Foundations of Cosmic Ray Astrophysics
Varenna 2022

Future facilities in high-energy astrophysics

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DESY-Zeuthen, Germany

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

H.E.S.S. DESY.

Who am I?

Presentation

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CTA, H.E.S.S., Humboldt-Stipendiat

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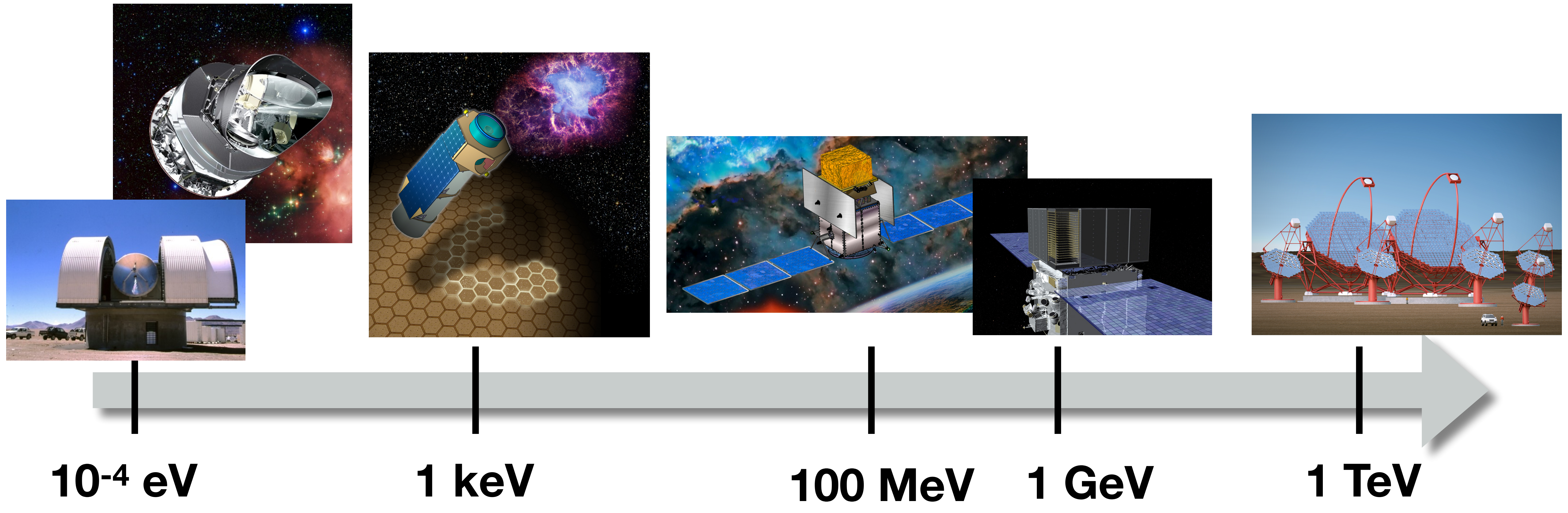


Some papers to read further:

* *TeV Instrumentation: current and future*, J. Sitarek 2022, https://arxiv.org/pdf/2201.08611.pdf
* *Ground-based detectors in very-high-energy gamma-ray astronomy*, M. de Naurois & D. Mazin, https://arxiv.org/pdf/1511.00463.pdf
* *The future of gamma-ray astronomy*, J. Knodlseder, https://arxiv.org/pdf/1602.02728.pdf
* *Ground- and Space-Based Gamma-Ray Astronomy*, S. Funk, https://www.annualreviews.org/doi/abs/10.1146/annurev-nucl-102014-022036

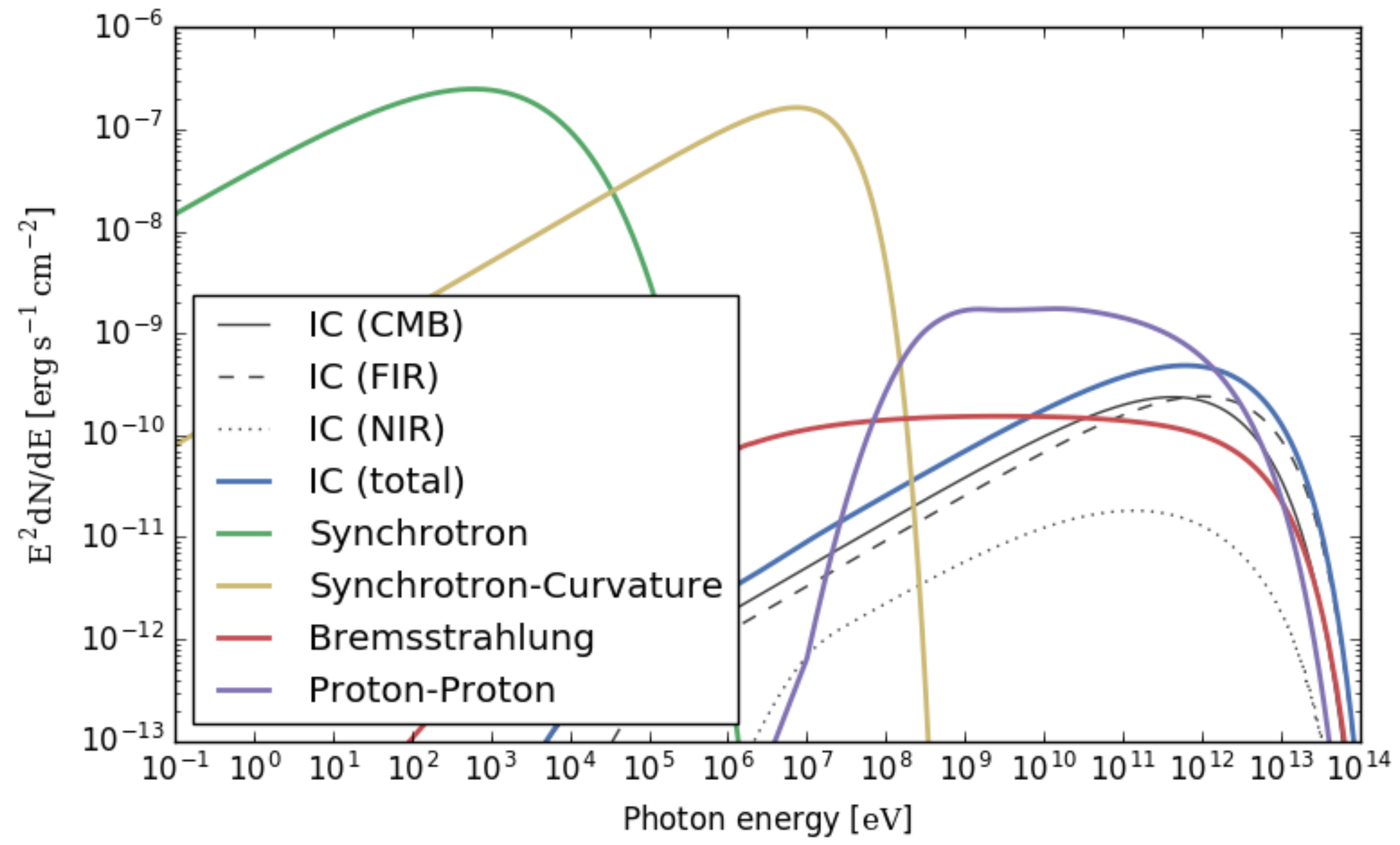
Content

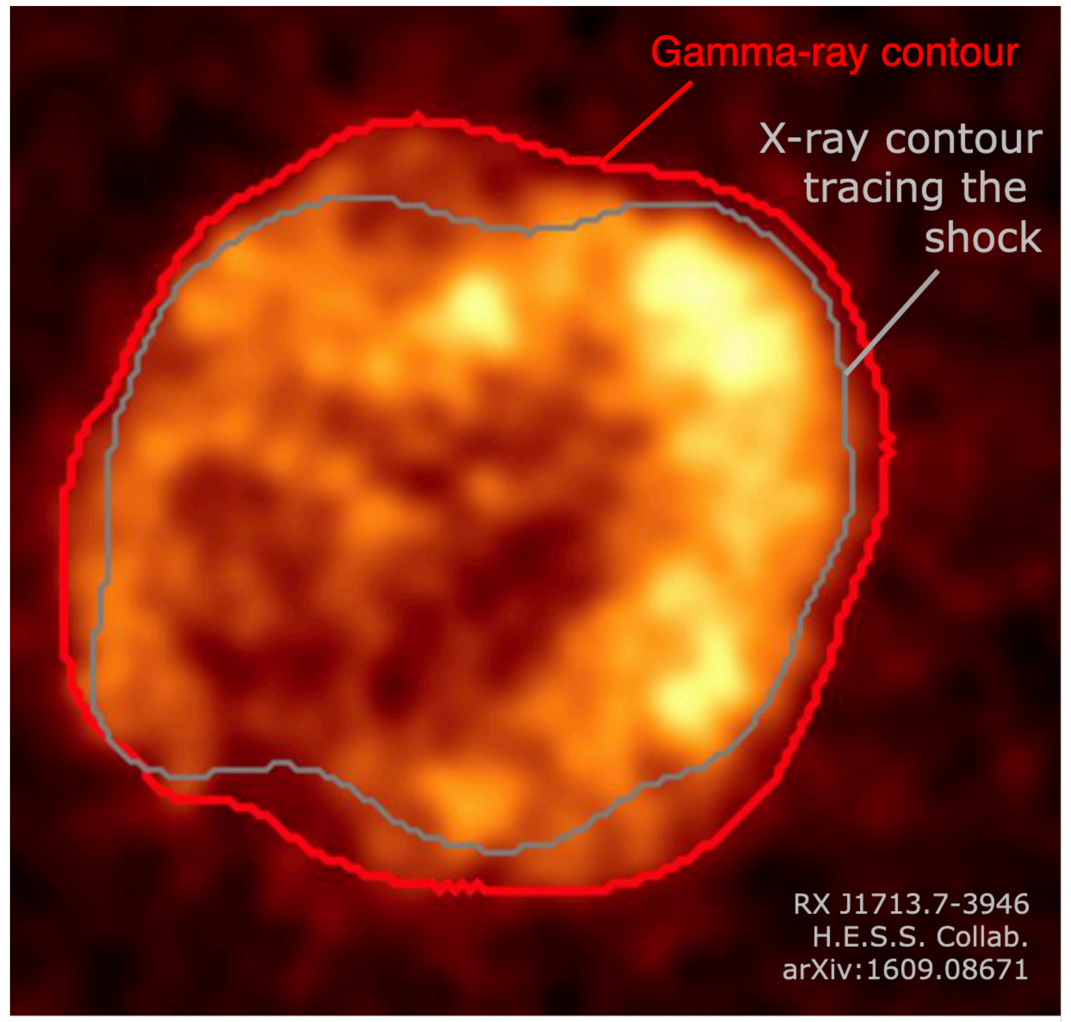
Instruments in the high energy regime

1. What type of radiation do we want to observe?
   => Spectral characteristics
   => Morphological characteristics
   => Time domain

2. How can we detect cosmic-rays/gamma-rays?
   => Instrumental techniques

3. What type of instruments we currently have?
   => Satellites
   => Imaging Array Cherenkov Telescopes (IACTs)
   => Surface Arrays (SA) and Water Cherenkov Detectors (WCD)
   => Cosmic-ray detectors*





Content

Instruments in the high energy regime

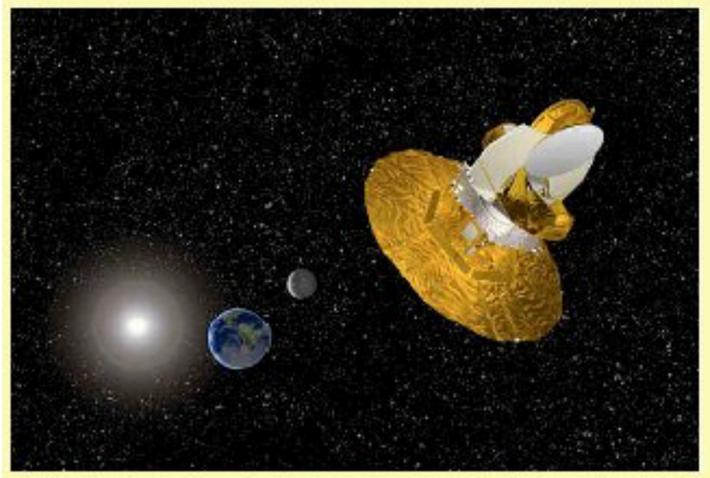
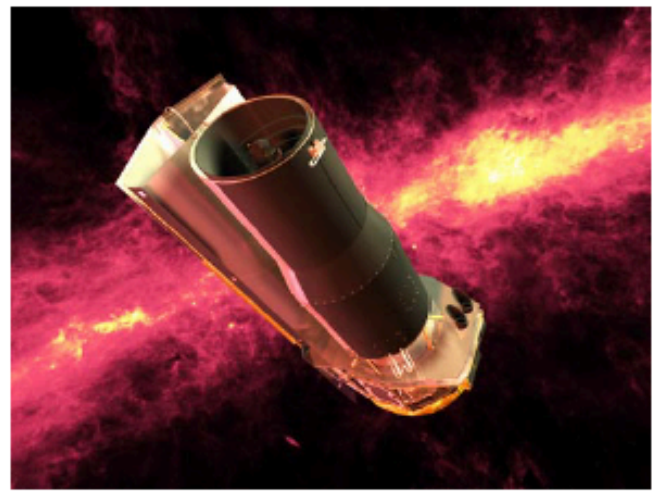
4. How can we improve them?

   => Planned detectors: SWGO and CTA
   => Other ideas ?

5. Multi-wavelength support

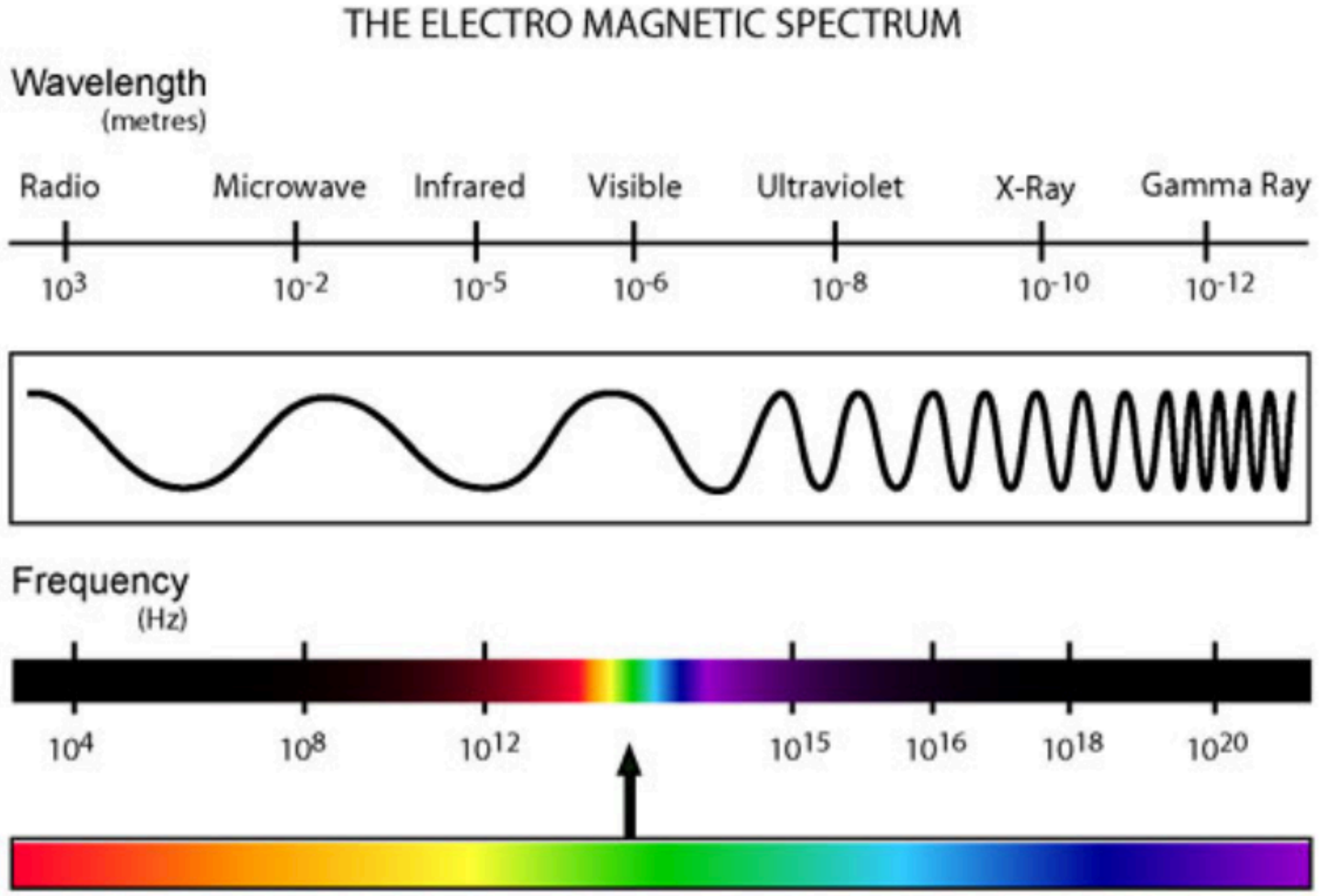
6. Brainstorming

1 Astronomy across the electromagnetic spectrum

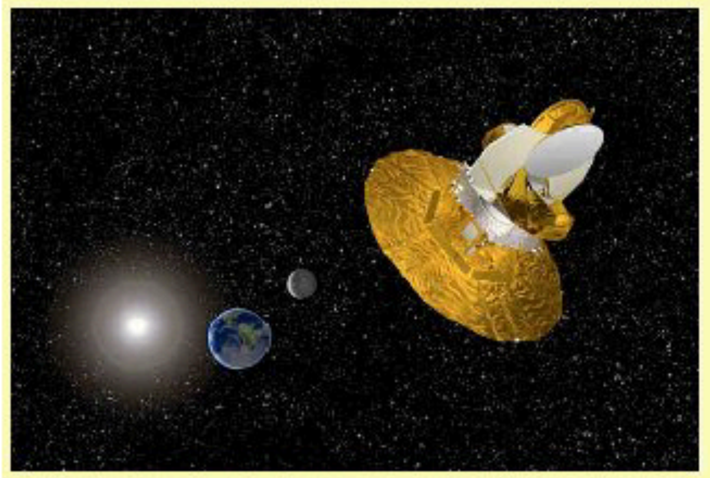


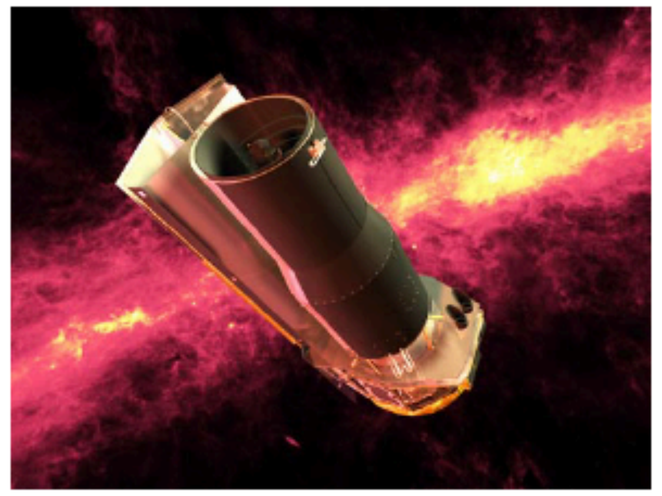


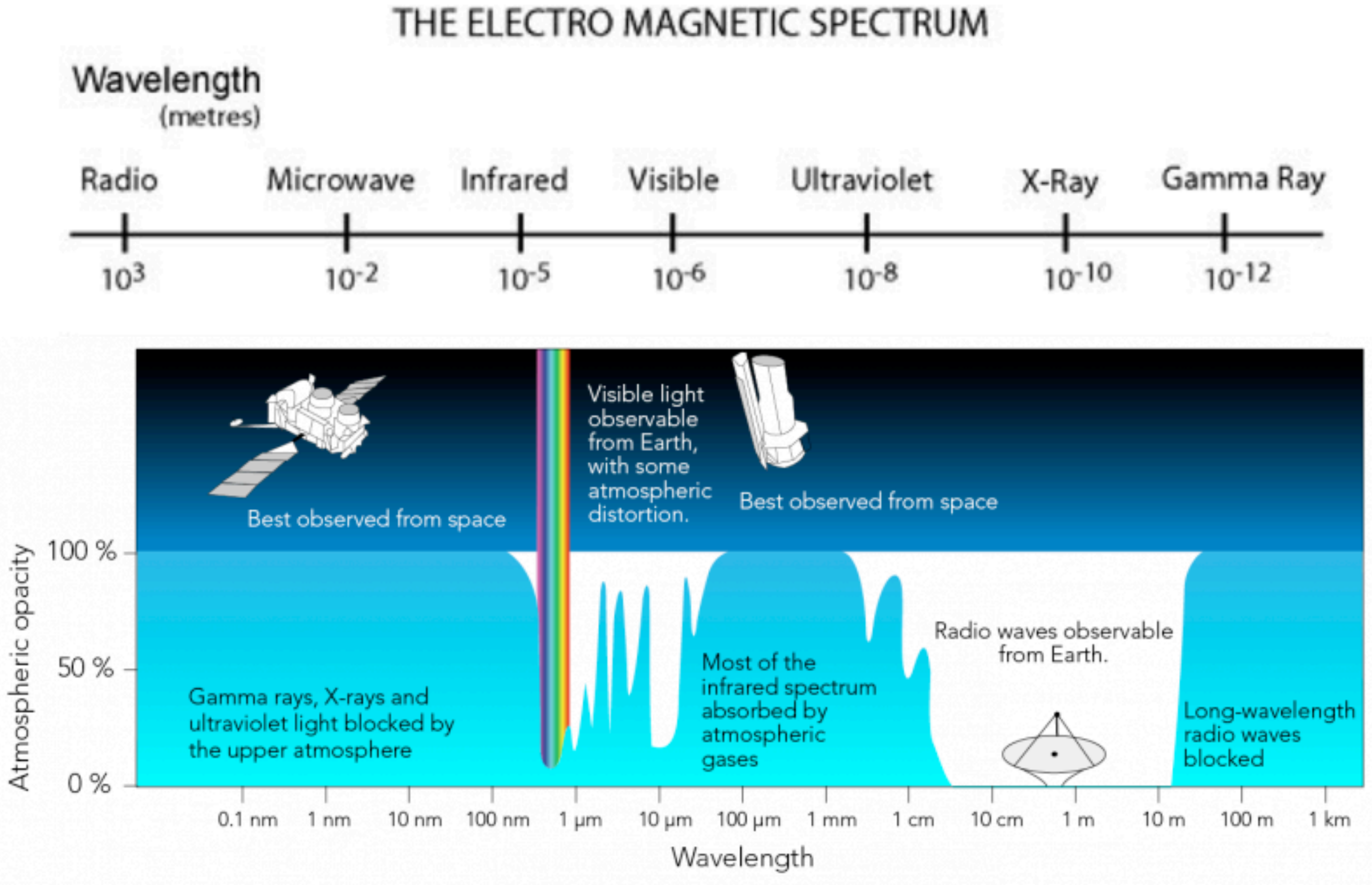





1 Astronomy across the electromagnetic spectrum







1 High energy astrophysics

High-energy particles/cosmic rays:
particles with energies much higher than the rest energy.

- For electrons, the rest energy is:

$$E = m_e c^2 \simeq 5 \times 10^5 \text{ eV}$$

- For protons:

$$E = m_p c^2 \simeq 10^9 \text{ eV}$$

Let's calculate the temperature necessary to reach this energies in a black body

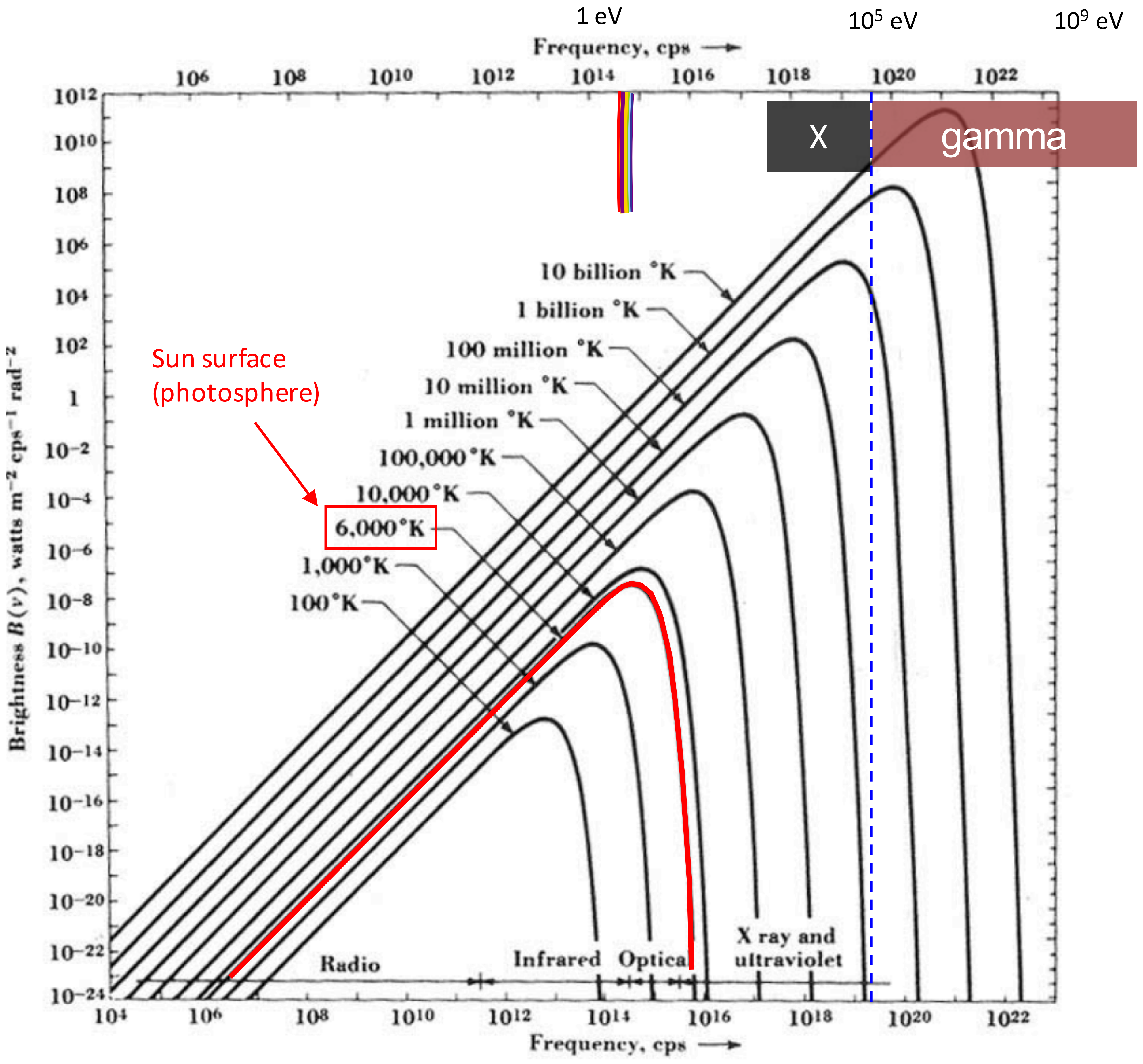
Black-body Spectrum

- For a thermal spectrum $< E > \sim \frac{3}{2} k_B T$:

  $(k_B = 8.62 \times 10^{-5} \text{eV K}^{-1})$

$$T \sim \frac{m_e c^2}{k_B} \sim 0.6 \times 10^{10} K$$

$$T \sim \frac{m_p c^2}{k_B} \sim 10^{13} K$$



- Need 10^9 K to produce MeV gamma-rays (10^{12} K for GeV gamma-rays)
- Such objects do exist (inside stars or in SNR explosions), but often screened or red-shifted
  => Non thermal processes dominate MeV - TeV gamma-ray

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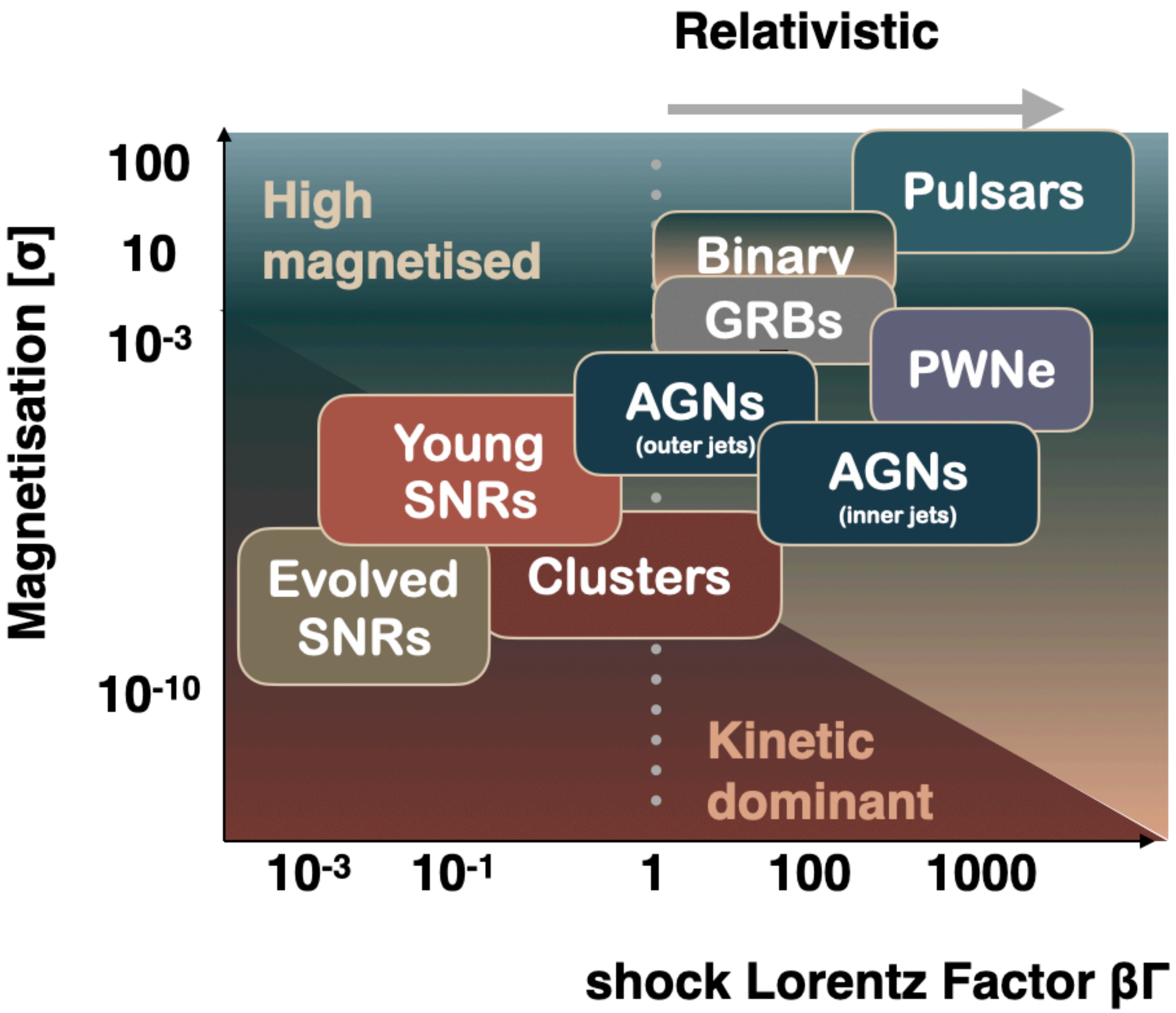

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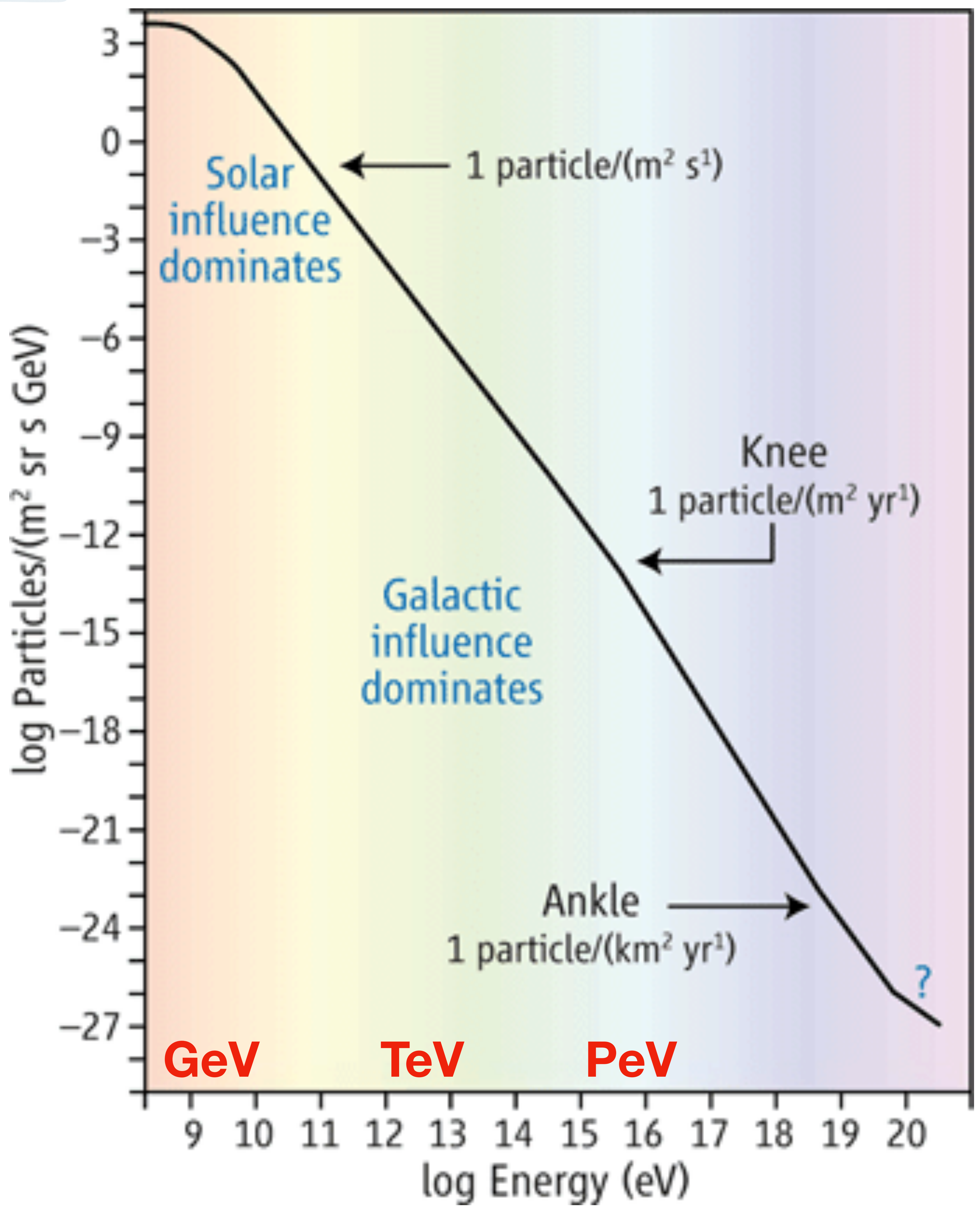
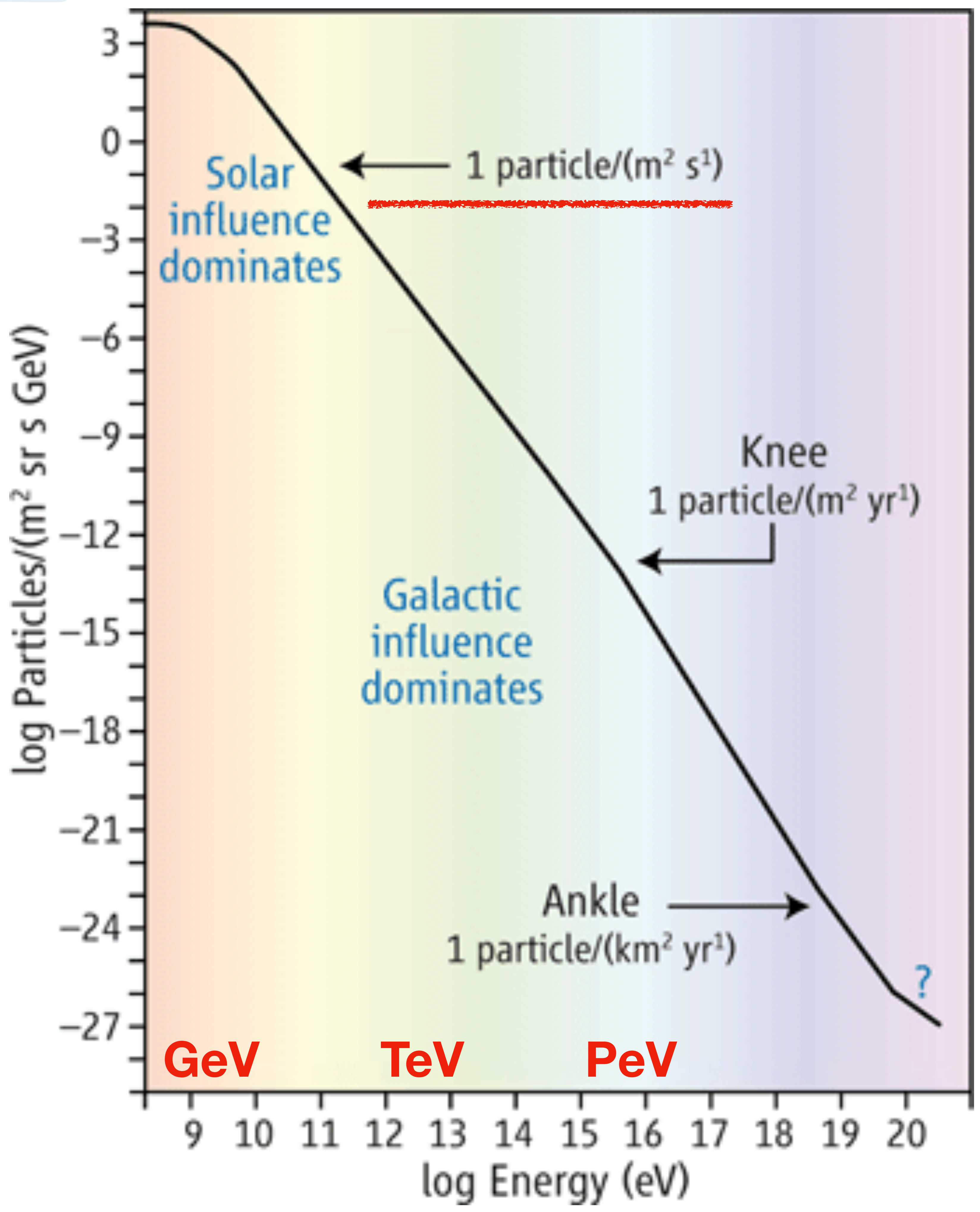
Cosmic ray Spectrum



- Statistics! the observed flux is low
- Mainly protons (+electrons and heavier nuclei) coming from beyond the Solar system and extending >10 decades in energy

Cosmic ray Spectrum



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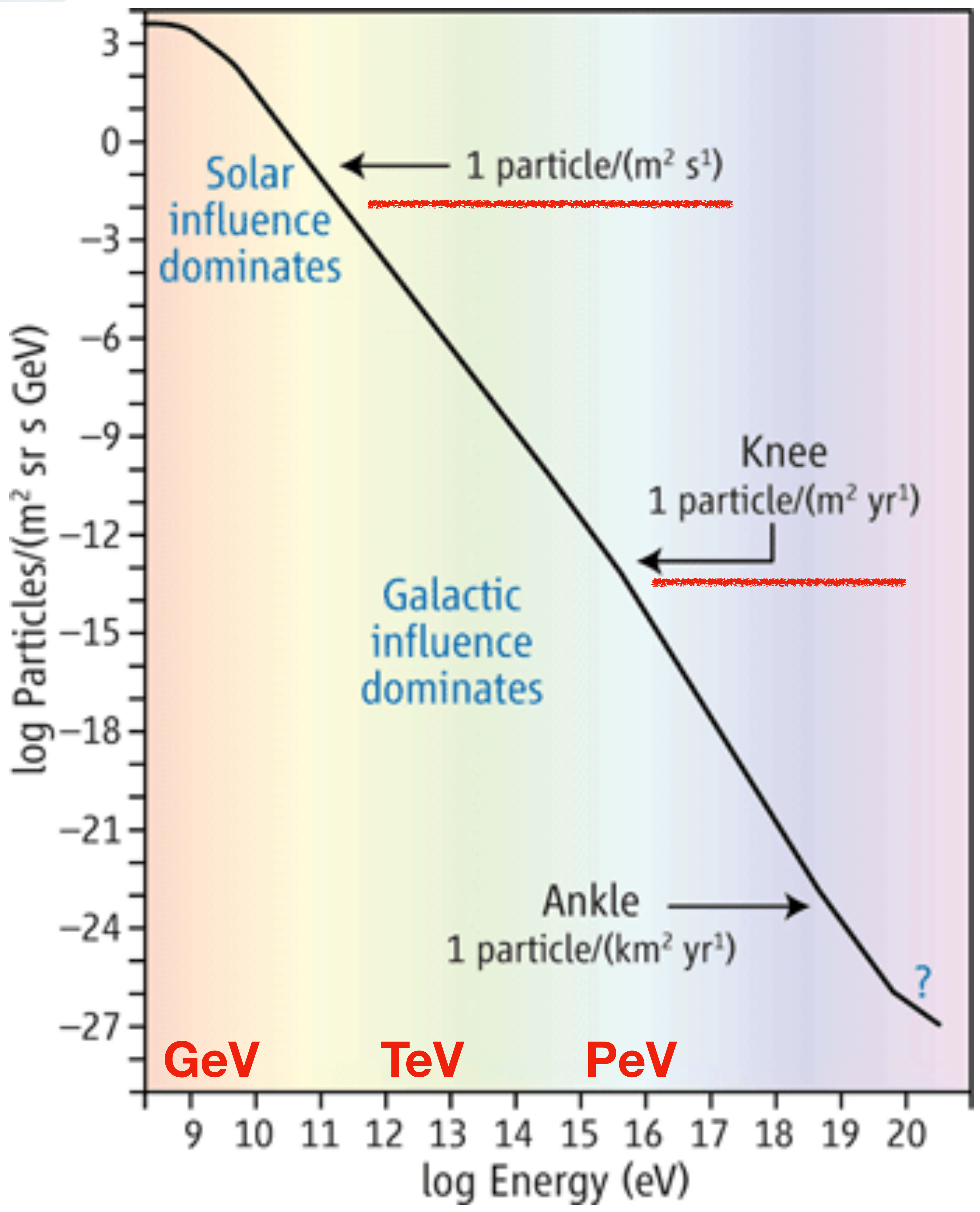

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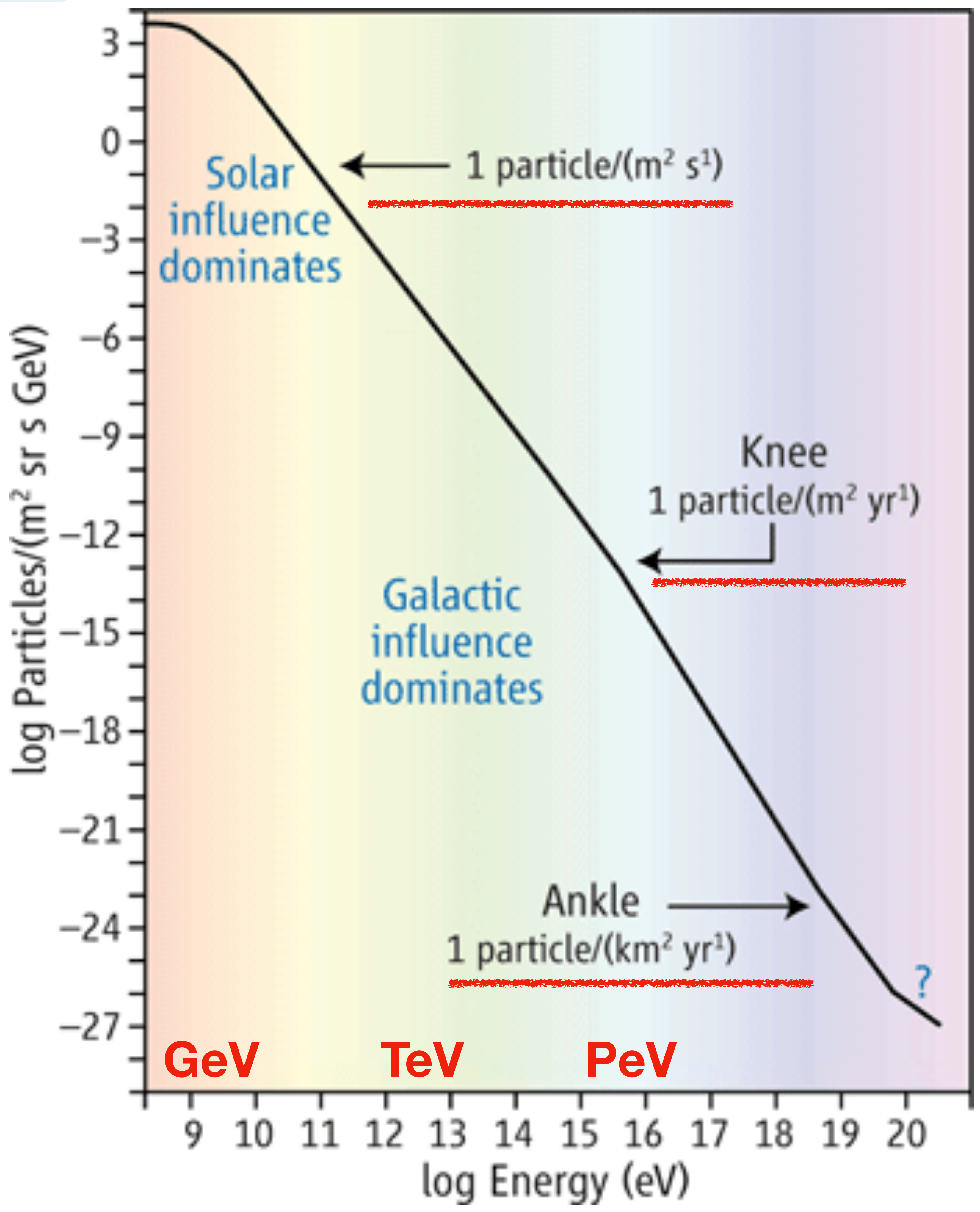

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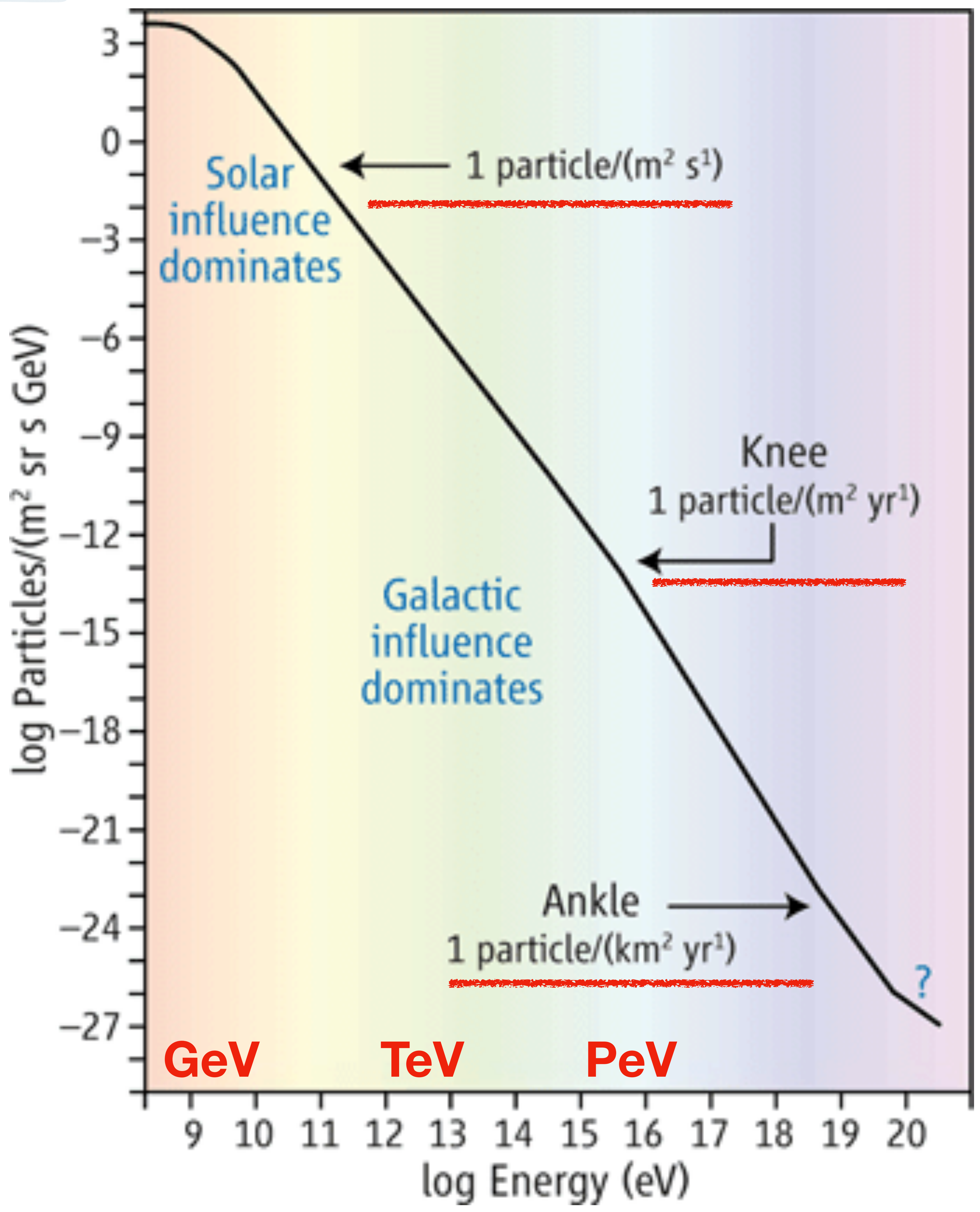

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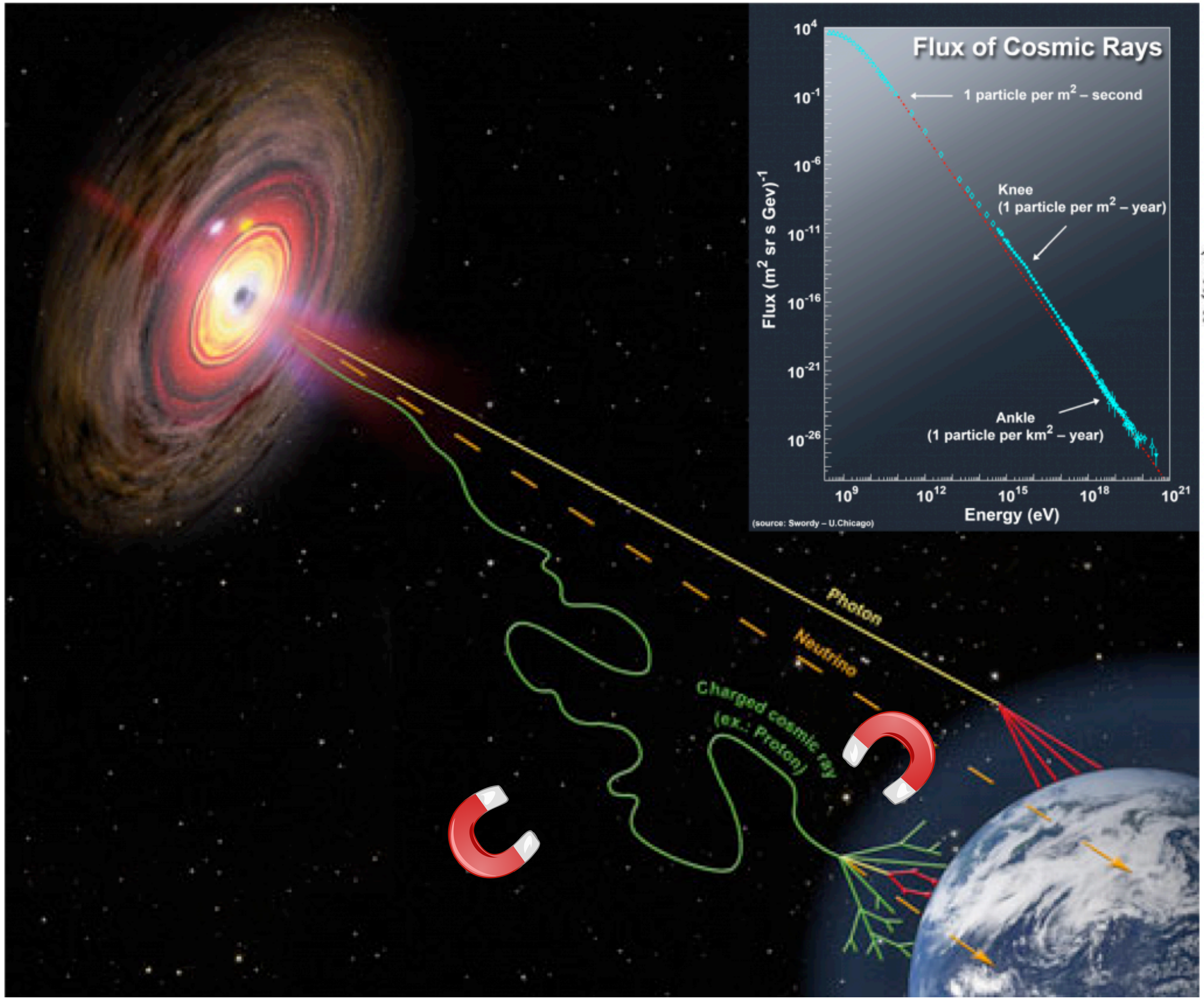
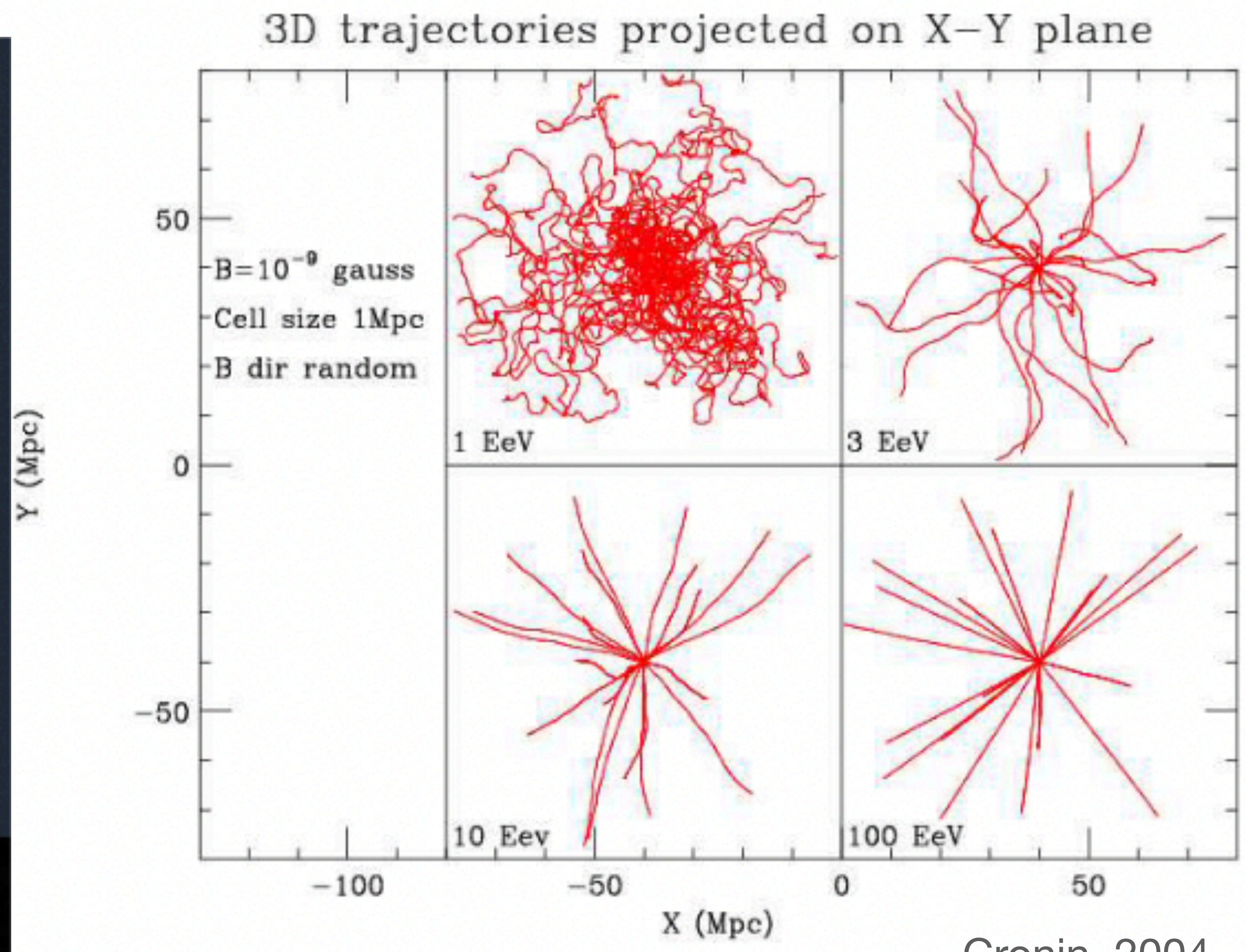
- Mainly protons (+electrons and heavier nuclei) coming from beyond the Solar system and extending >10 decades in energy
- CRs are charged particles => deflected by magnetic fields

Cosmic ray Spectrum



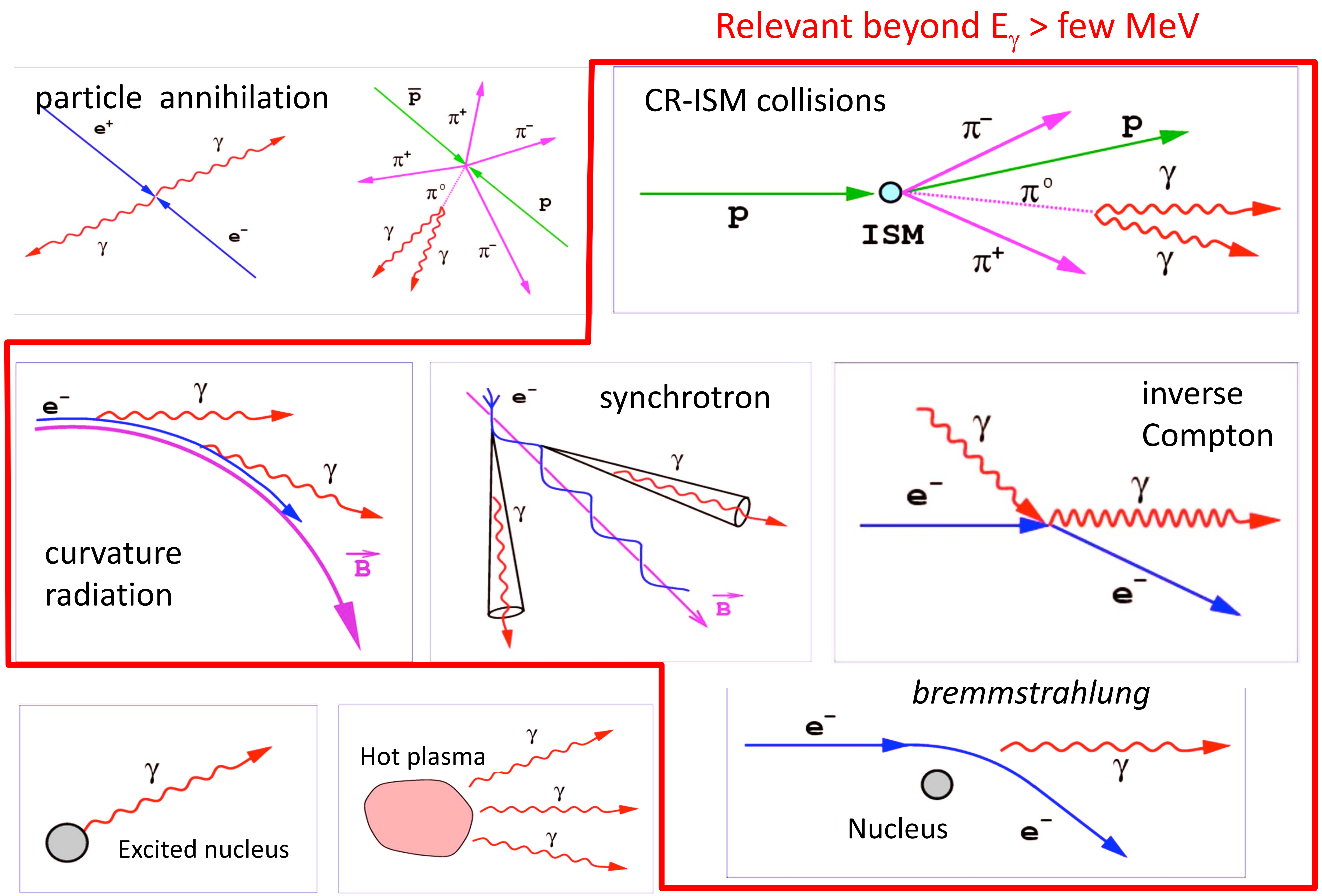


Cronin, 2004

For high energy astrophysics
we need neutral messengers

Gamma-ray radiation

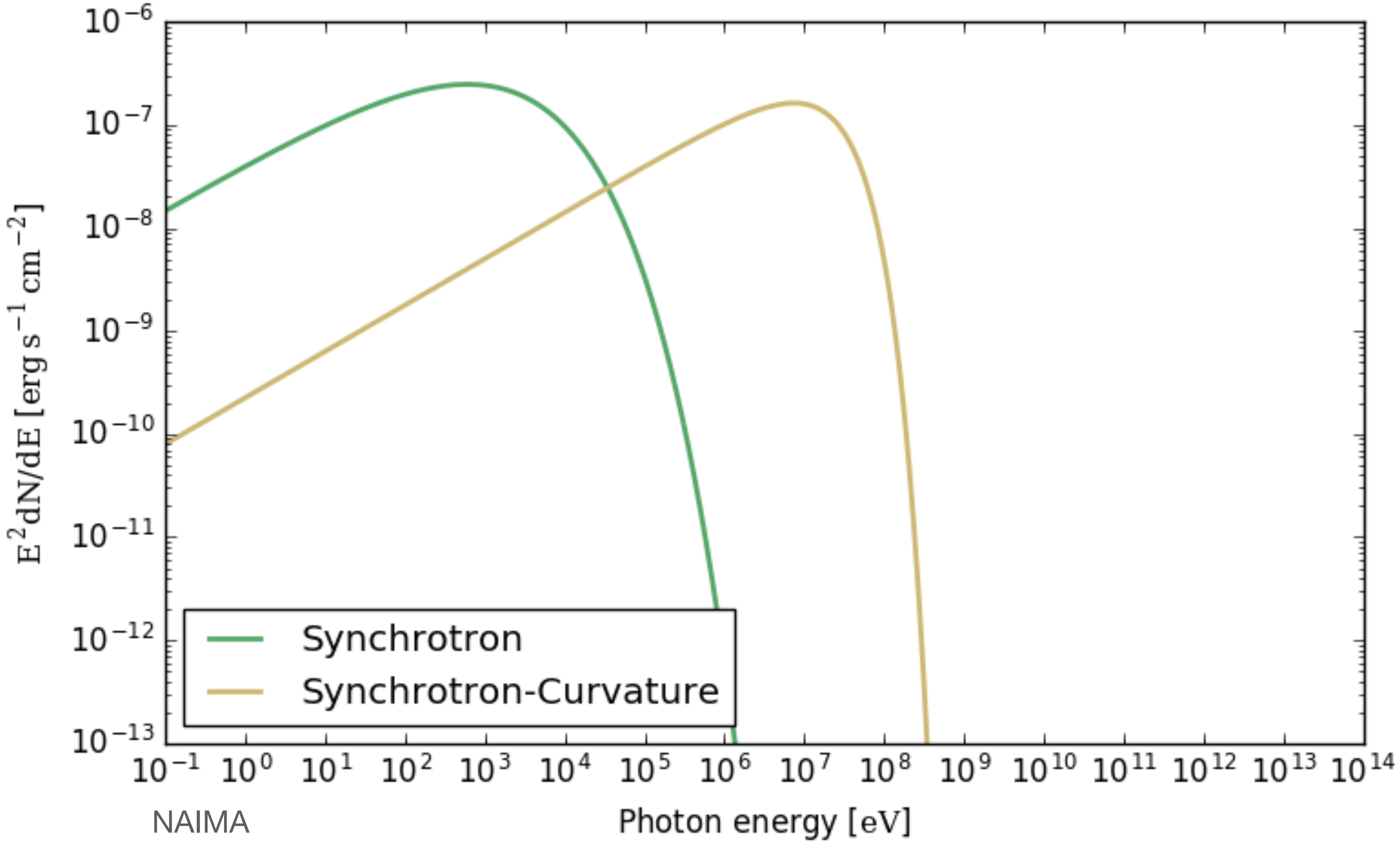
What type of radiation do we want to observe



Gamma-ray radiation

What type of radiation do we want to observe

=> Spectral characteristics



NAIMA

Synchrotron-Curvature

$e^{\pm} + \mathbf{B} \Rightarrow \gamma + e^{\pm}_{lowerE}$

Gamma-ray radiation

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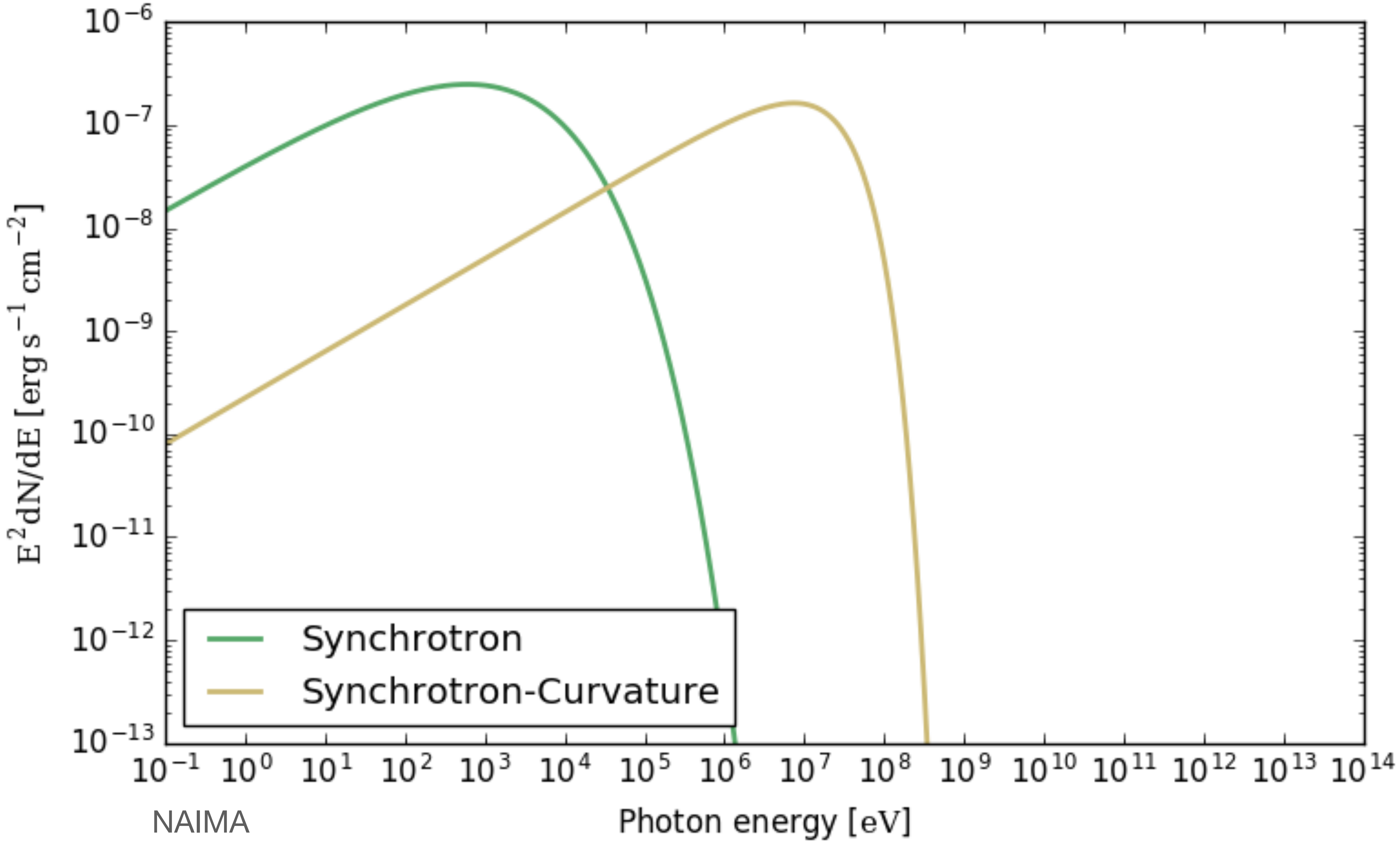

NAIMA

Synchrotron-Curvature

$e^{\pm} + \mathbf{B} \Rightarrow Y + e^{\pm}_{lowerE}$

Inverse Compton

$e^{\pm}_{HE} + Y_{LE} \Rightarrow e^{\pm}_{lowerE} + Y_{LE}$

1

Gamma-ray radiation

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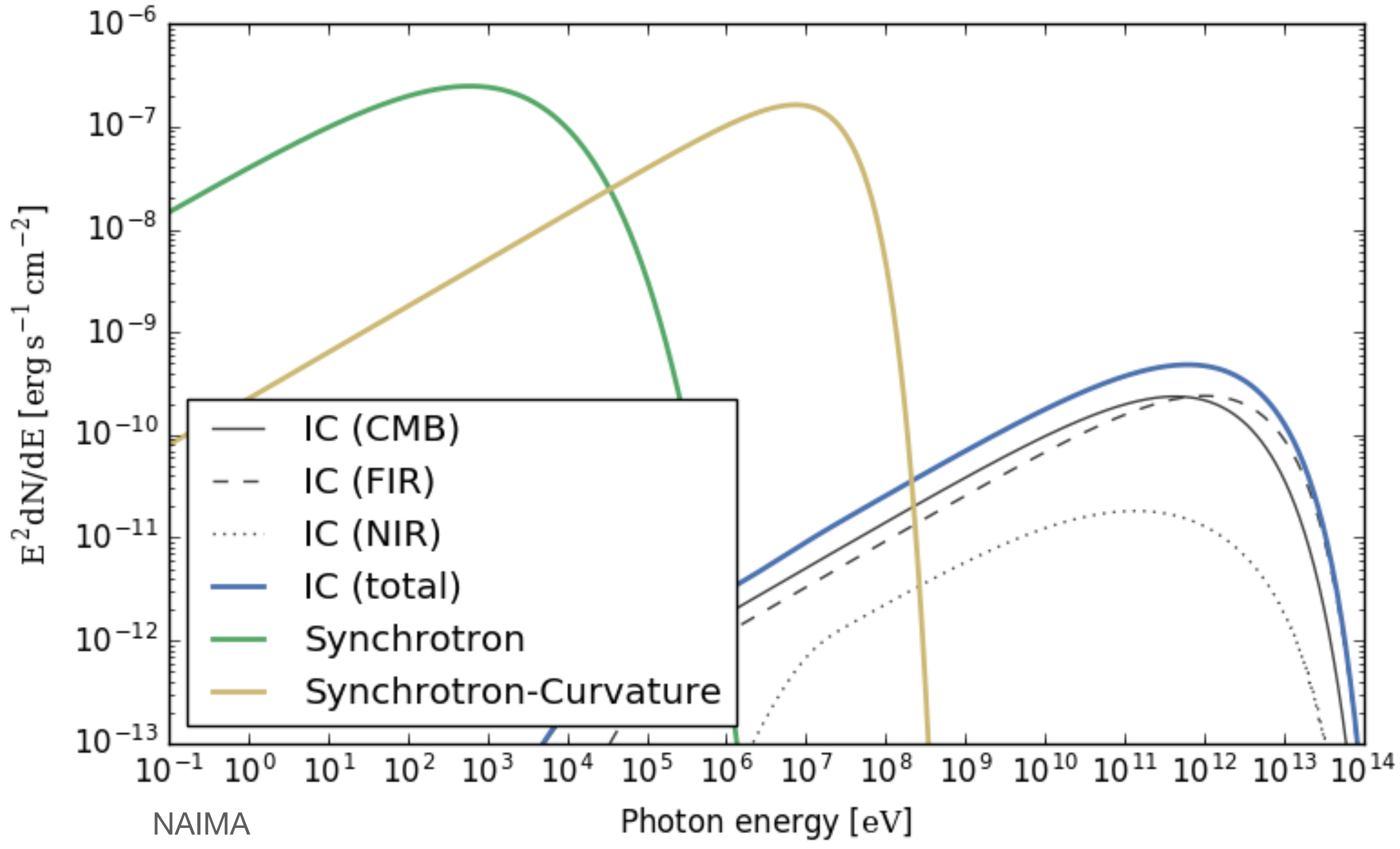

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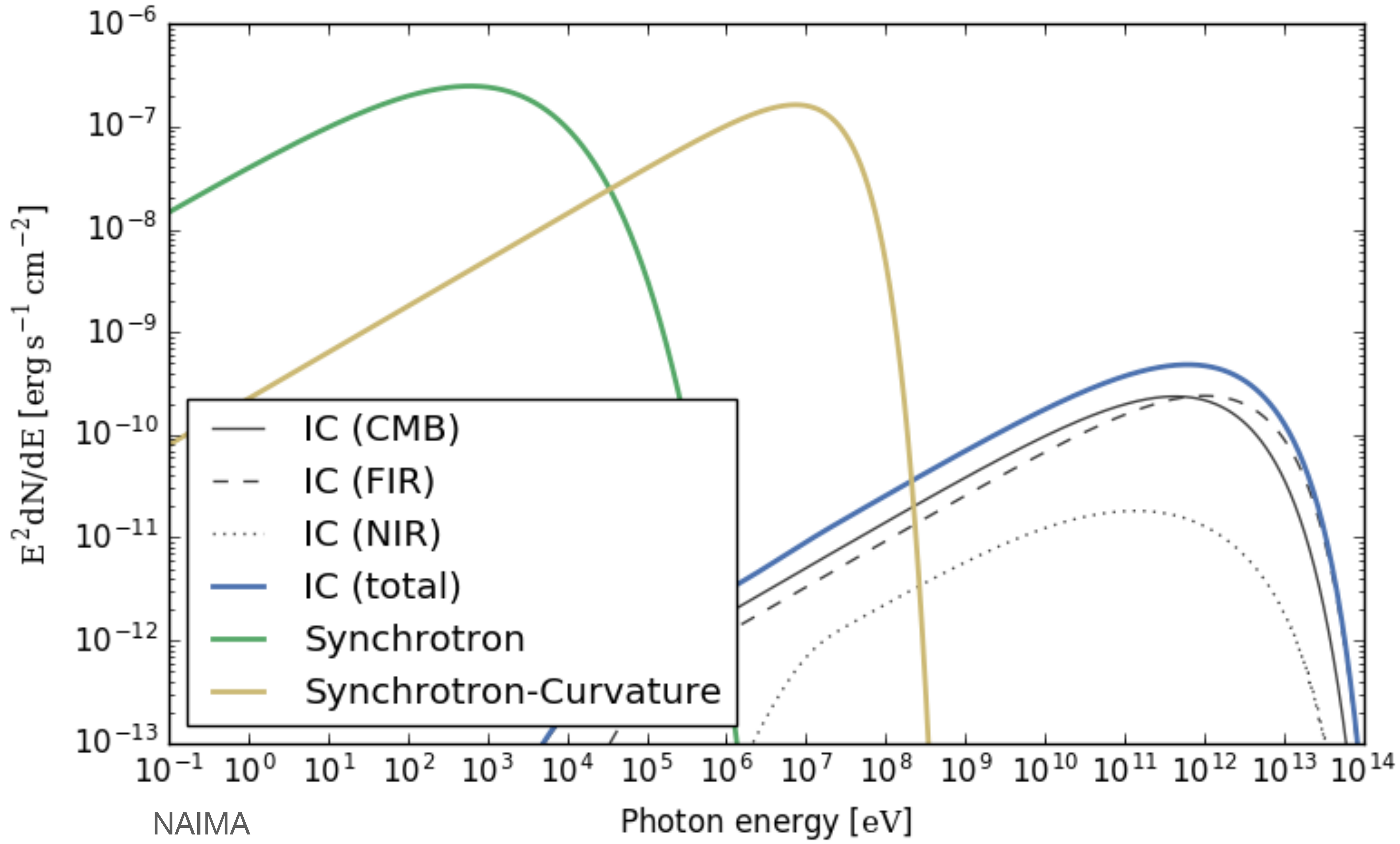

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$e^{\pm}$ + **B** ⇒ Y + $e^{\pm}_{lowerE}$

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Bremsstrahlung

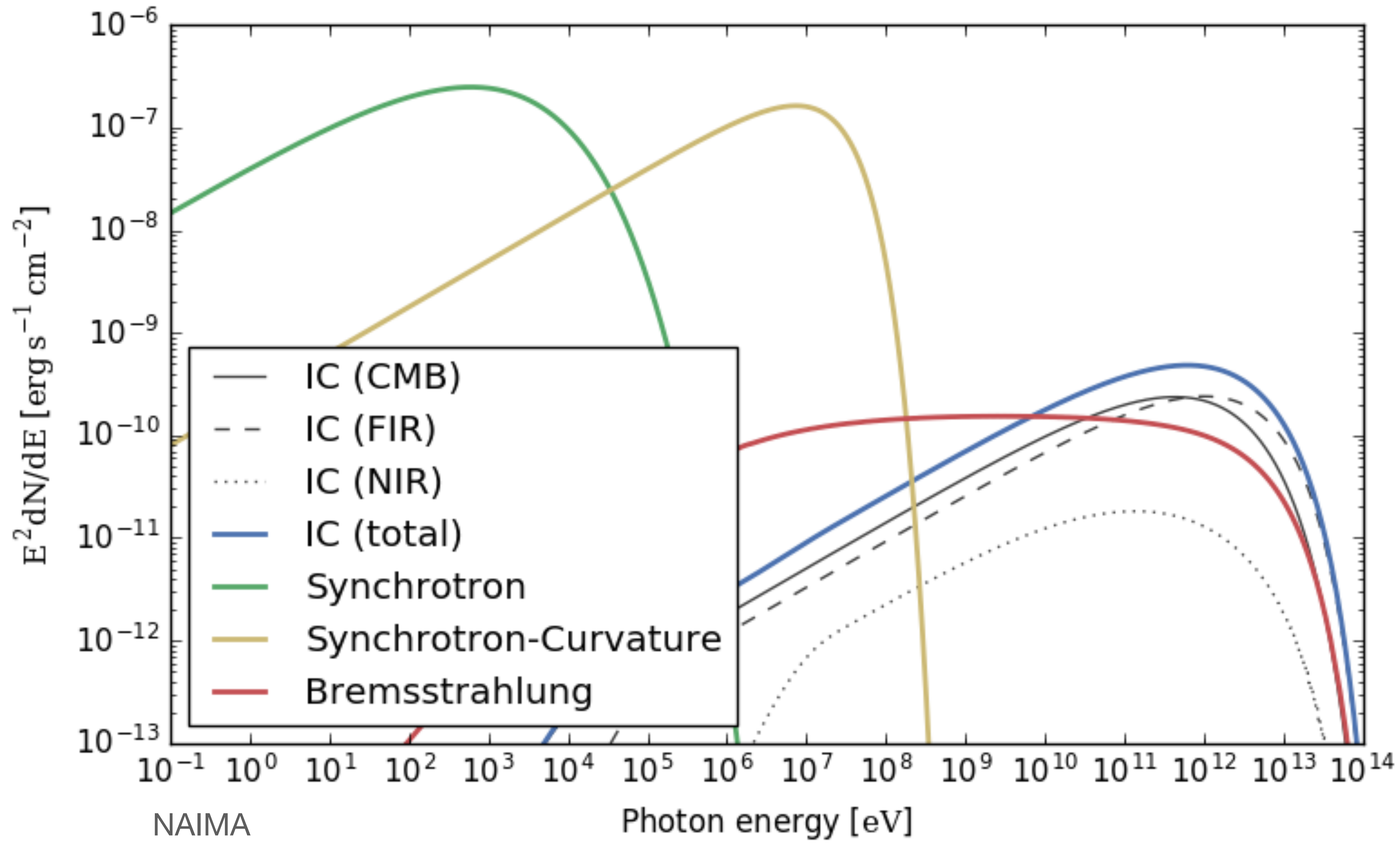
$e^{\pm}$ + N(e) ⇒ e' γN(e) , Eγ~1/2 Ee

1

Gamma-ray radiation

What type of radiation do we want to observe

=> Spectral characteristics



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$e^{\pm} + N(e) \Rightarrow e' \gamma N(e)$, $E\gamma \sim 1/2\ Ee$

DESY.

Gamma-ray radiation

What type of radiation do we want to observe

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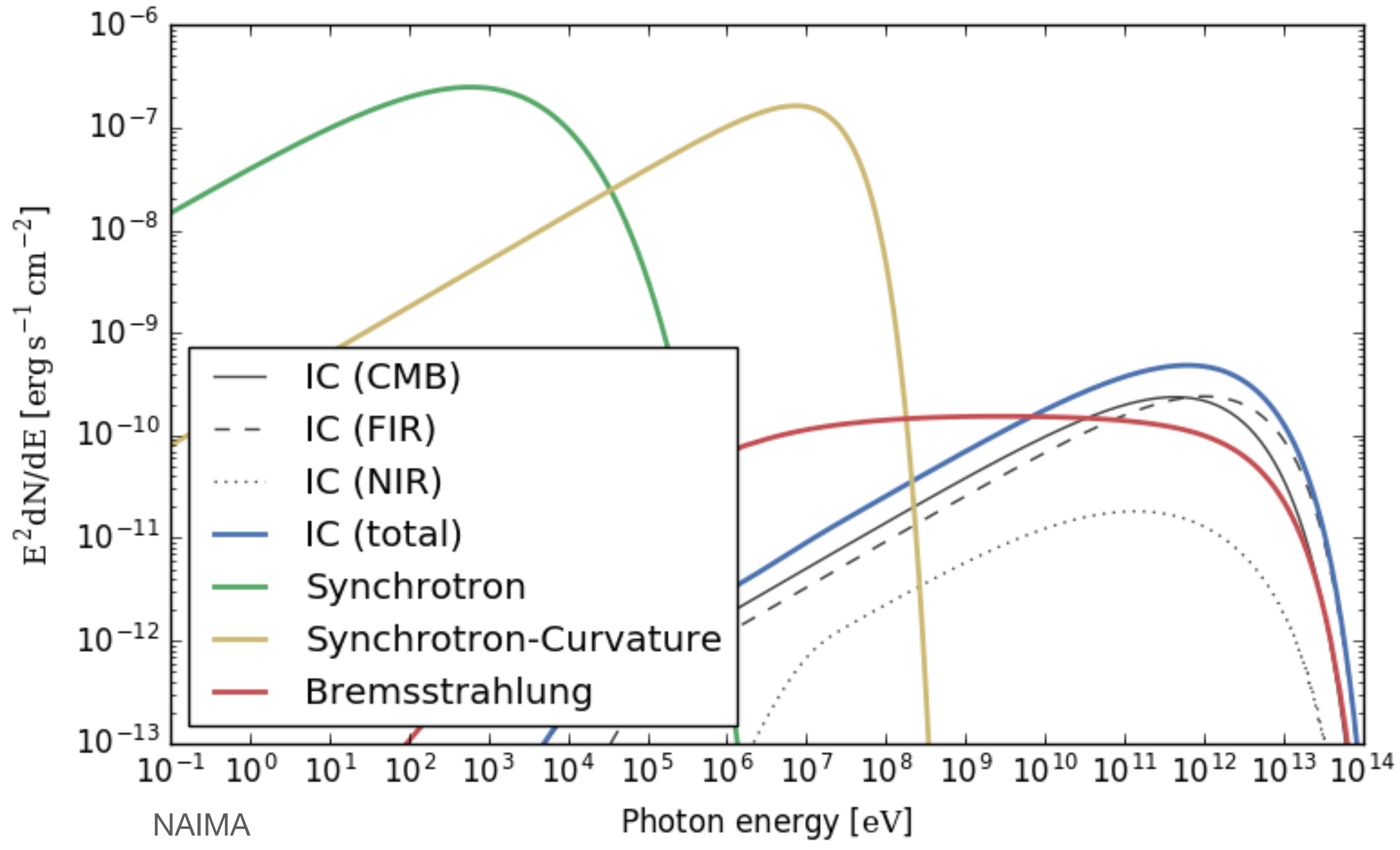

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$e^{\pm} + N(e) \Rightarrow e' \, \gamma N(e)$, $E\gamma \sim 1/2 \, Ee$

Proton-Proton

$p + p \Rightarrow \pi^{o} + \chi + .. + \pi^{\pm}$

$\hookrightarrow \gamma\gamma$ $\hookrightarrow \nu_{\tau,e}$

DESY.

Gamma-ray radiation

What type of radiation do we want to observe

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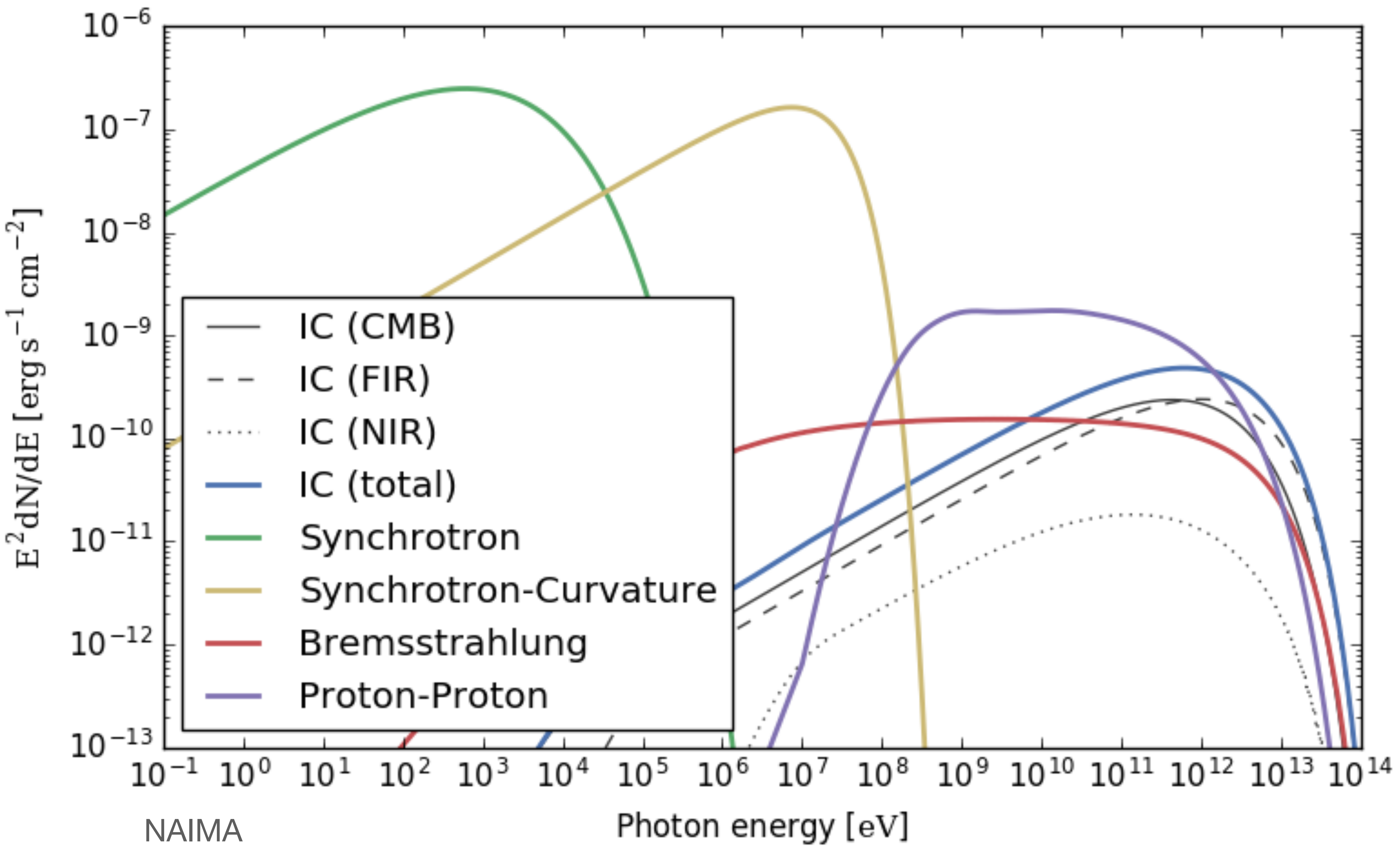

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DESY.

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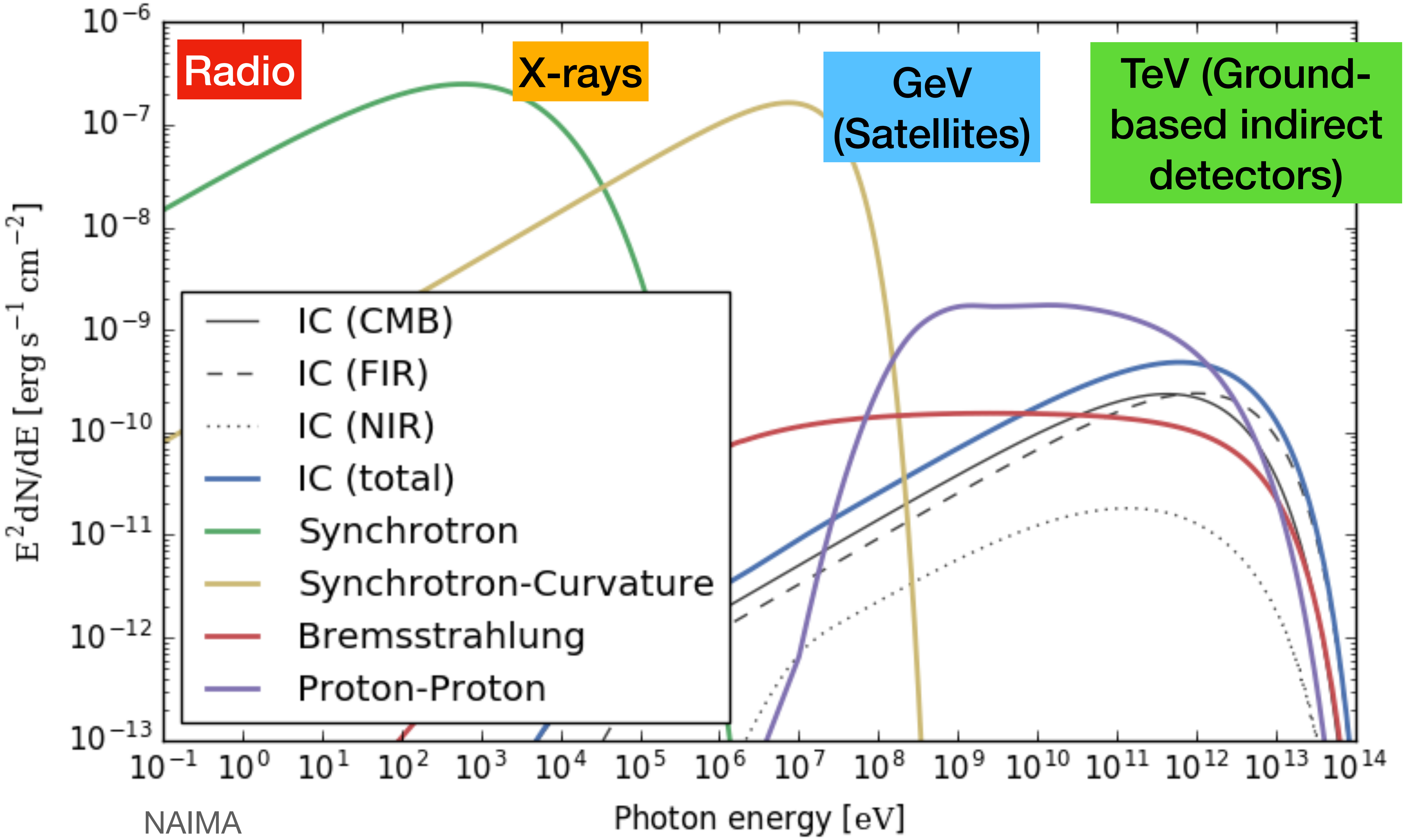


NAIMA

- Detection of photons from ~MeV up to ~PeV
- >> PeV => too low photon rate + CMB absorption

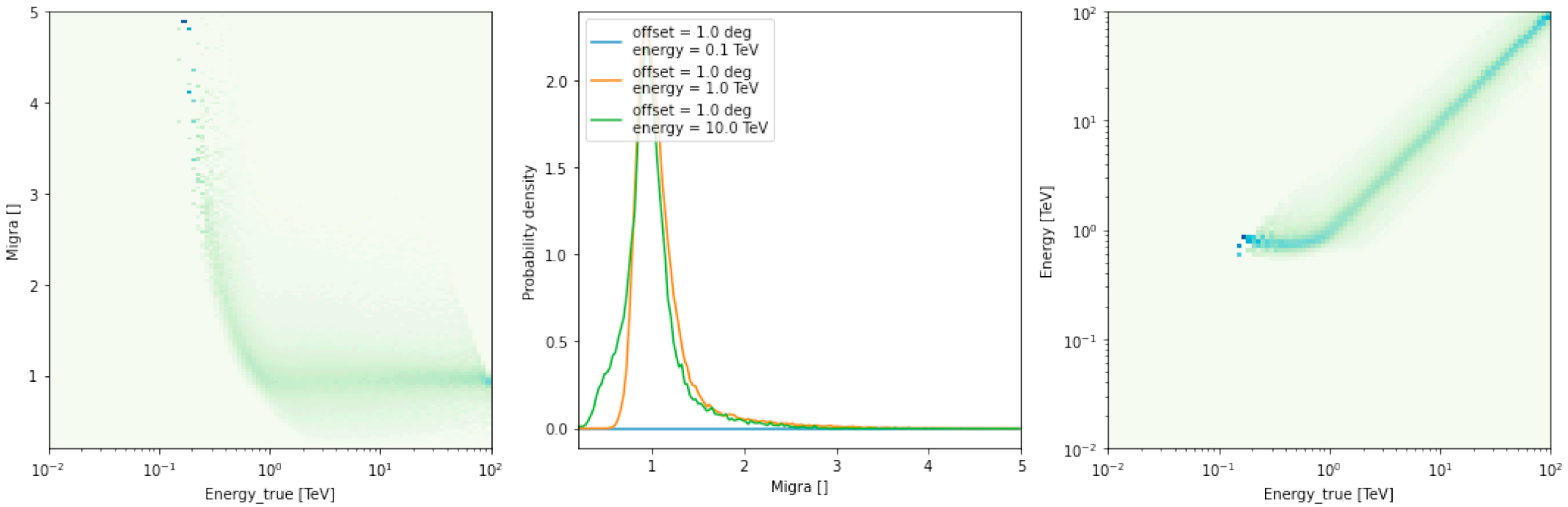
- **We need**:
  - Excellent energy reconstruction
  - Large collection areas

Gamma-ray radiation

What type of radiation do we want to observe?

