

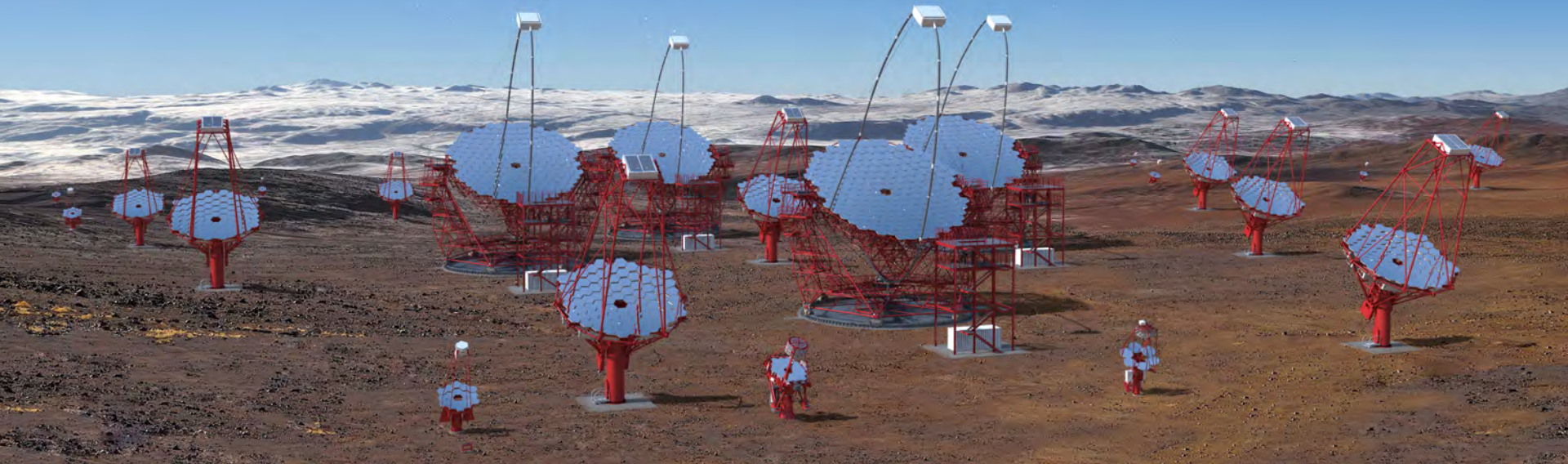


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cherenkov
telescope
array

The Cherenkov Telescope Array: key science projects and multi-wavelength synergies



Stefano Vercellone (INAF – OA Brera)
for the CTA Consortium

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Outline



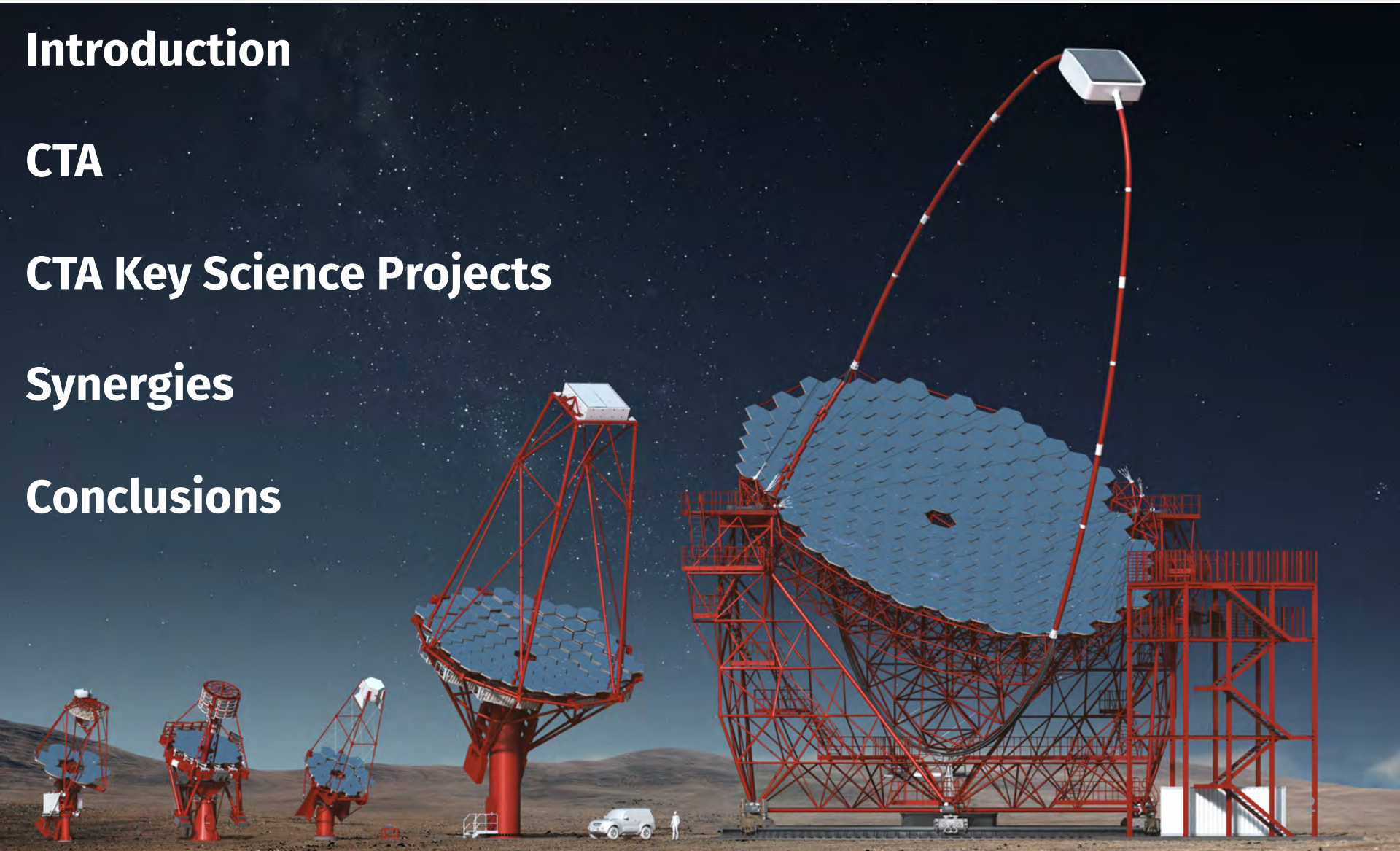
Introduction

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CTA Key Science Projects

Synergies

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Outline



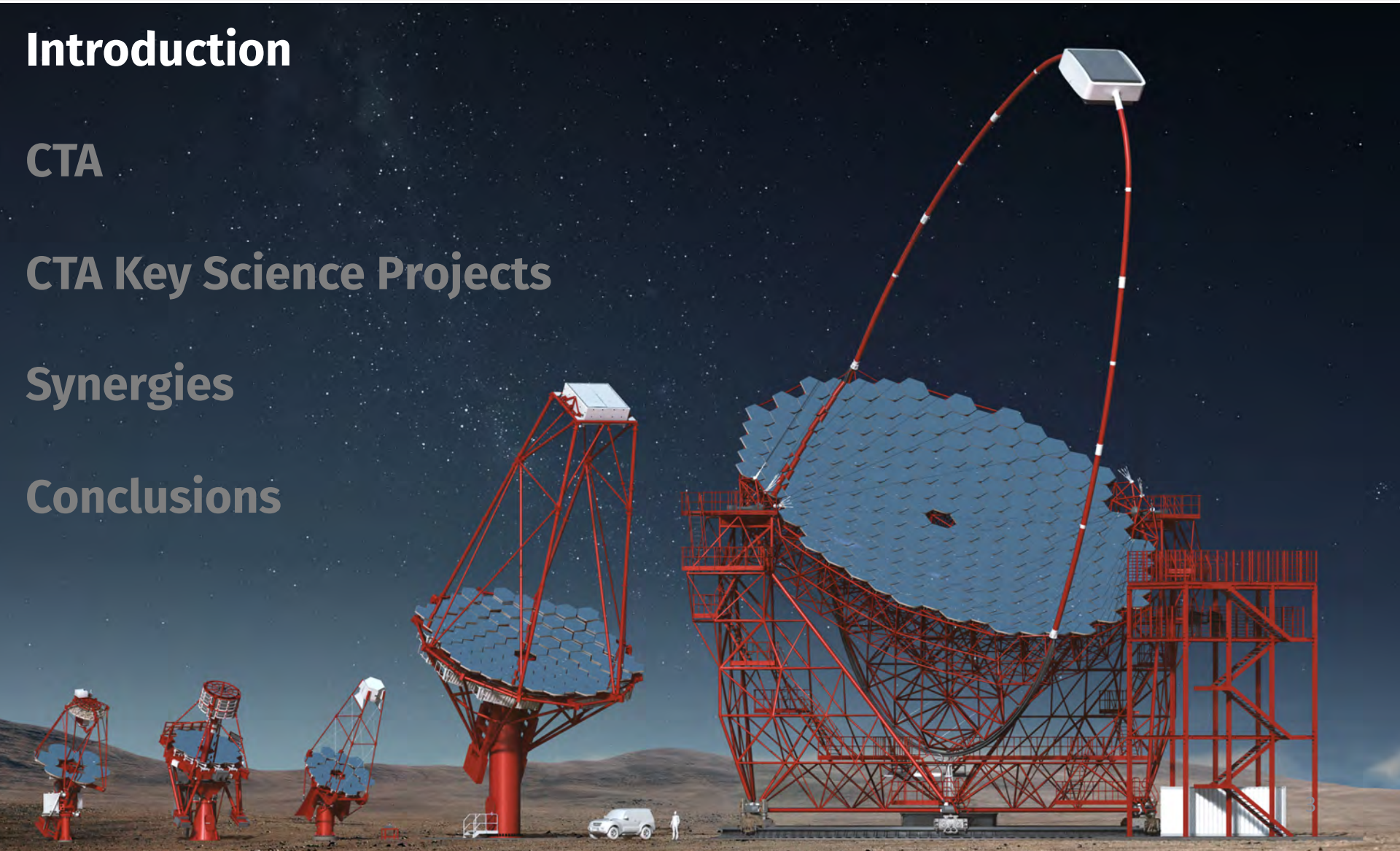
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VHE high-level timeline



445

CERENKOV LIGHT IMAGES OF EAS PRODUCED BY
PRIMARY GAMMA RAYS AND BY NUCLEI

Hillas, 1985

A. N. Hillas
Physics Department
University of Leeds, Leeds LS2 9JT, UK.

ABSTRACT

It is shown that it should be possible to distinguish a effectively between background hadronic showers and TeV showers from a point source on the basis of the width, orientation of the Cerenkov light images of the shower, the focal plane of a focusing mirror, even with a relatively coarse pixel size such as employed in the Mt. Hopkins d

1. Detection of point sources of cosmic rays

Certain X-ray binaries, pulsars and active galaxies appear to be gamma-ray sources - presumed to be gamma-ray sources have been detected by observing flashes of Cerenkov radiation in the upper atmosphere, but these do not stand against the intense isotropic background of ordinary proton showers. If the appearance of the Cerenkov flashes differs from that of showers, such of the background might be rejected. paper, Gwiley et al. (1) describe the modification of the Whipple Observatory (Mt. Hopkins, Arizona) to record data Cerenkov image on a 0.5° grid, using 37 photomultipliers in the plane of the focusing mirror. (A central photomultiplier is a ring of 6 others, then by a further ring of 12, and another whole forming a hexagonal grid pattern.) Predictions of the this system to air showers will be presented. Even though the width of shower images are less than 0.5°, the image diameter measured well enough to provide discrimination between types though the alignment of the short image with the source will clear than with finer angular resolution.

