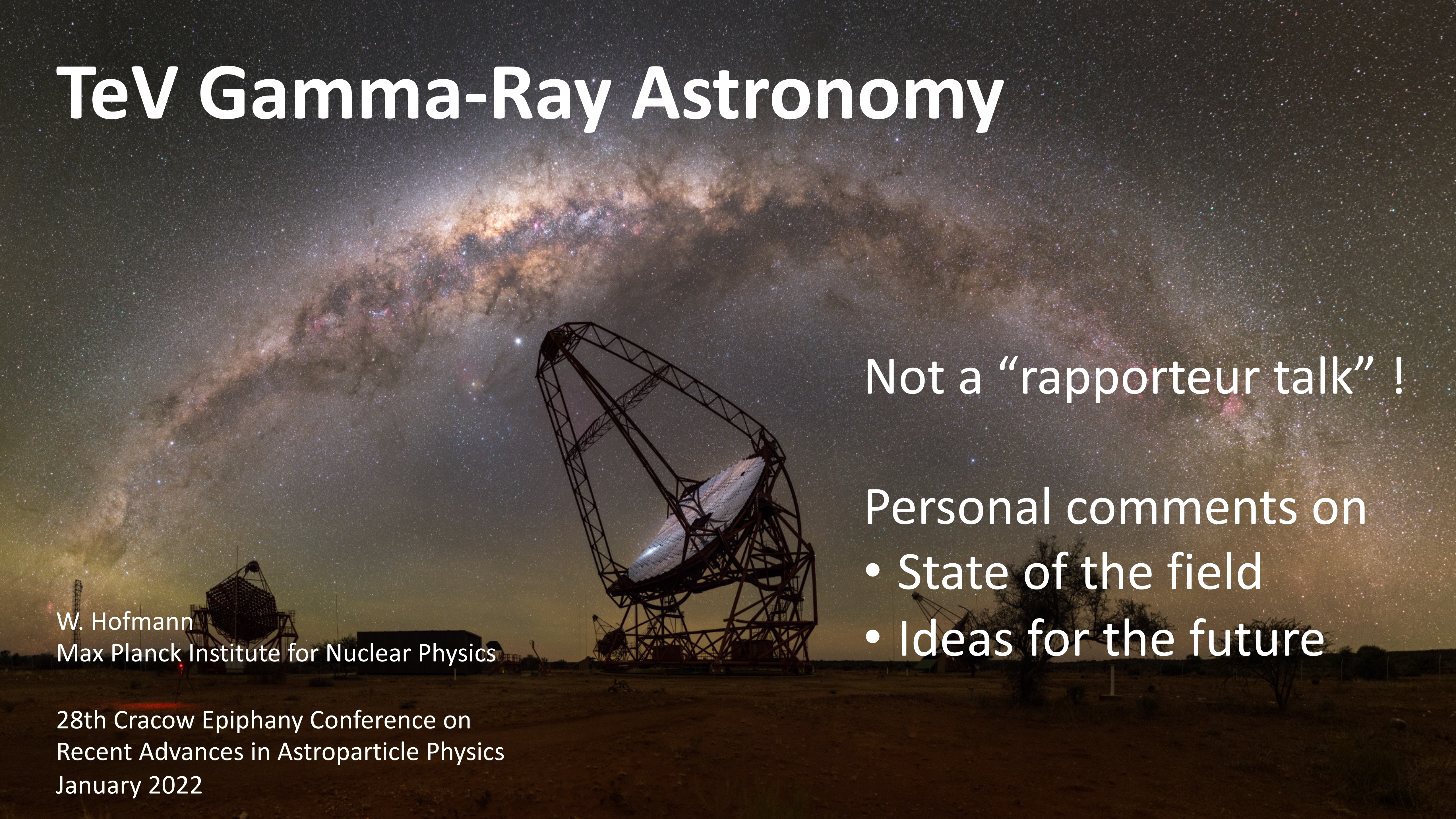
TeV Gamma-Ray Astronomy



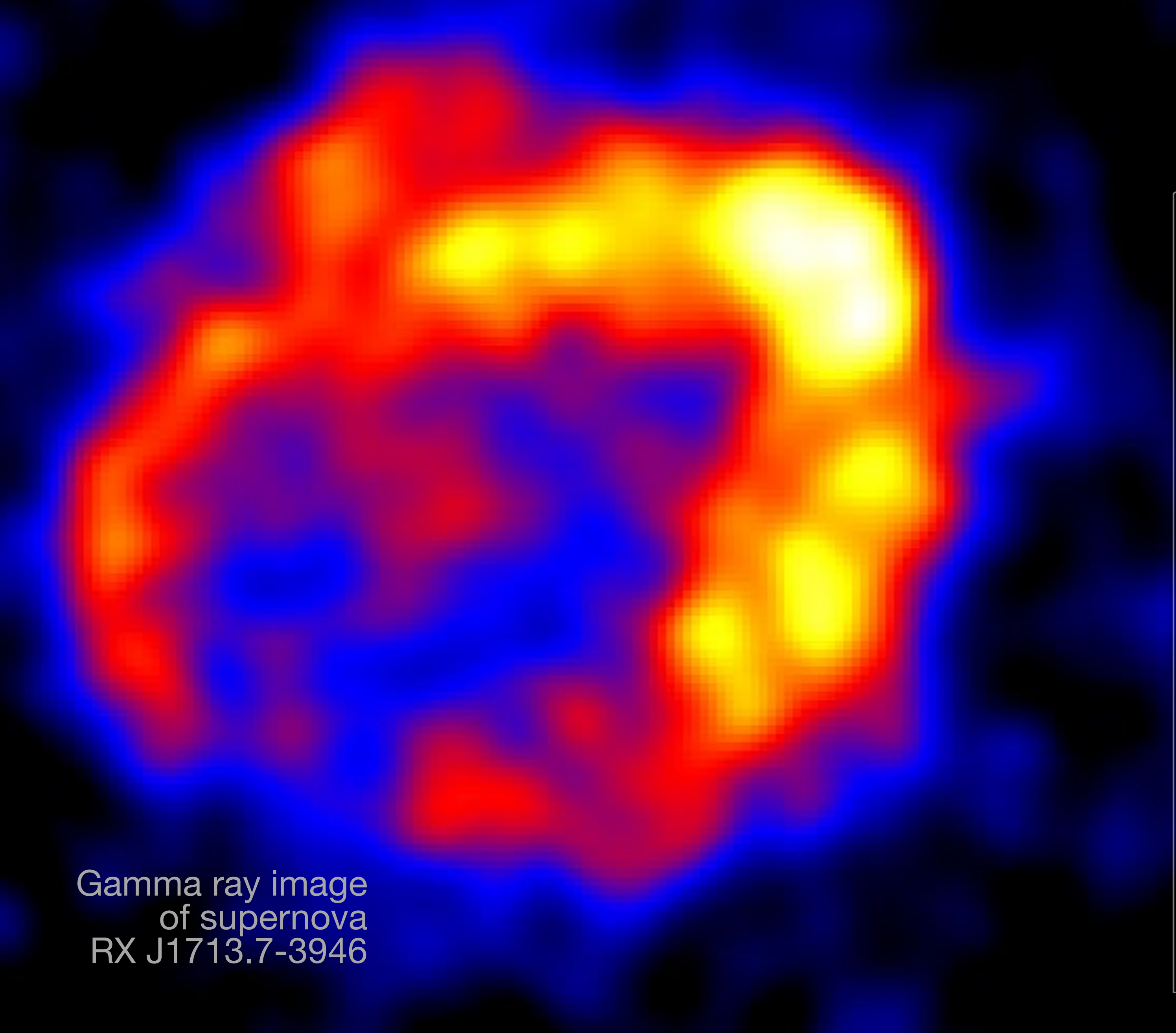
Not a “rapporteur talk” !

Personal comments on
- State of the field
- Ideas for the future

W. Hofmann
Max Planck Institute for Nuclear Physics

28th Cracow Epiphany Conference on
Recent Advances in Astroparticle Physics
January 2022

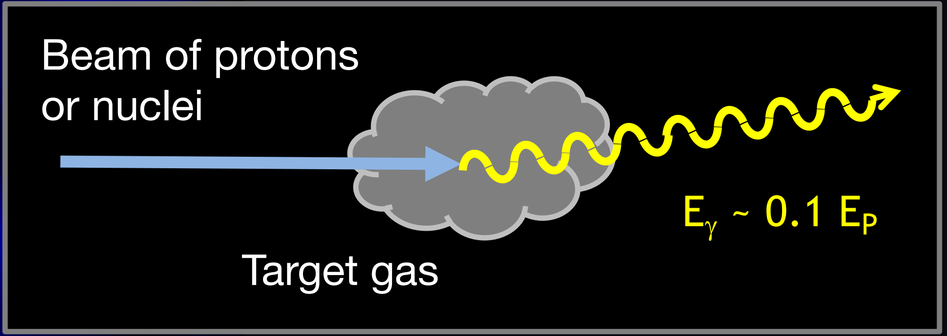
TeV ($10^{12 \pm 2}$ eV) domain

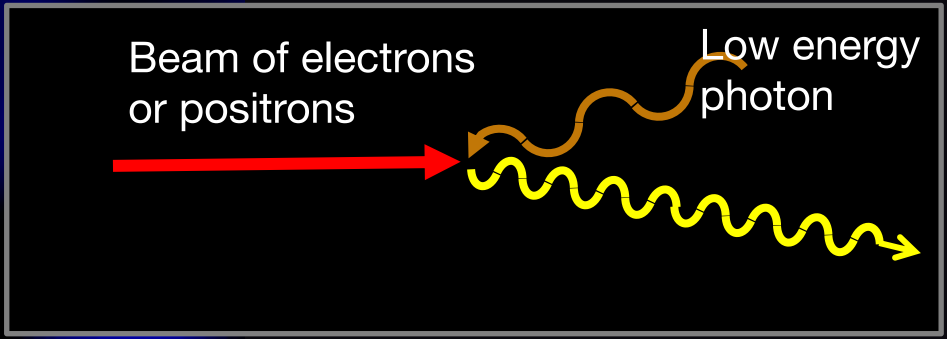


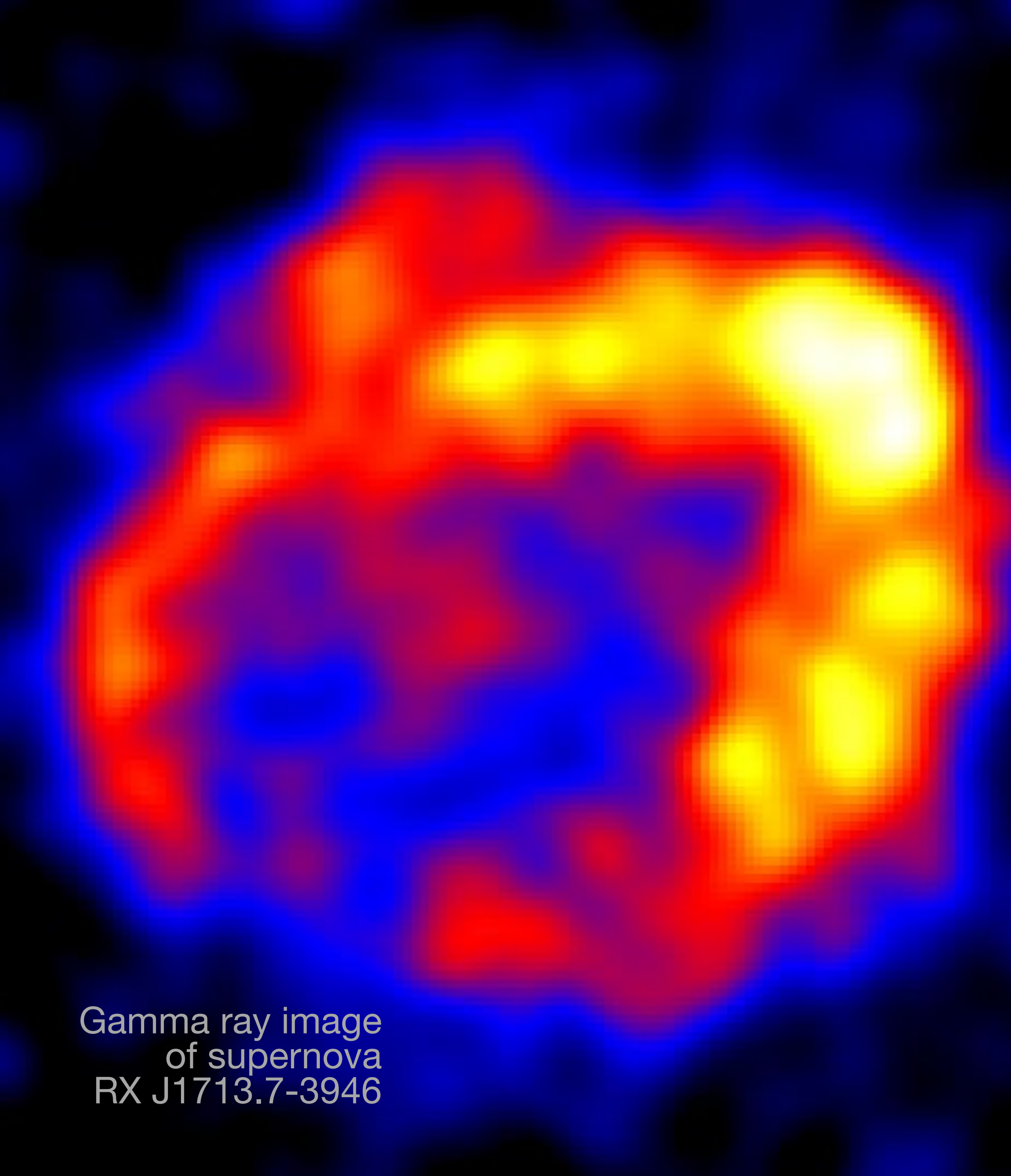
Gamma ray image
of supernova
RX J1713.7-3946

Gamma rays

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

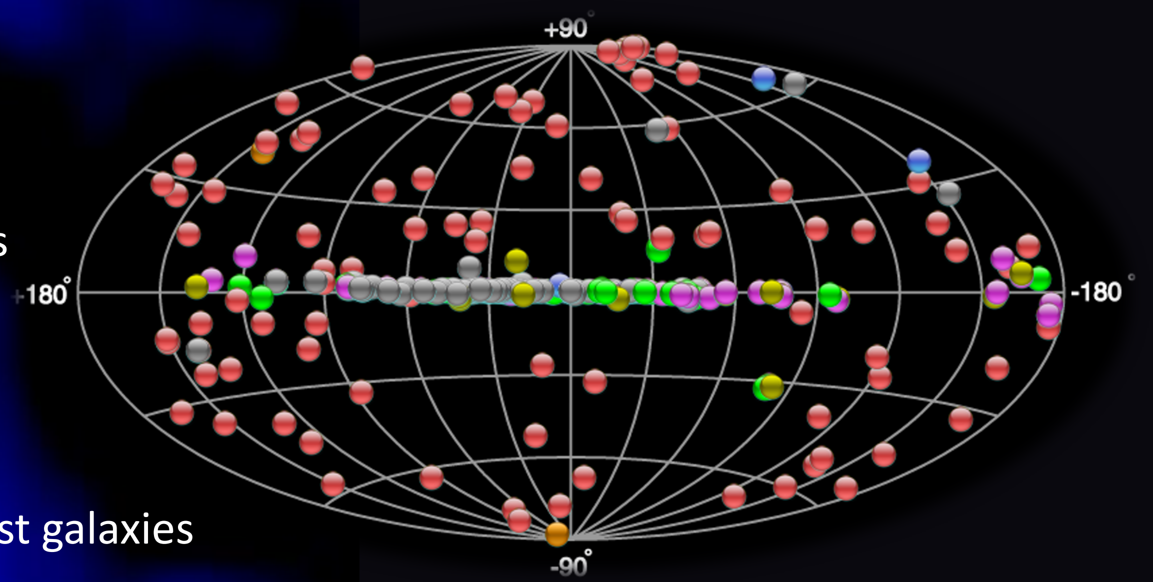






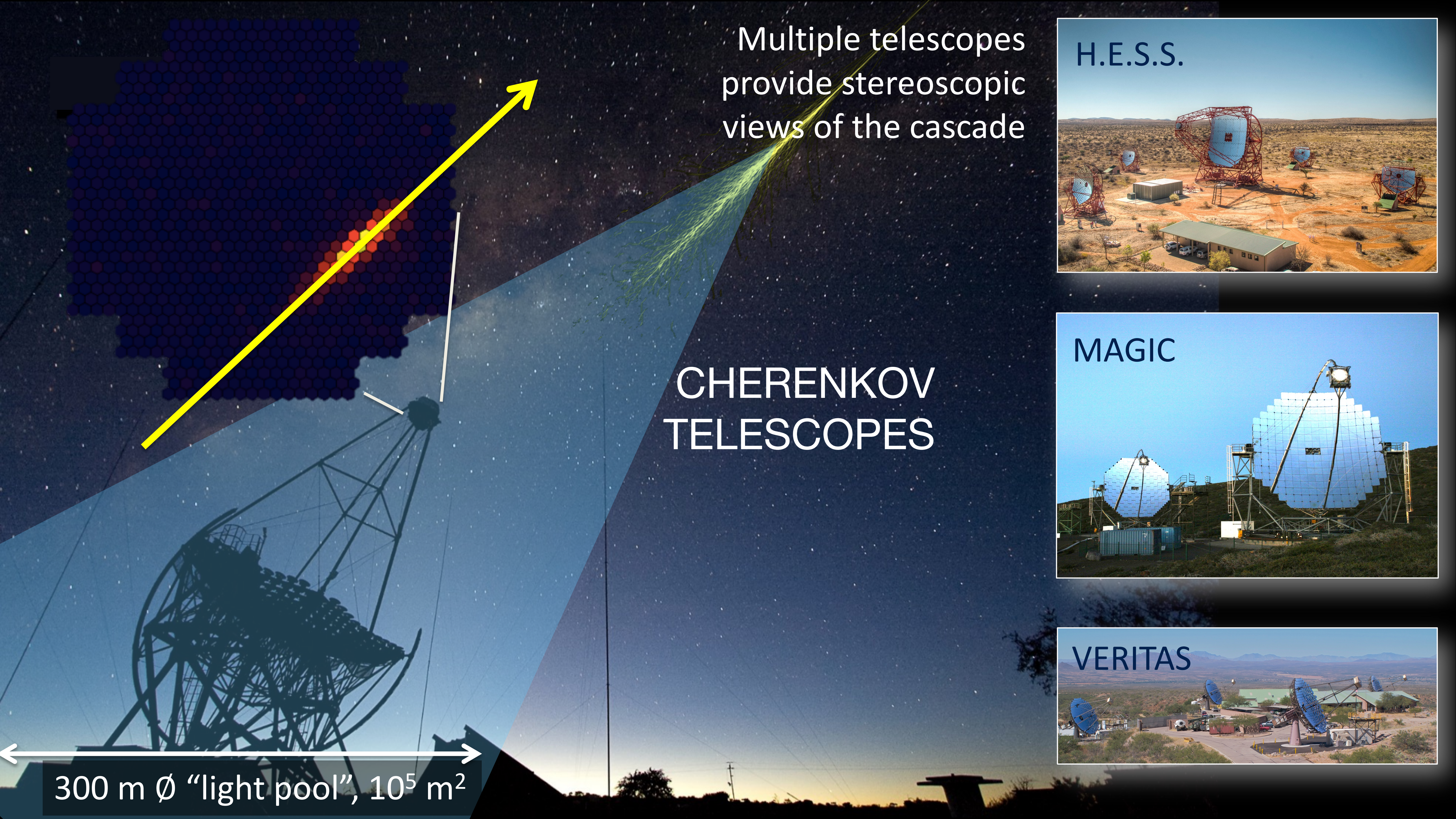
Gamma ray image
of supernova
RX J1713.7-3946

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


Multiple telescopes
provide stereoscopic
views of the cascade
CHERENKOV
TELESCOPES
300 m Ø “light pool”, 10^5 m^2
H.E.S.S.
MAGIC
VERITAS

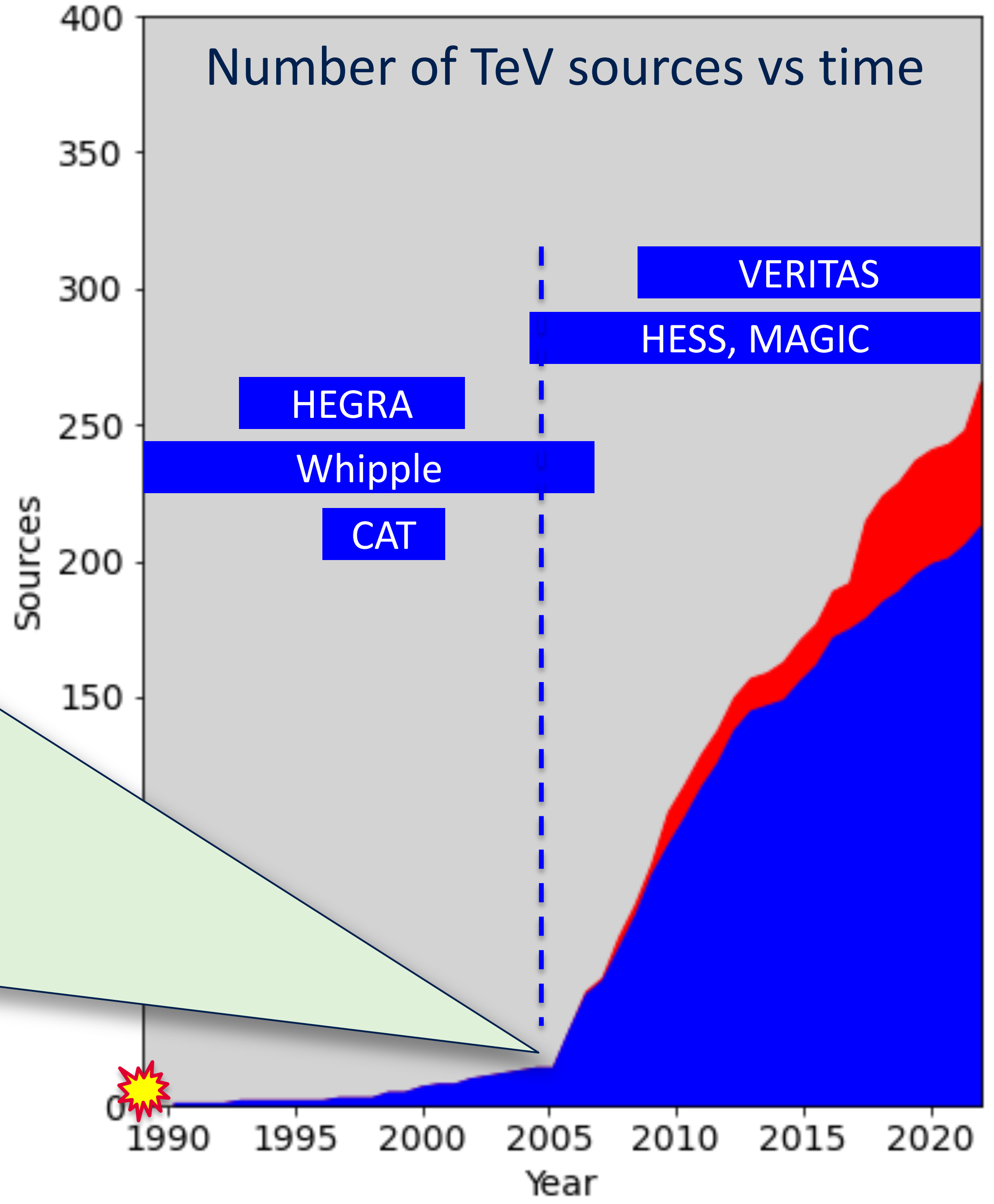
Sweet energy range for Cherenkov telescopes:

TeV domain (~100 GeV to few TeV)

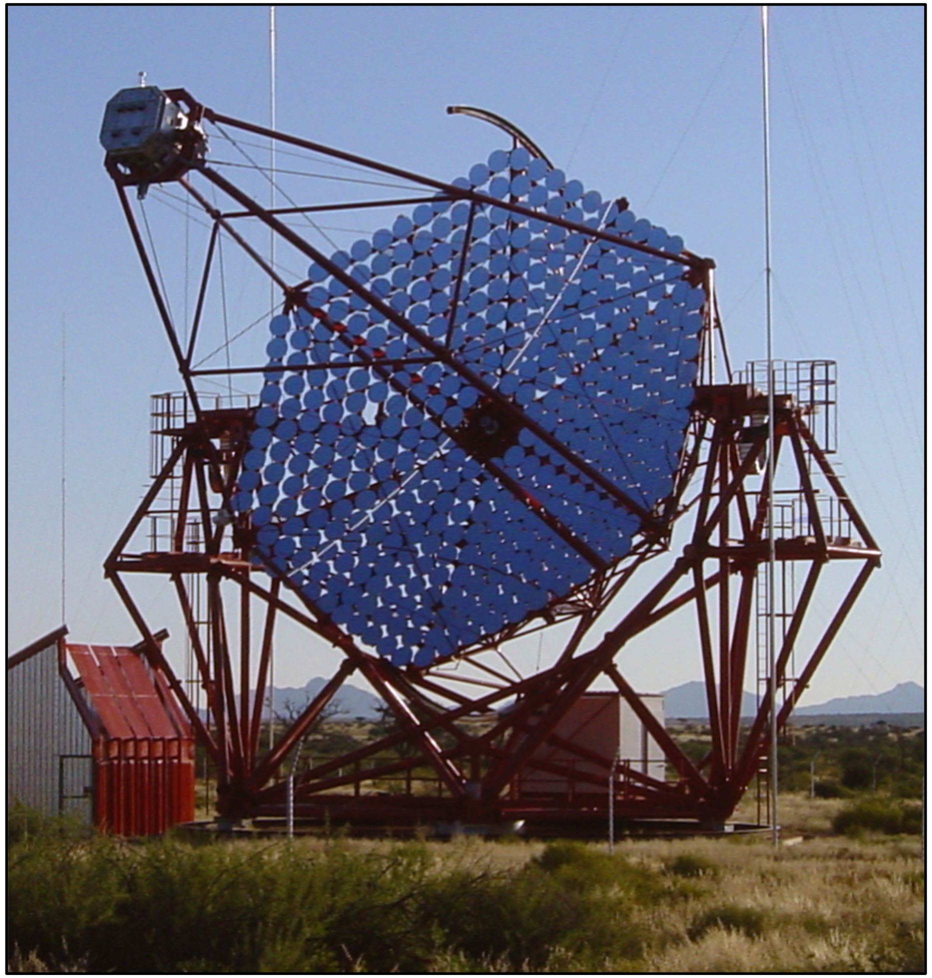
- Well-defined showers allowing efficient gamma-hadron separation
- Decent gamma-ray rates

