VHE Gamma-Ray Astronomy & the Decadal Survey

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GammaSIG, ~~7~~ 28 Jan 2022

Outline

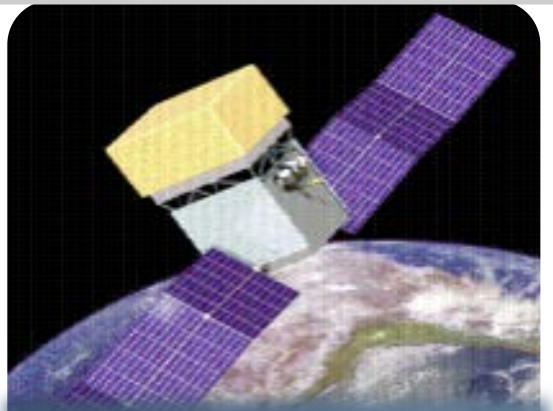
- Current status of the field
  - Some key results – current instruments
- Future prospects
  - Design drivers
  - The Decadal Survey
  - Instruments under development

- LE or MeV : 0.1 -100 MeV
- HE or GeV : 0.1 -100 GeV
- VHE or TeV : 0.1 -100 TeV

} domain of space-based astronomy

domain of ground-based astronomy

Gamma-Ray Instrument Synergies



Low-energy threshold - Satellites Fermi-LAT, AGILE: 100 MeV to > 30 GeV

Sky survey, transients

High sensitivity – Current IACTs H.E.S.S., MAGIC, VERITAS: 10s GeV to > 30 TeV

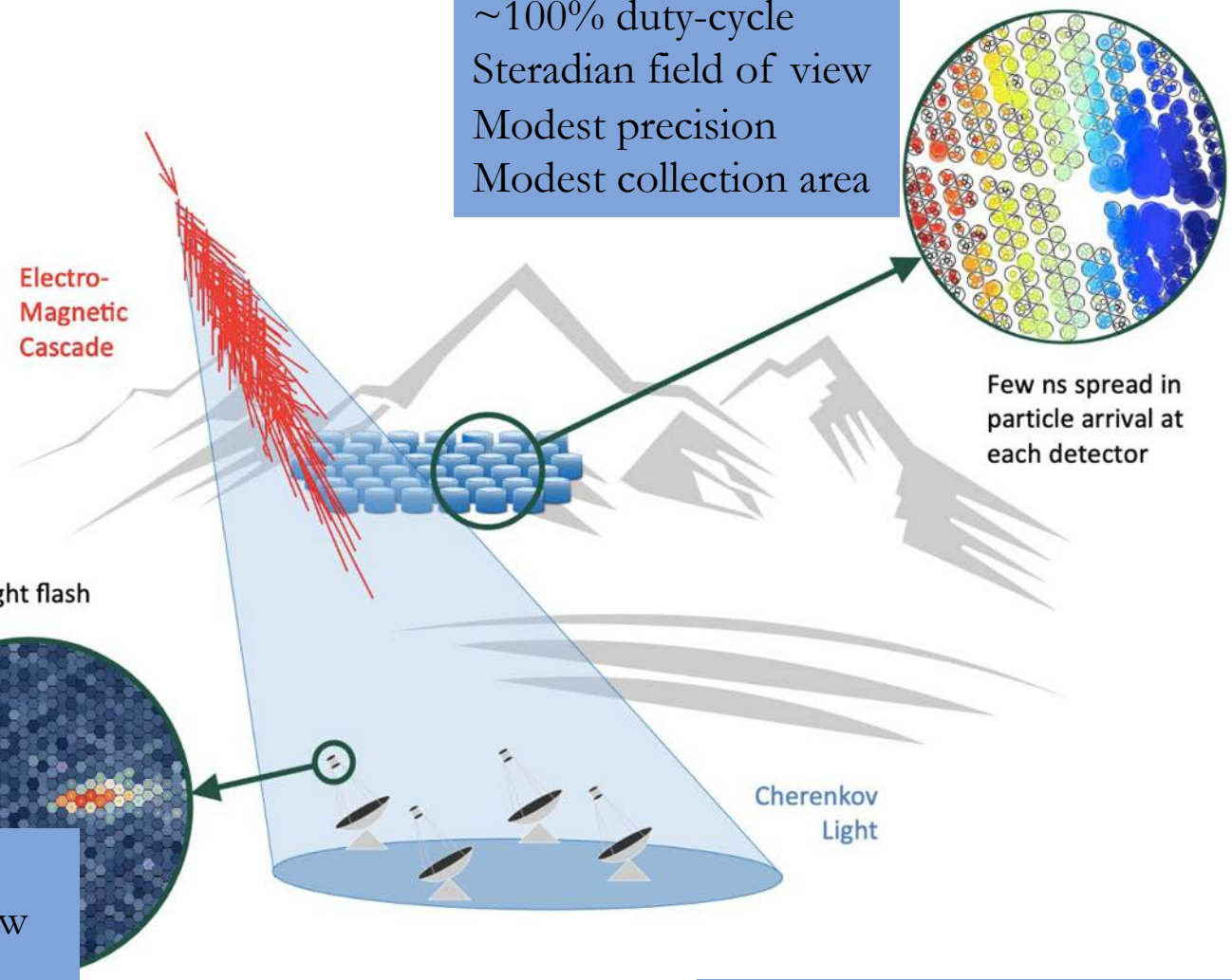
Exceptional sensitivity, but limited field of view, high resolution energy spectra, transients

Large-FoV arrays - HAWC, LHAASO: ~ 0.1 to 100 TeV

High duty cycle, extended sources

VHE Detection Techniques

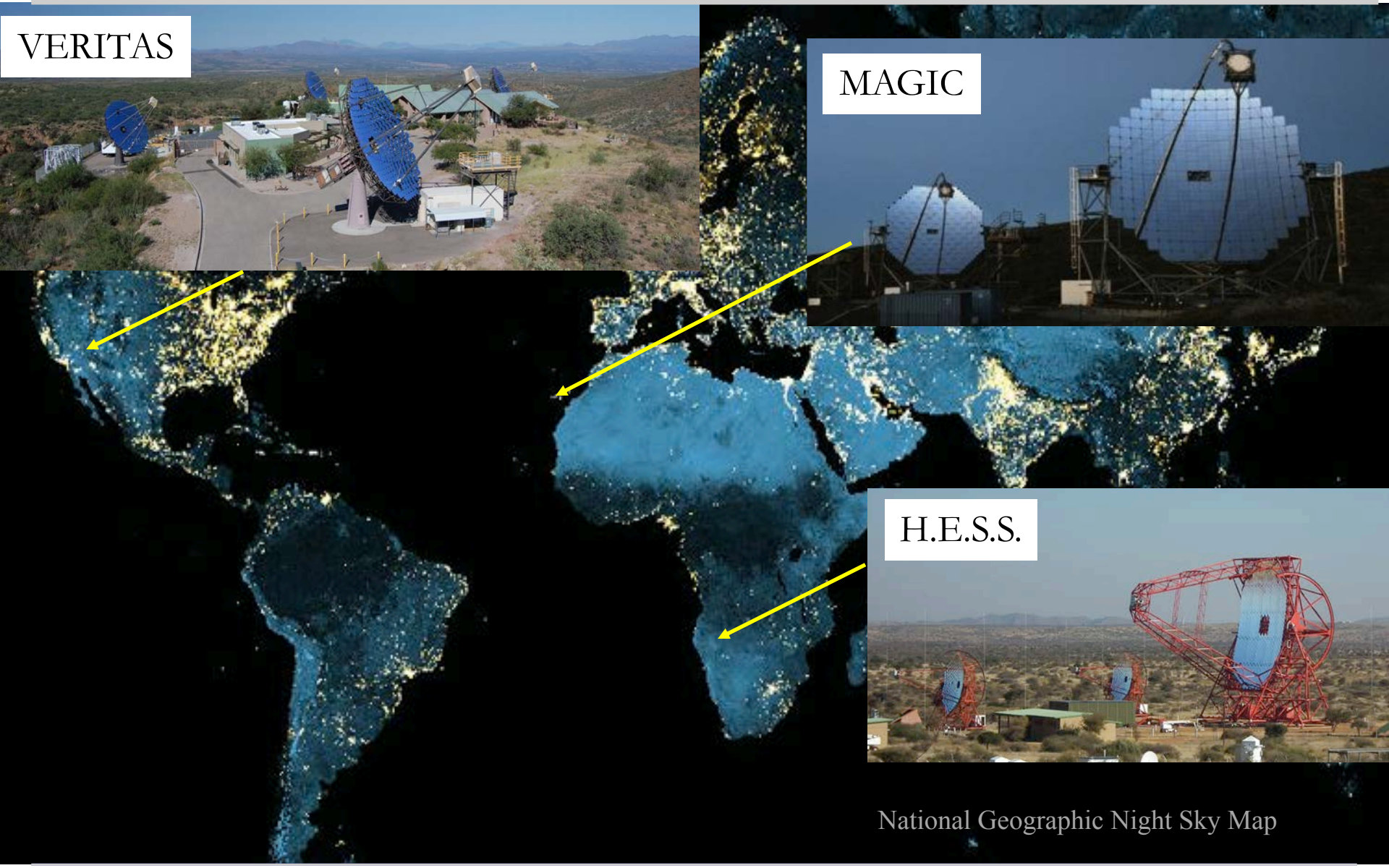
~100% duty-cycle
Steradian field of view
Modest precision
Modest collection area



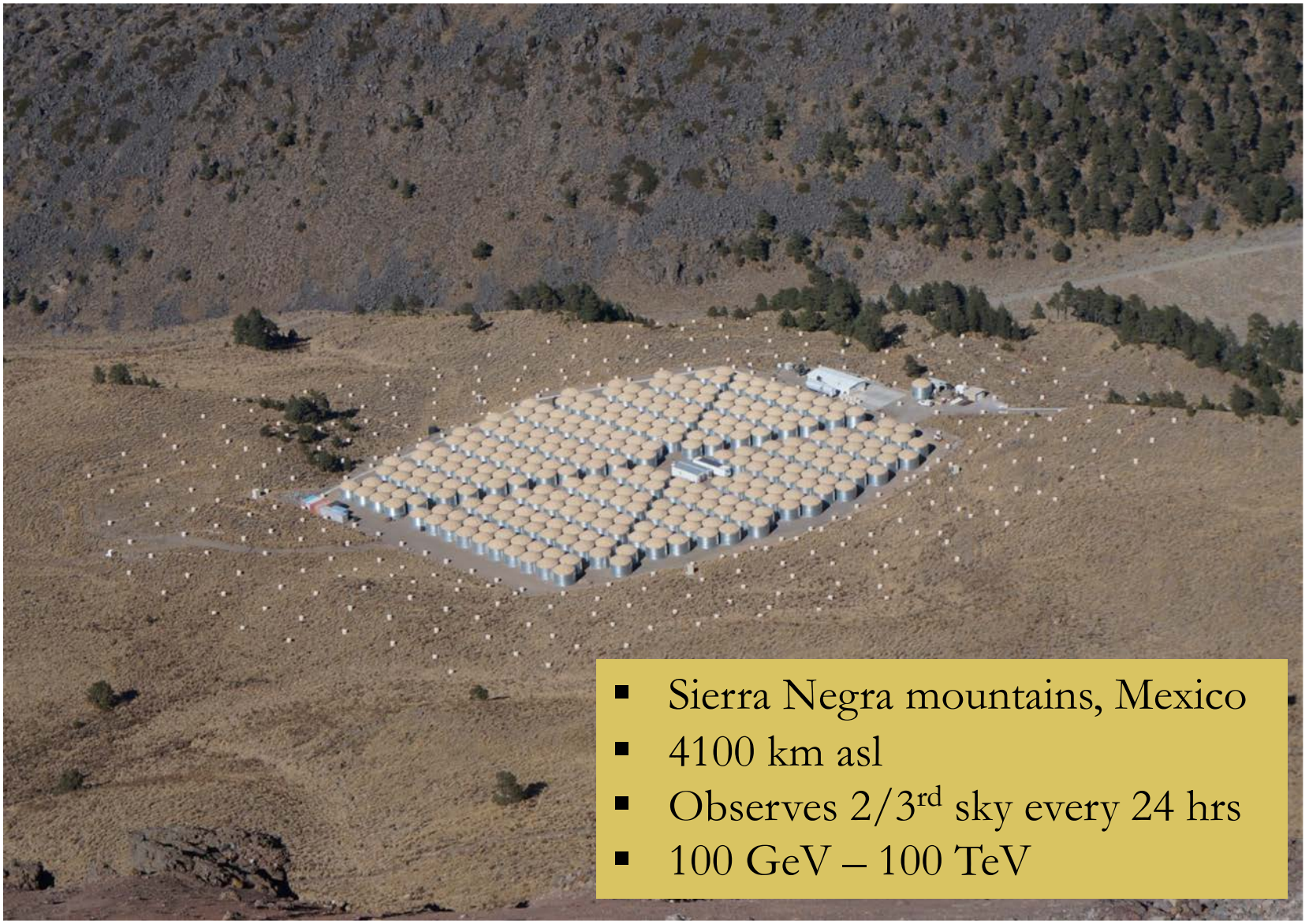
~15% duty-cycle
~4 degree field of view
High precision
Large collection area

