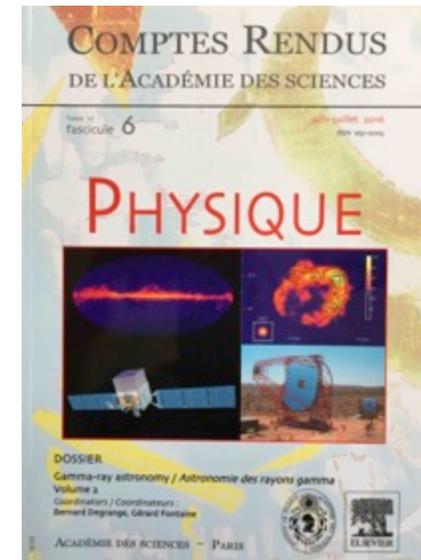


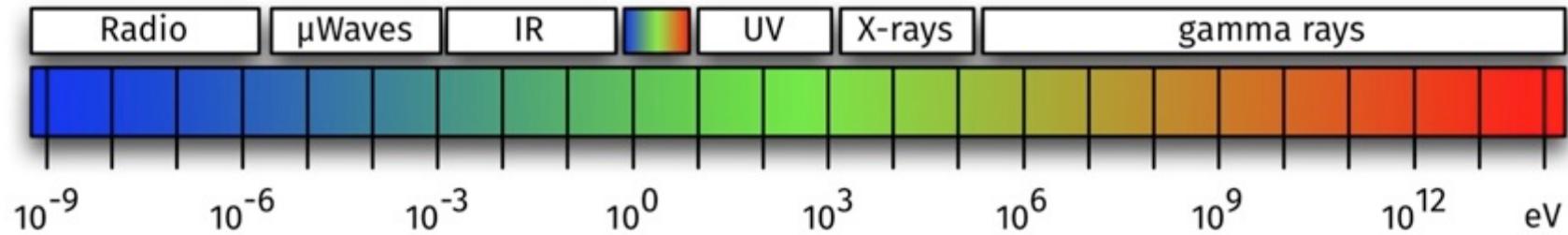
# The future of gamma-ray astronomy

Jürgen Knödlseder  
IRAP, Toulouse (France)

