High Energy Astrophysics and Cosmology in the era of all-sky surveys

Very-High-Energy Gamma-Ray Astronomy with CTAO

Status and Science at the Dawn of Operations

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Project Science Office
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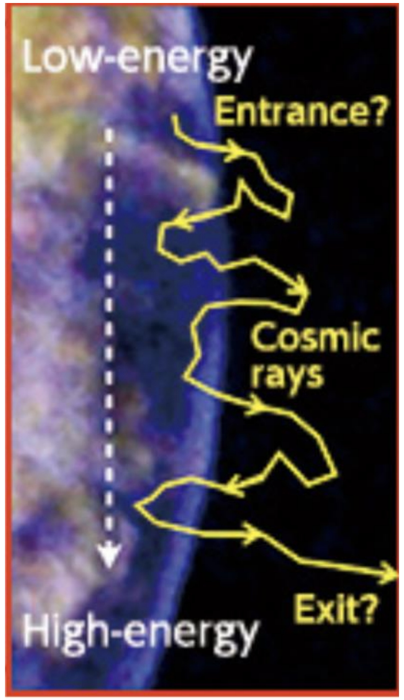
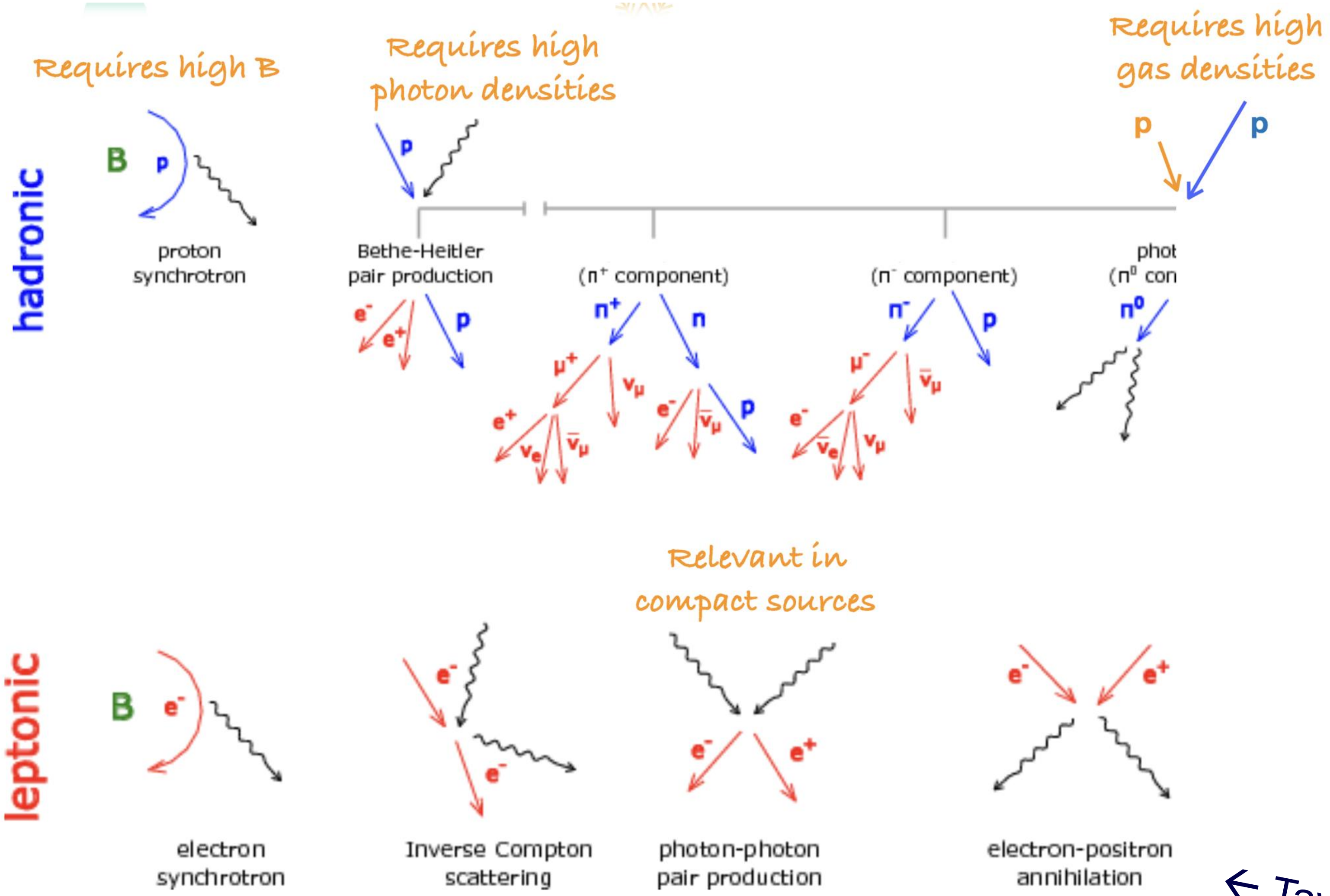
Quick facts on g-ray astrophysics

Non thermal Universe

Gamma rays trace particle acceleration in space



e.g. shock acceleration



← Tavecchio

Non thermal Universe

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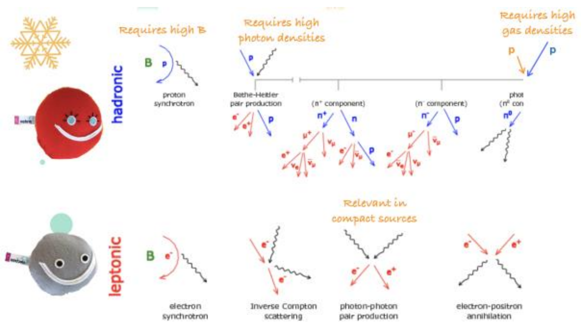
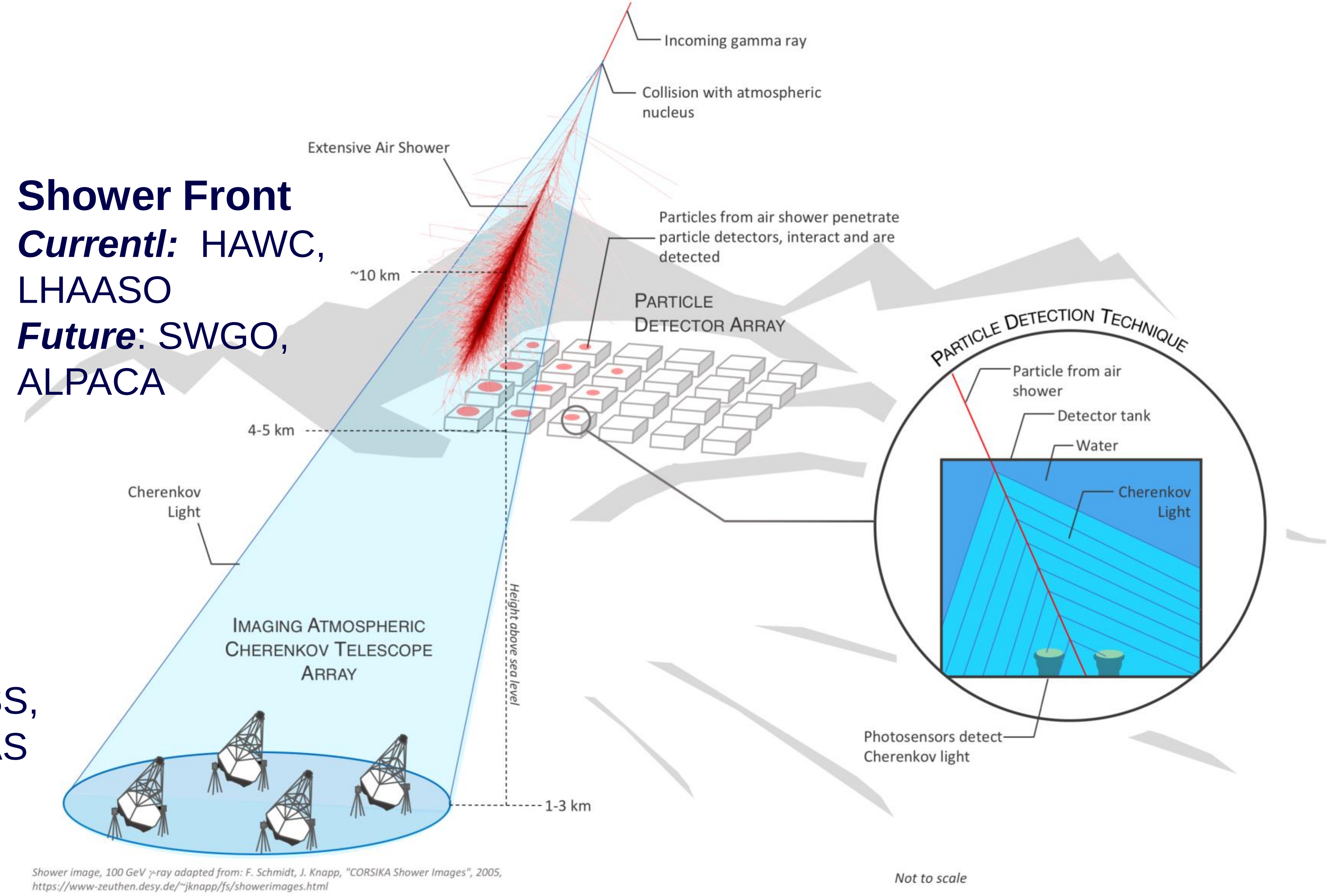


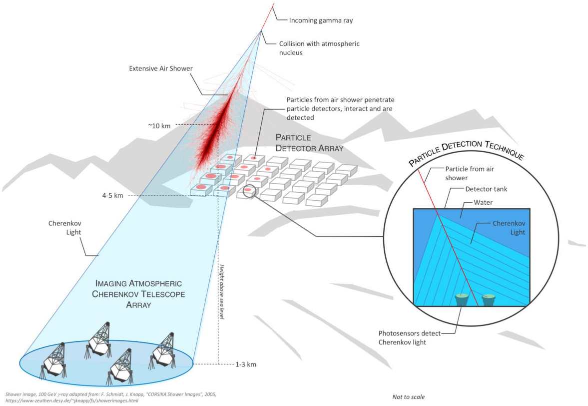
Ground-based g-ray Astrophysics

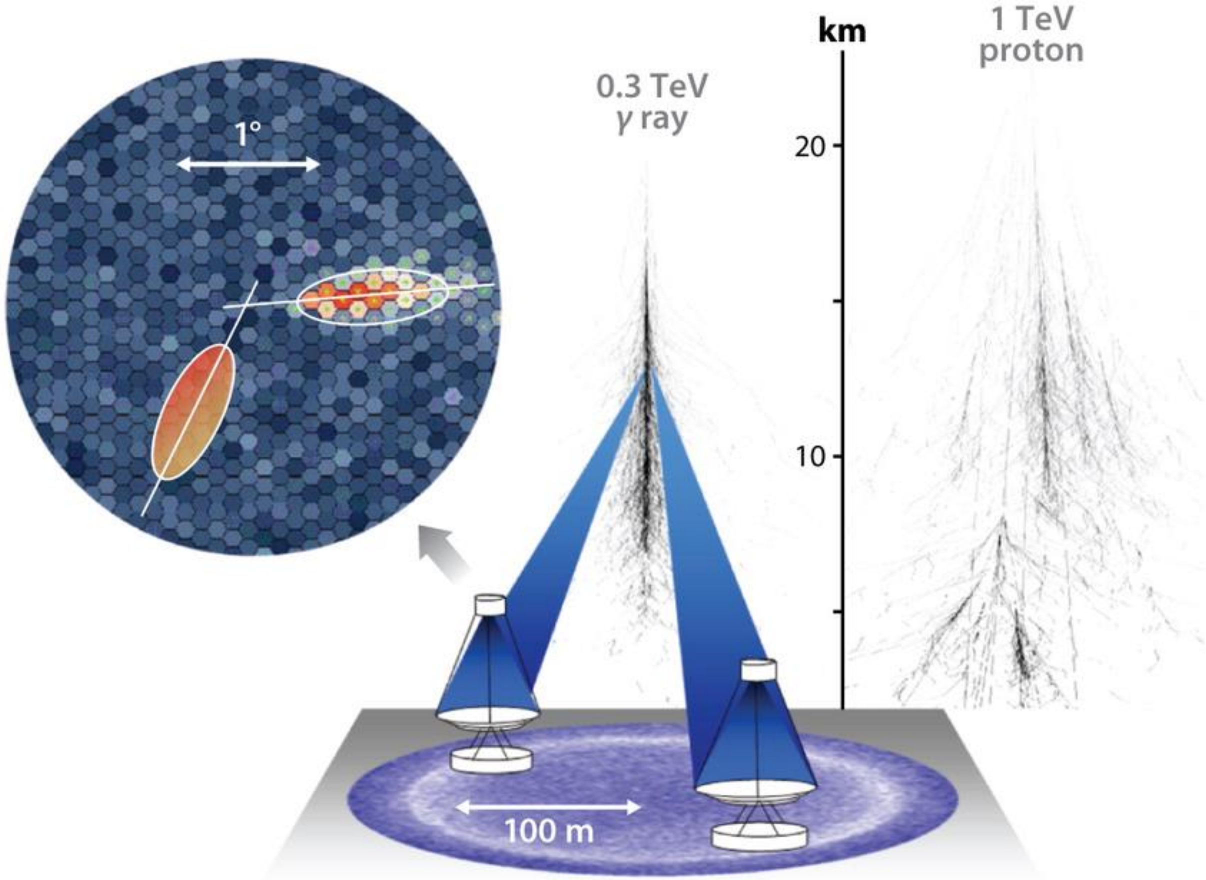
Shower Front
Currentl: HAWC, LHAASO
Future: SWGO, ALPACA



IACTS
Currently: HESS, MAGIC, VERITAS
Future: CTAO, Astri-MA, LACT

Ground-based g-ray Astrophysics





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

Telescopes Array:
- Improved sensitivity
- Better angular reconstruction

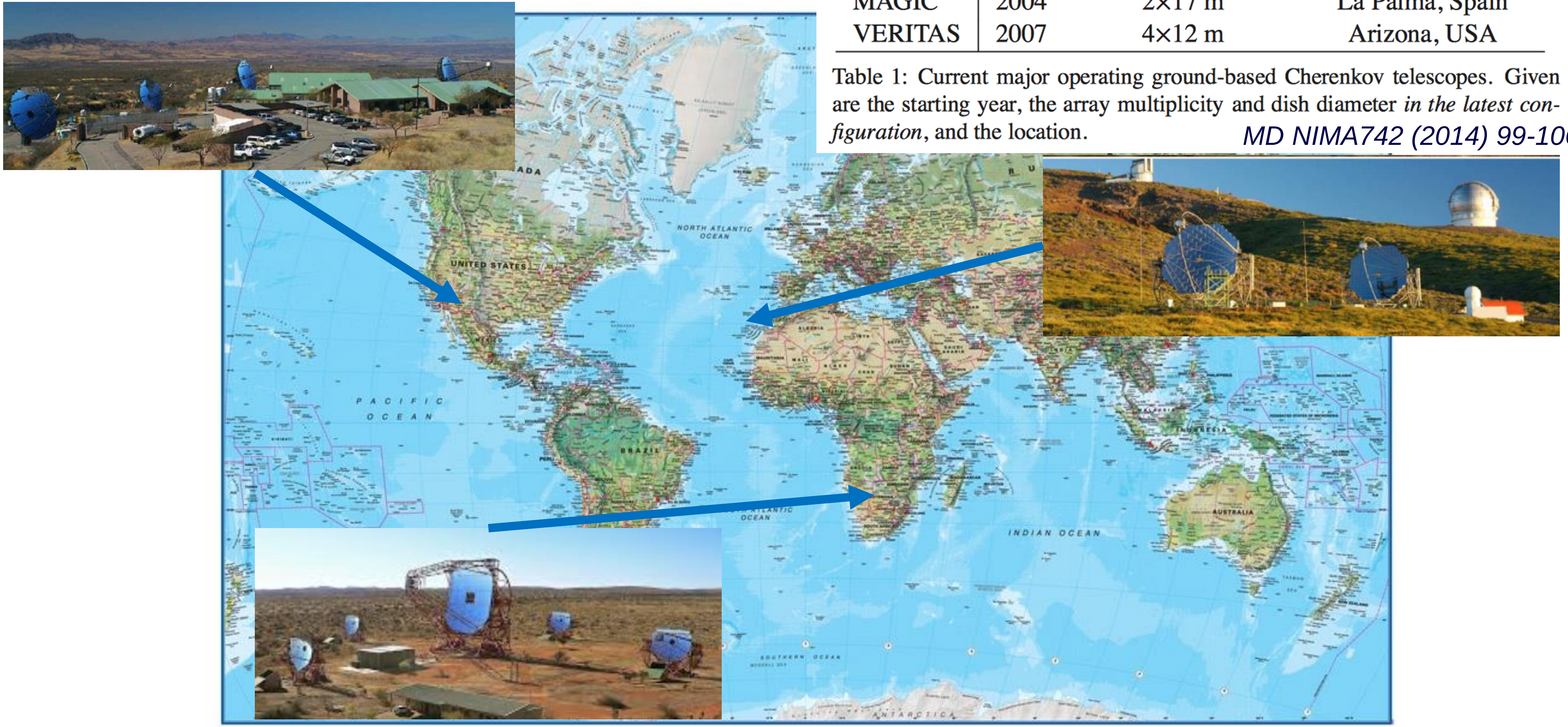
Remember
- Observed event is atmospheric shower: angular resolution cannot be <<0.1 deg
- Atmosphere is part of the detector
- Around 1e3/1e4 primary cosmic protons than gamma

Current IACTs

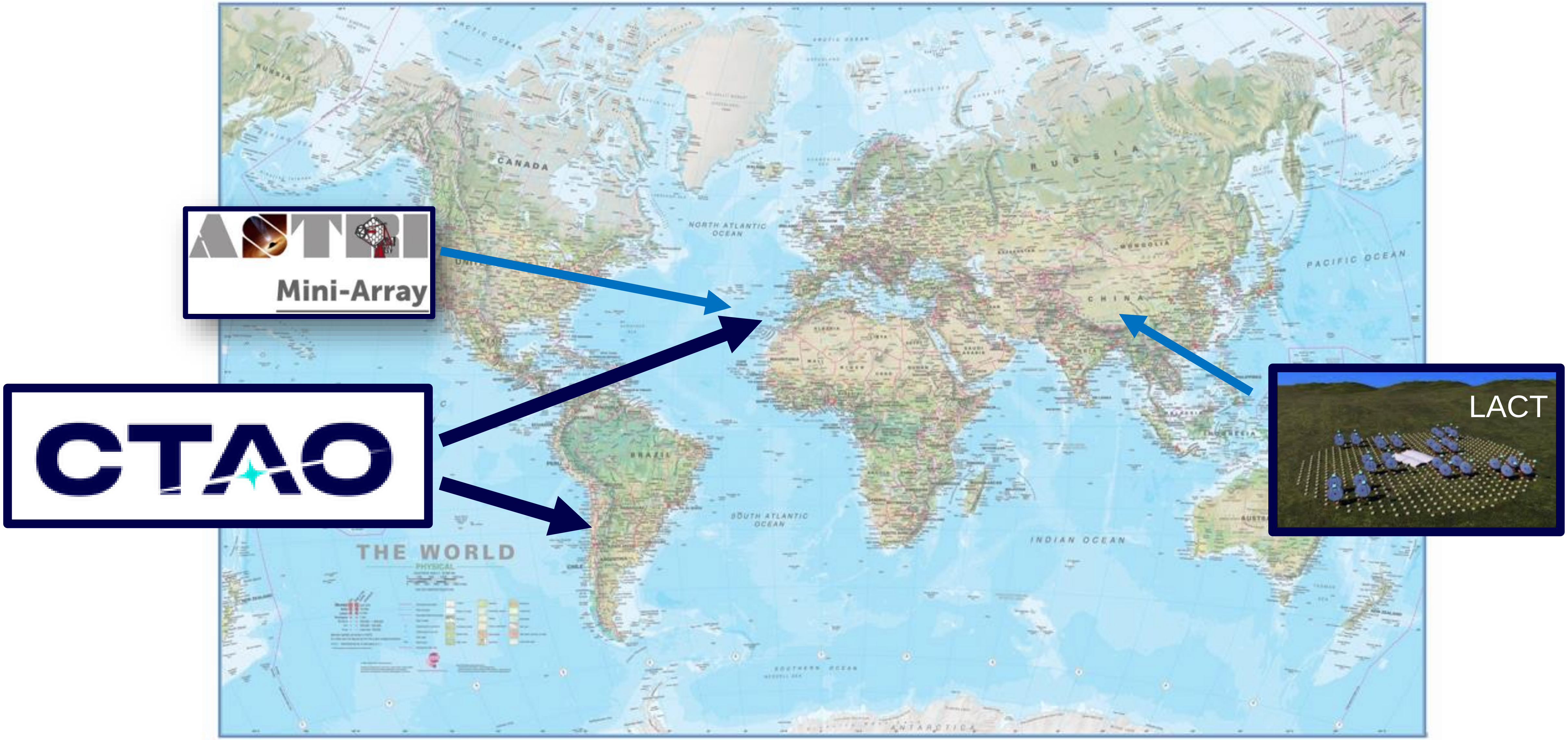
IACT	Year	Nr. tels & diameter	Location
~~Whipple~~	~~1968~~	~~1×12 m~~	~~Arizona, USA~~
H.E.S.S.	2003	4×12 m+1×28 m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA

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

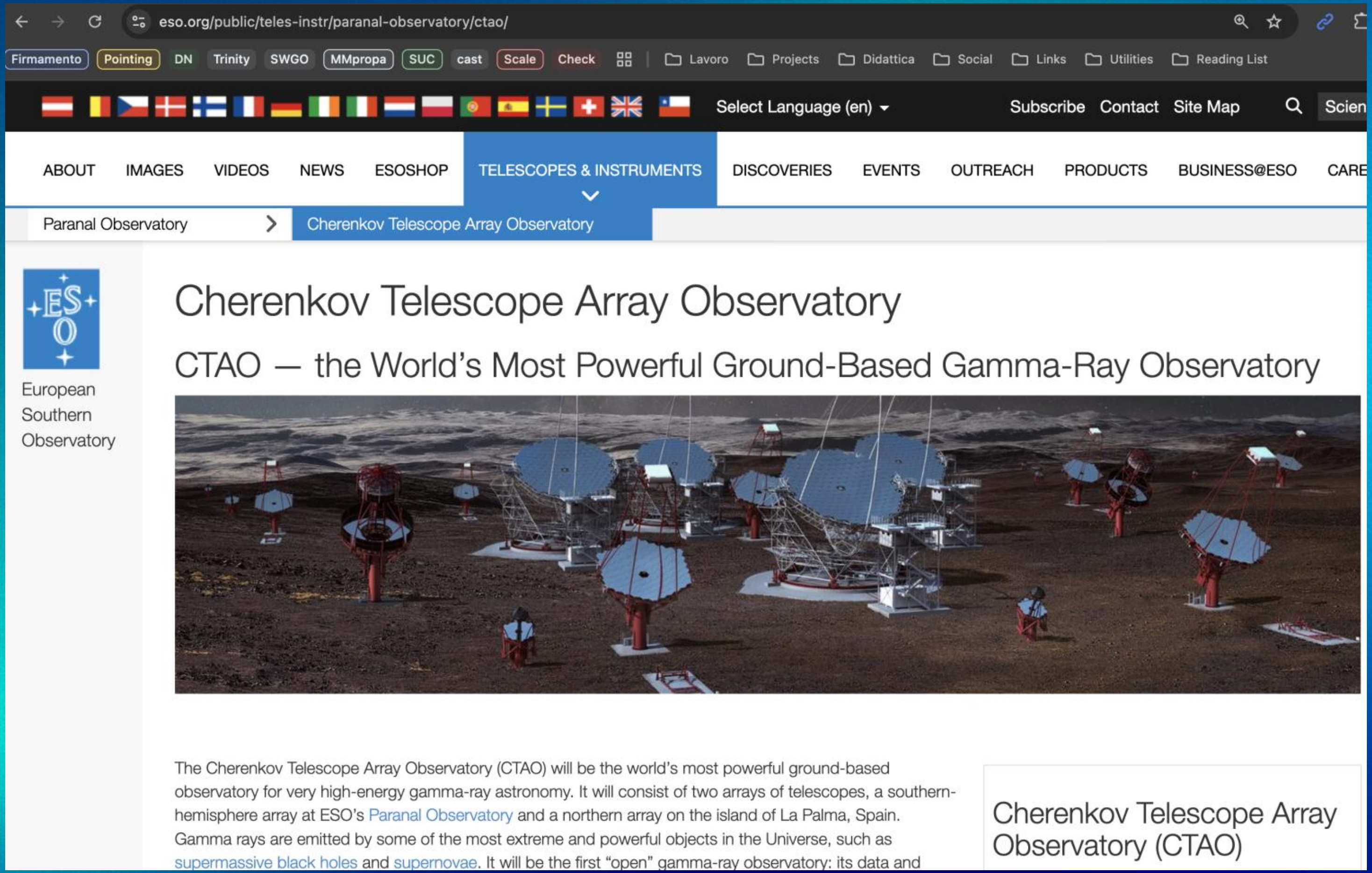


The Cherenkov Telescope Array Observatory

The Cherenkov Telescope Array Observatory

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

Funded by 9 EU member states (Austria, Croatia, Czech Republic, France, Germany, Italy, Poland, Slovenia), and Switzerland, ESO, and Japan
(Australia, Brazil, Netherlands and USA are in negotiation)

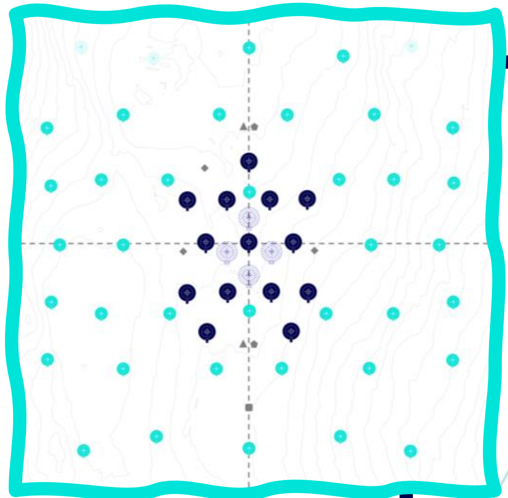


https://www.eso.org/public/teles-instr/paranal-observatory/ctao/

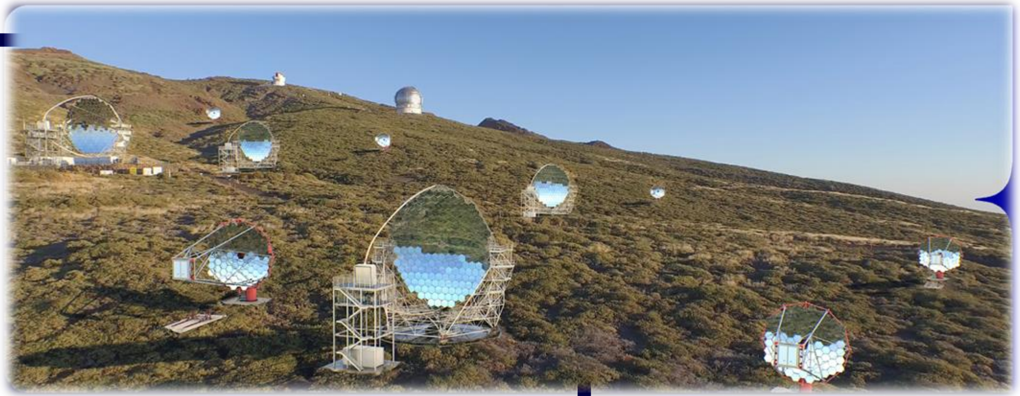
Headquarter: Bologna INAF-area
Science Data Management Center: DESY Zeuthen