What came together:

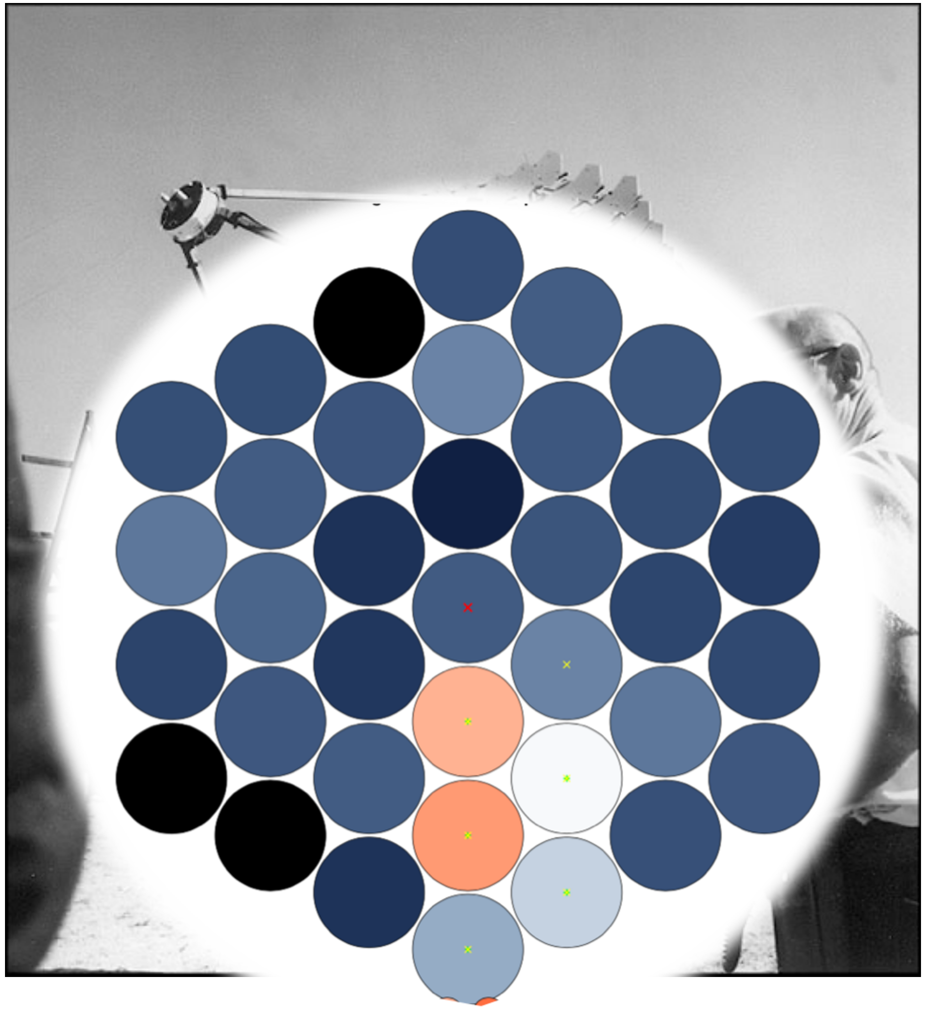
- Right dish size for decent photon statistics of images: 100+ m^2
- Right pixel size to resolve shower features: ~0.2^{o} or less
- Large field of view, to contain images and extended sources
- Multi-telescope stereoscopic imaging
- Advanced analysis algorithms
- Highly detailed simulations to tune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



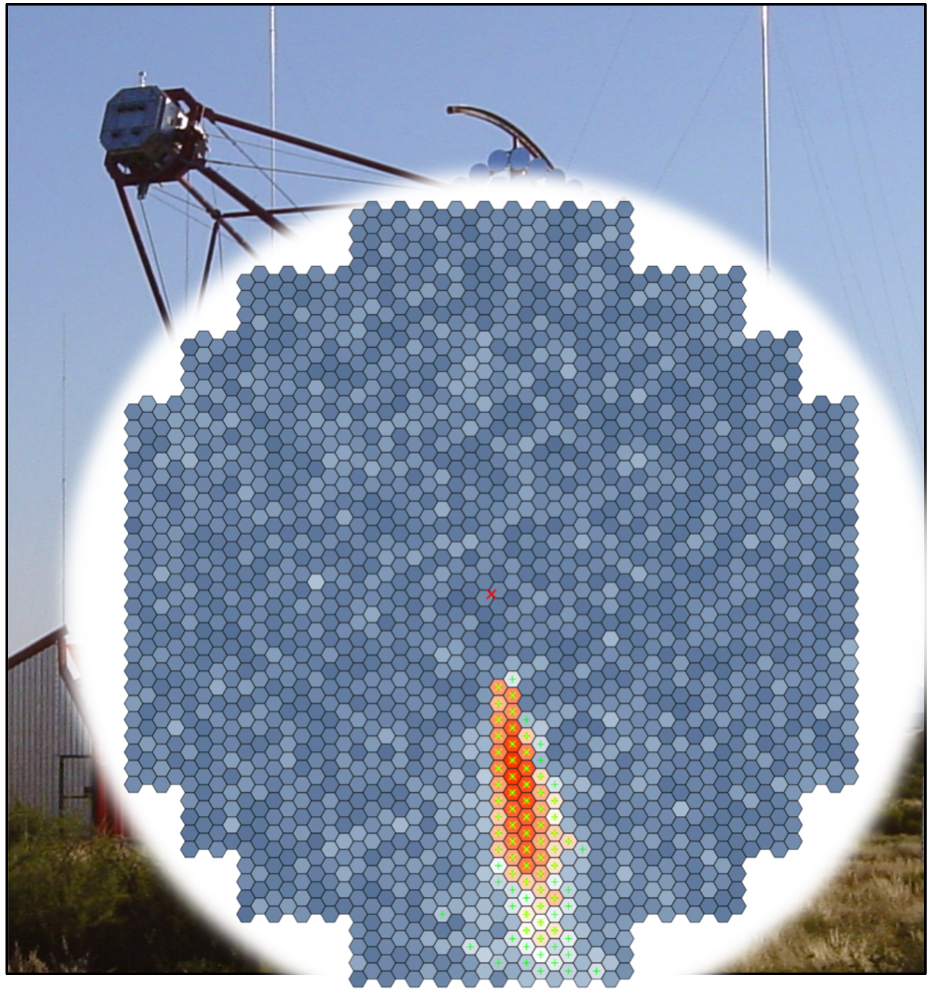
1989 VS TODAY



1989 VS TODAY

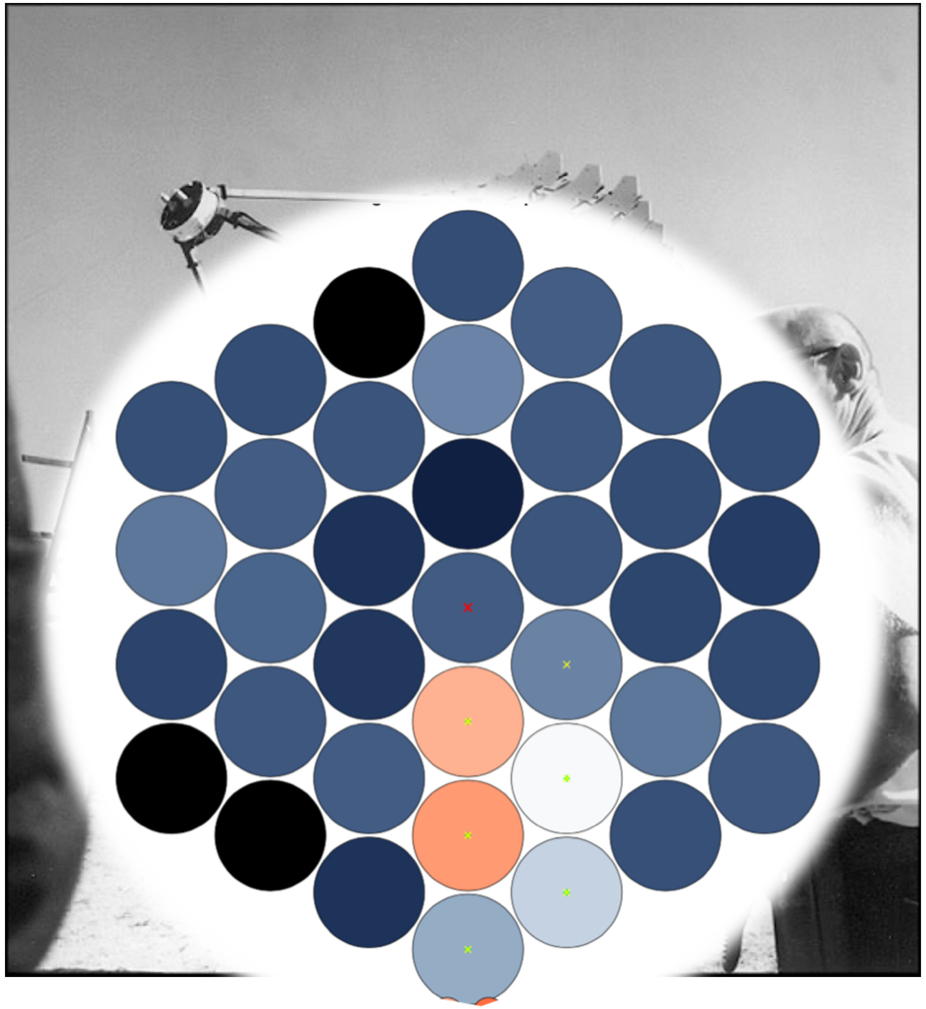


Whipple 1989 shower image



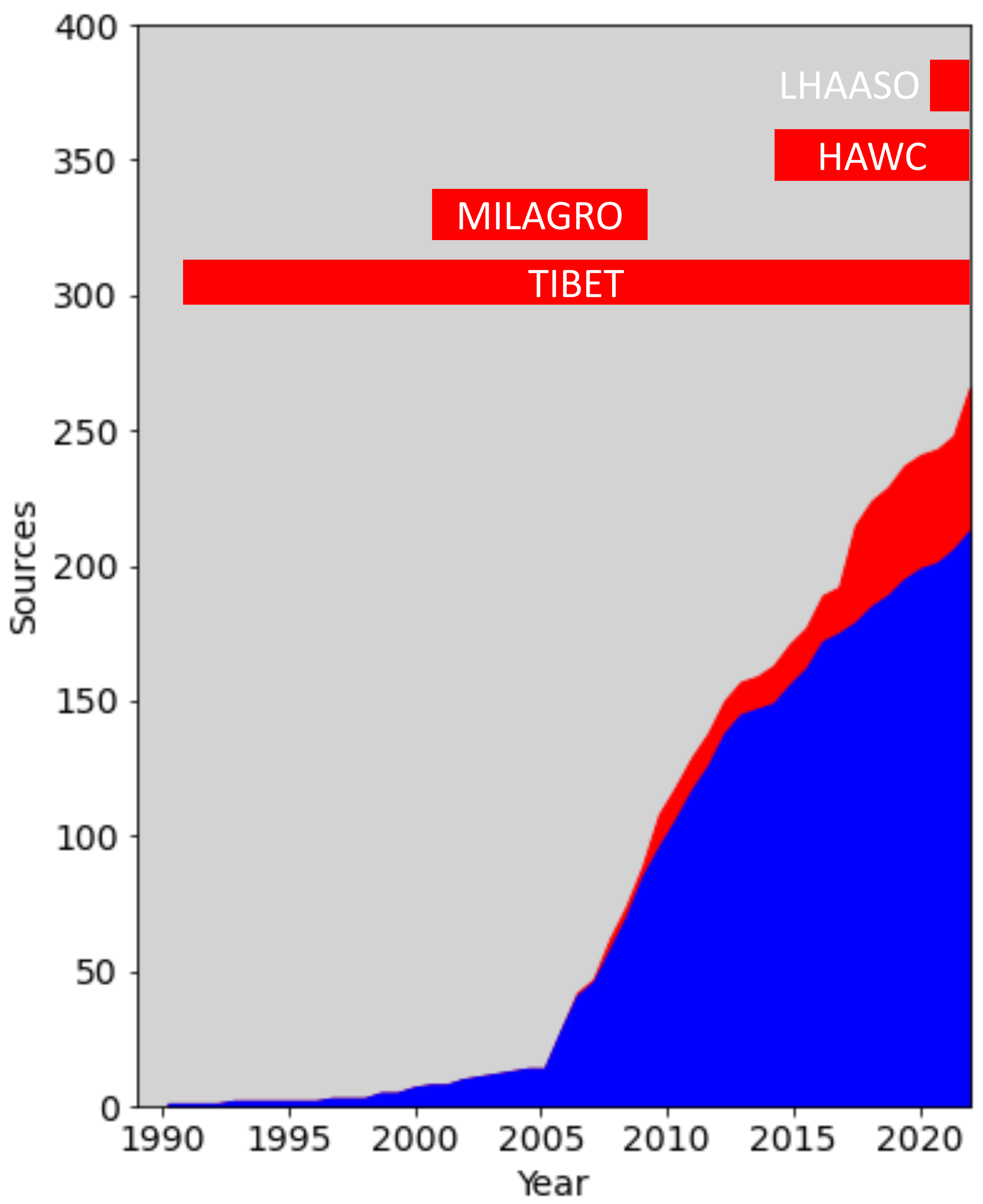
Modern camera

1989 VS TODAY



Whipple 1989 shower image

Modern array



LHAASO
HAWC
MILAGRO
TIBET
Sources
Year
0
50
100
150
200
250
300
350
400
1990
1995
2000
2005
2010
2015
2020

HAWC

Sierra Negra, Mexico
4100 m asl

Area: 22000 m^2, 60% active

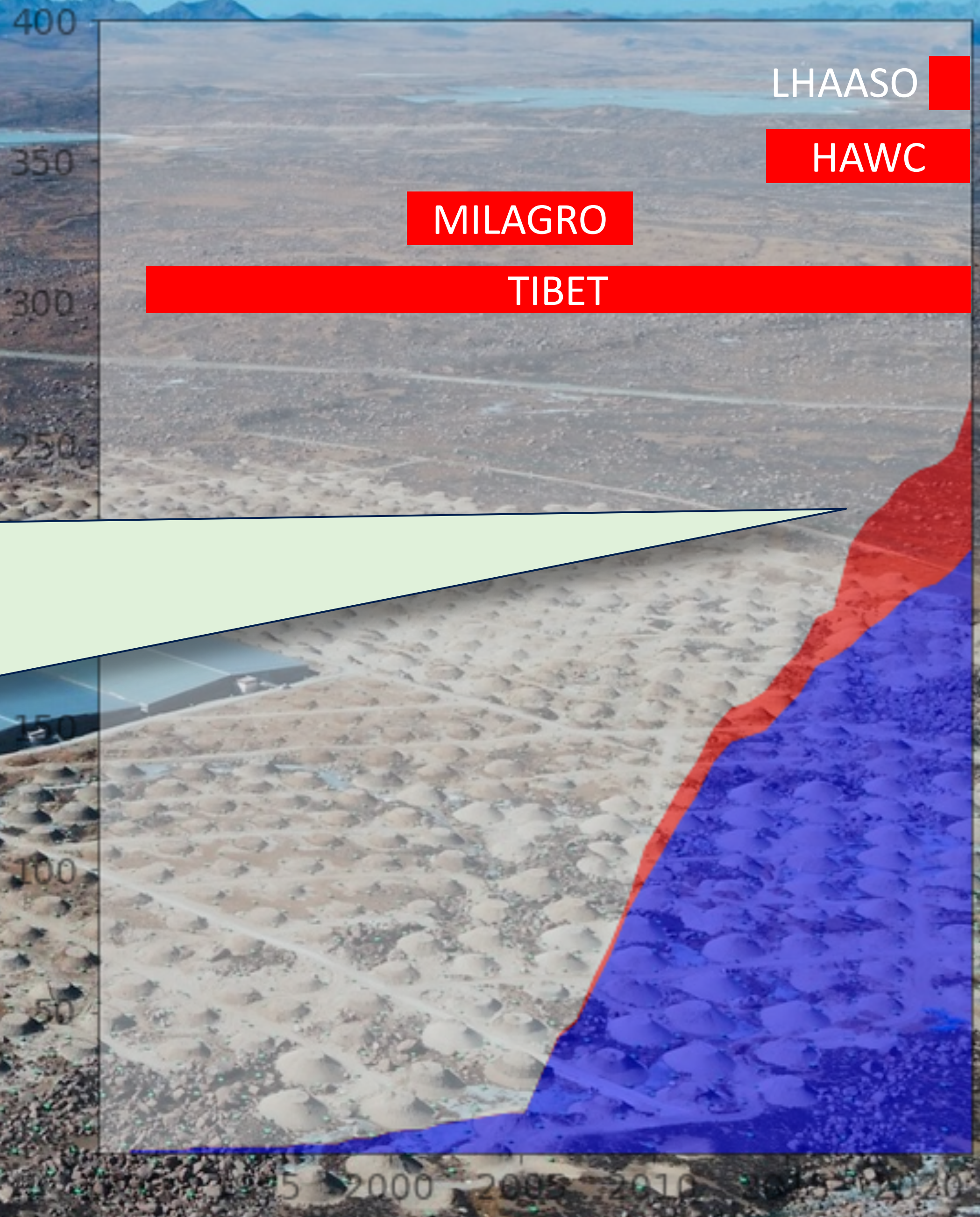

LHAASO
Sichuan, China
4410 m asl
LHAASO
HAWC
MILAGRO
TIBET
400
350
300
250
200
150
100
50
Sources
2000

LHAASO

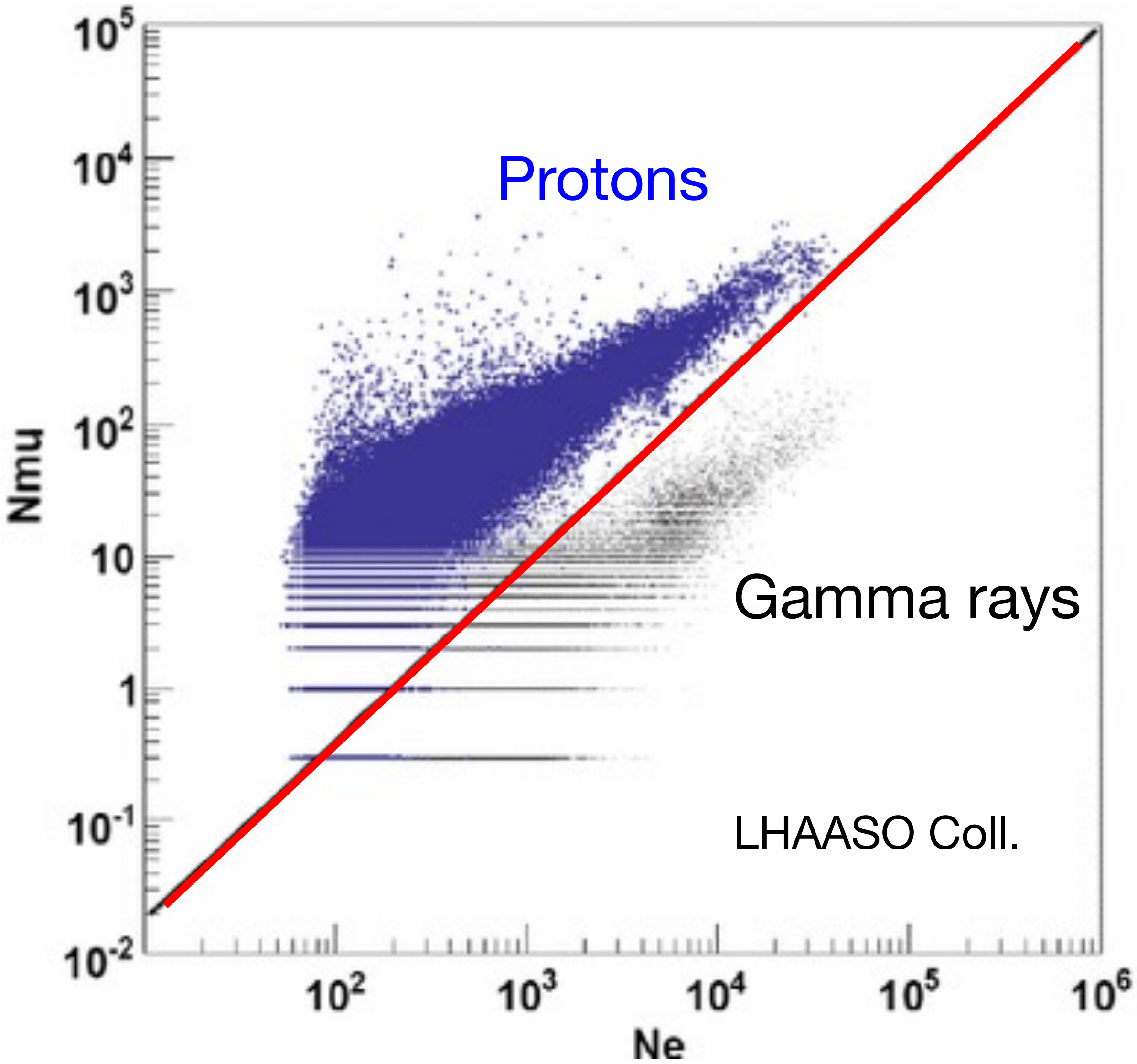
Sichuan, China
4410 m asl

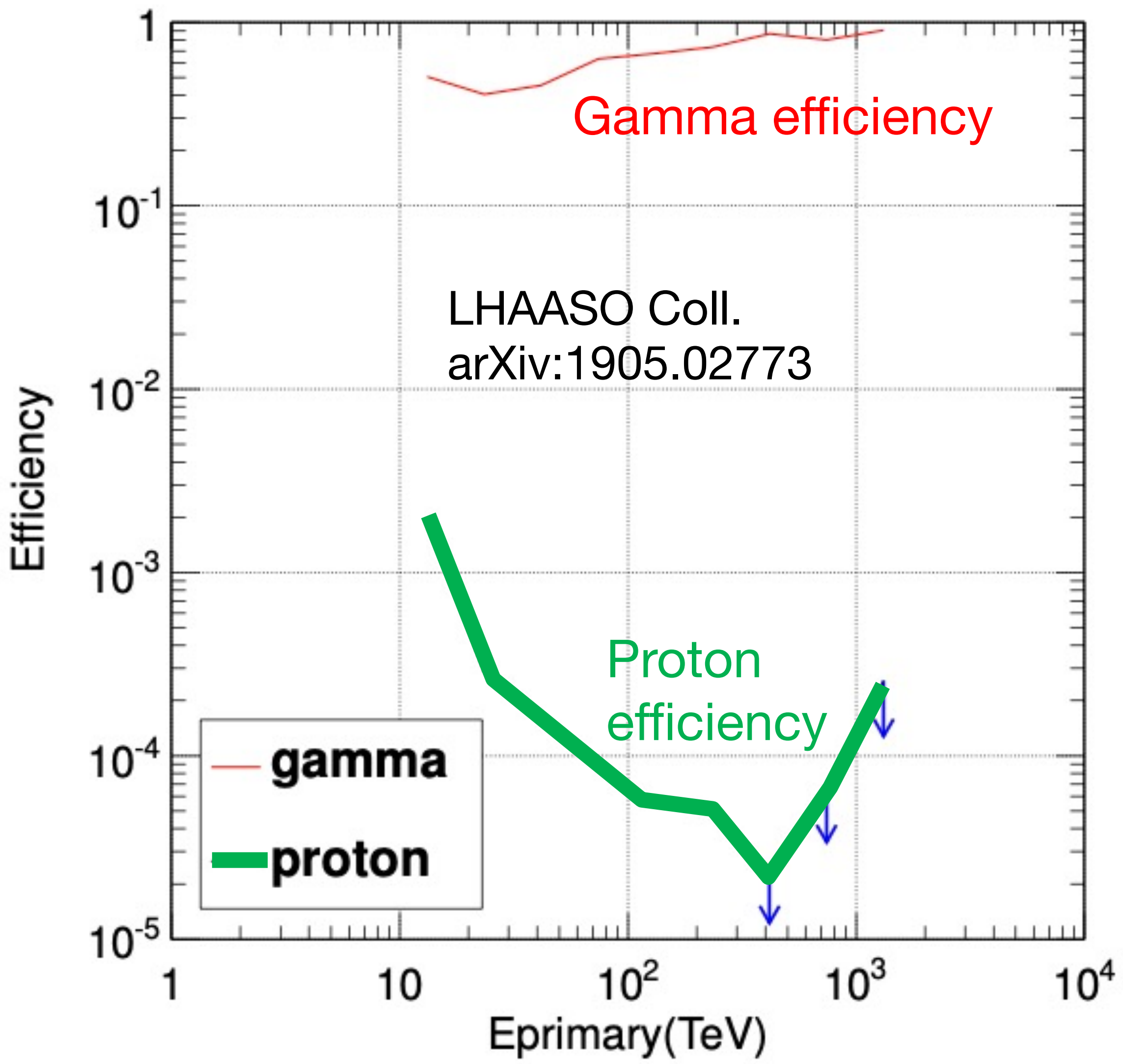
What came together:

- High-altitude arrays at 4000+ m asl
- Dense / calorimetric measurement of shower particles
- Array areas comparable to / larger than shower footprint
- Large-area muon identification



