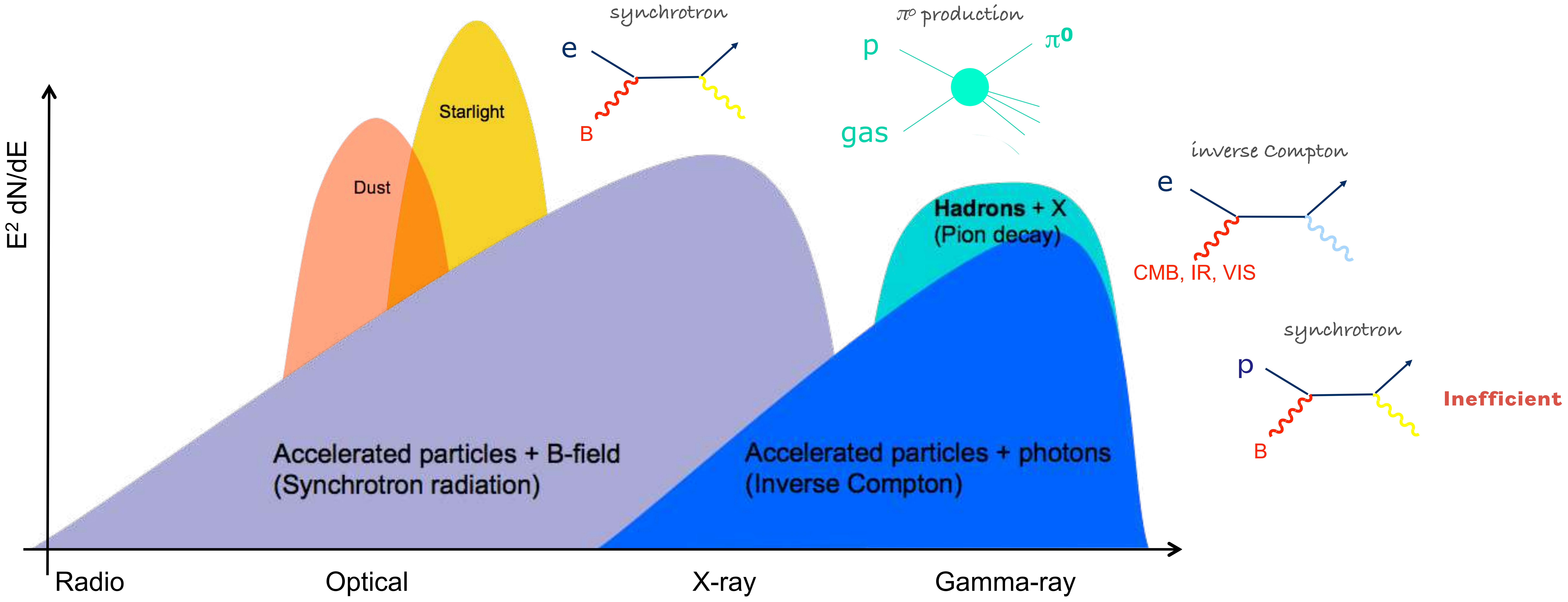
CBPF
Centro Brasileiro de Pesquisas Físicas
UNIDADE DE PESQUISA DO MCTI

CTA Coordination on Real-Time MWL and MM Astrophysics

université PARIS-SACLAY | INSTITUT PASCAL

ULISSES BARRES DE ALMEIDA - NOVEMBER 2023

Multi-wavelength view of non-thermal sources



The multi-messenger connection

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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

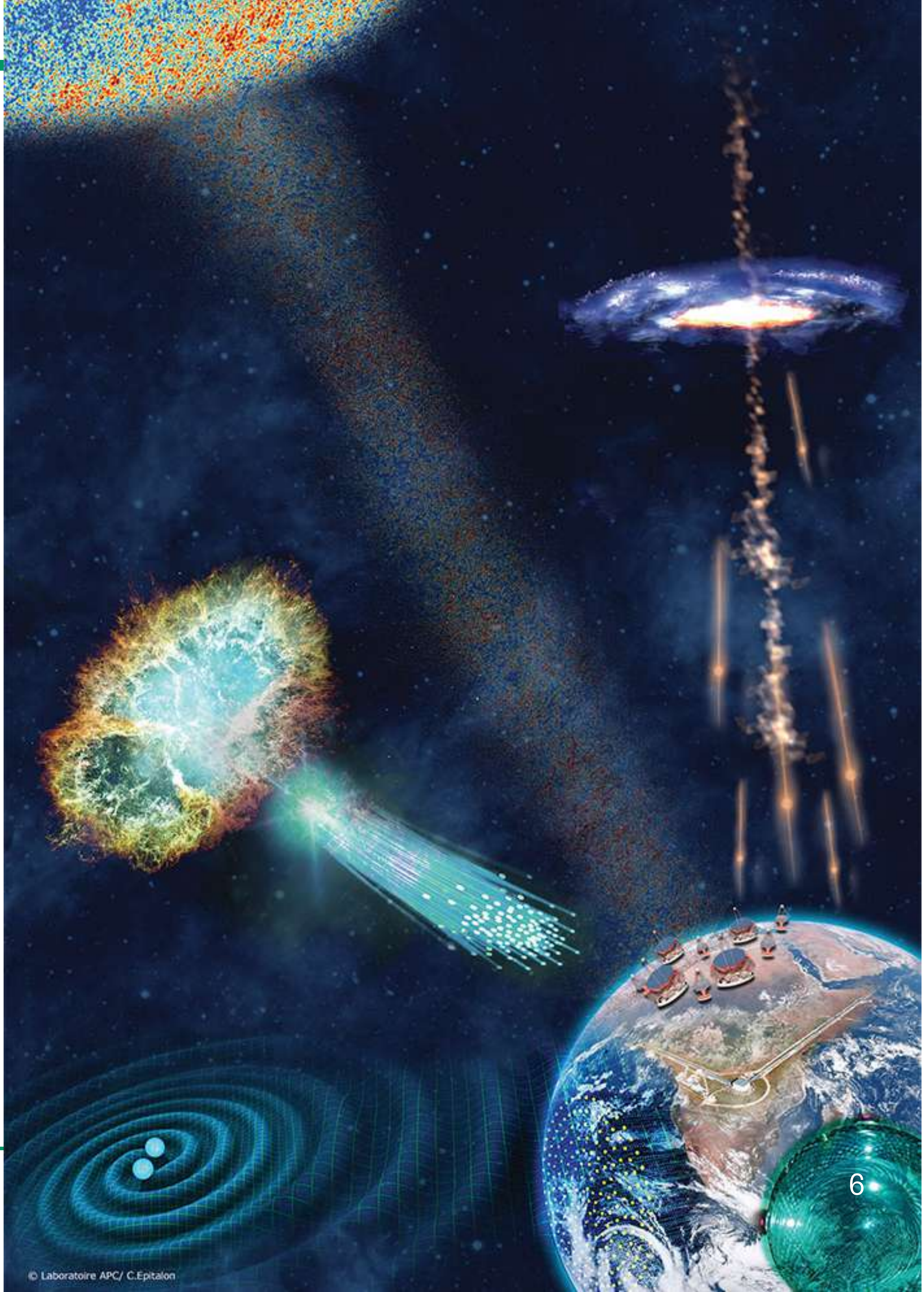
GRAVITATIONAL WAVES? PROBES OF COMPACT SOURCES

ALL-SKY SATELLITES
from MeV → GeV
Electro-
Magnetic
Cascade
~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
Few ns light flash
Cherenkov
Light
~15% duty-cycle
~4 degree field of view
High precision
Large collection area
from 10s GeV → 100 TeV

Gamma-ray Observatories Worldwide

Real-time / MM coordination with CTA...

