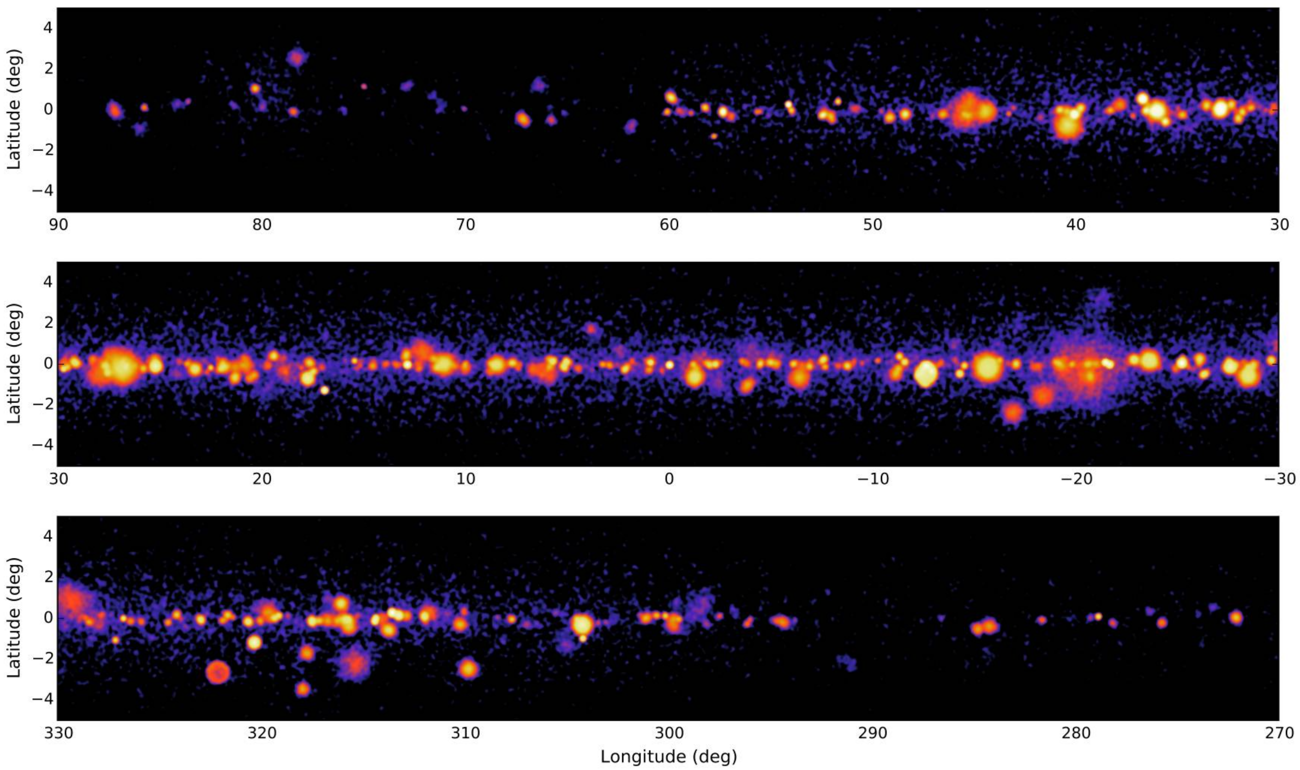
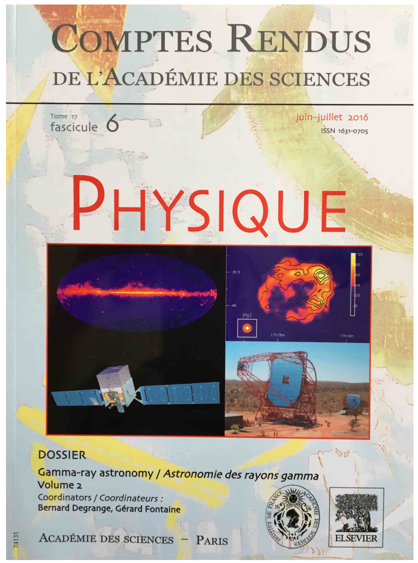


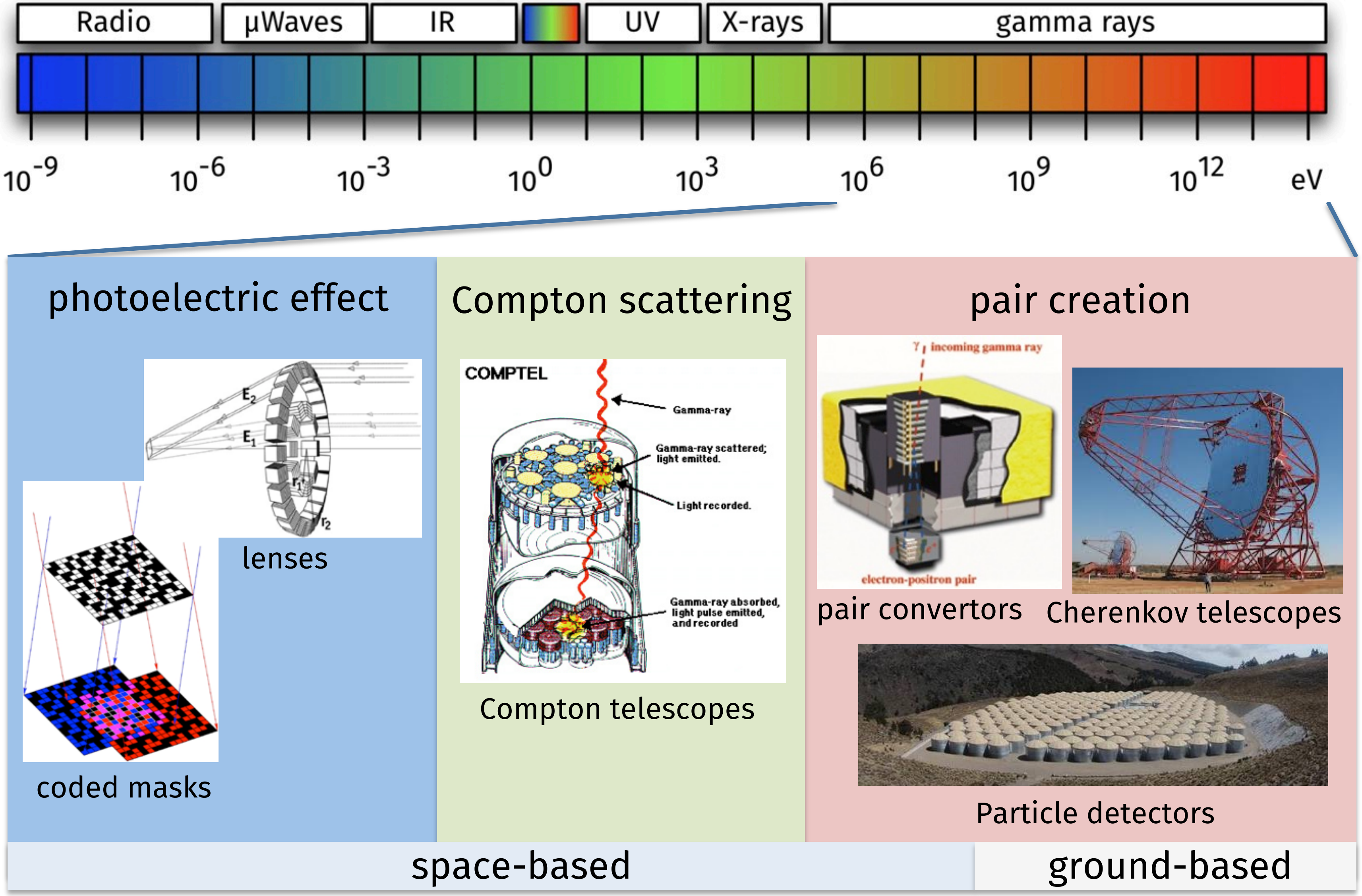
The future of gamma-ray astronomy

Jürgen Knödlseder
IRAP, Toulouse (France)

