Introduction to the Cherenkov Telescope Array

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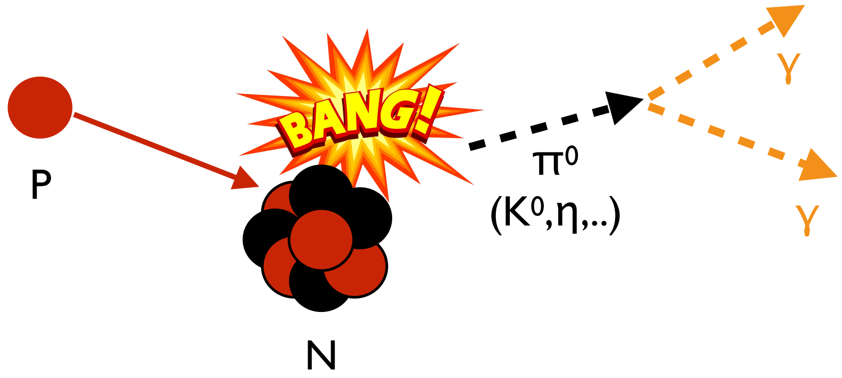
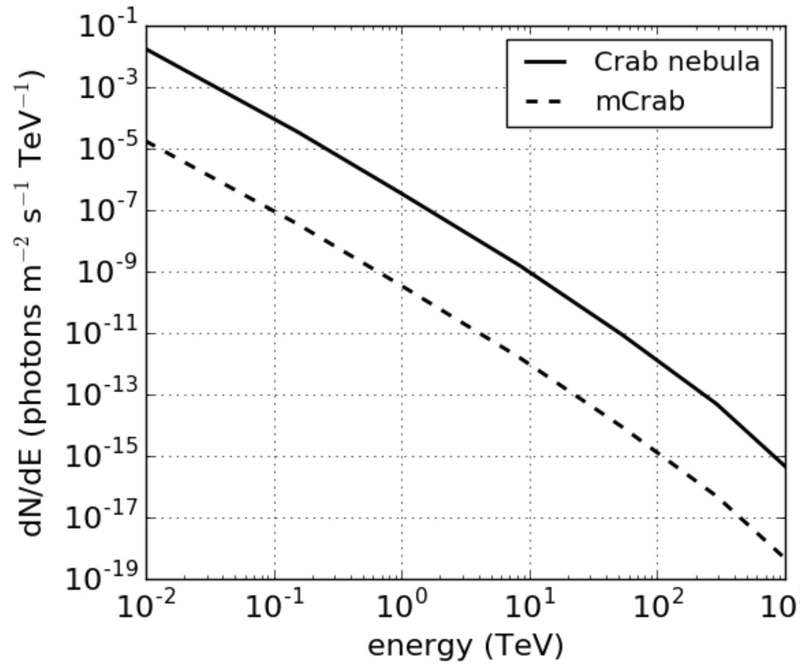
Inception: the quest for the sources of cosmic rays

- cosmic rays (CR)
  - relativistic particles up to 10^{20} eV
  - mostly nuclei (H, He, …)
  - sources still poorly known
  - deflected by magnetic fields → do not point to sources
- gamma rays from CR nuclei interactions with interstellar matter
  - through production of unstable particles that decay in gamma rays (lightest π^0)
  - **only observational tracer of highly relativistic nuclei**



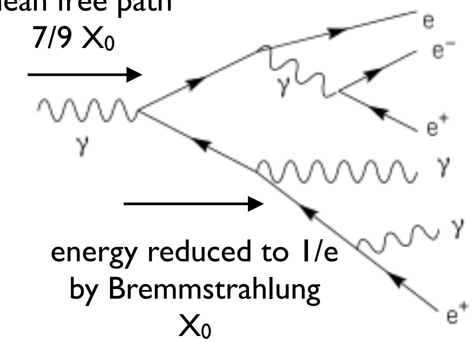
Why satellites don't make it to VHE

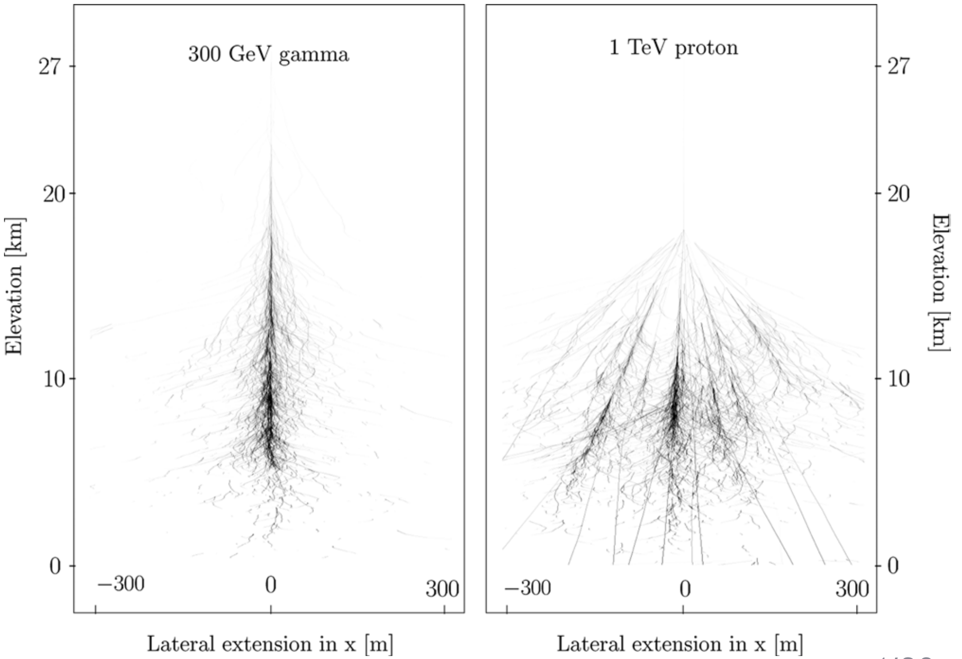
- size limitations due to space operations
  - calorimeter < 10 r.l., energy leakage → no good energy measurement
  - collection area < 1 m^2 → low count statistics
- need to reach PeV to prove CR acceleration in the Galaxy up to the knee (10^{15} eV)
- ground instruments more effective at very high energies (VHE) ≳ 100 GeV



Atmospheric showers

- gamma rays produce electromagnetic showers
  - 1 e/gamma generates 2 with 1/2 energy over scale of radiation length
  - shower growth: 2^N e/gamma with $1/2^N$ energy after N r.l.
  - process stops when approaching electron critical energy O(100 MeV), ionisation prevails over Bremmstrahlung
- cosmic-ray nuclei also produce showers
  - hadronic interactions can transfer higher transversal momentum → wider/patchier profile

