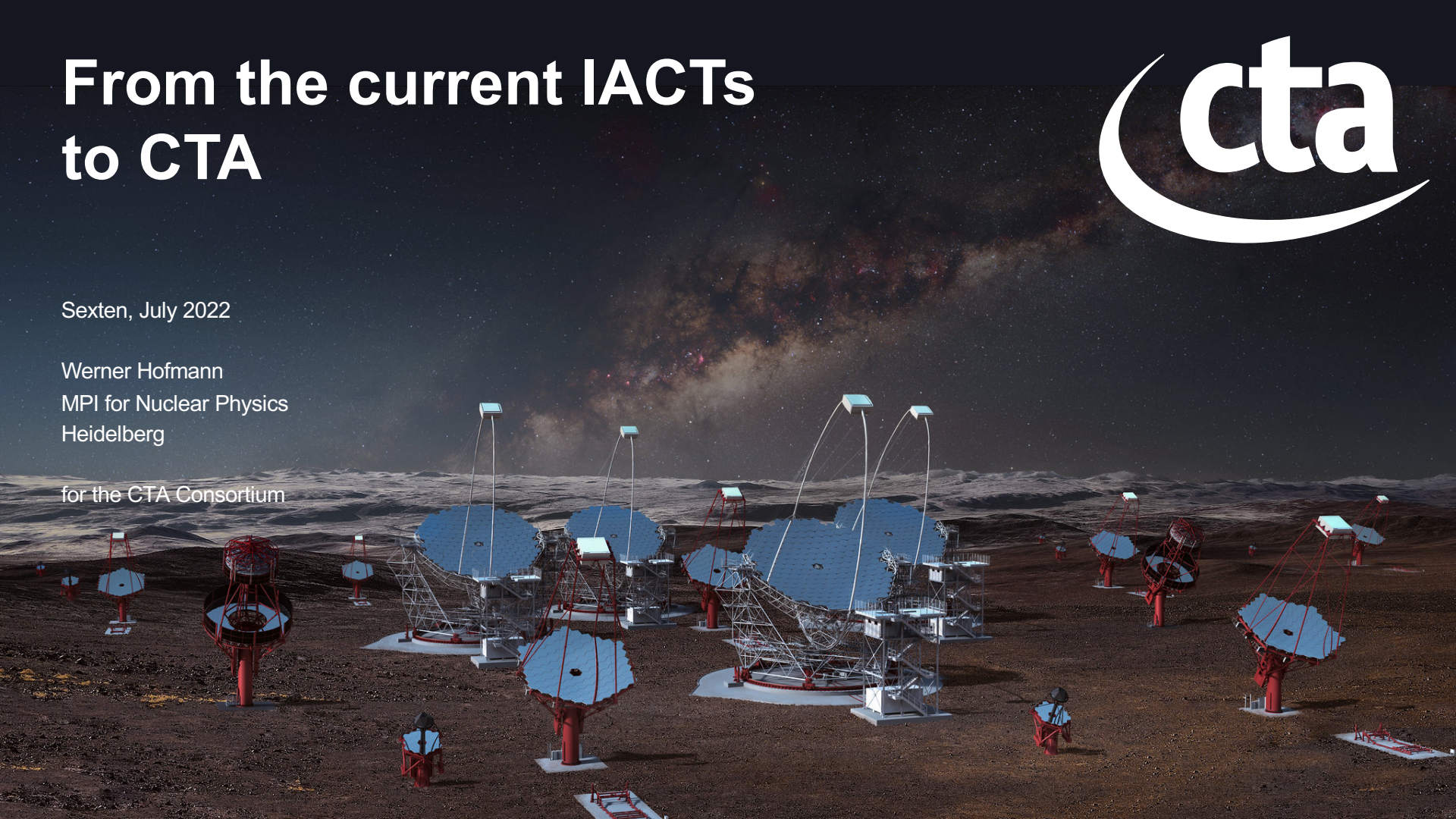
From the current IACTs to CTA

Sexten, July 2022

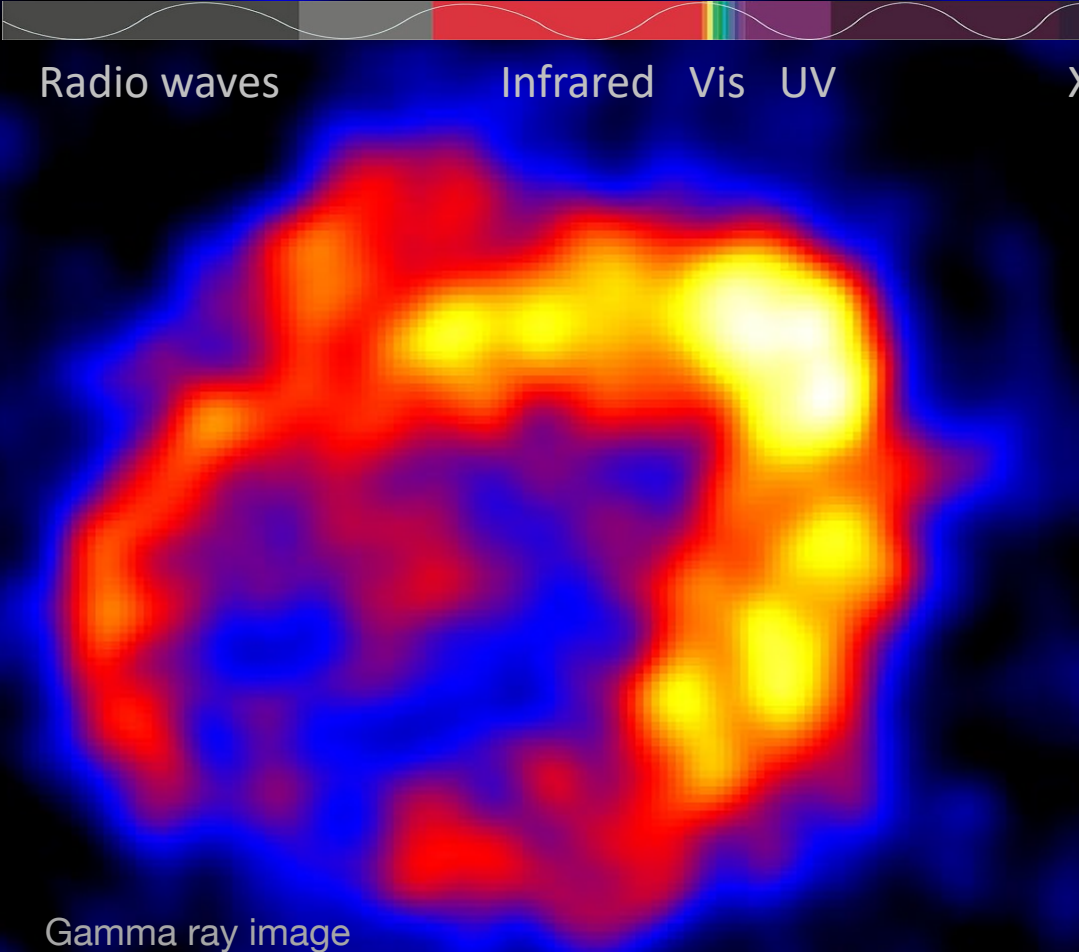
Werner Hofmann
MPI for Nuclear Physics
Heidelberg

for the CTA Consortium



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

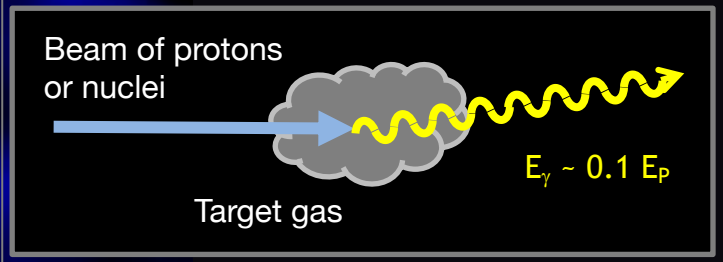
TeV ($10^{12 \pm 2}$ eV) domain

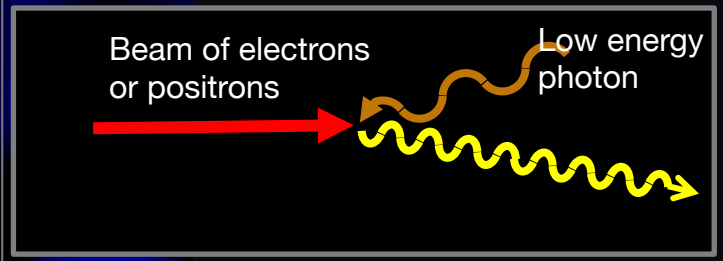


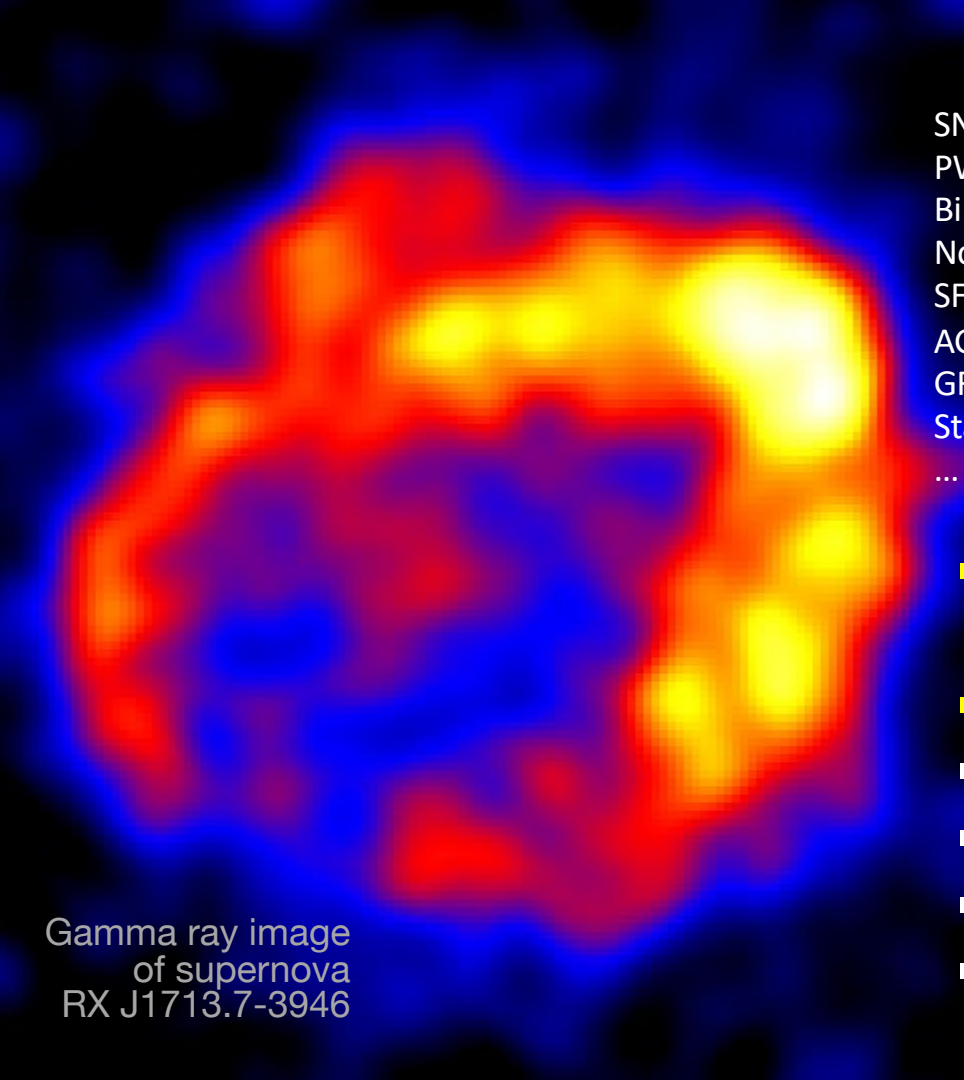
Gamma ray image of supernova RX J1713.7-3946

Gamma rays

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

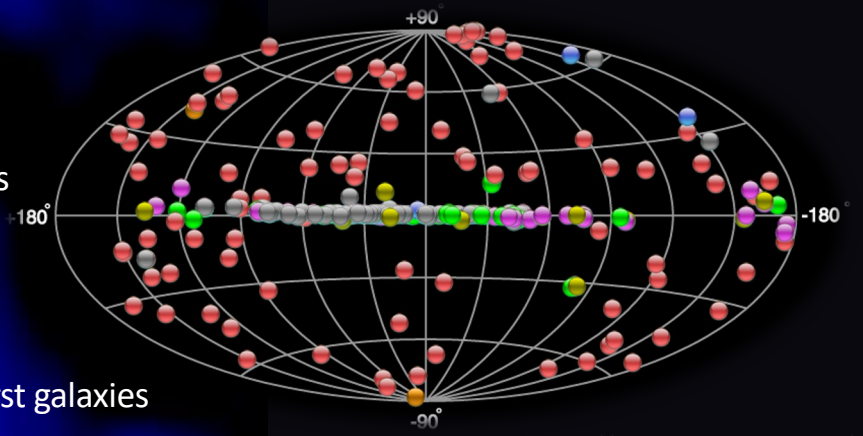






Gamma ray image
of supernova
RX J1713.7-3946

SNR
PWN
Binaries
Novae
SFR
AGN
GRBs
Starburst galaxies
…



http://tevcat.uchicago.edu/

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


CHERENKOV
TELESCOPES

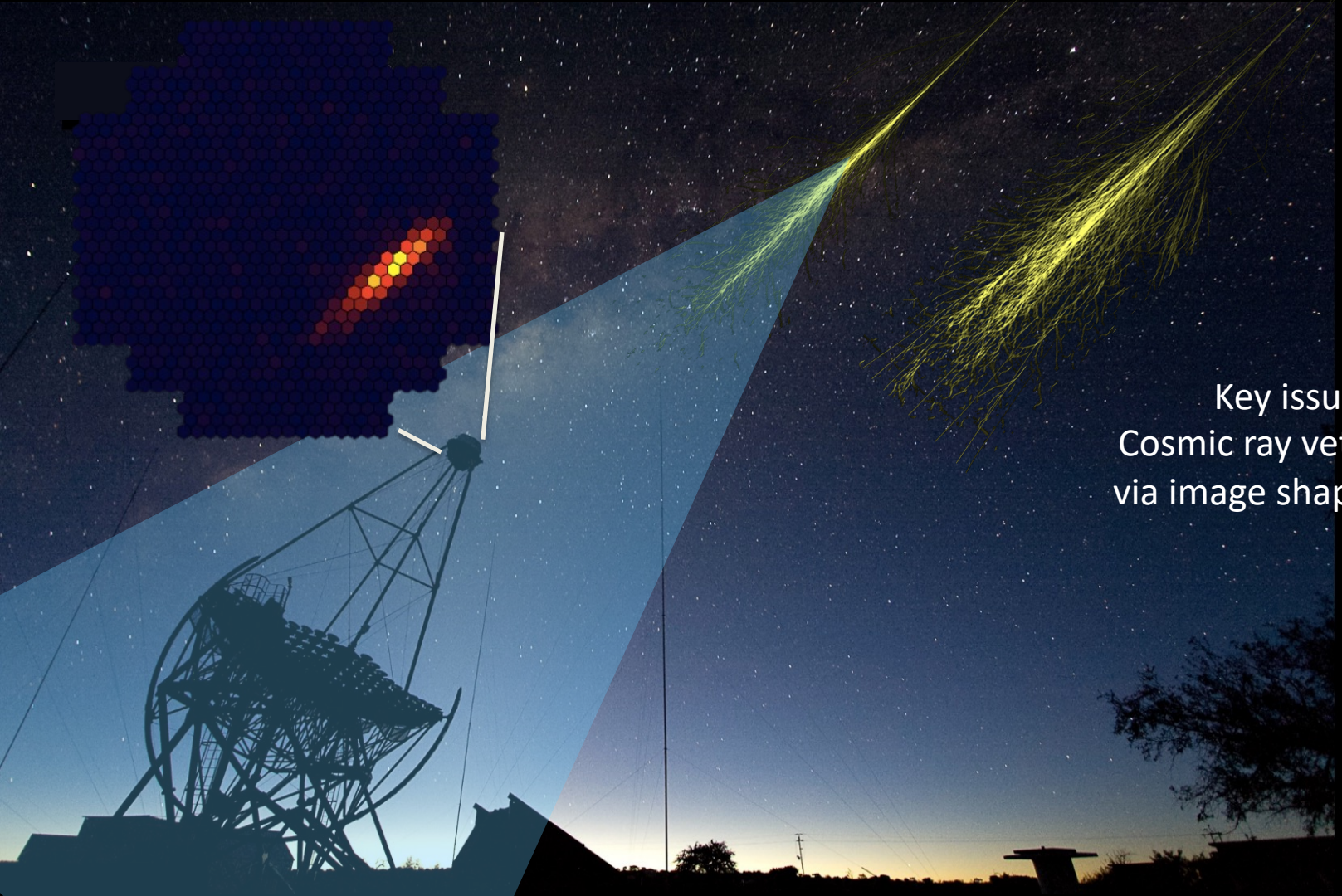
Multiple telescopes provide stereoscopic views of the cascade

4^0-5^0

CHERENKOV TELESCOPES

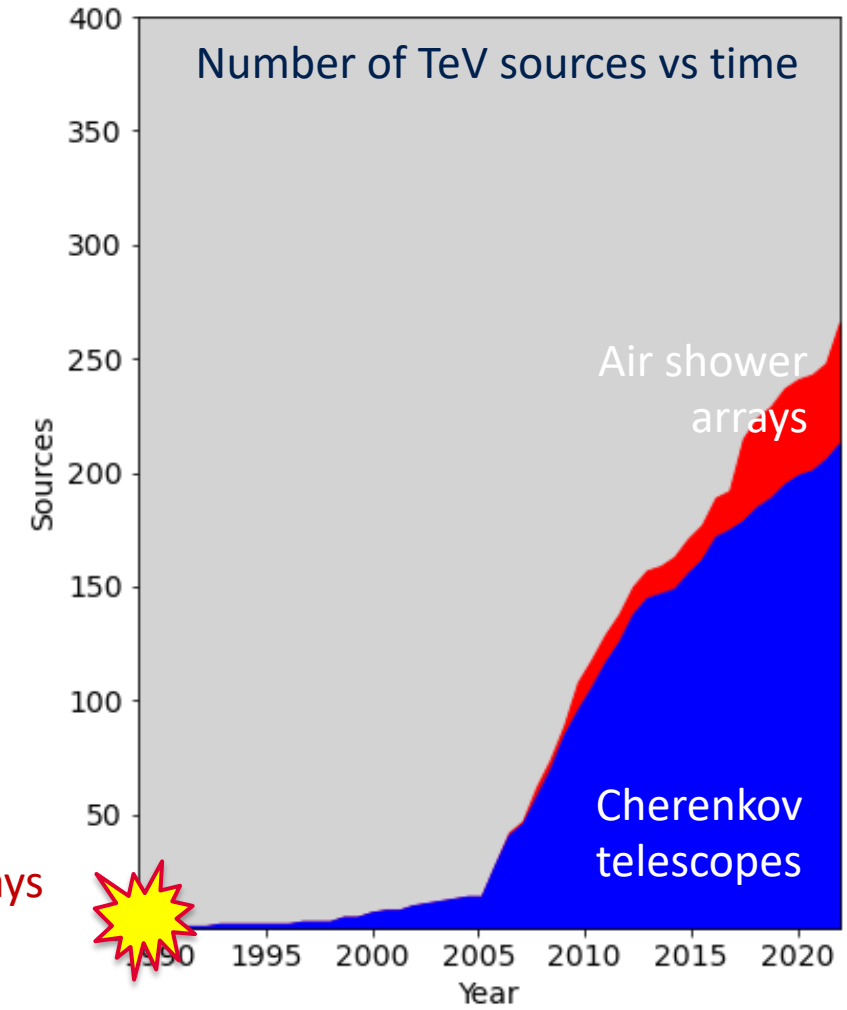
A bit like a meteor track, but
very faint (few photons per m^2)
very short-lived (some 10^{-9} seconds)

300 m Ø “light pool”, 10^5 m^2



Key issue:
Cosmic ray veto
via image shape

A BIT OF HISTORY – HOW IT ALL STARTED



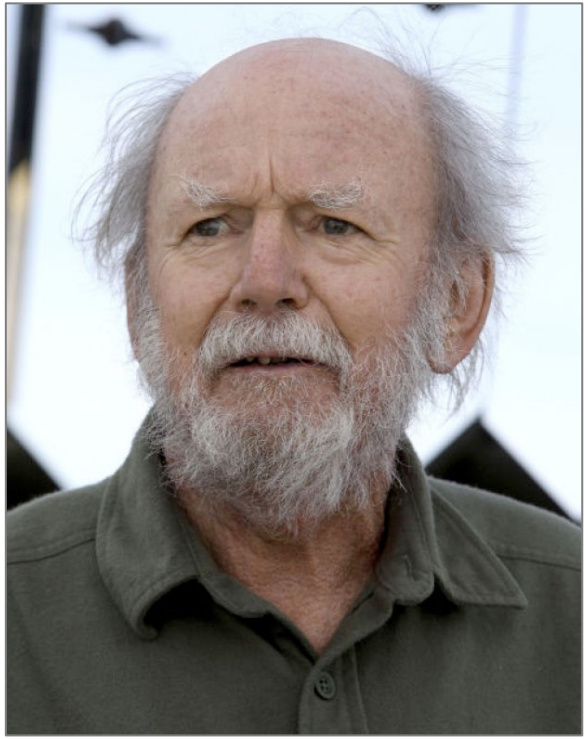
1989:
Discovery of TeV gamma rays from the Crab Nebula

