Cherenkov Telescope Array Observatory: the World's largest VHE gamma-ray observatory

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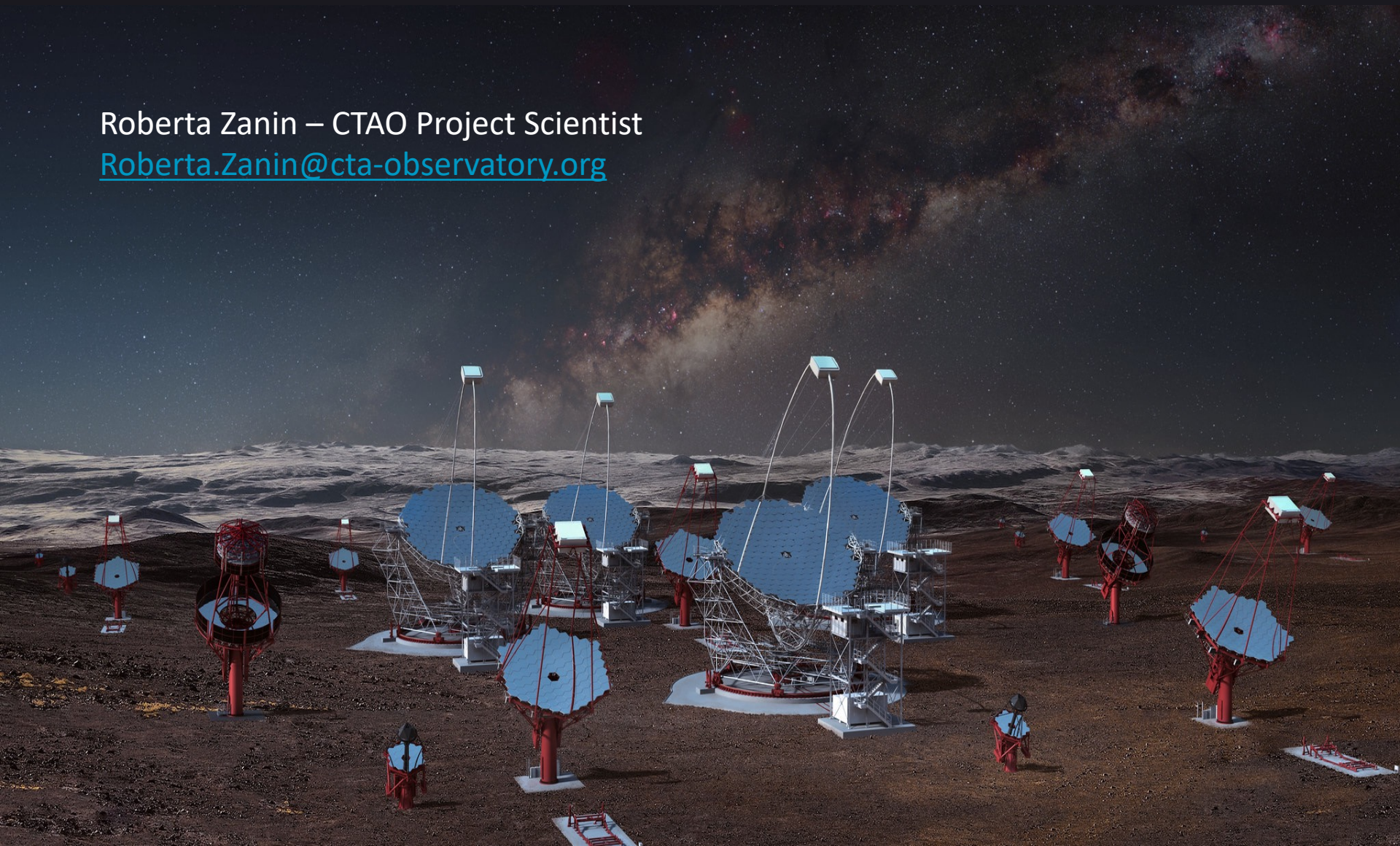


Outline

- **PART I**

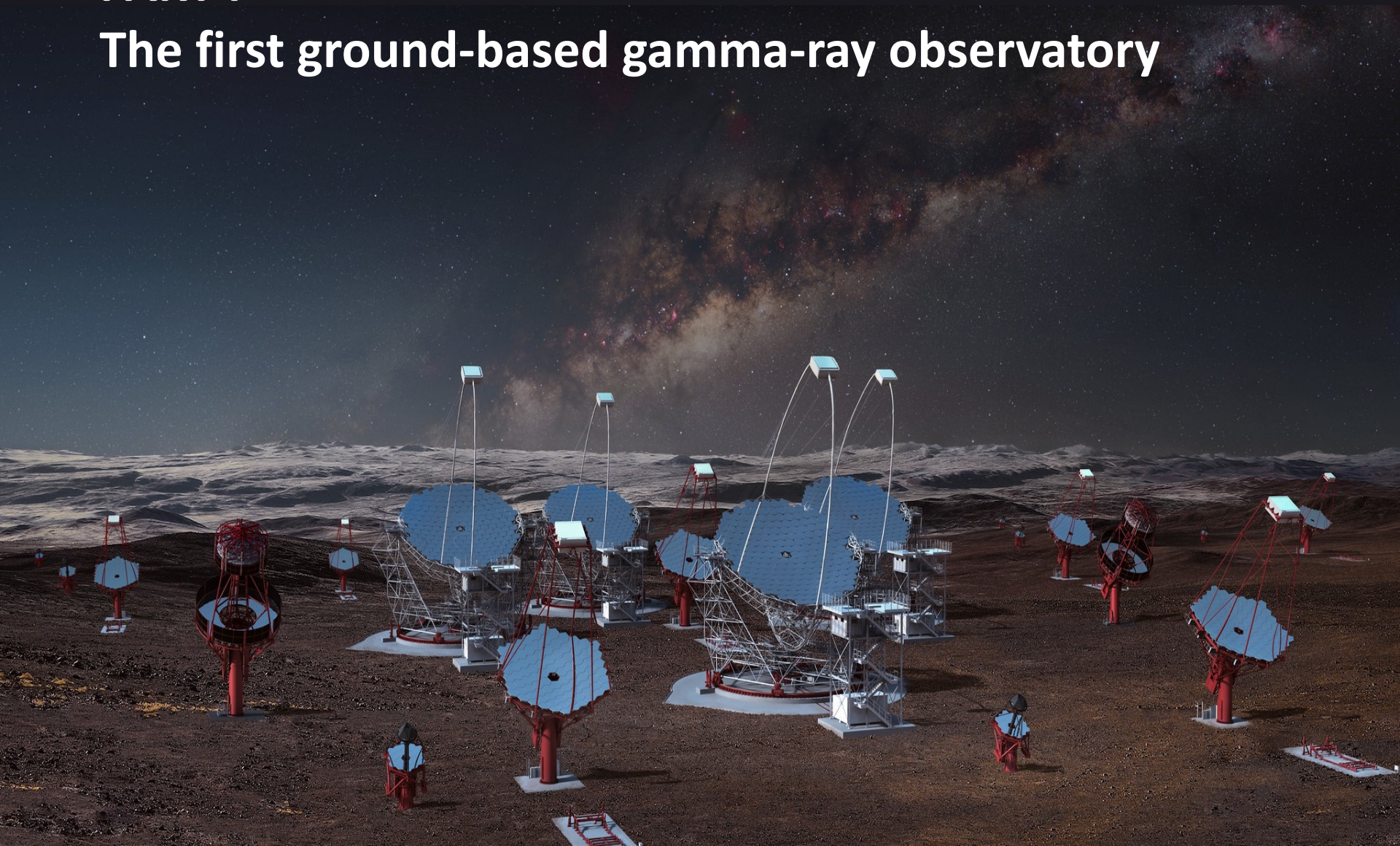
  intro to the Cherenkov Telescope Array Observatory
- **PART II**

  CTAO performance
- **PART III**

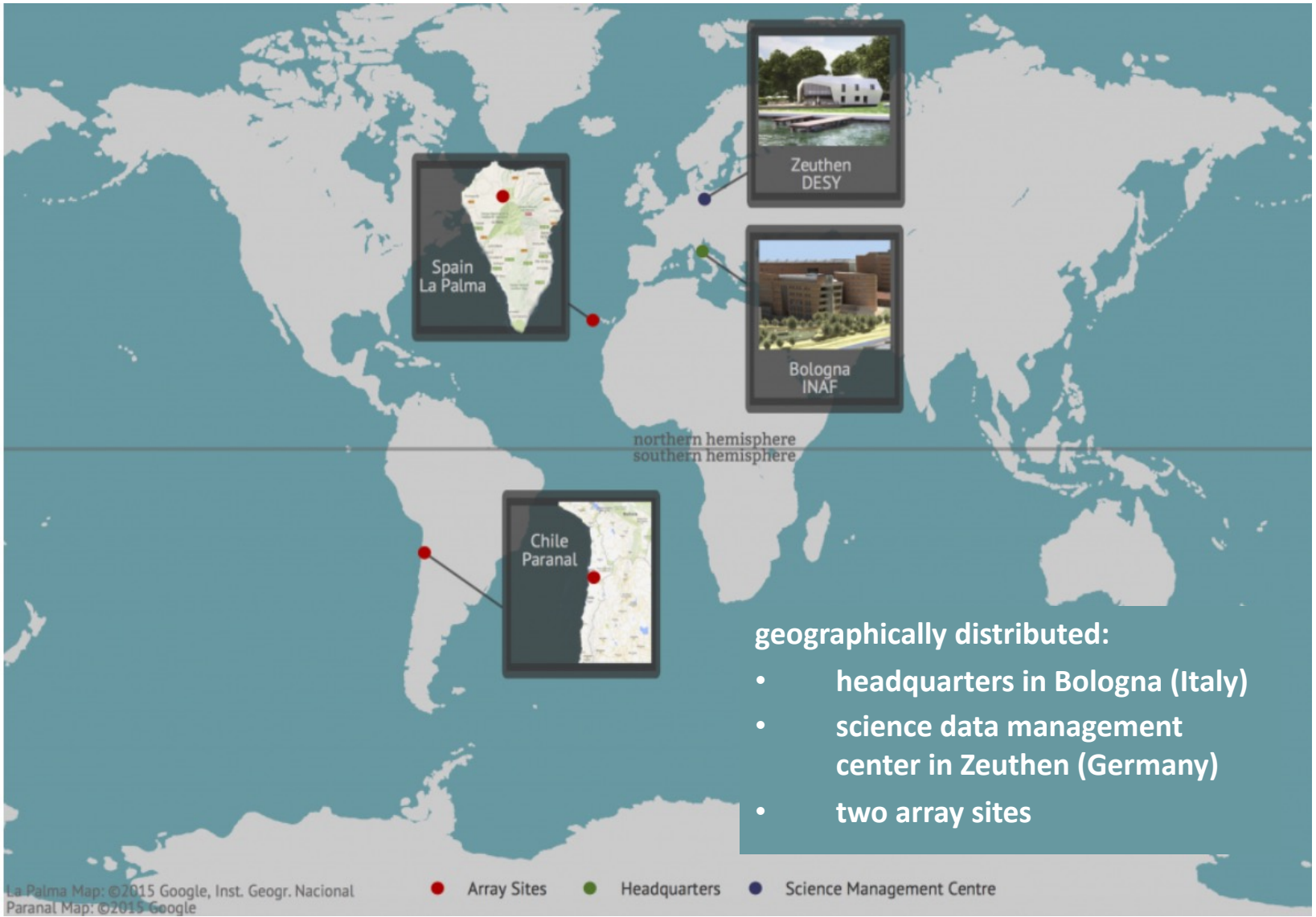
  CTAO science case
  (surveys, transients, pevatrons)
- **Part IV:**

  first results from LST-1: the first CTAO telescope under commission

PART I
The first ground-based gamma-ray observatory



CTA Observatory

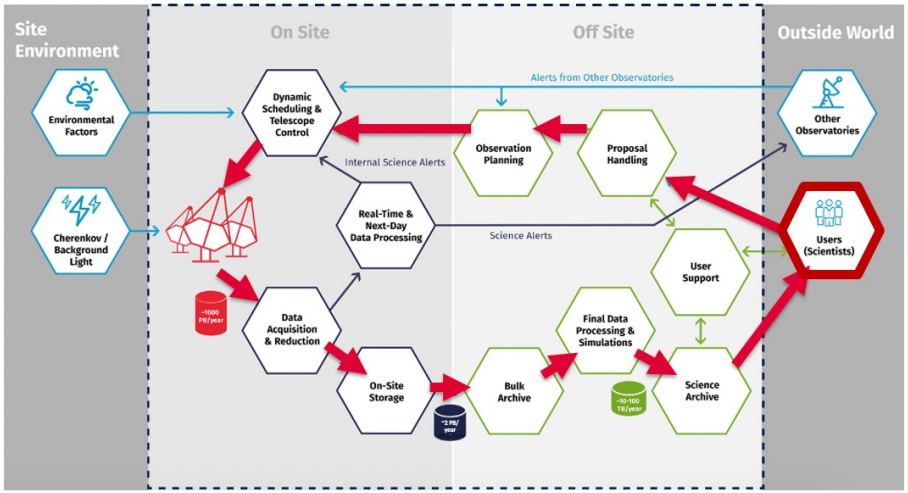


geographically distributed:

- **headquarters in Bologna (Italy)**
- **science data management center in Zeuthen (Germany)**
- **two array sites**

CTA Observatory

- **CTAO will deliver science-ready data & science analysis tools (SATs) to the worldwide scientific community**
  - **most of the observing time is allocated for scientists working in contributing countries**
  - **observations will have a proprietary period of about 1 year**
  - **once the proprietary period will be expired, data will become publicly available through the CTAO science portal**



CTA Observatory

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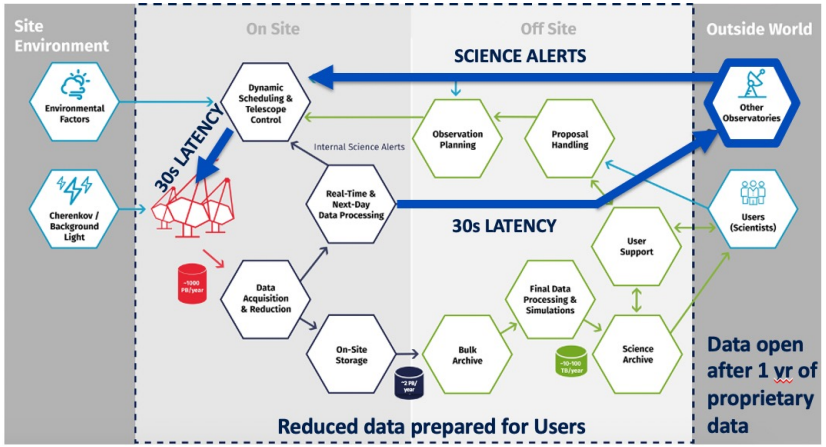
  - most of the observing time is allocated for scientists working in contributing countries
  - observations will have a proprietary period of about 1 year
  - once the proprietary period will be expired, data will become publicly available through the CTAO science portal
- CTAO will respond/provide science alert in less than 1’



Observing time allocation

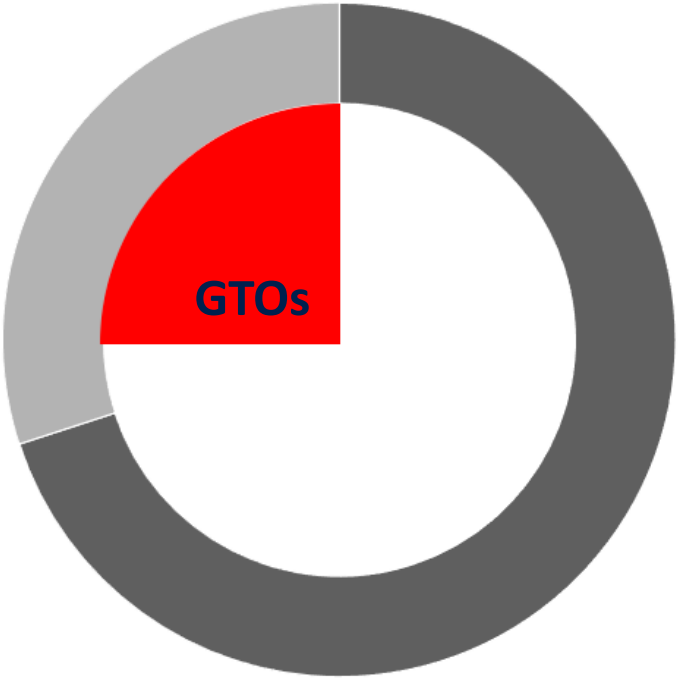
- the observing time will be allocated on the basis of scientific proposals reviewed by the Time Allocation Committee (TAC) and selected to maximize the science return
  - all scientific proposals will be reviewed by the TAC

- Astronomical observations are grouped into Observation Periods (OPs)
  - each OP lasts about one year
  - each OP is associated to an Announcement of Opportunity (AO) call issued by the Observatory through which the application for observing time is handled

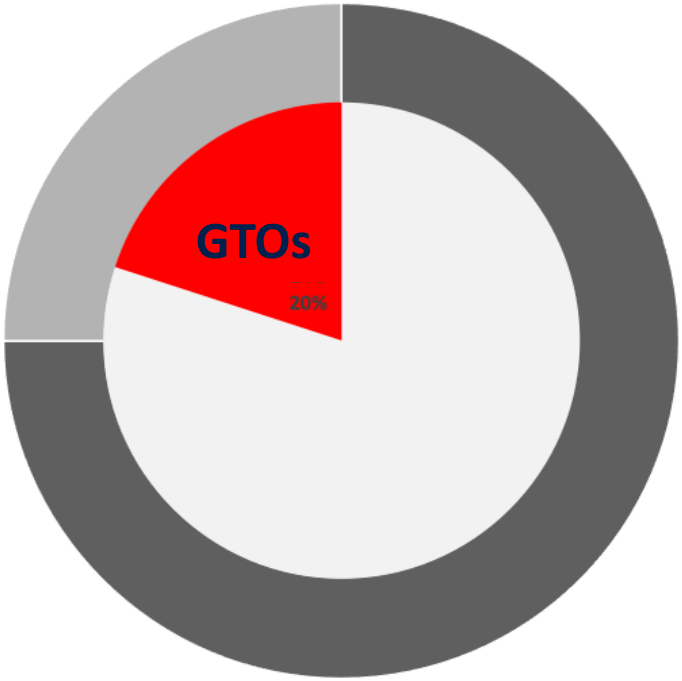
Guaranteed Time Observations (GTOs)

