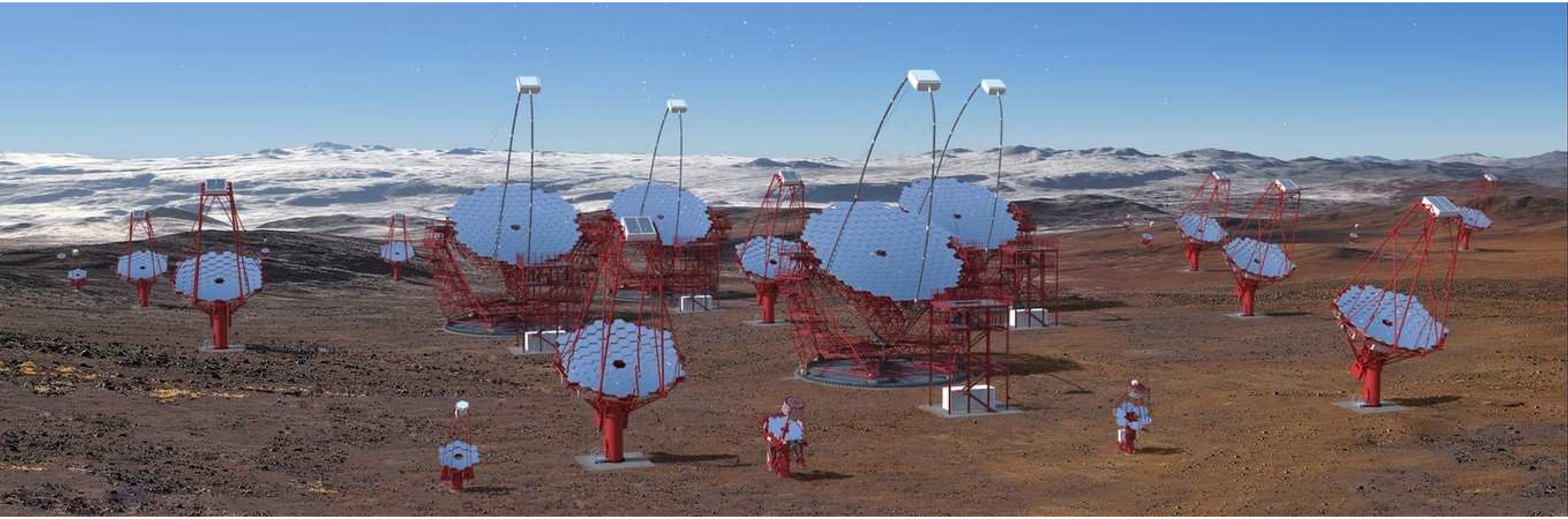
Transient sky with CTA



Southern Hemisphere Site Rendering; credit: Gabriel Pérez Diaz, IAC, SMM

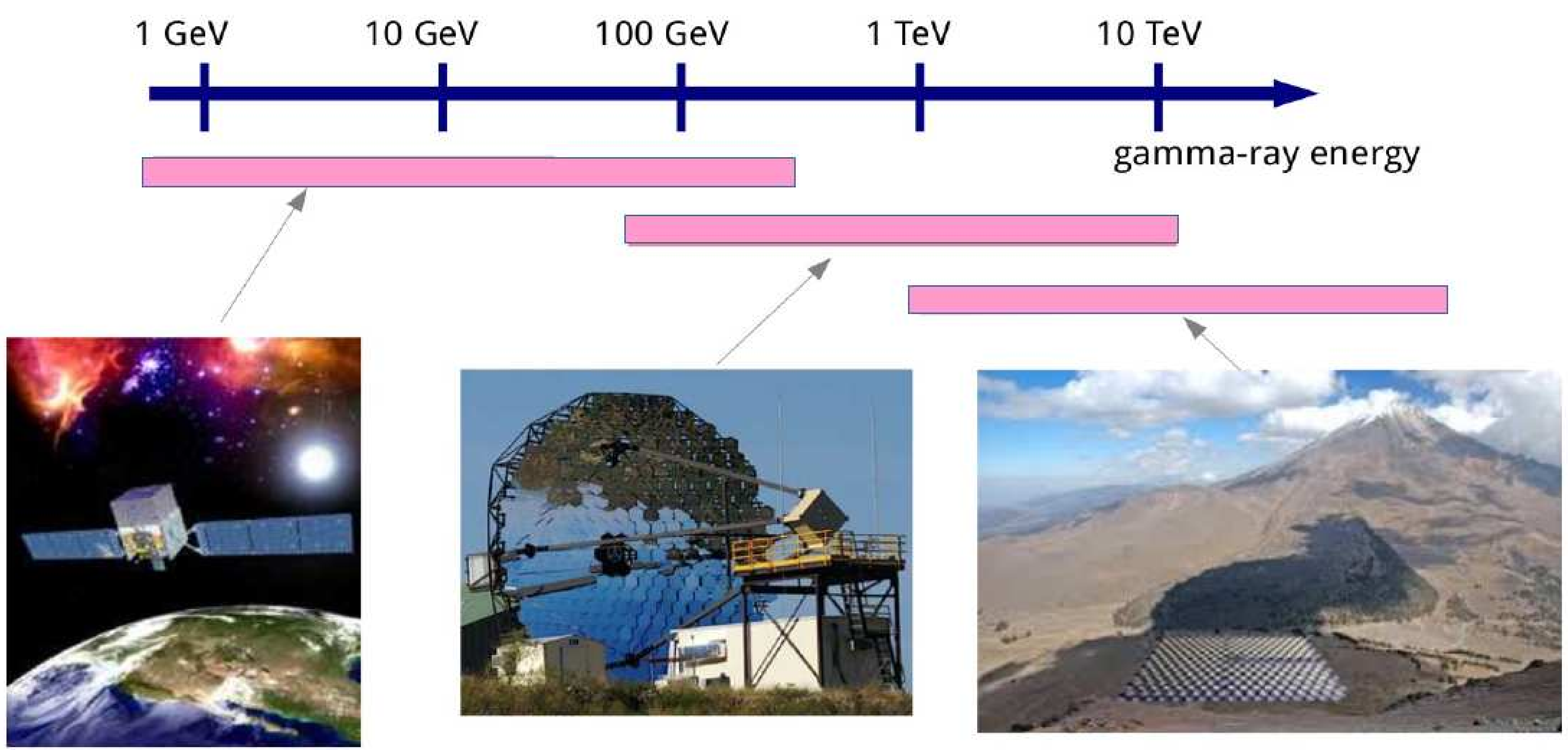
Pair production telescopes	Atmospheric Cherenkov tels.	Particle detector arrays
	 MAGIC, HESS, VERITAS, CTA	
0.1 - 100 GeV	30 GeV - 70 TeV, **~300 TeV for CTA**	100 GeV - 100 TeV
Space borne: limited in area	Large effective area	Large effective area
Nearly background free	Excellent background rejection	Very good background rejection
Large field of view / high duty cycle	Small field of view / low duty cycle	Large field of view / high duty cycle
All-sky survey and monitoring Extragalactic (AGNs, GRBs), PSRs, MQSO Dark matter	Study of known sources Deep survey of limited regions Morphology of TeV emitters (SNRs, PWN) High resolution spec. to 30 TeV	Partial (2/3) sky survey and monitoring Extended sources Transients (GRBs) > 30 GeV Spectra up to 100 TeV

Adapted from Justin Vandenbroucke

Gamma-ray instruments

Earth's atmosphere is opaque for gamma-rays

Direct detection in space ⟷ Indirect detection from ground



Satellites

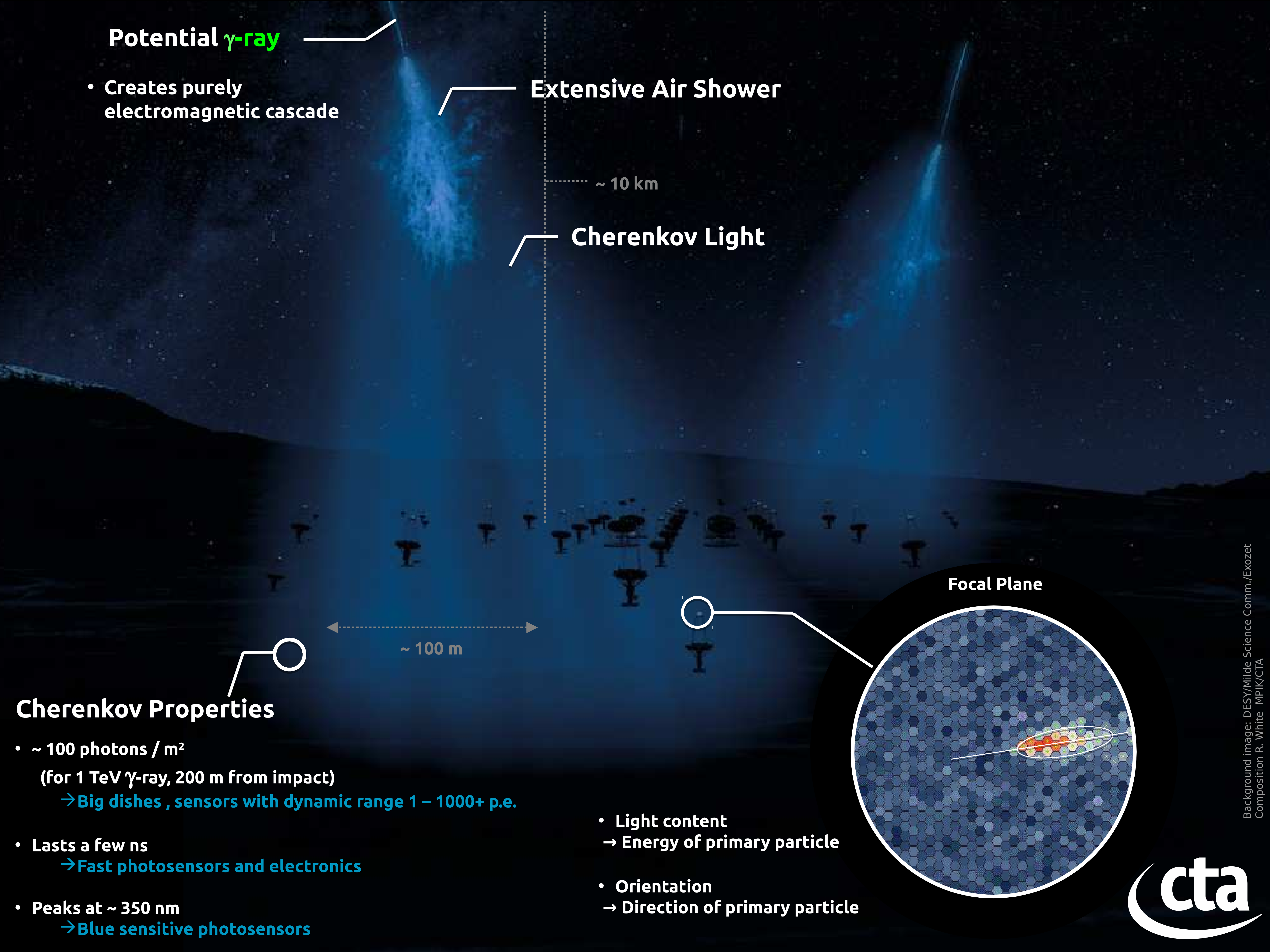
Cherenkov telescopes

Water Cherenkov detectors

Adapted from Justin Vandenbroucke

Transient sky with CTA

- Imaging Atmospheric Cherenkov Telescopes
- The Cherenkov Telescope Array
- CTA – a transient factory
- Prospect


Potential γ-ray
• Creates purely electromagnetic cascade
Extensive Air Shower
~ 10 km
Cherenkov Light
~ 100 m
Focal Plane
Cherenkov Properties
• ~ 100 photons / m^2
(for 1 TeV γ-ray, 200 m from impact)
→Big dishes , sensors with dynamic range 1 – 1000+ p.e.
• Lasts a few ns
→Fast photosensors and electronics
• Peaks at ~ 350 nm
→Blue sensitive photosensors
• Light content
→ Energy of primary particle
• Orientation
→ Direction of primary particle
Background image: DESY/Milde Science Comm./Exozet
Composition R. White MPIK/CTA
cta

Potential γ-ray

- Creates purely electromagnetic cascade

Extensive Air Shower

~ 10 km

Potential Cosmic-ray

- Dominates γ-ray rate, even after NSB is reduced
- Complex cascade
- Irregular images in the camera

→ Offline image analysis

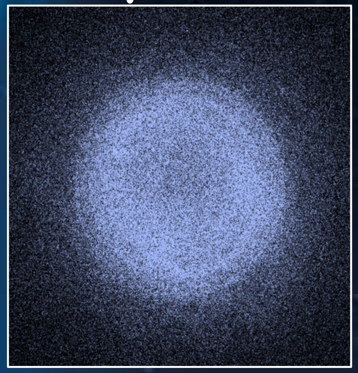
Night Sky Background

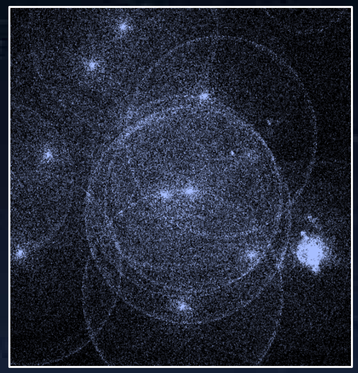
- Stars, airglow, Zodiacal light...
- Extra-galactic rate ~100 MHz per pixel (for 100m² dish, 0.15° pix)

→ Online trigger algorithm

Cherenkov Light

γ-ray | Cosmic-ray





Cherenkov light pool on the ground

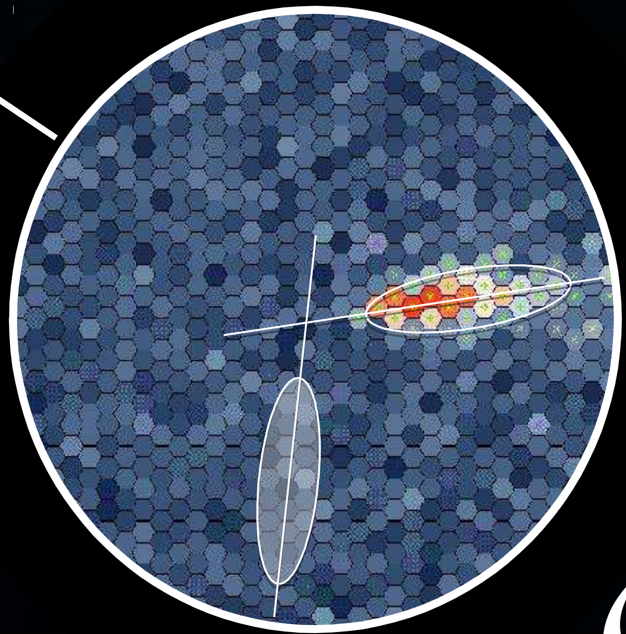
~ 100 m

Cherenkov Properties

- ~ 100 photons / m² (for 1 TeV γ-ray, 200 m from impact)
  →Big dishes , sensors with dynamic range 1 – 1000+ p.e.
- Lasts a few ns
  →Fast photosensors and electronics
- Peaks at ~ 350 nm
  →Blue sensitive photosensors

- Shape
  → γ/CR discrimination
- Light content
  → Energy of primary particle
- Orientation
  → Direction of primary particle