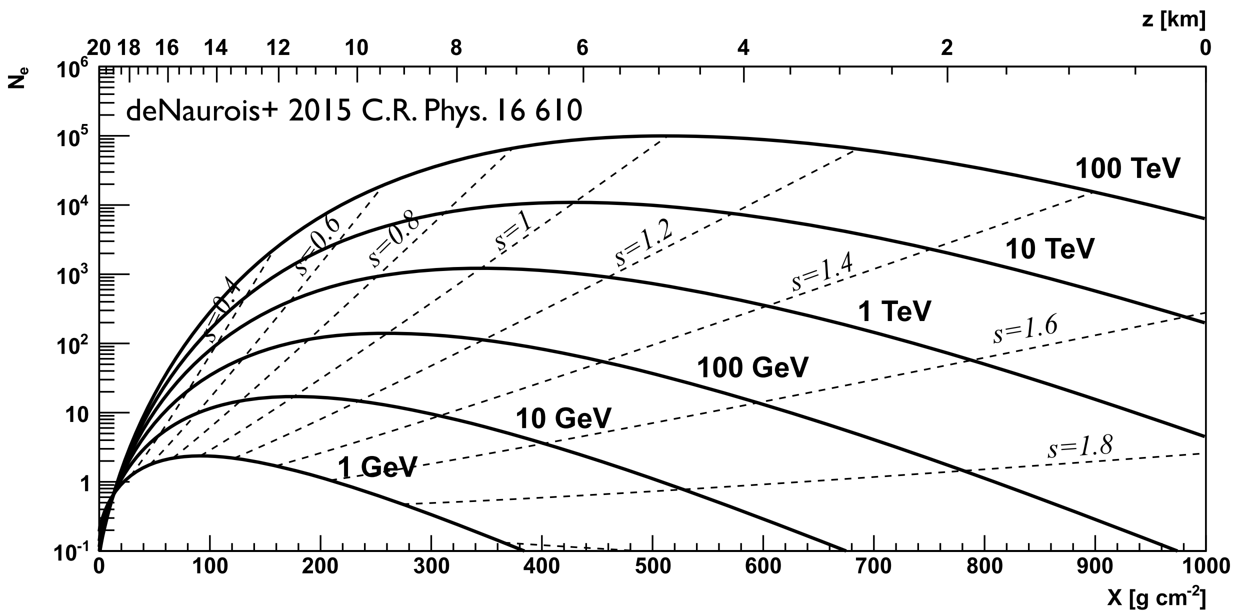




Aharonian+ 2008 R.P.Phys 71 096901

Atmospheric showers development

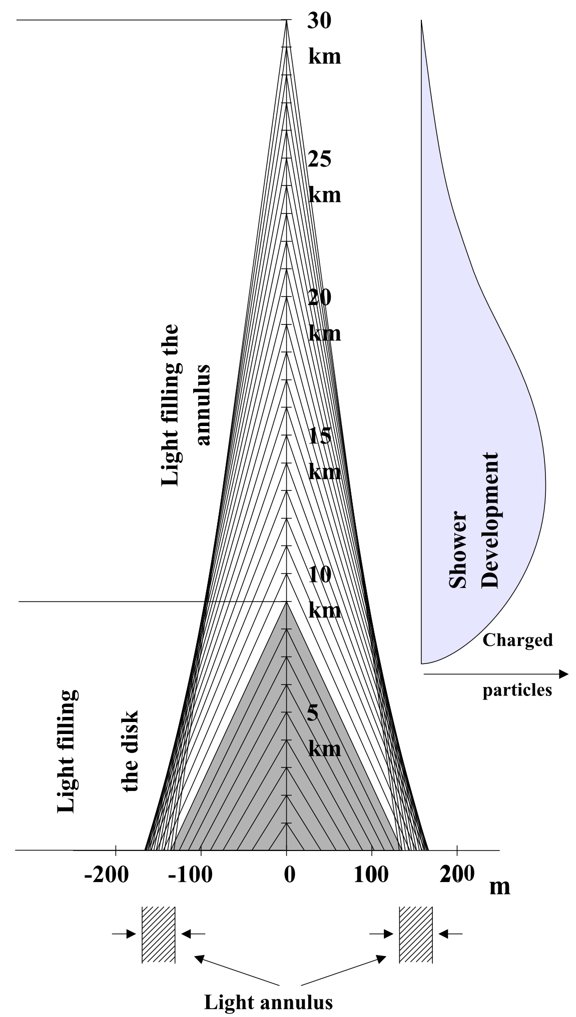
- the atmosphere has approximately an exponential density profile $\exp(-z/z_0)$ with $z_0 \sim 8$ km
- the radiation length in air is ~ 37 g cm^{-2} , the total depth at sea level is ~ 30 r.l.
- the shower maximum occurs at heights of 5 to 15 km (depending on energy)
- fluctuations in the em shower development are mainly due to fluctuations of first interaction depth
- shower opening
    - multiple Coulomb scattering causes a lateral opening of ~5°
    - Earth's magnetic field broadens the shower in the East-West direction



Cherenkov radiation

- ultrarelativistic electrons emit Cherenkov light at characteristic angle
- the Cherenkov light yield is approximately proportional to primary energy
- refraction index depends on density, exponential variation with altitude → angle varies from 0.2° at 30 km to 1.5° at sea level
  - rough focussing on 120-150 m ring
  - multiple Coulomb scattering creates exponential distribution of angles within O(5°)
- since electrons are superluminal photons duration of Cherenkov flash is short O(5 ns) on axis
- Cherenkov light is absorbed in the atmosphere
  - Rayleigh scattering (small particles), absorption length → λ^4
  - Mie scattering (large particles = aerosols), absorption length → λ
  - Ozone photodissociation, absorbs UV
  - scattering by water vapour