Beta Configuration approved

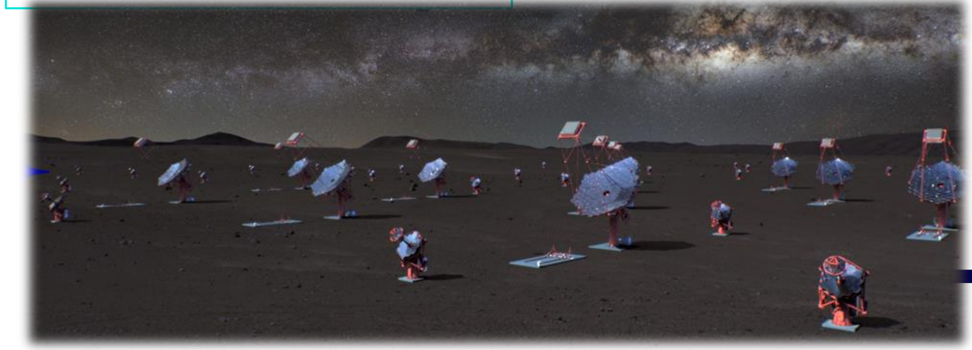
One observatory: two arrays. North (ORM), South (ESO Paranal)

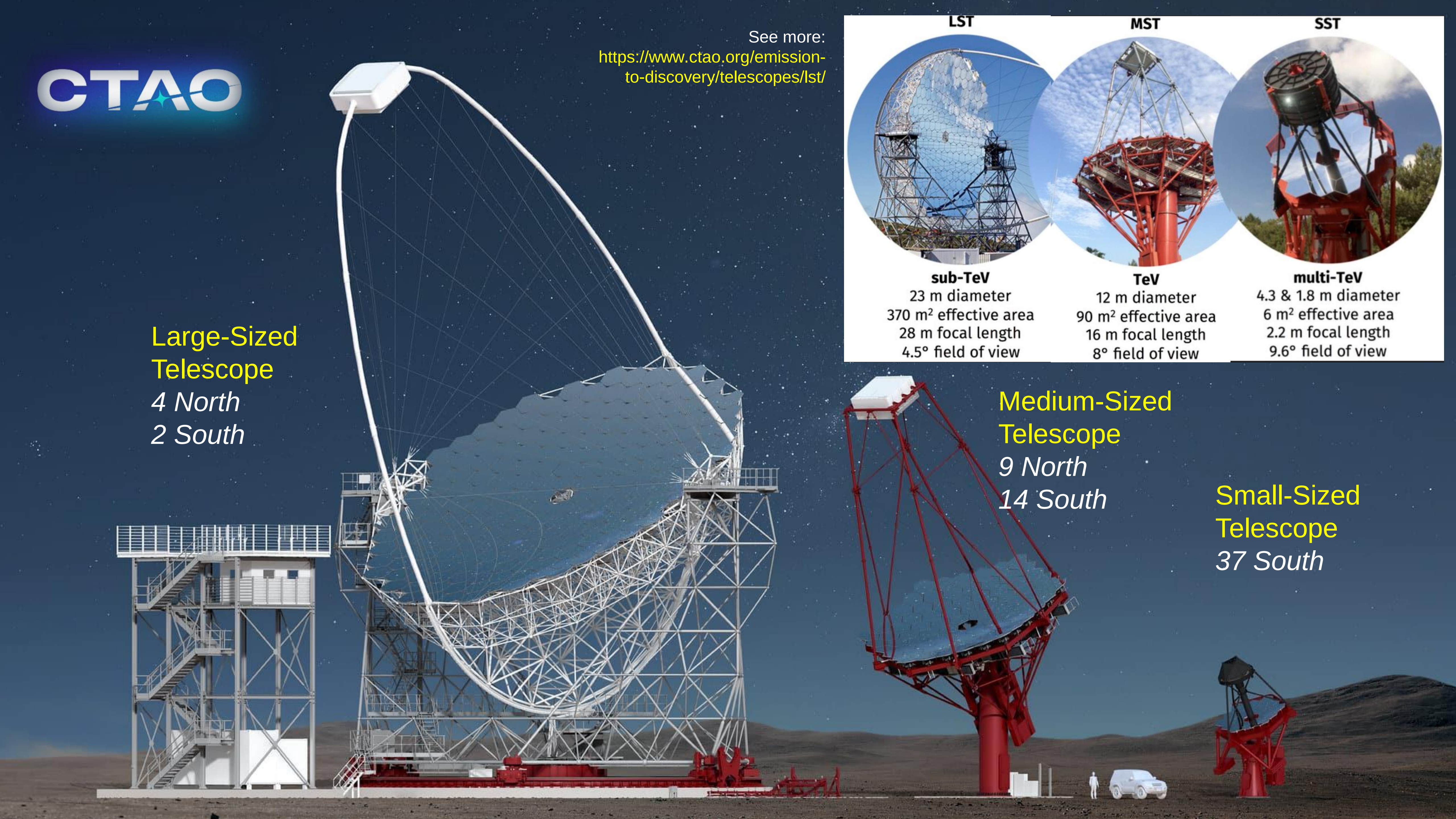


CTAO Southern Array
2 LSTs
14 MSTs
37 SSTs



CTAO Northern Array
4 LSTs
9 MST

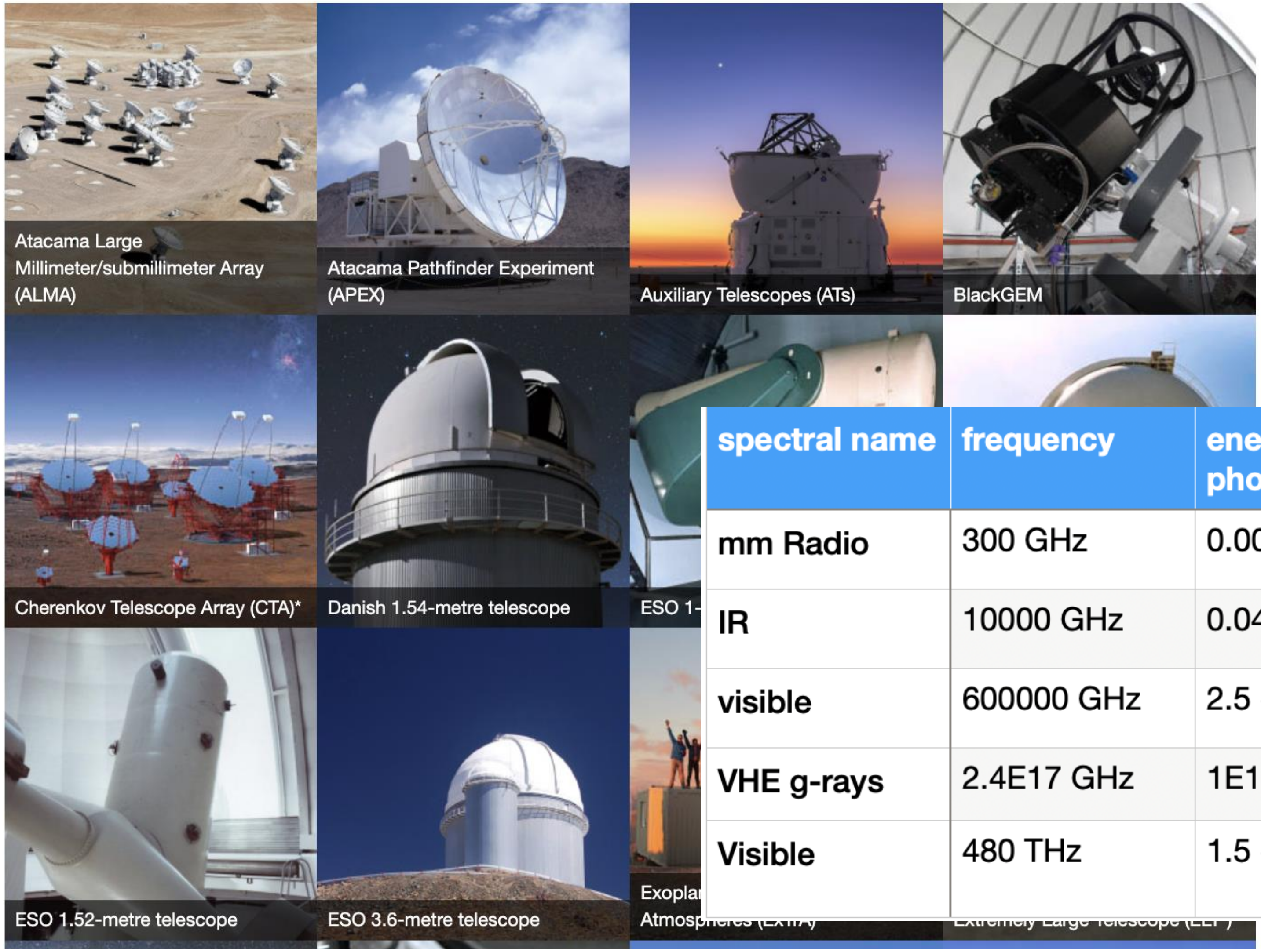



CTAO
See more:
https://www.ctao.org/emission-to-discovery/telescopes/lst/
LST
MST
SST
sub-TeV
23 m diameter
370 m² effective area
28 m focal length
4.5° field of view
TeV
12 m diameter
90 m² effective area
16 m focal length
8° field of view
multi-TeV
4.3 & 1.8 m diameter
6 m² effective area
2.2 m focal length
9.6° field of view
Large-Sized Telescope
4 North
2 South
Medium-Sized Telescope
9 North
14 South
Small-Sized Telescope
37 South

Regarding ESO participation

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.



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
Visible	480 THz	1.5 eV	1-50 muas	CTAO - Stellar Intensity Interf.

Largest optical surface in the world ☺

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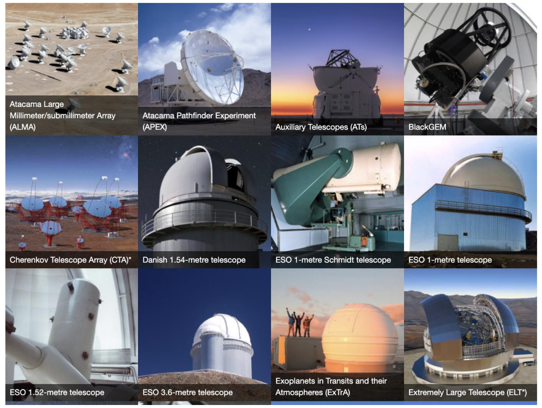
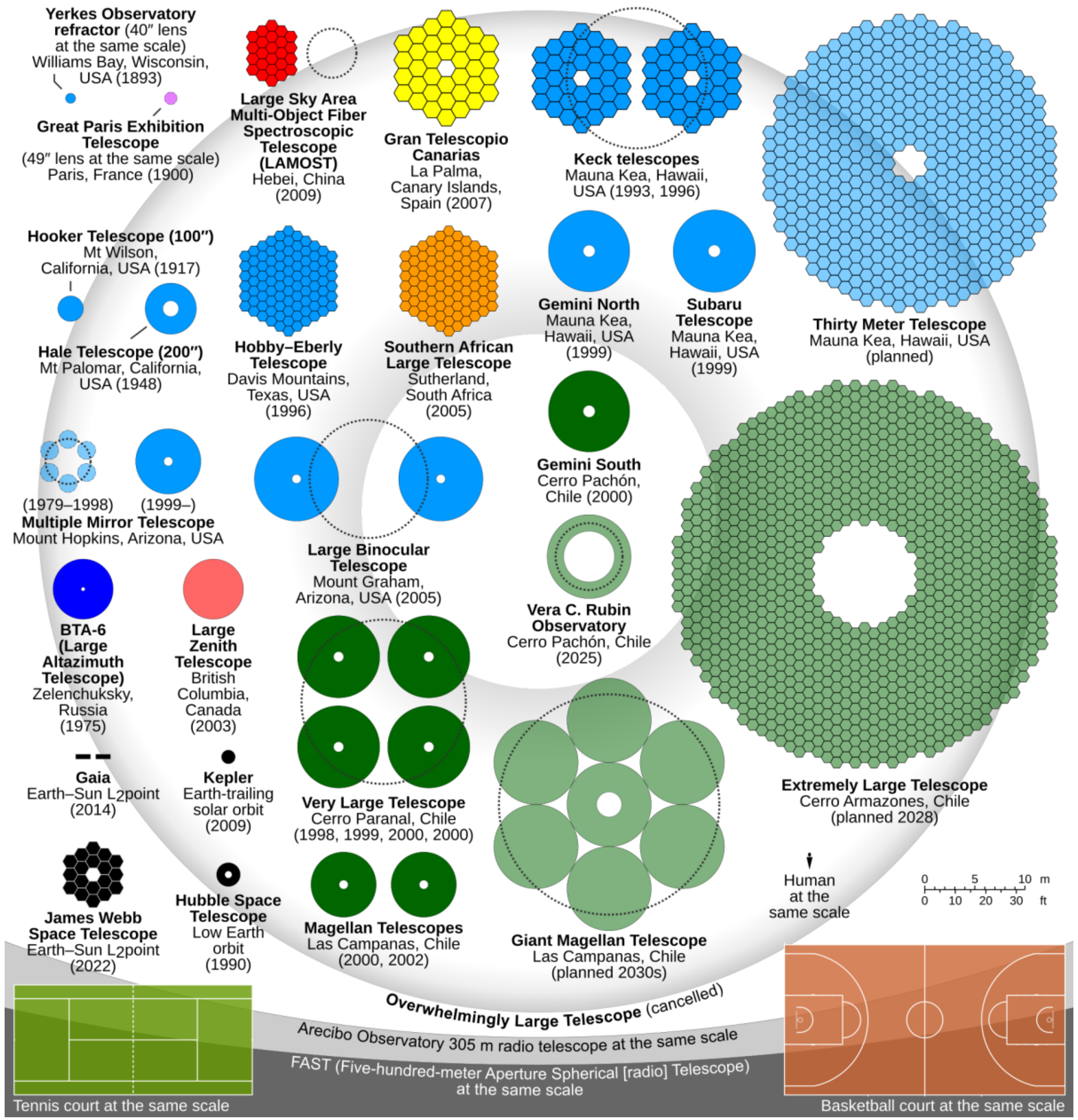
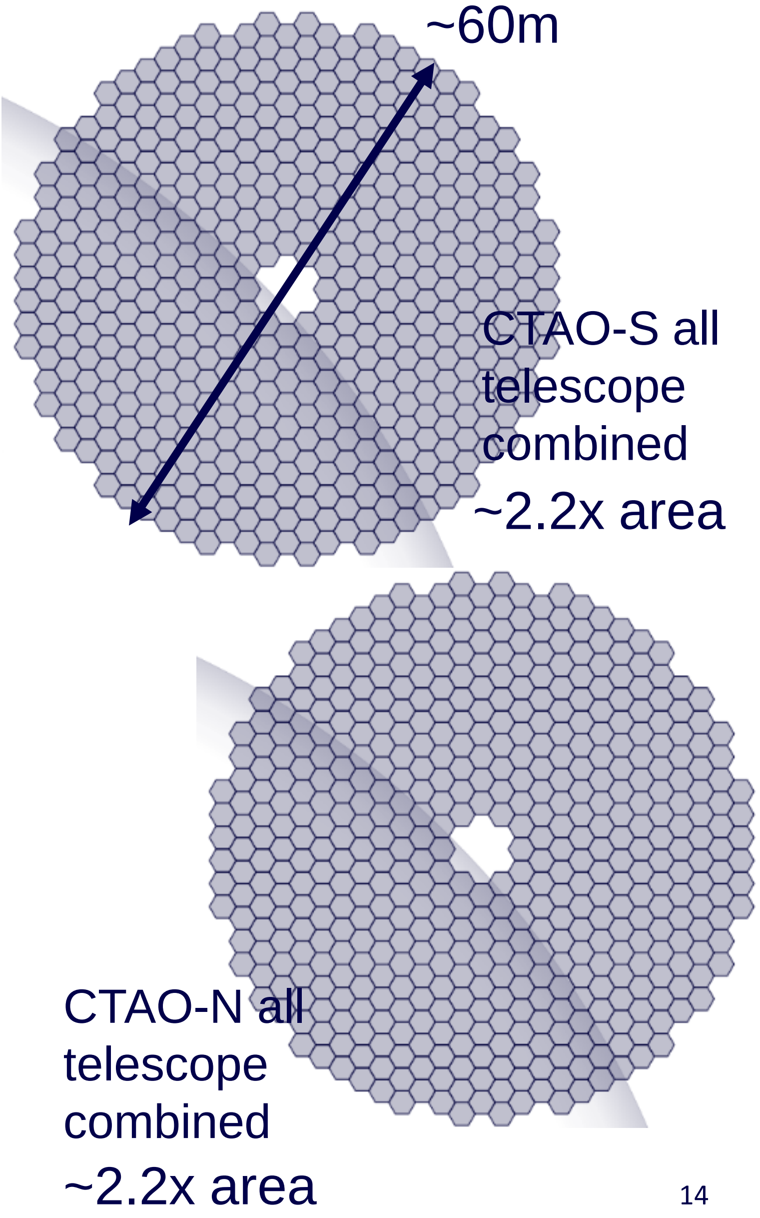
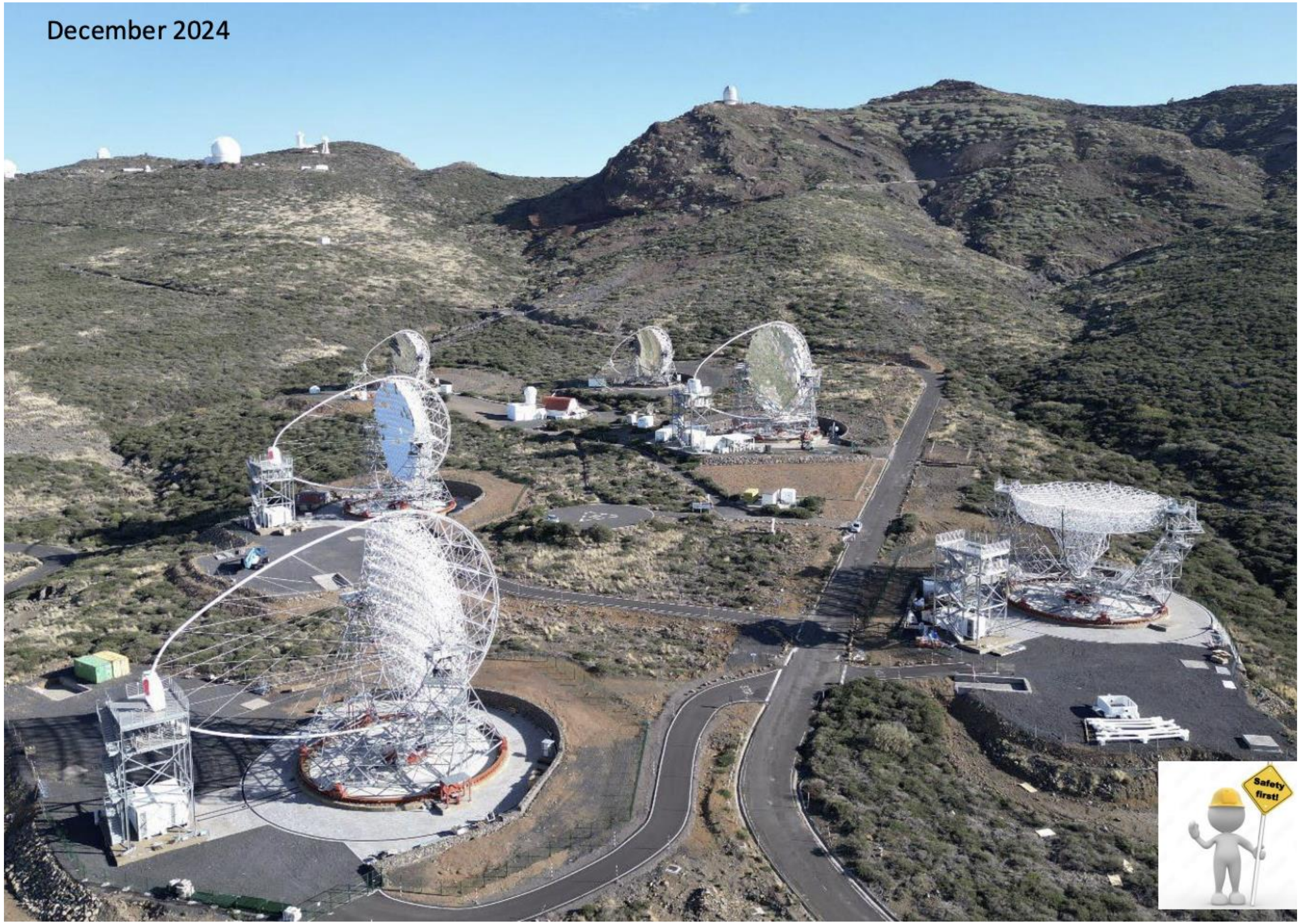




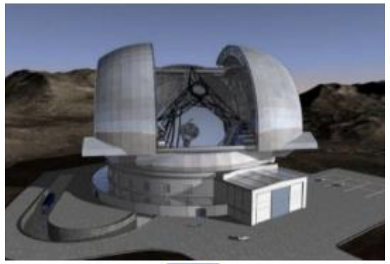


CTAO-North

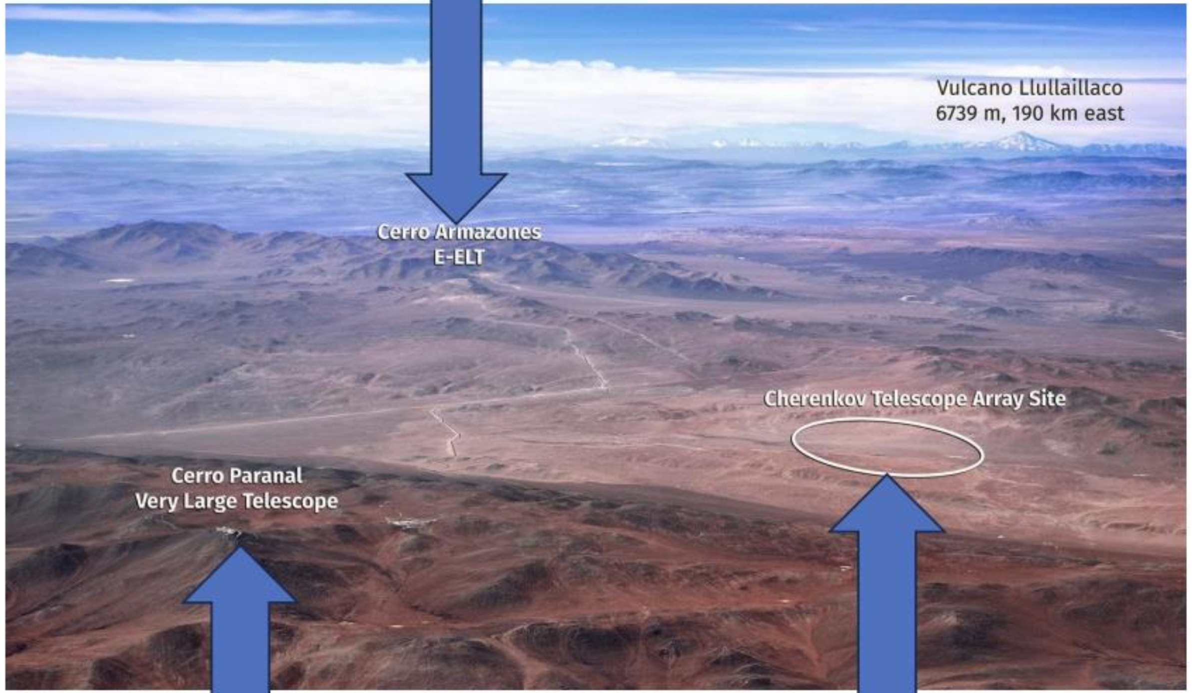


- LST1 in commissioning since 2018
  https://lst.iac.es/collaboration/publications

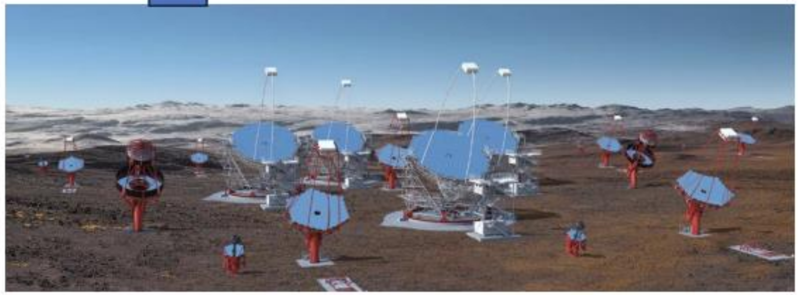
- +3 LSTs under completion
- +9 MSTs to arrive!
- + operational building, central calibration facilities, etc.