Slide courtesy Jim Hinton, ICRC 2021

The Three Major IACTs

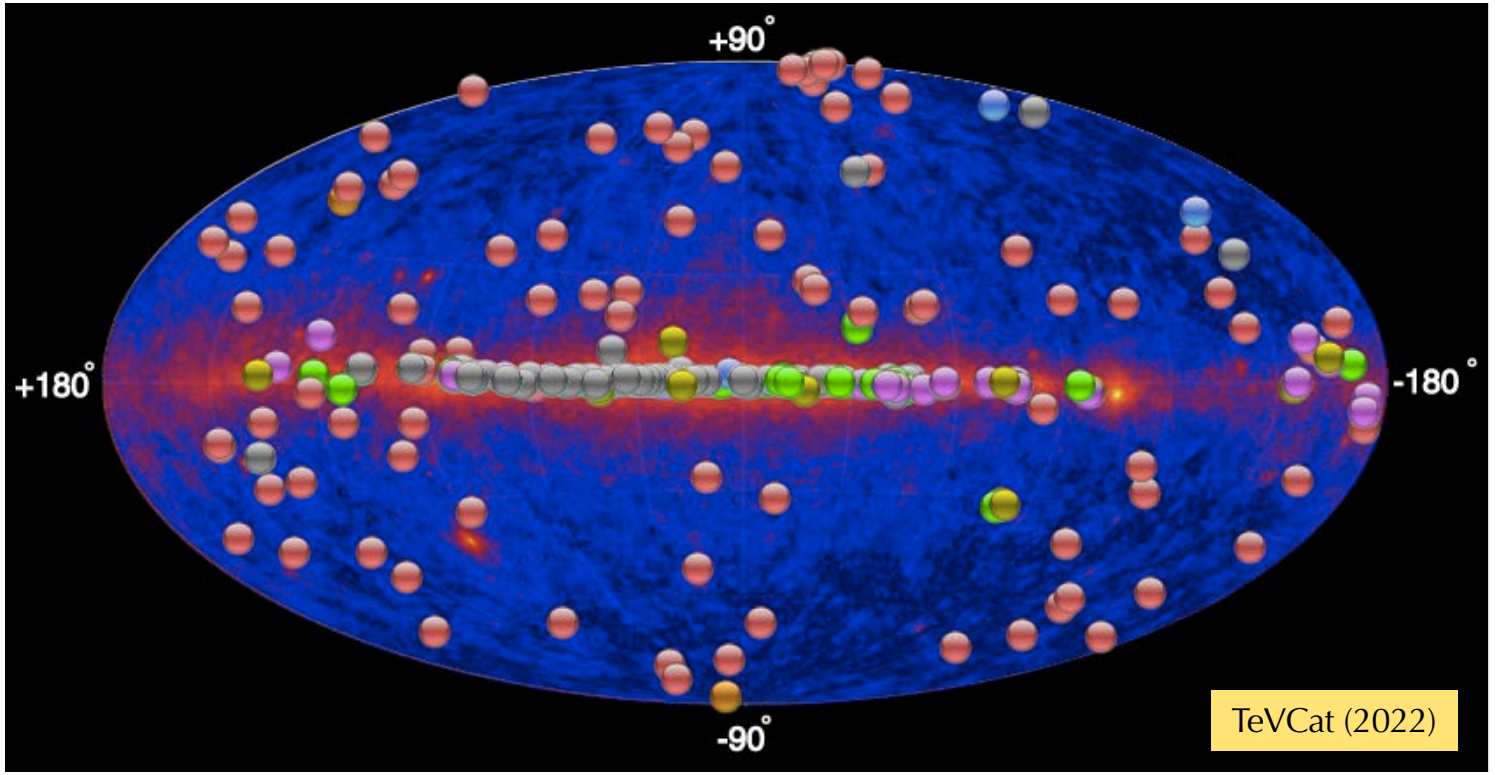


Water Cherenkov Detectors - HAWC



- Sierra Negra mountains, Mexico
- 4100 km asl
- Observes 2/3rd sky every 24 hrs
- 100 GeV – 100 TeV

VHE Gamma-Ray Sky

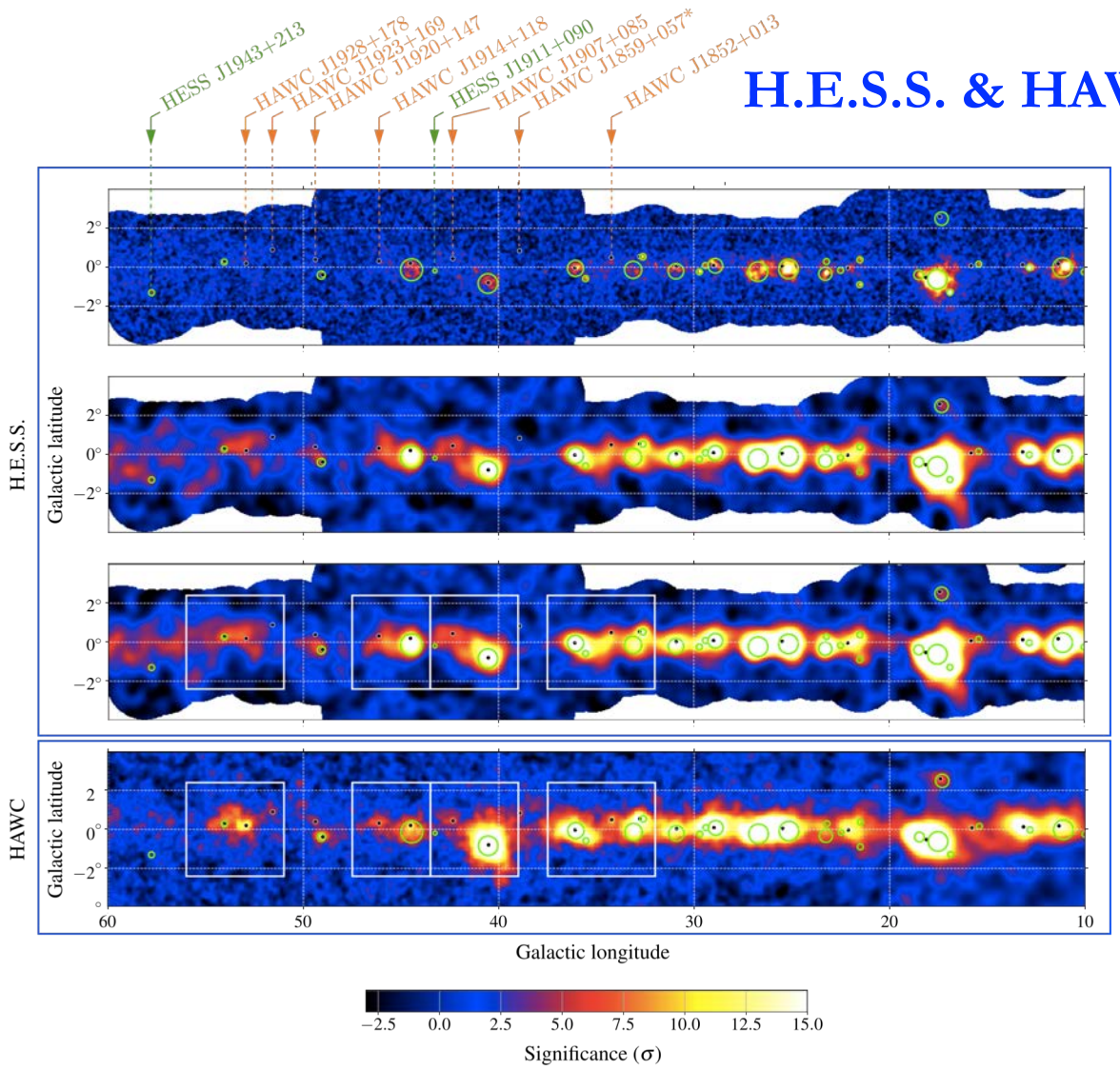


Source Types

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

- More than 200 sources
- 10 different source classes
- Detailed measurements of spectra and light curves

