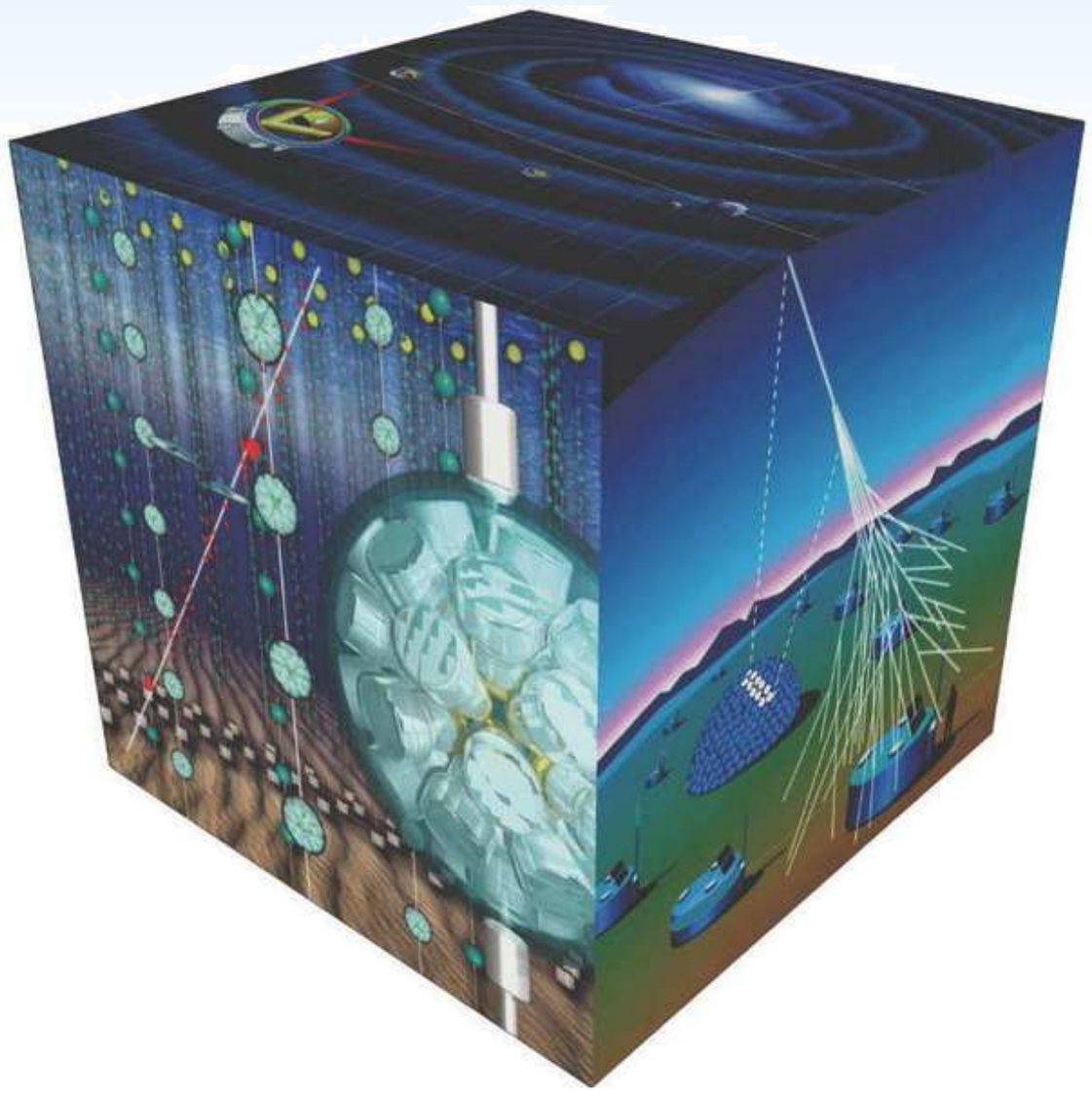
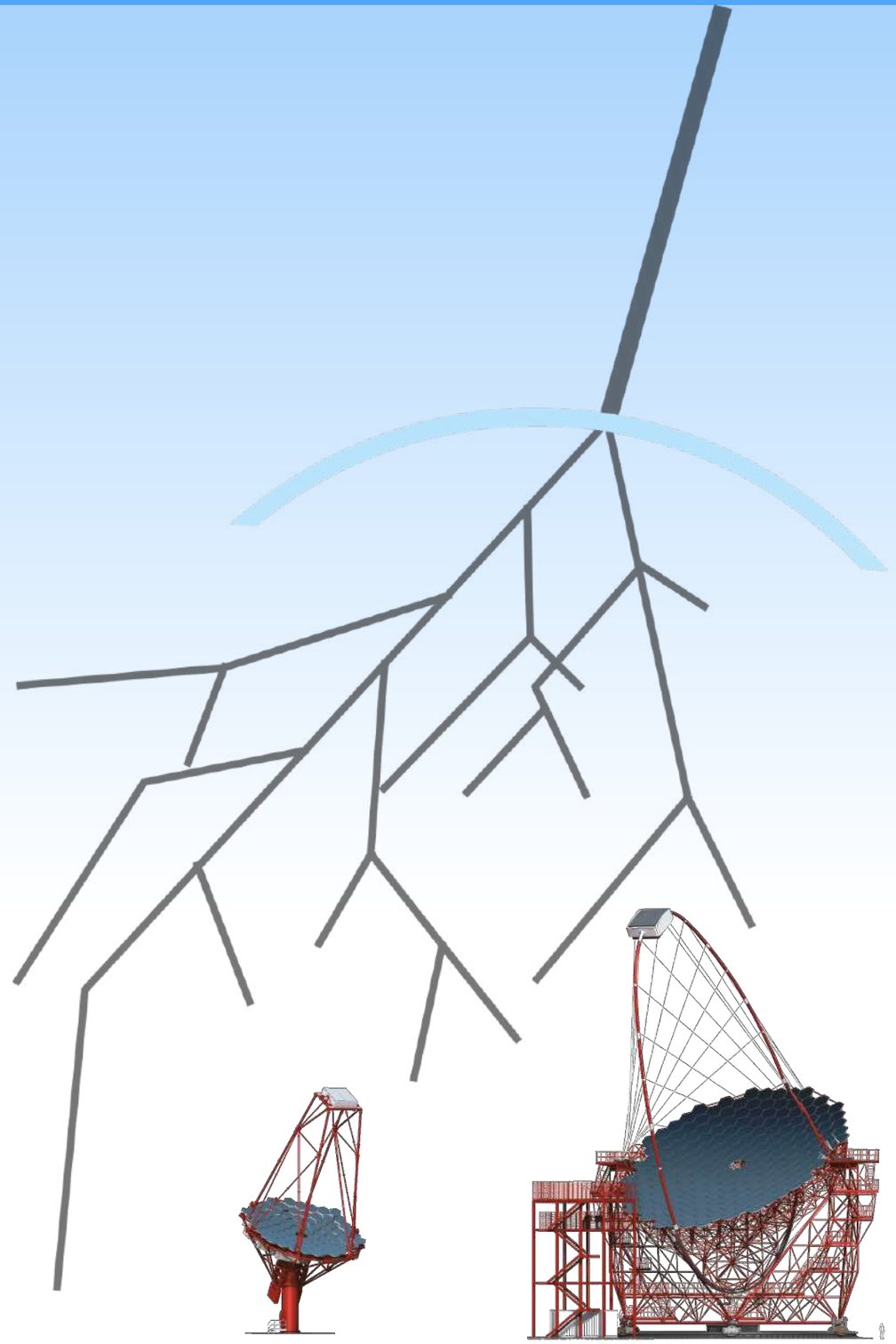
Science with CTA

MWL & Multi-messenger connections

Ulisses Barres de Almeida
Brazilian Center for Physics Research
& the CTA Consortium





CBPF
Centro Brasileiro de Pesquisas Físicas

MCTIC

cta
cherenkov telescope array

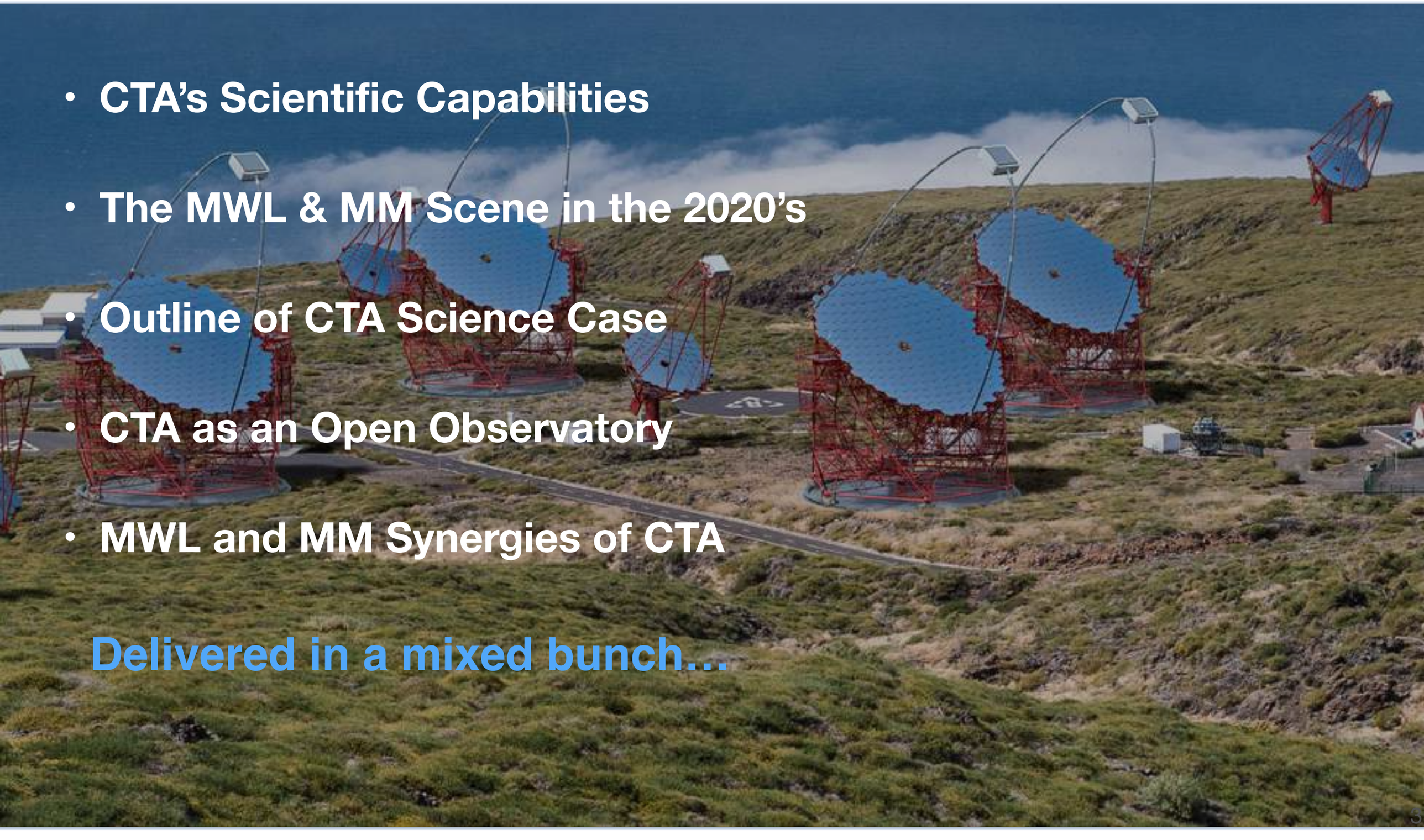
BASELINE DOCUMENT

A complete outlook on the CTA science and potentials.

Now available as a book by World Scientific.

Open access in astro-ph: arXiv:1709.07997

TOPICS OF THIS TALK

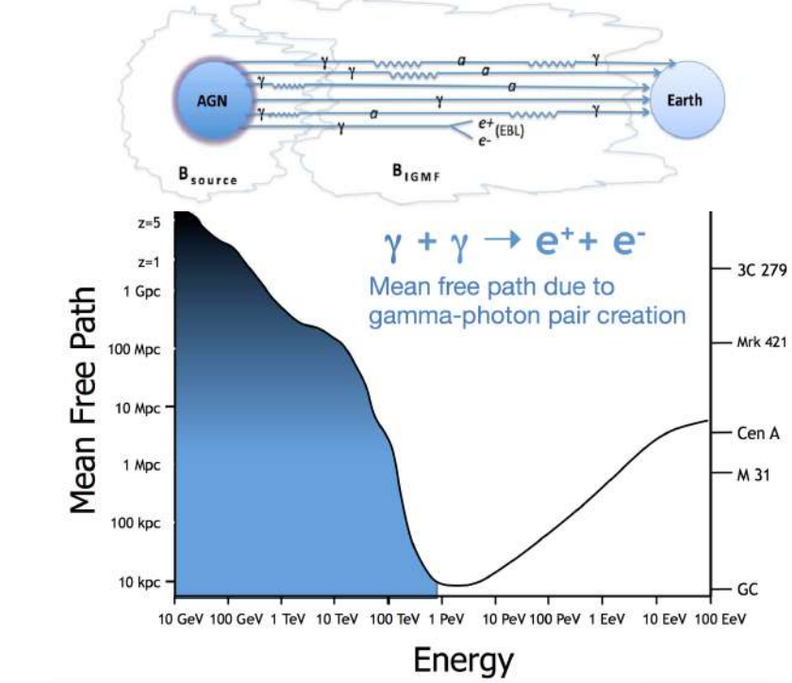


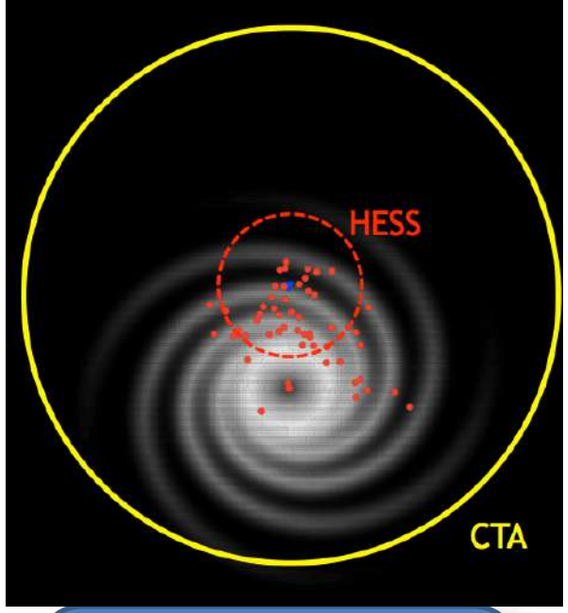
- **CTA's Scientific Capabilities**
- **The MWL & MM Scene in the 2020's**
- **Outline of CTA Science Case**
- **CTA as an Open Observatory**
- **MWL and MM Synergies of CTA**

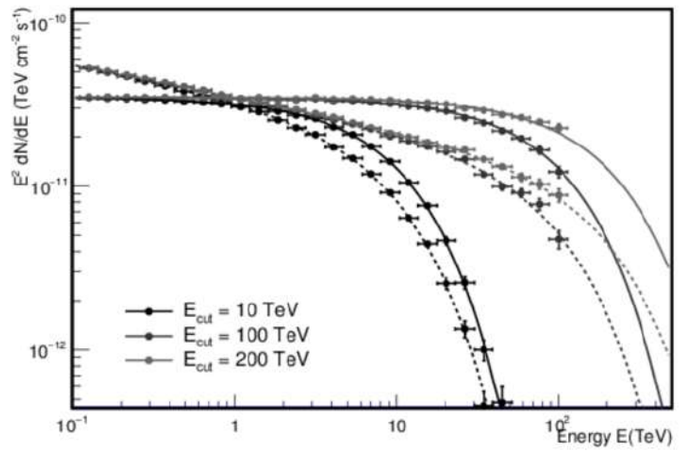
Delivered in a mixed bunch…

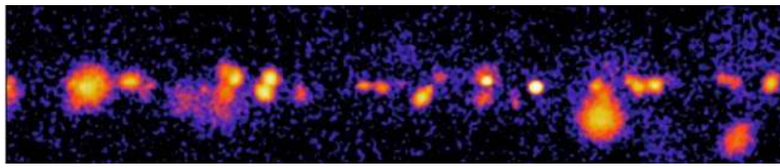
THE THICK OF CTA SCIENCE

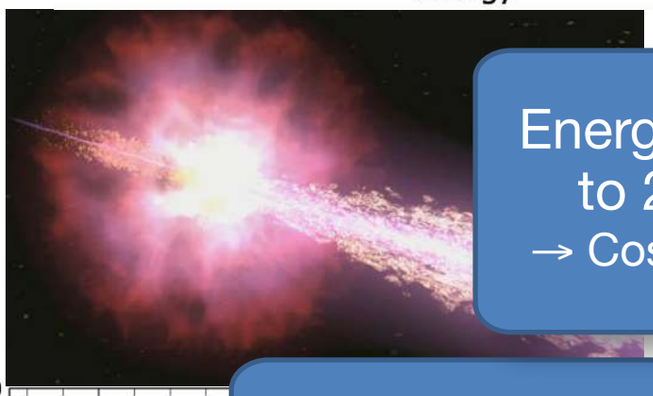
- Understanding the Origin and Role of Relativistic Cosmic Particles
  - What are the sites of **high-energy particle acceleration** in the universe?
  - What are the mechanisms for cosmic particle acceleration?
  - What role do accelerated particles play on star formation and galaxy evolution?
- Probing Extreme Environments
  - What physical processes are at work close to **neutron stars and black holes**?
  - What are the characteristics of **relativistic jets**, winds and explosions?
  - How intense are radiation fields and magnetic fields in cosmic voids?
- Exploring Frontier Physics
  - What is the **nature of dark matter**? How is it distributed?
  - Are there quantum gravity effects on photon propagation?
  - Do axion-like particles exist?