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

Science Verification (possibly open)

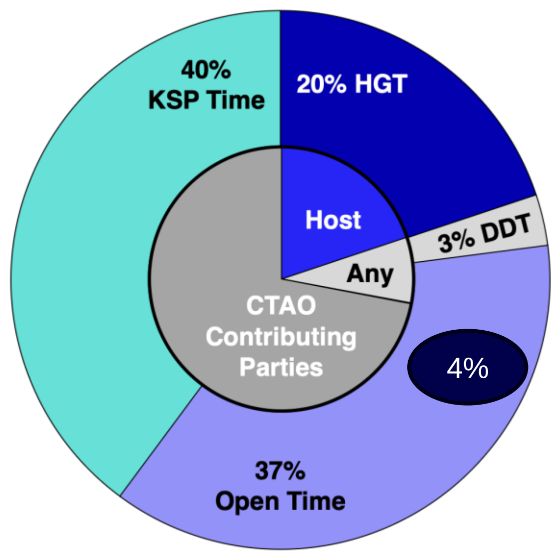
KSP+Open Time

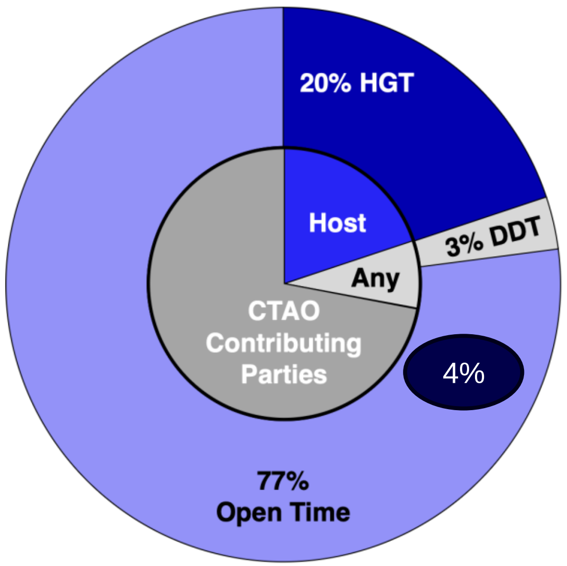
Open

Notes:
- In discussion
- Not to scale

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

Astronomers from Belgium, Denmark, Finland, Ireland, Netherlands*, Portugal, Sweden, UK will apply through ESO

New data access philosophy

CTAO

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 !GAMMA COMMUNITIES

https://vodf.readthedocs.io/

VODF very-high-energy open data format

https://gammapy.org/

A Python package for gamma-ray astronomy

DATA ACCESS

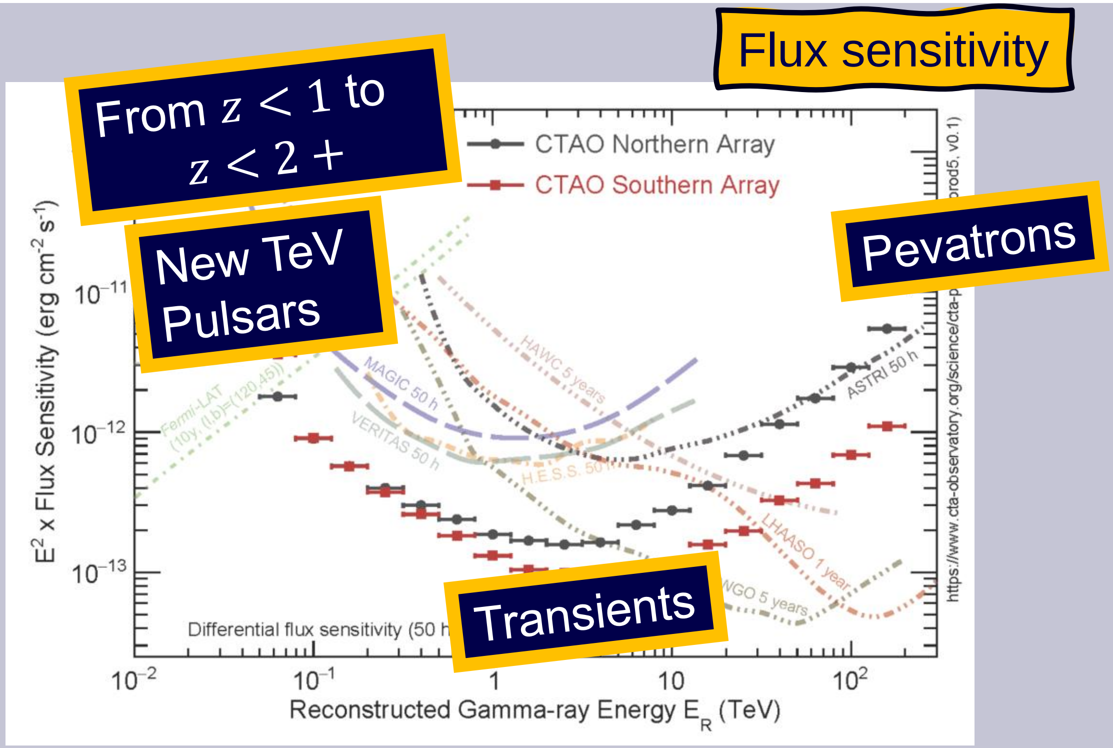
< 1y proprietary period for the PI

> 1y open public shared via CTAO Science Data Portal

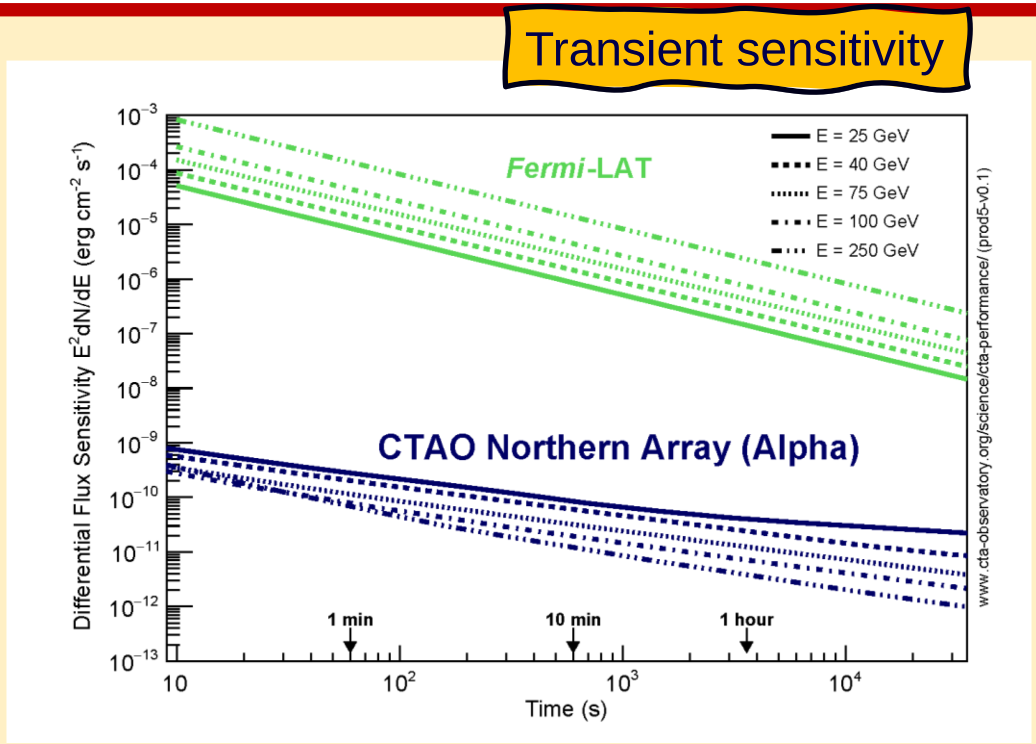
Science Data Challenge in Q4 2026

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

Performance and context: sensitivity



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



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

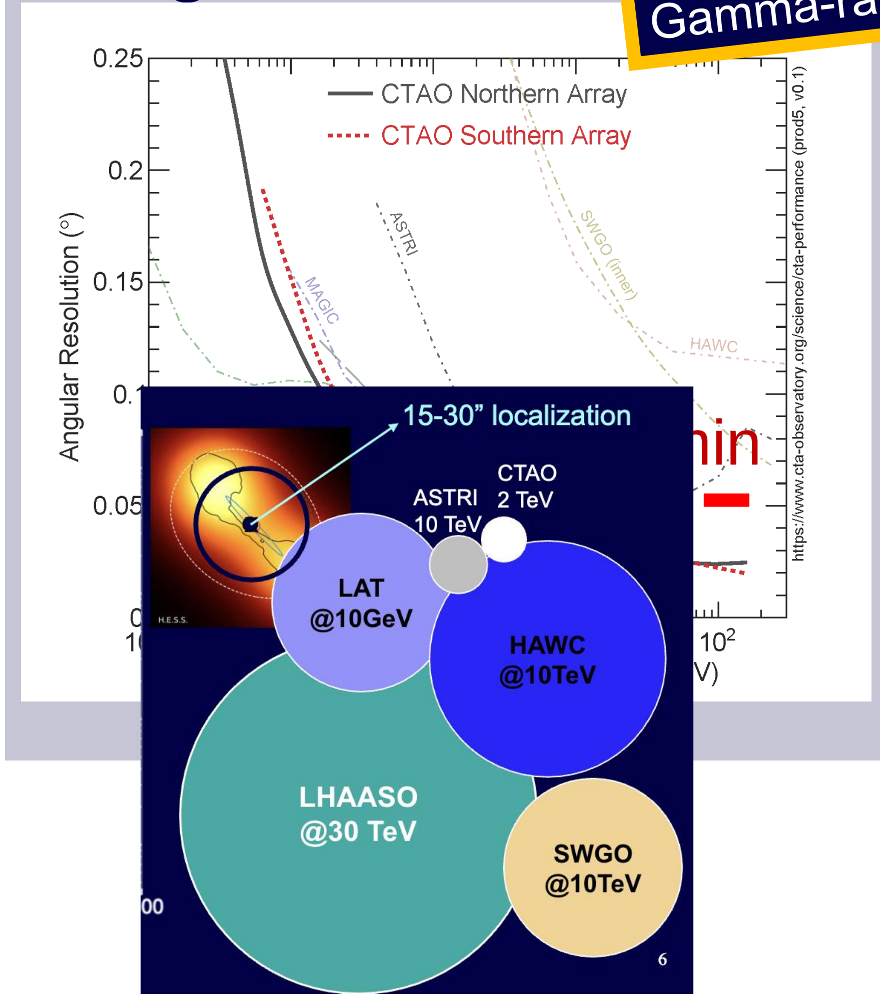
CTAO will be a time-domain instrument

Not only sensitivity

The leap from previous generation

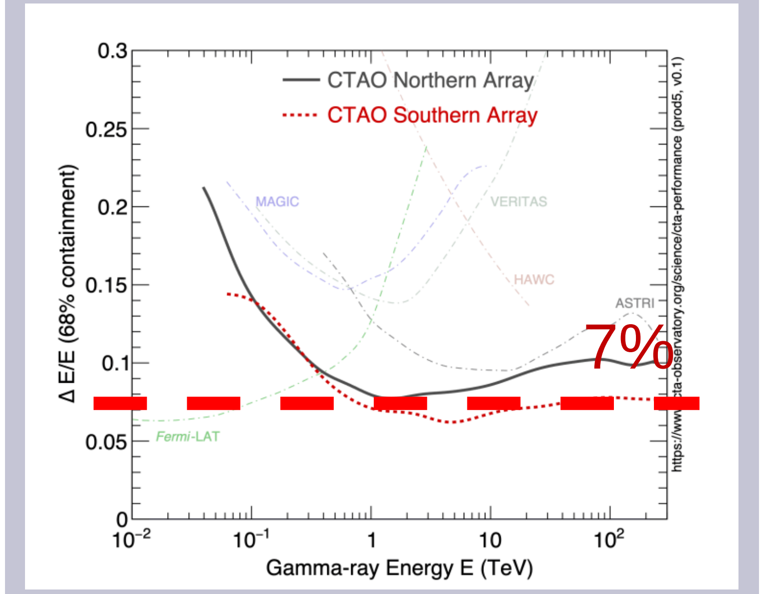
Cosmic Ray – Gamma-ray interplay

Angular Resolution



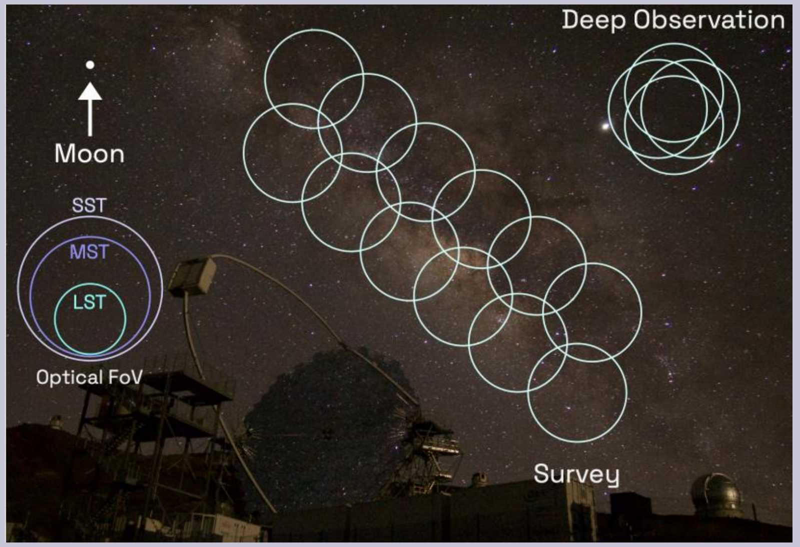
Precise modeling

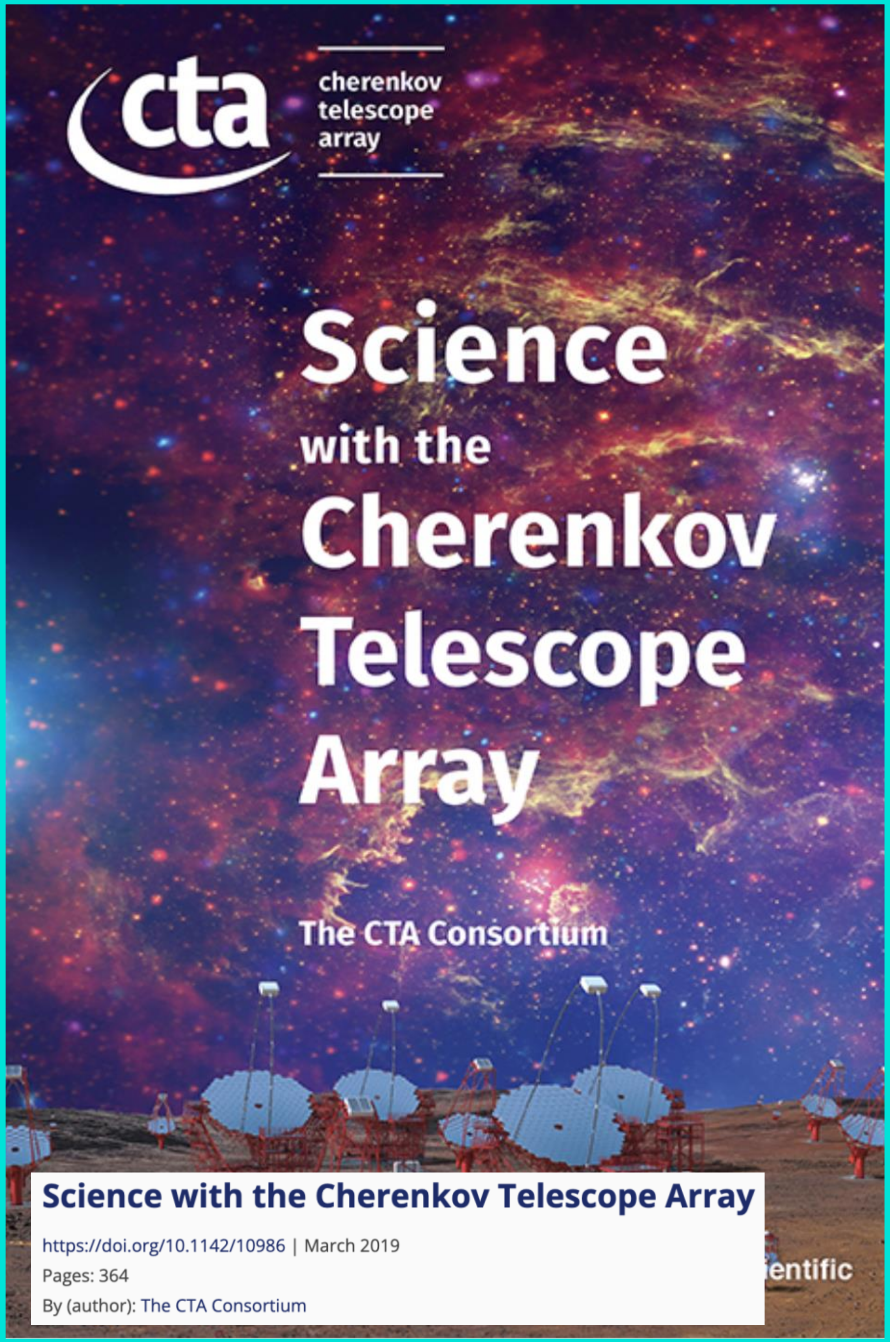
Energy Resolution



New operation mode: wide surveys

Obs. Modes and Field of view





Science with CTAO

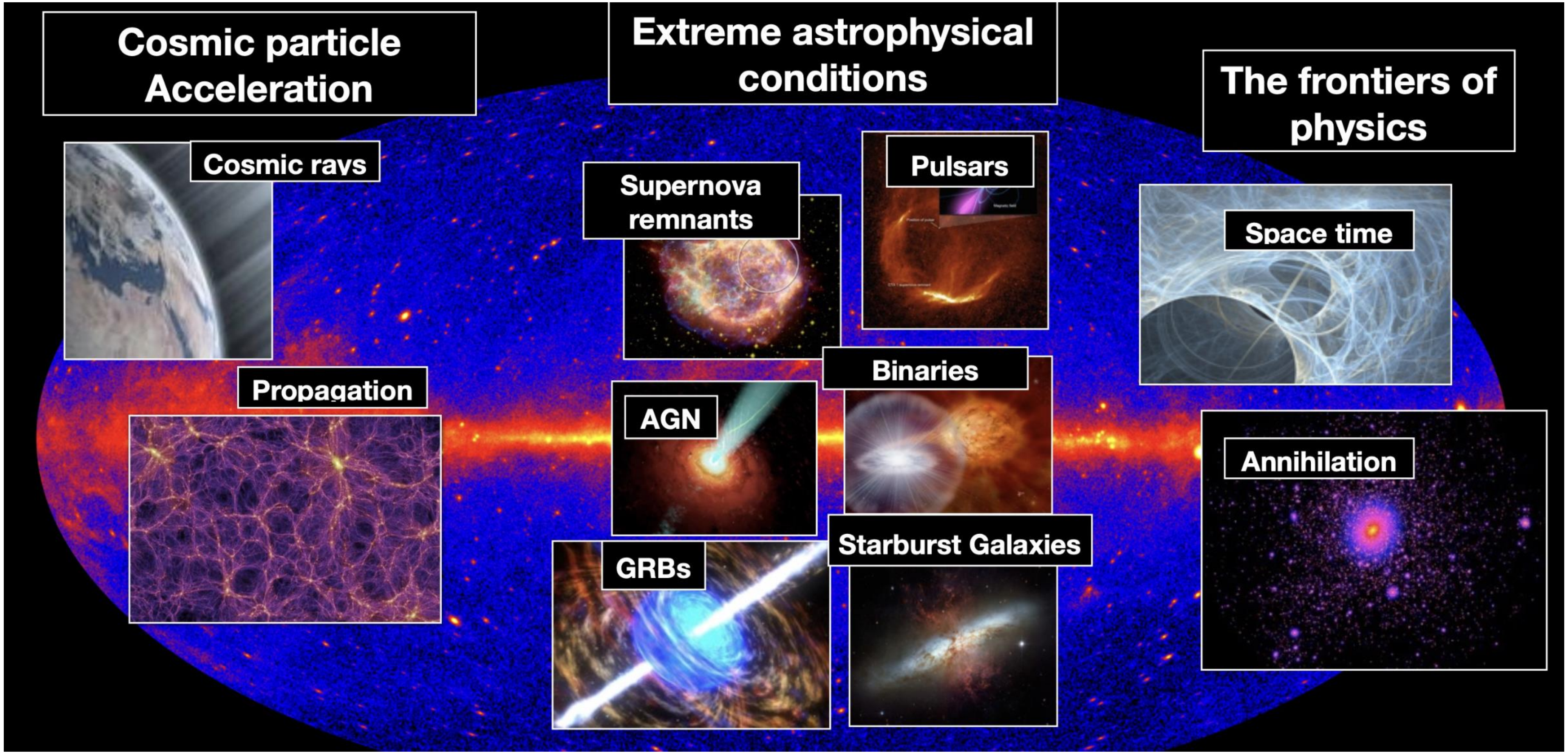
Personal taste.

VHE gamma-ray science

Theme I

Theme II

Theme III

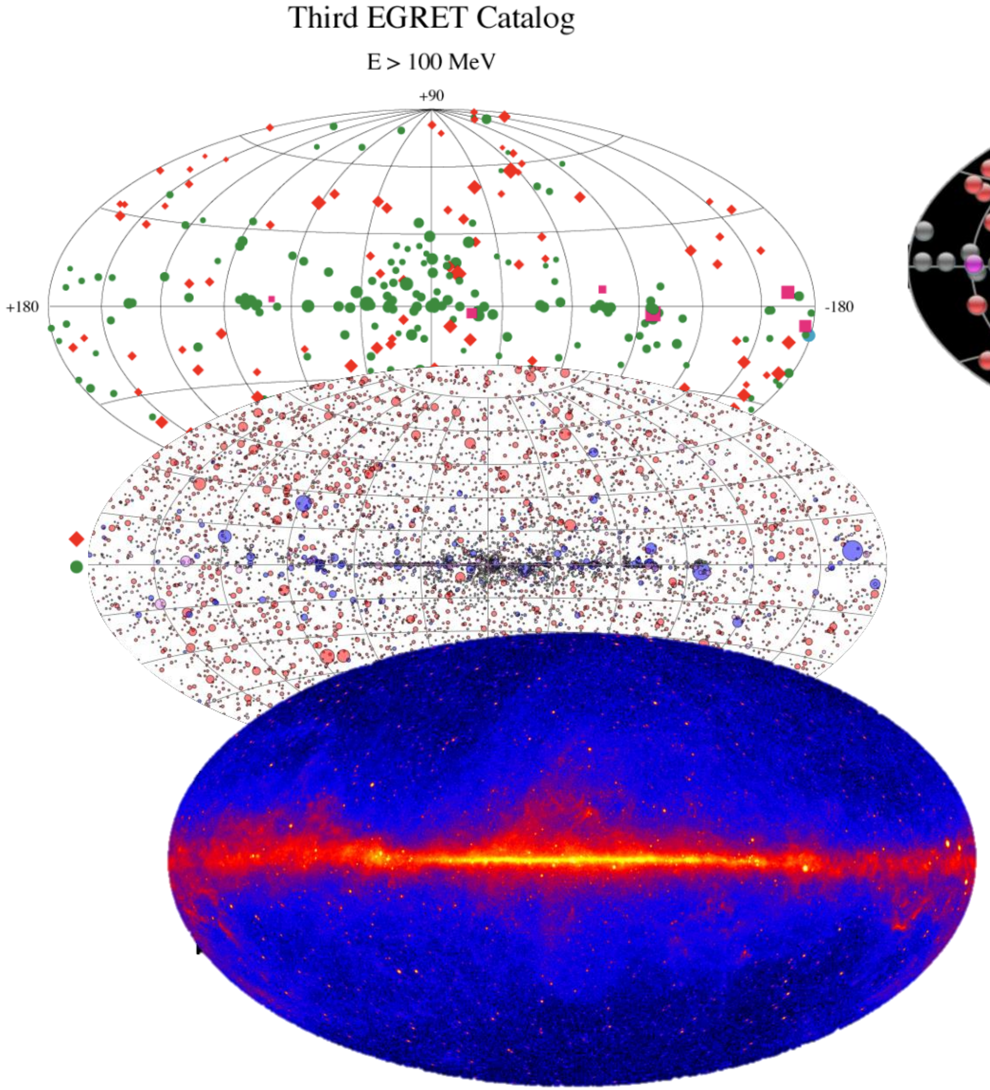


Will likely skip some of next slides

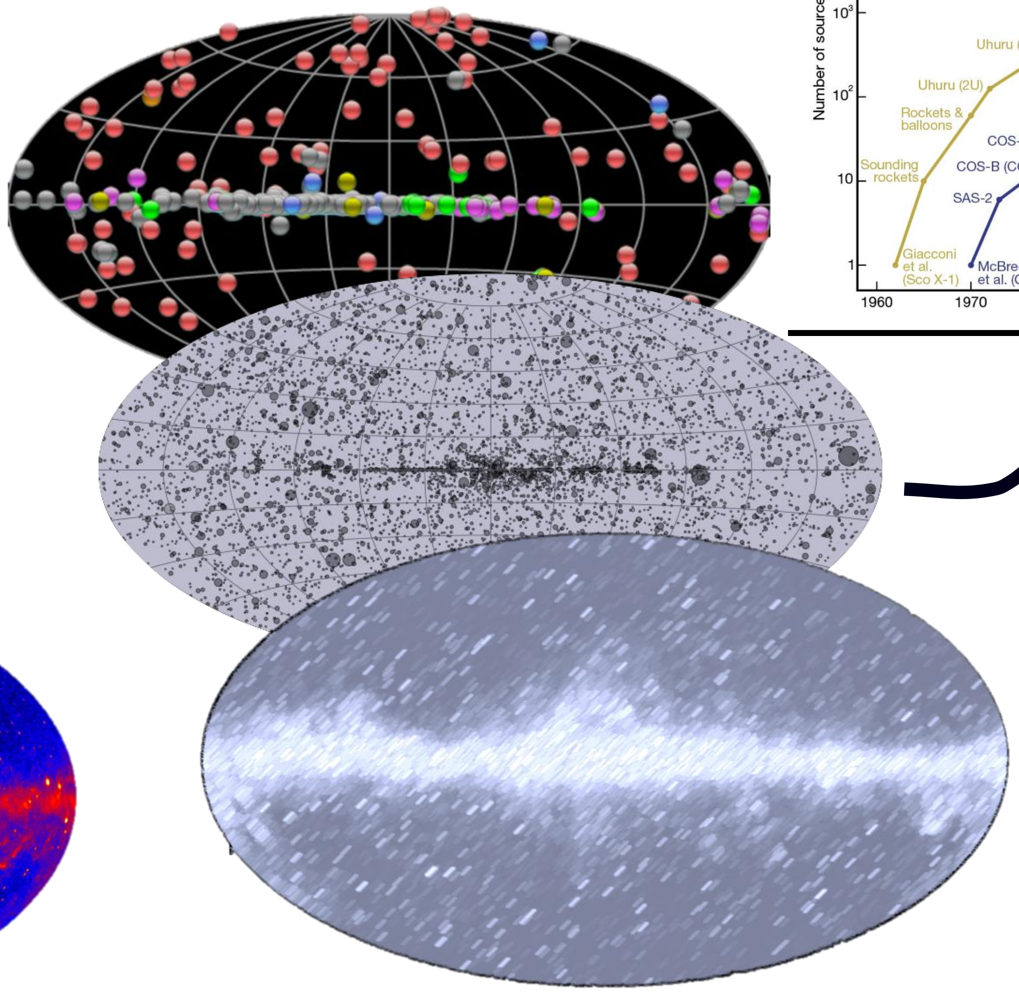
P. Andreani

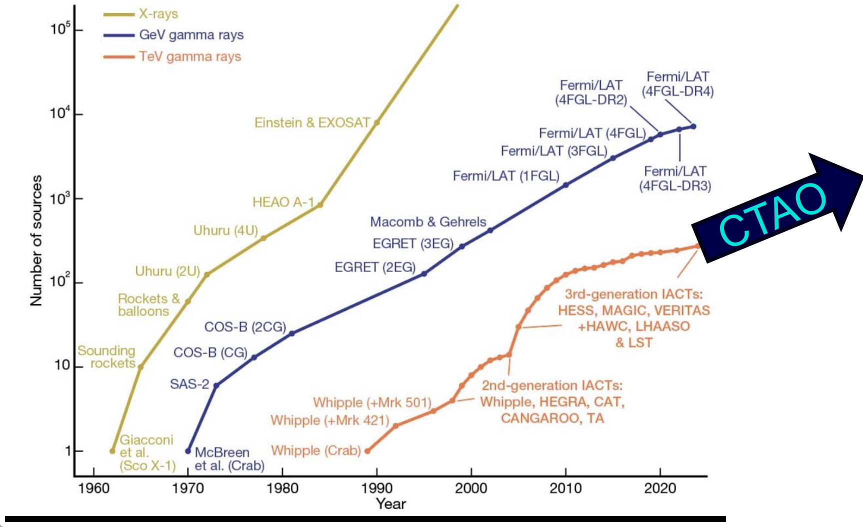
A revolution is coming

High-Energy



CTAO VHE





Kifune plot

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

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Theme 4 (new)

(Stellar) Intensity Interferometry

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

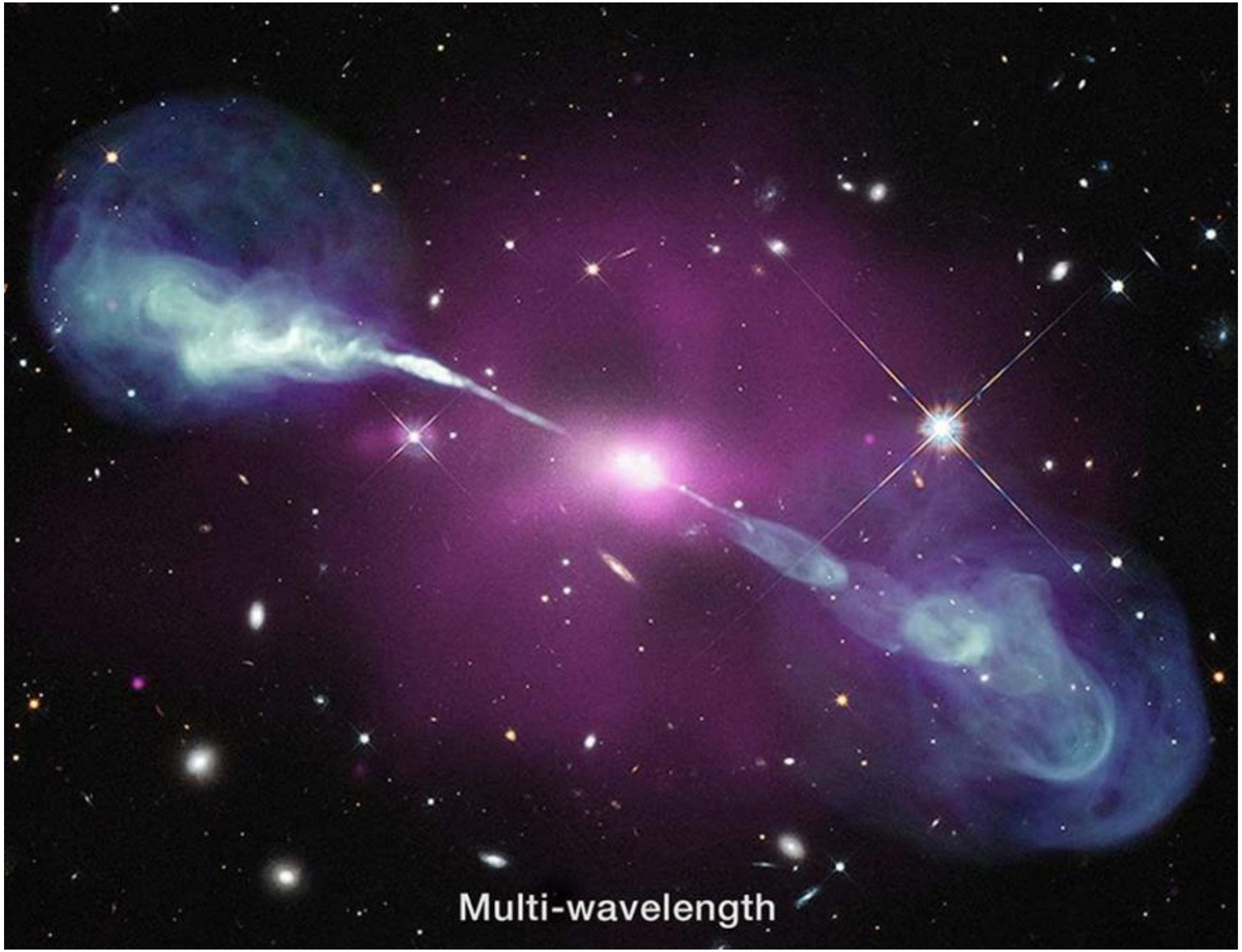
So, my choice

1. Paparazzi SMBHs, jets and alerts
2. Gravitational-lensed blazars
3. Closing in on GC energetics
4. Closing in on TeV WIMP-like DM
5. CR-heated star forming regions
6. Closing in on IGMF
7. SII