THE POWER OF LARGE-AREA MUON DETECTORS

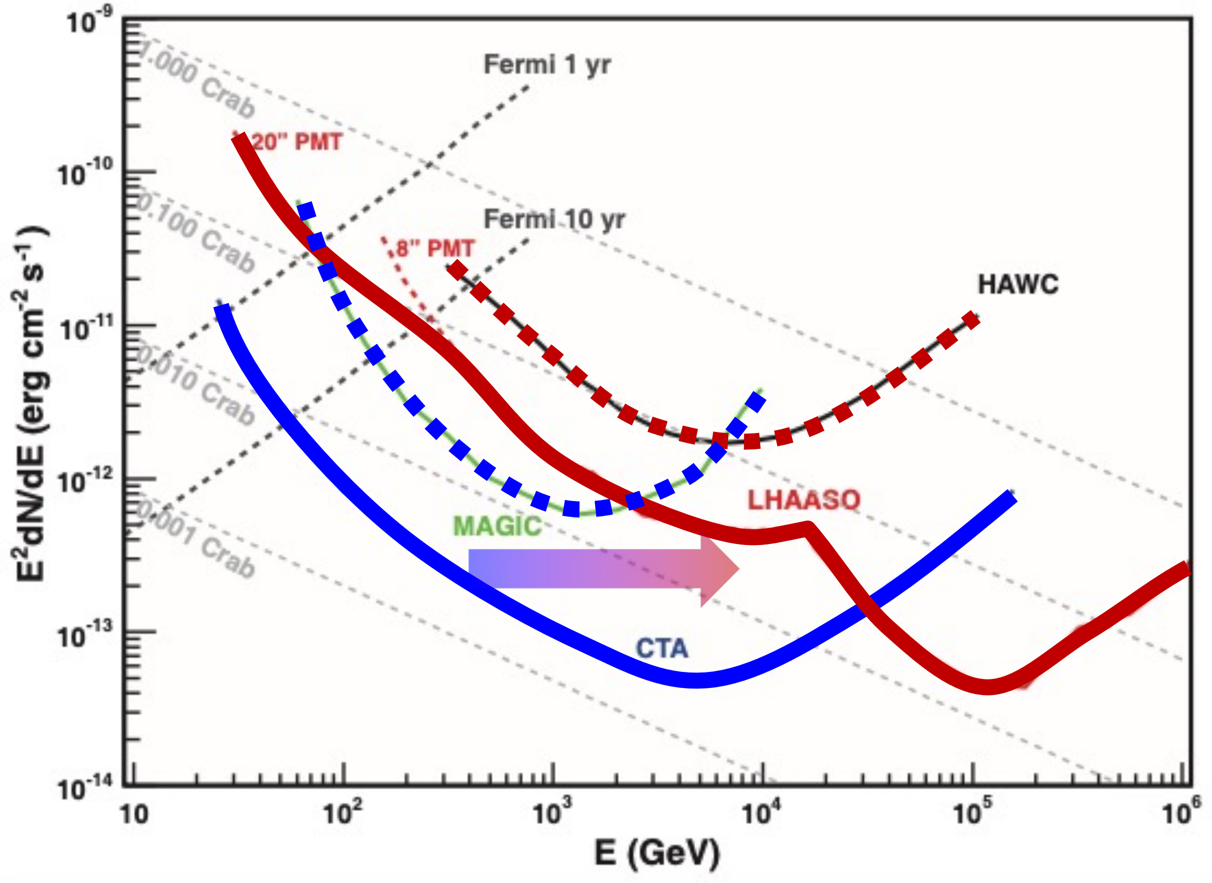




CHERENKOV TELESCOPES & GROUND ARRAYS

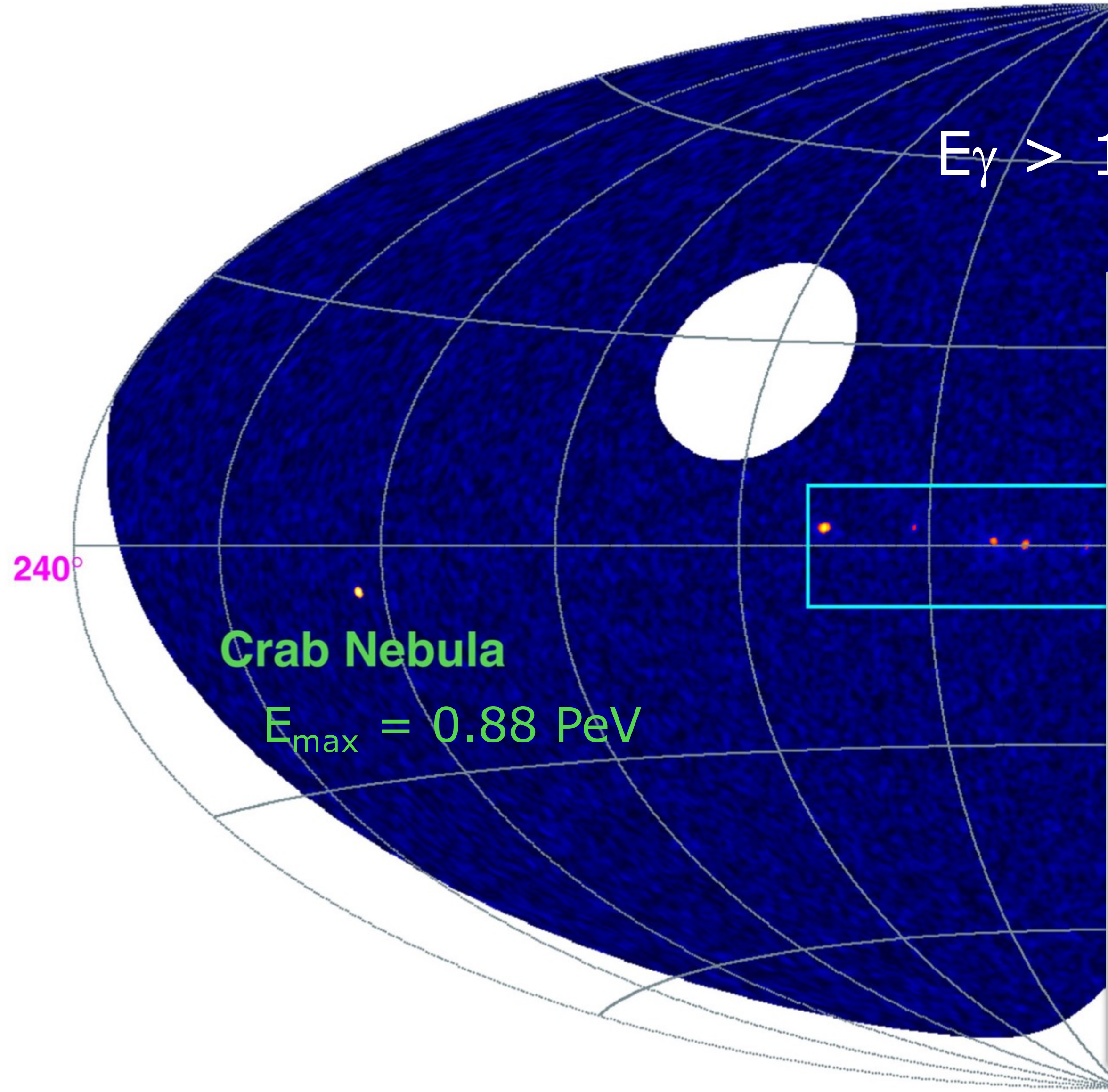
LHAASO White Paper
arXiv:1905.02773

	Cherenkov telescopes	Ground arrays
Exposure per source and year		**Factor O(10-100) advantage**
Field of view		**Factor O(10-100) advantage**
Duty cycle		**Factor O(10) advantage**
Energy threshold	**Factor O(10) advantage**	
Angular resolution	**Factor O(10) advantage**	
ToO response	some 10 s, upon alert	**Instantaneous**

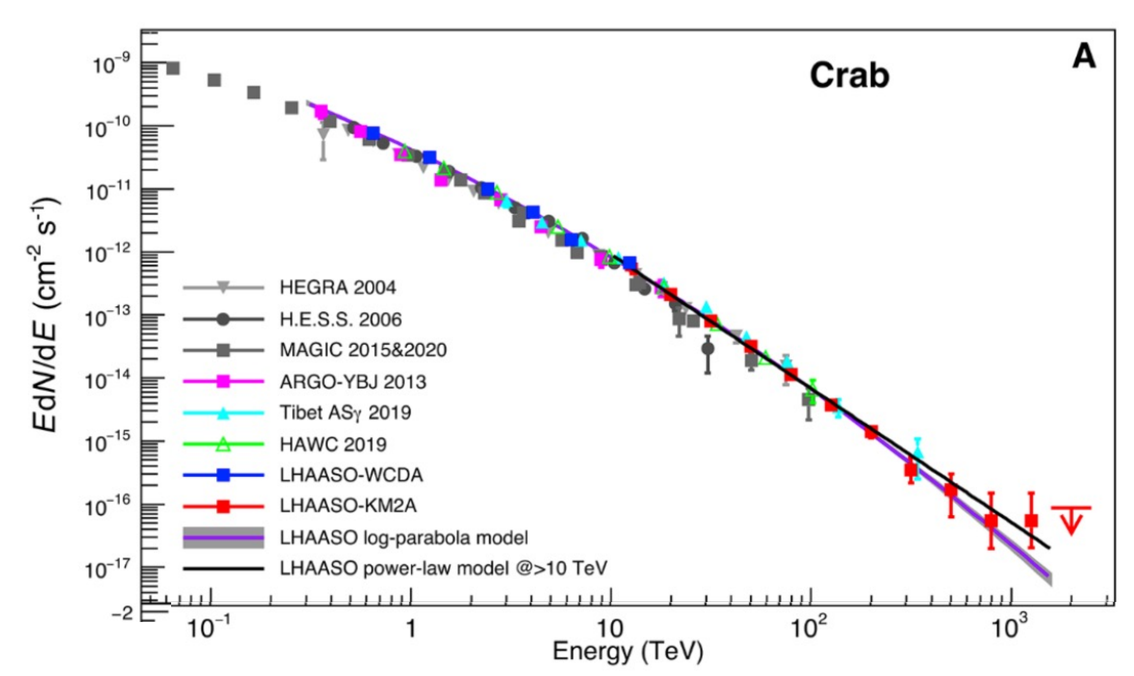


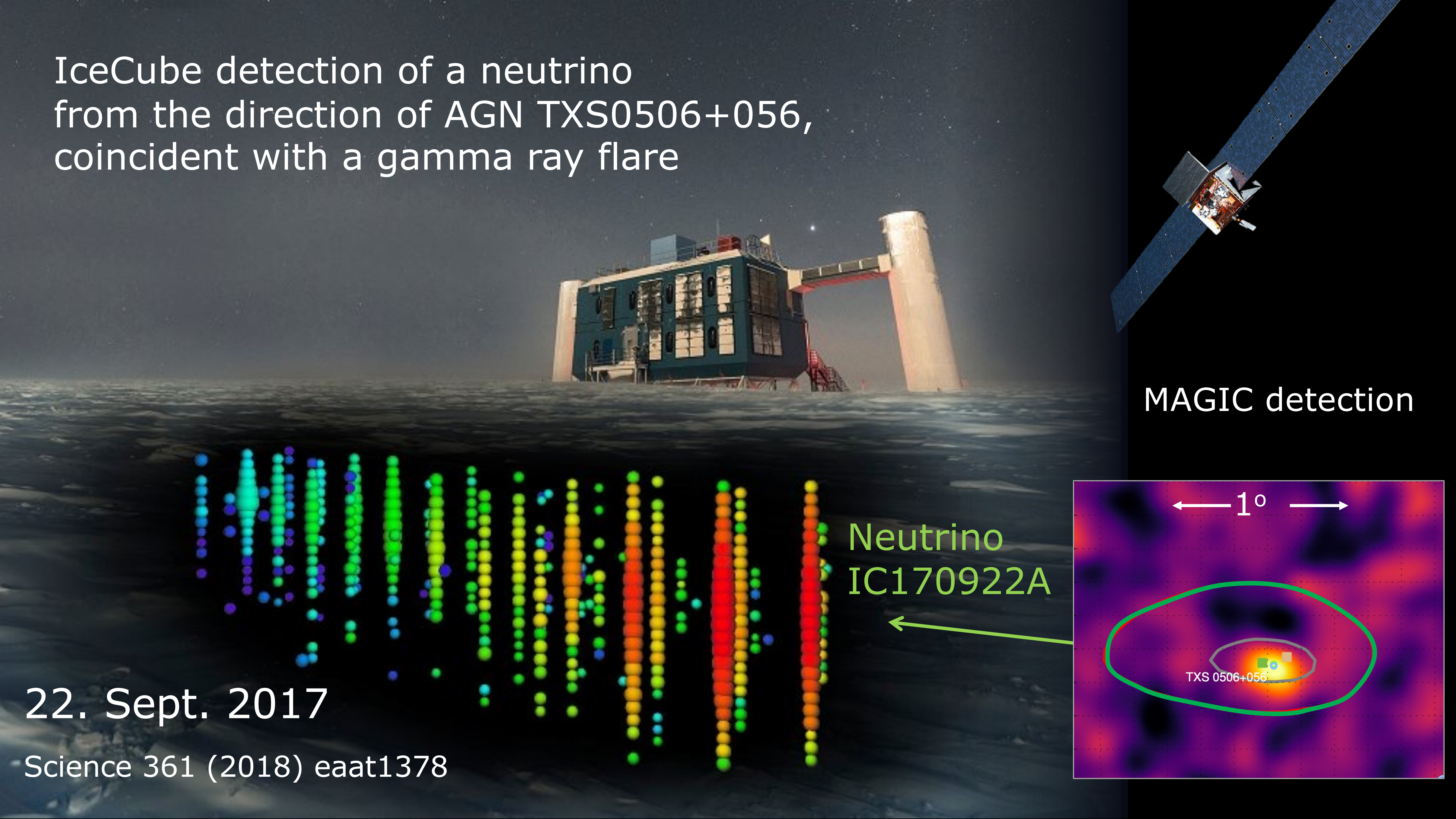
THE PeV (10^{15} eV) SKY

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

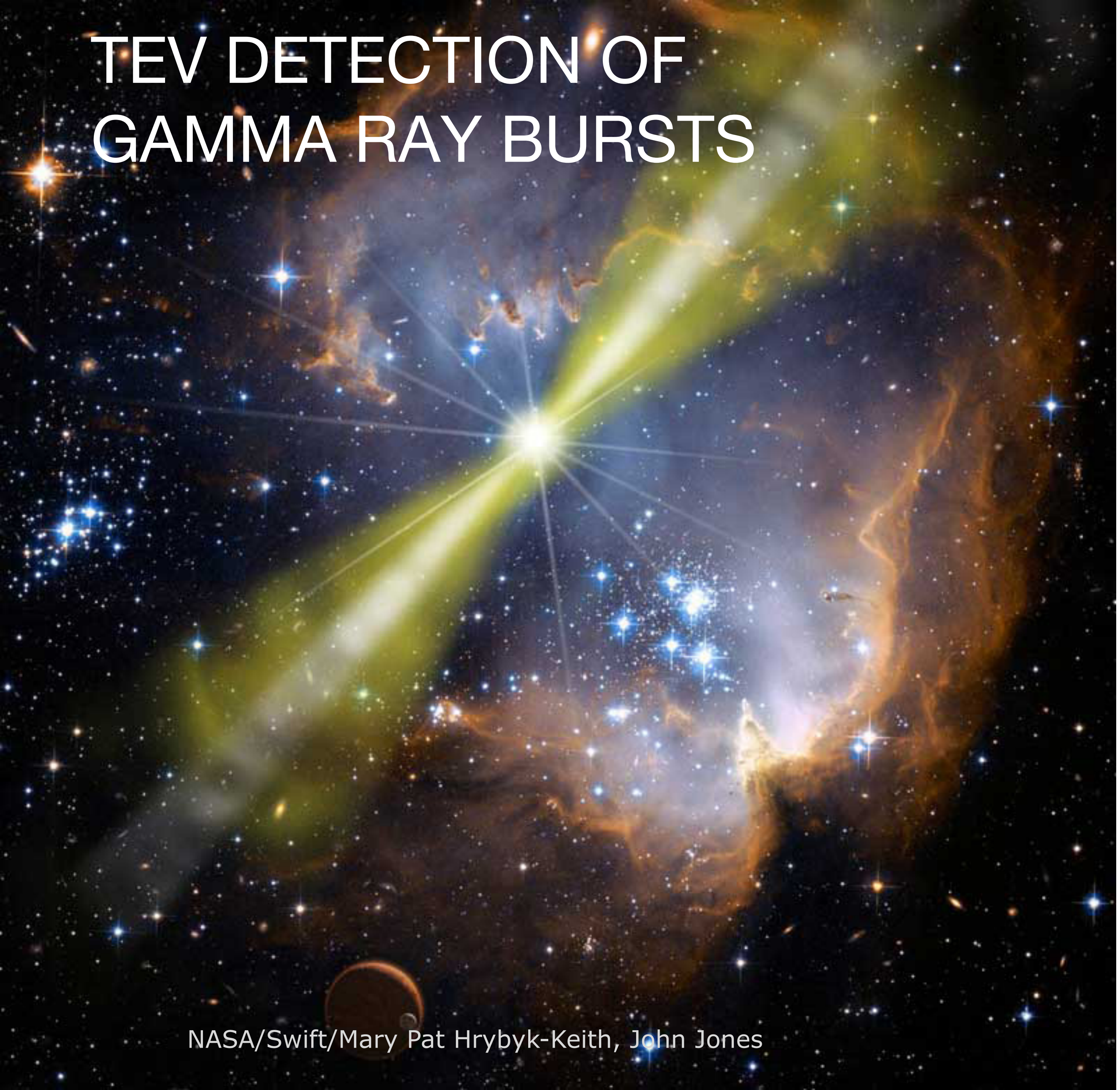


Z. Cao et al., Science 8 Jul 2021




IceCube detection of a neutrino
from the direction of AGN TXS0506+056,
coincident with a gamma ray flare
MAGIC detection
Neutrino
IC170922A
1°
TXS 0506+056
22. Sept. 2017
Science 361 (2018) eaat1378

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

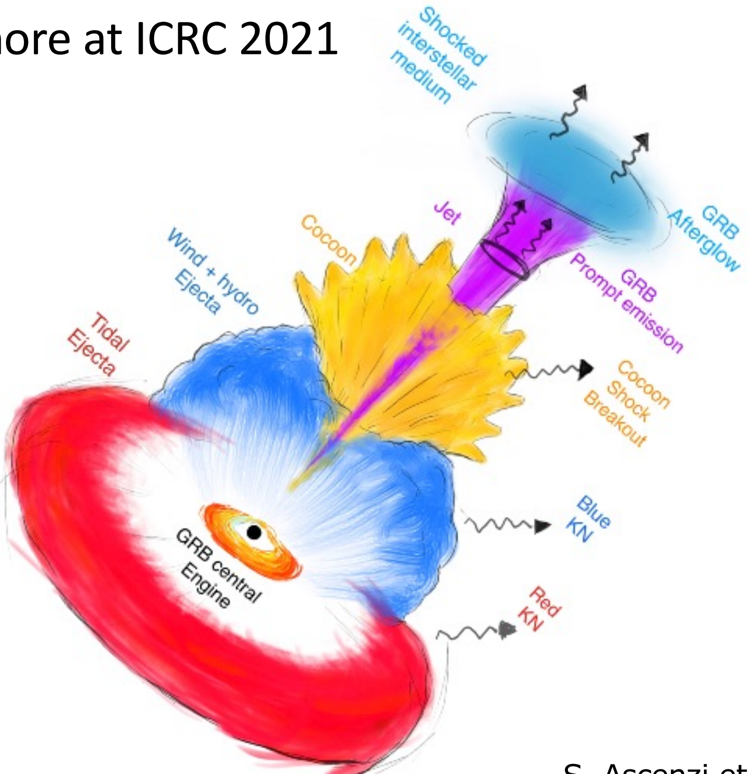
GRB 180720B

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

GRB 190829A

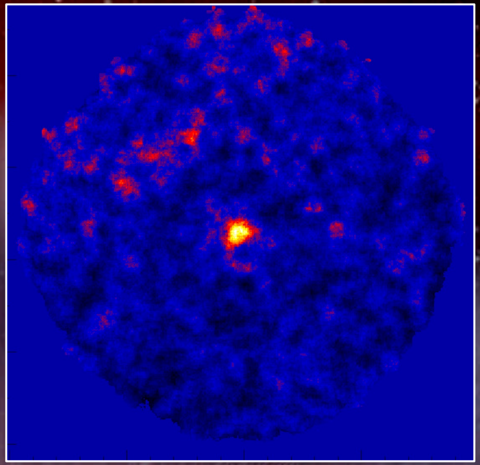
H.E.S.S. Coll., Science 372 (2021) 1081

+ 2 more at ICRC 2021



S. Ascenzi et al.
arXiv:2011.04001

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



WHAT DRIVES HIGH IMPACT RESULTS?

Number of H.E.S.S. Nature & Science papers

Year →

2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
	1	2	3			2						1	1		1	2	1	1

CT1-4 operational

New instrument

28 m telescope CT5 added

CT1-4 camera upgrade

CT5 camera upgrade

MWL/MM:

- Multimessenger observations of a flaring blazar coincident with high-energy neutrino
- A very-high-energy component deep in the gamma-ray burst afterglow
- Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow

Deep observations:

- The exceptionally powerful TeV gamma-ray emitters in the Large Magellanic Cloud
- Acceleration of petaelectronvolt protons in the Galactic Centre

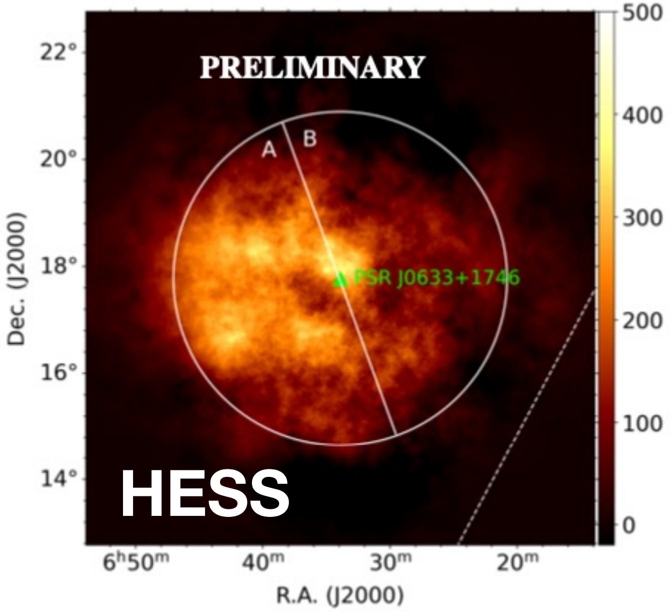
New analysis techniques

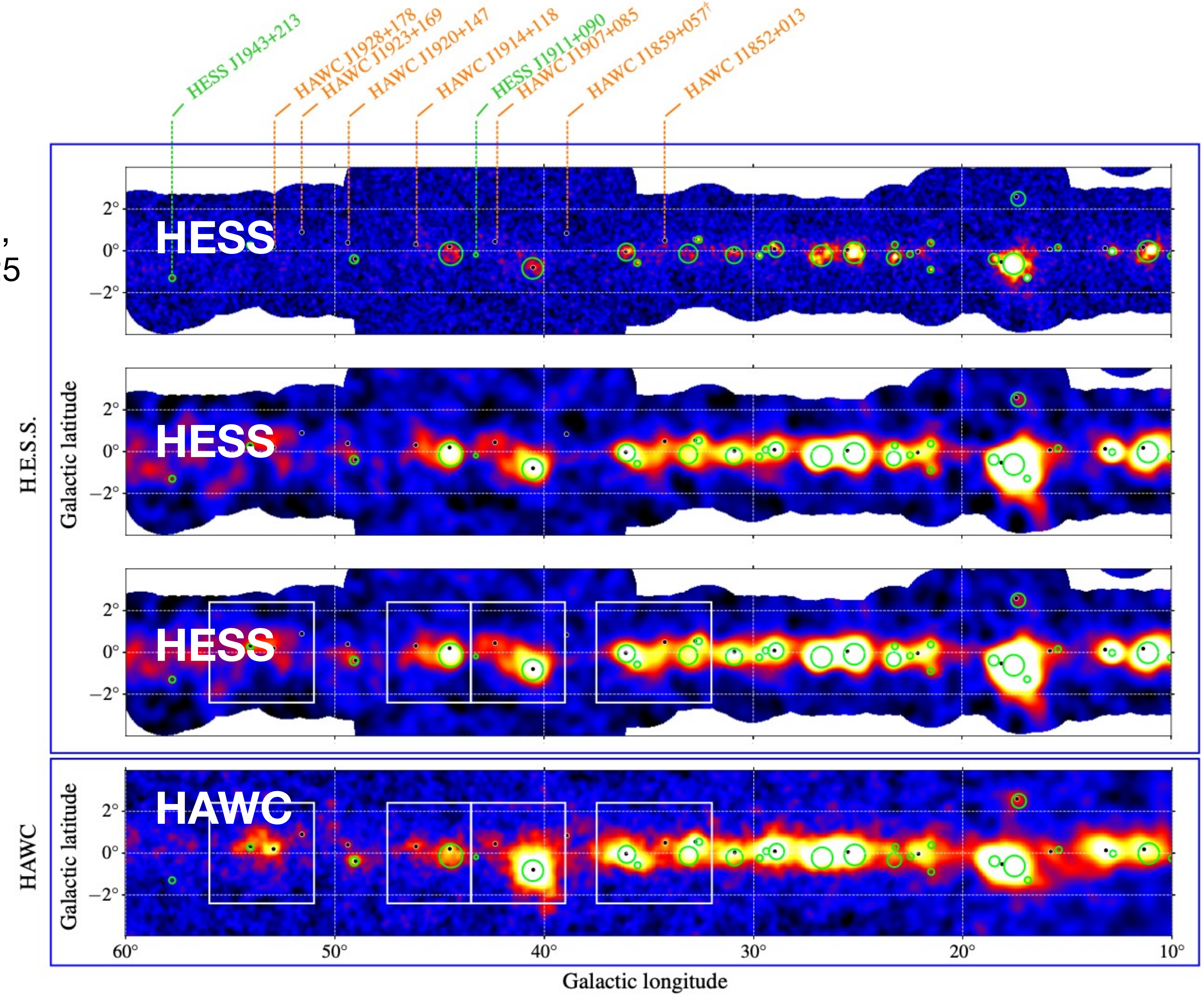
- Resolving the Crab pulsar wind nebula at teraelectronvolt energies
- Resolving acceleration to very high energies along the jet of Centaurus A