Focal Plane



Images from multiple telescopes overlaid

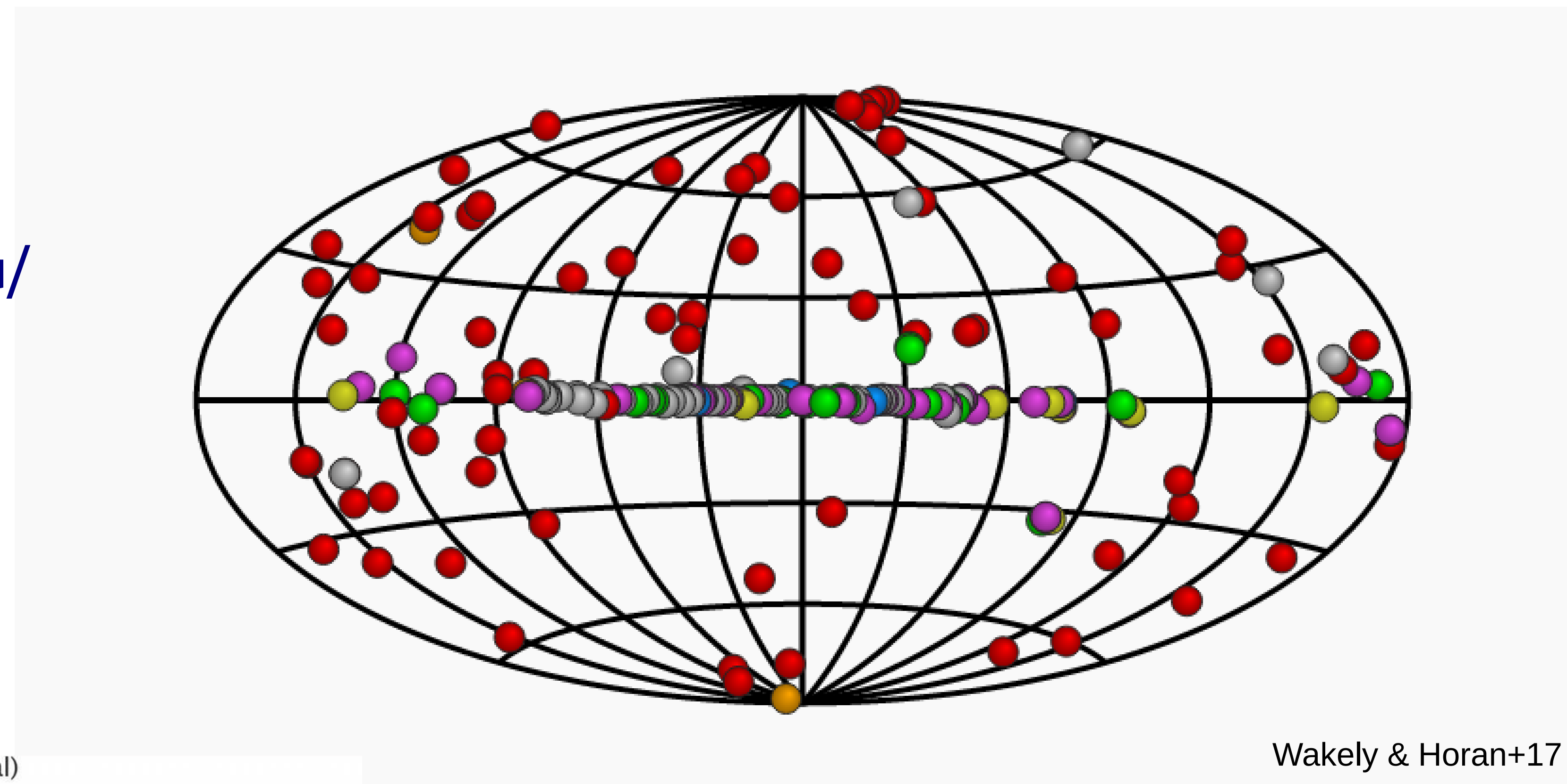
cta

Ground based IACTs

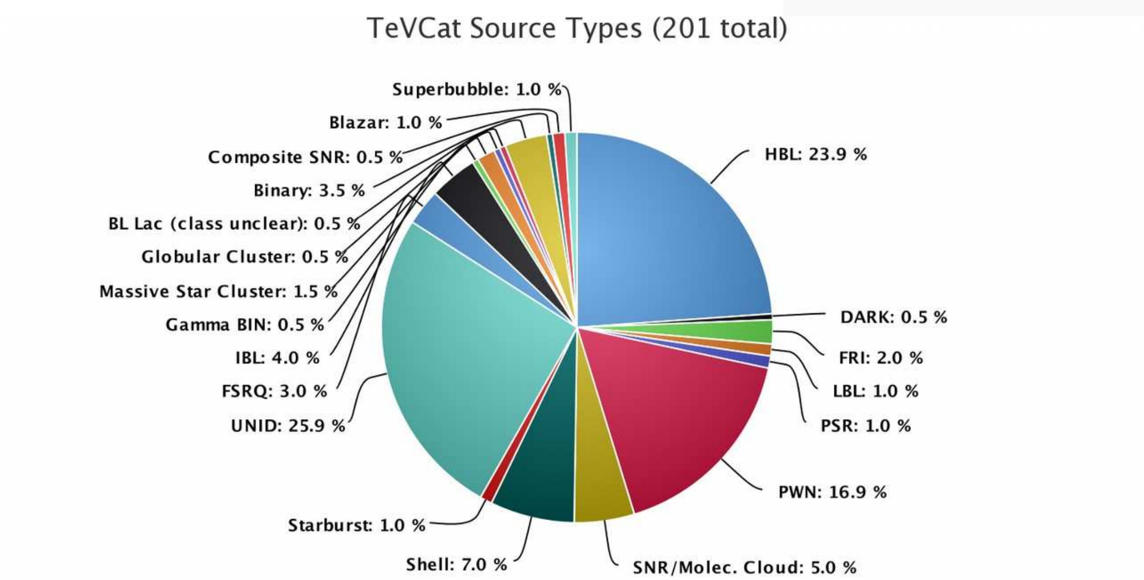
100 GeV – 50 TeV sky

TeVCat2
http://tevcat2.uchicago.edu/

H.E.S.S., MAGIC, VERITAS
~ 200 sources
E > 100GeV



Wakely & Horan+17



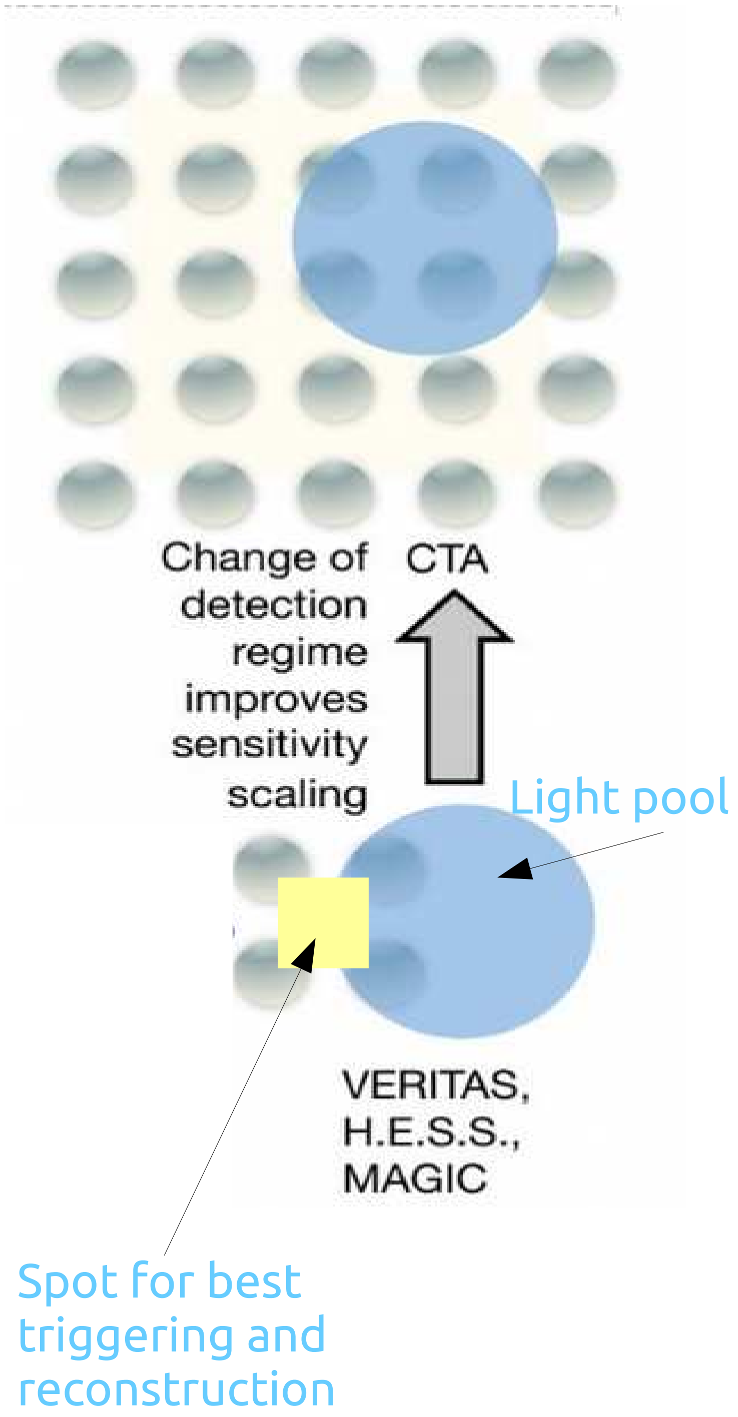
Adapted from S. Vercellone

Transient sky with CTA

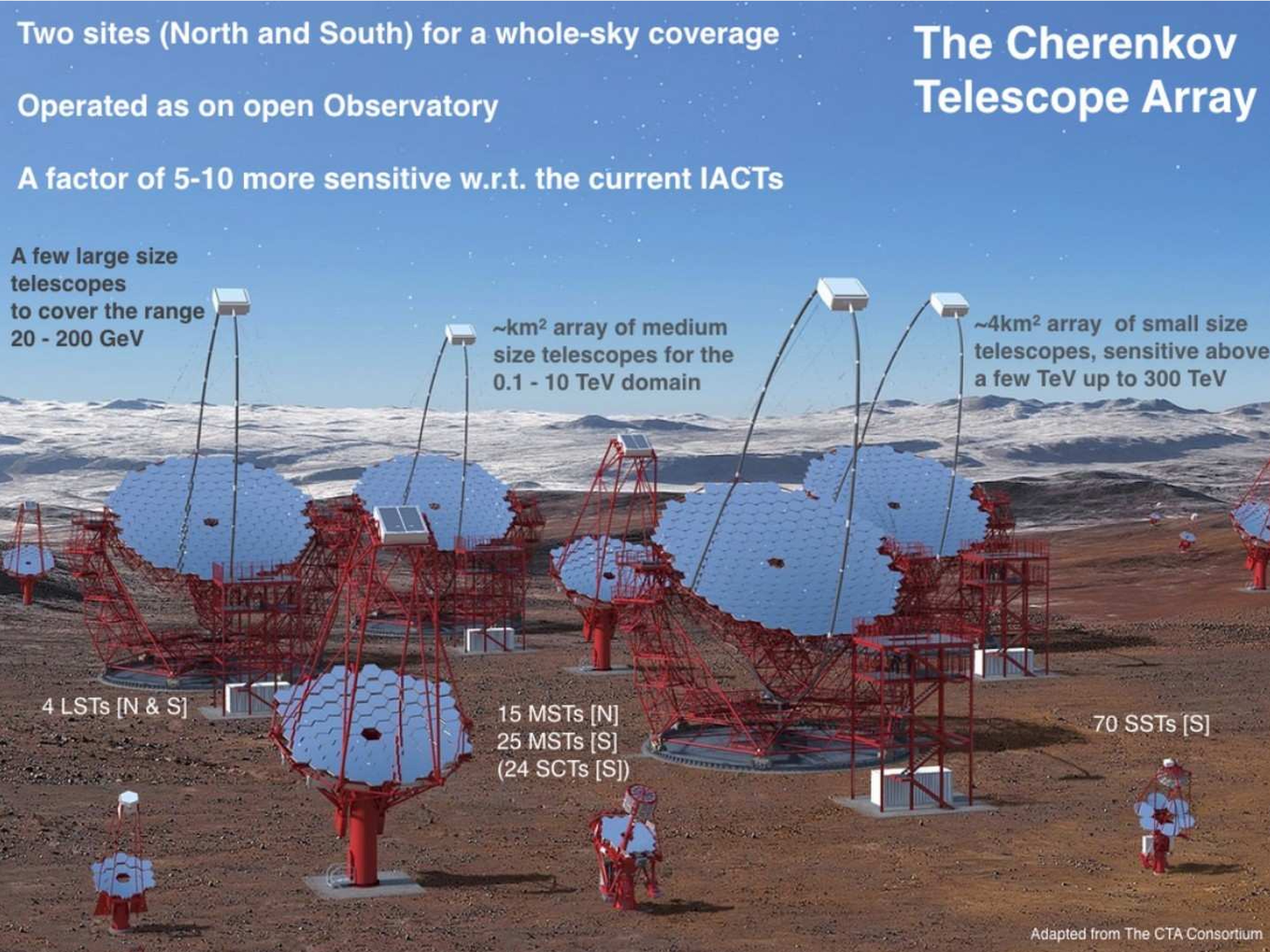
- Imaging Atmospheric Cherenkov Telescopes
- The Cherenkov Telescope Array
- CTA – a transient factory
- Prospect

Cherenkov Telescope Array

- CTA will — for the first time — deploy a large number of telescopes across areas that are **larger than the size of the Cherenkov light pool,** resulting in:
  - A dramatically **increased rate of air showers** contained within the footprint of the telescope array
  - An increased number of views of the air shower **from different viewing angles**, improving both the reconstruction of air-shower parameters, and the rejection of cosmic-ray induced air showers as the major source of sensitivity-limiting background
  - A **lower effective energy threshold** since, for contained showers, there are always telescopes in the region of highest density of Cherenkov light.

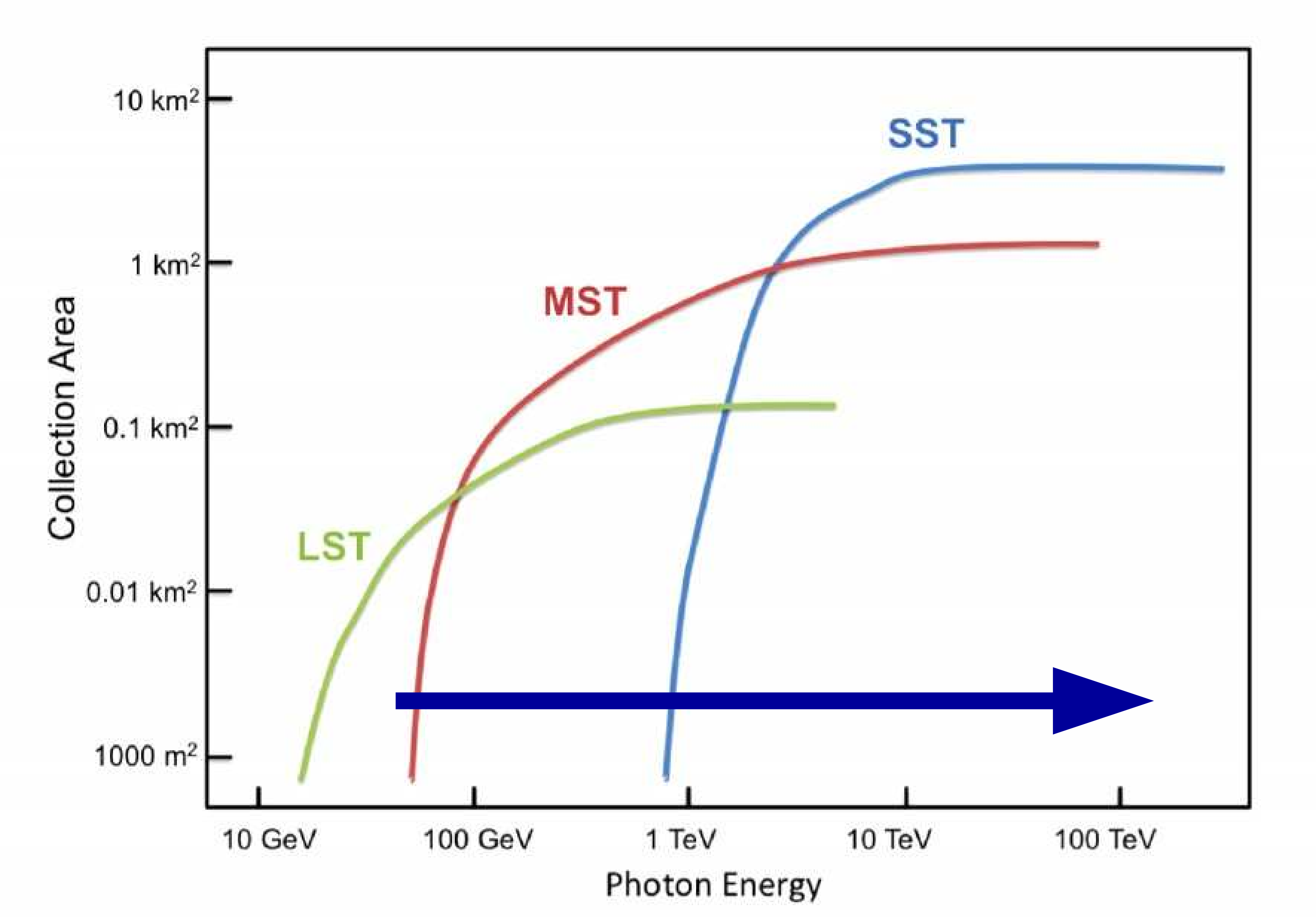


Adapted from V. Vassiliev


Two sites (North and South) for a whole-sky coverage
Operated as on open Observatory
A factor of 5-10 more sensitive w.r.t. the current IACTs
The Cherenkov Telescope Array
A few large size telescopes to cover the range 20 - 200 GeV
~km^2 array of medium size telescopes for the 0.1 - 10 TeV domain
~4km^2 array of small size telescopes, sensitive above a few TeV up to 300 TeV
4 LSTs [N & S]
15 MSTs [N]
25 MSTs [S]
(24 SCTs [S])
70 SSTs [S]
Adapted from The CTA Consortium

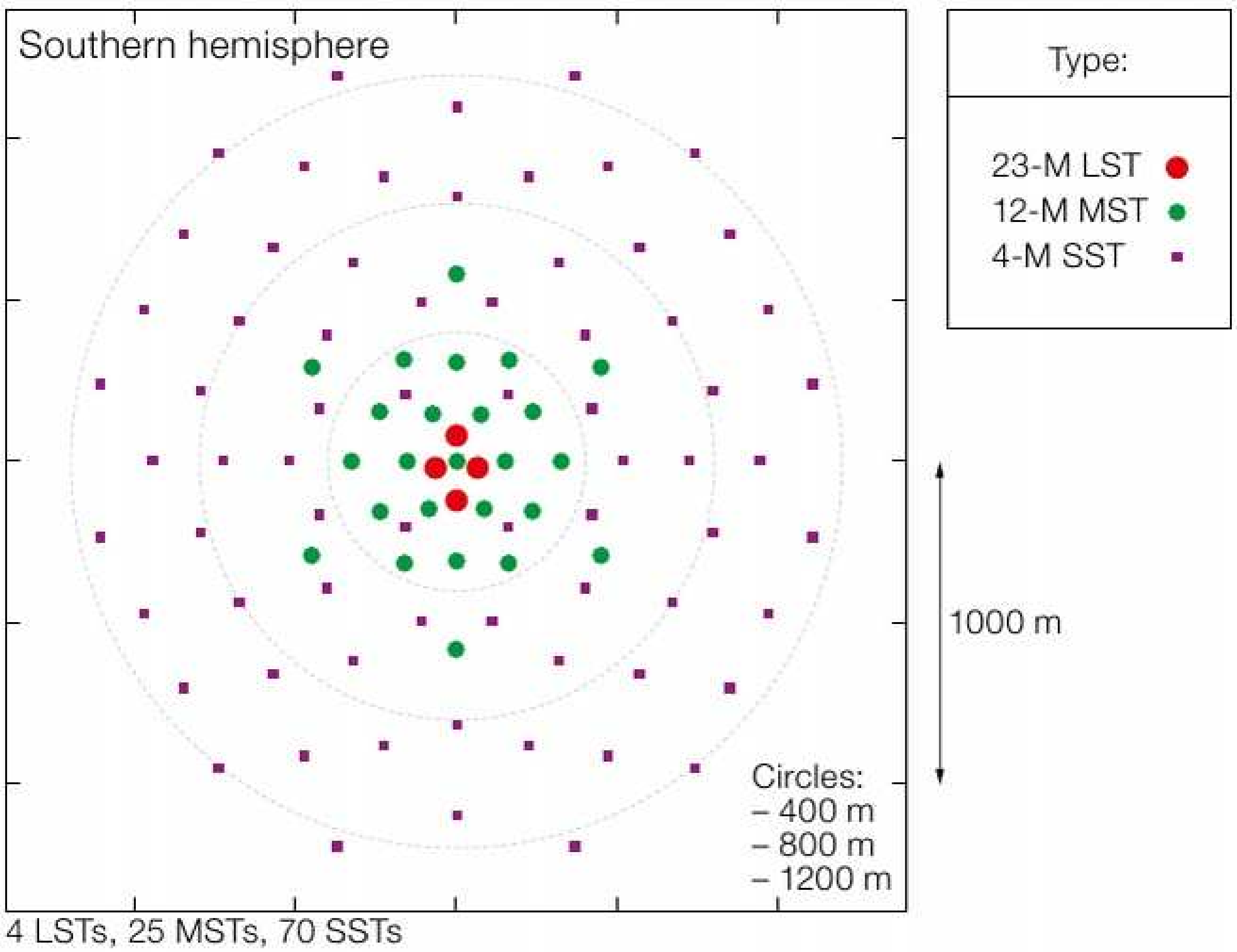
CTA telescopes

Effective Collection Area

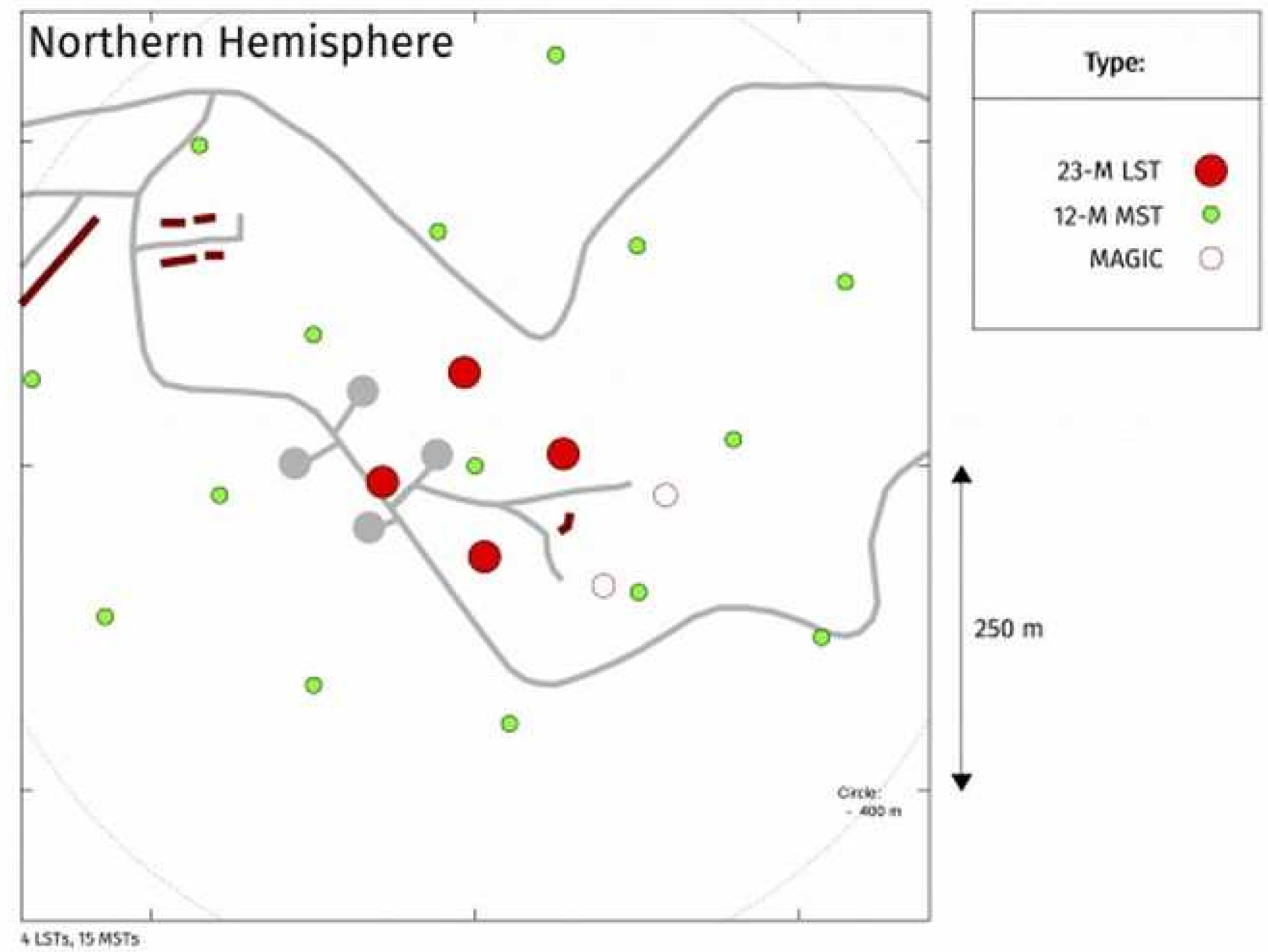


Decreasing gamma-ray flux (E^{-2} or faster) compensated by increasing effective area.

