GAMMA-RAY ASTRONOMY

Part 2.

A story of instruments

'arQus twinning; Bergen Padova 2022
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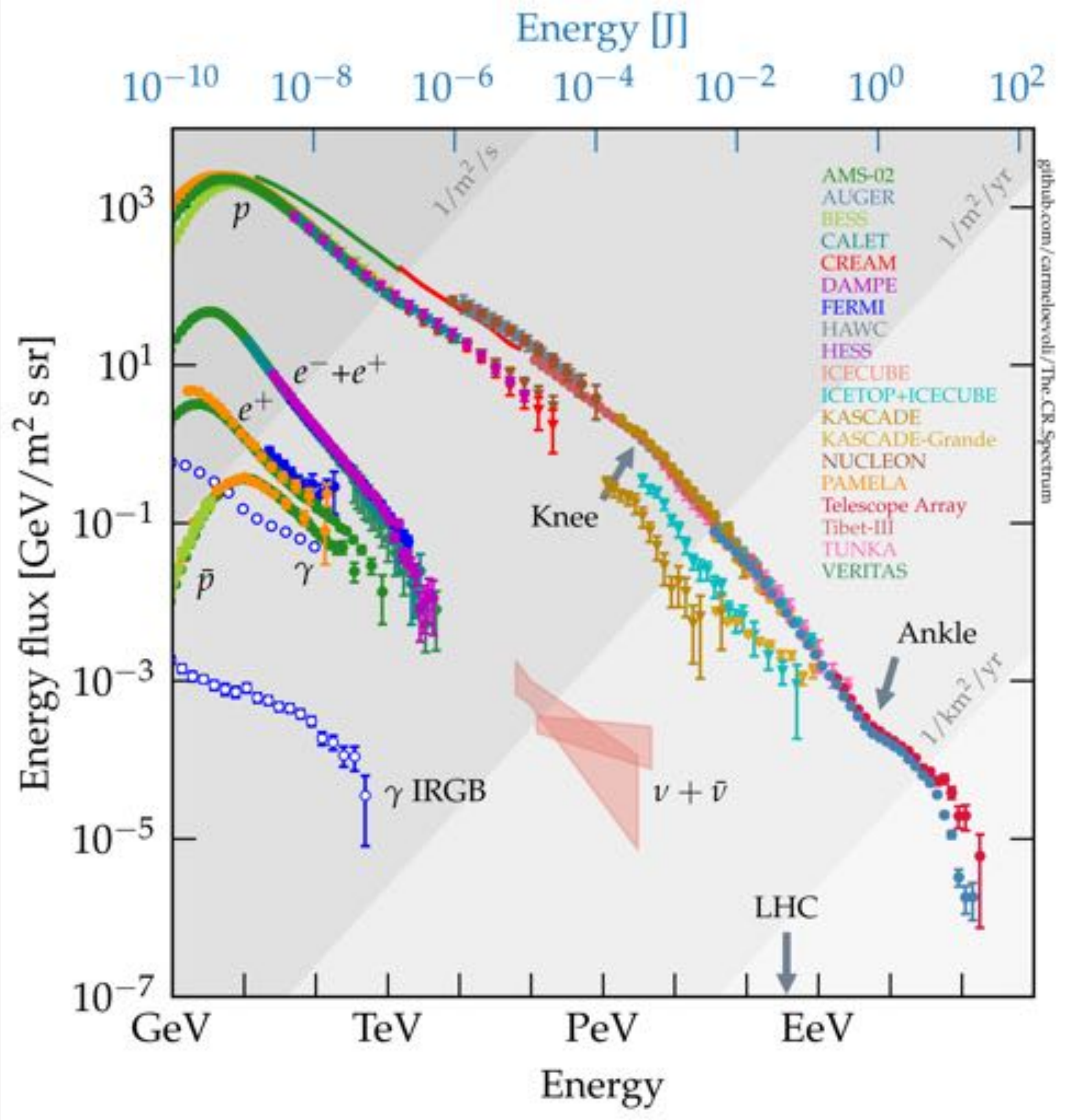
Program

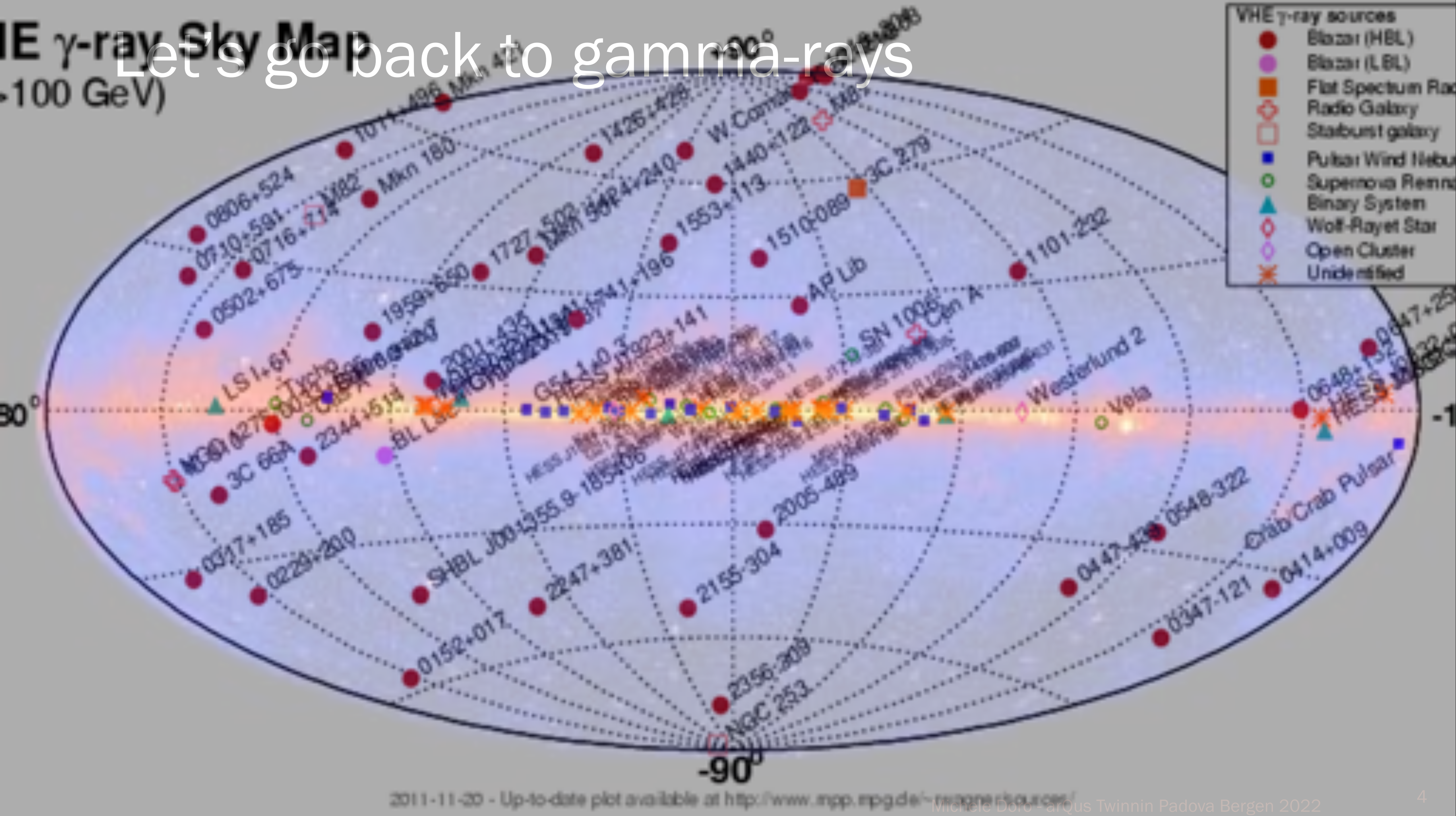
- Small recap
- The family of experiments
- Satellites instruments
- Ground-based Instruments

DISCLAIMER: USED MANY SLIDES FROM R. MIRZOYAN, https://agenda.infn.it/event/17979/timetable/#20200114

The amazing cosmic ray spectrum

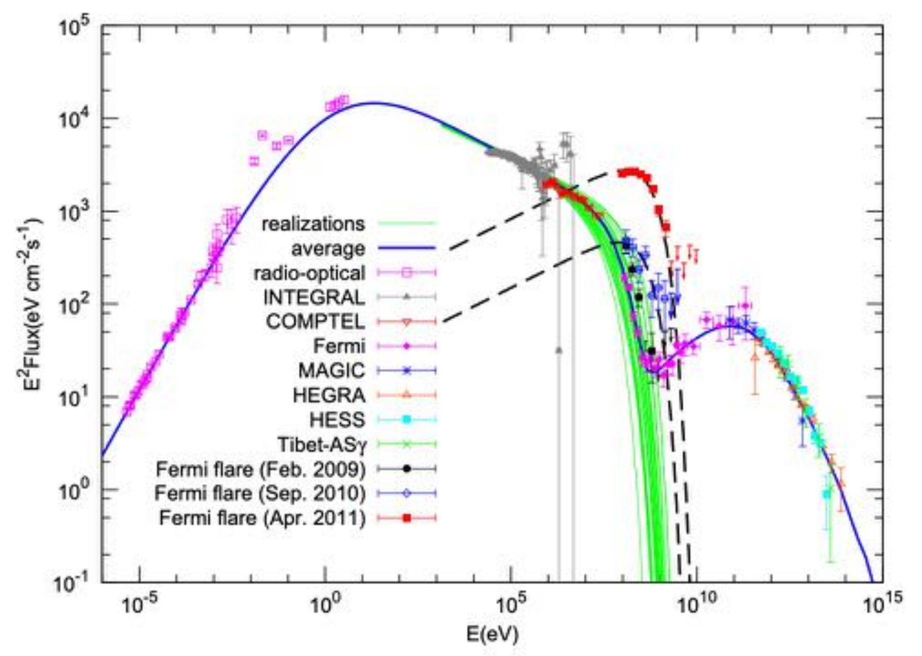


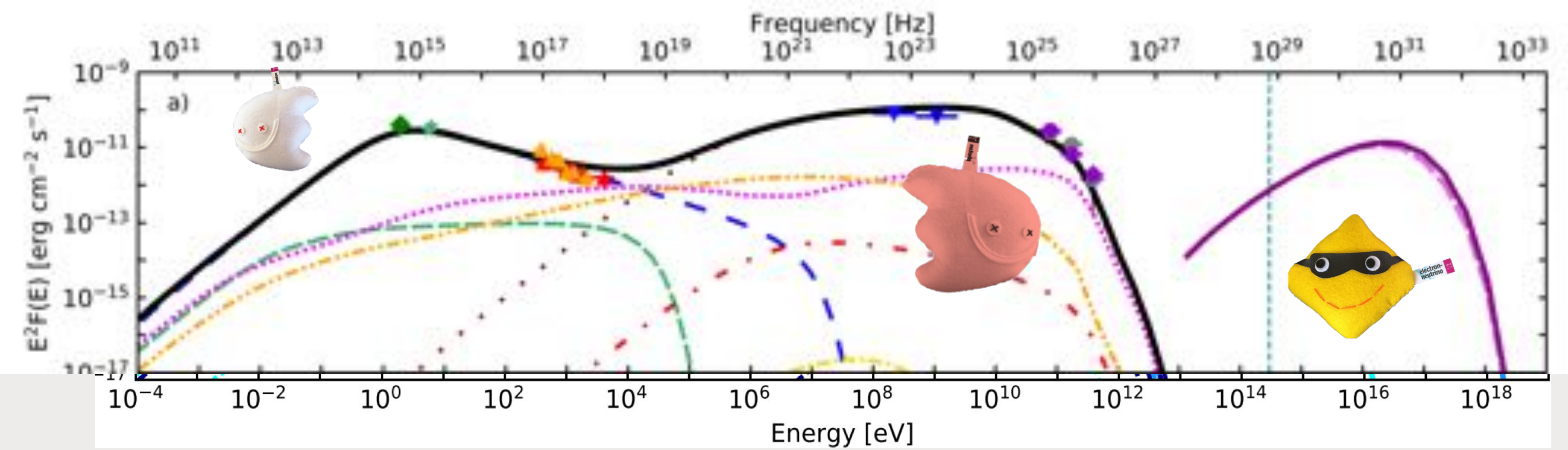
Let's go back to gamma-rays



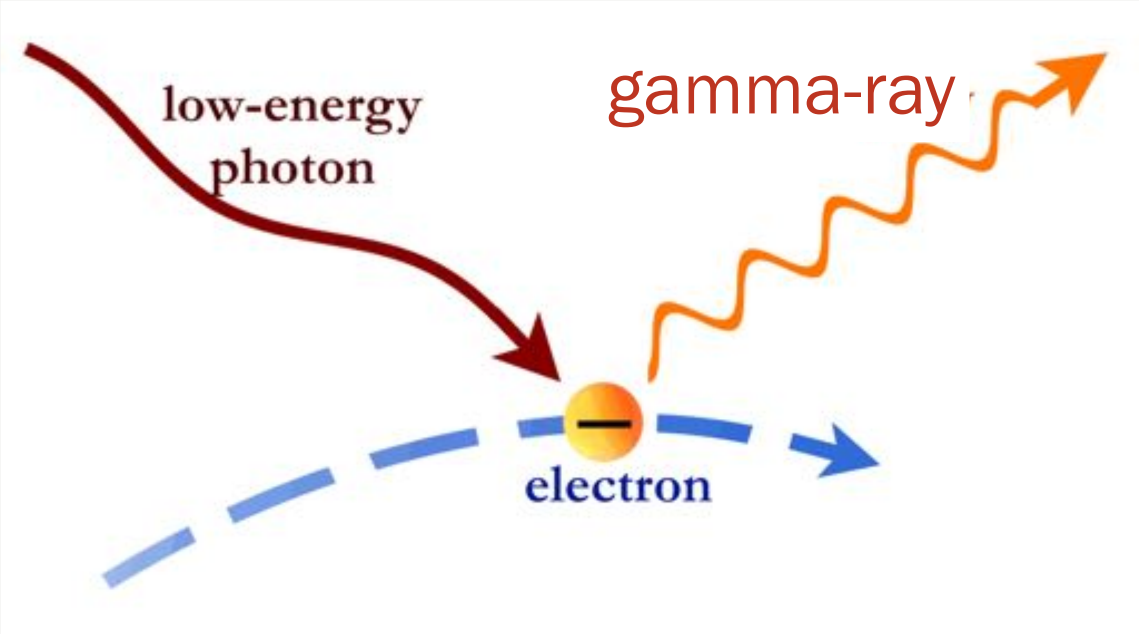
Multi-w multi-m

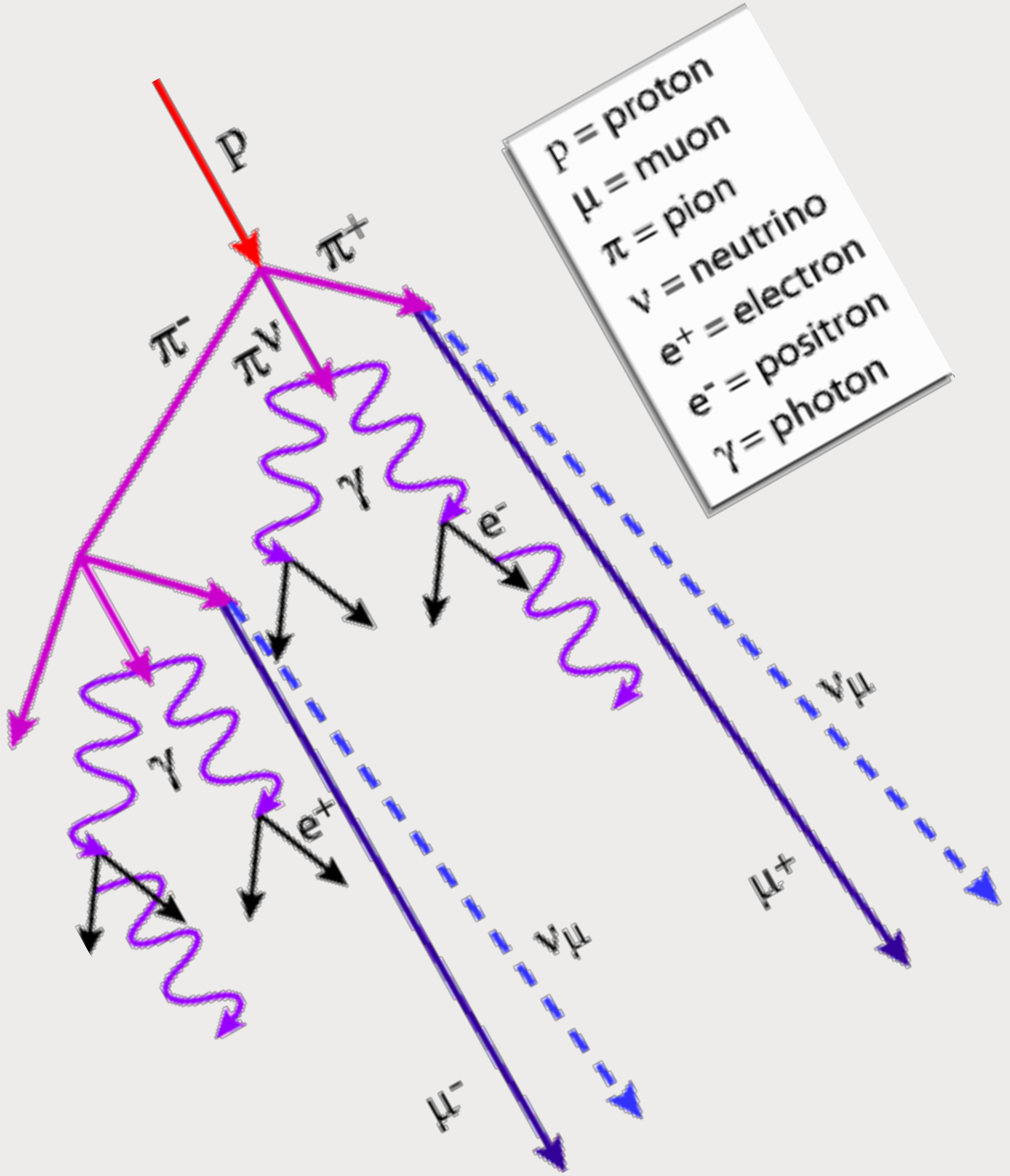
- From radio to gamma
- From gamma to neutrinos





Generate gamma-rays





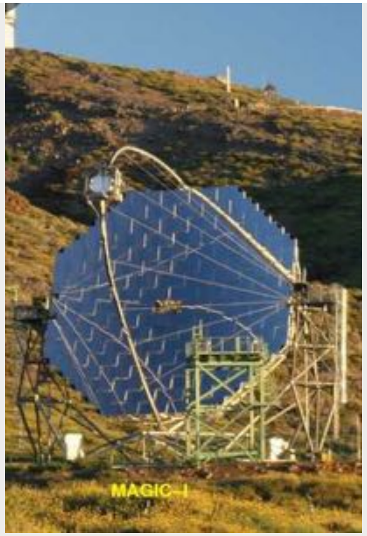
Instruments/ How to detect gamma-rays

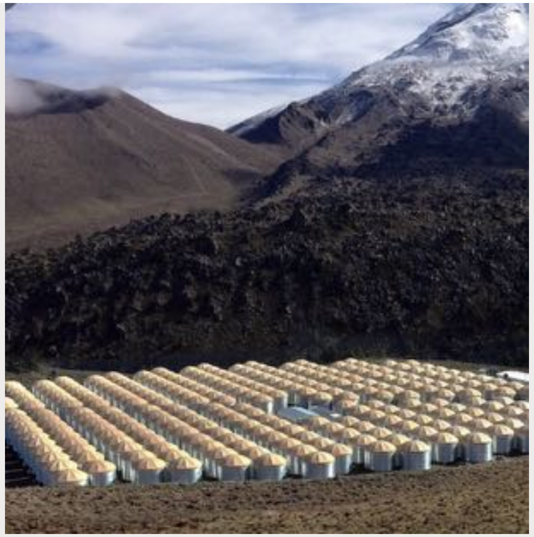
Gamma Ray (Cosmic-ray) Nomenclature

	Range	Type	Detection mec.	Experiments
LE	< 30 MeV	Balloon	Compton Effect	
HE	30 MeV–30 GeV	Satellite	Calorimeter	EGRET, Fermi Agile, DAMPE+
VHE	100 GeV–30 TeV	Ground	Atm.–Cherenkov	Whipple, HEGRA (past)
				MAGIC, HESS, Veritas CTA+
UHE	30 TeV–30 PeV	Ground	Water–Cherenkov	Milagro HAWC, +
EHE	> 30 PeV	Ground	Atm. Fluorescence	Hires, Auger TA

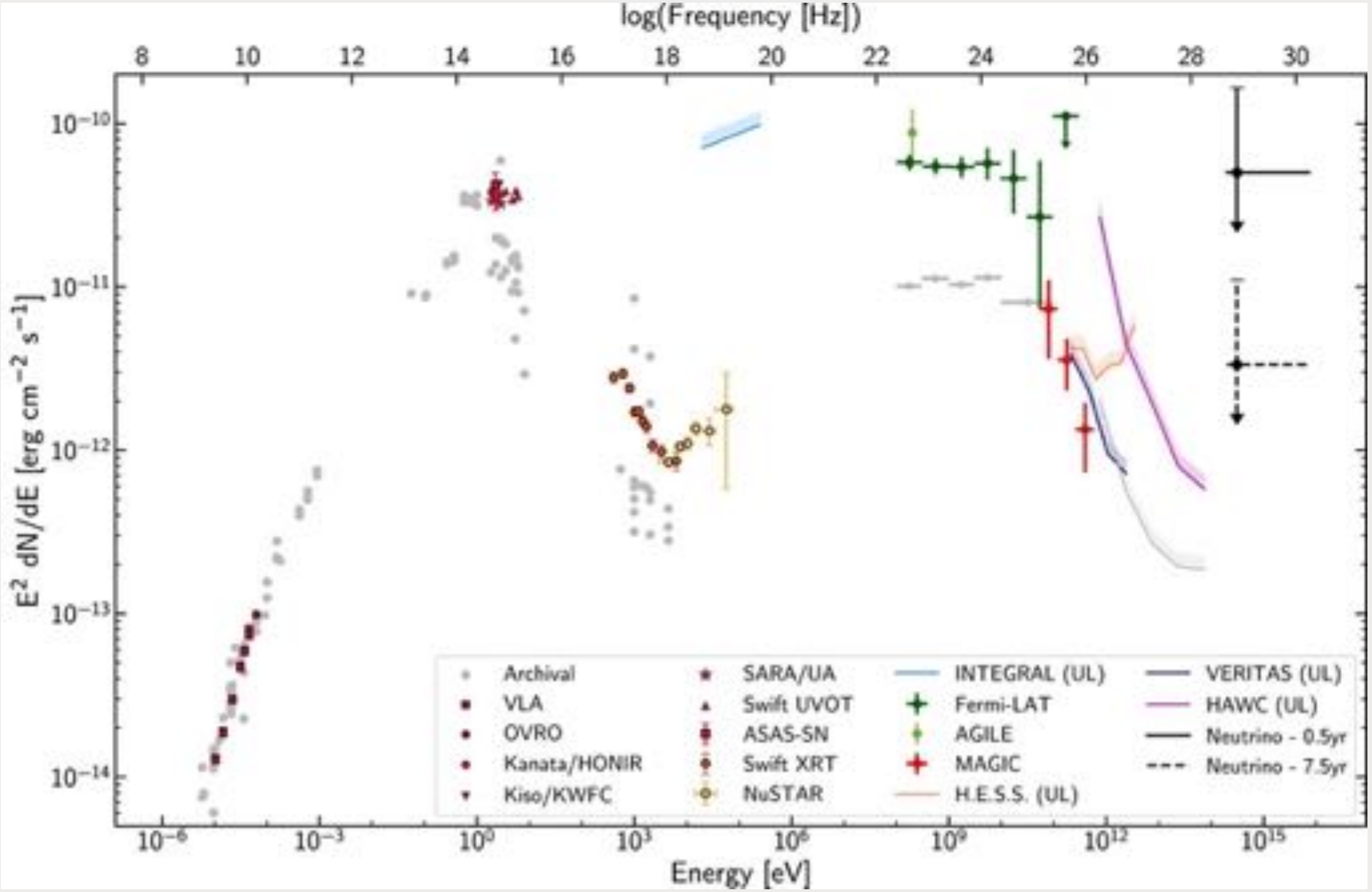
Table 1.1: Classification of γ–ray astronomy. The energy range, the main type of detector and the principal physical detection mechanism are reported, together with the principal experiments.







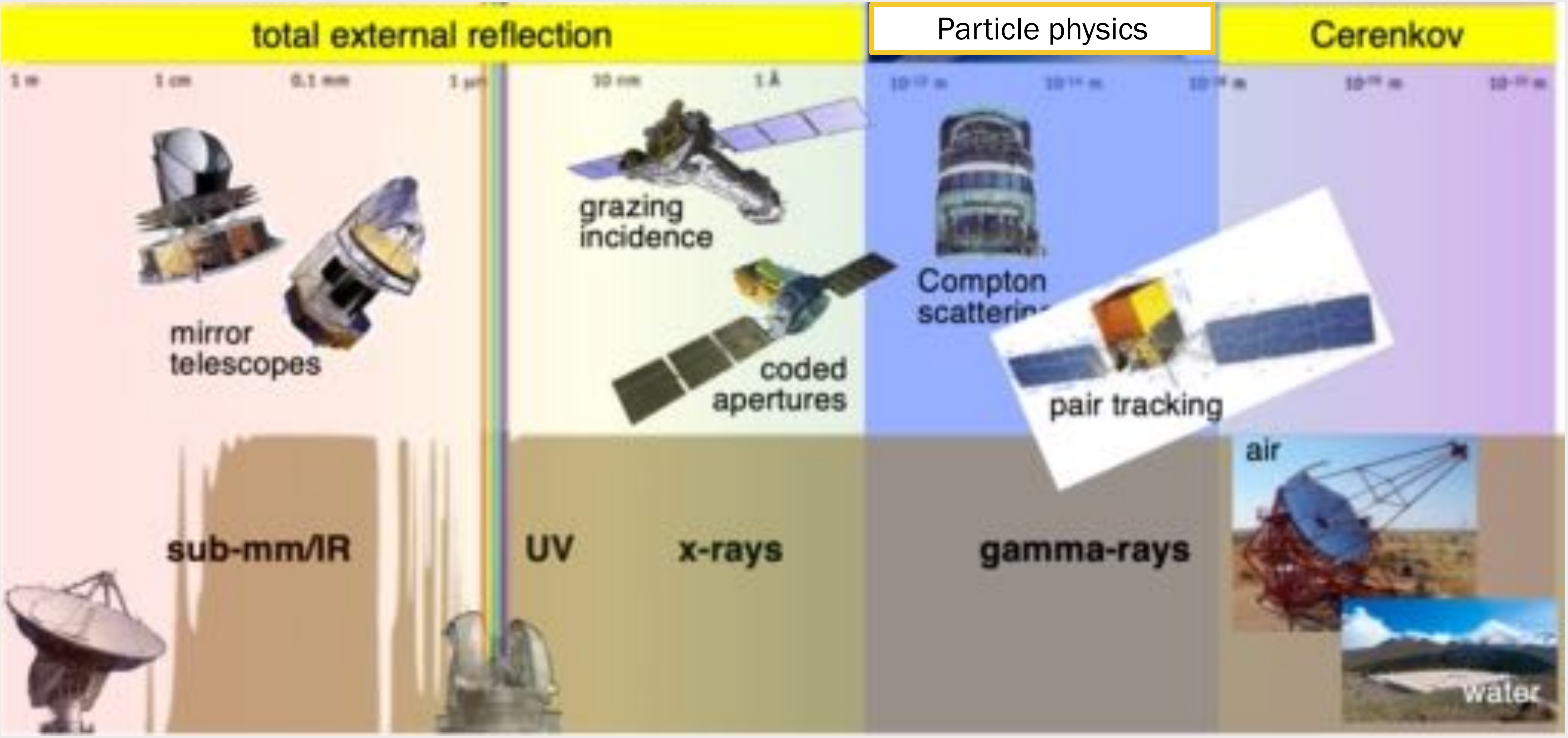

Single instrument?