1. Operate within a network of facilities from radio to gamma-rays
2. Explore the synergies with satellite and wide-field gamma-ray facilities
3. Ability to respond to alerts (from transients and MM events)
4. Achieve good angular resolution for counterpart association and temporal resolution for transient detection
5. Ideally, with a full sky coverage



Thanks to Werner Hofmann

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

CT1
operat

New instrument

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

Cost ~ 330 MEuro for construction (cash + in-kind)

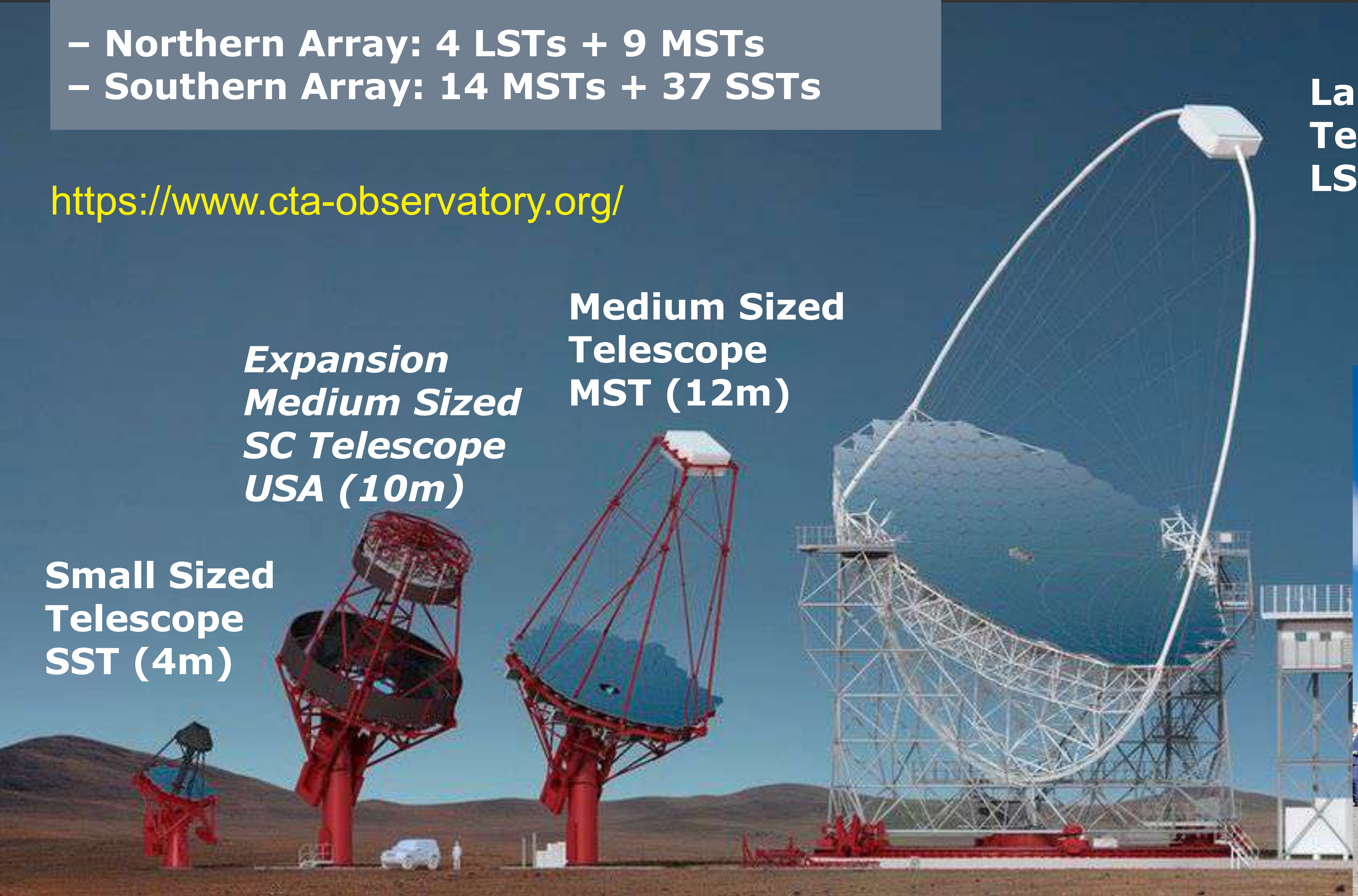
All construction funds available!

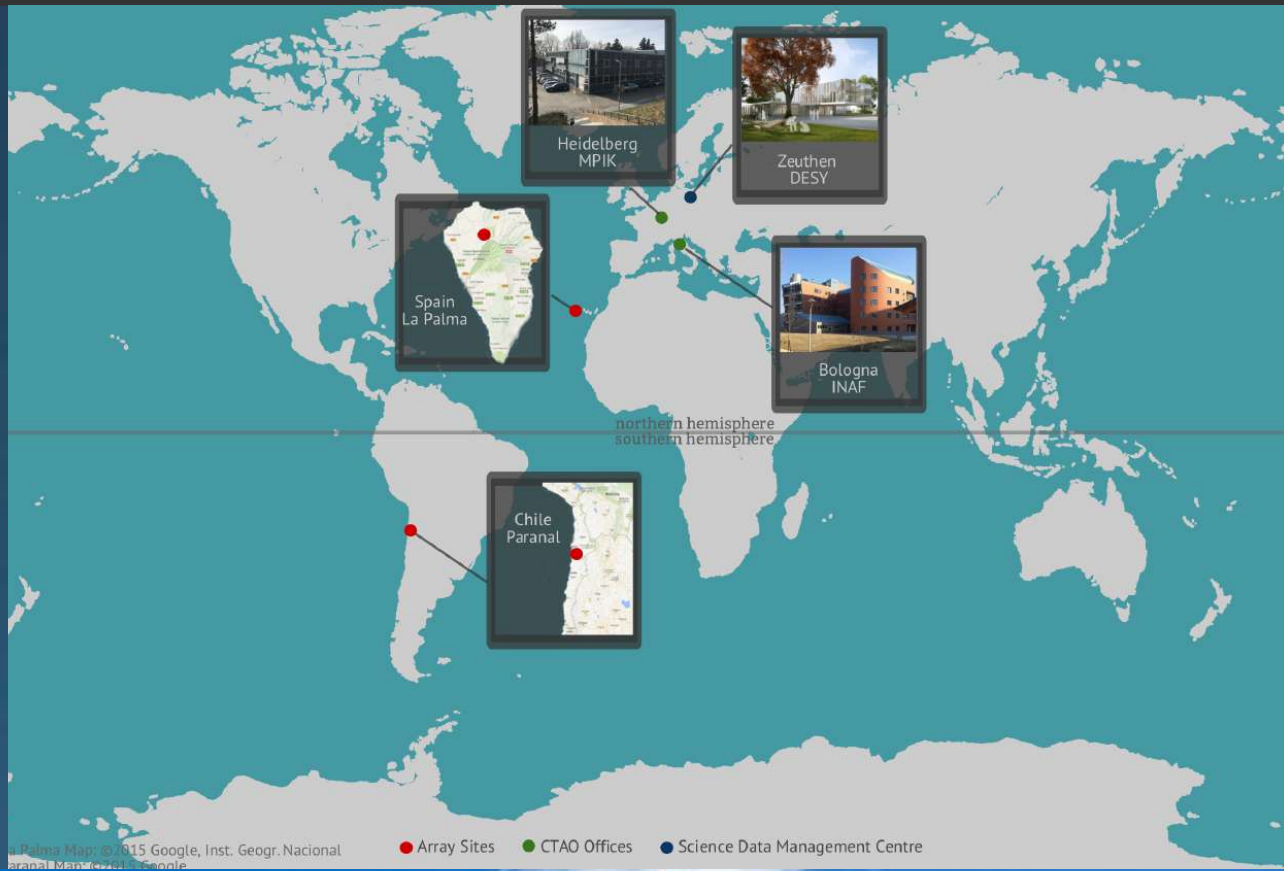
CTA Observatory (CTAO)
- CTA-North La Palma
  (1st telescope operating!)
- CTA-South in Chile
- CTA HQ, Bologna
- CTA Data Centre, Berlin