ANALYSIS

H.E.S.S. Collab.,
arXiv:2107.01425

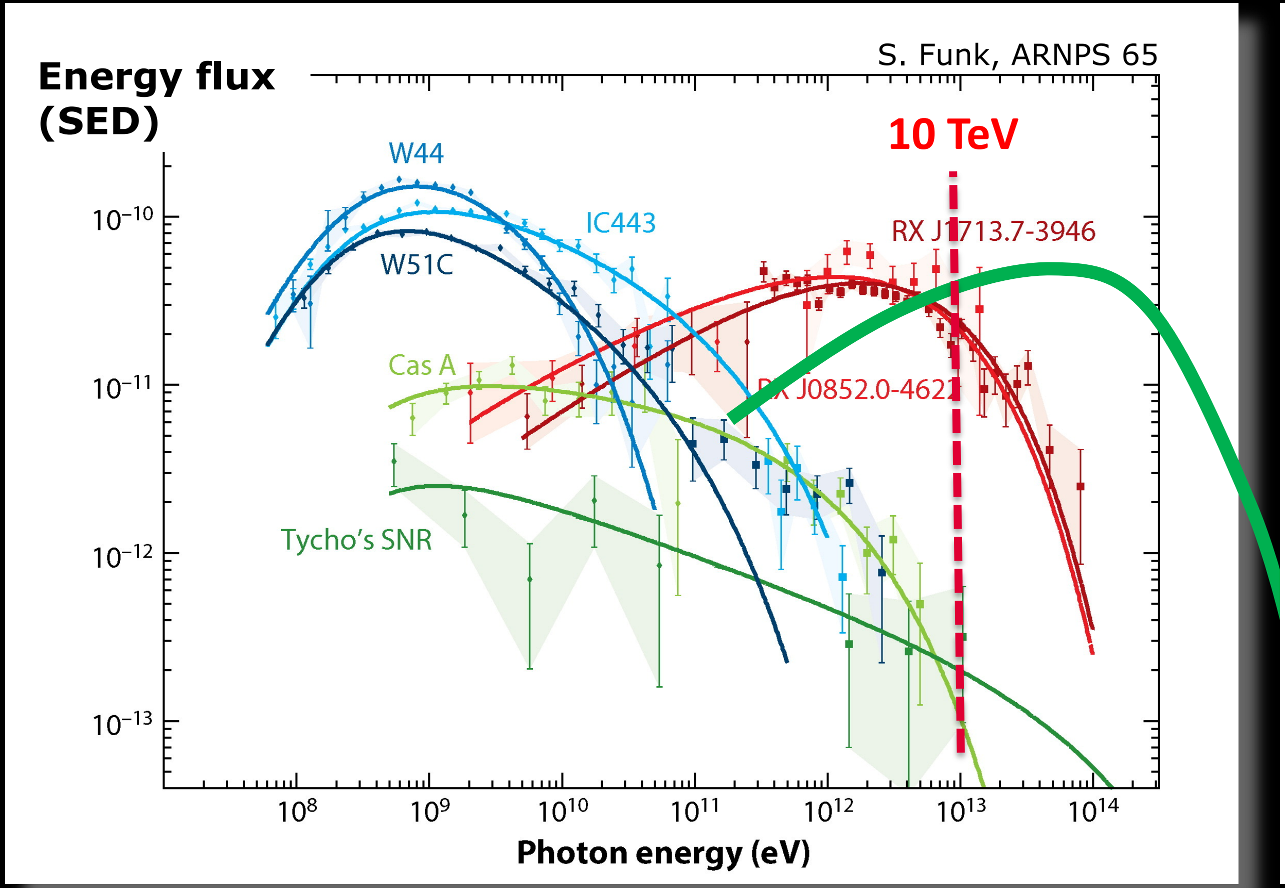
Geminga
A. Mitchell et al.,
H.E.S.S. Collab.
PoS(ICRC2021)780

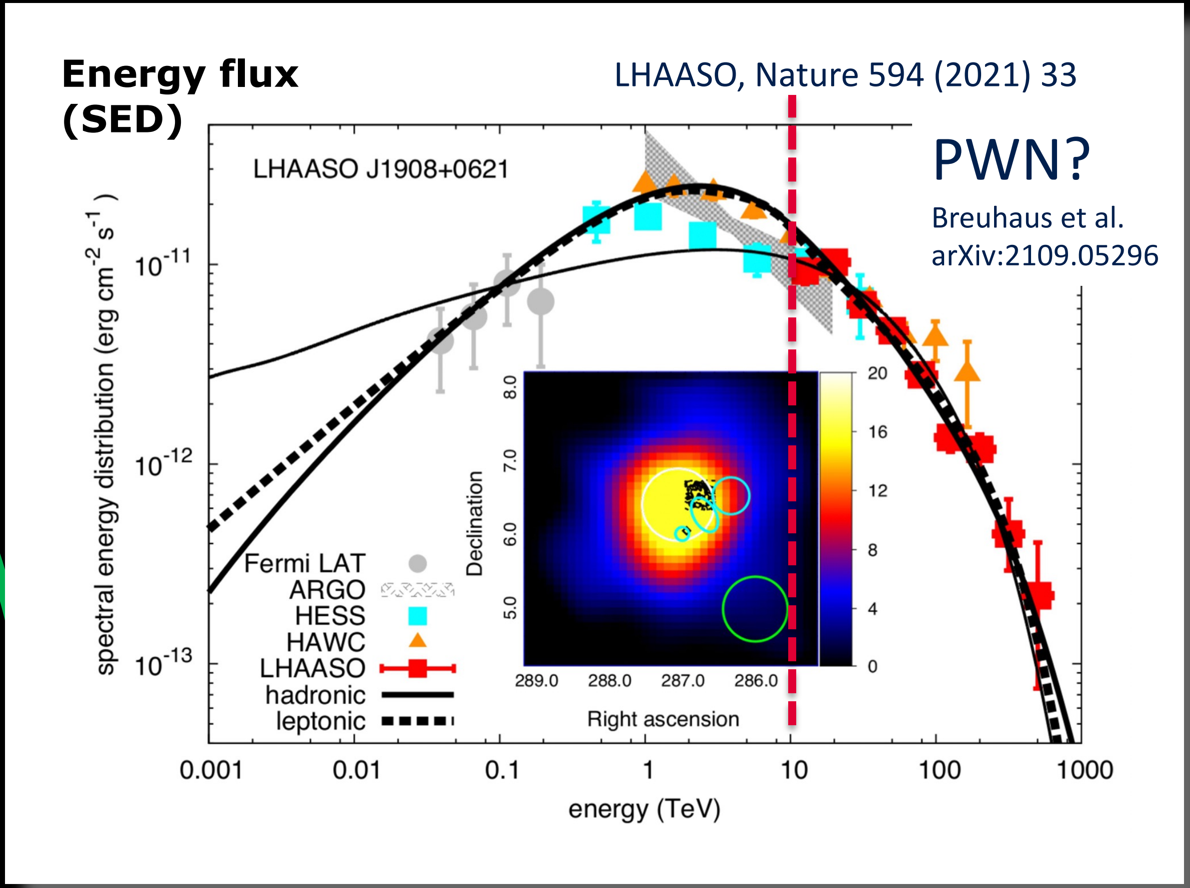




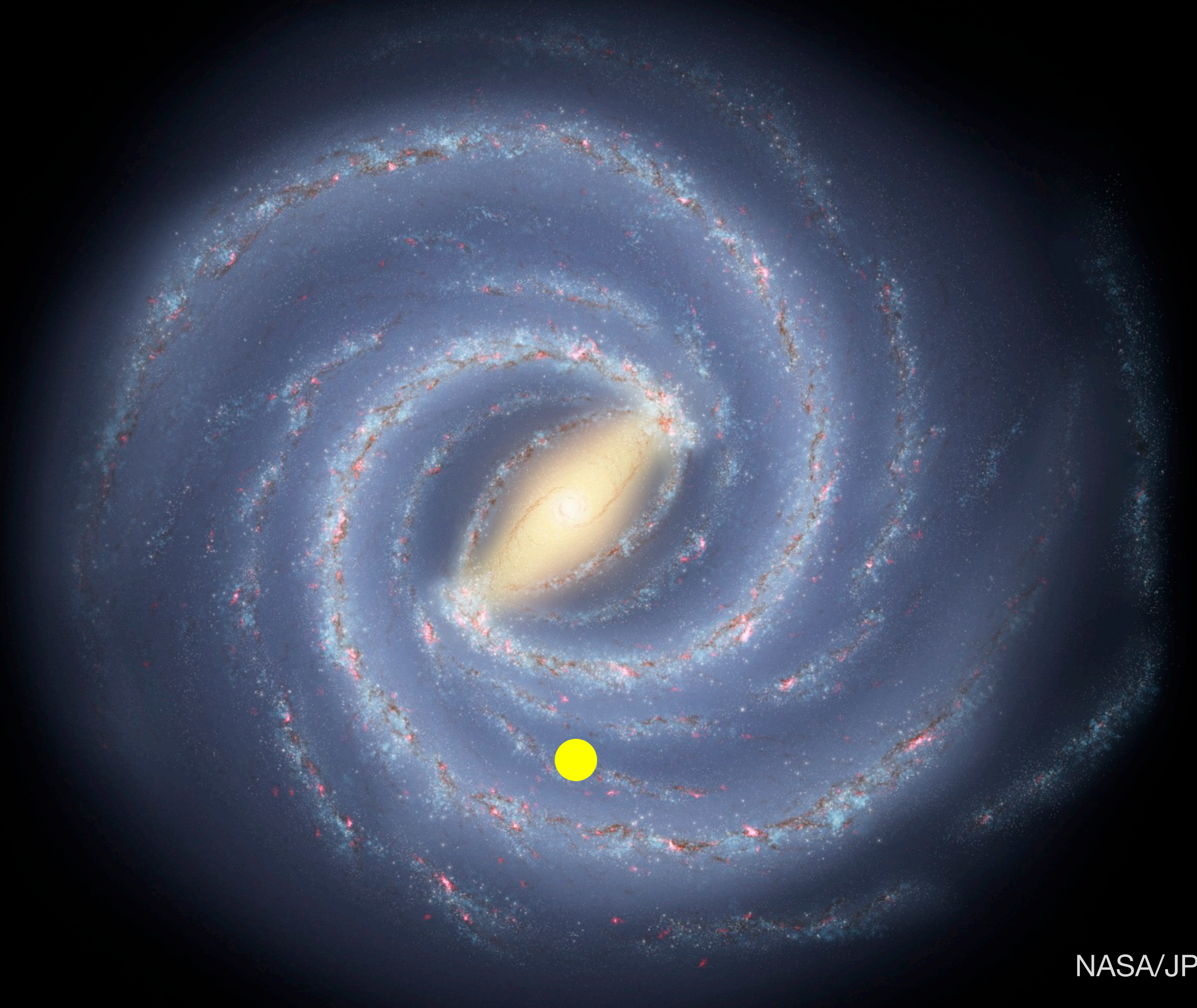
CHALLENGE: ORIGIN AND PROPAGATION OF CR

Gamma ray spectra of SNR

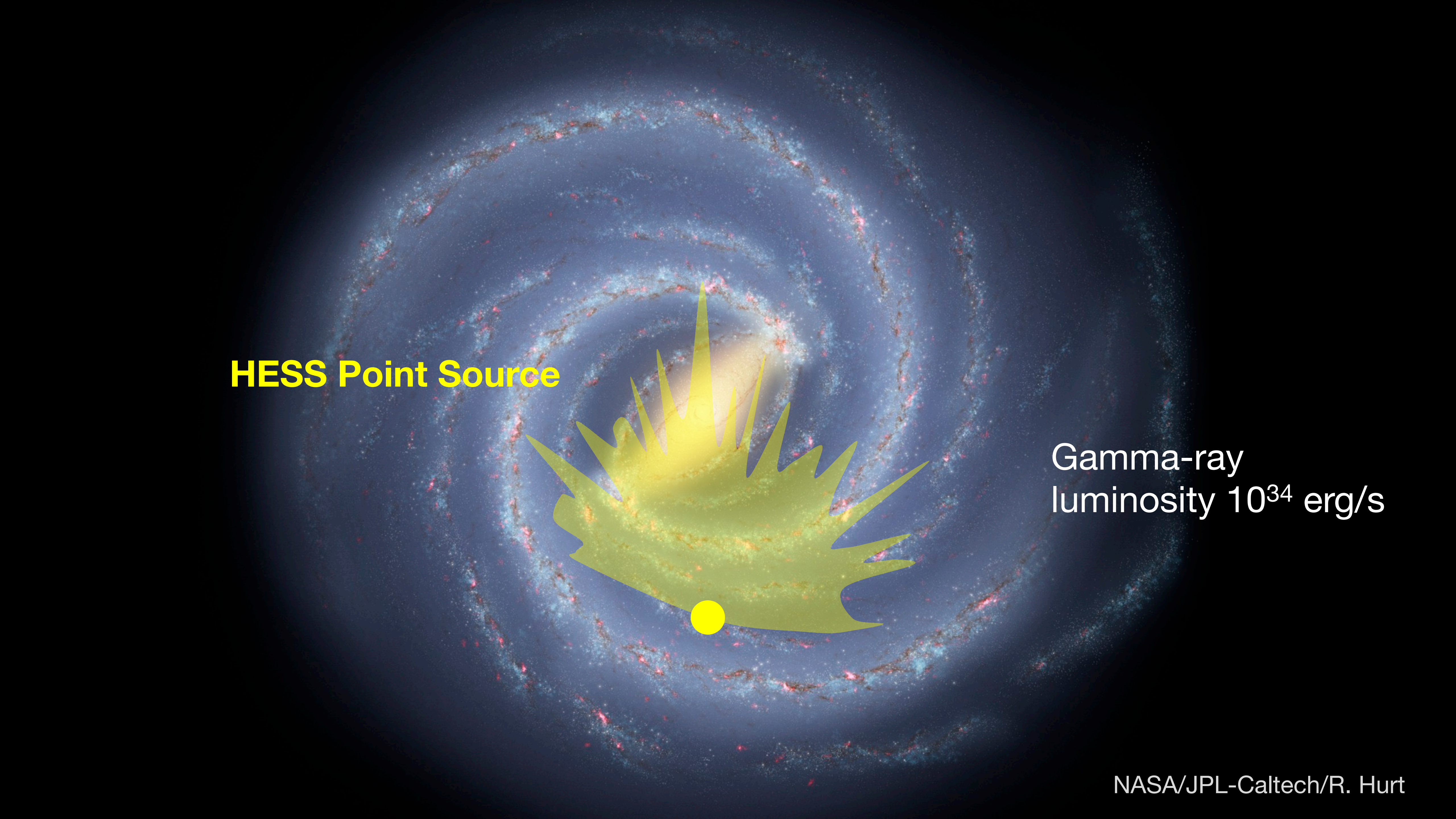


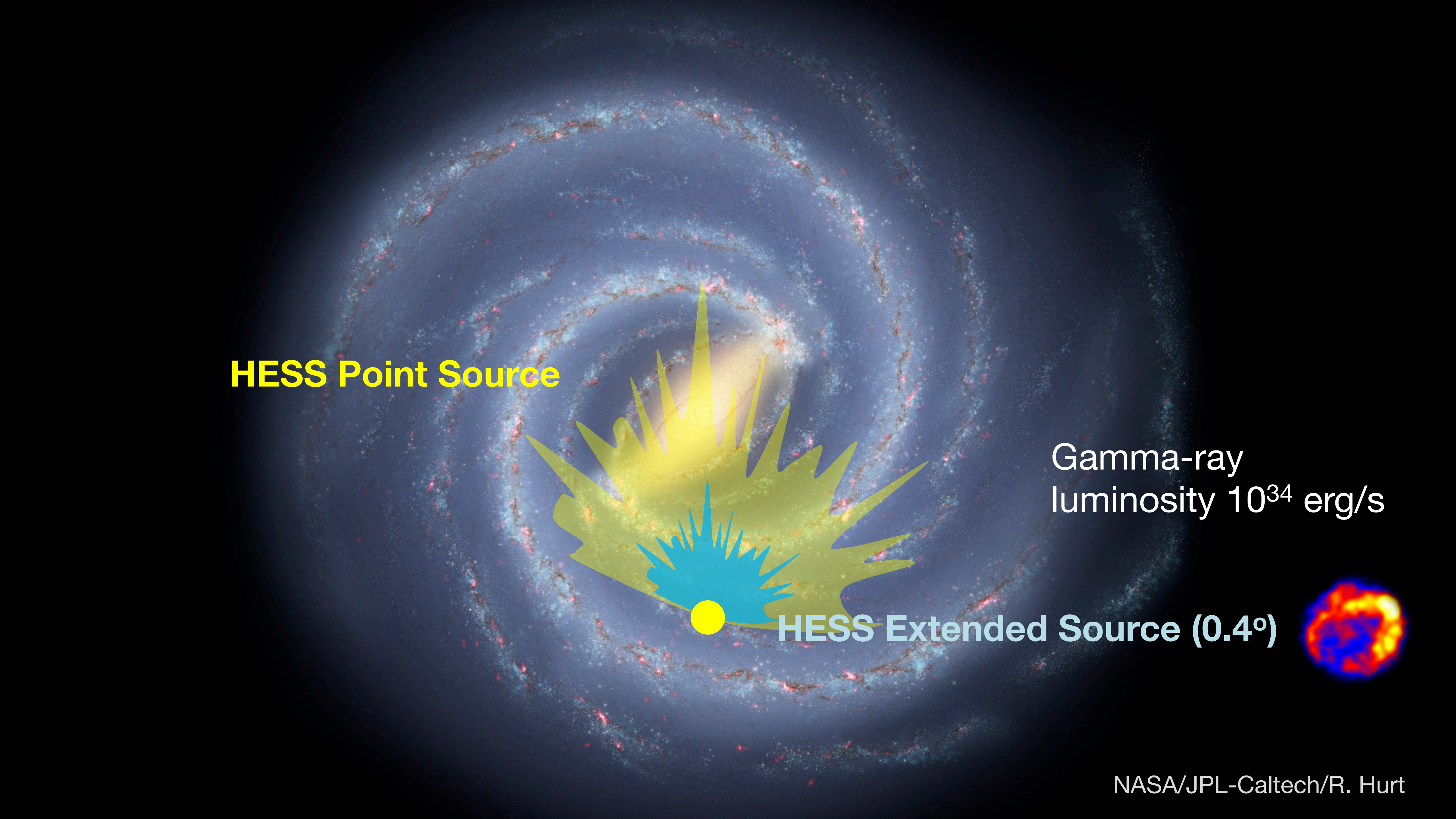


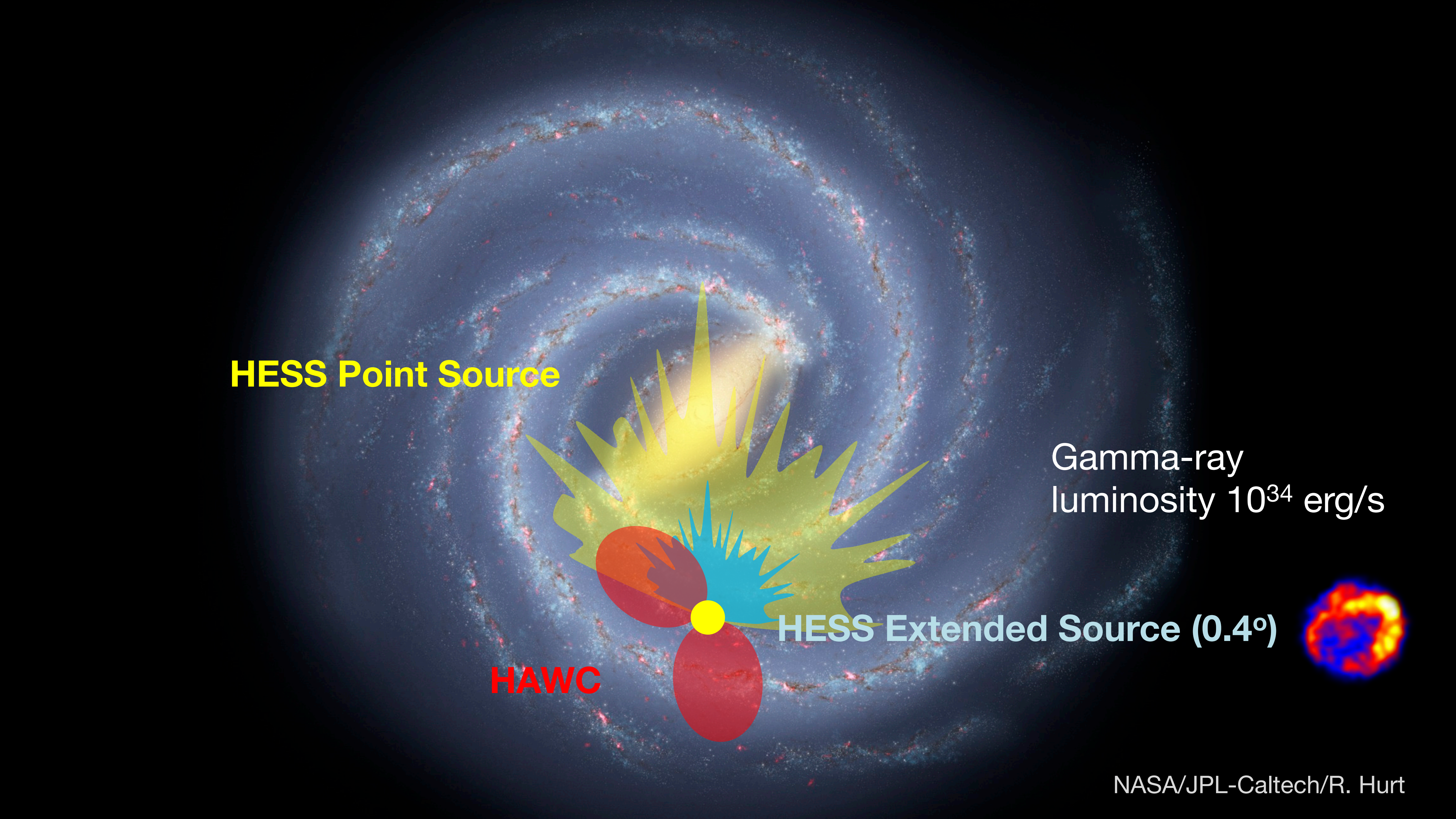
See also Tibet ASγ on SNR G106.3+2.7, arXiv:2109.0289



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 (0.4°)
NASA/JPL-Caltech/R. Hurt


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

CHALLENGE: COMPACT OBJECTS AS ACCELERATORS

AGN:

What is the jet made of?

How is it launched?

How are particles accelerated?

What causes the variability?

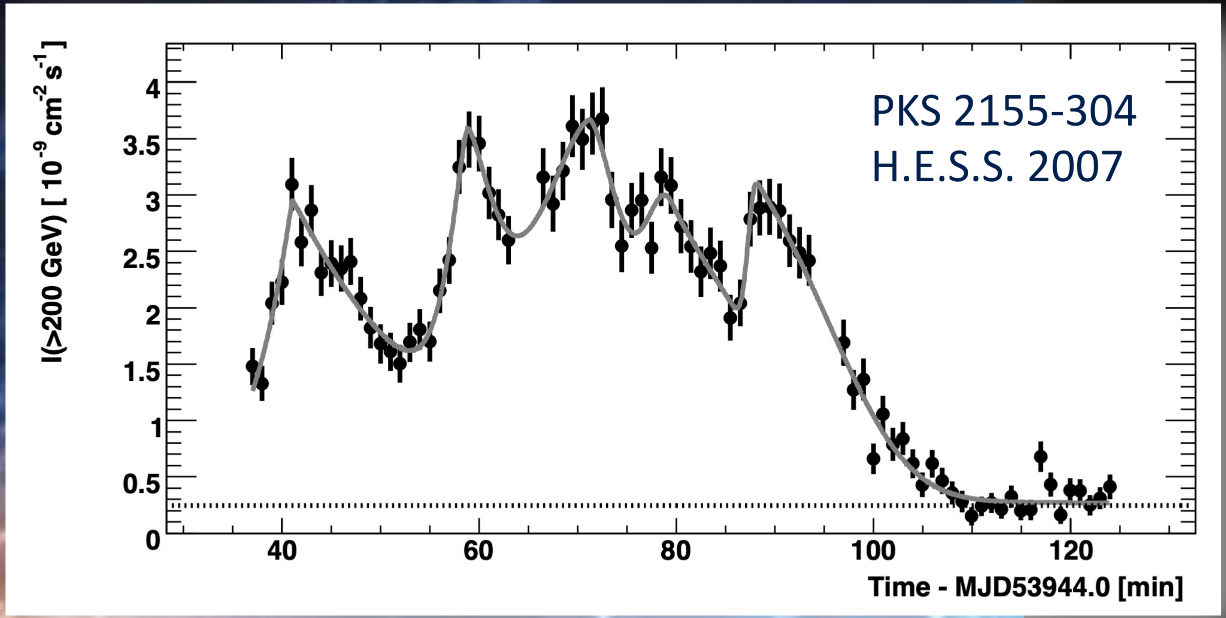
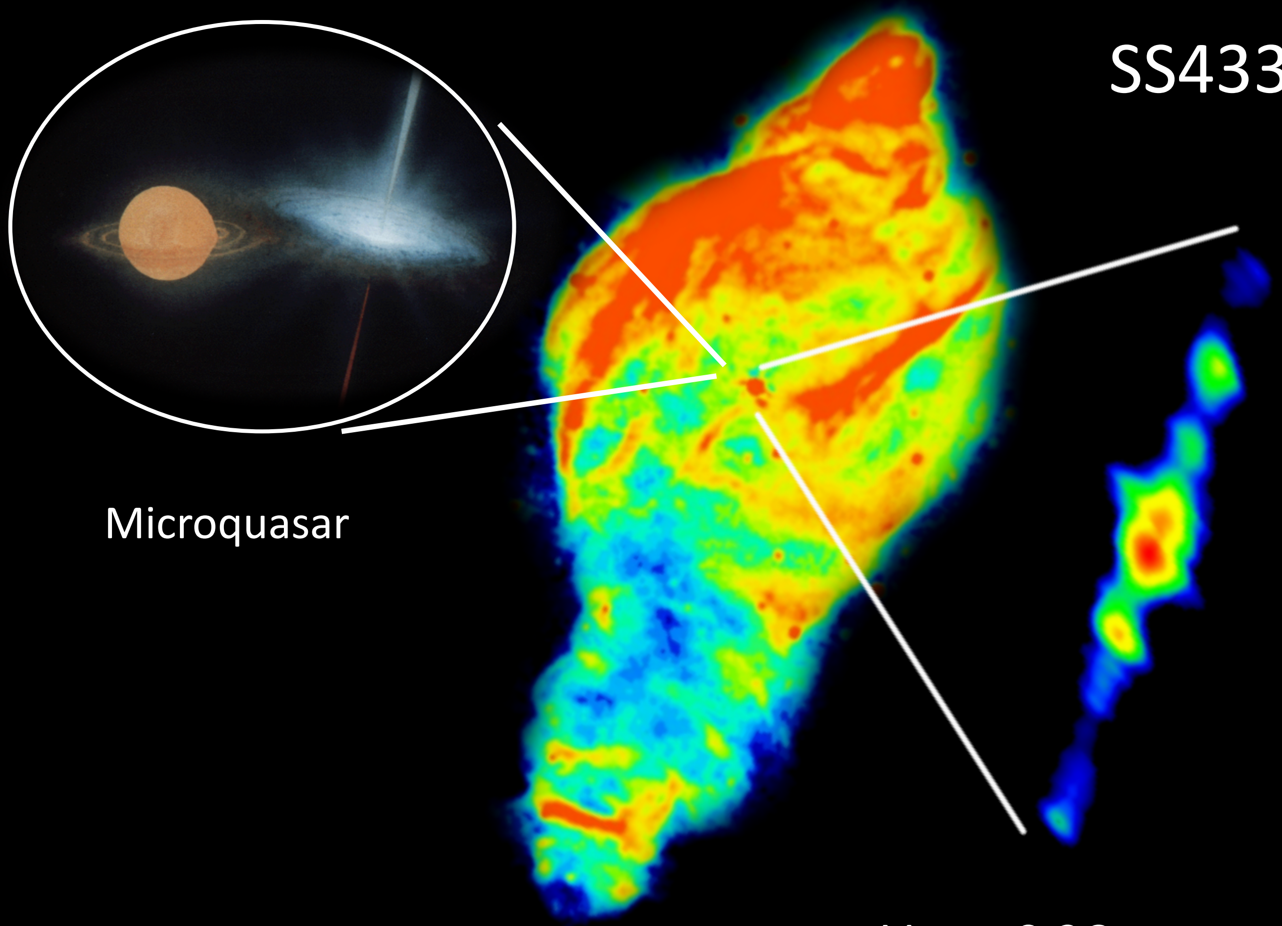