A BIT OF HISTORY:
GROUND-BASED GAMMA RAY ASTRONOMY 1989

Whipple Telescope 1968

Trevor Weekes

† 2014



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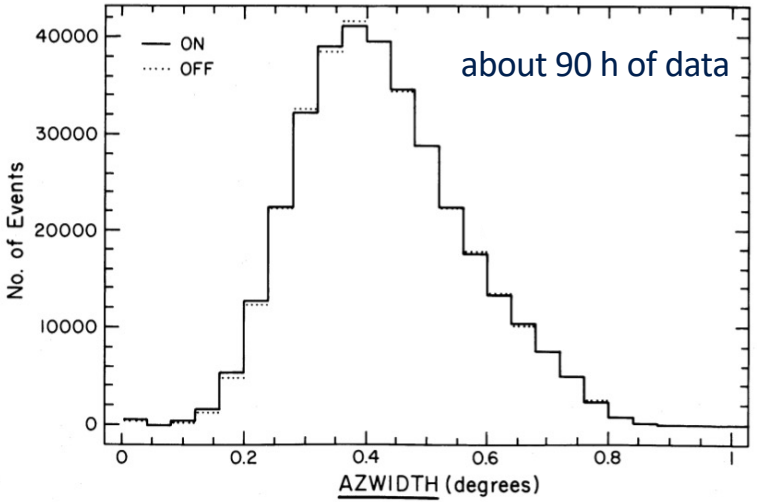
Whipple Telescope 1968

T. Weekes et al., ApJ 342 (1989) 379

"Observation of TeV Gamma Rays from the Crab Nebula using the Atmospheric Cerenkov Imaging Technique"



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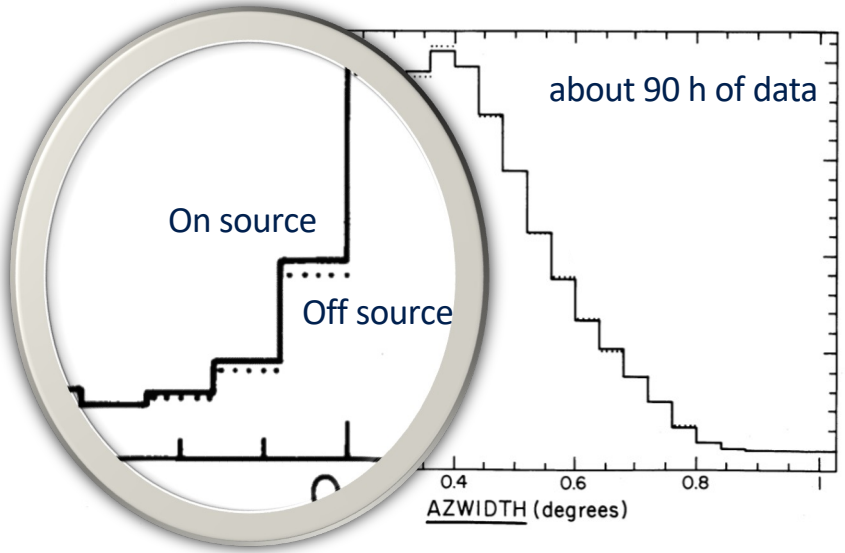
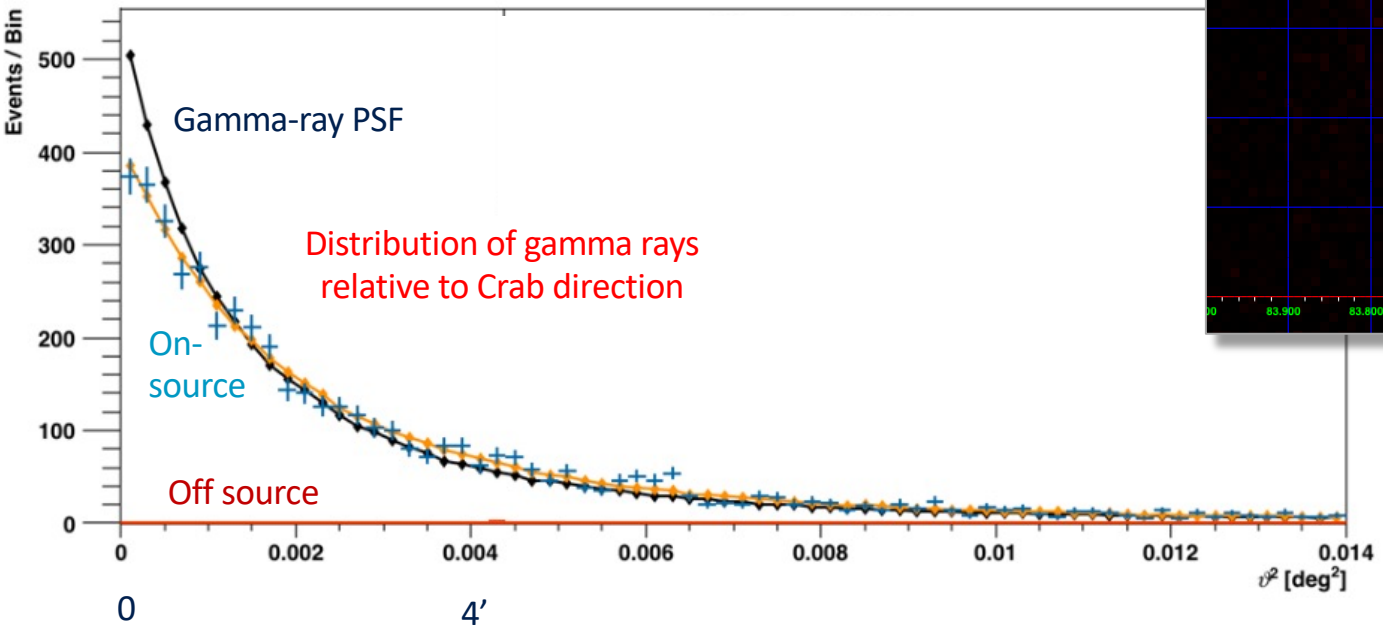
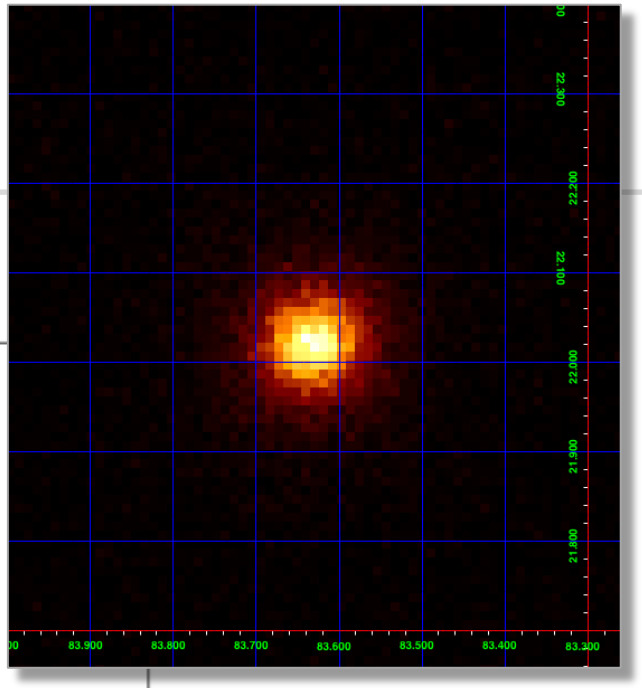


GROUND-BASED GAMMA RAY ASTRONOMY TODAY

H.E.S.S. Coll., Nature Astronomy 4 (2000) 167





Gamma-ray size of Crab Nebula: 52"±3"±8"

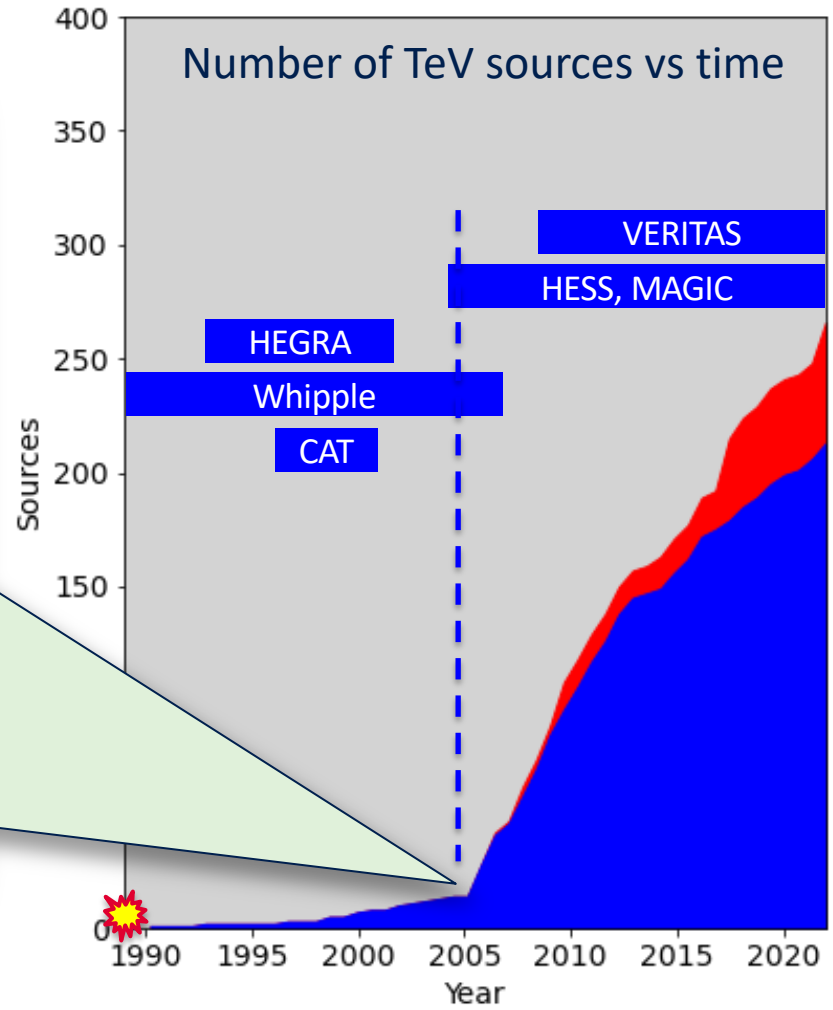
Sweet energy range for Cherenkov telescopes:

TeV domain (~100 GeV to few TeV)

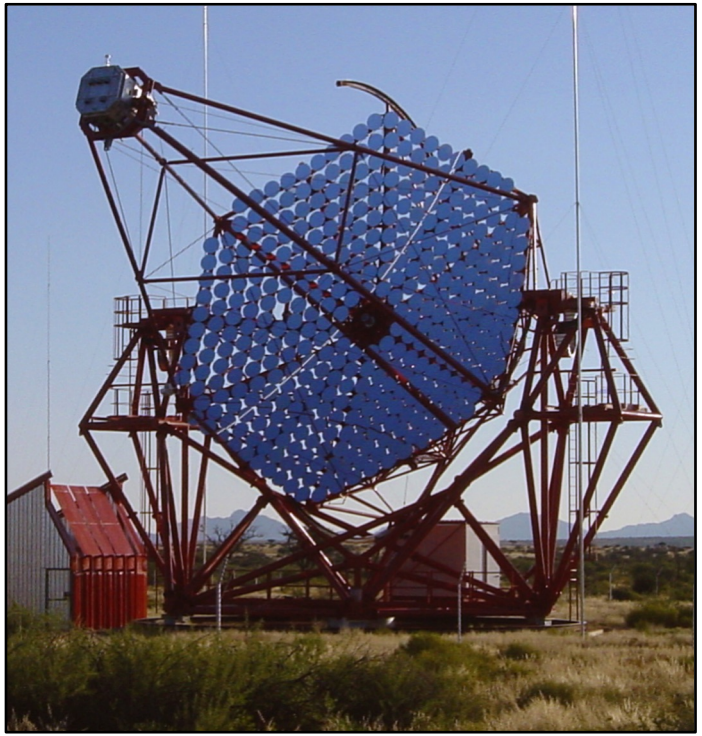
- Well-defined showers allowing efficient gamma-hadron separation
- Decent gamma-ray rates

What came together:

- Right dish size for decent photon statistics of images: 100+ m^2
- Right pixel size to resolve shower features: ~0.2° or less
- Large field of view, to contain images and extended sources
- Multi-telescope stereoscopic imaging
- Advanced analysis algorithms
- Highly detailed simulations to tune algorithms



1989 VS TODAY



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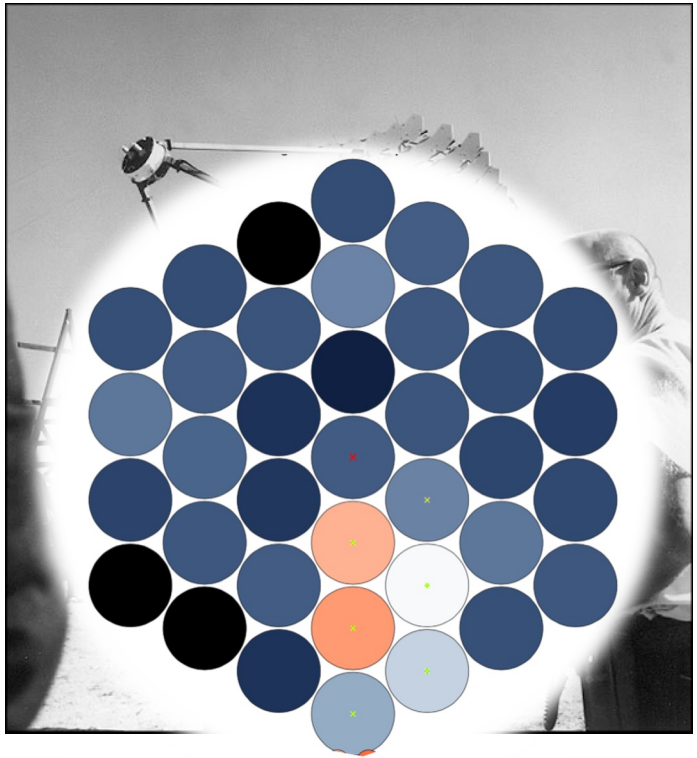
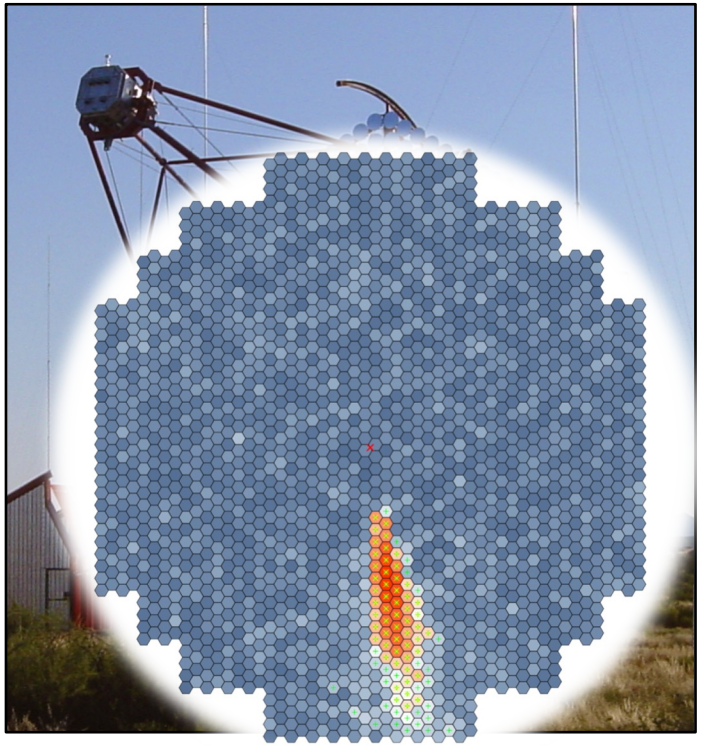
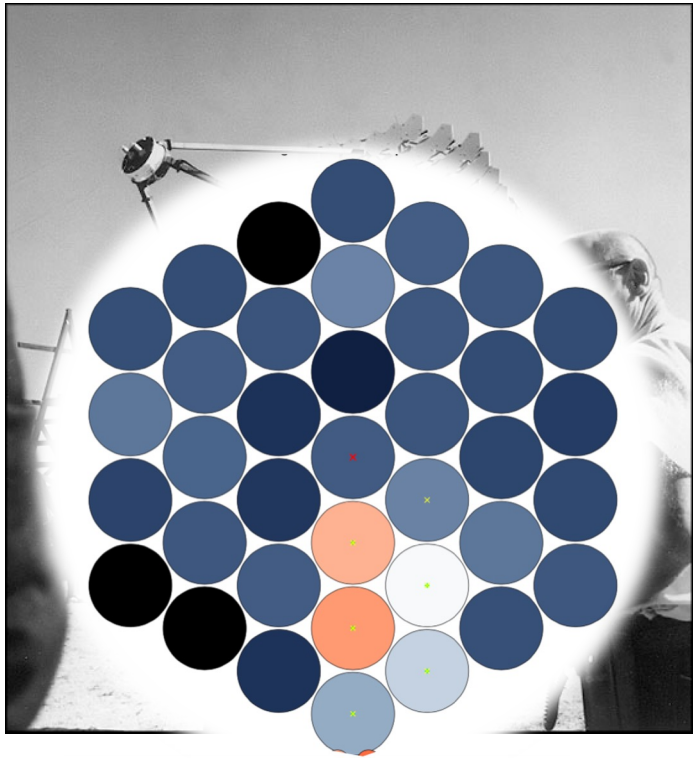


