The Cherenkov Telescope Array

Status and Science prospects

S. Ohm (DESY, Zeuthen)

Winterschool, Ooty (India), December 2016
(with slides adapted from Werner Hofmann, S. Vercelleone and other CTA members)

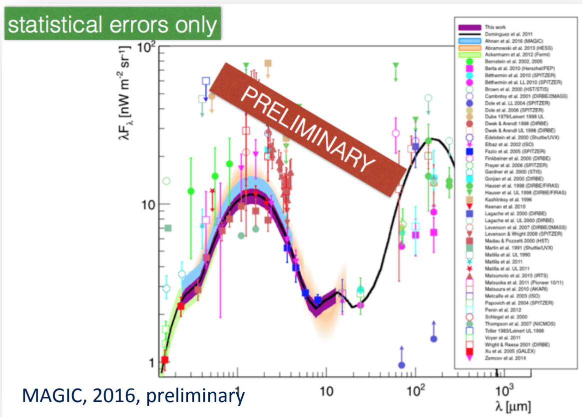
Outline

- Current instruments and their limitations

- The CTA project
  - Organization and timescales
  - Telescope types
  - Expected performance

- The Science with CTA

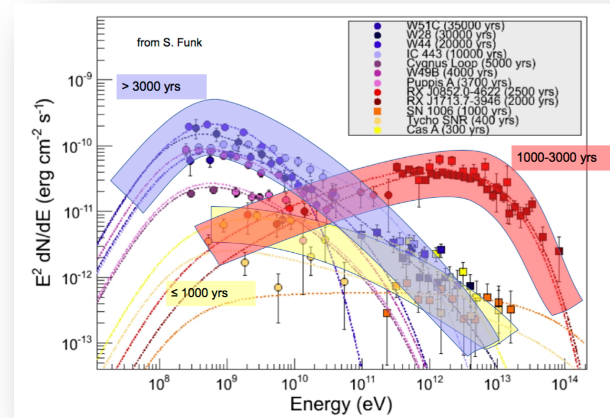
Evolution of the field



Key science

Deep exposures

Precision measurements



Time-domain

Transients

Multi-messenger

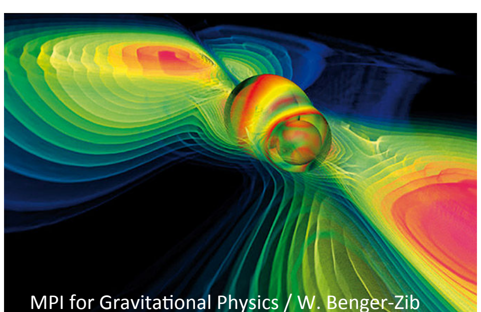
Multi-wavelength

Surveys

Population studies

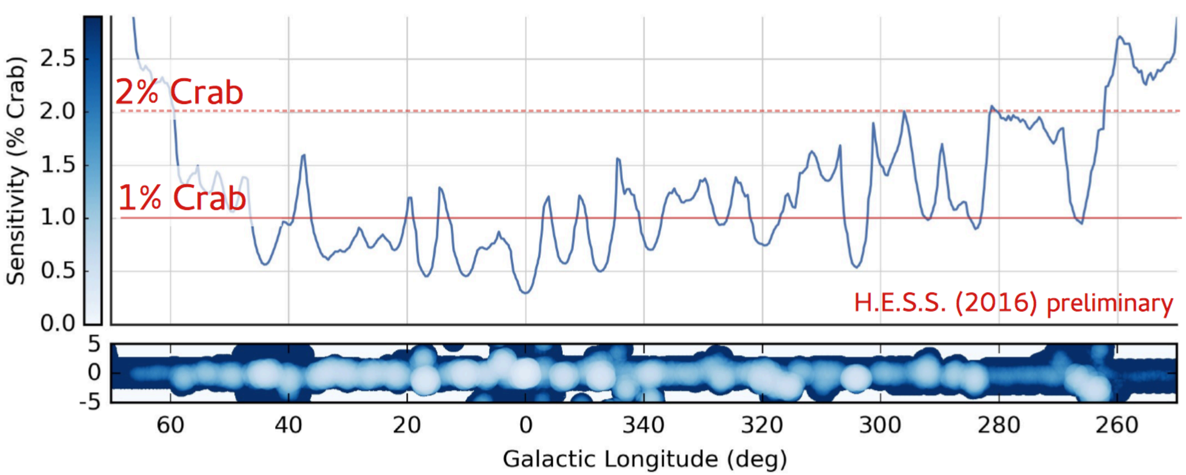
Initial discoveries

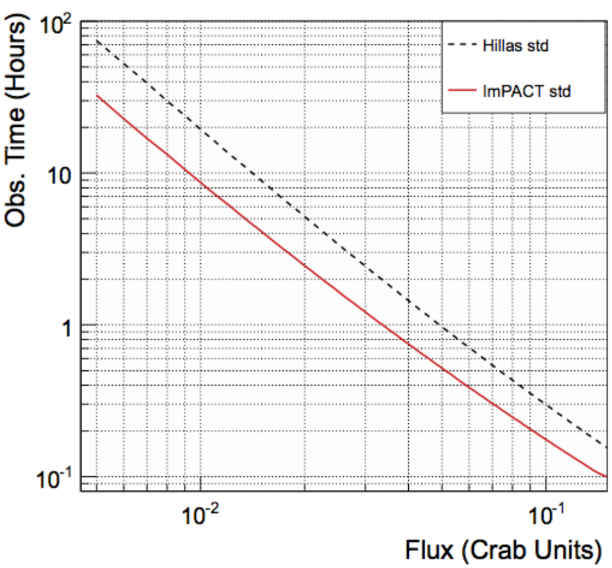
(first years of operation)



Where we are with current instruments

- Current instruments operate at the limit
  - ~1000 hours of observation time available per year
  - detection ≠ precision measurement
  - limited detection area and energy coverage
- Where things can be improved
  - hardware level (Mirrors, PMTs, trigger, readout)
  - software level (reconstruction, γ-hadron separation)





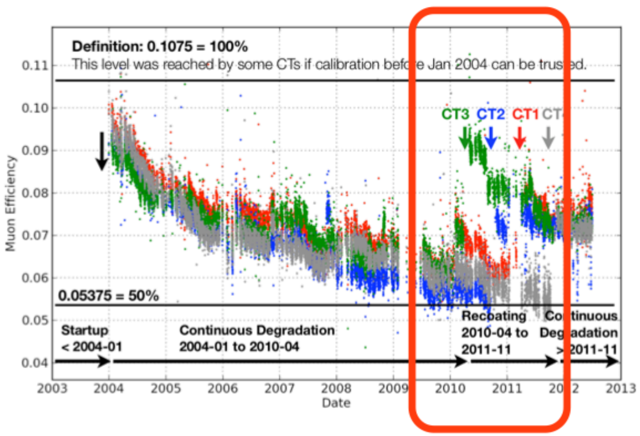
Improving existing instruments

- Capturing the faint Cherenkov light
  - e.g. VERITAS constantly recoats mirrors with recoating station on site
  - Winston cone cleaning/replacement
  - VERITAS upgraded PMTs → reduced energy threshold of the system by 30%
- Trigger and readout optimisation of Cherenkov cameras
  - VERITAS adjusted the trigger scheme for the high-QE PMTs
  - MAGIC changed the trigger to detect pulsed emission from the Crab

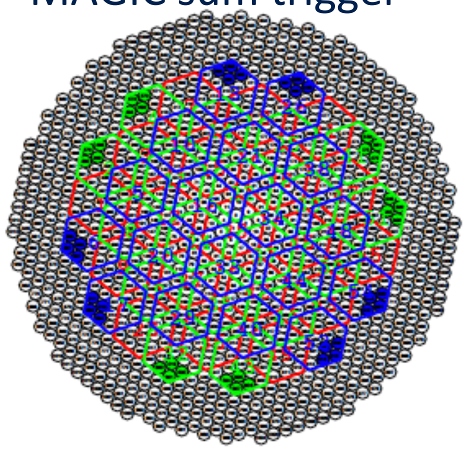
→ Can improve current instruments, but still costs money/manpower

→ Software/Algorithm improvements always help to explore full potential

HESS mirror recoating



MAGIC sum trigger



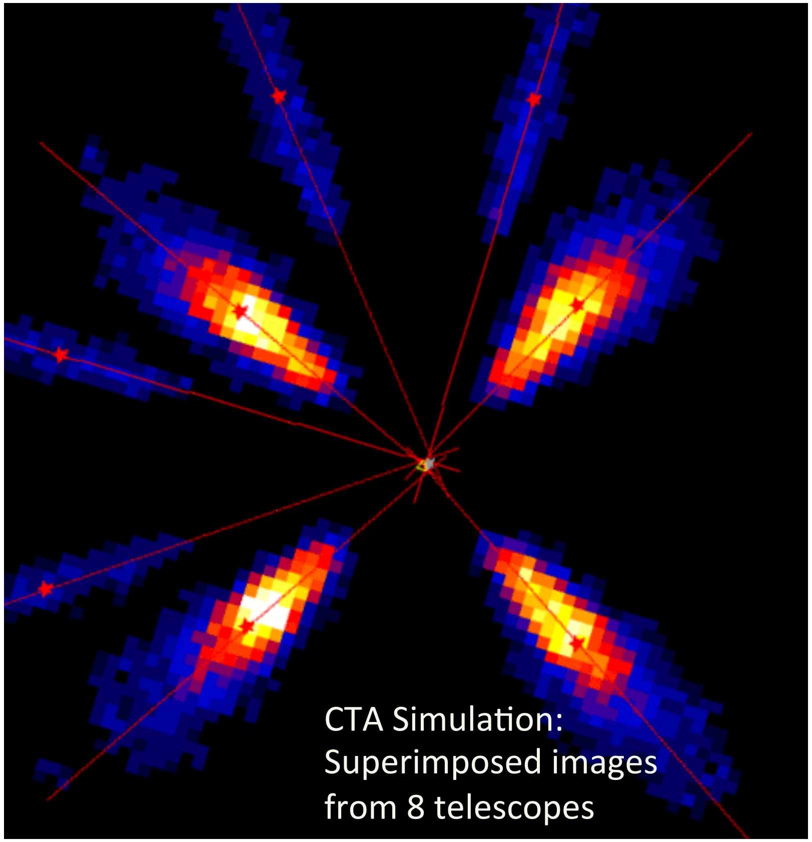
How to do better with IACTs?

- More events
  - More photons = better spectra, images, fainter sources

  → Larger collection area for γ rays
- Better events
  - More precise measurements of atmospheric cascades and hence primary γ rays

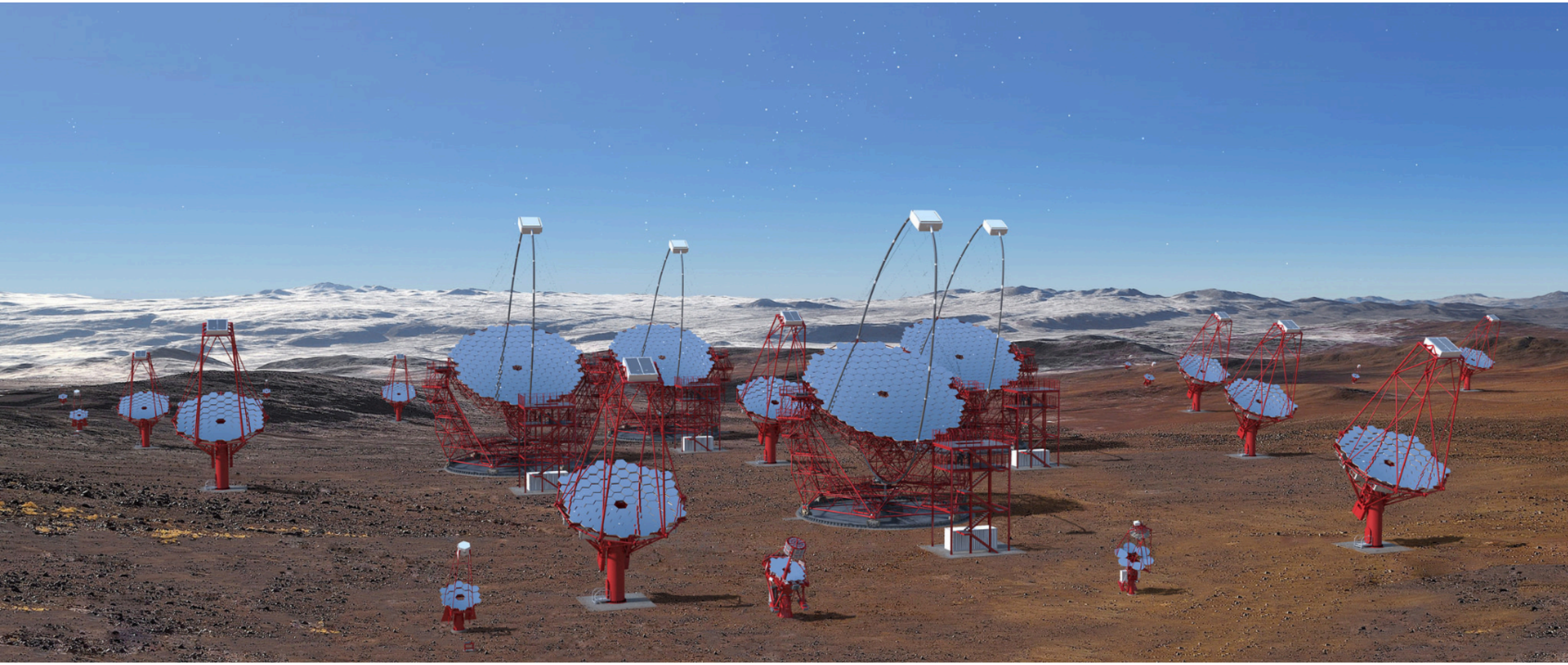
  → Improved angular resolution

  → Improved background rejection power
- ➢ More telescopes!