Illustration: Scientific American

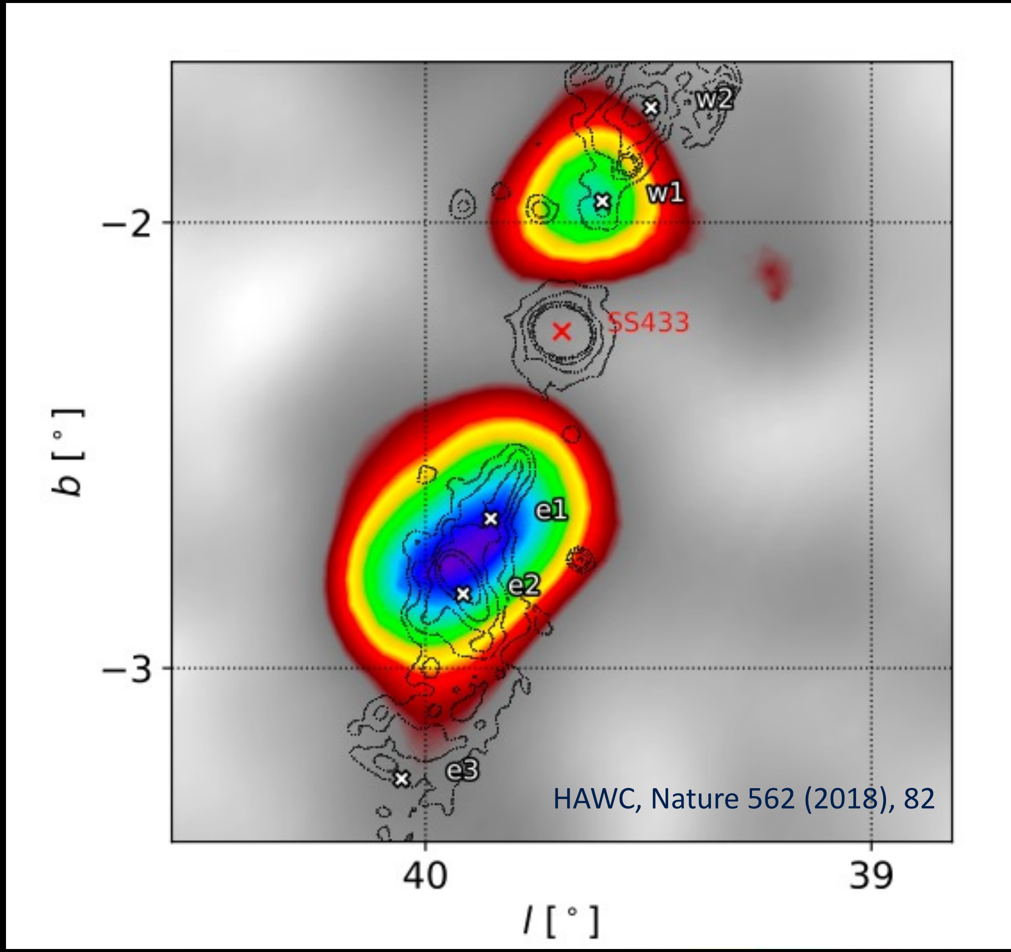
CHALLENGE: COMPACT OBJECTS AS ACCELERATORS

SS433



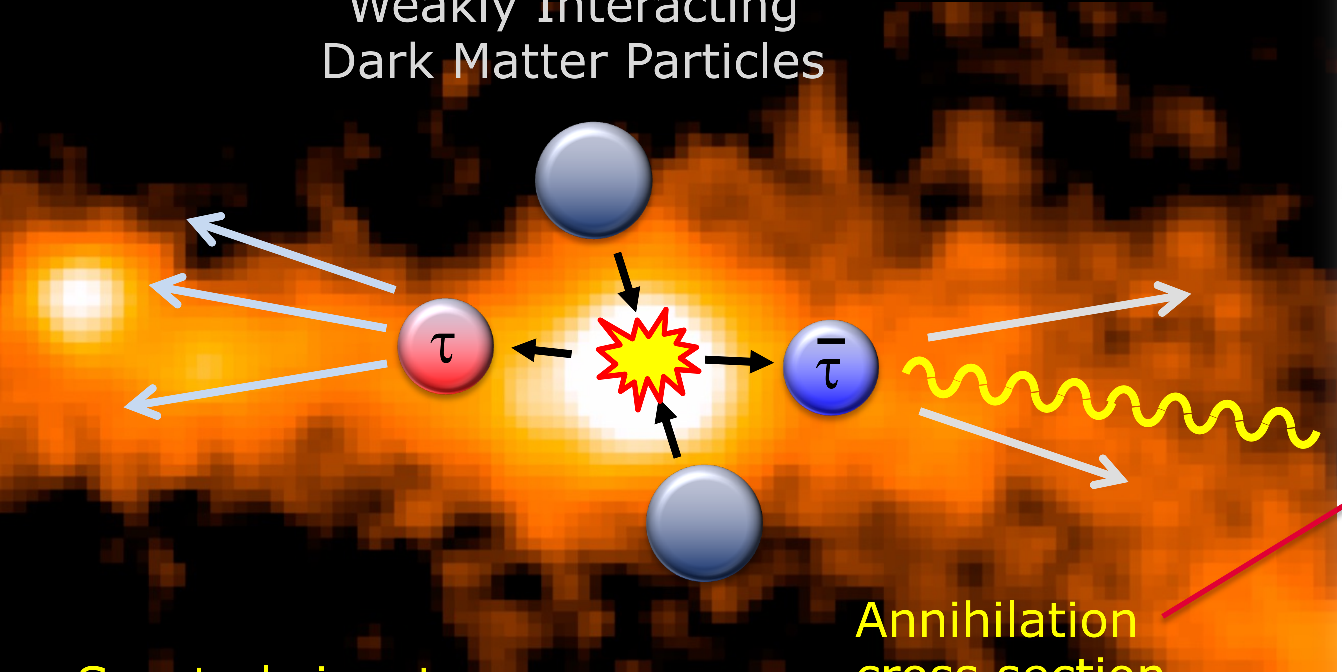
Microquasar

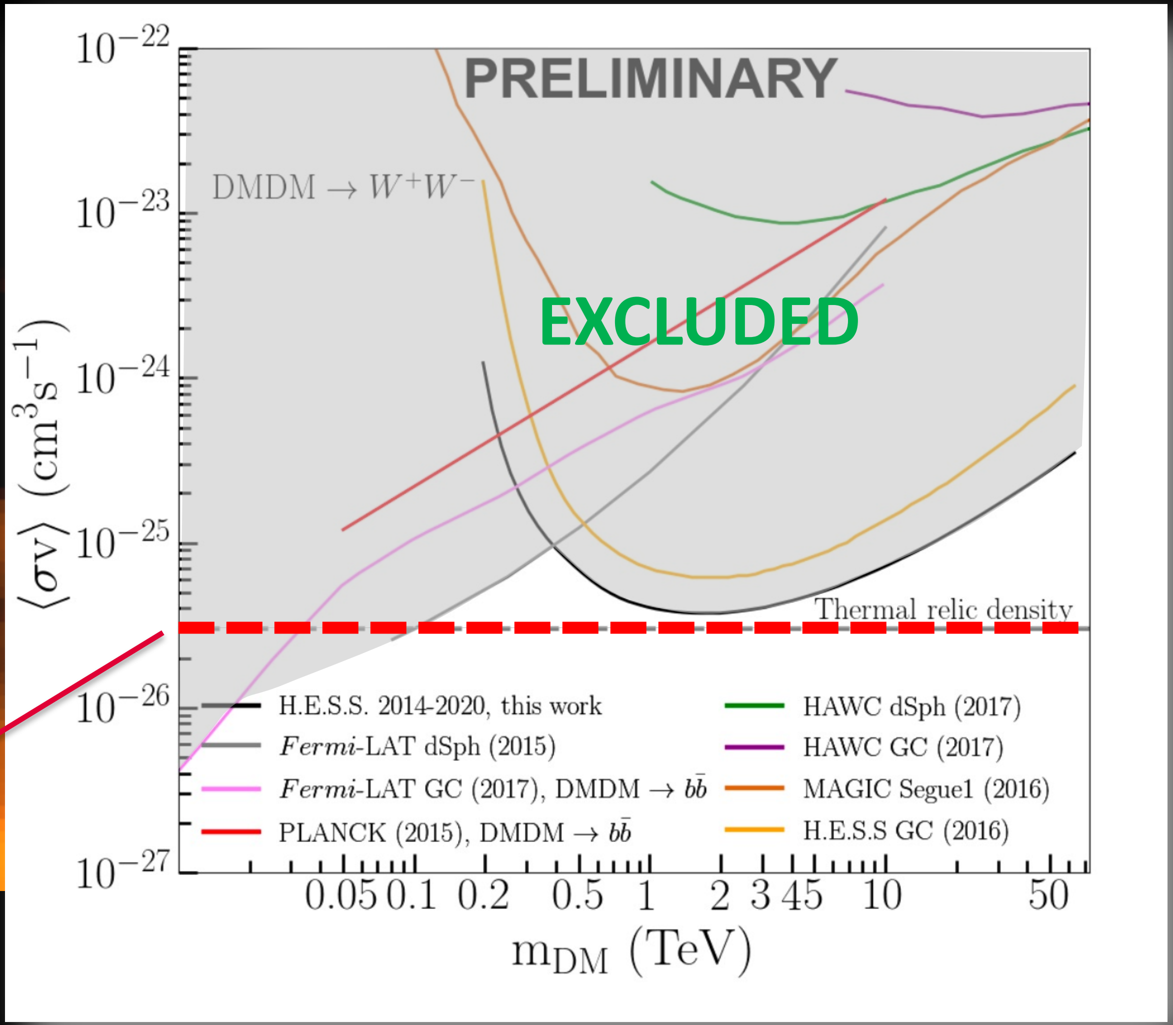
$V_{jet} \simeq 0.26\ c$



(VLA, NRAO/AUI) [Mioduszewski, NRAO/AUI/NSF]

CHALLENGE: DARK MATTER @ GC





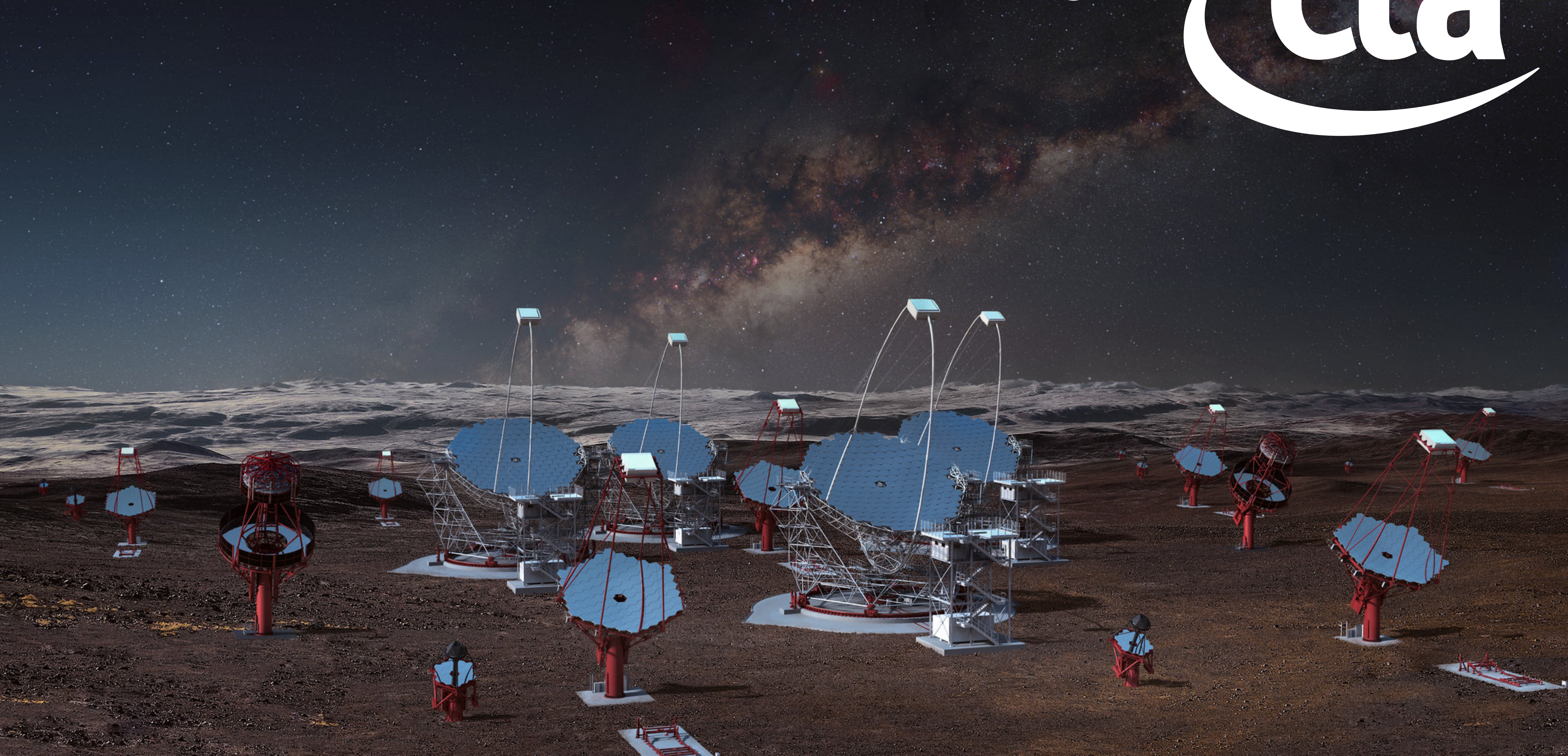
Spectral signature
known from particle physics

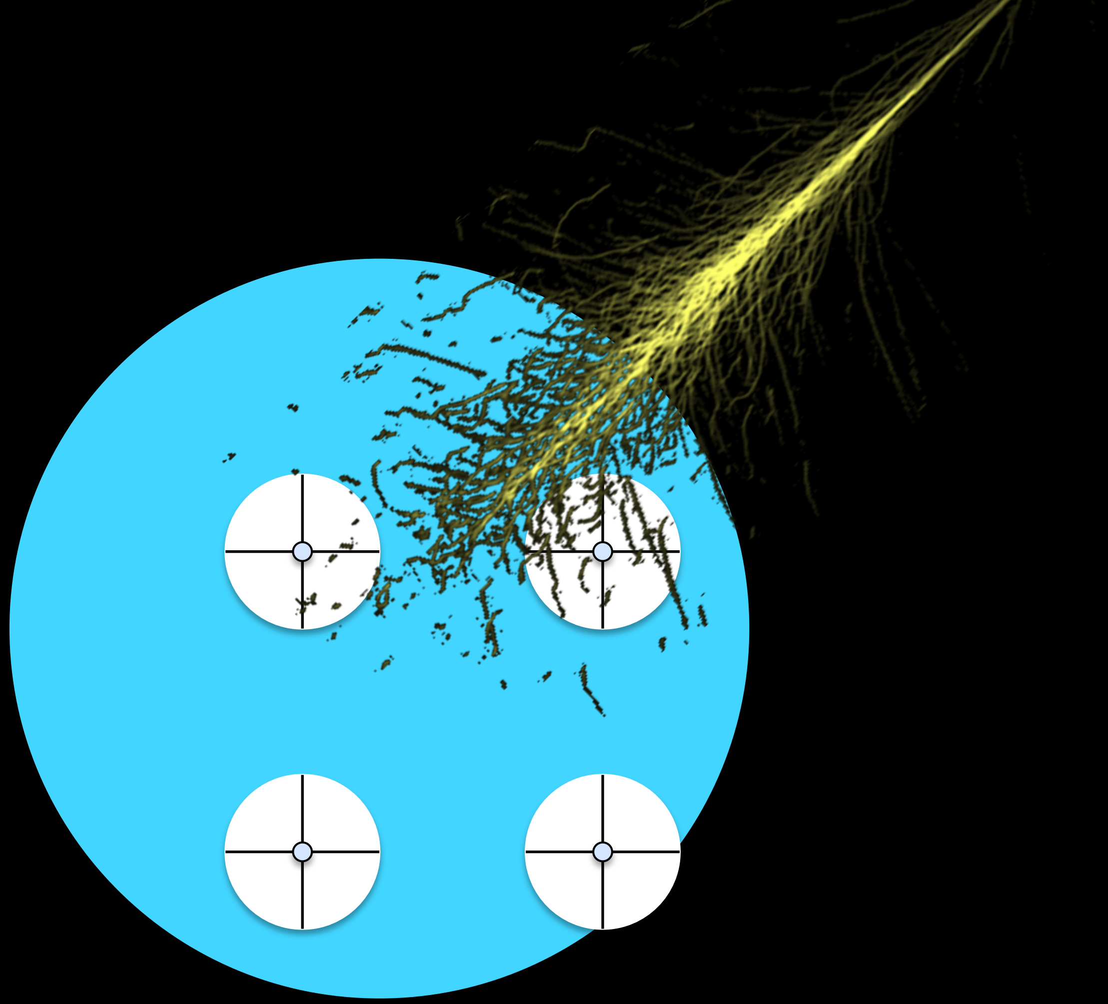
Annihilation
cross section
"known" from
Dark Matter
abundance

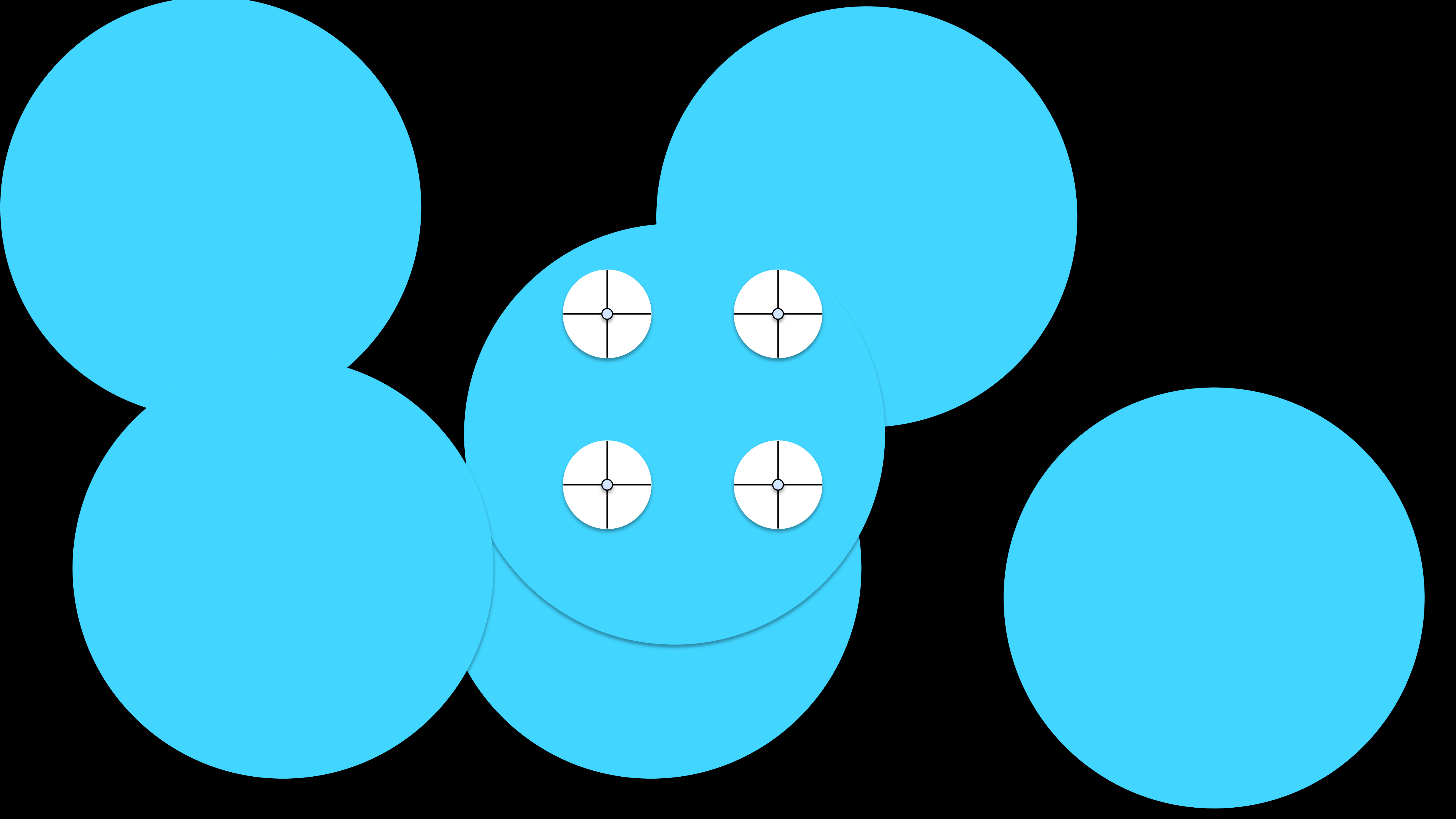
A. Montanari et al, PoS (ICRC2021)511

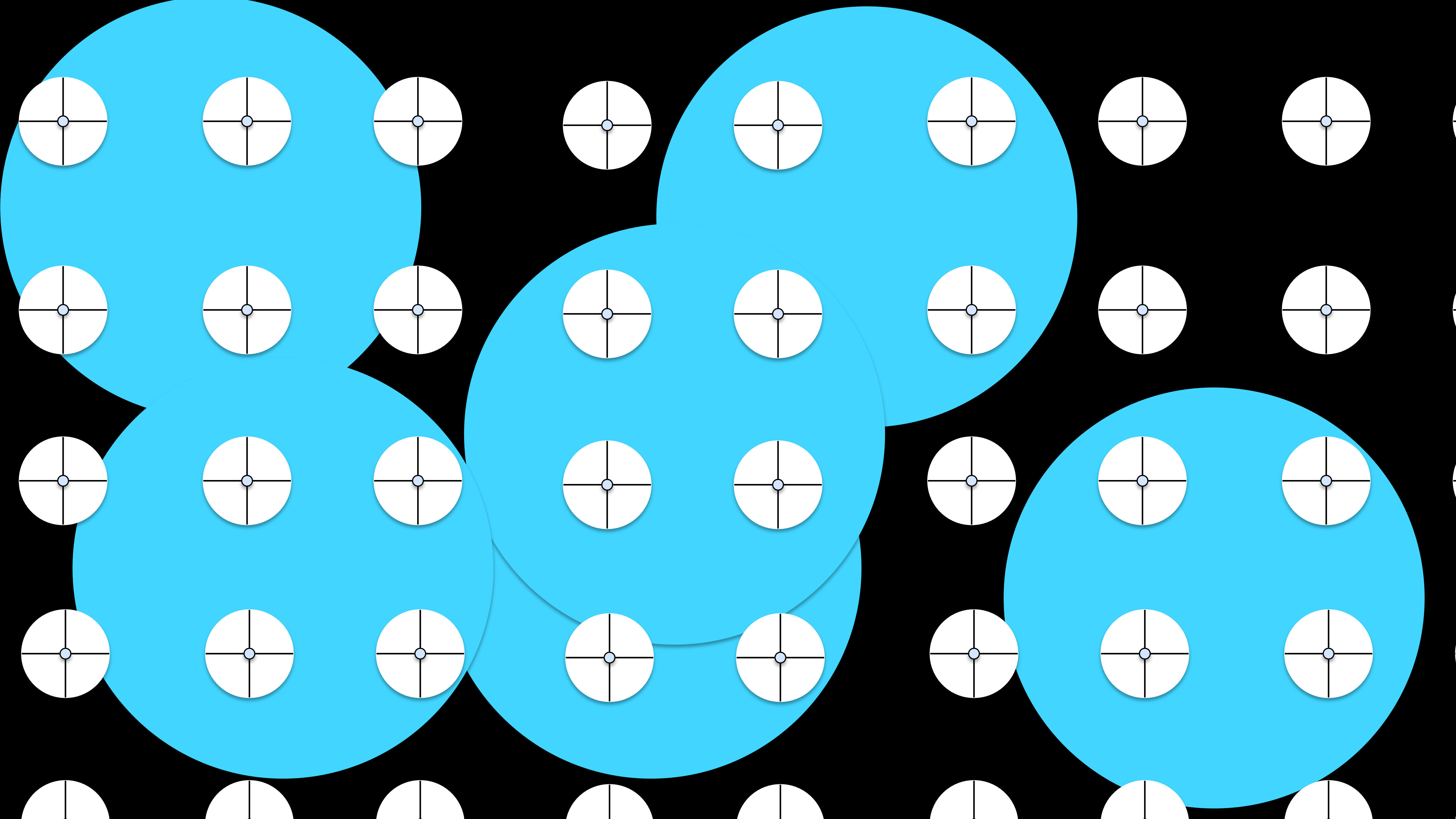
THE FUTURE (?)