Sensitive Surveys of the Galactic Plane



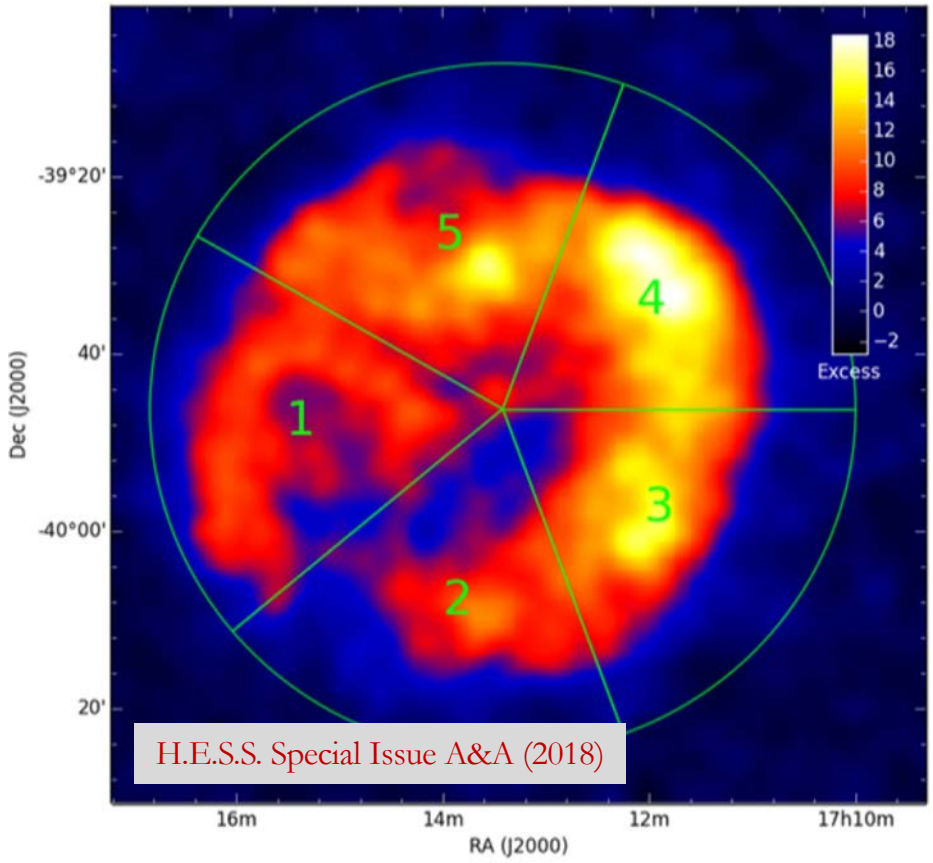
H.E.S.S. & HAWC Galactic Plane Surveys

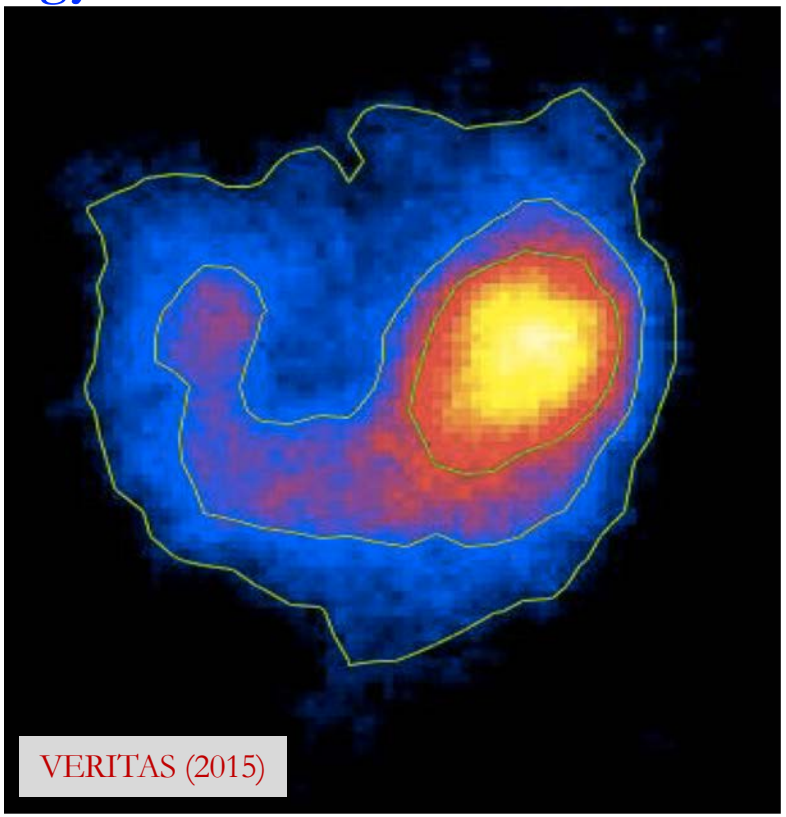
- H.E.S.S. survey of the Milky Way < 2% Crab Nebula sensitivity
- 78 sources in H.E.S.S. GPS
- Comparison of the Galactic plane observed with H.E.S.S. and HAWC: results are consistent

(H. Abdalla et al, ApJ, 2021; arXiv:2107.01425)

Precision Measurements: Supernova remnants

IACTs are able to resolve the morphology of some SNRs





RXJ 1713.7-3946: Spatially resolved spectra with unprecedented resolution (<0.05°)

- TeV shell morphology, close correlation with X-rays, provides insights into physical processes

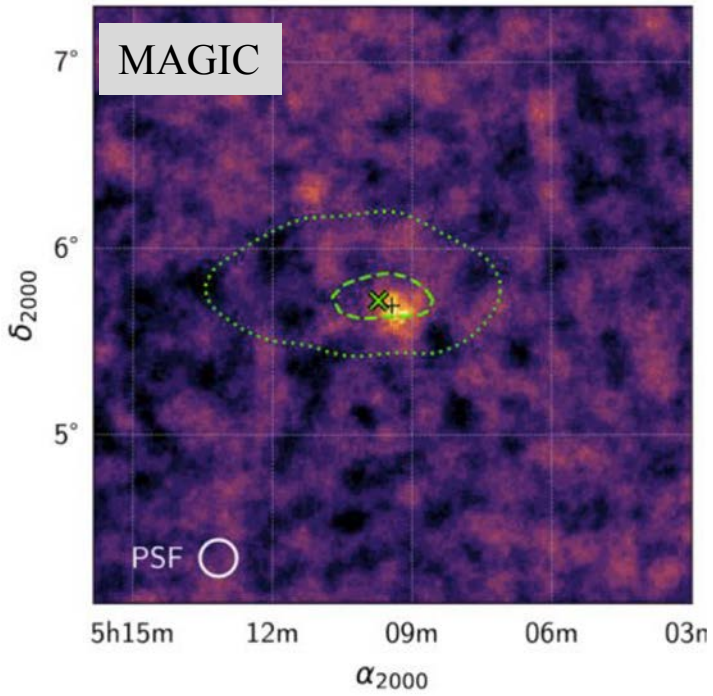
IC 443: Close match between GeV & TeV shell morphology and distribution of shocked gas

Multimessenger: Blazar - Neutrino Association

IC170922 and TXS 0506+056: First evidence (3σ) for a neutrino source

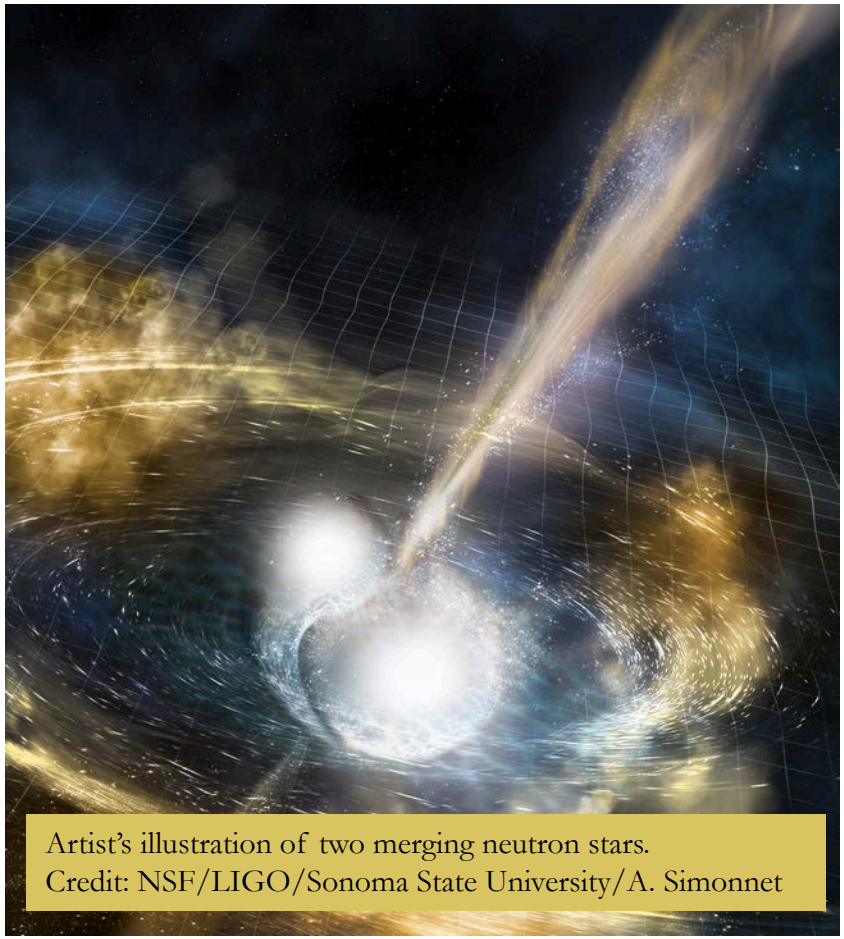
Are blazars the sources of the highest energy cosmic rays?

IceCube + MWL, Science, 361 (2018)

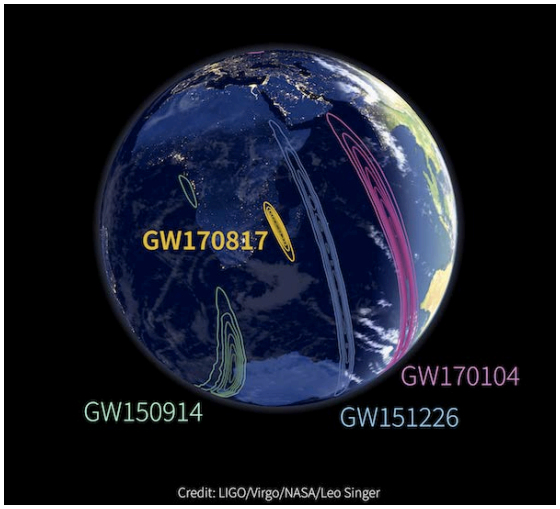


- Sept 22, 2017: Detection of a high-energy ν (E ~ 290 TeV) by IceCube

Multimessenger: EM Counterparts to Gravitational Waves



Artist's illustration of two merging neutron stars.
Credit: NSF/LIGO/Sonoma State University/A. Simonnet



- GW 170817: The first observation of GWs from a binary NS inspiral
- Detected by LIGO & VIRGO
- EM emission observed in multiple wavelength bands
- Associated with GRB170817A (GBM)
- z=0.0098
- Not detected by LAT or IACTs

LIGO, Phys. Rev. Lett., 119, 161101 (2017)

Gamma-Ray Bursts as VHE Sources

GRB 190114C (MAGIC Coll., Nature, 2020)
- long GRB, z = 0.42
- for 40' after T0 +60 s
- 0.2 -1 TeV

GRB 180720B (H.E.S.S. Coll., Nature, 2020)
- long GRB, z = 0.65
- after T0 + 10h

GRB 190829A (H.E.S.S. Coll., Science)
- long GRB, z = 0.078
- for 3 nights after T0 + 4,3h
- 0.18-3.3 TeV