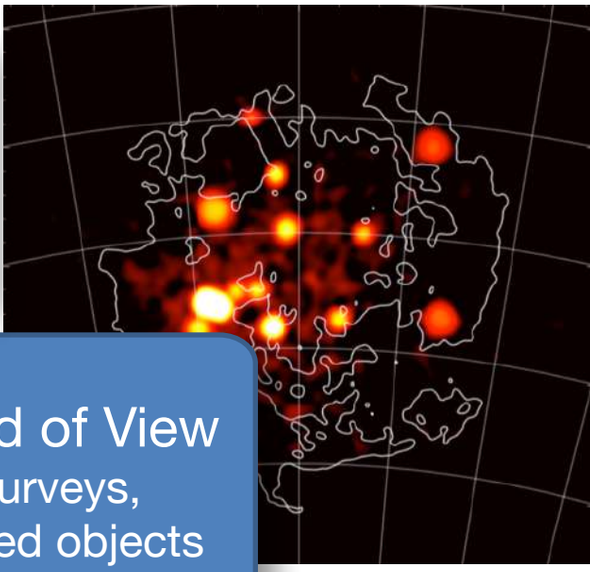


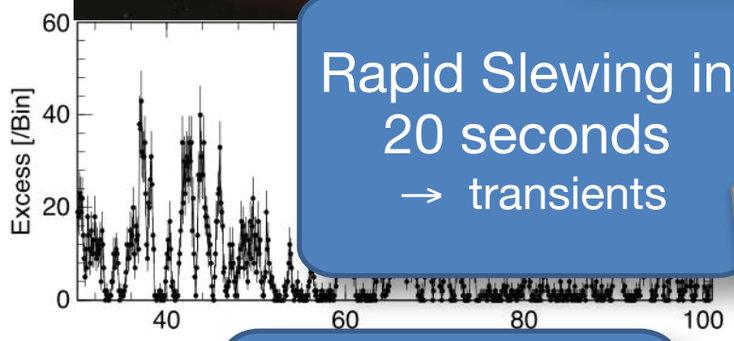


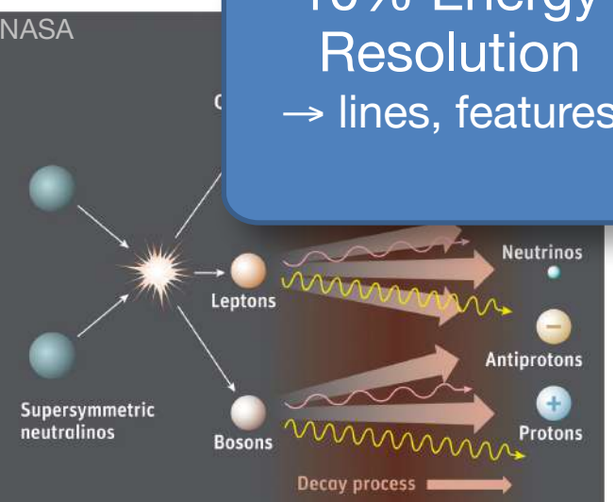


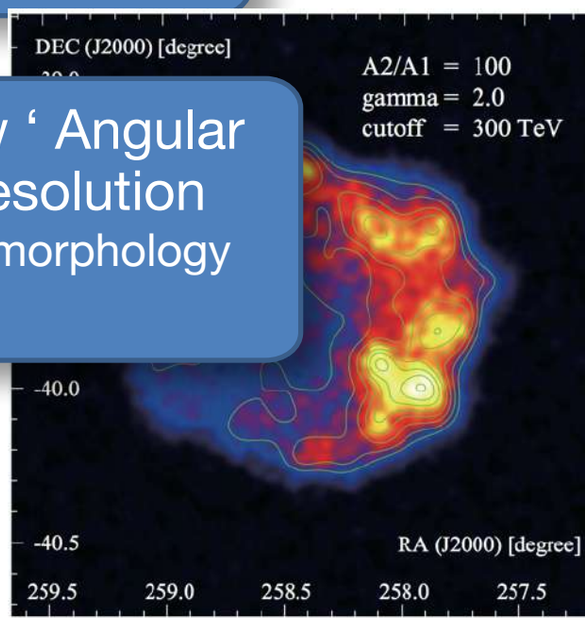












10 x Sensitivity, Large Collection Area
→ all topics

Energies down to 20 GeV
→ Cosmology++

Energies up to 300 TeV
→ Pevatrons

Rapid Slewing in 20 seconds
→ transients

8° Field of View
→ surveys, extended objects

10% Energy Resolution
→ lines, features

Few ‘ Angular Resolution
→ morphology

cta
cherenkov telescope array

Credit: Werner Hofmann

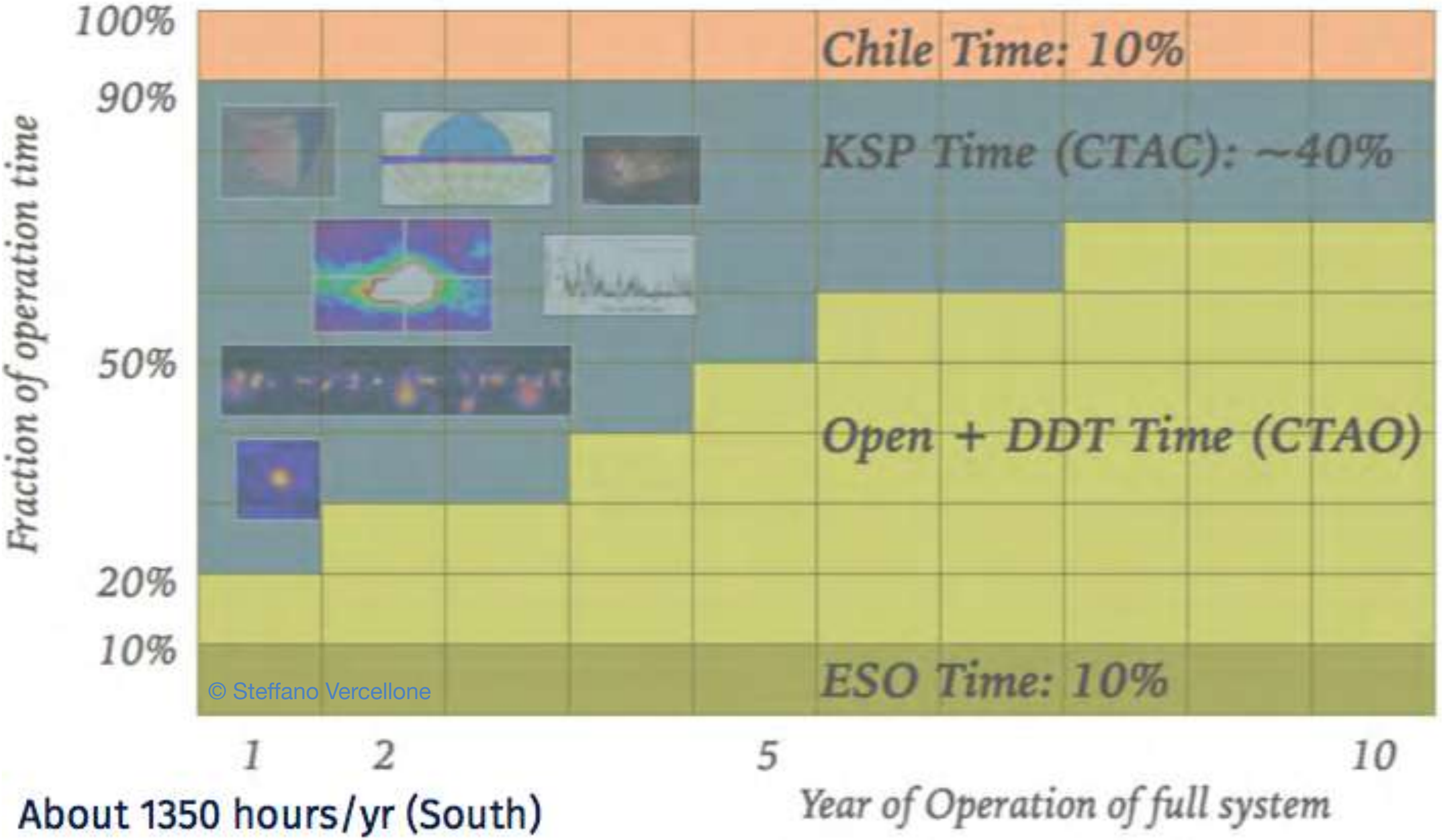
THE THICK OF CTA SCIENCE

- Understanding the Origin and Role of Relativistic Cosmic Particles
- Probing Extreme Environments
- Exploring Frontier Physics

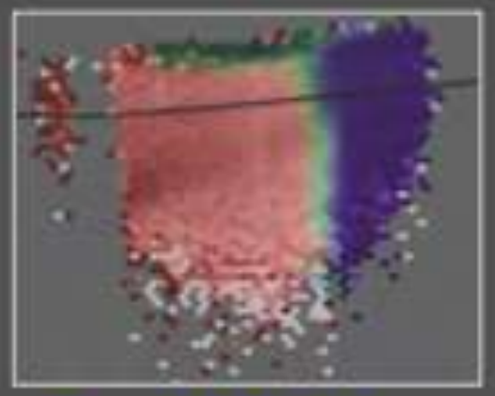
- 9 Key Science Projects (KSPs) and 1 DM Programme
  — KSPs are defined as a set of complex and time-demanding observations addressing multiple science questions within CTA themes

- Focuses on **major and legacy projects**
  — surveys and population studies for legacy catalogues and data sets
  — studies of sources as a class
  — plus focus on a few iconic objects

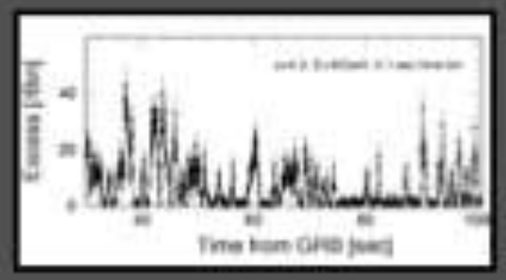
POSSIBLE KSP VS G.O. TIME BUDGET



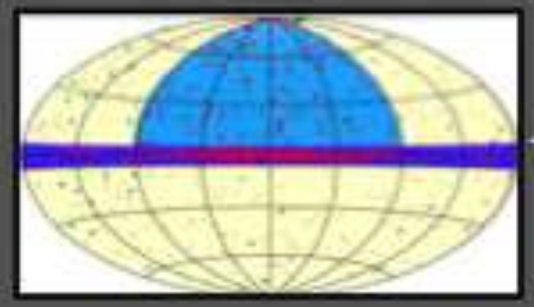
THE CTA KEY SCIENCE PROJECTS



Dark Matter Programme



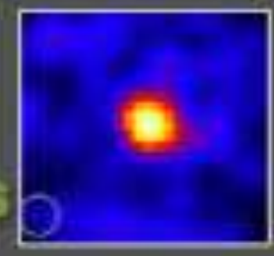
Transients



ExGal Survey

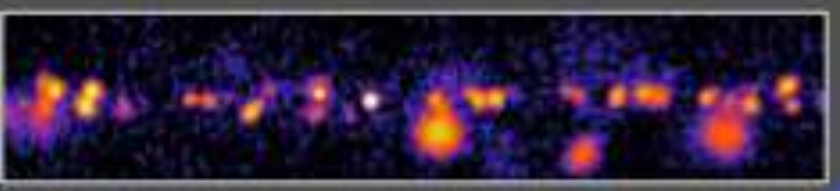
Extragalactic

Galaxy Clusters



Star Forming Systems

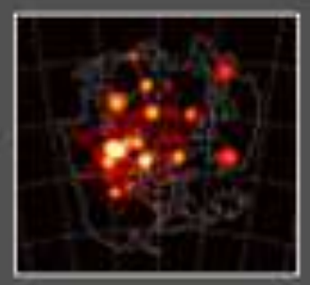
AGN



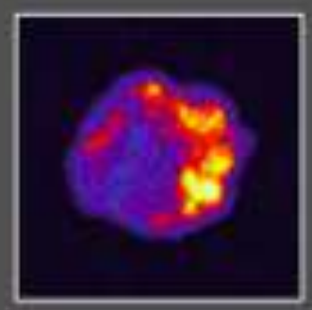
Galactic Plane Survey

Galactic

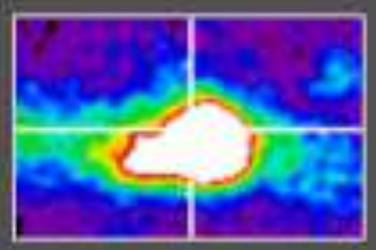
LMC Survey



PeVatrons



Galactic Centre Survey



cta
cherenkov telescope array

KSP VS. PROPOSAL-DRIVEN

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

Credits: Hofmann, Gamma 2016

- 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

26

THE THICK OF CTA SCIENCE

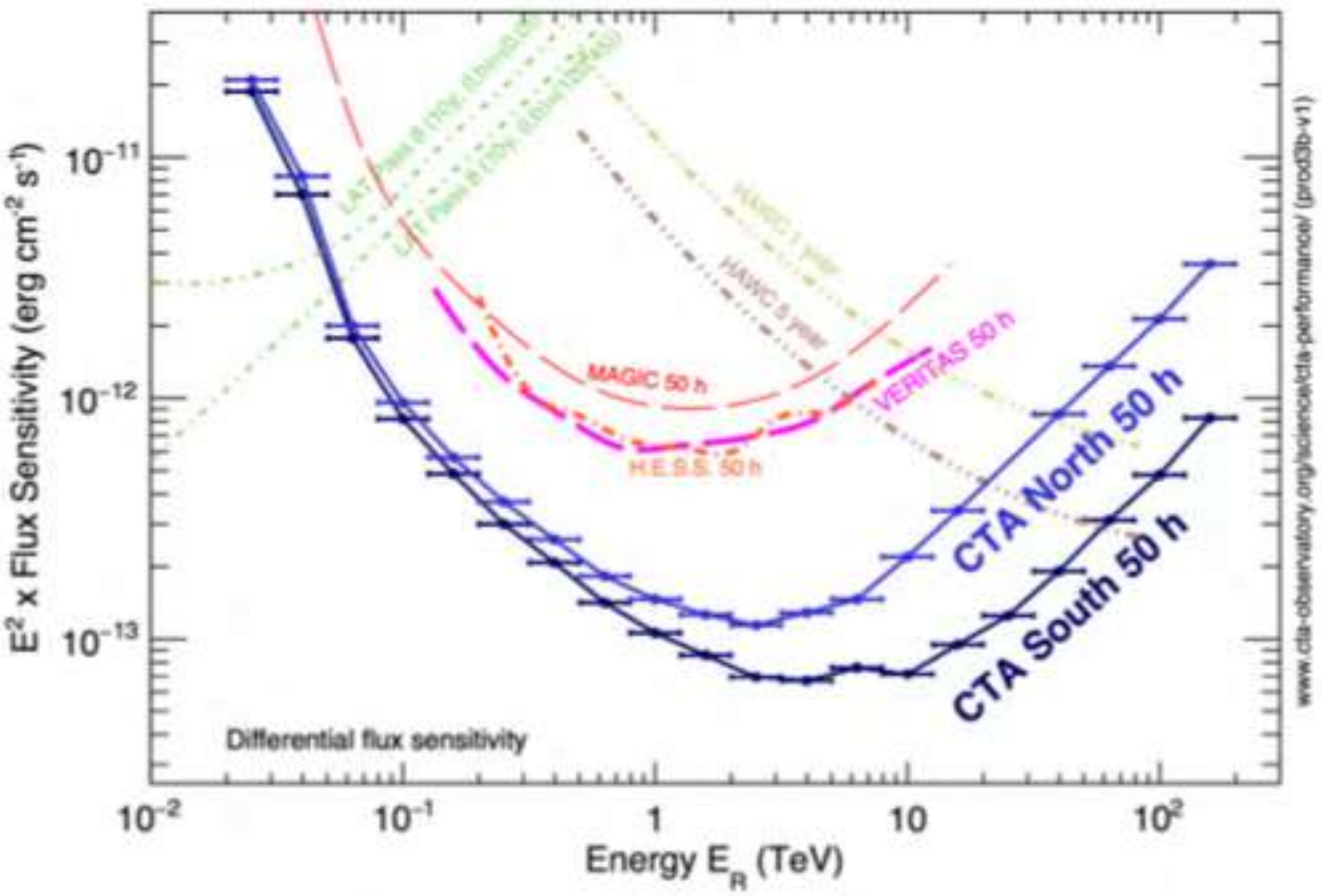
- 9 Key Science Projects (KSPs) and 1 DM Programme
  - KSPs are defined as a set of complex and time-demanding observations addressing multiple science questions within CTA themes

- Focuses on **major and legacy projects**
  - surveys and population studies for legacy catalogues and data sets
  - studies of sources as a class
  - plus focus on a few iconic objects

Cooperation potential

- guest observer proposal building on KSP results
- direct MWL / multi-messenger cooperation within KSPs

CTA PERFORMANCE IN CONTEXT I



A factor of **5-20x improvement** in differential sensitivity relative to current IACTS

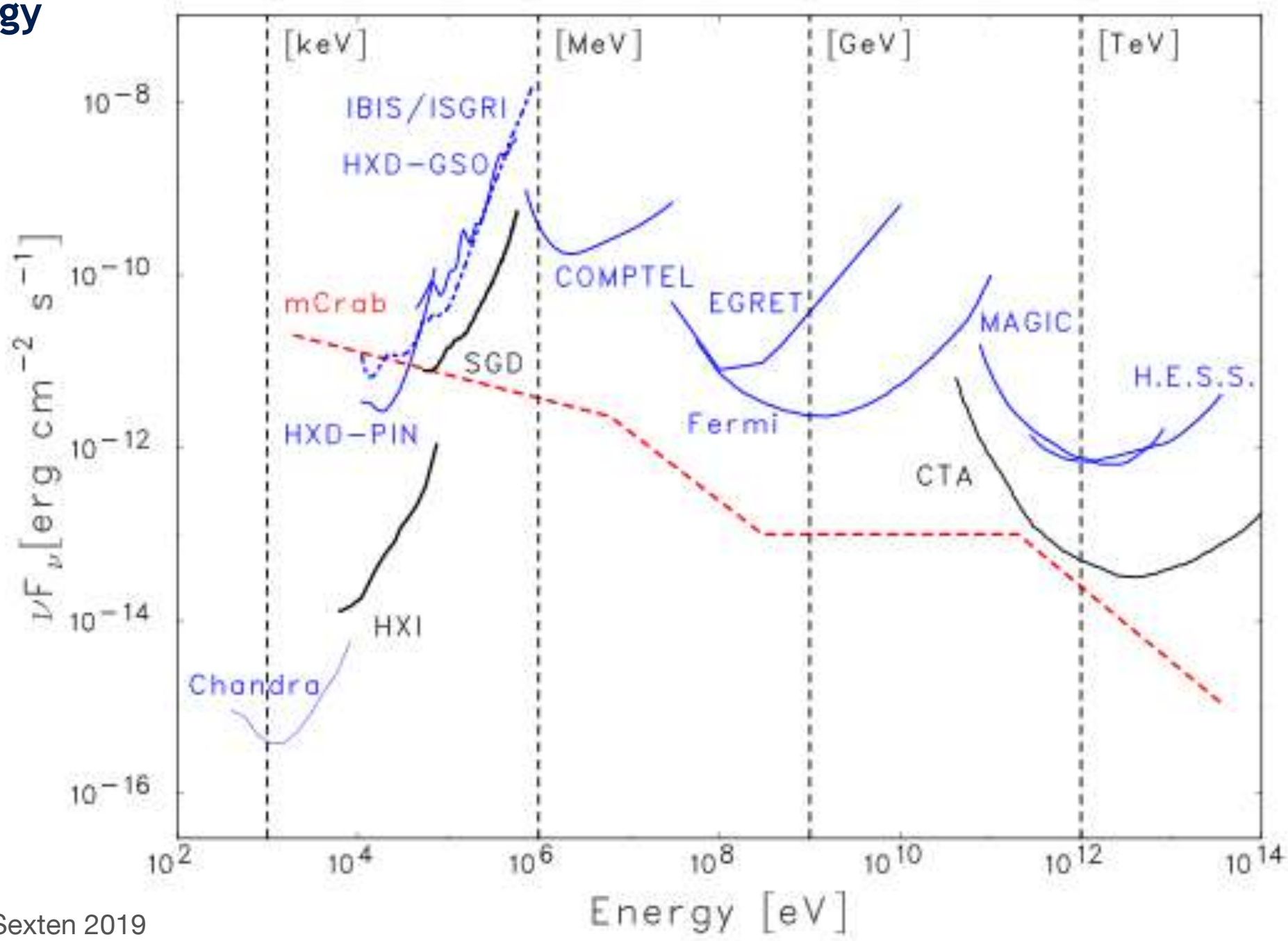
Extension of the accessible energy range **from below 100 GeV to above 100 TeV**