Gamma ray spectra with photon index -2 to -5

Not yet availbale

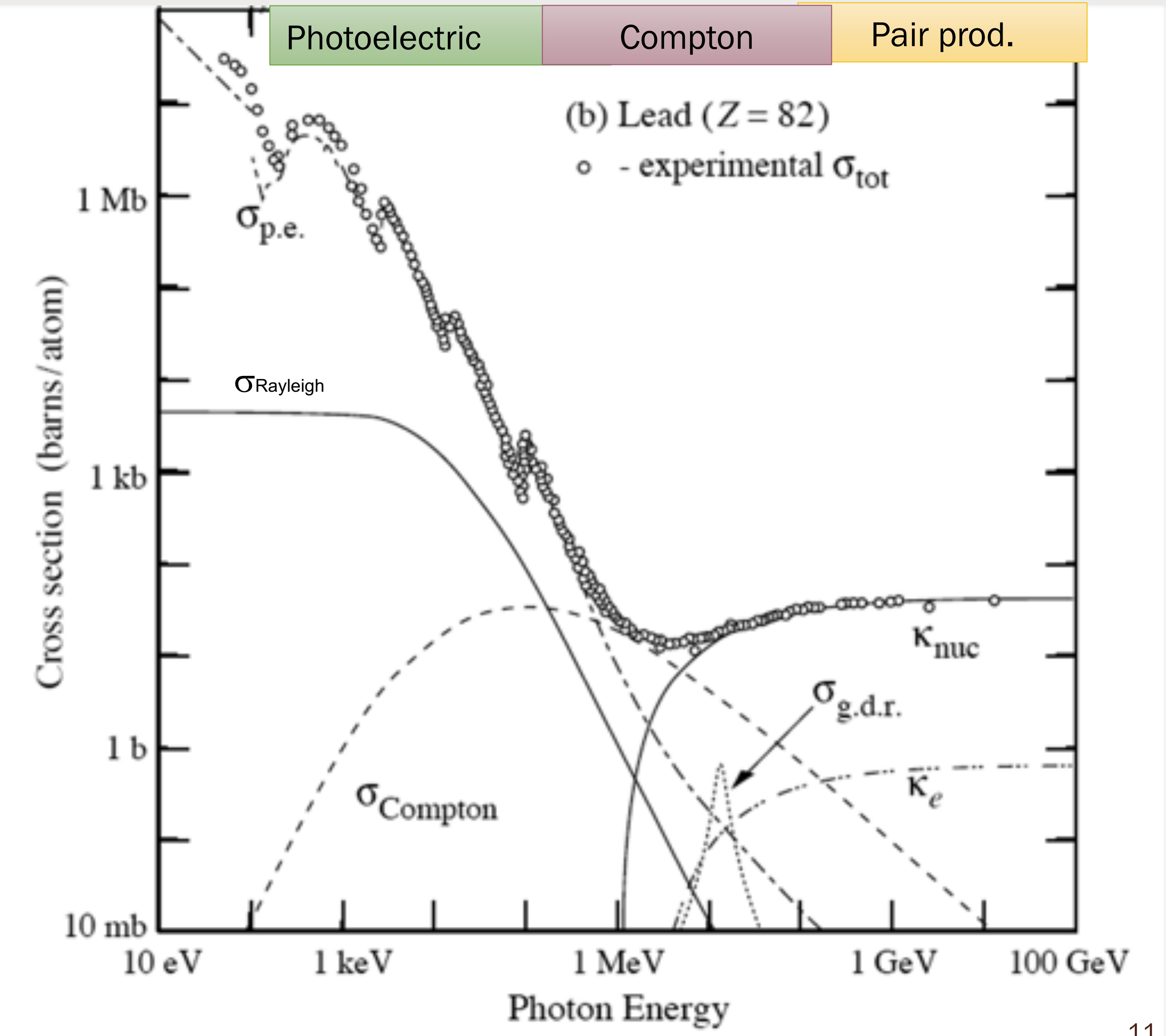
There is no gamma-ray "reflection"



Detection

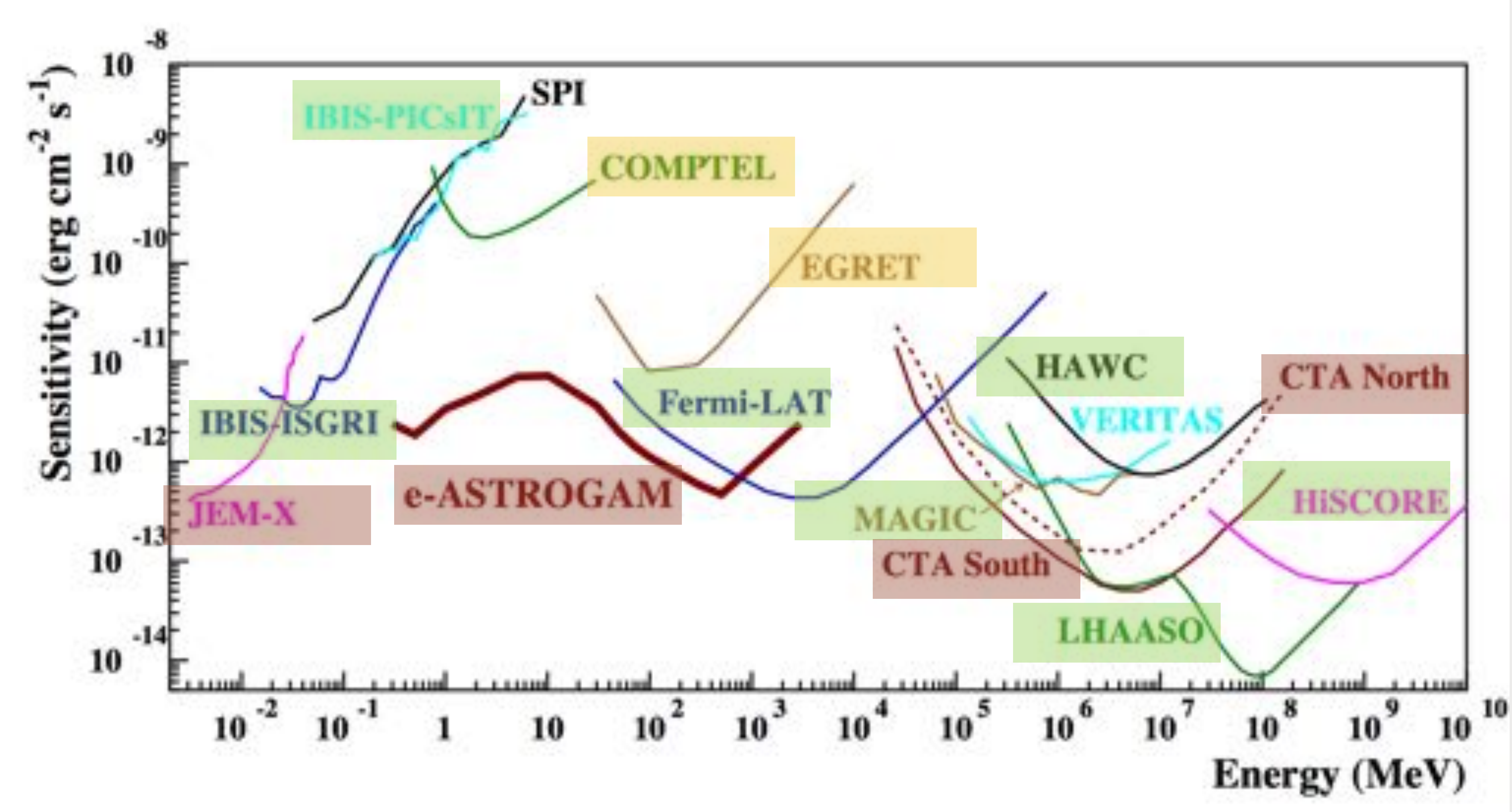
- Gamma rays cannot be reflected, and thus not concentrated (they interact with nuclei)
- The dominant interaction depends on the energy of the gamma ray

Photon interactions in Pb



Comparing experiments

Plot from https://arxiv.org/abs/1611.02232



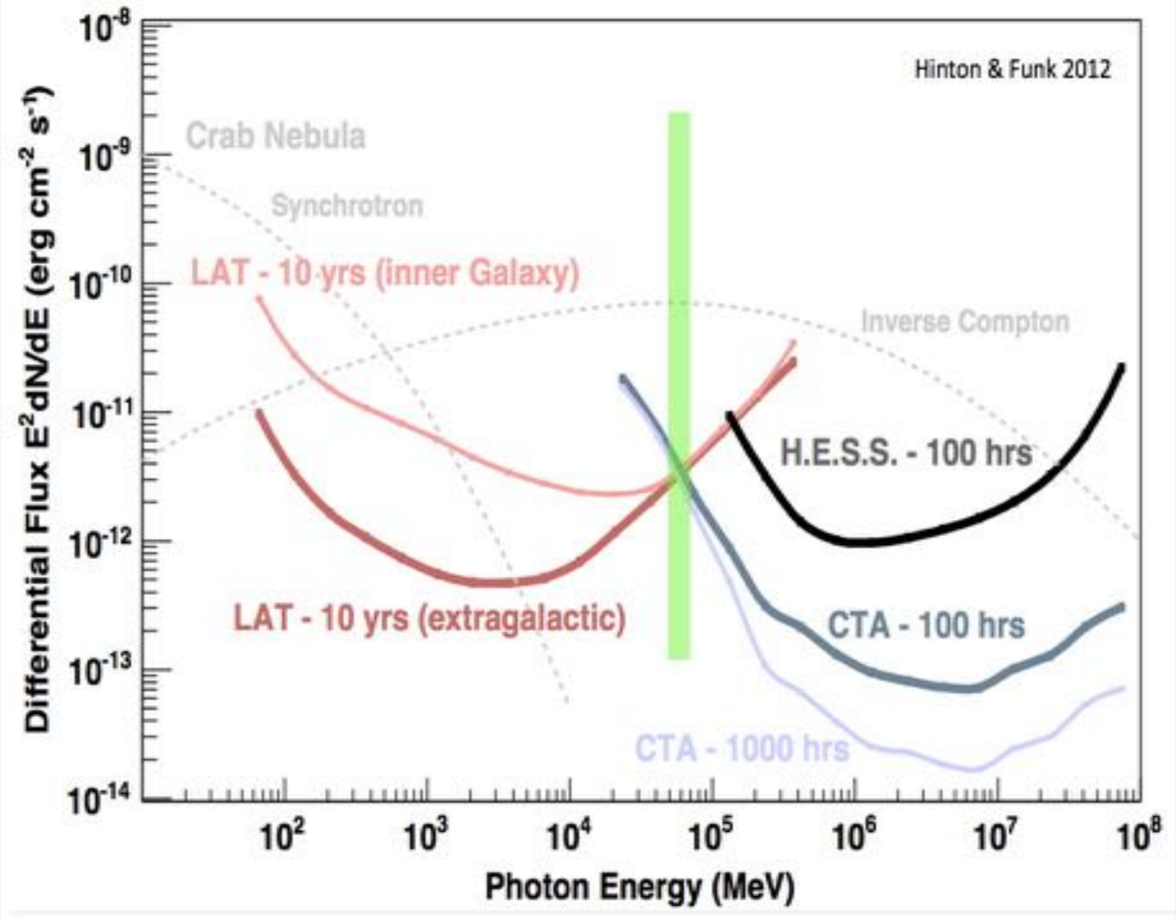
Past

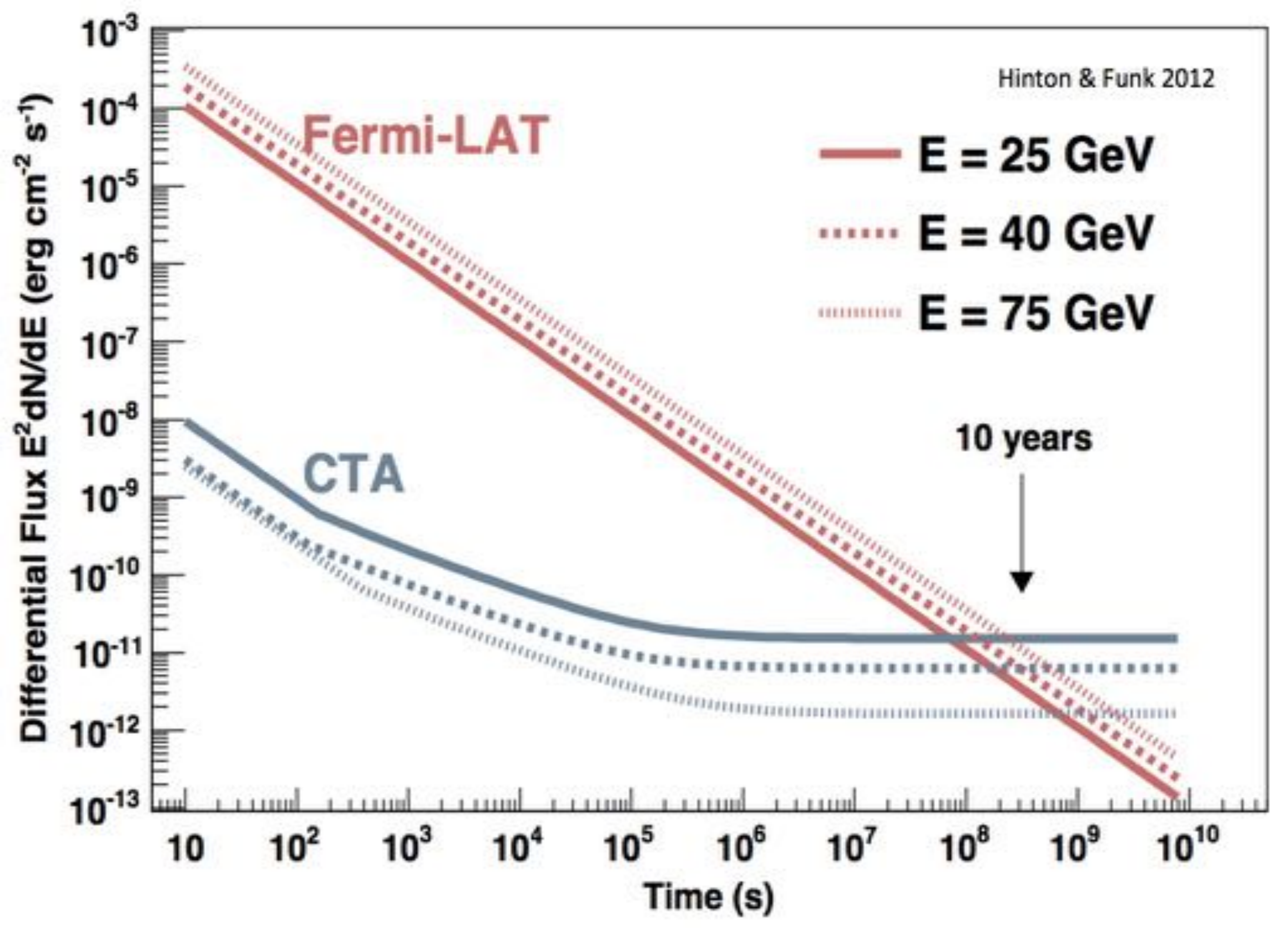
Present

Fture

Sensitivity is not the only thing that matters

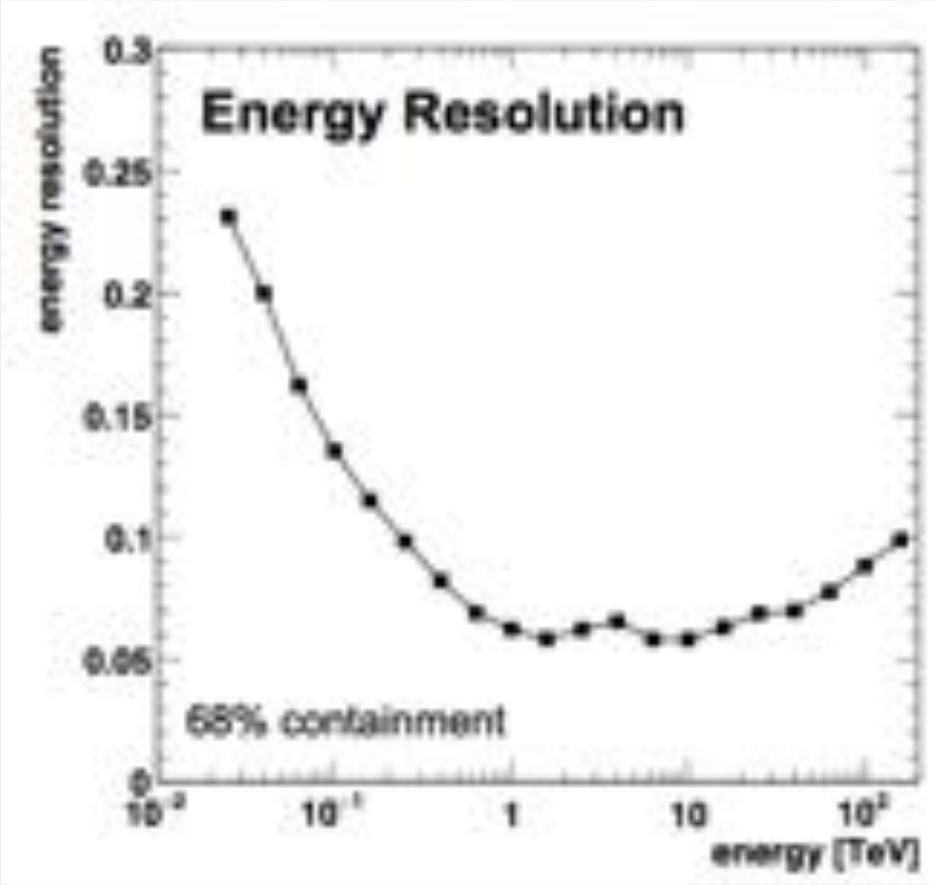
Steady and transient sensitivity



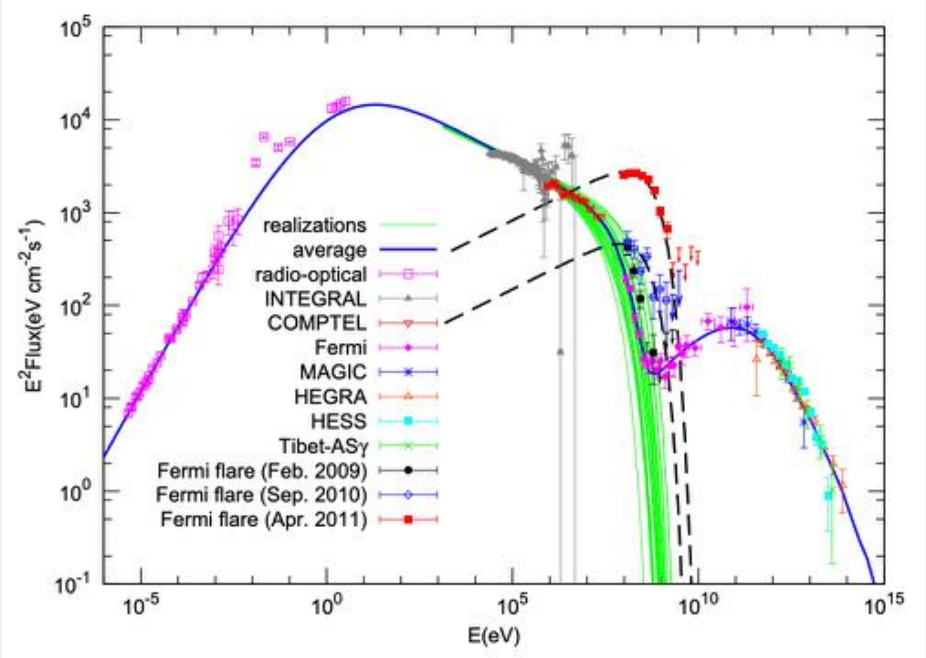


- Sensitivity is defined for INTEGRATION TIME

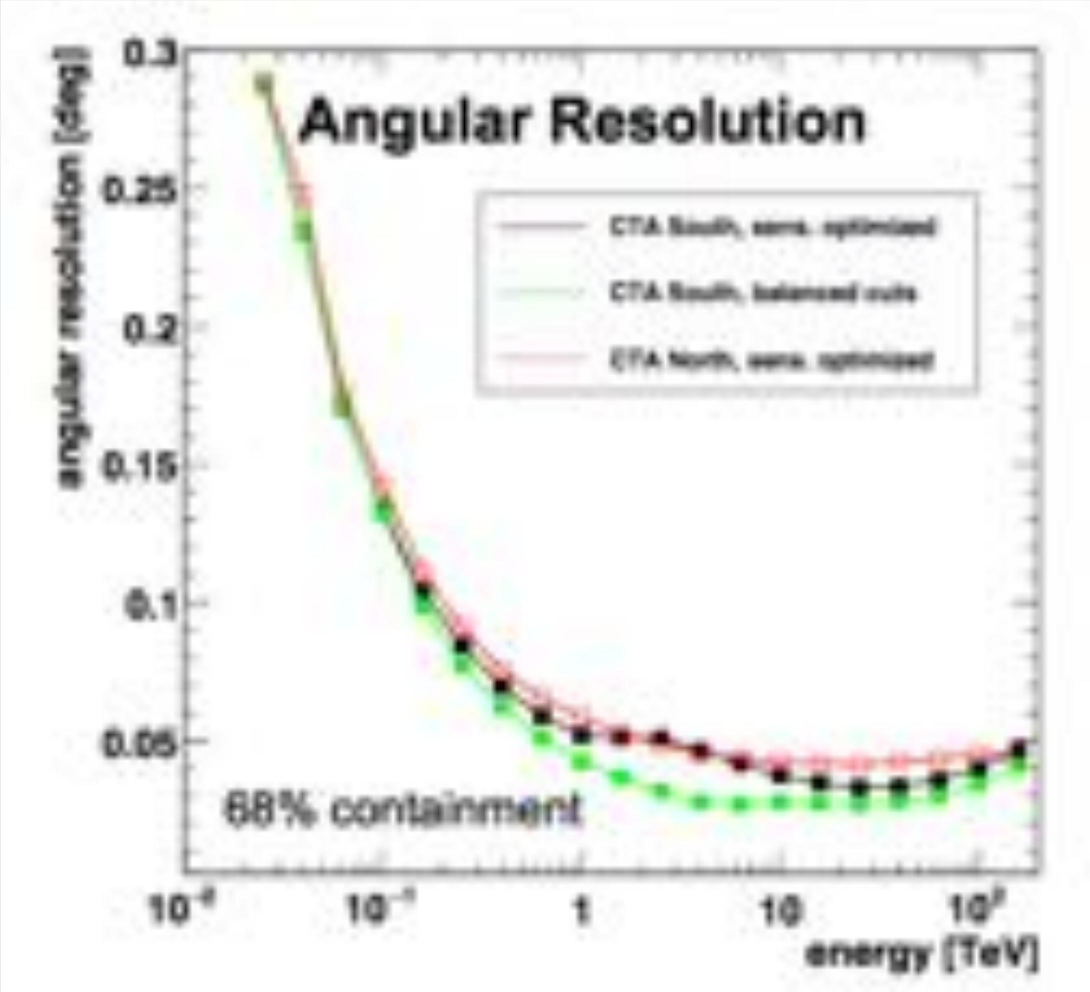
Energy resolution



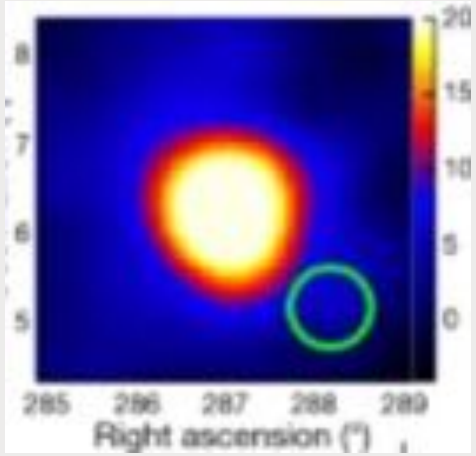
- The ability to discriminate between photon of similar energies
- Very important for spectral shape



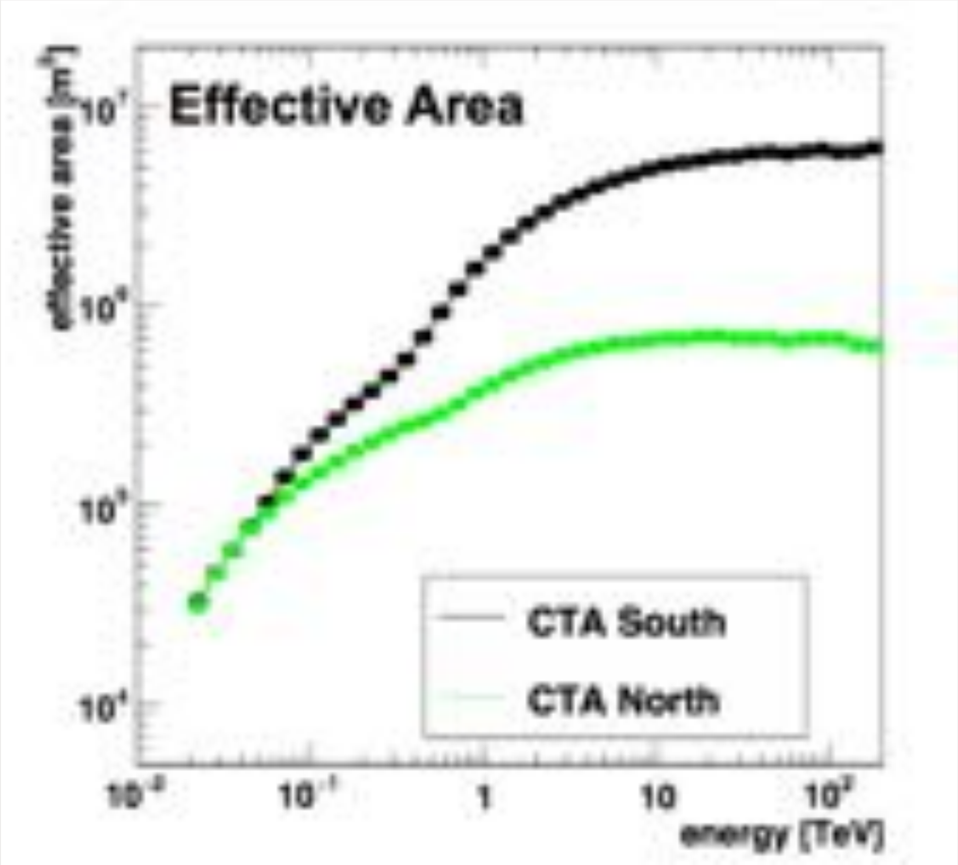
Angular resolution



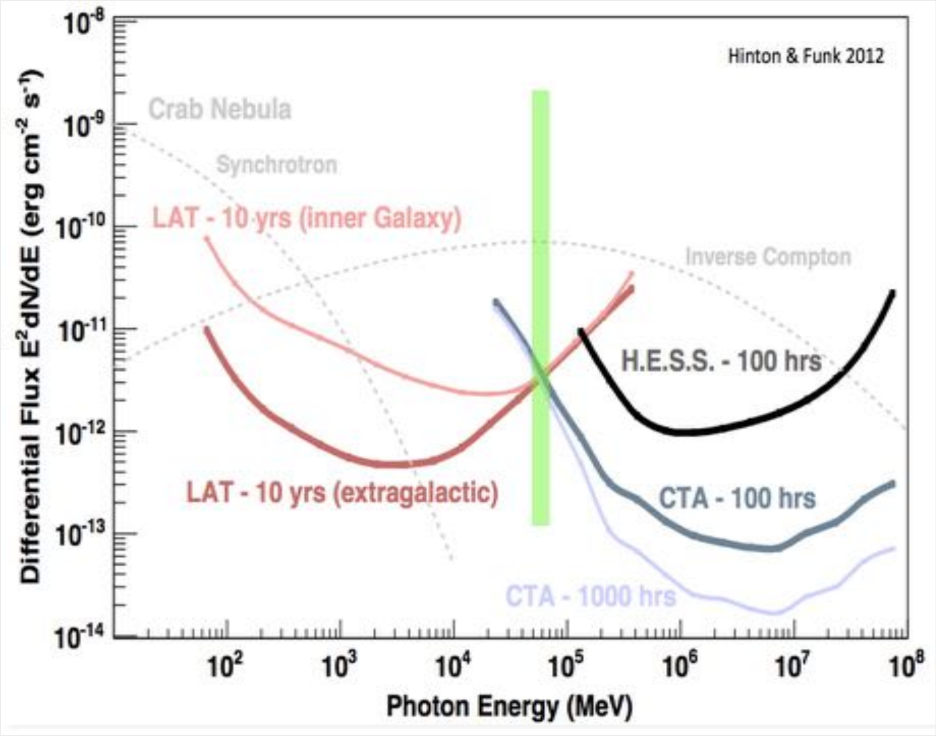
- The ability to discriminate photons from close angular distance
- Very important for morphology
- Objects smaller than minimum angular resolution are not resolved as extended…