Whipple 1989 shower image



Modern camera

1989 VS TODAY



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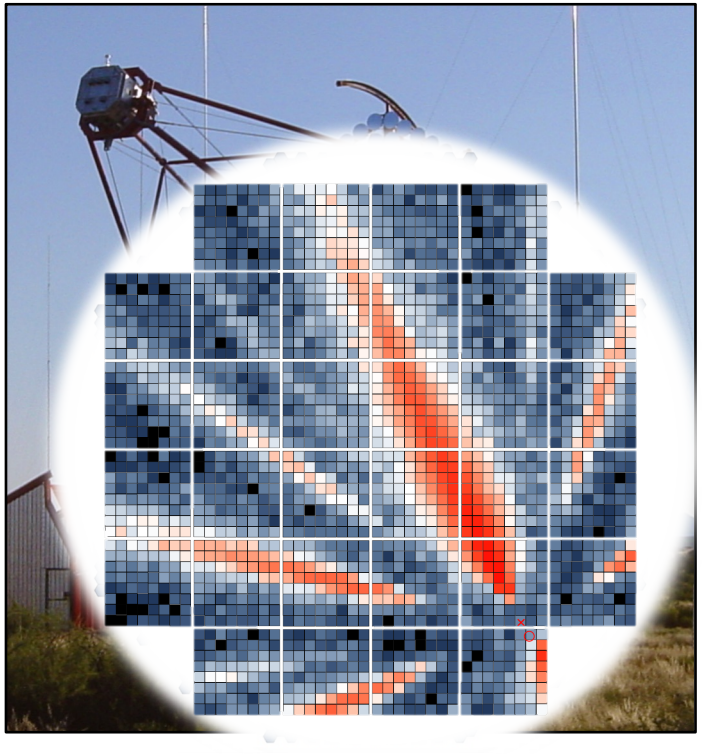
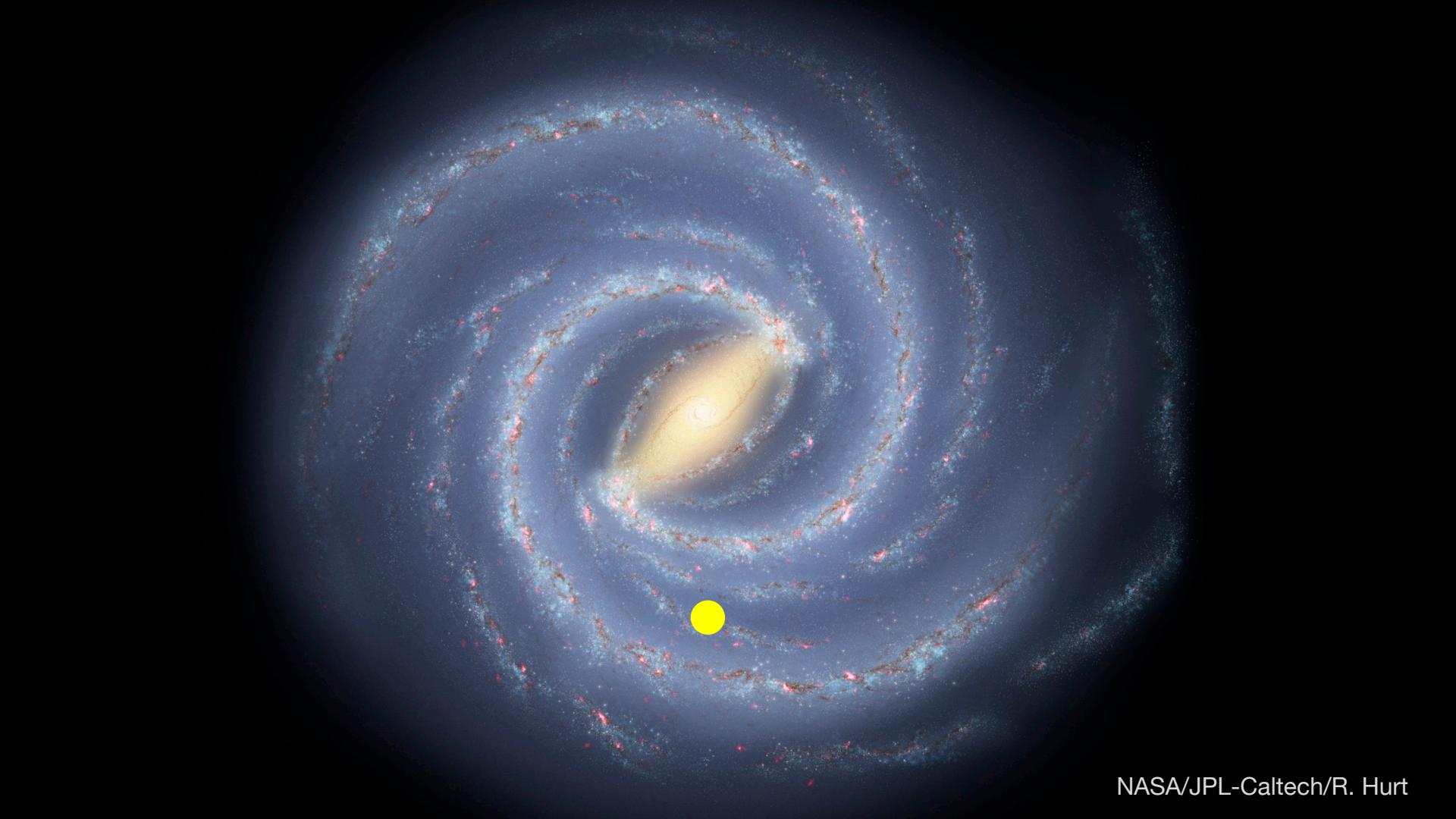
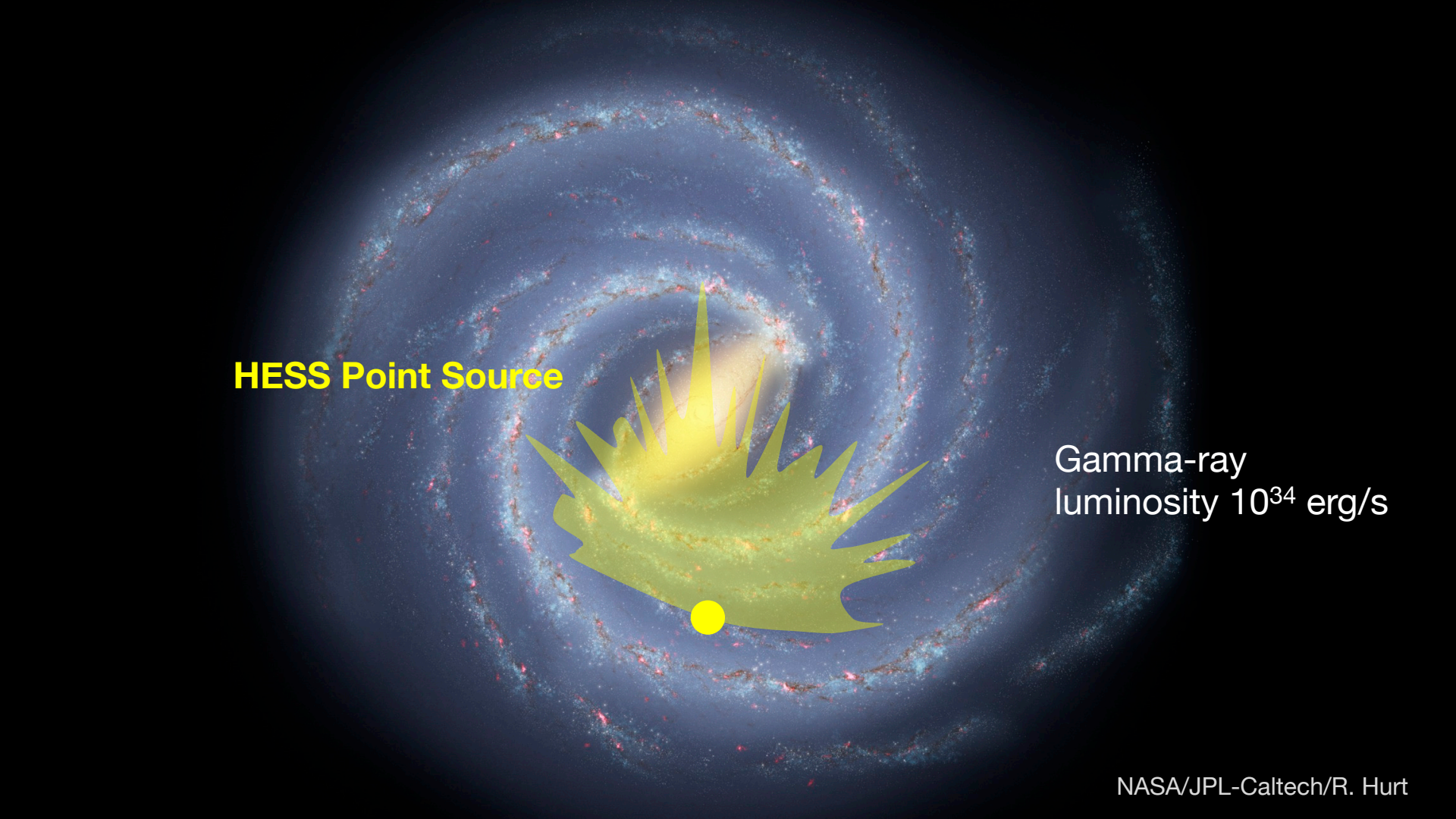
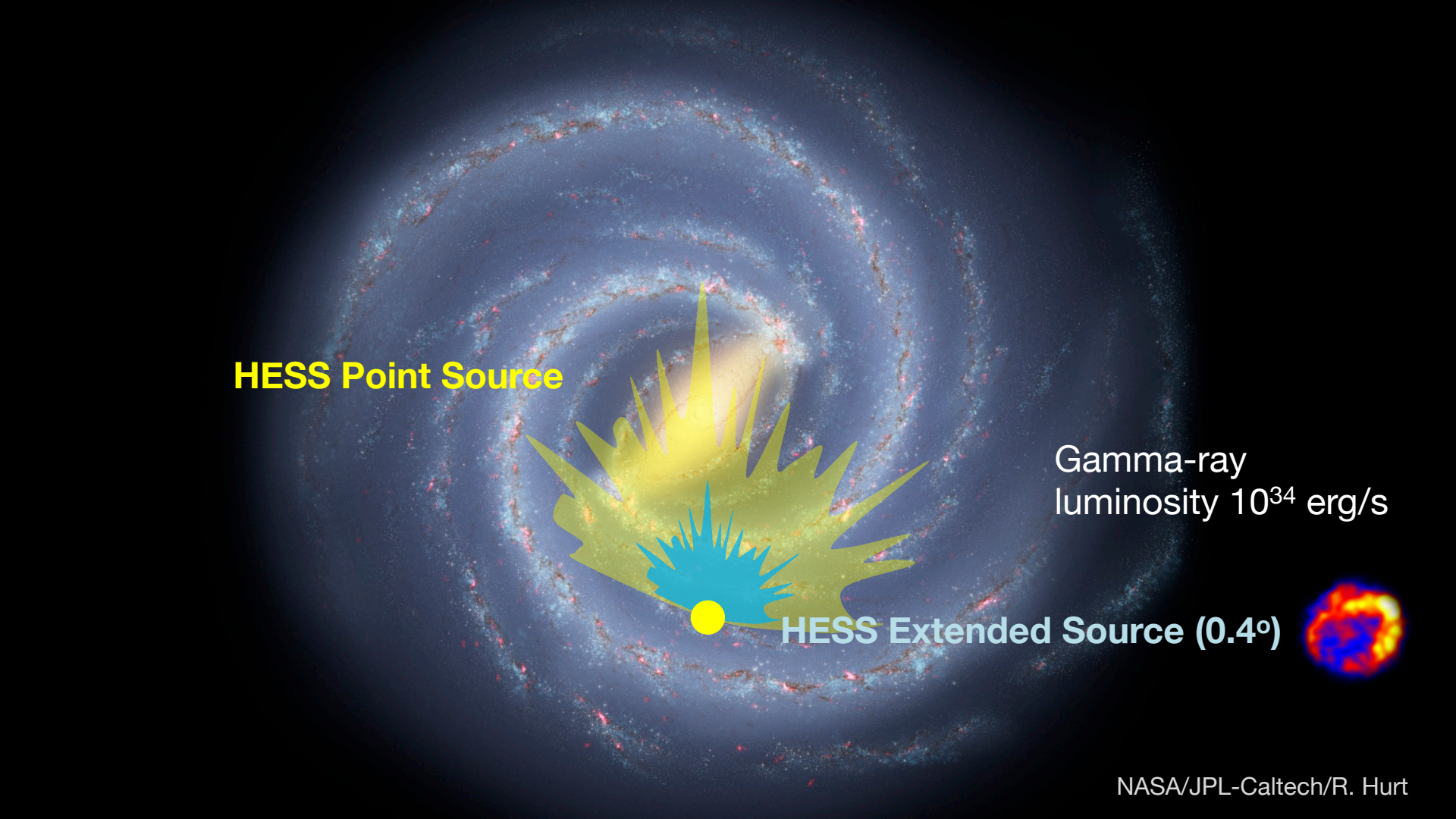


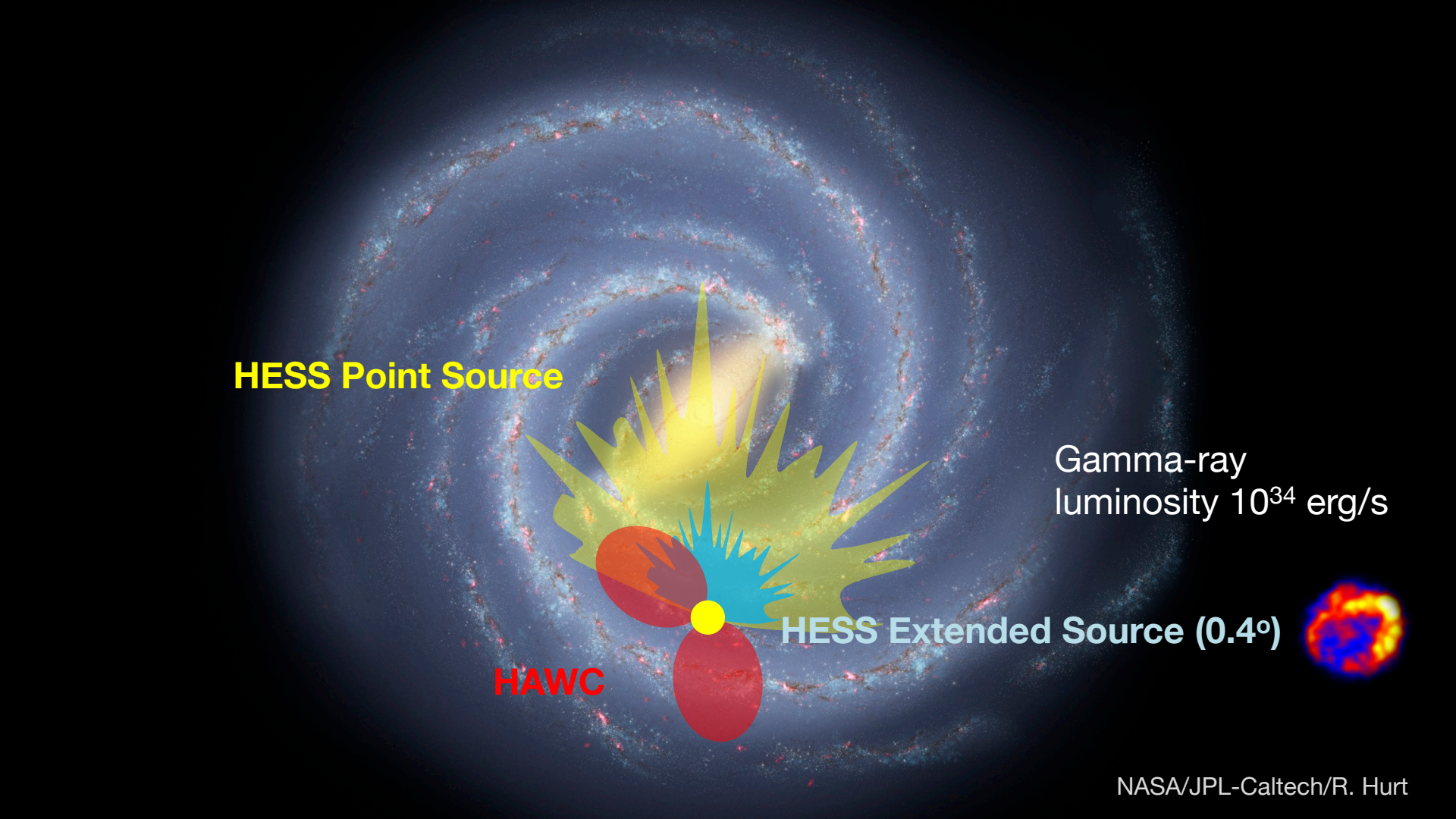
Modern array


2013-00


NASA/JPL-Caltech/R. Hurt

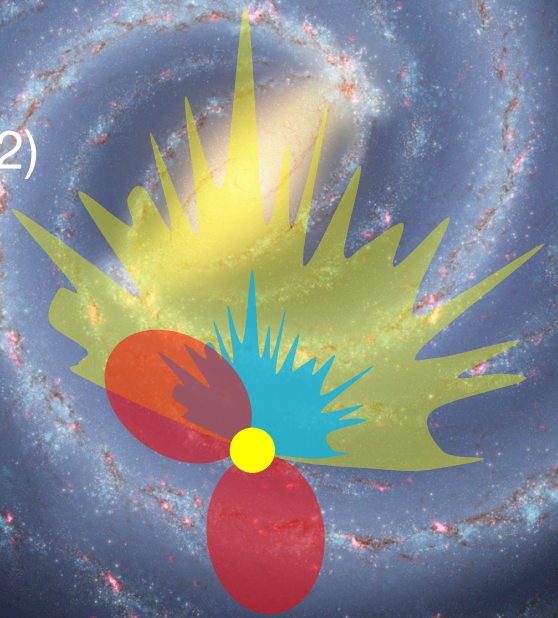

HESS Point Source
Gamma-ray
luminosity 10^{34} erg/s
NASA/JPL-Caltech/R. Hurt


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



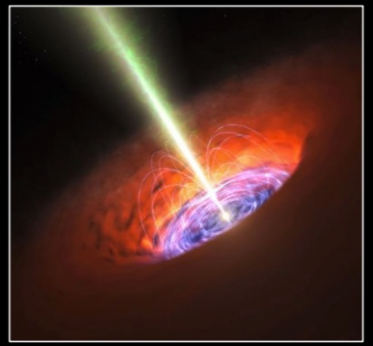
NASA/JPL-Caltech/R. Hurt

Theme 1: Cosmic Particle Acceleration

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

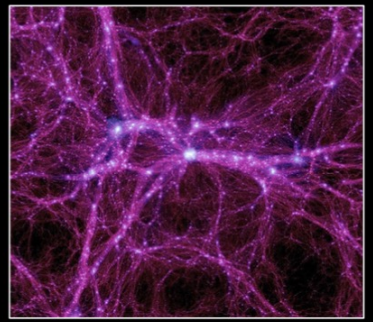
Theme 2: Probing Extreme Environments

- 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?



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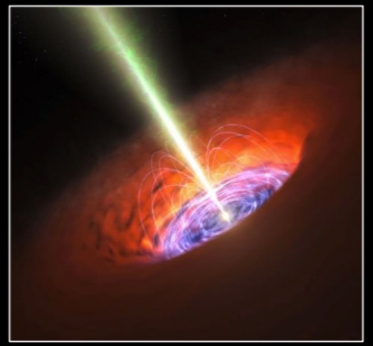

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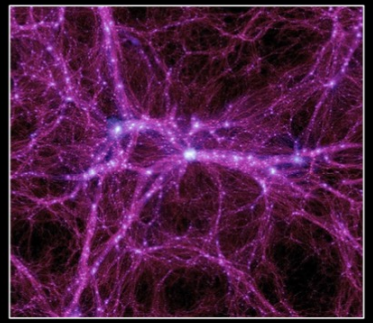


CHALLENGE: COMPACT OBJECTS AS ACCELERATORS

AGN:
What is the jet made of?
How is it launched?
How are particles accelerated?
What causes the variability?

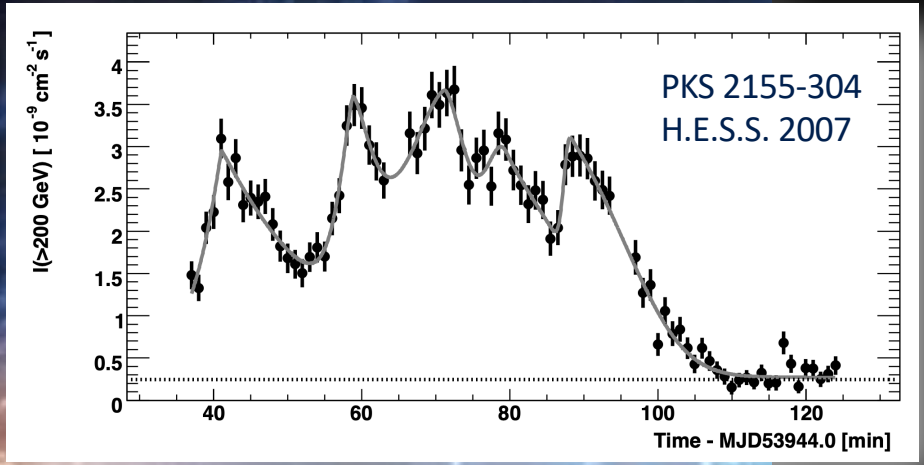


Illustration: Scientific American

TEV DETECTION OF GAMMA RAY BURSTS

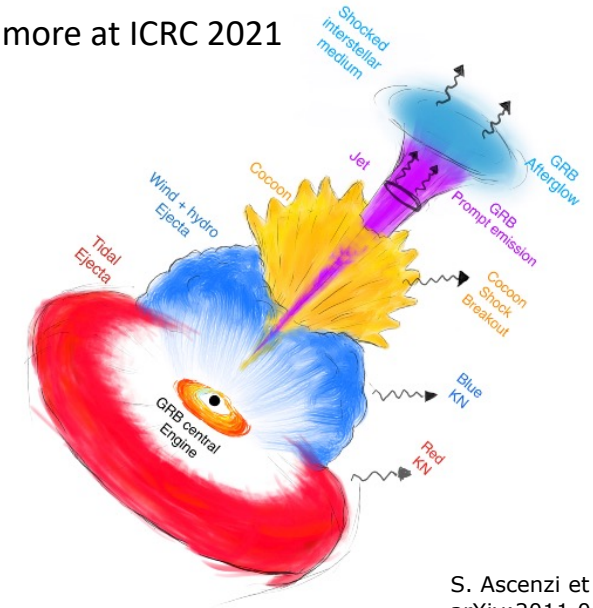
NASA/Swift/Mary Pat Hrybyk-Keith, John Jones

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

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

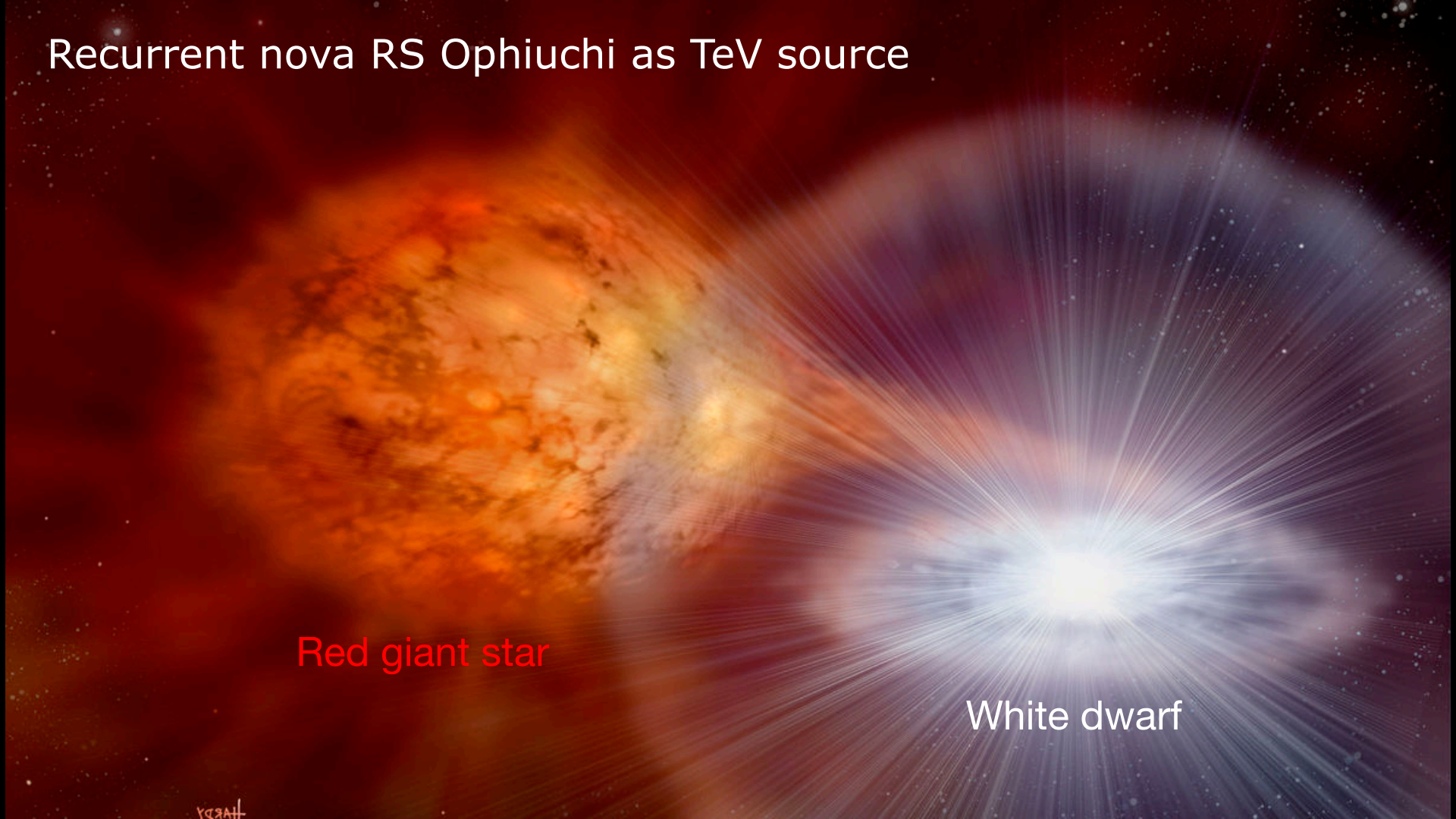
GRB 190829A
H.E.S.S. Coll., Science 372 (2021) 1081