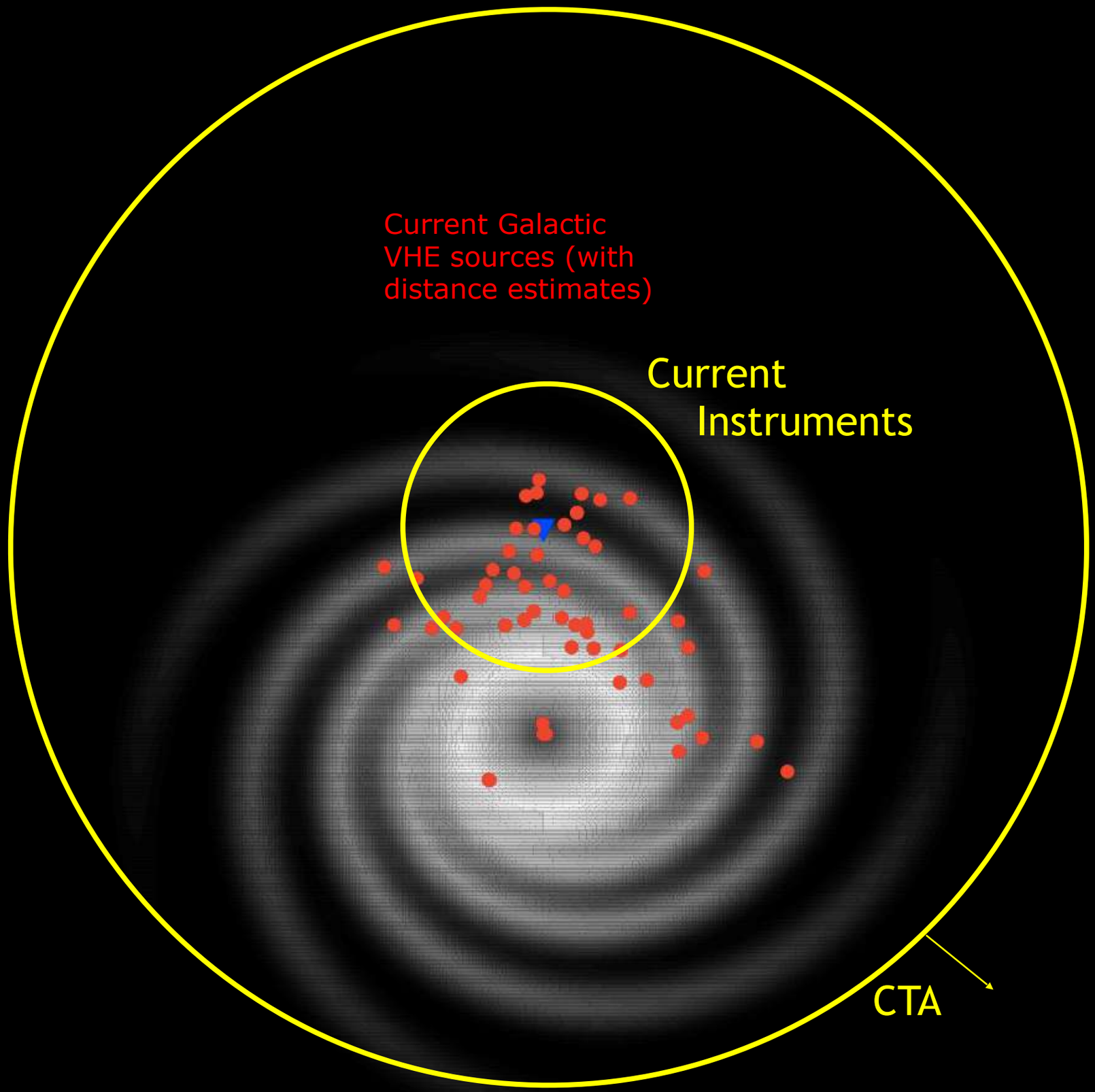
https://www.cta-observatory.org/science/cta-performance/

CTA PERFORMANCE IN CONTEXT II

Comparison with X-ray and other high-energy instruments

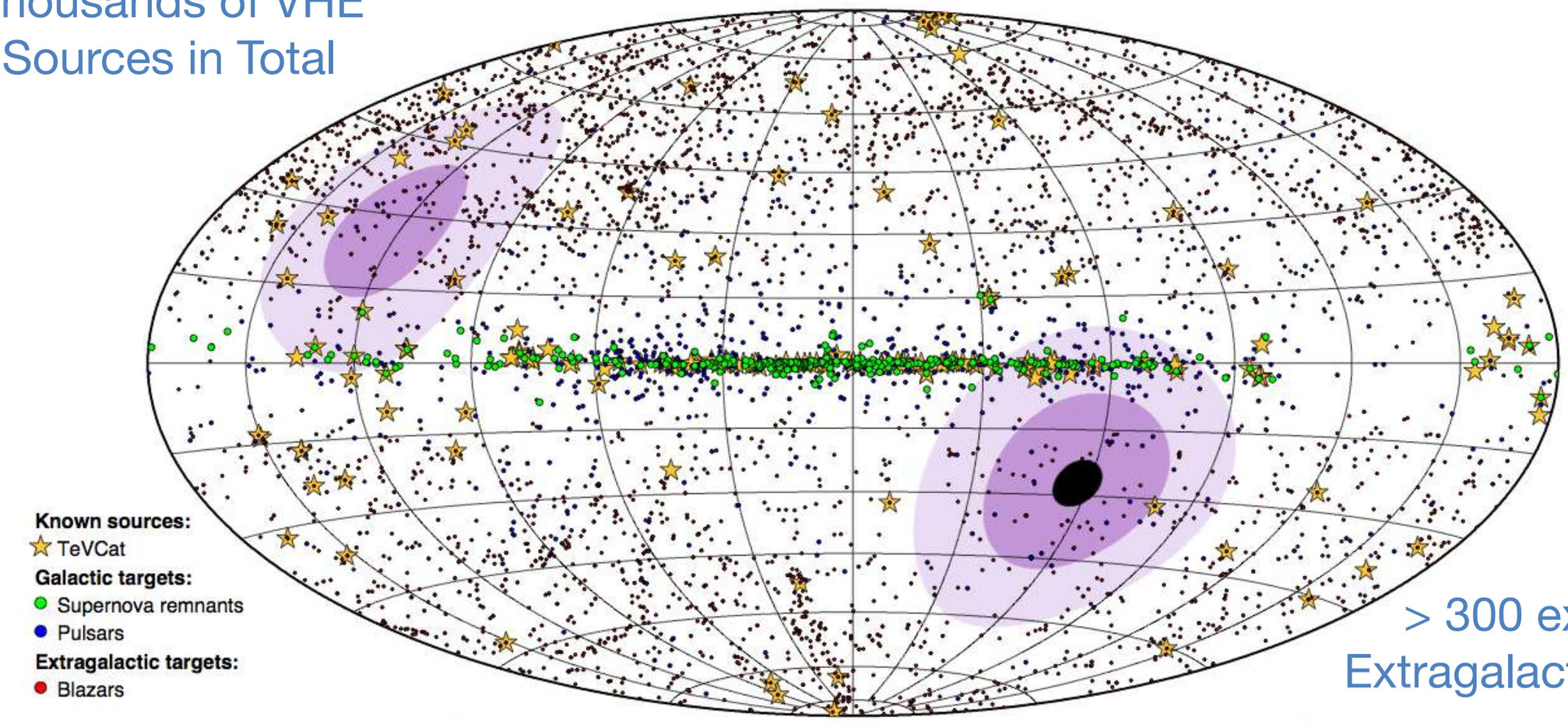
Takahashi et al. 2012



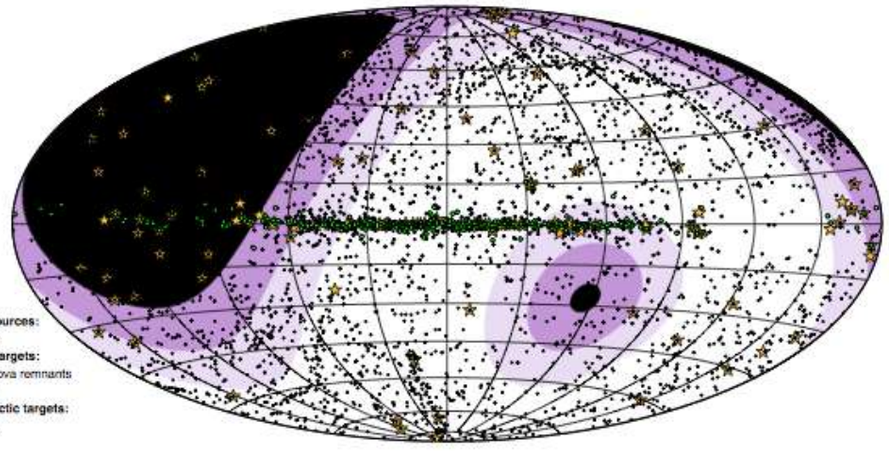

Current Galactic
VHE sources (with
distance estimates)
Current
Instruments
CTA

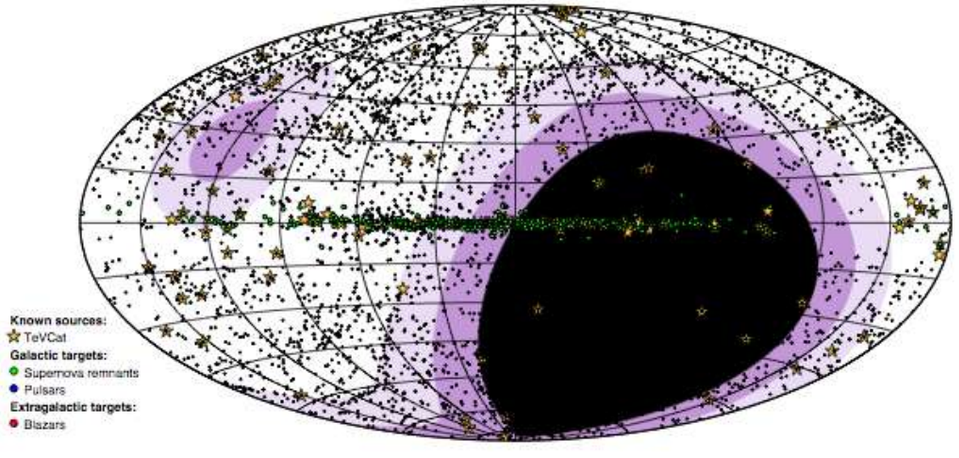
THE EXPECTED CTA ALL SKY VIEW

Thousands of VHE Sources in Total



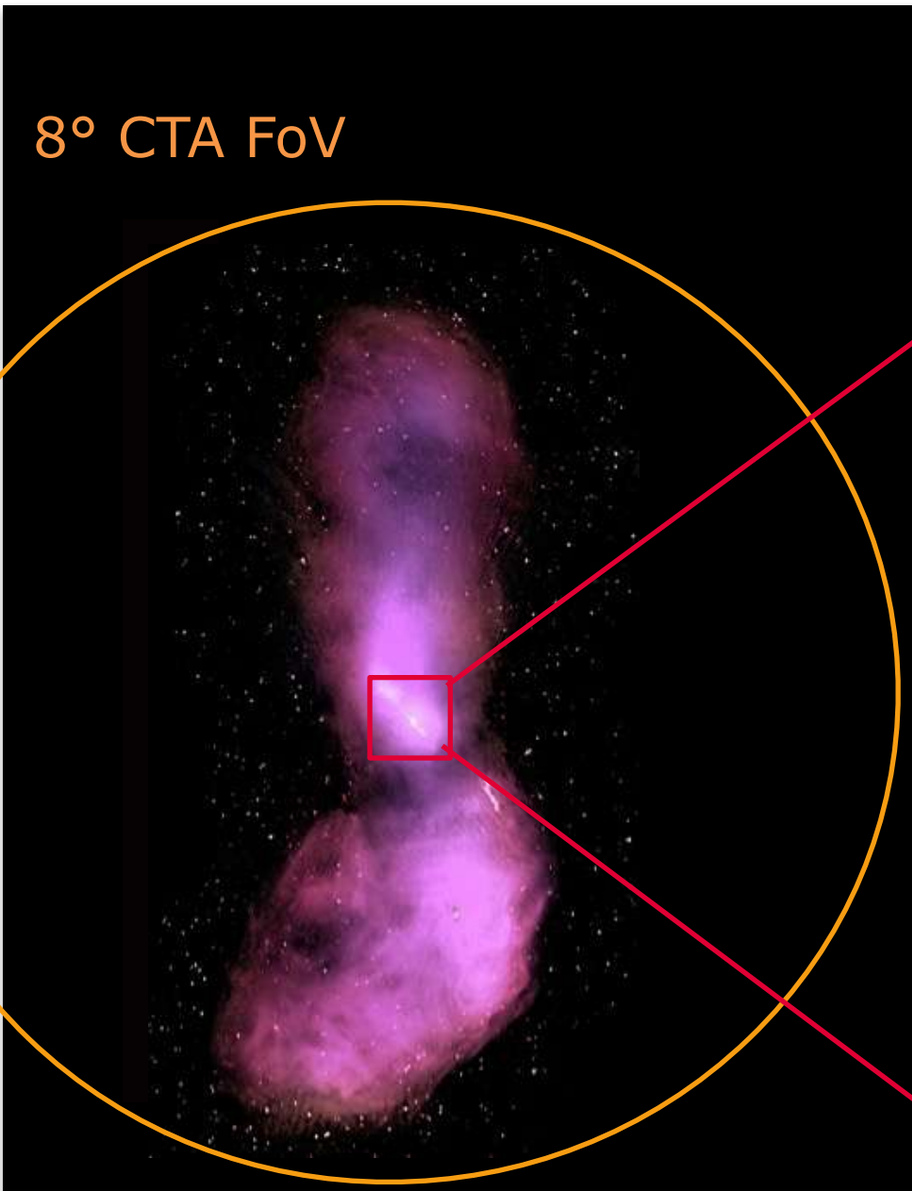
> 300 expected Extragalactic Objects

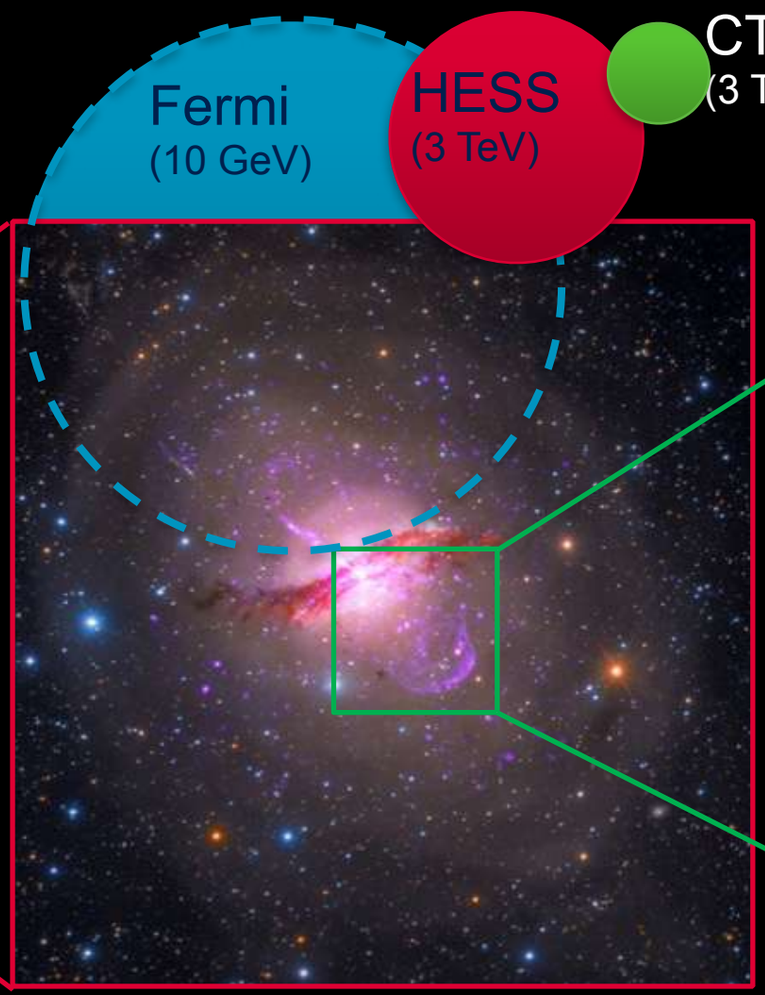


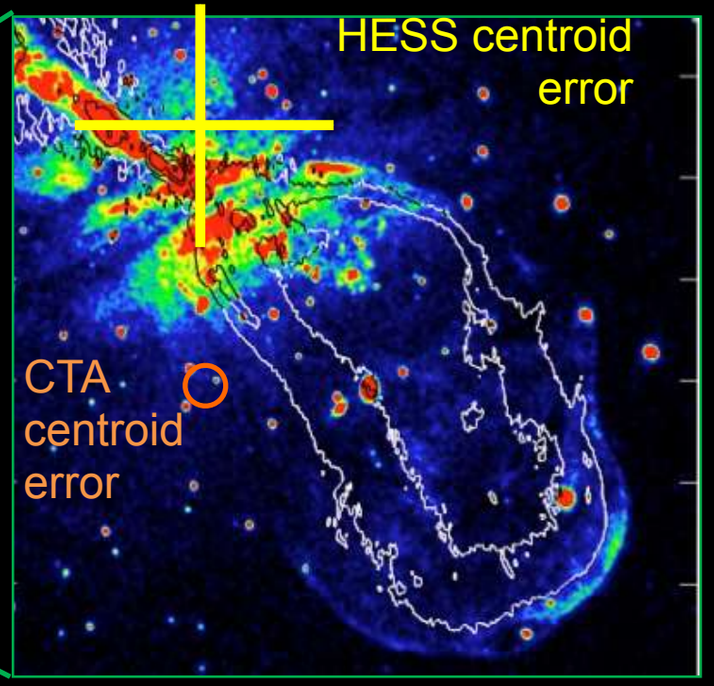


Credits: CTA Consortium

CTA PERFORMANCE IN CONTEXT II







Centaurus A, nearby radio galaxy

MWL counterparts of sources in catalogued data with new CTA deep view observations

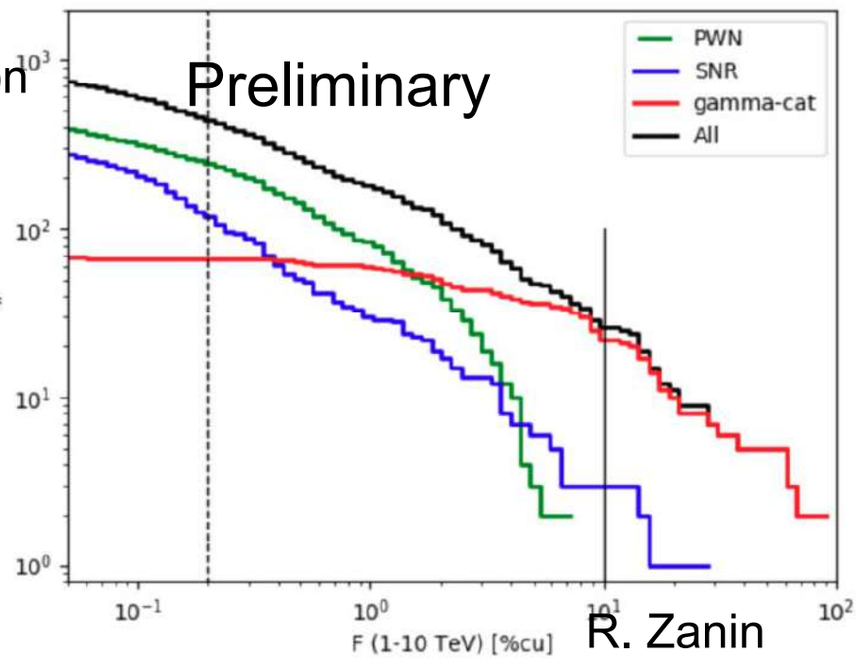
SURVEYS AND SOURCE POPULATIONS
LOG N - LOG S DISTRIBUTIONS