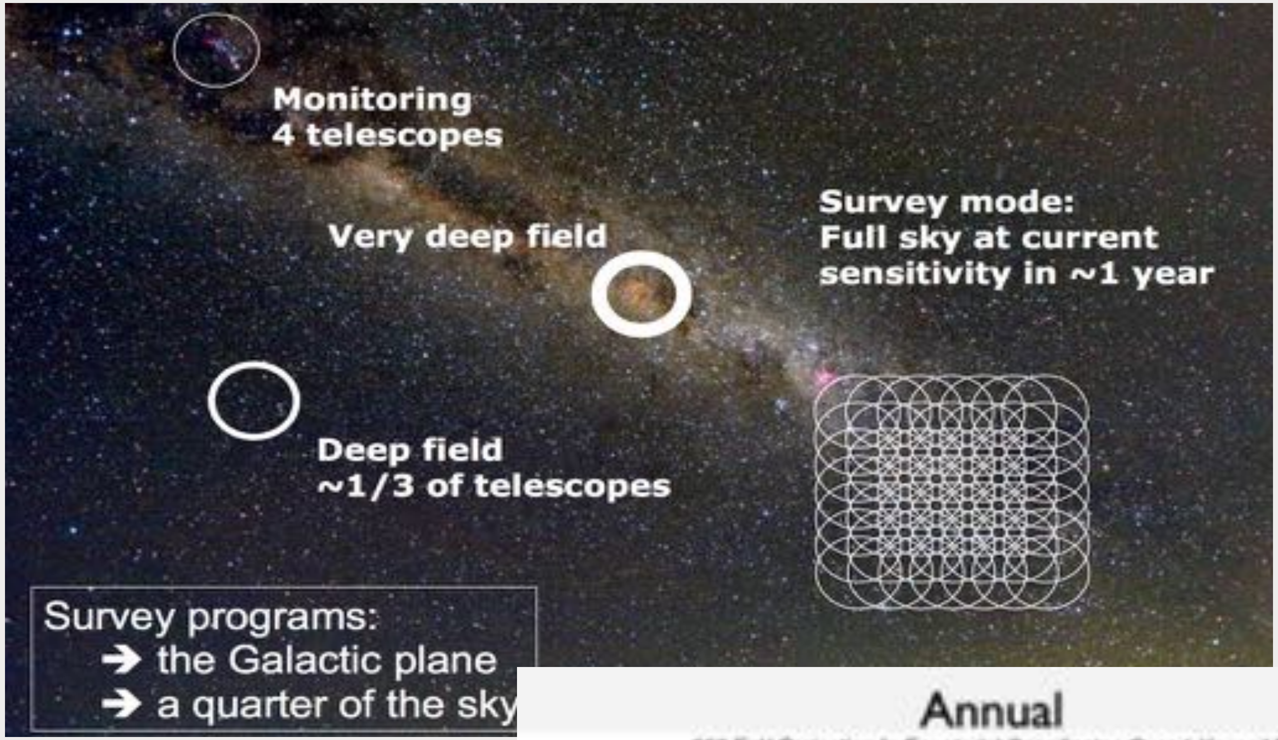
Ingredients to discovery



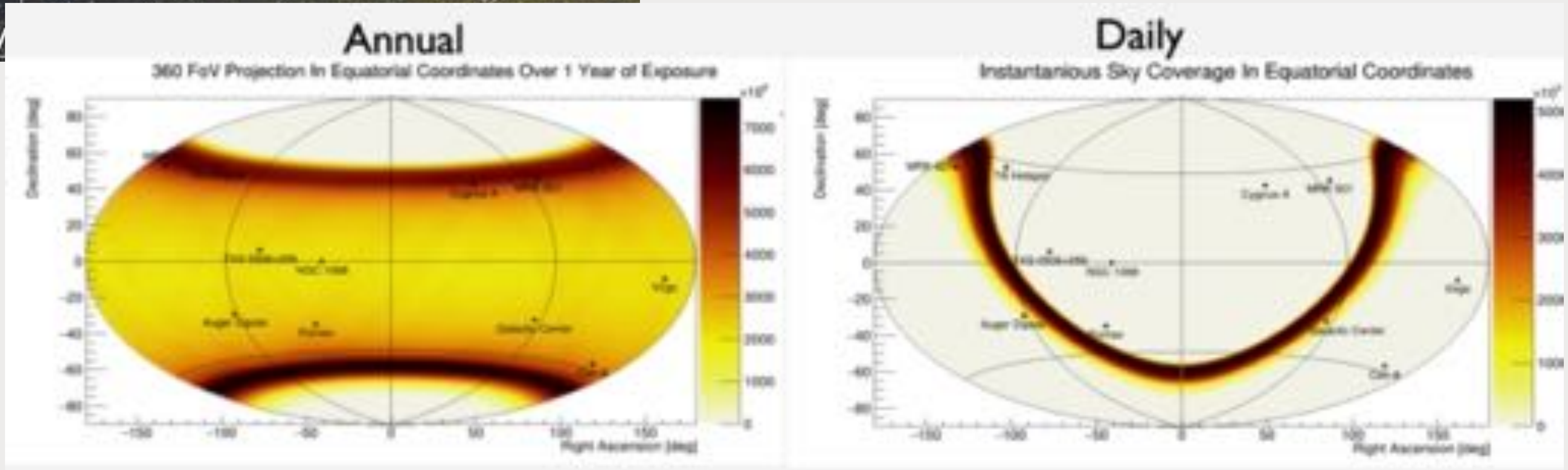
- The acceptance to photons of different energies is not the same



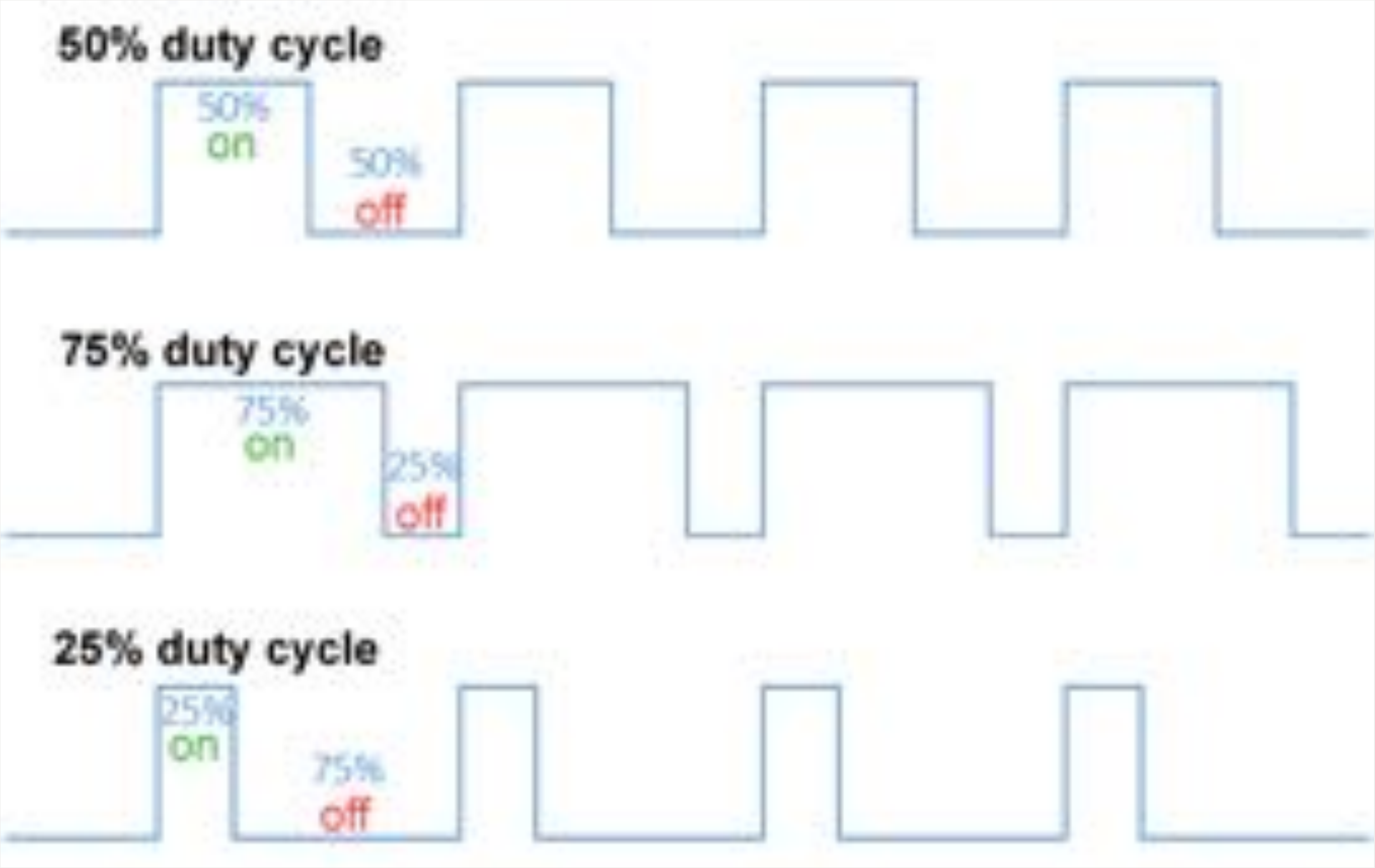
Field of view



- How large a sky fraction can be observed
  - *In a shot*
  - *In a night*
  - *In a year*



Duty cycle



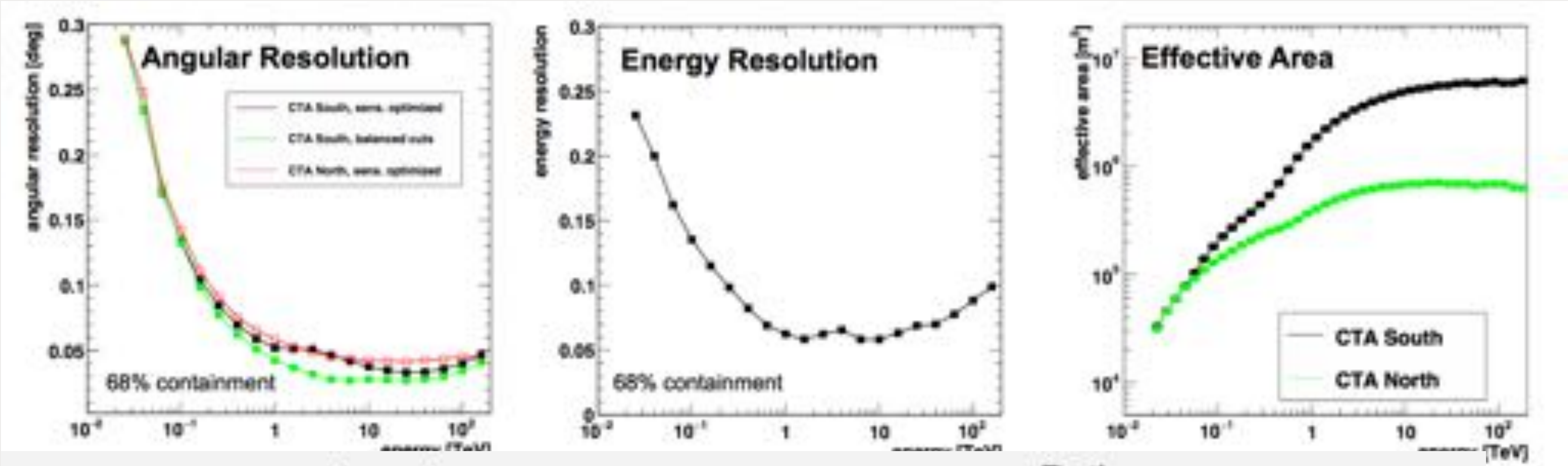
- Some instruments work during
  - *Moonless Night*
  - *Night*
  - *All-day*
- Duty cycle from 1000h/year to 9000h/year

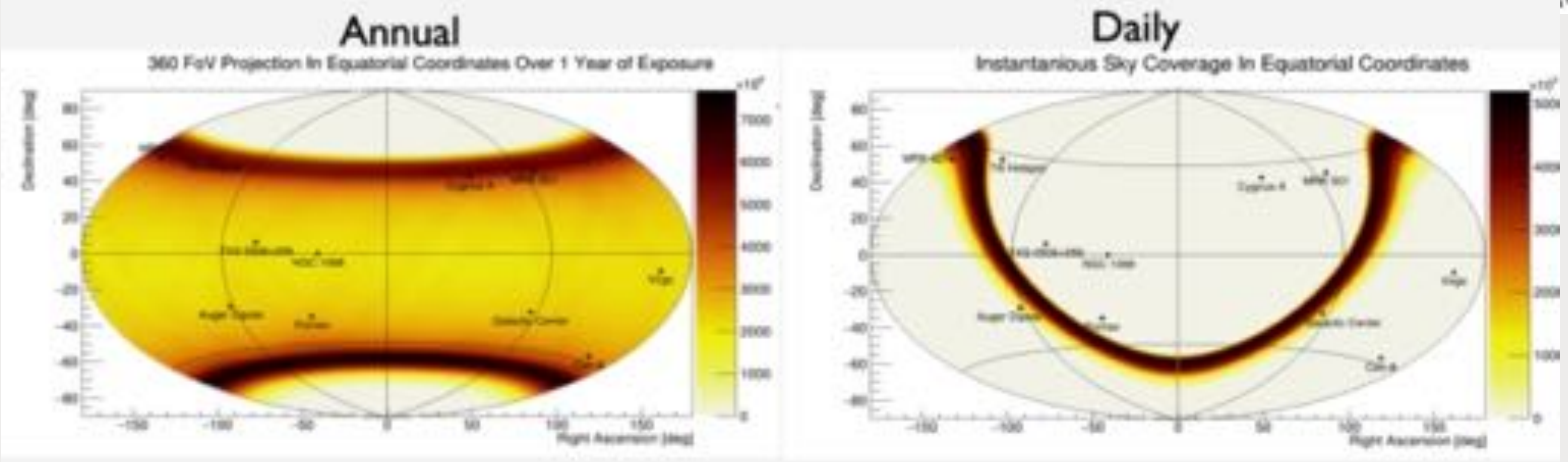
Other very interesting things to check

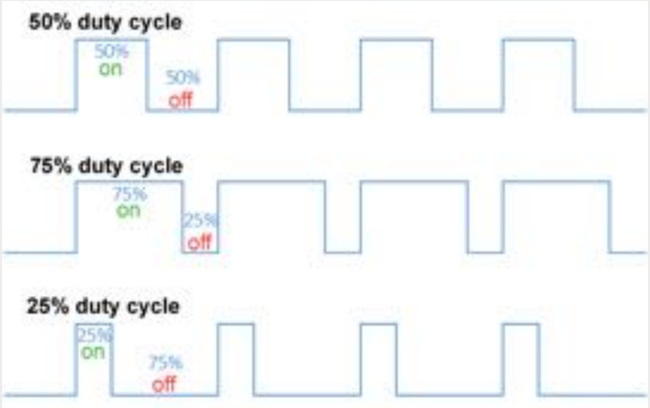
- Data
  - *Are the data public/available?*
  - *Are data available with what delay?*
- Software
  - *Is there any instrument related software?*
  - *Is there a general astro-software?*
- Science
  - *Is there a guest observer program?*

Do I have all the experimental knowledge to make a data reconstruction?

Ingredients to discovery





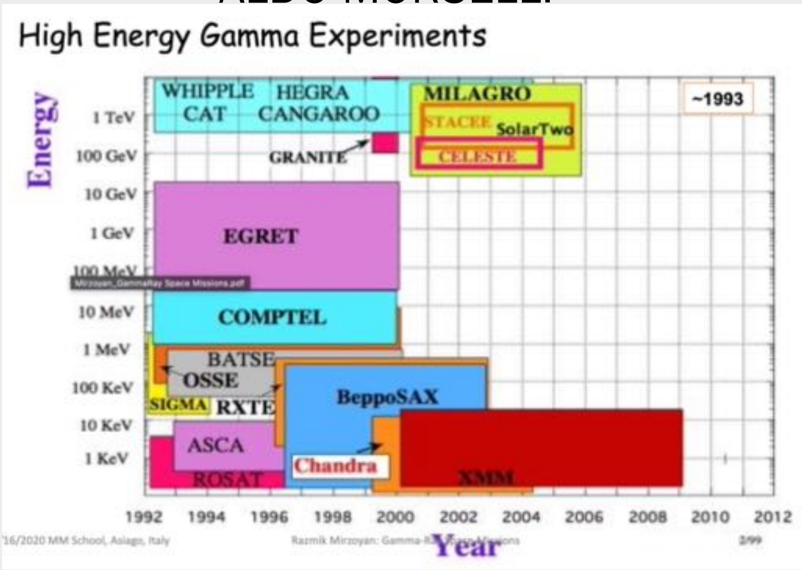


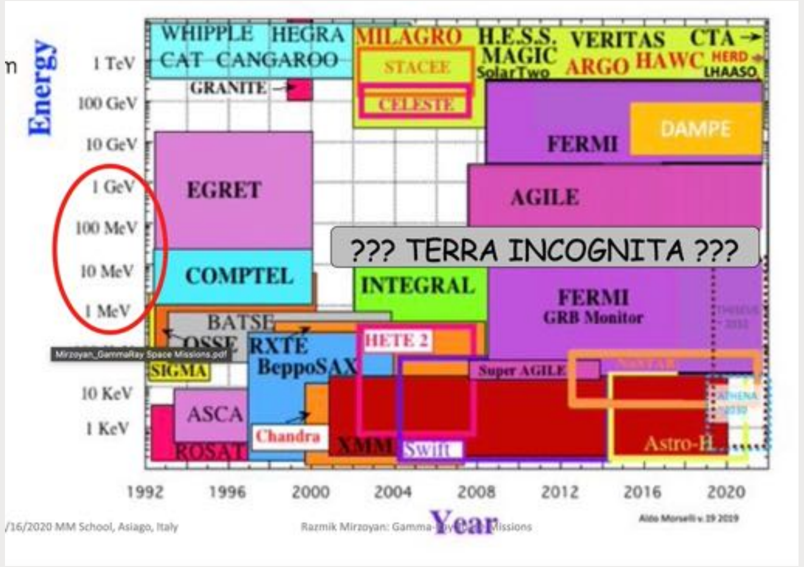
Not yet availbale

Many, so many, too many?

Ground	*Imaging Cherenkov*	WHIPPLE, Hegra,	MAGIC, HESS, VERITAS	CTA
	Non-imaging	Airobic, BLANCA	..	
	Water front particle sampler	Milagro, ARGO	HAWC,LHAASO	SWGO
	Fluorescence	Fly-s Eye, Hi-Res.	Auger	..
Atmosphere	*Baloon-borne mass spectrometer*	many	many	many
	Fluoresence	.	.	JEM-EUSO (CR physics
Space	*Coded-mask detectors*	.	integral-SPI	
	Compton detectors	.	INTEGRAL-	.
	Pair production detectors	COS,EGRET	AGILE, FERMI-LAT, HERD DAMPE	Astrogam/Amigo

ALDO MORSELLI





Still useful

PHYSICAL REVIEW LETTERS **122,** 041104 (2019)

Voyager 1 $e^{\pm}$ Further Constrain Primordial Black Holes as Dark Matter

Mathieu Boudaud[*] and Marco Cirelli[†]
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(Received 18 July 2018; revised manuscript received 26 November 2018; published 30 January 2019)

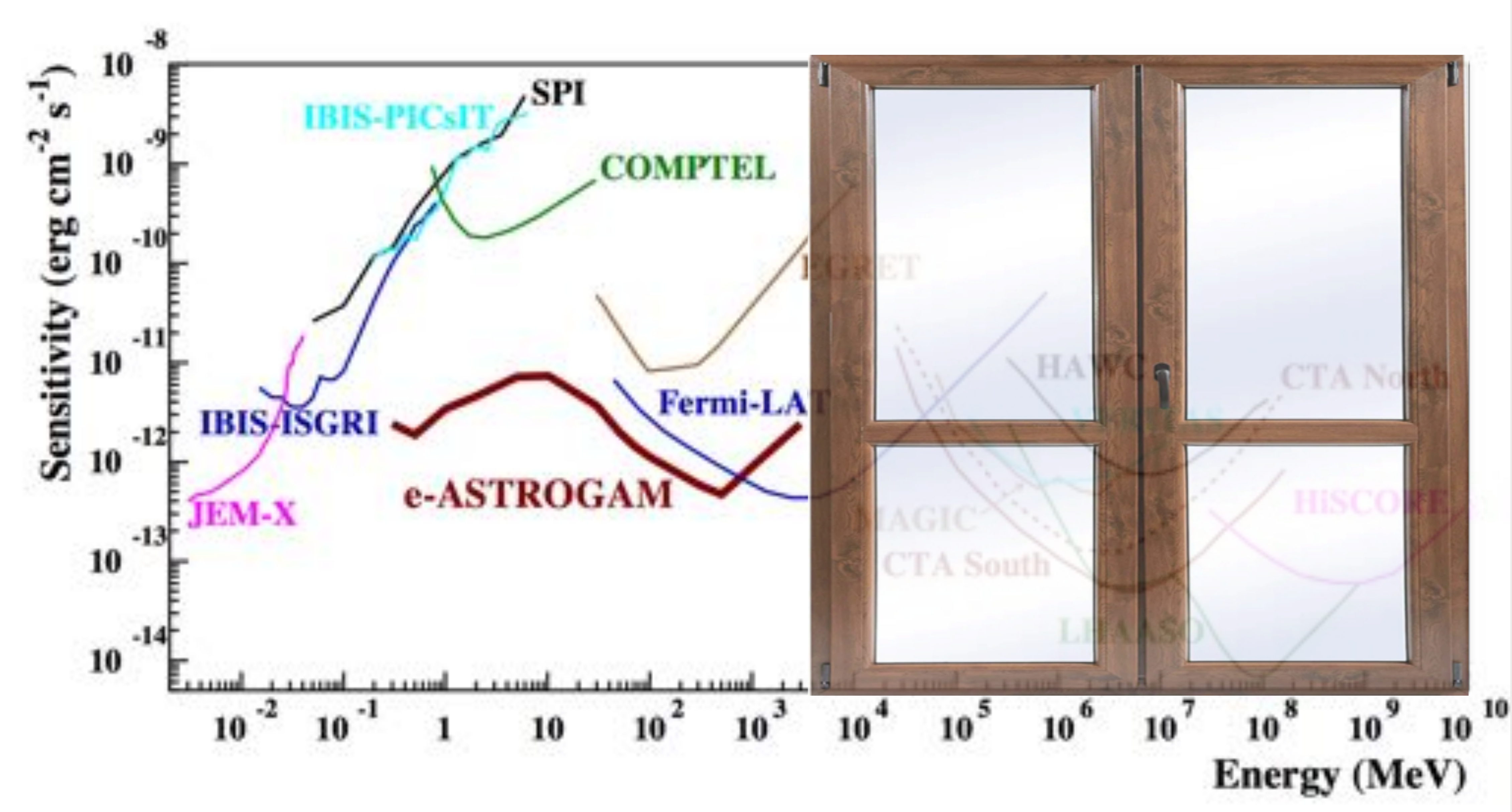
Primordial black holes (PBHs) with a mass $M \lesssim 10^{17}$ g are expected to inject sub-GeV electrons and positrons in the Galaxy via Hawking radiation. These cosmic rays are shielded by the solar magnetic field for Earth-bound detectors, but not for *Voyager 1*, which is now beyond the heliopause. We use its data to constrain the fraction of PBHs to the dark matter in the Galaxy, finding that PBHs with $M < 10^{16}$ g cannot contribute more than 0.1% (or less for a log-normal mass distribution). Our limits are based on local Galactic measurements and are thus complementary to those derived from cosmological observations.

DOI: 10.1103/PhysRevLett.122.041104

SATELLITES-KEV-MEV

CODED MASKS AND COMPTON

Where are we

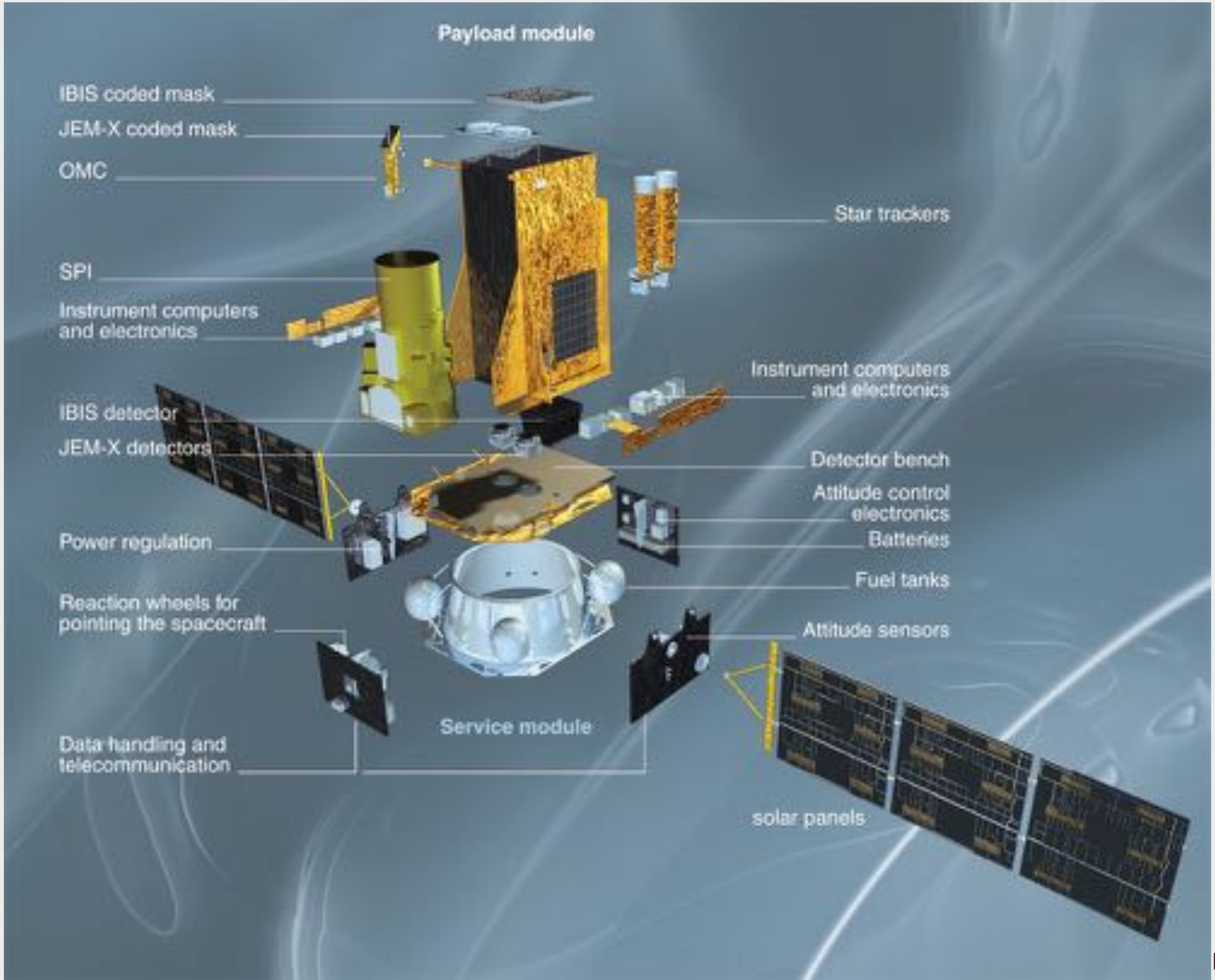

Sensitivity (erg cm^{-2} s^{-1})
SPI
IBIS-PICsIT
COMPTEL
EGRET
HAWC
CTA North
Fermi-LAT
IBIS-ISGRI
e-ASTROGAM
JEM-X
MAGIC
CTA South
HiSCORE
LHAASO
Energy (MeV)