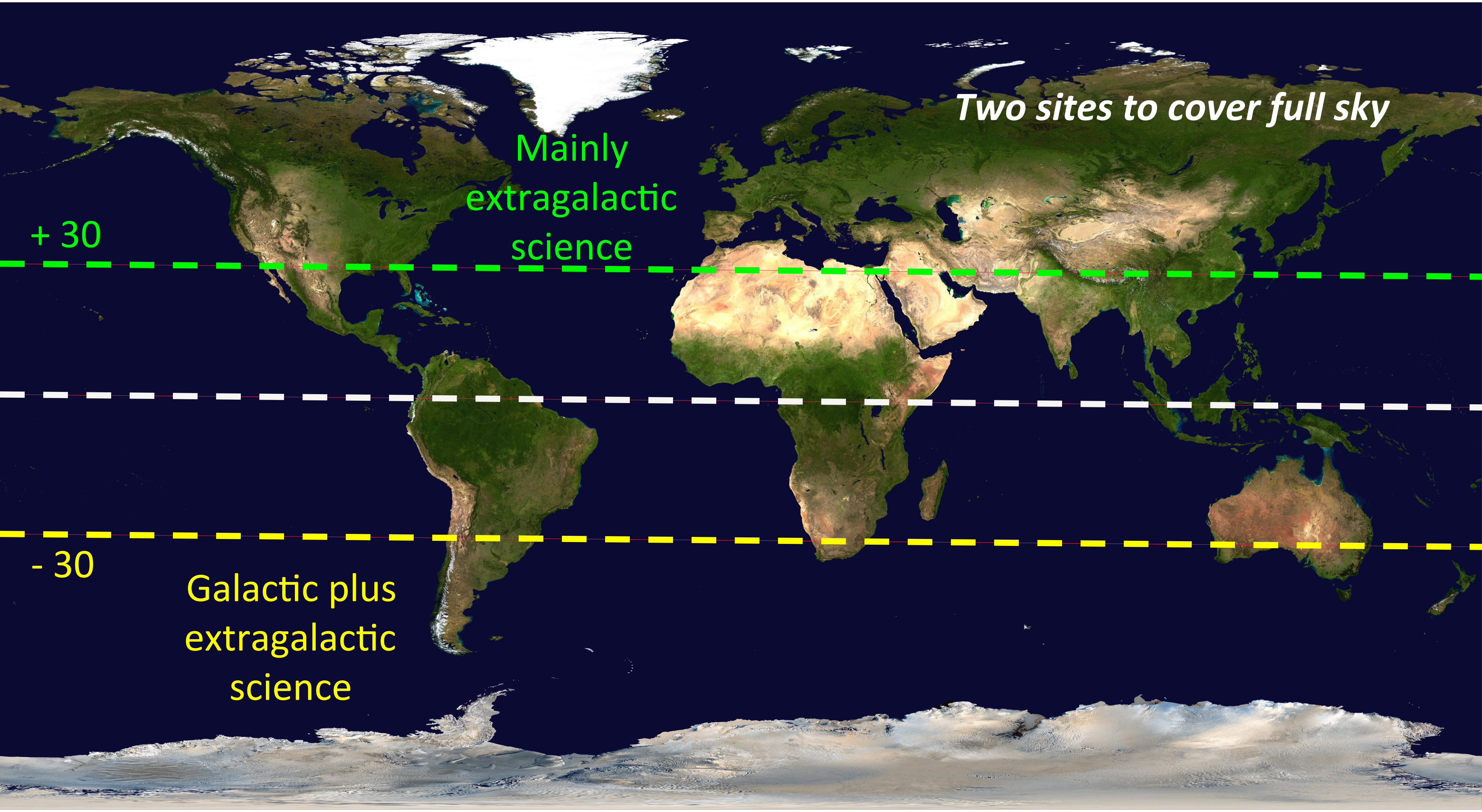
The Cherenkov Telescope Array

- 32 countries (including India), >200 institutions, >1350 consortium members



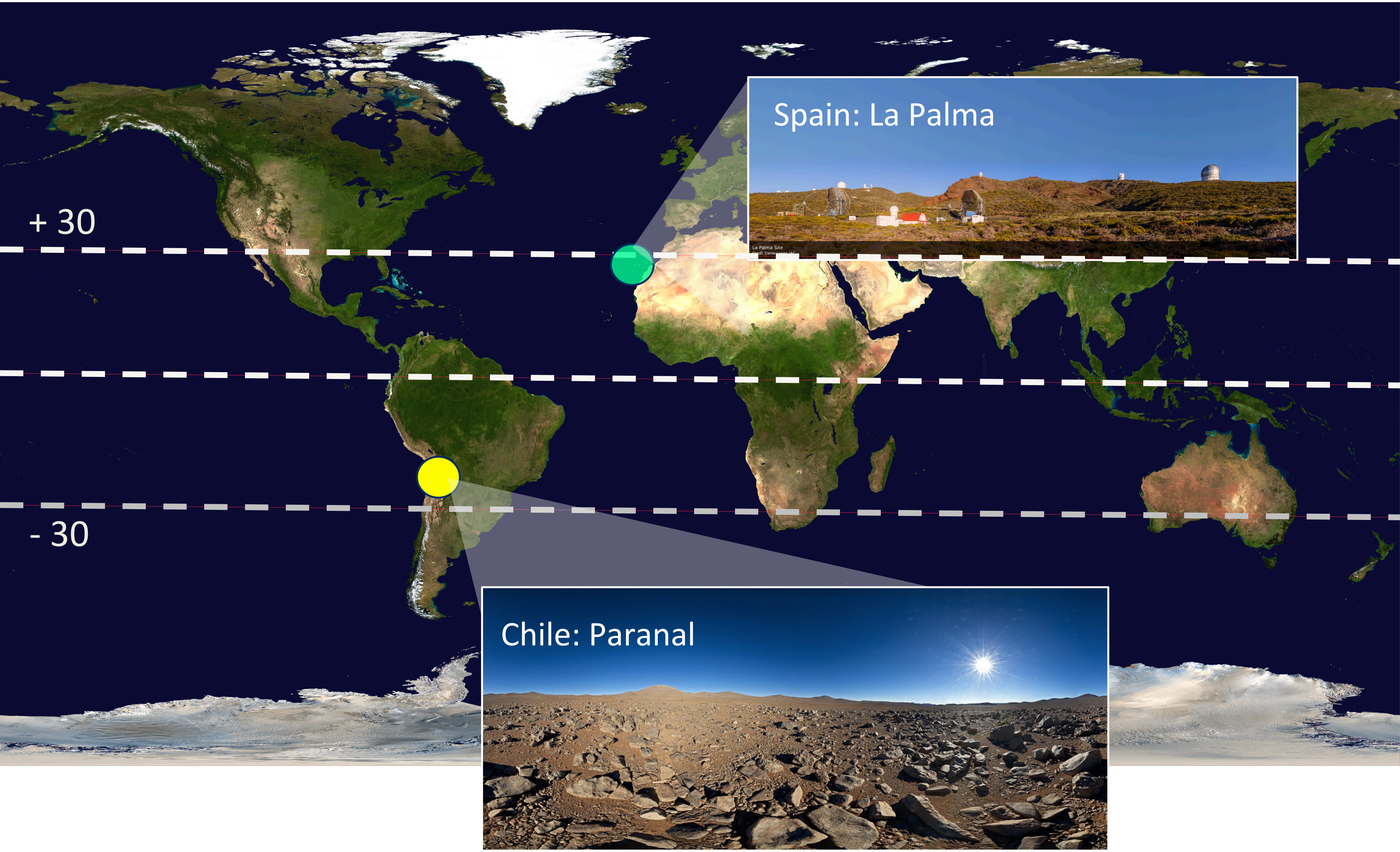
The CTA Consortium

CTA Sites



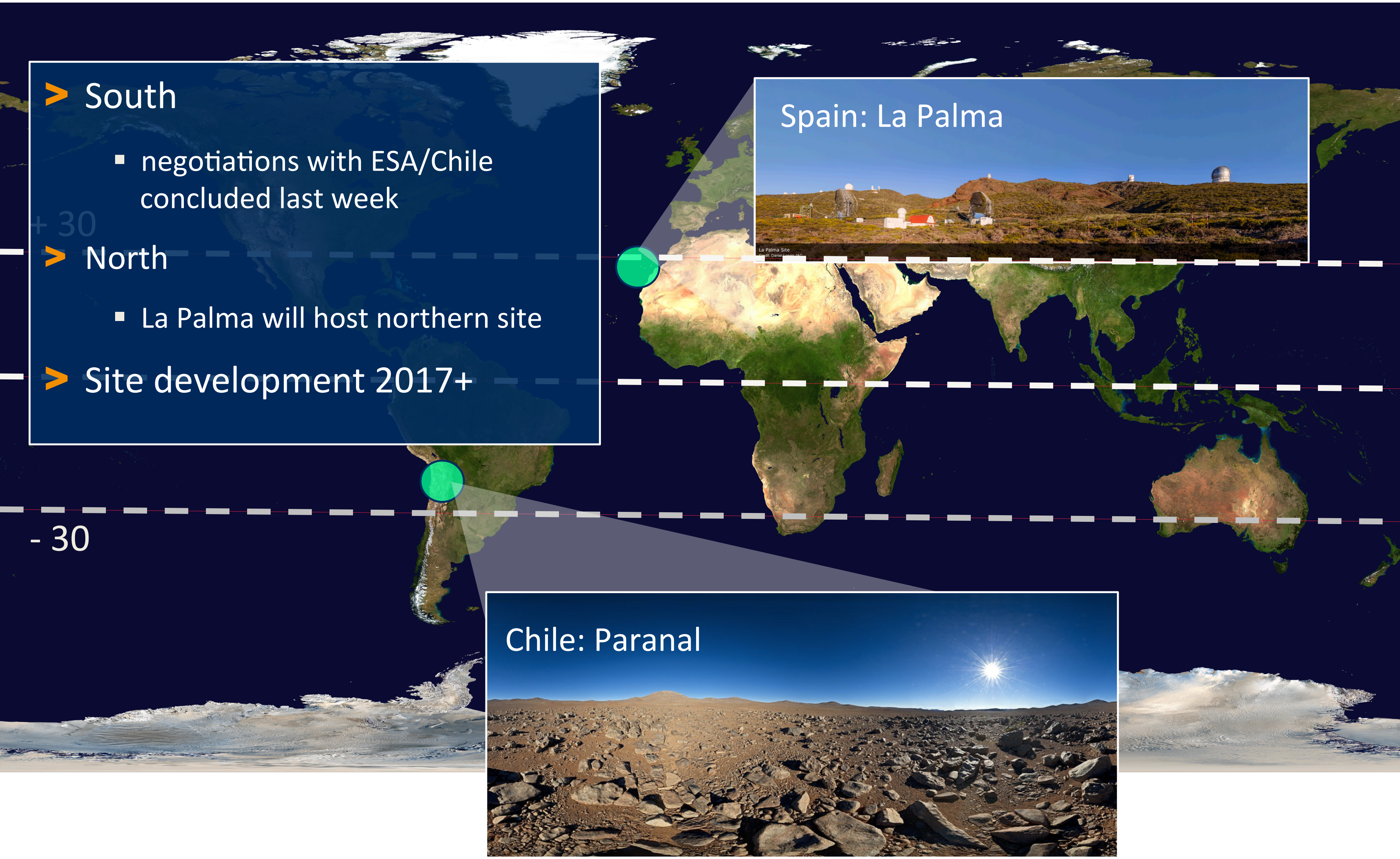
Two sites to cover full sky
Mainly extragalactic science
+ 30
- 30
Galactic plus extragalactic science

CTA Sites



CTA Sites

- South
  - negotiations with ESA/Chile concluded last week
- North
  - La Palma will host northern site
- Site development 2017+



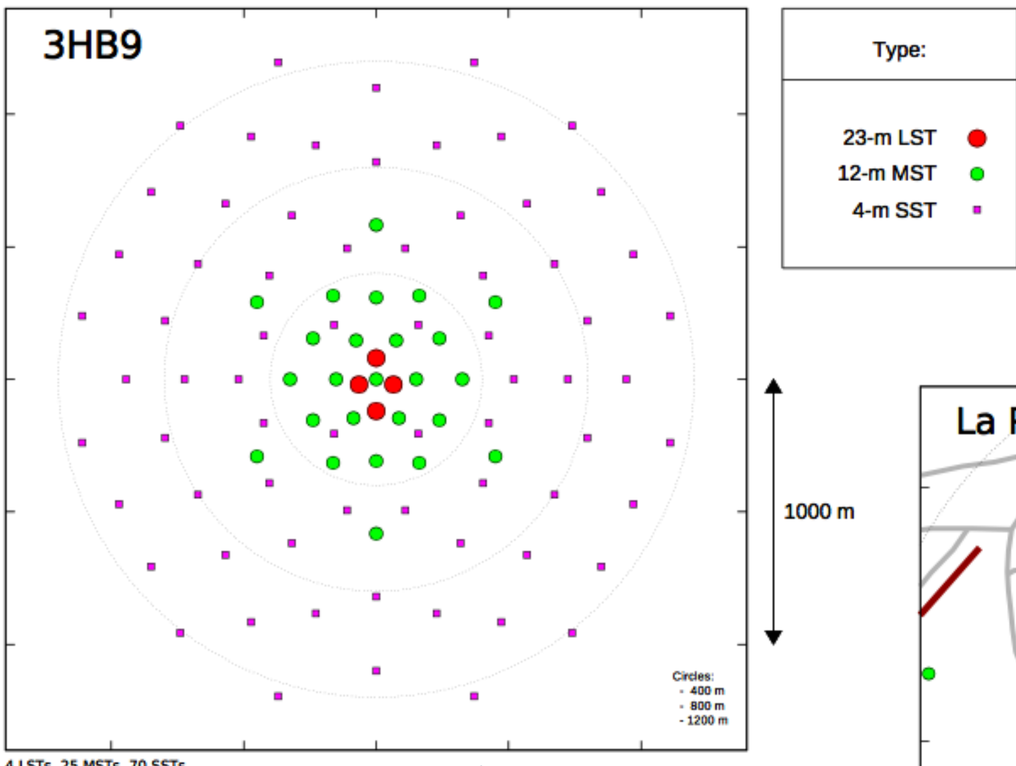
CTA Management

- Science Data Management Center
  - located in Berlin/Zeuthen (Germany)
  - coordinates science operations
  - software maintenance
  - data processing
  - provides data products
- Headquarter
  - located in Bologna (Italy)
  - central office responsible for overall administration
  - technical coordination and support

