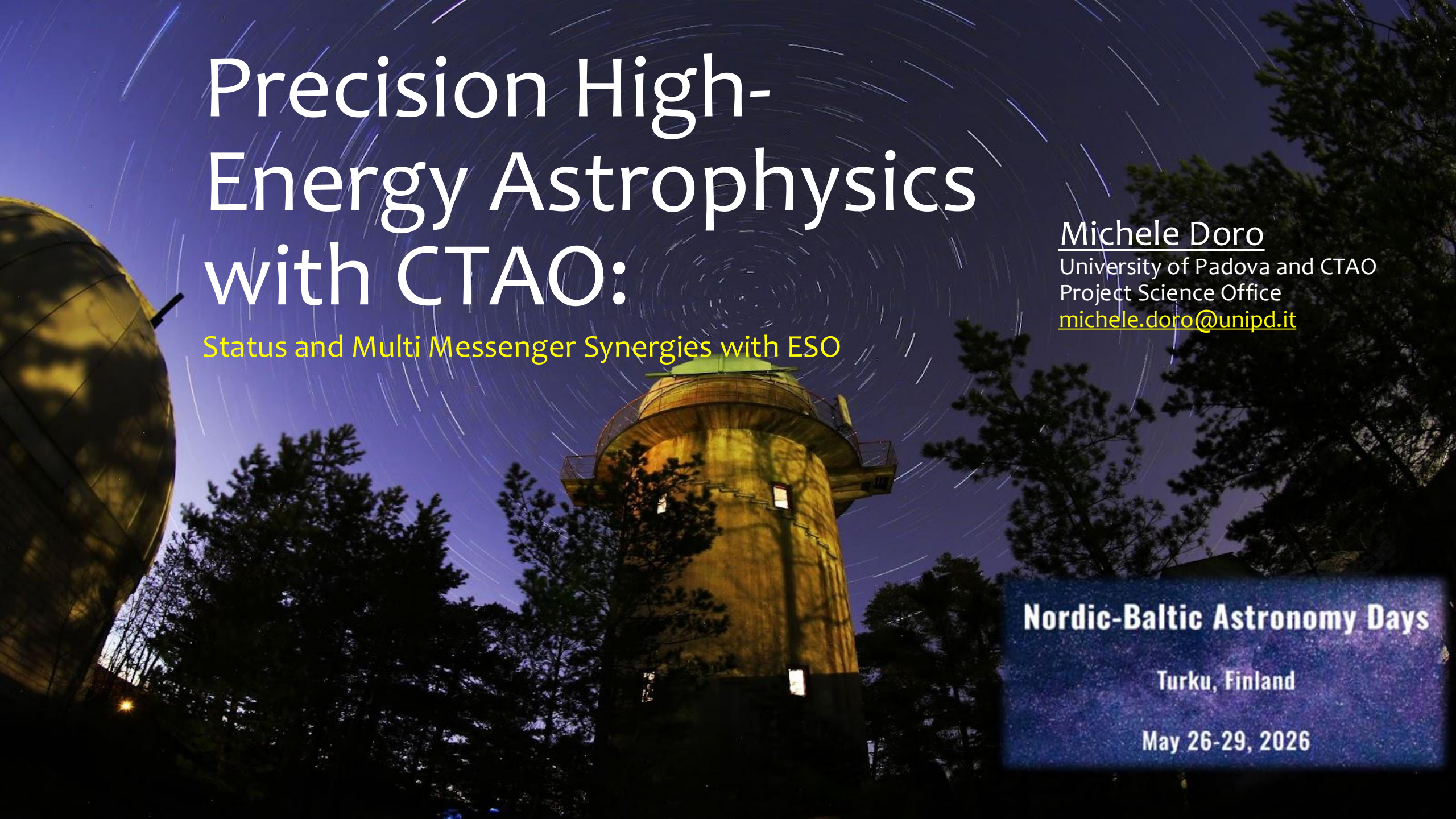
Precision High-Energy Astrophysics with CTAO:

Status and Multi Messenger Synergies with ESO

Michele Doro
University of Padova and CTAO
Project Science Office
michele.doro@unipd.it



Quick facts on g-ray astrophysics

Non thermal Universe

Gamma rays trace particle acceleration in space

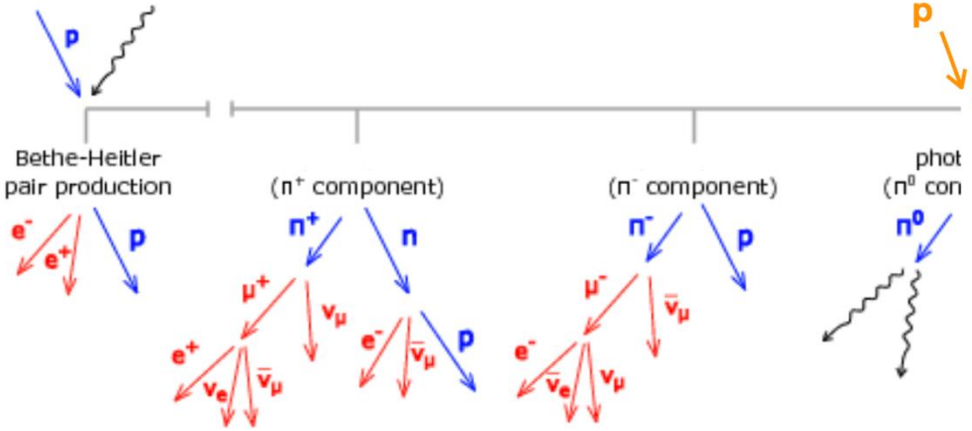
hadronic

Requires high B

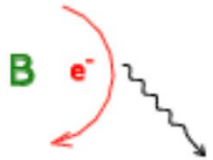
proton synchrotron

Requires high photon densities

Requires high gas densities

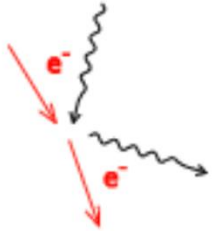


leptonic

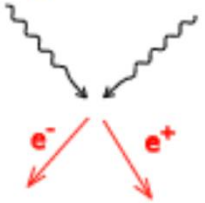


electron synchrotron

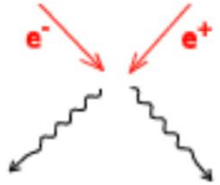
Relevant in compact sources



Inverse Compton scattering



photon-photon pair production

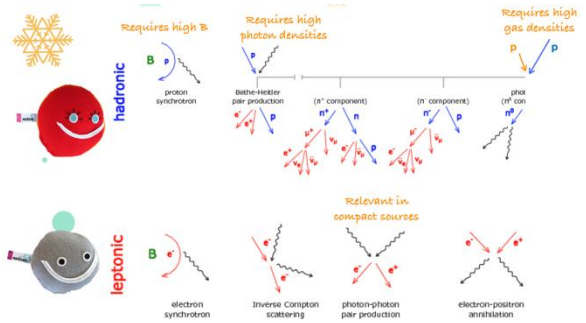


electron-positron annihilation

← Tavecchio

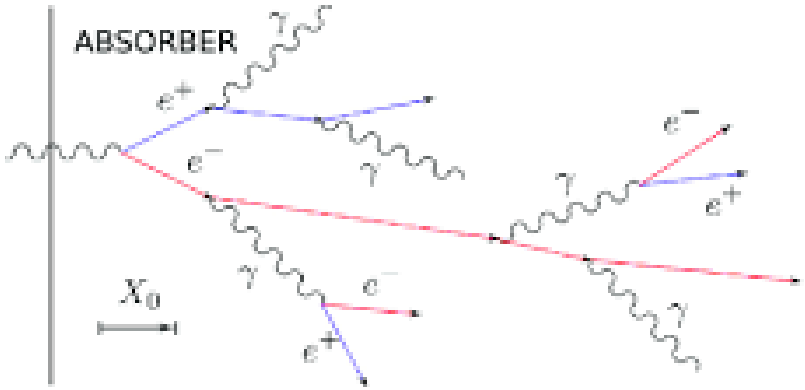
Non thermal Universe

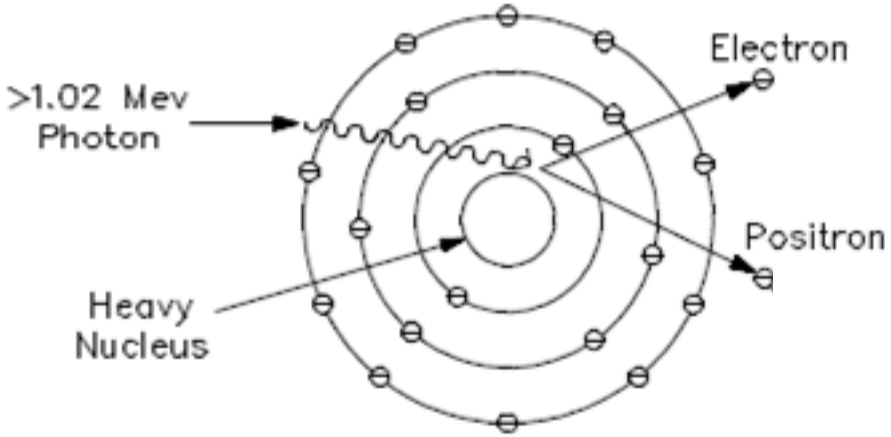
Gamma rays trace particle acceleration in space



High Energy Radiation

Thou shall not collect





- Above MeV, photons make subnuclear interactions
- Cannot be reflected!

High Energy Radiation

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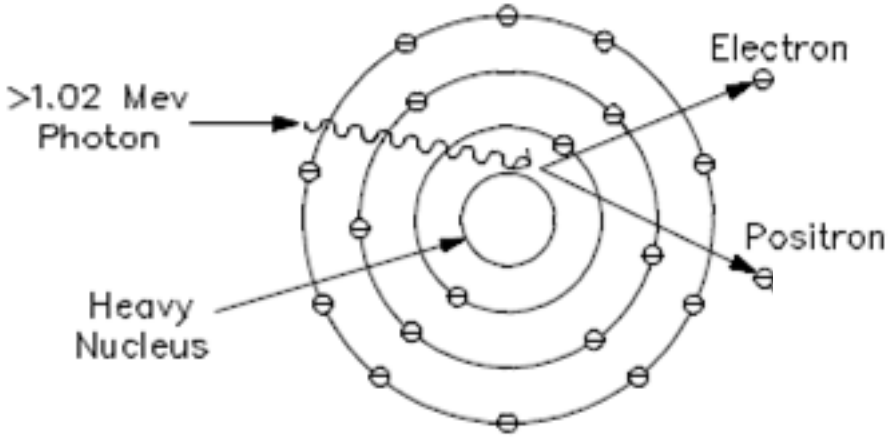

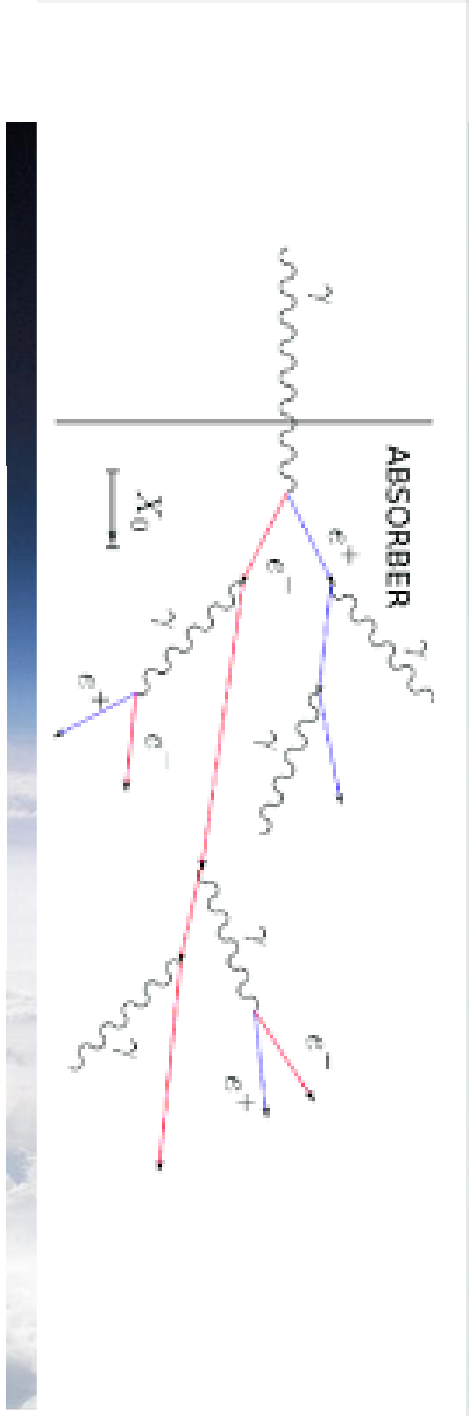

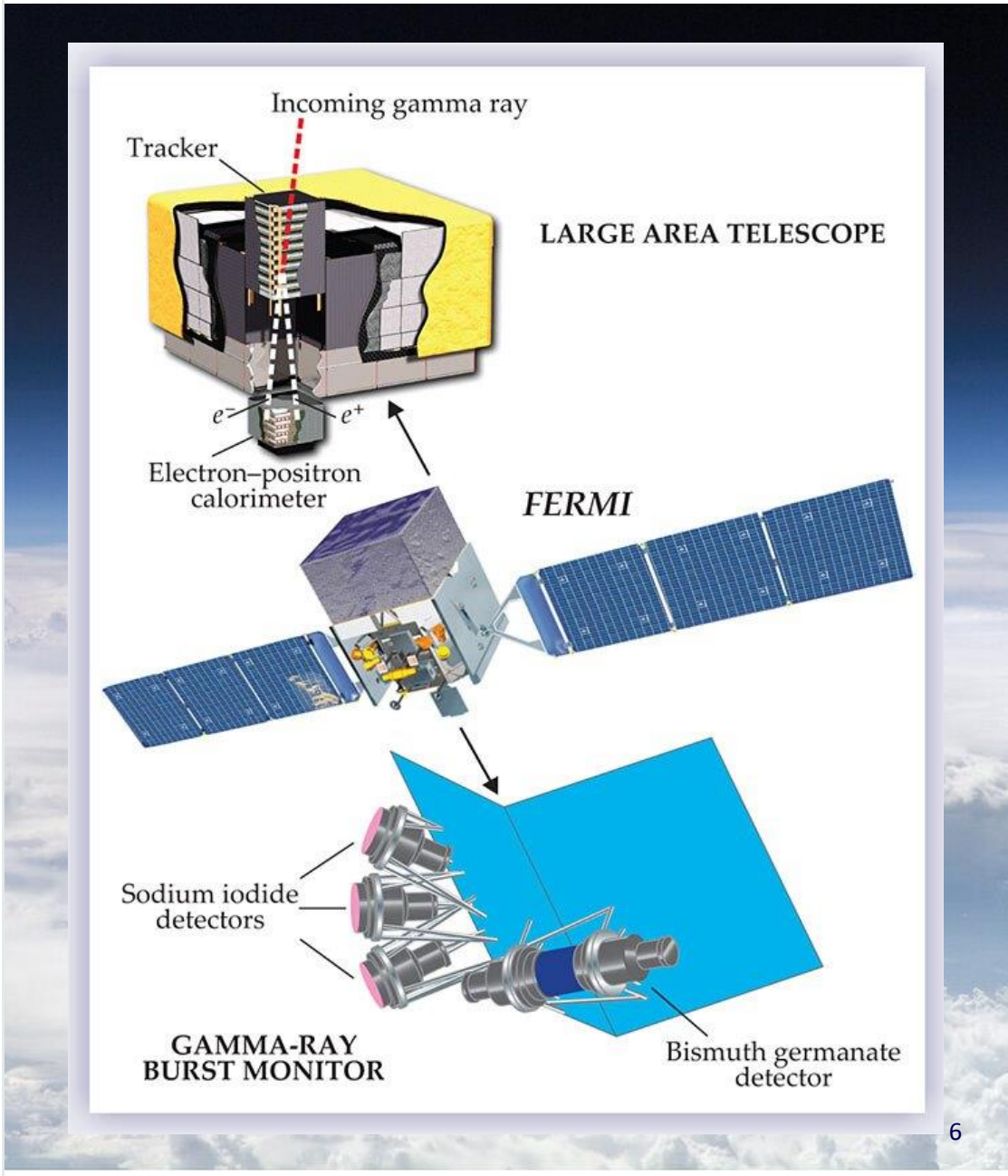

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High Energy Radiation

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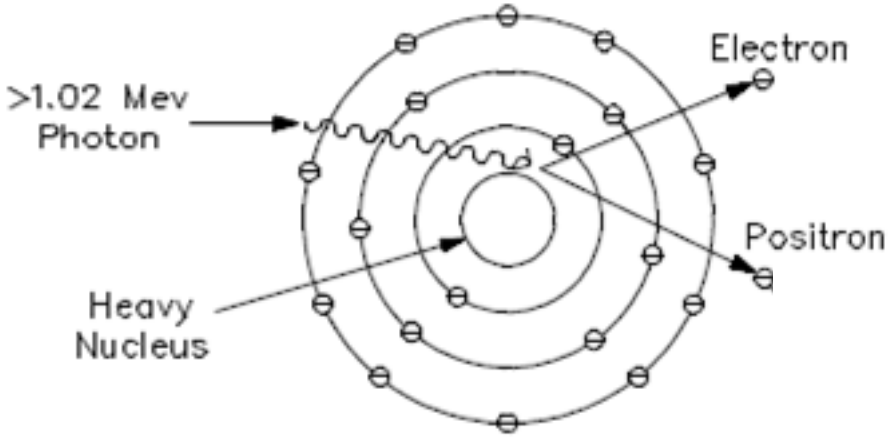

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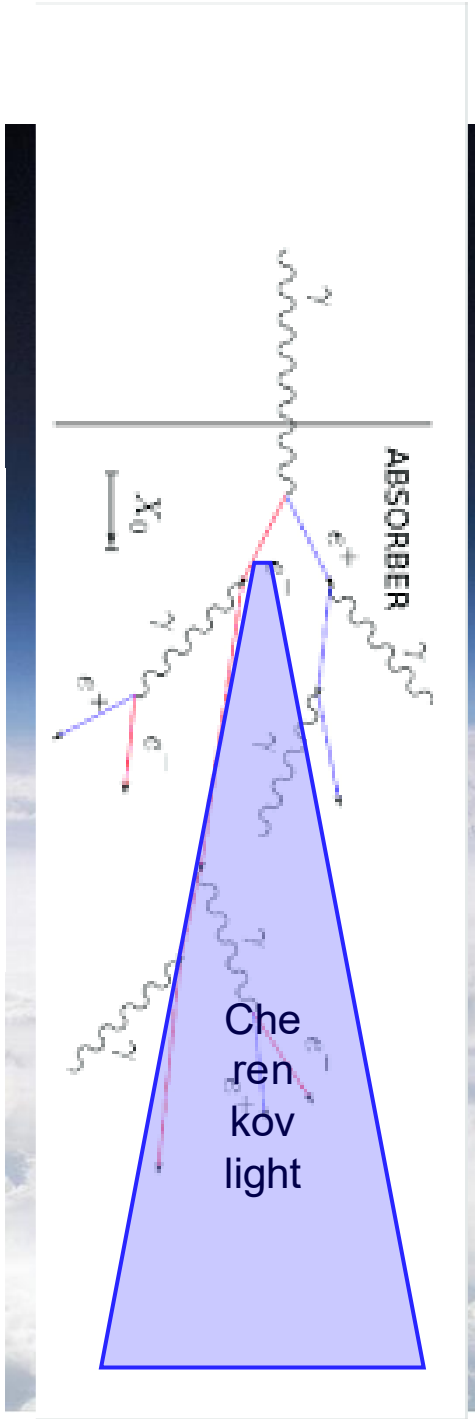
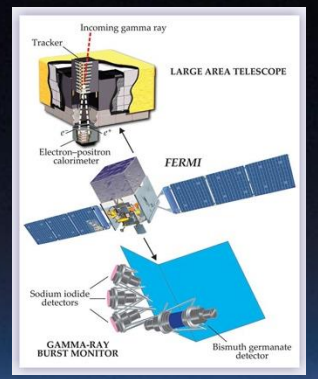
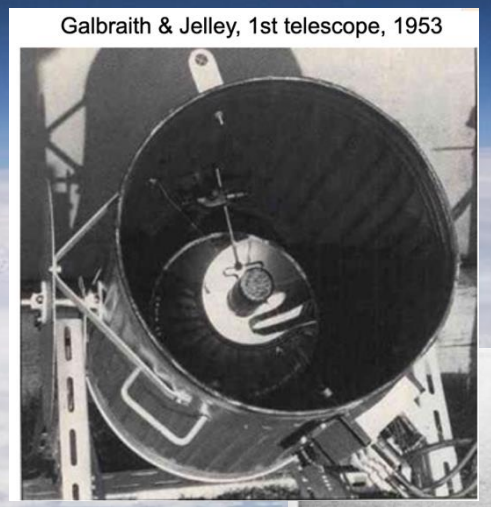
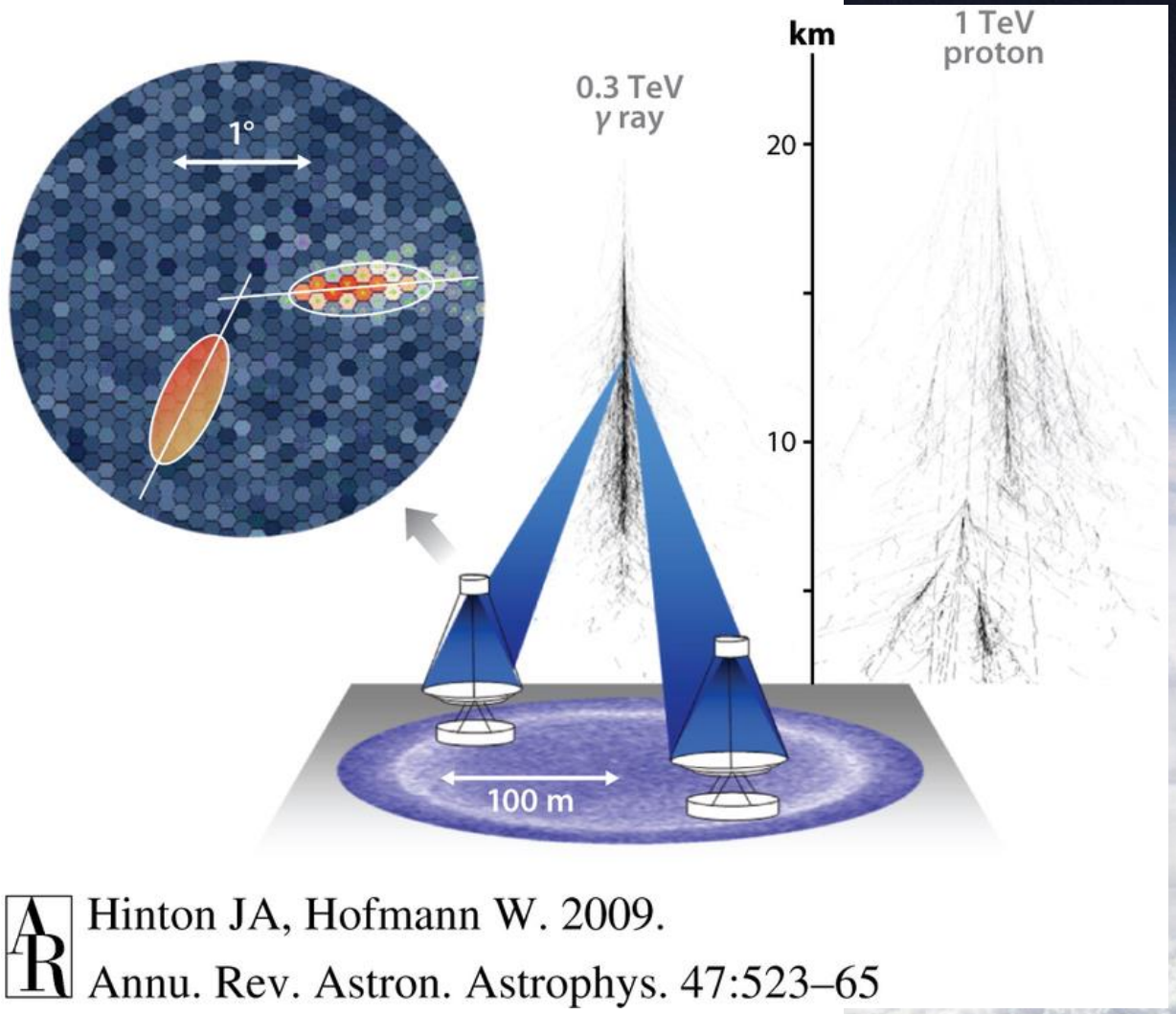