Selected Results from Ground-based Gamma-Ray Astrophysics and Near-Future Prospects *Dr Razmik Mirzoyan*

11:45 - 12:15

#1 Paparazzi at SMBHs

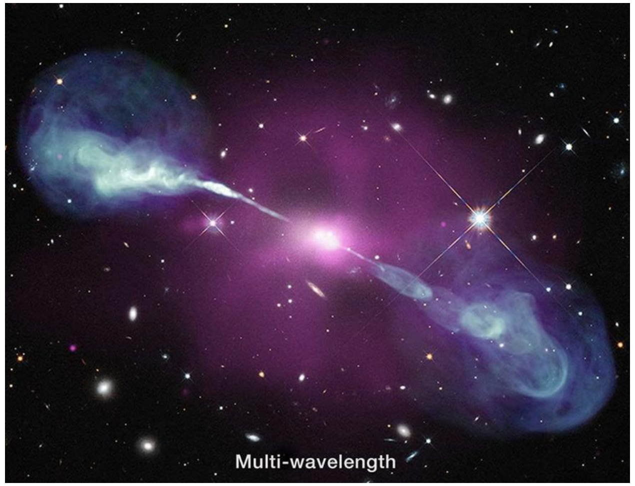


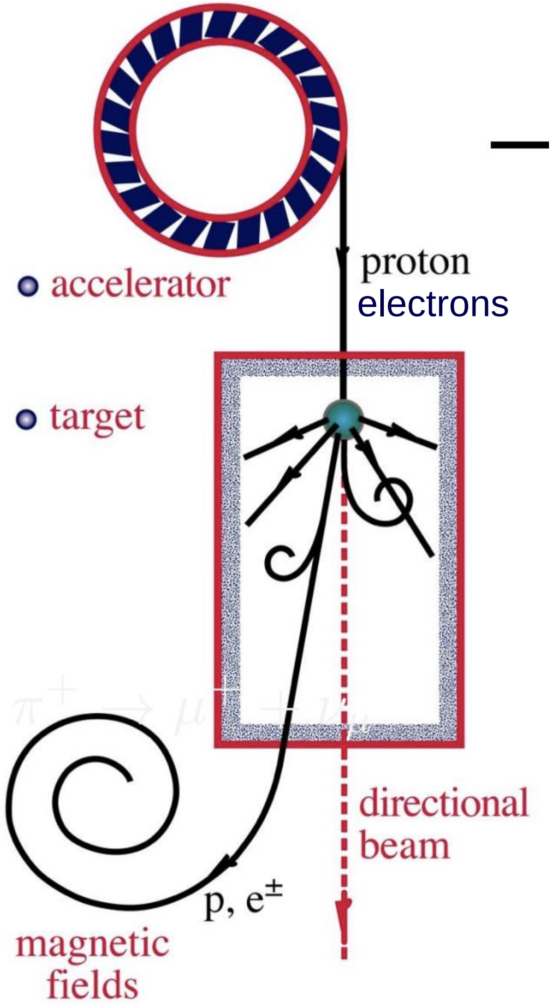
- In visible light, Hercules A a typical elliptical galaxy.
- In X-ray light, a giant cloud of MK gas heated by infall of matter into the super massive black hole
- Radio light shows jets of particles streaming away 1 million light-years in length.
- Gamma-rays… no morphology

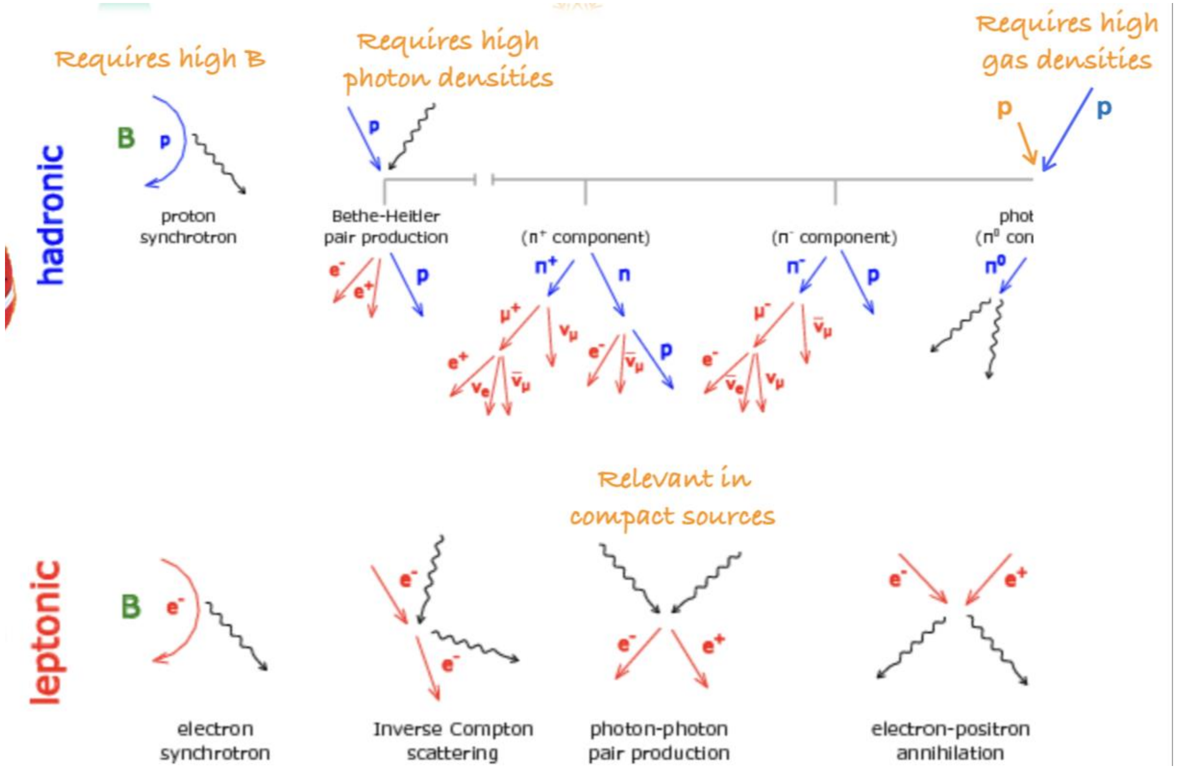
W Wikipedia
Paparazzi - Wikipedia

MWL

#1 All eyes at SMBHs

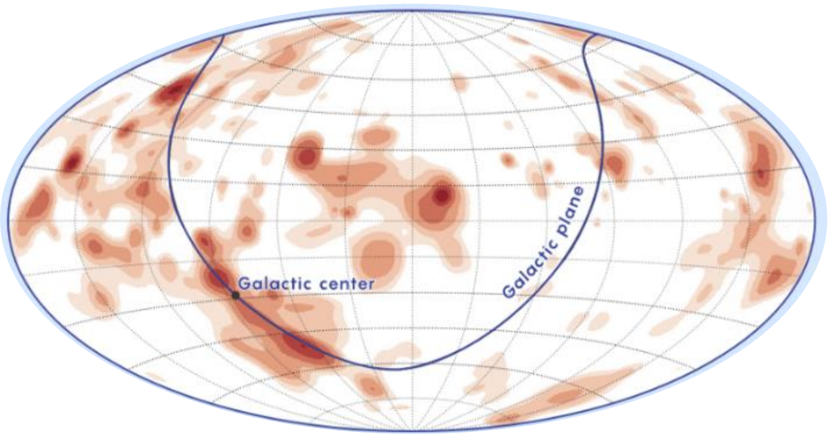






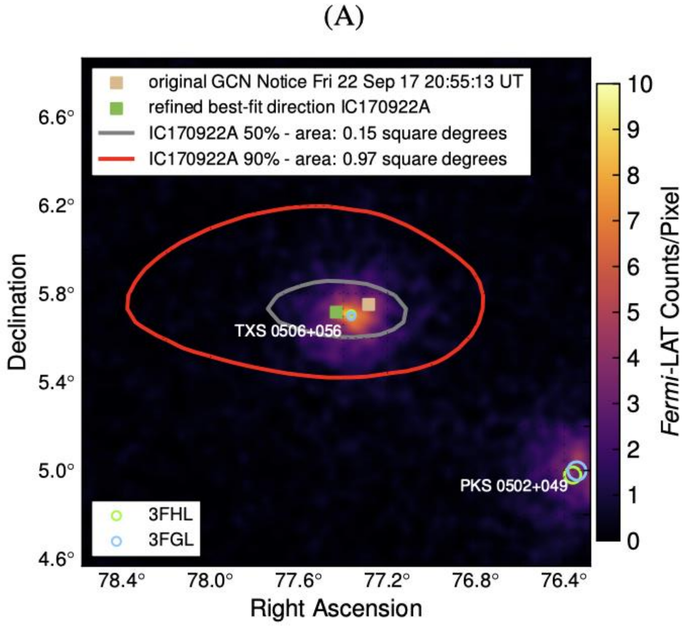
$$p + \gamma \rightarrow n + \pi^+$$
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
$$\rightarrow p + \pi^0$$
$$\pi^0 \rightarrow \gamma + \gamma$$

TeV g-rays & VHE neutrinos

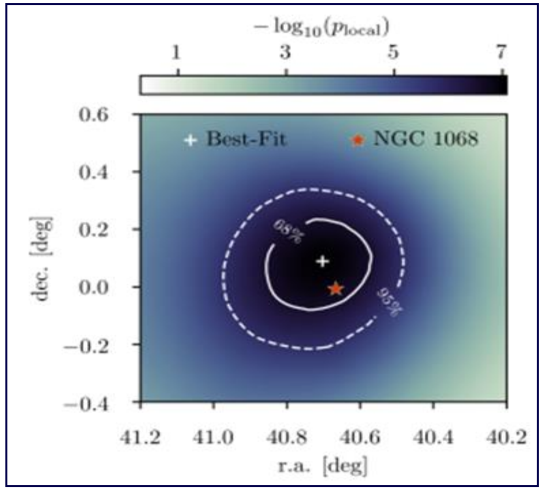


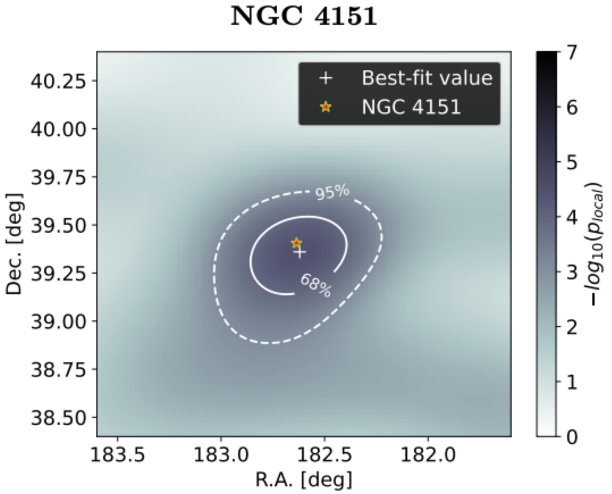
Diffuse / unresolved contribution from our Galaxy ~10% of all cosmic neutrinos

TXS 0506+056, Science 361. Birth of multi-messenger astrophysics



NGC 1068





NUCLEAR EMISSION IN SPIRAL NEBULAE*

Carl K. Seyfert†

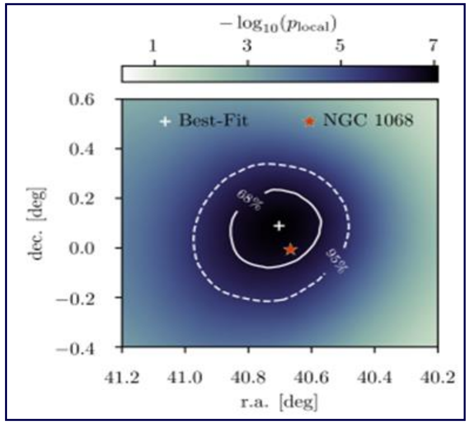
1943

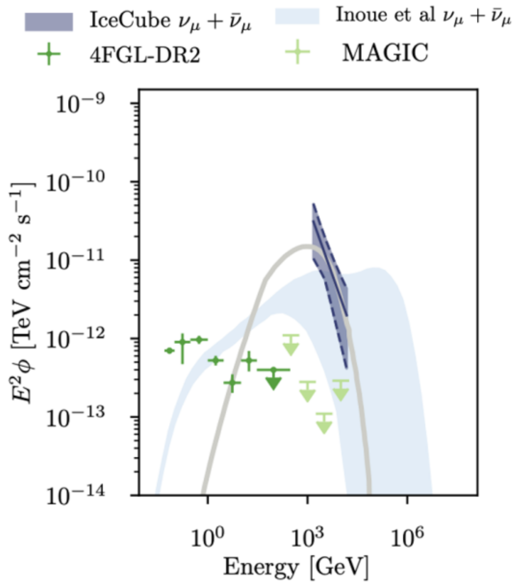
ABSTRACT

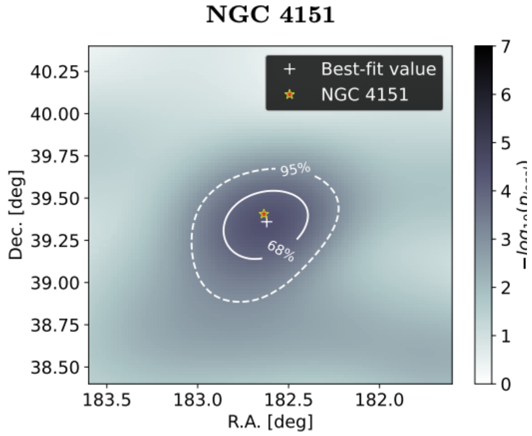
Spectrograms of dispersion 37–200 A/mm have been obtained of six extragalactic nebulae with high-excitation nuclear emission lines superposed on a normal G-type spectrum. All the stronger emission lines from λ 3727 to λ 6731 found in planetaries like NGC 7027 appear in the spectra of the two brightest spirals observed, NGC 1068 and NGC 4151.

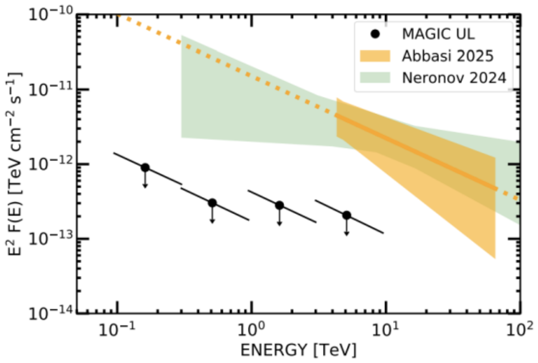
TeV g-rays & VHE neutrinos

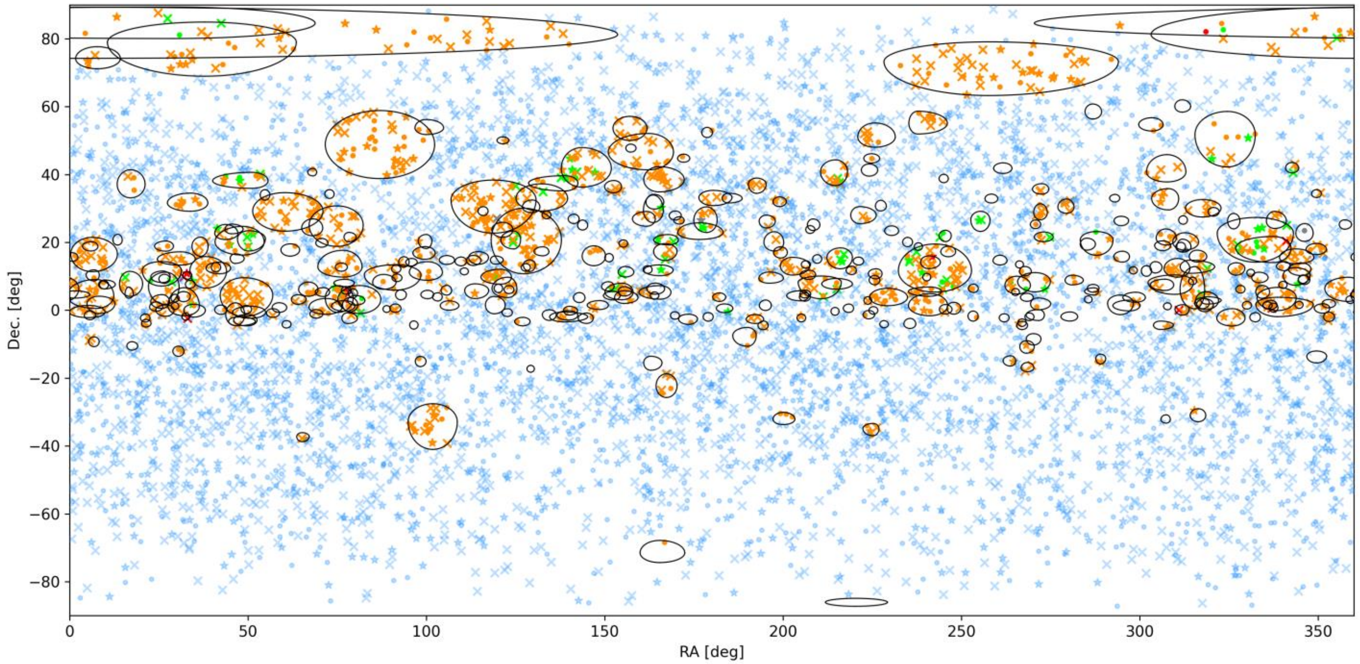
NGC 1068







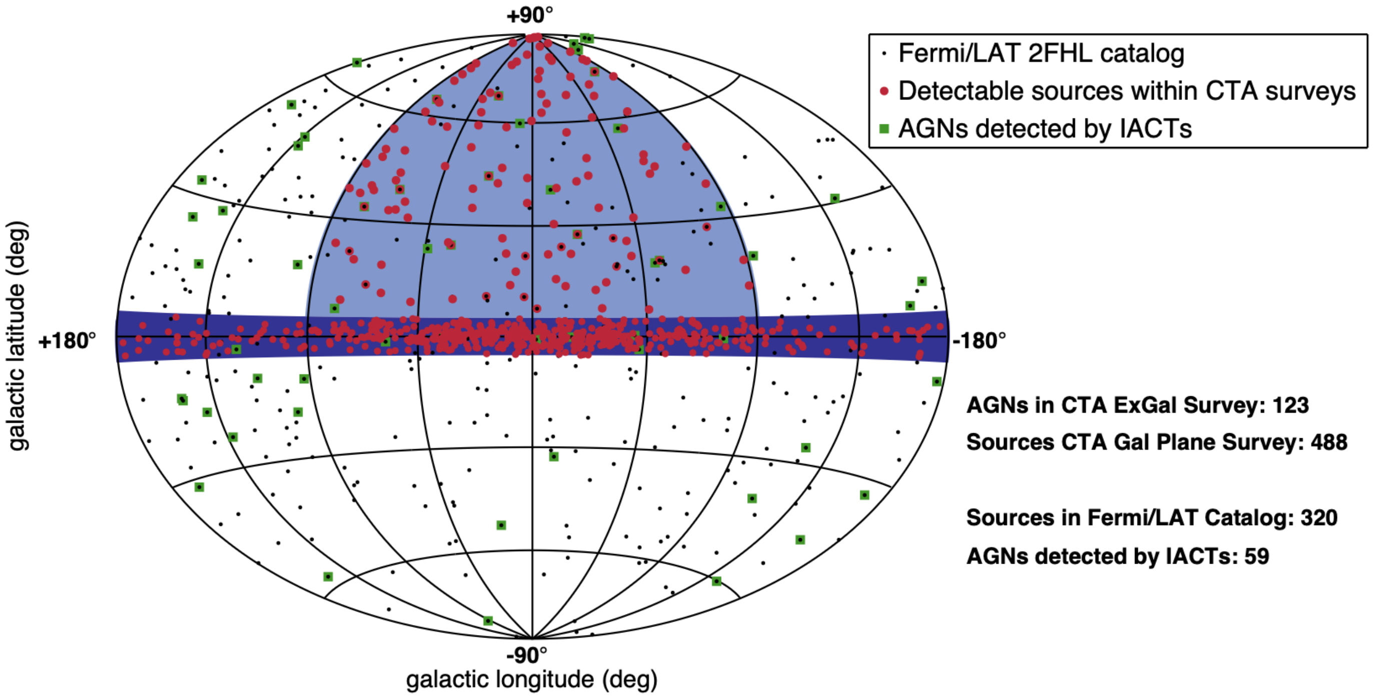


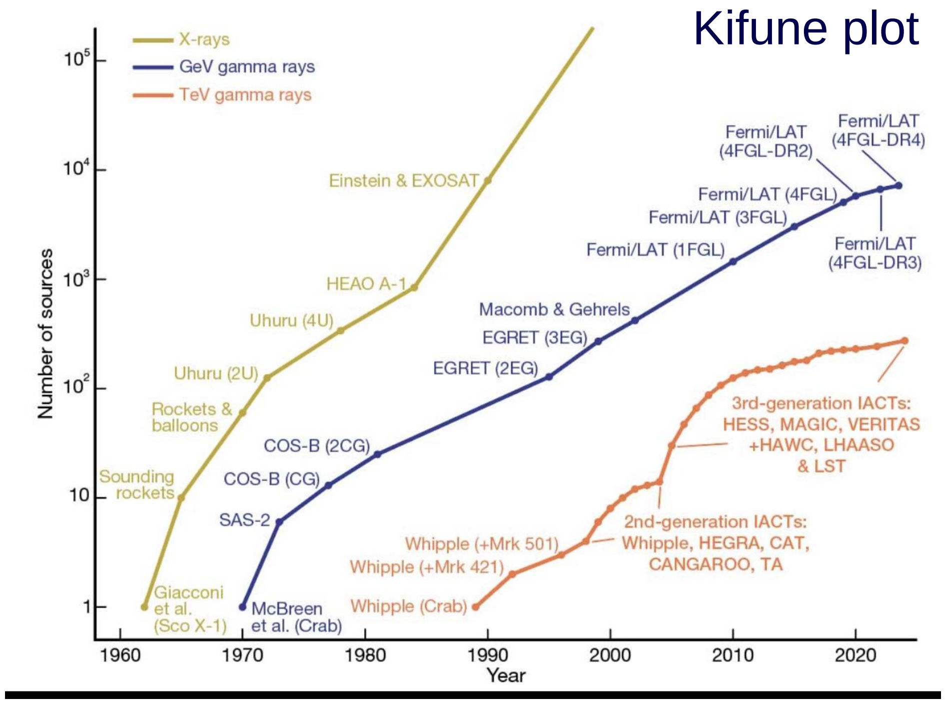


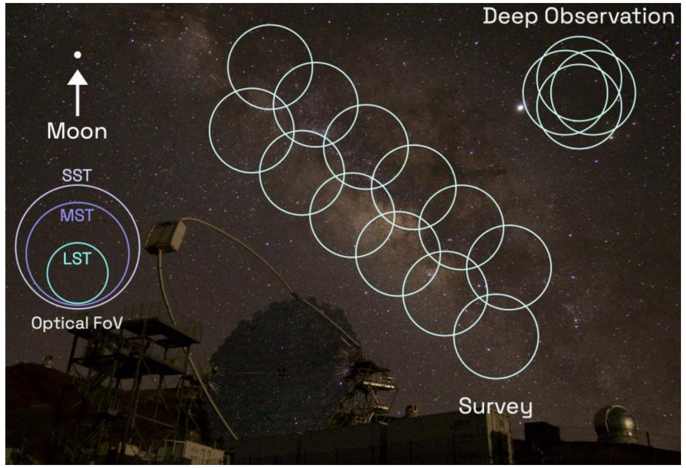
Search for spatial associations coinciding with major optical flares, NO CORRELATION FOUND…

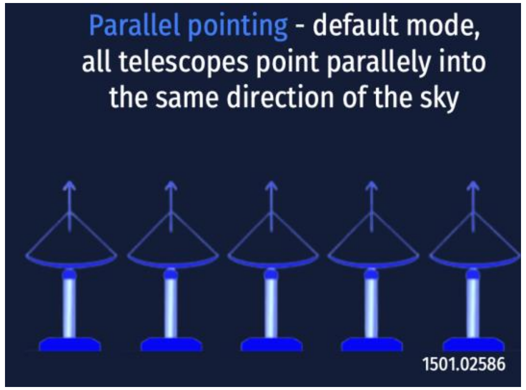
In both cases, gamma emission is 10/100 times less than neutrino, how so?
? Emission not in jet?
But cannot be so in TXS0506+605 [Fiorillo+ 9862025]