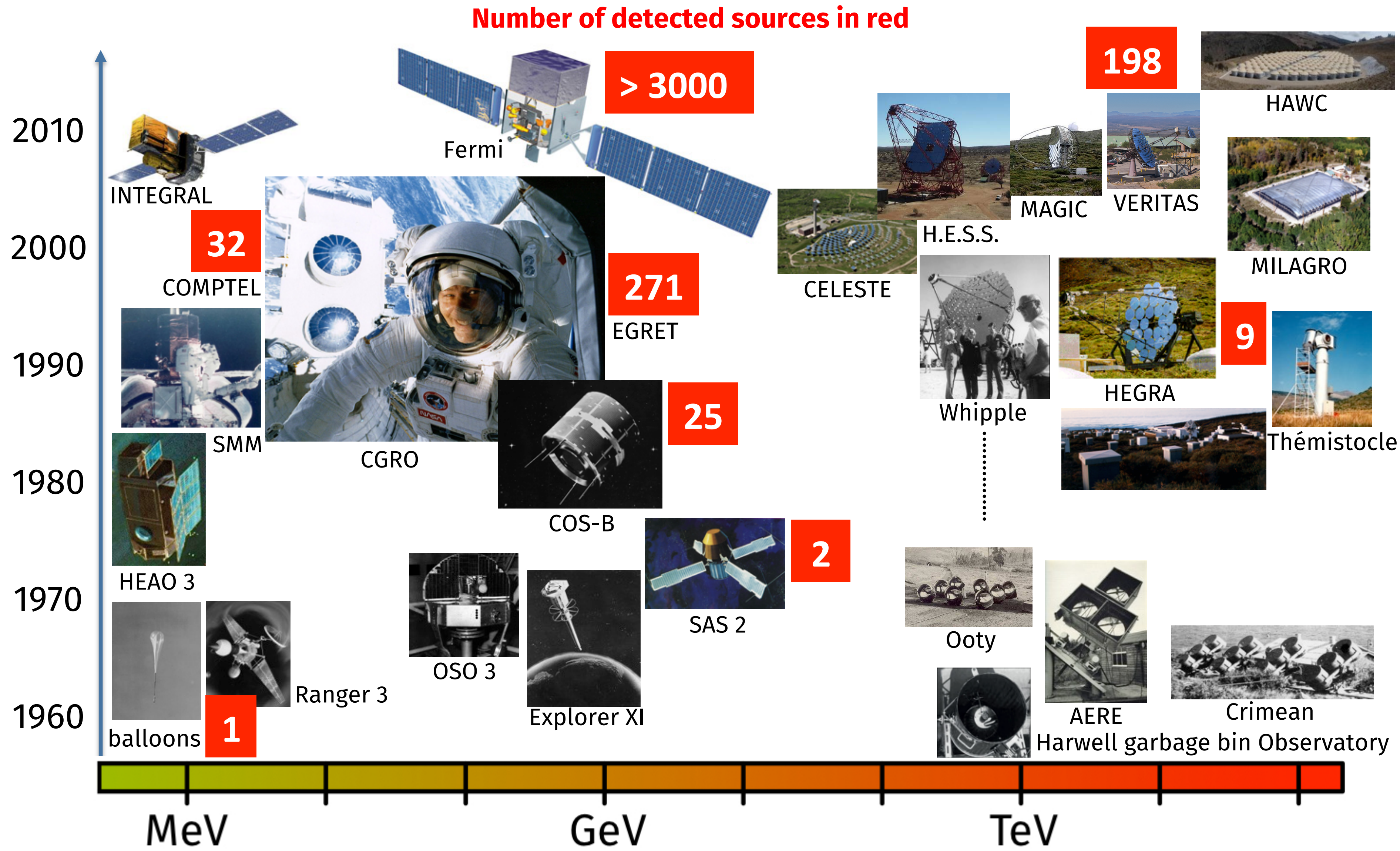


Comptes Rendus Physique, 2016
Vol. 17, Issue 6, pp. 663-678

Observing gamma rays



History of gamma-ray astronomy



Achievements

Nucleosynthesis in the Universe

2014: ^{56}Co lines from SN Ia
2003: ^{60}Fe lines from Galaxy
1994: ^{44}Ti lines from Cas A
1988: ^{56}Co lines from SN II
1984: ^{26}Al line from Galaxy
1973: GRB, solar deexcitation lines
1972: e^+e^- 511 keV line
1969: Crab pulsar
1962: Cosmic background
1958: Solar flare

Cosmic rays in the Galaxy and beyond

2013: Proton acceleration in SNR
2011: Crab nebula flares
2010: Fermi bubbles,
First radio galaxy lobe, First nova
2009: First millisecond pulsars,
First starburst galaxies
1993: Galactic origin of cosmic rays
1992: Diffuse LMC emission
1981: 25 point-like sources
1978: First blazar
1974: Crab pulsar
1972: Diffuse Galactic emission
1961: 22 photons > 50 MeV

Cosmic accelerators

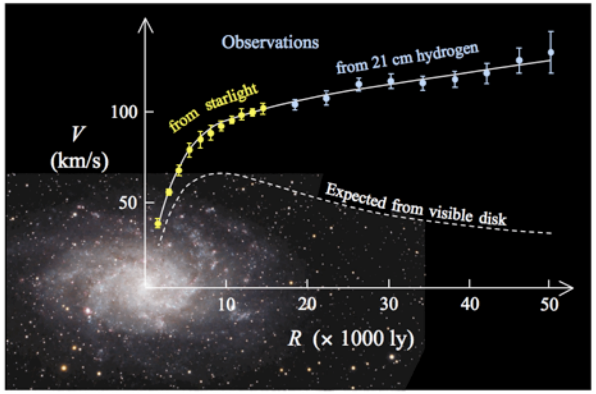
2009: First starburst galaxies
2008: Crab pulsar
2005: First binary
2004: First resolved SNR
2002: First unidentified TeV source
2000: First SNR
1992: Mkn 421
1989: Crab nebula

2010
2000
1990
1980
1970
1960

MeV GeV TeV

Scientific Challenges

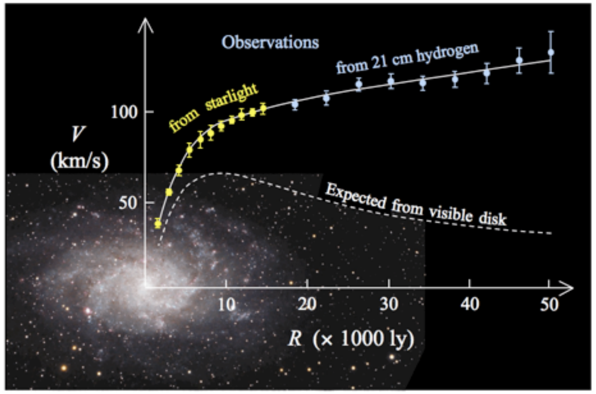
The nature of Dark Matter



- Indicates a major flaw in our understanding of nature
- Proposed solutions include new fundamental particles (WIMPs, axions, etc.)
- Decay products of these particles (or their effects) may be detectable in gamma rays

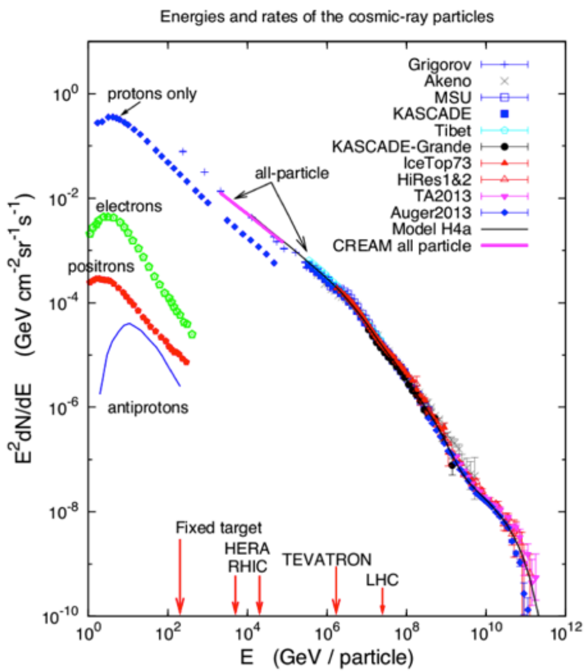
Scientific Challenges

The nature of Dark Matter



- Indicates a major flaw in our understanding of nature
- Proposed solutions include new fundamental particles (WIMPs, axions, etc.)
- Decay products of these particles may be detectable in gamma rays

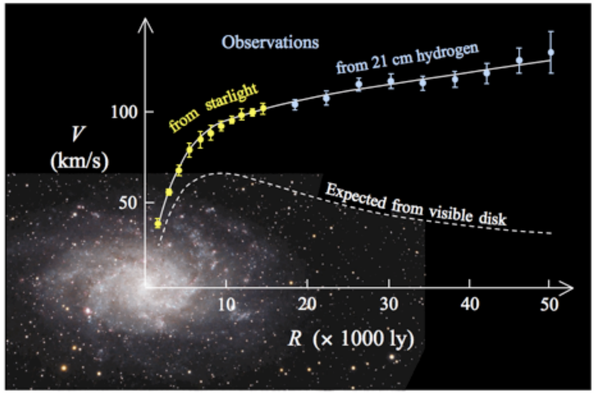
The origin of Cosmic Rays



- Unveiling the Galactic PeVatrons
- Impact of low-energy cosmic rays on interstellar chemistry
- Cosmic-ray propagation
- Impact of environment