2. Simulation of Cerenkov image patterns

A 3-dimensional Monte-Carlo calculation is used to simulate development. The computer program has been used previously investigations (2) and is much more detailed than is necessary ting Cerenkov processes, following particles down to an energy (far below the Cerenkov threshold), although "thin sampling" to follow particles below 1/4000 of the primary energy to real time. The model atmosphere is not isothermal. Hadronic collisions simulated both by a radial scaling model with rising cross and by a model with increased production of low-energy secondary to scaling) at high primary energies (though a less drastic than proposed by Młódczyk and Wolfendale, for example, as the particles in the fragmentation region - high x - are large. However, at TeV energies, there is little difference between being constrained by accelerator data, so the simulation results are put together in the presentations below.

though some loss of Cerenkov light by Rayleigh and a tail in the allowed for (2), scattered light is assumed not to be spread of the image (size $\sim 1^\circ$) in a clear mountain atmosphere.

provided by the NASA Astronaut

The basics

00 9.5-3

The Astrophysical Journal, 342:379-385, 1989 July 1
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Weeks et al., 1989

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKS,¹ M. F. CAWLEY,² D. J. FRIDAY,³ K. G. GERR,¹ A. M. HILLAS,¹ P. W. KWOK,¹ R. C. LAKE,¹ D. A. LEWIS,² D. MACOMBS,¹ N. A. PORTER,¹ P. T. REYNOLDS,^{1,3} AND G. VACANTI¹

Received 1989 August 1; accepted 1989 December 9

ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons $\text{cm}^{-2} \text{s}^{-1}$ above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuous emission from the pulsar cannot be ruled out, it seems most likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula. Subject headings: gamma rays: general - nebulae: Crab Nebula - pulsars - radiation mechanisms

1. INTRODUCTION

The observation of polarization in the radio, optical, and X-ray emission from the Crab Nebula is usually taken as confirmation of the synchrotron origin of the radiation and is a strong indication of the presence in the nebula of a reservoir of relativistic electrons with energies up to 1 TeV. The presence of the radio pulsar, PSR 0531, near the center of the nebula provides a source for the on-going injection of relativistic electrons into this reservoir. The collision of the synchrotron-radiating electrons with synchrotron-radiated photons within the nebula inevitably results in a hard photon spectrum (at some level) that extends from the X-ray into the gamma-ray energy range; the shape of the spectrum mirrors that of the soft photon spectrum but with greatly reduced intensity. The Compton synchrotron model of the nebula was first developed by Gould (1965) and was refined by Rieke and Weekes (1969) and by Griedley and Hoffmann (1971). A strong flux of gamma rays was predicted with maximum luminosity in the 0.1-1.0 TeV energy range. The gamma-ray flux level depends on the strength of the nebular magnetic field, which is a free parameter in the model and is little constrained by observations at other wavelengths. However, based on equipartition arguments, it is estimated to be $\sim 10^{-5}$ G.

The observation of a flux of 0.14 TeV gamma rays from the Crab Nebula was reported by the Wisconsin group using the atmospheric Cerenkov technique (Weekes et al. 1972), based on observations that spanned 3 years. The detection was still only at the 3 σ level. This demonstrates the relative weakness of the source and the lack of sensitivity of the technique. The detection of TeV gamma rays from the Crab Nebula is a confirmation of the Compton synchrotron model (Gould et al. 1972), based on measurements of the magnetic field. This measurement, which was conservatively interpreted as an upper limit, implies an average magnetic field of 3×10^{-6} G, or a radially symmetric (1,0) field with $B_\parallel = 1 \times 10^{-7}$ G at a distance of 0.1 pc from the pulsar (Griedley 1978).

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St. Francis College, Massachusetts,
University College, Dublin,
² University of Leeds,
³ Iowa State University.

1 source

>150 sources

Hinton & Hoffmann, 2009



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Teraelectronvolt Astronomy

J.A. Hinton¹ and W. Hofmann²

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² Department of Physics and Astronomy, Mt. Pinacoli Station, Mt. Kitzbühel, Hohenberg D-69629, Germany; email: werner.hofmann@phys.uni-erlangen.de

Ann. Rev. Astron. Astrophys. 2009.47:523-65

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0068-4146/09/070523-00

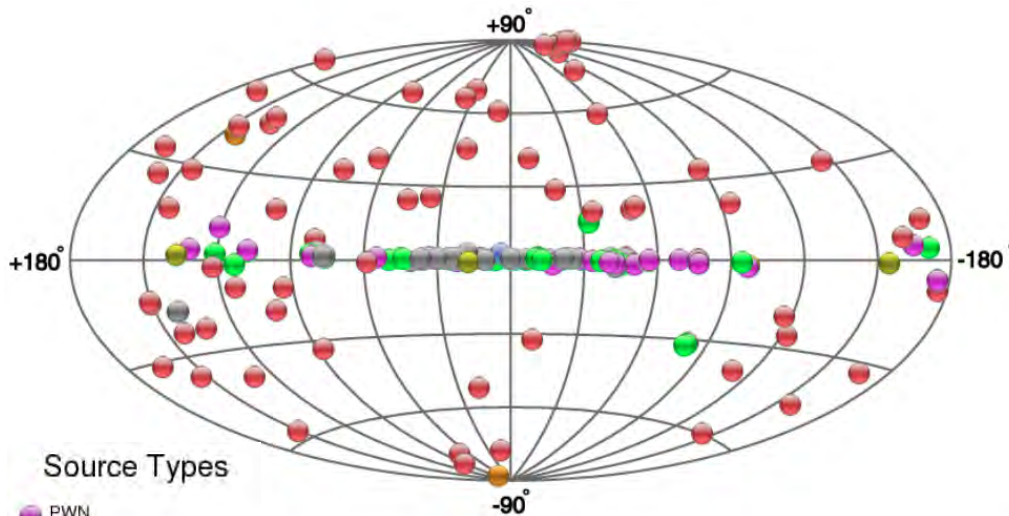
Key Words

gamma-ray astronomy, high-energy astrophysics

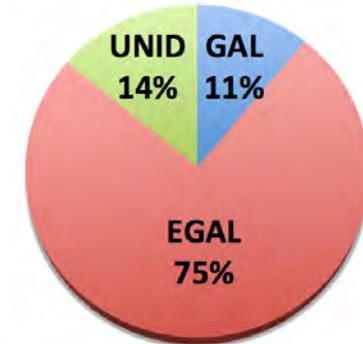
Abstract

Ground-based γ -ray astronomy, which provides access in the TeV energy range, is a young and rapidly developing discipline. Recent discoveries in this wavelength have important consequences for a wide range of topics in astrophysics and isotropic physics. This article is an attempt to review the experimental status of this field and to provide the basic formalism and concepts required to begin the interpretation of TeV observations.

The sky above 50 GeV



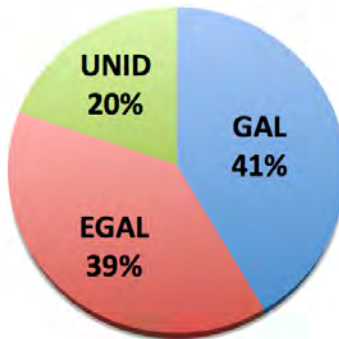
360 *Fermi*-LAT sources $E > 50$ GeV



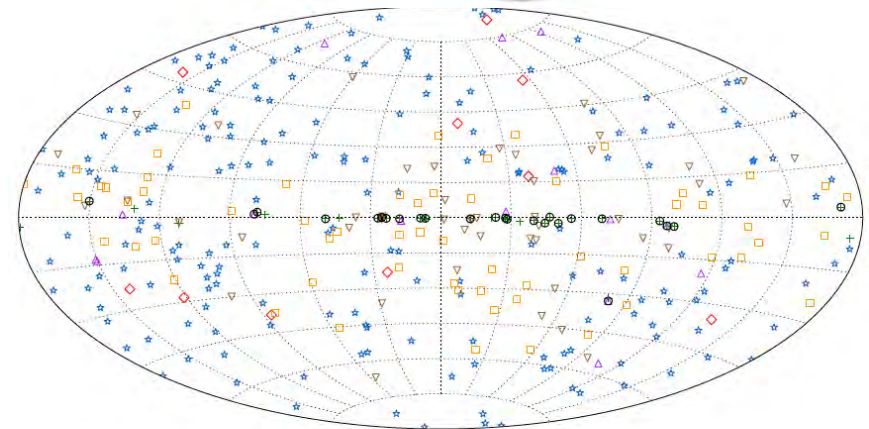
- Source Types
- PWN
 - Binary XRB PSR Gamma BIN
 - HBL IBL FRI FSRQ Blazar LBL AGN (unknown type)
 - Shell SNR/Molec. Cloud Composite SNR Superbubble
 - Starburst
 - DARK UNID Other
 - uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN BL Lac (class unclear) WR

Wakely & Horan <http://tevcat.uchicago.edu/>

~180 TeVcat sources



H.E.S.S.
MAGIC
VERITAS



- | | | | | | | | |
|---|---------------|---|---------|---|--------------|---|--------------|
| + | SNRs and PWNe | ★ | BL Lacs | □ | Unc. Blazars | ▽ | Unassociated |
| × | Pulsars | ◇ | FSRQs | △ | Others | ○ | Extended |

2FHL Ackermann+16

Only ~25% of the 2FHL sources have been previously detected by Cherenkov telescopes. **2FHL provides a reservoir of candidates to be followed up at very high energies.** 7

Outline



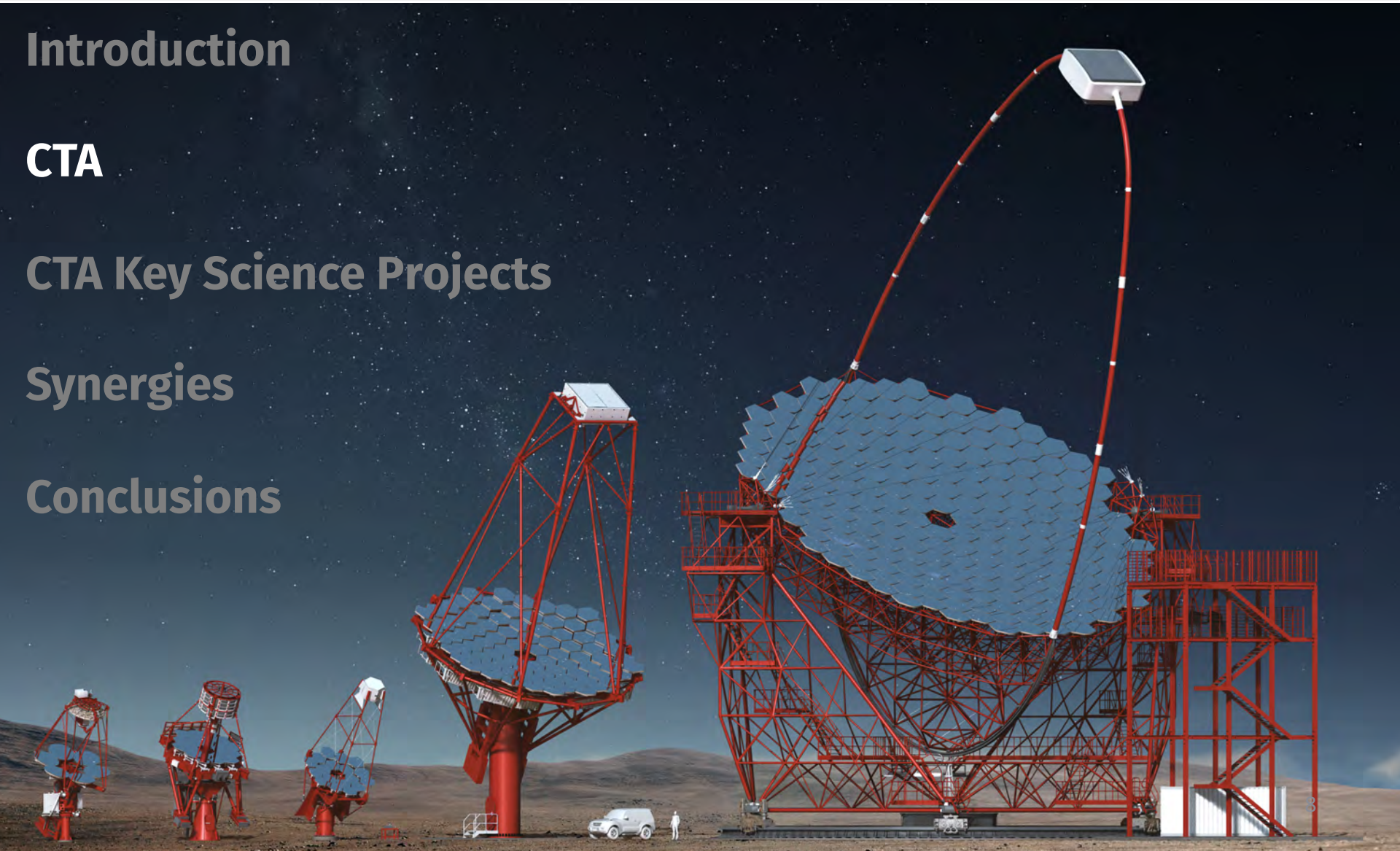
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Two sites (North and South) for a whole-sky coverage

Operated as an open Observatory

A factor of 5-20 more sensitive w.r.t. the current IACTs depending on the energy band