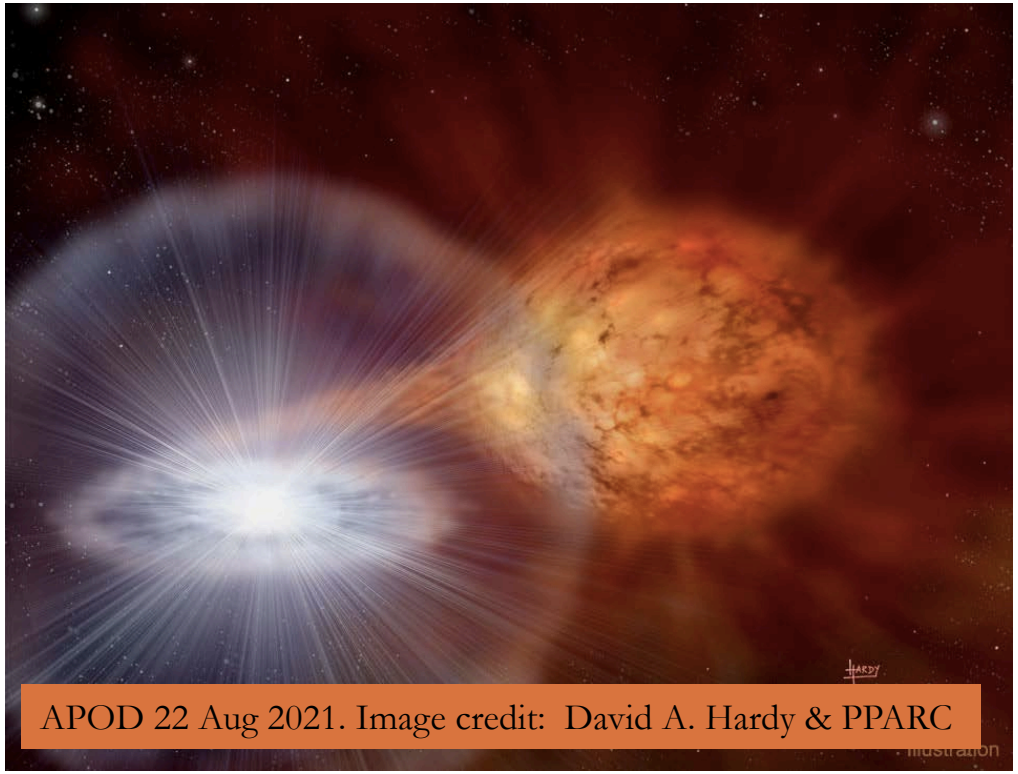
GRB 160821B (MAGIC Coll. ApjL 2021)
- short GRB, z =0.162
- 3σ @ E>500 GeV
- for 4h after T0+24s

GRB 201015A (PoS ID 305, Y.Suda)
- long GRB, z=0.42
- for 3.4 h after T0+40s
- 3.5σ above 50 GeV

GRB 201216C (PoS ID 395, S.Fukami)
- long GRB, z=1.1
- for 20' after T0+

Slide after R. Zanin ICRC 2021

Nova Shocks – New TeV Source Class



APOD 22 Aug 2021. Image credit: David A. Hardy & PPARC

August 2021, ATel #14844:
Detection of VHE gamma-ray emission from the recurrent nova RS Ophiuchi with H.E.S.S.

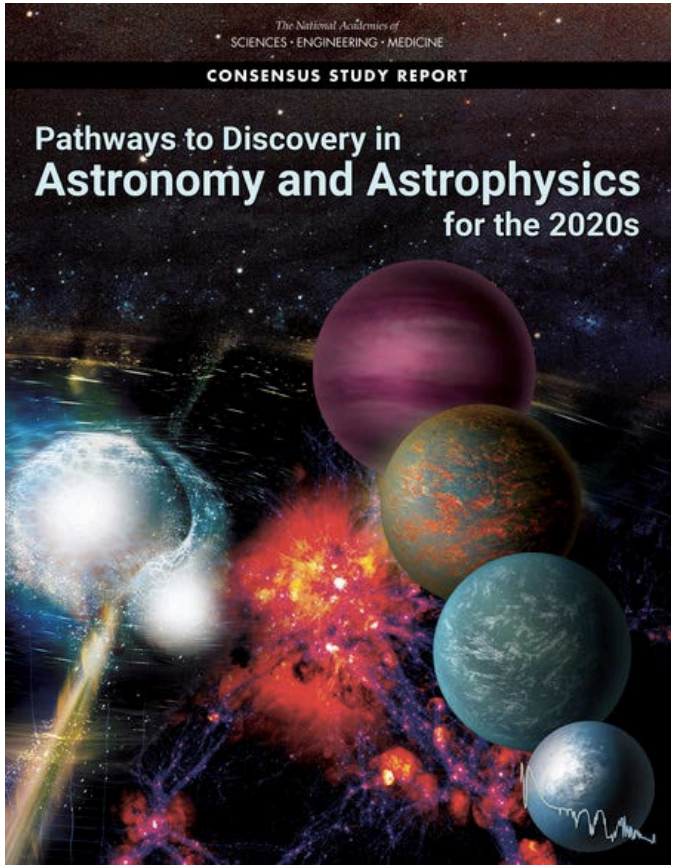
- RS Ophiuchi: High-mass WD/red giant binary, an orbital period of 455d
- Outburst of recurrent nova RS Ophiuchi, detected with Fermi/LAT
- $> 6\sigma$ detection by H.E.S.S.

Gamma-Ray Instruments

in the next decade

- LHAASO
- SWGO
- CTA

The Next Decade and Astro2020



Astro2020 Science

Astro 2020 Science:

Three science themes addressing fundamental and profound questions for humanity and for understanding our place in the space and time of the Cosmos.

A step-by-step path to discovering habitable worlds and life elsewhere.

Time-domain multi-messenger astrophysics to trace the earliest stages of the observable universe

Formation and evolution of stars and galaxies from the Big Bang to today

NSF Town Hall, Debra Fischer, Division Director NSF AST, 12 Jan 2022

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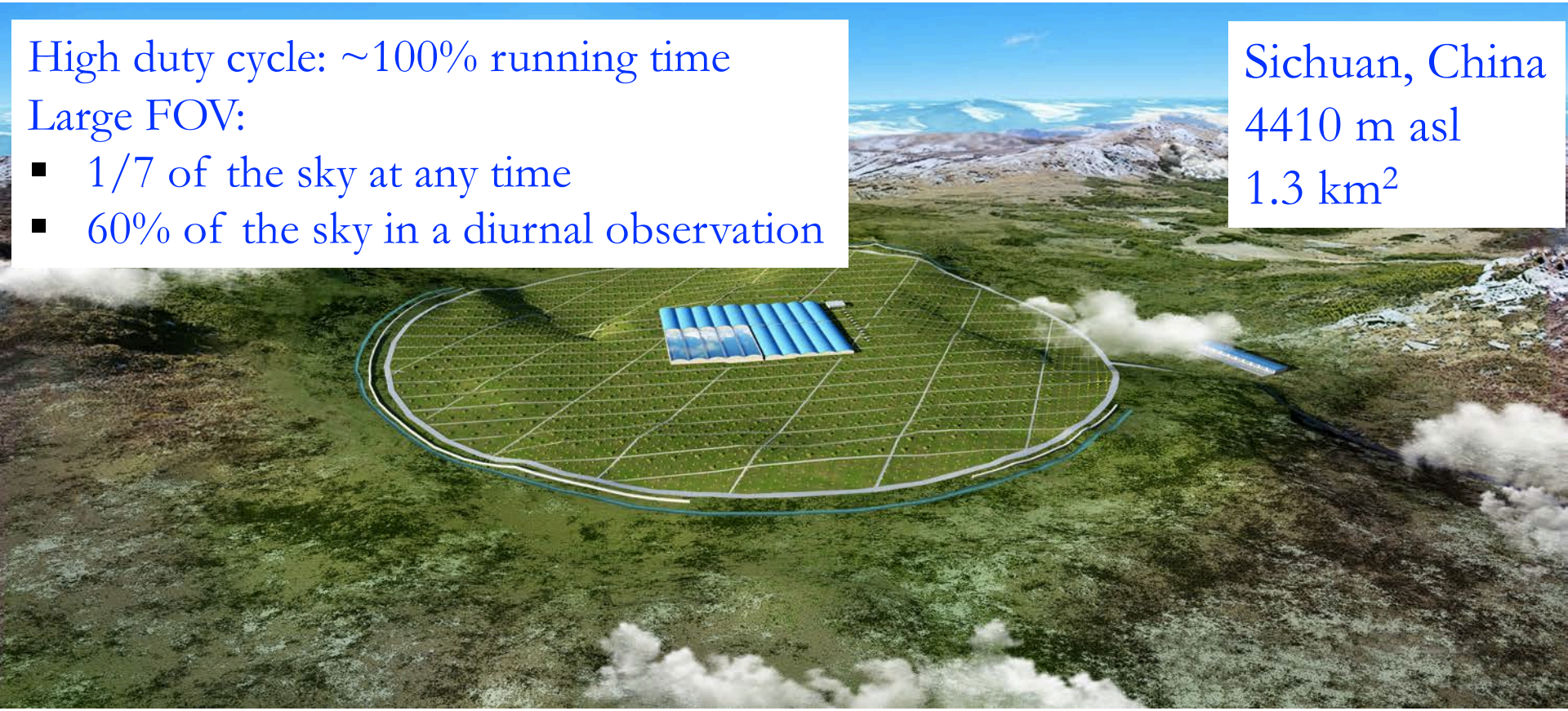
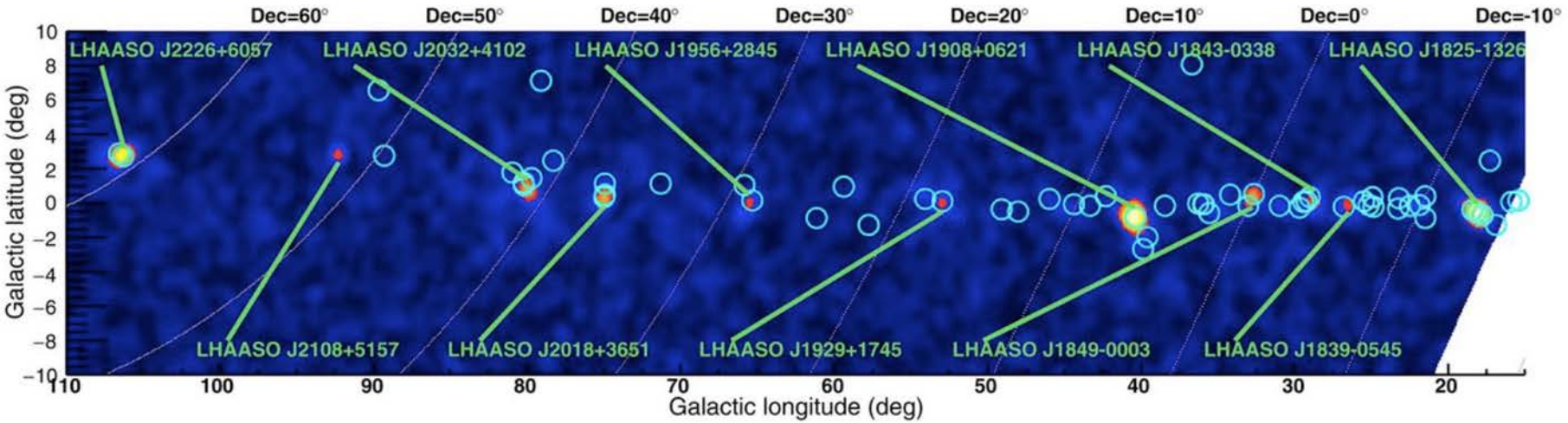
LHAASO