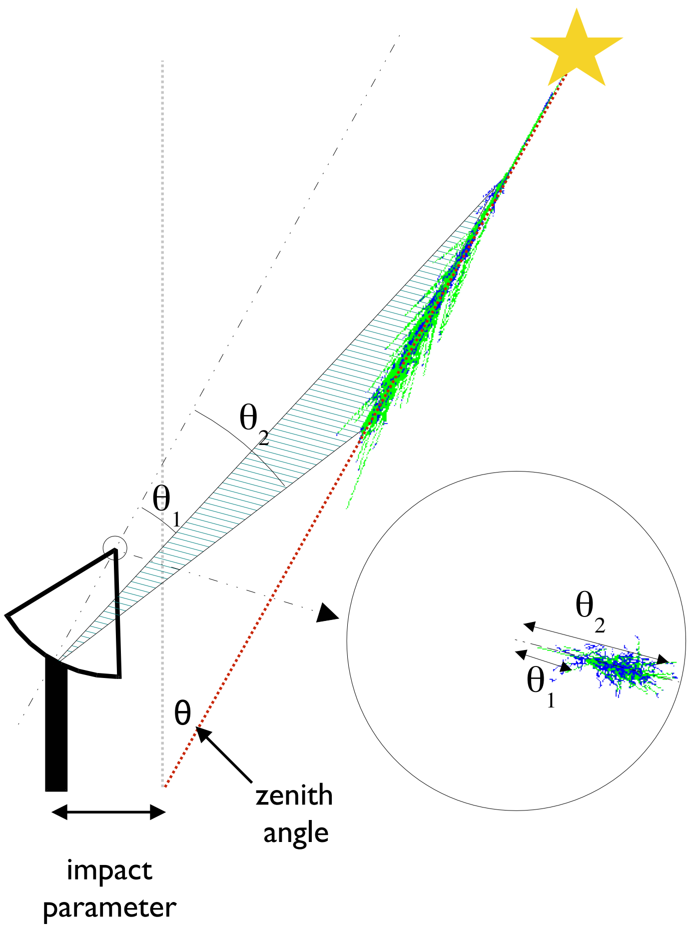
deNaurois+ 2015 C.R. Phys. 16 610



The imaging Cherenkov technique

deNaurois+ 2015 C.R. Phys. 16 610

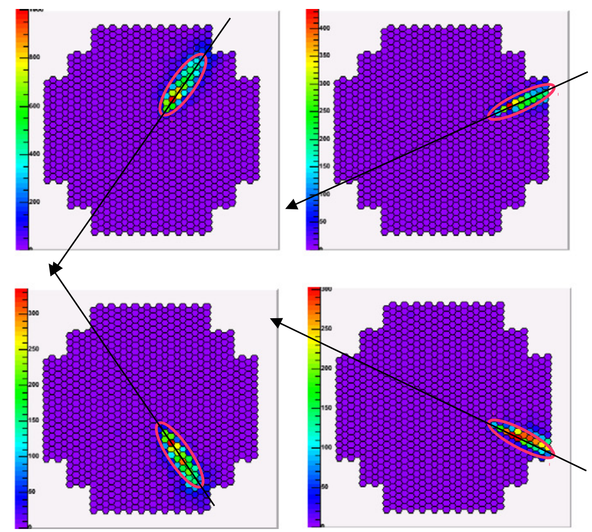
- elongated image pointing to source
- with increasing impact parameter
  - image more elongated
  - centroid farther from parallax
- with increasing energy
  - light amount increases
  - image length increases
- with increasing zenith angle
  - shower max distance increases as $l_{max} = z_{max}/\cos\theta$
  - image width/length smaller by a factor $\cos\theta$
  - radius of light pool larger by $1/\cos\theta$, thus light intensity smaller by $\cos^2\theta$
  - consequences: effective area and energy threshold increase as $1/\cos^2\theta$
- increasing altitude reduces the distance to the shower max, so opposite effects

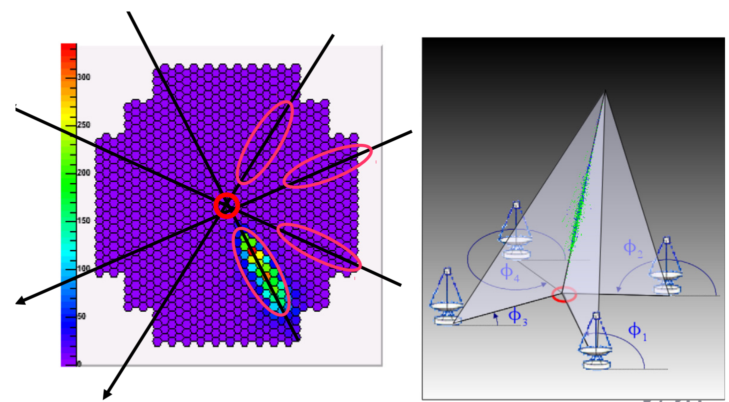


Imaging Cherenkov telescopes

- basic constituents
  - wide-field optical telescope (shower width 5°) with resolution O(0.1°) (internal structure of shower)
  - fast camera with 100 to > 1000 pixels that records images on timescales O(5 ns) to discriminate showers from fluctuations of night-sky background
  - altitude-azimuth mount to track sources during long exposures
- arrays of imaging Cherenkov telescopes
  - multiple telescopes spaced by 50-100 m (at least 2 to 4 see same shower light pool)
  - stereoscopic reconstruction of shower arrival direction and impact position
  - better gamma/hadron separation
- working principle
  - trigger when multiple pixels (or sum of multiple pixels) exceed some threshold within time coincidence window
  - array coincidence trigger helps with background rejection
- observing modes:
  - pointing known/putative sources
  - surveys (still limited because small field of view)
- require dark and clear-sky conditions

deNaurois+ 2015 C.R. Phys. 16 610





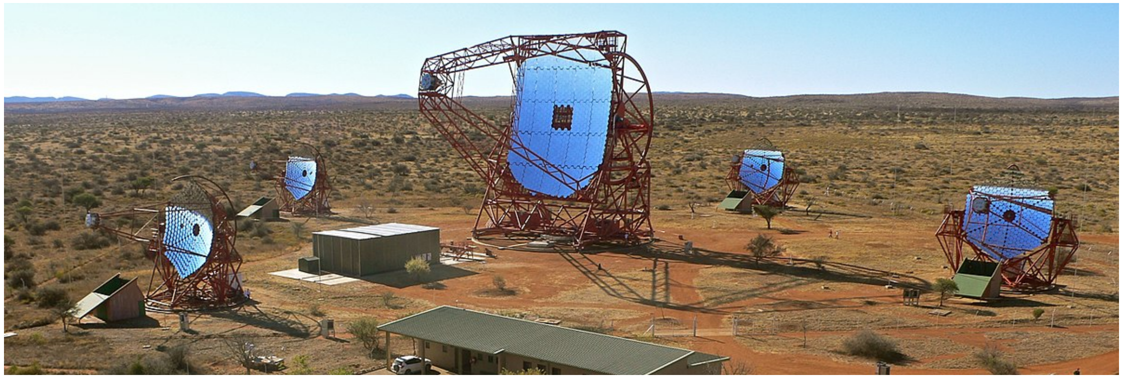
IACT history in a nutshell

- 1953: Galbraith measures Cherenkov light from atmospheric showers
- 1960s-1980s: several experiments try to measure gamma rays using shower Cherenkov light, no solid detection of gamma-ray sources
- 1990s: IACT astronomy begins
  - 1989: the Whipple collaboration detects gamma rays from the Crab Nebula with single IACT, few more sources follow
  - from 1993: the HEGRA collaboration performs the first stereoscopic observations with an array of 5 IACTs
  - from 1997: the CAT collaboration demonstrates the advantage of finely pixelated cameras
- 2000s-2010s: current generation IACTs, the coming of age of VHE astronomy

Whipple Telescope 1968

Current generation IACTs

H.E.S.S.
Namibia
4 + 1 telescopes
12 m + 28 m



VERITAS
Arizona
4 telescopes
10 m

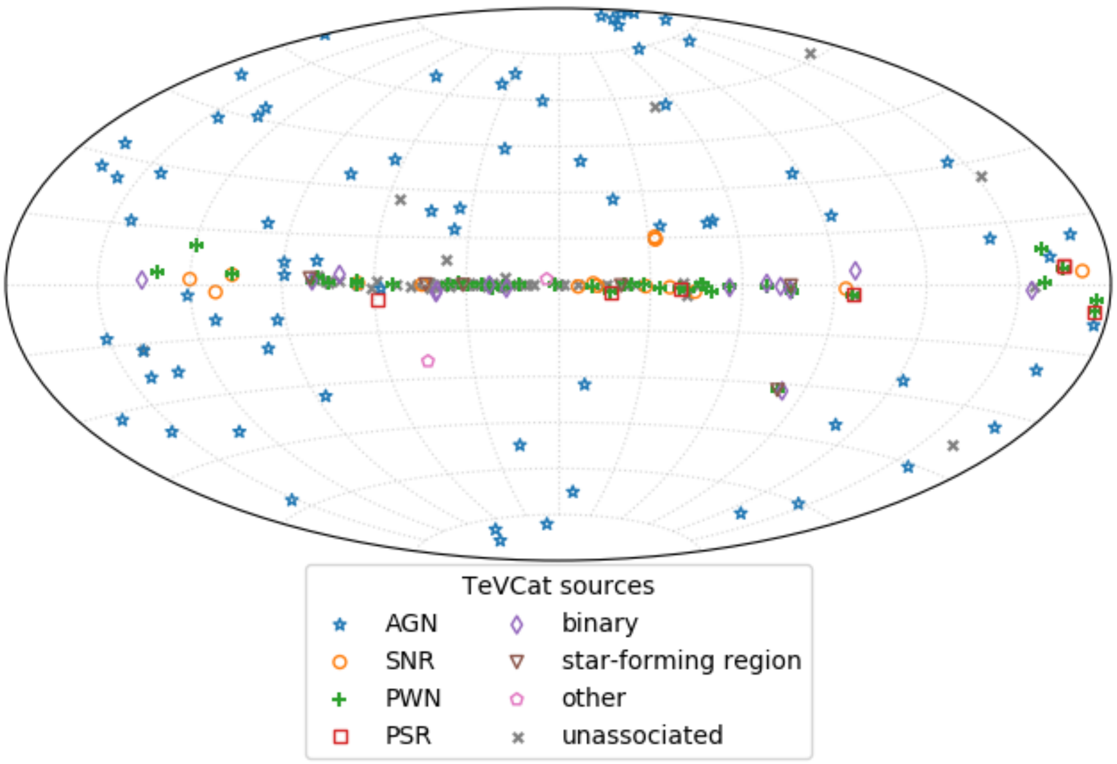
MAGIC
Canary Islands
2 telescopes
17 m

Astronomy with IACTs

- shows a different facet of the Universe
- images and maps with resolution close to human eye
- dynamic range of 3 orders of magnitude in energy
- time-domain astronomy on scales from minutes to years

