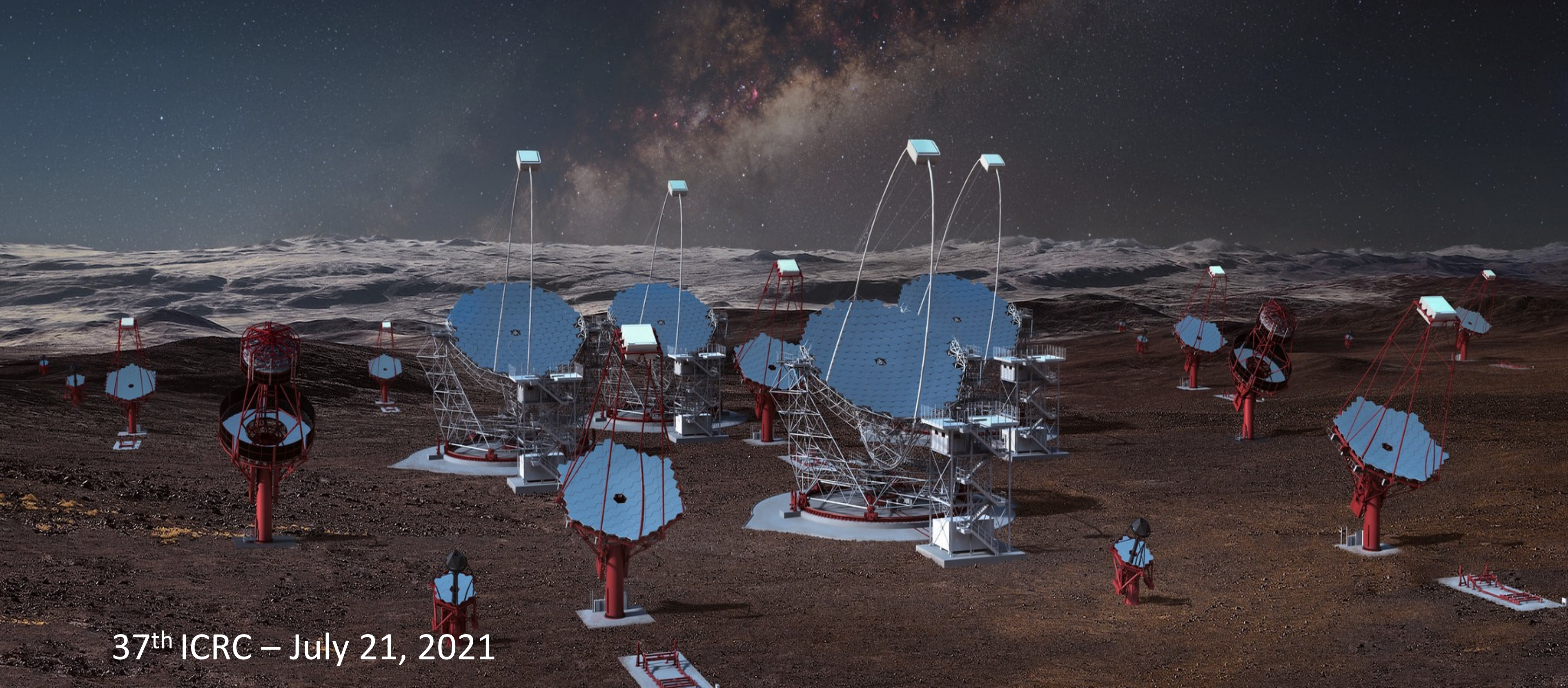
Cherenkov Telescope Array: the World's largest VHE gamma-ray observatory

Roberta Zanin – CTAO Project Scientist
Roberta.Zanin@cta-observatory.org
on behalf of the CTA Observatory, CTA Consortium & the CTA LST Collaboration



37th ICRC – July 21, 2021

Outline

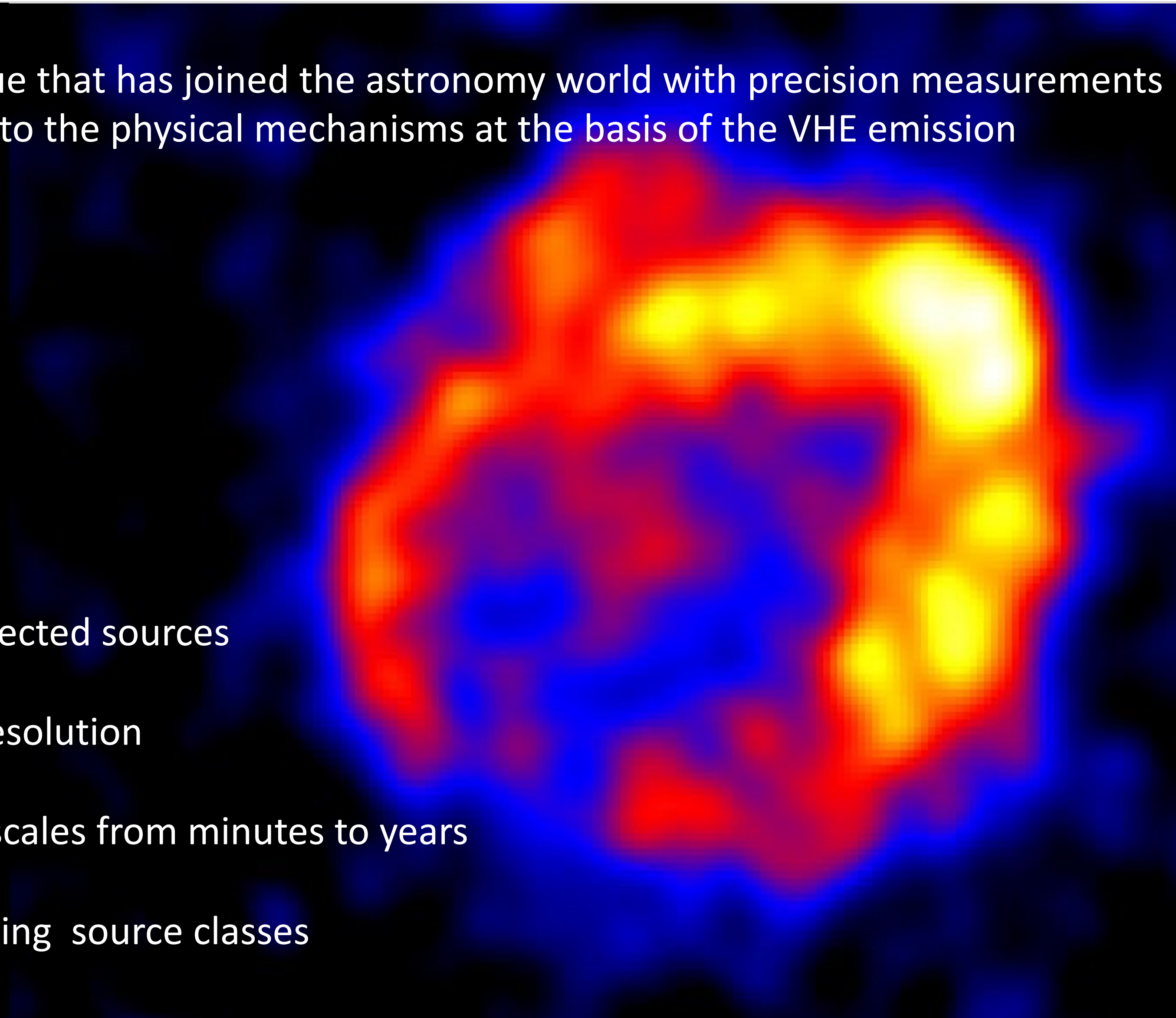
- Introduction
  - Why CTA?
  - The CTA design
- Few representative science cases
- First results from LST-1:
  the first CTA telescope under commission

Imaging Atmospheric Cherenkov Telescopes

Credits to W. Hoffmann

Real astronomy

A successful technique that has joined the astronomy world with precision measurements that provide insights to the physical mechanisms at the basis of the VHE emission



- more than 200 detected sources
- sky maps with 5’ resolution
- light curves on all scales from minutes to years
- ~10 different emitting source classes

A counterpart for a UHE neutrino?

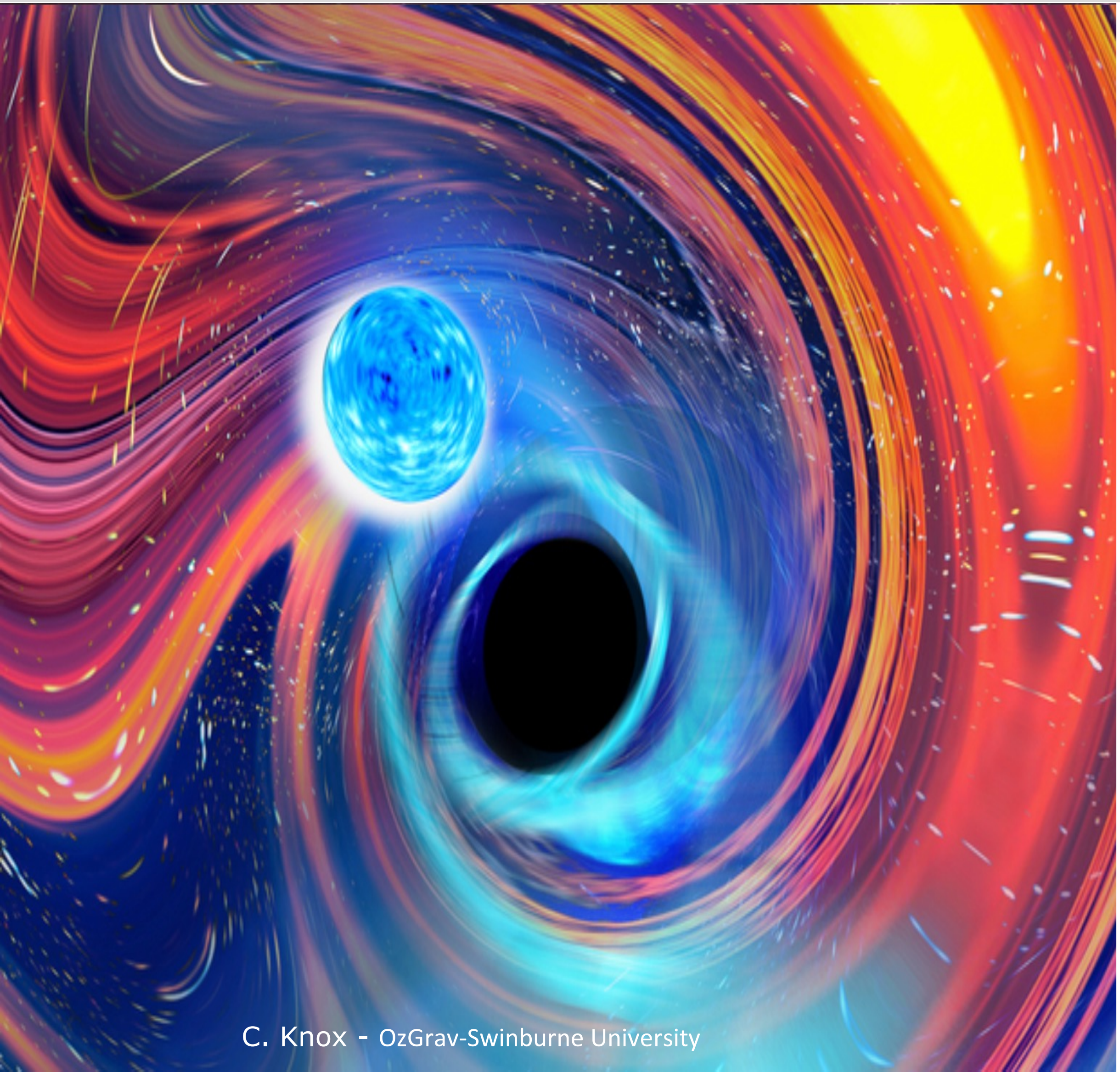
indication for a joint photon-ν emission from a blazar

- **TXS 0506+056** *(IceCube Coll. Science 2018)*
  - a 6 month-long gamma-ray flare with 2 UHE neutrinos in coincidence at 3σ level
  - a 3.5σ neutrino flare during 2014-2015 with no electromagnetic counterparts
  - a blazar sequence outlier *(Padovani+2019)*

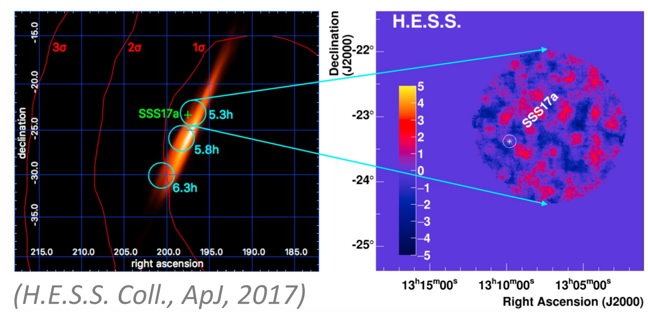
GRBs as VHE gamma-ray sources

- **GRB 190114C** *(MAGIC Coll., Nature, 2020)*
  - long GRB
  - z = 0.42
  - for 40' after T0 +60 s
  - 0.2 -1 TeV
- **GRB 180720B** *(H.E.S.S. Coll., Nature, 2020)*
  - long GRB
  - z = 0.65
  - after T_0 + 10h
- **GRB 190829A** *(H.E.S.S. Coll., Science)*
  - long GRB
  - z = 0.078
  - for 3 nights after T_0 + 4,3h
  - 0.18-3.3 TeV
- **GRB 160821B** *(MAGIC Coll. ApjL 2021)*
  - short GRB
  - z =0.162
  - 3σ @ E>500 GeV
  - for 4h after T_0+24s
- **GRB 201015A** *(PoS ID 305, Y.Suda)*
  - long GRB
  - z=0.42
  - for 3,4 h after T_0+40s
  - 3.5σ above 50 GeV
- **GRB 201216C** *(PoS ID 395, S.Fukami)*
  - long GRB
  - z=1.1
  - for 20' after T_0+56s
  - 6σ E<100 GeV

Electromagnetic counterparts to GWs



- **GW 170817** *(LIGO-VIRGO PhyRvL 2017)*
  - NS-NS merger
  - Associated to GRB170817A
  - z=0.0098
  - no detection by LAT on time scales larger than hr *(Fermi-LAT Coll. ApJ 2018)*
  - no detection by H.E.S.S. on the spot just 5.3 hr after the GW event *(H.E.S.S. Coll., ApJ, 2017)*



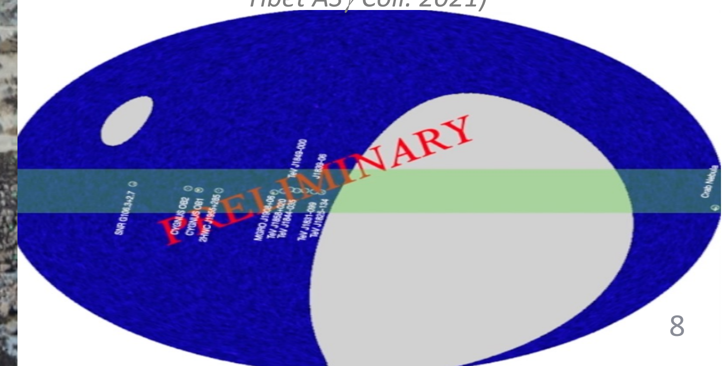
(H.E.S.S. Coll., ApJ, 2017)

- **GW200105 – GW200115** *(LIGO-VIRGO-KANGRA ApjL 2021)*
  - NS-BH merger
  - no electromagnetic counterpart (too large BH)

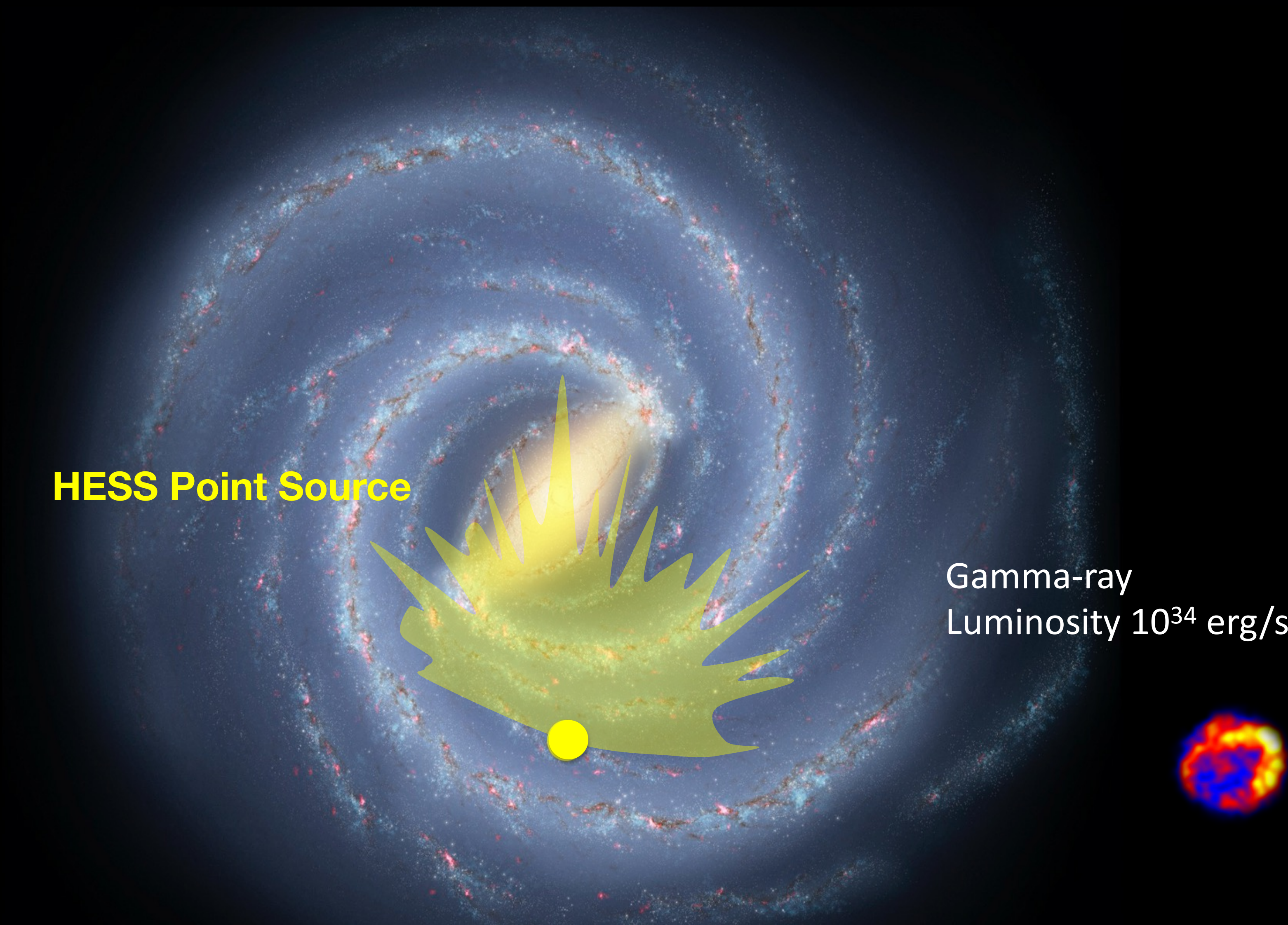
Hunt for extreme accelerators in our Galaxy

- **UHE photons up to 1.4 PeV from 12 Galactic sources** *(LHAASO Coll. Nature 2021)*
- **4 sources detected above 100 TeV by the Tibet ASγ** *(Tibet ASγ Coll. ID #334, ID #1430, ID #1421)*
- **HAWC published Galactic Plane map above 56 TeV** *(HAWC Coll. 2018)*

Tibet ASγ Coll. 2021)