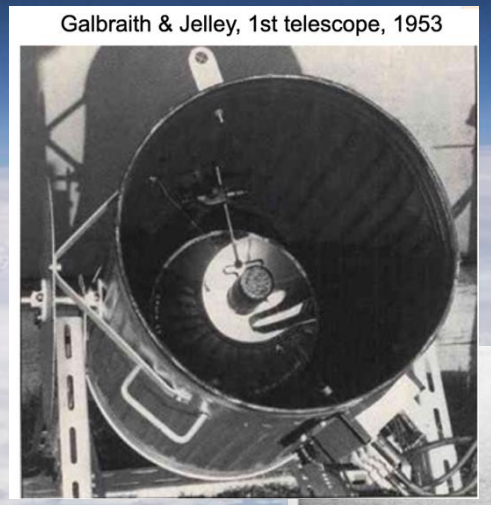




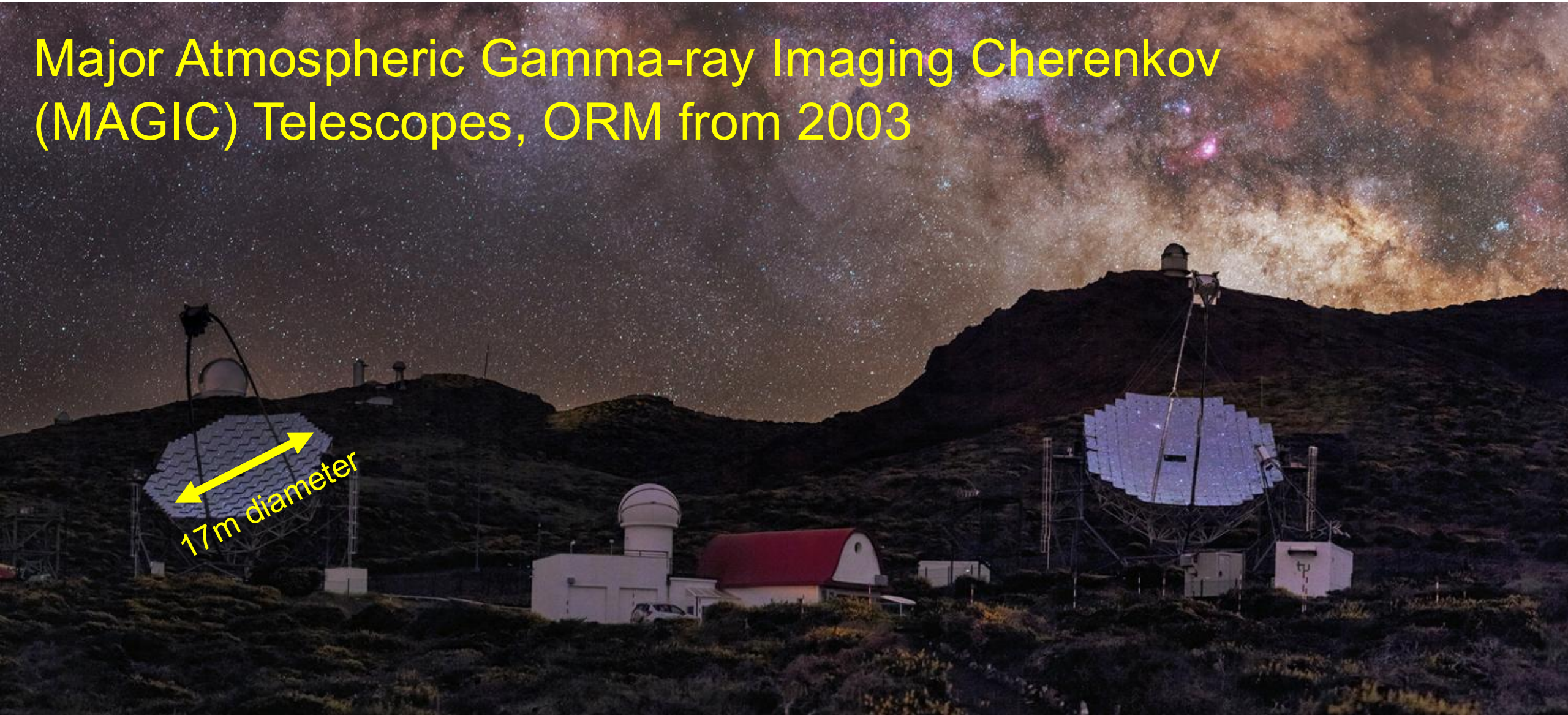
High Energy Radiation



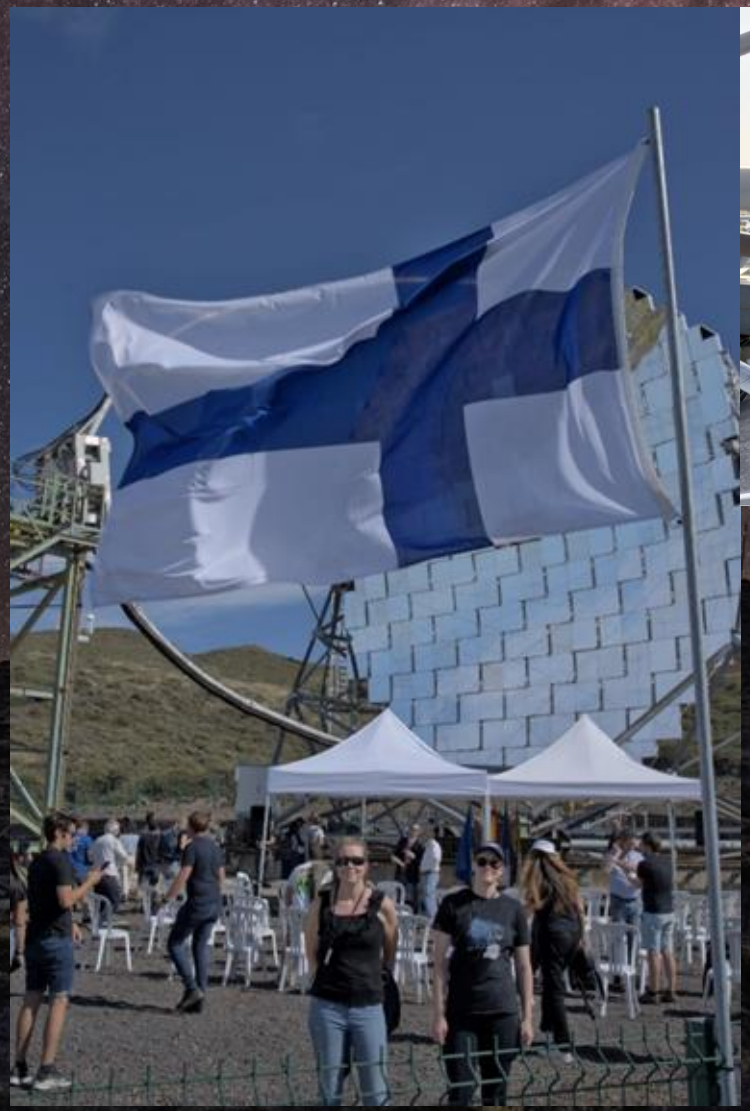
Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65



Now… much nicer



Always a Finnish instrument



Elina Lindfors

* EGAL coordinator and MWL coordinator

* PI program of target of opportunity program on flaring **blazars started in Cycle 1 and lasted all of 17 Cycles**

Always a Finnish instrument

Elina Lindfors

So long experience she is pictured in Tuorla museum!

Elina Lindfors

* EGAL coordinator and MWL coordinator

* PI program of target of opportunity program on flaring **blazars started in Cycle 1 and lasted all of 17 Cycles**

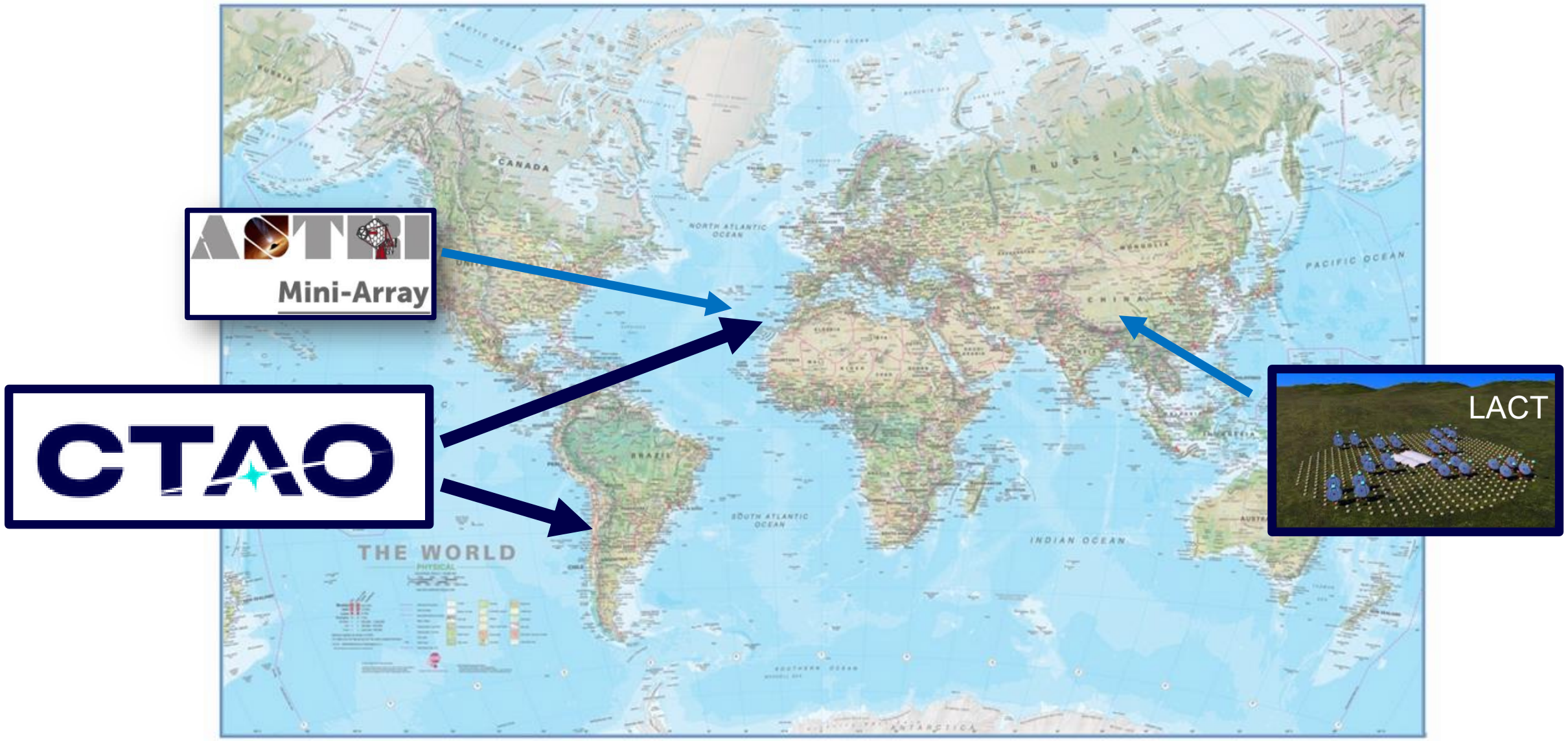
Current IACTs

IACT	Year	Nr. tels & diameter	Location
~~Whipple~~	~~1968~~	~~1×12 m~~	~~Arizona, USA~~
H.E.S.S.	2003	4×12 m+1×28 m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA

Table 1: Current major operating ground-based Cherenkov telescopes. Given are the starting year, the array multiplicity and dish diameter *in the latest configuration*, and the location.

MD NIMA742 (2014) 99-106

Incoming IACT arrays

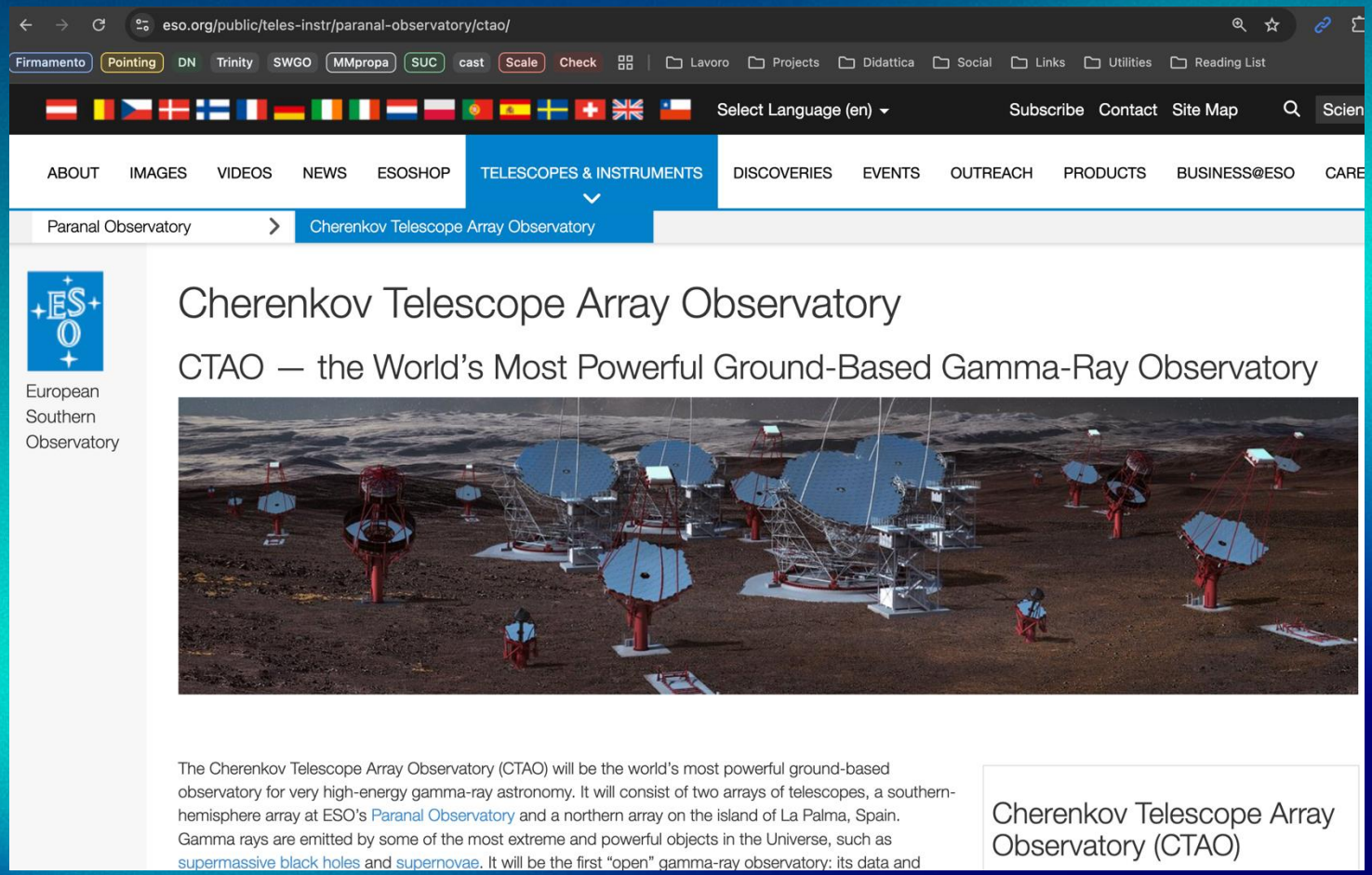


The Cherenkov Telescope Array Observatory

The Cherenkov Telescope Array Observatory

CTAO is an ERIC (European Research Infrastructure Center) since 7th Jan 2025

Funded by 9 EU member states, Switzerland, ESO, and Japan (Australia, Brazil and USA are in negotiation)

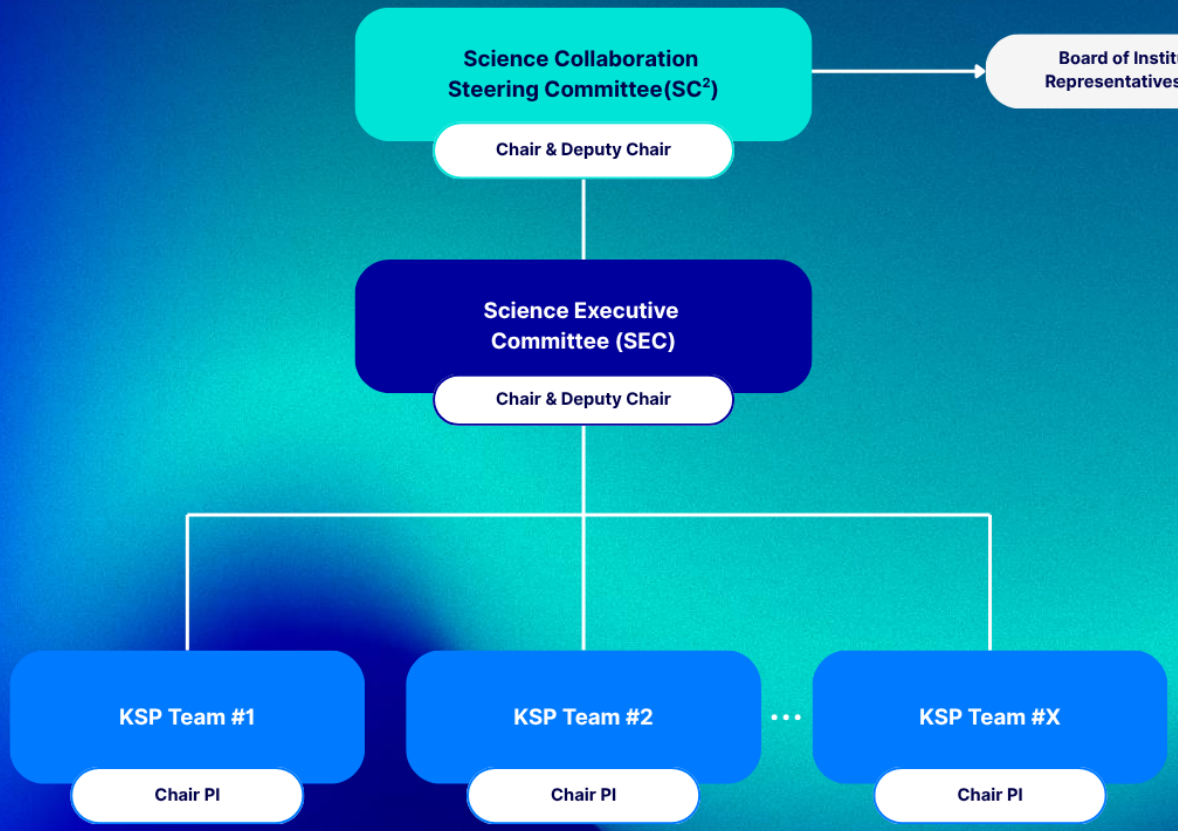


https://www.eso.org/public/teles-instr/paranal-observatory/ctao/

Headquarter: Bologna INAF-area

Science Data Management Center: DESY Zeuthen

CTA Science Consortium (TBD)



Built around KSPs, but can have wider scope

CORE TEAM MEMBERS

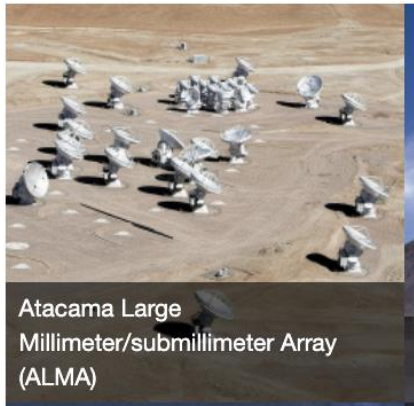
- only Contributing Parties researcher
- # proportional to construction share

EXTENDED TEAM MEMBERS

- CP & non-CP scientists
- # not limited

Telescopes currently operating or under construction

Here you see ESO's telescopes and telescopes hosted at ESO's sites. Those with marked with a * are currently under construction.