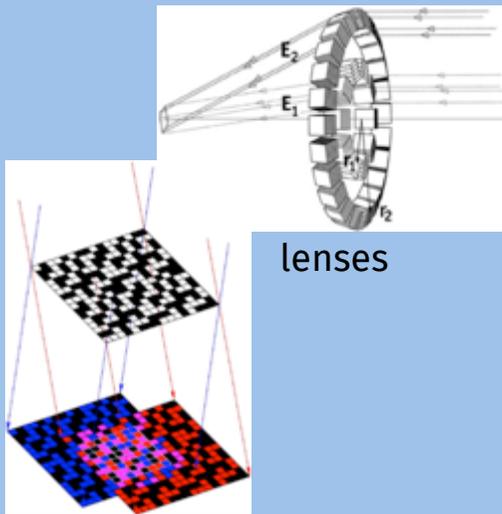


Comptes Rendus Physique, 2016  
Vol. 17, Issue 6, pp. 663-678

# Observing gamma rays



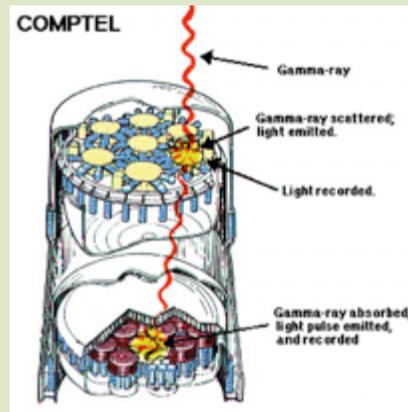
photoelectric effect



lenses

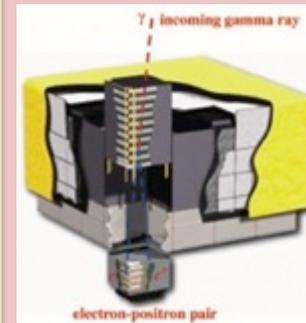
coded masks

Compton scattering



Compton telescopes

pair creation



pair converters Cherenkov telescopes

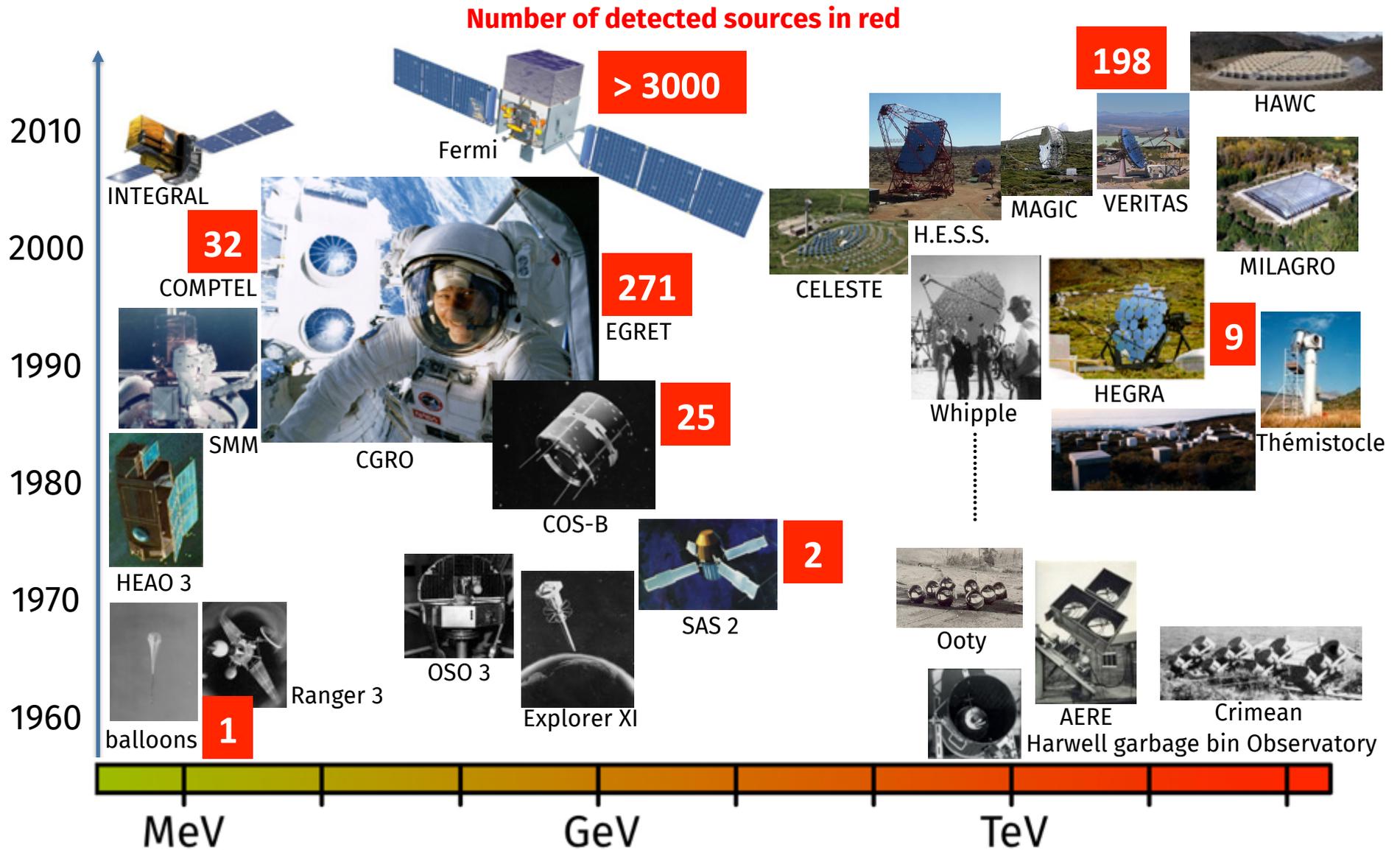


Particle detectors

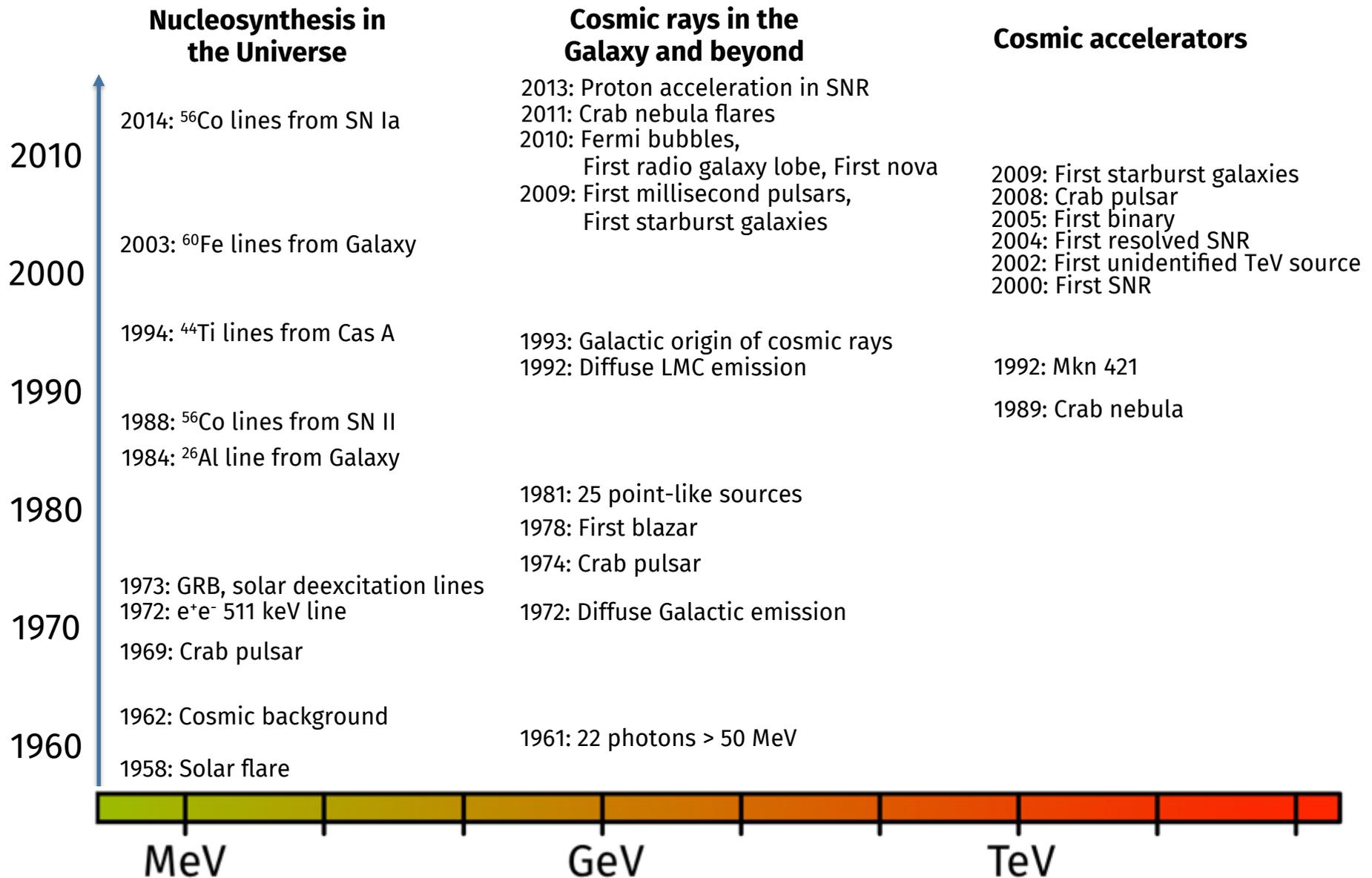
space-based

ground-based

# History of gamma-ray astronomy

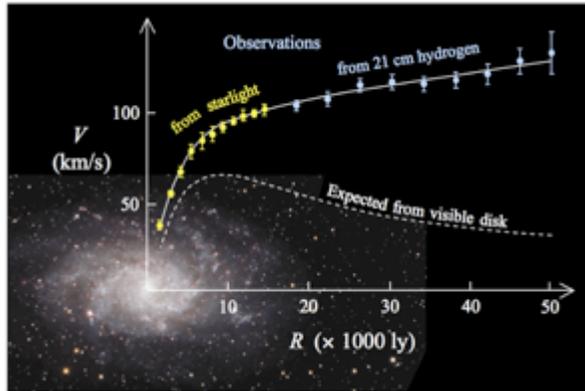


# Achievements



# Scientific Challenges

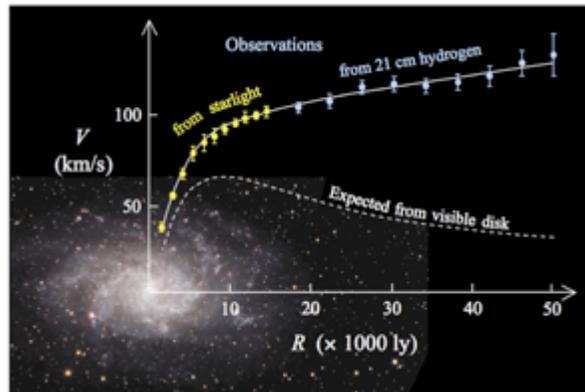
## The nature of Dark Matter



- 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

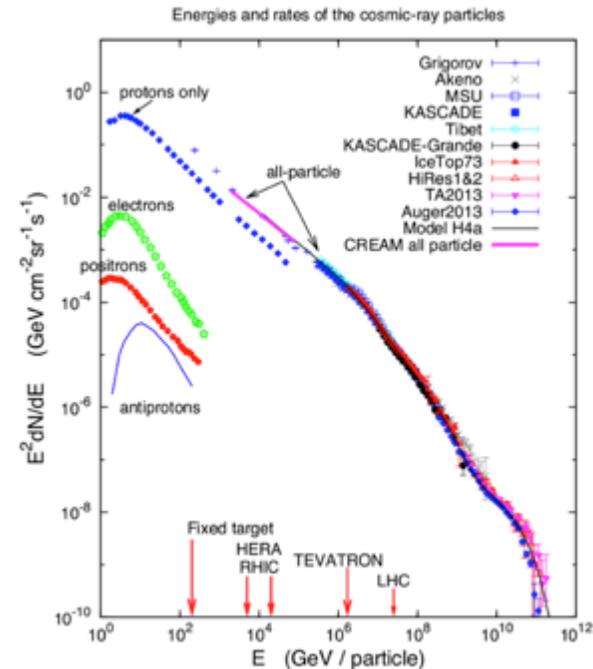
# Scientific Challenges

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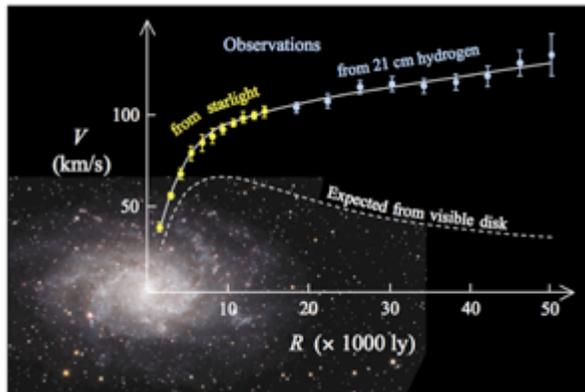
## The origin of Cosmic Rays