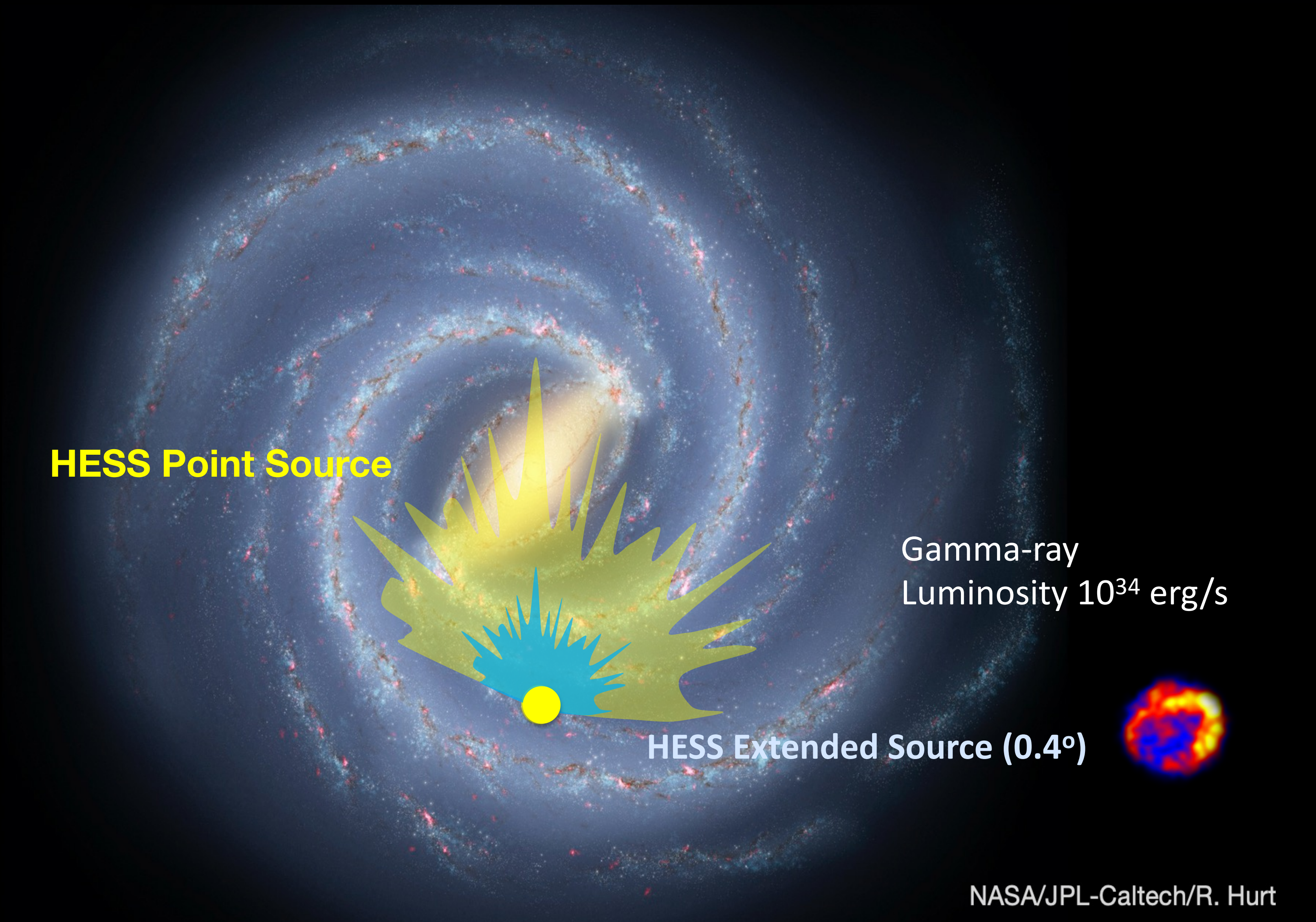


More to come

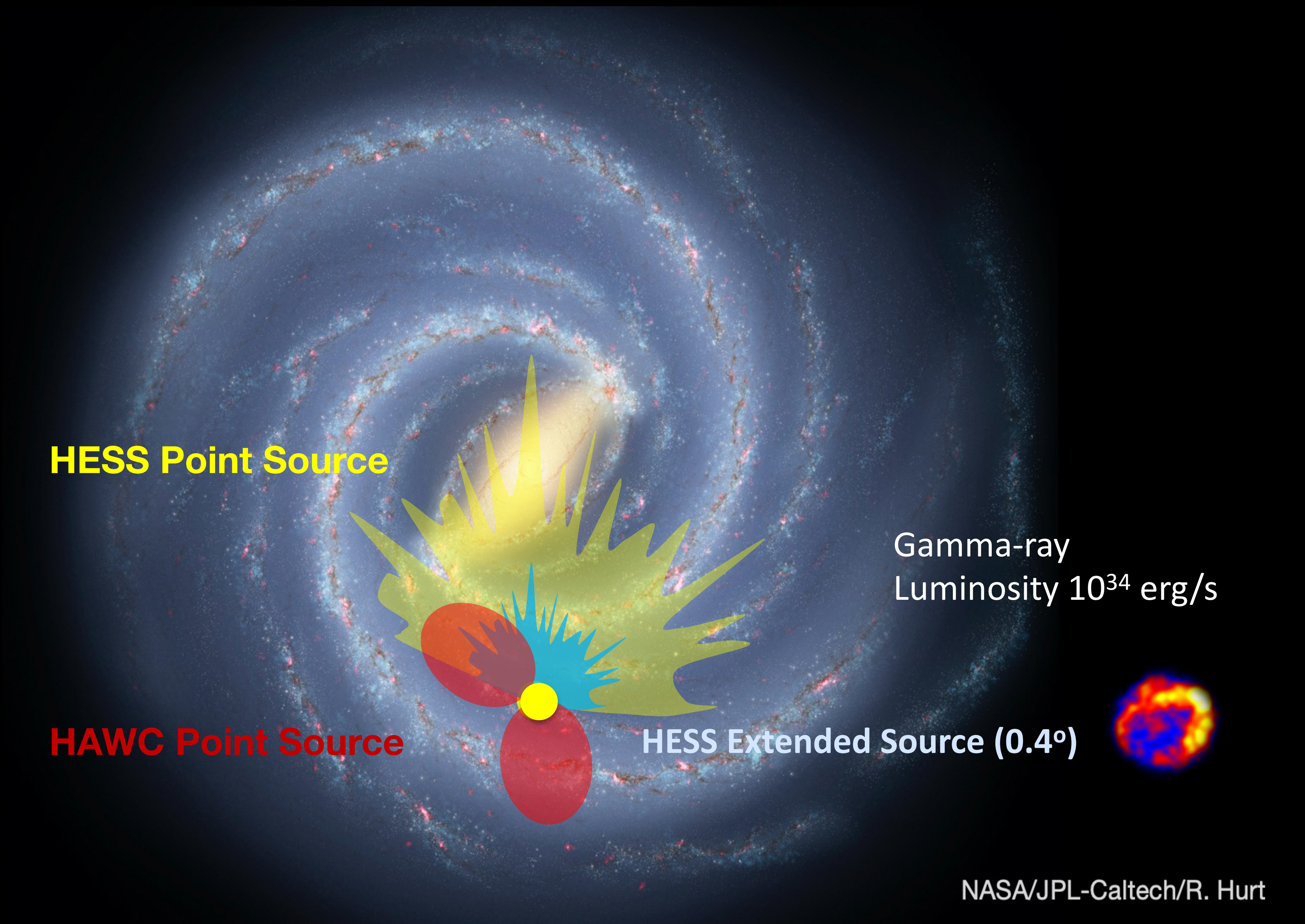


NASA/JPL-Caltech/R. Hurt

More to come

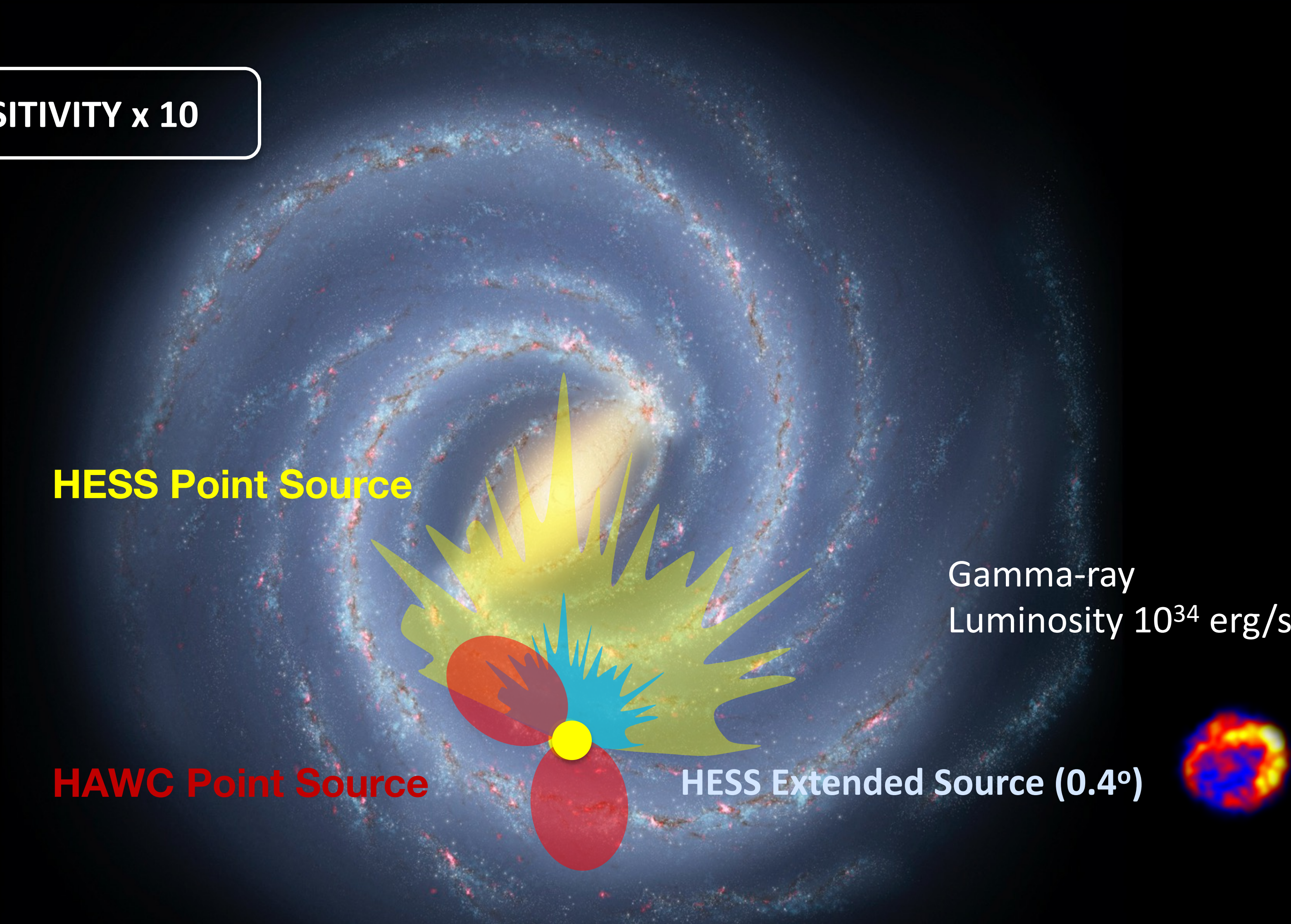

HESS Point Source
Gamma-ray
Luminosity 10³⁴ erg/s
HESS Extended Source (0.4°)
NASA/JPL-Caltech/R. Hurt

More to come


HESS Point Source
Gamma-ray
Luminosity 10^{34} erg/s
HAWC Point Source
HESS Extended Source (0.4°)
NASA/JPL-Caltech/R. Hurt

Design drivers for next generation IACT facility

SENSITIVITY x 10

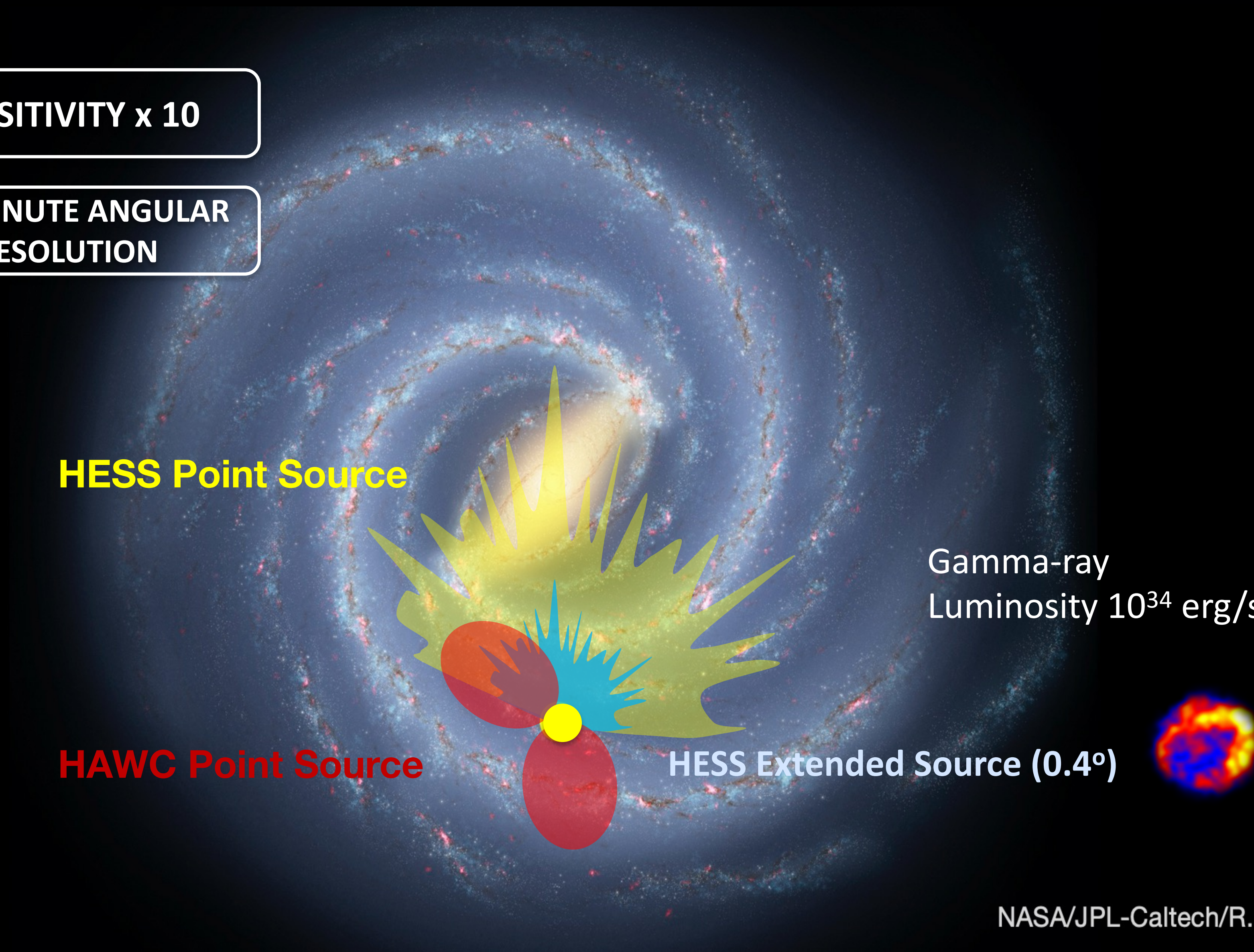


NASA/JPL-Caltech/R. Hurt

Design drivers for next generation IACT facility

SENSITIVITY x 10

ARCMINUTE ANGULAR RESOLUTION

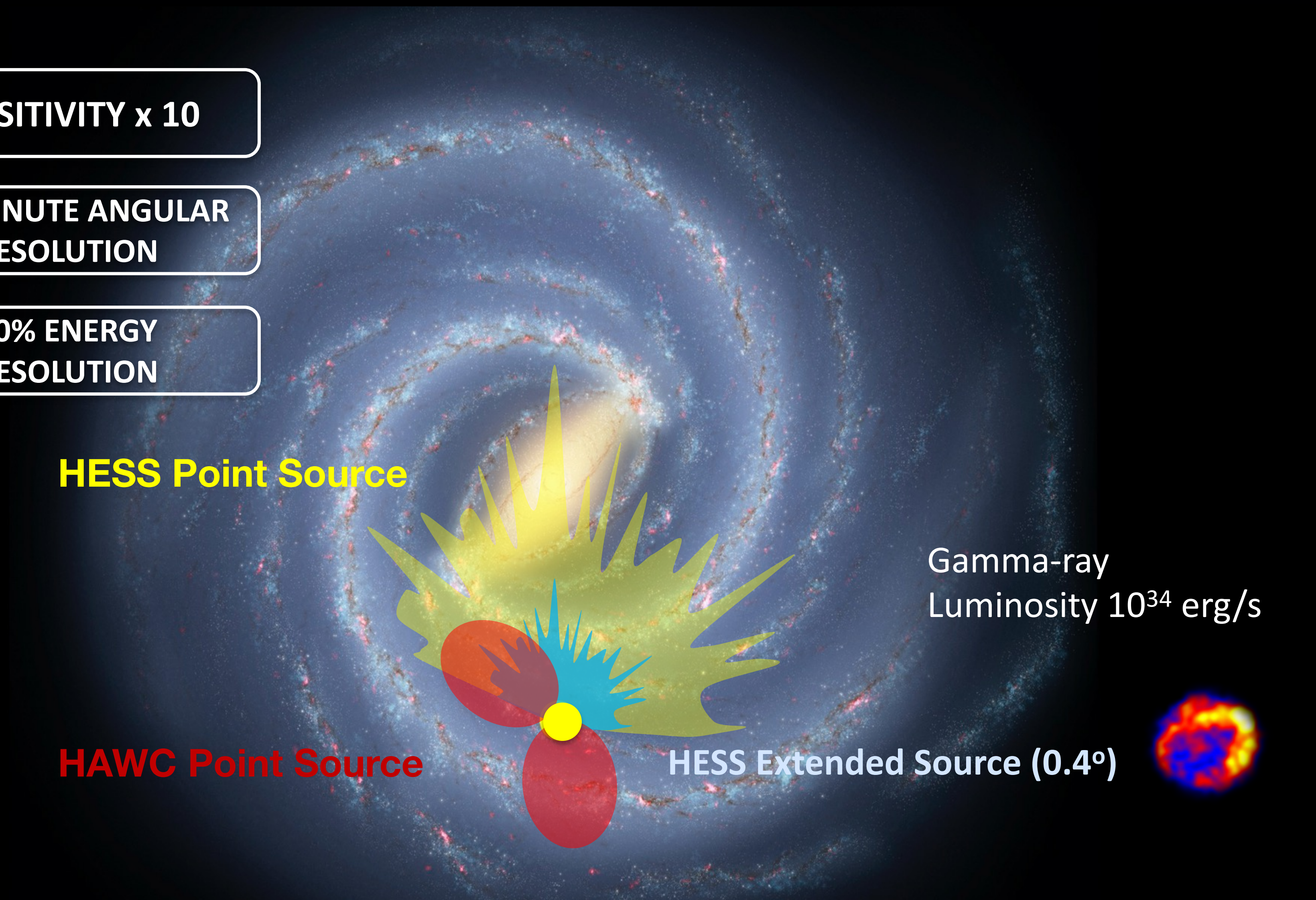


Design drivers for next generation IACT facility

SENSITIVITY x 10

ARCMINUTE ANGULAR RESOLUTION

10% ENERGY RESOLUTION



NASA/JPL-Caltech/R. Hurt

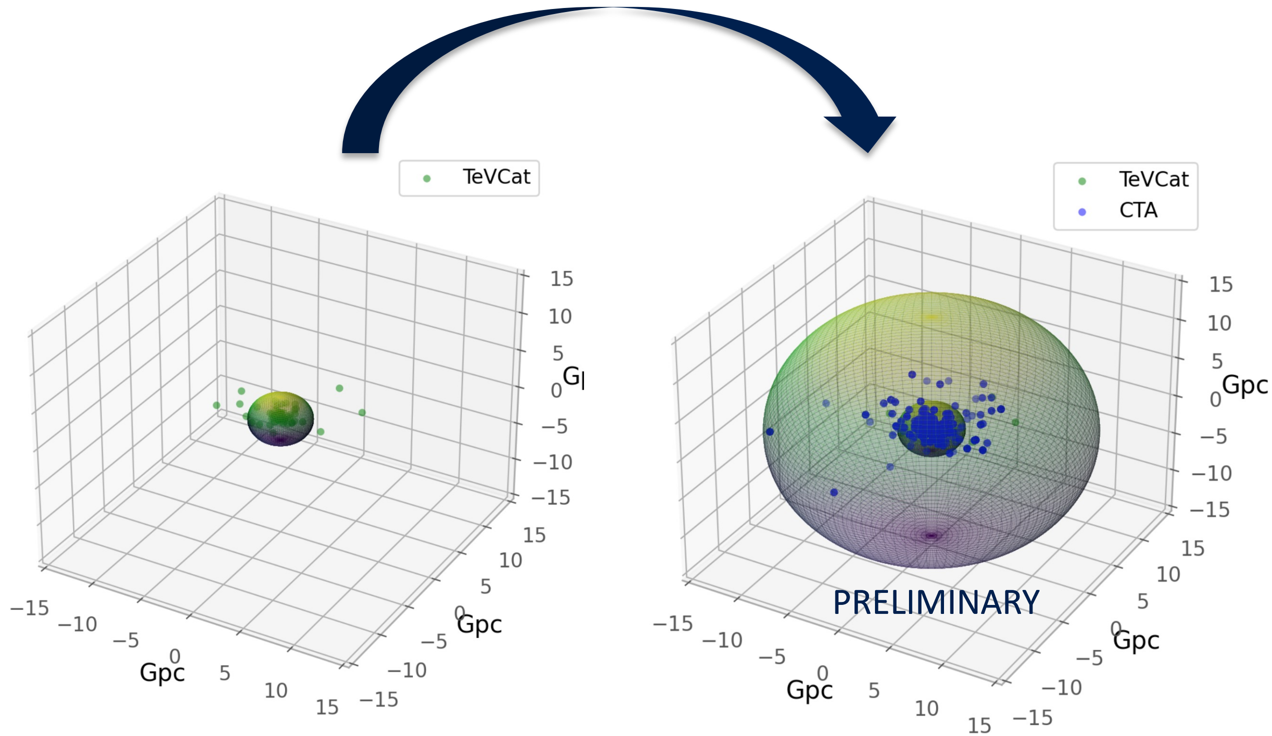
Design drivers for next generation IACT facility