=> Spectral characteristics

MUST: Good energy resolution (<20%) to resolve spectral features



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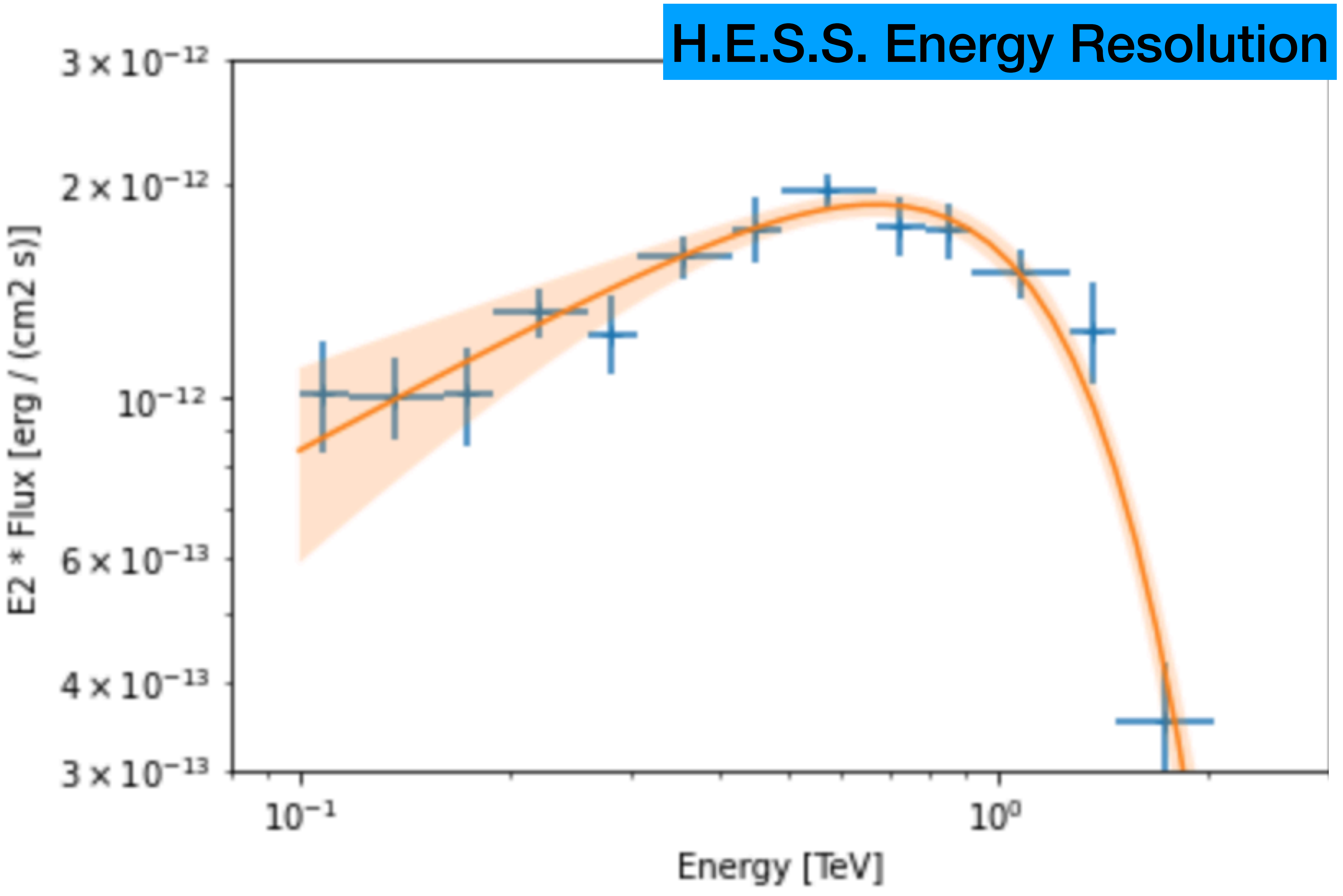
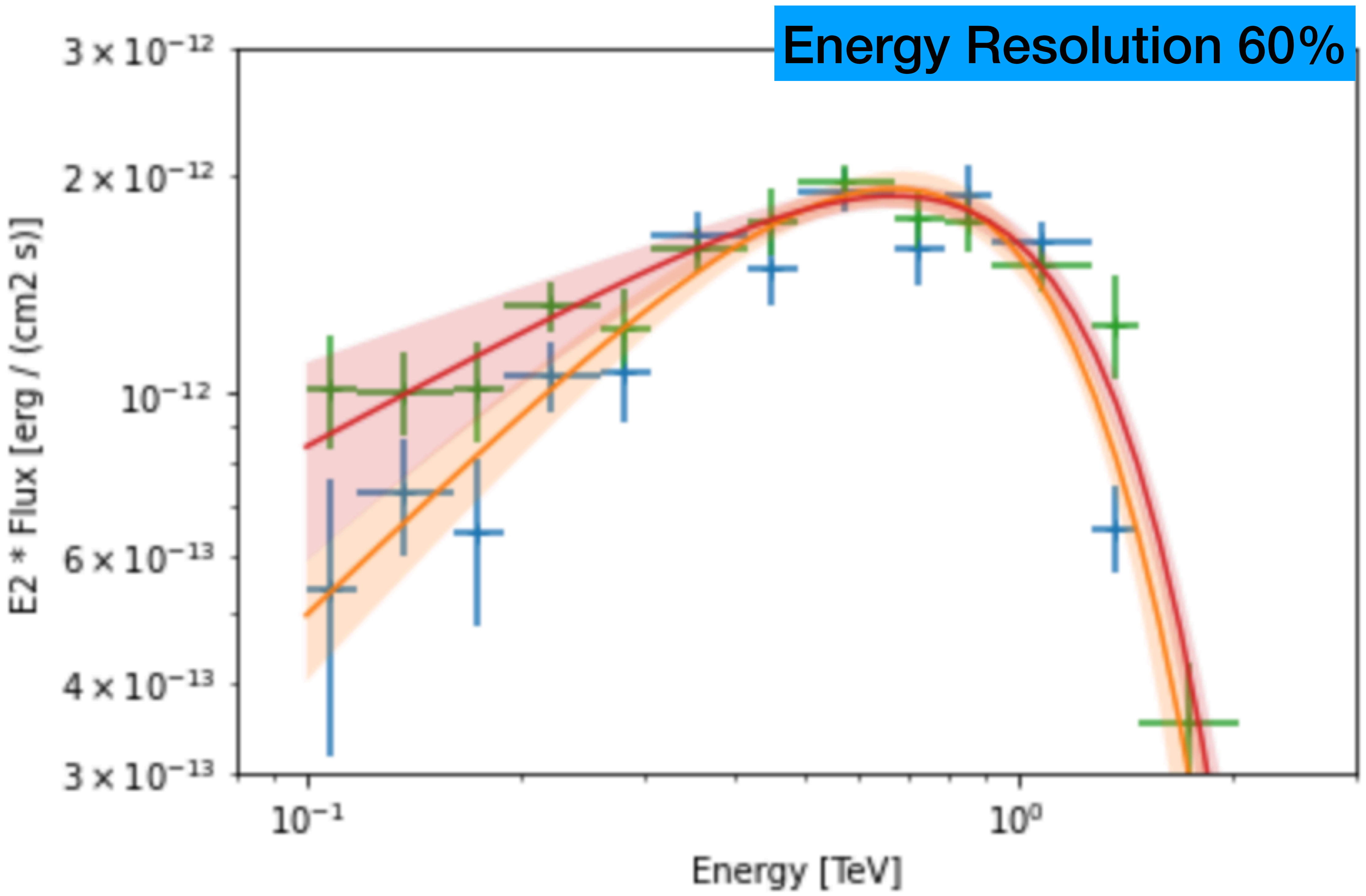


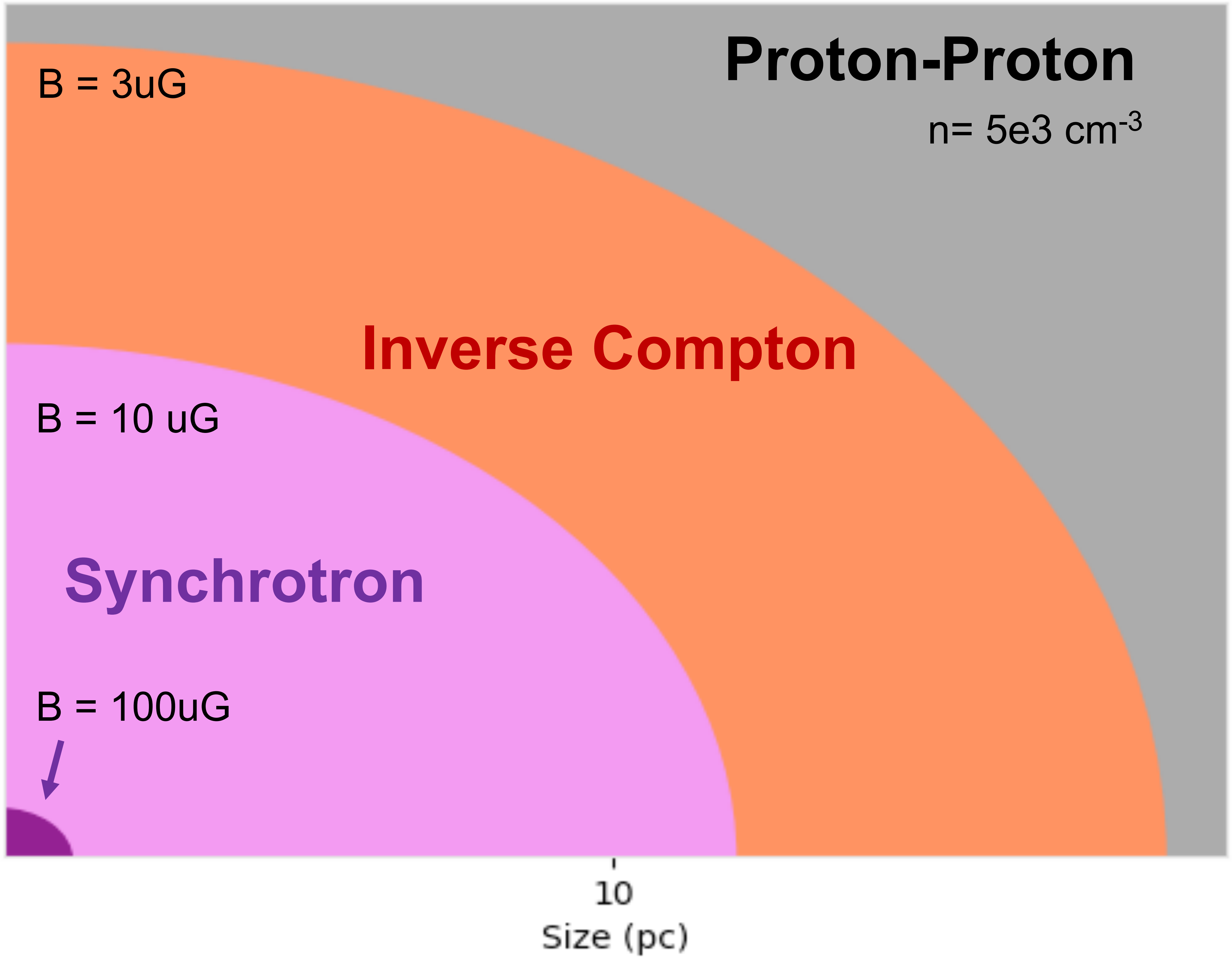


Gamma-ray radiation

What type of radiation do we want to observe?

=> Morphological characteristics

R= $2\sqrt{(D\ t)}$



1 Gamma-ray radiation

What type of radiation do we want to observe?

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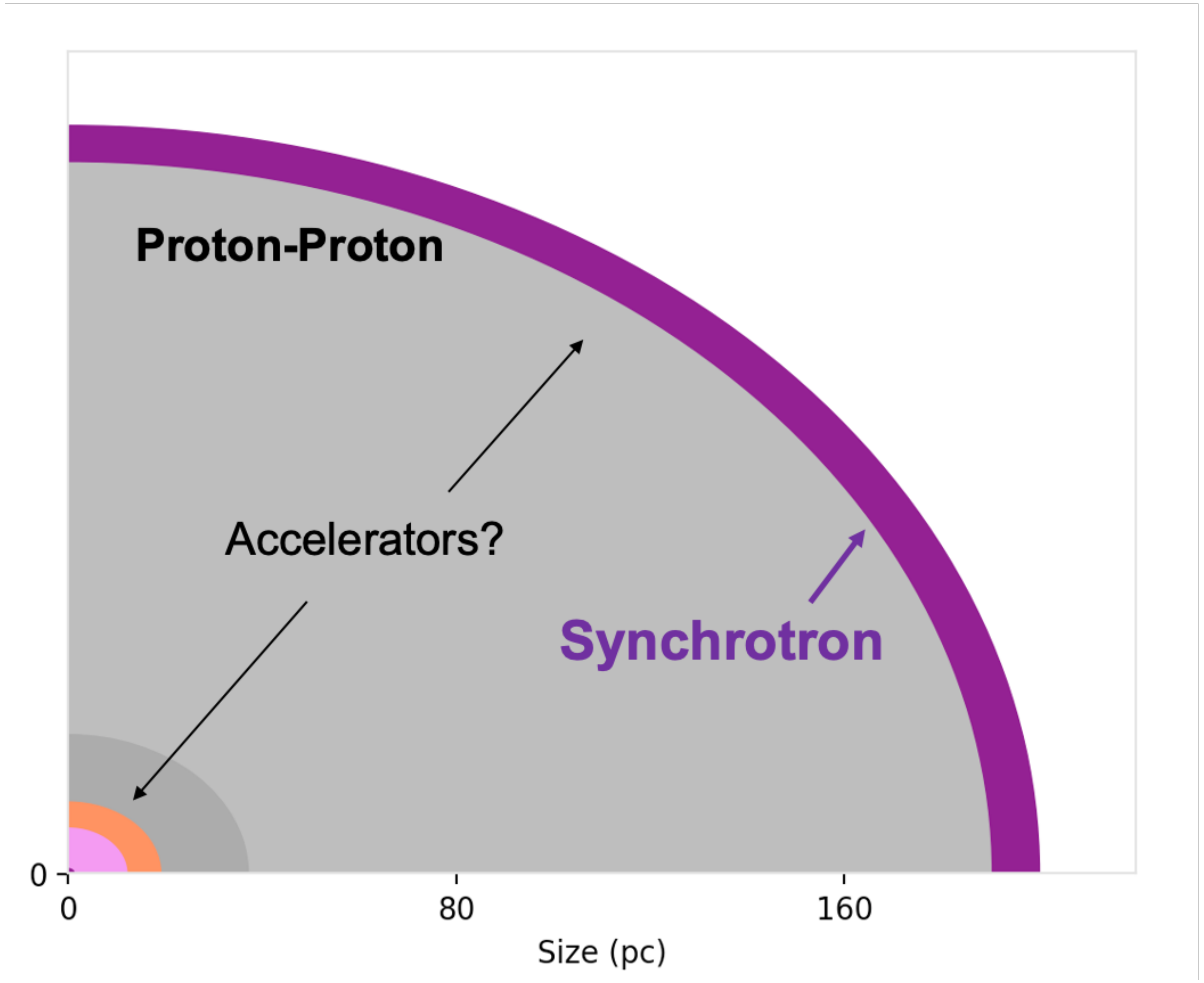

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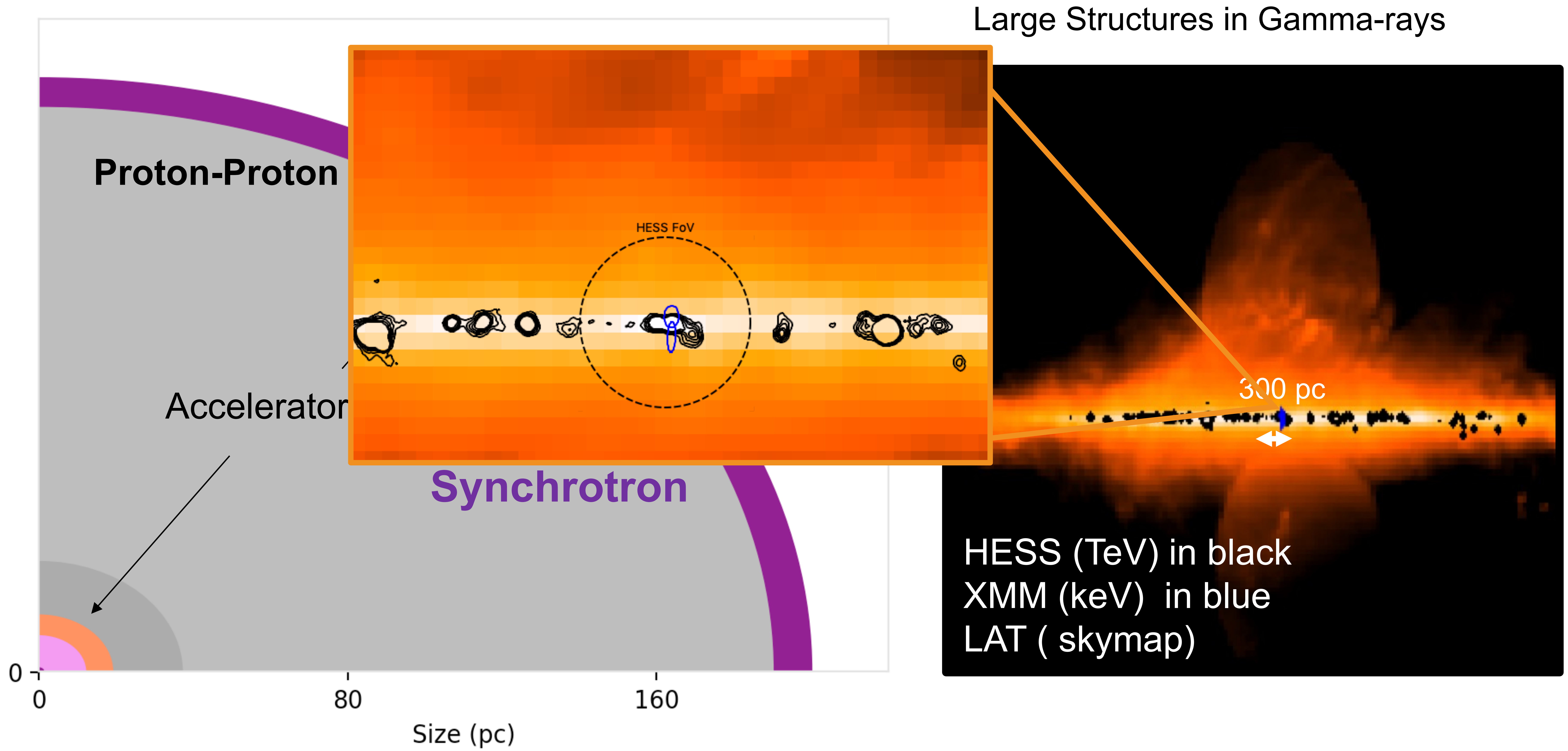


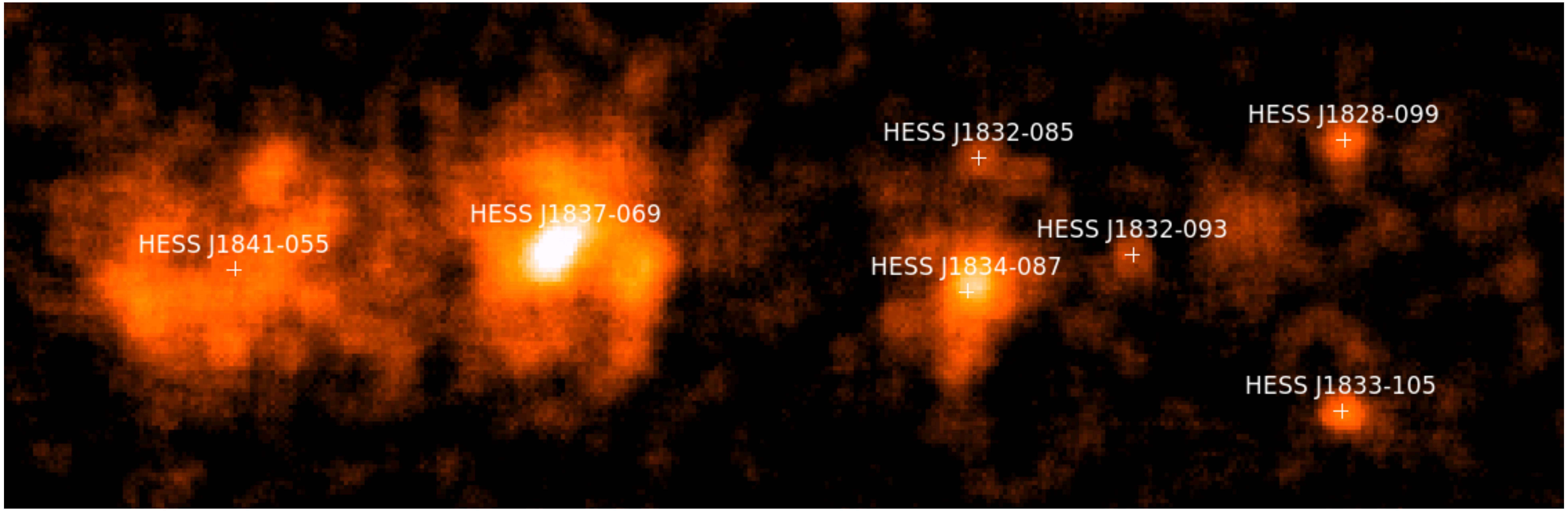
Gamma-ray radiation

What type of radiation do we want to observe?

=> Morphological characteristics

Large number of (extended) sources in the Galaxy
Diffuse emission steaming from active regions

maximise the sky coverage & minimising
the acceptance variations



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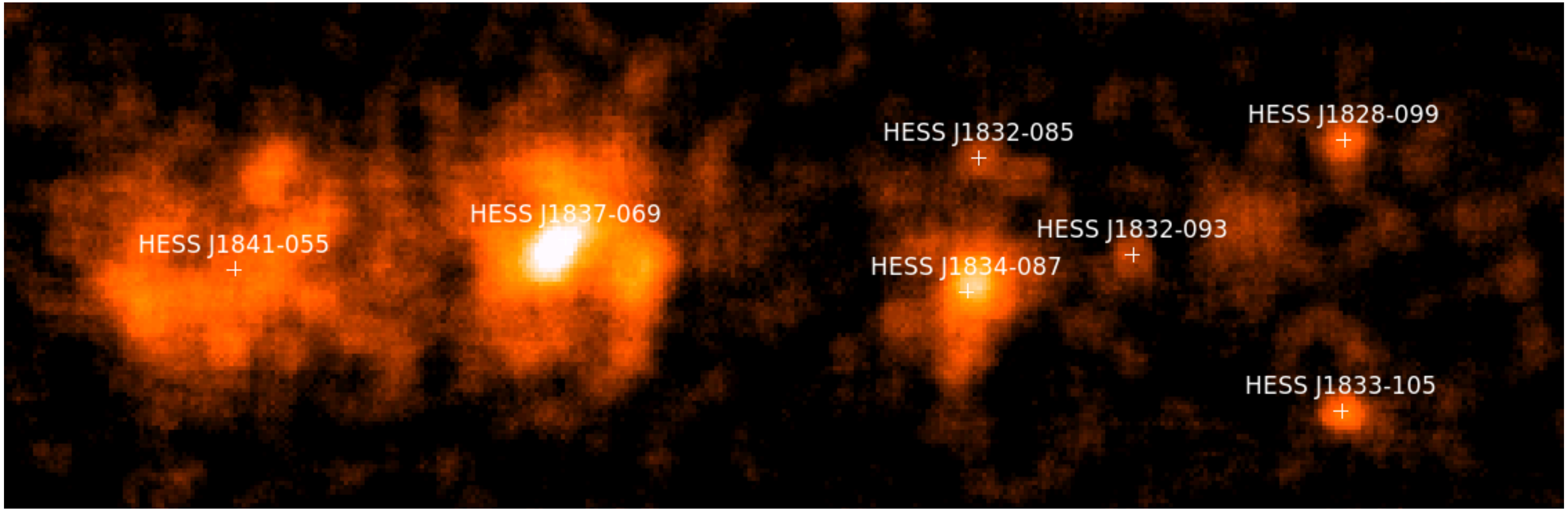

1 Gamma-ray radiation

What type of radiation do we want to observe?

=> Morphological characteristics

MUST: Good angular resolution to resolve source confusion, multiple components and acceleration sites

Gamma-ray radiation

What type of radiation do we want to observe?

=> Morphological characteristics

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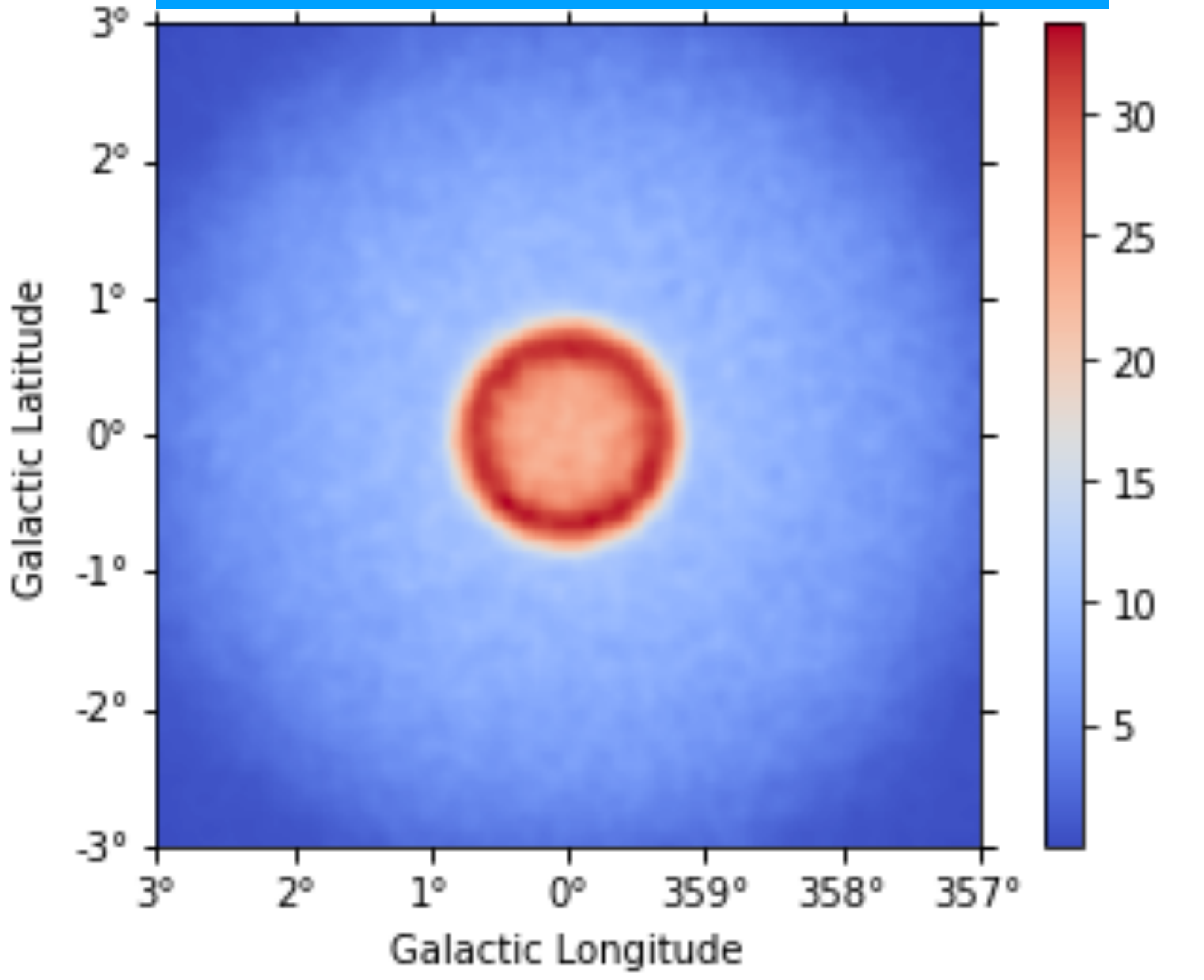
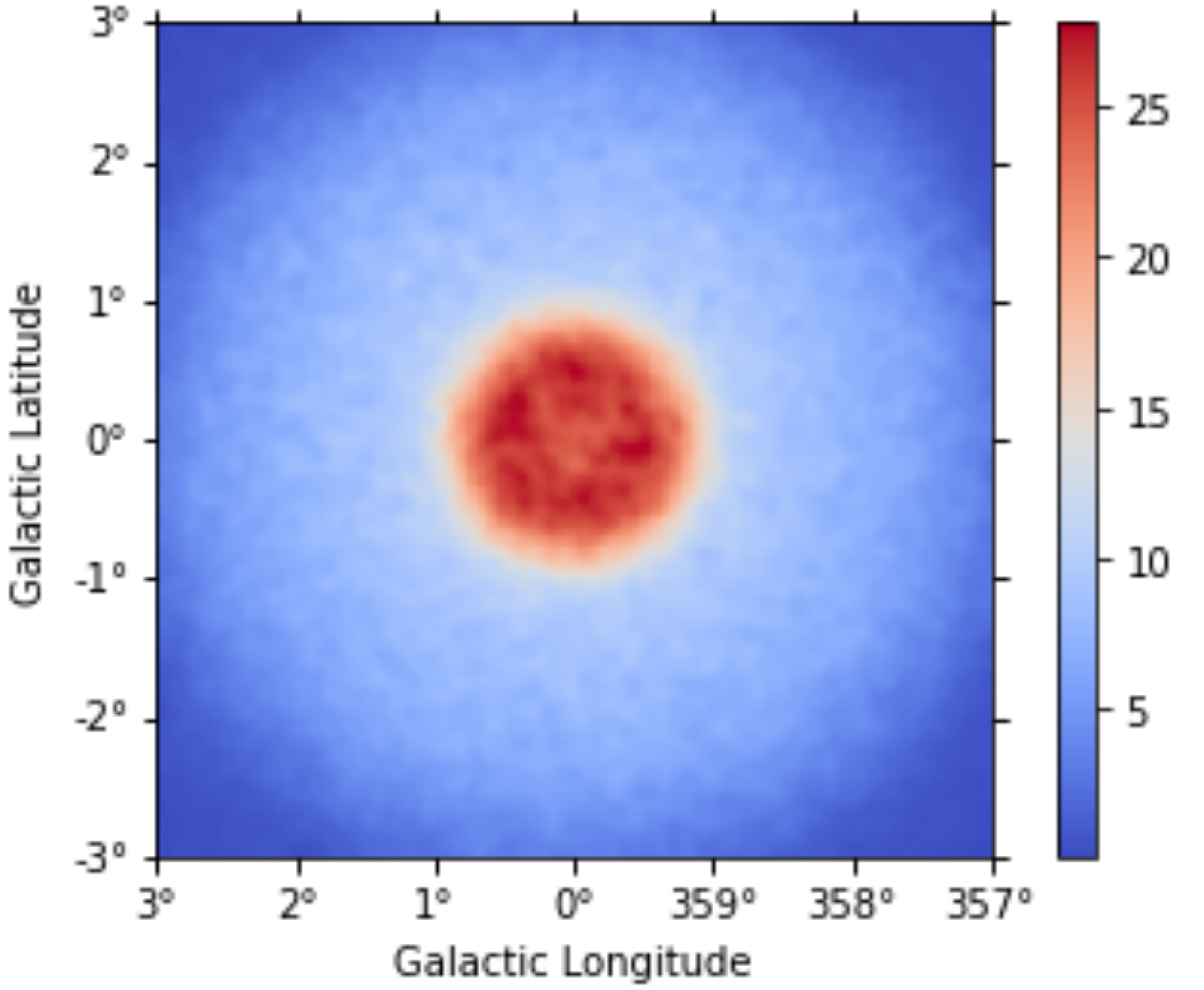
Simulation: shell-like source with radius=0.7° and width=0.1°

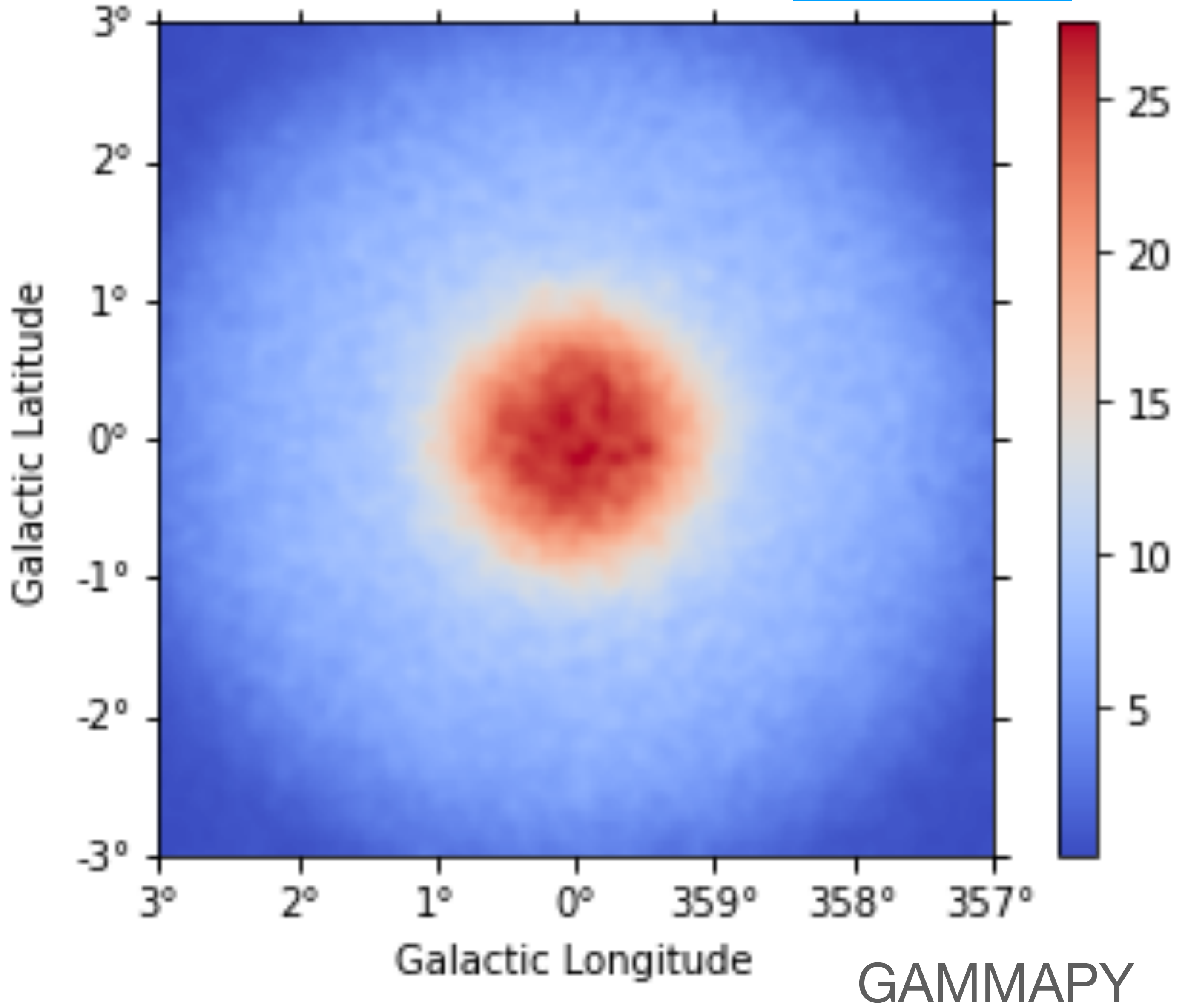
H.E.S.S. Angular Resolution



σ = 0.2°



σ = 0.3°



GAMMAPY

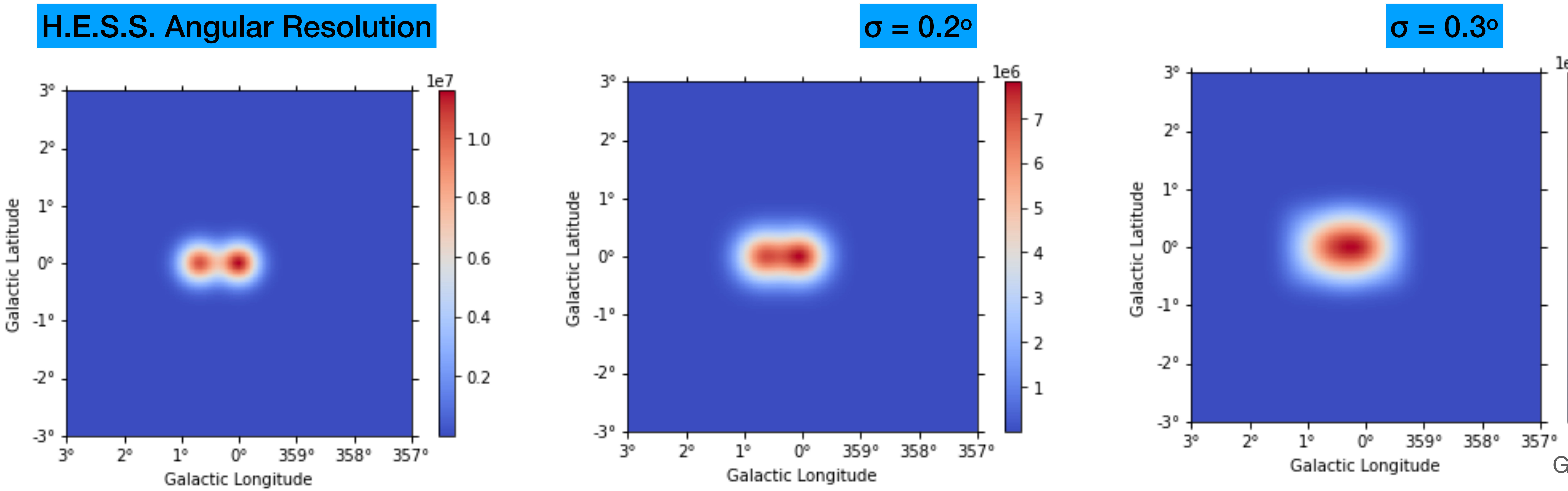
Gamma-ray radiation

What type of radiation do we want to observe?

=> Morphological characteristics

MUST: Good angular resolution to resolve source confusion, multiple components and acceleration sites

Simulation: two nearby (0.7°) sources (size=0.2°)



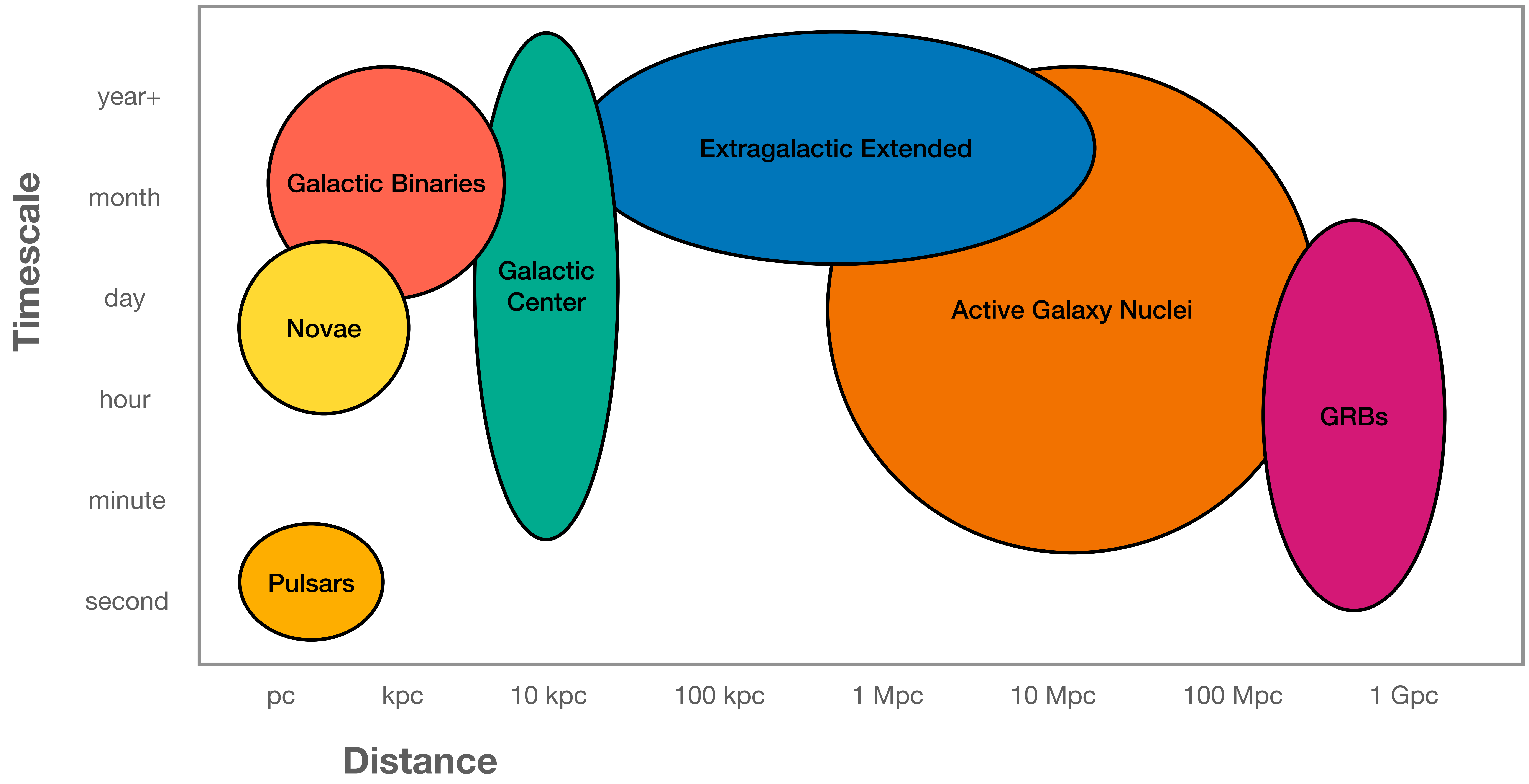
GAMMAPY

Gamma-ray radiation

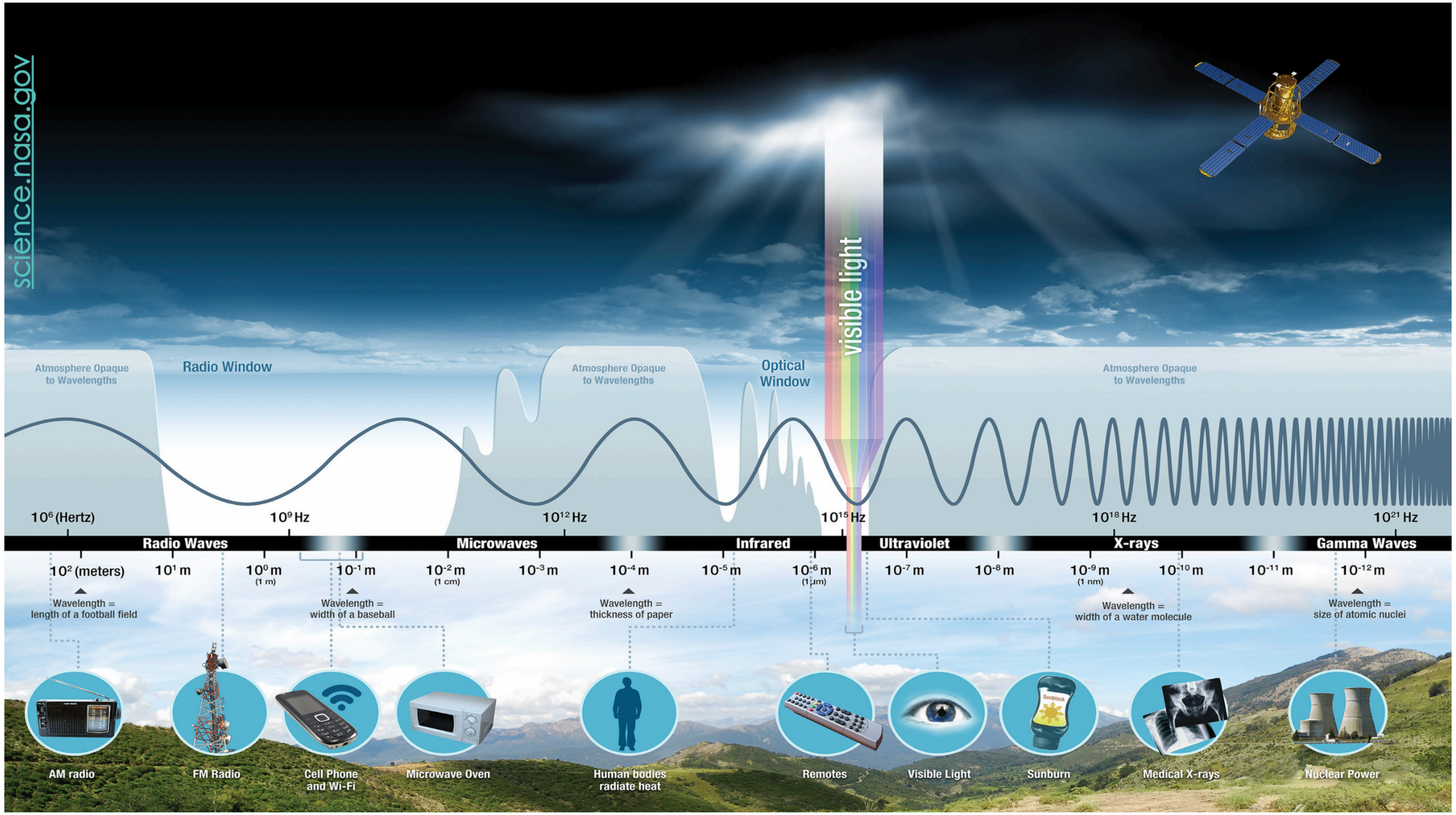
What type of radiation do we want to observe?

=> Time imprints

Adapted from J. Hinton



Gamma-ray detection
Instrumental techniques



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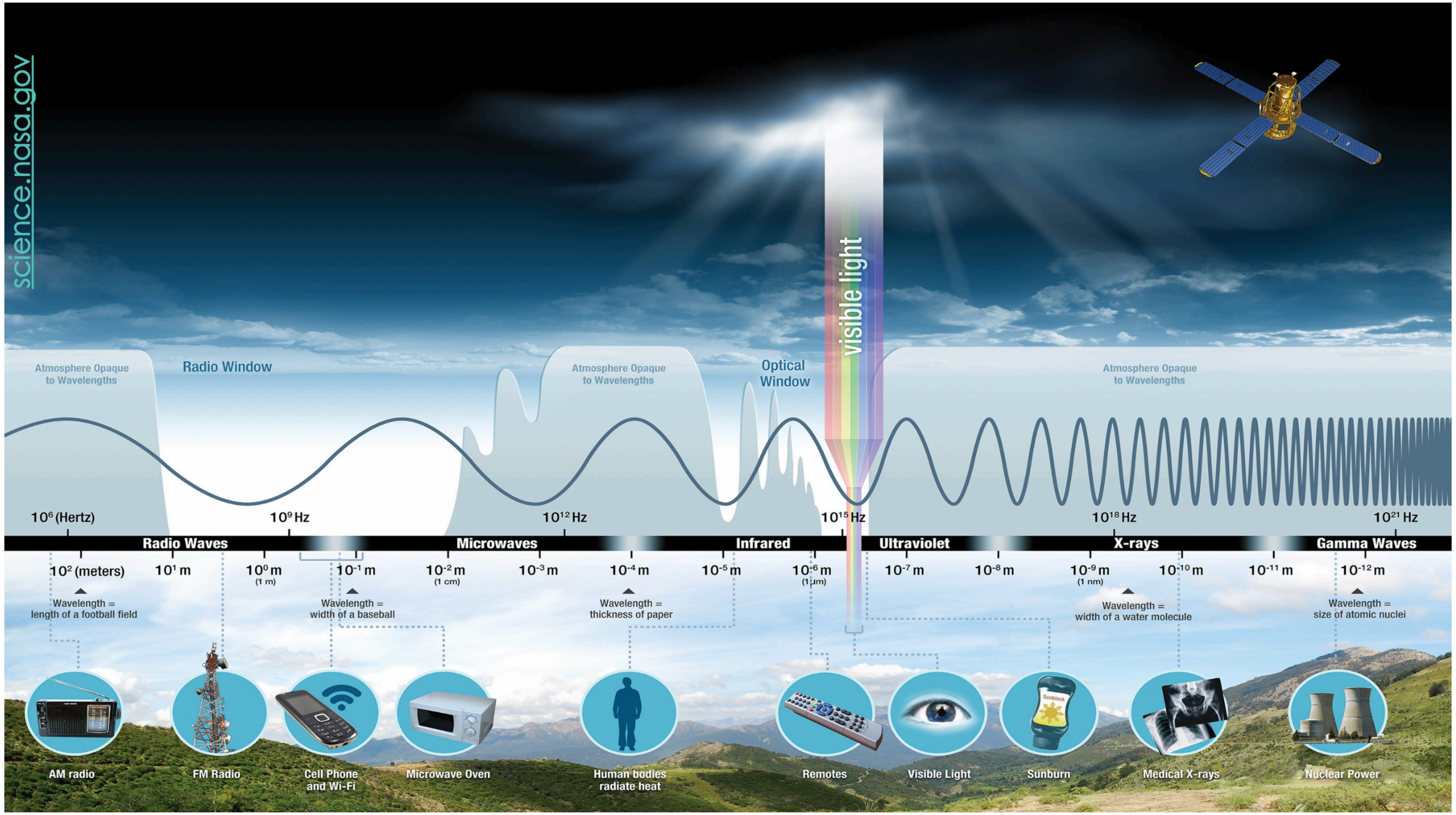
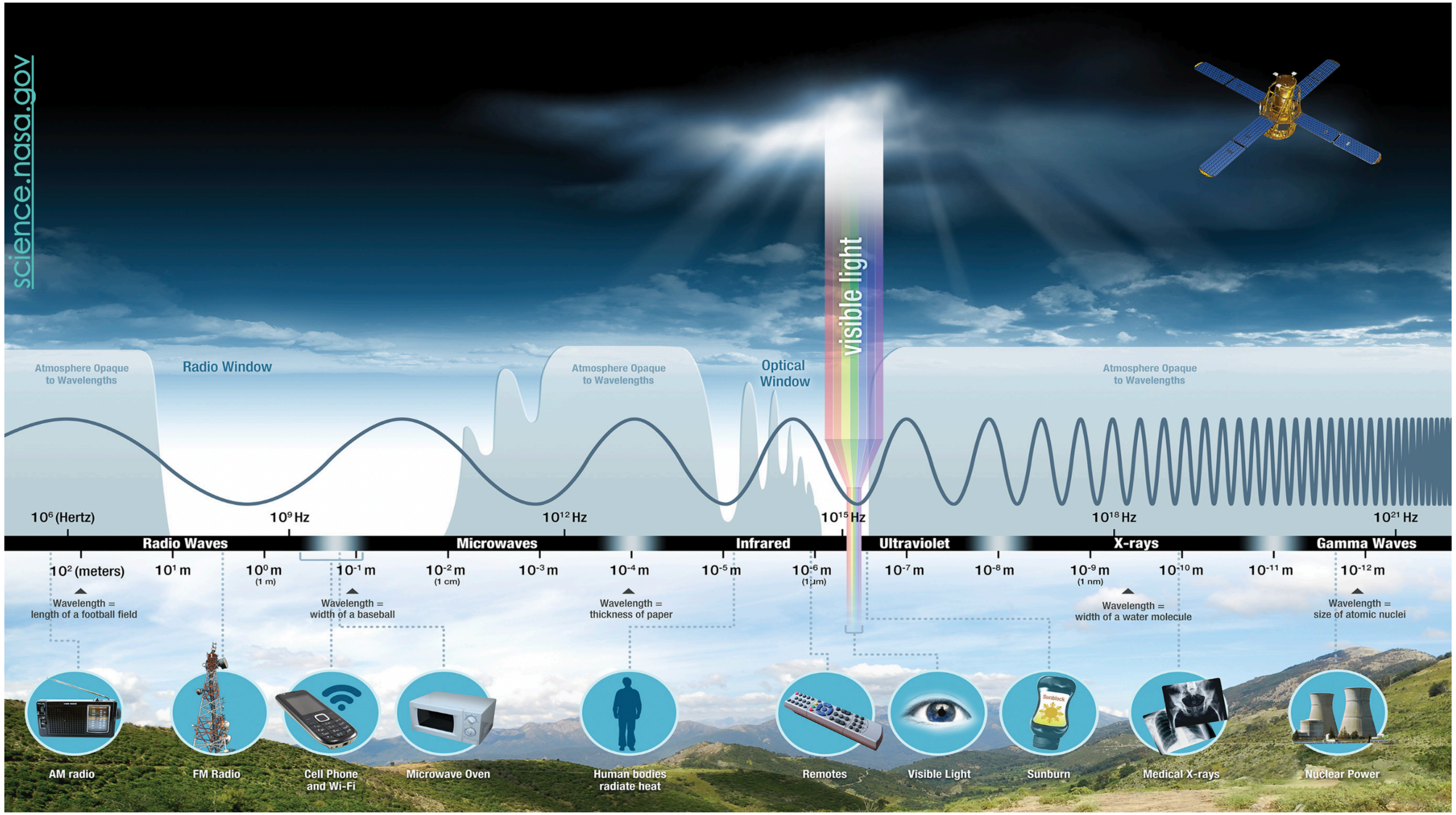


- Only photons in a very narrow window (radio and optical - look at the blue line!) are not absorbed in the atmosphere

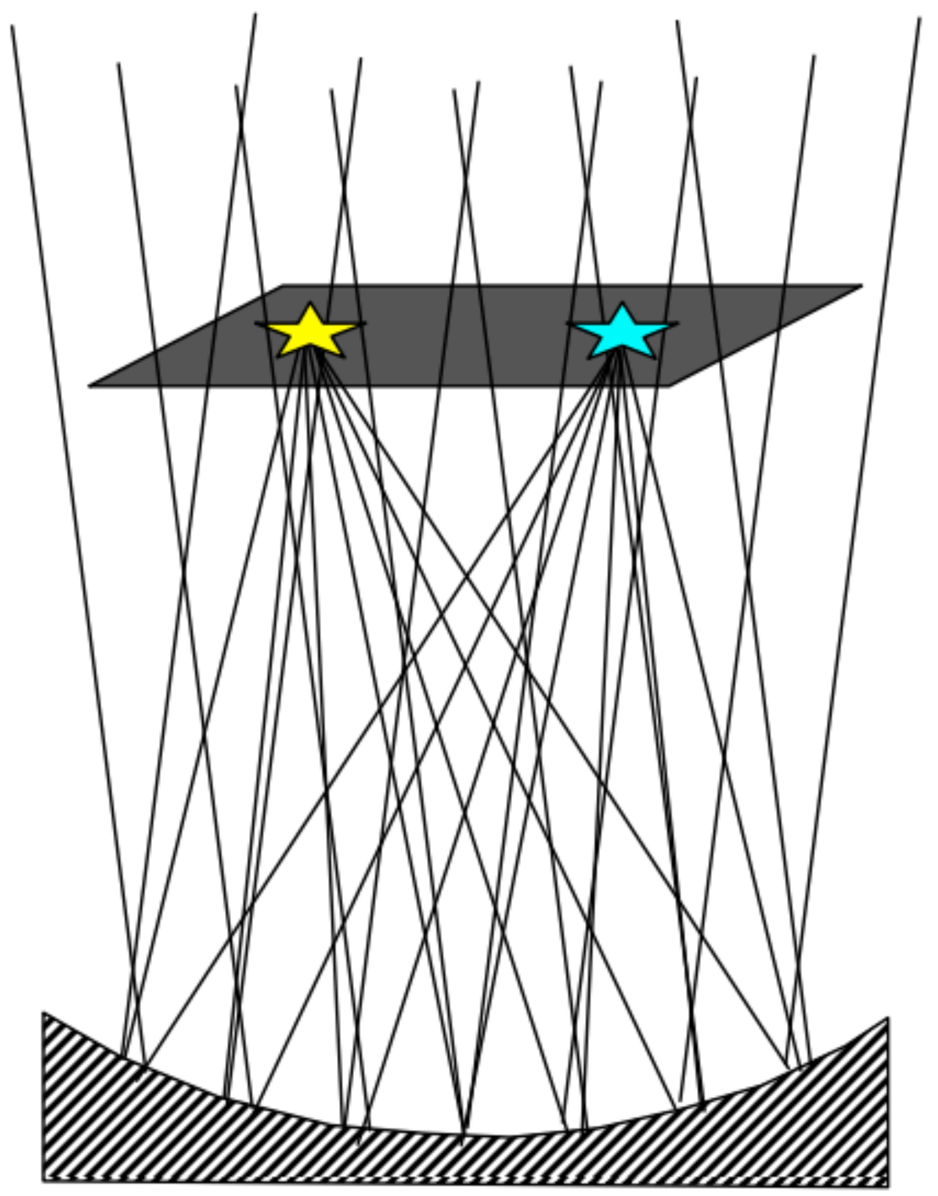
Gamma-ray detection
Instrumental techniques

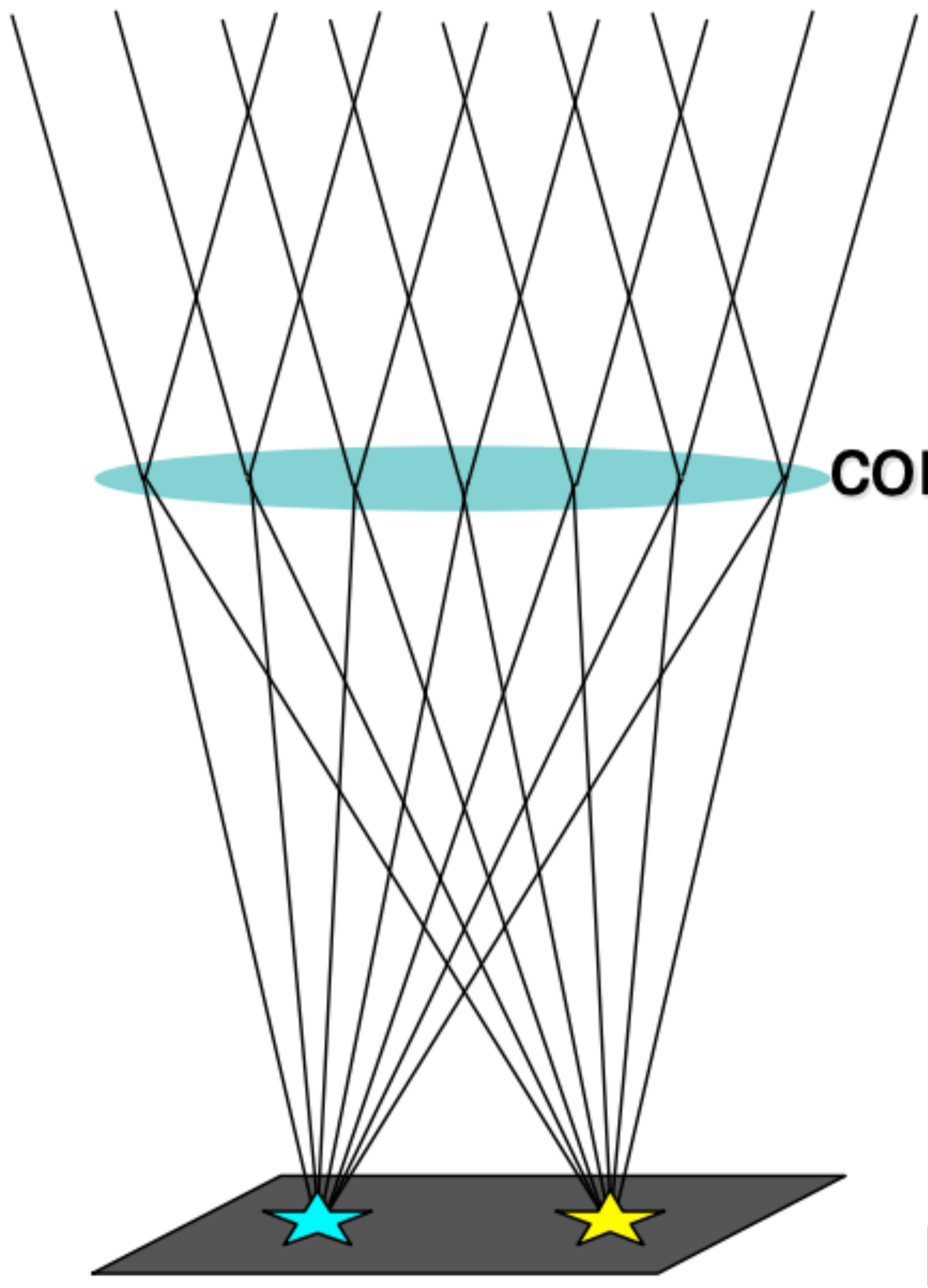


- Only photons in a very narrow window (radio and optical - look at the blue line!) are not absorbed in the atmosphere
- HE and VHE: Either put a detector above the atmosphere or look at the indirect radiation

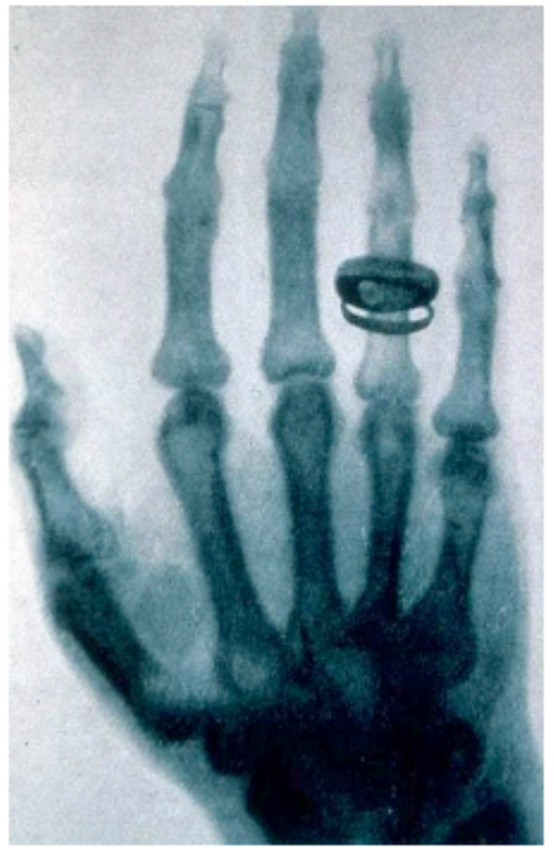
Gamma-ray detection
Instrumental techniques

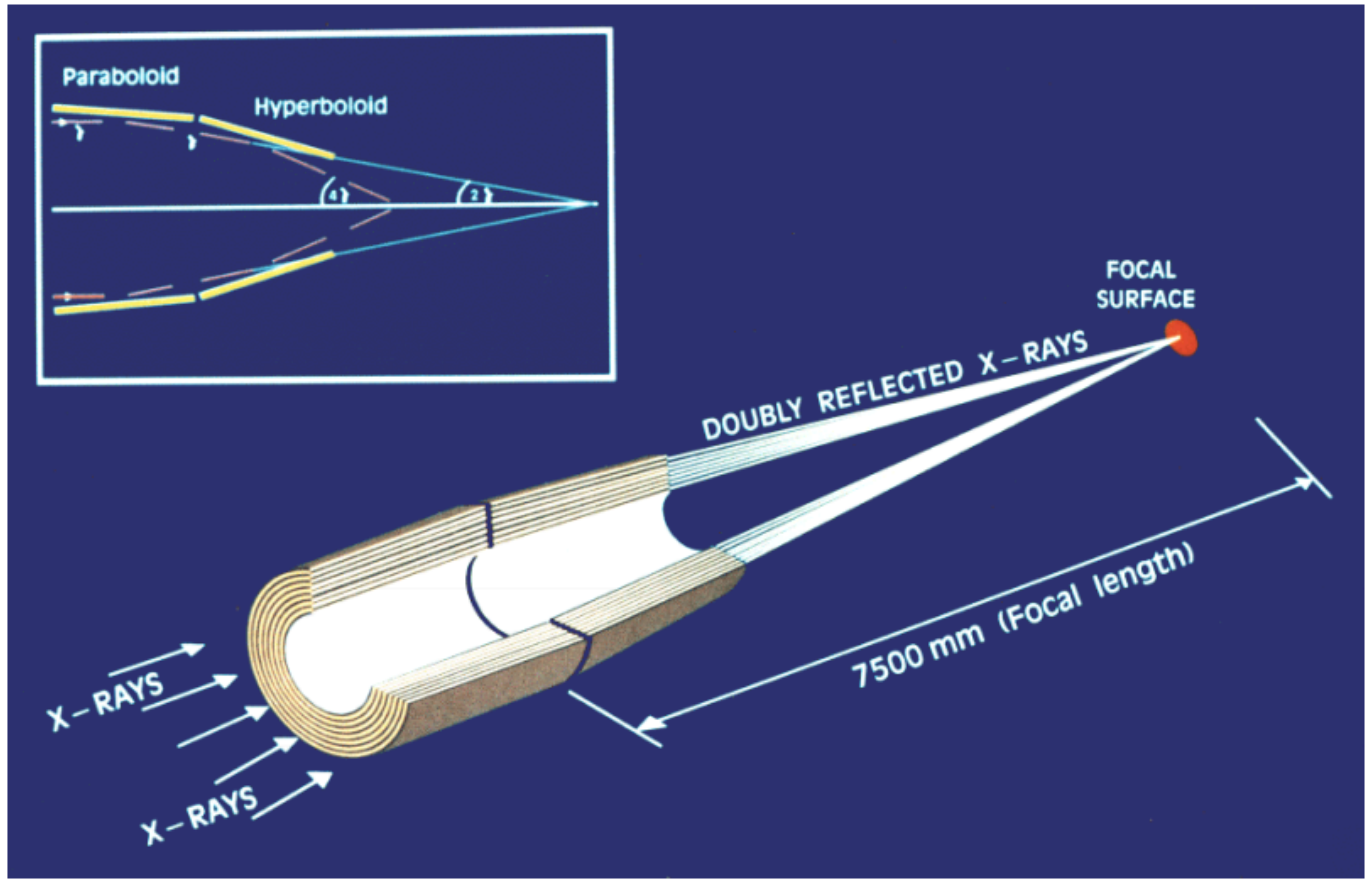
- *Imaging*: transform *directions* into *points* in a focal plane
- The photon detector in the focal plane can be a photographic film, the retina or an electronic device





- High energy photons are very *penetrating*... is it possible to build mirrors for them?

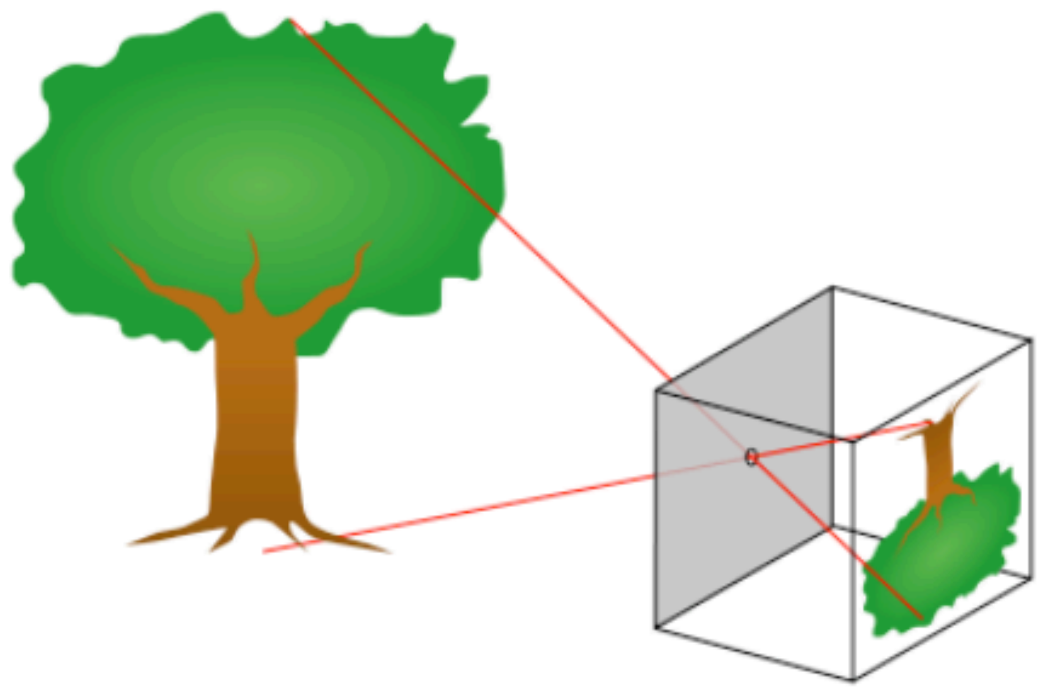




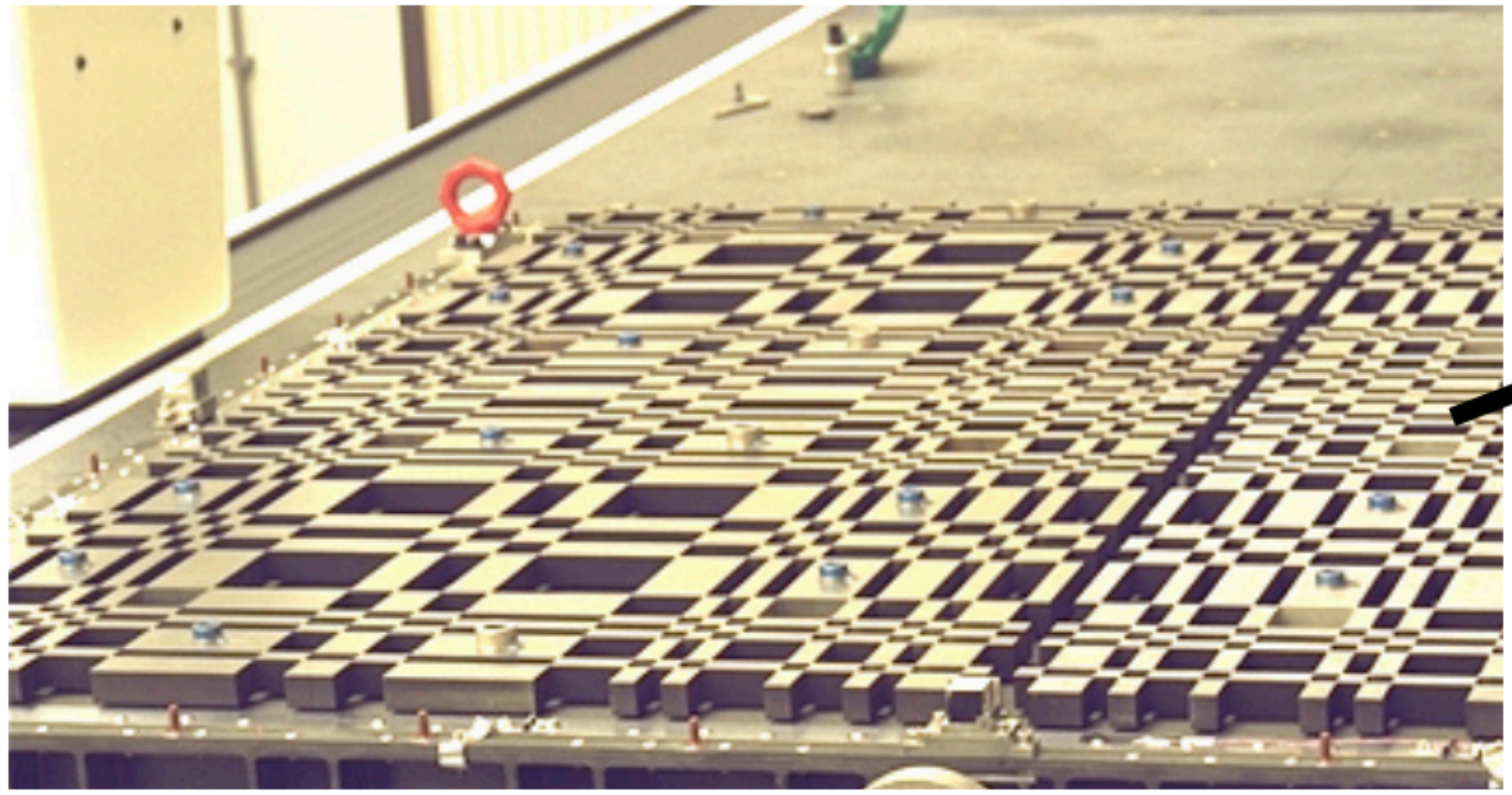
- Grazing incidence mirrors made of heavy metals (Au, Ir) effective up to E~10 keV. What can be done at higher E?

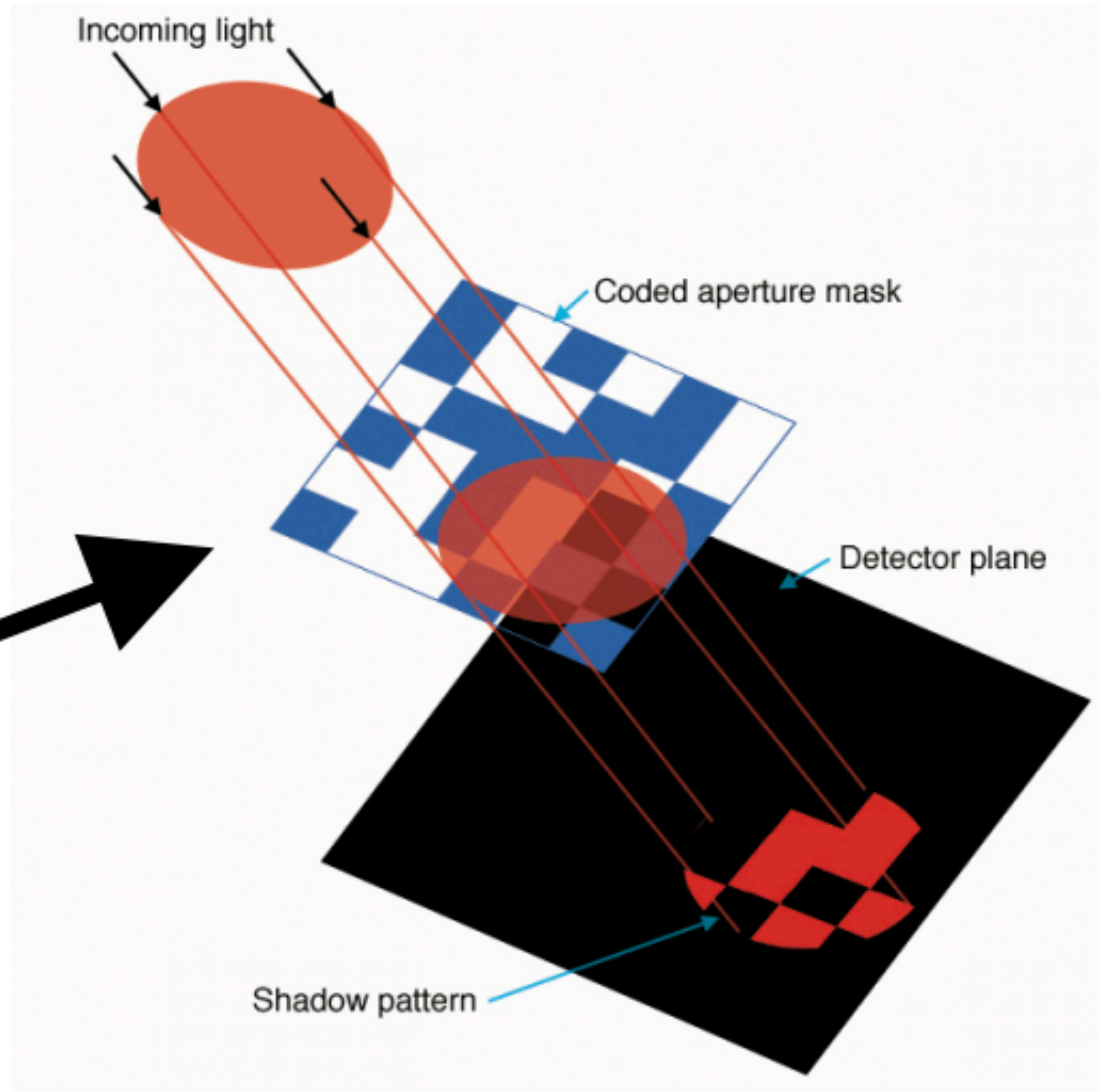
E = 10 keV - 10 MeV

Generalization of the principle of the pinhole camera (the simplest imaging device)

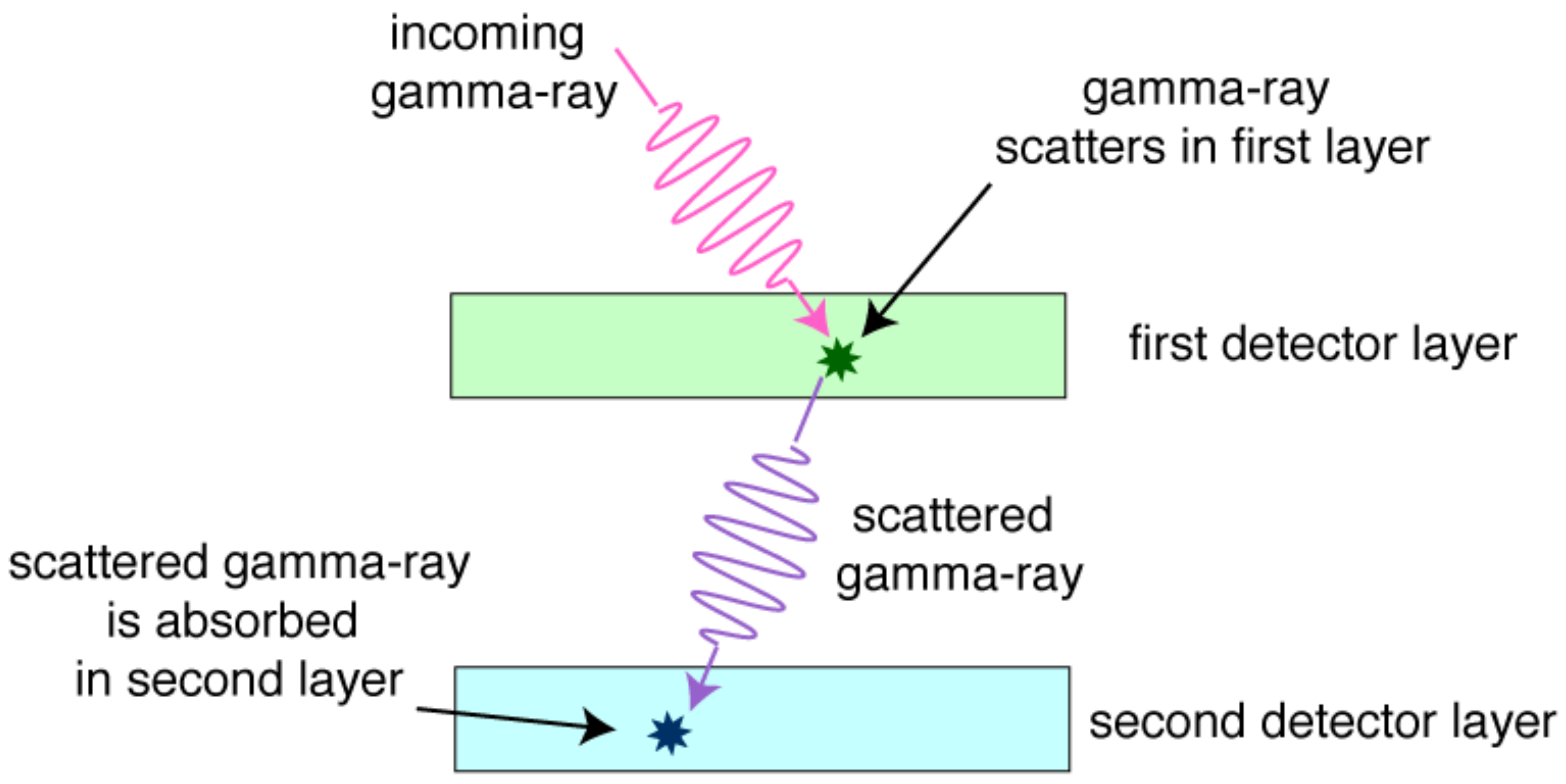


Coded aperture masks:

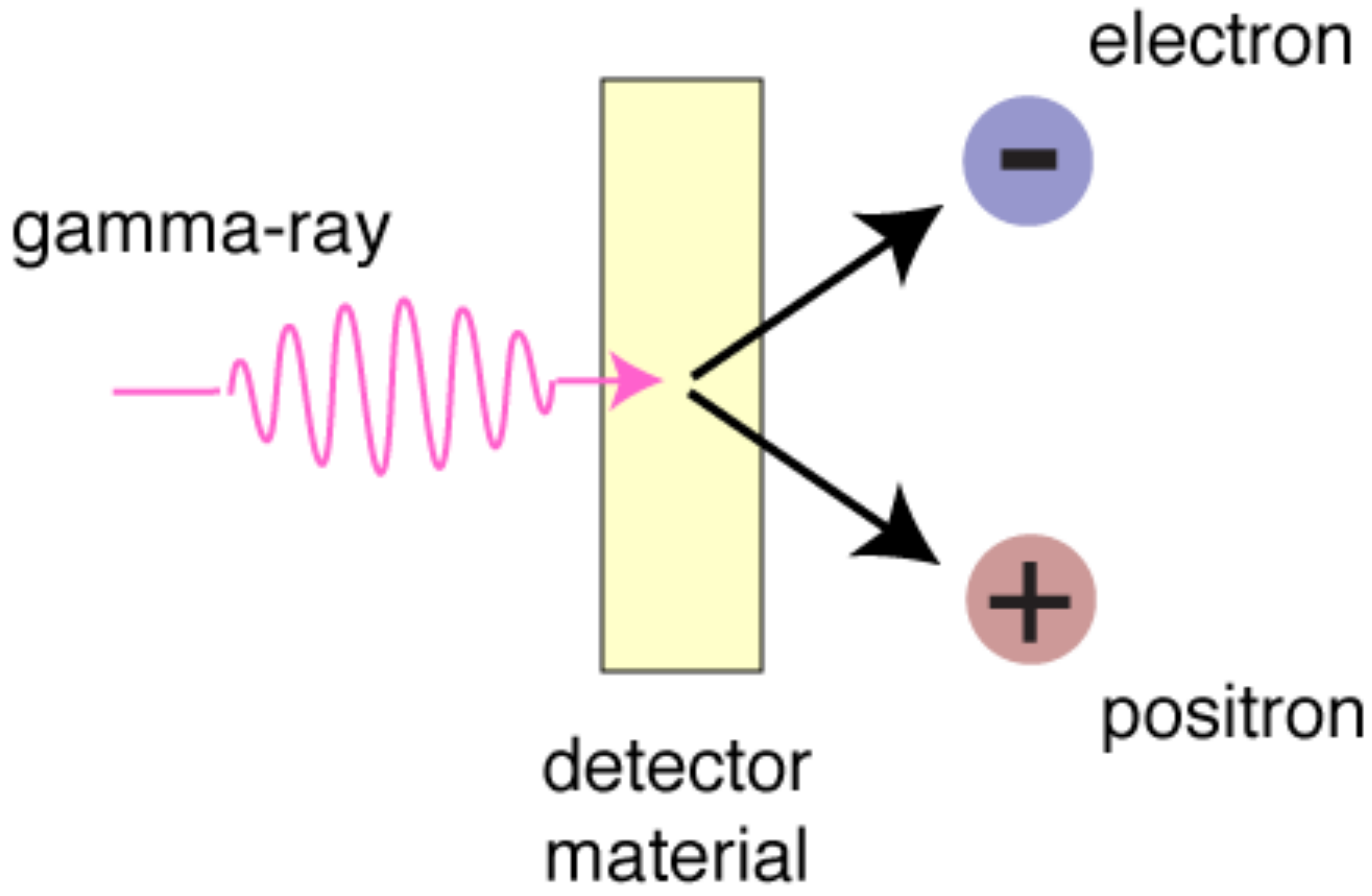


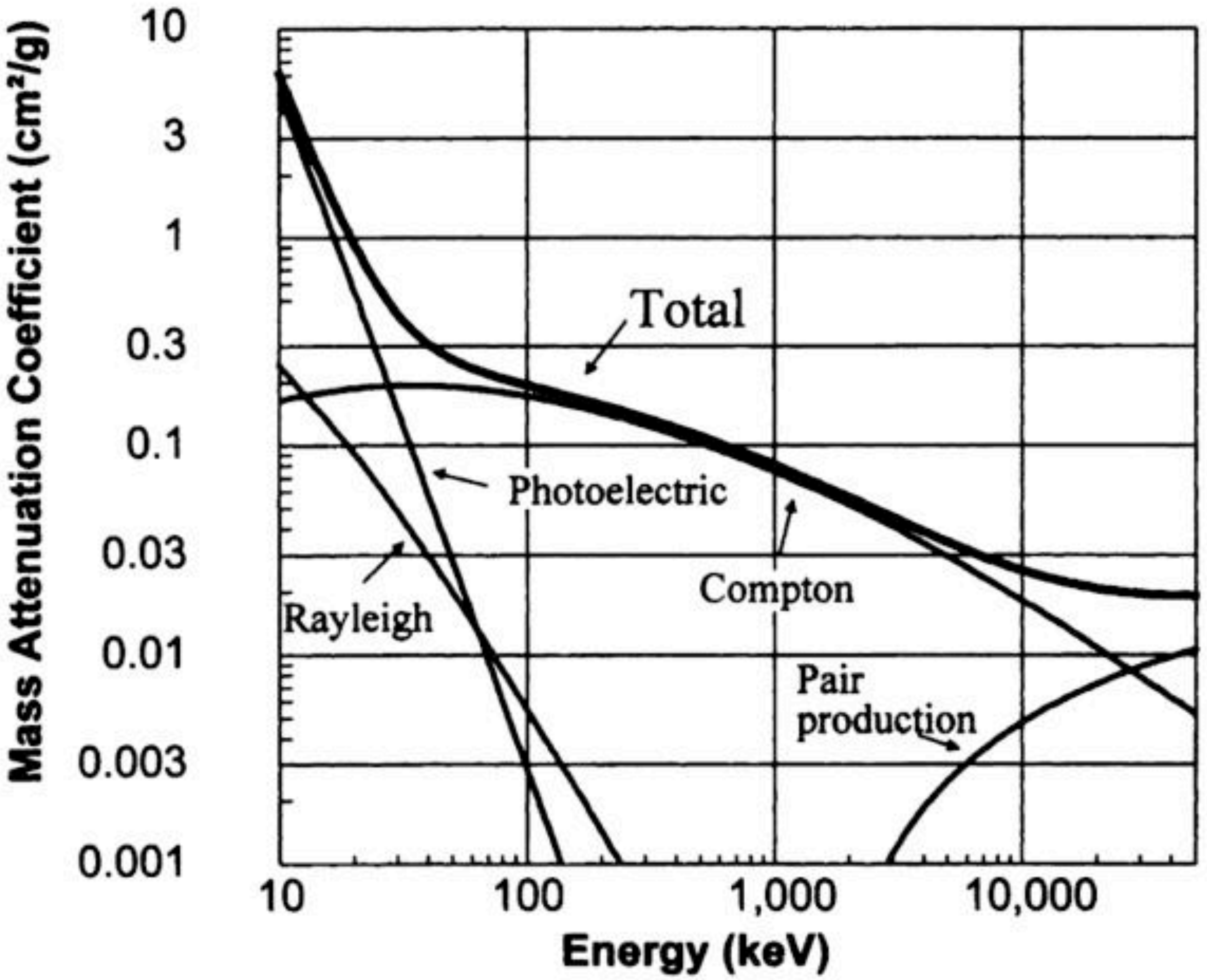


Compton scattering detector.



pair-production telescope





Detection of gamma rays can also be achieved through the production of secondary electrons

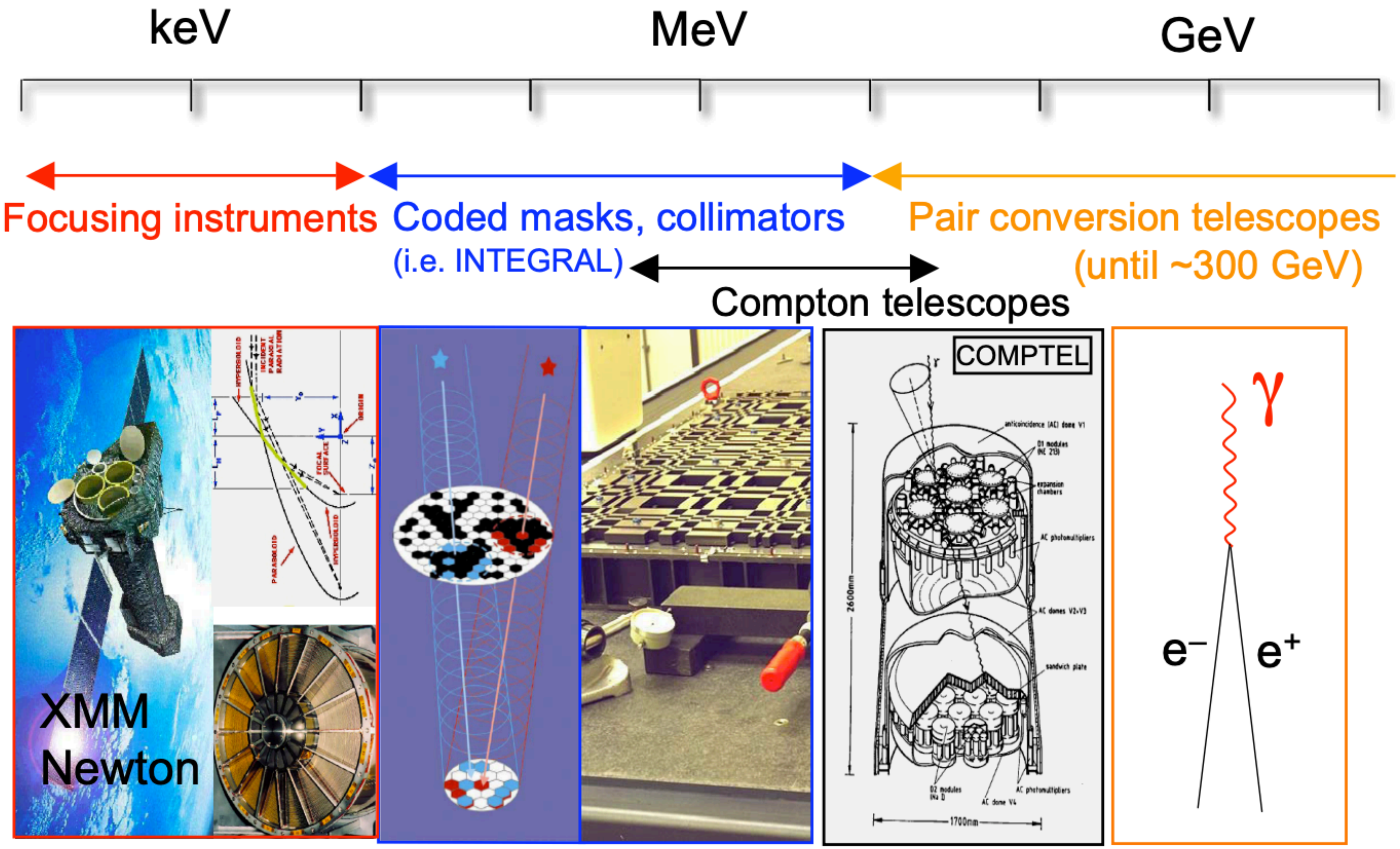
The dominant interaction (e.g. Compton scattering or pair production) depends on the energy of the γ-ray

Gamma-ray detection
Instrumental techniques

Once the gamma-ray has transferred all or part of its energy to secondary electrons, these have in turn to be detected:

- Gas-filled detectors (i.e. Spark chambers)
- Scintillator + photomultiplier tube
- Semiconductors