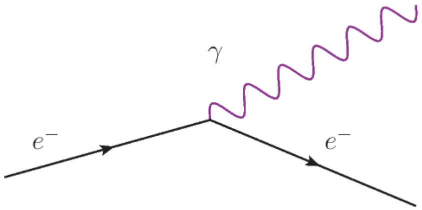
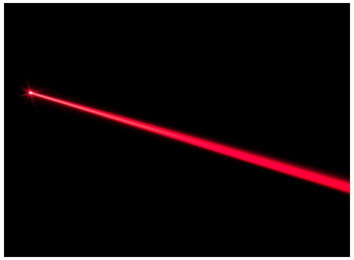
The coming of age of VHE astronomy

Sources detected by ground-based gamma-ray telescopes (TeVCat)



astounding variety of VHE emitters, attests to ubiquitous phenomena of extreme objects accelerating particles in the Universe

How a VHE gamma-ray is made

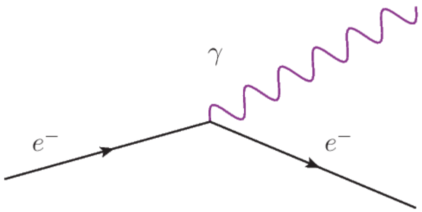
energy source	particle acceleration	particle interaction/ gamma-ray production	gamma-ray propagation
			

A probe of nonthermal phenomena

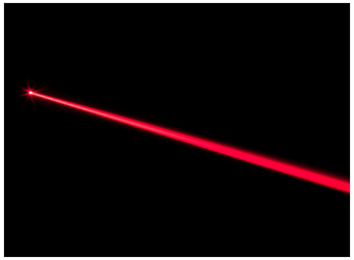
energy source

particle acceleration

particle interaction/
gamma-ray production



gamma-ray
propagation



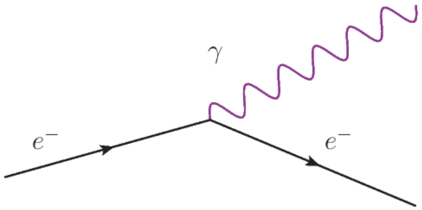
- cannot be produced by thermal processes:
  100 MeV → 2 x 10^{11} K (Wien's law)
- no nuclear gamma-ray lines beyond 10 MeV
- only production mechanism: **particle acceleration + radiative process**

1 - Origin and role of relativistic cosmic particles

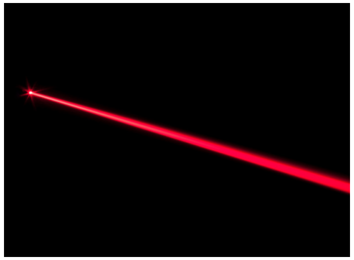
energy source

particle acceleration

particle interaction/ gamma-ray production

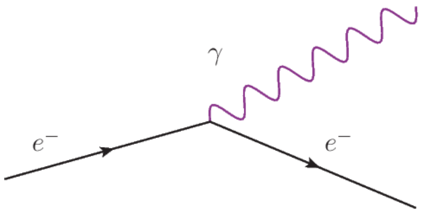
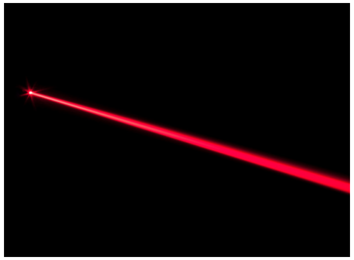


gamma-ray propagation



- **the original one**: what are the sites and mechanisms of cosmic-ray acceleration?
- what is the feedback of cosmic rays on star-formation and galaxy evolution?

2 - Probing extreme environments

energy source	particle acceleration	particle interaction/ gamma-ray production	gamma-ray propagation
			

- what physical processes are at work close to neutron stars and black holes?
- what are the characteristics of relativistic jets, winds and explosions?
- what is the nature of gamma-ray bursts, the Fermi bubbles … ?
- what are the electromagnetic counterparts to gravitational wave and neutrino sources?

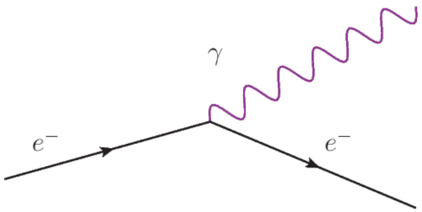
- how intense are radiation/ magnetic fields in extragalactic space and how do they evolve over cosmic time?

3- Exploring frontiers in Physics

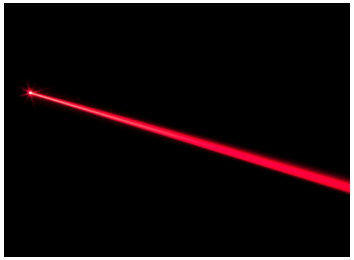
energy source

particle acceleration

particle interaction/
gamma-ray production



gamma-ray
propagation

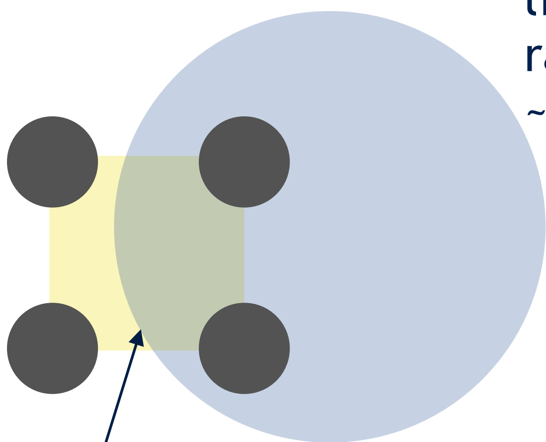


- what is the nature of dark matter and how is it distributed?

- are there quantum gravitational affects on photon propagation?
- do axion-like particles exist?