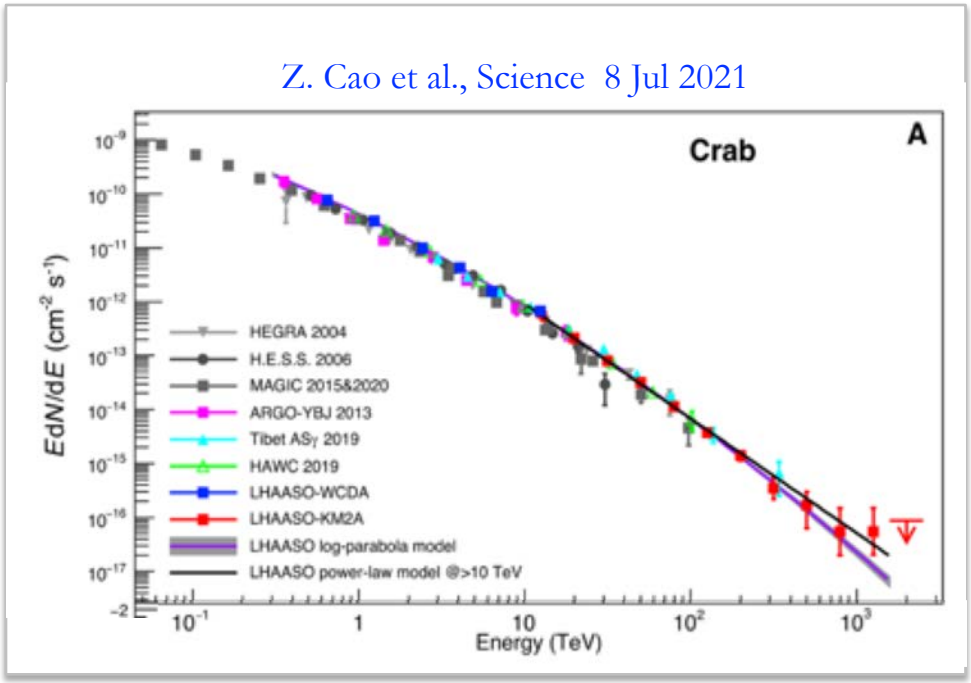
- WCDA (100 GeV - 30 TeV): VHE (>0.1 TeV) γ-ray astronomy
- KM2A (10 TeV - 10 PeV): UHE (>0.1 PeV) γ-ray astronomy
- WFCTA (10 TeV - 1 EeV)
- All detectors are in DAQ since July 2021

From R. Yang, CDY Extreme Accelerators Talk
https://cdy-institute.ie/

LHAASO – First Results



Z. Cao et al., Science 8 Jul 2021

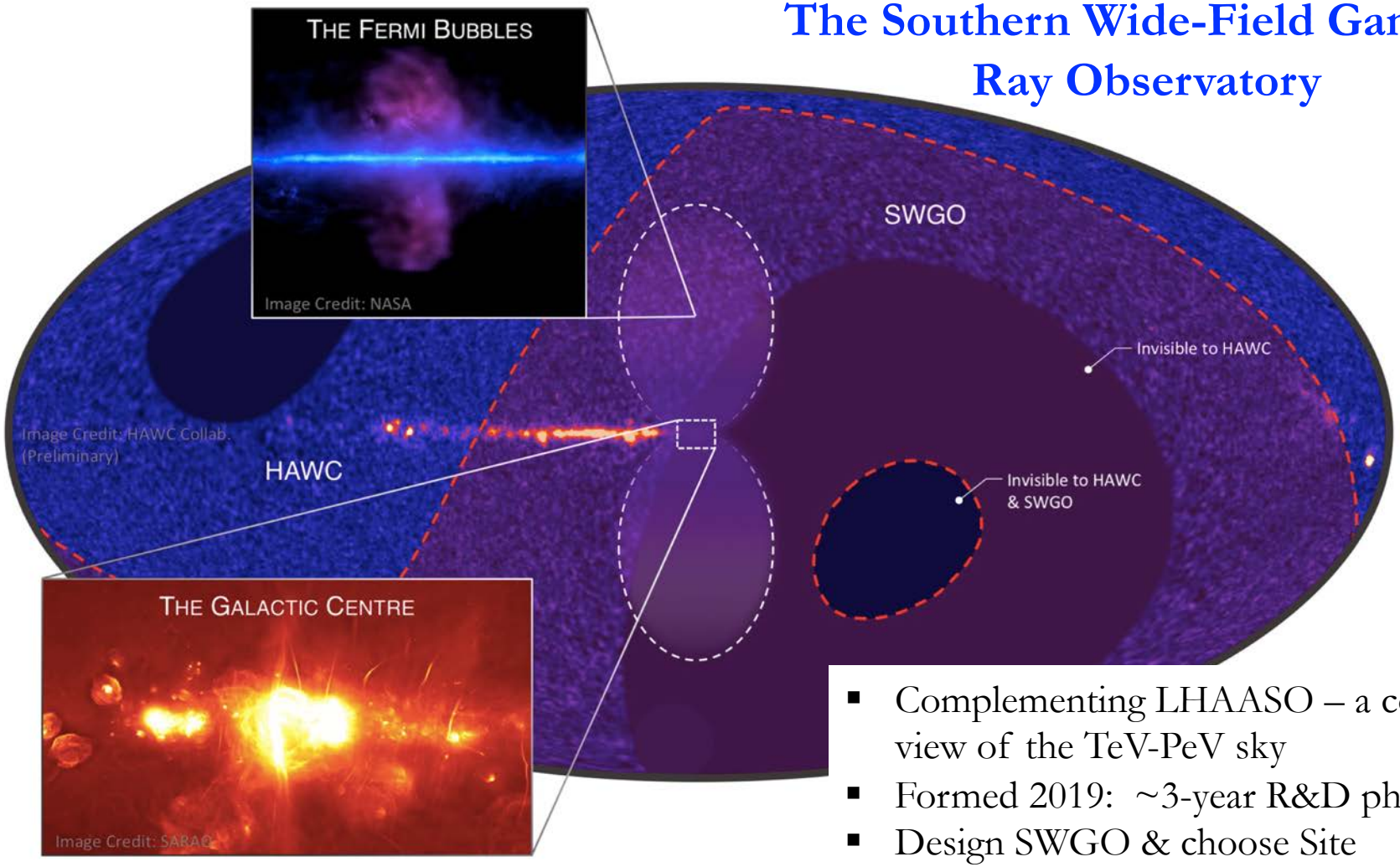


- Detection of more than 530 γ at energies above 100 TeV
- Up to 1.4 PeV from 12 UHE γ-ray sources with a statistical significance > 7σ (Cao et al. Nature, 594, 33, 2021)

Crab Nebula: An extreme electron accelerator: 2.3 PeV electrons

SWGO

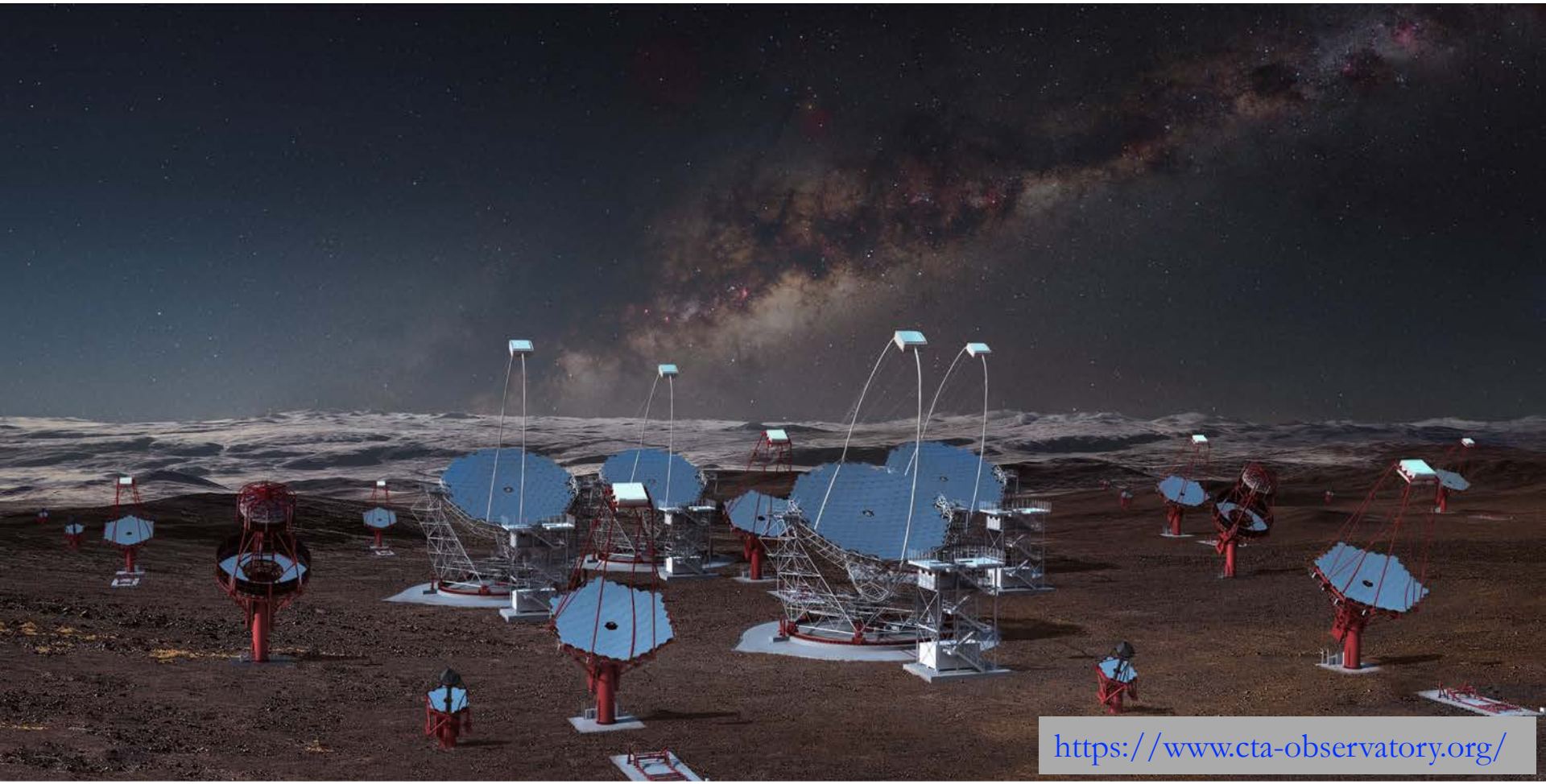
The Southern Wide-Field Gamma-Ray Observatory



- Complementing LHAASO – a complete view of the TeV-PeV sky
- Formed 2019: ~3-year R&D phase
- Design SWGO & choose Site
- Exploring three concepts → Tanks, artificial pond & natural lake