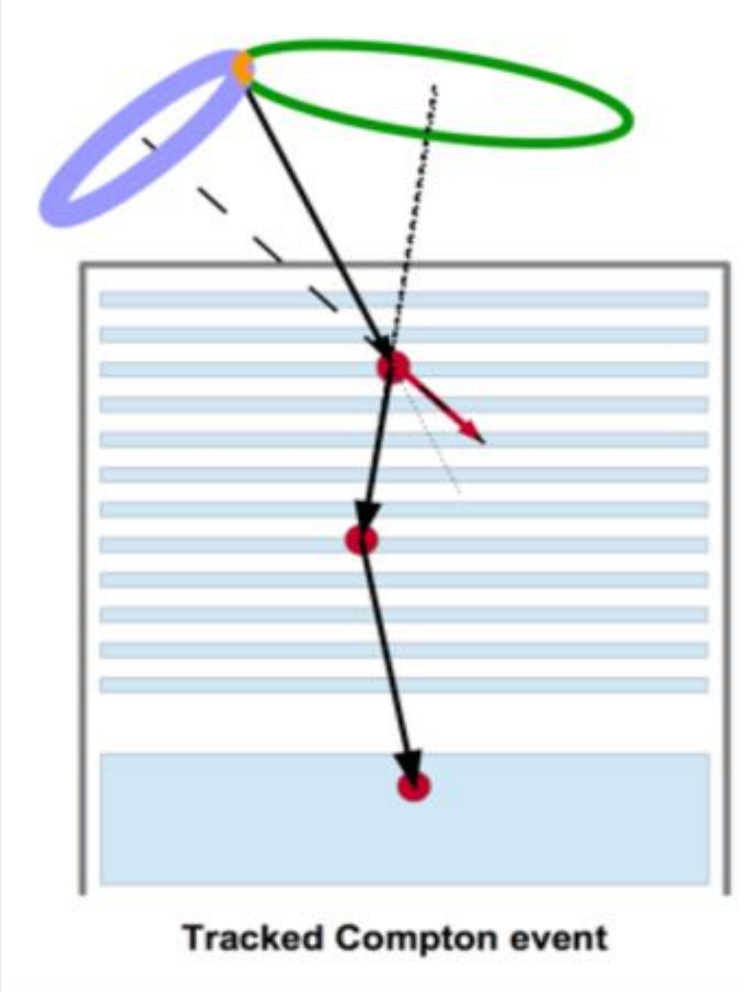
INTEGRAL

- INTEGRAL is dedicated to the fine spectroscopy (E/deltaE = 500) and fine imaging (angular resolution: 12 arcmin FWHM) of celestial gamma-ray sources in the energy range 15 keV to 10 MeV
- The INTEGRAL payload consists of the two main gamma-ray instruments
  - *the spectrometer SPI ,*
  - *the imager IBIS*
- INTEGRAL was launched on October 17, 2002

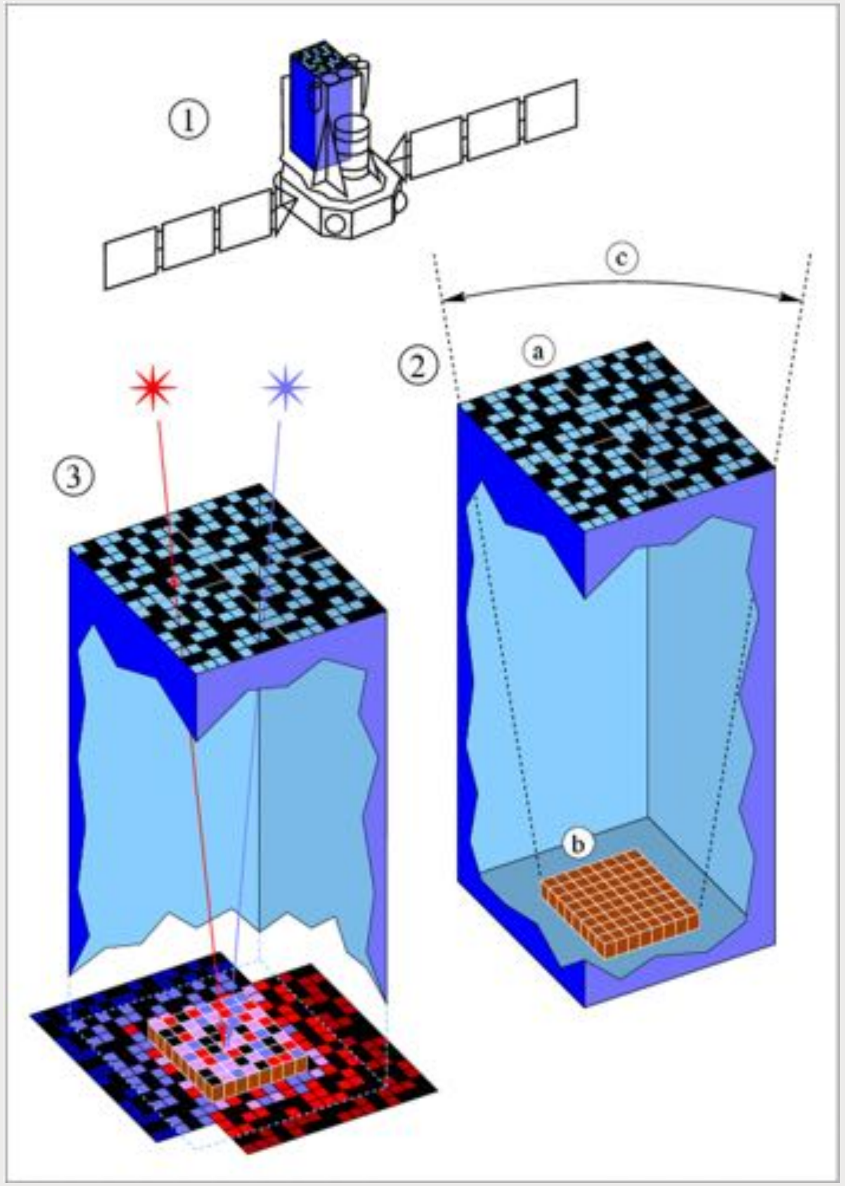
https://www.cosmos.esa.int/web/integral/mission-overview

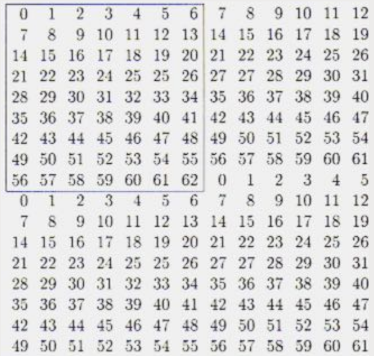
Integral


Payload module
IBIS coded mask
JEM-X coded mask
OMC
Star trackers
SPI
Instrument computers and electronics
Instrument computers and electronics
IBIS detector
JEM-X detectors
Detector bench
Attitude control electronics
Power regulation
Batteries
Fuel tanks
Reaction wheels for pointing the spacecraft
Attitude sensors
Service module
Data handling and telecommunication
solar panels


Tracked Compton event

Coded mask

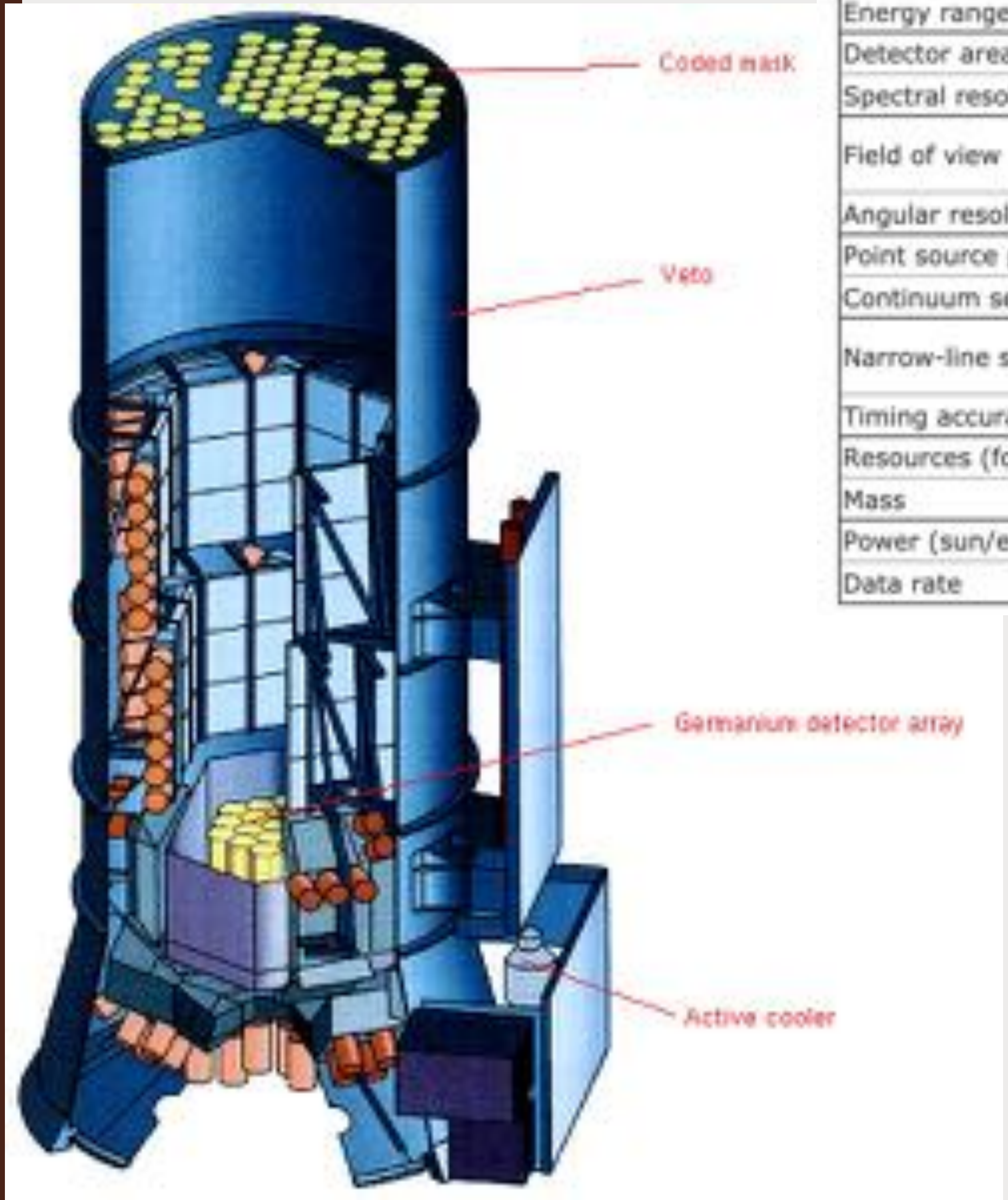




- Allows imaging and separating and locating sources.
- provides near-perfect background subtraction, the detector pixels can be considered to be split into two intermingled subsets,
  - *those capable of viewing the source and*
  - *those for which the flux is blocked by opaque mask elements.*
- *The shift of each projection encodes the position of the corresponding point source in the sky;*
- *the 'strength' of each projection encodes the intensity of the point source*

https://personal.sron.nl/~jeanz/cai/coded_intr.html

SPI

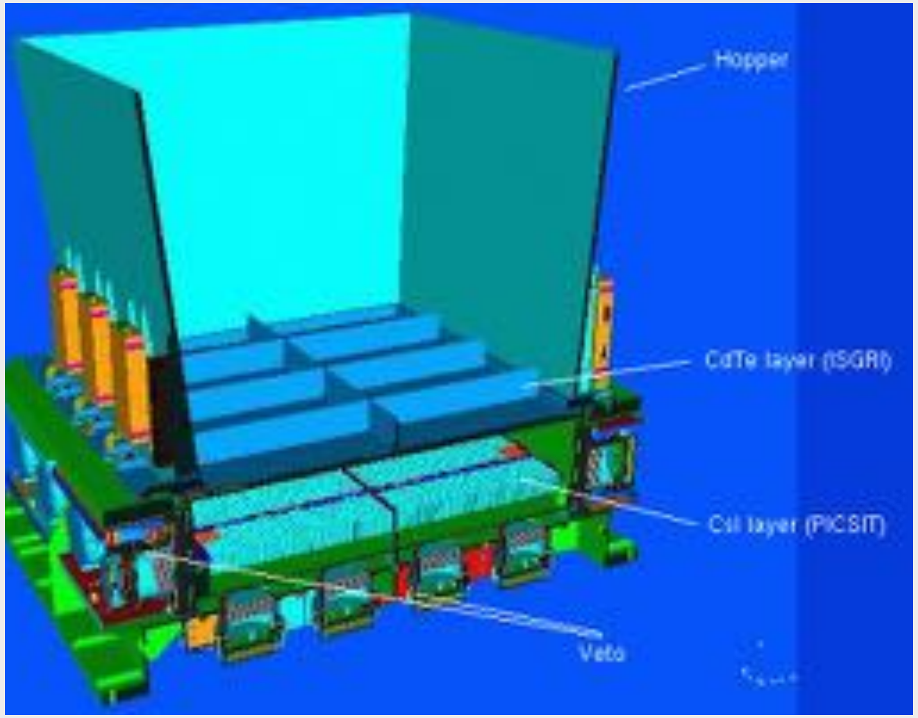


OVERVIEW OF SCIENTIFIC CAPABILITIES OF SPI

Energy range	18 keV - 8 MeV
Detector area	500 cm^2 (Ge - Germanium)
Spectral resolution	2.2 keV FWHM @ 1.33 MeV; $E/\Delta E = \sim 450$, for each detector
Field of view	fully coded: 14° flat to flat, 16° corner to corner zero coding (zero sensitivity): 32° flat to flat, 35° corner to corner
Angular resolution (point sources)	2.5° deg (FWHM)
Point source positioning	<1.3° for point sources (depending on point source intensity)
Continuum sensitivity*	8.8e-4 ph/(s cm^2 MeV) [3σ in 10e6 s, @ 1 MeV, $\Delta E = E/2$]
Narrow-line sensitivity*	2.4e-5 ph/(s cm^2 [3σ in 10e6 s, @ 1 MeV] 4.6e-5 ph/(s cm^2 [3σ in 10e6 s, @ 511 keV]
Timing accuracy (3σ)	0.129 ms
Resources (following EID-A allocation):	
Mass	1309 kg
Power (sun/eclipse)	385/110 W
Data rate	45 kbps

- SPI (SPectrometer on INTEGRAL)
  - *18 keV - 8 MeV energy range with an energy resolution of 2.2 keV (FWHM*
  - *array of 19 hexagonal high purity Germanium*
  - *A hexagonal coded aperture mask is located 1.7 m above the detection plane in order to image large regions of the sky (fully coded field of view = 16°) with an angular resolution of 2.5*

IBIS

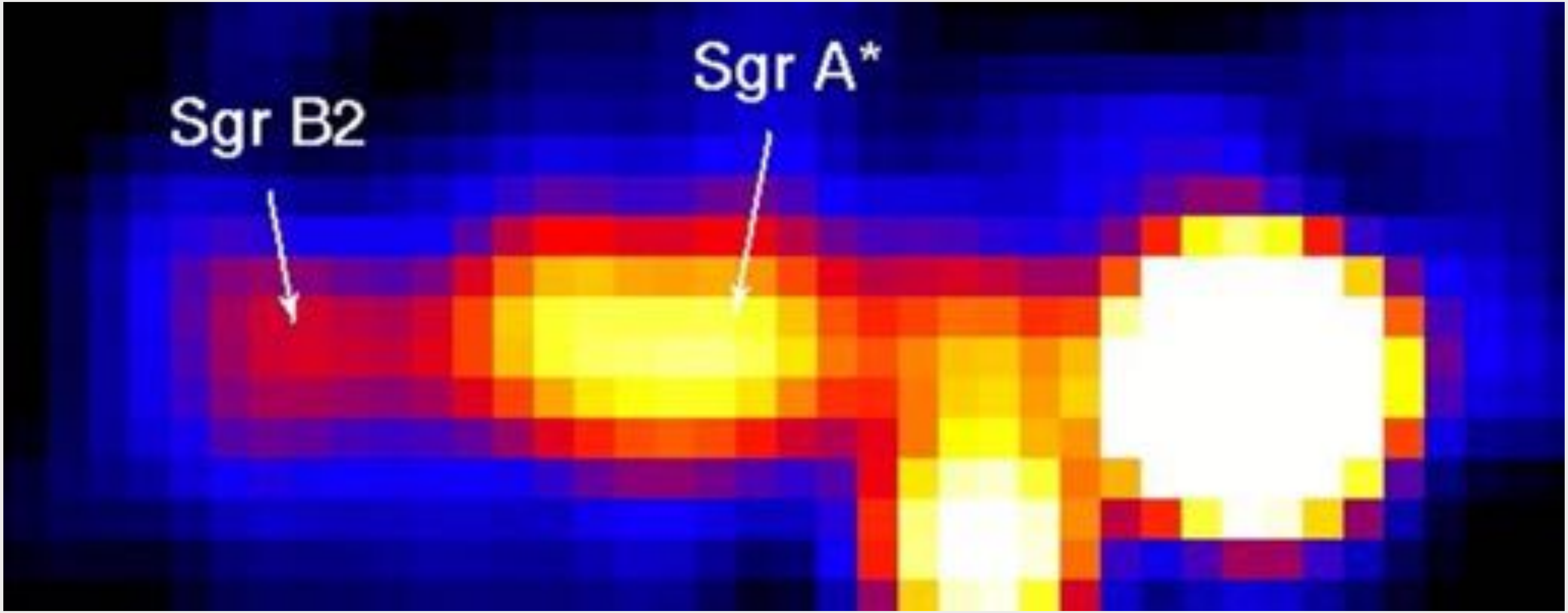


- IBIS, the Imager on Board the INTEGRAL Satellite
- 15 keV and 10 MeV.
- The total field of view (down to zero response) is 29.1° x 29.4°,

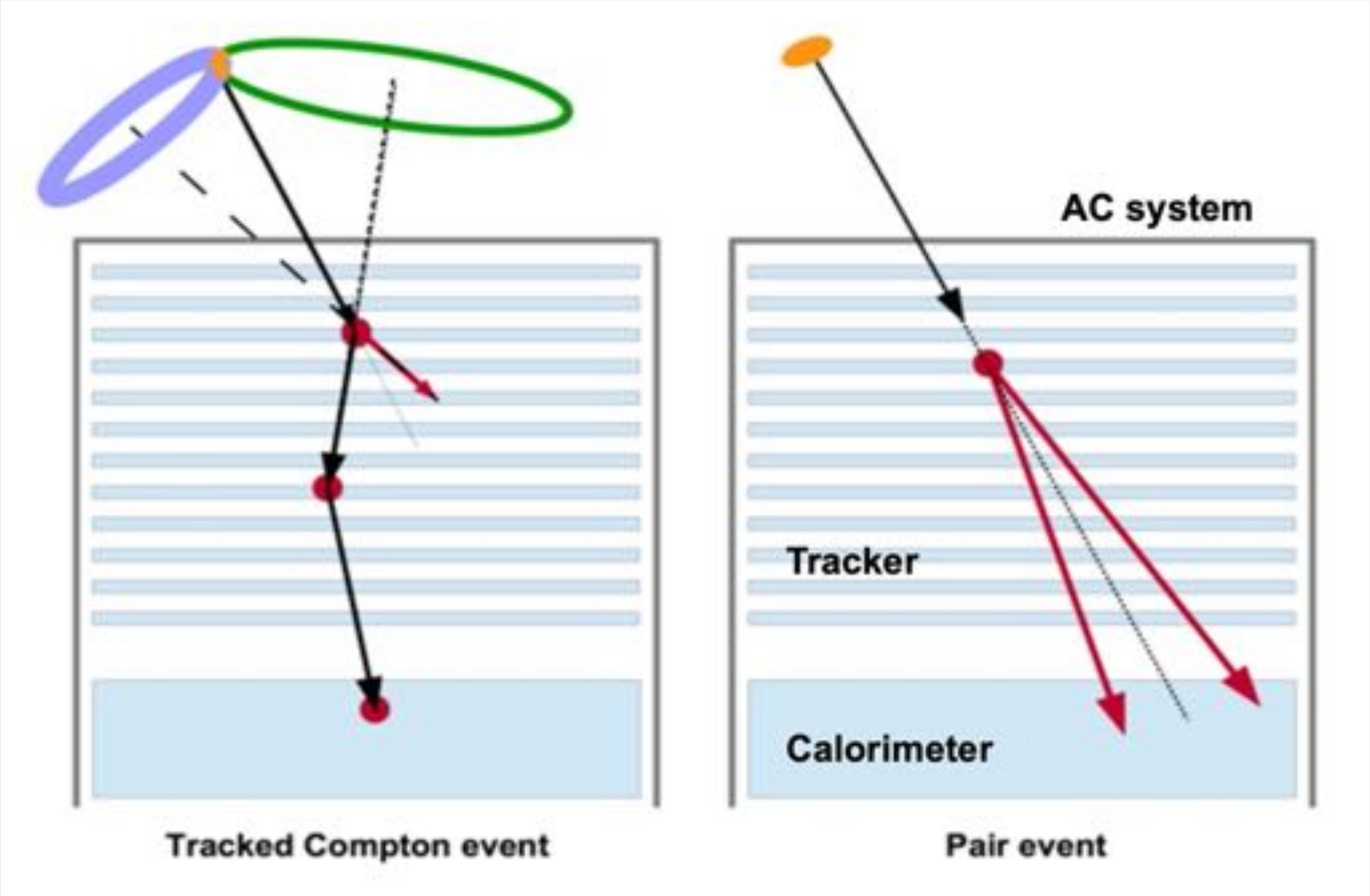
OVERVIEW OF SCIENTIFIC CAPABILITIES OF IBIS

Energy range	15 keV - 10 MeV
Detector area	2600 cm^2 (CdTe - Cadmium Telluride) 3000 cm^2 (CsI - Caesium Iodide)
Spectral energy resolution (FWHM)	8% @ 100 keV 10% @ 1 MeV
Field of view	8.3° x 8.0° (fully coded) 29.1° x 29.4° (down to zero response)
Angular resolution	12' FWHM
Point source location accuracy (90% error radius)	30" @ 100 keV (50σ source) 3' @ 100 keV (5σ source) 5-10' @ 1 MeV (5σ source)
Continuum sensitivity*	2.85e-6 ph/(s cm^2 keV) [3σ in 10e5 s, @ 100 keV, ΔE = E/2] 1.6e-6 ph/(s cm^2 keV) [3σ in 10e5 s, @1 MeV, ΔE = E/2]
Line sensitivity*	1.9e-5 ph/(s cm^2 [3σ in 10e6 s, @ 100 keV] 3.8e10-4 ph/(s cm^2 [3σ in 10e6 s, @ 1 MeV]
Timing accuracy	61 μs - 1 hr
Typical source location	30" @ 100 keV (50 sigma source) 3' @ 100 keV (5 sigma source)
Resources (following EID-A allocation):	
Mass	677 kg (+ 96 kg for tube inside PLM)
Power (sun/eclipse)	240/0 W
Data rate (solar maximum)	59.8 kbps
Date rate (solar minimum)	56.8 kbp

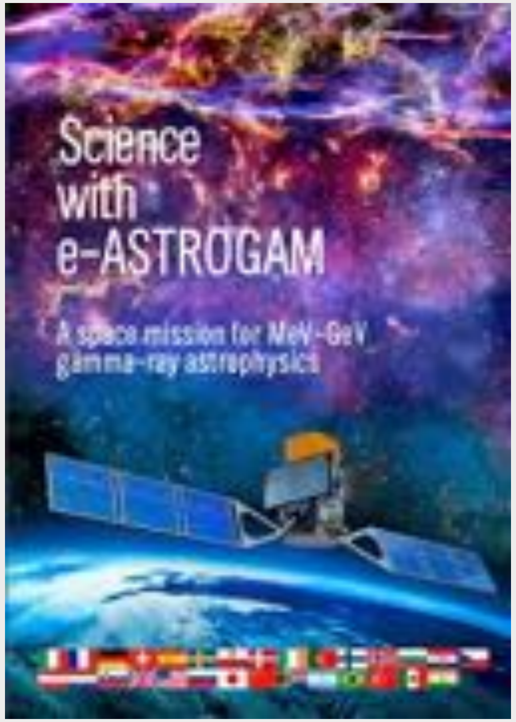
Galactic Center as seen by Integral-IBIS



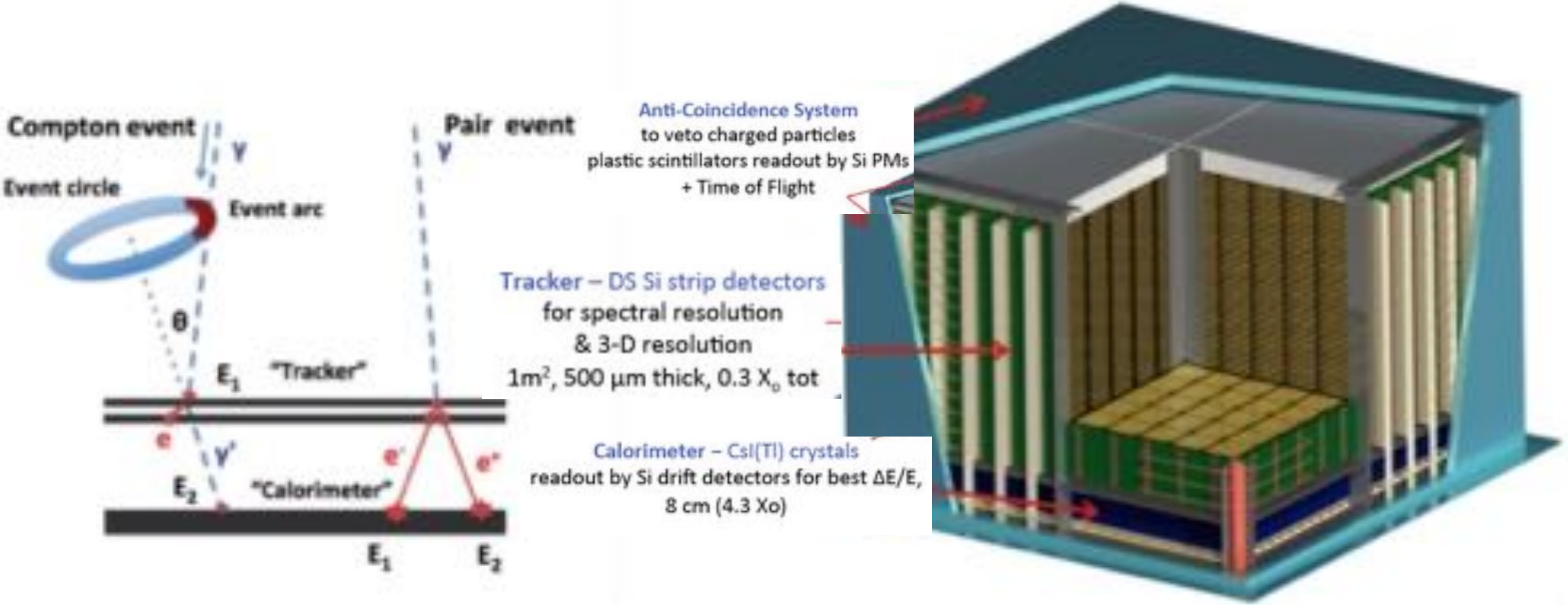
Compton+Pair = e-Astrogam/Amego



- By adding more layers +calorimeter one can see the full development of a pair produced by higher energy gamma-rays
- Two proposed sister instruments
  - *E-Astrogam*
  - *Amego*



https://arxiv.org/pdf/1711.01265.pdf



ASTROGAM is made of 56 Silicon planes, about 1 m^2 each, v

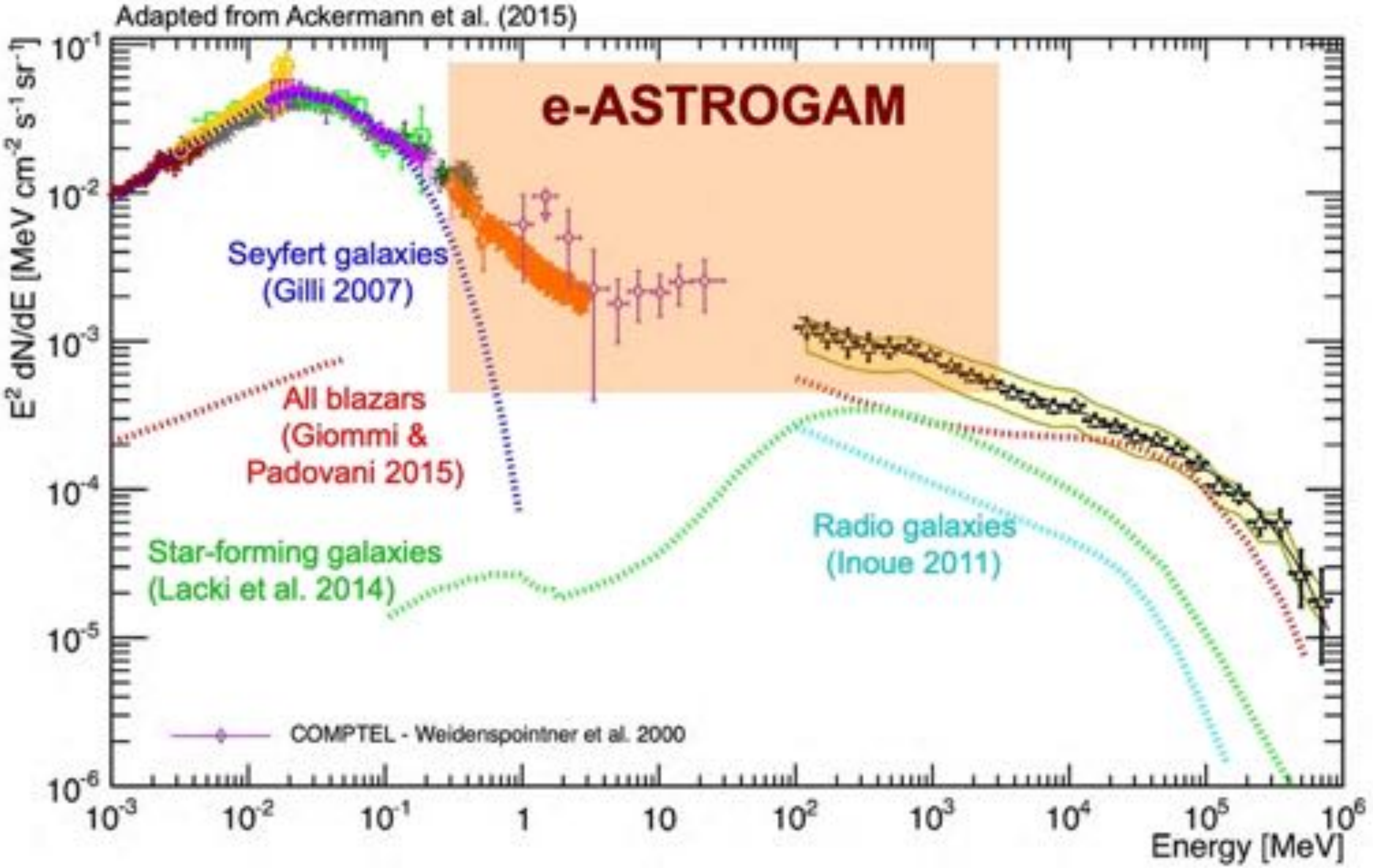
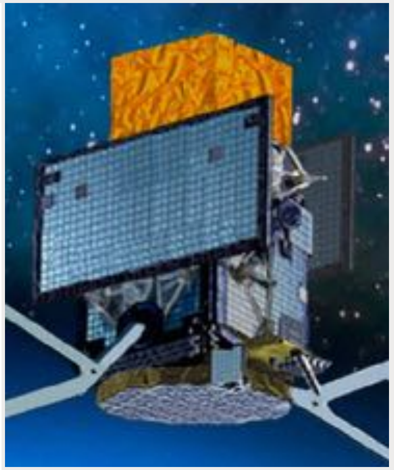

