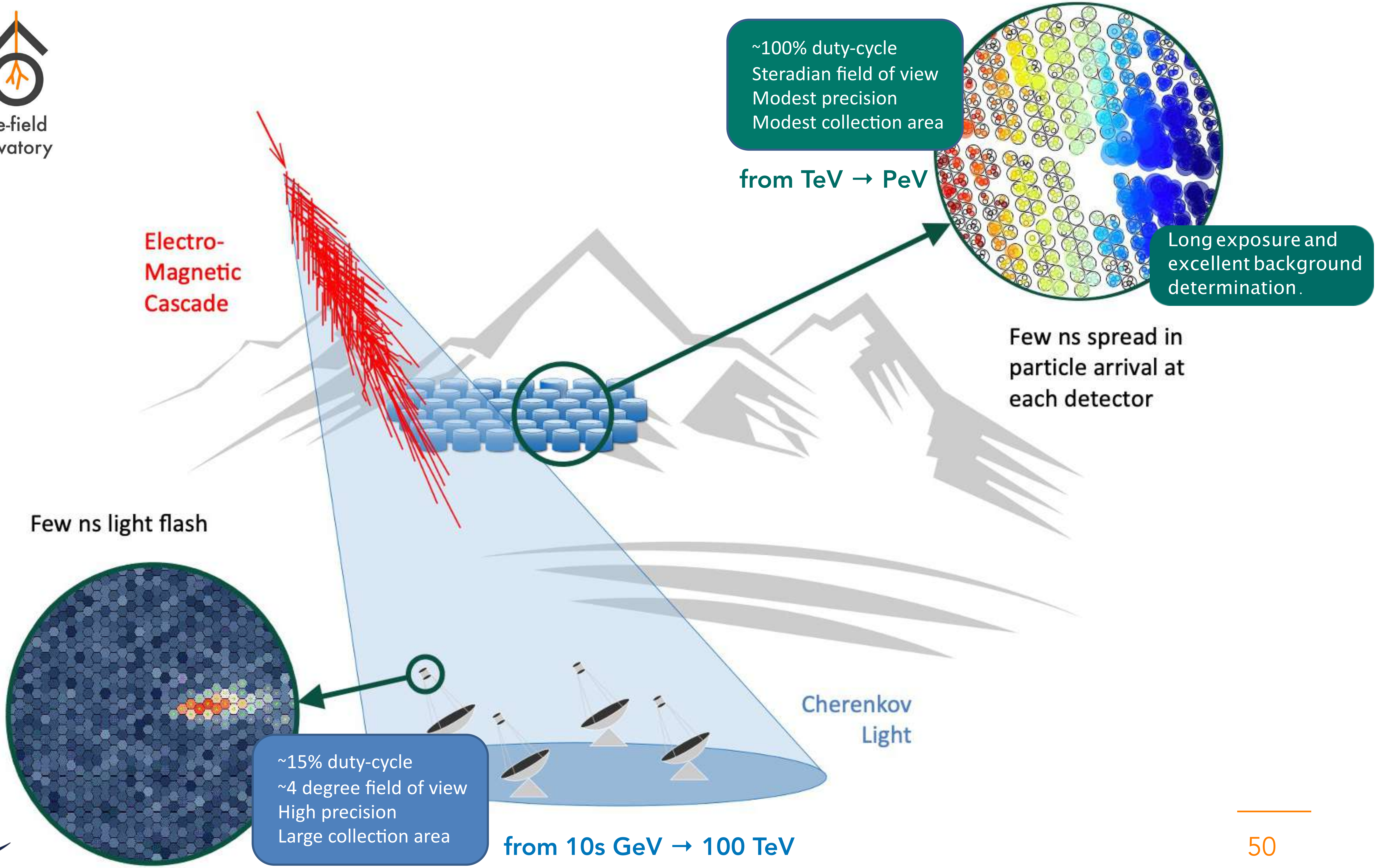
Follow-up spectroscopy - (a) Increase the capacity of spectroscopic follow-up, critical fro transient ID; **(b)** invest in integrating medium-to-small observatories and observation capabilities around the globe; **(c)** avoid duplication of efforts by means of improved communication protocols; **(d)**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

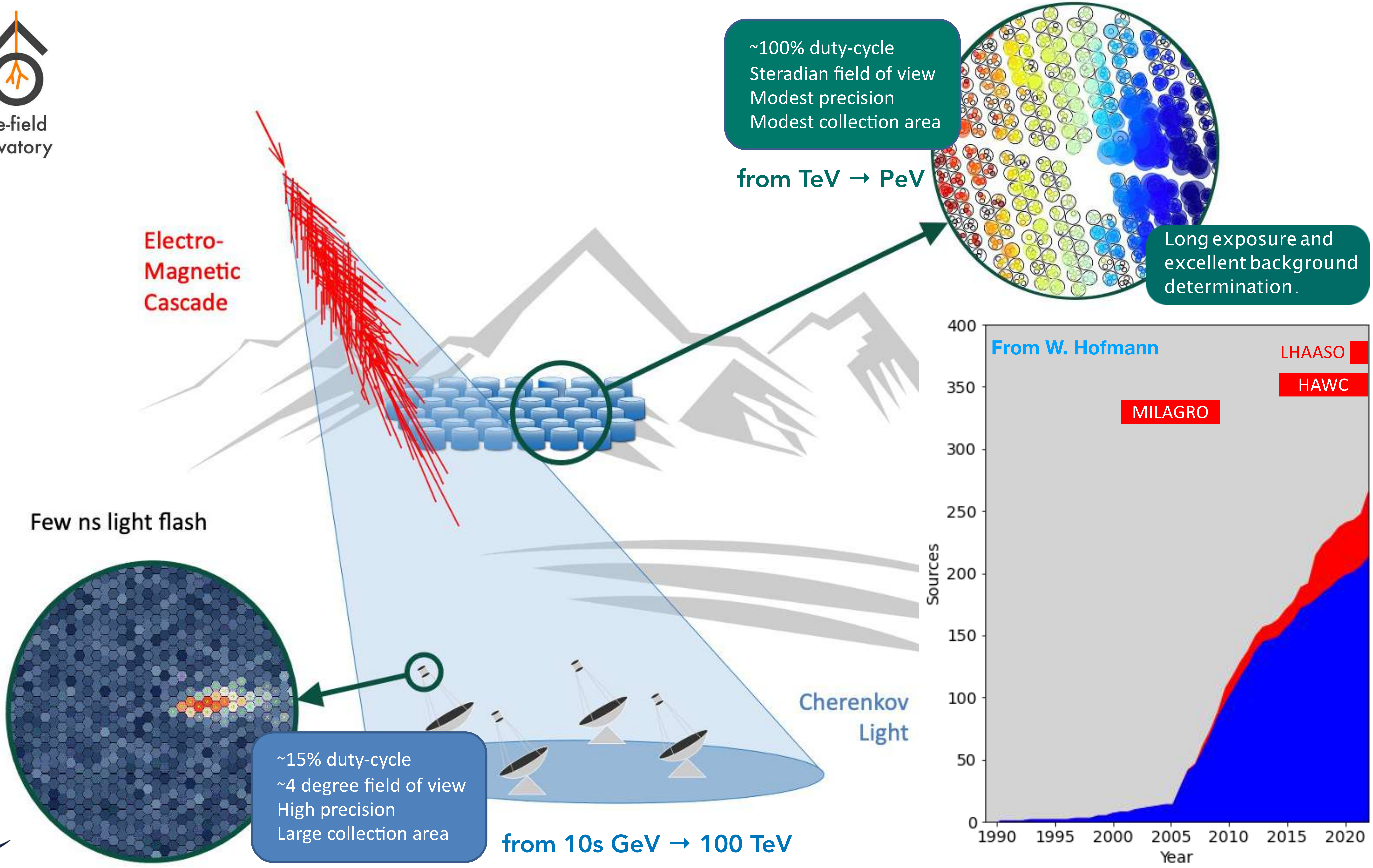
ToO Implementation - (a) Treat ToOs as part of the requirements definition process in the early stages of new facilities planning; **(b)** implement science-driven rather than "programatic considerations" on location and availability of ToO time whenever possible; **(c)** make choice allocation process 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.

Towards the UHE Regime



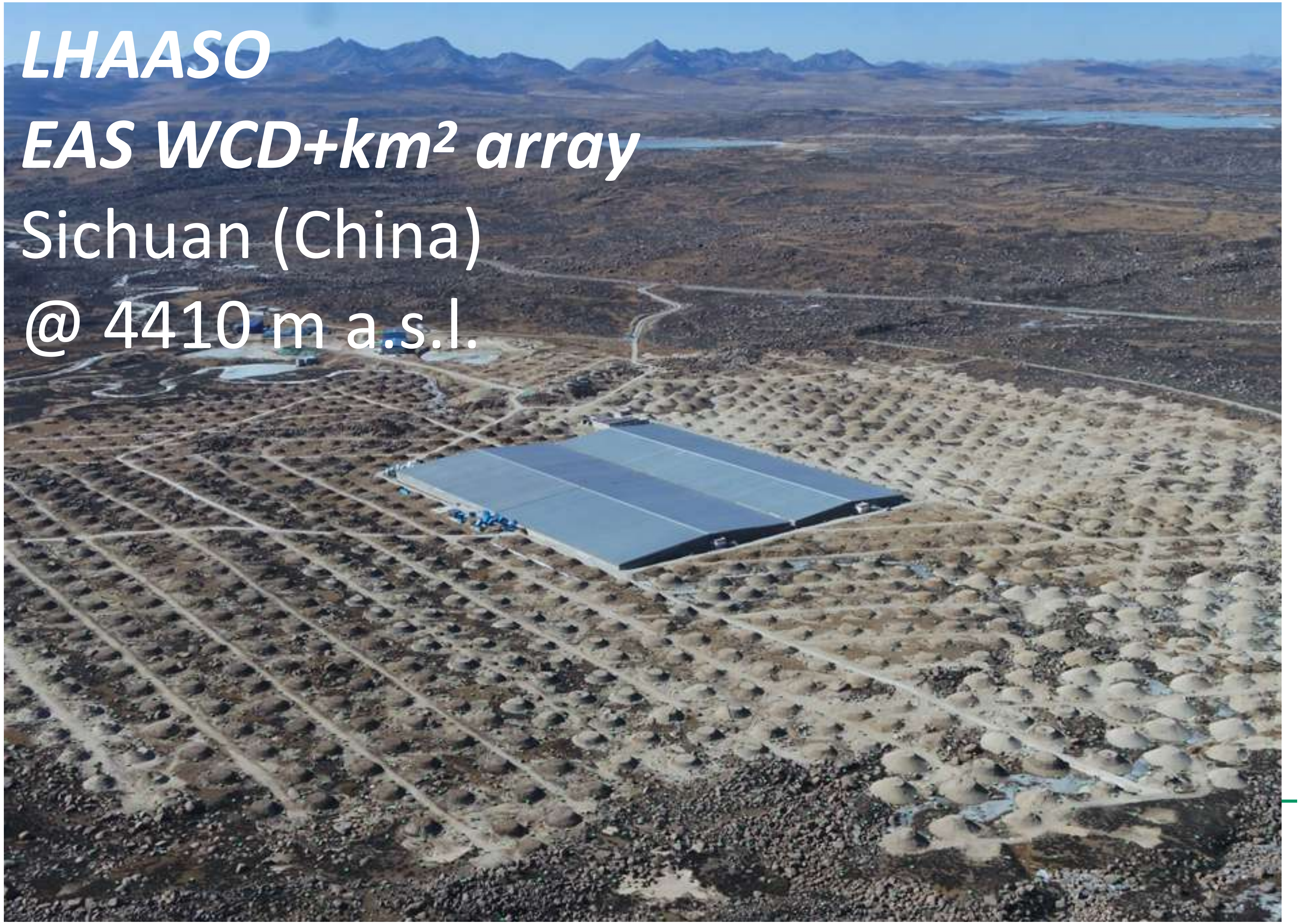

~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area
from TeV → PeV
Long exposure and excellent background determination.
Few ns spread in particle arrival at each detector
Electro-Magnetic Cascade
Few ns light flash
Cherenkov Light
~15% duty-cycle
~4 degree field of view
High precision
Large collection area
from 10s GeV → 100 TeV

SWGO
The Southern Wide-field Gamma-ray Observatory

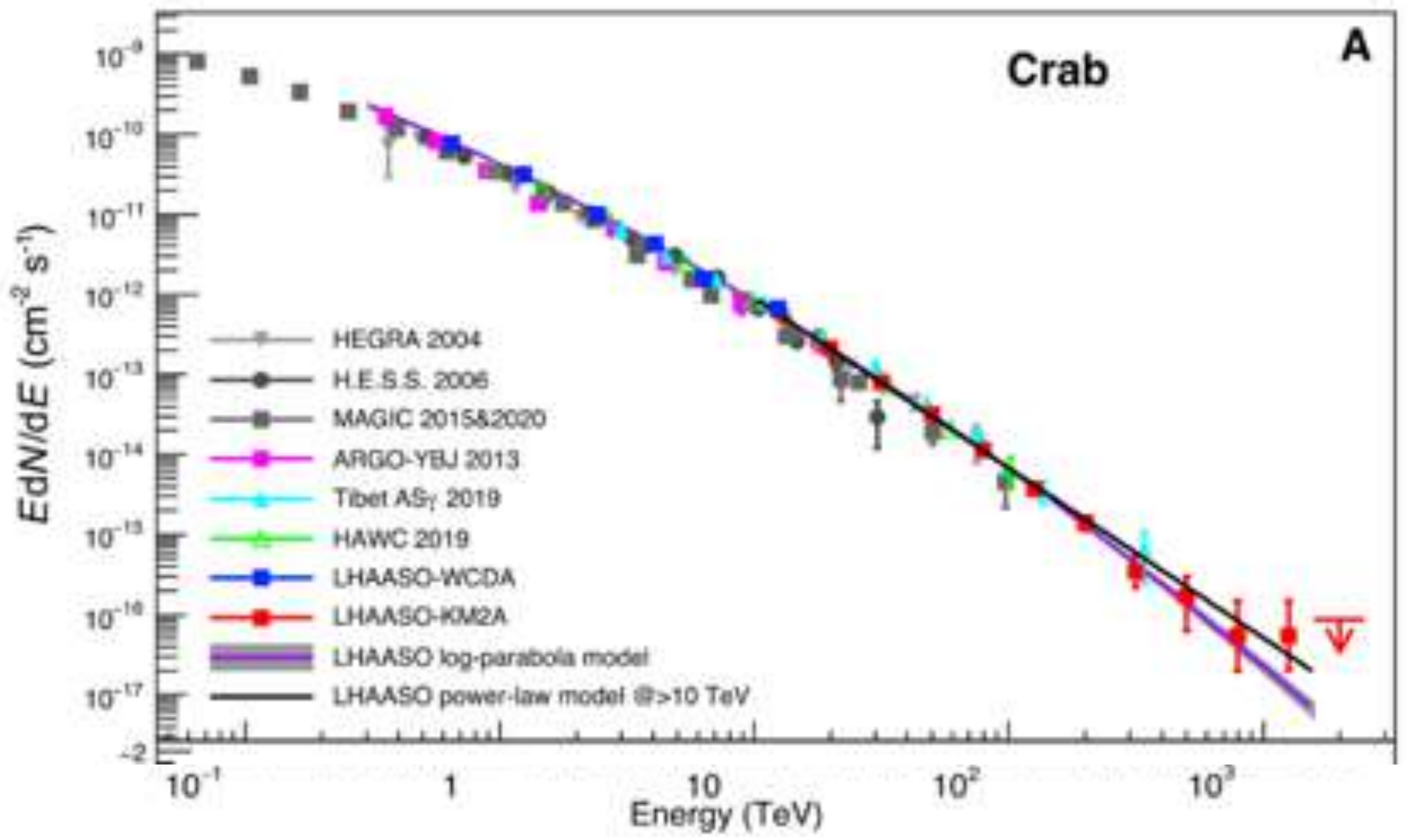


cta

A new piece in the MM board



Z. Cao et al., Science 8th Jul 2021



PeV gamma-rays from the Crab.

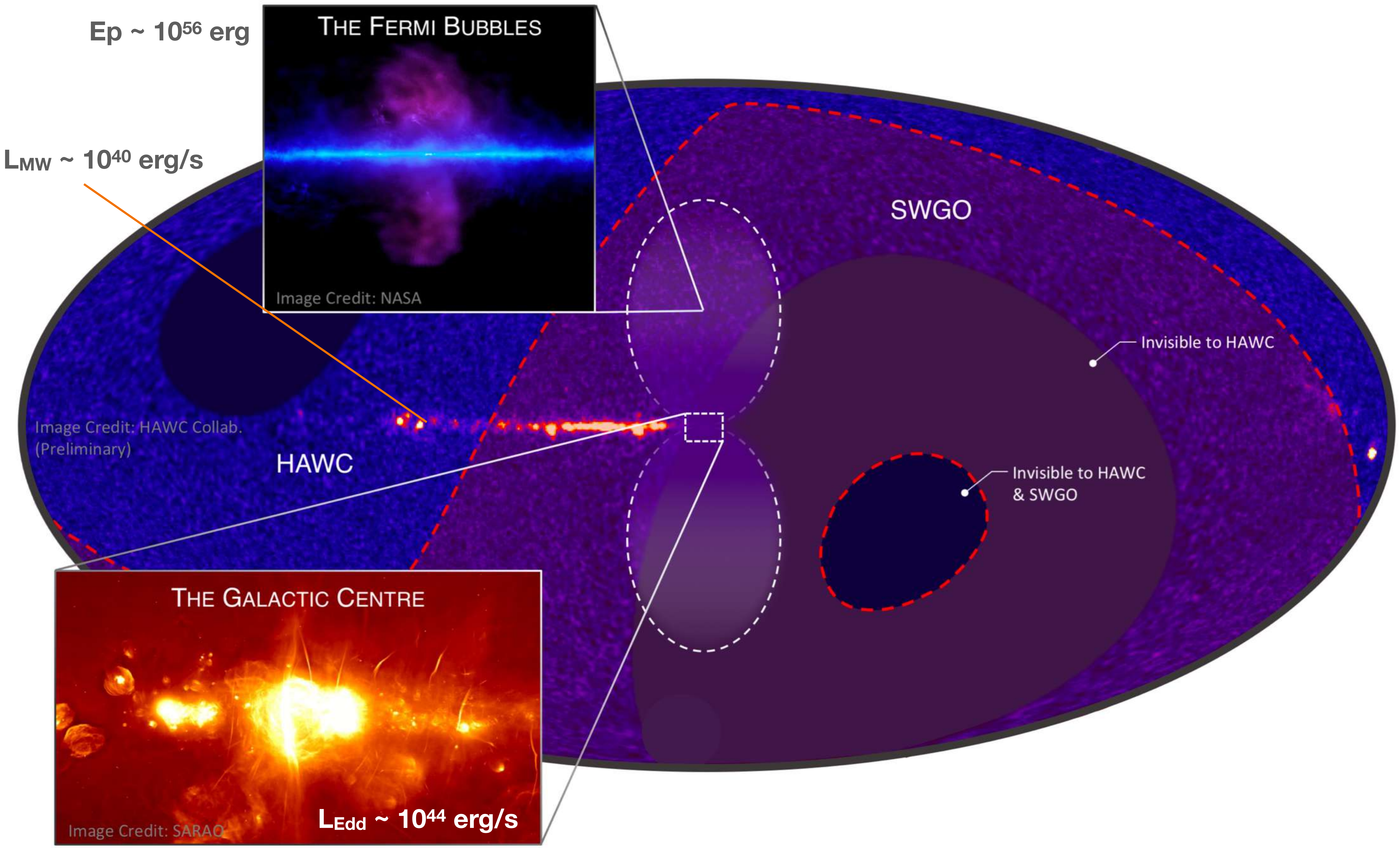
Wide-Field - circa 1 sr of the sky, with 100% duty cycle.