The Cherenkov Telescope Array

A few large size telescopes to cover the range 20 - 150 GeV

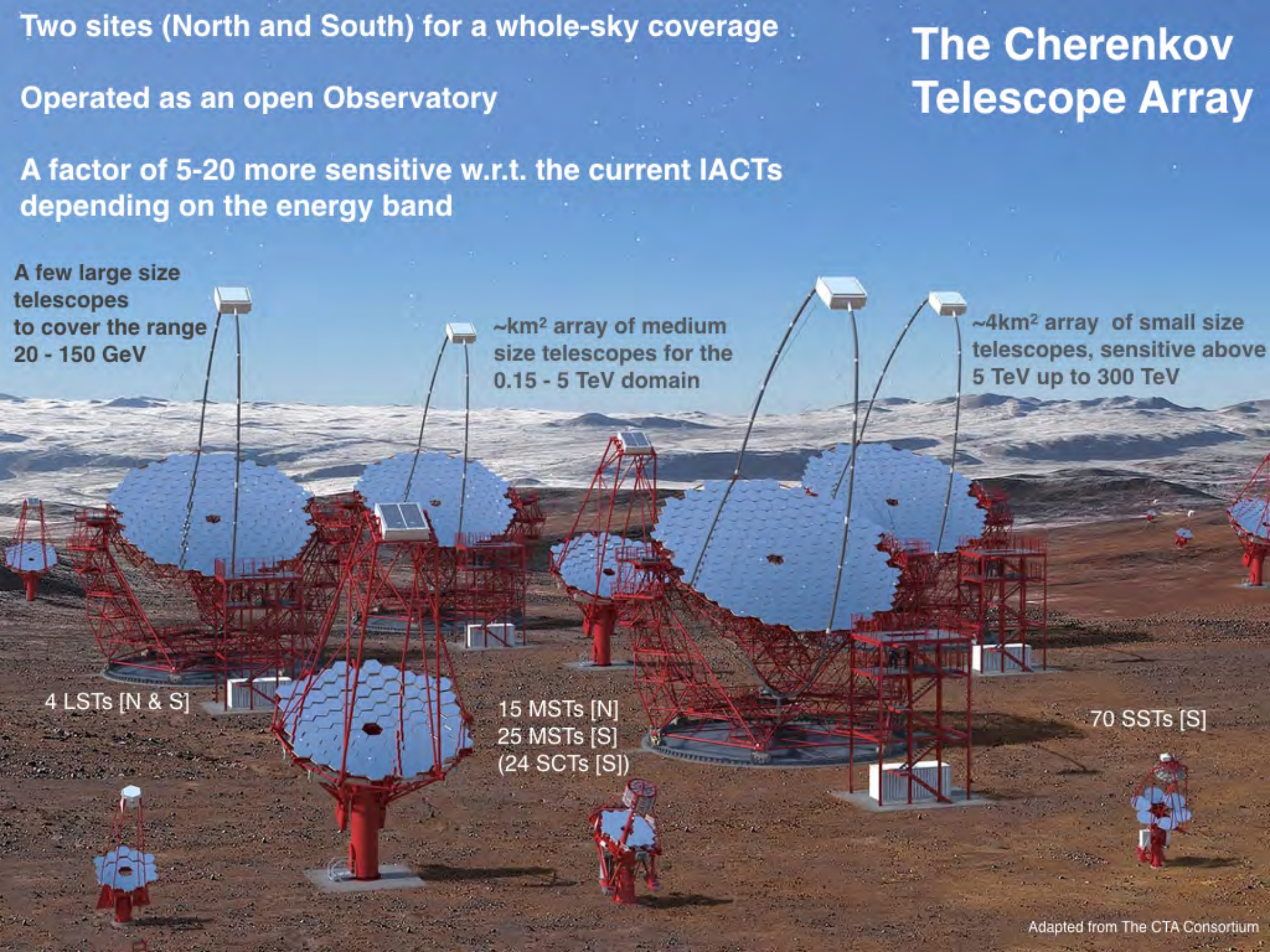
~km² array of medium size telescopes for the 0.15 - 5 TeV domain

~4km² array of small size telescopes, sensitive above 5 TeV up to 300 TeV

4 LSTs [N & S]

15 MSTs [N]
25 MSTs [S]
(24 SCTs [S])

70 SSTs [S]



Where to find us



High-level timeline and proposed layout



Project Phases

Pre-Construction

Current Phase

Pre-Production

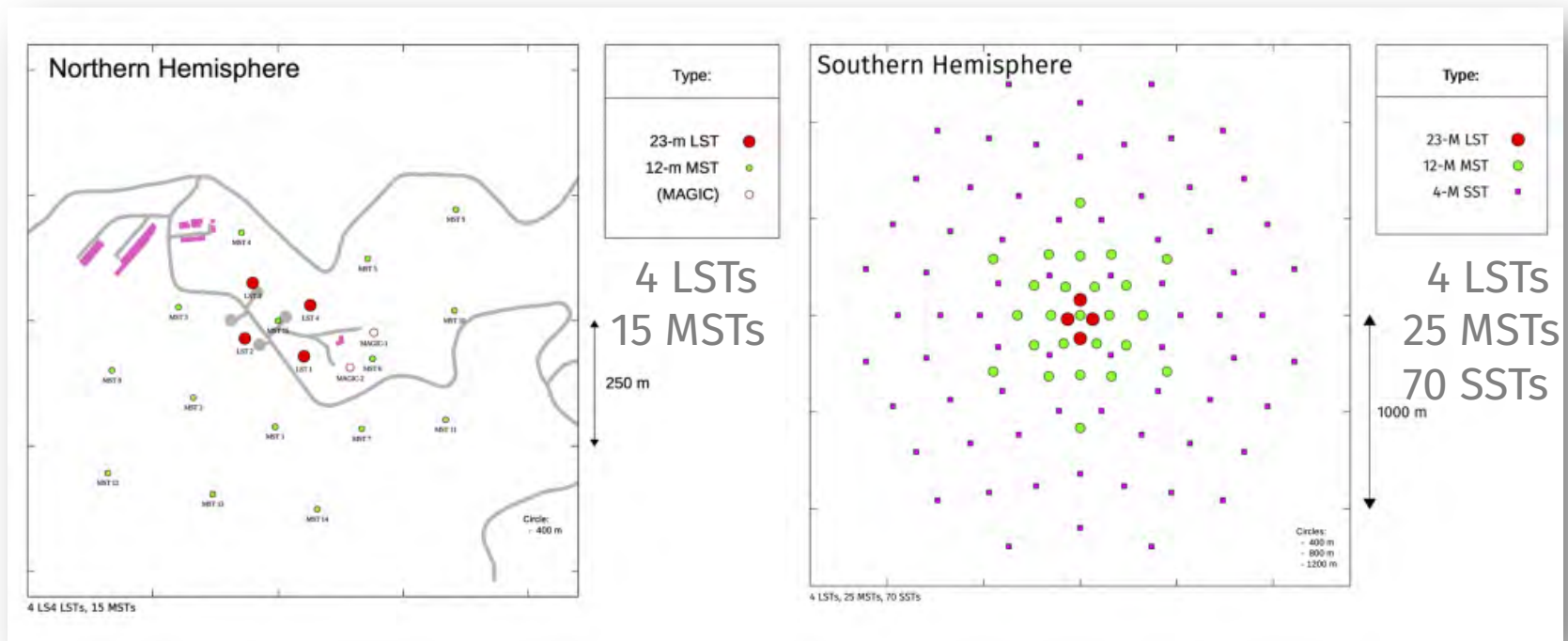
2019-2021

Production

2021-2025



First Pre-Production
Telescopes on Site



Large Size Telescope



- La Palma LST-1 prototype operational in 2018.
- <http://www.lst1.iac.es/webcams/>

Medium Size Telescope Prototype



https://www-zeuthen.desy.de/cta_cam/photogallery/content/index.html



Prototype
Berlin-Adlershof

Small size telescope prototypes



SST-2M GCT prototype in Paris



SST-1M prototype in Krakow

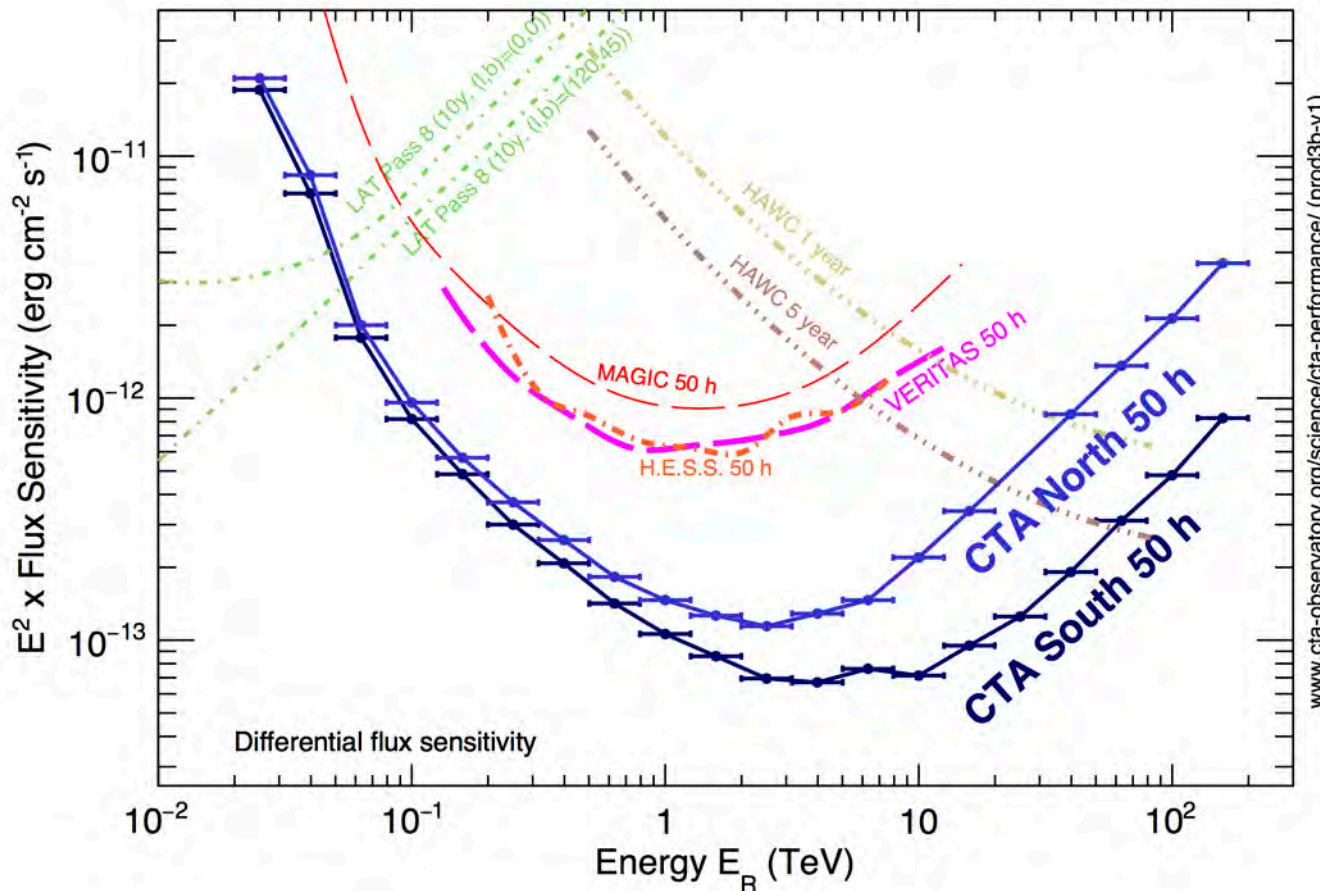


SST-2M ASTRI prototype on Mt. Etna (Sicily)