- GTOs: a fraction of the observing bime arising from contractual obligations of CTAO ERIC.
  - from Hosting Agreements with IAC and ESO

CTAO Northern array



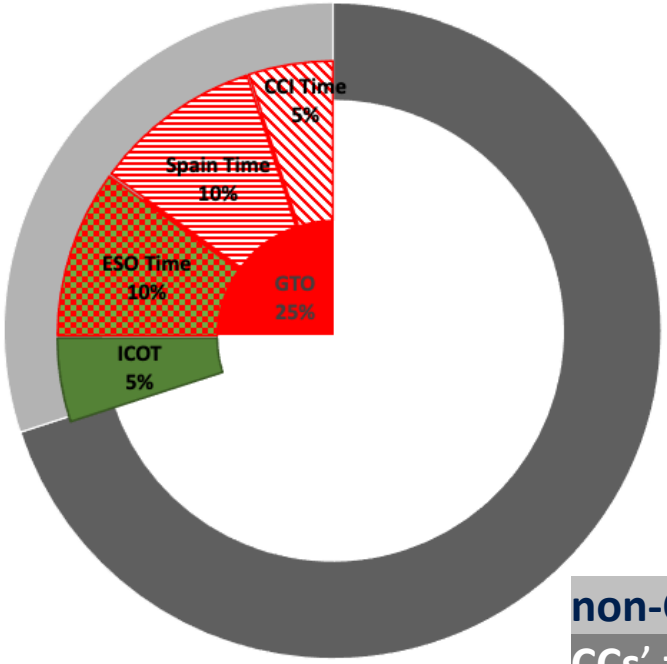
CTAO Southern array



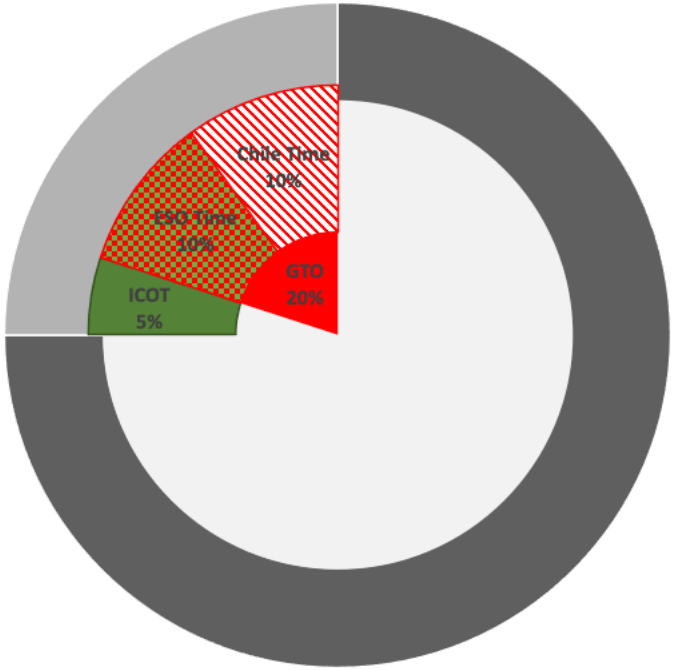
International Community Observing Time

- **International Community Observing Time (ICOT)** is a small fraction of the observing time that is available by meritorious proposals by researchers of non-contributing-countries, and shall be approved by the CTAO ERIC Council.
  - The 5% in the pie chart TBD

CTAO Northern array



CTAO Southern array

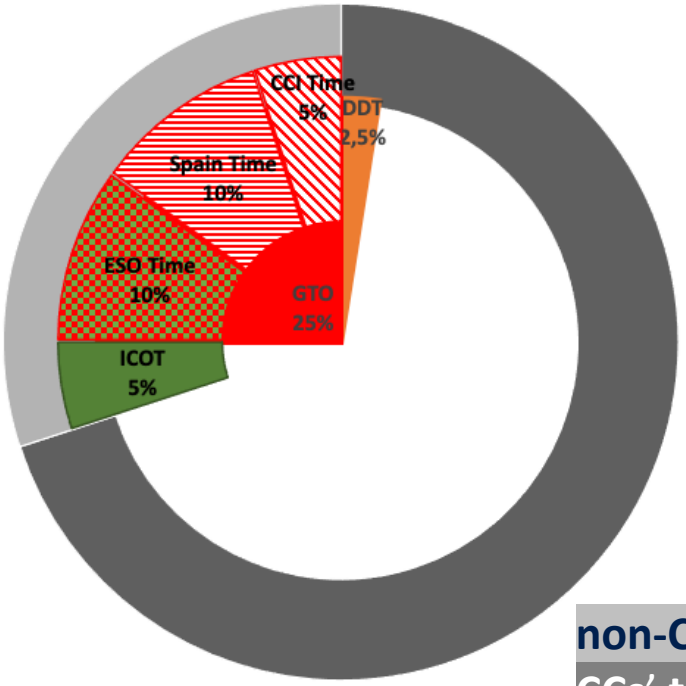


non-CC's time
CCs' time

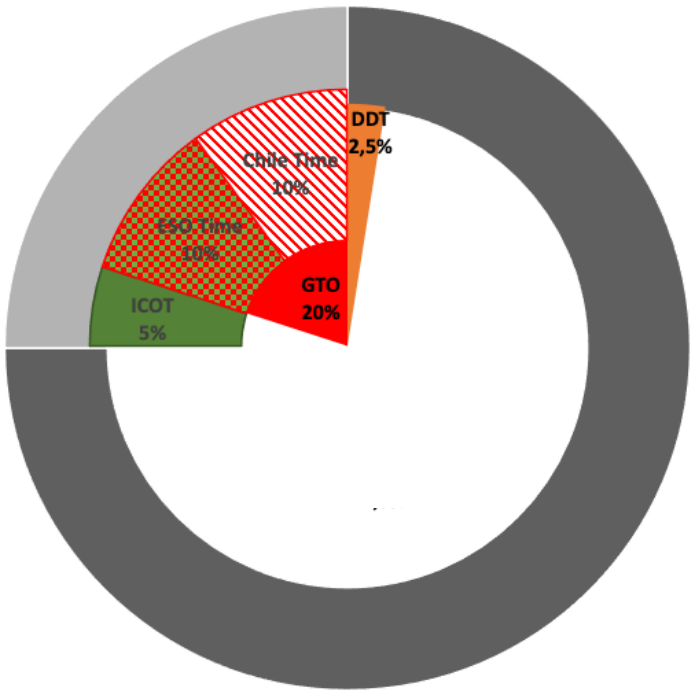
Contributing Countries (CCs)' Time

- CCs' Time is split into 2 categories depending on the type of proposal: **KSP time and Open CCs' Time**
- **the fraction of KSP time versus Open CCs' time is still an open point**
- **KSP time is given to one unique scientific collaboration as reward for in-kind contributions to the CTAO construction project**

CTAO Northern Array



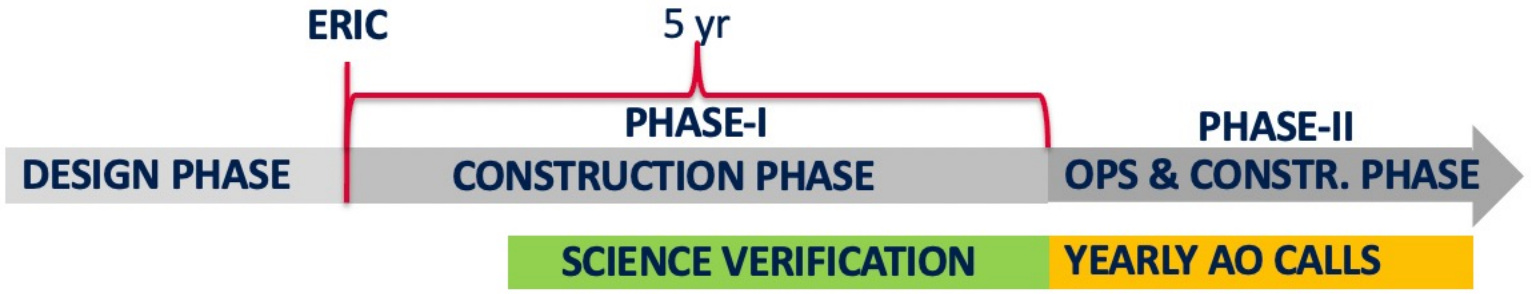
CTAO Southern Array



non-CC's time
CCs' time

CTAO construction phase

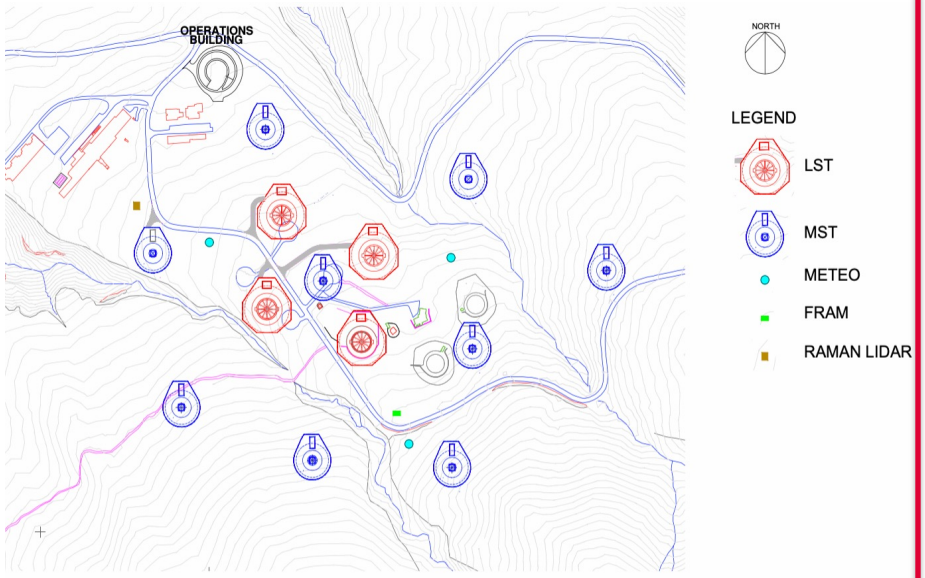
- **CTAO construction scope is agreed**
- The construction phase will start with the establishment of the final legal entity:
  CTAO European Research Infrastructure Consortium (ERIC)
  - Step 2 application submitted last week→ ERIC operative beginning 2023
  - last about 5 yr
- **Early science operations foreseen during the construction phase**



The two initial CTAO arrays: the Alpha Configuration

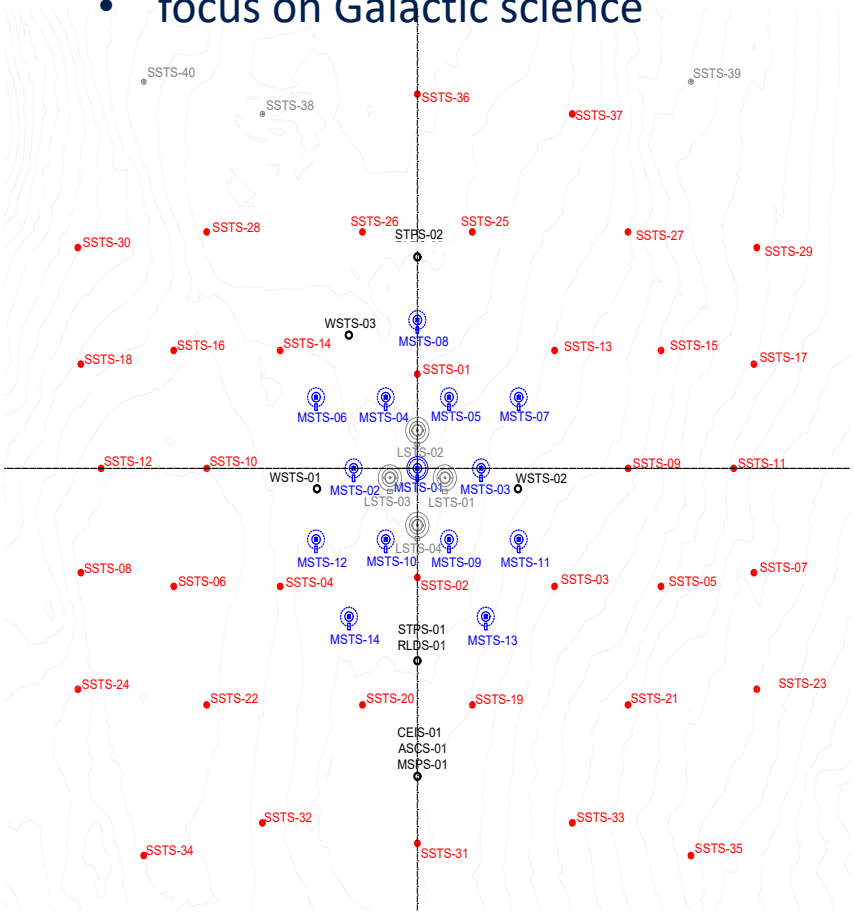
CTAO Northern Array

- **4 LSTs + 9 MSTs**
- 0,25 km^2 footprint
- focus on extra-Galactic science



CTAO Southern Array

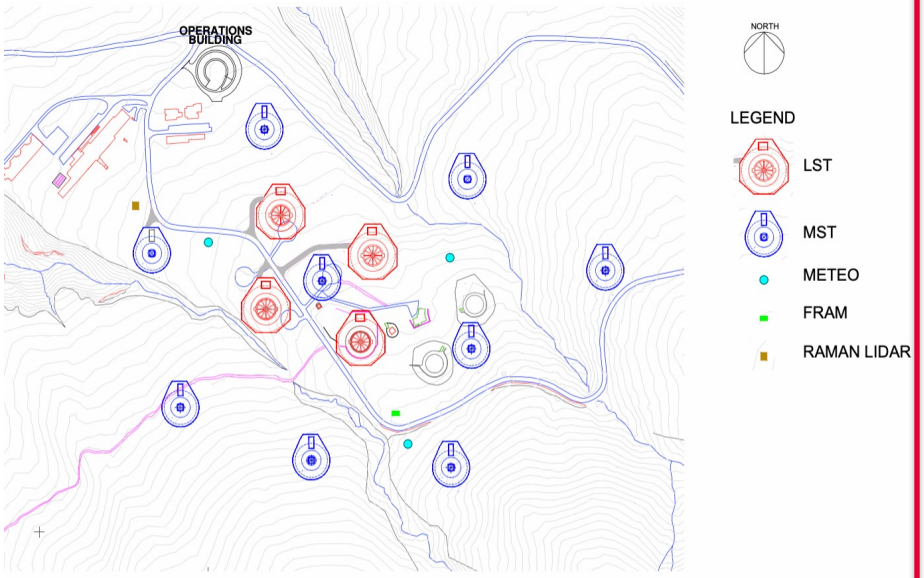
- **14 MSTs + 37 SSTs**
- 3 km^2 footprint
- focus on Galactic science



CTA+ (PNRR): the Beta Configuration

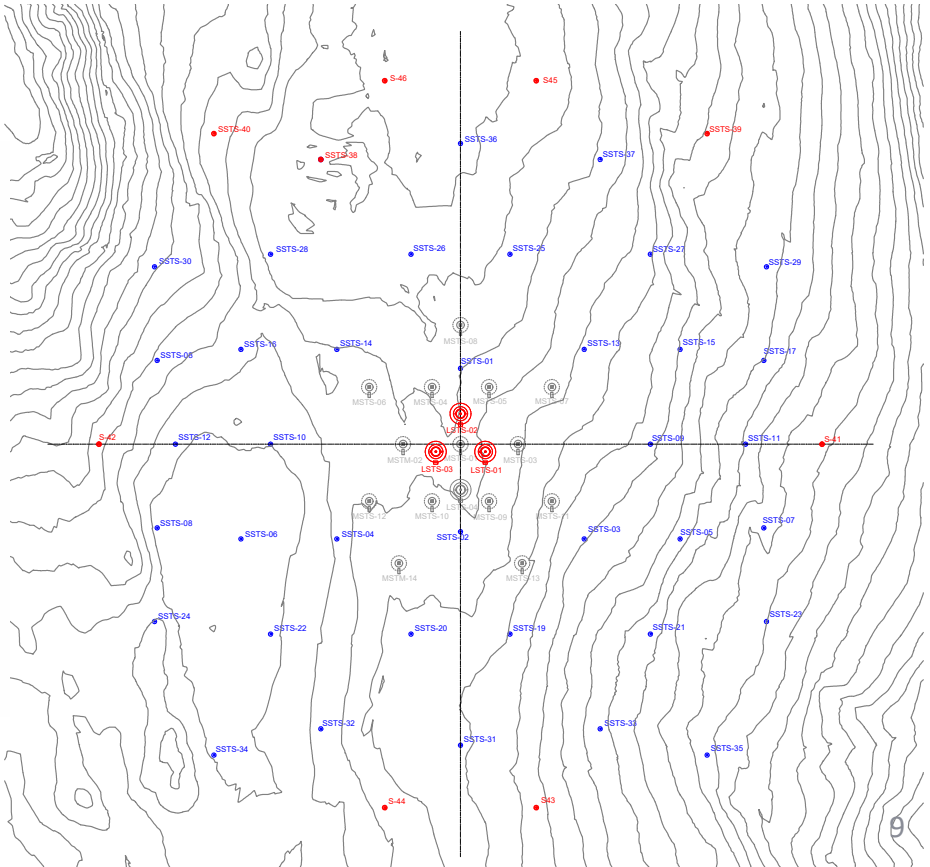
CTAO Northern Array

- **4 LSTs + 9 MSTs**
- 0,25 km^2 footprint
- focus on extra-Galactic science



CTAO Southern Array

- **2/3 LSTs + 14 MSTs + 46 SSTs**
- 3 km^2 footprint
- focus on Galactic science