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

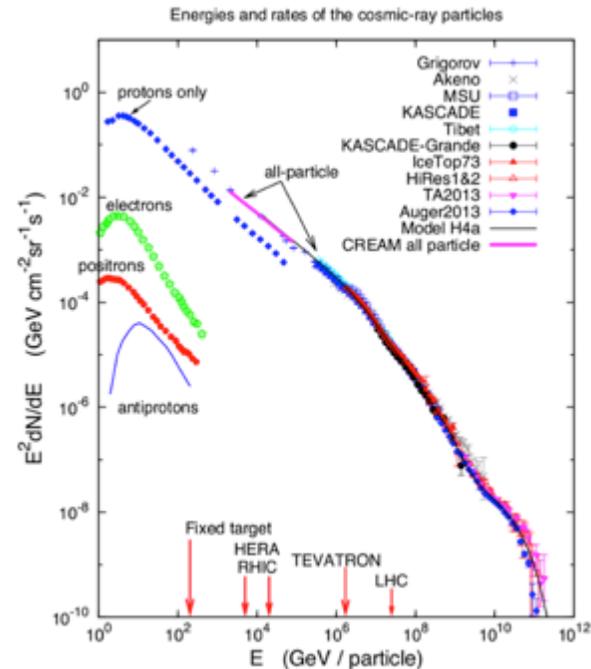
# Scientific Challenges

## The nature of Dark Matter



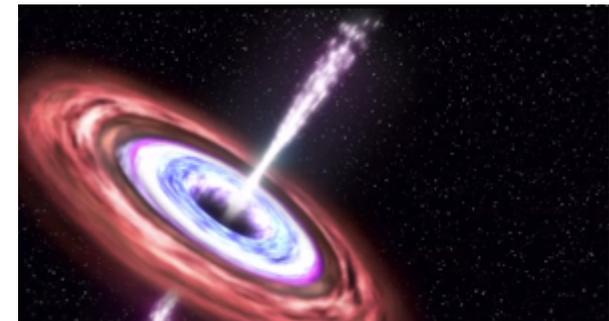
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## The origin of Cosmic Rays



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

## The physics of Particle Acceleration



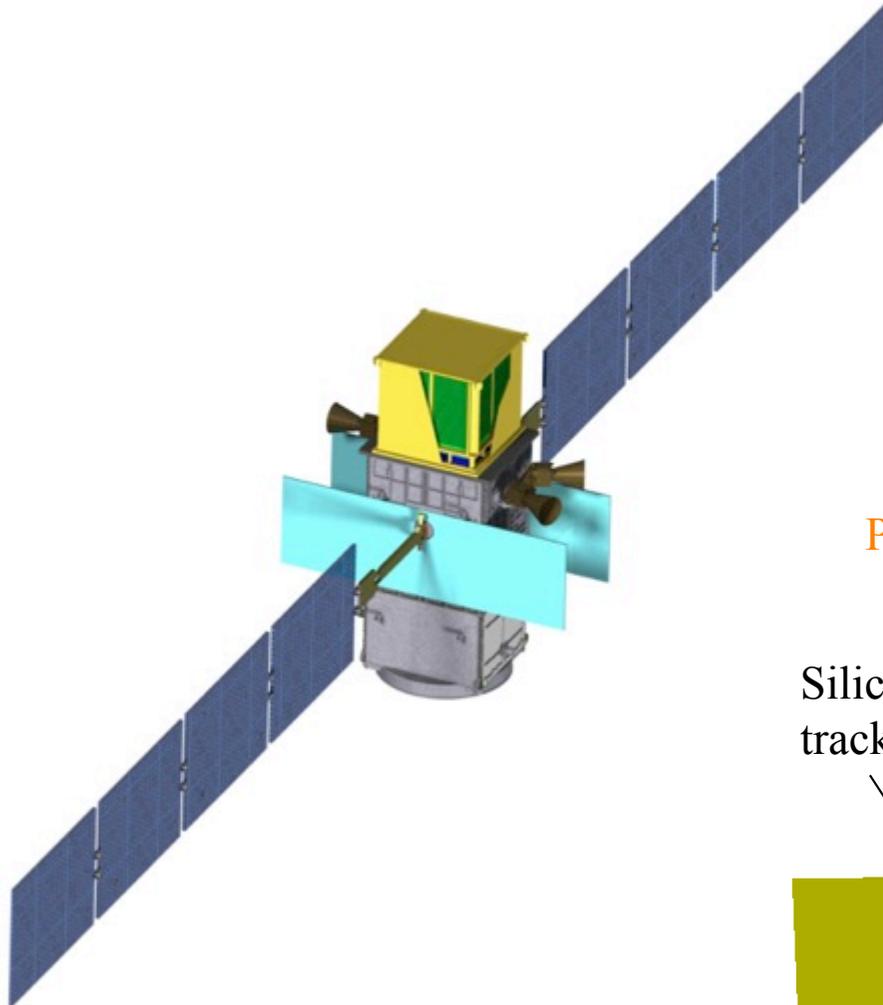
- What mechanisms are actually at operation in a given source?
- Insights from variability (time domain astronomy)
- Elusive source classes

# Space-based projects

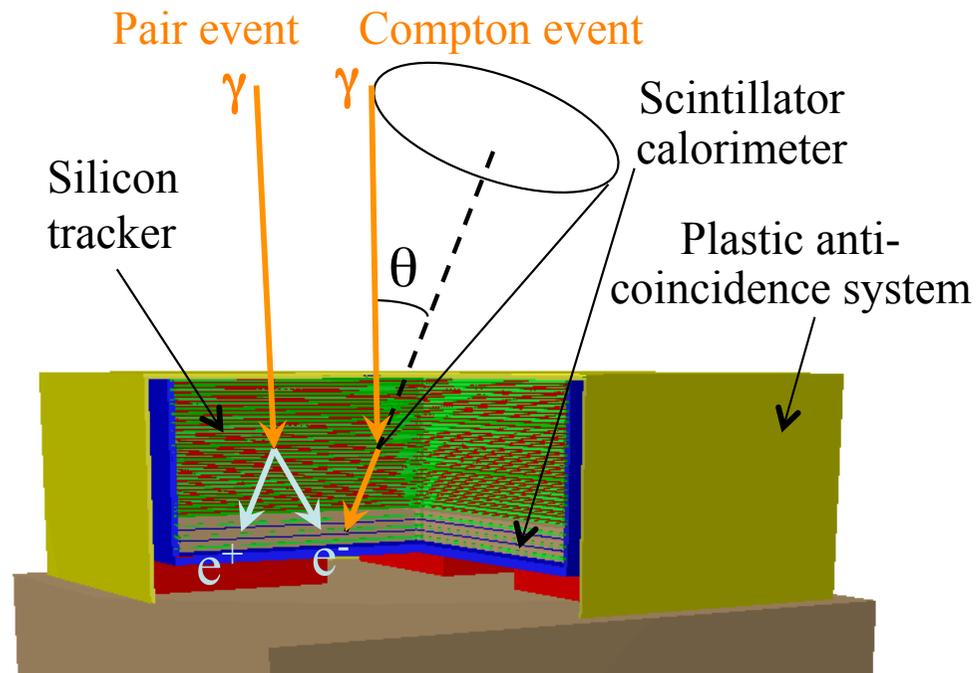
Parameter	AdEPT	e-ASTROGAM	CALET	DAMPE	GAMMA-400	HARPO	HERD	PANGU
Context	R&D	M5?	ISS	China	Russia	R&D	China	ESA/CAS?
Launch date	–	2029?	launched	launched	~2021	–	>2020	2021?
Energy range (GeV)	0.005–0.2	0.0003–3	0.02–10000	2–10000	0.1–3000	0.003–3	0.1–10000	0.01–5
Ref. energy (GeV)	0.07	0.1	100	100	100	0.1	100	1
$\Delta E/E$	30%	30%	2%	1.5%	1%	10%	1%	30%
$A_{\text{eff}}$ (cm <sup>2</sup> )	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 <sub>4</sub>	Si + BGO	Si + CsI	TPC	Si + LYSO	Si (fib.) + <b>B</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**