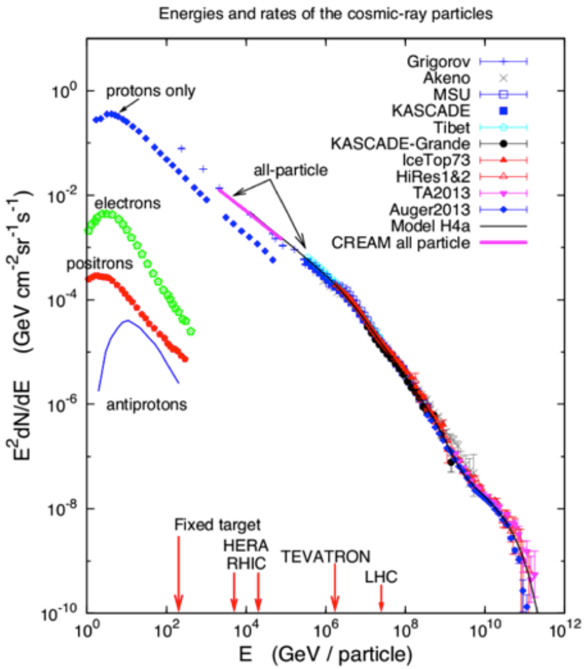
Scientific Challenges

The nature of Dark Matter



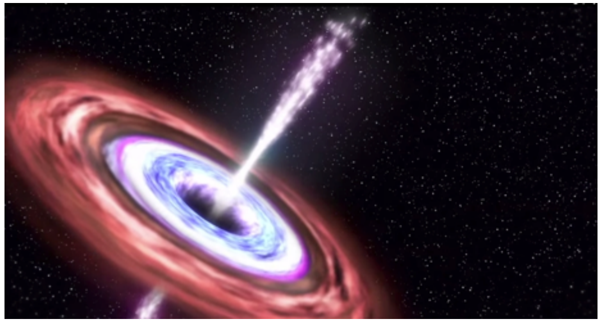
- Indicates a major flaw in our understanding of nature
- Proposed solutions include new fundamental particles (WIMPs, axions, etc.)
- Decay products of these particles may be detectable in gamma rays

The origin of Cosmic Rays



- Unveiling the Galactic PeVatrons
- Impact of low-energy cosmic rays on interstellar chemistry
- Cosmic-ray propagation
- Impact of environment

The physics of Particle Acceleration



- What mechanisms are actually at operation in a given source?
- Insights from variability (time domain astronomy)
- Elusive source classes

Space-based projects

Parameter	AdEPT	e-ASTROGAM	CALET	DAMPE	GAMMA-400	HARPO	HERD	PANGU
Context	R&D	M5?	ISS	China	Russia	R&D	China	ESA/CAS?
Launch date	–	2029?	launched	launched	~2021	–	>2020	2021?
Energy range (GeV)	0.005–0.2	0.0003–3	0.02–10000	2–10000	0.1–3000	0.003–3	0.1–10000	0.01–5
Ref. energy (GeV)	0.07	0.1	100	100	100	0.1	100	1
$\Delta E/E$	30%	30%	2%	1.5%	1%	10%	1%	30%
A_{eff} (cm^2)	500	1500	t.b.d.	3000	5000	2700	t.b.d.	180
Sensitivity (mCrab)	10	10	1000	100	100	1	10	t.b.d.
Field of view (sr)	t.b.d.	2.5	1.8	2.8	1.2	t.b.d.	t.b.d.	2.2
Angular resolution	1°	1.5°	0.1°	0.1°	0.02°	0.4°	0.1°	0.2°
MDP (10 mCrab)	10%	20%	–	–	–	t.b.d.	–	t.b.d.
Technology	TPC	Si + CsI	fib. + $PbWO_4$	Si + BGO	Si + CsI	TPC	Si + LYSO	Si (fib.) + **B**

- Detection sensitivities are still poor in the MeV domain
- Considerable potential exists in using modern, **space-proven** highly pixelised semiconductor detectors in a **compact configuration** with a **minimum amount of passive material** to detect gamma rays through Compton and pair creation interactions

- At GeV energies, succeeding to Fermi-LAT will be challenging (Fermi spacecraft weight is 4.3 tons, difficult to build a much bigger detector)
- Area of improvement is angular resolution (i.e point spread function); can be achieved by **decreasing density of tracker** and **increasing spacing between tracker and calorimeter**

- **Potential to cover both aspects in a single mission**

Space-based projects

Parameter	AdEPT	e-ASTROGAM	CALET	DAMPE	GAMMA-400	HARPO	HERD	PANGU
Context	R&D	M5?	ISS	China	Russia	R&D	China	ESA/CAS?
Launch date	–	2029?	launched	launched	~2021	–	>2020	2021?
Energy range (GeV)	0.005–0.2	0.0003–3	0.02–10000	2–10000	0.1–3000	0.003–3	0.1–10000	0.01–5
Ref. energy (GeV)	0.07	0.1	100	100	100	0.1	100	1
$\Delta E/E$	30%	30%	2%	1.5%	1%	10%	1%	30%
$A_{\rm eff}$ (cm^2)	500	1500	t.b.d.	3000	5000	[illegible]	t.b.d.	[illegible]
Sensitivity (mCrab)	10	10	1000	100	100	1	10	t.b.d.
Field of view (sr)	t.b.d.	2.5	1.8	2.8	1.2	t.b.d.	t.b.d.	2.2
Angular resolution	1°	1.5°	0.1°	0.1°	0.02°	0.4°	0.1°	0.2°
MDP (10 mCrab)	10%	20%	–	–	–	t.b.d.	–	t.b.d.
Technology	TPC	Si + CsI	fib. + $PbWO_4$	Si + BGO	Si + CsI	TPC	Si + LYSO	Si (fib.) + **B**

See presentation by Peter von Ballmoos

- Detection sensitivities are still poor in the MeV domain
- Considerable potential exists in using modern, **space-proven** highly pixelised semiconductor detectors in a **compact configuration** with a **minimum amount of passive material** to detect gamma rays through Compton and pair creation interactions

- At GeV energies, succeeding to Fermi-LAT will be challenging (Fermi spacecraft weight is 4.3 tons, difficult to build a much bigger detector)
- Area of improvement is angular resolution (i.e point spread function); can be achieved by **decreasing density of tracker** and **increasing spacing between tracker and calorimeter**

- **Potential to cover both aspects in a single mission**

Ground-based projects

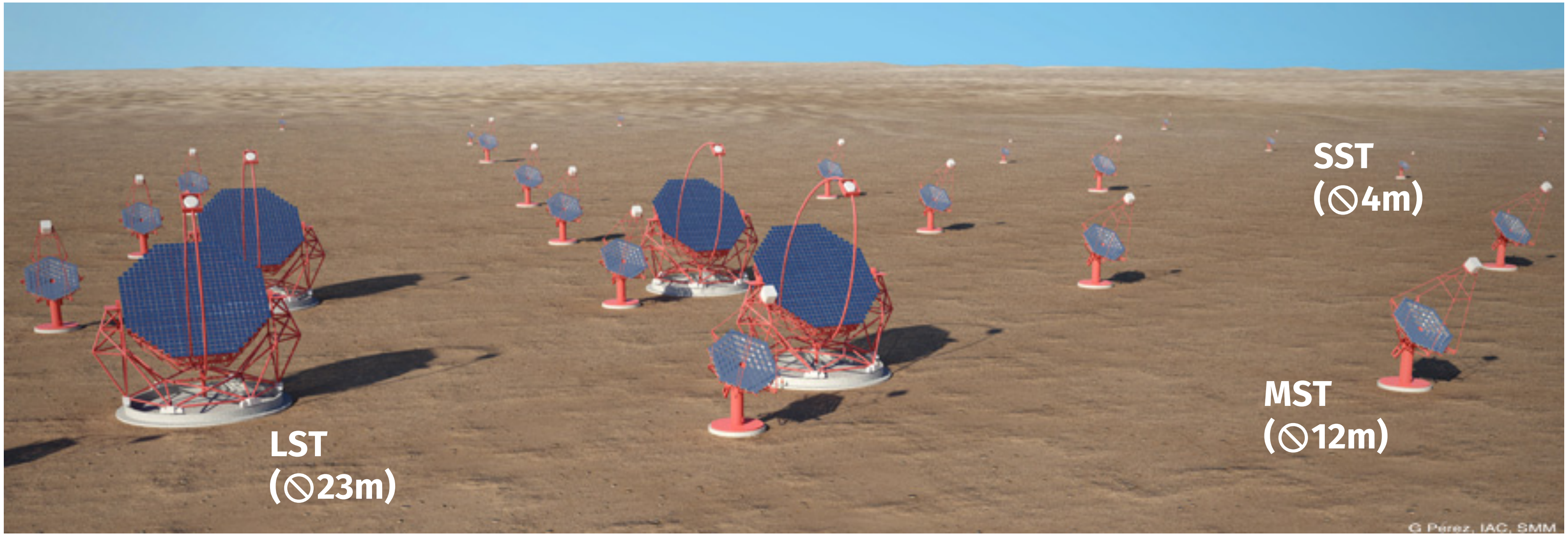
Parameter	CTA	HAWC	HiSCORE	LHAASO	MACE
Site(s)	t.b.d.	Sierra Negra (Mexico)	Tunka Valley (Russia)	Daocheng (China)	Hanle (India)
Altitude (m)	$\sim$ 2000	4100	675	4300	4270
Latitude	t.b.d.	19°N	51.8°N	29°N	32.8°N
Start of operations	2020	started	t.b.d.	2020?	2016
Lifetime (years)	30	10	t.b.d.	$>$ 10	t.b.d.
Energy range (TeV)	0.02–300	0.1–100	50–10 000	0.1–1000	t.b.d.
$\Delta E/E$	10%	50%	10%	20%	t.b.d.
A_{eff} (m^2)	3×10^6	30 000	10^8	8×10^5 (KM2A) 10^6 (WCDA)	t.b.d.
Sensitivity (mCrab)	1	50	100	10	t.b.d.
Field of view	5°–10°	1.8 sr	0.6 sr	1.5 sr	4°
Angular resolution	0.05°	0.5°	0.1°	0.3°	t.b.d.