CTA Timeline

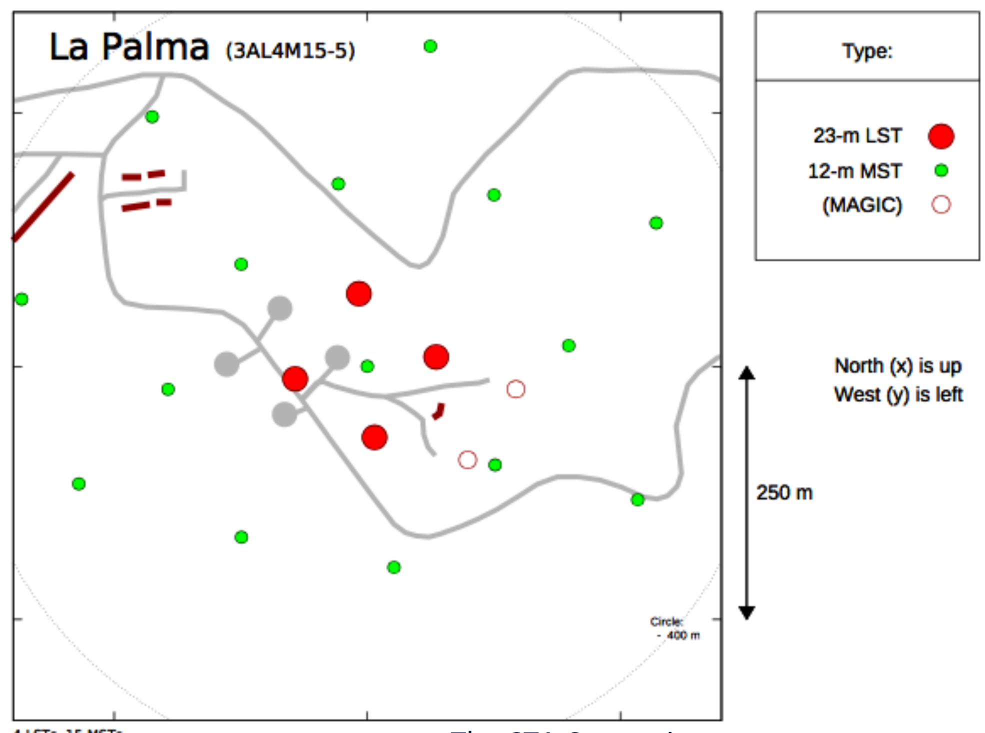
- Optimizing array layouts
  - 2006 – 2008: analytical analysis of telescope configurations
    - need for three telescope types
  - 2008 – 2009: 1^{st} large-scale Monte-Carlo production
    - definition of telescope characteristics, requirements
  - 2012 – 2015: 2^{nd} large-scale Monte-Carlo production
    - site dependence, telescope spacing
  - 2015 – 2016: 3^{rd} large-scale Monte-Carlo production
    - fine tuning of layouts for selected sites

Final array layouts



The CTA Consortium

North:
4 LST
15 MST



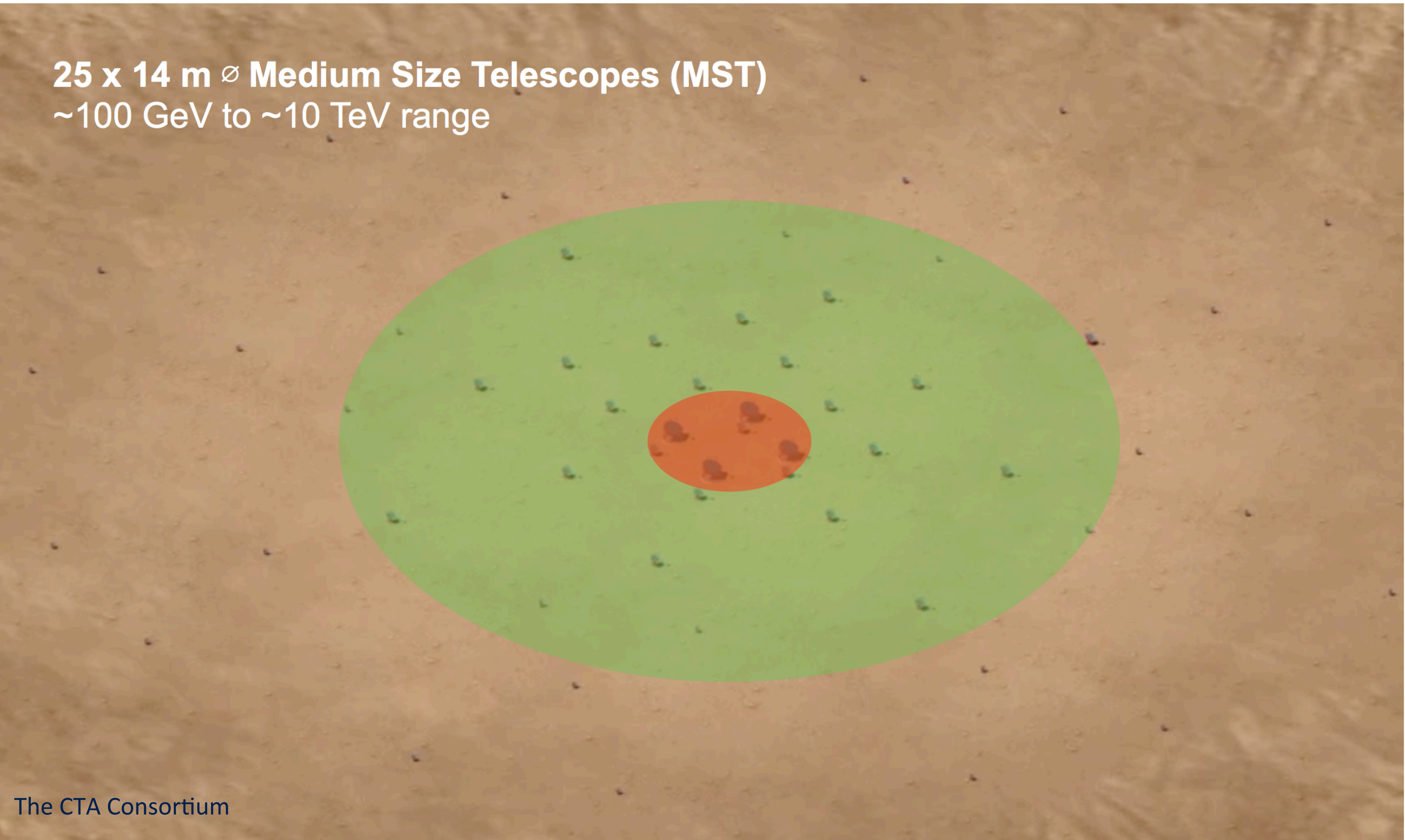
The CTA Consortium

South:
4 LST
25 MST
70 SST

The Cherenkov Telescope Array
(South Site)

The Cherenkov Telescope Array
(South Site)

The Cherenkov Telescope Array
(South Site)



The Cherenkov Telescope Array
(South Site)

Large-Size Telescope

- 23 m diameter, 389 m^2 dish area
- 28 m focal length
- 1.5 m mirror facets

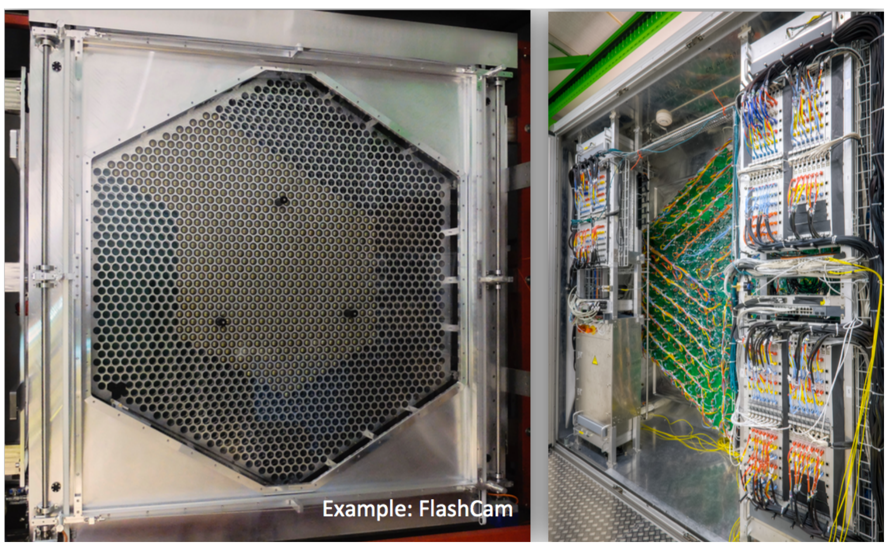
- 4.5° FoV
- 0.1° pixels
- Carbon-fibre structure for 20 s positioning
- Active mirror control
- LST prototype operational by end 2017

The CTA Consortium

Medium-Size Telescope

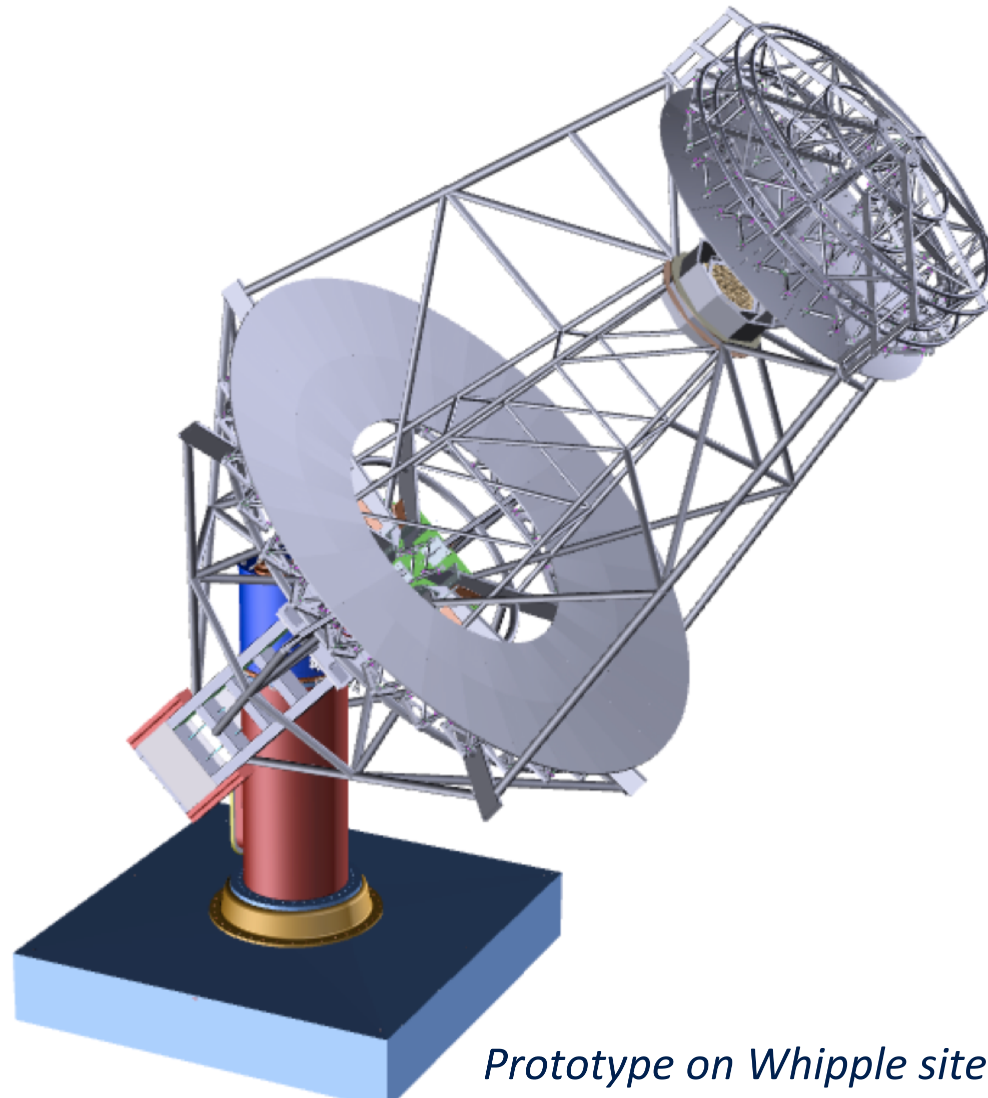
- 100 m^2 dish area
- 16 m focal length
- 1.2 m mirror facets

- 7.7° FoV
- ~2000 x 0.18° pixels



Medium-Size Telescope: Dual Mirror

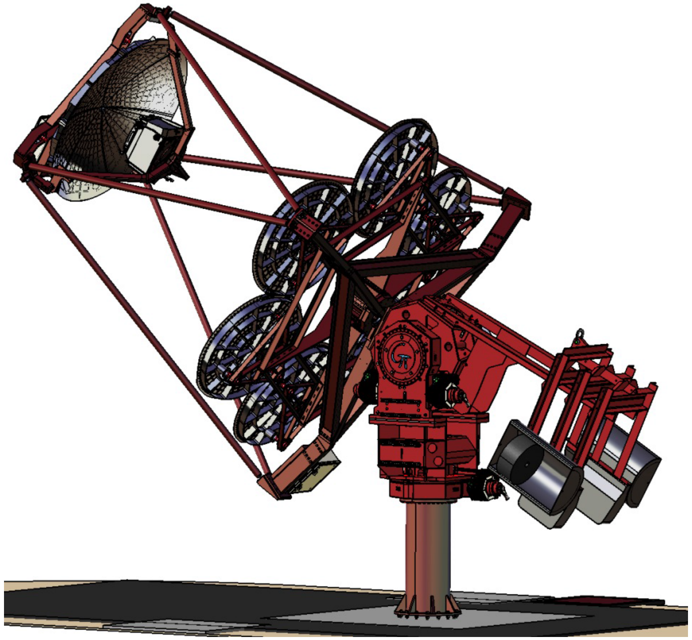
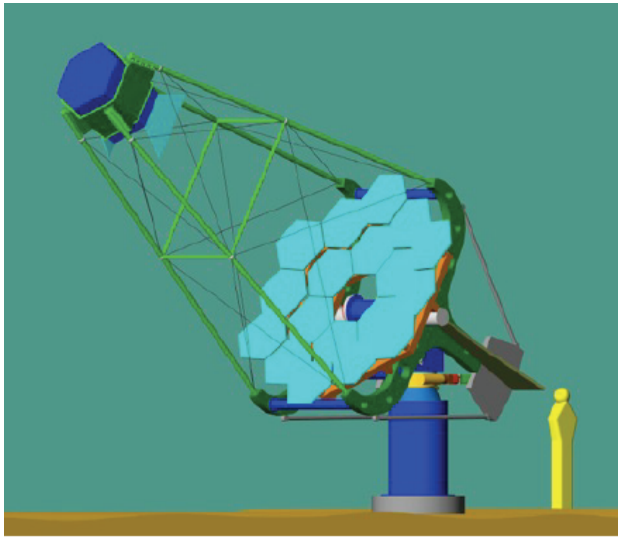
- 9.7 m primary
- 5.4 m secondary
- 5.6 m focal length
- 40 m^2 eff. coll. area
- 8° FoV
- **~11328 x 0.07° SiPM pixels**