# e-ASTROGAM



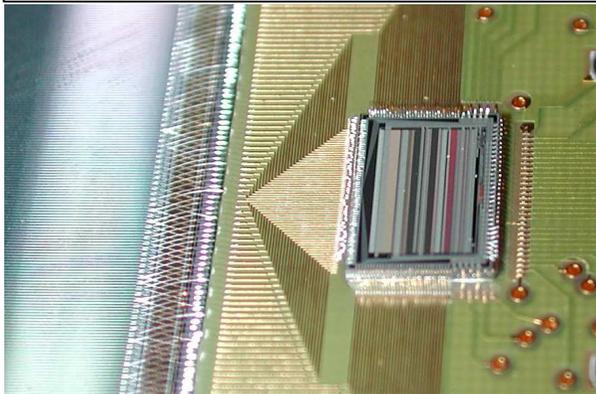
- Sub MeV – GeV domain, polarimetry
- Compton and pair conversion telescope
- Detector
  - Double sided Silicon strip (DSSD) tracker
  - 3D imaging scintillator CsI(Tl) calorimeter read out by Si drift diodes
  - Plastic anticoincidence shield read out by SiPM
- Using technology heritage from existing satellites
- Proposed as ESA M5 mission
- Similar concept proposed as NASA MIDEX (ComPair)



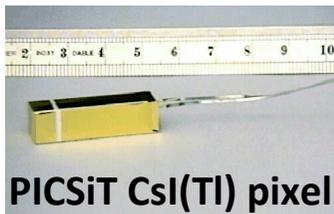
# e-ASTROGAM hardware

8

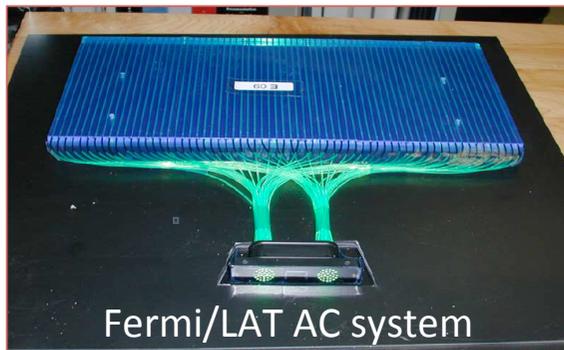
Detail of the detector-ASIC bonding in the AGILE Si Tracker



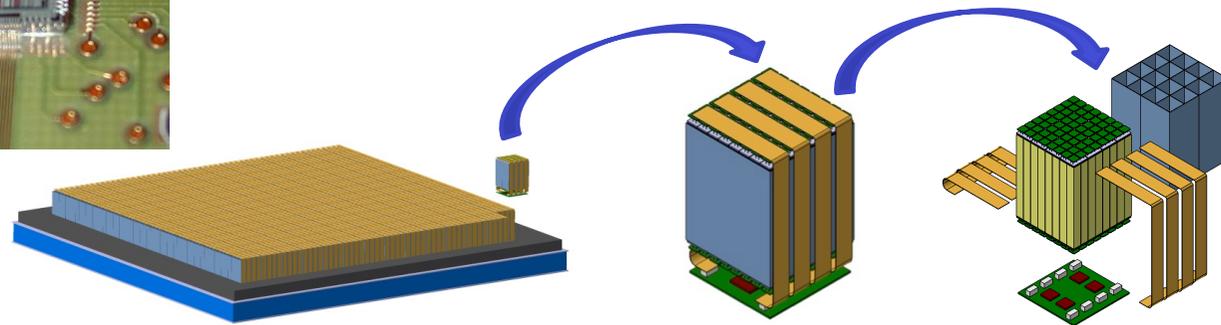
- **Tracker:** 56 layers of 4 times 5×5 DSSDs (5600 in total) of 500  $\mu\text{m}$  thickness and **240  $\mu\text{m}$  pitch**
- DSSDs bonded strip to strip to form 5×5 ladders
- **Light and stiff mechanical structure**
- **Ultra low-noise** front end electronics



PICSiT CsI(Tl) pixel



Fermi/LAT AC system

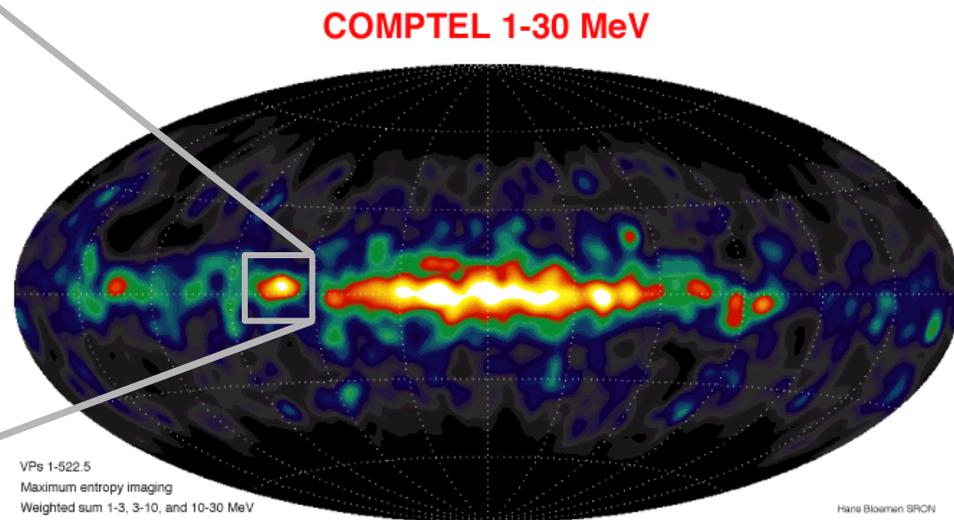
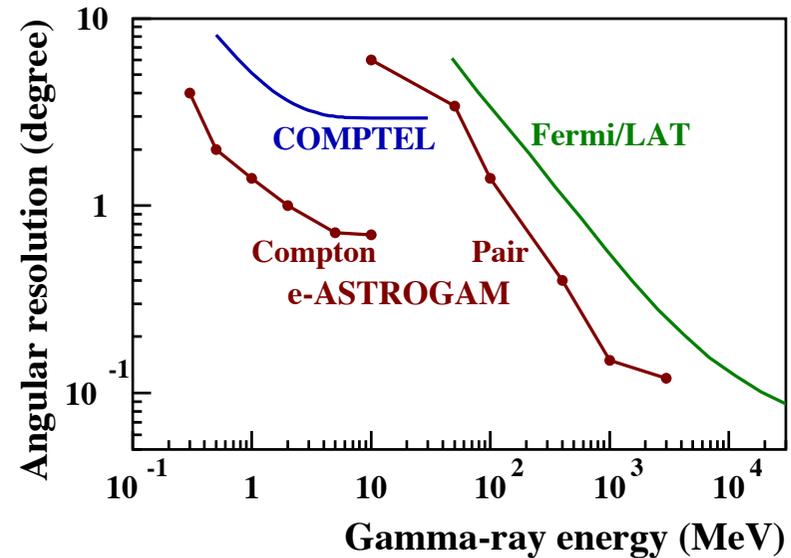
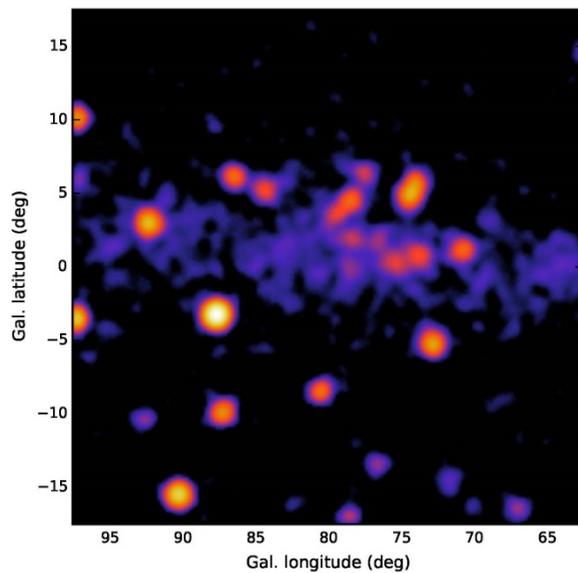


- **Calorimeter:** 8464 CsI(Tl) bars coupled at both ends to **low-noise Silicon Drift Detectors**
- **ACD:** segmented plastic scintillators coupled to SiPM by optical fibers
- **Heritage:** AGILE, Fermi/LAT, AMS-02, INTEGRAL, LHC/ALICE...