+ 2 more at ICRC 2021



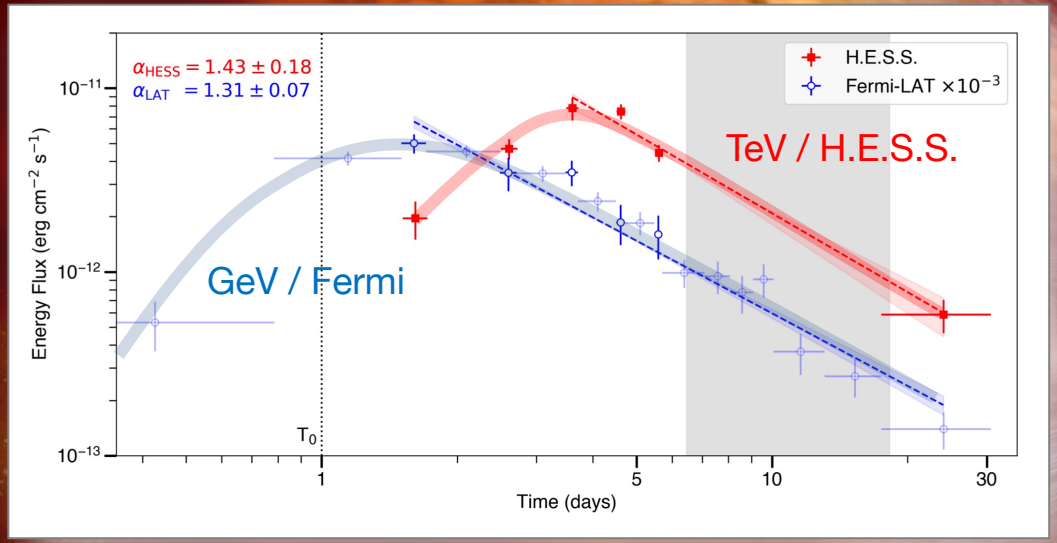
S. Ascenzi et al.
arXiv:2011.04001

Recurrent nova RS Ophiuchi as TeV source



Recurrent nova RS Ophiuchi as TeV source

H.E.S.S. ATEL #14844, Aug. 10
H.E.S.S. Science Mar. 2022
MAGIC Nature Astronomy 2022



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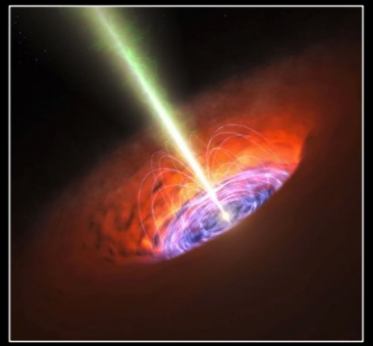

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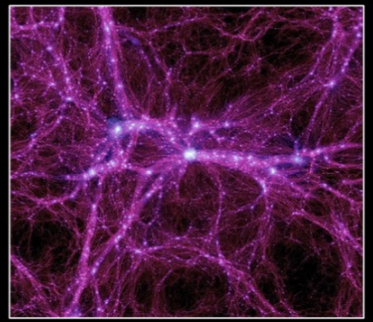
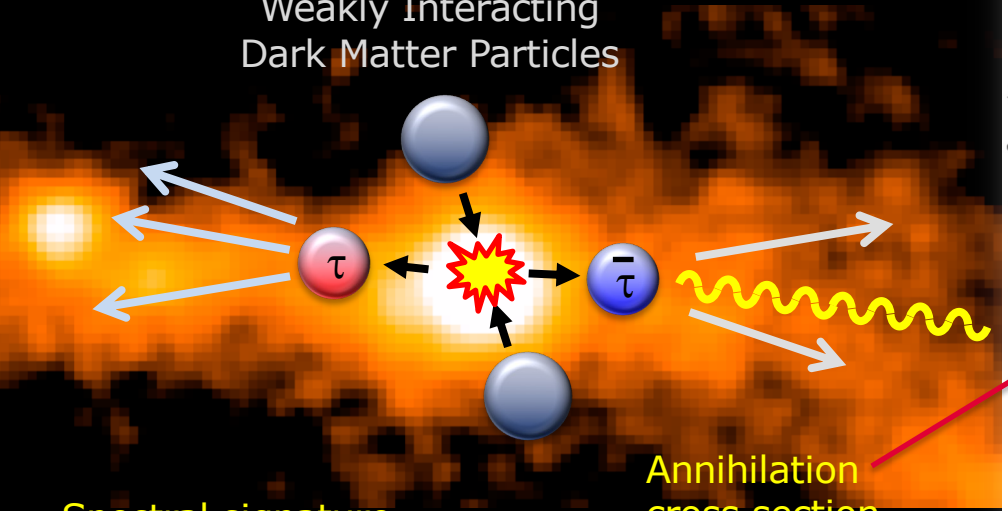
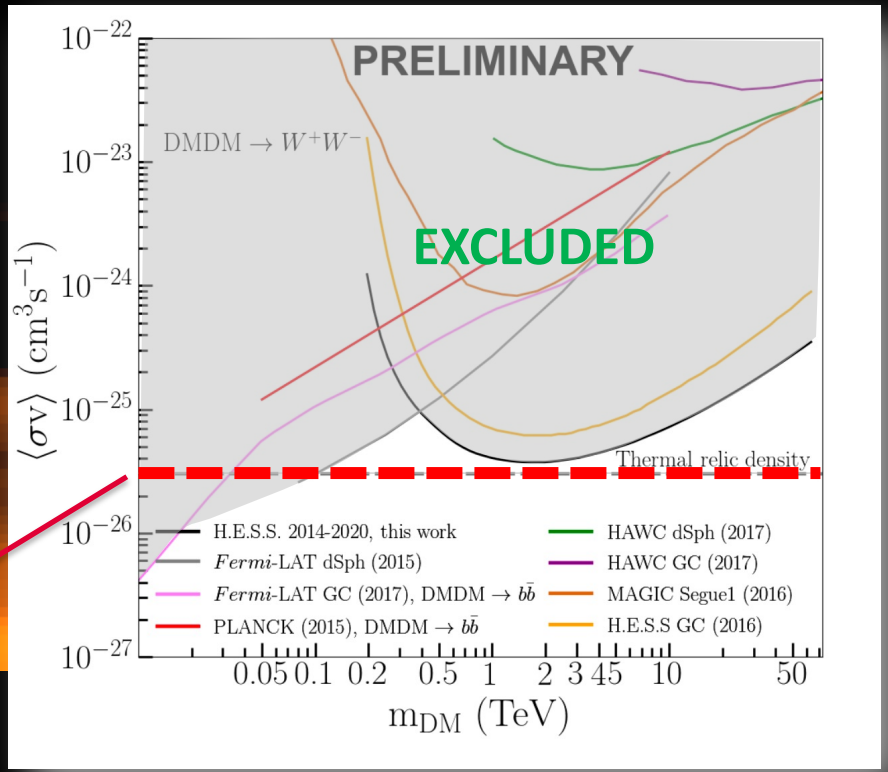


CHALLENGE: DARK MATTER @ GC



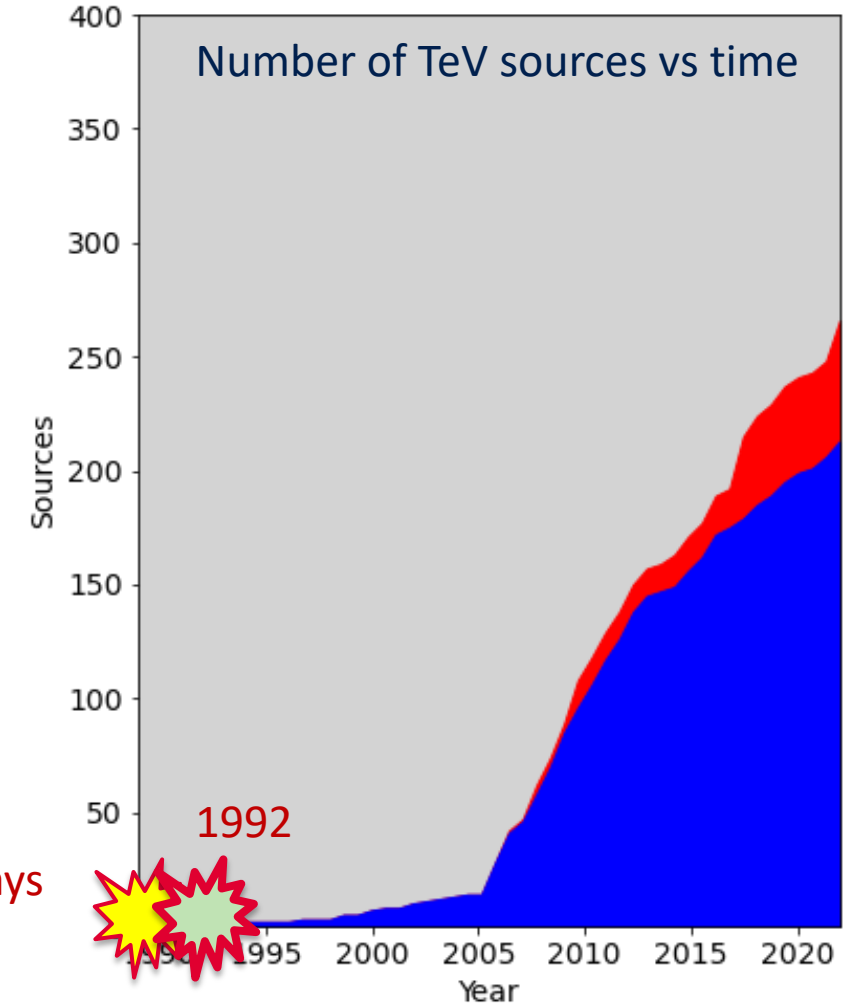
Spectral signature
known from particle physics

Annihilation
cross section
"known" from
Dark Matter
abundance



A. Montanari et al, PoS (ICRC2021)511

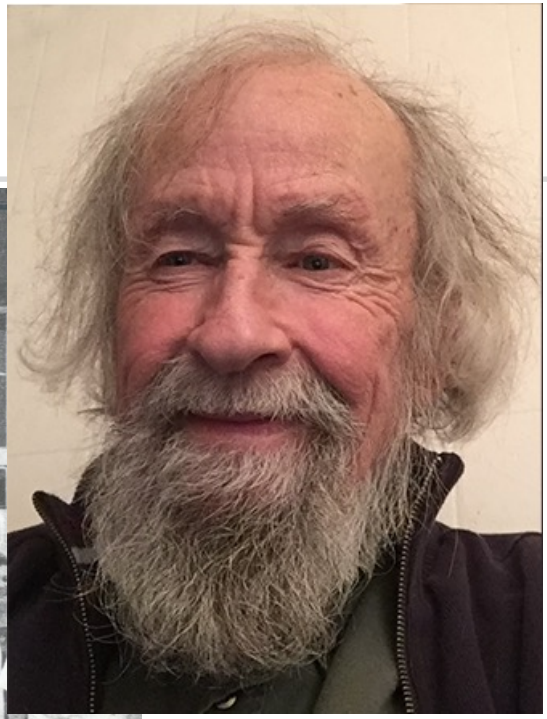
A BIT MORE HISTORY



1989:
Discovery of TeV gamma rays
from the Crab Nebula

THE 1992 PALAISEAU WORKSHOP

organized by Patrick Fleury and Guiseppe Vacanti



† 2017

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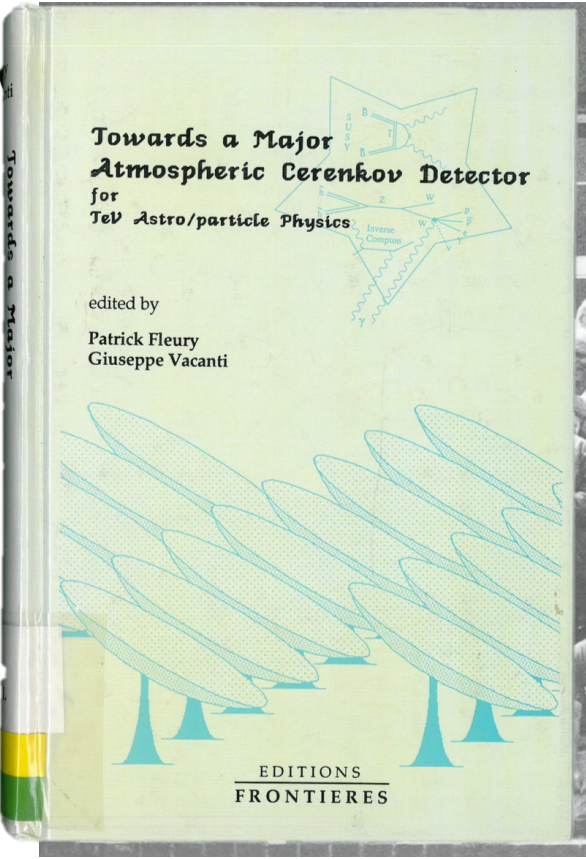
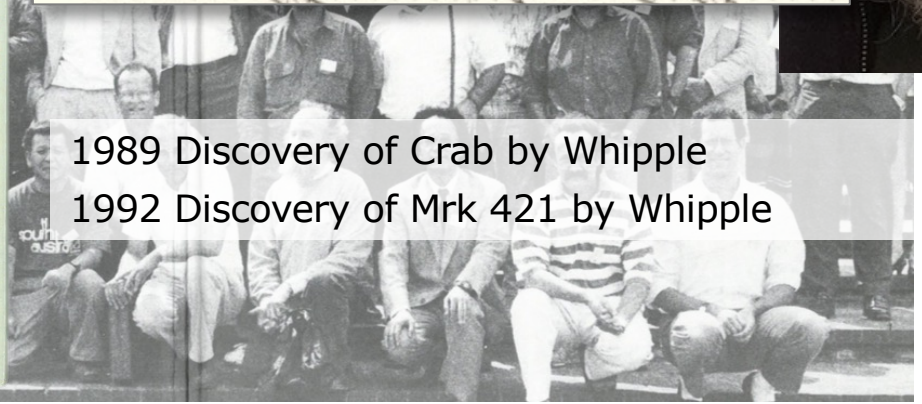
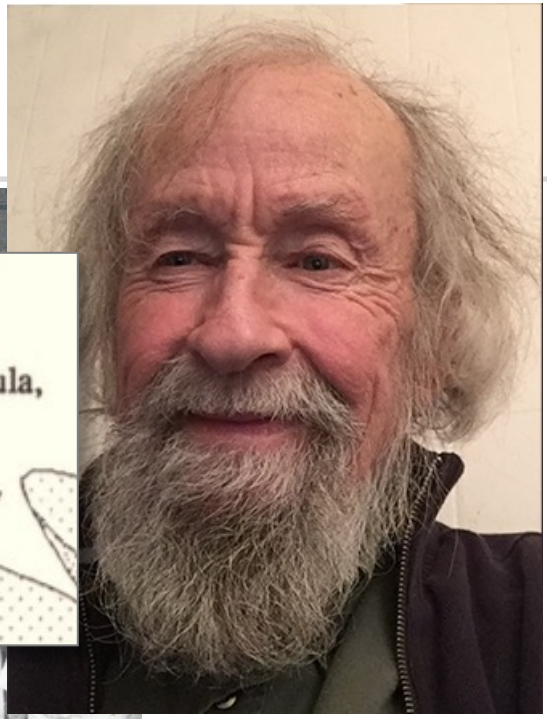


Following the observation of TeV gamma ray emission from the Crab Nebula, it seems desirable that a major program be set forth by the international community to develop TeV γ-Astronomy.



1989 Discovery of Crab by Whipple

1992 Discovery of Mrk 421 by Whipple



† 2017

AFTER PALAISEAU & FOLLOW-UP WORKSHOPS

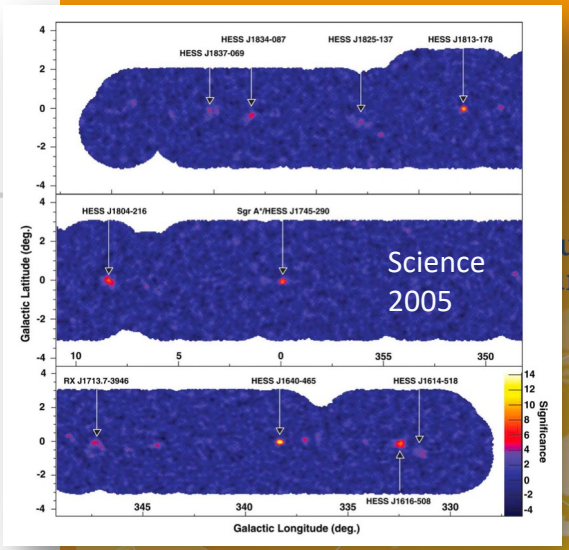
CANGAROO H.E.S.S. MAGIC VERITAS

... BUT WE FINALLY GOT IT RIGHT!

CANGAROO H.E.S.S. MAGIC VERITAS

cta

THE CHERENKOV TELESCOPE ARRAY



ESFRI

EUROPEAN ROADMAP FOR RESEARCH INFRASTRUCTURES

European Strategy Forum on Research Infrastructures

cta

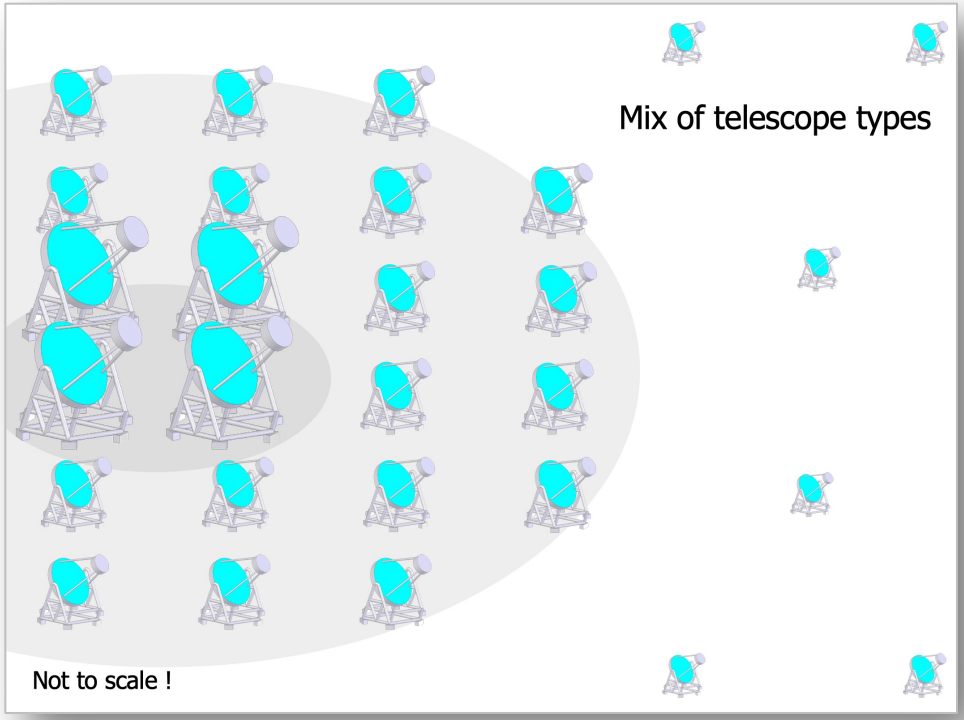
Established in 2002 to create and maintain a roadmap of major European research infrastructures