From Hinton, 2021 ICRC

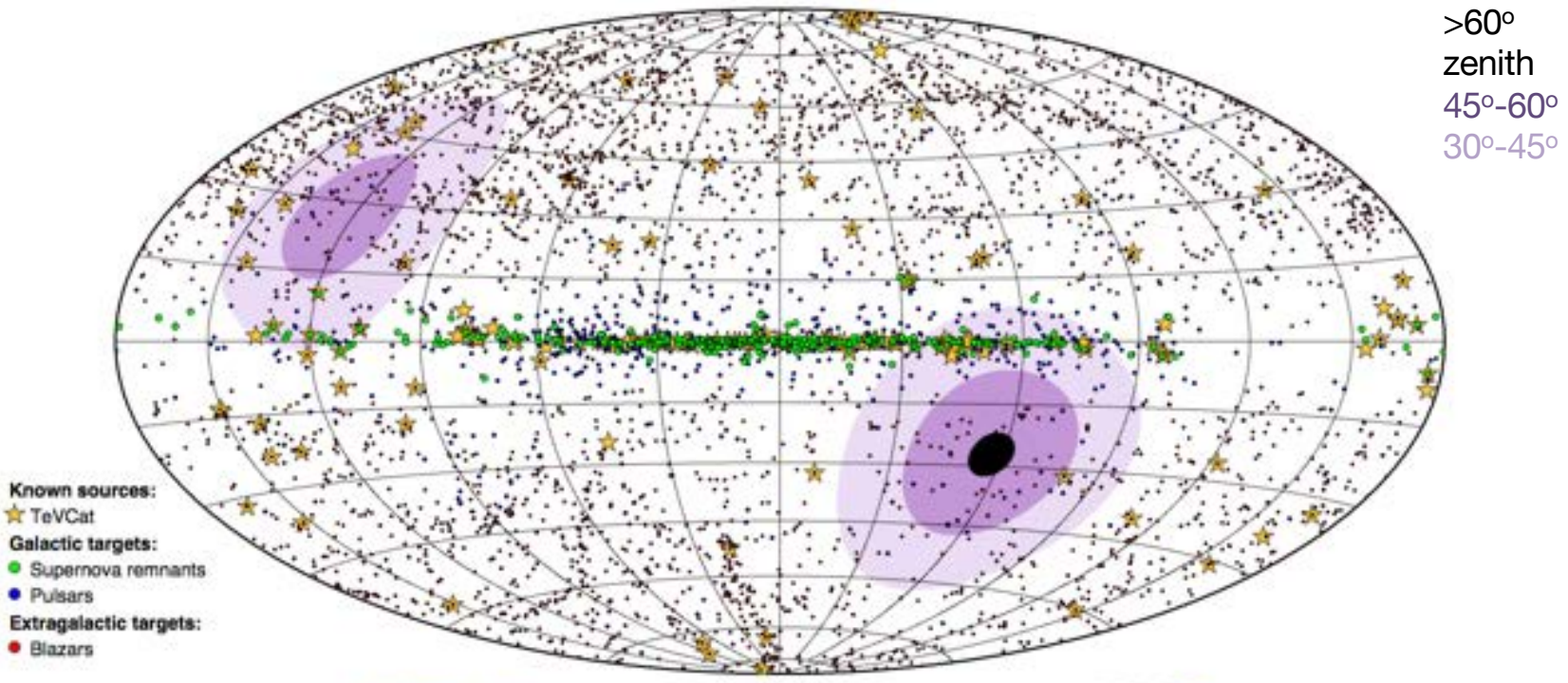
The Cherenkov Telescope Array (CTA)



Latest updates from Roberta Zanin
(CTAO Project Scientist)
ICRC 2021

25 Countries
Over 150 Institutes
About 1500 Members

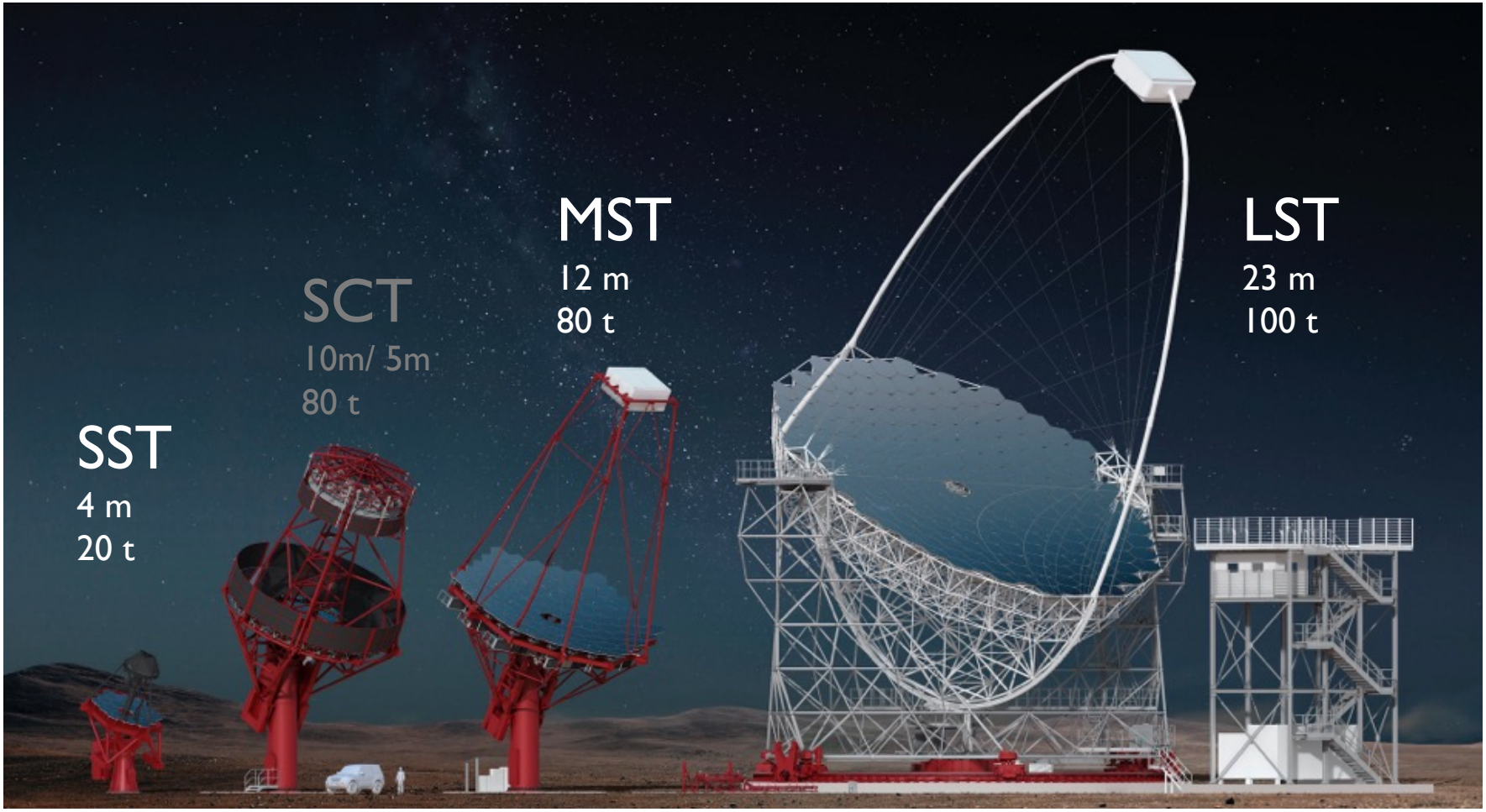
CTA DESIGN drivers



- Sensitivity (x10)
- Full-sky coverage, larger FoV (x2)
- Wide energy range: 20 GeV to 300 TeV
- Arc-min angular resolution
- 10% energy resolution
- Rapid slewing for transient follow-up

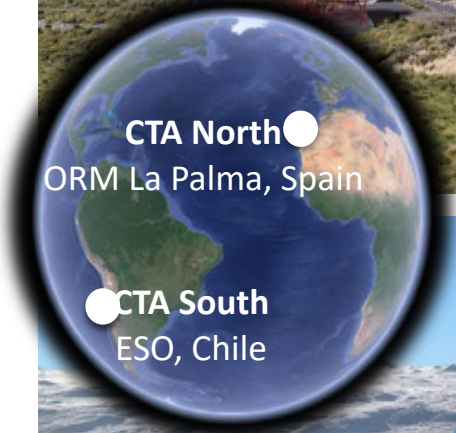
CTA Telescope Designs: (Enhancement Phase)

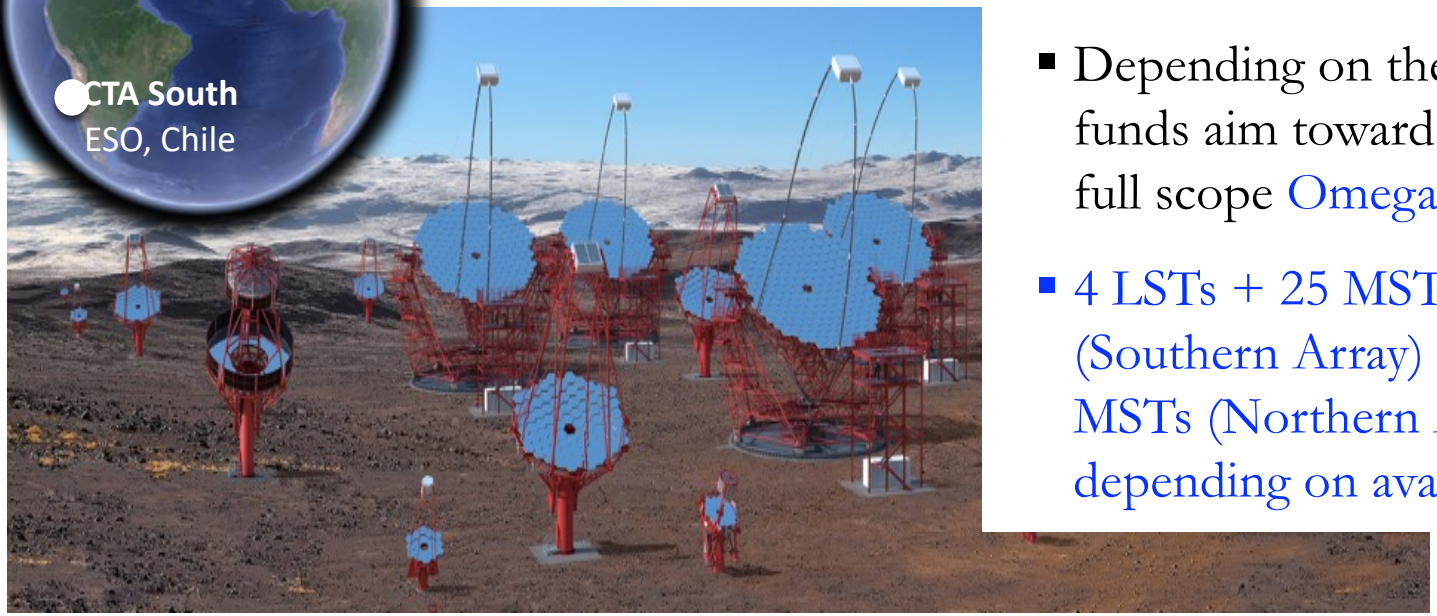
https://www.cta-observatory.org/project/technology/