CTA Arrays "alpha" Configuration

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

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





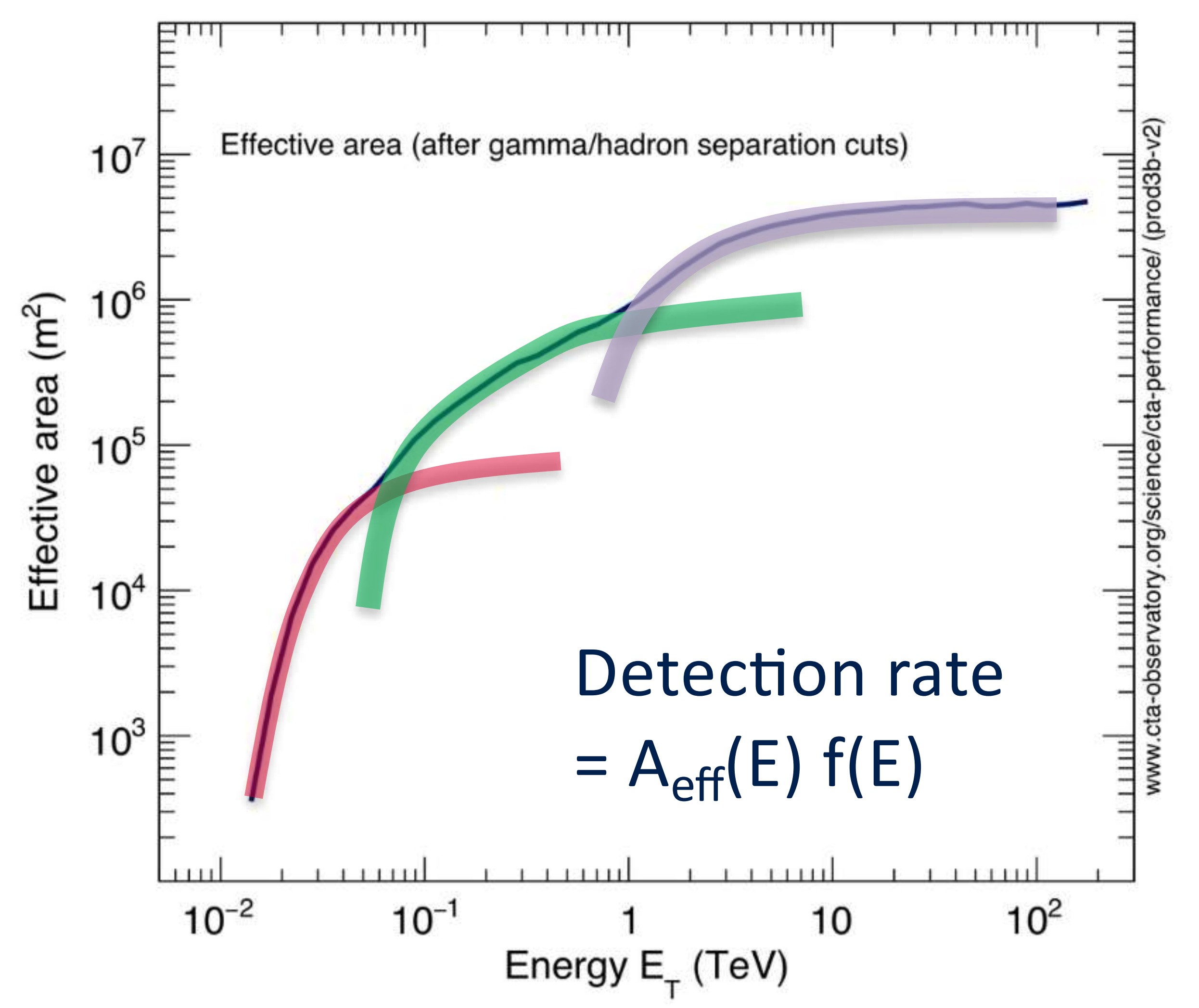
10 GeV | **100 GeV** | **1 TeV** | **10 TeV** | **100 TeV**