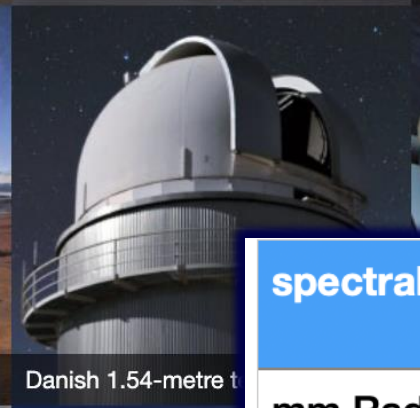

Atacama Large Millimeter/submillimeter Array (ALMA)

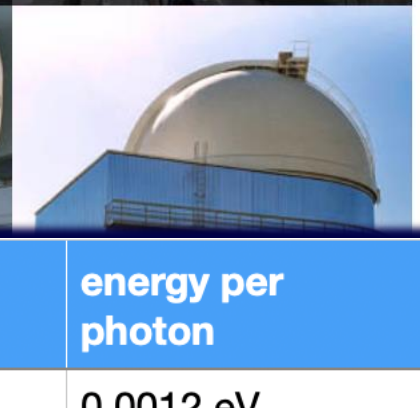

Atacama Pathfinder Experiment (APEX)


Auxiliary Telescopes (ATs)


BlackGEM


Cherenkov Telescope Array (CTA)*


Danish 1.54-metre t




ESO 1.52-metre telescope


ESO 3.6-metre telesc

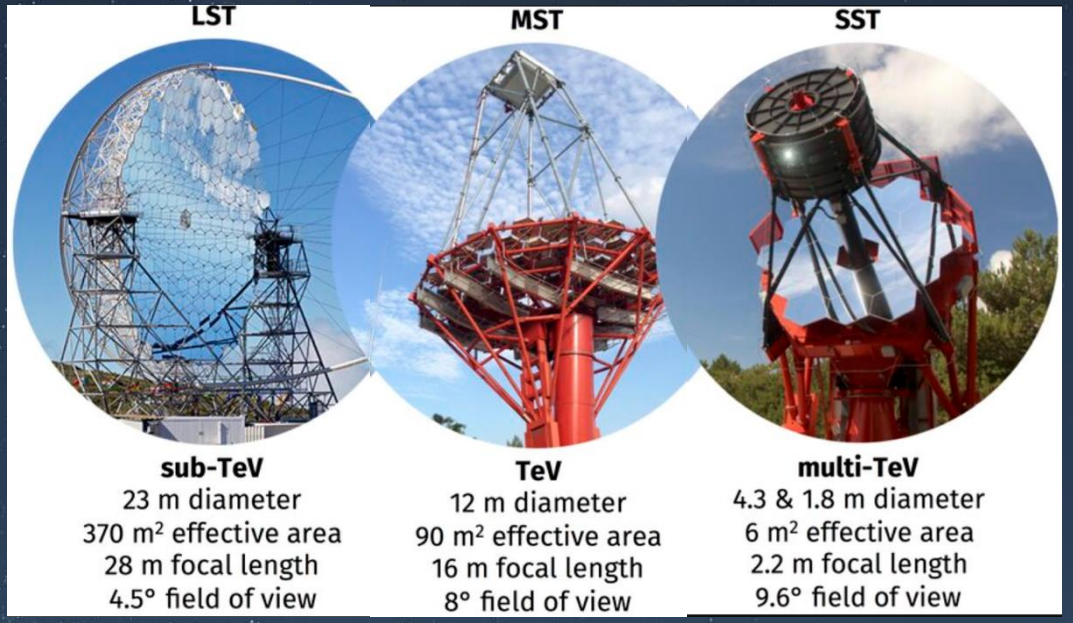
Atmospheres (EXTRA)

Extremely Large Telescope (ELT*)

spectral name	frequency	energy per photon	typical angular resolution	ESO instrument
mm Radio	300 GHz	0.0012 eV	~0.01–1 arcsec	ALMA
IR	10000 GHz	0.042 eV	~0.005–0.05 arcsec	VLT / ELT
visible	600000 GHz	2.5 eV	~0.005–0.02 arcsec	VLT / ELT
VHE g-rays	2.4E17 GHz	1E12 eV = 1 TeV	~1-5 arcmin	CTAO

CTAO

See more:
https://www.ctao.org/emission-to-discovery/telescopes/lst/



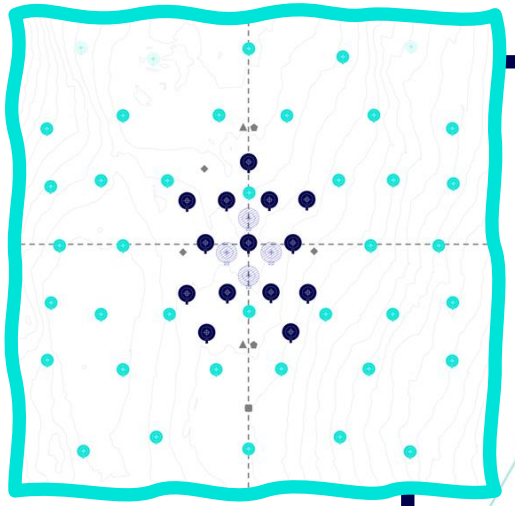
Large-Sized Telescope
4 North
2 South

Medium-Sized Telescope
9 North
14 South

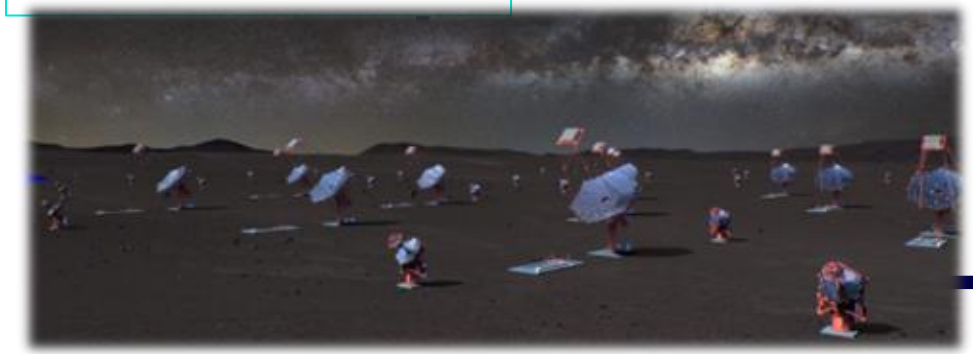
Small-Sized Telescope
37 South

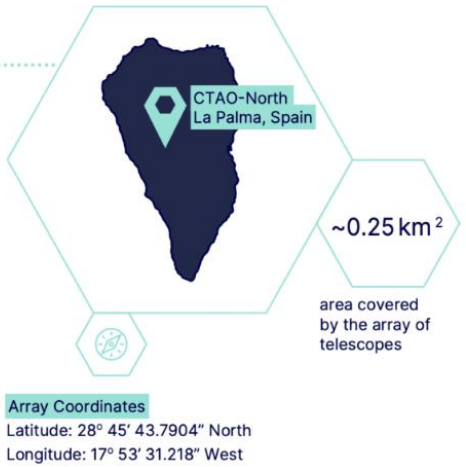
Beta Configuration approved

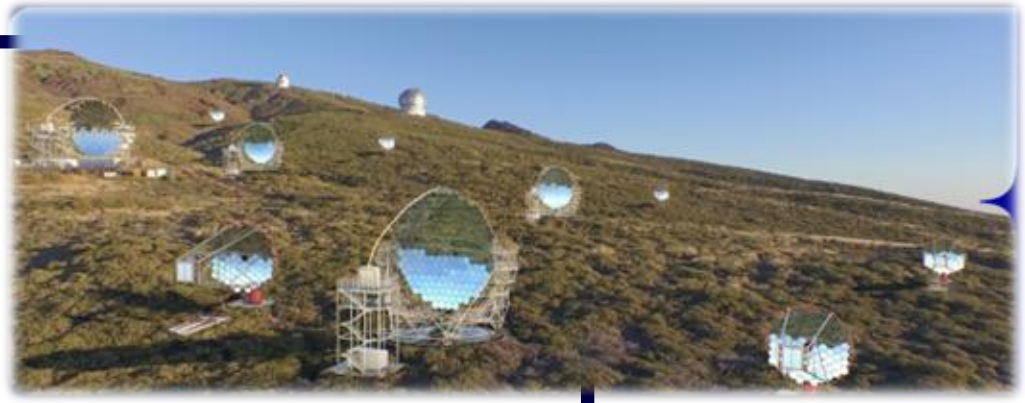
One observatory: two arrays. North (ORM), South (ESO Paranal)



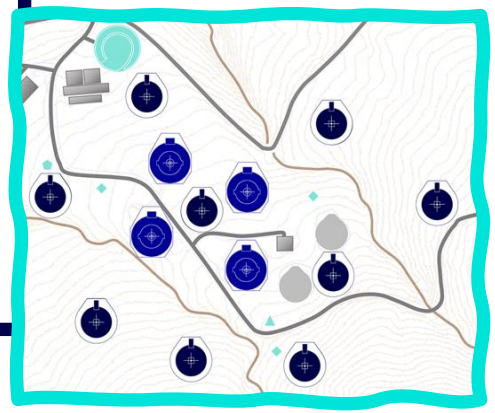
CTAO Southern Array
14 MSTs
37 MSTs
2 LSTs



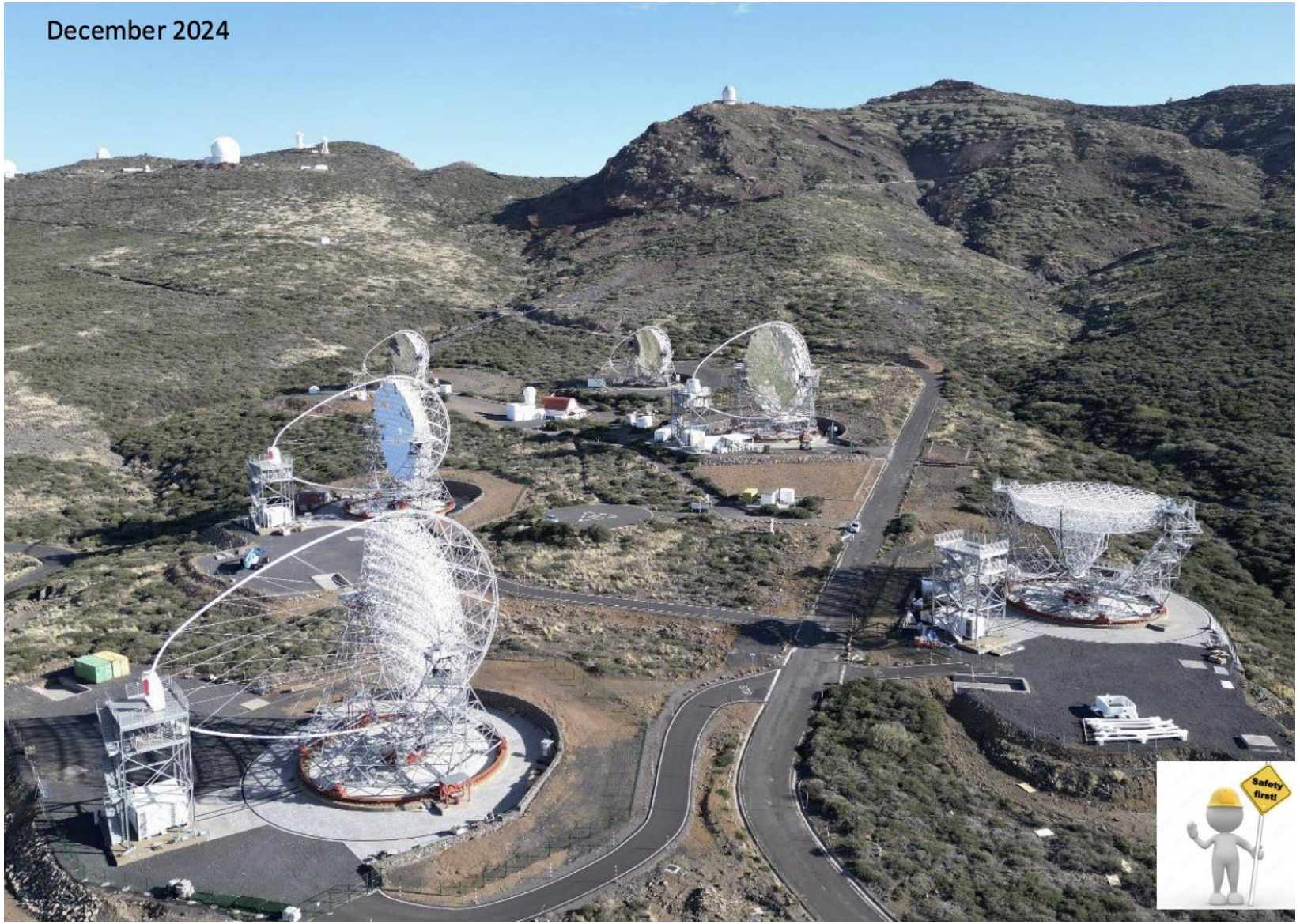




CTAO Northern Array
4 LSTs
9 MST

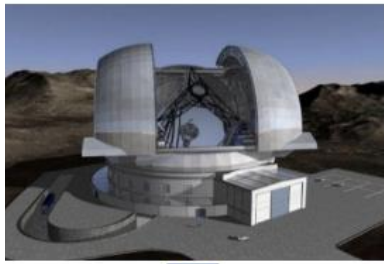


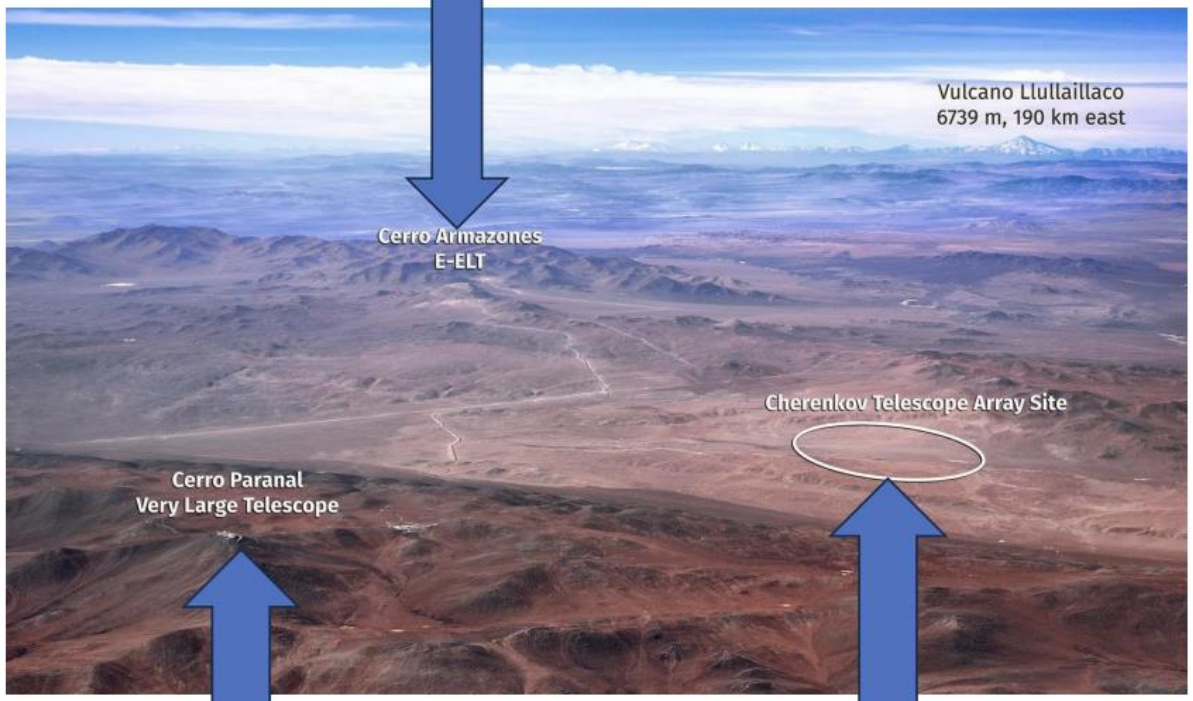
CTAO-North



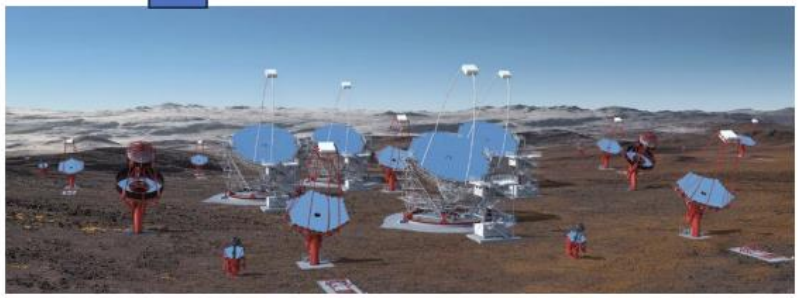
- 1 LSTs operational since 8y https://lst.iac.es/collaboration/publications
- +3 LSTs under completion
- +9 MSTs to arrive!
- + operational building, central calibration facilities, etc.

Construction - South





Construction facility



5 SSTs and 2 MSTs will be shipped and installed in 2026/2027

Phased scientific exploitation (in prep)

2025 2027 **CONSTRUCTION PHASE**

2030 **OPERATION PHASE**

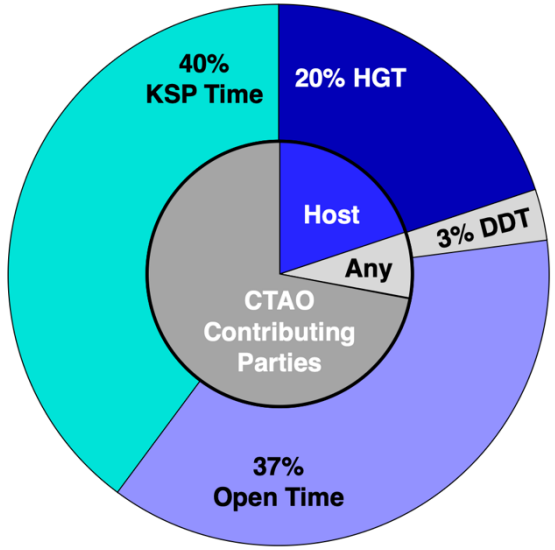
EARLY SCIENCE PHASE | STEADY-STATE OPERATION PHASE

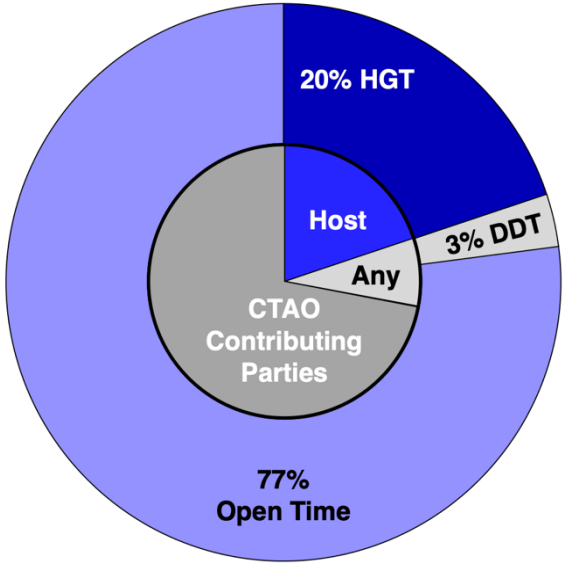
Notes:
- In discussion
- Not to scale

Science Verification (possibly open) | **KSP+Open Time** | **Open**

ESO:
10% North
10% South

ESO in the north!