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

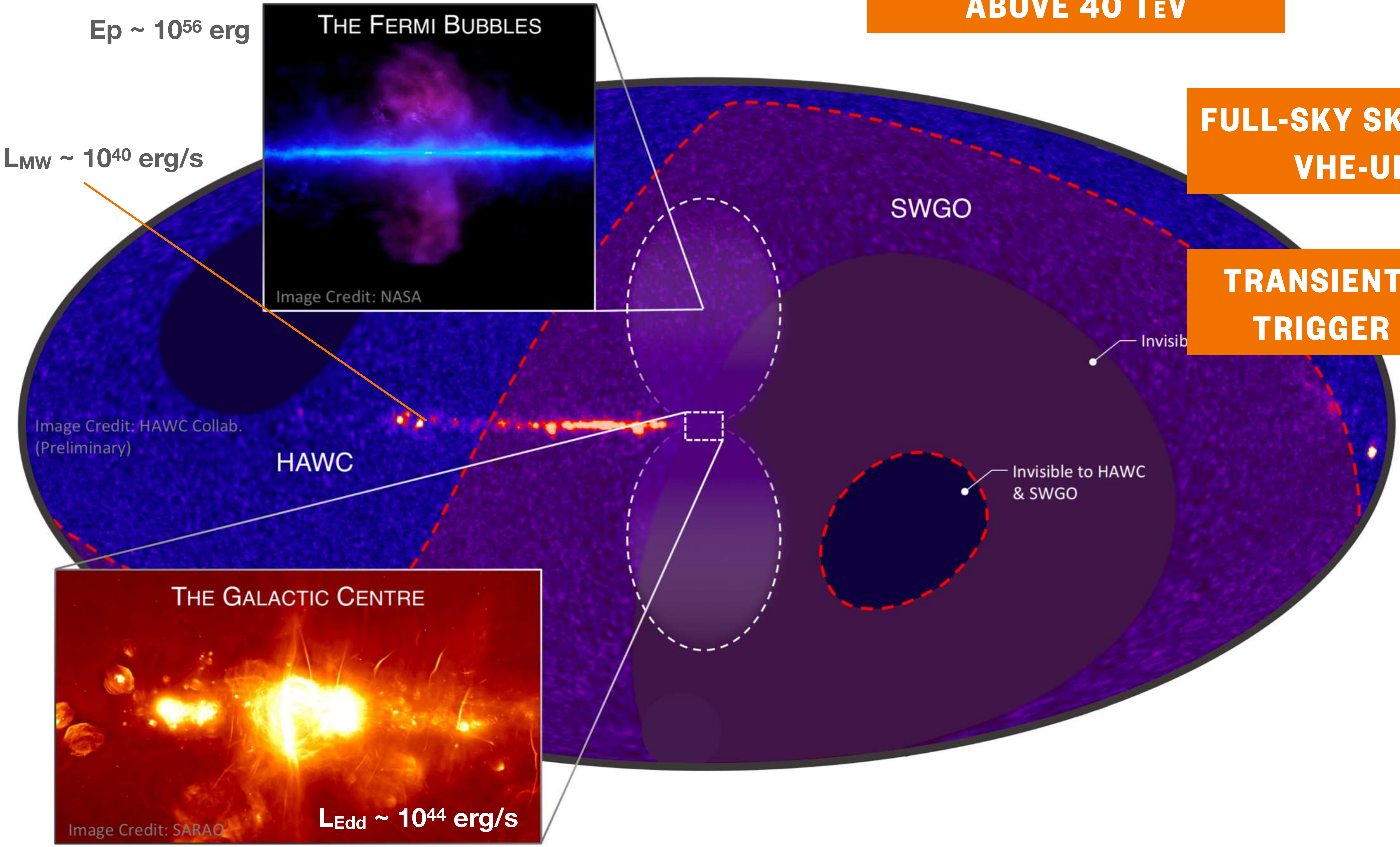
A Wide-Field Experiment in the South



SWGO
The Southern Wide-field Gamma-ray Observatory

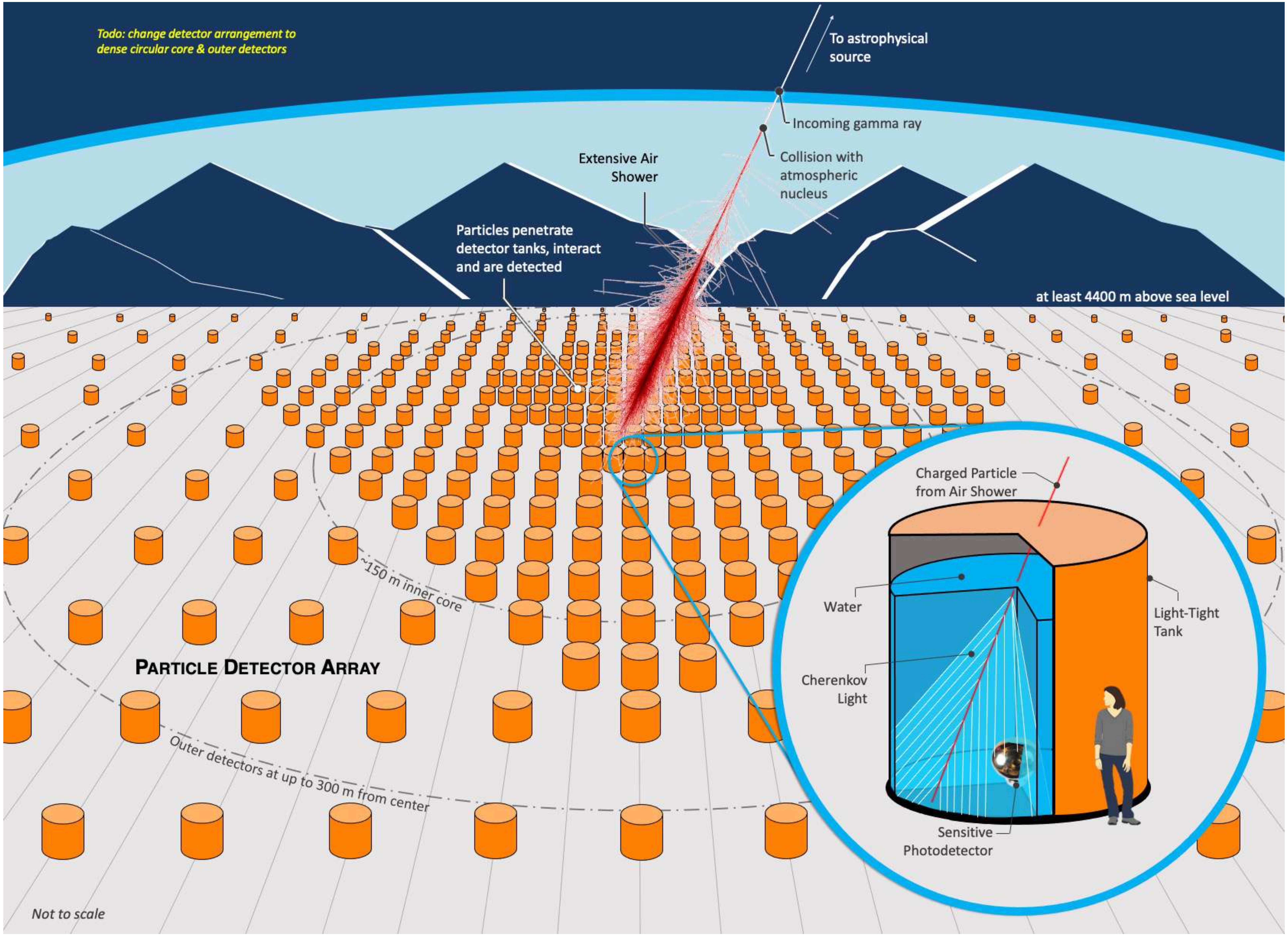
A Wide-Field Experiment in the South

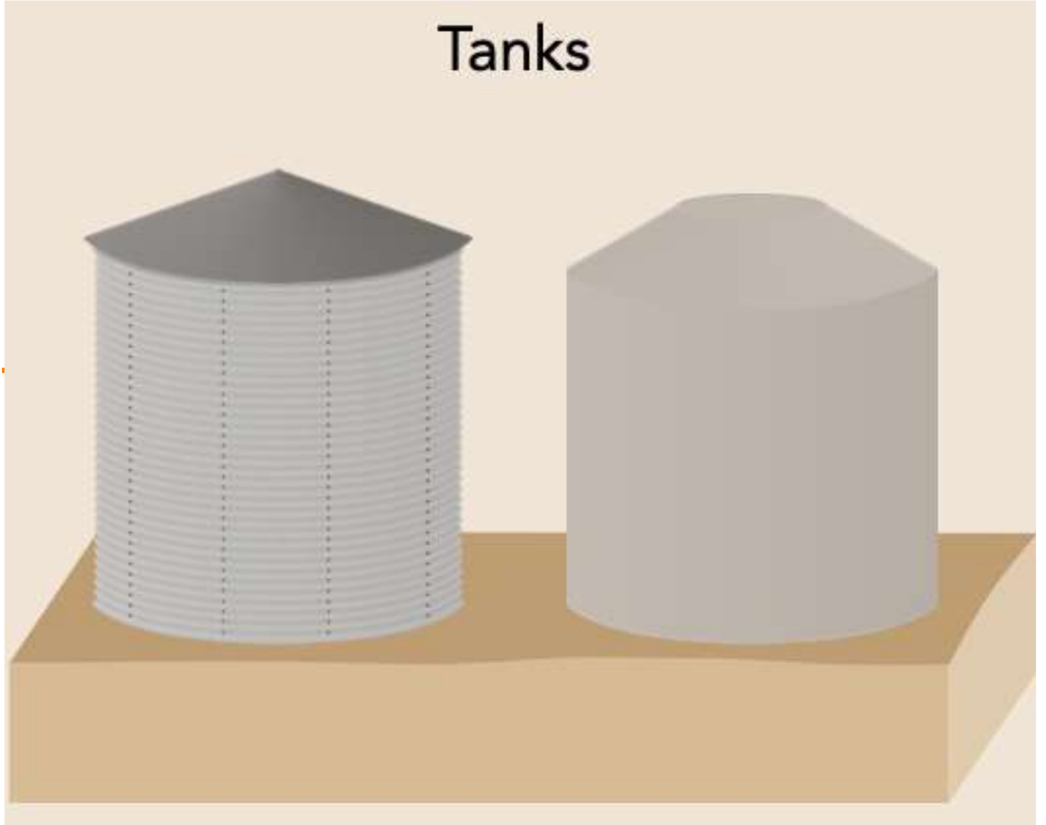
LEADING TECHNIQUE ABOVE 40 TeV



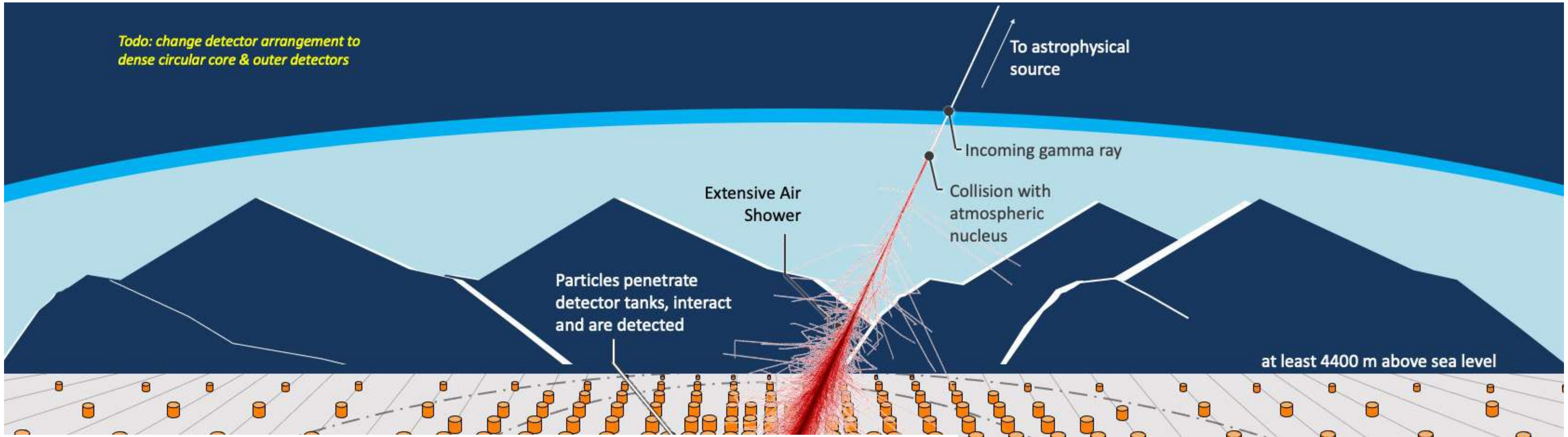
FULL-SKY SKY SURVEY IN THE VHE-UHE REGIMES

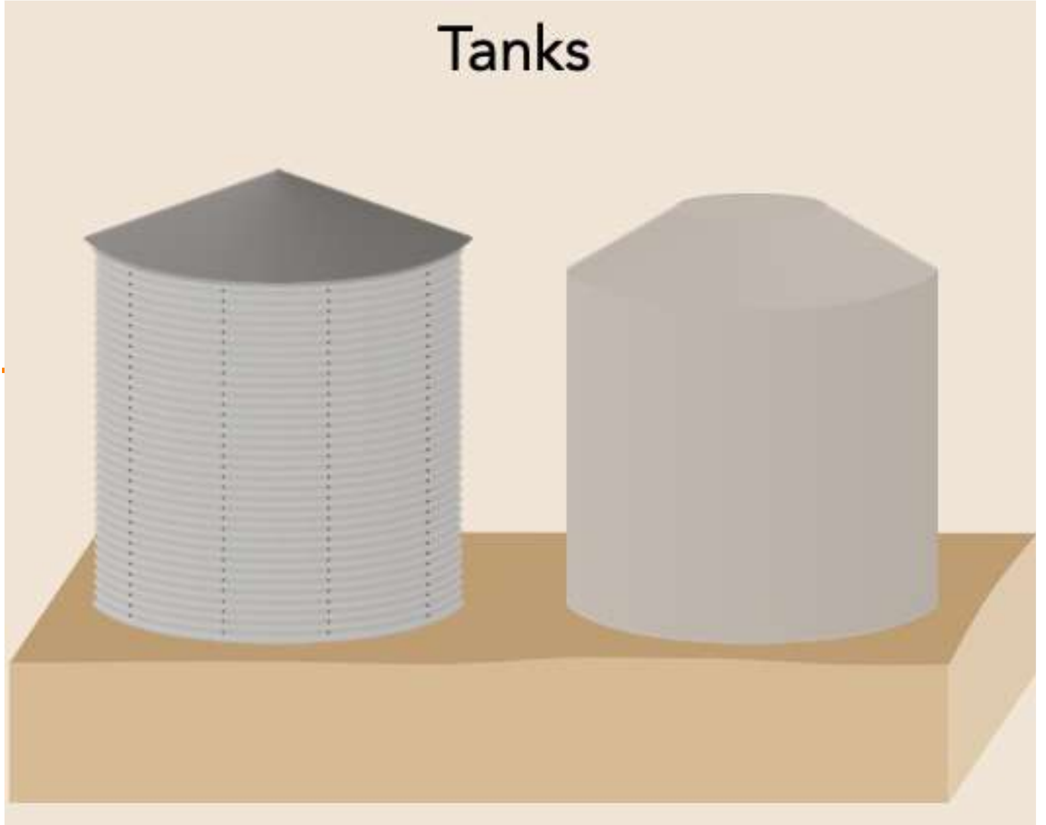
TRANSIENT SCIENCE & VHE TRIGGER / MONITORING


Todo: change detector arrangement to
dense circular core & outer detectors
To astrophysical
source
Incoming gamma ray
Collision with
atmospheric
nucleus
Extensive Air
Shower
Particles penetrate
detector tanks, interact
and are detected
at least 4400 m above sea level
~150 m inner core
PARTICLE DETECTOR ARRAY
Outer detectors at up to 300 m from center
Charged Particle
from Air Shower
Water
Light-Tight
Tank
Cherenkov
Light
Sensitive
Photodetector
Not to scale