$1000\ \gamma$ / h km^2

$10\ \gamma$ / h km^2

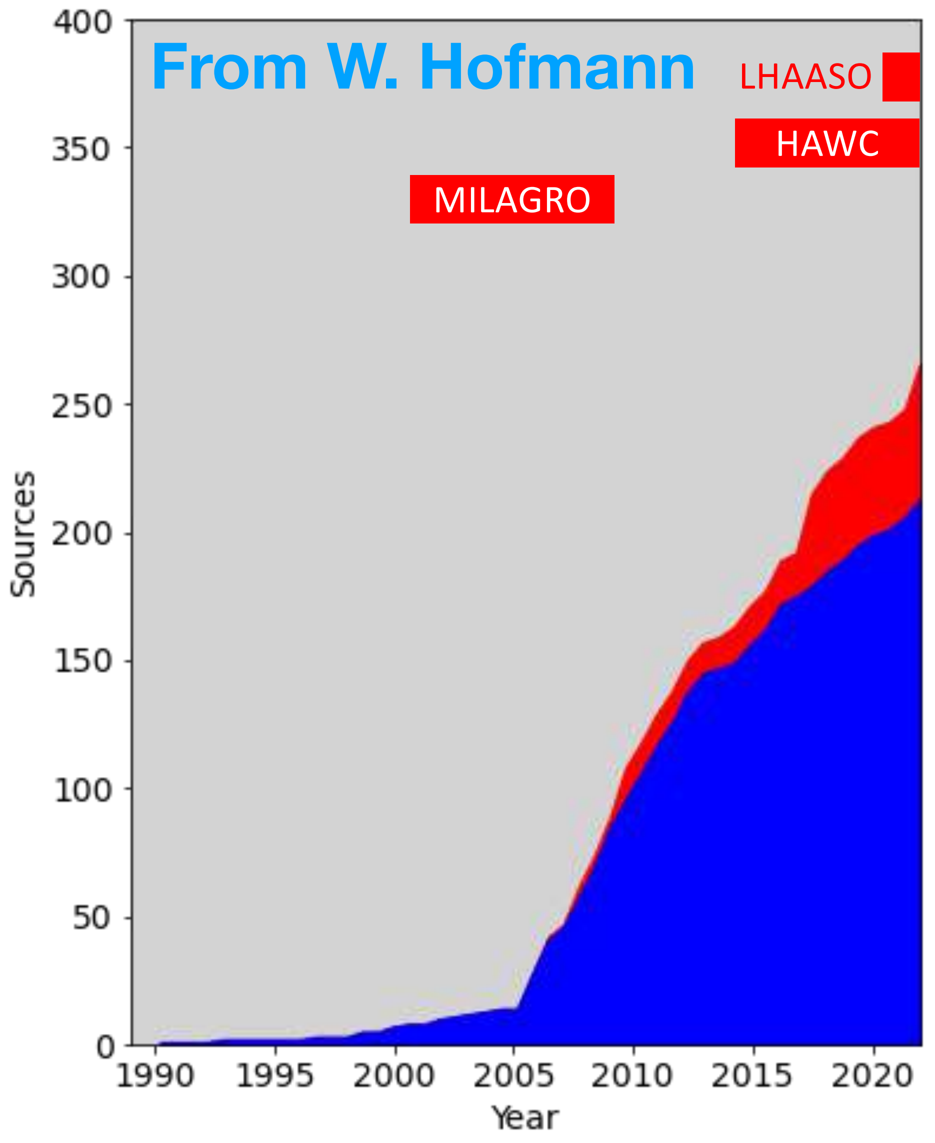
$0.1\ \gamma$ / h km^2

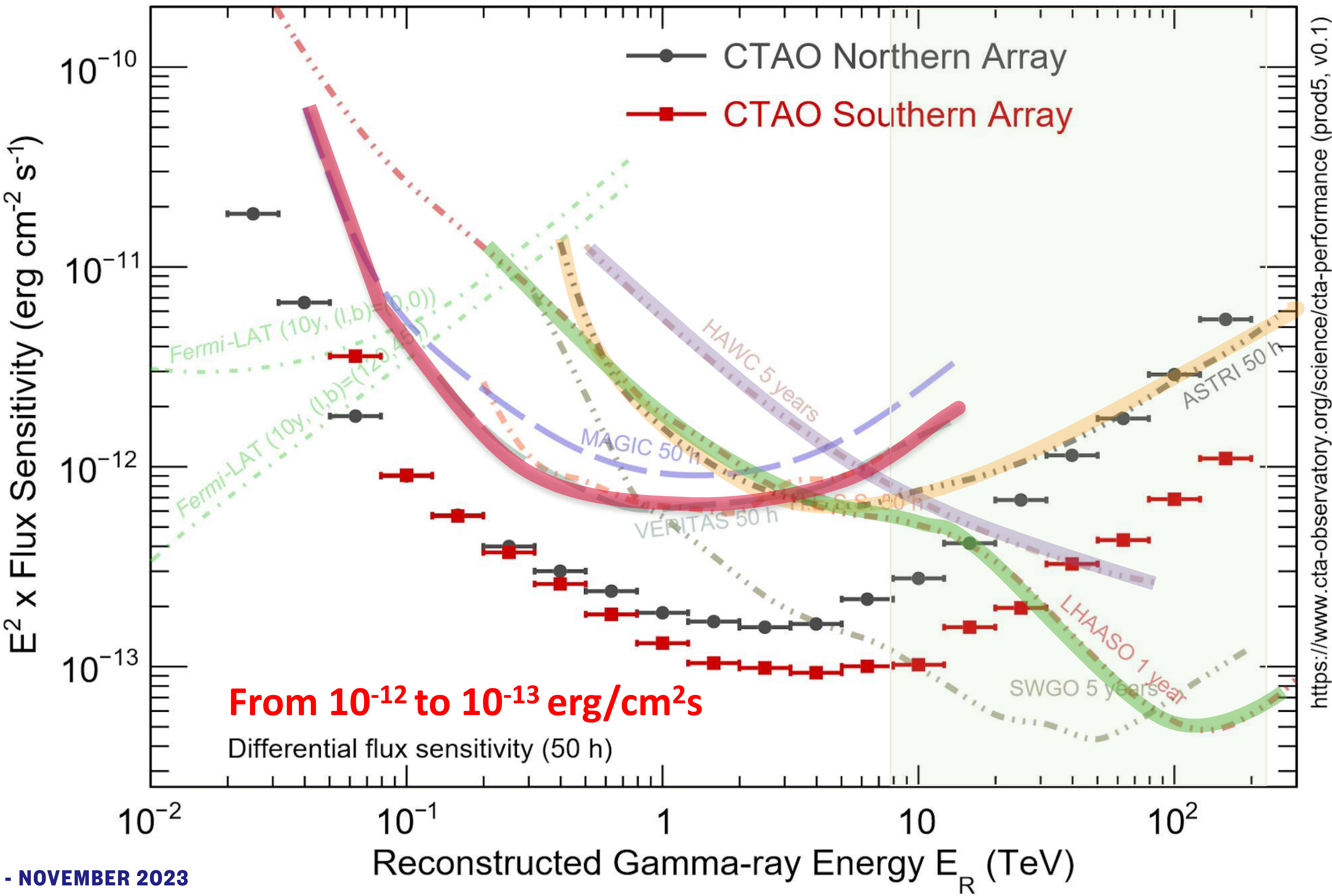
Cherenkov Telescope Array layout



Southern array
of Cherenkov telescopes
- about 3 km across

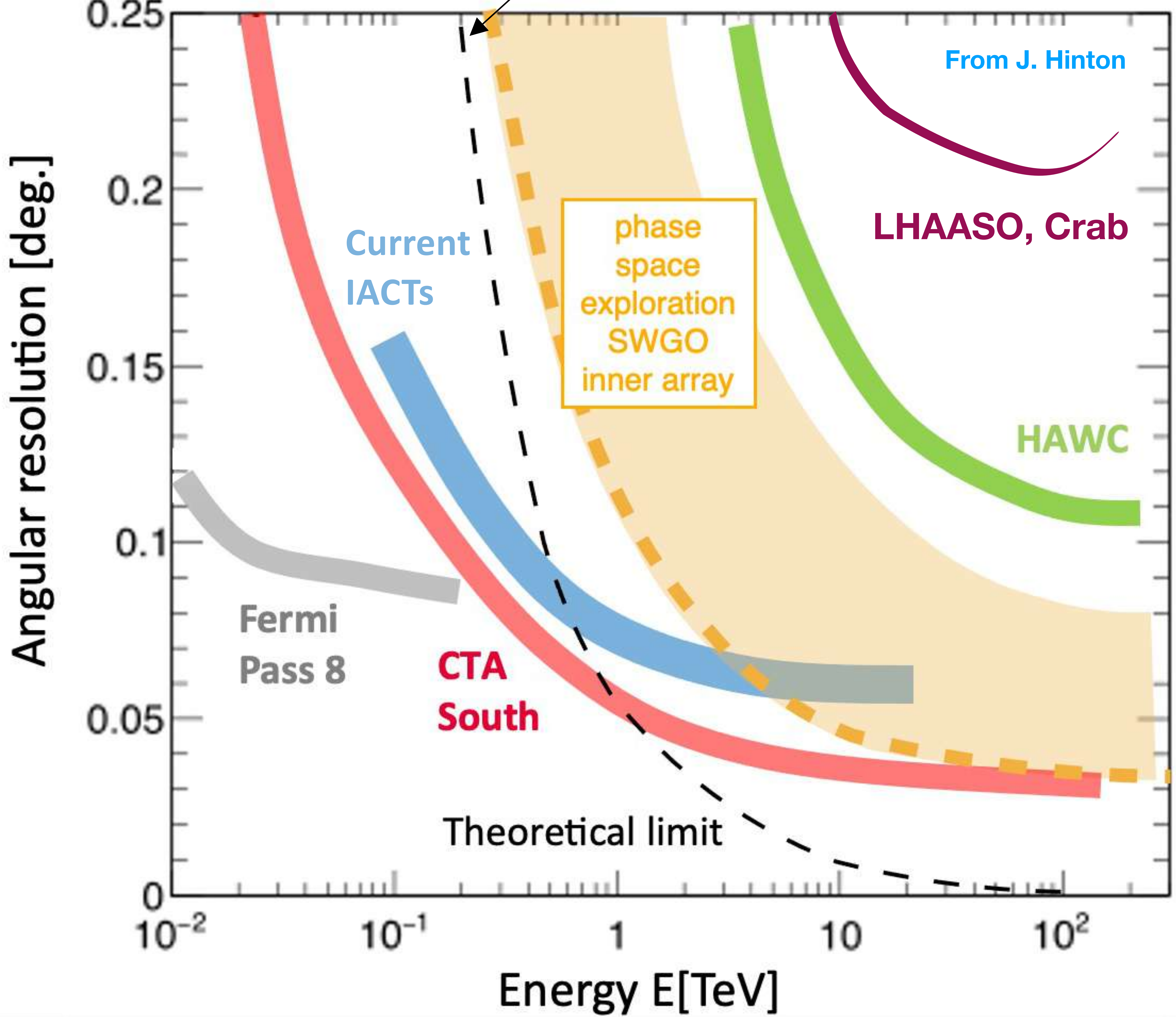
Gamma-ray Capabilities





Angular Resolution

Hofmann (2020) Astroparticle Physics 123, 102479



CTA as a player in the MWL+MM arena

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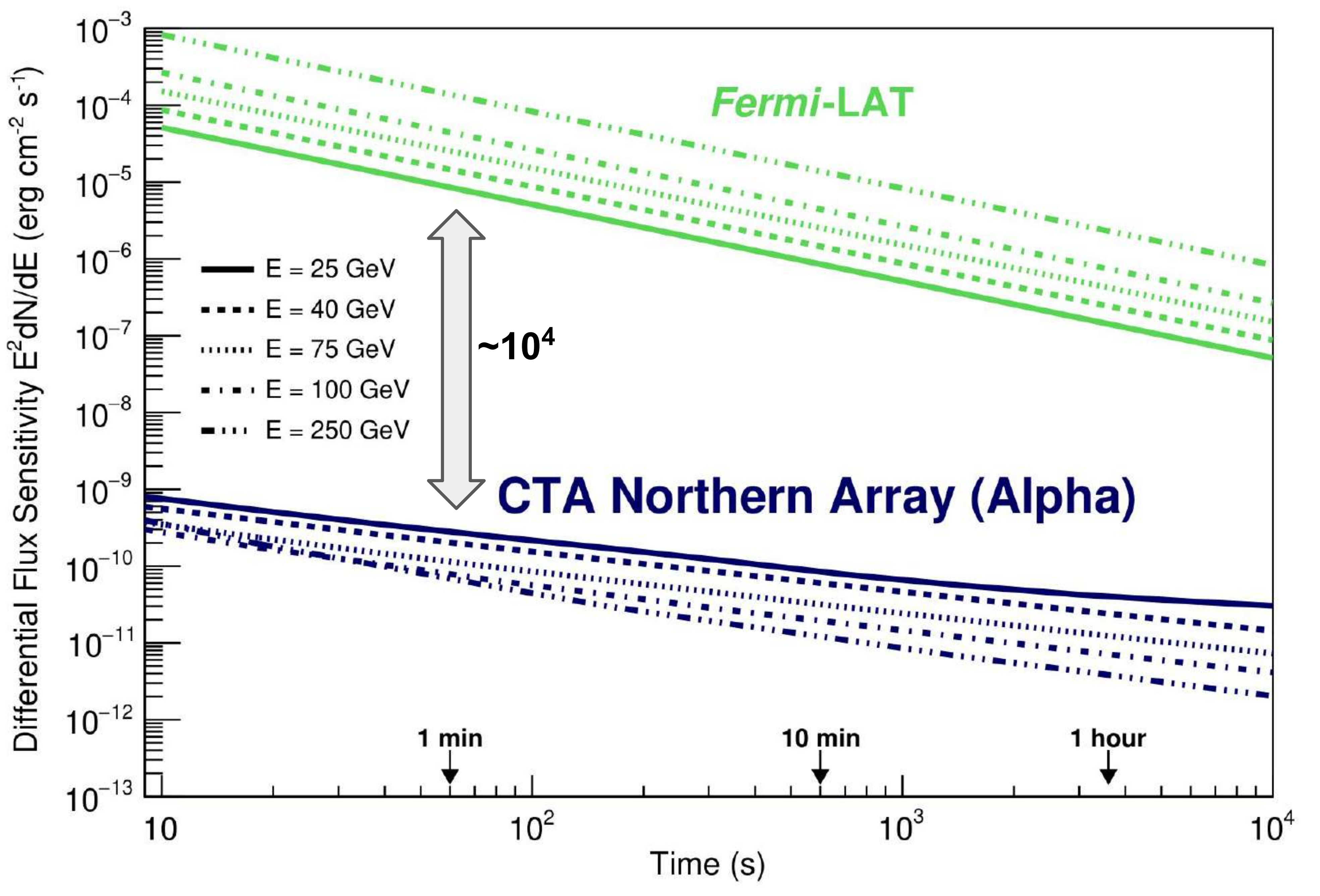
CTA will be the largest <u>(open)</u> observatory in the VHE range (20 GeV - 300 TeV), with two sites in both hemispheres for full sky access

