The Cherenkov Telescope Array and its Science

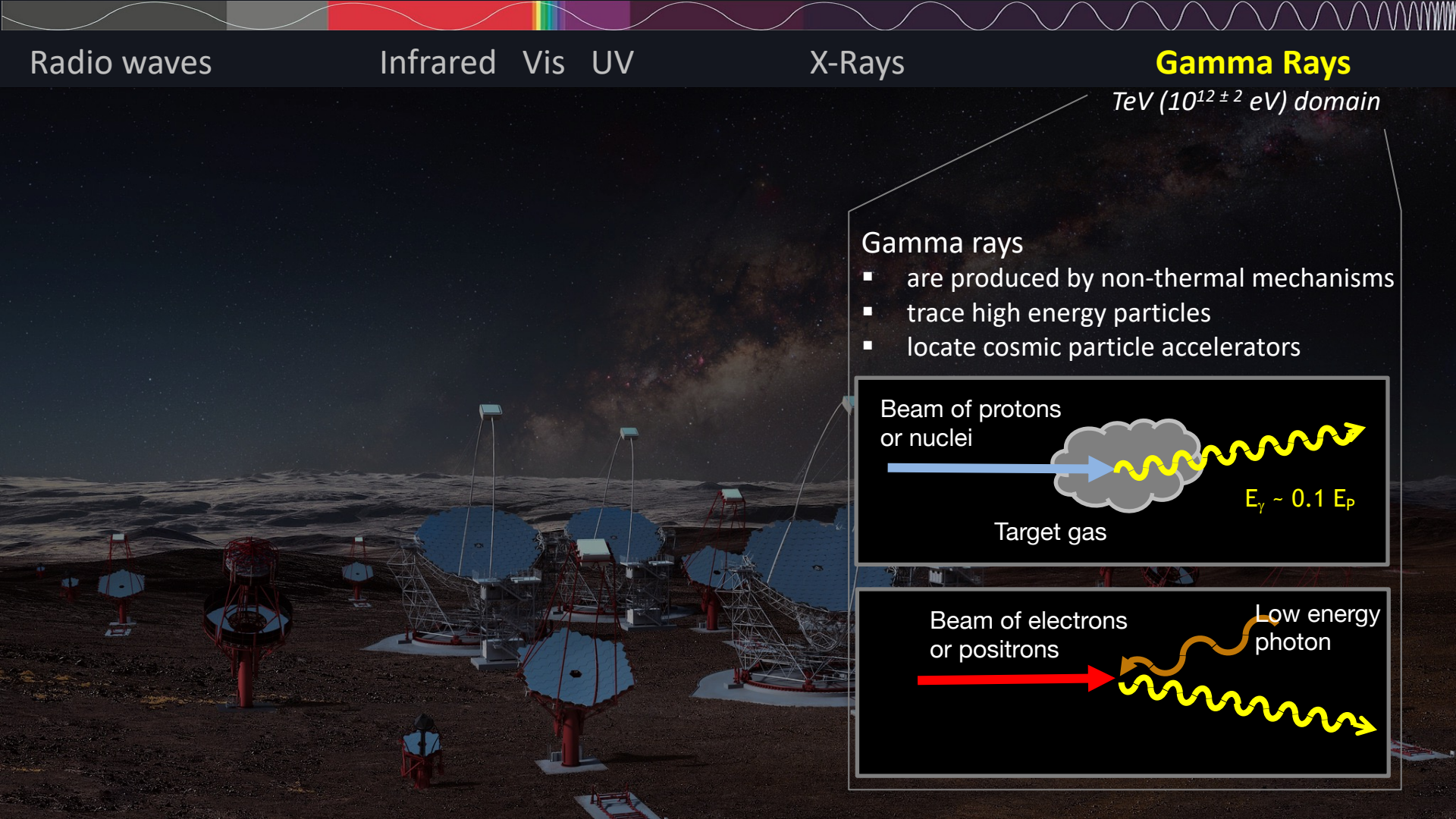
Paris-Saclay Astroparticle Symposium 2021
Nov. 25, 2021

Werner Hofmann
MPI for Nuclear Physics
Heidelberg

for the CTA Consortium

Radio waves Infrared Vis UV X-Rays **Gamma Rays**

TeV ($10^{12 \pm 2}$ eV) domain



Gamma rays

- are produced by non-thermal mechanisms
- trace high energy particles
- locate cosmic particle accelerators

Multiple telescopes provide stereoscopic views of the cascade

CHERENKOV TELESCOPES

A bit like a meteor track, but
very faint (few photons per m^2)
very short-lived (some 10^{-9} seconds)

300 m Ø “light pool”, 10^5 m^2

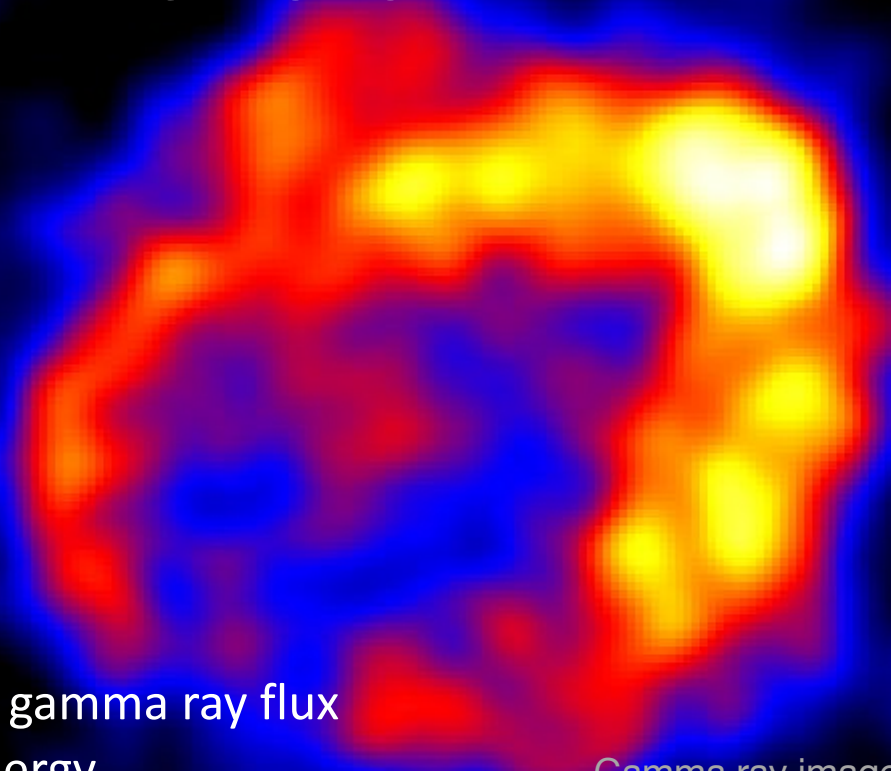

2003-09

GROUND-BASED GAMMA RAY ASTRONOMY

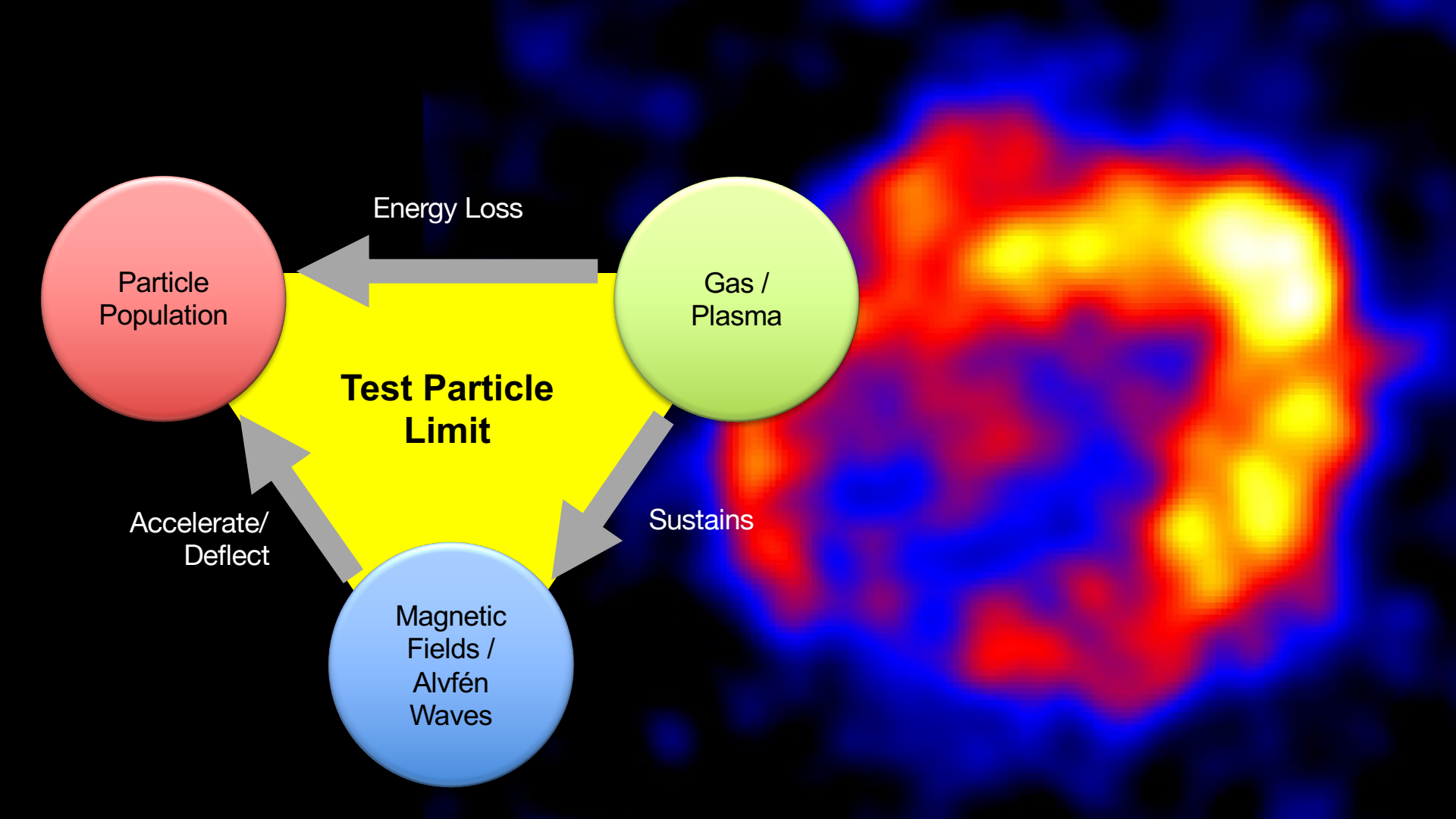
Real Astronomy!

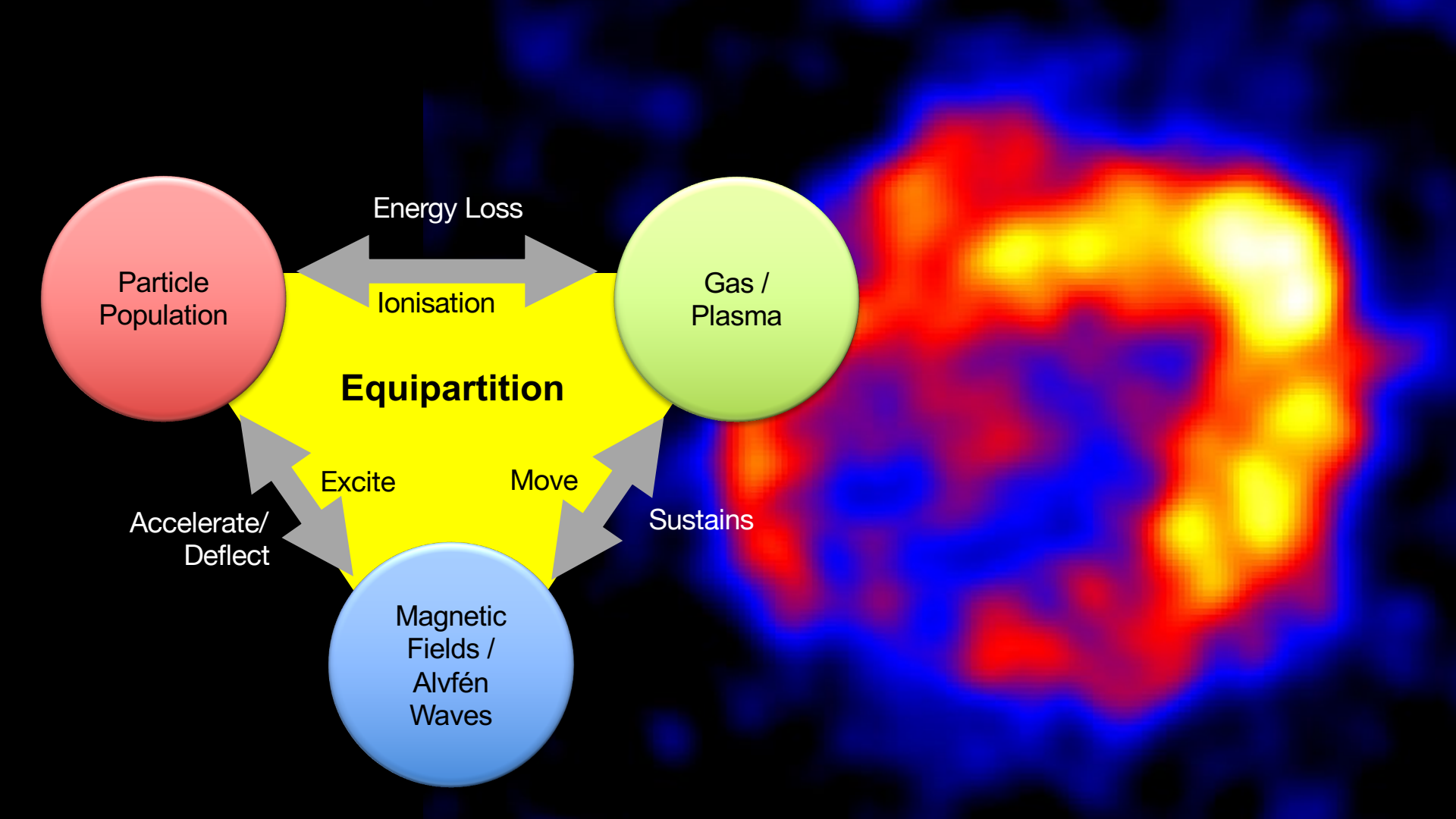
showing a different sky

- Sky maps with 5’ resolution
- Over 200 detected sources,
  covering 3 orders of magnitude in gamma ray flux
- Energy spectra over 3 decades in energy
- Light curves on all scales from minutes to years

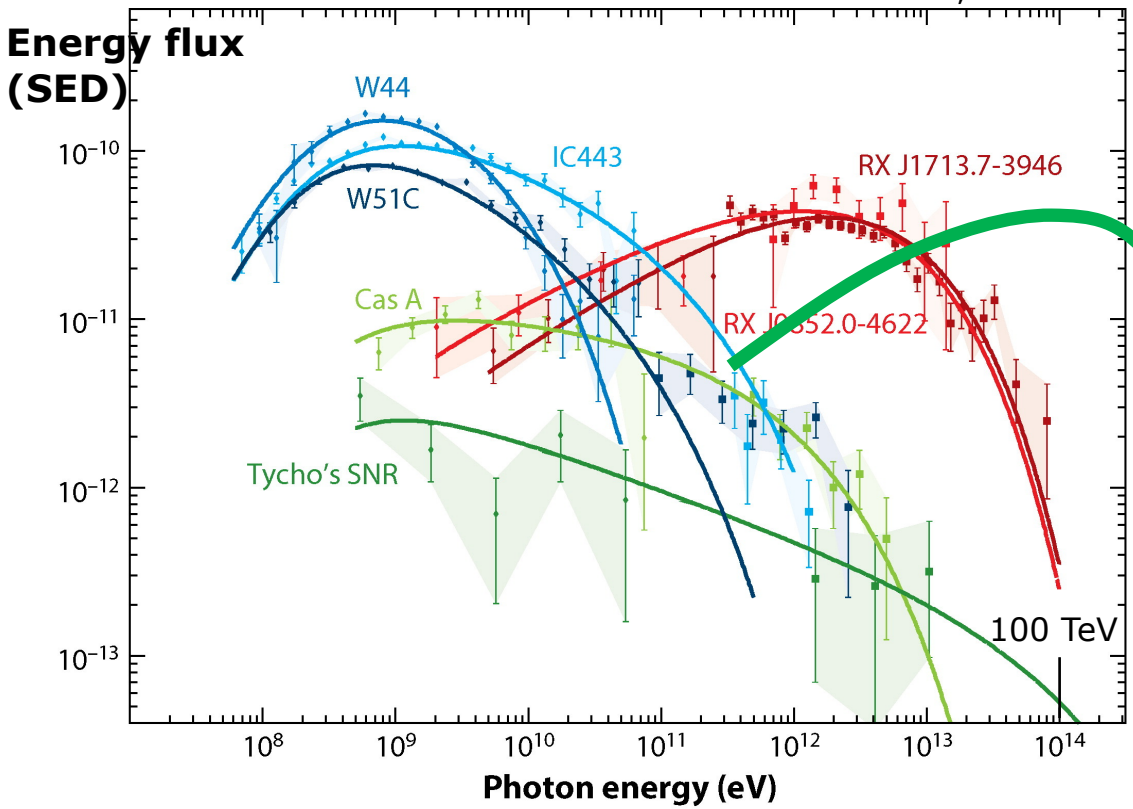


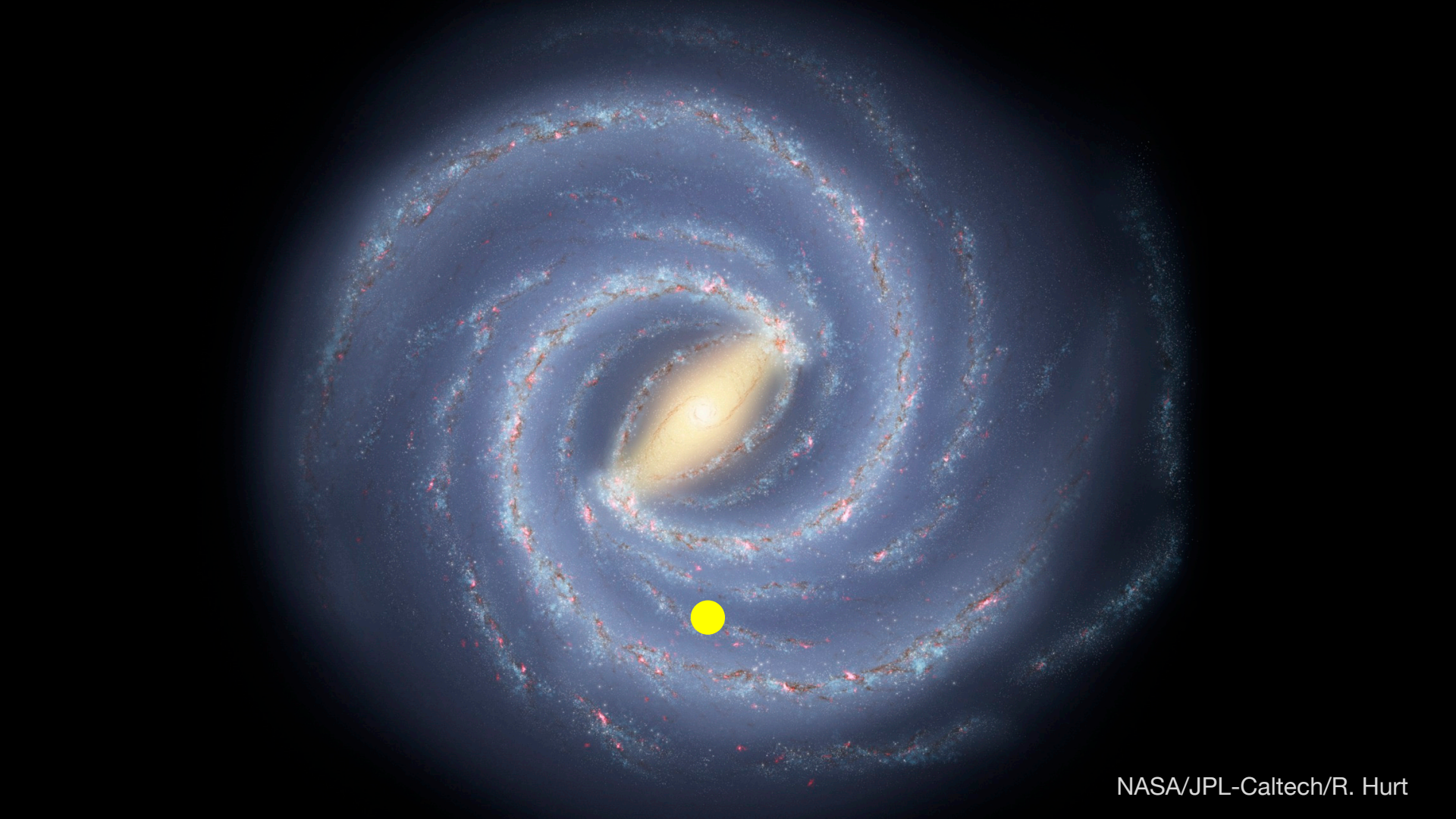
Gamma ray image
of supernova
RX J1713.7-3946