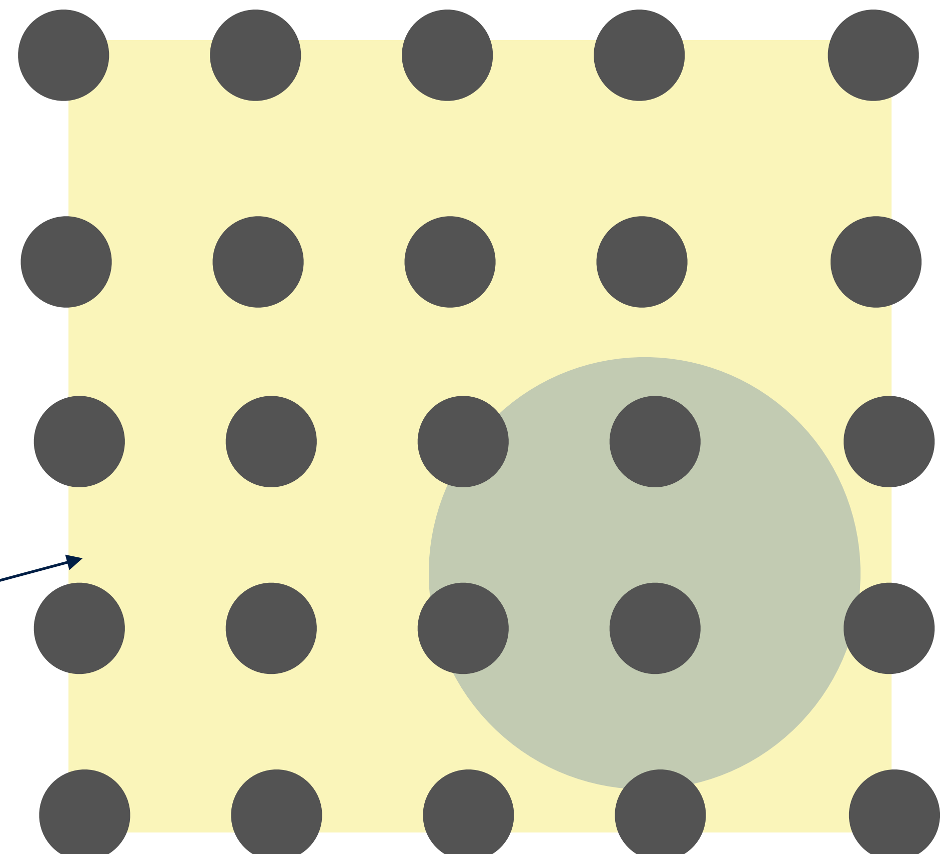
CTA: the concept

Credit: Werner Hofmann



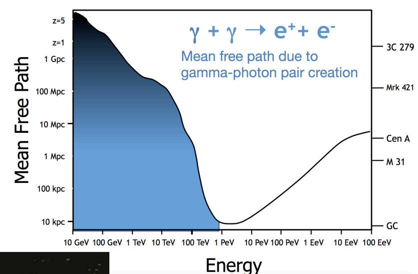
light-pool
radius 100-150 m
~ telescope spacing

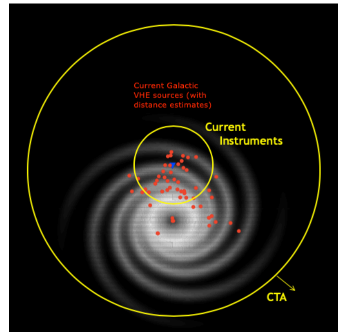
sweet spot for trigger
and reconstruction:
most showers miss it

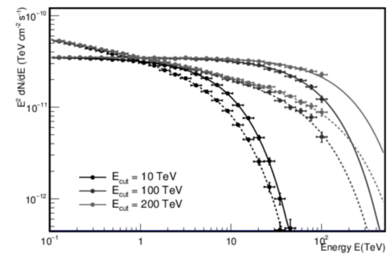


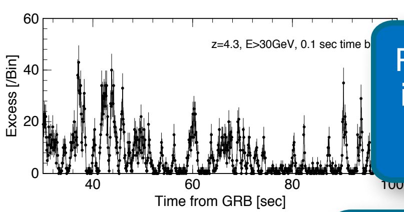
large detection area
more images per shower
lower trigger threshold

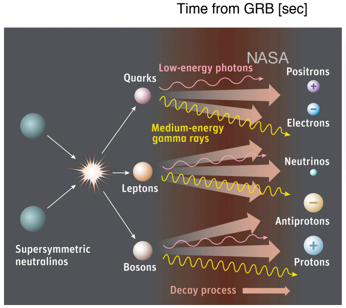
Design drivers

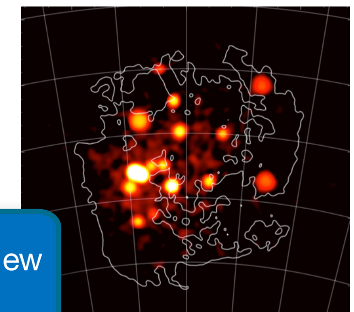


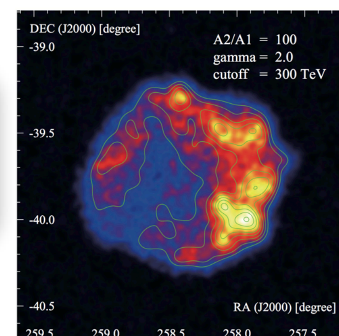












Energies down to 20 GeV
→ Cosmology++

10 x Sensitivity, Large Collection Area
→ all topics

Energies up to 300 TeV
→ Pevatrons

Rapid Slewing in 20 seconds
→ transients

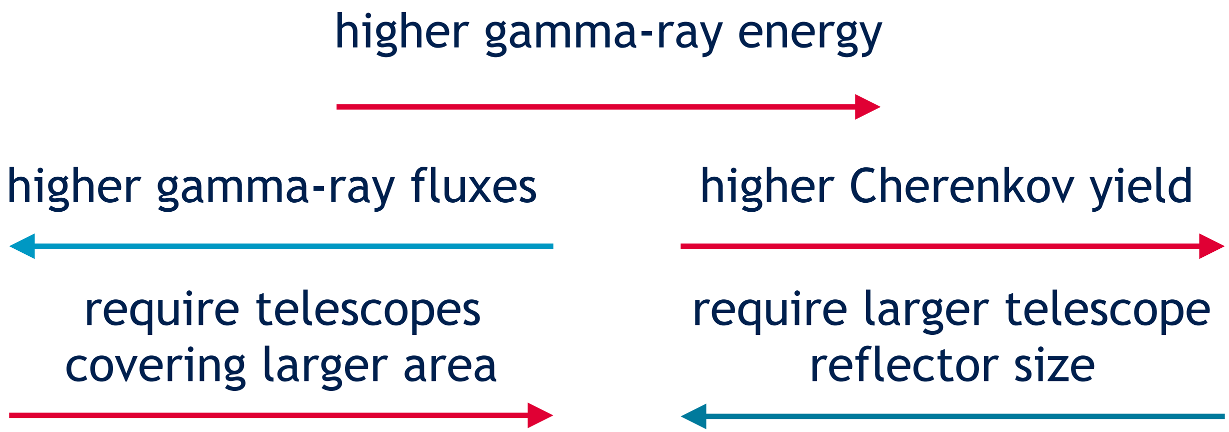
8° Field of View
→ surveys, extended objects