Telescope layout



Southern Site

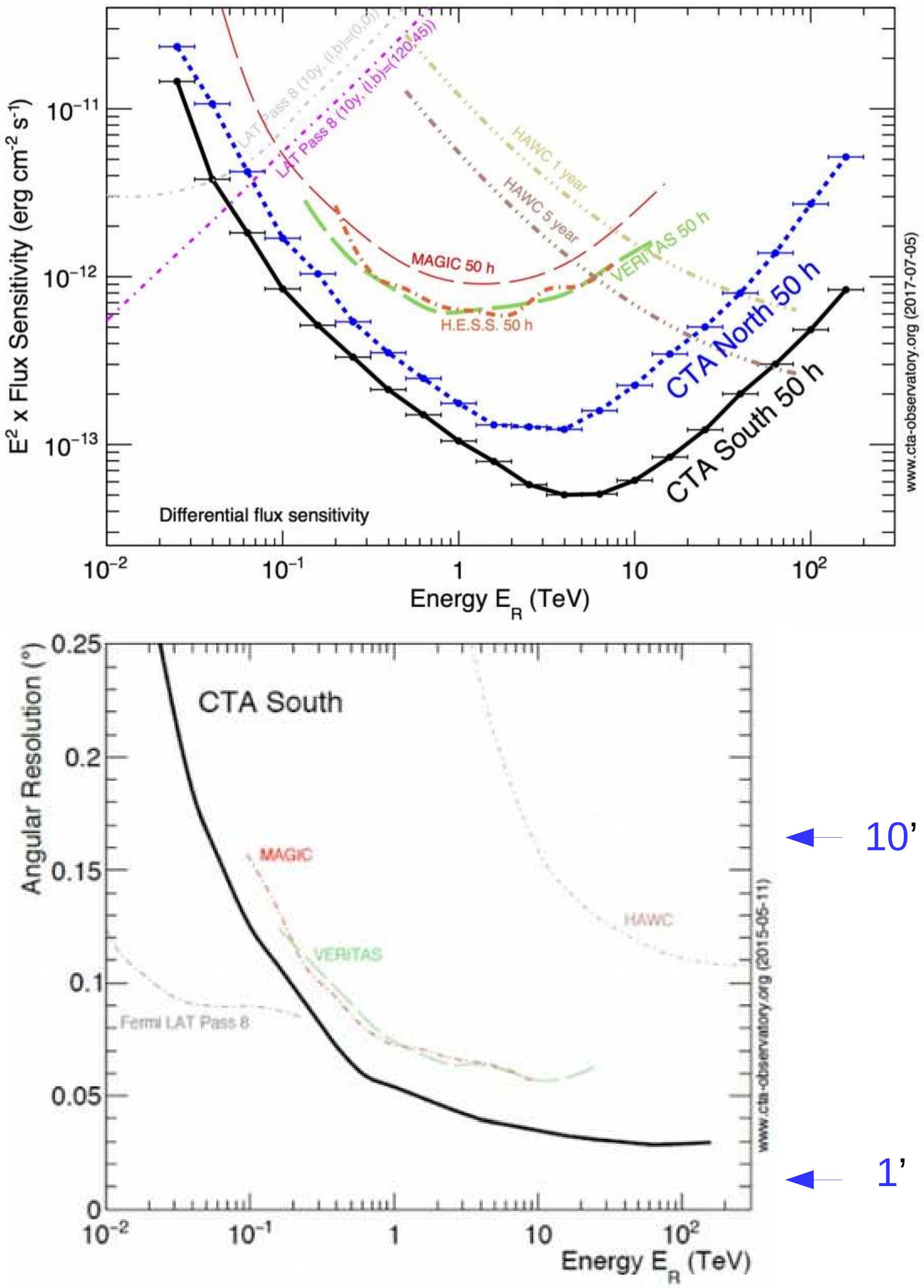


Northern Site

Credit : The CTA consortium

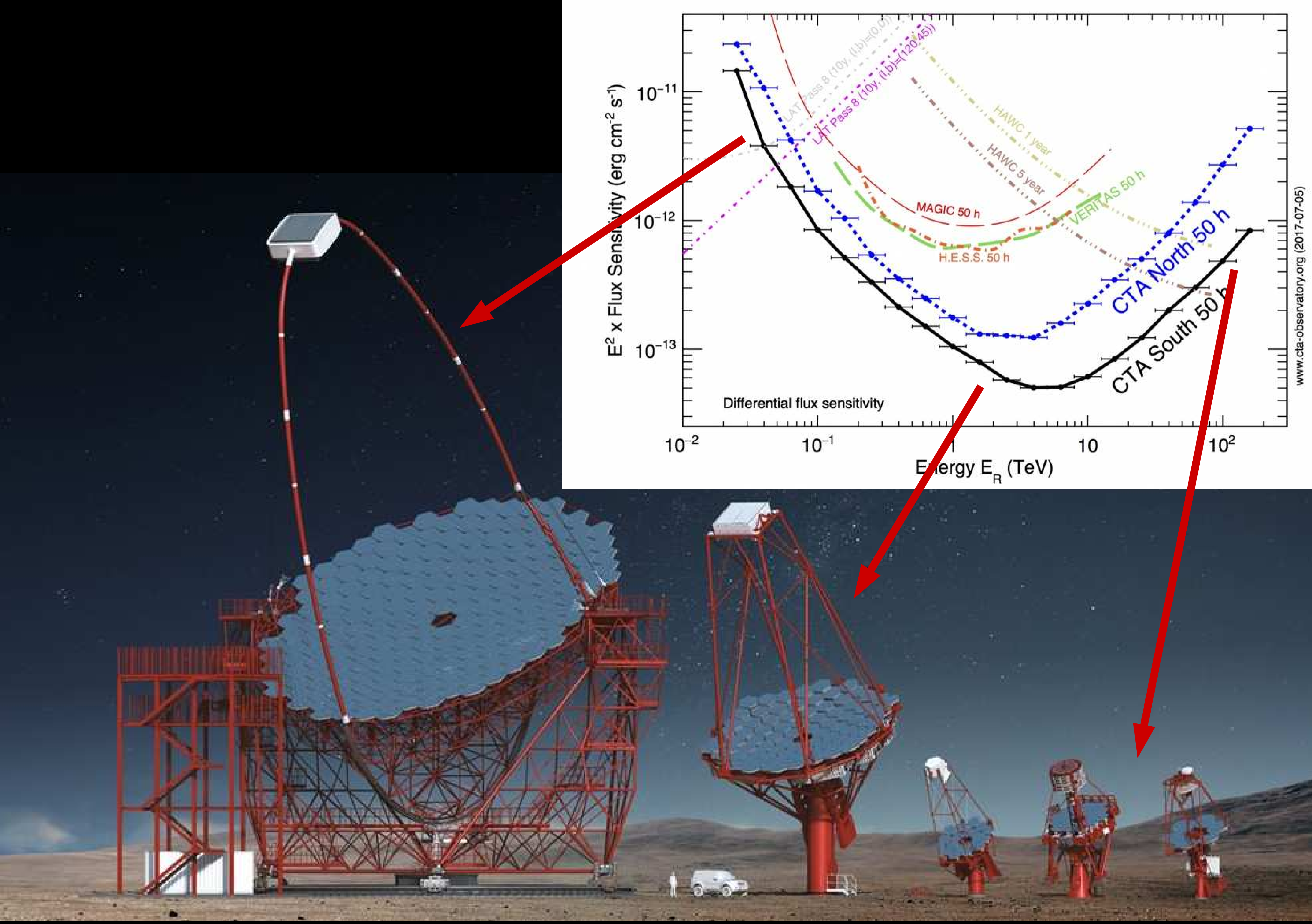
Expected performance

- **Sensitivity gain x 10**
  - access VHE populations across entire Galaxy
  - sample fast variability (AGN, GRB)
- **Broad energy coverage**
  - < 100 GeV to reach higher redshifts
  - > 10 TeV to search for PeVatrons
- **FoV > 8° (> 1TeV)**
  - measure diffuse emissions
  - efficient survey of large fields
- **Arcmin angular resolution**
  - resolve extended sources (SNR, starbursts, PWN...)

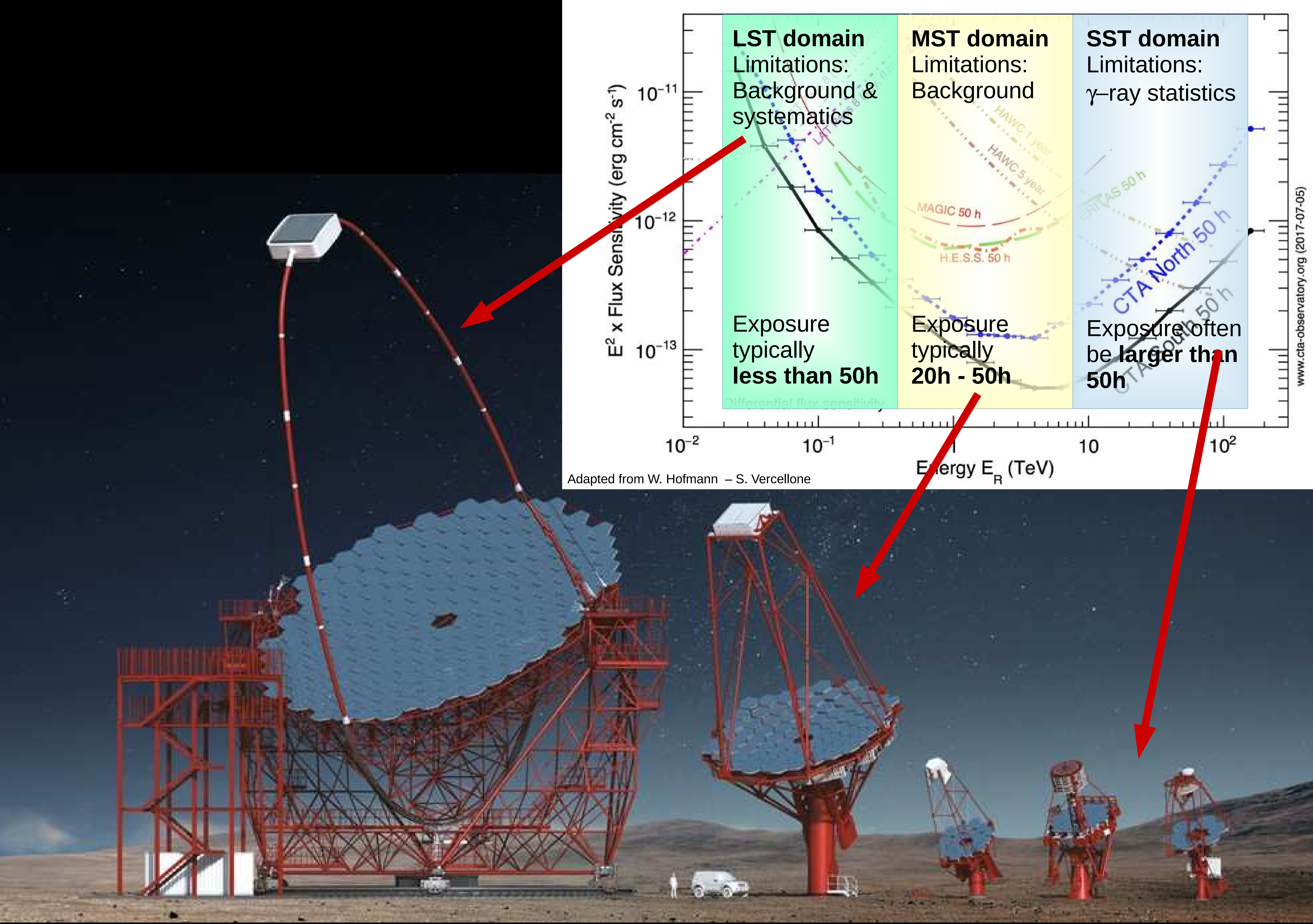


Instrument response functions at the following URL:
https://www.cta-observatory.org/science/cta-performance/

Credits: The CTA Consortium



E² x Flux Sensitivity (erg cm⁻² s⁻¹)
10⁻¹¹
10⁻¹²
10⁻¹³
10⁻²
10⁻¹
1
10
10²
Energy E_R (TeV)
Differential flux sensitivity
LAT Pass 8 (10y, (l,b)=(0,0))
LAT Pass 8 (10y, (l,b)=(120,45))
HAWC 1 year
HAWC 5 year
MAGIC 50 h
VERITAS 50 h
H.E.S.S. 50 h
CTA North 50 h
CTA South 50 h
www.cta-observatory.org (2017-07-05)



Adapted from W. Hofmann – S. Vercellone

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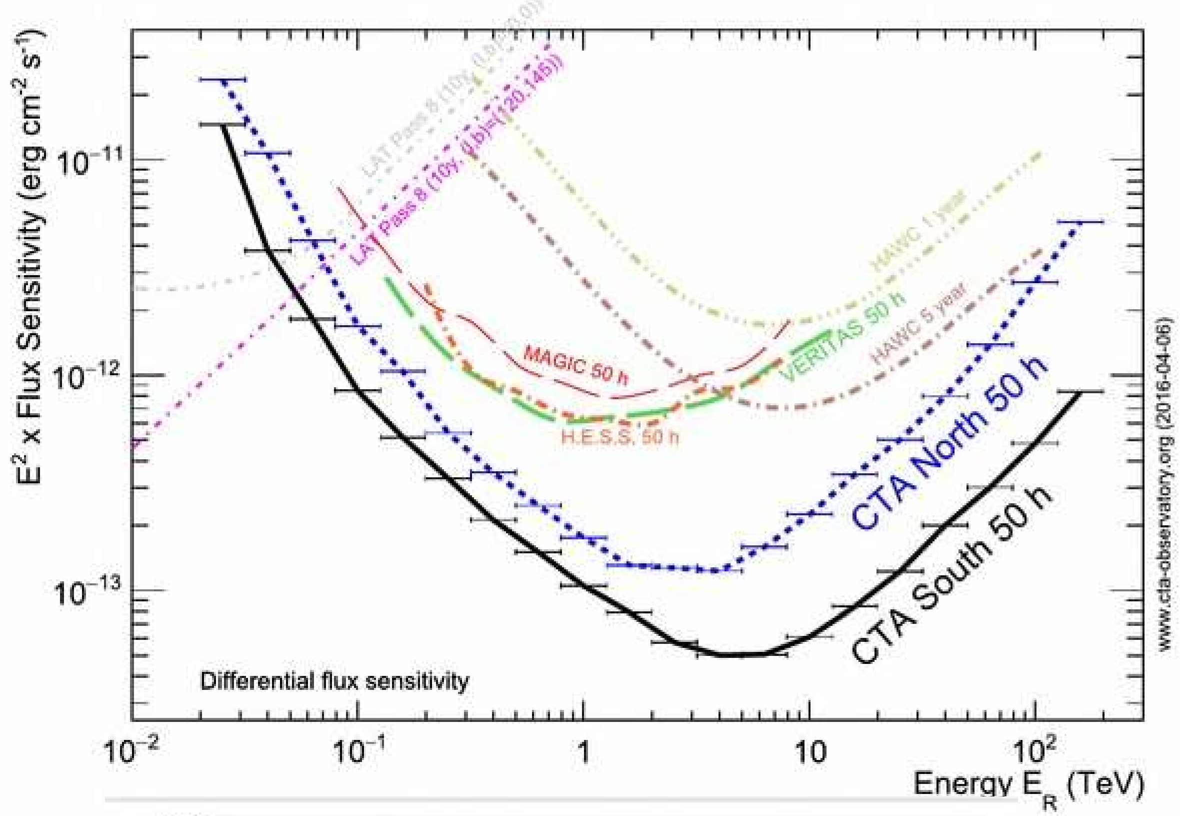