Adapted from Ackermann et al. (2015)
e-ASTROGAM
Seyfert galaxies
(Gilli 2007)
All blazars
(Giommi &
Padovani 2015)
Star-forming galaxies
(Lacki et al. 2014)
Radio galaxies
(Inoue 2011)
COMPTEL - Weidenspointner et al. 2000
E² dN/dE [MeV cm⁻² s⁻¹ sr⁻¹]
Energy [MeV]

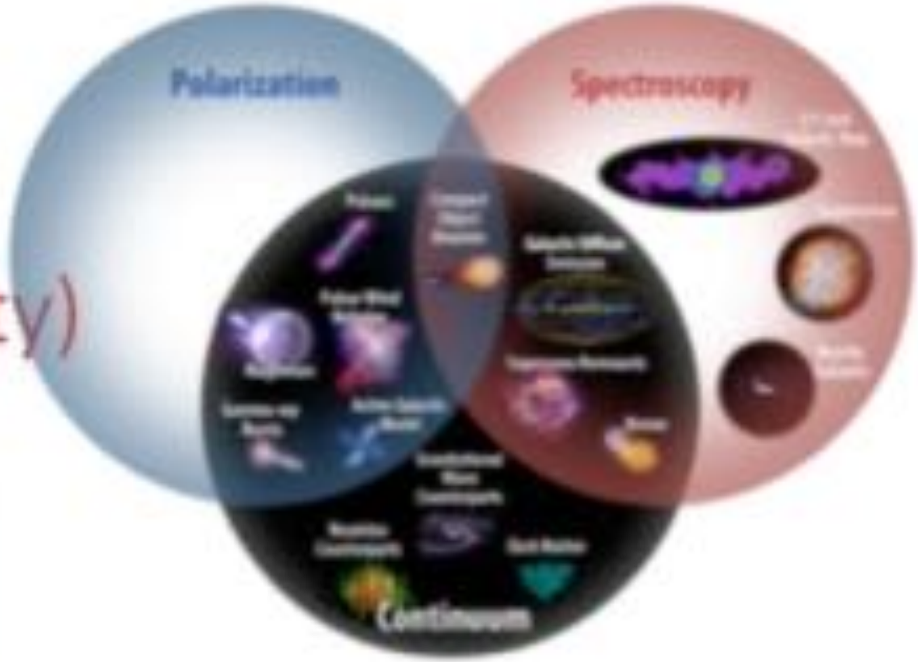
Table 1.1.1: e-ASTROGAM scientific requirements.

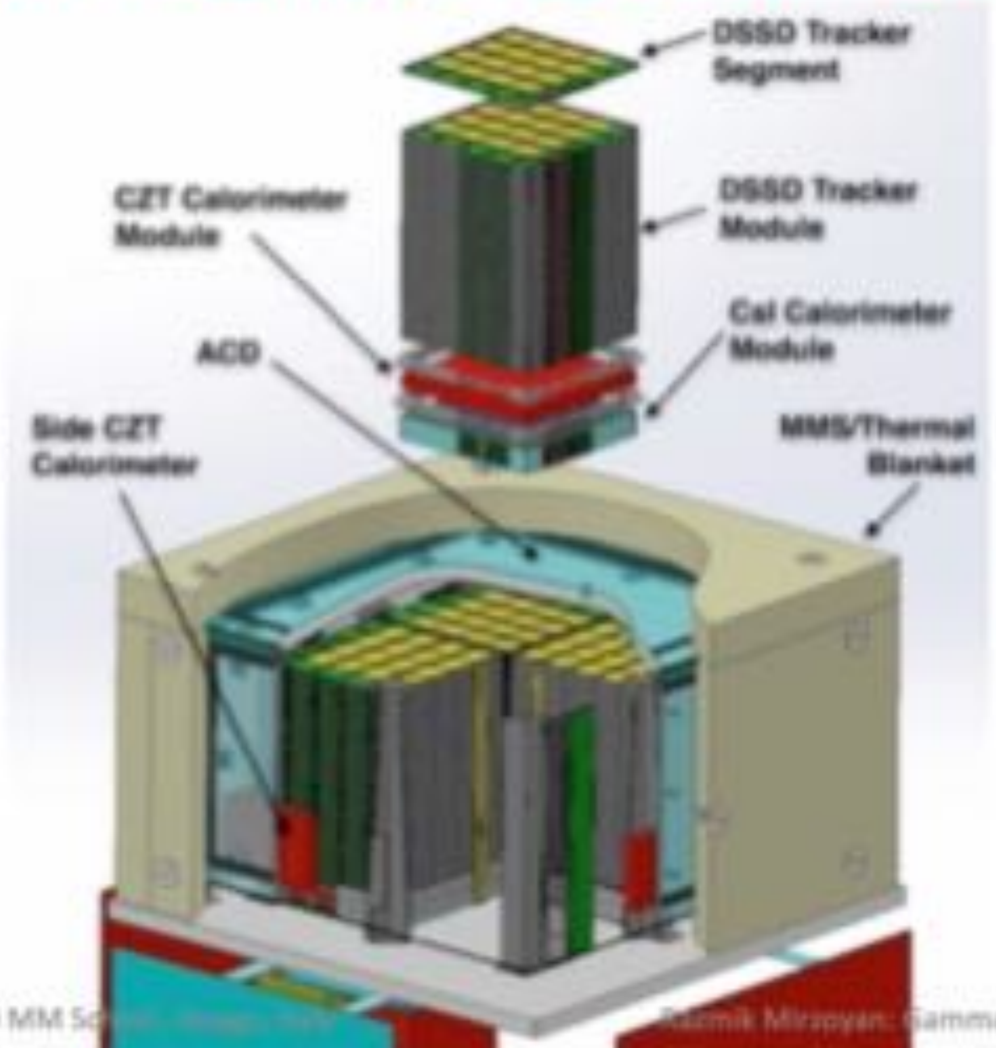
Parameter	Value
Energy bands:	0.3 MeV – 3 GeV (Gamma-ray imager: Tracker + Calorimeter) 30 keV – 200 MeV (Calorimeter burst search)
Gamma-ray imager FOV (at 100 MeV)	≥ 2.5 sr
Gamma-ray imager Continuum flux sensitivity at 3σ confidence level	$< 2\times10^{-5}$ MeV cm^{-2} s^{-1} at 1 MeV ($T_{obs} = 10^6$ s effective observation time) $< 5\times10^{-5}$ MeV cm^{-2} s^{-1} at 10 MeV ($T_{obs} = 10^6$ s, high-latitude source) $< 3\times10^{-6}$ MeV cm^{-2} s^{-1} at 500 MeV ($T_{obs} = 10^6$ s, high-latitude source)
Gamma-ray imager Line flux sensitivity at 3σ confidence level	$< 5\times10^{-6}$ ph cm^{-2} s^{-1} for the 511 keV line ($T_{obs} = 10^6$ s effective obs. time) $< 5\times10^{-6}$ ph cm^{-2} s^{-1} for the 847 keV SN Ia line ($T_{obs} = 10^6$ s) $< 3\times10^{-6}$ ph cm^{-2} s^{-1} for the 4.44 MeV line from LECRs ($T_{obs} = 10^6$ s)
Gamma-ray imager angular resolution	≤ 1.5° at 1 MeV (FWHM of the angular resolution measure) ≤ 1.5° at 100 MeV (68% containment radius) ≤ 0.2° at 1 GeV (68% containment radius)
AC particle background rejection efficiency	> 99.99 %
Polarization sensitivity	MDP < 20% (99% c.l.) for a 10 mCrab source (0.3-2 MeV, T_{obs} = 1 yr) Detection of a polarization fract. ≥ 20% in more than 20 GRBs per year
ΔE/E (Gamma-ray imager)	3.0% at 1 MeV 30% at 100 MeV
ΔE/E (Calorimeter burst)	< 25% FWHM at 0.3 MeV < 10% FWHM at 1 MeV < 5% FWHM at 10 MeV



A sister experiment: AMEGO (NASA)

(two brands, one community)



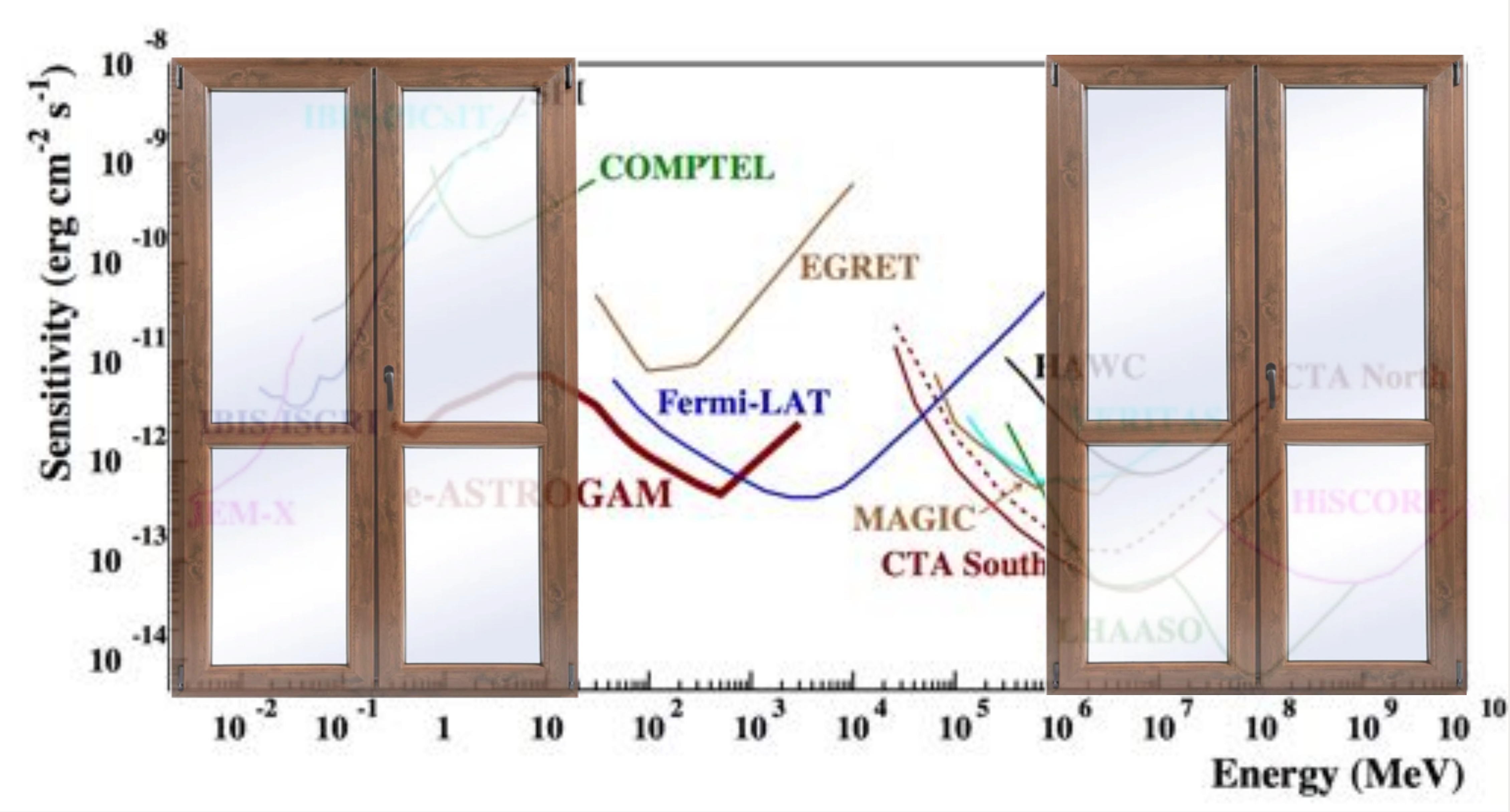


- ~20% smaller tracker
- CZT calorimeter layer

SATELLITE – GEV

PAIR PRODUCTION

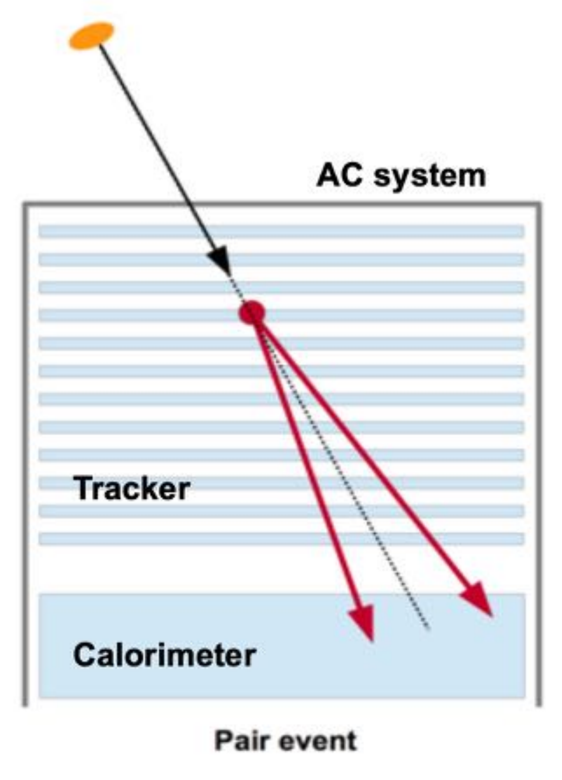
Where are we



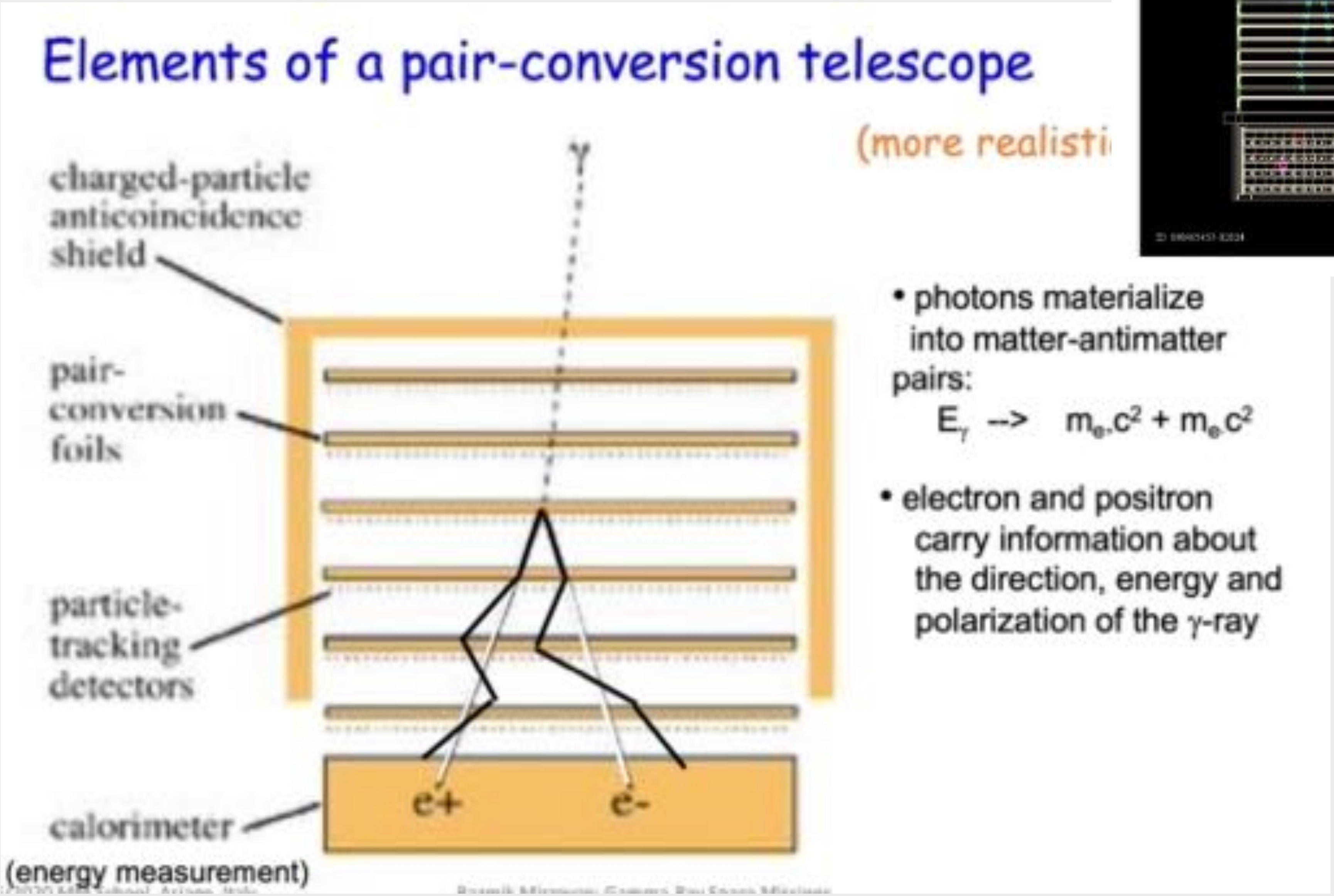
Sensitivity (erg cm^{-2} s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
COMPTEL
EGRET
Fermi-LAT
GAM
MAGIC
CTA South
HAWC
CTA North
HiSCORE
LHAASO
IBIS/ISGRI
JEM-X
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Energy (MeV)

Fermi!

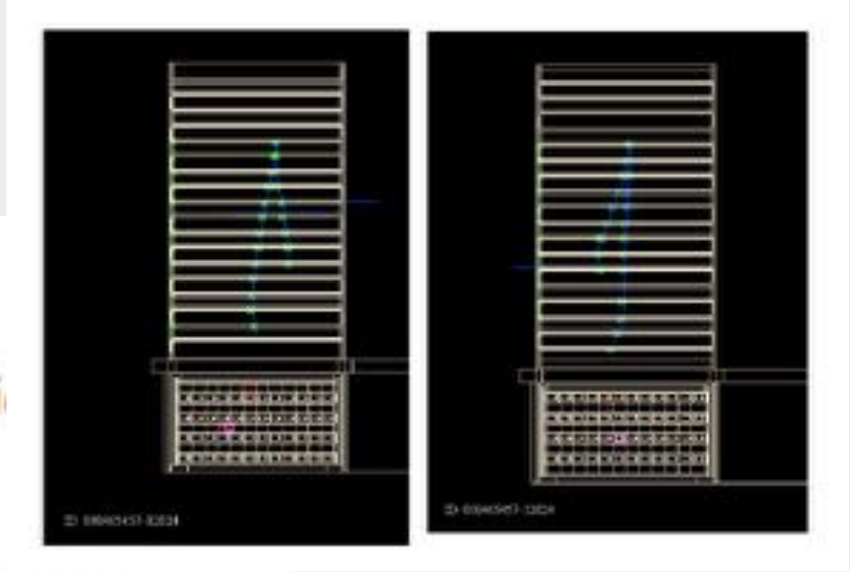
Fermi
Gamma-ray Space Telescope



A PP event



Elements of a pair-conversion telescope
(more realisti
γ
charged-particle anticoincidence shield
pair-conversion foils
particle-tracking detectors
calorimeter
(energy measurement)
e+
e-
• photons materialize into matter-antimatter pairs:
E_γ --> $m_{e^+}c^2 + m_{e^-}c^2$
• electron and positron carry information about the direction, energy and polarization of the γ-ray



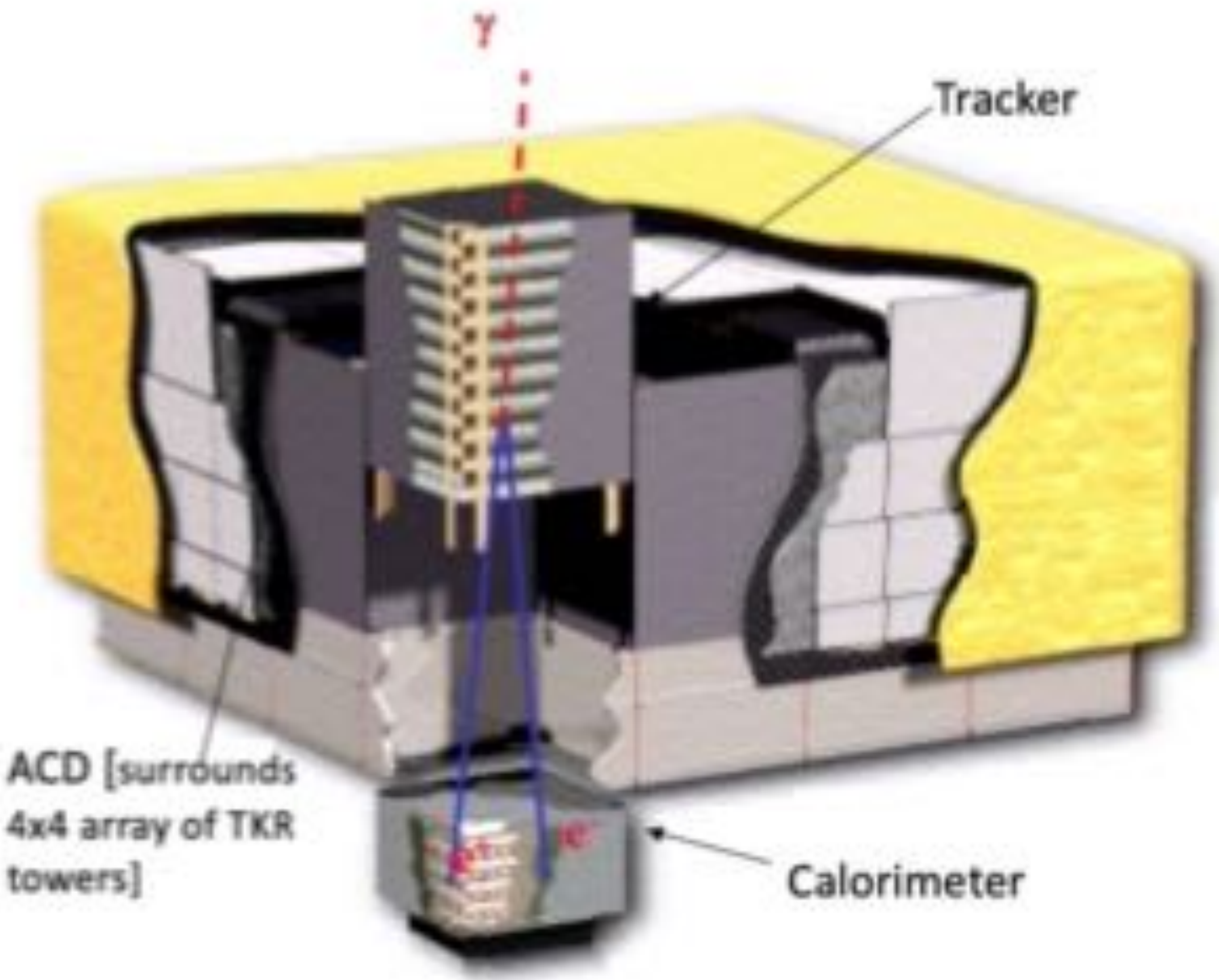
Fermi LAT: A Telescope Without Lenses

- Precision Si-strip Tracker (TKR)
  70 m^2 of silicon detectors arranged in 36 planes. 880,000 channels.

- Hodoscopic CsI Calorimeter(CAL)
  1536 CsI(Tl) crystals in 8 layers, total mass 1.5 tons.

- Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles.

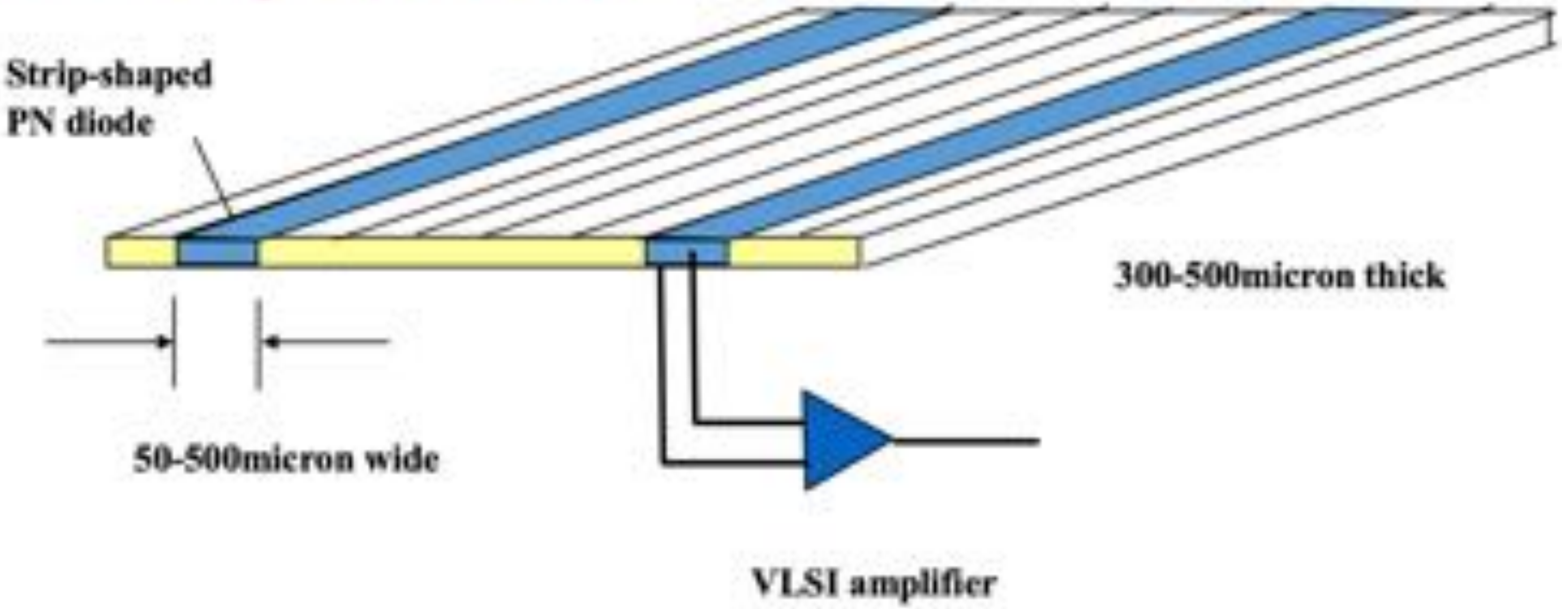
- Electronics System Includes flexible hardware trigger and onboard computing.