The Galaxy with CTA - Presented at the 1st CTA Symposium

Population Studies

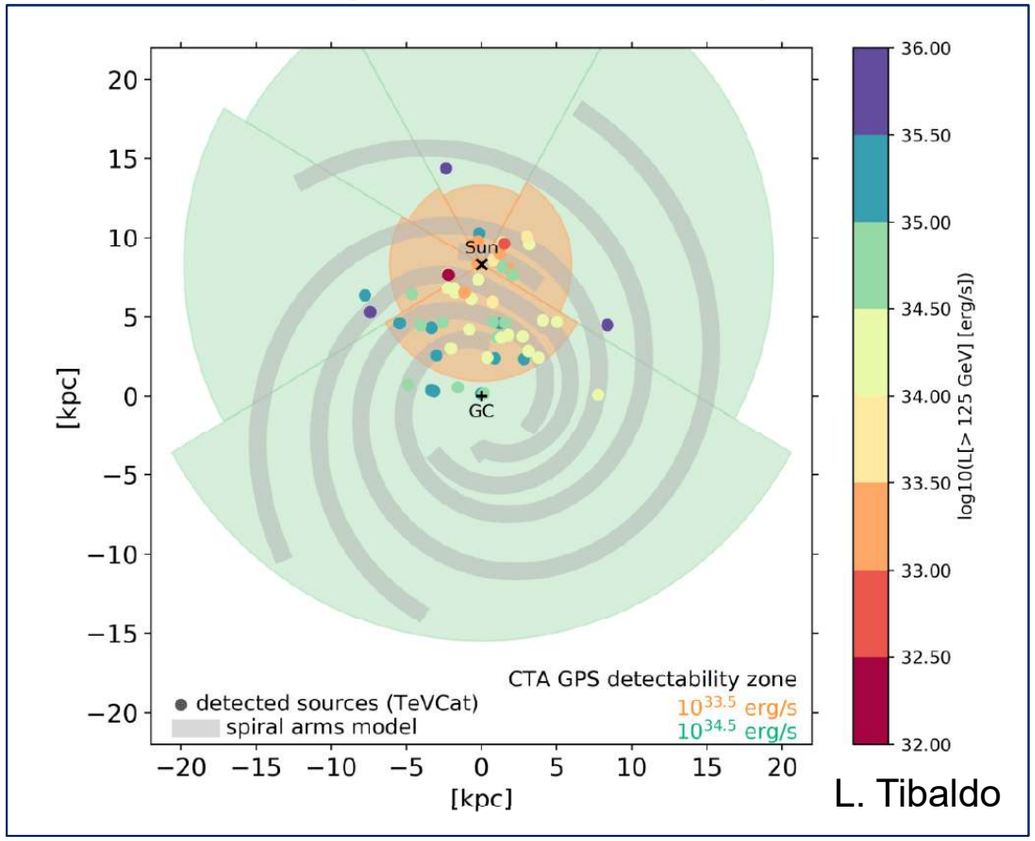
population models

detected sources



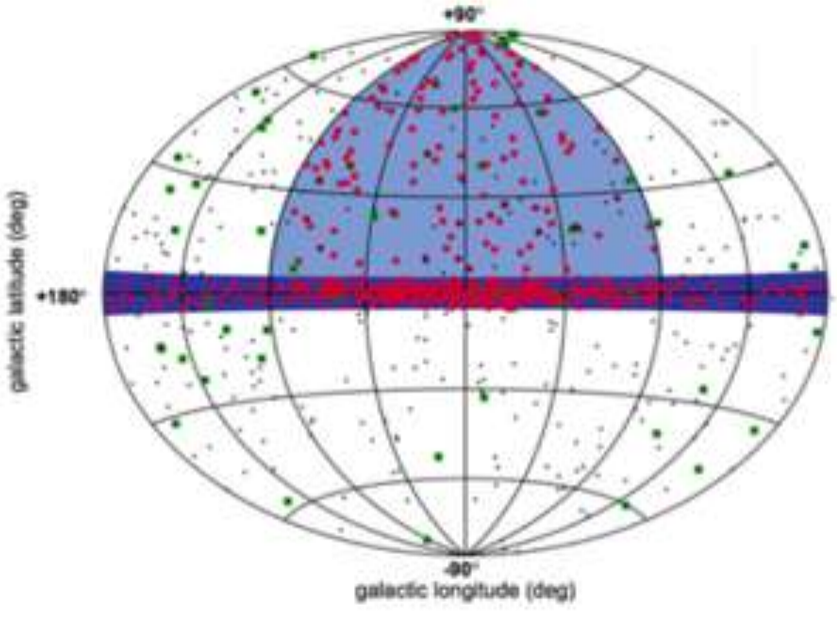
R. Zanin

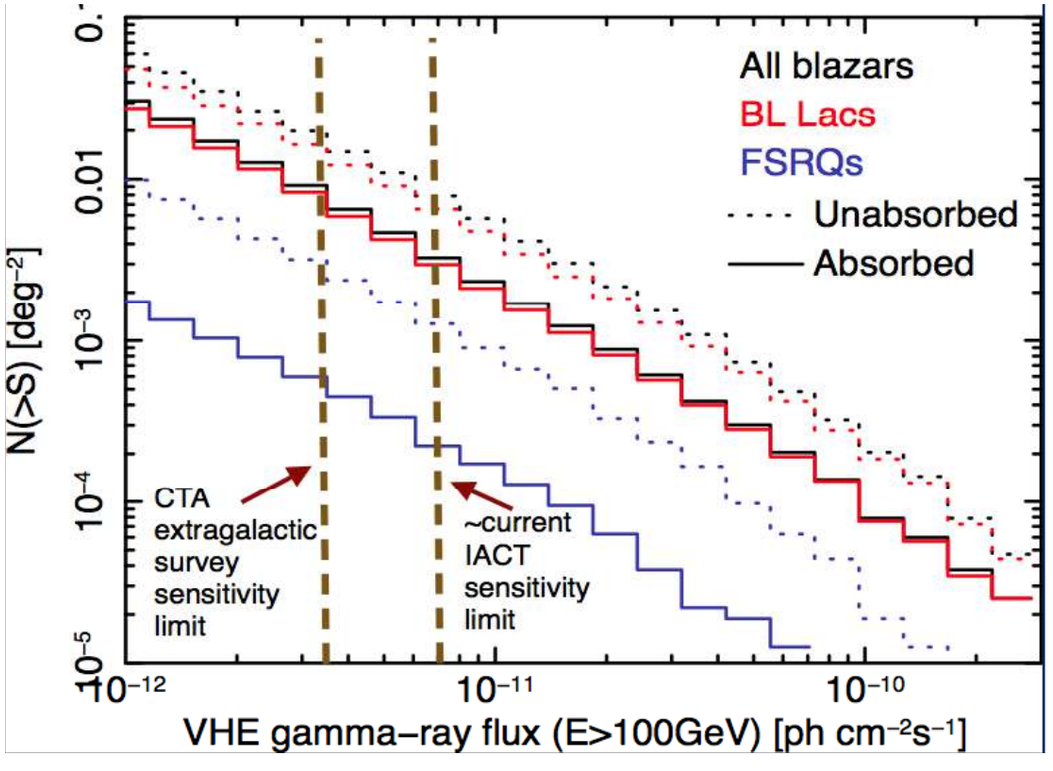
Reaching the entire Galaxy



L. Tibaldo

First time at VHEs for the **extraglactic sky**





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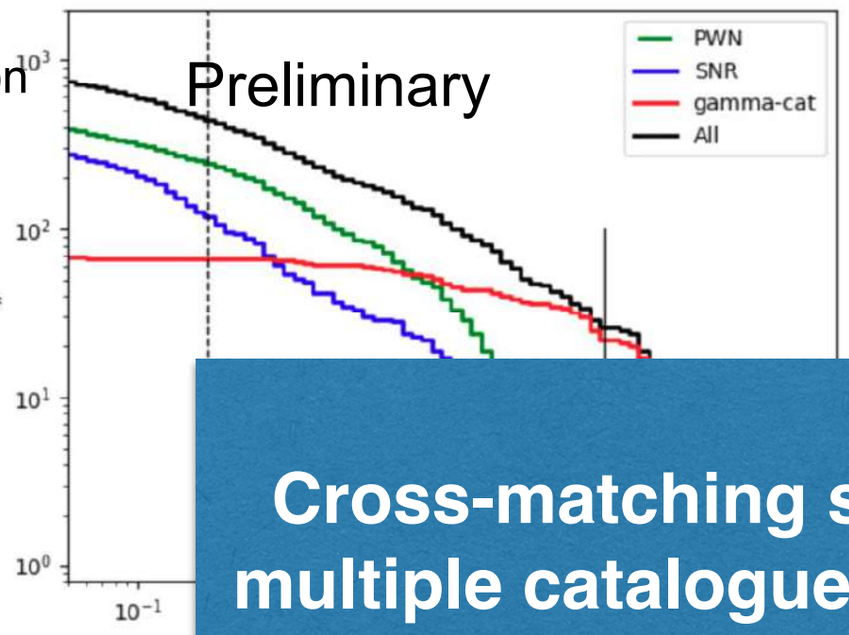

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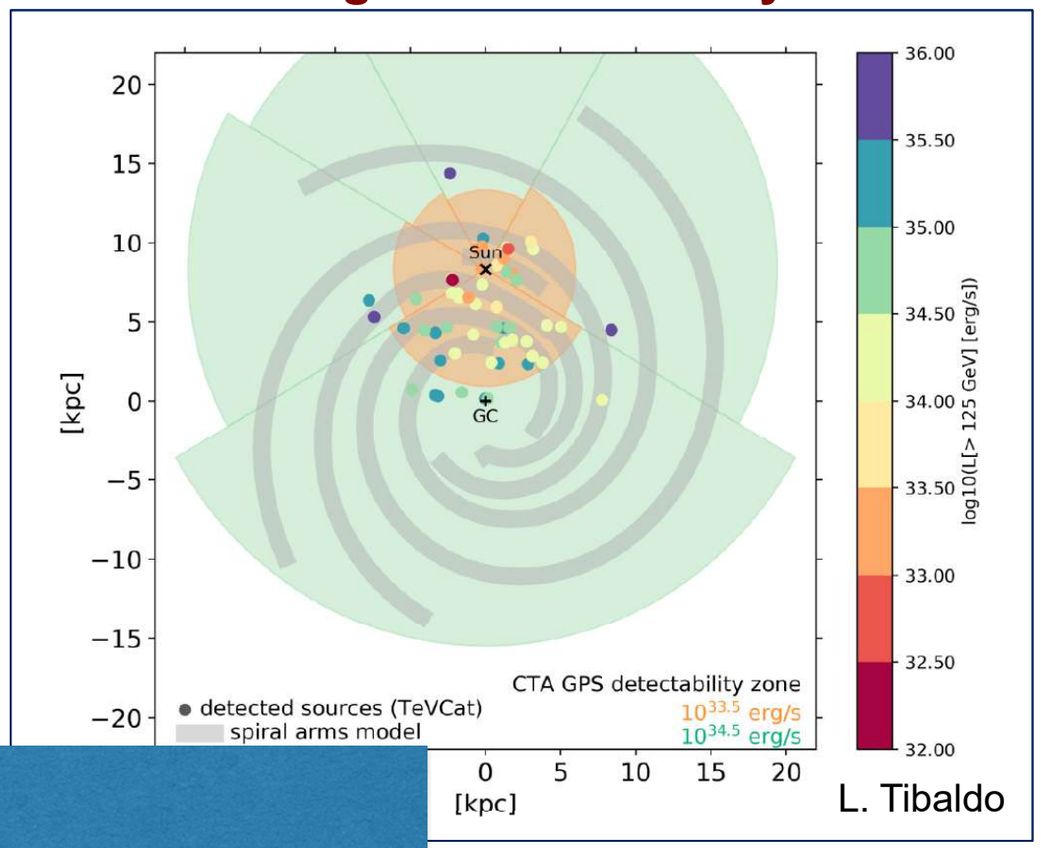
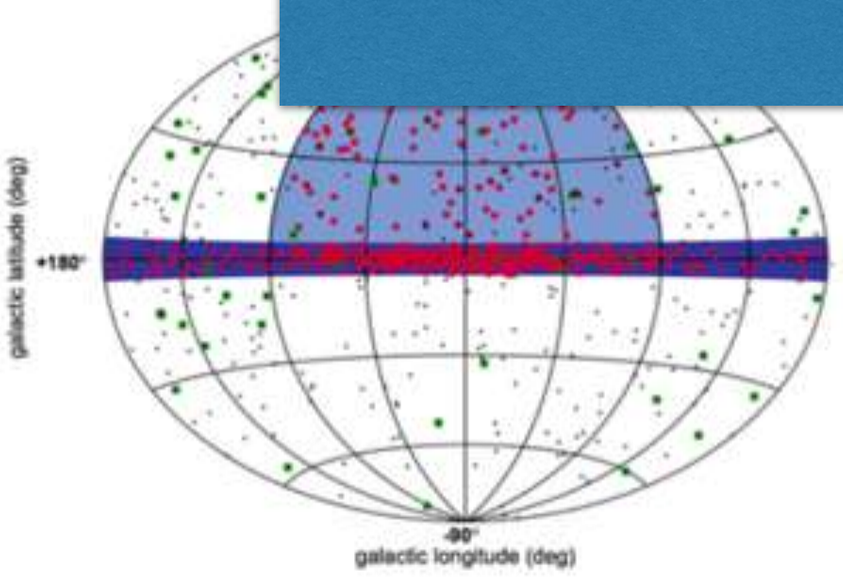
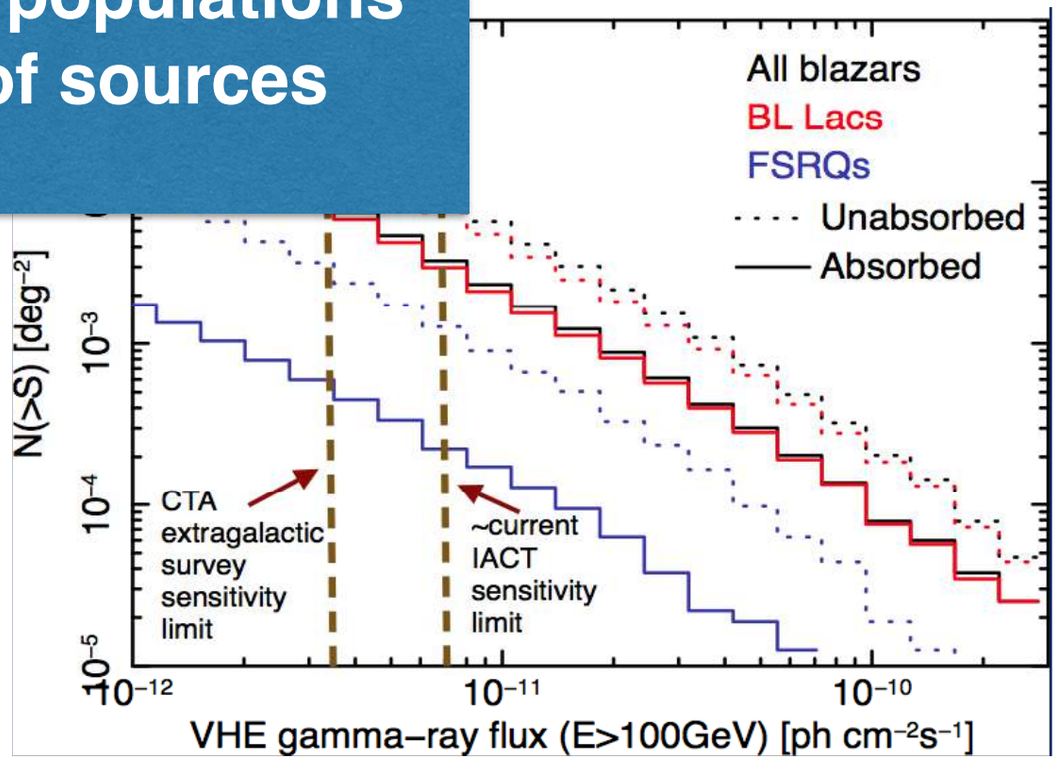


Cross-matching studies with multiple catalogues in MWL for complete view of populations and evolution of sources

First time at VHEs for the **extraglactic sky**

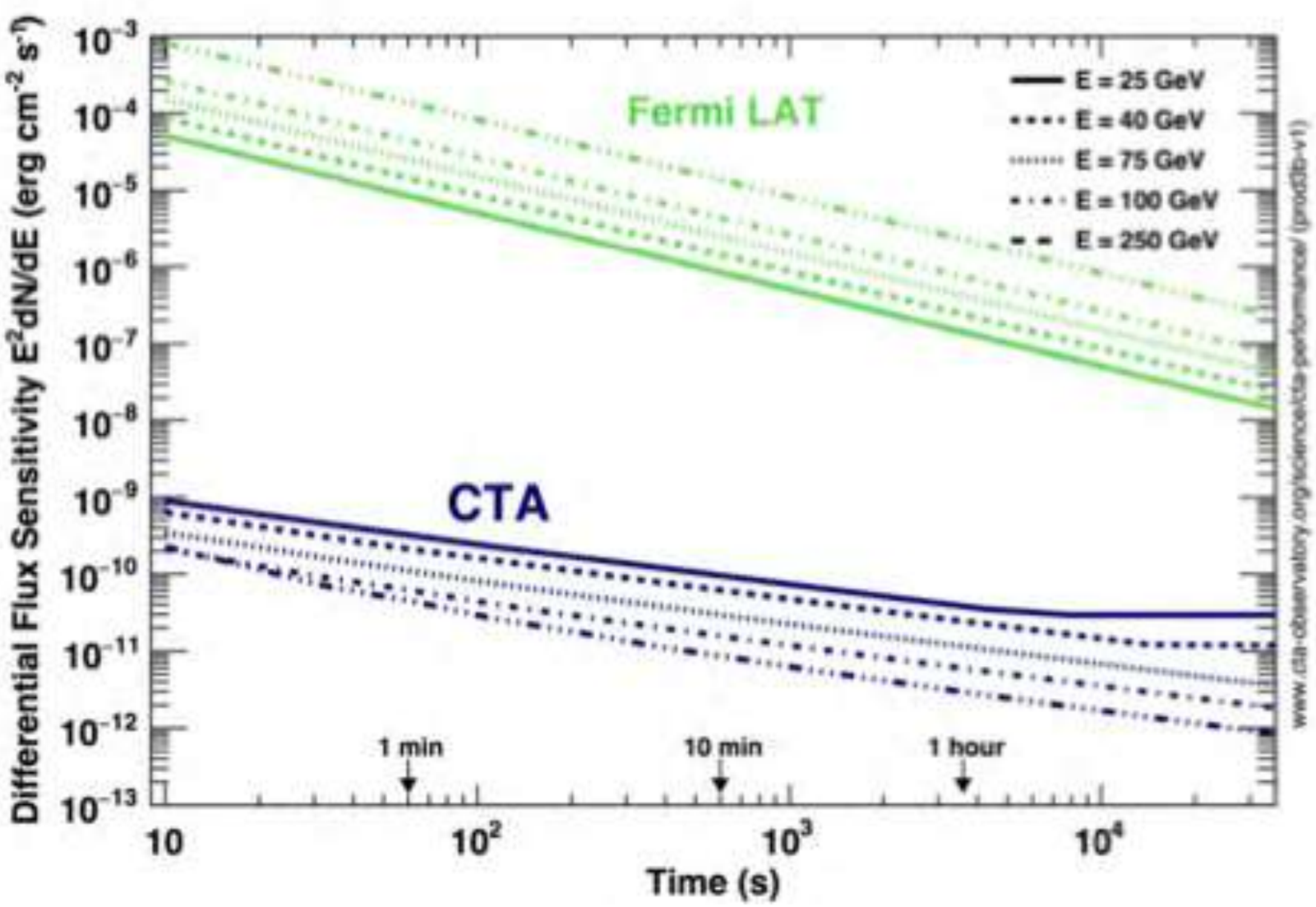




CTA PERFORMANCE IN CONTEXT II: TRANSIENTS

CTA will be a high-energy **transient factory**

Orders of magnitude **advantage over Fermi-LAT** in intra-day timescales: GRBs, AGN flares, binaries.