Legend
CP = contributing parties
Any = CP+ non CP
Host = host countries
KSP = Key Science Projects
Open = proposal-based
HGT = Host Granted Time (ESO, Spain)
DDT = Director Discr. Time

Danish, Finnish, Swedish astronomers will apply through ESO 10%+10% + any

Open-Observatory

A novelty in the field

Current generation:
H.E.S.S., MAGIC, VERITAS
operated as experiments:

- Proprietary data format
- Private data access
- Limited guest observation program

DATA FORMAT

- CTAO has defined a data format (DL3) compliant with VODF and subscribed by HE, VHE + nu communities
- CTAO science analysis tools based on gammapy [www.gammapy.org]

MINIMIZE EFFORT FOR ESO COMMUNITIES

https://vodf.readthedocs.io/

VODF very-high-energy open data format

https://gammapy.org/

A Python package for gamma-ray astronomy

DATA ACCESS

< 1y proprietary period for the PI

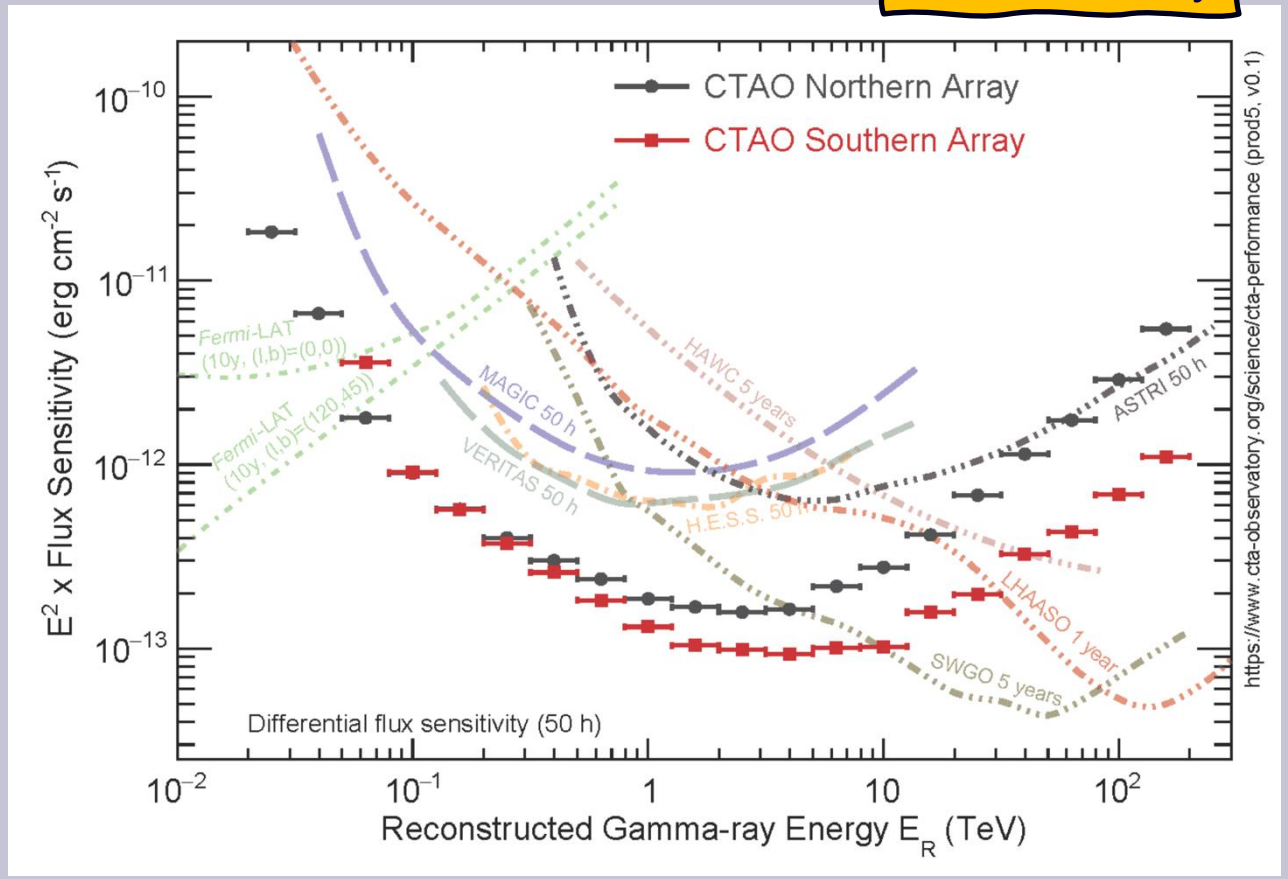
> 1y open public shared via CTAO Science Data Portal

Science Data Challenge in Q4 2026

- Fully open and blind
- Get external acquainted with CTAO data
- Award!

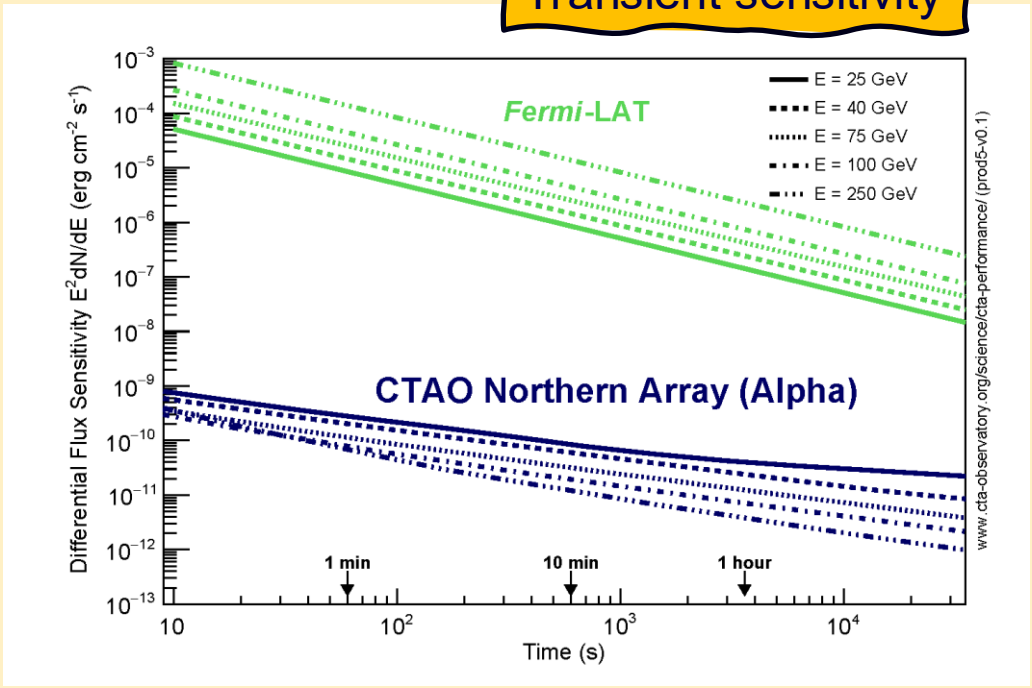
Performance and context: sensitivity

Flux sensitivity



- Complements Fermi-LAT (LE) and LHAASO (HE)
- 10x sensitivity than prev. generation
- More sensitive instrument between 0.1-30 TeV

Transient sensitivity

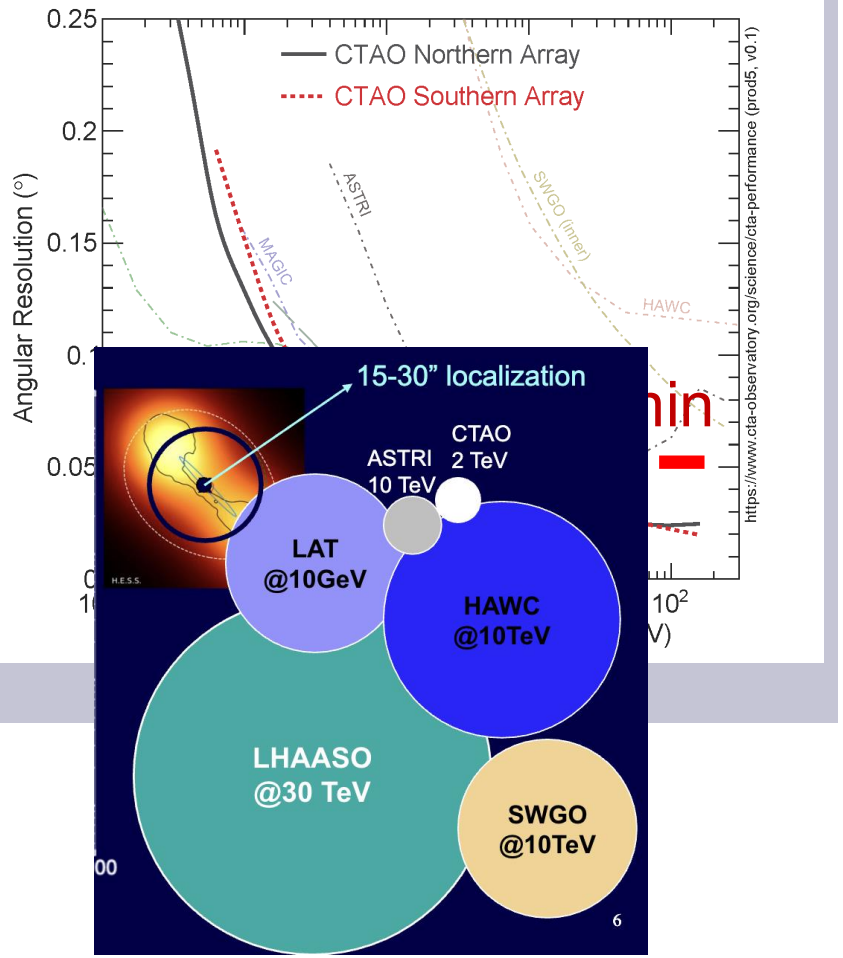


- Unbeaten transient sensitivity!
- Orders of magnitudes more sensitive for duration below 10h
- Cons: field of view of <10deg

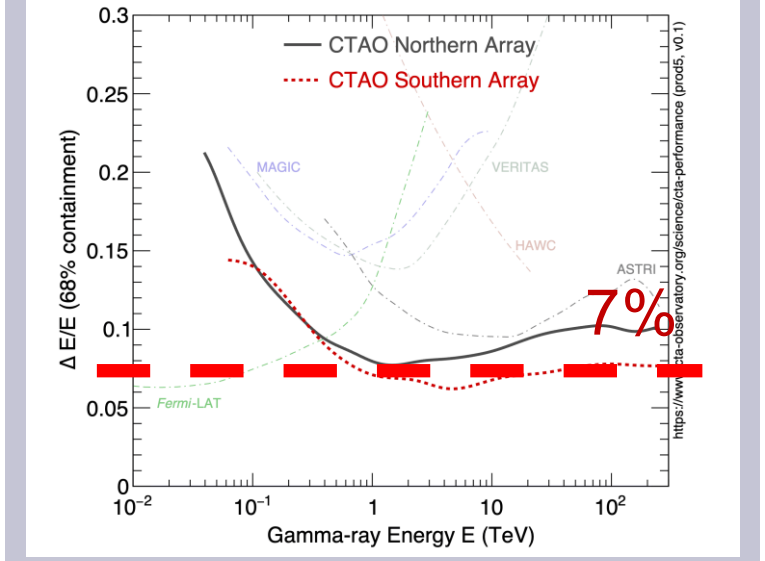
Not only sensitivity

The leap from previous generation

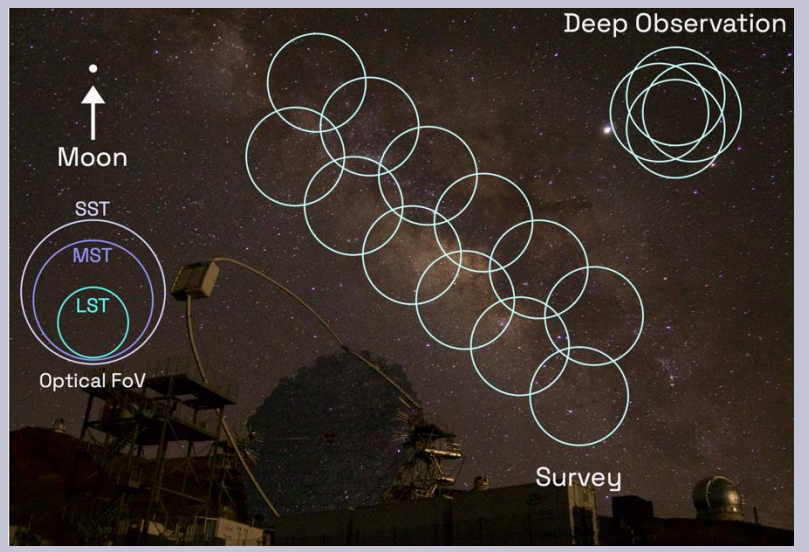
Angular Resolution

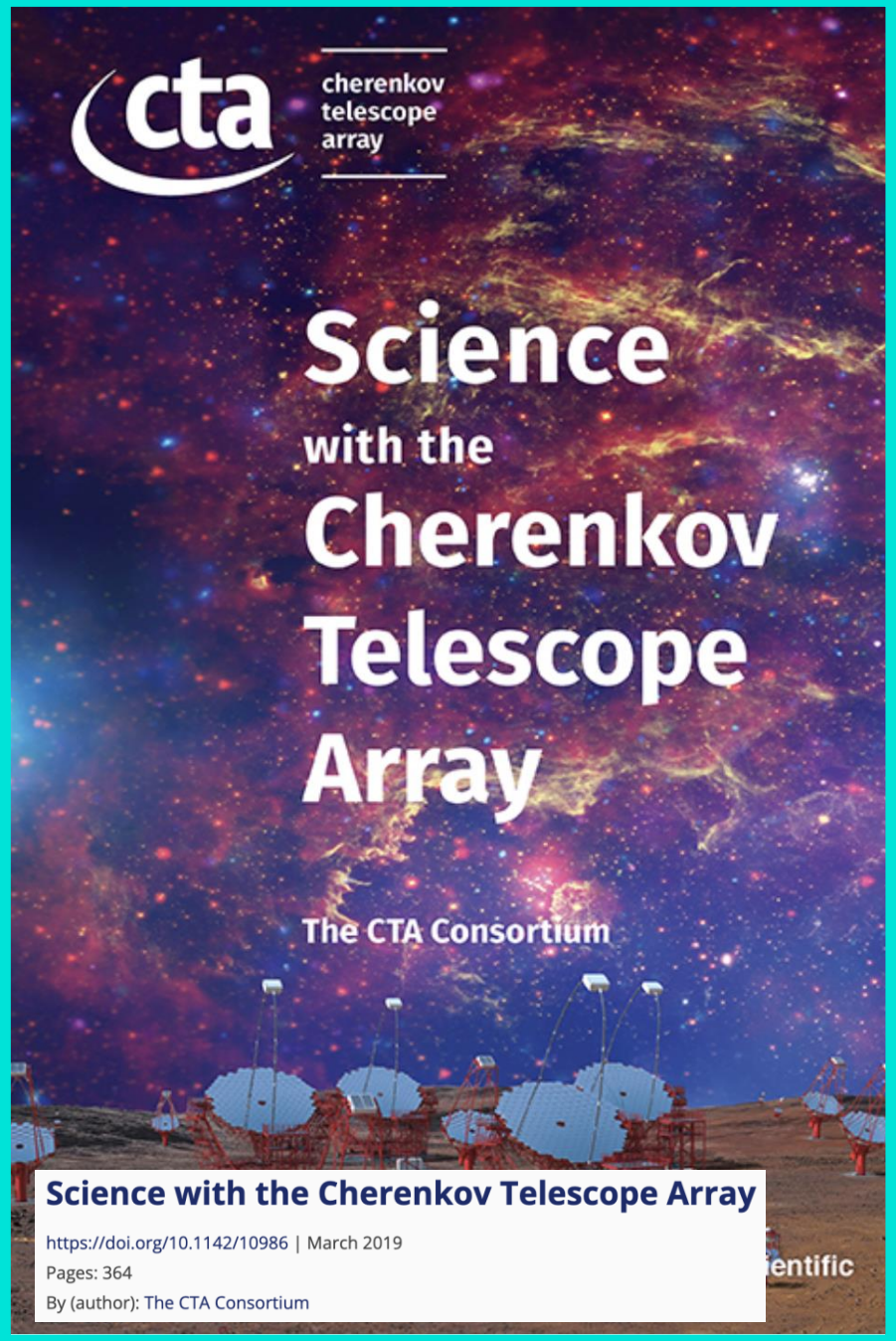


Energy Resolution



Obs. Modes and Field of view



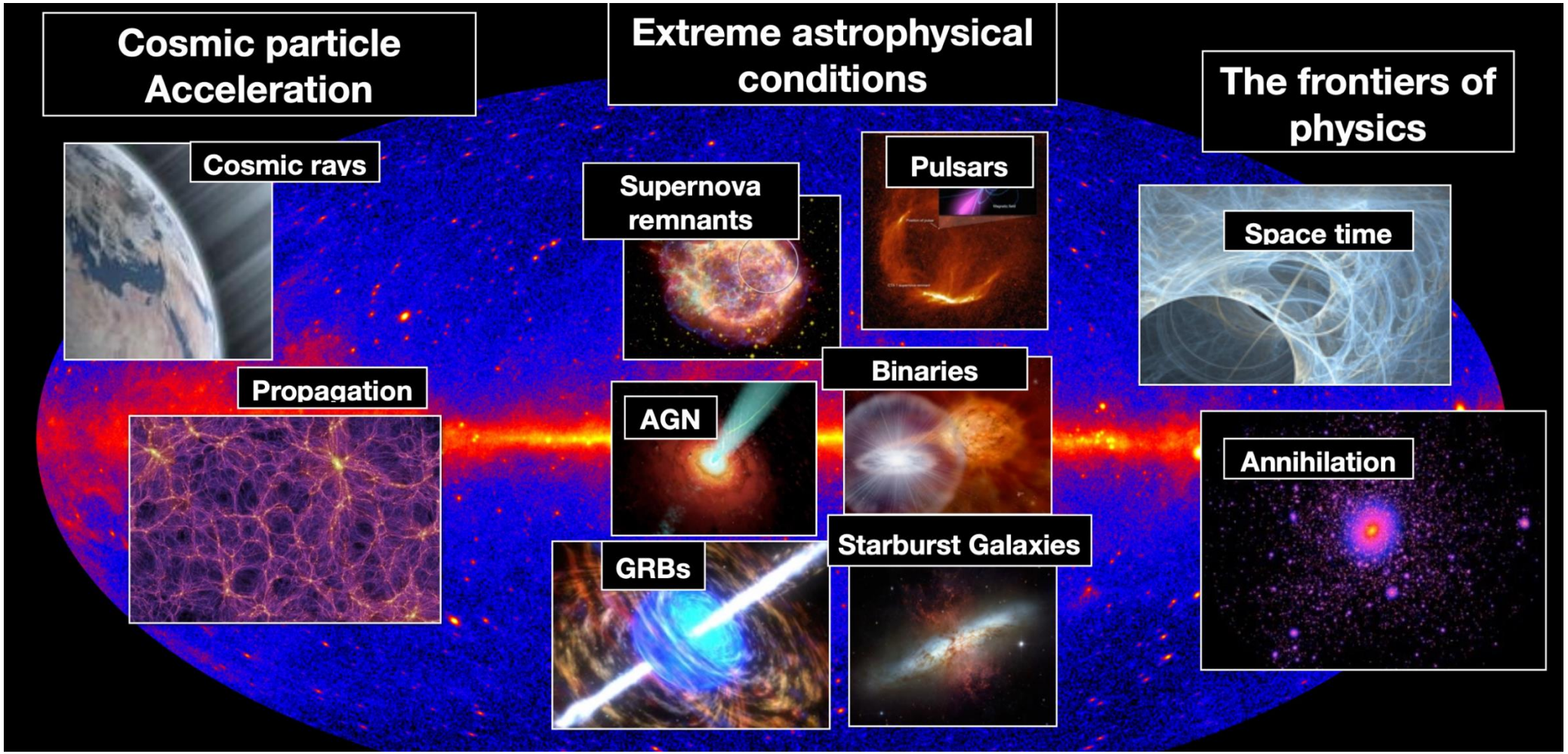


Science with CTAO

Focus: synergies with ESO

VHE gamma-ray science

Theme I | Theme II | Theme III



See backup material for more detailed list

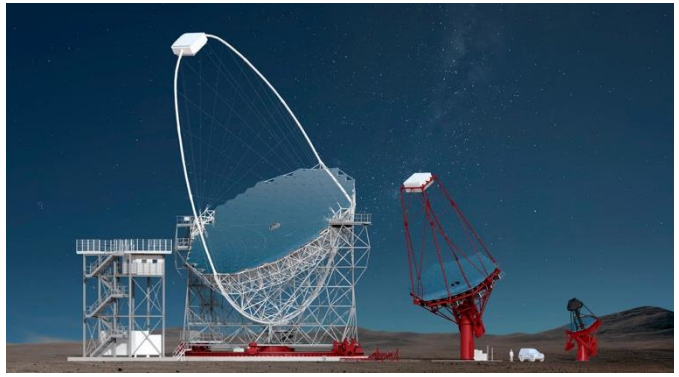
P. Andreani

New generation, how this will change?

Next generation.

