Gamma-Ray Astronomical Experiments

Gordon Research Conference
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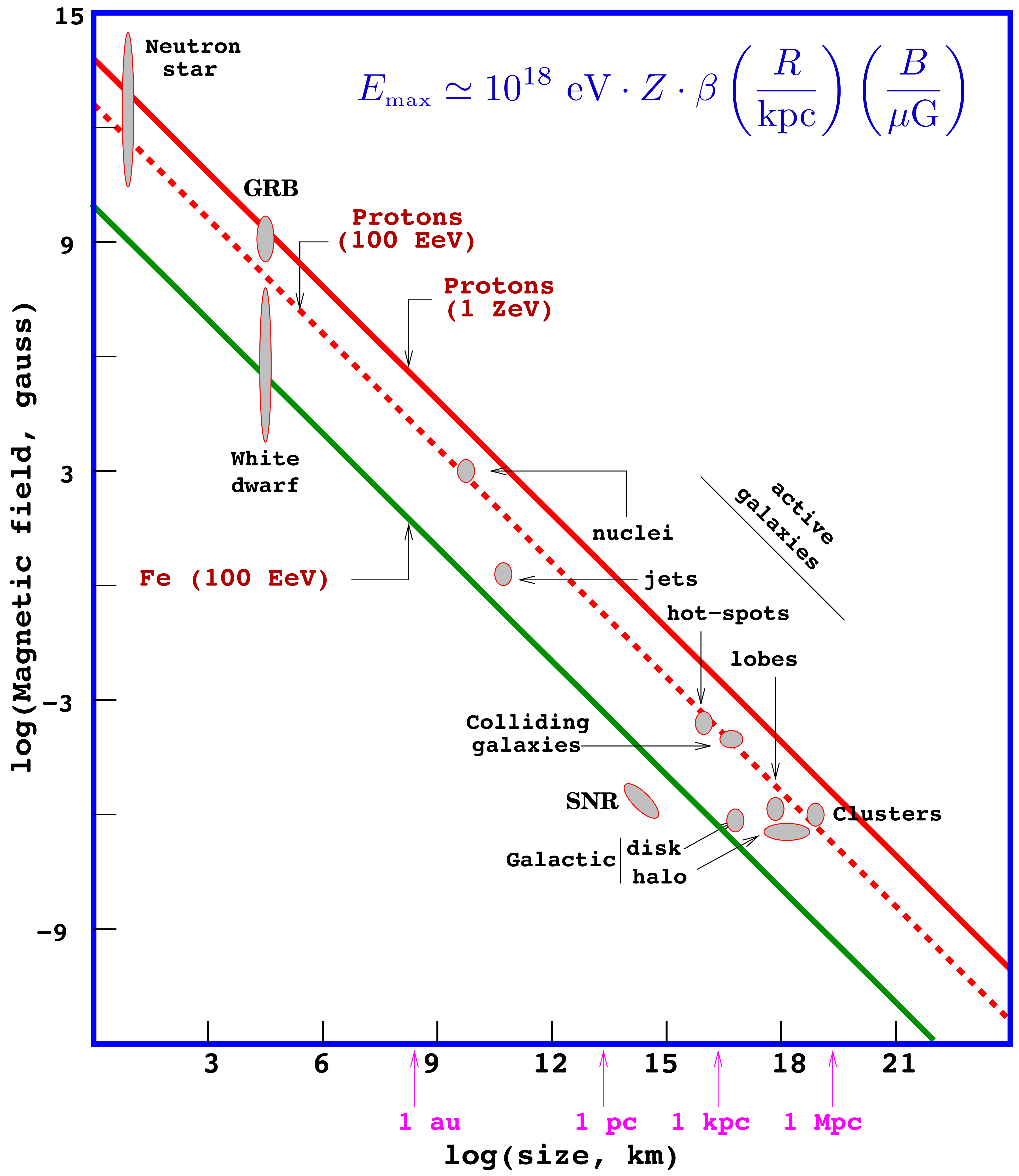
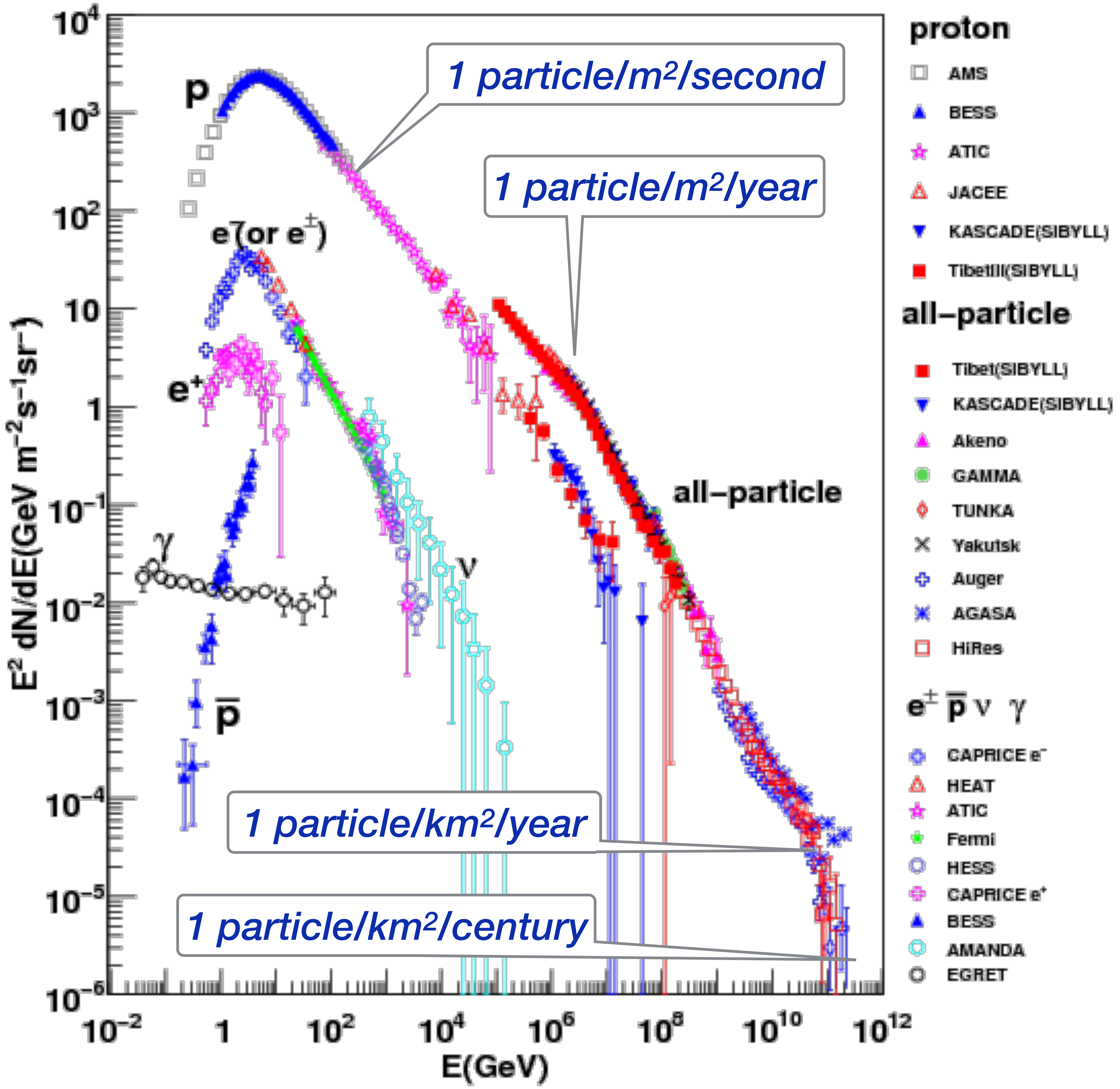
FACULTÉ DES SCIENCES

What we know/guess of about cosmic rays





- *In the end CRs are the 4th substance of the visible Universe (after the matter, radiation and magnetic fields)*

γ-ray Science

- **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 cherenkov telescope array

What we can learn from γ-ray

Gamma ray flux composition

superposition of resolved point and diffuse sources, and of background diffuse emission of galactic/extragalactic origin

Very good E energy& angular Resolution

Stability of PSF over FoV
Large FoV, Duty Cycle

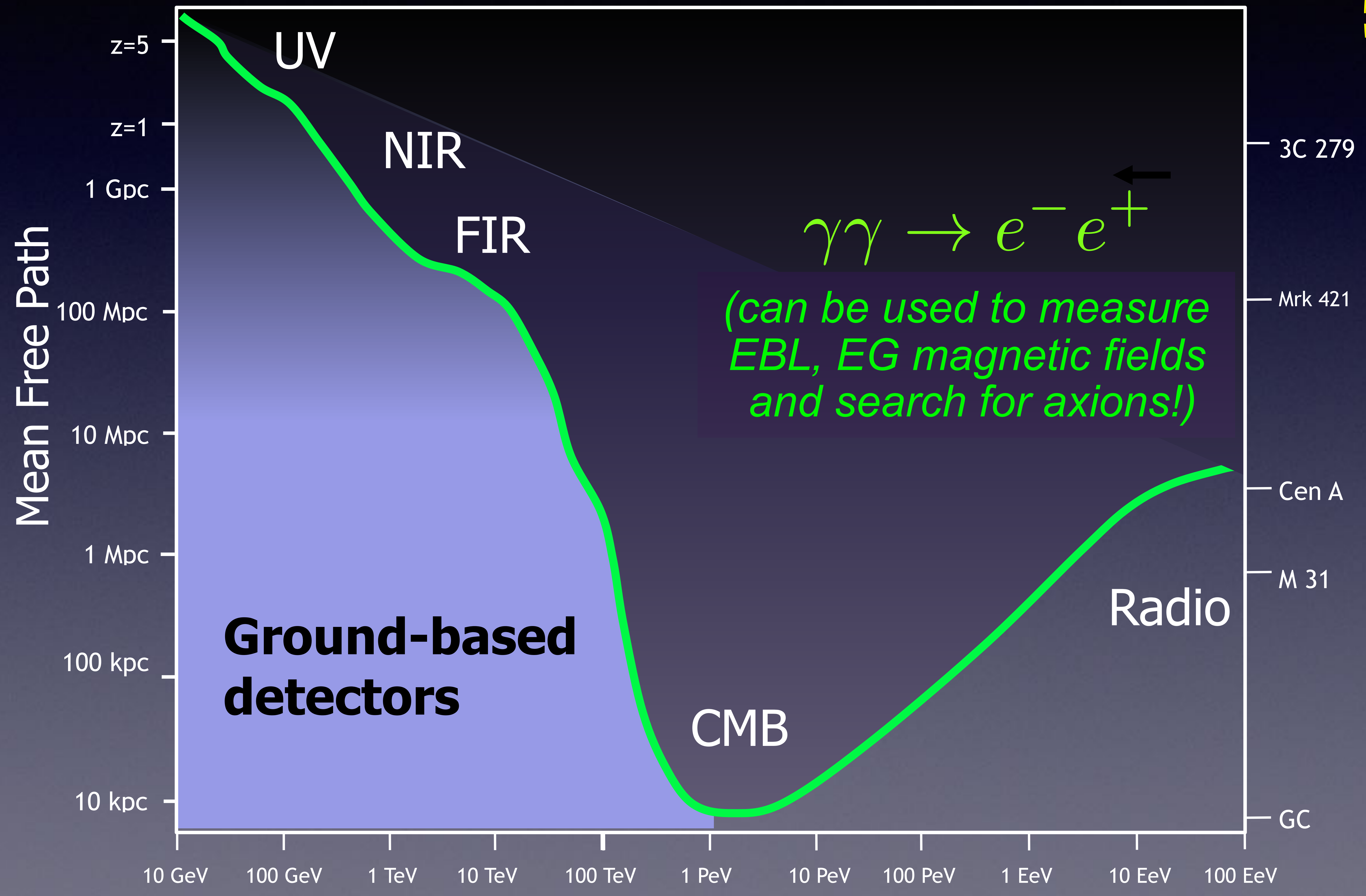
$$\phi_\gamma(E,\Omega) = \sum_{j\in\{\text{Galactic}\}} \phi_j(E,\Omega_j) + \phi^{\text{Galactic}}_{\text{diffuse}}(E,\Omega)$$

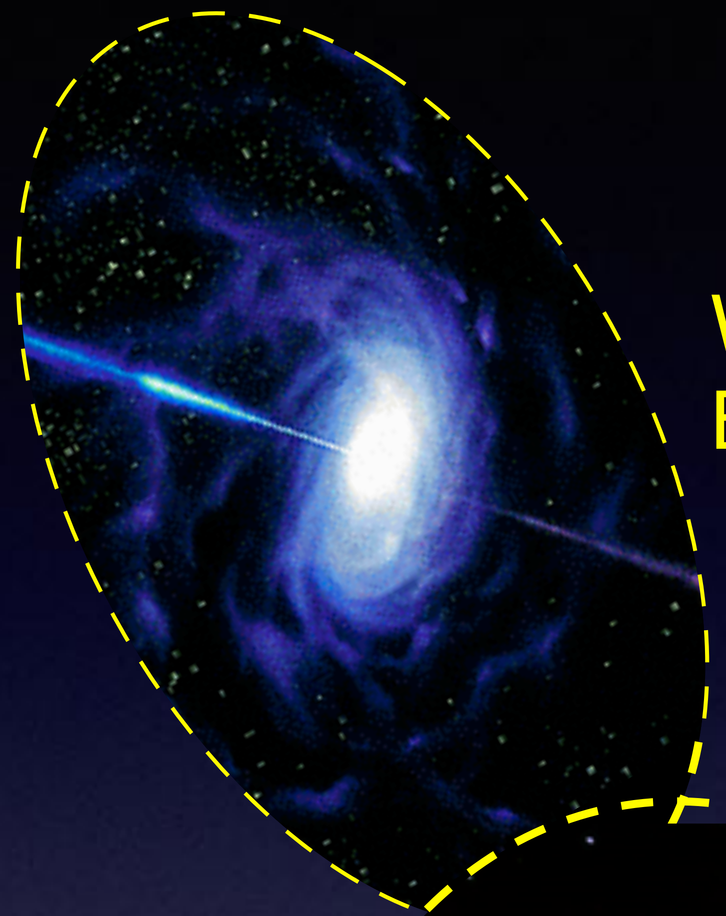
$$+ \sum_{j\in\{\text{Extragalactic}\}} \phi_j(E,\Omega_j) + \phi^{\text{Extragalactic}}_{\text{diffuse}}(E,\Omega)$$

Sinergy!

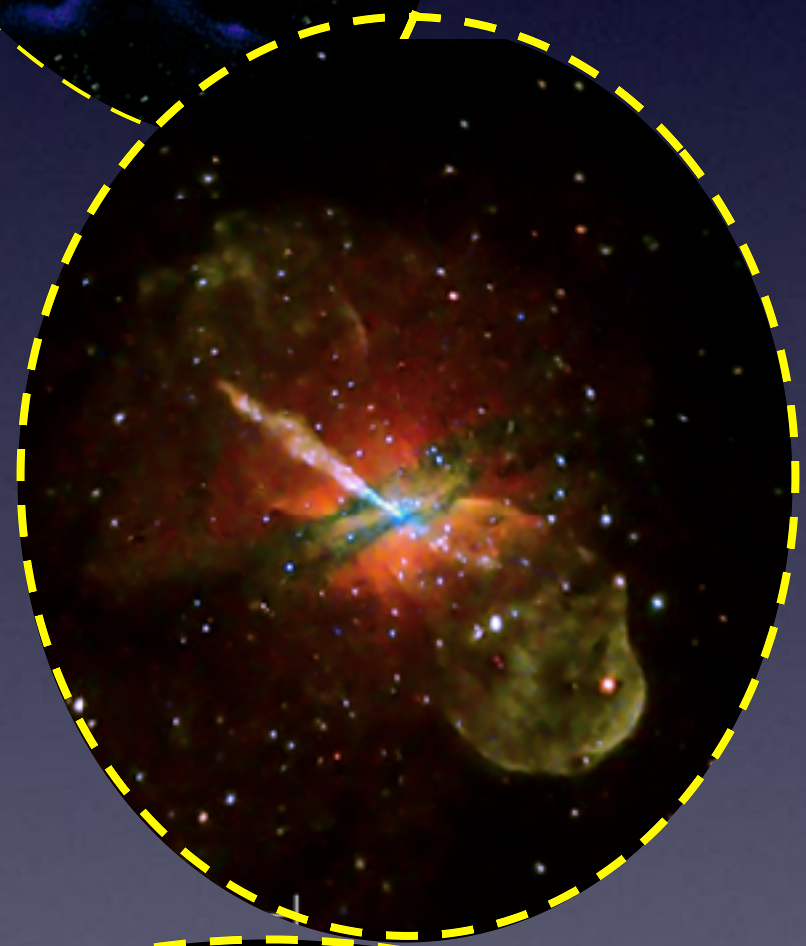
$$\phi^{\text{Extragalactic}}_{\text{diffuse}}(E,\Omega) = \phi^{\text{Extragalactic}}_{\text{unresolved sources}}(E) + \phi^{\text{Extragalactic}}_{\text{diffuse}}(E,\Omega)$$

How far can we see: the γ Horizon

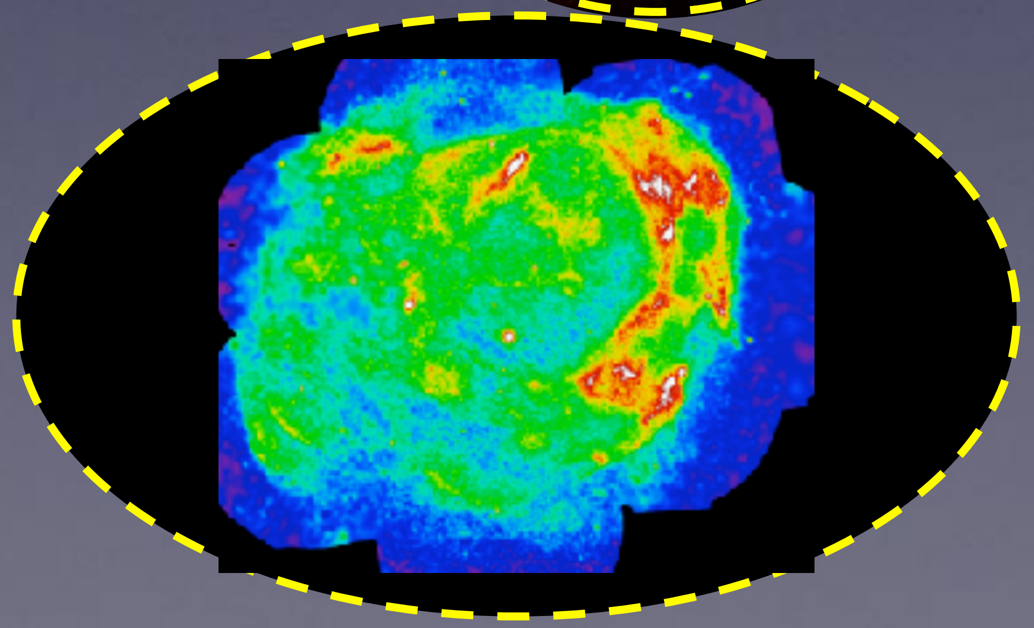




Whole universe visible
Beamed sources, time variability



Precision study of local EG sources, resolved morphology



Precision study of Galactic CR sources, up to the knee

The atmosphere is a calorimeter

Isothermal Hydrostatic atmosphere

$\rho(z) = \rho_0 e^{-z/z_0}$ $\quad z_0 = RT/gM = 8.4\ km$

1st Interaction:

$X_0 \simeq 37\ g/cm^2$

$\lambda_{pair} = 9/7\ X_0 \simeq 50\ g/cm^2$

$X = X_A\ e^{-z/z_0}$ and $X_A \simeq 10^3\ g/cm^2$

$z_{pair} = z_0 \ln(X_A/\lambda_{pair})$ ➡ $25\ km$

Shower Max

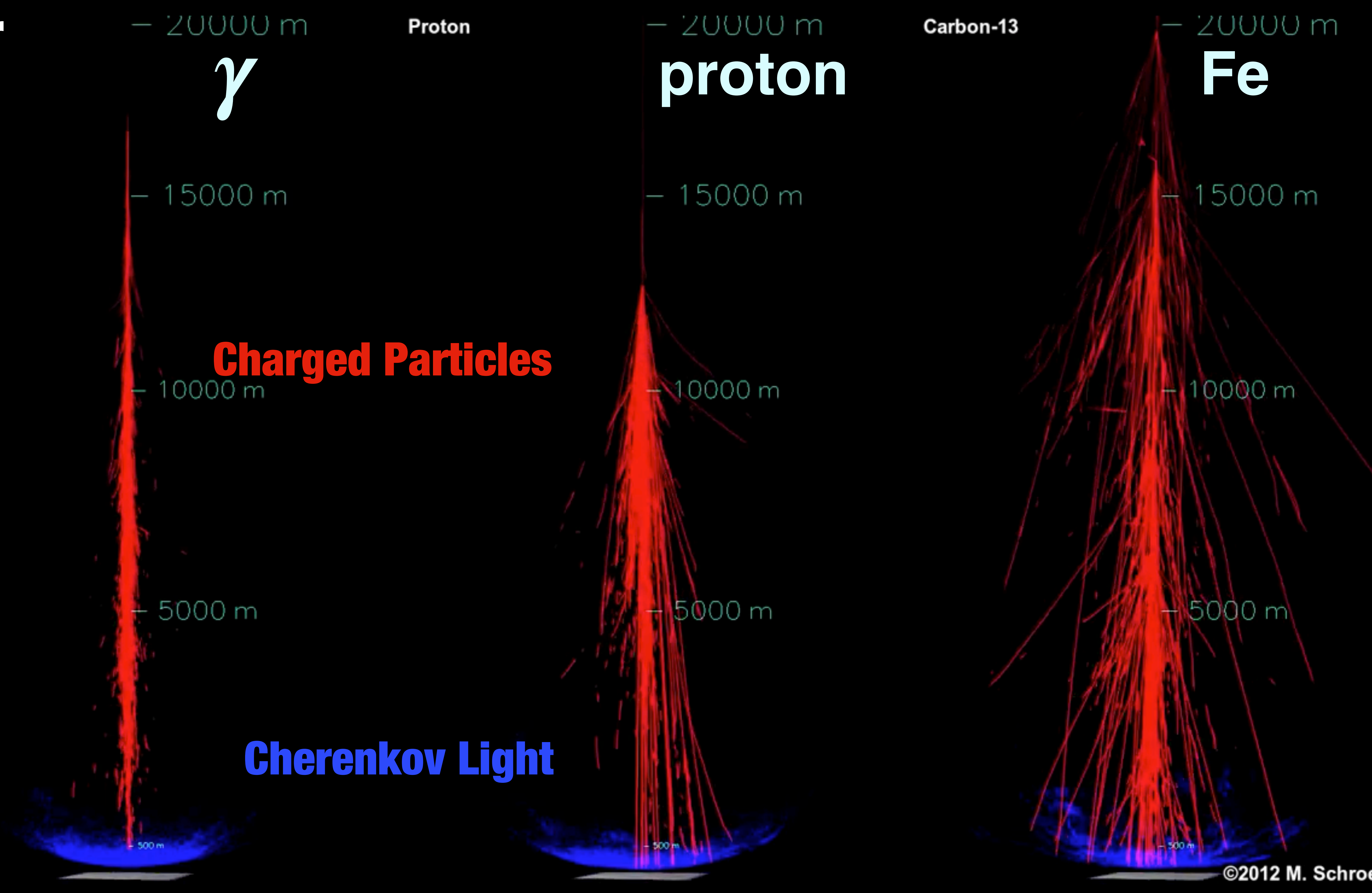
$X_{max} \simeq X_0\ \ln(E/E_C)/\ln 2$

$z_{max} = z_0 \ln(X_A/X_{max})$

$30\ GeV$ ➡ $12\ km$

$1\ TeV$ ➡ $8\ km$

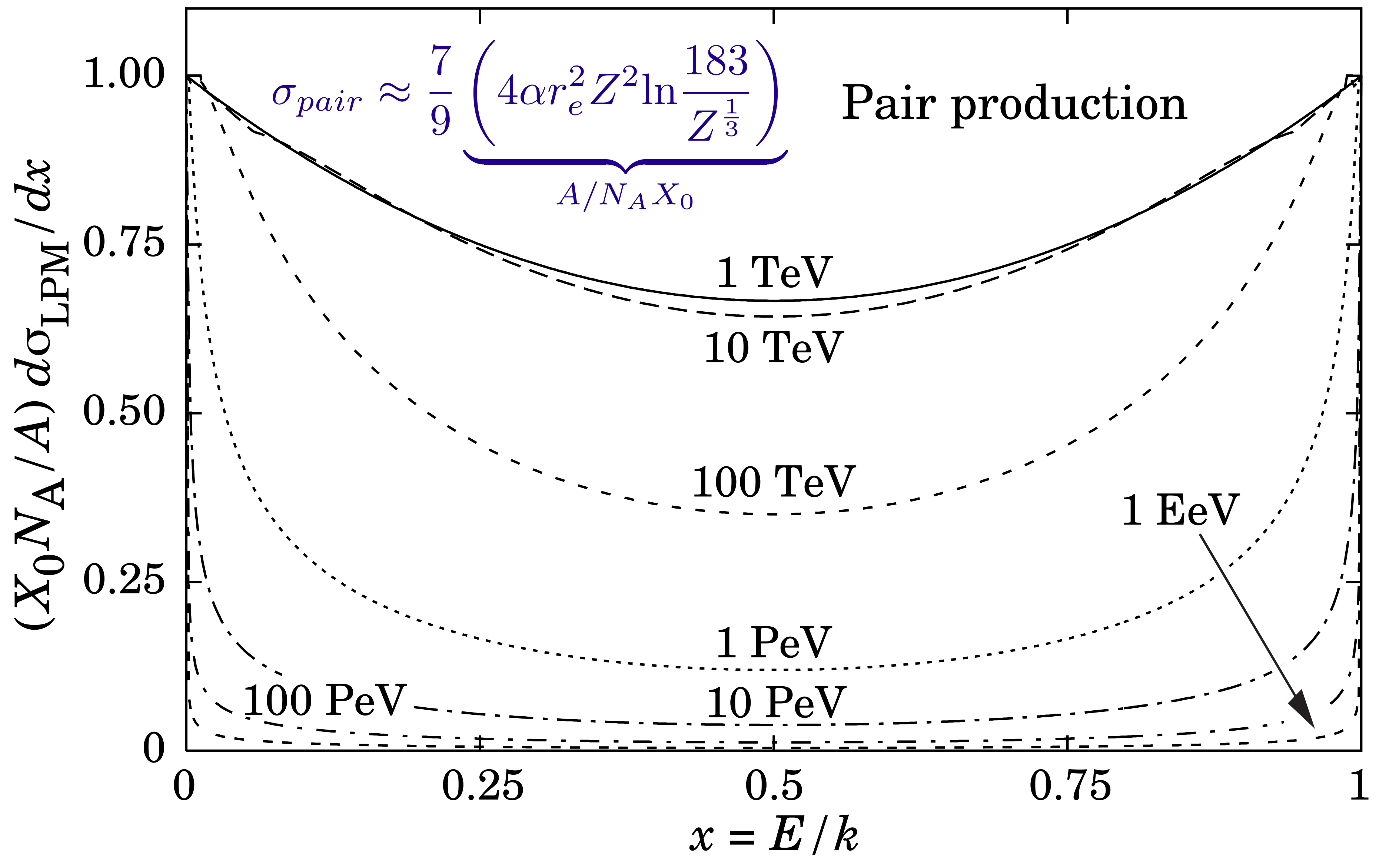
$1\ PeV$ ➡ $5\ km$



- For a vertical shower, it is a calorimeter of about ***26 X_0 (radiation length)*** and ***15 λ (interaction length)***
- ATLAS calorimeter has ***27 X_0. and 11 λ*** !