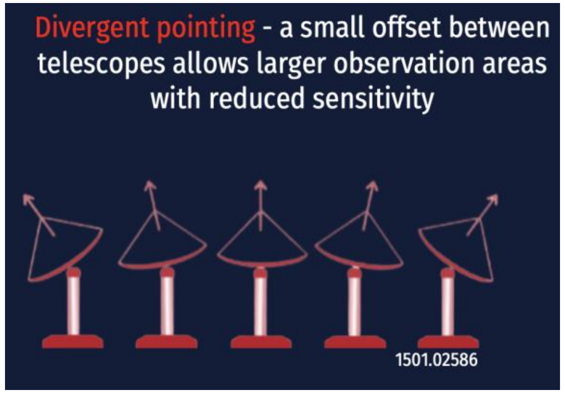
CTAO: a blazar factory



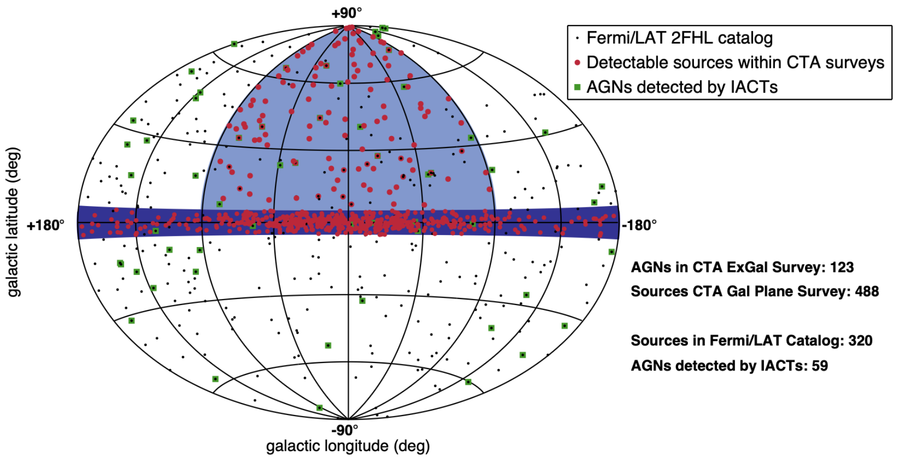


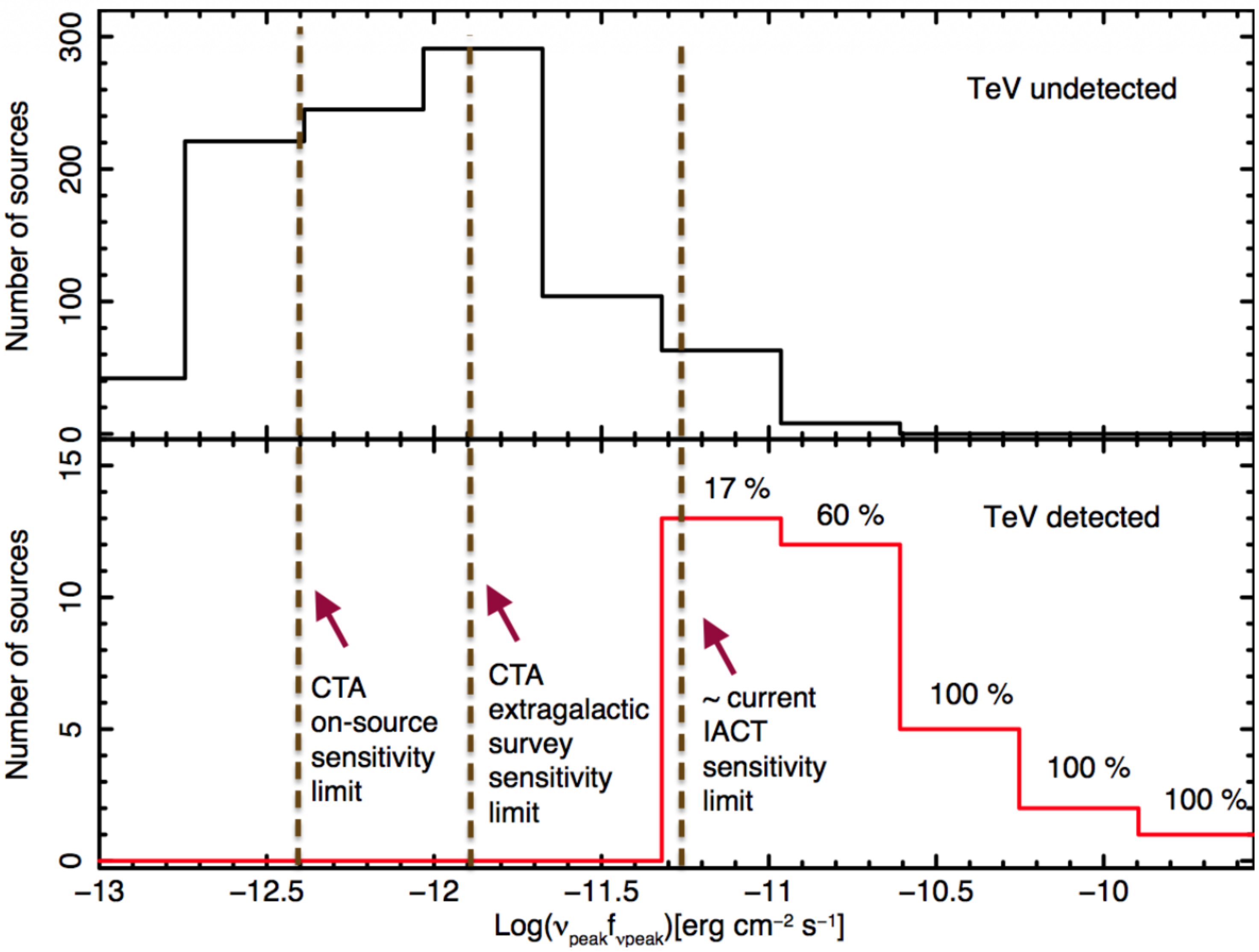




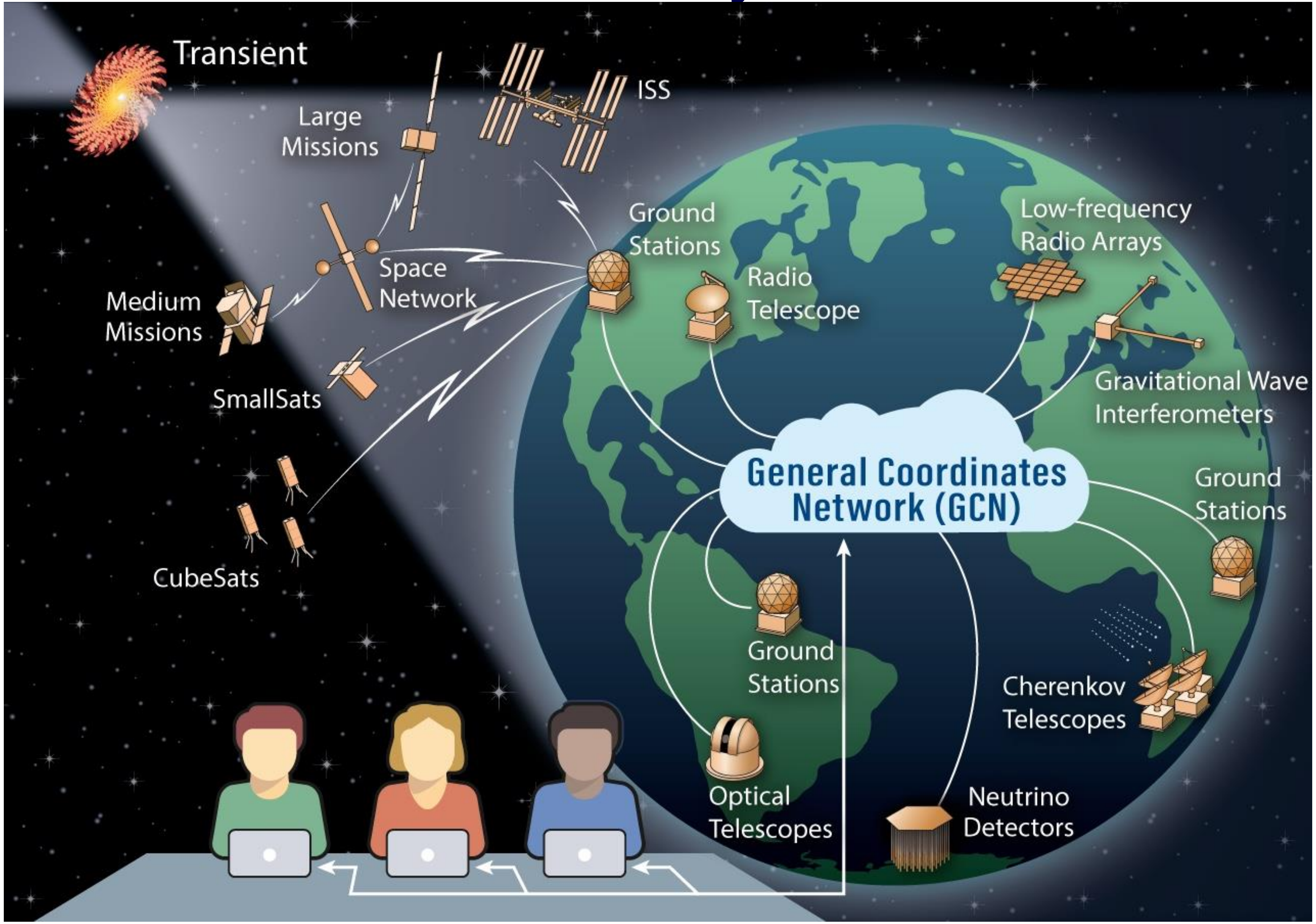


CTAO: a blazar factory





Coordinate Alert System

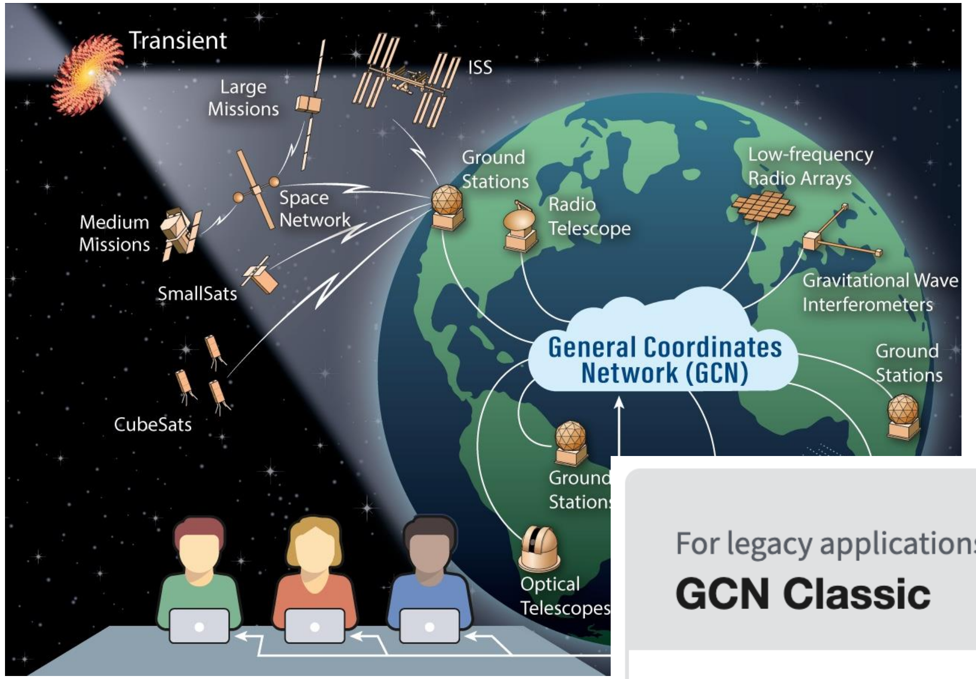


GCN:
NASA's Time-Domain and Multimessenger Alert System

GCN distributes alerts between space- and ground-based observatories, physics experiments, and thousands of astronomers around the world.

Current IACTs most successful program is ToO through alerts

So far mostly 1 to 1 agreements

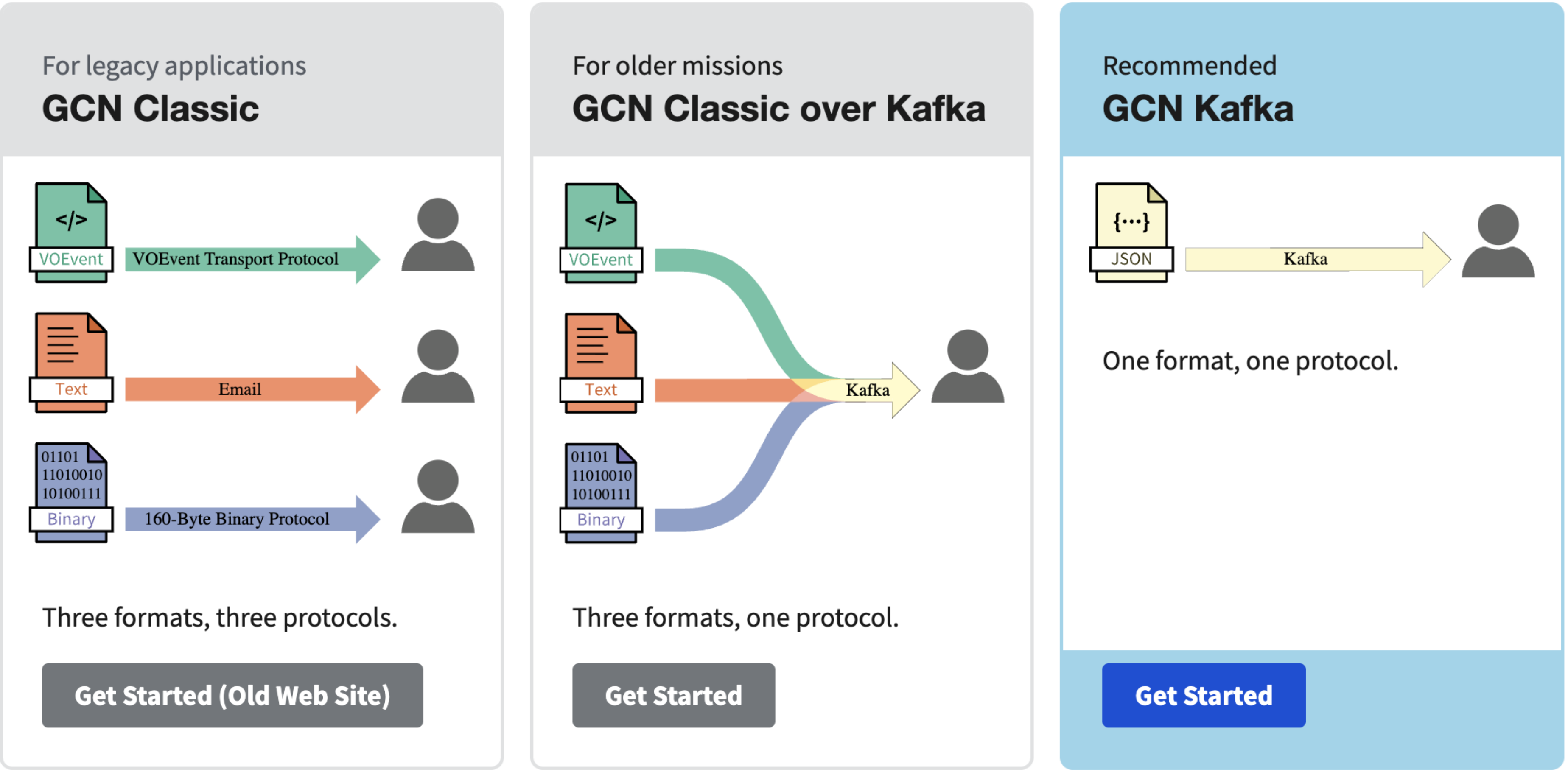


Soon, advanced broker system to receive/transmit/select alerts

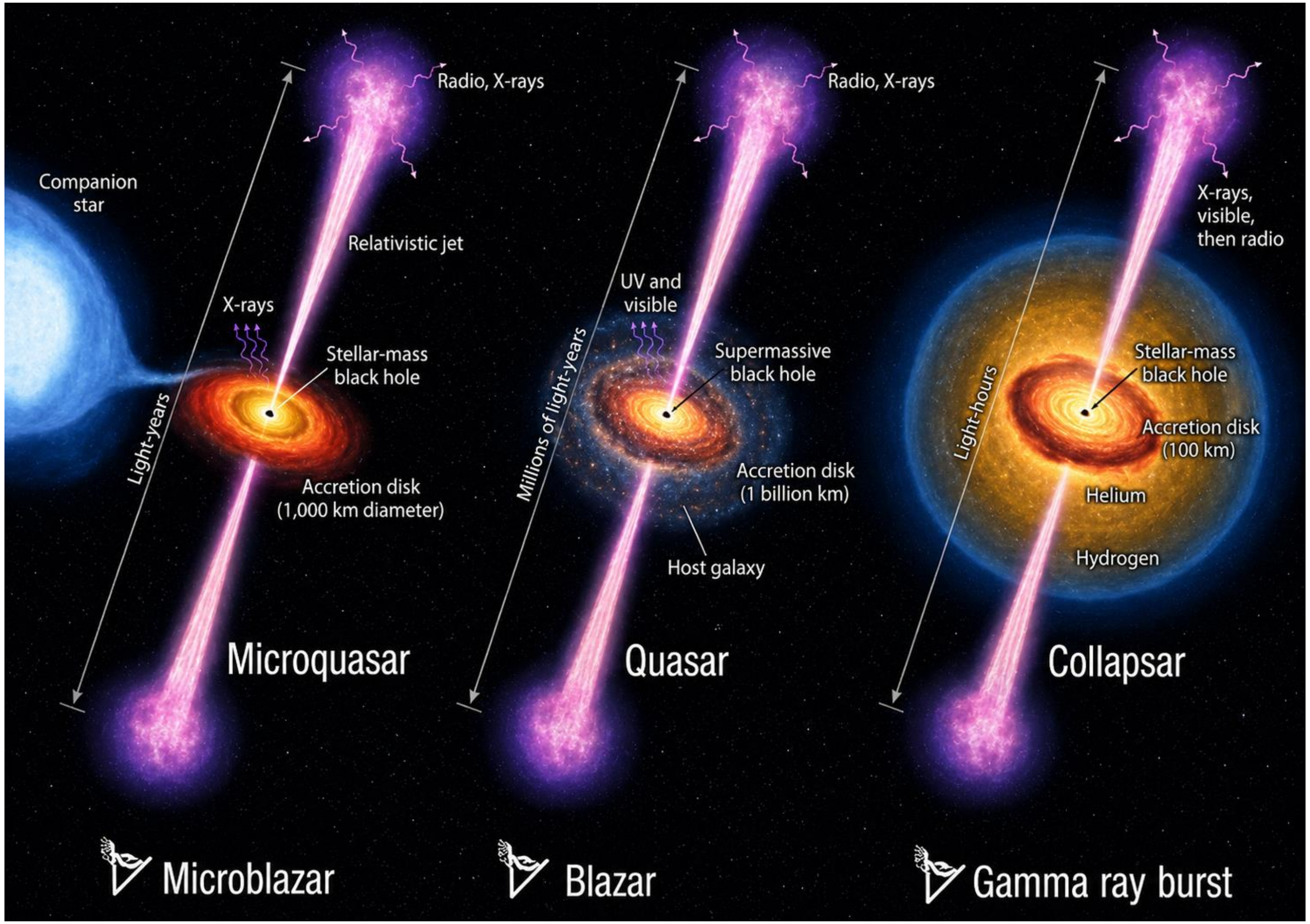
GCN:
NASA's Time-Domain and Multimessenger Alert System

GCN distributes alerts between space- and ground-based observatories, physics experiments, and thousands of astronomers around the world.

CTAO aim to have advanced *alert strategy* with complex <u>smart adaptive scheduling</u>



#1a Ultrarelativistic jets

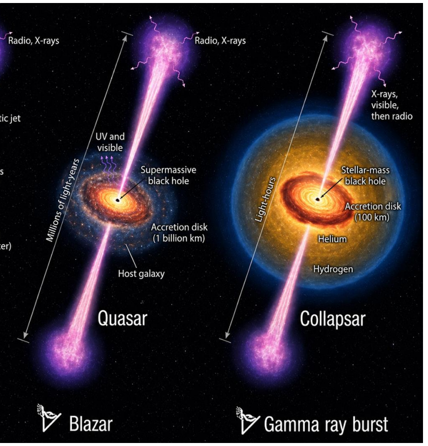


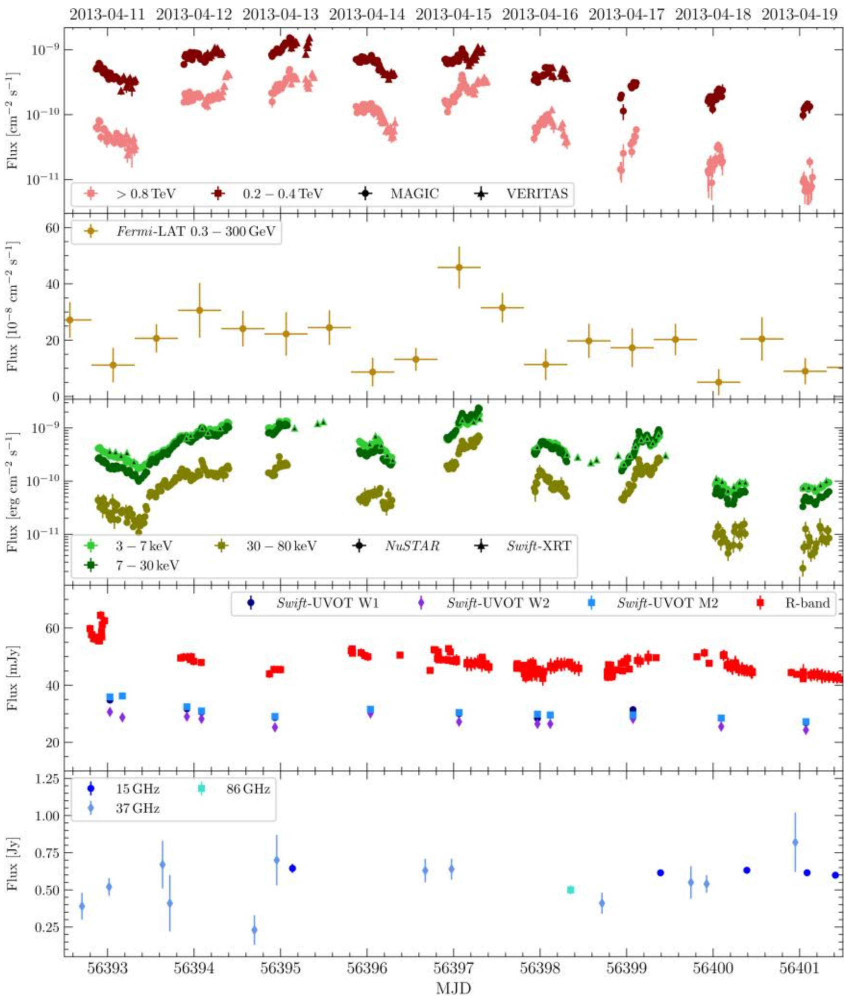
Mirabel & Rodríguez (1998/1999), colored with AI

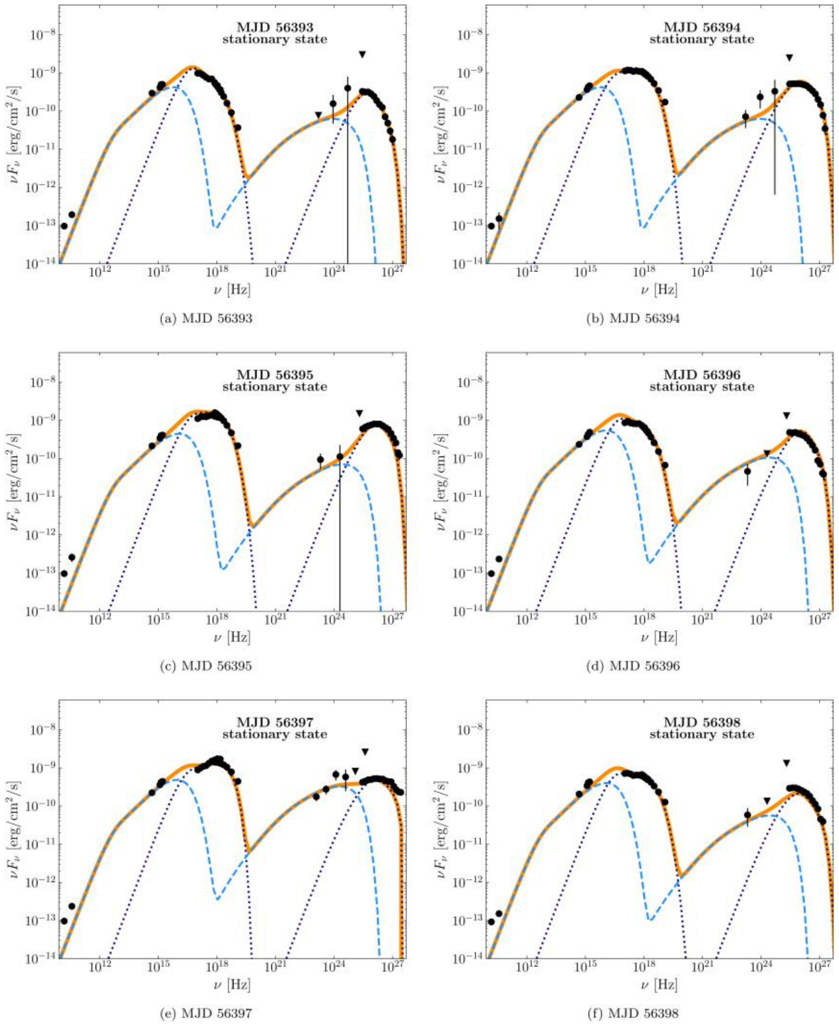
- Relativistic jets at all scales: microquasars, jetted-AGNs, GRBs.
- Lorenz factor from few to hundreds → luminosity boost, time scale compression
- Many Questions:
  - How the jet is launched in the first place? What is the role of infalling material
  - How is collimated? What is the shape of the 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?
  - …

#1a Ultrarelativistic jets

MAGIC, Astroph. J. 998

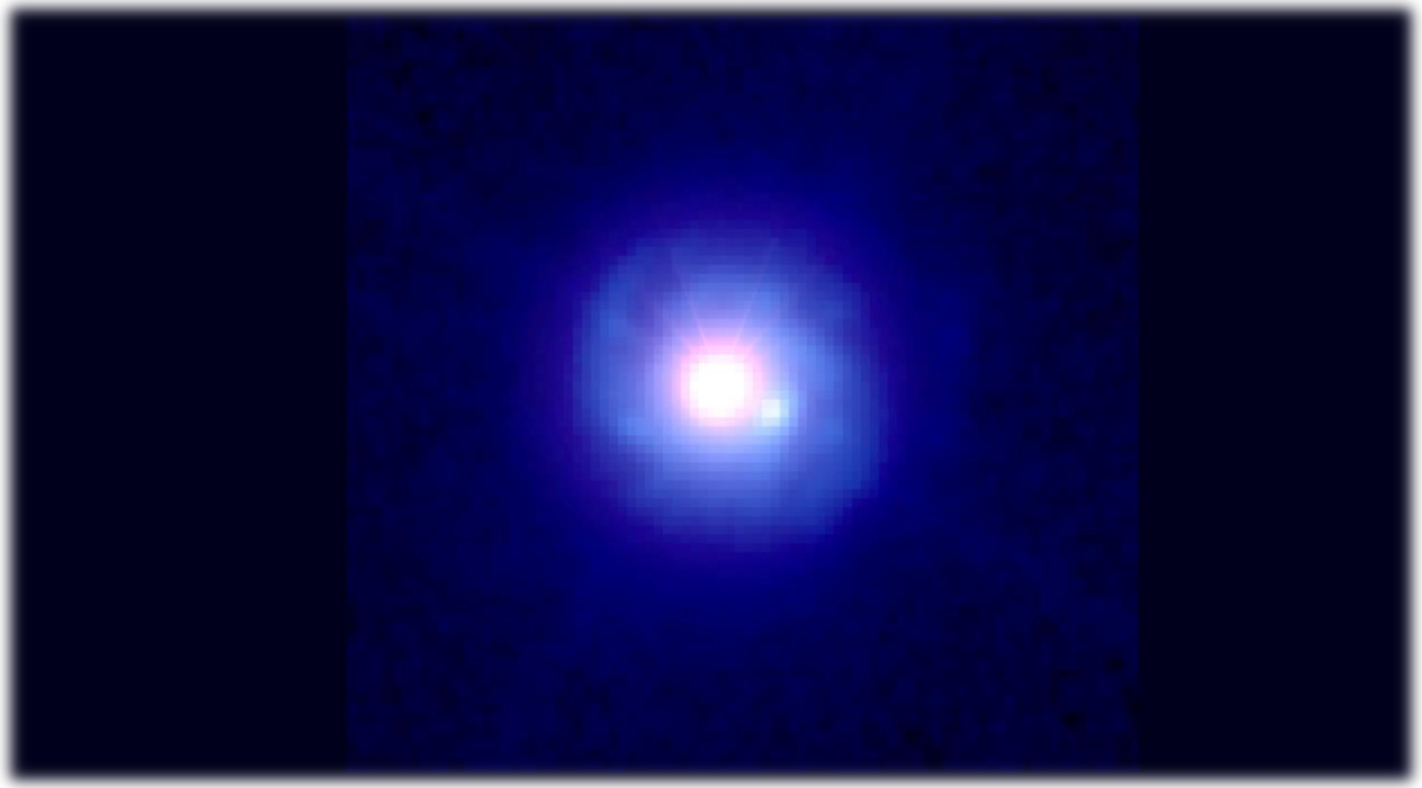






- VLBI → morphology of magnetic field
- mm (e.g ALMA) → gas, dust
- X/gamma (cosmic rays acceleration)
- Polarimetry
- …