10% Energy Resolution
→ lines, features

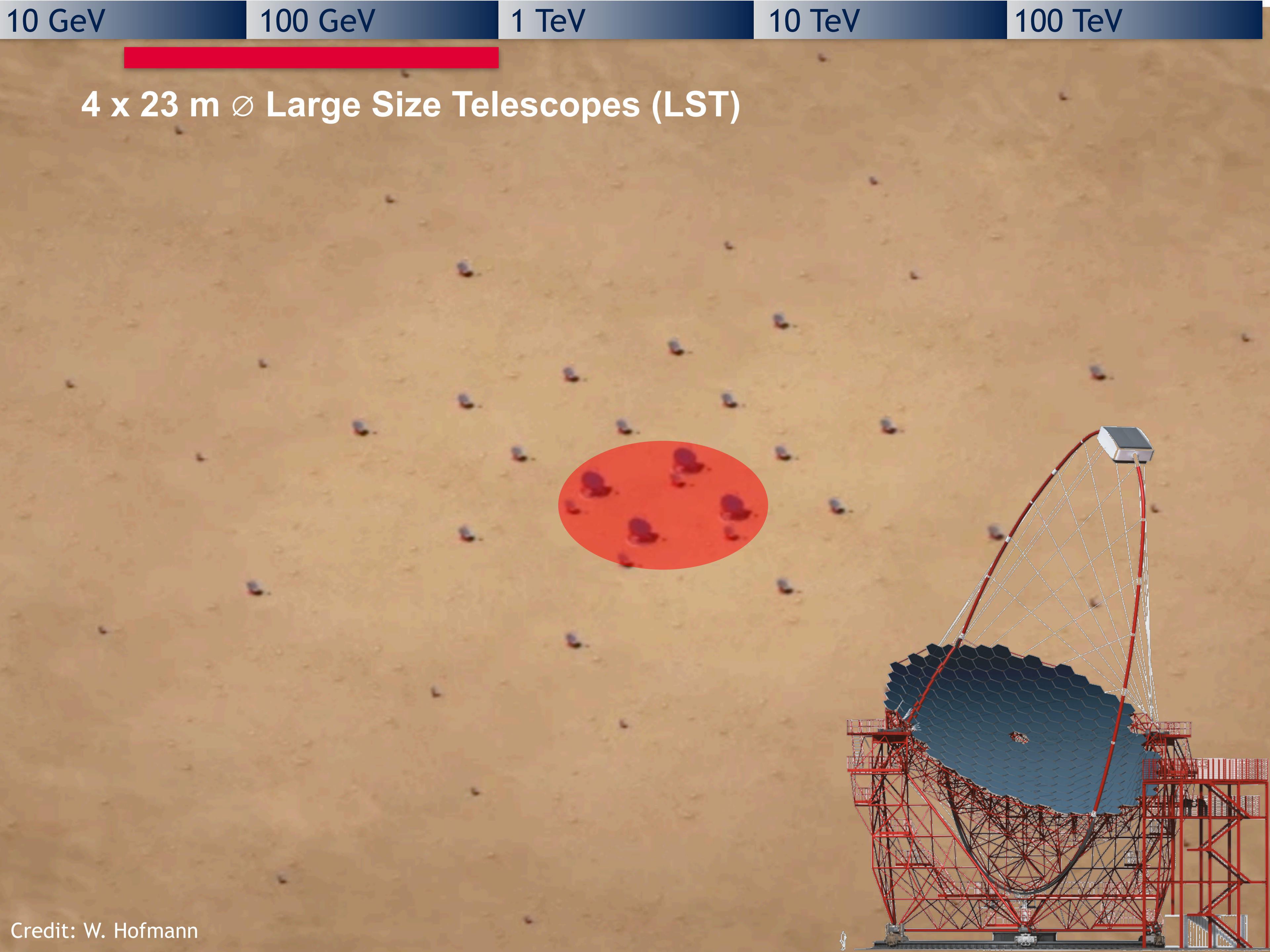
Few ' Angular Resolution
→ morphology

cta

A size for every energy



- at low energies Cherenkov yield is lower → require larger telescope reflector size
- at high energies gamma-ray fluxes are lower → require to cover larger ground area with telescopes
- need to find a cost-effective compromise to cover large energy range!



10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
4 x 23 m ∅ Large Size Telescopes (LST)
Credit: W. Hofmann

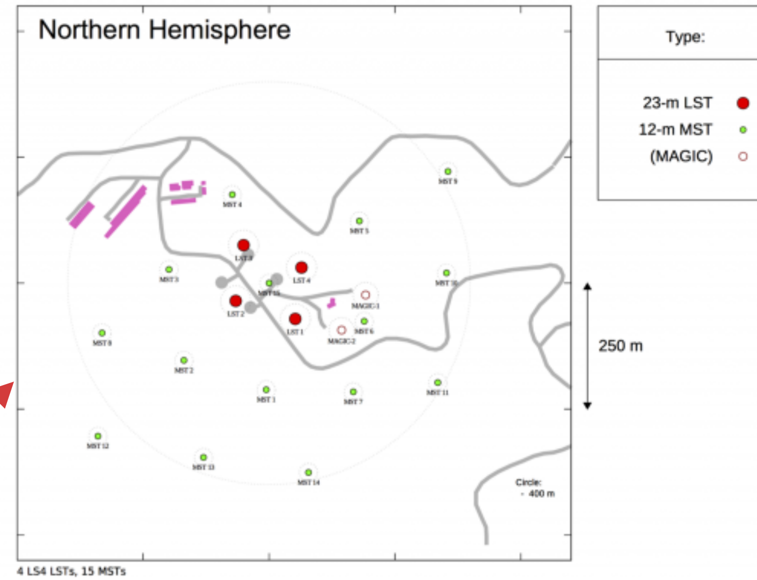

10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
25 x 12 m ∅ Medium Size Telescopes (MST)
(North: 15)
Credit: W. Hofmann


10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
70 x 4 m ∅ Small Size Telescopes (SST)
(South)
Credit: W. Hofmann

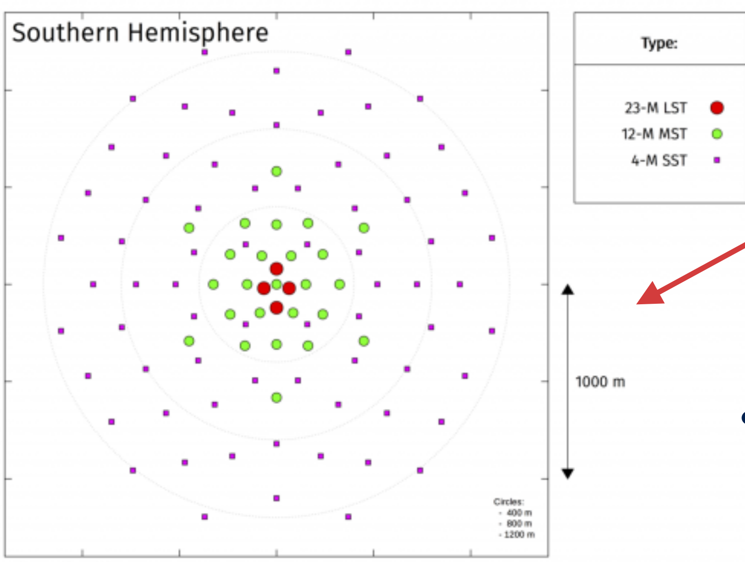
Sites and layout

- two sites for full sky coverage
- SSTs only in Southern hemisphere owing to easier access to Milky Way (extragalactic VHE gamma rays absorbed by EBL)