# e-ASTROGAM science potential

- Improve angular resolution close to the Compton physical limits

Simulation of the Cygnus region in the 1 – 3 MeV energy band using the e-ASTROGAM PSF, from an extrapolation of the 3FGL source spectra to low energies



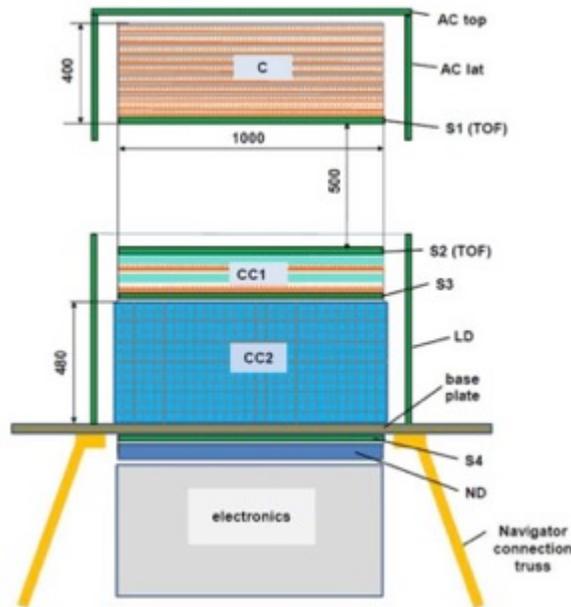
V. Tatischeff for the e-ASTROGAM Collaboration

28<sup>th</sup> Texas Symposium

13–18 December 2015

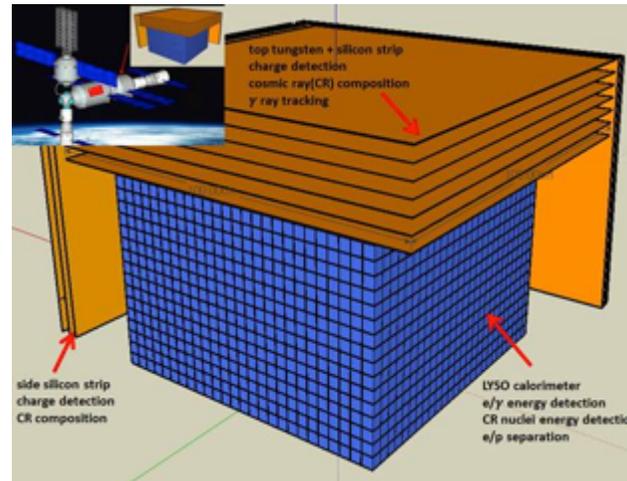
# Some other projects

## Gamma-400



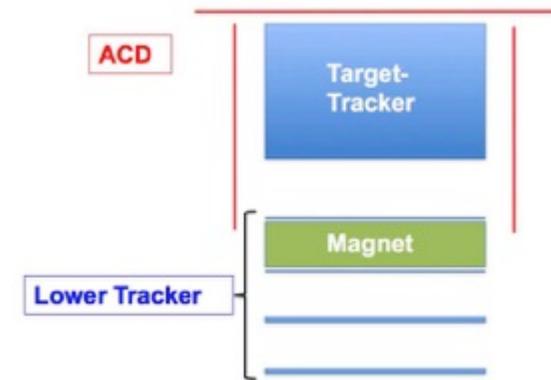
- Fermi/LAT-like with increased spacing between tracker and calorimeter
- Better angular resolution
- Poorer sensitivity
- Status unclear

## HERD



- Primarily a particle detector (like CALET, DAMPE)
- GeV (- TeV) domain
- 3-D cubic calorimeter surrounded by microstrip silicon trackers from five sides
- Weight limited to 2 tons (half of Fermi-LAT)
- Will be placed aboard Chinese space station (2020+)

## Pangu



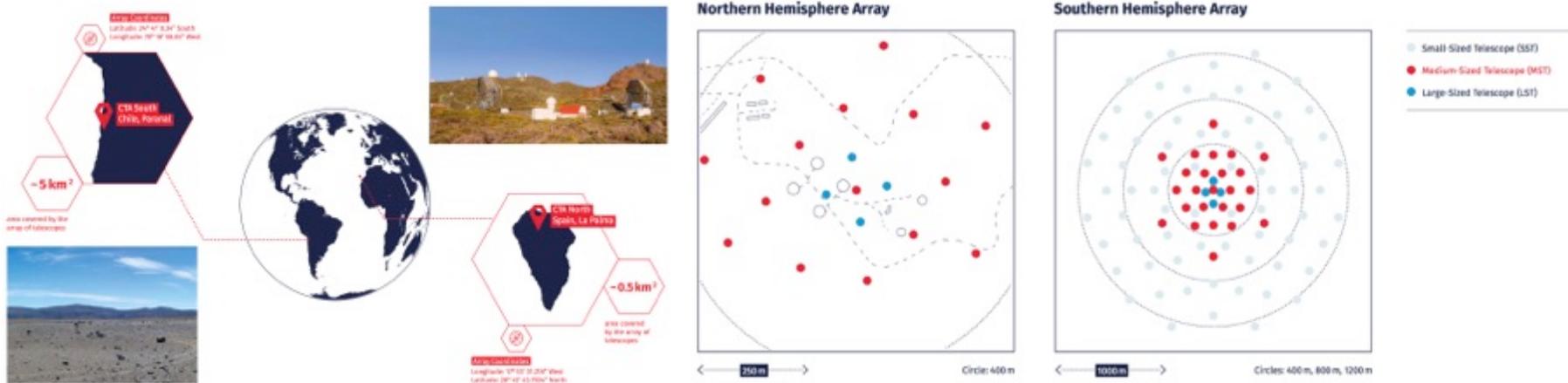
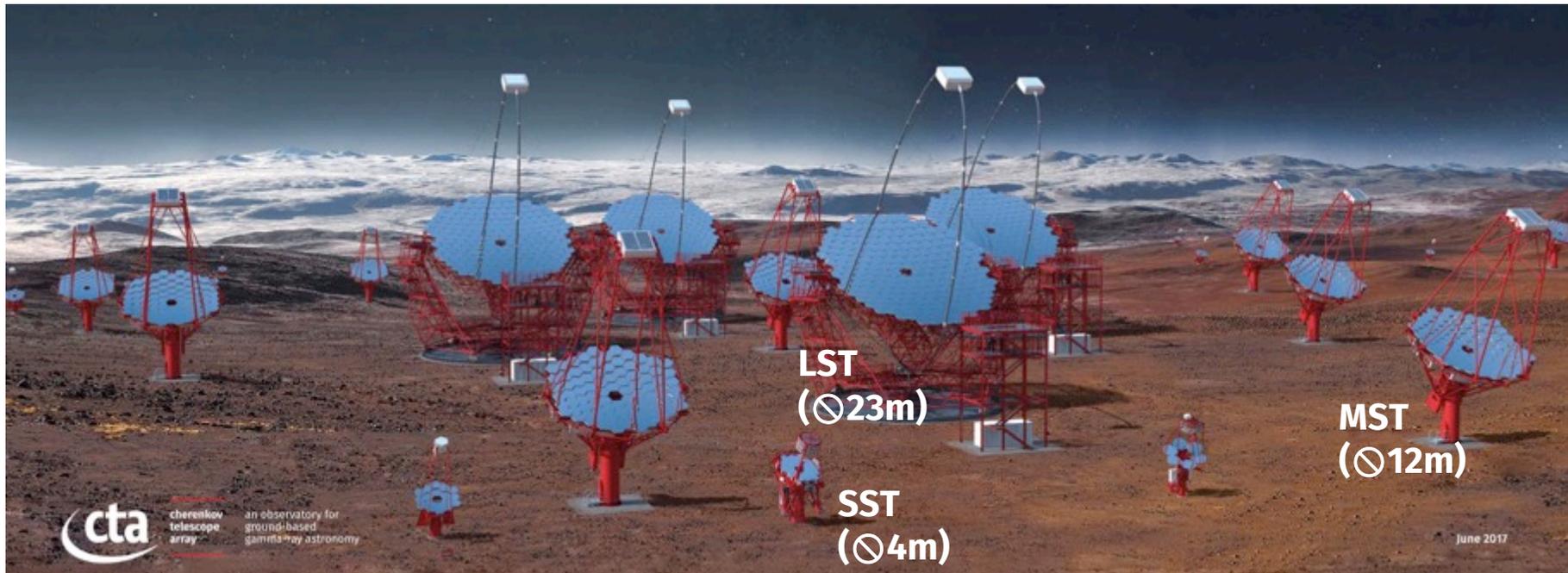
- Few MeV – GeV domain, polarimetry
- Pair conversion telescope
- Tracker combined with magnetic spectrometer to fit into 60 kg payload allocation
- Submitted unsuccessfully to joint ESA/CAS small mission call