The Cherenkov Telescope Array









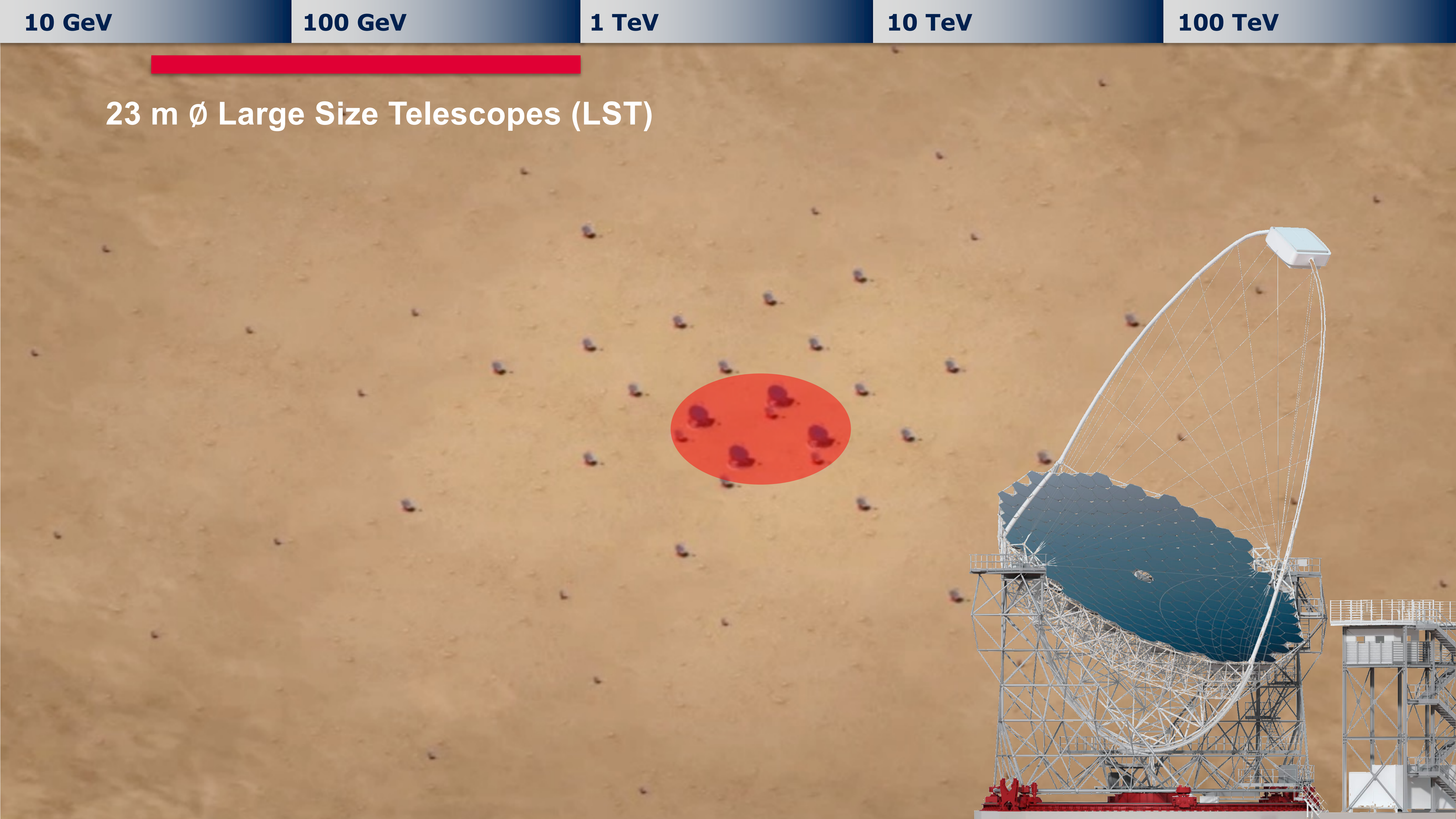
10 GeV	100 GeV	1 TeV	10 TeV	100 TeV

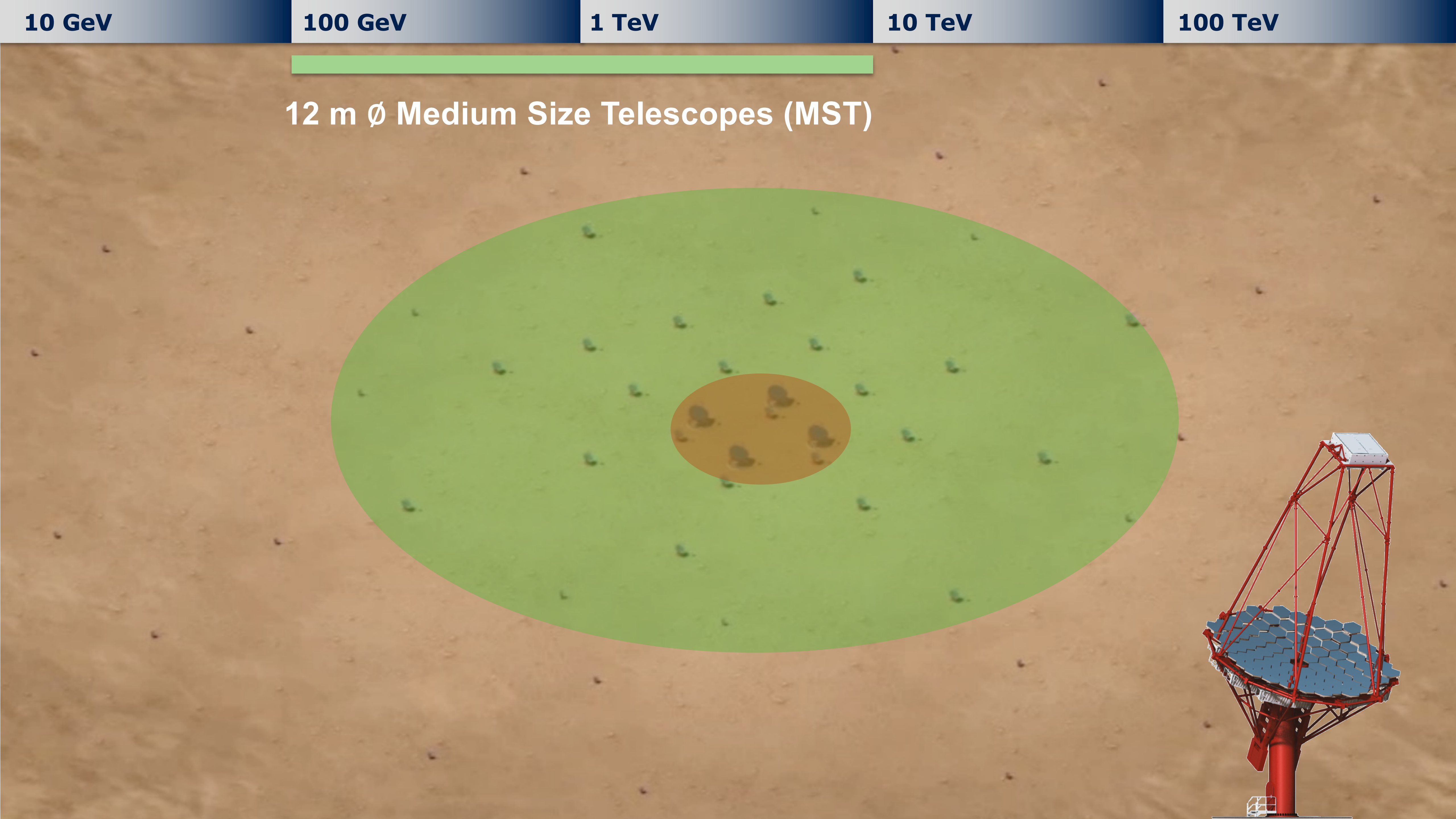
1000 γ / h km^2

10 γ / h km^2

0.1 γ / h km^2

Southern array ("Omega Config.")
of Cherenkov telescopes
- about 3 km across


10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
23 m Ø Large Size Telescopes (LST)


10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
12 m ø Medium Size Telescopes (MST)

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

4 m Ø Small Size Telescopes (SST) (South)

4+ decade energy range (20 GeV – 300 TeV)

Peak sensitivity better than 10^{-13} erg/cm^{2}s

Over two orders of magnitude gain in survey speed

Fast slewing for transient follow up

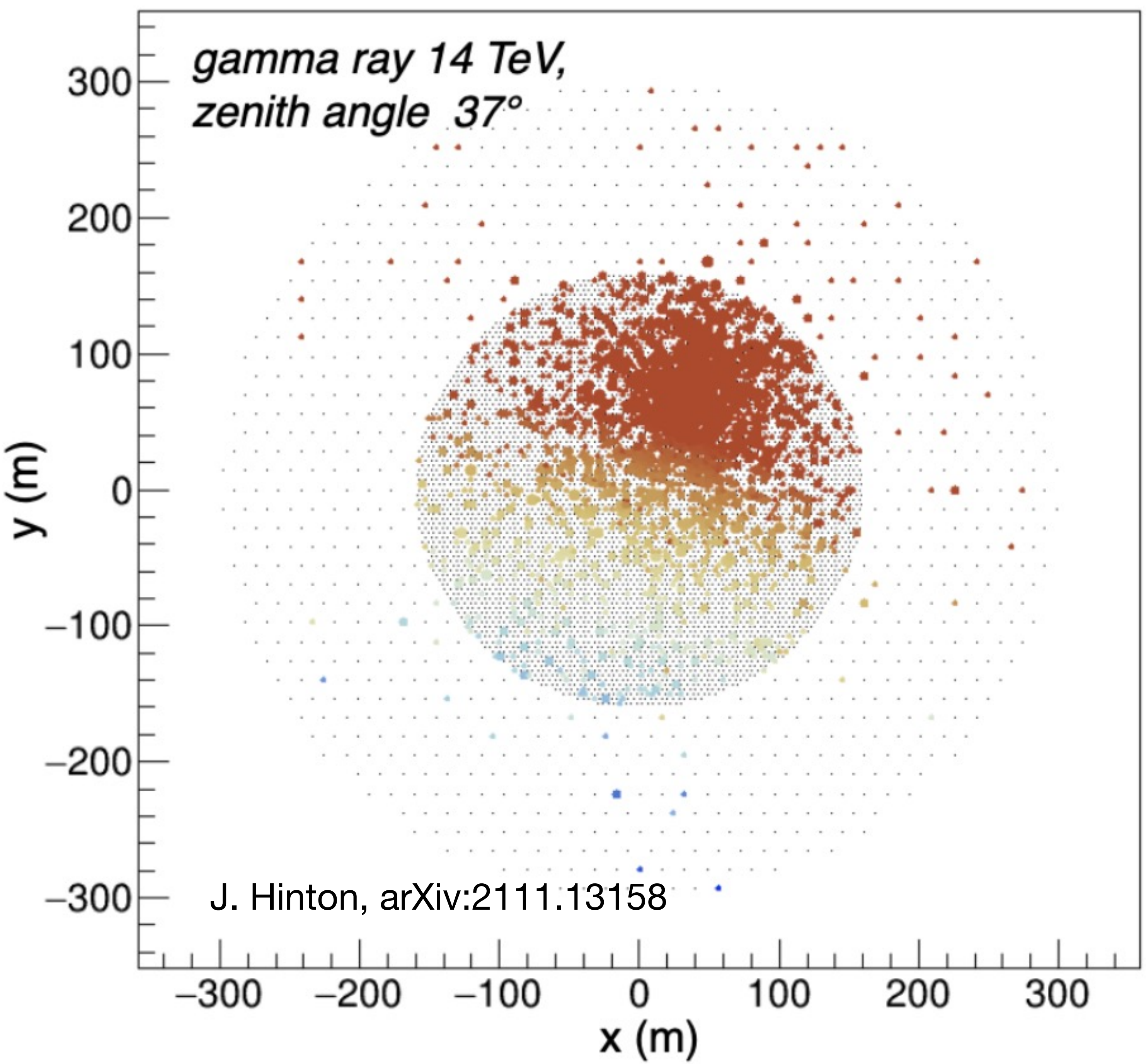
Open observatory

SWGO

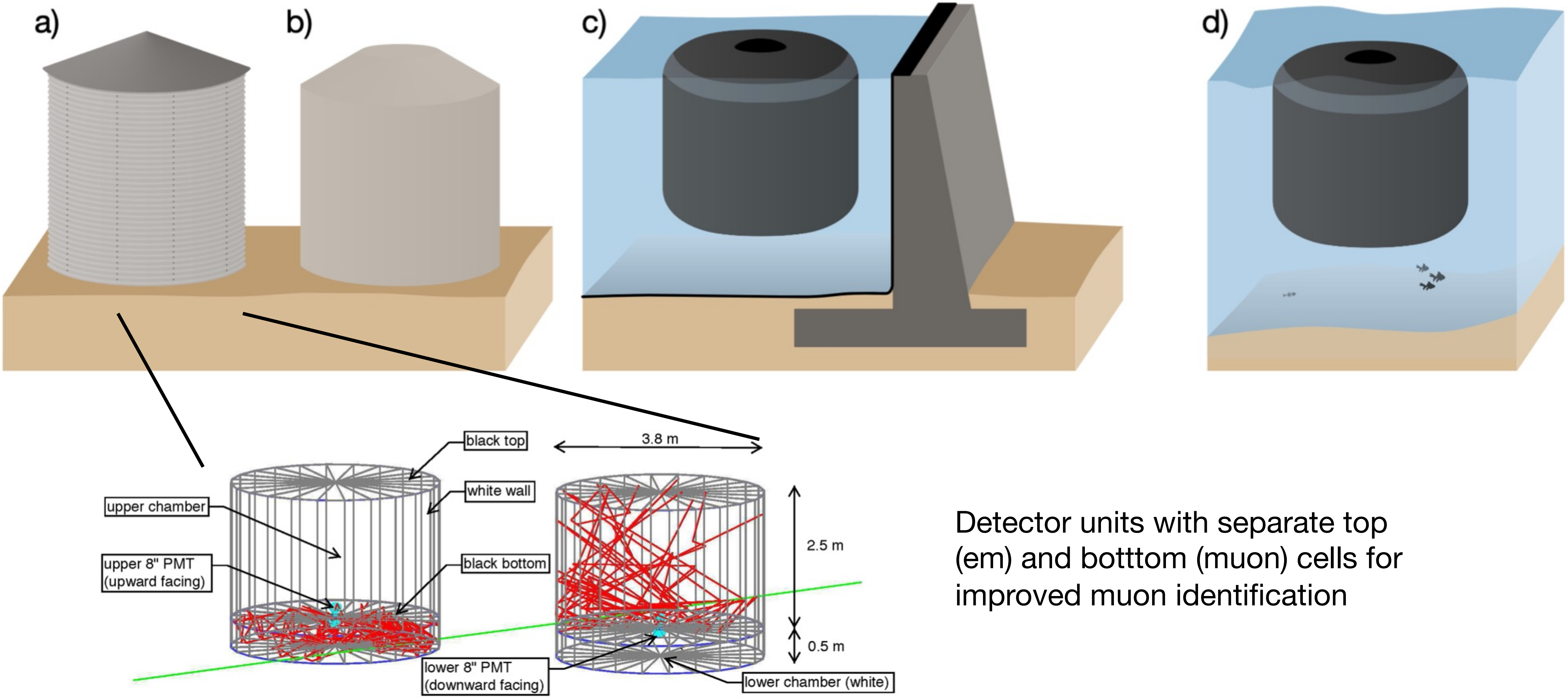
The Southern Wide-field Gamma-ray Observatory

Large & dense water Cherenkov array in South America,
between 10 and 30 degrees south,
at an altitude of 4.4 km or higher

Currently in the middle of a 3-year R&D programme towards a proposal



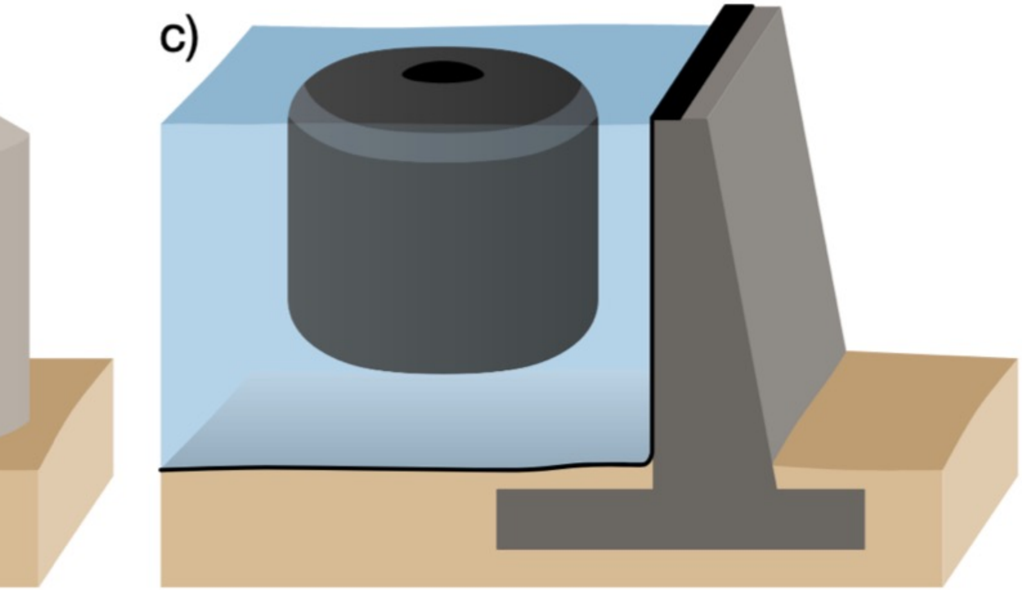
SWGO WATER CHERENKOV DETECTOR OPTIONS



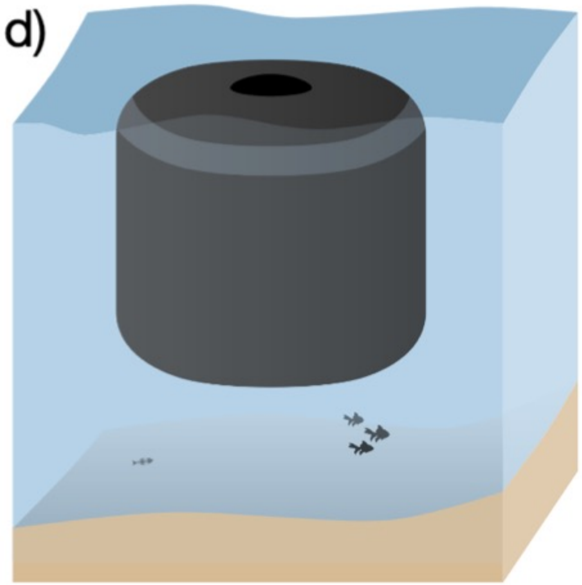
Detector units with separate top (em) and botttom (muon) cells for improved muon identification

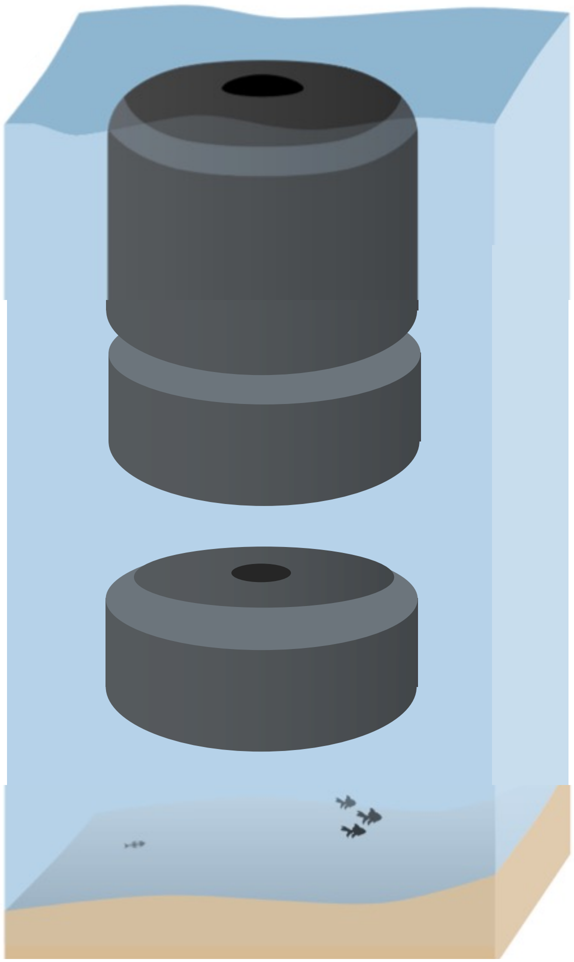
SWGO DETECTOR OPTIONS

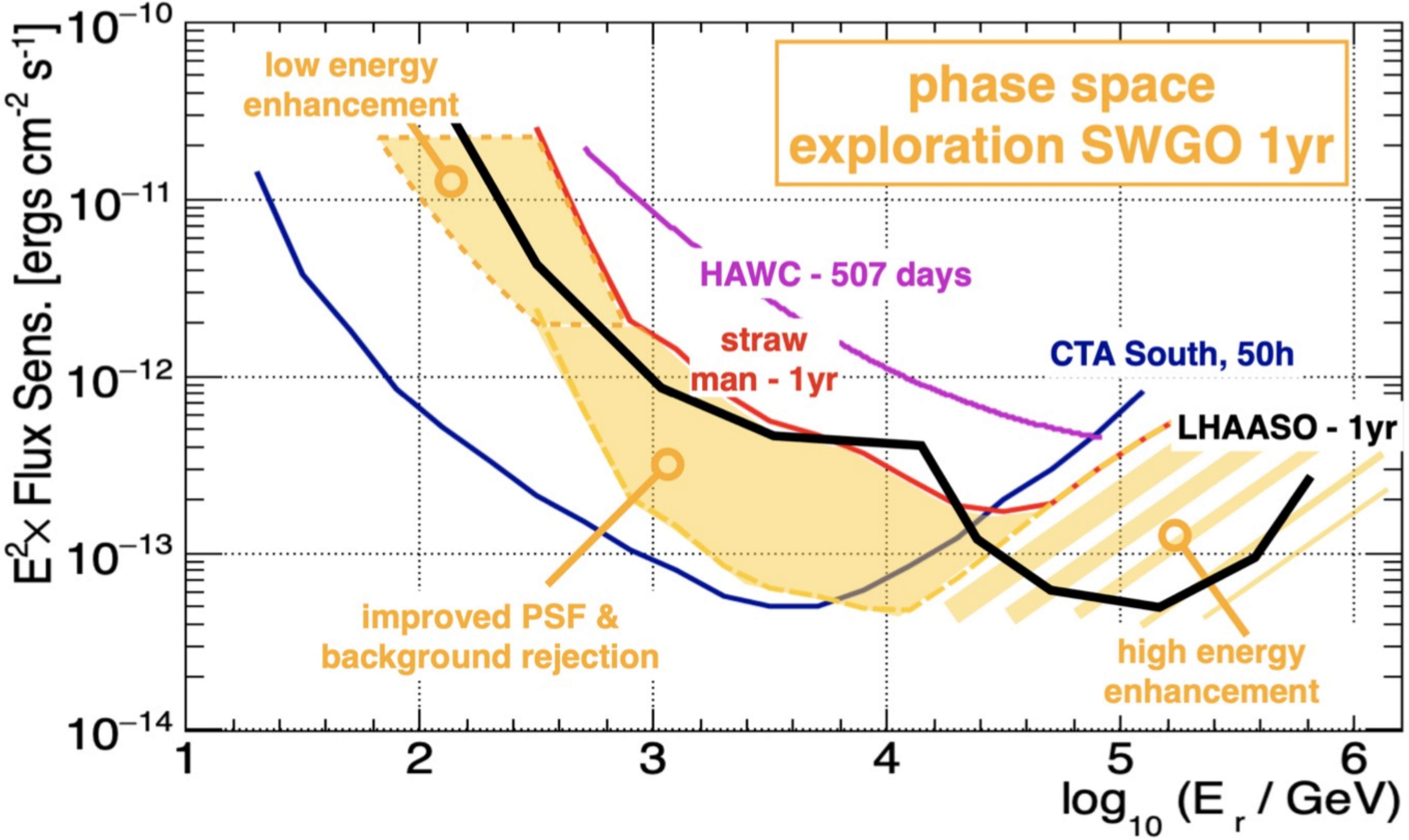
c)



d)







phase space exploration SWGO 1yr
low energy enhancement
HAWC - 507 days
straw man - 1yr
CTA South, 50h
LHAASO - 1yr
improved PSF & background rejection
high energy enhancement
$E^2 \times$ Flux Sens. [ergs cm^{-2} s^{-1}]
$\log_{10}$ (E_r / GeV)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
2
3
4
5
6

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

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

The PeV domain

Needs huge effective area

100+ km^2yr

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

The TeV domain

Boost sensitivity
Sub-arc-minute resolution

The PeV domain

Needs huge effective area
100+ km^2yr

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

The TeV domain

Boost sensitivity
Sub-arc-minute resolution

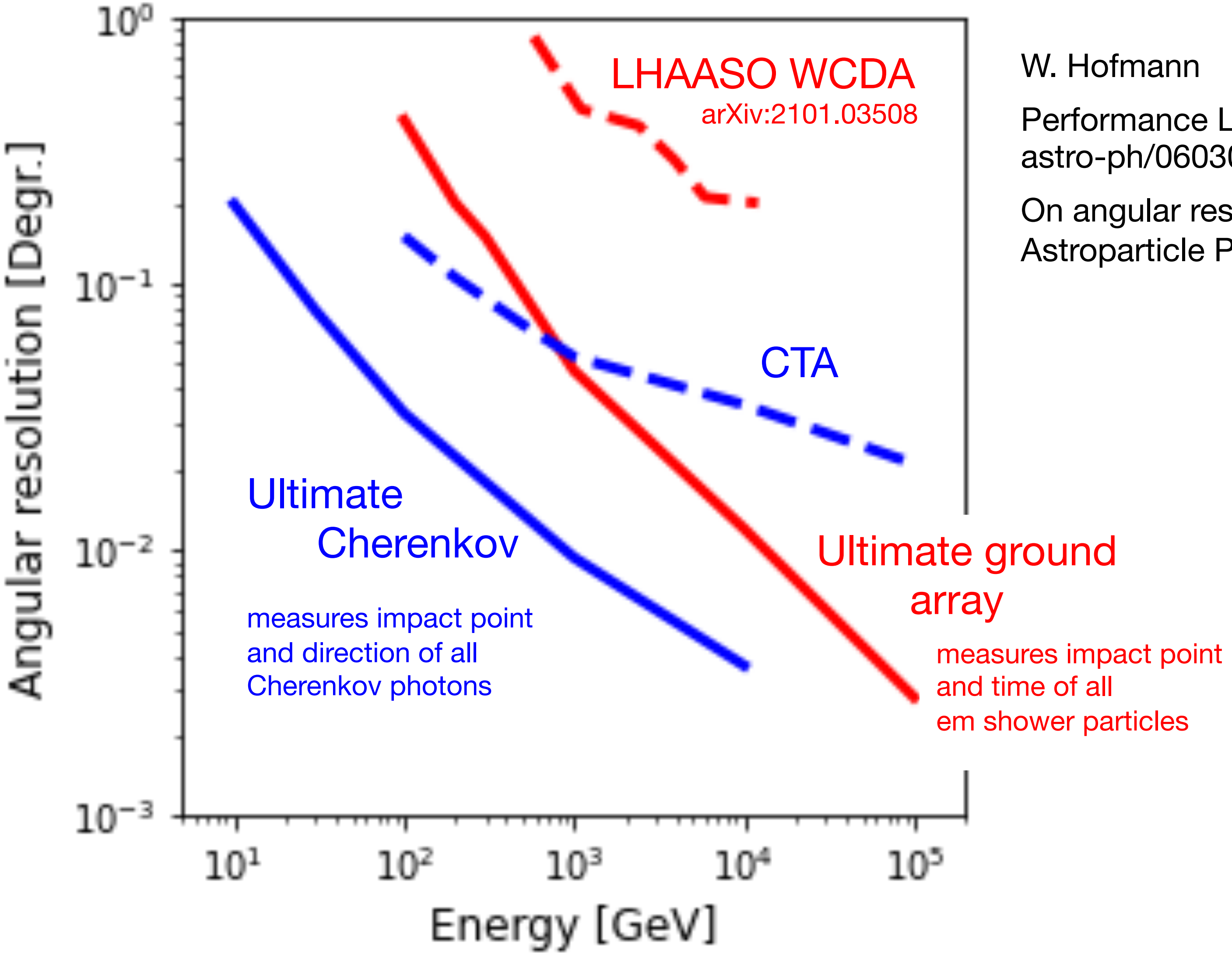
The GeV domain

GeV
astronomy
from the ground?