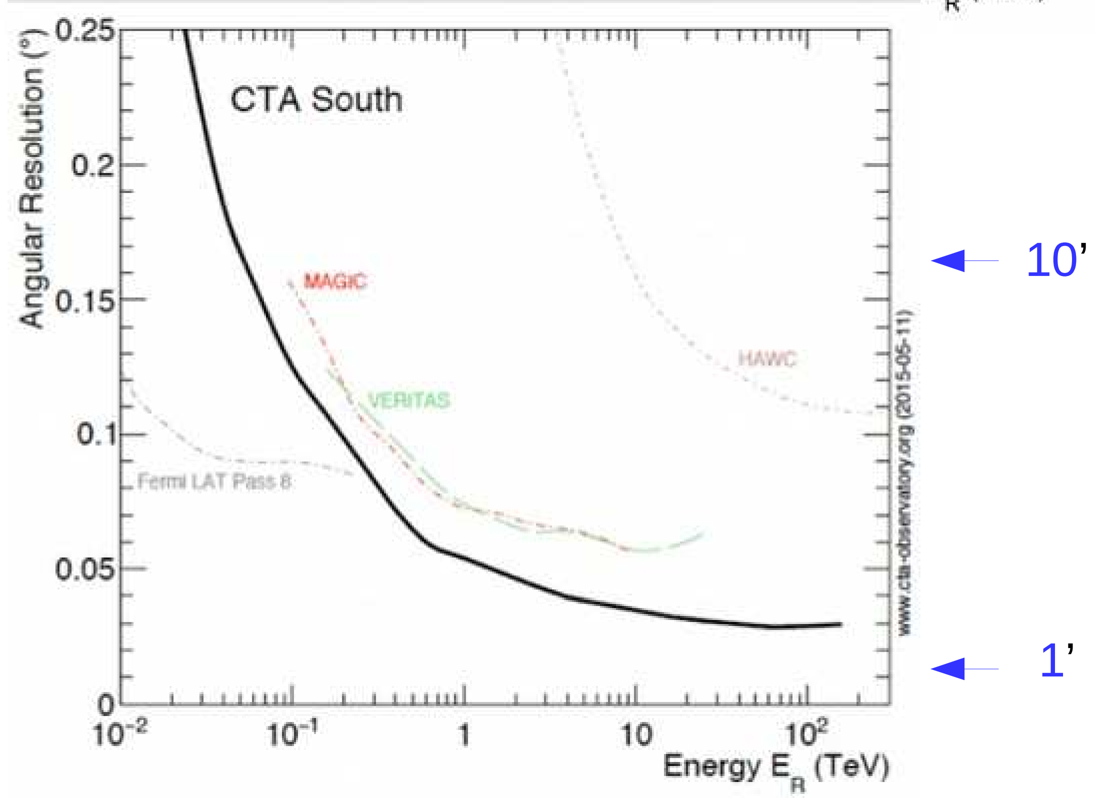

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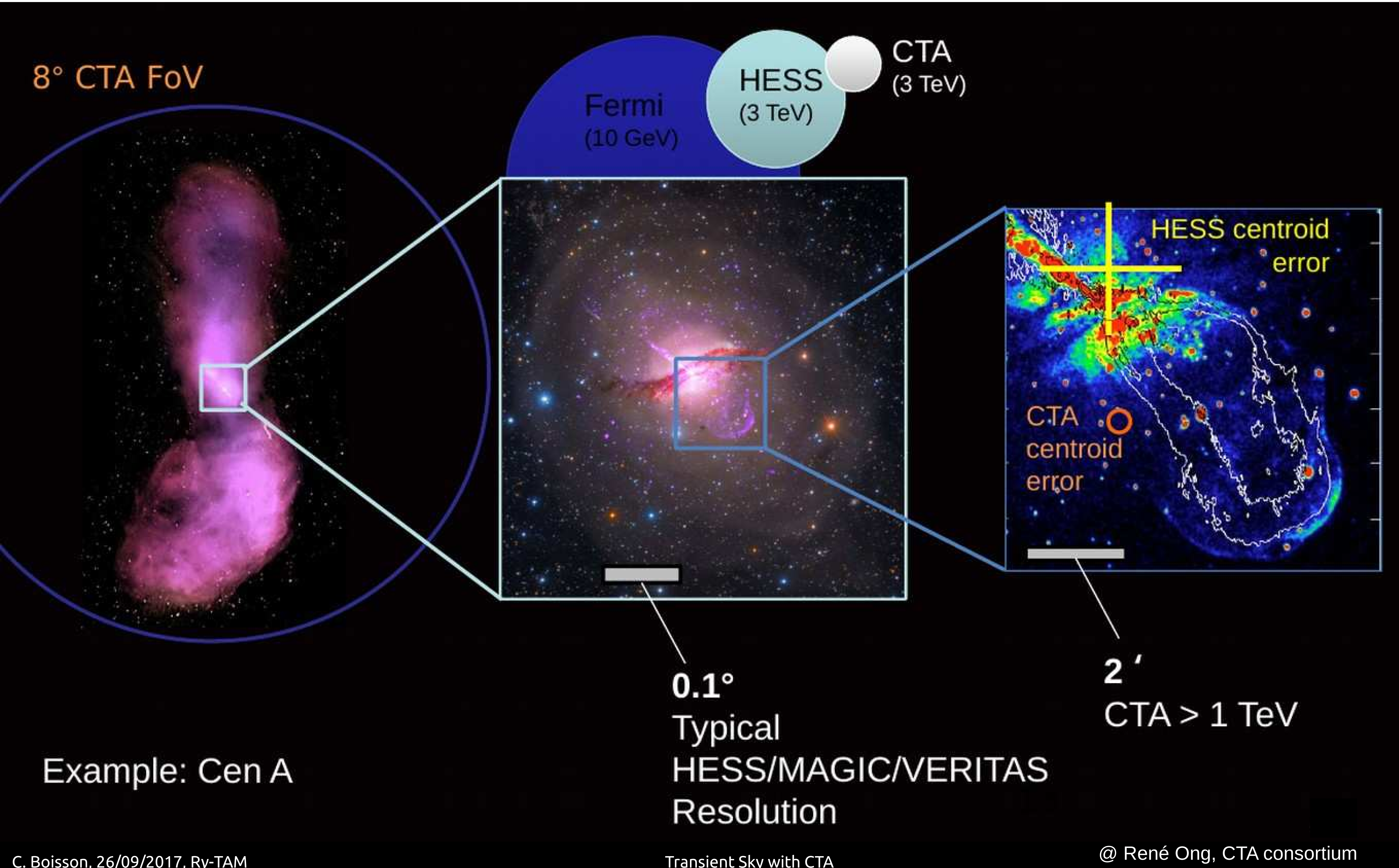
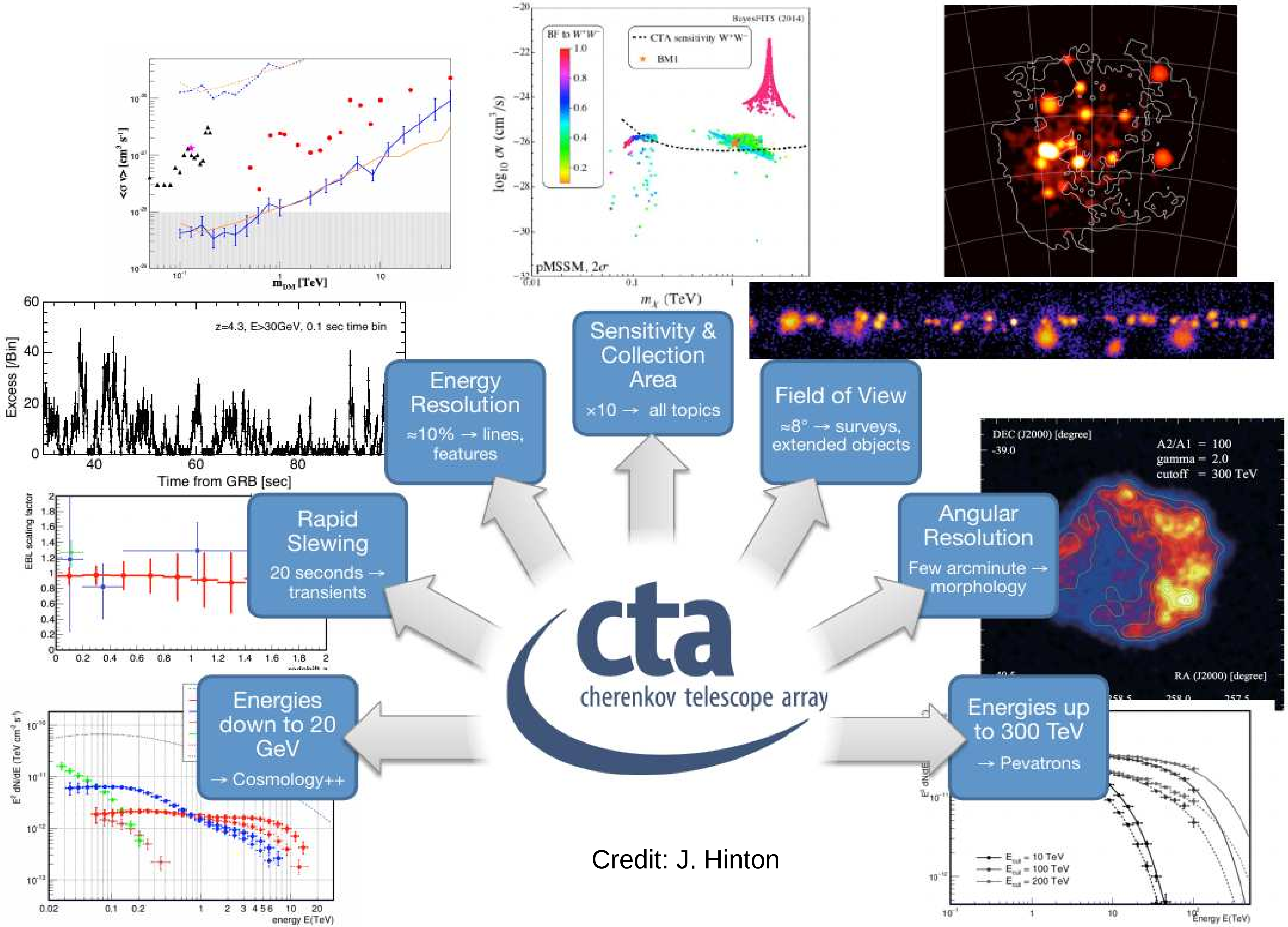
Credits: The CTA Consortium

Expected performance



CTA Science

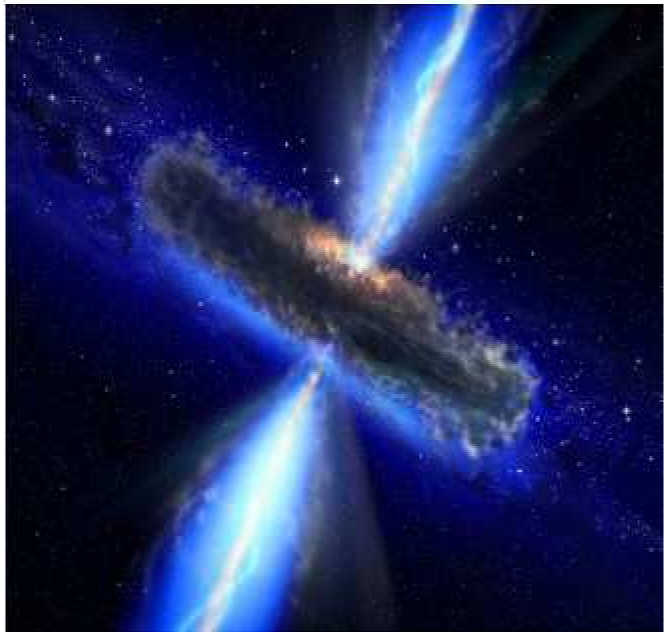


Credit: J. Hinton

CTA main scientific themes

Probing the "non-thermal" Universe at GeV-TeV using gamma-rays

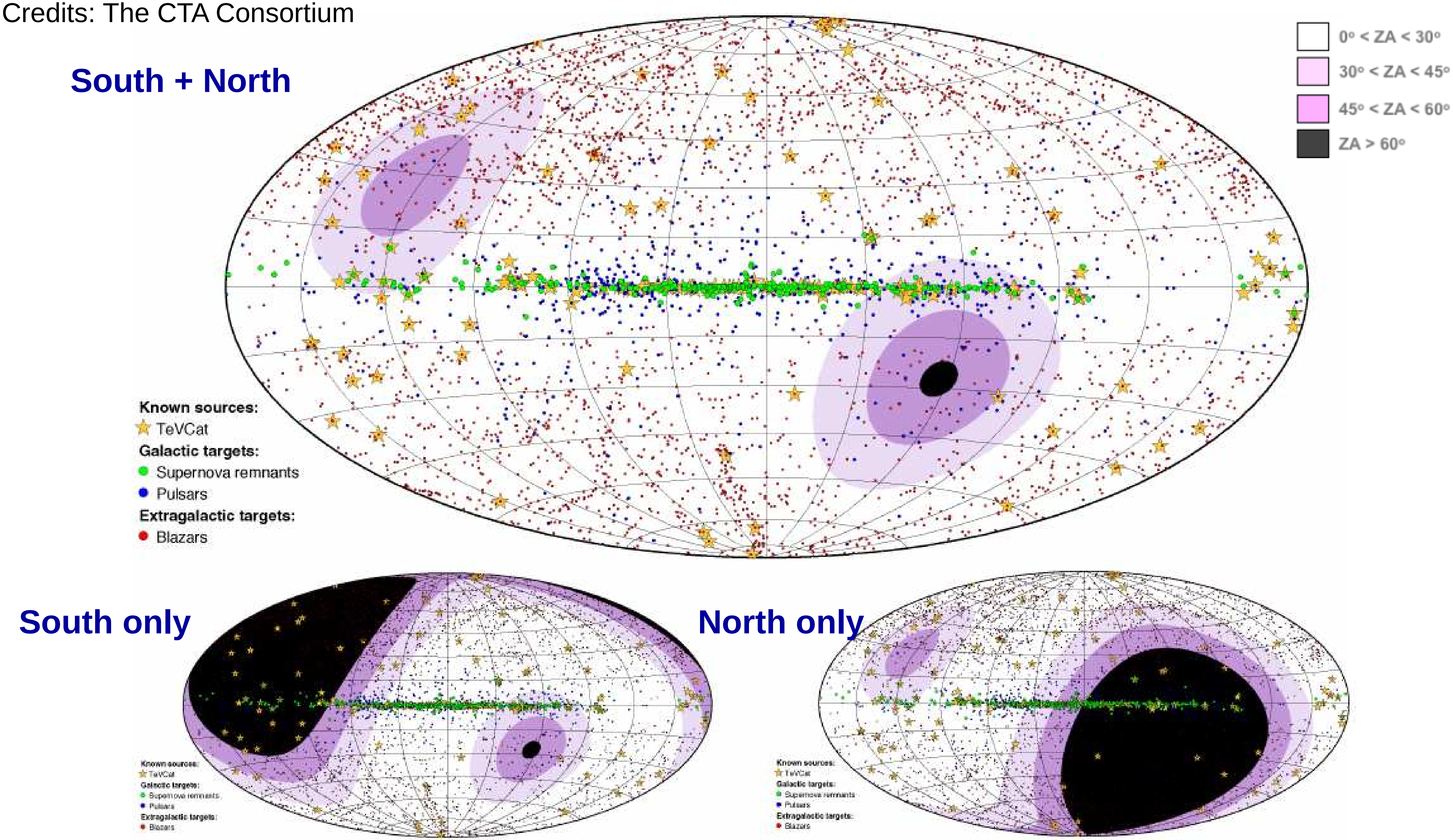
- Cosmic Particle Acceleration
  - Origin
  - Acceleration site & mechanism
  - Feedback of accelerated particles on star formation and galaxy evolution
- Probing Extreme Environments
  - Physical processes at vicinity of neutron stars and black holes
  - Characteristics of relativistic jets, winds and explosions
  - Exploring cosmic voids
- Exploring Frontiers in physics
  - Nature of Dark Matter
  - Test of Lorentz Invariance
  - Existence of Axion-like particles



More information on Astroparticle Physics, Vol. 43, 1-356 (2013)

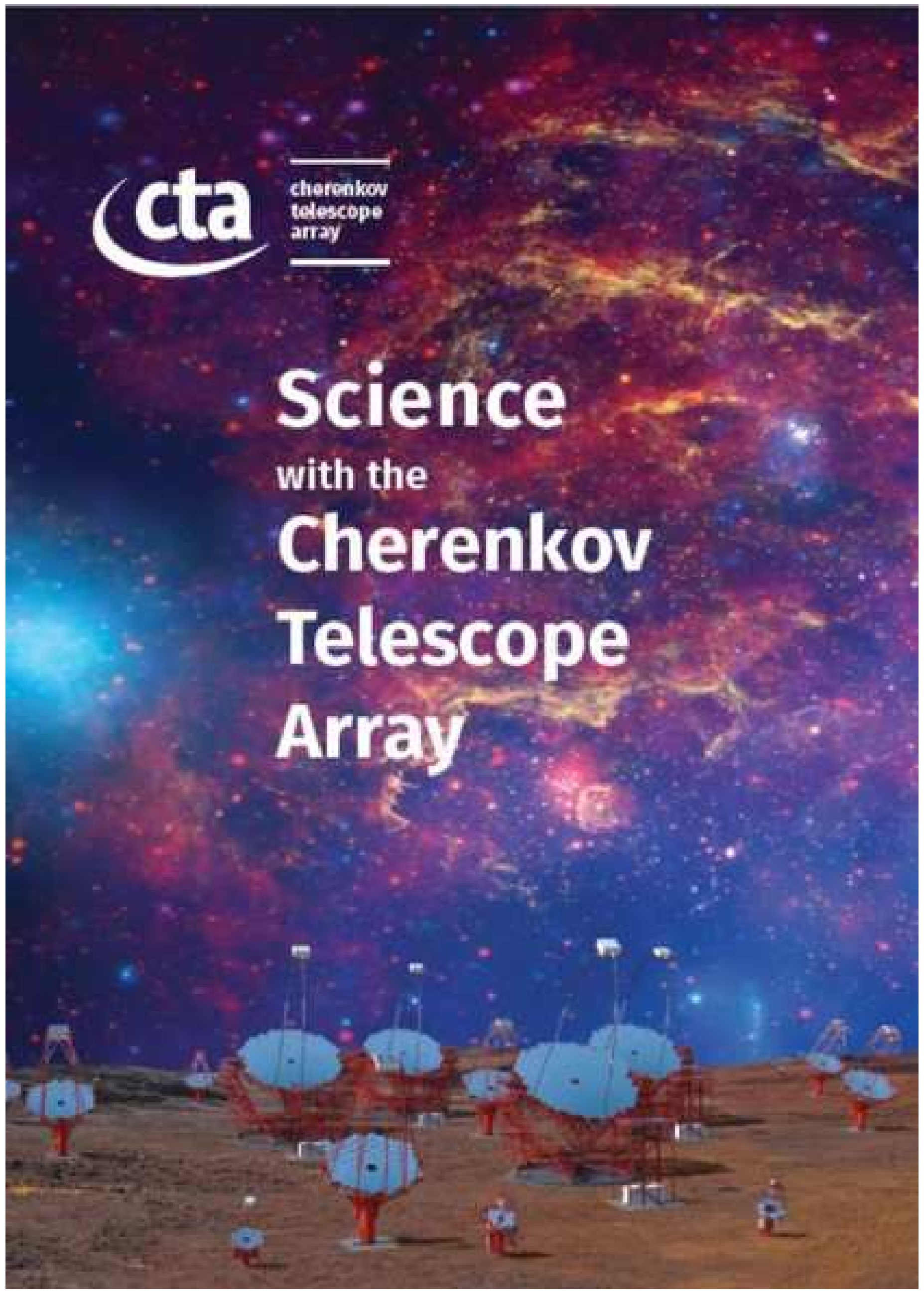
CTA as an all-sky Observatory

Credits: The CTA Consortium



Galactic plus extragalactic science **Mainly extragalactic science**

Key Science Projects



ArXiv 1709.07997

- Production of **legacy data-sets** of high scientific value to the wider community
- KSP rather than Guest Observer program :
  - very large observing time needed,
  - potentially systematics limited data set requiring CTAC expertise
  - need of coherent approach across multiple targets or pointings