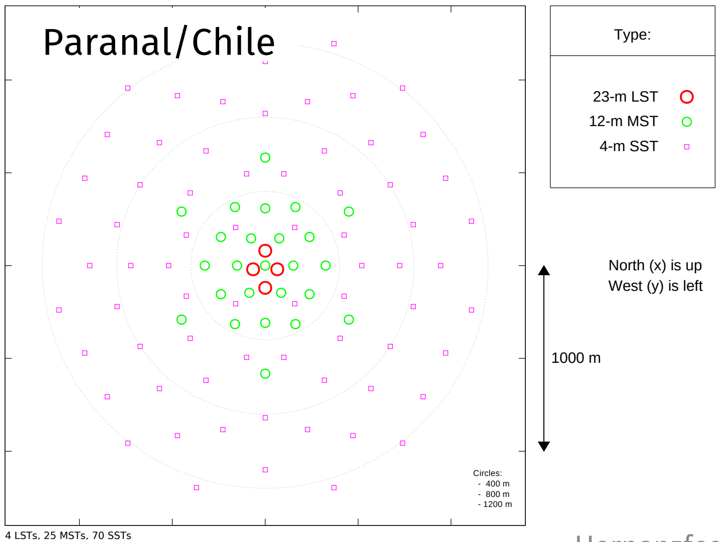
- Imaging Air Cherenkov Telescopes (IACTs) have been proven most efficient to study gamma-ray induced atmospheric Cherenkov light (excellent angular resolution, strong background rejection power)
- Drawbacks are low duty cycles (~10%) and narrow fields of view (~5°)
- Performance increase through **more telescopes** covering a **larger area** and eventually using **SiPM instead of PMTs**

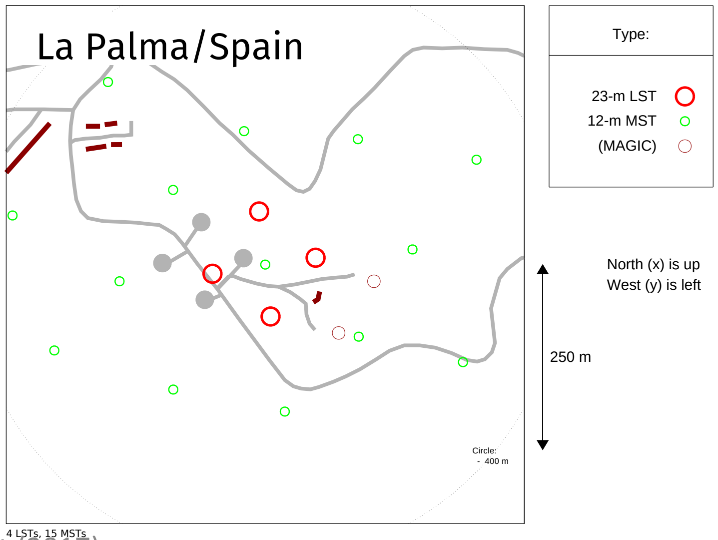
- Water Cherenkov Detectors (WCDs) are most successful devices for studying the tails of extended air showers (“tail catcher detectors”)
- While modest in angular resolution and background rejection, they have excellent duty cycles and wide field of view (complementary to IACTs)
- Performance increase through **larger surface areas**, moving the detector to **higher altitude**, and improving the **detector configuration**