- 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 between in 2027 : contemporaneous to a new generation of MWL and MM instruments

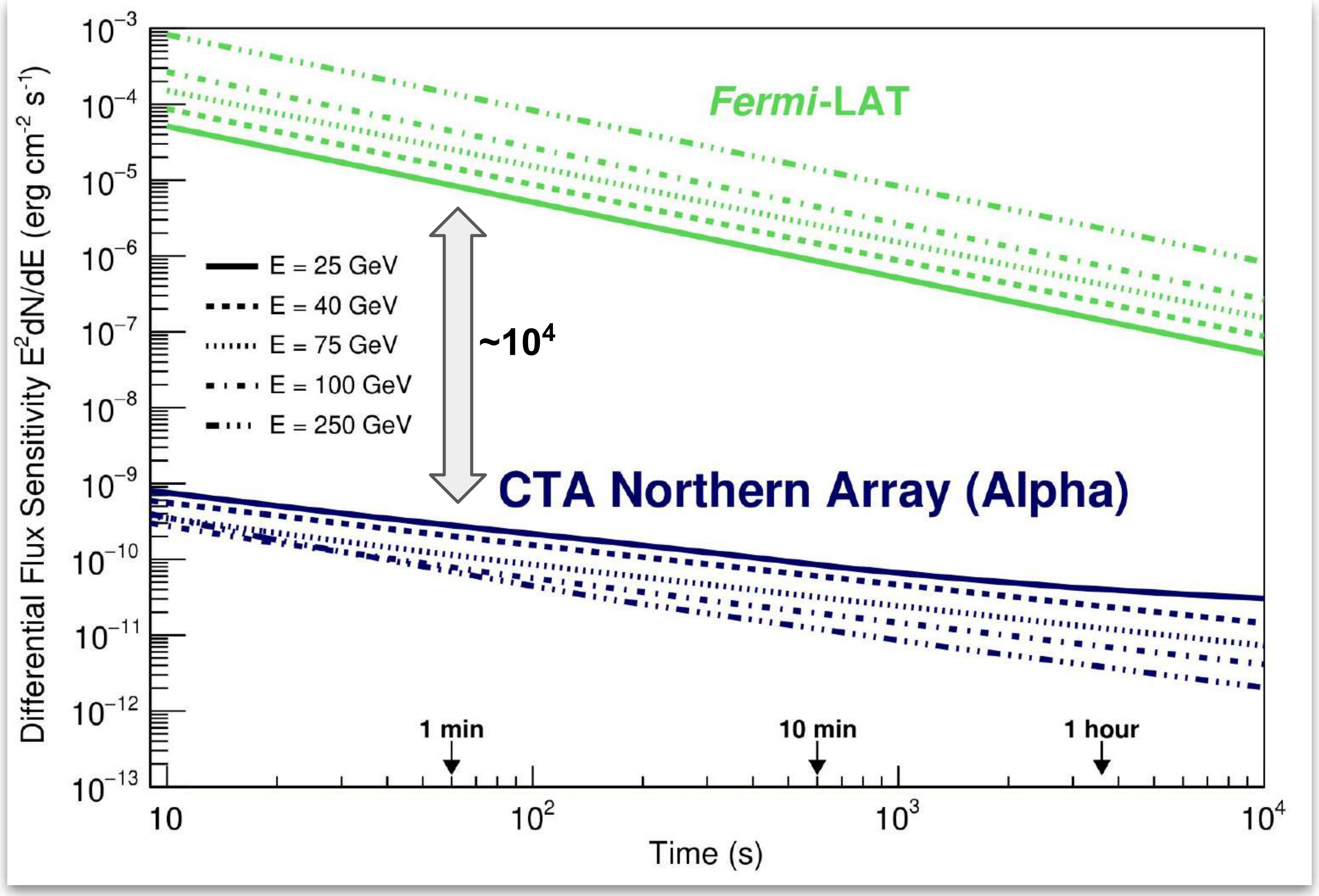


https://www.cta-observatory.org

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, ~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.



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CTA follow-up observation strategy

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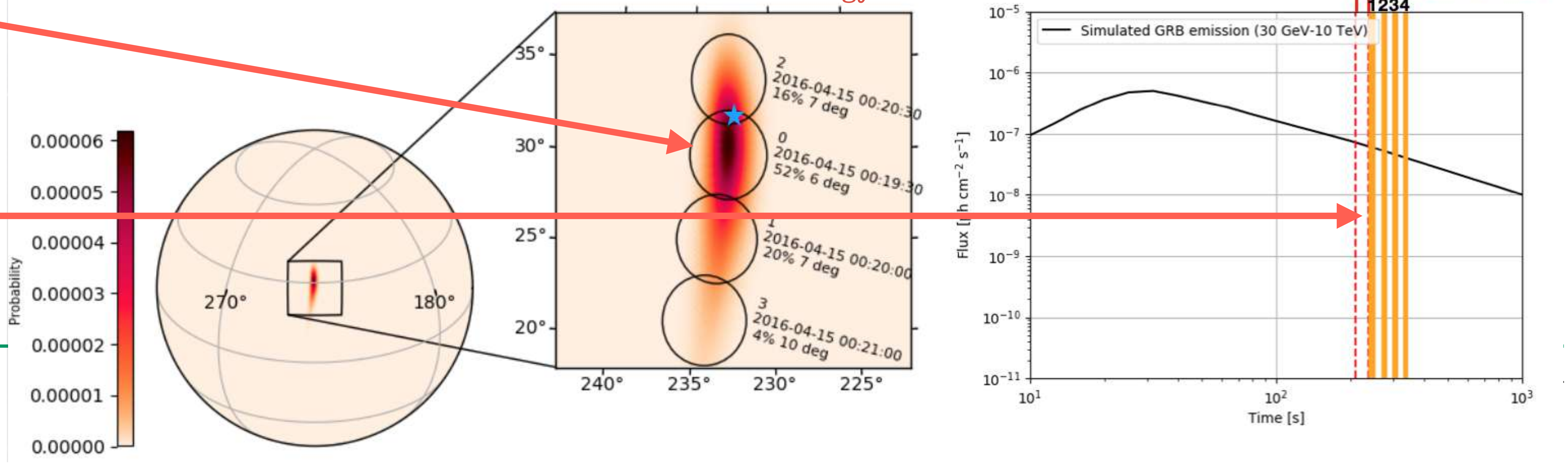
- **CTAO will perform regular (1-3x per week) follow-up observations of GW-GRB and (golden) ν alerts**
- **The observational strategy** is a key element for the success of the programme
  - Optimal pointing pattern to cover the largest total alert uncertainty region (10-1000 deg^2)
  - Optimal pointing 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