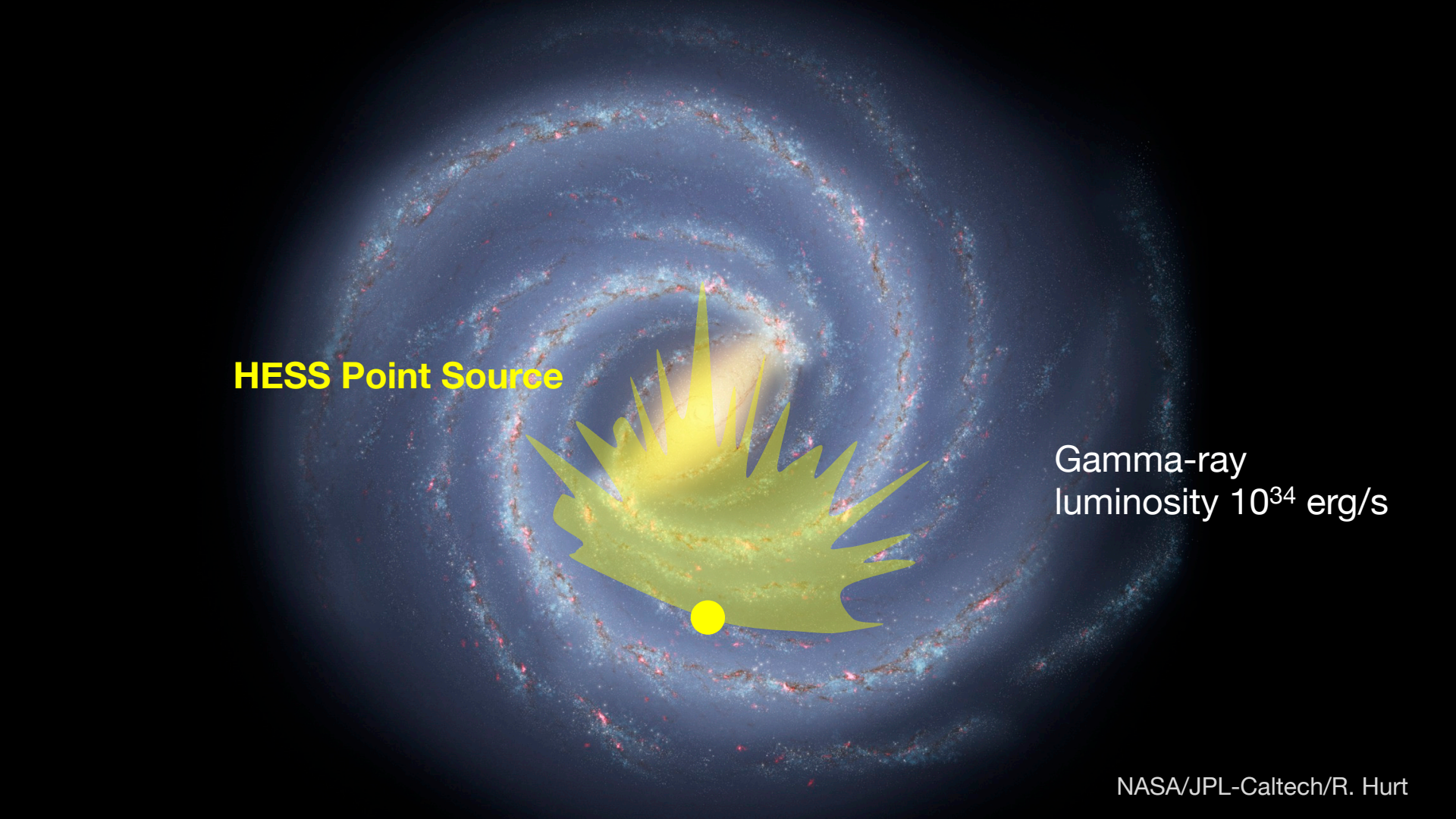

Energy Loss
Particle Population
Gas / Plasma
Test Particle Limit
Accelerate/ Deflect
Sustains
Magnetic Fields / Alvfén Waves

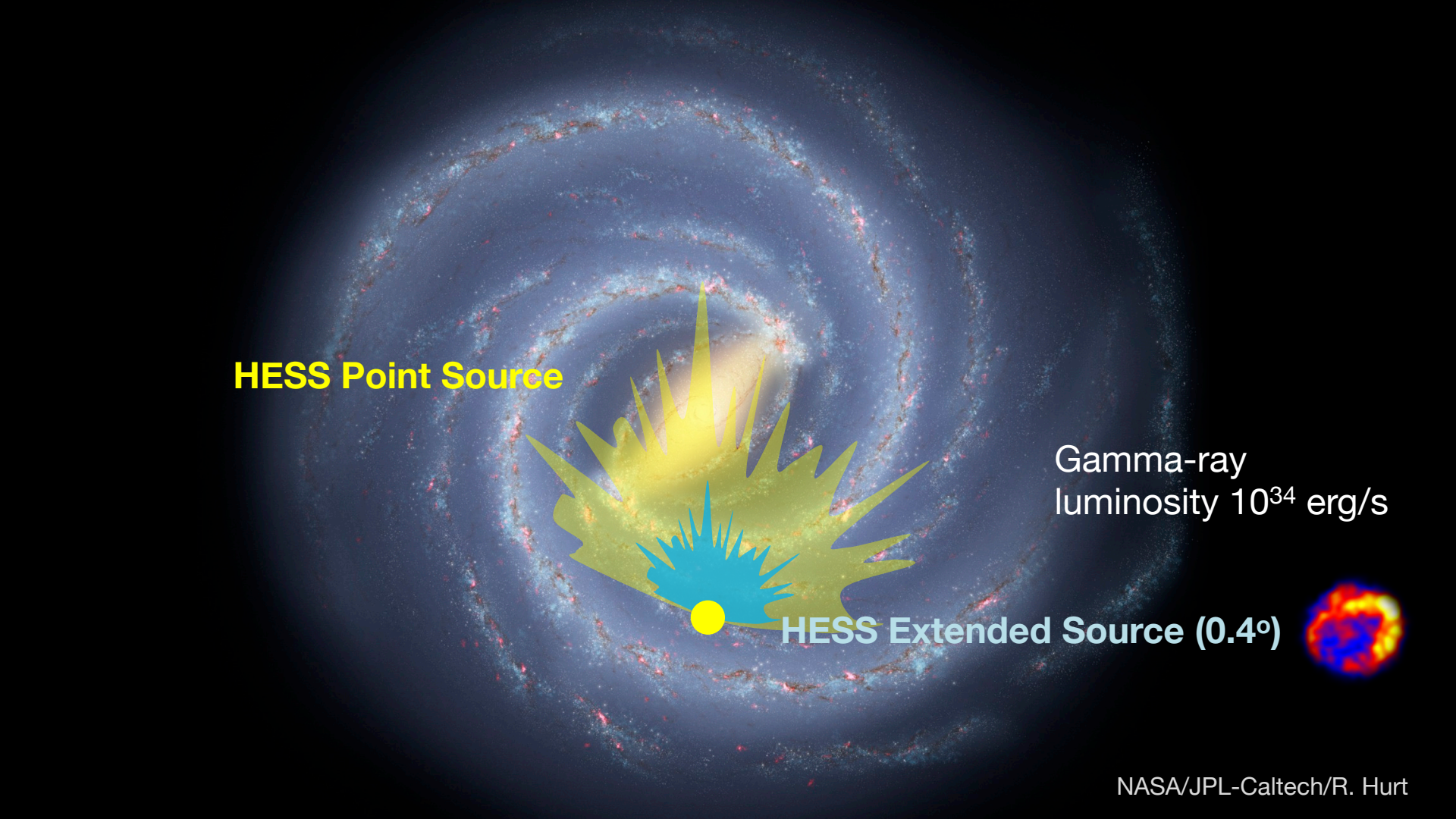

Energy Loss
Particle Population
Ionisation
Gas / Plasma
Equipartition
Excite
Move
Accelerate/ Deflect
Sustains
Magnetic Fields / Alvfén Waves

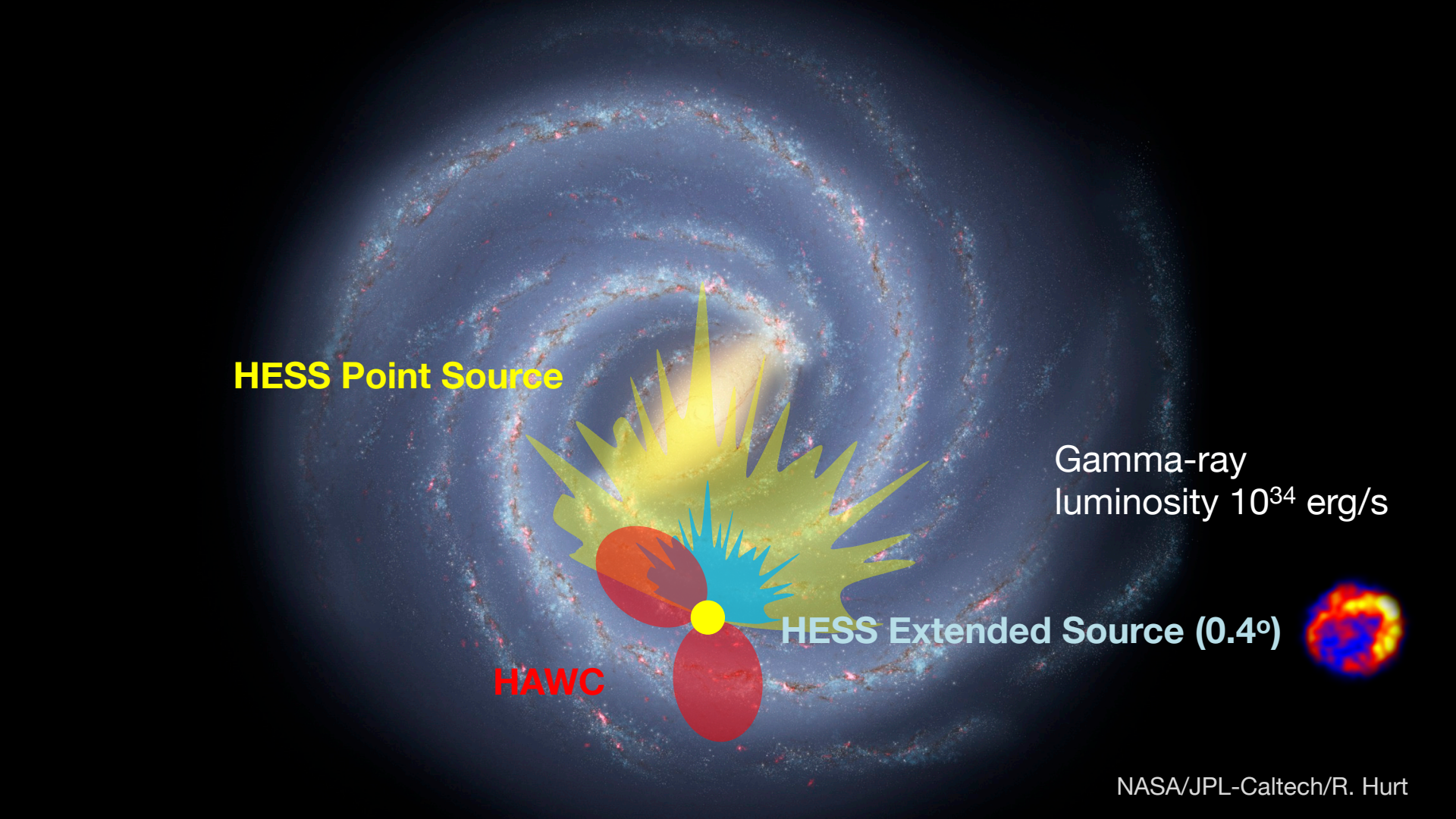
S. Funk, ARNPS 65




NASA/JPL-Caltech/R. Hurt

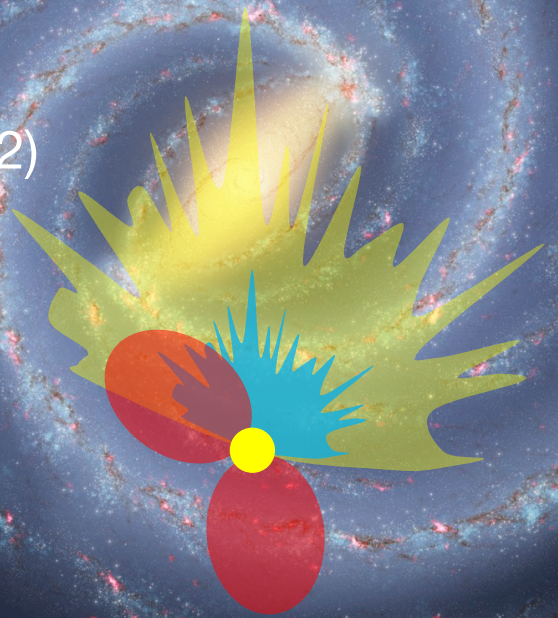

HESS Point Source
Gamma-ray
luminosity 10^{34} erg/s
NASA/JPL-Caltech/R. Hurt


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


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

Design drivers

- Sensitivity (x10)
- Full-sky coverage
- Wide energy range – 20 GeV to 300 TeV
- Larger field of view (x2)
- Few arc-min angular resolution
- Rapid slewing for transient follow-up



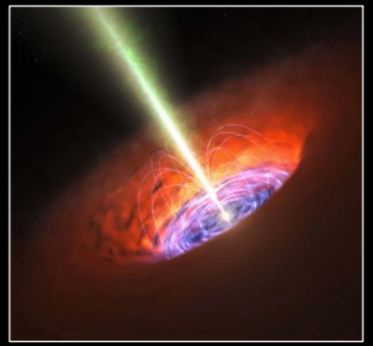
NASA/JPL-Caltech/R. Hurt

Theme 1: Cosmic Particle Acceleration

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

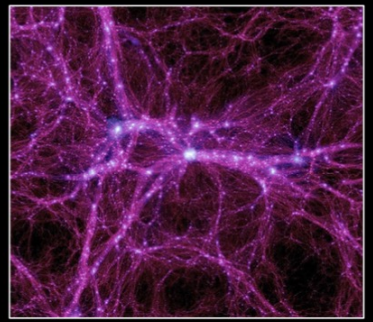
Theme 2: Probing Extreme Environments

- Processes close to neutron stars and black holes?
- Characteristics of relativistic jets, winds and explosions?
- Cosmic voids: their radiation fields and magnetic fields



Theme 3: Physics Frontiers

- What is the nature of Dark Matter?
- Is the speed of light a constant?
- Do axion-like particles exist?



TEV DETECTION OF GAMMA RAY BURSTS

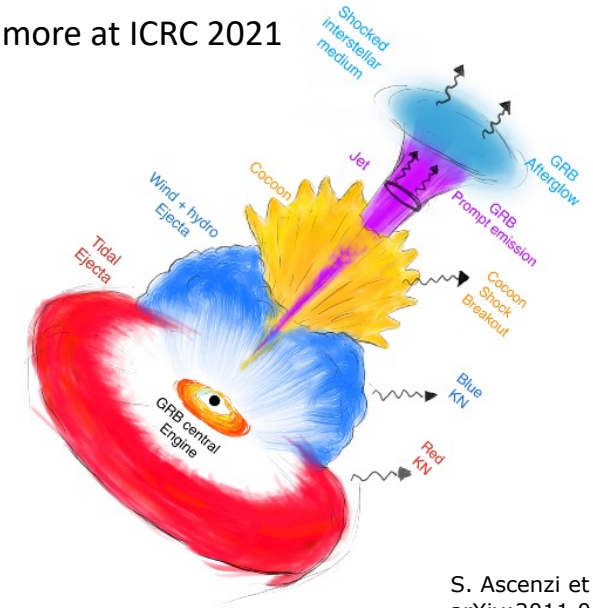
NASA/Swift/Mary Pat Hrybyk-Keith, John Jones

GRB 190114C
MAGIC Coll. +
Nature 575 (2019) 455
Nature 575 (2019) 459

GRB 180720B
H.E.S.S. Coll., Nature 575 (2019) 464

GRB 190829A
H.E.S.S. Coll., Science 372 (2021) 1081

+ 2 more at ICRC 2021

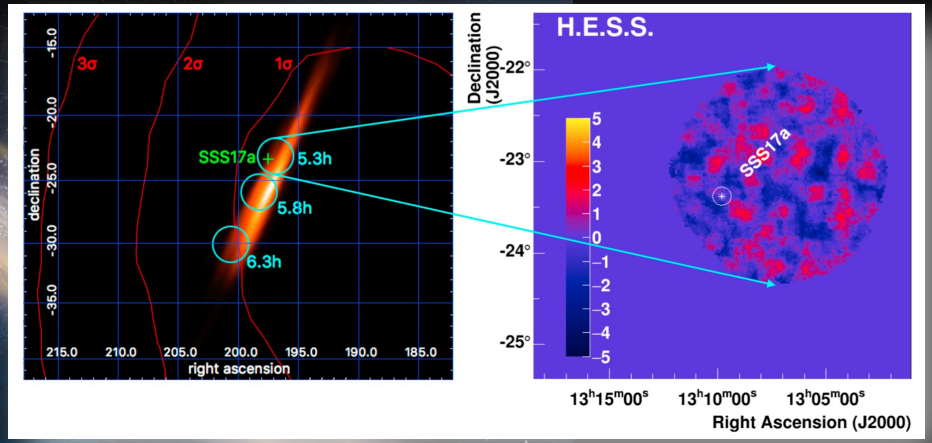


S. Ascenzi et al.
arXiv:2011.04001

Multi-Messenger Observations of a Binary Neutron Star Merger

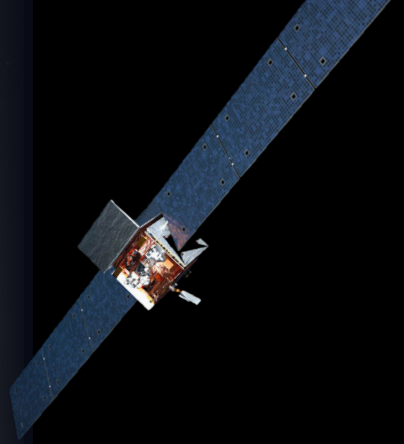
LIGO, Virgo, Fermi GBM, INTEGRAL, …
ApJL 848 (2017) L12

H.E.S.S. Coll., Astrophys. J. Lett. 850 (2017) L22



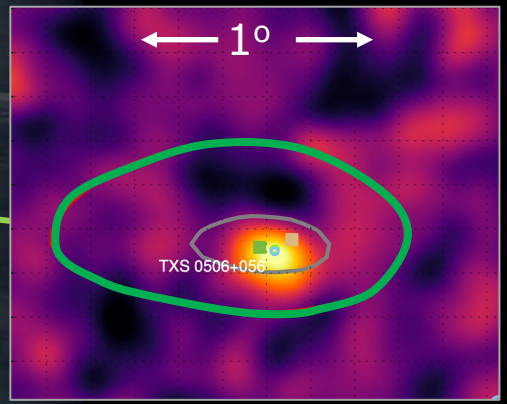
Neutron star merger
NSF/LIGO/Sonoma State University/A. Simonnet

IceCube detection of a neutrino
from the direction of AGN TXS0506+056,
coincident with a gamma ray flare



MAGIC detection

Neutrino
IC170922A

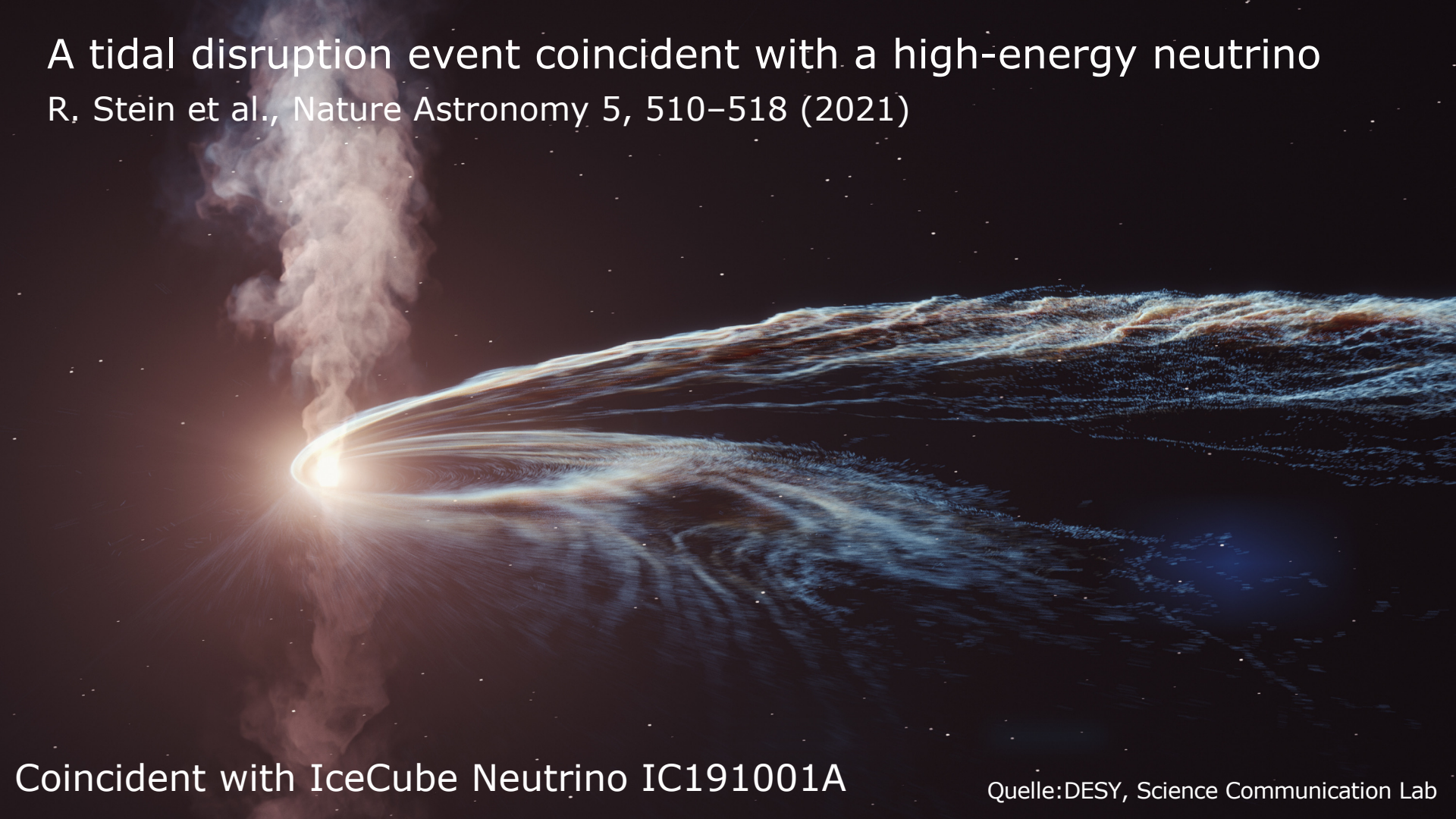


22. Sept. 2017

Science 361 (2018) eaat1378

A tidal disruption event coincident with a high-energy neutrino

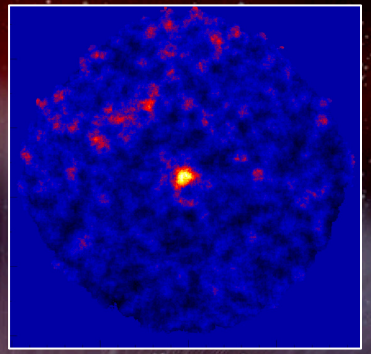
R. Stein et al., Nature Astronomy 5, 510–518 (2021)