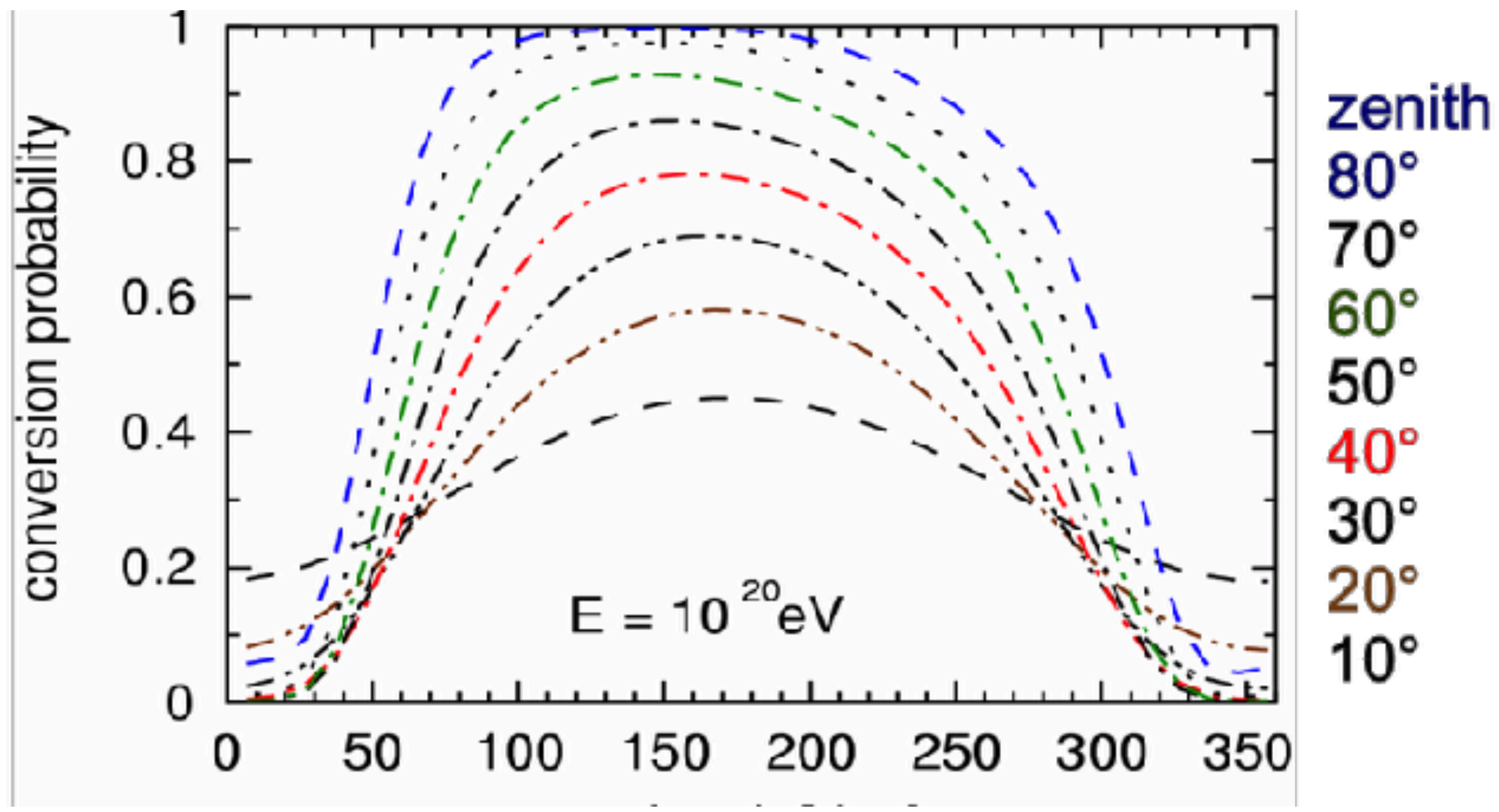
6

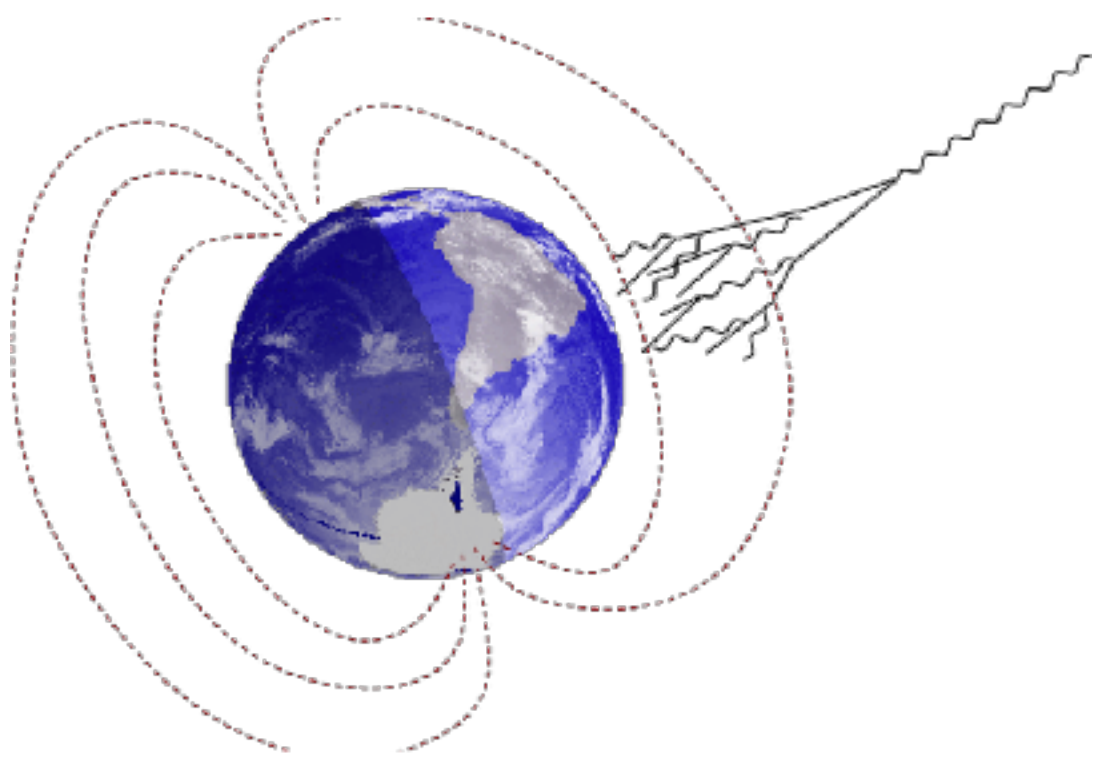
Landau-Pomeranchuk Migdal Effect

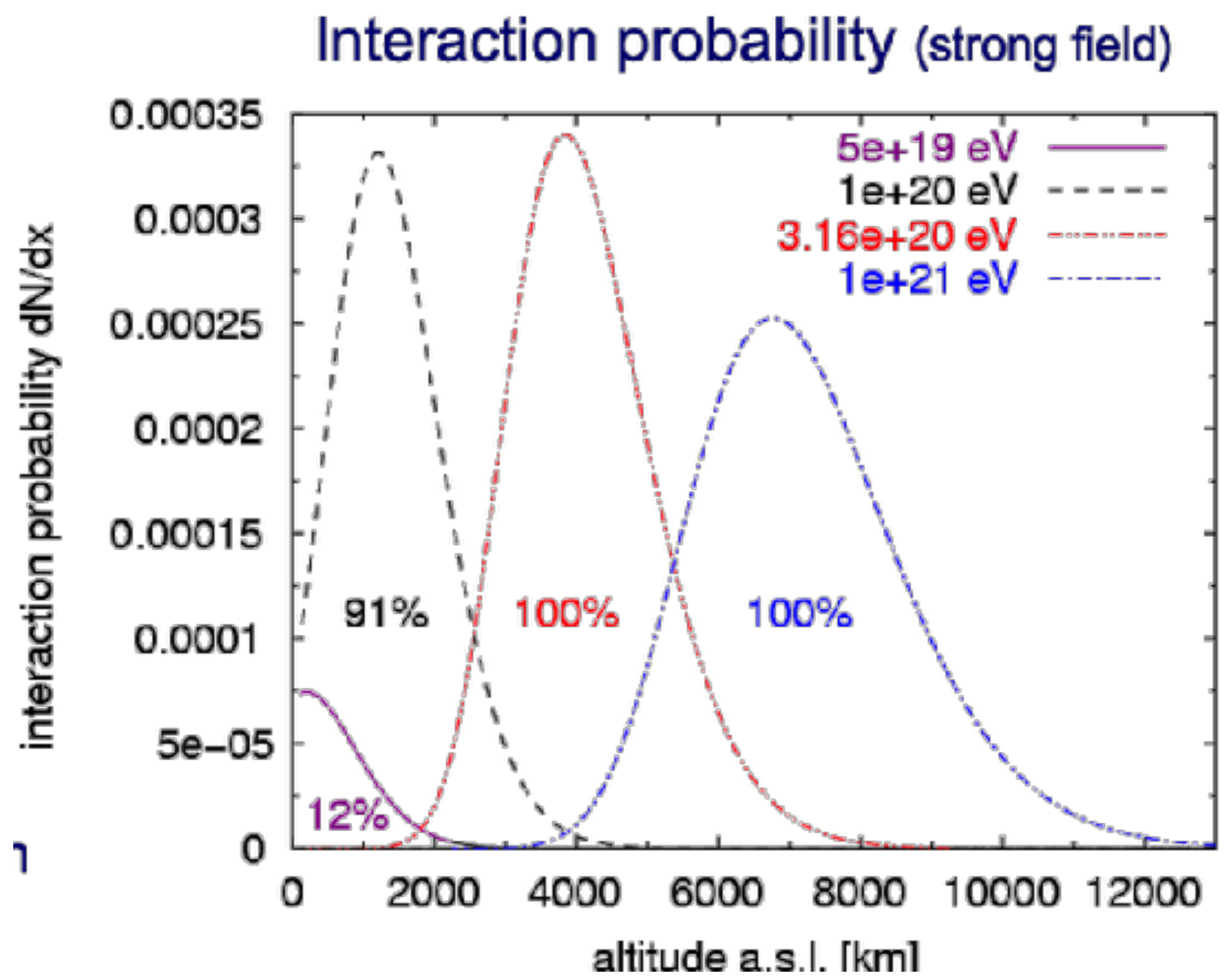


- at ultrahigh energies Landau Pomeranchuk Migdal effect:
  - quantum mechanical interference between amplitudes from different scattering centers;
  - relevant scale formation length - length over which highly relativistic electron and photon split apart.
  - interference (generally) destructive → reduced cross section for a given, very high photon energy
  - Effect visible for $E(1-x)>E_{LPM}$
  - $E_{LPM}=7.7\ X_0$ TeV/cm

Geomagnetic pre-Showering







A UHE gamma ray crossing magnetic field lines can produce, e± pair which synchrotron-radiate in the magnetic field, producing additional high-energy gamma rays.

A different cascade develops but the global effect is similar to adding some radiation lengths above the atmosphere

Ground-base Cosmic-ray physics

EAS Detectors
(HAWC, LHAASO)

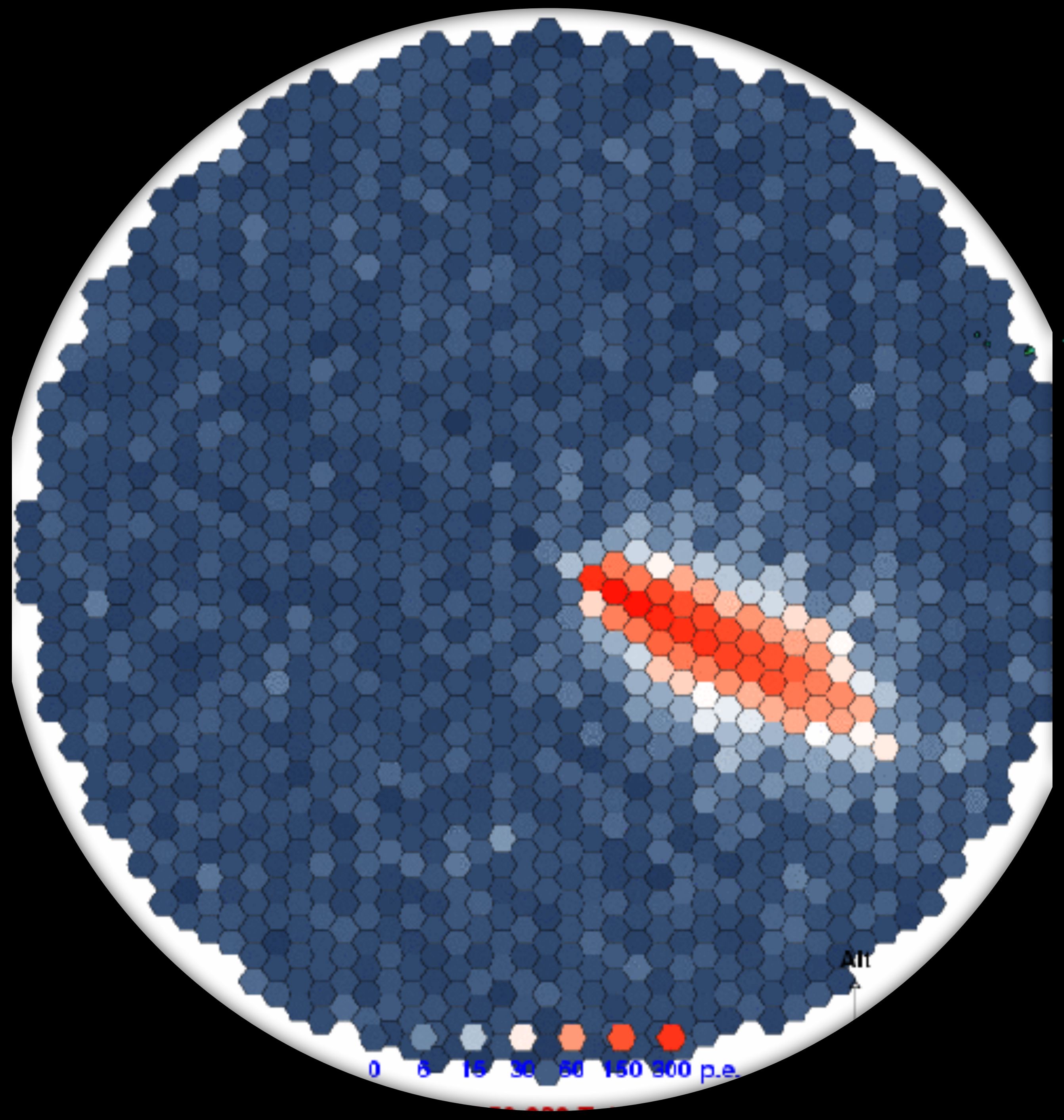
Cherenkov Telescopes
HESS, MAGIC,VERITAS, CTA

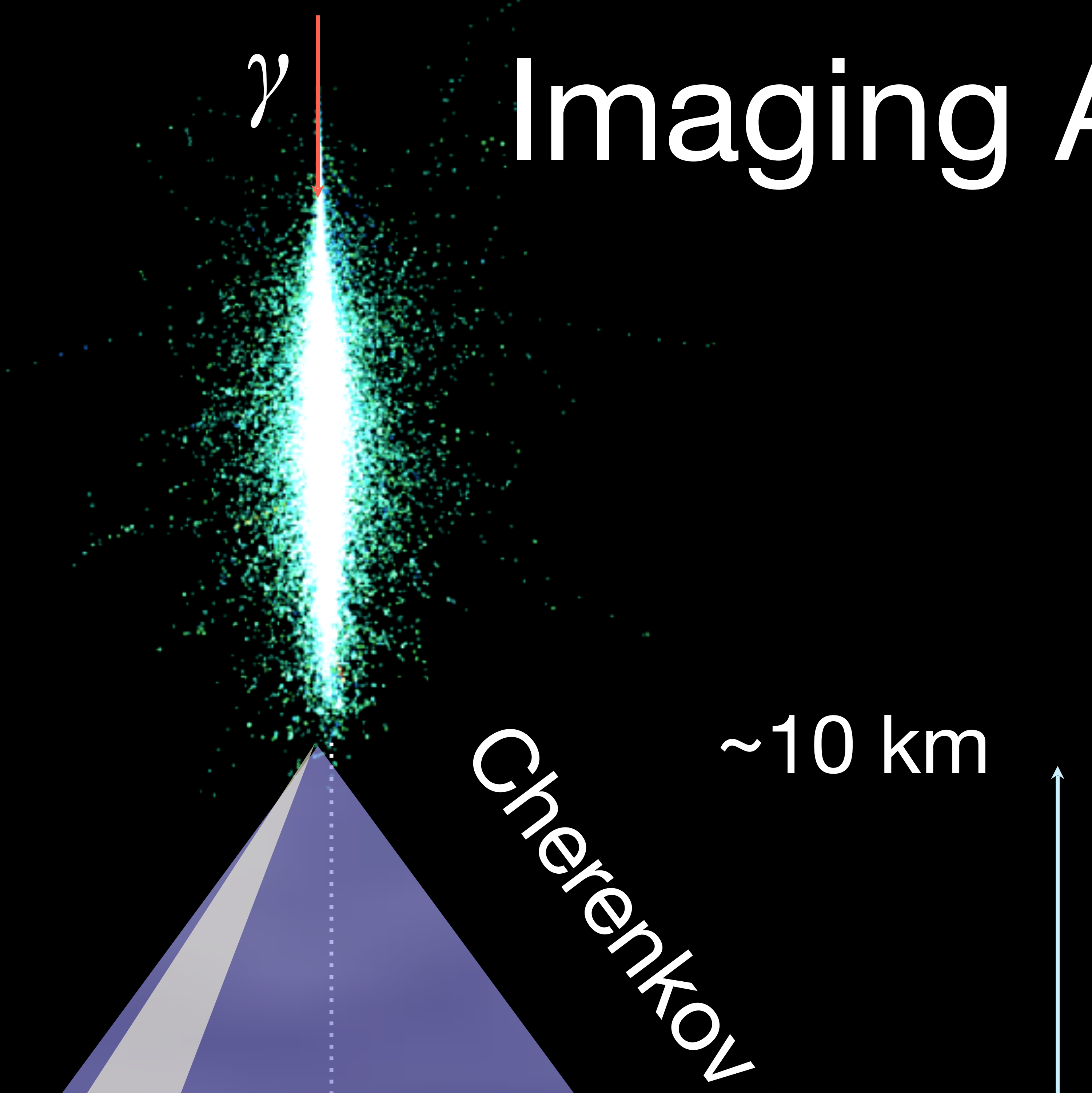
	EAS-D	IACT
Duty-Cycle	High (≈100%)	Low (≈10-15%)
Field-of-View	Large (2 sr)	Small (4-5 deg)
Sensitivity	Good Sensitivity (5-10% Crab flux)	High Sensitivity (< mCrab flux)
Maximum Energy	~ PeV	<100 TeV
Energy Resolution	Modest (~30-40%)	Very Good (~15%)
Energy Threshold	High (~TeV)	Very Low (~10 GeV)
Angular resolution	Good (0.2-0.8 deg)	Excellent (≈0.05 deg)
Effective Area	decrease with zenith	increase with zenith
Background rejection	Good (~80%)	Excellent (>99%)
Zenith dependence	Very Strong ($[\cos\vartheta]^7$)	Weak ($[\cos\vartheta]^{2.7}$)

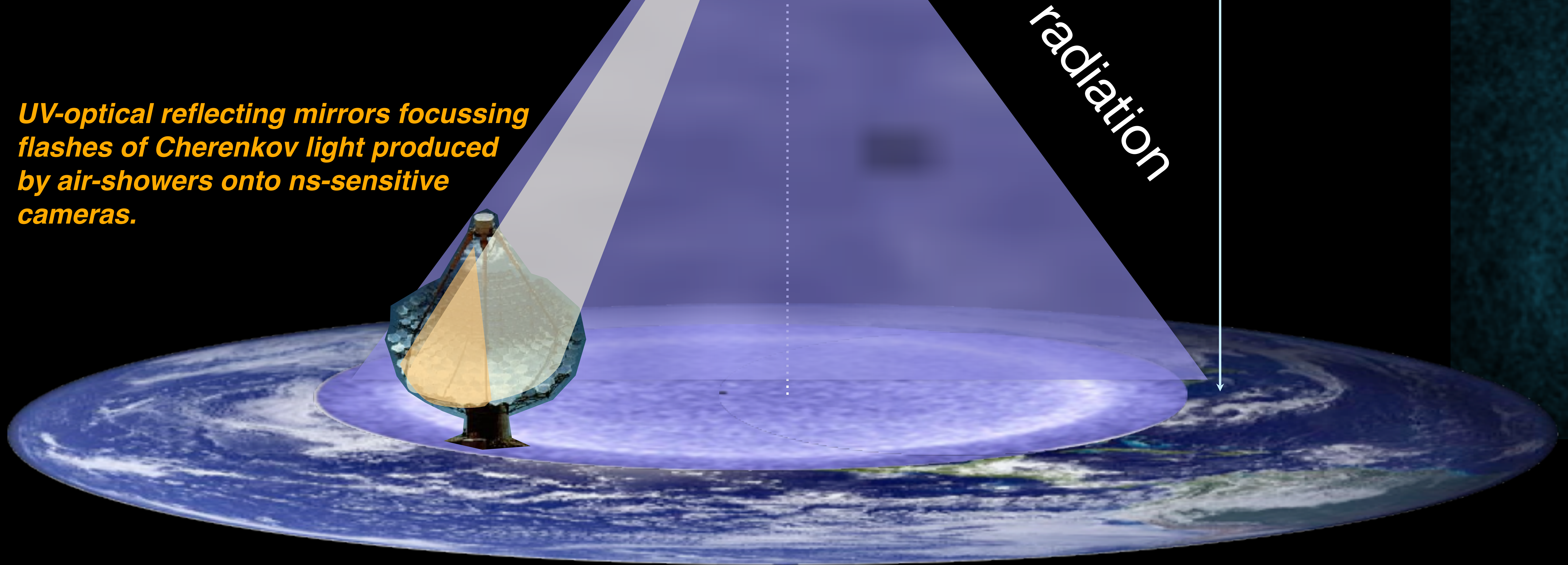

VERITAS
Arizona
MAGIC II
Canary Island
HAWC
Mexico
TIBET-AS
Pierre Auger
Argentina
H.E.S.S. Namibia


LHAASO
Sichuan - China
CTA
North - Canary Island
South - Paranal -Chile

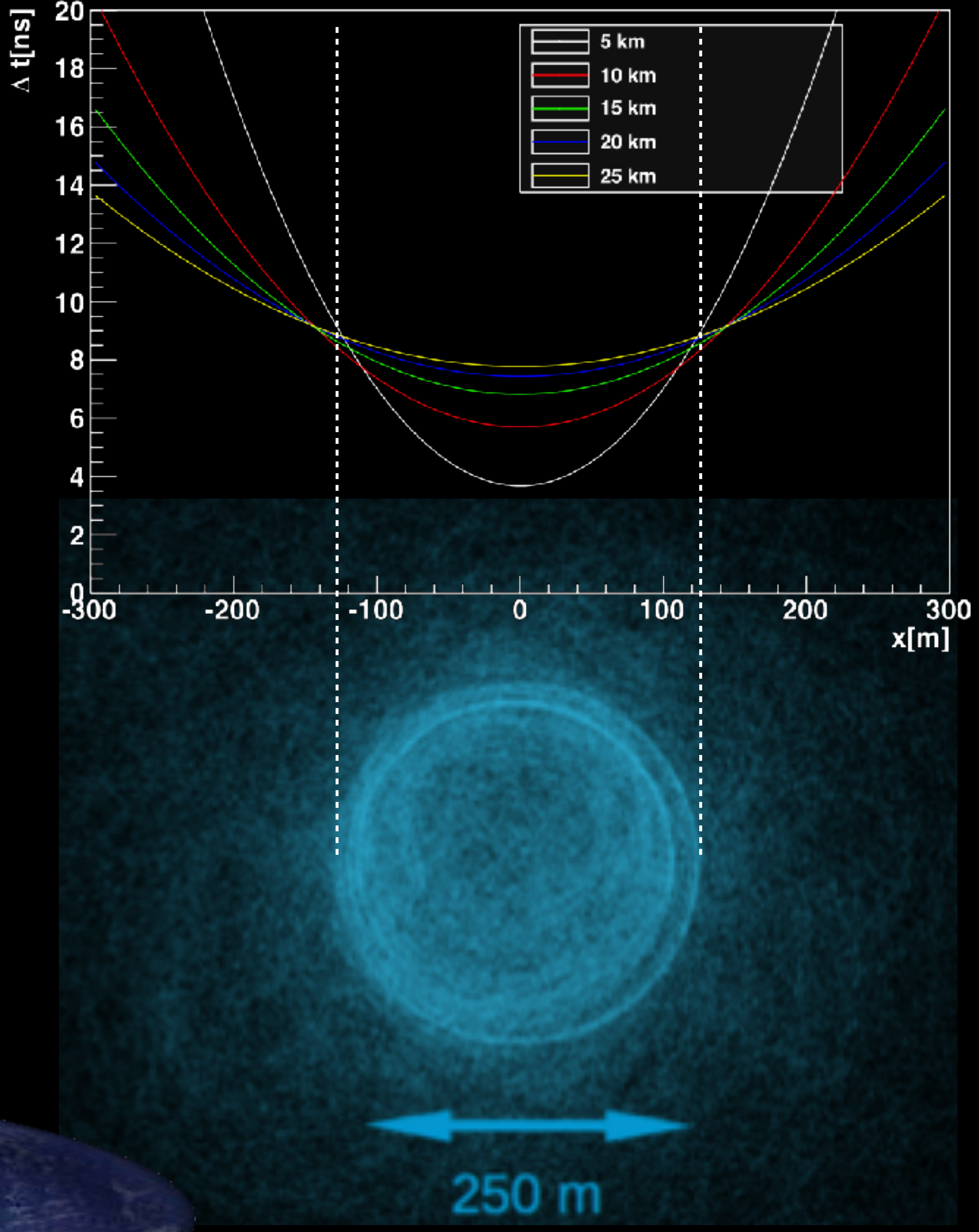
Imaging Air Cherenkov Telescope







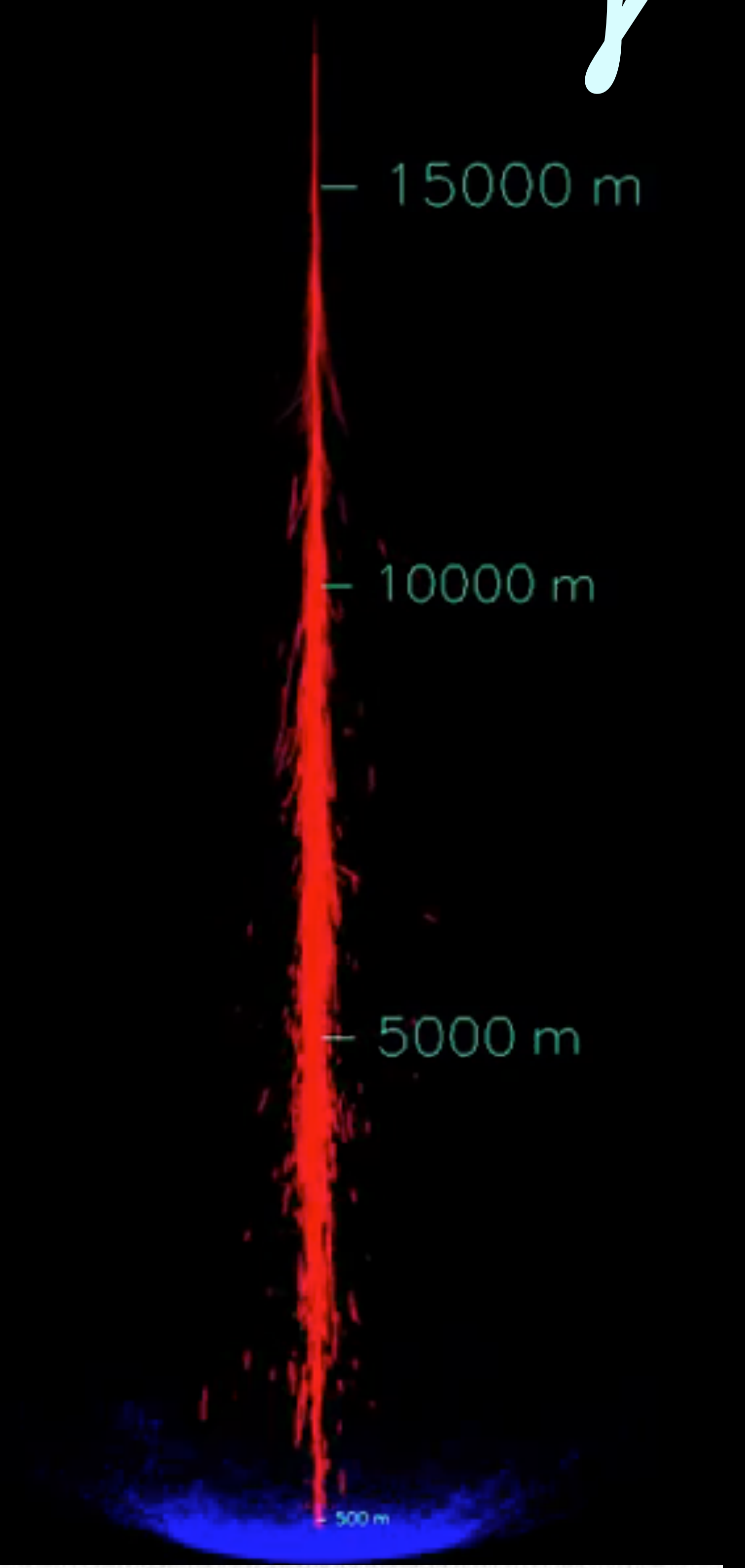
UV-optical reflecting mirrors focussing flashes of Cherenkov light produced by air-showers onto ns-sensitive cameras.