# Ground-based projects

Parameter	CTA	HAWC	HiSCORE	LHAASO	MACE
Site(s)	Paranal (Chile) / La Palma (Spain)	Sierra Negra (Mexico)	Tunka Valley (Russia)	Daocheng (China)	Hanle (India)
Altitude (m)	2150 / 2200	4100	675	4300	4270
Latitude	-24.6° / +28.8°	19°N	51.8°N	29°N	32.8°N
Start of operations	2023	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.
$A_{\text{eff}}$ (m <sup>2</sup> )	$3 \times 10^6$	30 000	$10^8$	$8 \times 10^5$ (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**

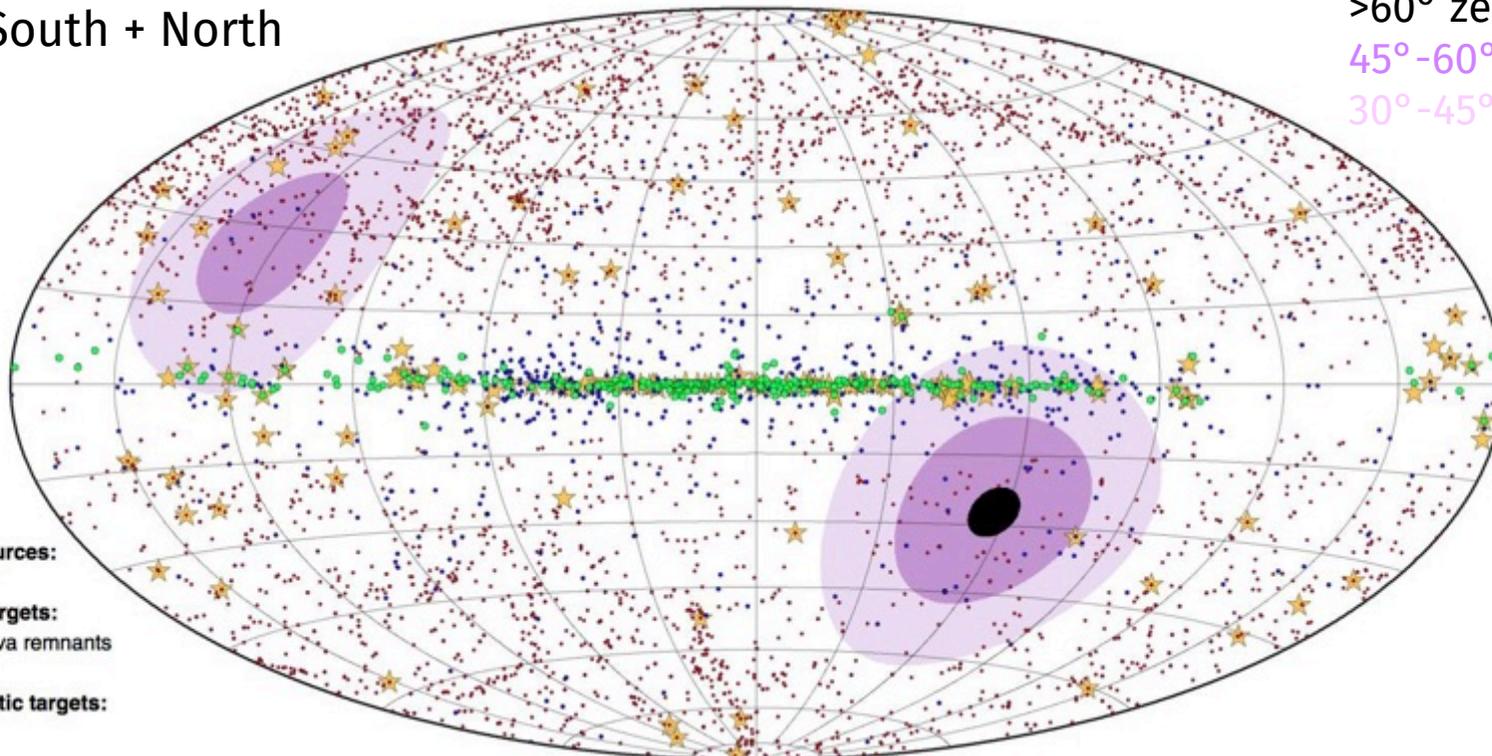
# Cherenkov Telescope Array



# All Sky coverage

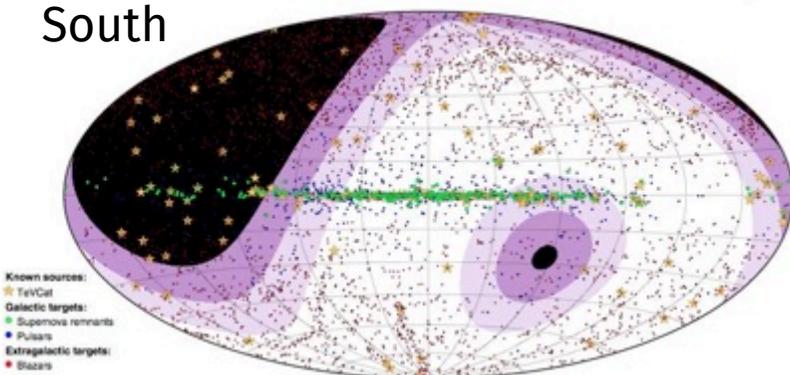
South + North

>60° zenith  
45°-60°  
30°-45°



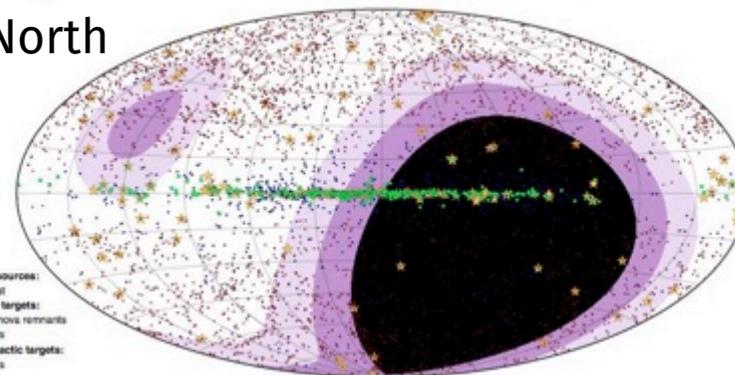
- Known sources:**
- ★ TeVCat
- Galactic targets:**
- Supernova remnants
- Pulsars
- Extragalactic targets:**
- Blazars

South



- Known sources:**
- ★ TeVCat
- Galactic targets:**
- Supernova remnants
- Pulsars
- Extragalactic targets:**
- Blazars