Cherenkov Telescope Array

Open observatory with a projected lifetime of 30 years - initial commitment of partners to operate it for 10 years

A user facility / proposal-driven observatory

A global project : >1000 scientists and engineers across ~32 countries

Full operation will start in 2024

Cherenkov Telescope Array

CTA Observatory

- Total amount of science observation time for each of the two CTA Observatory sites : 2000 h/year to 2600 h/year total :
  - about 1000 h/year (prime time, moon well below horizon)
  - plus about 300 h/year (including moon time with somewhat degraded performance).
- For part of the observation time, telescope arrays may be split up into sub-systems, effectively increasing the available observation time by another 20–30%.
- Execution of observations in service mode
- Data proprietary period of one year
- Flare/burst advocate role to be defined

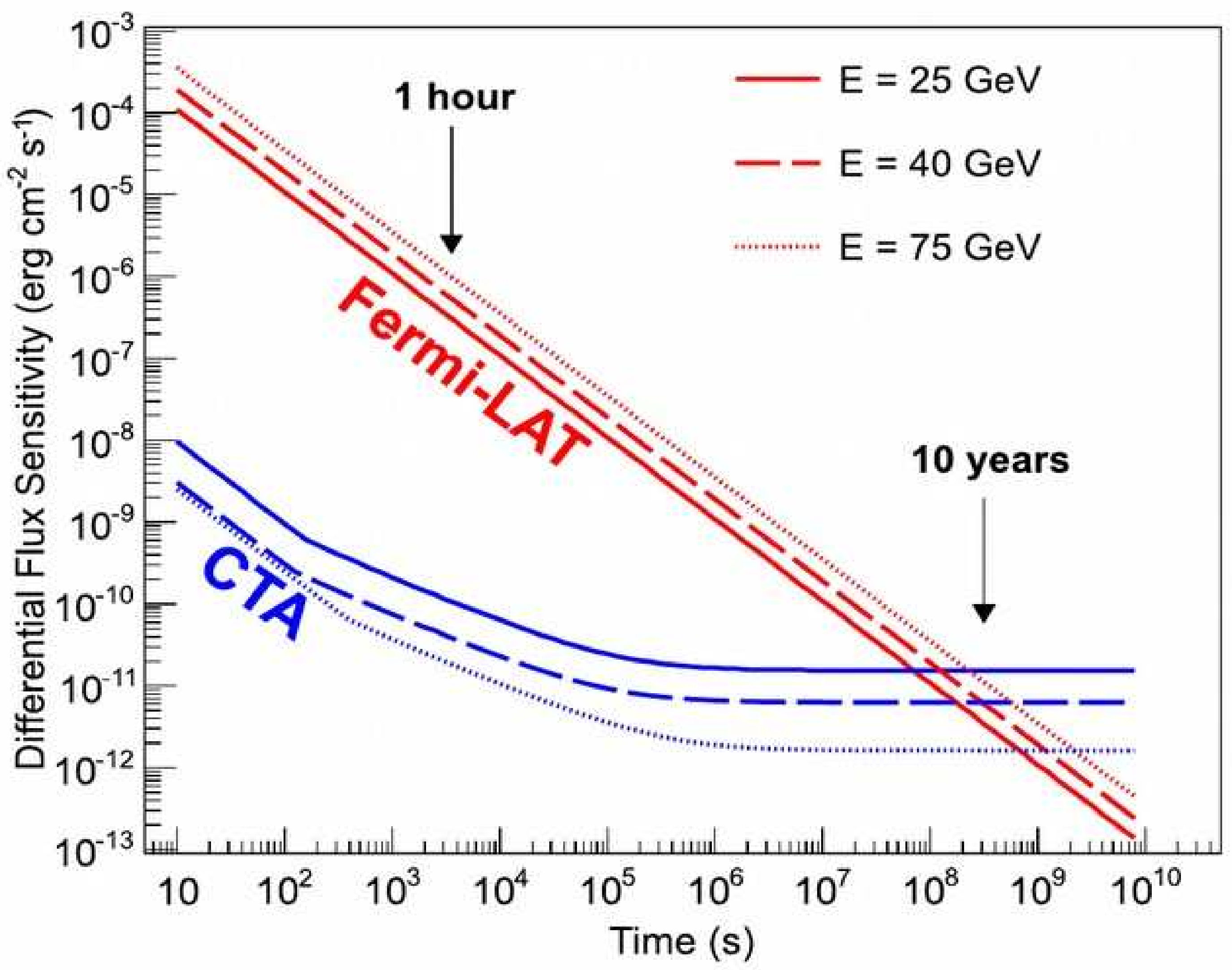
CTA Observatory

- The guest observer (GO) programme
  - by which users can obtain access to proprietary observation time, submitting proposals in response to announcements of opportunity (AOs). Typical GO proposals will require between a few hours to 100 h of observation time.
  - **ToO proposals**
- The key science projects (KSPs)
  - Large programmes that ensure that the key science issues for CTA are addressed in a coherent fashion, and generate legacy data products; they require from several 100 h to beyond 1000 h of observation time.
  - Legacy programmes as long term monitoring
- Director's discretionary time (DDT)
  - a small fraction of observation time reserved for, for example, unanticipated targets of opportunity.
- Archive access
  - under which all CTA gamma-ray data will be openly available, after a **proprietary period**.

Transient sky with CTA

- Imaging Atmospheric Cherenkov Telescopes
- The Cherenkov Telescope Array
- CTA – a transient factory
- Prospect

CTA – a transient factory



Adapted from Funk & Hinton, 2012

- **Huge advantage over Fermi** in energy range of overlap for ~minute to ~week timescale phenomena
  - Explosive transients
  - AGN/XRB flares
  - Binary systems
  - FRBs...
- **Disadvantage over Fermi**
  - Limited FoV (compared to Fermi)
  - Prompt reaction to external trigger is critical

CTA – Variable universe

- Ability to probe short timescales at the highest energies
  - explore the connection between accretion and ejection phenomena surrounding compact objects
  - study phenomena occurring in relativistic outflows,
  - open up significant phase space for serendipitous discovery

- Ability to respond very rapidly, both to external alerts and in delivery of alerts to other observatories.
  - The repointing times (to and from anywhere in the observable sky) will be 20 s for LSTs and 60 s for the MSTs and SSTs.

- Wide field of view (> 8 °, MSTs & SSTs) + unprecedented sensitivity of CTA => serendipitous detection of transient or variable VHE emission likely.
  - CTA is equipped with a low-latency (real-time) analysis pipeline which will monitor the field of view for variability on a wide range of timescales.
  - The detection of a gamma-ray event in the field and the **issuing of an alert** will be possible **within 60 s**.
  - CTA will itself respond to such alerts by repositioning and modification of the observing schedule, as well as alerting other observatories to allow rapid follow-up.

CTA – short timescale capabilities

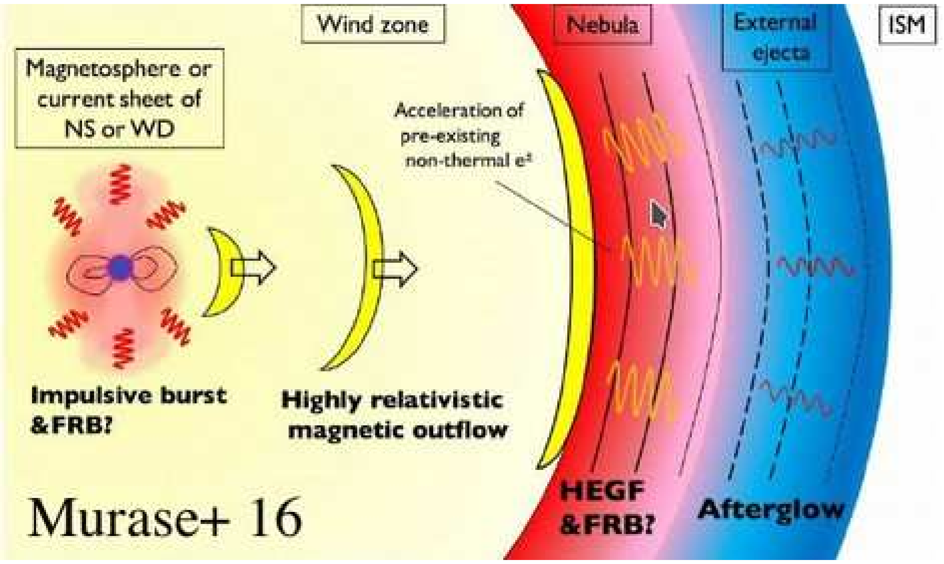
- Transients — a programme **responding to** a broad range of multi-wavelength and multi-messenger **alerts**, including GRBs, gravitational wave transients and VHE neutrino transients as well as self trigger.

  Rapid feedback to the wider community on the VHE gamma-ray properties of transients is a key element.

- Active Galaxies — where flaring activity forms a key part of the science case, with **rapid bi-directional information flow again critical**. Blazars exhibit the fastest known variability (1 min timescales) at TeV energies and blazar flares can be used to probe diffuse fields (EBL, IGMF...), Lorentz Invariance, as well as cast light on the physics of the ultra-relativistic inner jets of these systems.

- Galactic Plane Survey — multiple observations of every part of the Plane allow the identification of objects variable on timescales from seconds to months, including for example the expected discovery of many new gamma-ray binaries.

Transients



Credits: The LIGO Scientific Collaboration

- **Transients** are a diverse population of astrophysical objects.

  Prominent **emitters of high-energy gamma-rays**

  or

  Sources of non-photonic, multi-messenger signals such as **cosmic rays, neutrinos and/or gravitational waves**.

- Possible classes of targets :
  - Gravitational wave transients
  - High-energy neutrino transients
  - Serendipitous VHE transients
  - Gamma-ray bursts
  - Radio, optical, and X-ray transients (TDEs, SN shock breakout events, FRBs, new transients)
  - Galactic transients (microquasars, PWN flares, novae, etc)
  - AGN flares
  - (Transient survey with divergent pointing / tiling)

Follow up

- **Gamma-ray bursts**
  - based on external alerts from monitoring facilities
    - mostly Swift, Fermi-GBM, SVOM
    - can also expect from Fermi-LAT, HAWC, LHAASO
    - GAIA, LSST etc ?
  - thought to be triggered by special types of stellar collapse and merger events involving NS and/or BH – light curves and spectra with high statistic per burst

- Strategy :
  - ~20s for LST on source, <60s MST, ST
  - Expected rate ~ 12 alerts/yr/site - full array, LST crucials (Fermi-GBM with localisation errors > LST FoV → tiling observations)
  - All alerts in dark time accessible FoV with zenith angle < 70° followed for 2 hr
  - Real Time Analysis crucial (30s latency) → If detection, observe as long as the target remains detectable

Follow up

- **Galactic transients**
  - based on **external alerts** from monitoring facilities
  - compact objects with different types of jets and winds – sporadic outbursts – includes Crab nebula up to 100 TeV

    flares from pulsar wind nebulae (PWNe; relativistic outflows driven by rotating NSs), jet ejection events from microquasars and other X-ray binaries (NS or BH accreting matter from a stellar companion) , novae (explosions on the surfaces of white dwarfs)

- Strategy :
  - Trigger criteria still to be defined – source by source basis though
  - Continuation is contingent on the discovery of new sources with fast variability

Follow up

- **X-rays, optical/IR and radio transients**
  - based on **alerts from “transient factory”** facilities
  - Includes tidal disruption events, supernova shock breakout events, fast radio bursts…

- Strategy :
  - Expected rate for sources of interest as eg TDE ~ GRBs
  - Explicit strategy not easy to determine in advance – actual latency of optical or radio TF as the extent of information that will be available are unknown – pb for fast transients as FRBs
  - Filtering criteria based on optical mag, nova type properties of the HE gamma rays detected by Fermi… to be added → optimal methodology for selecting the interesting TF prior to early science
  - As for GRBs – go for 2hrs then exposure extended if RTA reveals a transient system

Follow up

- **High-energy neutrinos**
  - Based on **alerts from neutrino observatories**
  - Follow up of selected alerts – search for the electromagnetic counterpart, to identify neutrino origin and possibly give insight on extragalactic and/or Galactic cosmic rays as well
  - 3 types of alerts IC, HESE, ESE

- Strategy :
  - Expected rate ~ a few/yr/site
  - Follow-up for alerts from IceCube and high energy neutrino observatories of candidate muon neutrino-induced track events is already the case with current IACTs
  - Unbiased full-sky scan of predefined source list
  - All alerts in dark time accessible FoV with zenith angle < 70° followed for 2 hr

Follow up

- **GW transients**
  - Based on **alerts from GW observatories –** MoU with Ligo-Virgo
  - Follow up of selected alerts – TeV emission from black hole or neutron star mergers, including those producing gamma-ray bursts

- Strategy :
  - Expected GW NS-mergers < a few/yr/sky → < 1/ few yr / site , GRB ~ < 0.03/yr/site
  - Follow-up of low latency GW alerts → large areas of sky → tiling or divergent pointing
  - Sizable uncertainties
  - As for GRBs – go for 2hrs with additionnal exposure extended in the case of positive detection

Alert

- **Transient survey**

  possibly effective for surveys of persistent point sources

  - GRBs from onset : prompt emission physics (crucial but poorly understood)
  - Lorentz invariance violation (big improvement over Fermi)
  - Unbiased transient survey e.g. FRBs

  Transient occuring In the FoV (not necessarily detectable)

  GRBs: all of sky ~1000/yr (BAT+GBM)

  GRBs: all of sky ~6000/dy

  if FoV~300 deg2

  ~ 8 GRBs /yr → 1 / 1000hr

  ~ 45 FRBs /yr → 2 / 1hr

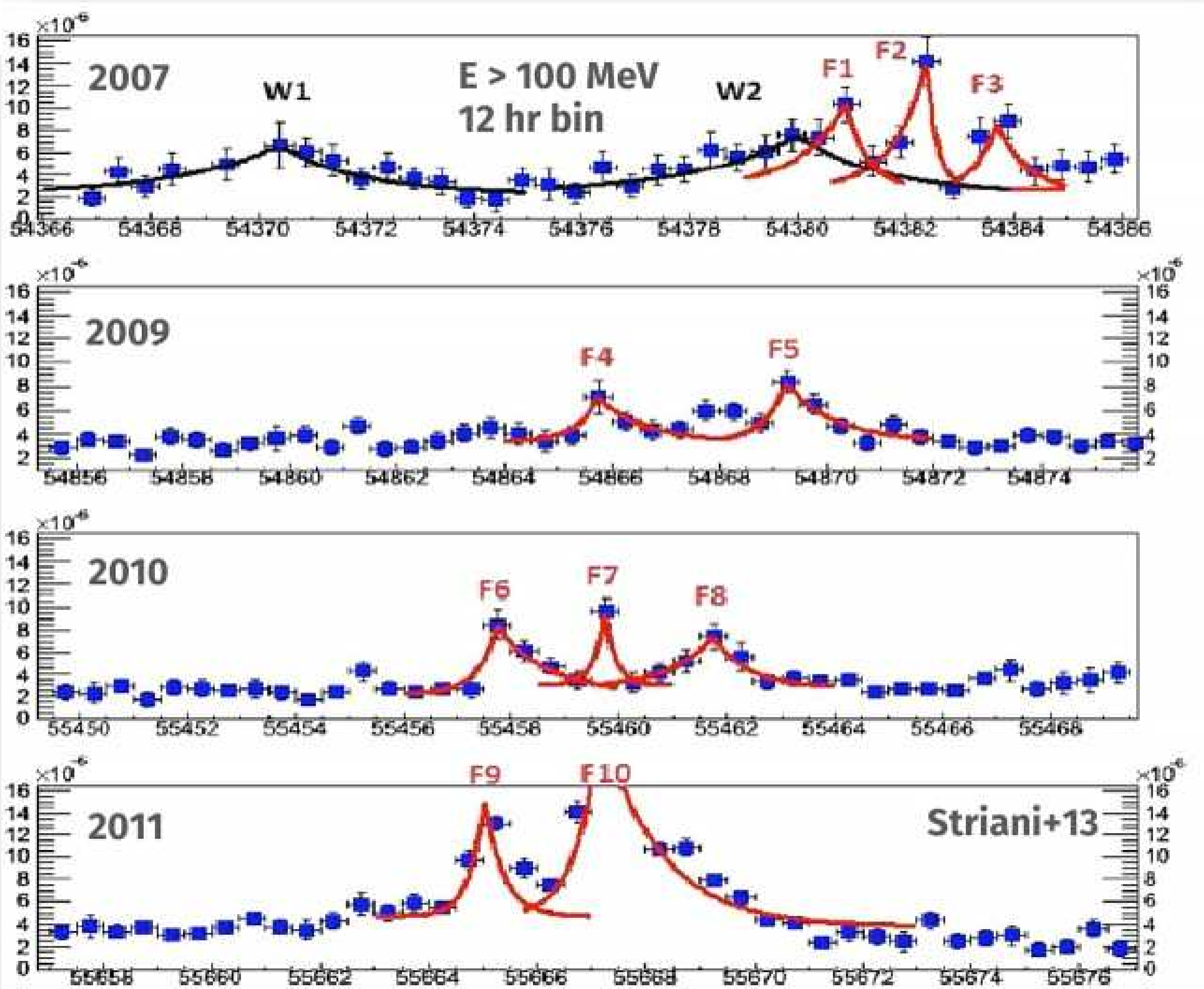
Alert

- **Serendipitous VHE transients**
  - **identified via the CTA real-time analysis** during scheduled CTA observations
  - The **RTA** can recognize new transients or flaring states of known sources at very high energies anywhere in the FoV and automatically issue alerts within **30 s**
  - **On site analysis** (**~ 10 hr** after data taking) could also provide serendipitous VHE transients in the FoV → follow up could be conducted during the subsequent night

- Strategy :
  - Observe as long as possible after detection, take decision next day

→ alerts to other observatories/facilities

Crab pulsar wind nebula

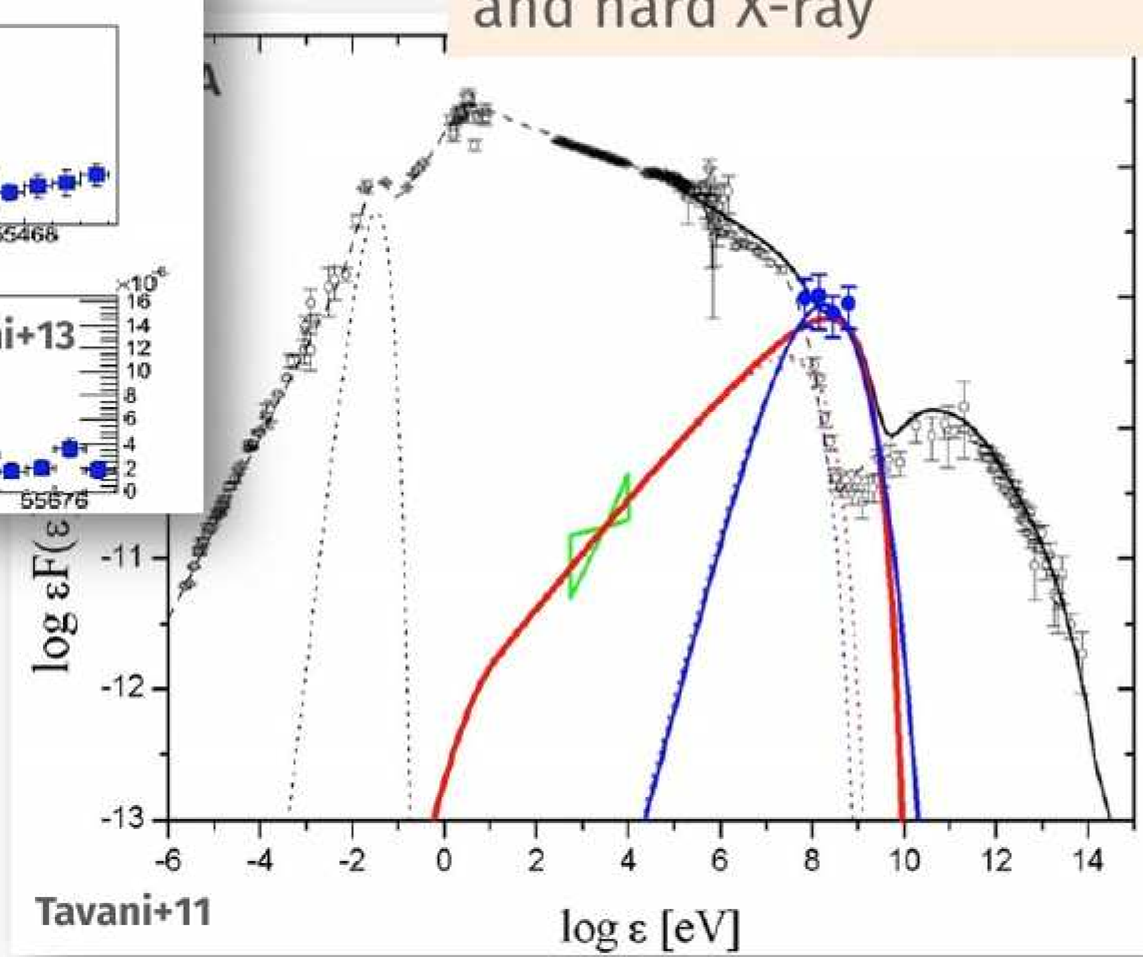


Crab is highly variable (a factor of 5-10) in the AGILE and *Fermi*-LAT energy band.