- **Open access observatories**

Cherenkov Telescope Array

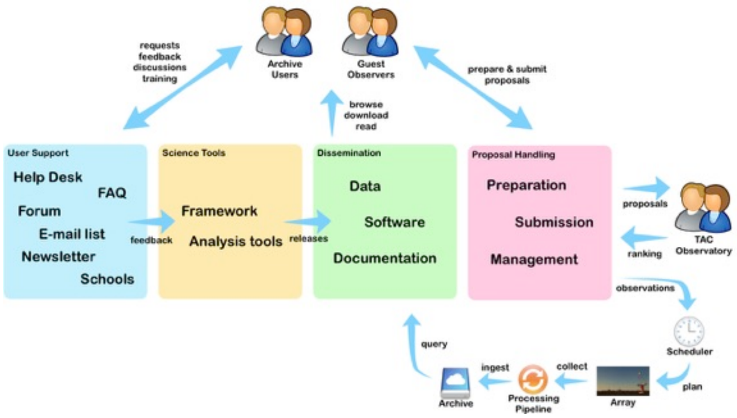






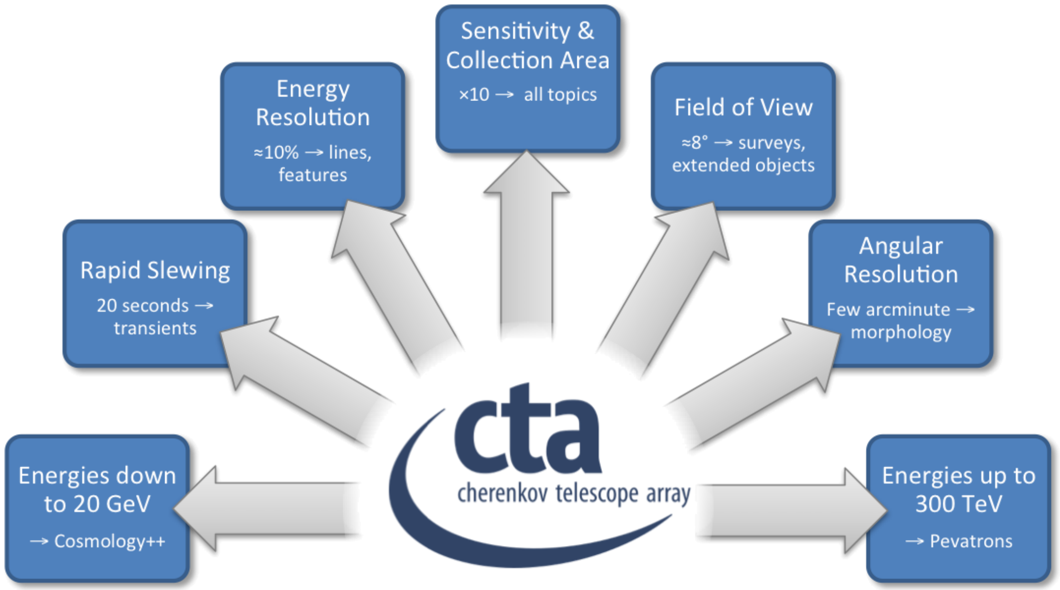
Cherenkov Telescope Array

An Open Observatory



A world-wide endeavour

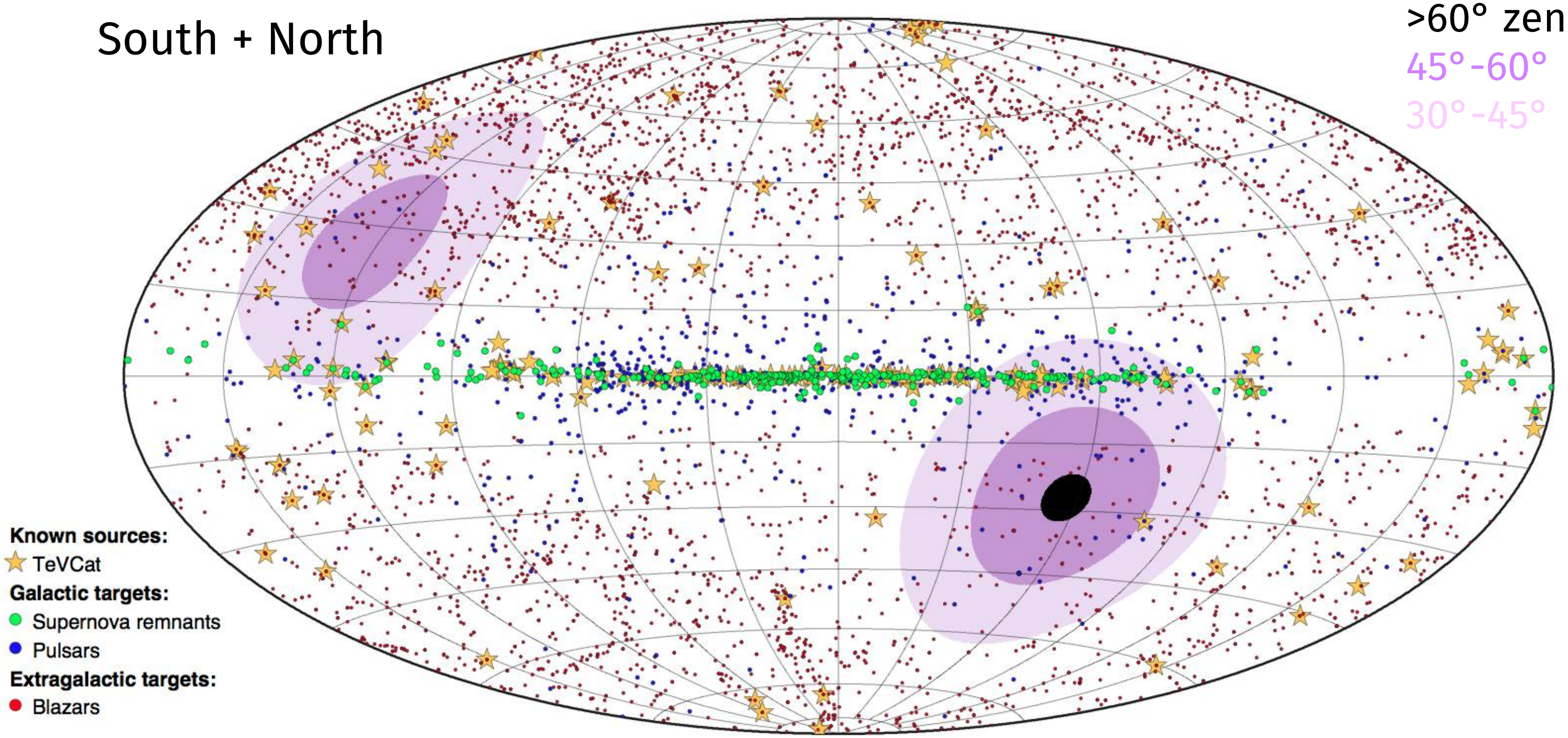
Improvements everywhere



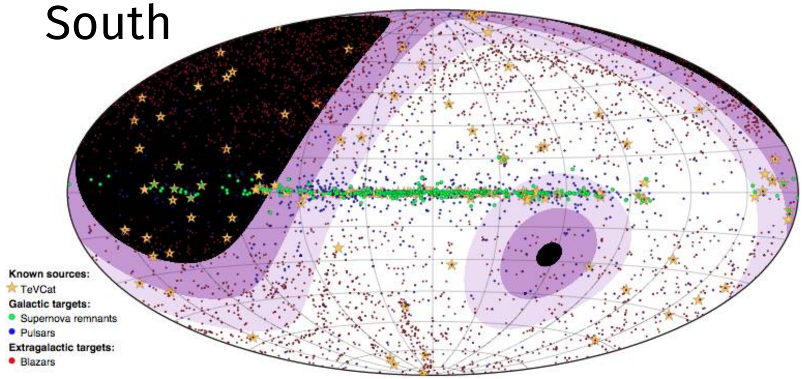
All Sky coverage

>60° zenith
45°-60°
30°-45°

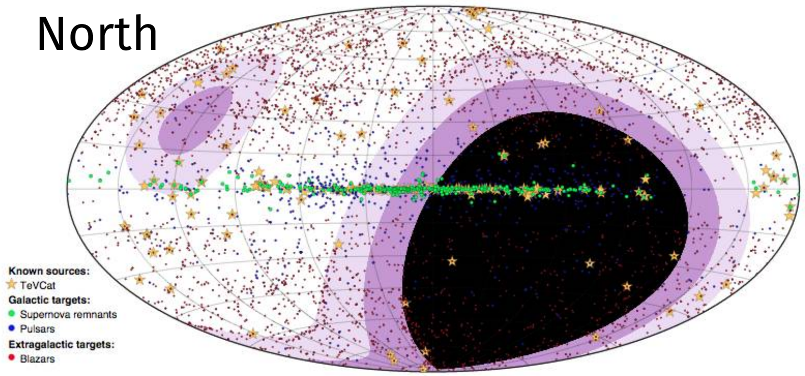
South + North



South



North



Expected performance

Sensitivity gain

- access VHE populations across entire Galaxy
- sample fast variability (AGN, GRB)

FoV > 8°

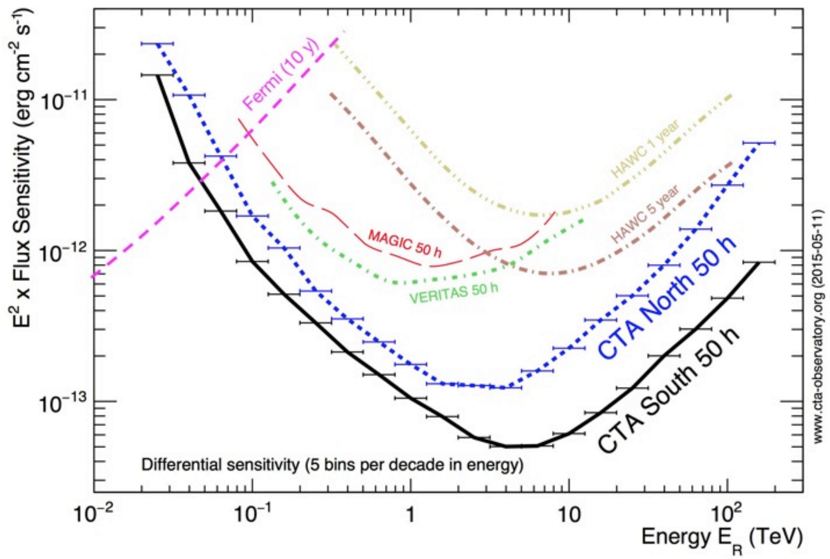
- measure diffuse emissions
- efficient survey of large fields

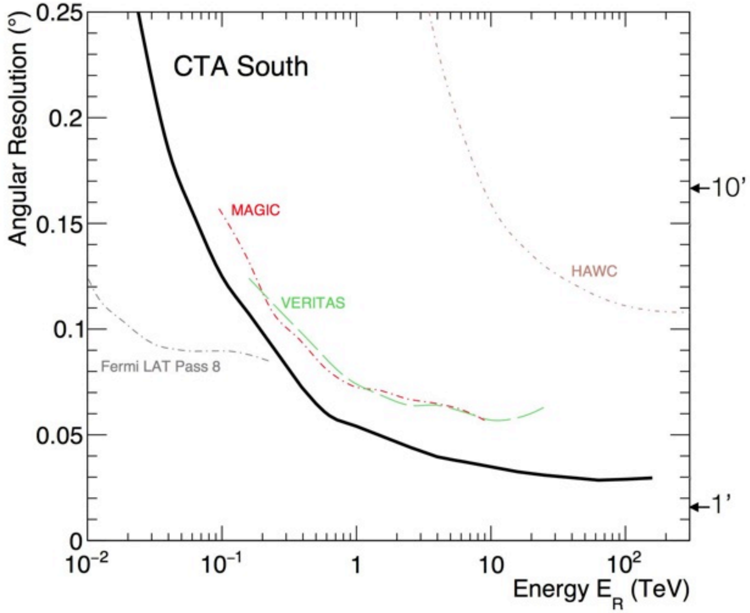
Arcmin angular resolution

- resolve extended sources (SNR, starbursts)