© CTA Consortium, “Science with CTA Book”

CTA PERFORMANCE IN CONTEXT II: TRANSIENTS

CTA will be a high-energy **transient factory**

Orders of magnitude **advantage over Fermi-LAT** in intra-day timescales: GRBs, AGN flares, binaries.

First time detection of a GRB at sub-TeV energies; MAGIC detects the GRB 190114C

ATel #12390; *Razmik Mirzoyan on behalf of the MAGIC Collaboration*
on 15 Jan 2019; 01:03 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Gamma Ray, >GeV, TeV, VHE, Request for Observations, Gamma-Ray Burst

Referred to by ATel #: 12395, 12475

Tweet

The MAGIC telescopes performed a rapid follow-up observation of GRB 190114C (Gropp et al., GCN 23688; Tyurina et al., GCN 23690, de Ugarte Postigo et al., GCN 23692, Lipunov et al. GCN 23693, Selsing et al. GCN 23695). This observation was triggered by the Swift-BAT alert; we started observing at about 50s after Swift T0: 20:57:03.19. The MAGIC real-time analysis shows a significance >20 sigma in the first 20 min of observations (starting at T0+50s) for energies >300GeV. The relatively high detection threshold is due to the large zenith angle of observations (>60 degrees) and the presence of partial Moon. Given the brightness of the event, MAGIC will continue the observation of GRB 190114C until it is observable tonight and also in the next days. We strongly encourage follow-up observations by other instruments. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) and K. Noda (nodak@icrr.u-tokyo.ac.jp). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

CTA PERFORMANCE IN CONTEXT II: TRANSIENTS

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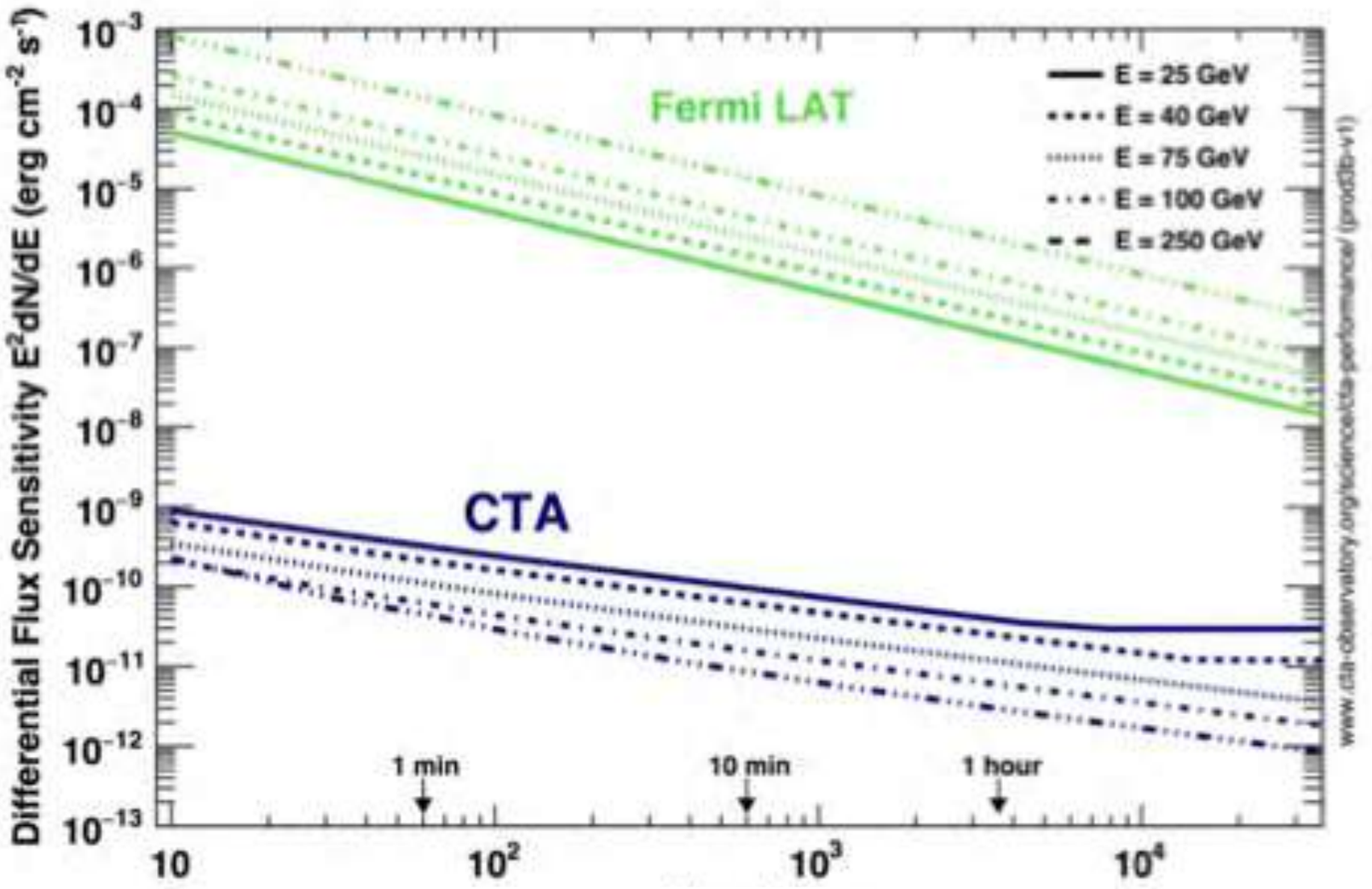
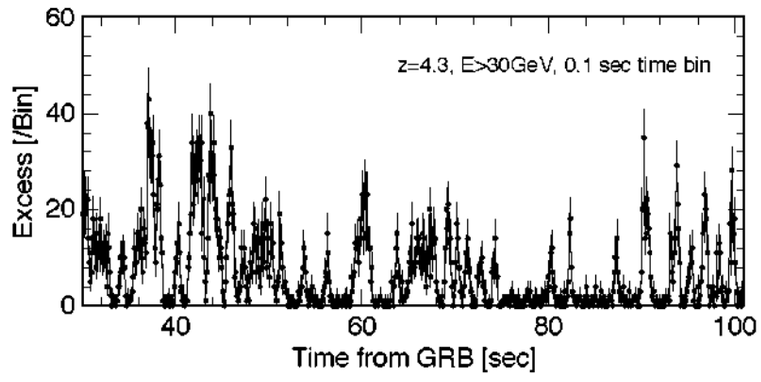
Orders of magnitude **advantage over Fermi-LAT** in intra-day timescales: GRBs, AGN flares, binaries.





GRB (z=4.3) Light curve

© CTA Consortium, "Science with CTA Book"

Caveat & Synergies: Limited FoV, depending on external triggers.

THE MWL & MM SCENE FOR CTA

2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025

⇐ CTA Prototypes ⇒ Science Verification ⇒ User Operation

Low Frequency Radio
- LOFAR
- MWA
- MWA (upgrade)
- VLITE on JVLA --> (~2018? LOBO)
- FAST

Mid-Hi Frequency Radio
- JVLA, VLBA, eMerlin, ATCA, EVN, JVN, KVN, VERA, LBA, GBT…(many other smaller facilities)
- ASKAP
- Kat7 --> MeerKAT --> SKA Phase 1
- SKA1&2 (Lo/Mid)

(sub)Millimeter Radio
- JCMT, LLAMA, LMT, IRAM, NOEMA, SMA, SMT, SPT, Nanten2, Mopra, Nobeyama … (many other smaller facilities)
- ALMA
- EHT (prototype —> full ops)

Optical Transient Factories/Transient Finders
- iPalomar Transient Factory —> (~2017) Zwicky TF
- LSST (buildup to full survey mode)
- PanSTARRS1 —> PanSTARRS2
- BlackGEM (Meerlicht single dish prototype in 2016)

Optical/IR Large Facilities
- VLT, Keck, GTC, Gemini, Magellan…(many other smaller facilities)
- HST
- WFIRST
- JWST
- GMT
- eELT (full operation 2024) & TMT (timeline less clear)?

X-ray
- Swift (incl. UV/optical)
- XMM & Chandra
- NuSTAR
- IXPE
- ASTROSAT
- ATHENA (2028)
- HXMT
- NICER
- XARM
- eROSITA

Gamma-ray
- SVOM (incl. soft gamma-ray + optical ground elements)
- INTEGRAL
- Fermi
- HAWC
- Gamma400 (2025+)
- DAMPE
- LHAASO

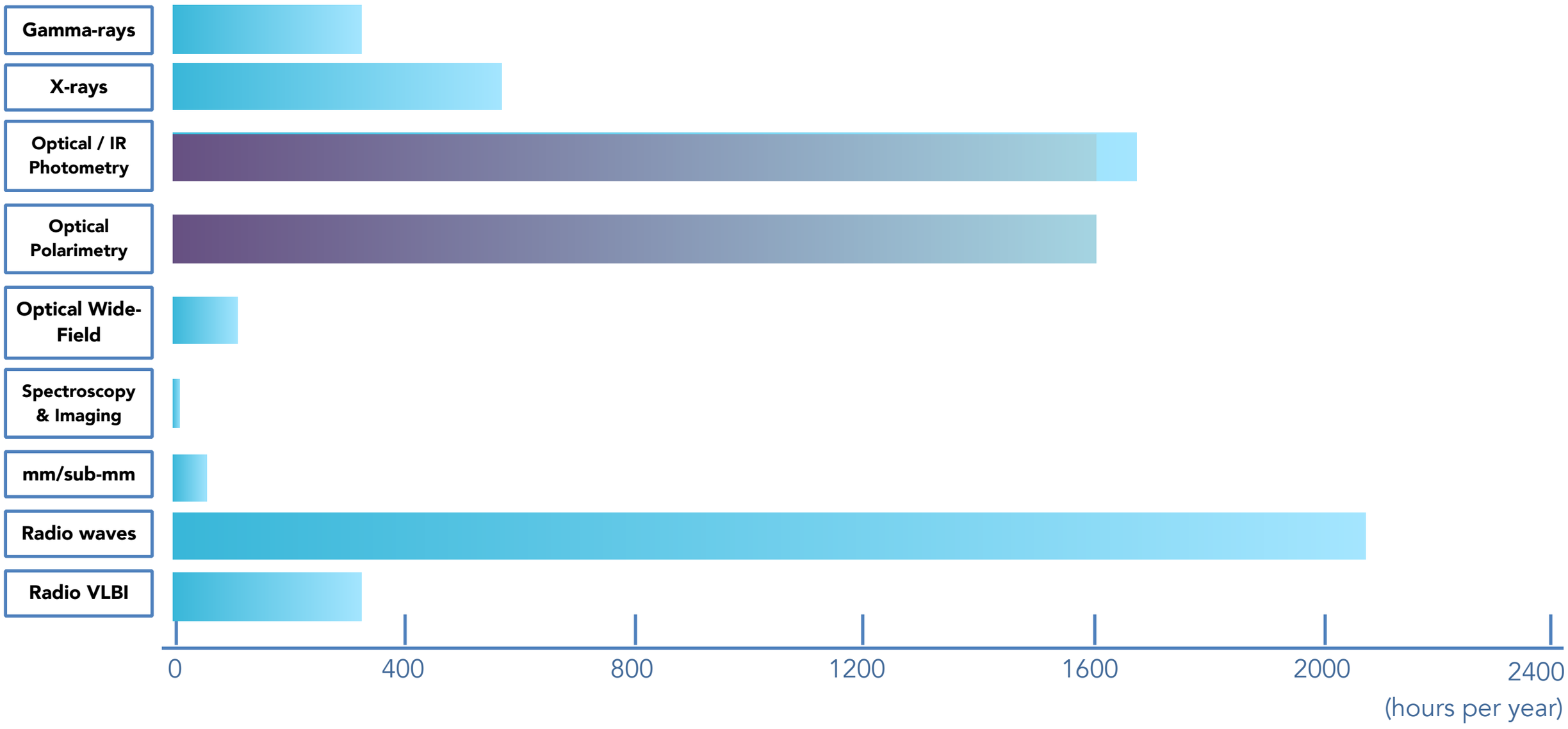
Grav. Waves
- Advanced LIGO + Advanced VIRGO (2017) (—upgrade to include LIGO India—)
- Einstein Tel.?
- KAGRA

Neutrinos
- IceCube (SINCE 2011)
- IceCube-Gen2? ⇒
- ANTARES
- KM3NET-1
- KM3NET-2 (ARCA)
- KM3NET-3

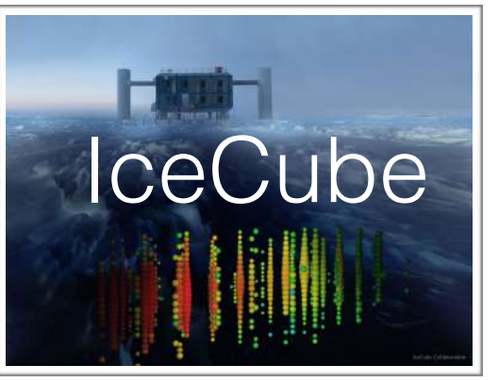
UHE Cosmic Rays
- Telescope Array ⇒ upgrade to TAx4
- Pierre Auger Observatory ⇒ upgrade to Auger Prime

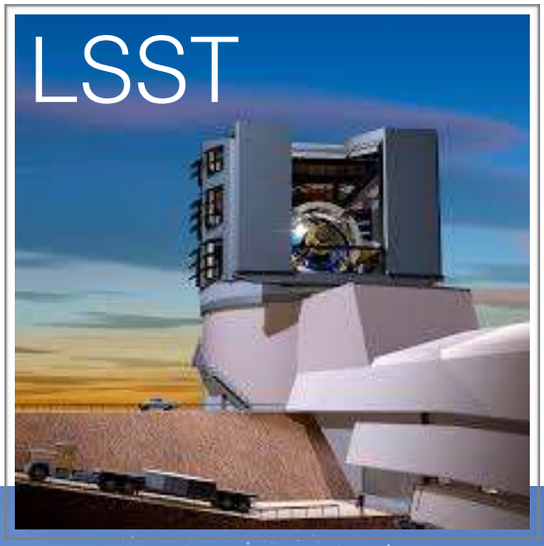
EXTERNAL DATA
TIME DEMAND SUMMARY

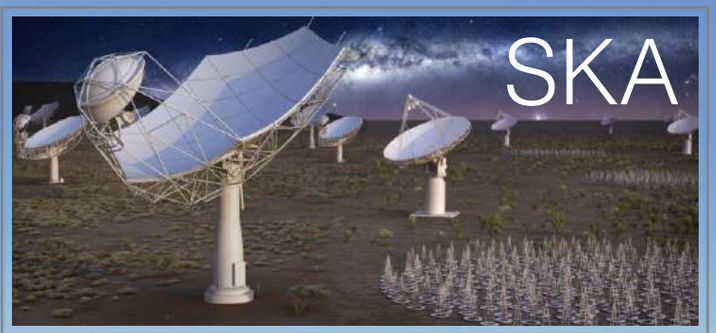
Time estimations for both observatory sites.

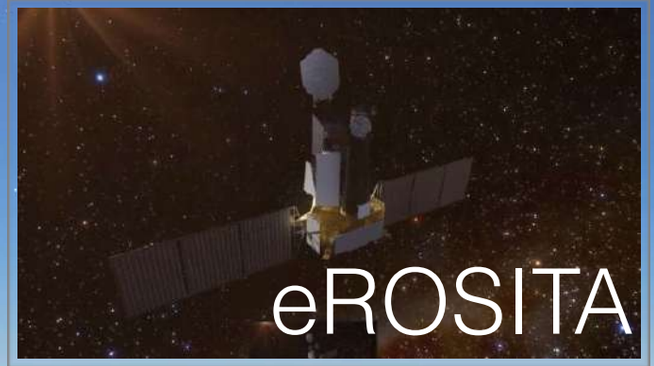


SYNERGIES





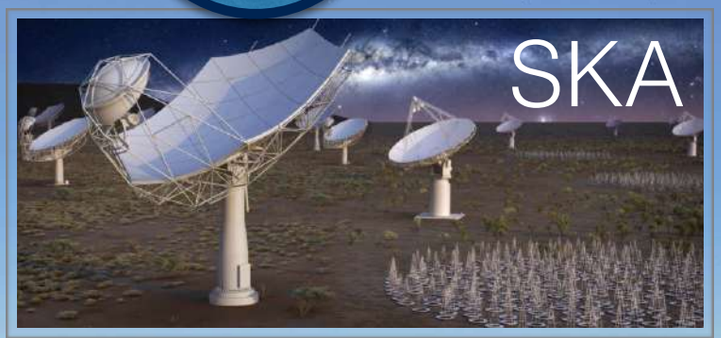




SYNERGIES

ToOs

Transients



Catalogues

Source Views

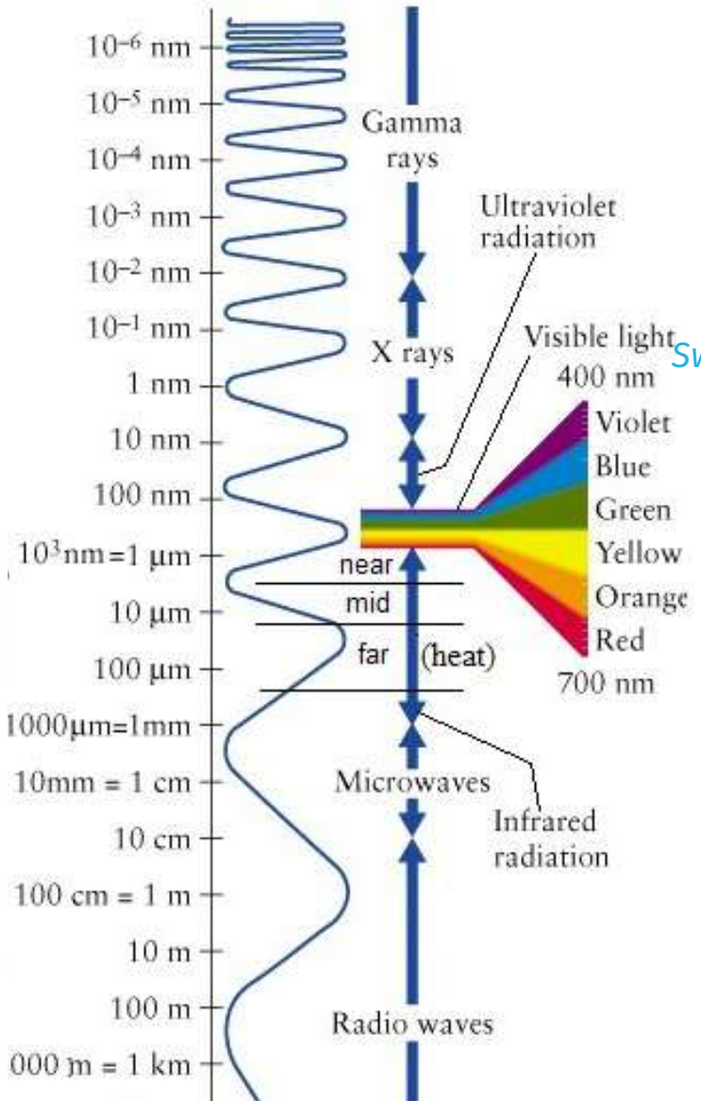
Wide-band

Spectrum

SYNERGIES

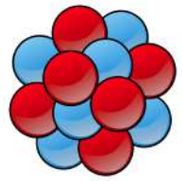
A complex scenario, of multi-dimensional relations across the observational spectrum….