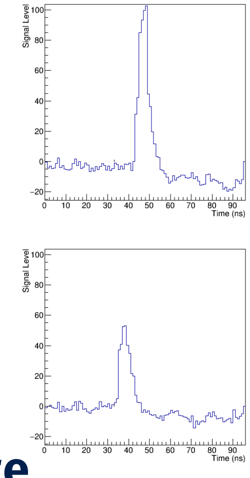
Prototype on Whipple site

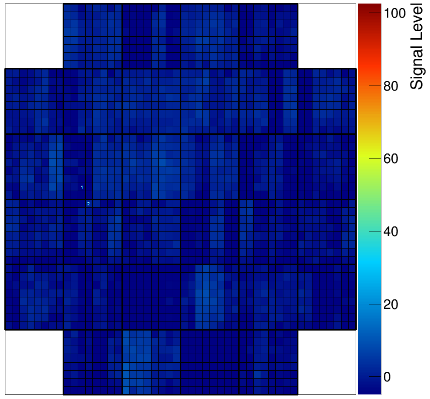
Small-Size Telescope (2 concepts)

- Three different designs
- Dual-mirror telescopes reduce costs of Cherenkov cameras
- But challenging in terms of pointing, shadowing, novel SiPMs

Small-Size Telescope (2 concepts)

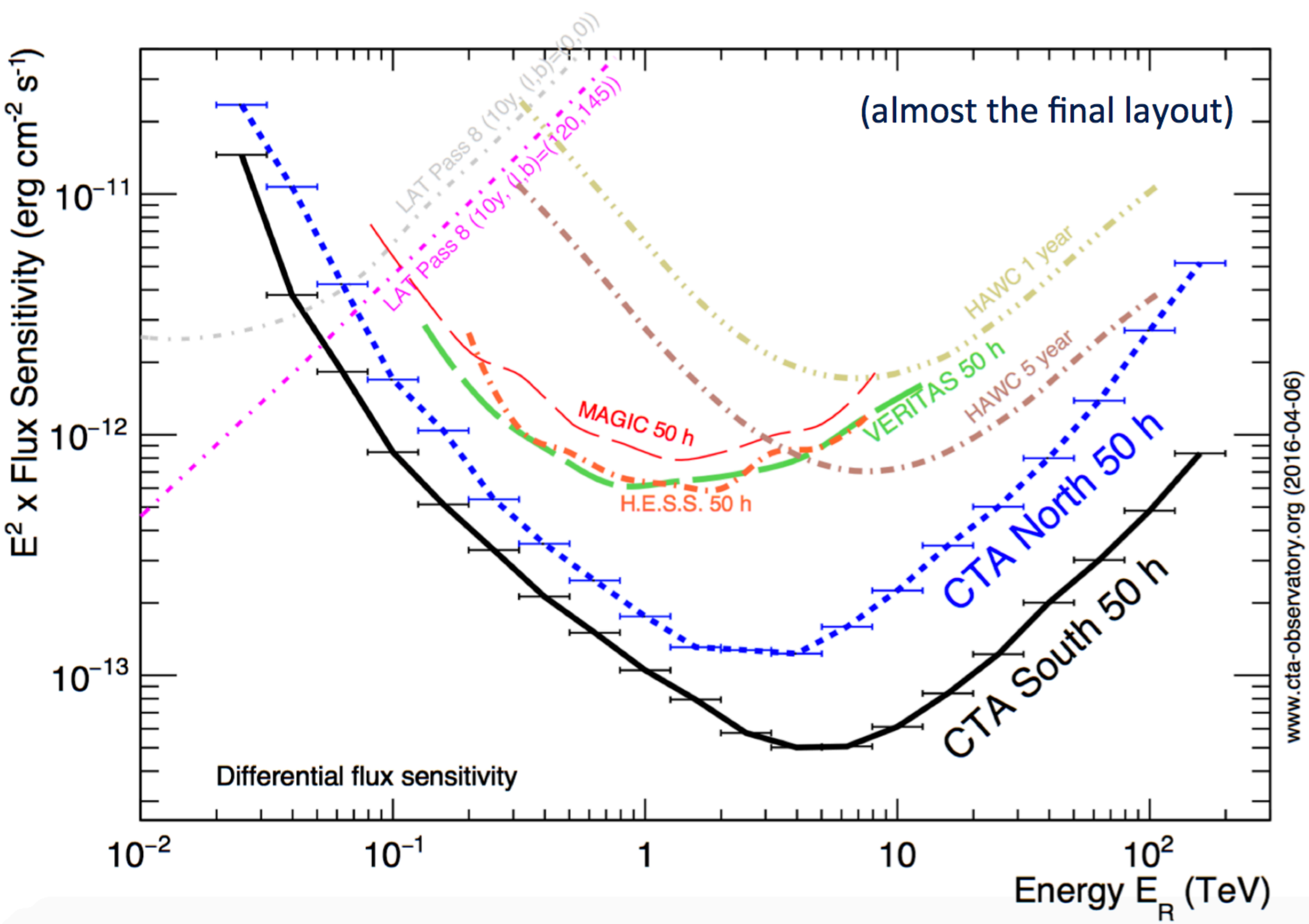




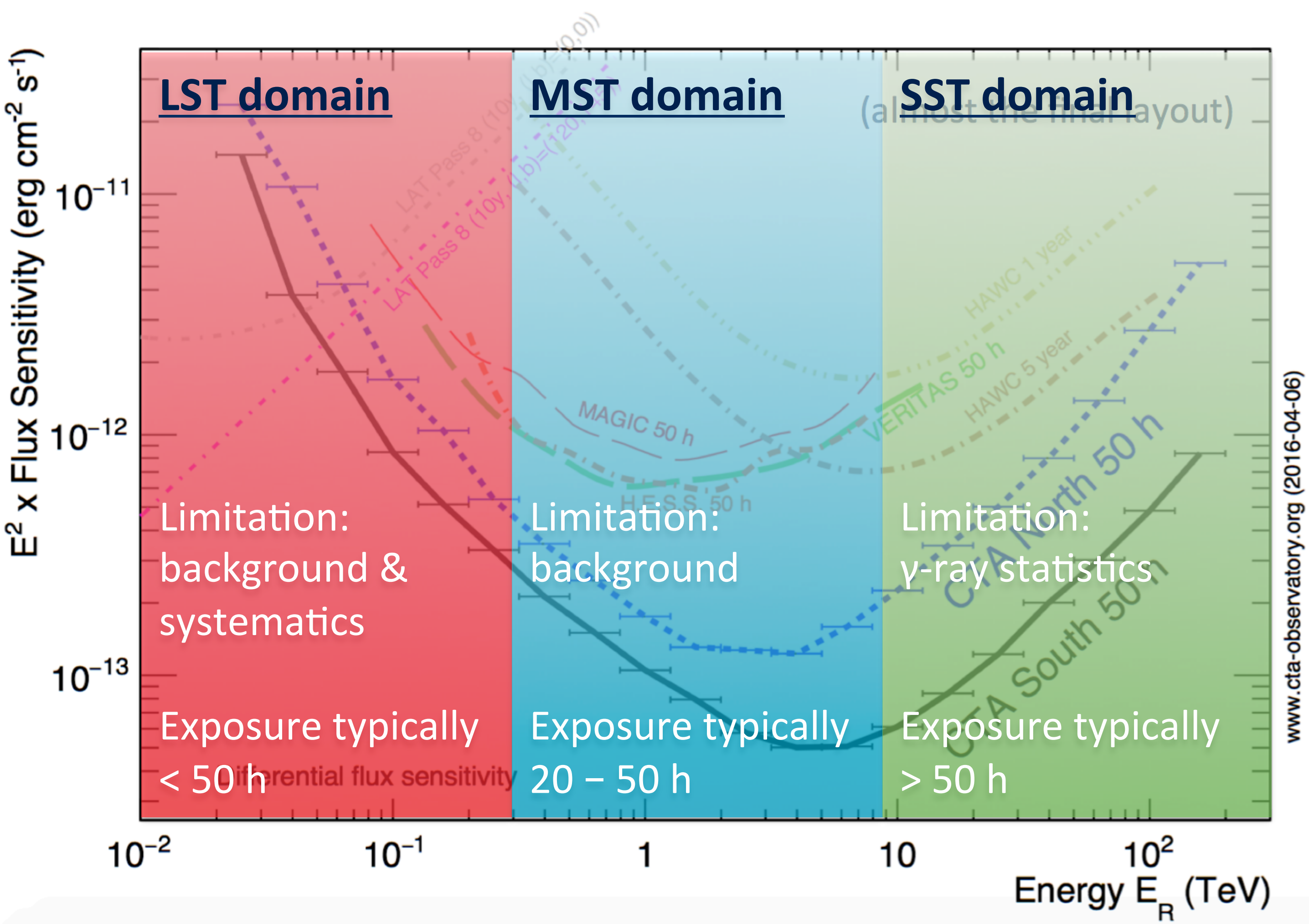
- ~8 m² dish area
- 9° FoV
- ~0.2° pixels

~ 70 MSTs on South site

CTA Sensitivity (50 hrs)

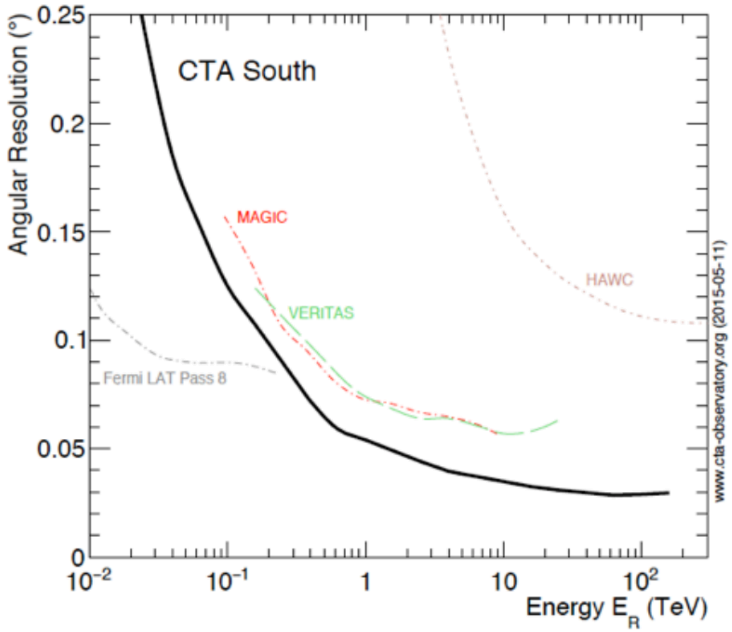


CTA Sensitivity (50 hrs)

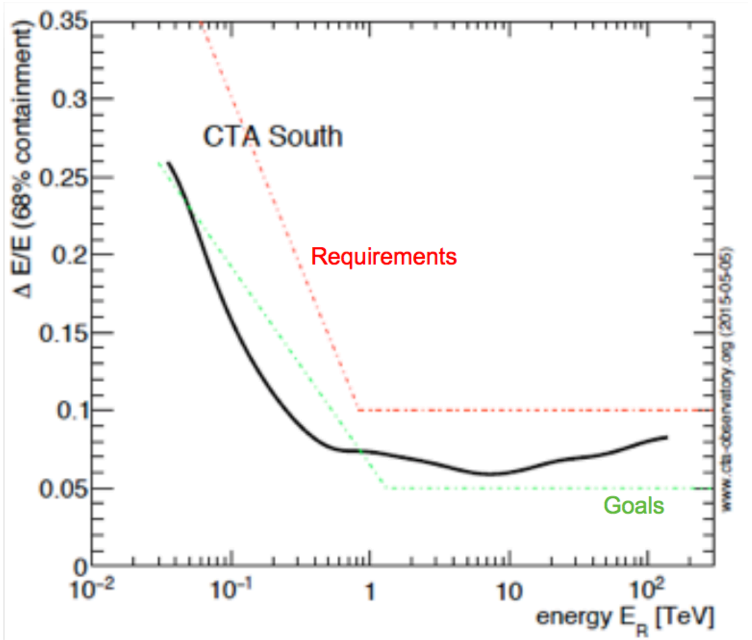


CTA Performance

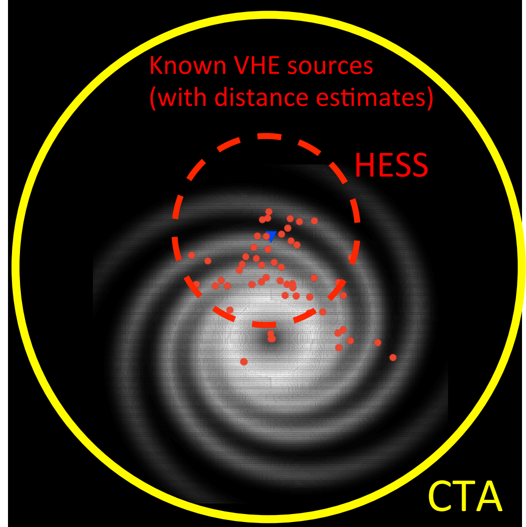
- Angular Resolution



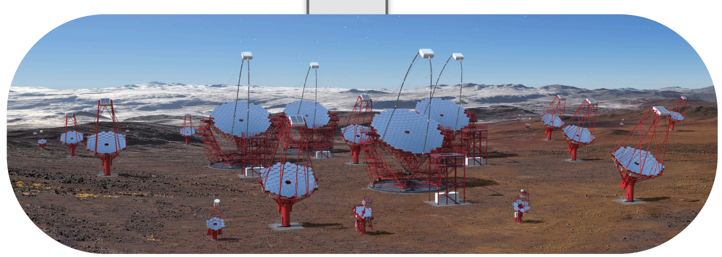
- Energy Resolution



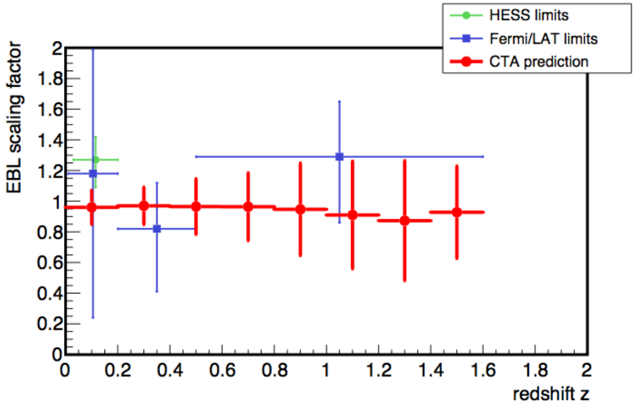
- Optimization of event selection can further improve angular/energy resolution
- Instrument Response Functions available online:
  - https://portal.cta-observatory.org/Pages/CTA-Performance.aspx