La Palma, Canary Islands, Spain

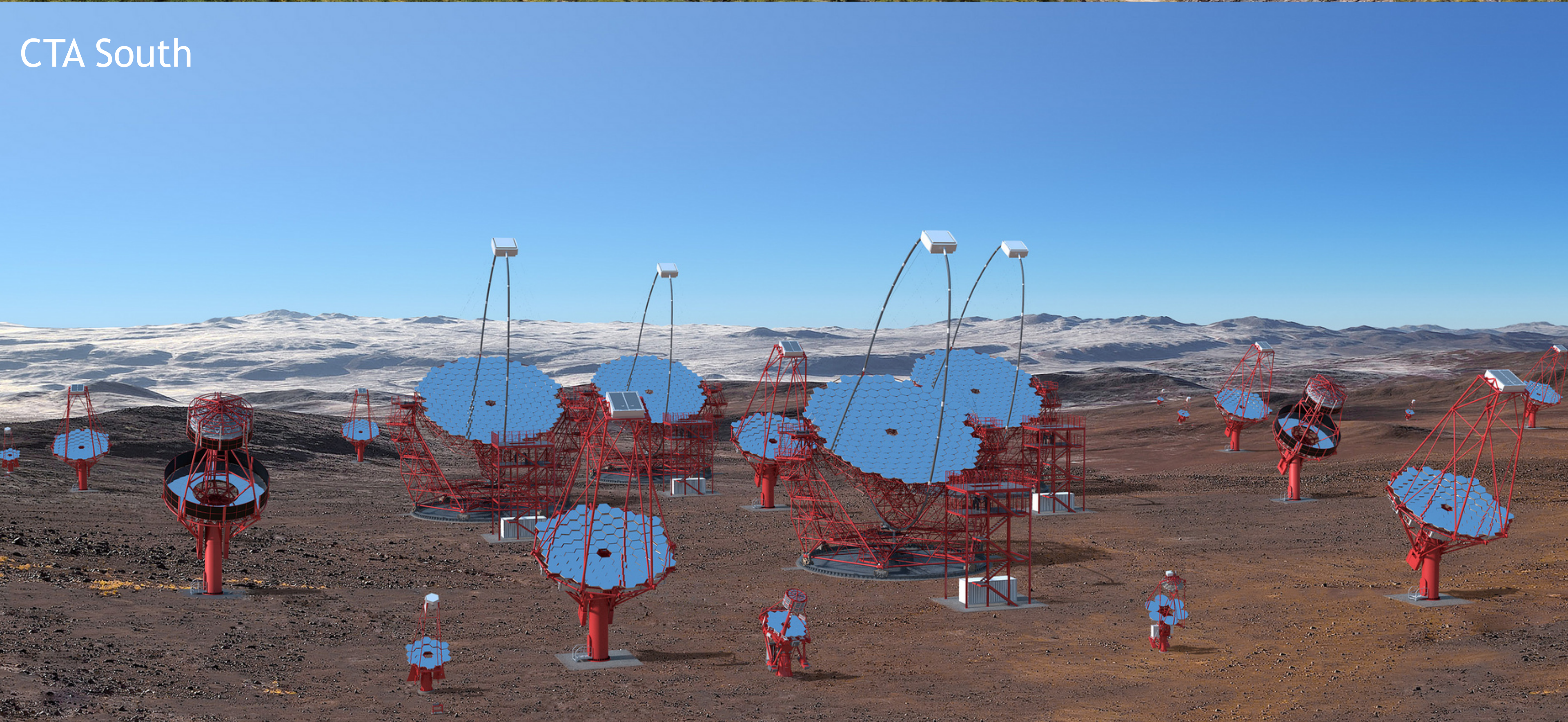


Paranal, Chile

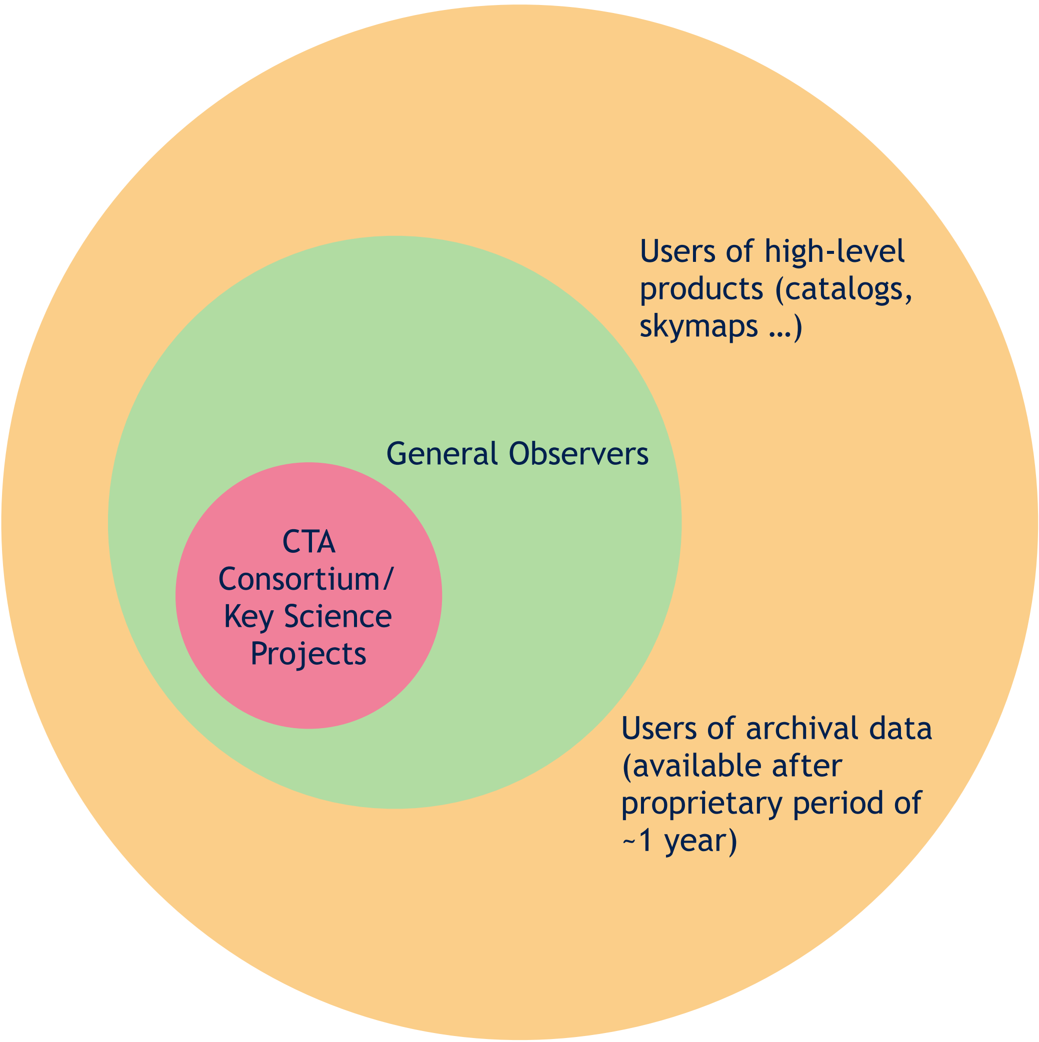


- exact layout chosen to optimise Science performance within environmental contraints (CTAC, 2019 Astropart. Phys 111, p. 35-53)