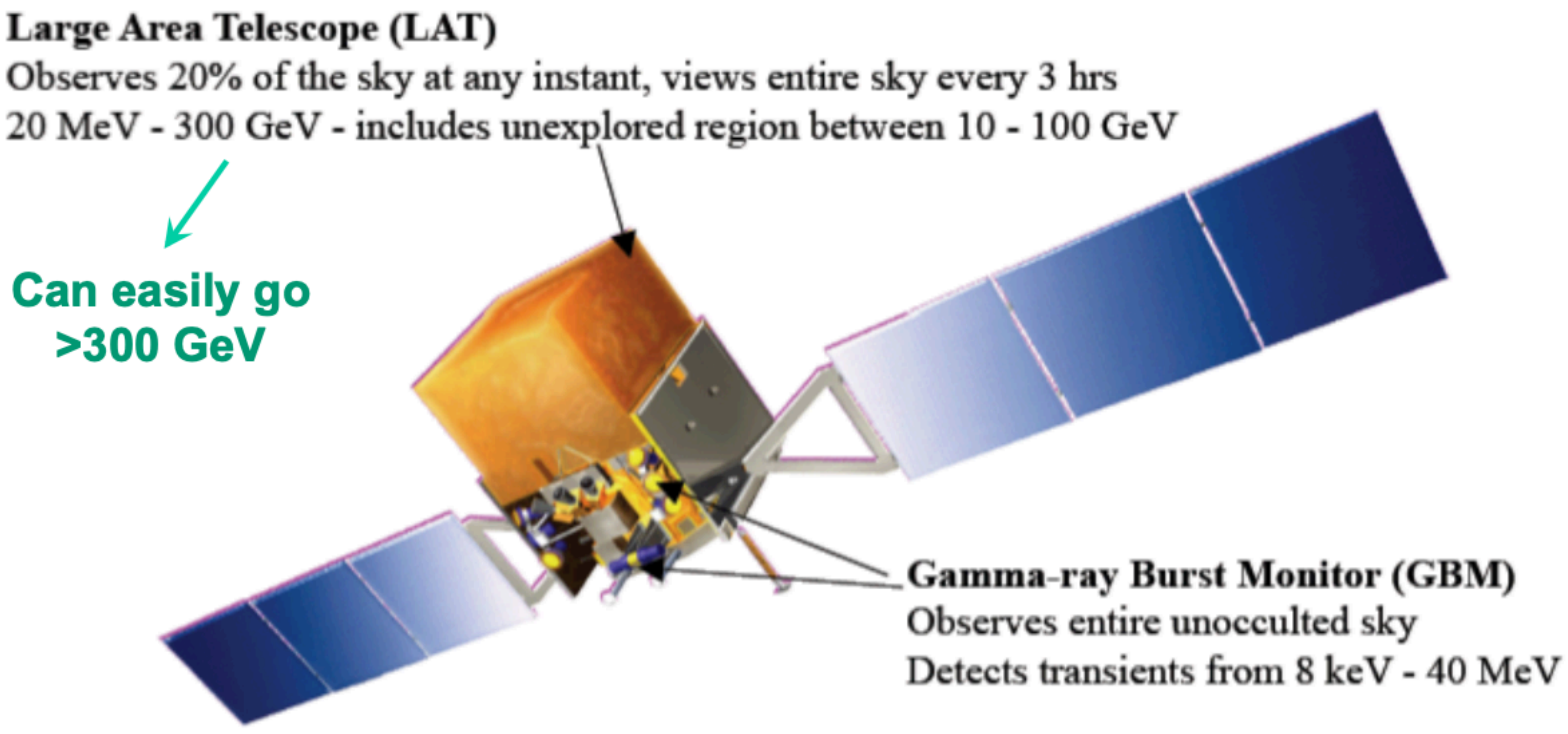
X-ray and γ-ray astronomy

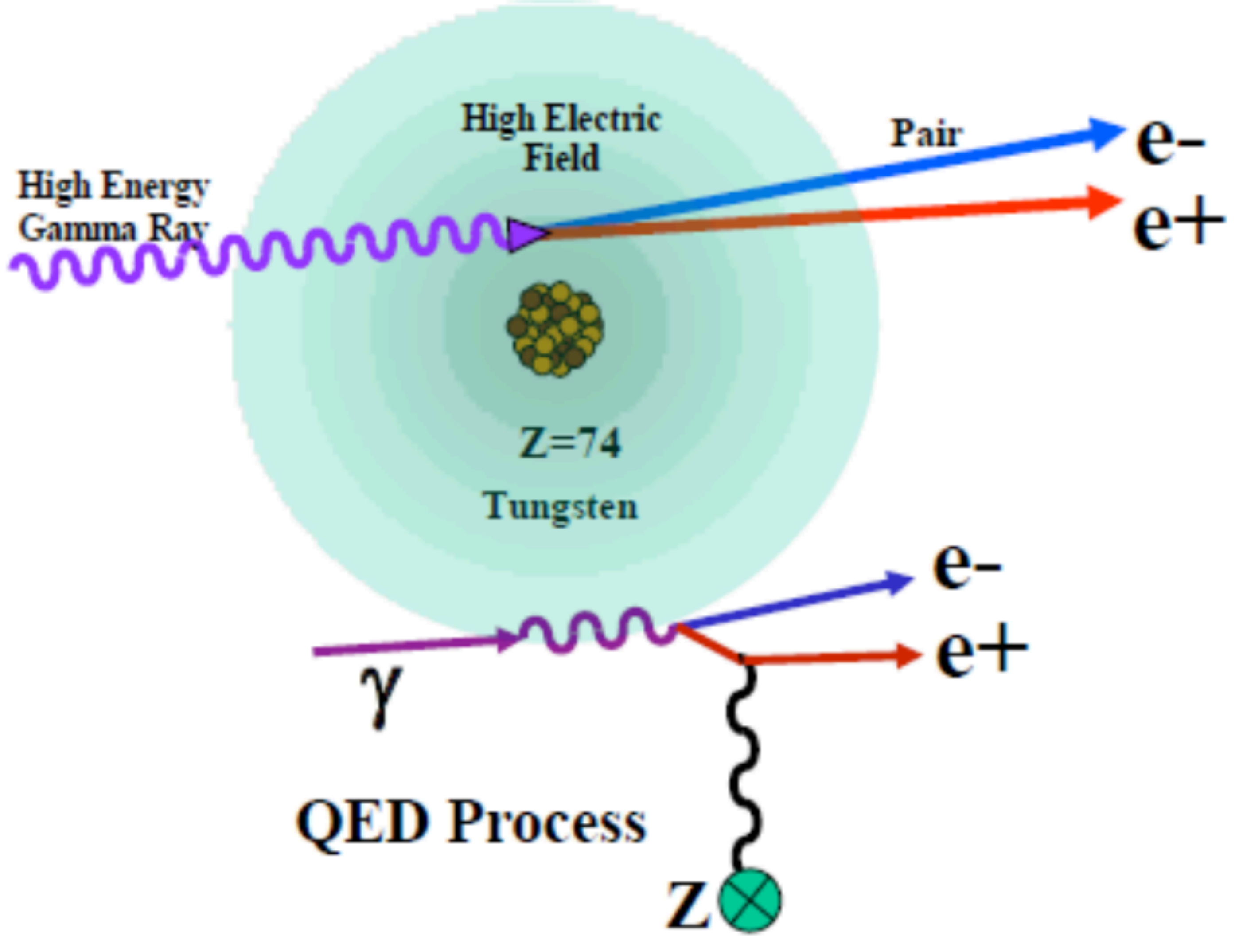


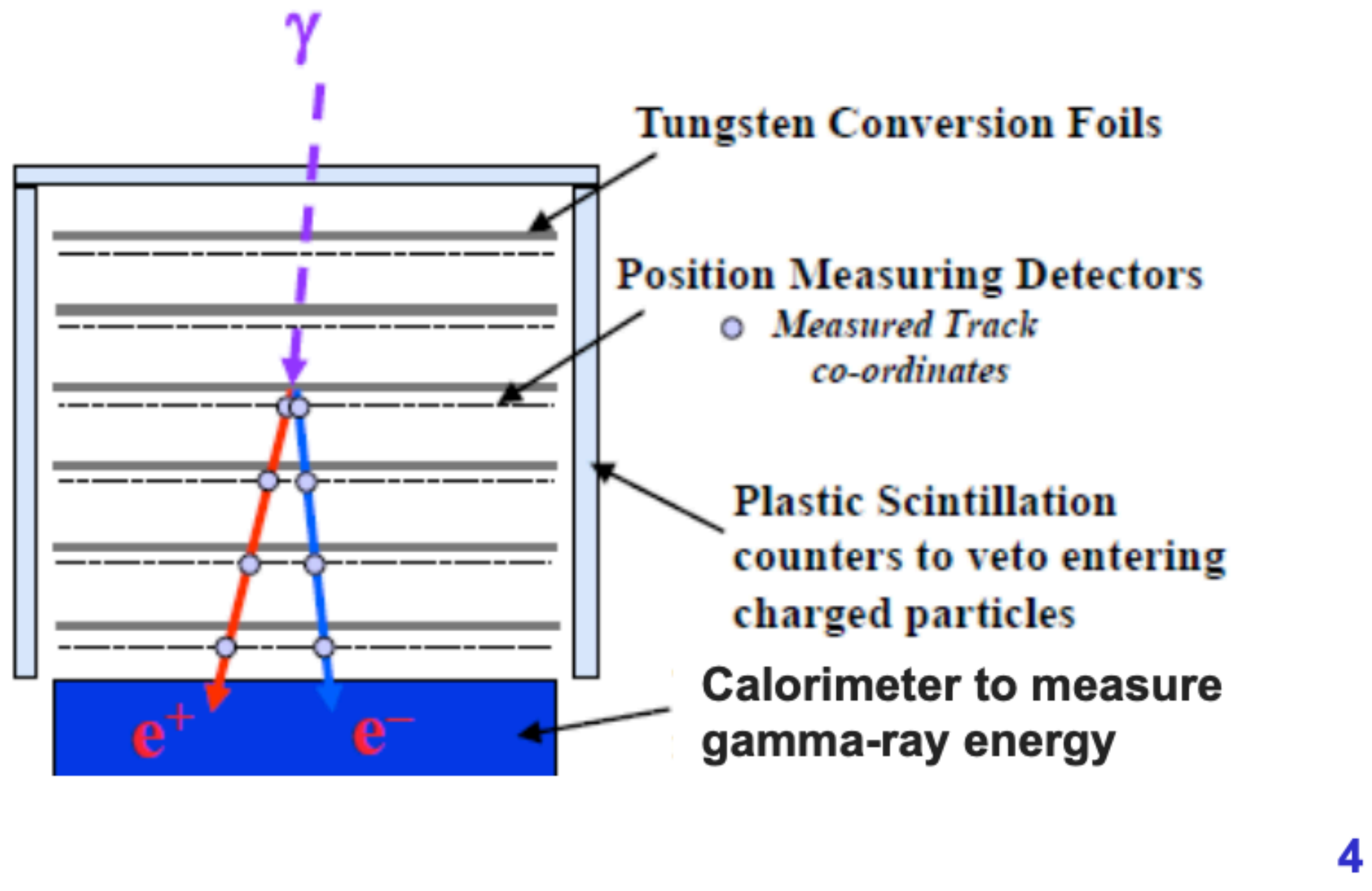
Gamma-ray detection

Satellites (E > 100 MeV)

Based on Pair-Conversion mechanism







Gamma-ray detection

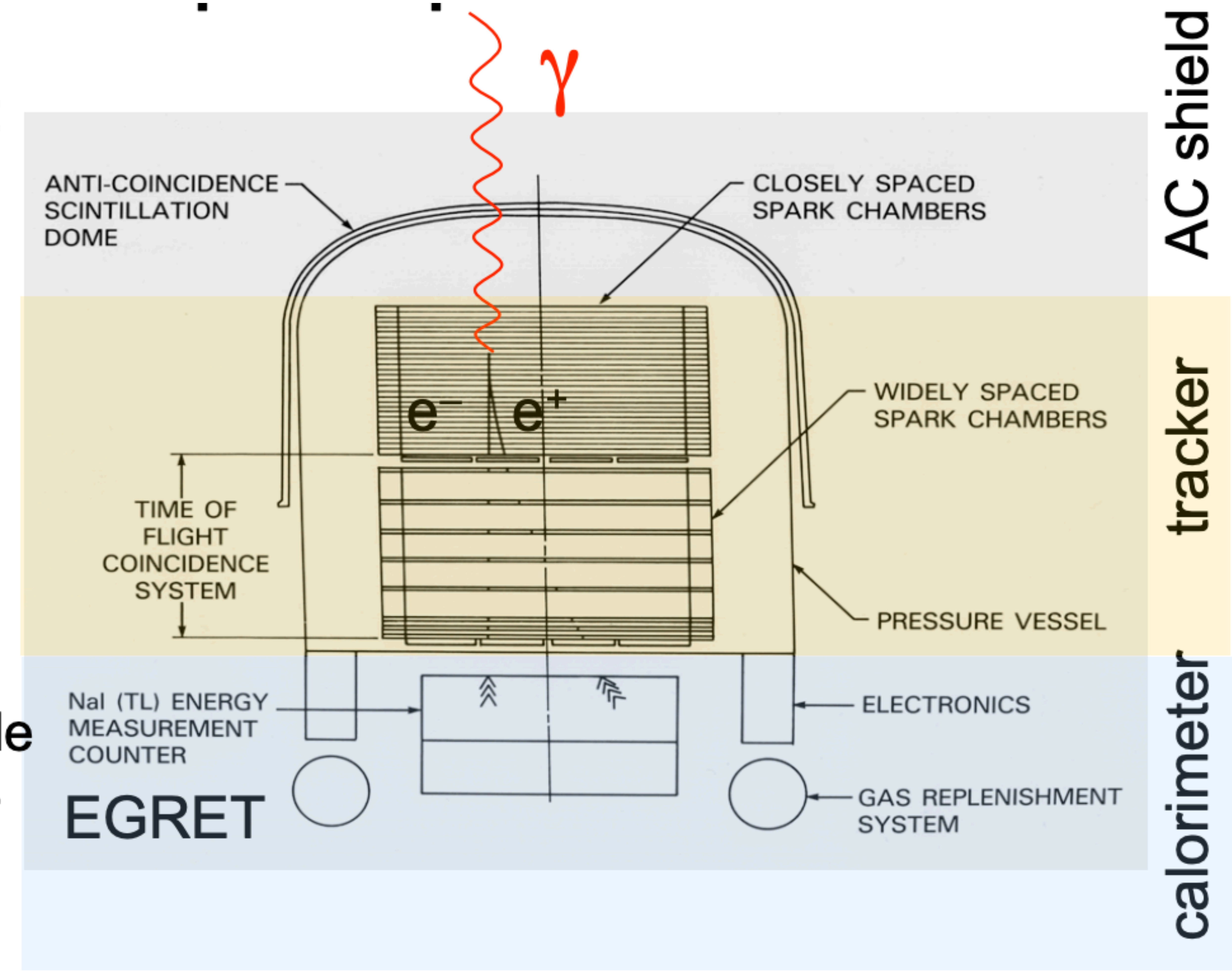
Satellites (E > 100 MeV)

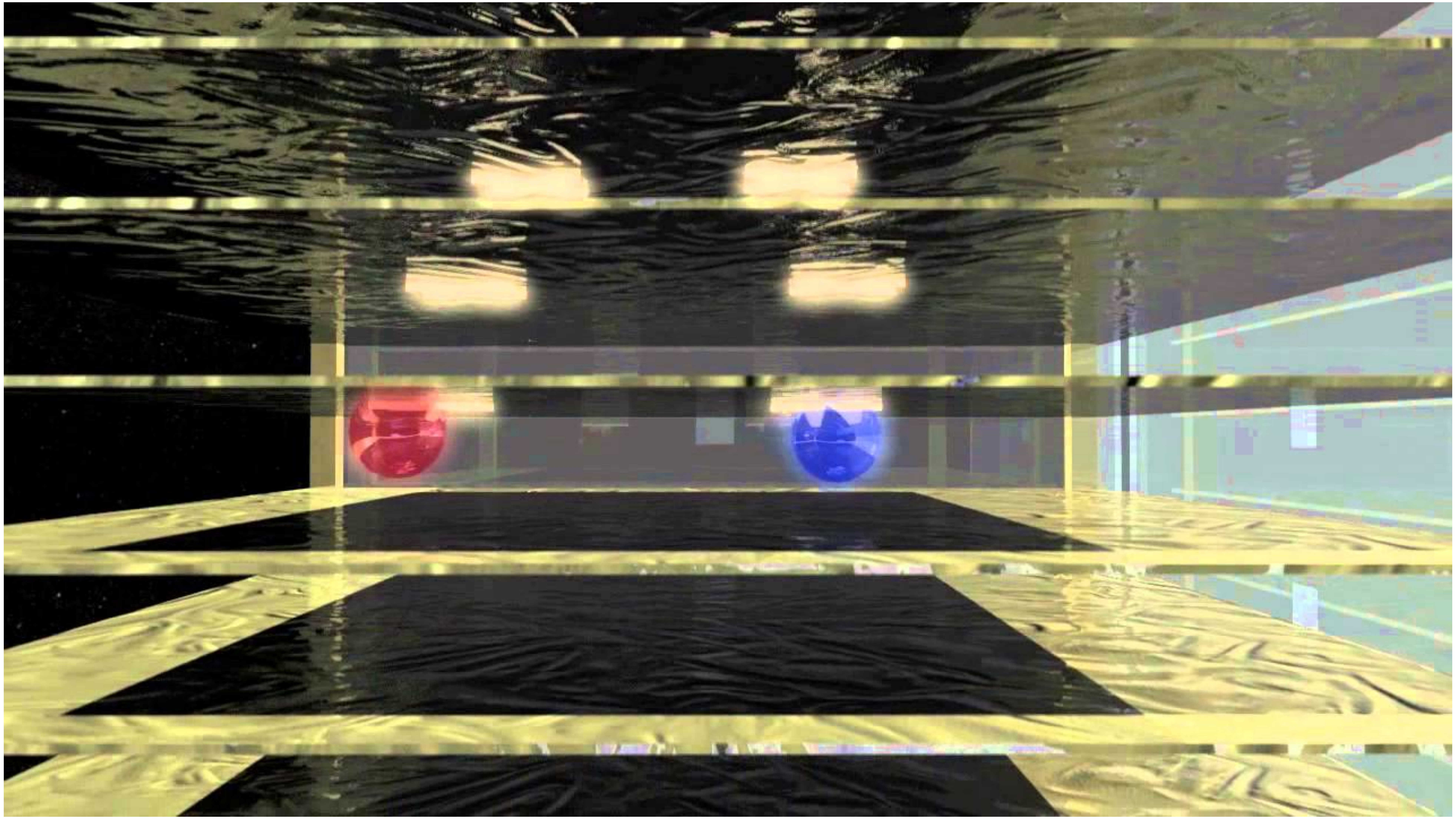
Three main parts:

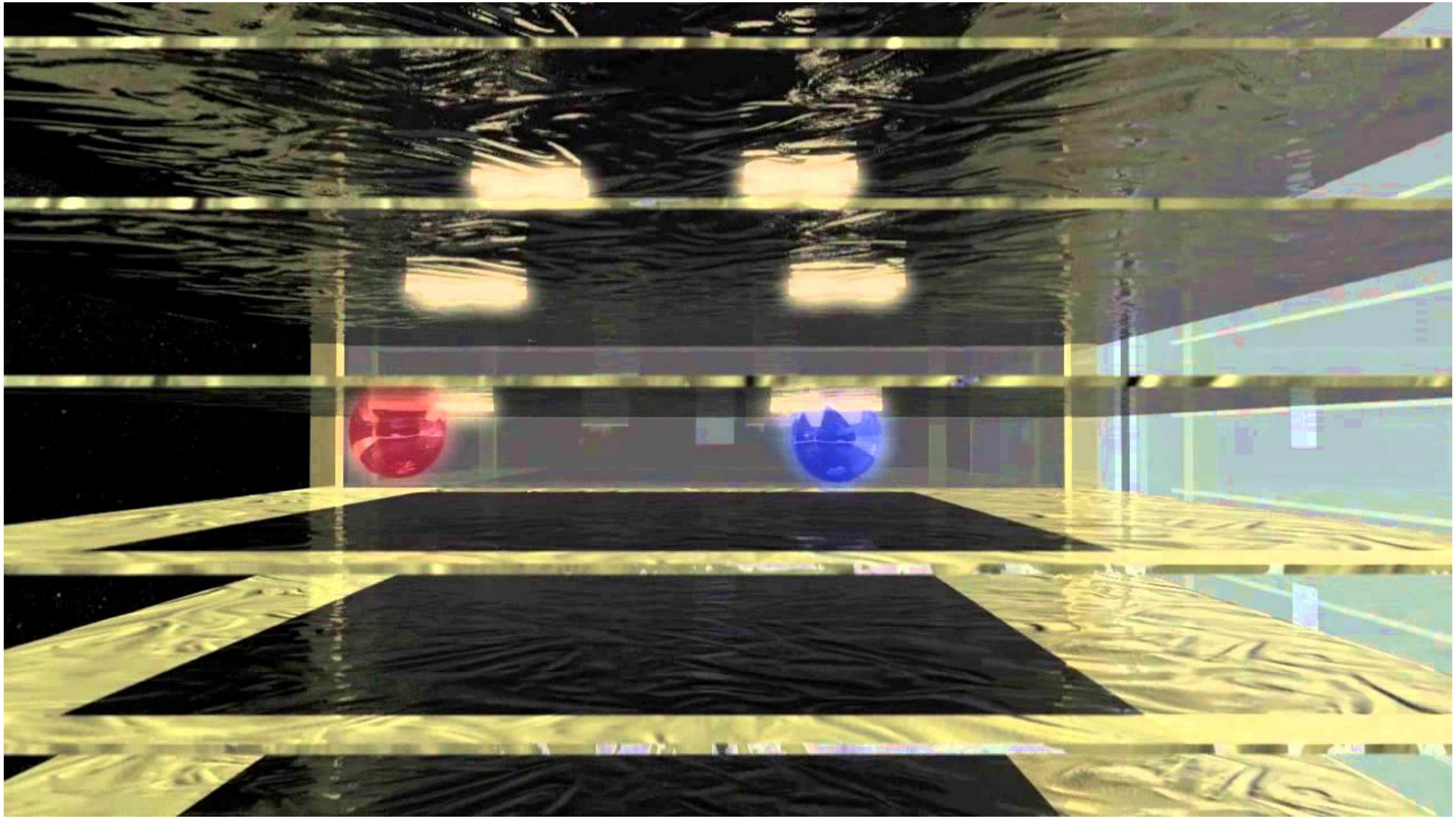
A tracker to determine the trajectory of the $e^{\pm}$

A calorimeter for measuring the energy

An “active shield” against charged cosmic rays (particle detector set in anti-coincidence)



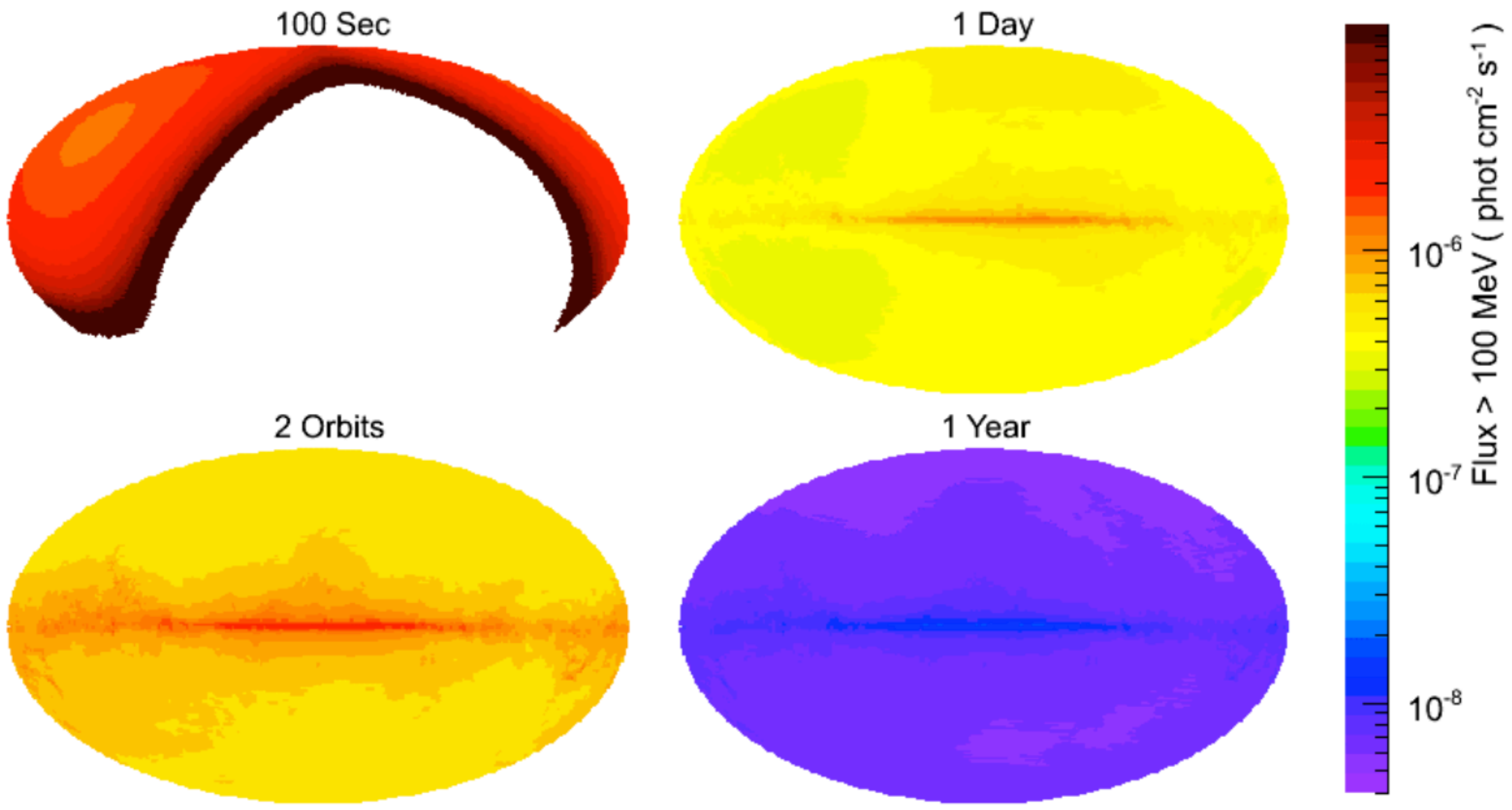




Gamma-ray detection

Satellites (E > 100 MeV)

Large FoV: LAT scans the entire sky every 3 hours (two orbits)

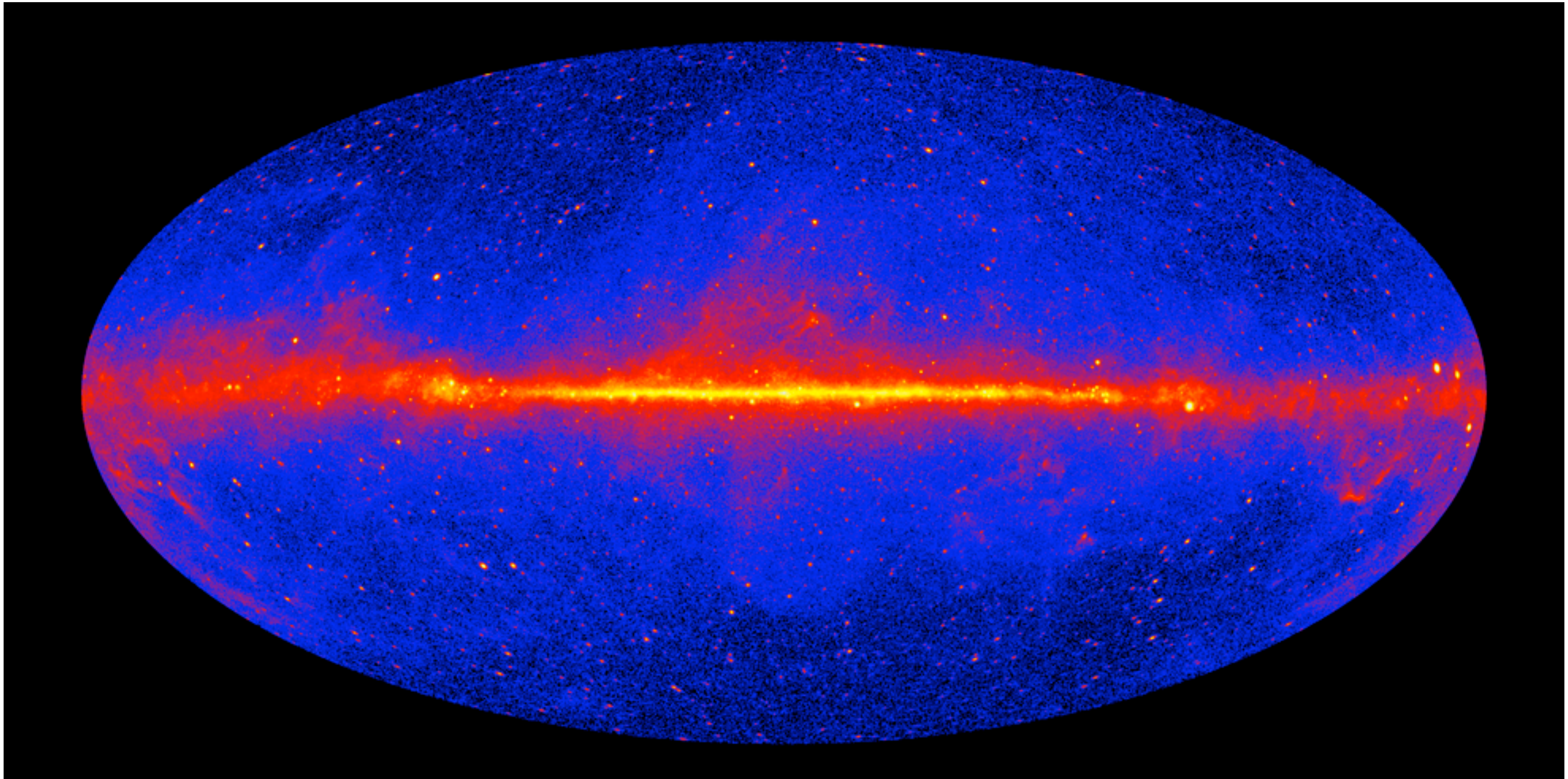


LAT sensitivity in different time scales *(J. McEnery)*

Gamma-ray detection

Satellites (E > 100 MeV)

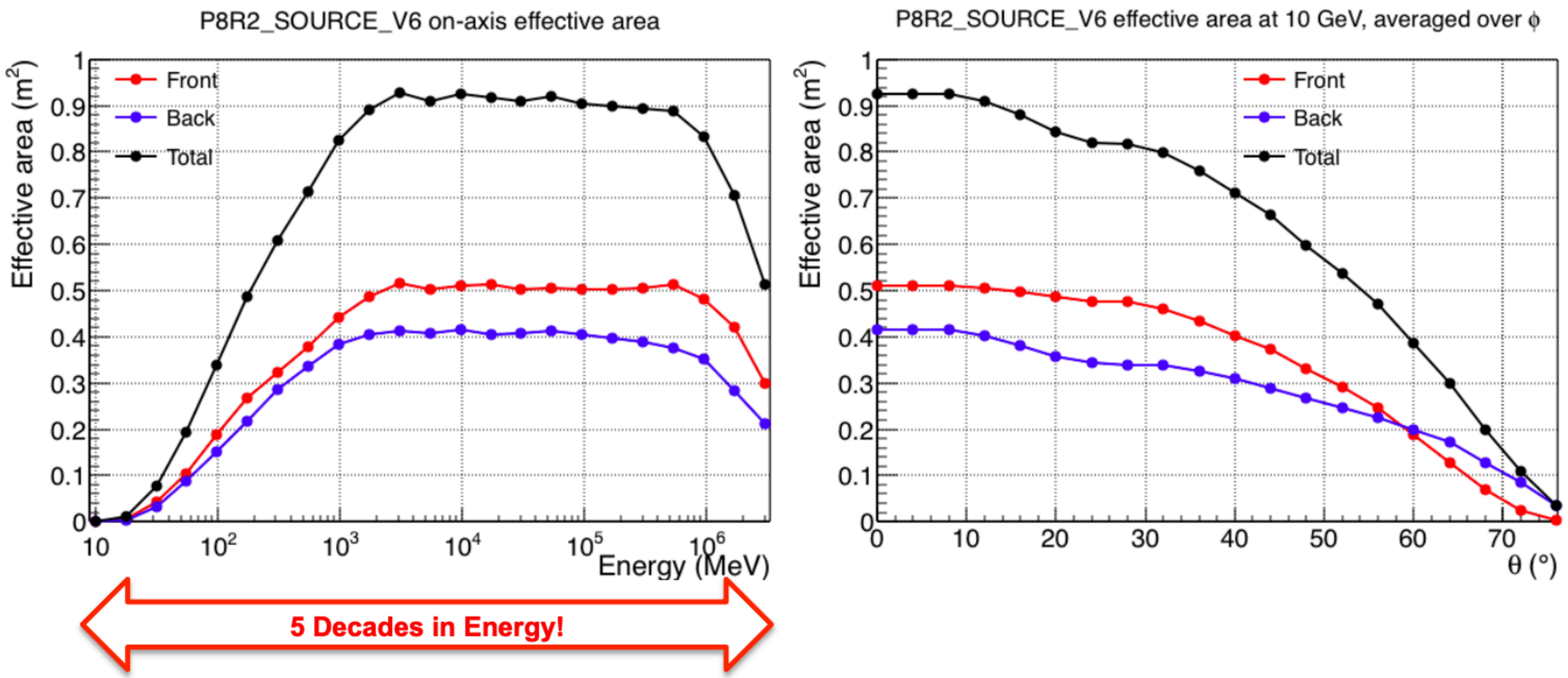
NASA, 2022



Gamma-ray detection

Satellites (E > 100 MeV)

Fermi Collaboration

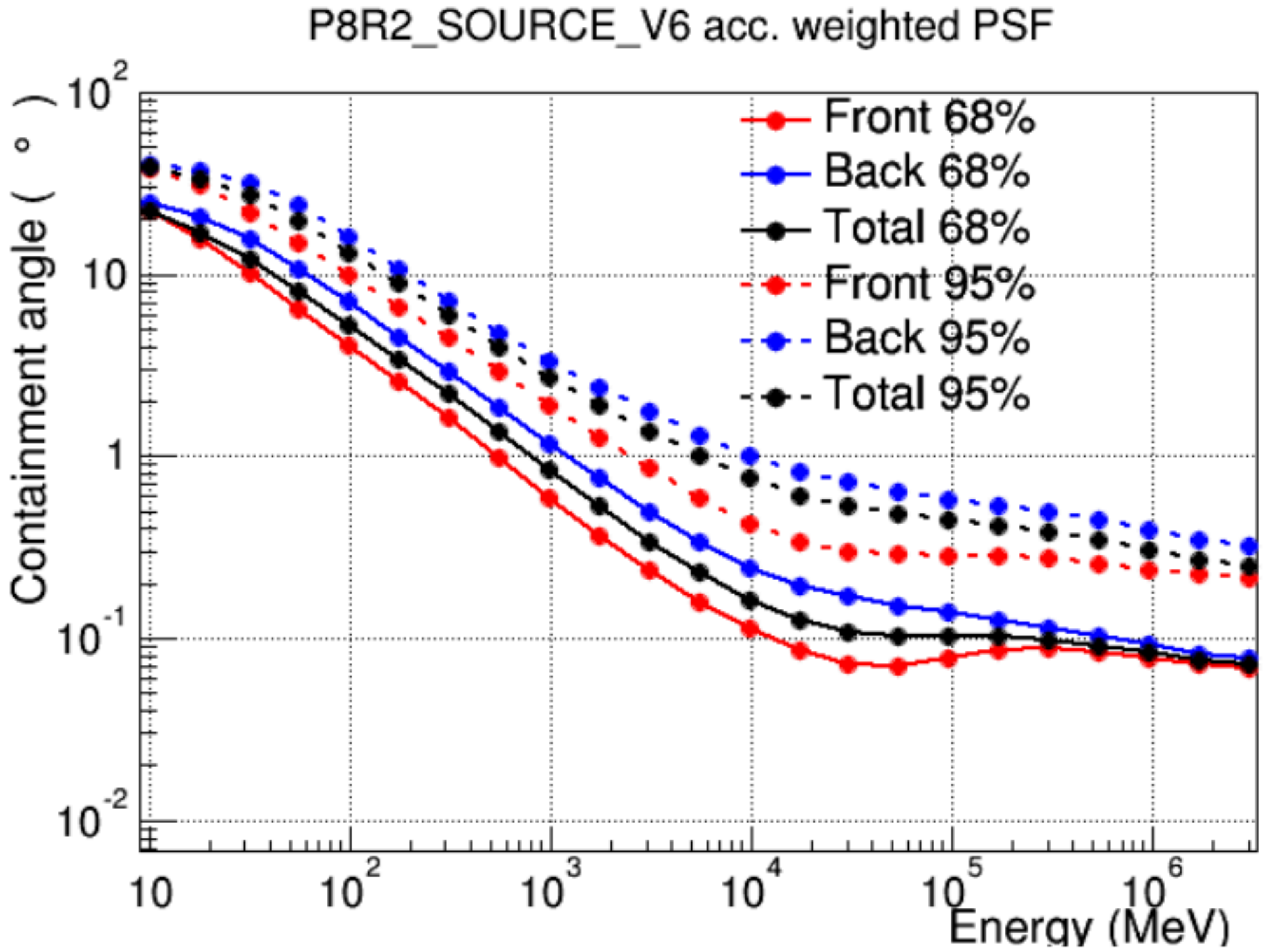


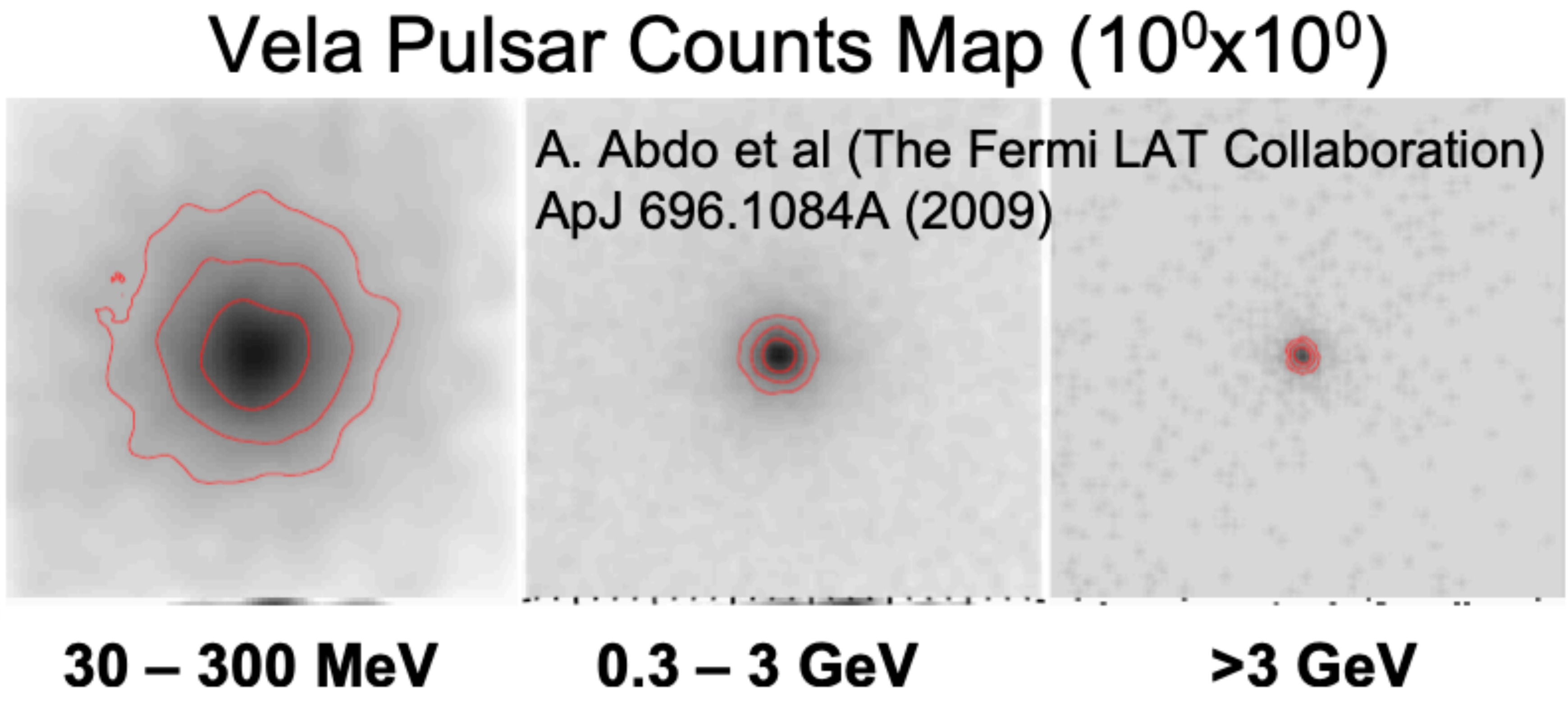
- **< 100 MeV limited by 3 in-a-row trigger requirement & drop in pair production cross section**
- **> 100 GeV limited by backsplash**
- **See arXiv:1206.1896 for more info on Fermi LAT performance/ validation**

Gamma-ray detection

Satellites (E > 100 MeV)

Fermi Collaboration



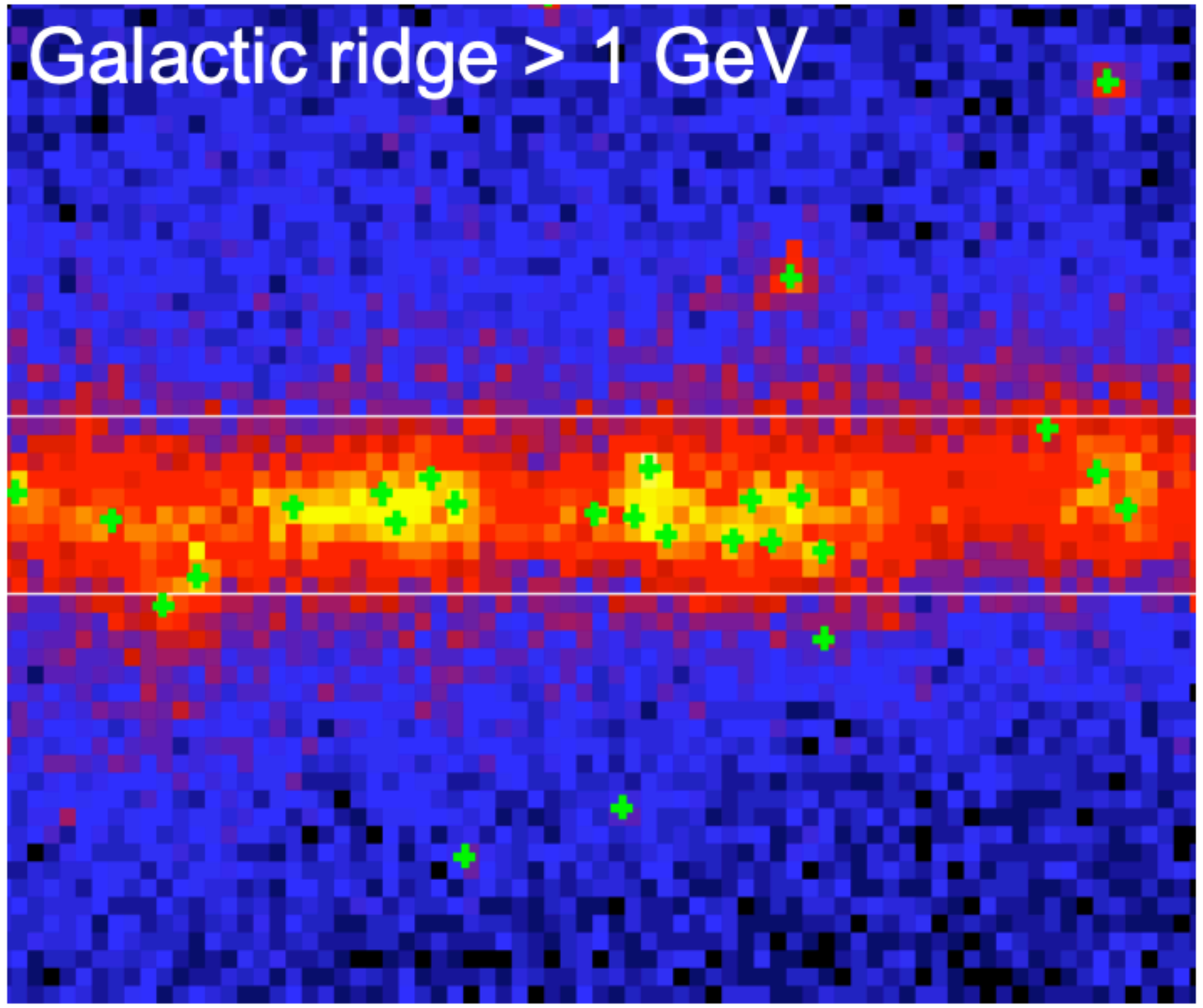


- **Low energies limited by multiple scattering at low E**
- **High energies limited by strip pitch at high E (pitch = 228 μm)**
- **See arXiv:1206.1896 for more info on Fermi LAT performance/ validation**

Gamma-ray detection

Satellites (E > 100 MeV)

Fermi Collaboration



Maximum likelihood method: model γ-ray emission as sum of sources and diffuse background (from GALPROP)

Free parameters of the model include the description of each source spectrum, its position and whether or not it exists

Some sources may be due to not well modeled diffuse emission!

Gamma-ray detection

Satellites (E > 100 MeV)

- Main background => Gamma-ray diffuse emission from the CR sea

- Small effective area results in extremely low
detection rates at E > 100 GeV, even for strong sources :
$F_{\text{Crab Nebula},E>100GeV}$ @ 100 photons/m^2/year
That means: 1 gamma-ray / 3 hours above 30 GeV

- Calorimeter depth ≤ 10 radiation lengths, which corresponds to ~1 ton per m^2 (which is hard to put into orbit) => VHE showers leak out of the calorimeter

Gamma-ray detection

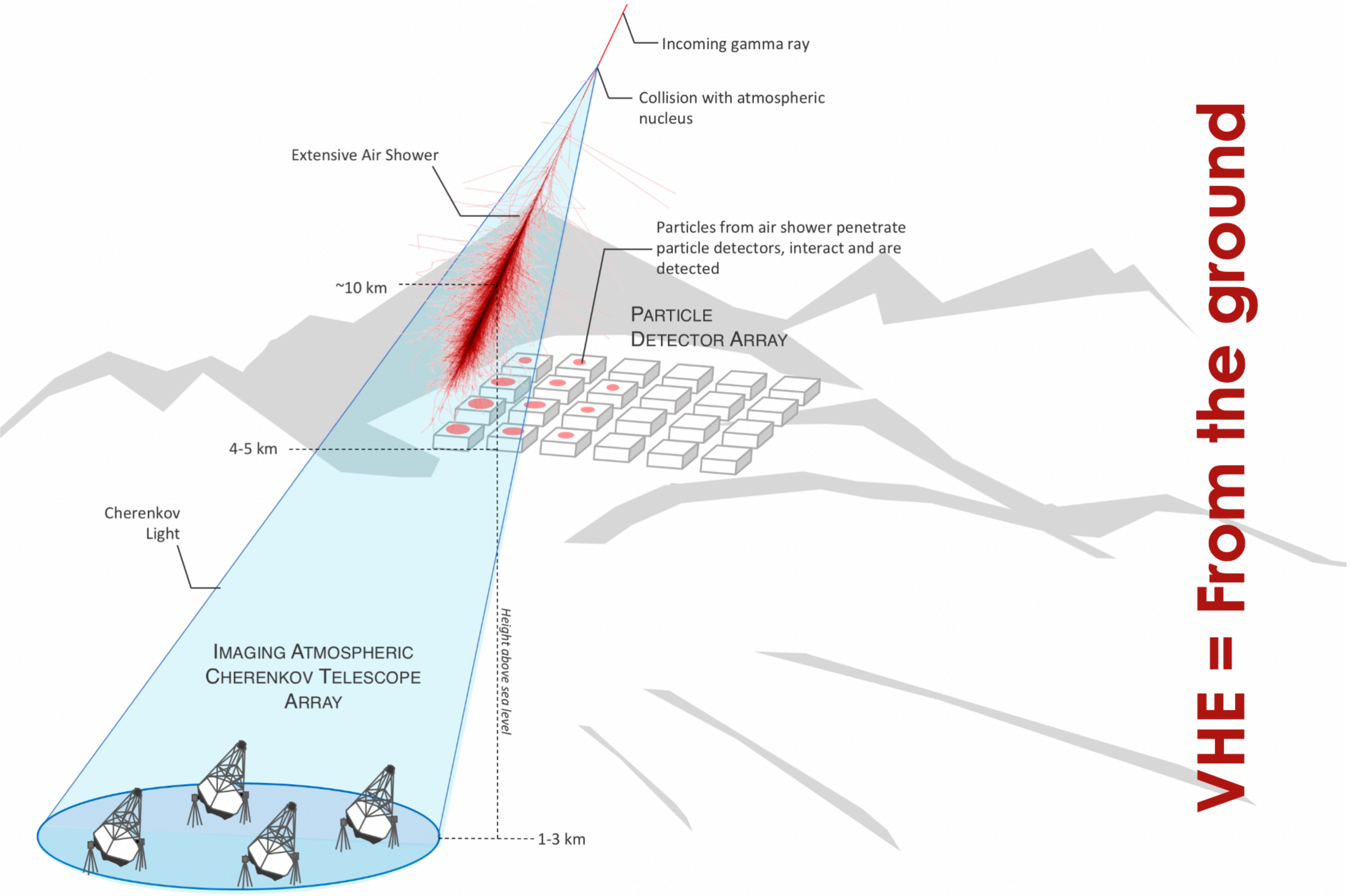
Satellites (E > 100 MeV)

- Current satellites are too small to “stop” VHE g-rays, and also fail to collect enough of them
- Fortunately, for the same reason, the Earth’s atmosphere is too thin to *avoid* the effects of the absorption of a VHE g-ray to be detectable from the ground

=> Solution: a “pair conversion telescope” in which the atmosphere is part of the detector

Gamma-ray detection

Ground-based detectors (E > 50 GeV)



A. Mitchell, rapporteur talk at ICRC 2021, arXiv:2109.13753v1

VHE = From the ground

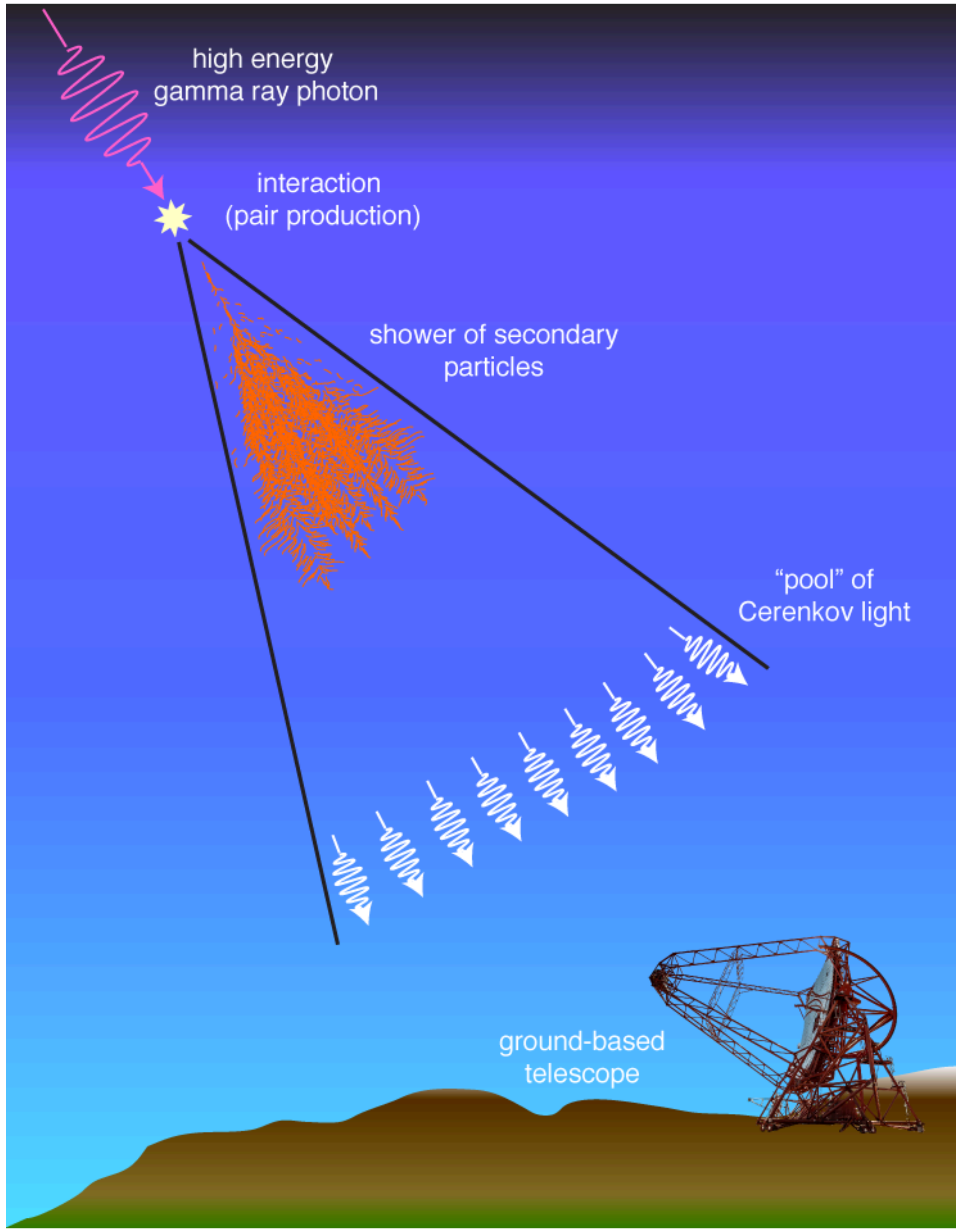
Gamma-ray detection

Extensive Air Showers (EAS)

- Discovered in 1938 by Pierre Auger

Most frequent processes in showers:

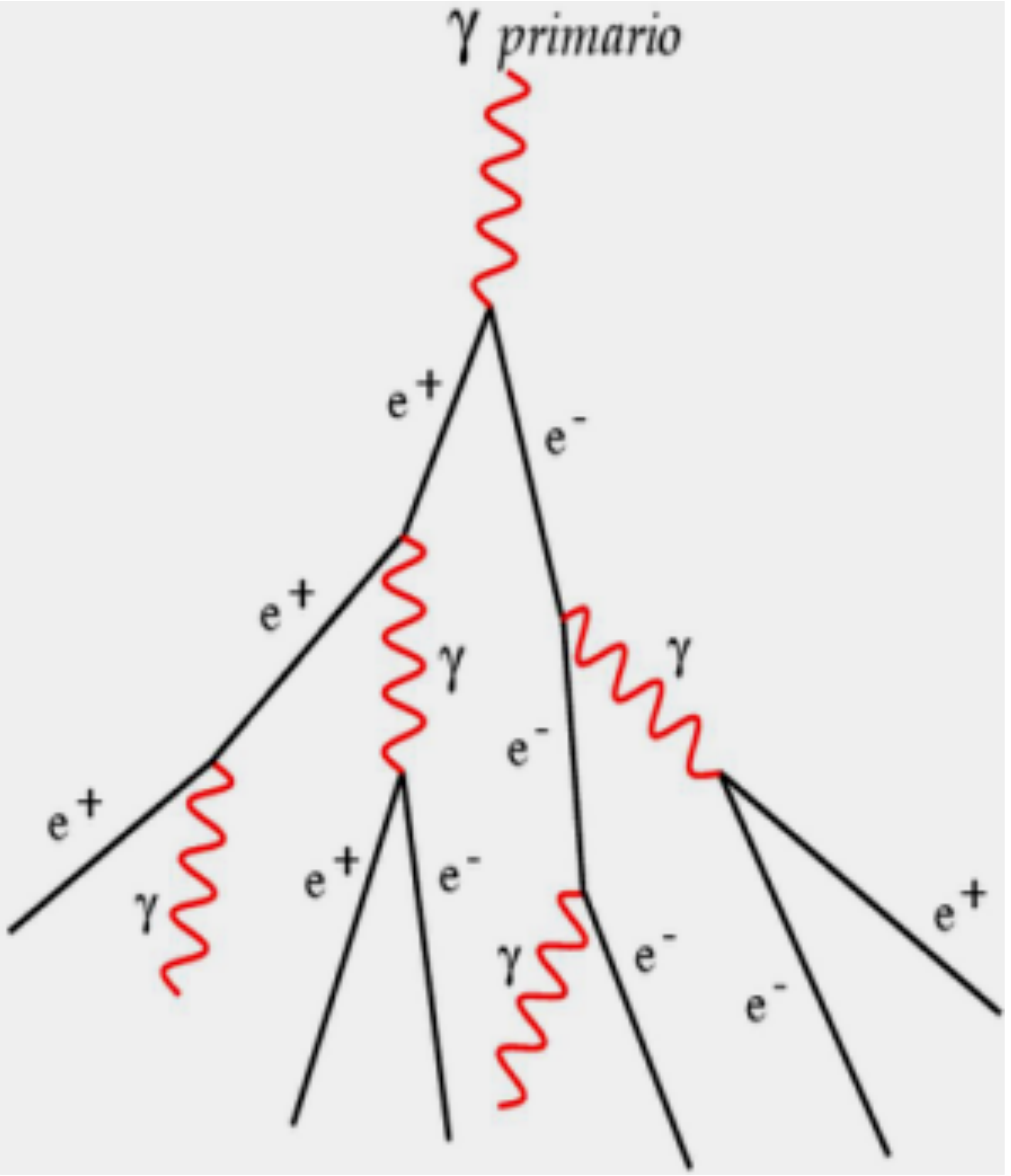
- Electromagnetic showers:
  - $\gamma \longrightarrow e^+ e^-$ (pair production)
  - $e^\pm \longrightarrow \gamma$ (*bremsstrahlung*)
- Hadronic showers:
  - CR + atm. nucleus $\longrightarrow \pi^\circ, \pi^\pm + N^*$
  - $\pi^\pm \longrightarrow \mu^\pm + \nu$
  - $\pi^\circ \longrightarrow \gamma\gamma \longrightarrow$ e.m. showers



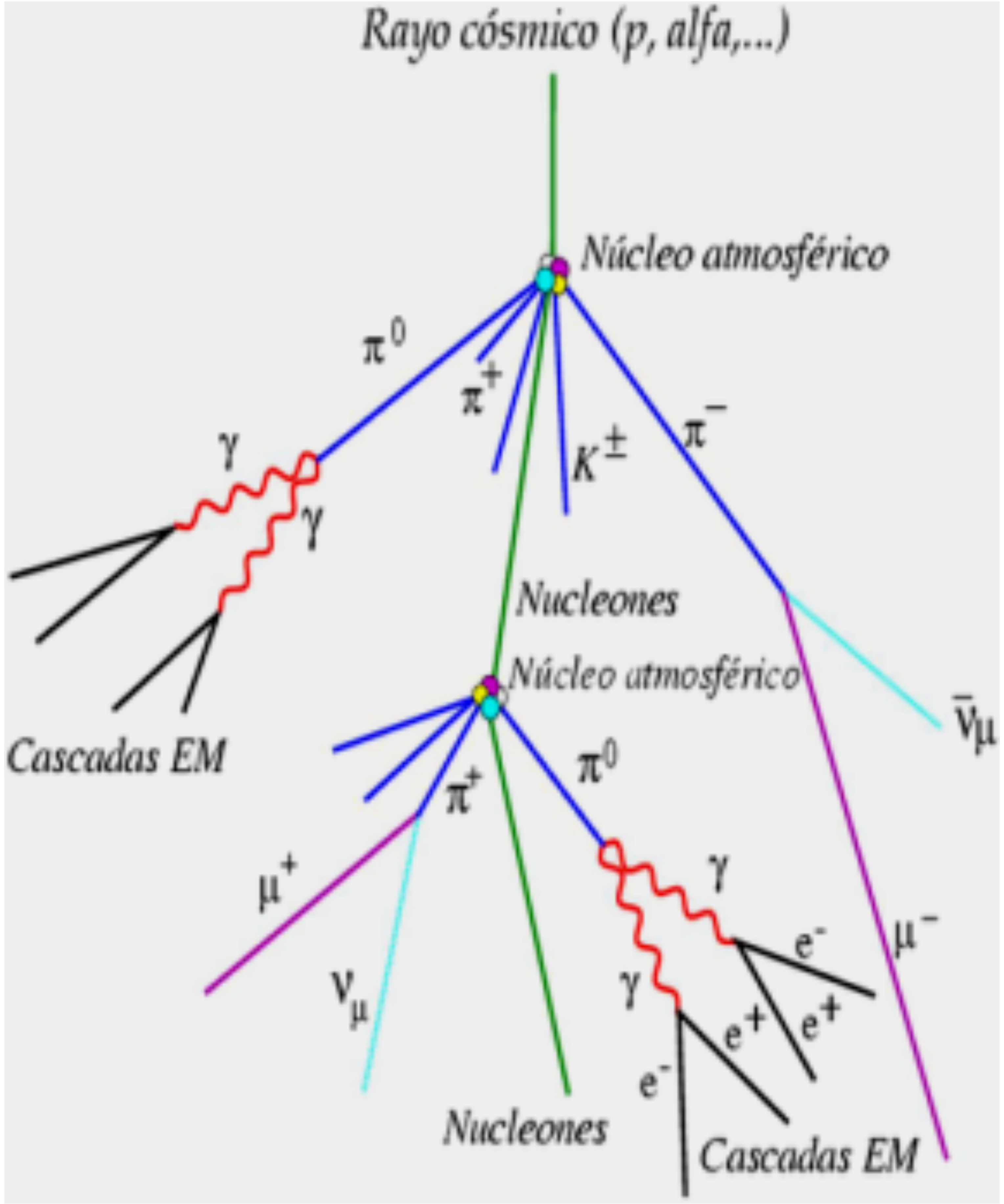
Gamma-ray detection

Extensive Air Showers (EAS)

Electromagnetic



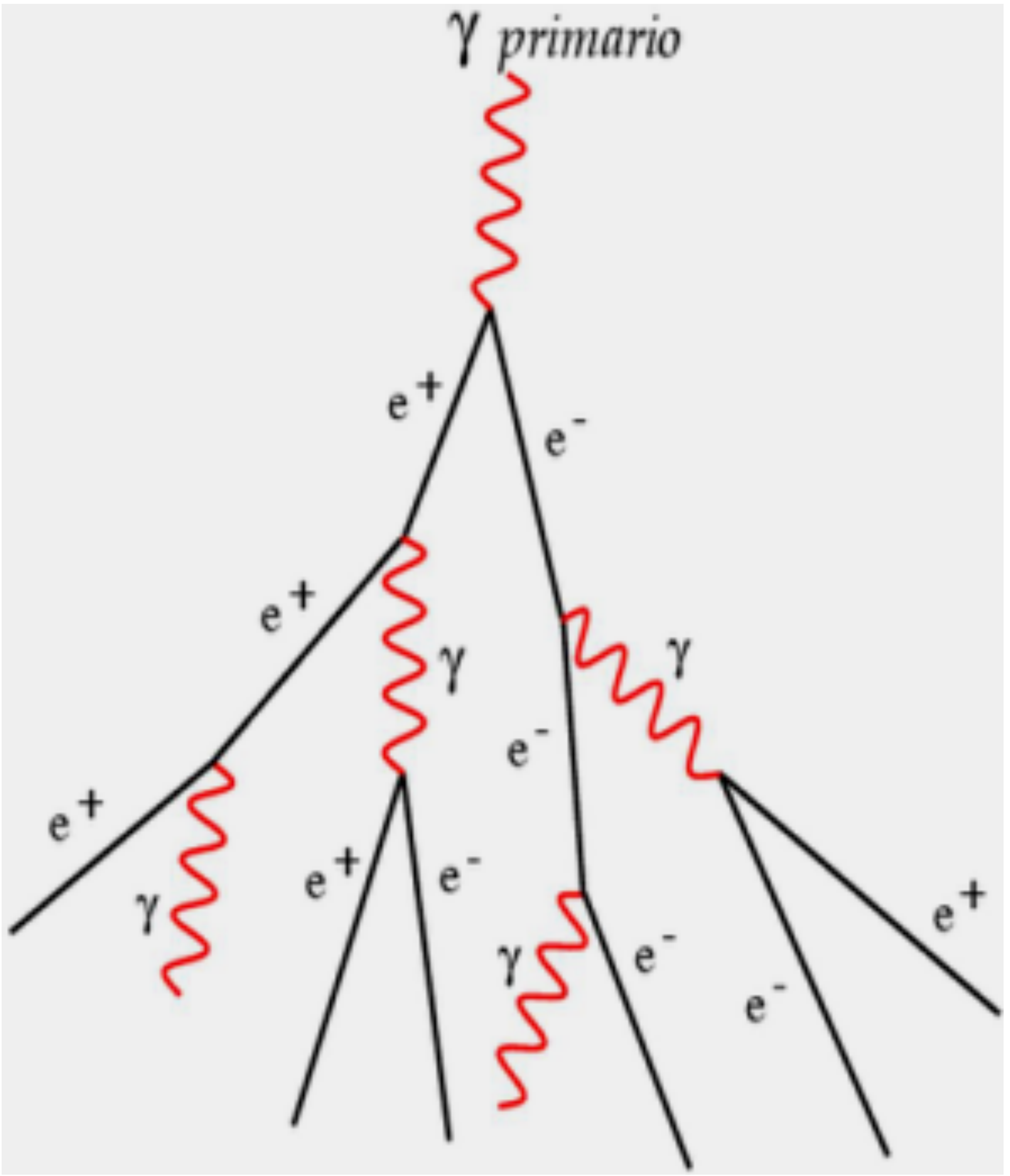
Hadronic



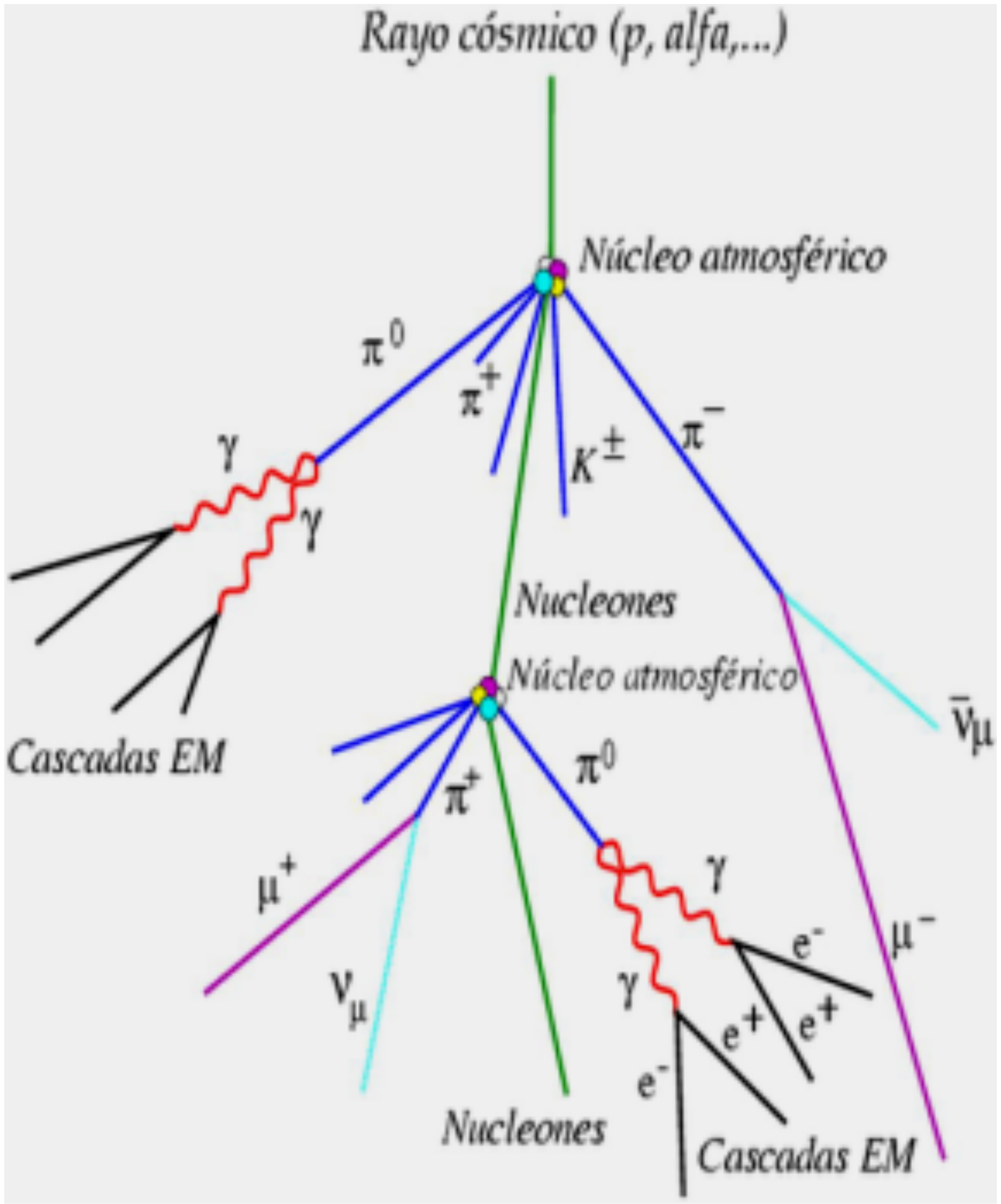
Gamma-ray detection

Extensive Air Showers (EAS)

Electromagnetic

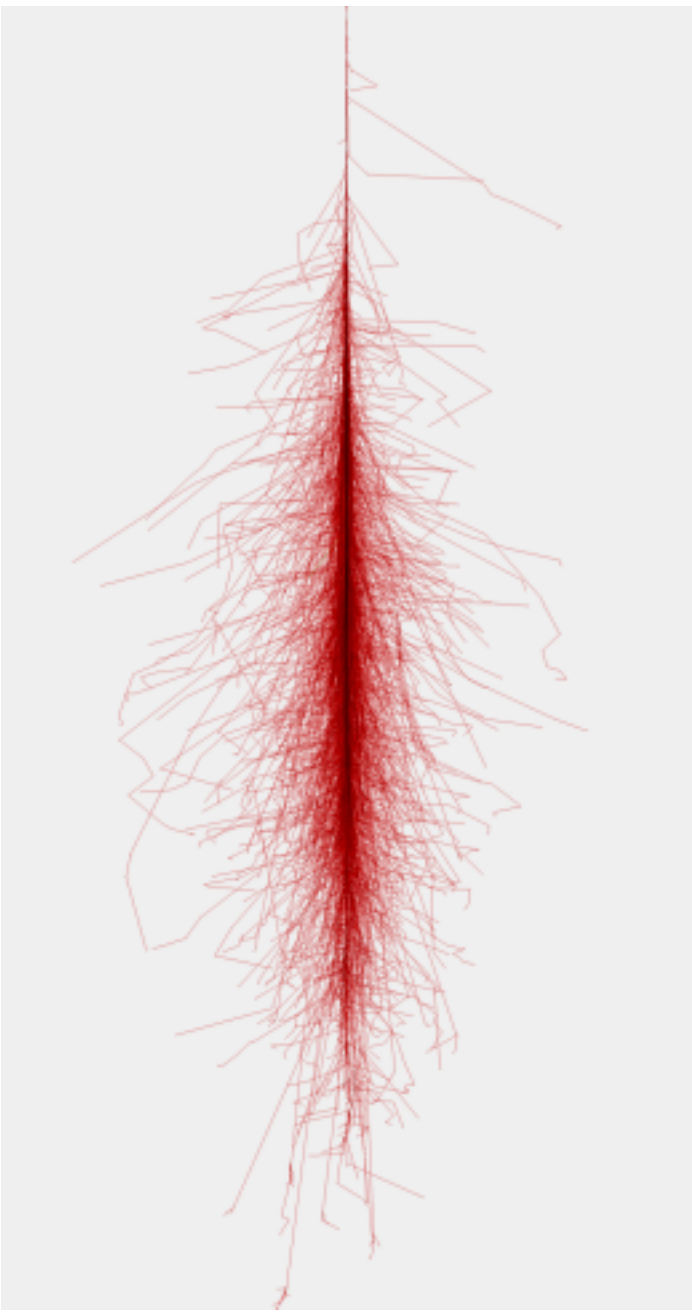


Hadronic

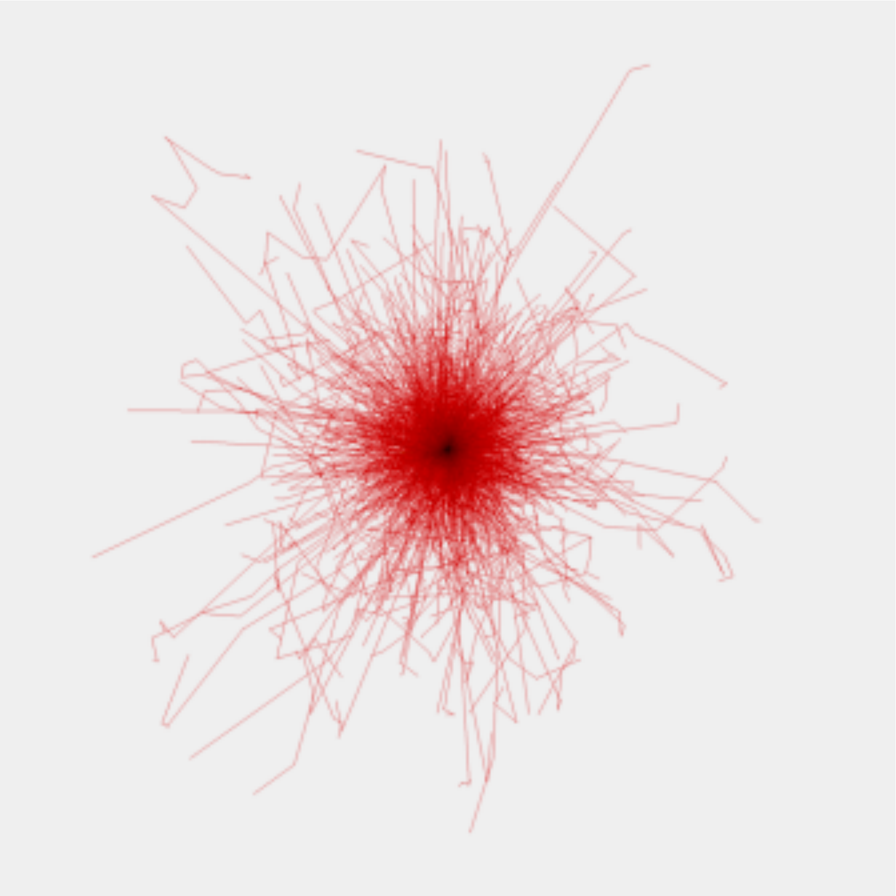


Gamma-ray detection

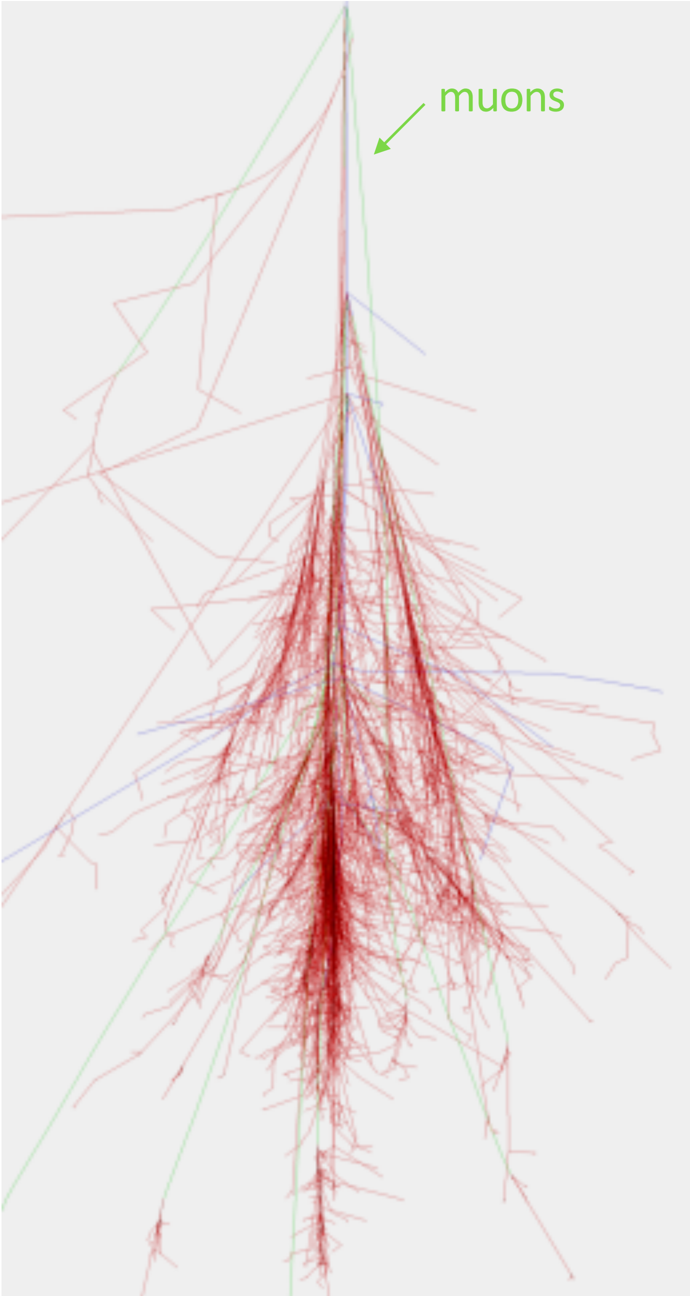
Extensive Air Showers (EAS)



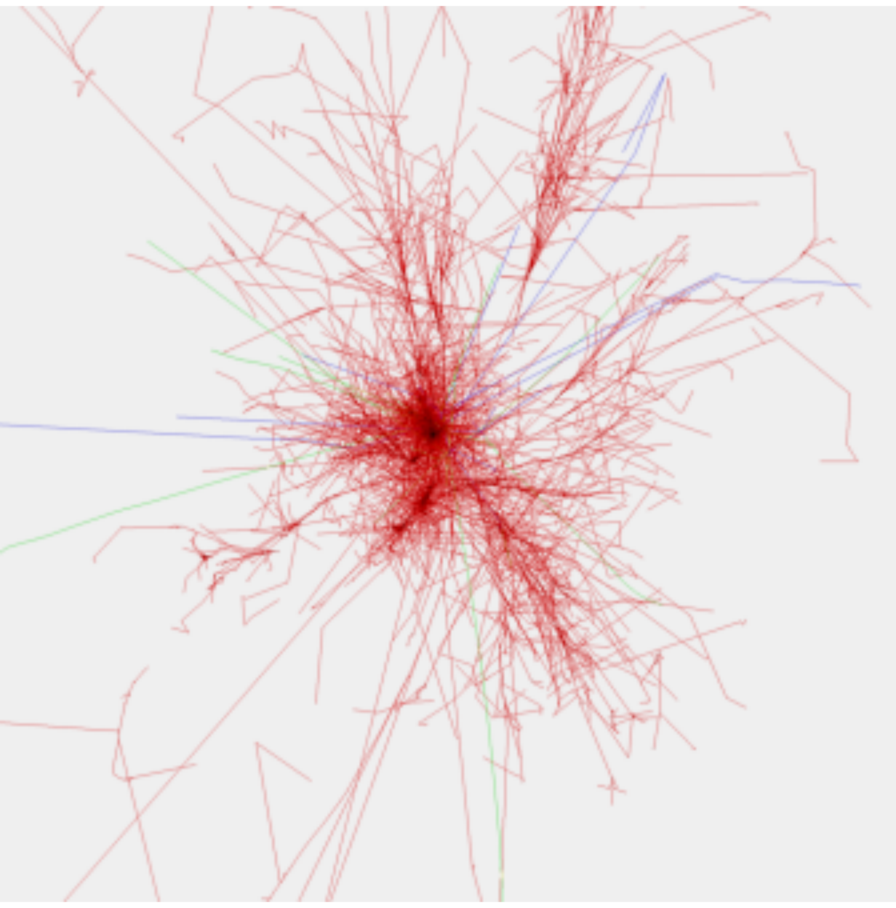
Simulated gamma
50 GeV



Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html



Simulated proton
100 GeV



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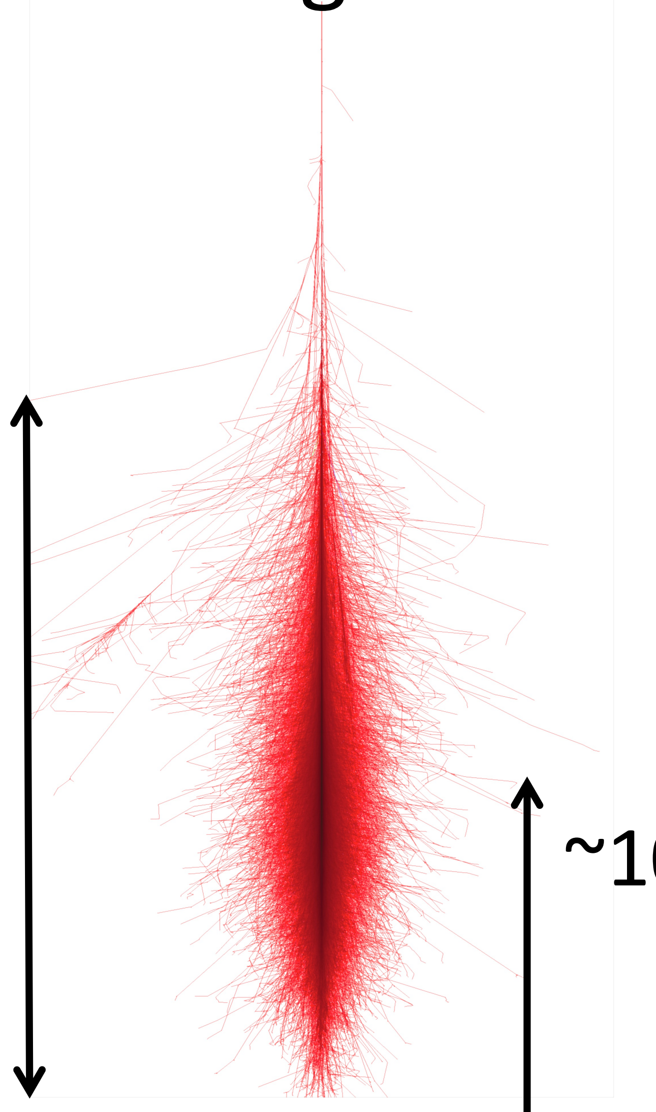
http://www.ast.leeds.ac.uk/~fs/showerimages.html

Gamma-ray detection

Extensive Air Showers (EAS)

1 TeV gamma



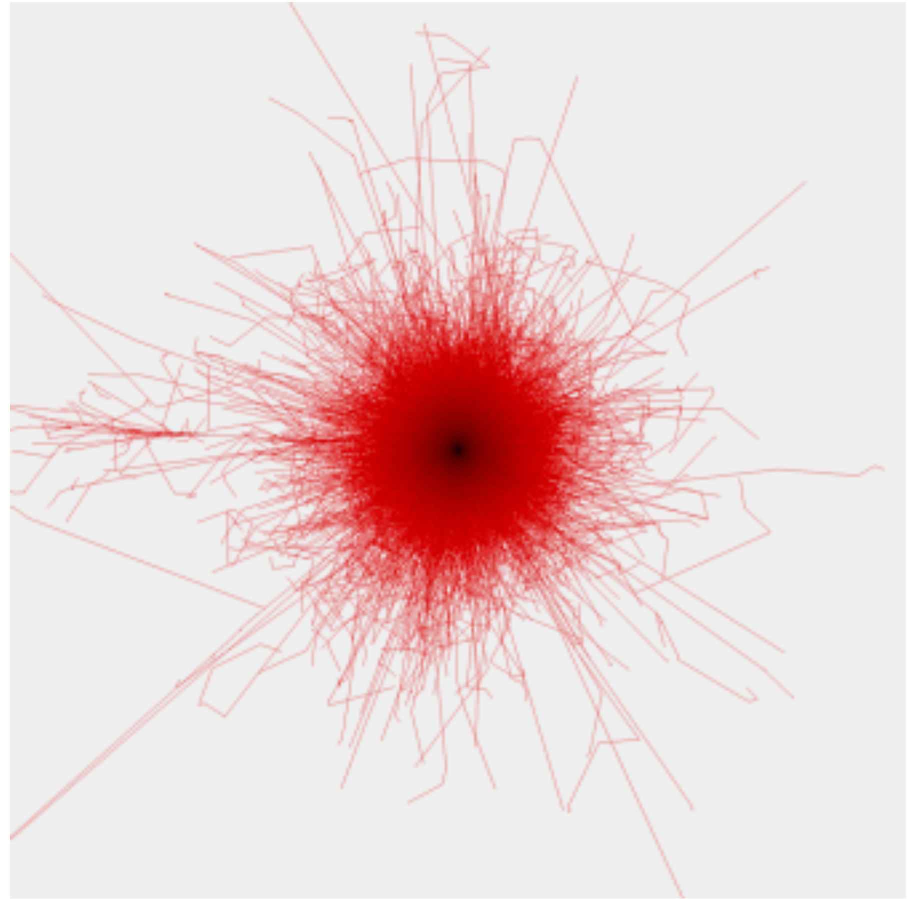
~ 5 km

~20 m

~10 km above sea level

Rough dimensions

Simulated gamma 1 TeV



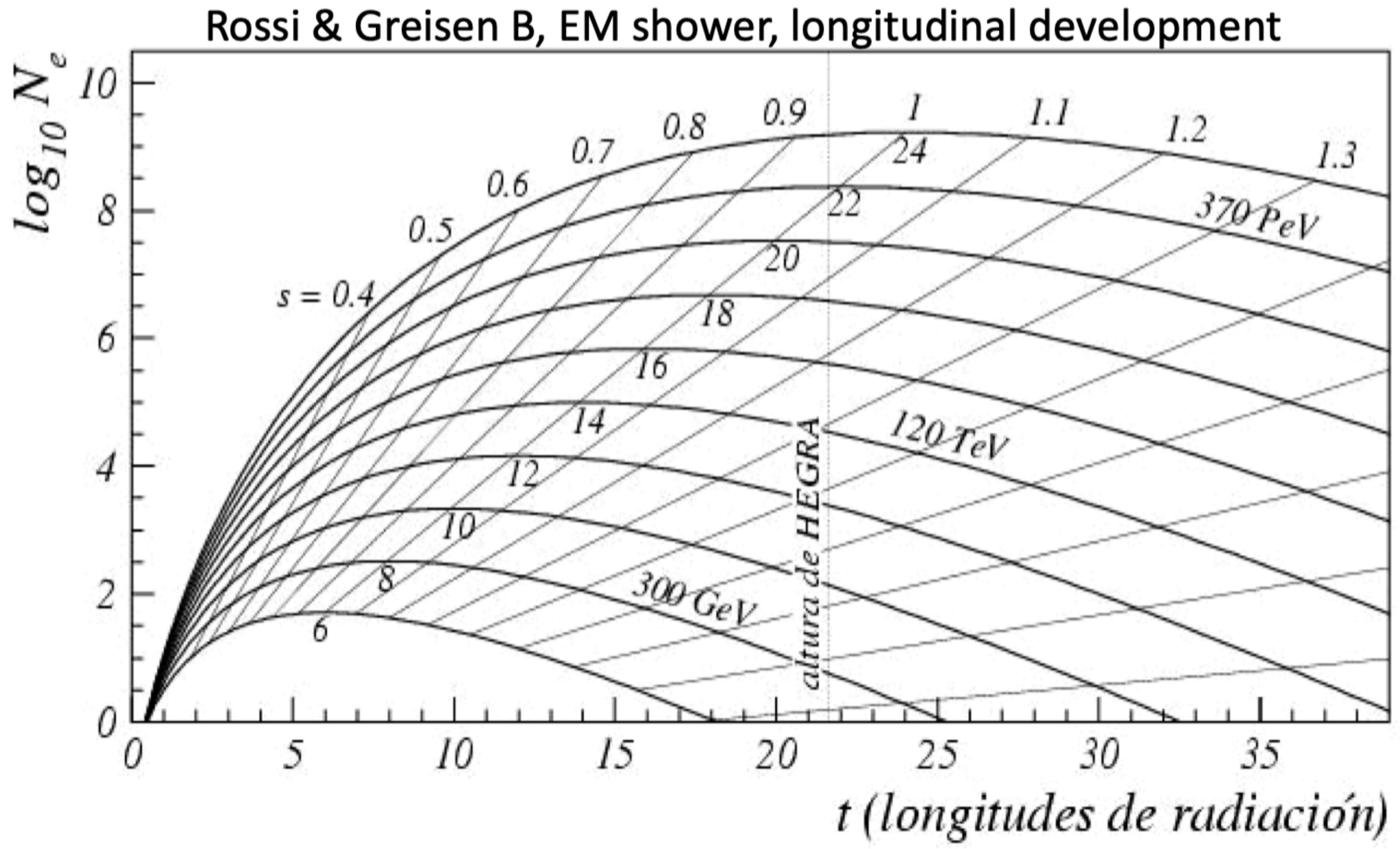
Fabian Schmidt, Leeds university
http://www.ast.leeds.ac.uk/~fs/showerimages.html

(note that x-axis scale is always exaggerated for viewing purposes)

Gamma-ray detection

Extensive Air Showers (EAS)

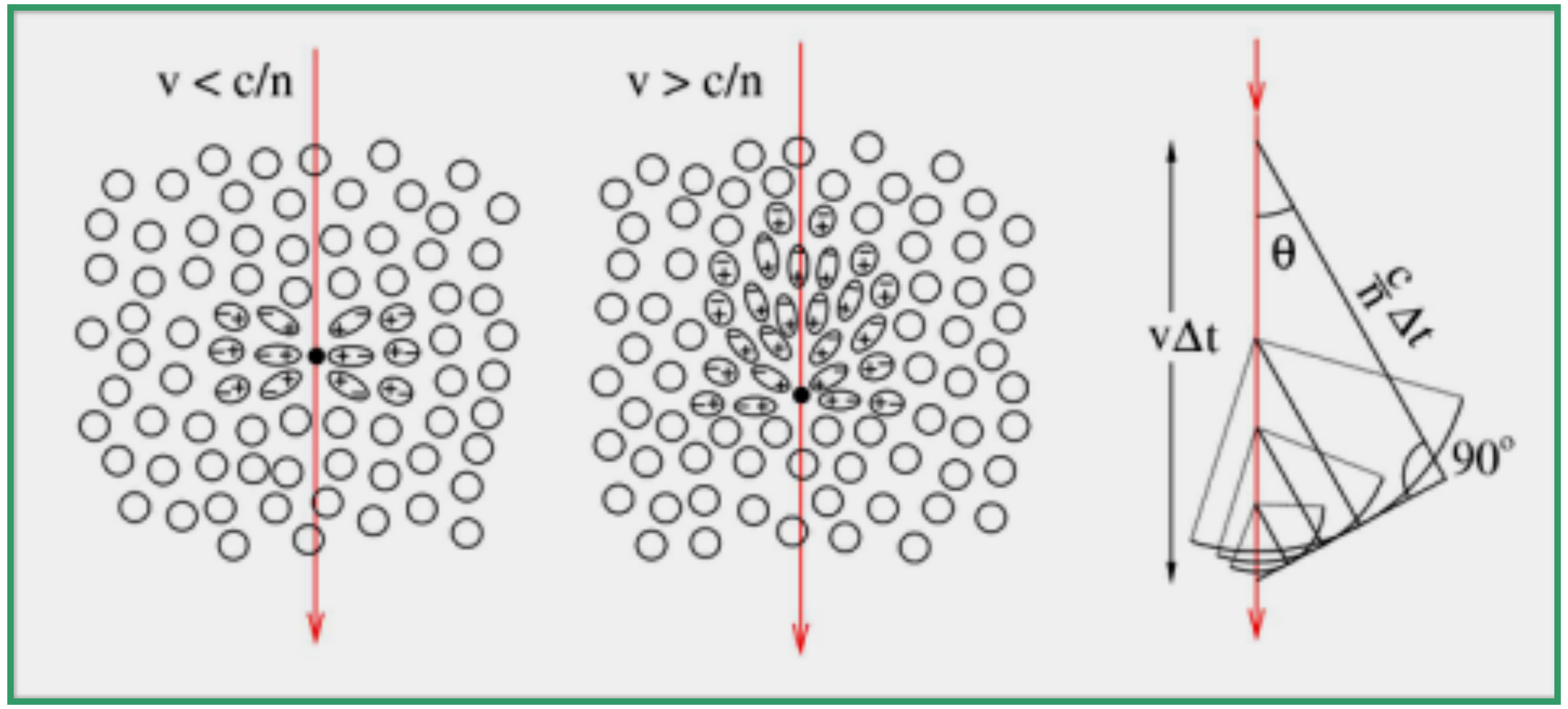
- The altitude of the detector helps on detecting showers at different energies
- How to detect these particles? **Cherenkov radiation**



Gamma-ray detection

Cherenkov radiation

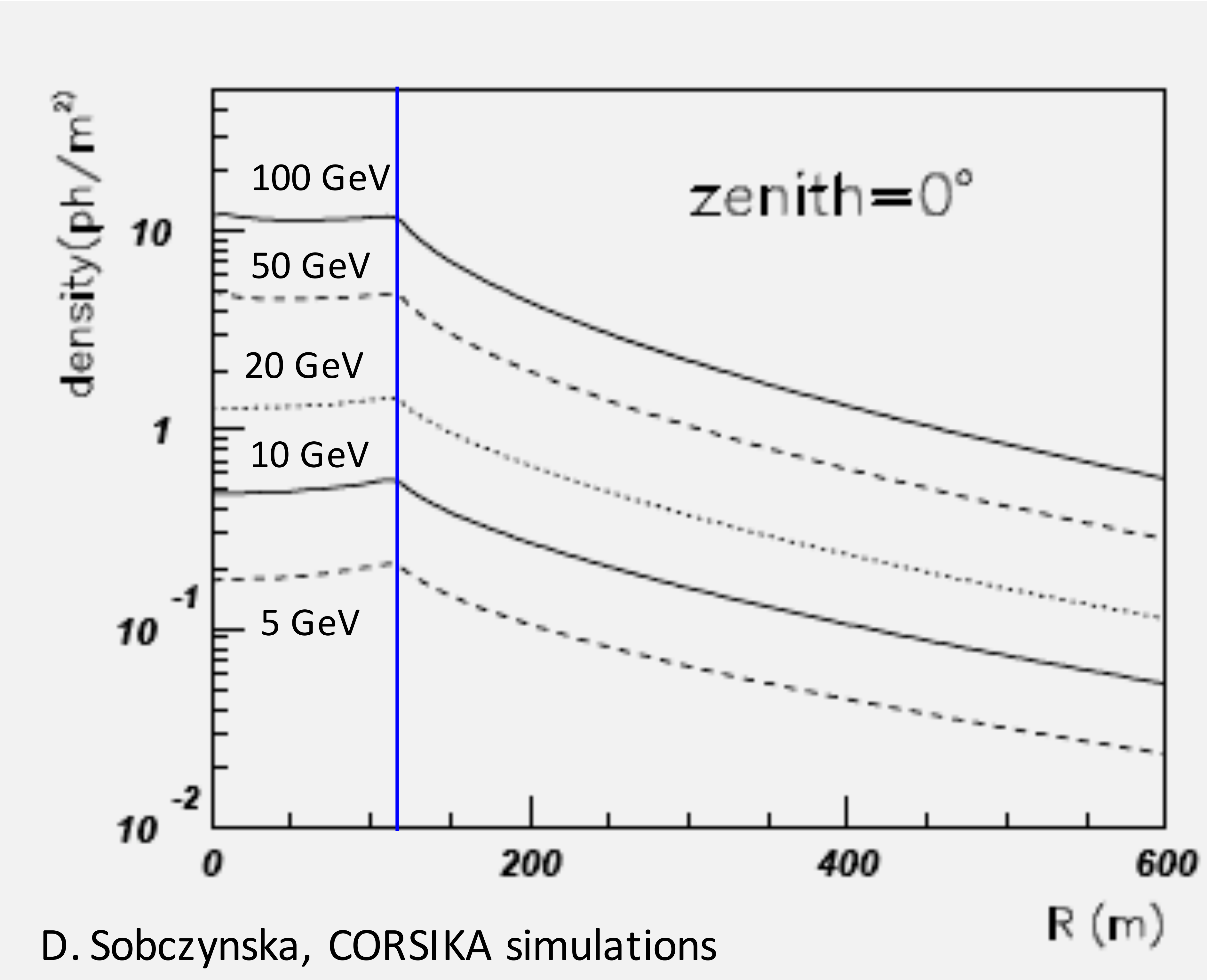
- Emitted whenever a charged particle traverses a medium at a speed larger than that of light in the medium
- The radiation results from the reorientation of electric dipoles induced by the charge in the medium. When $v > c/n$ the contributions from different points of the trajectory arrive in phase at the observer as a narrow light pulse



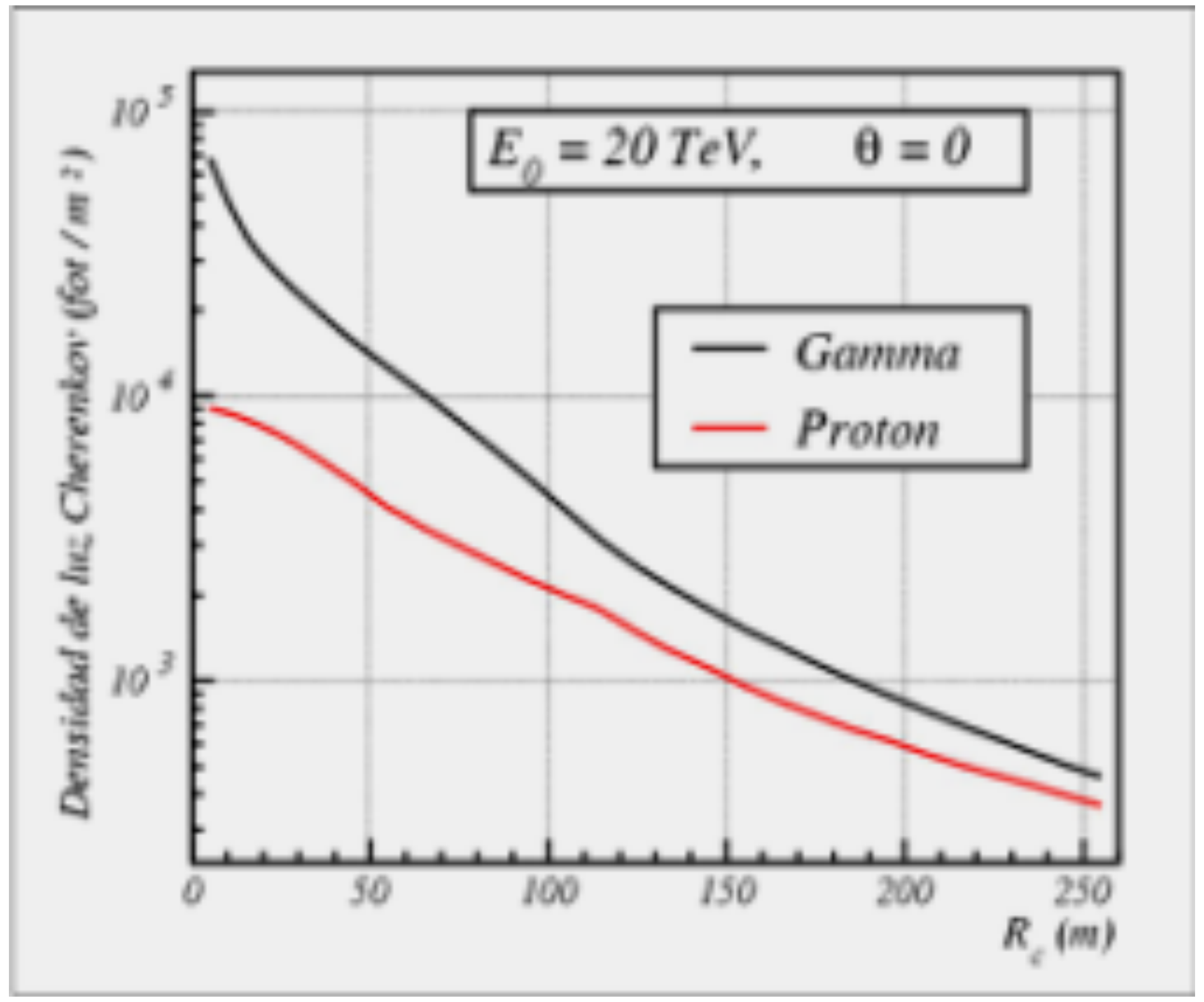
Gamma-ray detection

Cherenkov radiation

If $e^{\pm}$ shower extinguishes before reaching observation level (E< a few TeV) : Plateau up to the hump, then fast drop



Else, C-light density is maximum at shower core and drops exponentially with R



Note above: for a given E_0, a γ-ray produces far less light than a hadron!