#2 Strong Gravitationally Lensed Blazars

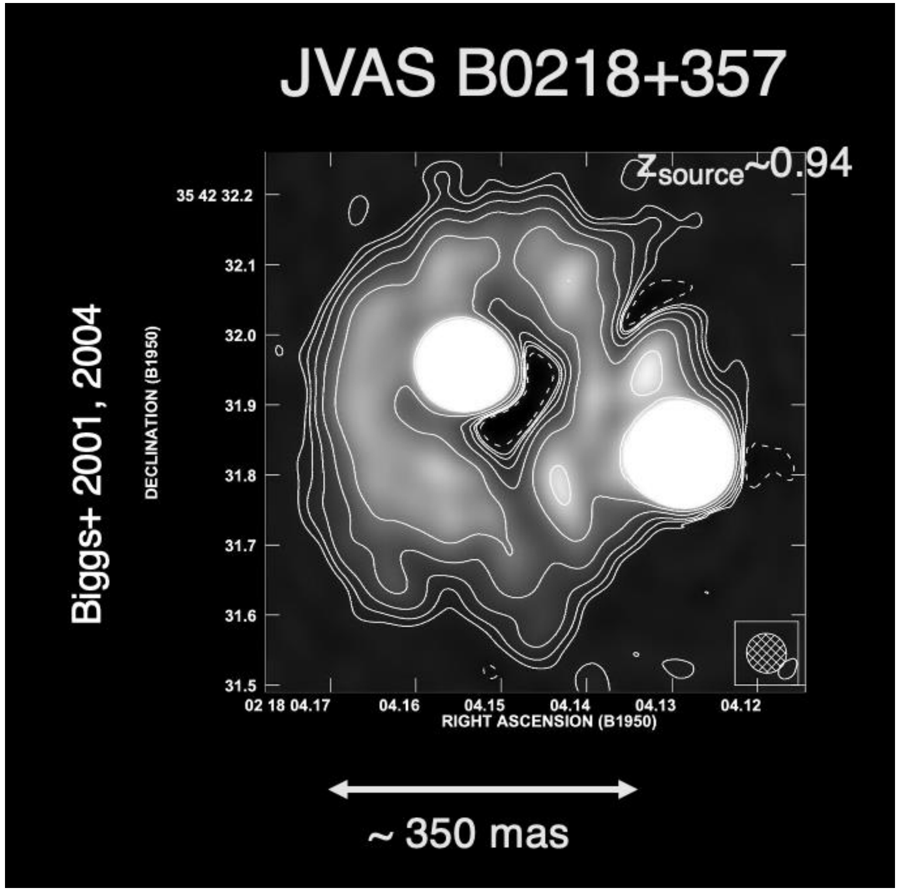


The lensing system JVAS B0218+357

Credit: NASA's Goddard Space Flight Center – data from Fermi Large Area Telescope Cheung et al. 2016 (Fermi-LAT time delay measurement)

- B2 0218+35 macro-lensed system: blazar at z~1 and elliptical lens at z~0.7
- Radio observation return mas position resolution

#2 Strong Gravitationally Lensed Blazars



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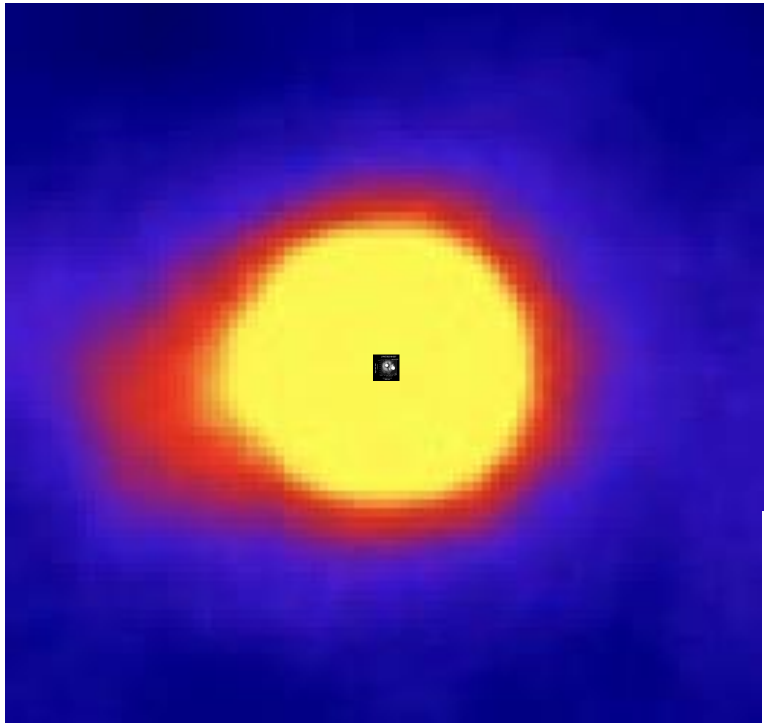
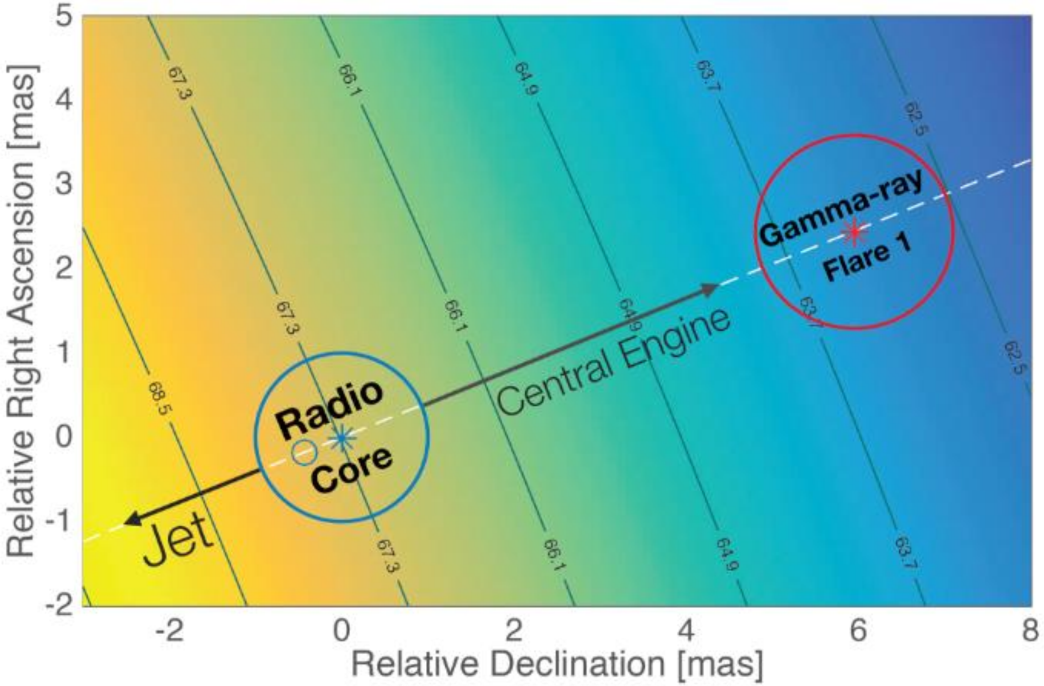
#2 Strong Gravitationally Lensed Blazars



- Gamma-rays? Time delays between A and B can be used to
  - Constrain the radio/gamma relative location in the jet at mas
  - And/or the Hubble constant!

$$h = \frac{d(1+z_L)(\theta_B^2 - \theta_A^2)}{2c\,\Delta t}$$

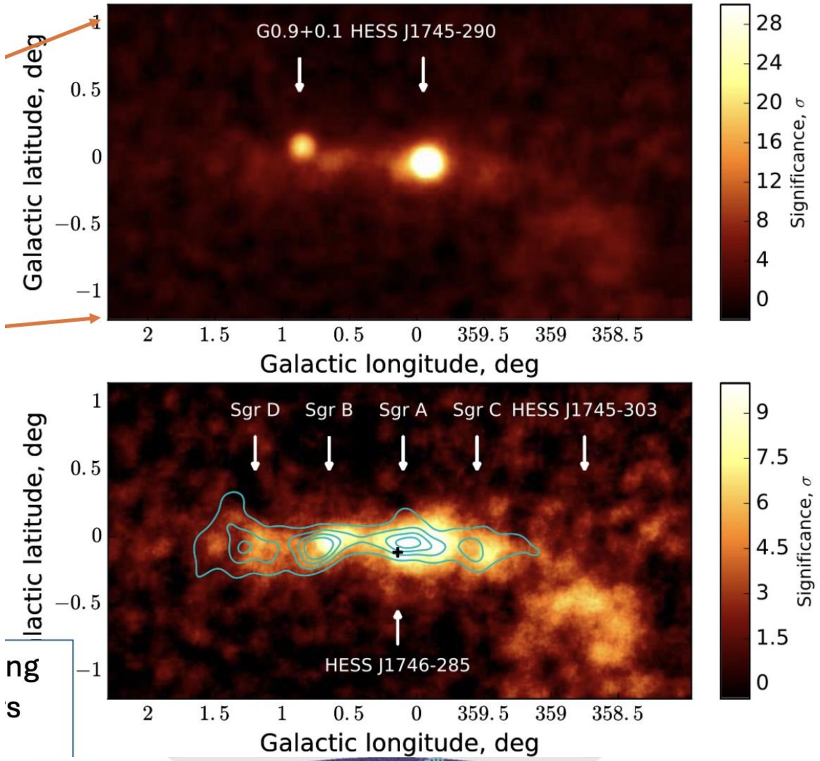


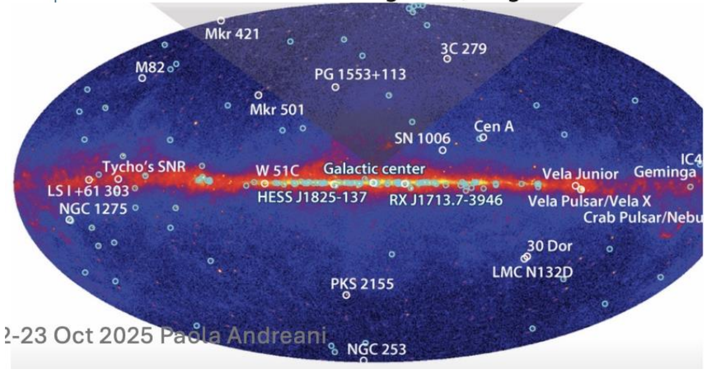
The Hubble parameter obtained based on the position of the radio core and this time delay corresponds to H0 = 63.64 ±0.67 km s−1Mpc−1 (Planck H0 = 67.3 ±1.2)

See, Greaux talk on Thu on Hubble Constant w/ IACTs

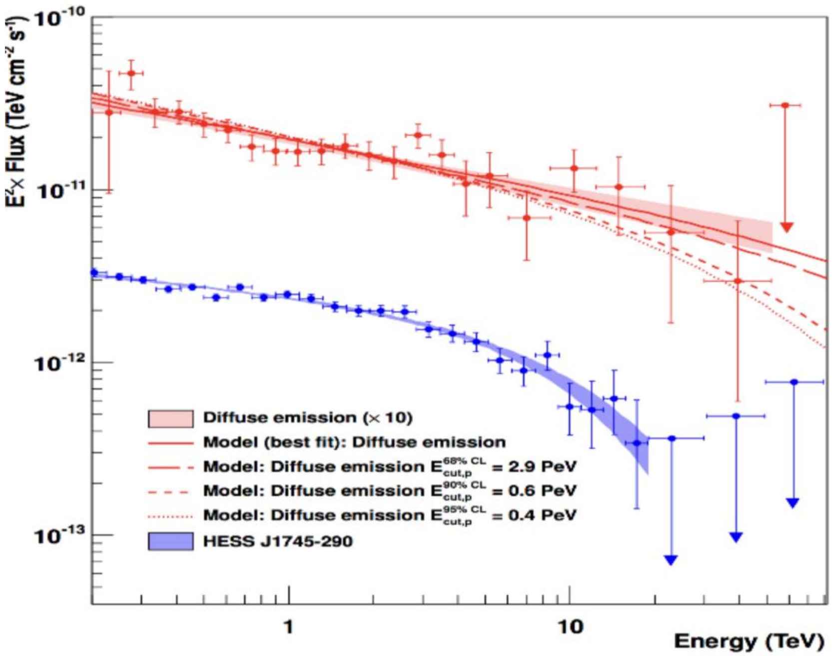
#3 Closing in on the GC energetics

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

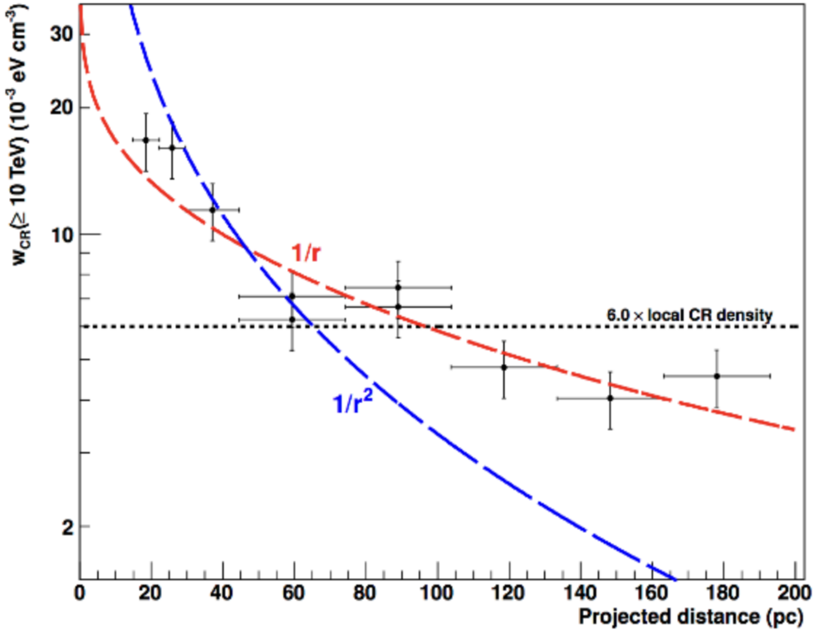




Diffuse VHE gamma-ray emission correlated with the dense molecular gas distribution

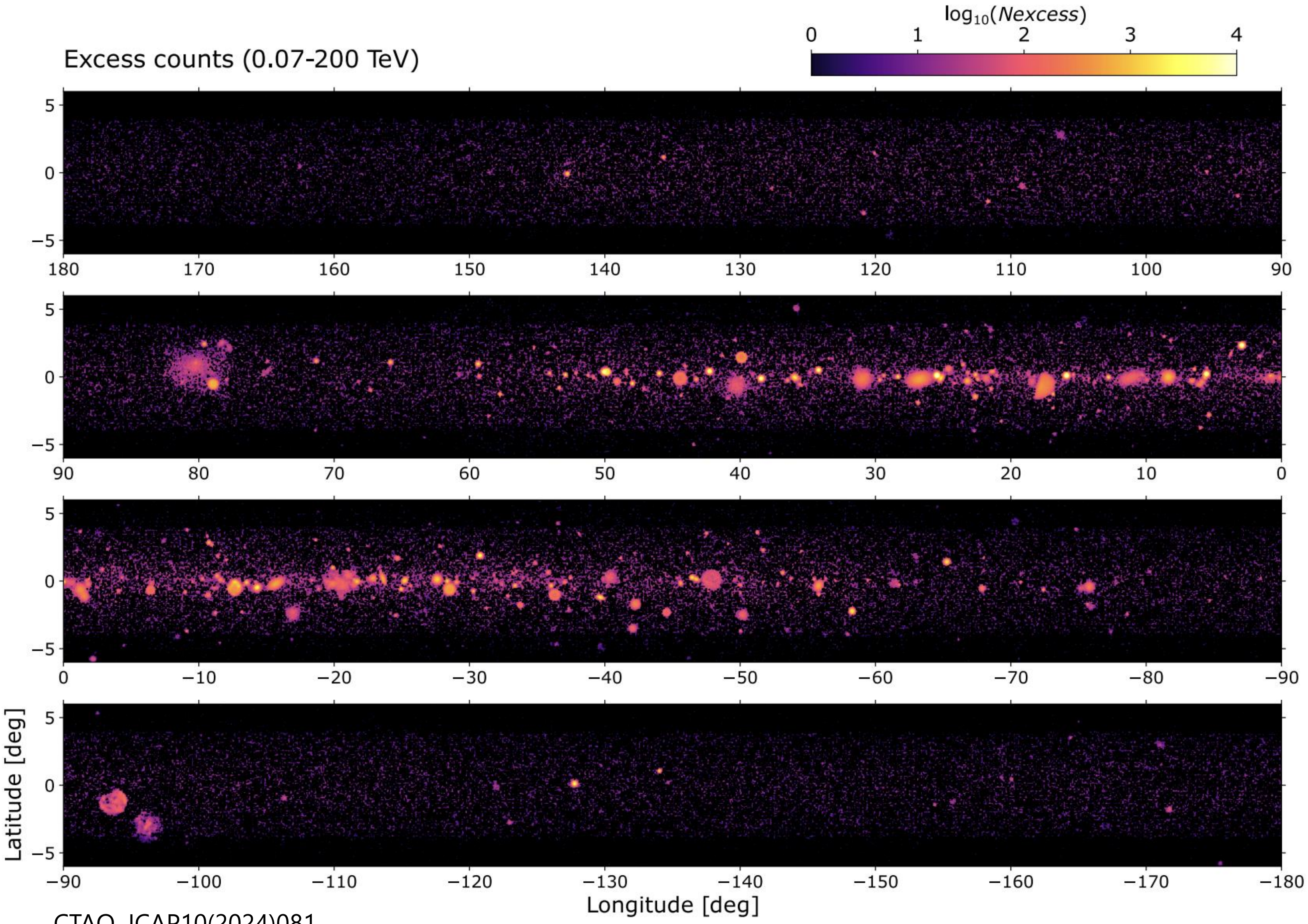


Spectrum extends deep into TeV with hints of cutoff (MAGIC, 20 TeV) debating the nature of GC as Pevatrons. HAWC detected > 100 TeV g-rays

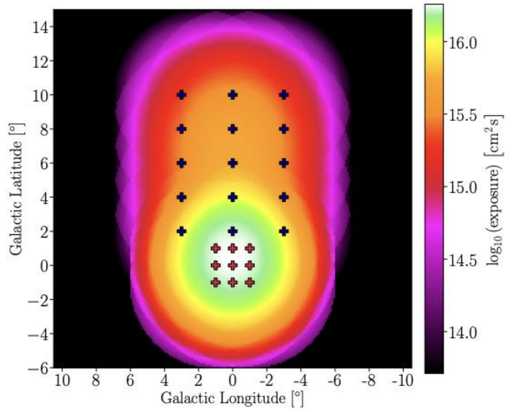


CR energy density profile scaling as 1/r from Sgr A* points to a central CR source, a continuous accelerator operating within the central 200 pc

#3 Closing in on the GC energetics



CTAO, JCAP10(2024)081



CTAO JCAP 01 (2021) 057

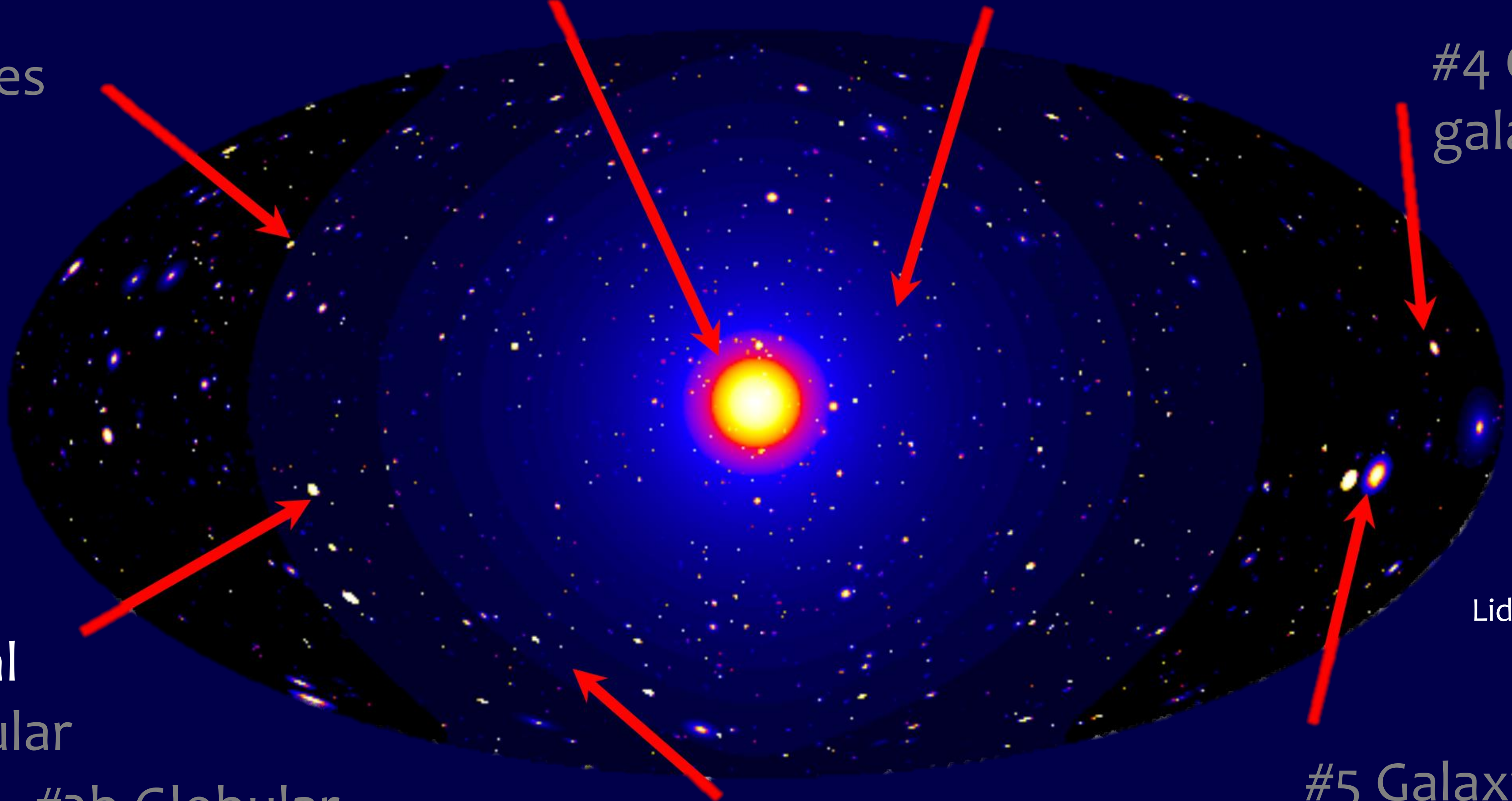
- CTAO key science case is the galactic plane with deep survey on the galactic center
- Can resolve point like and diffuse emission correlated with clouds