Fully automatic tiling observation strategy



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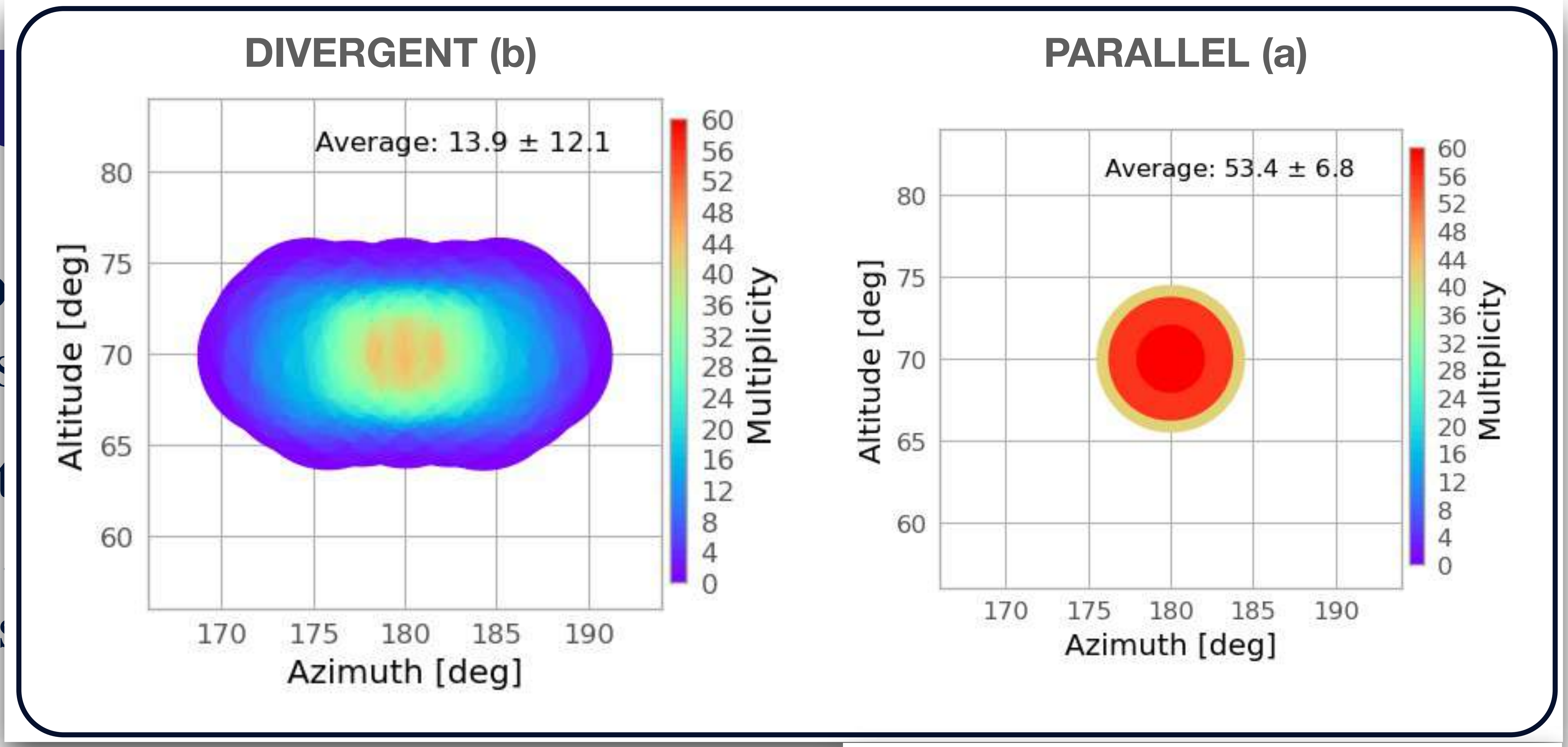

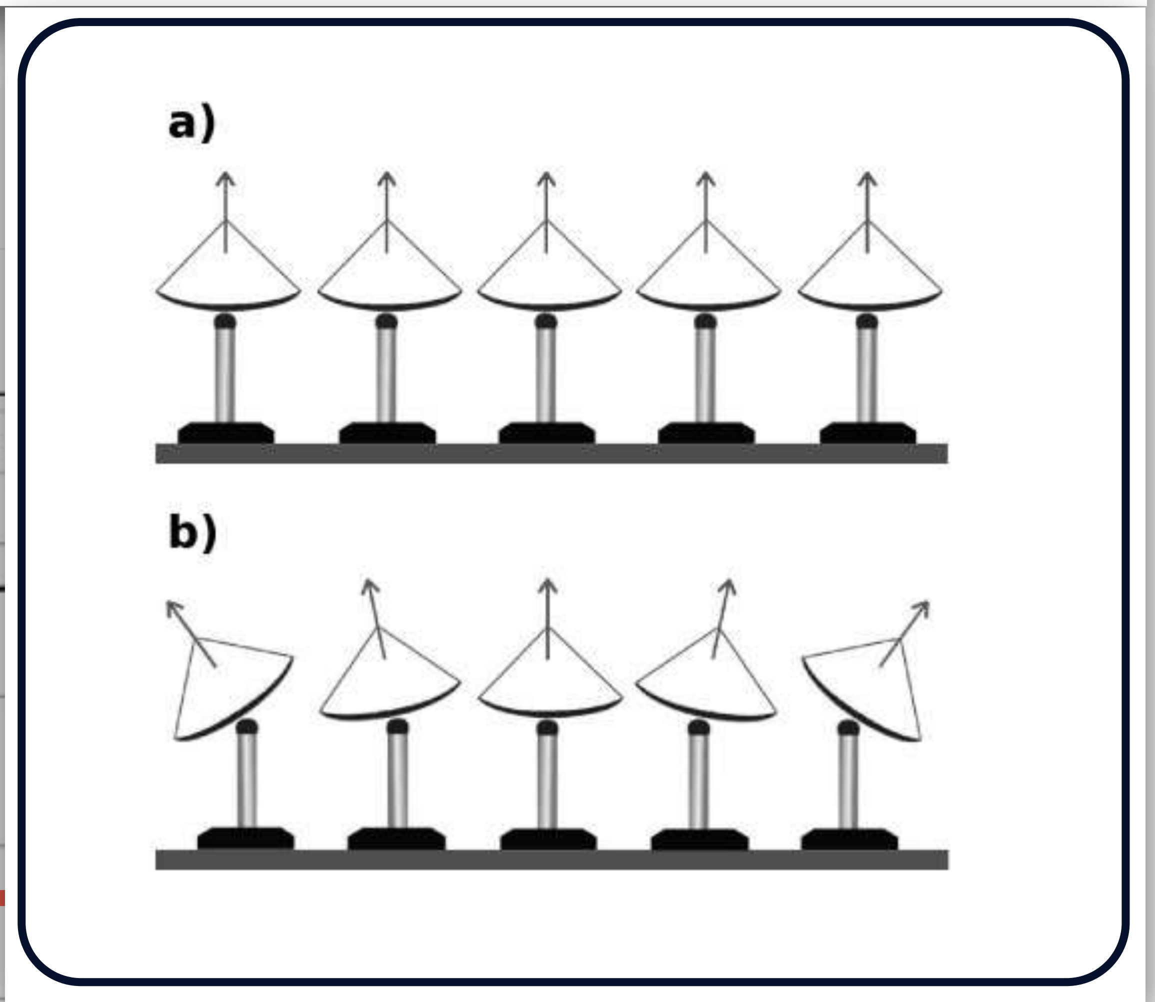

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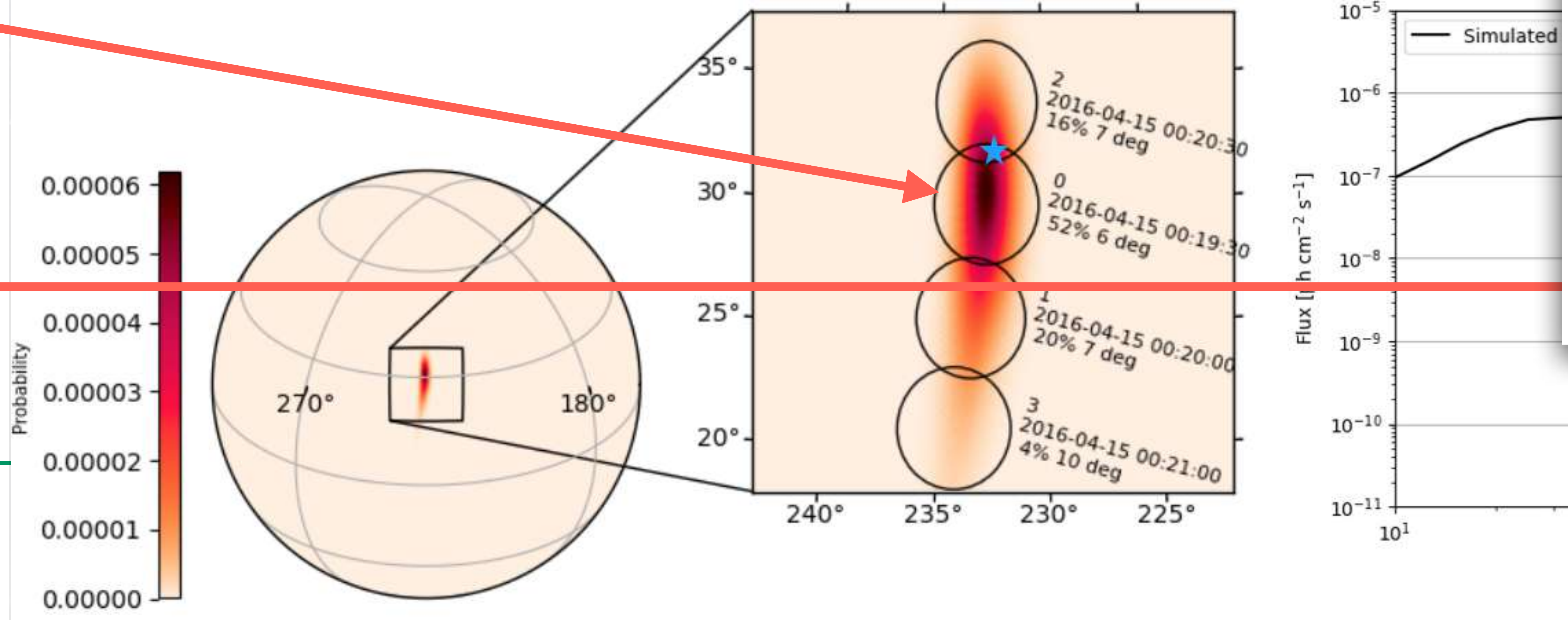