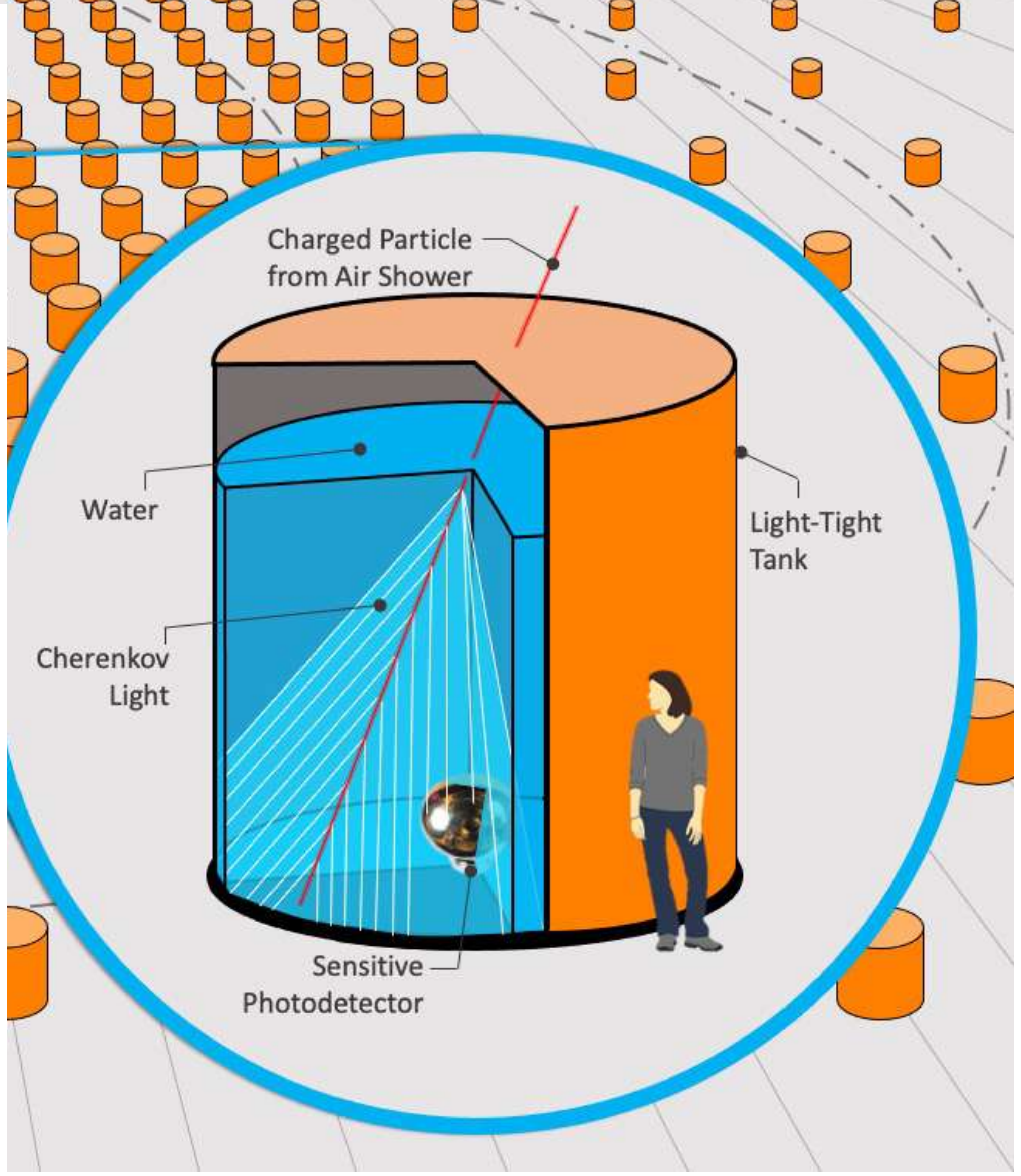

Tanks


Natural Lake



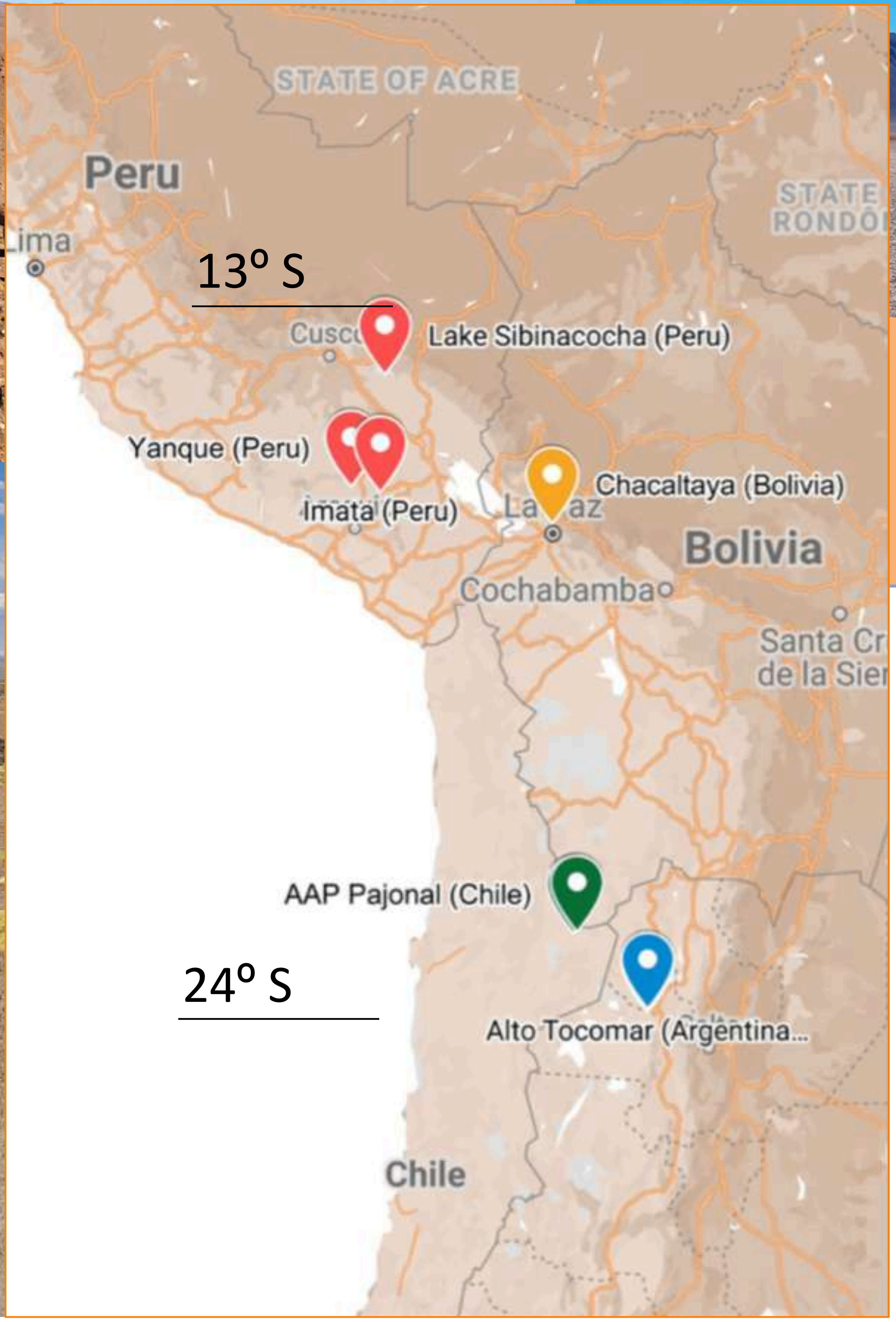


Science Case	Design Drivers	Benchmark Description
Transient Sources: Gamma-ray Bursts	Low-energy sensitivity & Site altitude[a]	Min. time for 5σ detection: F(100 GeV) = 10^{-8} erg/cm^2.s, PWL index = -2., F(t) $\propto t^{-1.2}$
Galactic Accelerators: PeVatron Sources	High-energy sensitivity & Energy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

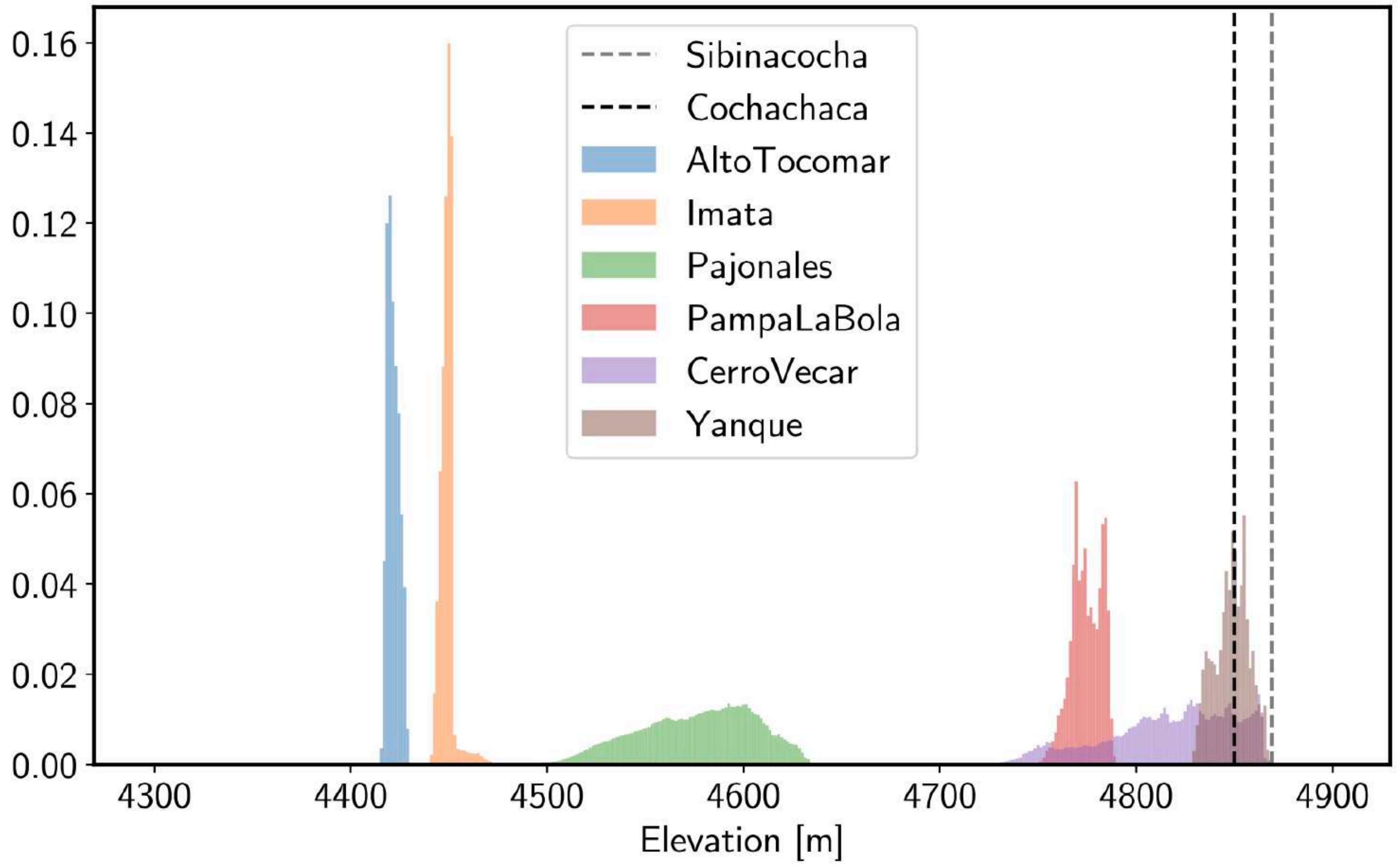


SWGO
The Southern Wide-field Gamma-ray Observatory

A Wide-field Gamma-ray Observatory in the South



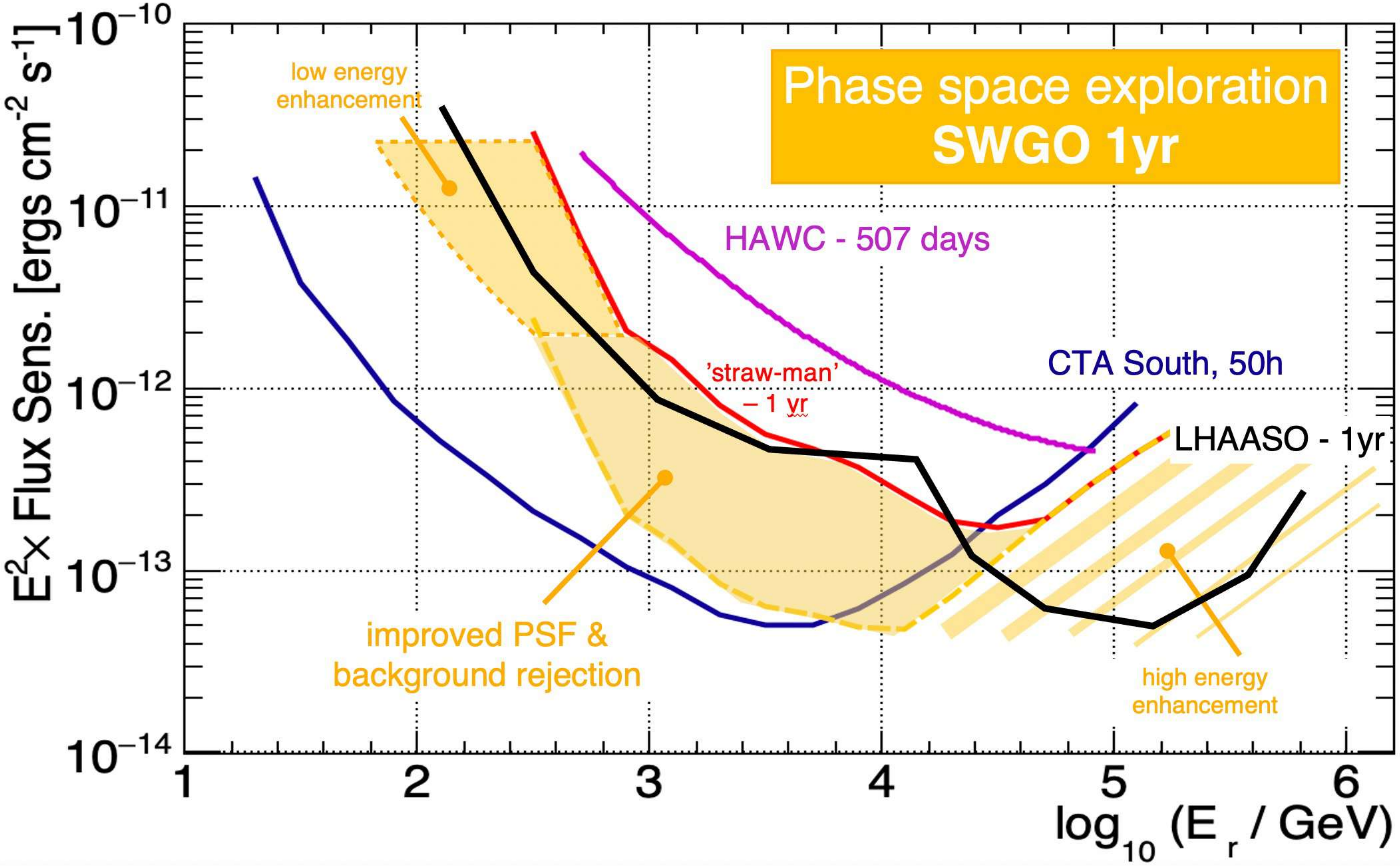
2020-21: Site Candidacies
2022-23: Site Characterization
2024 (July): Site Selection!