CTA+ (PNRR): training Italian scientific community

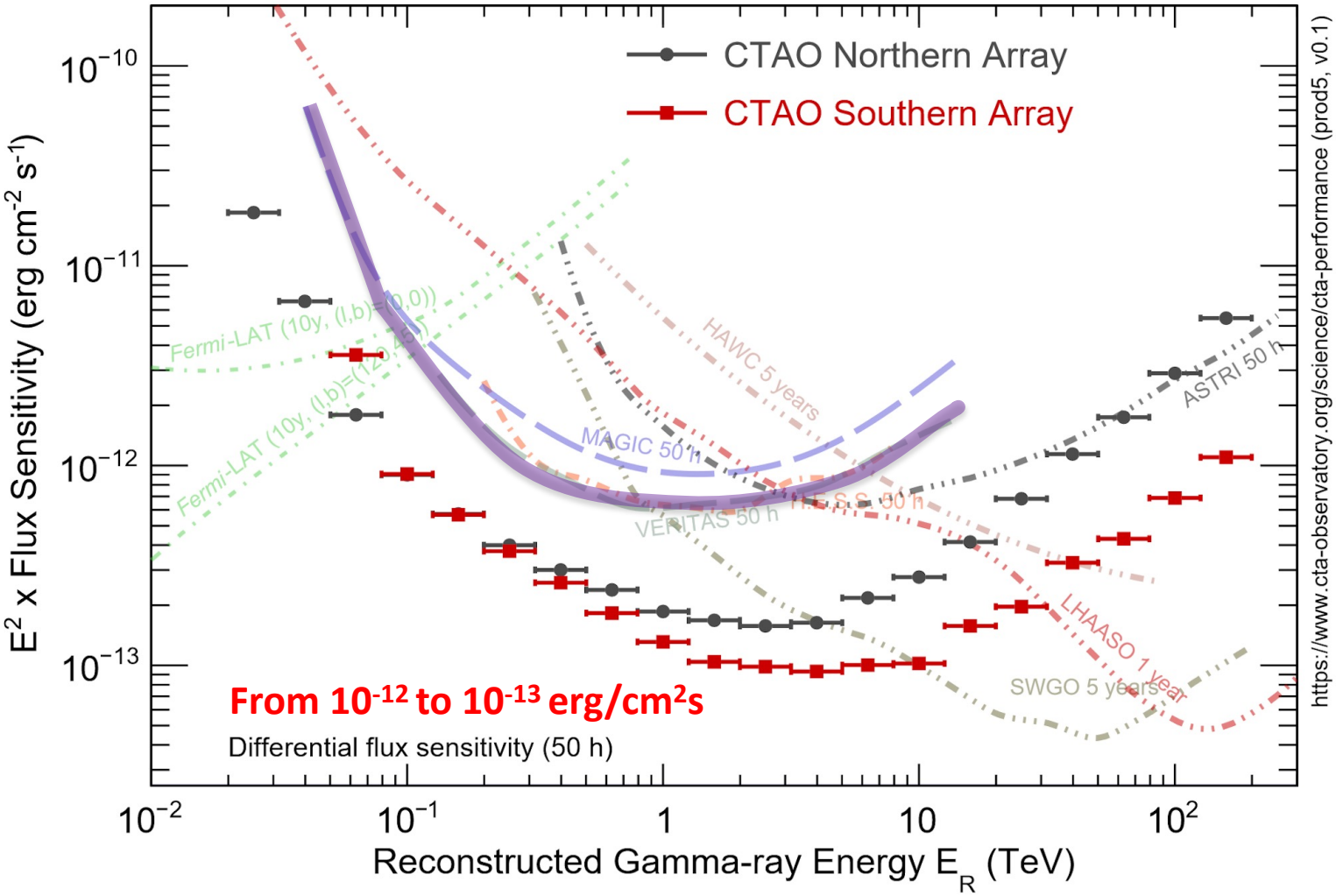
- training young generation of scientists
  - International PhD school on gamma-ray astronomy
  - ~ about 10* new PhD students on gamma-ray astronomy around Italy
  - Italian network of PhD students on gamma-ray astronomy
- boost scientific enviromenet around the HQs in Bologna
  - 1 RTD-A* at UniBO + 4* postdocs
  - Specific course on gamma-ray astronomy for the master?
- support EPO programs related to gamma-ray astronomy

Right moment to get onboard!

*negotiations did not happen so far. Please take all this as preliminary (proposal-level)

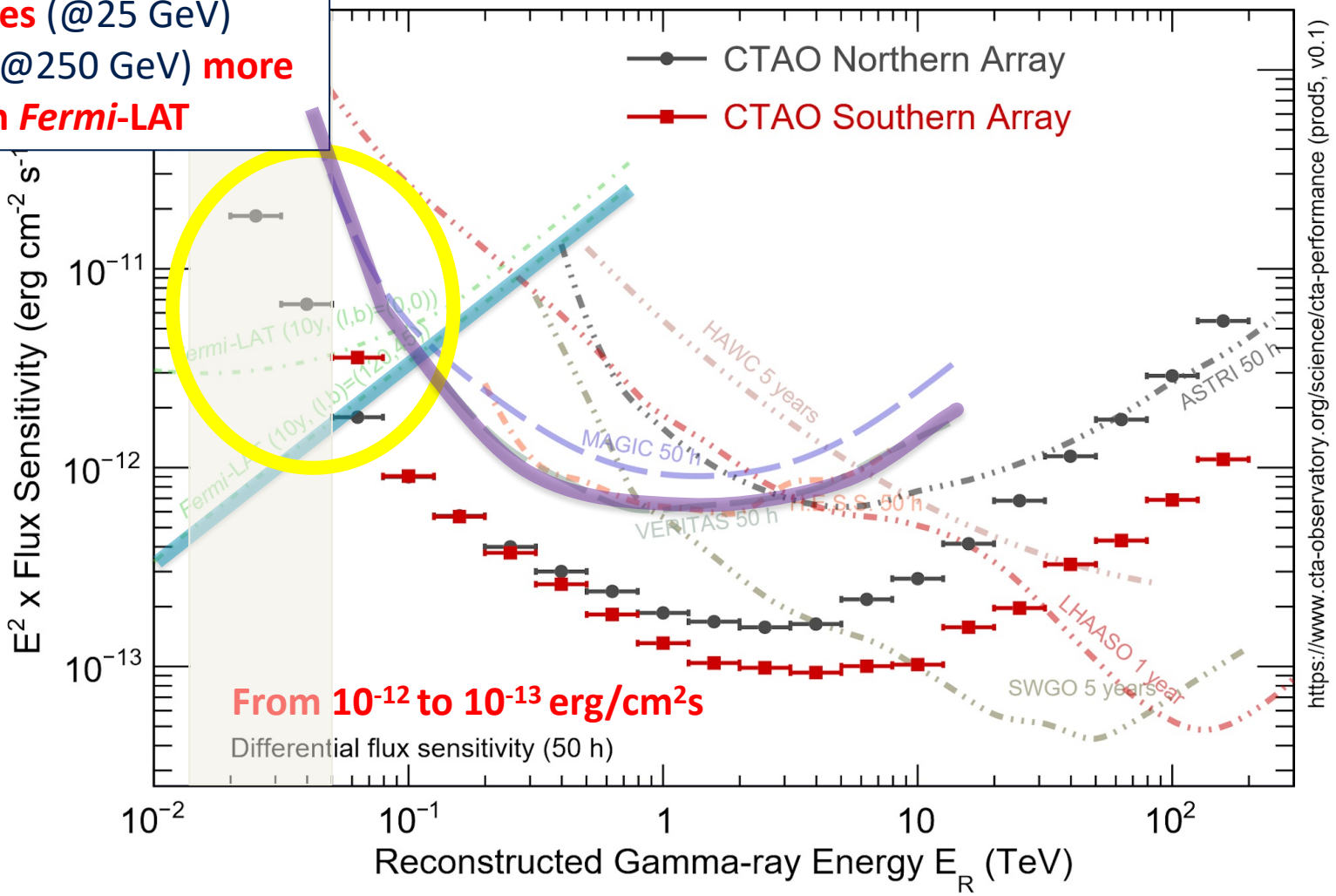
PART II
CTAO performance

CTAO performance (Alpha Configuration)

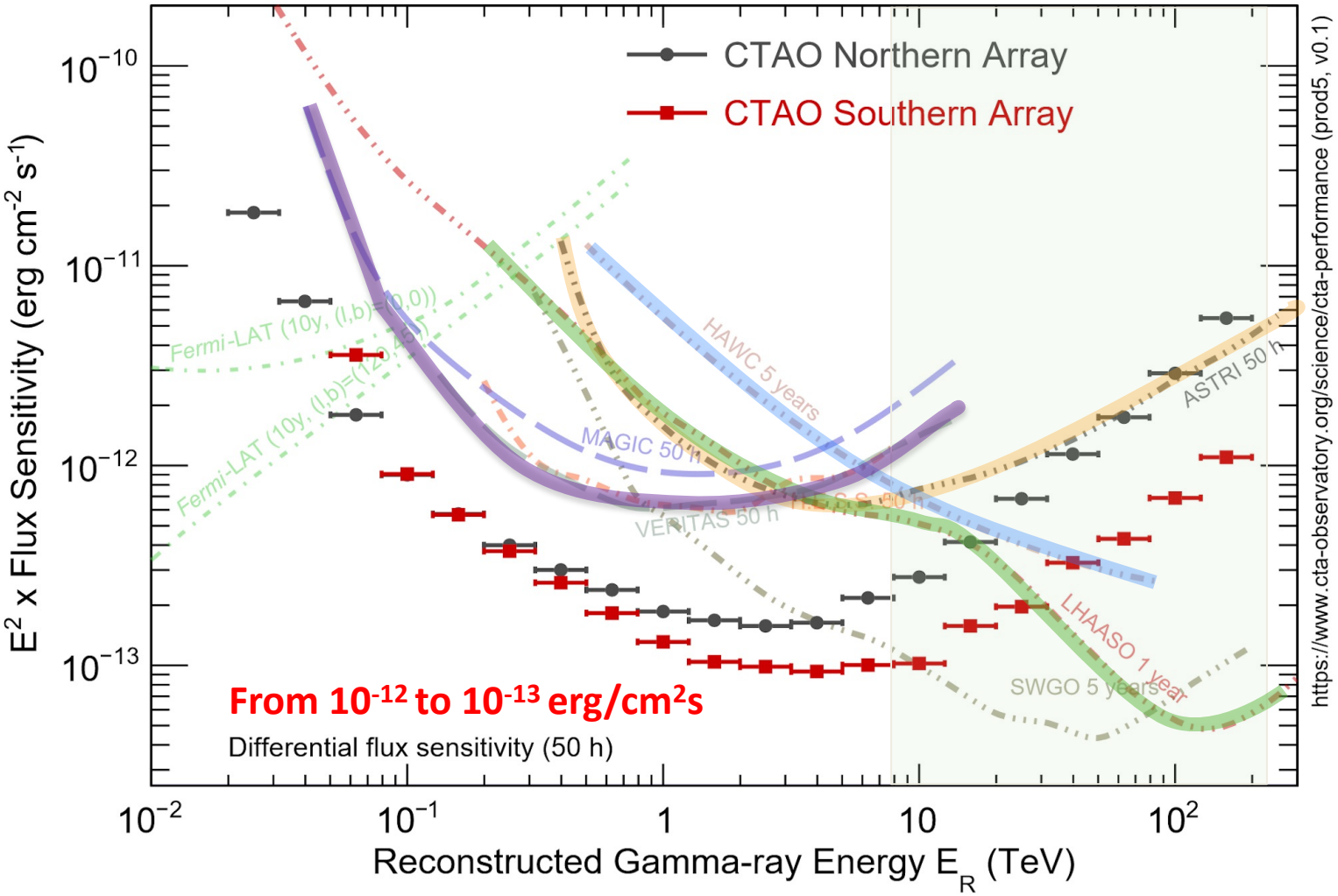


CTAO performance (Alpha Configuration)

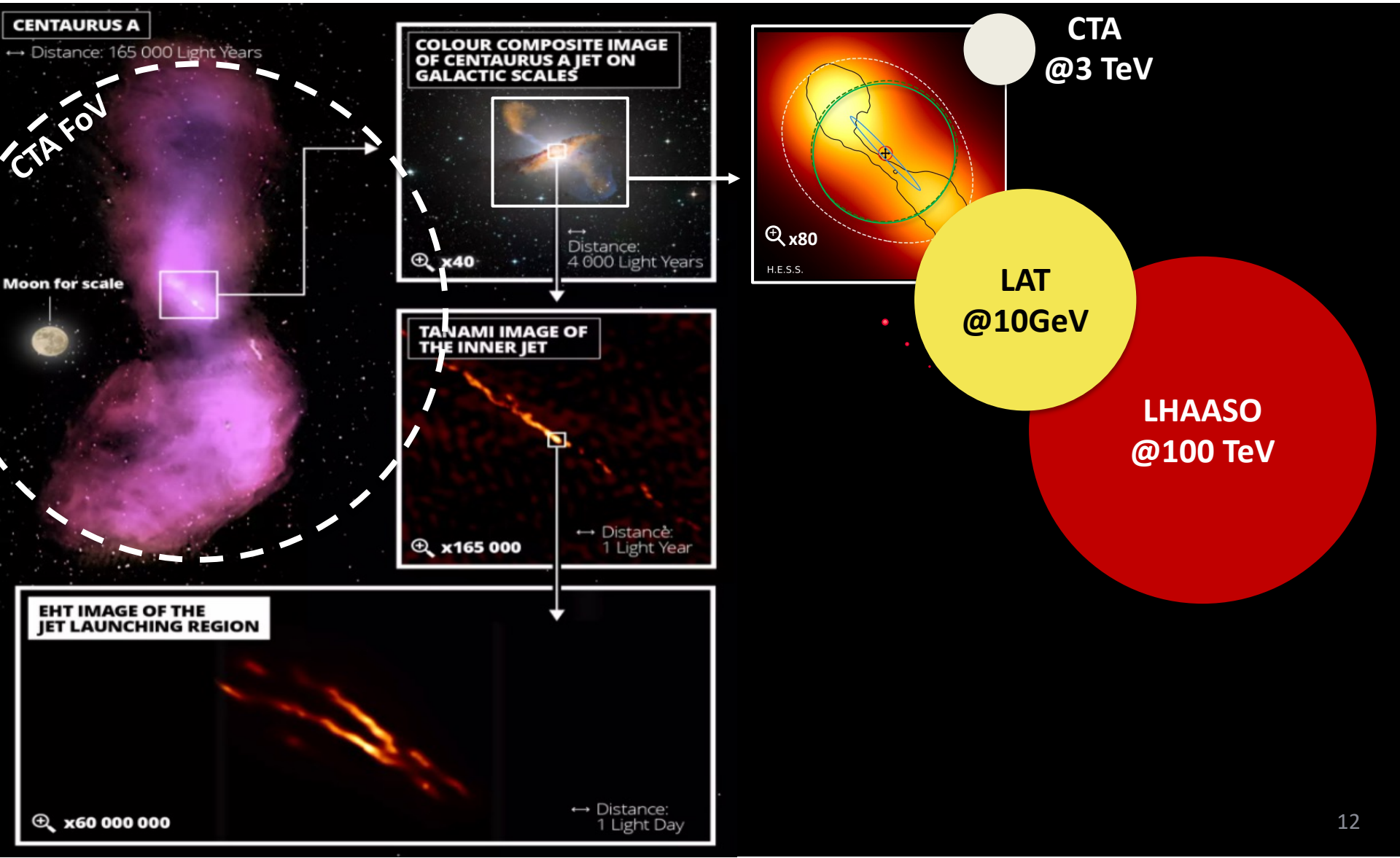
On time scales <1 h
CTA is **10^3 times** (@25 GeV)
to **10^6 times** (@250 GeV) **more sensitive than *Fermi*-LAT**



CTAO performance (Alpha Configuration)



CTAO performance (Alpha Configuration)



PART III
CTAO Science Case

CTAO main scientific themes

COSMIC PARTICLE ACCELLERATION

- How & where particles are accelerated?
- How do they propagate?
- What is their impact on the environment?

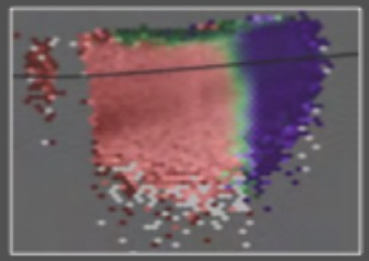
PROBING EXTREME ENVIROMENTS

- Which are the processes close to neutron stars and black holes?
- Which are the processes in relativistic jets, winds and explosions
- What are the cosmic voids?

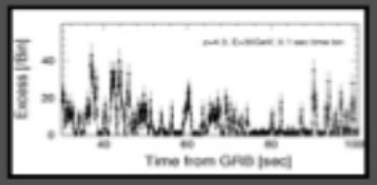
PHYSICS FRONTIERS - BEYOND THE STANDARD MODEL

- What's the nature of the dark matter? How is it distributed?
- Do axion-like particles exist?
- Is the speed of light a constant for high-energy photons?