SENSITIVITY x 10

ARCMINUTE ANGULAR RESOLUTION

10% ENERGY RESOLUTION

WIDE ENERGY RANGE 20 GeV – 300 TeV



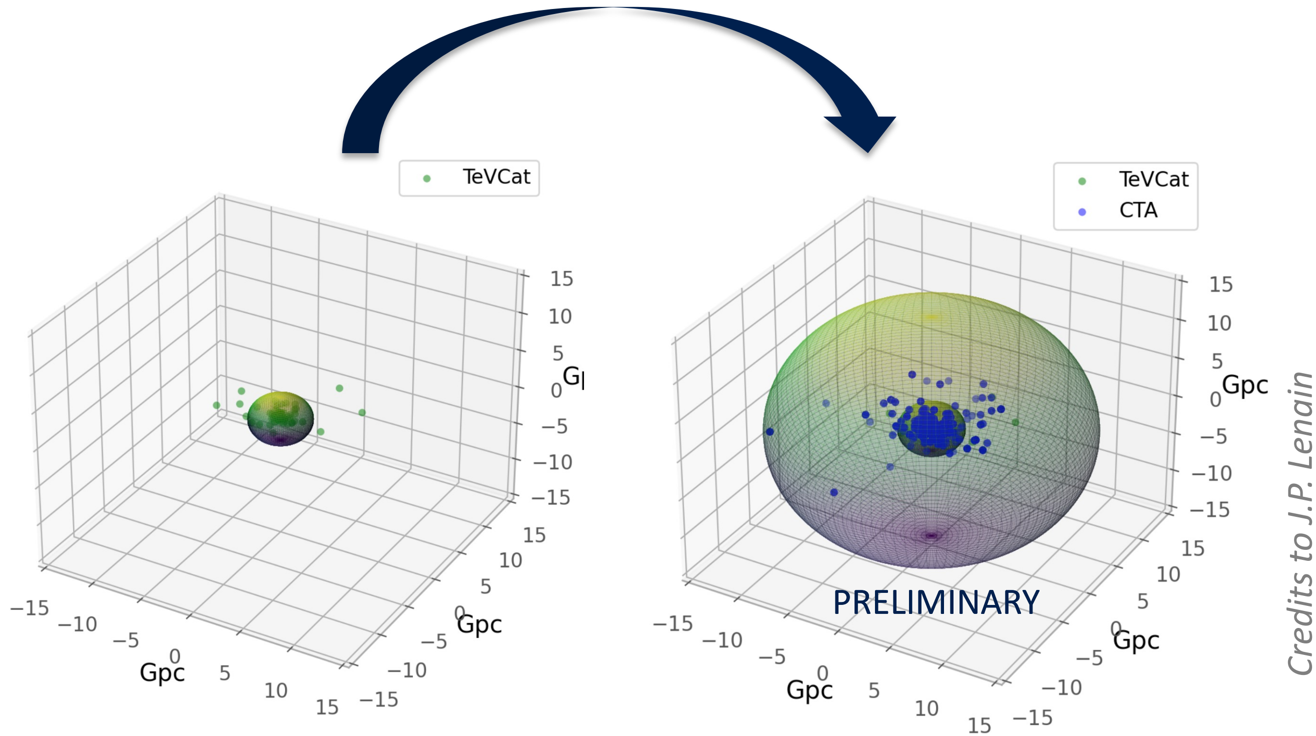
Energy Threshold ~ 80 GeV

Energy Threshold ~ 20 GeV

Credits to J.P. Lenain

Design drivers for next generation IACT facility

- **SENSITIVITY x 10**
- **ARCMINUTE ANGULAR RESOLUTION**
- **10% ENERGY RESOLUTION**
- **WIDE ENERGY RANGE 20 GeV – 300 TeV**
- **FoV x 2**



Energy Threshold ~ 80 GeV

Energy Threshold ~ 20 GeV

Design drivers for next generation IACT facility

SENSITIVITY x 10

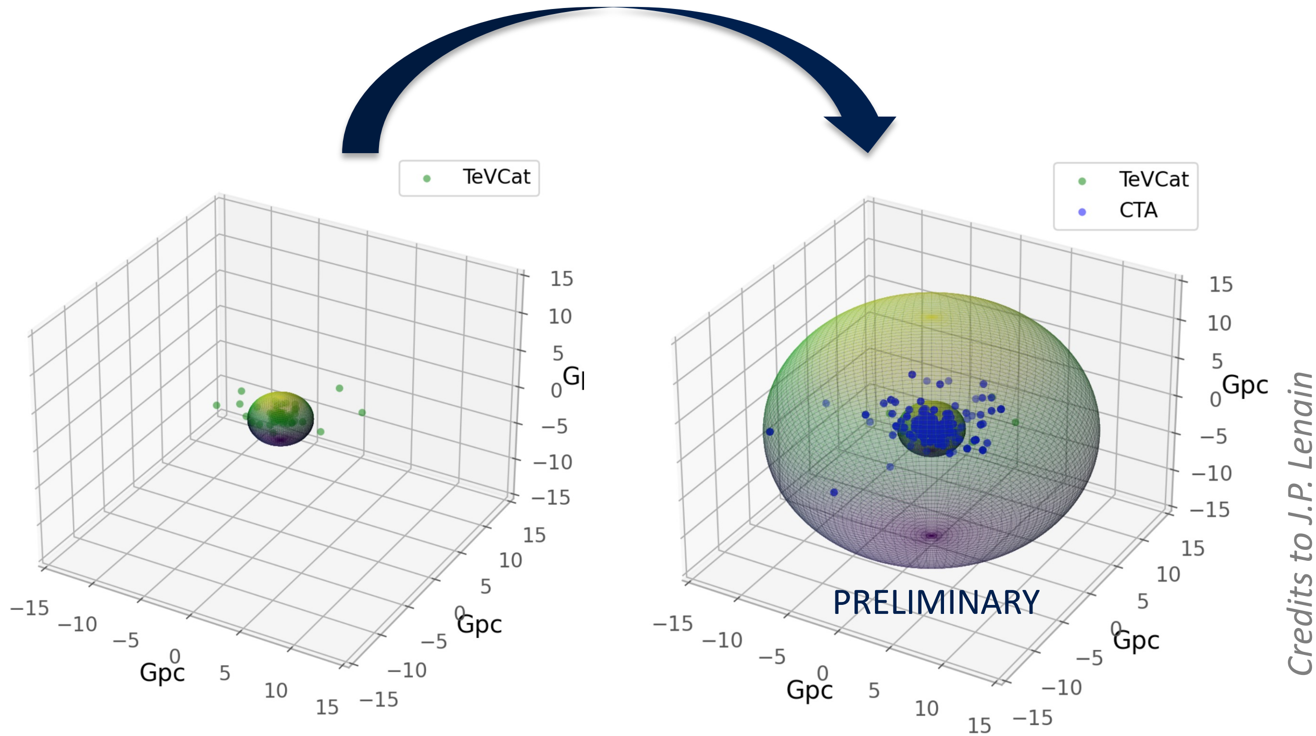
ARCMINUTE ANGULAR RESOLUTION

10% ENERGY RESOLUTION

WIDE ENERGY RANGE 20 GeV – 300 TeV

FoV x 2

FULL SKY COVERAGE

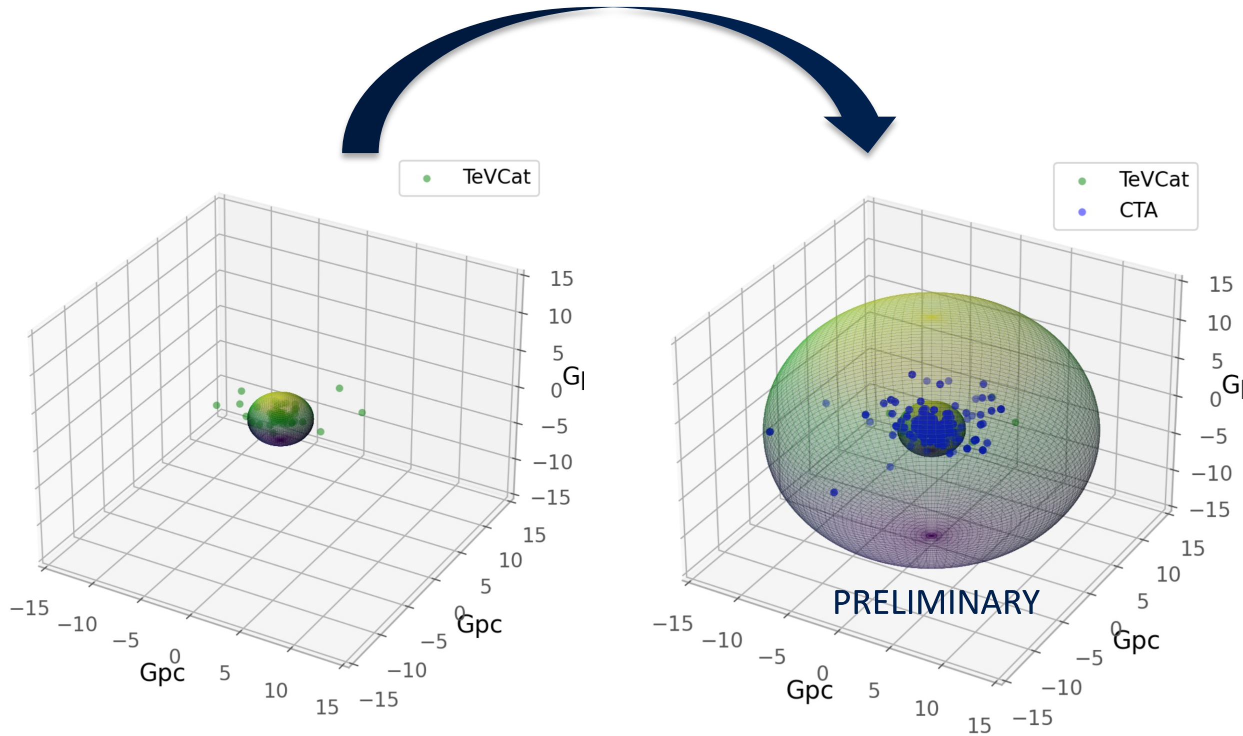


Energy Threshold ~ 80 GeV

Energy Threshold ~ 20 GeV

Design drivers for next generation IACT facility

- **SENSITIVITY x 10**
- **ARCMINUTE ANGULAR RESOLUTION**
- **10% ENERGY RESOLUTION**
- **WIDE ENERGY RANGE 20 GeV – 300 TeV**
- **FoV x 2**
- **FULL SKY COVERAGE**
- **30 s RESPONSE TO EXTERNAL ALERTS**

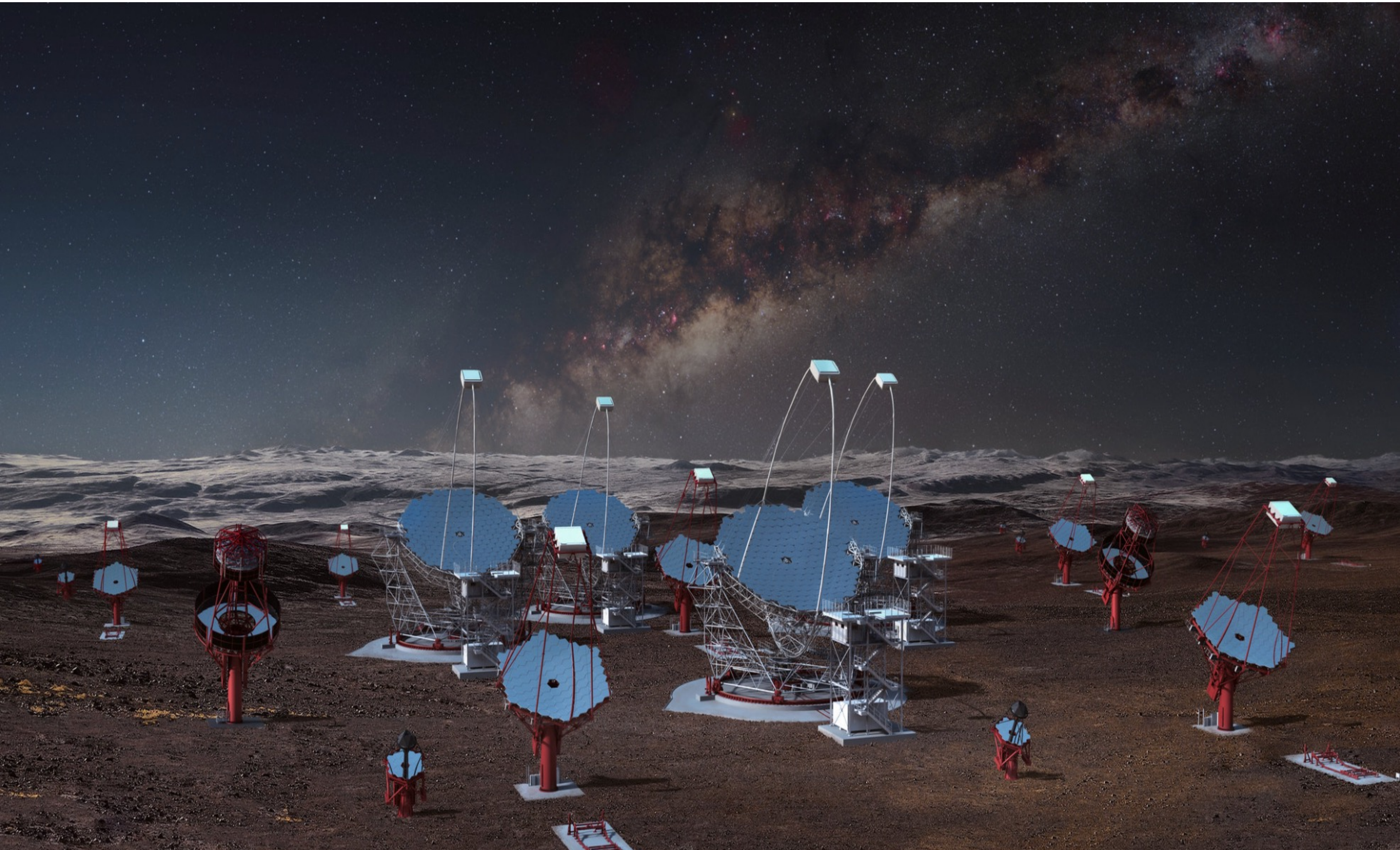


Energy Threshold ~ 80 GeV

Energy Threshold ~ 20 GeV

Credits to J.P. Lenain

The Cherenkov Telescope Array Observatory

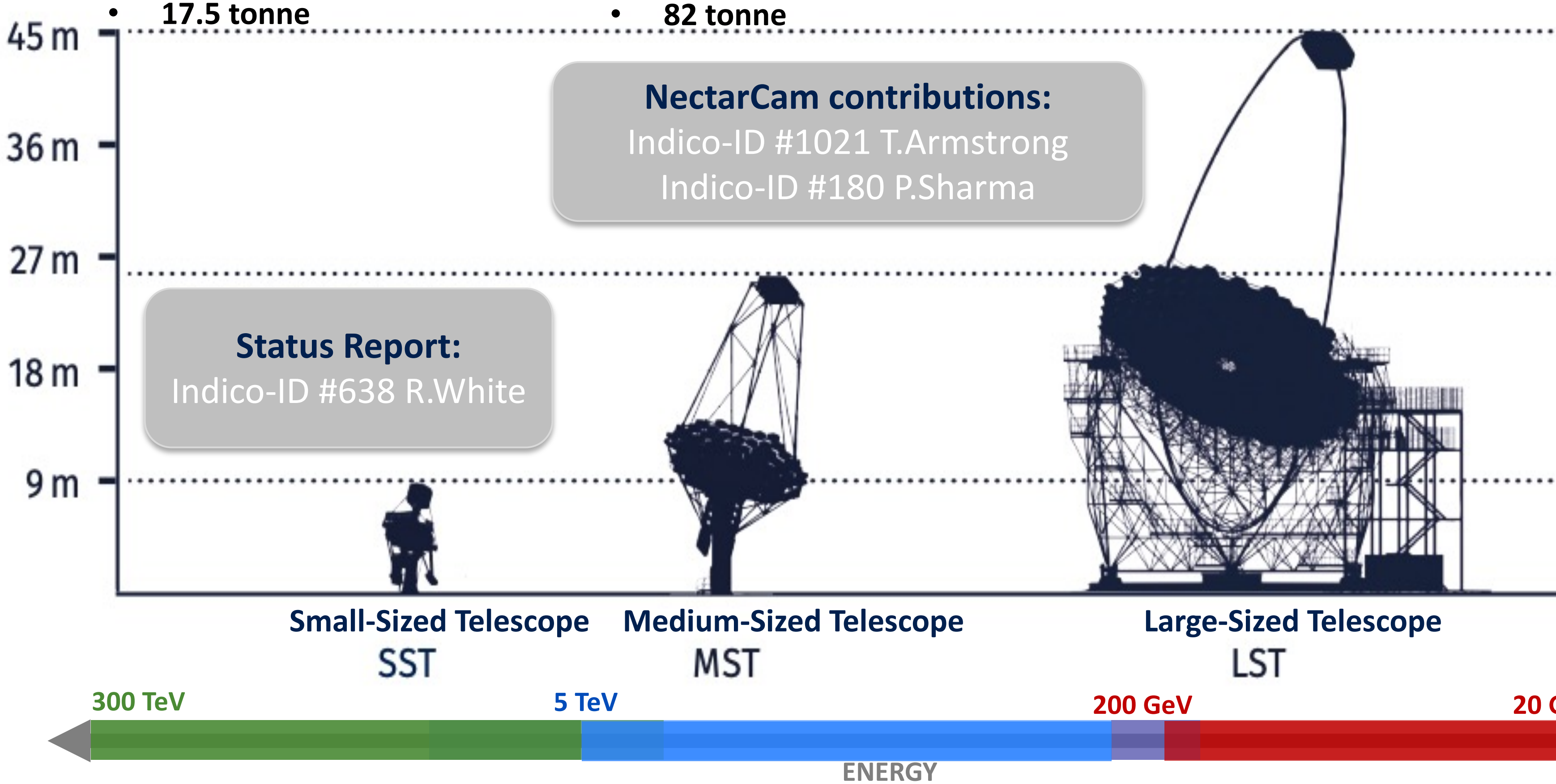


3 telescope designs

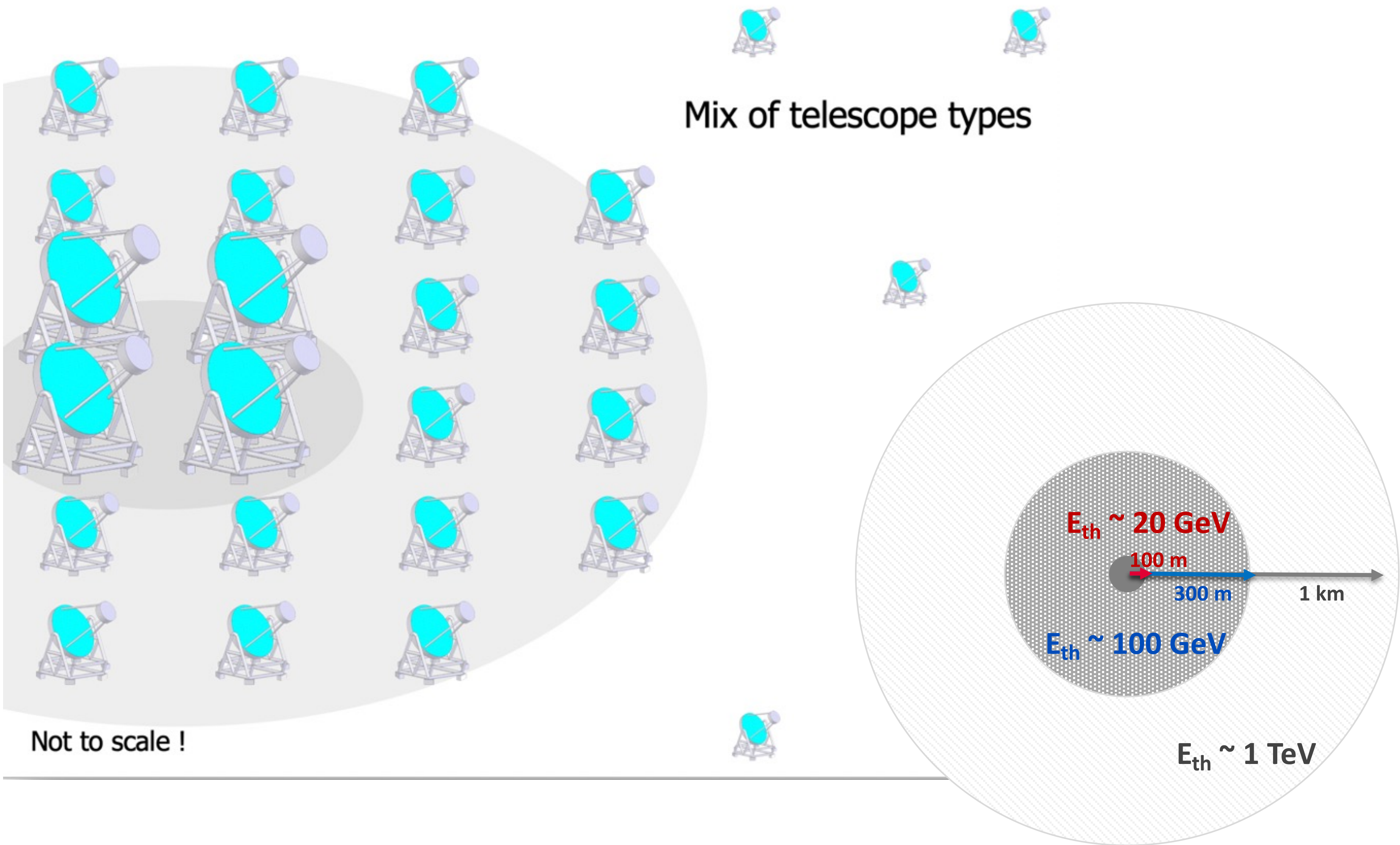
- 2-mirror Schwarzschild-Couder optical design
- 4.3 m ∅ primary reflective surface
- SiPM camera: 2048 pixels (0.16 °)
- 8.8° FoV
- 17.5 tonne