CTA's quantitative improvement

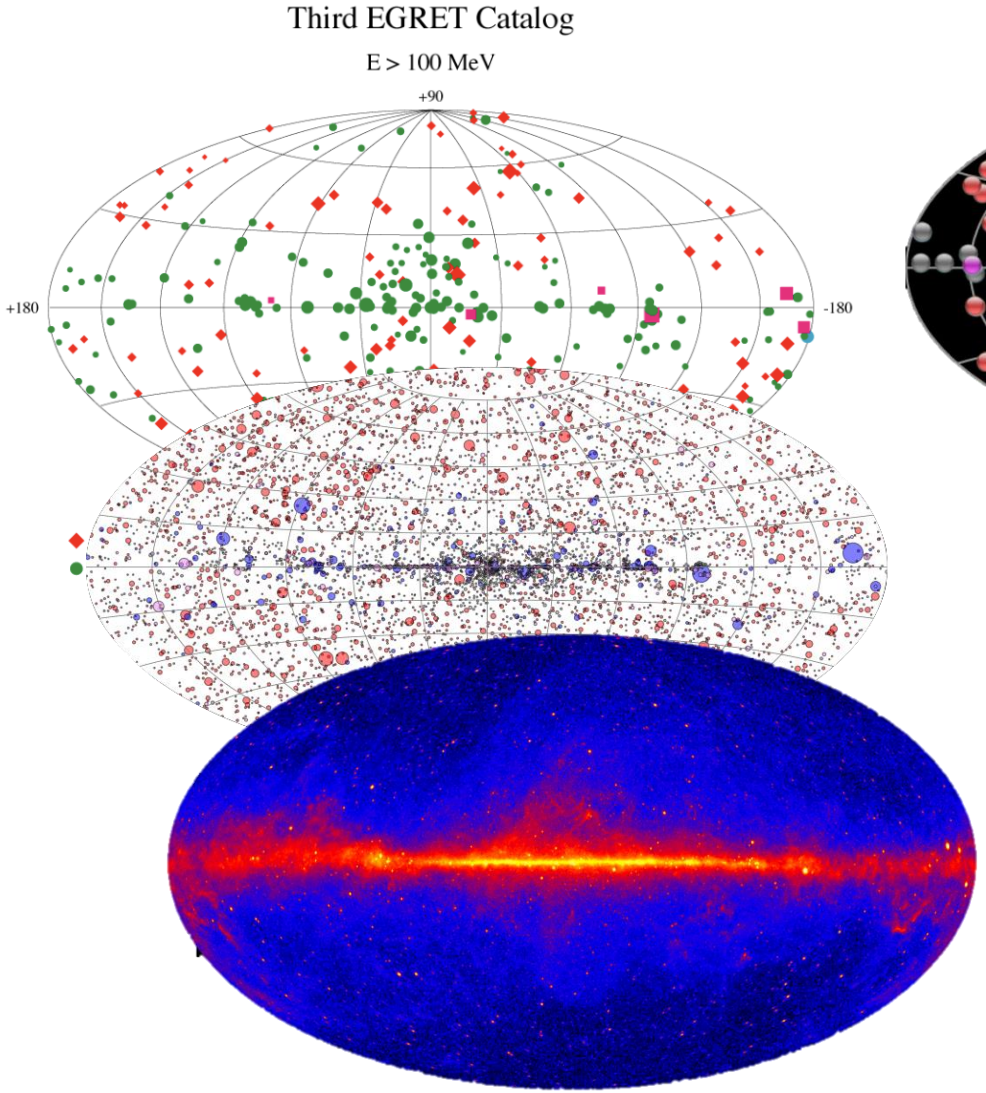
Quantity	Pre-CTA (H.E.S.S./MAGIC/VERITAS)		CTA expected
Energy range	0.05–20 TeV	~2x	0.02–300 TeV
Flux sensitivity	10^{-12}–10^{-11} erg cm^{-2} s^{-1}	~10x	10^{-13}–10^{-14} erg cm^{-2} s^{-1}
Energy resolution	15–20 %	~3x	5–10 %
Angular resolution	0.1°	~5x	0.02°
Temporal resolution	minutes	~5x	tens of seconds



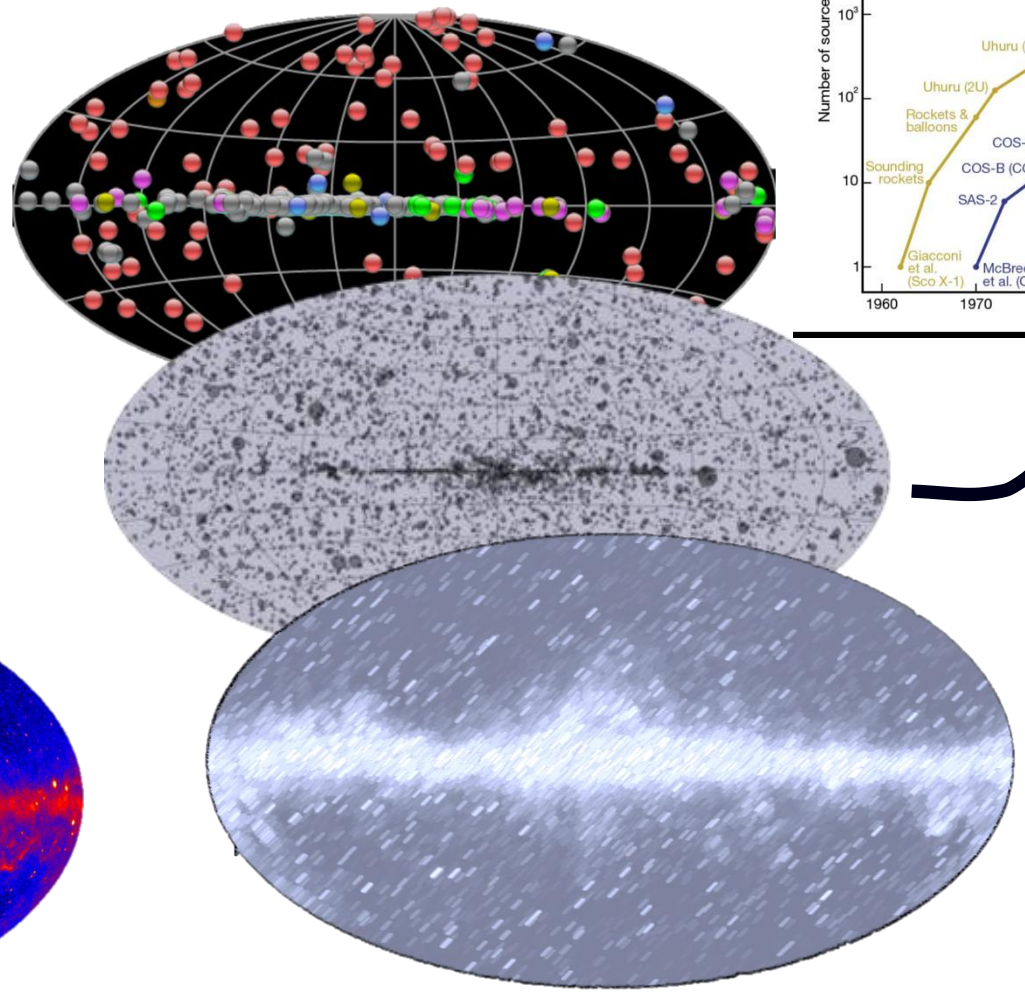
- From ~100 TeV emitters to ~1000
- From z<1 to z~2, a new horizon
- Precision spectral-spatial measurement
- A time-domain machine!

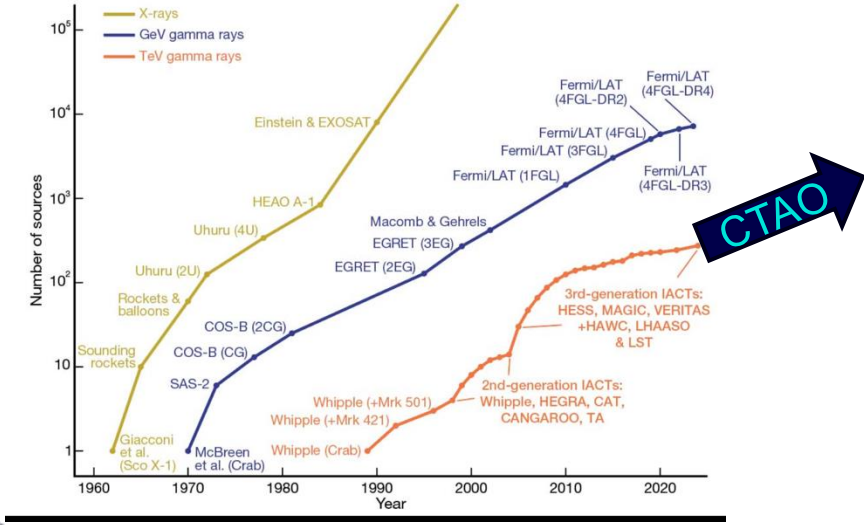
A revolution is coming

High-Energy



CTAO VHE





Kifune plot

In Rovaniemi…

Theme 1

Understanding the Origin and Role of Relativistic Particles in the Universe

- **Galactic PeVatrons**

  Identify sources capable of *accelerating cosmic rays to PeV* energies.

  Key targets: Galactic Center, young supernova remnants (SNRs),+.

- **Supernova Remnants (SNRs) and the Origin of Cosmic Rays**

  Study *acceleration, diffusion, and escape* of particles.

  Combine CTA data with Fermi, radio, and X-ray observations.

- **Pulsar Wind Nebulae (PWNe)**

  Examine leptonic acceleration, cooling, and nebular structure.

- **Binary Systems**

  Investigate *particle acceleration* in compact binaries, microquasars.

- **Star-forming Systems**

  Explore *collective acceleration* in starburst regions and OB associations.

- **Cosmic-Ray Diffusion and Propagation**

  Probe *cosmic-ray transport* through molecular clouds and diffuse emission.

Theme 2

Probing Extreme Environments

- **Active Galactic Nuclei (AGN)**
  Study particle acceleration, jet formation, B-field and variability.
  Profound transient and multi-w program
- **Radio Galaxies and Misaligned AGN**
  Test jet models and large-scale VHE emission.
- **Gamma-Ray Bursts (GRBs)**
  Explore prompt and afterglow VHE emission; Lorentz factor limits; new physics.
- **Pulsars and Magnetospheres**
  Search for VHE pulsed emission; constrain emission zones.
- **The Galactic Center Environment as a whole**
  Study diffuse gamma-ray emission, potential PeVatron, and dark matter.
- **Clusters of Galaxies**
  Probe cosmic-ray confinement, cluster energetics and intracluster medium heating.

Theme 3

Exploring Frontiers in Physics

- **Dark Matter Searches**

  WIMP *annihilation/decay* from Galactic Center, dwarf spheroidals, galaxy clusters.

- **Lorentz Invariance Violation (LIV)**

  Use GRBs and AGN flares to test quantum-gravity effects through *time-delay and threshold effects*

- **Axion-like Particles (ALPs)**

  Search for photon–ALP mixing through *irregularities in spectra and photon-recovery*.

- **Cosmic-Ray Electron Spectrum**

  Measure *local spectrum* up to tens of TeV to test nearby sources.

  Expected performance in *heavier CRs*

- **Extragalactic Background Light (EBL)**

  Constrain EBL density through *attenuation of AGN and GRB spectra.*

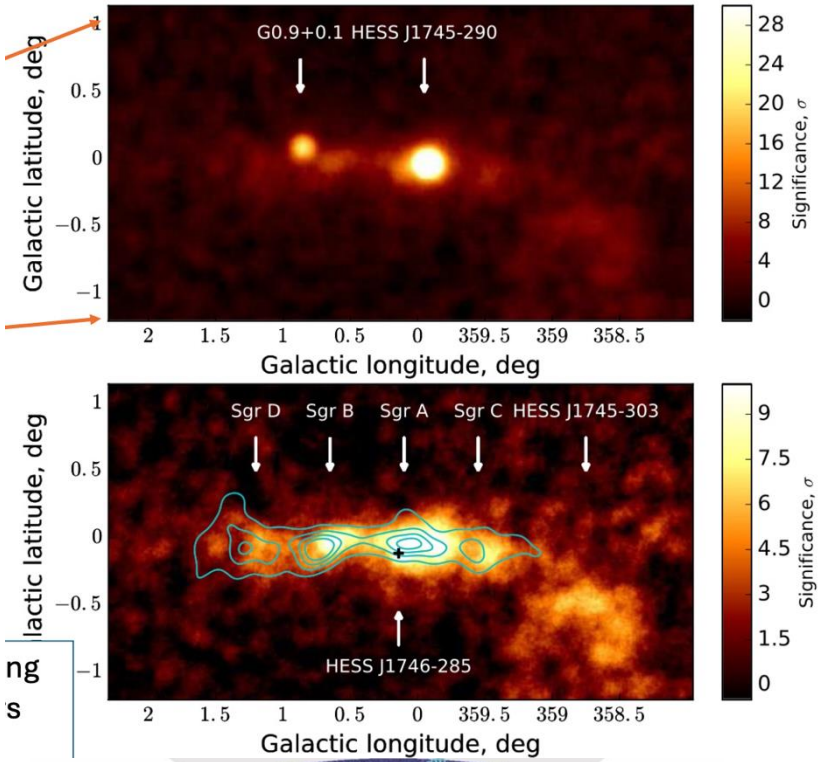
- **Cosmology and Intergalactic Magnetic Fields (IGMF)**

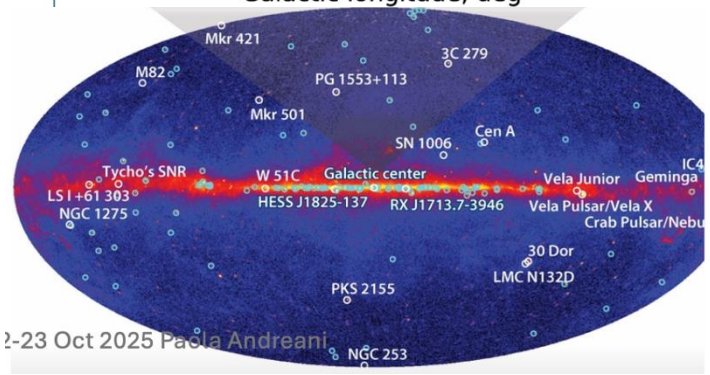
  Study pair cascades and delayed emission to probe IGMF strength

New Theme : Intensity Interferometry

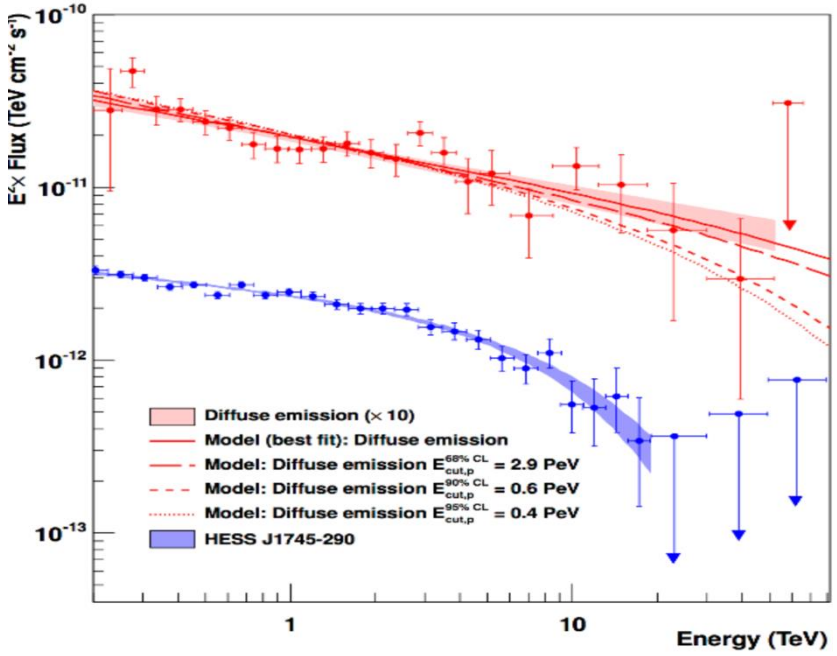
#1 CMZ: CTAO and ALMA, VLBI

H.E.S.S. Collaboration (2016, Nature)



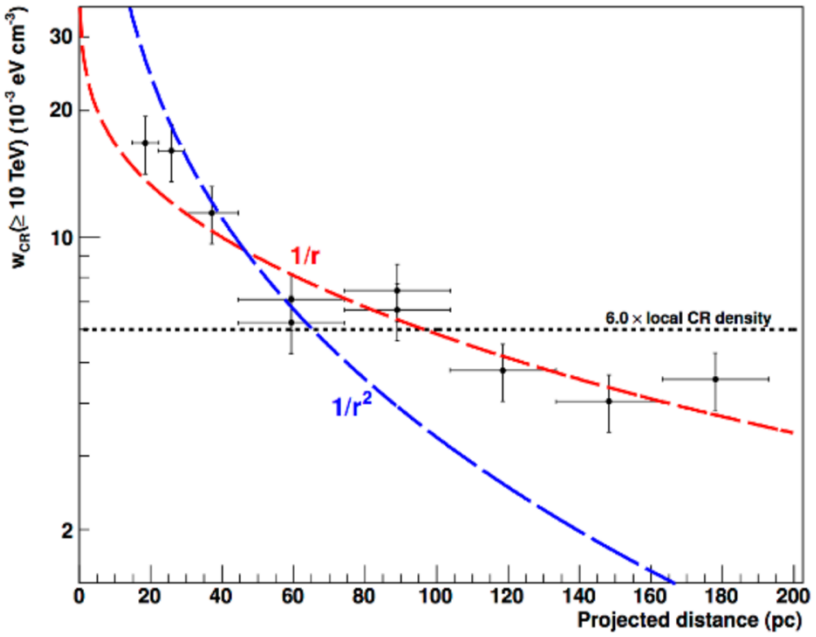


Diffuse VHE gamma-ray emission correlated with the dense molecular gas distribution

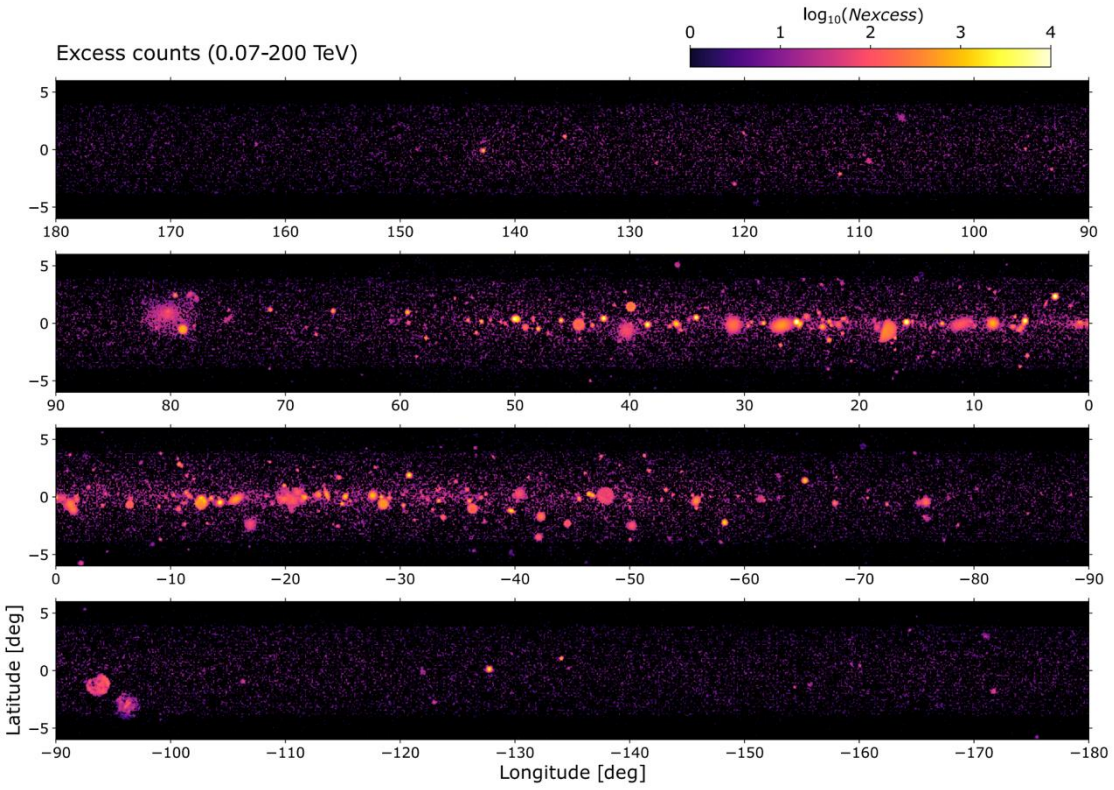


Spectrum extends deep into TeV with hints of cutoff (MAGIC, 20 TeV) debating the nature of GC as Pevatrons. HAWC detected > 100 TeV g-rays

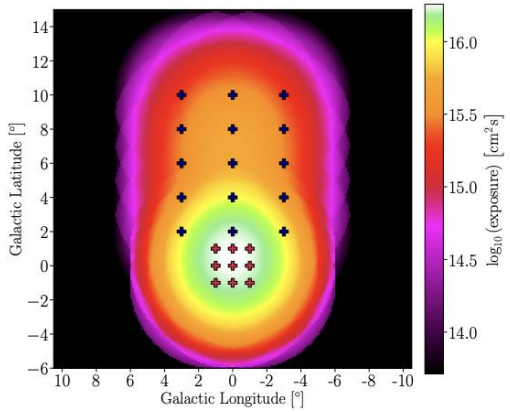
CR energy density profile scaling as 1/r from Sgr A* points to a central CR source, a continuous accelerator operating within the central 200 pc



#1 CMZ: CTAO and ALMA



CTAO, JCAP10(2024)081



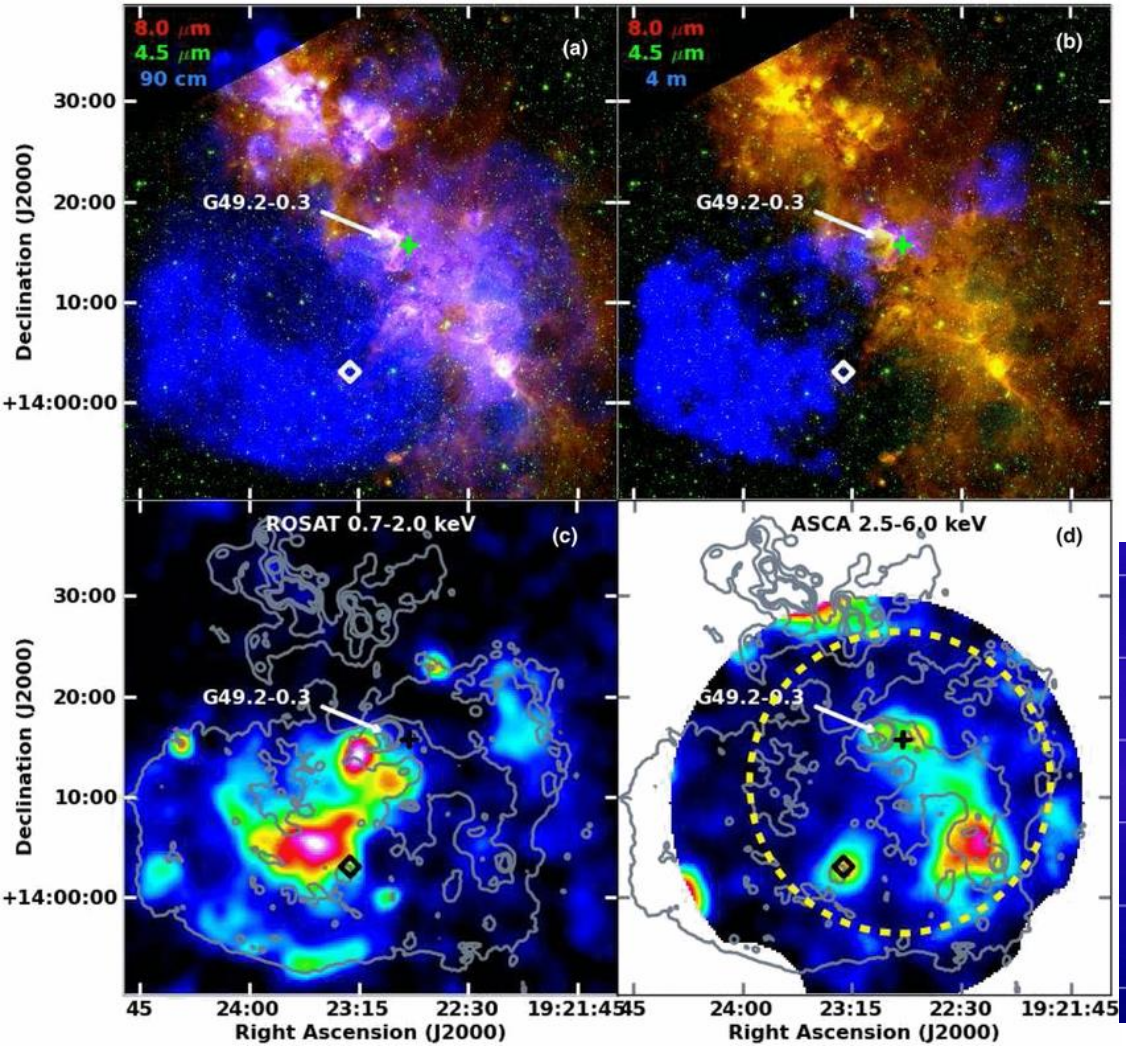
CTAO JCAP 01 (2021) 057

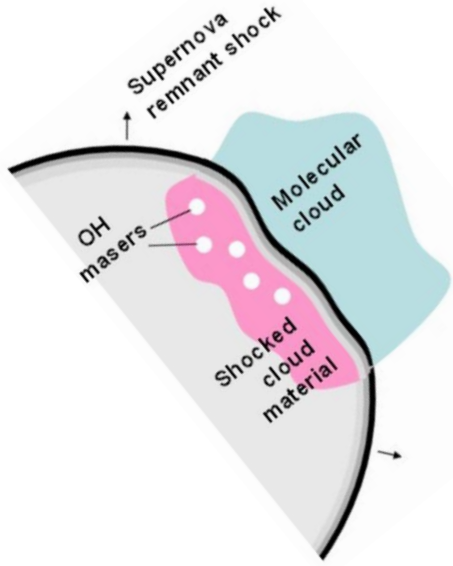
- CTAO key science case is the galactic plane with deep survey on the galactic center
- Can resolve point like and diffuse emission correlated with clouds
- ALMA probes the molecular gas + magnetic fields (VLBI)

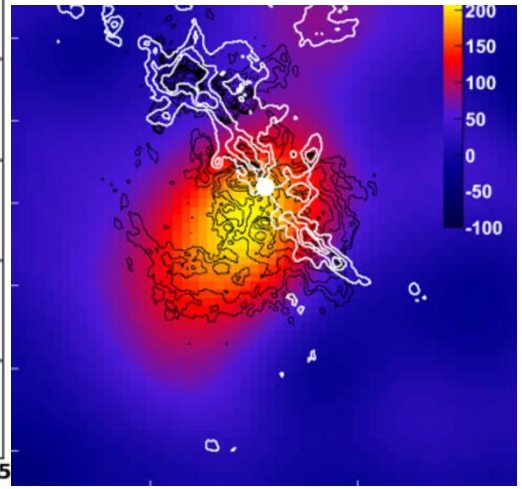
Full strategy and synergy not yet investigated, please join!