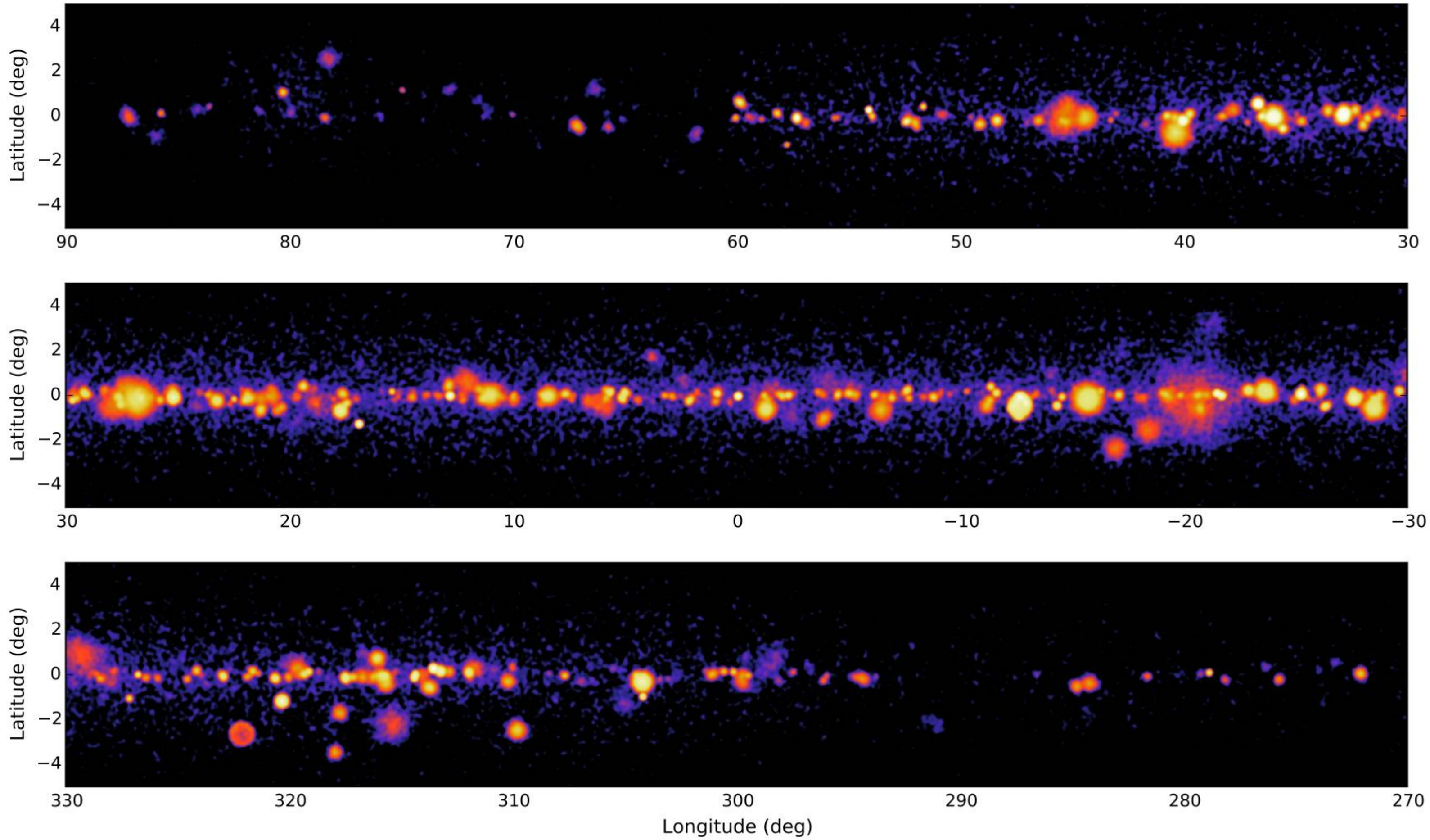
Broad energy coverage

- < 100 GeV to reach higher redshifts
- > 10 TeV to search for PeVatrons





Key Science



Planned surveys: a deep view of the high-energy Universe

Full galactic plane (1620 h)
Deep survey of the Galactic Centre region (825 h)
The Large Magellanic Cloud (340 h)
One-pi extragalactic survey down to 6 mCrab (500 h)

Large size telescopes

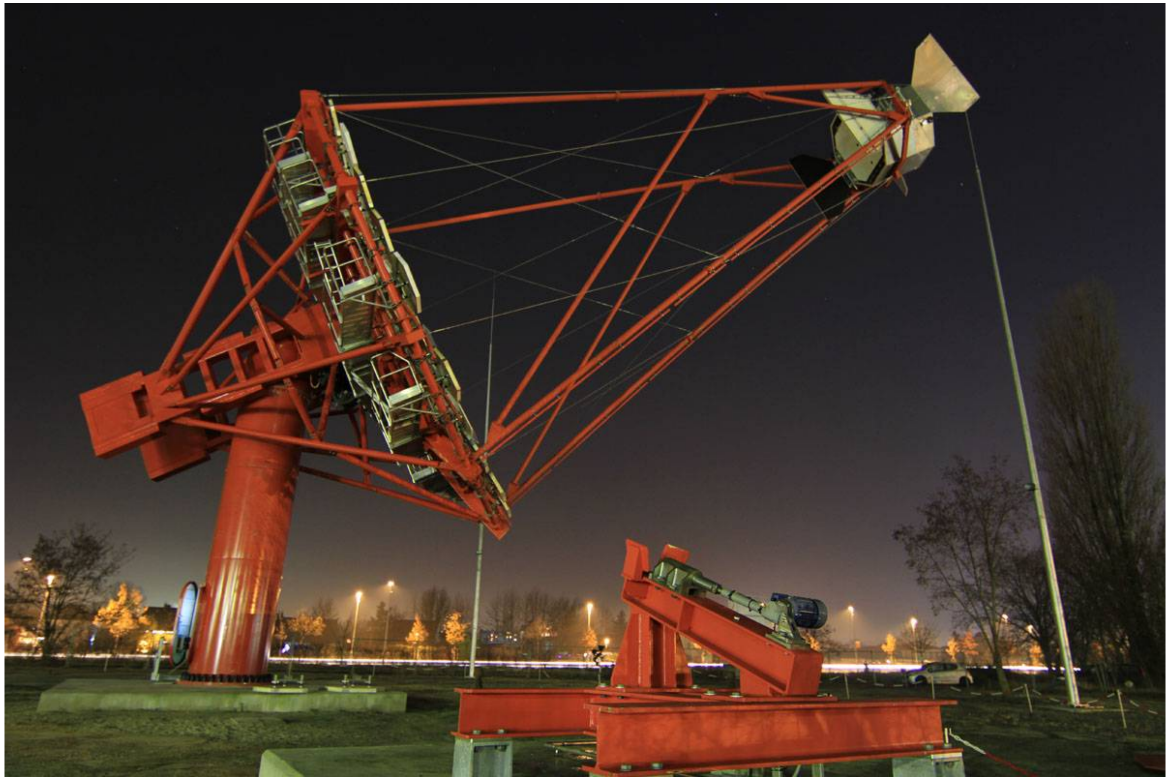
Science drivers
- Lowest energies (< 200 GeV)
- Transient phenomena
- DM, AGN, GRB, pulsars

Characteristics
- Parabolic design
- 23 m diameter
- 370 m^2 effective mirror area
- 28 m focal length
- 1.5 m mirror facets
- 4.5° field of view
- 0.11° PMT pixels
- active mirror control
- Carbon-fibre arch structure (fast repointing)

Array layout
- South site: 4
- North site: 4

Status
- Some elements prototyped
- First full telescope under construction in La Palma (http://www.lst1.iac.es/webcams.html)

Mid size telescopes



Science drivers
- Mid energies (100 GeV – 10 TeV)
- DM, AGN, SNR, PWN, binaries, starbursts, EBL, IGM

Characteristics
- Modified Davies-Cotton design
- 12 m diameter
- 90 m^2 effective mirror area
- 1.2 m mirror facets
- 16 m focal length
- 8° field of view
- 0.18° PMT pixels

Array layout
- South site: 25
- North site: 15

Status
- Telescope prototyped (Berlin-Adlershof)
- Prototype cameras under construction (2 types: NectarCAM & FlashCam)

Small size telescopes

Characteristics
- Davies-Cotton design
- 4 m diameter
- 8.5 m² effective mirror area
- 5.6 m focal length
- 9° field of view
- 0.24° SiPM pixels