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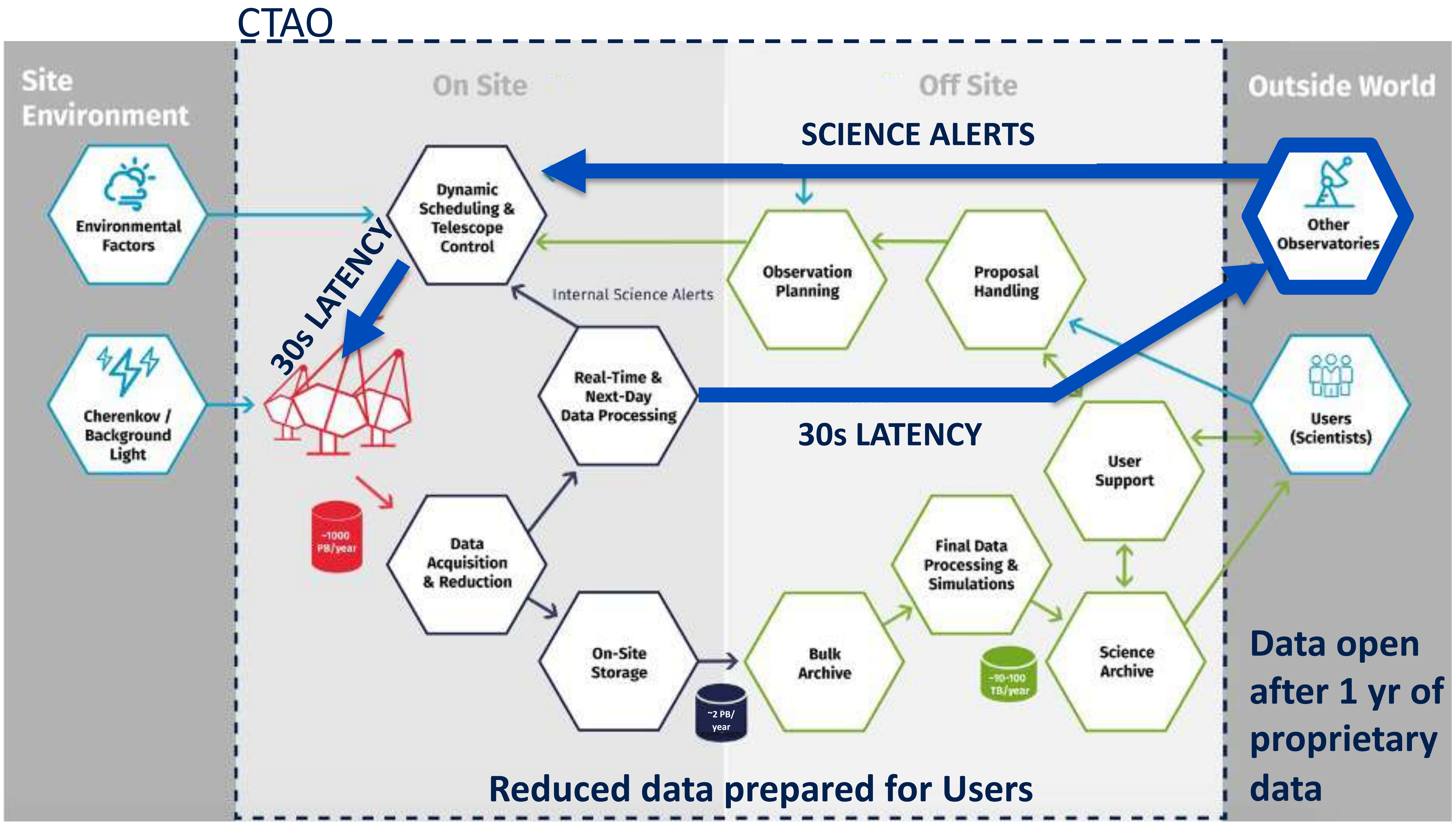
CTA Operations : alert and follow-up



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

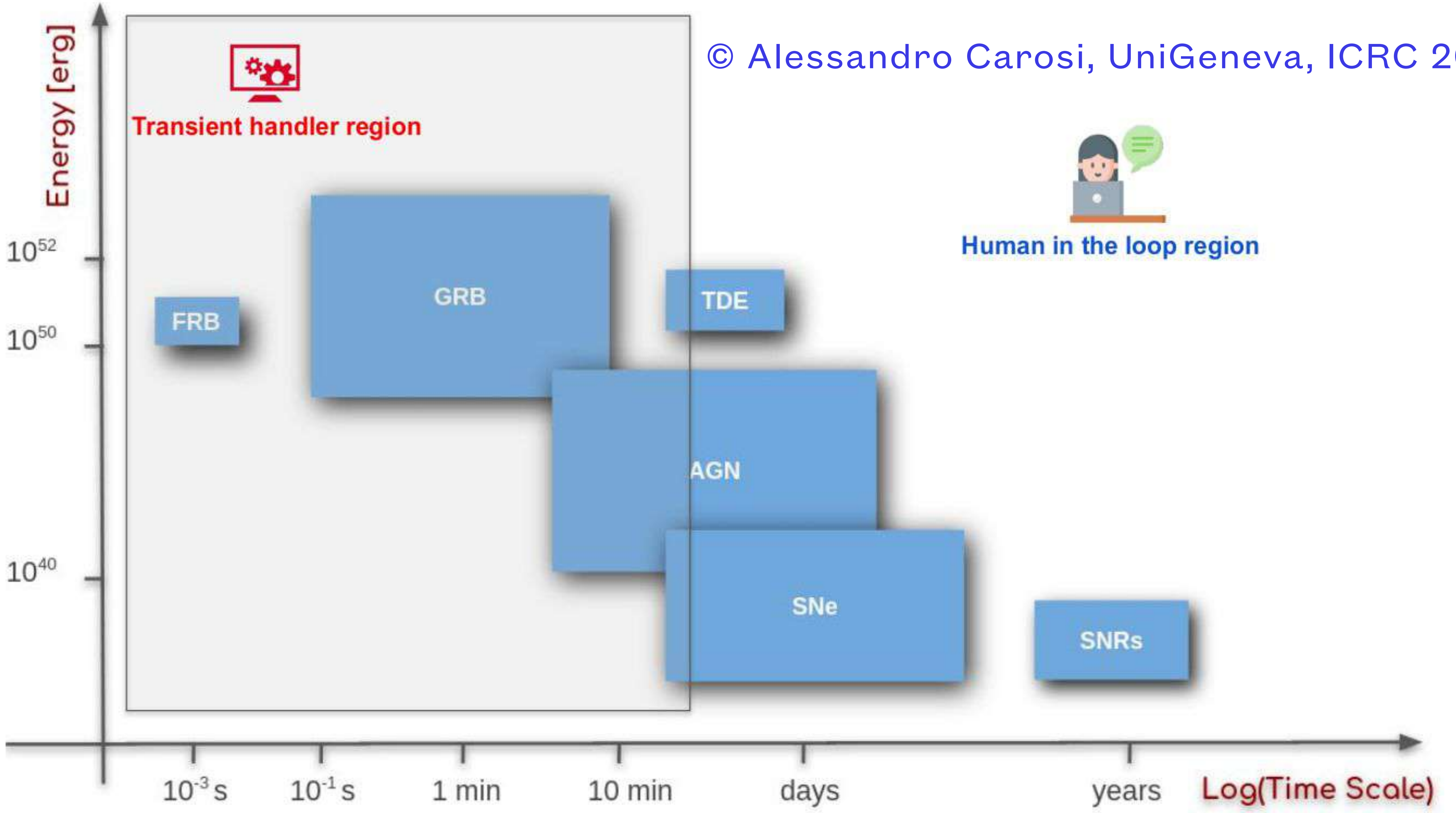
Efficient science alert generation - Alerts will be generated with a latency of 30s

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 Operations : coordination

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



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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

Building operational requirements for CTAO

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 for 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.