© Jonathan Biteau

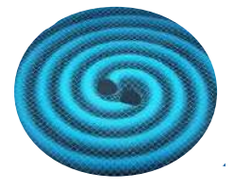


SGSO, M@TE, LHAASO, HAWC, FACT

KM3, GRAND, ARIANNA, ARA



AugerPrime
TA x 4



Fermi-LAT

NuStar, HXMT, AstroSAT

Swift-UVOT/XRT, eROSITA, eXTP

Chandra

HST, adaptative optics

Optical support telescope, Liverpool, WEBT

SAM/SOAR, SharCS/Lick
X-shooter/ESO, ESI/Lick

JWST, SPICA

ALMA

ATCA
Metsähovi
OVRO
VLBA

Long-term monitoring
E. Lindfors

Cen A & M 87
T. Hovatta

Wide-field obs.
also used for GW
GOTO, zPTF,
LSST, BlackGem

Extragalactic survey
T. Hovatta, F. d'Ammando, A. Zech

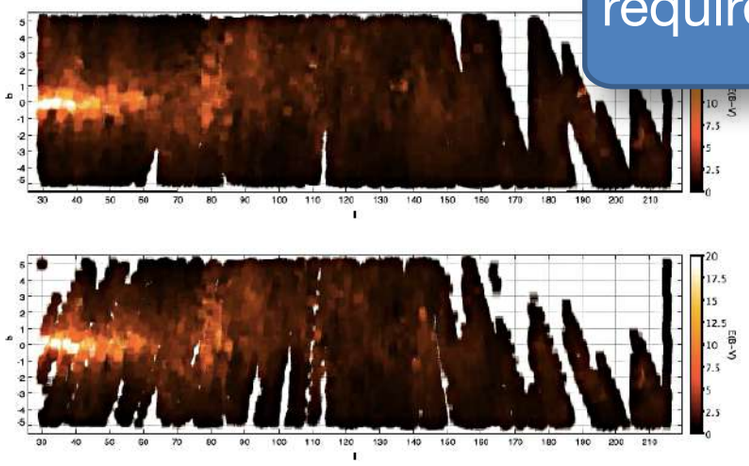
AGN targets
A. Zech

Redshift
P. Goldoni

Flares
T. Hovatta, E. Lindfors

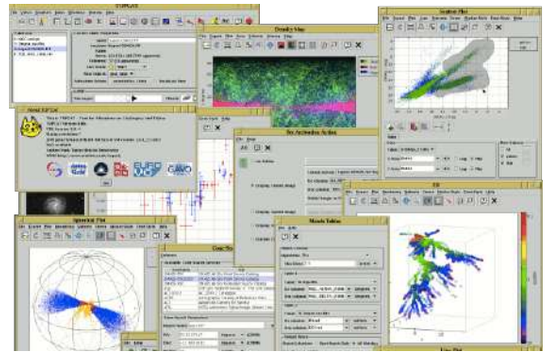
Propagation
EBL, hadron beams
J. Biteau, M. Meyer, F. Tavecchio

CTA MWL / MULTI-MESSENGER NEEDS



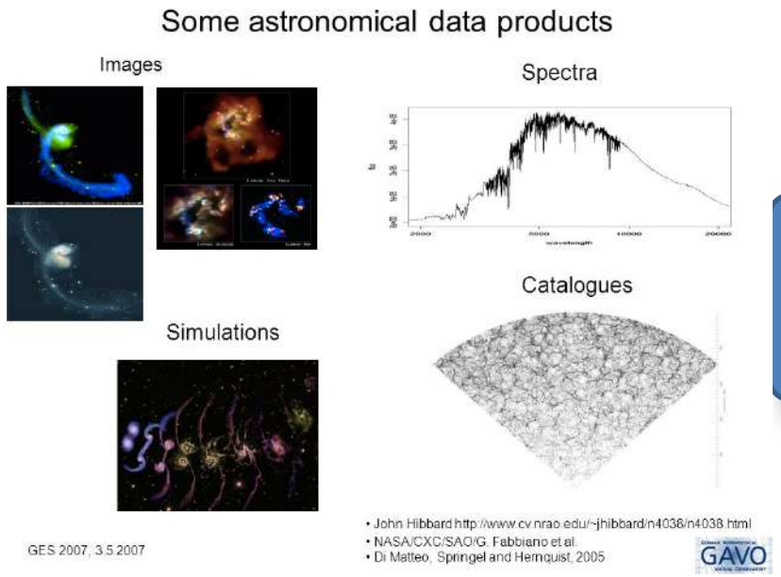
Data quality requirements

mwl / multi-messenger requirements & strategy



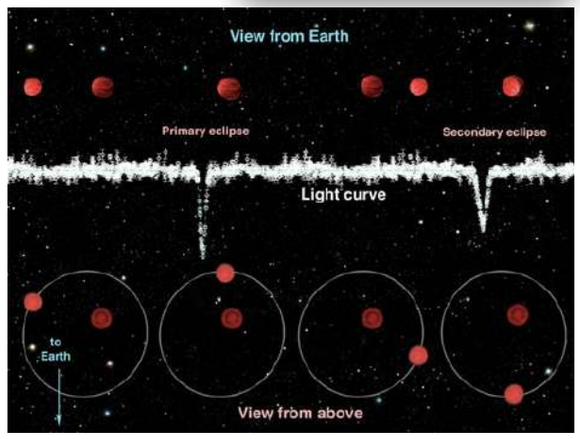
Data accessibility

Observation time requirements

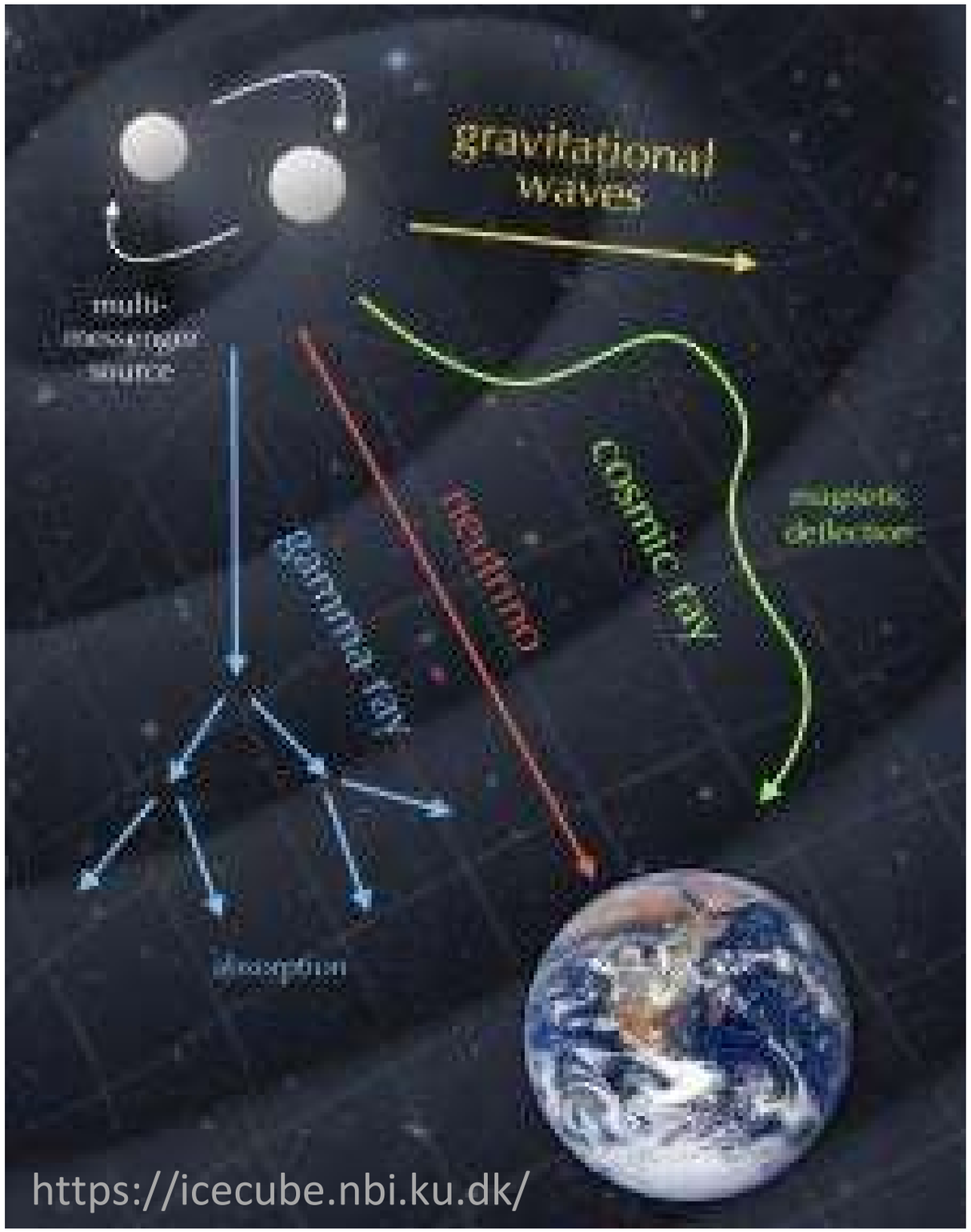


Required data products

Observation Strategy

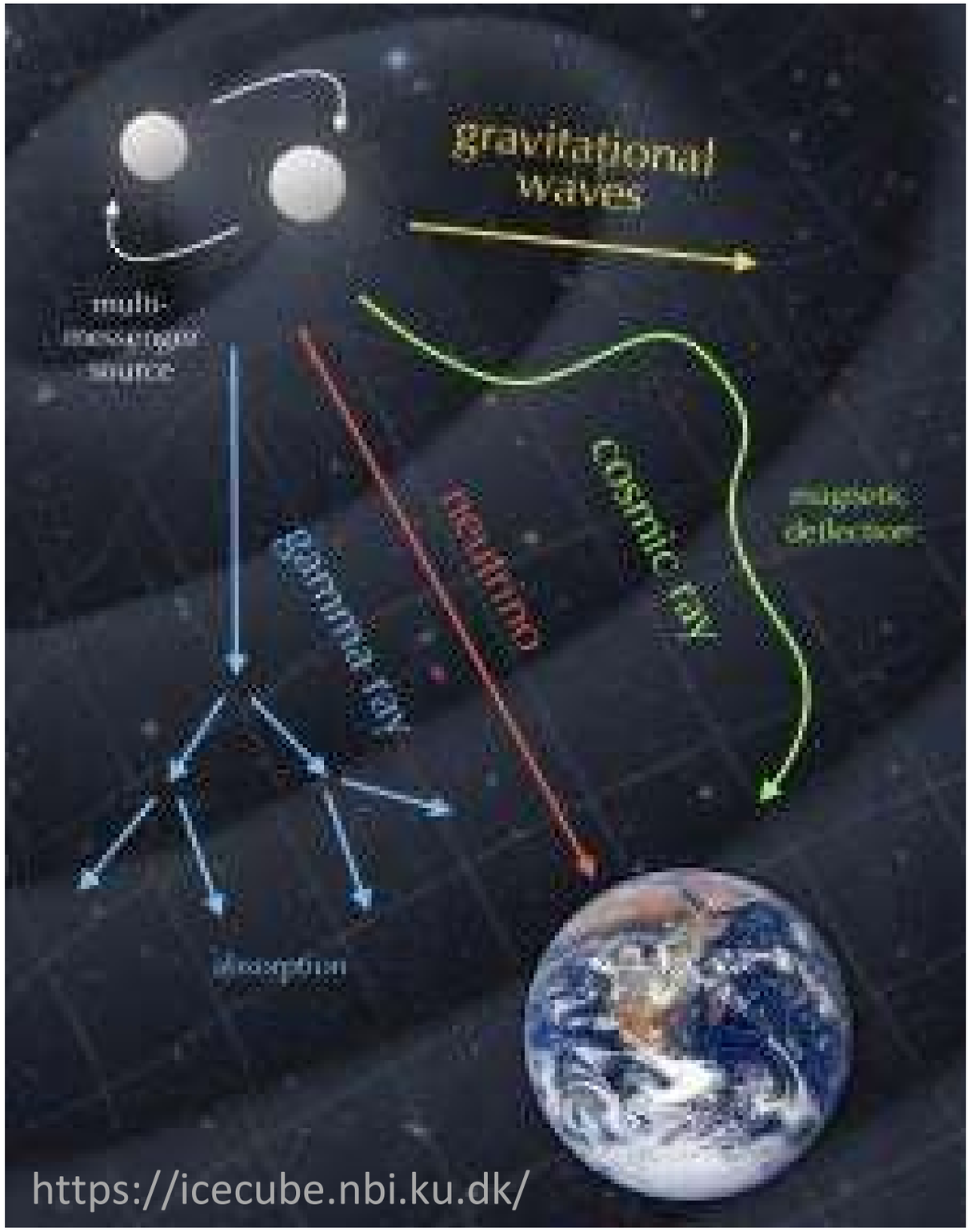


EXTREME TRANSIENTS



https://icecube.nbi.ku.dk/

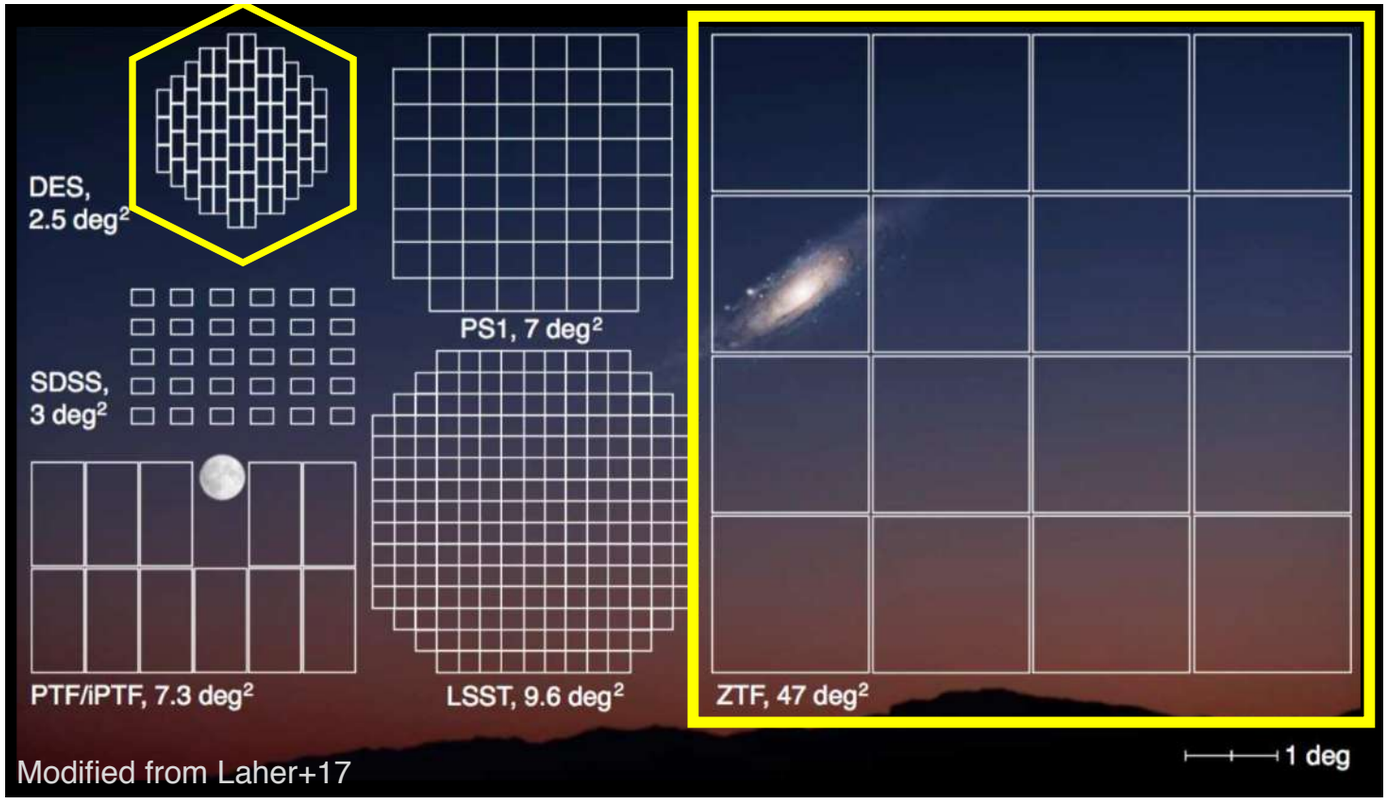
EXTREME TRANSIENTS



EXTREME TRANSIENTS

Rapid response challenge:

- technological = rapid response capability through hardware + software
- multi-instrumental coordination and alerts = VOEvents, GCNs, Telegrams…
- which sources to follow and how to manage the numerous alerts…?