CTA Performance



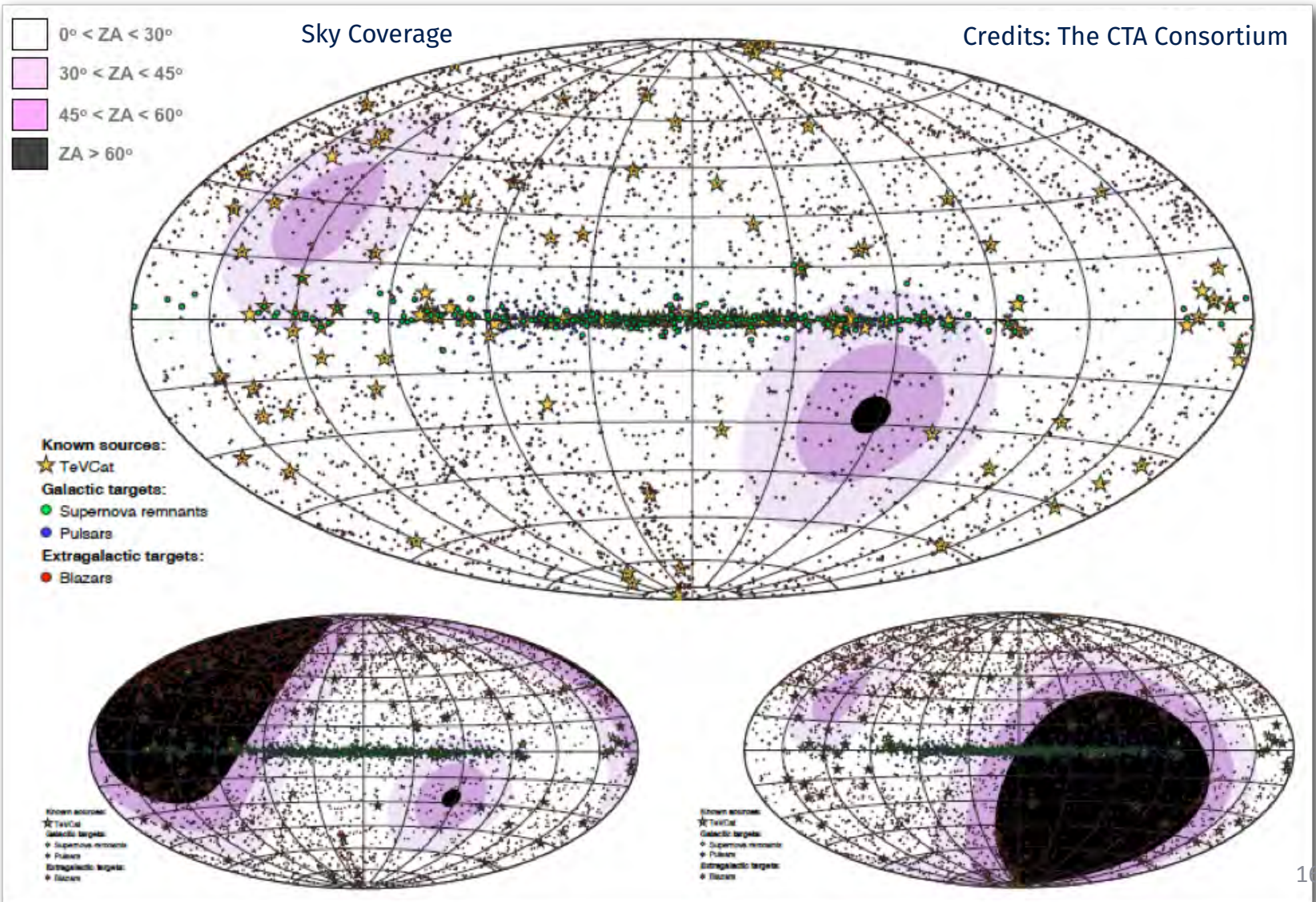
Differential Sensitivity



A factor of **5-20 improvement** in sensitivity depending on energy, relative to current IACTs.

Extension of the accessible energy range from **well below 100 GeV to above 100 TeV.**

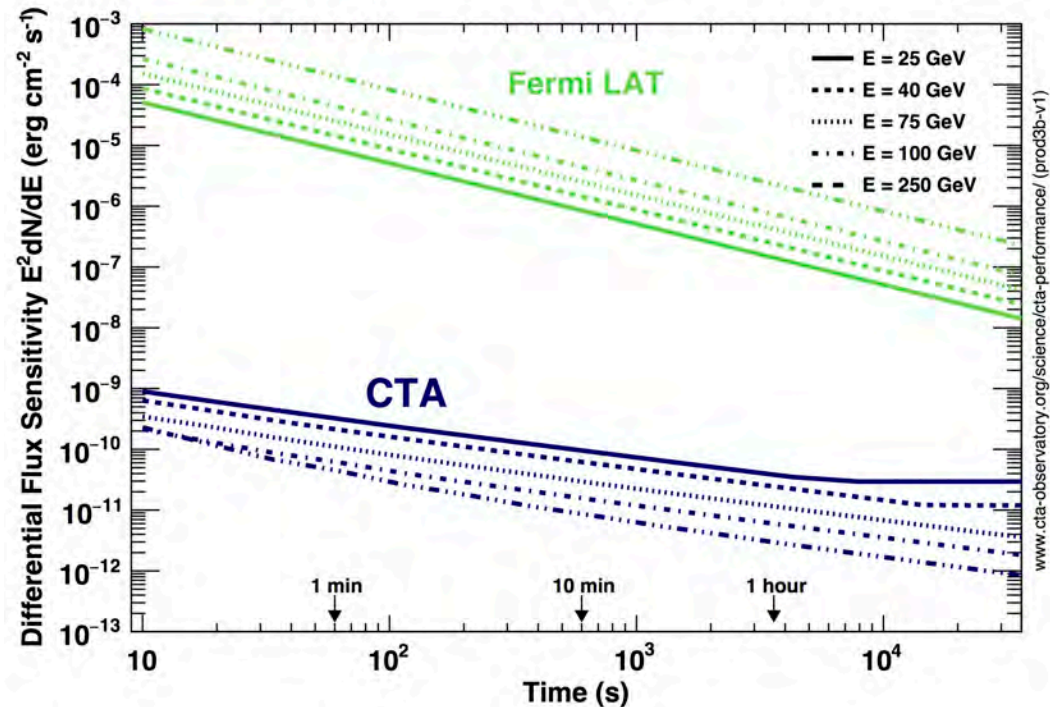
CTA as an *all-sky* Observatory



CTA as a transient factory



- **Huge advantage over Fermi** in energy range of overlap for ~minute to ~day timescale phenomena
 - Explosive transients
 - AGN flares
 - Binary systems
 - *Real-time analysis SW is crucial*
- **Disadvantage over Fermi**
 - Limited FoV (compared to Fermi)
 - Prompt reaction to external trigger is critical



Outline



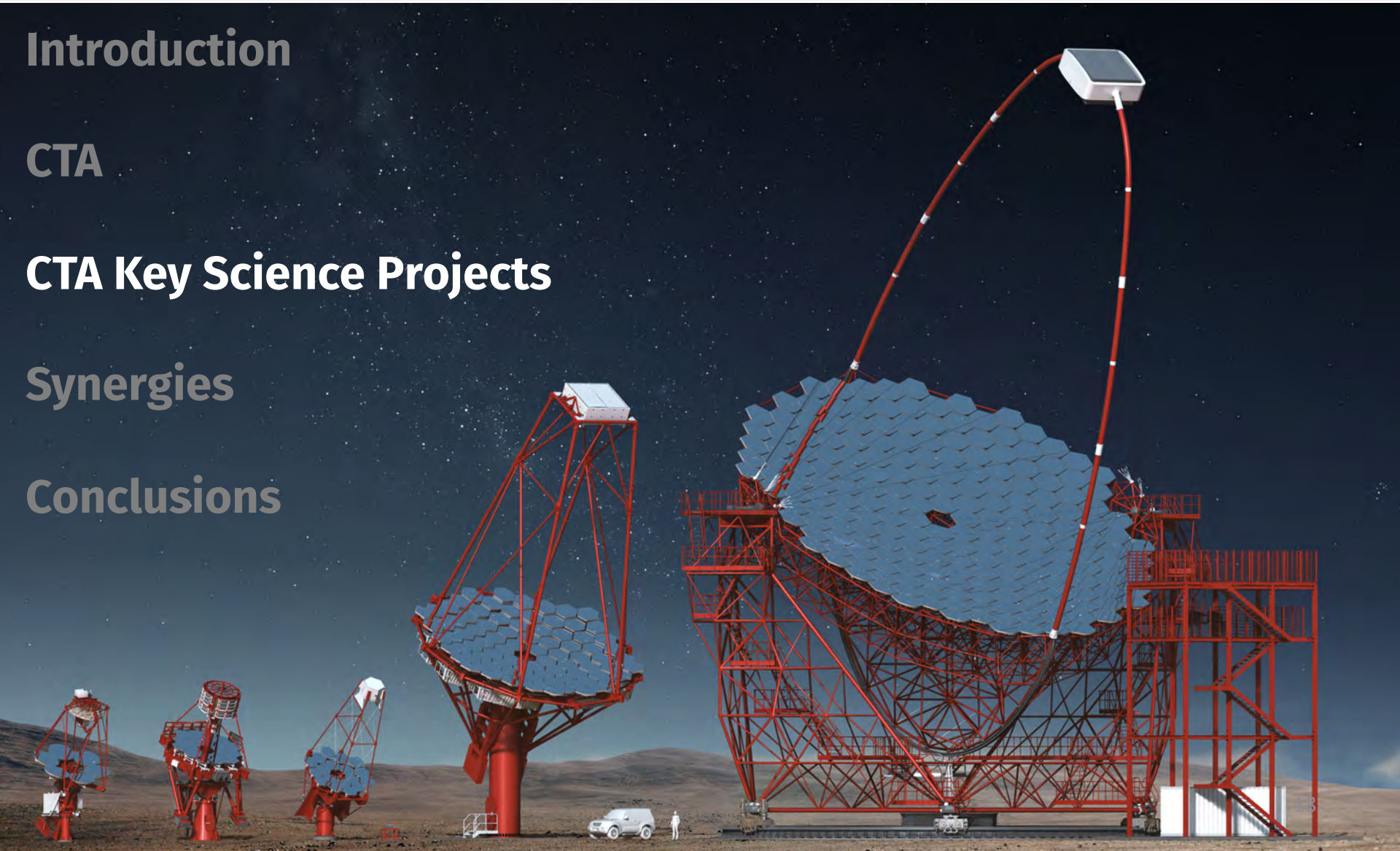
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Science Themes

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?
- Processes in relativistic jets, winds and explosions?
- Exploring cosmic voids

Theme 3: Physics Frontiers – beyond the SM

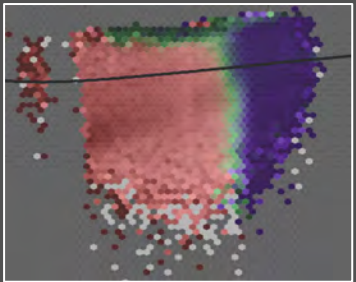
- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high energy photons?
- Do axion-like particles exist?

CTA Observing Programme

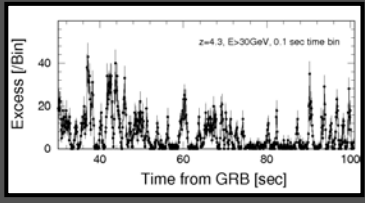
- **9 Key Science Projects (KSPs) and 1 DM Programme**
 - **KSPs are a sets of observations addressing multiple science questions within CTA themes**

- Focused on **major legacy projects:**
 - surveys & population studies (providing legacy data-sets)
 - large classes of sources
 - a few iconic objects

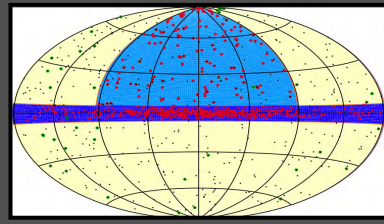
- Large potential for **guest observer proposals**
 - building on results from the KSP surveys



Dark Matter Programme

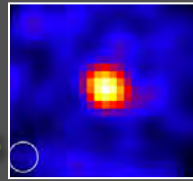


Transients



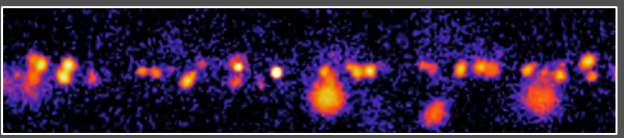
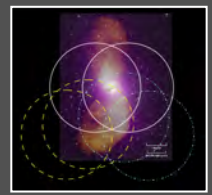
ExGal Survey

Galaxy Clusters



Star Forming Systems

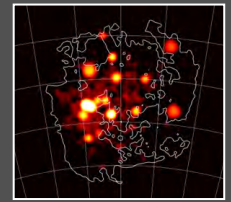
AGN



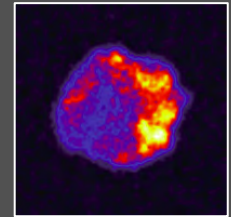
Galactic Plane Survey

Galactic

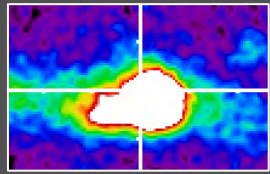
LMC Survey



PeVatrons



Galactic Centre Survey



Science with the Cherenkov Telescope Array

Science with CTA

[arXiv:1709.07997](https://arxiv.org/abs/1709.07997)

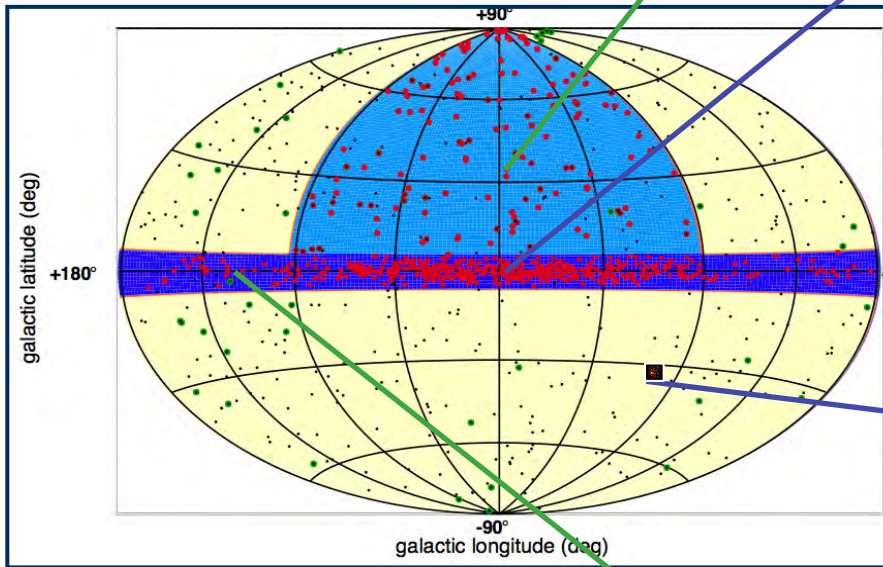
To be published as a book & open-access online version by World Scientific.