Coincident with IceCube Neutrino IC191001A

Quelle:DESY, Science Communication Lab

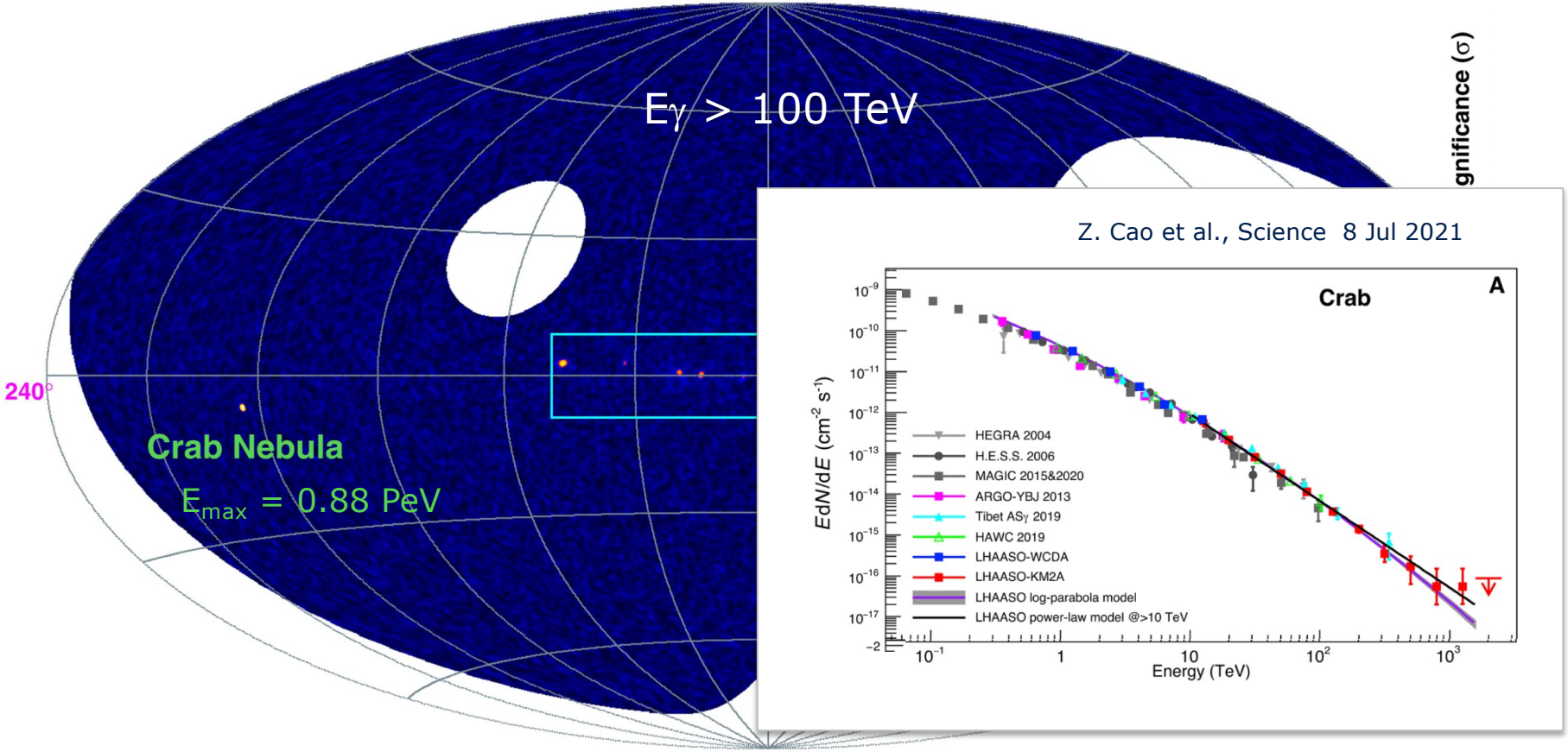
Recurrent nova RS Ophiuchi as TeV source
H.E.S.S. ATEL #14844, Aug. 10




LHAASO
Sichuan, China
4410 m asl

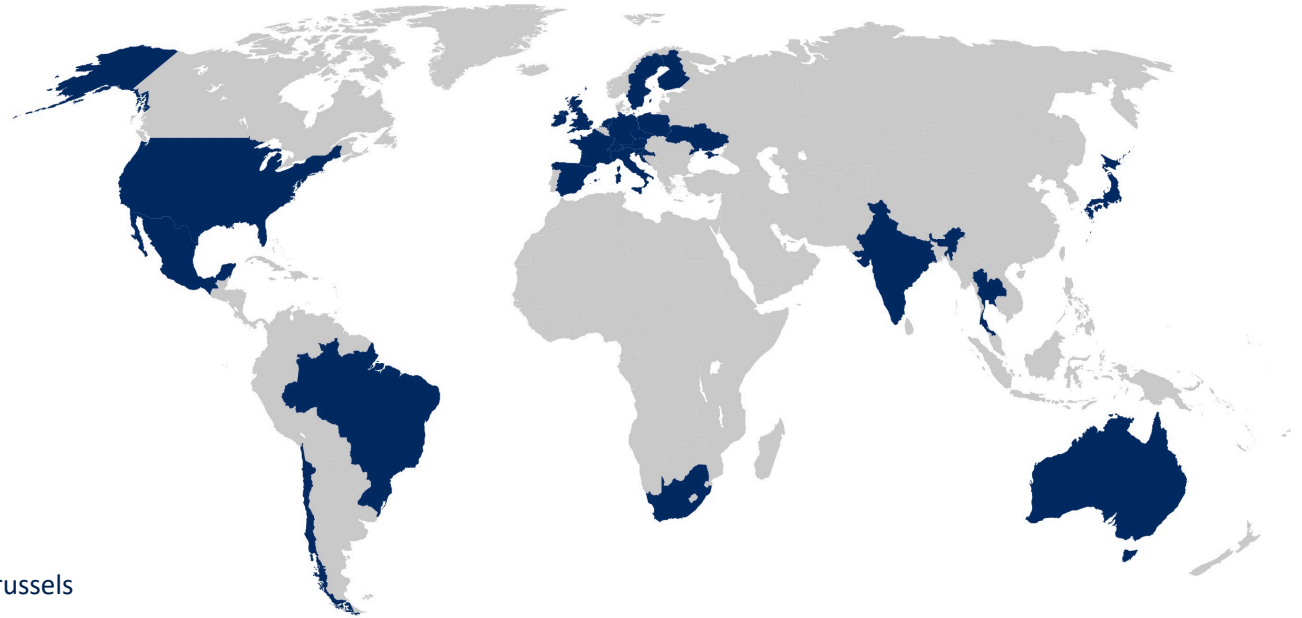
THE PeV (10^{15} eV) SKY

LHAASO Coll., Z. Cao et al.,
Nature, 17 May 2021



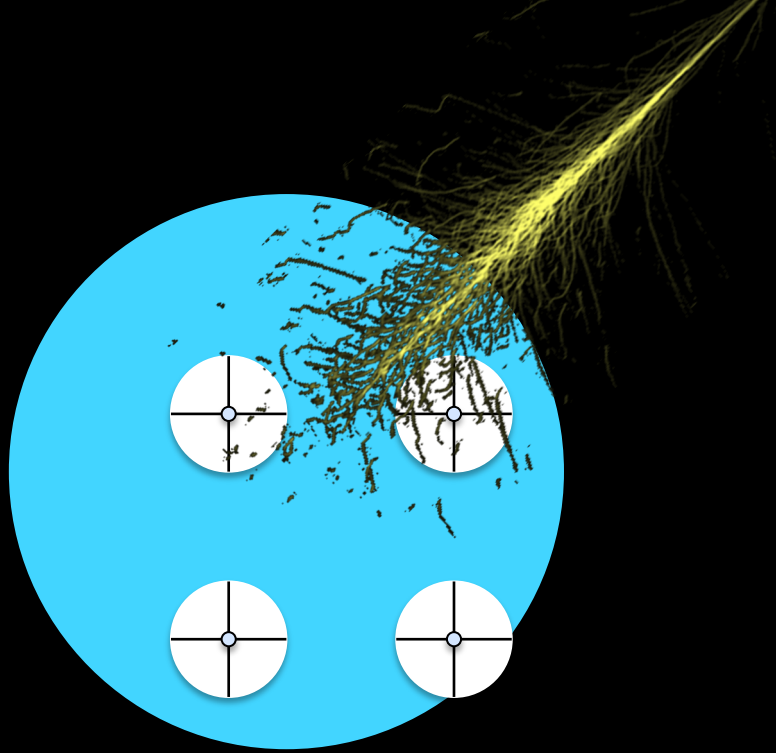
THE CHERENKOV TELESCOPE ARRAY

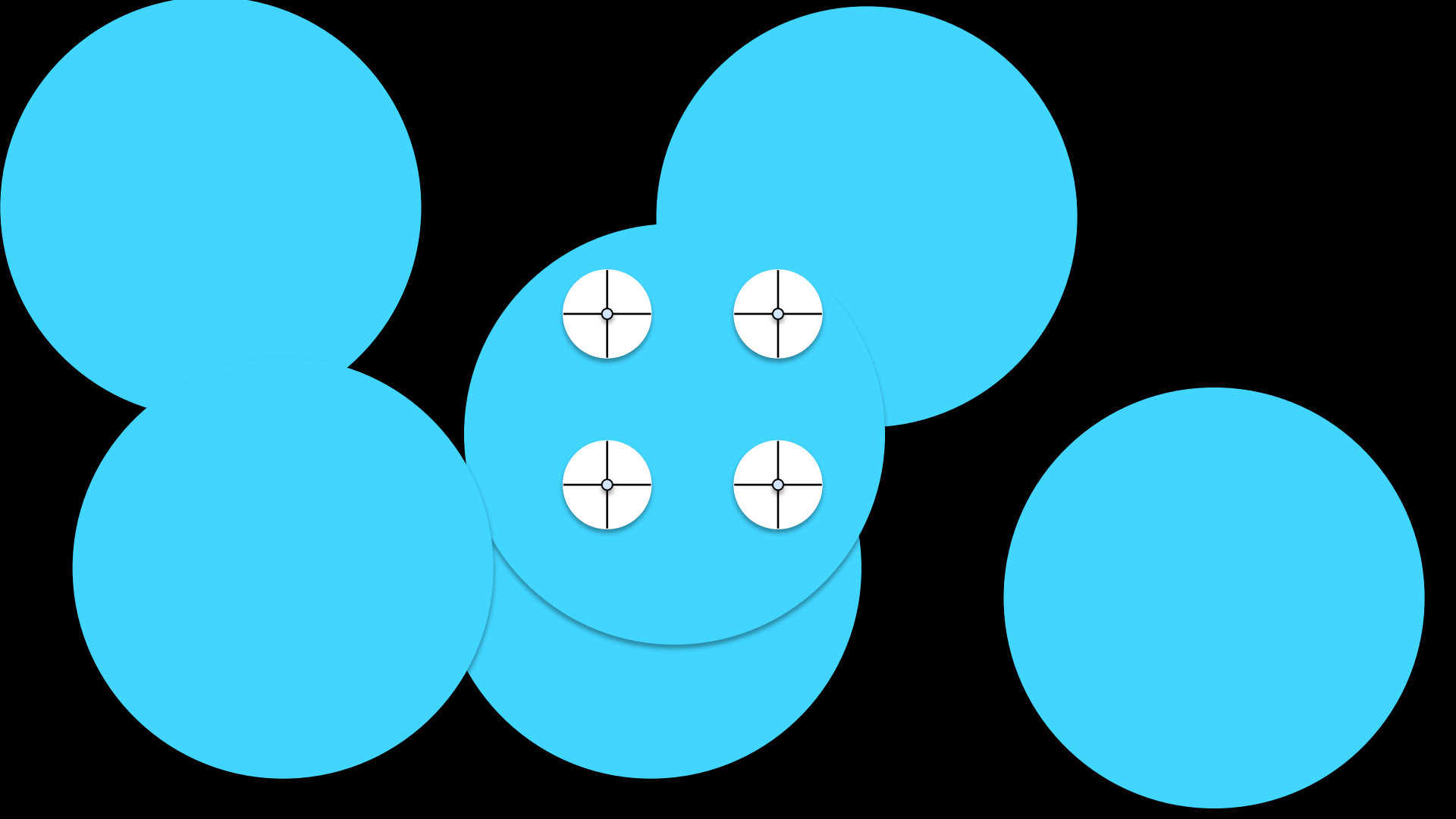
THE CTA CONSORTIUM

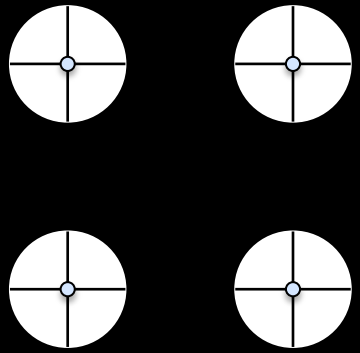


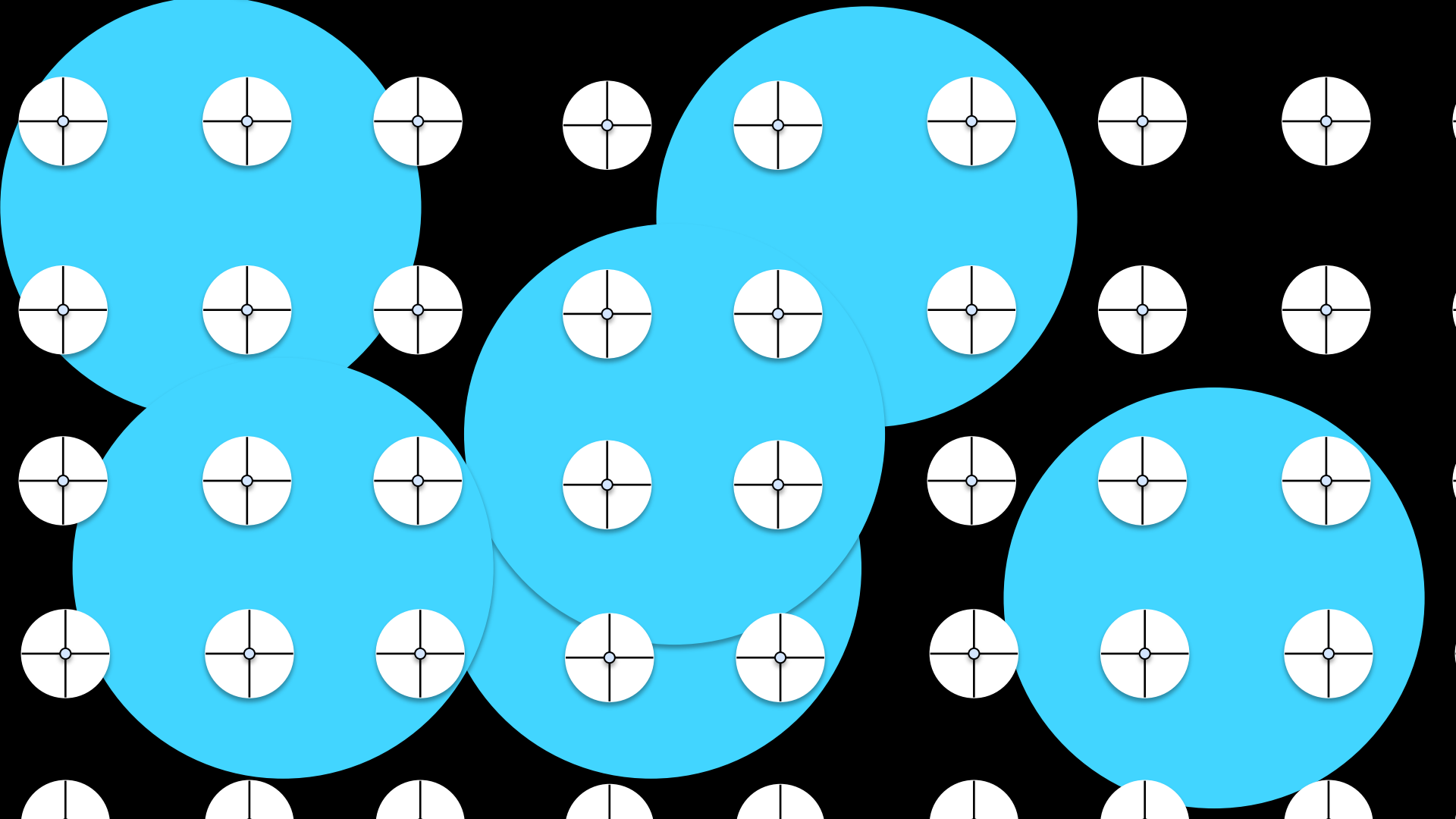
25 Countries
over 150 Institutes
about 1500 Members

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





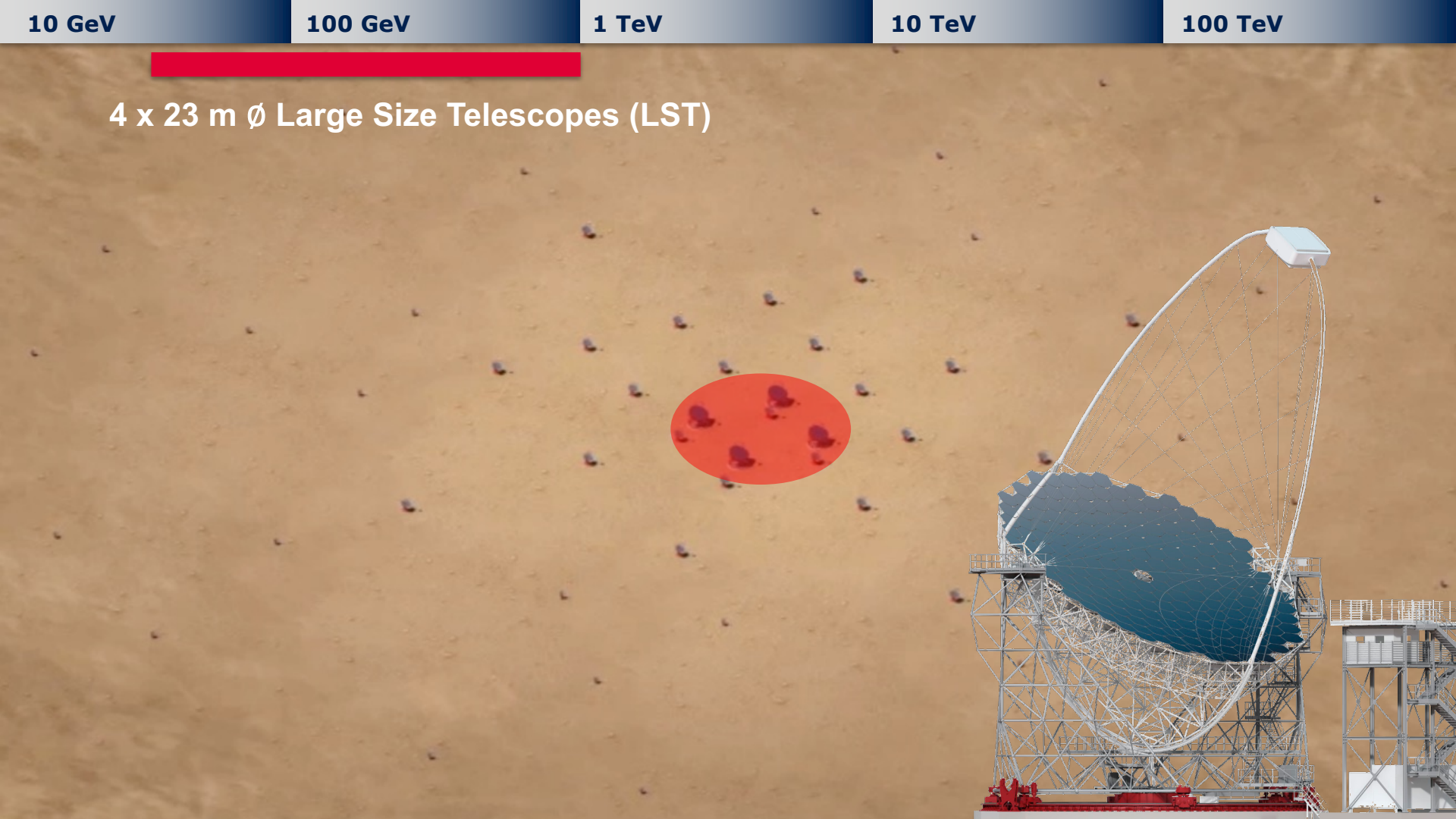





10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1000 γ / h km²
10 γ / h km²
0.1 γ / h km²
Southern array
of Cherenkov telescopes
- about 3 km across

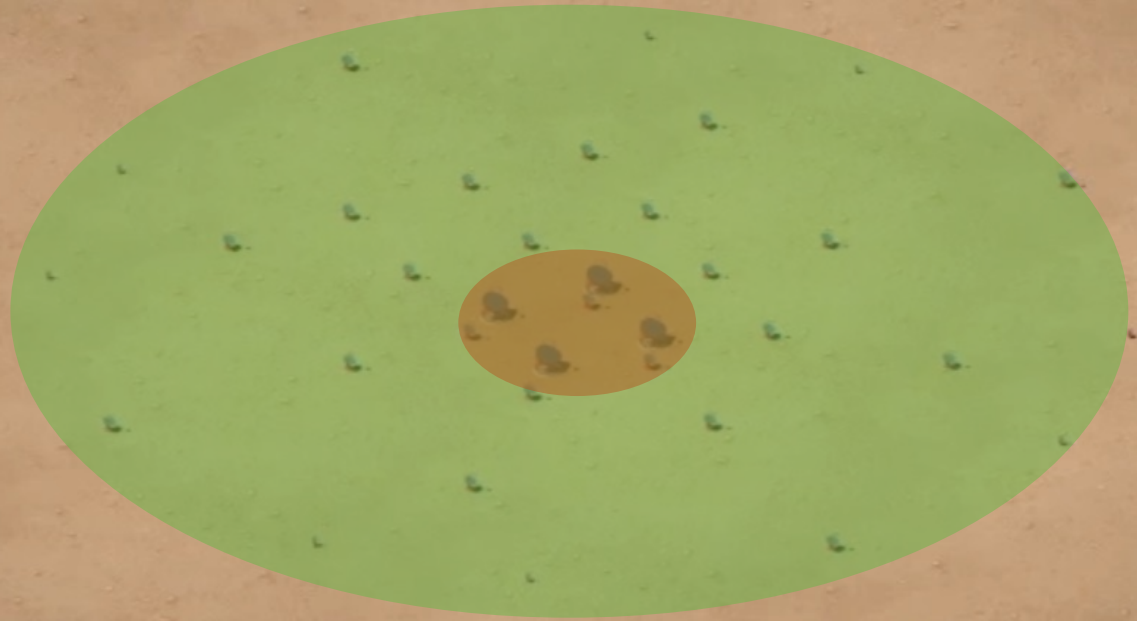
10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