Amazing satellites

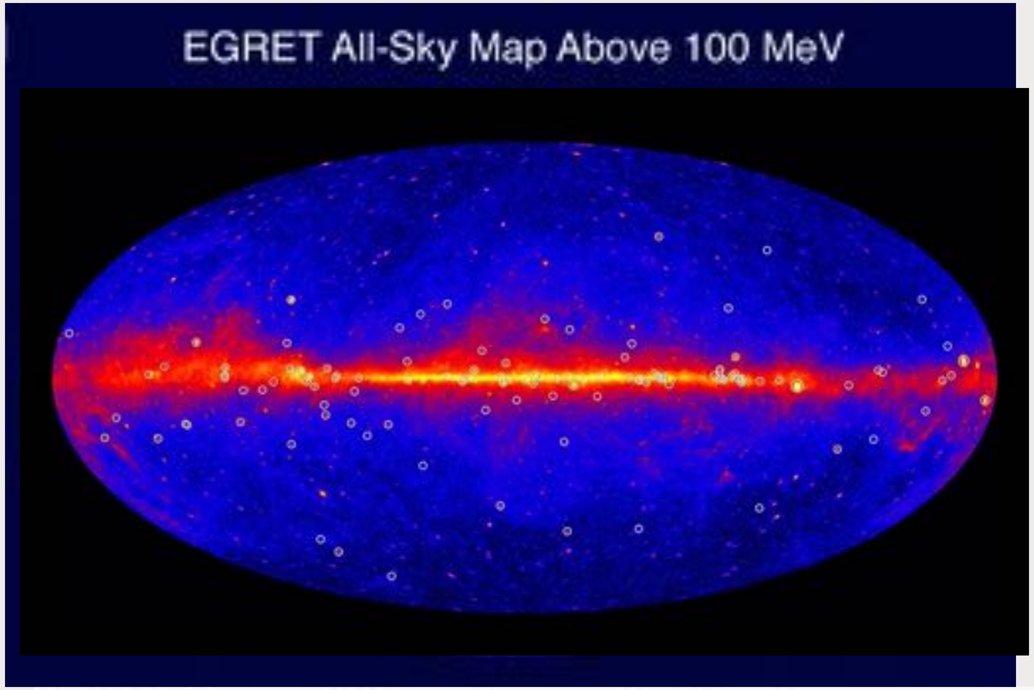
Particle physics detectors

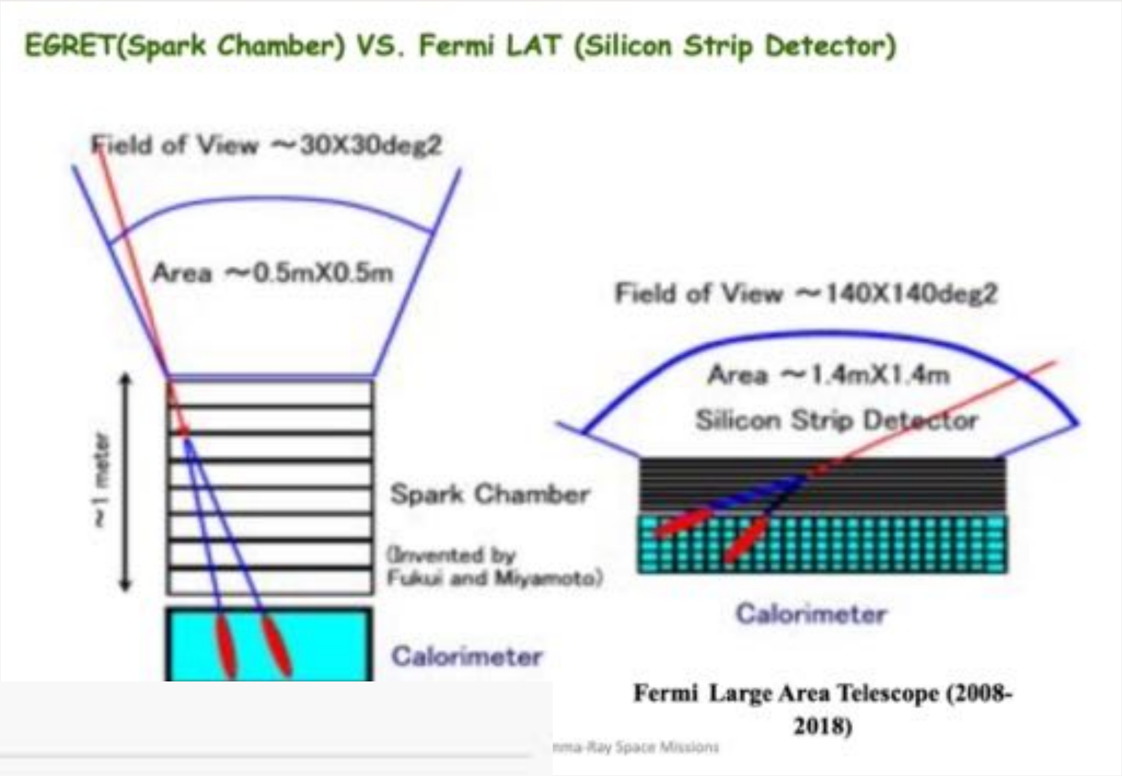
- **Silicon strip detector**



Stable particle tracker that allows micron-level tracking of gamma-rays

Well known technology in Particle Physics experiments.
Used by our collaboration in balloon experiments (MASS, TS93, CAPRICE),
on MIR Space Station (SilEye) and on satellite (NINA)



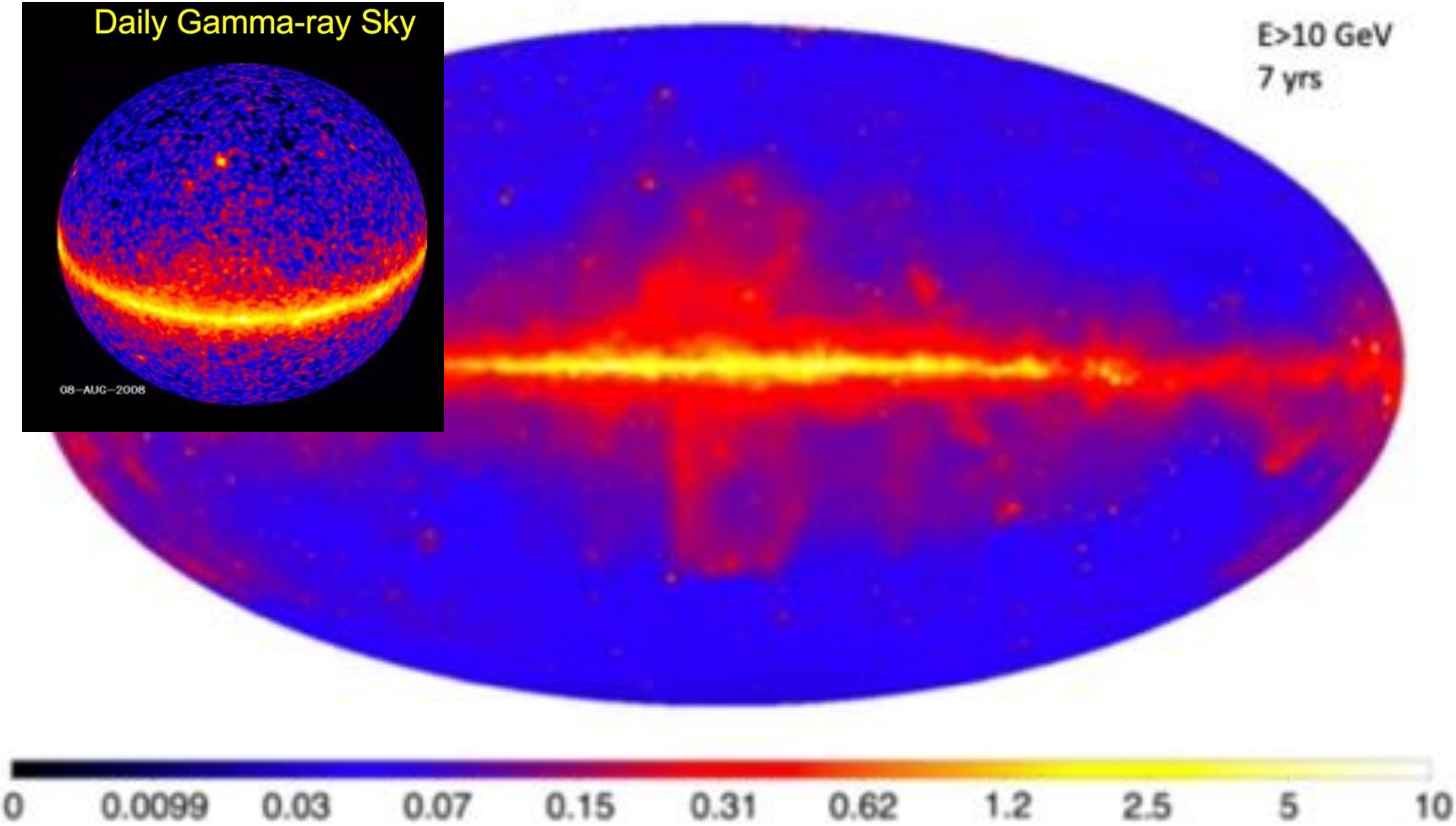


LAT Specifications & Performance

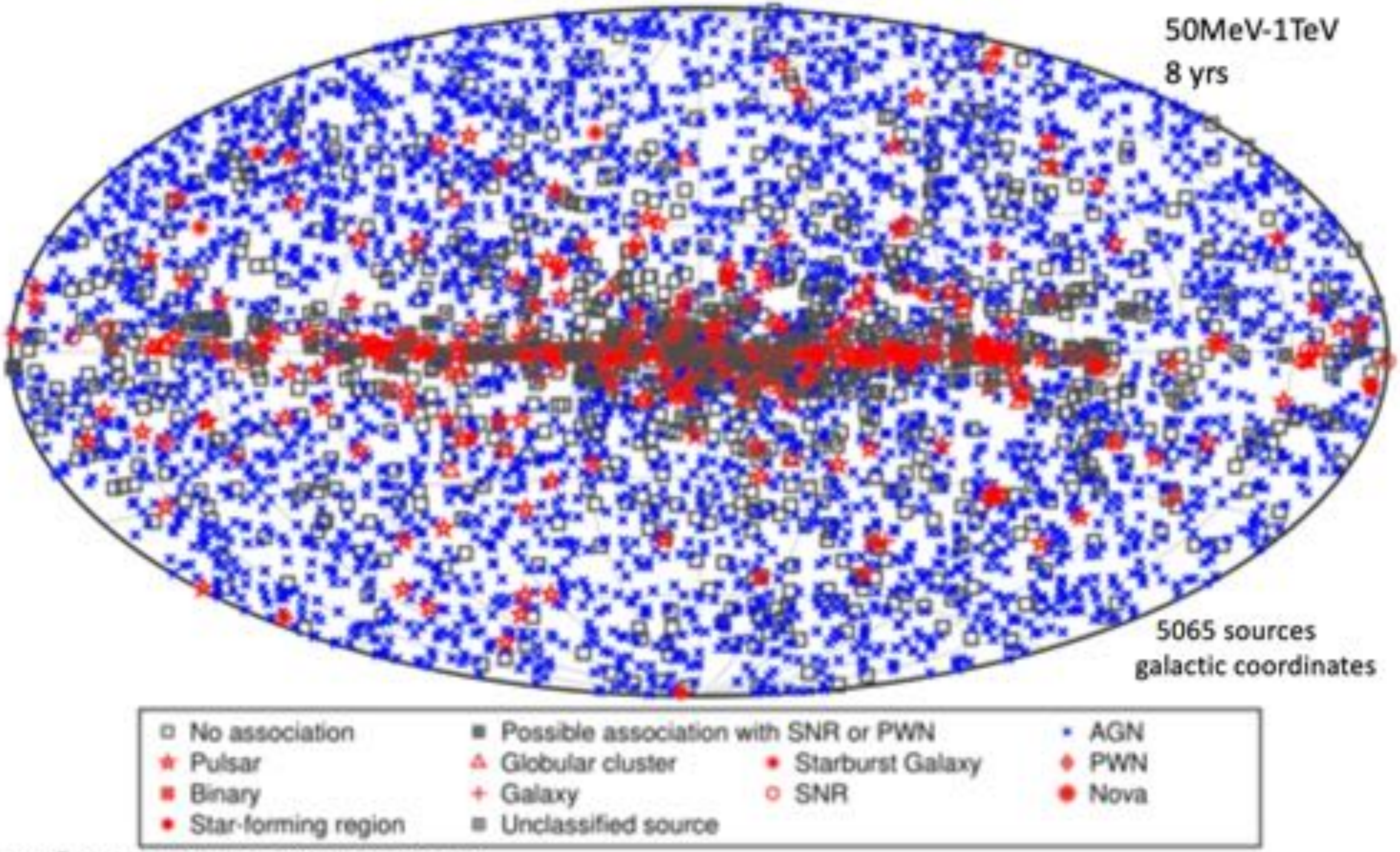
Quantity	LAT (Minimim Spec.)	EGRET
Energy Range	20 MeV - 300 GeV	20 MeV - 30 GeV
Peak Effective Area [1]	> 8000 cm^2	1500 cm^2
Field of View	> 2 sr	0.5 sr
Angular Resolution [2]	< 3.5° (100 MeV) < 0.15° (>10 GeV)	5.8° (100 MeV)
Energy Resolution [3]	< 10%	10%
Deadtime per Event	< 100 µs	100 ms
Source Location Determination [4]	< 0.5'	15'
Point Source Sensitivity [5]	$< 6 \times 10^{-9}$ cm^{-2} s^{-1}	$\sim 10^{-7}$ cm^{-2} s^{-1}

GeV revolution
Mother and daughter

The sky in gamma-rays

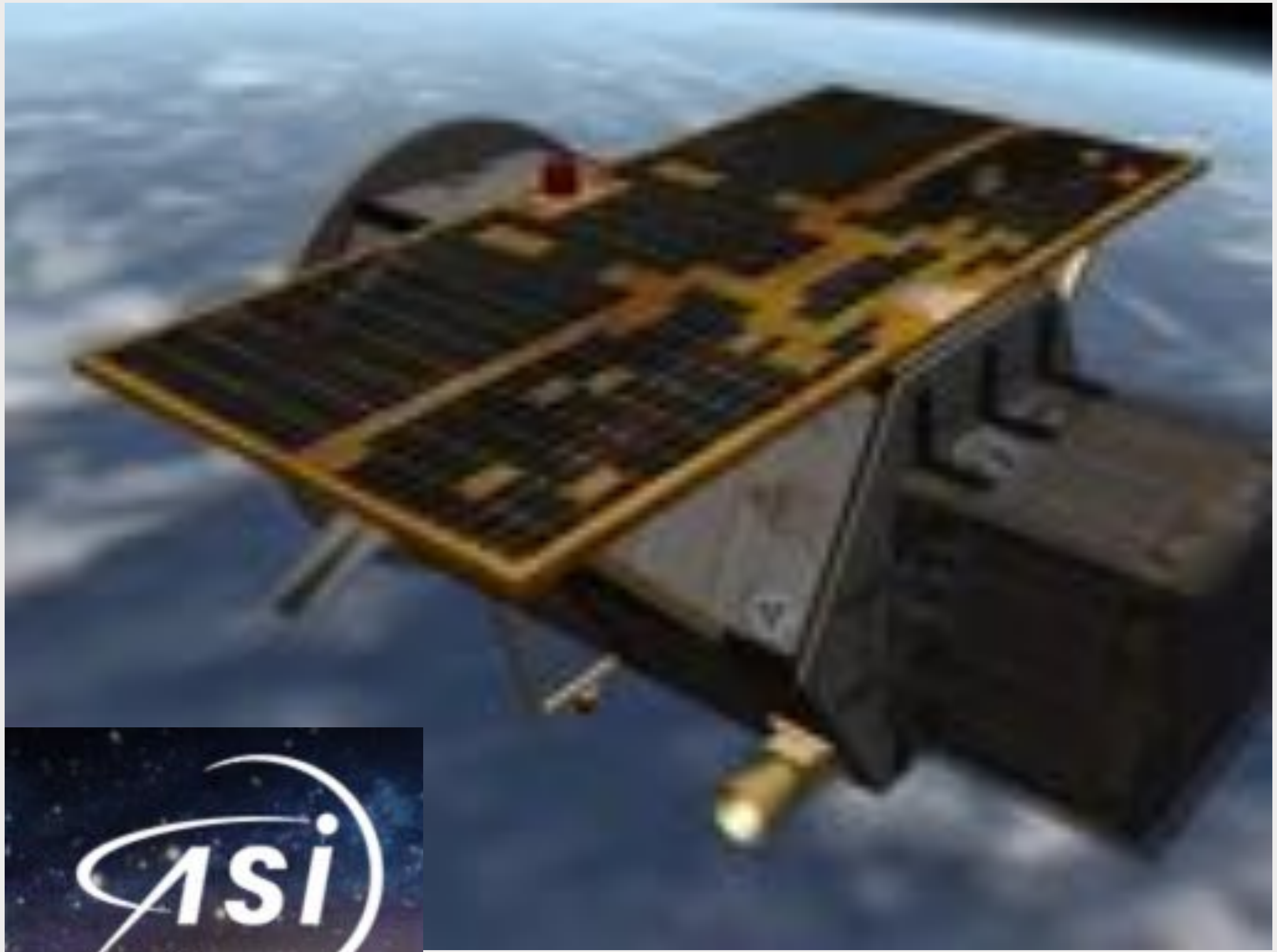


The sky in gamma-rays 4th source catalog



Fermi Fouth Source Catalog, arXiv:1902.10045_v3

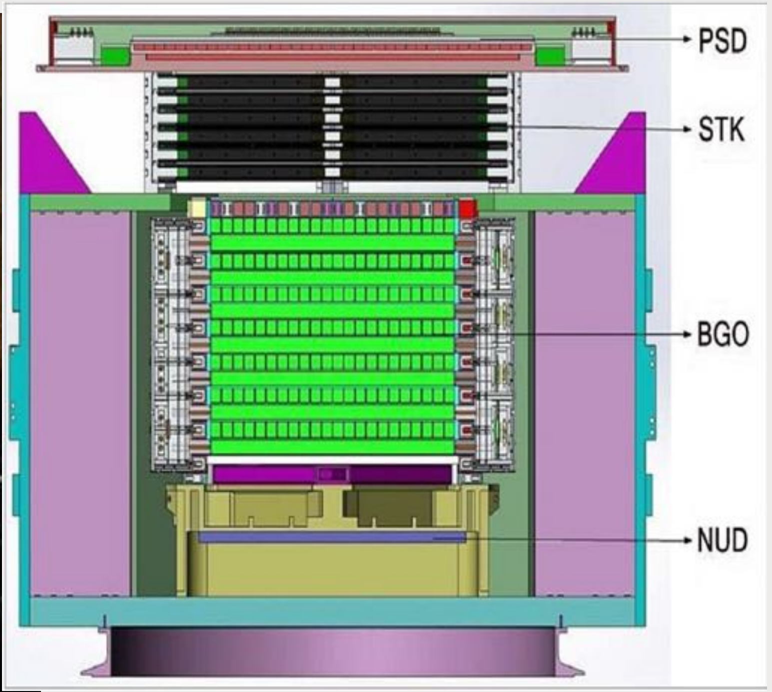
AGILE



http://www.agilescienceapp.it /

- Launched in 2007
- Should have been a precursor of LAT

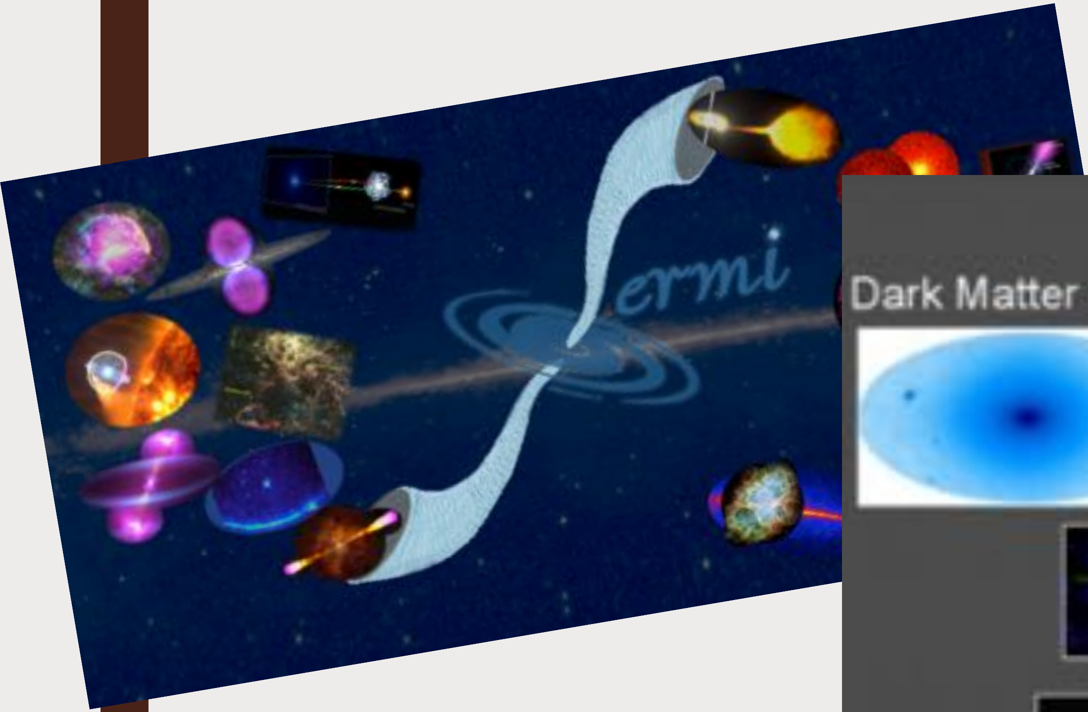
DAMPE (Dark Matter Particle Explorer)

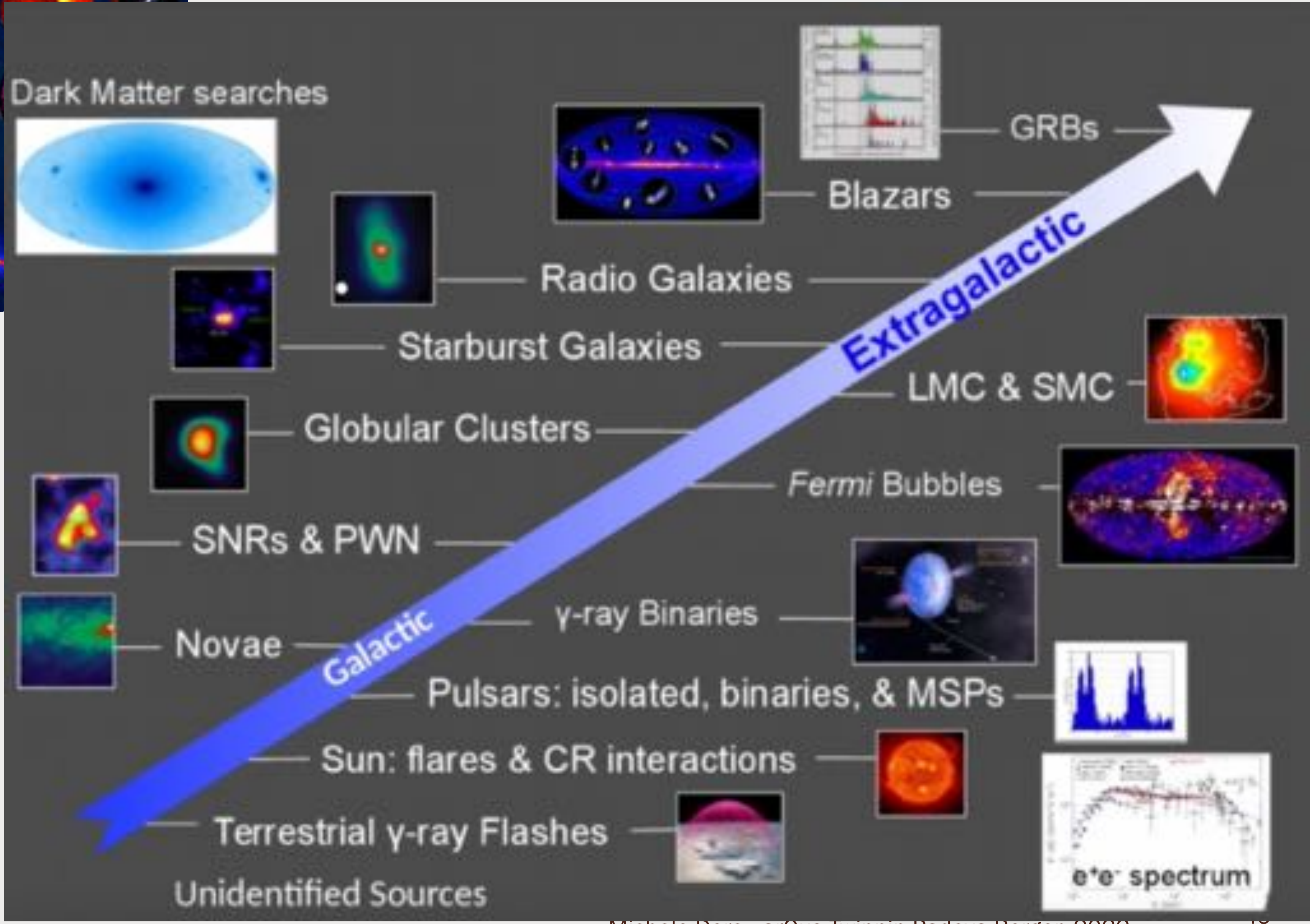


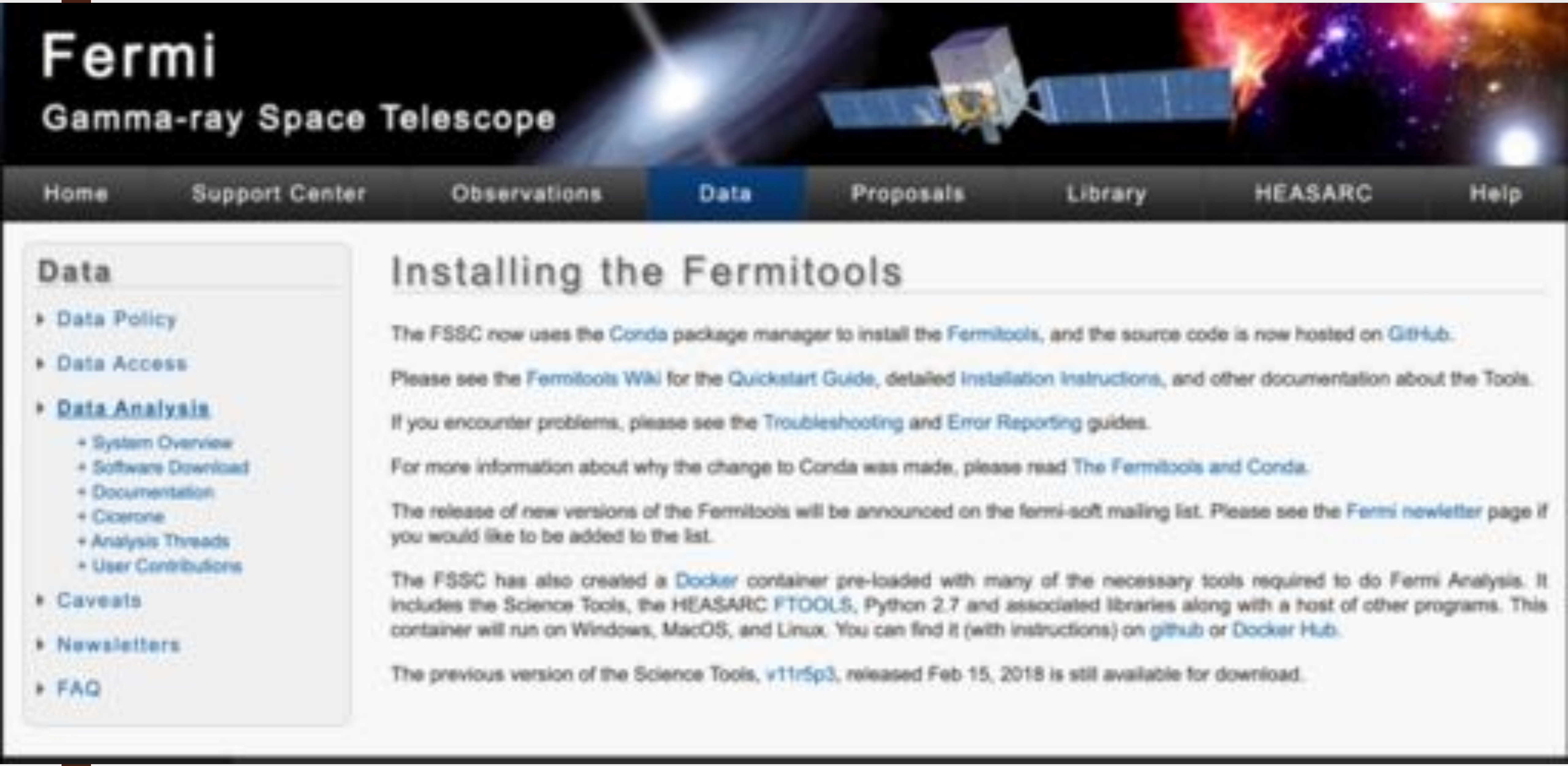
Mostly Chinese mission

https://directory.eoportal.org/web/eoportal/satellite-missions/d/dampe

Science with Fermi






Fermi
Gamma-ray Space Telescope
Home
Support Center
Observations
Data
Proposals
Library
HEASARC
Help
Data
Data Policy
Data Access
Data Analysis
System Overview
Software Download
Documentation
Cicerone
Analysis Threads
User Contributions
Caveats
Newsletters
FAQ
Installing the Fermitools
The FSSC now uses the Conda package manager to install the Fermitools, and the source code is now hosted on GitHub.
Please see the Fermitools Wiki for the Quickstart Guide, detailed Installation Instructions, and other documentation about the Tools.
If you encounter problems, please see the Troubleshooting and Error Reporting guides.
For more information about why the change to Conda was made, please read The Fermitools and Conda.
The release of new versions of the Fermitools will be announced on the fermi-soft mailing list. Please see the Fermi newletter page if you would like to be added to the list.
The FSSC has also created a Docker container pre-loaded with many of the necessary tools required to do Fermi Analysis. It includes the Science Tools, the HEASARC FTOOLS, Python 2.7 and associated libraries along with a host of other programs. This container will run on Windows, MacOS, and Linux. You can find it (with instructions) on github or Docker Hub.
The previous version of the Science Tools, v11r5p3, released Feb 15, 2018 is still available for download.