Adding U.S.-led Schwarzschild-Couder Telescope (SCT) dual-mirror design

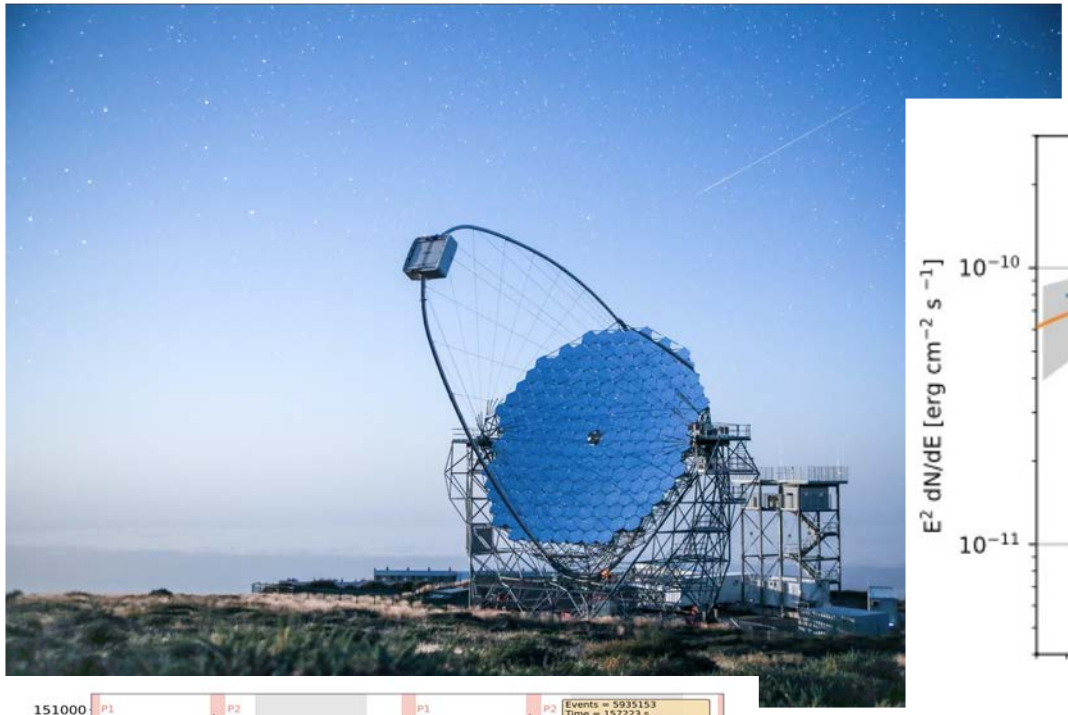
CTA Project Phases



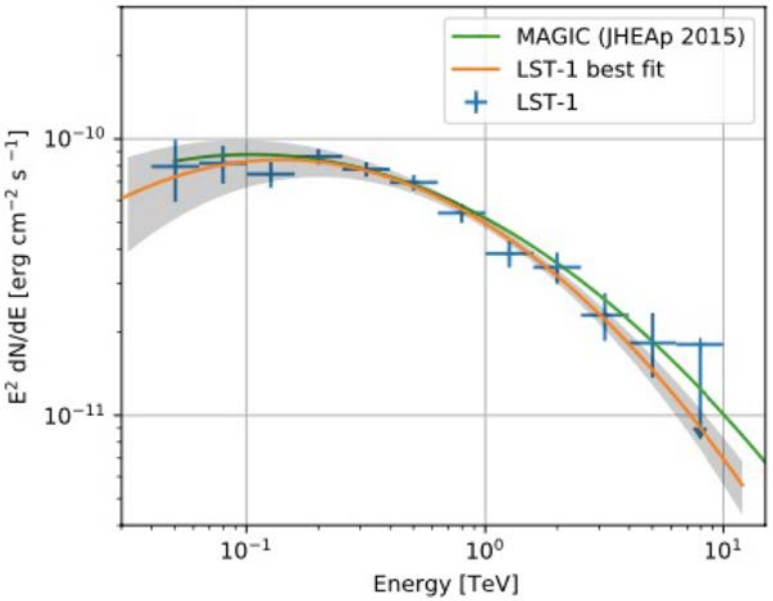


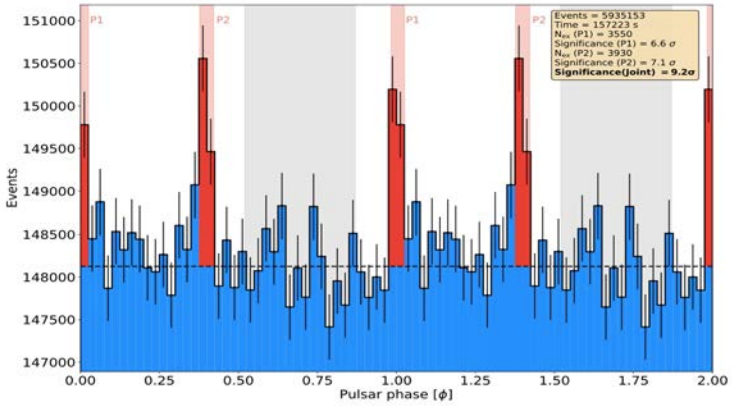
- **Construction phase (5 years):** Alpha configuration: Southern Array: 14 MSTs + 37 SSTs; Northern Array: 4 LSTs + 9 MSTs
- **Operation & Enhancement phase**
- Depending on the availability of funds aim towards deployment of full scope Omega configuration
- 4 LSTs + 25 MSTs + 70 SSTs (Southern Array) and 4 LSTs + 15 MSTs (Northern Array), depending on available funds

CTA Large-Sized Telescope



LST-1 already performing science

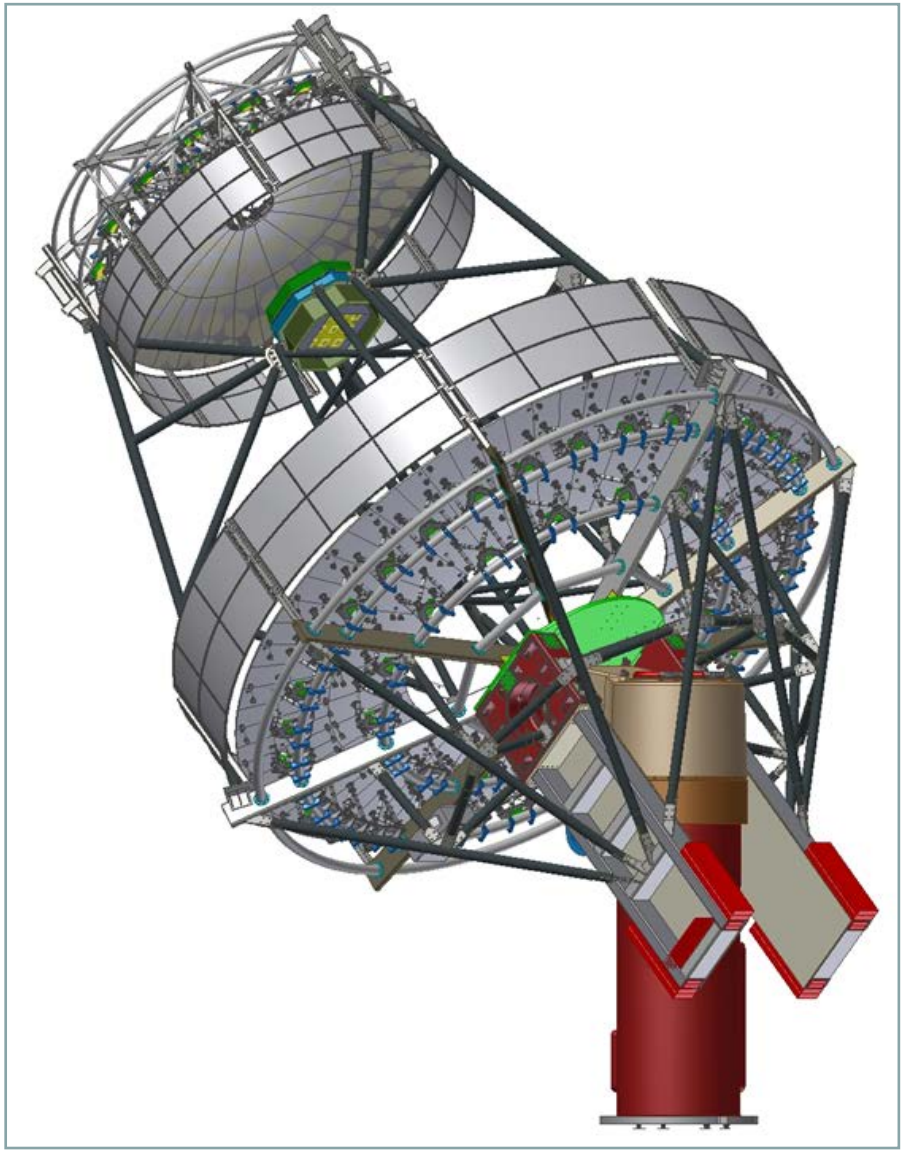




- Detection of Crab Nebula and pulsar
- AGN Detections: Mrk 501, Mrk 421, 1ES 1959+650, 1ES 0647+250 and PG 1553+113

CTA LST Project ICRC 2021
R. Zanin ICRC 2021

The SCT: big eyes with a sharper view



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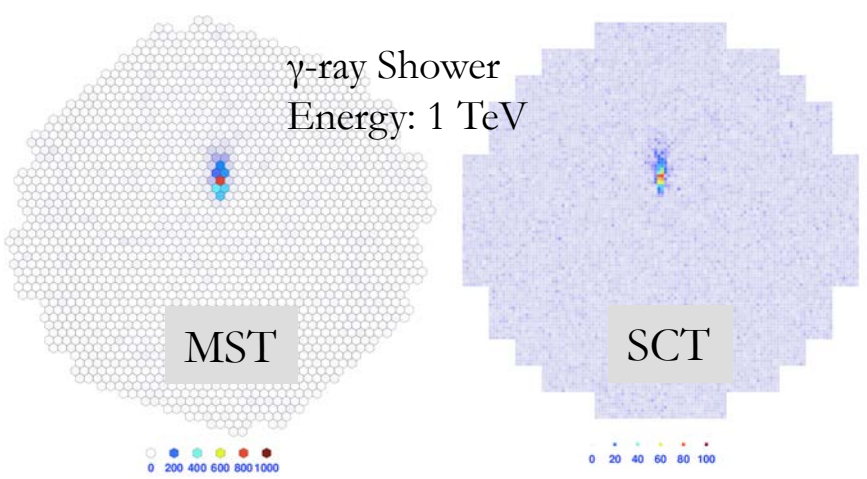
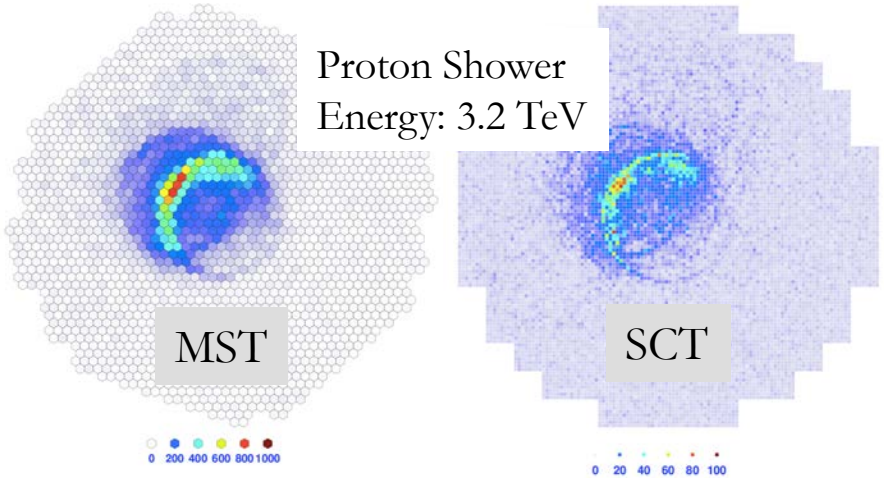


DC-MST Images
7.7° field of view, 0.17° pixels
1,855 channels



SCT Images
8° field of view, 0.067° pixels
11,328 channels

- Superior optical angular resolution over a wide (~8°) field of view
- Light focused on a smaller surface → enables the use of state-of-the-art sensors
- Better sensitivity and reduced observation time
- Better γ-ray PSF across the FoV for morphology, survey, and transients