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

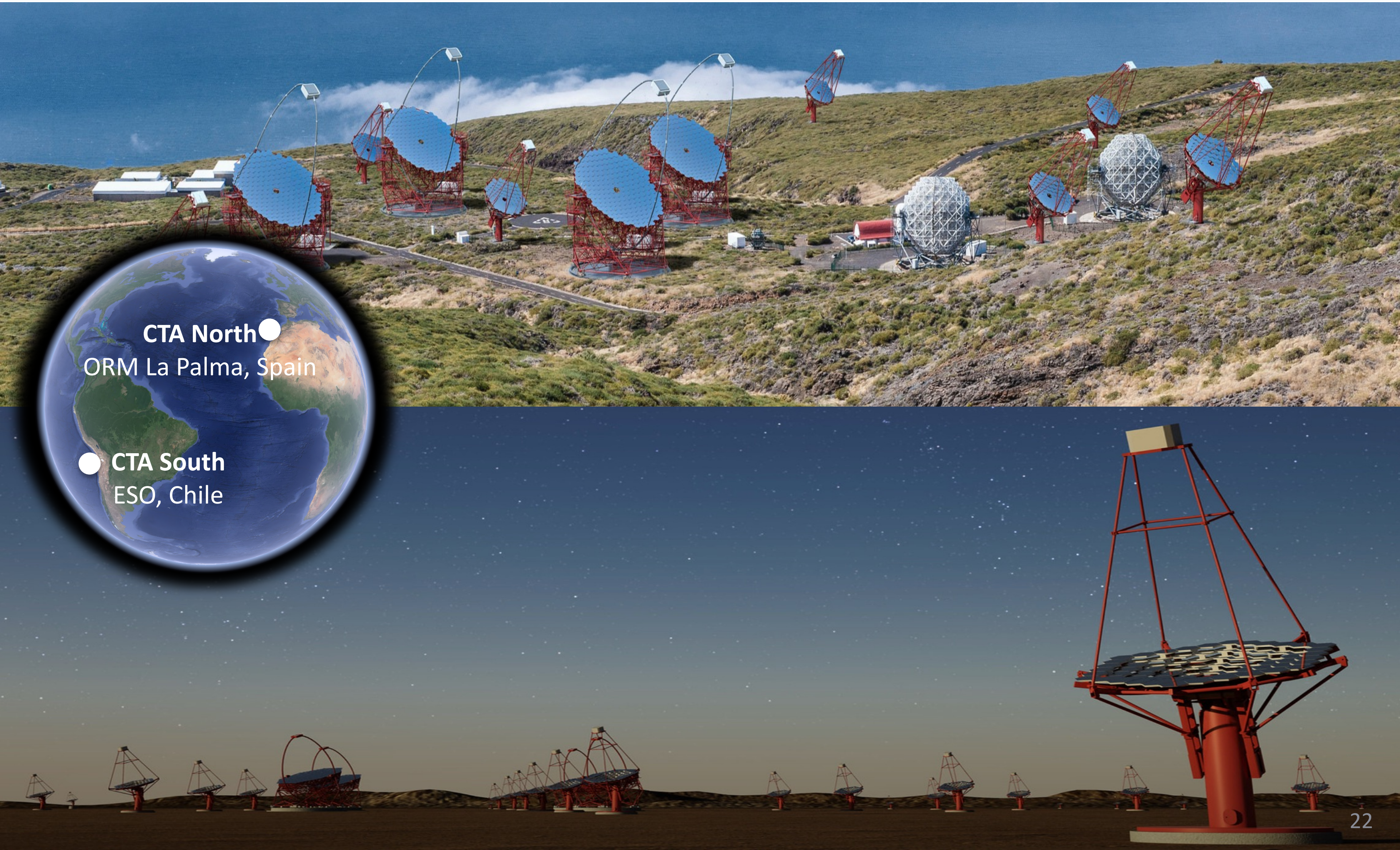
- Parabolic optical design
- 23 m ∅ reflective surface
- PMT camera: 1855 pixels (0.1°)
- 4.3° FoV
- 100 tonne



Array design



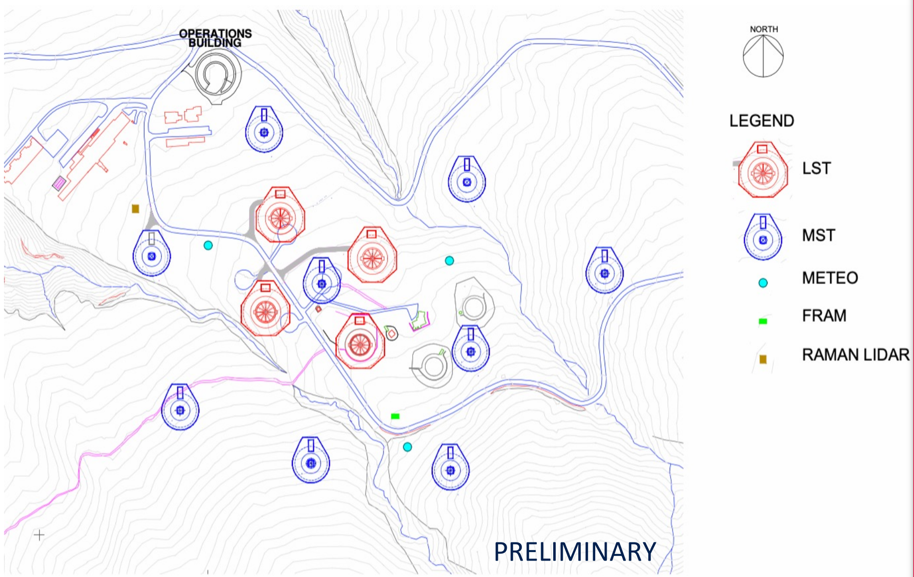
Full sky coverage



The two initial CTAO arrays: the Alpha Configuration

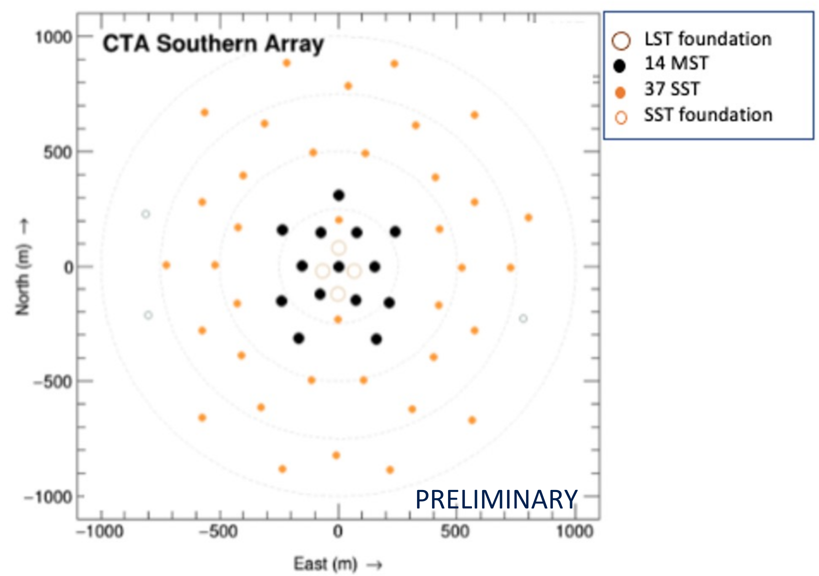
CTAO Northern Array

- **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



Array Layout Optimization
ID #88 O.Gueta

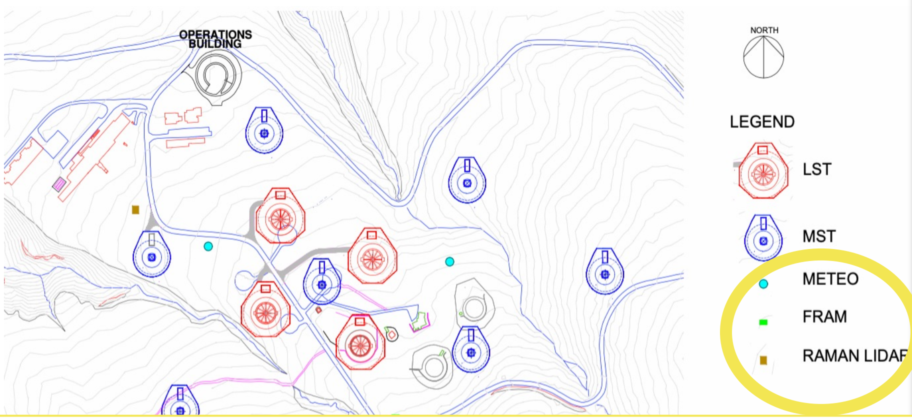
The two initial CTAO arrays: the Alpha Configuration

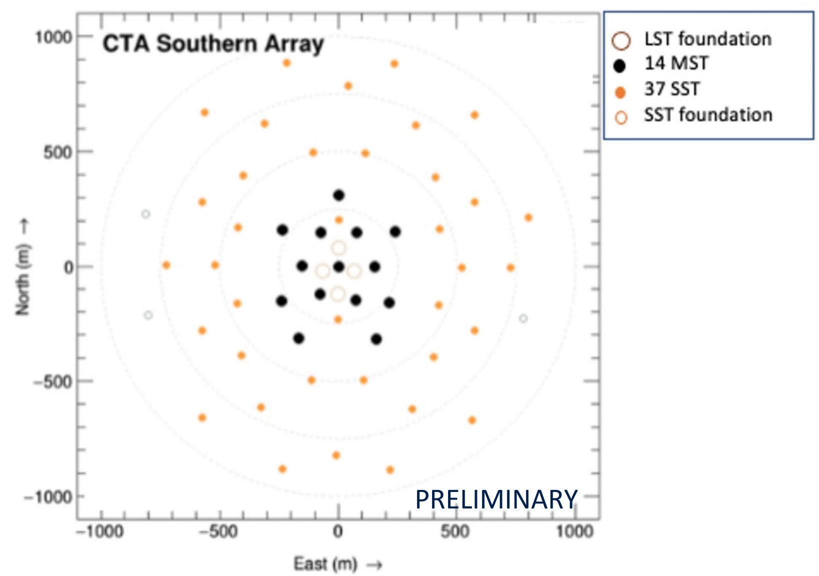
CTAO Northern Array

- **4 LSTs + 9 MSTs**
- 0,25 km² footprint
- focus on extra-Galactic science

CTAO Southern Array

- **14 MSTs + 37 SSTs**
- 3 km² footprint
- focus on Galactic science





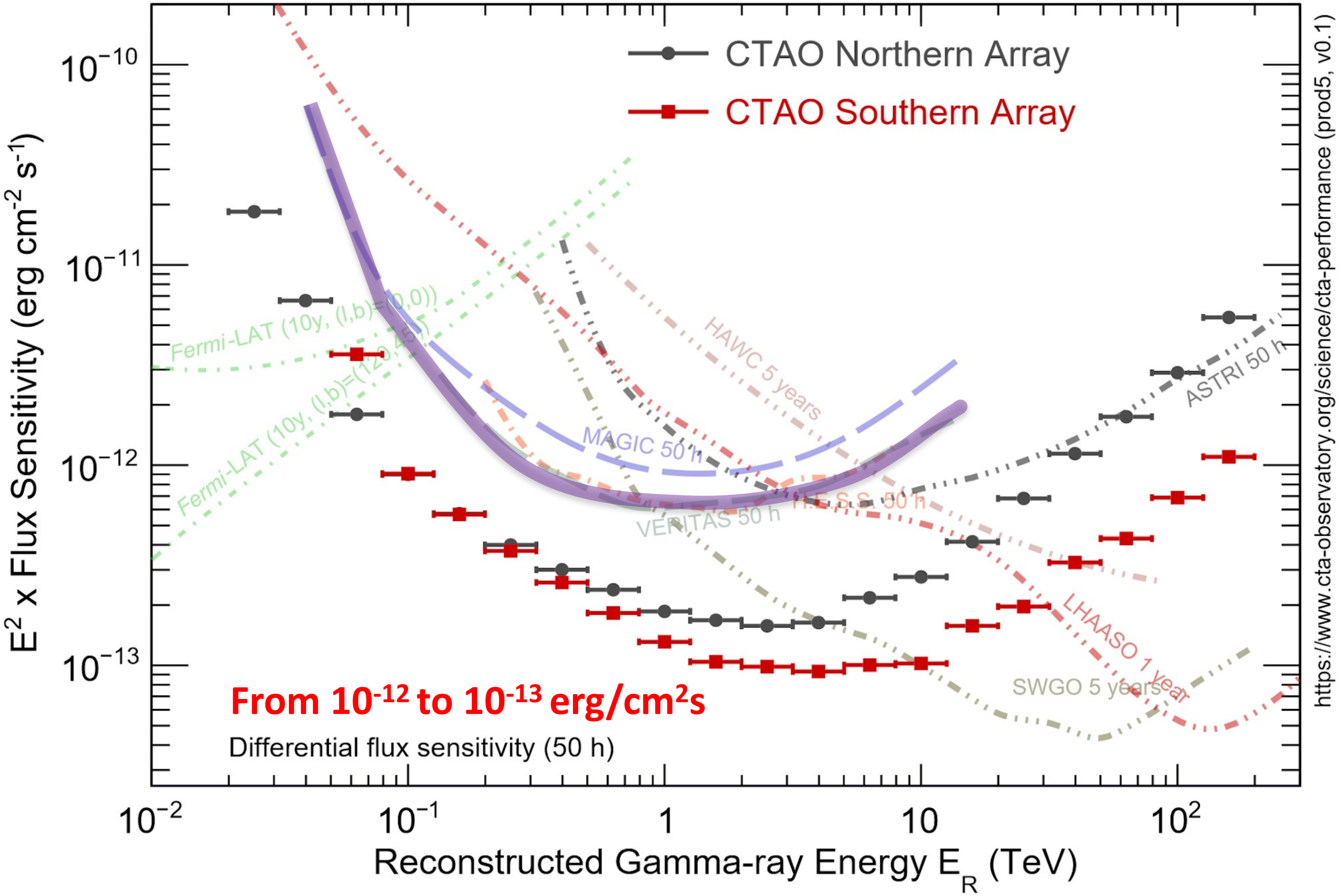
Atmospheric characterization devices are key to keep the systematic uncertainties within requirements

- The impact of atmospheric conditions is larger close to threshold

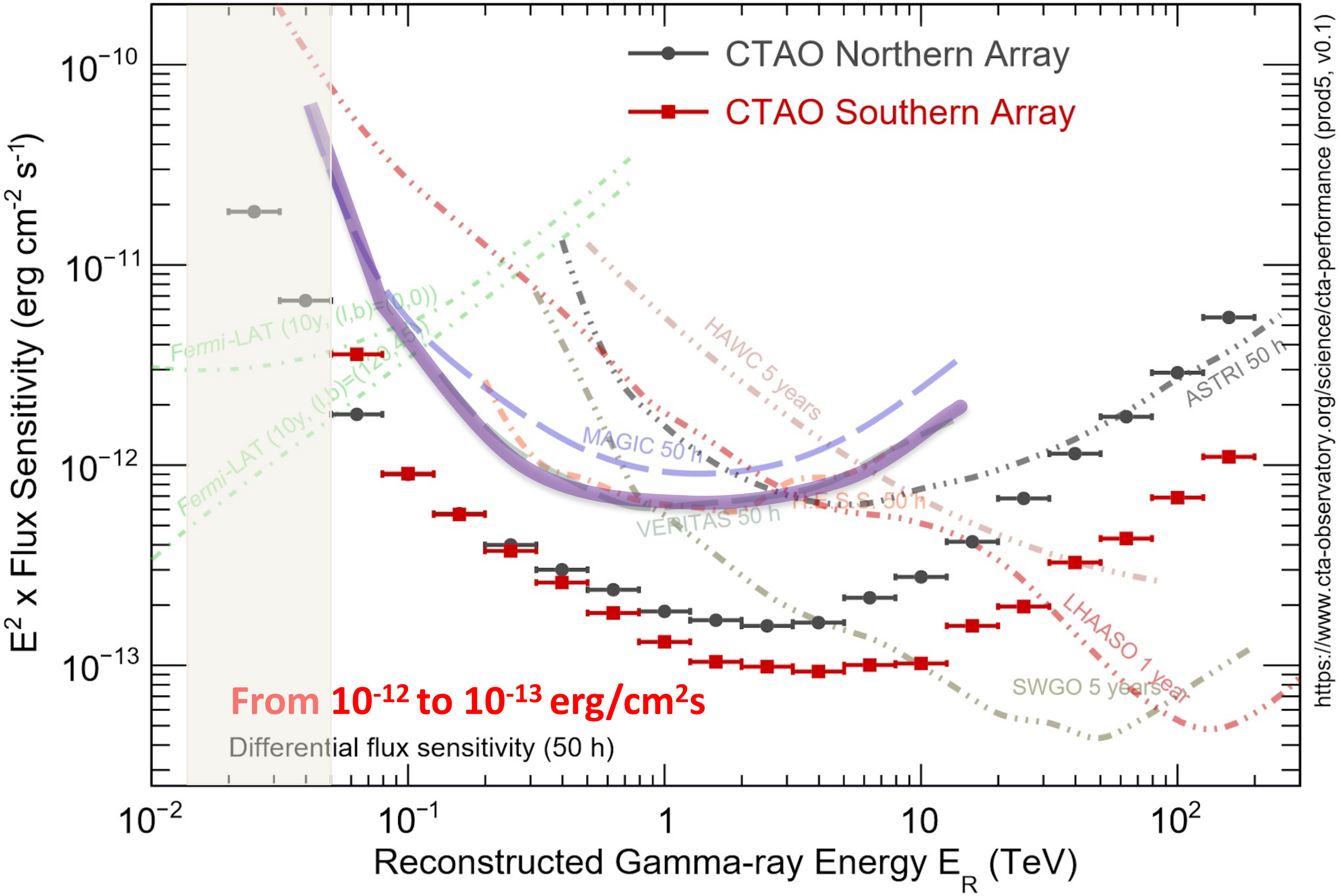
ID #773 M.Pecimotika

Array Layout Optimization
ID #88 O.Gueta

CTAO performance (Alpha Configuration)