THE ASTROPHYSICAL JOURNAL, 724:1044–1082, 2010 December 1 doi:10.1088/0004-637X/724/2/1044

GIANT GAMMA-RAY BUBBLES FROM *FERMI*-LAT: ACTIVE GALACTIC NUCLEUS ACTIVITY OR BIPOLAR GALACTIC WIND?

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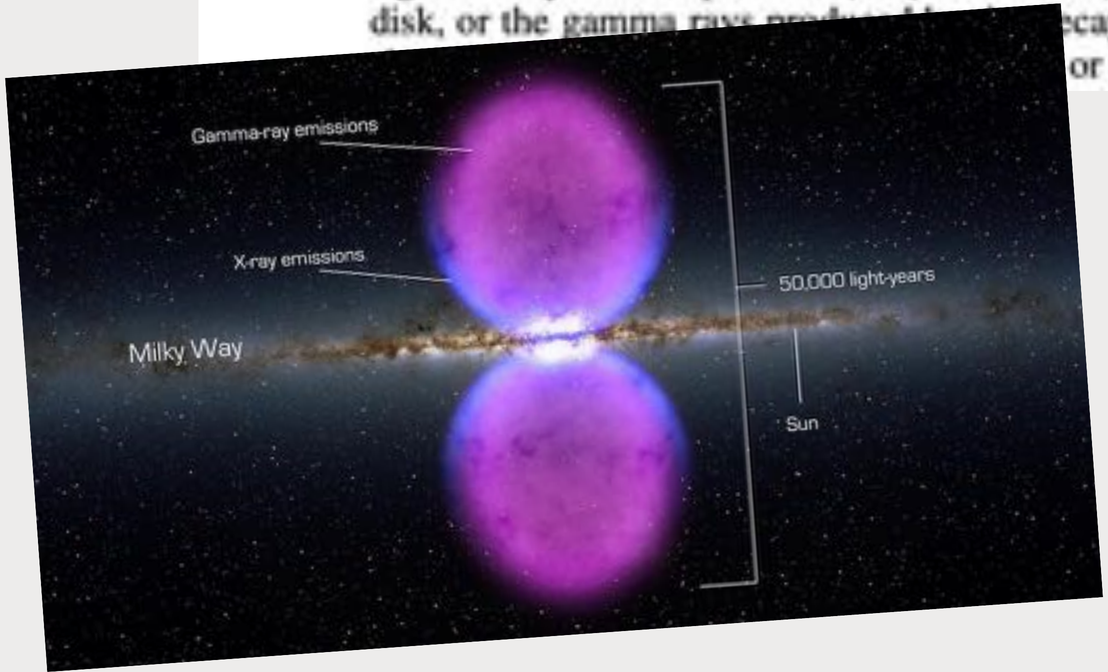
Received 2010 June 2; accepted 2010 September 23; published 2010 November 10

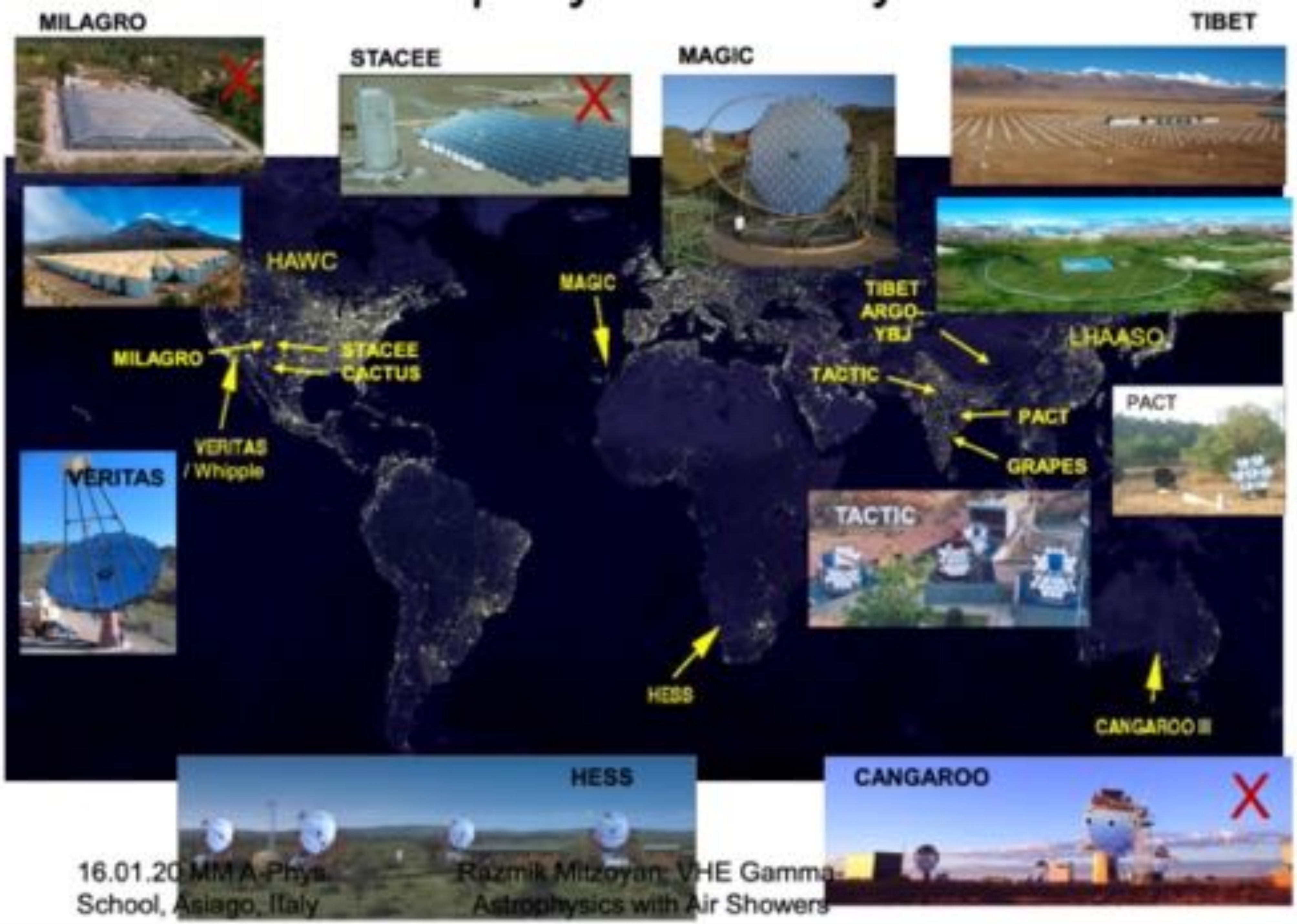
ABSTRACT

Data from the *Fermi*-LAT reveal two large gamma-ray bubbles, extending 50° above and below the Galactic center (GC), with a width of about 40° in longitude. The gamma-ray emission associated with these bubbles has a significantly harder spectrum ($dN/dE \sim E^{-2}$) than the inverse Compton emission from electrons in the Galactic disk, or the gamma rays ... ecay of pions from proton–interstellar medium collisions. There is no ... or gamma-ray intensity within the bubbles, or between the north and



Citations (706)

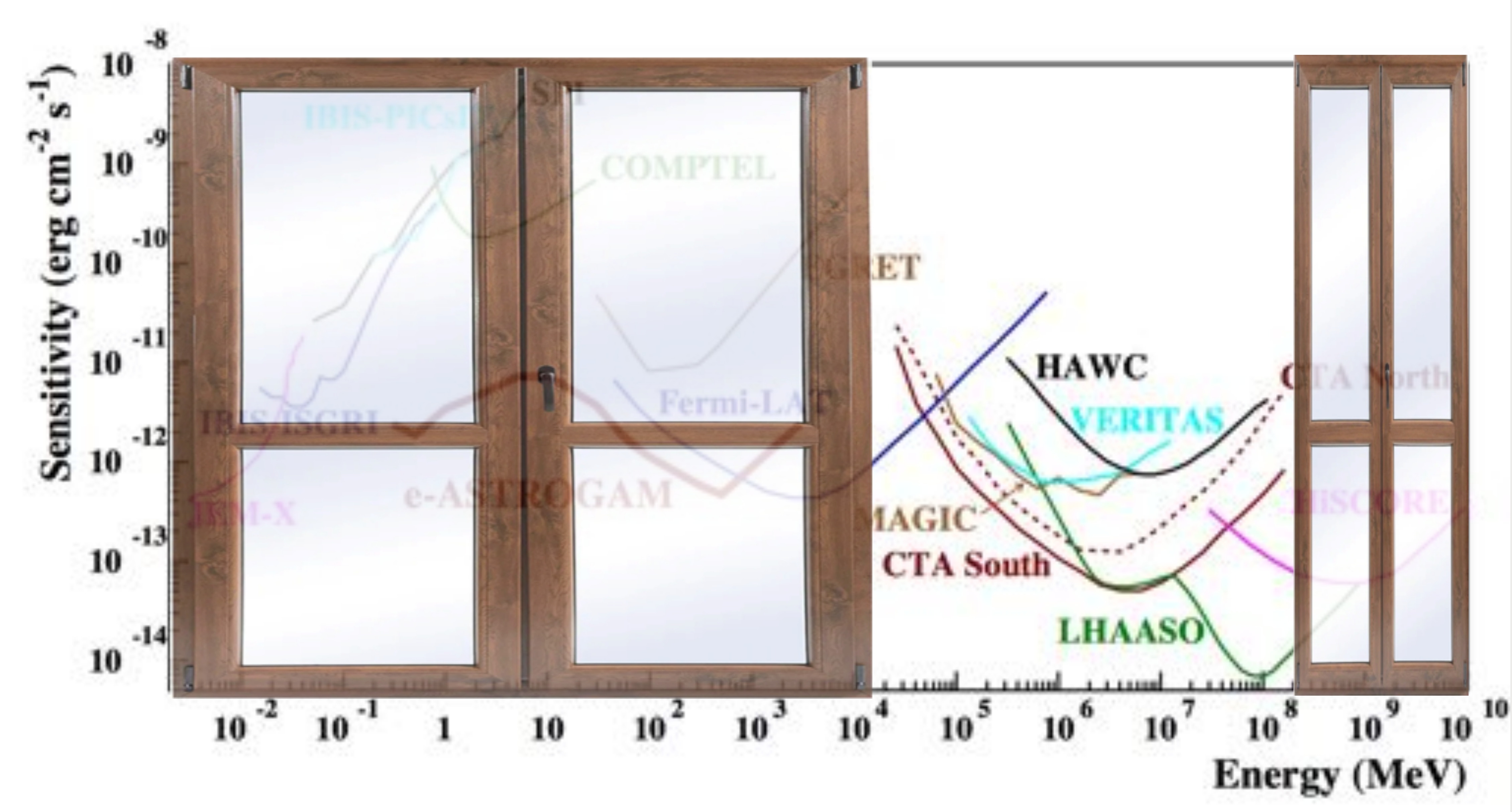
GROUND -BASED!


MILAGRO
STACEE
MAGIC
TIBET
HAWC
MAGIC
TIBET
ARGO-
YBJ
LHAASO
MILAGRO
STACEE
CACTUS
TACTIC
PACT
PACT
GRAPES
VERITAS
/ Whipple
VERITAS
TACTIC
HESS
CANGAROO III
HESS
CANGAROO
16.01.20 MMA-Phys.
School, Asiago, Italy
Razmik Mirzoyan: VHE Gamma
Astrophysics with Air Showers

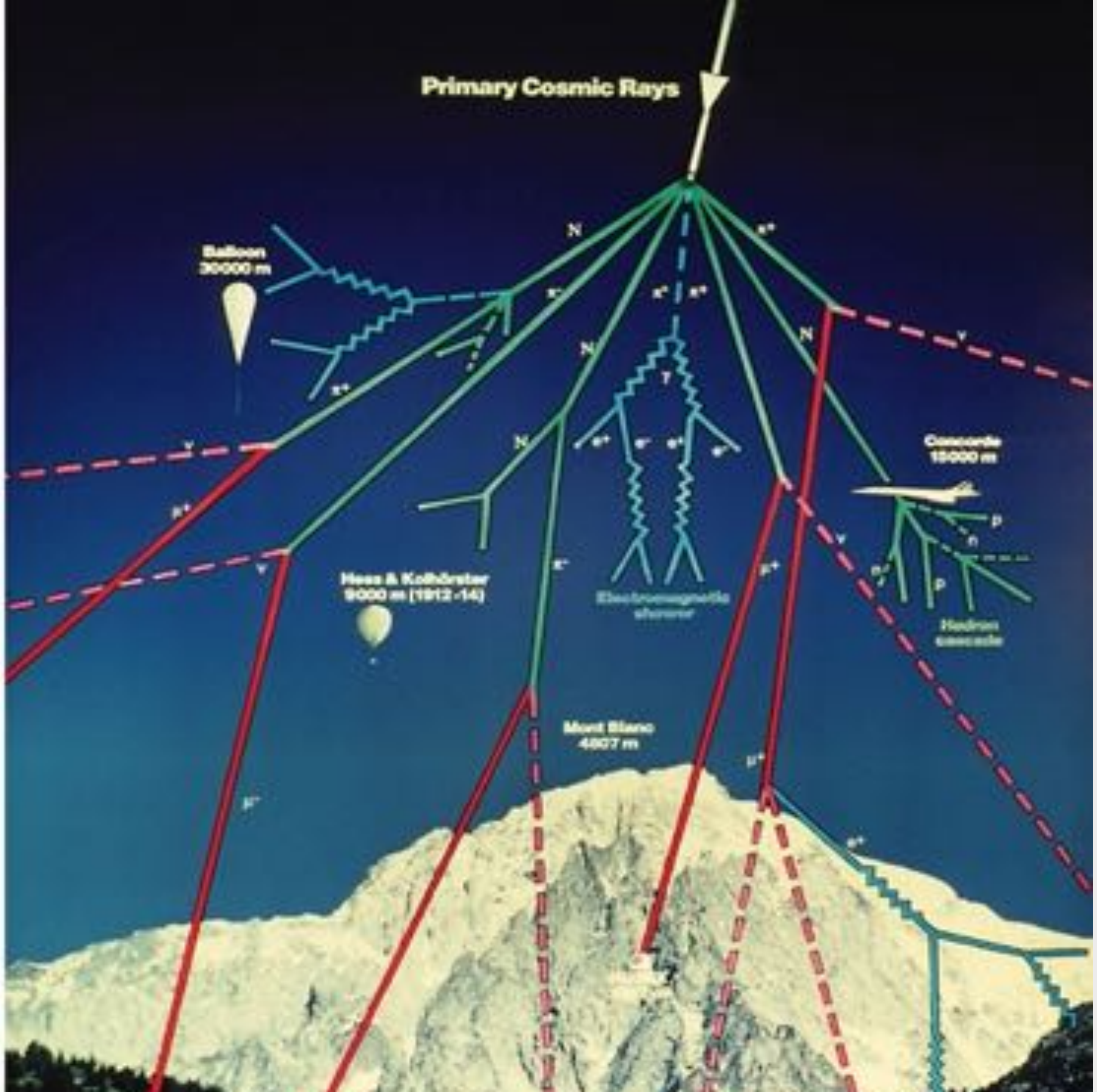
GROUND-TEV-SMALL FOV

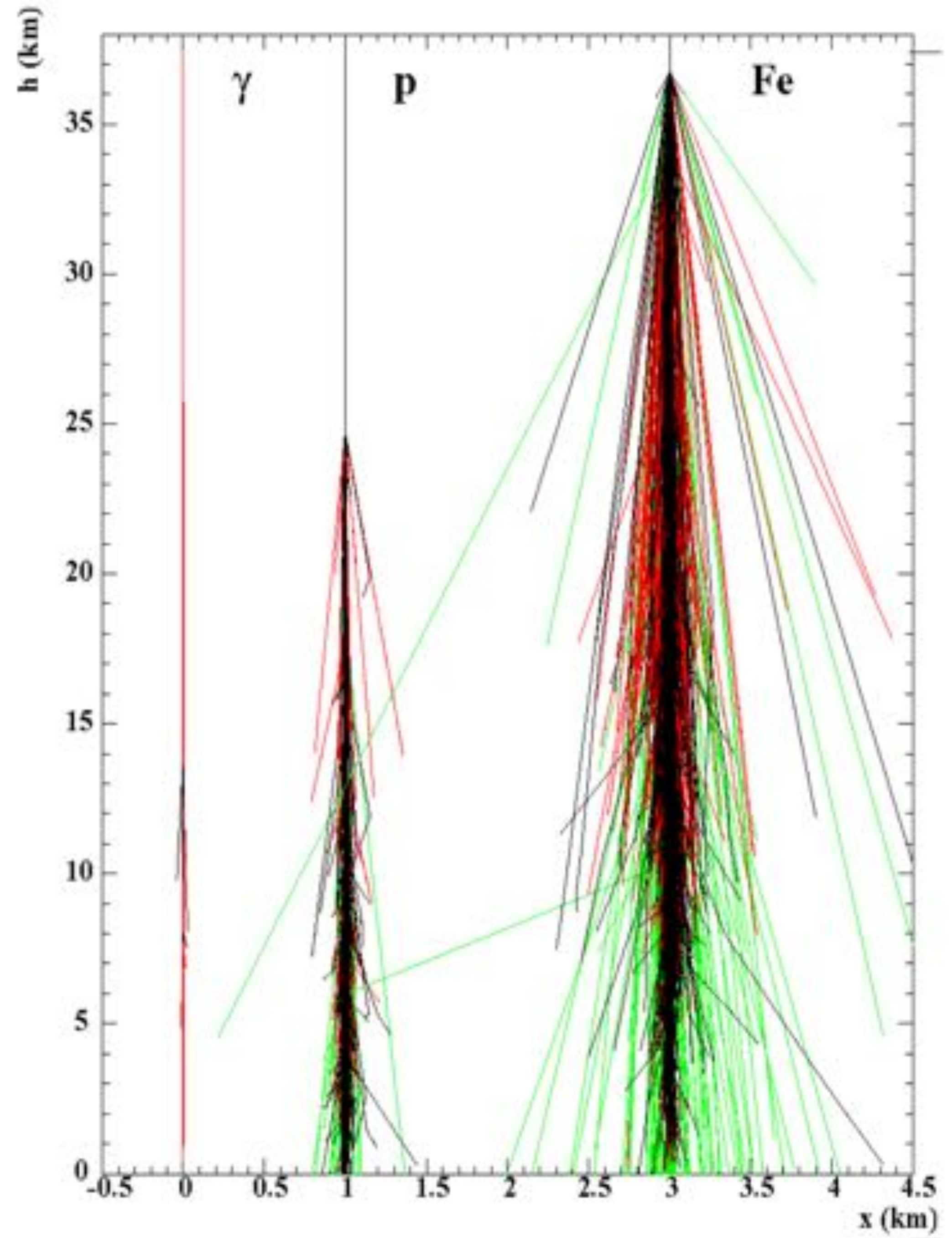
IMAGING CHERENKOV

Where are we

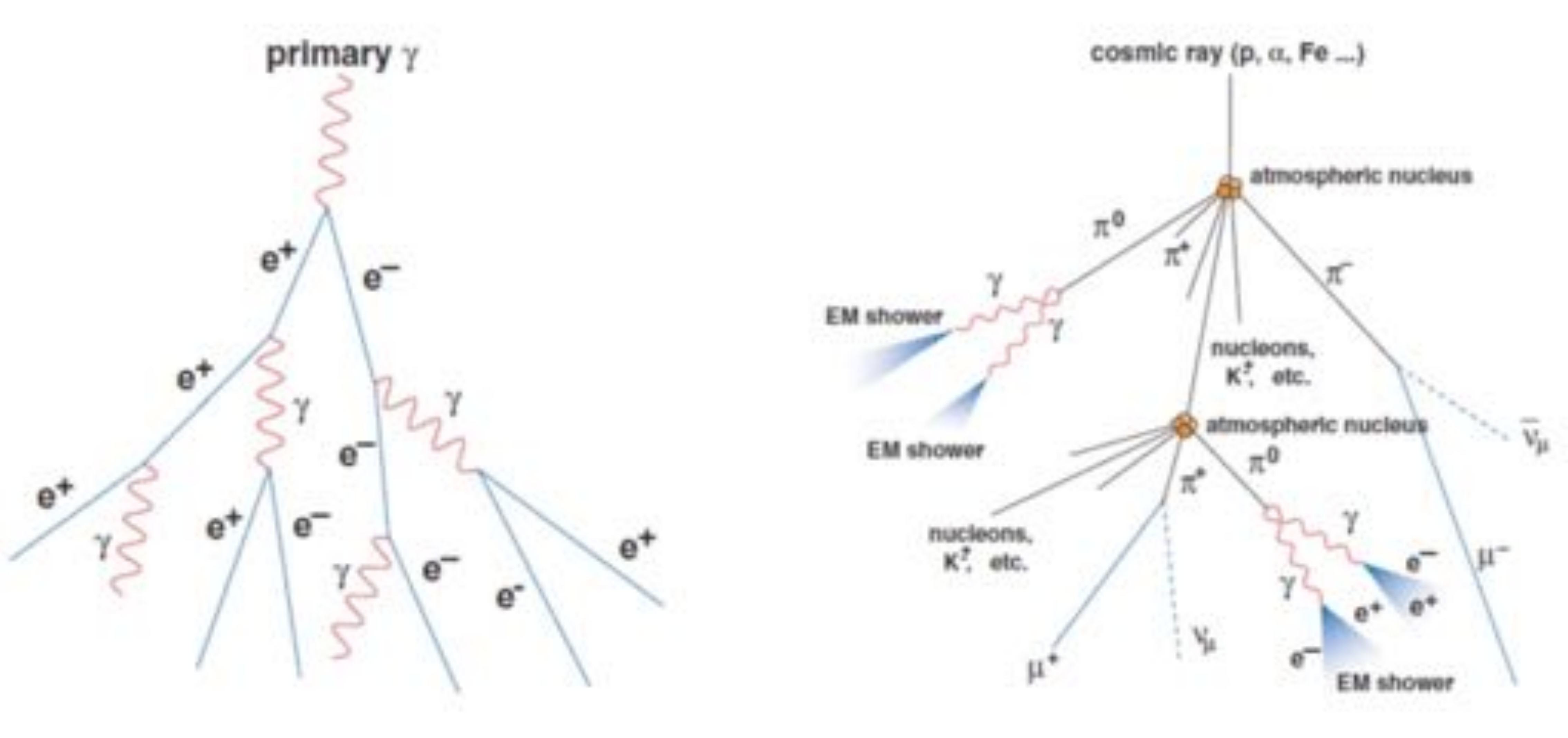


Sensitivity (erg cm^{-2} s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
COMPTEL
Fermi-LAT
IBIS/ISGRI
e-ASTROGAM
JEM-X
HAWC
VERITAS
CTA North
MAGIC
CTA South
LHAASO
10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}
Energy (MeV)


Primary Cosmic Rays
Balloon 30000 m
Concorde 15000 m
Hess & Kolhörster 9000 m (1912 -14)
Electromagnetic shower
Hadron cascade
Mont Blanc 4807 m

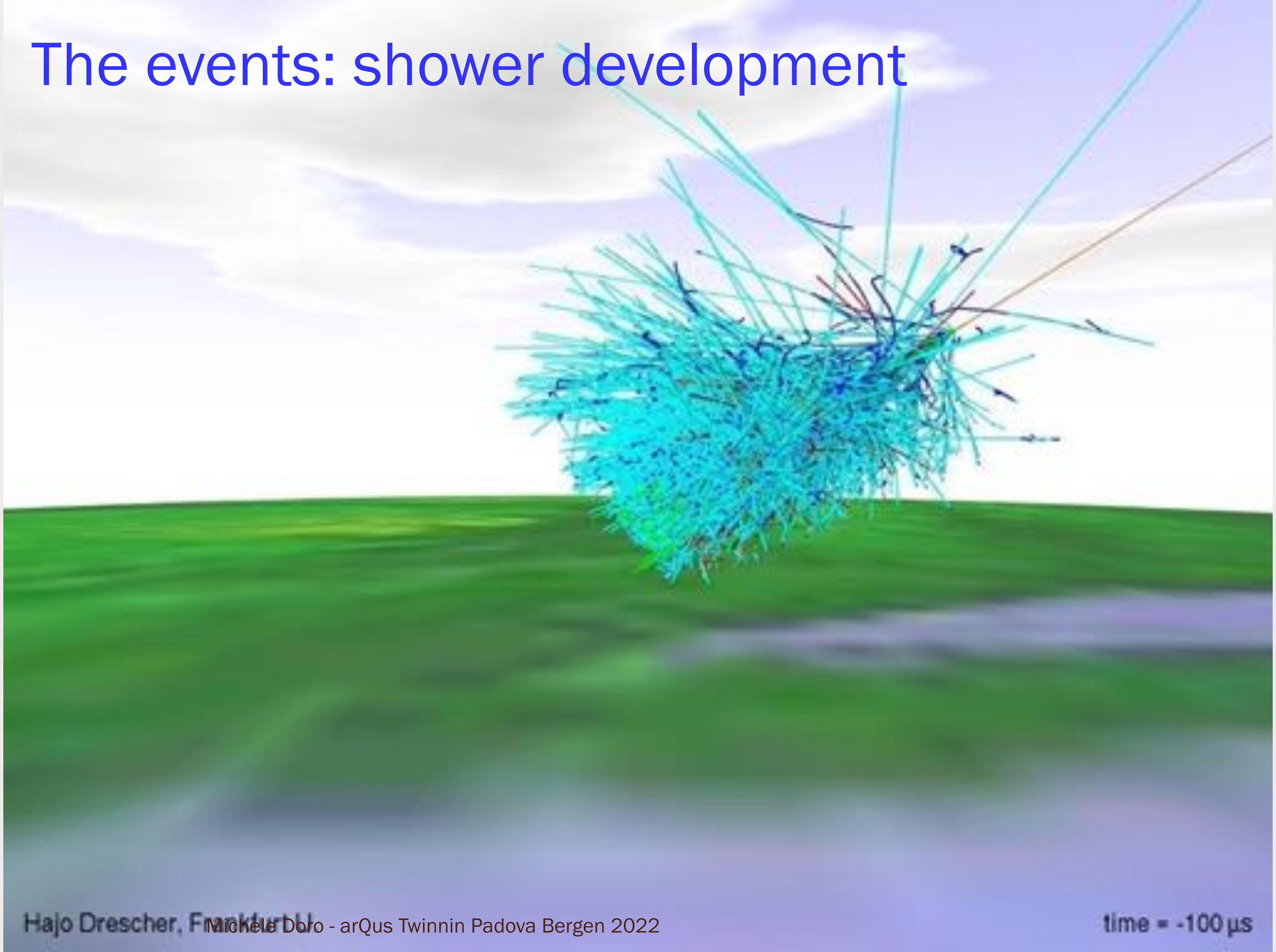

h (km)
γ
p
Fe
35
30
25
20
15
10
5
0
-0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
x (km)