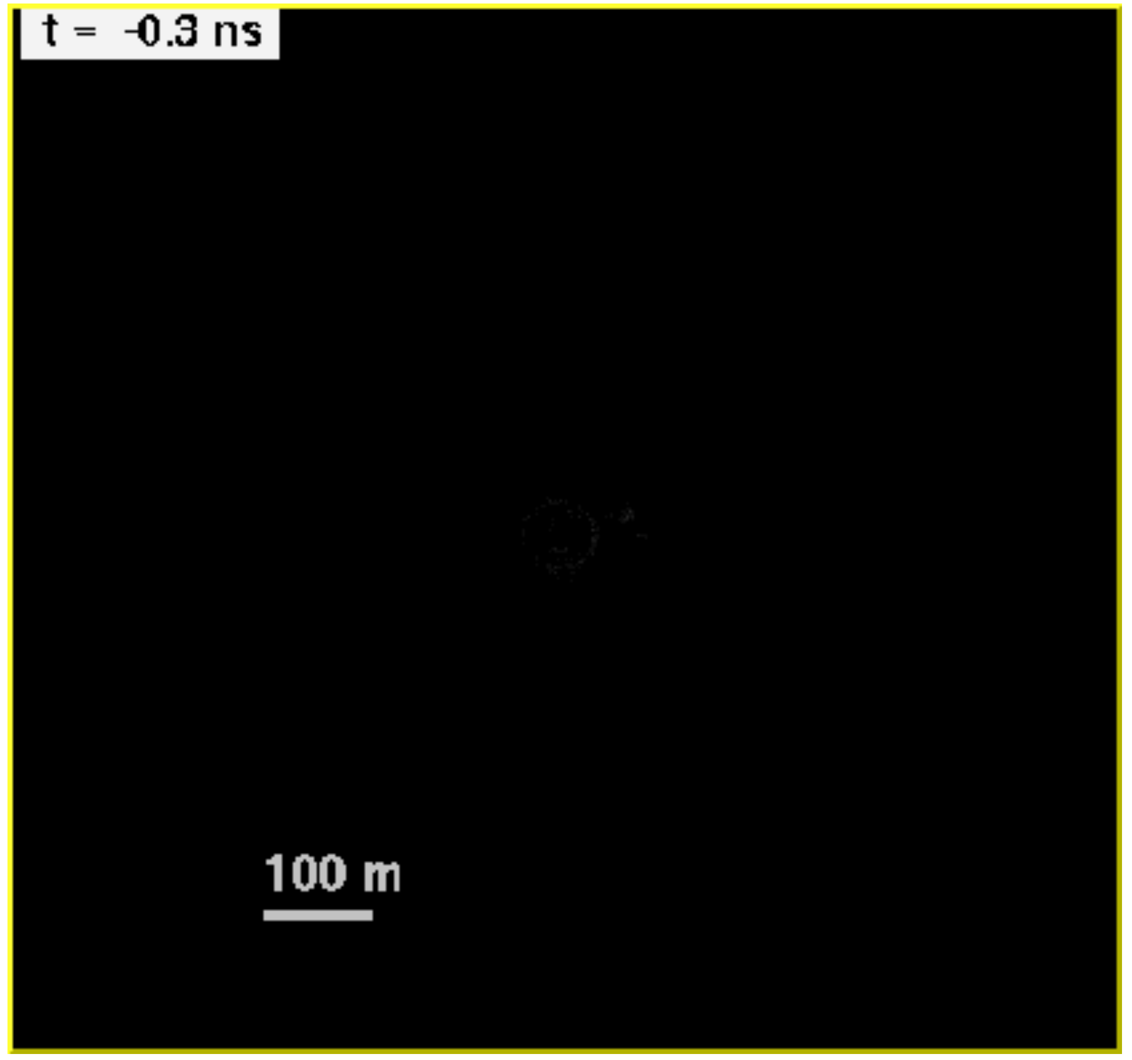
Gamma-ray detection

Cherenkov radiation

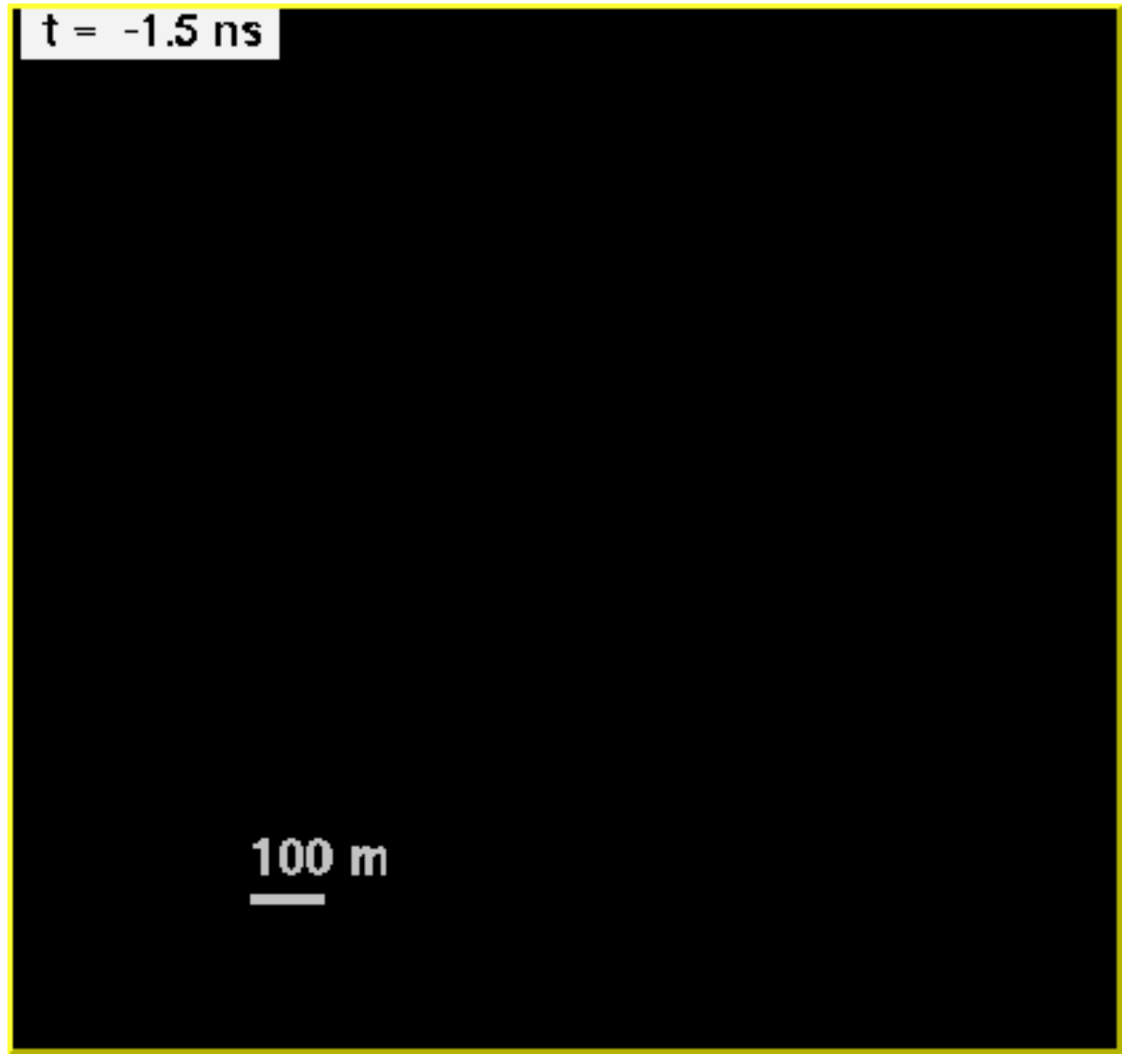
Arrival of Cherenkov light on the ground

- Good news: the effects of the interaction of a VHE g-ray in the atmosphere are spread over a large area on the ground
  => very large effective areas are achievable
  => VHE g-ray astronomy is feasible despite the low fluxes

Gamma 100 GeV



Proton 200 GeV



CORSIKA simulation, A. Moralejo

- Problem: CR showers are more numerous and represent an isotropic background

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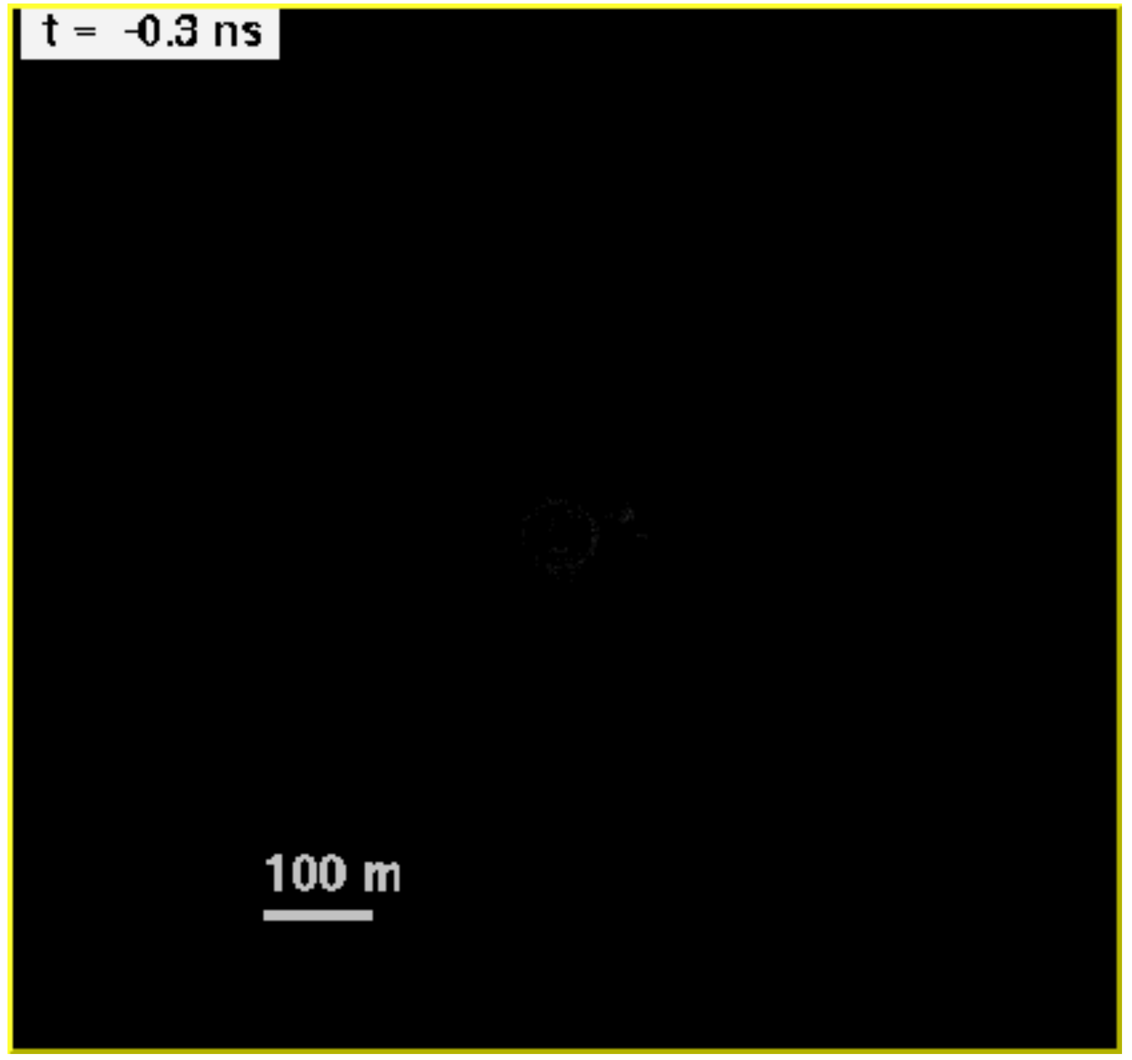

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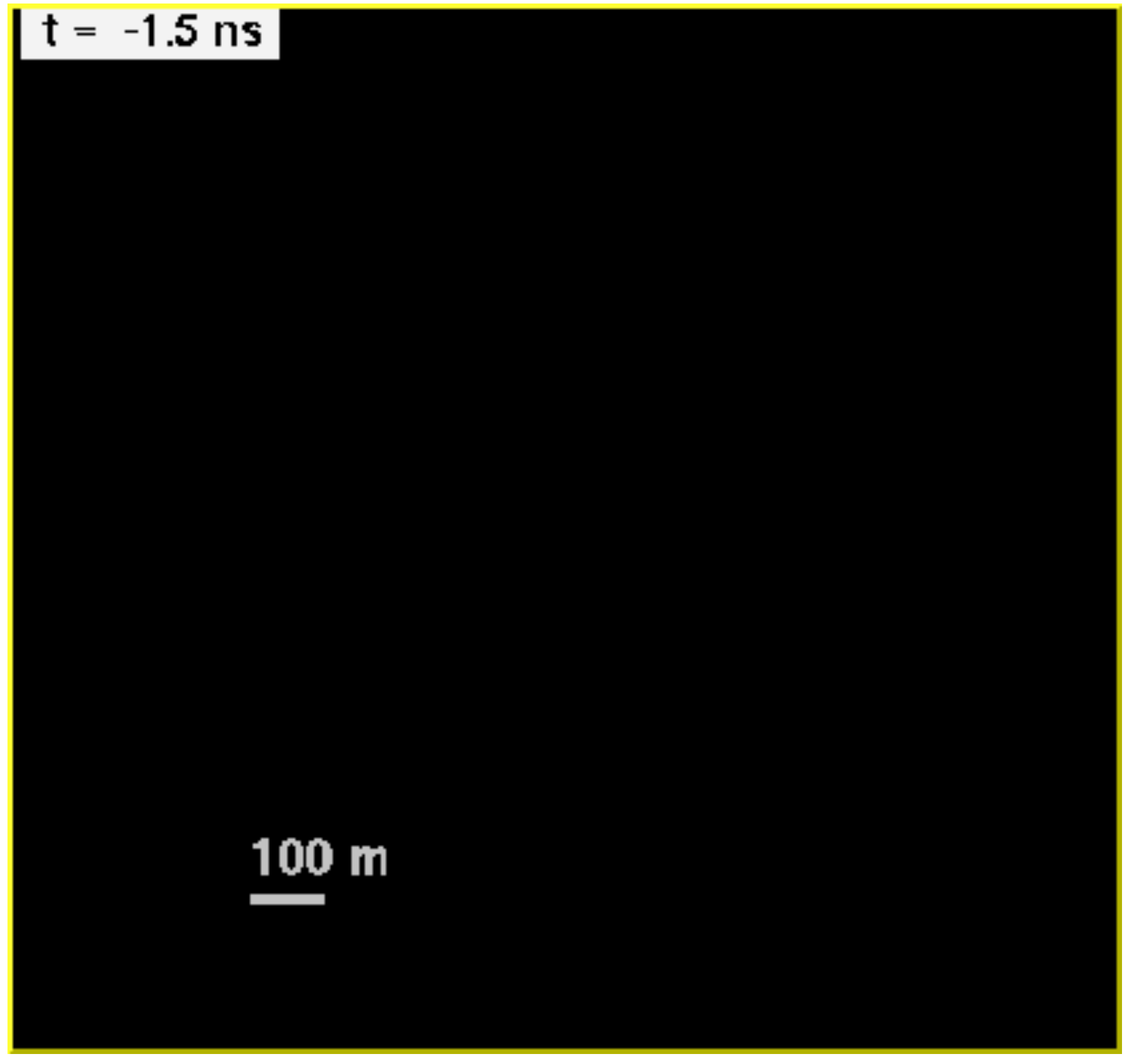

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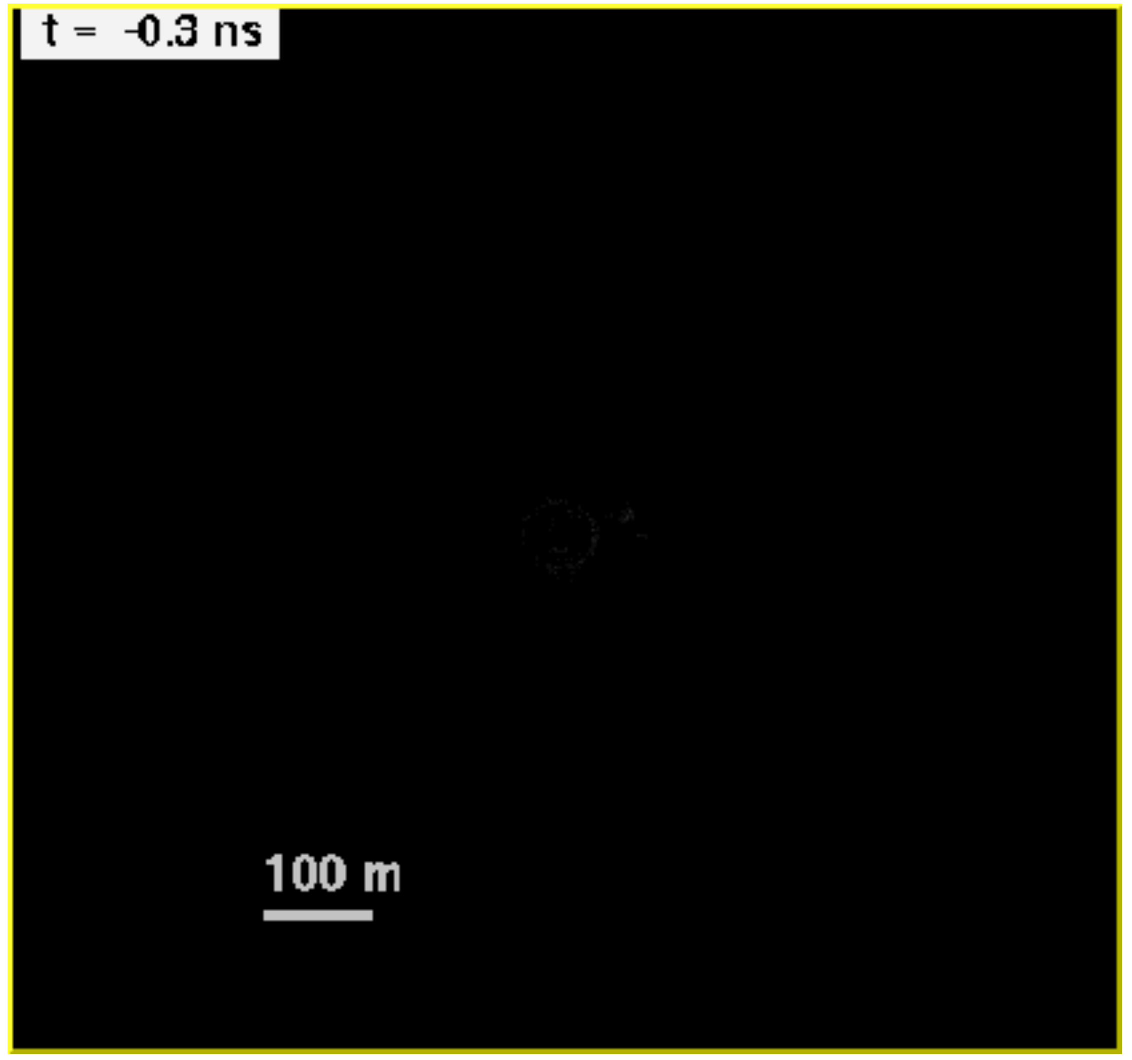

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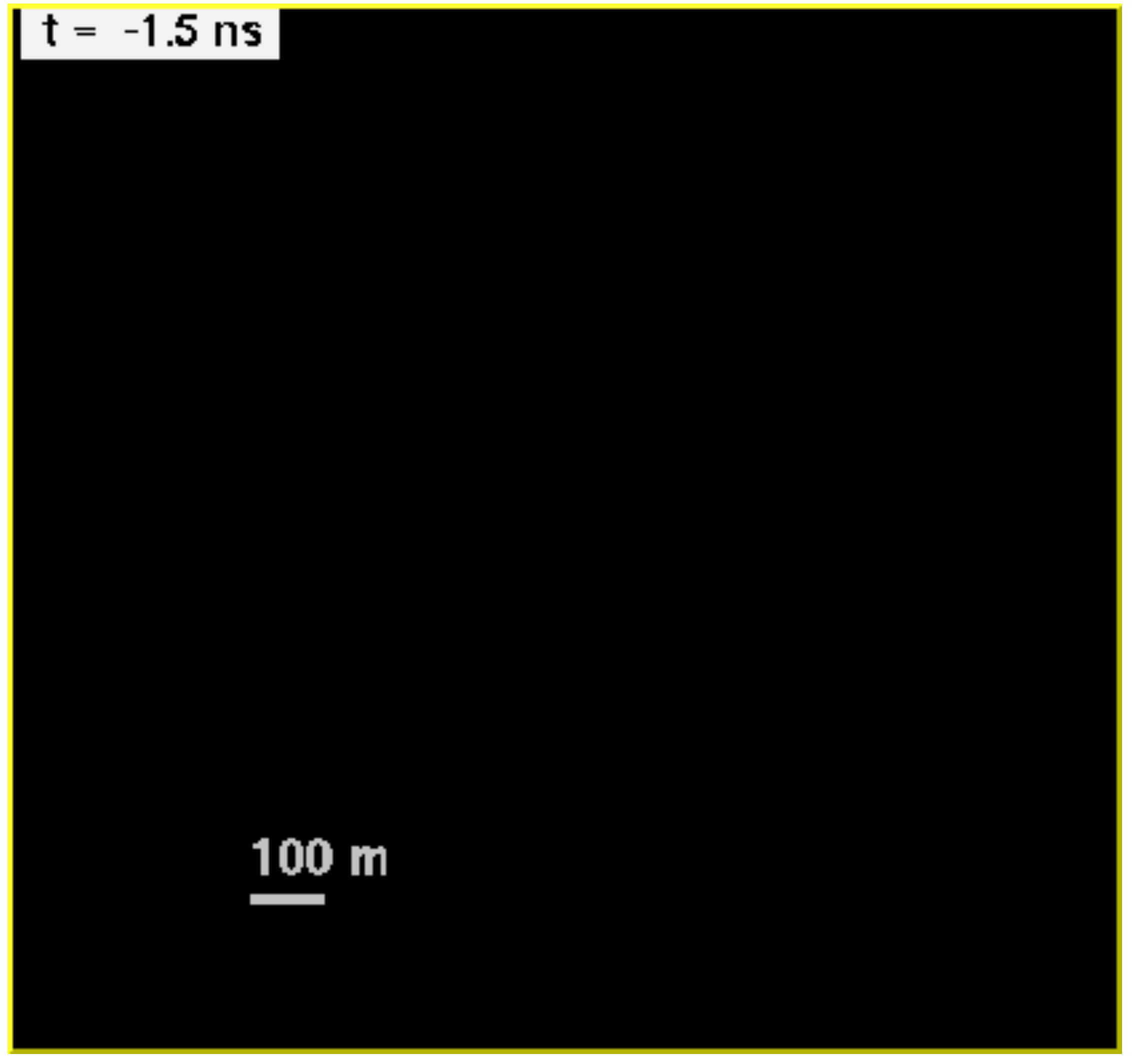


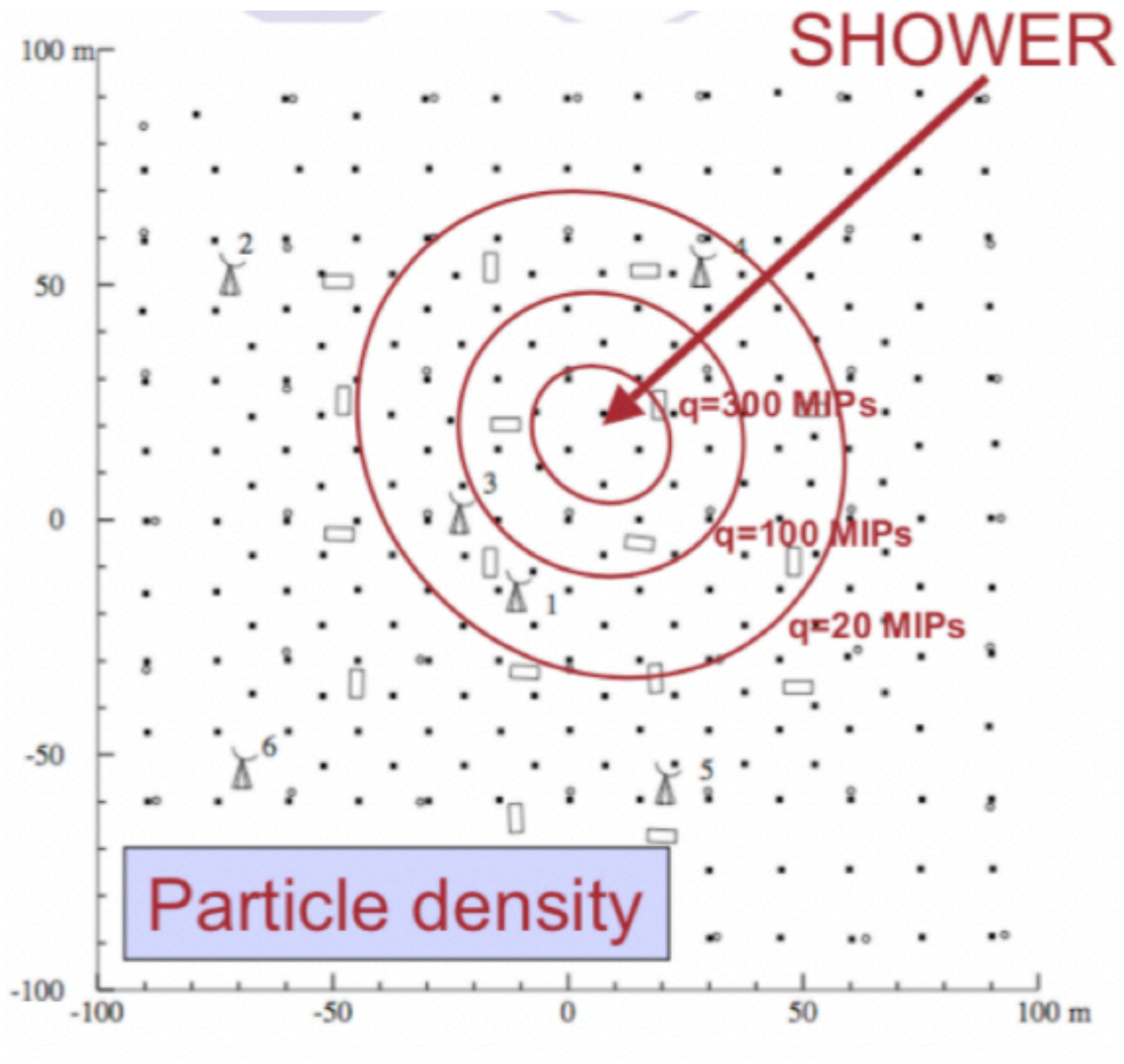
CORSIKA simulation, A. Moralejo

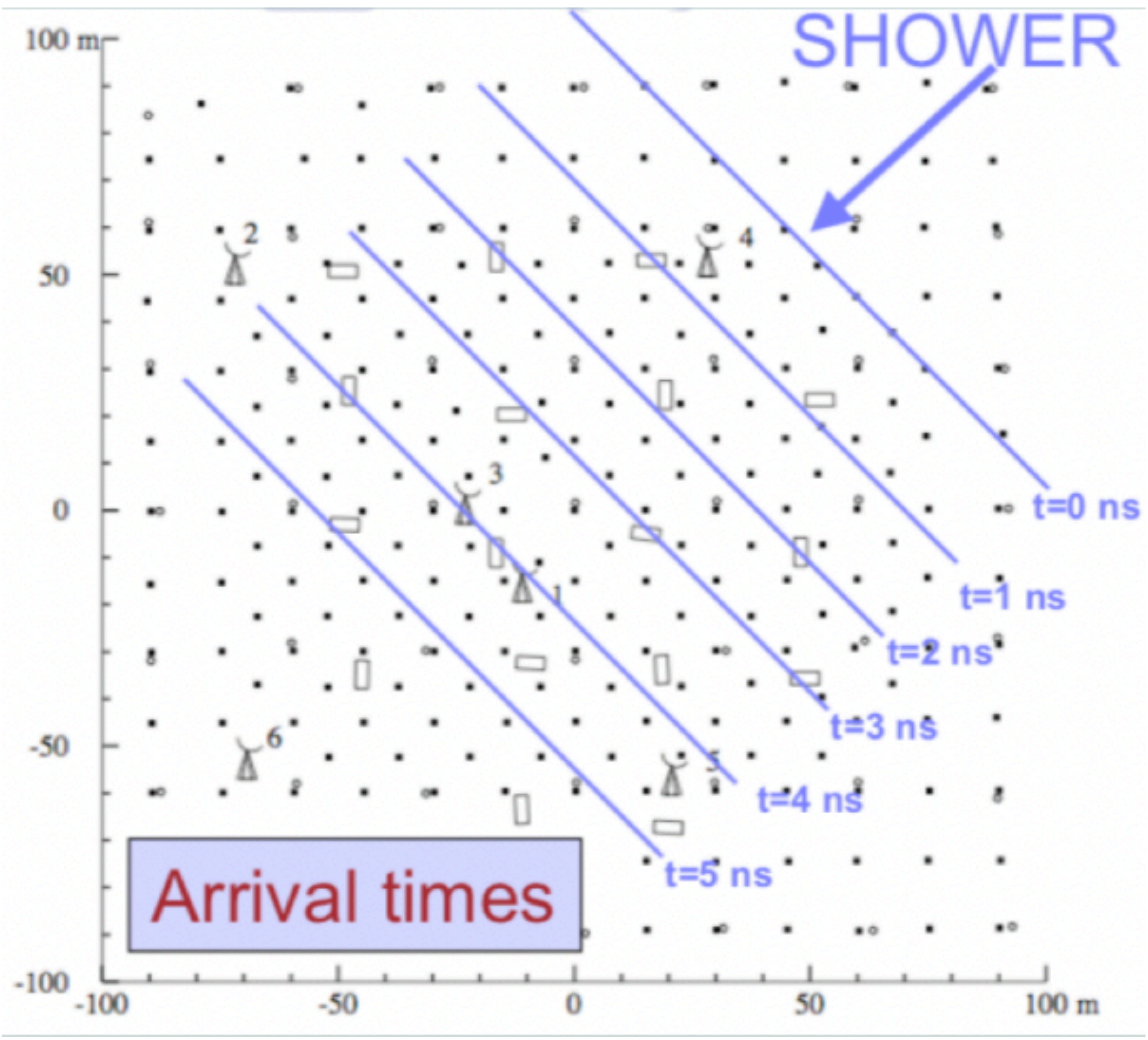
- Problem: CR showers are more numerous and represent an isotropic background

Gamma-ray detection

Arrays of particle detectors

- Detectors sample the tail of atmospheric shower that reaches the ground.
- Available information: particle density and arrival time at each detector position.





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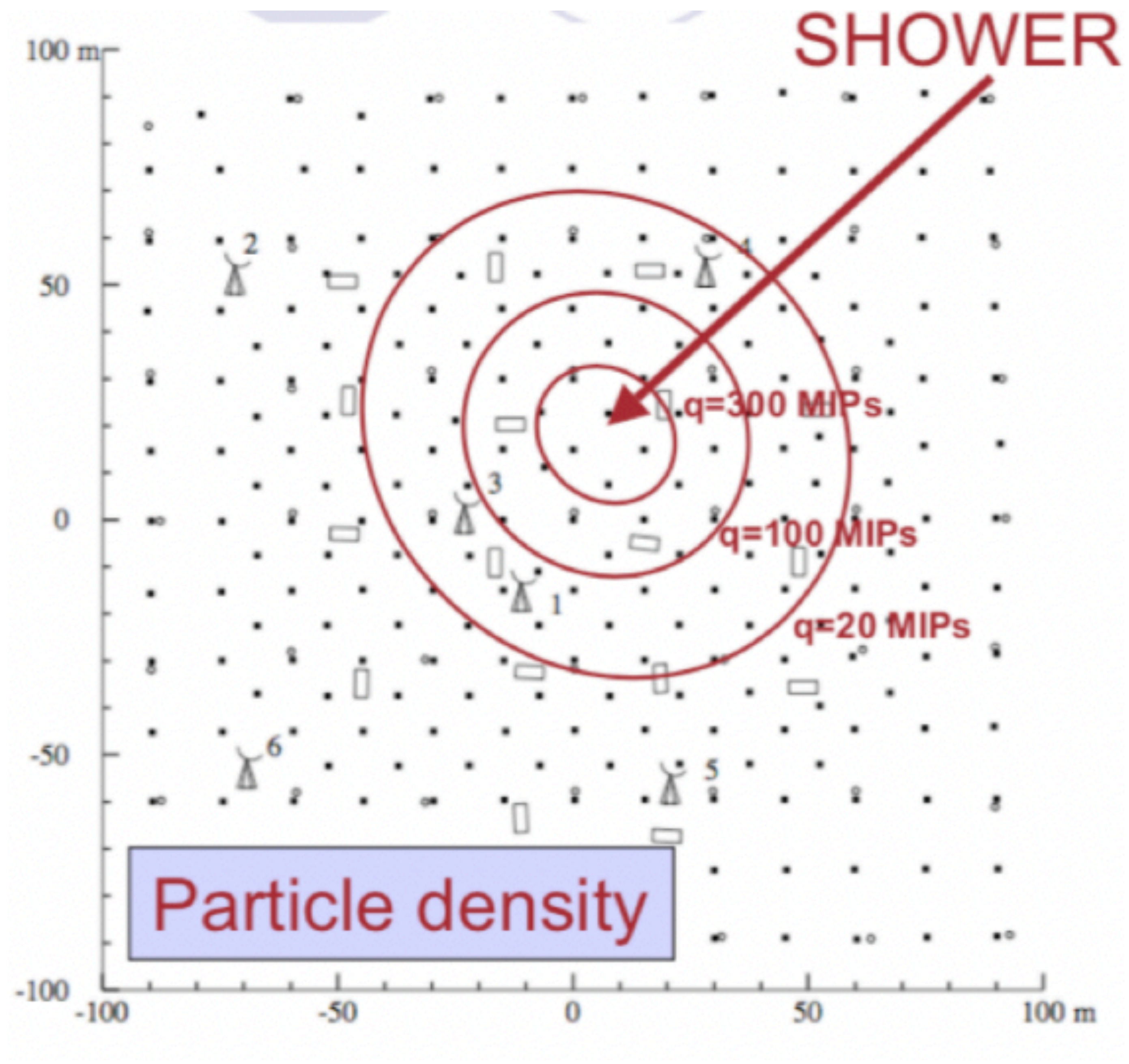
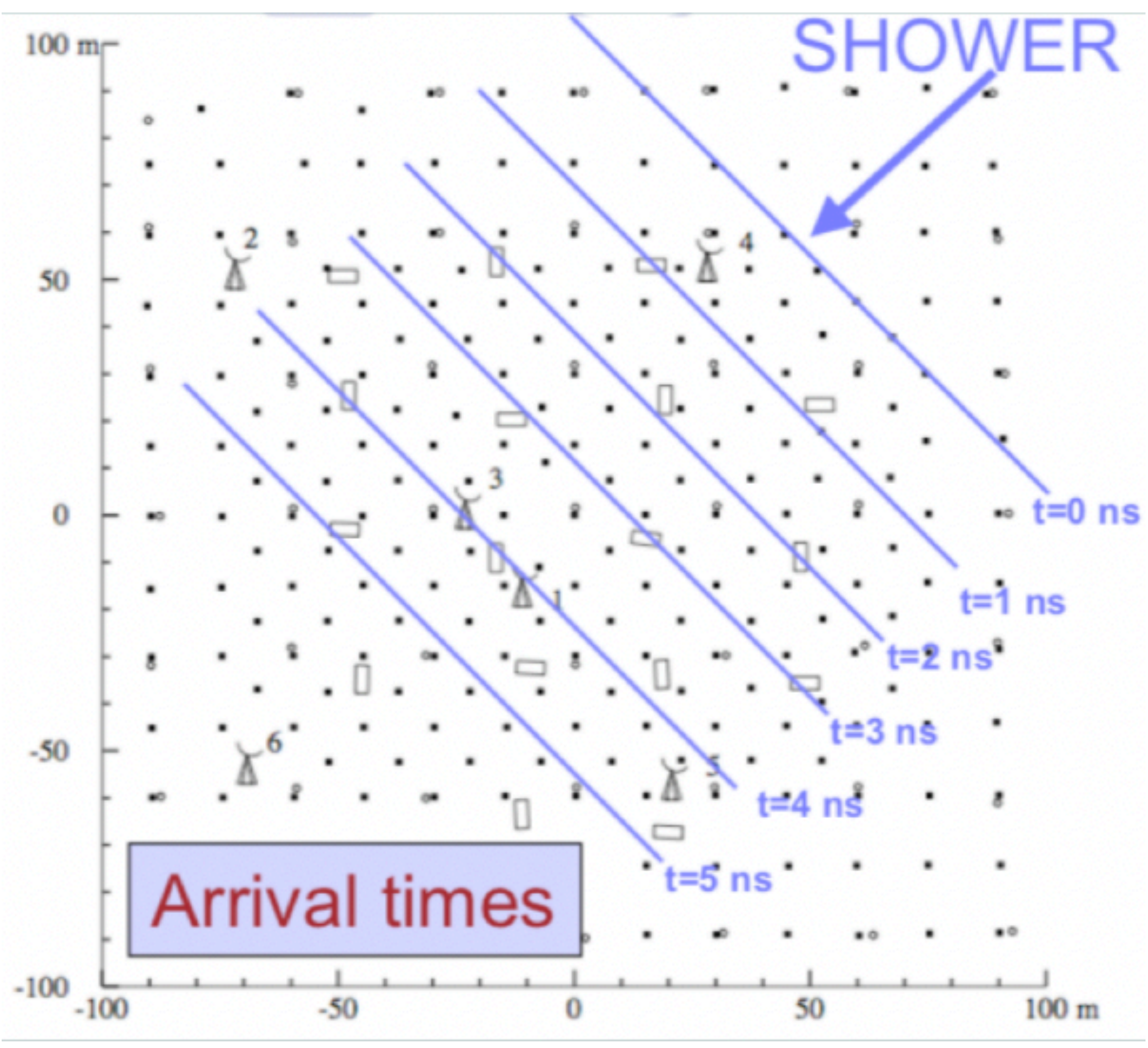




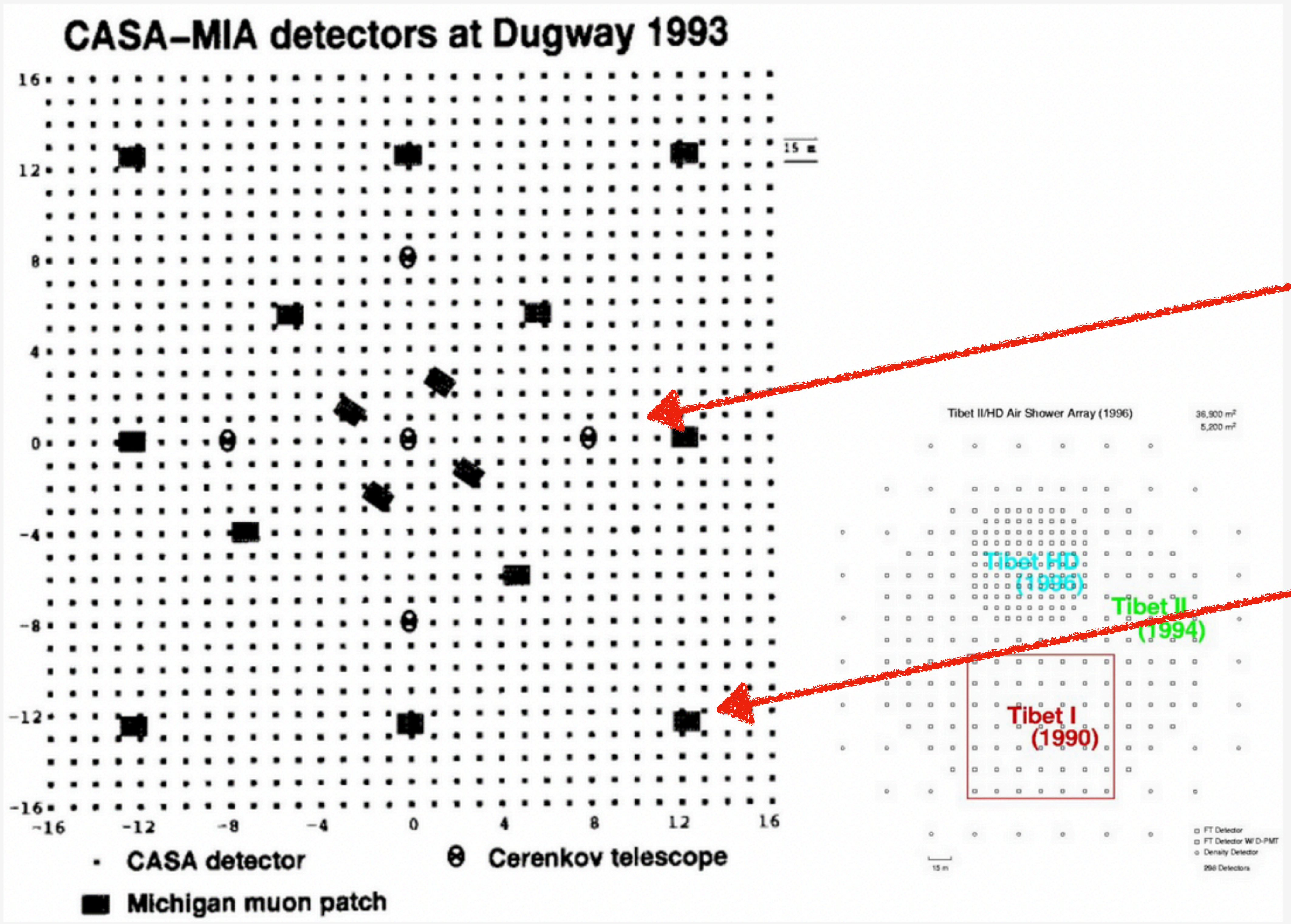
- Angular and energy resolutions are limited: we are only sampling the tail.
- g-hadron separation possible through density inhomogeneities in CR showers, specially “muon tagging.”
- Duty cycle 100%: operate day and night.
- Large FOV: several srad.

Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both)

Figure 1. Schematic of layouts of the CASA-MIA array and AS$_\gamma$ in phases before 2002.



- Threshold (CASA-MIA/1600 m) ~ 0.1 PeV
- Threshold (ASg / 4300 m) ~ 10 TeV

Cherenkov telescopes

Muon detectors

Gamma-ray detection

Arrays of particle detectors

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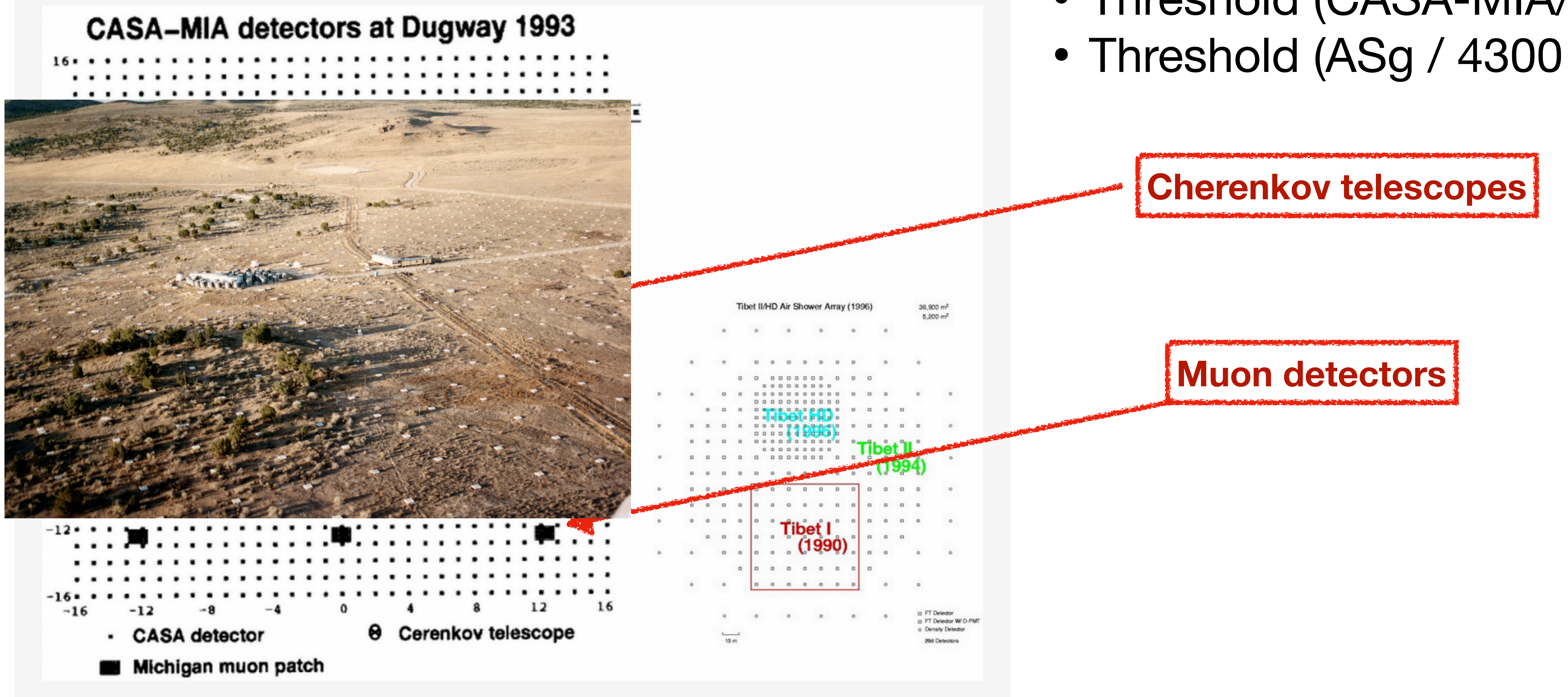

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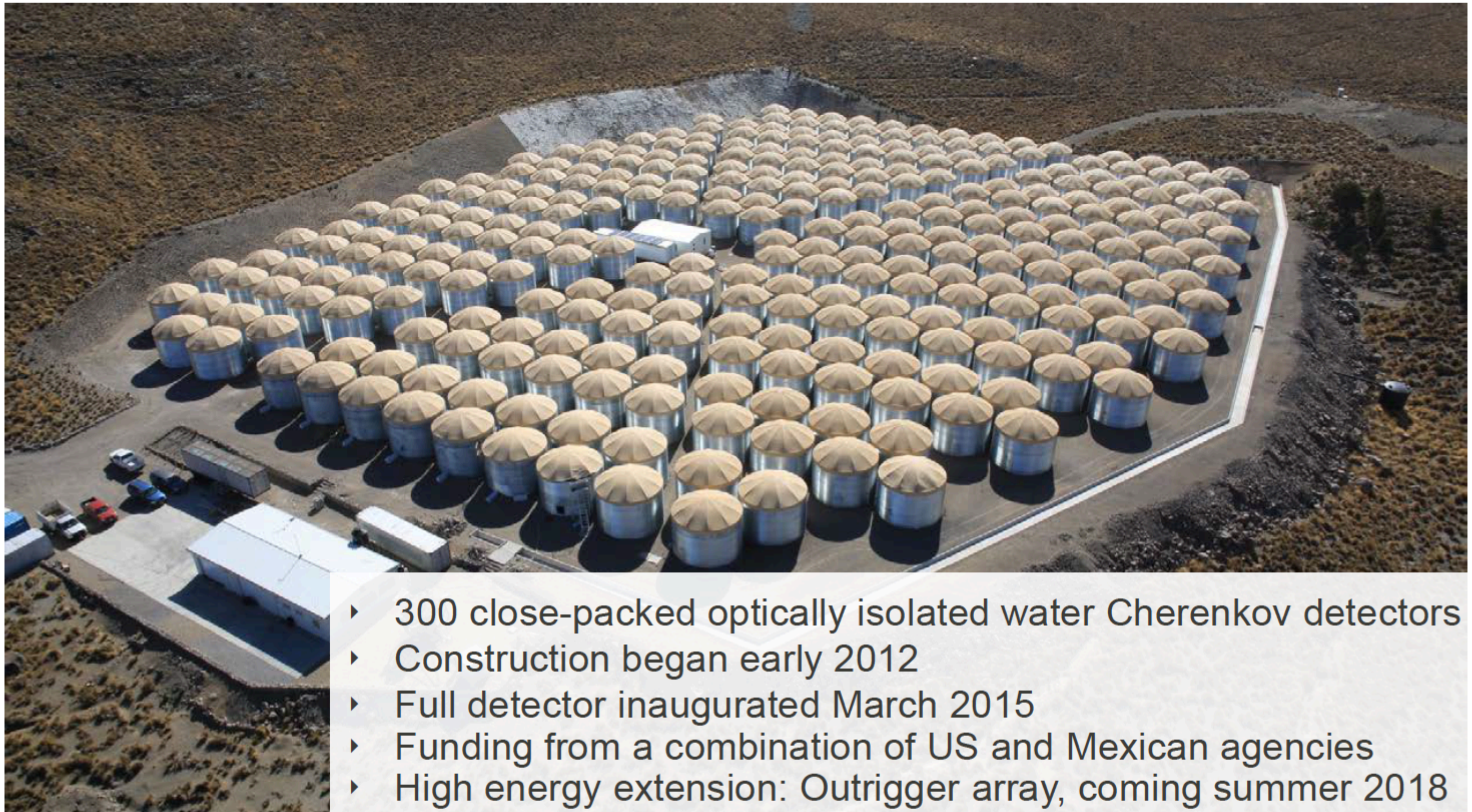
Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both): HAWC



Gamma-ray detection

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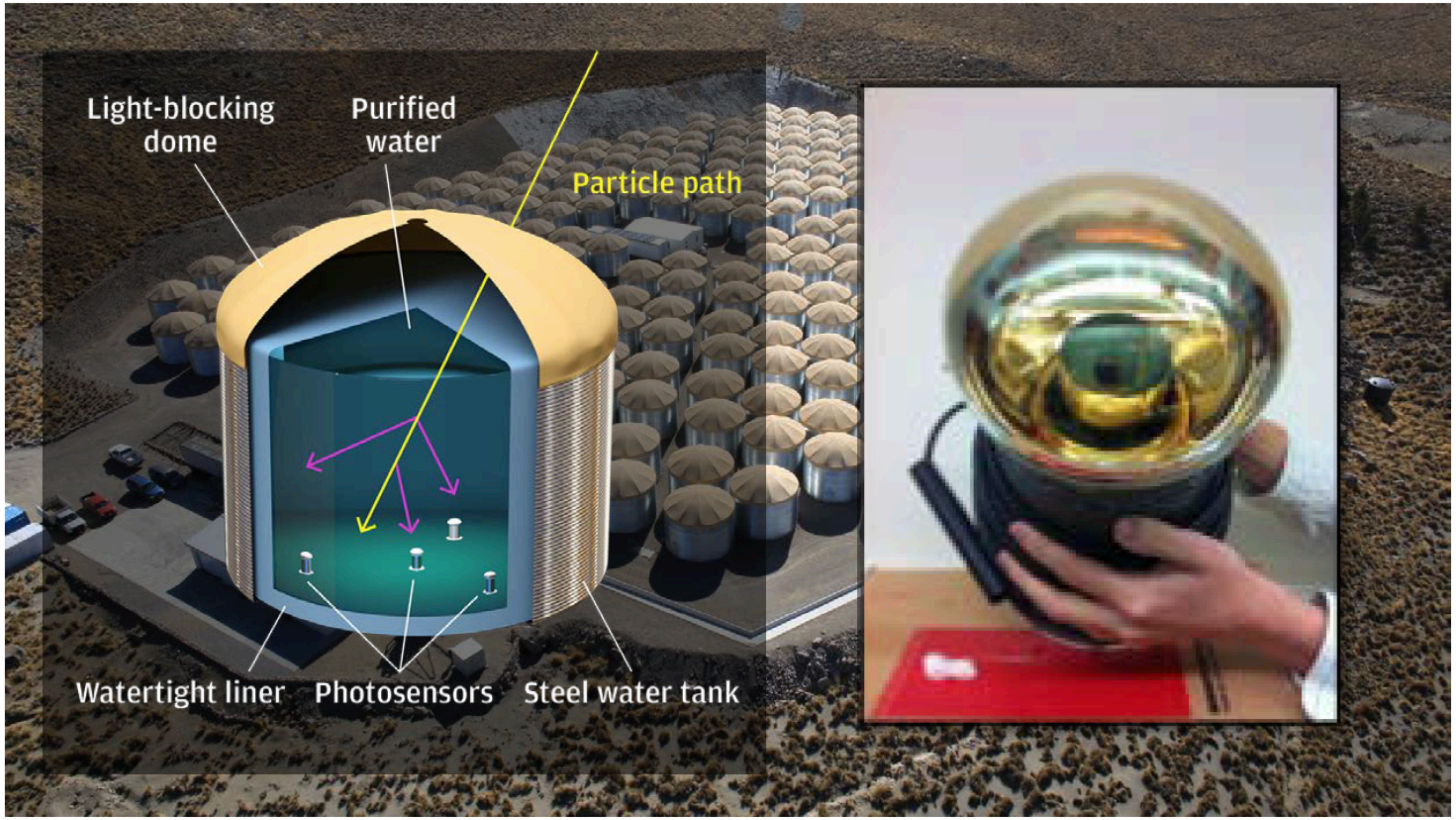

Gamma-ray detection

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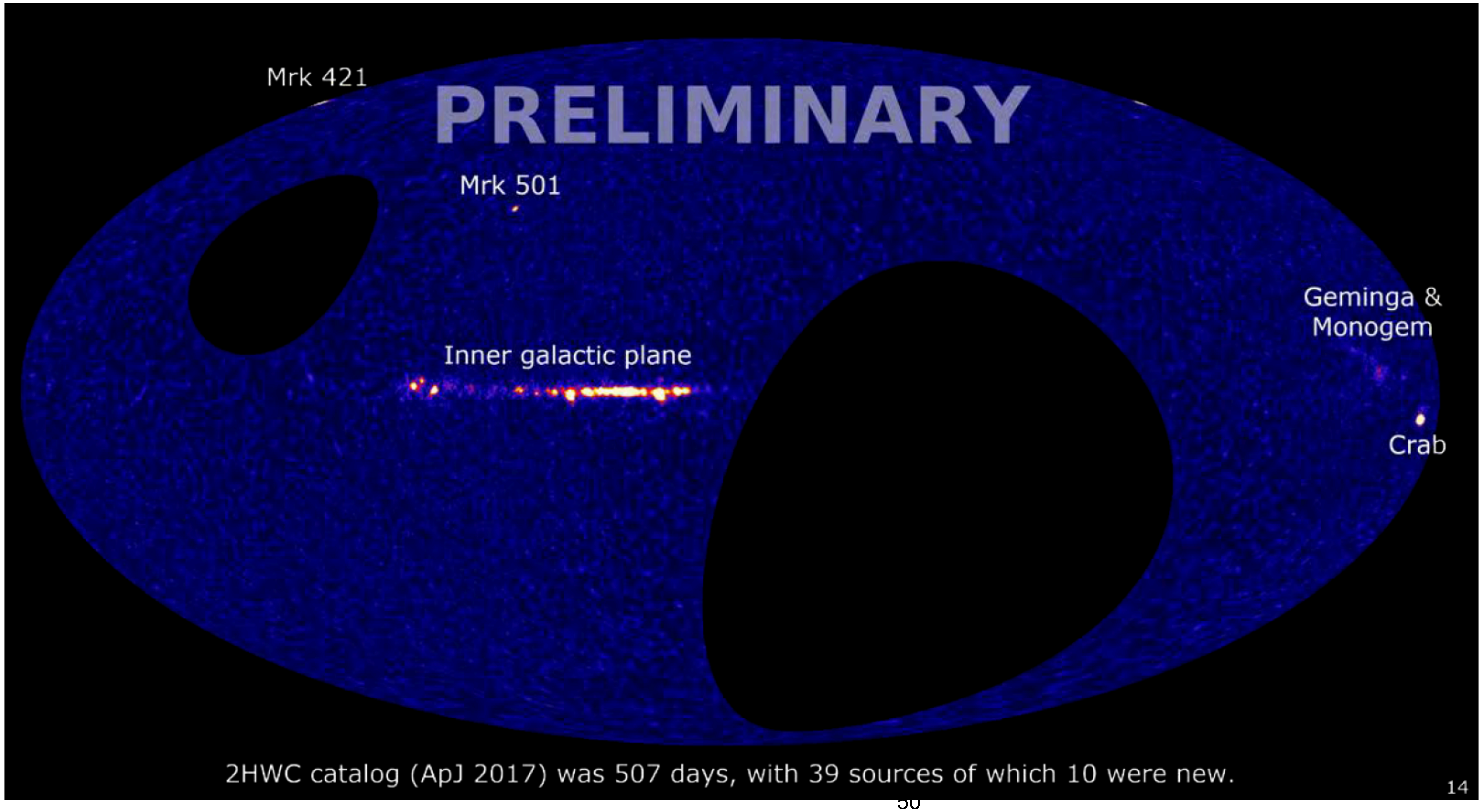
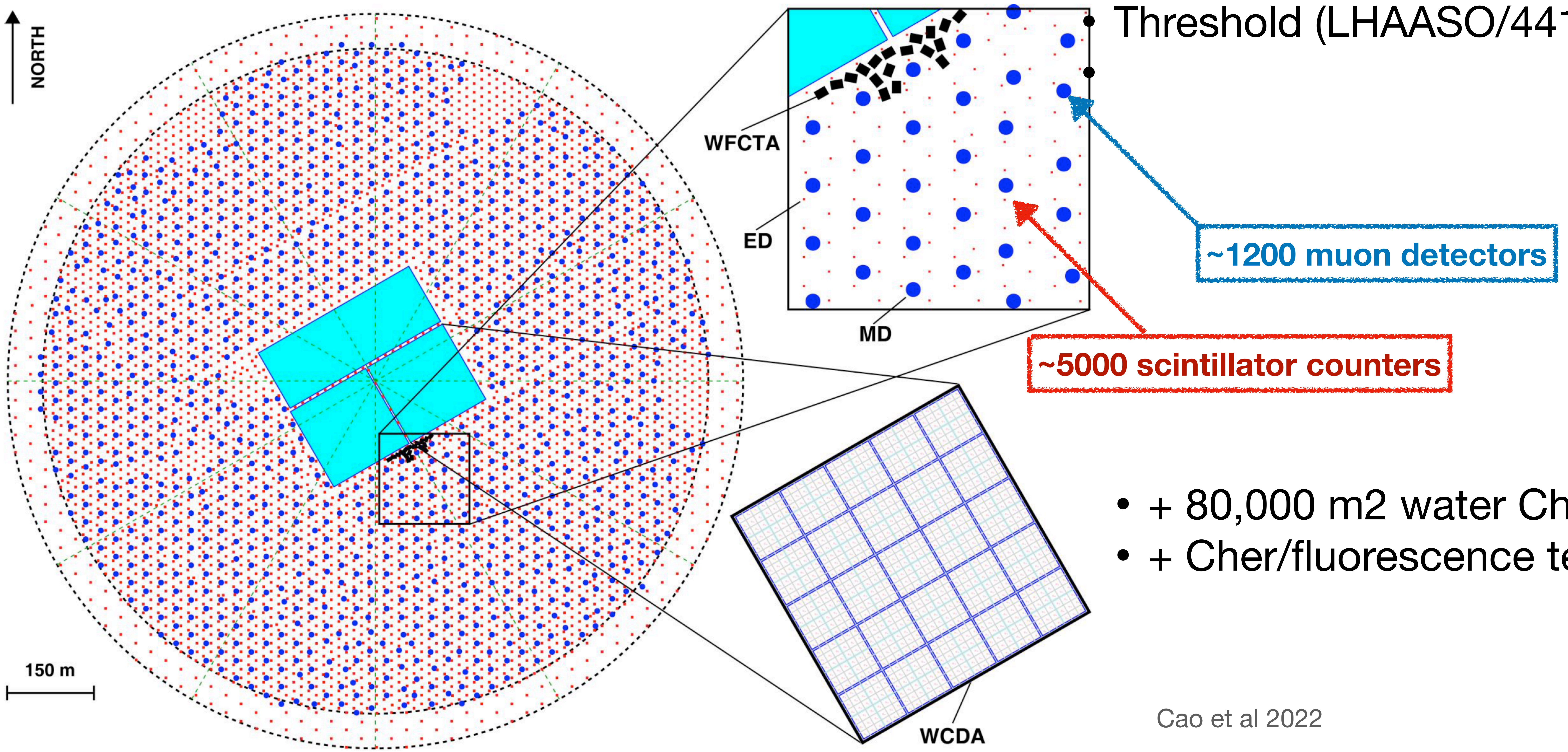


Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both) : **LHAASO**



- Threshold (LHAASO/4410 m) ~ 30 TeV
-

- + 80,000 m2 water Cherenkov
- + Cher/fluorescence telescopes

Cao et al 2022

Gamma-ray detection

Arrays of particle detectors

- Particle detectors can be scintillators or water tanks (or both) : **LHAASO**

Threshold (LHAASO/4410 m) ~ 30 TeV

~1200 muon detectors

0 scintillator counters

- + 80,000 m2 water Cherenkov
- + Cher/fluorescence telescopes

Cao et al 2022

Gamma-ray detection

Arrays of particle detectors

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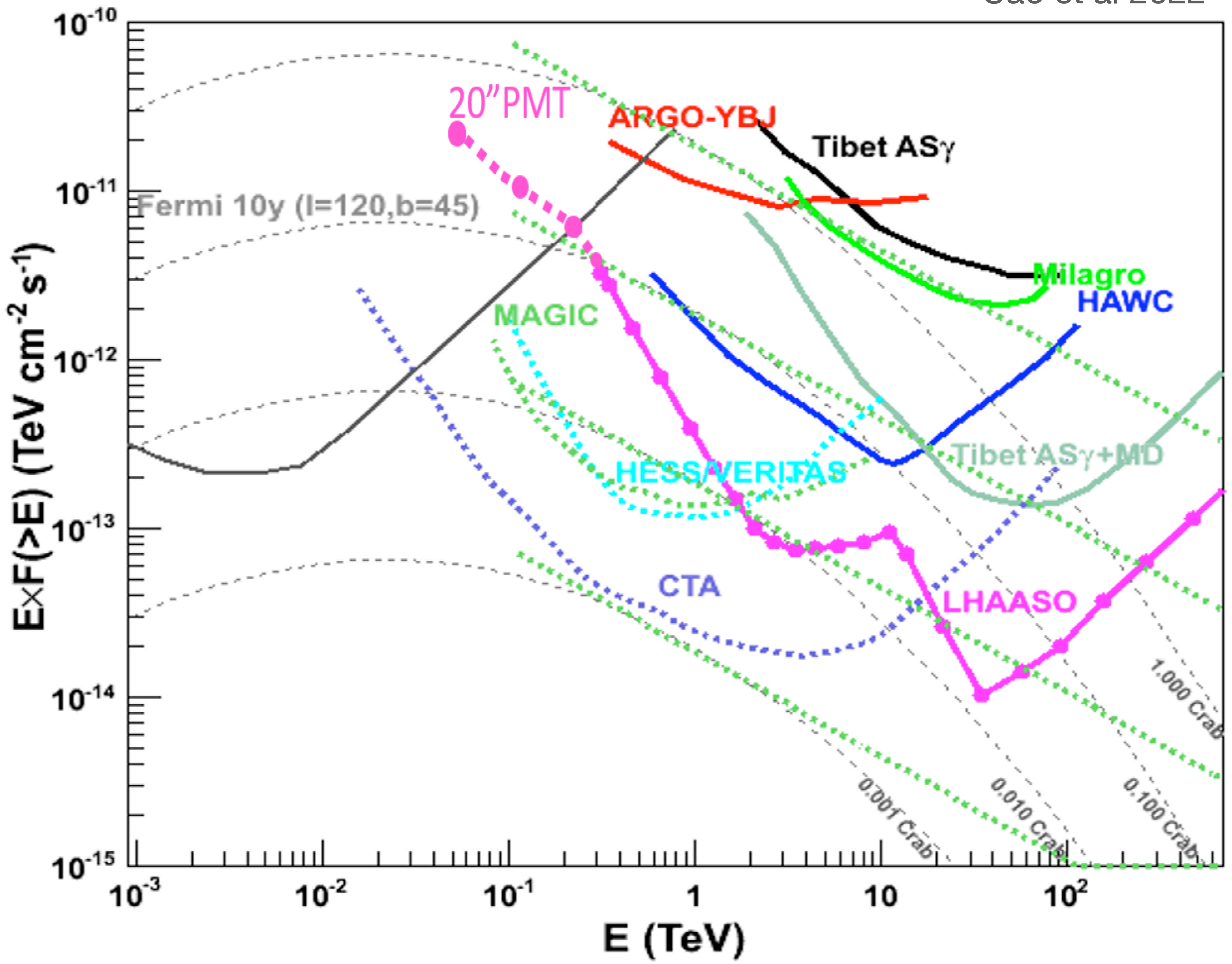
Cao et al 2022



Gamma-ray detection

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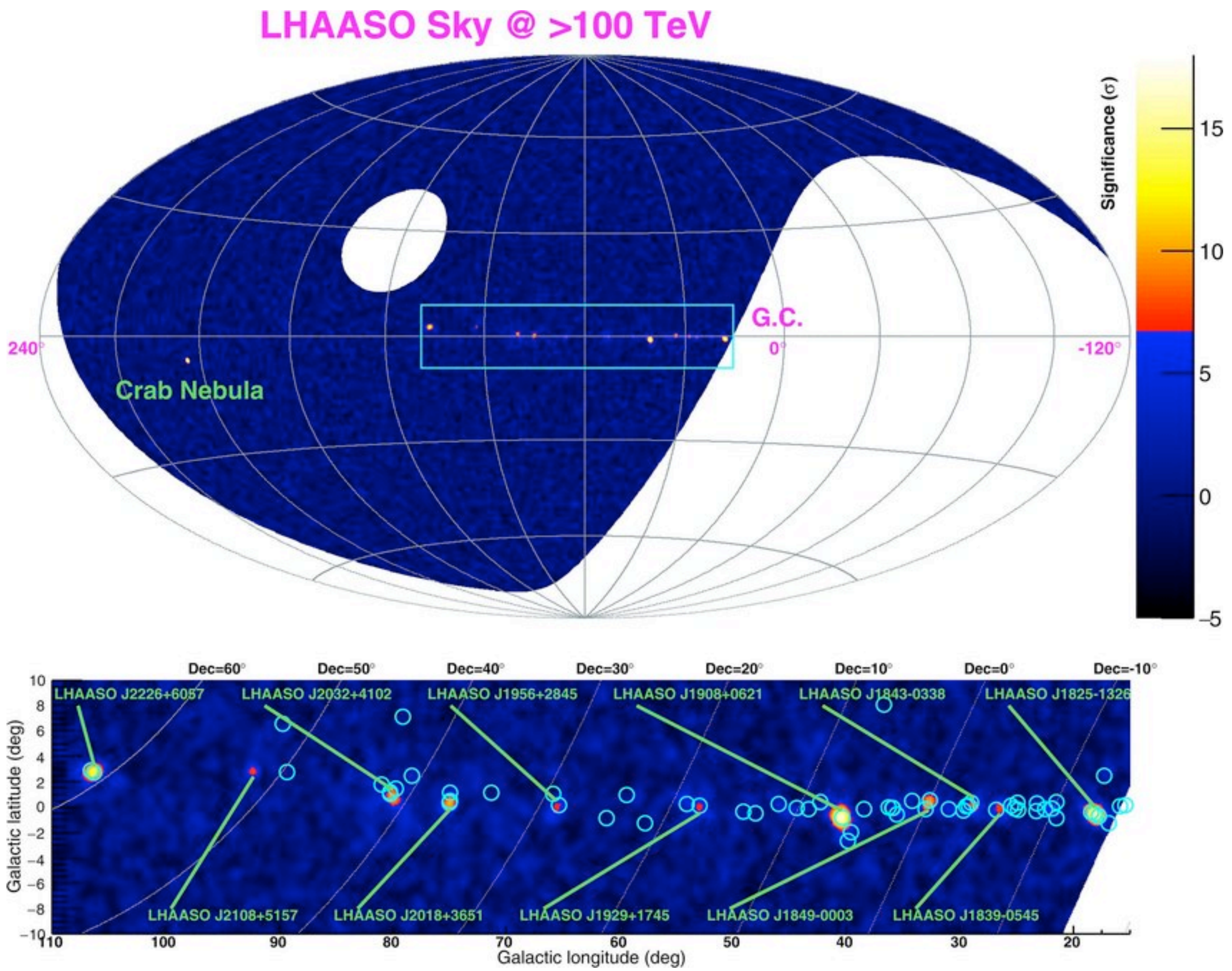
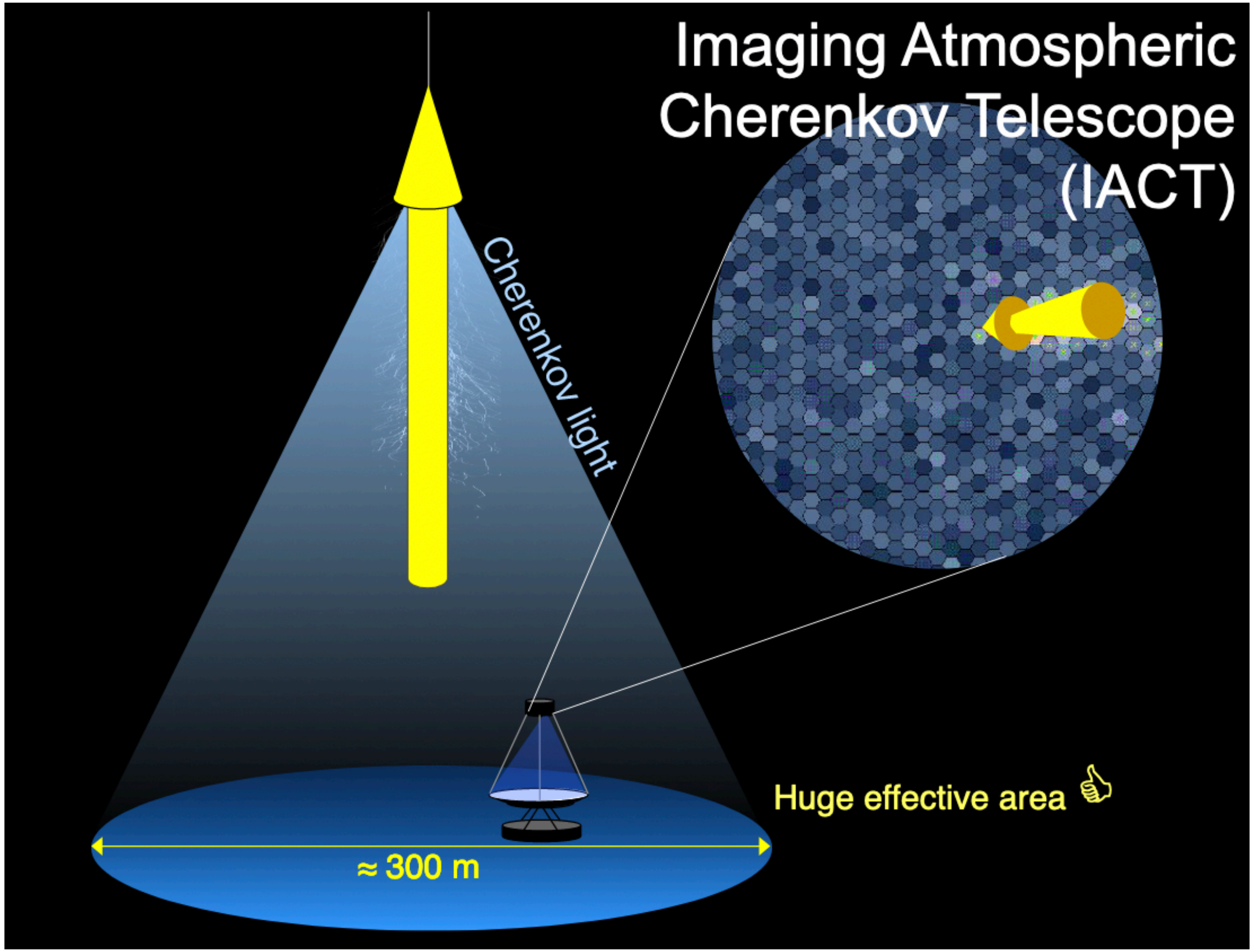
Cao et al 2022



- Even on top of the highest mountains, the number of particles reaching the ground for showers initiated by γ's of E < a few hundred GeV is very small $\Rightarrow$ a different technique is needed for γ astronomy, other than the direct detection of shower particles
- The atmospheric Cherenkov light from EAS can be used for this purpose
- Large photon collection areas are desirable (fainter showers $\Rightarrow$ lower energy threshold)
- Caveat: low duty cycle ≈ 10% (clear, dark nights)

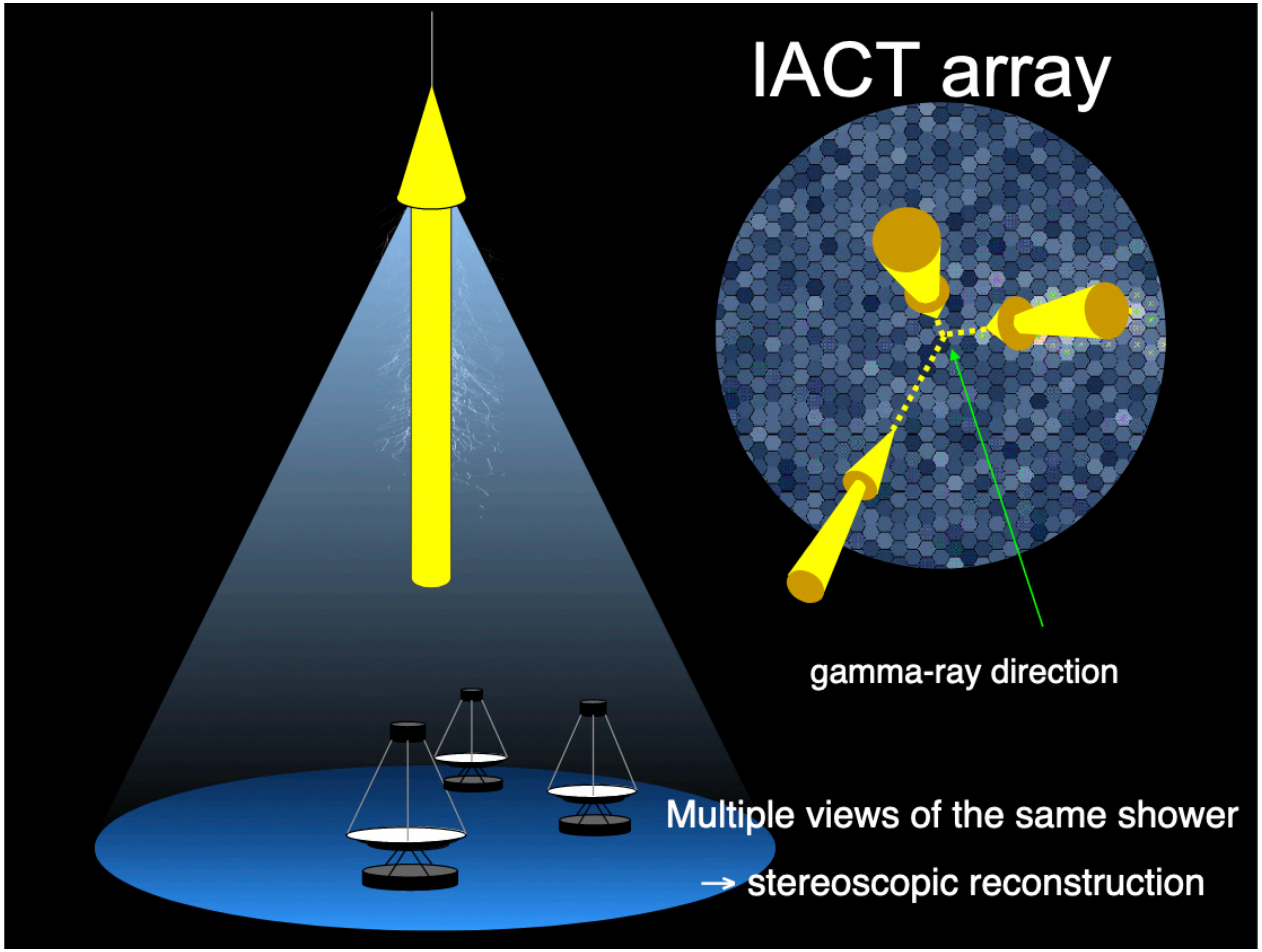
Gamma-ray detection

The Cherenkov Technique



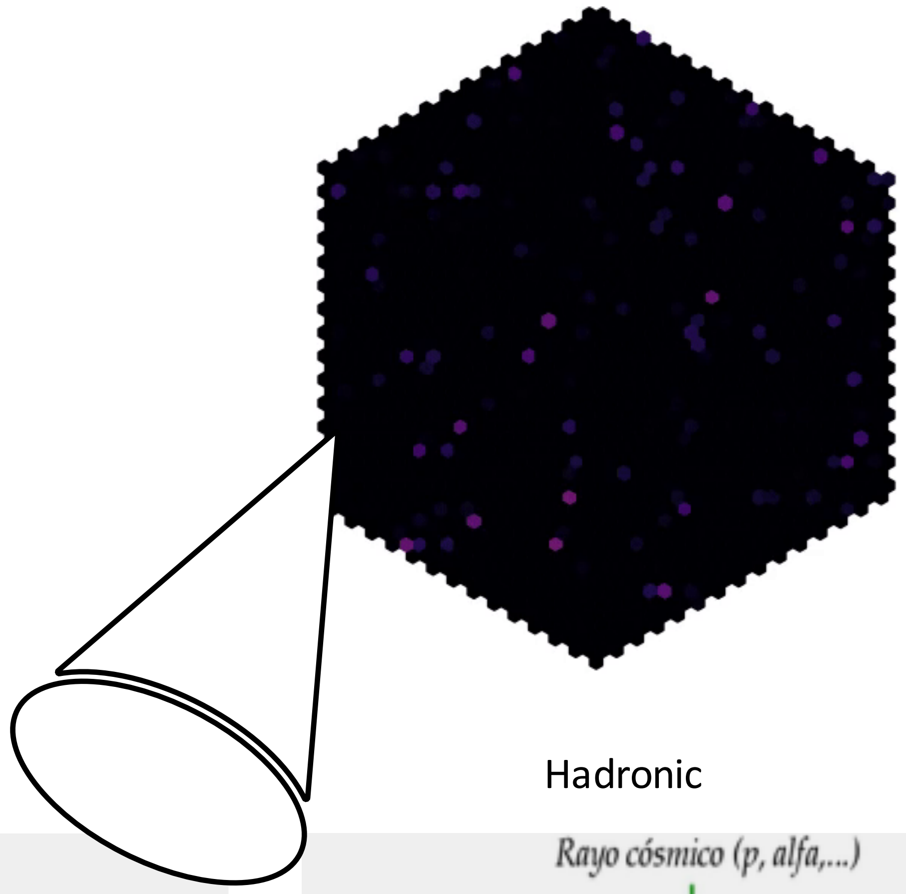
Gamma-ray detection

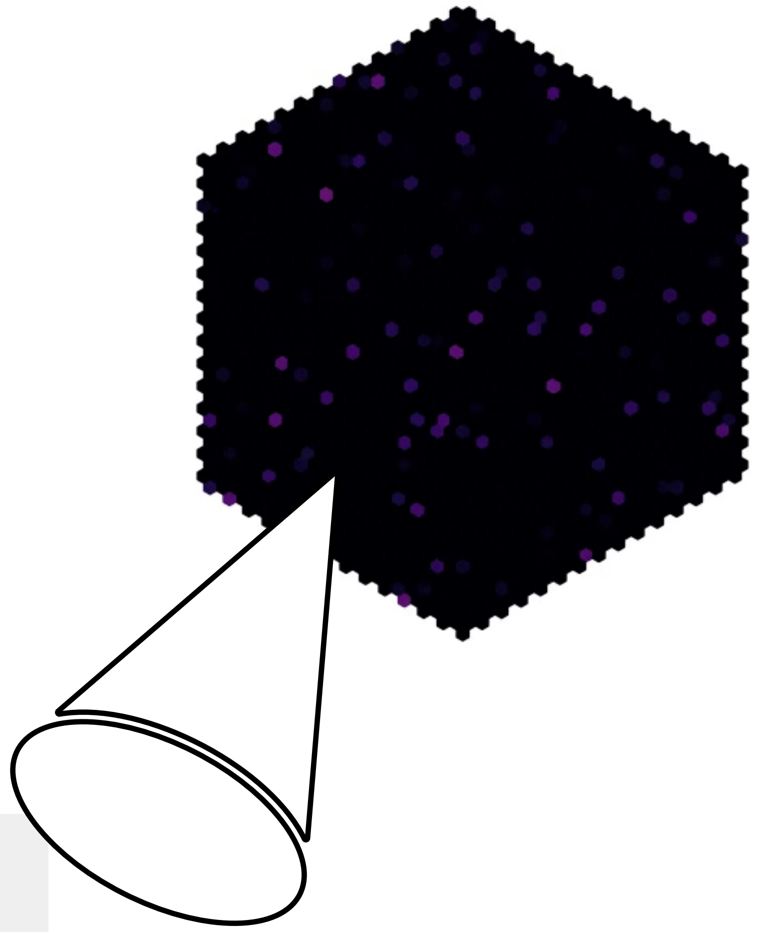
The Cherenkov Technique

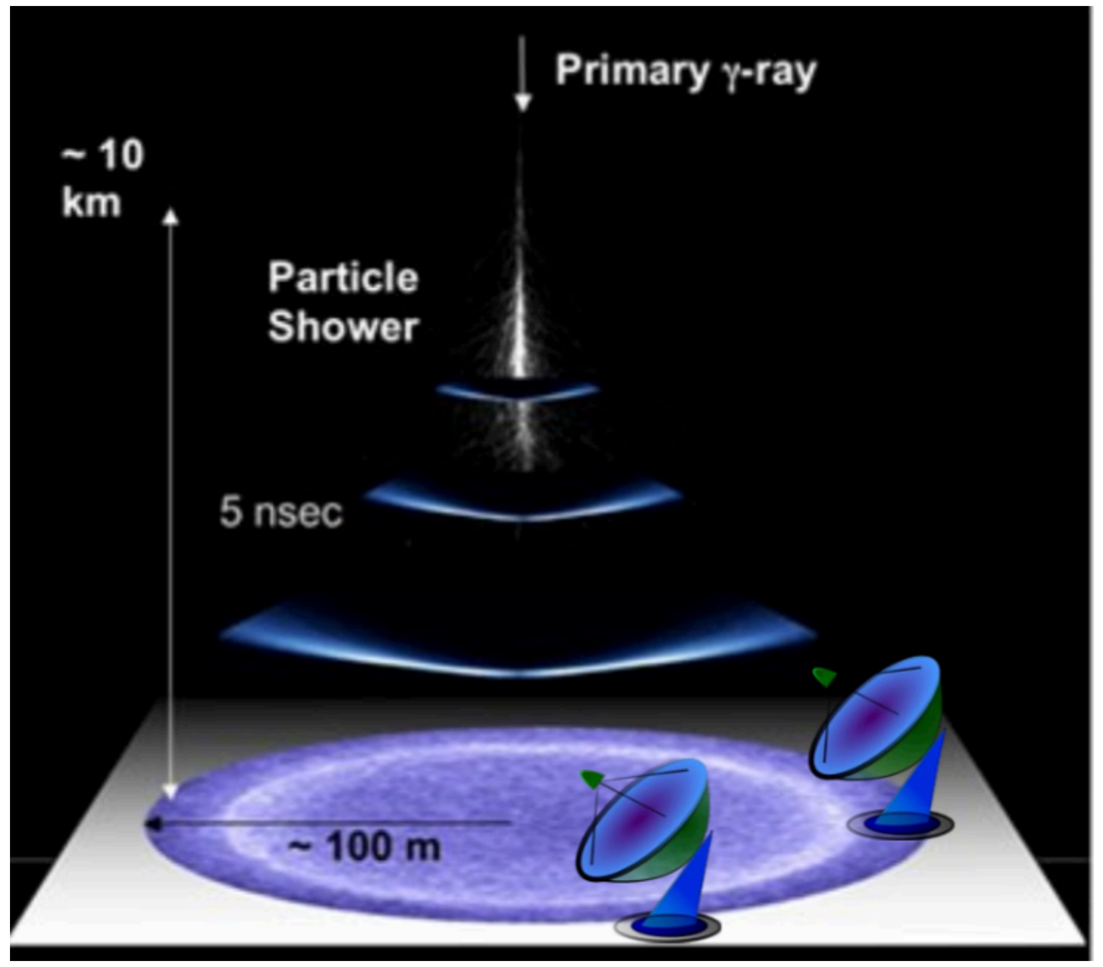


The IACT Technique

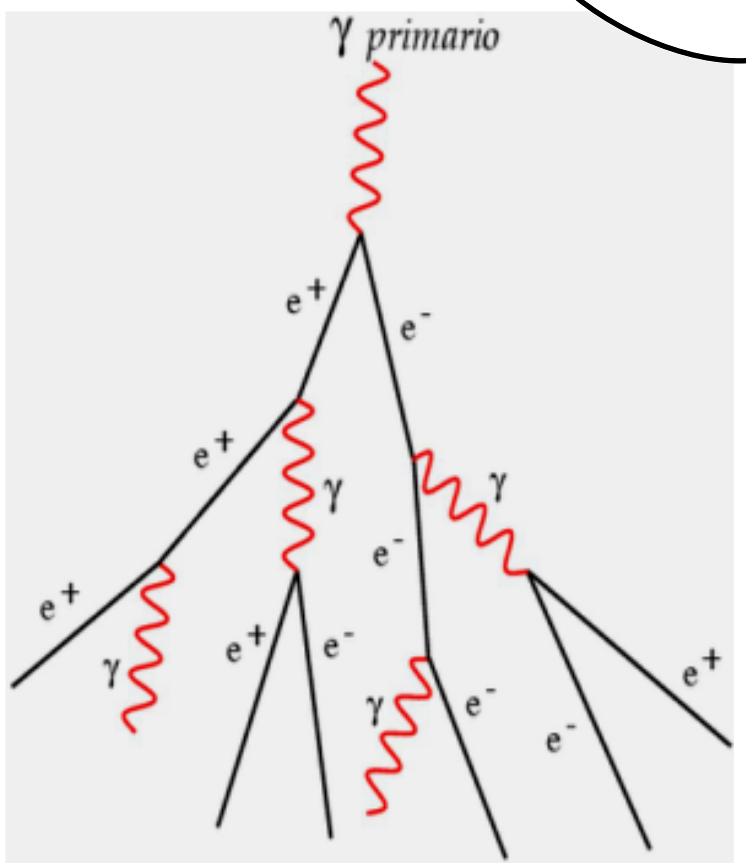
Detecting high energy photons



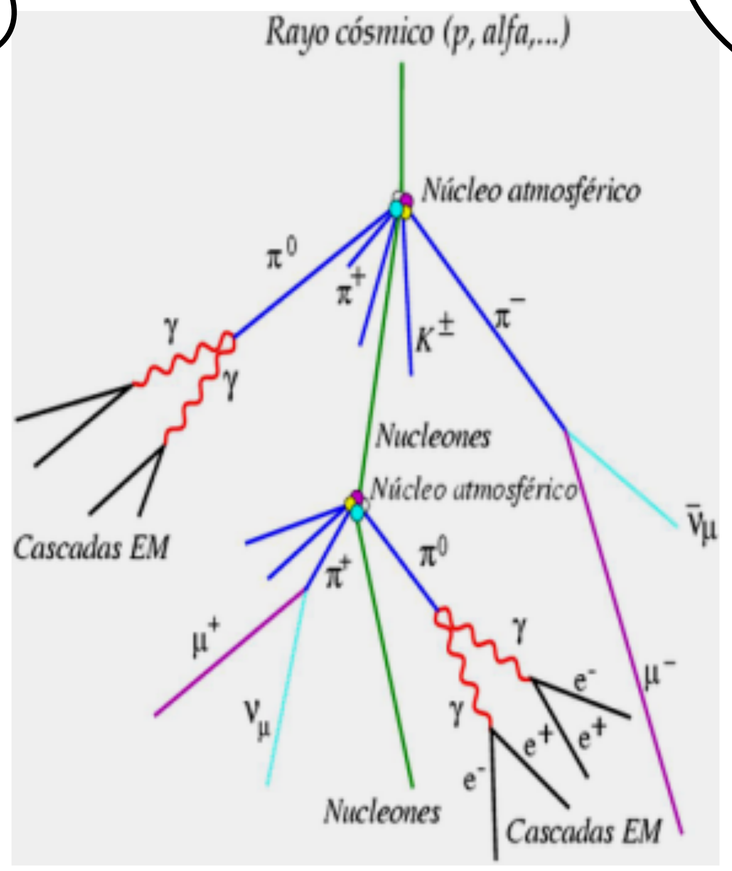


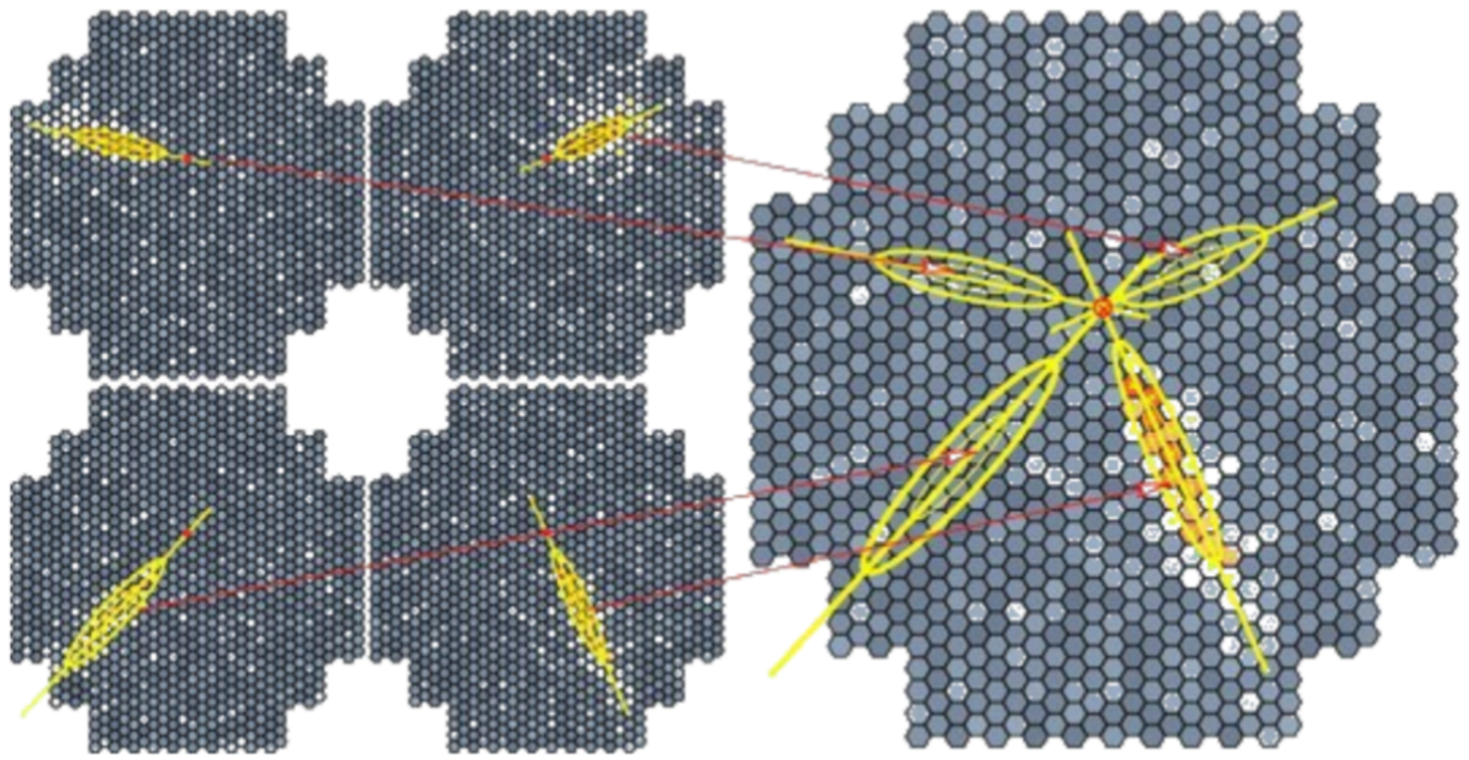


Electromagnetic



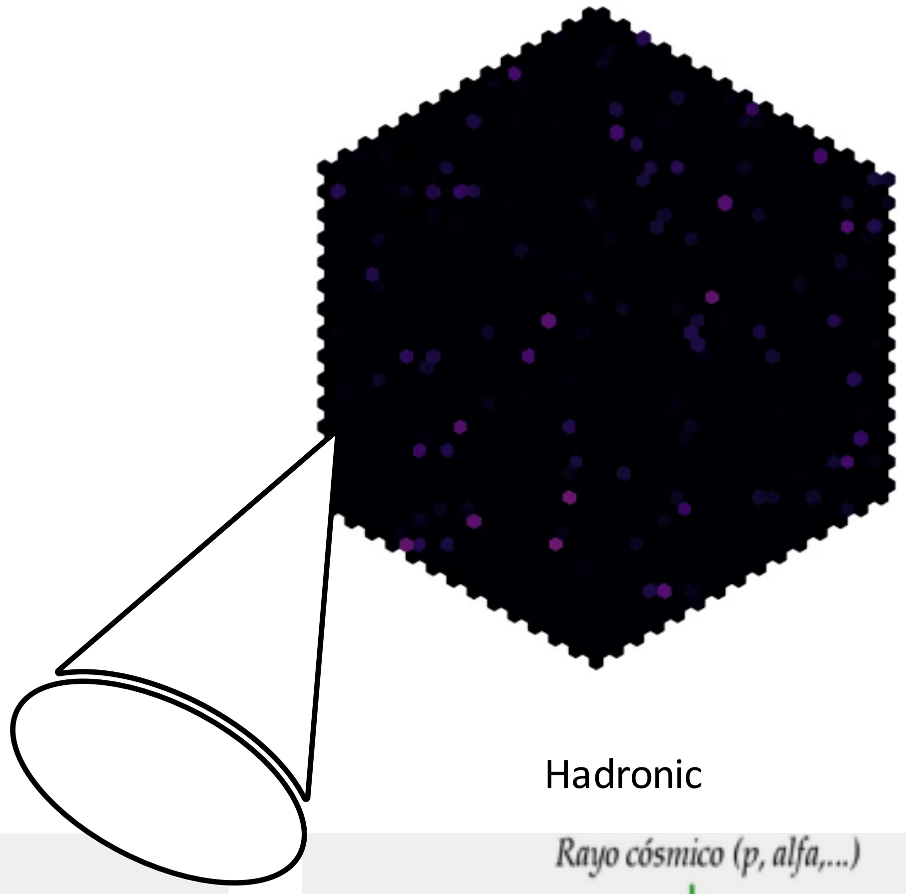
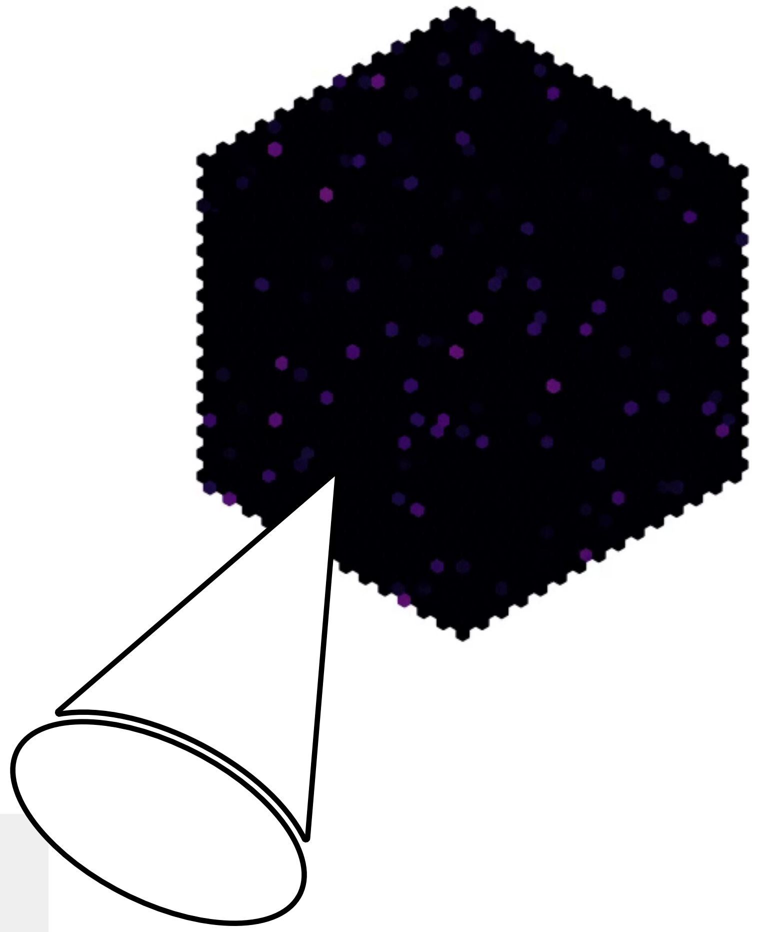
Hadronic