Status
- Prototype telescope built
- Camera prototype under commissioning

Characteristics
- Schwarzschild-Couder design
- 4.3 m primary diameter
- 1.8 m secondary diameter
- 6 m² effective mirror area
- 2.2 m focal length
- 9.6° field of view
- 0.17° SiPM pixels

Status
- Prototype telescope built
- Camera prototype installed

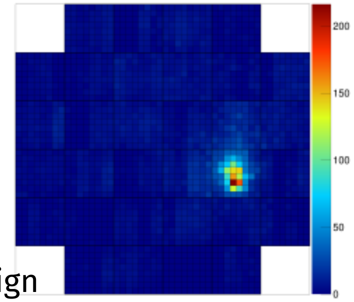
Characteristics
- Schwarzschild-Couder design
- 4 m primary diameter
- 2 m secondary diameter
- 6 m² effective mirror area
- 2.3 m focal length
- 8.6° field of view
- 0.16° SiPM pixels

Status
- Prototype telescope structure built
- Tested with MAPMT-based CHEC camera

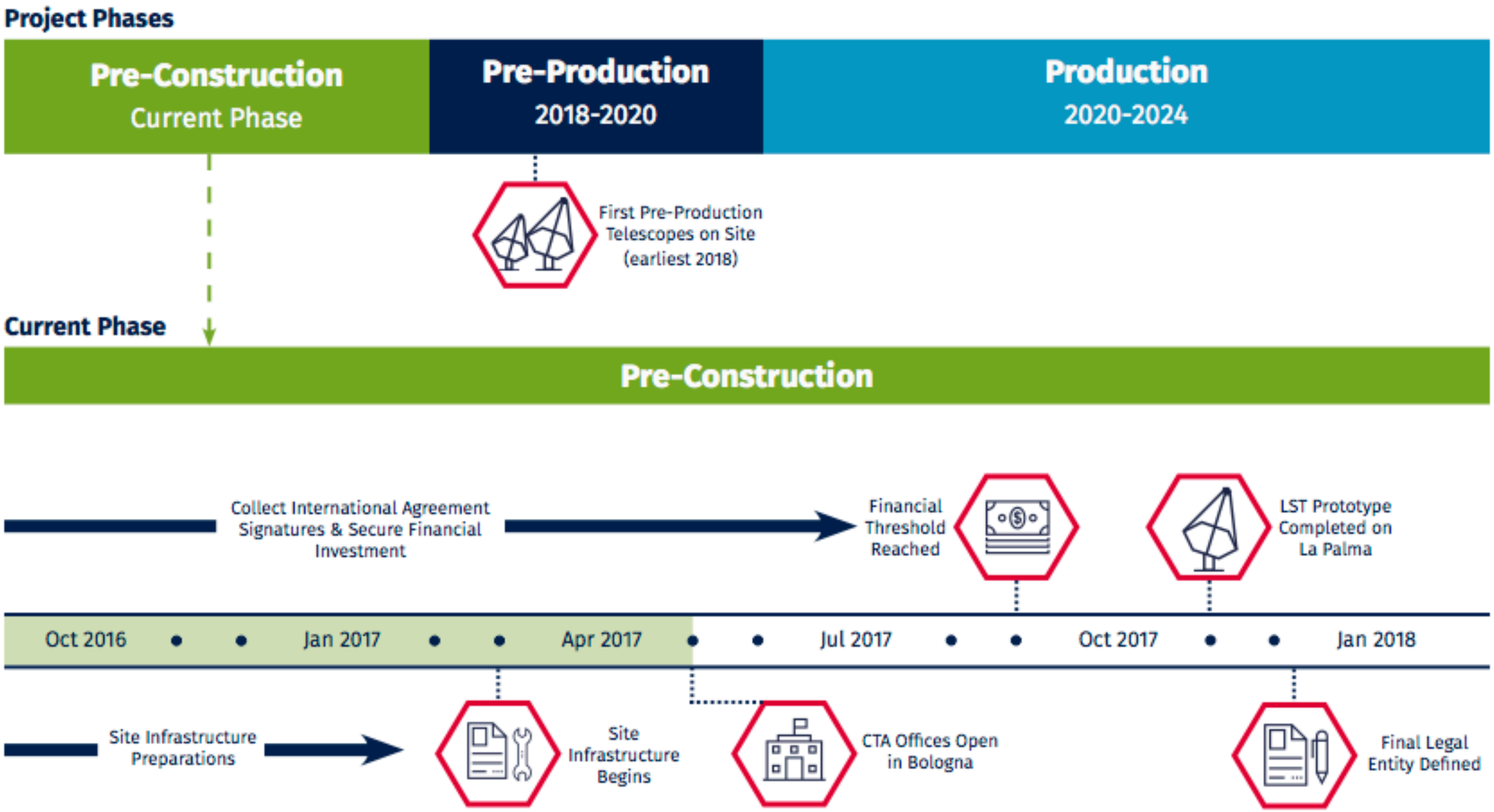
Science drivers
- Highest energies (> 5 TeV)
- Galactic science, PeVatrons