+ Plus a number of all-sky (or large-fraction thereof) instruments in the multi-messenger, radio and high-energy domains
+ Many events constituting on potentially interesting, rare, high-scientific return events, but no guarantee…

EXTREME TRANSIENTS

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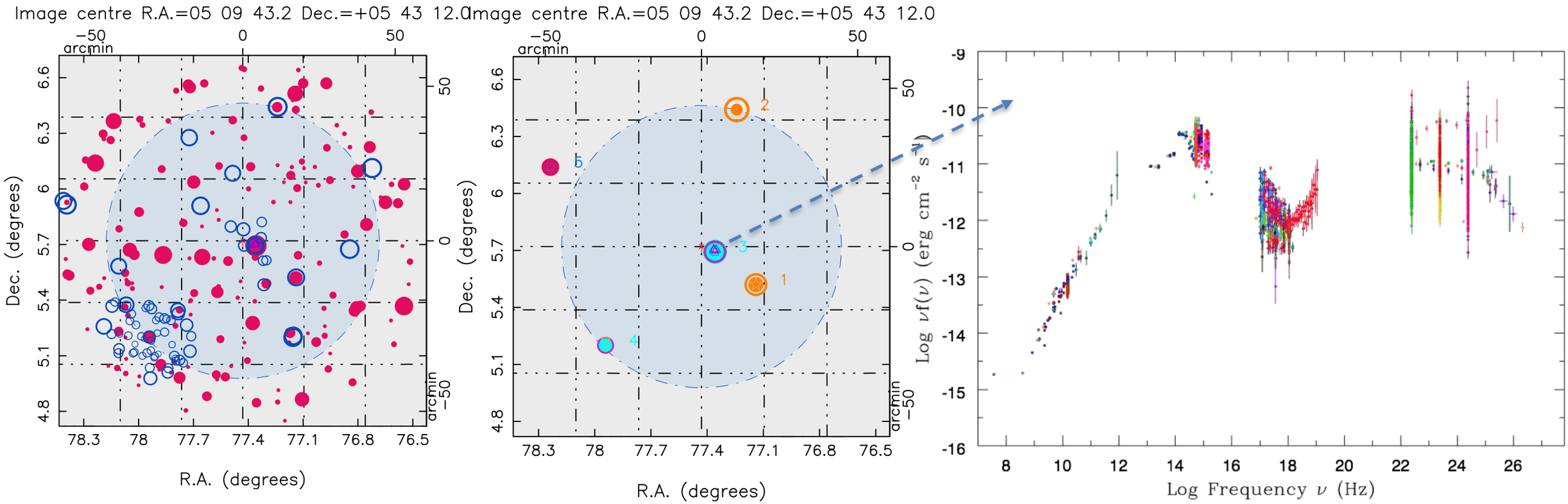

+ counterpart search of multi-messenger events => decision on follow-ups may depend on some form of real-time physically meaningful cross-matching : a case for advanced A.I. applications in CTA

EXTREME TRANSIENTS

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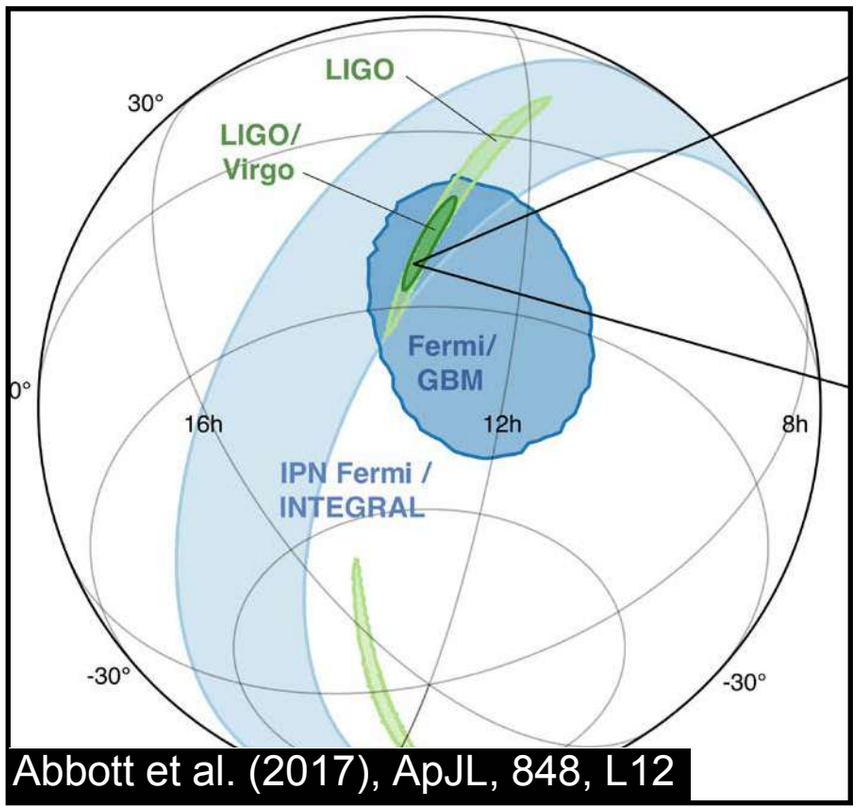
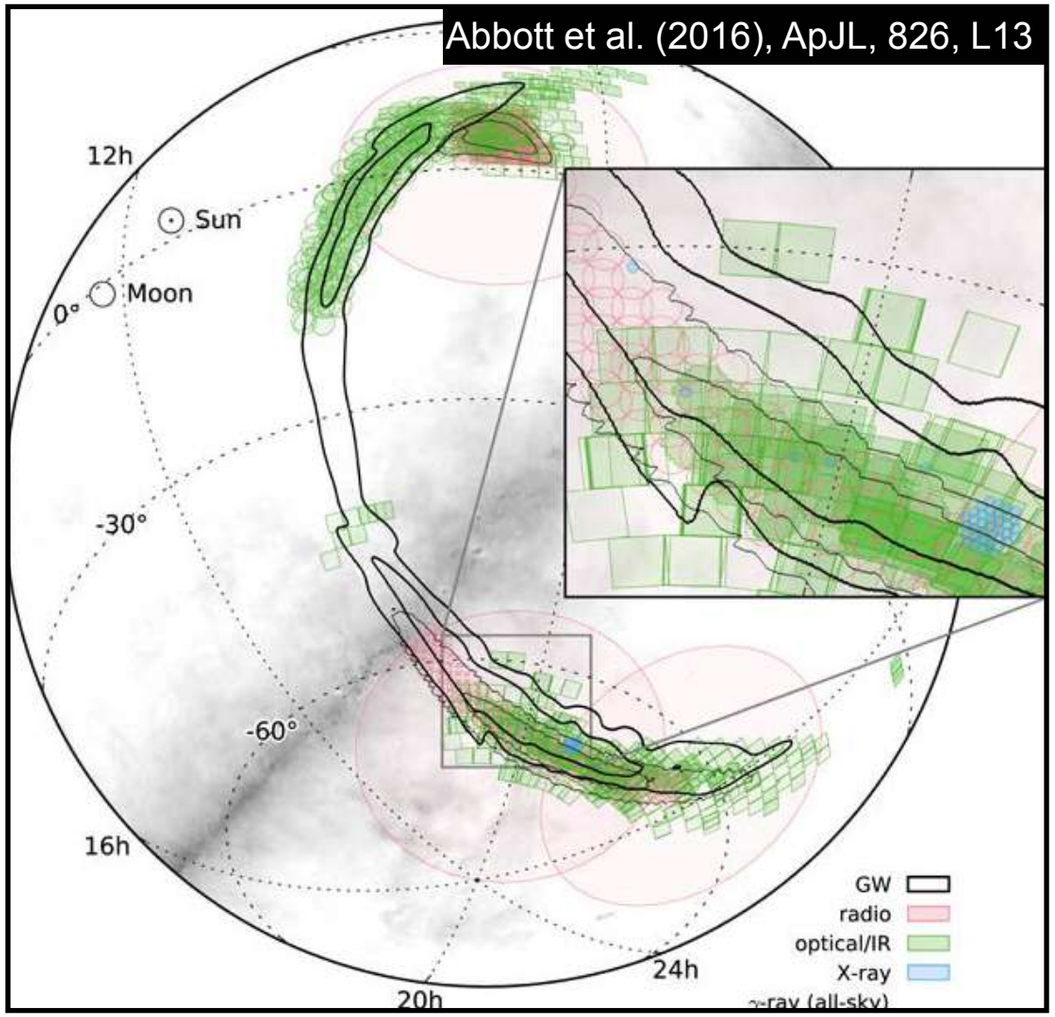
Dealing with poor location accuracy for follow-ups:

- neutrino accuracy >> 1°
- GW events ~ 100s square degrees



Abbott et al. (2017), ApJL, 848, L12



Abbott et al. (2016), ApJL, 826, L13

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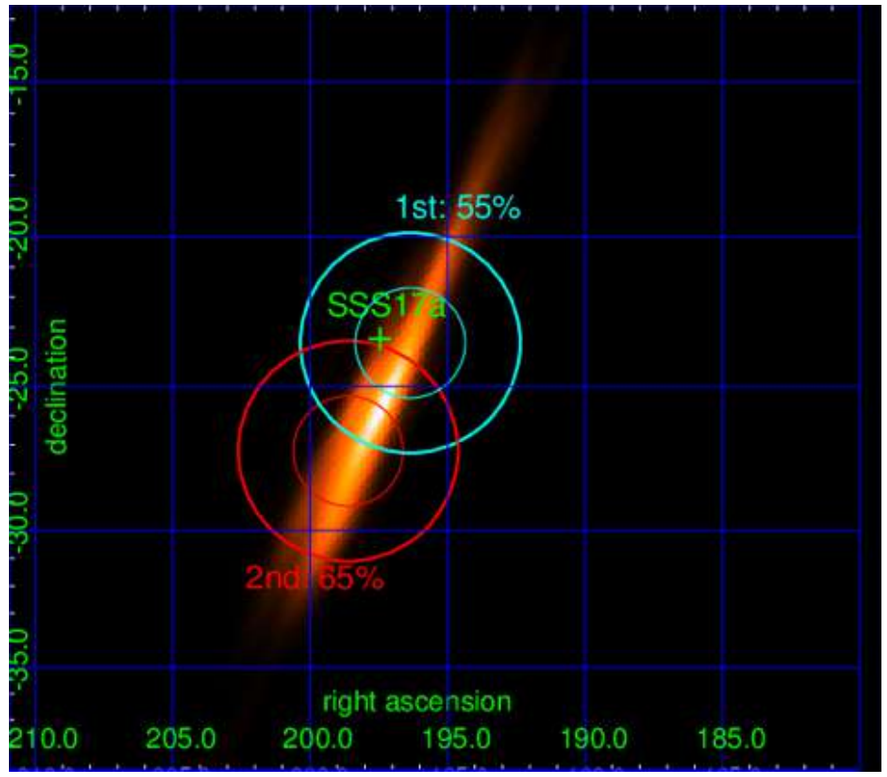

Simulated response to the VIRGO+LIGO event GW170817 requires only two CTA pointings.

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Serendipity and external triggers by CTA:

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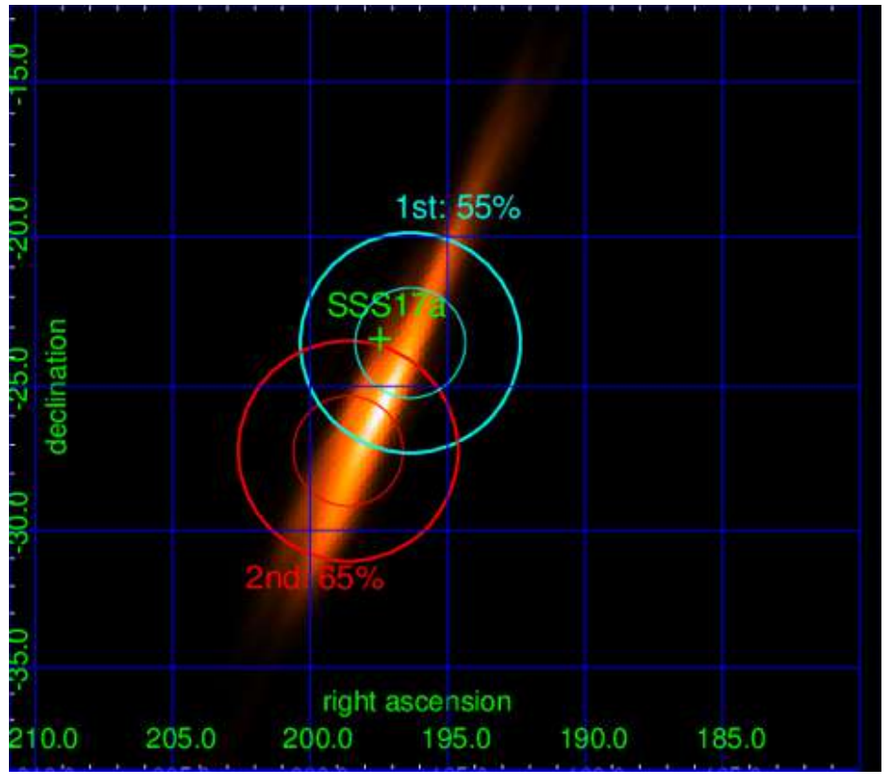
- RTA analysis detection of transients is a basic requirement for enabling MWL follow-ups



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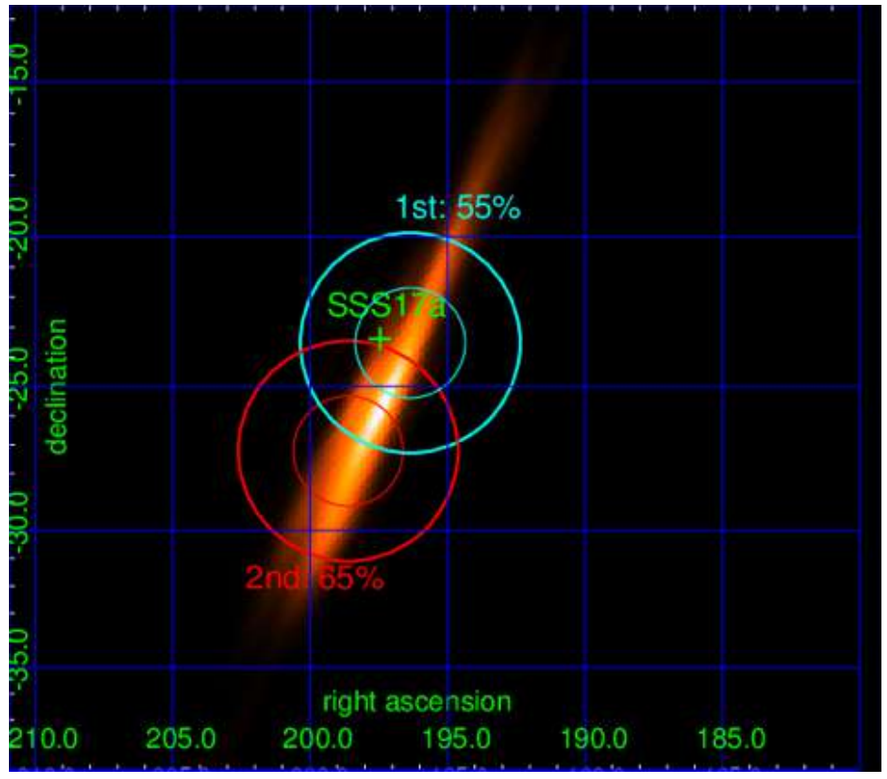
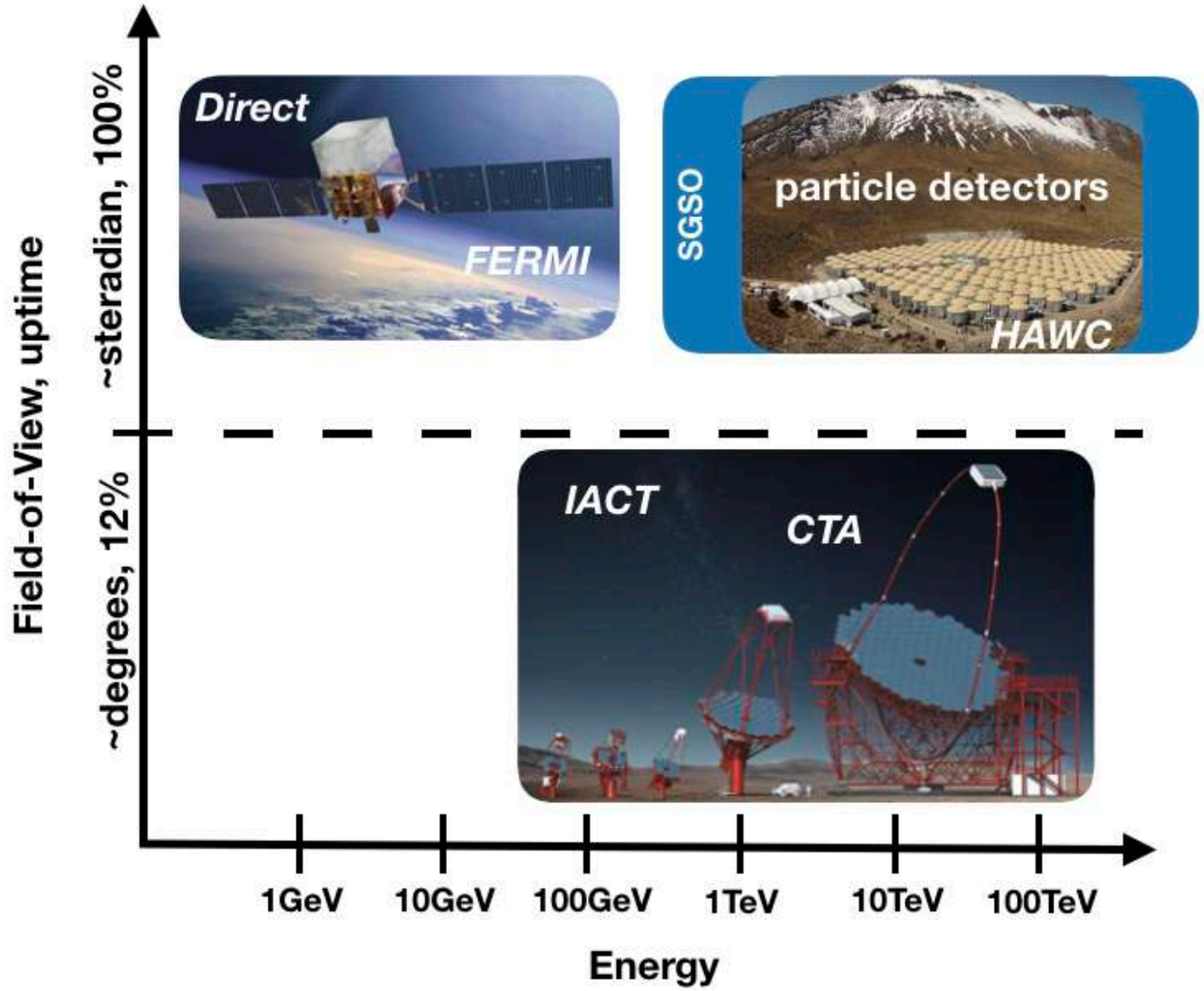
FAST RADIO BURST COUNTERPARTS?



Simulated response to the VIRGO+LIGO event GW170817 requires only two CTA pointings.