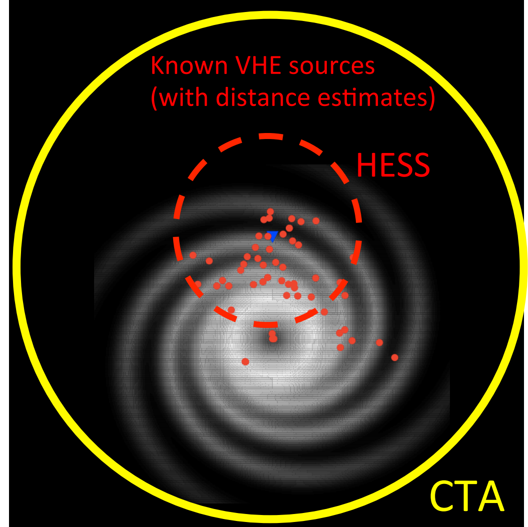


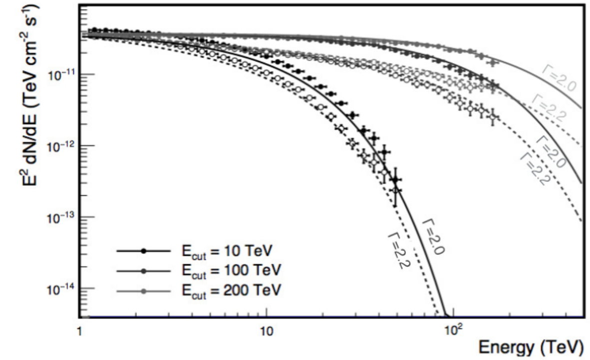
10 x Sensitivity,
Large Collection
Area
→ all topics



CTA Science



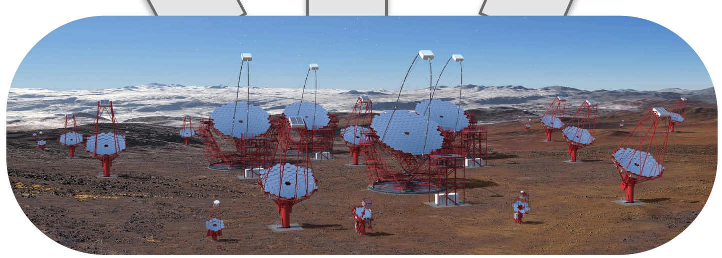




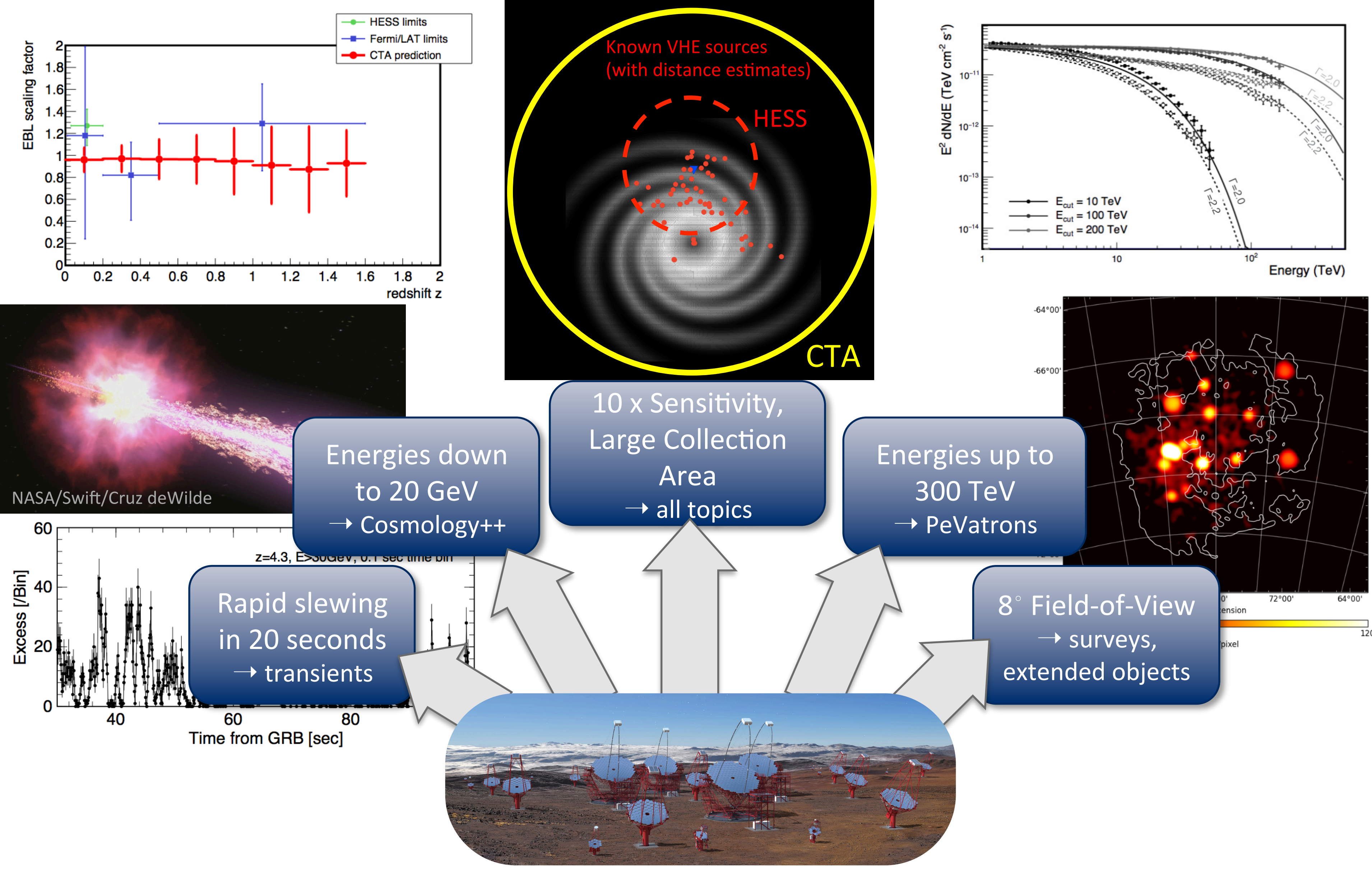
Energies down to 20 GeV
→ Cosmology++

10 x Sensitivity, Large Collection Area
→ all topics

Energies up to 300 TeV
→ PeVatrons

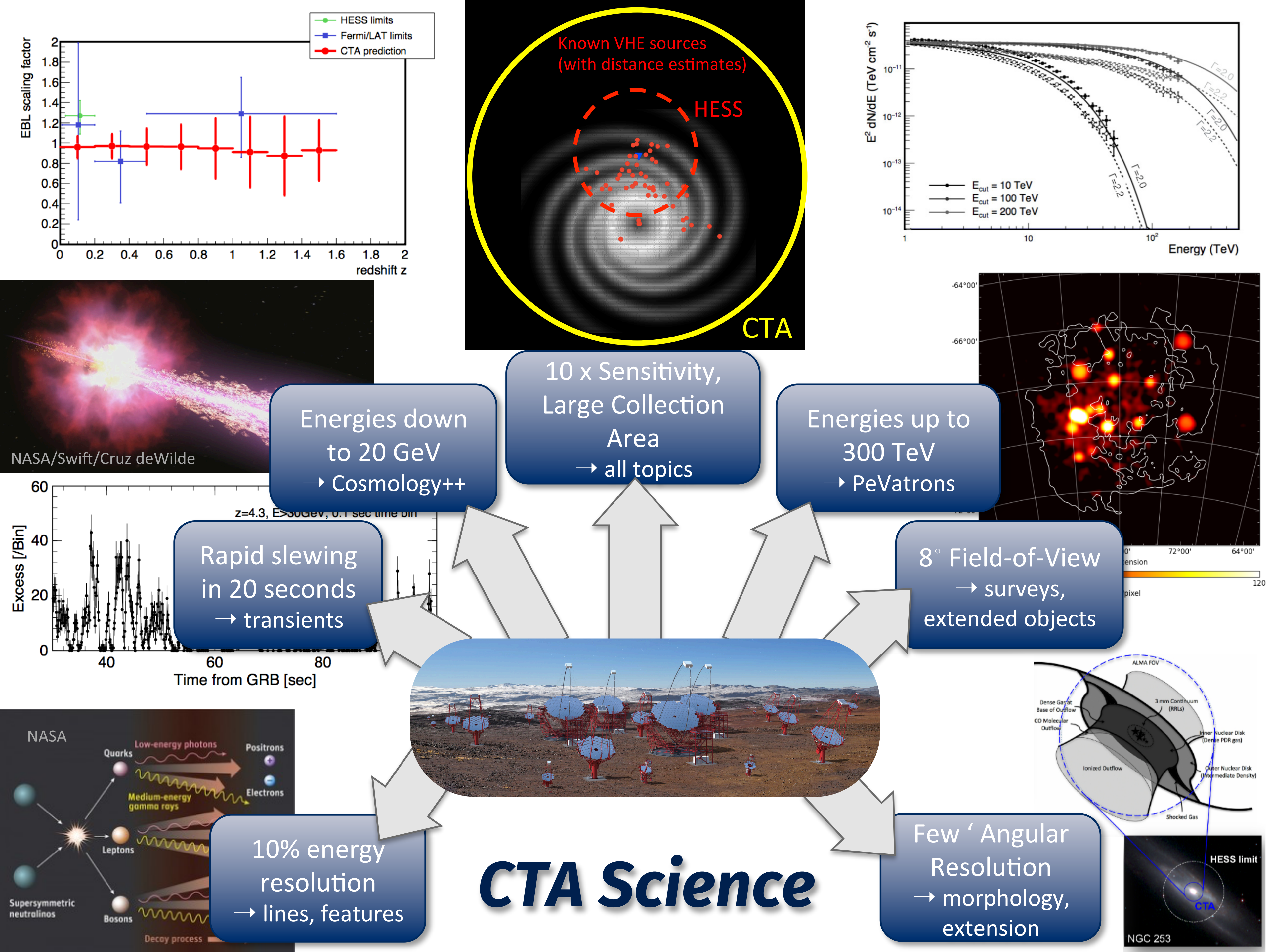


CTA Science



HESS limits
Fermi/LAT limits
CTA prediction
EBL scaling factor
redshift z
Known VHE sources
(with distance estimates)
HESS
CTA
E² dN/dE (TeV cm⁻² s⁻¹)
Energy (TeV)
Ecut = 10 TeV
Ecut = 100 TeV
Ecut = 200 TeV
NASA/Swift/Cruz deWilde
Excess [/Bin]
Time from GRB [sec]
z=4.3, E>30GeV, 0.1 sec time bin
Energies down to 20 GeV
→ Cosmology++
10 x Sensitivity, Large Collection Area
→ all topics
Energies up to 300 TeV
→ PeVatrons
Rapid slewing in 20 seconds
→ transients
8° Field-of-View
→ surveys, extended objects

CTA Science



HESS limits
Fermi/LAT limits
CTA prediction
EBL scaling factor
redshift z
Known VHE sources
(with distance estimates)
HESS
CTA
E² dN/dE (TeV cm⁻² s⁻¹)
Energy (TeV)
E_cut = 10 TeV
E_cut = 100 TeV
E_cut = 200 TeV
NASA/Swift/Cruz deWilde
Energies down to 20 GeV → Cosmology++
10 x Sensitivity, Large Collection Area → all topics
Energies up to 300 TeV → PeVatrons
Rapid slewing in 20 seconds → transients
8° Field-of-View → surveys, extended objects
Excess [/Bin]
Time from GRB [sec]
NASA
Quarks
Low-energy photons
Positrons
Electrons
Medium-energy gamma rays
Leptons
Supersymmetric neutralinos
Bosons
Decay process
10% energy resolution → lines, features
CTA Science
Few ' Angular Resolution → morphology, extension
ALMA FOV
HESS limit
CTA
NGC 253

CTA Science Themes

- **Cosmic Particle Acceleration**
  - How and where are particles accelerated?
  - How do they propagate?
  - What is their impact on the environment?
- **Probing Extreme Environments**
  - Processes close to neutron stars and black holes
  - Processes in relativistic jets, winds and explosions
  - Exploring cosmic voids
- **Physics frontiers – beyond the Standard Model**
  - What is the nature of Dark Matter? How is it distributed?
  - Is the speed of light a constant for high-energy photons?
  - Do axion-like particles exist?