The Survey KSPs



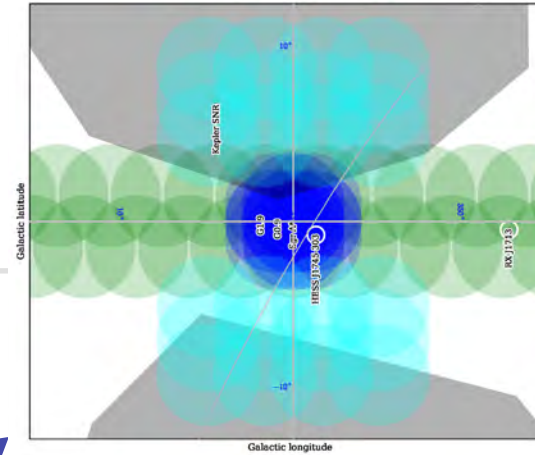
Extragalactic Survey:

Unbiased survey of $\frac{1}{4}$ sky to ~ 6 mCrab
VHE population study, duty cycle
New, unknown sources; O(1000) h



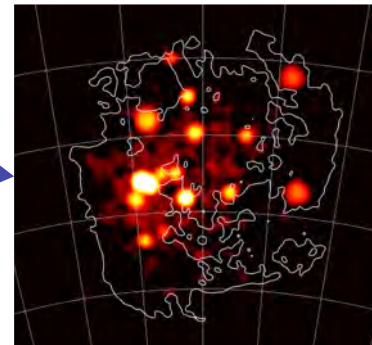
Galactic Plane Survey:

Survey of entire plane to ~ 2 mCrab
Galactic source population: SNRs, PWNe, etc.
PeVatron candidates, early view of GC, O(1620) h



Galactic Centre Survey:

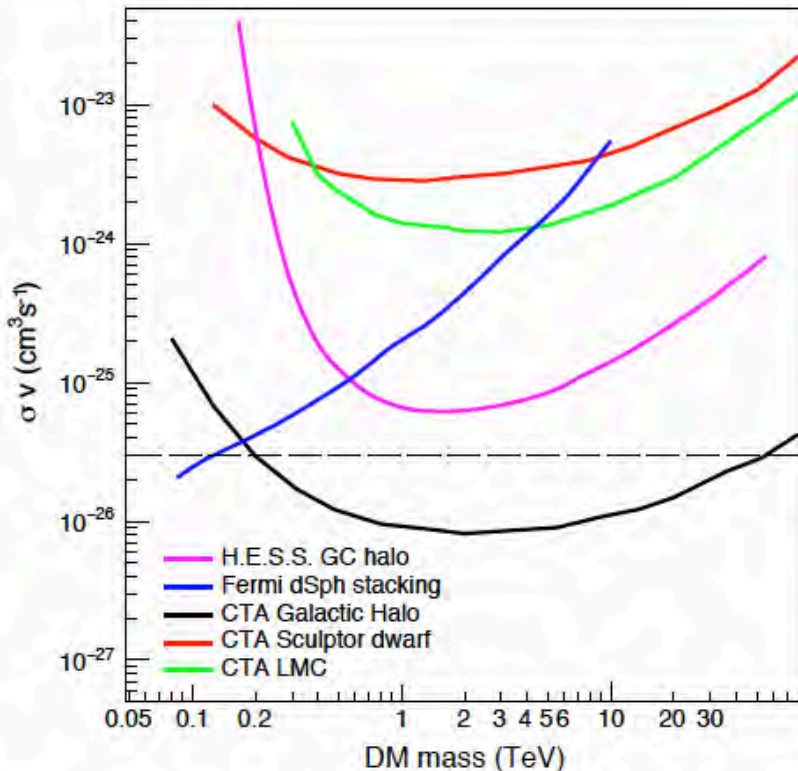
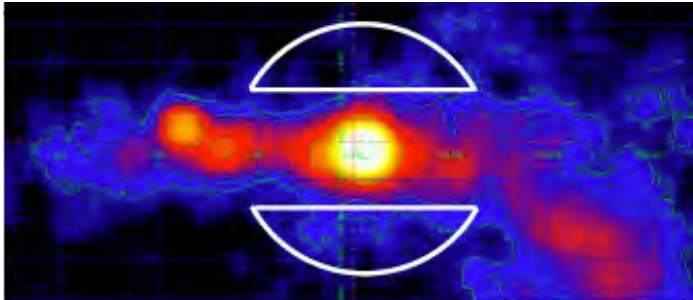
ID of the central source
Spectrum, morphology of diffuse emission
Deep DM search; base of the Fermi Bubbles
Central exposure: O(525) h, $10^\circ \times 10^\circ$: O(300) h



Large Magellanic Cloud Survey:

Face-on satellite galaxy with high SFR
Extreme Gal. sources, diffuse emission (CRs)
DM search; O(340) h in six pointings

The Dark Matter Programme



- **Key target: Galactic Centre halo**
 - Deep observation O(525 h) to reach canonical thermal cross-section for wide WIMP mass range
- **Complementary observations**
 - Dwarf Sph. Galaxies O(100 h)
 - LMC O(340 h)
 - Perseus Gal. Cluster O(300 h)
 - Expect strategy to evolve with new information

Outline



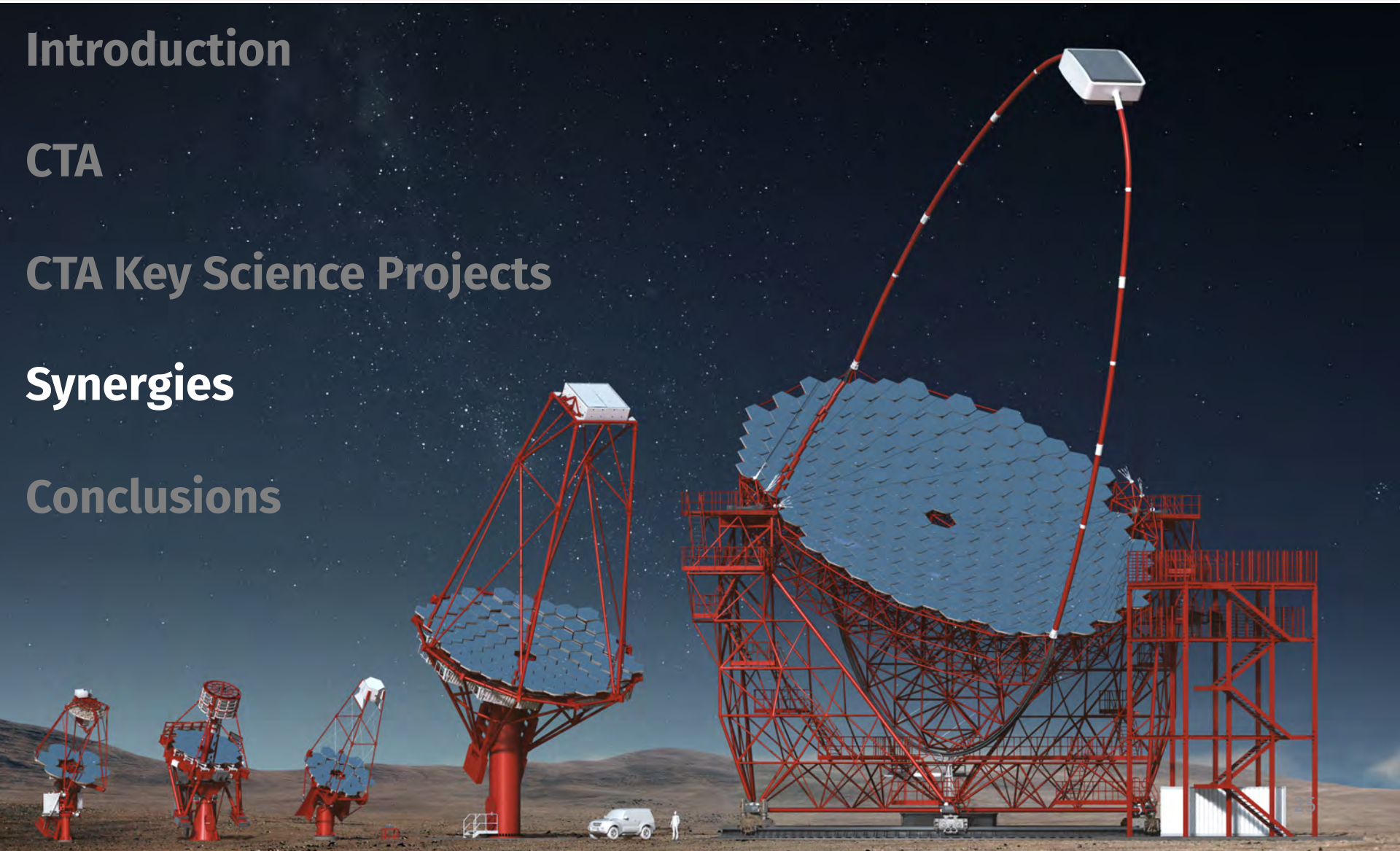
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KSPs vs. proposal-driven programs



Key Science Projects

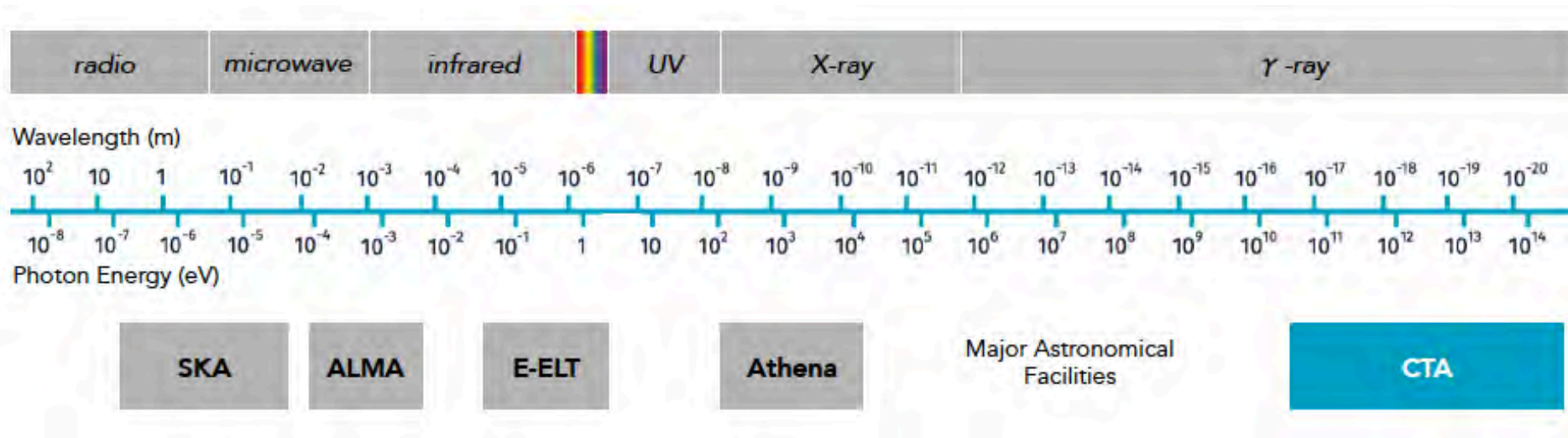
- Ensure that important science questions for CTA are addressed in a coherent fashion and with a well-defined strategy,
- Conceived to provide legacy data sets for the entire community

Example: galactic and extragalactic surveys

- Deep investigation of known sources
- Follow-up of KSP discovered sources
- Multiwavelength campaigns
- Follow-up of ToOs from other wavebands / messengers
- Search for new sources
- ...