GAMMA-RAY SYNERGIES

Complementarity in the field

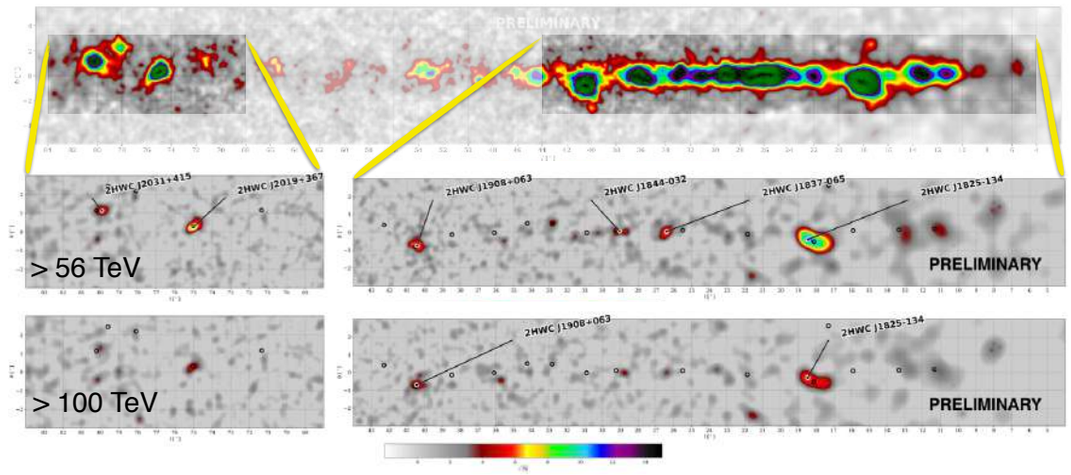


GAMMA-RAY SYNERGIES

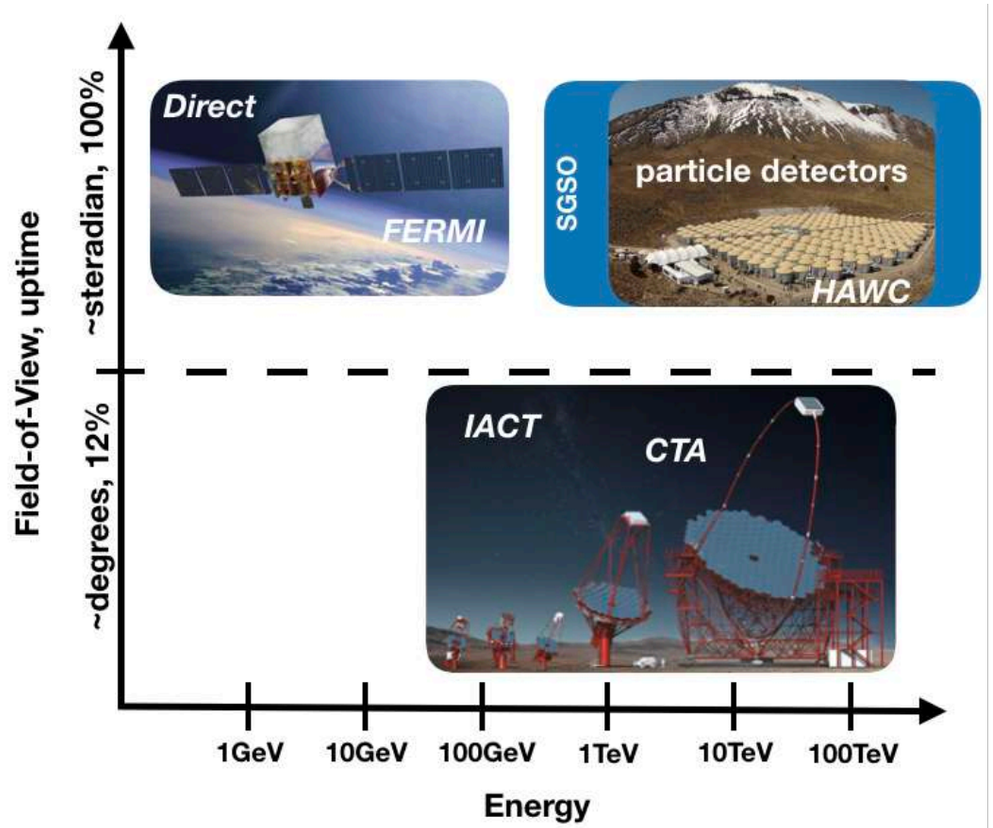
Complementarity in the field

Highest energy sky maps

- leading the way in the search for the highest energy sources in the galaxy



© Petra Huntemeyer, HAWC



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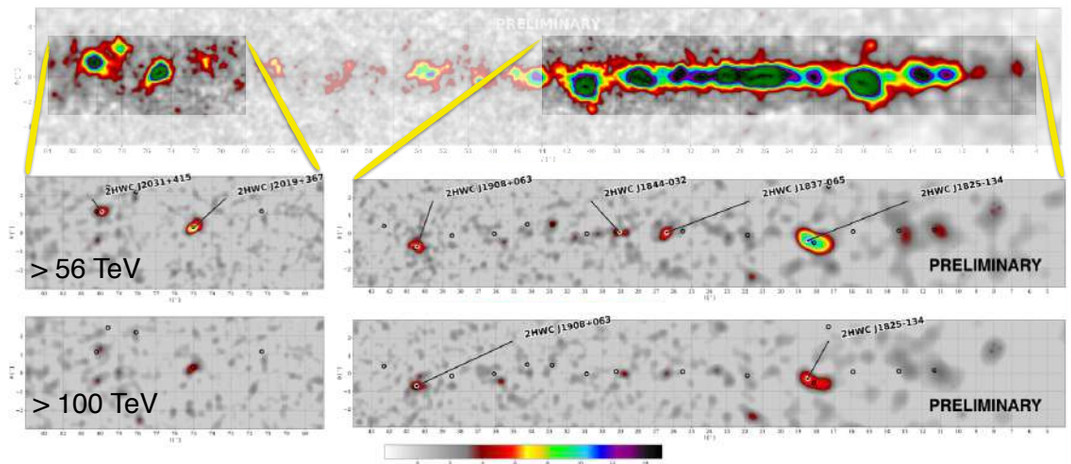
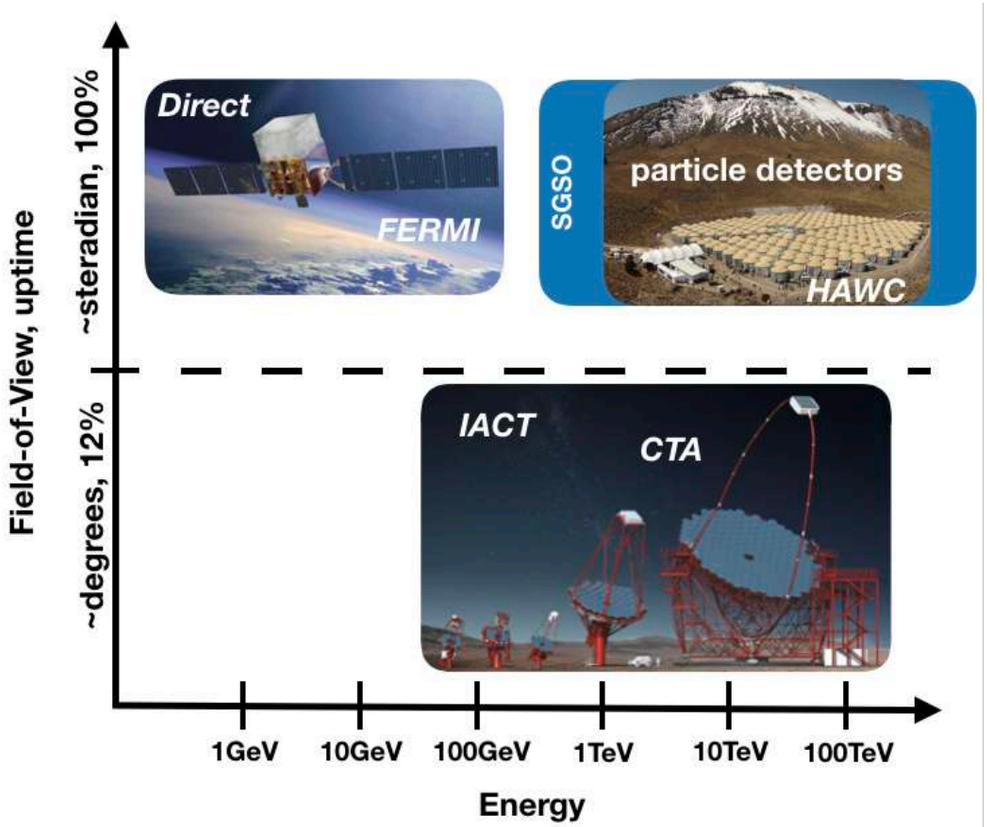
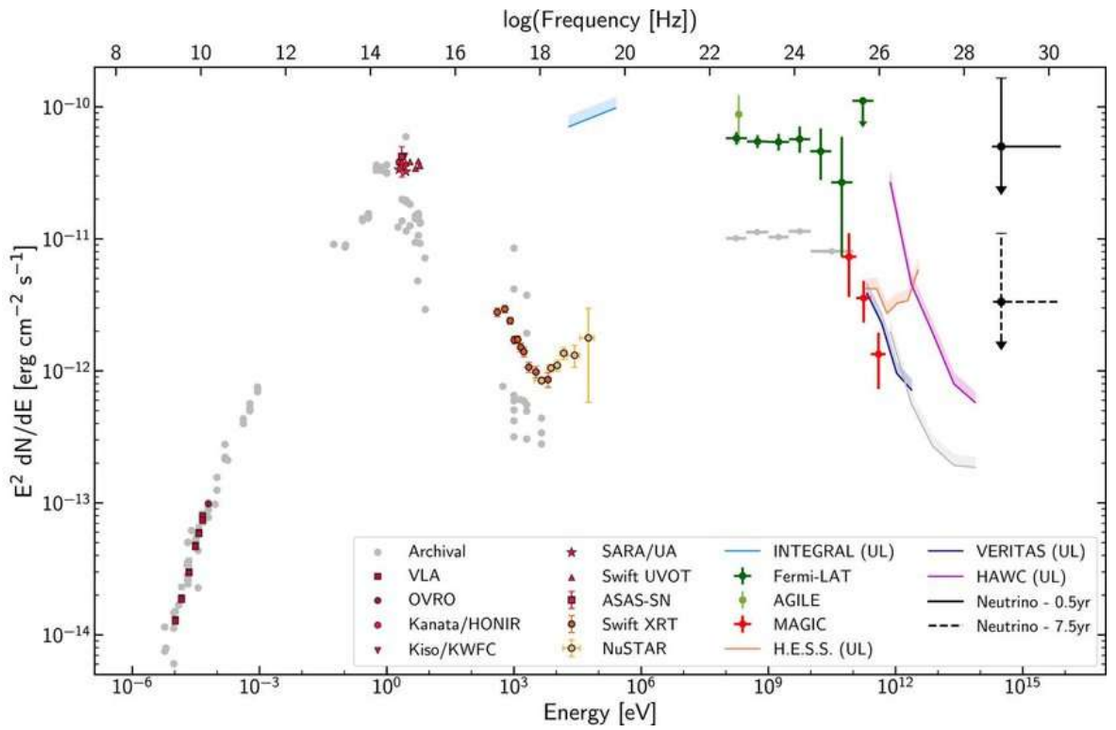


© Petra Huntemeyer, HAWC



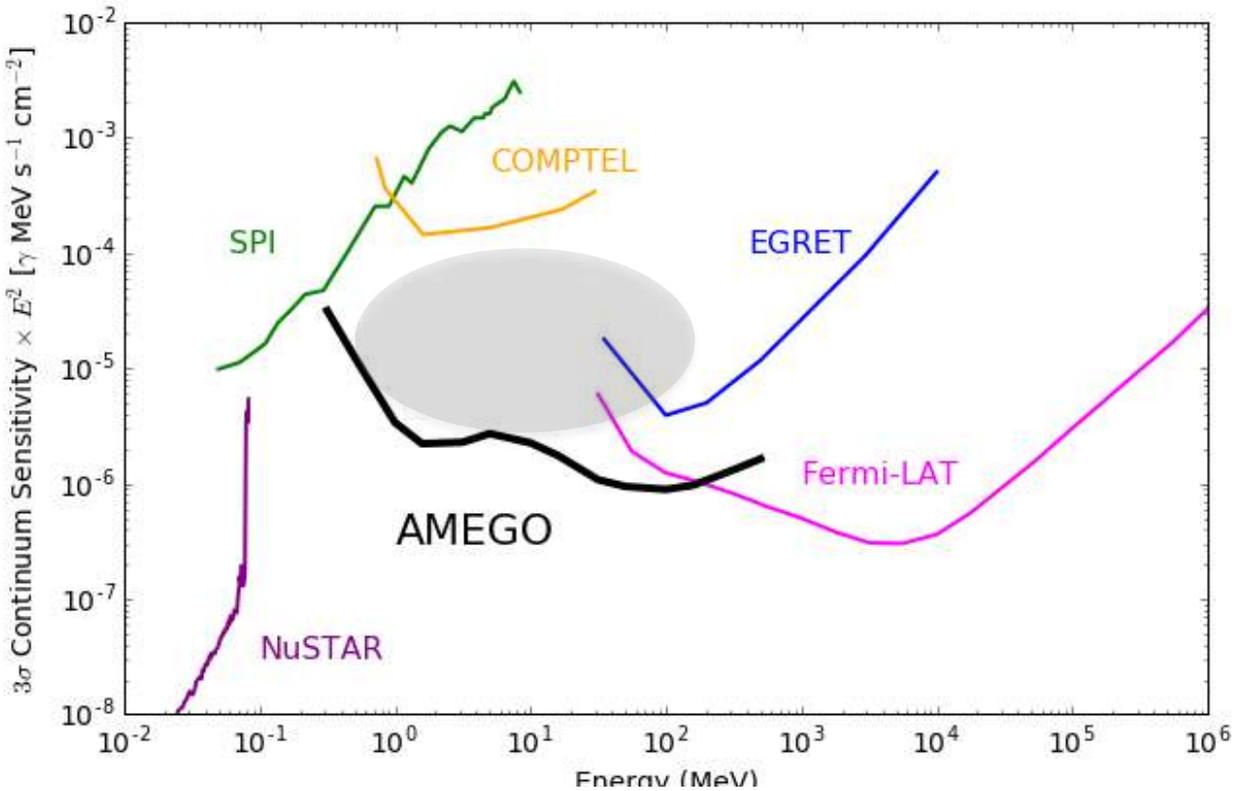
High-energy SEDs for MM events

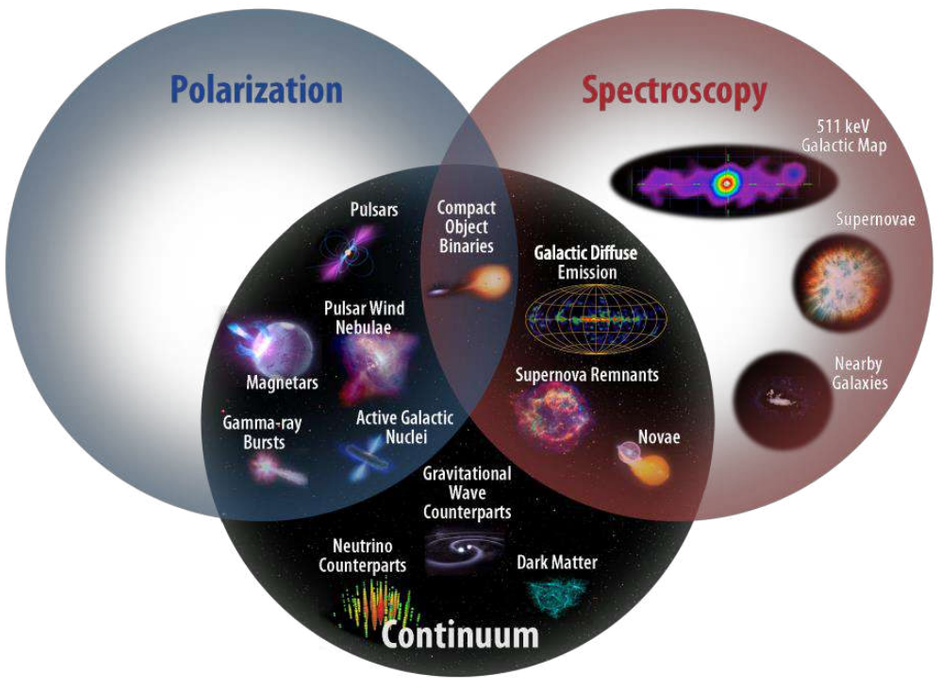
- the case of the neutrino event associated to TXS blazar source.



GAMMA-RAY SYNERGIES: FUTURE FACILITIES

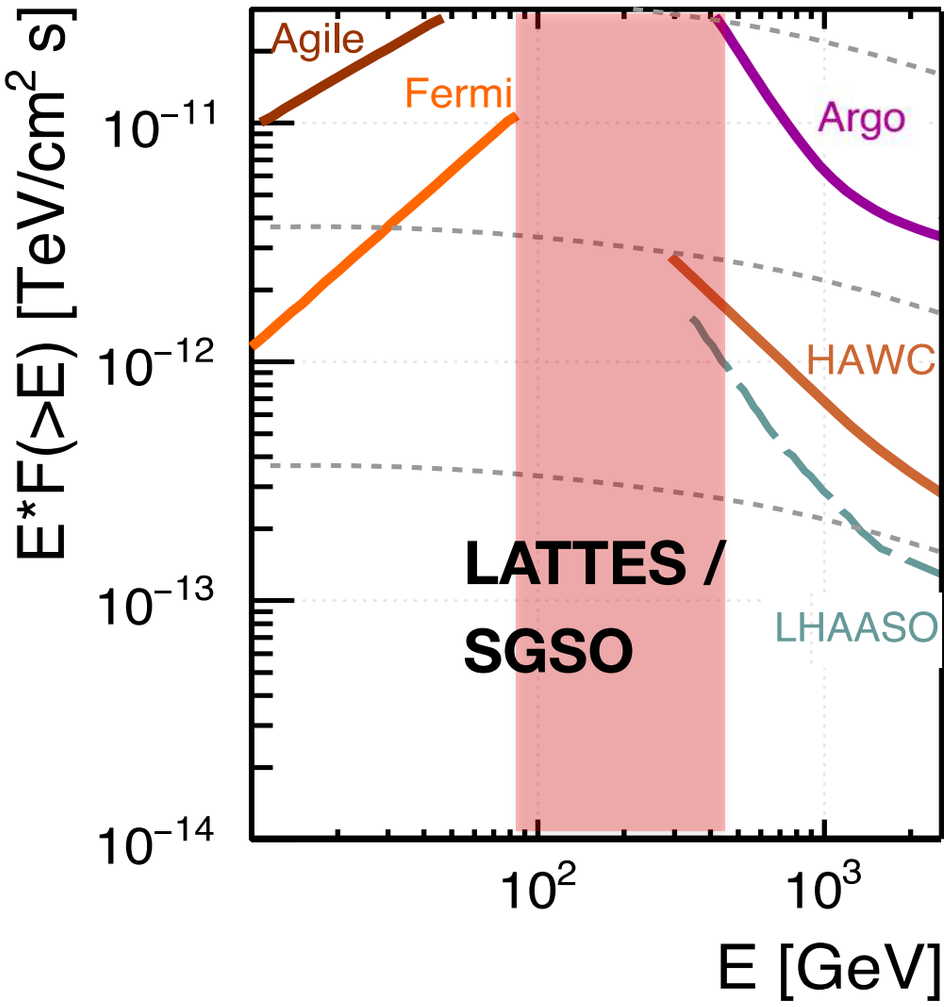
In Space





- bridging fundamental gap + unique polarimetric capability in the 100s keV range

On the ground



- wide-field of view experiment in the < 100- 300 GeV range

A CONCEPTUAL SUMMARY….

Working out the MWL / MM synergies for CTA…

© after & adapted from Ana Bonaldi, SKA

Targeted observations and surveys

- Matching MWL resolution
- Archival data x-match
- Re-analysis and planning

Triggered observations and transients

- Crucial time-coordination
- Short time-resolution goal
- fast trigger & response
- real-time source ID

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- Matching MWL resolution
- Archival data x-match
- Re-analysis and planning

- Reduce instrumental sys
- increase info content
- break degeneracies
- full science potential

Triggered observations and transients

- Crucial time-coordination
- Short time-resolution goal
- fast trigger & response
- real-time source ID

THANK YOU!

ulisses@cbpf.br