#2 Star-forming regions: CTAO and ALMA

From Andreani, Trigo ESO newsletter May 26



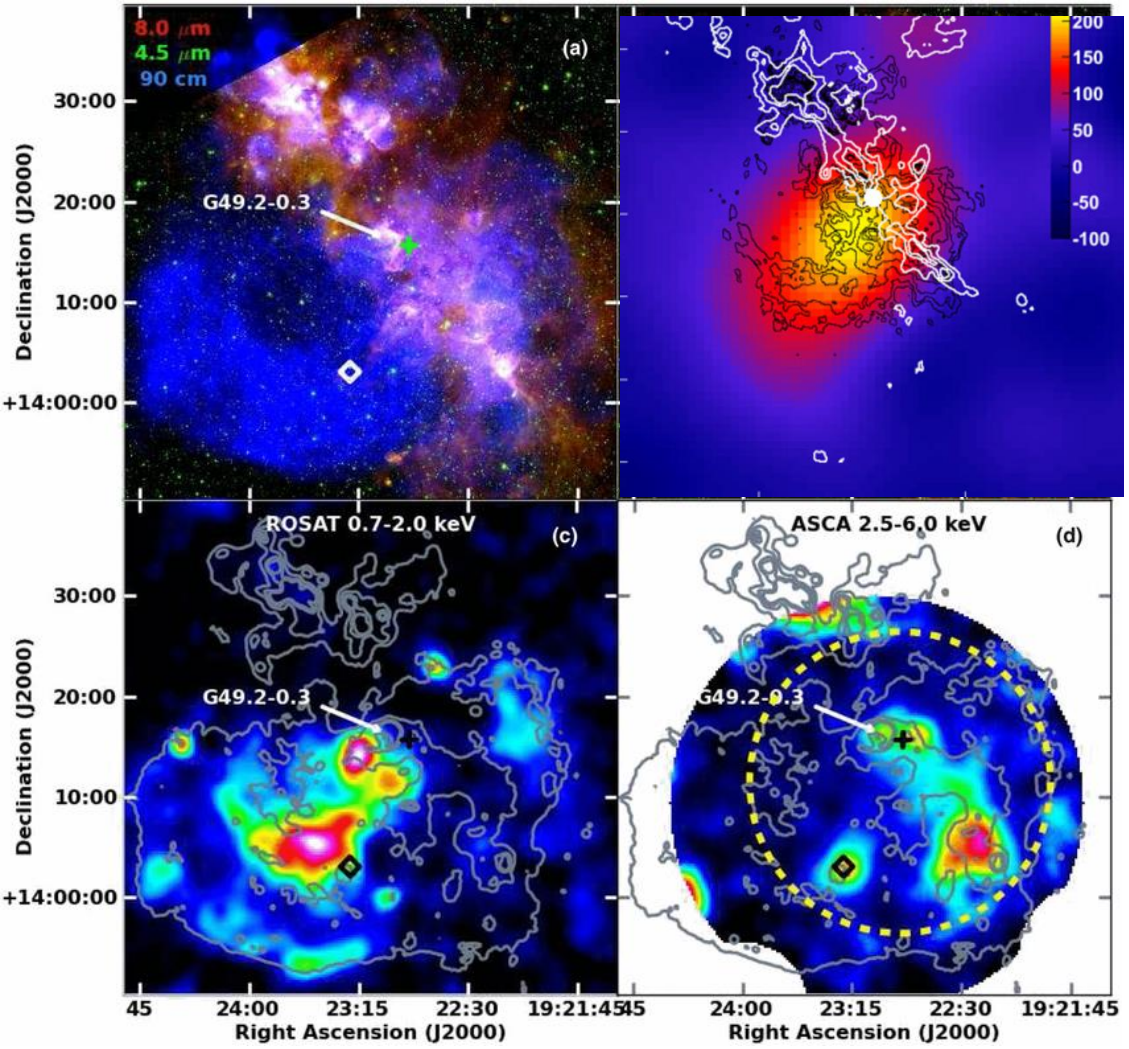




- W51 complex star forming regions:
  - SNR CRs ionize material more than radiation and alter fragmentation of H2 → traced by CTAO gamma-rays
  - mm-ALMA trace gas and synch radiation in B-fields and emission lines from various isotopologues

#2 Star-forming regions: CTAO and ALMA

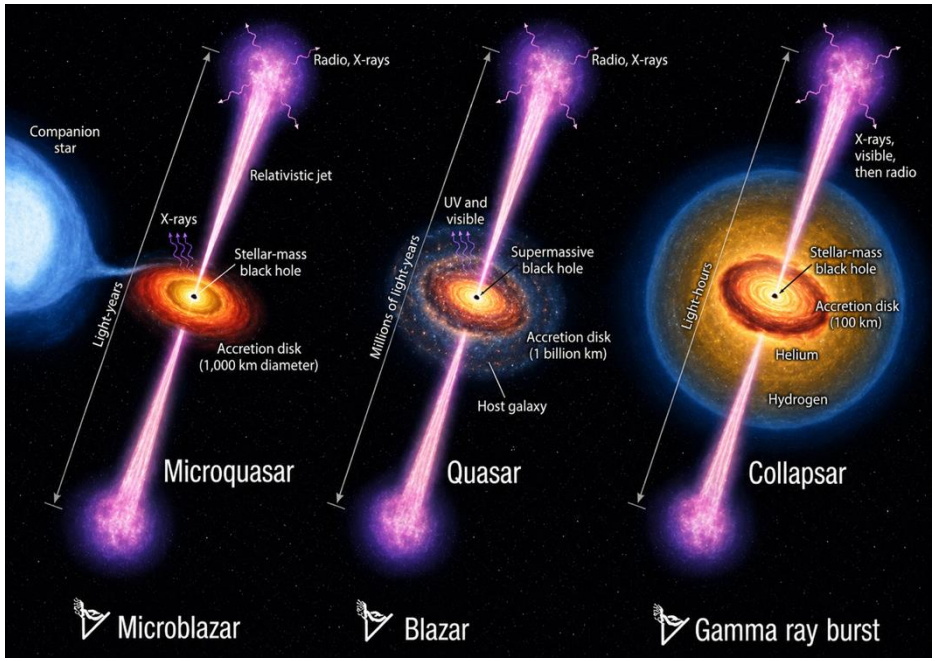
From Andreani, Trigo ESO newsletter May 26



- CTAO and ALMA can jointly answer questions such as :
  - Does gamma-rays trace mm (gas) morphology?
  - Are CRs hadronic in these class of targets? Pion bump in the spectrum
  - Is CRs population peculiar? match to local ISM or enhanced near the SNR shock?
  - Is there a top-heavy stellar initial mass function?

- To be explored!

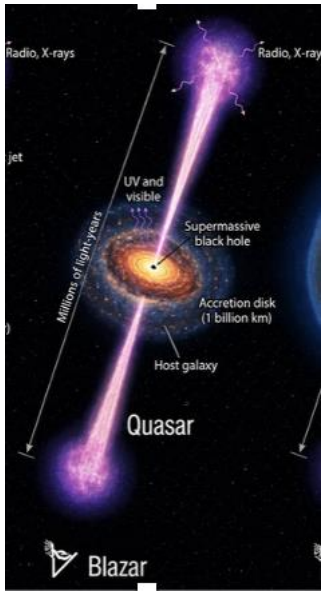
#3 Ultrarelativistic jets

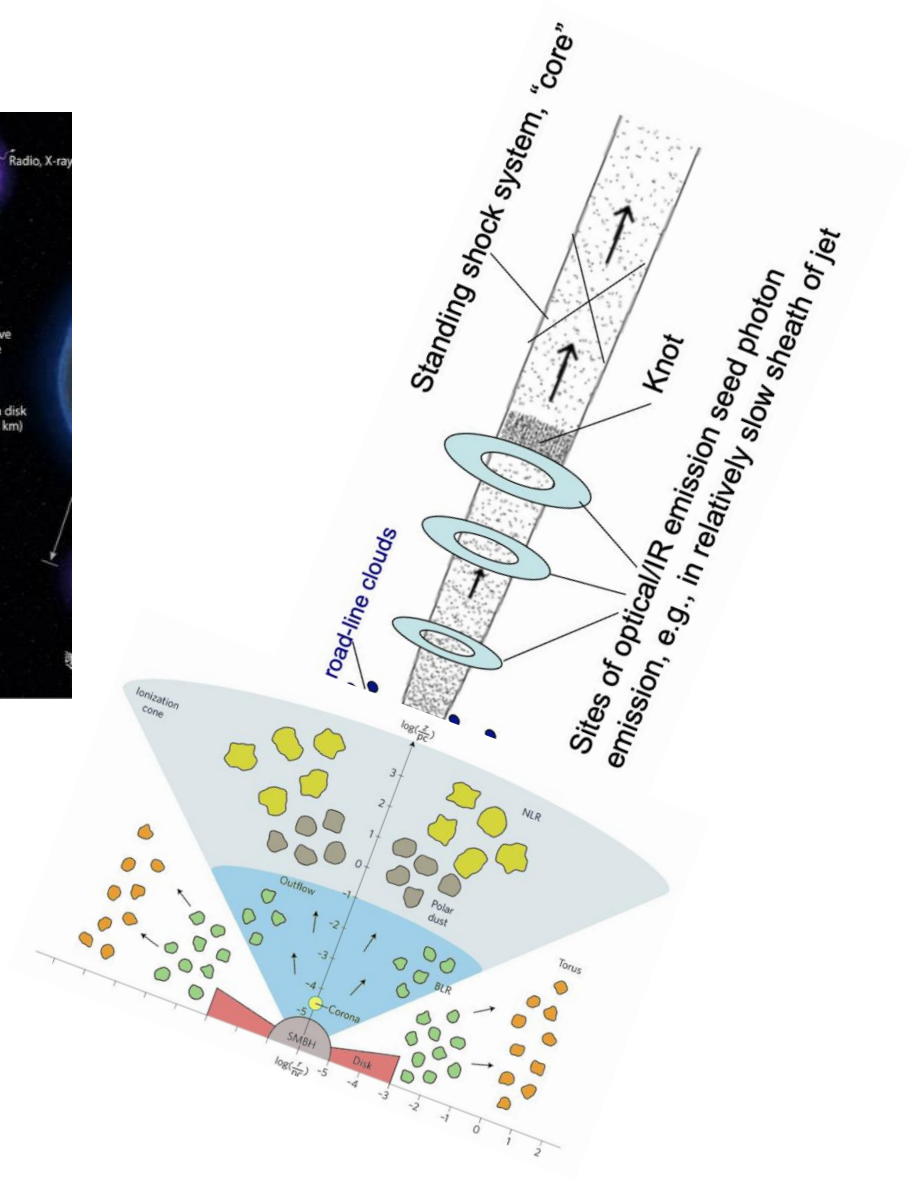


Mirabel & Rodríguez (1998/1999), colored with AI

- Relativistic jets at all scales: microquasars, jetted-AGNs, GRBs.
- Lorenz factor from few to hundreds → luminosity boost, time scale compression
- Many Questions:
  - How the jet is launched in the first place? What is the role of infalling material
  - How is collimated? What is the shape of the magnetic field
  - How are particles accelerated? Are they leptons or hadrons?
  - How are gamma-ray (and neutrinos) generated? Where?
  - Why do such objects flare so often and are wavelength correlated?
  - …
- CTAO
  - Now 100s of sources, 1000s with CTAO
  - Improved time-domain sensitivity

#3.1 jetted AGNs CTAO VLTI/GRAVITY

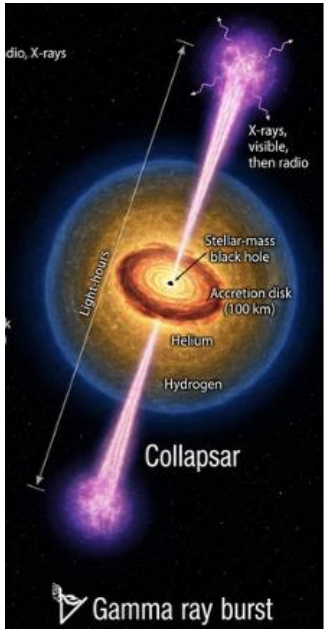


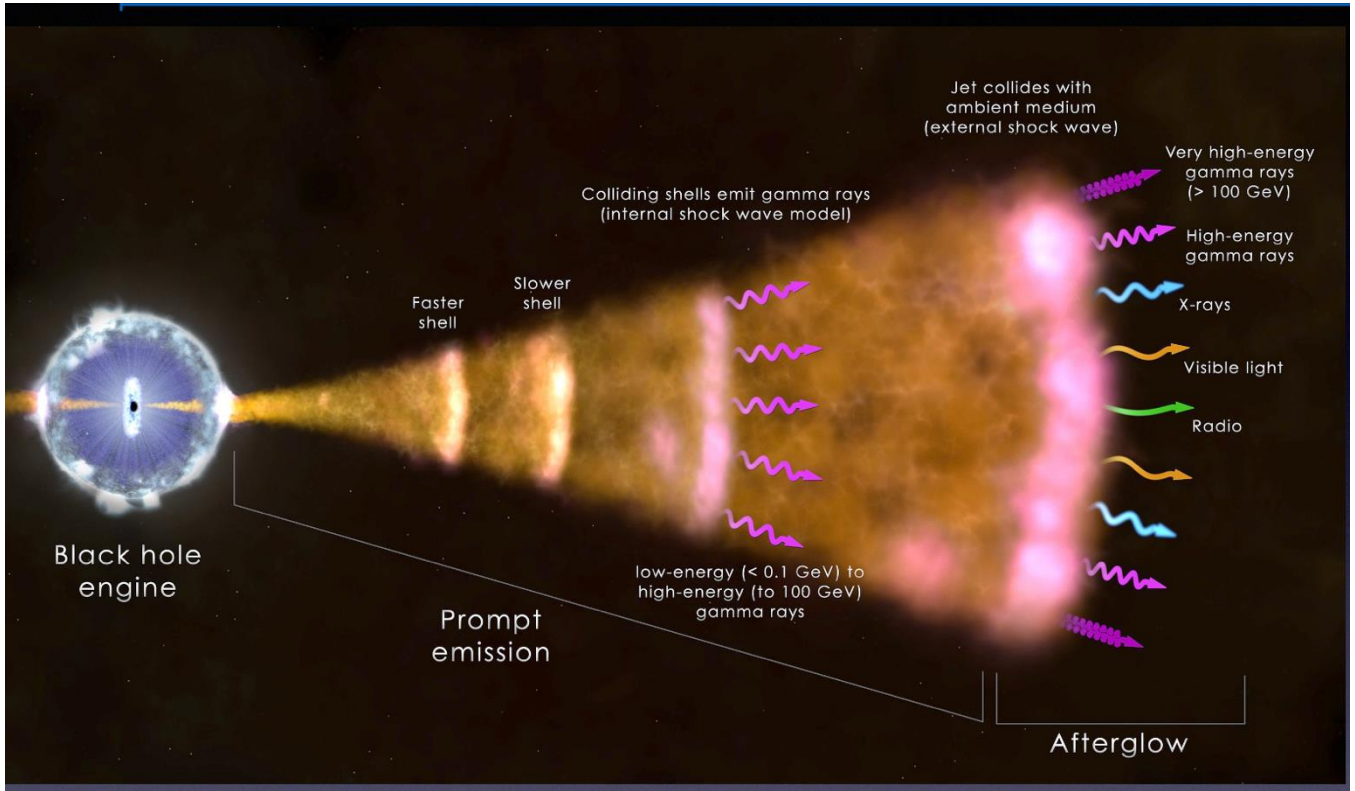


- CTAO measures fast and highest-energy output of the relativistic jet
- GRAVITY/VLTI instead probes the innermost parsecs

- Does flux change simultaneously?→ flare localization
- Are g-ray absorbed in BLR and torus? Neutrinos and IR can escape
- Observation in inner jet determine what seed photon fields are available

#3.2 Gamma-ray burst jets

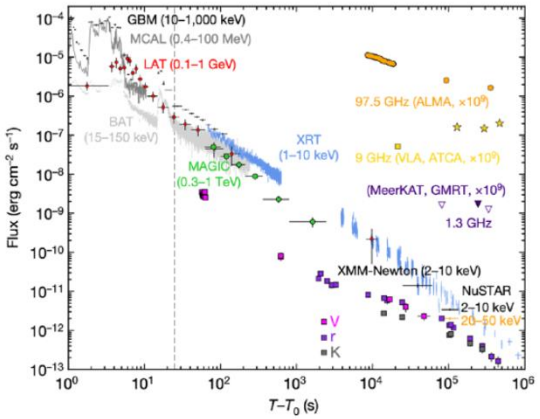




GRB	Detector	z	t_{max}	γ (EBL corr)	α	Highest E
180720B	HESS	0.65	12h	**1.6**	?	0.4 TeV
190114C	MAGIC	0.42	40min	2.22	1.6	1 TeV
190829A	HESS	0.08	**56h**	2.07	1.09	4 TeV
201216C	MAGIC	**1.1**	2h	3.15	0.62	0.2 TeV
221009A	LHAASO	0.15	1h	2.3	1.1/2.2	**13 TeV**

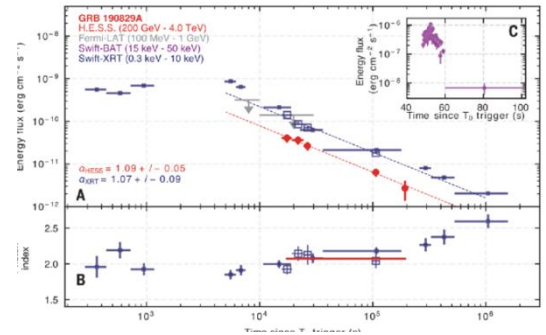
GRB 190114C

[MAGIC, Nature 575 (2019)]



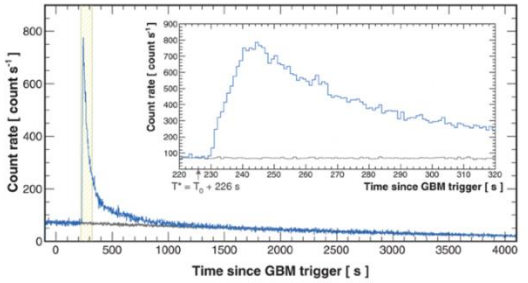
GRB 190829A

[H.E.S.S. et al., Science 372 (2021)]