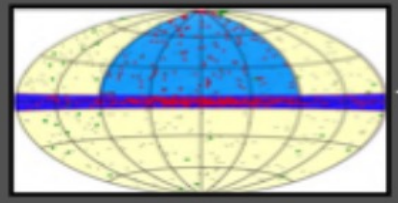
CTAO Science Program



Dark Matter Programme



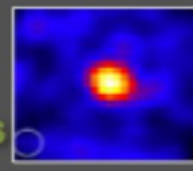
Transients



ExGal Survey

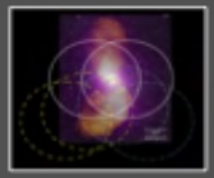
Extragalactic

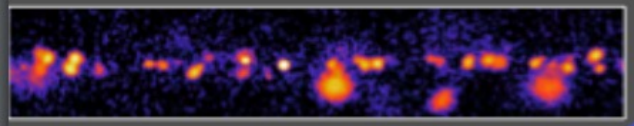
Galaxy Clusters



Star Forming Systems

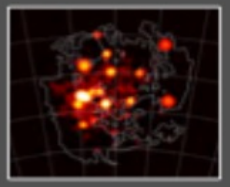
AGN





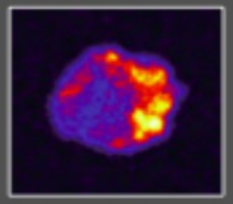
Galactic

LMC Survey

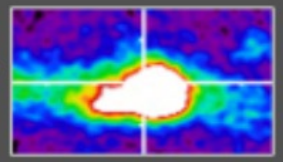


Galactic Plane Survey

PeVatrons



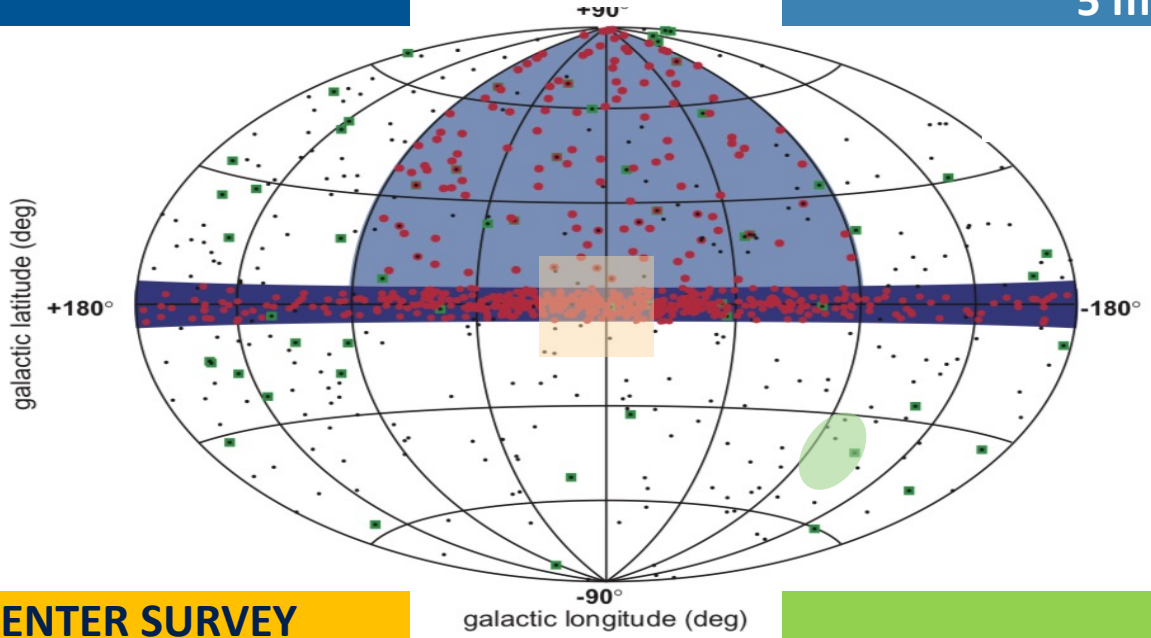
Galactic Centre Survey



CTAO surveys

GALACTIC PLANE SURVEY
not uniform sensitivity across the plane 2-4 mCrab
pilot survey: first results after ~1 yr

EXTRAGALACTIC SURVEY
unbiased survey of VHE sky → huge discovery space
25% of the sky
5 mCrab



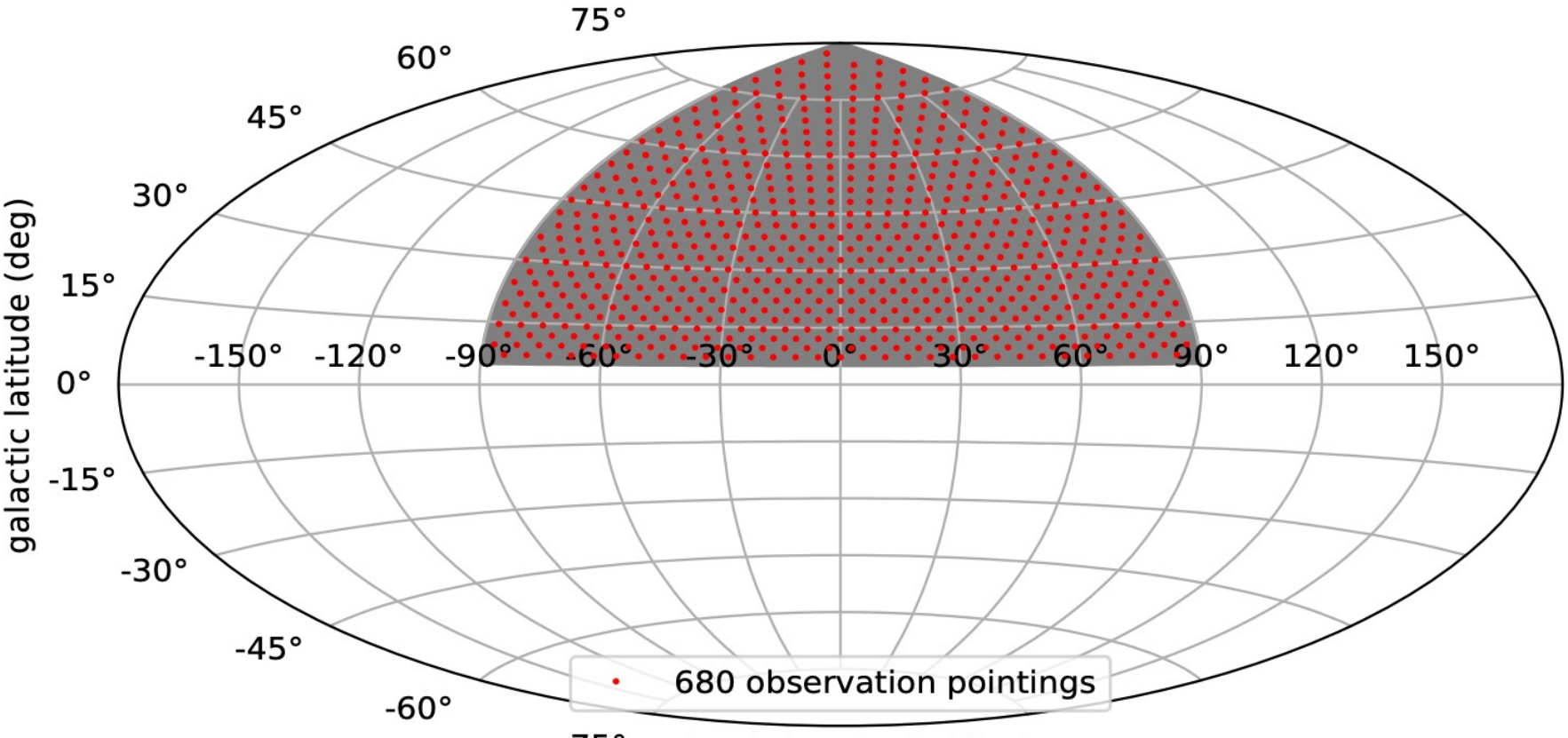
GALACTIC CENTER SURVEY
deeper observations around the GC
10◦ x 10◦
2 mCrab

LARGE MAGELLANIC CLOUD SURVEY
1.5-2 mCrab

Extragalactic survey

see talk by Patrizia

- Original idea:
  - 25% sky coverage: b> 5 ° & |l|<90°
  - targeted integral sensitivity 6 mCrab
  - pointing direction uniformly distributed on a grid of 3.7° separation
    60% by the Southern array and 40% by the Northern array



Extragalactic survey

see talk by Patrizia

- Defining the BL LAC luminosity function

  (Ajello, M., et al. 2014, ApJ, 780, 73)

  - Luminosity function:

$$\Phi(L_\gamma, z=0, \Gamma) = \frac{A}{\ln(10) L_\gamma} \left[\left(\frac{L_\gamma}{L_*} \right)^{\gamma_1} + \left(\frac{L_\gamma}{L_*} \right)^{\gamma_2} \right]^{-1} e^{-0.5[\Gamma - \mu(L_\gamma)]^2/\sigma^2}$$

  - Luminosity-Dependent Density Evolution (LDDE):

$$\Phi(L_\gamma, z, \Gamma) = \Phi(L_\gamma, z=0, \Gamma) \times e(z, L_\gamma)$$

$$e(z, L_\gamma) = \left[\left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{-p_1(L_\gamma)} + \left(\frac{1+z}{1+z_c(L_\gamma)} \right)^{-p_2(L_\gamma)} \right]^{-1}$$

  - Pure Luminosity Evolution (PLE):

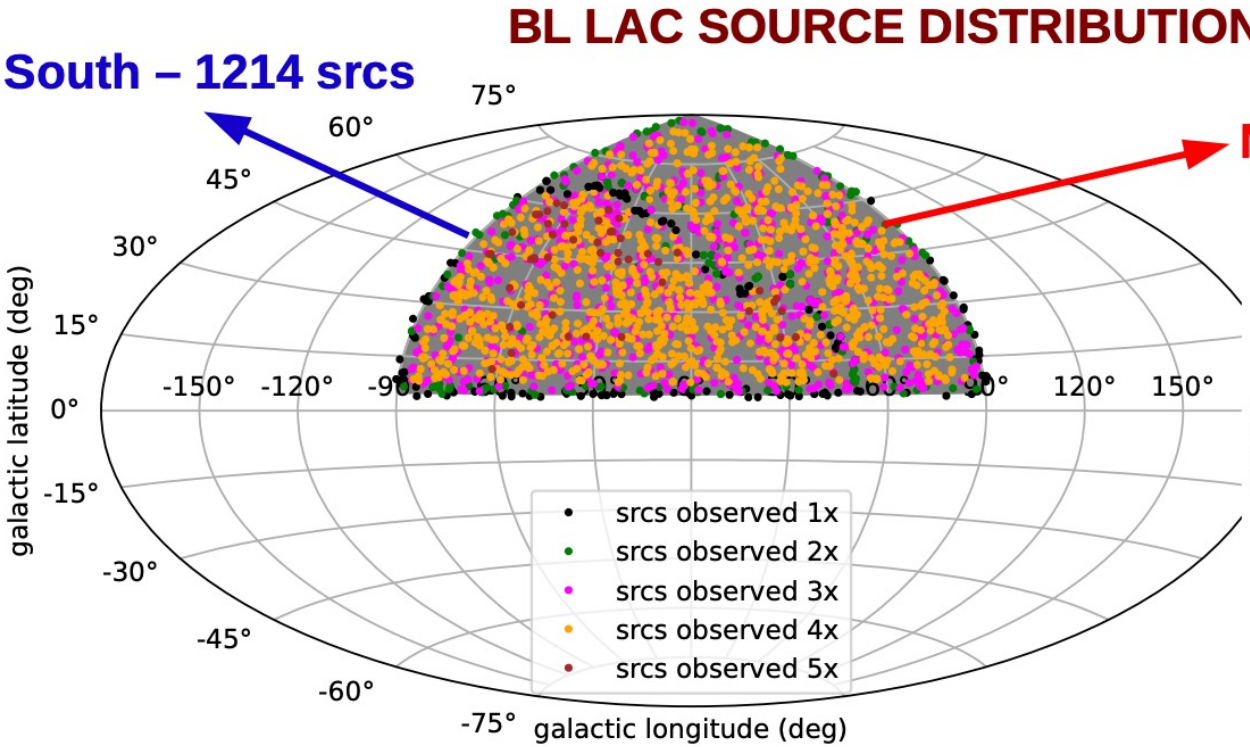
$$\Phi(L_\gamma, z, \Gamma) = \Phi(L_\gamma / e(z), \Gamma).$$

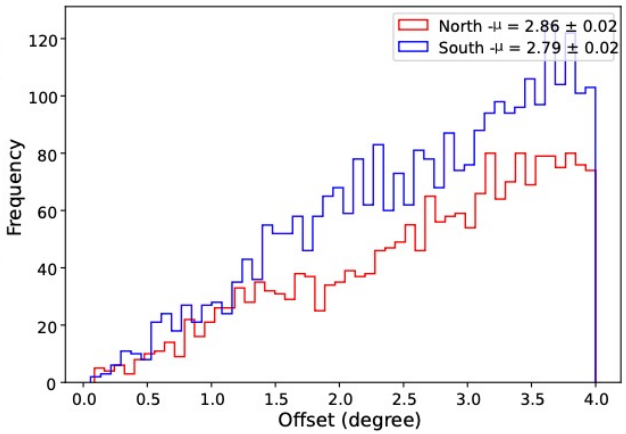
$$e(z) = (1+z)^{k_d} e^{z/\xi}, \longrightarrow k_d = k^* + \tau \times (\log_{10}(L_\gamma) - 46).$$

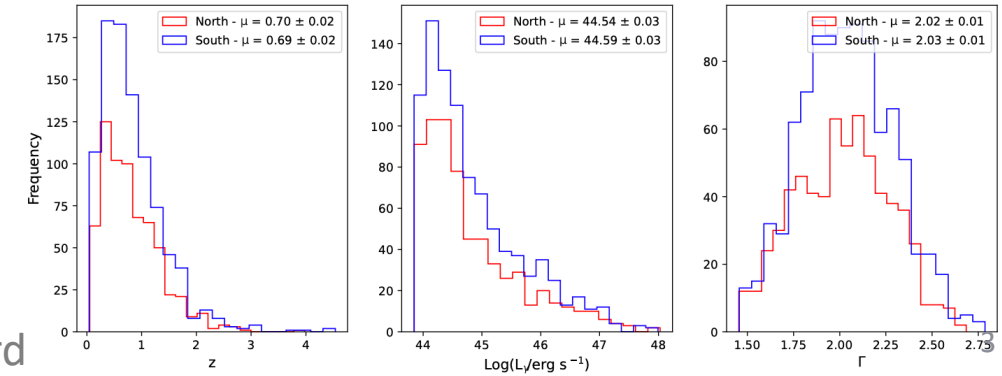
Credits to L.A. Pereira, V. de Souza, E. Lindford, T. Hassan

Extragalactic survey

see talk by Patrizia







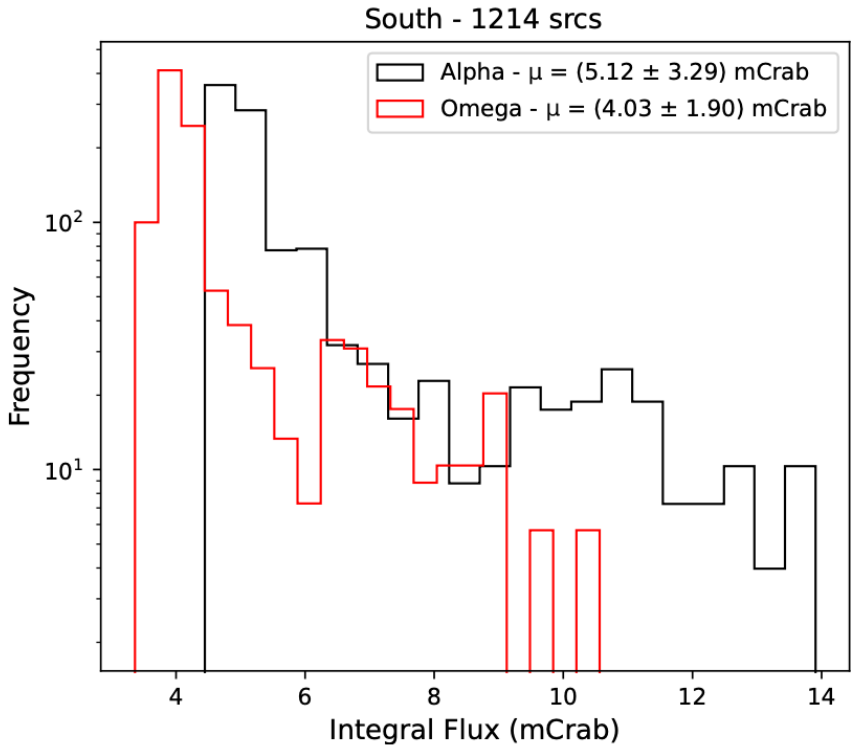
Credits to L.A. Pereira, V. de Souza, E. Lindford

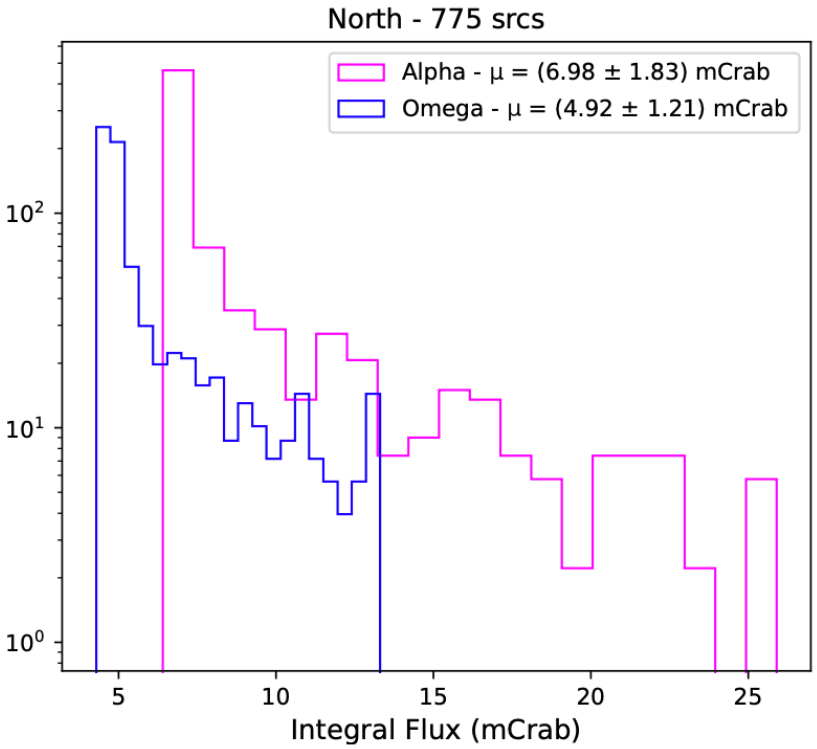
Extragalactic survey

see talk by Patrizia

INTEGRAL SENSITIVITY DISTRIBUTION

1mCrab = 5.08 x 10^{-13} cm^{-2} s^{-1} (E > 125 GeV)



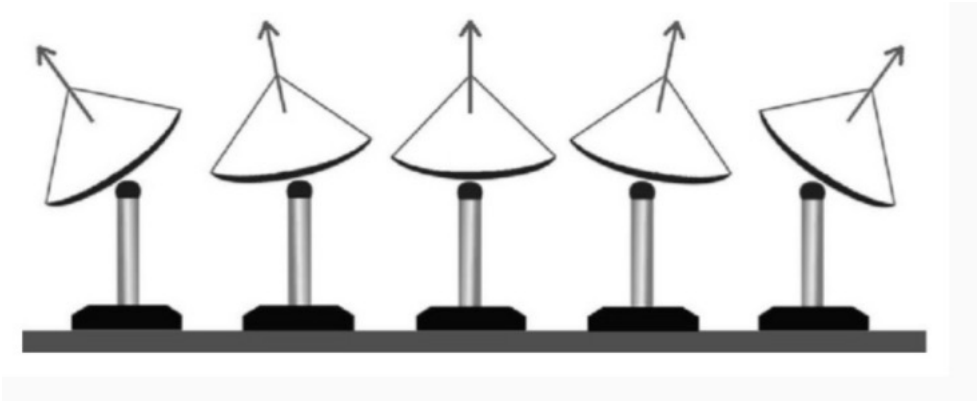


Credits to L.A. Pereira, V. de Souza, E. Lindford, T. Hassan

Extragalactic survey

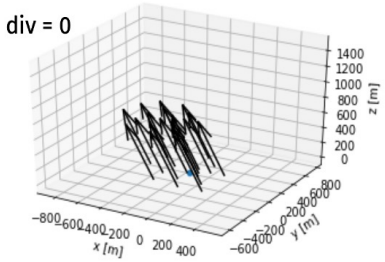
Personal considerations:

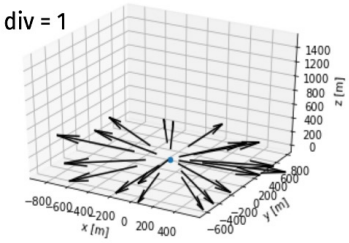
- Excellent work to reproduce the original assumptions with latest IRFs and SATs
  - now beta configuration needs to be considered
  - LST performance in the current IRFs a bit too optimistic
- Is there margin for observation strategy optimization?
  - North vs South
  - 25% sky coverage versus sensitivity
  - check overlap with the GC center survey
- How can we fit the divergent array pointing mode?