CTA Science Programme

- **Key Science Projects**
  - Ensure important science questions are addressed coherently early on in the project
  - Conceived to provide legacy data sets for the entire community

Example: Galactic and extragalactic surveys

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

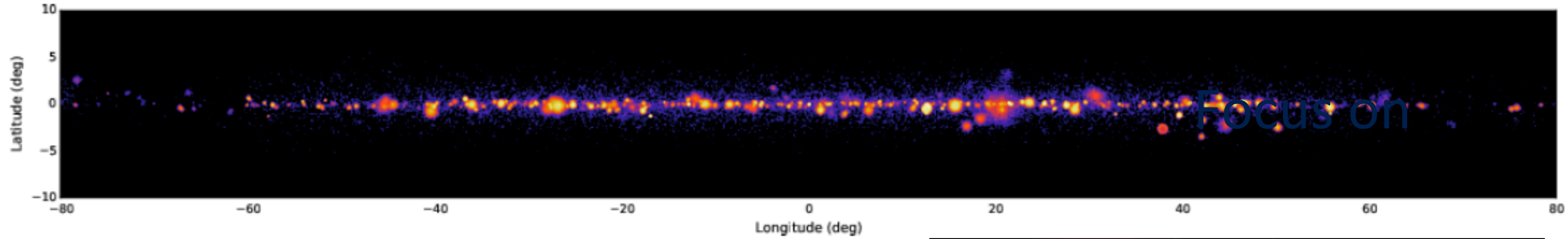
→ **Proposal-Driven User Programme**

Time

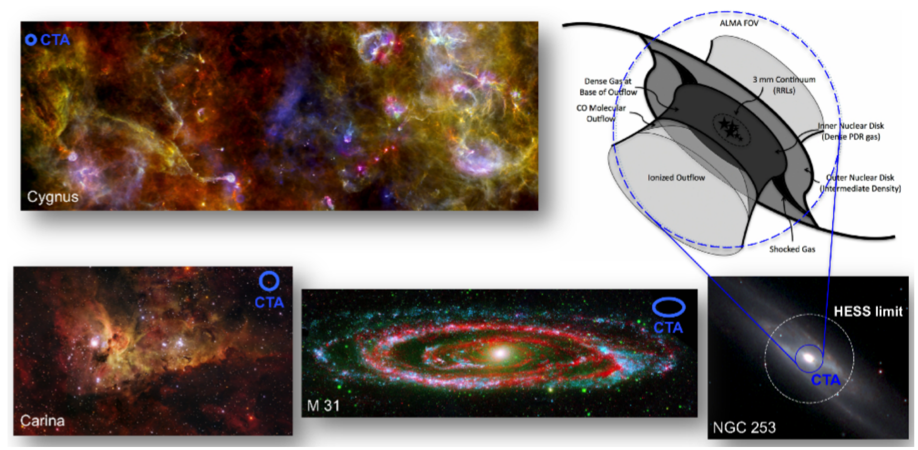
CTA Key Science Projects

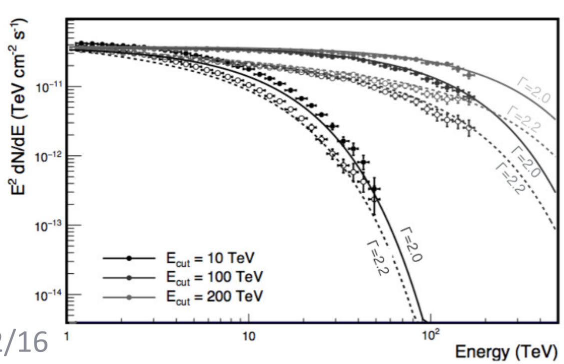
1. Dark Matter Programme
2. Galactic Centre Survey
3. Galactic Plane Survey
4. Large Magellanic Cloud Survey
5. Extragalactic Survey
6. Transients
7. Cosmic-ray PeVatrons
8. Star-forming Systems
9. Active Galactic Nuclei
10. Cluster of Galaxies
11. Non-Gamma-ray Science

CTA Science: Focus on

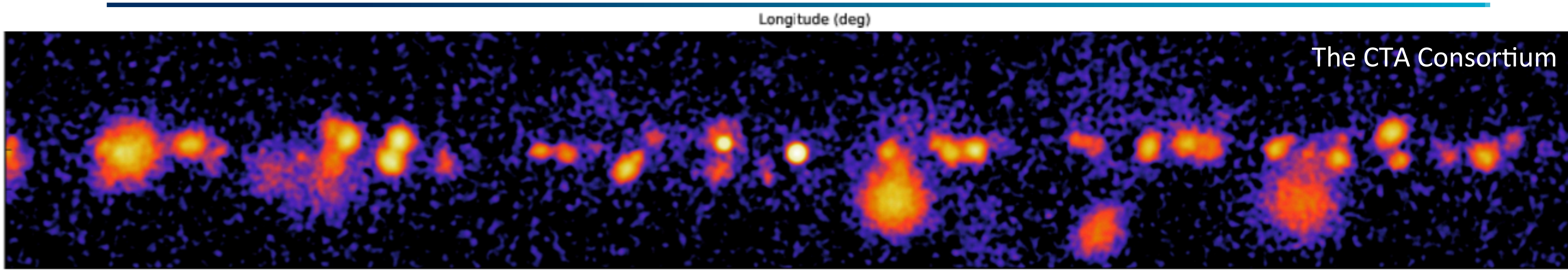


- Surveys
  - Galactic Plane
  - Large Magellanic Cloud
- Transients
- Cosmic-ray PeVatrons
- Star-forming systems





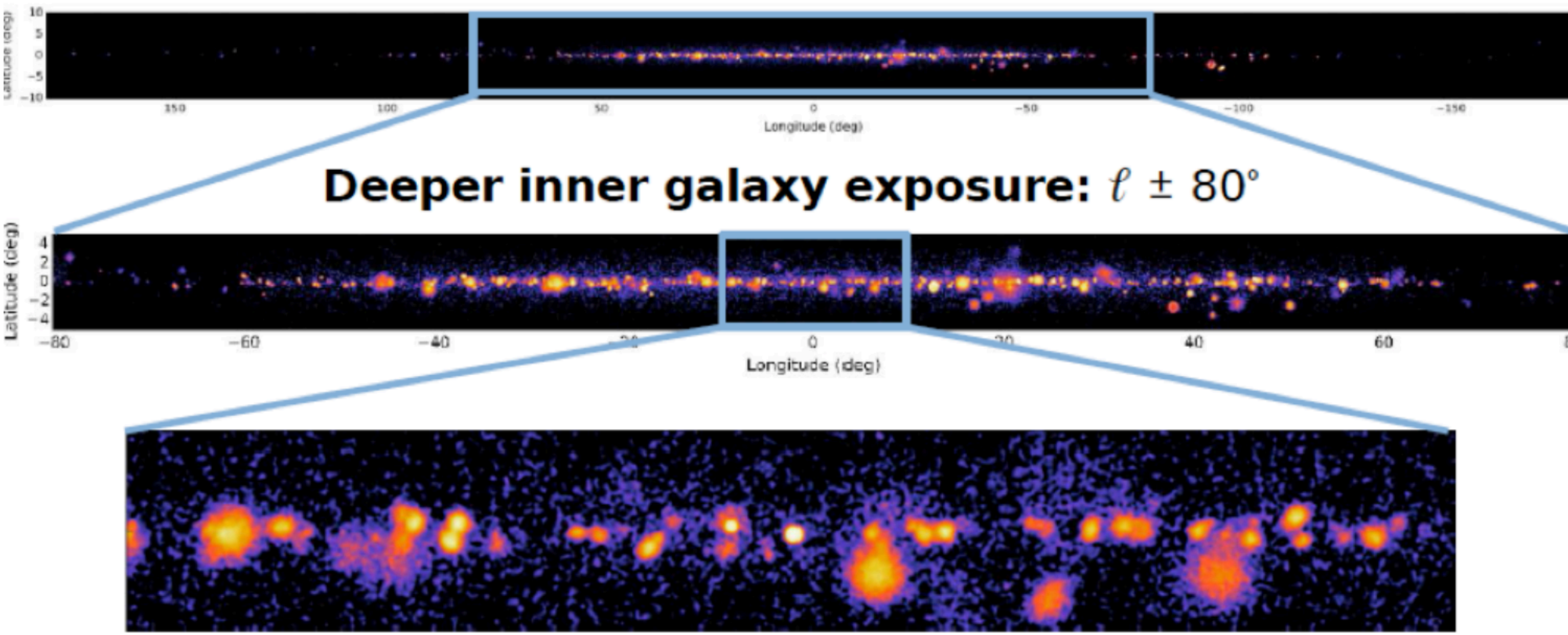
CTA Science: Galactic Plane Survey



- CTA will conduct a survey of the entire Galactic plane (GPS)
- The GPS will be 5 – 20 times more sensitive than current instruments such as HESS, HAWC or VERITAS
- Survey will provide
  - complete and systematic view of the Milky Way at γ-ray energies
  - detailed description of source populations (e.g. SNRs, PWNe)
  - complete picture of the Galactic diffuse emission
  - a comprehensive data set and catalogue of γ-ray sources

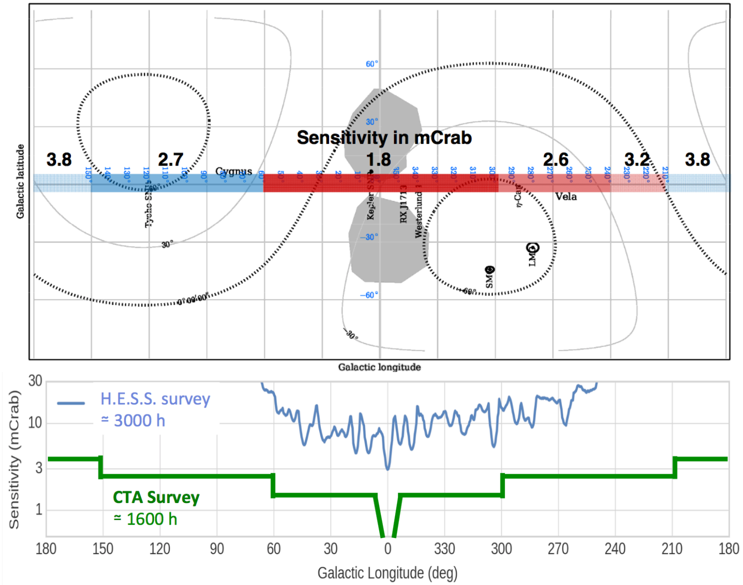
CTA Science: Galactic Plane Survey

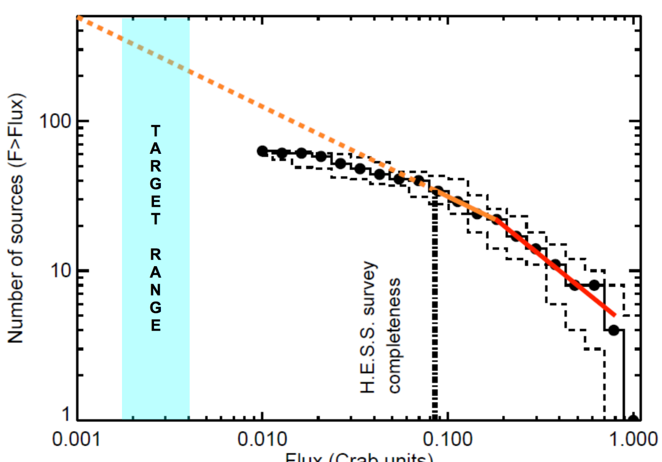
Full-plane coverage: longitude ± 180°, latitude b ± 10°



Fine detail revealed with **~arcmin PSF**

CTA Science: Galactic Plane Survey

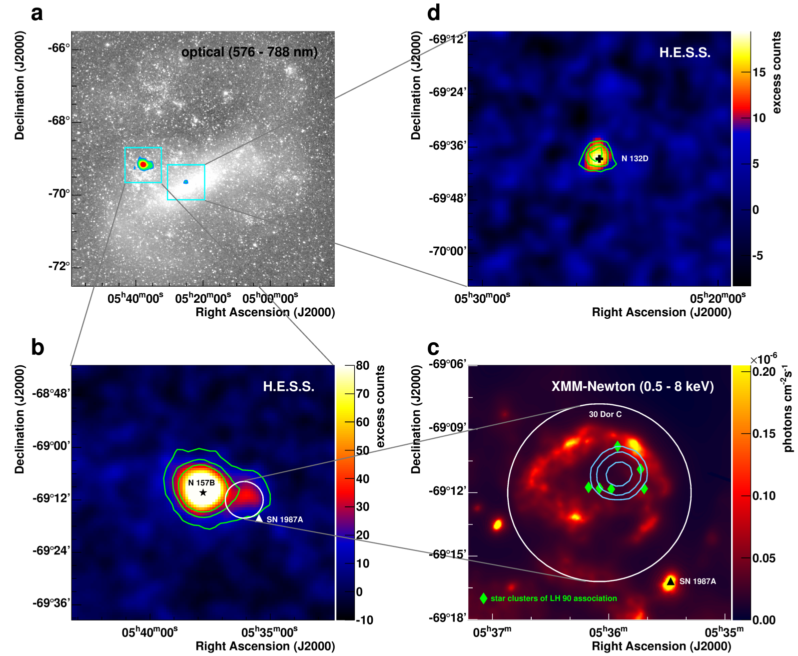




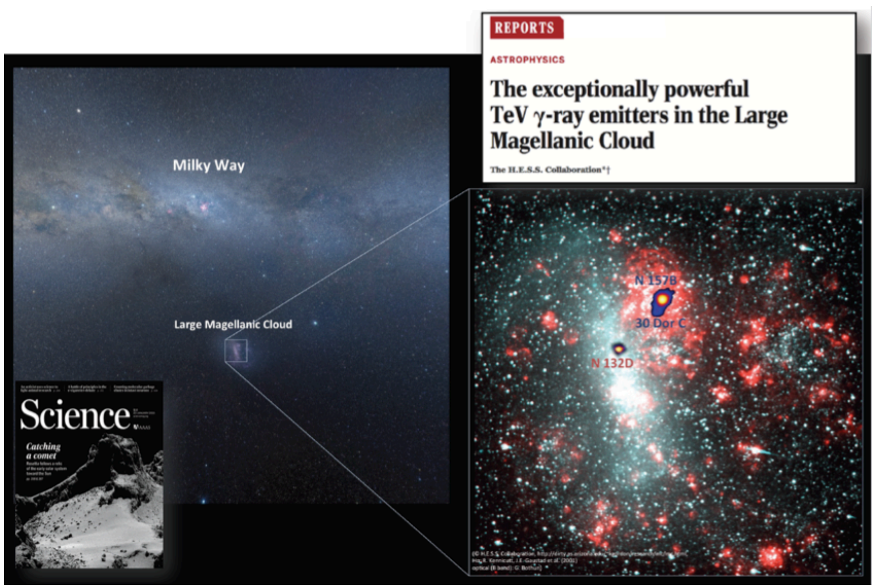
- Expected results
  - Detection of 300 – 500 new γ-ray emitters (many SNRs, PWNe)
  - Discovery of Galactic PeVatrons
  - Discovery of new γ-ray binaries
  - (Hopefully) discovery of new and unexpected source classes
  - Production of a multi-purpose legacy data set
  - GPS will produce and regularly release sky maps and catalogues to the community

The current view of the LMC

- First glimpse of LMC population of particle accelerators
  - → First detection of stellar-like CR sources in external galaxy
  - → Independent probe of Galactic accelerators



HESS, Science (2015)



- Sources
  - All major Galactic source classes found in LMC
  - + a superbubble
  - + diffuse, + γ-ray binary @ HE