CTA North


CTA South

CTA: the first VHE observatory



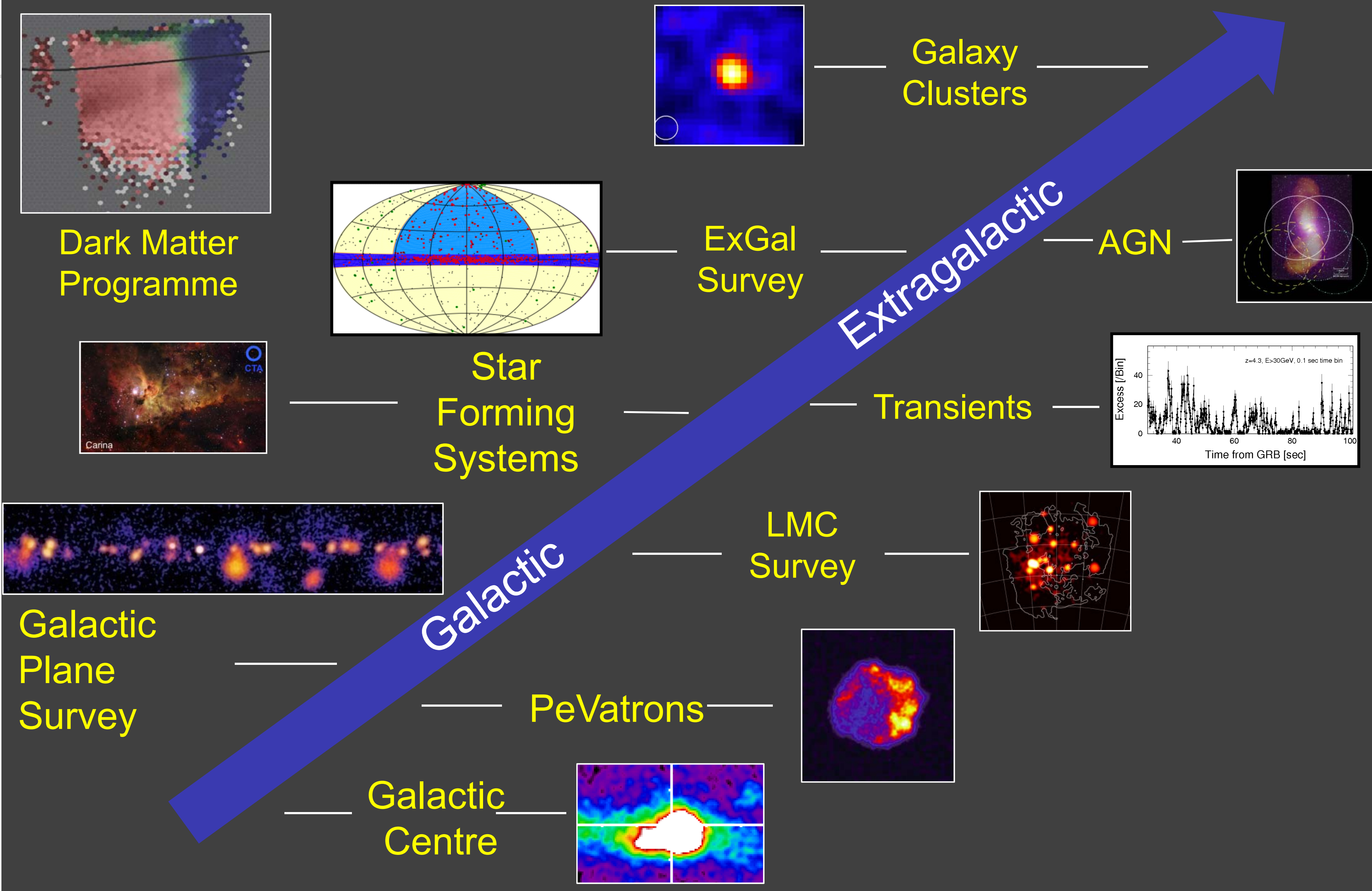
- ~40% of observing time over first 10 years for Consortium Key Science Projects (KSPs)
- rest of the time open to general observers (GO)
- ultimately **all data public** (candidate photon lists with measured properties) + **software tools to perform scientific analysis**

The Key Science Projects

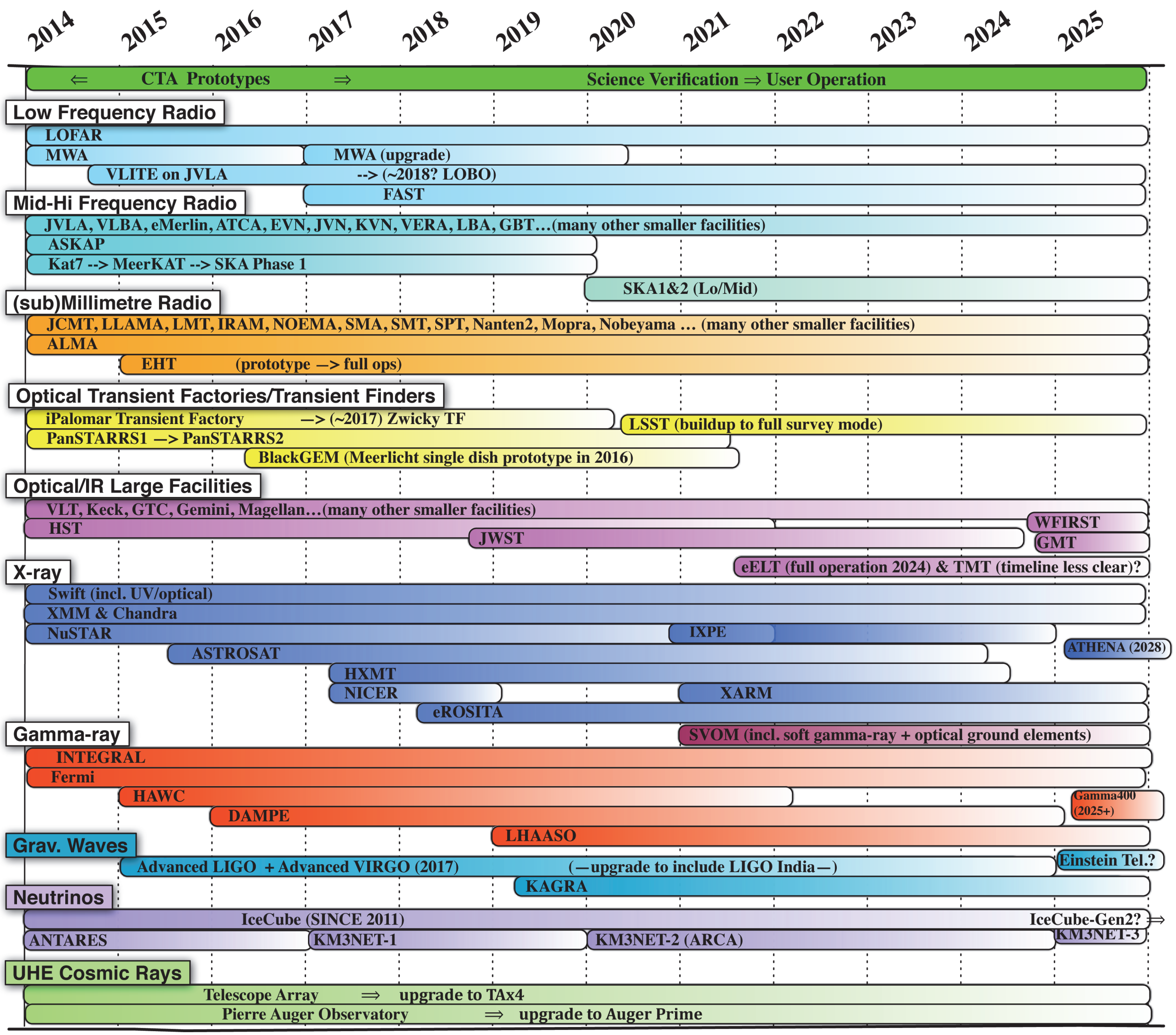
- provide major insight into one or more of the key scientific questions
- large observational programmes difficult to achieve for GO (e.g., surveys)
- require deep expertise with IACT technique/CTA instruments only available in CTAC
- provide early legacy datasets/ products to seed the GO programme

https://arxiv.org/abs/1709.07997
https://www.worldscientific.com/worldscibooks/10.1142/10986

CTA Key Science Projects



Multiwavelength/messenger synergies



Summary

- The imaging atmospheric Cherenkov technique represents a mature way to carry out observations of the VHE sky
- VHE observations give us fundamental insight on the nonthermal phenomena in the Universe
  - origin and role of relativistic cosmic particles
  - extreme environments
  - frontiers of Physics
- CTA is the next-generation VHE observatory
  - designed to explore the entire sky with unprecedented performance over largest ever energy range
  - rich and diverse Key Science Projects & open to the entire astronomy/astroparticle community