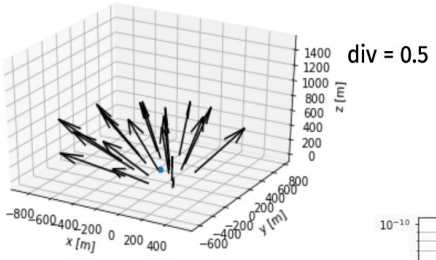


Divergent array pointing mode

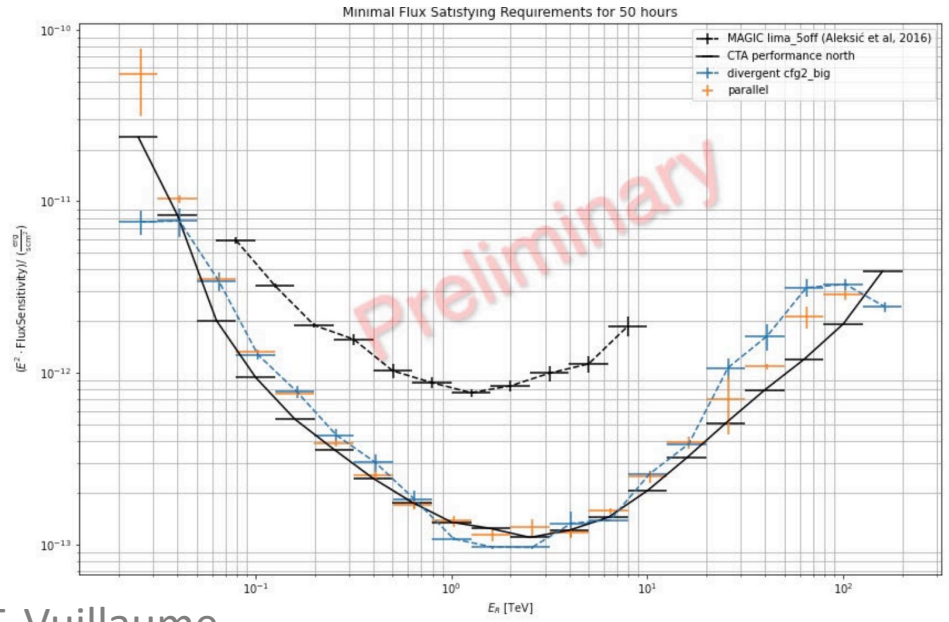
The "umbrella" mode
= 1 parameter to parametrize the divergent pointing







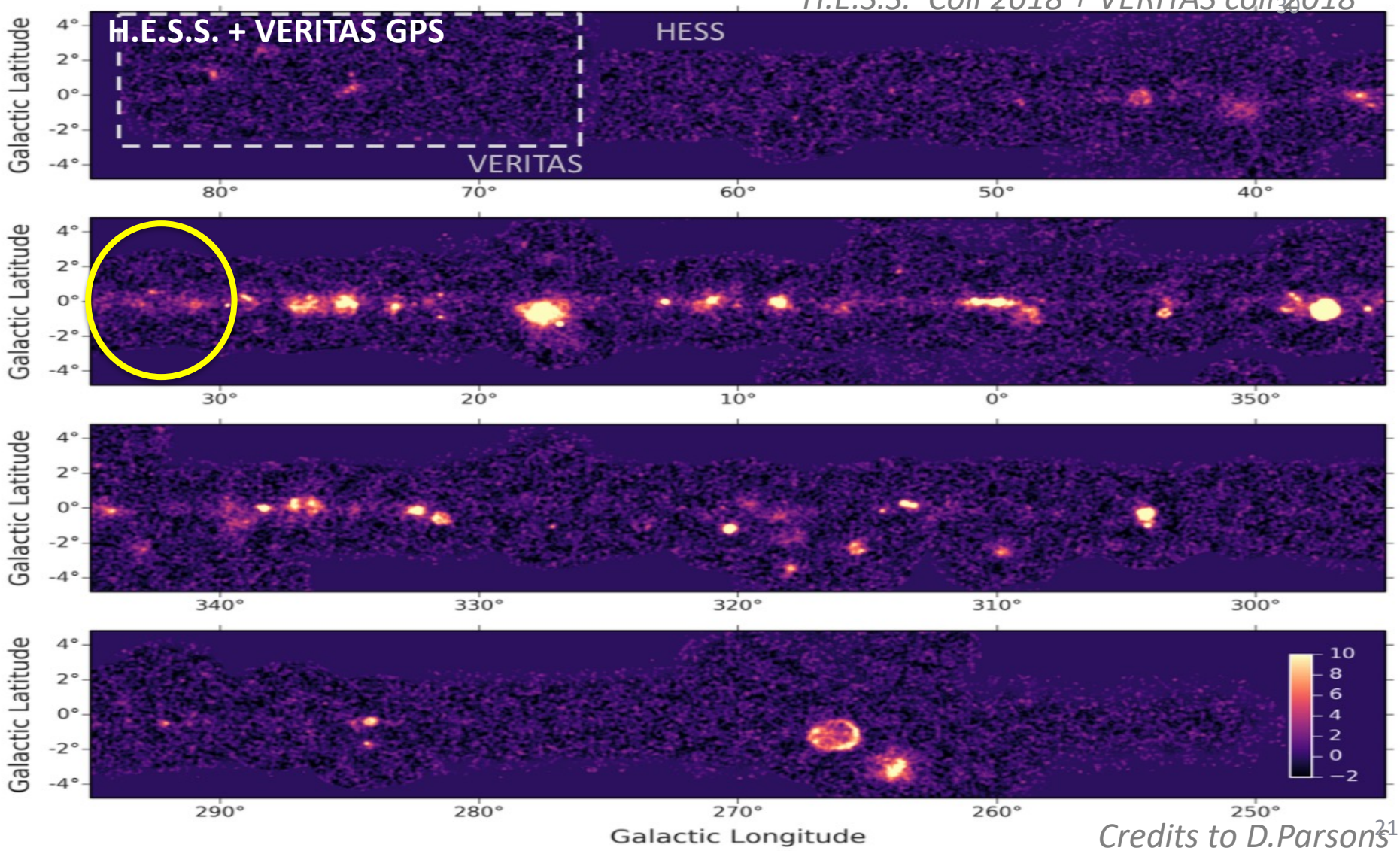
	parallel	cfg1.5	cfg2	cfg3	cfg4	cfg5
HFoV (deg^2)	46.5	69.62	93.70	140.3	186.37	233
Overall average multiplicity	16.25	10.85	8.06	5.38	4.05	3.24
MSTs average multiplicity	15	10.02	7.44	4.97	3.74	3
LSTs average multiplicity	4	3.41	2.98	2.41	2.05	1.8
LSTs HFoV (deg^2)	14.5	17	19.47	24.04	28.32	32.38



Credits to A. Domini, I. Burelli, F. Longo, T. Vuillaume

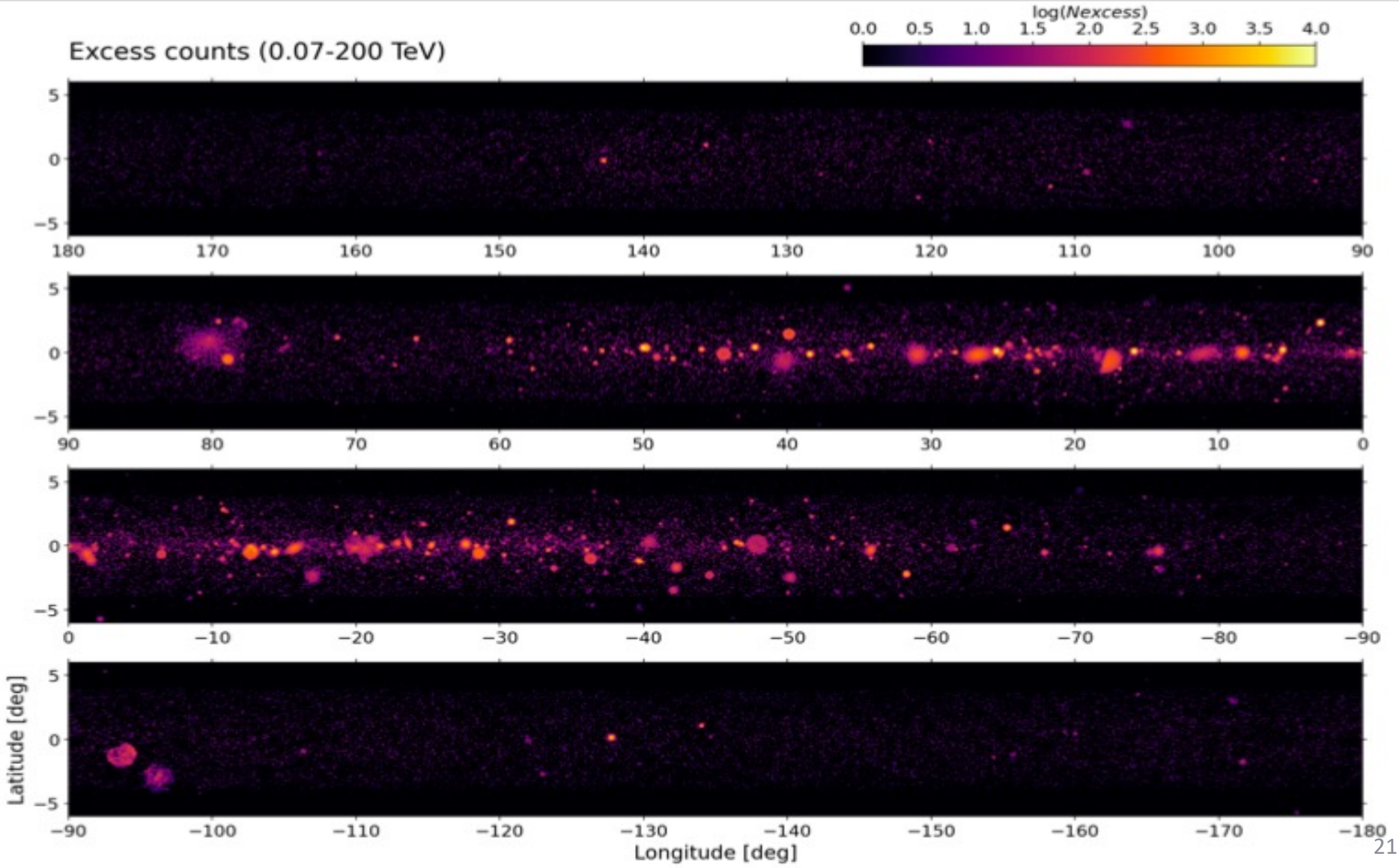
Galactic plane survey

H.E.S.S. Coll 2018 + VERITAS coll 2018



Credits to D.Parsons

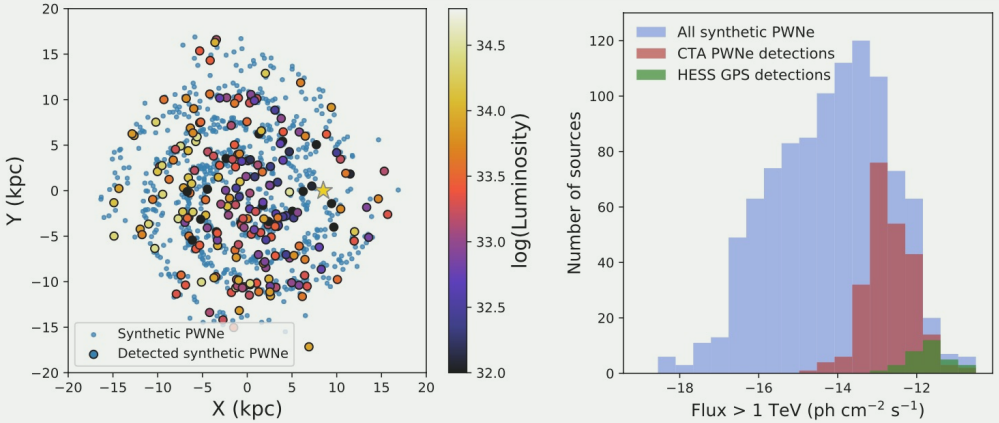
Galactic Plane Survey



Source population studies

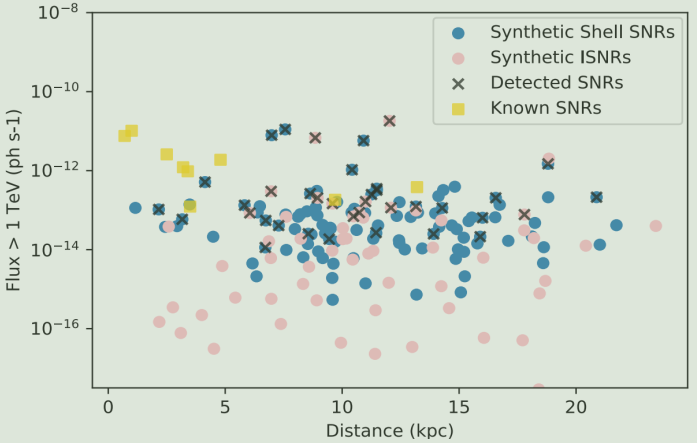
see talk by Barbara

PWNe



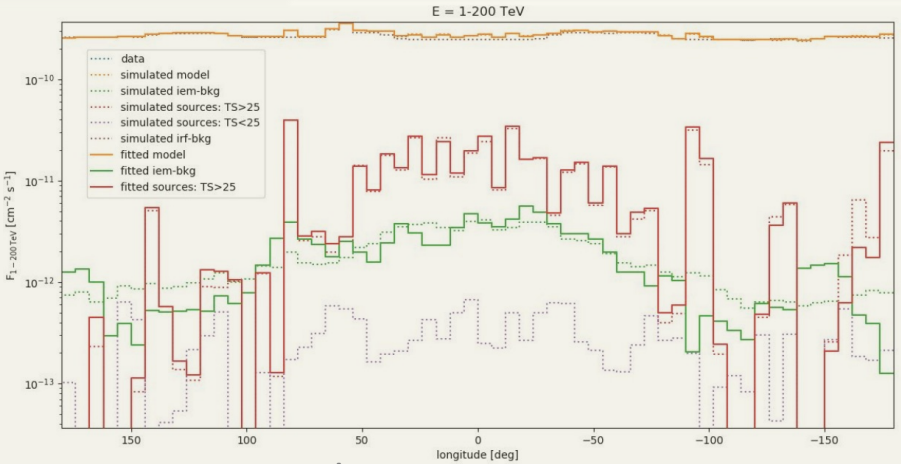
- transformational jump in population size to the PWNe field

SNRs



- SNRs up to other side of the Galaxy
- 5-10 times better flux sensitivity

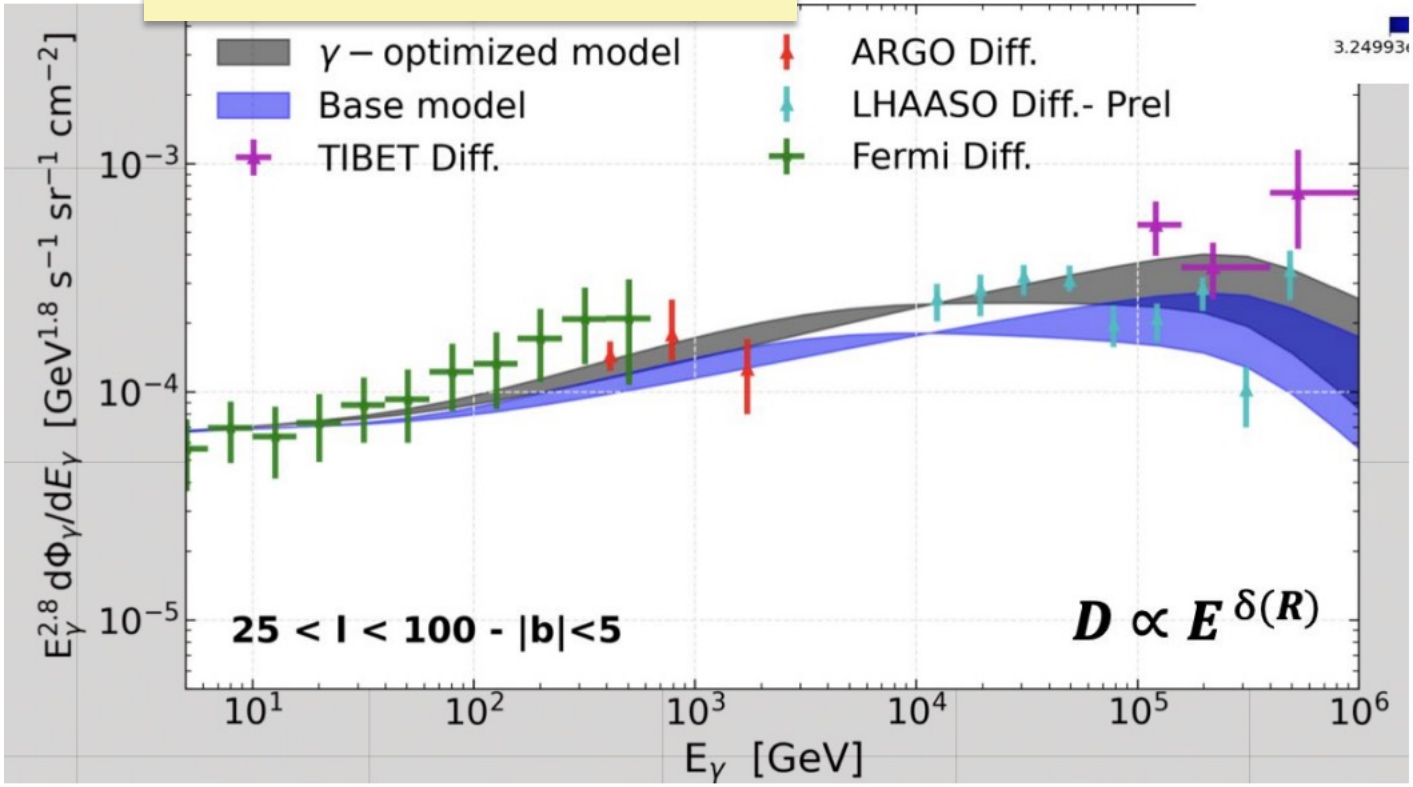
- fundamental a good understanding of the interstellar emission model