The CTA SCT Project

- Jan 23, 2019: First light of the prototype SCT (pSCT)
- May 2020: Detection of the Crab Nebula reported (Astropart. Phys., 128, 102562, 2021)
- Oct 2020: CTA Consortium endorses the development and construction of SCTs to enhance and complement DC-MSTs
- Ongoing: Instrumentation of the focal plane to 11k+ channels with upgraded SiPMs
- 2023: Expected completion of pSCT camera upgrade to full 8° field of view

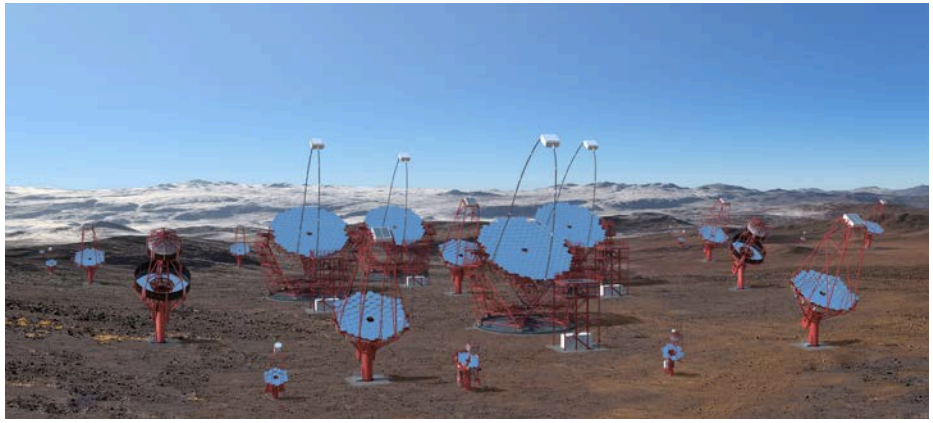
Astro 2020 Decadal Survey endorses CTA-US contributions of SCT telescopes as an essential element of US multimessenger strategy

Astro2020 Decadal Survey:

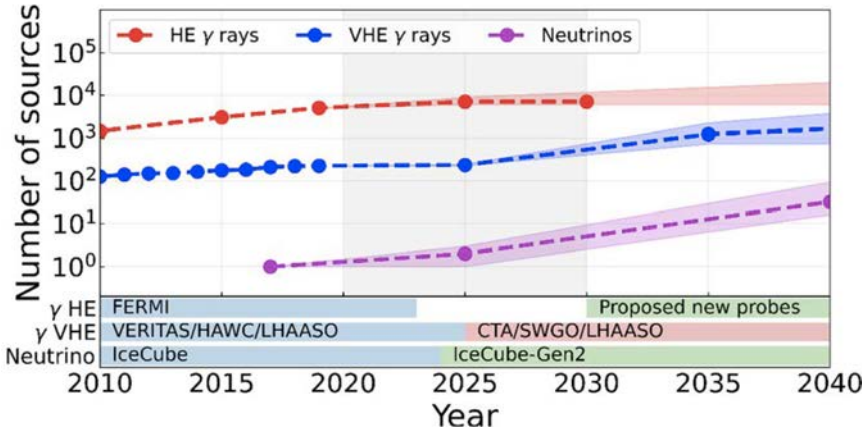
Panel of Particle Astrophysics and Gravitation Recommendations

- **VHE/UHE γ-Ray Astronomy**
  - US participation in CTA Ground Based Observatory
  - CTAO is mature project, ready to move forward
  - 10 SCT Telescopes- completed design, move to production
  - $40M US Construction costs , $3M/year US operations costs

- **US participation in SWGO**
  - $20M US Construction cost
  - Southern hemisphere extension of an air shower detector array for VHE γ-ray astronomy based upon HAWC technology

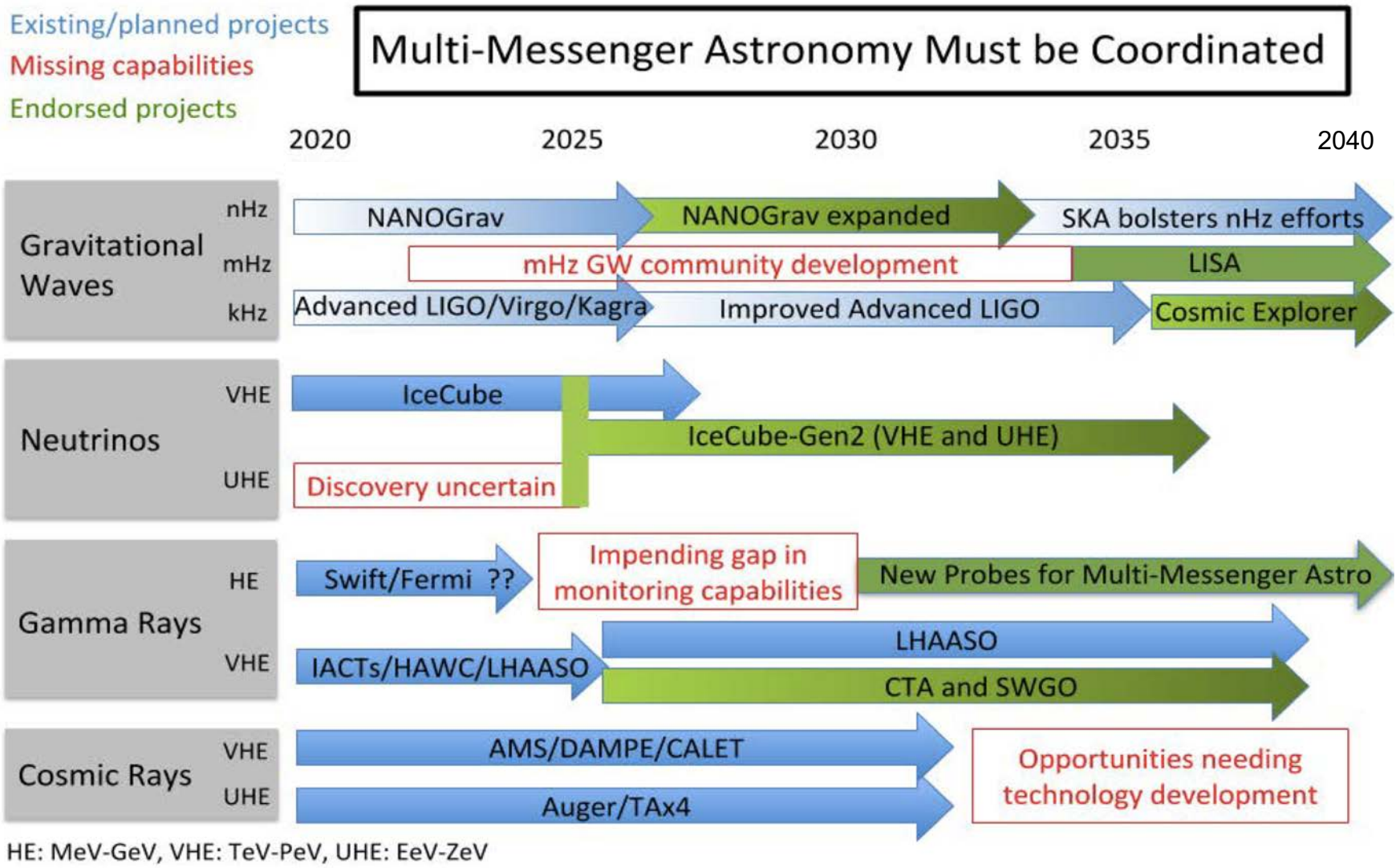


Slide from Dave Kieda, CTA Meeting 2021



Astro2020 Decadal Survey:

Continuity of Multi-messenger Capabilities

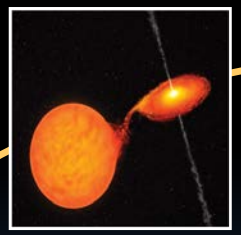


Exploring the non-thermal Universe "ASTRO"

Pulsars/PWN

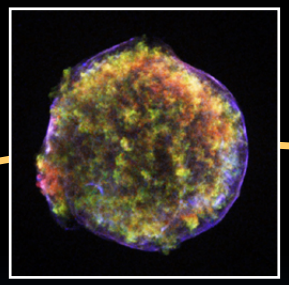
NS dynamo winds

Binaries



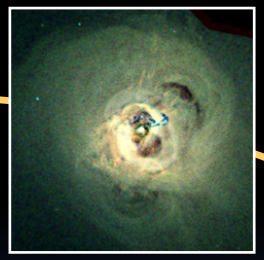
Jets, winds

SNRs



Shocks Fermi Mech.

Starbursts

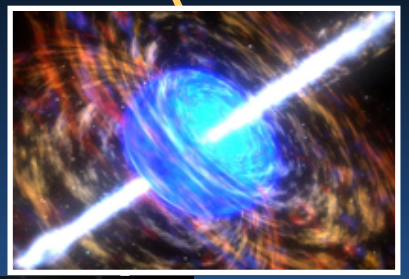


SN activity Cosmic rays

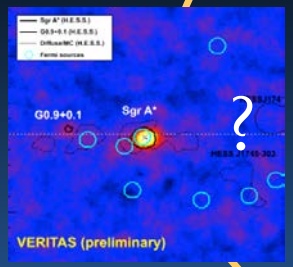
AGN

SMBH accretion, jets

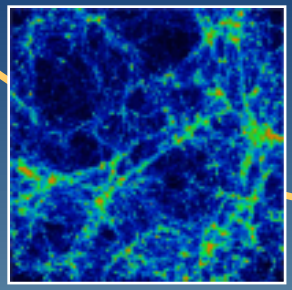
GRBs



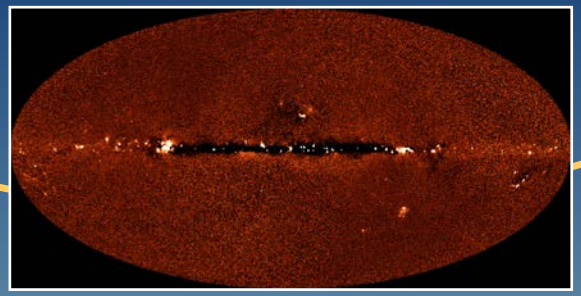
VHE γ-rays



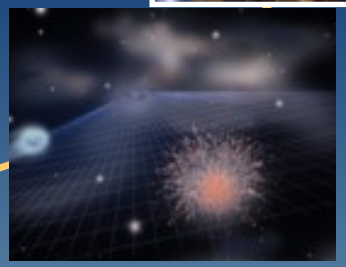
Unknowns (Gal Center)



Dark Matter



Cosmological Fields



PBHs, QGrav

Probing New Physics at GeV/TeV scale "PARTICLE"

Slide from Rene Ong

Summary and Outlook

- CTA will cover 20 GeV to 300 TeV range, with superior angular resolution and sensitivity
- LHAASO will have unprecedented reach >20 TeV -- Ideal for PeVatron searches
- SWGO will complement LHAASO – a complete view of the TeV-PeV sky
- Synergy between IACTs and Water Cherenkov detectors: Detailed morphology study of PeVatrons, TeV halo, supernova shells now possible
- TeV instruments will be critical partners in multimessenger studies
- Complementary coverage with satellite missions in the MeV – GeV range will be crucial

Thank you