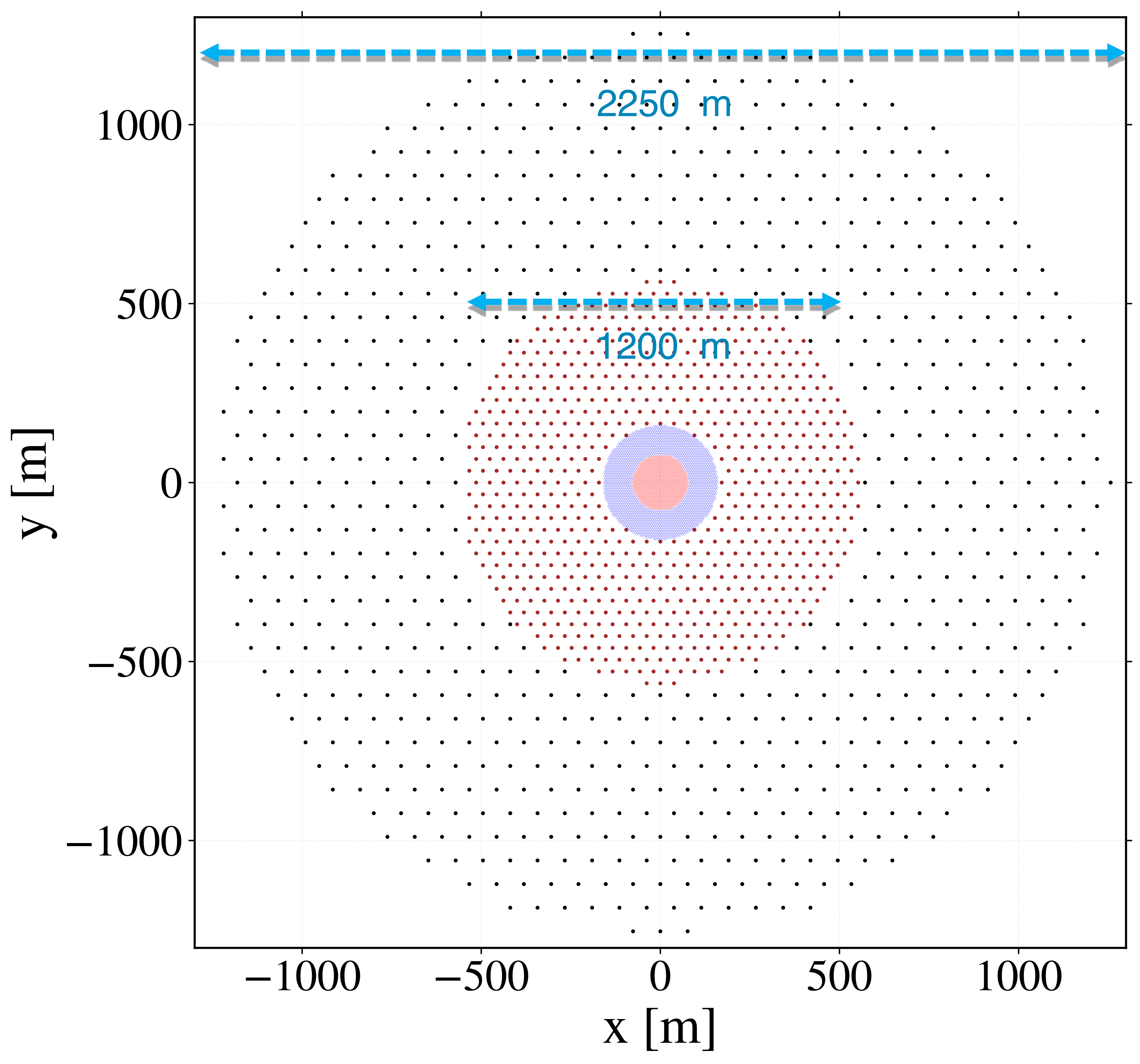
Phase Space Exploration

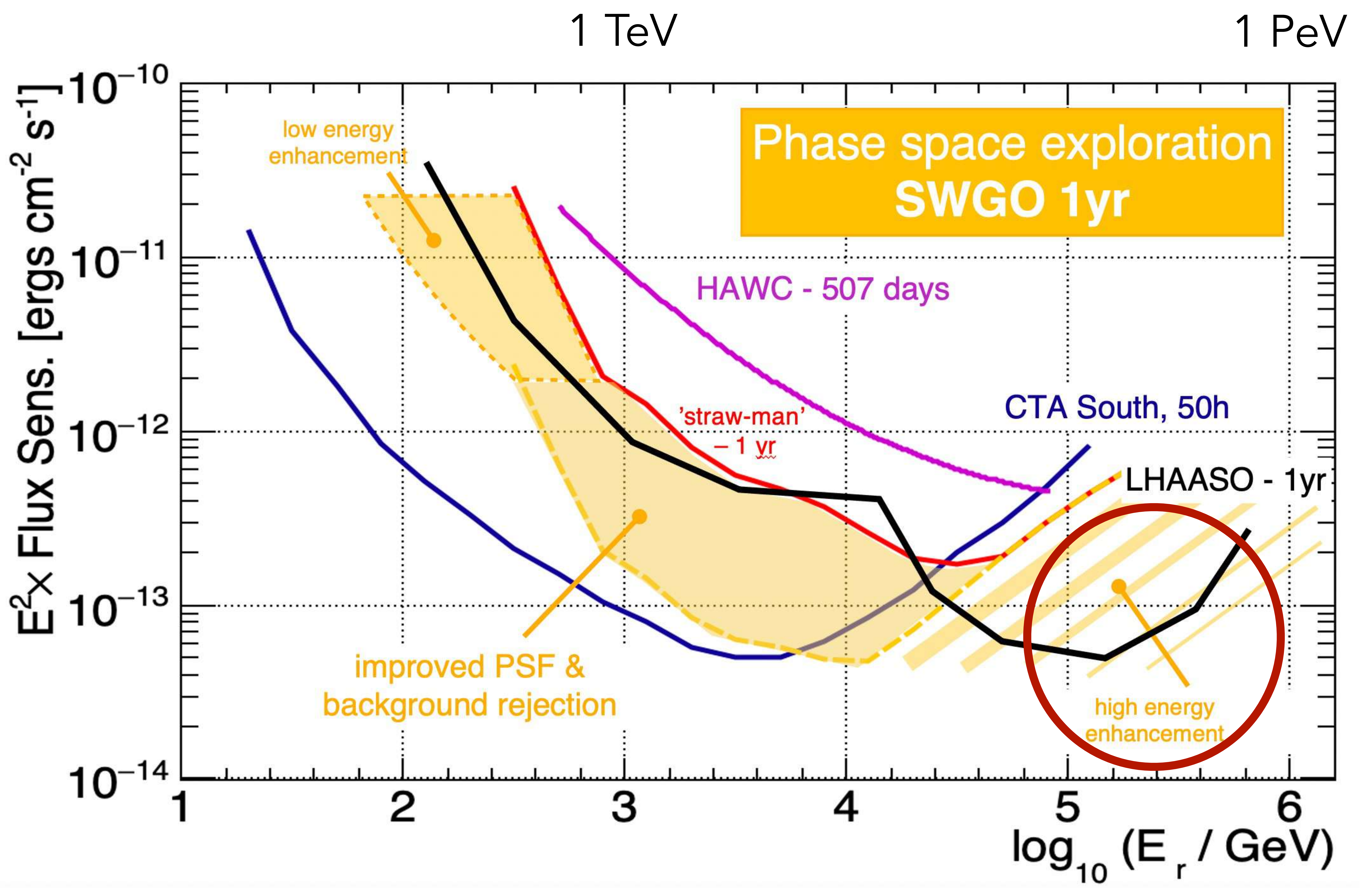
1 TeV

1 PeV



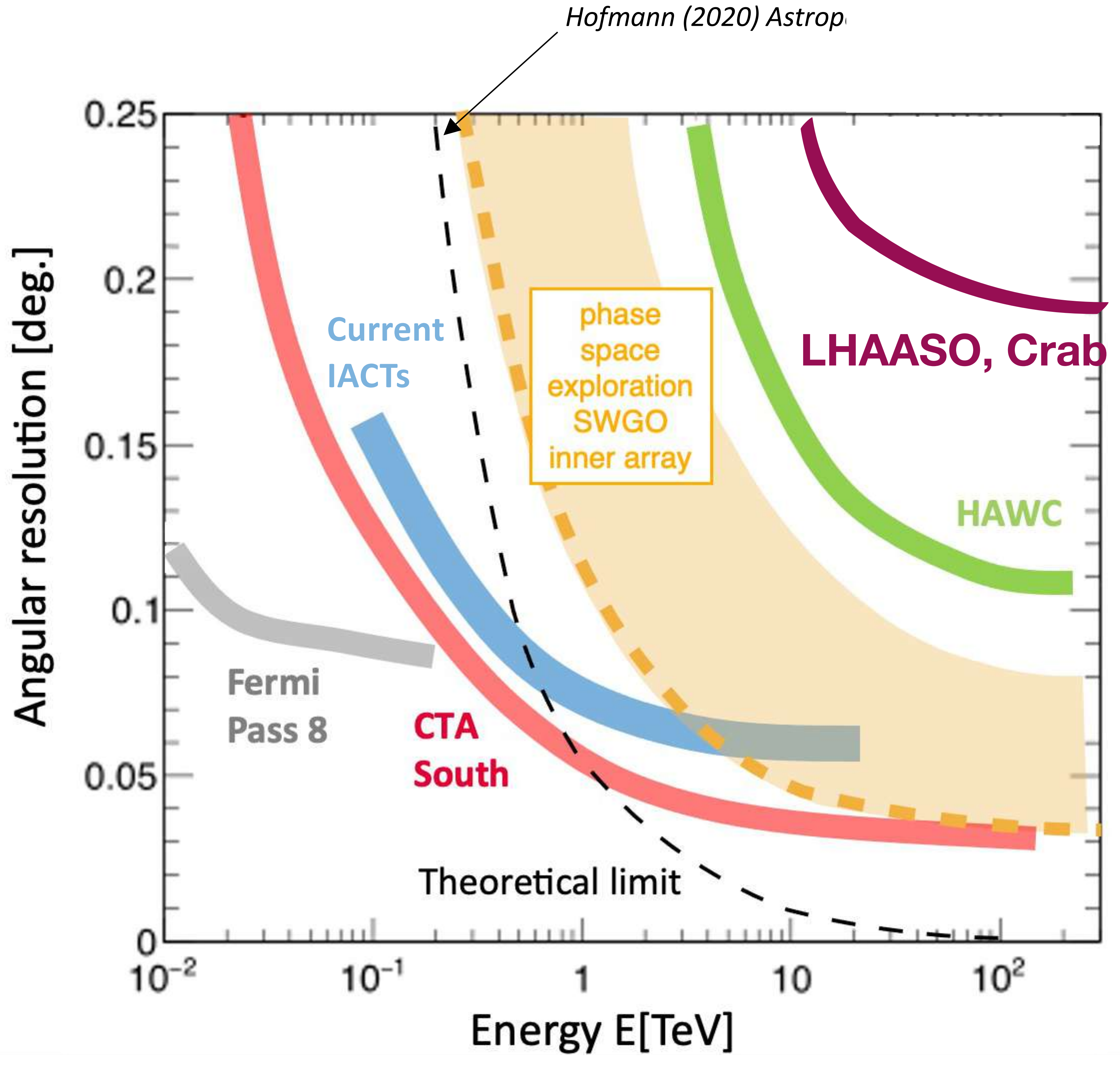
Phase Space Exploration

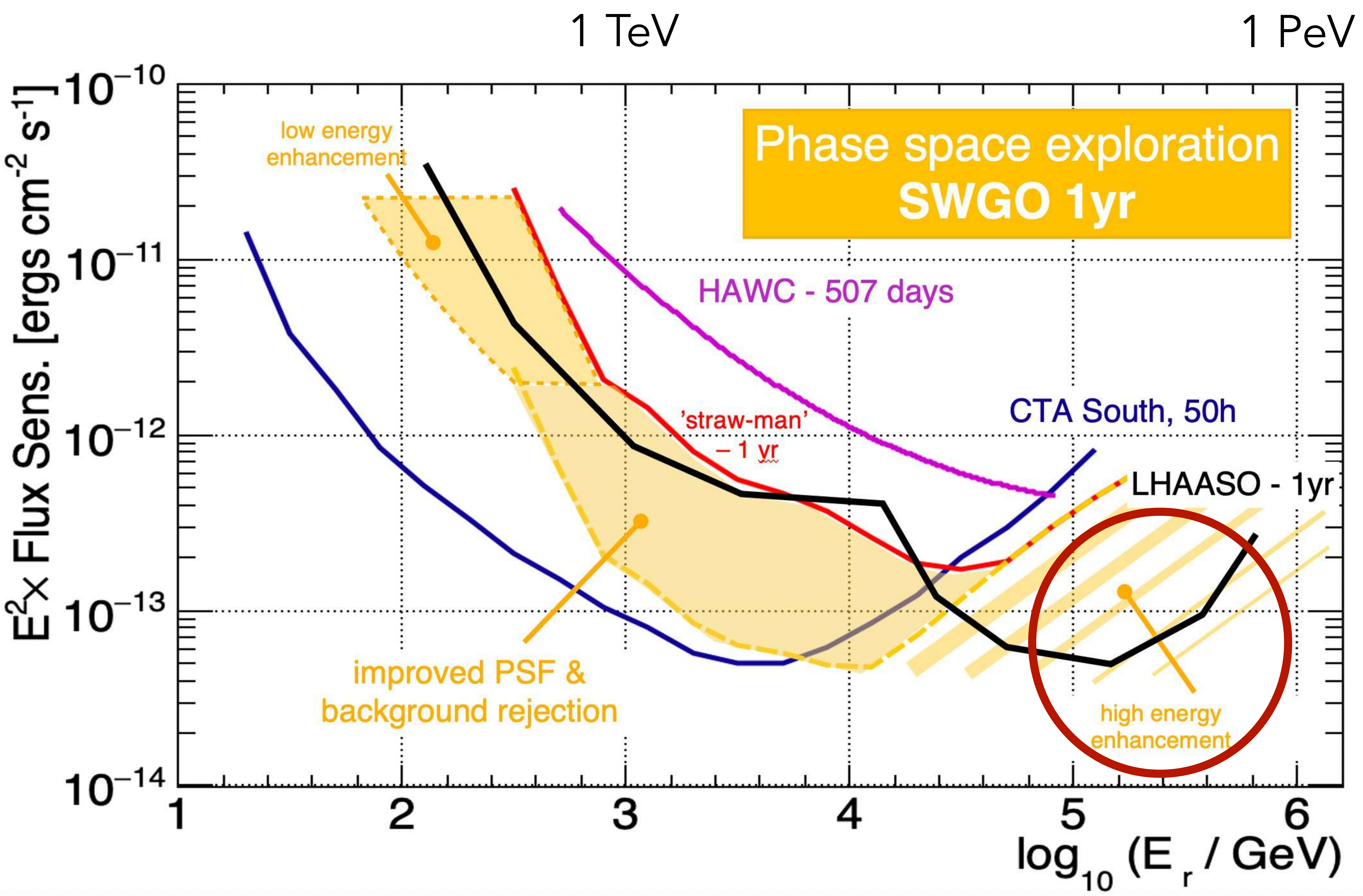




- **Potential Expansion towards the PeV energy scale**
  - ✓ achieved with O(km2) area array

Phase Space Exploration





- **Angular Resolution?**
  - ✓ Goal is to achieve unprecedented resolution at UHE regime

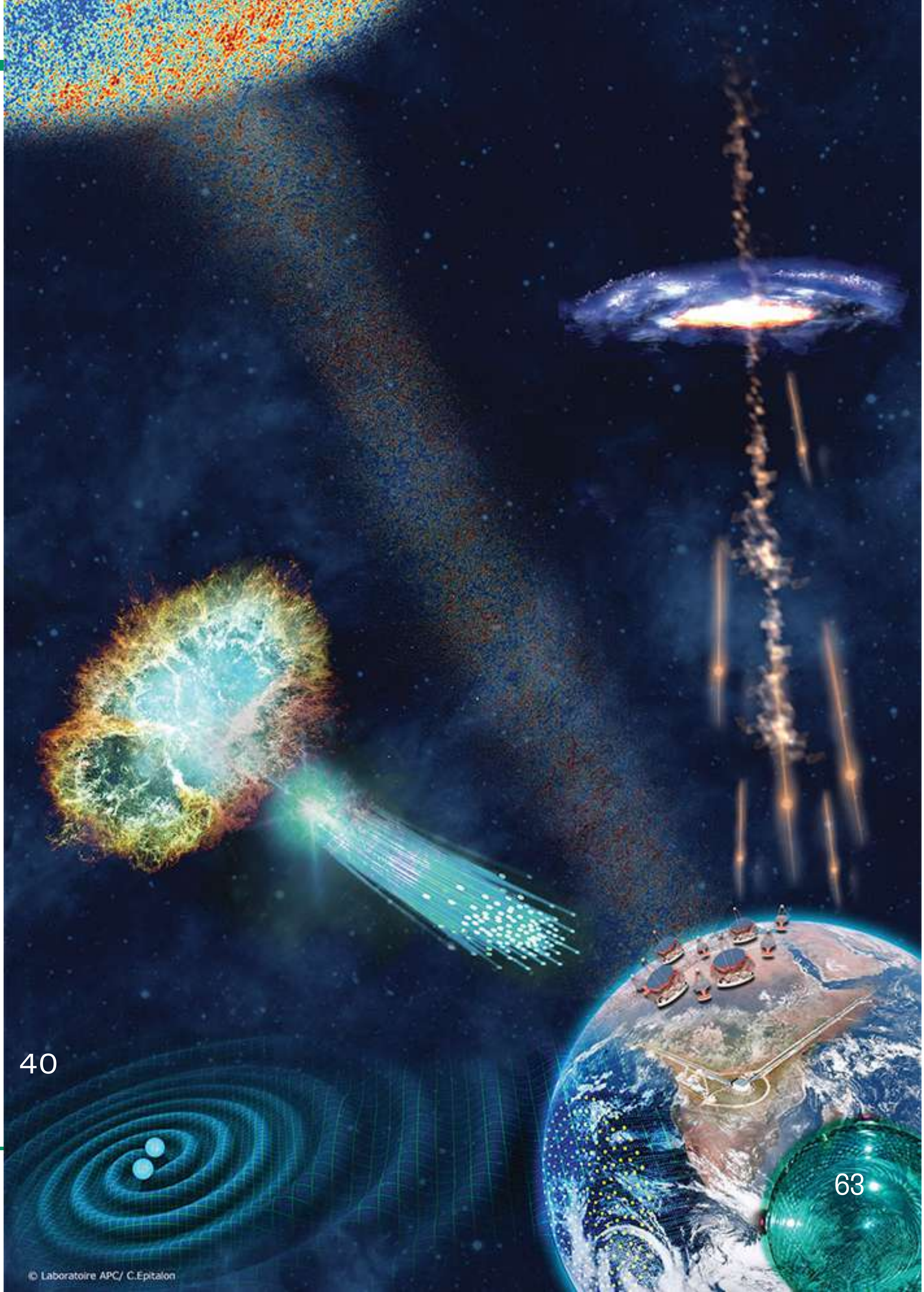
Transients with SWGO

- Short-timescale sensitivity of ground-particle detectors is much worse than IACTs at low E! But room for improvement < 1 TeV

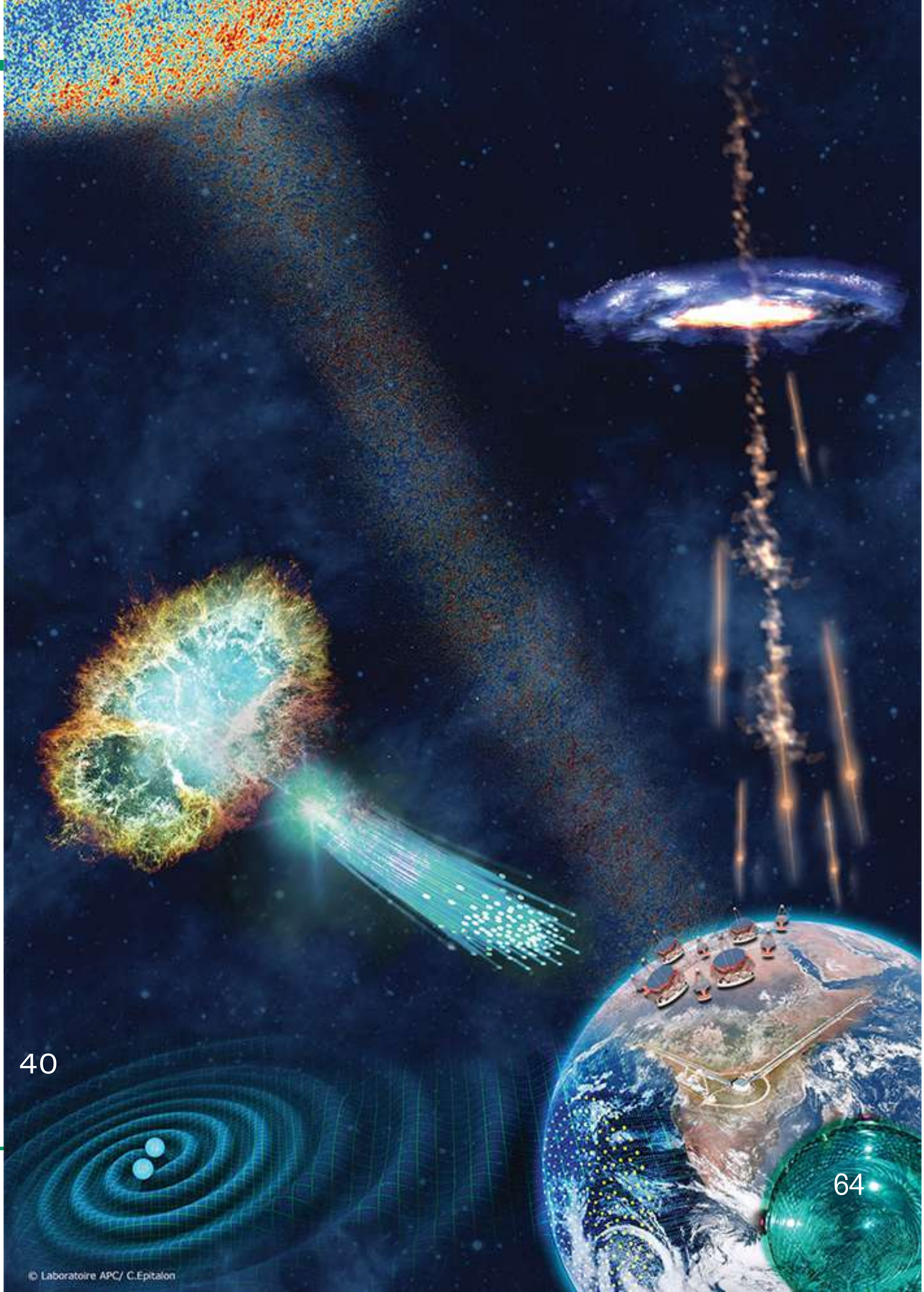
- And a number of other advantages…
  - → **100% duty cycle** → higher rate and monitoring capability of transients → bridging the gap with satellite facilities
  - → **Serendipitous view** - observation of onset / prompt emission of GRBs
  - → **A trigger instrument**!
    - ✓ Blind searches and offline checks for afterglow triggers
      - Critical synergy with IACTs and other MWL + MM instruments

✧ **SWGO can bring the 10s deg² error boxes (GBM, GW) down to ~ deg²**

Thank you!