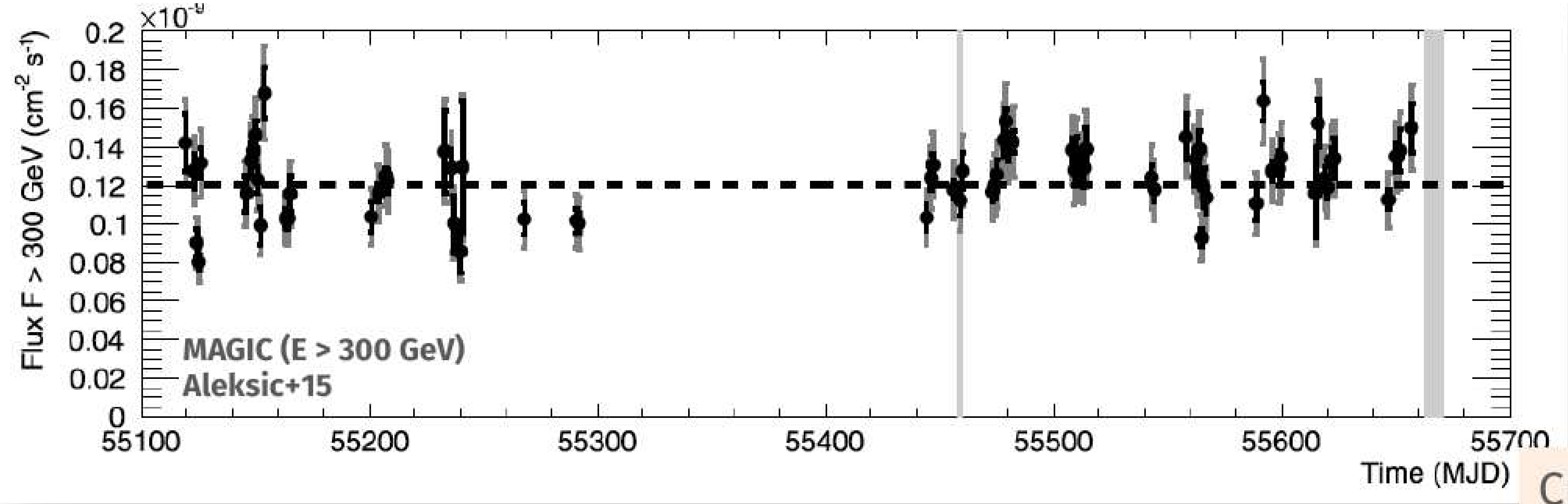
No variability in the soft and hard X-ray

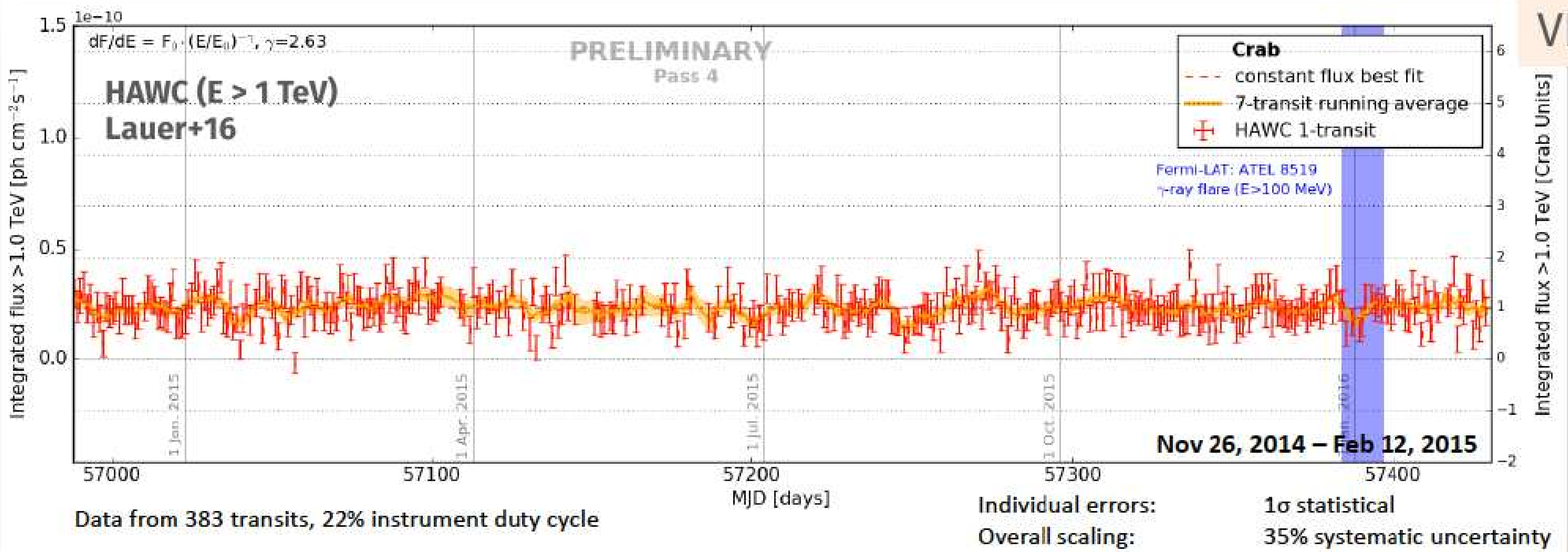
Power-law acceleration by shock- driven plasma wave turbulence within a ~1-day timescale?

Several tens of theoretical papers!



Crab pulsar wind nebula





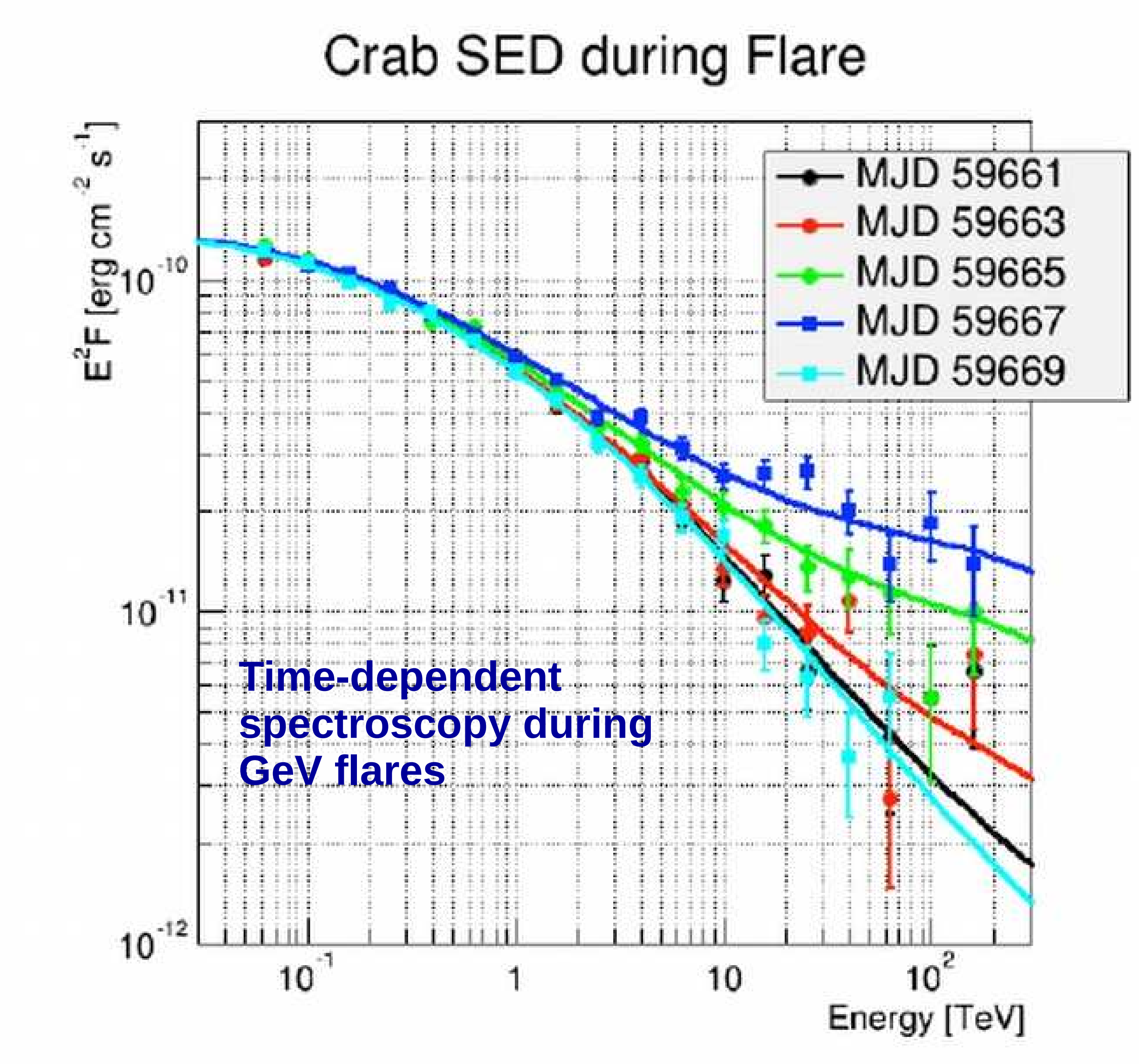
Crab is stable at VHE !

Transients - Simulations

Crab pulsar wind flare

Assuming that the Crab nebula high-energy flares are due to synchrotron emission, to detect the **variable inverse-Compton component at multi-TeV energies**, we would need to monitor the source for **4 h/night during approximately 10 nights**. With this strategy we could unveil the nature of these flares.

Inverse-Compton component of the 2011 April Crab flare assuming Γ=70. **The variable tail from 10 to 100 TeV is clearly detectable.**



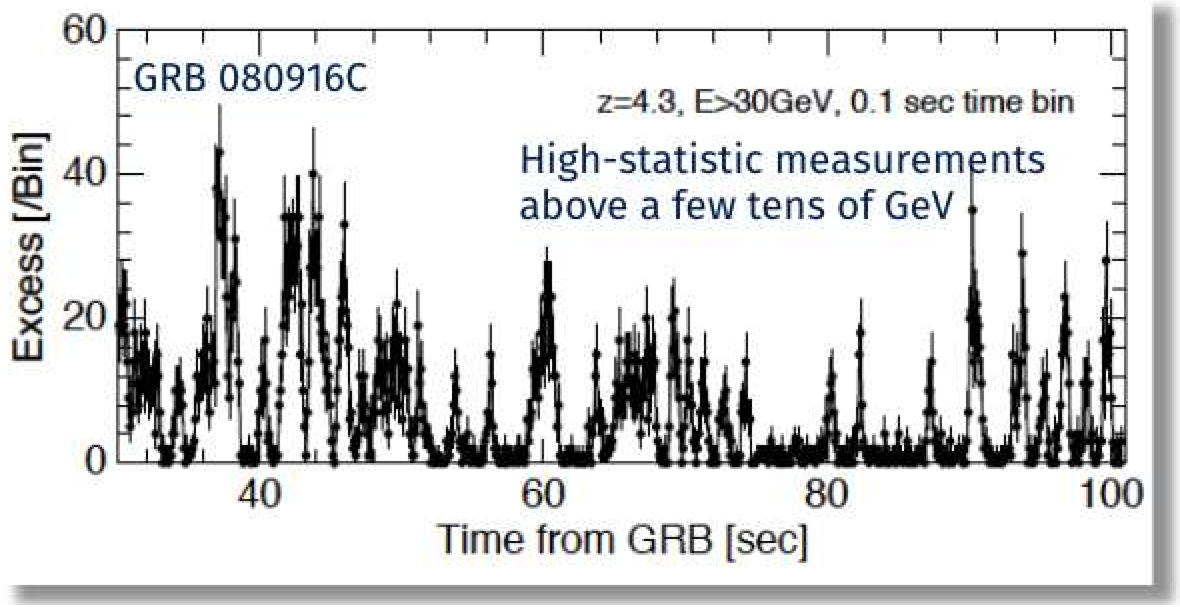
Transients - Simulations

Gamma-ray bursts

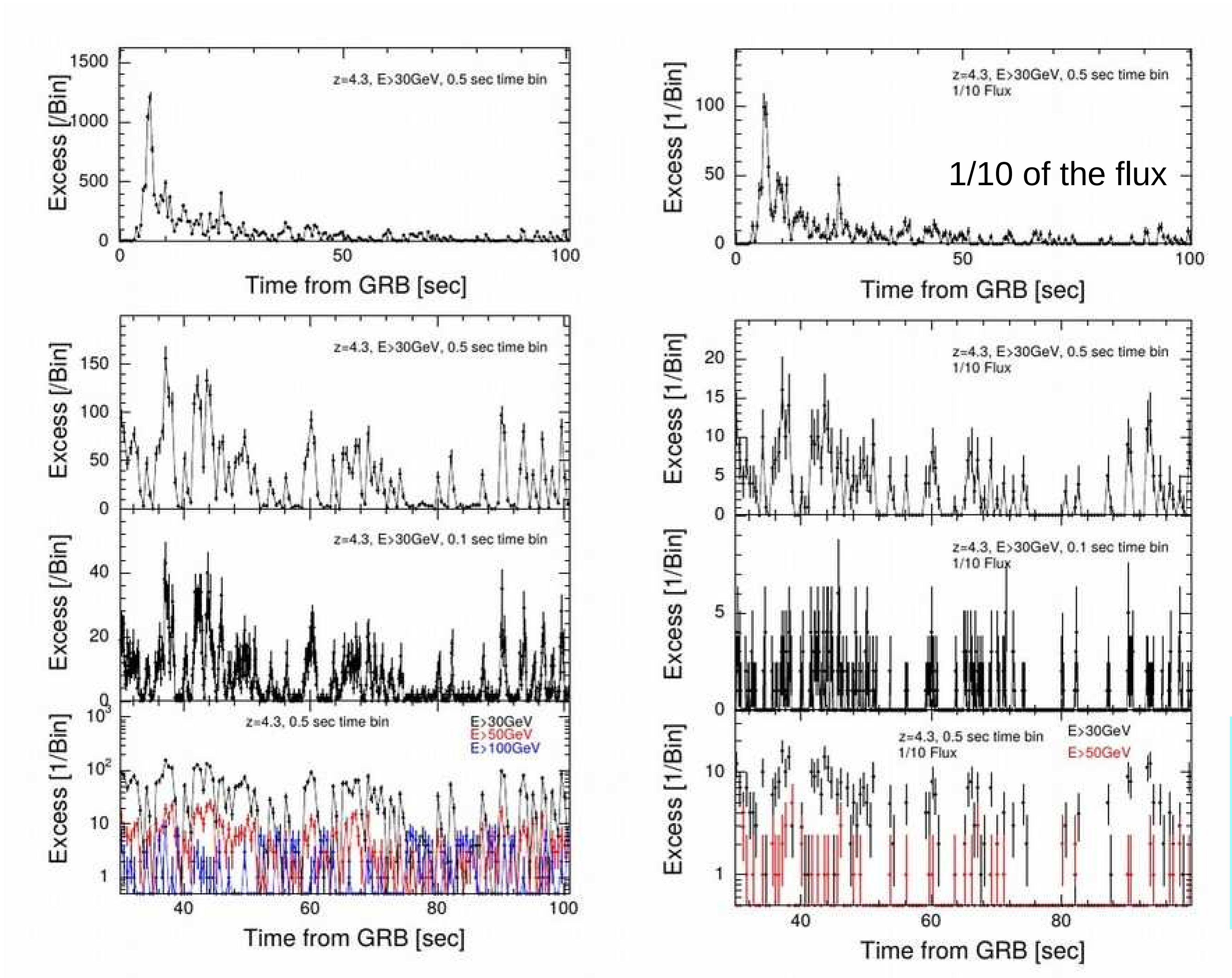
CTA is potentially capable of **resolving GRBs light curve in much detail** for such bright bursts.

Assumed GRB template = measured Fermi-LAT light curve above 0.1 GeV, extrapolating the intrinsic spectra to VHE with power-law indices as determined by Fermi-LAT.

We expect to detect ~1 GRB yr/ site



Simulated burst LC



Light curve from trigger

Assuming 30 s slew

Expect far superior photon statistics compared to Fermi-LAT above a few GeV.

Inoue et al, Astroparticle Physics, Vol. 43, 1-356 (2013)

Active Galactic Nuclei

AGNs are known to emit **variable radiation** across the entire electromagnetic spectrum up to multi-TeV energies, with fluctuations **on time-scales** from **several years down to a few minutes.**

VHE observations of active galaxies harbouring super massive black holes and ejecting relativistic outflows represent a unique tool to probe the **physics of extreme environments**, to obtain precise measurement of the **extragalactic background light** (EBL) and to constrain the strength of the intergalactic magnetic field (IGMF).