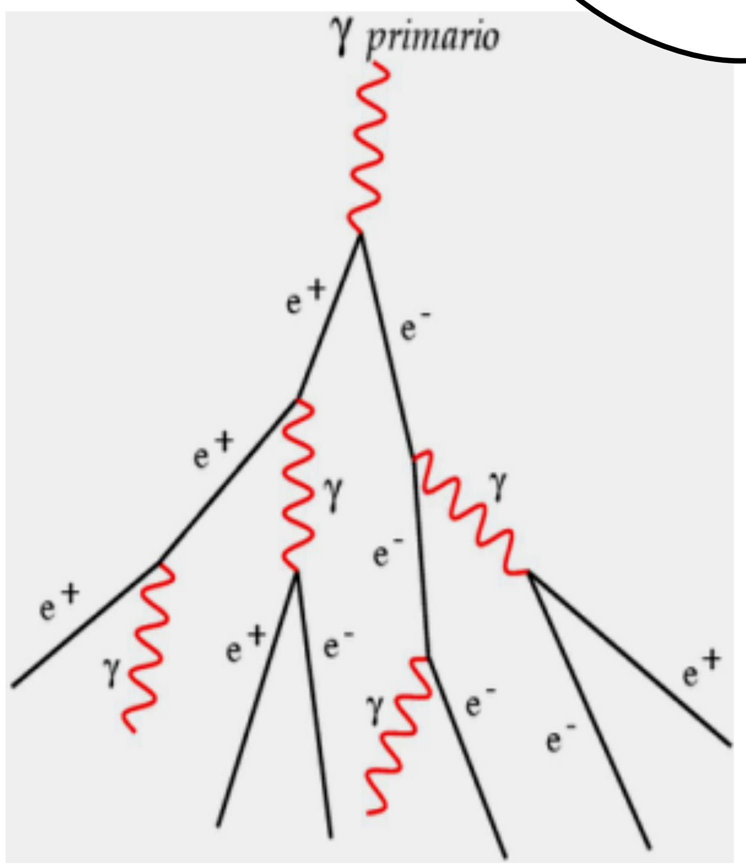


The IACT Technique

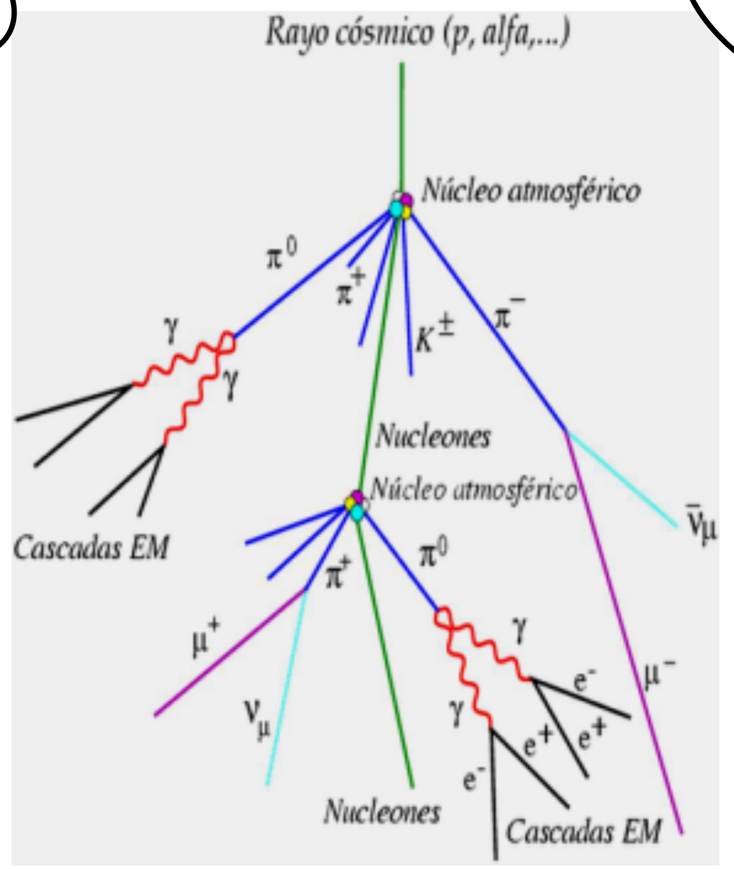
Detecting high energy photons

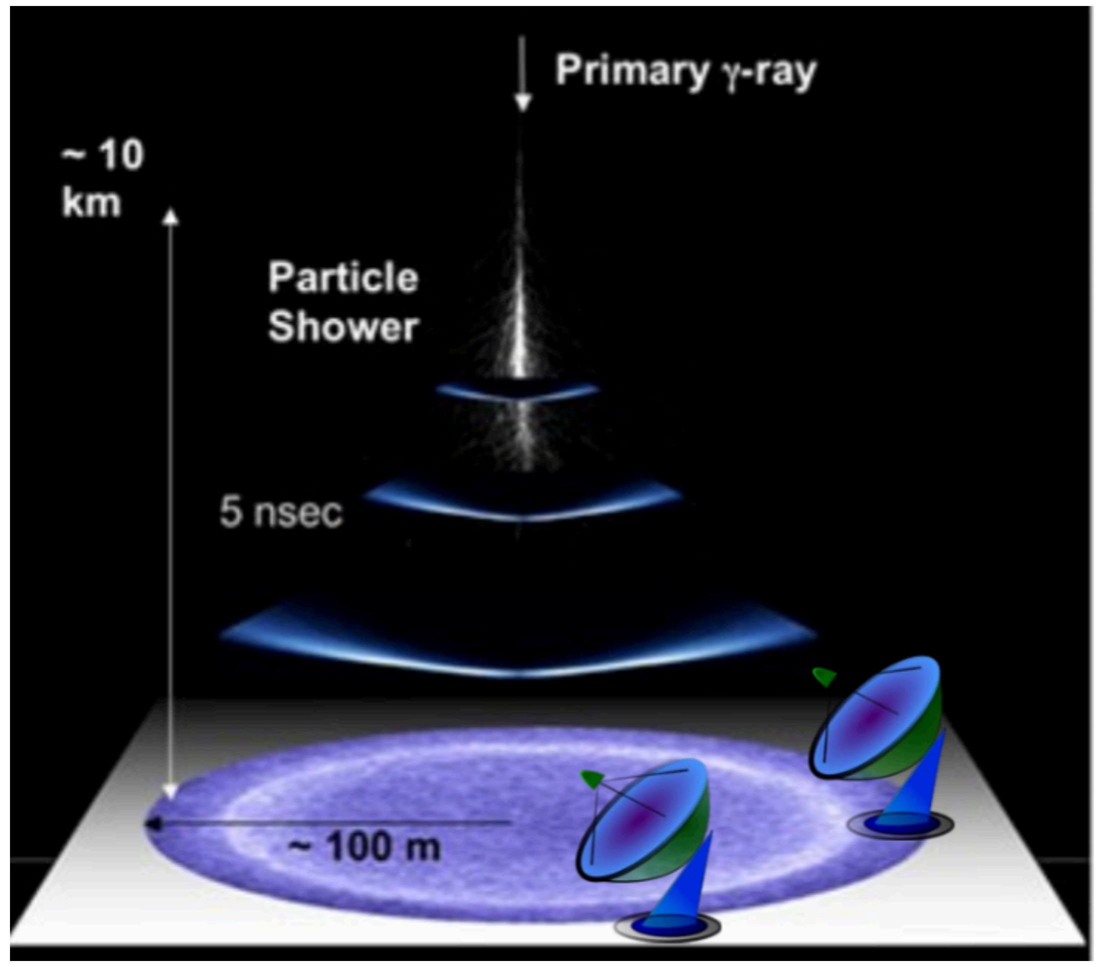



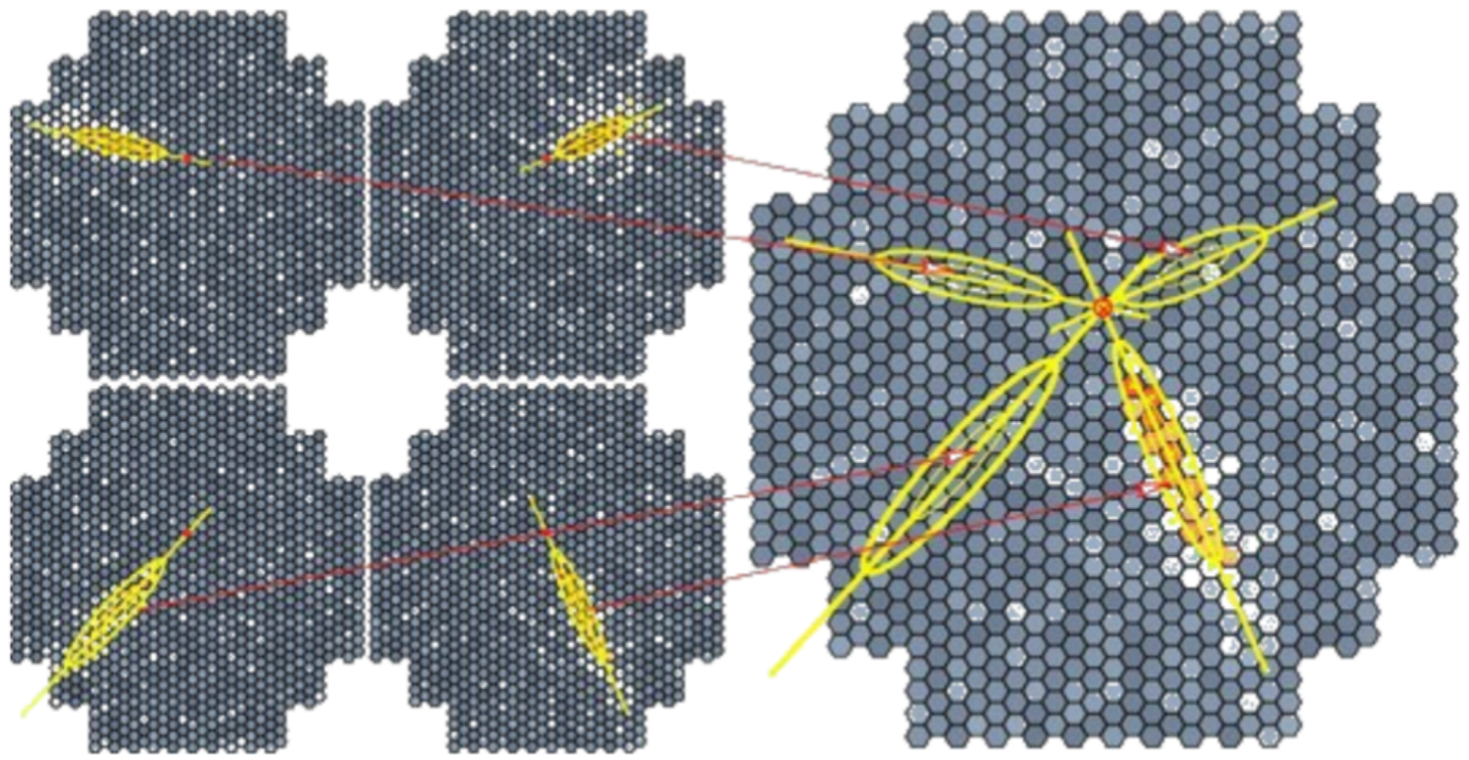
Electromagnetic



Hadronic

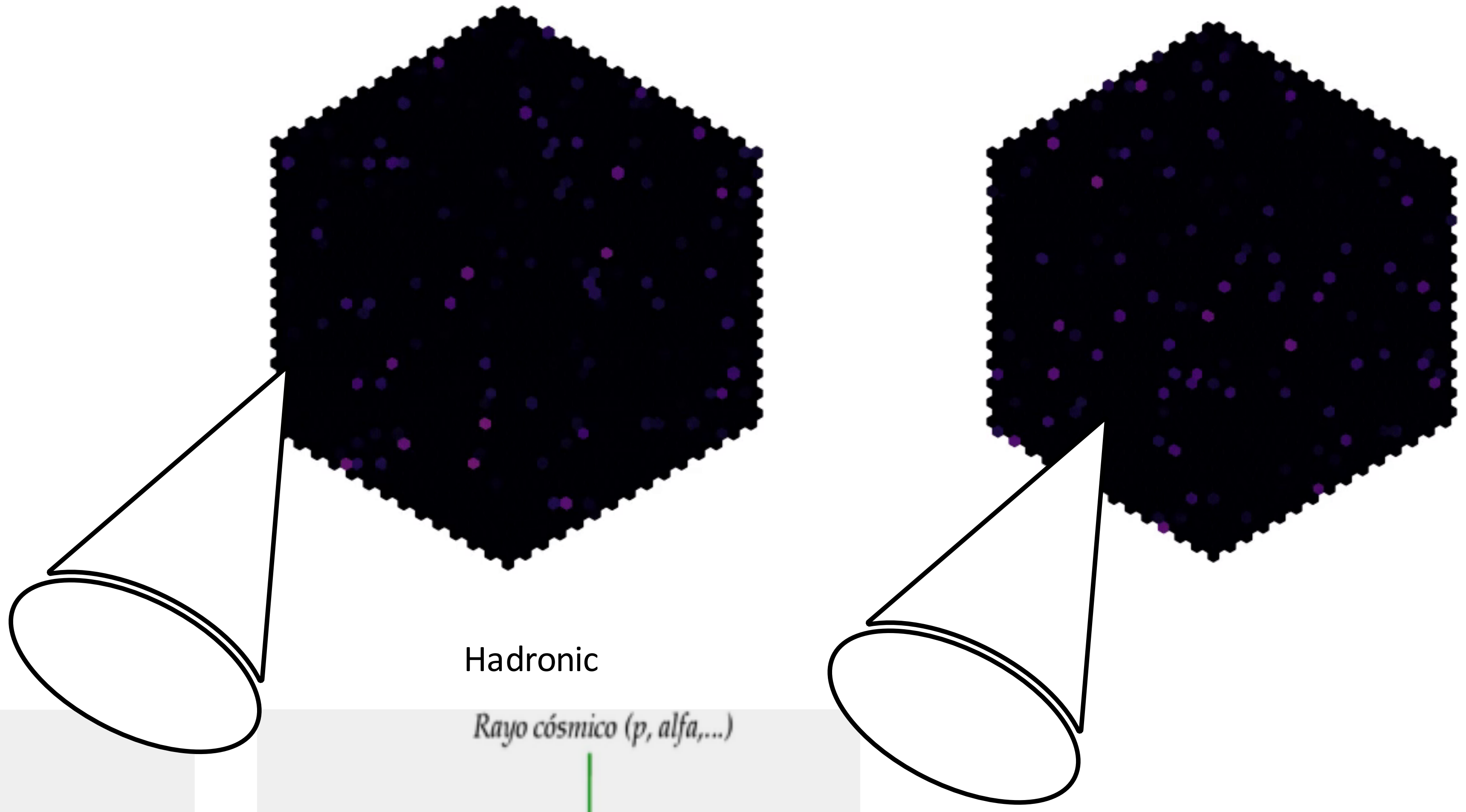


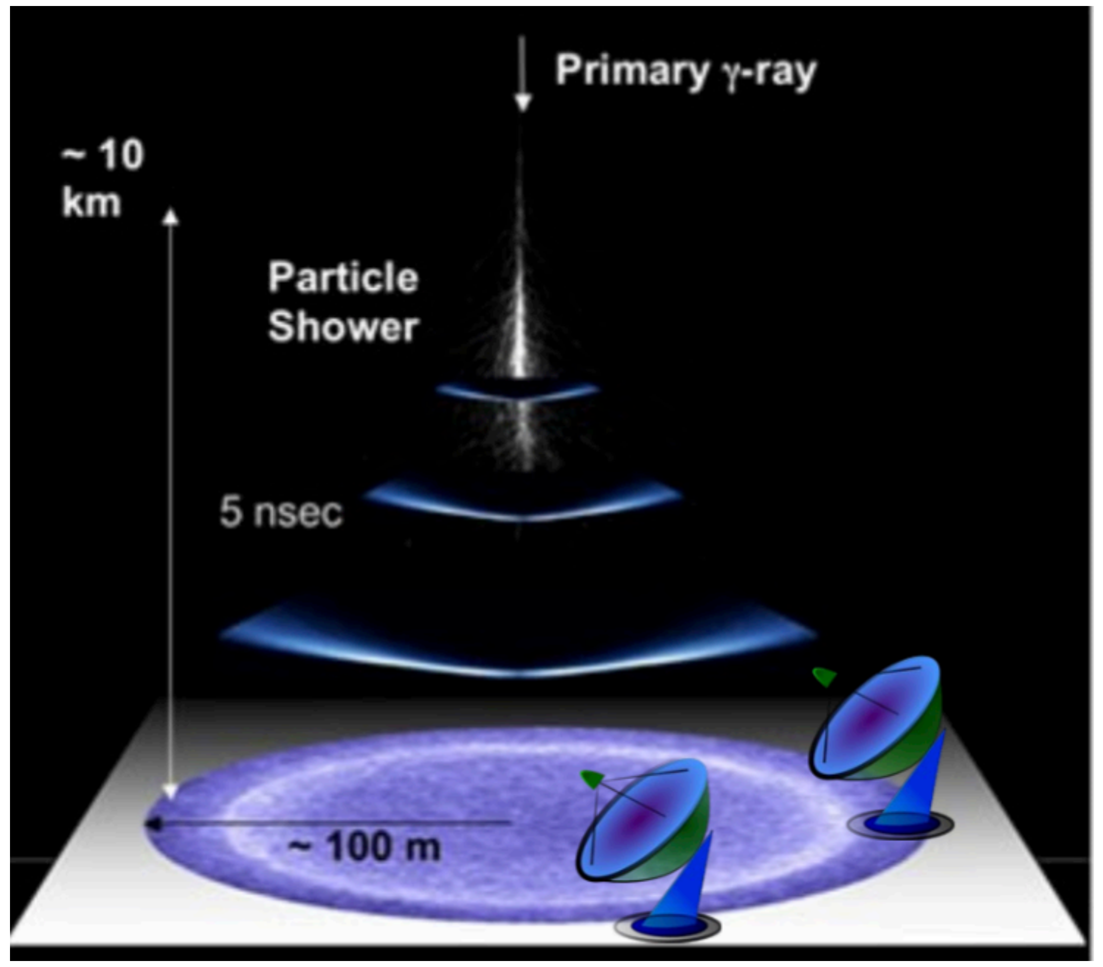


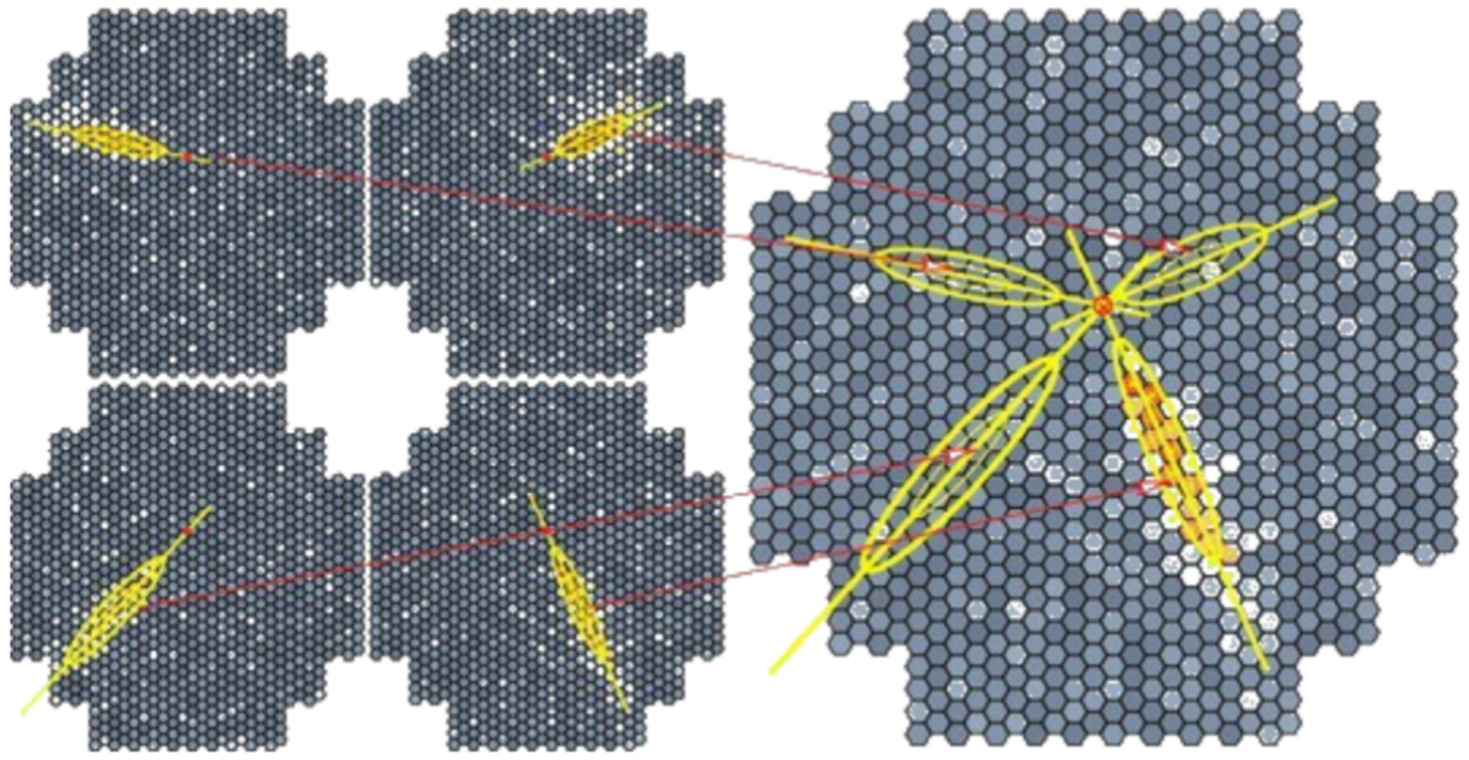


The IACT Technique

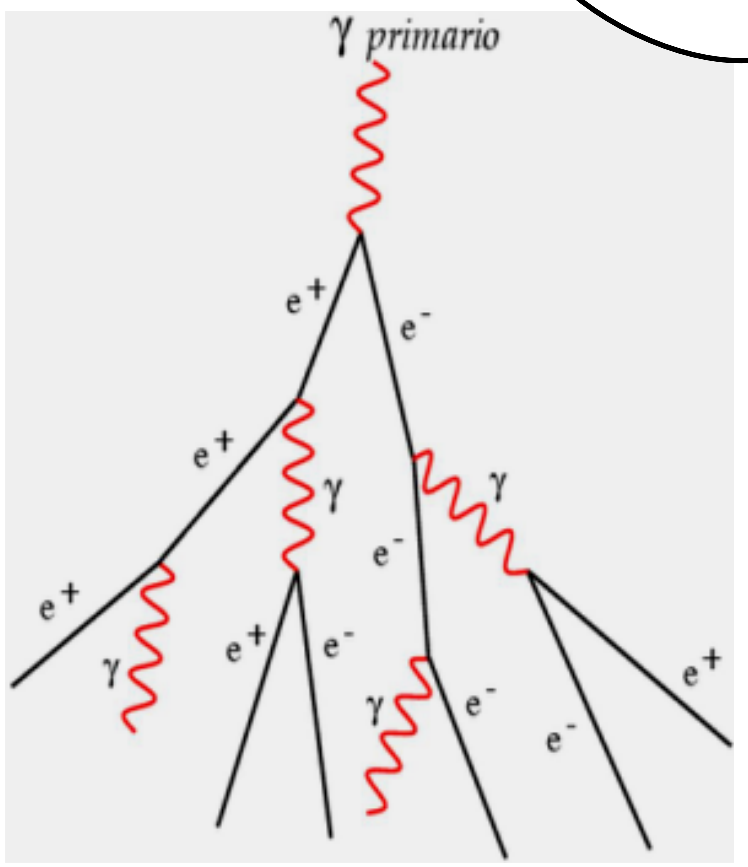
Detecting high energy photons



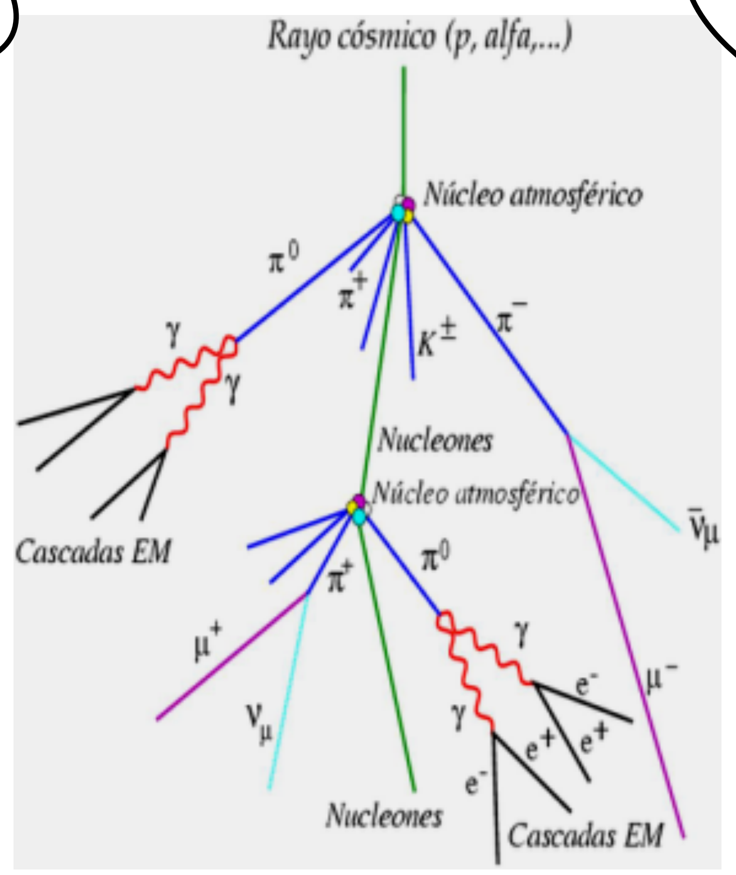




Electromagnetic

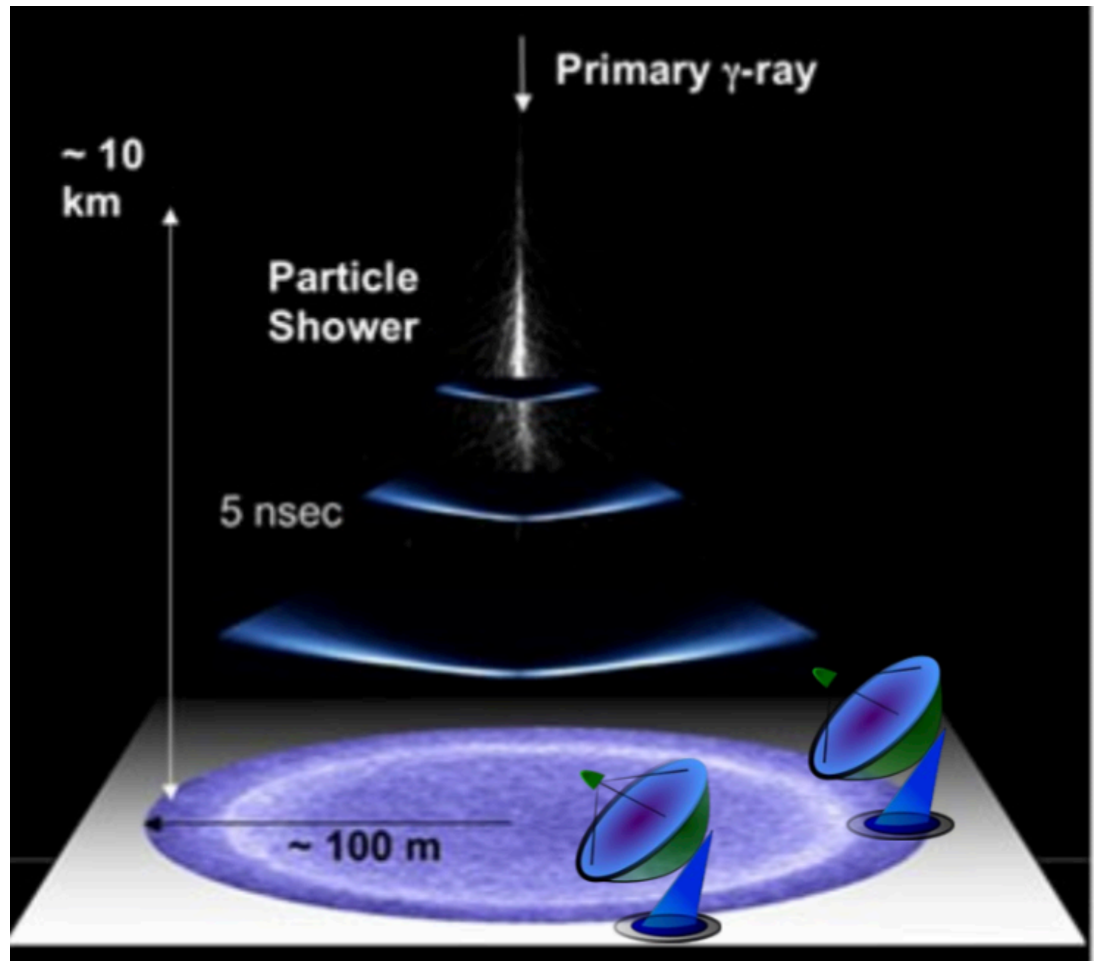


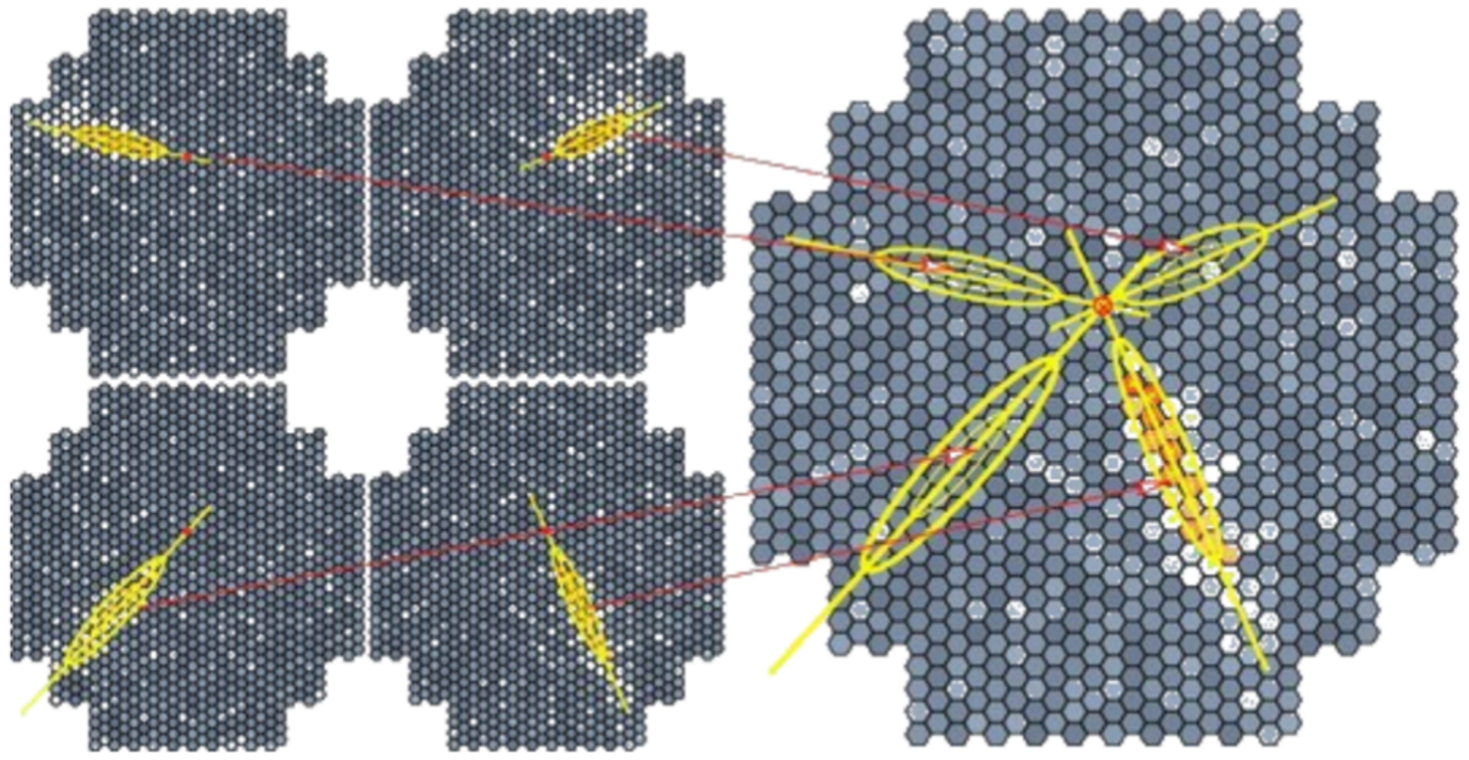
Hadronic

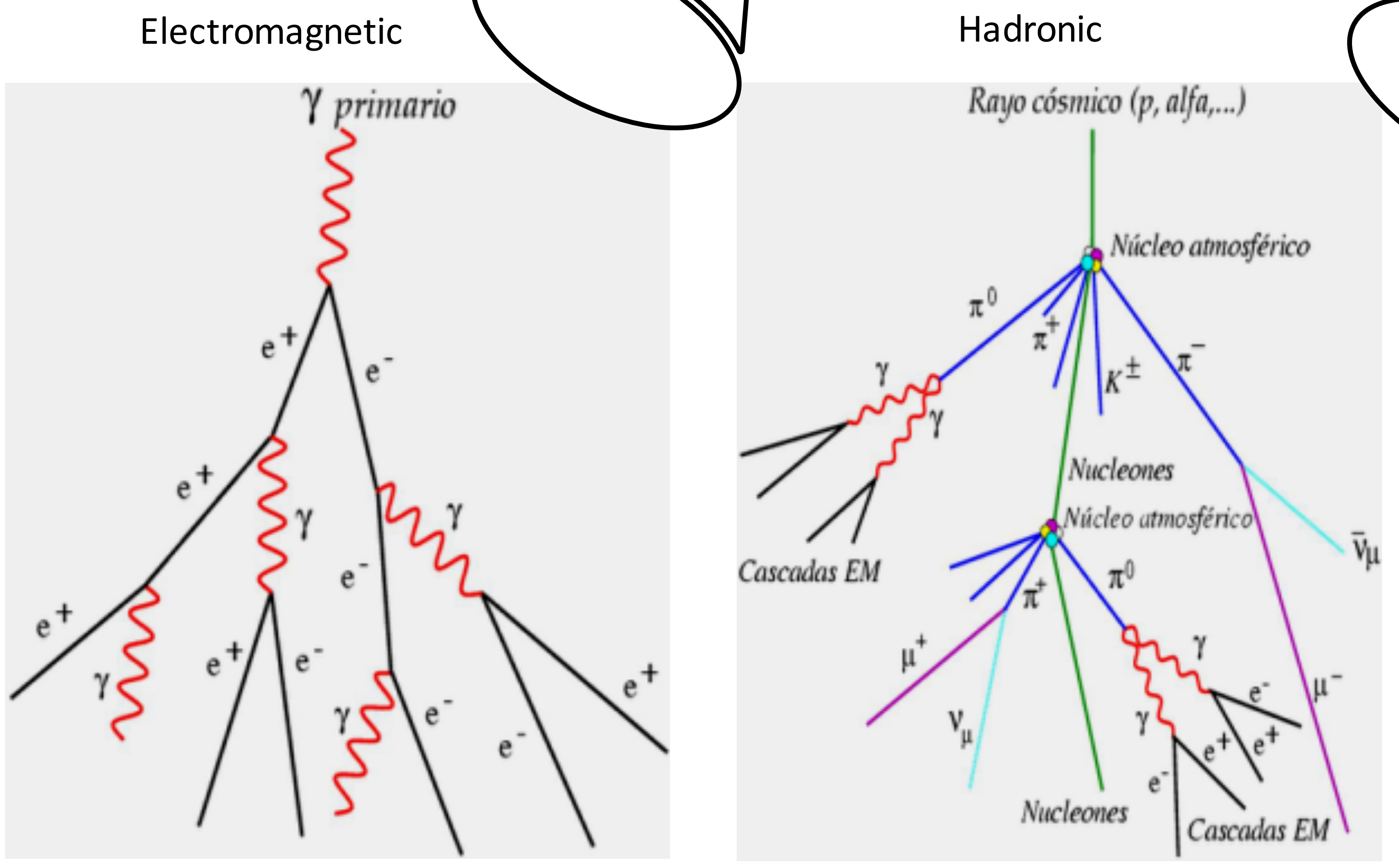


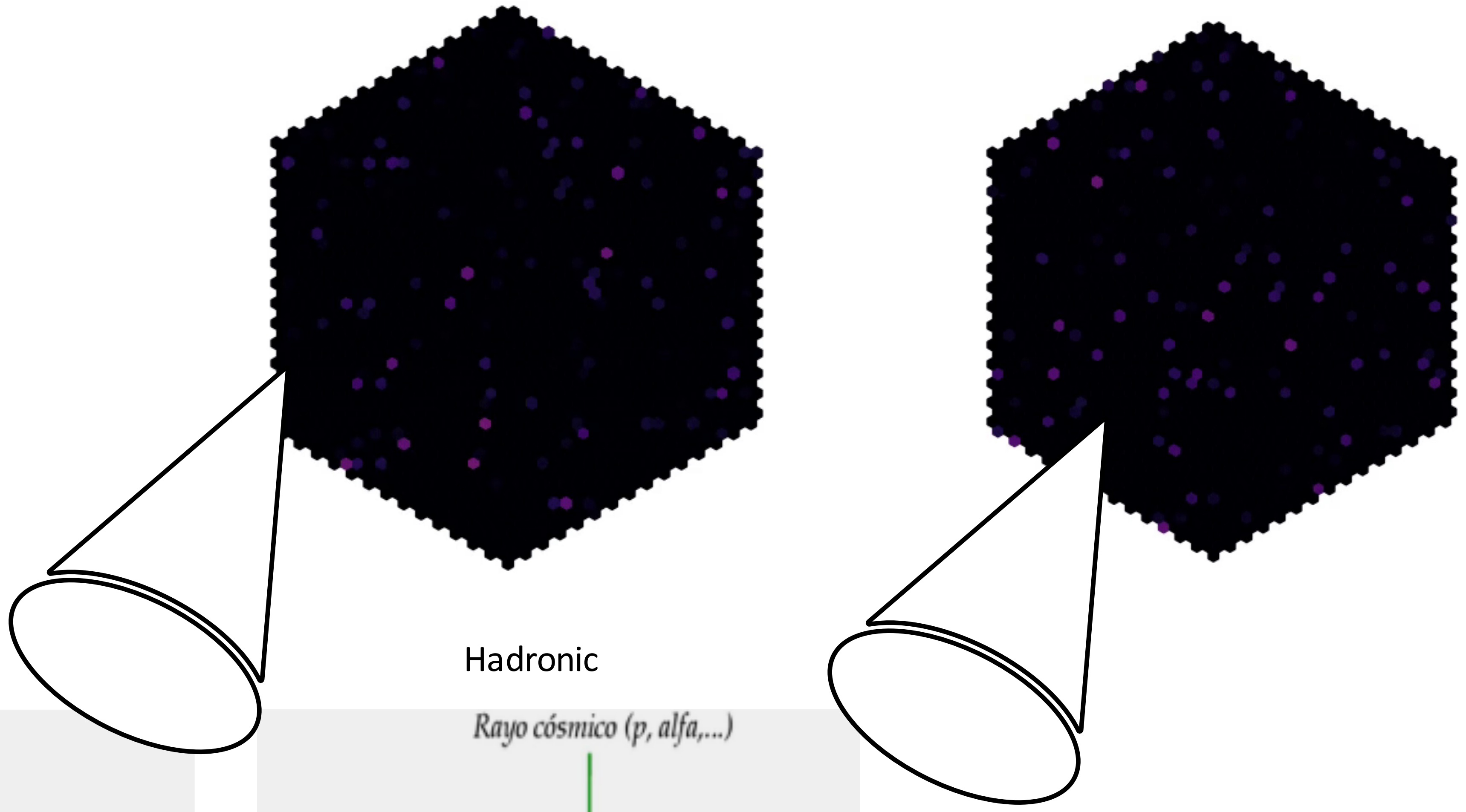
The IACT Technique

Detecting high energy photons





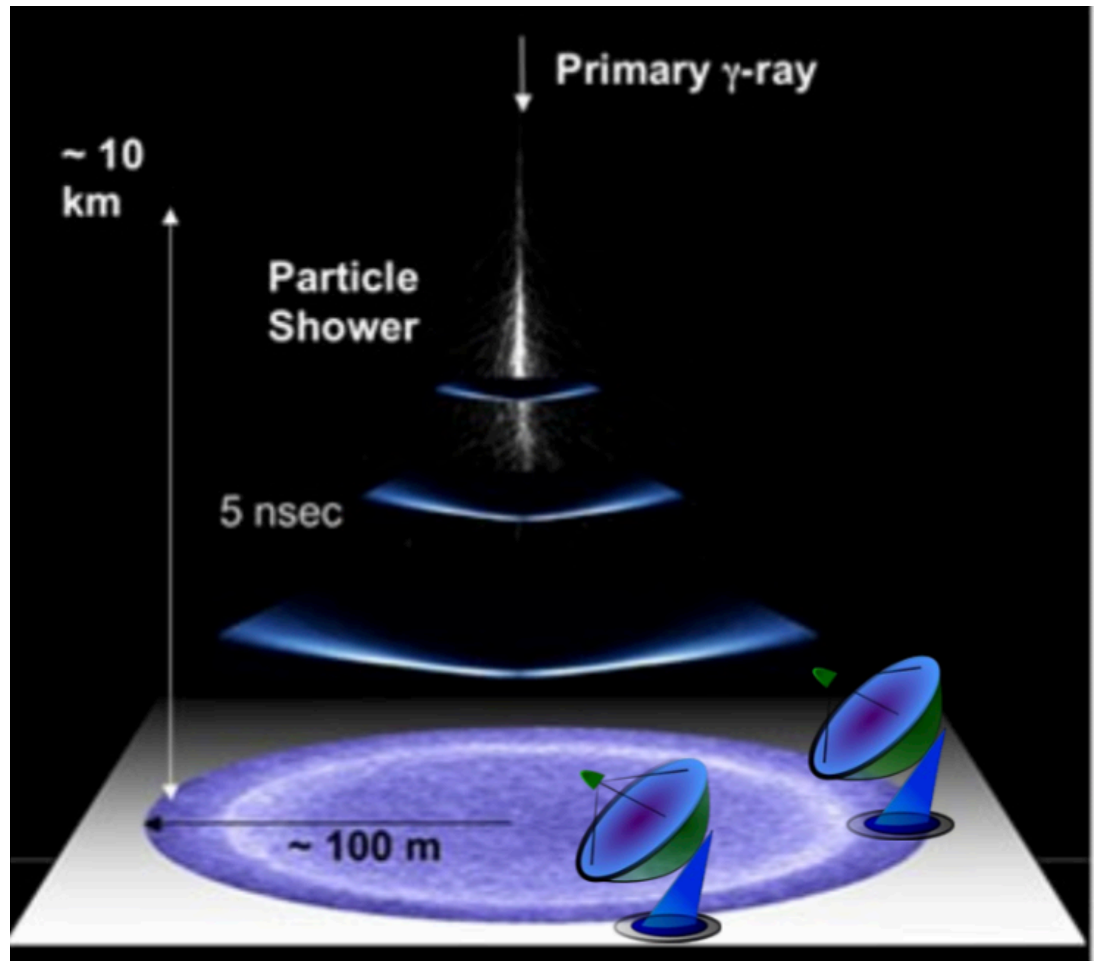


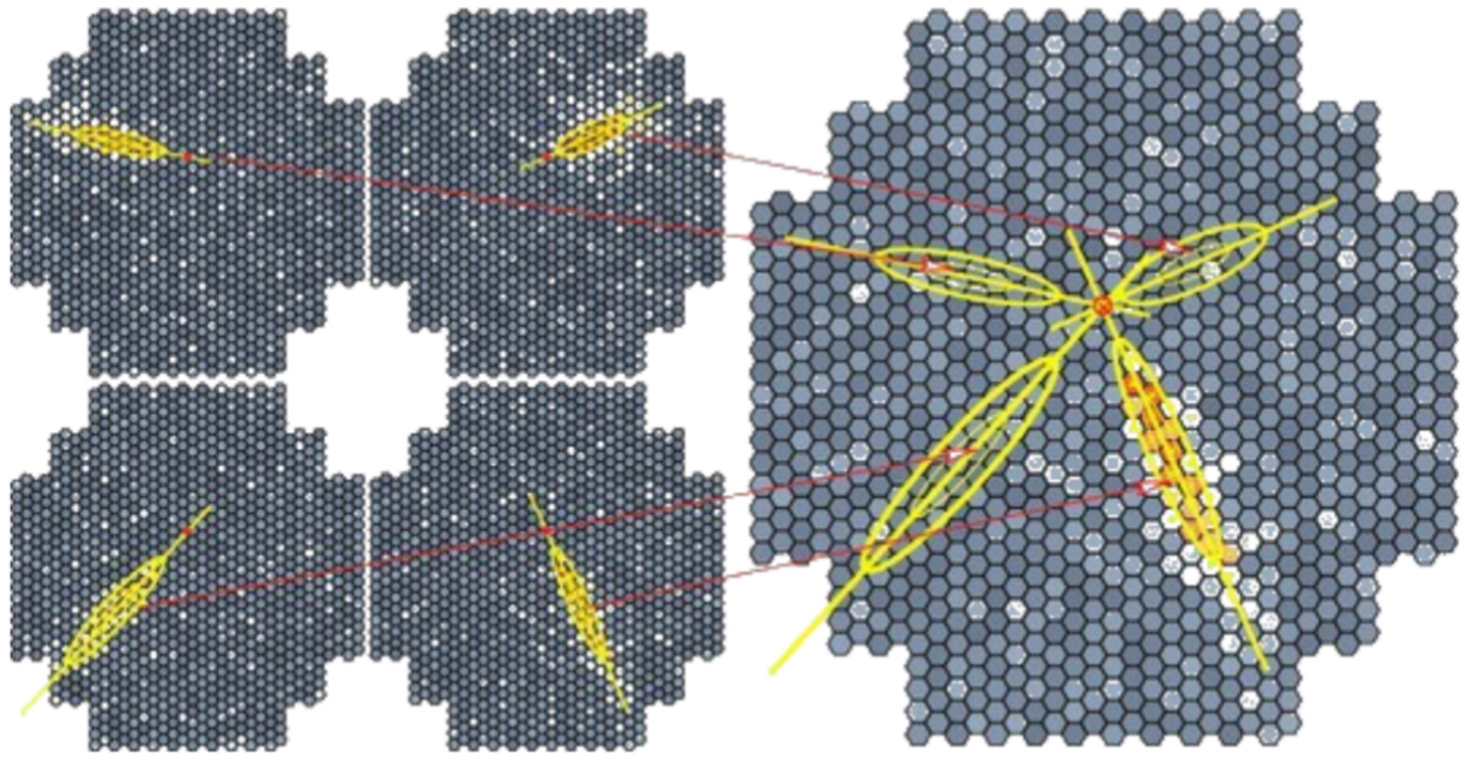


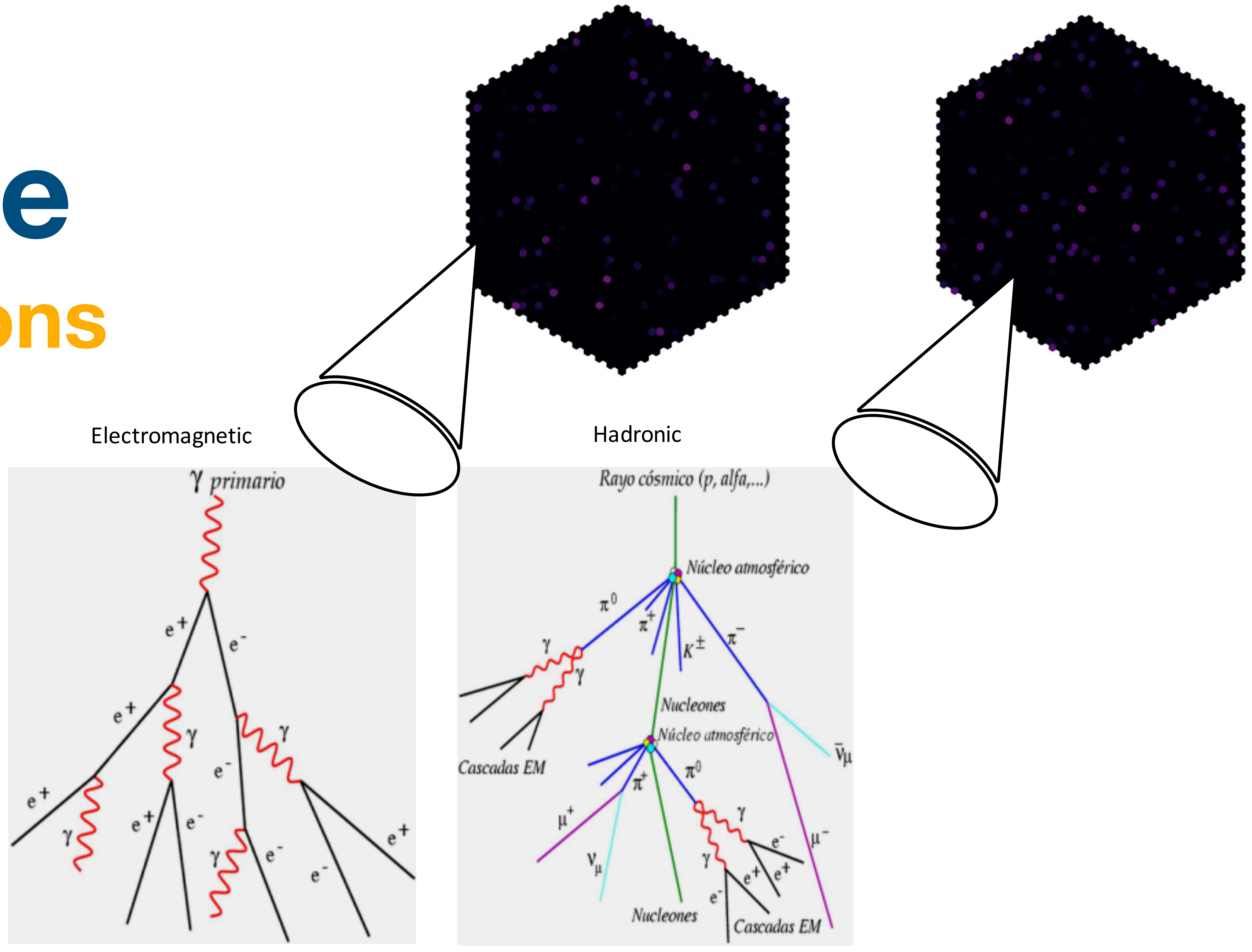
DESY.

The IACT Technique

Detecting high energy photons



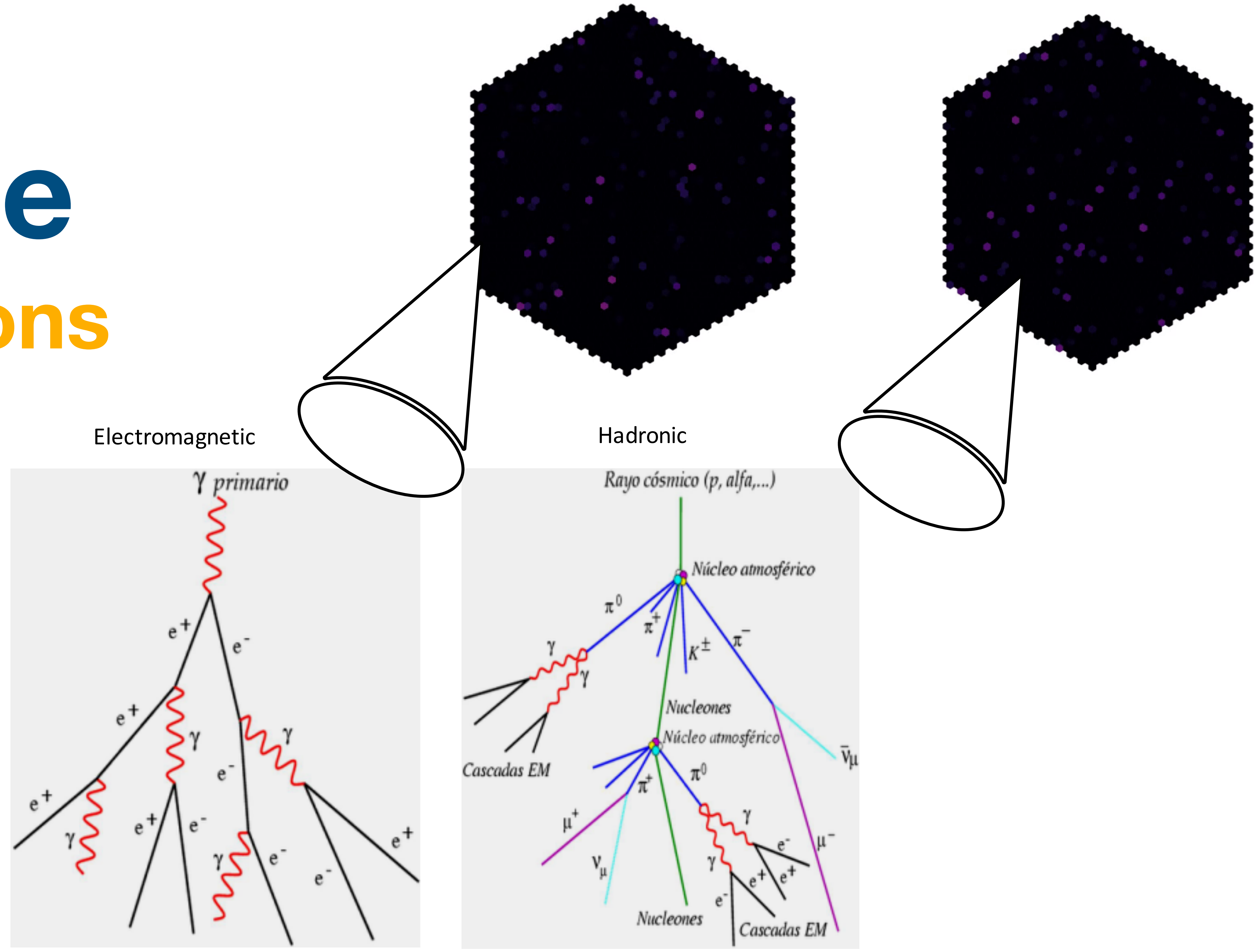


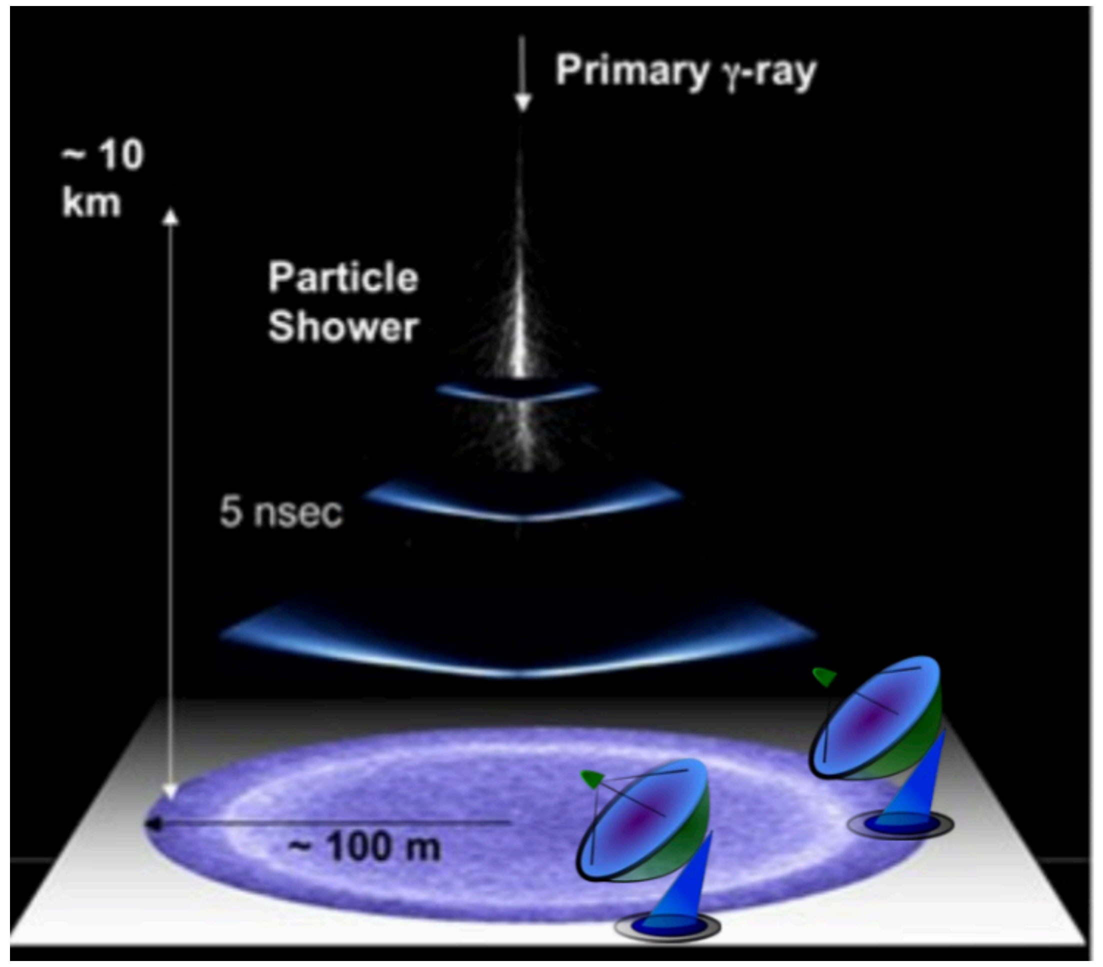


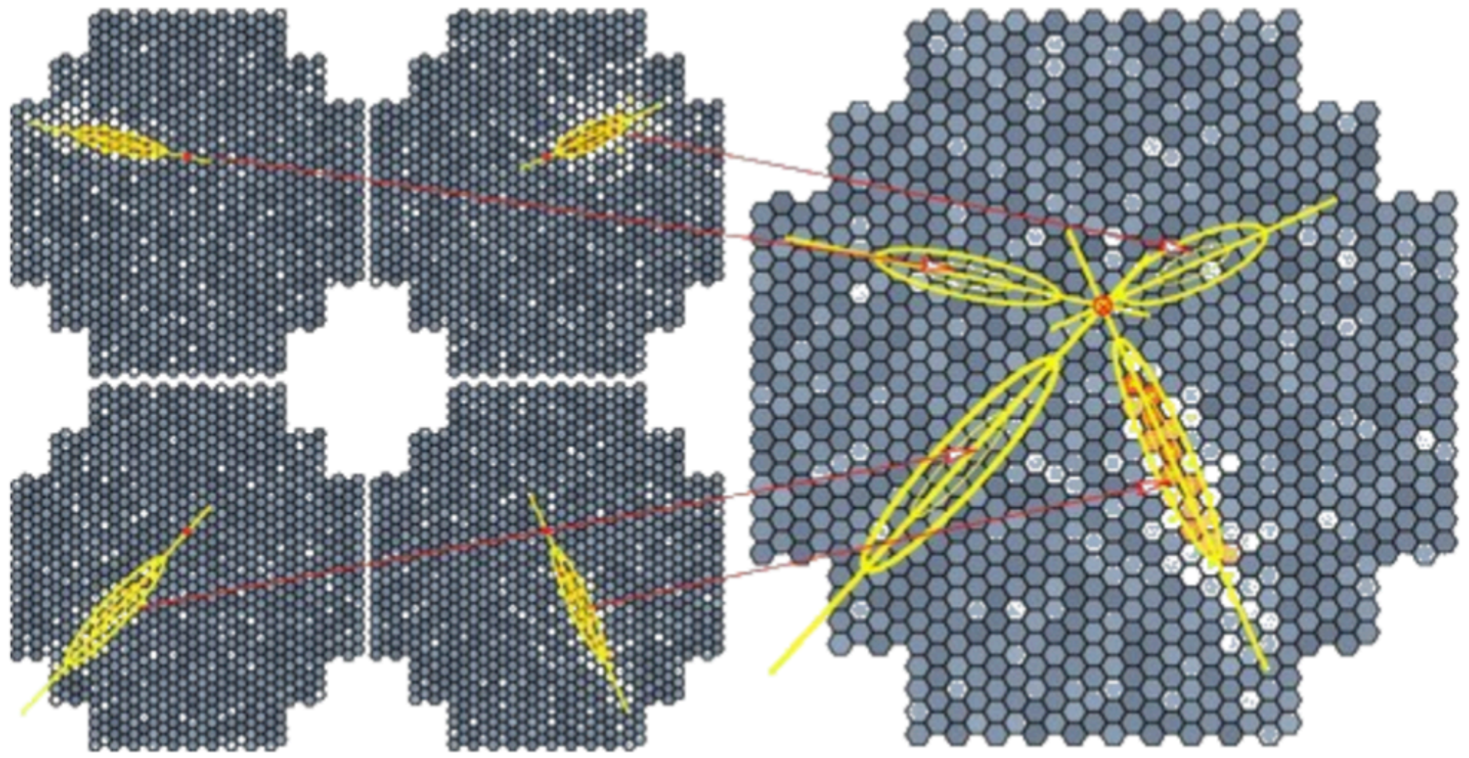
- From the shape => gamma/hadron separation

The IACT Technique

Detecting high energy photons



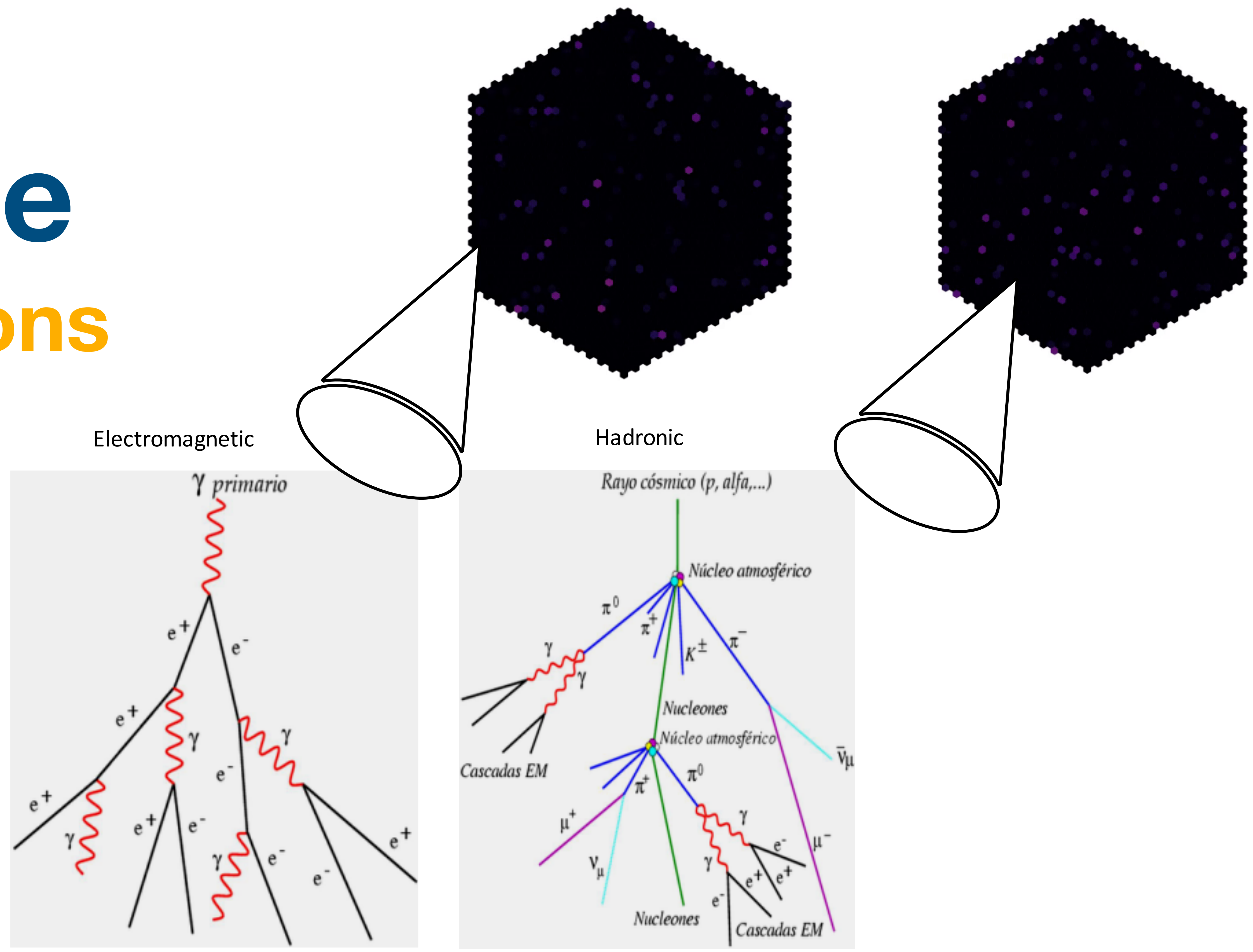


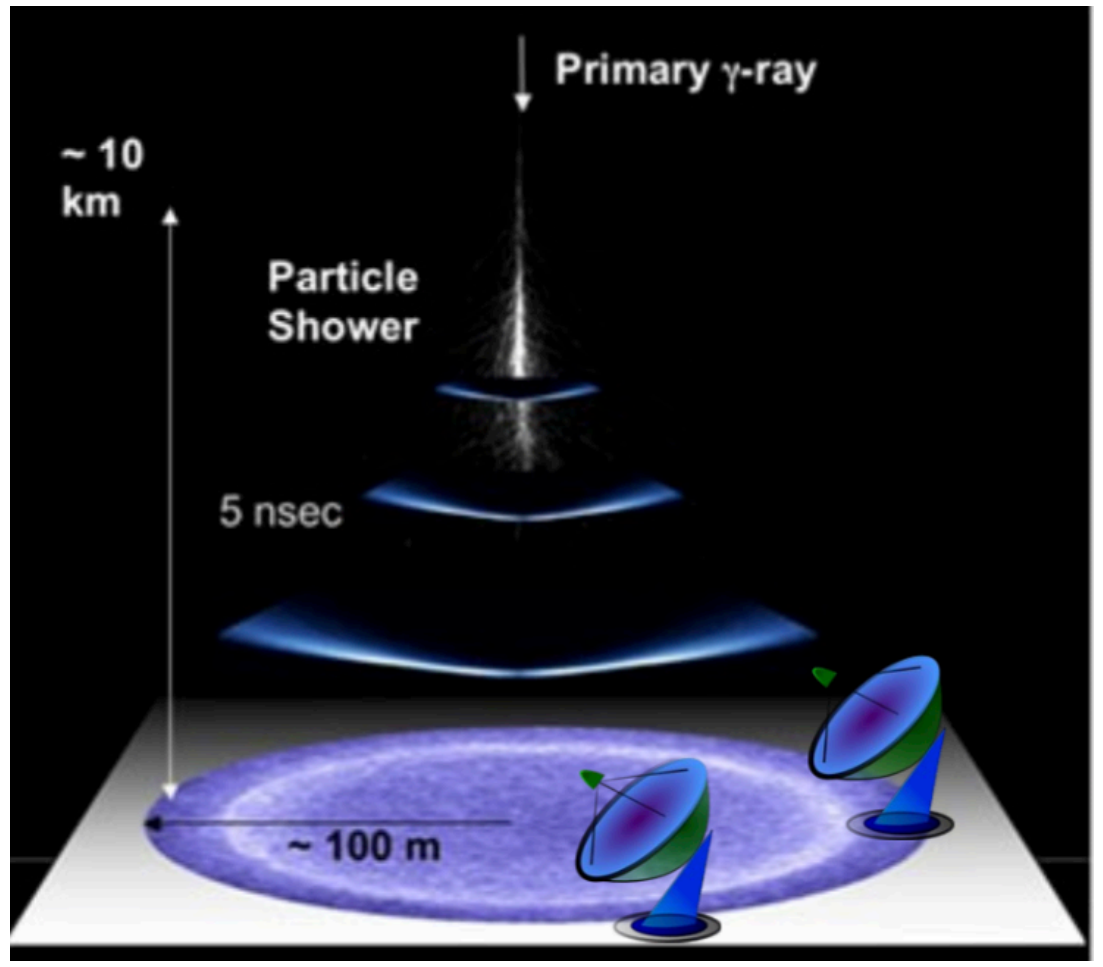


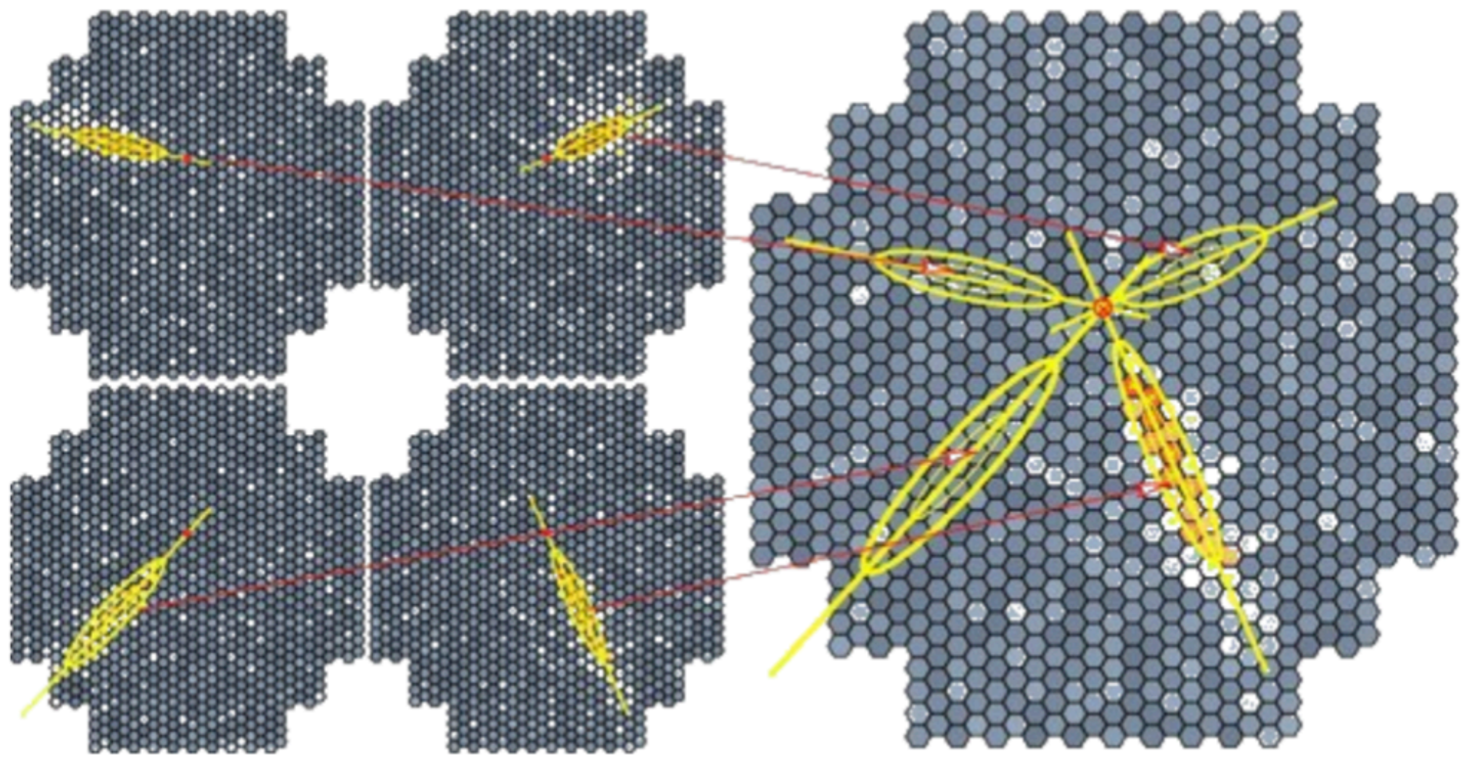
- From the shape => gamma/hadron separation
- From the axis => arrival direction / angular resolution

The IACT Technique

Detecting high energy photons



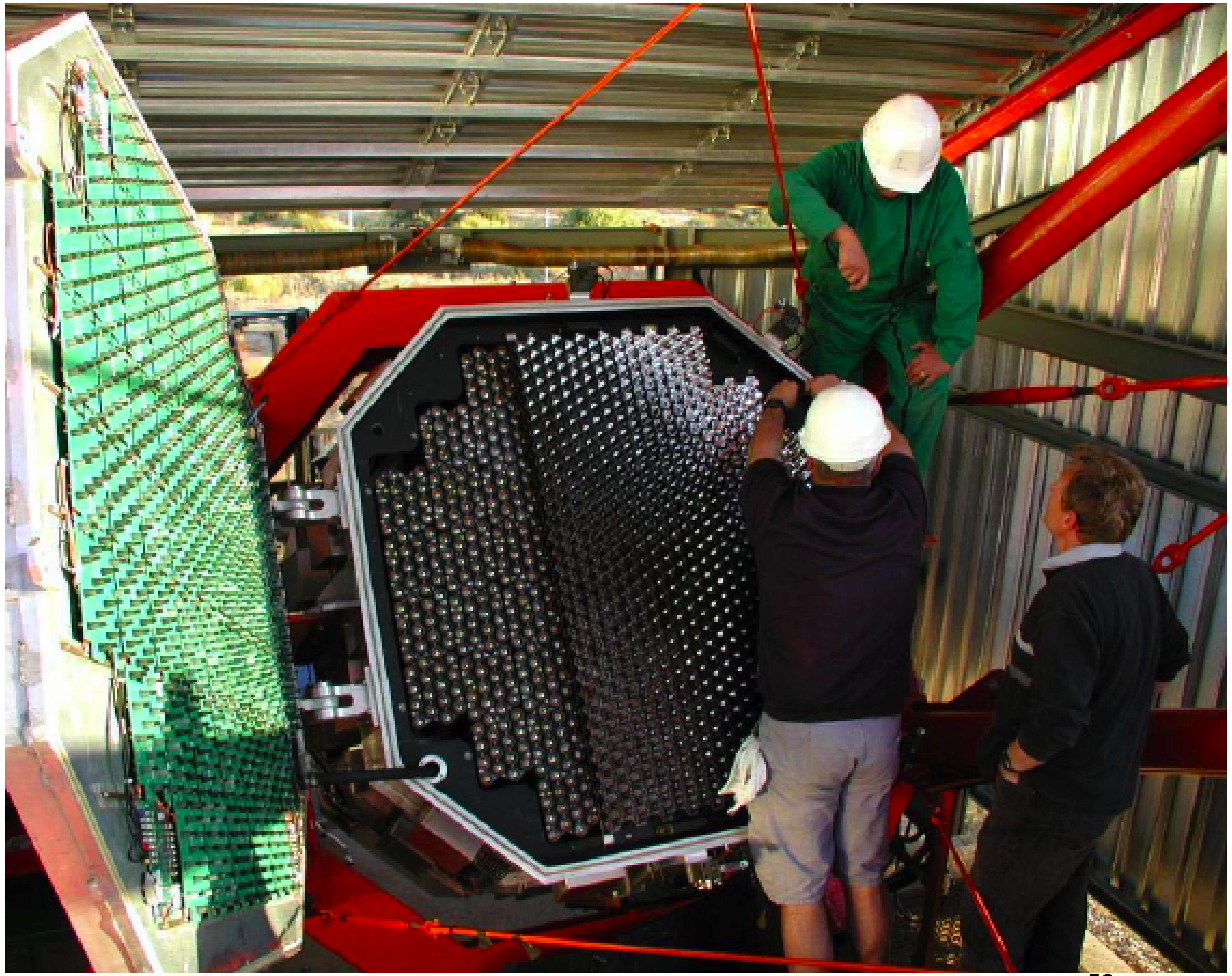


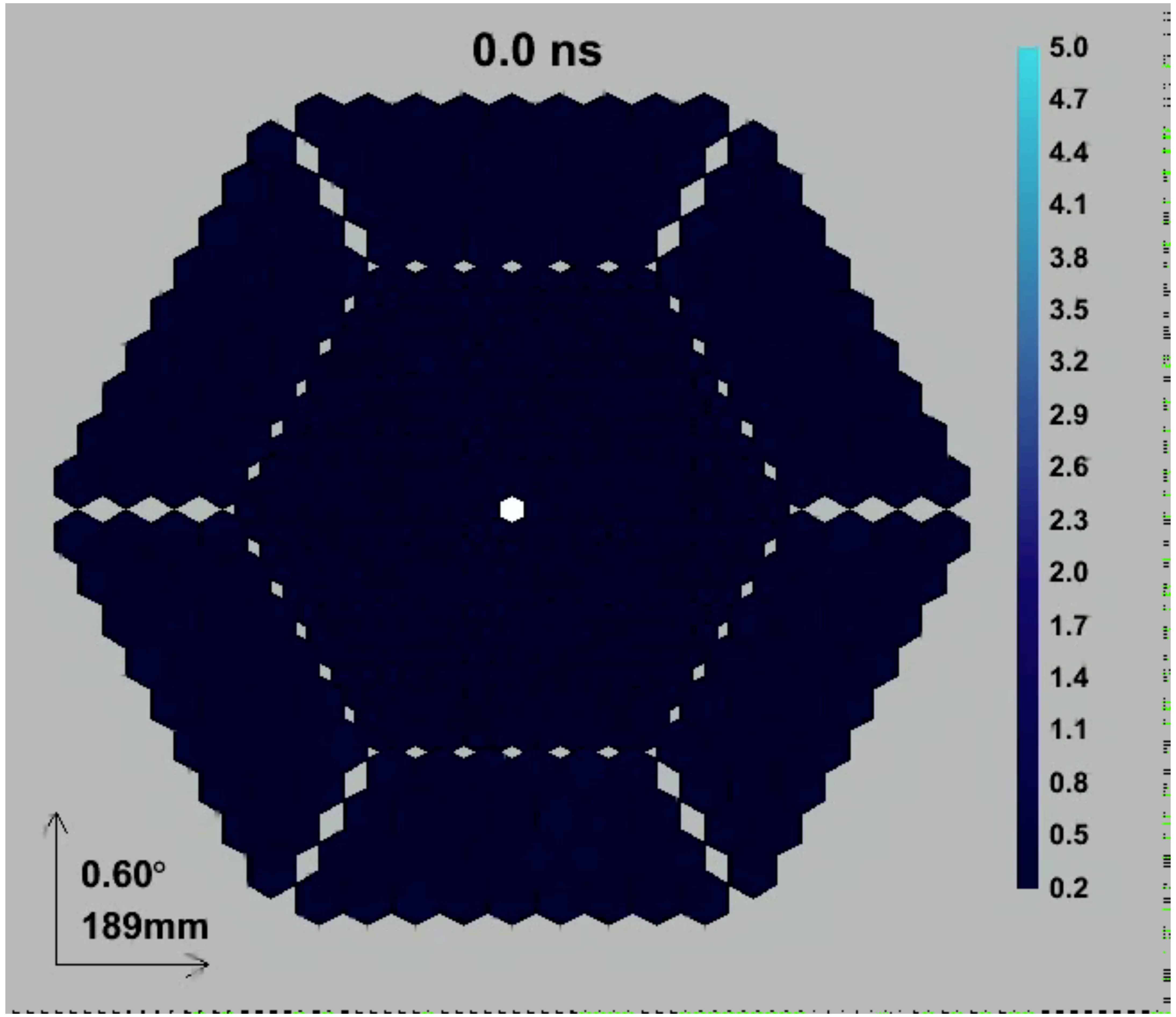


- From the shape => gamma/hadron separation
- From the axis => arrival direction / angular resolution
- From the 'size' => light / energy resolution

Gamma-ray detection

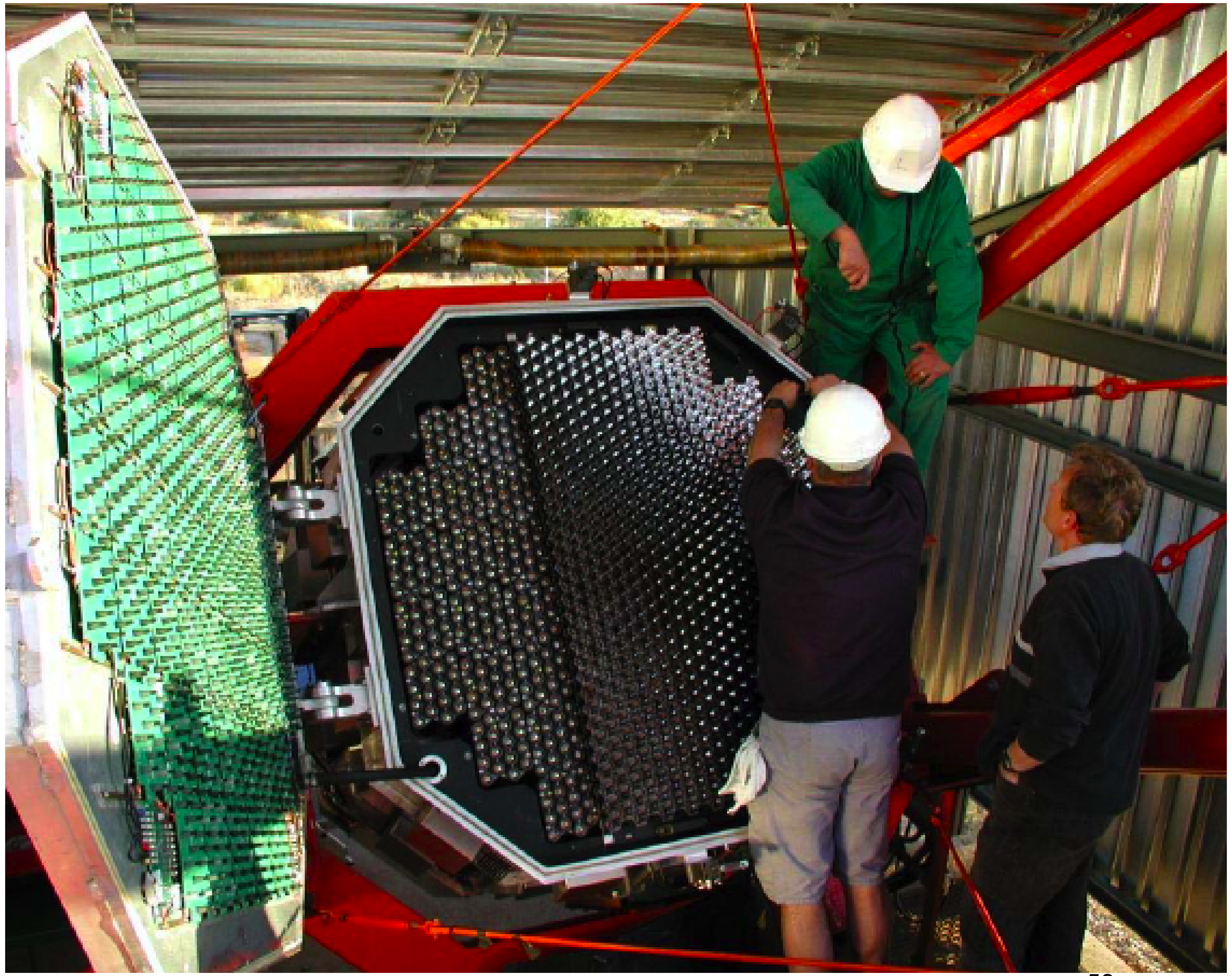
The Cherenkov Technique

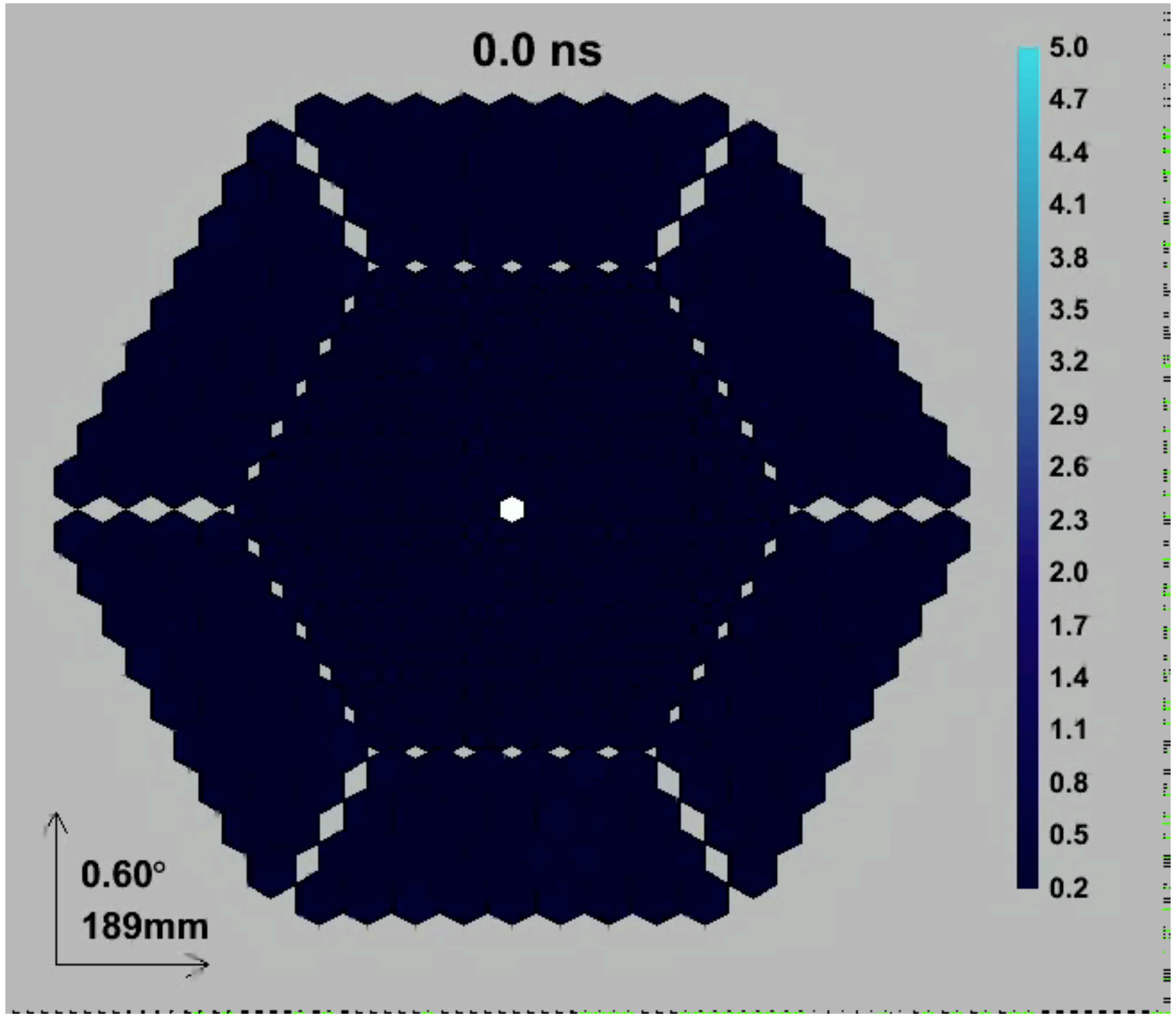




Gamma-ray detection

The Cherenkov Technique



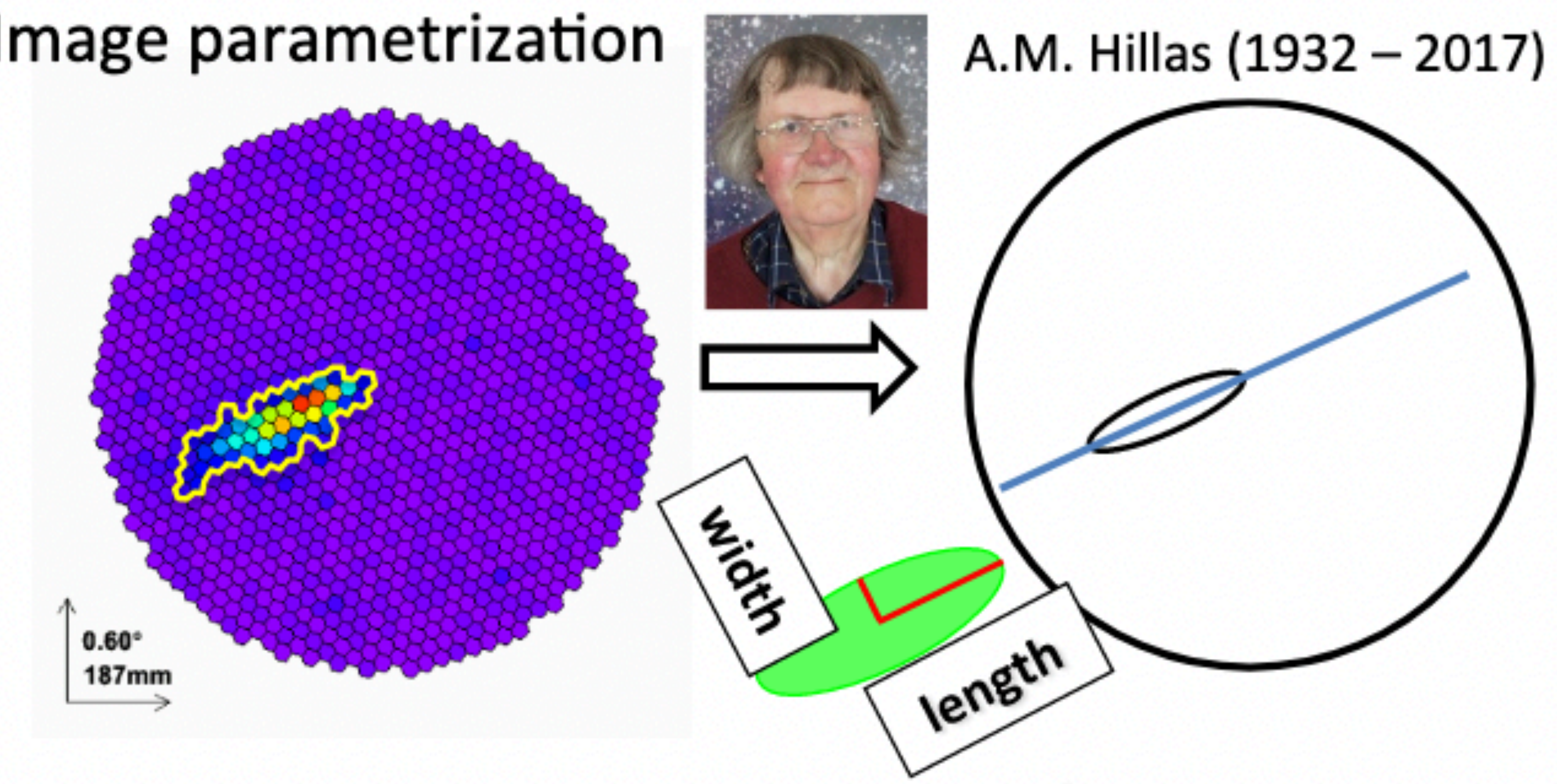


Gamma-ray detection

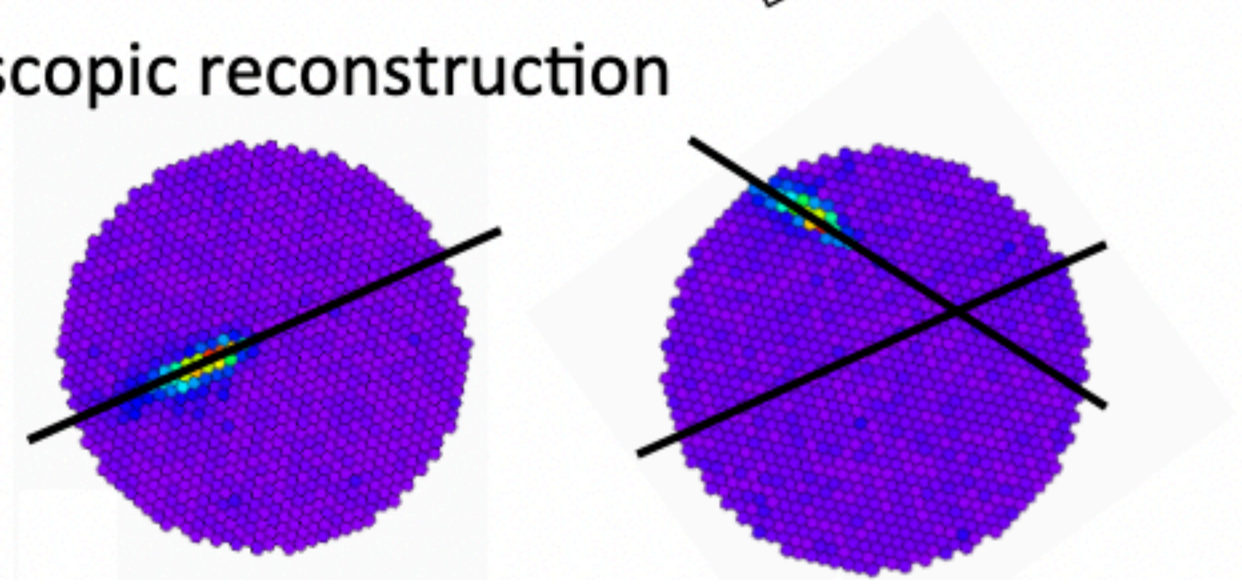
The Cherenkov Technique

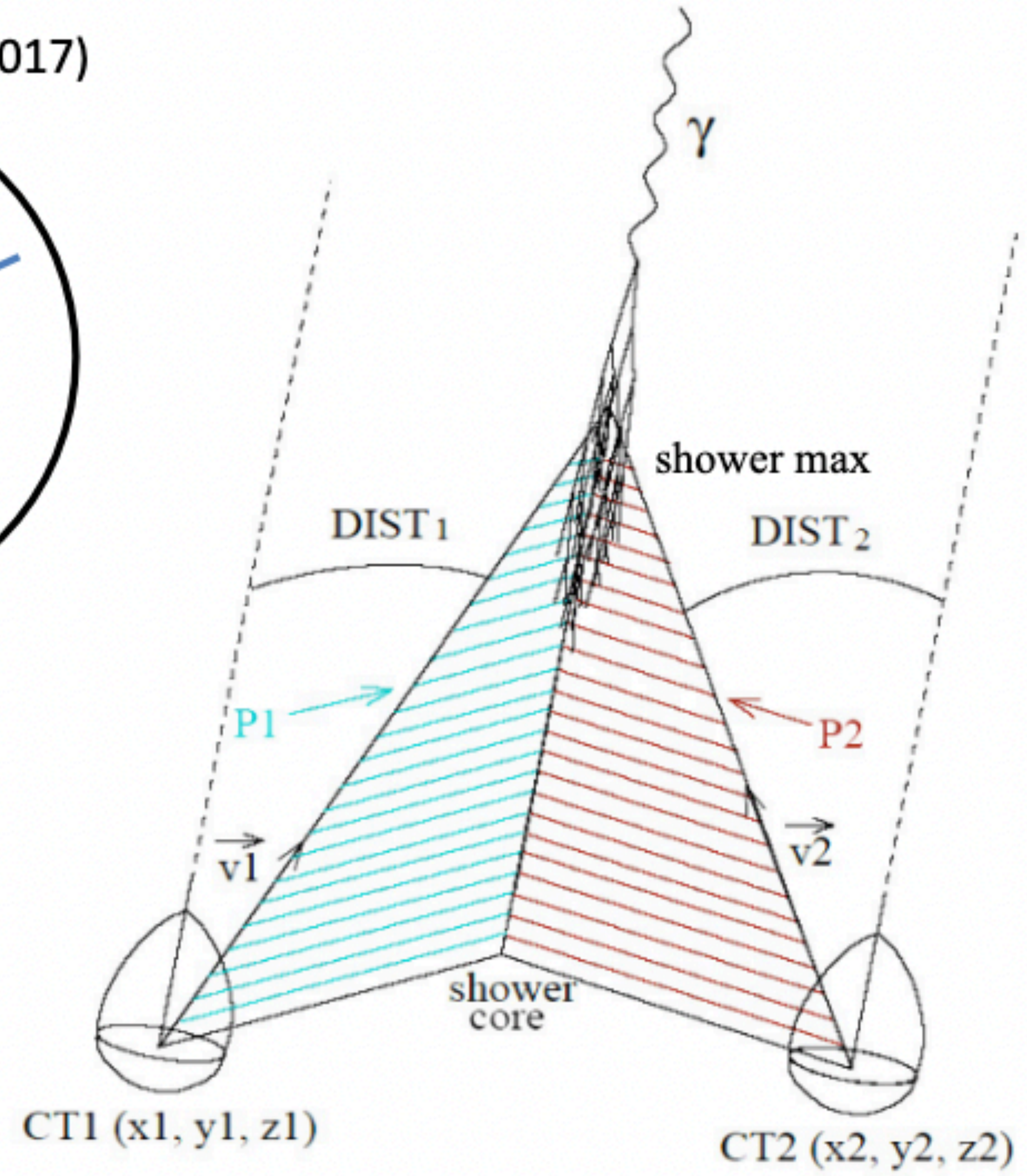
- Keep only pixels significantly above the background light fluctuations
- Calculate a small set of parameters describing the image: Size (total # of p.e.), main axis, Width, Length (2nd order moments - "Hillas parameters"), time gradient along major axis...