Extra Slides



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

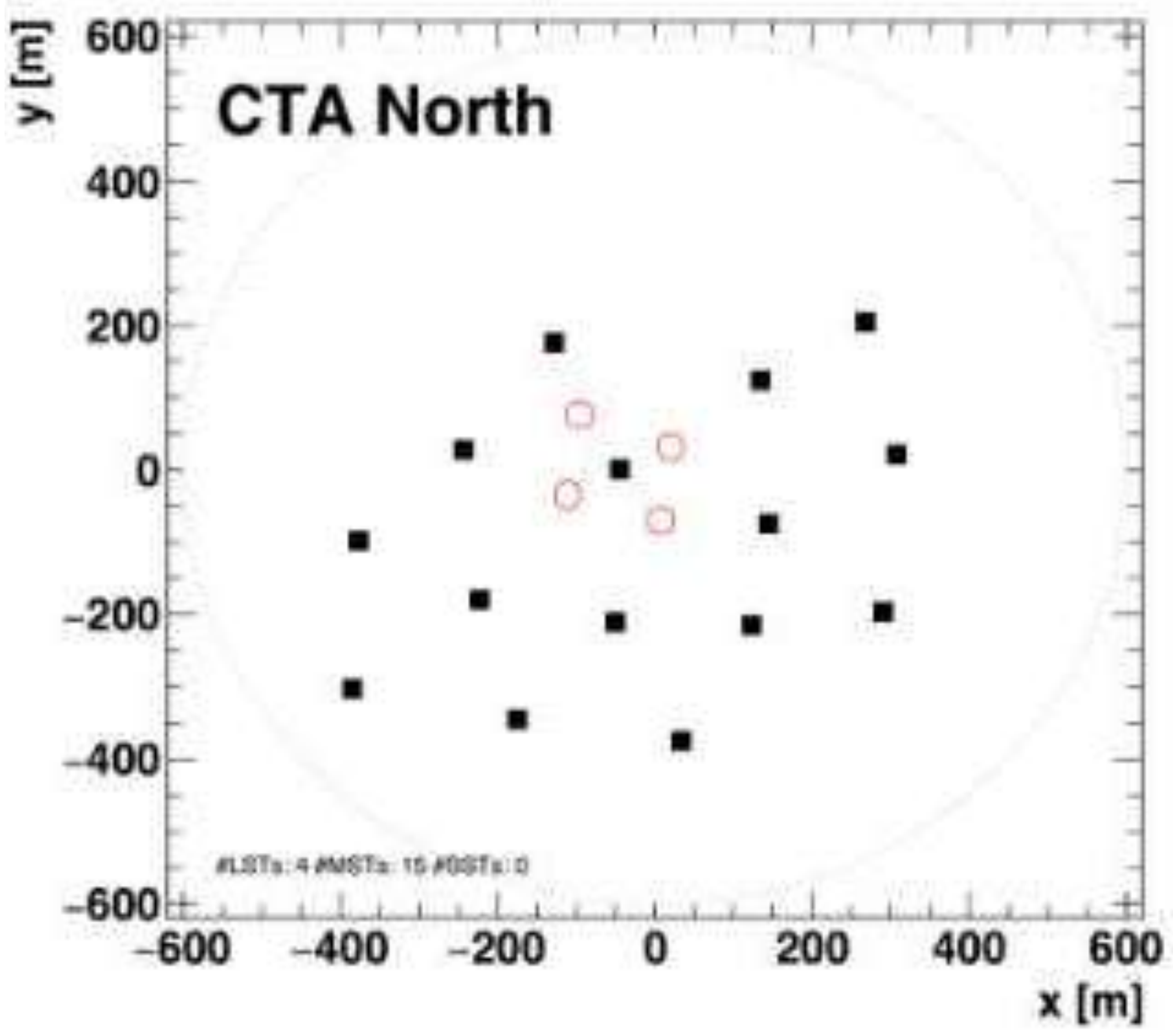
Alpha Configuration

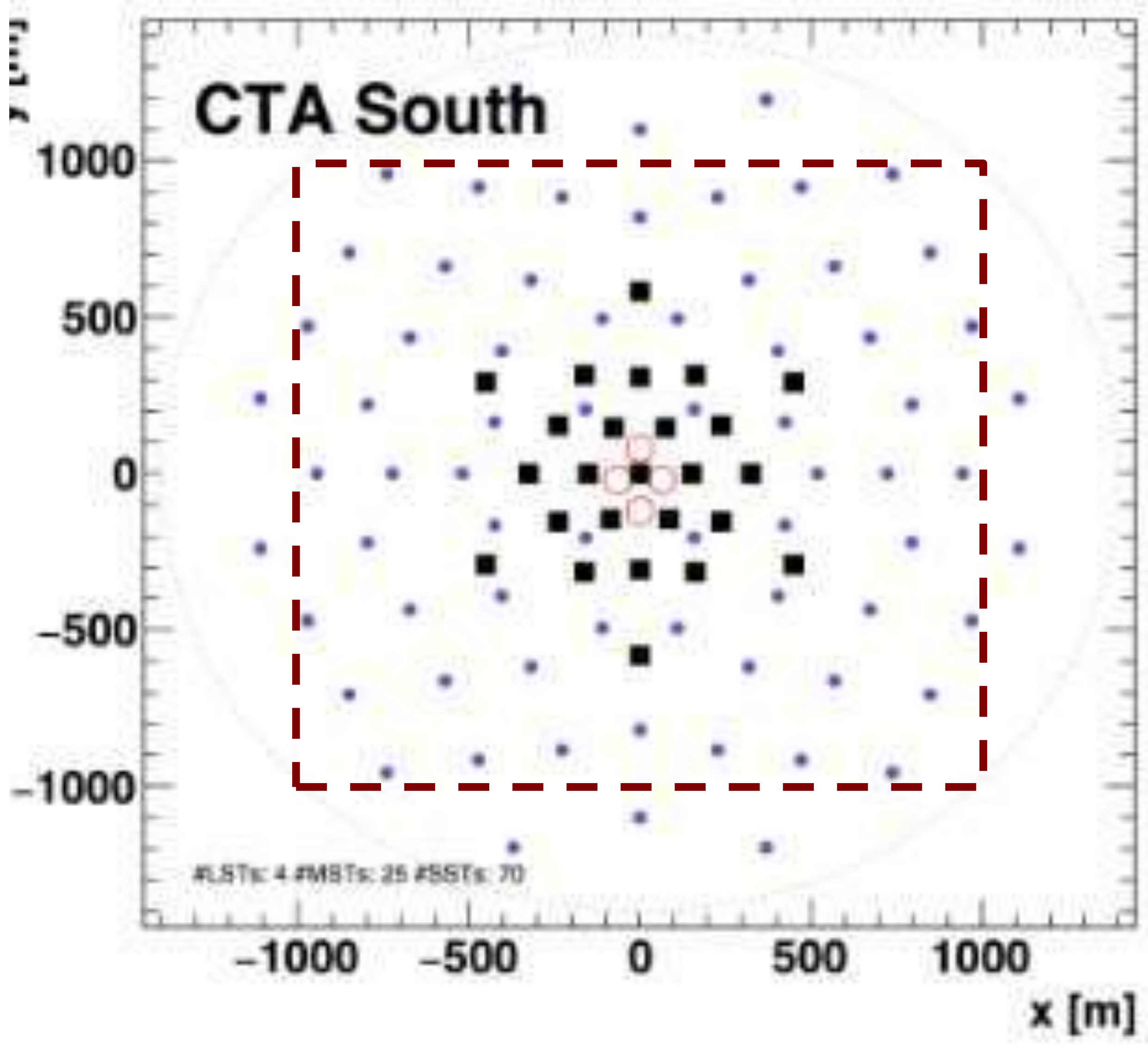
The starting (funding-secured) point

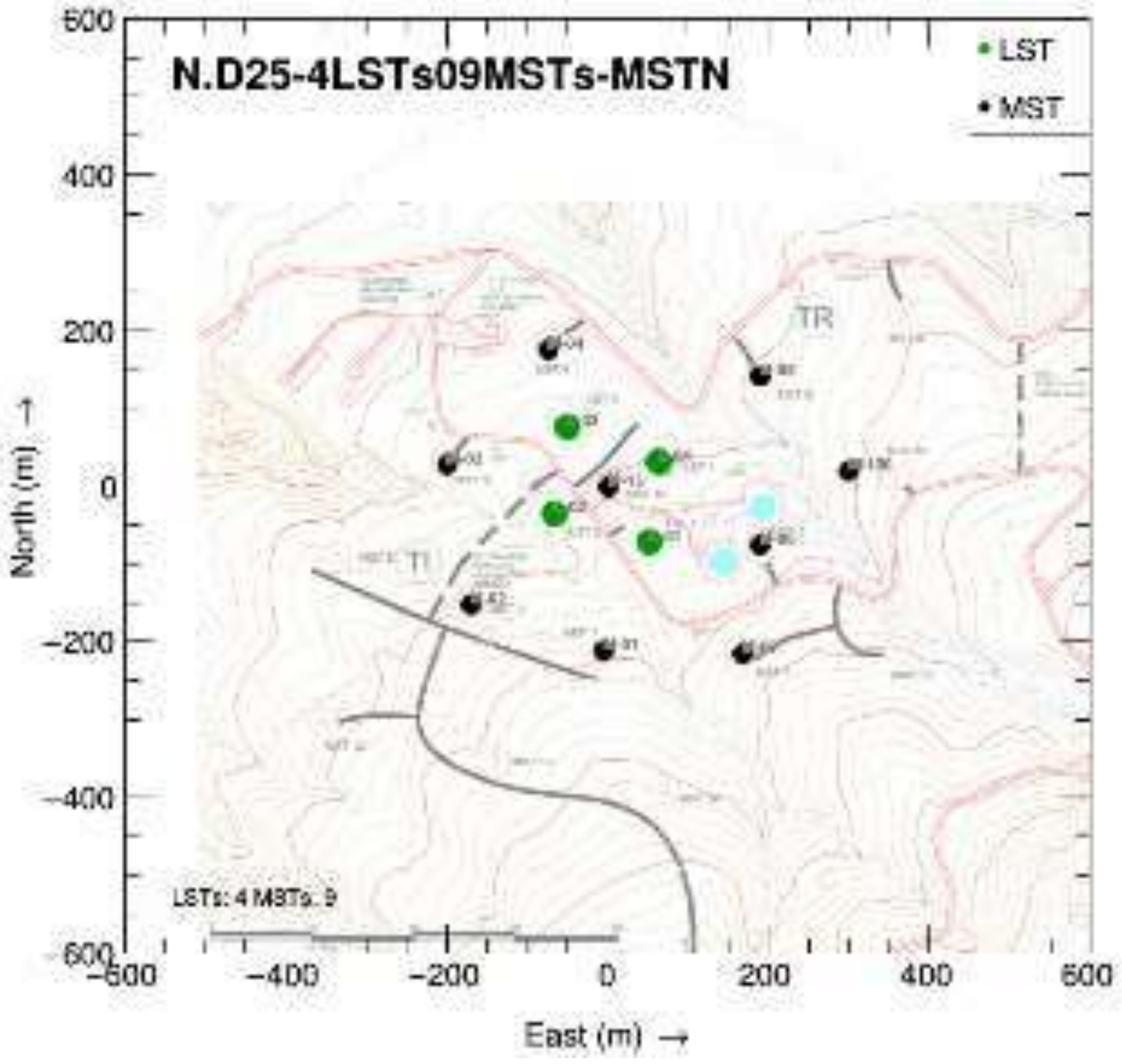
- North: 4 LSTs, 9 MSTs
- South: 0 LSTs, 14 MSTs, 37 SSTs

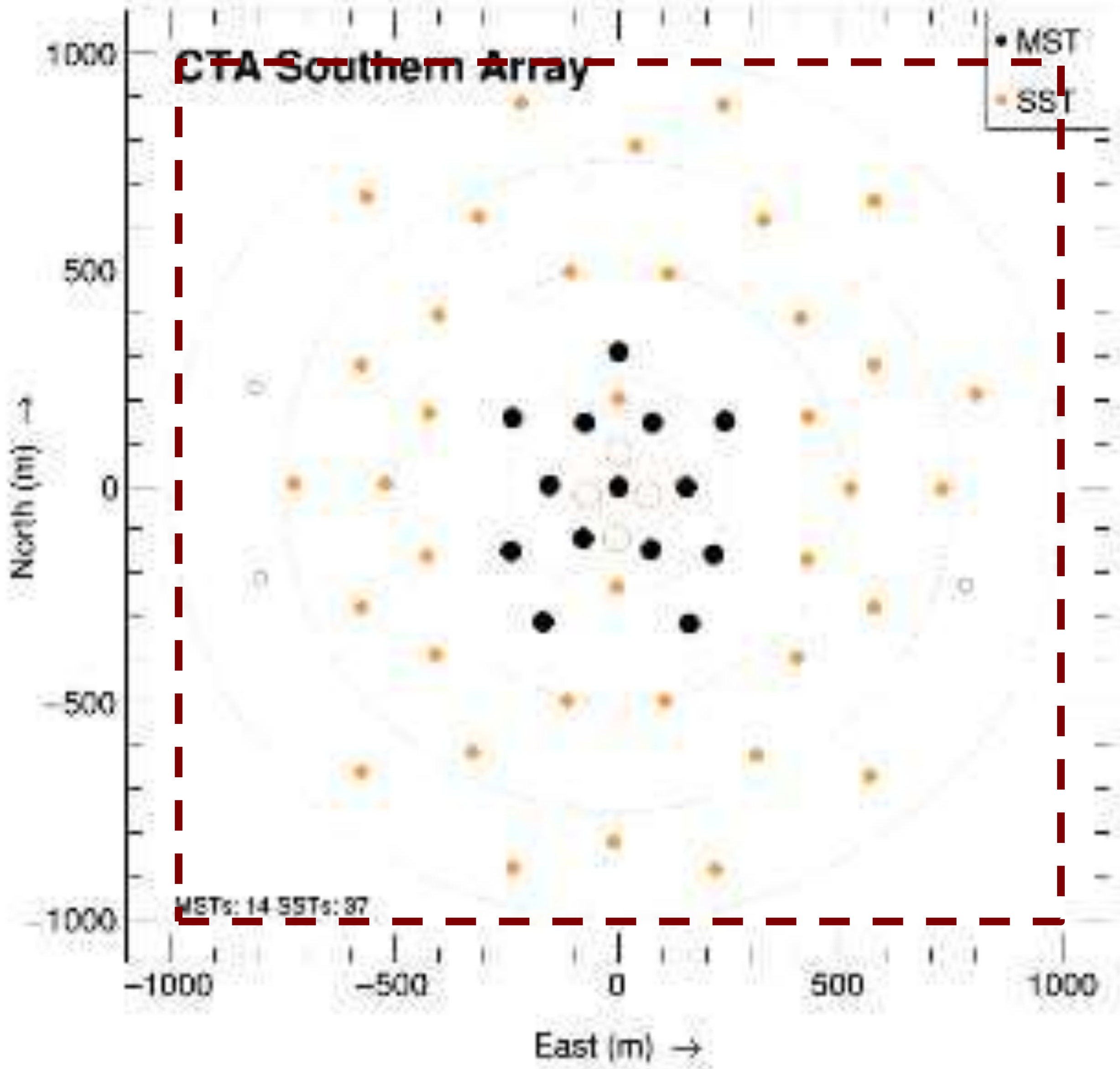
(For transients, slewing times and E threshold increased)

Beware of possible beta configuration with LSTs in South!









GW COSMoS (Patricelli et al. 2018)

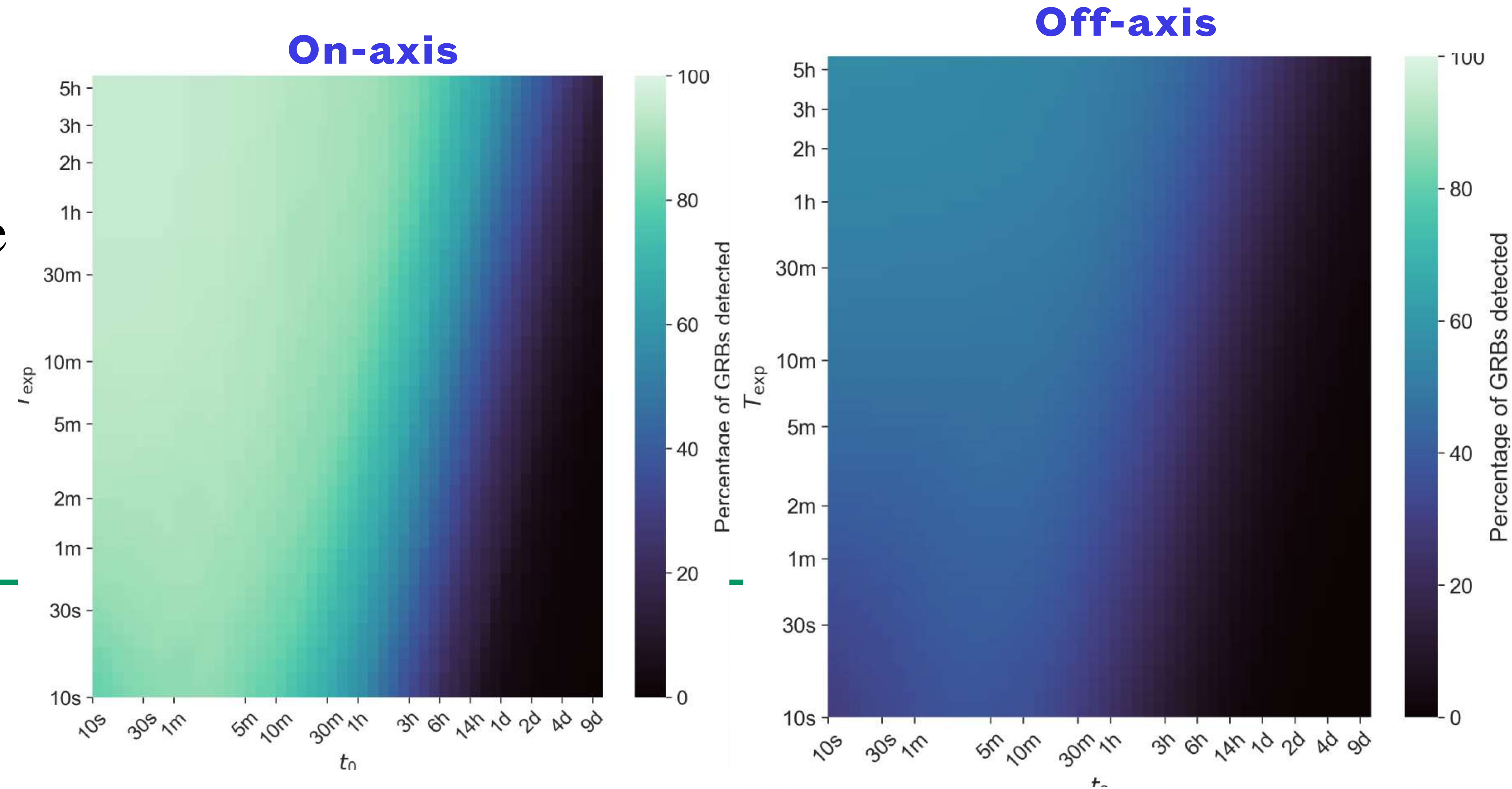
https://doi.org/10.6084/m9.figshare

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 ~ -2.2 (GRB 190114C)
- Principal GRB detectability factors: GW alert latency (~ mins) + CTA alert response (~ 30 s), positional uncertainty of GW.