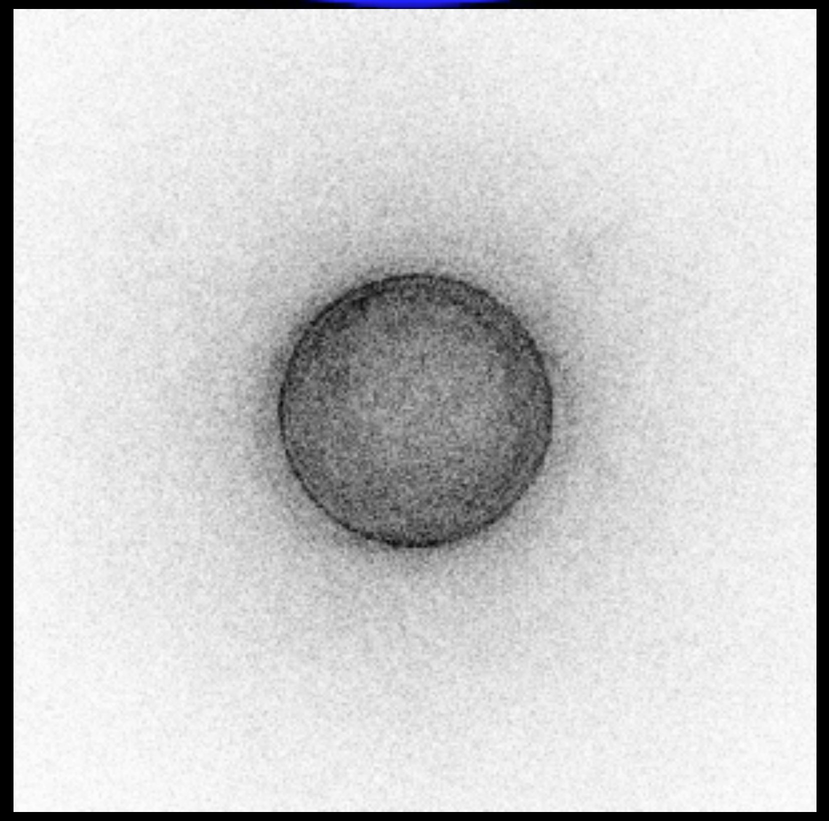


Light pool on ground

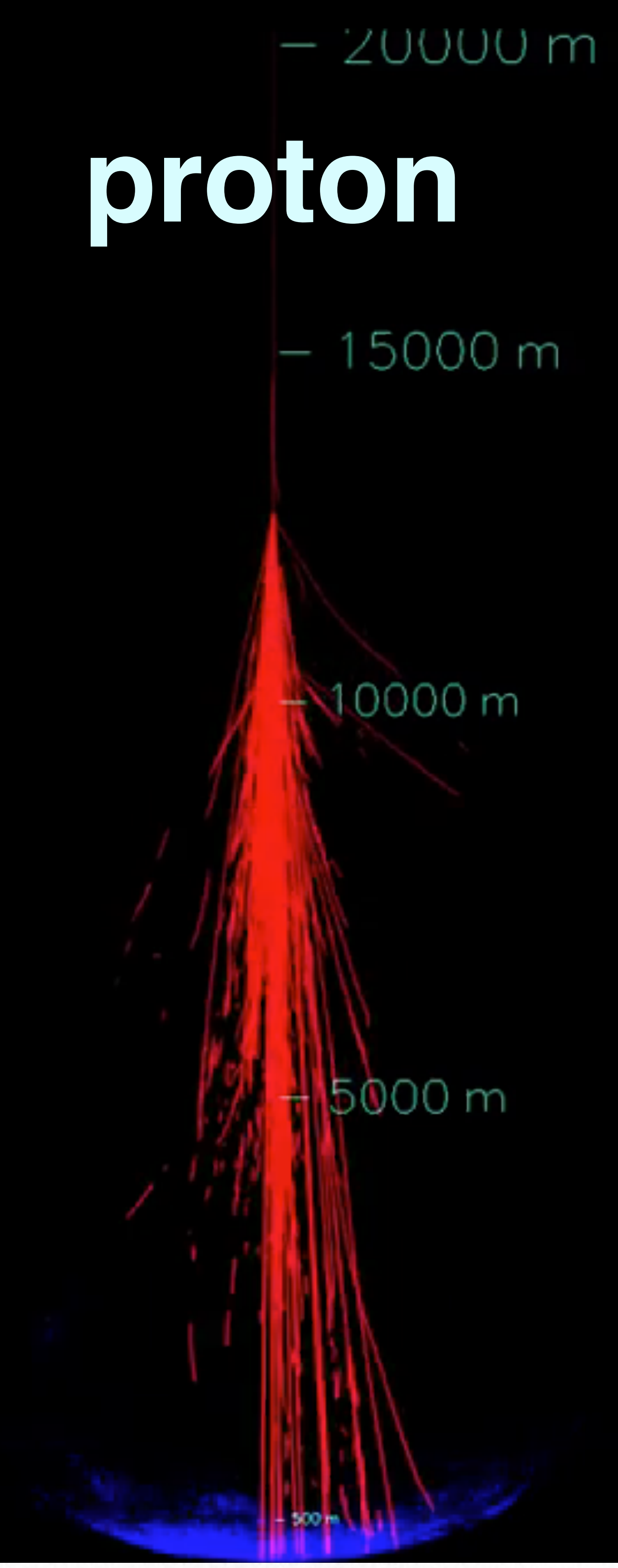
Hadrons/γ separation is fundamental

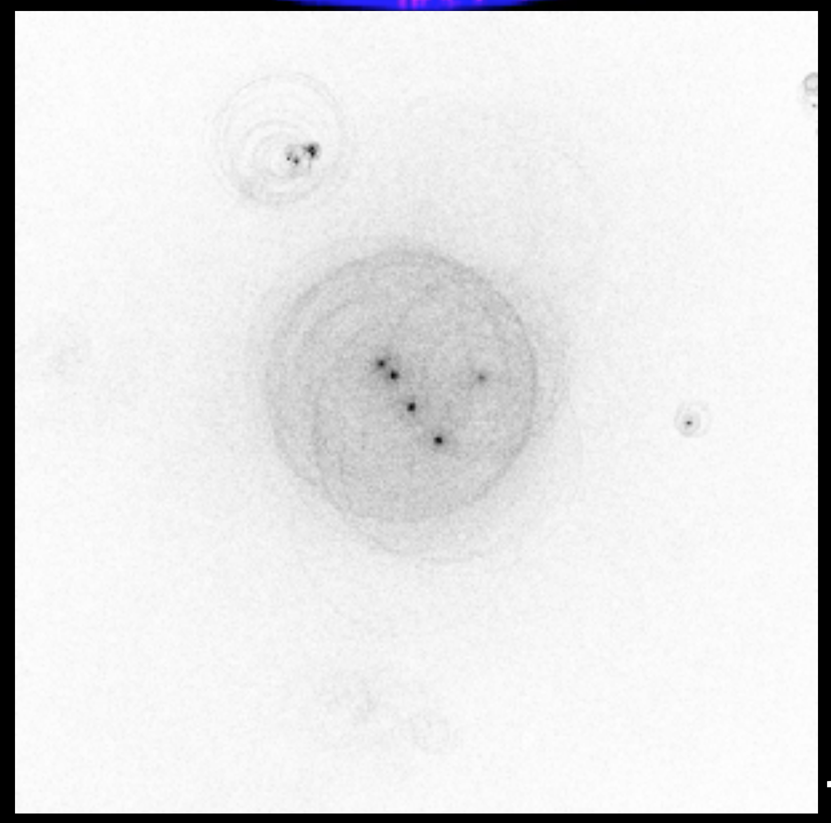
γ





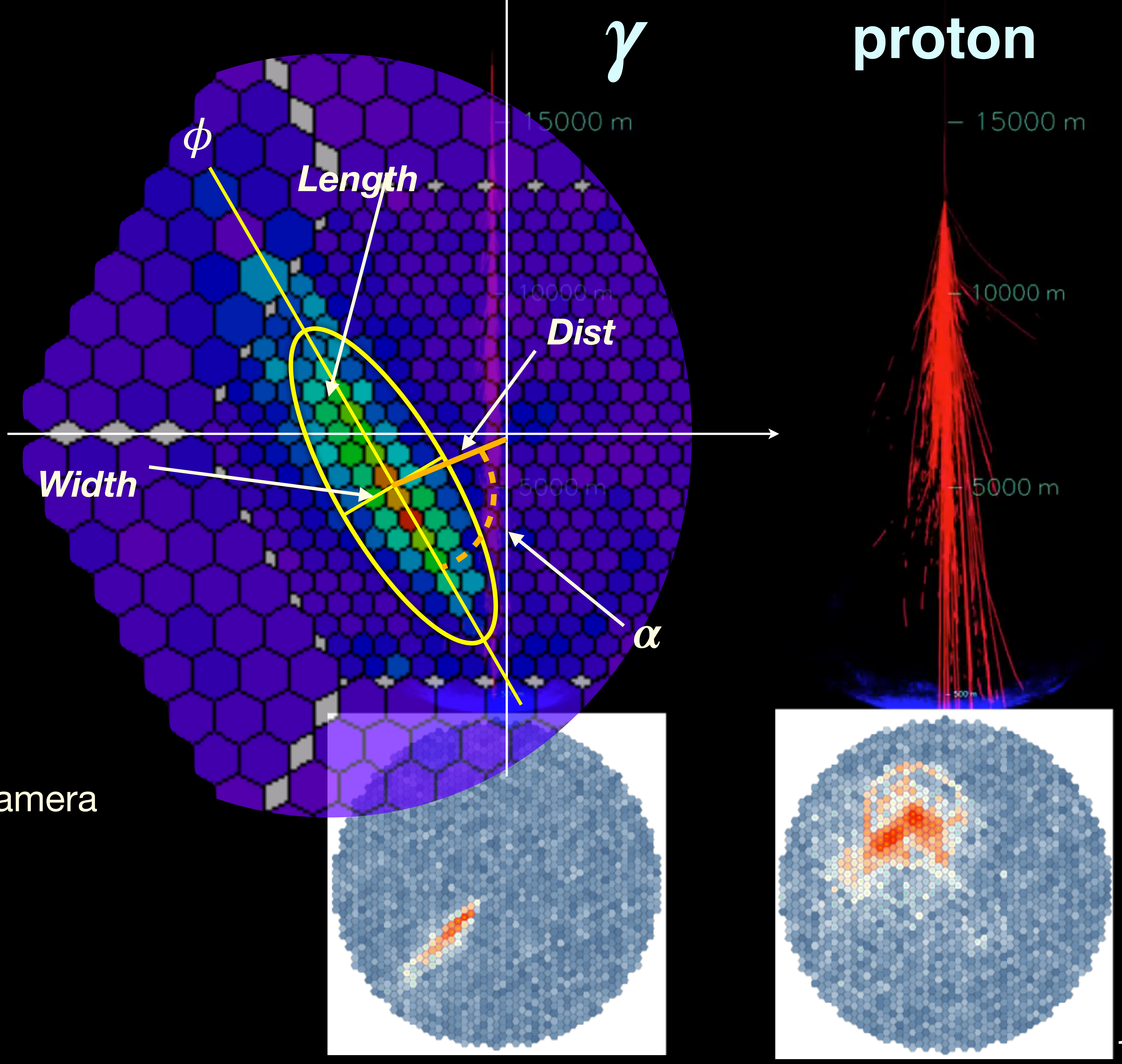
proton





Hadrons/γ separation is fundamental

Image Shape
↳ *Particle type*
Intensity of the Image
↳ *Shower Energy*
Orientation of the image
↳ *Shower Direction*



Hillas Parameters

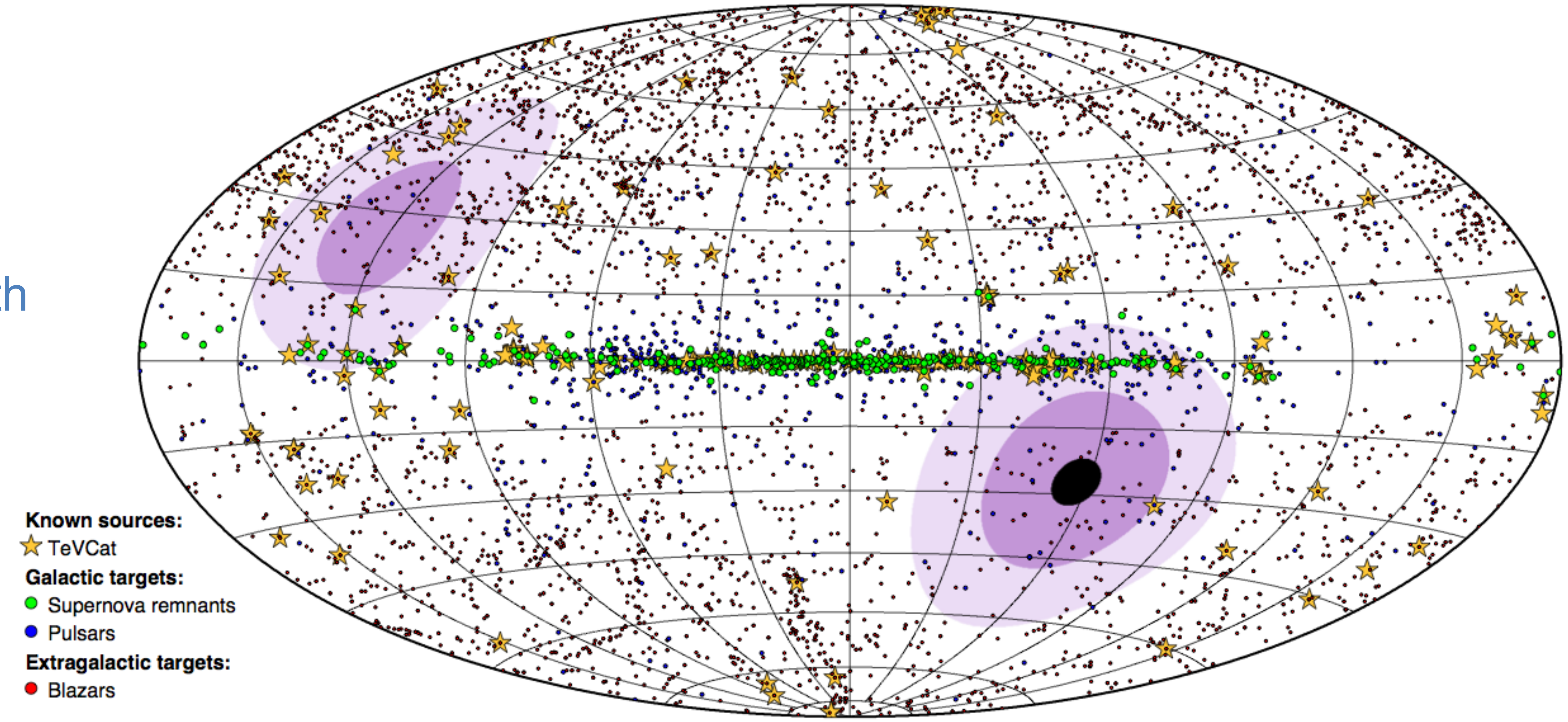
➡ **L** = length and **W**= width of the ellipse
➡ **SIZE** (total image amplitude)
➡ **d** nominal distance (between the centre of the camera and the image centre of gravity)
➡ ϕ azimuthal angle of the image main axis
➡ α orientation angle

THE CTA CONSORTIUM

31 Countries
over 200 Institutes
over 1400 Members

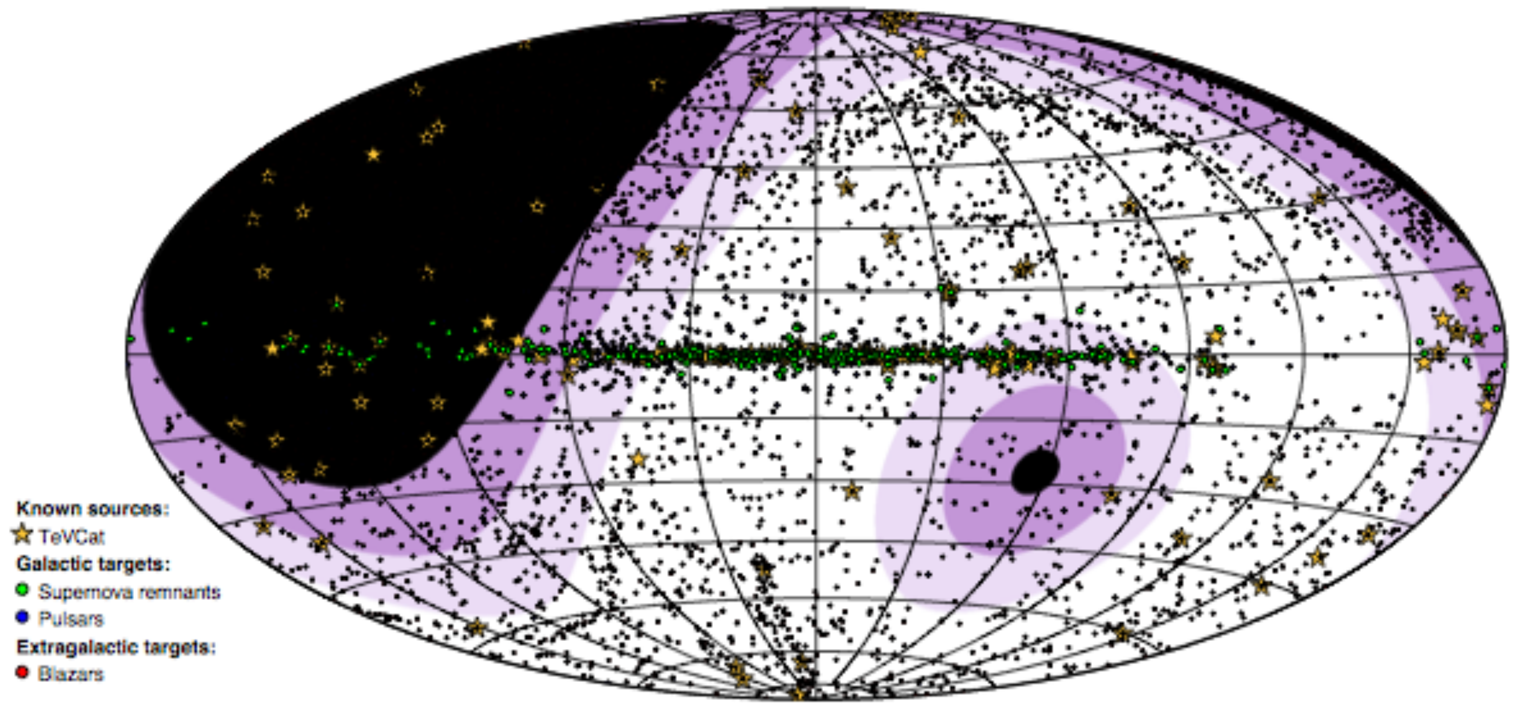
Design Driver - Full Sky sensitivity

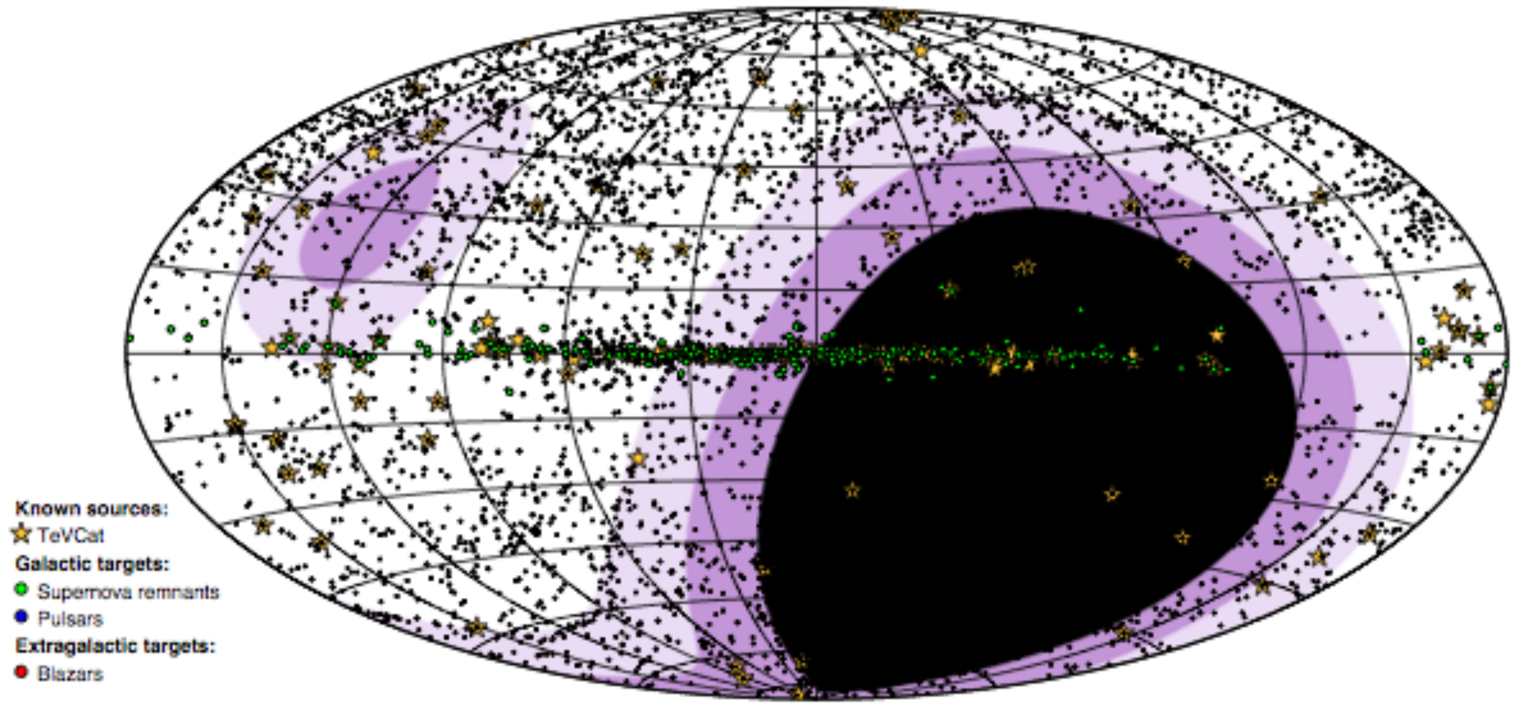
North+South



>60º zenith
45º-60º
30º-45º

South





North

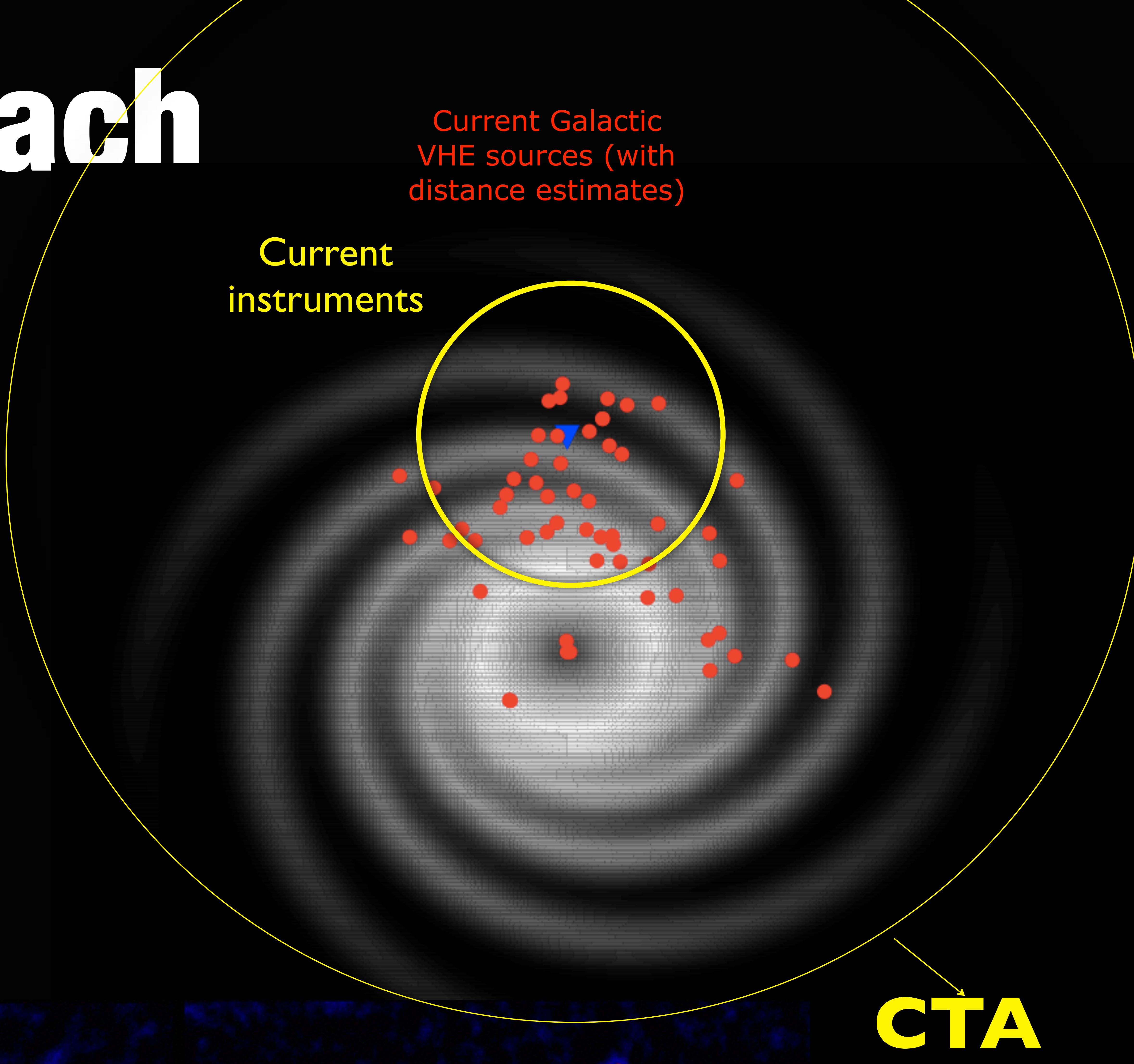
CTA Reach

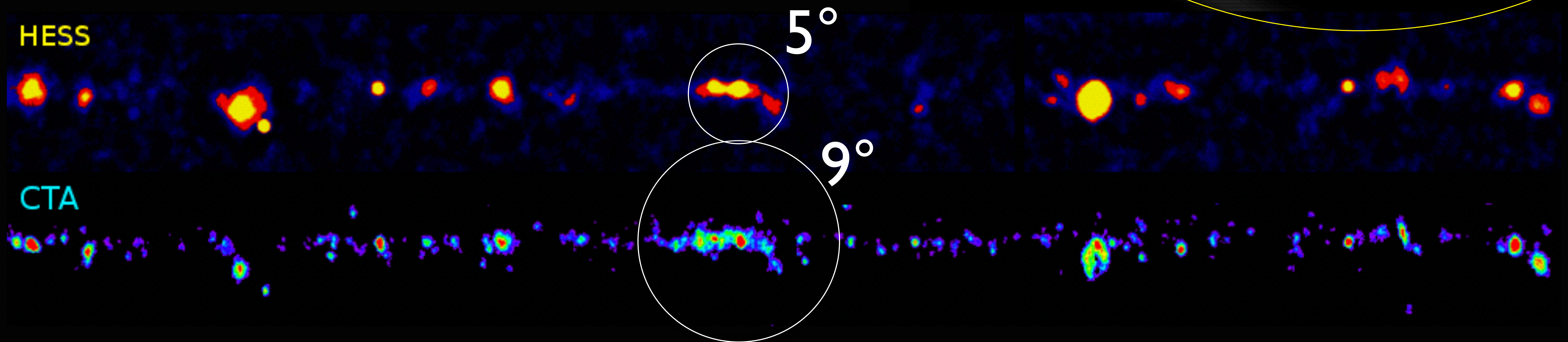
➡e.g. **Galactic objects**

- Newly born pulsars and the supernova remnants
  - have typical brightness such that HESS etc can see only relatively local (typically at a few kpc) objects
- CTA will see **whole** Galaxy

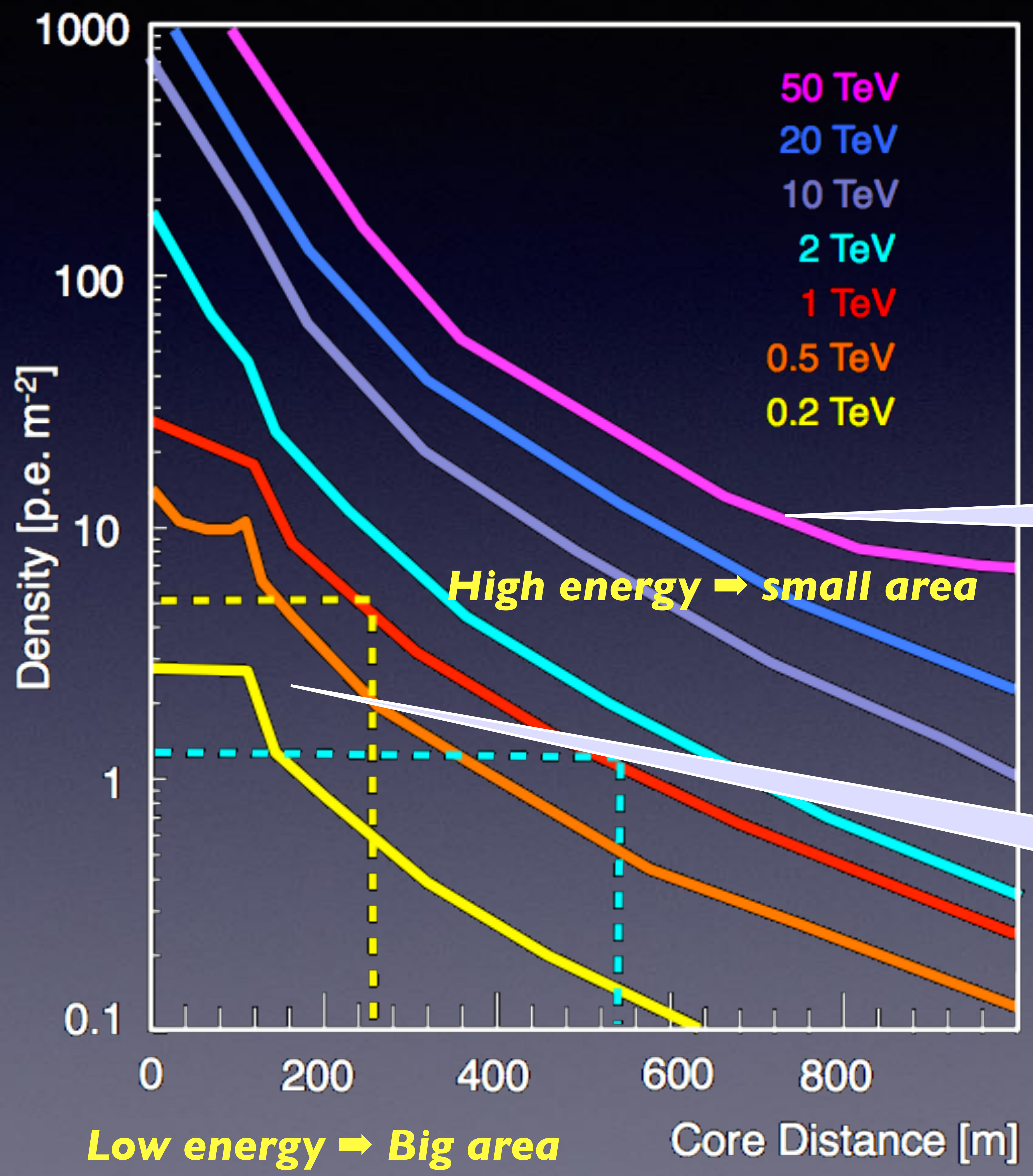
➡Field of view + sens.