GRB 221009A

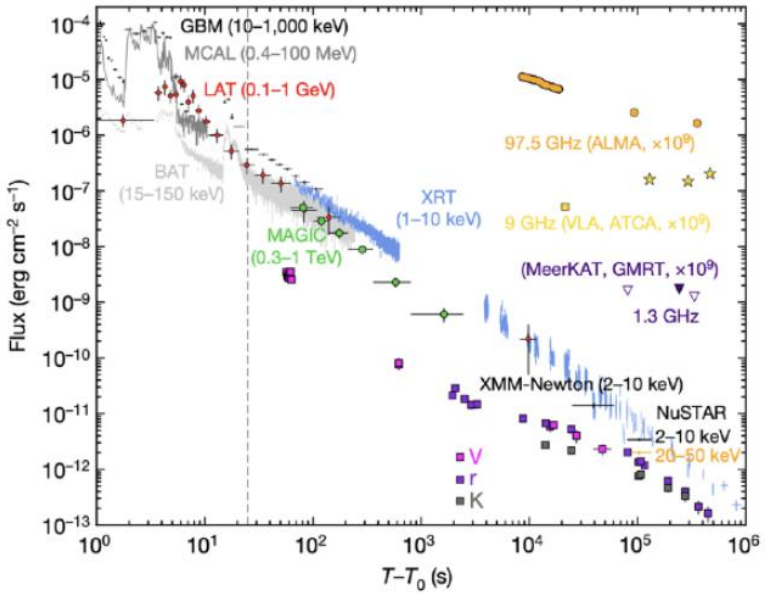
[LHAASO, Science 380 (2023)]



#3.2 Gamma-ray burst jets

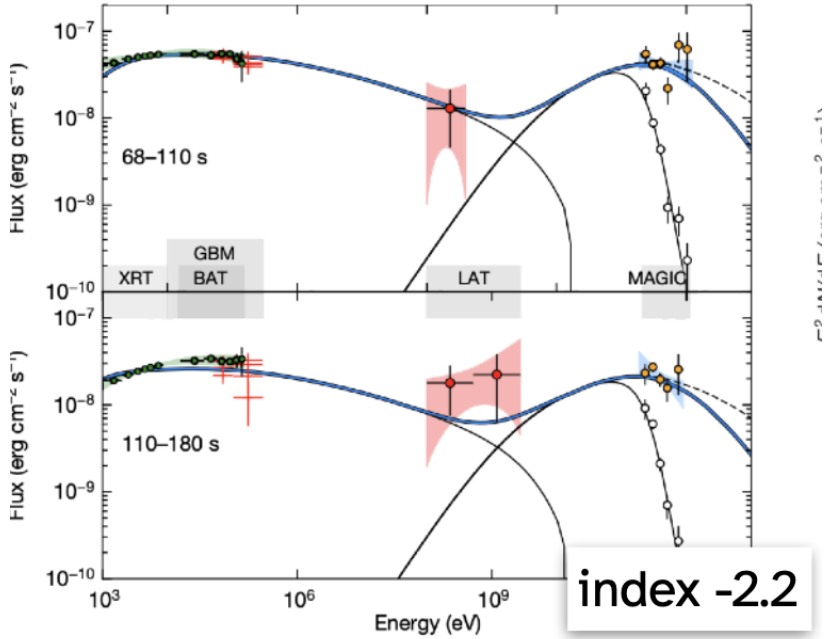
GRB 190114C

[MAGIC, Nature 575 (2019)]



GRB 190114C

[MAGIC, Nature 575 (2019)]



MAGIC detects a distinct sub-TeV emission component consistent with synchrotron self-Compton (SSC) in external shock or reversed shock

- mm-emission is expected in the early **afterglow**
- **reverse shocks** often peak in the mm/sub-mm band on hour timescales
- ALMA probes the regime where the synchrotron spectrum **transitions between self-absorbed and optically thin emission.**

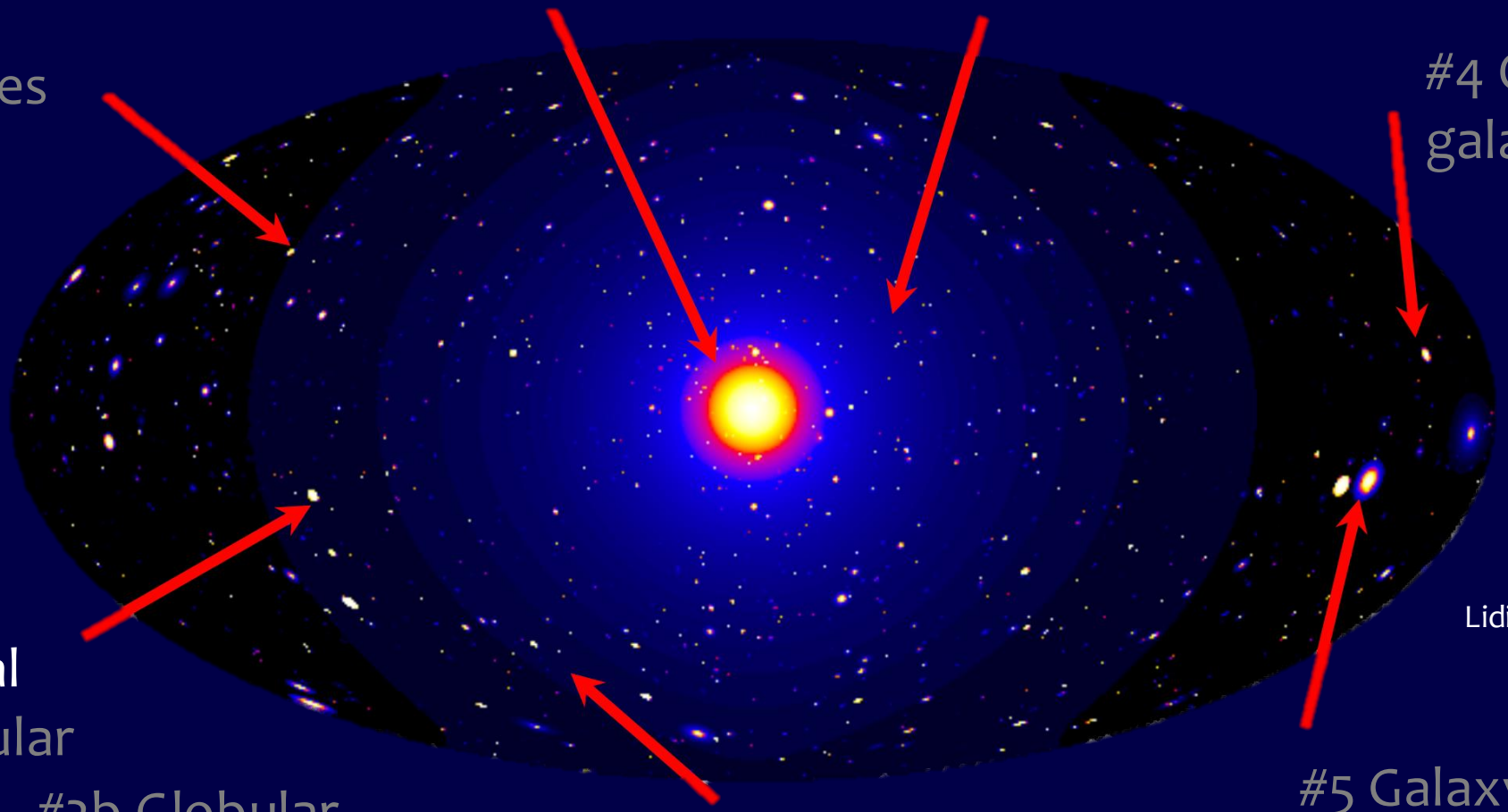
- *Automatic follow-up strategies to be defined!*

#4 Dark Matter hiding places

#1 Galactic Center and halo

#3 Dark subhaloes

#4 Other galaxies



#2 Dwarf galaxies (MW satellites) Spheroidal and Irregular

Lidia Pieri+

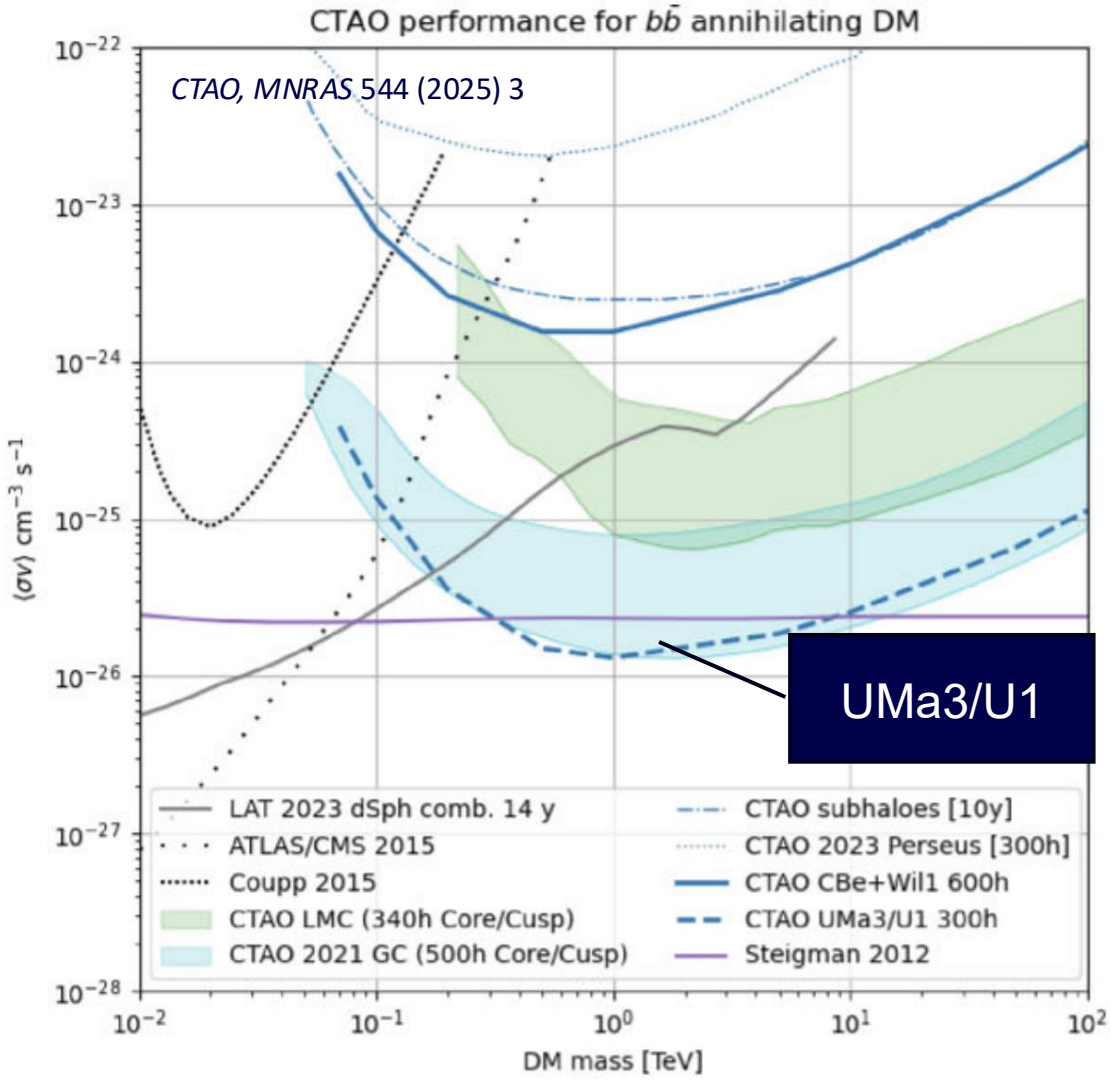
#2b Globular clusters

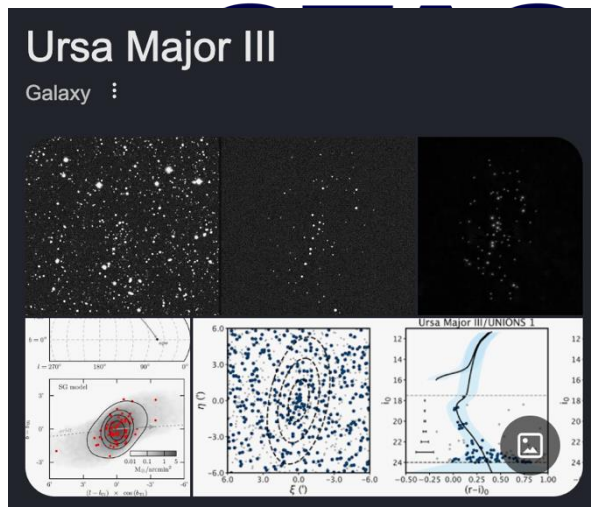
#6 Diffuse signal, lines, holes in stellar streams, …

#5 Galaxy clusters

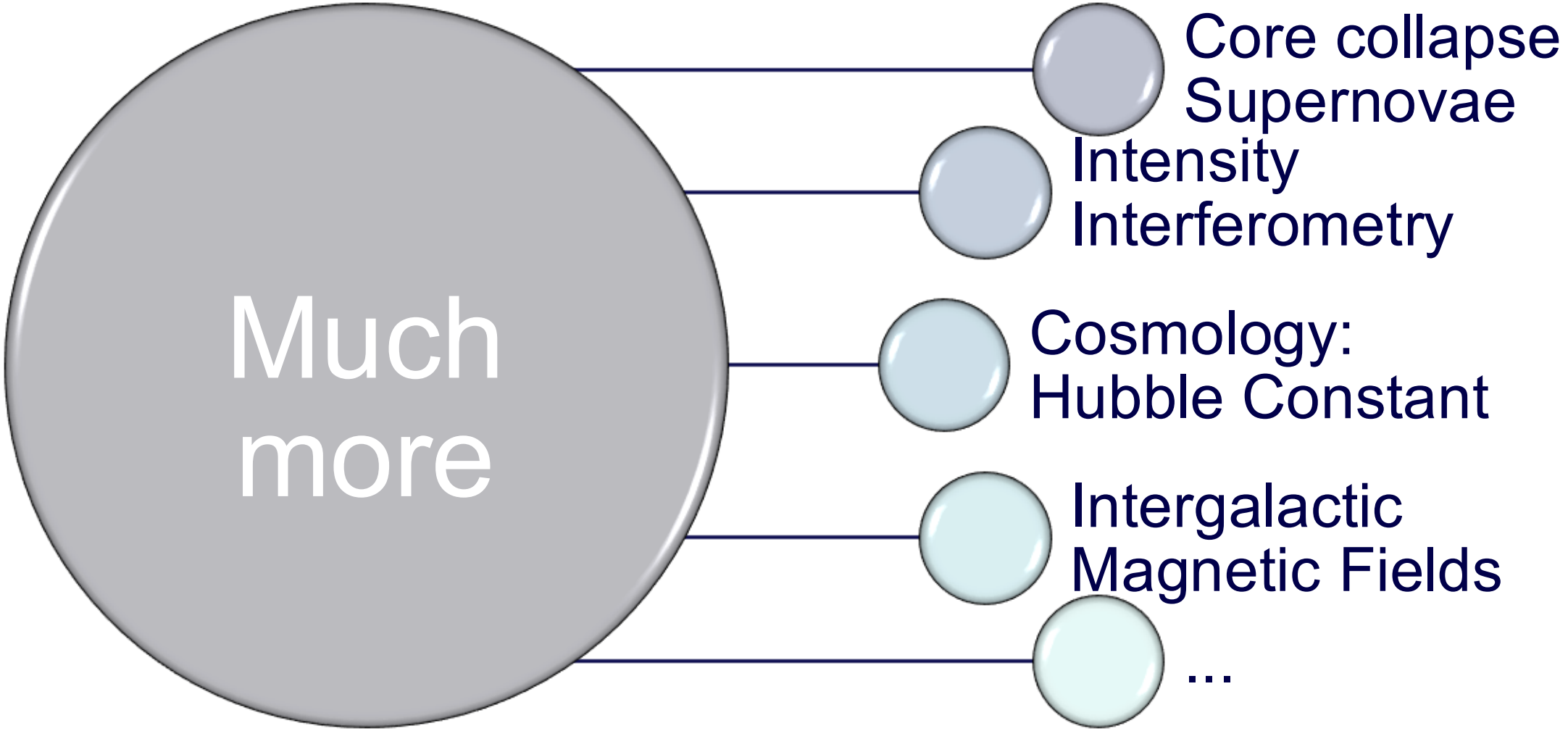
#4 CTAO-VLT/FLAMES VISTA/4MOST

Searching for the faintest dSphs





- Galactic Center dominates but strong astrophysical contamination, dSPhs cleanest DM target
- Faintest dwarf spheroidal galaxies may contain a lot of dark matter (M/L>>1000)
  - E.g. UMa3/U1
- Stellar association, characterization and velocity spread of utmost importance to determine dark matter astrophysical factor


Much more
Core collapse Supernovae
Intensity Interferometry
Cosmology: Hubble Constant
Intergalactic Magnetic Fields
...

Time to Take-home

New era

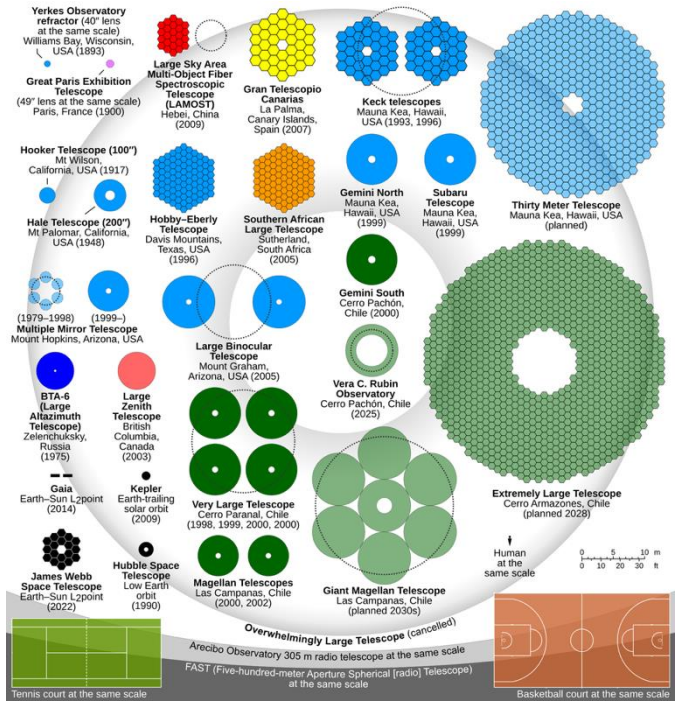
Gamma-ray astrophysics relates to

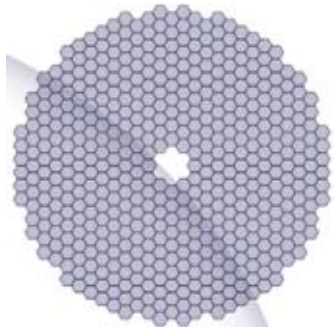
[MWL]	[MM]	[Time]
• Astrophysical regions emitting at all wavelengths	• Neutrinos • GW	• Non-thermal nature

Required novel challenges in coordination

Mutual Alert	Joint Schedule	Data ready
• Define criteria, MoU	• Monitoring and ToO campaigns	• Quick and easy

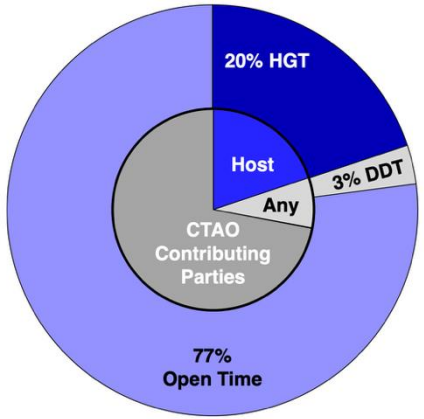
2030s, the era of Big (Astronomical) Data





CTA –South all telescope combined (Biteau)

- In the **past decades** we have seen birth of multi-messenger astrophysics, and strengthen the mwl networks
- In the **next decade**, massive amount of precision data: Multi-wavelength and multi-messenger. Challenging but exiting times.
- We need **to coordinate**: alerts, shared programs, shared data access, **especially within ESO**



- A step in this direction (in discussion today):

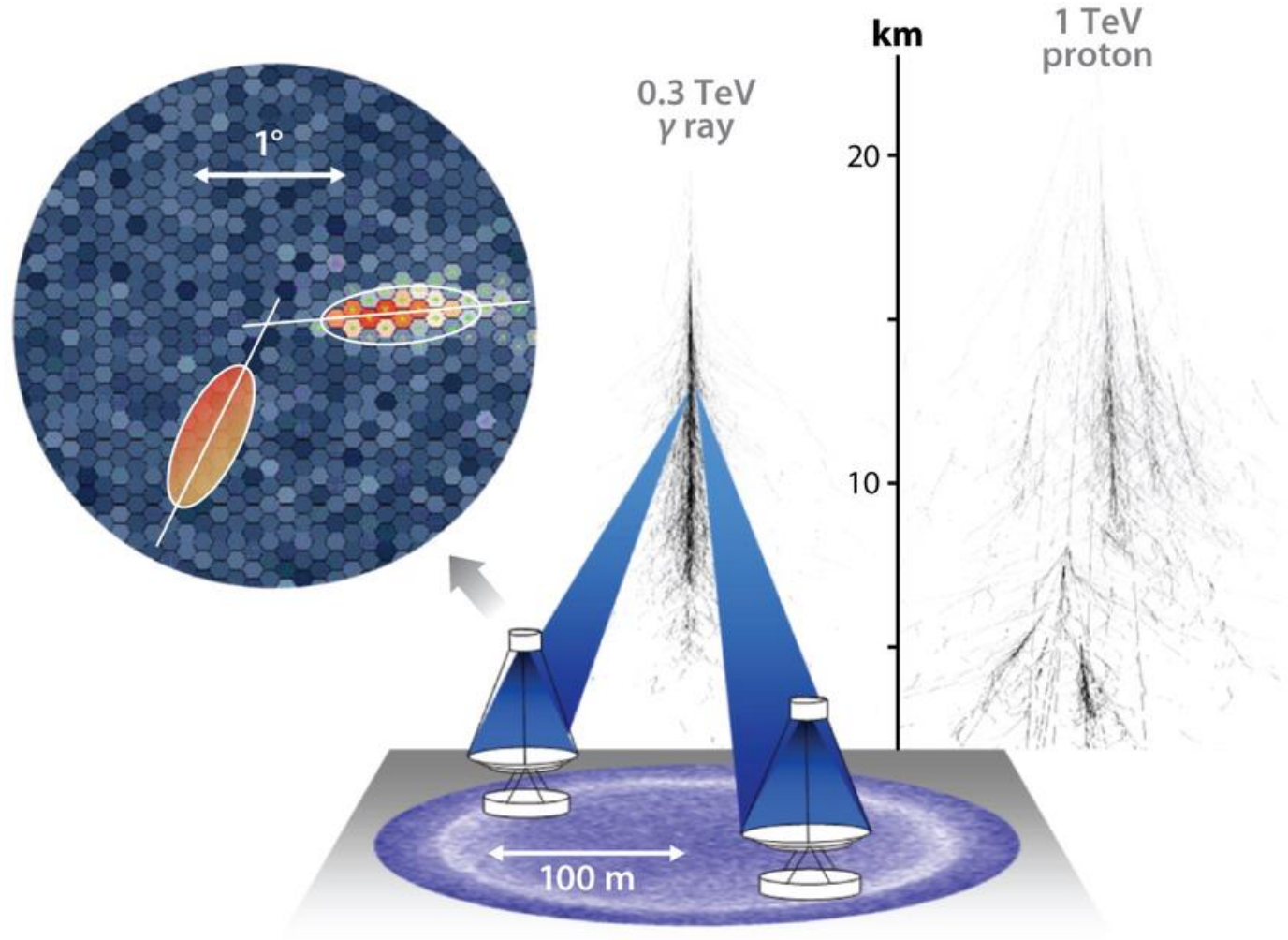
  We are currently proposing that ESO time (>10% South, >10% North) is given for ESO-synergy proposals

Know your new instrument!