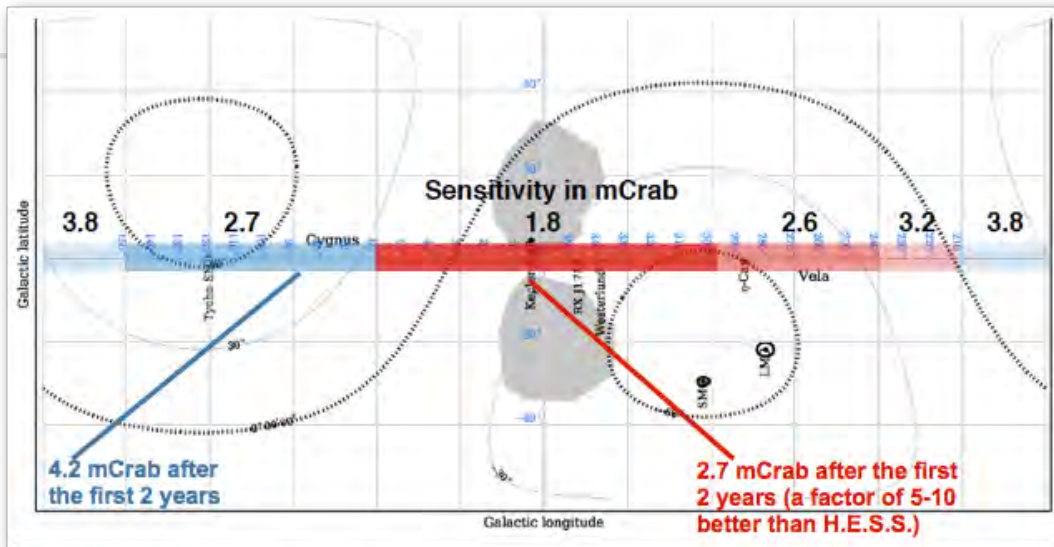
Proposal-Driven User Programme

Synergies during CTA operation

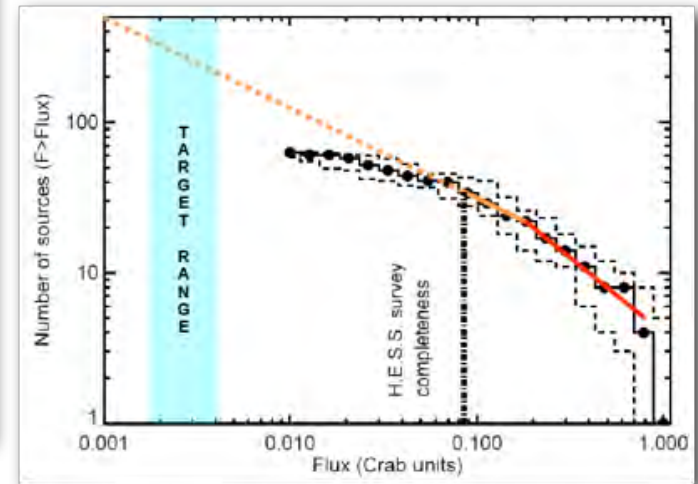


These are just a few of the future major multi-wavelength facilities available during the CTA era.

Galactic Plane Survey

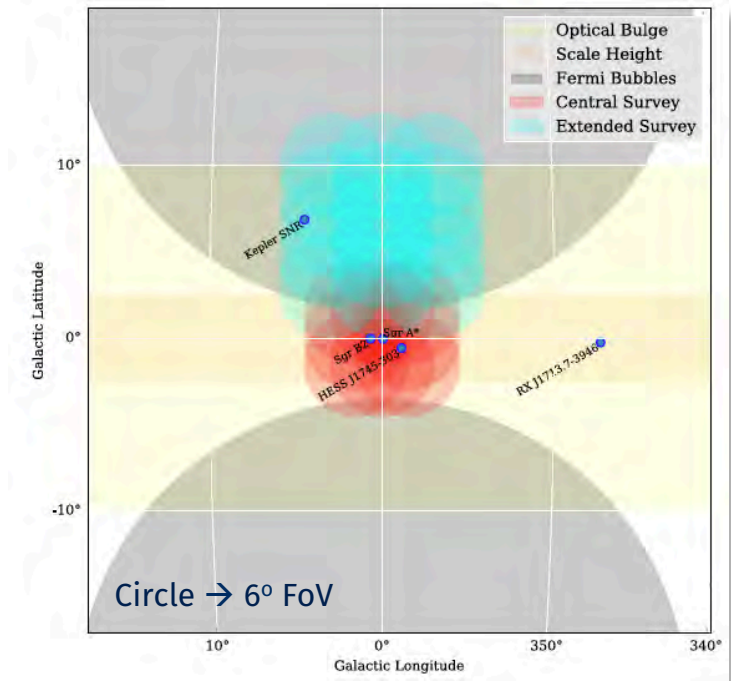
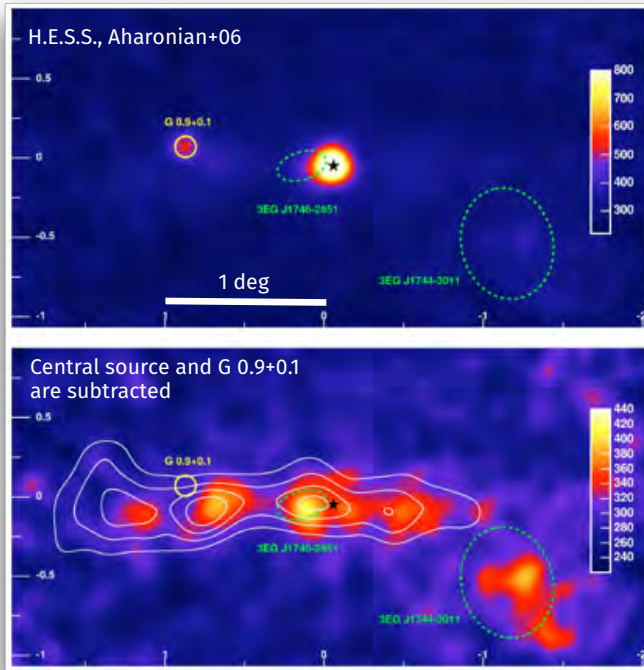


The CTA Consortium



- Discovery of PeVatron candidates → origin of cosmic rays
- Detection of many new VHE sources $O(300 - 500)$, particularly PWNe and SNRs
- Discovery of new VHE gamma-ray binaries
- Production of a multi-purpose legacy data set
- **Radio/mm and X-ray facilities** → PSR ephemerides, **PWNe/SNRs morphology/SEDs**, MWL **phase-resolved studies in binaries**, **cross-correlation of catalogs** and identification of new VHE sources, ...
- **Non-thermal X-ray emission** → a natural **tracer of locations of extreme particle acceleration**.

Galactic Centre Survey



- Determination of the nature of the central source
- A detailed view of the VHE diffuse emission
- Search for variability in the VHE source near Sgr A*
- Studying the interaction of the central source with neighboring clouds
- Global **VLBI array at mm/sub-mm frequencies**, → direct **imaging of the jet-launching regions** of key sources such as Sgr A*
- AGNs **optical polarisation** studies of jets → derivation of **magnetic field parameters** that can be used to improve SED modeling and emission-region localisation

The CTA Consortium

LMC Survey

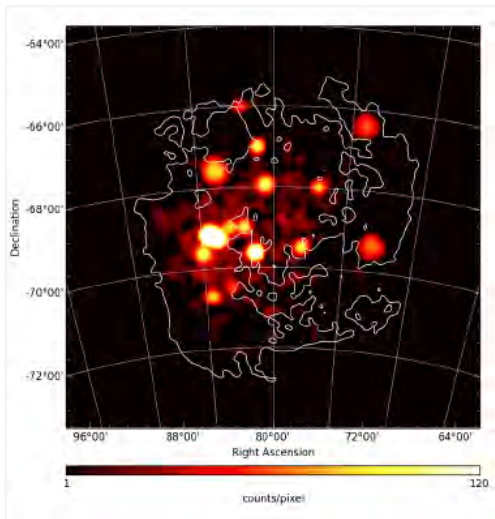


The **Large Magellanic Cloud (LMC)** is one of the nearest **star-forming galaxies**, at a distance of 50 kpc ($\pm 2\%$ \rightarrow important for source energetics).

Its activity is attested by more than 60 supernova remnants, dozens to hundreds of HII regions, bubbles and shells observed at various wavelengths.

It is a unique place to obtain a resolved, global view of a star-forming galaxy at TeV energies.

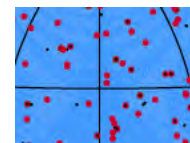
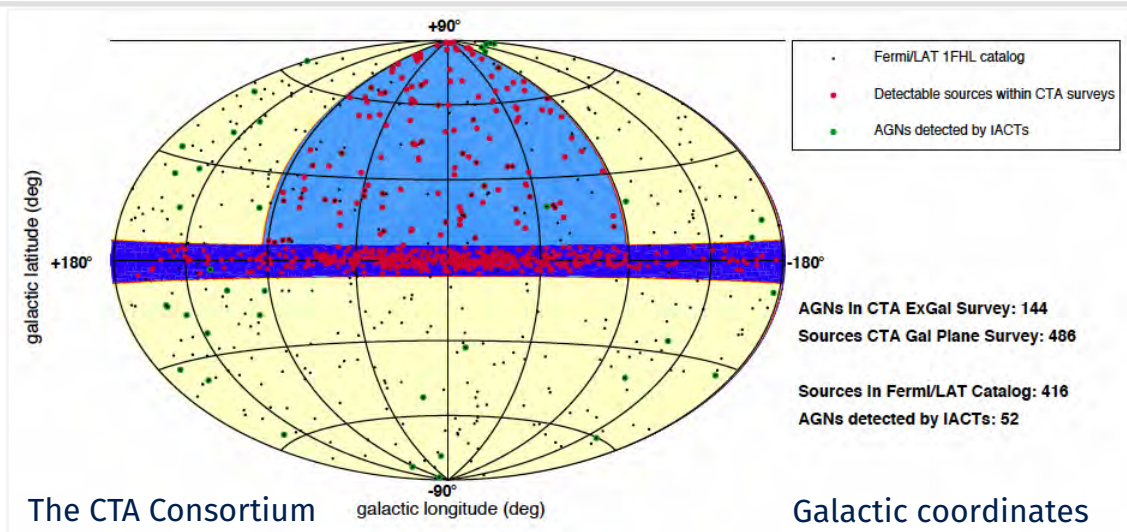
Credits: Schaefer 2015



Mapping of the interstellar gas over wide areas is absolutely essential to enable **identification of sources** within large scale surveys such as that of the LMC.

(Sub)-millimeter wavelengths \rightarrow detailed **understanding of the environment** into which shock waves propagate and through which accelerated particles are transported and interact.

Extra-galactic Survey



1/4 of the sky ($\sim 10^4 \text{ deg}^2$)
Limiting flux $\sim 5 \text{ mCrab}$

$O(100)$ AGNs in 10^4 deg^2

The survey would connect with the Galactic Plane Survey ($|b| < 5^\circ$) over Galactic longitude $-90^\circ < l < 90^\circ$.

Several highly interesting regions such as the Virgo & Coma clusters, the Fermi Bubbles (North) and Cen A (South) will be covered by the proposed survey.

eROSITA will be the first imaging **all-sky survey in the 2–10 keV** range \rightarrow a primary reference for CTA source identification and **multi-wavelength correspondences**.

Multi-messenger Astrophysics window is open !



nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

ANATOMY OF A KILONOVA

Aftermath of the merger between two neutron stars
PAGES 64-67, 71, 75, 80 & 81

Detection of a gravitational wave event following a GRBs onset and its MWL follow-up

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:26 GMT
FROM: Erik Blaufuss at U. Maryland/IceCube <blaufuss@icecube.umd.edu>

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel
Credential
Subjects: Optical, Gamma Ray
Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration on 28 Sep 2017; 10:10 UT*
Credential Certification: *David J. Thompson (David.J.Thompson@nasa.gov)*

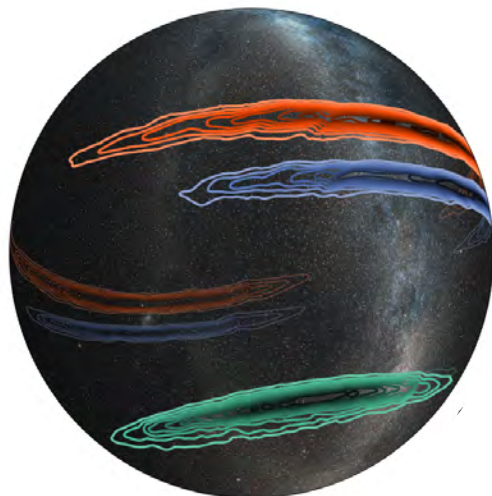
Subjects: Gamma Ray, Neutrinos, AGN

Possible association of an extra-galactic source with an IceCube neutrino event.

Transients



Credits: The LIGO Scientific Collaboration



Transients are a diverse population of astrophysical objects. Some are known to be prominent **emitters of high-energy gamma-rays**, while others are sources of non-photonic, multi-messenger signals such as cosmic rays, **neutrinos and/or gravitational waves** (GW → MoU already signed).