Credits to B. Olmi, F. Acero, L. Tibaldo, Q. Remy, … CTAC Galactic WG

CR propagation

see talk by Barbara

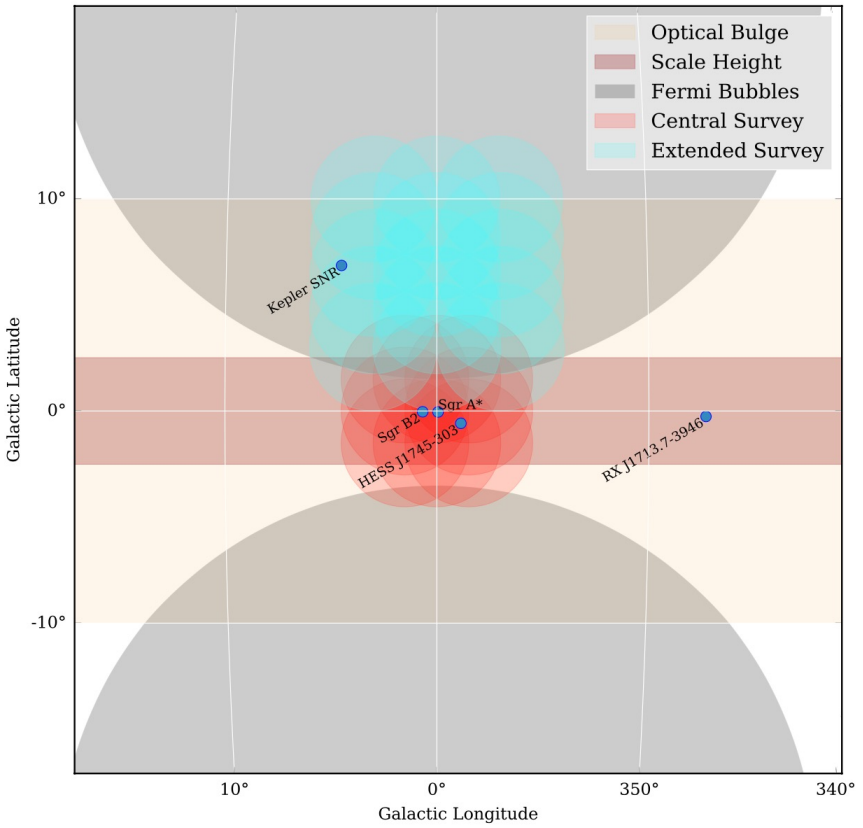


- Recent theoretical developments in interstellar emission modelling informed by LHAASO, Tibet as preparatory work for the study of CR propagation
  - the CTA range is crucial
  - better understanding of unresolved source is required

Credits to P. de la torre Luque, D. Gaggero, G. Morlino, … CTAC CR WG

Galactic Centre survey

- galactic centre region in terms of simulations is treated as any other part of the Galaxy!
- quite some margin for observational strategy optimization



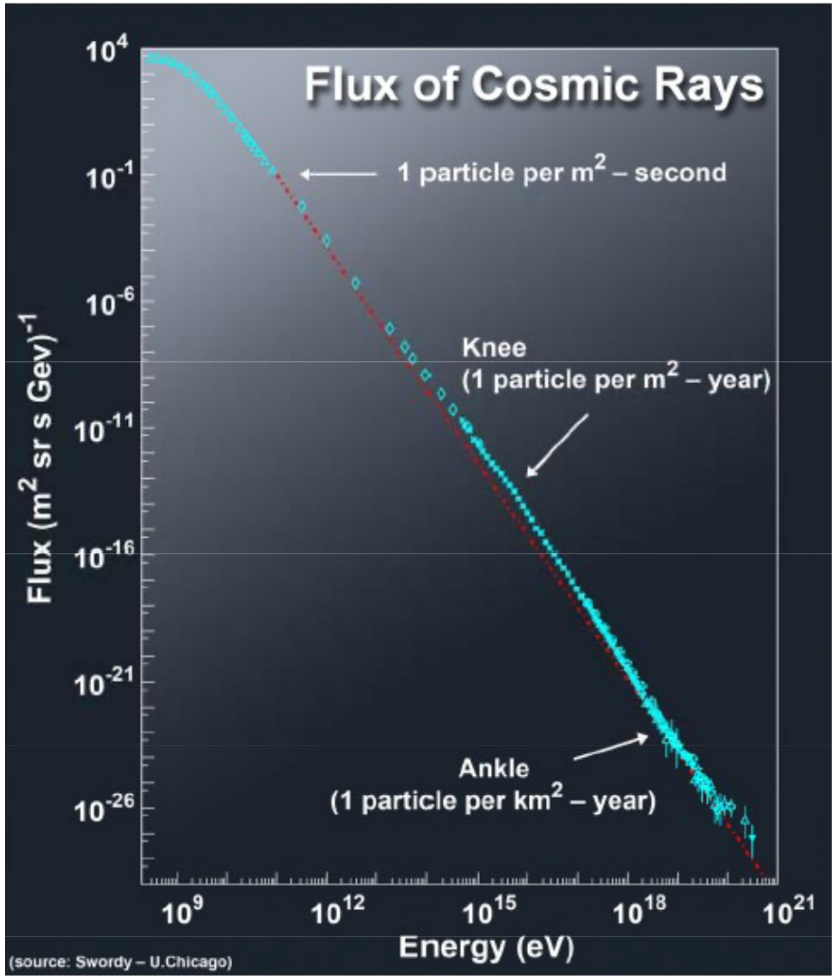
the Italian community has a huge expertise in GC survey at lower frequencies

see talk Angela & Raffaella

PeVatrons searches

see talk by Barbara

Q: What sources accelerate hadrons up to the knee?

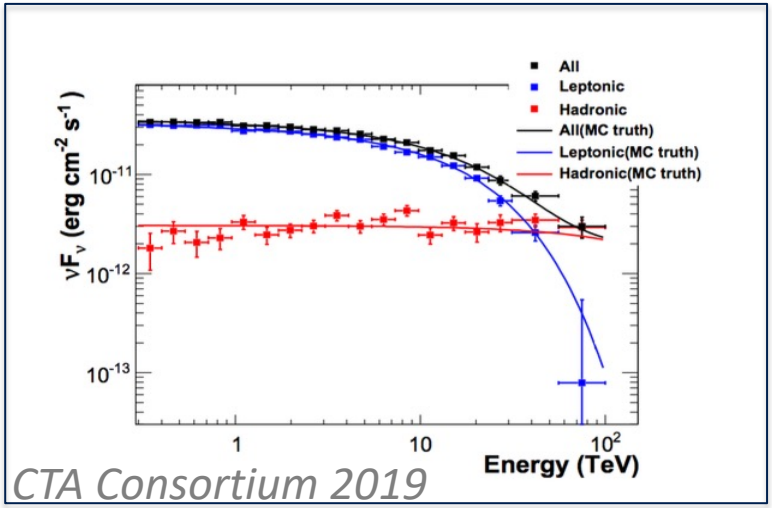


- CR origin: ~100 yr mystery!
- Standard picture: shock-acceleration in SNRs – satisfies power & spectrum
- BUT only few SNRs provide good evidence for hadronic acceleration & only up to <100 TeV

PeVatrons searches

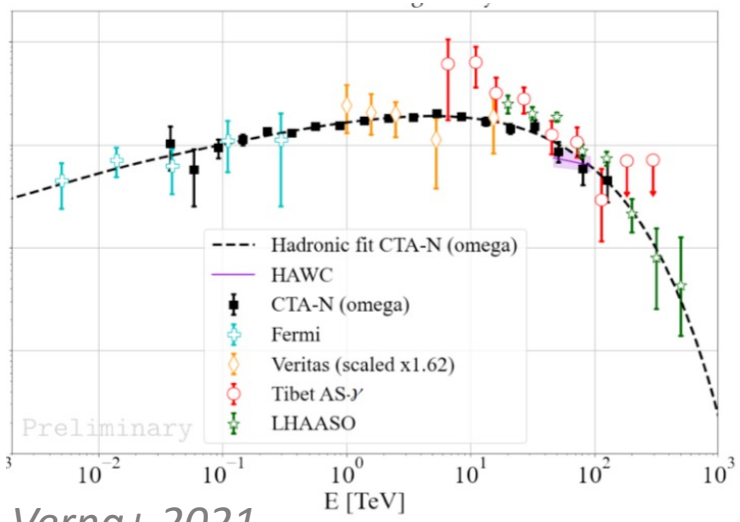
see talk by Barbara

- Search for gamma-ray sources with spectral cutoff of at least 50 GeV
  - Candidate selection on GPS results (10h exposure) based on the lower limit of spectral cutoff



CTA Consortium 2019

TEST CASE: G106.3+2.7



Verna+ 2021

- Spectral measurements may not be enough to disentangle between hadronic and leptonic origin
- morphological studies will provide important clues given the CTAO's excellent angular resolution

Transients in the multi-messanger era

GRBs

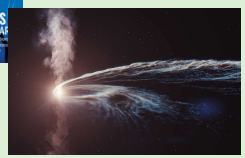
Q: How do the prompt and afterglow dynamics work?

GW COUNTERPARTS

Q: What's the link between the progenitor event and the emerging GRB?

UHE NEUTRINOS COUNTERPARTS

Q: What's the origin of the TeV-PeV cosmic neutrinos?



Tidal Disruption Event - Stein+ 2021

NOVAE

Q: Is there a population of VHE novae?

RS Oph - H.E.S.S. Coll. ATEL #14844

GW - GRB - UHE ν follow-up observations

simulation of source population based on open-source theoretical codes

- GRB → POSyTIVE *(Bernardini+2019)*
- ν source population → FIRESONG *(Tung+2021)*
  - resemble diffuse astrophysical ν flux
- NS-NS mergers → GWCOSMoS db *(Patricelli+2018)*

estimation of gamma-ray emission based on phenomenological assumptions

optimization of the CTAO observation strategy

simulation of CTAO response

Estimation of the CTAO detection rate

GW - GRB - UHE ν follow-up observations

simulation of source population based on open-source theoretical codes

- GRB → POSyTIVE *(Bernardini+2019)*
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estimation of gamma-ray emission based on phenomenological assumptions

optimization of the CTAO observation strategy

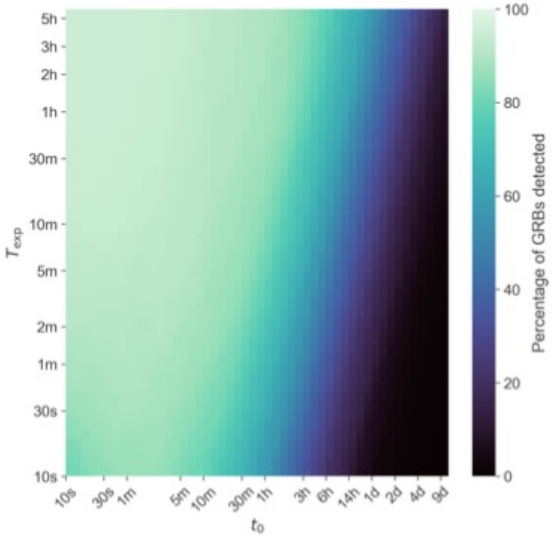
simulation of CTAO response

Estimation of the CT detection rate

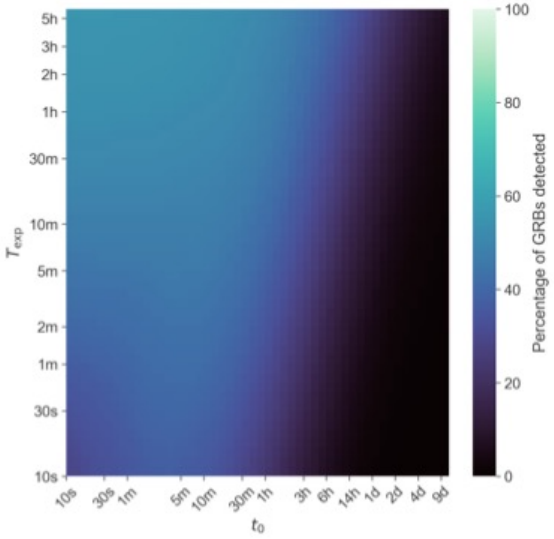
2-3 GRB per year!

GW - GRB - UHE ν follow-up observations

SHORT GRBs

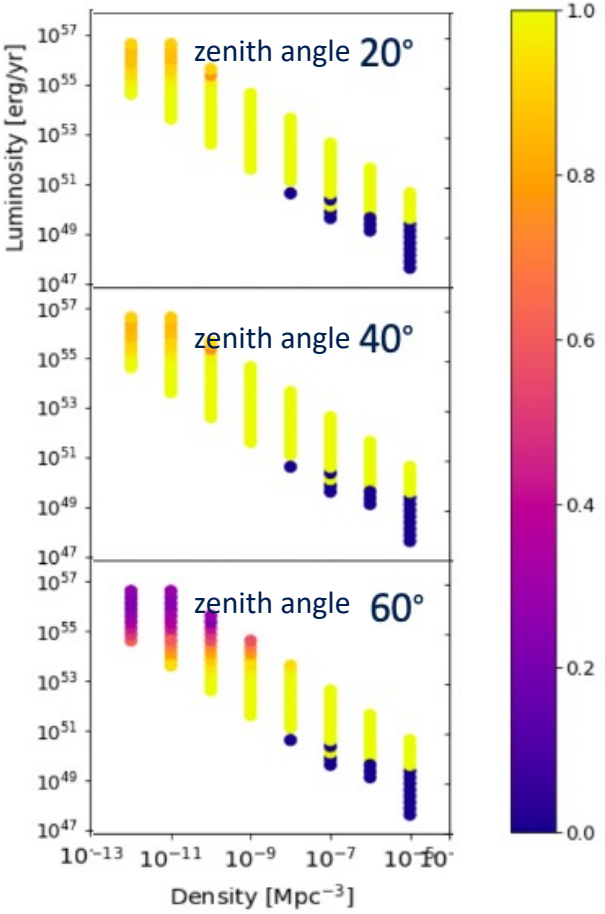


(c) CTA North, z20°, ($\theta_{view} < 10°$)



(d) CTA North, z20°, ($\theta_{view} < 45°$)

UHE ν events



very large parameter phase space

- intrinsic physical parameters ($\theta_{view,}$ Luminosity, Density)
- observational parameters

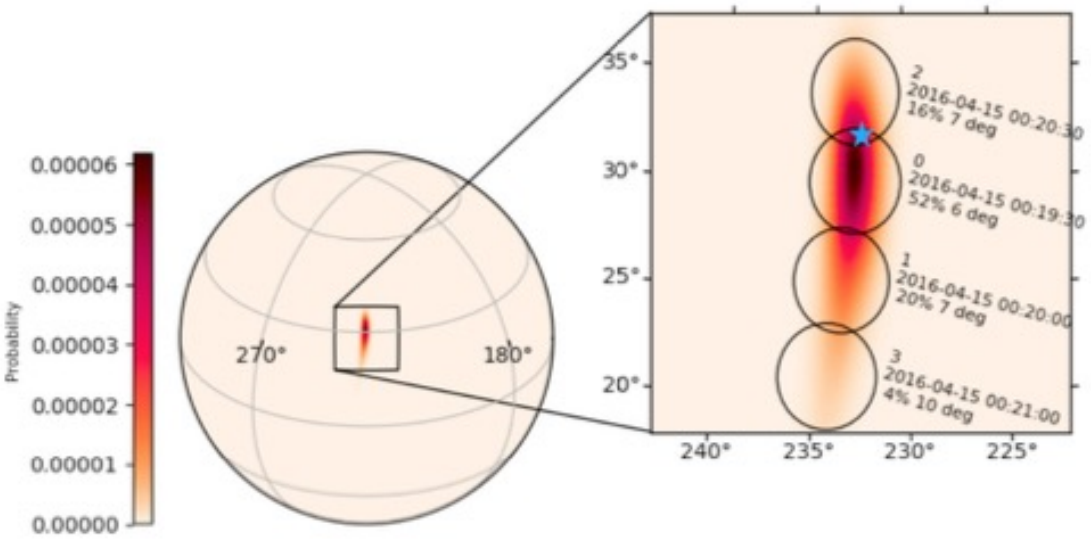
prospects for detection are very promising!

CTAO will have the opportunity to shed light on the physics behind the most extreme accelerators in the Universe

GW - GRB - UHE ν follow-up observations

- **Observational strategies: key element for the success**
  - **Optimal pointing pattern** to cover the largest total alert uncertainty region (10-100 deg^2) *(Patricelli+2018, Bartos+2019)*
  - **Optimal pointing cadence:** exposure time selected to achieve 5σ detection
  - **Site coordination** to prioritize best observational conditions (sky brightness, zenith angle, sky quality) to guarantee lowest energy threshold
  - Phenomenological considerations: galaxy density for GW events
  - **Divergent array pointing mode** to increase the FoV

see talk by Barbara, Giancarlo, Cristina, Paolo, Antonio, Paola & Eleonora
→ Italian community is playing a major role already



Credits to B. Patricelli, A. Stamerra, F. Longo, … CAC transient WG

Much more

- galactic transients (microquasars, magnetar flares, …)

see talk by Vito

- gamma-ray binaries → search for periodic emission
  - Optimal laboratories to study time-dependent formation of pwne
- AGN flaring events

see talk by Patrizia

- pulsars
  - a huge potential but some preparatory work needs to be done not really planned

Is there any interest?