- Survey speed ~300×HESS





ENERGY COVERAGE AND AREA



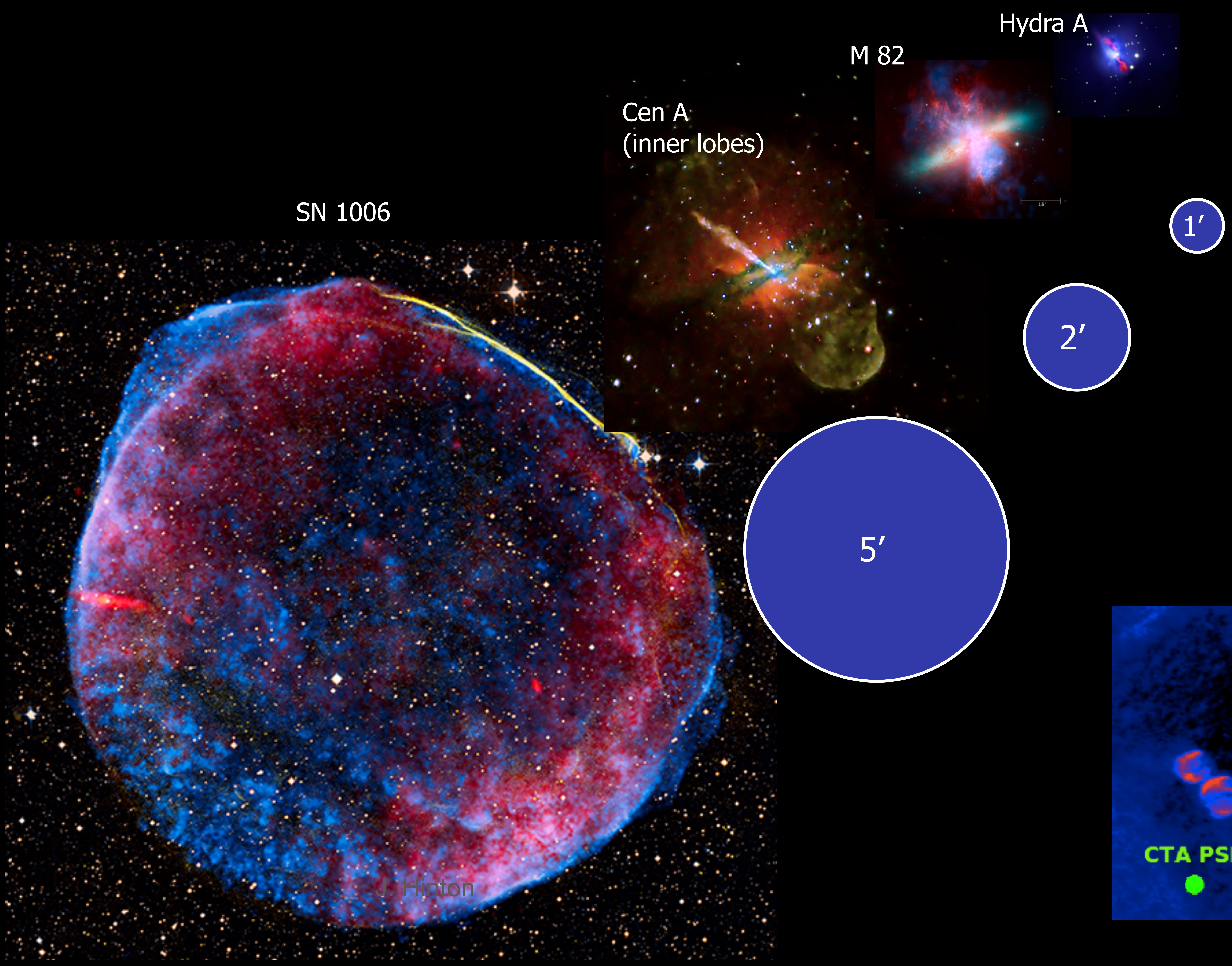
Energy threshold depends on collection area of a single telescope

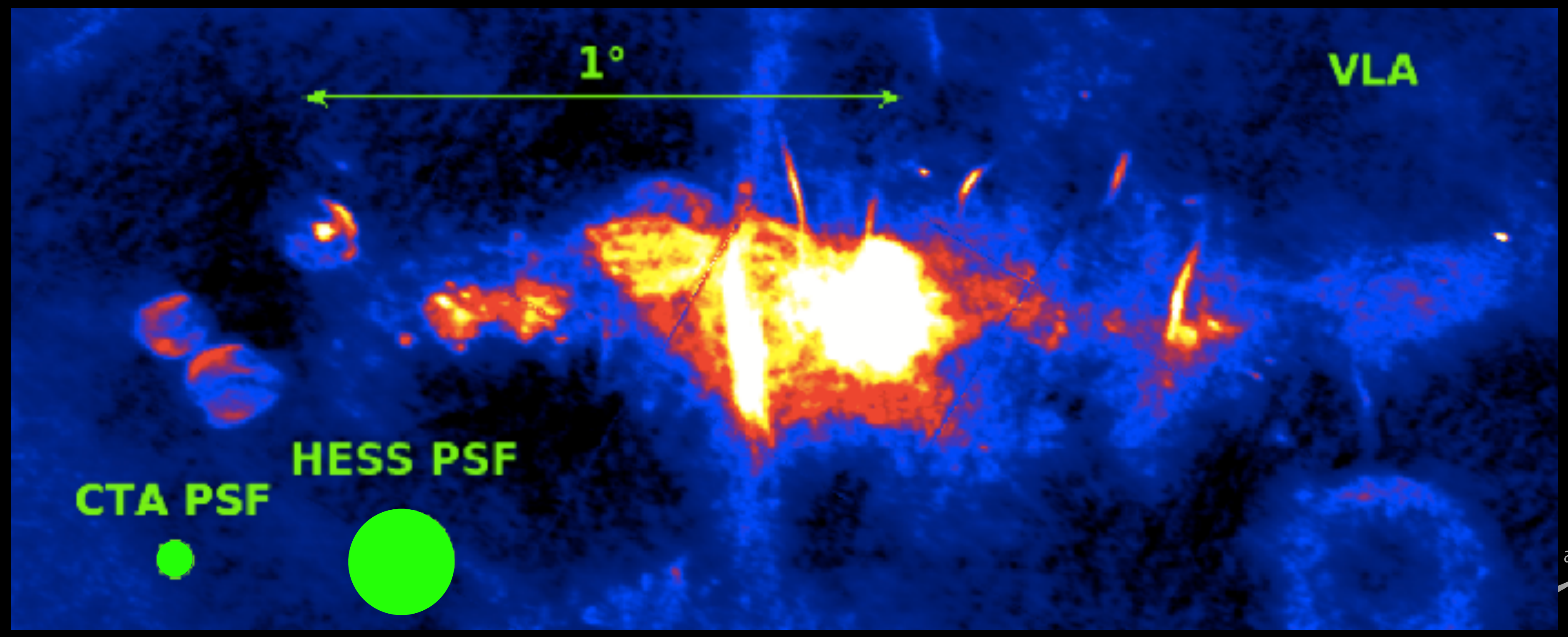
$$N_{pe} = \rho_{ph} \times A \times R \times QE \times f$$

At the highest energies, images will be visible at large distances

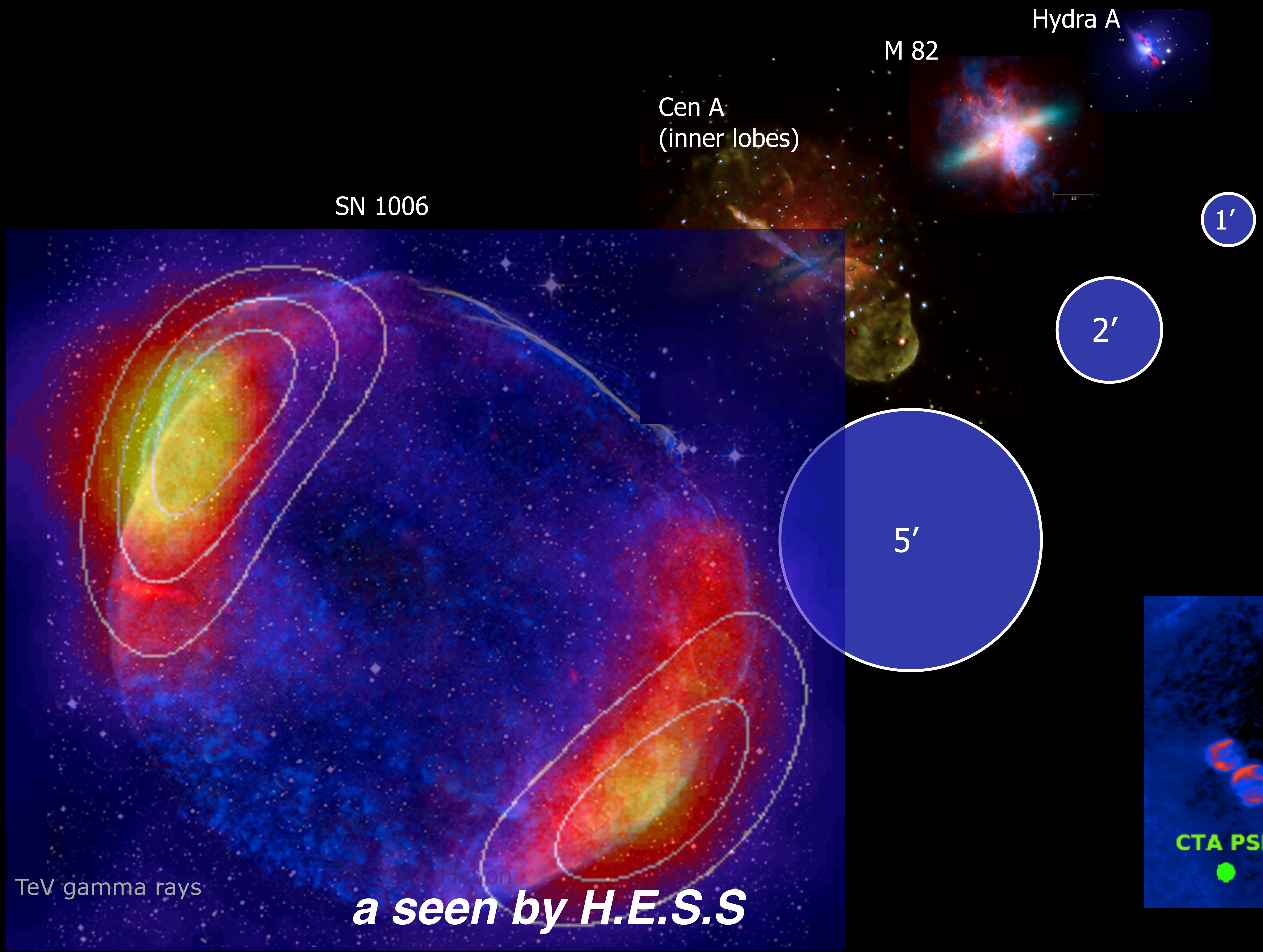
At lowest energies, few photons even in the core of the shower

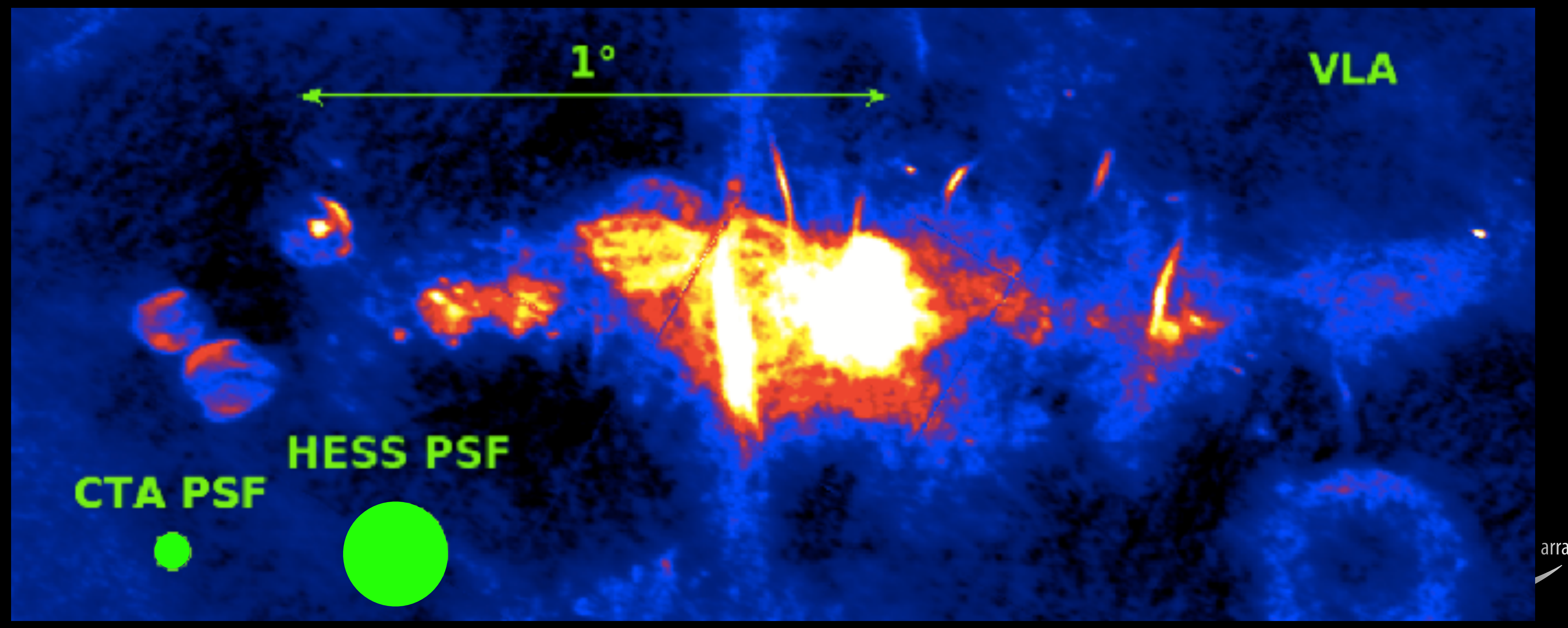
Better Angular Resolution





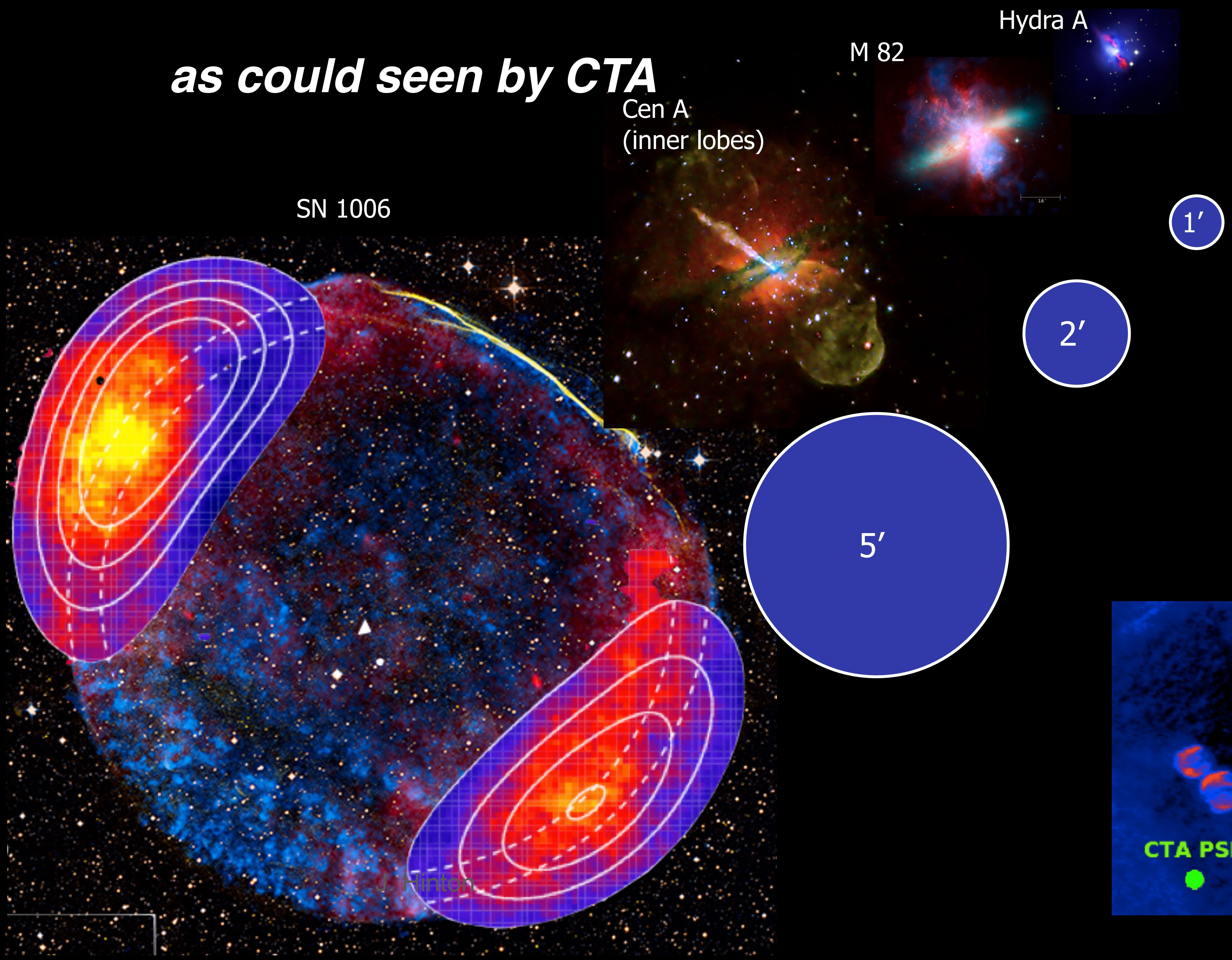
Better Angular Resolution

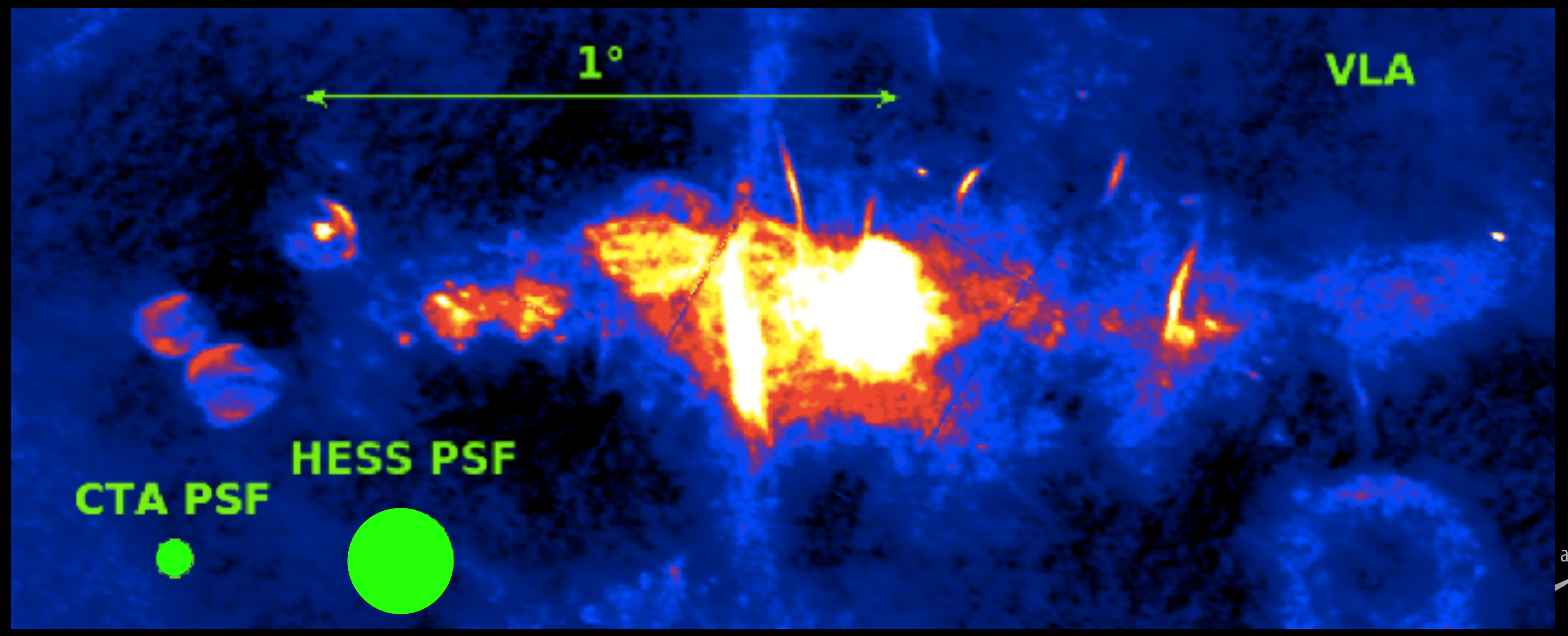




Better Angular Resolution

as could seen by CTA



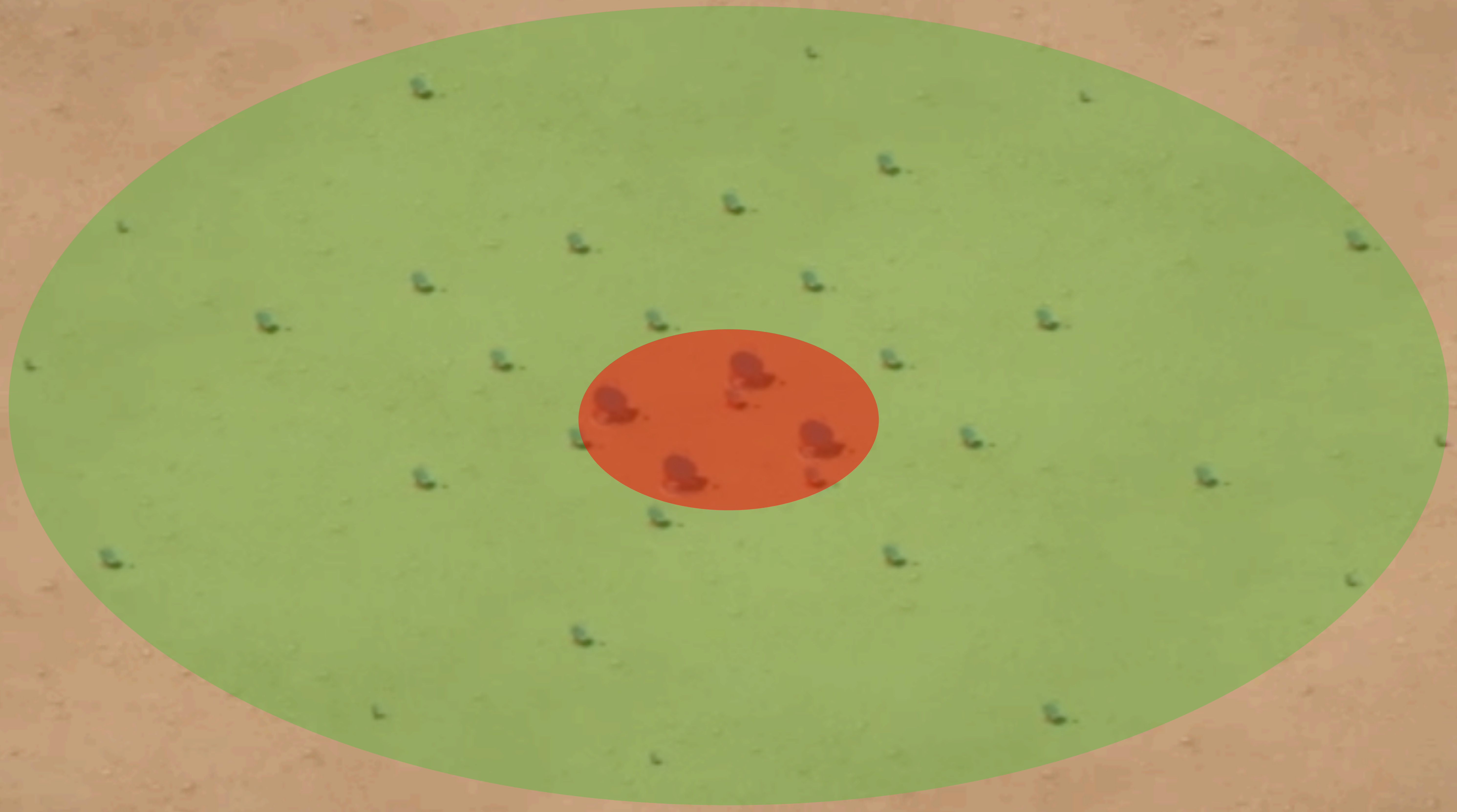


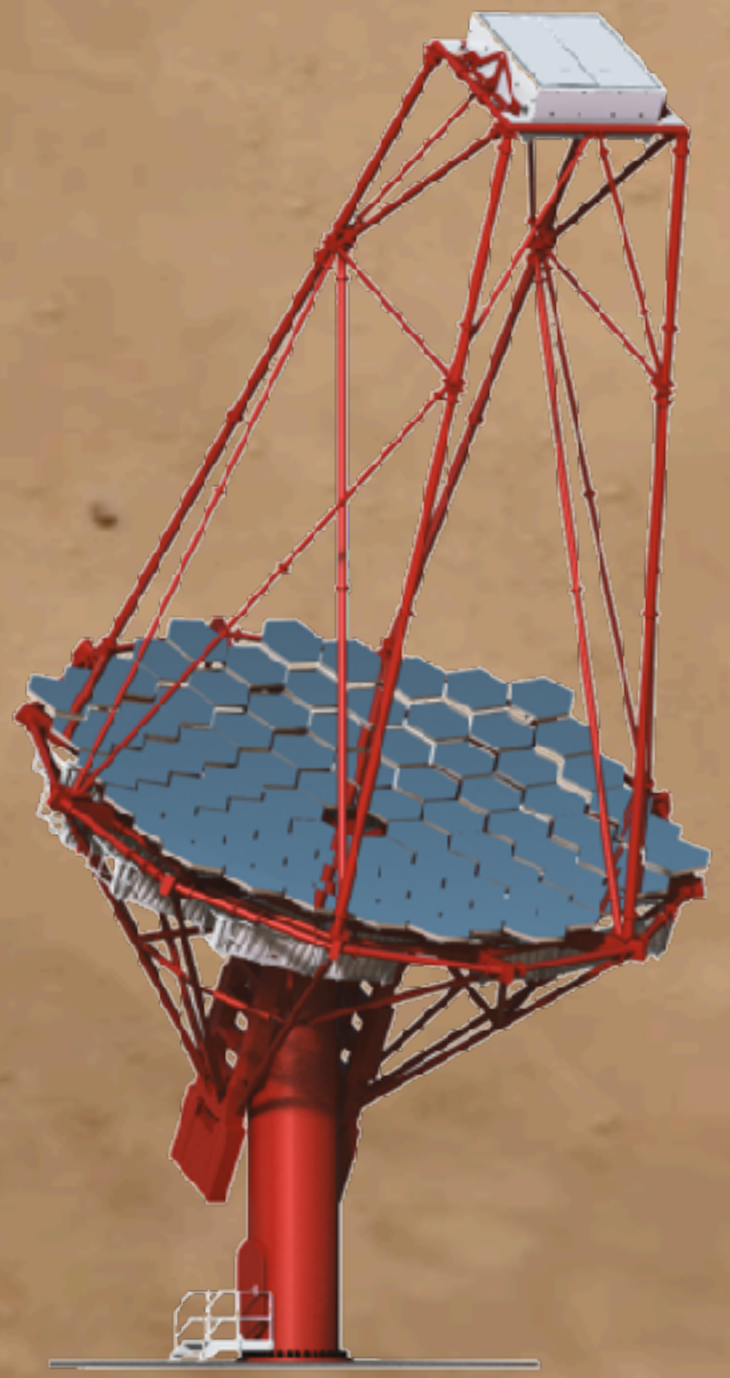

10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1000 γ/h·km²
10 γ/h·km²
0.1 γ/h·km²
4S + 4 N: 23 m ∅ Large Size Telescopes (LST)
Southern array
of Cherenkov telescopes
- about 3 km across

10 GeV	100 GeV	1 TeV	10 TeV	100 TeV

1000 γ/h·km² | *10 γ/h·km²* | *0.1 γ/h·km²*

25 S + 15 N: 12 m ∅ Medium Size Telescopes (MST)

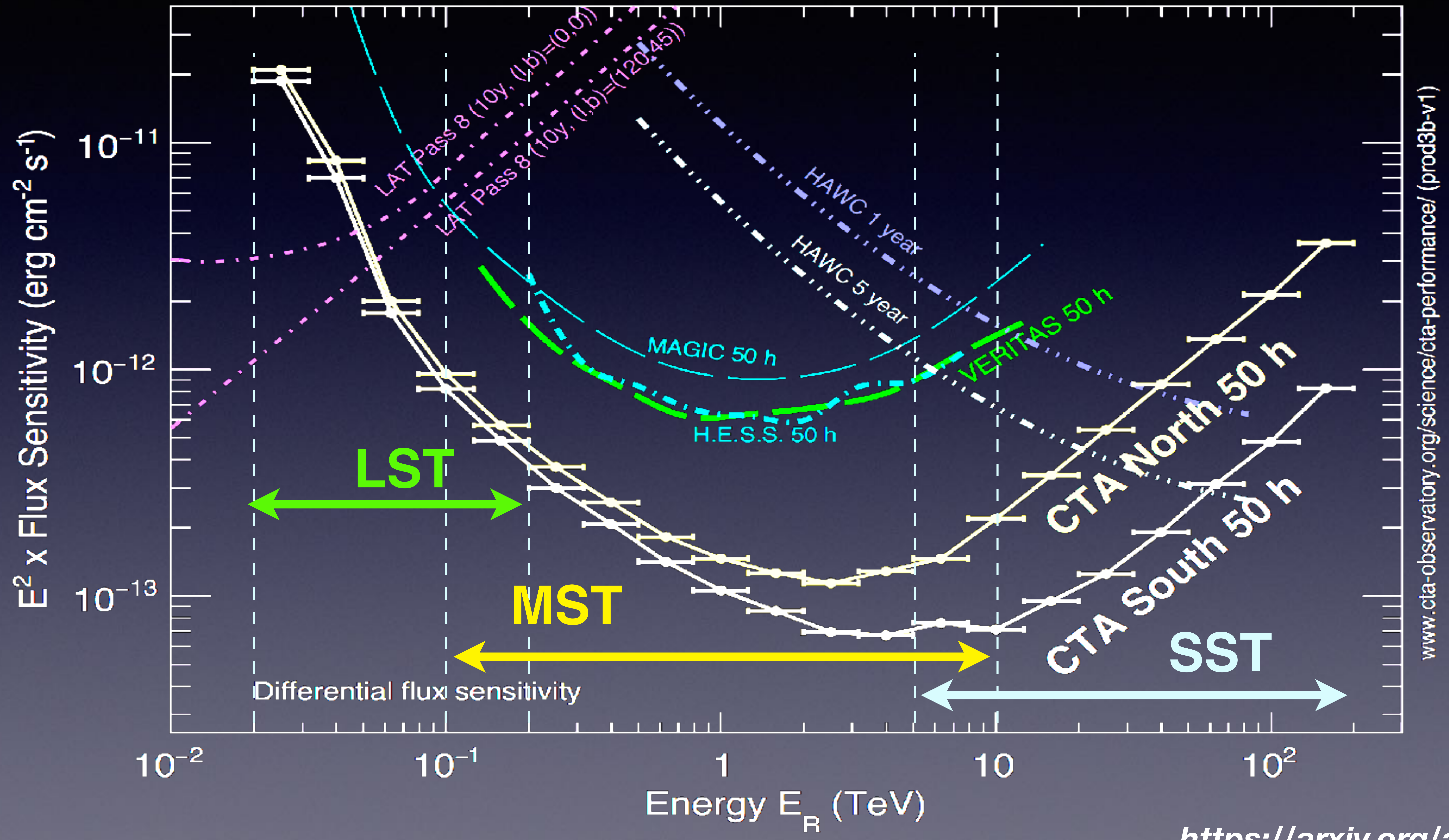




Southern array
of Cherenkov telescopes
- about 3 km across

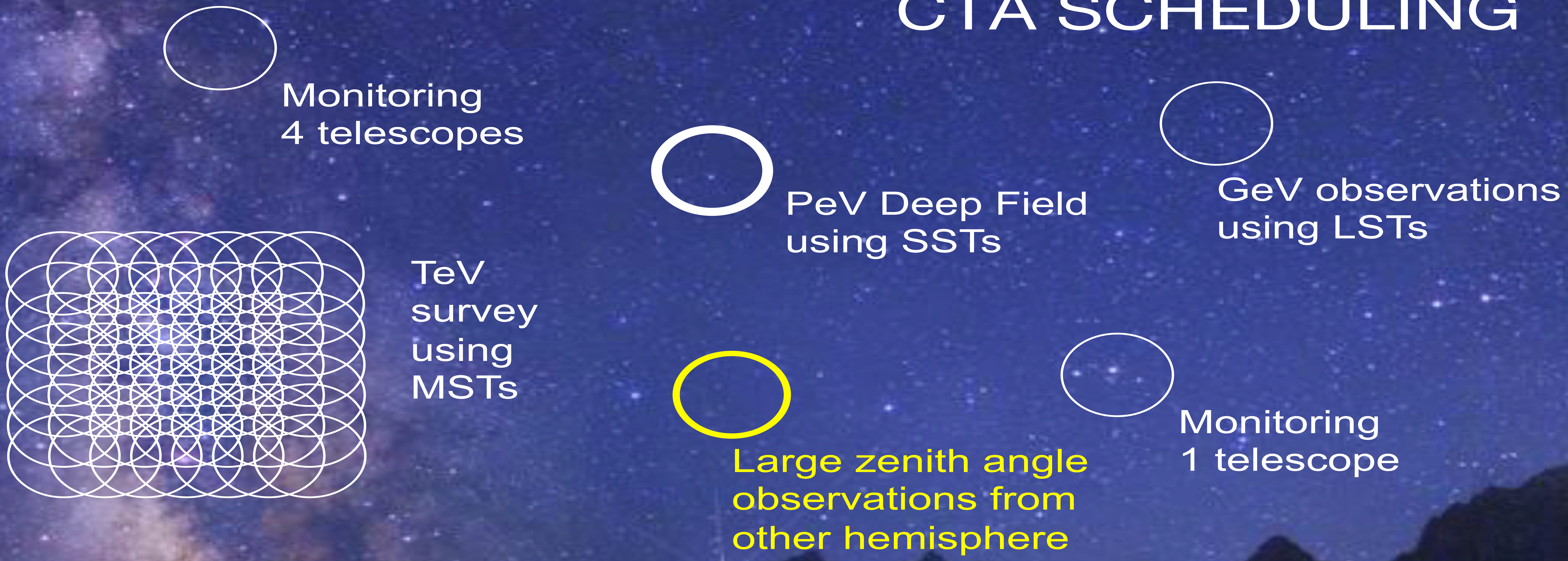
10 GeV
100 GeV
1 TeV
10 TeV
100 TeV
1000 γ/h·km²
0.1 γ/h·km²
70 S: 4 m ∅ Small Size Telescopes (SST)
Southern array
of Cherenkov telescopes
- about 3 km across