Image parametrization



Stereoscopic reconstruction





Moralejo 2018

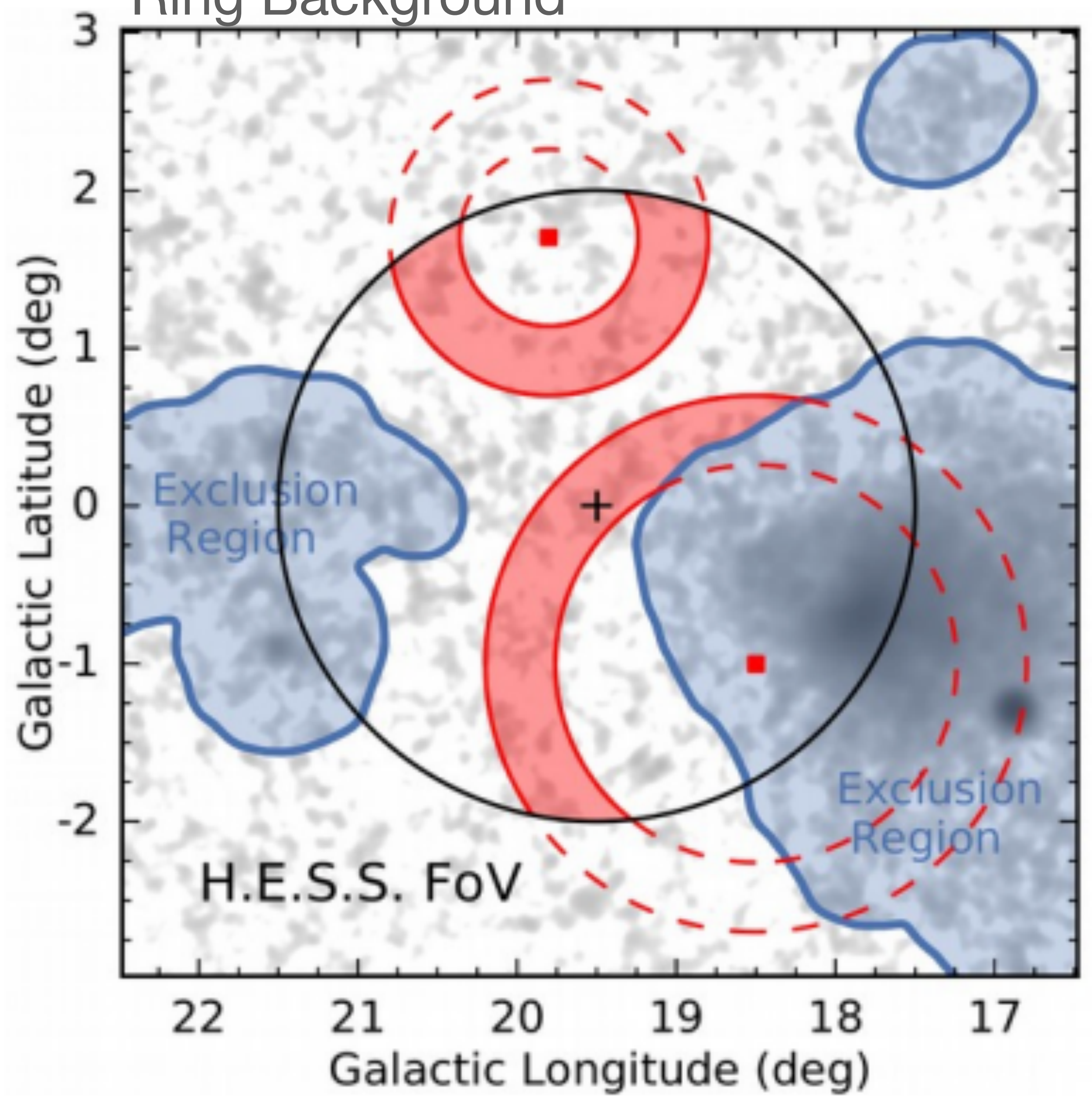
Gamma-ray detection

The Cherenkov Technique

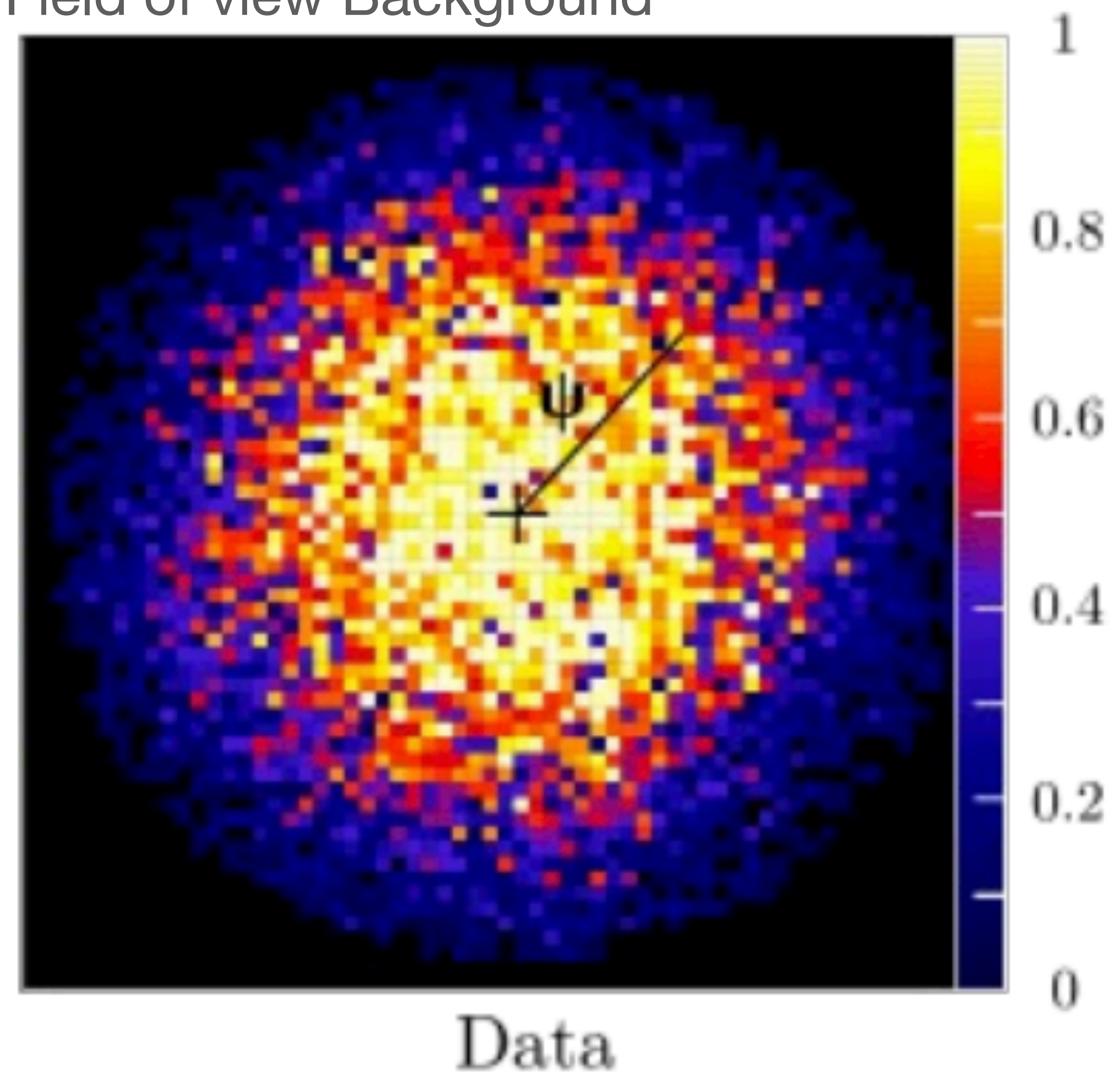
- Improve analysis for large FoV

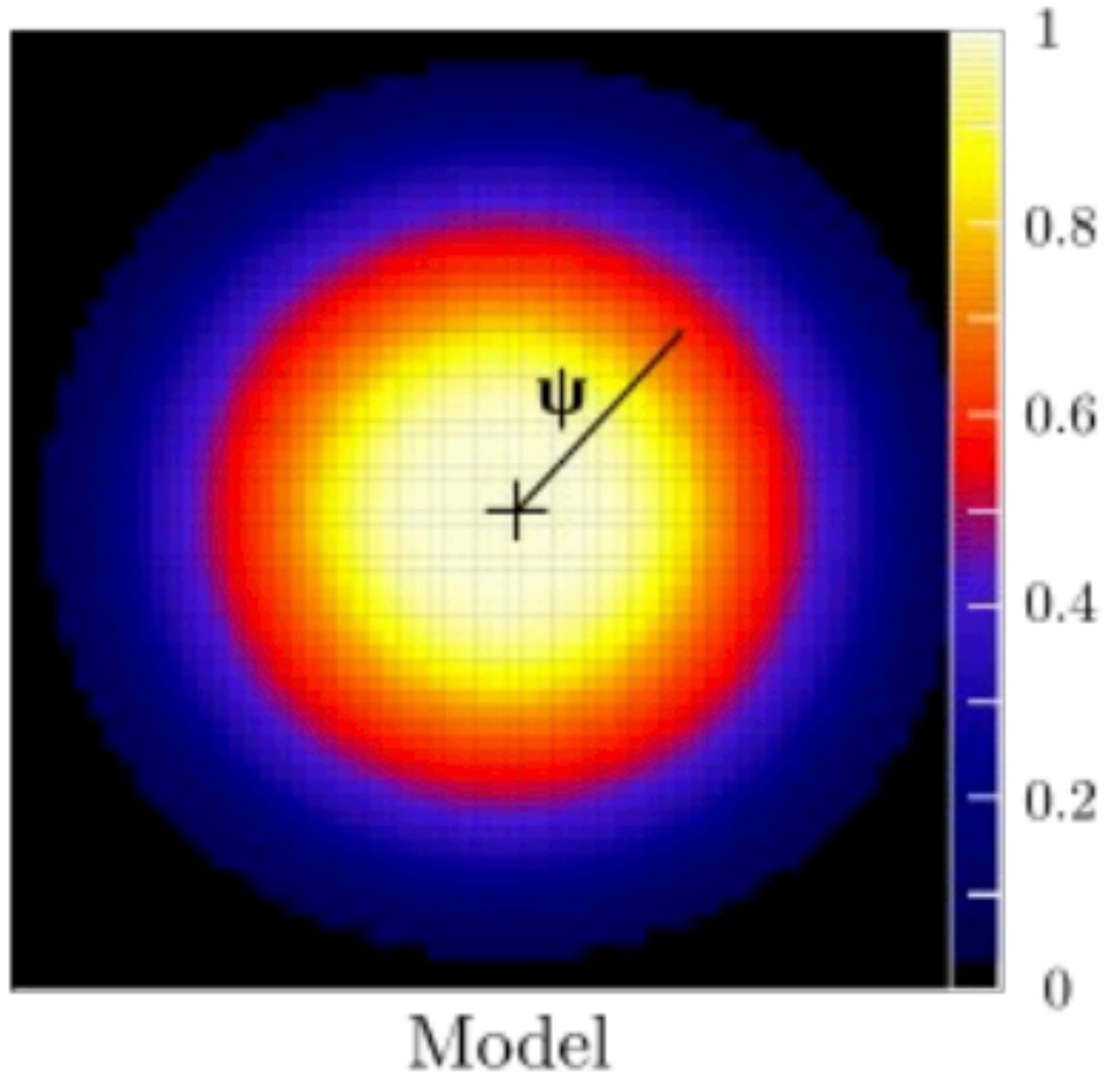
→ uses the whole FoV
→ tabulated using extragalactic FoVs, for different zenith angles
→ applied for each run separately
→ assume radial symmetry

Ring Background



Field of view Background

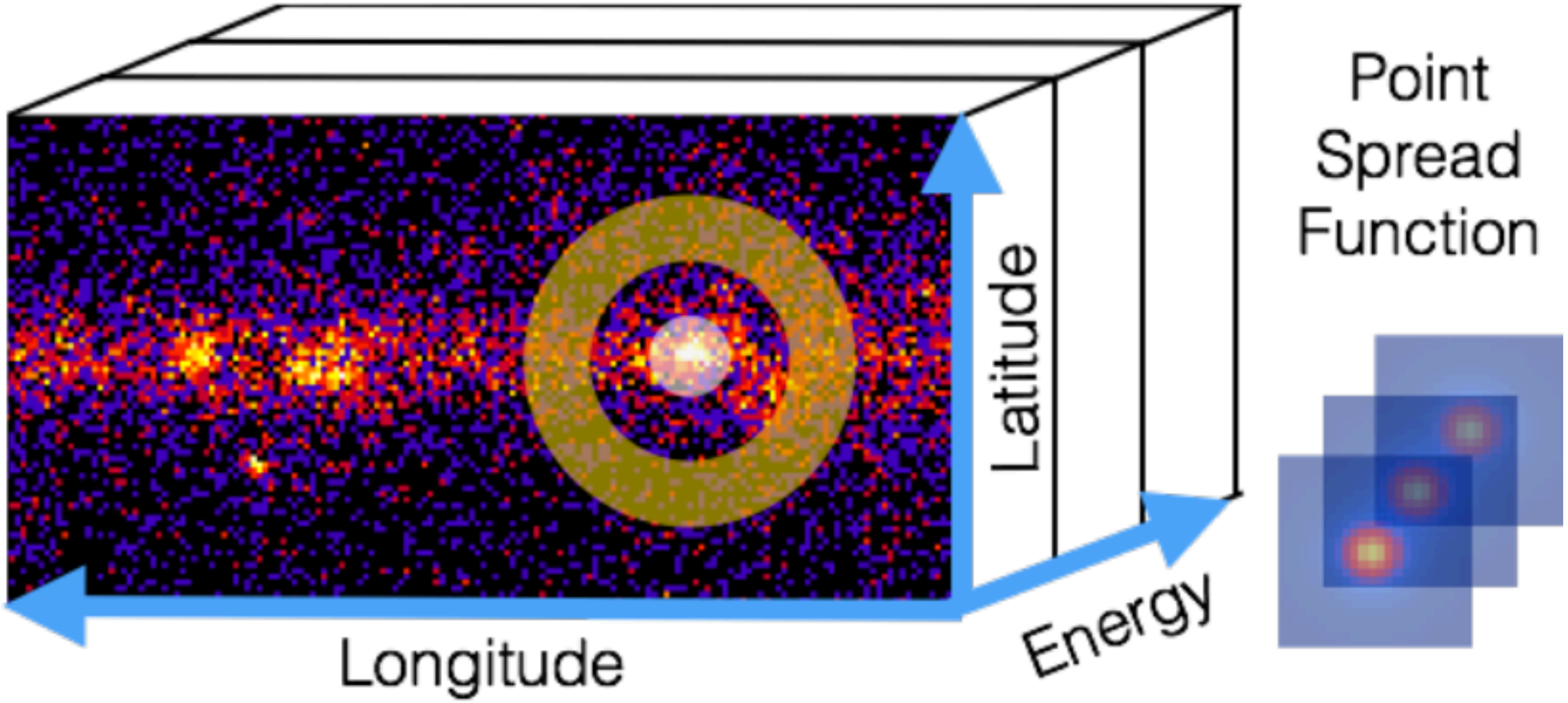




Gamma-ray detection

The Cherenkov Technique

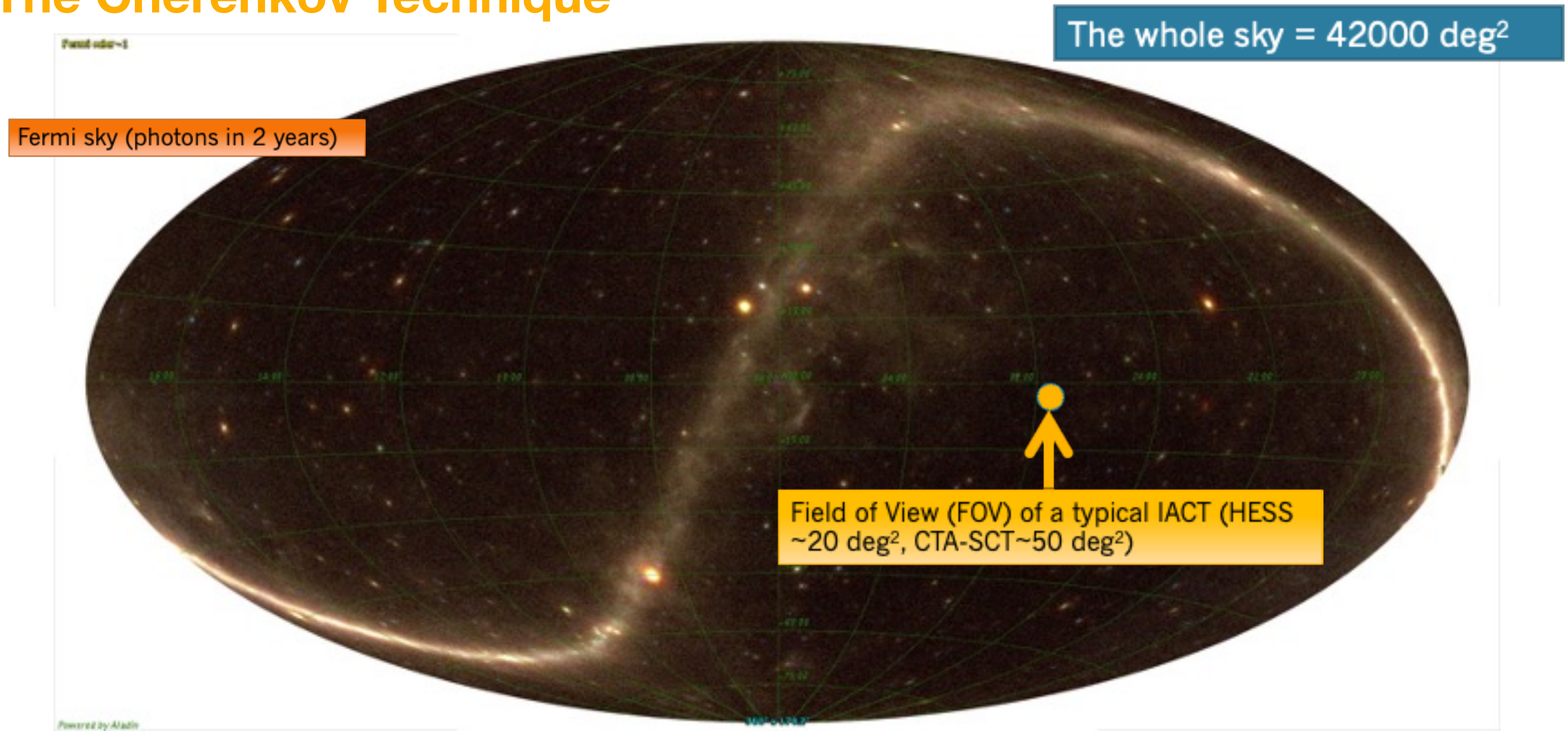
- Improved reconstruction techniques (3D)



Moralejo 2018

Gamma-ray detection

The Cherenkov Technique

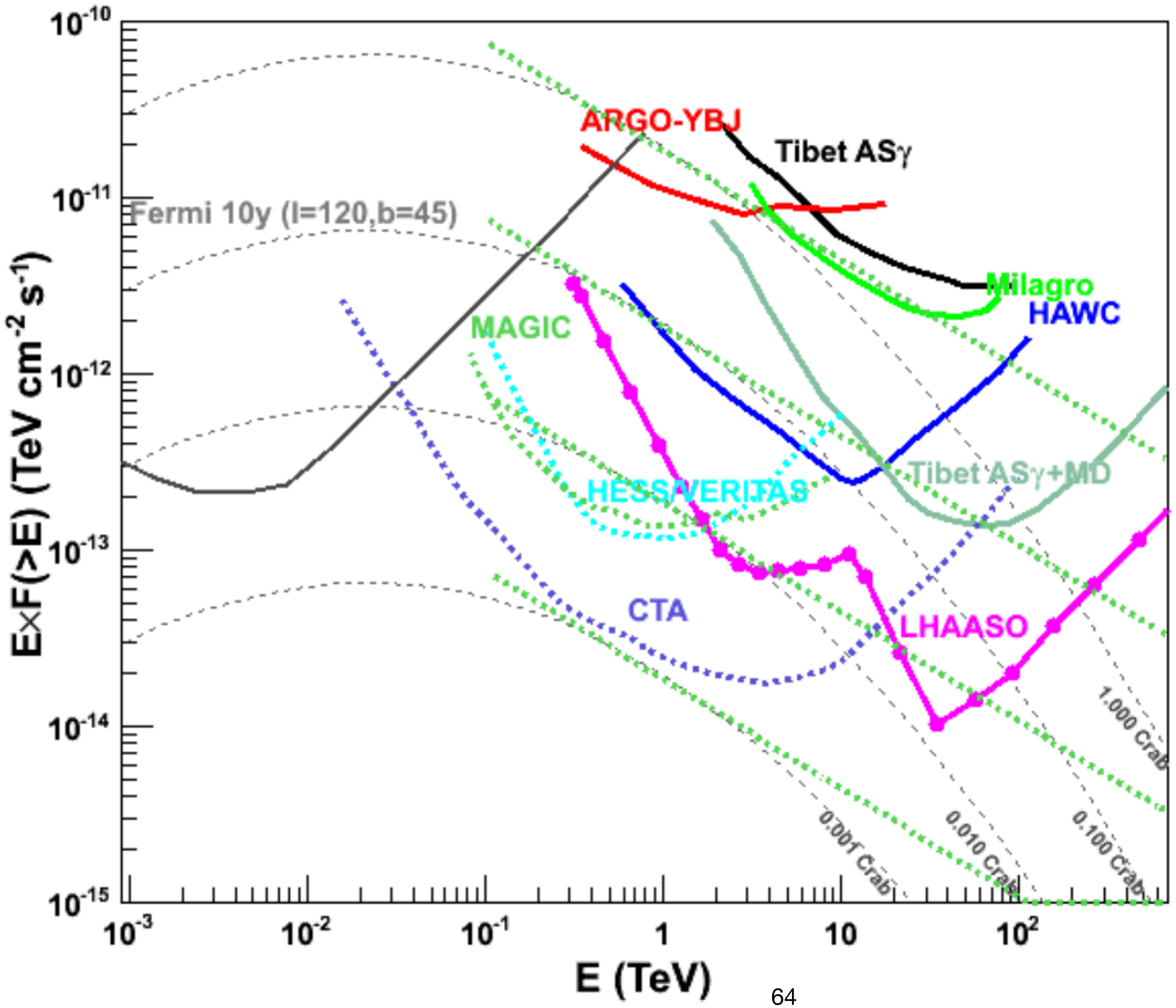



H.E.S.S. (Namibia)
4 x 108 m2 (since 2003)
1 x 614 m2 (since 2012)


MAGIC (La Palma)
2 x 236 m2 (since 2003 / 2009)

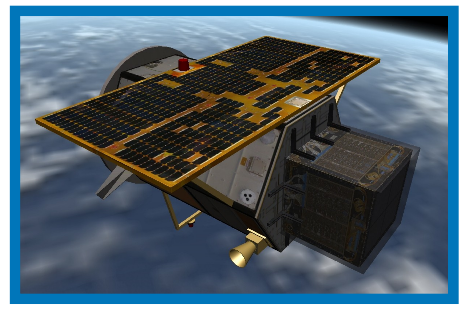

VERITAS (Arizona)
4 x 110 m2 (since 2007)

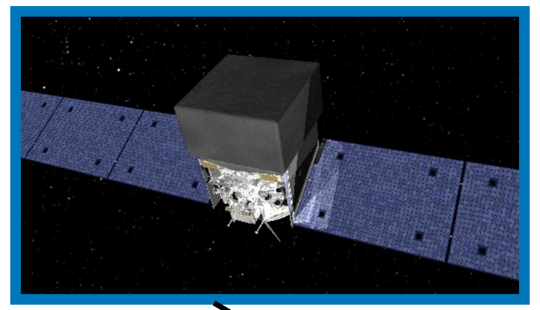
Gamma-ray detection
Pros and Cons



Gamma-ray detection

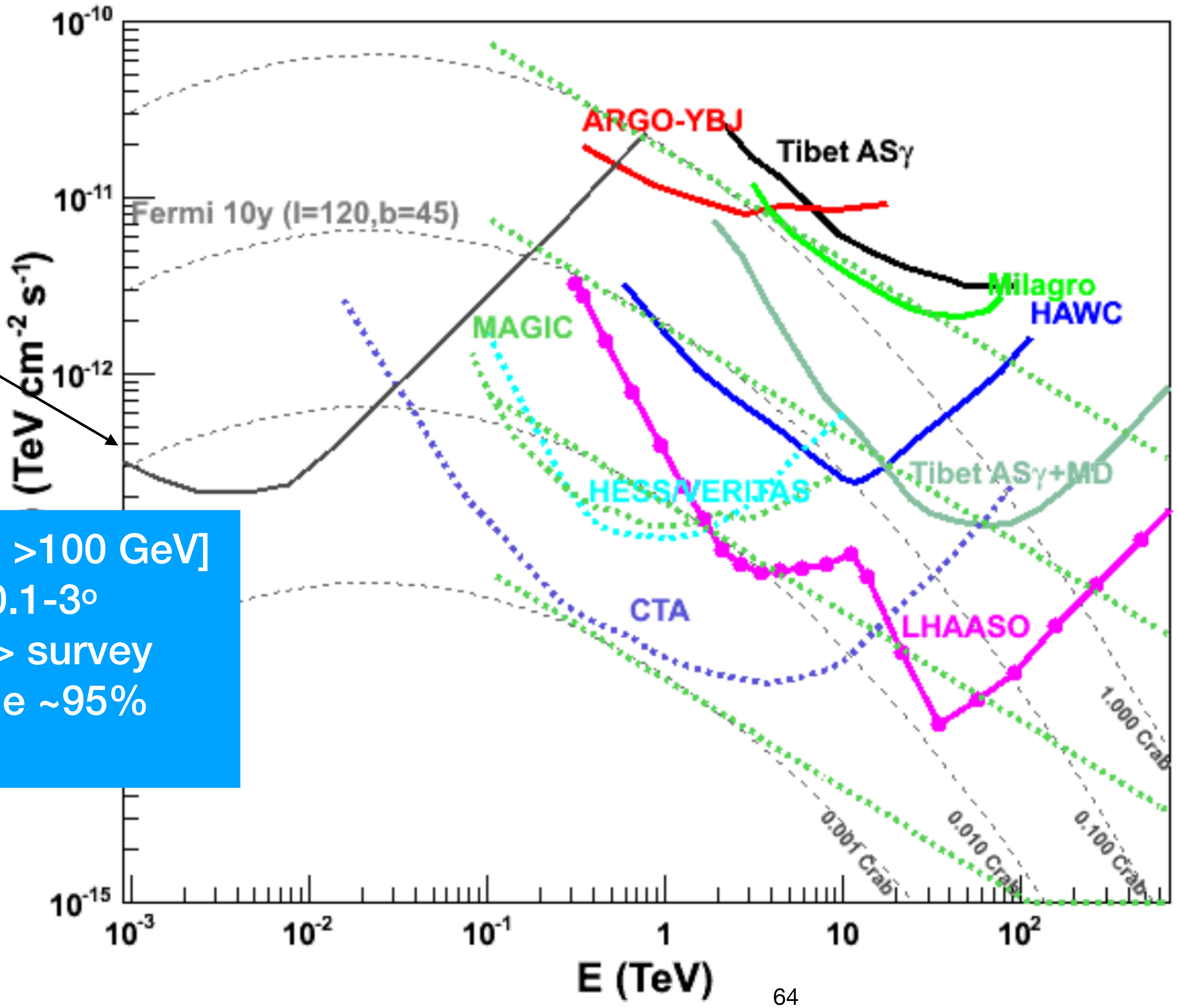
Pros and Cons





Satellites

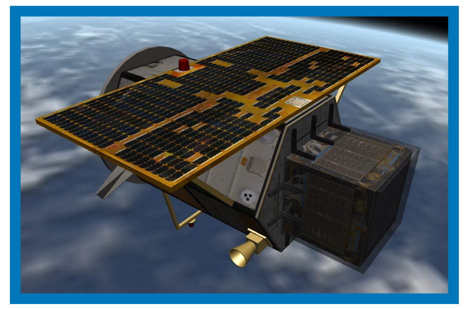
E=[100MeV - >100 GeV]
PSF ~0.1-3°
Aperture > survey
Duty Cycle ~95%

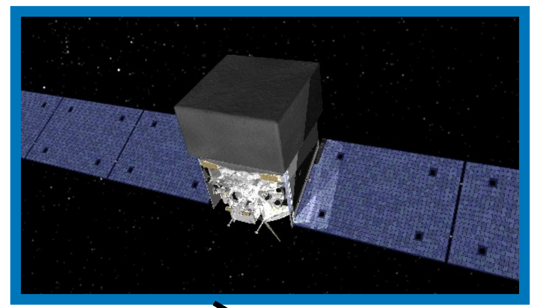


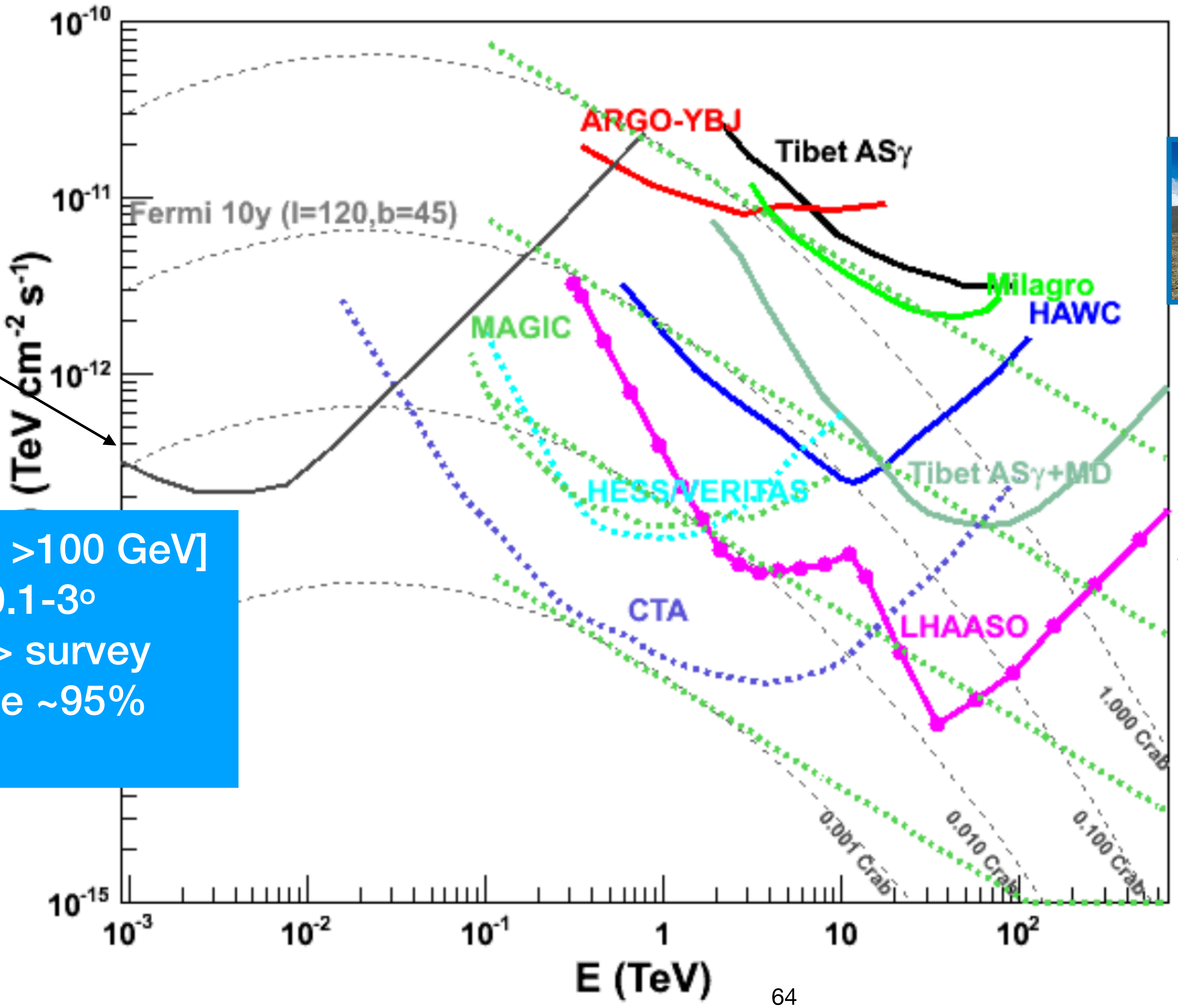
DESY.

Gamma-ray detection

Pros and Cons







E=[10 - >1000] TeV
PSF ~0.2-0.7º
Aperture > 2 sr
Duty Cycle ~90%

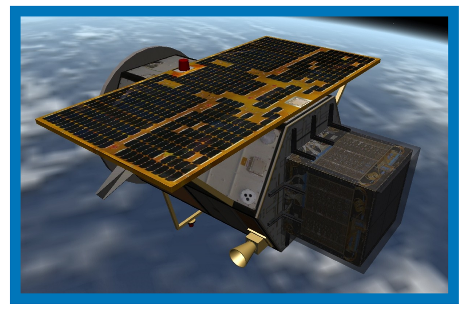
Particle Detectors

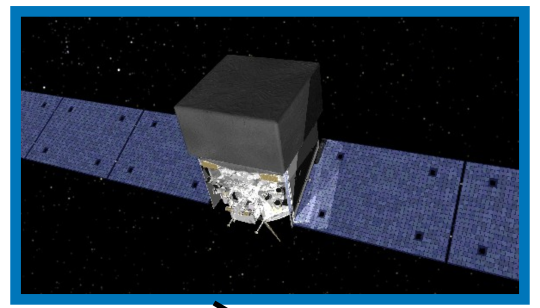
Satellites

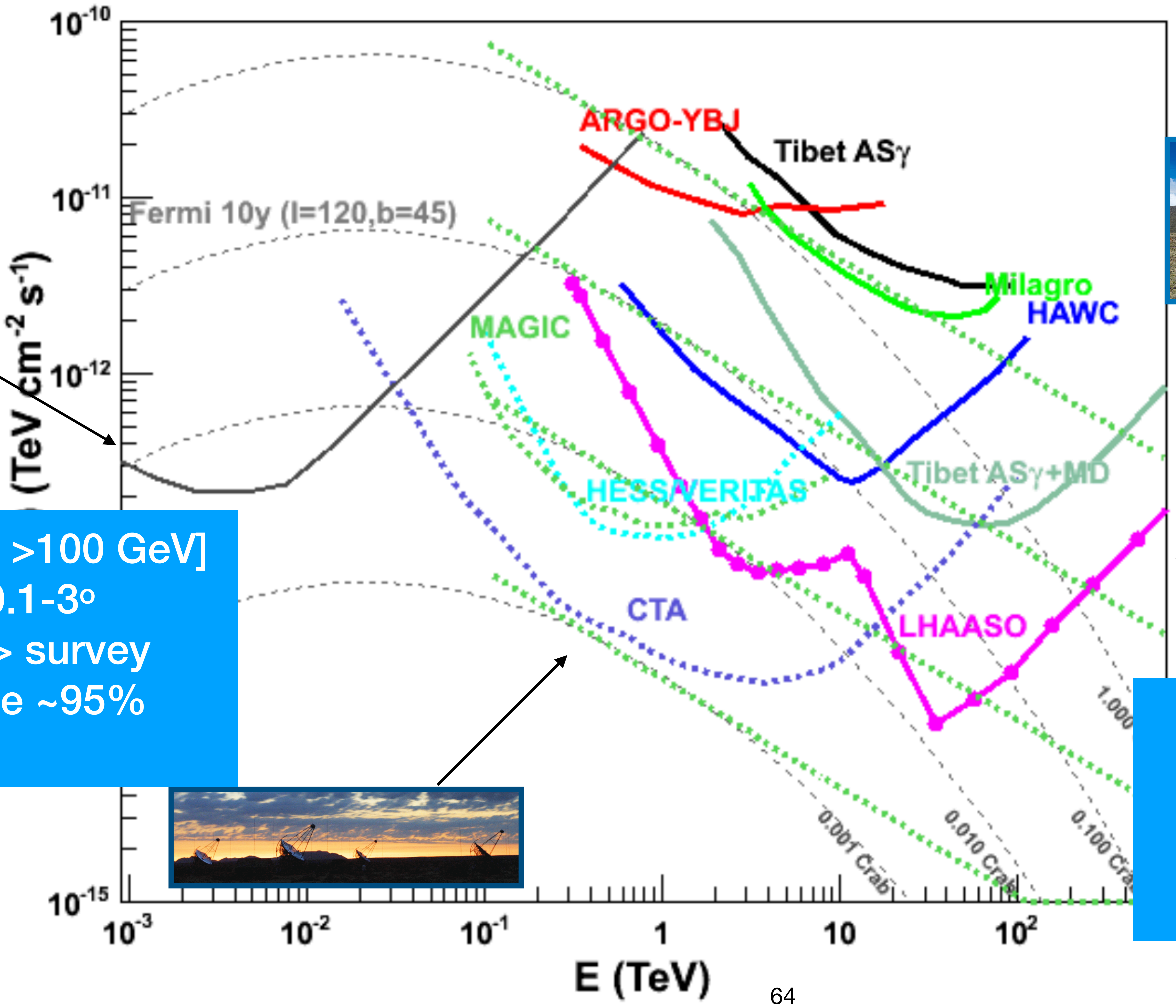
E=[100MeV - >100 GeV]
PSF ~0.1-3º
Aperture > survey
Duty Cycle ~95%

Gamma-ray detection

Pros and Cons







E=[10 - >1000] TeV
PSF ~0.2-0.7°
Aperture > 2 sr
Duty Cycle ~90%

Particle Detectors

Satellites

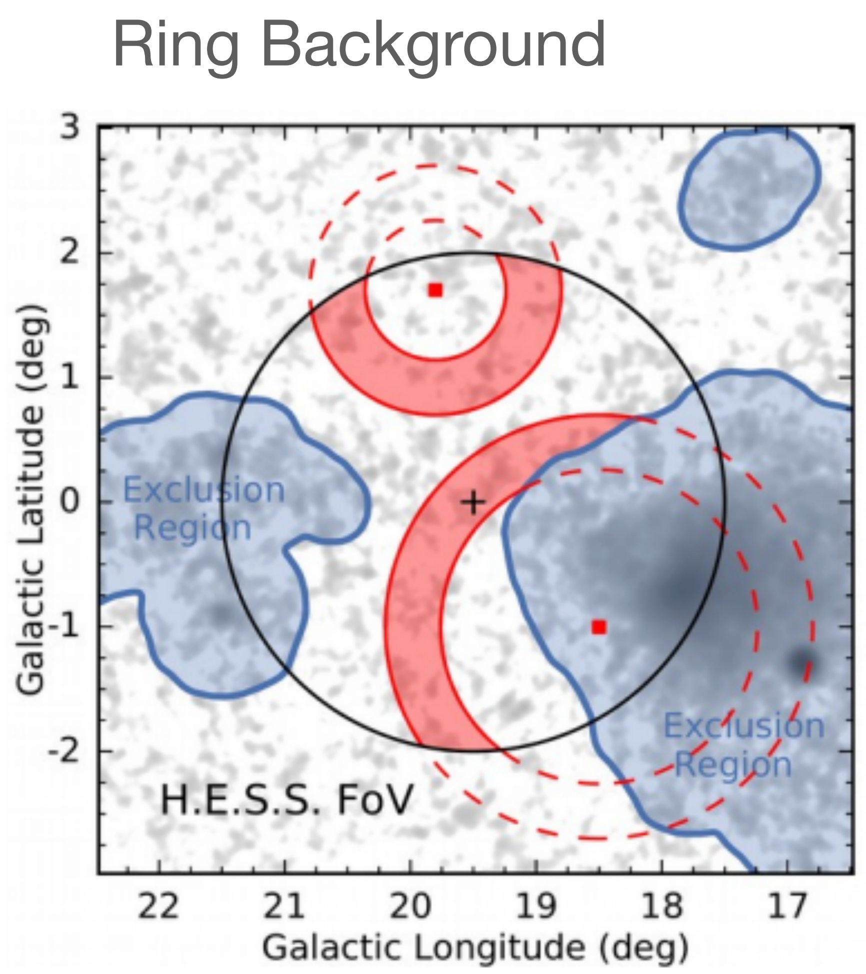
E=[100MeV - >100 GeV]
PSF ~0.1-3°
Aperture > survey
Duty Cycle ~95%

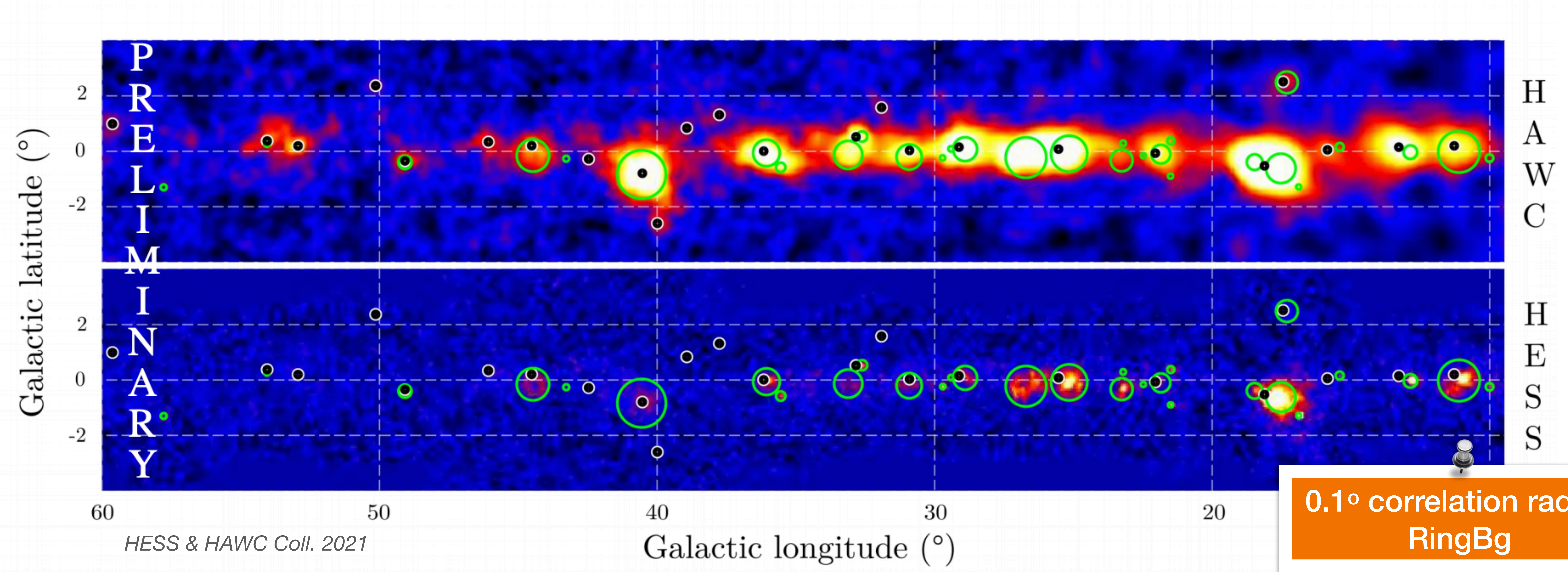
IACTs

E=[0.02 - 100] TeV
PSF ~0.05°
Aperture ~0.003 sr
Duty Cycle ~10%

Gamma-ray detection

Pros and Cons





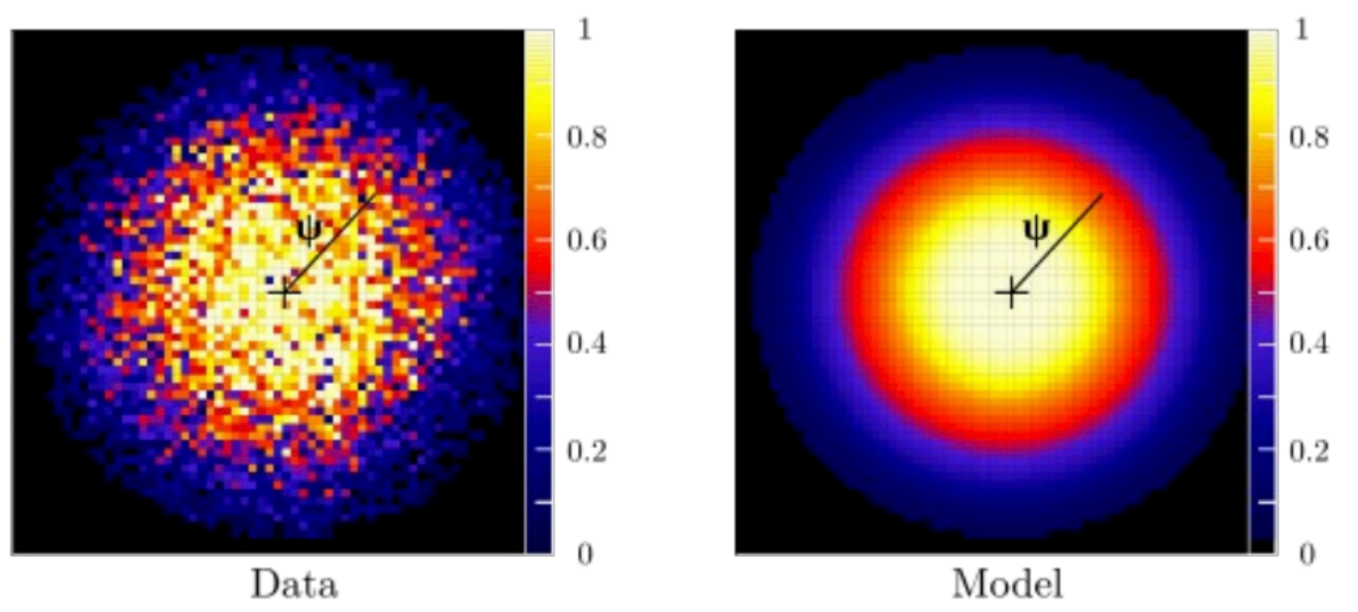
0.1° correlation radius
RingBg

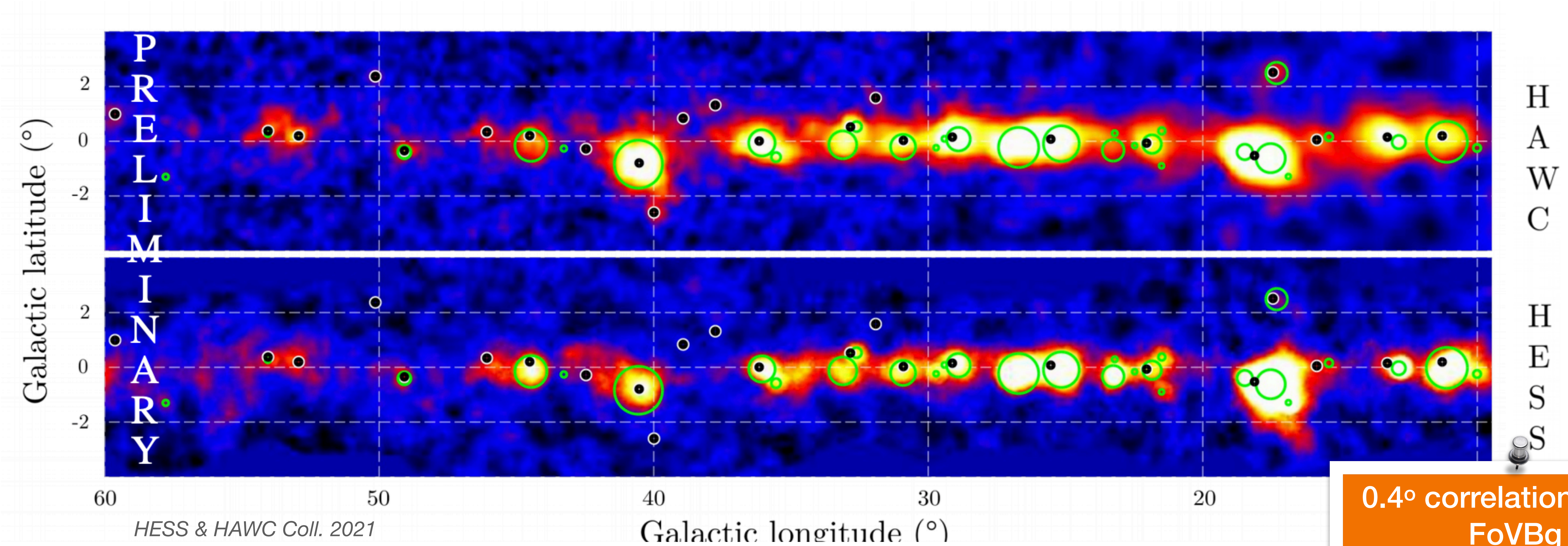
DESY.

Gamma-ray detection

Pros and Cons

Field of view Background





HESS & HAWC Coll. 2021

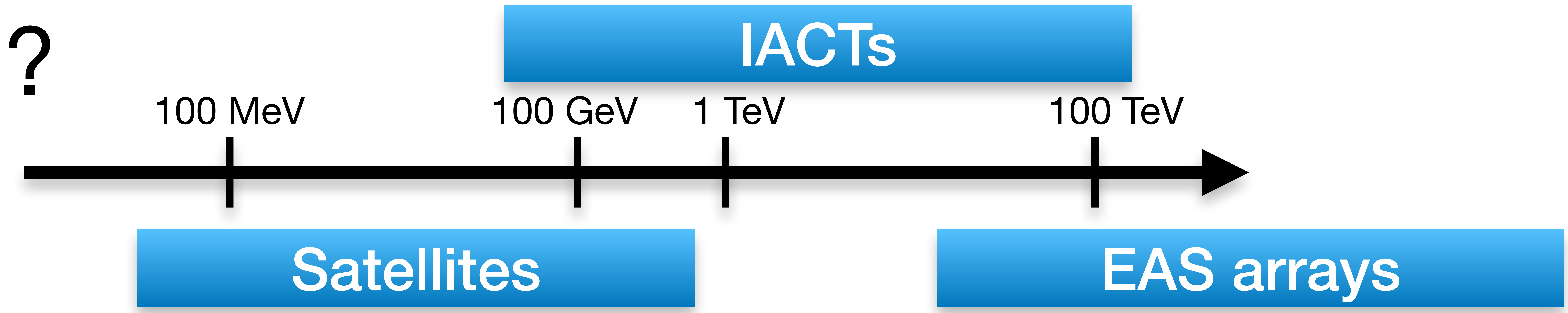
0.4° correlation radius FoVBg

DESY.

Future facilities

Planned instruments

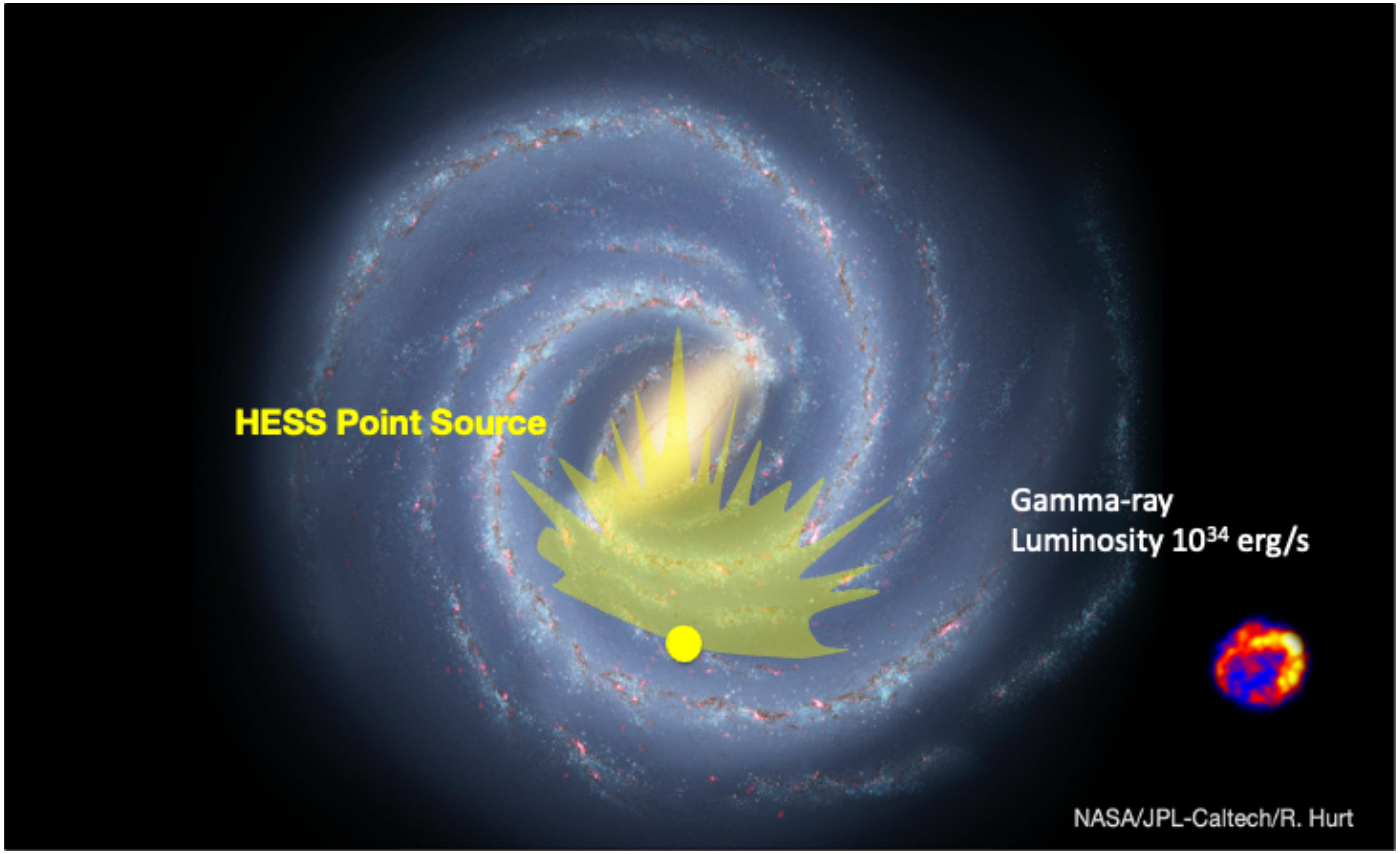
- What kind of instruments we need? **=> What kind of science goals we want to achieve?**



Future facilities

Planned instruments

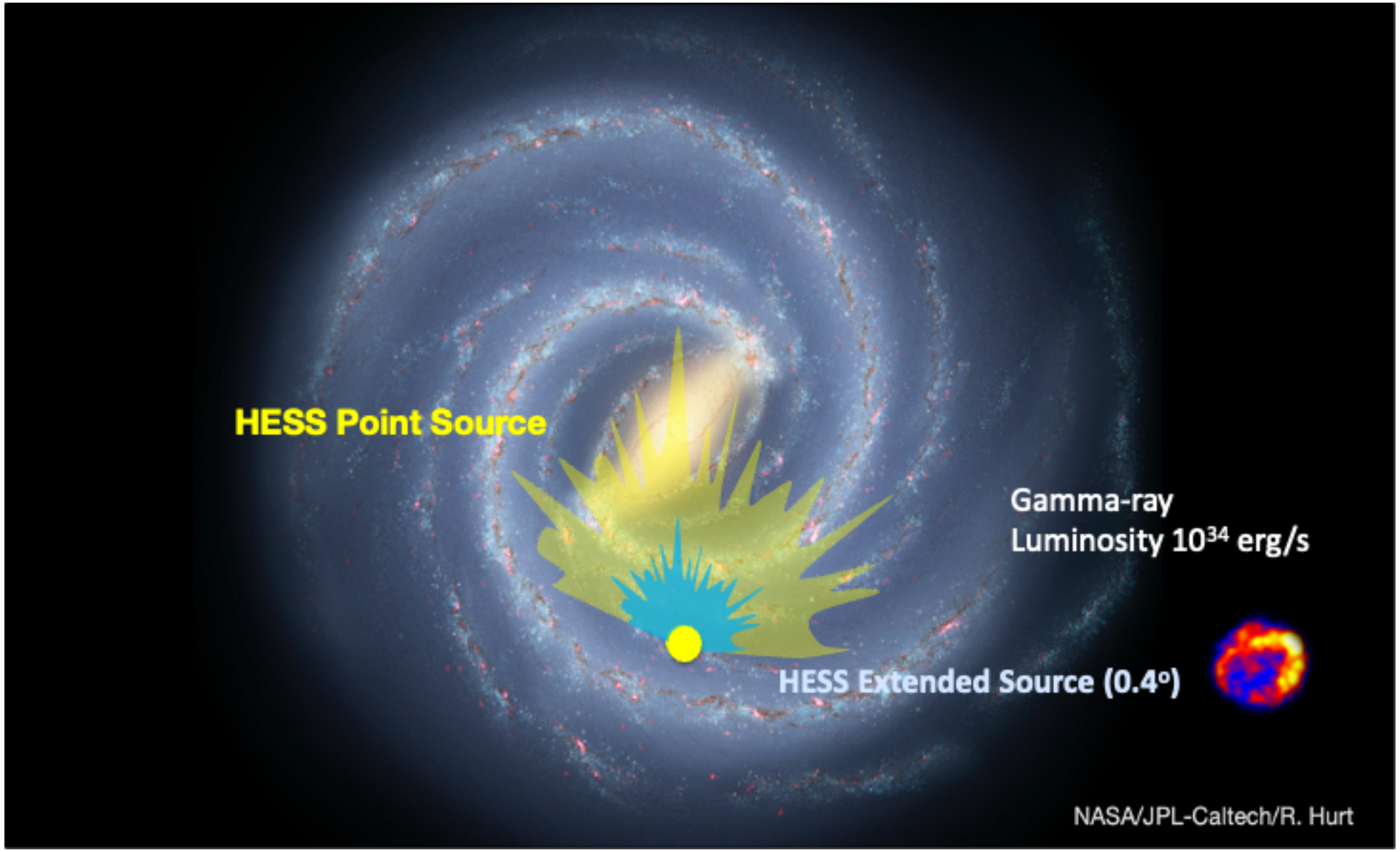
Understanding particle acceleration in our Galaxy



Future facilities

Planned instruments

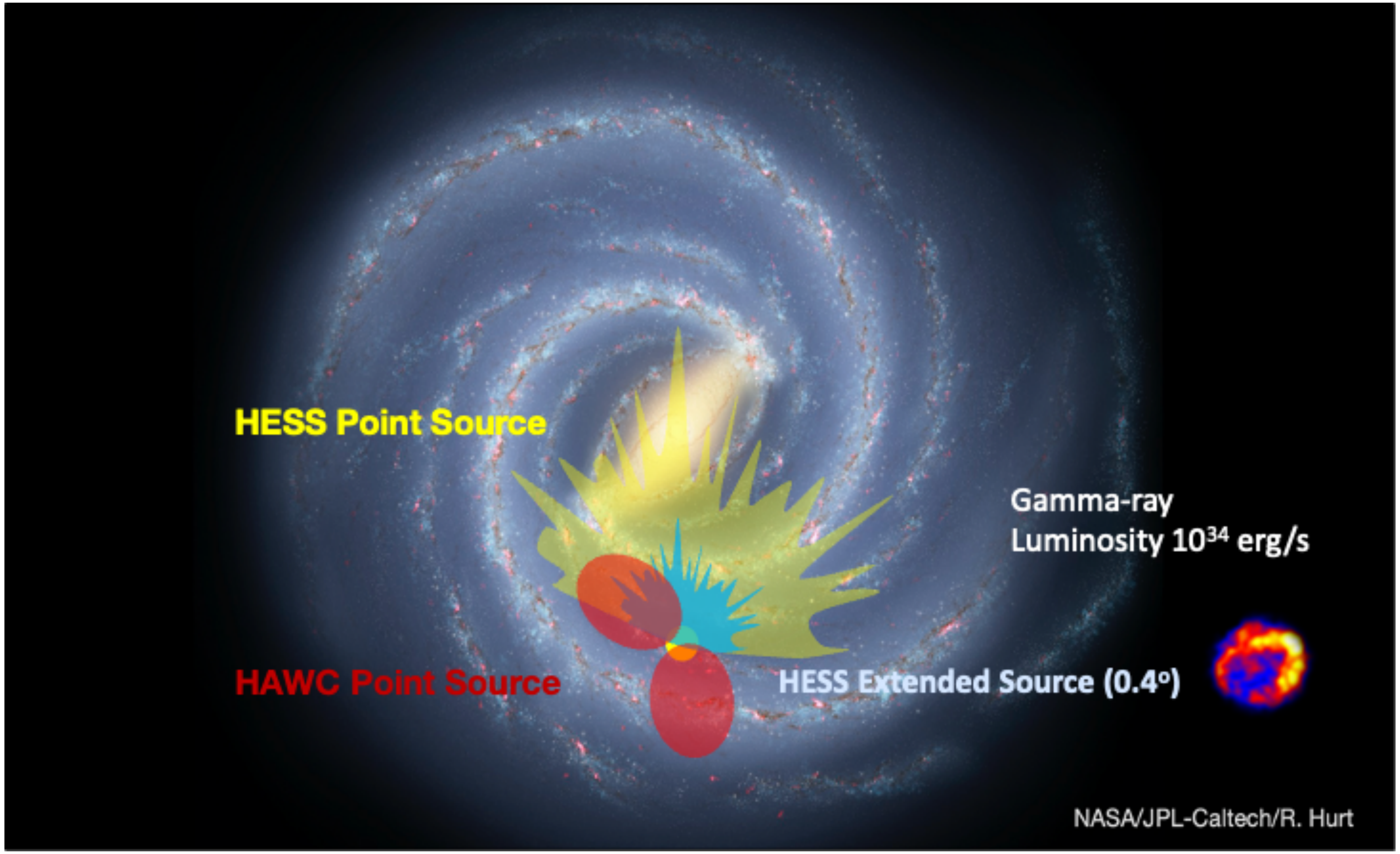
Understanding particle acceleration in our Galaxy



Future facilities

Planned instruments

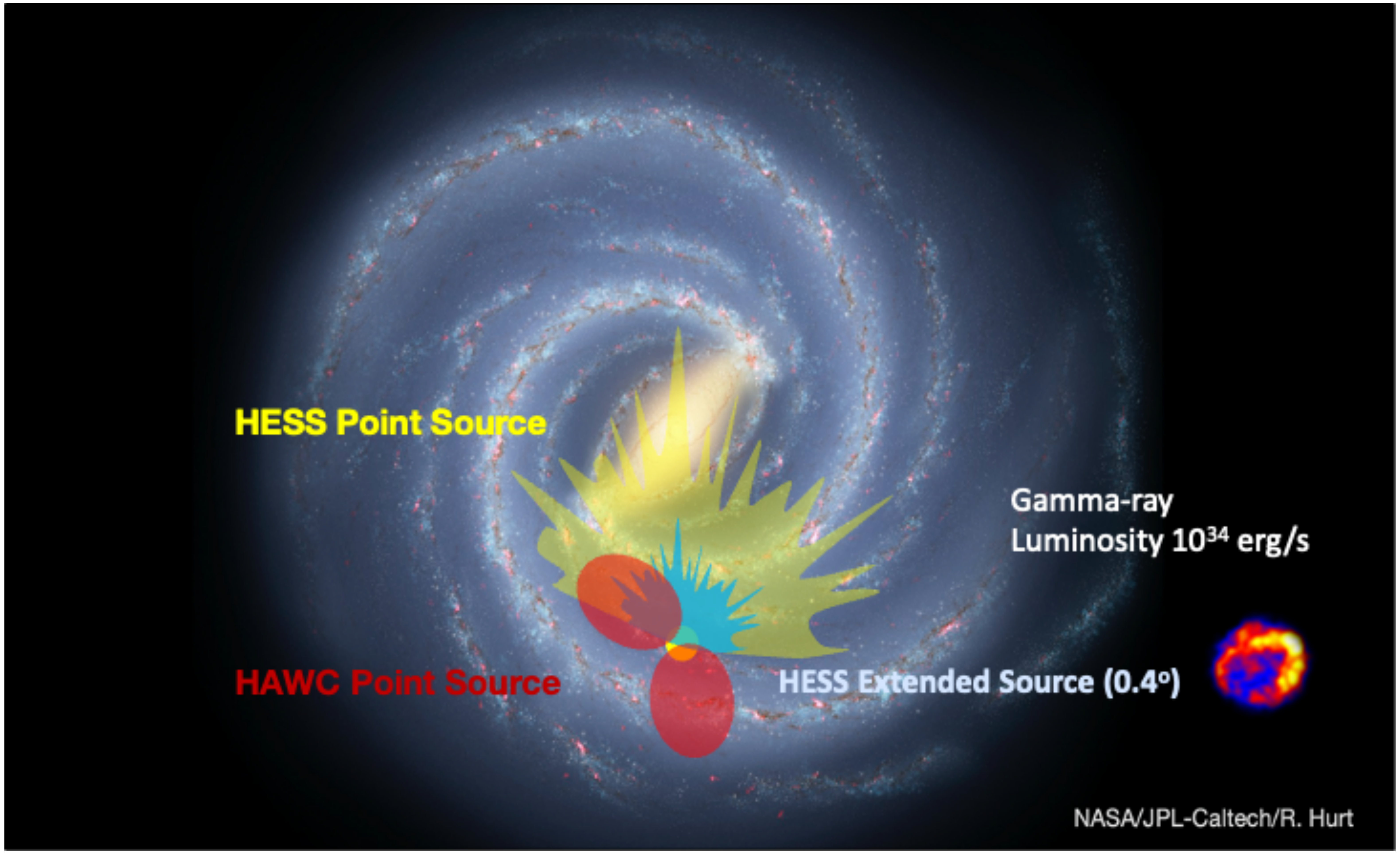
Understanding particle acceleration in our Galaxy



Future facilities

Planned instruments

Understanding particle acceleration in our Galaxy



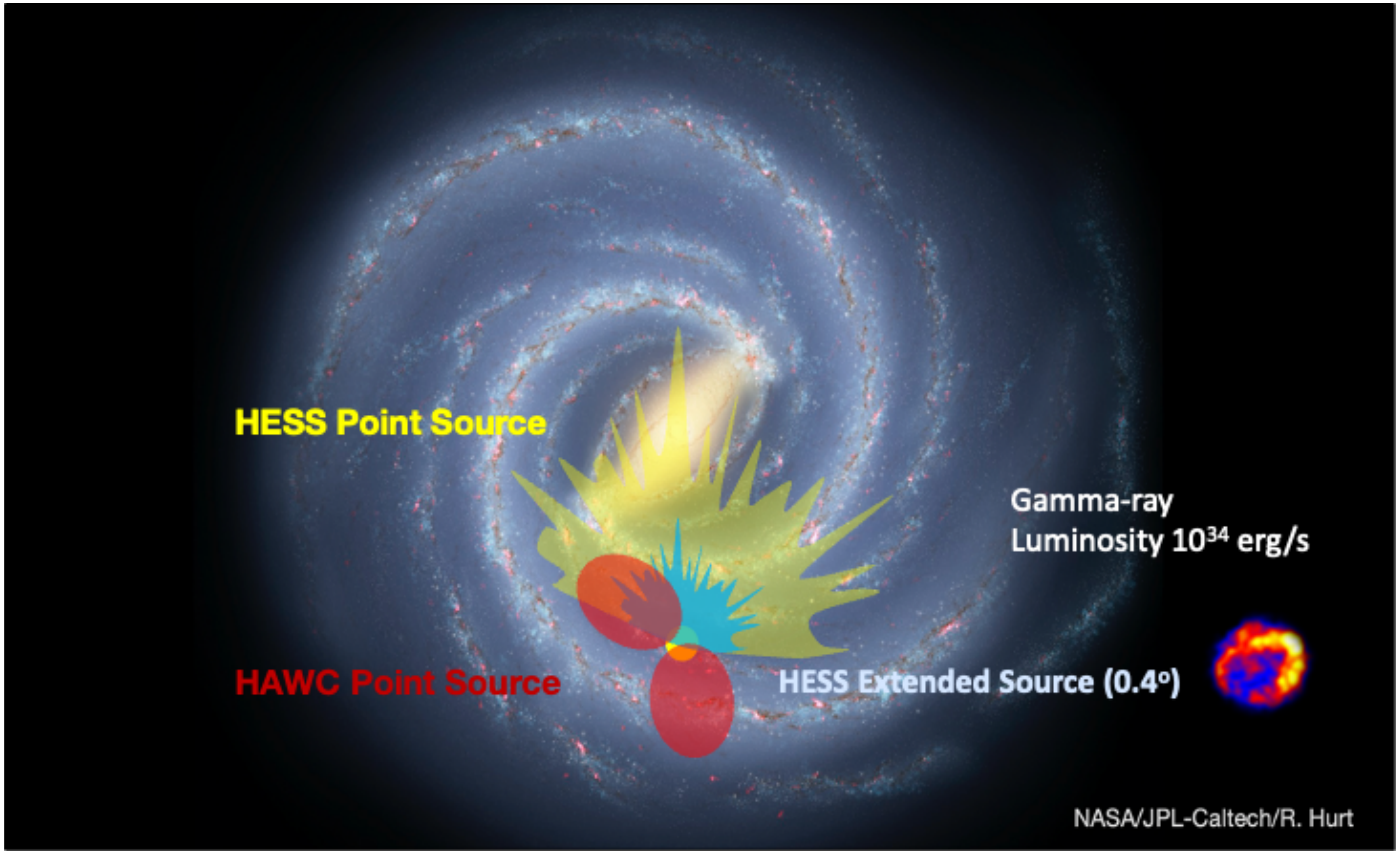
4

Future facilities

Planned instruments

Understanding particle acceleration in our Galaxy

Sensitivity x 10



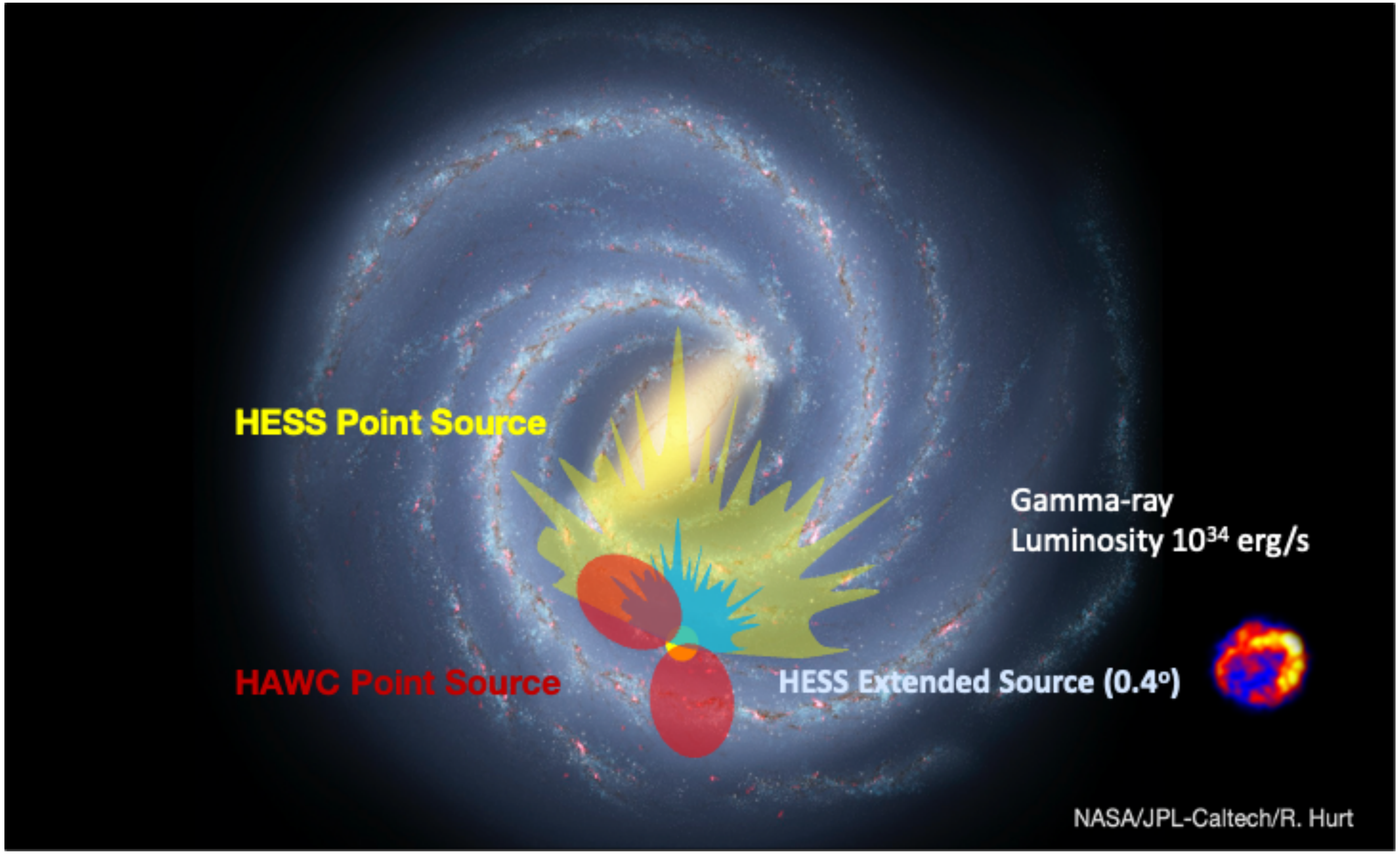
Future facilities

Planned instruments

Understanding particle acceleration in our Galaxy

Sensitivity x 10

Arcminutes Angular Resolution



Future facilities

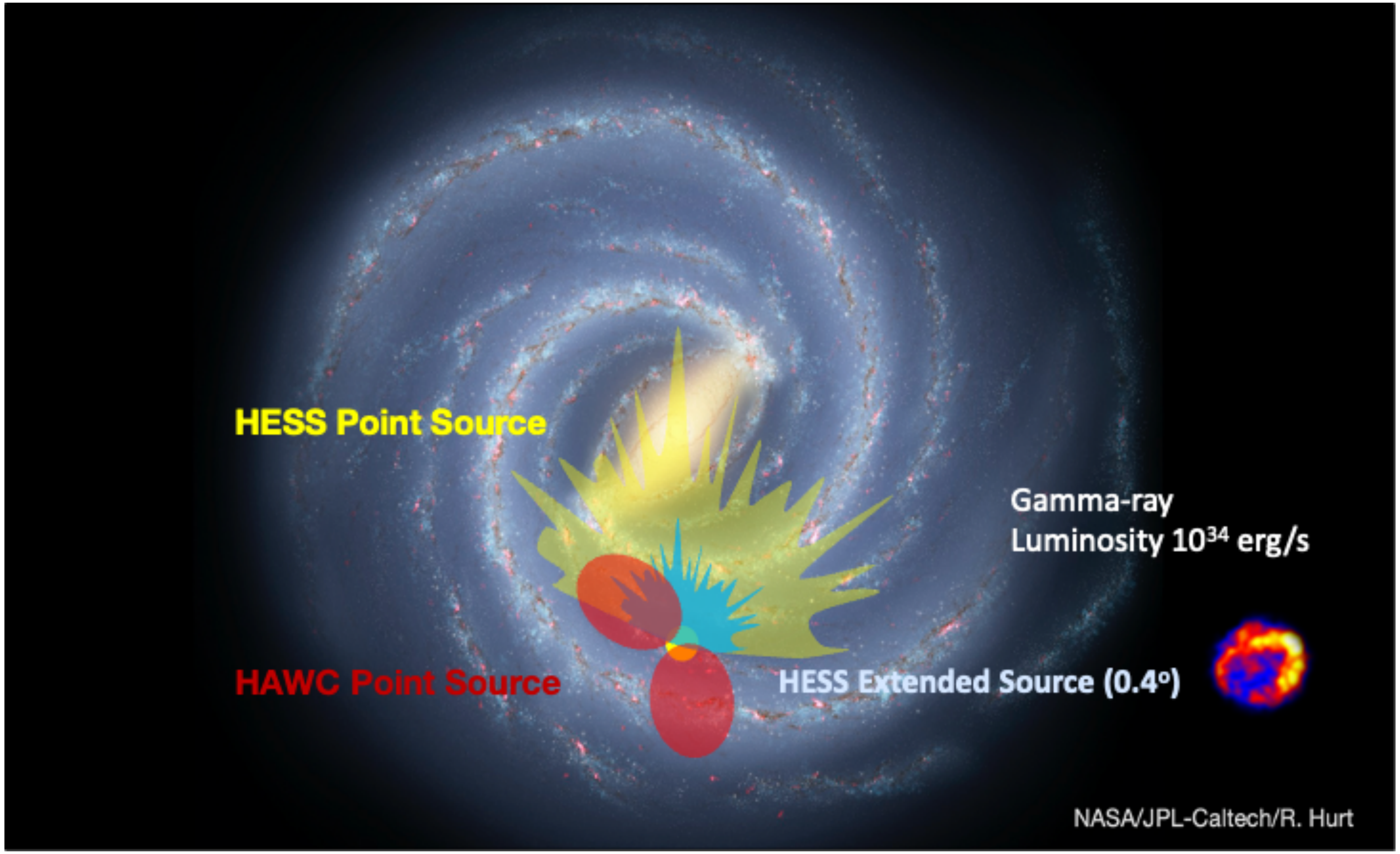
Planned instruments

Understanding particle acceleration in our Galaxy

Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution



Future facilities

Planned instruments

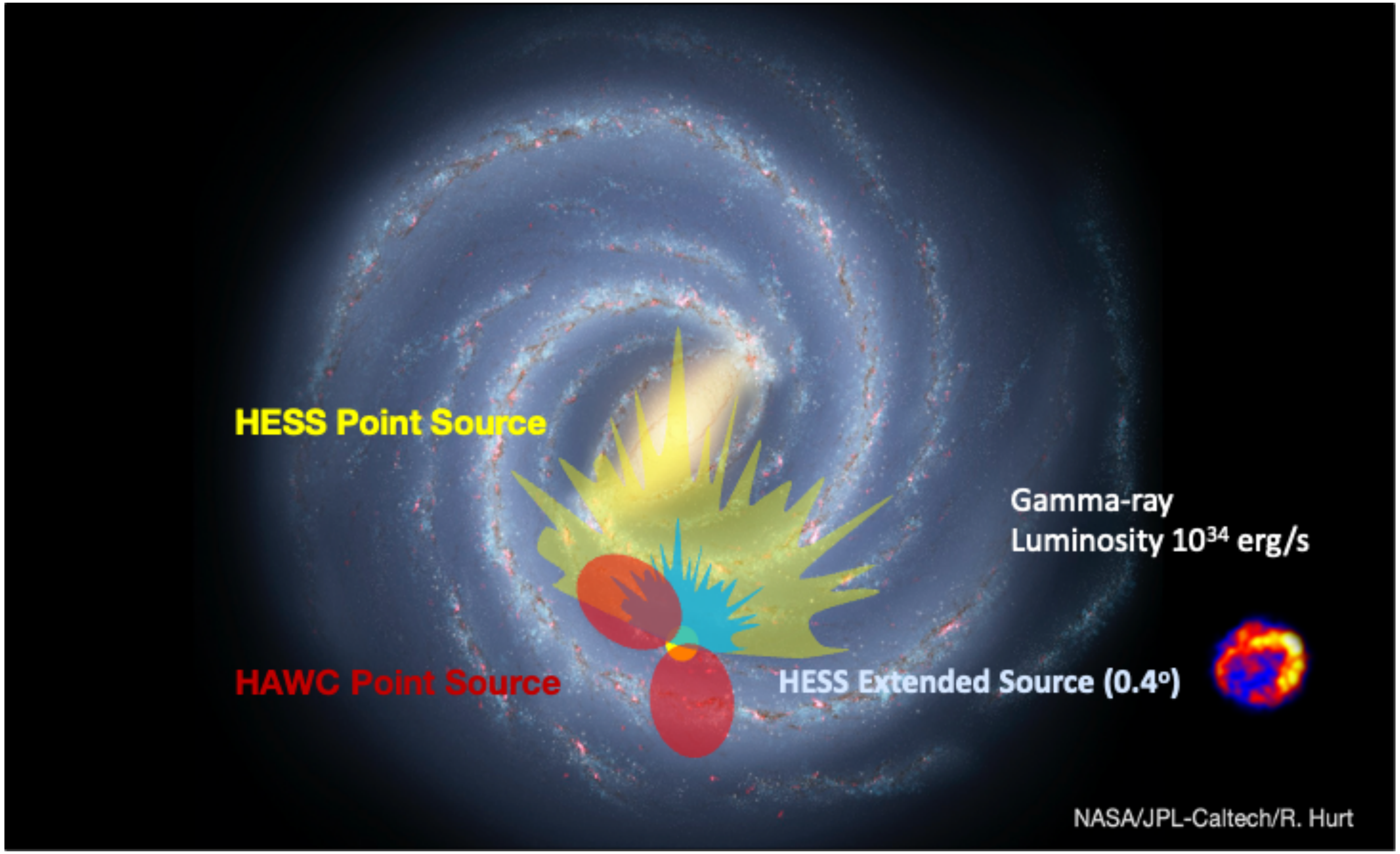
Understanding particle acceleration in our Galaxy

Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range



Future facilities

Planned instruments

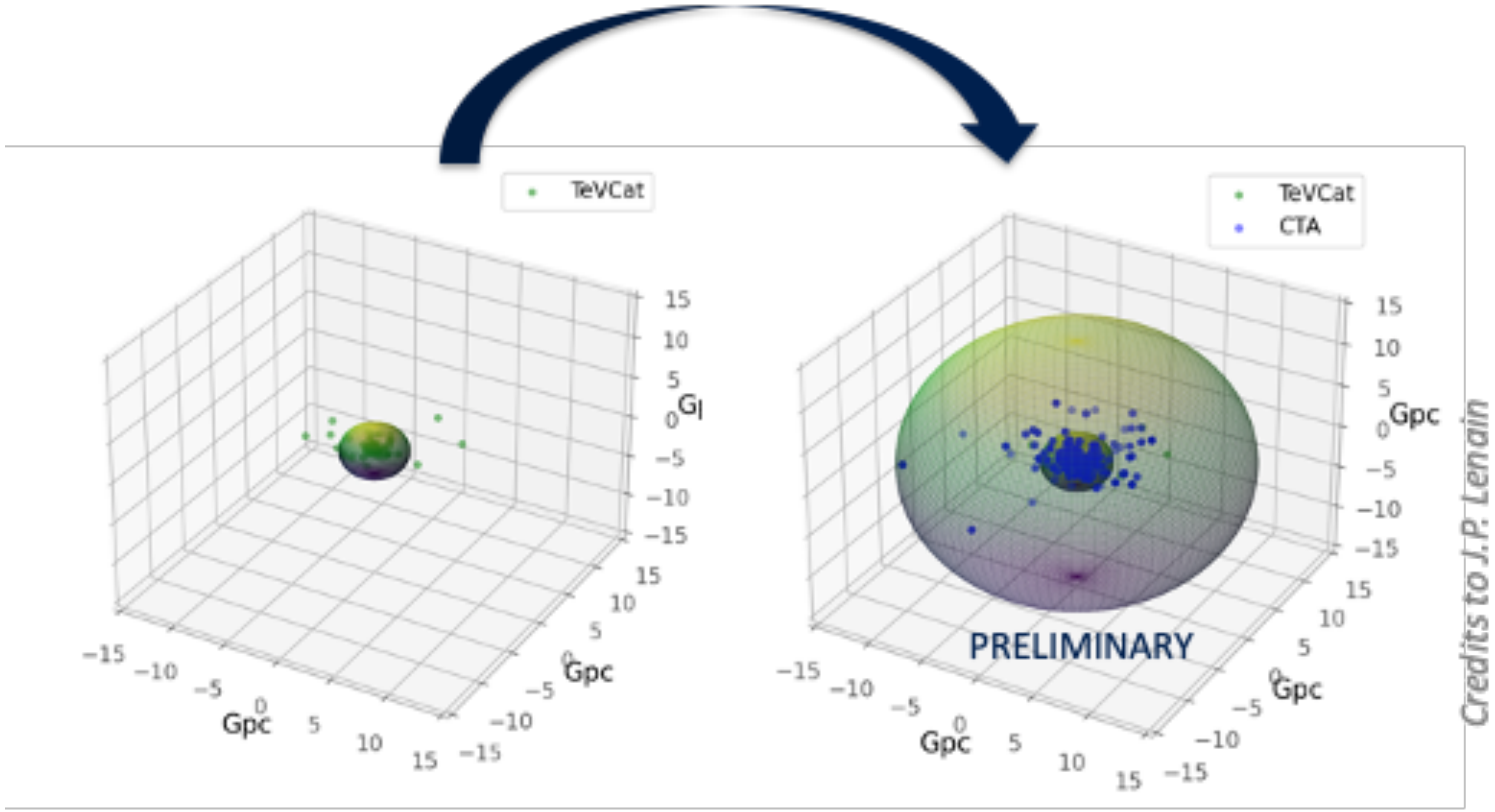
Understanding particle acceleration in our Galaxy

Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range



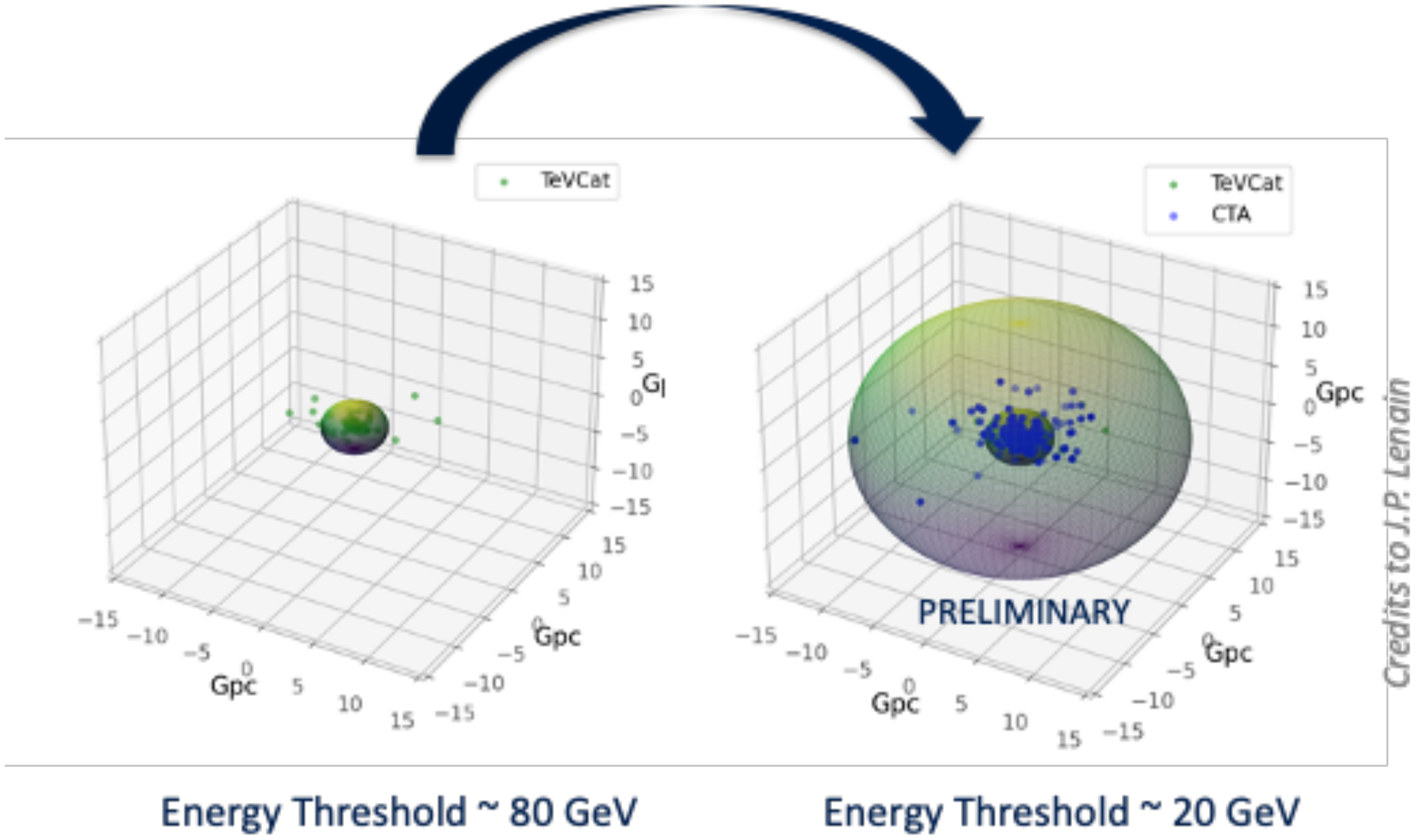
Energy Threshold ~ 80 GeV   Energy Threshold ~ 20 GeV

Future facilities

Planned instruments

Understanding particle acceleration in our Galaxy

- Sensitivity x 10
- Arcminutes Angular Resolution
- 10% Energy Resolution
- Wide Energy Range
- Full Sky Coverage



Future facilities

Planned instruments

A Census of Cosmic Particle Accelerators, at all scales

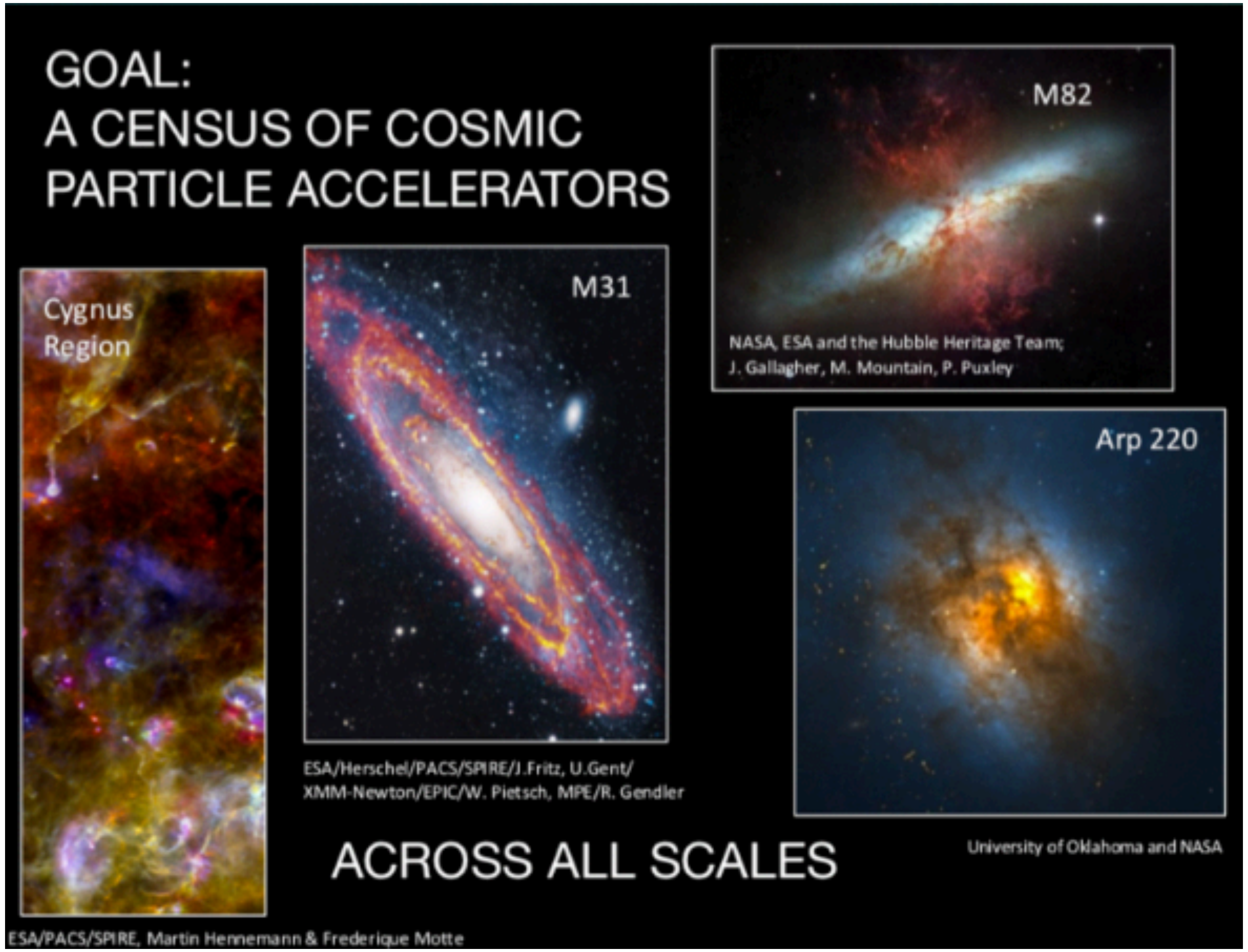
Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range

Full Sky Coverage



Low energies

Future facilities

Planned instruments

Large scale gamma-ray emission

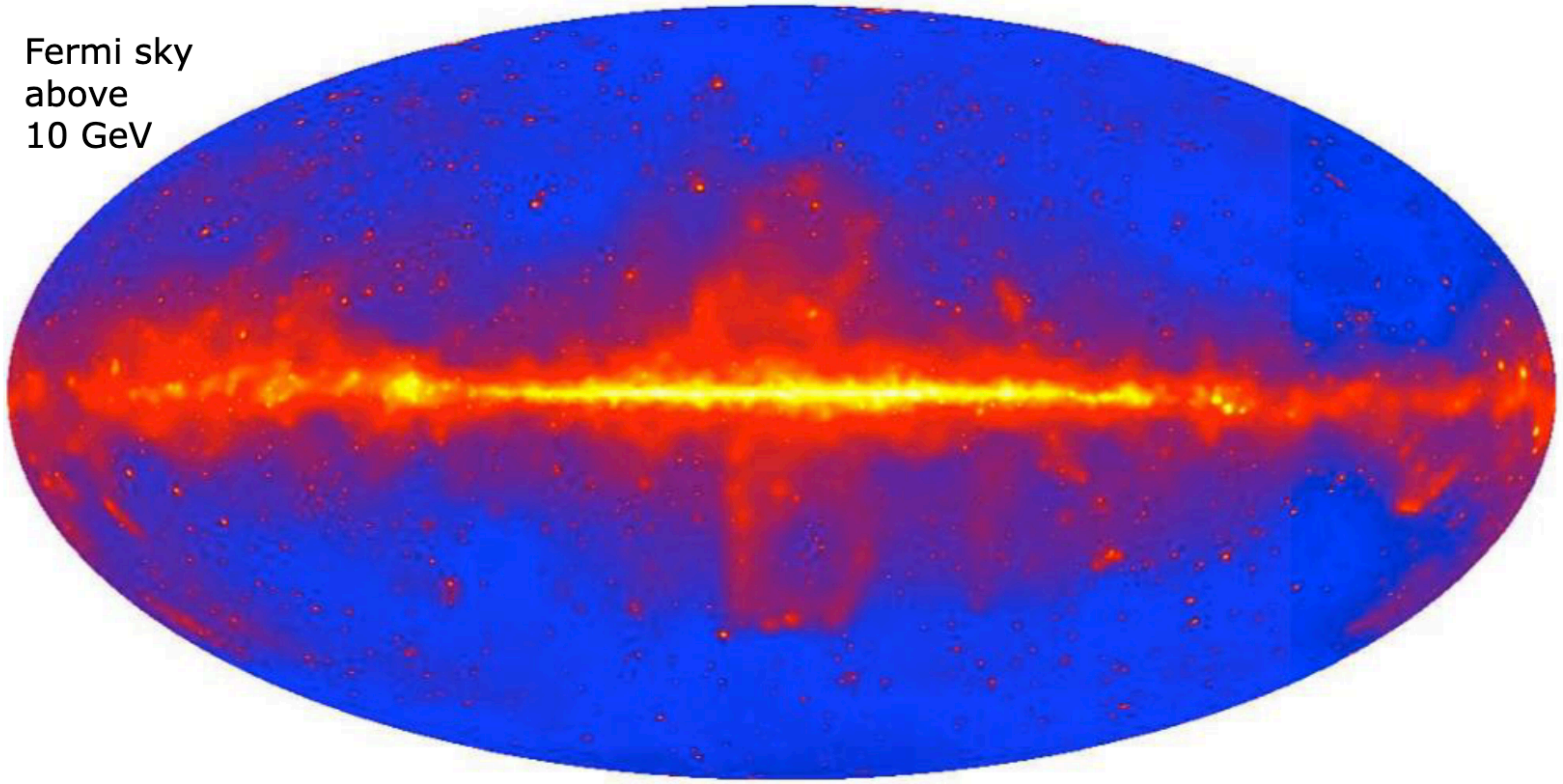
Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range