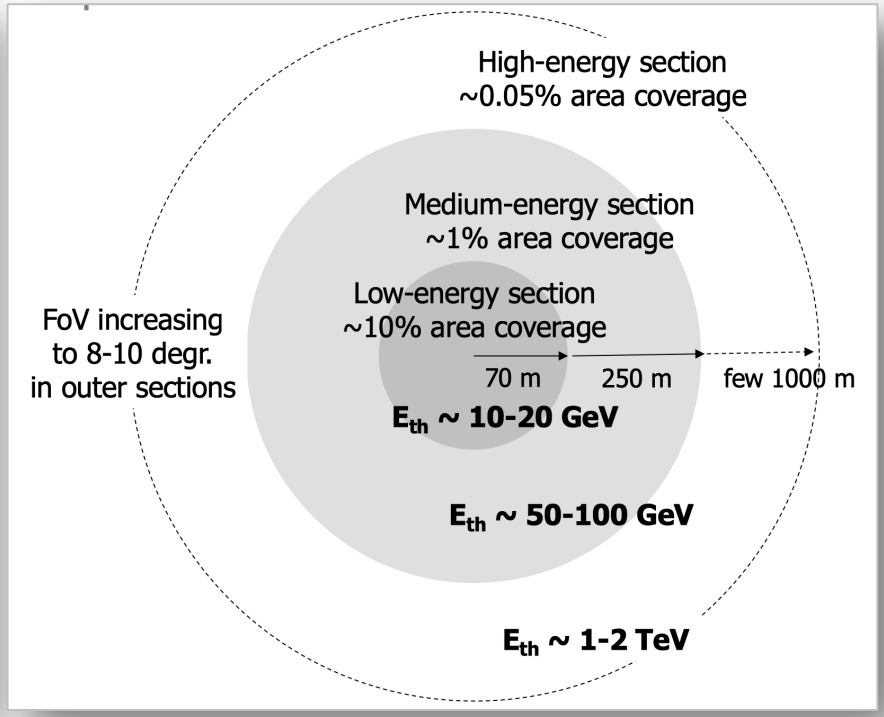
Few-page LoI submitted in November 2005; project form submitted in January 2006

"Emerging Project" on 2006 Roadmap
Project on the 2008 Roadmap
"Landmark" on the 2018 Roadmap

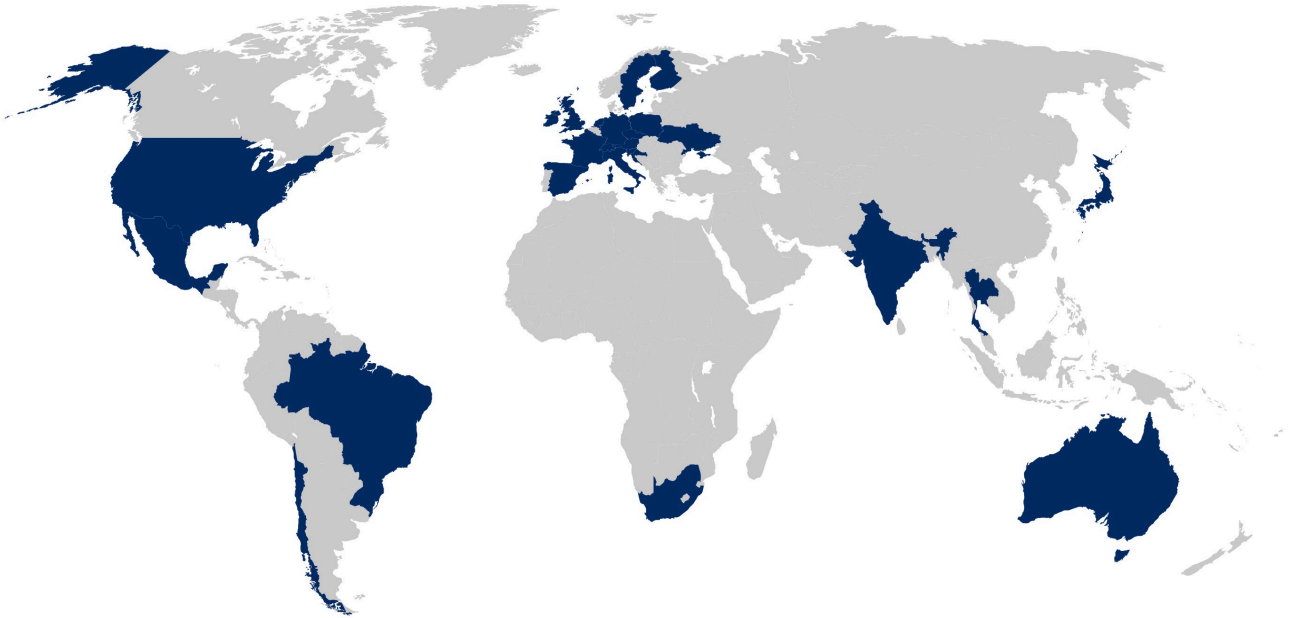
1. Project's name and descriptive title
CTA: An advanced facility for ground-based high-energy gamma ray astronomy
2. Short description of project and main characteristics
Imaging atmospheric Cherenkov telescopes have proven an extremely successful approach to gamma ray astronomy in the energy range above a few tens of GeV. The proposed facility will

MARCH 8, 2006, ESFRI BRUSSELS



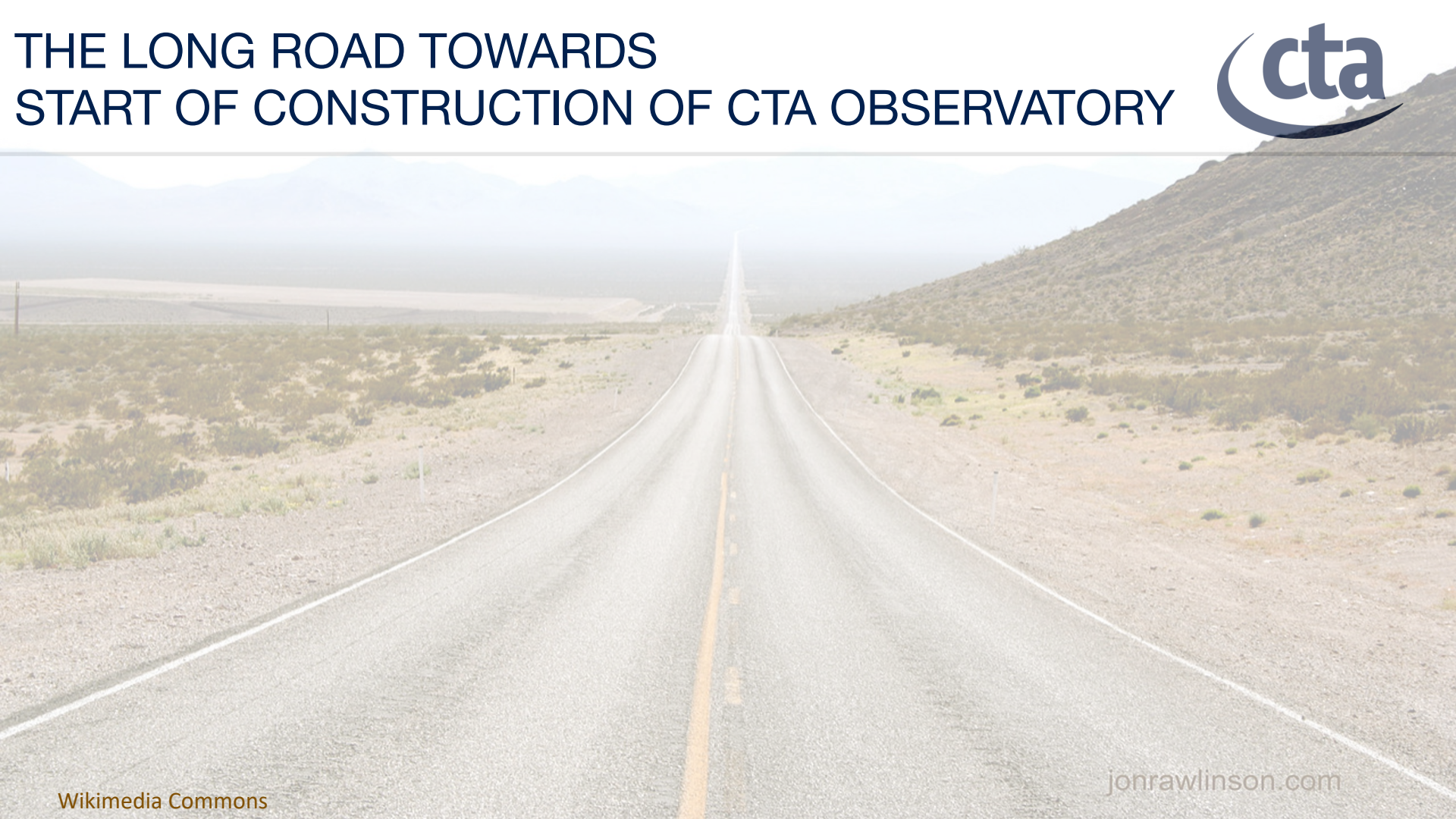


THE CTA CONSORTIUM



25 Countries
over 150 Institutes
about 1500 Members

THE LONG ROAD TOWARDS START OF CONSTRUCTION OF CTA OBSERVATORY



Wikimedia Commons

CTA DECLARATION OF INTENT
HEIDELBERG, JULY 18, 2012

CTA Resource Board

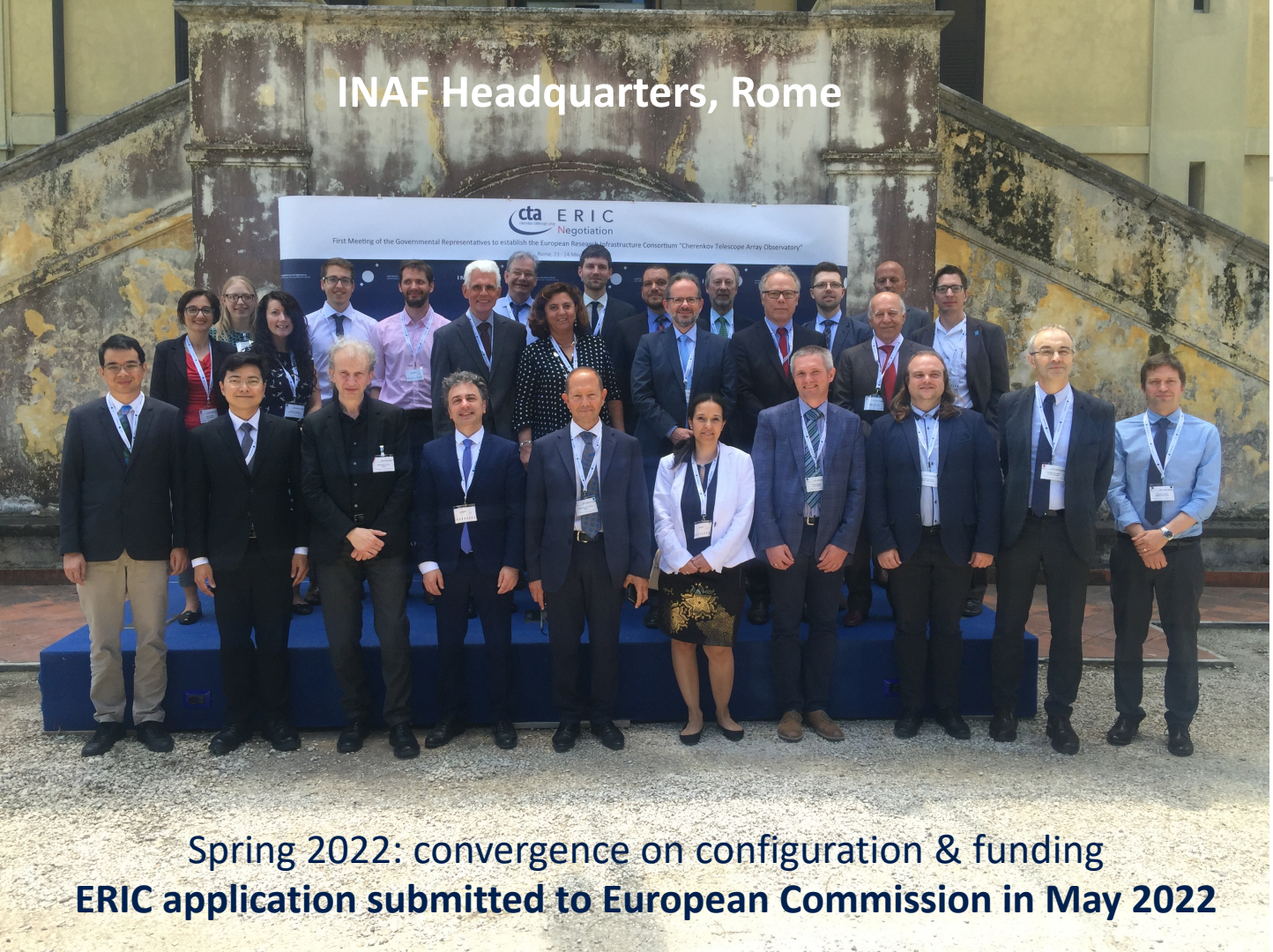
"By signing this Declaration of Intent, the signatories – Ministries and Funding Agencies – wish to express their common interest in participating in the construction and operation of CTA. "

JULY 2014:
FOUNDING THE CTA OBSERVATORY GMBH

Interim legal entity,
based in Heidelberg

Initially 3 shareholders
representing
Germany, Italy, Switzerland

Now shareholders from
11 countries, plus ESO

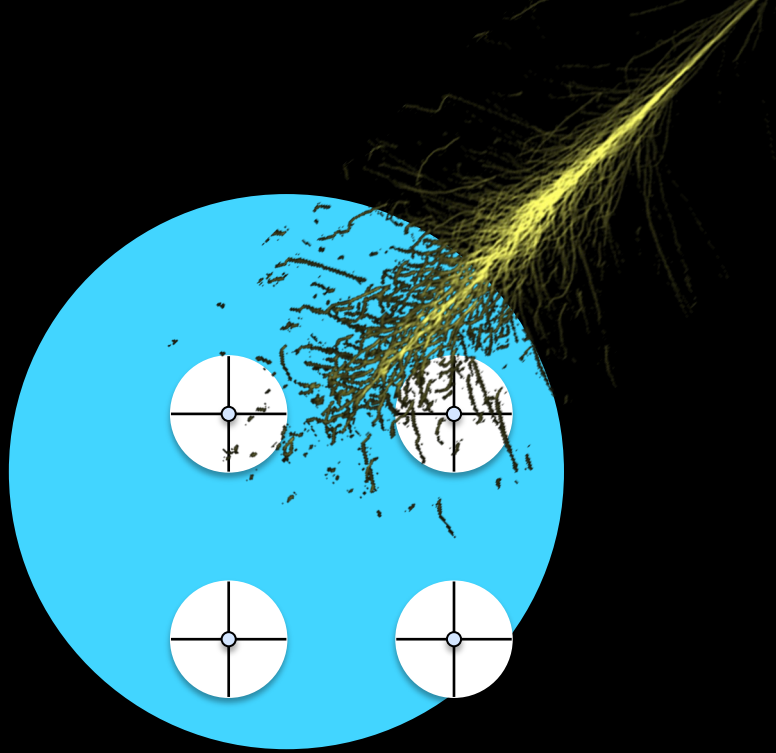


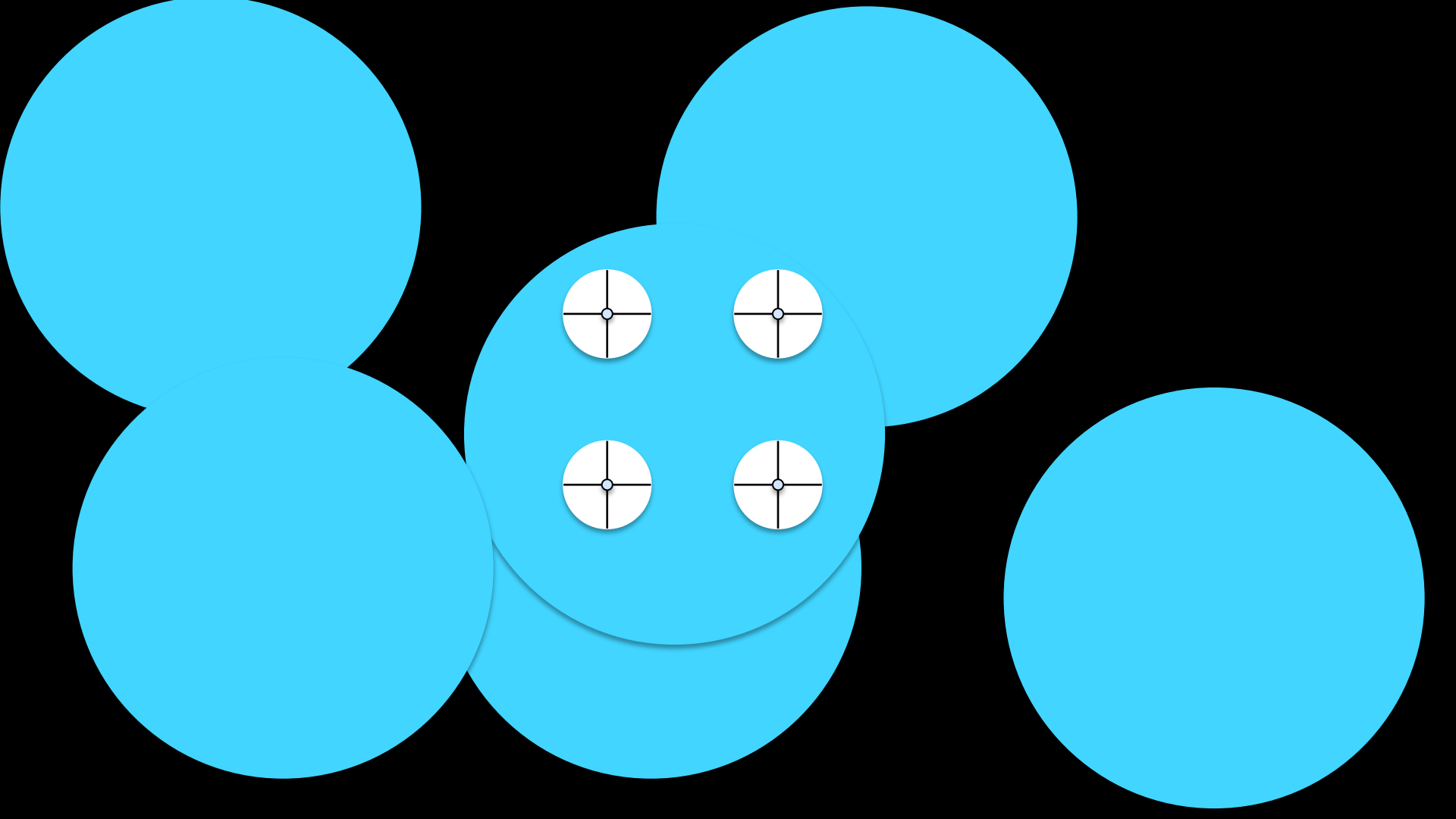
Spring 2022: convergence on configuration & funding

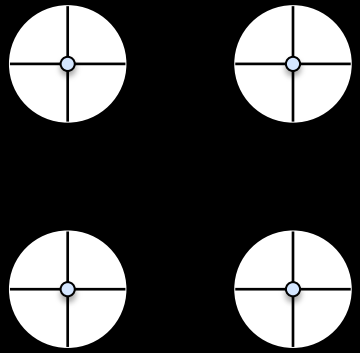
ERIC application submitted to European Commission in May 2022

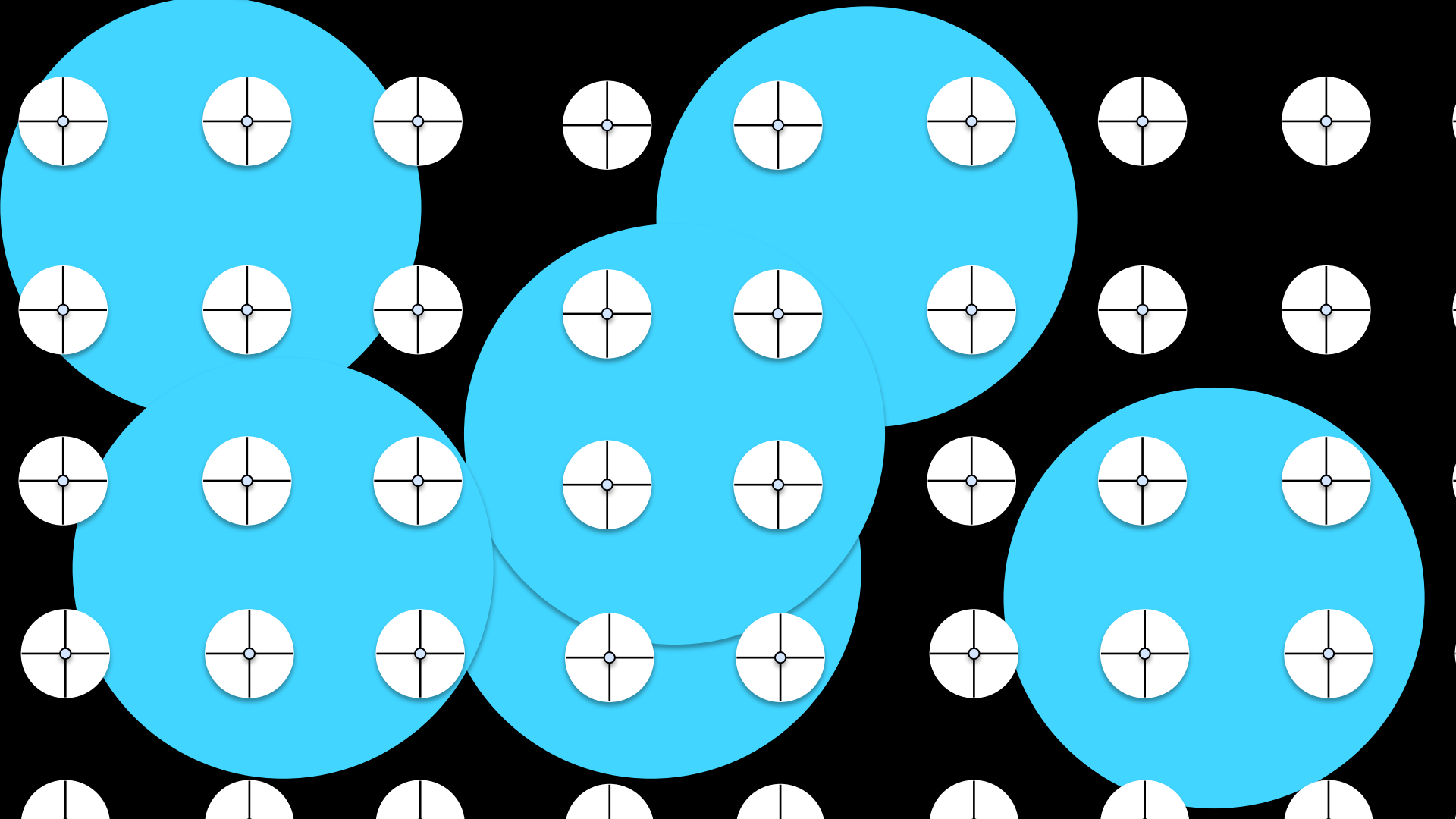
May 2018:
First meeting of the Board of Government Representatives

for founding the CTA Observatory ERIC (a European legal entity where Governments are members)