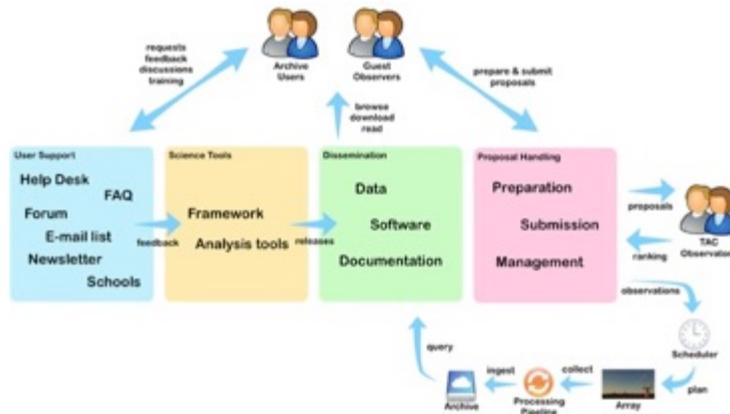
North



- Known sources:**
- ★ TeVCat
- Galactic targets:**
- Supernova remnants
- Pulsars
- Extragalactic targets:**
- Blazars

# Cherenkov Telescope Array

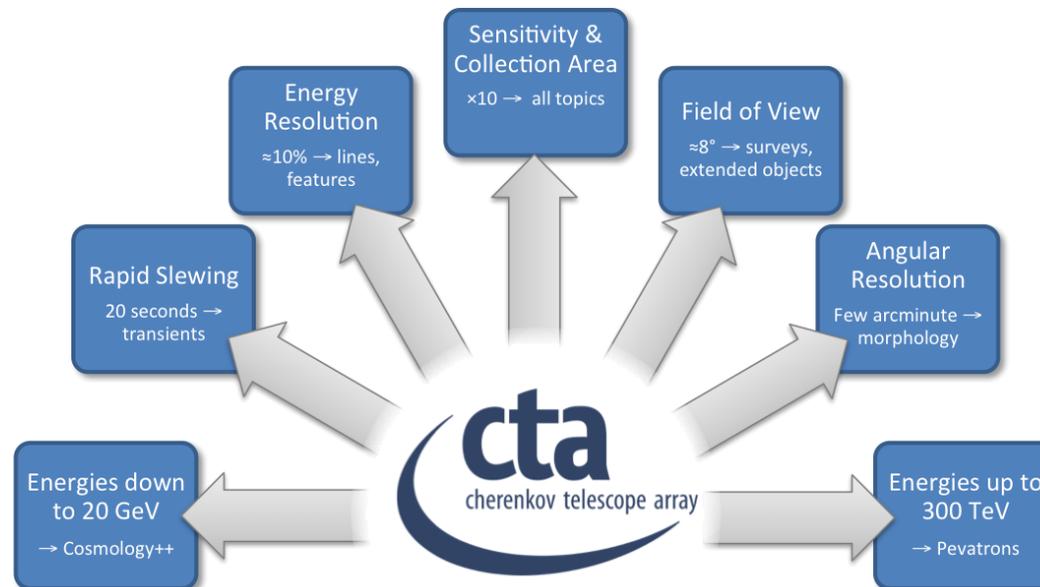
## An Open Observatory



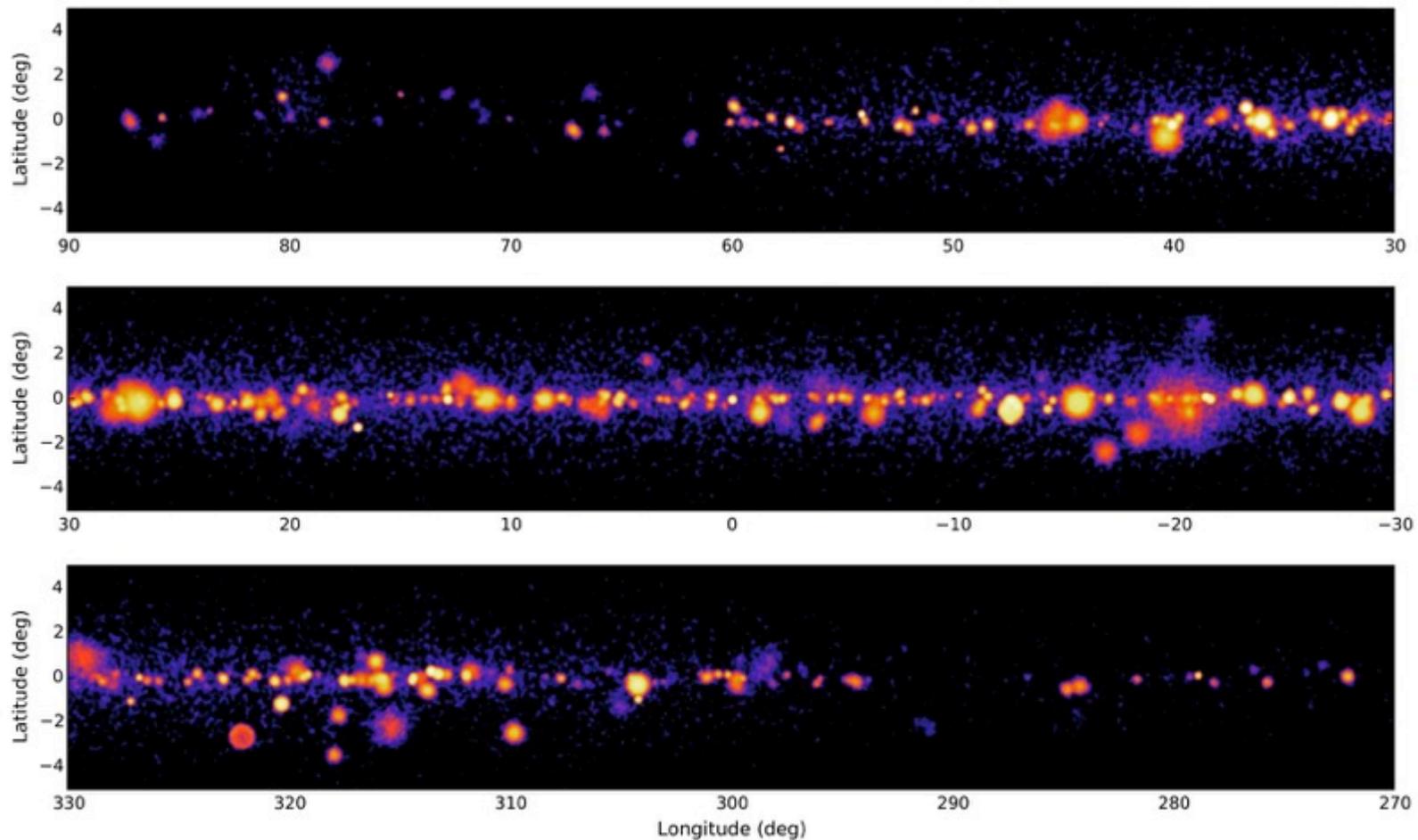
## A world-wide endeavour



## Improvements everywhere



# 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

- 23 m diameter
- 370 m<sup>2</sup> effective mirror area
- 28 m focal length
- 4.5° field of view

## Array layout

- South site: 4
- North site: 4

## Status

- Some elements prototyped
- Telescope prototype under construction in La Palma (<http://www.lst1.iac.es/webcams.html>)



20 July 2017

# Medium size telescopes



## Science drivers

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

## Characteristics

- 12 m diameter
- 90 m<sup>2</sup> effective mirror area
- 16 m focal length
- 8° field of view

## Array layout

- South site: 25
- North site: 15

## Status

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

# Small size telescopes



**SST 1M**

## Characteristics

- 4 m diameter
- 7.5 m<sup>2</sup> effective mirror area
- 5.6 m focal length
- 9° field of view

## Status

- Prototype telescope built
- Camera prototype under commissioning



**ASTRI**

## Characteristics

- 4.3 m primary diameter
- 1.8 m secondary diameter
- 6 m<sup>2</sup> effective mirror area
- 2.2 m focal length
- 9.6° field of view

## Status

- Prototype telescope built
- Camera prototype installed



**GCT**

## Characteristics

- 4 m primary diameter
- 2 m secondary diameter
- 6 m<sup>2</sup> effective mirror area
- 2.3 m focal length
- 8.6° field of view