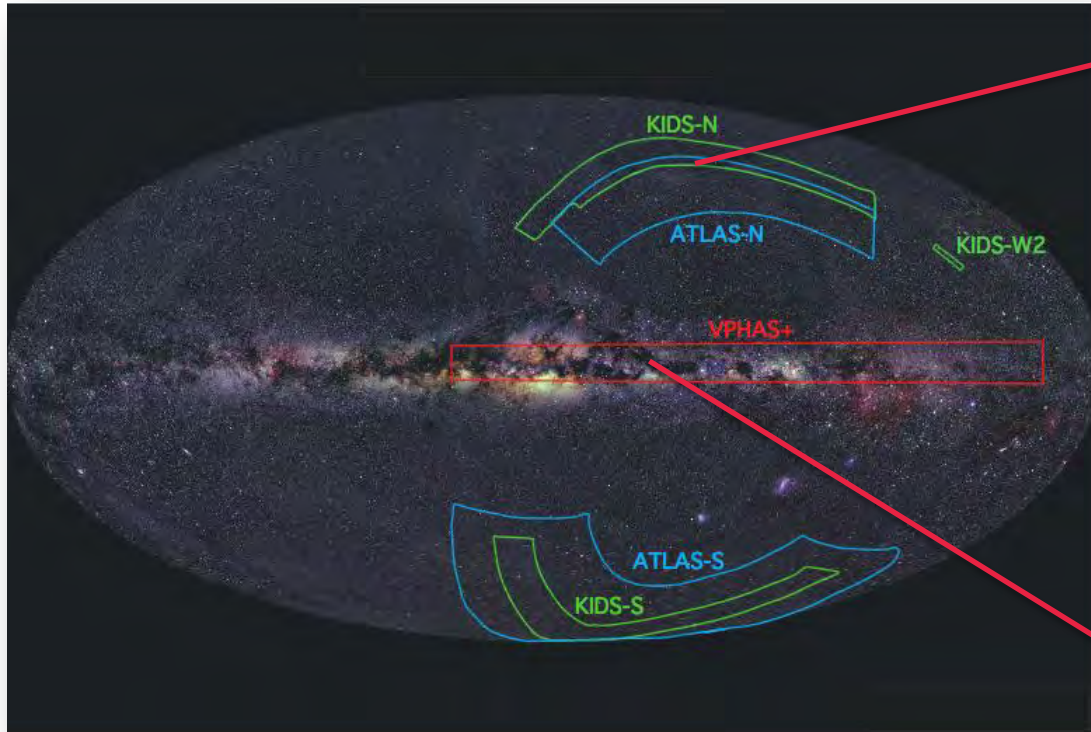
Transient Factories & SKA

These facilities will generate **overwhelming number of triggers.**

It is key to understand the potential for VHE follow-up and **define appropriate response criteria.**

Priority	Target class	Observation times (h yr ⁻¹ site ⁻¹)			
		Early phase	Years 1–2	Years 3–10	Years 1–10
1	GW transients	20	5	5	
2	HE neutrino transients	20	5	5	
3	Serendipitous VHE transients	100	25	25	
4	GRBs	50	50	50	
5	X-ray/optical/radio transients	50	10	10	
6	Galactic transients	150	30	0(?)	

Follow-up priority	Target class	Detected @ HE	Trigger	Rate (yr ⁻¹)	Urgency	Activity duration	Obs. time (h) /night	Total time (h)	Site
1	Magnetar giant flares	–	MeV	0.1	1 min	1–2 d	Max. 1	10	A/B
2	PWN flares: Crab nebula	Y	HE	1	1 d	5–20 d (HE)	4	50	S&N
3	HMXB microquasars: Cyg X-3	Y	HE/X-ray	0.5	1 d	50–70 d (HE)	Max. 1	50	N
	Cyg X-1	Y	HE/X-ray	0.2	1 d	1–10 d ?	Max. 1	30	N
4	Unidentified HE transients	Y	HE	1	1 d	?	2	20	A/B
5	LMXB microquasars	?	X-ray/radio	1	1 d	Weeks	2	20	A/B
6	Novae	Y	HE/opt.	2	1 d	Weeks	2	20	A/B
7	Transitional pulsars	Y	Radio/opt.	0.5	1 d	Weeks	2	20	A/B
8	Be/X-ray binary pulsars	N	X-ray	1	1 d	Weeks	2	20	A/B



Synergies with the CTA
EGAL survey KSP.

Synergies with the CTA
Galactic Plane survey
KSP and all KSPs
investigating Galactic
objects (**PeVatrons**,
Galactic Center, ...)

Credits: VST Scientific Collaboration

Outline



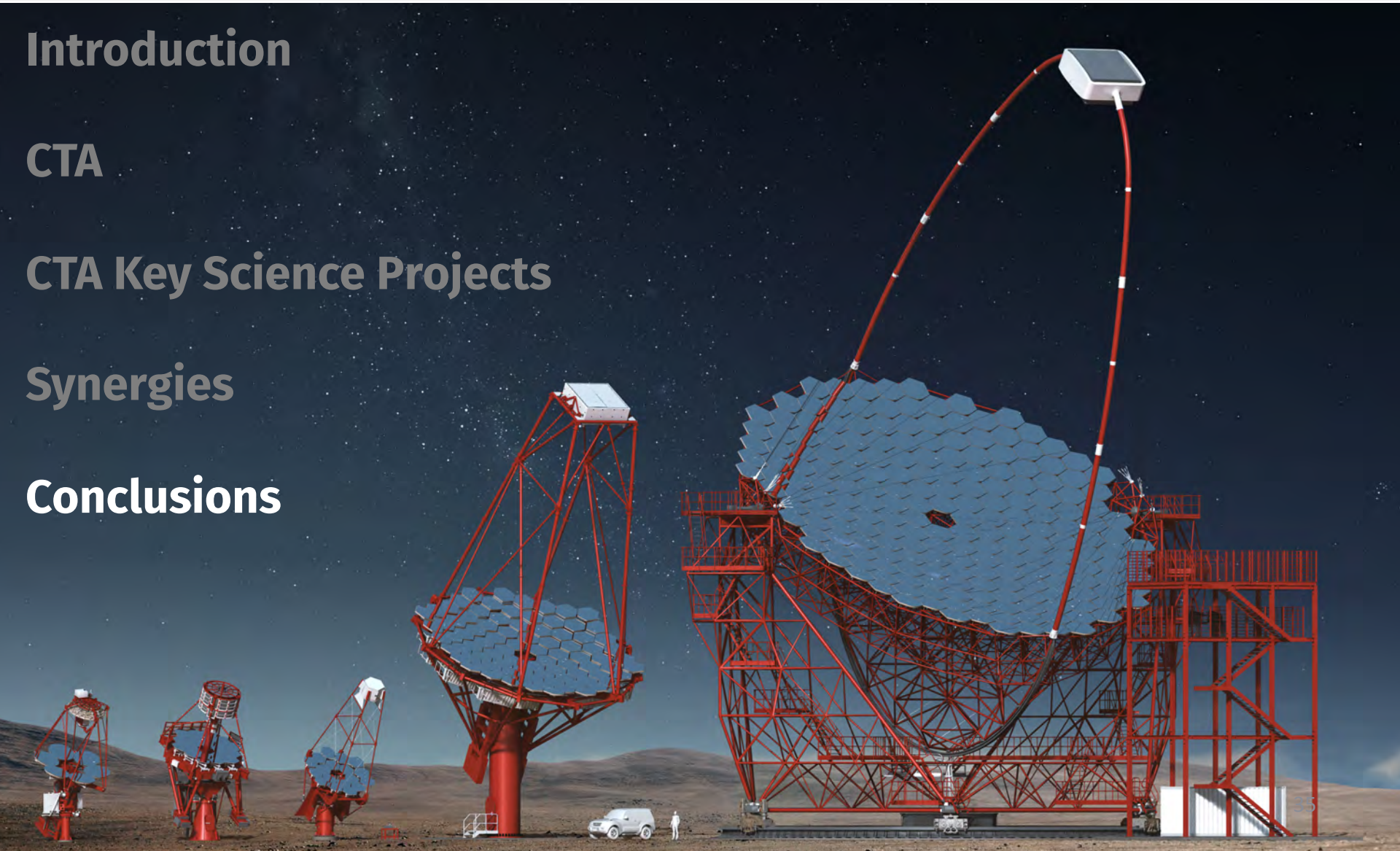
Introduction

CTA

CTA Key Science Projects

Synergies

Conclusions



CTA will be an **Observatory** open to the scientific community.

Science will focus on cosmic particle acceleration, extreme environments, and physics beyond the standard model.

Proprietary time (significant fraction in the first years) will be articulated in **Key Science Projects**.

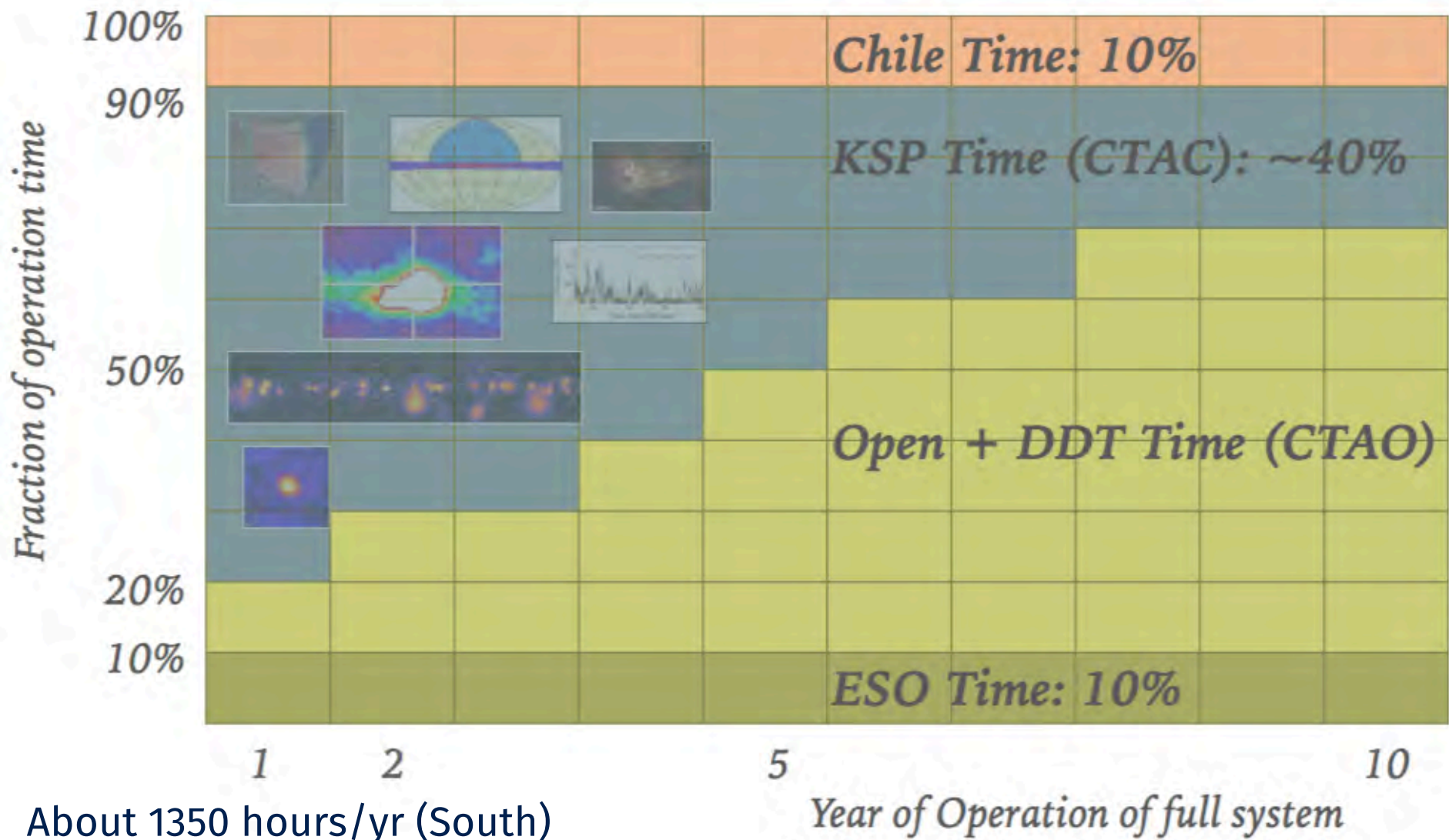
Large potential for **Guest Observer proposals** – e.g., building on results from the KSP surveys.

CTA will have important **synergies** with many astronomical and astro-particle facilities.