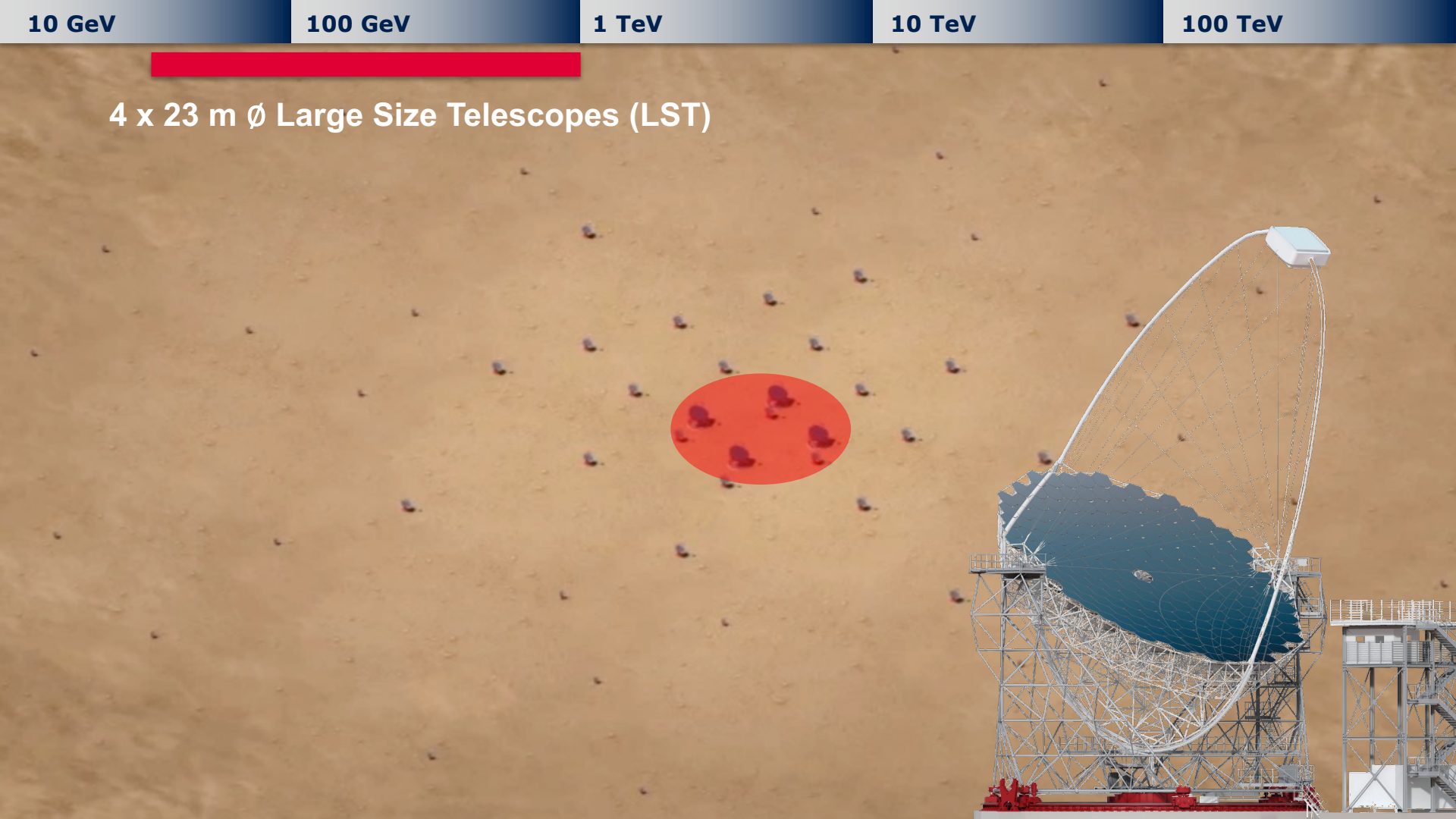





10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1000 γ / h km²
10 γ / h km²
0.1 γ / h km²
Southern array
of Cherenkov telescopes
- about 3 km across

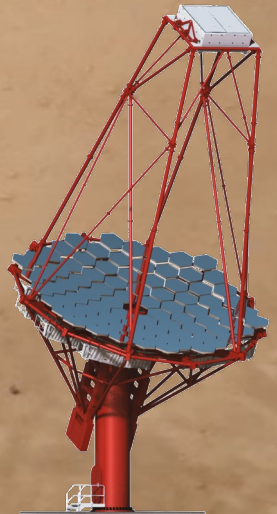
10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

4 x 23 m ø Large Size Telescopes (LST)



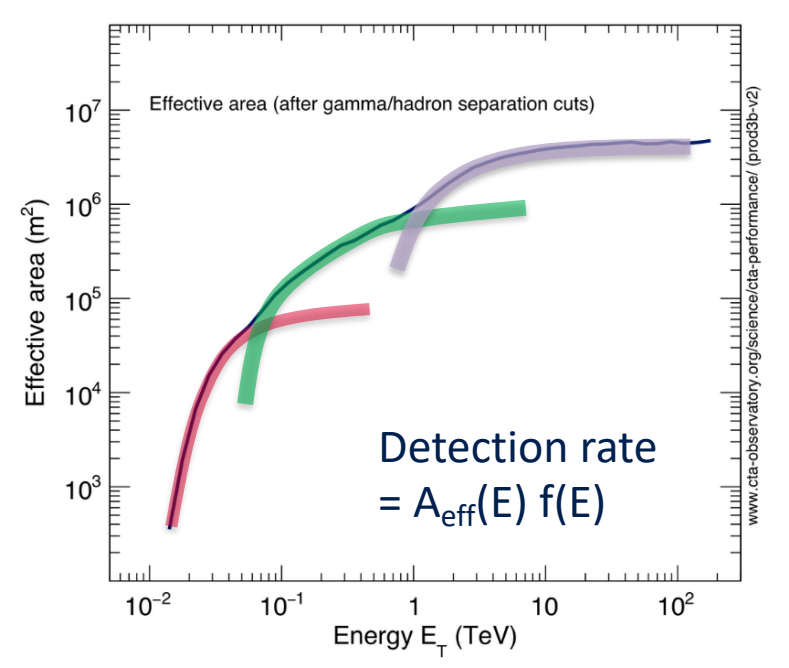
10 GeV | 100 GeV | 1 TeV | 10 TeV | 100 TeV

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



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

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

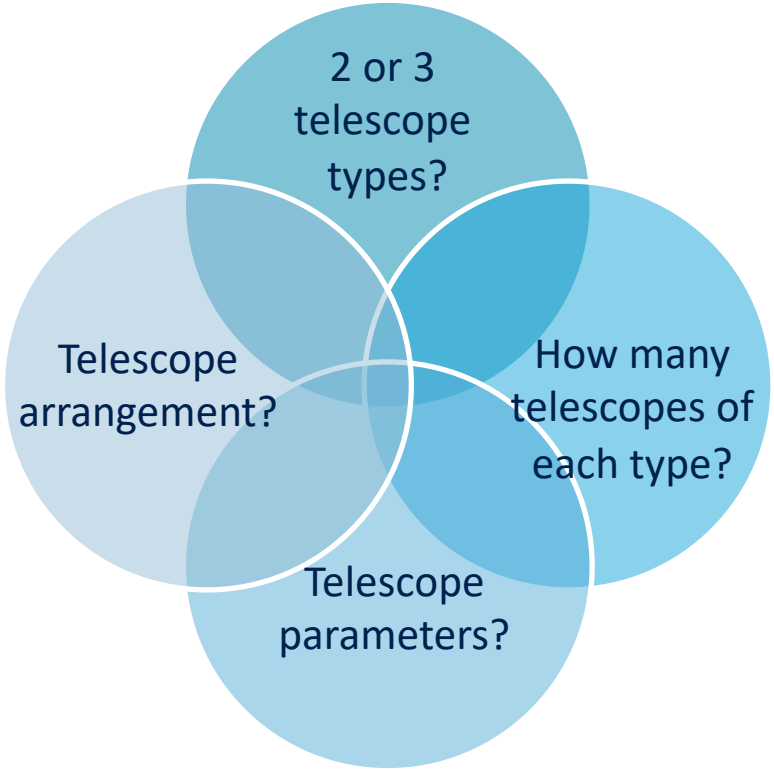


Compared to current instruments
up to 400 x increased survey speed

OPTIMIZING THE CTA ARRAYS

K. Bernlöhr et al., Astropart. Phys. 43 (2013) 171
T. Hassan et al., Astropart. Phys. 93 (2017) 76
A. Acharyya et al., arXiv 1904.01426 (2019)

Questions



Approach

Experience, analytical models & cost models

Square grids of telescopes

Plausible array layouts

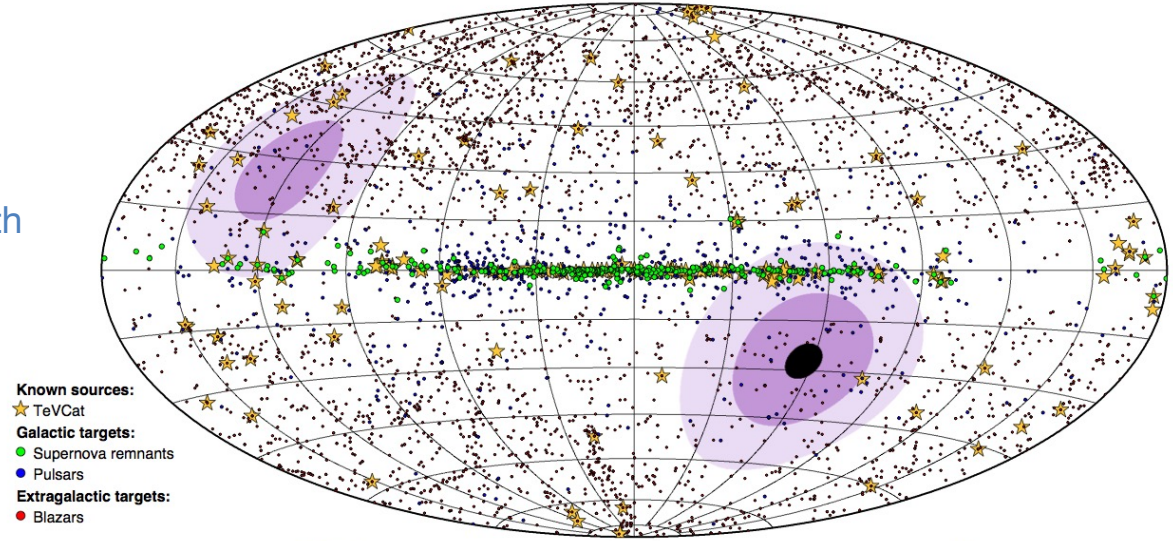
Freeze telescope numbers and parameters

Optimize and fine-tune layout (at % level)

Simulations using tens of millions CPU-h

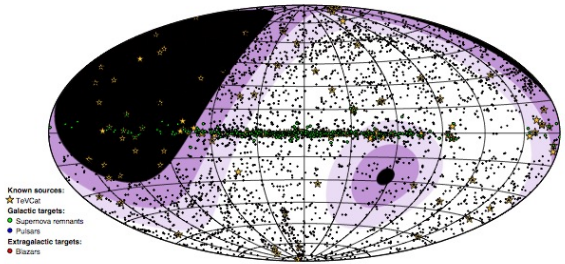
DESIGN DRIVER: FULL-SKY COVERAGE

North+South

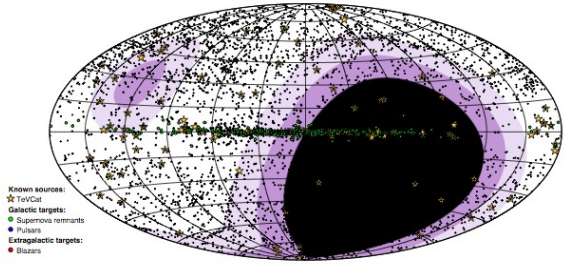


>60° zenith
45°-60°
30°-45°

South

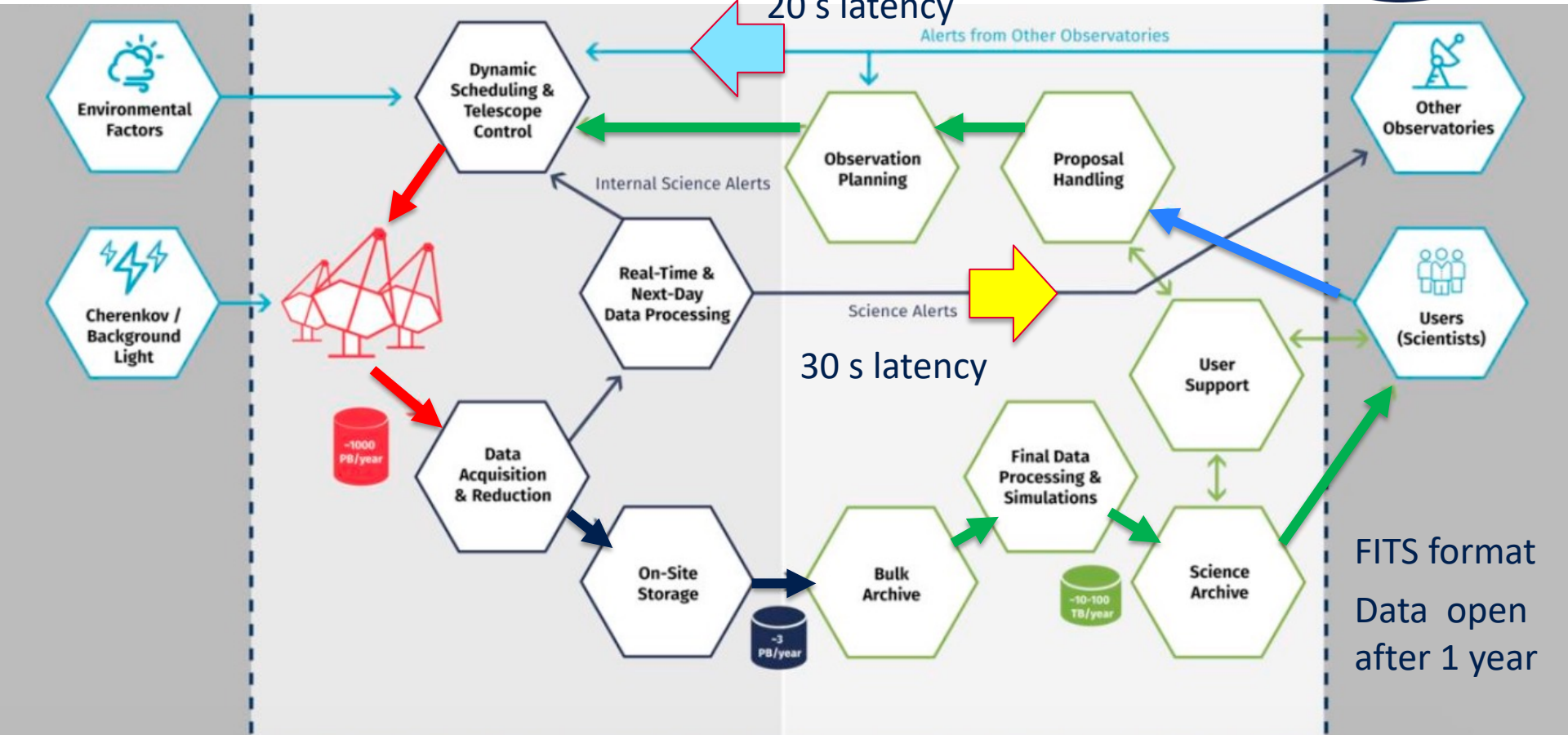


North



CTA OBSERVATORY

Alerts & ToOs



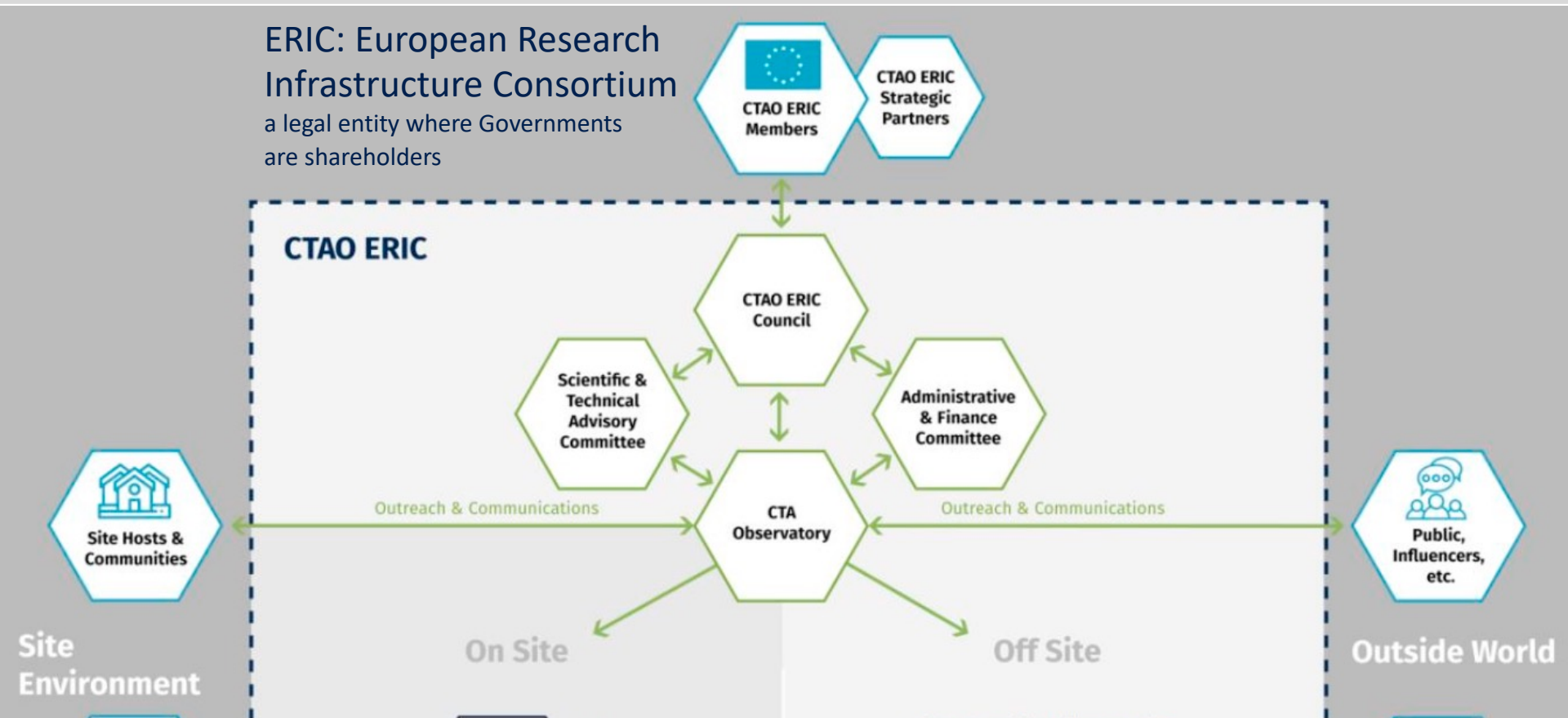
FITS format

Data open after 1 year

CTA OBSERVATORY

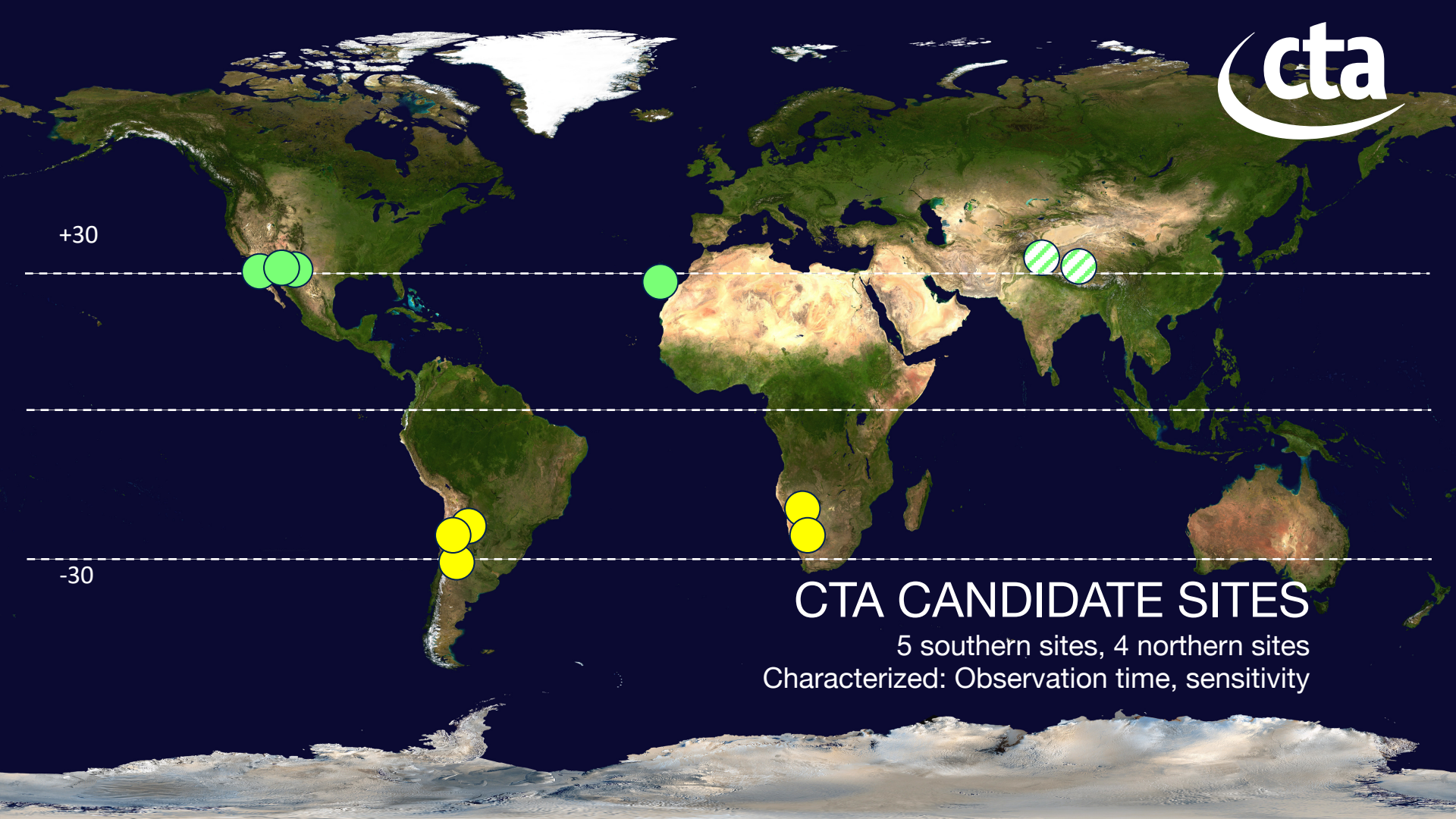
ERIC: European Research Infrastructure Consortium