- dark matter searches
- gamma-ray cosmology (EBL, IGMF,…)

PART IV
LST-1 first results

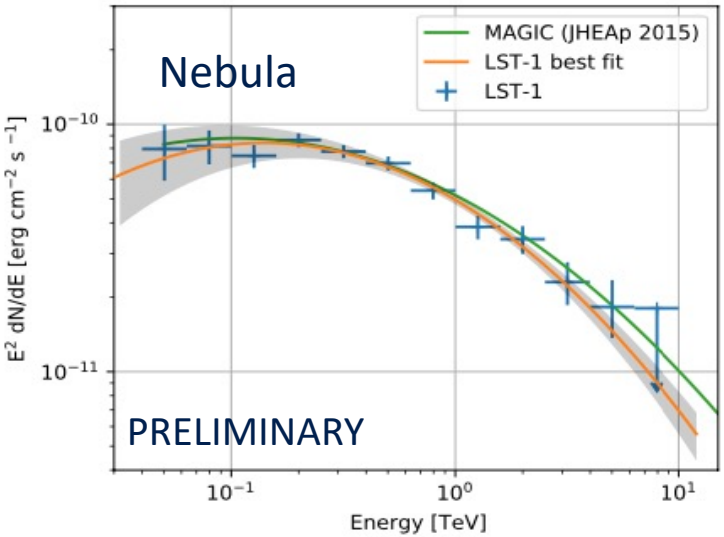
LST-1 already performing science

INAUGURATED IN OCTOBER 2018

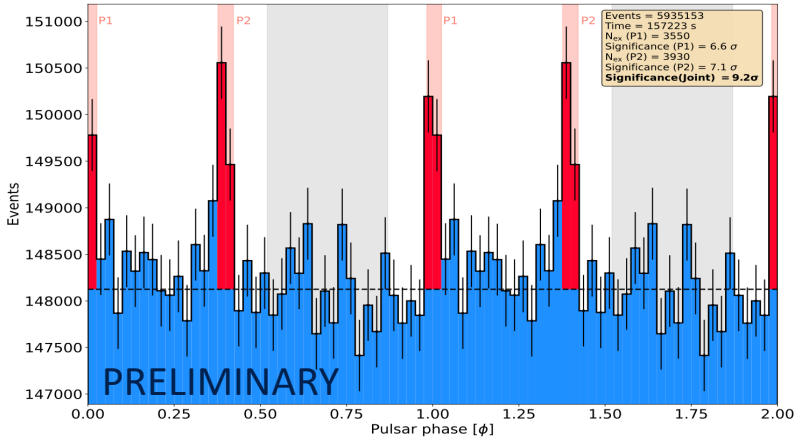
250 hr of GAMMA-RAY OBSERVATIONS ALREADY TAKEN

LST-1 already performing science

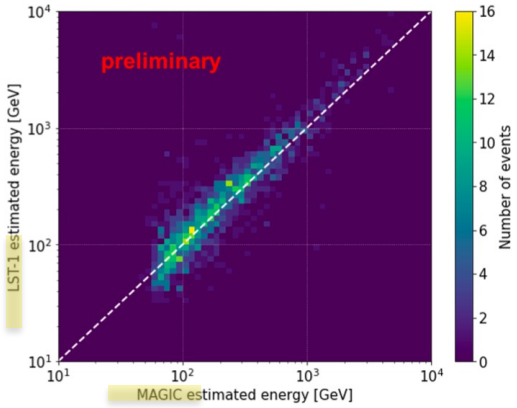
Always starting from the Crab as reference source to verify the scientific performance

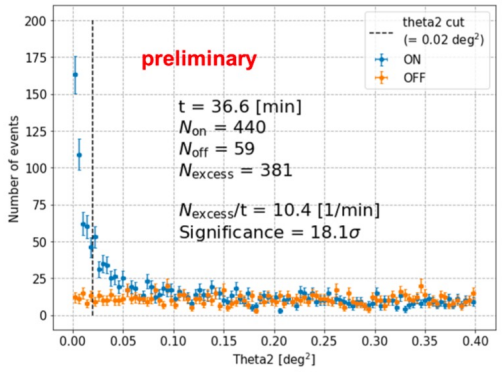


Pulsar: energy threshold ~50 GeV



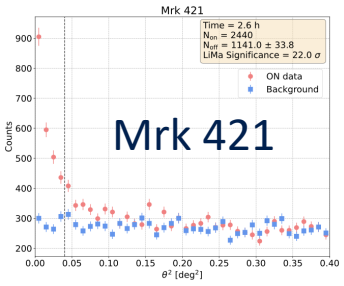
Cross calibration LST-1 with MAGIC **&** **combined LST-1 – MAGIC analysis**

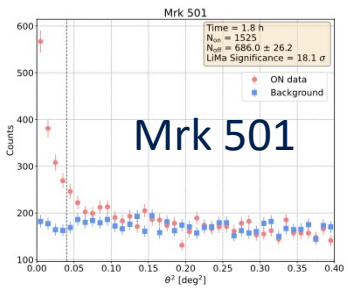




LST-1 already performing science

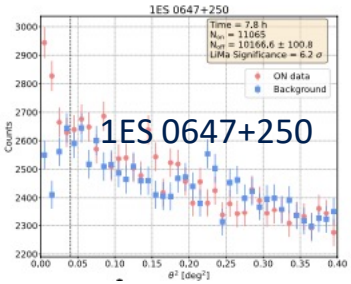
Several known gamma-ray sources already detected, mainly AGNs

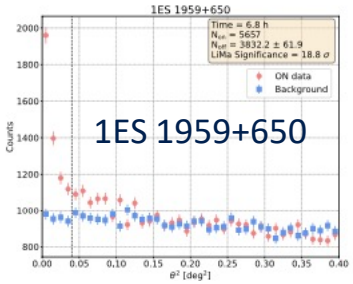


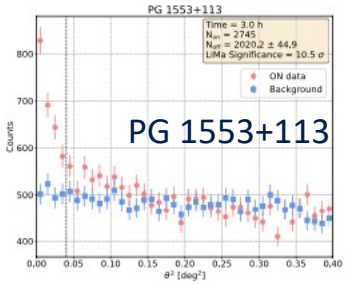


Detection of very-high-energy gamma-ray emission from BL Lac with the LST-1

ATel #14783; *Juan Cortina for the CTA LST collaboration* on 13 Jul 2021; 21:03 UT
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)



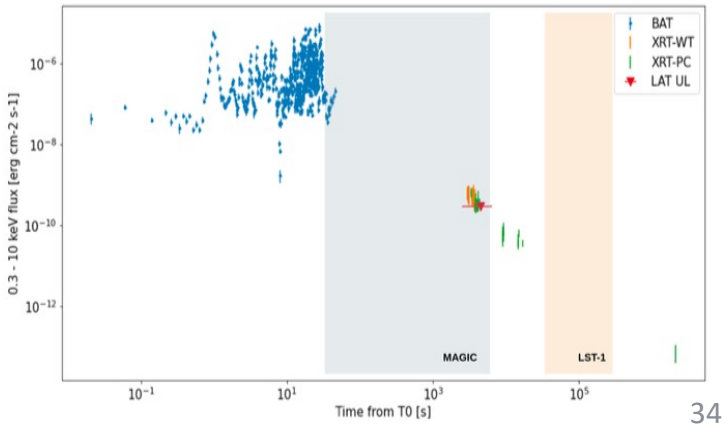




First follow-up of GRBs and neutrino golden events

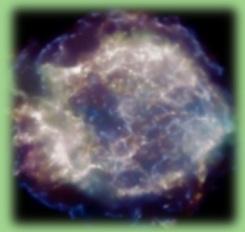
GRB 201216C
GRB 210217A
GRB 210511B
IC 210210A

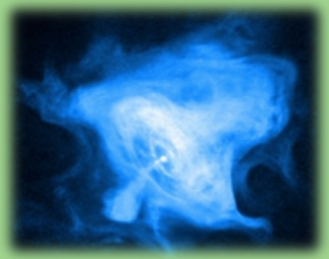
- detected by MAGIC pointing in < 1’
- z = 1.1
- LST-1 pointed at it 22 hr after the GRB event



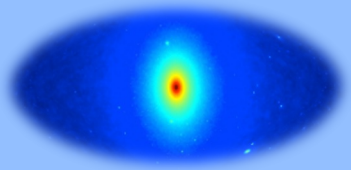
CTAO: a phase transition in VHE γ-ray astronomy

In-depth understanding of known objects and their mechanisms





Expected discoveries of new object classes

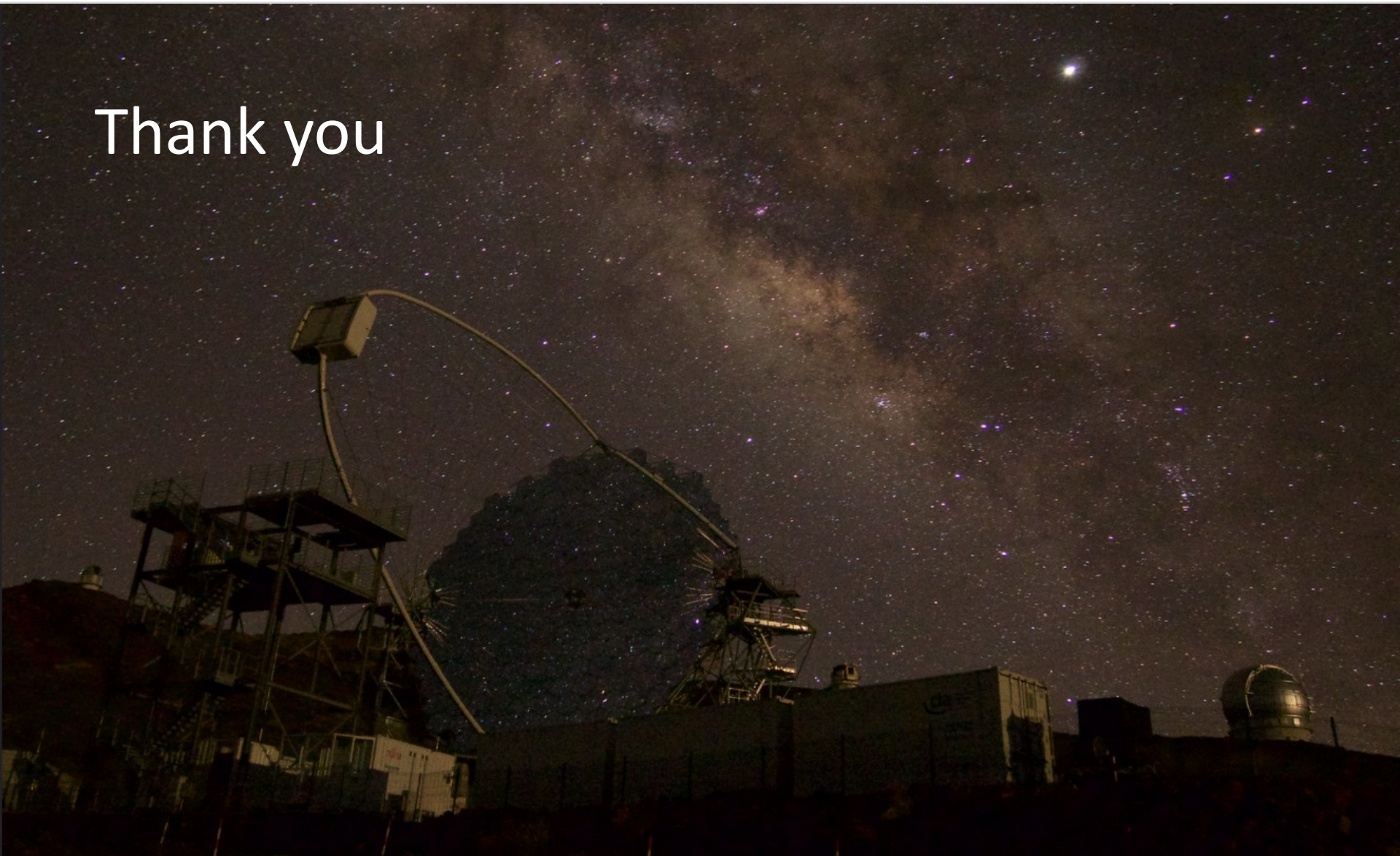


The fun part:
Things we haven't thought of

?

cherenkov telescope array

Thank you

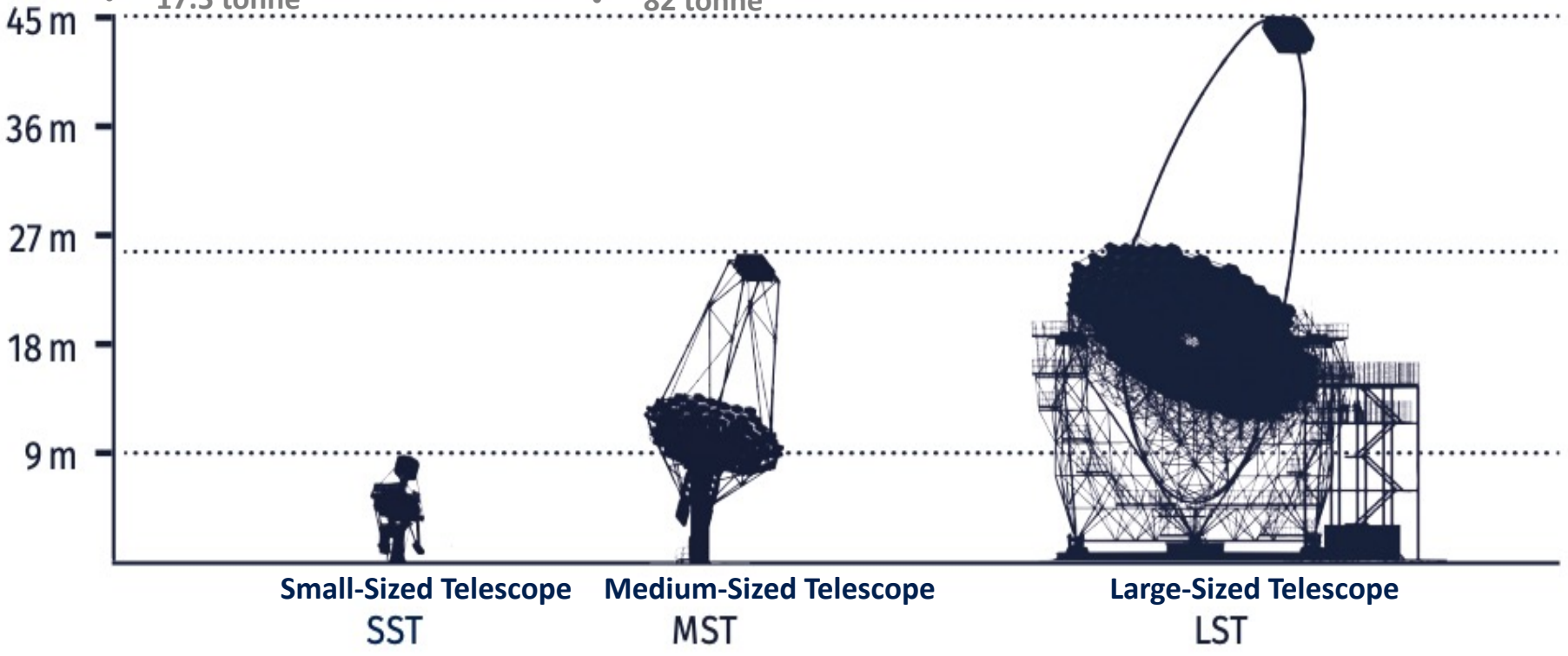


3 telescope designs

- 2-mirror Schwarzschild-Couder optical design
- 4.3 m ⌀ primary reflective surface
- SiPM camera: 2048 pixels (0.16°)
- 8.8° FoV
- 17.5 tonne

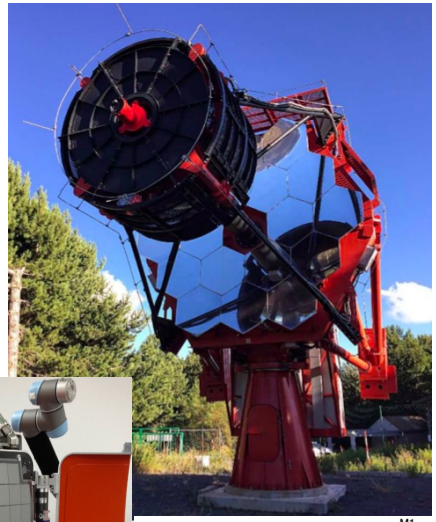
- Davies-Cotton optical design
- 12 m ⌀ reflective surface
- PMT camera – 2 designs:
  - NectarCam: 1855 pixels
  - FlashCam: 1764 pixels
- ~7° FoV
- 82 tonne

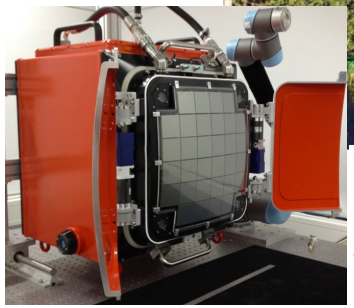
- Parabolic optical design
- 23 m ⌀ reflective surface
- PMT camera: 1855 pixels (0.1°)
- 4.3° FoV
- 100 tonne

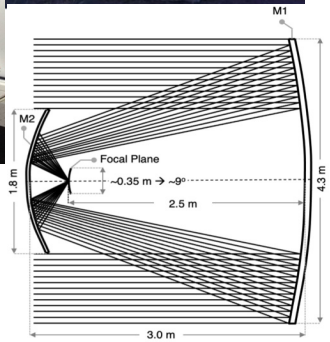


3 telescope prototypes

Small-Sized Telescope





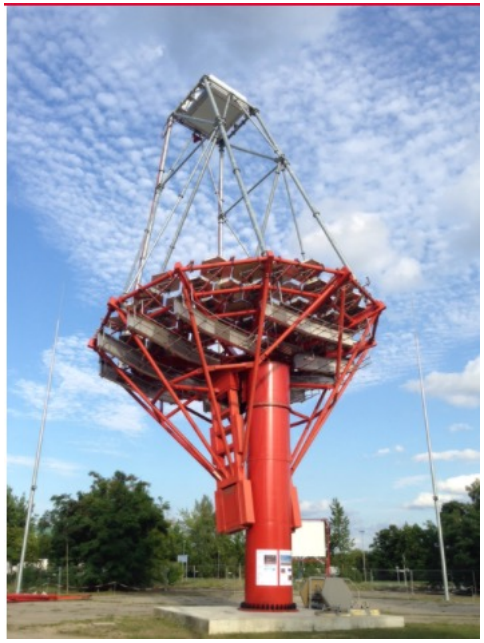


A&A 634, A22 (2020)