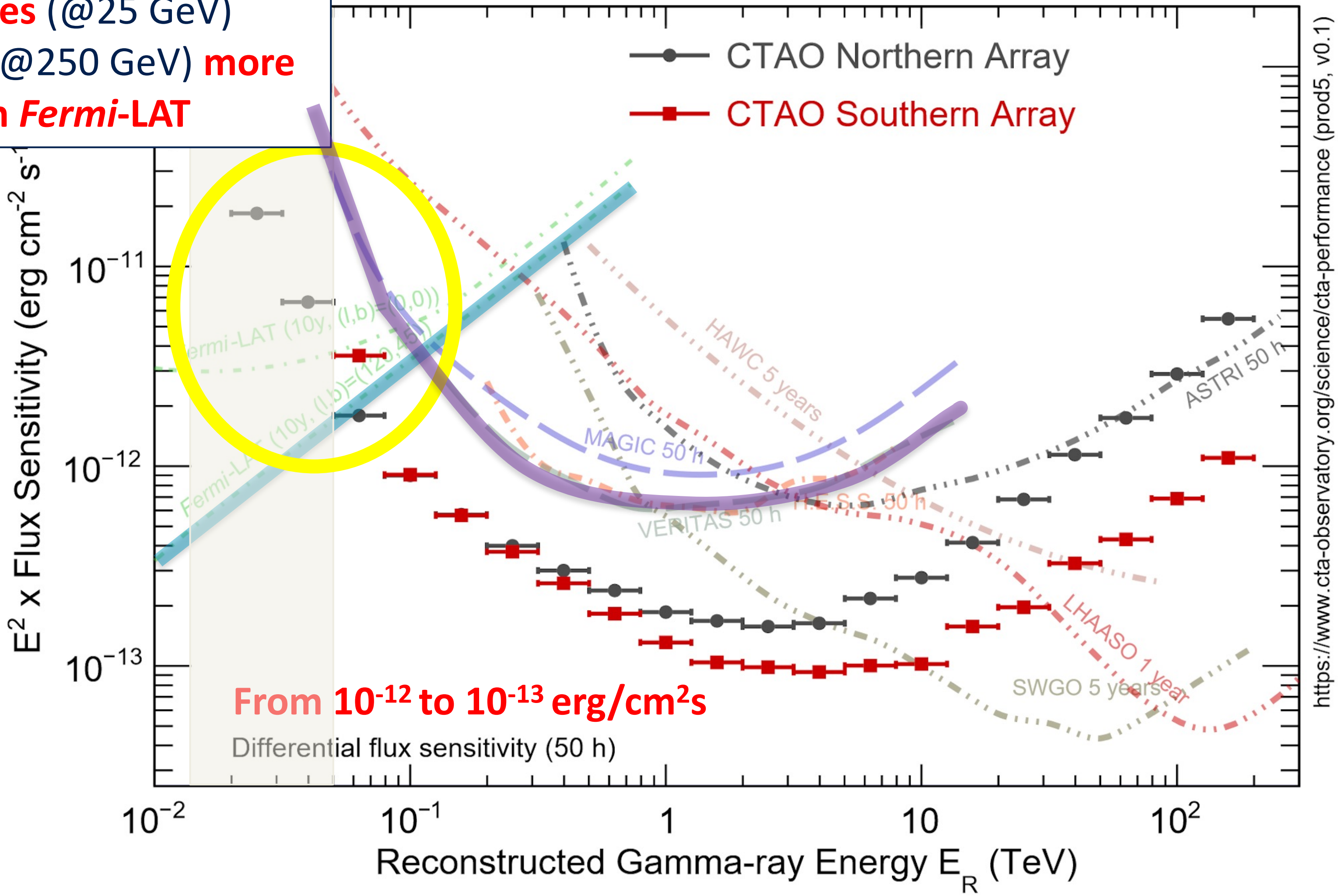


CTAO performance (Alpha Configuration)

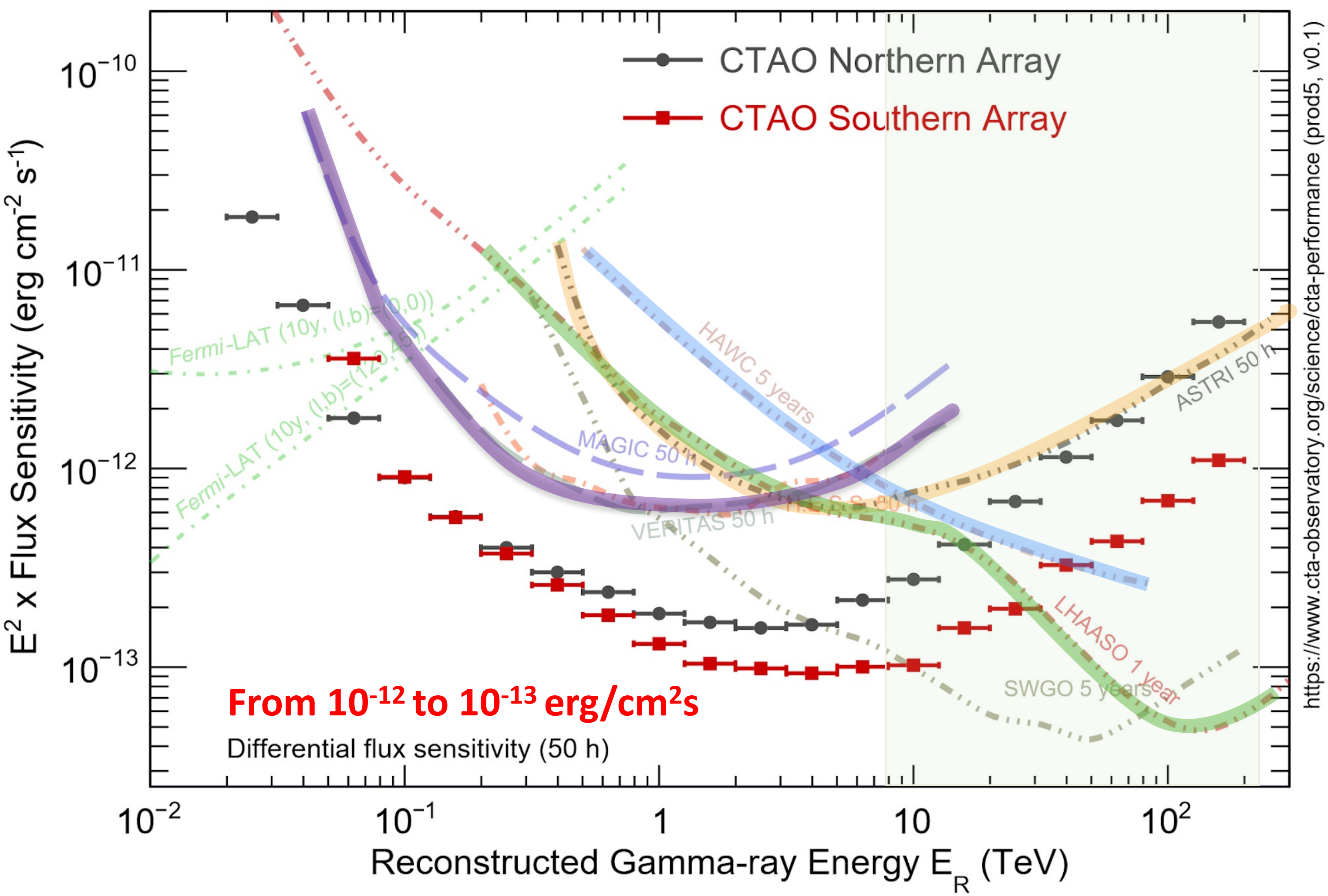


CTAO performance (Alpha Configuration)

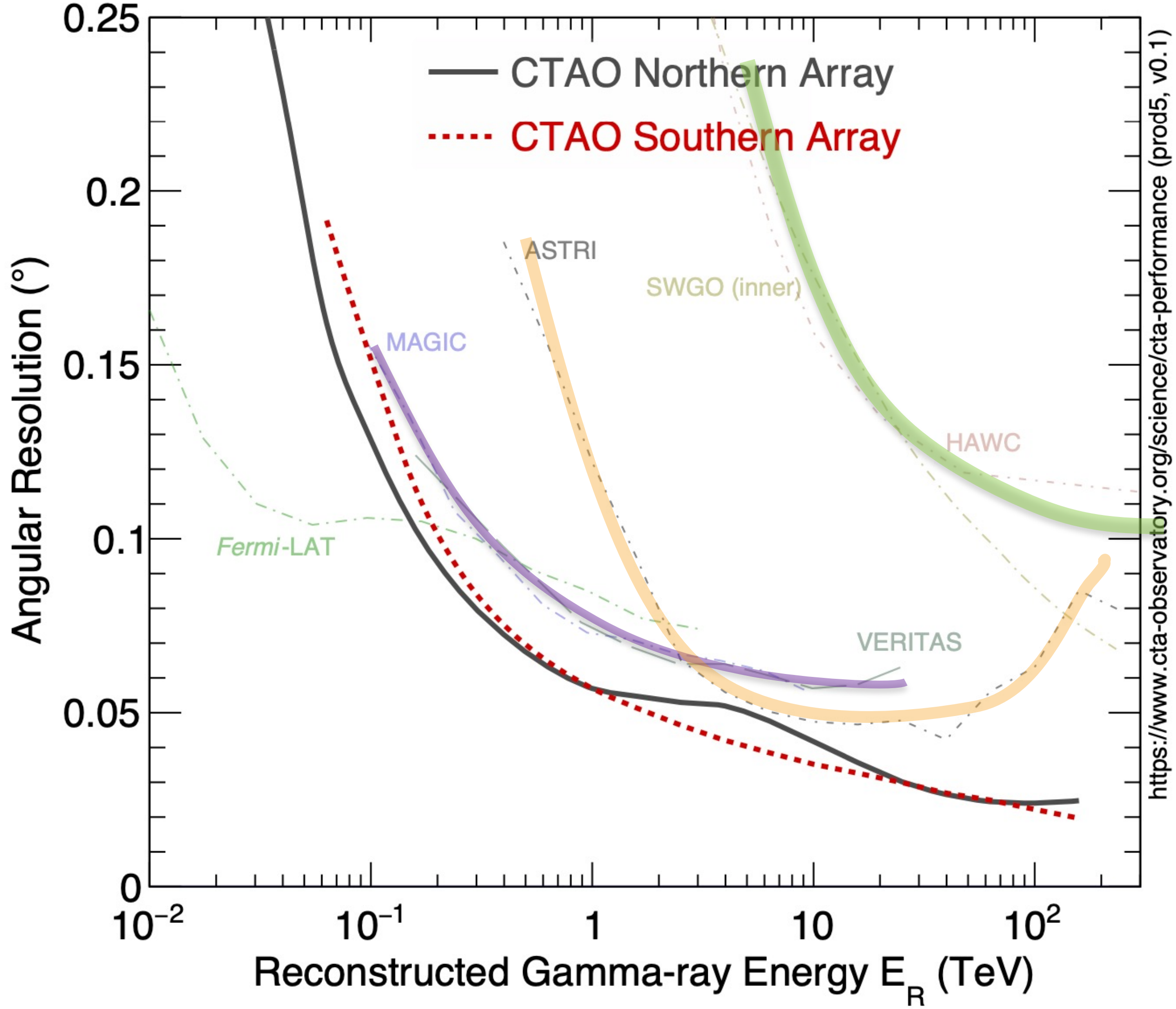
On time scales <1 h
CTA is **10³ times** (@25 GeV) to **10⁶ times** (@250 GeV) **more sensitive than *Fermi*-LAT**



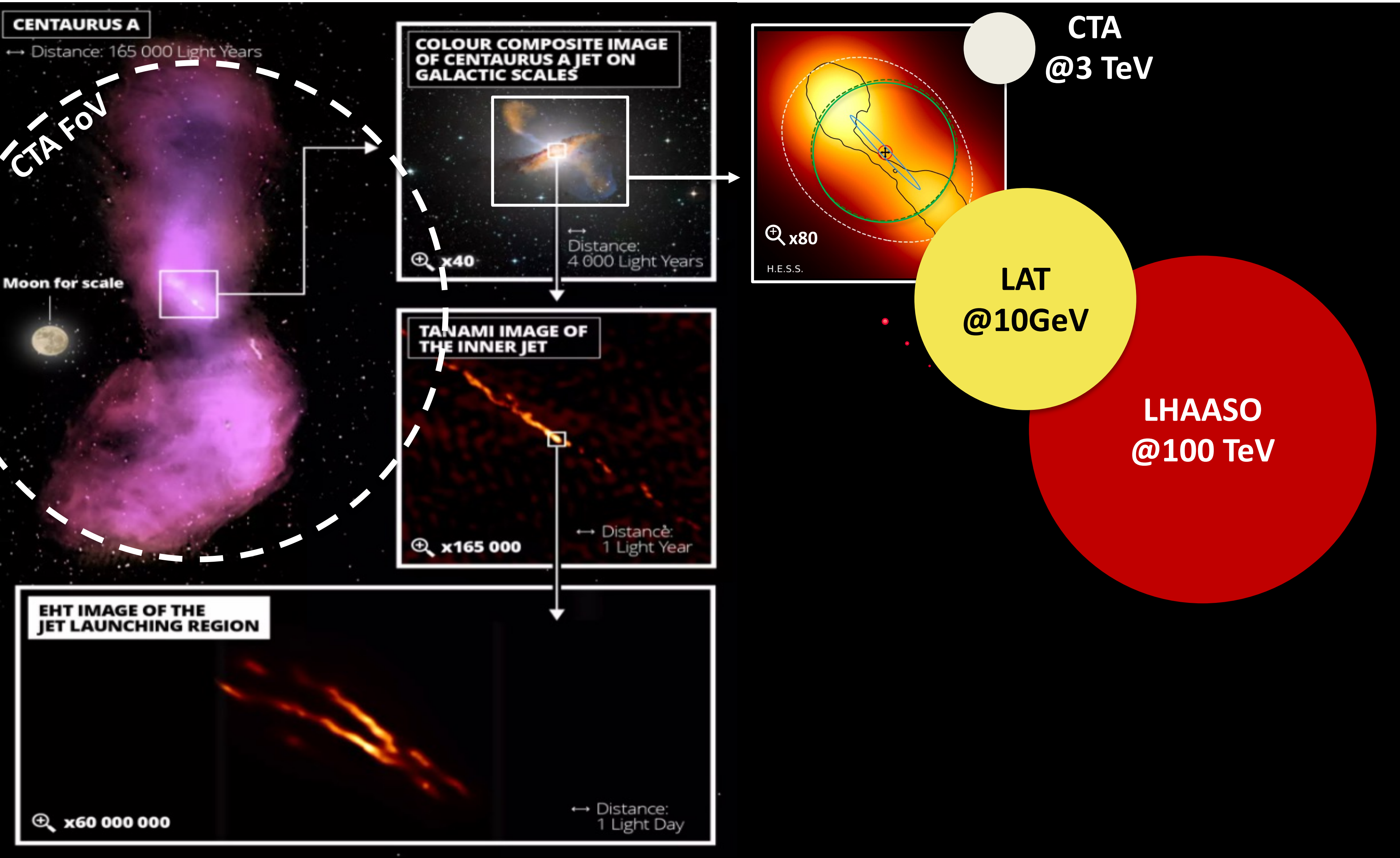
CTAO performance (Alpha Configuration)



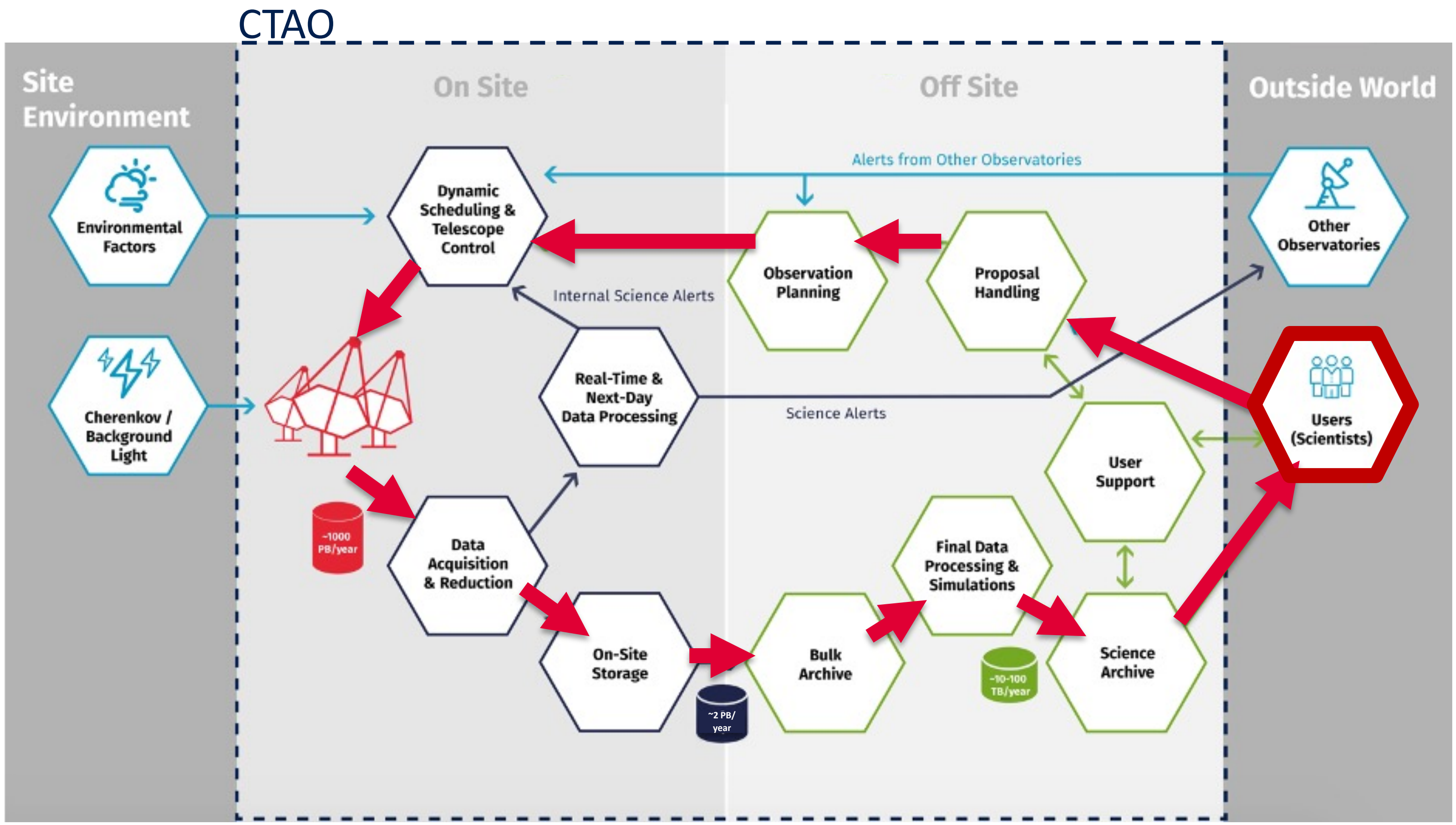
CTAO performance (Alpha Configuration)



CTAO performance (Alpha Configuration)