The PeV domain

Needs huge effective area
100+ km^2yr

WHAT'S THE LIMIT? ANGULAR RESOLUTION

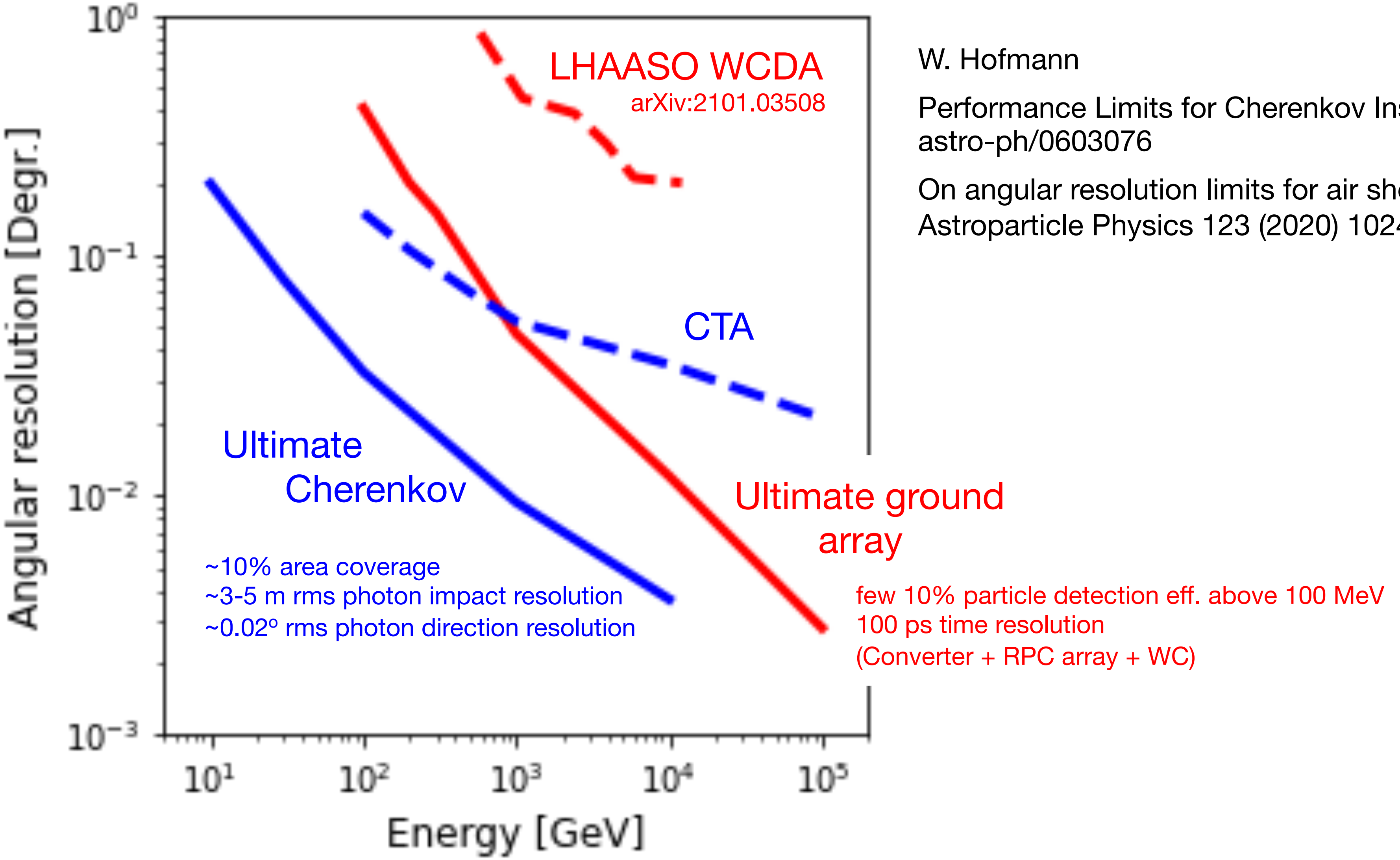


W. Hofmann

Performance Limits for Cherenkov Instruments
astro-ph/0603076

On angular resolution limits for air shower arrays
Astroparticle Physics 123 (2020) 102479

WHAT'S THE LIMIT? ANGULAR RESOLUTION



W. Hofmann

Performance Limits for Cherenkov Instruments astro-ph/0603076

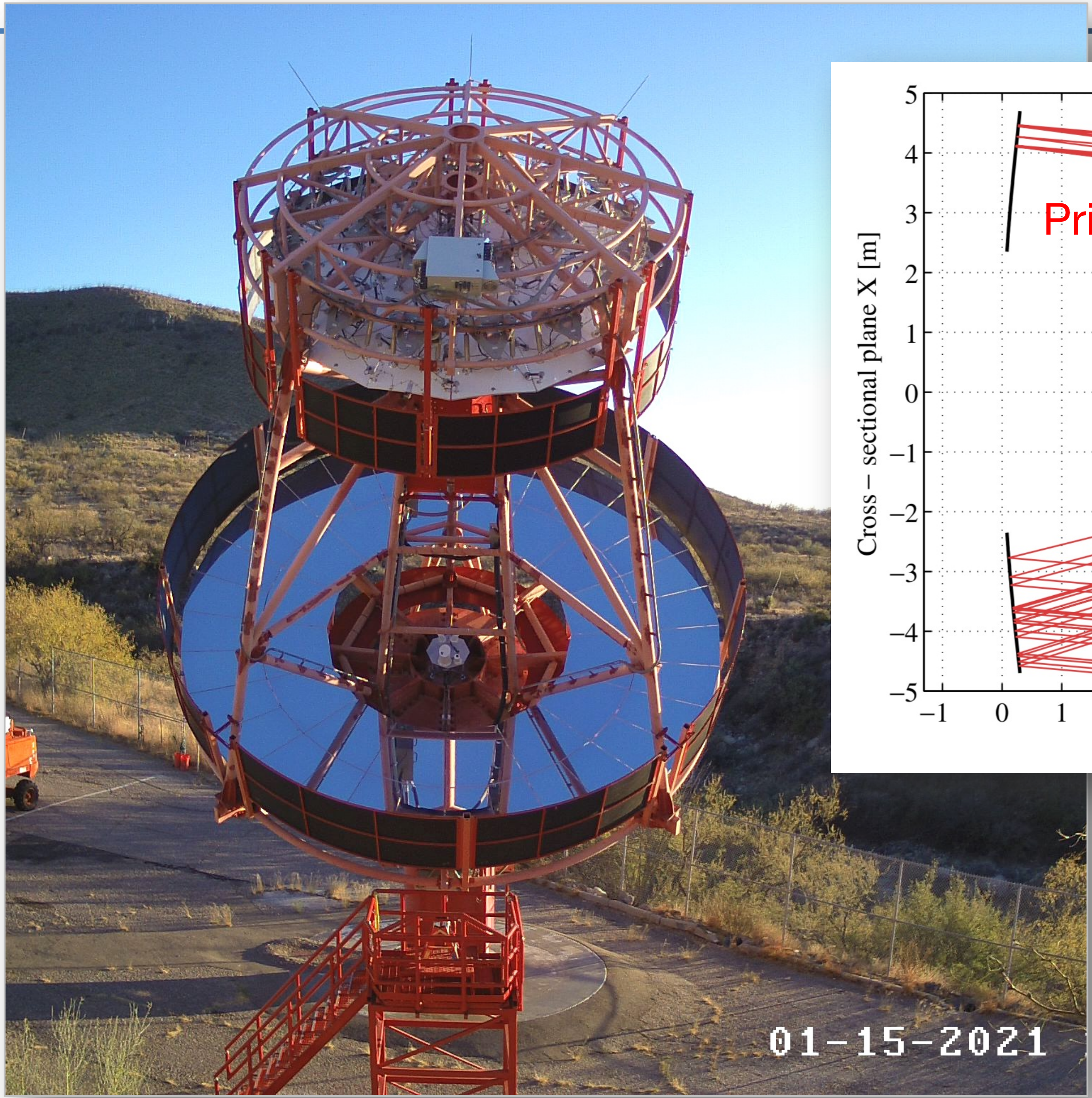
On angular resolution limits for air shower arrays Astroparticle Physics 123 (2020) 102479

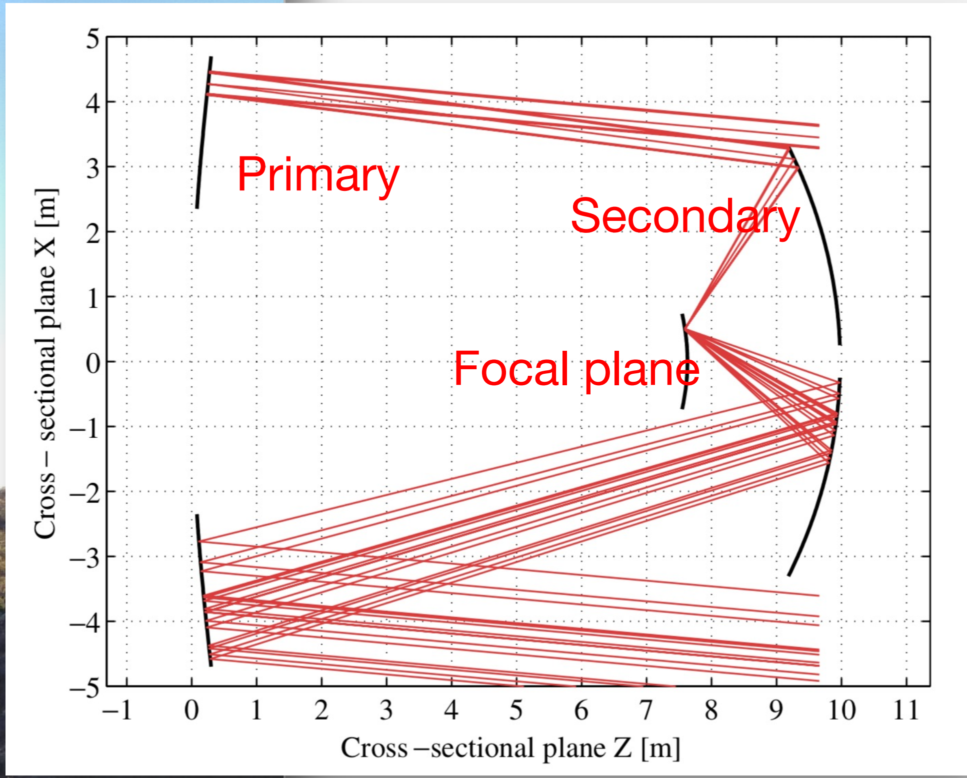
NOVEL IACT OPTICS CONCEPTS

CTA Schwarzschild-Couder Telescope

proposed for
CTA enhancement

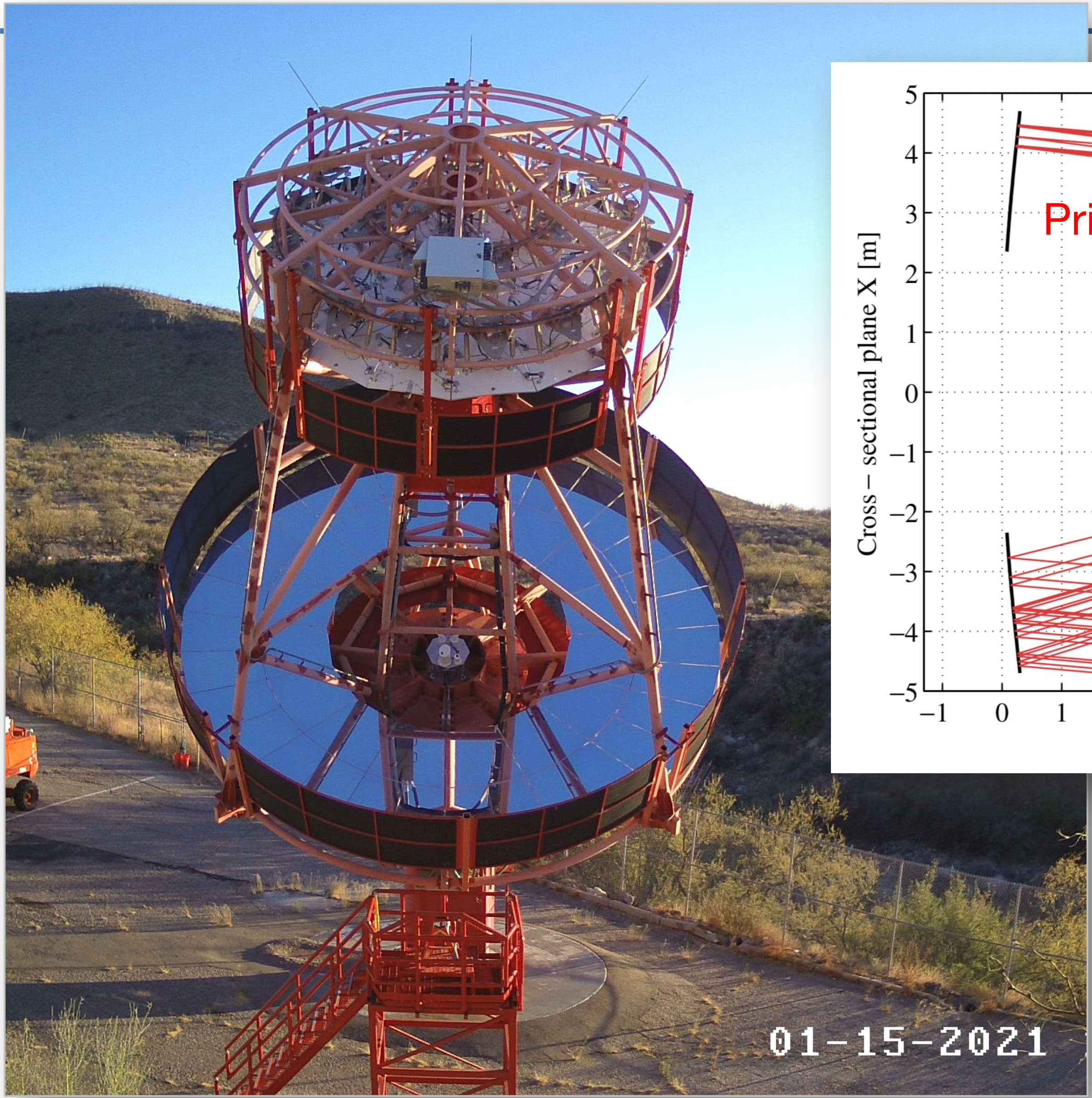
NOVEL IACT OPTICS CONCEPTS

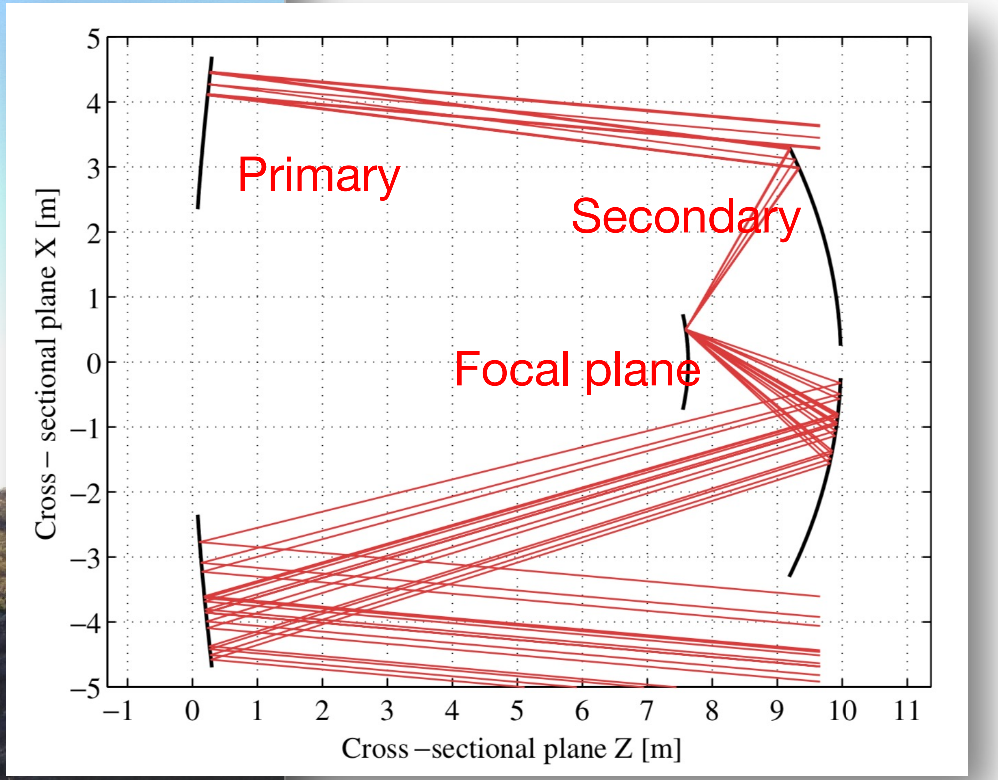




V. Vassiliev et al.
Astroparticle Physics
28 (2007) 10

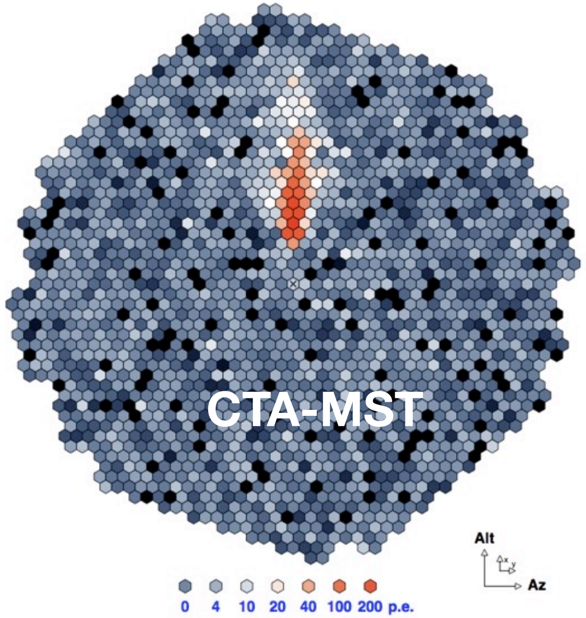
NOVEL IACT OPTICS CONCEPTS

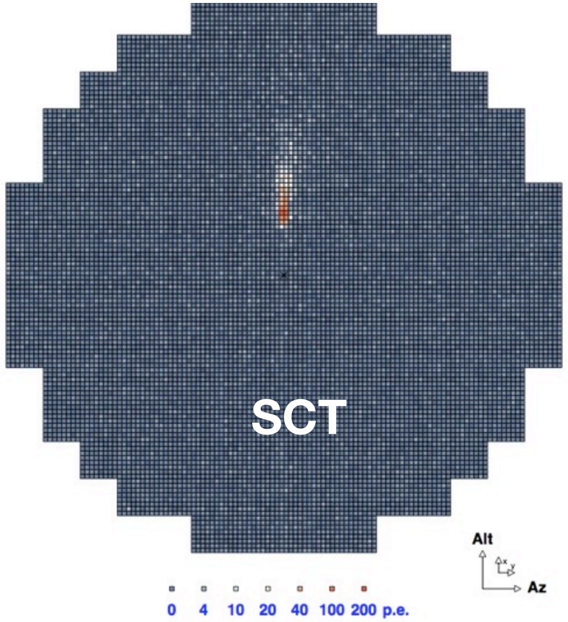




- Aspherical dual mirrors compensate optical aberrations → very good optical psf
- Small focal plane ideal for silicon sensors → small pixels

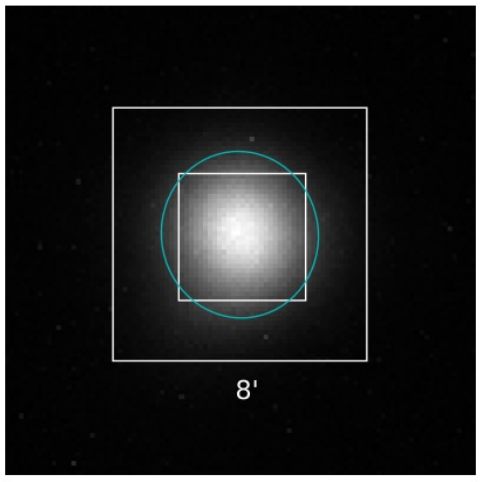
NOVEL IACT OPTICS CONCEPTS



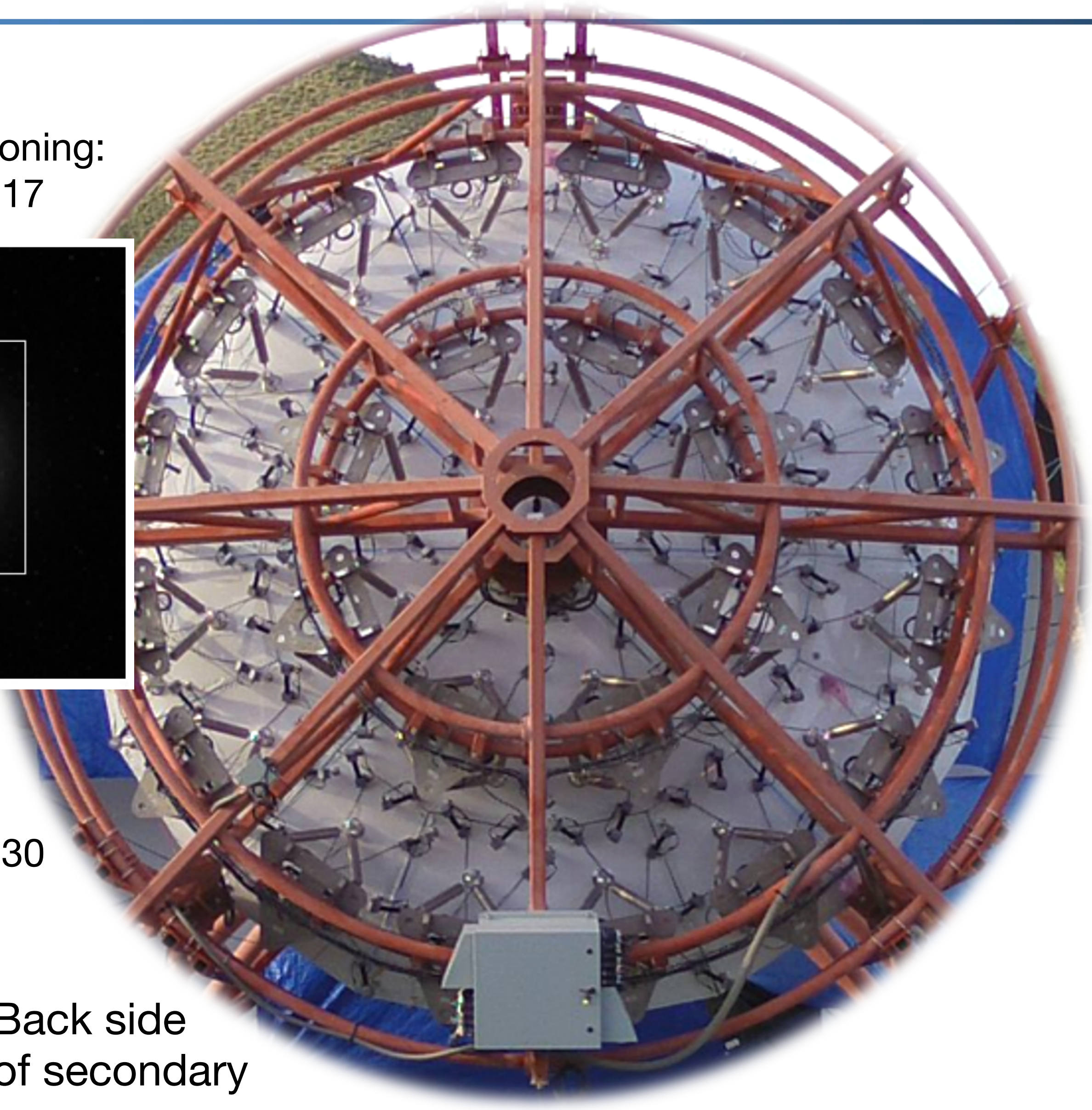


NOVEL IACT OPTICS CONCEPTS

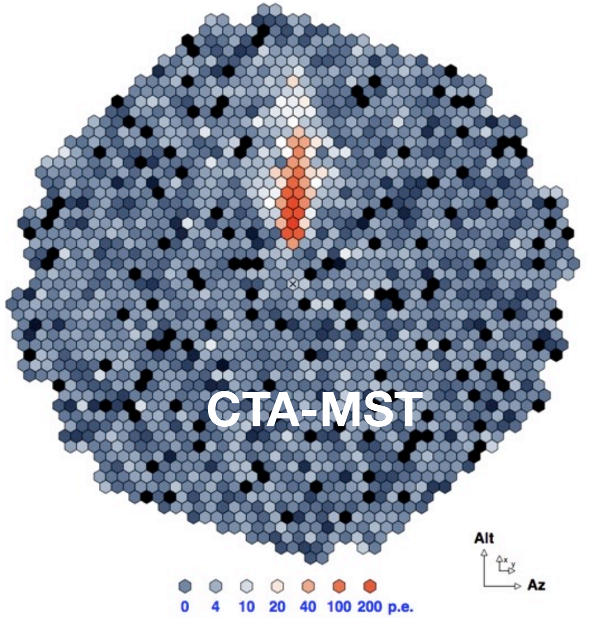
Optics commissioning:
PoS(ICRC2021)717

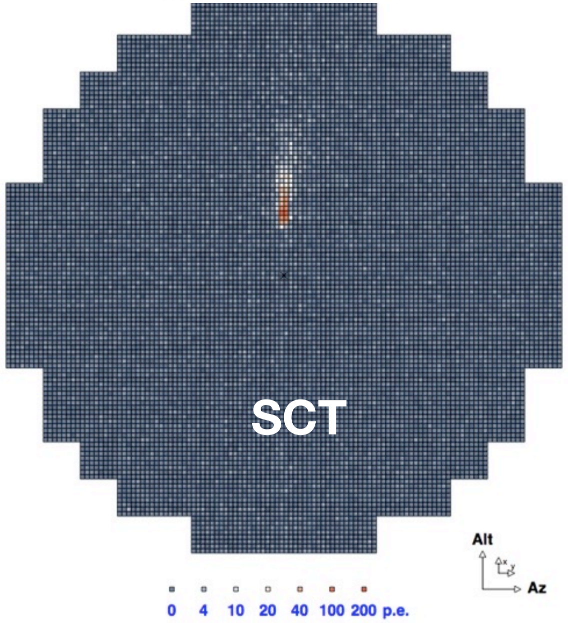


Crab detection:
PoS(ICRC2021)830



Back side
of secondary





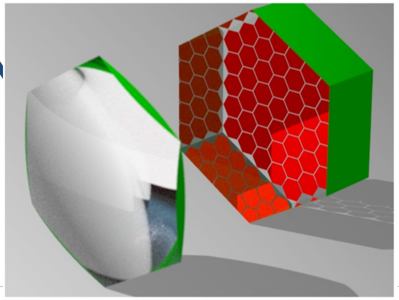
NOVEL IACT OPTICS CONCEPTS:
THE PLENOSCOPE