Full Sky Coverage



Low energies

Large Field of View

Future facilities

Planned instruments

Understanding jets and relativistic outflows such GRBs

Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range

Full Sky Coverage

Low energies

Large Field of View

4

Future facilities

Planned instruments

Understanding jets and relativistic outflows such GRBs

Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range

Full Sky Coverage

Low energies

Large Field of View

Fast response to Transients

Future facilities

Planned instruments

Searching for the electromagnetic counterpart of gravitational waves

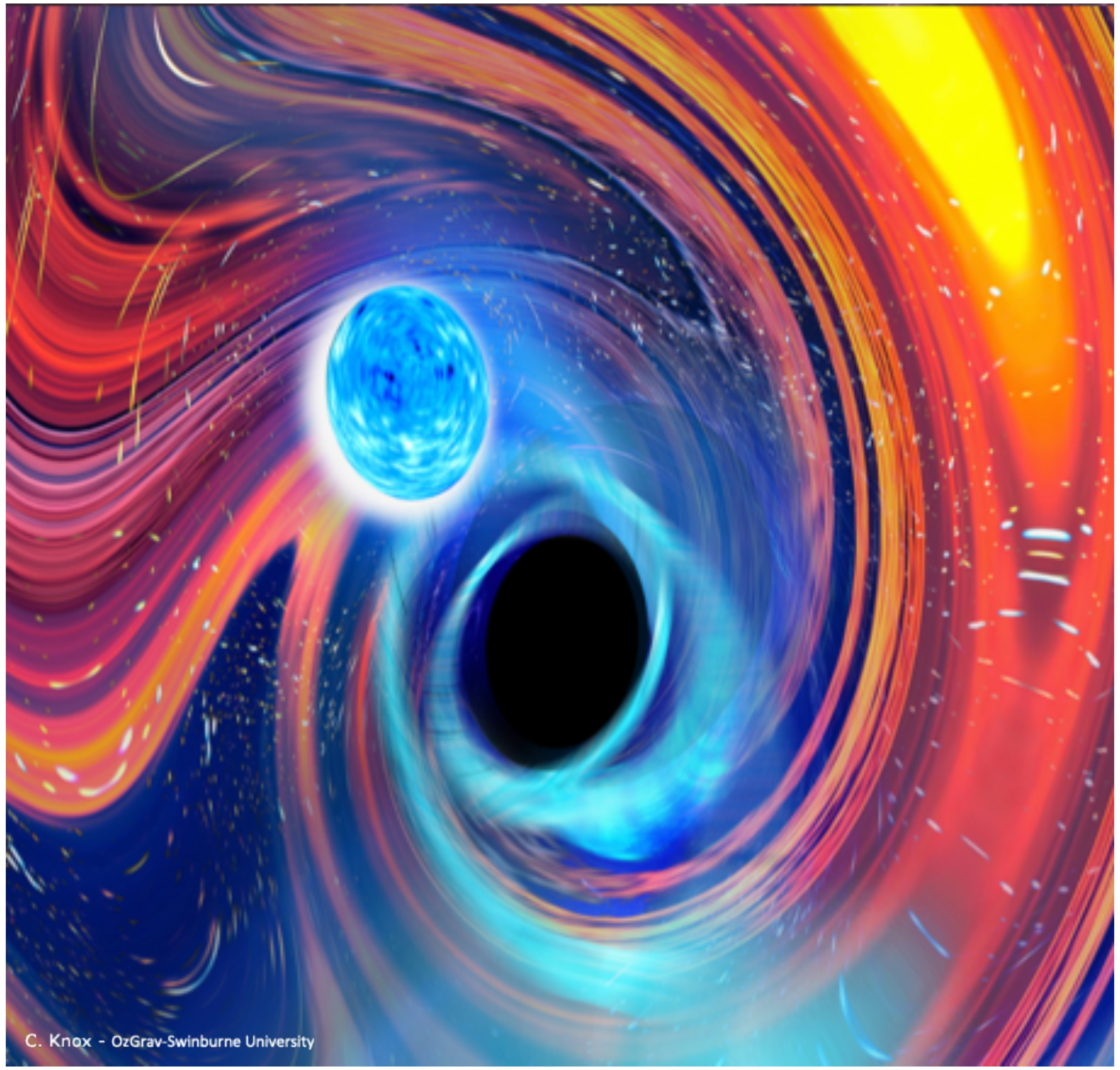
Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range

Full Sky Coverage



Low energies

Large Field of View

Future facilities

Planned instruments

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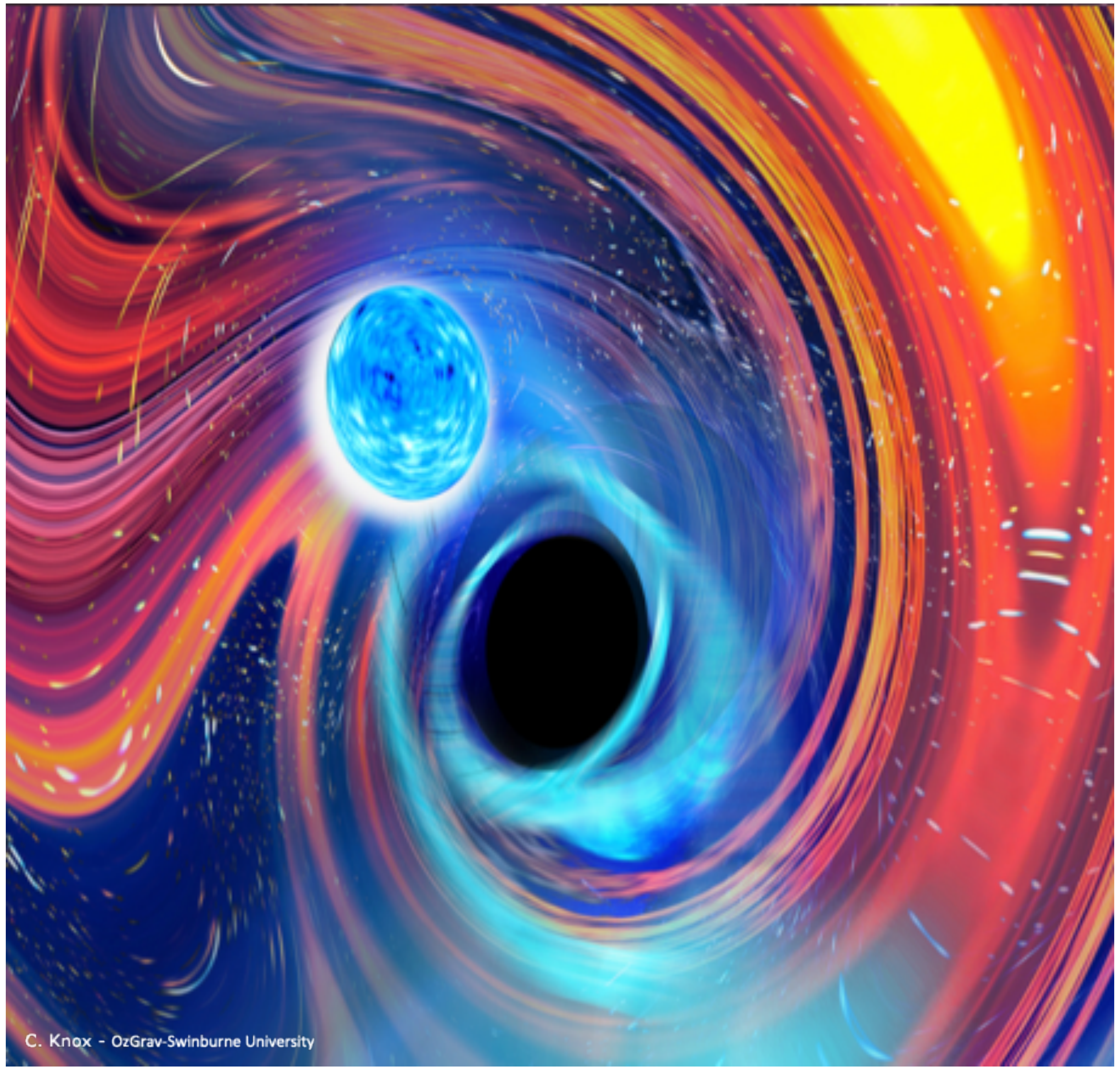


Low energies

Large Field of View

Fast response to Transients

Future facilities

Planned instruments

Understanding the medium through propagation of CRs (EBL, LIV)

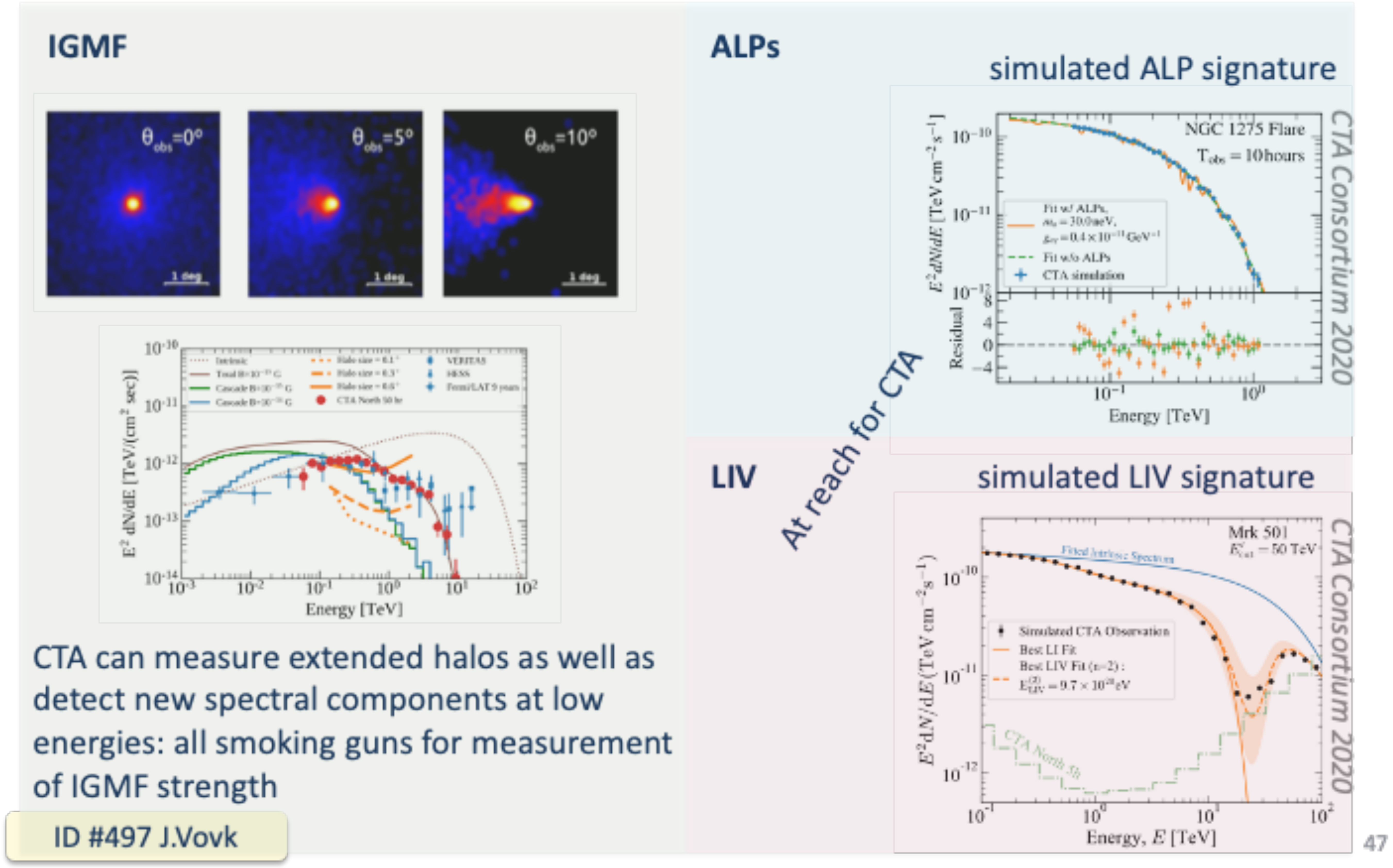
Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range

Full Sky Coverage



Low energies

Large Field of View

Future facilities

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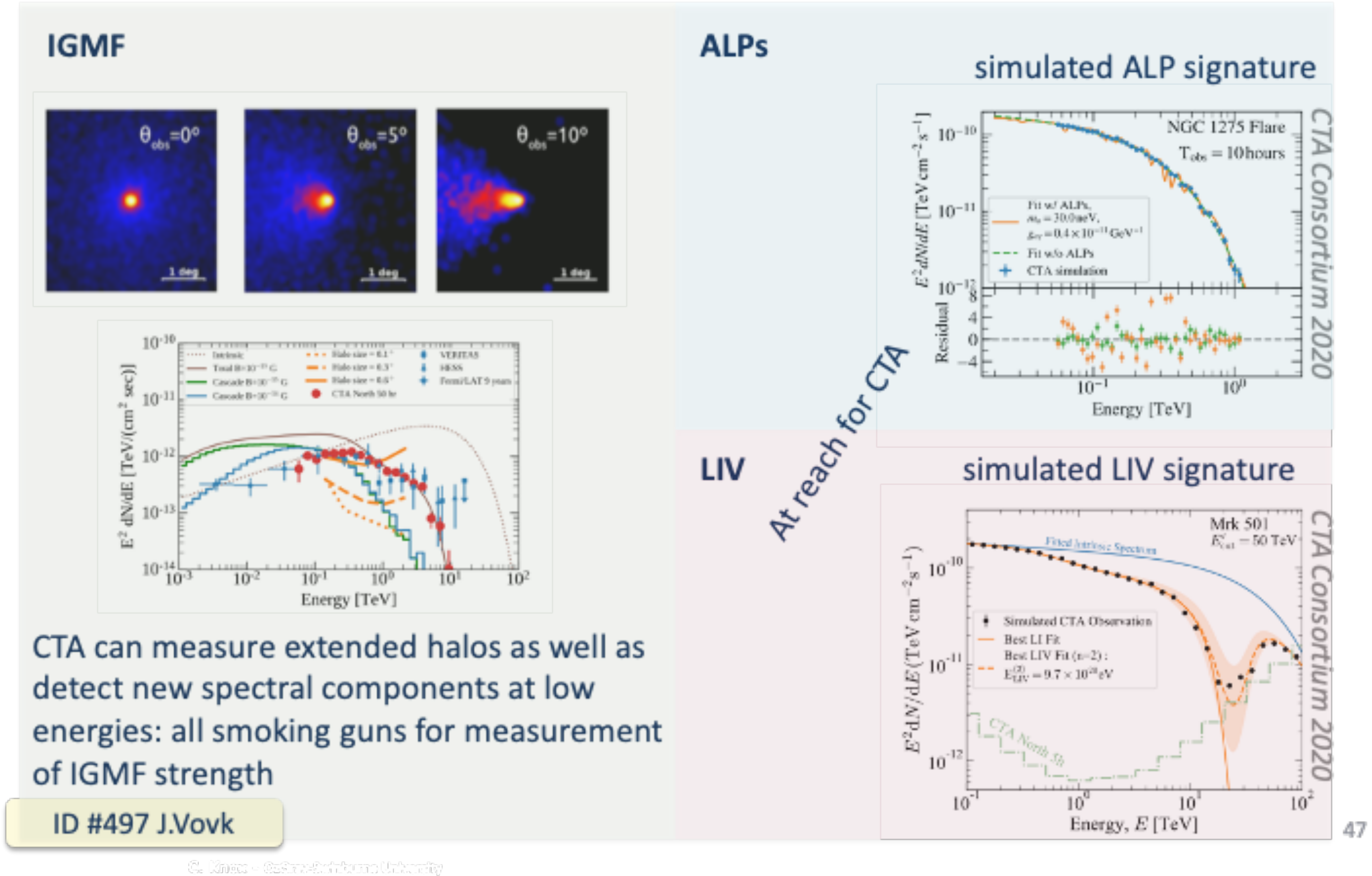


Low energies

Large Field of View

Fast response to Transients

Future facilities

Planned instruments

Trace annihilation or decaying relics

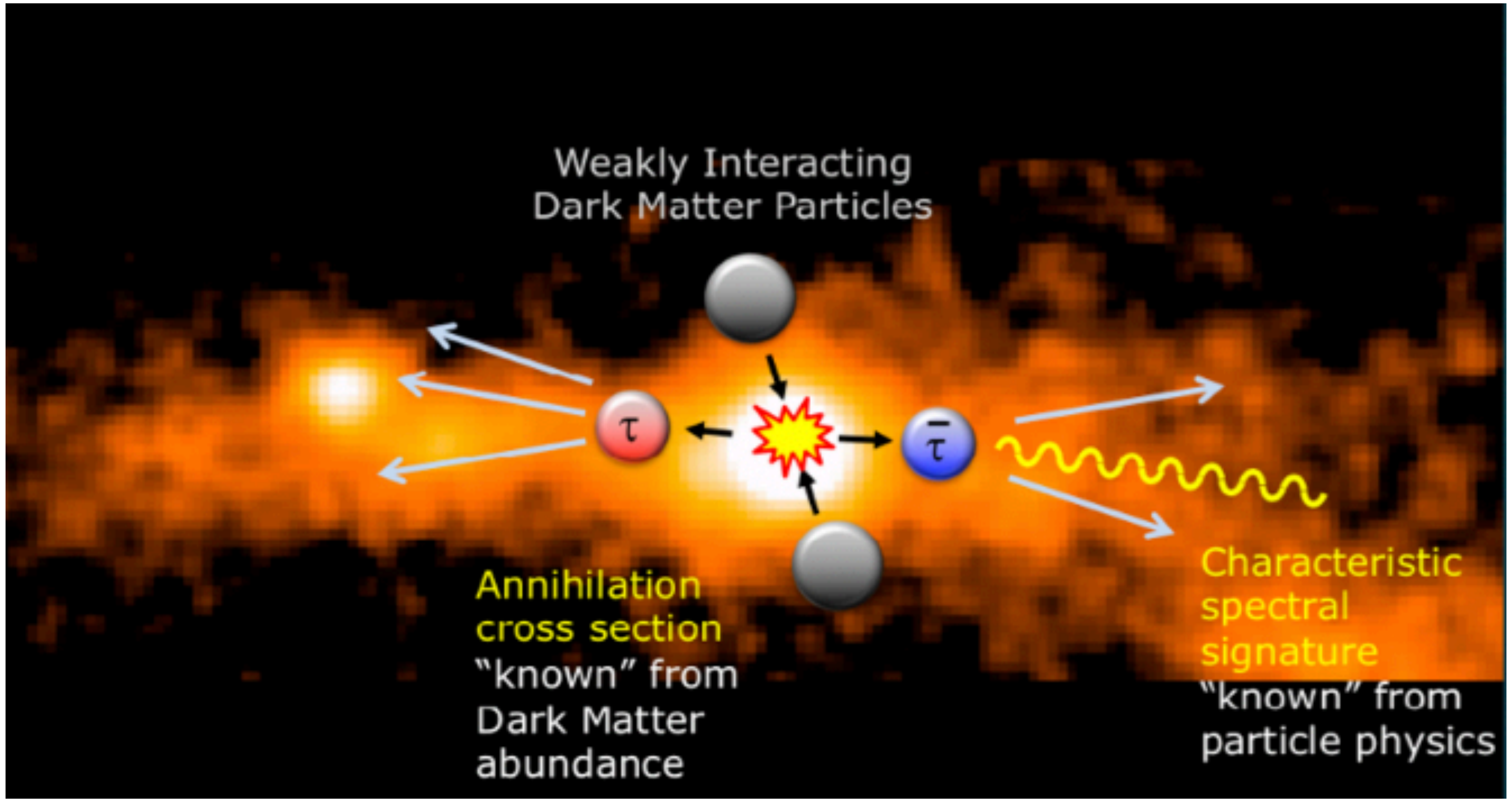
Sensitivity x 10

Arcminutes Angular Resolution

10% Energy Resolution

Wide Energy Range

Full Sky Coverage



Low energies

Large Field of View

Future facilities

Planned instruments

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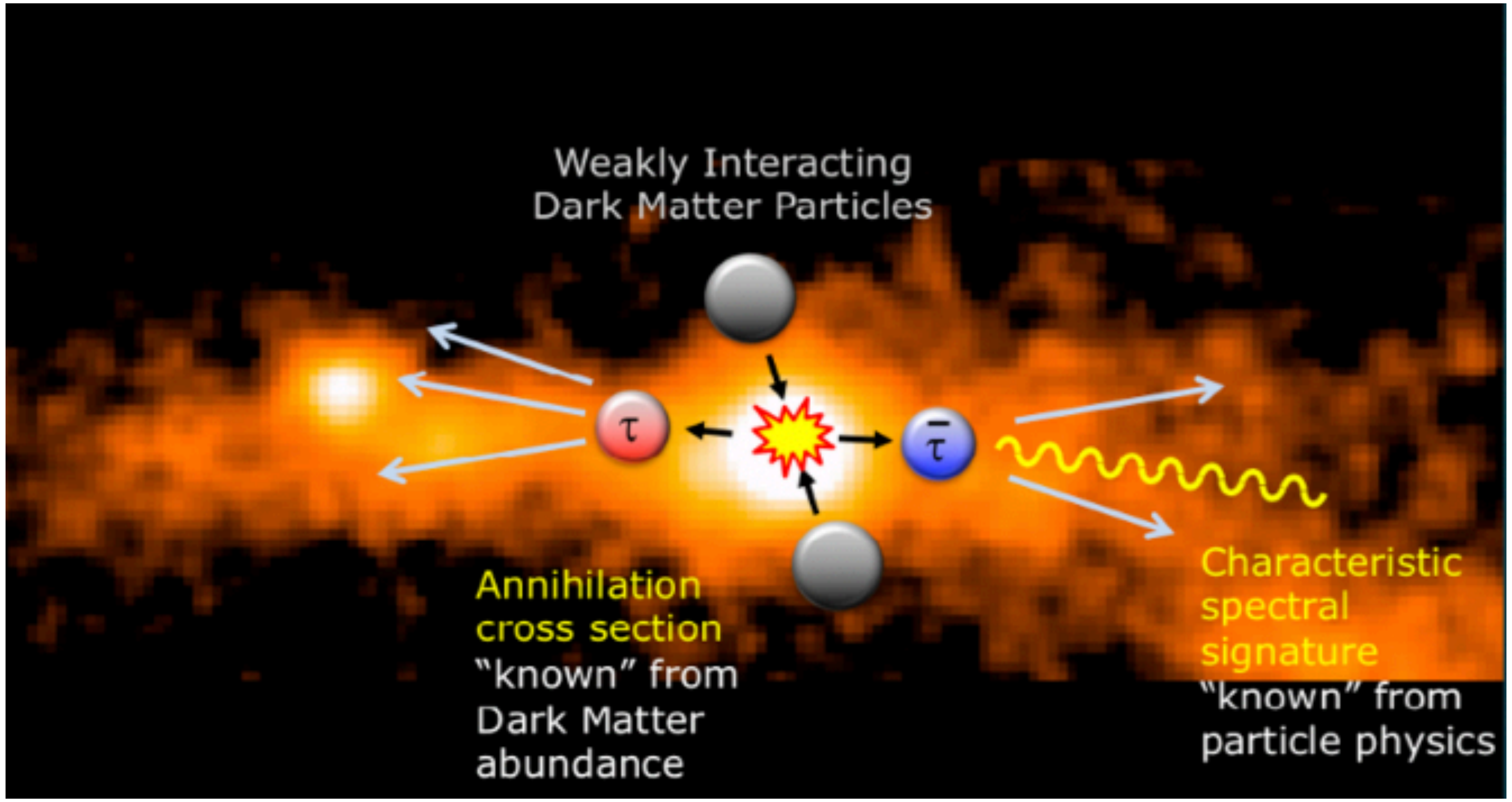

- Low energies
- Large Field of View
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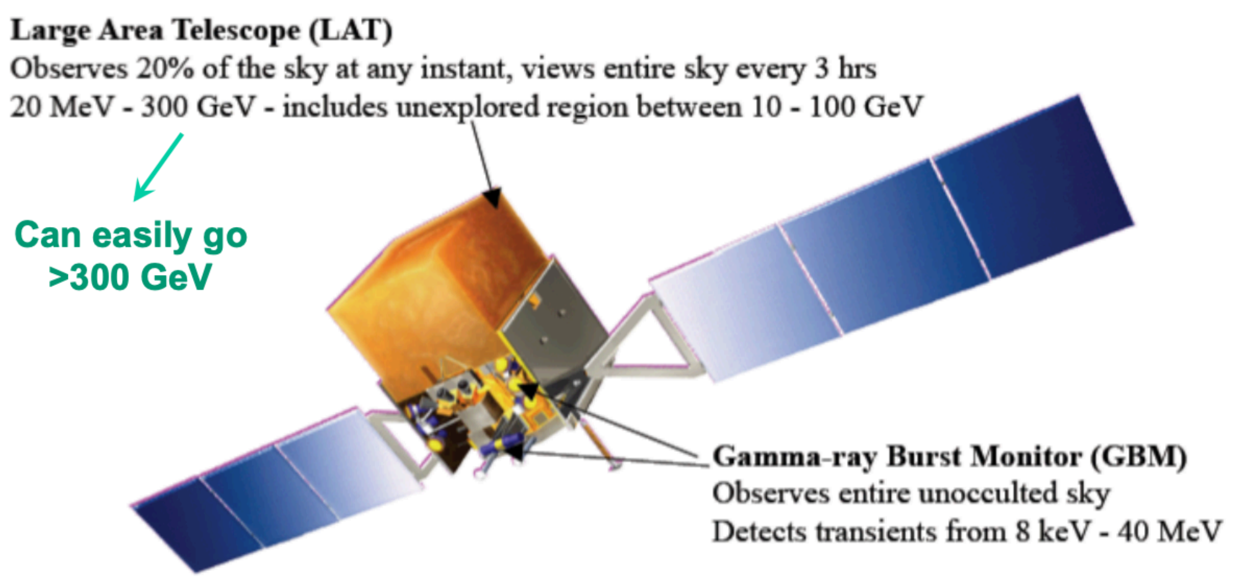
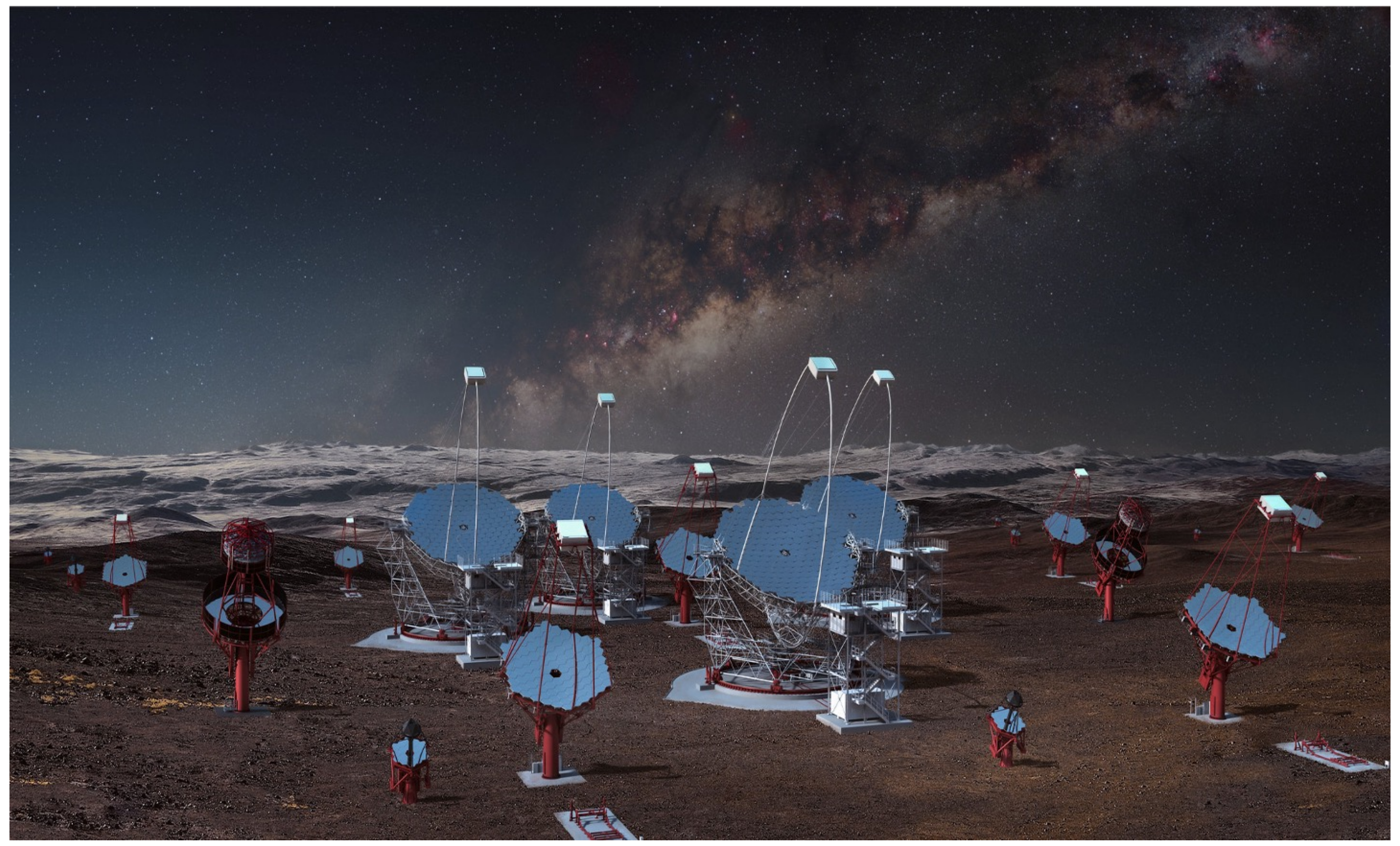
Future facilities
Planned instruments

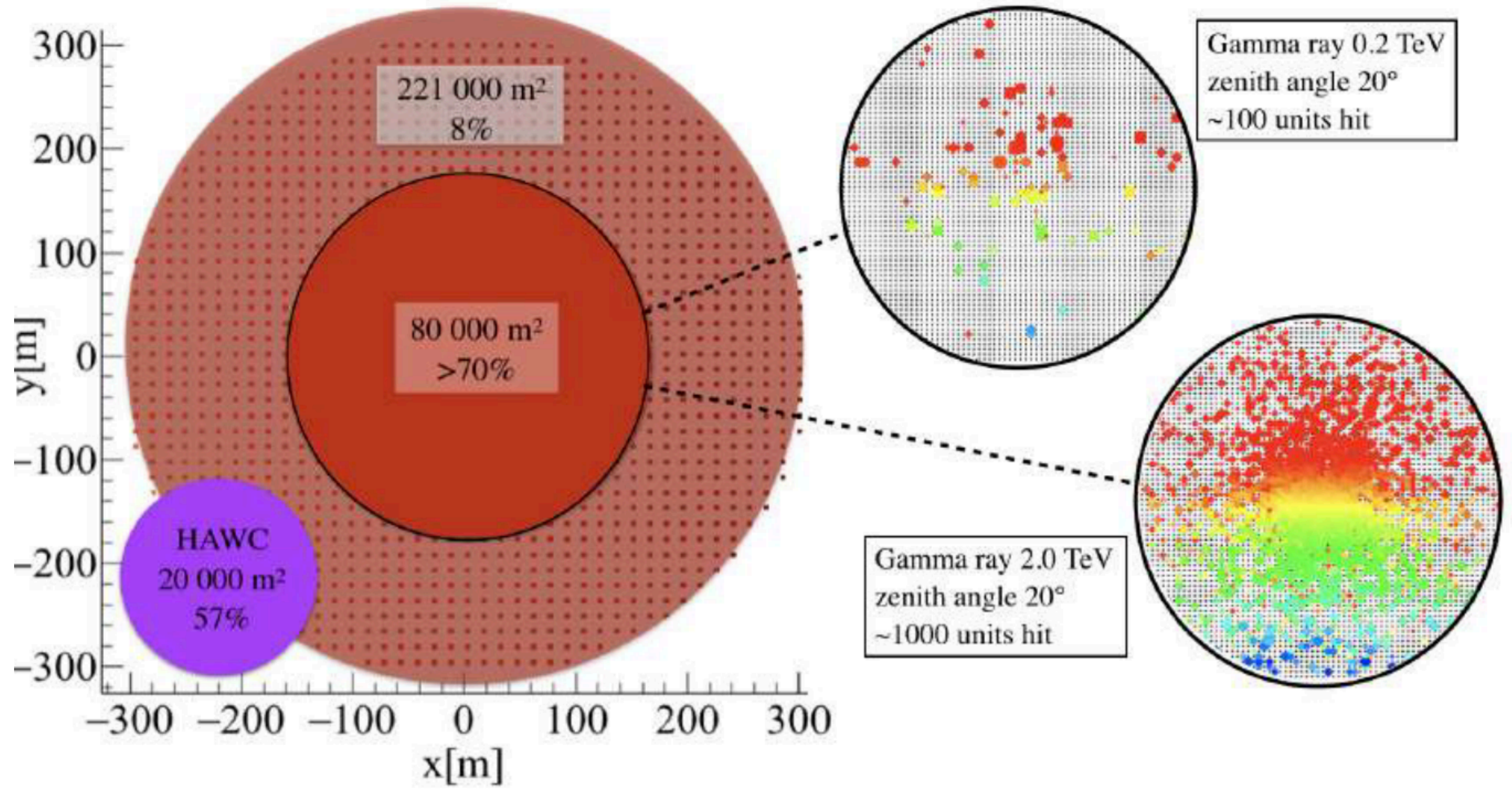


eASTROGAM
DAMPE
AdePT
HERD
….

cta
cherenkov telescope array



SWGO
The Southern Wide-field Gamma-ray Observatory



- 'Strawman' - reference detector layout
  EPJ-C, H. Schoorlemmer, J.A. Hinton, R. Lopez-Coto, (2019)

MeV - GeV **GeV - > 100 TeV** **PeV**

Future facilities

The Cherenkov Telescope Array (CTA)

=> Increase Collection Area

cta
cherenkov telescope array

Future facilities

The Cherenkov Telescope Array (CTA)

Sensitivity x 10

=> Increase Collection Area

Future facilities

The Cherenkov Telescope Array (CTA)

Sensitivity x 10

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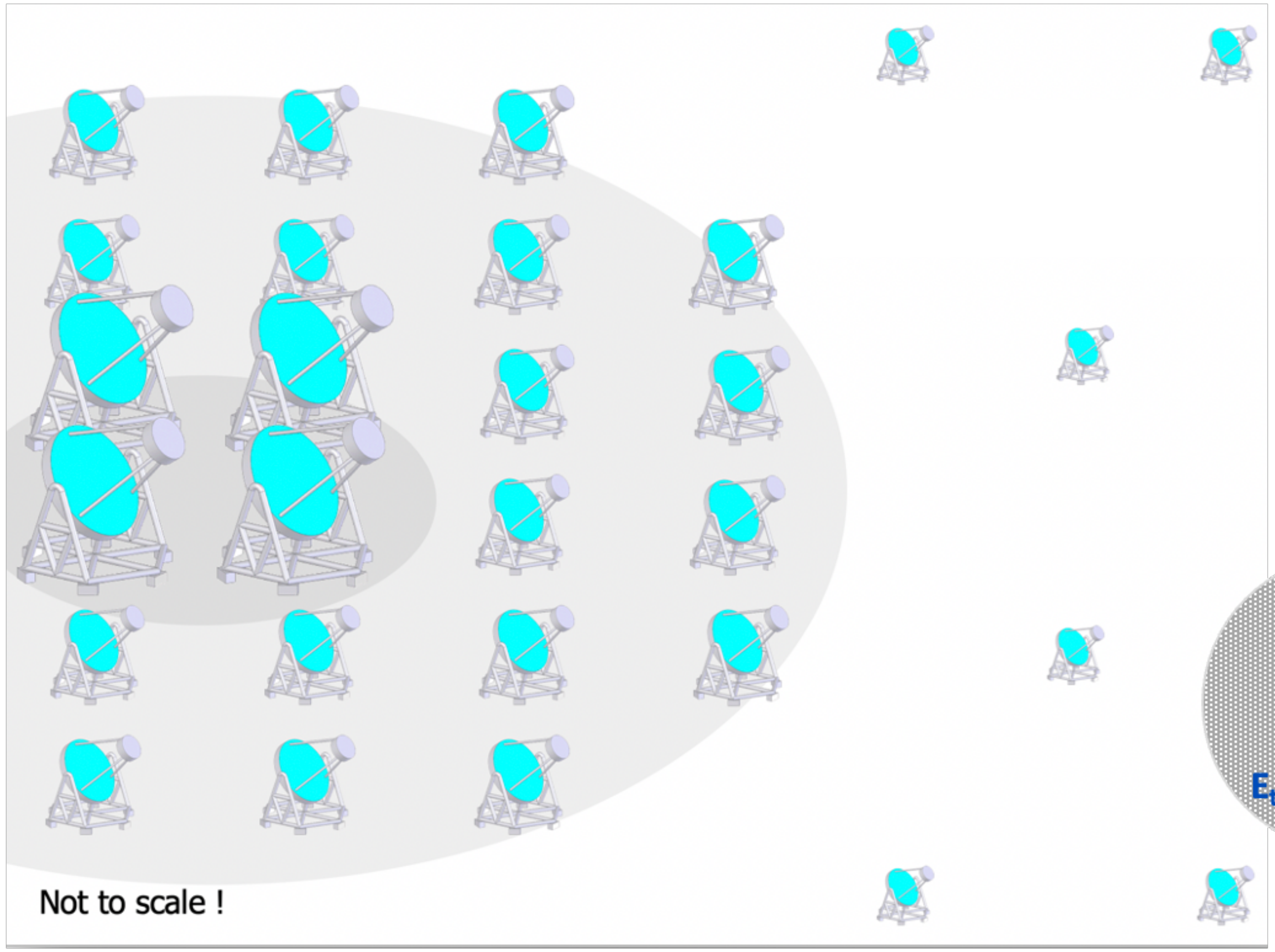
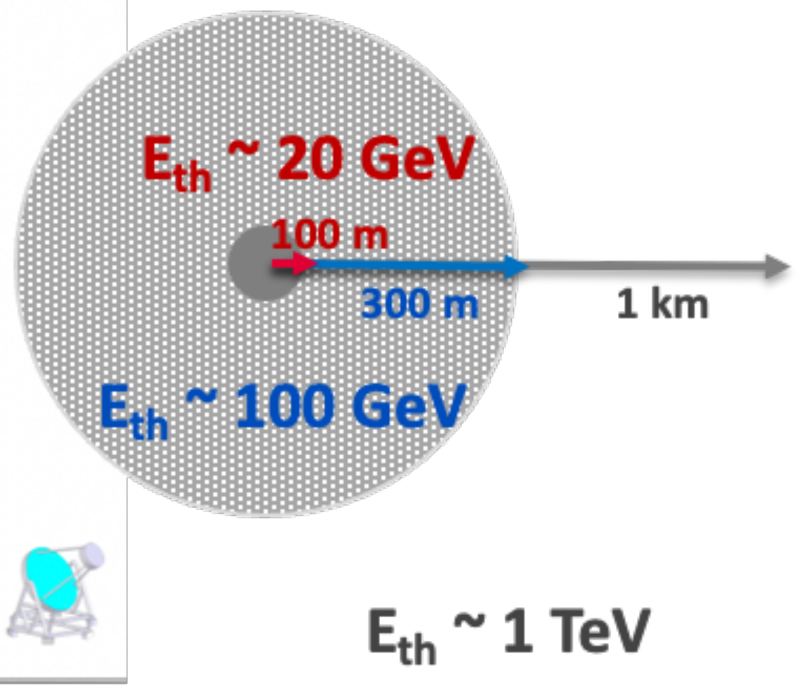




cta cherenkov telescope array

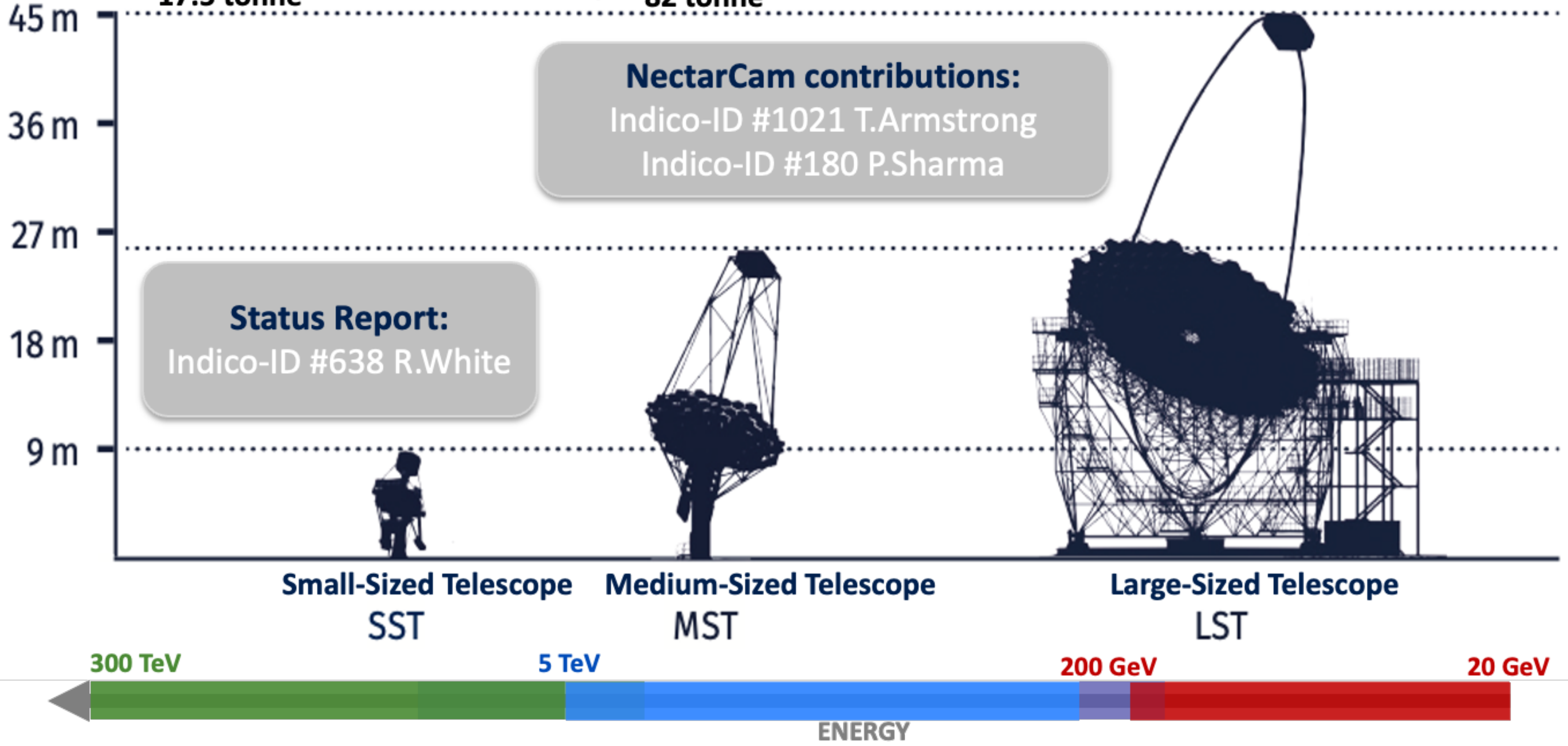
Future facilities

The Cherenkov Telescope Array

- 2-mirror Schwarzschild-Couder optical design
- 4.3 m ∅ primary reflective surface
- SiPM camera: 2048 pixels (0.16°)
- 8.8° FoV
- 17.5 tonne

- Davies-Cotton optical design
- 12 m ∅ reflective surface
- PMT camera – 2 designs:
  - NectarCam: 1855 pixels
  - FlashCam: 1764 pixels
- ~7° FoV
- 82 tonne

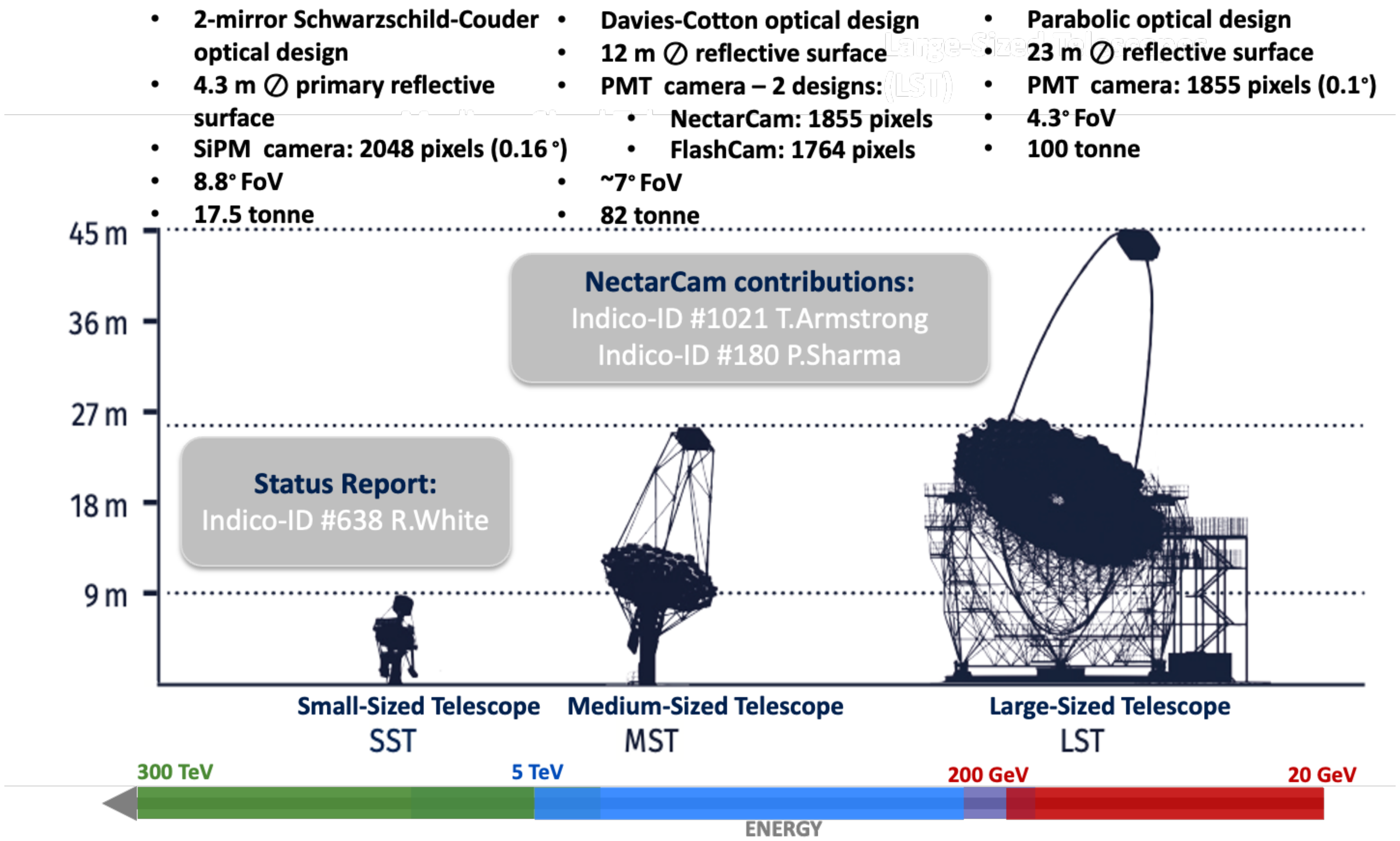
- Parabolic optical design
- 23 m ∅ reflective surface
- PMT camera: 1855 pixels (0.1°)
- 4.3° FoV
- 100 tonne



- Low energies
- Large Field of View
- Arcminutes Angular Resolution
- 10% Energy Resolution
- Wide Energy Range

Future facilities

The Cherenkov Telescope Array



- Low energies
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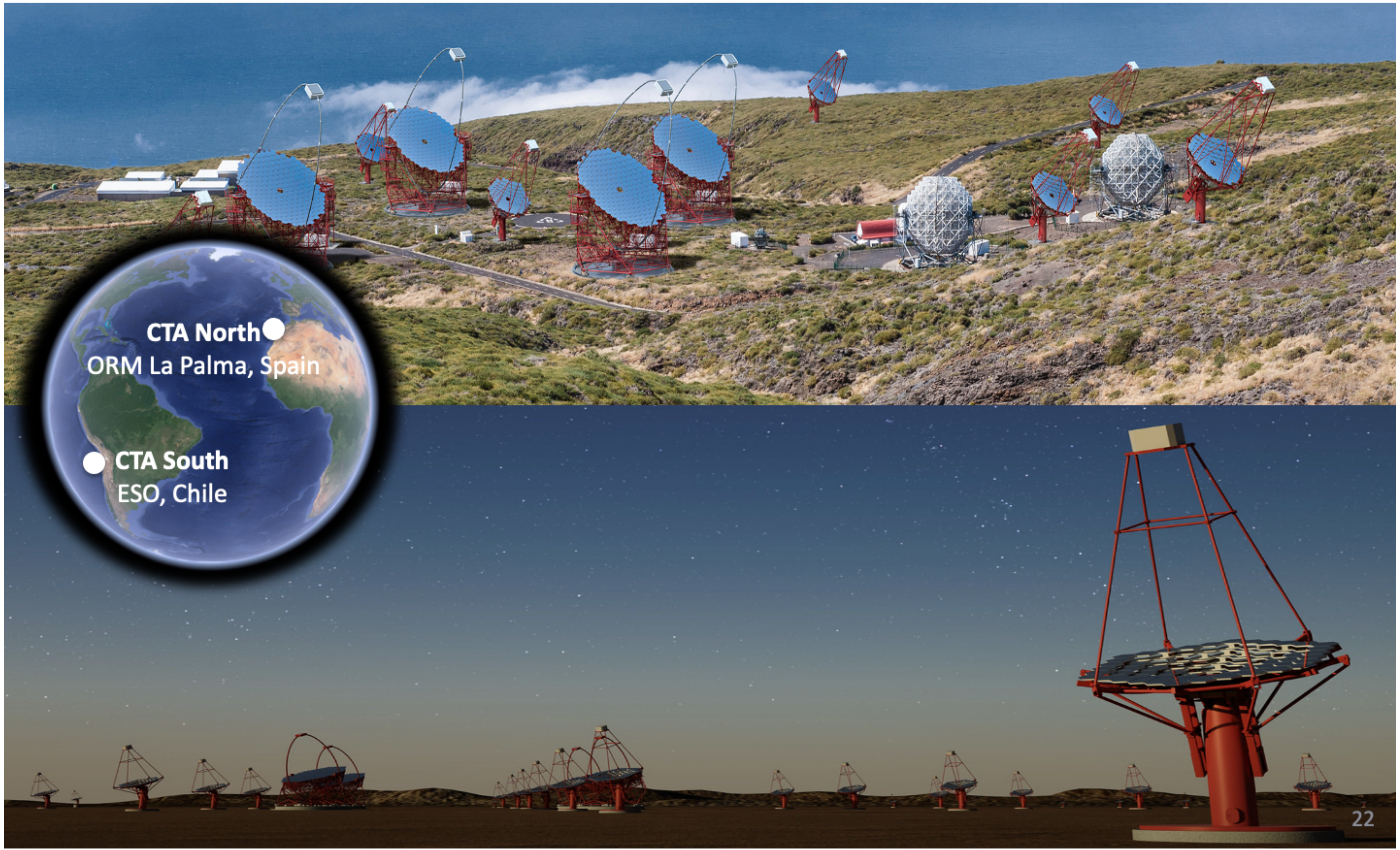
- Wide Energy Range
- Fast response to Transients

Future facilities

The Cherenkov Telescope Array

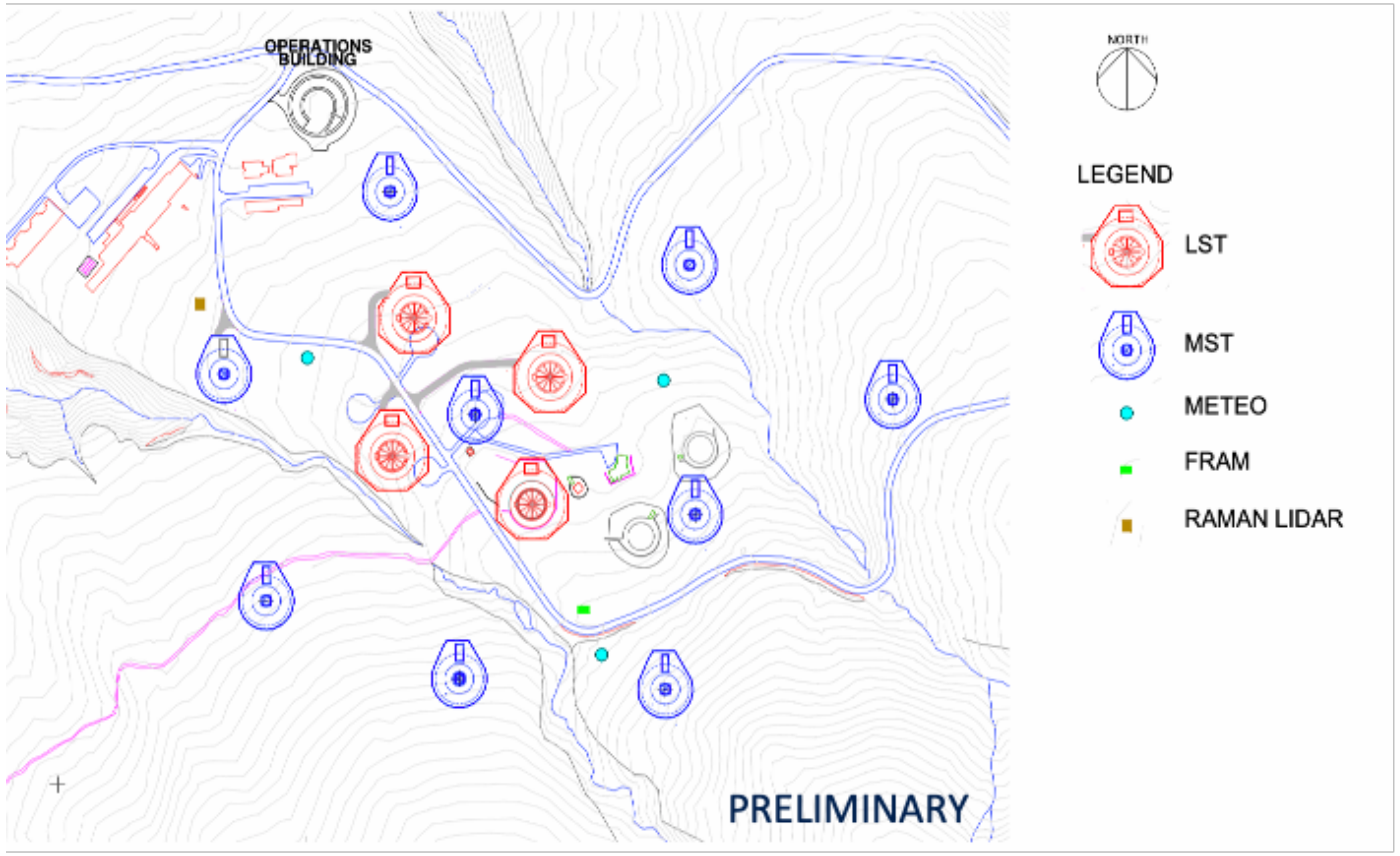
One observatory with two sites



Full Sky Coverage

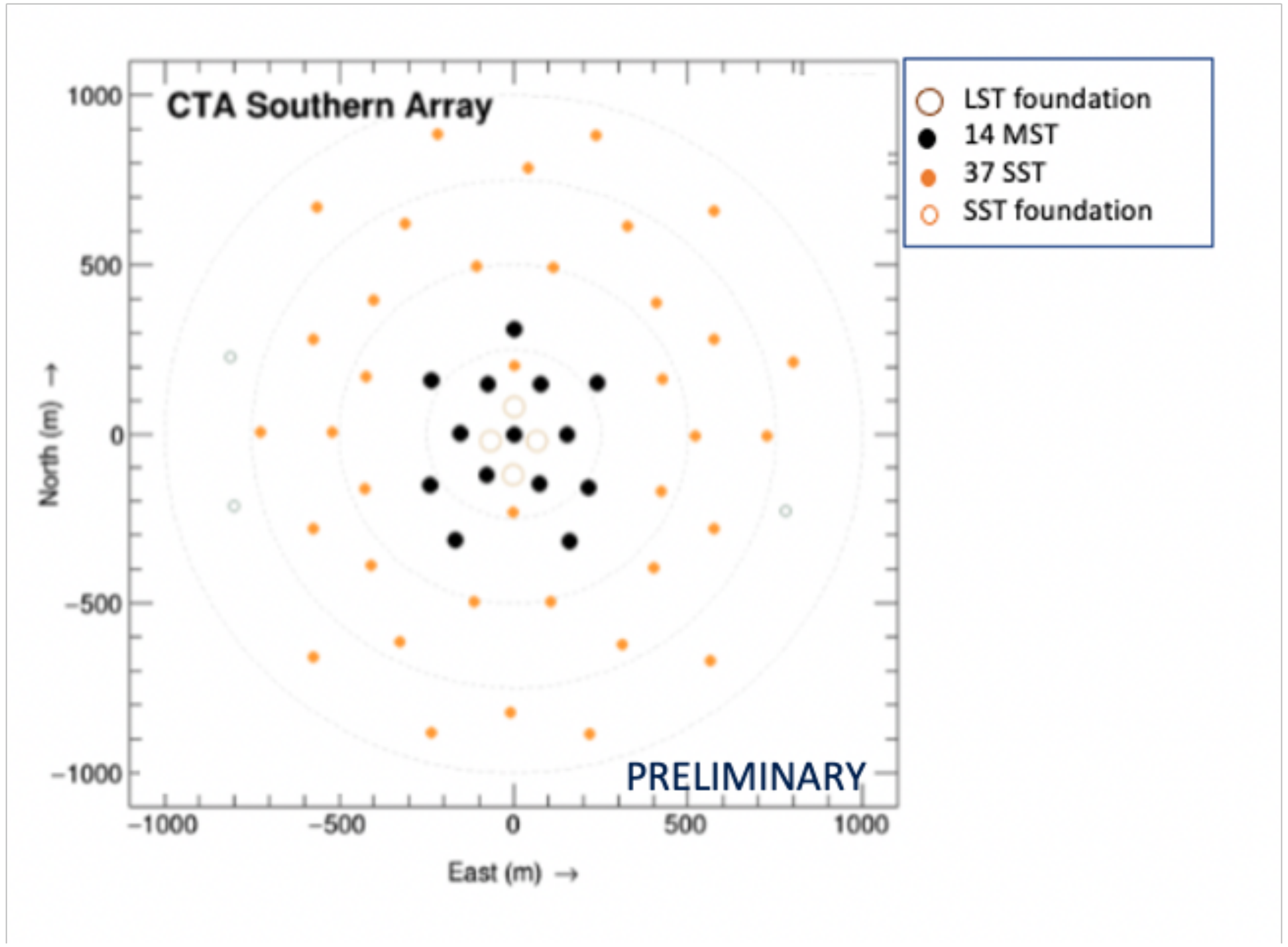
CTAO Northern Array

- **4 LSTs + 9 MSTs**
- 0,25 km² footprint
- focus on extra-Galactic science



CTAO Southern Array

- **14 MSTs + 37 SSTs**
- 3 km² footprint
- focus on Galactic science



Future facilities

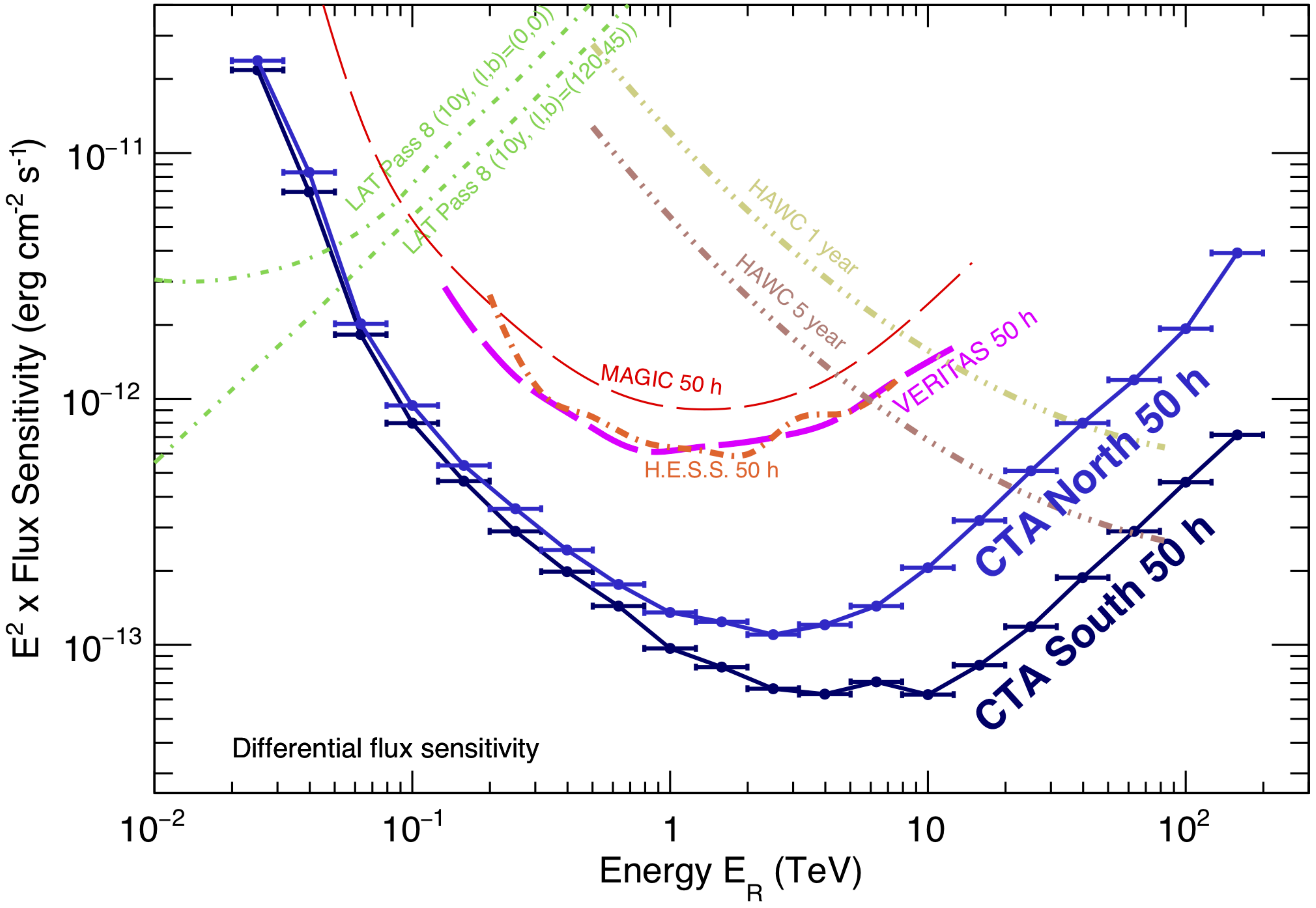
The Cherenkov Telescope Array

Boosting:

- Increase sensitivity by up to a factor ~6 at 1 TeV
- Increase the detection area for transients and at the highest energies
- Increase the angular resolution/maintaining a large FoV

New:

- Energy coverage: tens of GeV => >100 TeV (~300 TeV)
- 2 Sites, flexibility of operation, allowing for sub-arrays and multi-mode
- Operate as an observatory



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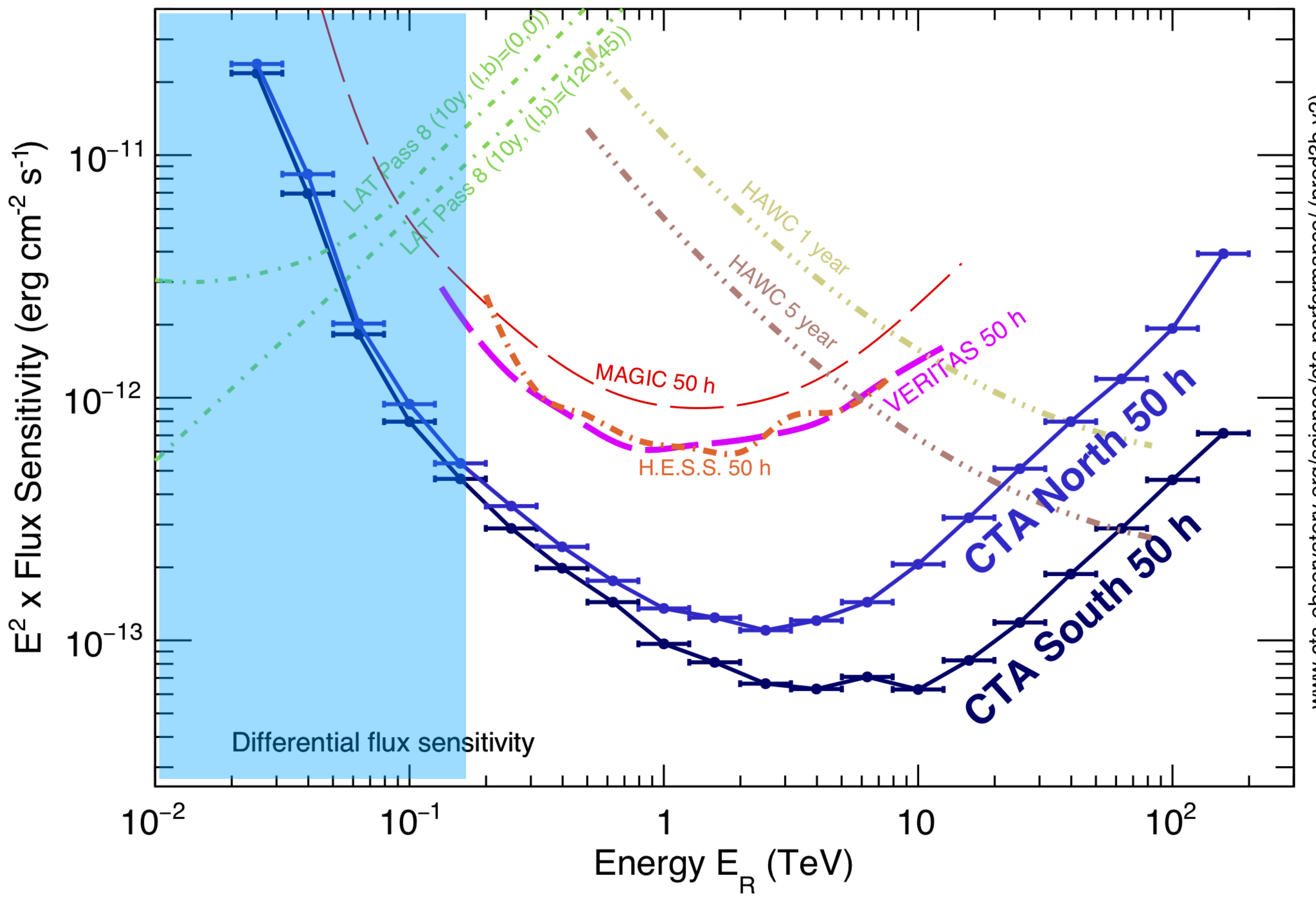

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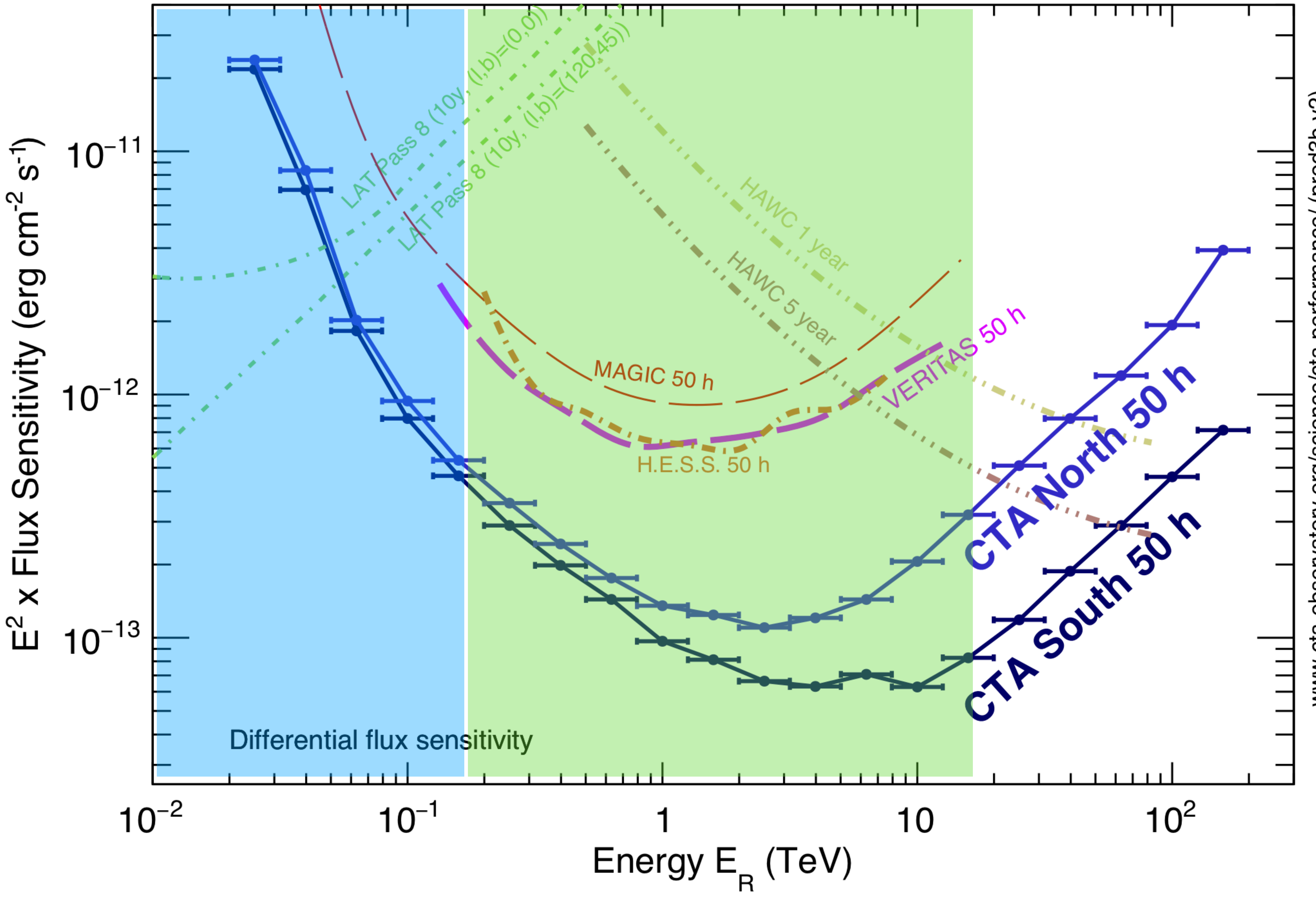

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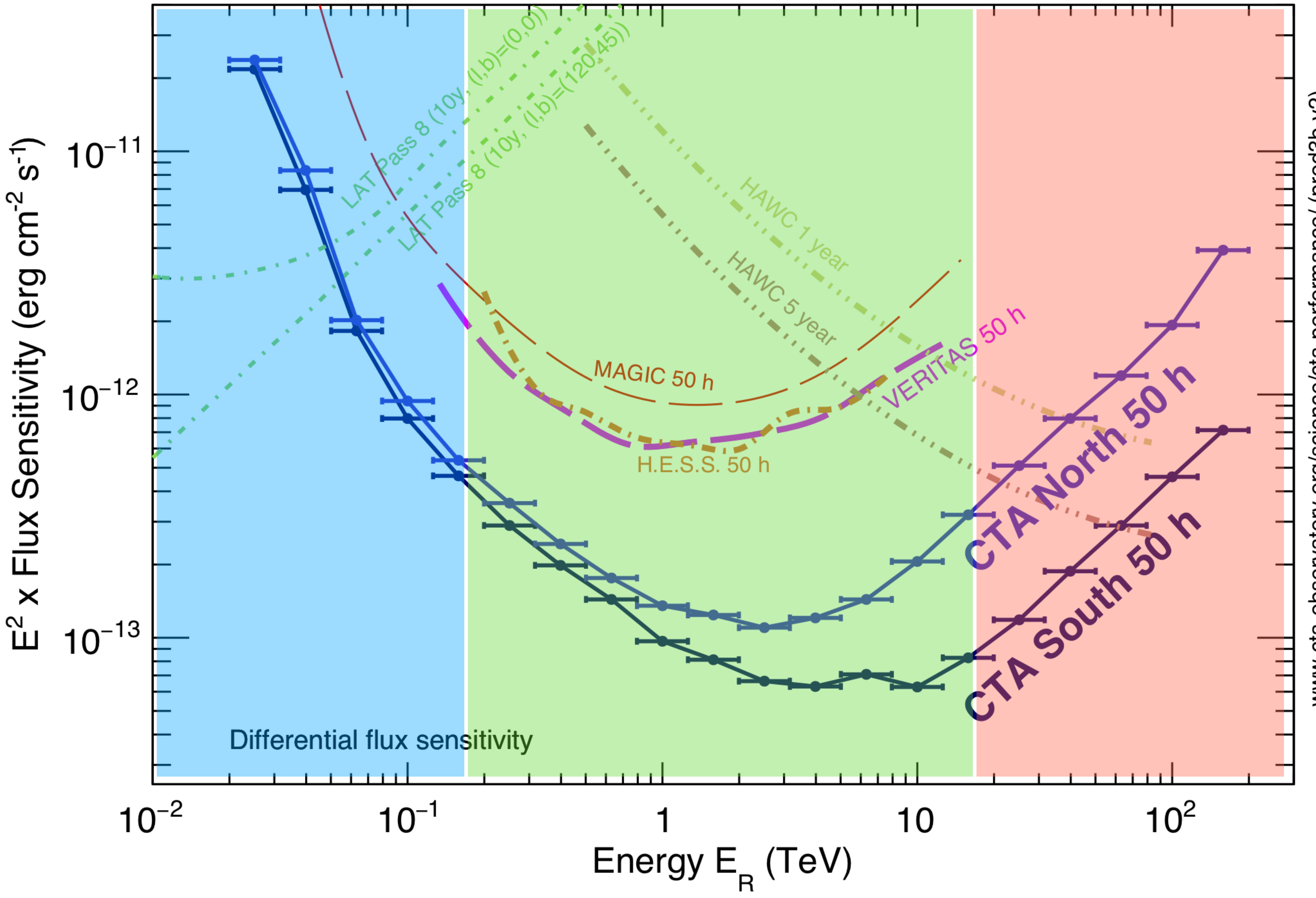
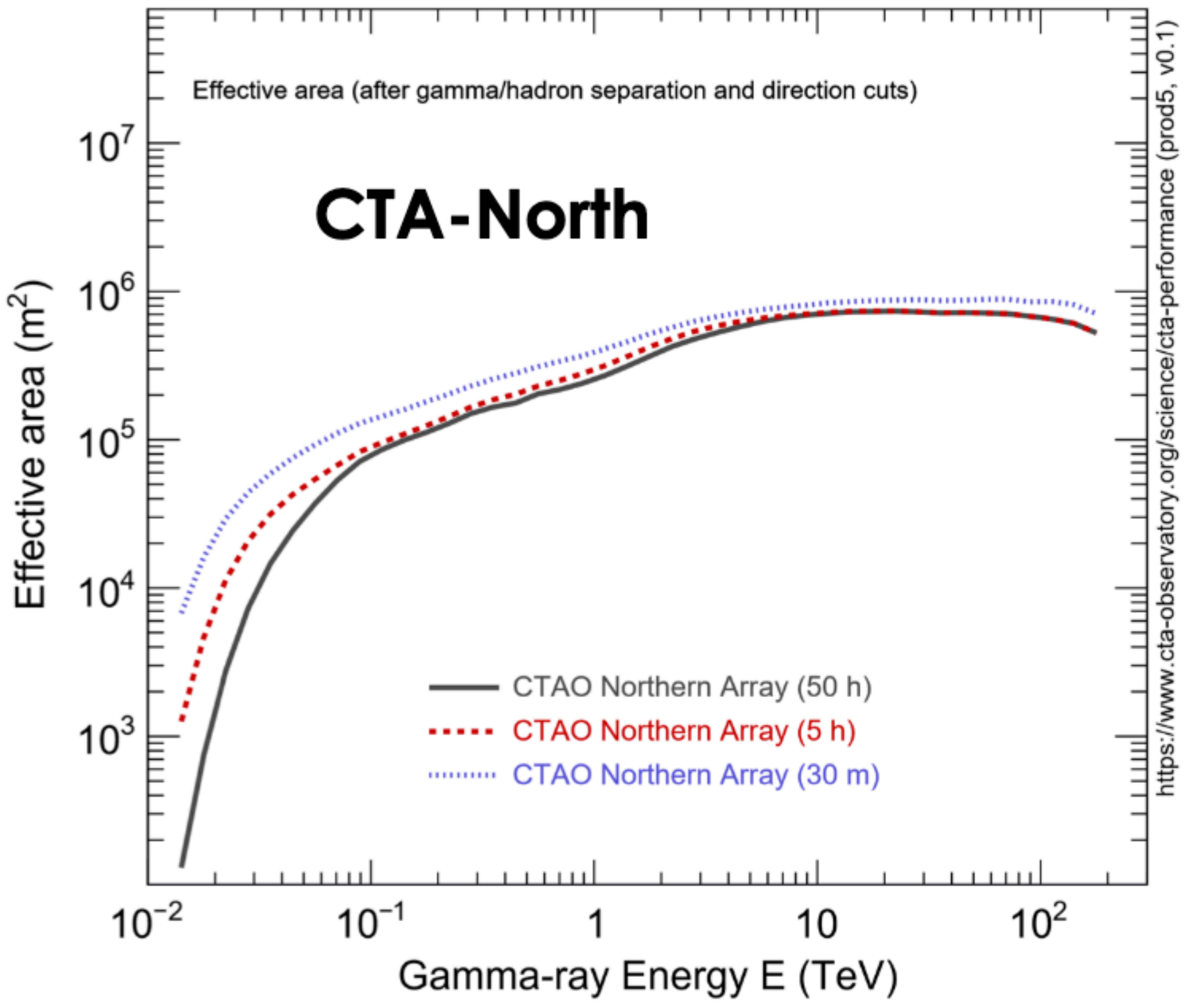
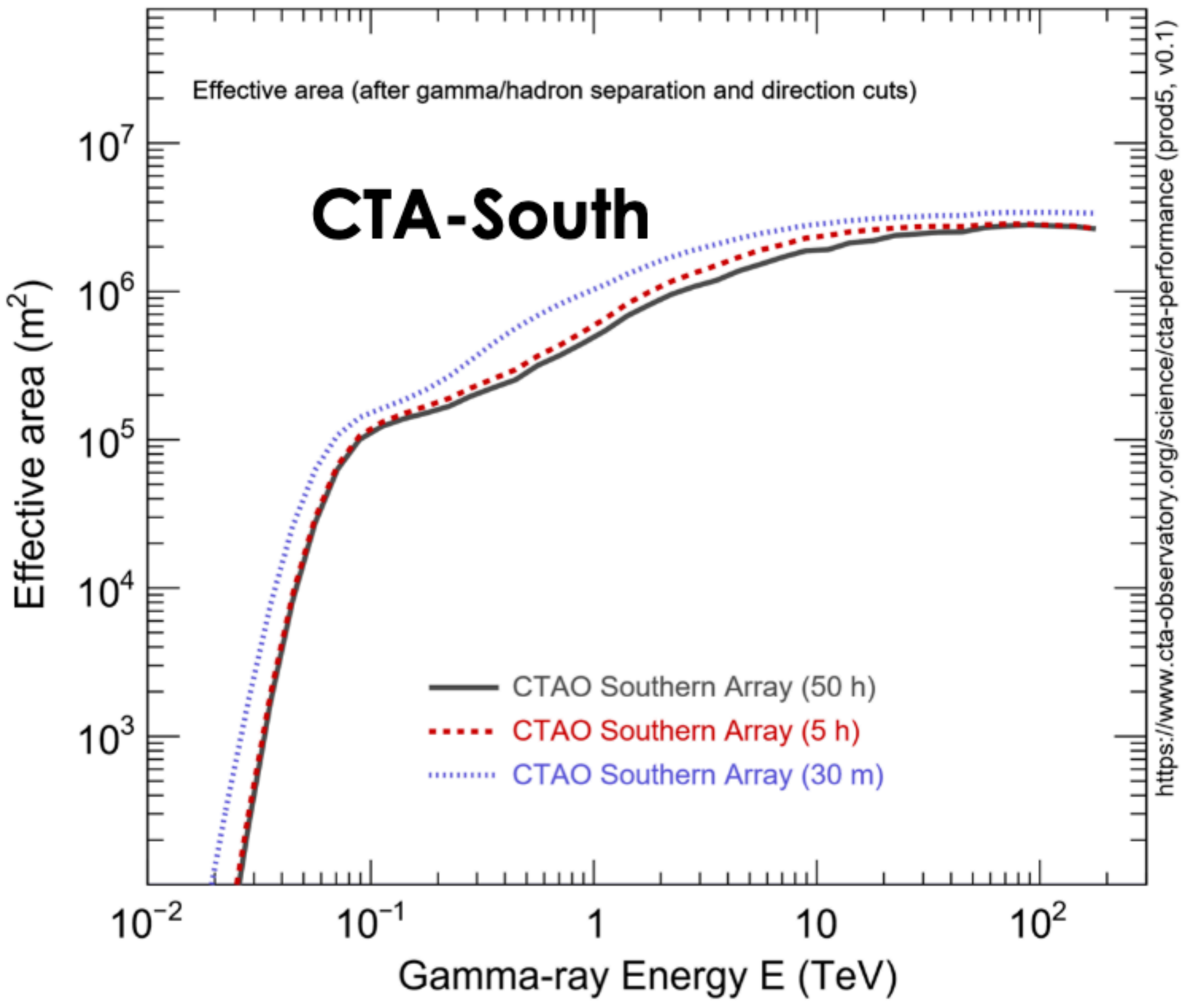


Future facilities

The Cherenkov Telescope Array

Large Collection Area

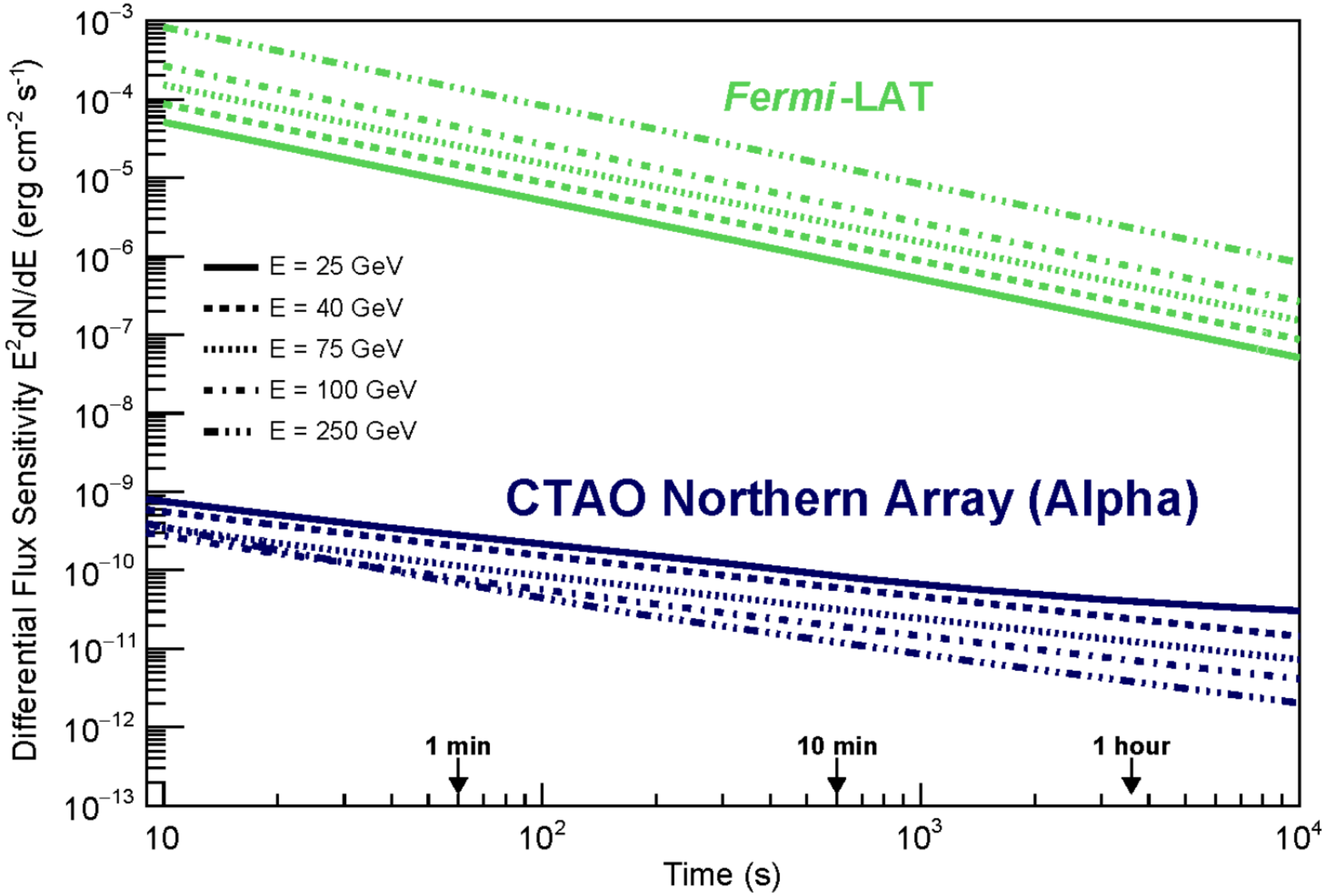




Future facilities

The Cherenkov Telescope Array

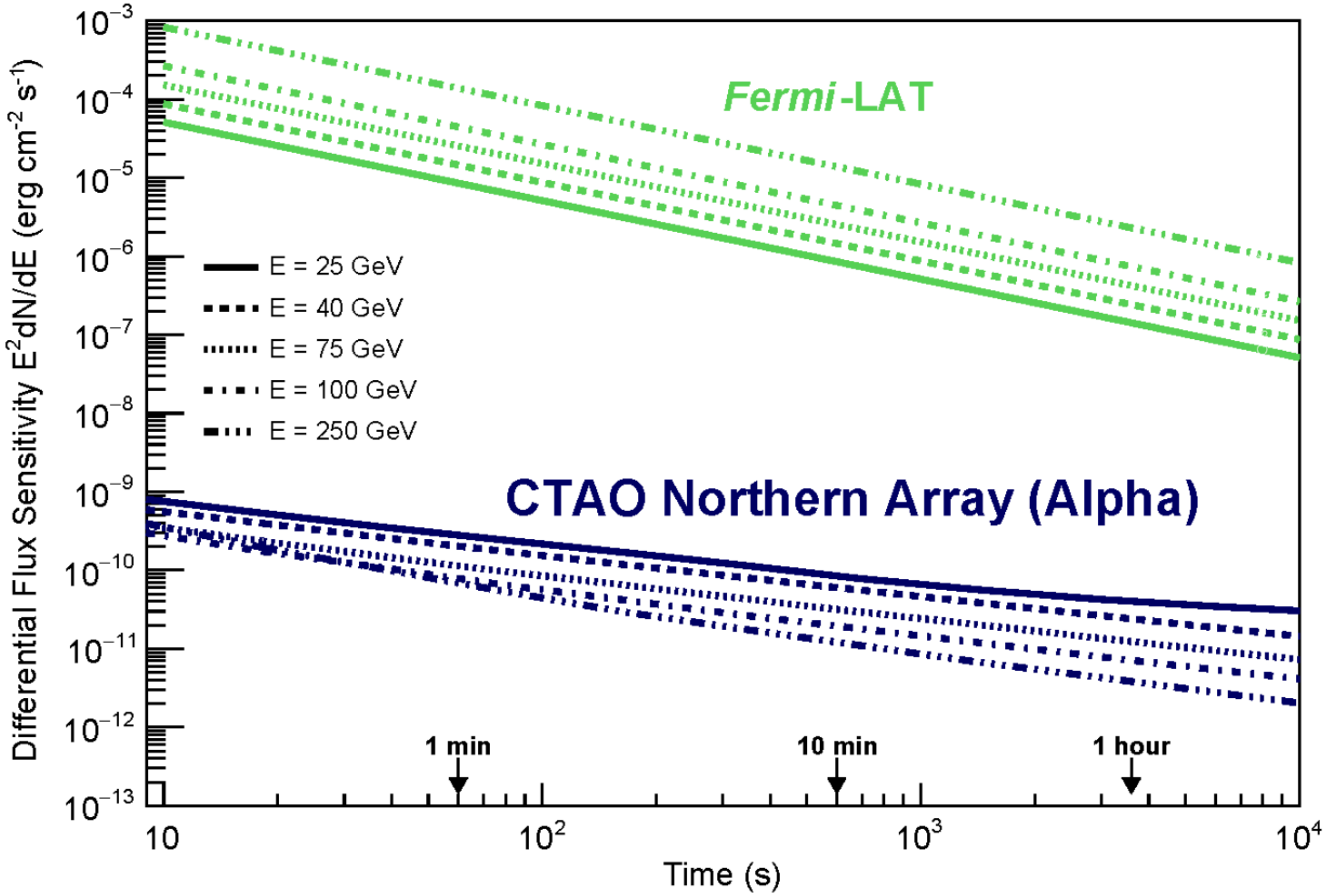
Sensitivity to transient events



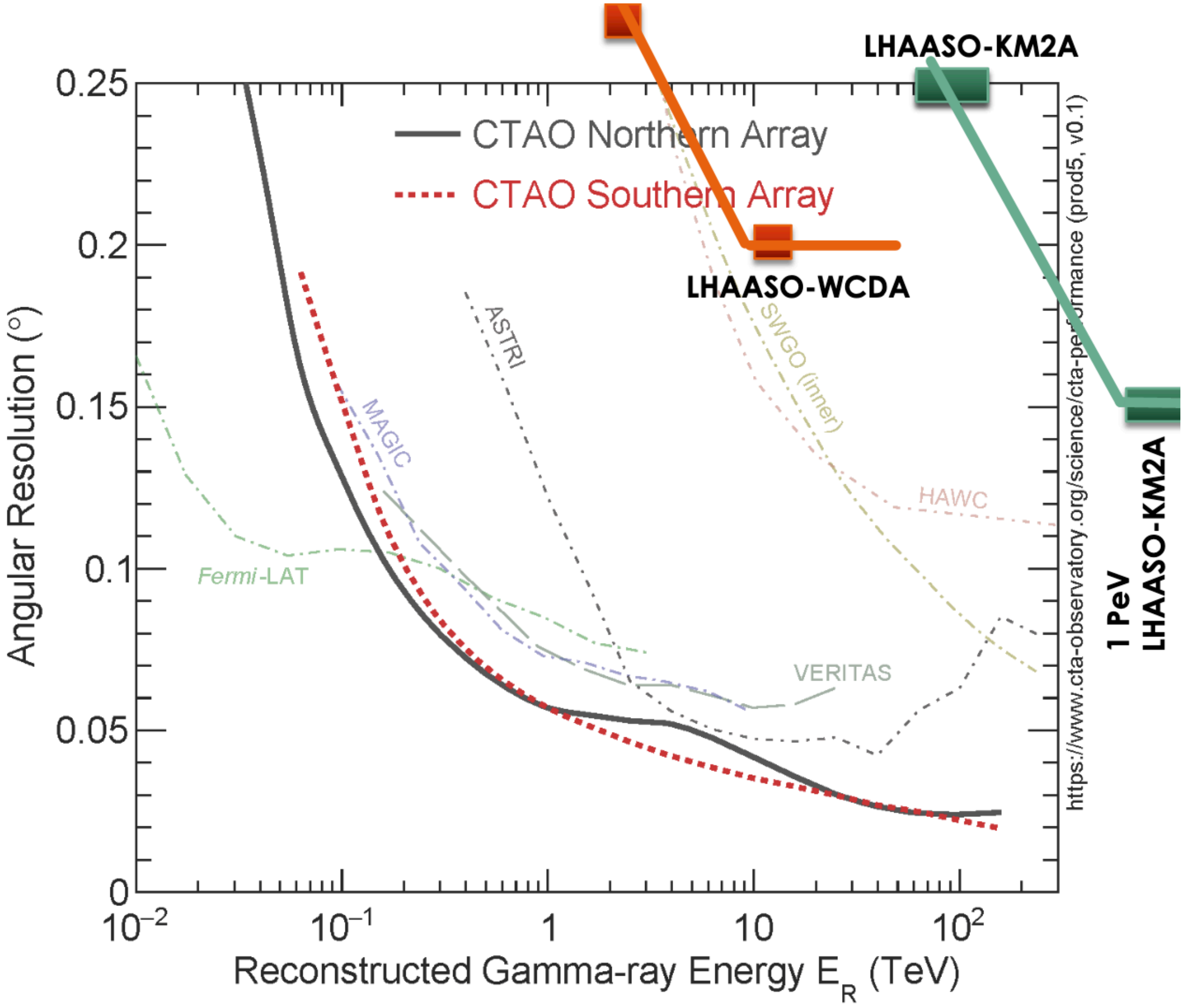
Future facilities

The Cherenkov Telescope Array

Sensitivity to transient events



Angular resolution



First CTA telescope on site: LST-1

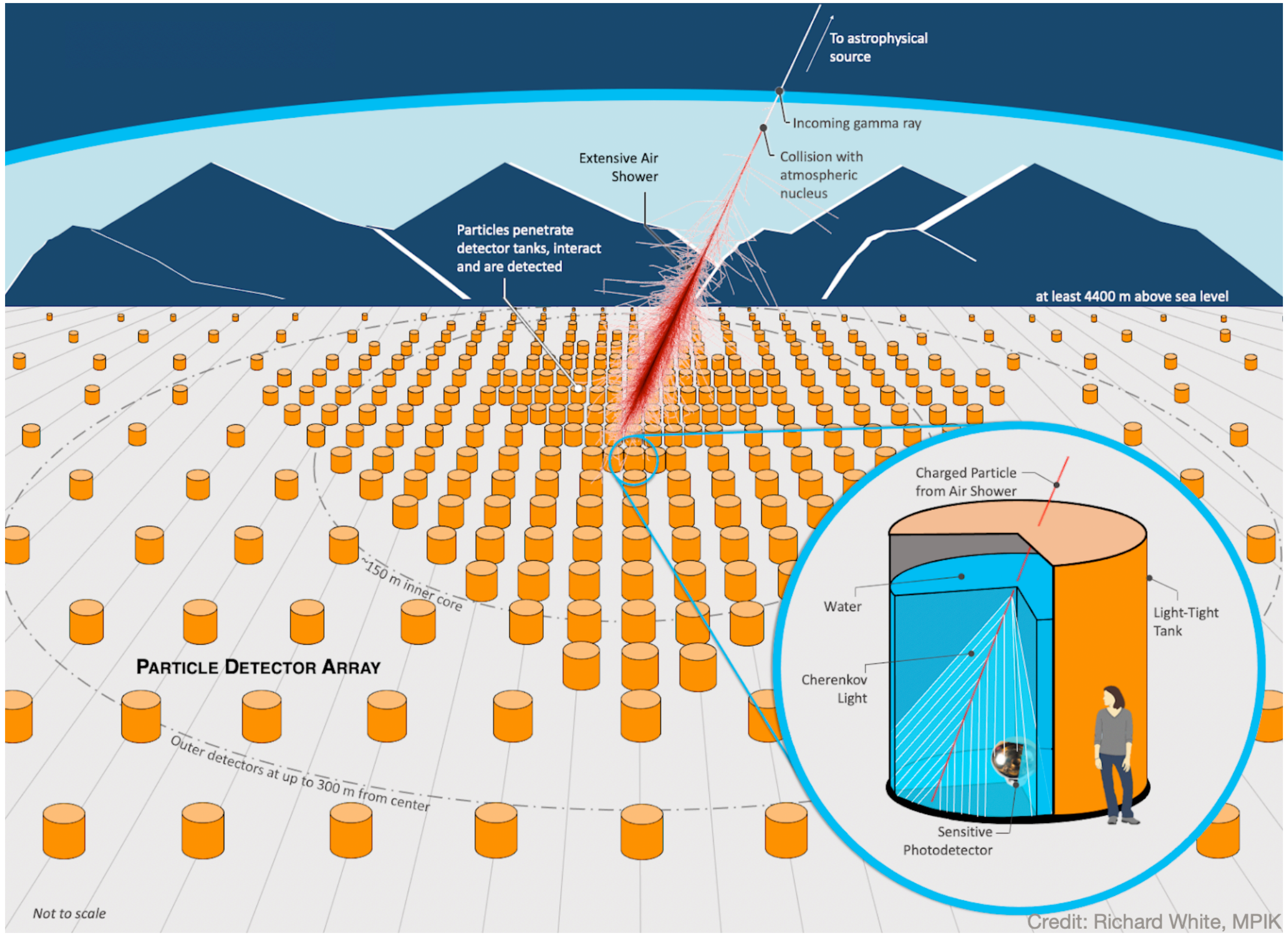
LSTs: The largest telescopes, the lowest energies

- LST (⦸23m): mirror of 400 m^2!
- Targeting an energy threshold <u>~20 GeV.</u> Stereo observations at the lowest energies ever observed from the ground.
- Good overlap with satellites but with <u>collection areas >10^4 times larger</u>
- Able to reposition to any place in the sky within 20 seconds: GRBs.