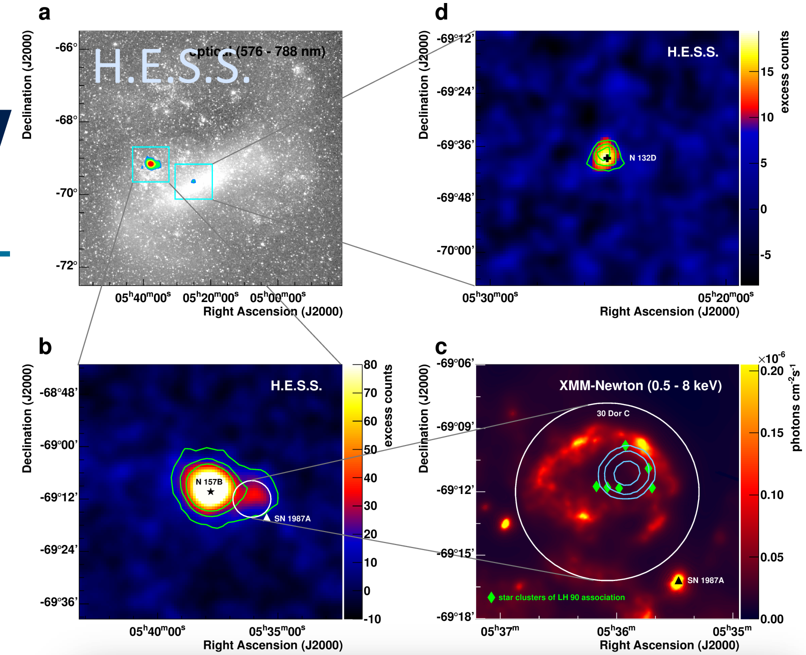
CTA Science: The LMC survey

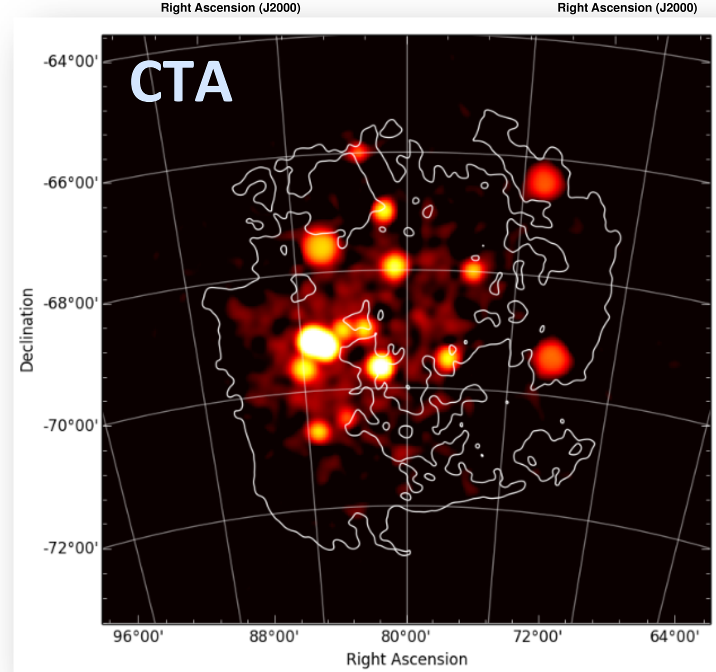
- PWN N157B
  - Environment is important
- SNR N132D
  - middle-aged SNR still accelerating particles to 10s of TeVs
- Superbubble 30 Dor C
  - first of its kind detected at VHE
- CTA simulations include
  - currently detected sources, + 10 point-like sources with $L(E > 1\ \mathrm{TeV}) \sim 10^{34}\ \mathrm{erg\ s^{-1}}$
  - handful of regions enriched in CRs
  - diffuse emission component

→ Excellent prospects for CTA

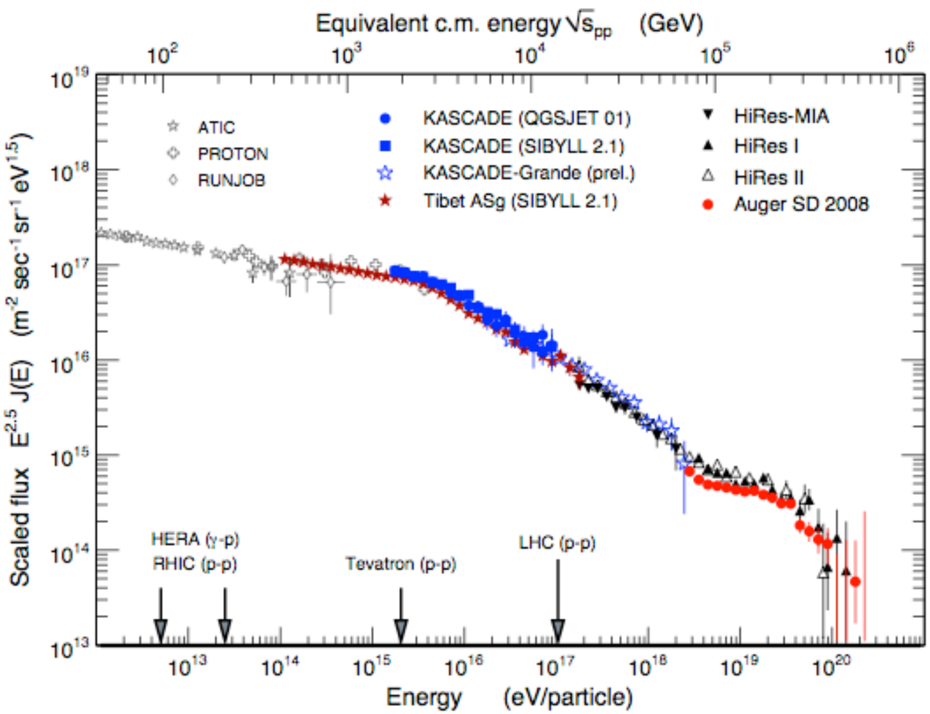
→ Detailed comparison of LMC and Milky Way source populations

→ Possibility to detect diffuse emission



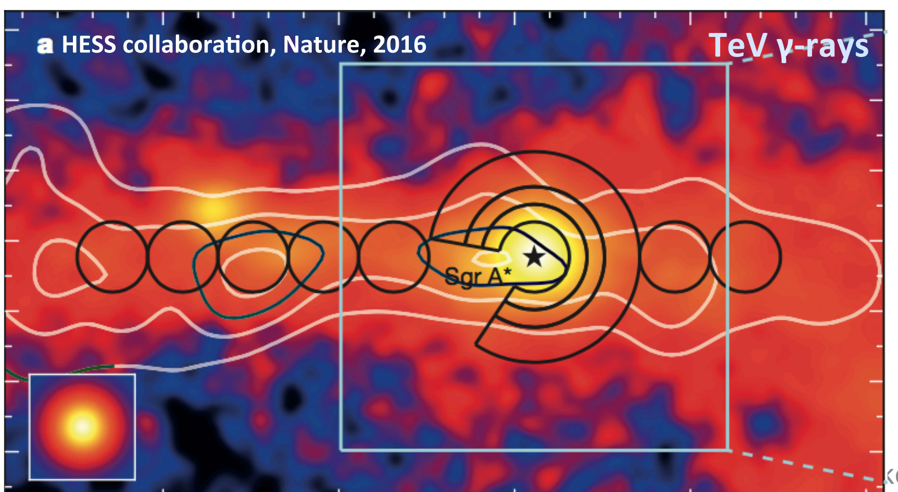


Why are PeVatrons interesting?

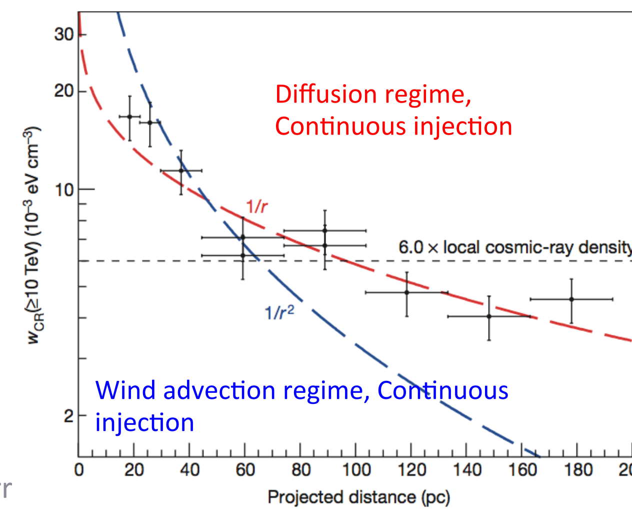


- Origin of cosmic rays
  - primarily energetic nuclei that fill Galaxy up to the knee in the CR spectrum
  - SNRs accelerate protons to GeV
  - SNRs accelerate electrons to >TeV
- γ-ray emission often ambiguous
- We know PWNe can accelerate electrons to ~PeV energies
- So far no proof for accelerators of CR nuclei to >PeV
- If γ-ray spectrum extends to hundreds of TeV energies, origin must be hadronic

Galactic PeVatrons

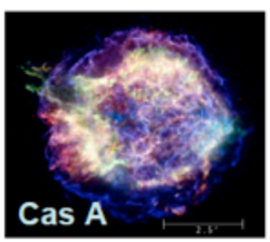


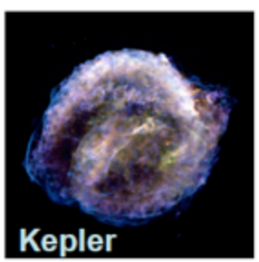
- Milky Way hosts super-massive black hole in centre (Sgr A*)
- HESS detects γ-rays from Sgr A* and diffuse emission along ridge
- No cut-off in diffuse emission spectrum
- Interpretation
  - Sgr A* accelerates CRs up to PeV energies
  - CRs diffuse away and interact with gas in the central molecular zone

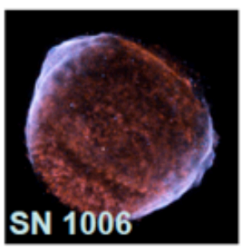


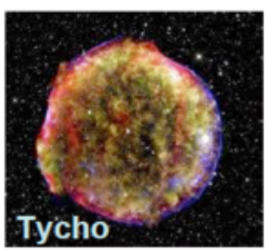
CTA Science: PeVatrons

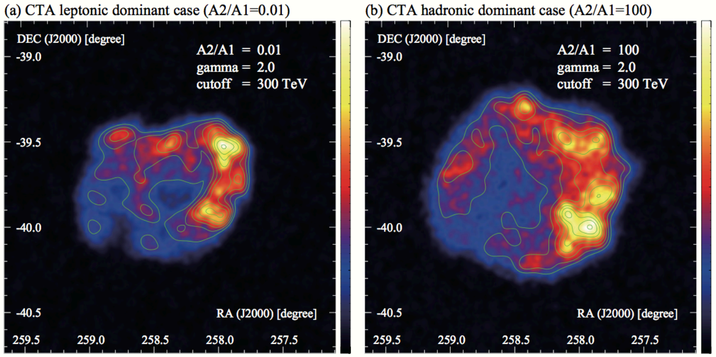
- There is a PeVatron in the Galactic Centre complex
- SNRs at early stages are prime PeVatron candidates
- Current generation instruments are rather limited in detection area
- CTA strategy
  - deep observations of known sources with very hard spectra
  - search for diffuse gamma-ray emission from the vicinity of prominent gamma-ray bright SNRs
- Candidates
  - RX J1713-3946 + surroundings
  - vicinity of historical SNe
  - possibly other objects (stellar clusters?!)





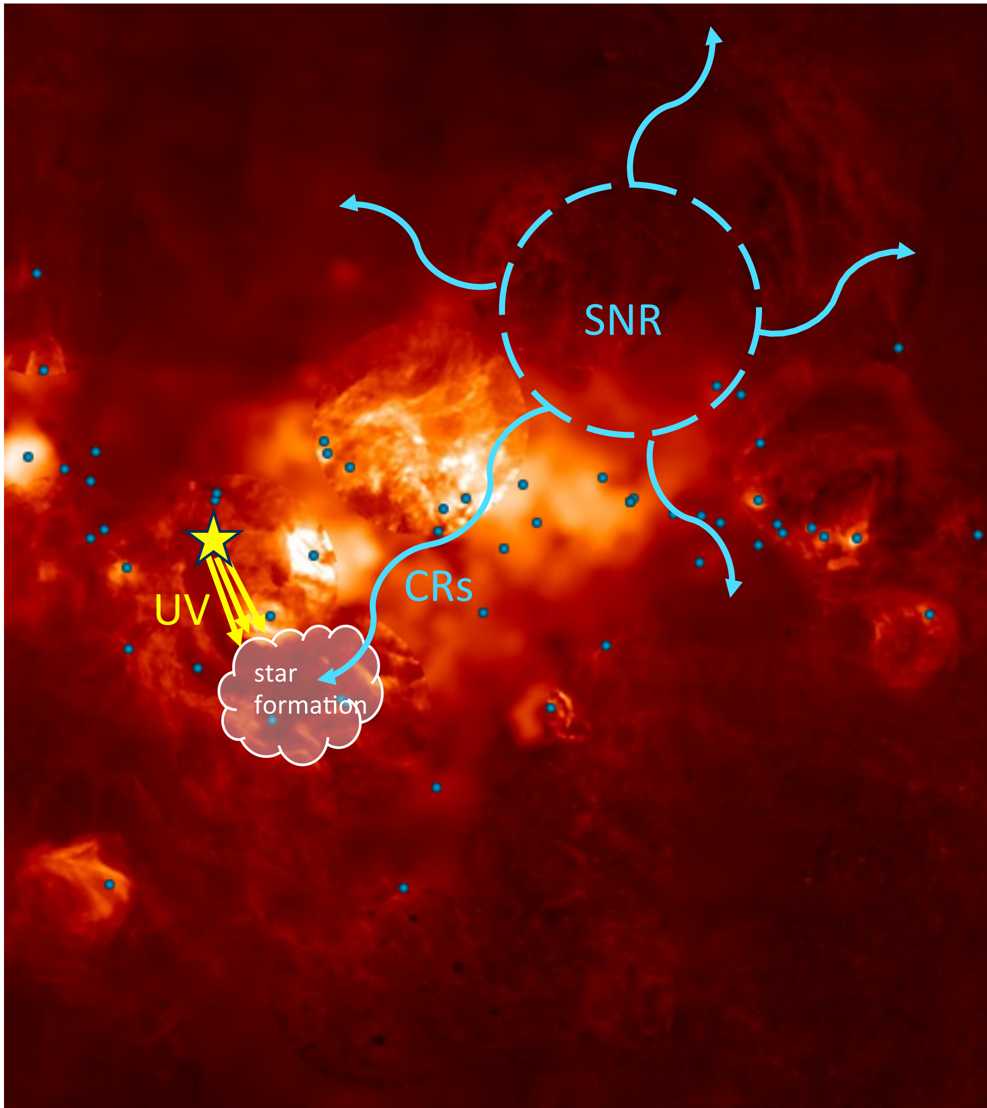






The CTA Consortium

Star-formation and cosmic rays



- Most massive stars are born, live and die in star-forming regions
- SNRs as main CR sources
- CRs penetrate deep into molecular clouds (unlike UV radiation)
  - CR ionisation
  - B-field amplification
- CRs ionisation regulates astrochemistry
- CRs can impact star-formation process
- Increasing evidence that CRs may play a major role in galaxy formation and evolution
- Link between CRs and star-formation process not well understood