Thanks

Backups

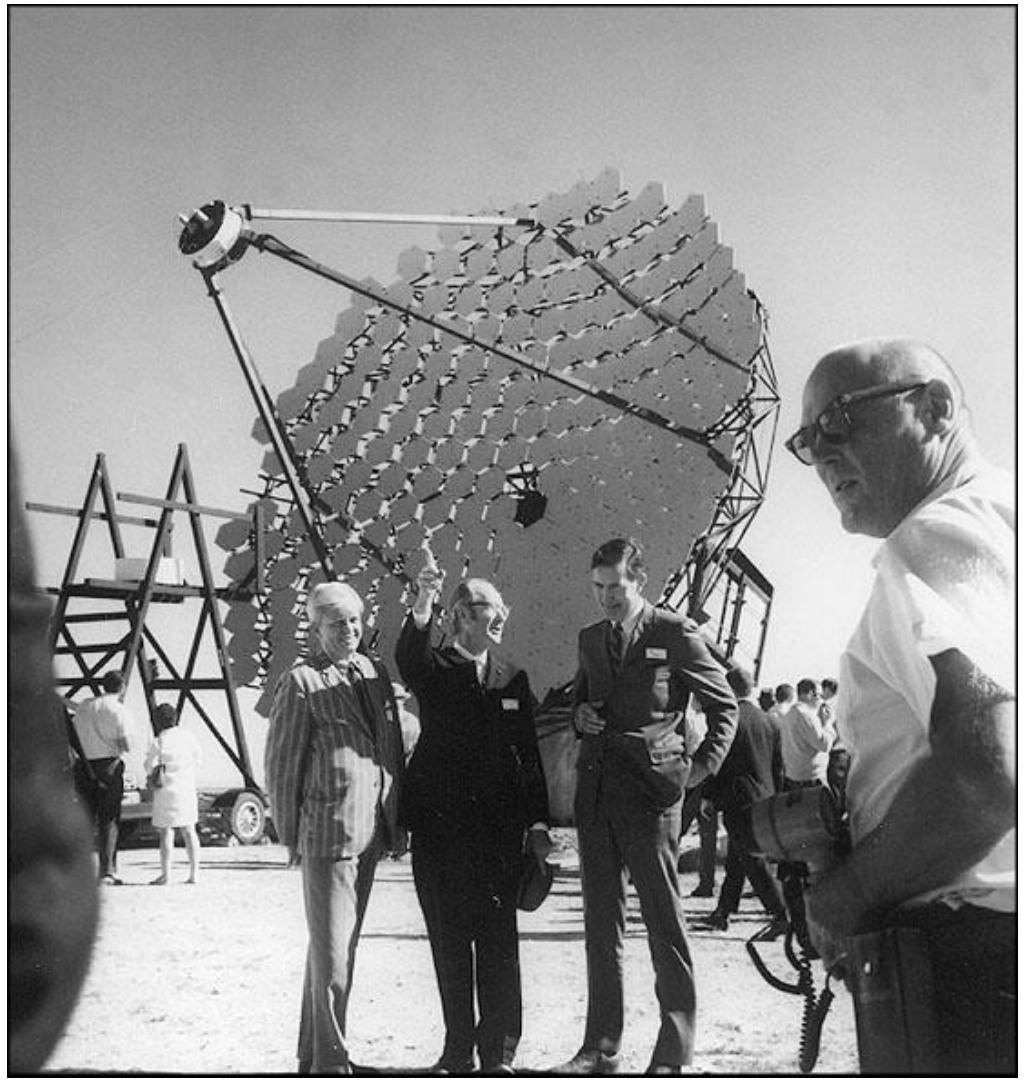
Imaging Atmospheric Cherenkov Technique (IACT)



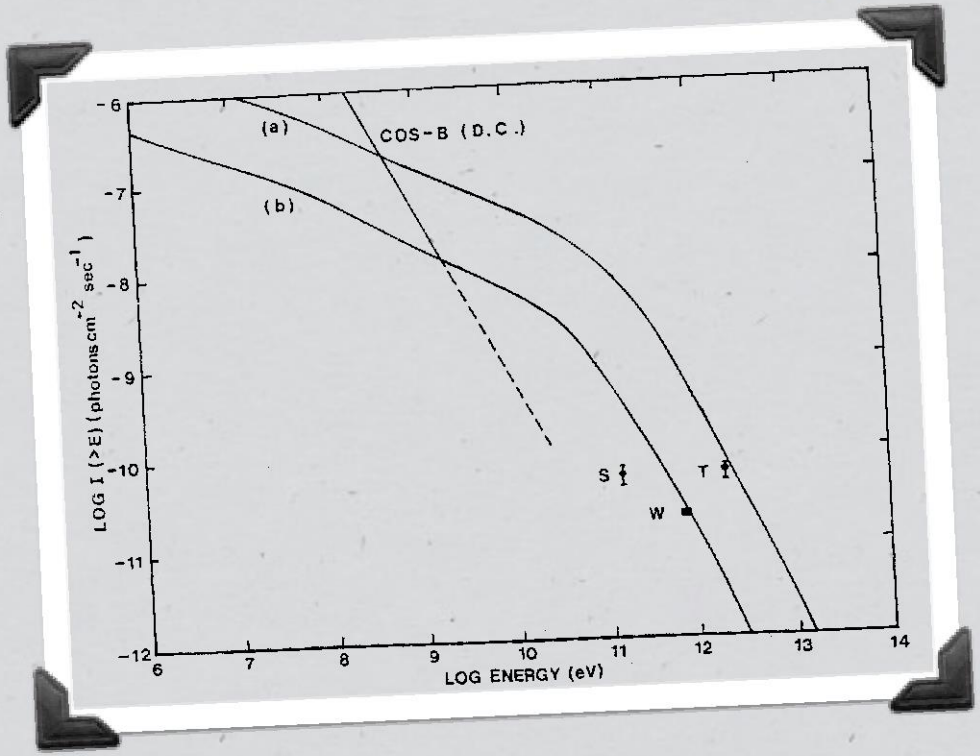
Hinton JA, Hofmann W. 2009.
Annu. Rev. Astron. Astrophys. 47:523–65

Whipple (M. Hopkins, 12m, 1989)

When we first saw the Crab Nebula

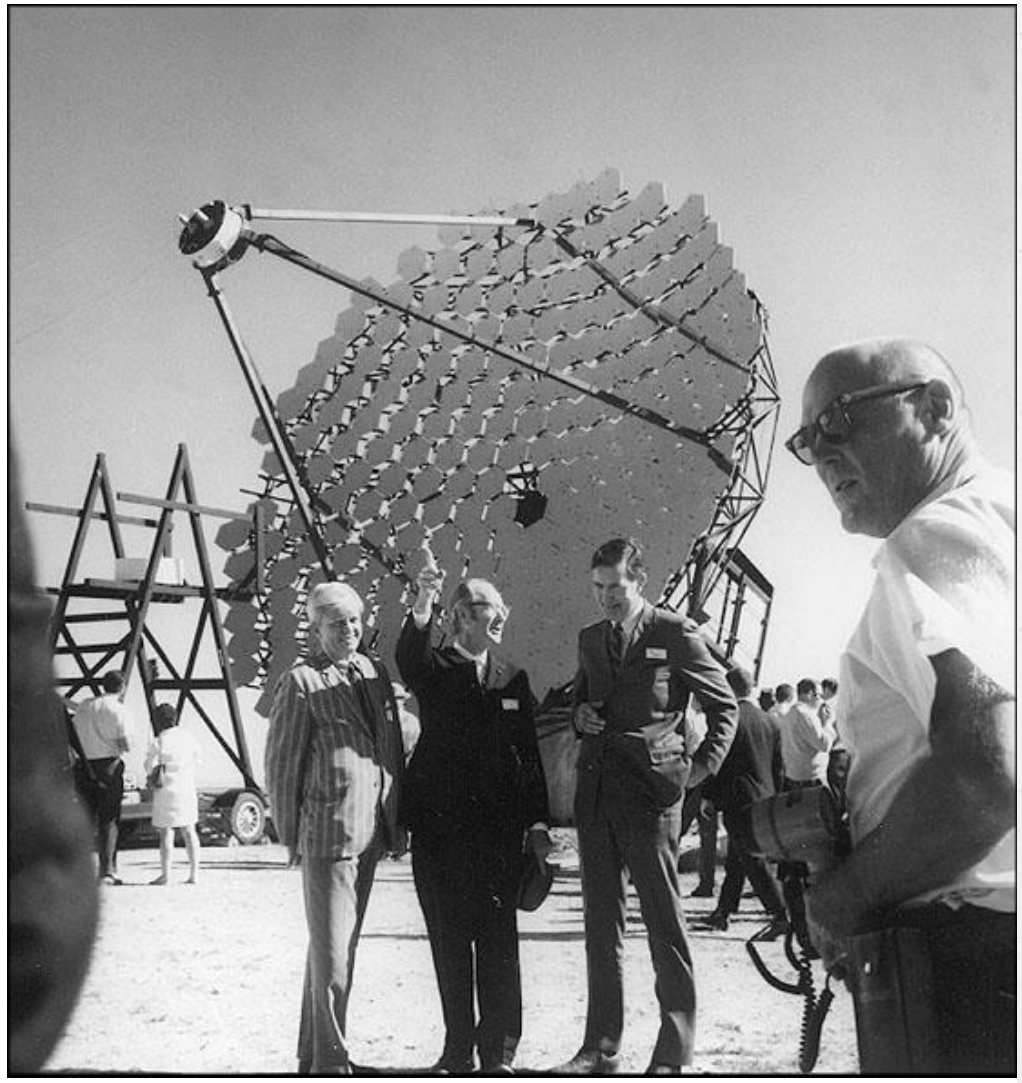


1989: When I first saw the Crab Nebula with Whipple



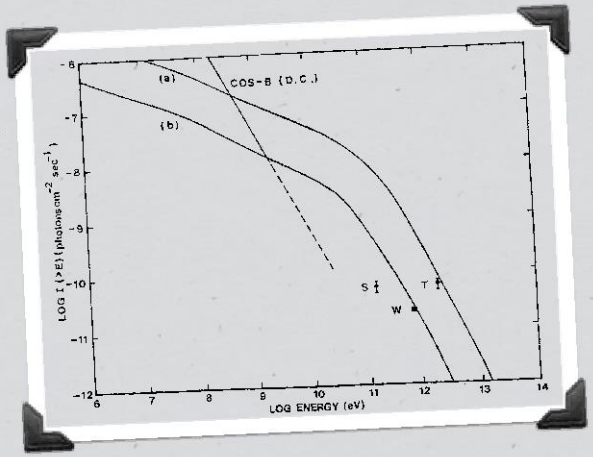
MAGIC, HESS, VERITAS

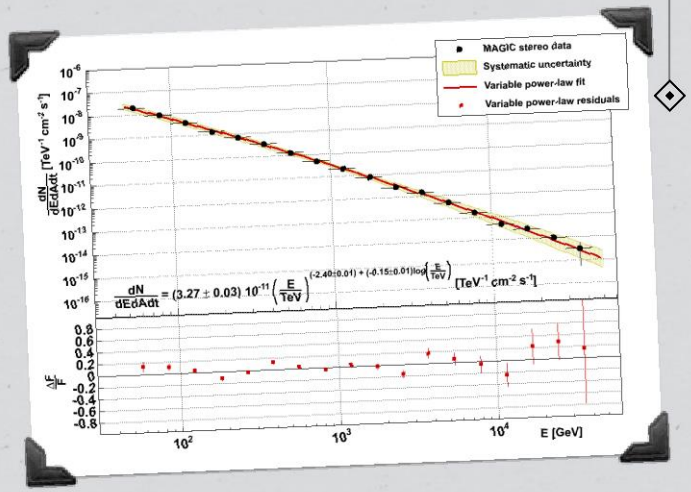
20 years later

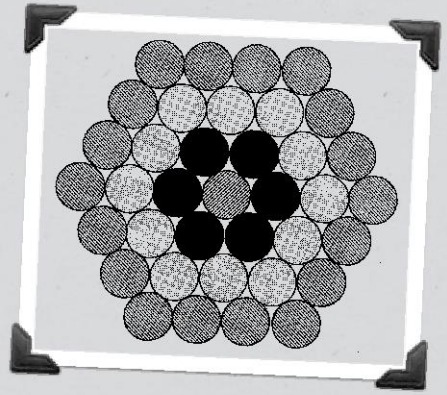


Family album

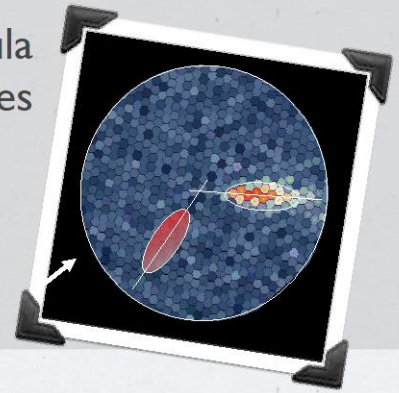
1989: When I first saw the Crab Nebula with Whipple



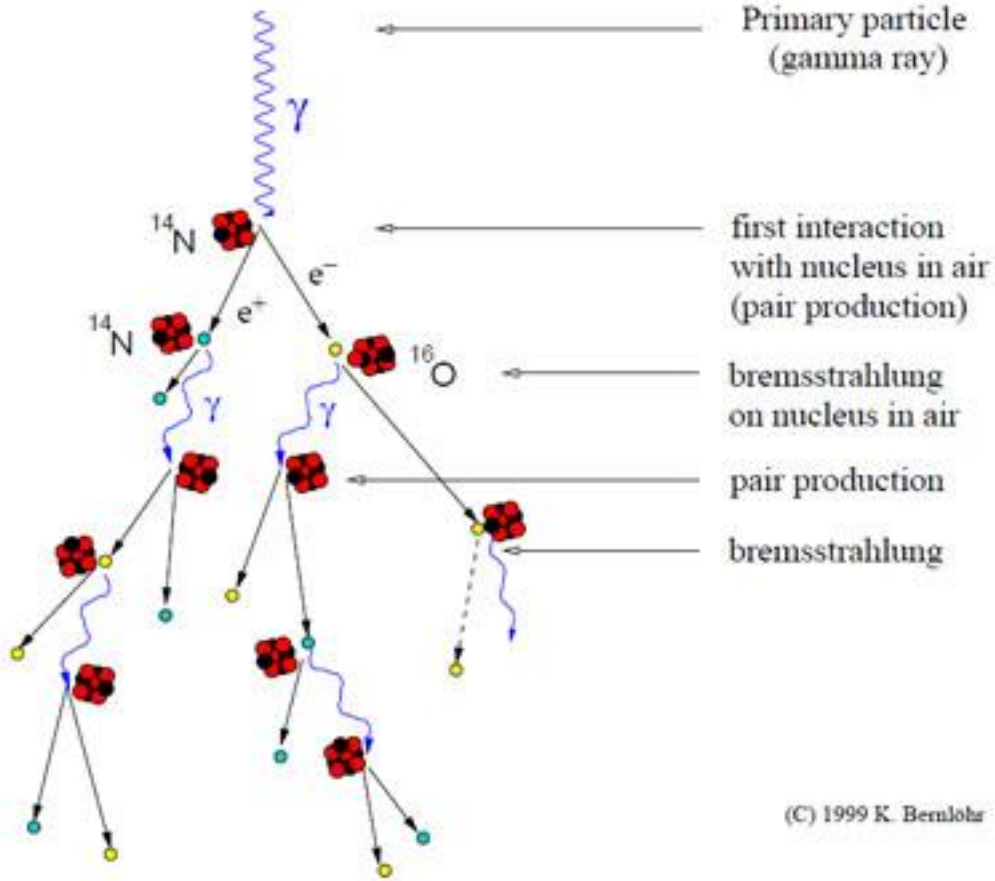




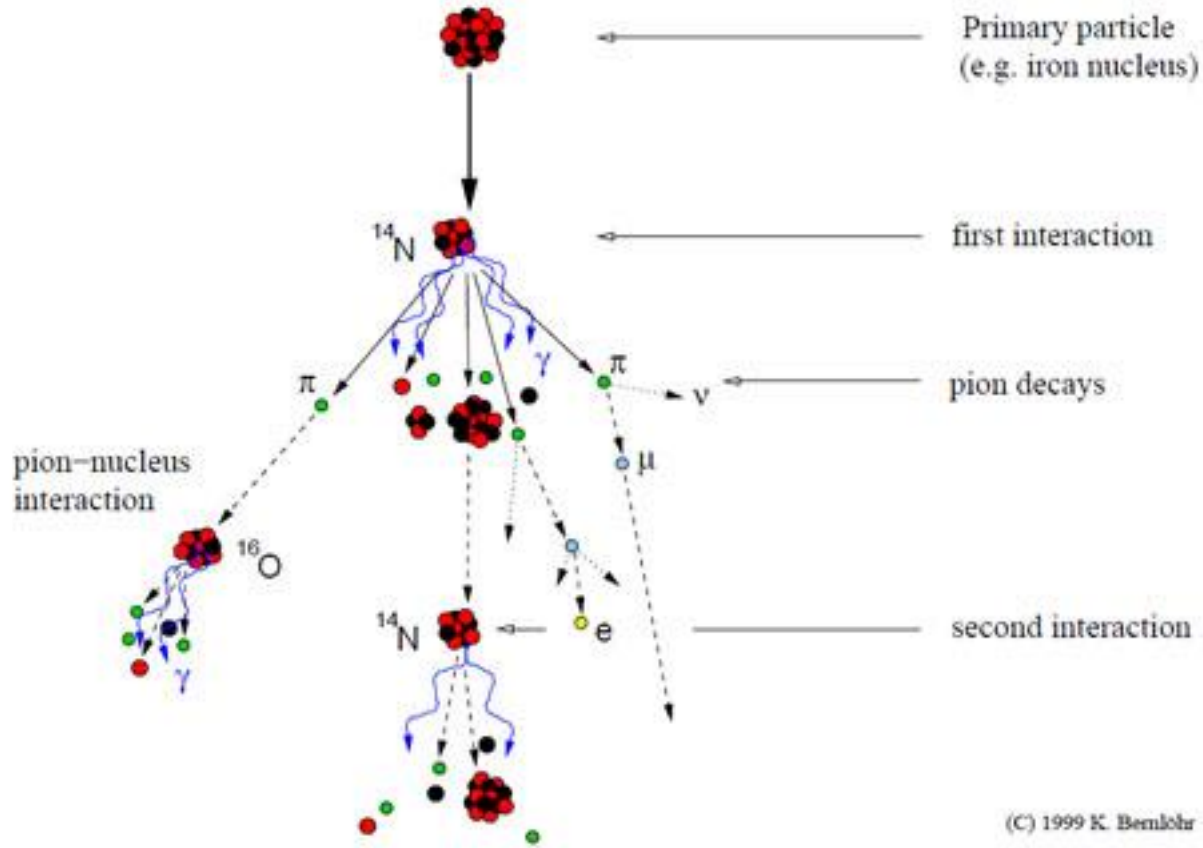
2012: Crab Nebula with MAGIC eyes



Development of gamma−ray air showers



Development of cosmic−ray air showers



Key Science Projects (KSPs)

Ideas put forward by CTAO Consortium

- KSP will be awarded to the CTAO Science Collaboration consisting of contributors to the construction project
- Common ideas:
  - Long/multi-y observations (300+h),
  - Several science cases,
  - Coherent analysis fashion

FURTHER READINGS

- **Galactic Centre:** Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre JCAP 01 (2021) 057
- **Galactic Plane Survey:** Prospects for a survey of the galactic plane with the Cherenkov Telescope Array JCAP 10 (2024) 081

Galactic transient sources with the Cherenkov Telescope Array Observatory, MNRAS 540 (2025) 1, 205

- **Large Magellanic Cloud:** Sensitivity of the Cherenkov Telescope Array to TeV photon emission from the Large Magellanic Cloud MNRAS 523 (2023) 4, 5353
- **Dark Matter Programme:** Prospects for γ-ray observations of the Perseus galaxy cluster with the Cherenkov Telescope Array JCAP 10 (2024) 004, Dark matter line searches with the Cherenkov Telescope Array JCAP 07 (2024) 047, Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation JCAP 02 (2021) 048, **Prospects for dark matter observations in dwarf spheroidal galaxies with the Cherenkov Telescope Array Observatory** MNRAS 2025