CTA Sensitivity



https://arxiv.org/abs/1709.07997

CTA SCHEDULING



- CTA North and South through single portal, common calls for proposals, identical tools
- Queue mode scheduler taking into account actual sky conditions, sub-arrays & conditions requested in proposal, priorities, TOOs

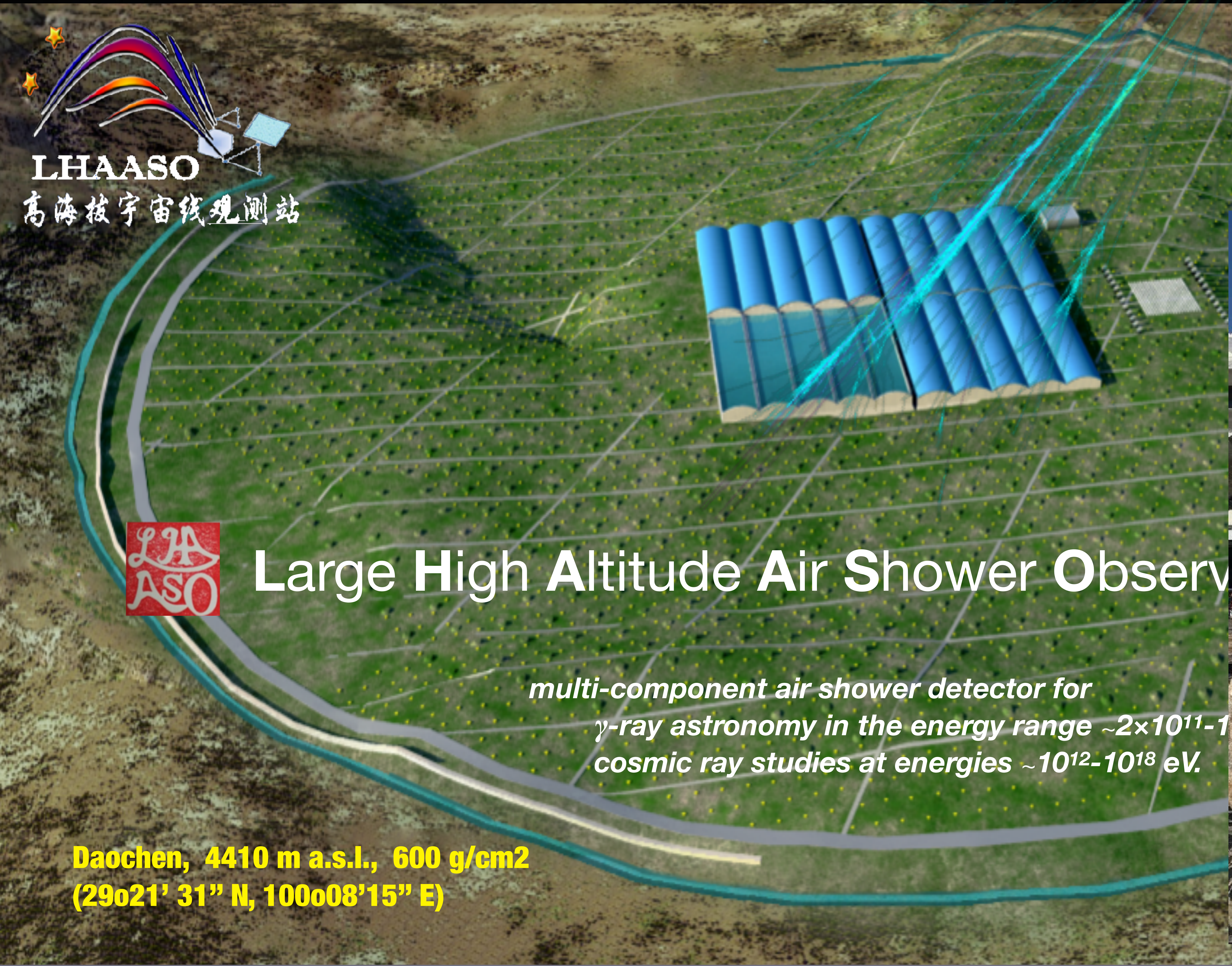
Science Themes & Key Science Projects

			Survey						Key Objects			
Theme	**Question**		**Dark Matter Programme**	**Galactic Centre Survey**	**Galactic Plane Survey**	**LMC Survey**	**Extra-galactic Survey**	**Transients**	**Cosmic Ray PeVatrons**	**Star-forming Systems**	**Active Galactic Nuclei**	**Galaxy Clusters**
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	


CTA North
La Palma, Spain
CTA South
ESO, Chile


CTA North
La Palma, Spain
CTA South
ESO, Chile

LHAASO
高海拔宇宙线观测站

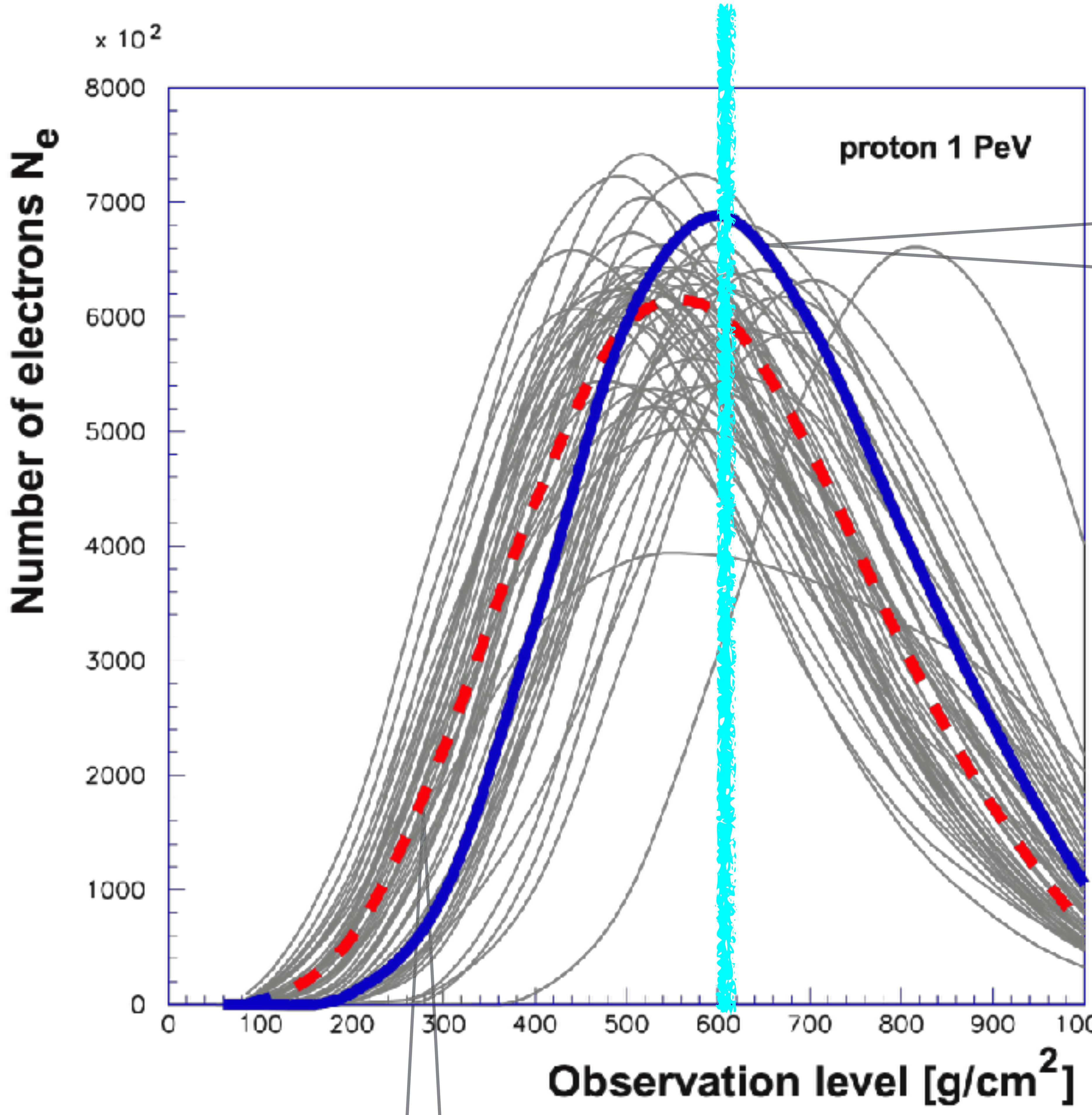


Large High Altitude Air Shower Observ

multi-component air shower detector for
γ-ray astronomy in the energy range ~2×10^{11}-1
cosmic ray studies at energies ~10^{12}-10^{18} eV.

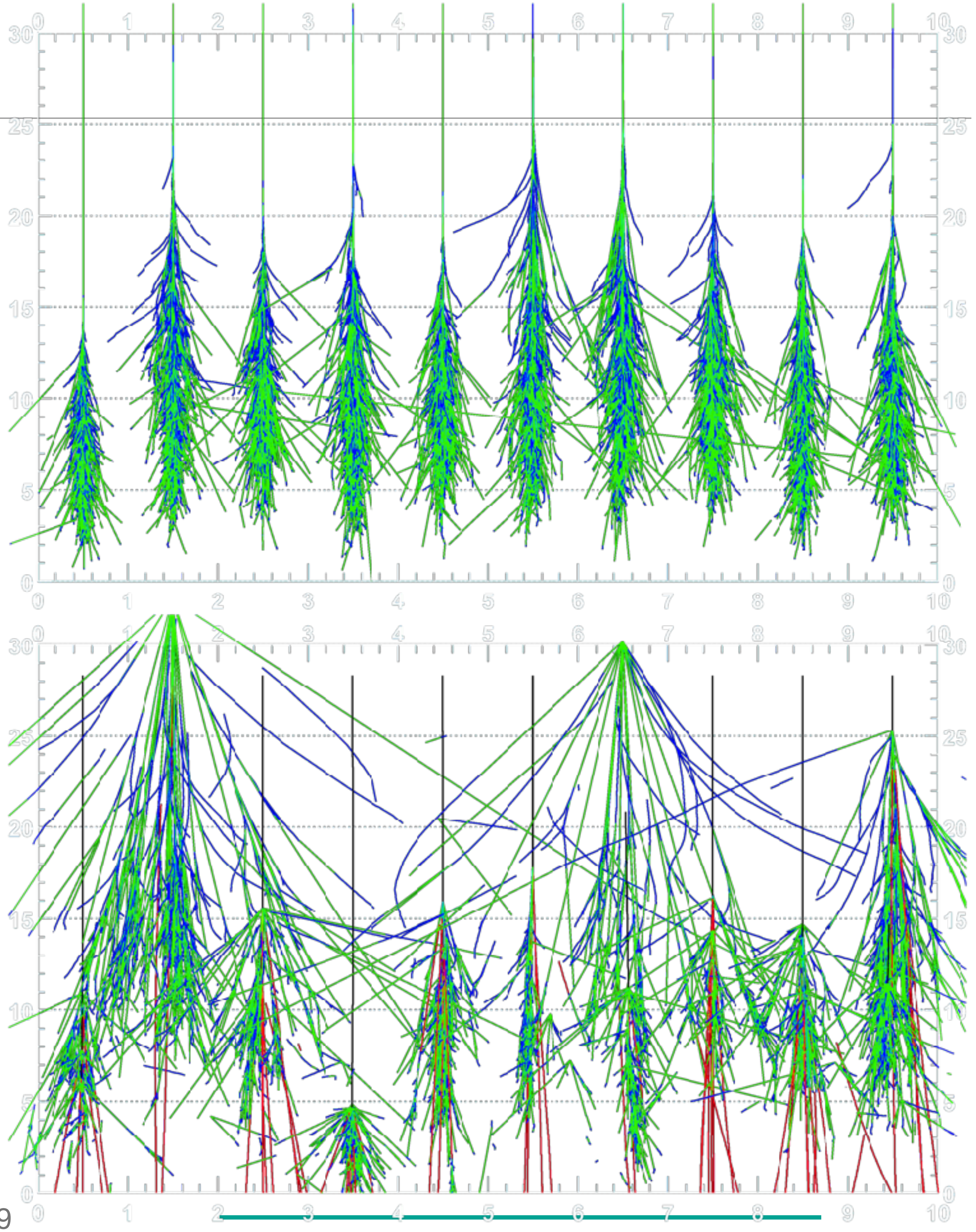
Daochen, 4410 m a.s.l., 600 g/cm2
(29o21' 31" N, 100o08'15" E)

Fluctuations

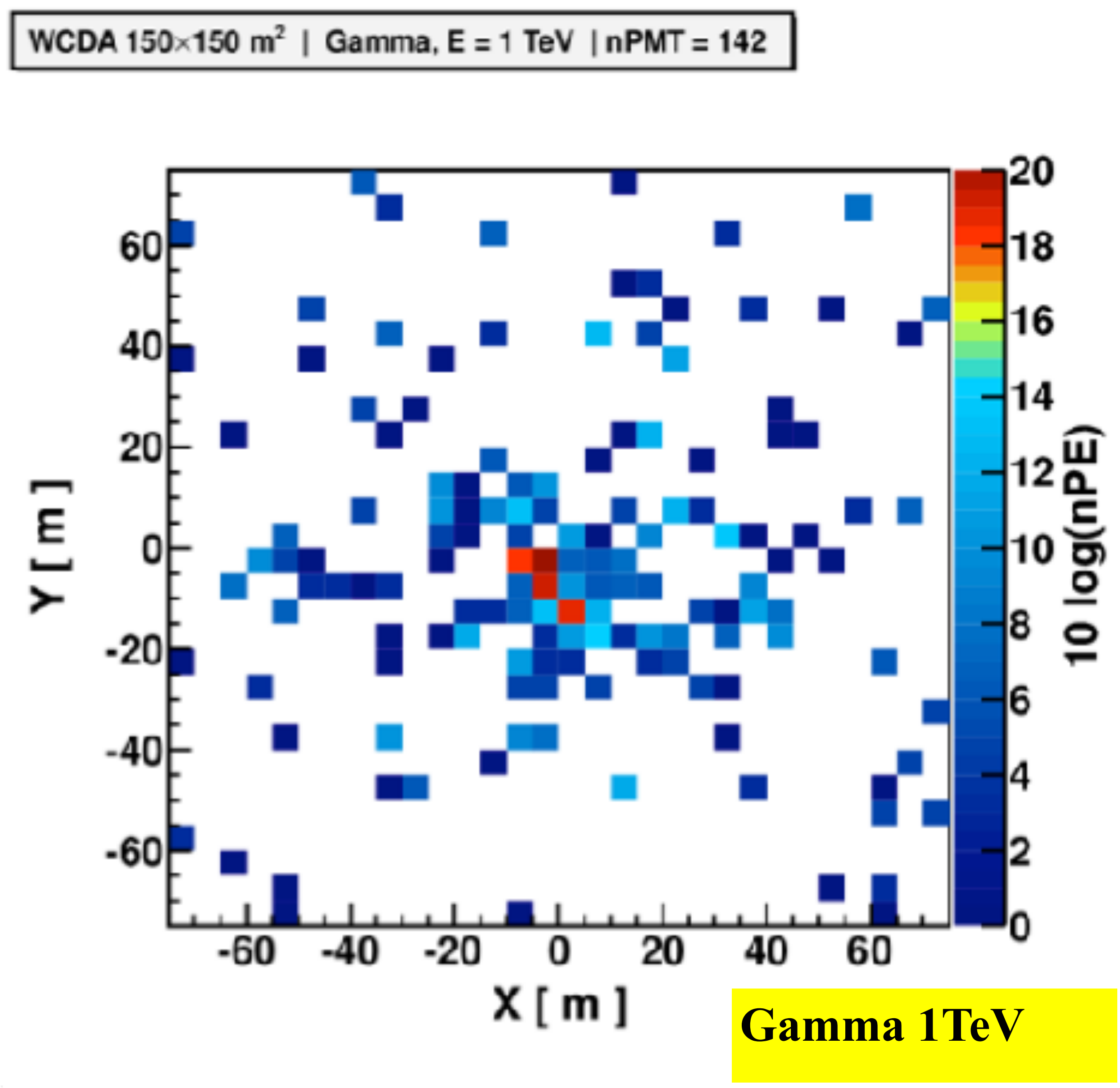


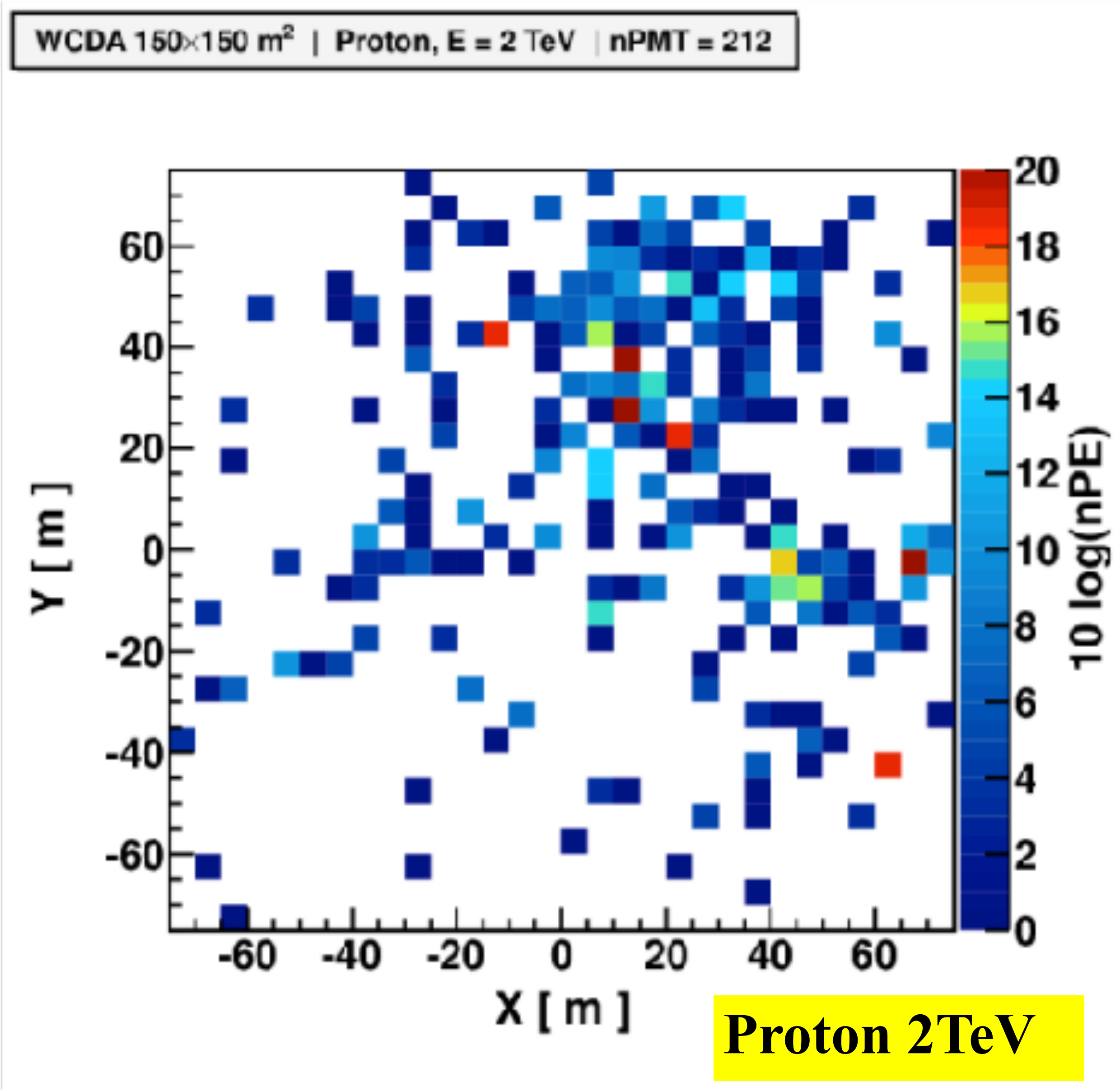
Shower with an $N_e = \langle N_e \rangle$

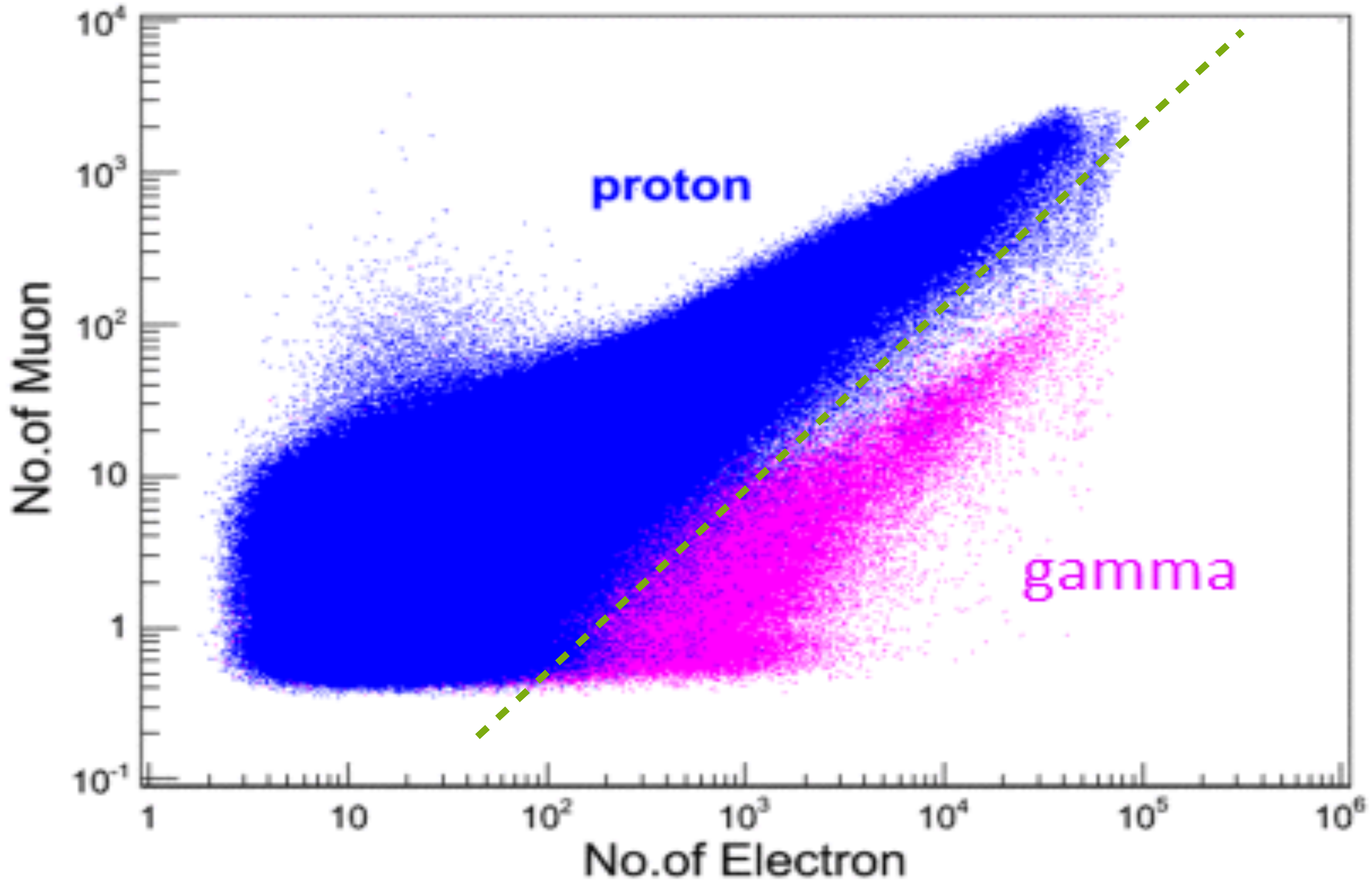
Shower with an $X_{max} = \langle X_{max} \rangle$



Gamma/Hadron separation



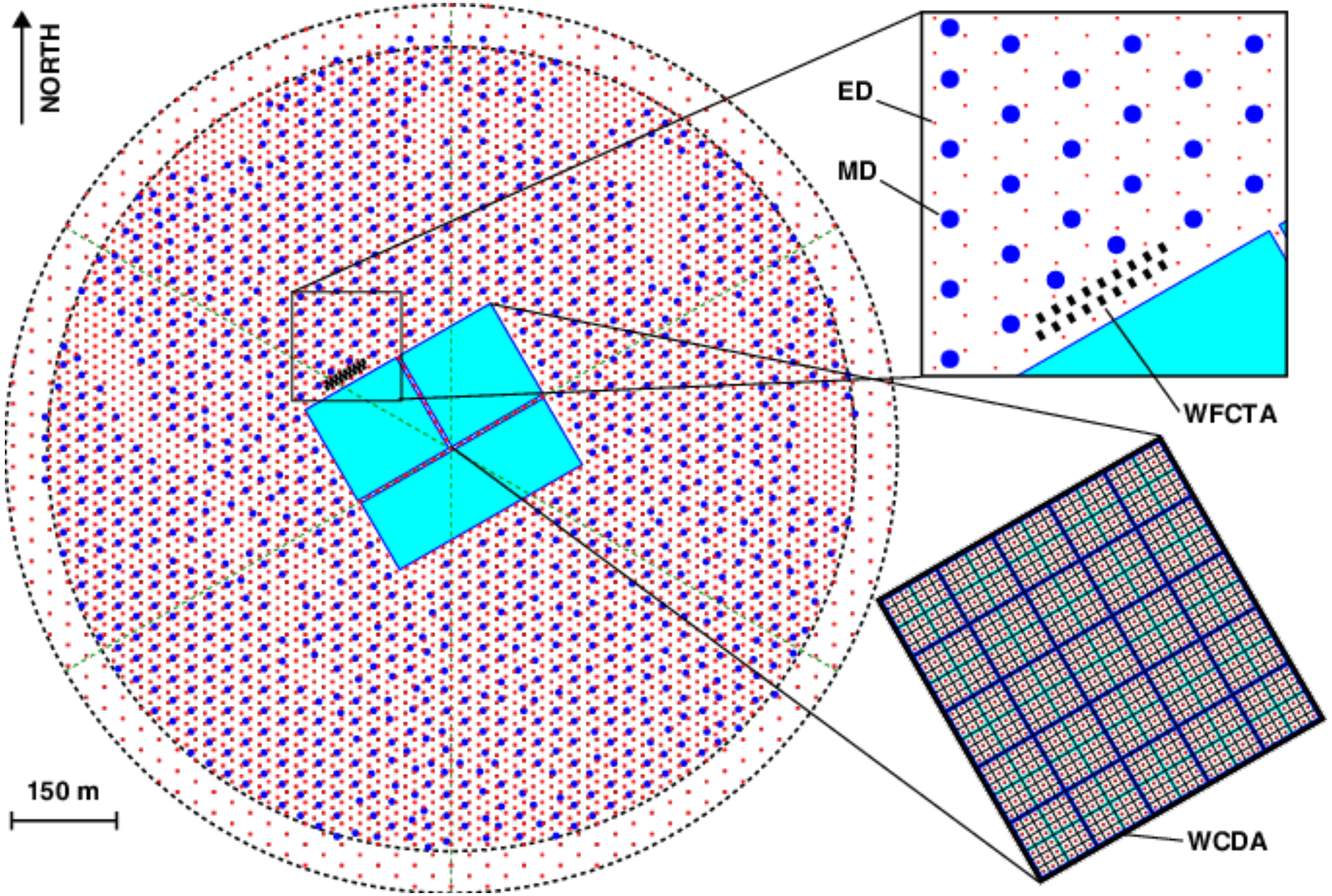




- Shower shape can be used to separate gamma/from hadron (Low energy)

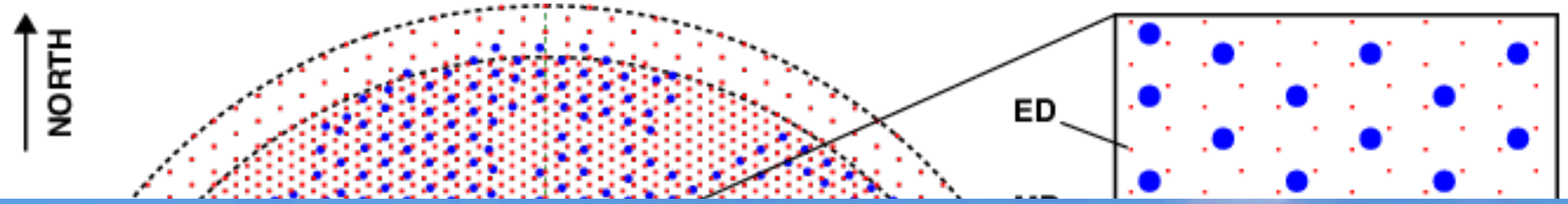
- But more powerful is the measurement of the ***Electron*** and ***Muon*** content (High energy)

LHAASO Layout



- **WCDA - Water Cherenkov Detector Array**
  - Measuring shower direction and location
- **KM2A - Km-square array**
  - Measuring shower direction and location
  - Measuring μ–content with the largest MD array ever
  - Clean γ selection
- **WFCTA - Wide Fielf-of-view Cherenkov array**
  - Extend energy range
  - Measure Shower fluorescent light
  - Particle discrimination for composition study at knee