Prospects for detection are overall promising:

- **For t ~ T_0+30s;** c. 90% (on-axis) / 50% (off-axis) GRBs detectable with exposure < 30 min
- **For t_0 ~ T_0+10 min;** c. 90% (on-axis) / 50% (off-axis) GRBs detectable with exposure ~ 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 ρ = 10^{-12} to 10^{-5} Mpc^{-3}
Luminosities: L_{ν} = 5×10^{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

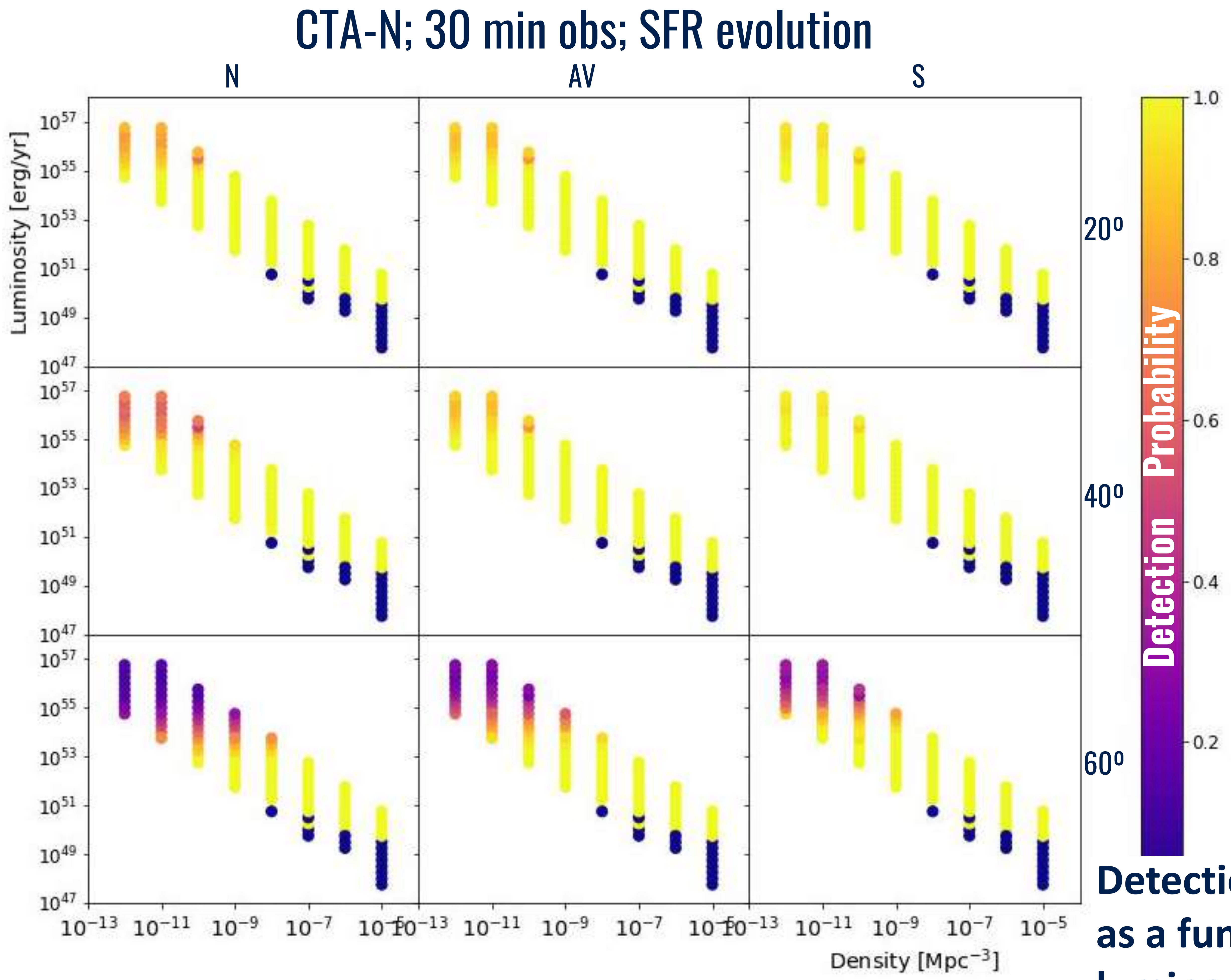
All the sources are assumed to have the same flare duration in their reference frame (110 days @z TXS)

Assuming IC Gold alerts and events always observable by CTA

O. Sergijenko

Neutrino FIRESONG (Tung et al. 2021)

https://github.com/ChrisCFTung/FIRESONG



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

Steady Sources

Assuming these sources will be always observable by CTA:

At low-mid zeniths (20º-40º) CTA-N detects all sources up to ρ= 10^{-9} Mpc^{-3}

Drastic performance loss, up to 65%, at high zeniths (60º)

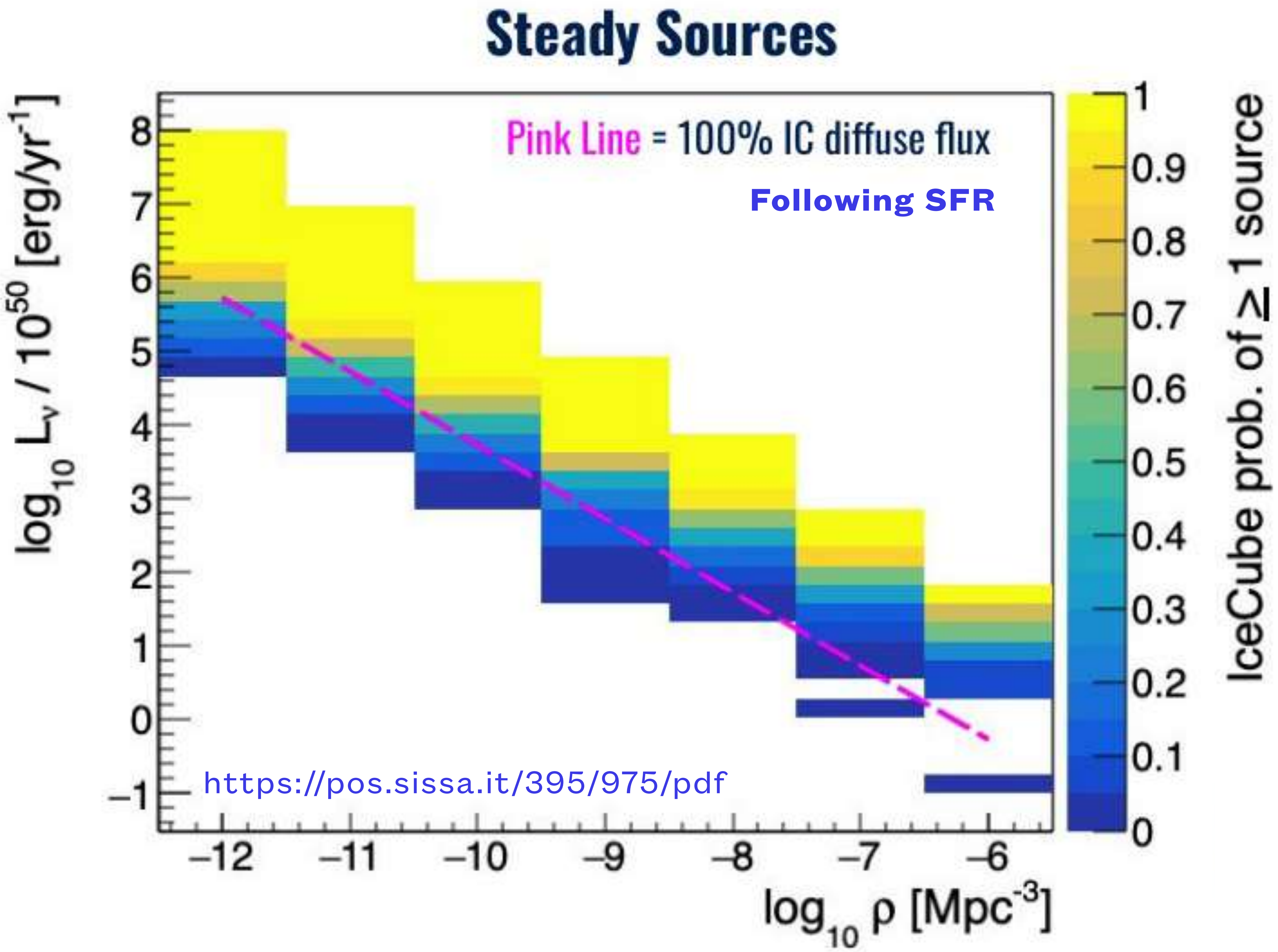
Magnetic field effect: 10-30% difference for low to high zeniths

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

O. Sergijenko

Neutrino FIRESONG (Tung et al. 2021)

https://github.com/ChrisCFTung/FIRESONG



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O. Sergijenko

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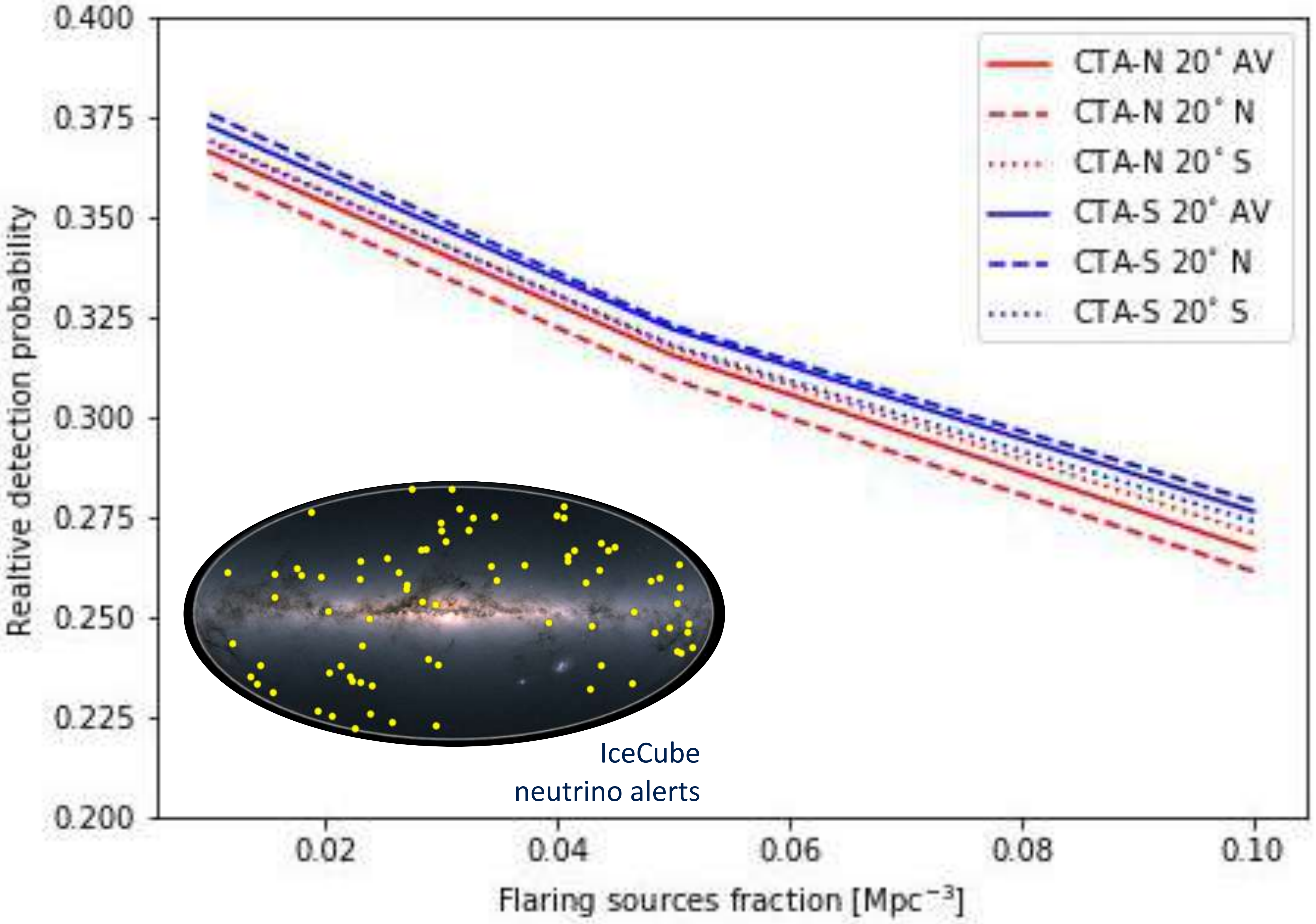
CTA 30 mins obs; Flaring blazars



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 20º and 40º zenith IRFs (difference < 1%), decreases by 4% for 60º

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

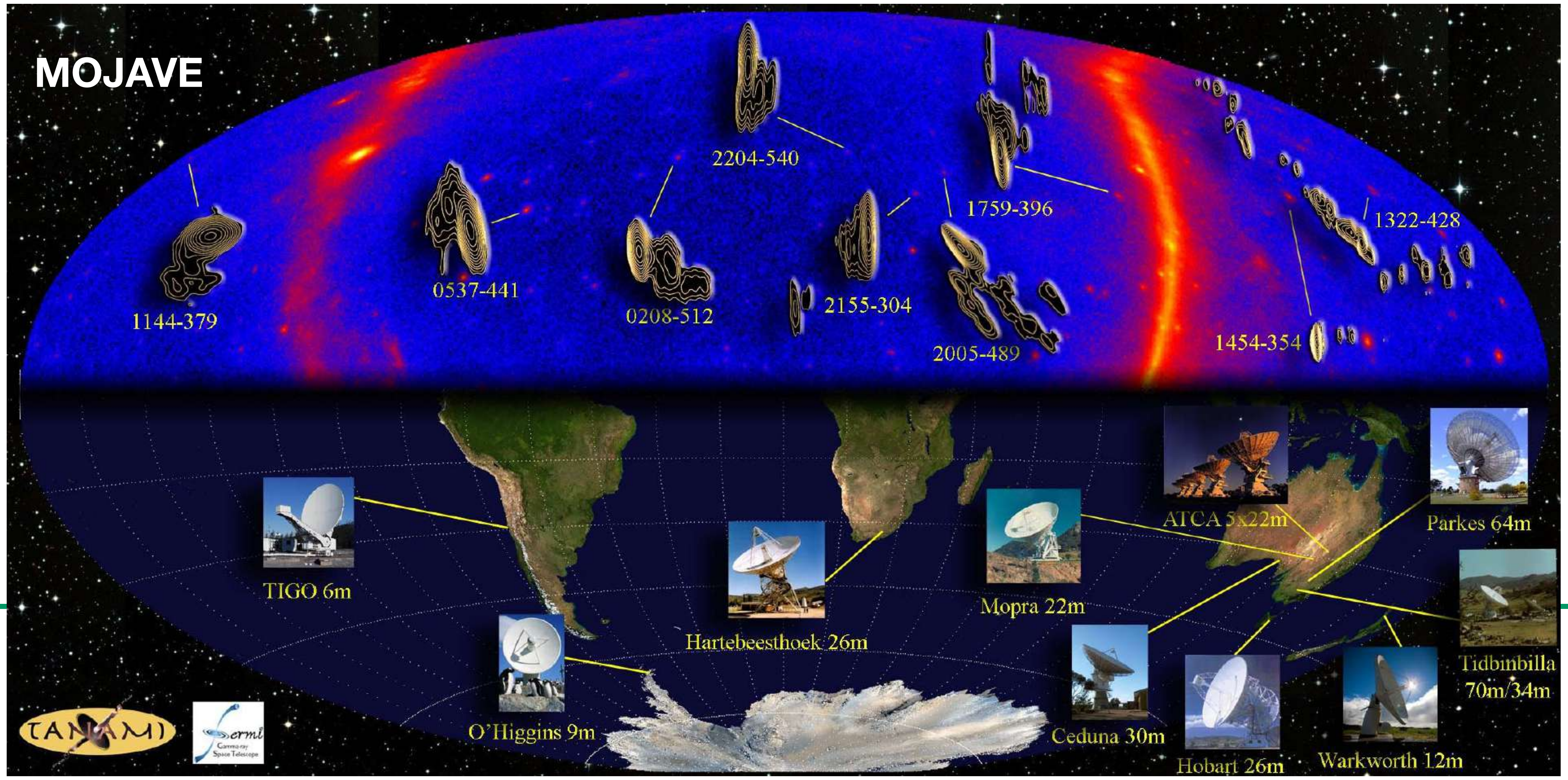
O. Sergijenko

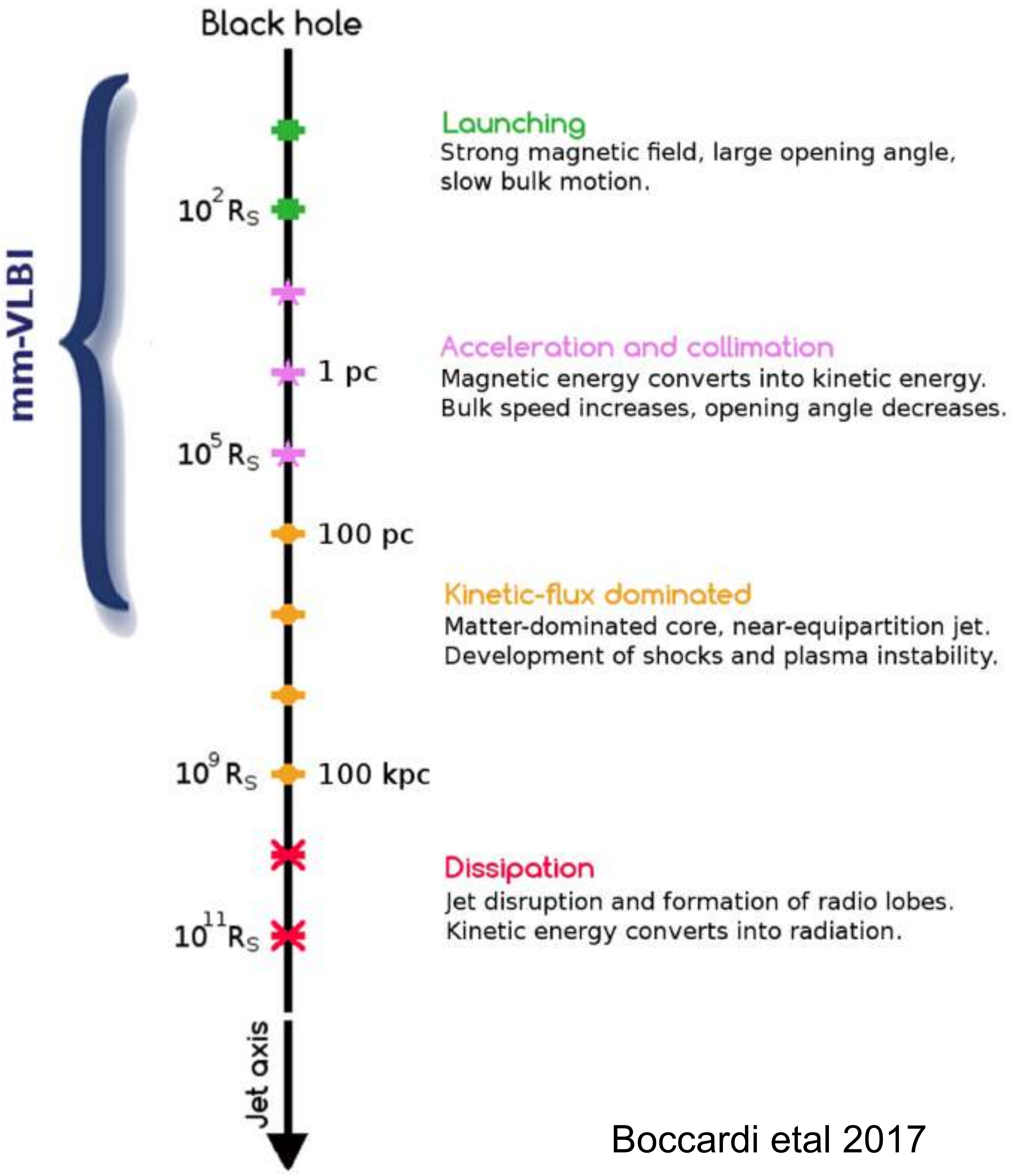
CTA Synergies with VLBI

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.





Boccardi etal 2017

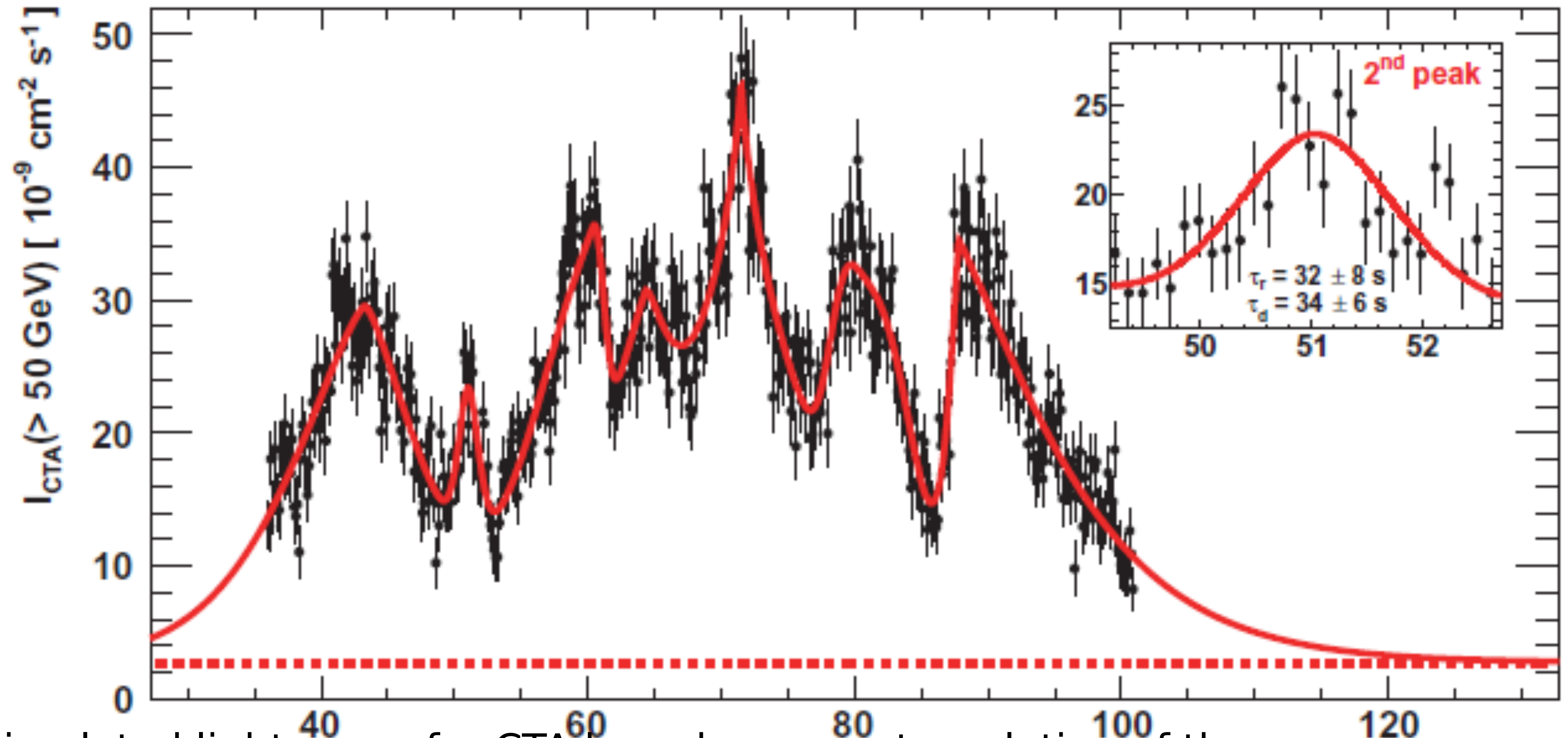
CTA Synergies with VLBI

serrapilheira CBPF

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).