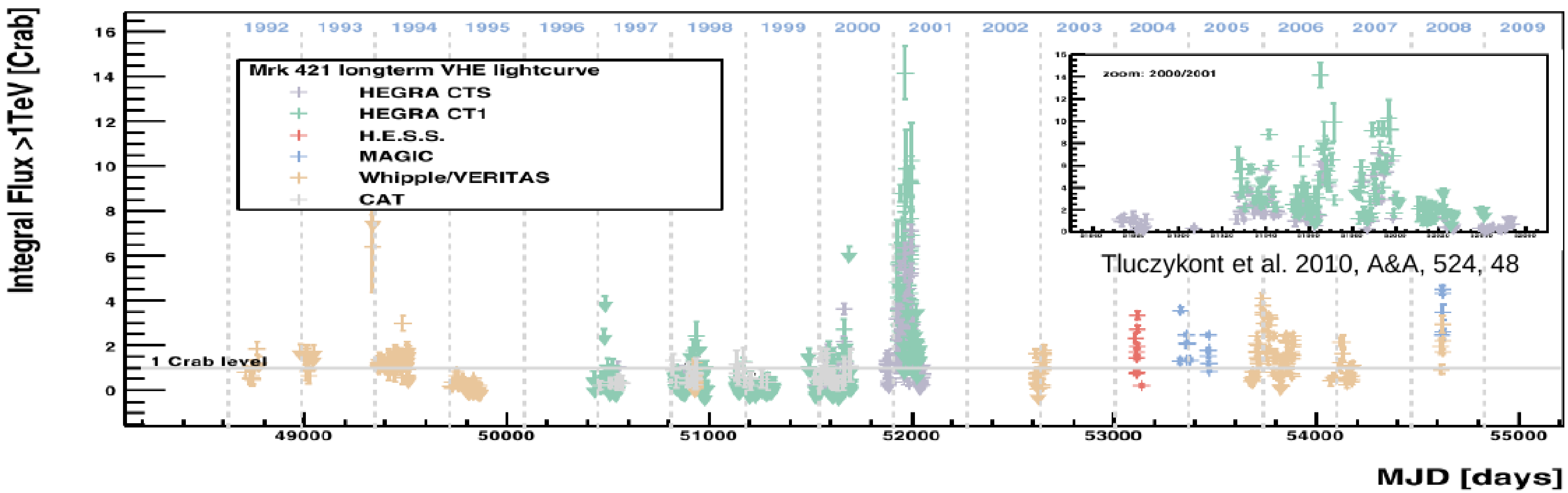
Credits: ESA/NASA

AGNs also useful to investigate fundamental physics phenomena such as the Lorentz invariance violation.

AGN flare monitoring motivation

- Sampling VHE fluxes below the light-crossing timescale of the SMBH affords valuable insights into the inner workings of AGN.

- To date, observations of a few extreme flare events have:
  - Highlighted the severe limitations of standard emission models (eg. HESS observations of PKS 2155-304)
  - Suggested more sophisticated models (eg. MAGIC observations of IC310)



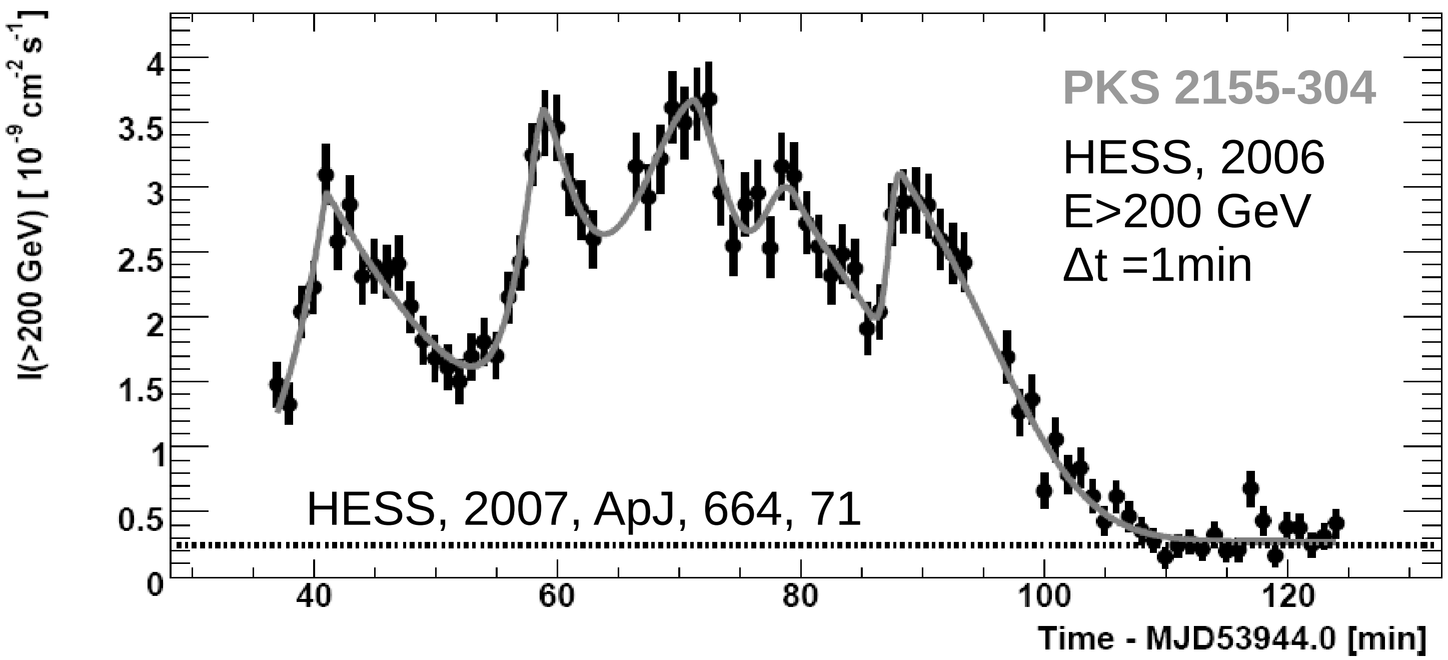
Tluczykont et al. 2010, A&A, 524, 48

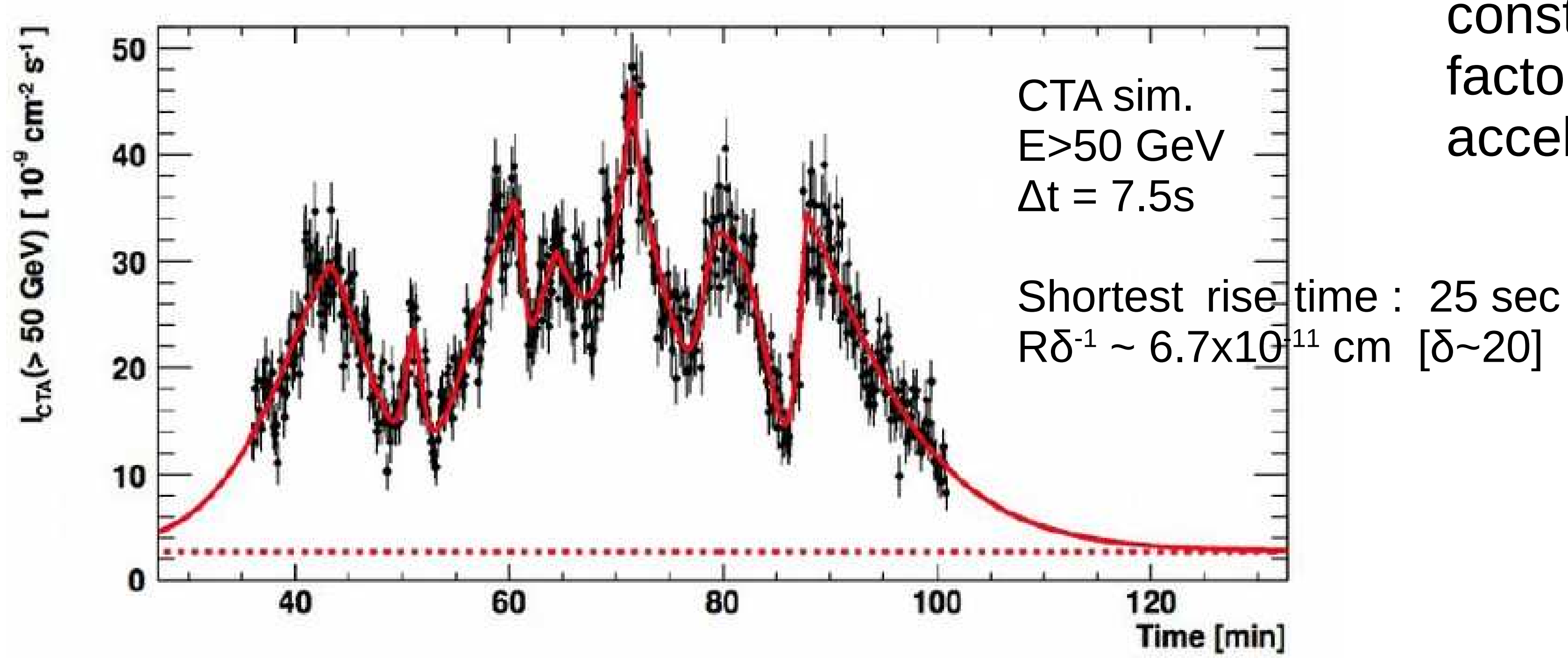
AGN - Flare monitoring strategy

- 2 complimentary approaches to catch flares
  - **External triggers** from eg. Fermi-LAT, HAWC, LHASSO or future instruments eg SVOM, ASTROGAM, ATHENA, LSST, SKA, GAMMA400 → ~25 flare alerts / yr
  - **Internal triggers from CTA subarray snapshots** of ~80 AGN (both known **and** potential VHE emitters)

    → Astronomer's Telegrams, VOEvent, alerts within MoUs,...
- Snapshot program using subarrays of CTA to take short exposure of ~80 AGN at ~20% crab flux sensitivity
  - Both known and potential VHE emitter
  - FSRQs through to UHBLs, Fermi-LAT detected radio galaxies & NLS1s
- ~20 sources per week per site, ~1 hr per night total per site
  - Assuming flaring probability of ~1%, based on current duty cycle knowledge, expect around **20 flares per year per site**

AGN – Simulations

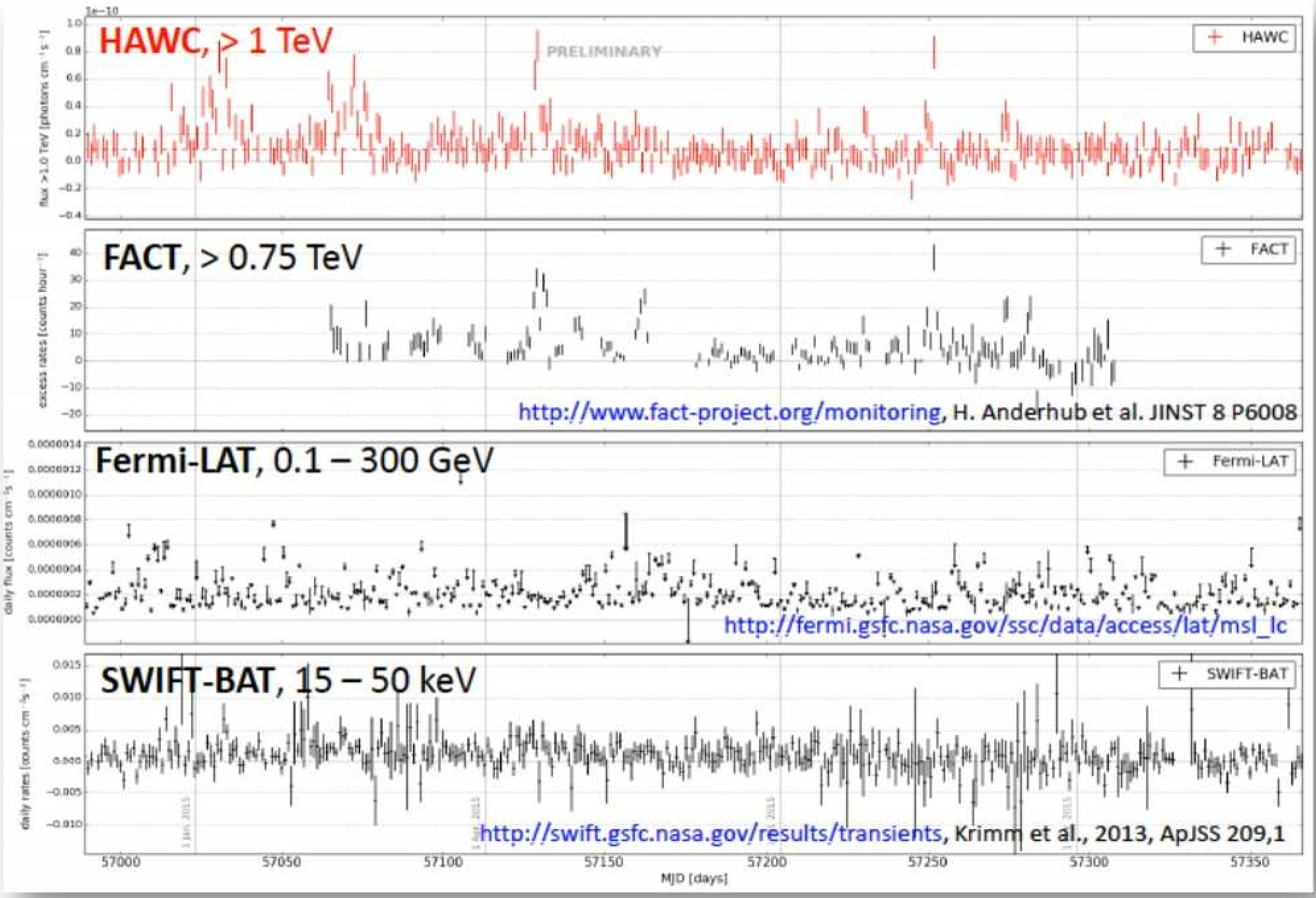




Size (location, nature) of the emission region ?

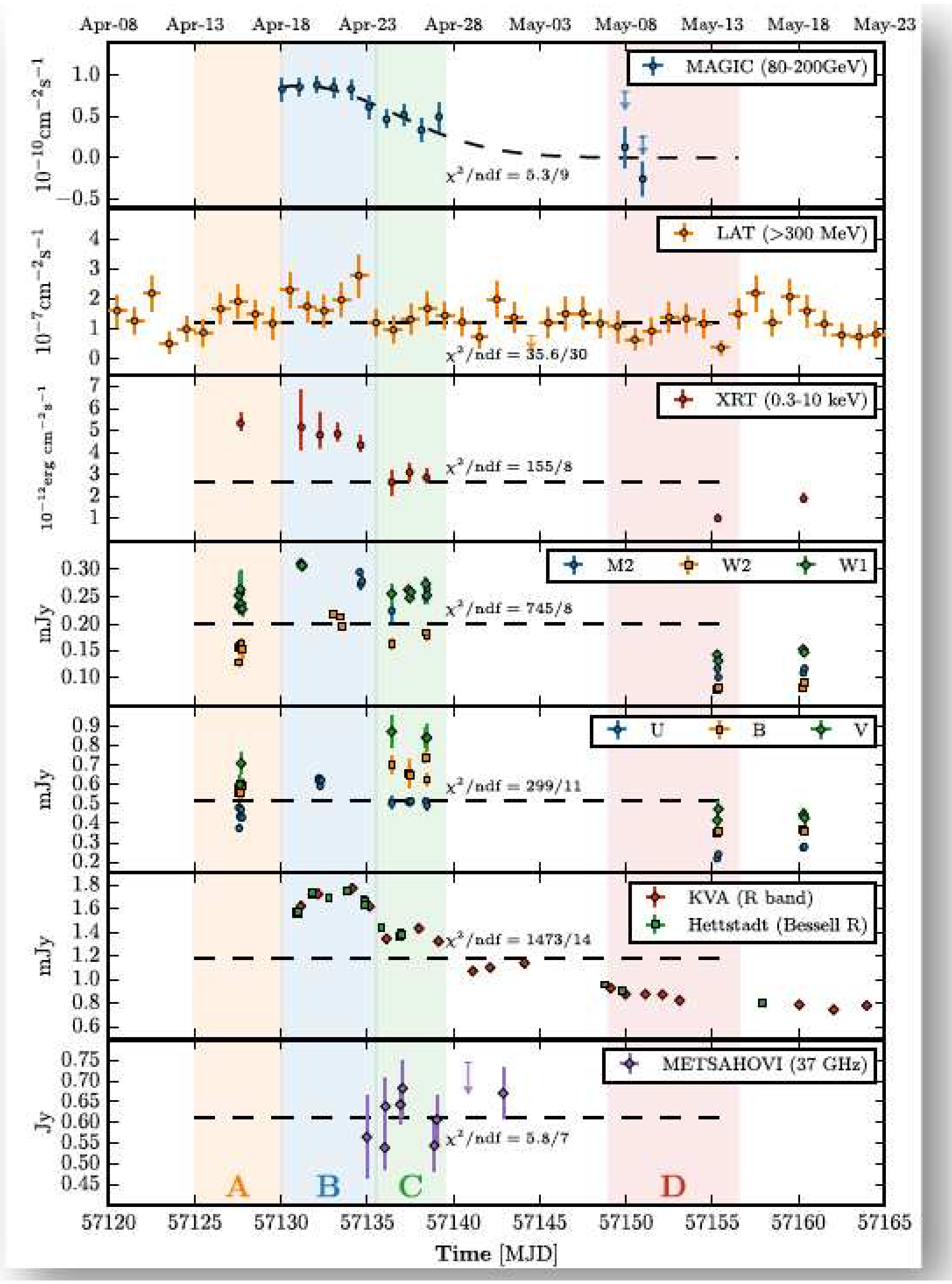
Such measurements put strong constraints on the bulk Doppler factor, as well as on particle acceleration and cooling processes.