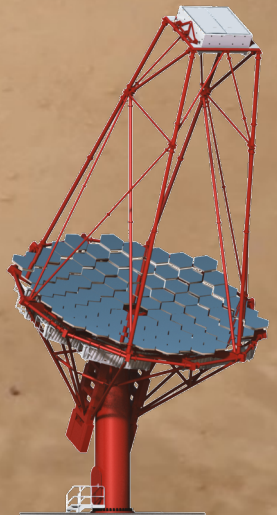
4 x 23 m ø Large Size Telescopes (LST)



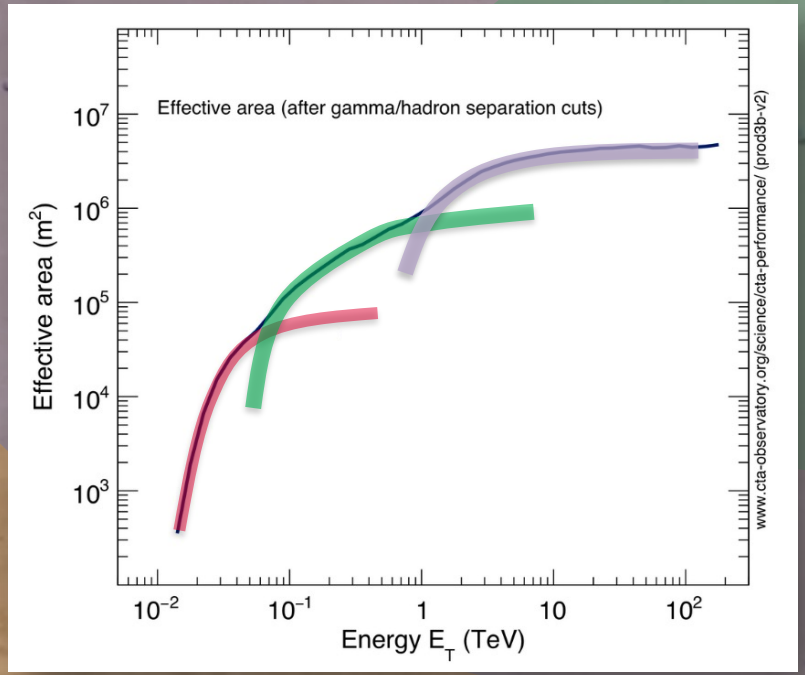
10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

25 x 12 m ø Medium Size Telescopes (MST) (North: 15)





70 x 4 m ∅ Small Size Telescopes (SST) (South)



Optimising the CTA array layout & fine-tuning at % level

K. Bernlöhr et al., Astropart. Phys. 43 (2013) 171

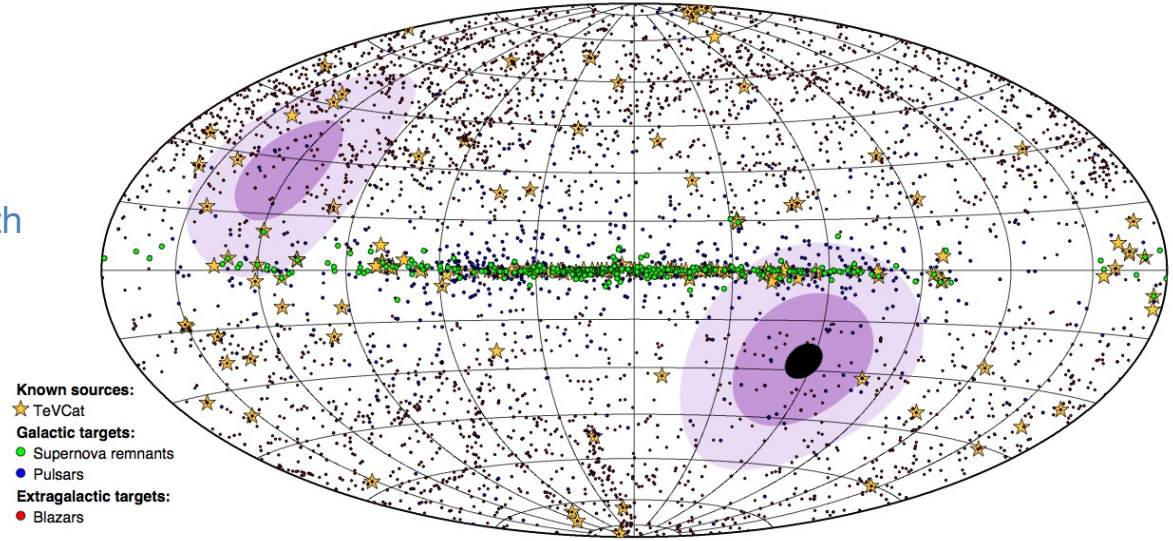
T. Hassan et al., Astropart. Phys. 93 (2017) 76

A. Acharyya et al., Astropart. Phys. 111 (2019) 35

Compared to current instruments up to 400 x increased survey speed

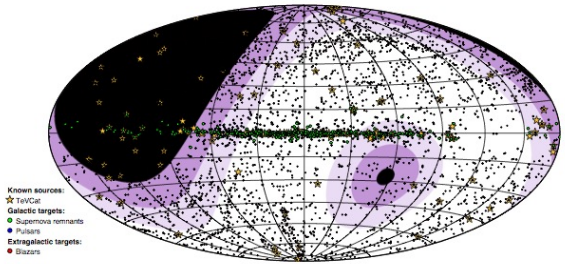
DESIGN DRIVER: FULL-SKY COVERAGE

North+South

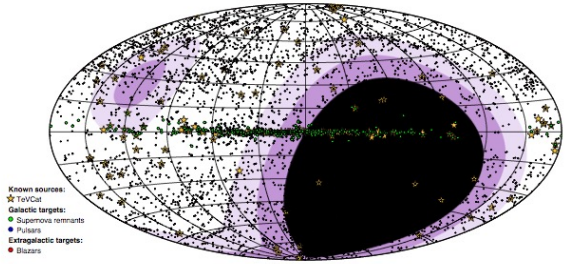


>60° zenith
45°-60°
30°-45°

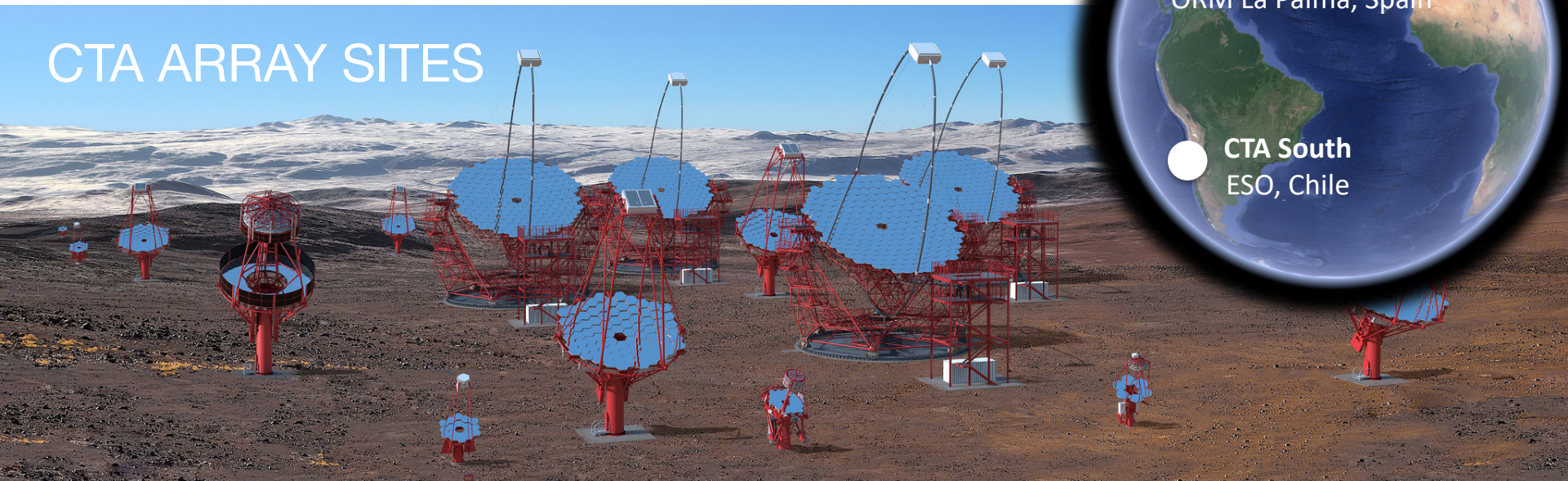
South



North

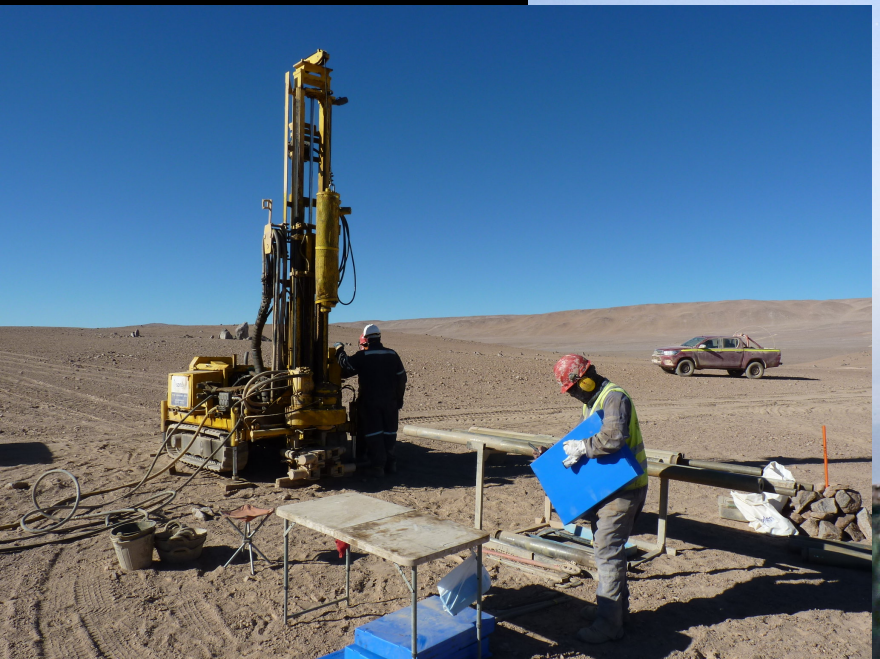


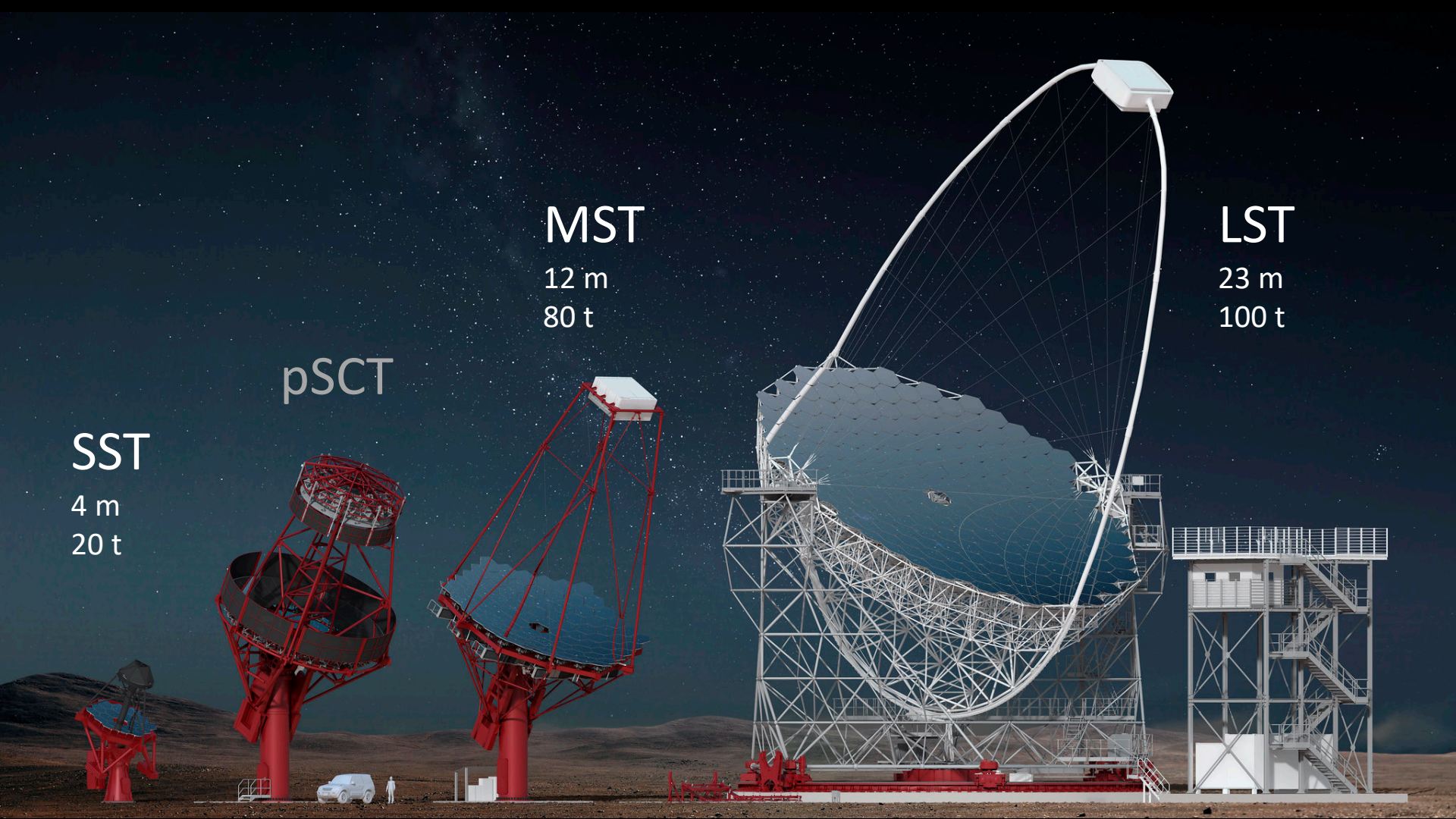
CTA ARRAY SITES




CTA-South Site
ESO Paranal
Vulcano Llullaillaco
6739 m, 190 km east
Cerro Armazones
E-ELT
Cherenkov Telescope Array Site
Cerro Paranal
Very Large Telescope

WHERE ARE WE REGARDING CTA CONSTRUCTION




SST
4 m
20 t
pSCT
MST
12 m
80 t
LST
23 m
100 t

COPE

PoS(ICRC2021)806

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)

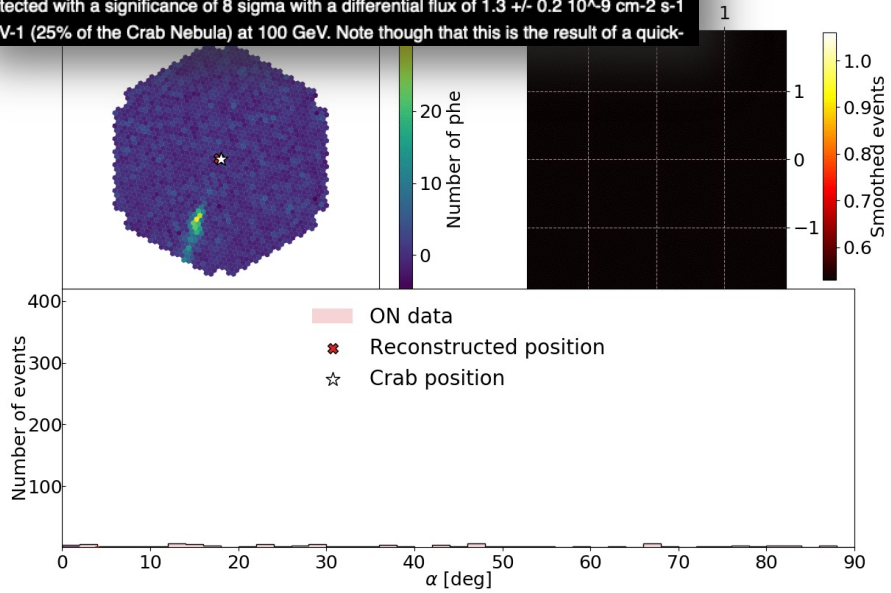
Subjects: TeV, VHE, Request for Observations, AGN, Blazar, Transient

Referred to by ATel #: 14820, 14826, 14839

Tweet

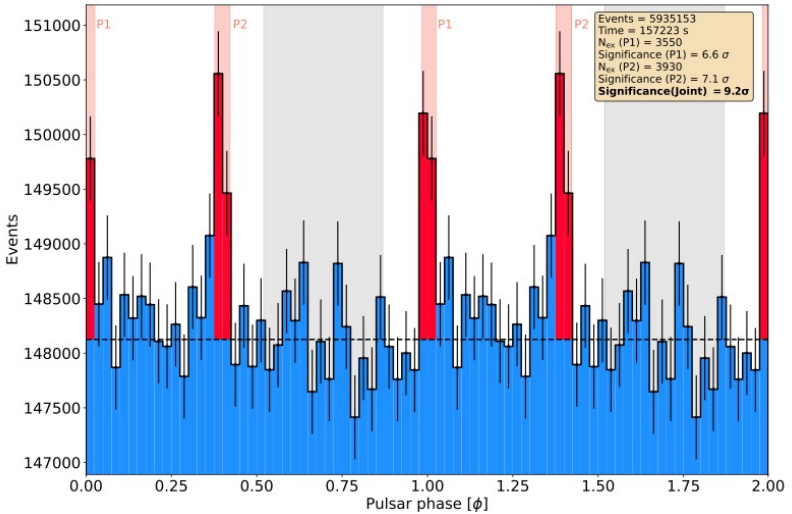
ATel#14783

The LST-1 telescope has observed an increase in the very-high-energy (VHE; >100 GeV) gamma-ray flux from BL Lacertae (RA=22:02:43.3, DEC=+42:16:40, J2000.0). The preliminary offline analysis of the LST-1 data taken on 2021/07/11 (MJD 59406), triggered by an increase of the optical flux (see ATEL #14773 and references therein), has been detected with a significance of 8 sigma with a differential flux of 1.3 +/- 0.2 10^-9 cm-2 s-1 TeV-1 (25% of the Crab Nebula) at 100 GeV. Note though that this is the result of a quick-



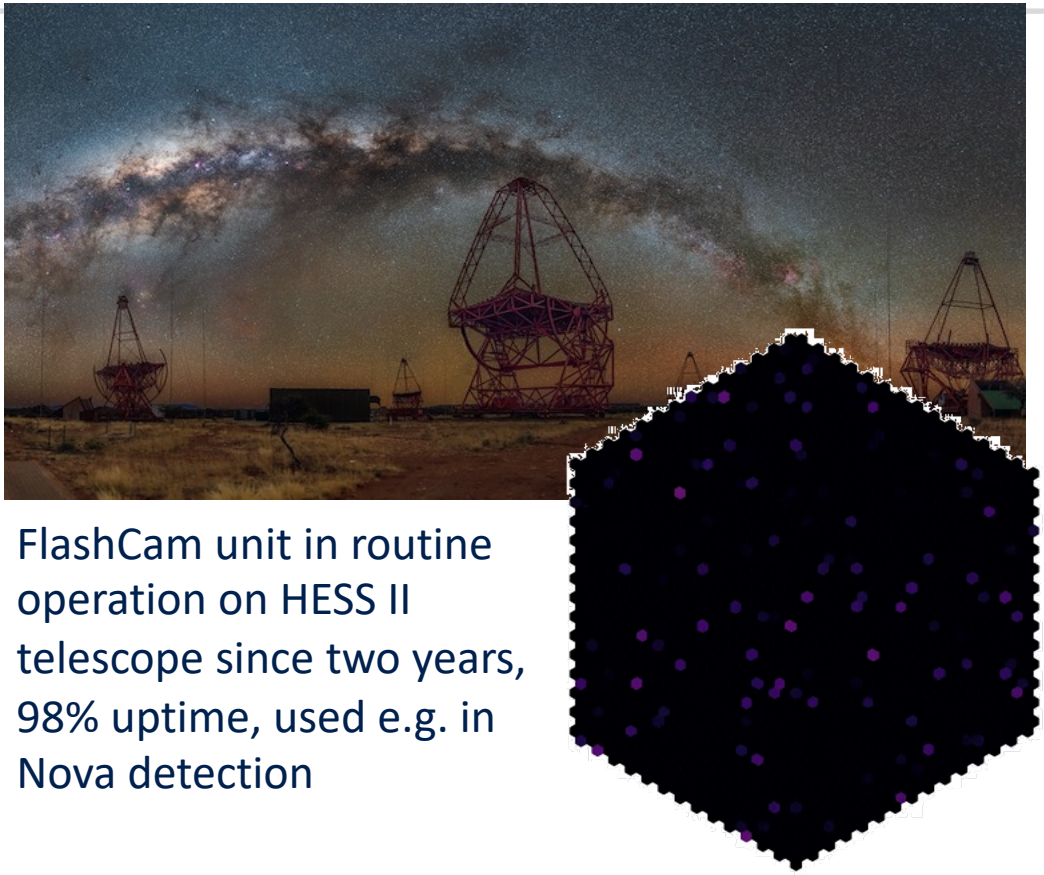
AGN Detections: Mrk 501, Mrk 421, 1ES 1959+650, 1ES 0647+250 and PG 1553+113