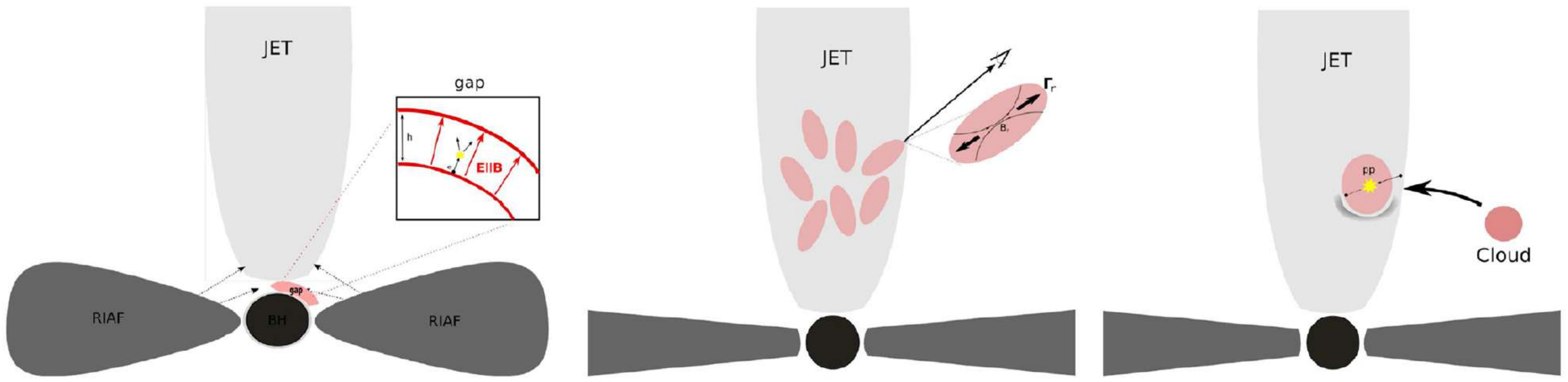
Detailed spectra of emitting regions: combine resolved VLBI spectral data and gamma-ray spectra to provide a deeper look into the gamma-ray emitting process in AGN.



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

Variability seen in γ-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 ~ 8, providing a view at AGN and IGM evolution.

CTA Synergies with X-rays

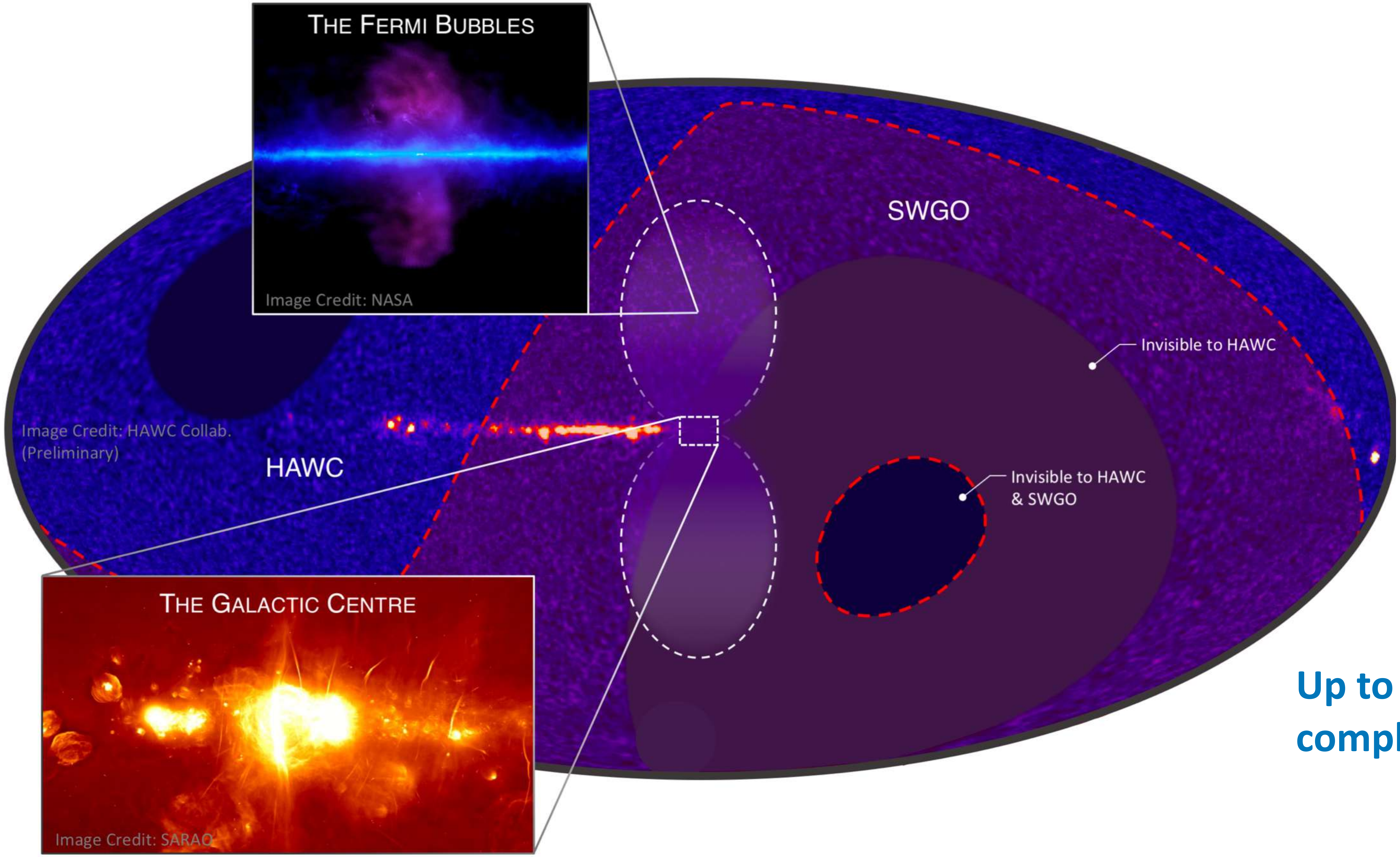
ATHENA will be a major X-ray Mission (planned, 2028) with wide-field / high-spectral and imaging capability at ~ keV energies.

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

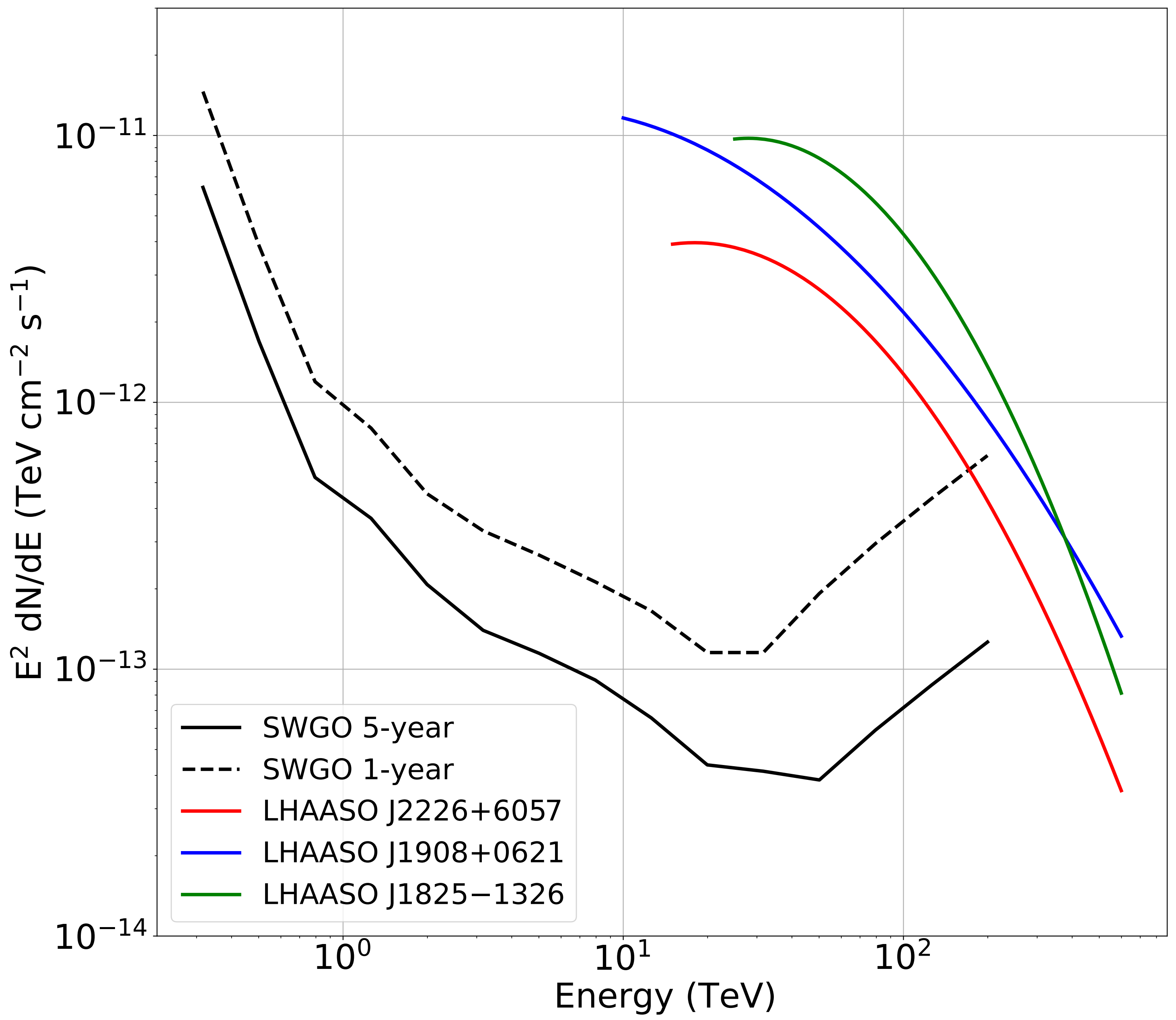
Gamma-ray burst science: As Swift has demonstrated, there is great potential for synergies in GRB science between THESEUS and CTA, in the provision and follow-up of triggers — critically important here is also the future availability of a GeV gamma-ray mission (such as Fermi-LAT today) to help select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

A Wide-Field Experiment in the South



Galactic Accelerators:

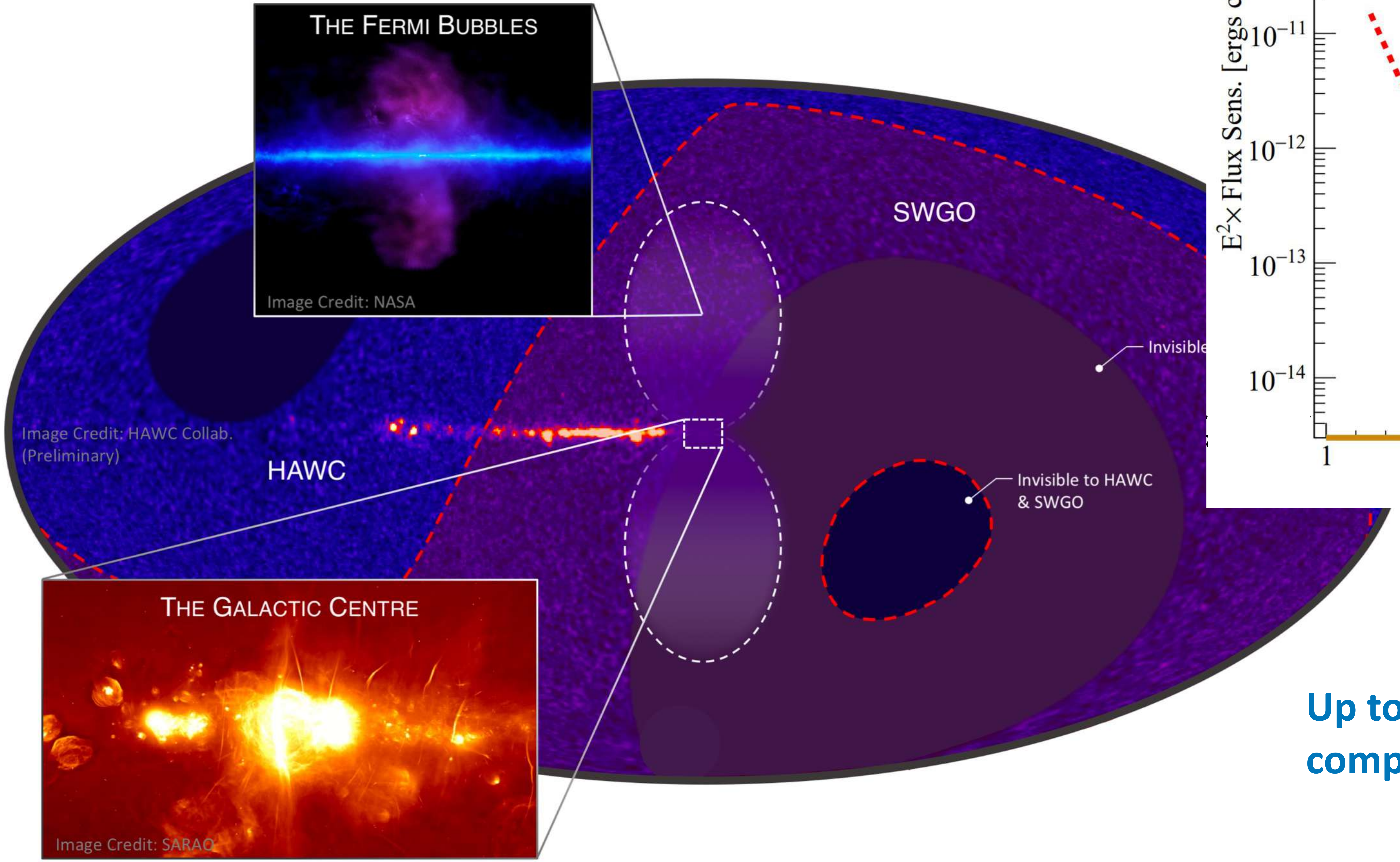
PeVatron Sources

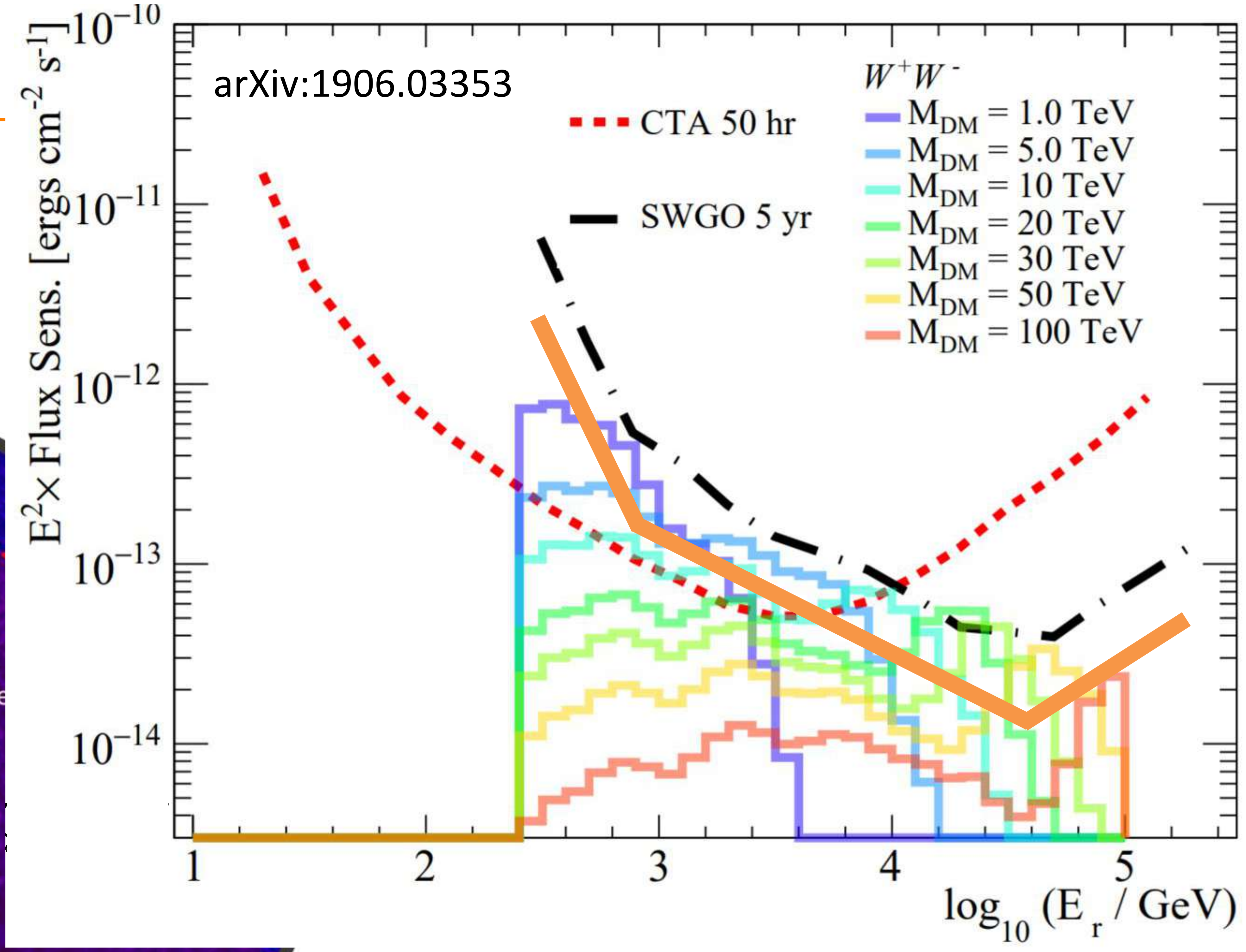


Up to ultra-high energies, > 100 TeV, complementary to CTA measurements

A Wide-Field Experiment in the South

SWGO The Southern Wide-field Gamma-ray Observatory





Fundamental Physics:

Dark Matter from GC Halo

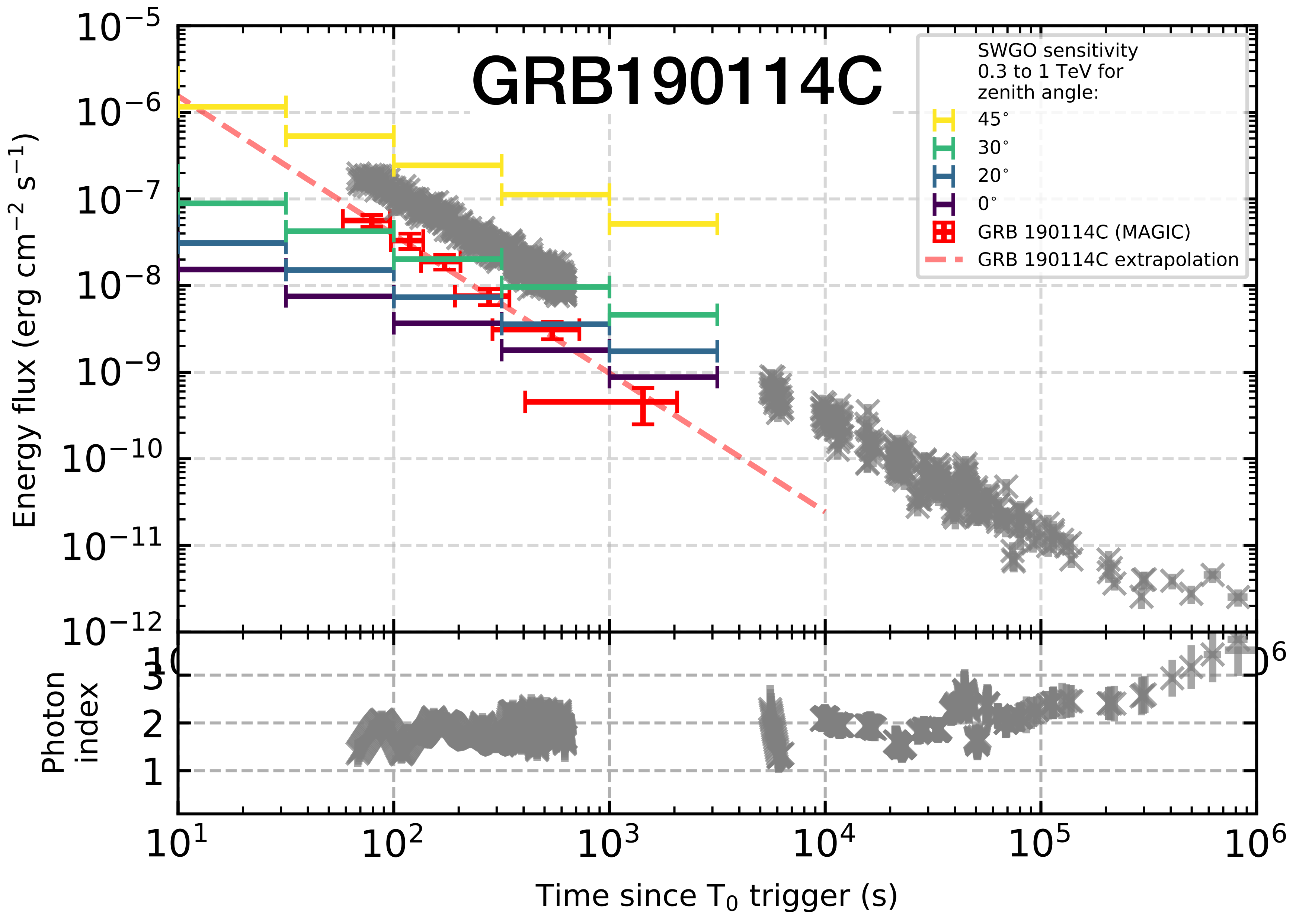
+ other DSphs in the Southern Sky

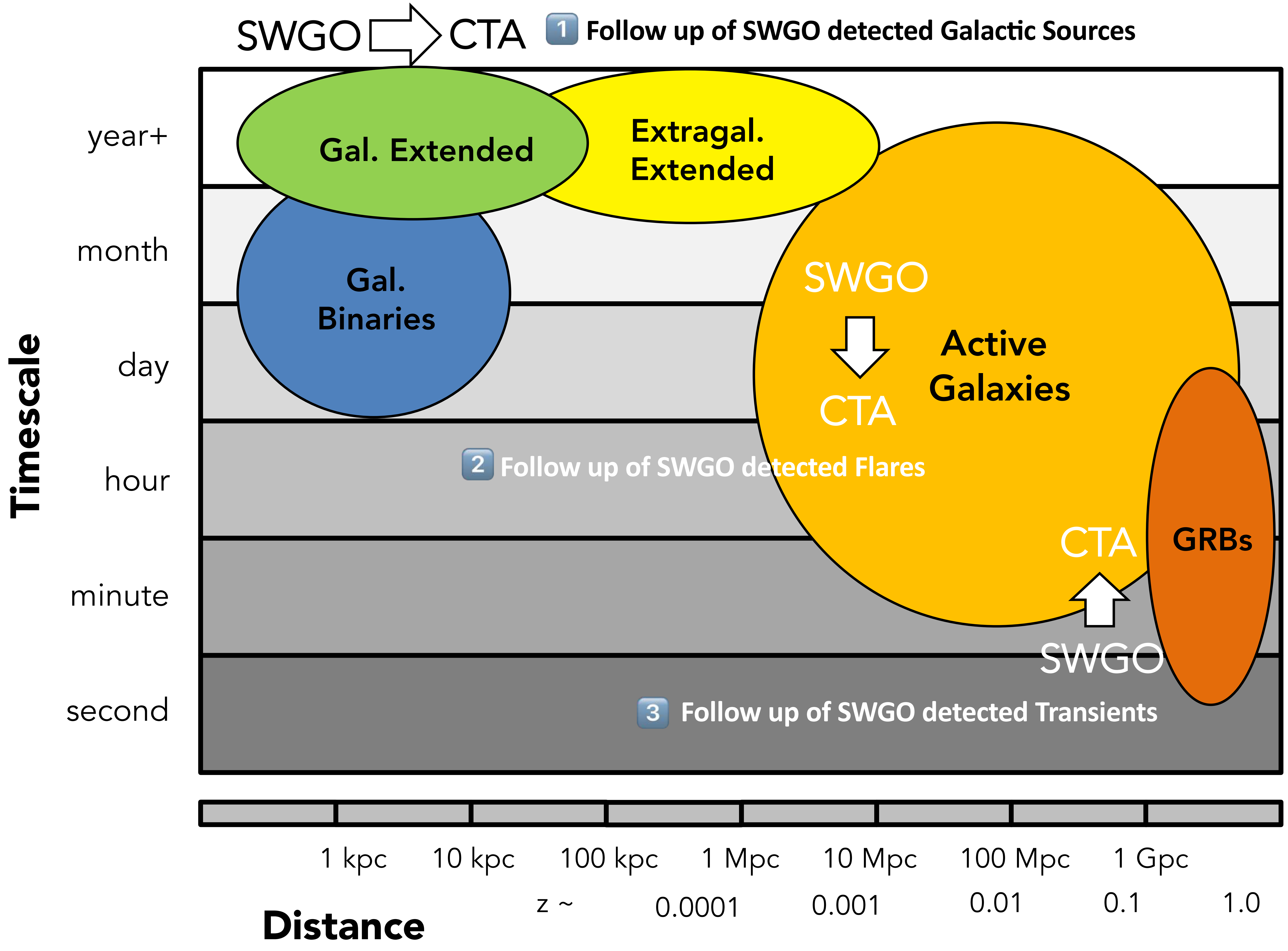
Up to ultra-high energies, > 100 TeV, complementary to CTA measurements.

The Southern Wide-field Gamma-ray Observatory

A Wide-Field Experiment in the South

- **Transient Synergies with CTA-S**
  - ✓ relevant piece in the multi-messenger scenario



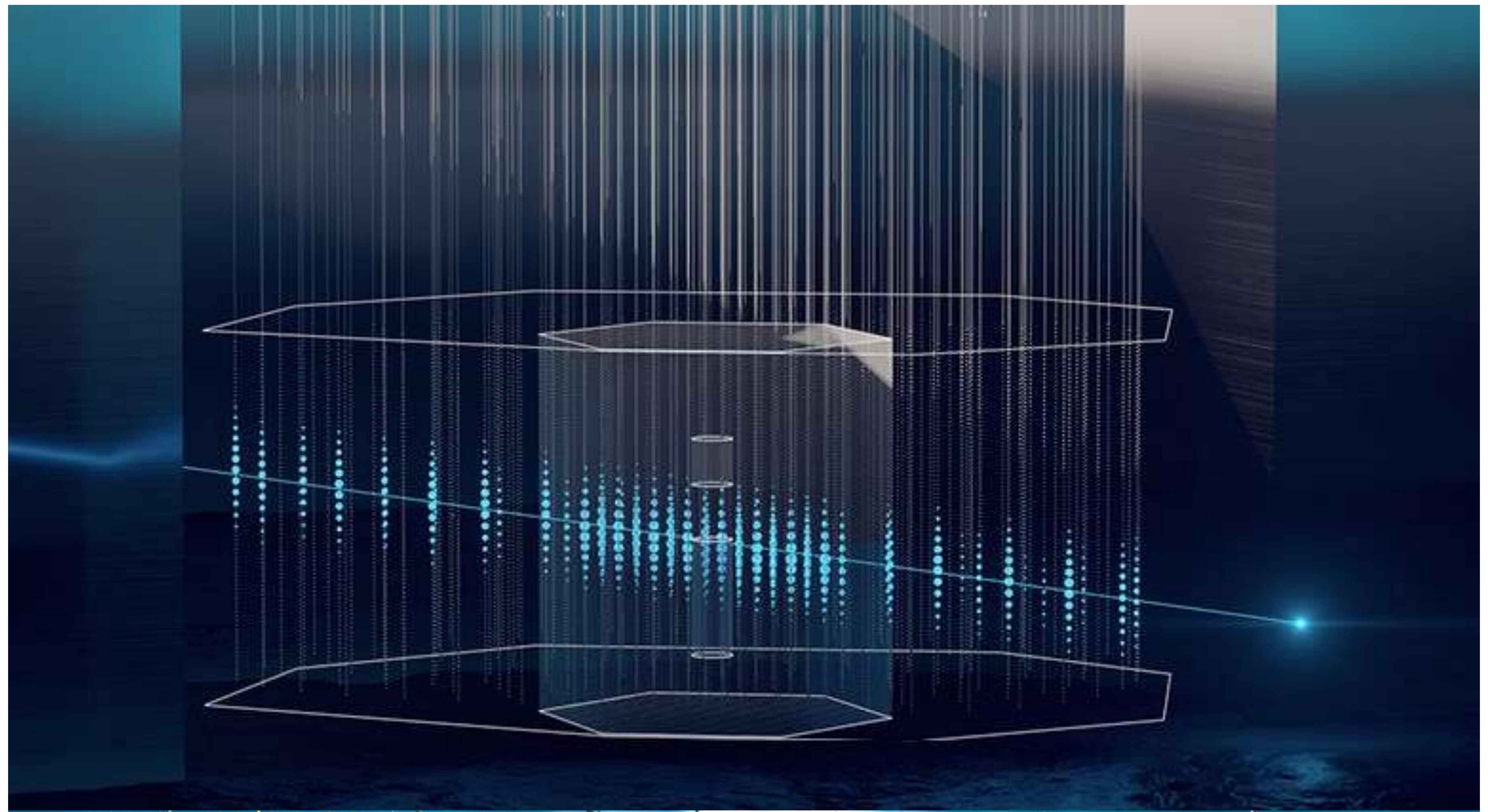


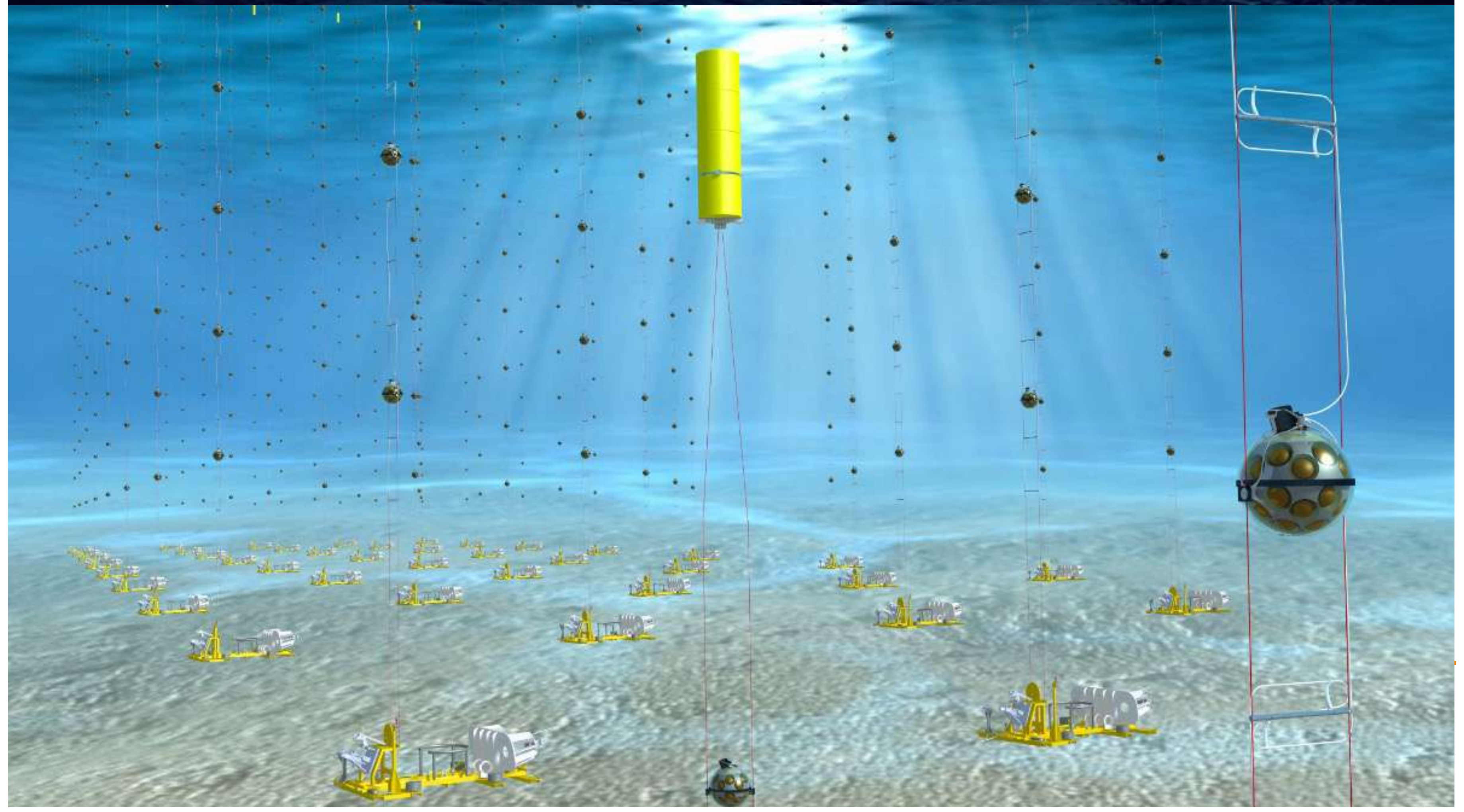
SWGO
The Southern Wide-field Gamma-ray Observatory

A Wide-Field Experiment in the South

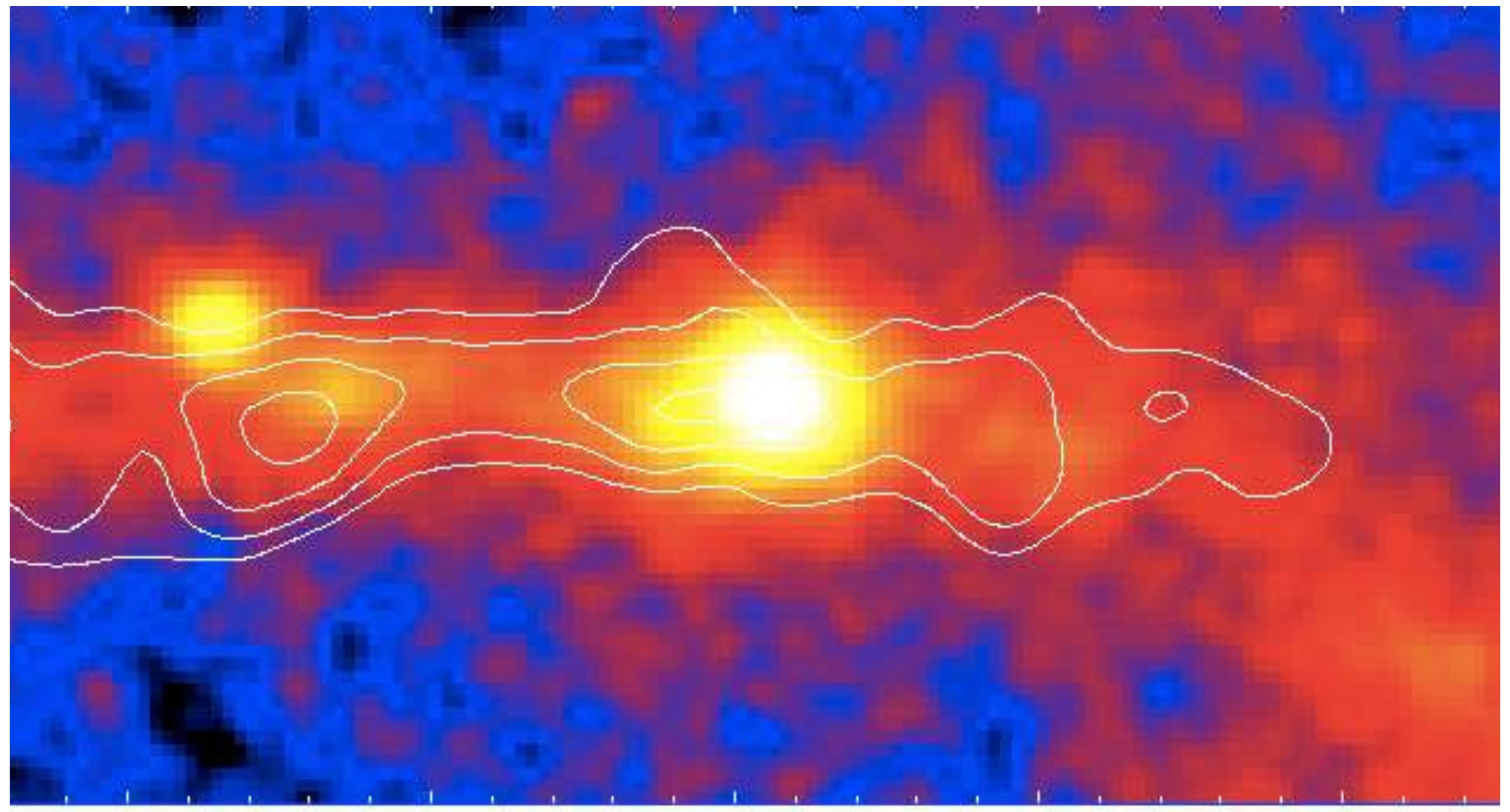
- **Neutrino Synergies**
  - ✓ complementary to new generation of experiments
  - ✓ mapping diffuse emission and separating IC / pion-decay components

- **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/