Star-forming systems

- Star-formation was and still is a hot topic in astrophysics
- Particle acceleration and star formation happen on many spatial scales
  - FIR – radio correlation holds over six orders of magnitude in SFR
  - similar relation holds at GeV energies (Ackermann++, 2012)
    - calorimetric fraction changes as a function of SFR
- <u>Main questions to answer</u>

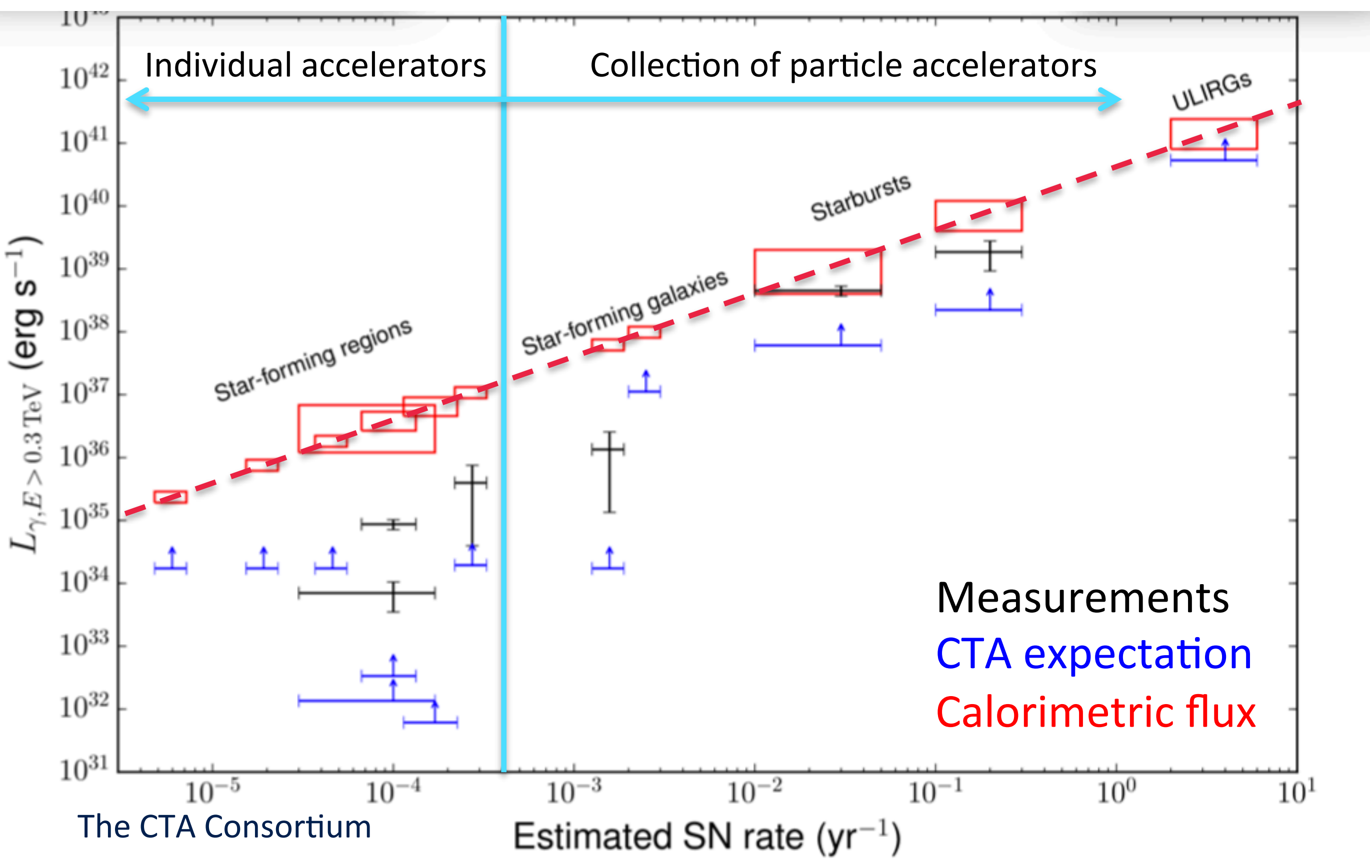
1. What is the relationship between star-formation and particle acceleration in systems on all scales? Does a universal far-infrared/TeV luminosity relationship exist?
2. How does the calorimetric fraction change as a function of SFR and does equipartition hold in star-forming systems?
3. What is the contribution of different source classes to the CR population in star-forming systems? Where and when are particles accelerated, how do they leave and what is their impact on the surrounding ISM?

CTA Science: Star-forming systems

- CTA strategy
  - study nearby galaxies with varying SFRs for global properties
  - study Galactic star-forming regions to investigate
    - different source classes
    - particle transport via energy-dependent morphologies
    - HII regions and stellar clusters at different evolutionary stages to disentangle stellar winds from winds + SNRs
- Targets
  - Galactic stellar clusters and HII regions
    - Carina, Cygnus, Westerlund 1
  - Nearby star-forming and starburst galaxies
    - LMC, M31
    - NGC 253, M82, Arp 220

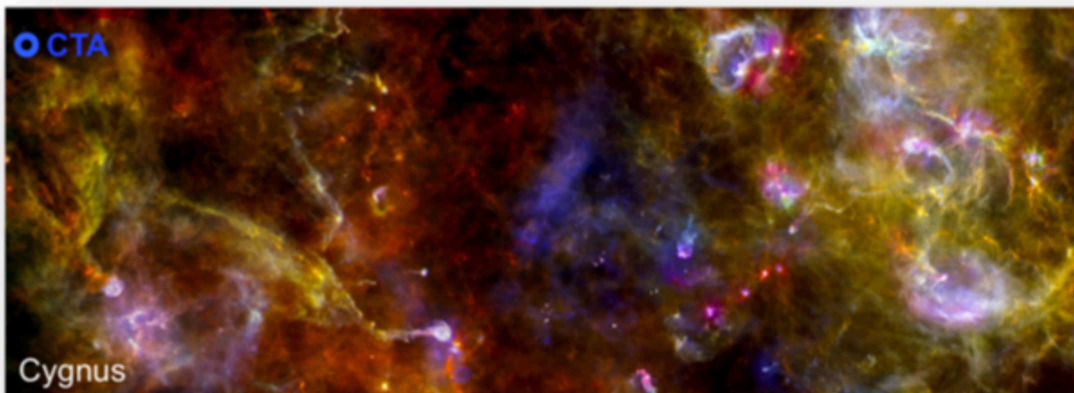
CTA Science: Star-forming systems

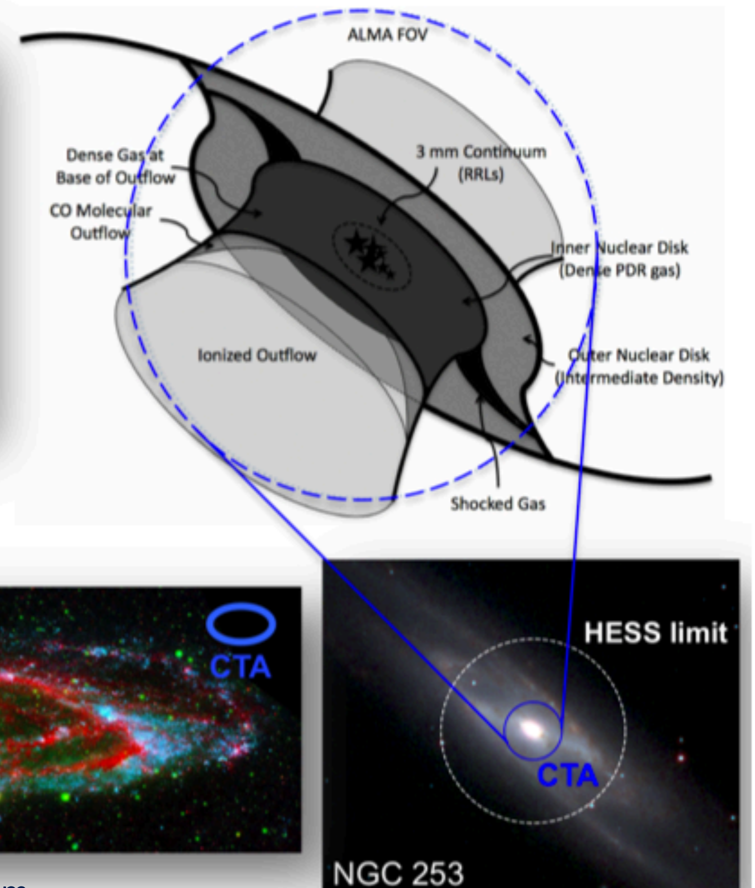
- Calculate maximum γ-ray flux to be expected for given object
- Compare with existing measurements
- Compare to CTA sensitivity



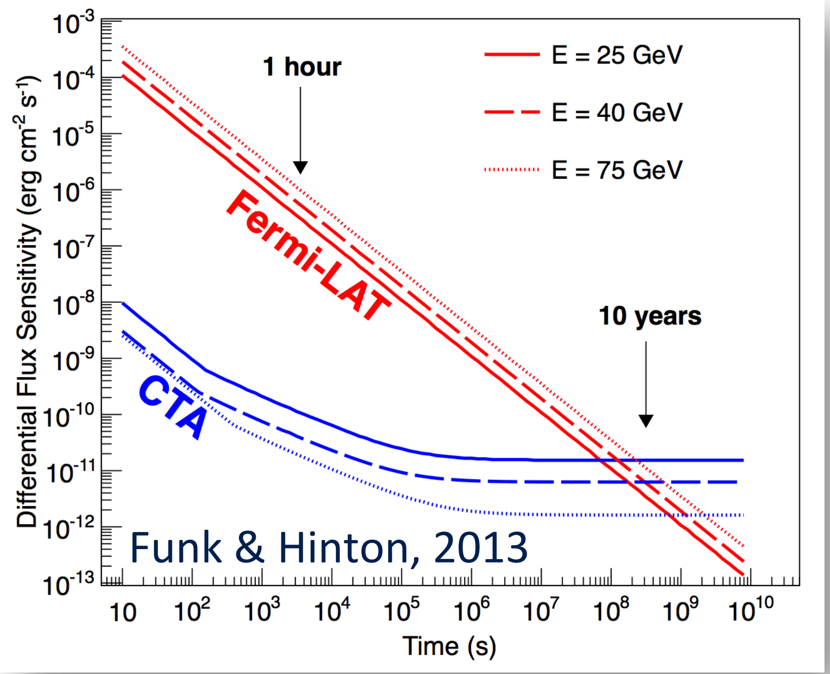
CTA Science: Star-forming systems

- Measuring the fraction of CR energy going into γ-rays for an entire galaxy isn't enough
- Will need to look at individual objects in detail





CTA Science: Transients

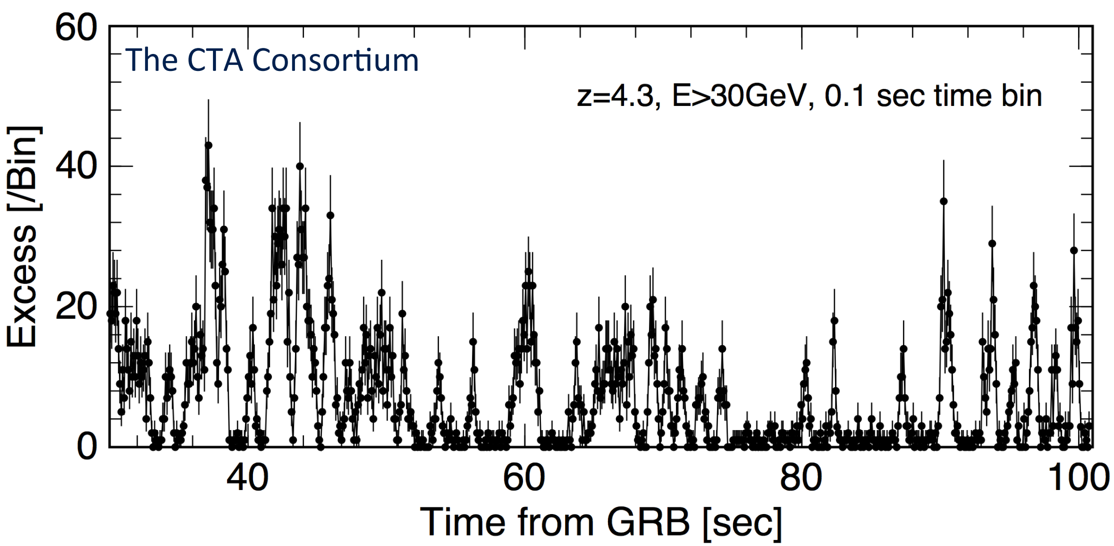


CTA is a transient machine!

- Transients
  - flaring or explosive astrophysical events, often associated with non-thermal emission, and HE γ-rays
  - potentially sources of non-photonic signals (UHE CRs, ν's, GWs)
  - often associated with catastrophic events involving NSs & BHs
  - probe most extreme physical conditions in the universe
- Potential targets
  - Gamma-ray bursts
  - Galactic transients (e.g. PWN flares, μQSO's, accreting compact objects)
  - High-energy neutrino and GW transients
  - X-ray, optical and radio transients
  - Serendipitous VHE transients

CTA Transient science: GRBs

- GRBs
  - the most luminous cosmic explosions (after the big bang)
  - two types: long (> 2 sec) and short (0.01 – 2 sec), believed to be caused by core-collapse SNe, and NS-NS or NS-BH merger)
  - take Fermi-LAT GRB 080916C as template and extrapolate to CTA
  - expected rate is ~1 GRB / yr / site



Summary

- CTA will be operated as an observatory, open to the scientific community
- CTA is well on track, with major milestones being achieved in the past two years (e.g. site, headquarter and science data management center selection)
- Science with CTA being developed to prepare for early and key science observations
- Strong synergies with current and upcoming multi-wavelength and multi-messenger facilities
- We’ve come a long way, but there is light at the end of the tunnel…