First detection of the Crab Nebula at TeV energies with a Cherenkov telescope in a dual-mirror Schwarzschild-Couder configuration: the ASTRI-Horn telescope

S. Lombardi[1,2,*], O. Catalano[3,*], S. Scuderi[4,*], L. A. Antonelli[1,2], G. Pareschi[5], E. Antolini[6], L. Arrabito[7], G. Bellassai[8], K. Bernlöhr[9], C. Bigongiari[1], B. Biondo[3], G. Bonanno[8], G. Bonnoli[5], G. M. Böttcher[10],

Medium-Sized Telescope

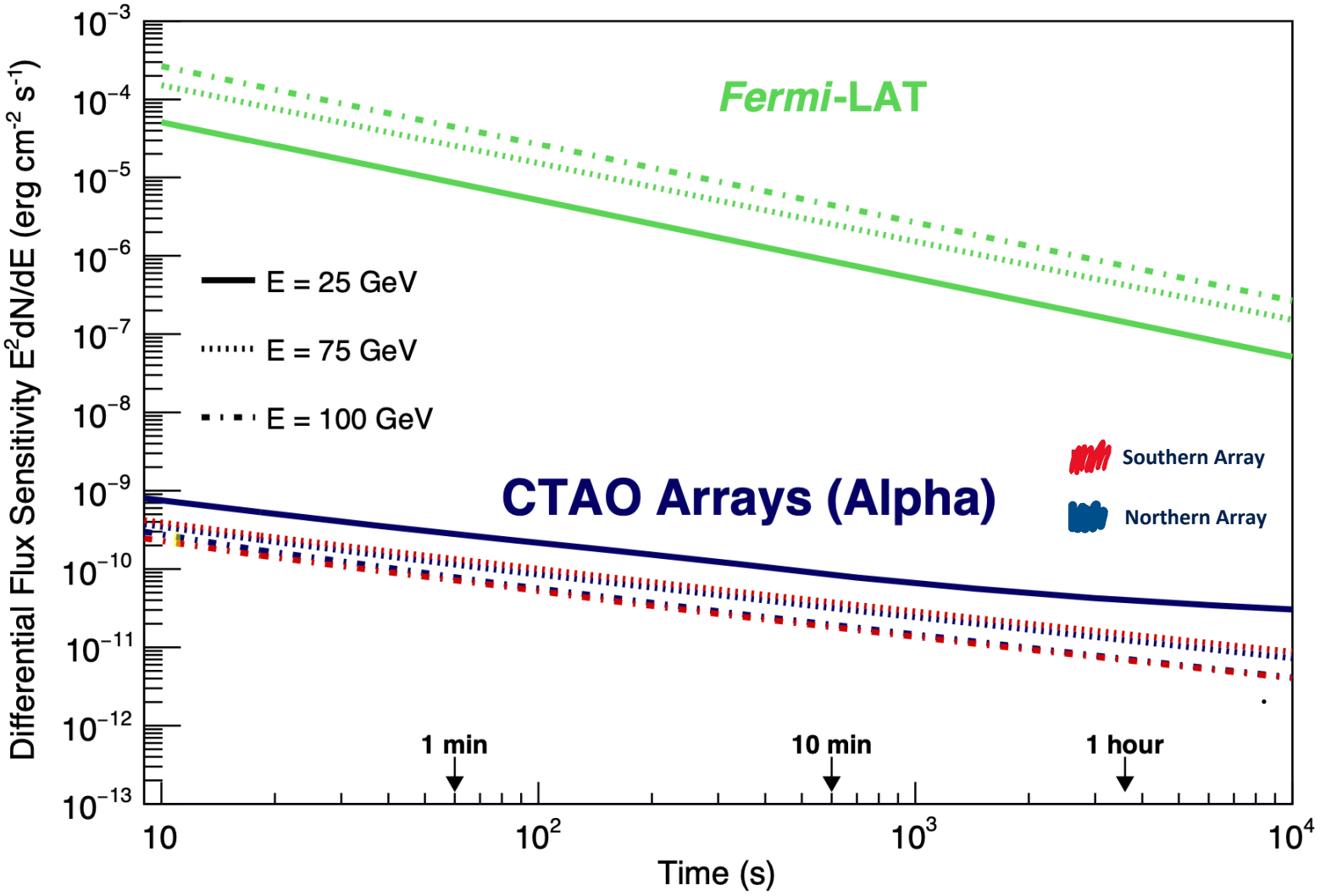


Large-Sized Telescope

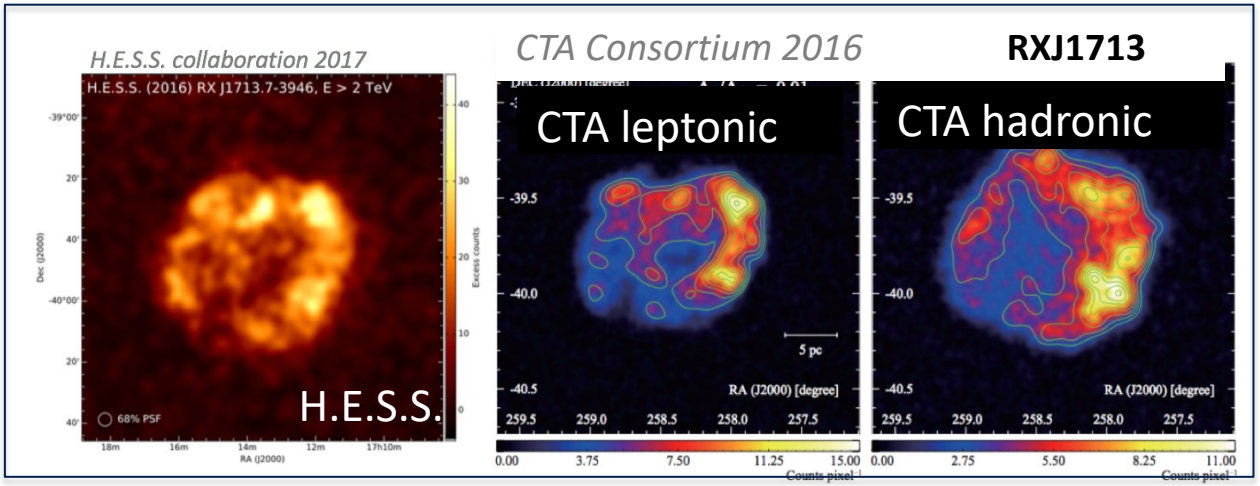
Detection of very-high-energy gamma-ray emission from BL Lac with the LST-1

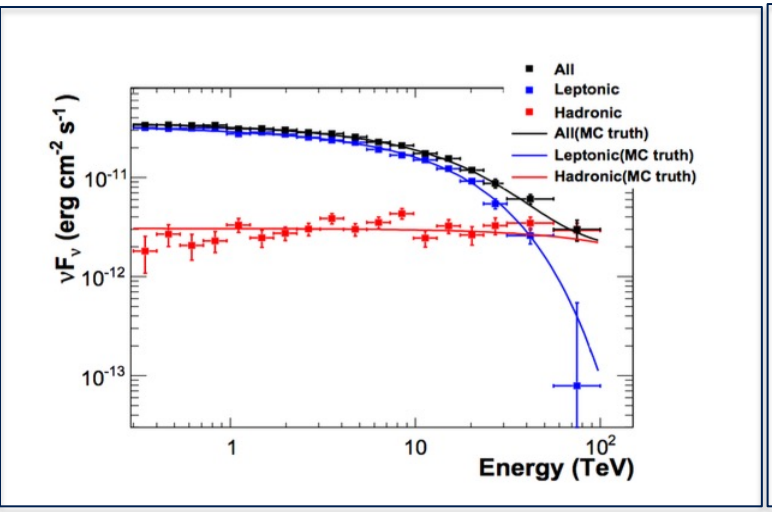
ATel #14783; *Juan Cortina for the CTA LST collaboration*
on 13 Jul 2021; 21:03 UT
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)

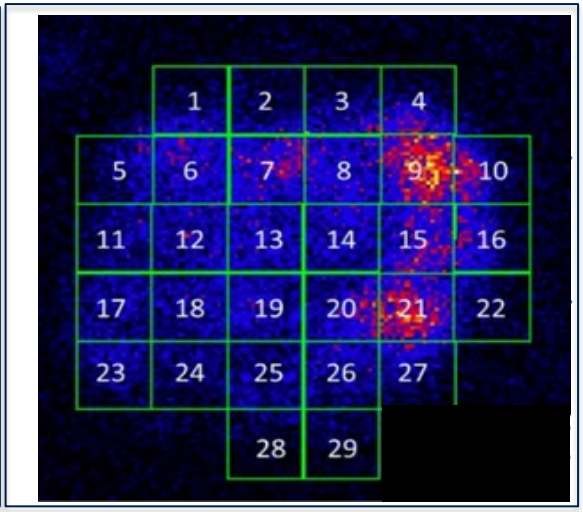
CTAO performance (Alpha Configuration)



Morphological & Spectral studies





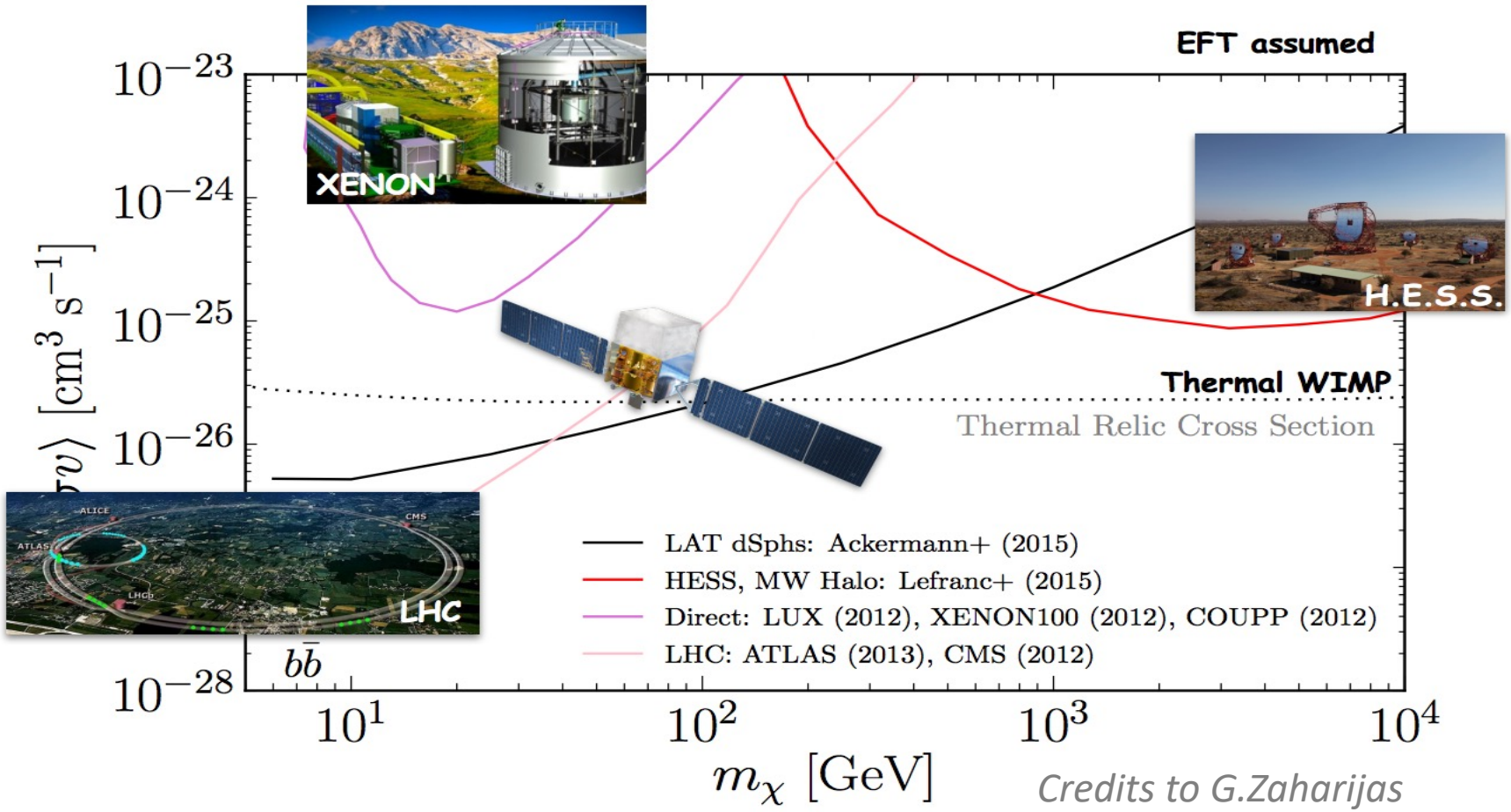


sub-arcminute resolution

spatial resolved spectroscopy

<10% energy resolution

Dark matter search

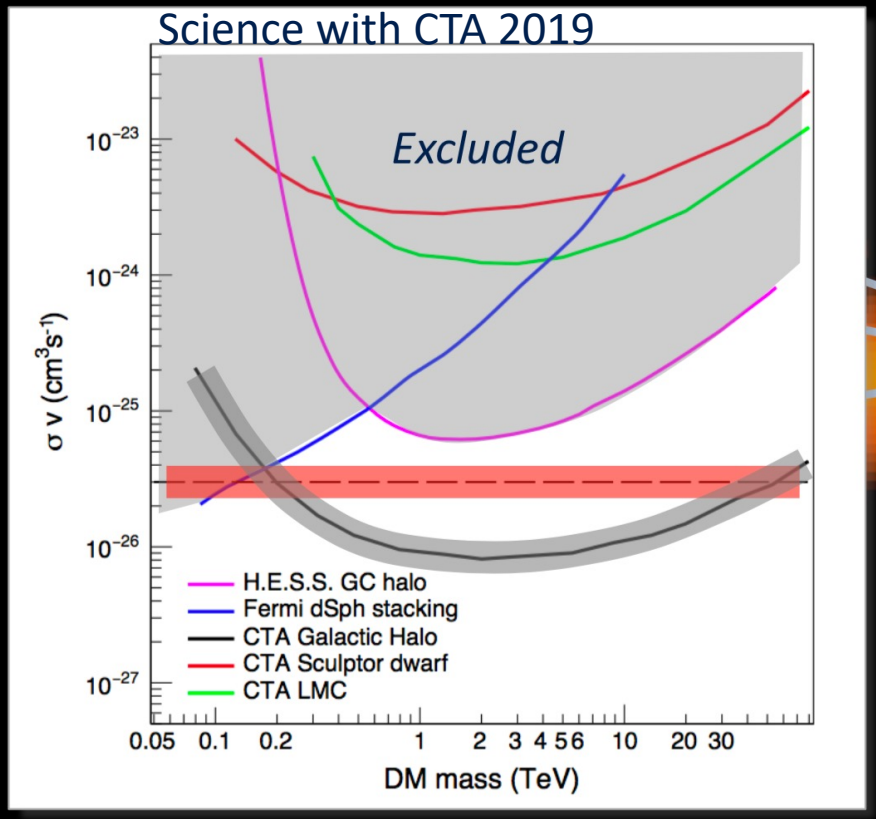


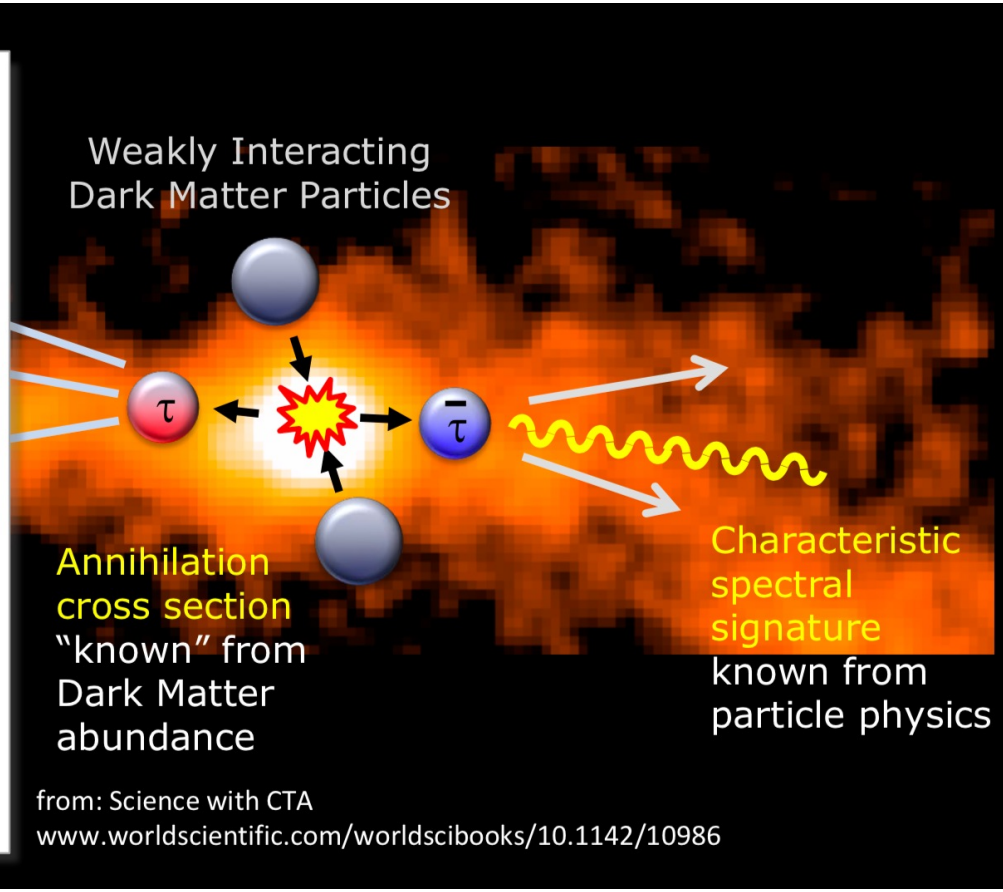
Credits to G.Zaharijas

- WIMP is not ruled out *(Leane+ 2018)*
- The TeV mass domain is unexplored

Dark matter search

- CTAO will constrain the WIMP paradigma in case of non-detection





from: Science with CTA
www.worldscientific.com/worldscibooks/10.1142/10986