June 2020: Detection of Crab Pulsar



MEDIUM-SIZED TELESCOPE

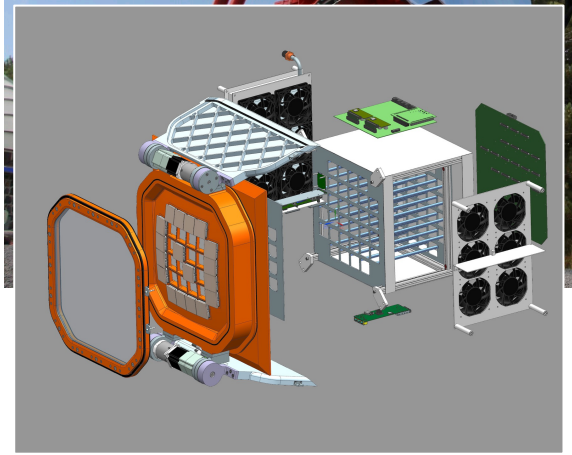
Prototype operated in Berlin-Adlershof for several years;
Two PMT cameras: NectarCAM and FlashCam (N/S split)

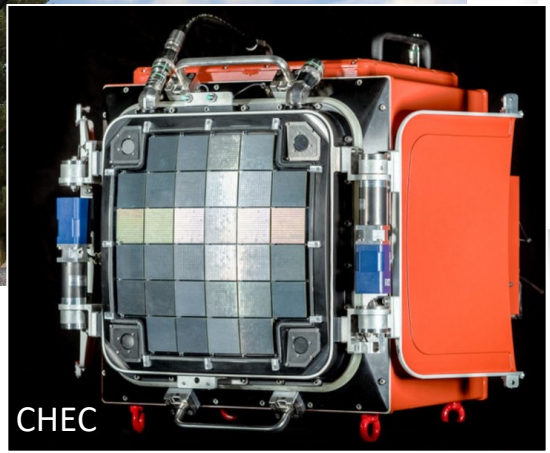


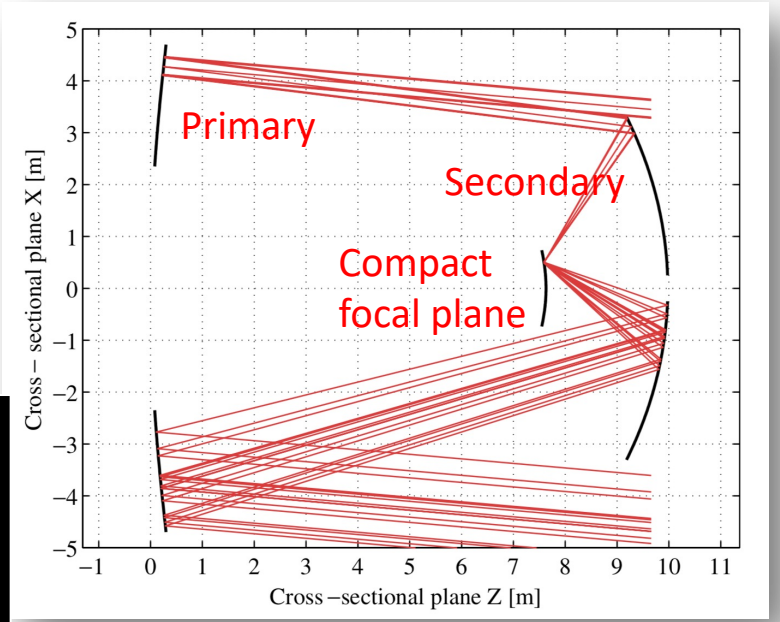
FlashCam unit in routine operation on HESS II telescope since two years, 98% uptime, used e.g. in Nova detection

SMALL-SIZED TELESCOPE

Dual-mirror design
with SiPMT camera



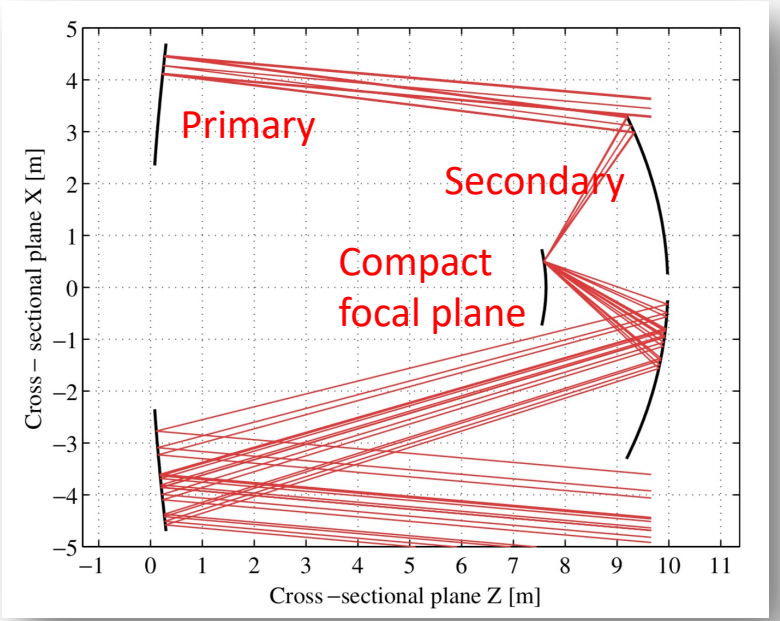




V. Vassiliev et al.
Astroparticle Physics
28 (2007) 10

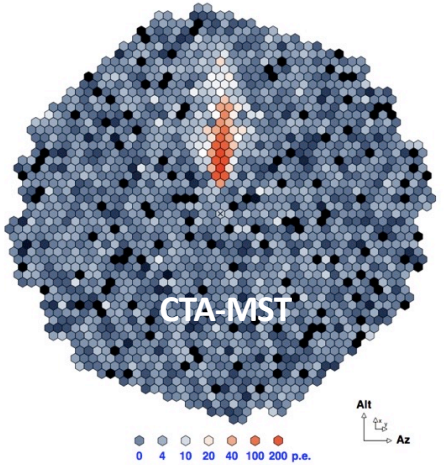
SCT TELESCOPE

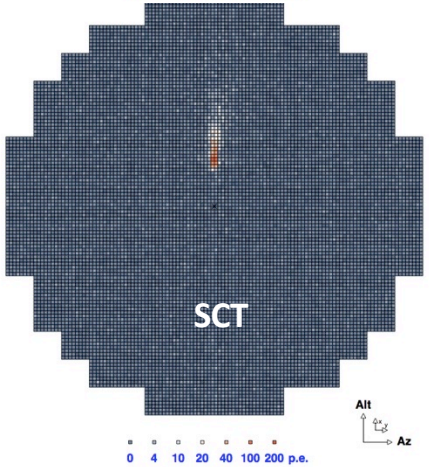
Dual-mirror design
with SiPMT camera

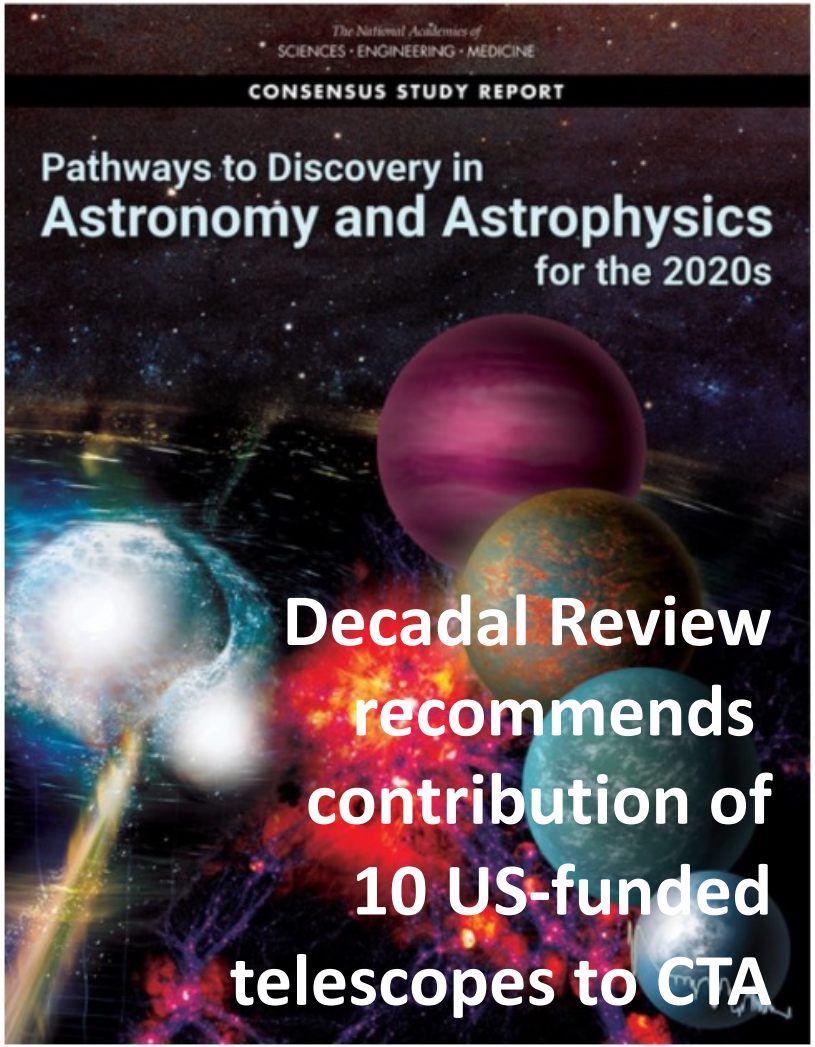


V. Vassiliev et al.
Astroparticle Physics
28 (2007) 10

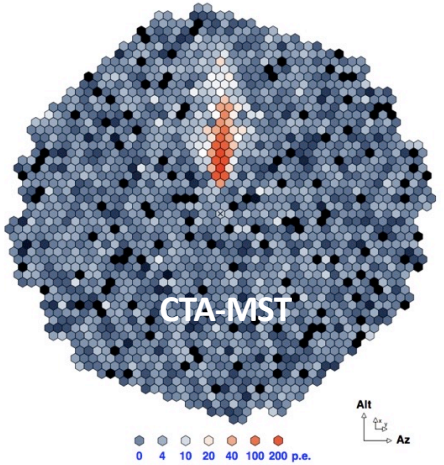
SCT TELESCOPE

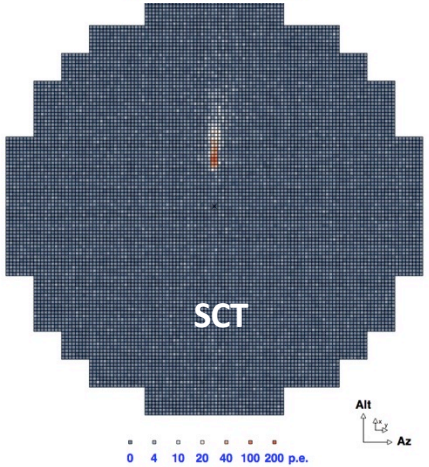






Decadal Review recommends contribution of 10 US-funded telescopes to CTA

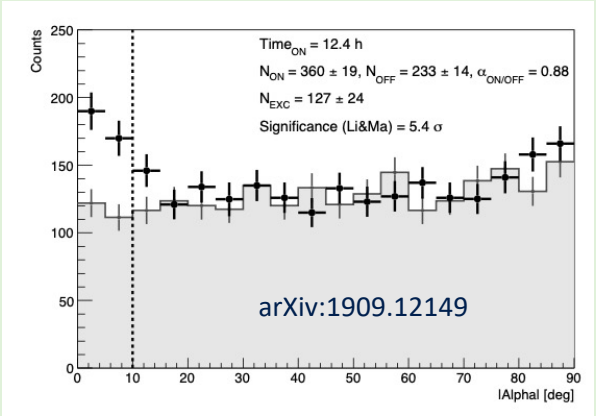


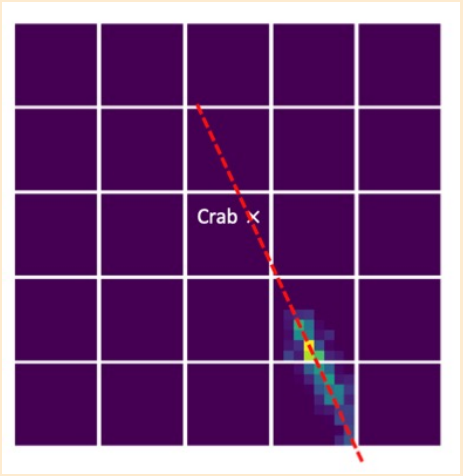


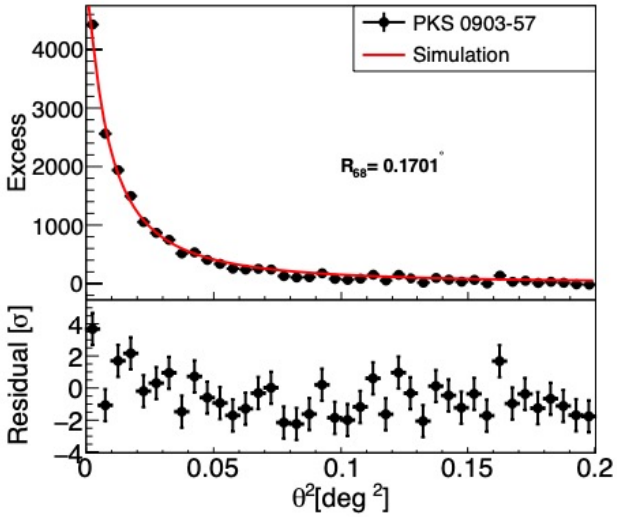
Ba
of

PERFORMANCE VALIDATION

Crab detection using Single ASTRI-SST

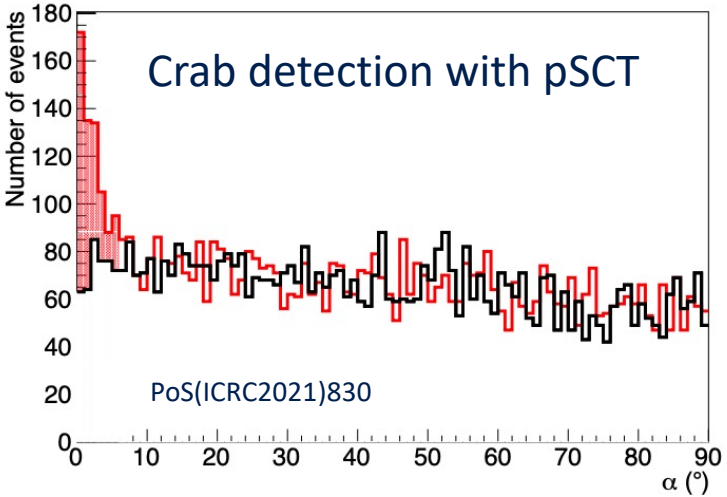






AGN detection with MST-FlashCam on HESS CT5

PoS(ICRC2021)76



CTA CONSTRUCTION

Funding limitations require temporary specialization of sites ("Alpha Configuration"):

- North: Low energy / extragalactic science
  - all 4 LSTs but slightly reduced number of MSTs (9)
- South: High energy / galactic science
  - initially no LSTs, reduced numbers of MSTs (14), SSTs (37)
  - highest priority for next step: adding LSTs

Late June 2021: Agreement reached on CTA configuration and funding; cost book and S&T description approved

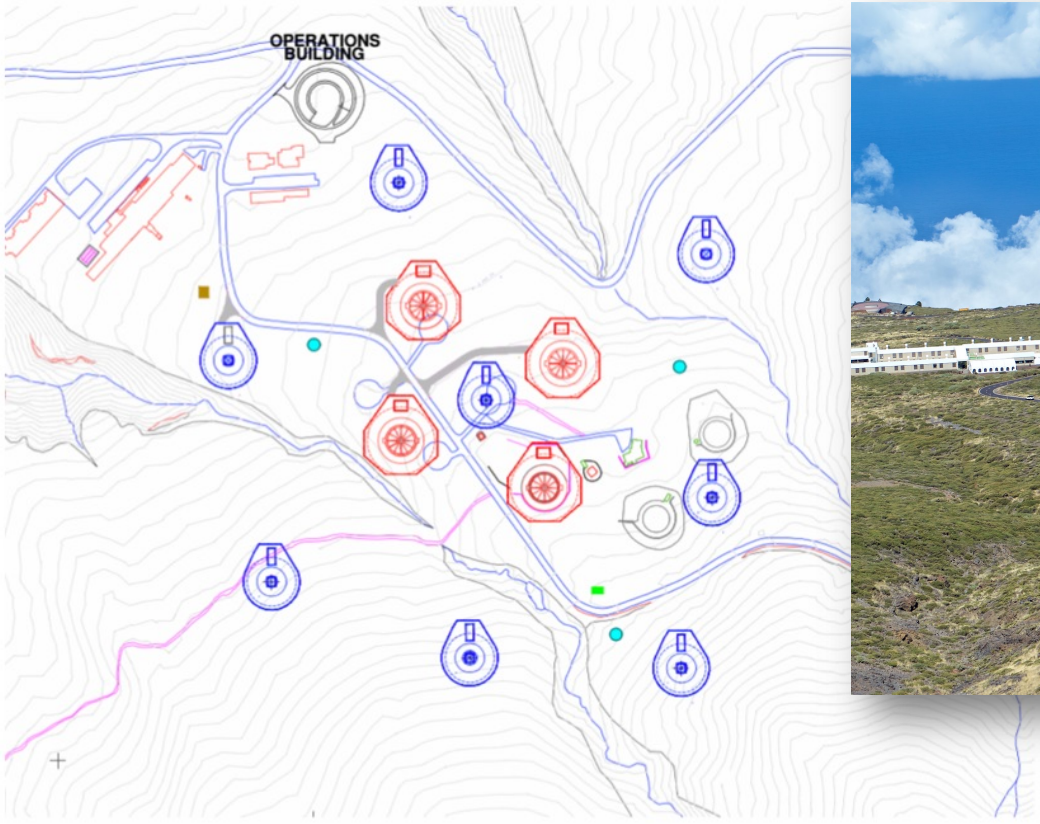
North:

- LST1 under commissioning
- Contracts for LST2-4 and 1st MST underway; for MST2-5 tender open

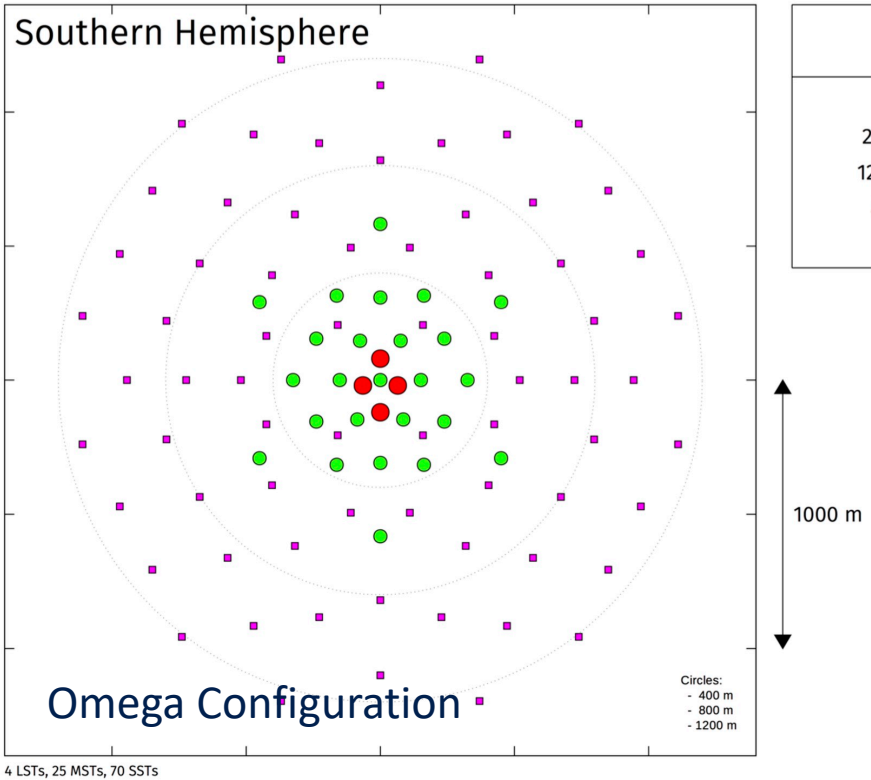
South:

- Procurement of site access road & power systems
- Release of funding for large-scale construction after CTA Observatory ERIC is established (2022)
- 5 year construction phase (but early operation during construction)