a legal entity where Governments are shareholders



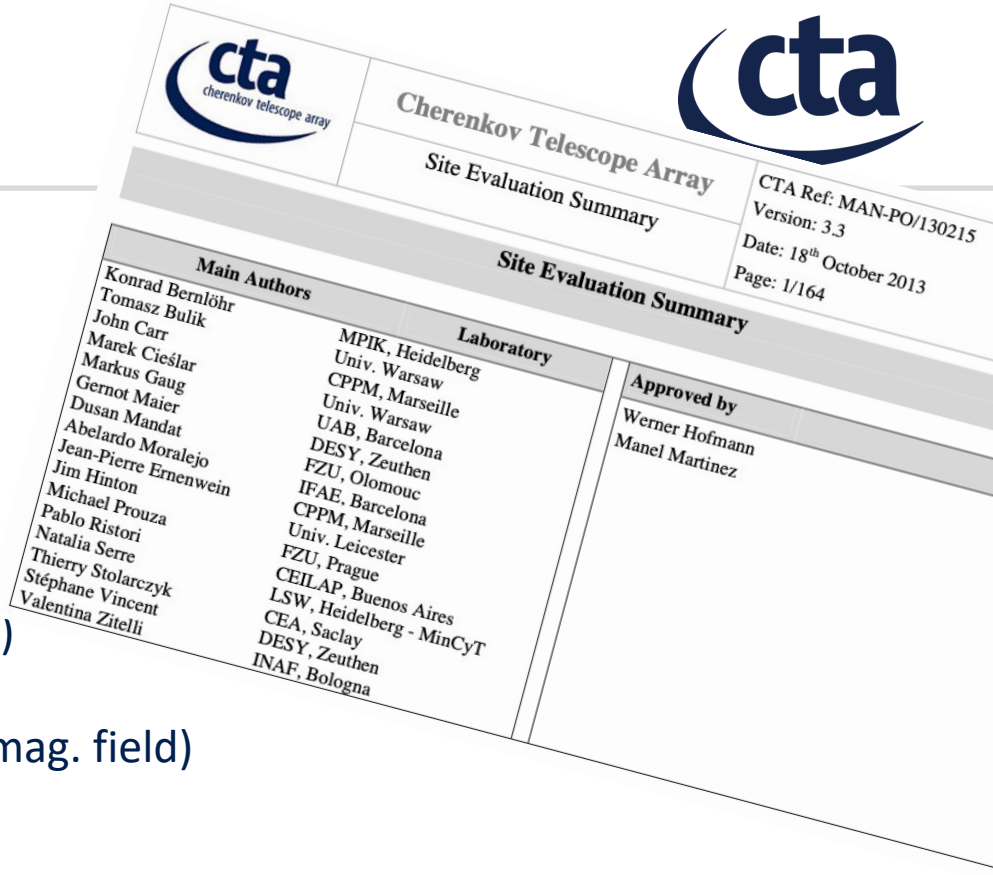
CTA Site Selection

2008 - 2018


+30
-30
CTA CANDIDATE SITES
5 southern sites, 4 northern sites
Characterized: Observation time, sensitivity

CRITERIA

- Area, flatness, elevation
- Fraction of clear nights
  - North: 71 – 79% clear night hours
  - South: 77 – 89% clear night hours
- Environmental conditions
- Atmos. transmission (⇐ aerosol content)
- Night sky brightness
- Science performance (⇐ elevation, geomag. field)
- Hazards and risks
- Construction costs
- Operating costs
- Environment for site personnel



cherenkov telescope array

Cherenkov Telescope Array

Site Evaluation Summary

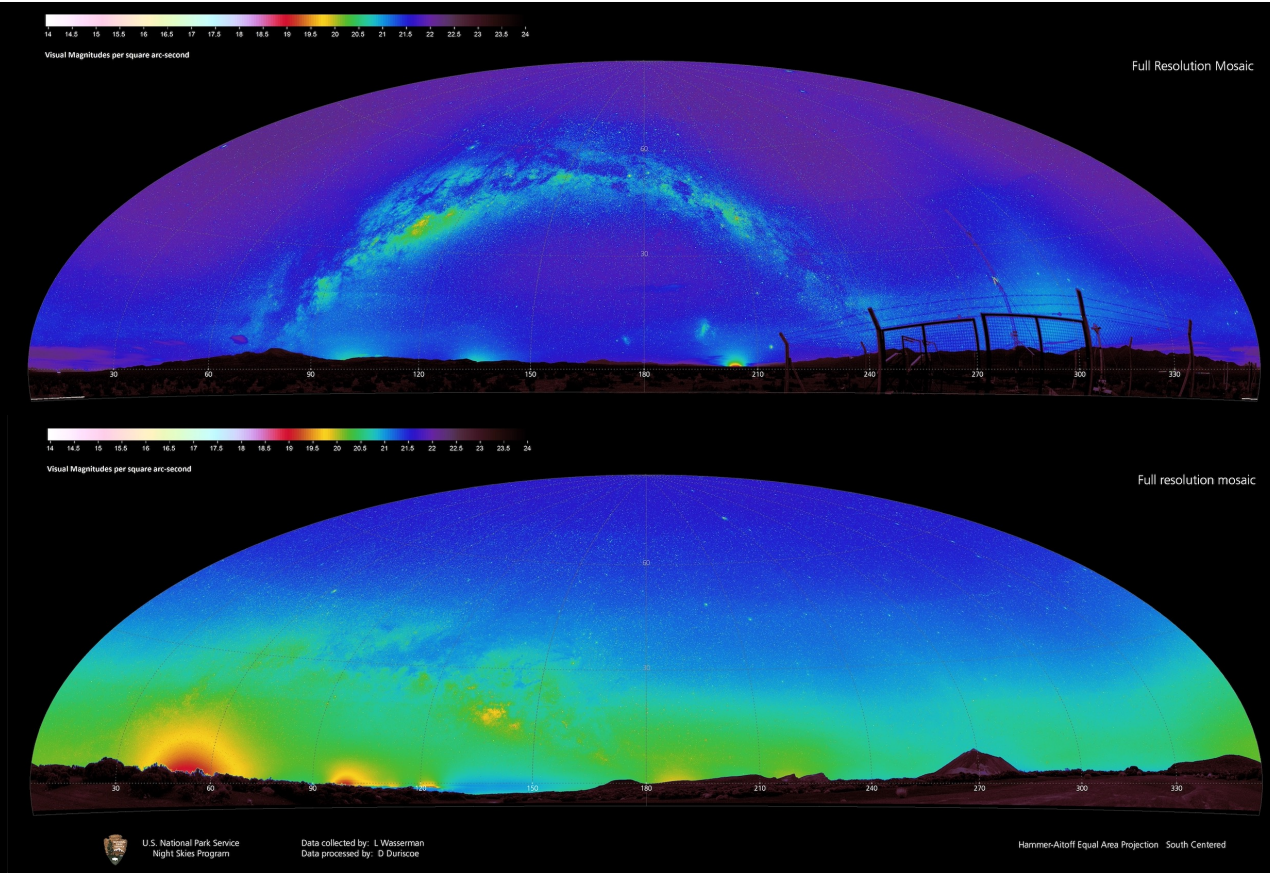
CTA Ref: MAN-PO/130215
Version: 3.3
Date: 18th October 2013
Page: 1/164

Site Evaluation Summary

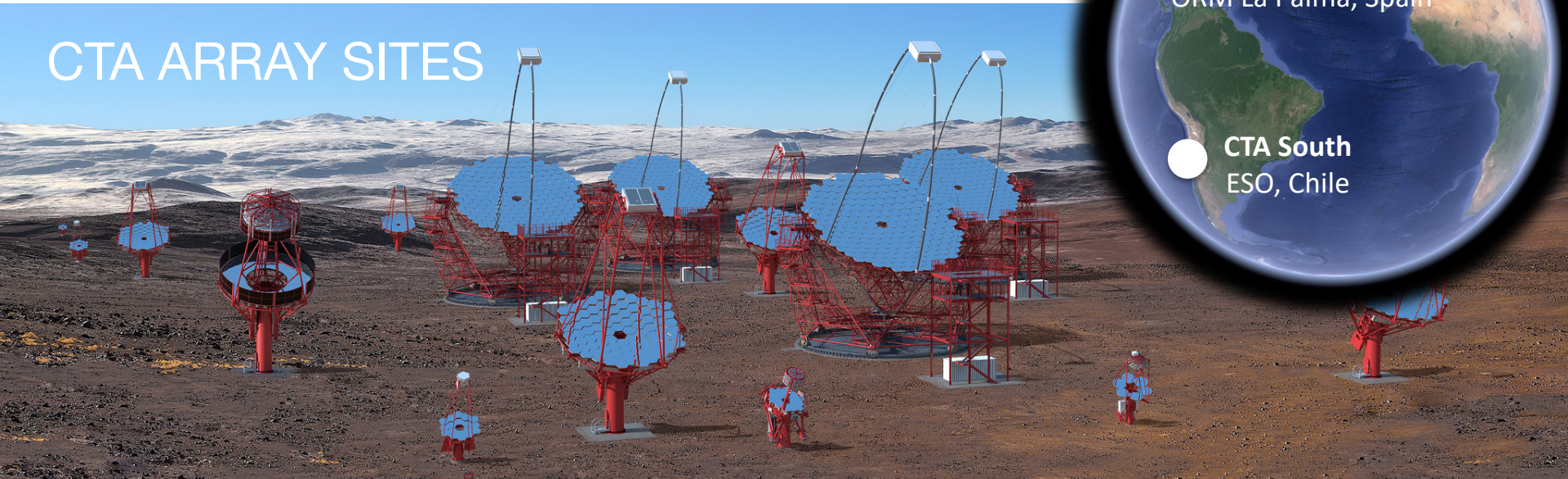
Main Authors	Laboratory
Konrad Bernlöhr	MPIK, Heidelberg
Tomasz Bulik	Univ. Warsaw
John Carr	CPPM, Marseille
Marek Cieślar	Univ. Warsaw
Markus Gaug	UAB, Barcelona
Gernot Maier	DESY, Zeuthen
Dusan Mandat	FZU, Olomouc
Abelardo Moralejo	IFAE, Barcelona
Jean-Pierre Ernenwein	CPPM, Marseille
Jim Hinton	Univ. Leicester
Michael Prouza	FZU, Prague
Pablo Ristori	CEILAP, Buenos Aires
Natalia Serre	LSW, Heidelberg - MinCyT
Thierry Stolarczyk	CEA, Saclay
Stéphane Vincent	DESY, Zeuthen
Valentina Zitelli	INAF, Bologna

Approved by
Werner Hofmann
Manel Martinez

NIGHT SKY BRIGHTNESS

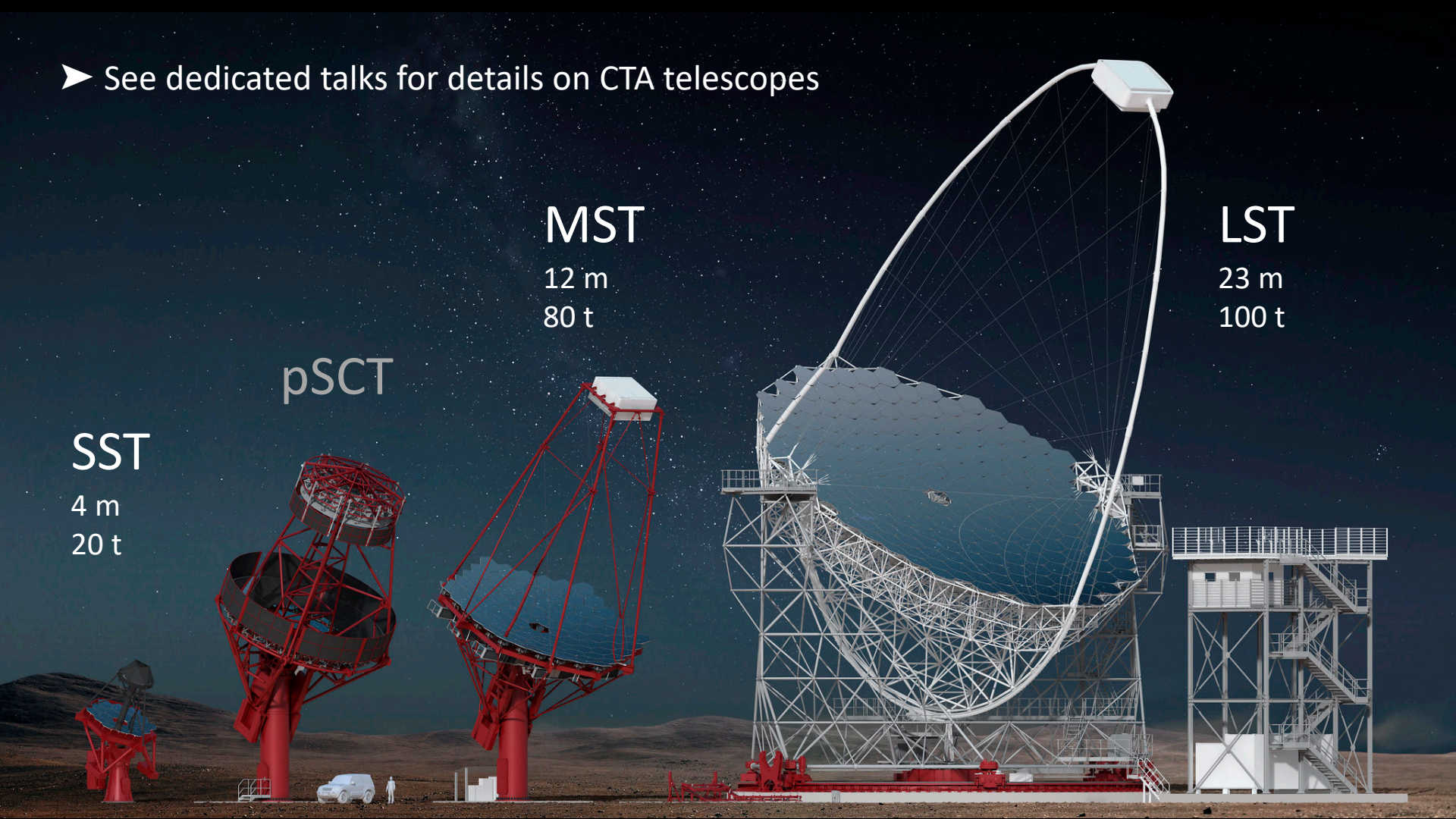


CTA ARRAY SITES



CTA TELESCOPES & CTA CONSTRUCTION

North

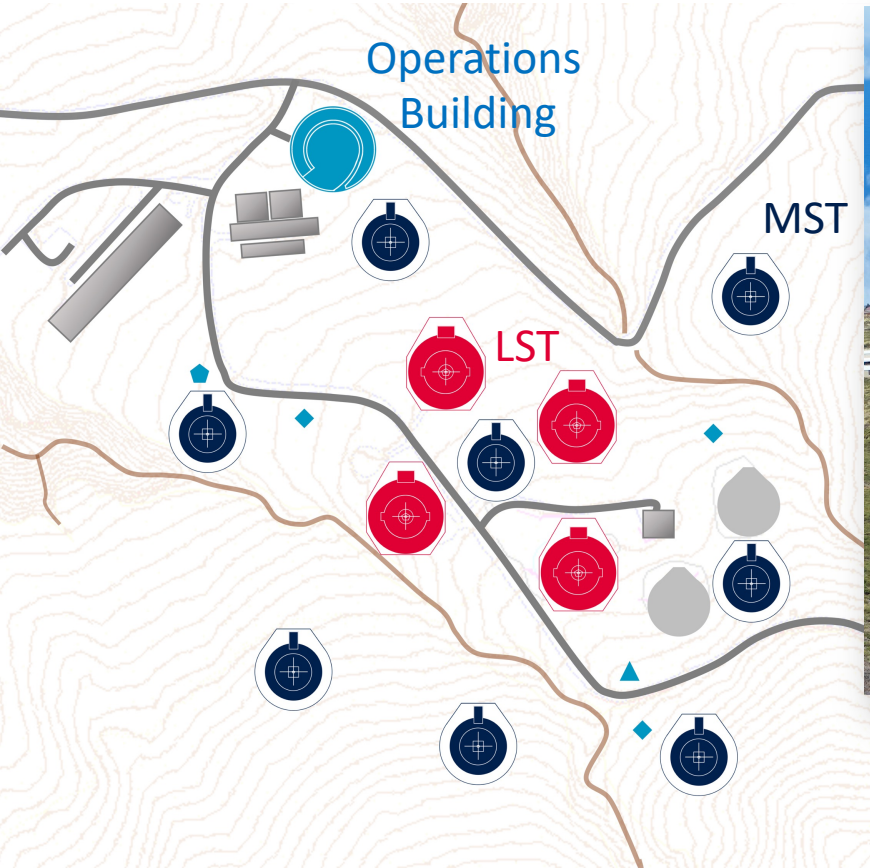

➤ See dedicated talks for details on CTA telescopes
MST
12 m
80 t
LST
23 m
100 t
pSCT
SST
4 m
20 t

CTA CONFIGURATION

			"Omega" configuration	"Alpha" configuration (ERIC subm.)	July 2022
South	LST	20 - 150 GeV	4	0	2
	MST	150 GeV – 5 TeV	25	14	14
	SST	5 TeV – 300 TeV	70	37	42
	Total		**99**	**51**	**58**
North	LST	20 GeV - 150 GeV	4	4	4
	MST	150 GeV – 5 TeV	15	9	9
	Total		**19**	**13**	**13**

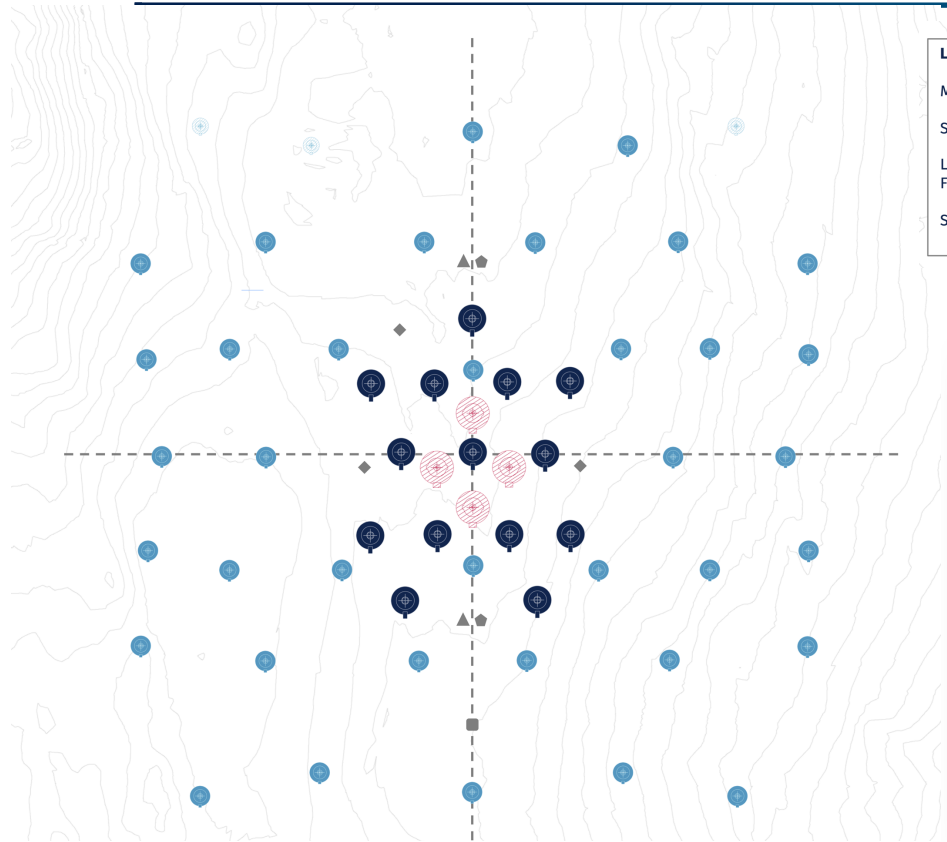
additional
Italian funding

CTA NORTH ARRAY only large and medium-sized telescopes




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

CTA SOUTH ARRAY



LEGEND

- Medium-Sized Telescope (MST)
- Small-Sized Telescope (SST)
- Large-Sized Telescope (LST) Foundation
- SST Foundation