Array layout
- South site: 70
- North site: -

First CTA light



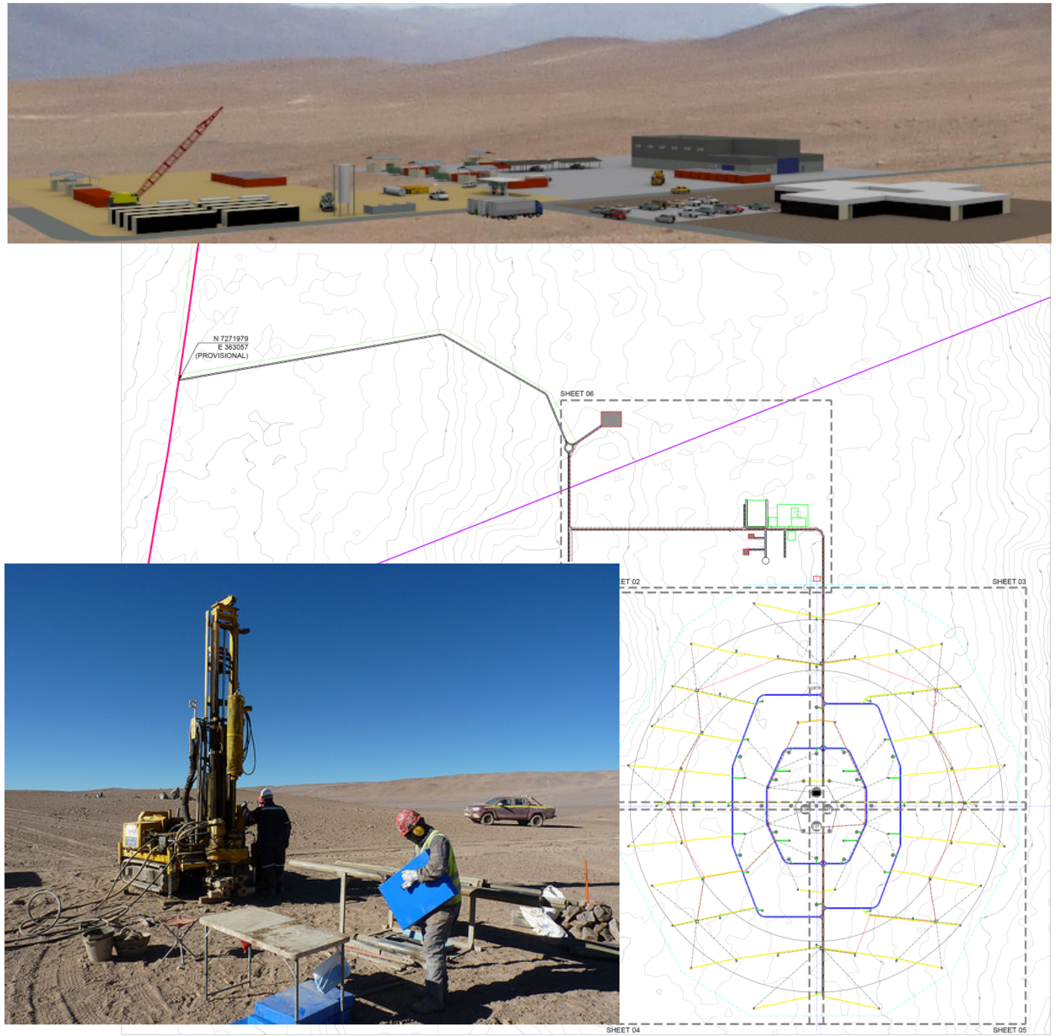
Calendar



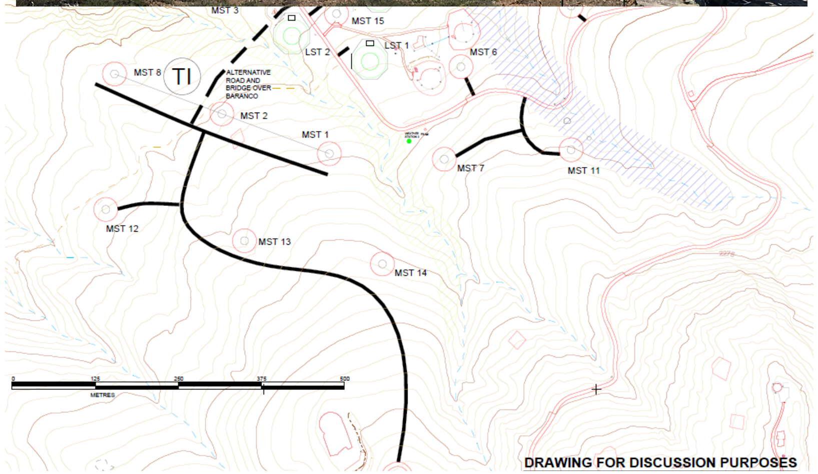
Project Phases
Pre-Construction
Current Phase
Pre-Production
2018-2020
Production
2020-2024
First Pre-Production Telescopes on Site (earliest 2018)
Current Phase
Pre-Construction
Collect International Agreement Signatures & Secure Financial Investment
Financial Threshold Reached
LST Prototype Completed on La Palma
Oct 2016
Jan 2017
Apr 2017
Jul 2017
Oct 2017
Jan 2018
Site Infrastructure Preparations
Site Infrastructure Begins
CTA Offices Open in Bologna
Final Legal Entity Defined

CTA site work

Chile (South)



La Palma (North)



Some other projects

HiSCORE

- Non-imaging air-shower Cherenkov light-front sampling
- Up to 100 km^2 area covered
- Wide field of view (~0.6 sr)
- Extend sensitivity to the PeV regime
- Complemented by IACTs and surface & underground stations for measuring muon component of air showers

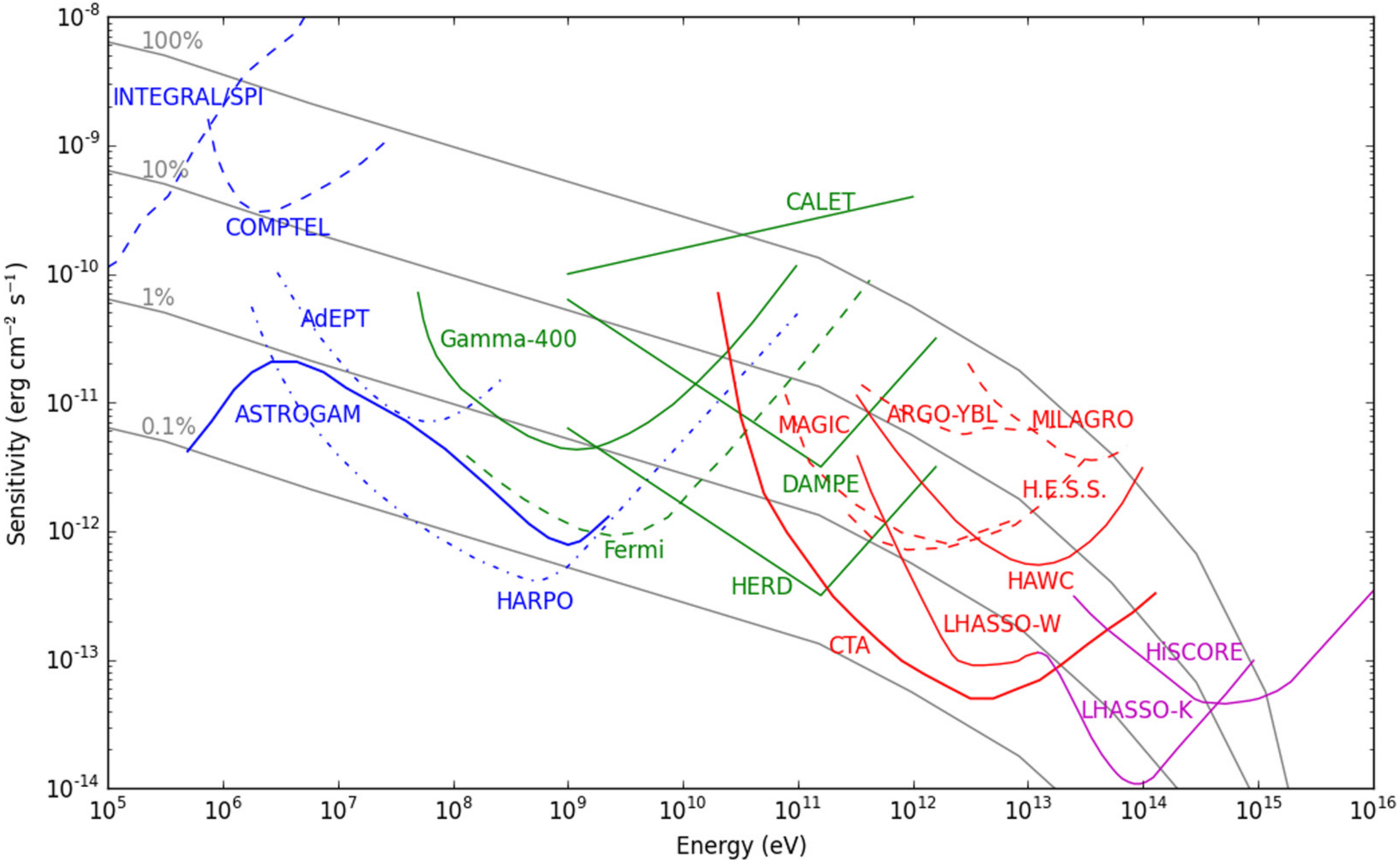
LHAASO

- Hybrid detector array
- Gamma ray detectors
  - Large (4 x HAWC) Water Cherenkov detector array (0.1-30 TeV)
  - Electromagnetic particle detectors and muon detectors (30-1000 TeV)

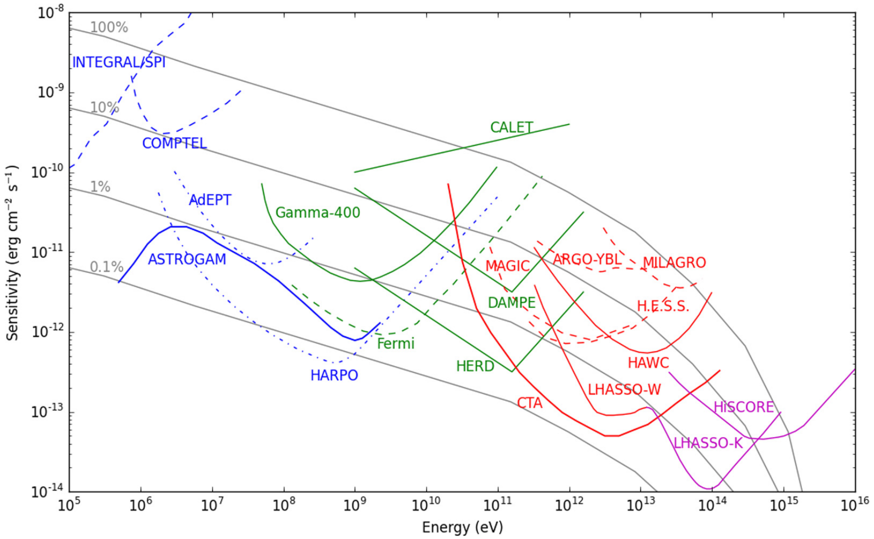
MACE

- 21 m diameter IACT to be installed at Hanle (4270 m a.s.l)
- Design inspired from MAGIC

Sensitivity: past – present – future



Conclusions



Ground-based

- The **Cherenkov Telescope Array** will expand on all aspects of current IACTs (**sensitivity**, **energy range**, **angular resolution**)
- Will enable
  - **WIMP detections** from few 100 GeV to few TeV
  - search of **PeVatrons** in the entire Galaxy
  - measurement of **sub-minute variability** in AGN
  - comprehensive **population studies** of particle accelerators
  - studies of **particle acceleration** in and **particle propagation** near individual sources

Space-based

- An instrument covering the **MeV – GeV** energy range has the **highest discovery potential (e.g. e-ASTROGAM, ComPair)**
- Will enable
  - measurement of **pion-bumps** characteristic of hadronic accelerators in many sources
  - study of the still elusive **low-energy cosmic-ray component**
  - observation of **gamma-ray lines** (nucleosynthesis, de-excitation, e^+e^- annihilation)
  - **gamma-ray polarisation** measurements