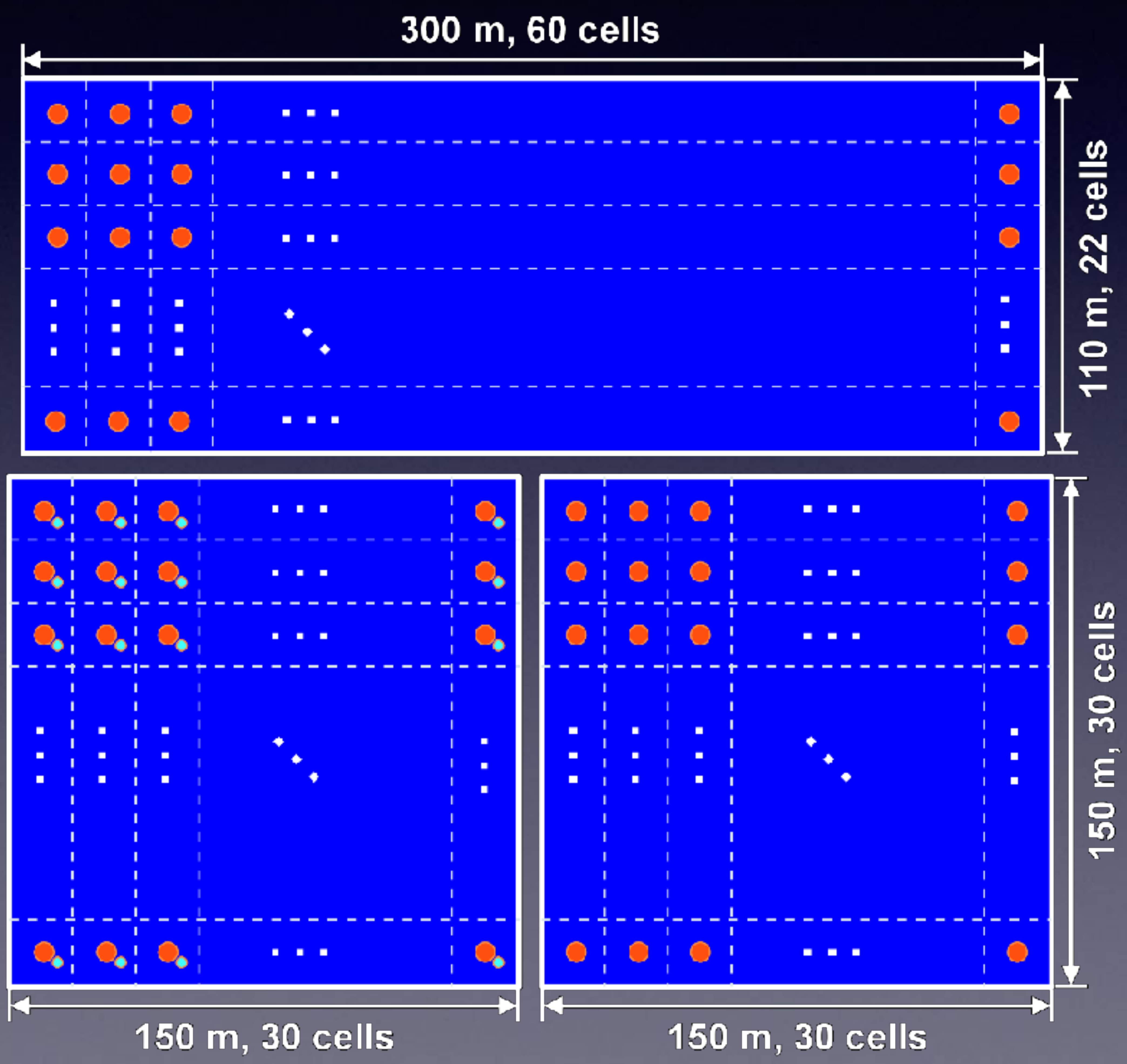
LHAASO Layout

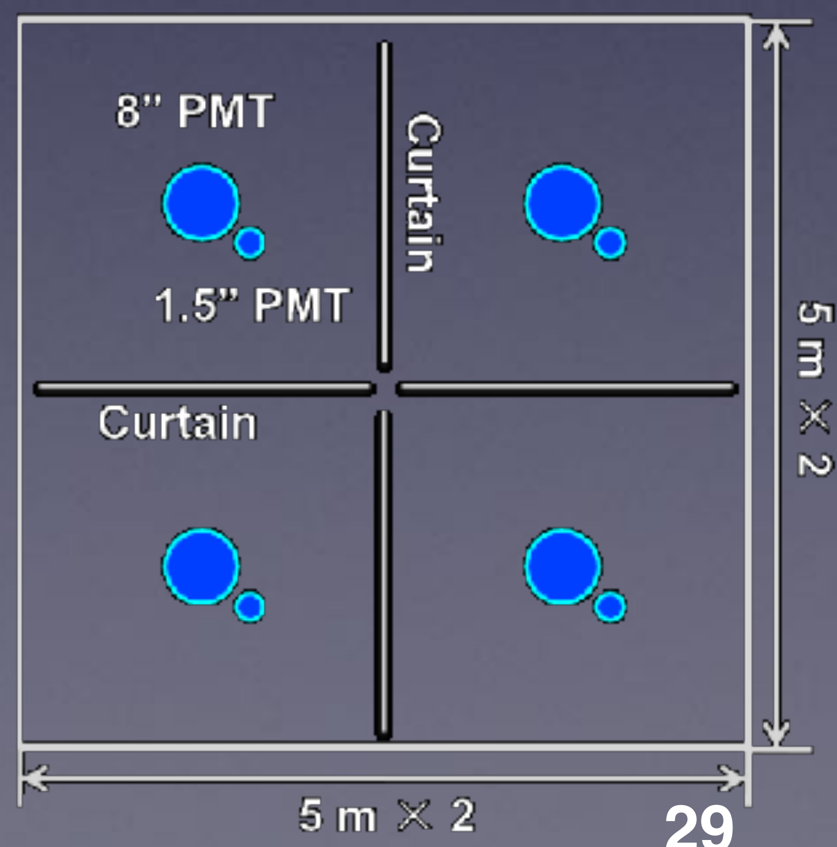


- **WCDA - Water Cherenkov Detector Array**
  - Measuring shower direction and location

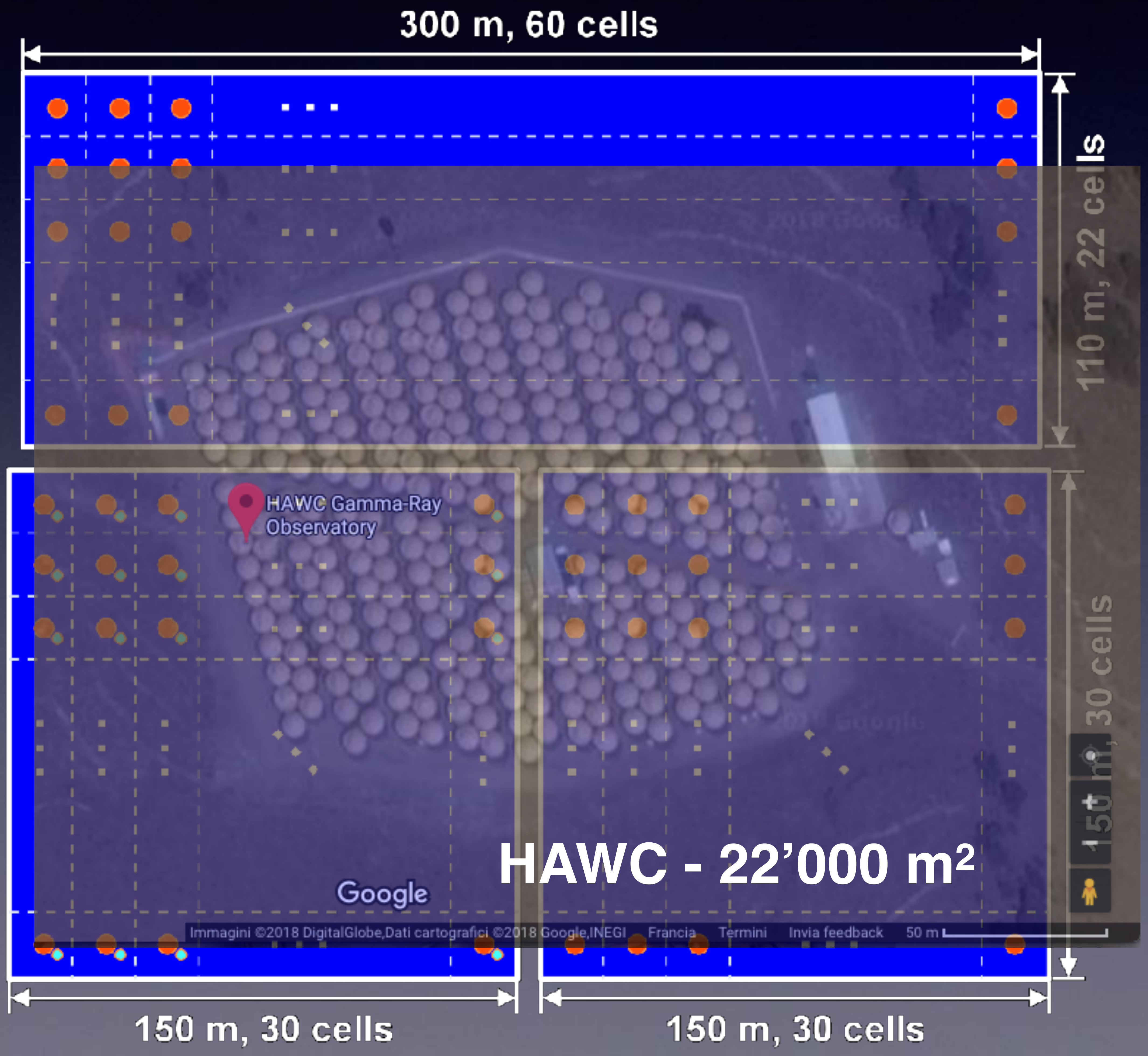
study at knee

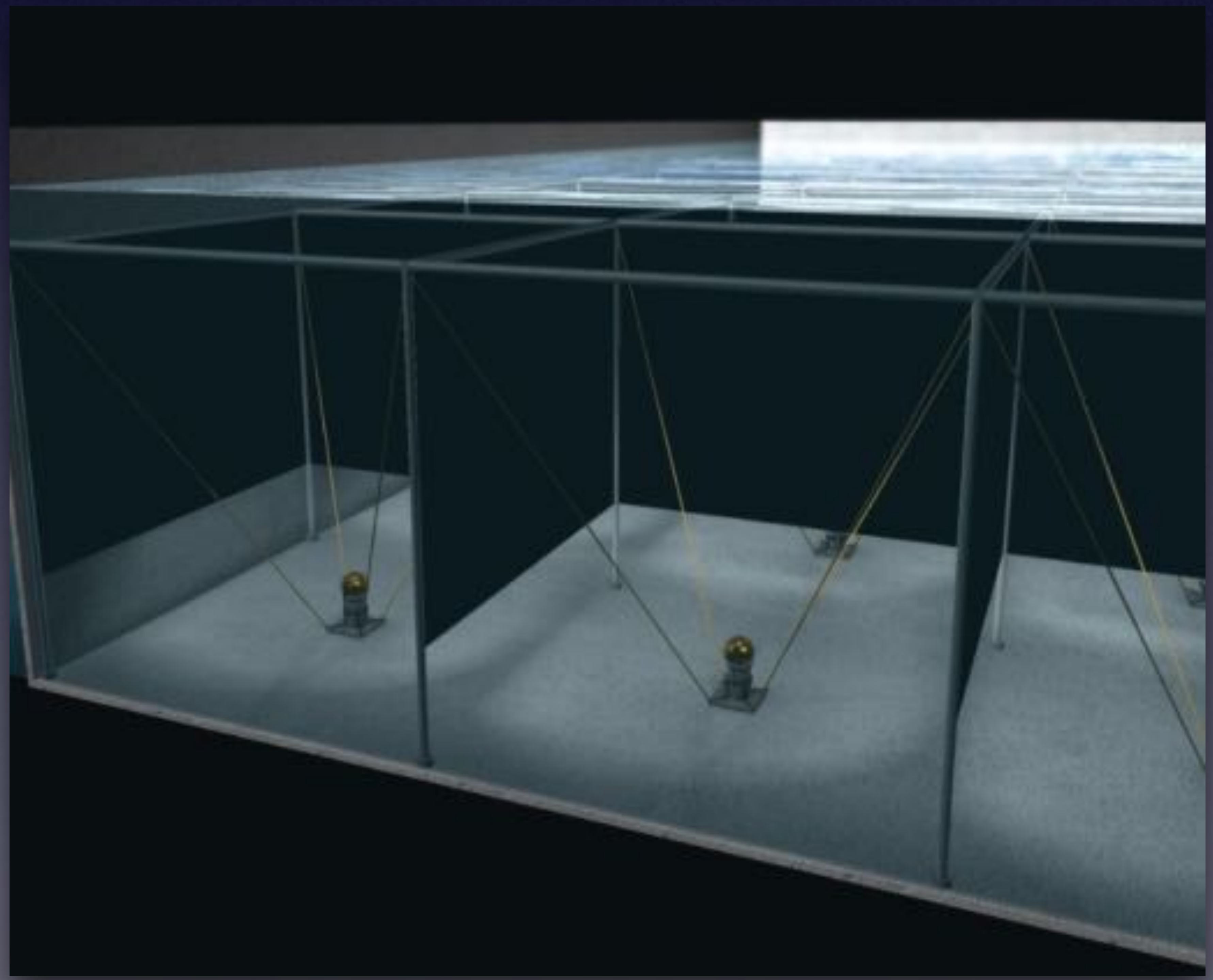
Water Cherenkov Detector Array

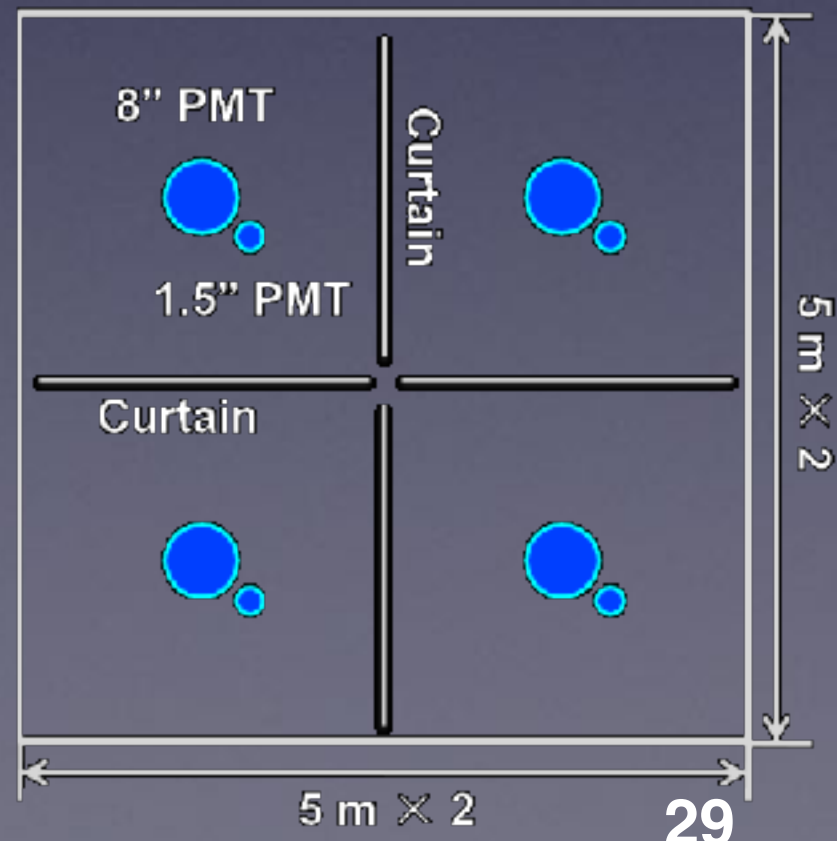




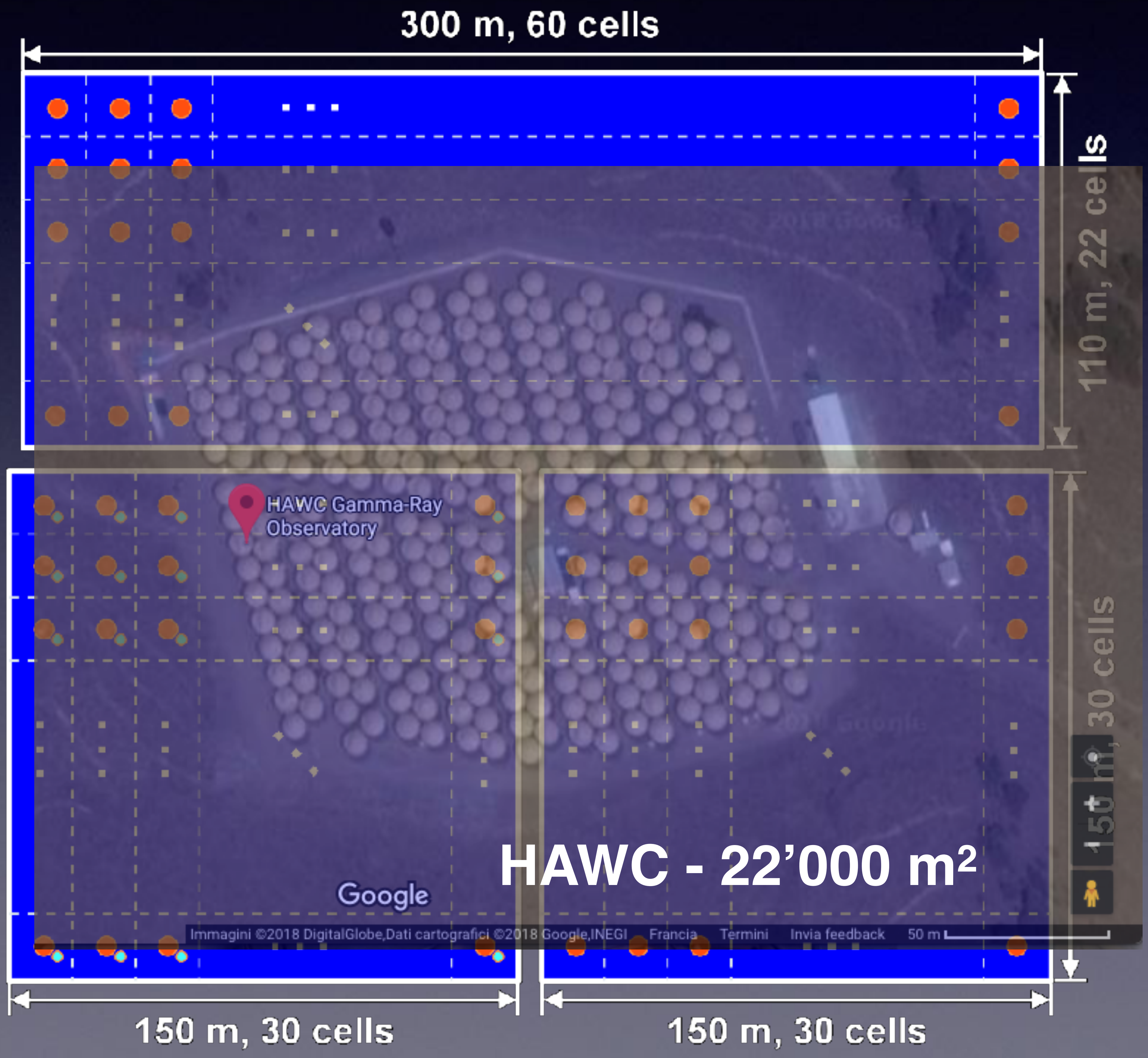
Water Cherenkov Detector Array

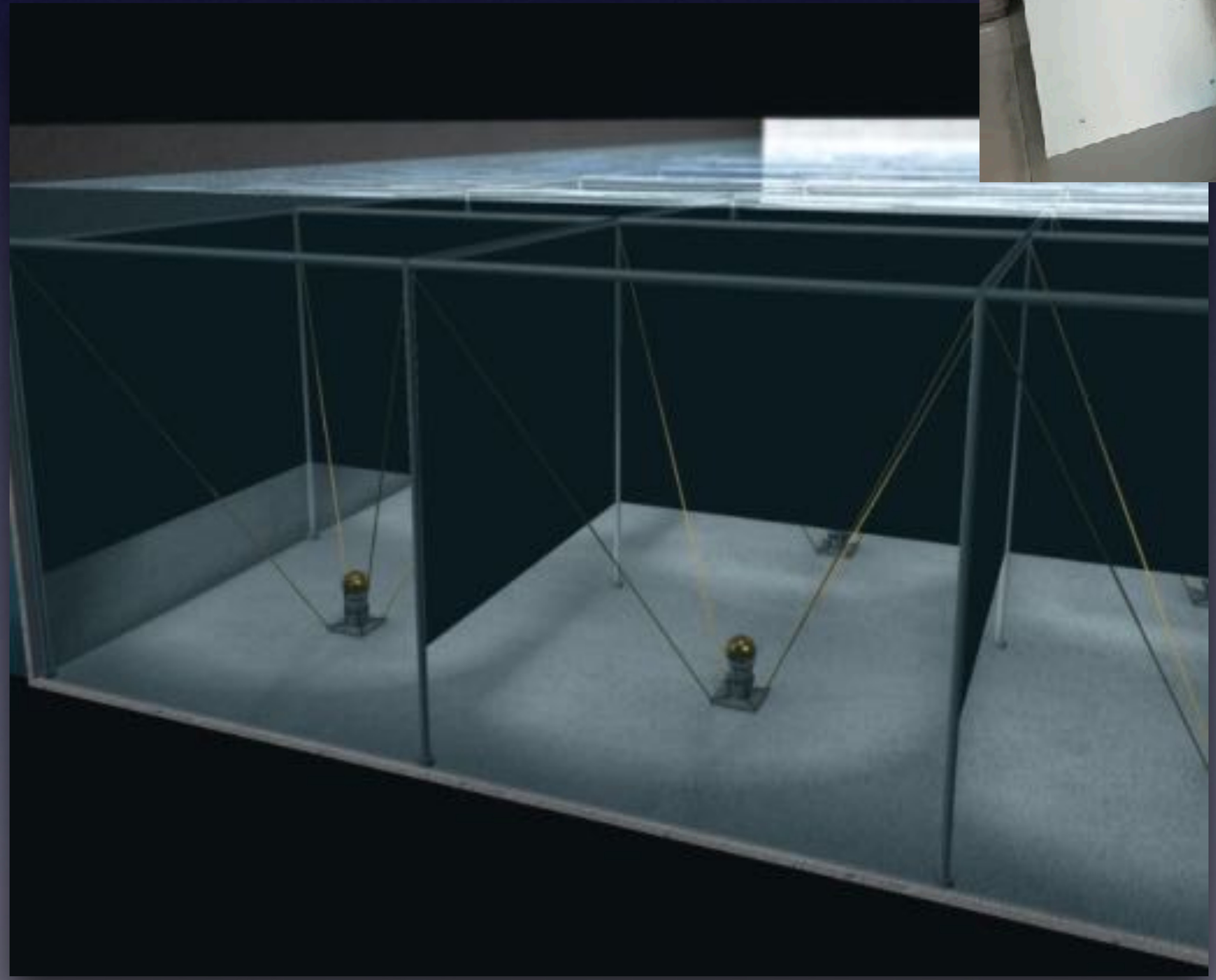


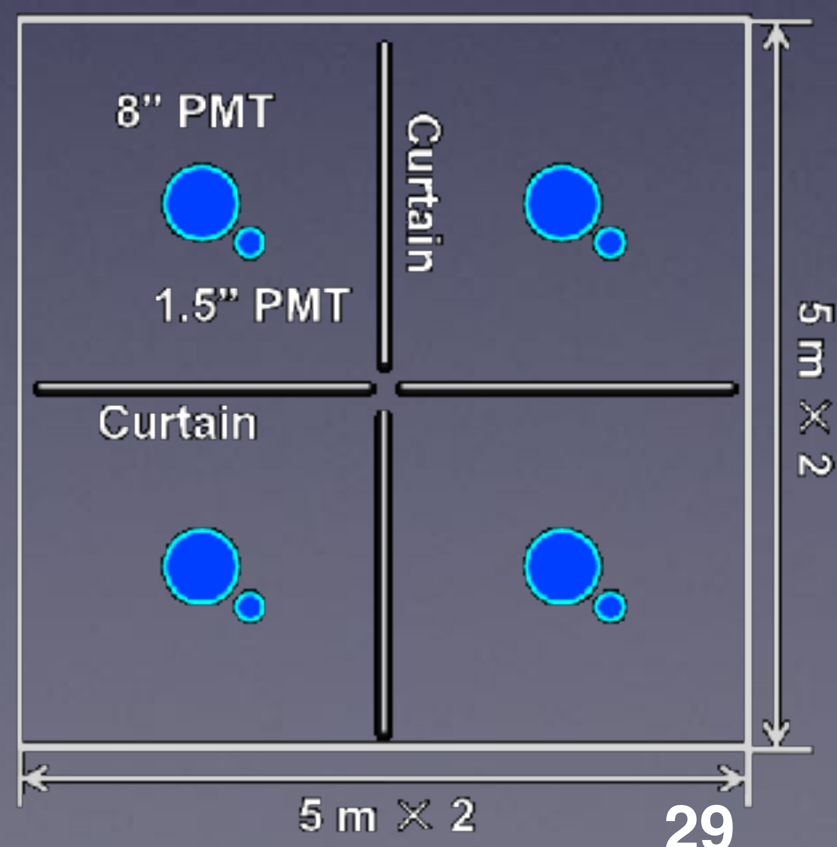




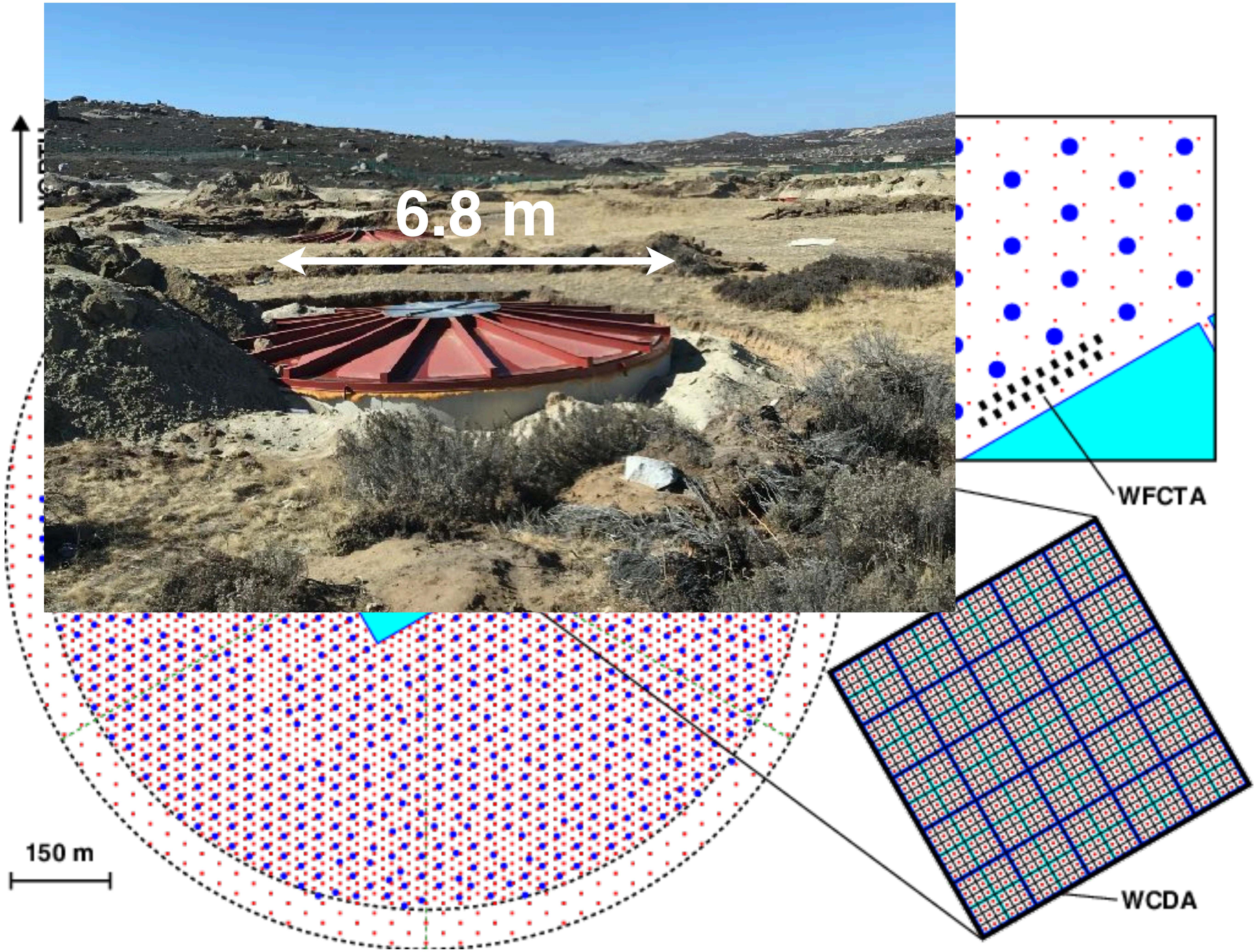
Water Cherenkov Detector Array





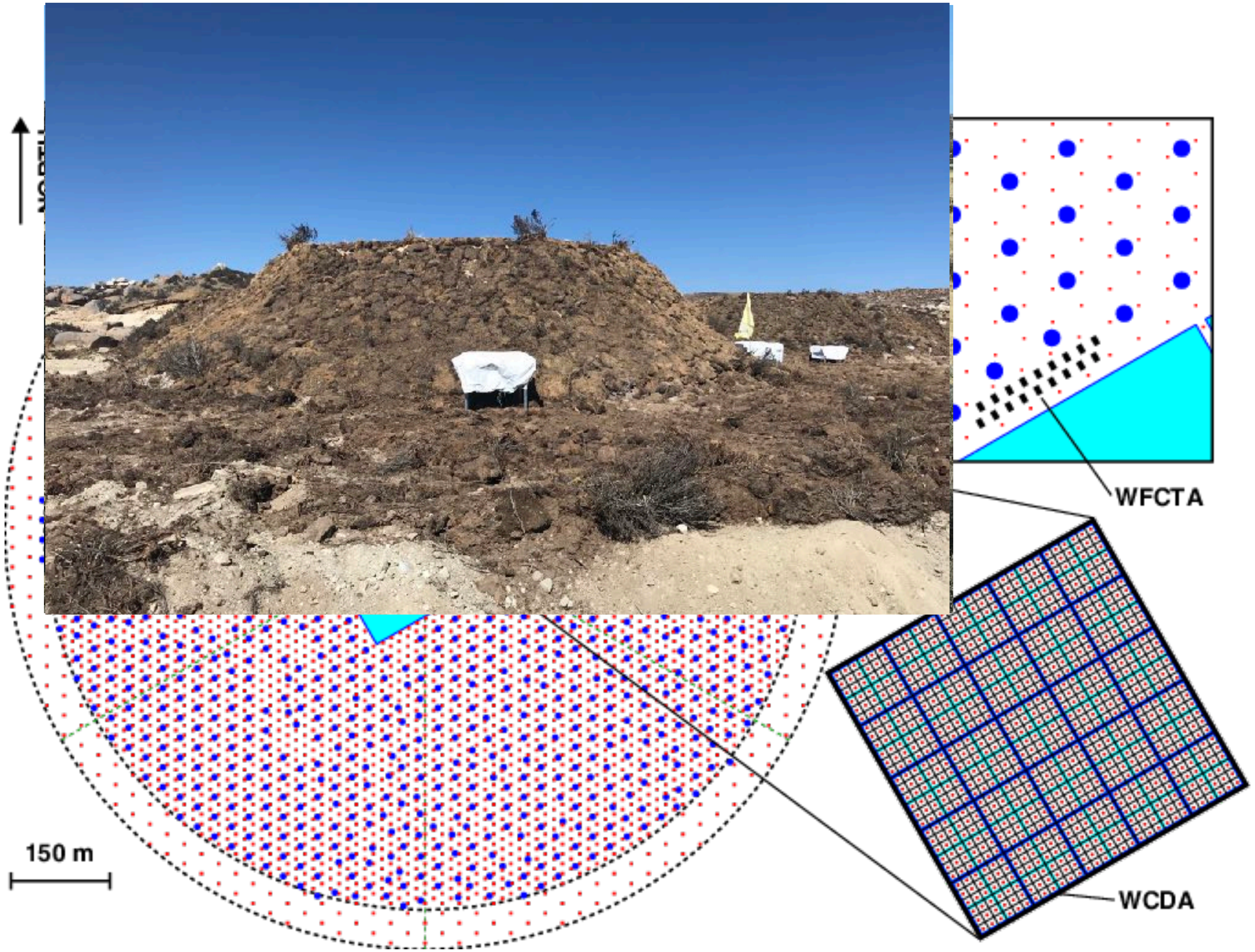


LHAASO Layout



- **WCDA - Water Cherenkov Detector Array**
  - Measuring shower direction and location
- **KM2A - Km-square array**
  - Measuring shower direction and location
  - Measuring μ–content with the largest MD array ever
  - Clean γ selection
- **WFCTA - Wide Fielf-of-view Cherenkov array**
  - Extend energy range
  - Measure Shower fluorescent light
  - Particle discrimination for composition study at knee