## Status

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

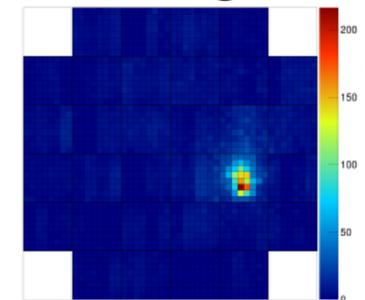
## Science drivers

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

## Array layout

- South site: 70
- North site: -

## First CTA light

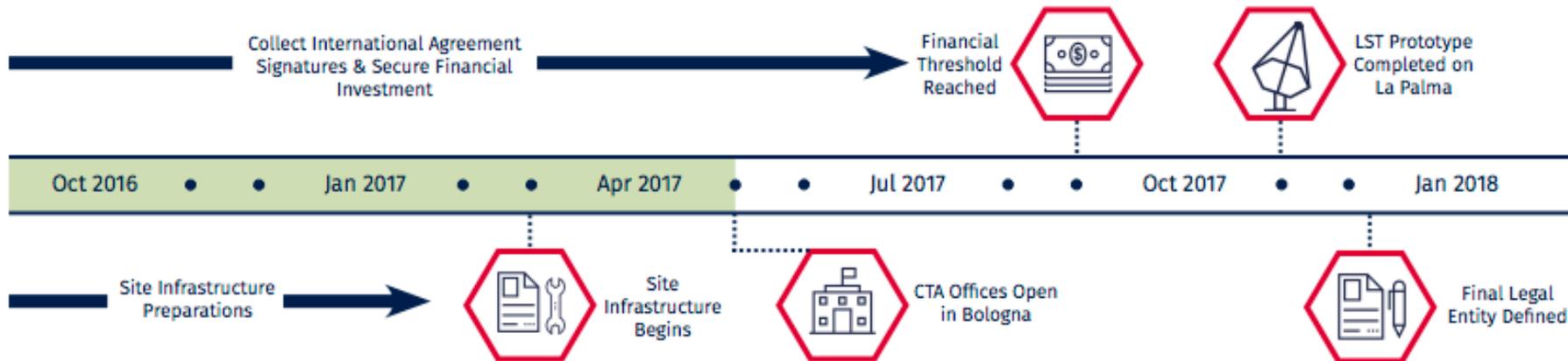


# Calendar

## Project Phases



## Current Phase



# Some other projects

## HiSCORE



- Non-imaging air-shower Cherenkov light-front sampling
- Up to 100 km<sup>2</sup> 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



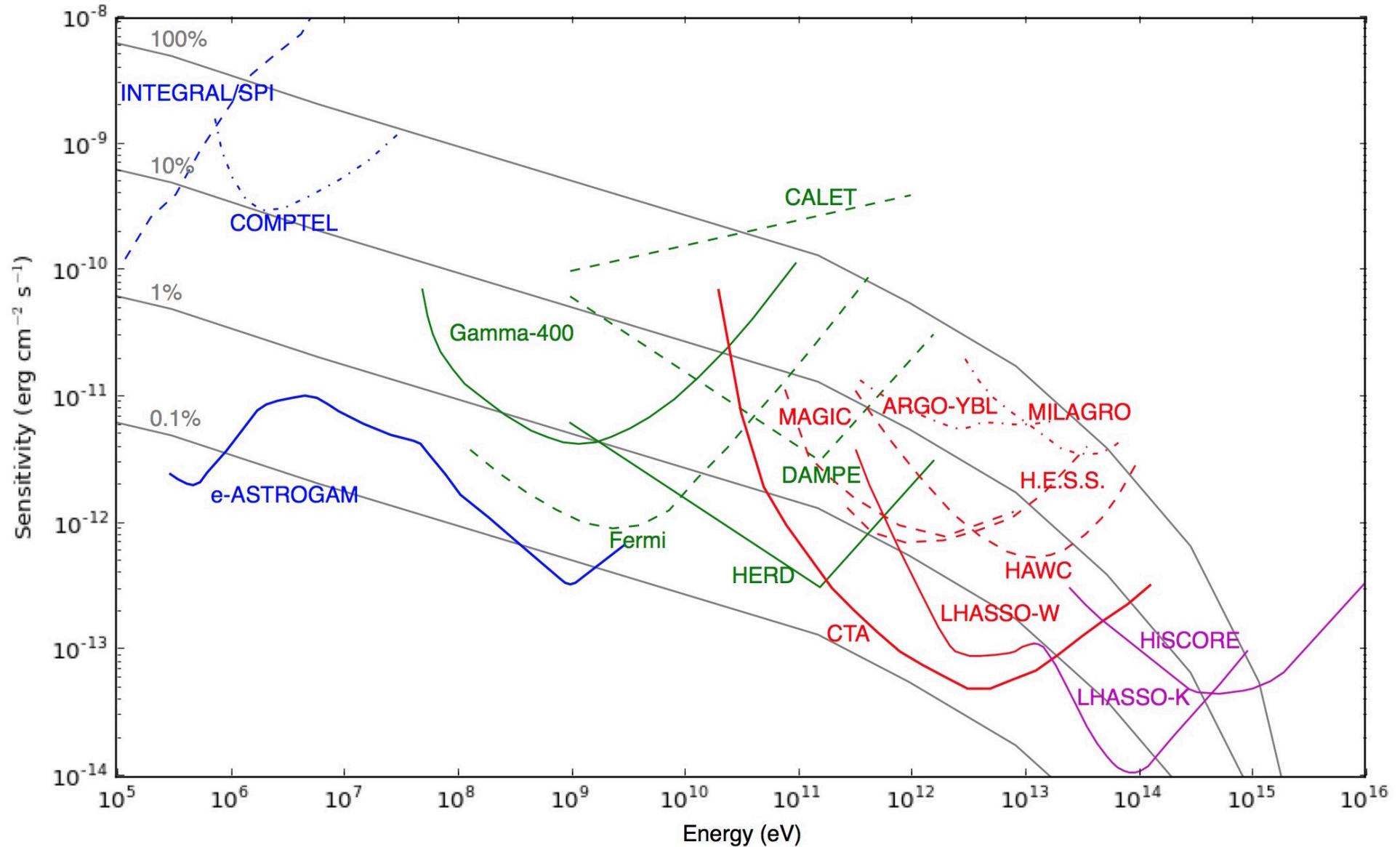
- Hybrid detector array
- Gamma ray detectors
  - Large (4 x HAWC) Water Cherenkov detector array (0.1-30 TeV)
  - Electromagnetic particle detectors and muon detectors (30-1000 TeV)

## MACE

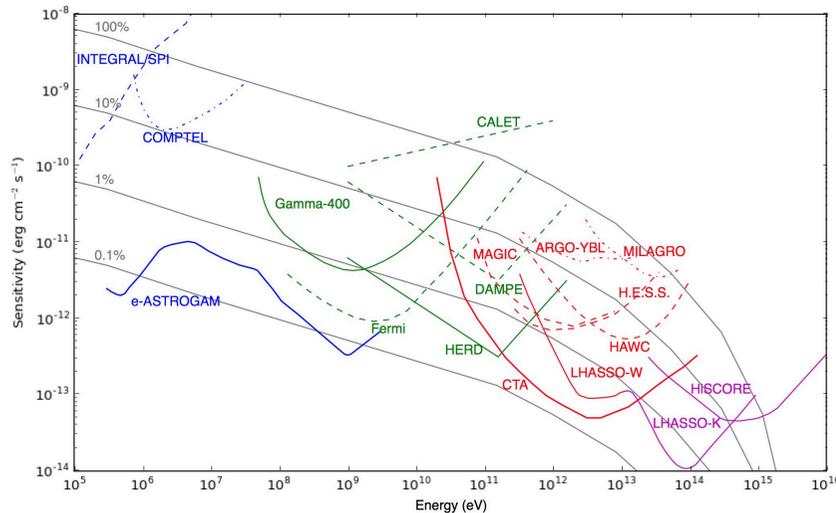


- 21 m diameter IACT to be installed at Hanle (4270 m a.s.l.)
- Design inspired from MAGIC

# Sensitivity: past – present – future



# Conclusions



## 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

## 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