S.A. Mueller
arXiv:1904.13368

NOVEL IACT OPTICS CON
THE PLENOSCOPE

S.A. Mueller
arXiv:1904.13

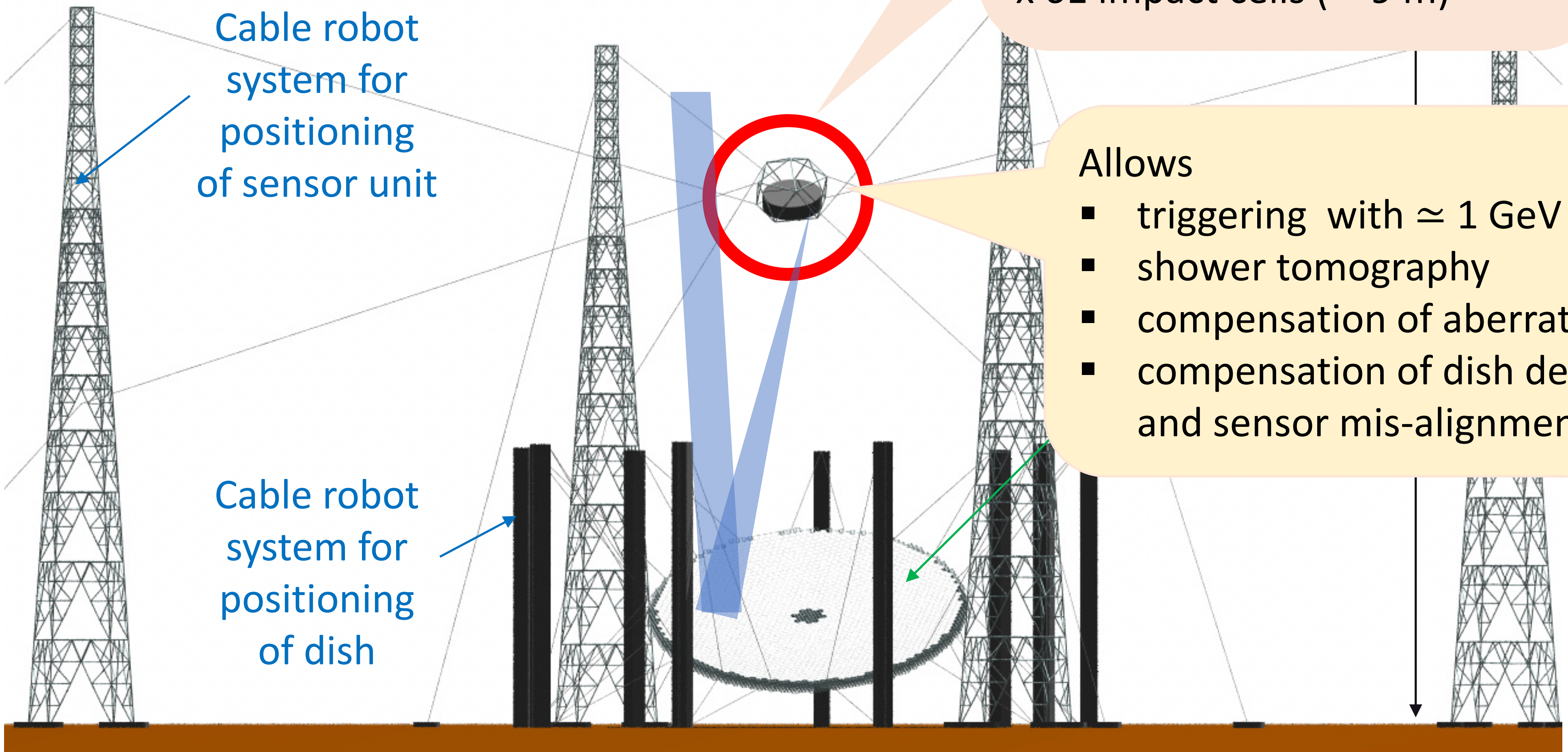
Direction pixel



"Light field" camera measures

- Direction of photon
- Impact position on mirror
- Time

8443 direction pixels ($\simeq$ 0.07°)
x 61 impact cells ($\simeq$ 9 m)



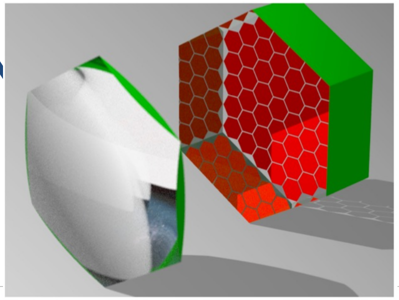
Allows

- triggering with $\simeq$ 1 GeV threshold
- shower tomography
- compensation of aberrations
- compensation of dish deformation and sensor mis-alignment

NOVEL IACT OPTICS CON
THE PLENOSCOPE

S.A. Mueller
arXiv:1904.13

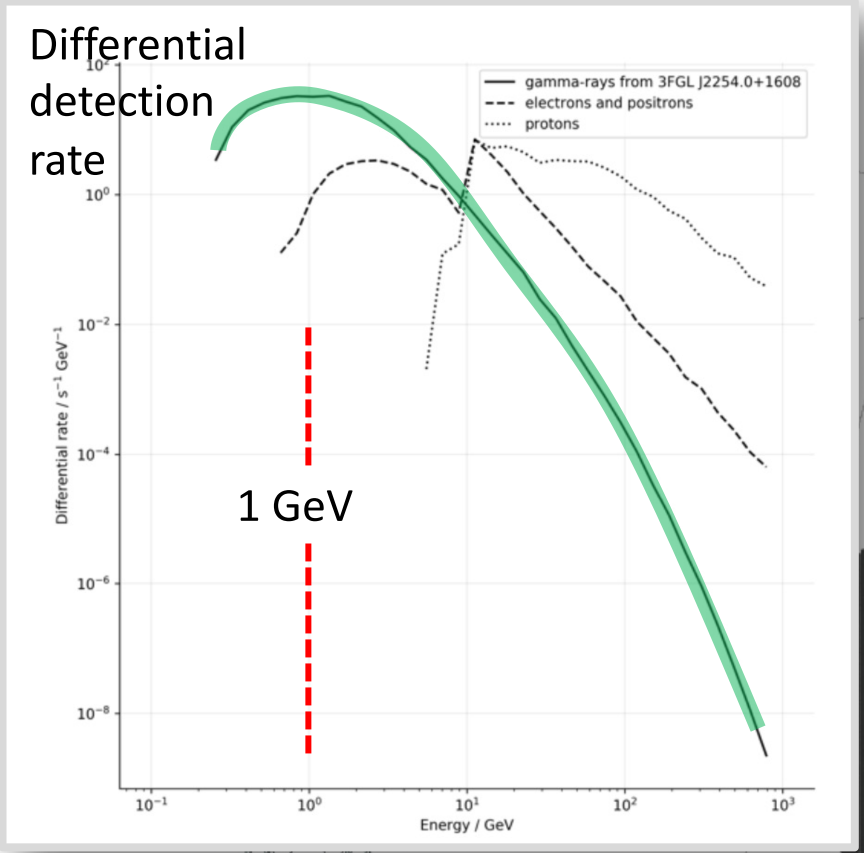
Direction pixel

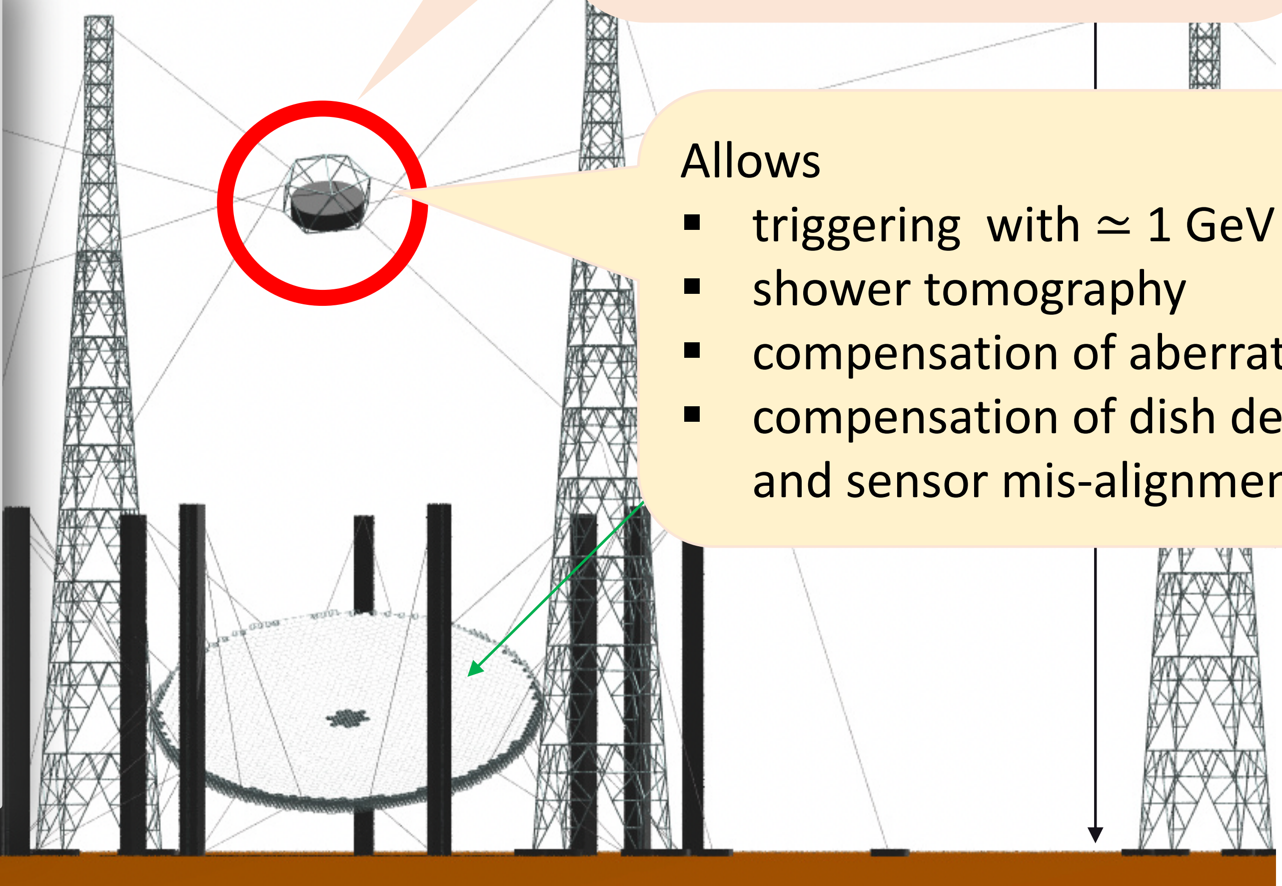


“Light field” camera measures

- Direction of photon
- Impact position on mirror
- Time

8443 direction pixels (≃ 0.07°)
x 61 impact cells (≃ 9 m)





Allows

- triggering with ≃ 1 GeV threshold
- shower tomography
- compensation of aberrations
- compensation of dish deformation and sensor mis-alignment

IMPROVING IACT BACKGROUND REJECTION

- Better imaging
- Better gamma-ray PSF
- **Muon detection**

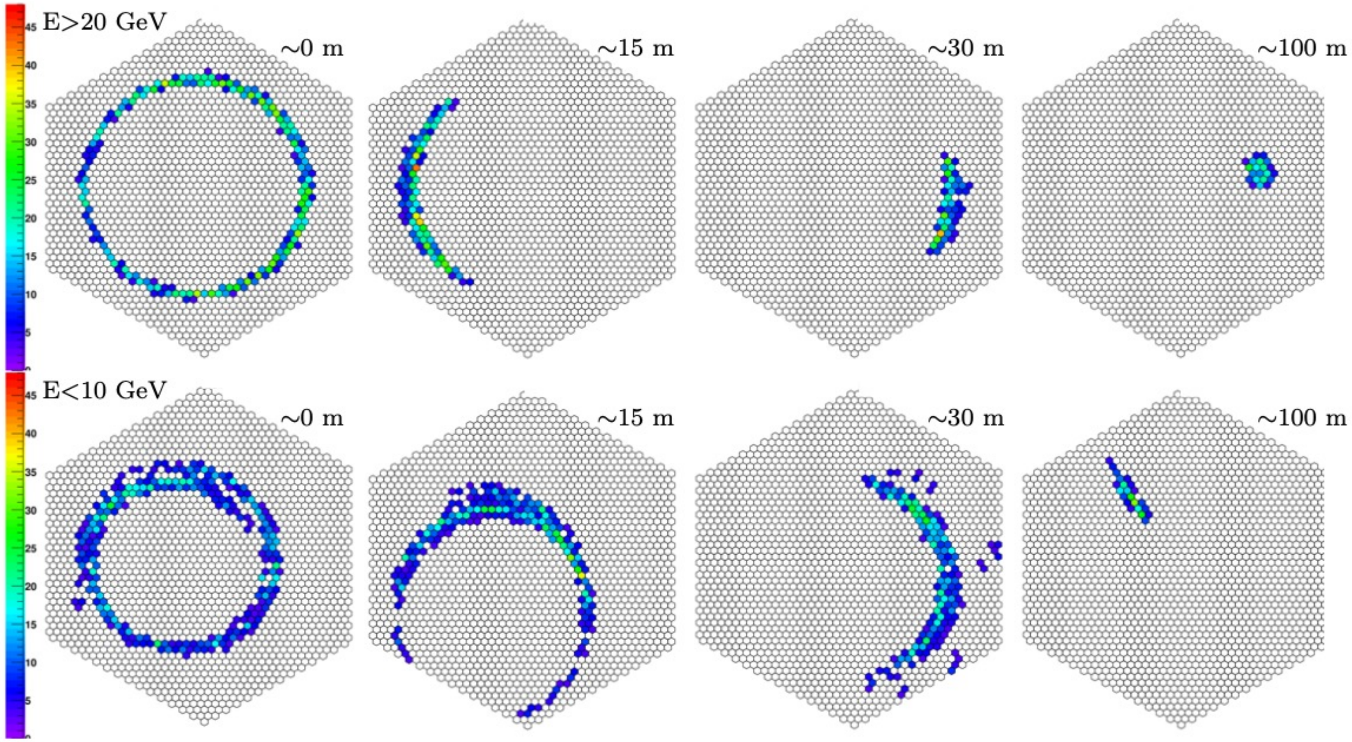
Muon effective area:

28 m telescope: $A_{eff} \simeq 30000 - 50000\ m^2$ (r ~ 110 m)

12 m telescope: $A_{eff} \simeq 4000 - 5000\ m^2$ (r ~ 35 m)

Potential background rejection

- up to 10^3 at 25 TeV
- up to 10^5 at 100 TeV

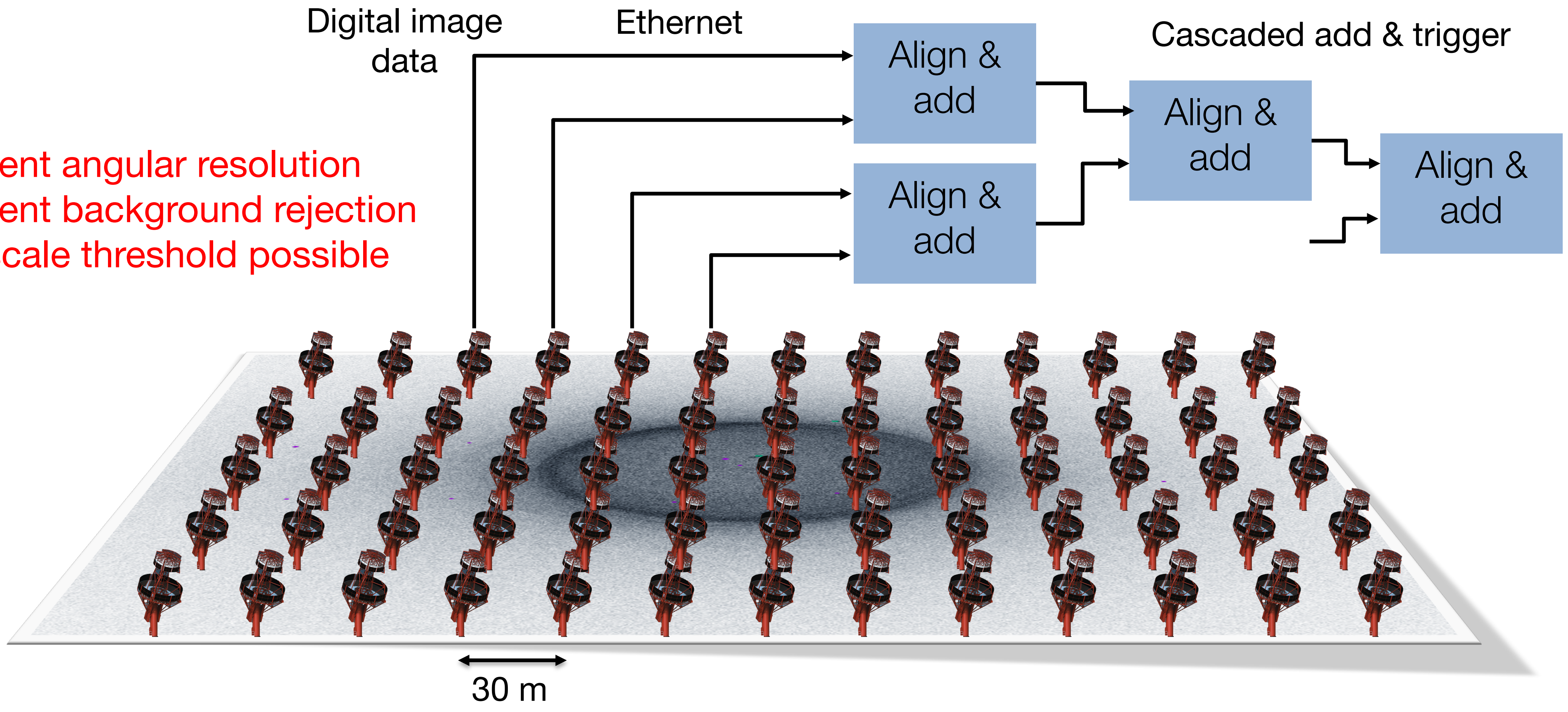


L. Olivera-Nieto et al., arXiv:2111.12041

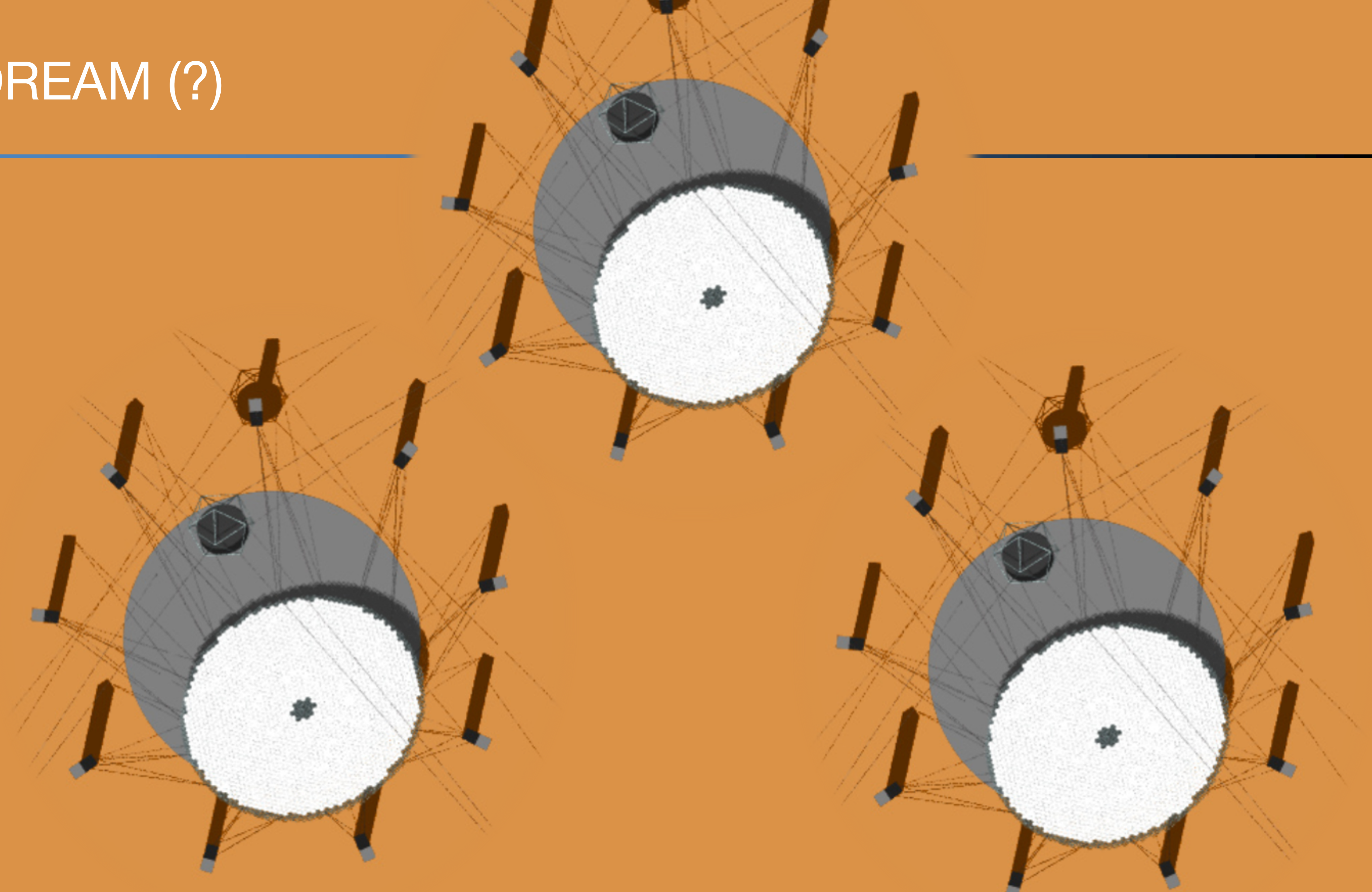
Muons in a 28 m IACT (H.E.S.S. CT5)

DREAM (?)

Excellent angular resolution
Excellent background rejection
GeV-scale threshold possible



DREAM (?)



TEV GAMMA RAY ASTRONOMY

- A mature field, with Cherenkov arrays and ground particle detectors providing complementary capabilities
- Probes a wide range of topics from astrophysics, particle physics, cosmology

- Many exciting results
- Many open questions
- Powerful next-generation instruments starting or in advanced planning

- Detection technologies have significant potential & reach
- Key issue: large scale / low cost production and deployment of detector elements