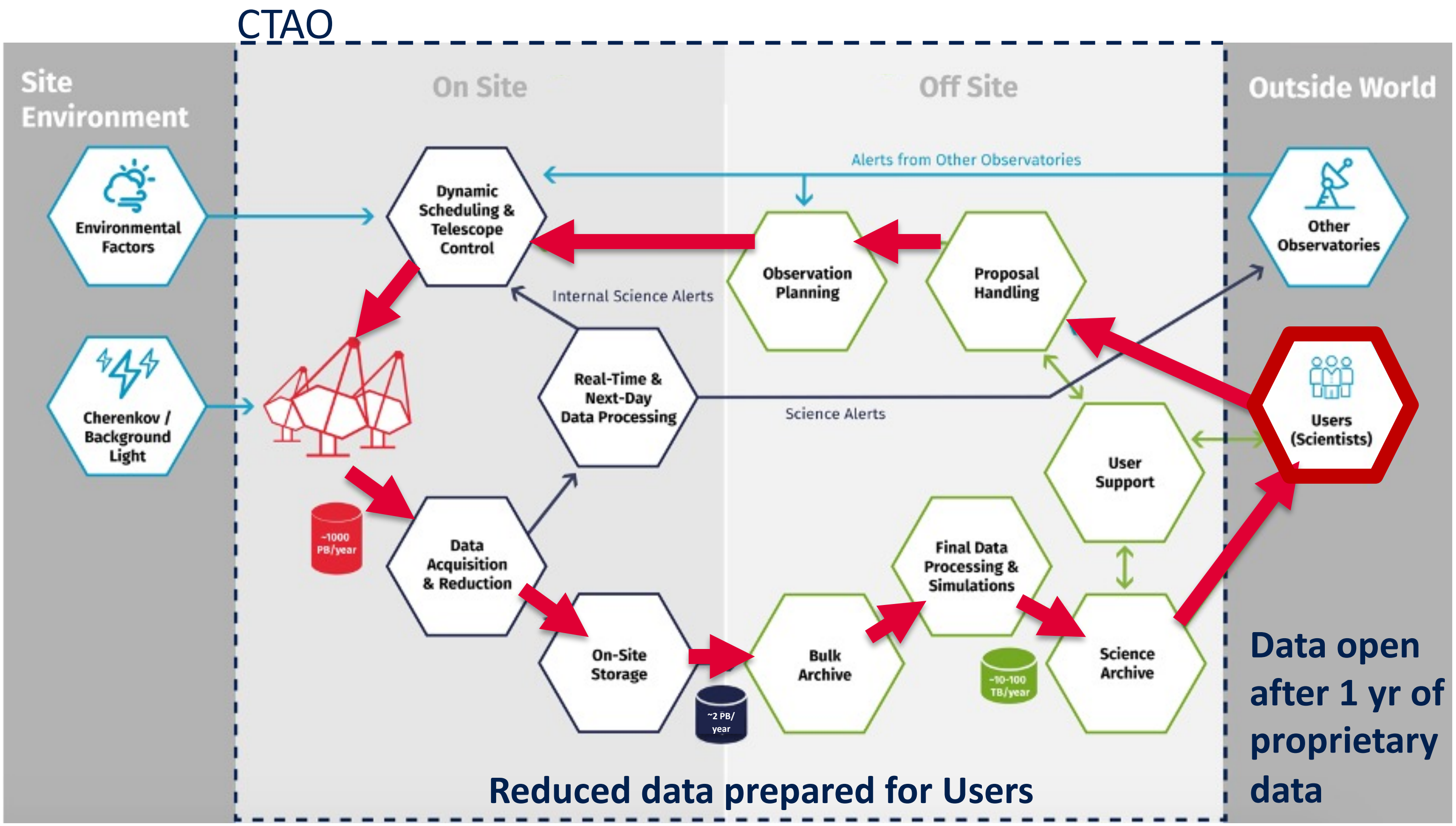


CTA Observatory



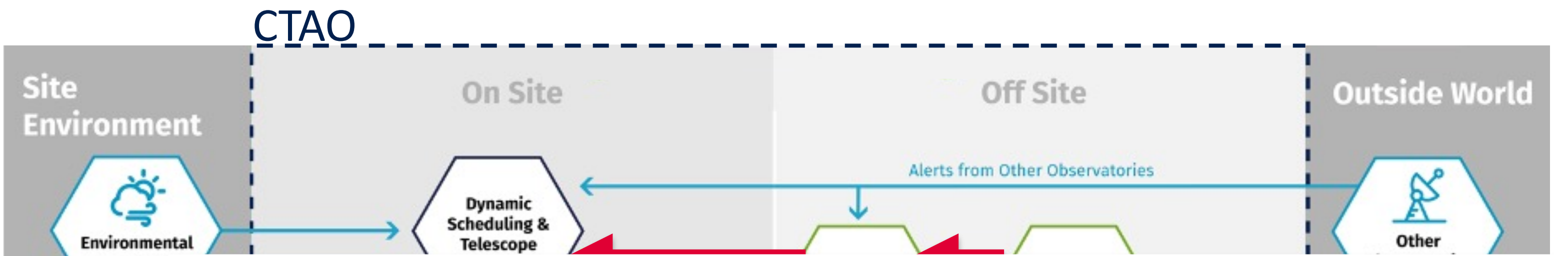
- **Proposal driven observatory**: standard proposals & Key Science Projects
- **Proposals evaluated on scientific merits** by a Time Allocation Committee

CTA Observatory



Prototype data reduction pipeline: ID #962 M.Noethe
Novel data reduction algorithm: ID #459 G.Emery
Deep learning for data reduction pipelines: ID #710 T.Miener
Convolutional Networks for data reduction: ID #1440 P.Grespan & ID #272 M.de Bony de Lavergne & ID #168 J.Aschersleben

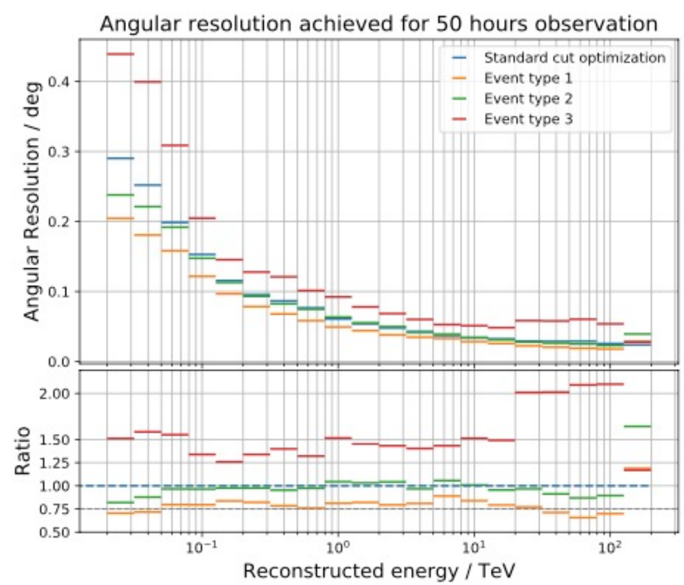
CTA Observatory



EVENT-TYPE BASED ANALYSIS UNDER EVALUATION

Events are divided into sub-samples based on their reconstruction quality

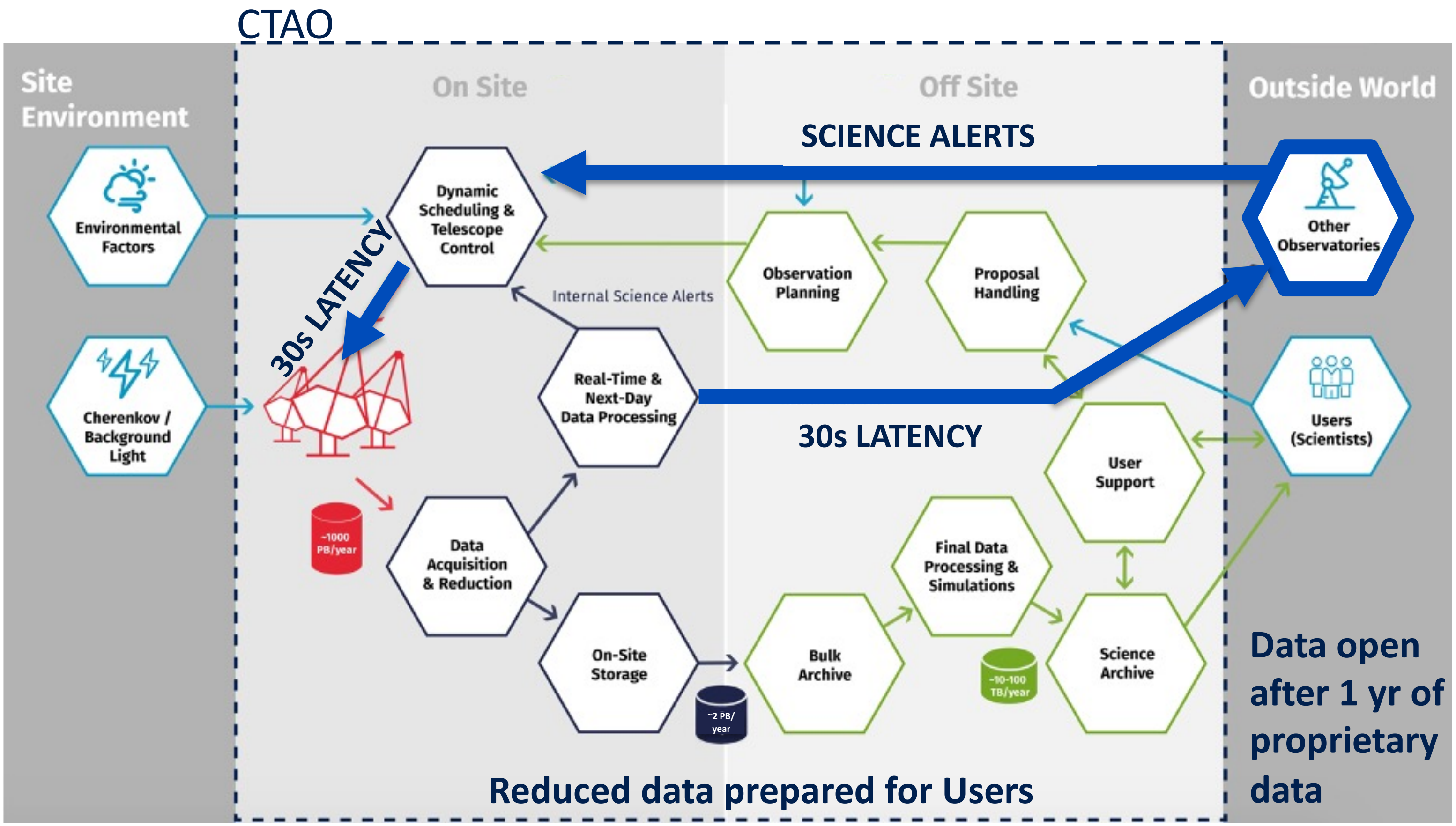
Sub-samples of different quality events are treated as independent observations, each with its IRFs



GREAT POTENTIAL TO IMPROVE CTA CAPABILITIES !

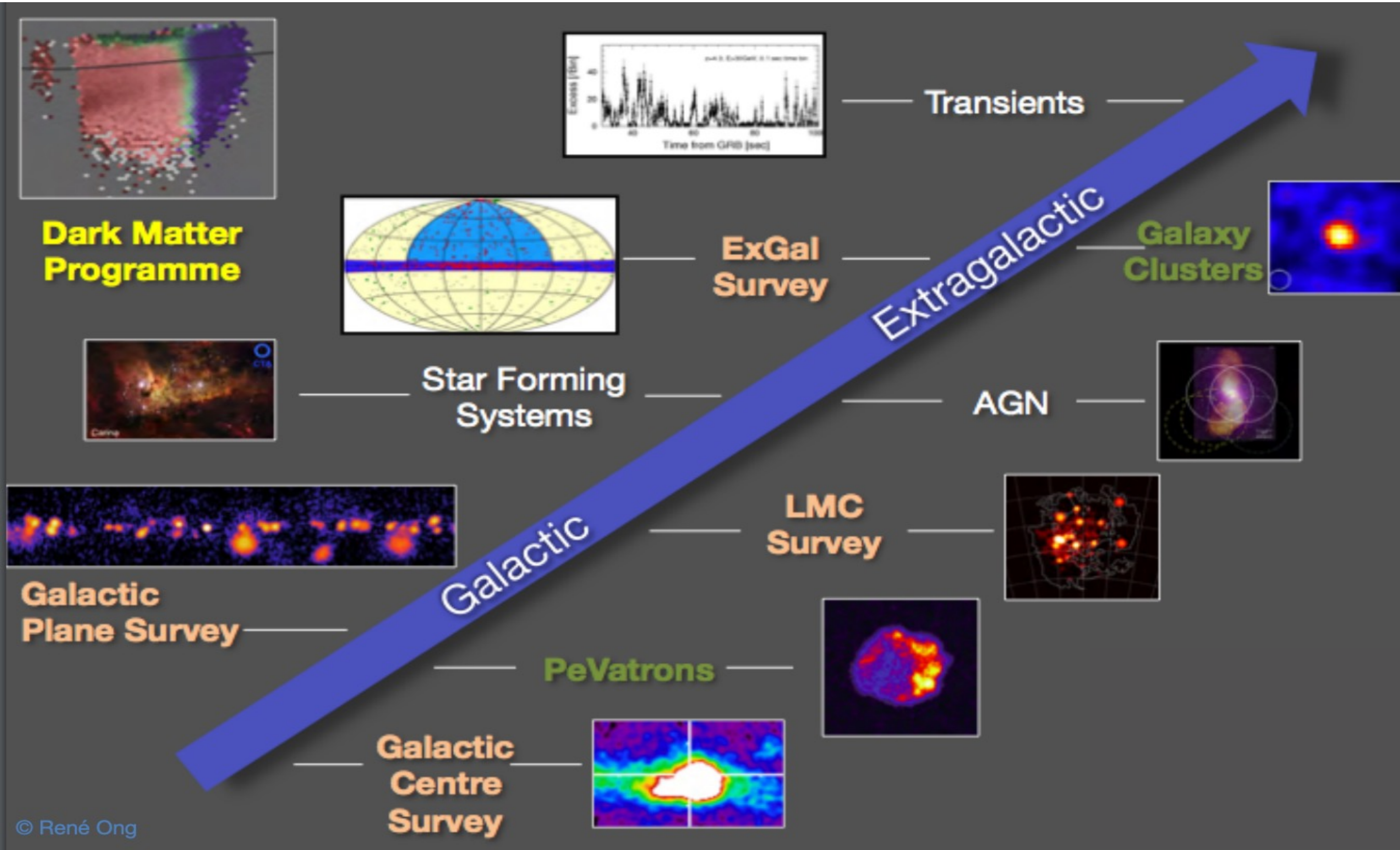
ID #773 T.Hassan

CTA Observatory



Science Alert Generator: ID #773 A.Bulgarelli
Short-term Detection Methods: #156 A.Di Piano
ACADA: #227 A.Costa

CTA Science Program



GW - GRB - UHE ν follow-up observations

simulation of source population based on open-source theoretical codes

→

estimation of gamma-ray emission based on phenomenological assumptions

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

↓

optimization of the CTAO observation strategy

↓

simulation of CTA response

↓

Estimation of the CTA detection rate

MM program: Indico-ID #833 A.Carosi
GRB: Indico-ID #1471 L.Nava
GW: Indico-ID #326 B.Patricelli
ν: Indico-ID #329 O.Sergijenko

GW - GRB - UHE ν follow-up observations

simulation of source population based on open-source theoretical codes

→

estimation of gamma-ray emission based on phenomenological assumptions

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

optimization of the CTAO observation strategy

simulation of CTA response

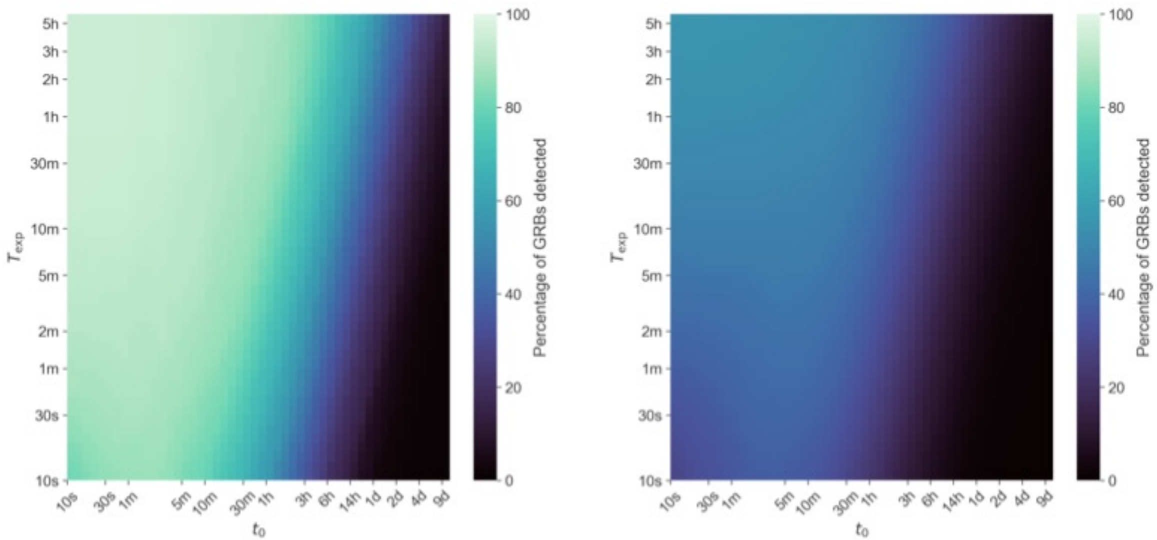
Estimation of the CT[A] detection rate

2-3 GRB per year!

MM program: Indico-ID #833 A.Carosi
GRB: Indico-ID #1471 L.Nava
GW: Indico-ID #326 B.Patricelli
ν: Indico-ID #329 O.Sergijenko

GW - GRB - UHE ν follow-up observations

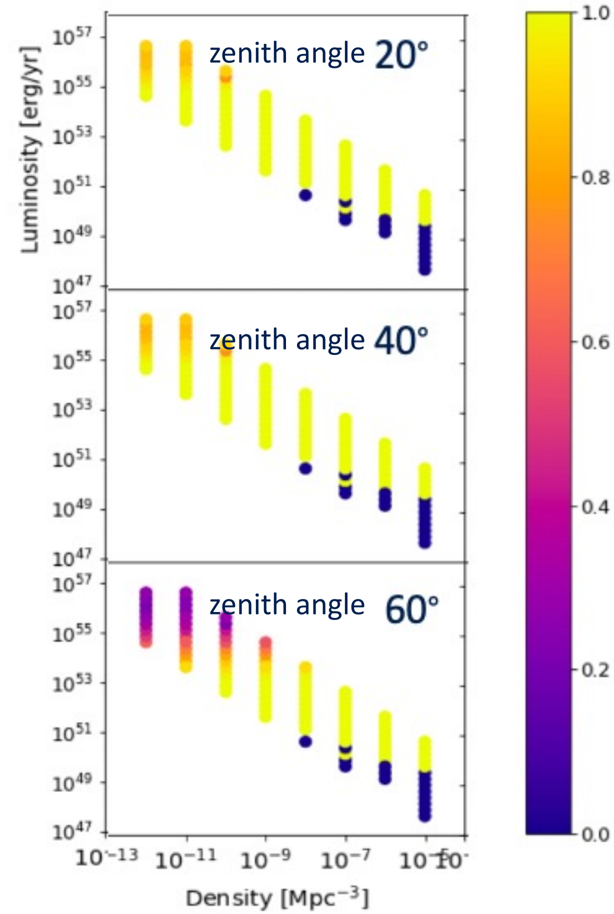
SHORT GRBs



(c) CTA North, z20°, ($\theta_{\text{view}} < 10°$) **(d)** CTA North, z20°, ($\theta_{\text{view}} < 45°$)

ID #326 B.Patricelli

UHE ν events



ID #329 O.Sergijenko

very large parameter phase space

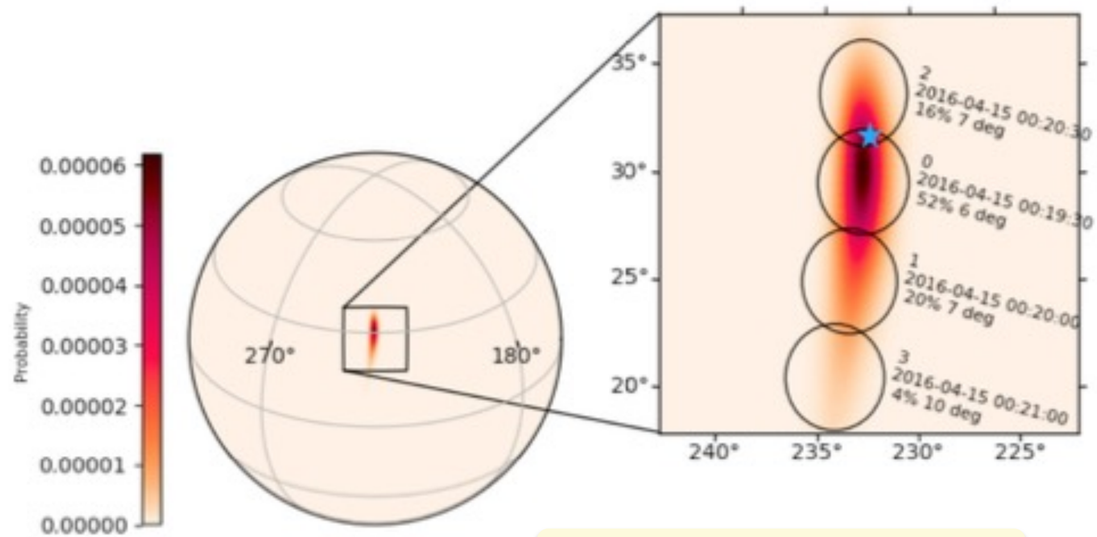
- intrinsic physical parameters (θ_{view}, Luminosity, Density)
- observational parameters

prospects for detection are very promising!