Blazar monitoring at HE/VHE

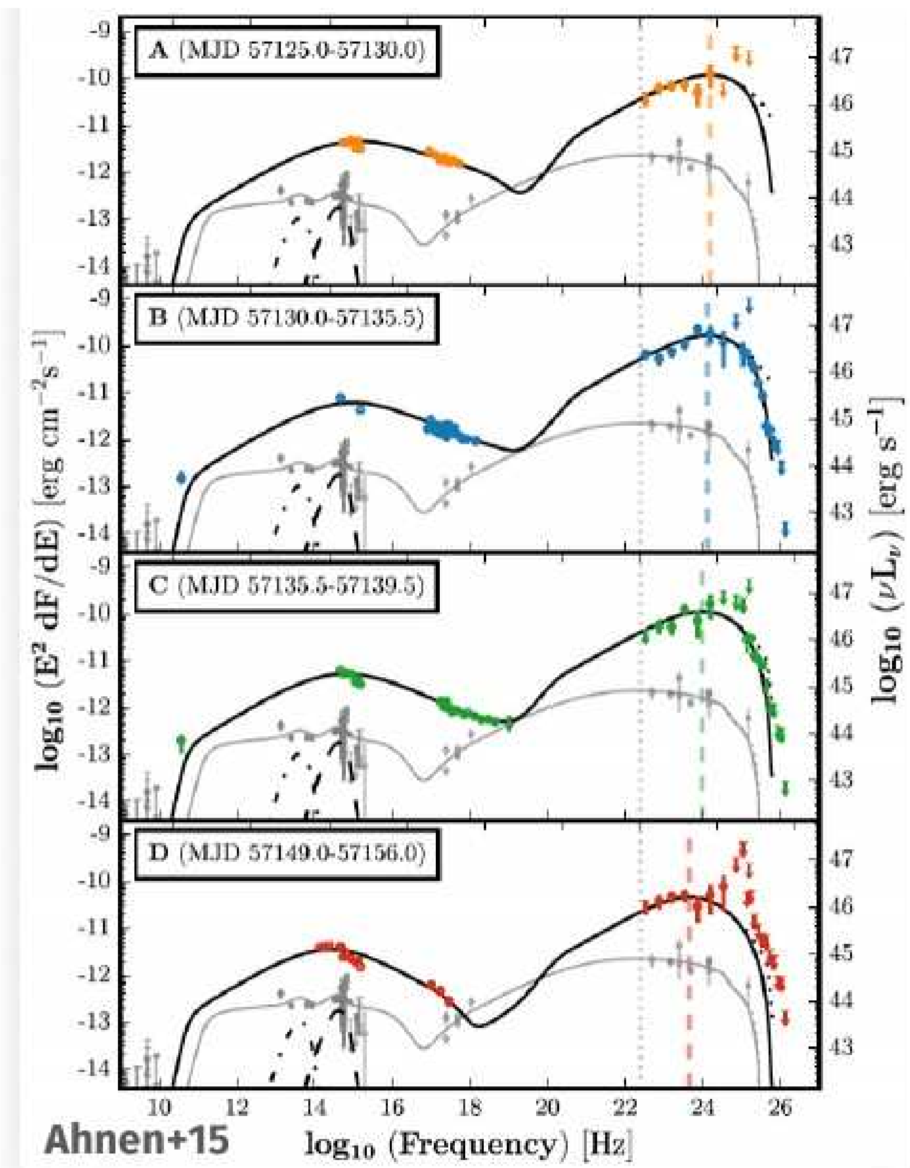


Lauer+16

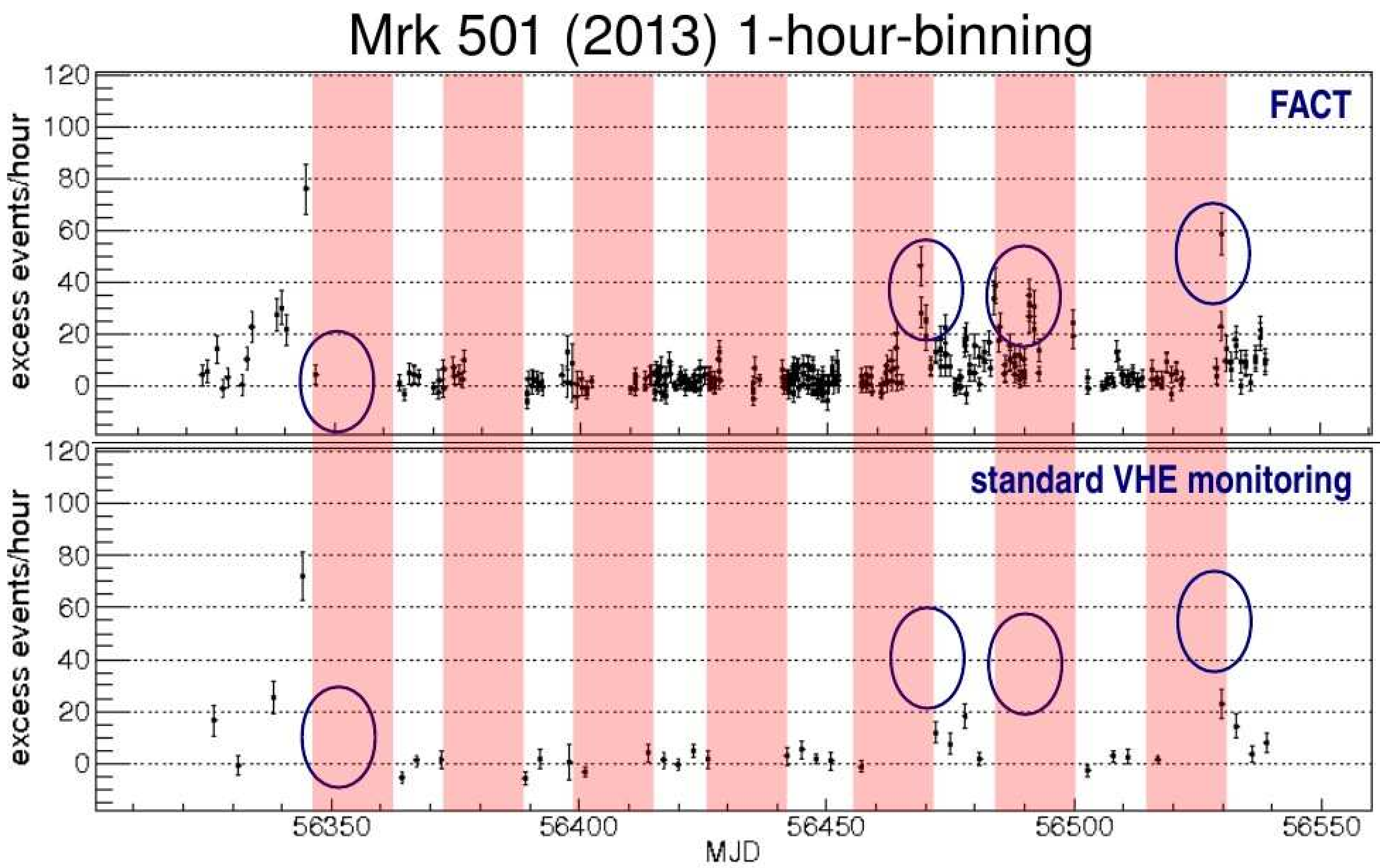
FSRQ – PKS 1441+25



The location of the emitting region:
- **in the jet outside the BLR during the period of high activity**
- **partially within the BLR during the period of low activity (quiescent typical state)**



FACT – VHE alerts



All data ~410h

Moon < 65%
1h every
~ 3rd night
→ ~32h

Transient sky with CTA

- Imaging Atmospheric Cherenkov Telescopes
- The Cherenkov Telescope Array
- CTA – a transient factory
- Prospect & Conclusion

ToO programme

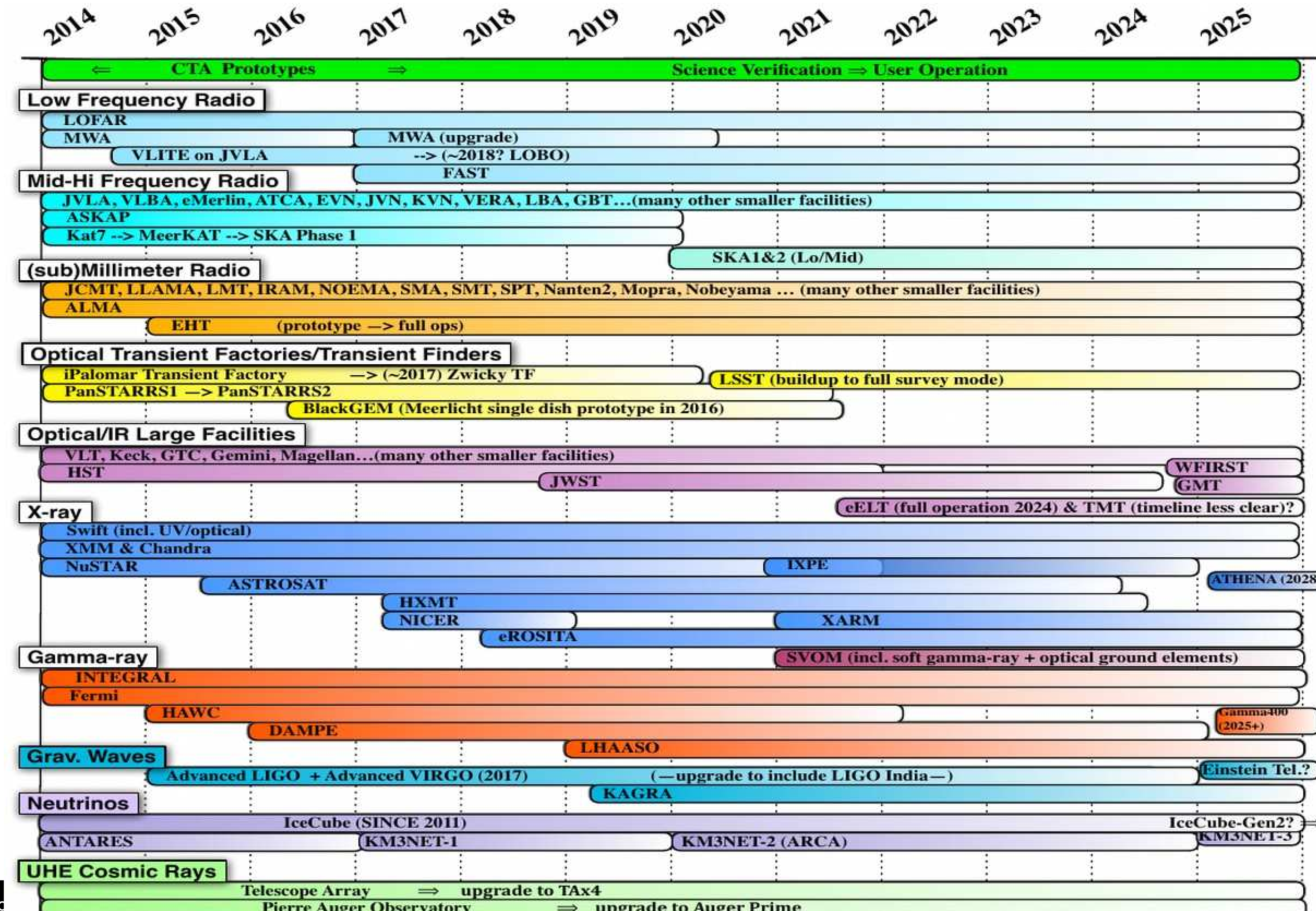
- Already an important part of the current IACT observing programs
  - Handling of alerts
  - Filtering of alerts
  - Triggering criteria - Priori
  - Processing and follow-up

- Issues
  - Latency between e.g. GCN alerts and reception by facilities
  - Standards for the generation, dissemination, distribution, and reaction to multi-messenger events → long term maintenance
  - MoU

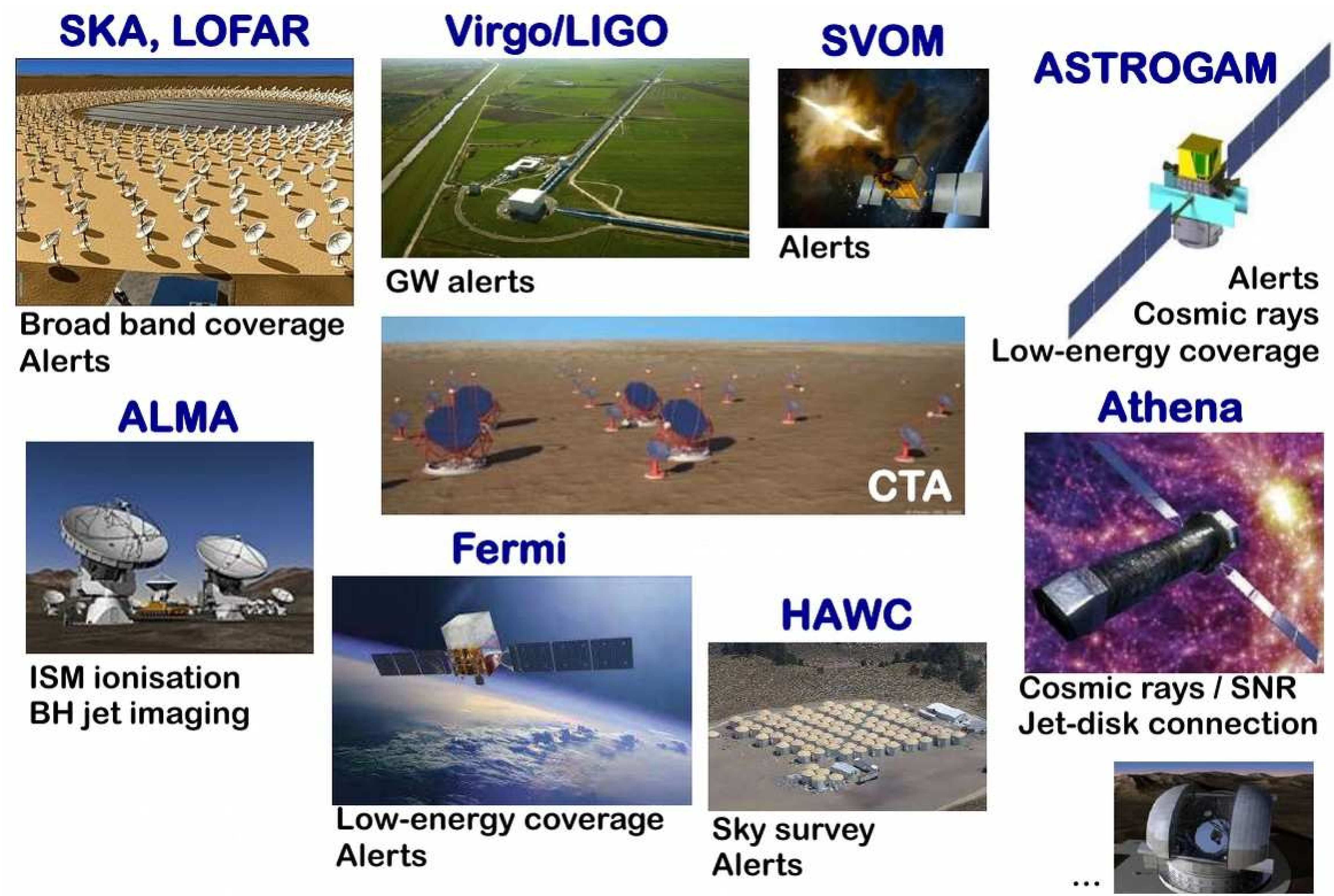
CTA

- The time domain challenge
  - Discovery & follow-up – Flare / Burst advocate
  - Technology for *alerts* and *politics* (VOEvent – prioritarization / MoU…)
  - Time delay between issue and reception of alerts
  - Alerts but also SHARING
- Importance of real-time analysis
- The multi-messenger landscape
- Importance of multiwavelength
- Optical dedicated telescope

Synergies during CTA operations



CTA / Synergies / MWL



Conclusion

- Crucial advantages over Fermi, current IACTs
  - large effective area
  - all sky coverage, versatile pointing, real-time analysis...
- Exciting new prospects for:
  - GRBs: prompt - detailed spectra, light curves...
    afterglow - new components beyond sync.
  - FRBs: test of origin(s)
  - GW: localization, SGRB/FRB connection, merger physics...
- Unbiased transient search via tiling or divergent pointing
- Others: neutrinos, Galactic transients, etc...

Conclusion

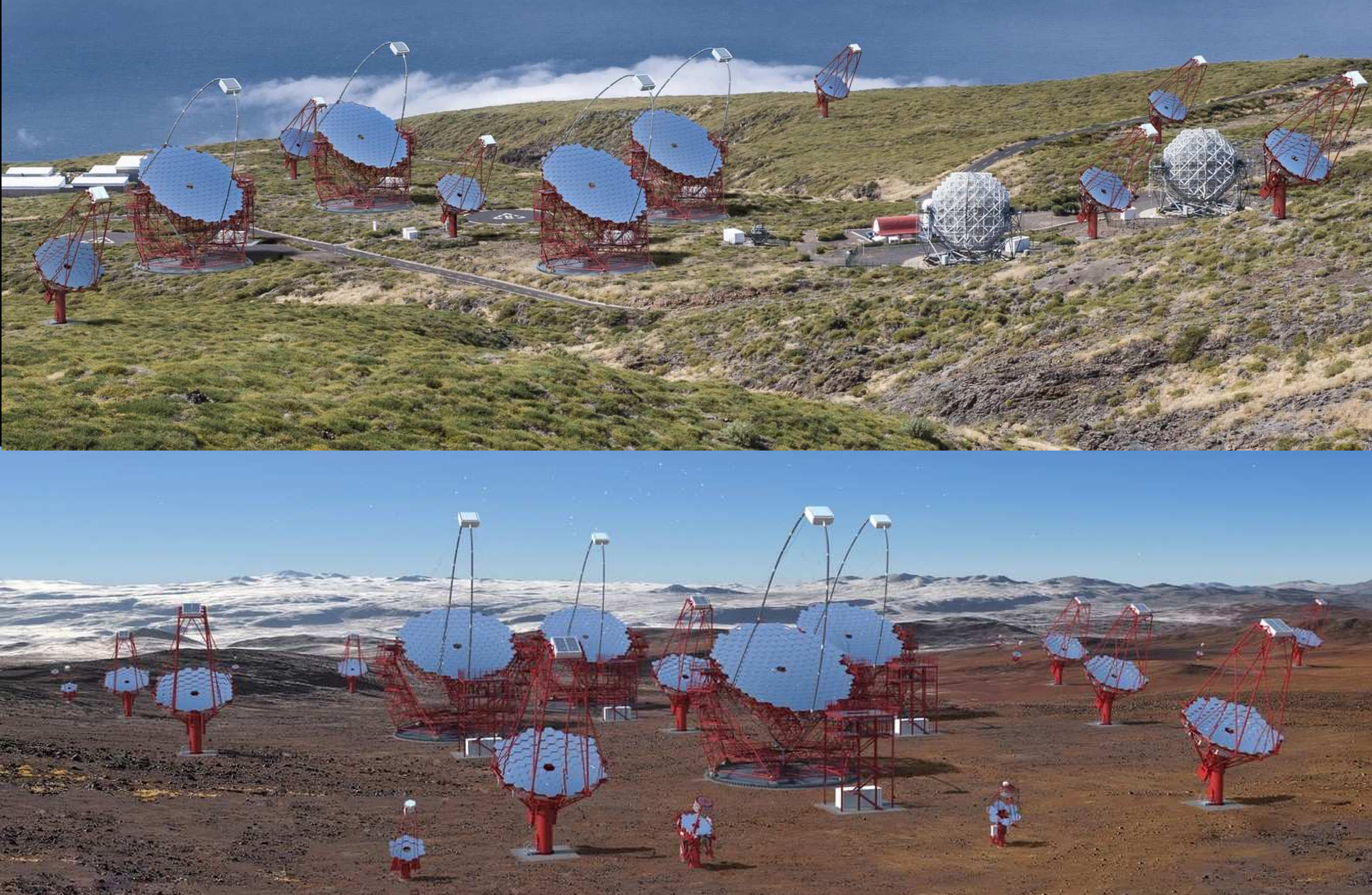
- CTA early science expected~ 2021:

  Improved sensitivity, resolution, pointing accuracy, fast slewing, RTA ➠ truly versatile telescope for a very wide range of science projects

- CTA represents new transition from experiment to observatory: opens door to community access, end user support

  But CTA's full potential will be reached only with strong synergy across the EM spectrum - multiwavelength / multimessenger

cta cherenkov telescope array



Nortthern and Southern Hemisphere Site Rendering; credit: Gabriel Pérez Diaz, IAC, SMM