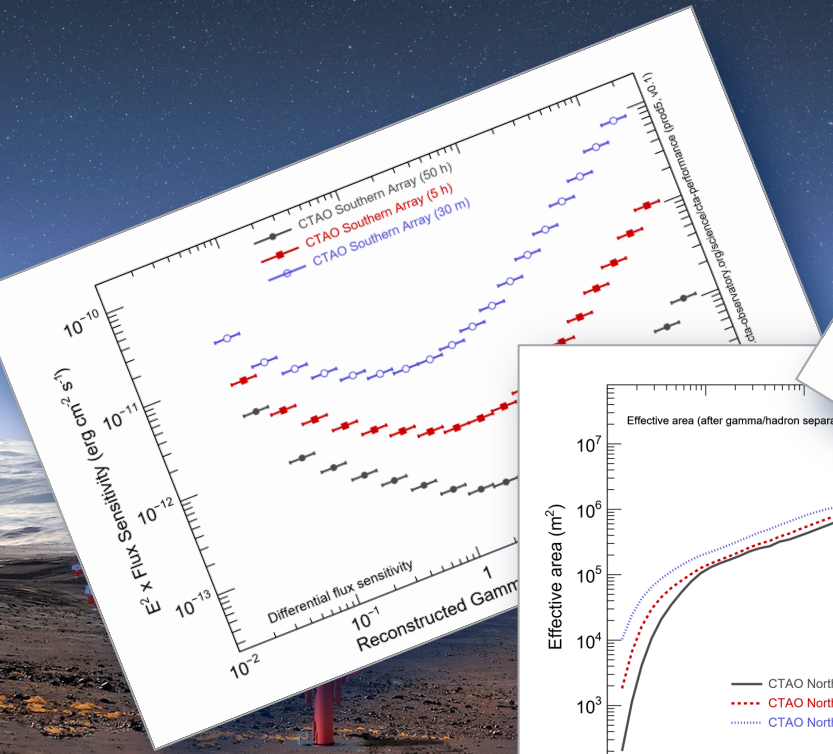
Access road

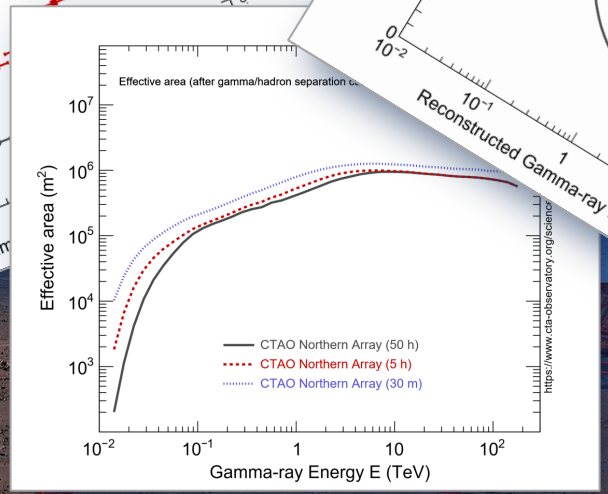
Weekes and Rieke
1967, at the site of
the present Whipple Observatory

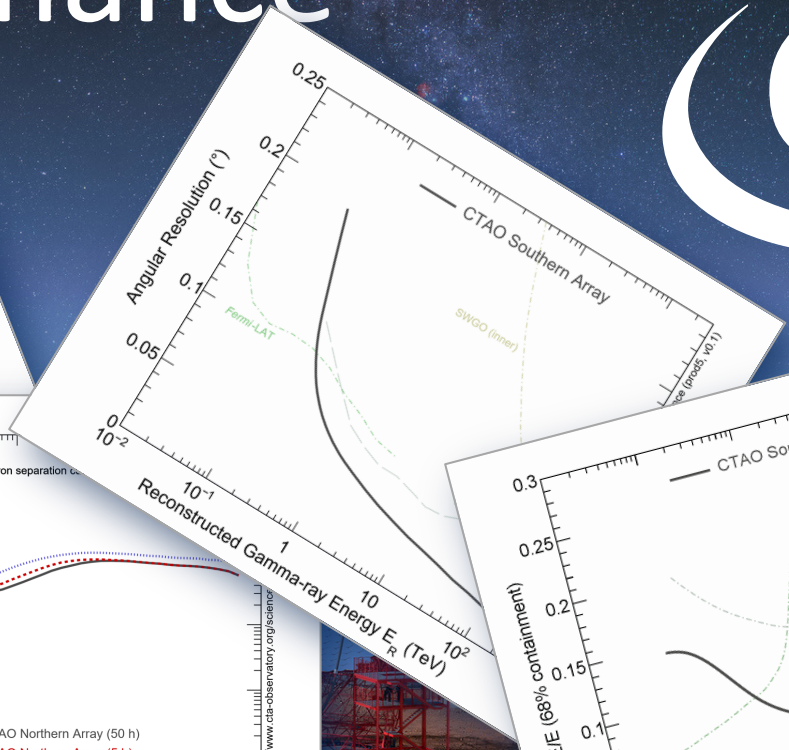
Somewhere on the Wipple observatory…

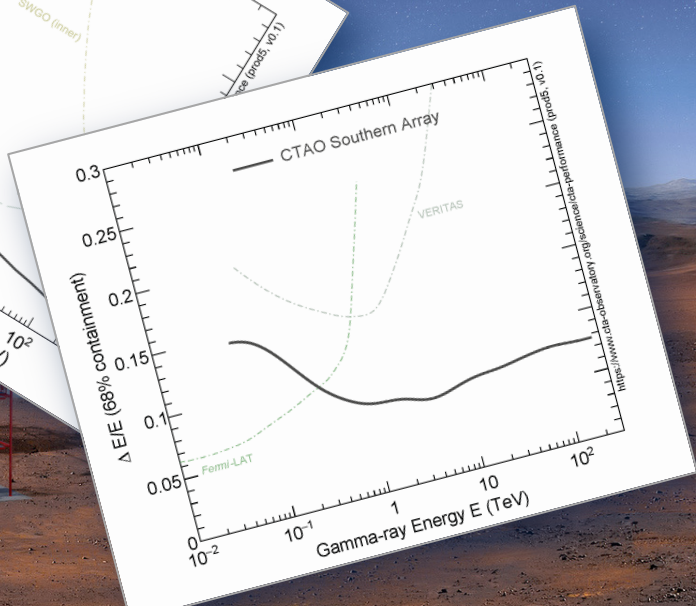
pSCT Inauguration
January 17, 2019
Whipple Observatory

CTA Performance







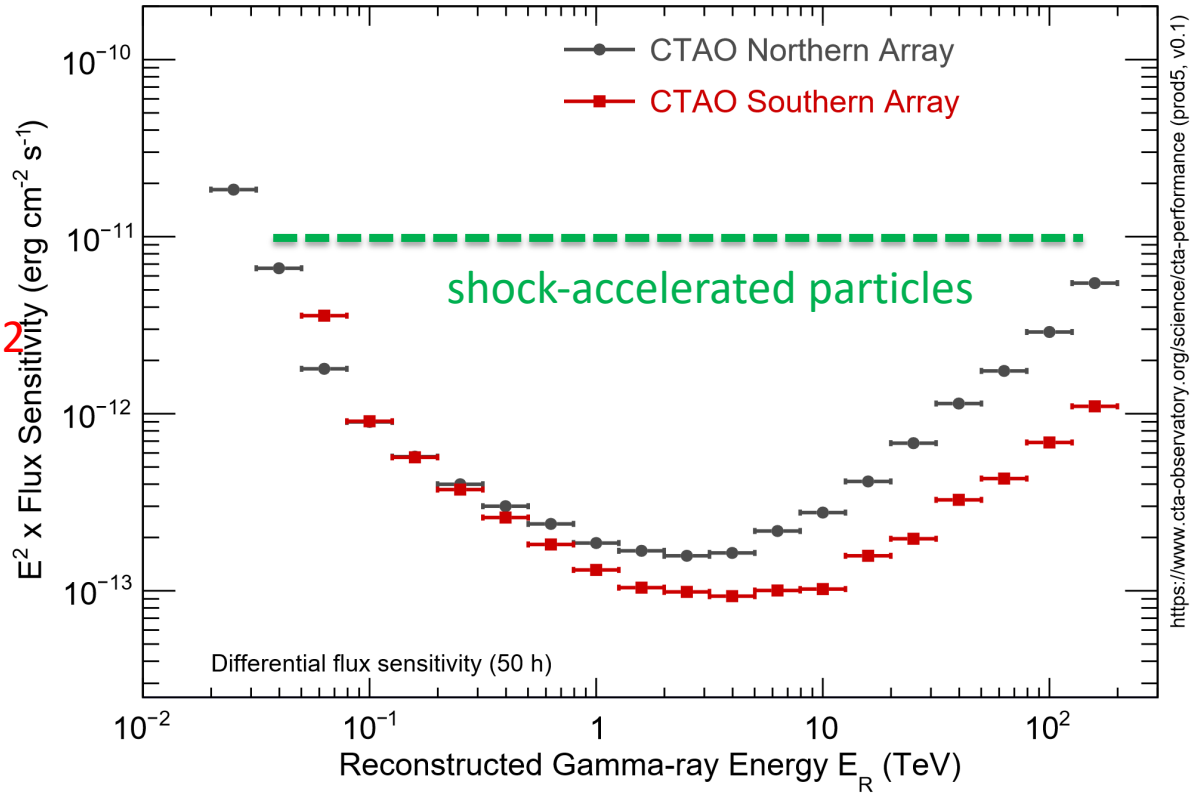


SENSITIVITY OF THE CTA ARRAYS

$E^2\phi(E) = E^2 dN/dE = E\, dN/d\log(E)$

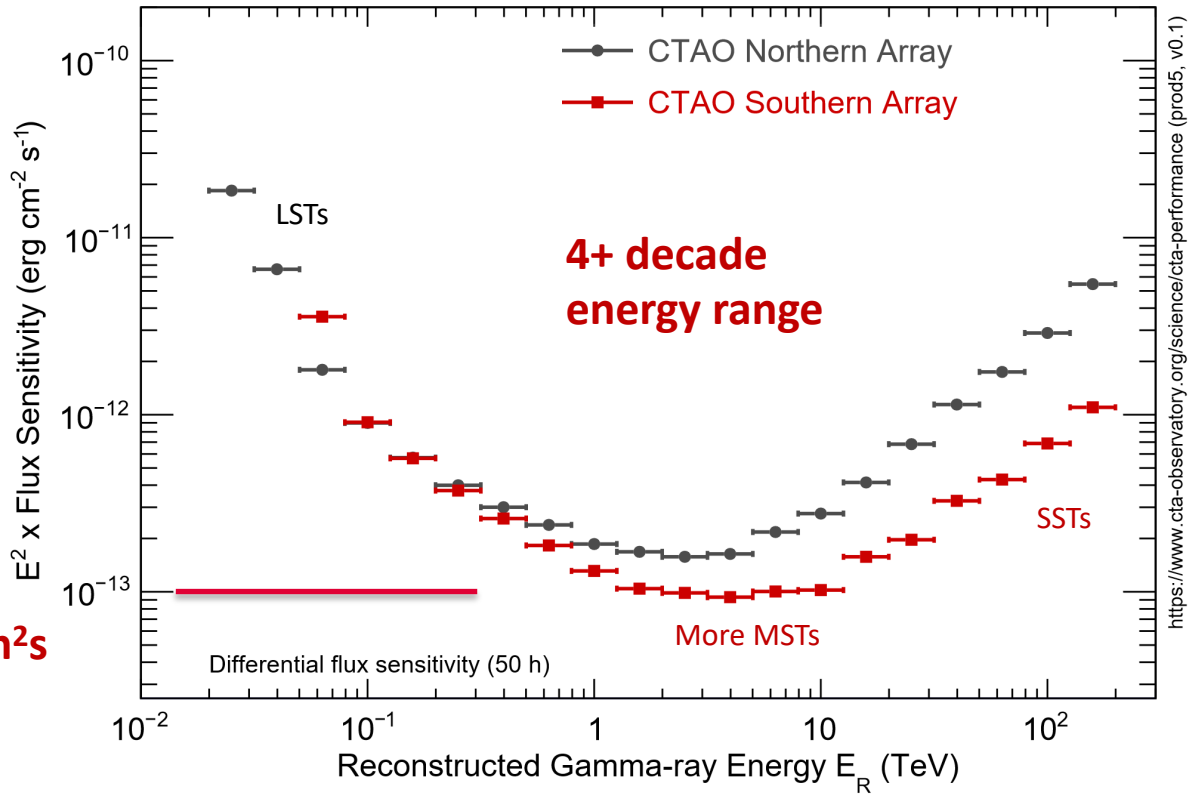
Energy flux per $\Delta\log(E) = 0.2$ interval

for $dN/dE \sim E^{-2}$
$E^2\phi(E) = \text{const}$



Alpha Configuration, 50 h

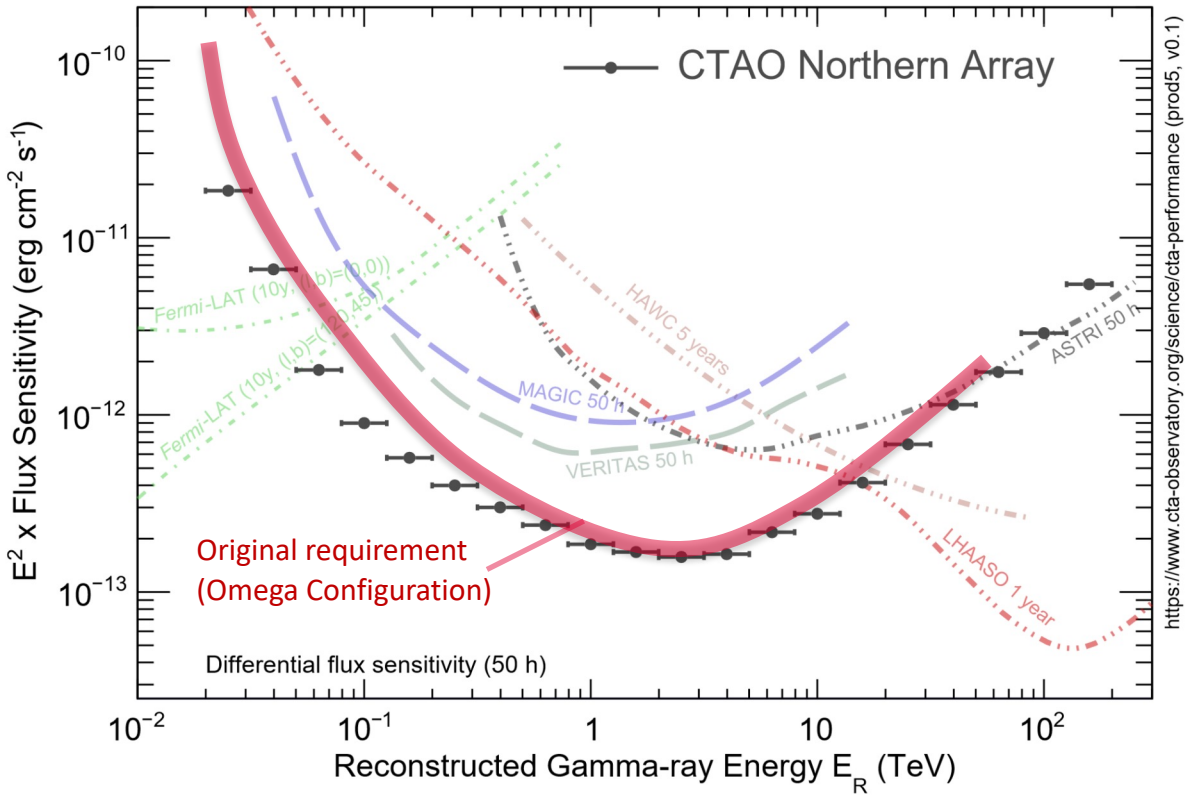
SENSITIVITY OF THE CTA ARRAYS



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

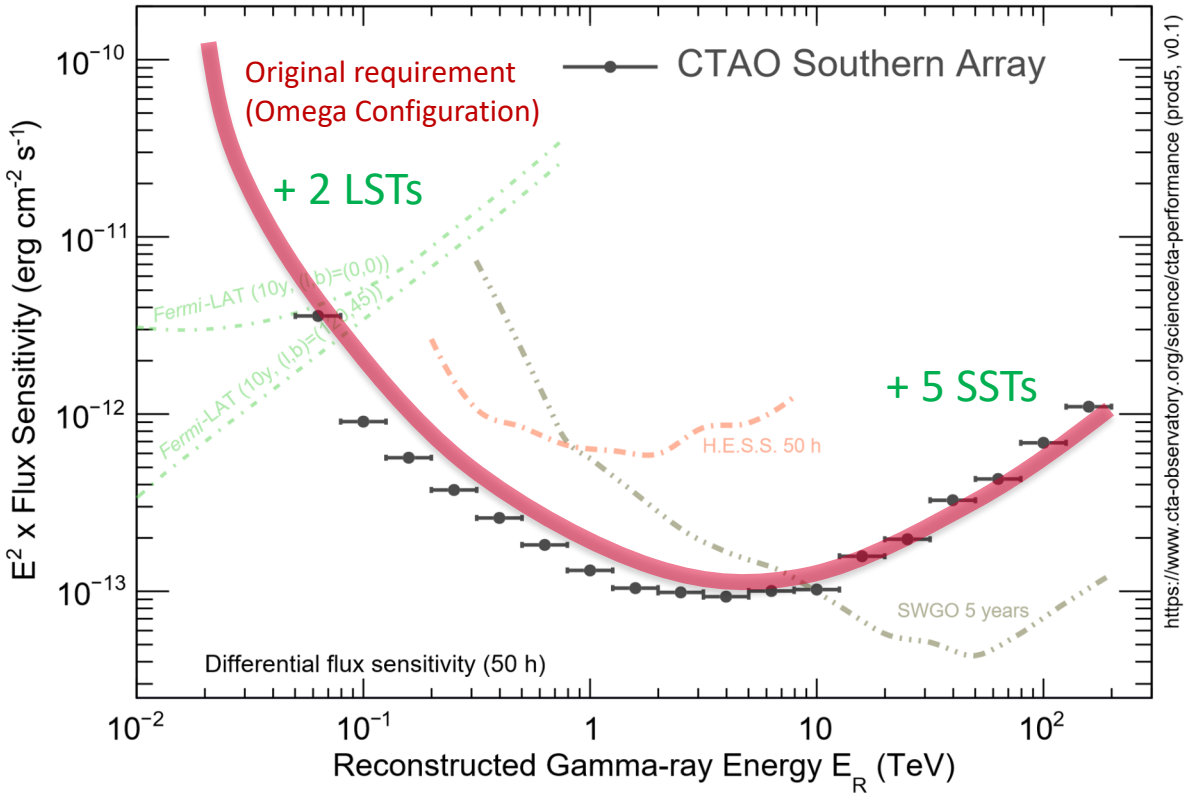
Alpha Configuration, 50 h

SENSITIVITY: NORTHERN ARRAY



Alpha Configuration, 50 h

SENSITIVITY: SOUTHERN ARRAY



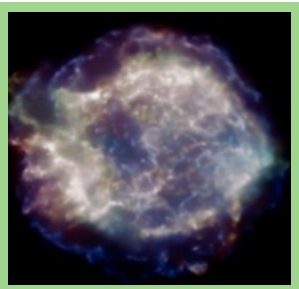
Alpha Configuration, 50 h

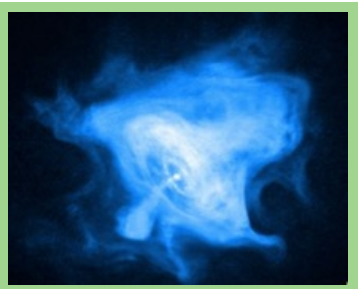
➤ See dedicated talks for details on CTA science, in particular Franz

www.worldscientific.com/worldscibooks/10.1142/10986

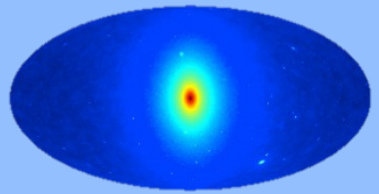
CTA: ENABLING A “PHASE TRANSITION” IN VERY HIGH ENERGY GAMMA RAY ASTRONOMY

In-depth understanding
of known objects and
their mechanisms





Expected discoveries
of new object classes



The fun part:
Things we haven’t thought of

?