CTA 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

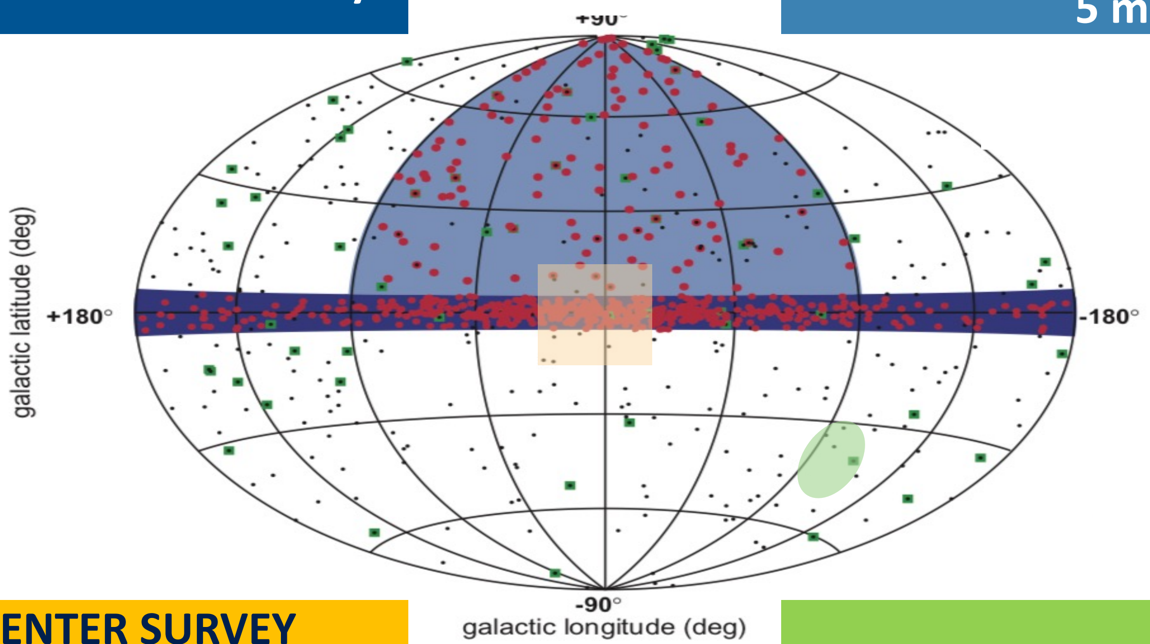


ID #326 B.Patricelli

Census of VHE sky: CTA surveys

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

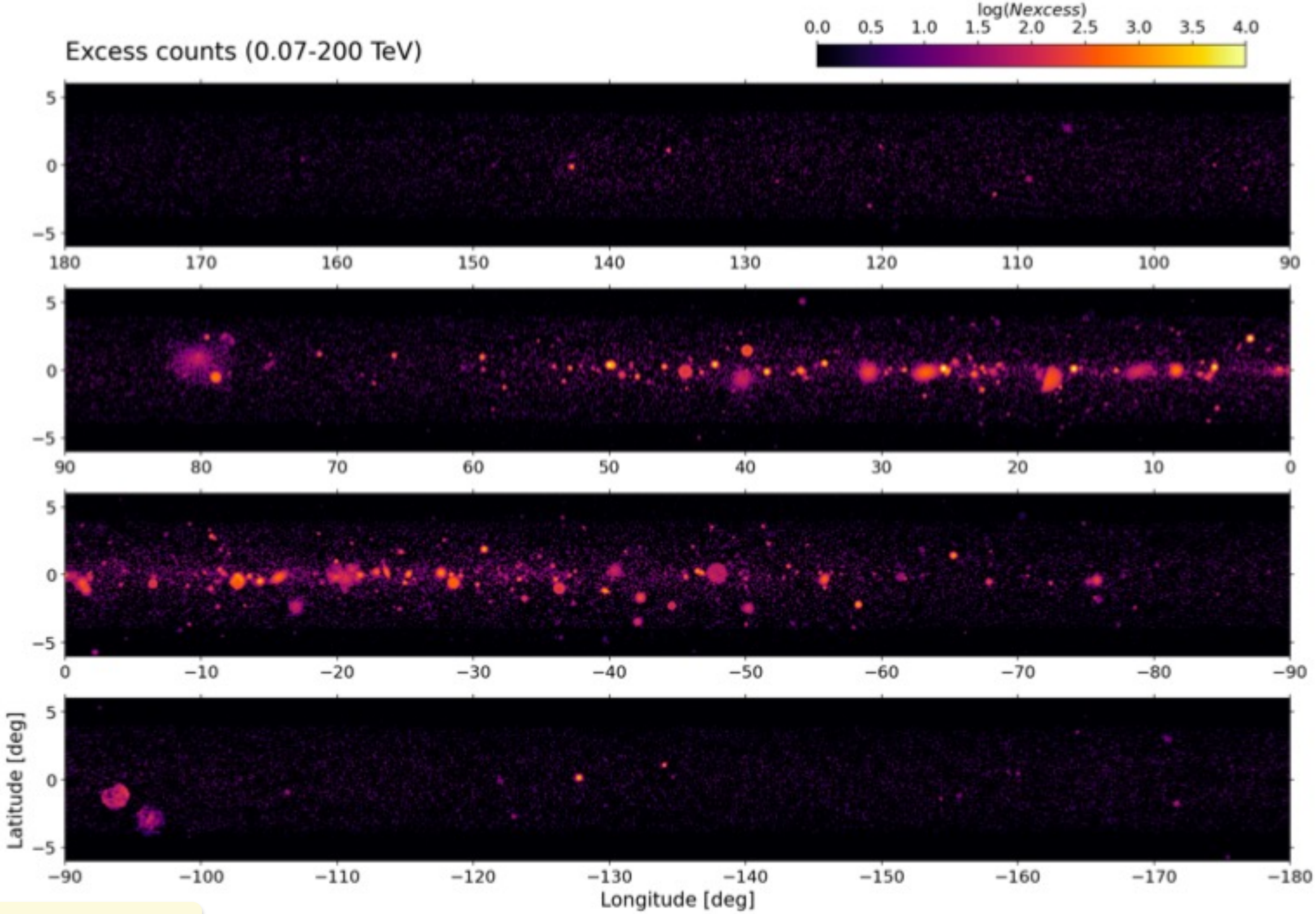
EXTRAGALACTIC SURVEY
first unbiased survey of VHE sky → huge discovery space
25% of the sky
5 mCrab



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

LARGE MAGELLANIC CLOUD SURVEY
in only 10 pointings

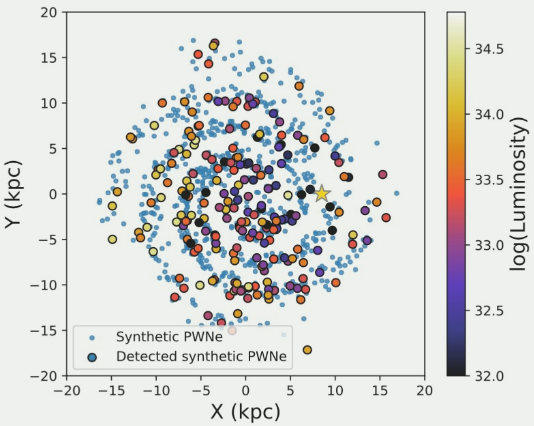
Galactic Plane Survey

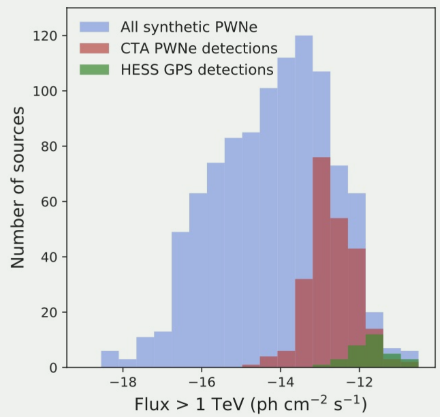


ID #329 Q.Remy

Source population studies

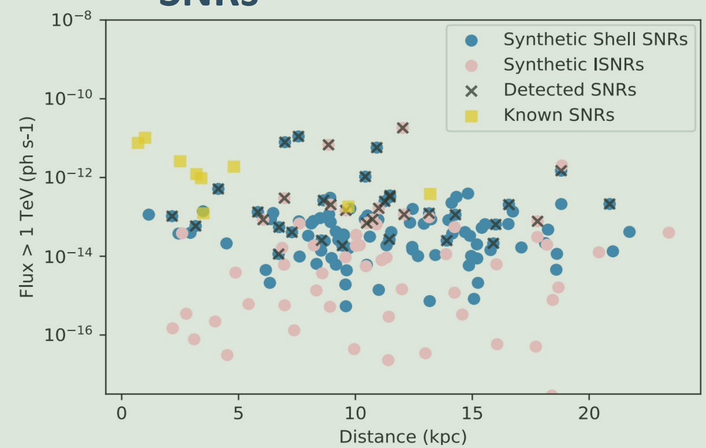
PWNe





- transformational jump in population size to the PWNe field

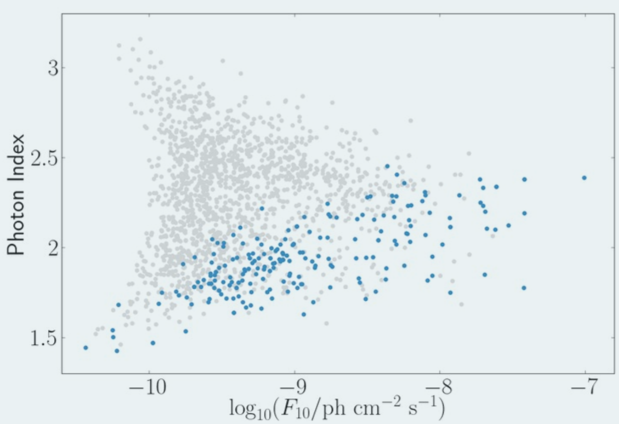
SNRs

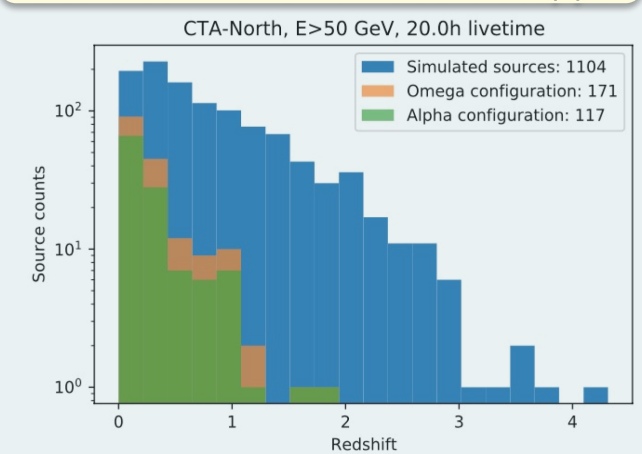


- SNRs up to other side of the Galaxy
- 5-10 times better flux sensitivity

CTA GPS: ID #329 Q.Remy
Obs bias in GPS: ID #311 C.Steppa

AGNs

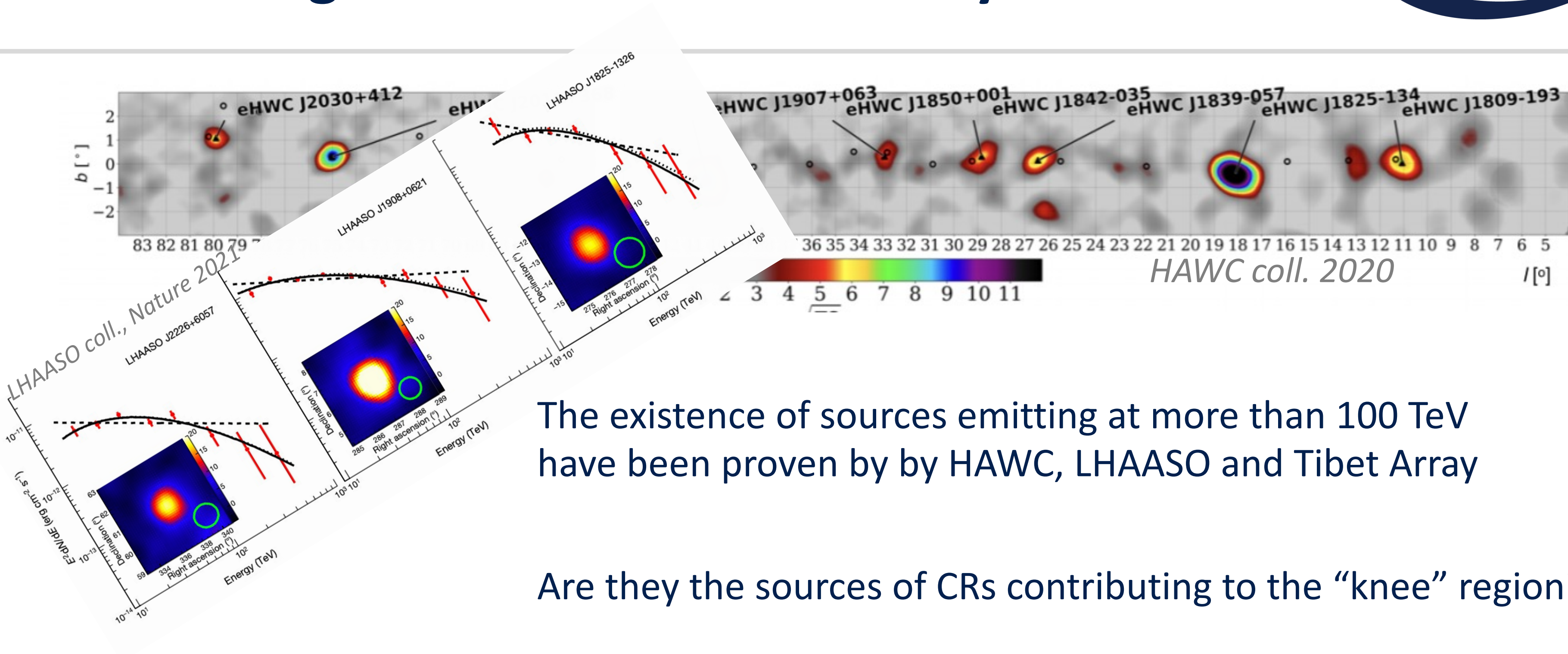




- factor >2 detected non-flaring AGNs
- enlarge the γ-ray horizon up to z≃2

ID #245 A.Brown

The strength: precision-study capabilities origin of Galactic Cosmic Rays



HAWC coll. 2020
LHAASO coll., Nature 2021

The existence of sources emitting at more than 100 TeV have been proven by by HAWC, LHAASO and Tibet Array

Are they the sources of CRs contributing to the “knee” region?

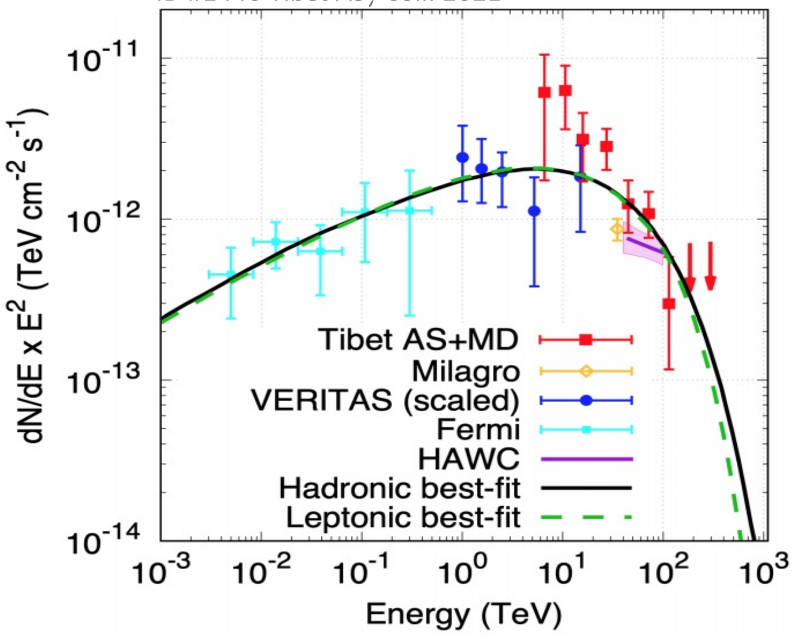
Only the synergy between these instruments and IACTs, specifically CTAO, and neutrino experiments can provide a univocal answer to this question

The strength: precision-study capabilities origin of Galactic Cosmic Rays

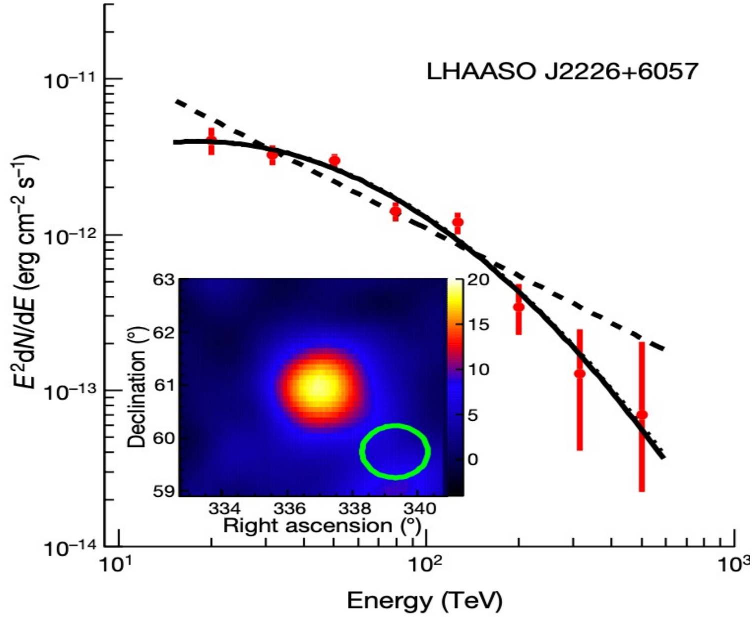
Test case: G106.3+2.7

Is the emission seen by HAWC/LHAASO/Tibet ASγ of hadronic or leptonic origin?

ID #1440 Tibet ASγ Coll. 2021

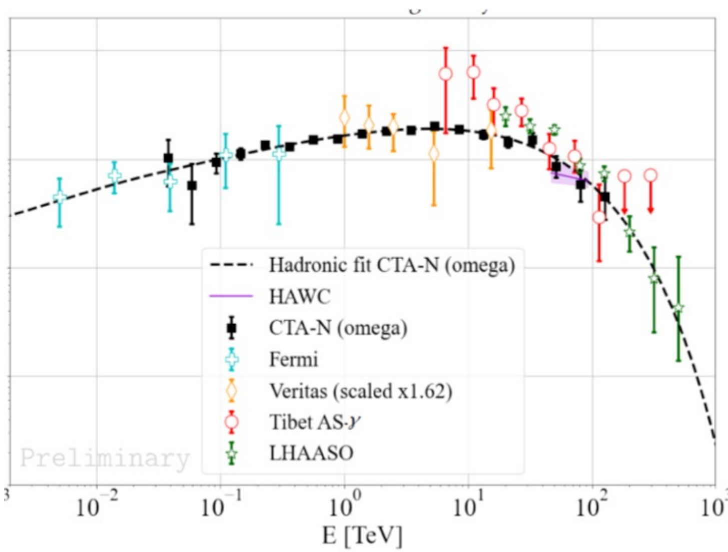


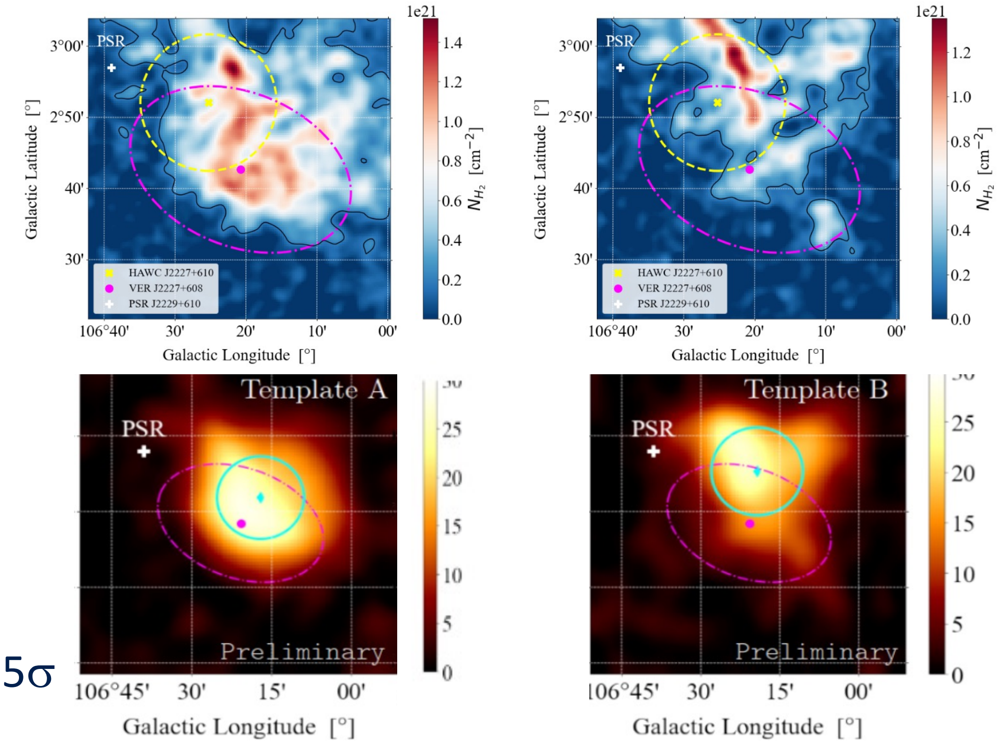
LHAASO Coll. Nature 2021



The strength: precision-study capabilities origin of Galactic Cosmic Rays

Test case: G106.3+2.7
Is the emission seen by HAWC/LHAASO/Tibet Array of hadronic or leptonic origin?