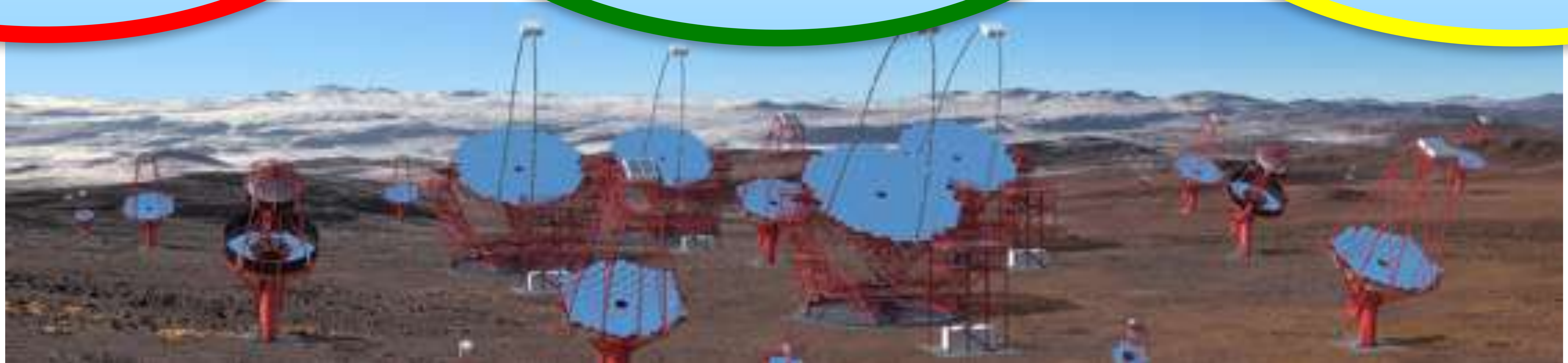
CTA SYNERGIES WITH MWL INSTRUMENTS

© slide by Werner Hofmann

Target selection & ToOs

Object characterization

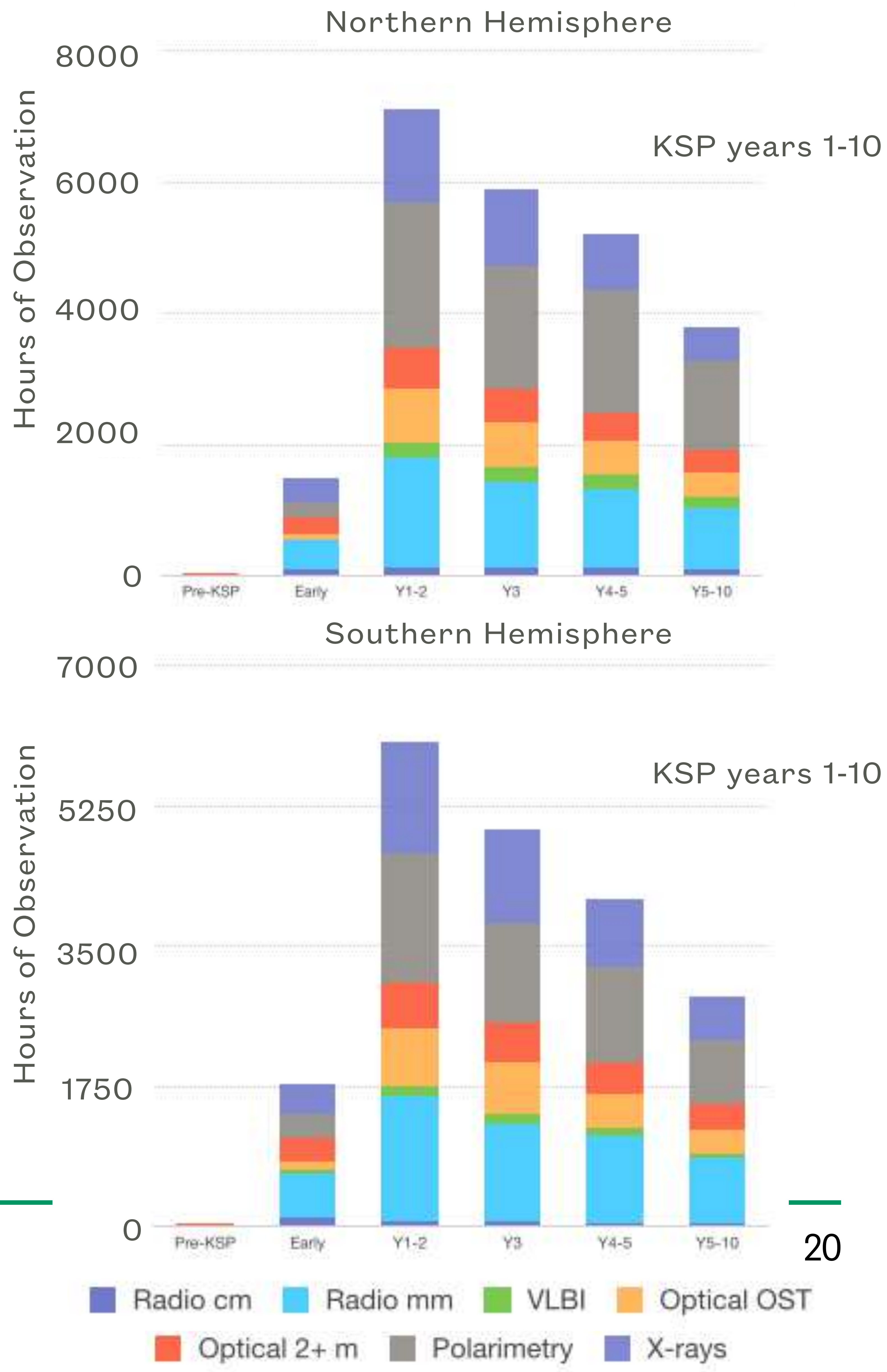
Wide-band / MM SED



CTA MWL & MM Needs

The achievement of the **CTA core Science Goals** depends on a wealth of MWL and MM data (often involving intense coordination between facilities).

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.						🟠				🟢



MM Perspective from Astro 2020

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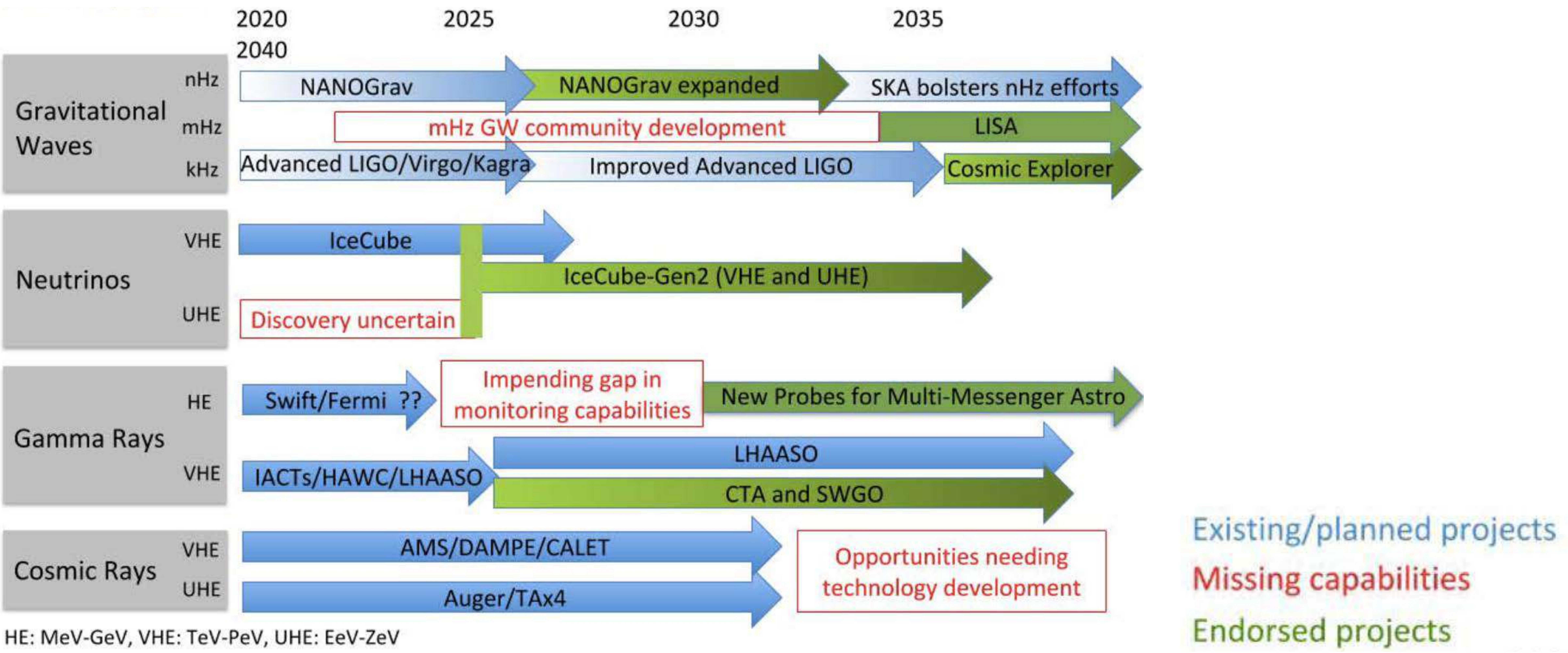

Thank you for the attention!