#4 Dark Matter hiding places

#1 Galactic Center and halo

#3 Dark subhaloes

#4 Other galaxies



#2 Dwarf galaxies (MW satellites) Spheroidal and Irregular

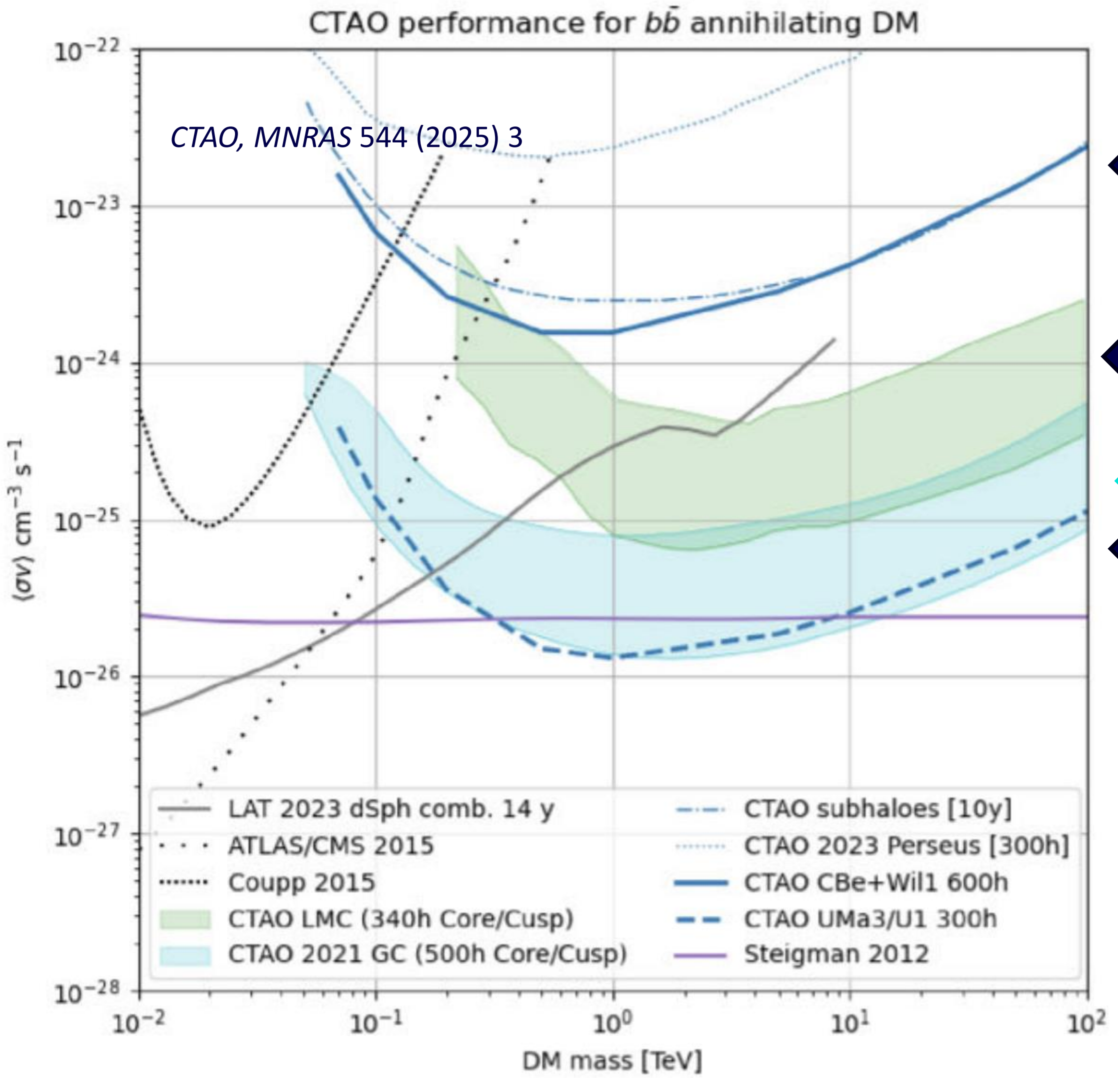
Lidia Pieri+

#2b Globular clusters

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

#5 Galaxy clusters

#4 Closing up on TeV WIMP-like DM

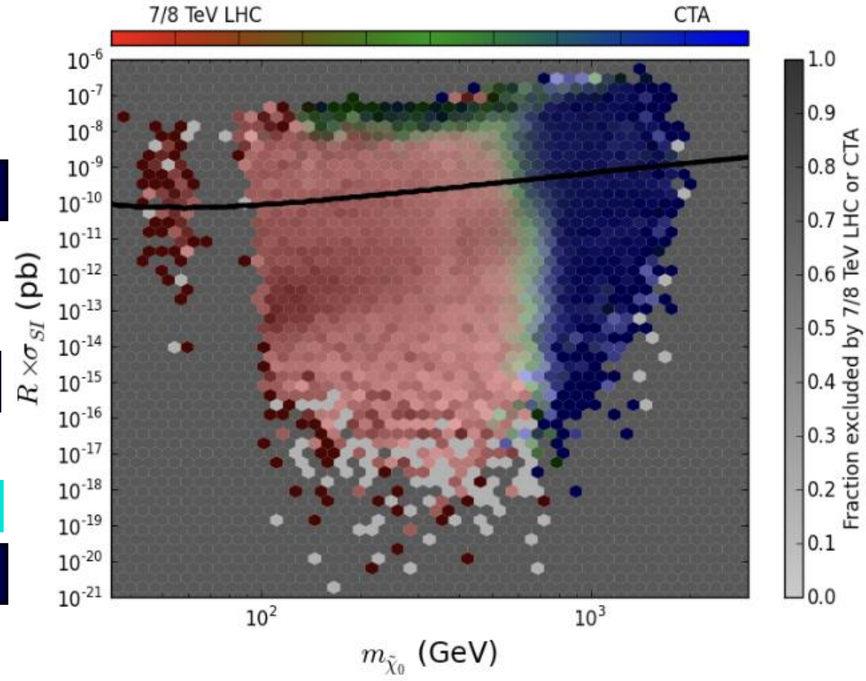


Current dSph

LMC

Galactic Center

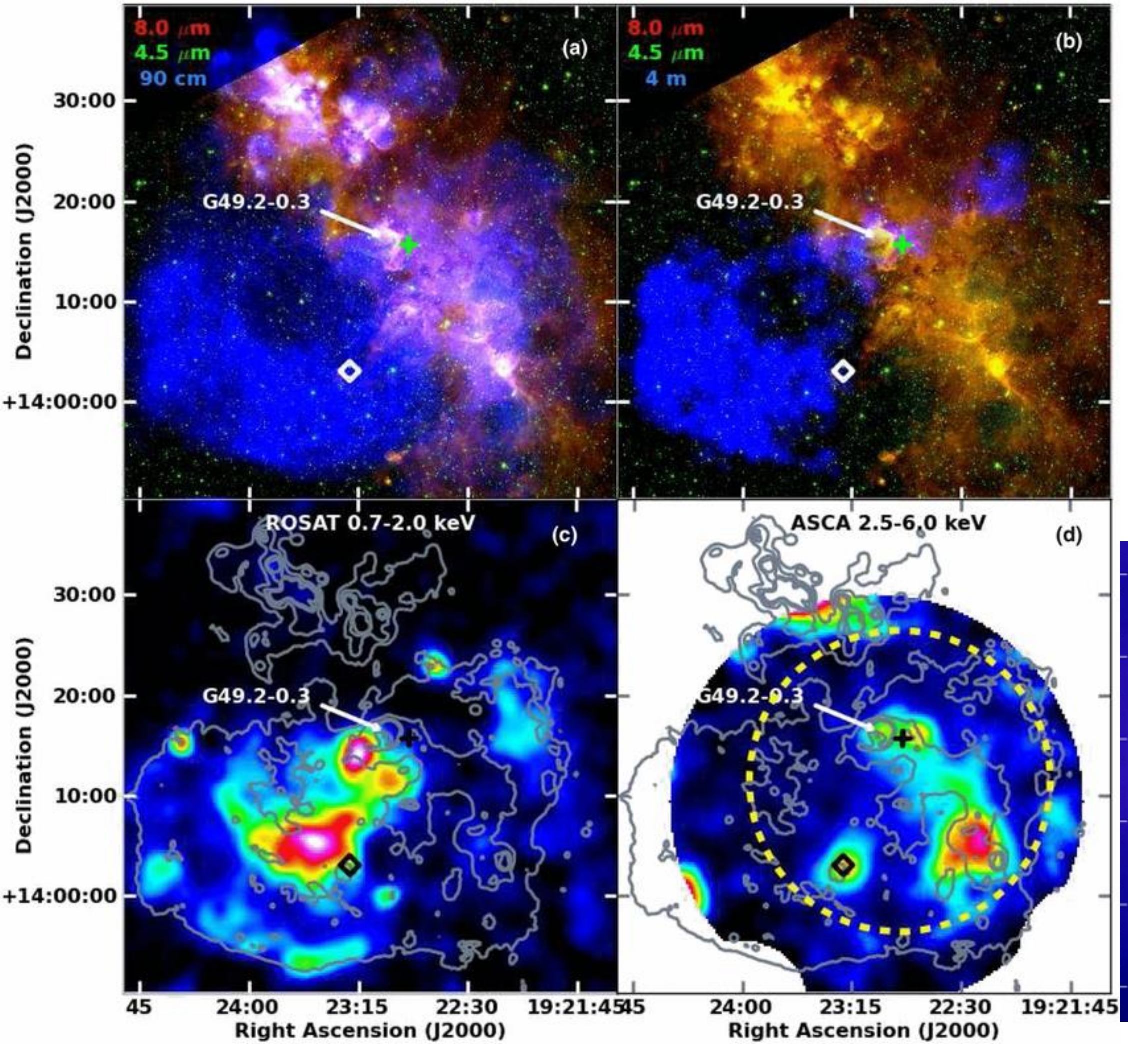
Champion dSph

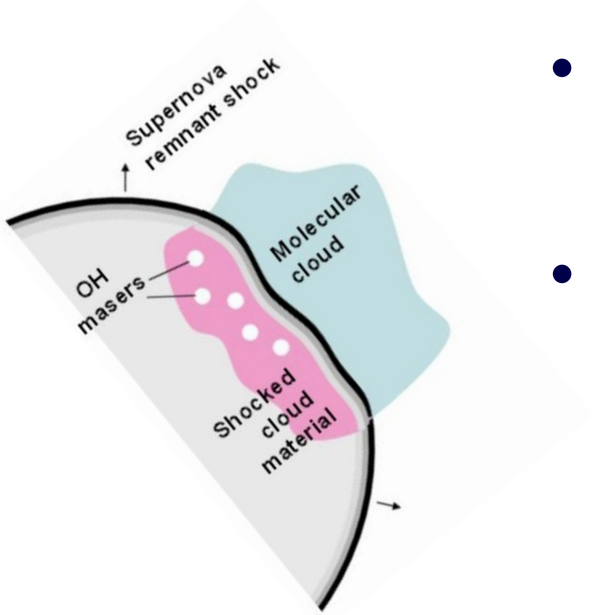


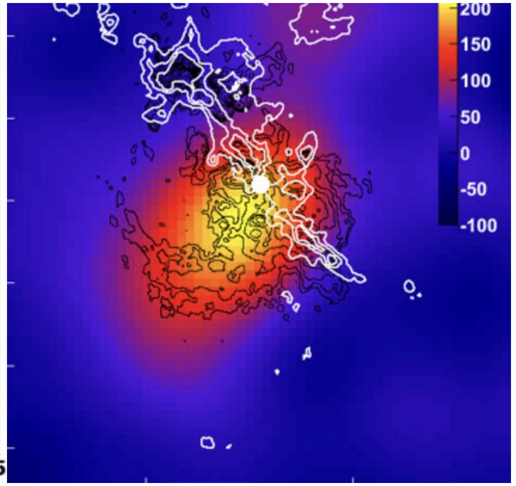
TeV DM is uniquely observed with CTAO

#5 CR-driven stellar birth

From Andreani, Trigo ESO newsletter May 26



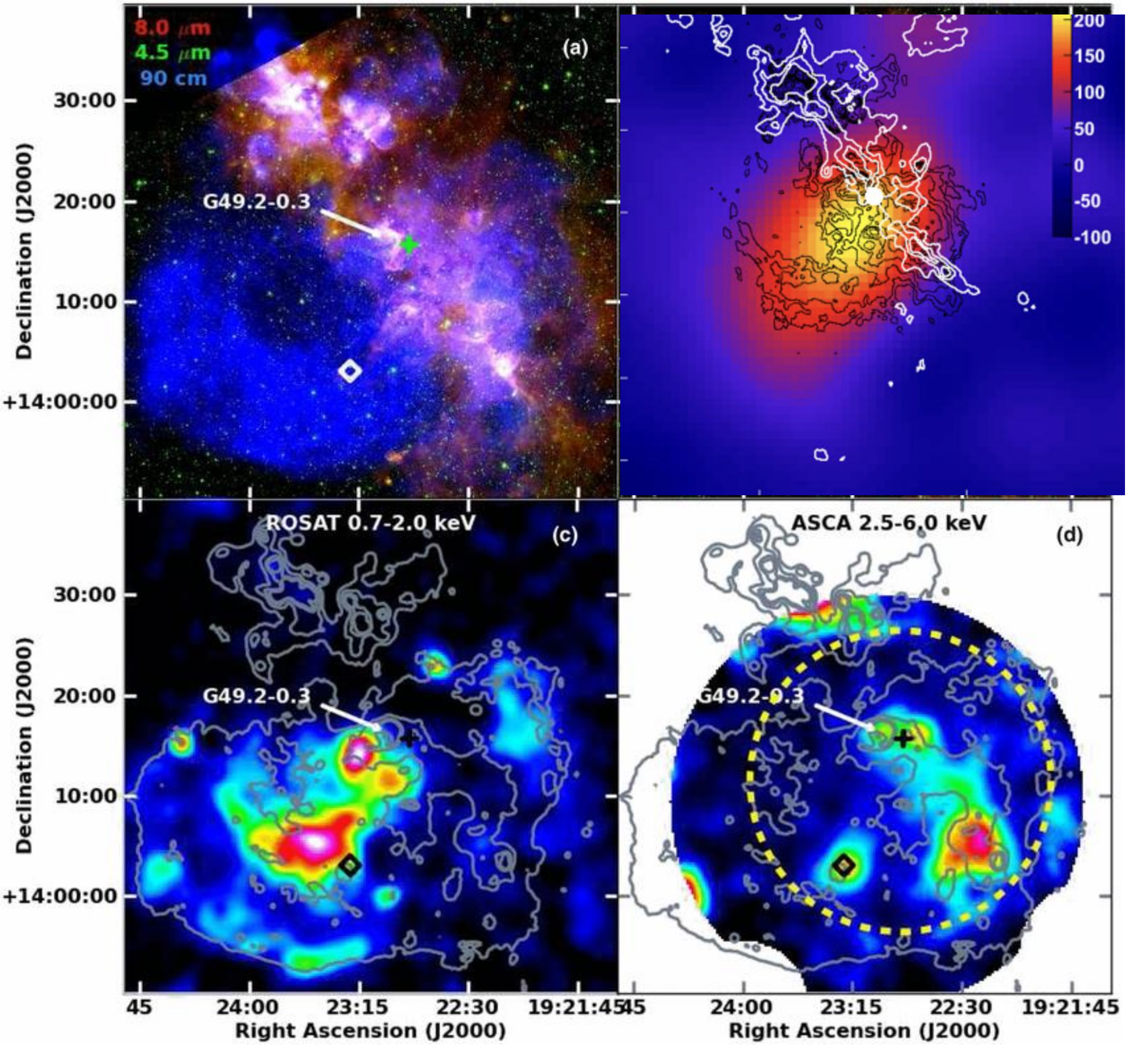




- Sinergy ESO: CTAO-ALMA
- W51 complex star forming regions:
  - SNR CRs ionize material more than radiation and alter fragmentation of H2 → traced by CTAO gamma-rays
  - mm-ALMA trace gas and synch radiation in B-fields and emission lines from various isotopologues

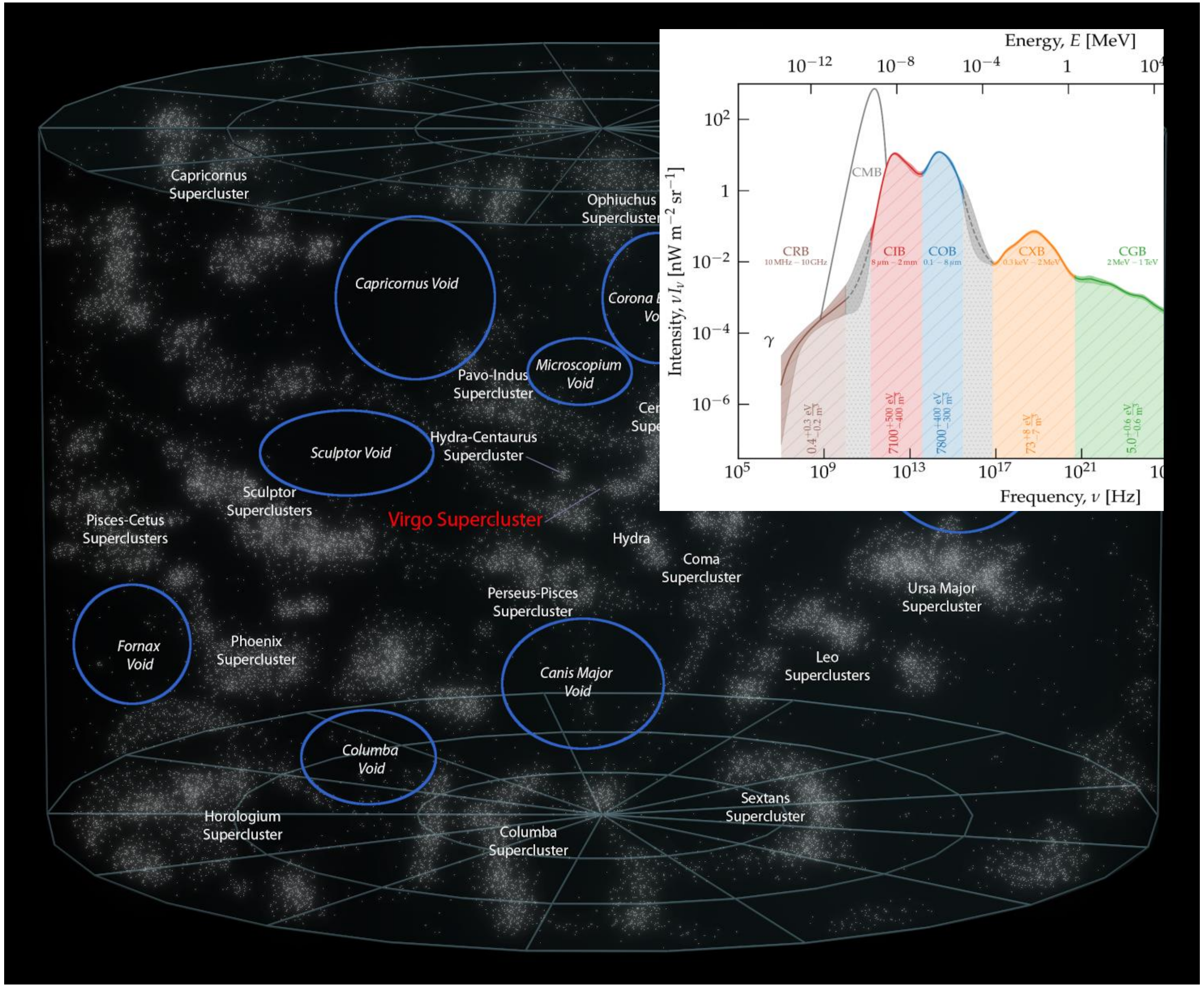
#5 CR-driven stellar birth

From Andreani, Trigo ESO newsletter May 26



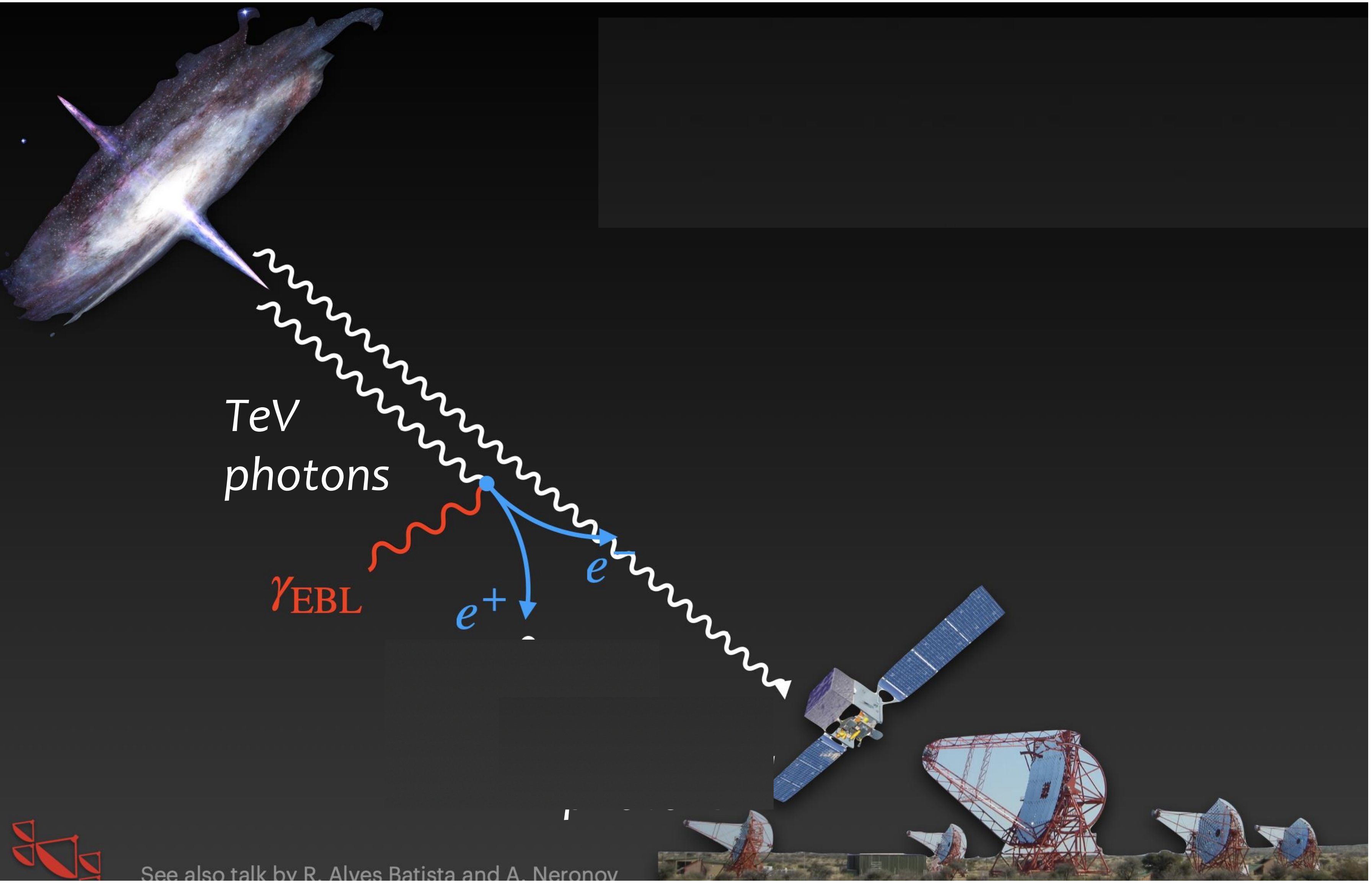
- CTAO and ALMA can jointly answer questions such as :
  - Does gamma-rays trace mm (gas) morphology?
  - Are CRs hadronic in these class of targets? Pion bump in the spectrum
  - Is CRs population peculiar? match to local ISM or enhanced near the SNR shock?
  - Is there a top-heavy stellar initial mass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

#6 What's in the great dark voids



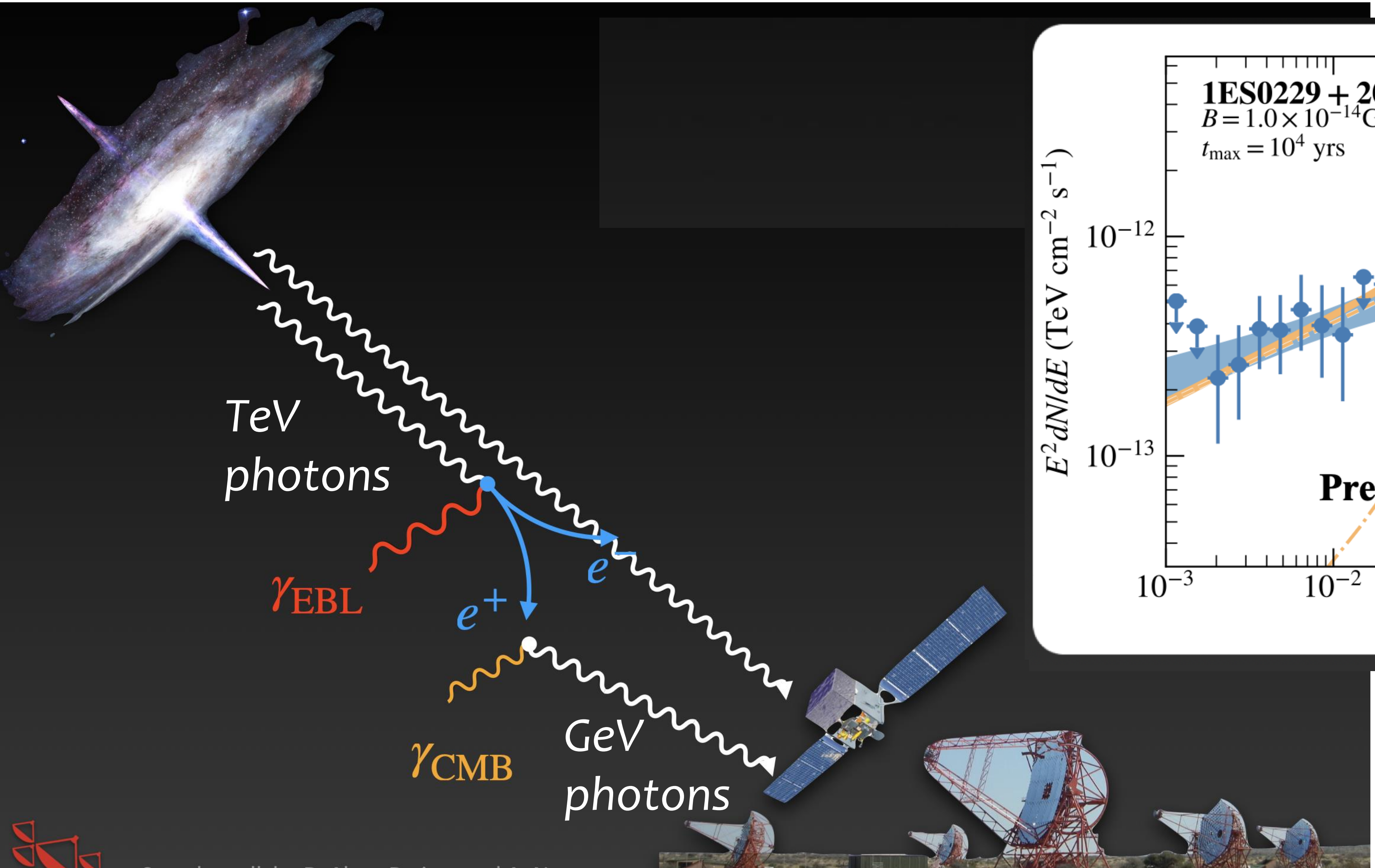
- There are great empty volumes in the Universe. No matter, but plenty of EBL, CMB photons… and magnetic fields yes!
- Primordial Magnetic Fields (PMFs), post-processed by the formation of structures, they tell us about fundamental physics involved in the early Universe

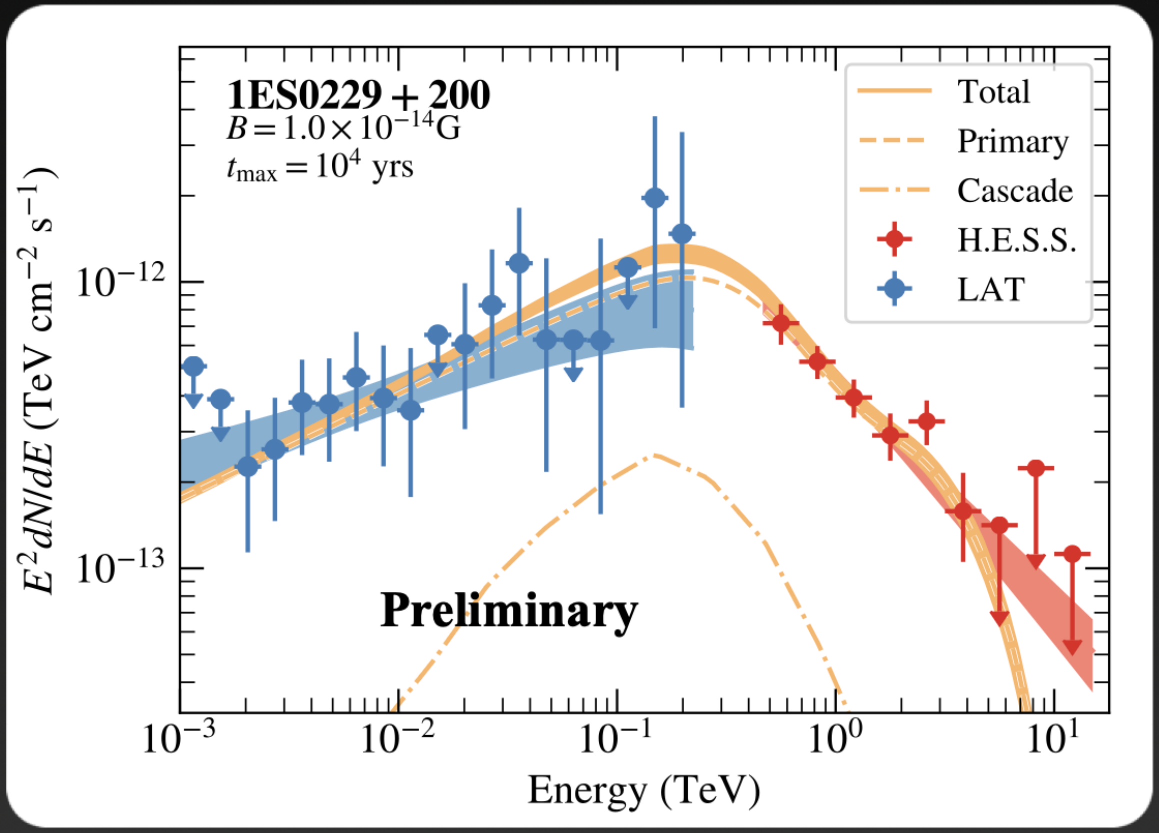
#6 The Magnetic Field in the Voids



- EBL light reprocess TeV gamma-rays to GeV gamma-rays

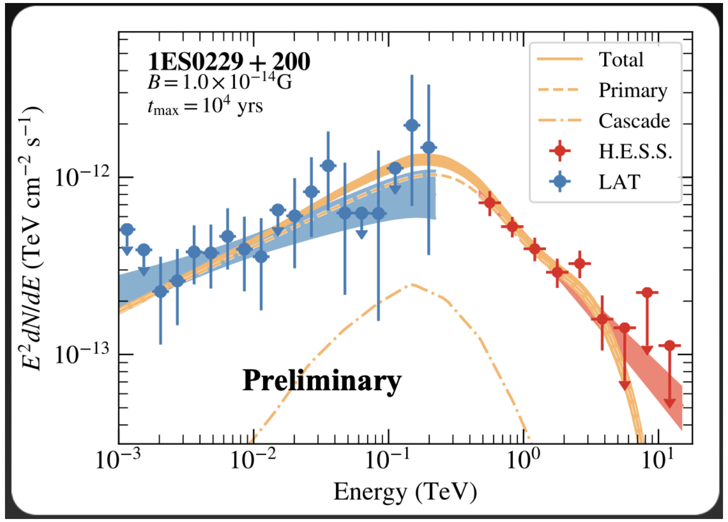
#6 The Magnetic Field in the Voids

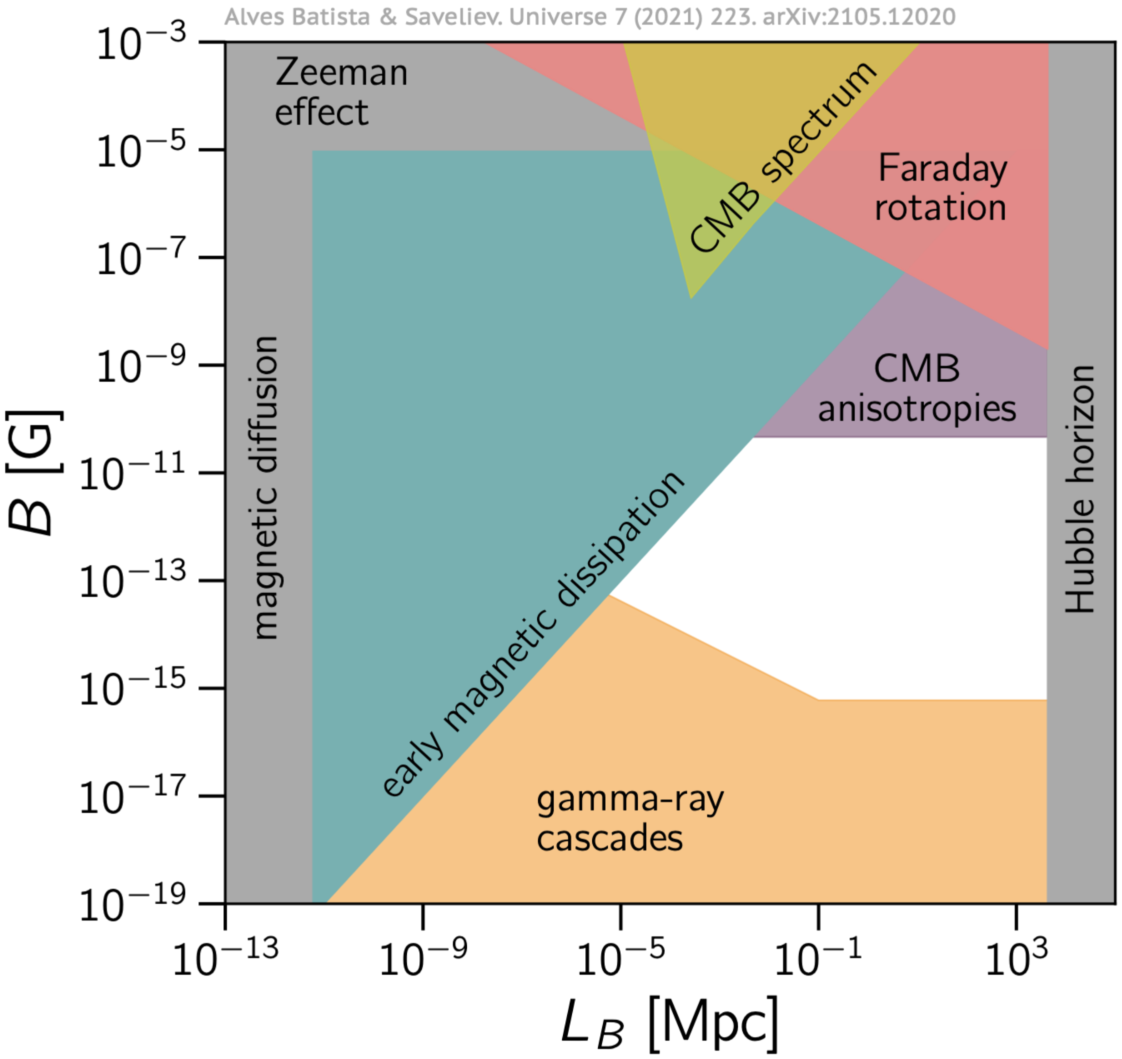




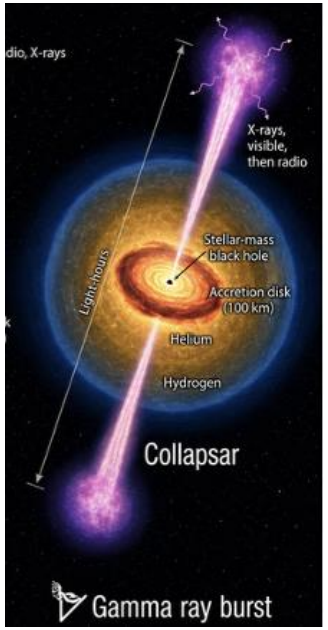
See also talk by R. Alves Batista and A. Neronov