CTA will be able to detect the spectral cut-off at ~50 TeV in 50 hr at more than 5σ

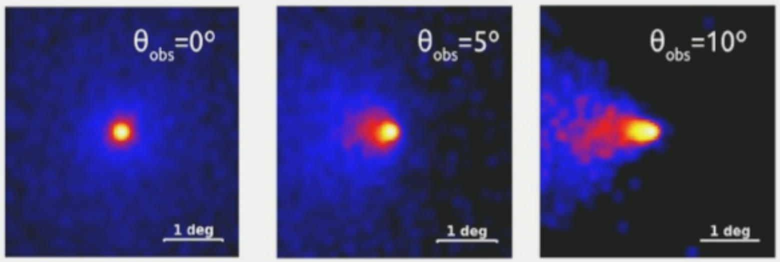
not enough to disentangle between hadronic or leptonic origin

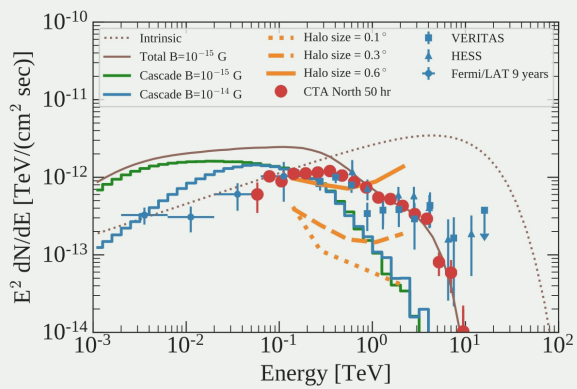
morphological studies will provide important clues given the CTA's excellent angular resolution

ID #1140 G.Verna

The strength: precision-study capabilities constraining γ-ray propagation

IGMF



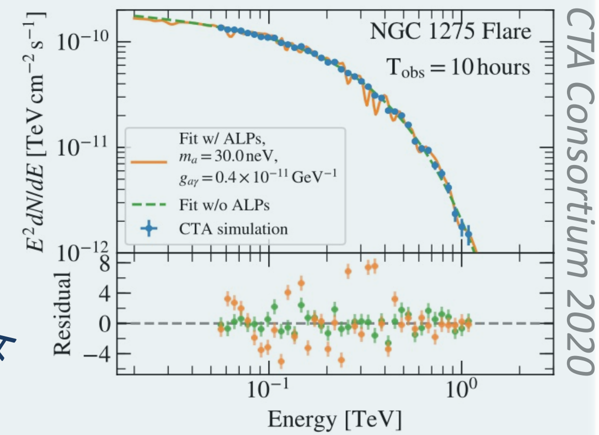


CTA can measure extended halos as well as detect new spectral components at low energies: all smoking guns for measurement of IGMF strength

ID #497 J.Vovk

ALPs

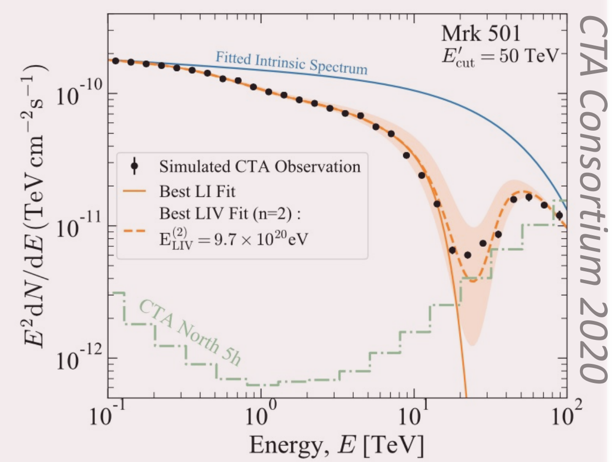
simulated ALP signature



At reach for CTA

LIV

simulated LIV signature



Other science cases

This talk does not include a comprehensive overview of all CTA science cases

- **Search for new classes of Galactic gamma-ray emitters**

  Galactic transients: ID #224 A.López-Oramas

- **Indirect measurements of the EBL** *(CTA Consortium 2020)*

  Galactic transients: ID #497 J.Vovk

- **Searches for dark matter** *(CTA Consortium 2020)*

  In the GC: ID #316 C.Eckner
  In Galaxy Clusters: ID288 # J.Pérez-Romero
  In dark sub-halos: ID #544 J.Coronado-Blázquez

- **Searches for VHE gamma-ray pulsars**

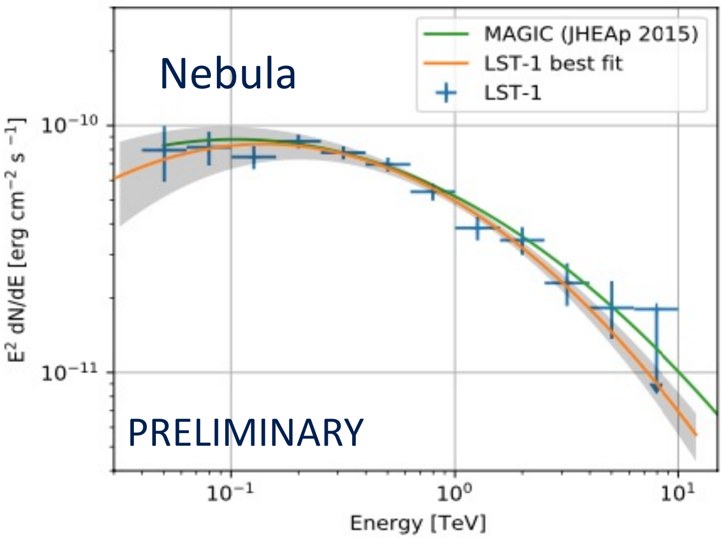
and much more in "Science with CTA"
https://www.worldscientific.com/worldscibooks/10.1142/10986

LST-1 already performing science

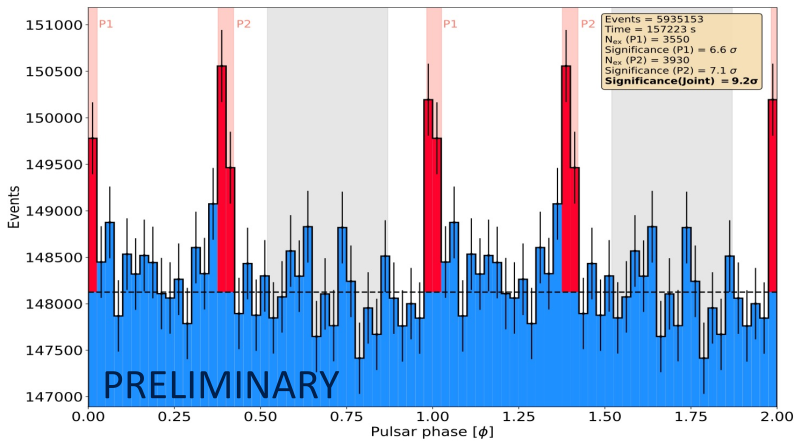
Camera Calibration:
ID#531 Y. Kobayashi
Camera Commissioning:
ID#509 T.Saito
Pointing System:
ID#392 L.Foffano

LST-1 already performing science

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

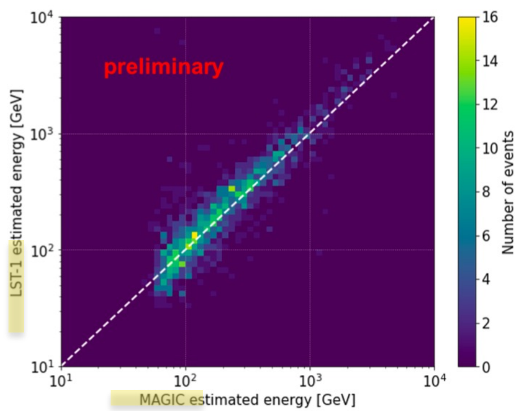


Pulsar: energy threshold ~50 GeV

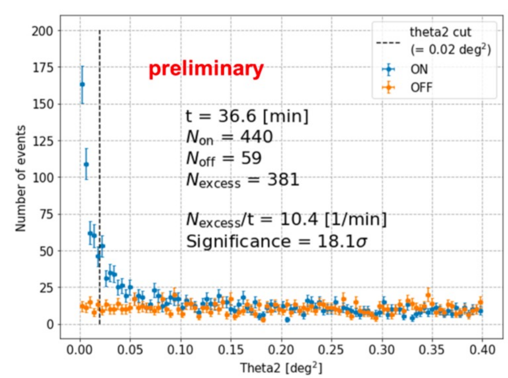


ID #395 R.Lopez-Coto

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



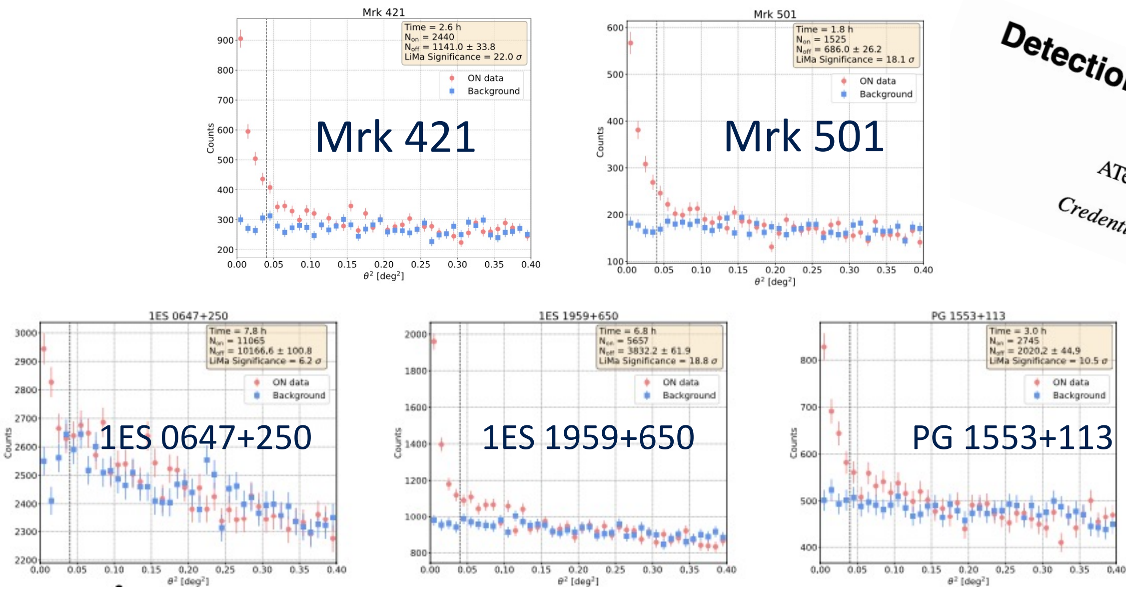
ID #560 Y.Ohtani



LST-1 already performing science

ID #395
R.Lopez-Coto

Several known gamma-ray sources already detected, mainly AGNs



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

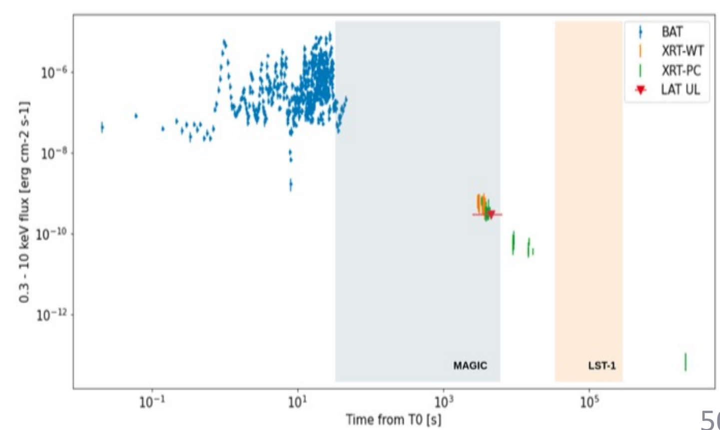
ATel #14783; *Juan Cortina for the CTA LST collaboration*
on 13 Jul 2021; 21:03 UT
Credential Certification: Juan Cortina (Juan.Cortina@ciemat.es)

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

ID #835 A. Carosi



CTAO Construction phase is about to start

- **CTAO construction scope is agreed**
- The construction phase will start with the establishment of the final legal entity:
  CTAO European Research Infrastructure Consortium (ERIC)
  - by Summer/End 2022
  - last about 5 yr
- **Early science operations foreseen during the construction phase**

Announcement
2021-June-25

The Board of Governmental Representatives Approves the CTAO's Cost Book and Scientific & Technical Description

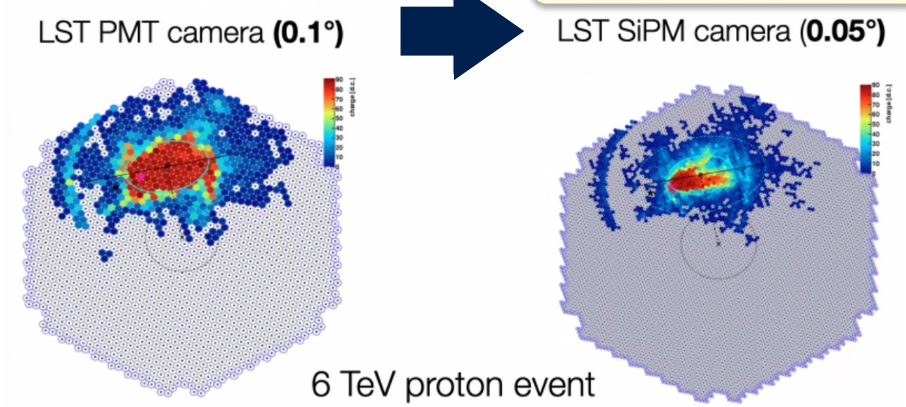
geographically distributed:

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

Already looking into potential future development programmes for CTAO

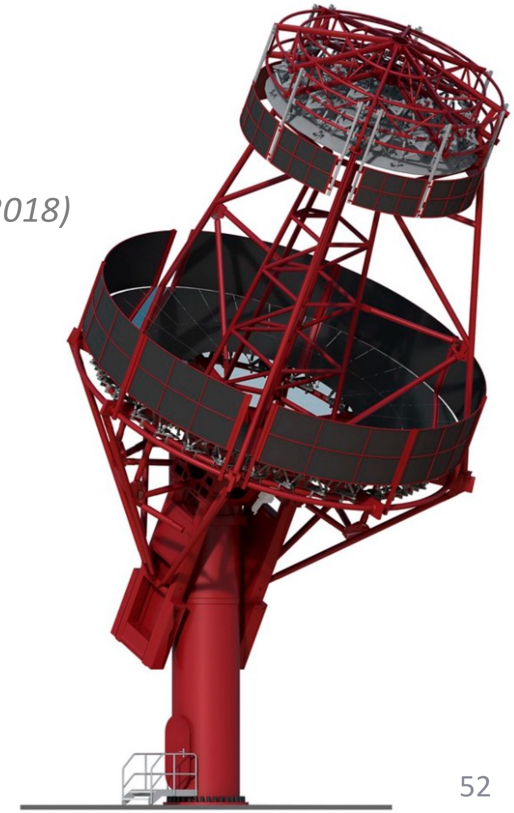
- **LST-like SiPM camera**

ID #347 M.Heller



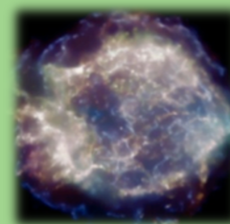
- **Stellar intensity interferometry capabilities** *(Dravins+2014, Colin+2018)*
  - PoC observations by MAGIC and VERITAS show the great scientific potential *(ID #803, ID #710, ID #693)*
- **Schwarzschild-Couder Telescope (SCT): another design for a future CTAO MST**
  - factor 1.5-2 better angular resolution
  - 25% better sensitivity
  - key technologies demonstrated by prototype

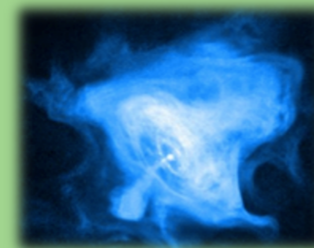
Camera Design: ID #1027 L.Taylor
Optical System: ID #474 D.Ribeiro
Crab detection: ID #830 B.Mode



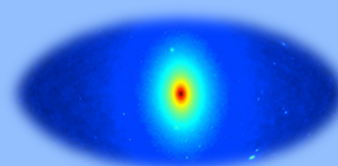
CTA: a phase transition in VHE γ-ray astronomy

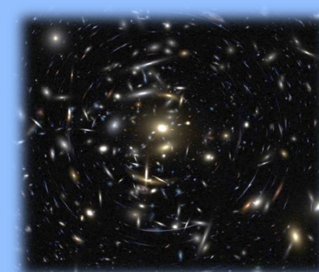
In-depth understanding of known objects and their mechanisms





Expected discoveries of new object classes





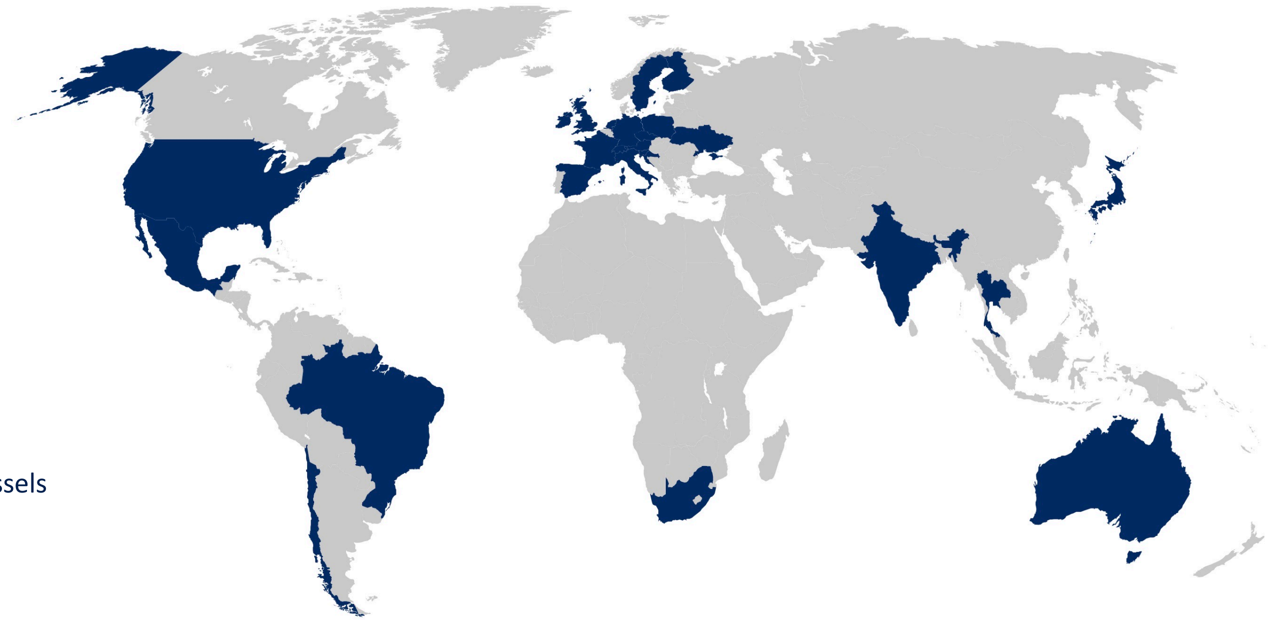
The fun part:
Things we haven't thought of

?

cta cherenkov telescope array

Thank you

CTA Consortium



25 Countries
over 150 Institutes
over 1000 Scientists

Effort started in 2006
March 8, 2006: first presentation in Brussels

CTA LST Collaboration

- The CTA LST Collaboration consists of 250+ scientists from 12 countries
- Learn more at : https://www.cta-observatory.org/project/technology/lst/ and https://www.lst1.iac.es/collaboration.html