LHAASO Layout



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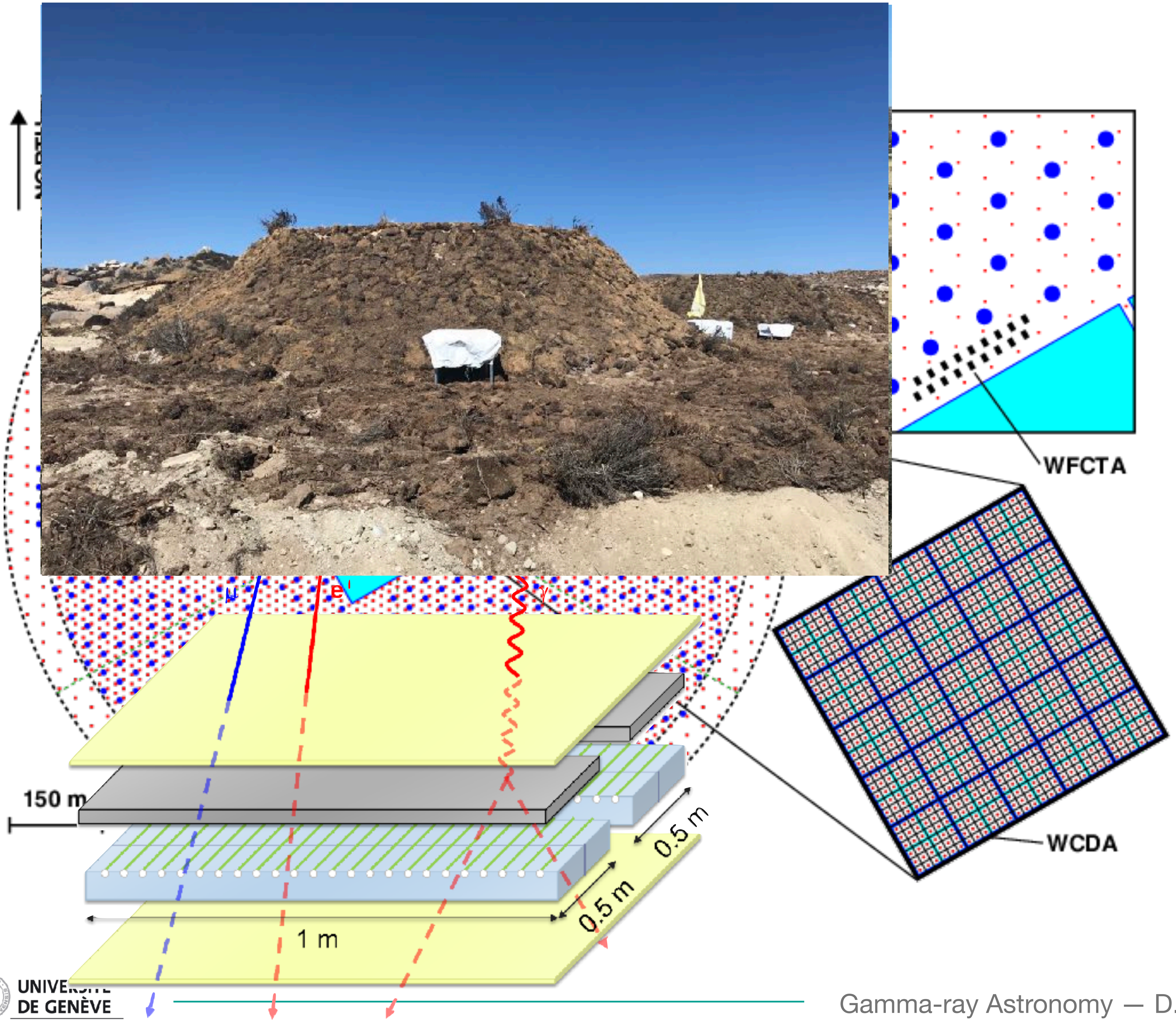

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  - Measuring shower direction and location
- **KM2A - Km-square array**
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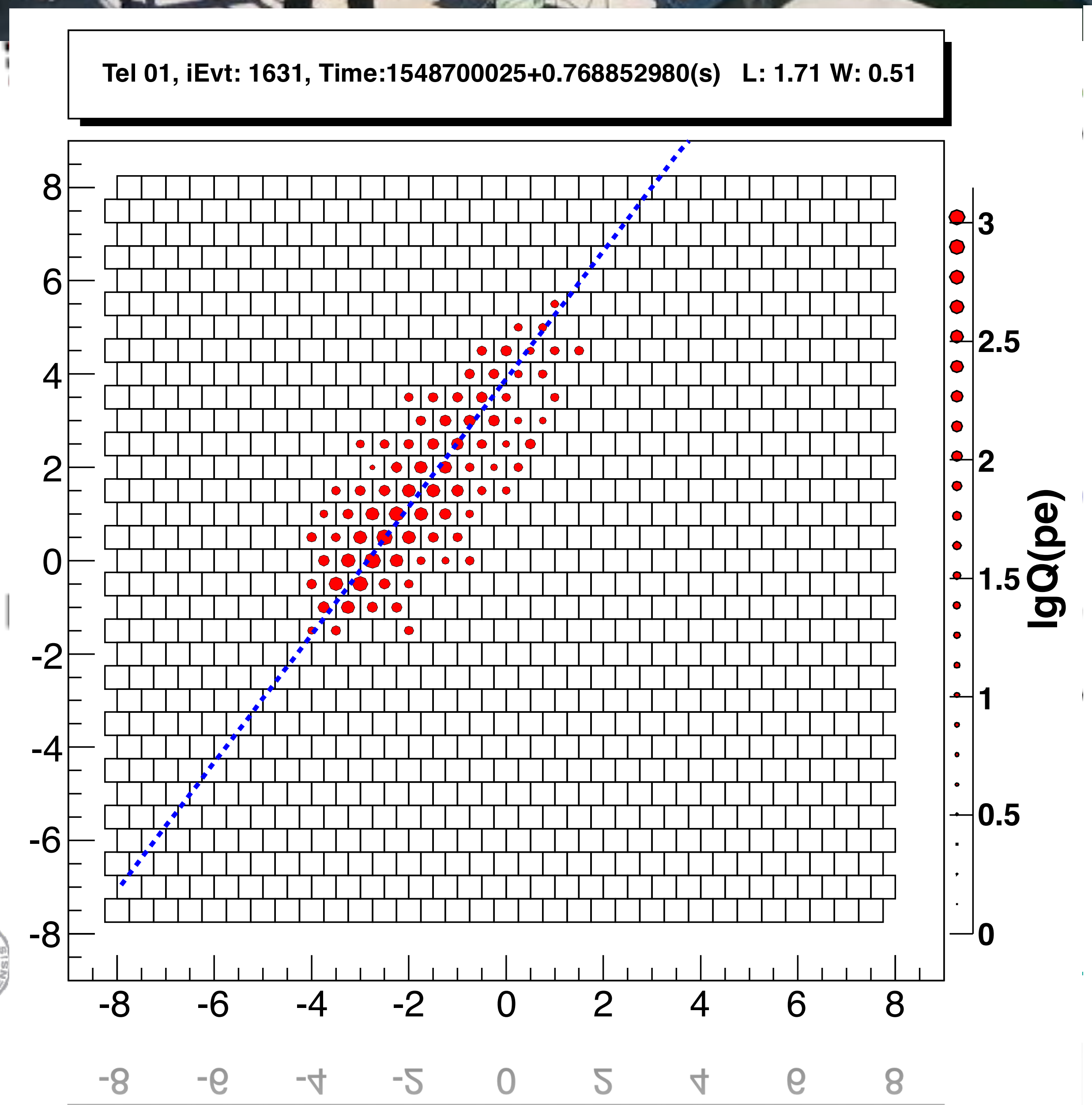
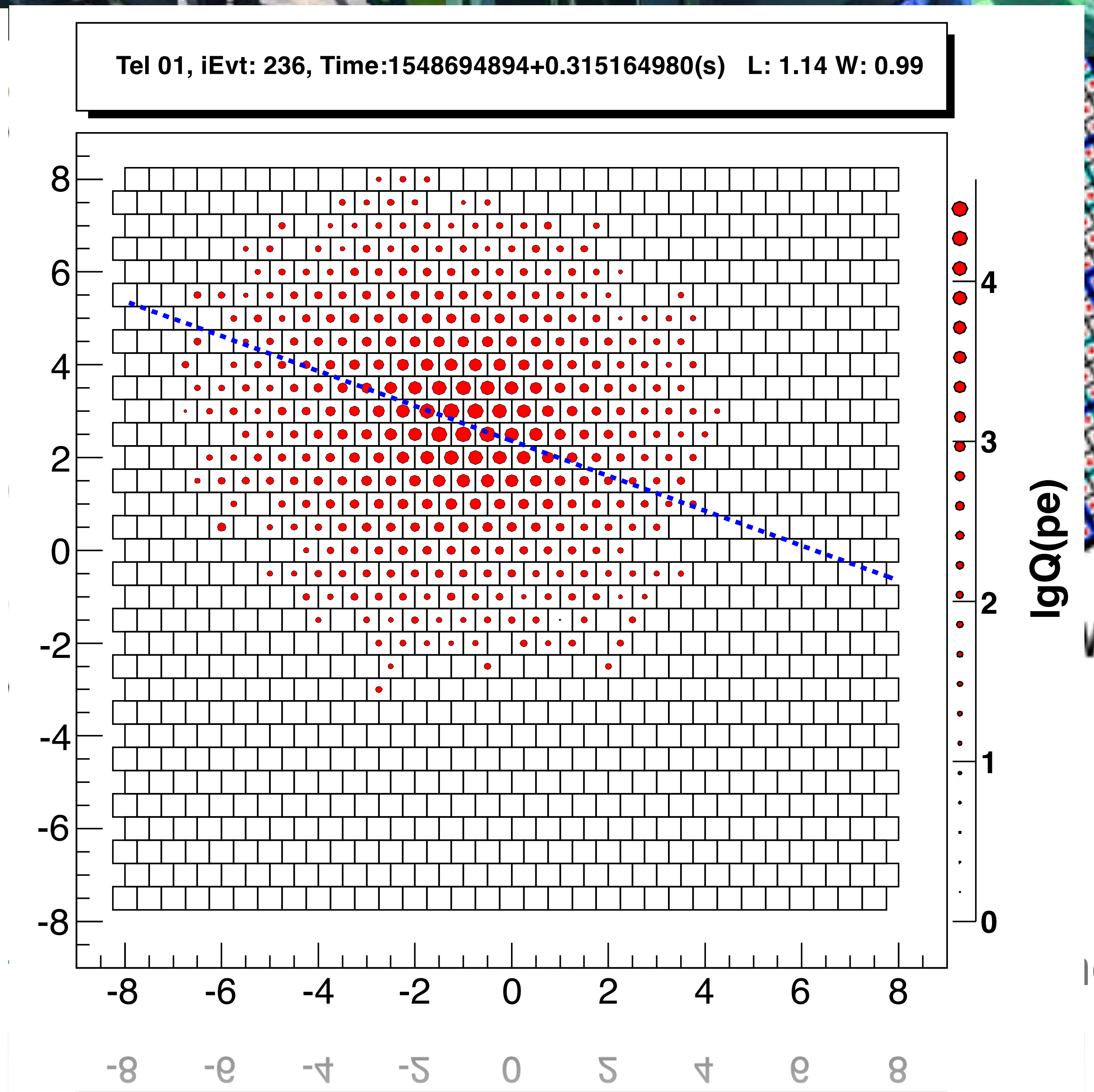
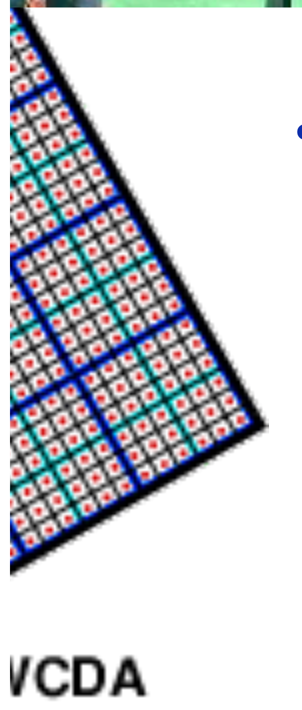
  - Measure Shower fluorescent light
  - Particle discrimination for composition study at knee

LHAASO Layout

- **CDA - Water Cherenkov Detector Array**
  - Measuring shower direction and location
- **2A - Km-square array**
  - Measuring shower direction and location
  - Measuring μ–content with the largest MD array ever
  - Clean γ selection







- **WFCTA - Wide Fielf-of-view Cherenkov array**
  - Extend energy range
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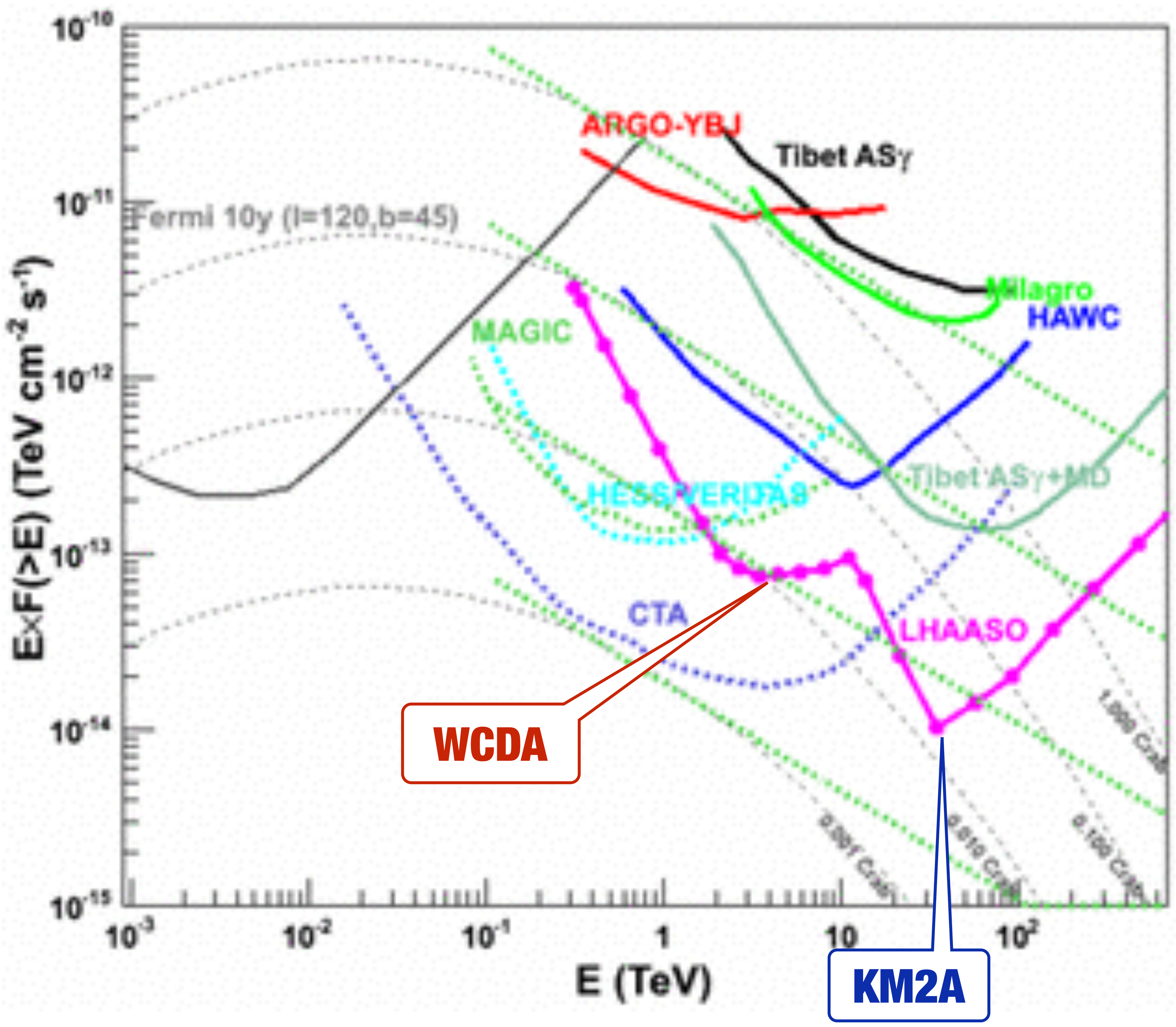
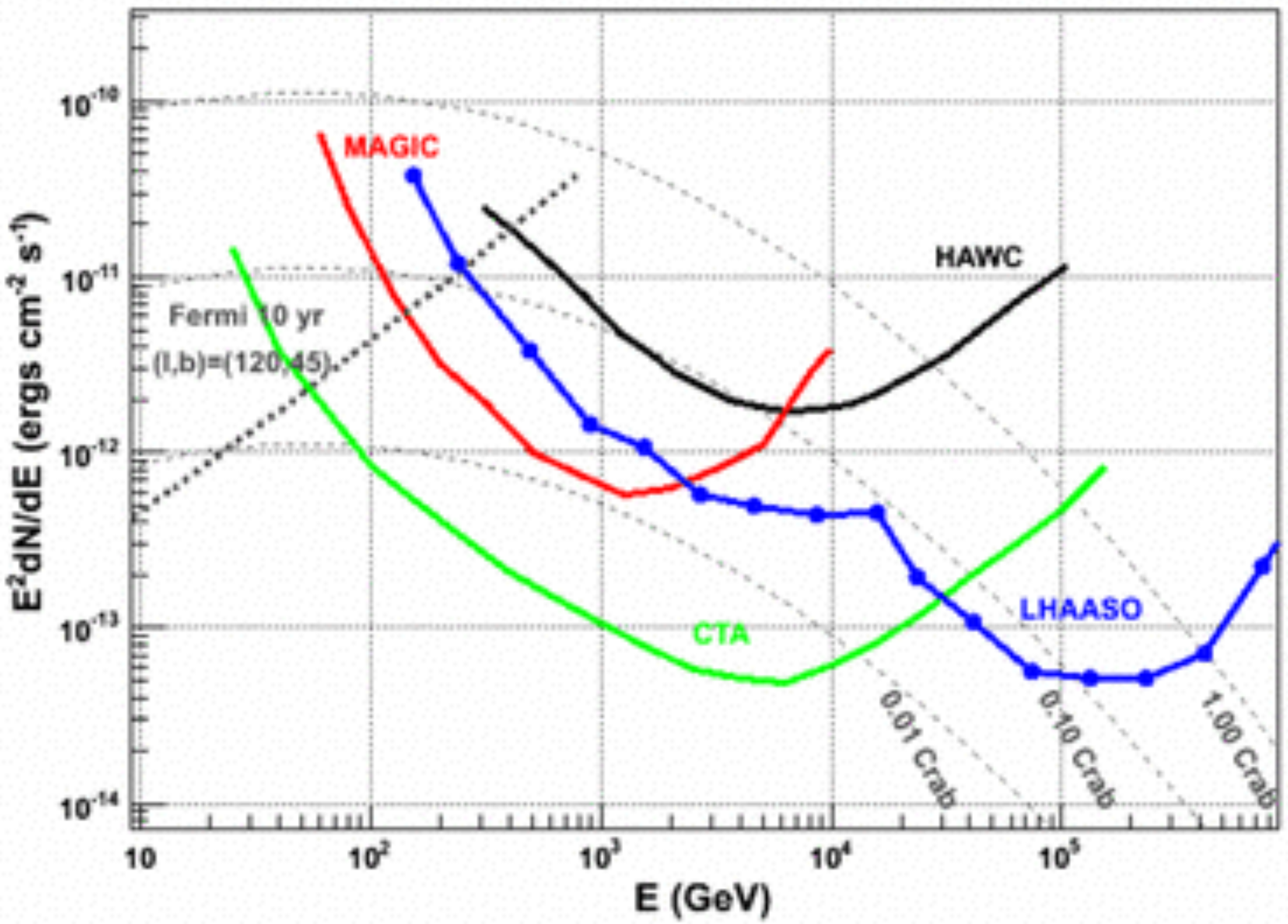
LHAASO Sensitivity