CTA NORTH ARRAY



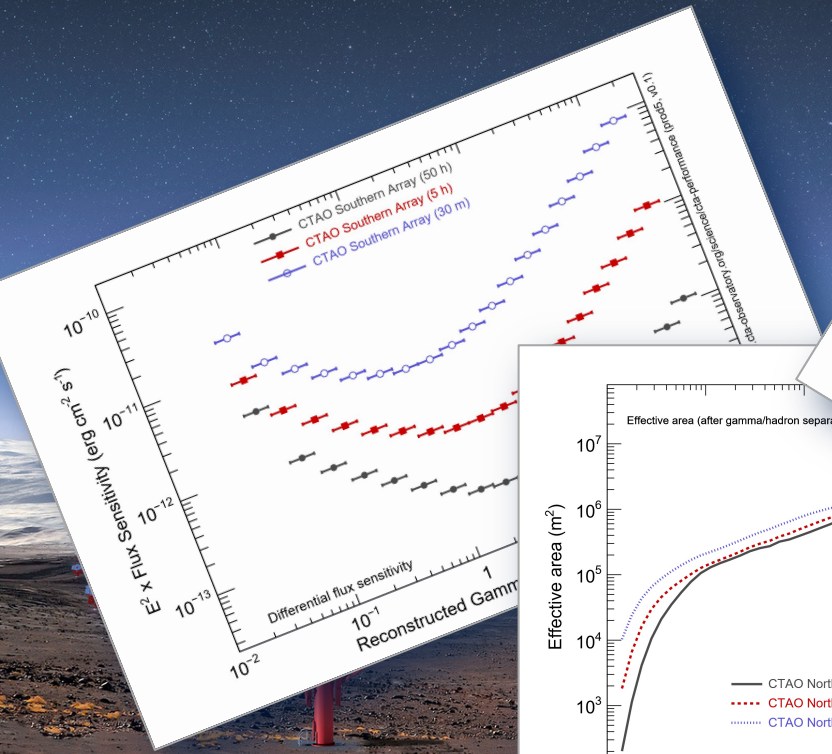
CTA SOUTH ARRAY

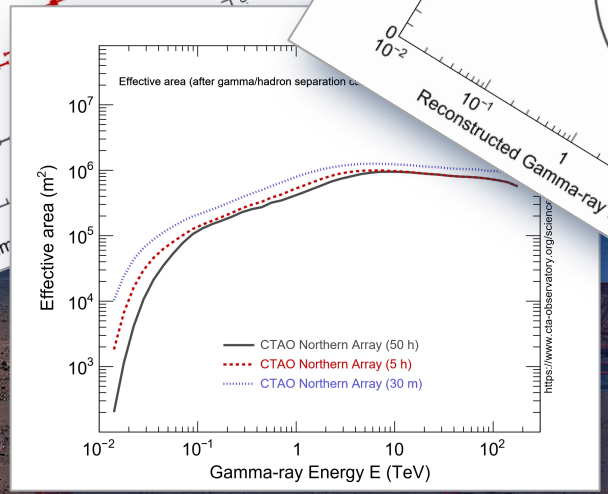


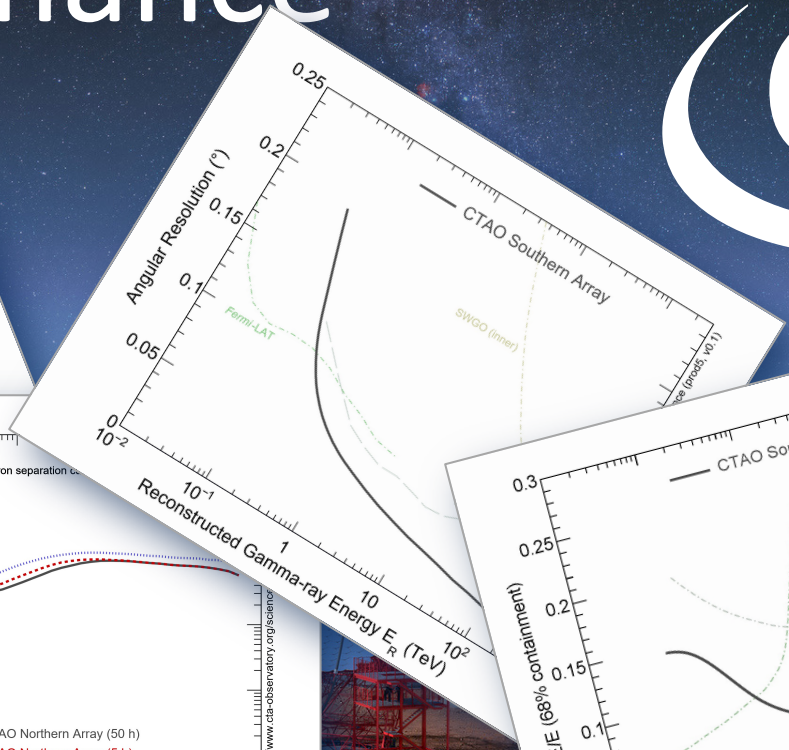
Fine-tuning of placement of alpha configuration telescopes ongoing

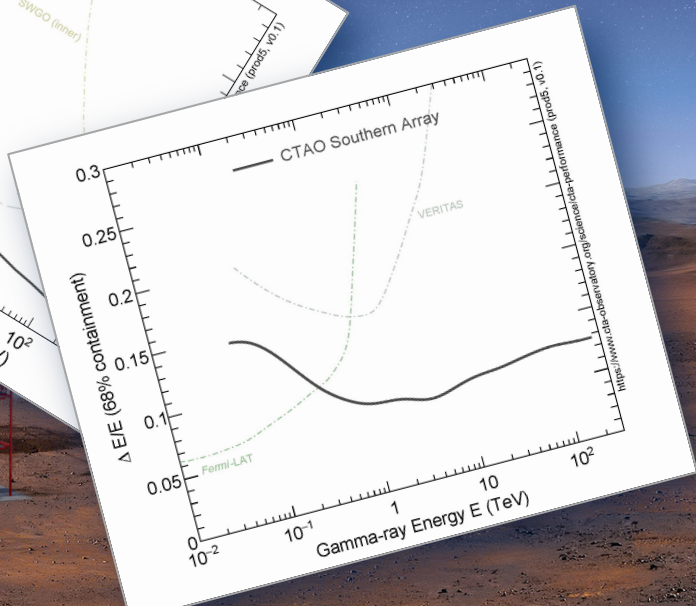
LST	4	→	4 foundations
MST	25	→	14
SST	70	→	37

CTA Performance

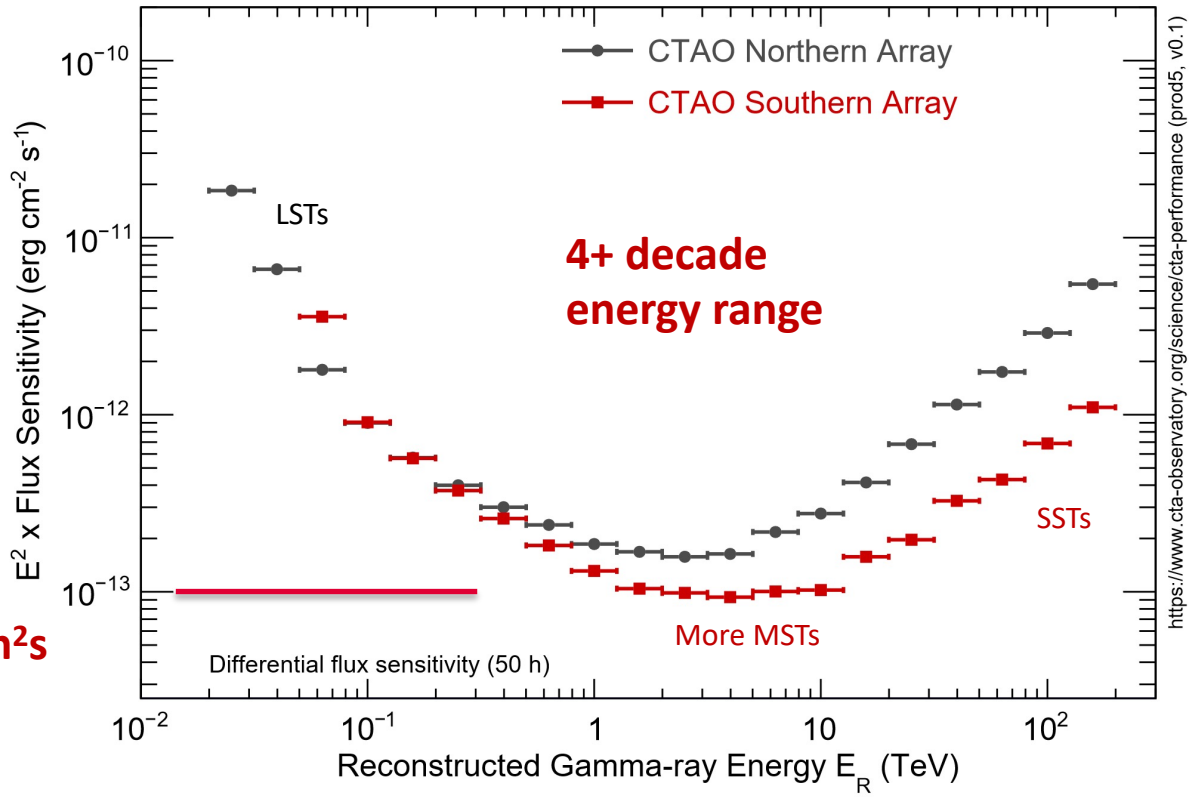








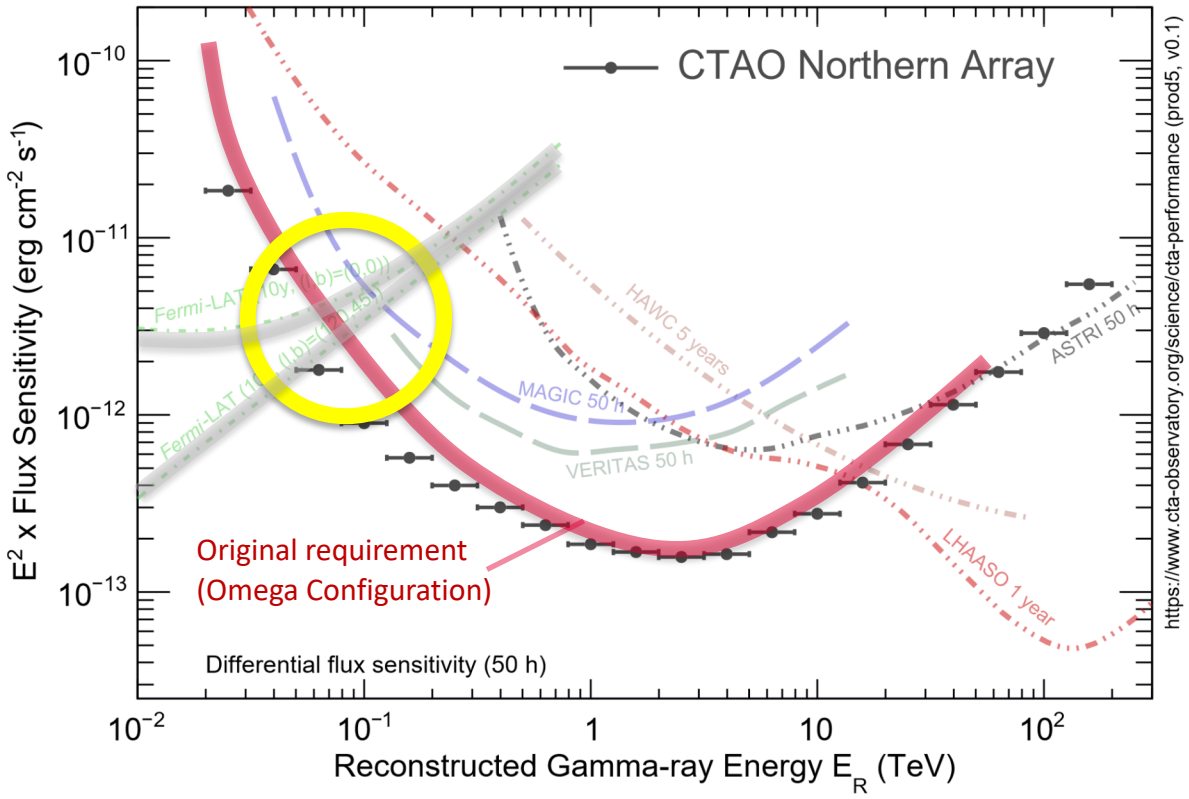
PERFORMANCE OF THE CTA ARRAYS



From 10^{-12} erg/cm²s to 10^{-13} erg/cm²s

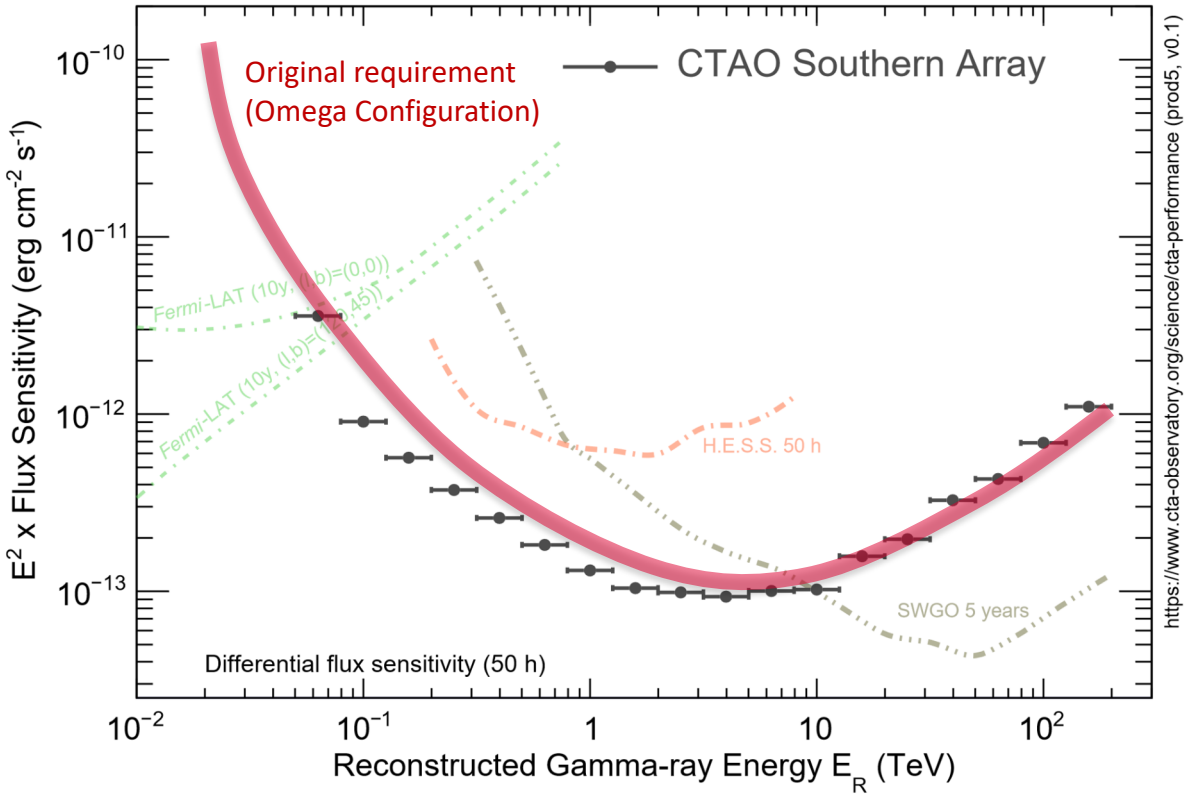
Alpha Configuration, 50 h

SENSITIVITY: NORTHERN ARRAY



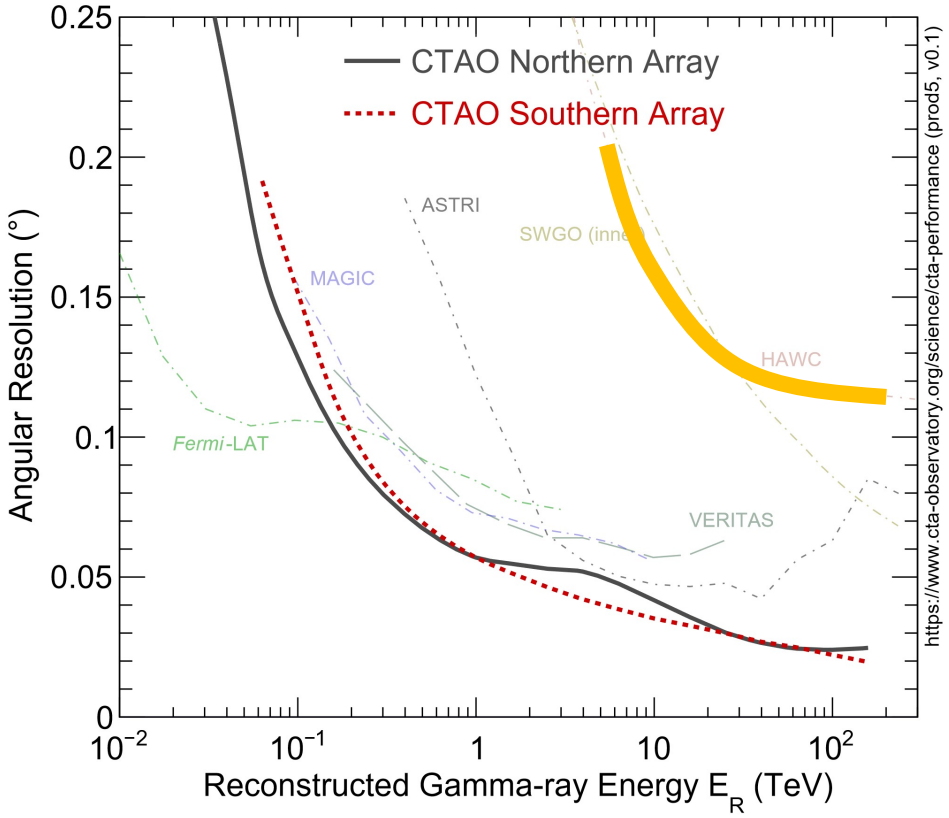
Alpha Configuration, 50 h

SENSITIVITY: SOUTHERN ARRAY

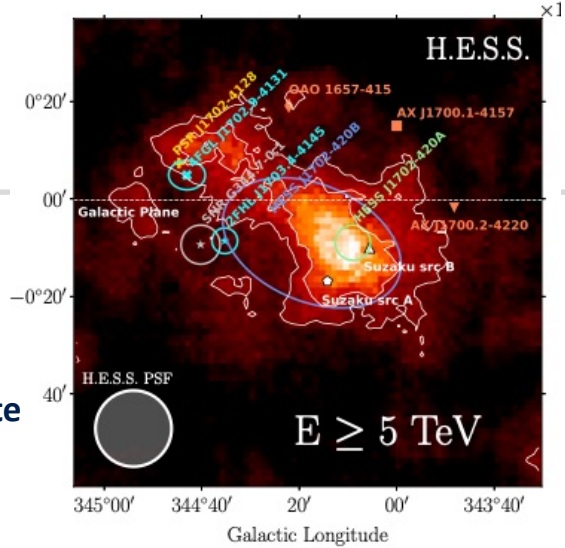


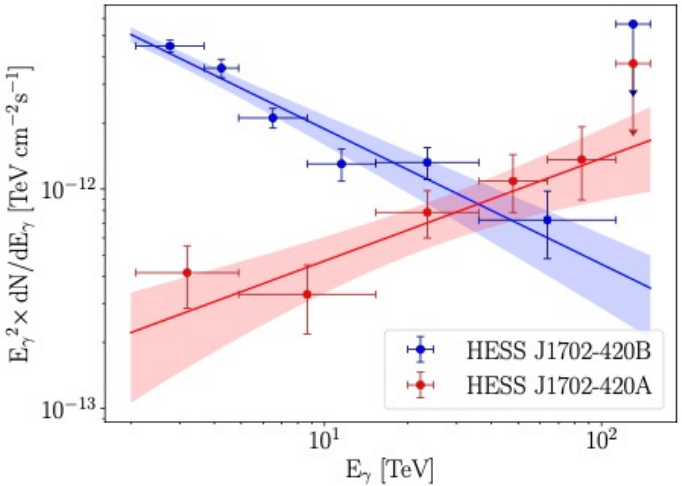
Alpha Configuration, 50 h

ANGULAR RESOLUTION



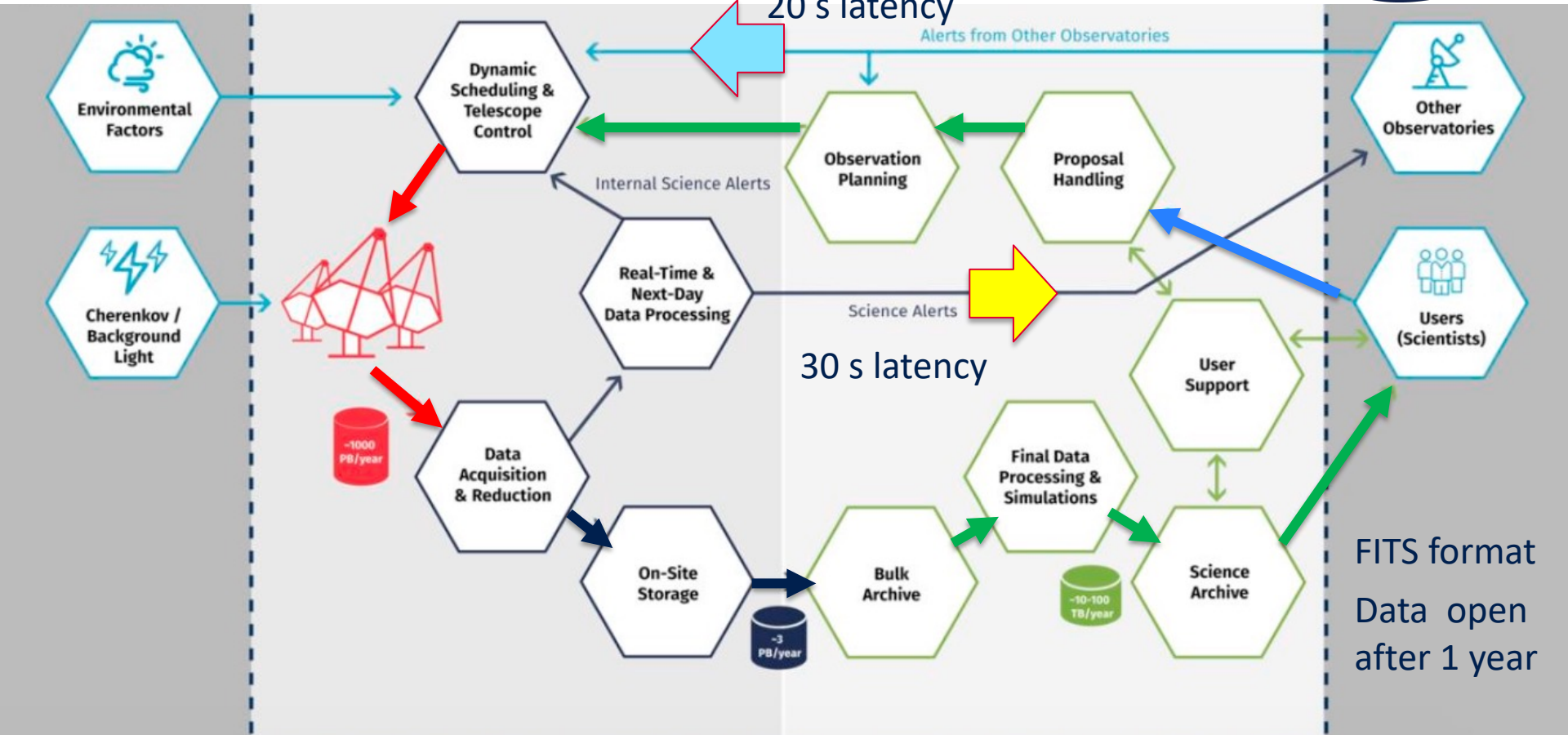
Pevatron candidate
HESS J1702-420
arXiv:2106.06405