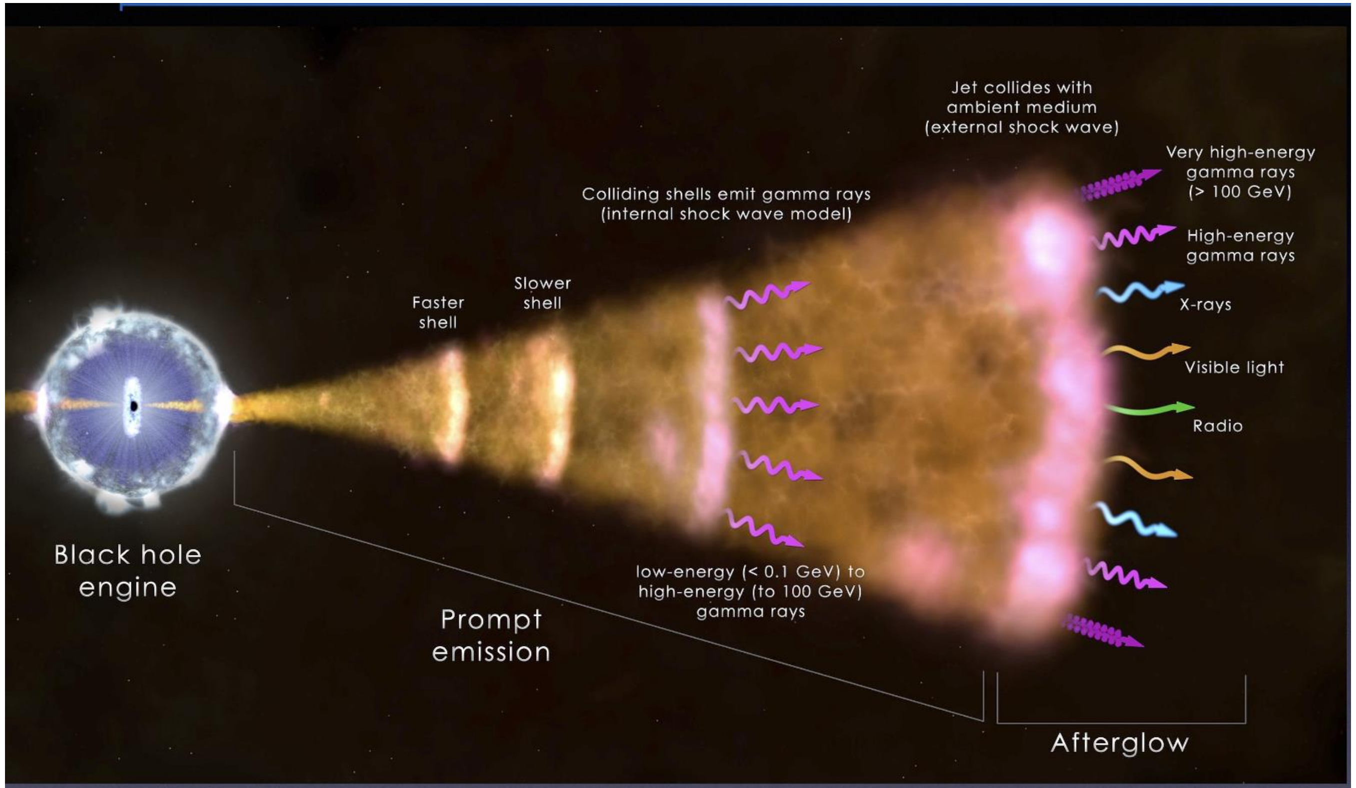
#6 The Magnetic Field in the Voids





#7 Gamma-ray burst jets

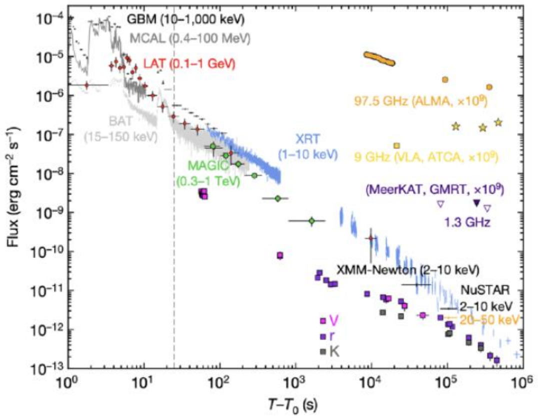




GRB	Detector	z	t_{max}	γ (EBL corr)	α	Highest E
180720B	HESS	0.65	12h	**1.6**	?	0.4 TeV
190114C	MAGIC	0.42	40min	2.22	1.6	1 TeV
190829A	HESS	0.08	**56h**	2.07	1.09	4 TeV
201216C	MAGIC	**1.1**	2h	3.15	0.62	0.2 TeV
221009A	LHAASO	0.15	1h	2.3	1.1/2.2	**13 TeV**

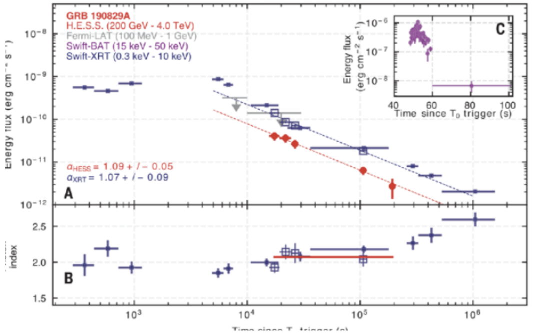
GRB 190114C

[MAGIC, Nature 575 (2019)]



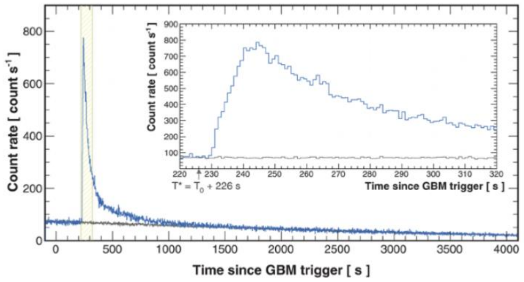
GRB 190829A

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



GRB 221009A

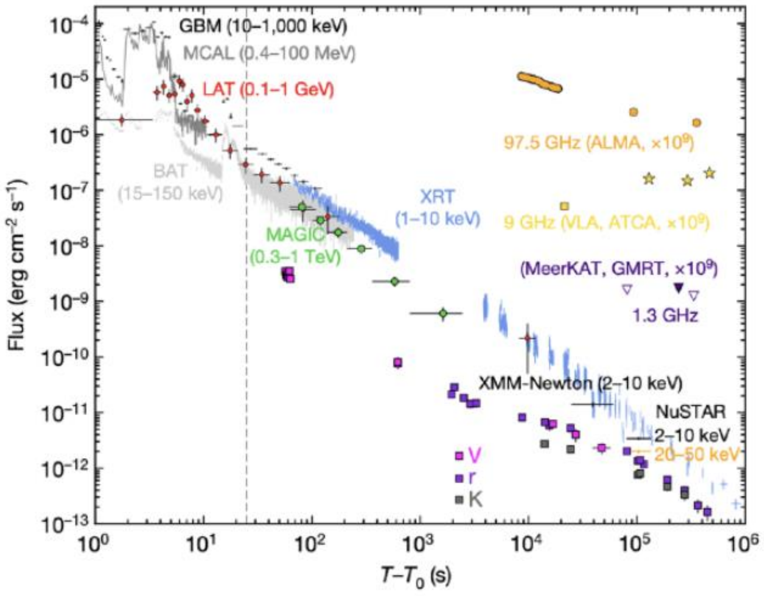
[LHAASO, Science 380 (2023)]



#7 Gamma-ray burst jets

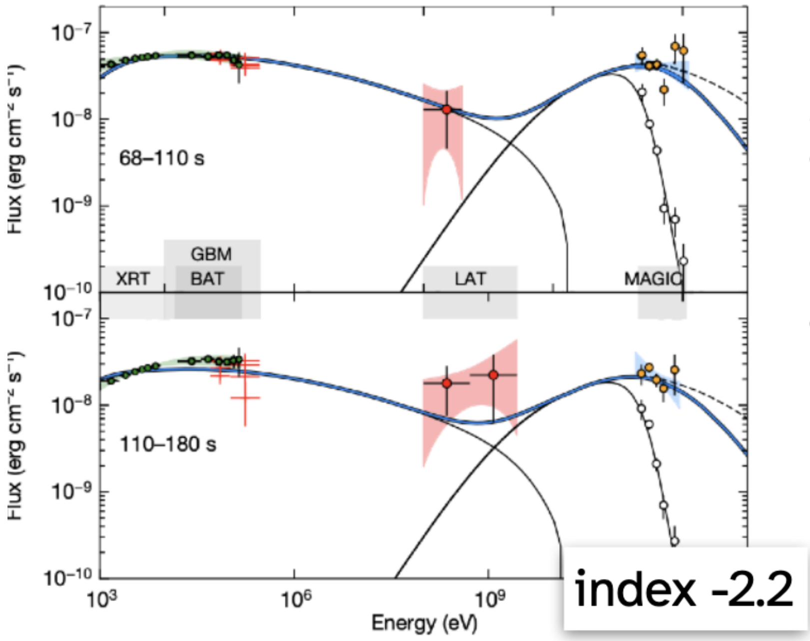
GRB 190114C

[MAGIC, Nature 575 (2019)]



GRB 190114C

[MAGIC, Nature 575 (2019)]

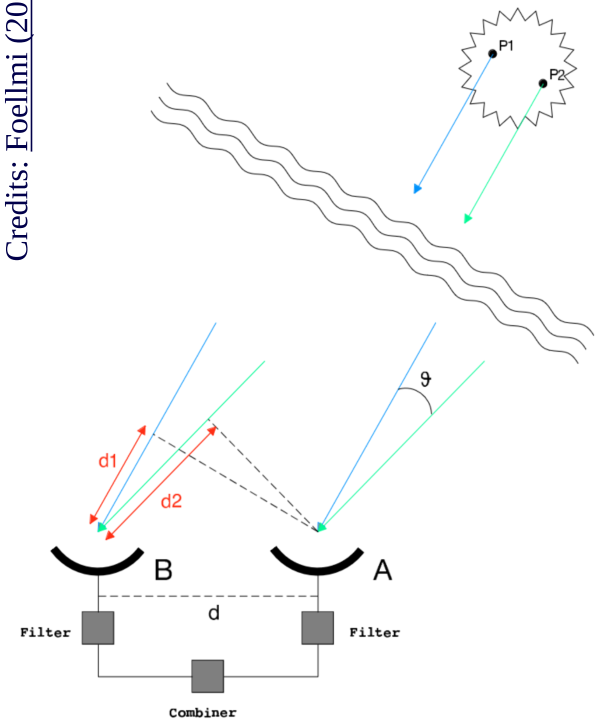


- CTAO has best performance > 20 GeV
- Fast repositioning ~20sec of LSTs
- GRB hunter!

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

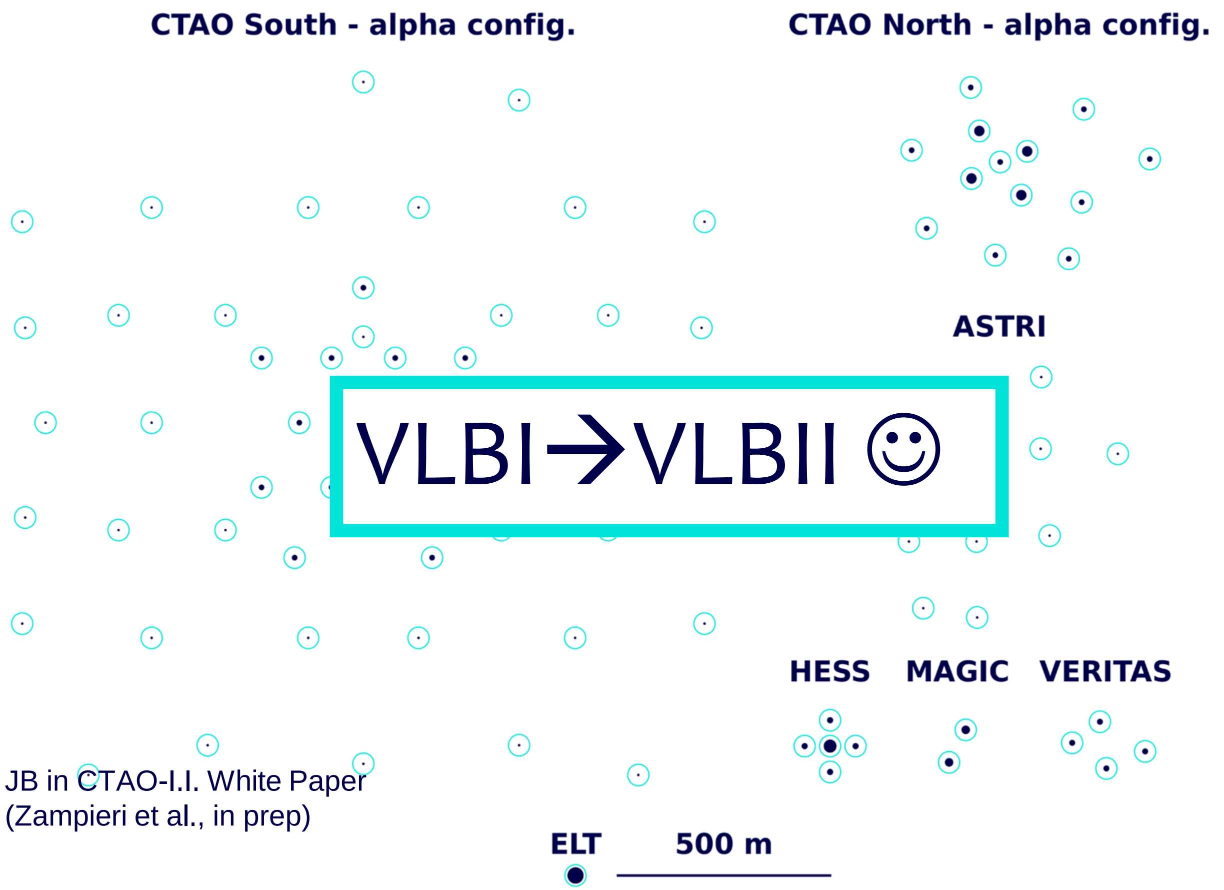
#8 Intensity Interferometry

Credits: Foellmi (2009)



Intensity interferometry: 2nd order correlation

- **Poor SNR: need bright & small targets**
- Very large baselines (> km)
- Efficient at short wavelength (blue, UV)
- Insensitive to the atmospheric turbulence

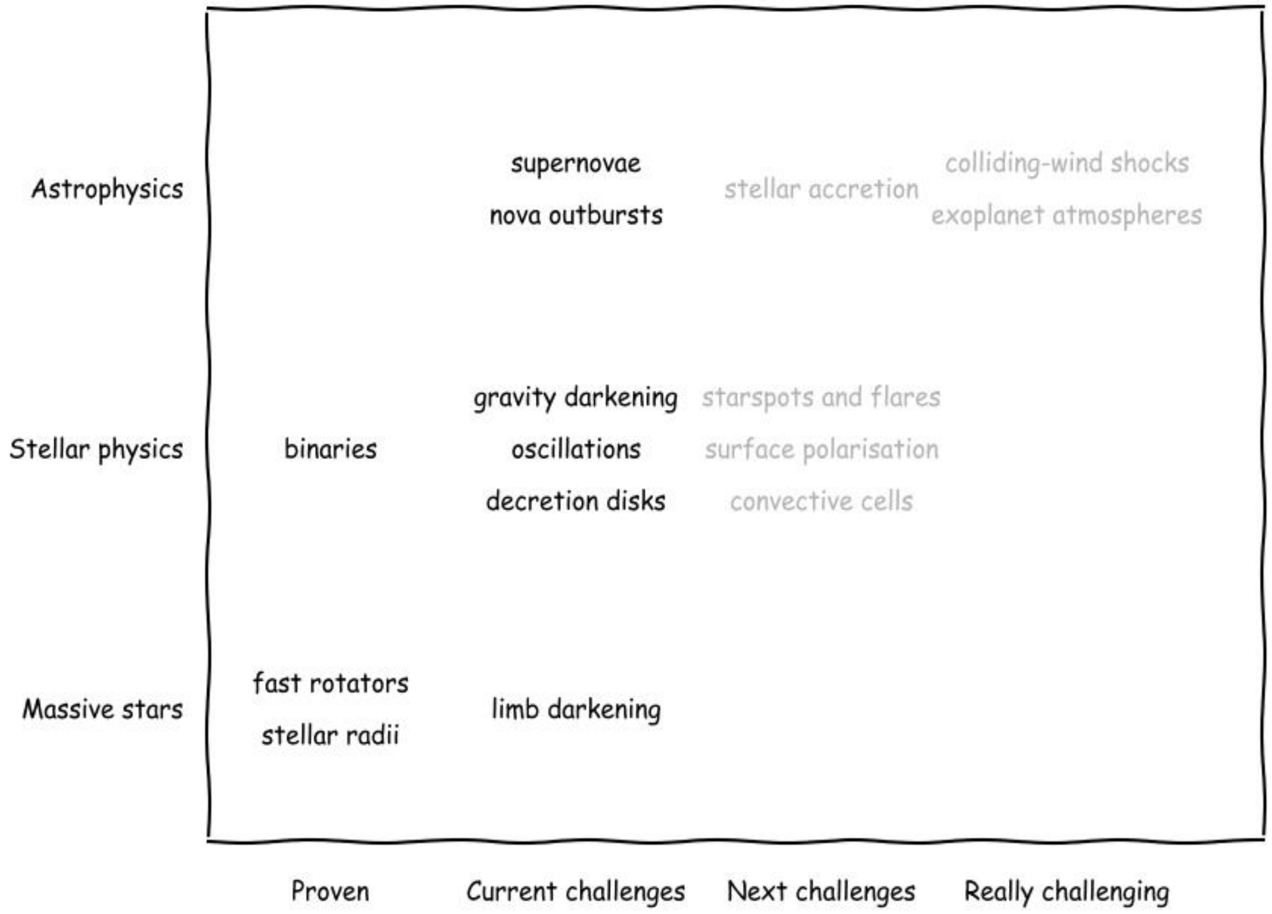


JB in CTAO-I.I. White Paper
(Zampieri et al., in prep)

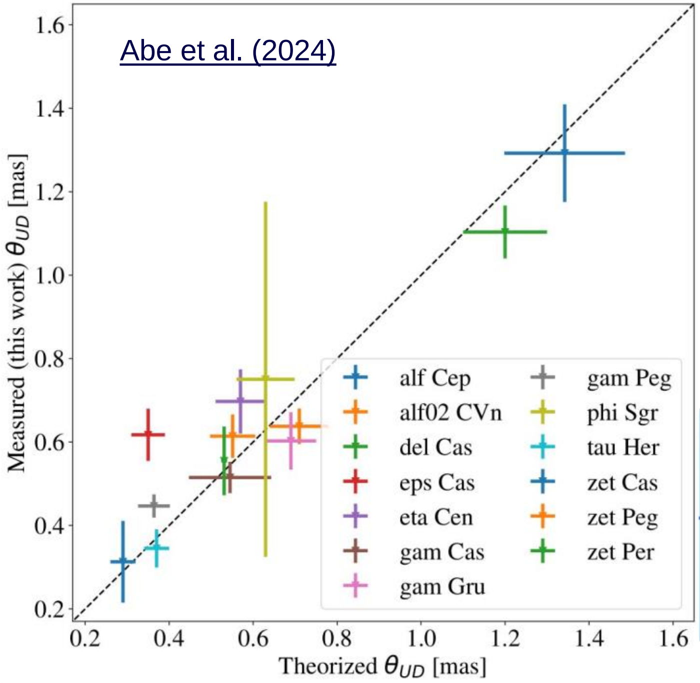
$$1.22\frac{\lambda}{D} = 0.2\,\mathrm{mas} \times \left(\frac{\lambda}{400\,\mathrm{nm}}\right)\left(\frac{D}{500\,\mathrm{m}}\right)^{-1}$$
$$= 50\,\mu\mathrm{as} \times \left(\frac{\lambda}{400\,\mathrm{nm}}\right)\left(\frac{D}{2\,\mathrm{km}}\right)^{-1}$$

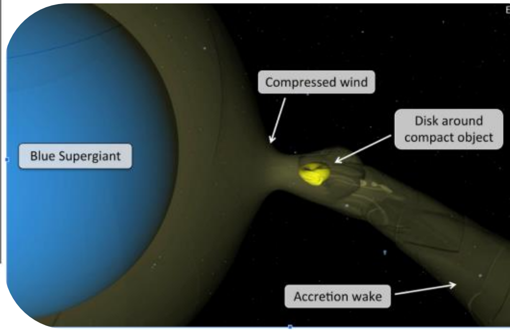
#8 SII

P. Saha in CTAO-I.I. White Paper (Zampieri et al., in prep)

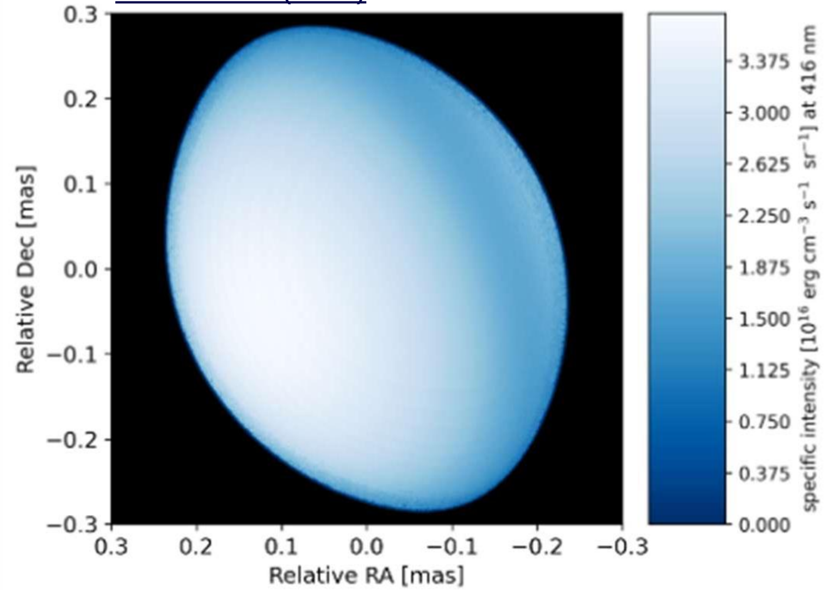


Abe et al. (2024)



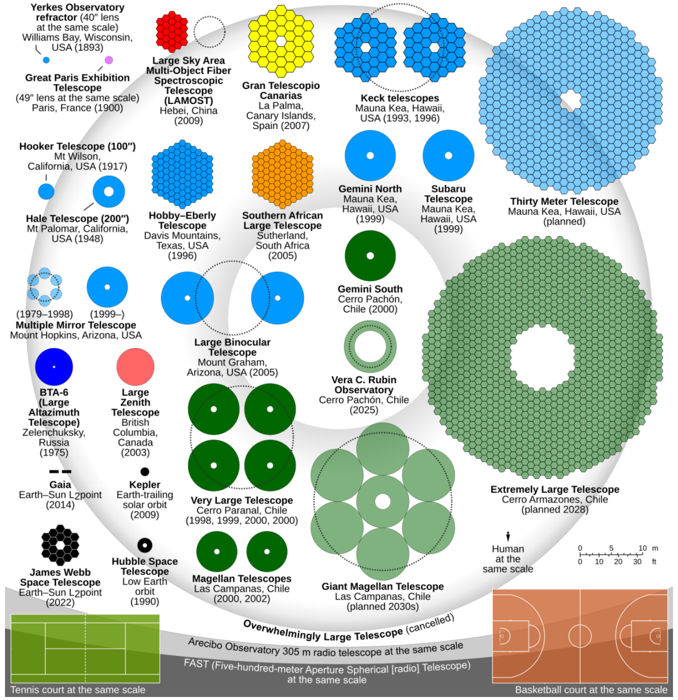


Archer et al. (2025)

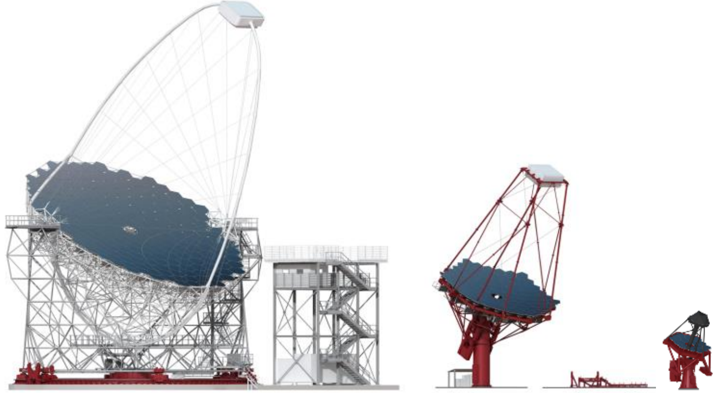


Conclusions

2030s, the era of Big (Astronomical) Data



- In the **past decade** 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. NEED BETTER THEORIES FOR BETTER DATA
- We need **to coordinate**: alerts, shared programs, shared data access,



CTAO engines warming up, stay tuned!

Thanks