Future facilities

Southern Wide-Field Gamma-ray Observatory

=> Larger Collection Area

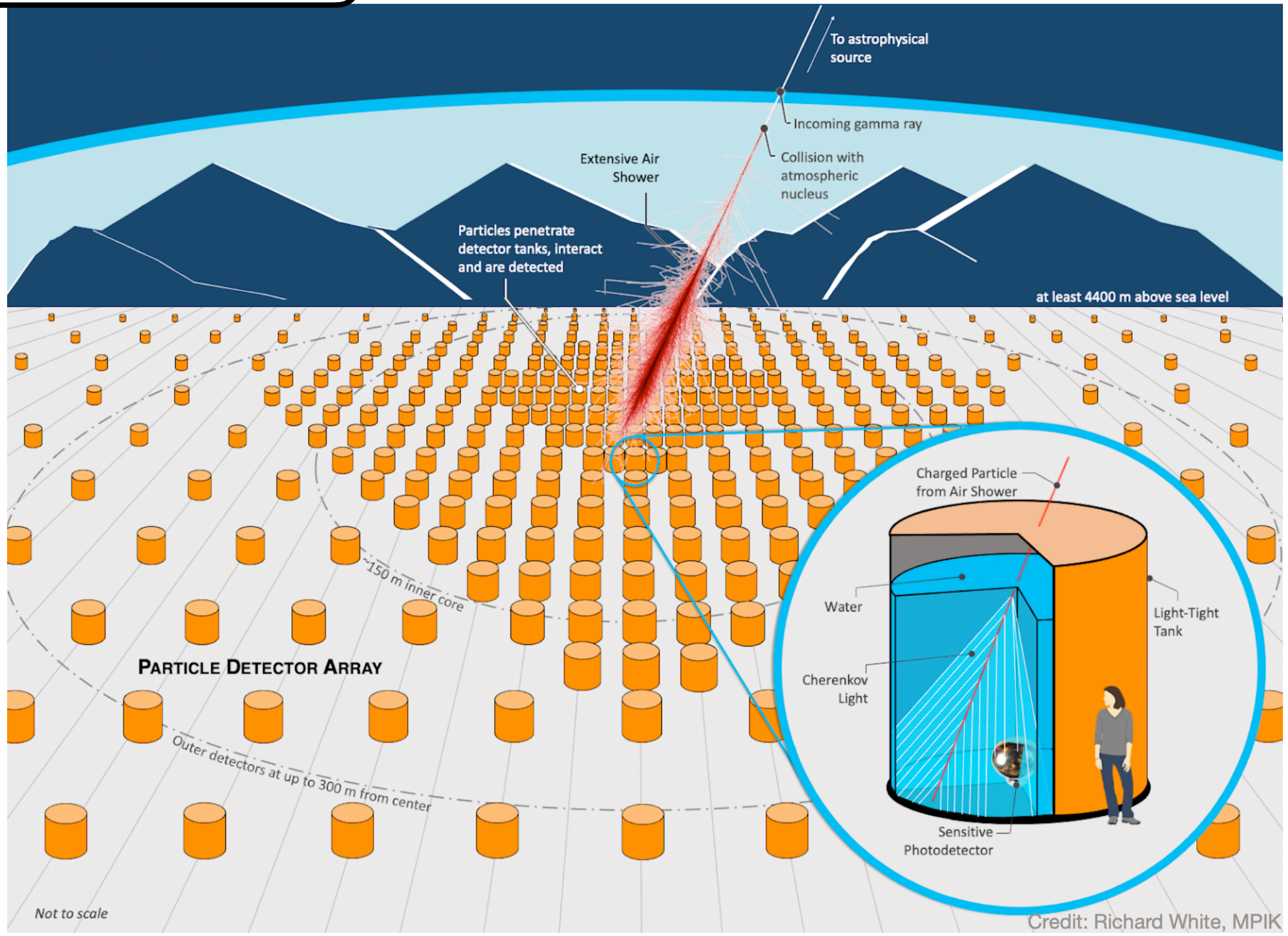


- High-altitude particle detector above 4.4 km a.s.l
- Latitude range between 15 and 30 degrees South
- Wide energy range reaching down to 100 GeV and 100+ TeV

Future facilities

Southern Wide-Field Gamma-ray Observatory

Sensitivity x 10 => Larger Collection Area



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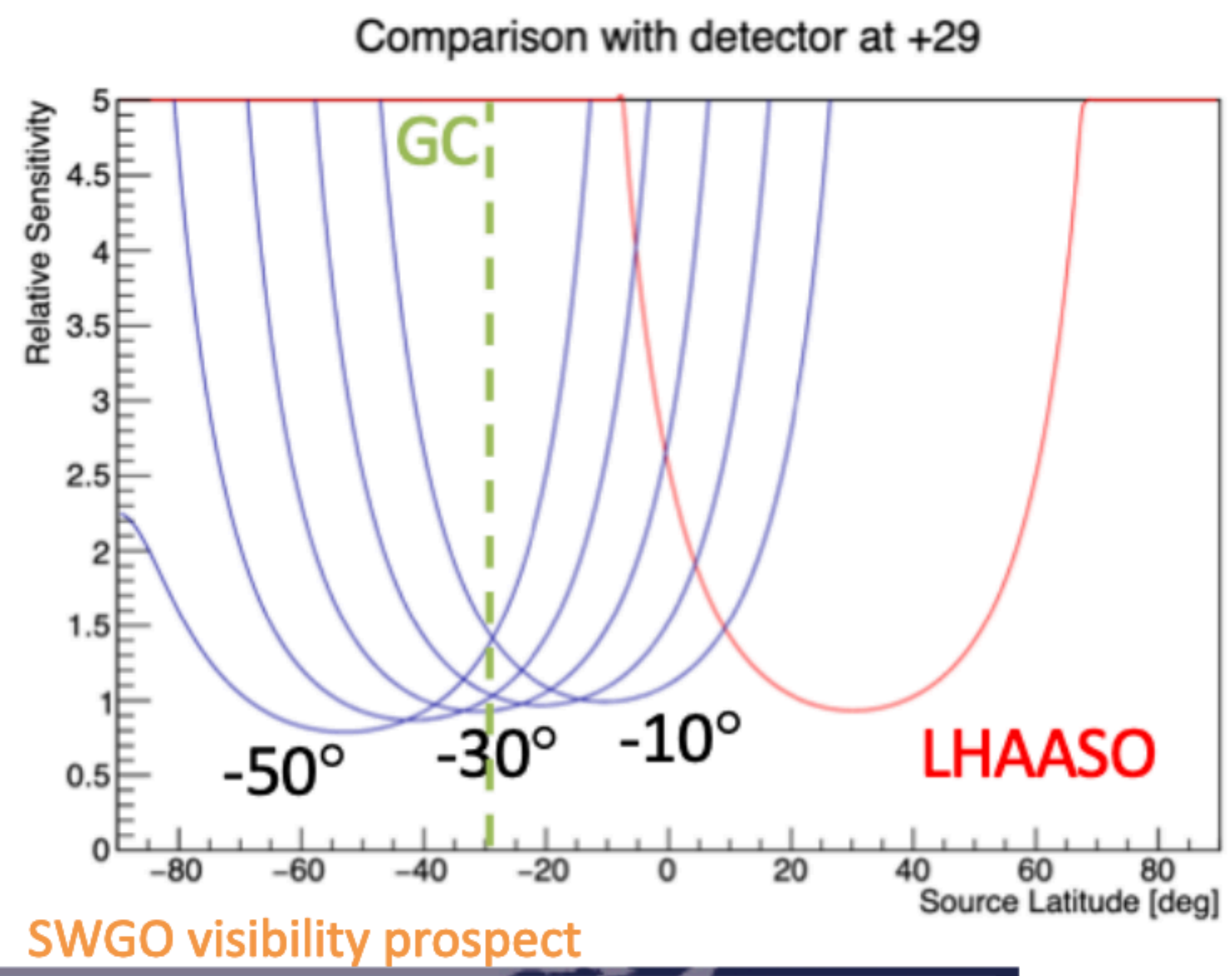
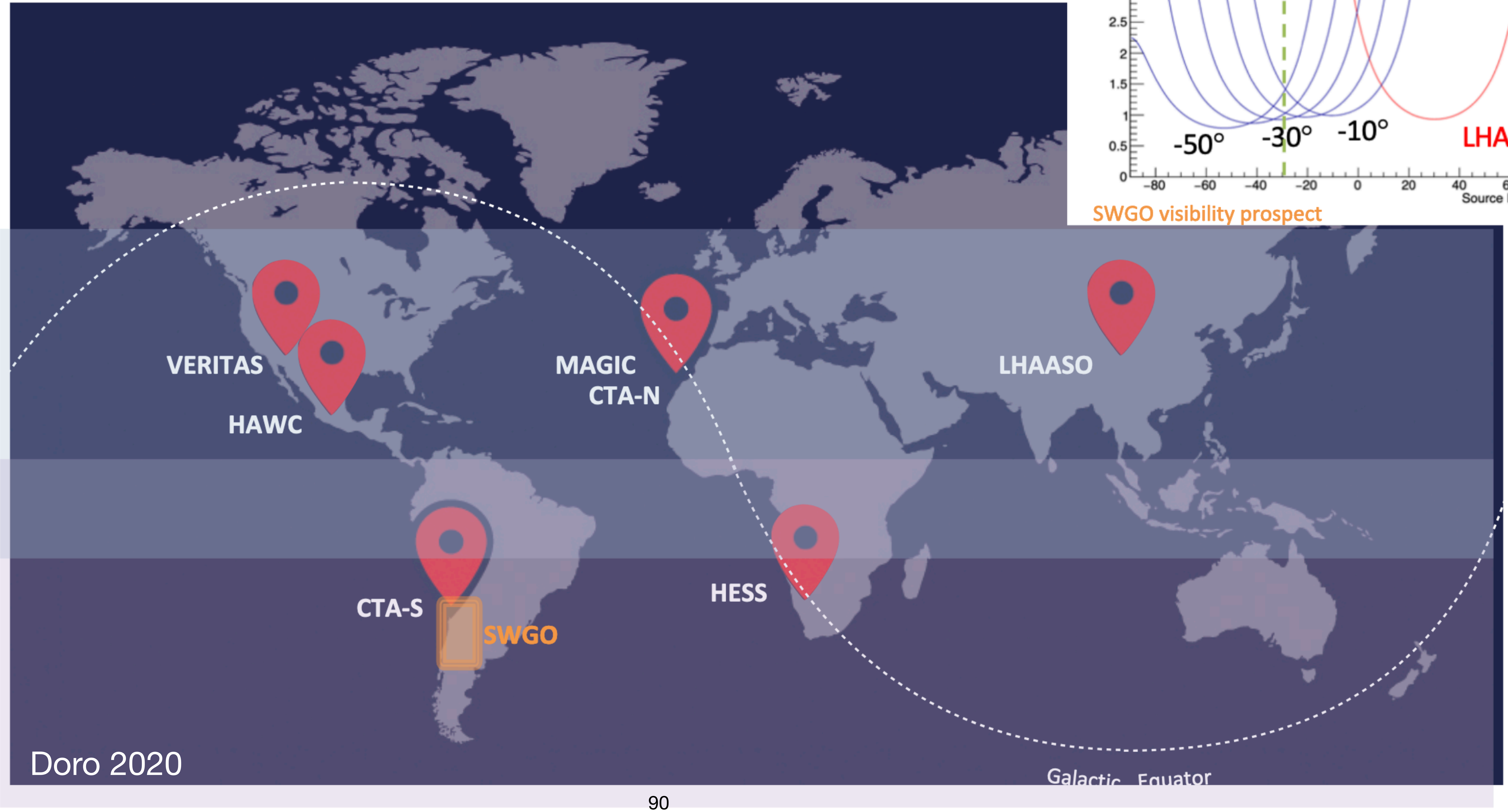
Future facilities

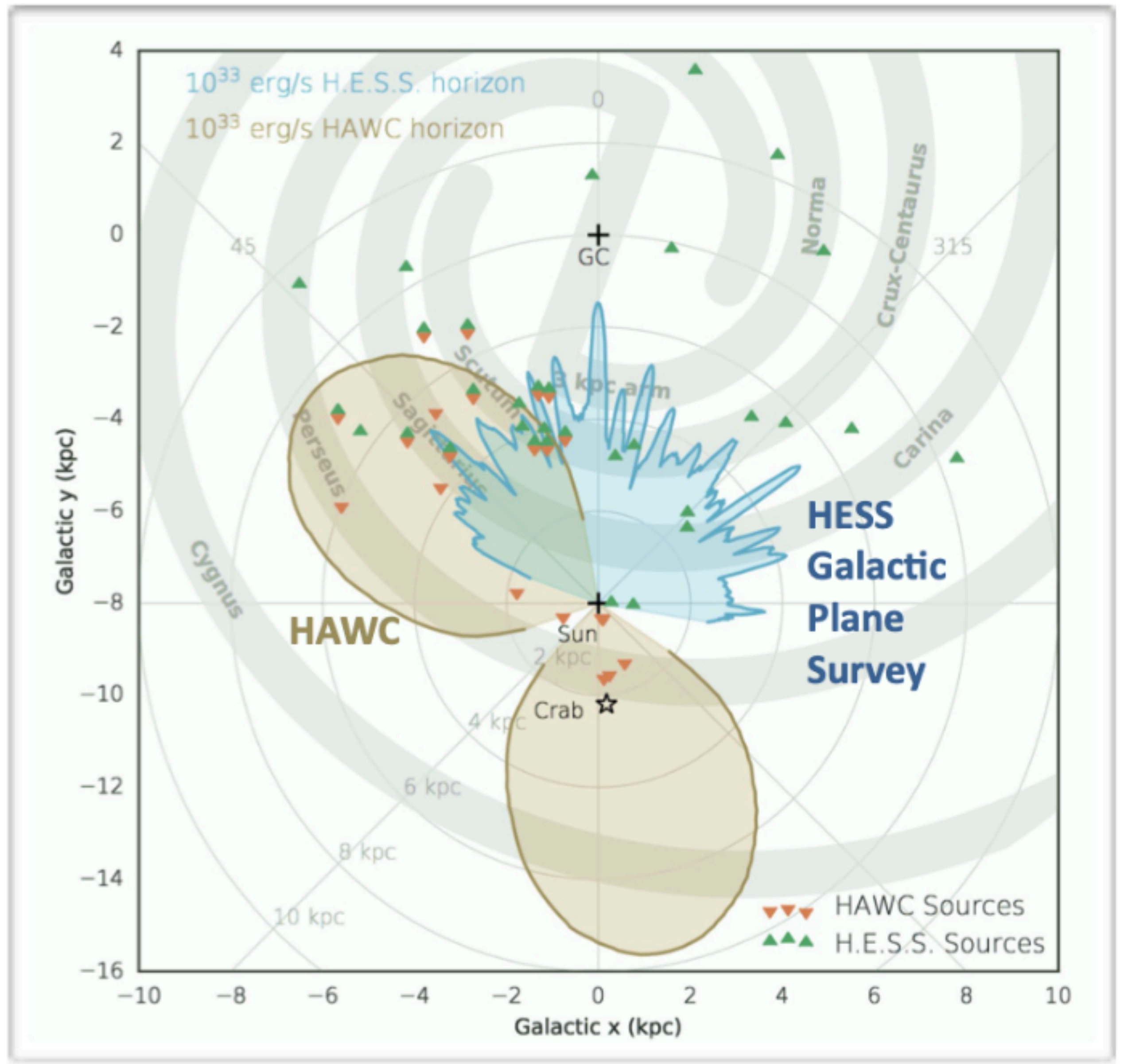
Southern Wide-Field Gamma-ray Observatory



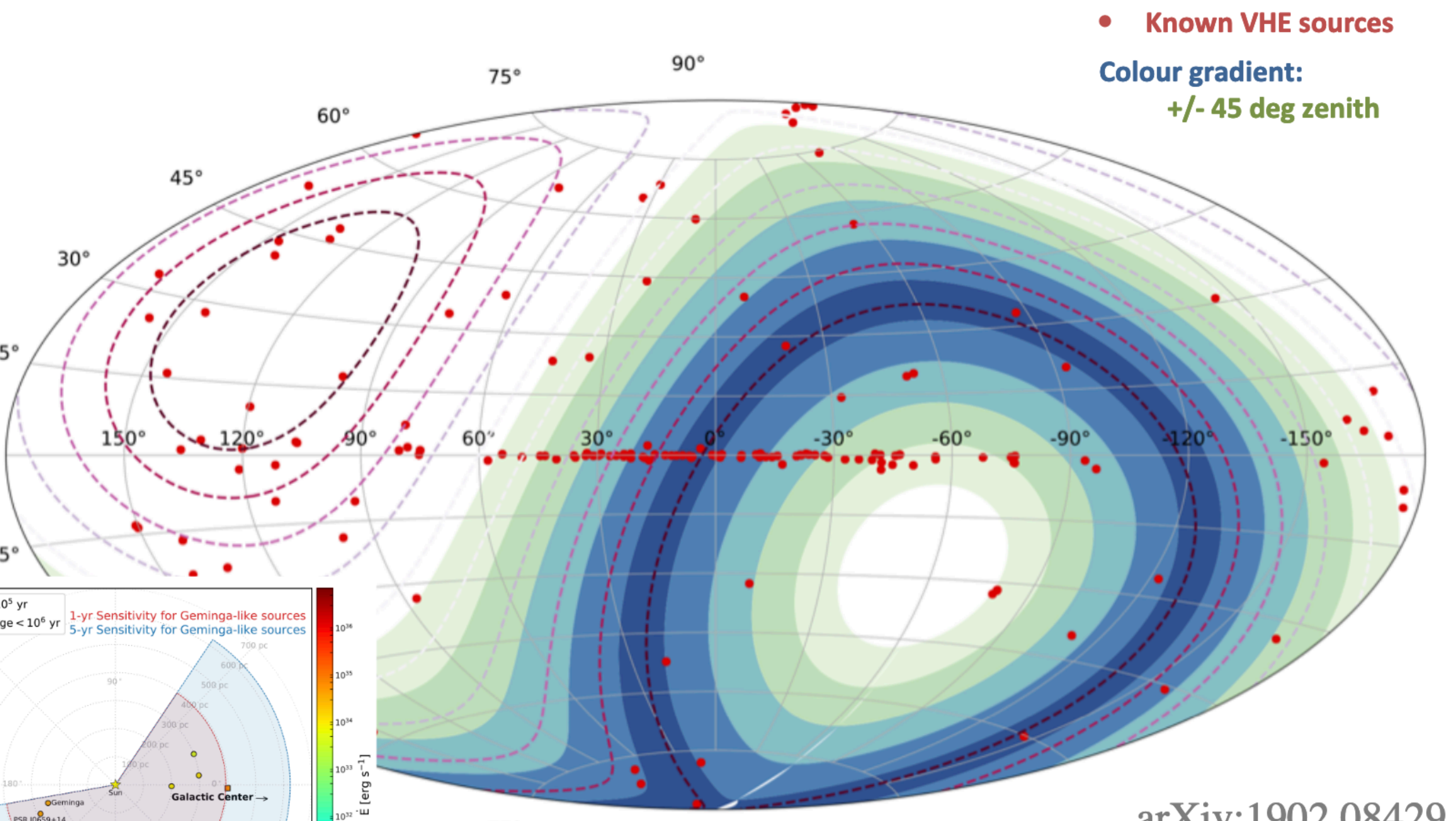


Future facilities

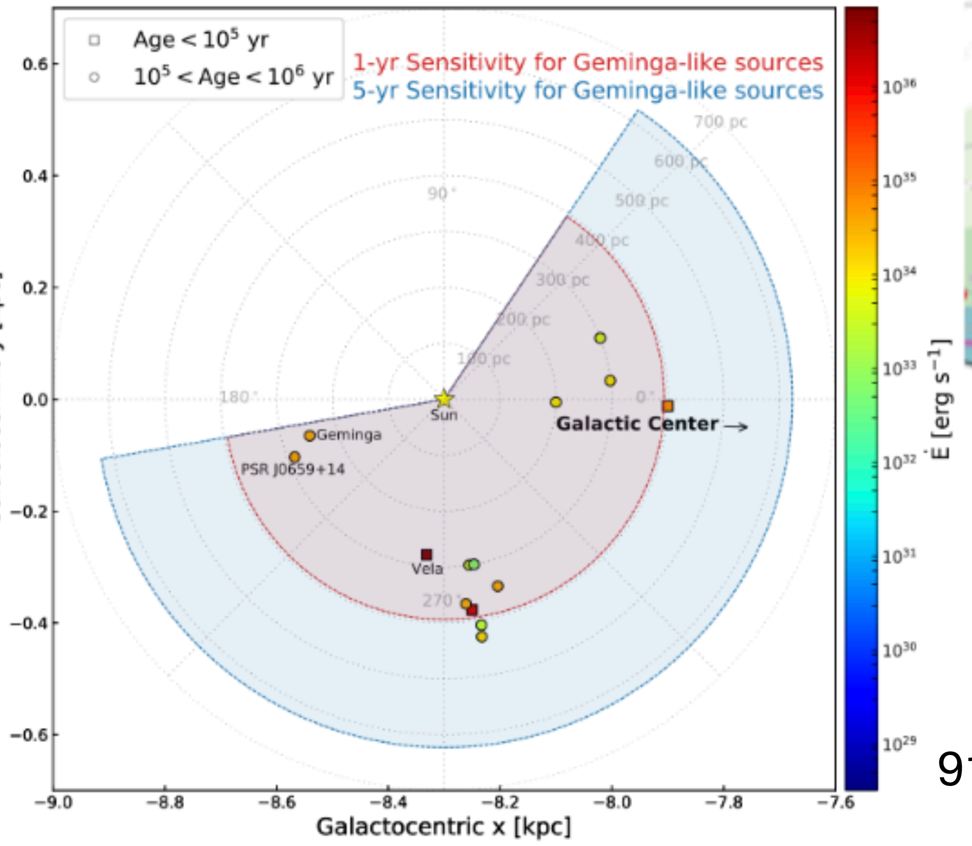
Southern Wide-Field Gamma-ray Observatory



Doro 2020



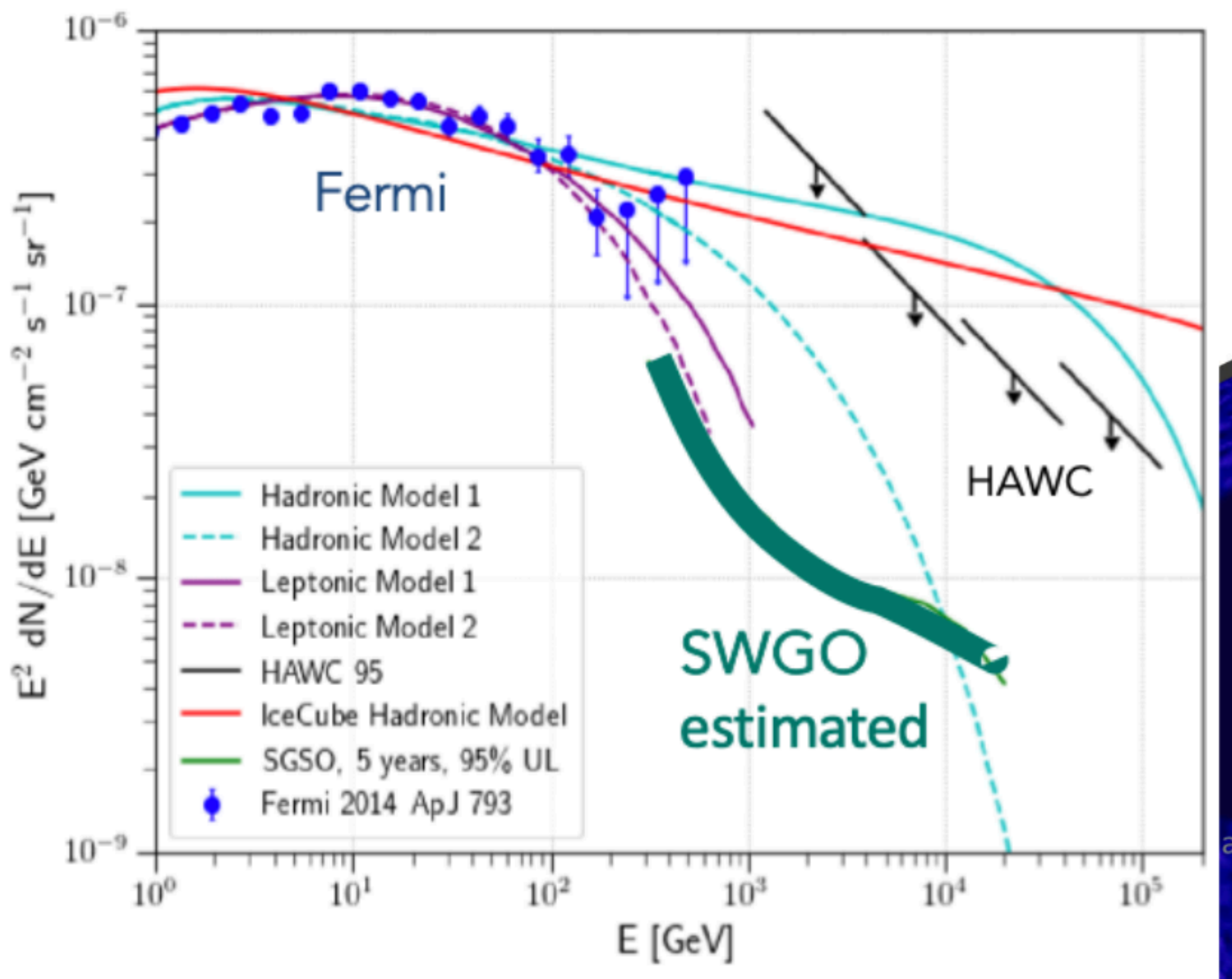
SWGO will complement the view of the Galactic source population towards the highest energies and will greatly expand our reach for disclosing the full Galactic population of high-energy accelerators.

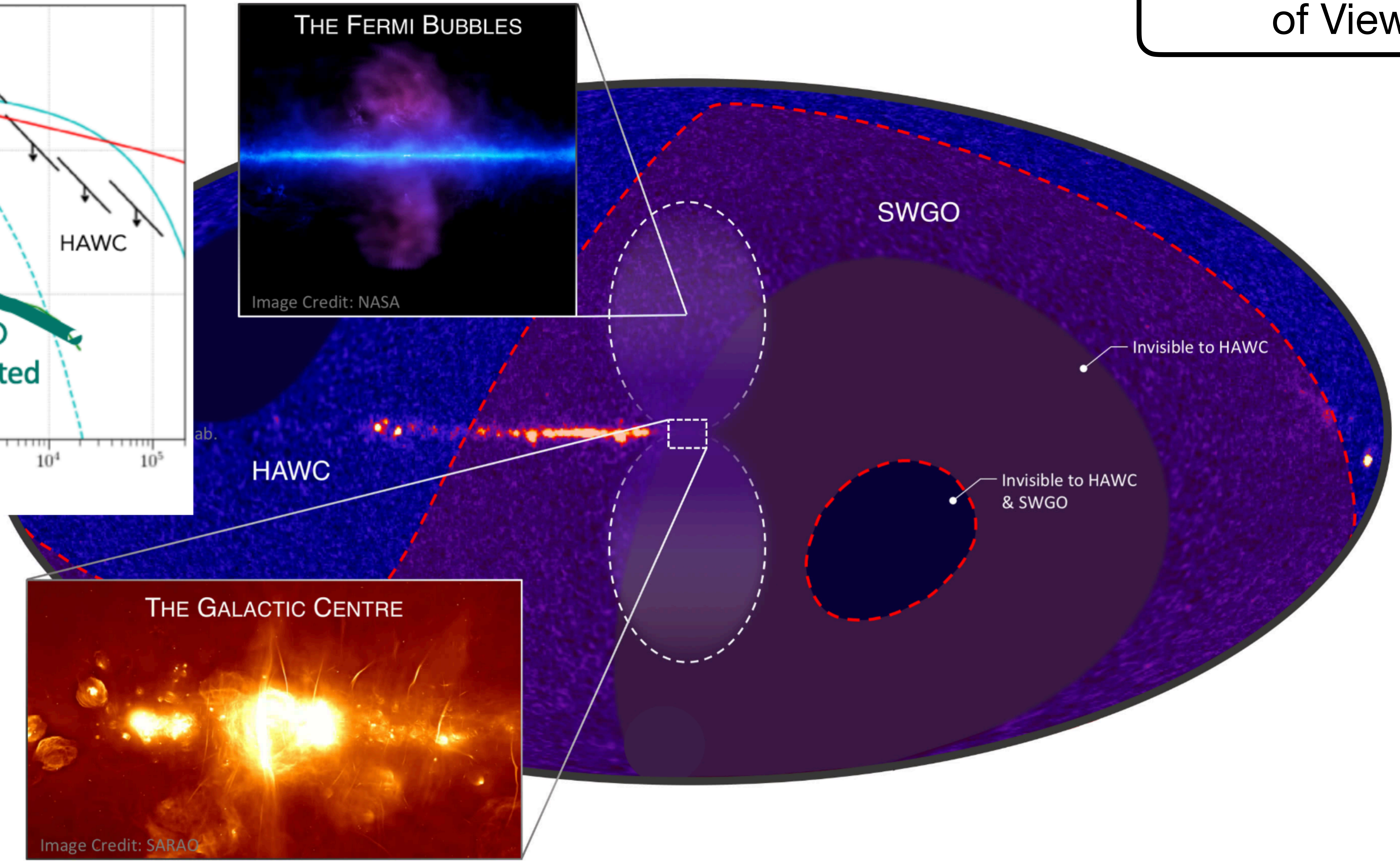


Future facilities

Southern Wide-Field Gamma-ray Observatory

Large Field of View



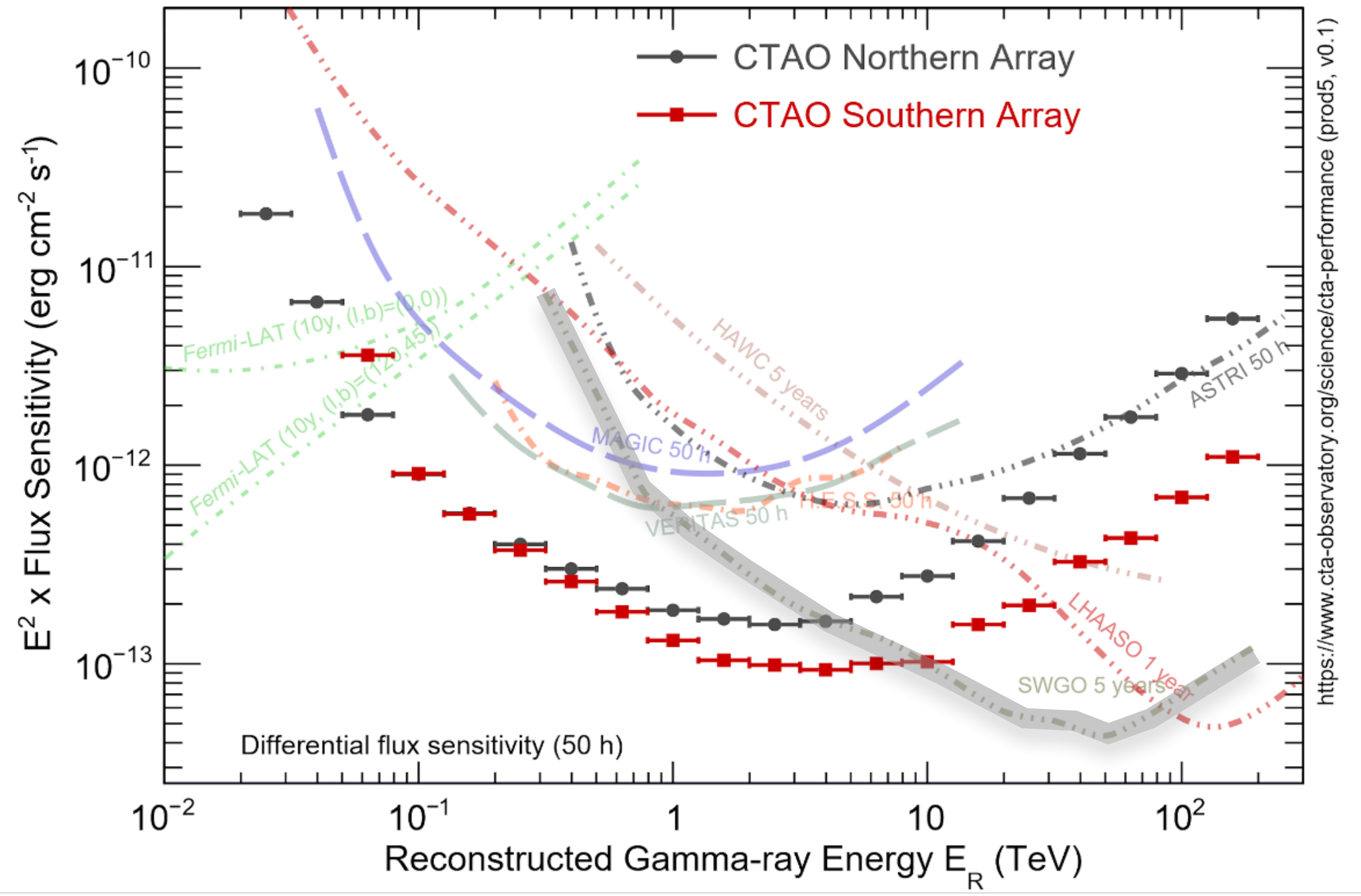


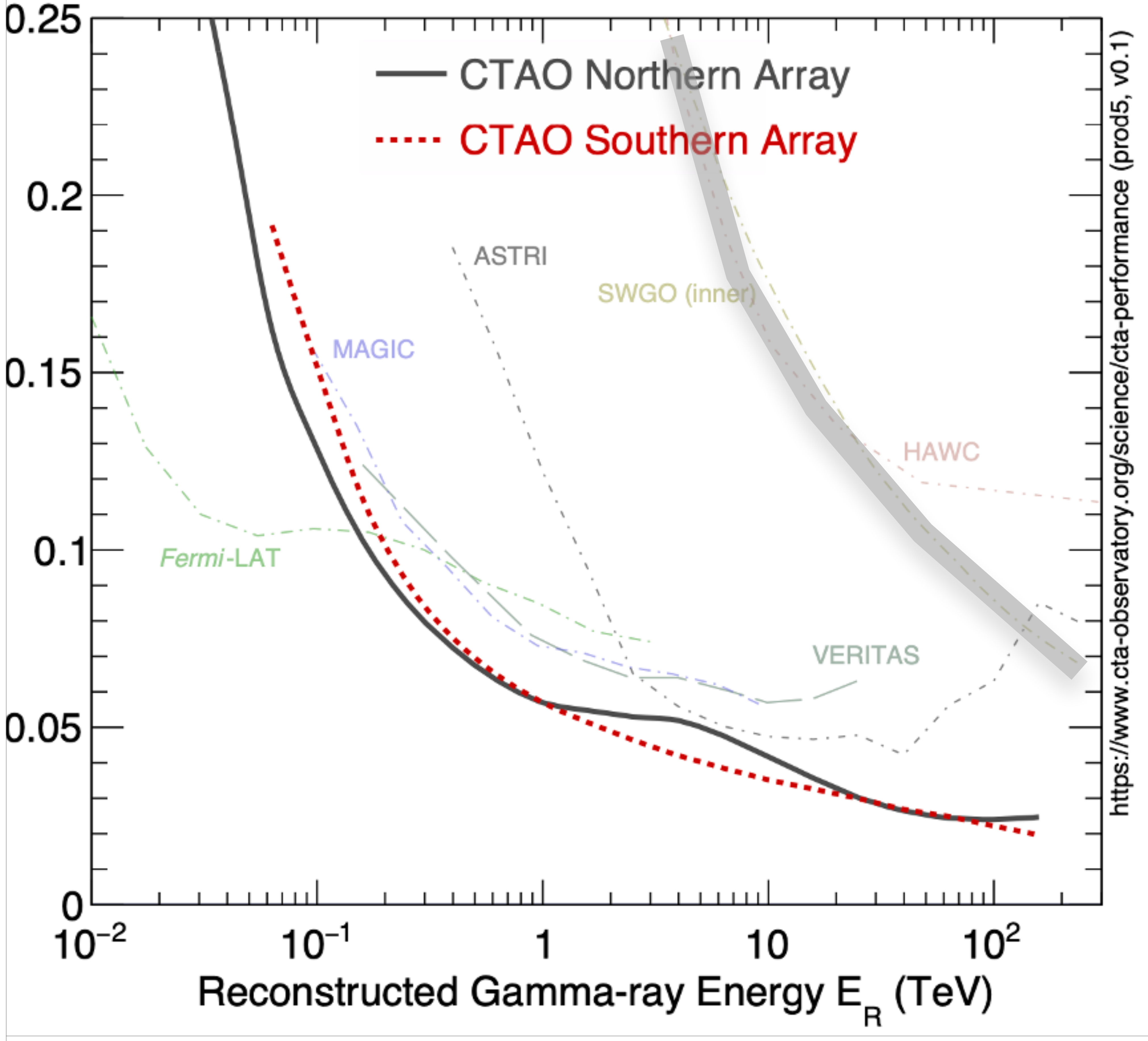
Crucial access to the Galactic Plane and the Galactic Center, and a complementary view of the sky with HAWC and LHAASO for cosmic-rays and diffuse emission studies.

Science Case: https://arxiv.org/abs/ 1902.08429

Future facilities

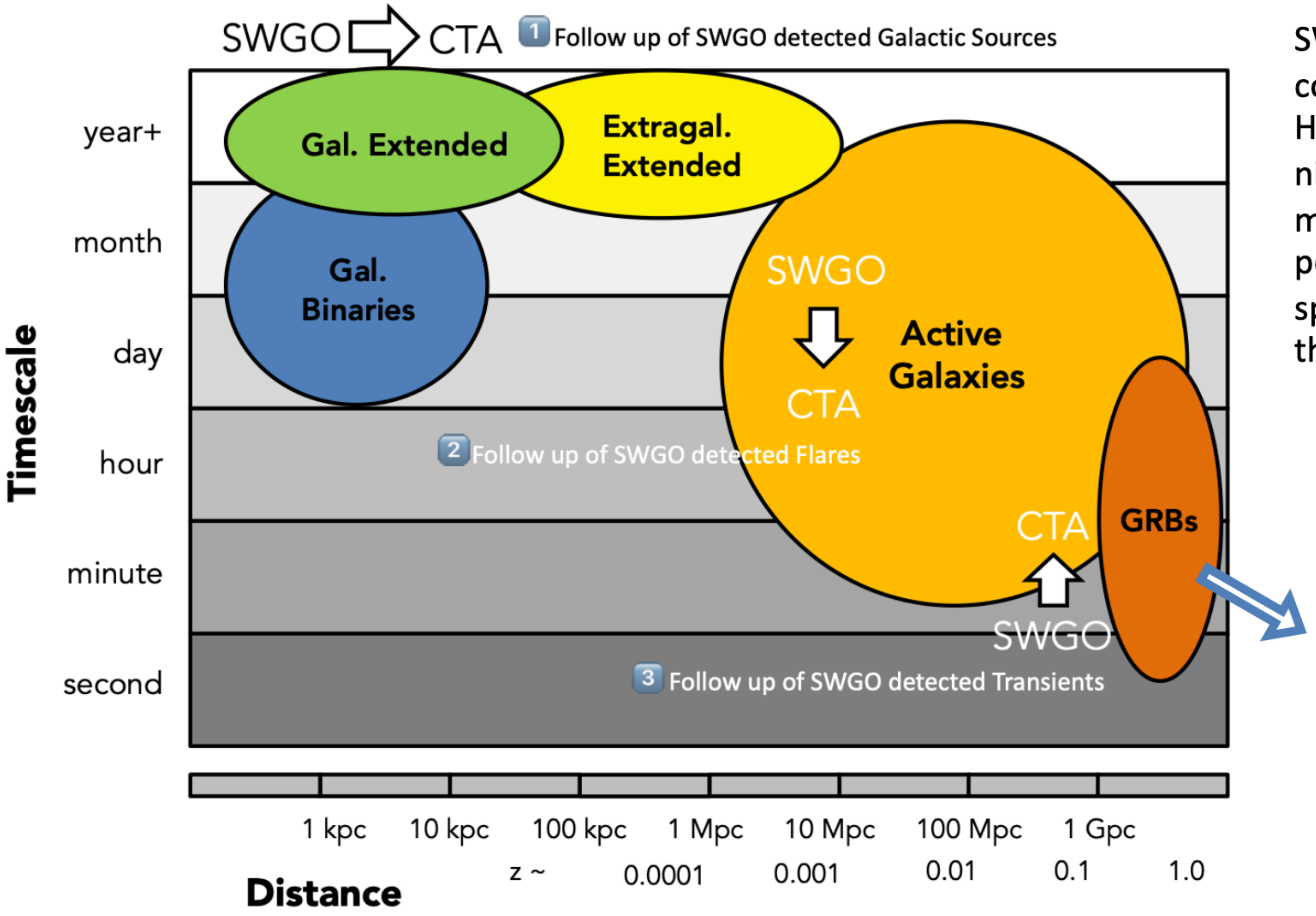
Complementary instruments





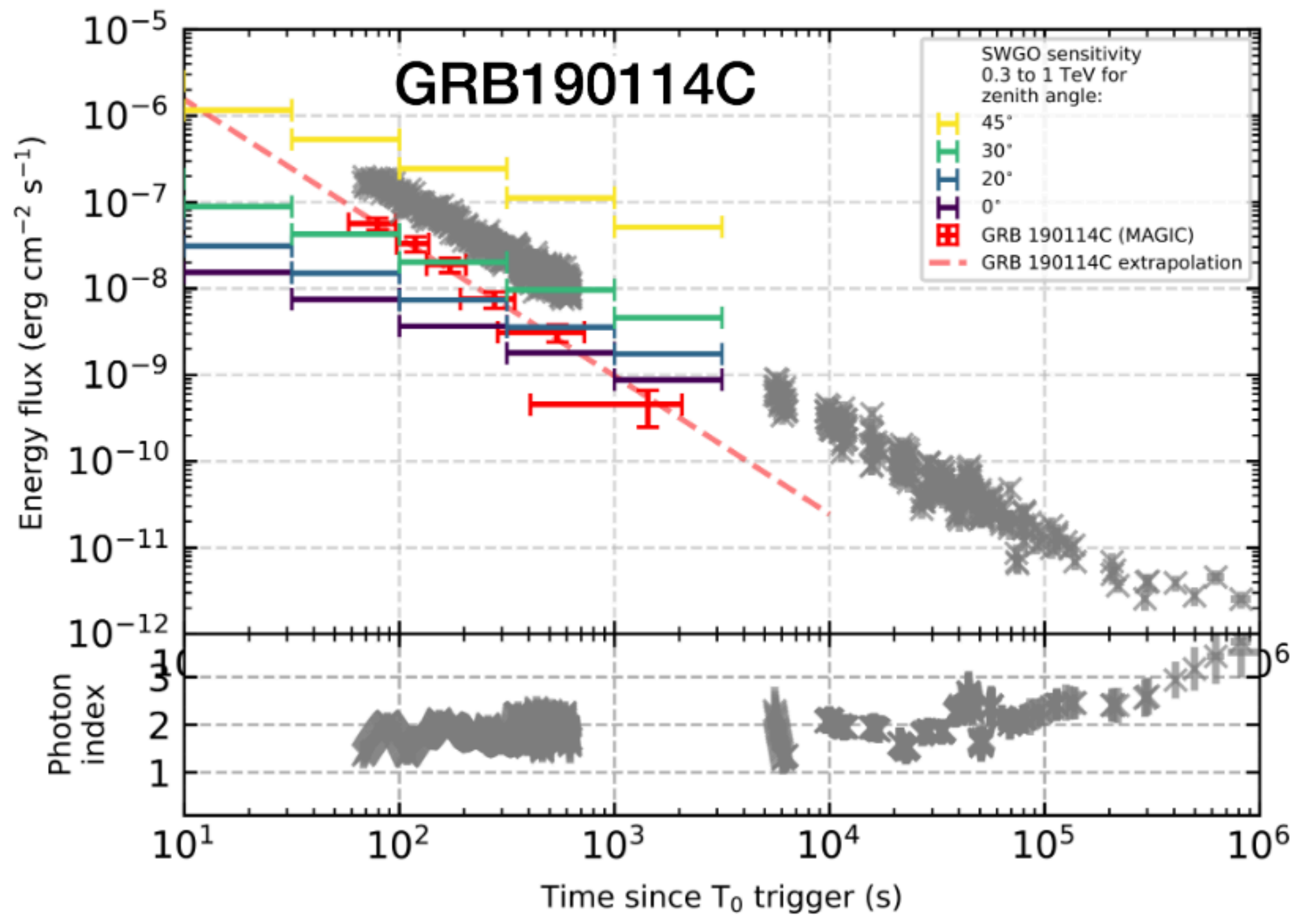
Future facilities

Complementary instruments



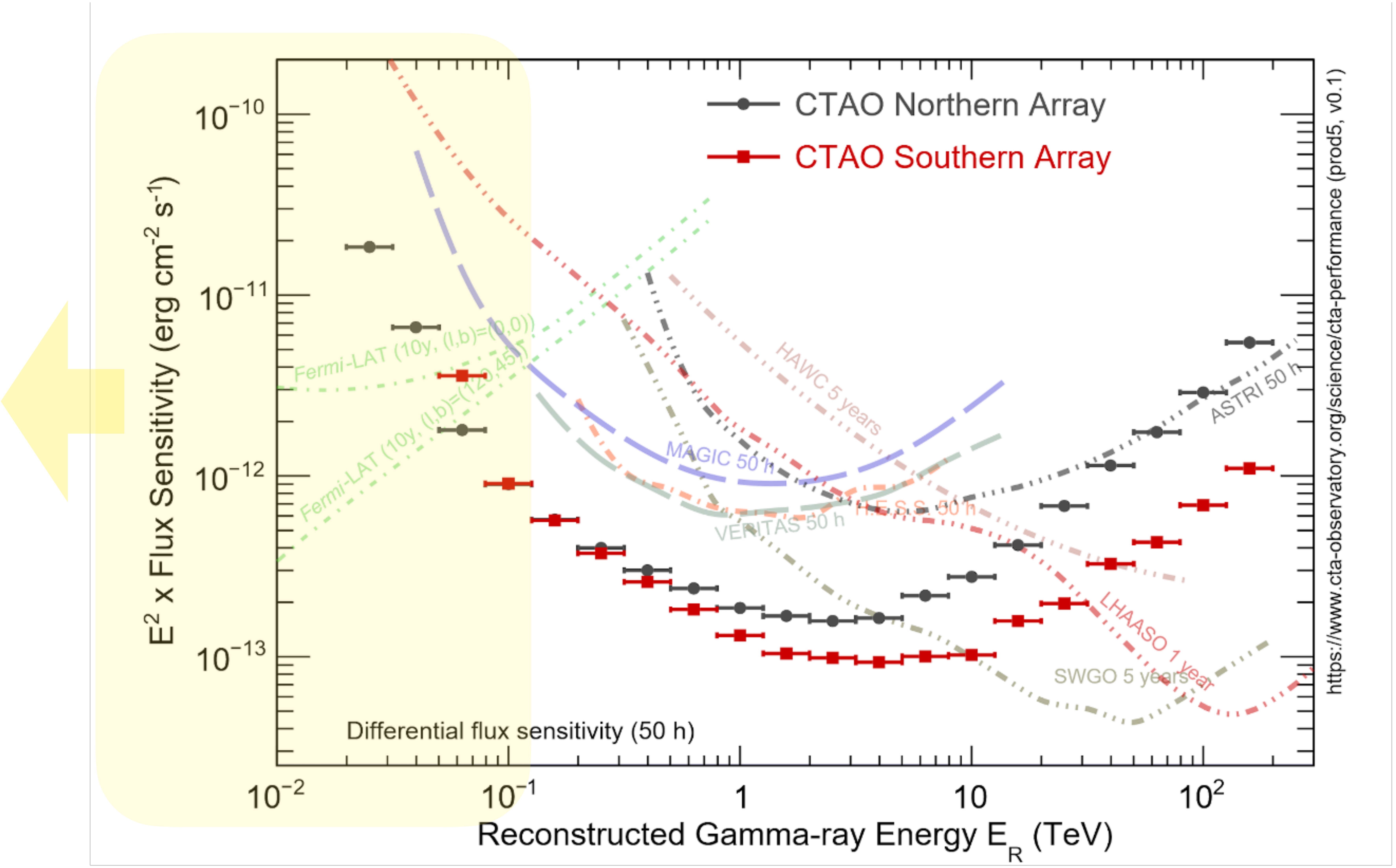
Plot by Jim Hinton

SWGO will provide the necessary complement to observation of the Southern Hemisphere transient sky, filling-up a missing niche in the global network of multi-messenger astronomy. It will also work as a powerful trigger for transient observations, specially for GRBS, with peak performance at the short < 1 ks timescale.



Future facilities

More ideas?

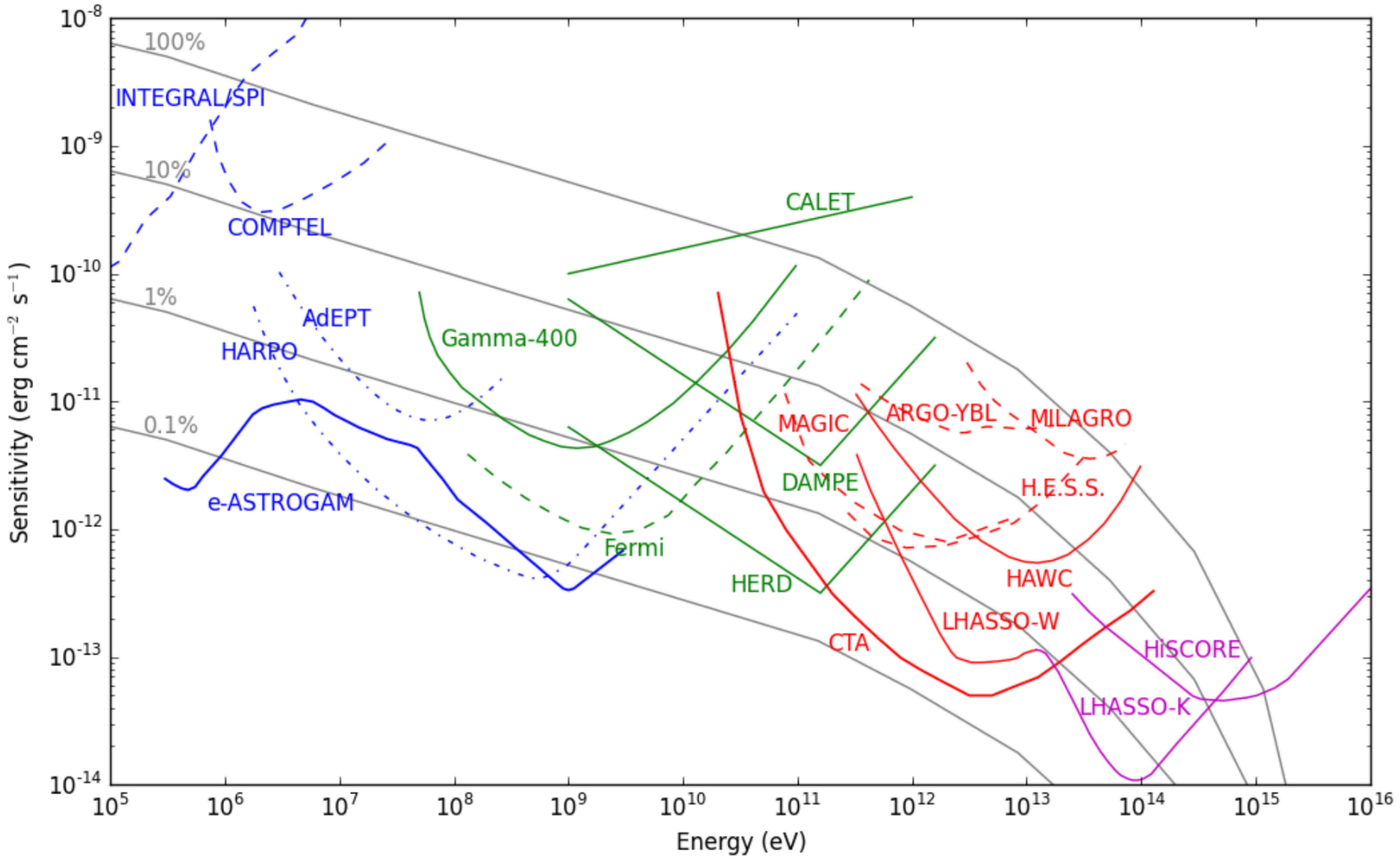


Future facilities

More ideas?

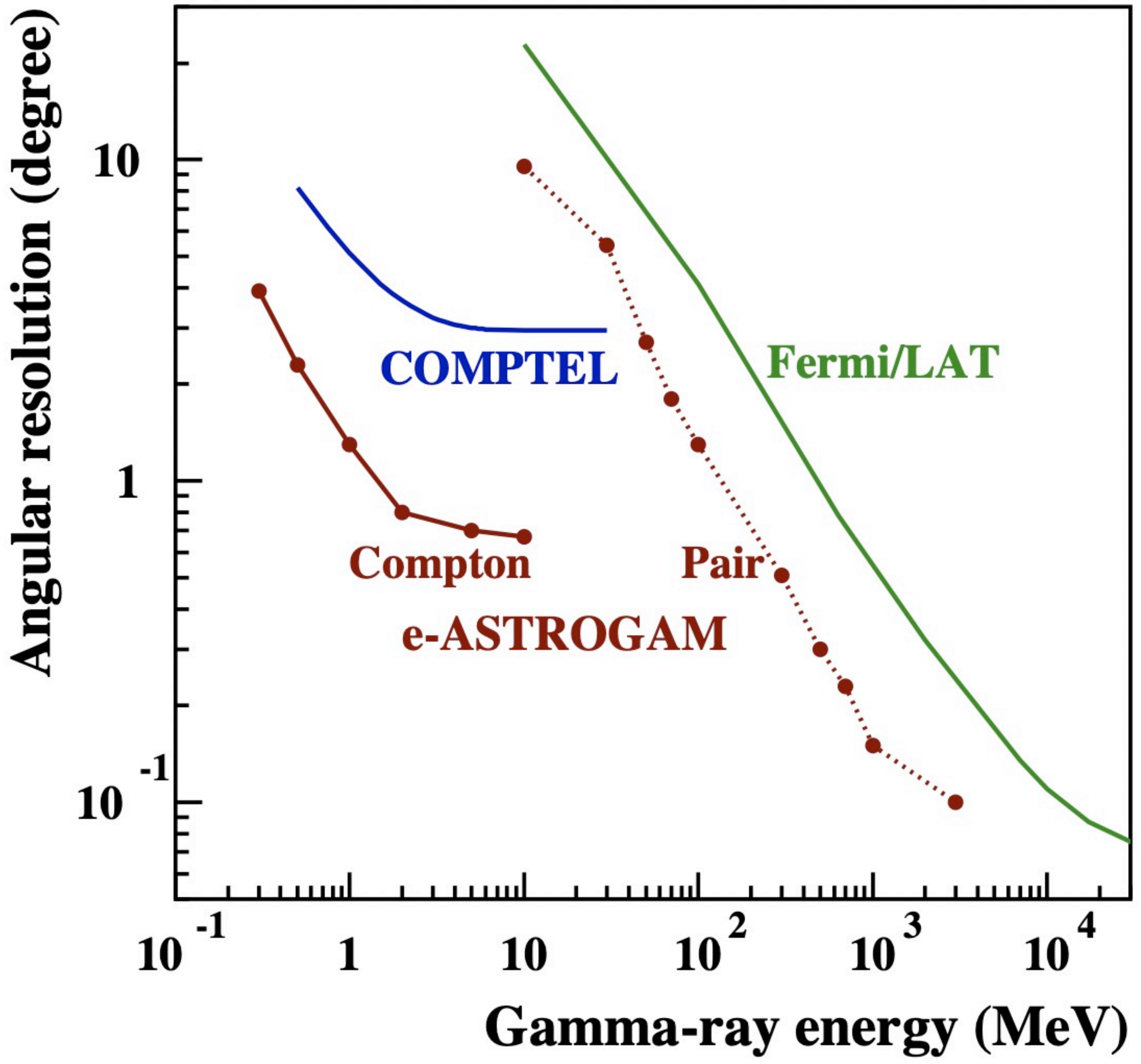
- A GeV telescope much bigger than LAT to increase the effective detection area would soon hit the maximum capacities of existing (and also planned) launch vehicles.
  => Improve angular resolution
  => decrease the density of the material in the tracker / space the tracking element apart

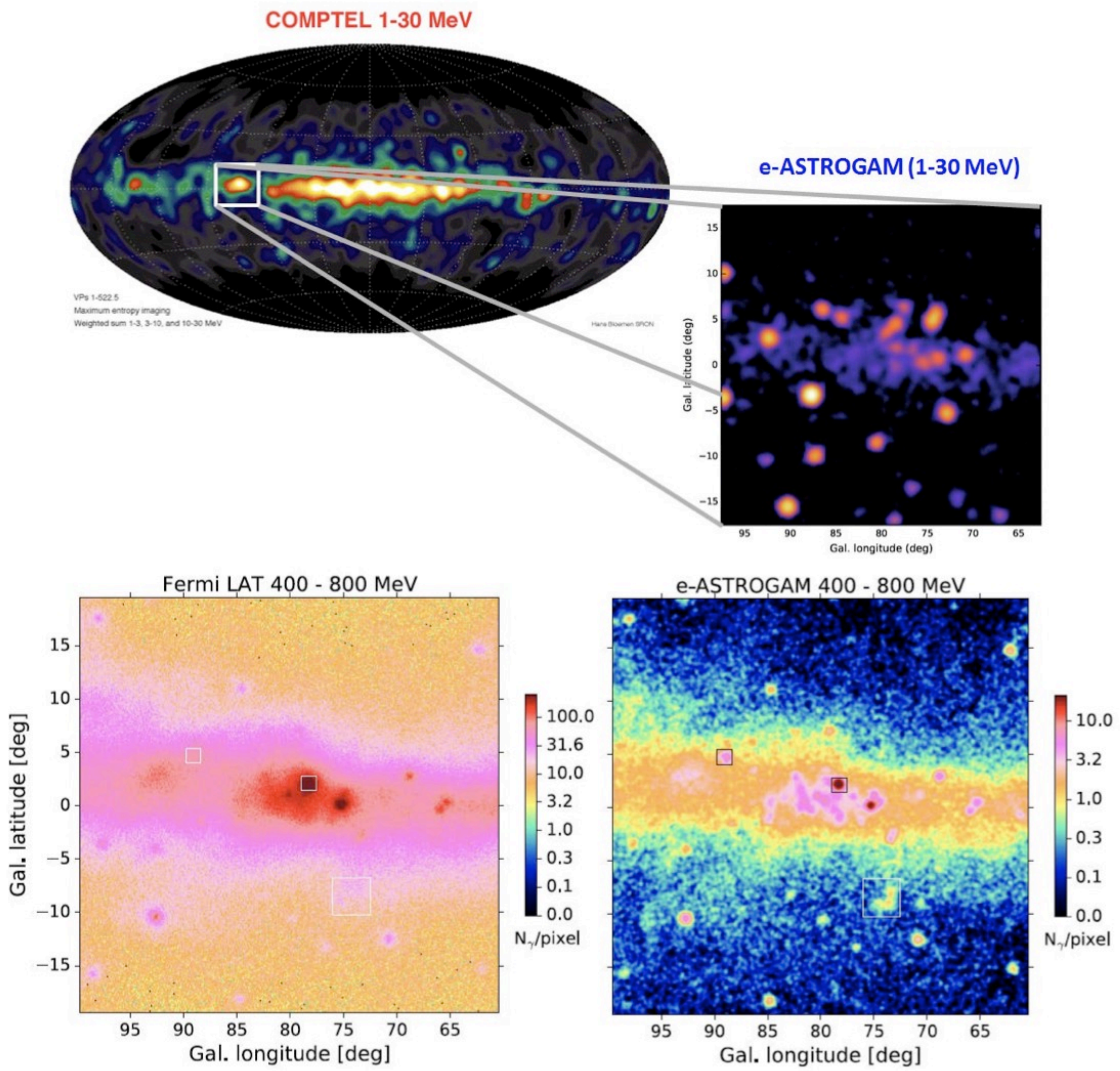
- The TPC (gaseous time projection chamber) serves as three-dimensional imager of electron-positron pair tracks arising from pair conversion of incoming photons in the detector volume.
- Silicon tracker, a 3D-imaging scintillator calorimeter, and a plastic scintillator anti-coincidence shield



Future facilities

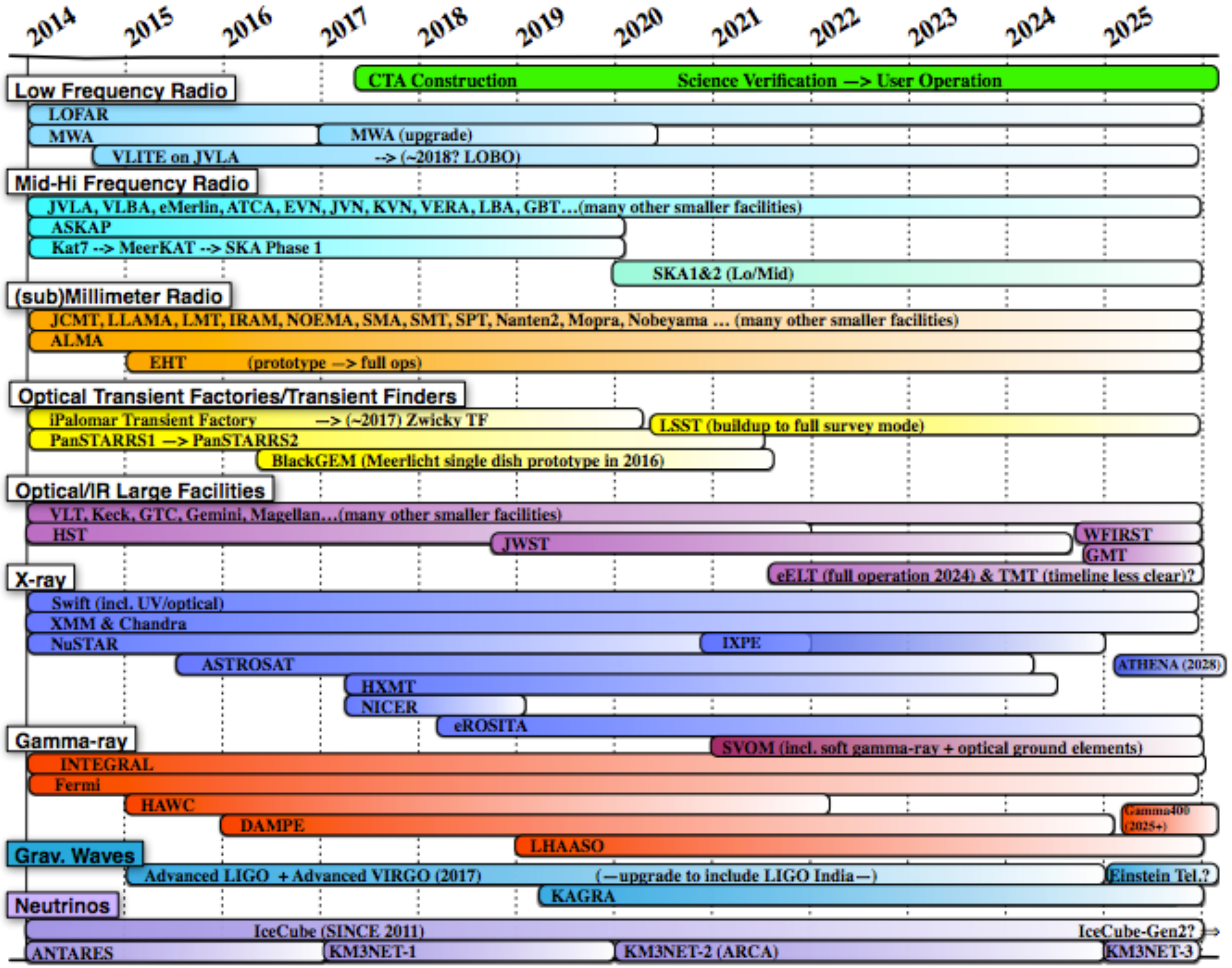
More ideas?





5 The Multi-Wavelength Picture

The Multi-Wavelength Picture

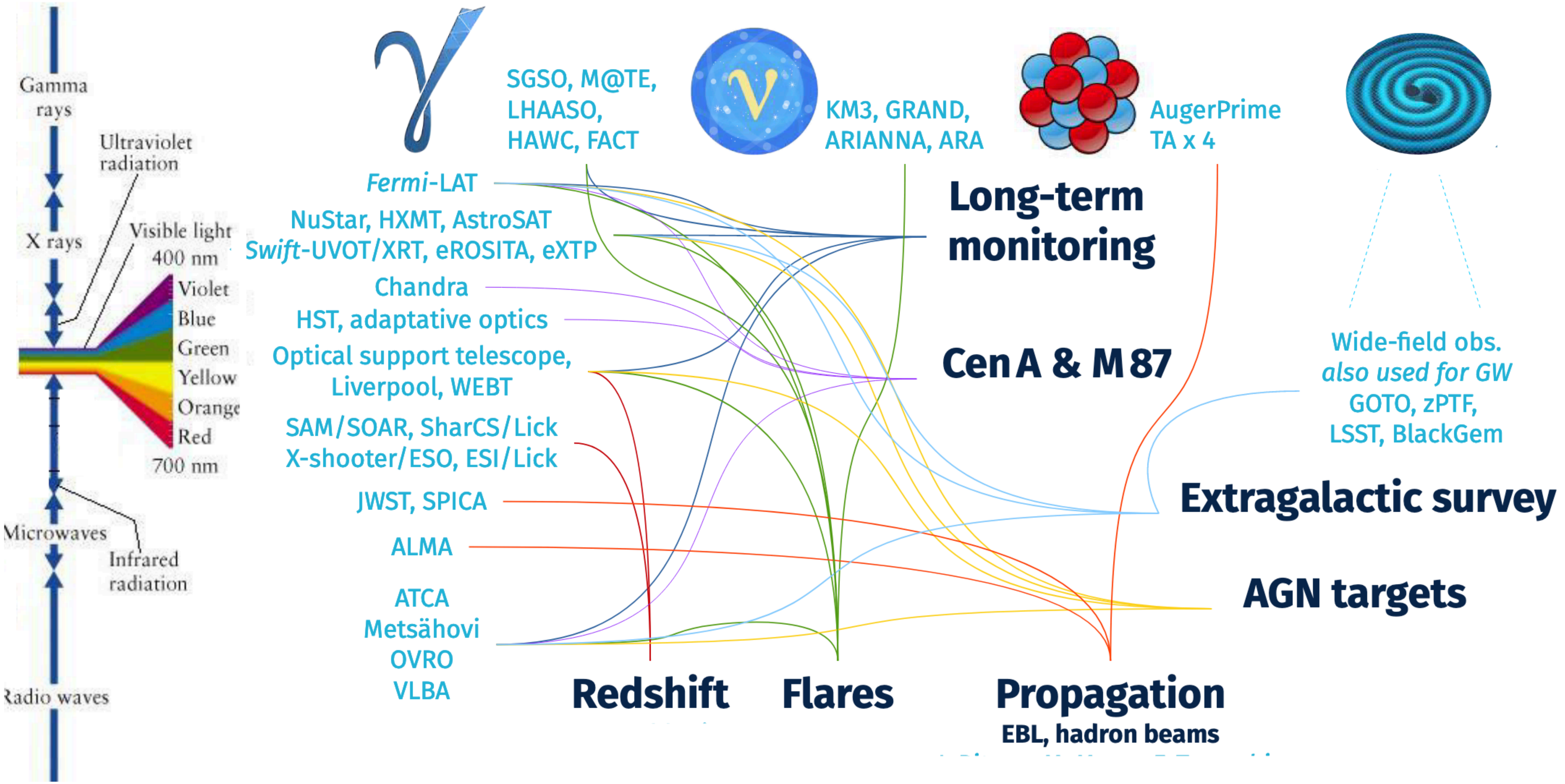


The Multi-Wavelength Picture

Band or Messenger	Astrophysical Probes	Galactic Plane Survey	LMC & SFRs	CRs & Diffuse Emission	Galactic Transients	Starburst & Galaxy Clusters	GRBs	AGNs	Radio Galaxies	Redshifts	GWs & Neutrinos
Radio	Particle and magnetic-field density probe. Transients. Pulsar timing.	✔	✔	✔	✔	✔	✔	✔	✔		✔
(Sub)Millimetre	Interstellar gas mapping. Matter ionisation levels. High-res interferometry.	✔	✔	✔		✔		✔	✔		
IR/Optical	Thermal emission. Variable non-thermal emission. Polarisation.	✔	✔	✔	✔	✔		✔	✔	✔	
Transient Factories	Wide-field monitoring & transients detection. Multi-messenger follow-ups.						✔	✔			✔
X-rays	Accretion and outflows. Particle acceleration. Plasma properties.	✔	✔	✔	✔	✔	✔	✔	✔		✔
MeV-GeV Gamma-rays	High-energy transients. Pion-decay signature. Inverse-Compton process	✔	✔	✔	✔	✔	✔	✔			✔
Other VHE	Particle detectors for 100% duty cycle monitoring of TeV sky.	✔	✔	✔		✔		✔			
Neutrinos	Probe of cosmic-ray acceleration sites. Probe of PeV energy processes.			✔			✔	✔			✔
Gravitational Waves	Mergers of compact objects (Neutron Stars). Gamma-ray Bursts.						✔				✔

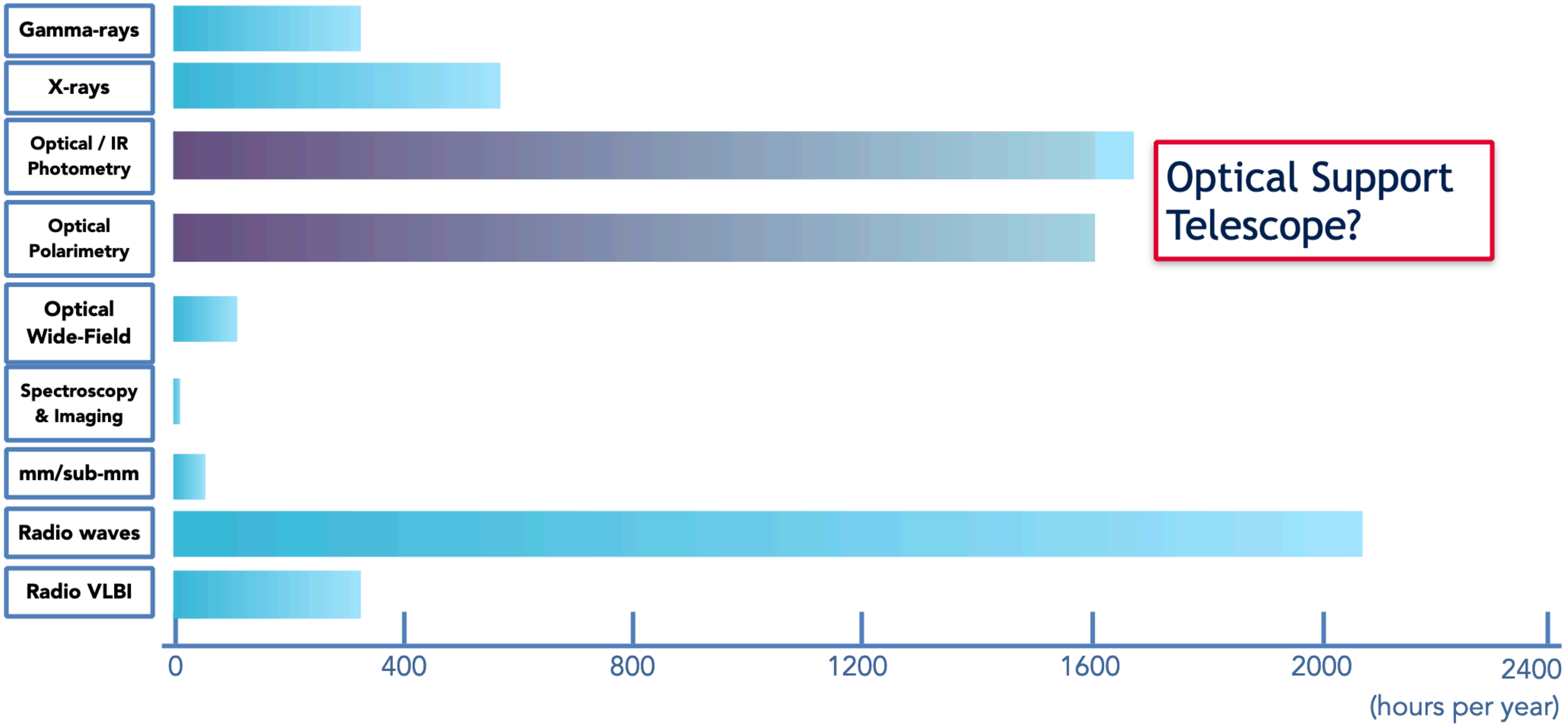
de Almeida 2019

The Multi-Wavelength Picture



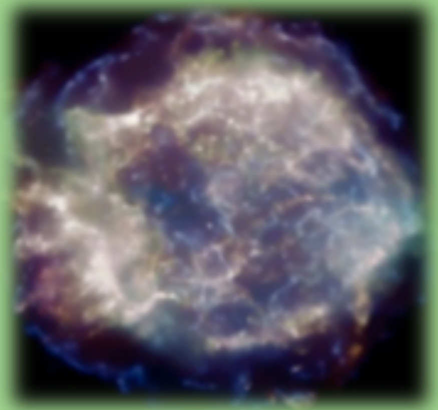
de Almeida 2019

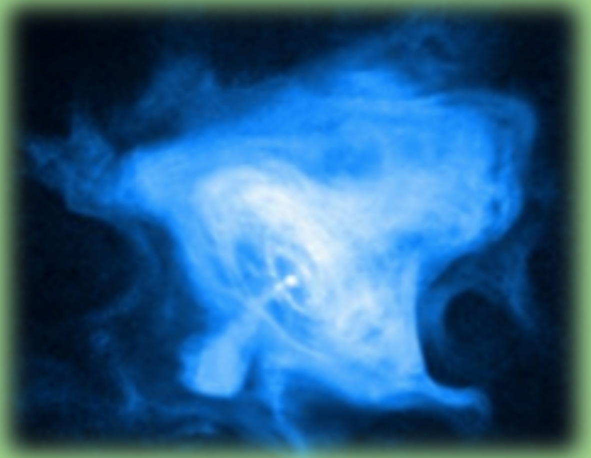
The Multi-Wavelength Picture



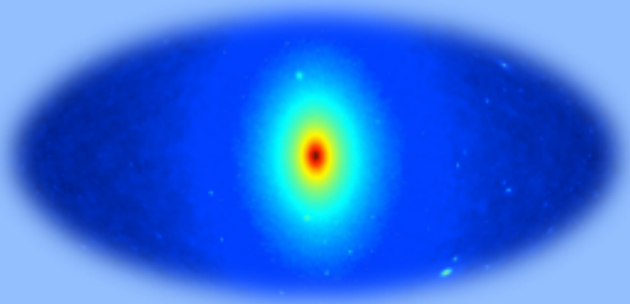
What do we expect in the next years?

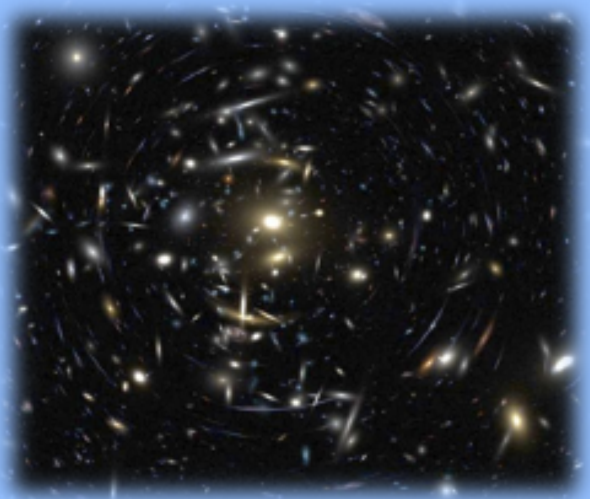
In-depth understanding of known objects and their mechanisms





Expected discoveries of new object classes





The fun part:
Things we haven't thought of

?

1. Choose your fav science case(s)

2. Think what do you need to prove your hypothesis

    1. which energy range?
    2. what do you expect to see in terms of spectrum/ morphology/time-domain?

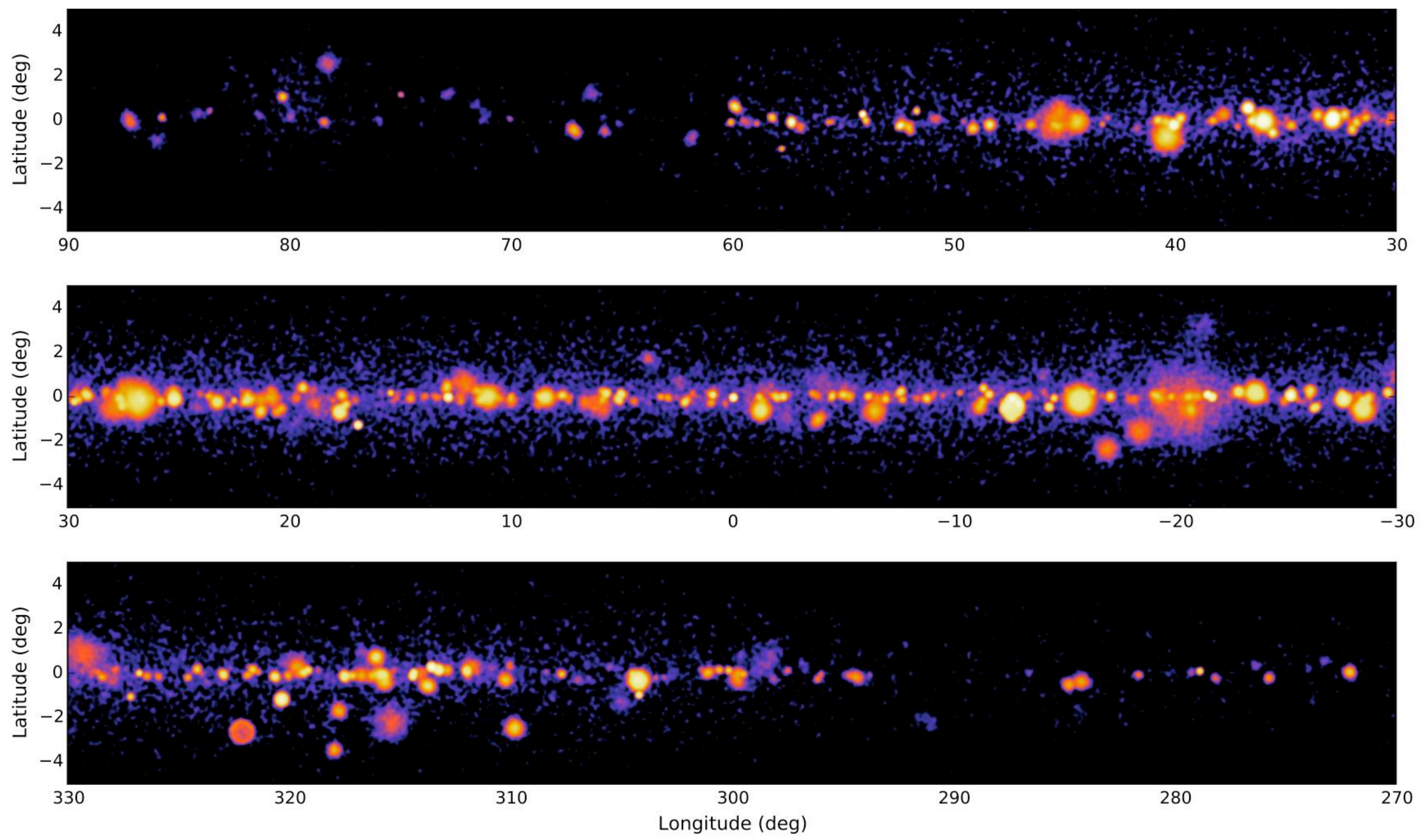
3. How precise does your measurement has to be?

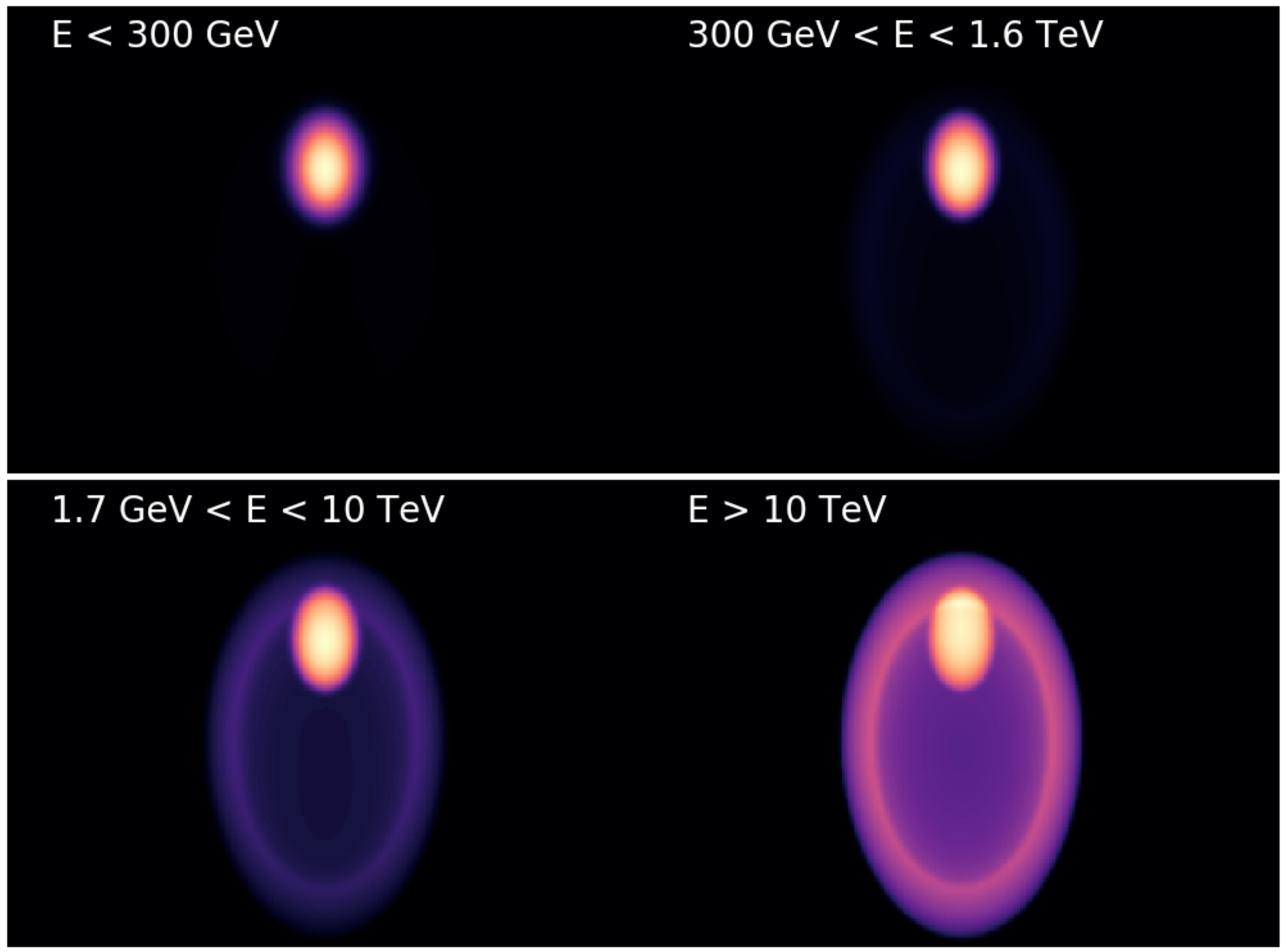
4. Do you need MWL support?

5. What type of instrument you need in the gamma-ray?

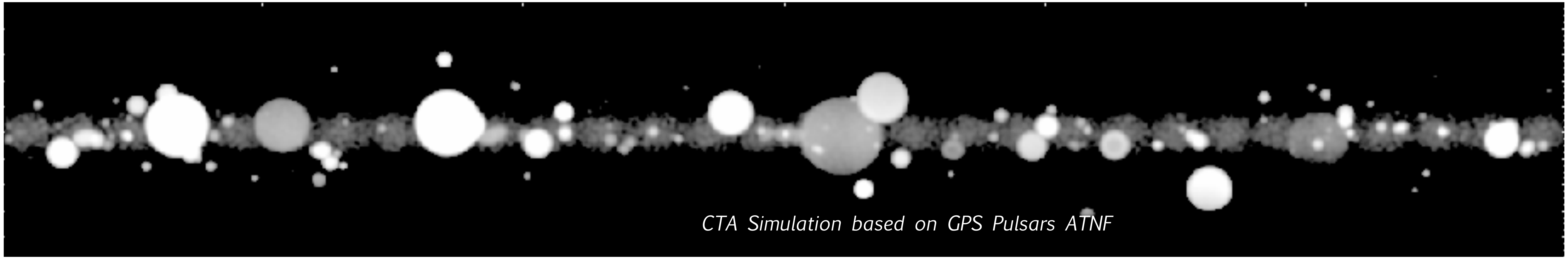
6. If you would have an infinity amount of money, what type of instrument could we build? how can you improve the current and planned instruments?

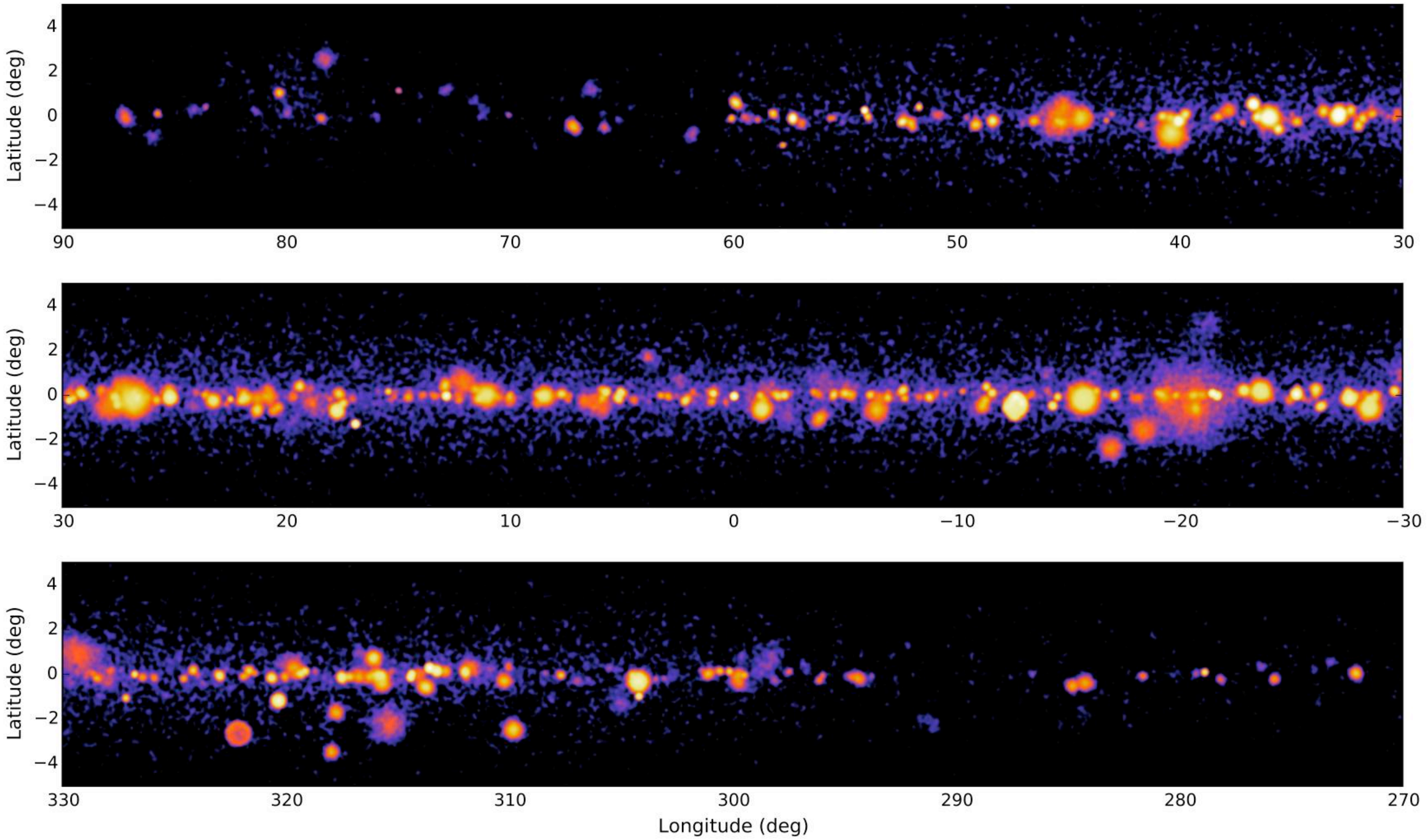
Source Confusion

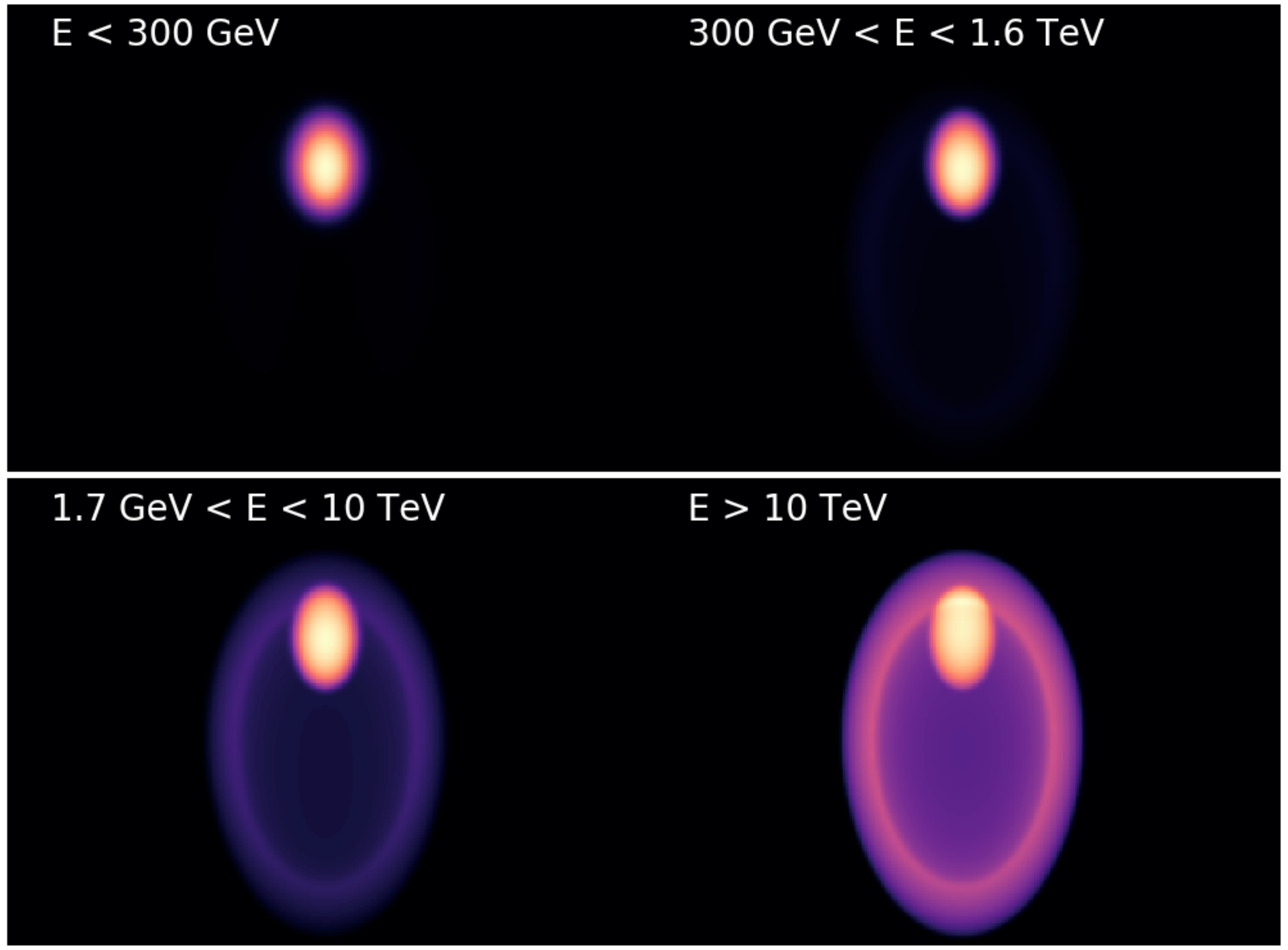




Source Confusion







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?	2015	2015	$\sim$ 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**

Table 1
Summary of instruments and mission concepts for space-based gamma-ray astronomy (see text). MDP indicates the minimum detectable polarisation of an instrument. Detector technologies comprise time projection chambers (TPC), silicon trackers (Si), cesium iodide scintillators (CsI), scintillating fibers (fib.), lead tungstate scintillators ($PbWO_4$), bismuth germanate scintillators (BGO), lutetium yttrium orthosilicate scintillators (LYSO), and magnetic spectrometers (**B**).