CTA OBSERVATORY

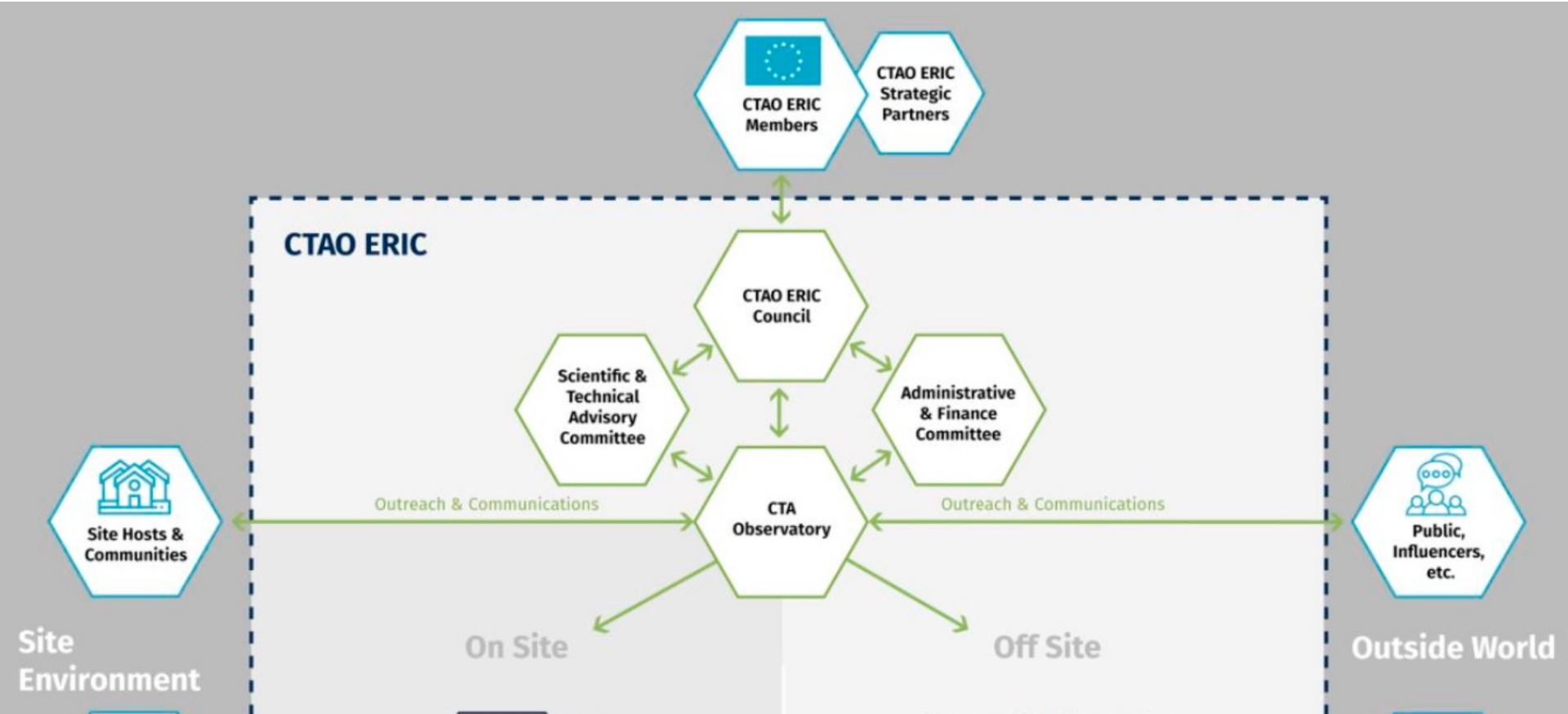
Alerts & ToOs



FITS format

Data open after 1 year

CTA OBSERVATORY

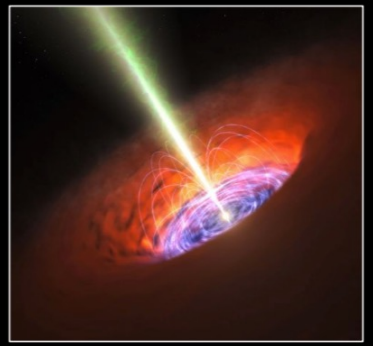


Theme 1: Cosmic Particle Acceleration

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

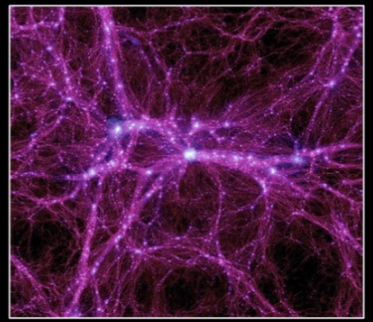
Theme 2: Probing Extreme Environments

- Processes close to neutron stars and black holes?
- Characteristics of relativistic jets, winds and explosions?
- Cosmic voids: their radiation fields and magnetic fields



Theme 3: Physics Frontiers

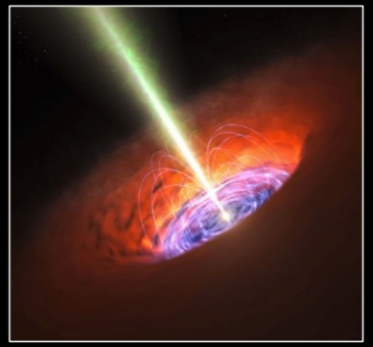
- What is the nature of Dark Matter?
- Is the speed of light a constant?
- Do axion-like particles exist?

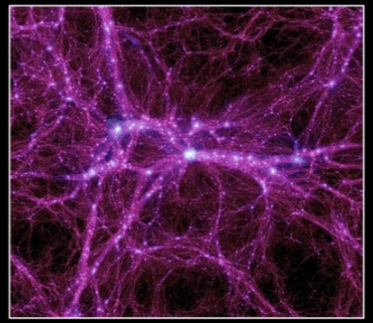


Addressing these questions requires large and coherent data sets, including

- Sky surveys for a census of cosmic accelerators
- Deep observations of key objects
- Long-term observations of variable sources
- Rapid follow-up of transient phenomena

→ Key Science Projects





KEY SCIENCE PROJECTS

1. Dark Matter Programme
2. Galactic Centre
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Beyond Gamma Rays

Surveys

Key objects

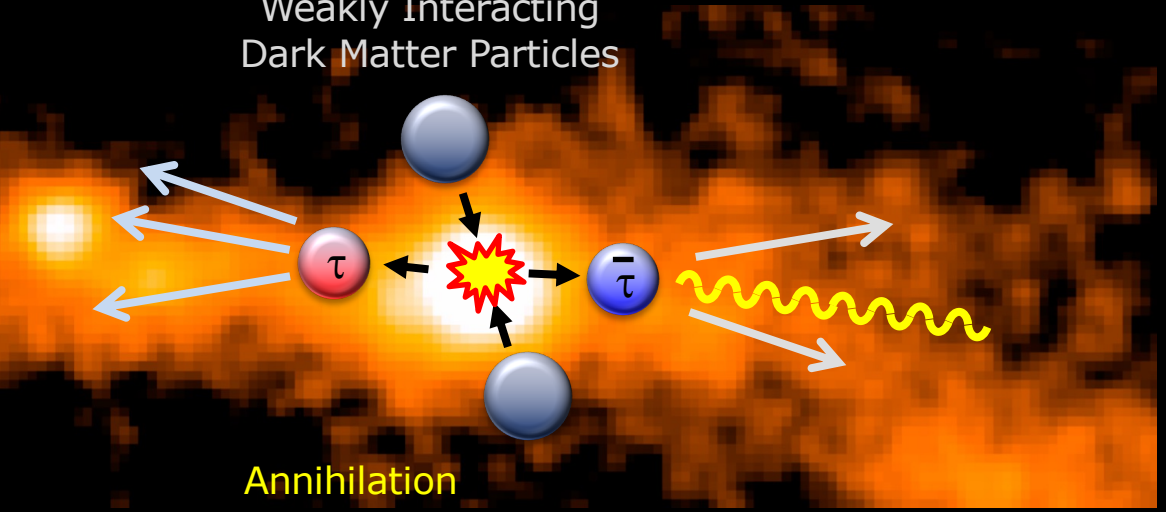
www.worldscientific.com/worldscibooks/10.1142/10986

GALACTIC CENTER & DARK MATTER KSPs

M.A. Garlick / HESS

NASA/ESA

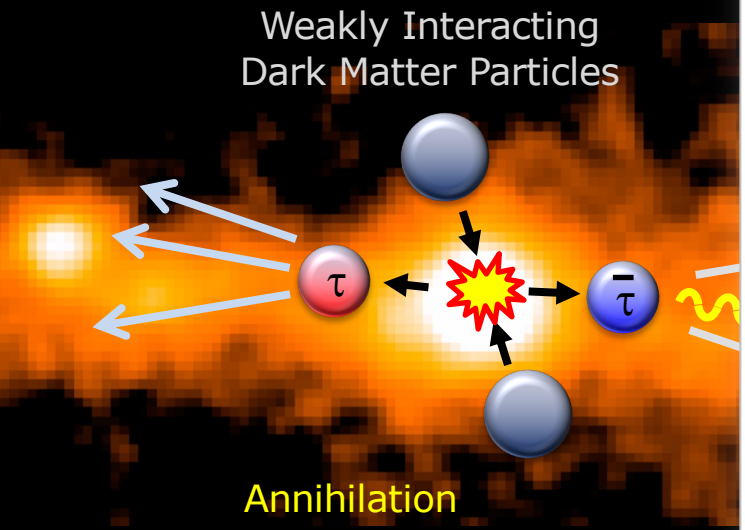
GALACTIC CENTER & DARK MATTER KSPs



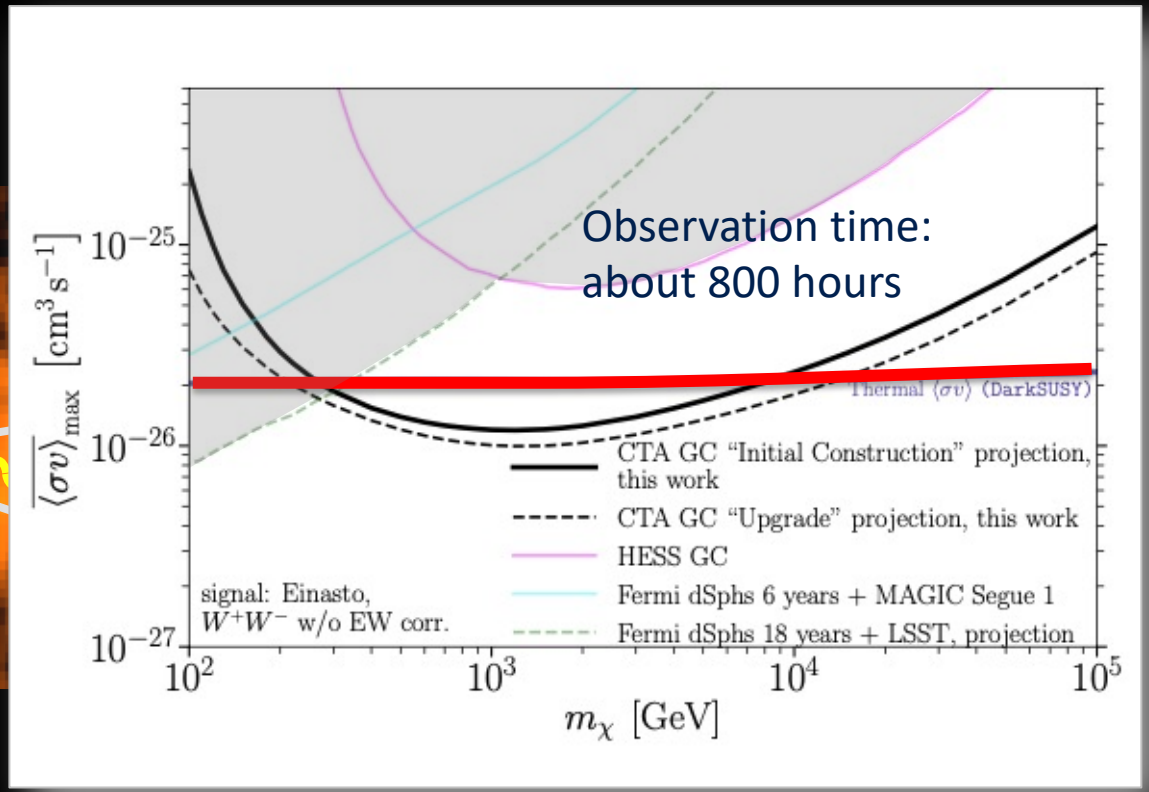
Annihilation cross section "known" from Dark Matter abundance

Characteristic spectral signature known from particle physics

GALACTIC CENTER & DARK MATTER KSPs

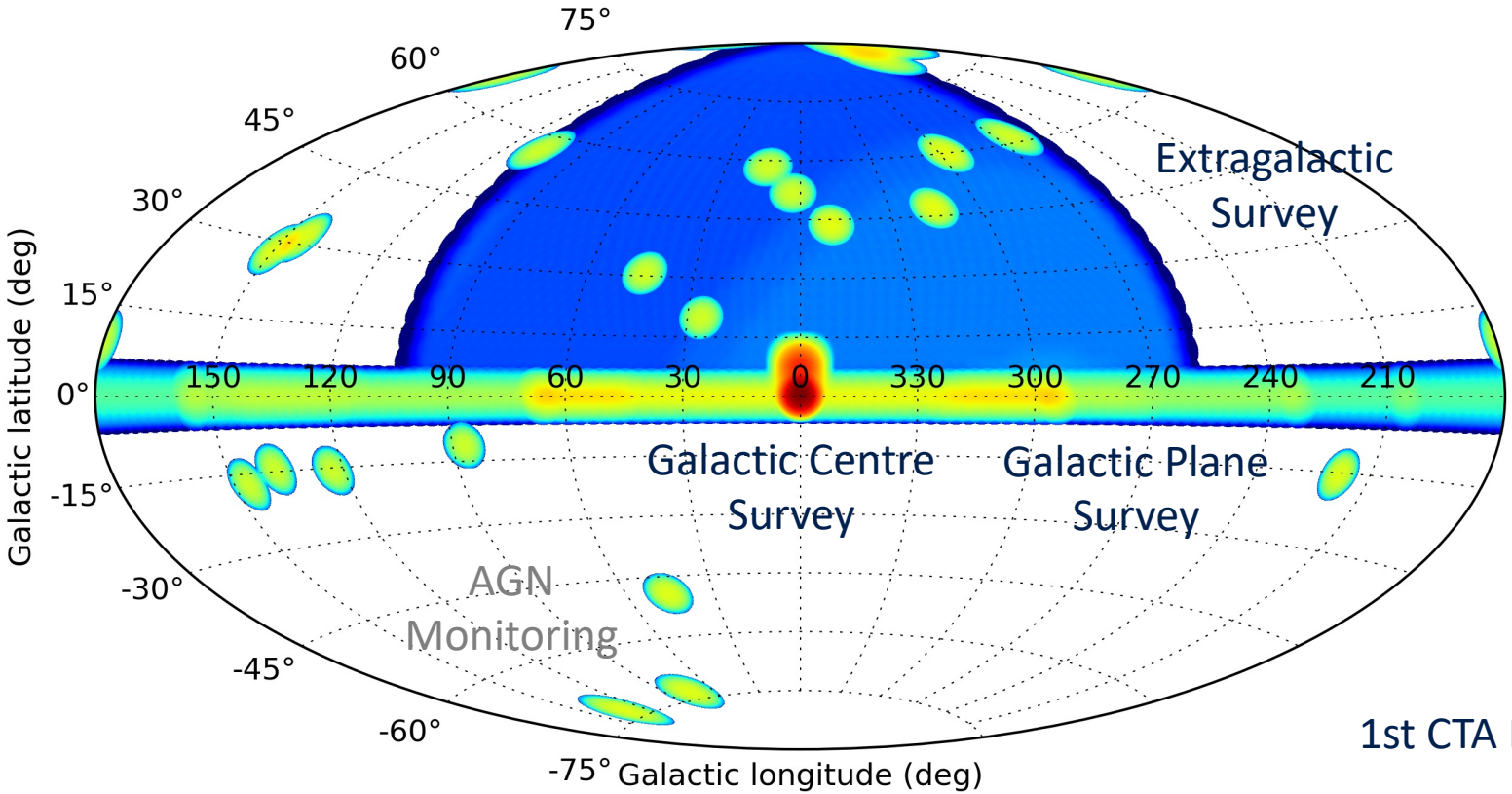


Annihilation cross section "known" from Dark Matter abundance



arXiv:2007.16129

SURVEY KSPs

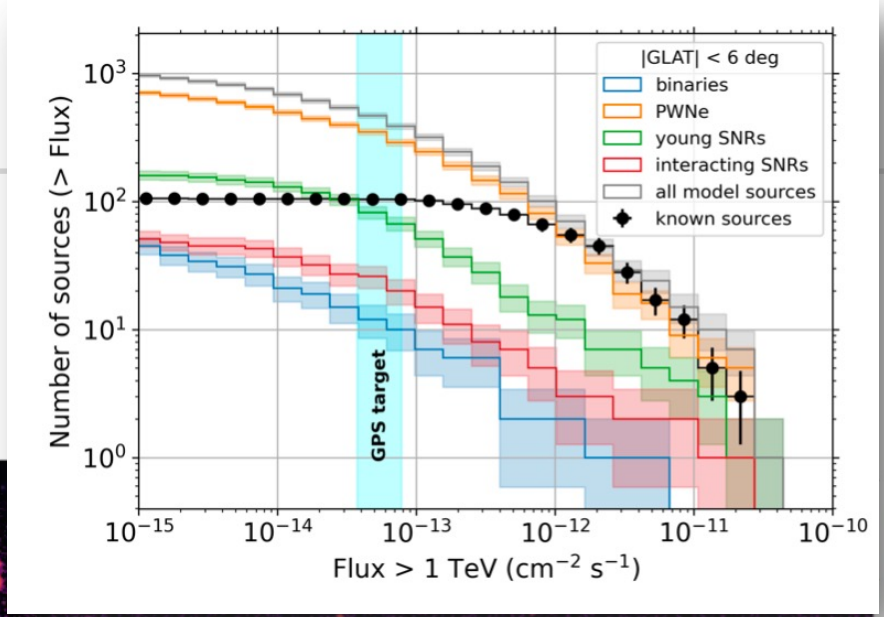


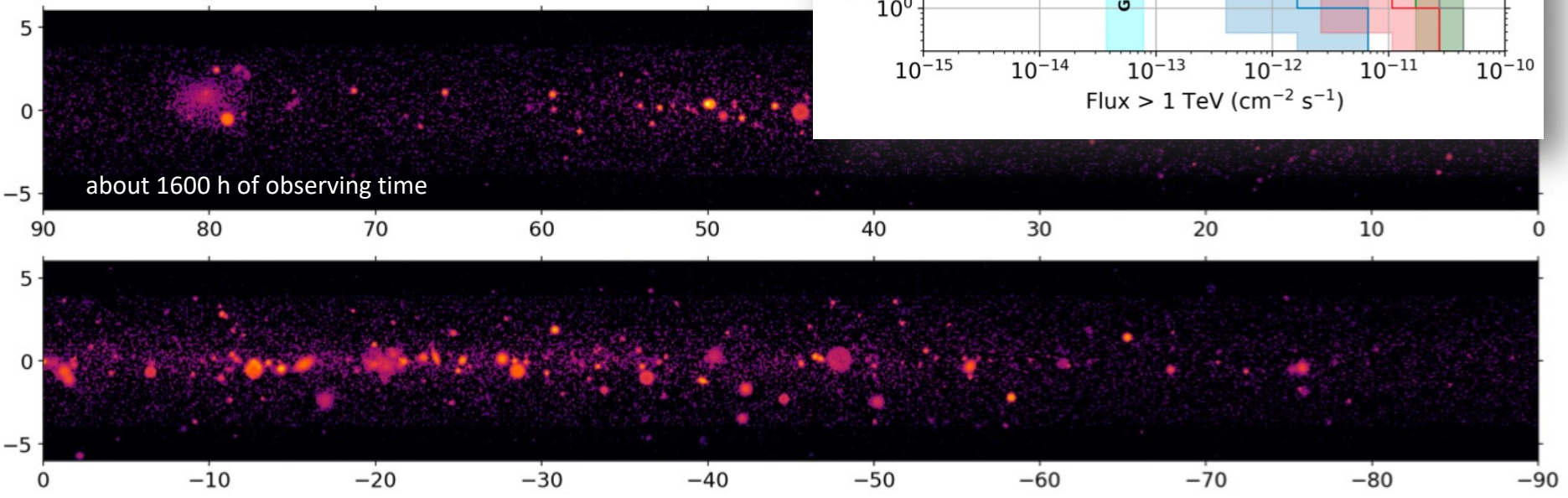
Exposure
1st CTA Data Challenge

GALACTIC PLANE SURVEY

PoS(ICRC2021)886

expect about
500 source detections

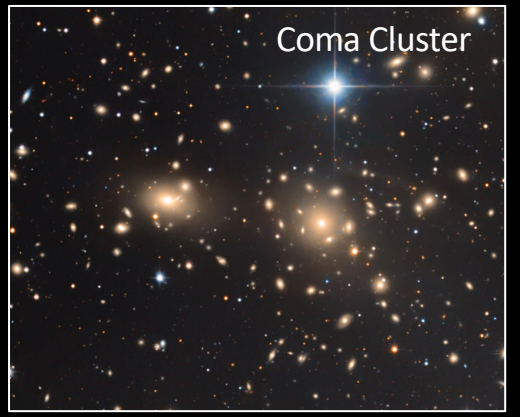




A CENSUS OF COSMIC PARTICLE ACCELERATORS

J.Fritz,
W. Pietsch,
R. Gendler

Hubble Heritage Team



R. Carroll,
R. Gendler
B. Franke

Univ. of Oklahoma
& NASA

ACROSS ALL COSMIC SCALES

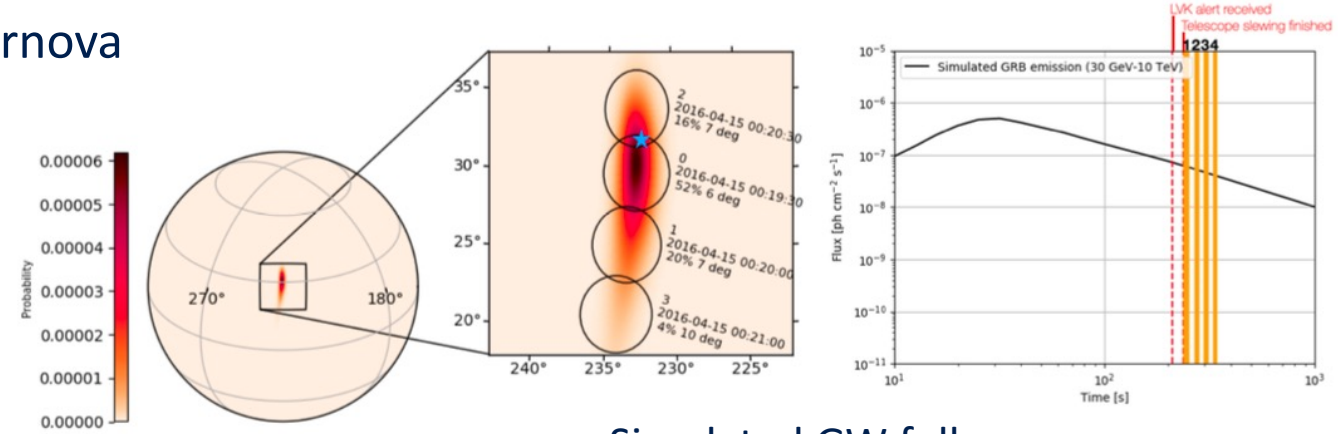
KEY ASPECT OF CTA SCIENCE: TRANSIENT FOLLOW-UP