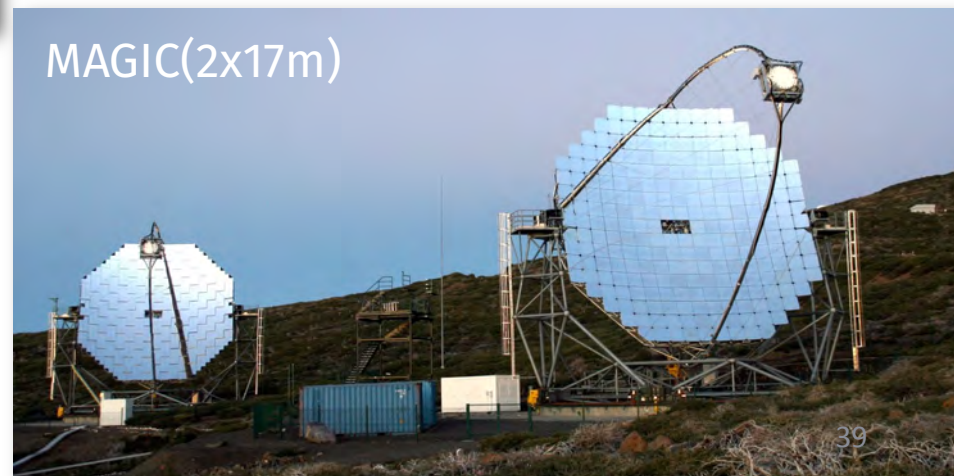
Backup



Possible KSP vs GO time budget



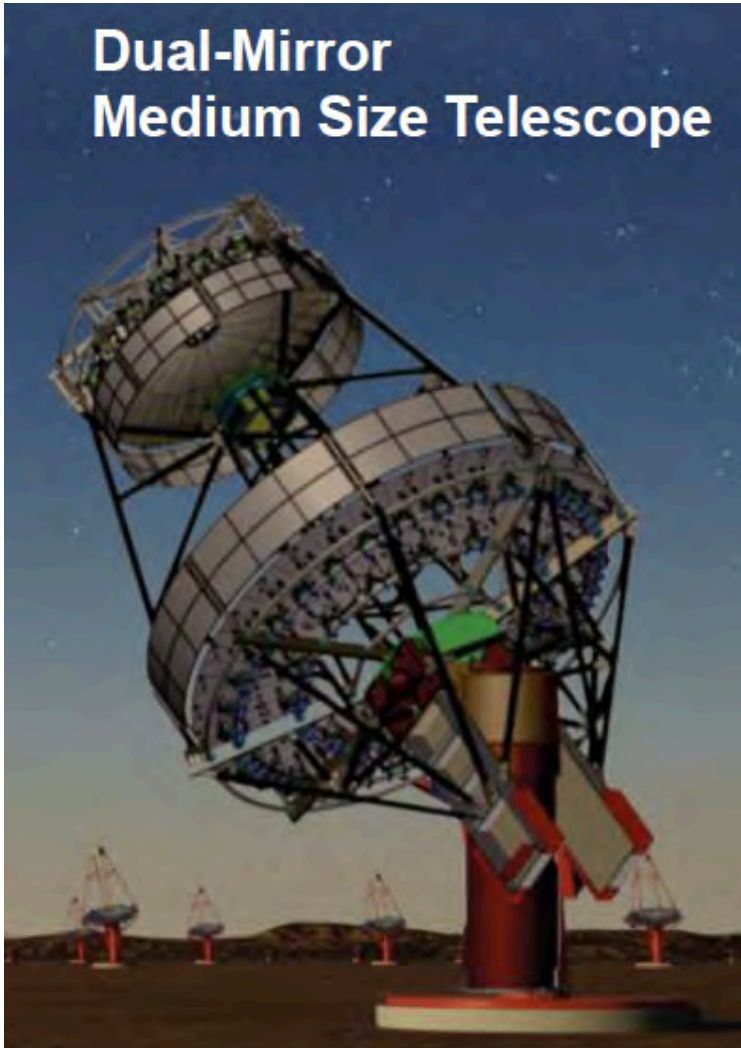
The current IACT status



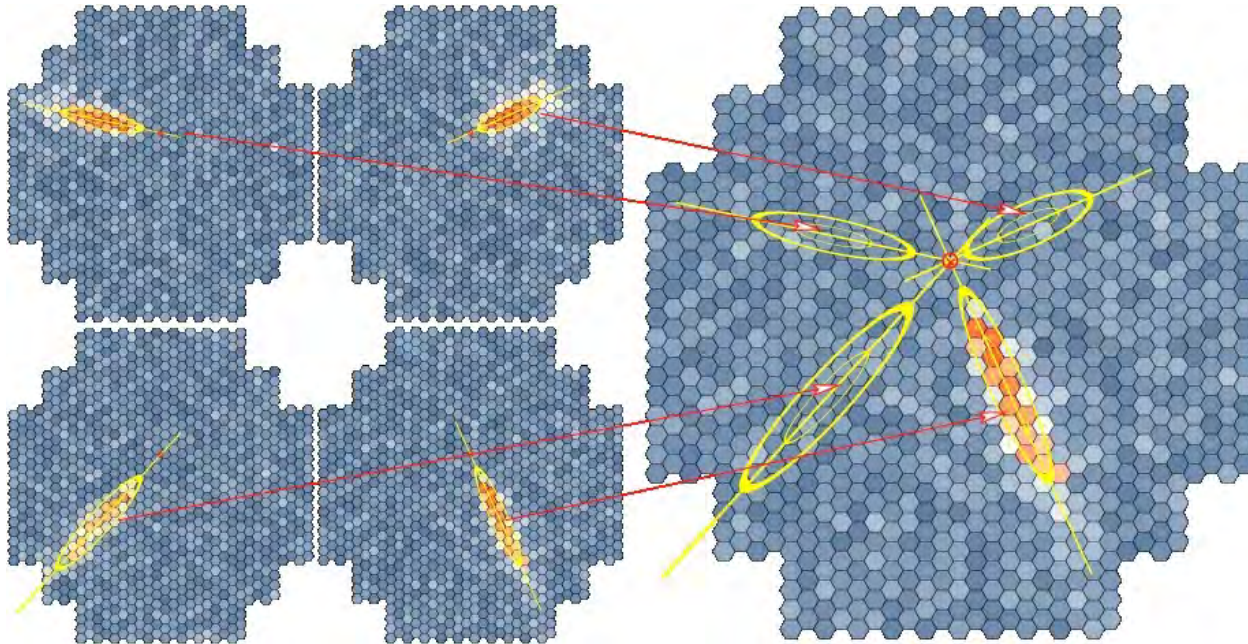
Dual-mirror MST prototype



Dual-Mirror Medium Size Telescope



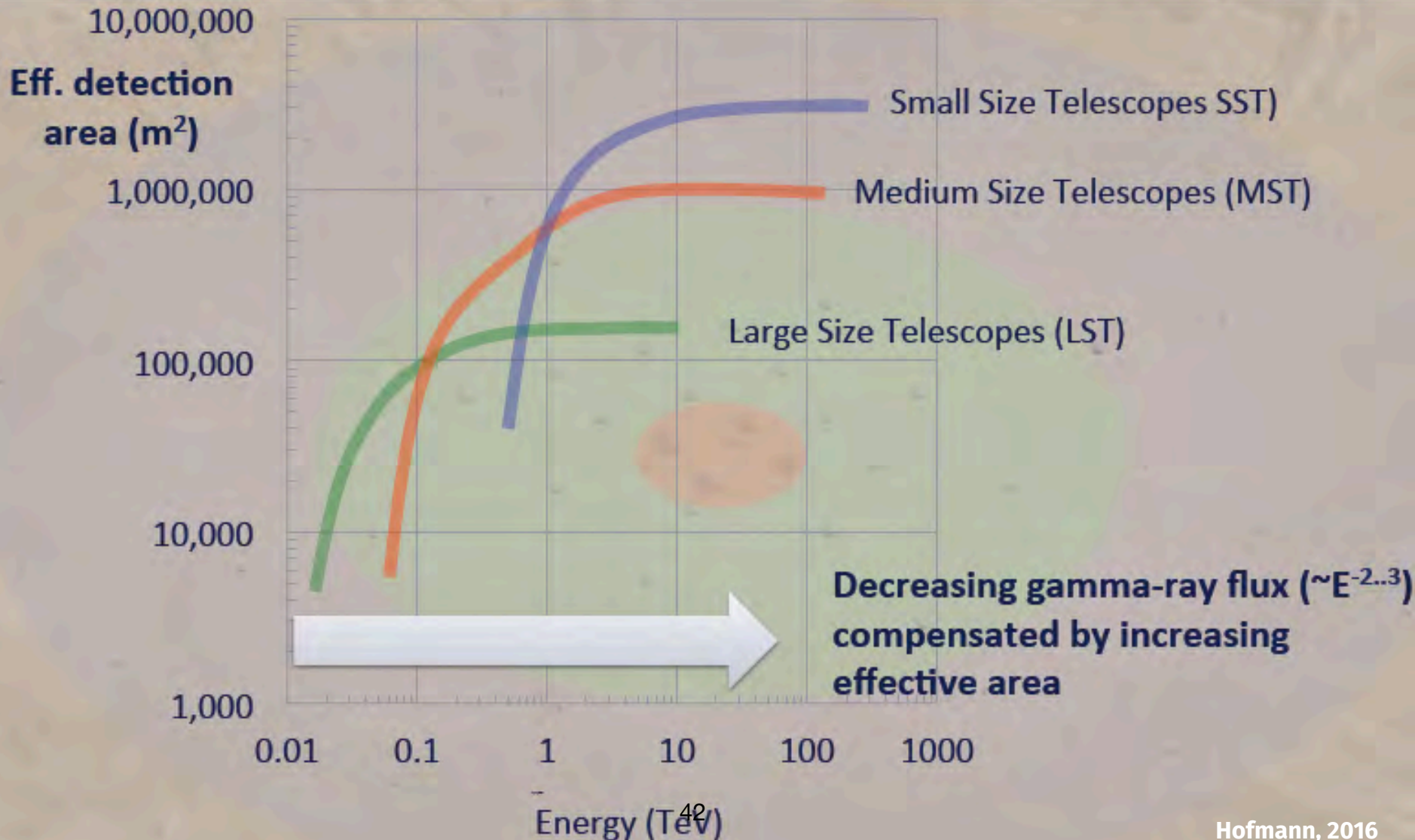
The Cherenkov Telescopes



The intersection of major axes on the common FOV gives source position on the sky.

**More on the Cherenkov technique, sources and physics in:
Hinton & Hofmann, 2009, ARAA, 47, 523**

Effective area for gamma-ray detection



ASTRI: Etna is an astronomical site...

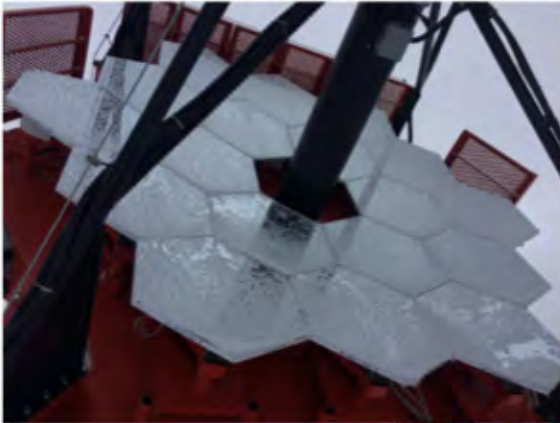


Credits: Pareschi

... in a peculiar environment...



... where Winter may be severe...



Credits: G. Leto

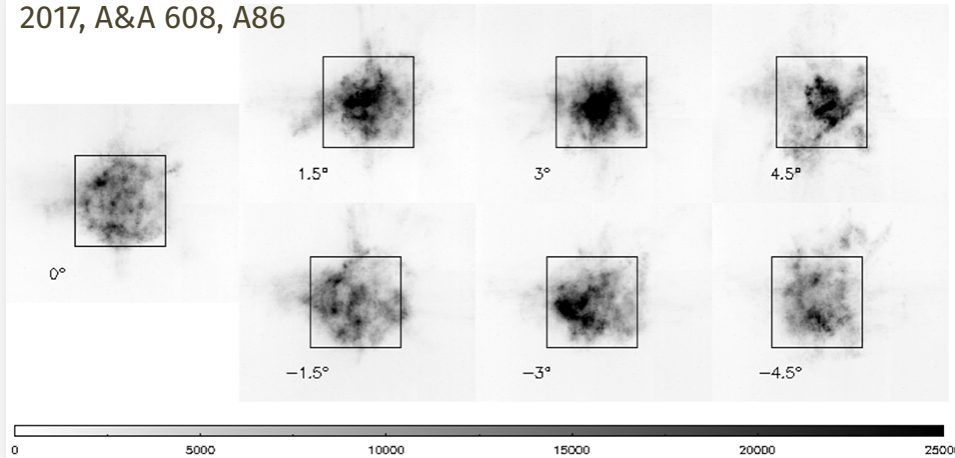


Winter 2014- 2015

... which we pass in full colours !

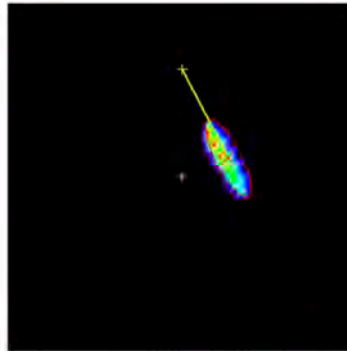


Giro, Canestrari, Sironi et al.
2017, A&A 608, A86



First ever optical characterization of a Schwarzschild-Couder telescope up to 4.5° off-axis.

First Cherenkov light acquired by the ASTRI camera of a shower generated by cosmic rays in the Earth's atmosphere.



Credits: ASTRI Team, May 2017