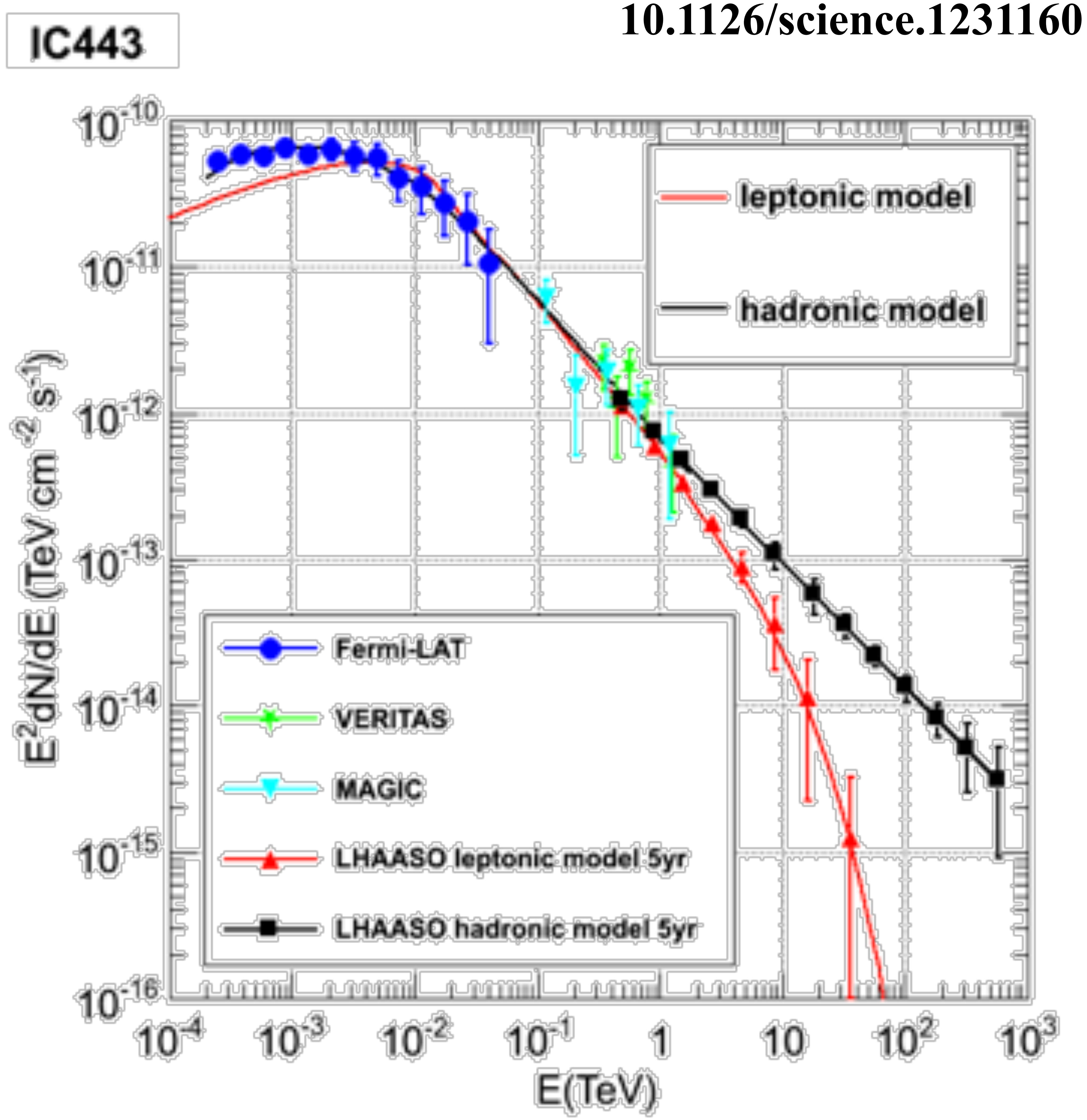
Integral

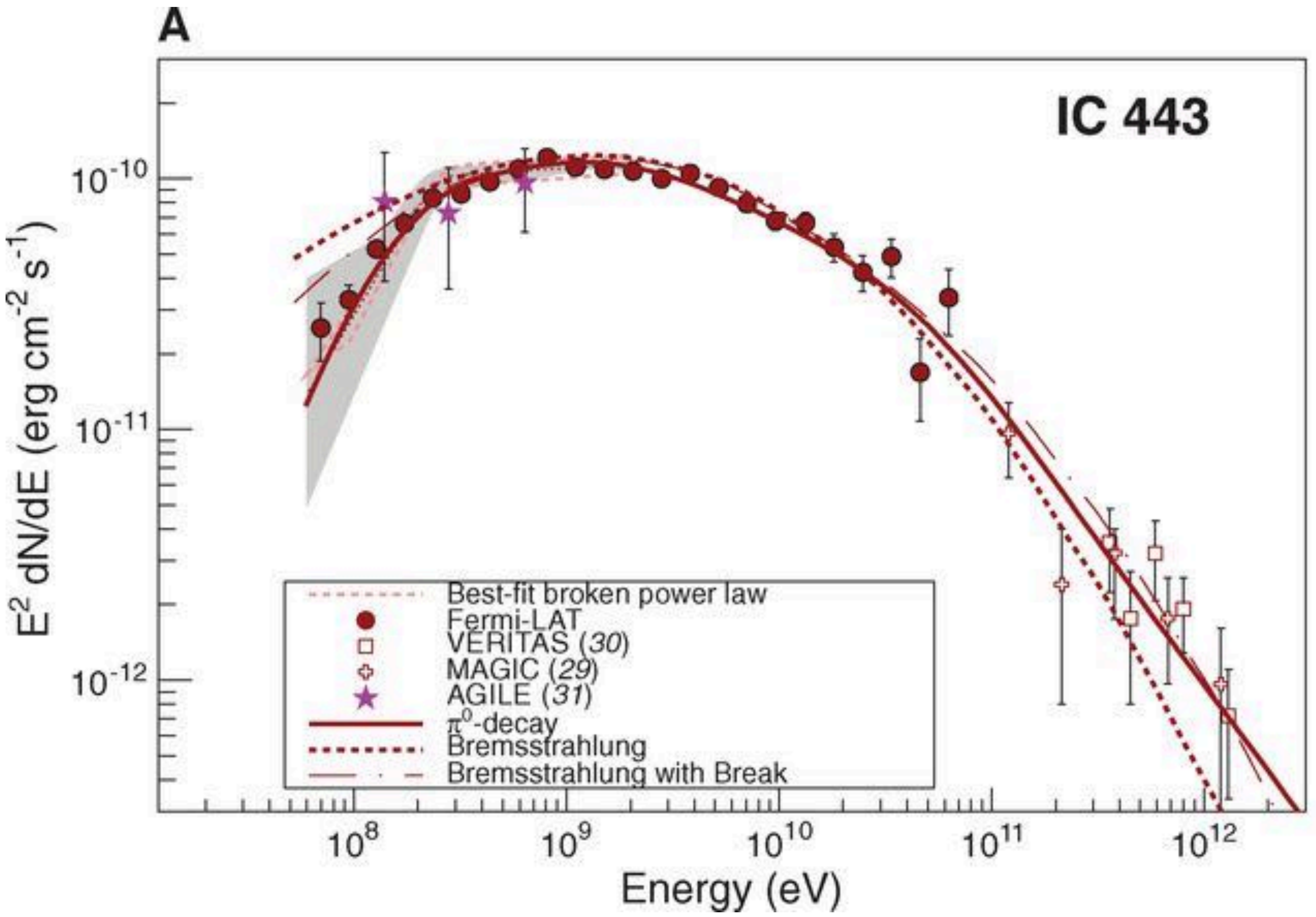


Differential

Hadronic vs Leptonic

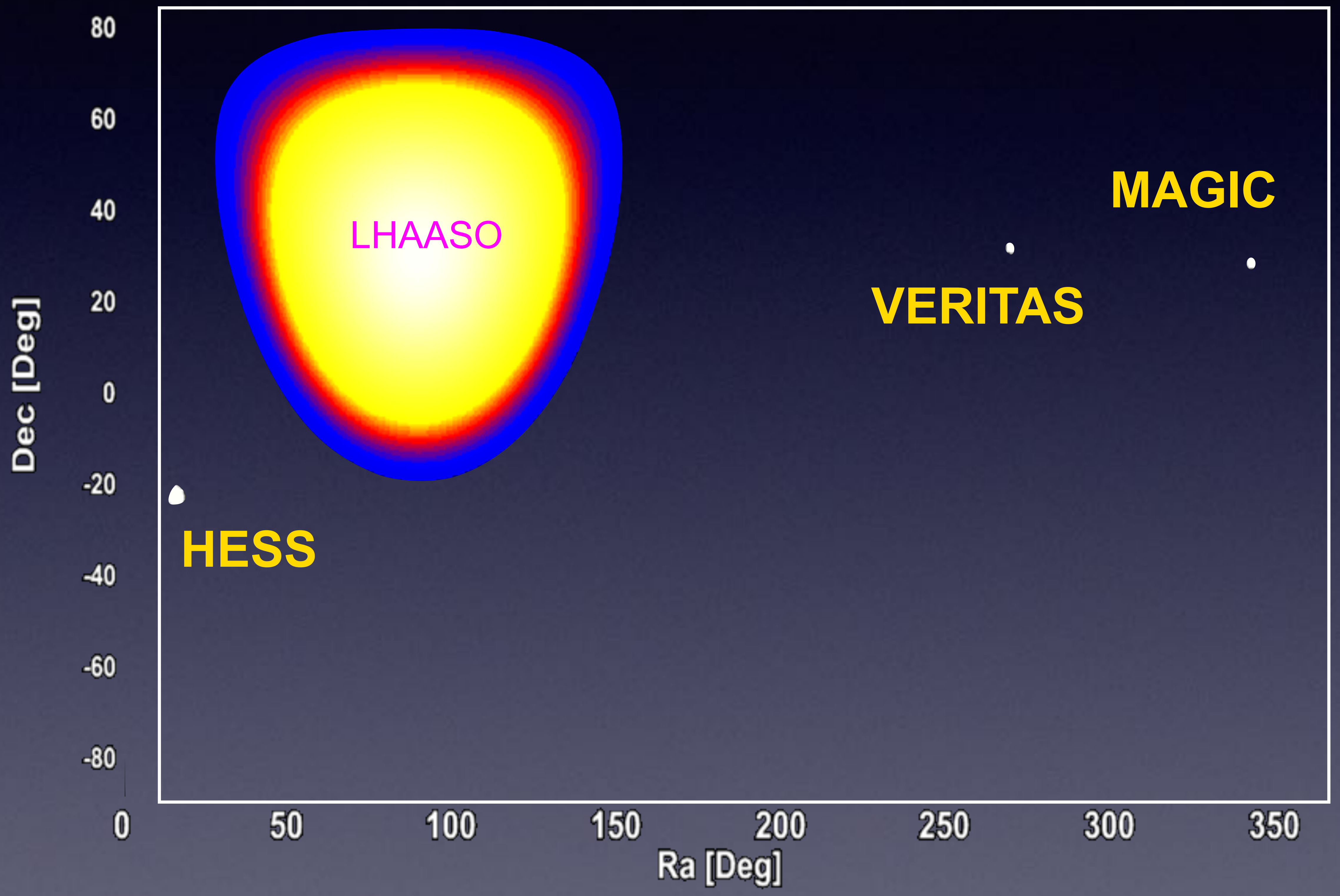
10.1126/science.1231160



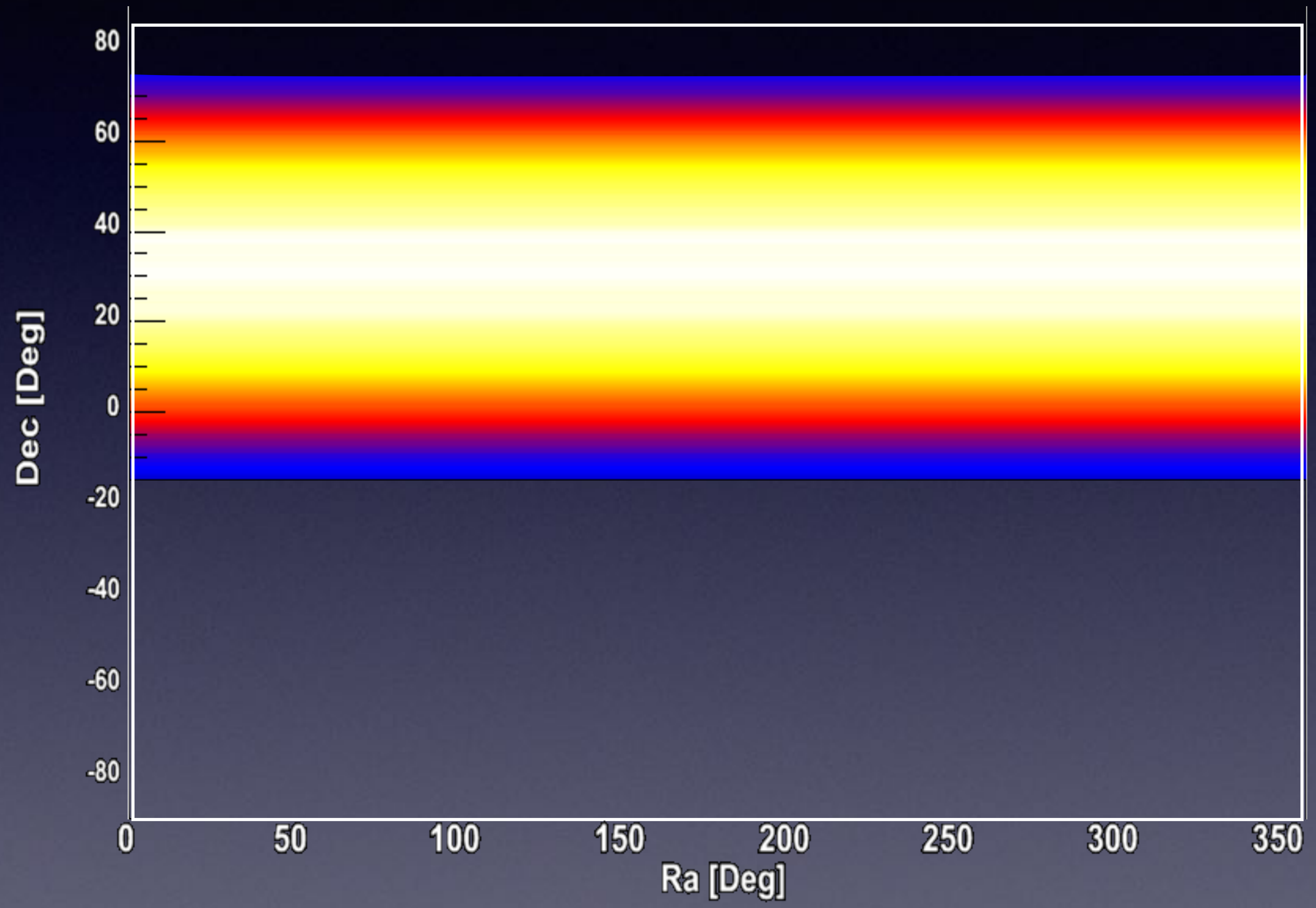


M. Ackermann et al. Science 2013;339:807-811 Science AAAS

Wide FOV γ-ray Astronomy

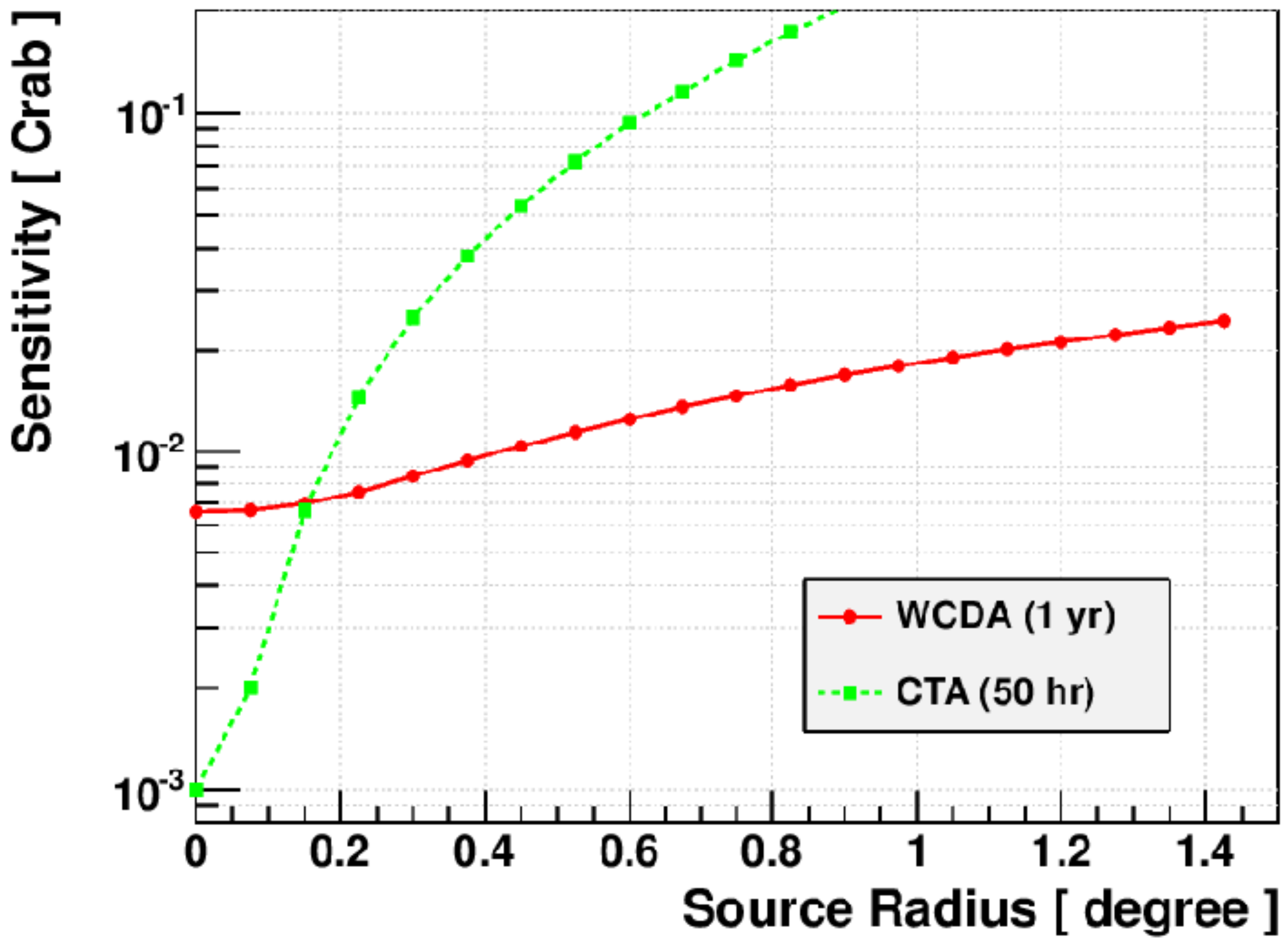


- 1/7 of the sky at any moment



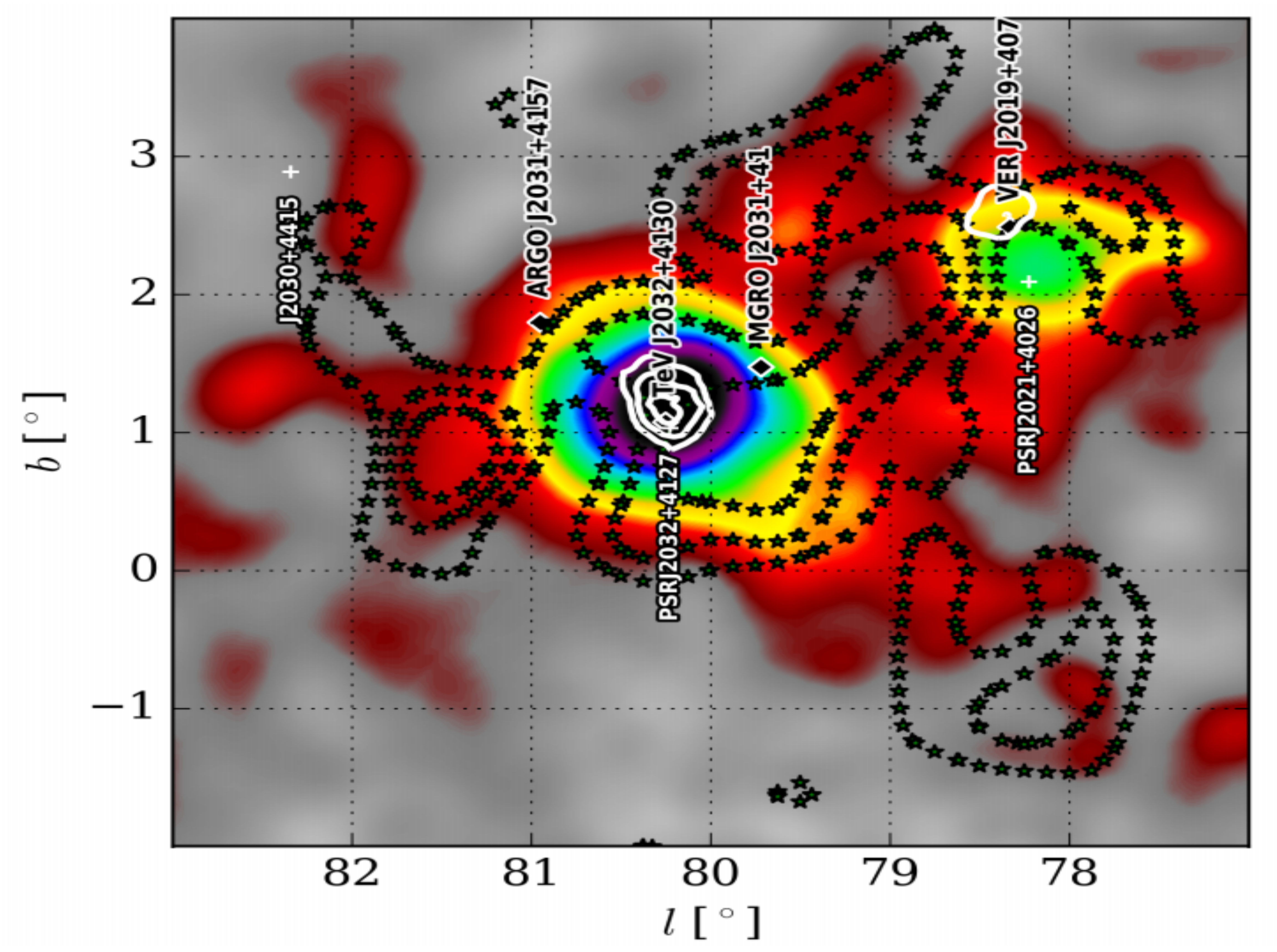
- 60% in the sky per day day (24h)

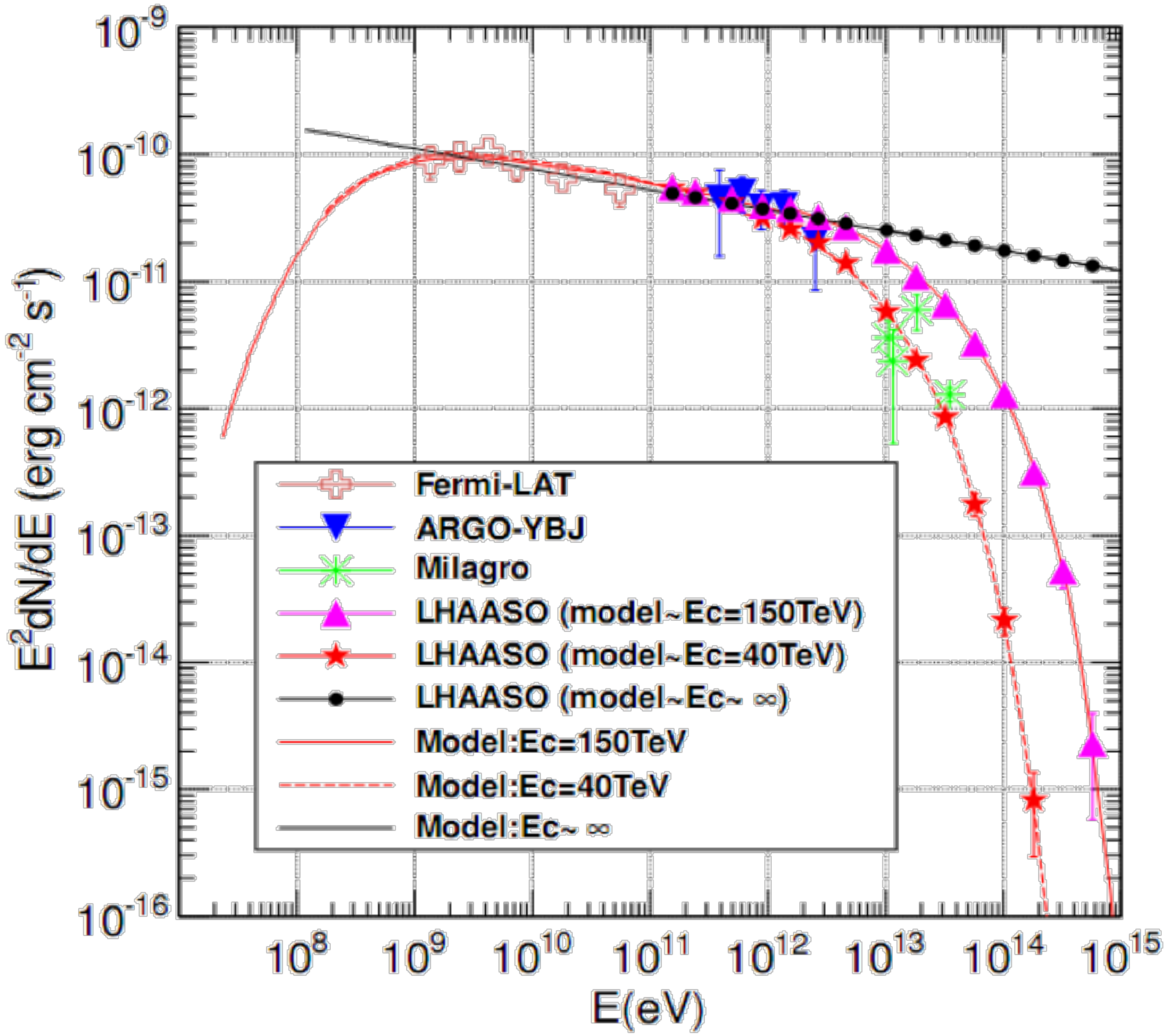
Extended Source sensitivity



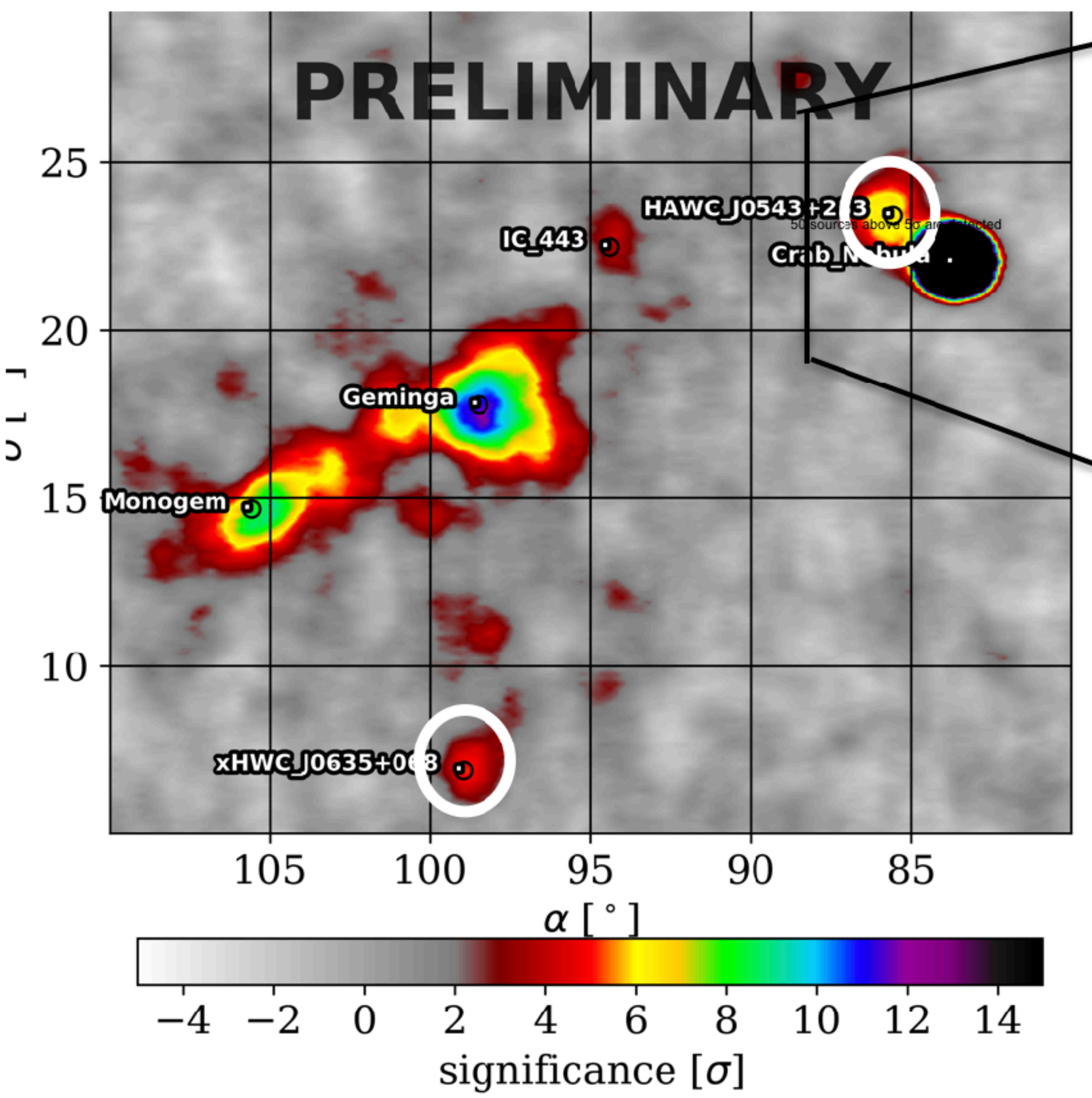
Extended Source sensitivity

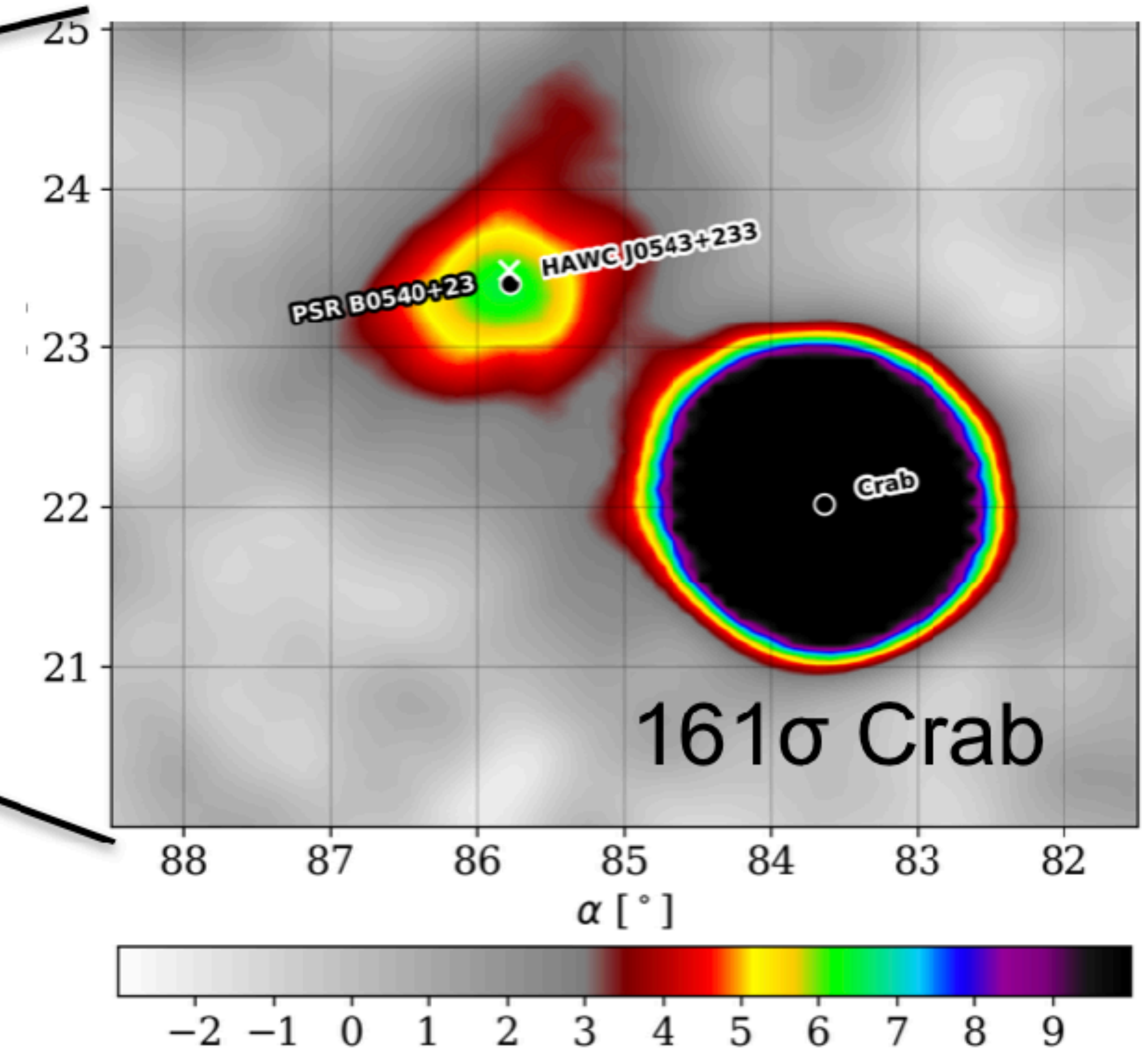
Cygnus Cocoon





Discovery Potential: Hiding in Plane Sight





Another middle age PWN similar to Geminga and B0656+14
$\dot{E} = 4.1 \times 10^{34}$ erg s−1,
d = 1.56 kpc, τ = 253 kyr

Can test if all are Geminga-like

HAWC J0543+233: http://www.astronomerstelegram.org/?read=10941
HAWC J0635+070: http://www.astronomerstelegram.org/?read=12013

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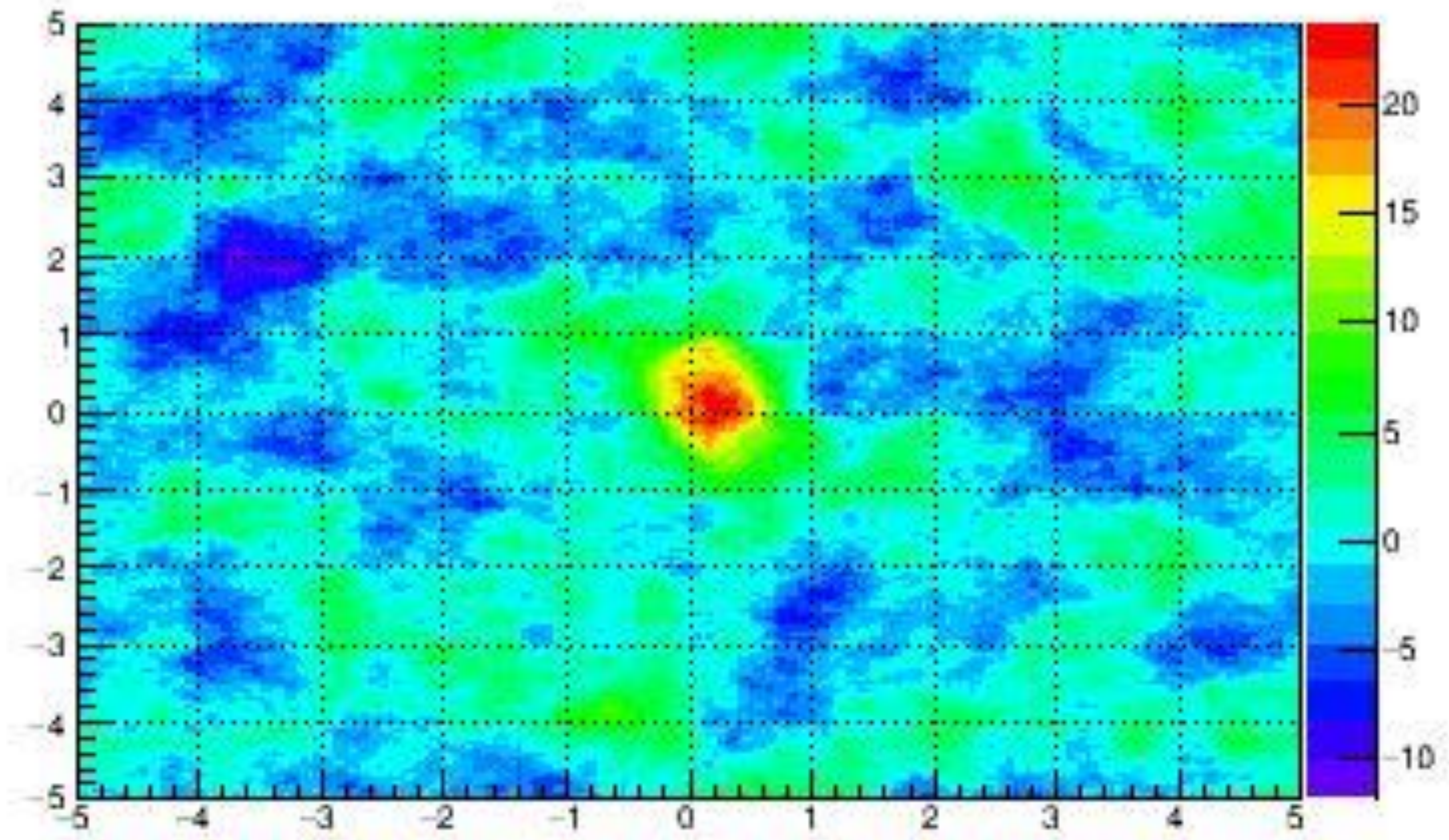

Crab Observation *LHAASO Data 137 hours (April-June 2019)*

Can test if all are Geminga-like

EAS Arrays & IACT complementary => synergy

- Important to establish Synergies to make real progress in understanding the non Thermal Universe

- Northern hemisphere
  - LHAASO and CTA North could exploit such synergy, almost same latitude sam sky coverage
    - Easy to share alerts and Surveys
    - But Key Science project are different, different allocation of observation time
  - A new Asian IACT Array near LHAASO to work in coordination?
    - Have a common Key science program, have a common scheduler?
    - How should it look like?

- Southern Hemisphere
  - CTA is under construction and a new EAS Array (SGSO) is being studied.