Gamma-ray bursts
Gravidational waves
Neutrino follow-up
Galactic transients
Core-collapose supernova

AGN flares

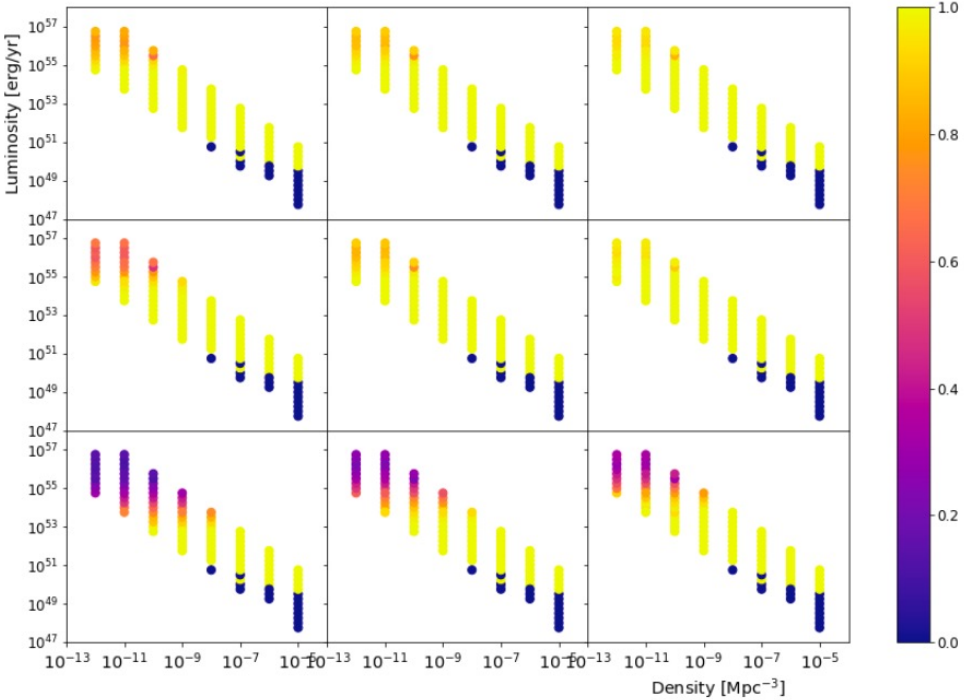
see
PoS(ICRC2021)736
PoS(ICRC2021)784
PoS(ICRC2021)937
PoS(ICRC2021)975
PoS(ICRC2021)998

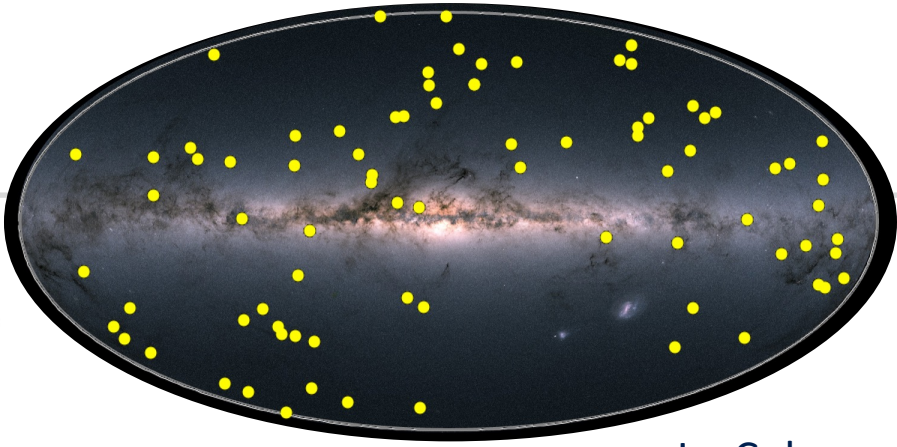
Expect 1-2 GRB detections / year



Simulated GW follow-up
PoS(ICRC2021)998

NEUTRINO FOLLOW-UP





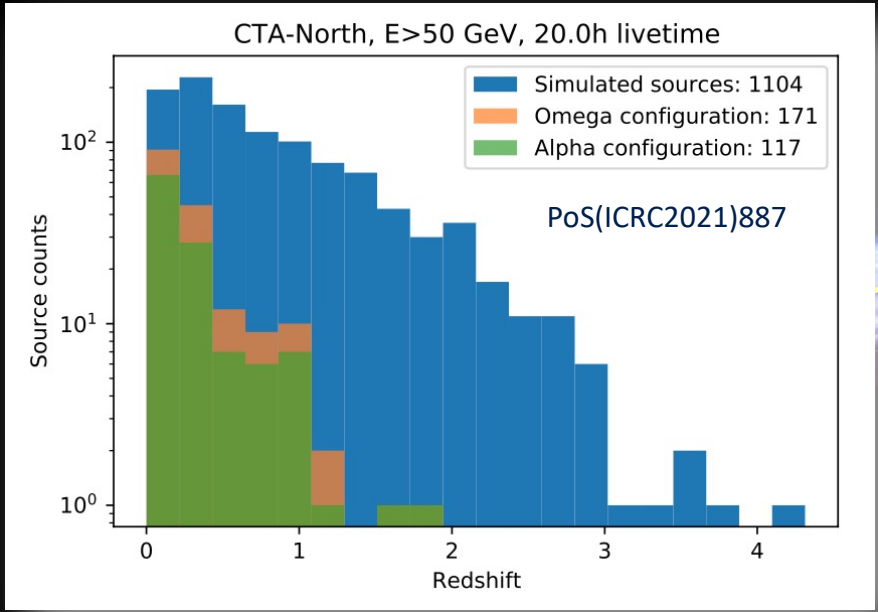
IceCube
neutrino alerts

Detection probability as a function of source luminosity and local density of sources, for 30 exposure

PoS(ICRC2021)975

AGN KEY SCIENCE PROJECT

What is the jet made of?
How is it launched?
What causes the variability?

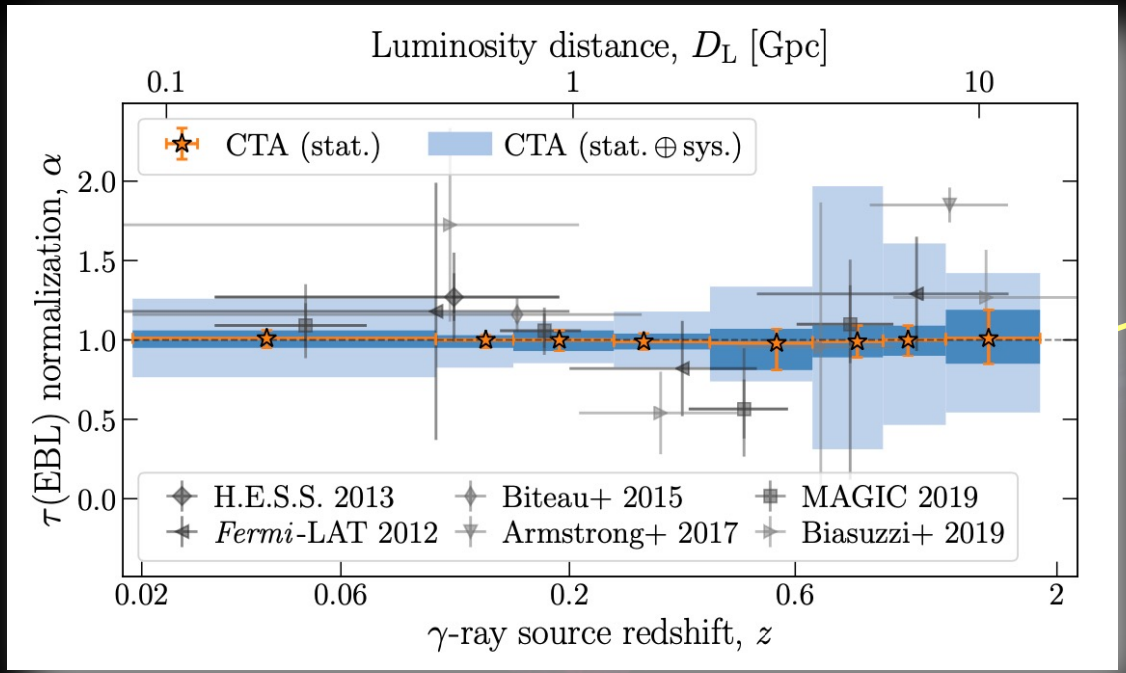


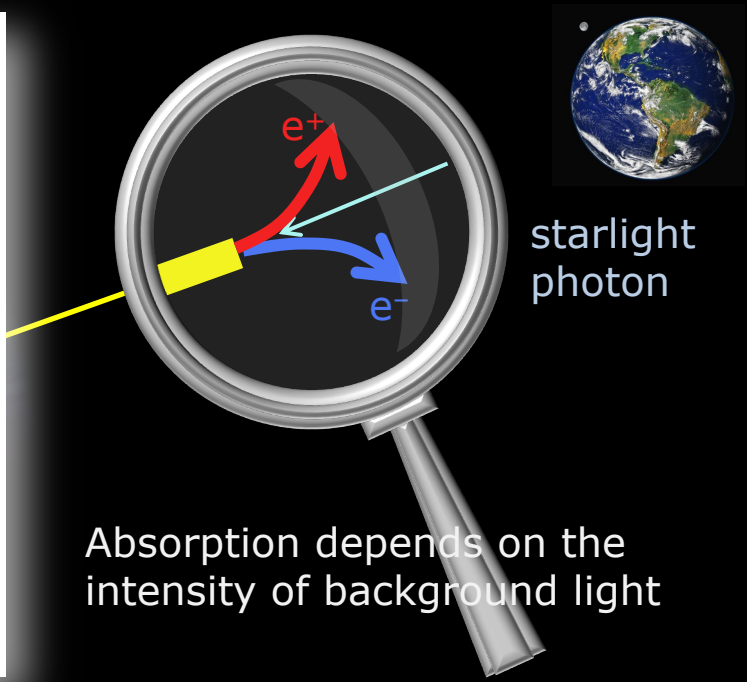
- Long-term monitoring of selected AGN over 10 years
- Follow-up of flaring AGN
- High-quality measurement of selected AGN spectra

Total observation time:
about 3000 hours

PHOTON PROPAGATION: EXTRAGALACTIC BACKGROUND LIGHT

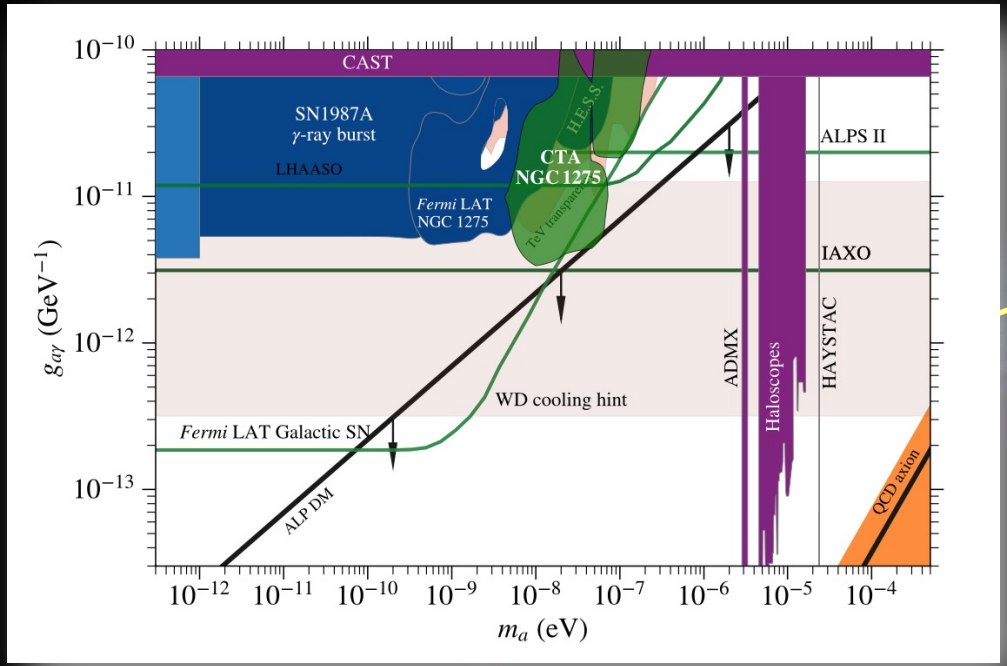
arXiv:2010.01349

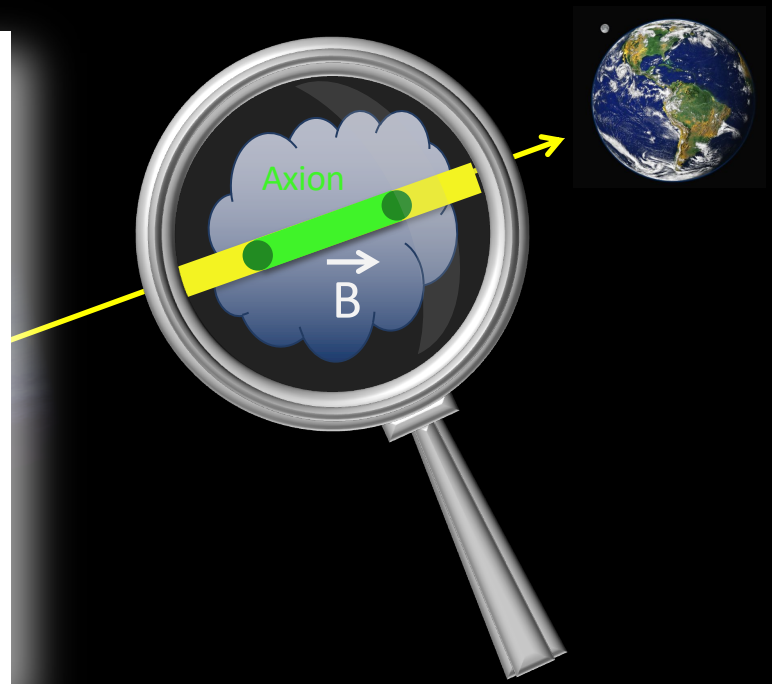




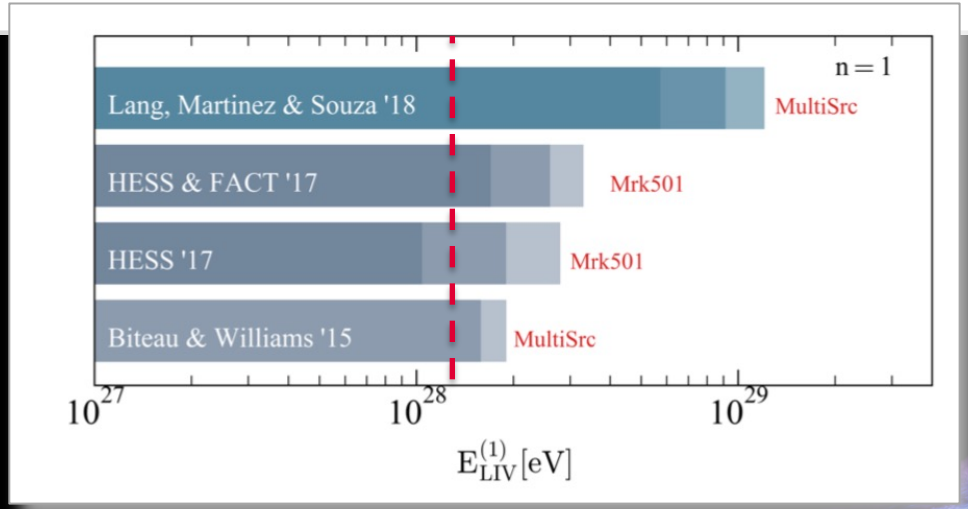
PHOTON PROPAGATION: PHOTON-AXION OSCILLATIONS

arXiv:2010.01349



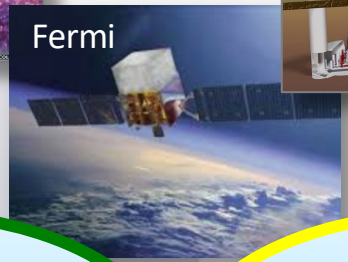


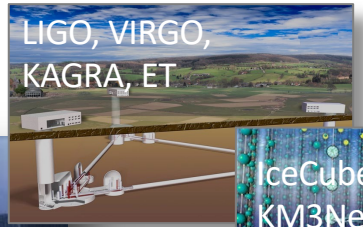
PHOTON PROPAGATION: VIOLATION OF LORENTZ INVARIANCE

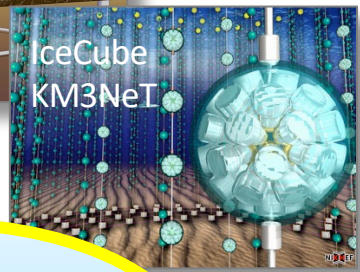


Current instruments:
H. Martinez-Huerta et al.
arXiv:1901.03205

KSPs LIVE IN A MULTIWAVELENGTH & MULTIMESSENGER WORLD



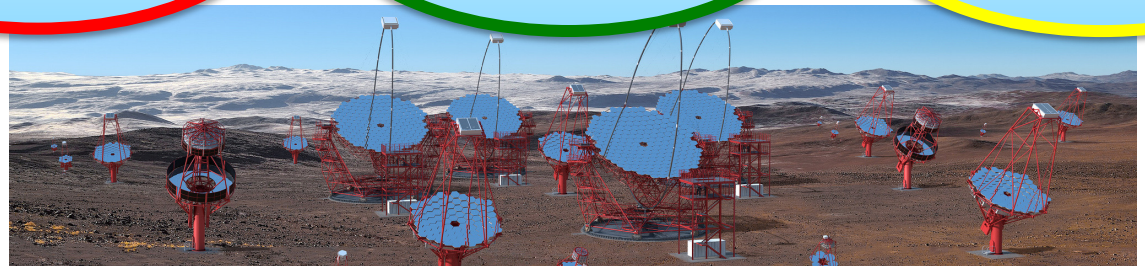




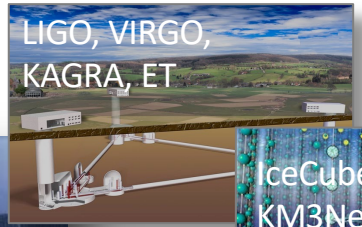
Target selection & ToOs

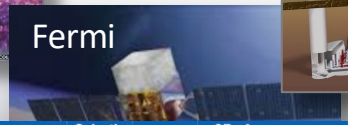
Object characterization

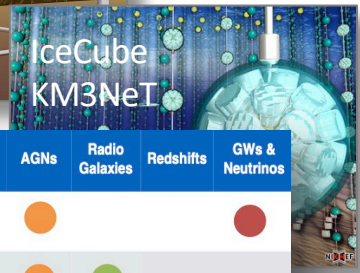
Wide-band / MM SED



KSPs LIVE IN A MULTIWAVELENGTH & MULTIMESSENGER WORLD

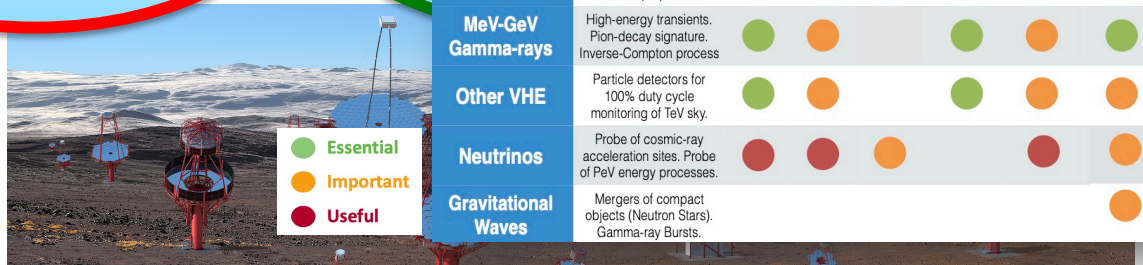






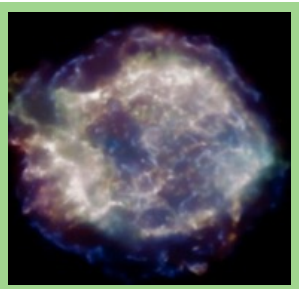
Target selection & ToOs

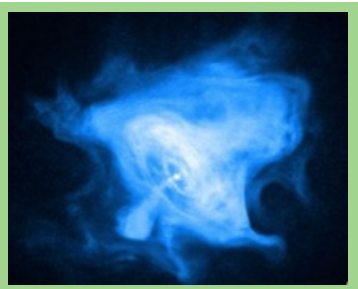
Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	●	●	●	●	●	●	●			●
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	●	●		●	●	●	●	●		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	●	●		●	●	●	●	●	●	●
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.				●		●	●			●
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	●	●	●	●	●	●	●	●		●
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	●	●		●	●	●	●	●		●
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	●	●		●	●	●	●			●
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.	●	●	●		●	●	●			●
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						●				●



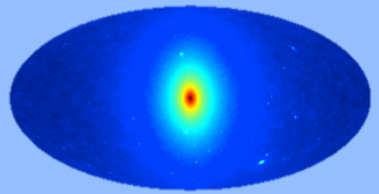
CTA: ENABLING A “PHASE TRANSITION” IN VERY HIGH ENERGY GAMMA RAY ASTRONOMY

In-depth understanding
of known objects and
their mechanisms





Expected discoveries
of new object classes



The fun part:
Things we haven’t thought of

?