Extended Atmospheric Shower (EAS)

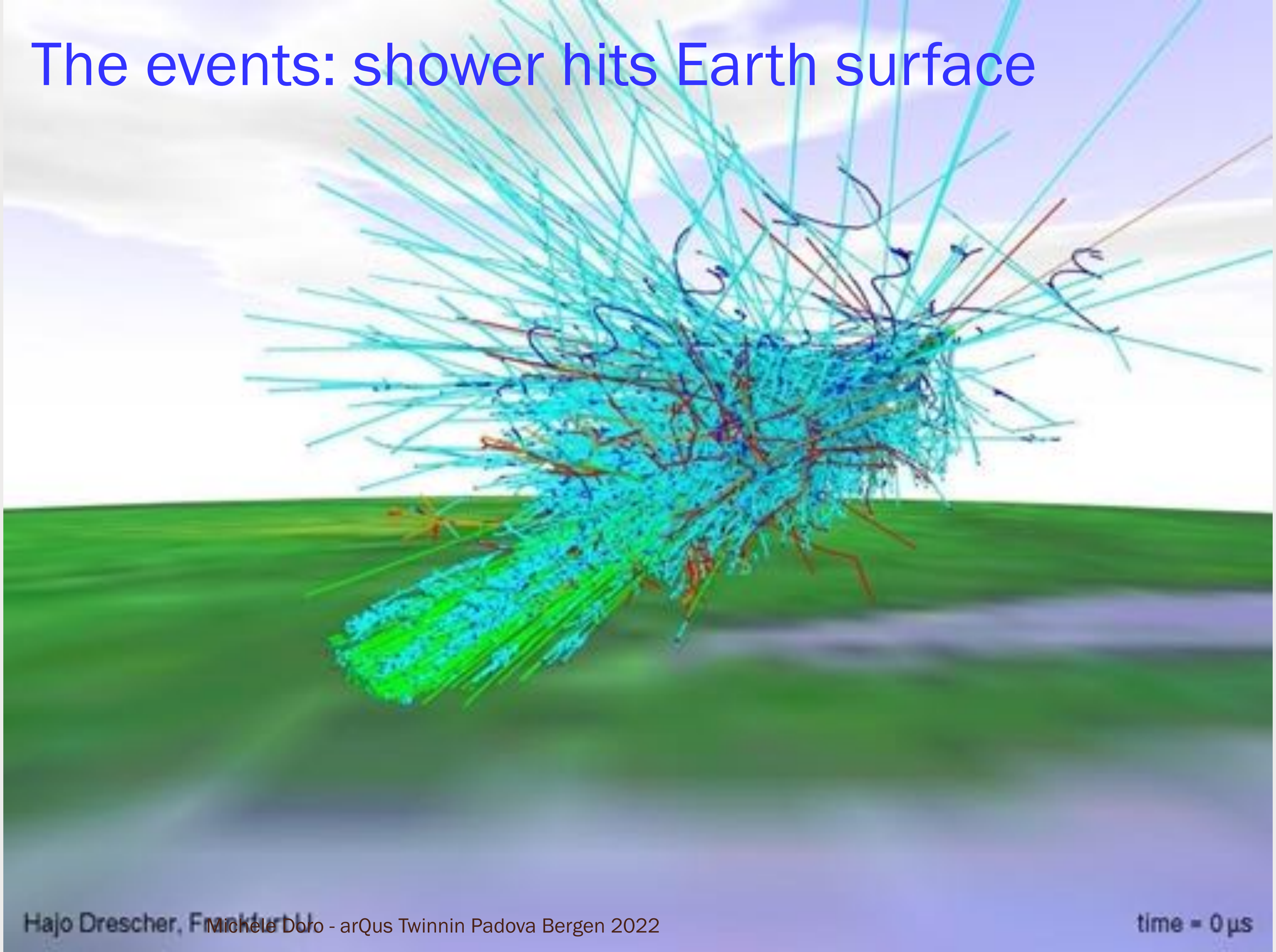


The events: shower development

The events: shower development

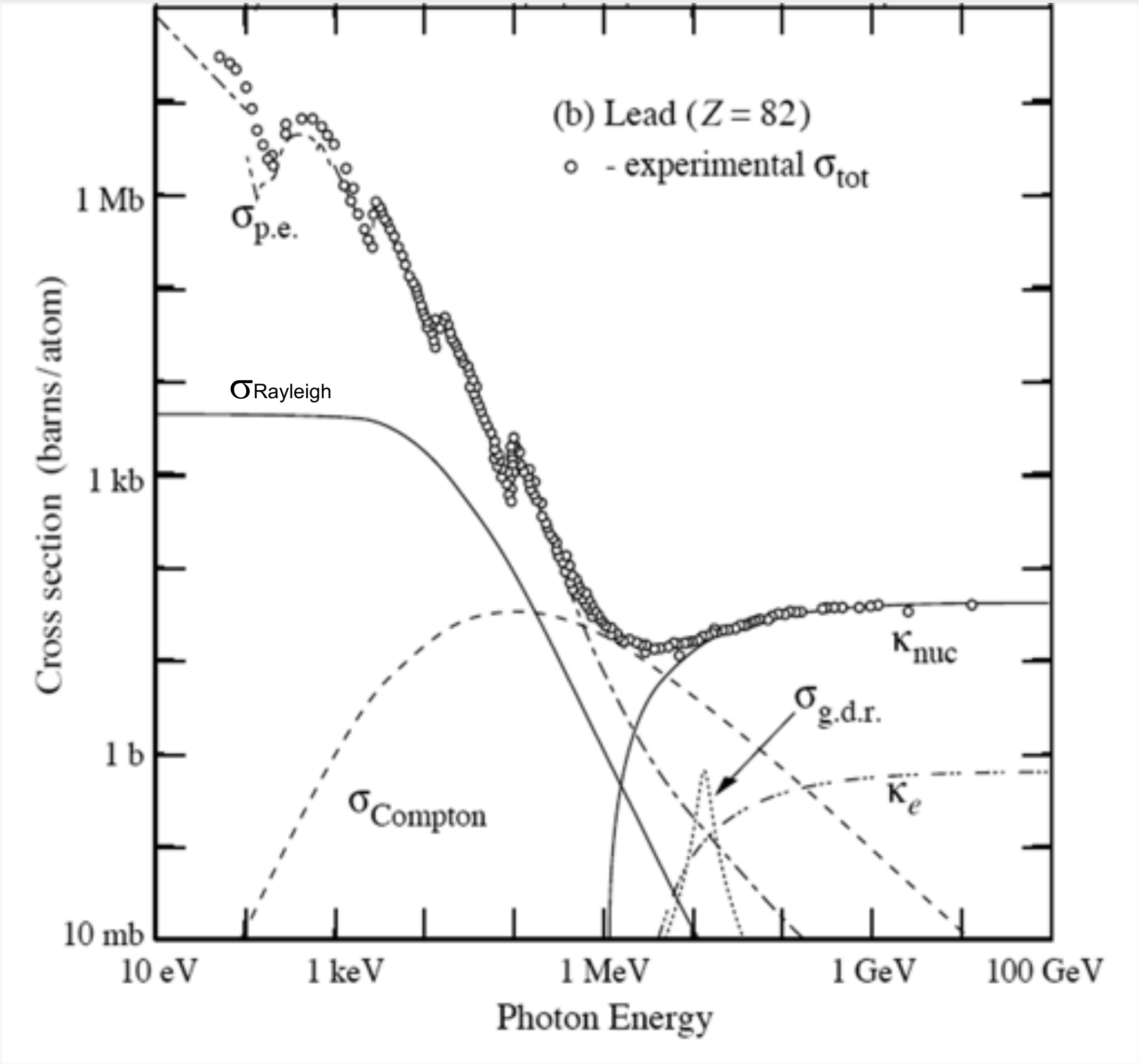


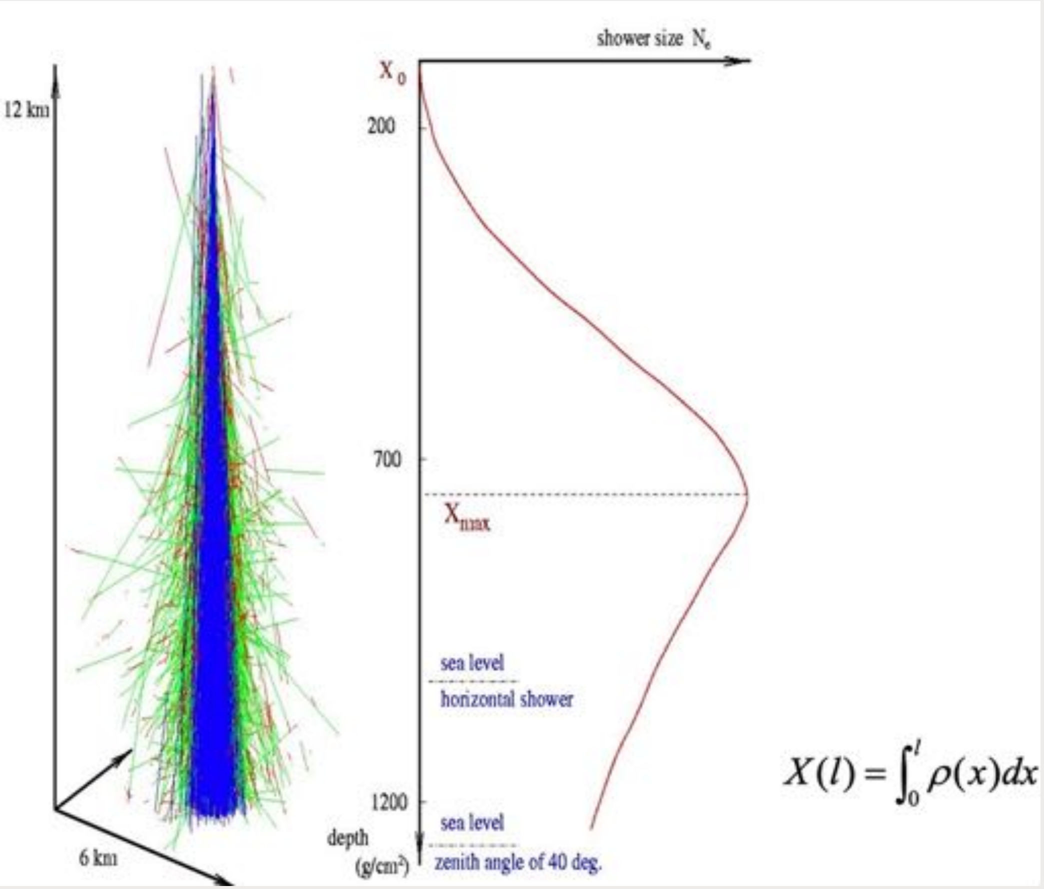
The events: shower hits Earth surface



HOW TO DETECT THE SHOWER?

The shower dies of photo-eletric effect

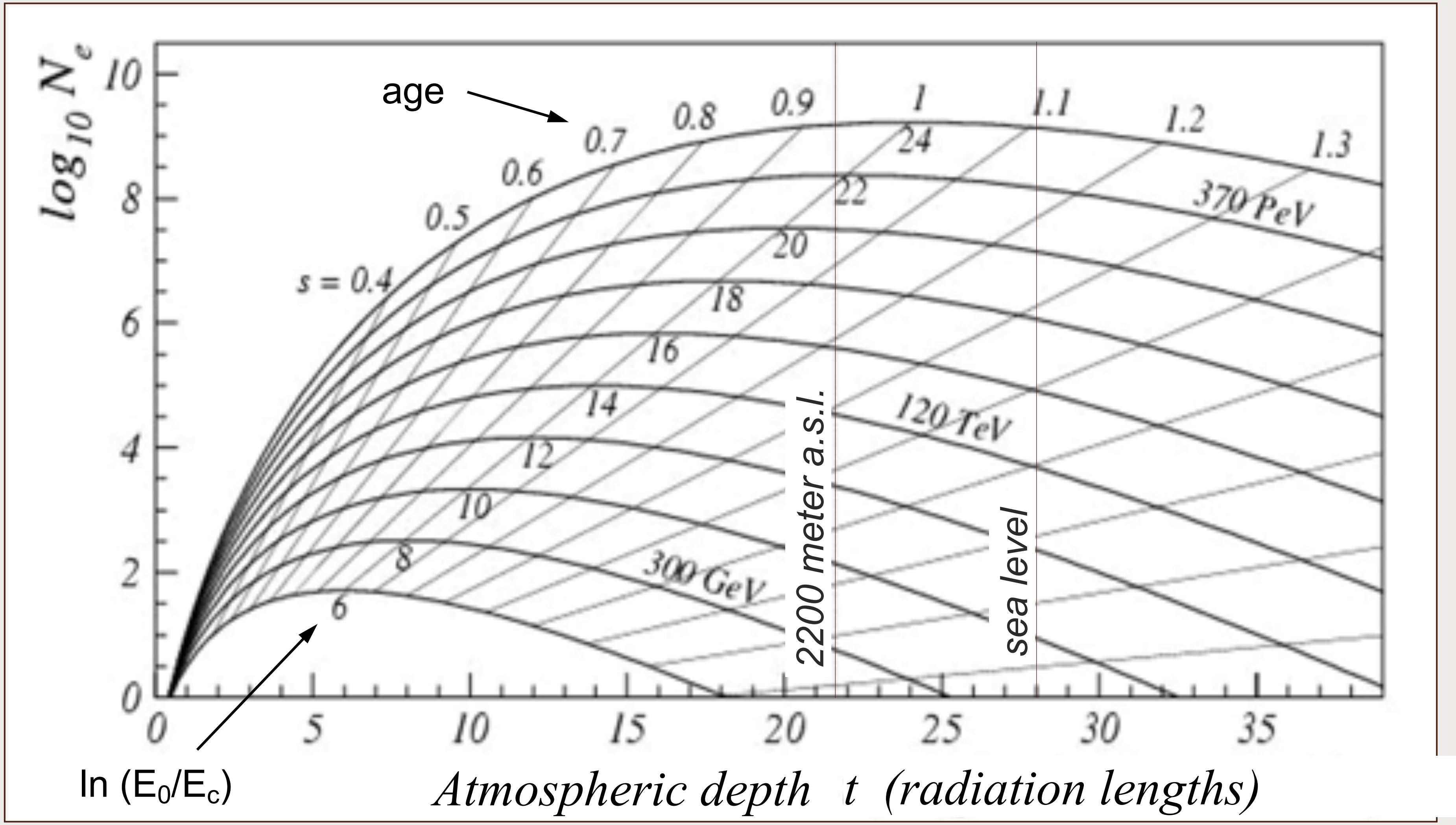




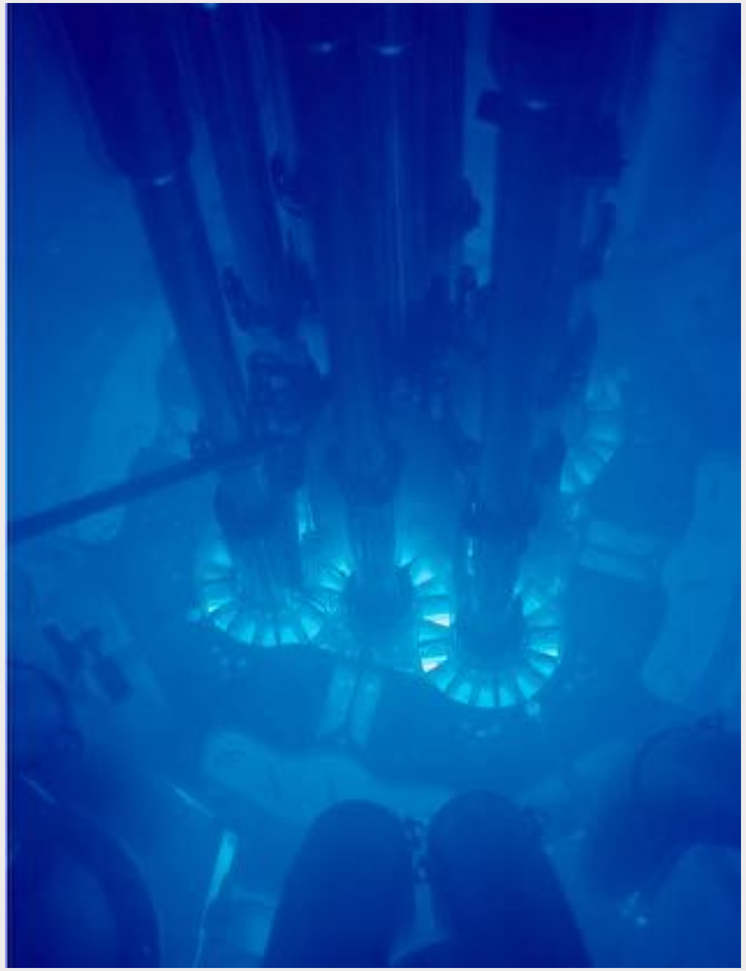
Longitudinal EM shower development

Rossi & Greisen approximation B

Bruno Rossi



Pavel Cherenkov



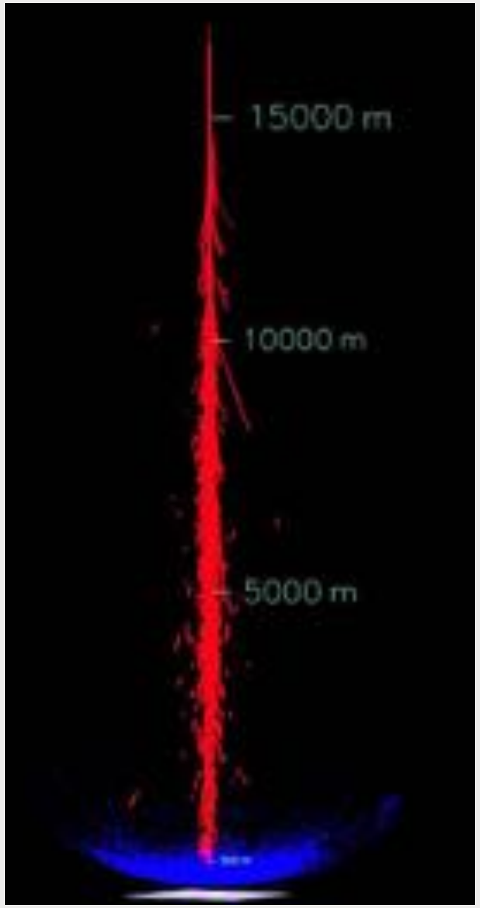
- Had to find the fluorescence nature of solvents of uranium salts, emitting bluish light
- Big was his surprise that also pure solvents and even water were emitting the annoying background light
- Initially complaning about his boss: he had to spend >1-1,5 hours in a dark, cold cellar, for accomodating his eyes
- He noticed that the emission is not chaotic, but is related to the track of moving particle.

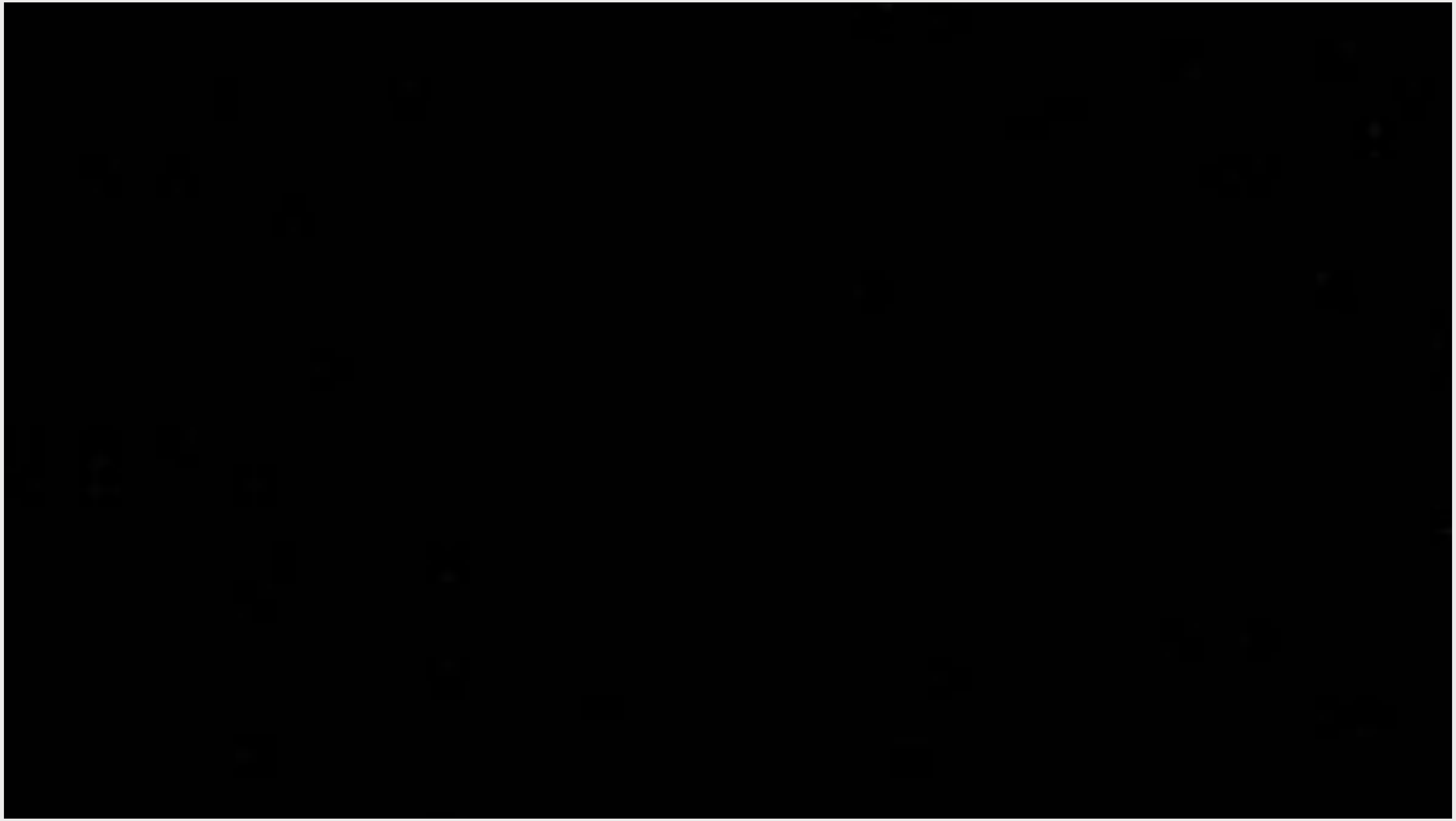
Cherenkov radiation in the atmosphere

In 1948, P.M.S. Blackett suggested that secondary CR's should produce Cherenkov radiation which would account for a fraction 10^{-4} of the total night sky light

Pulses of Cherenkov light from air showers were first recorded by Galbraith and Jelley in 1953

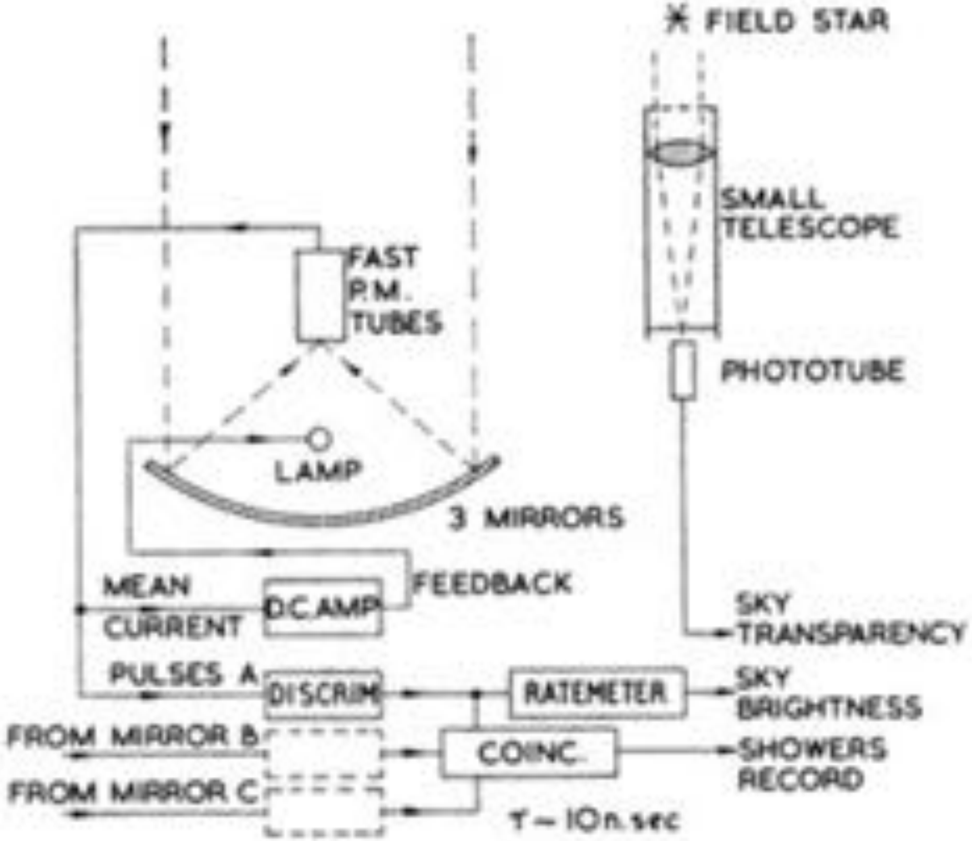
Cherenkov flashes





Be creative

- The classical PMTs have radically improved the situation

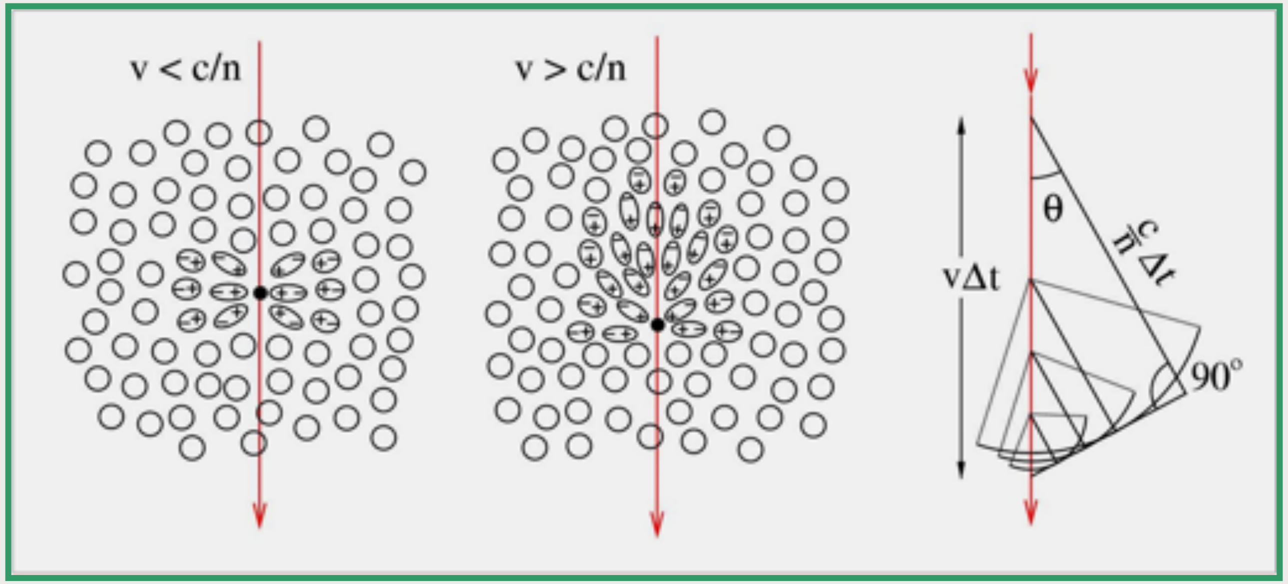


Galbraith & Jelley, 1st telescope, 1953

The 1st large-scale instrument for γ astronomy

Crimea, Chudakov et al., 1960-64

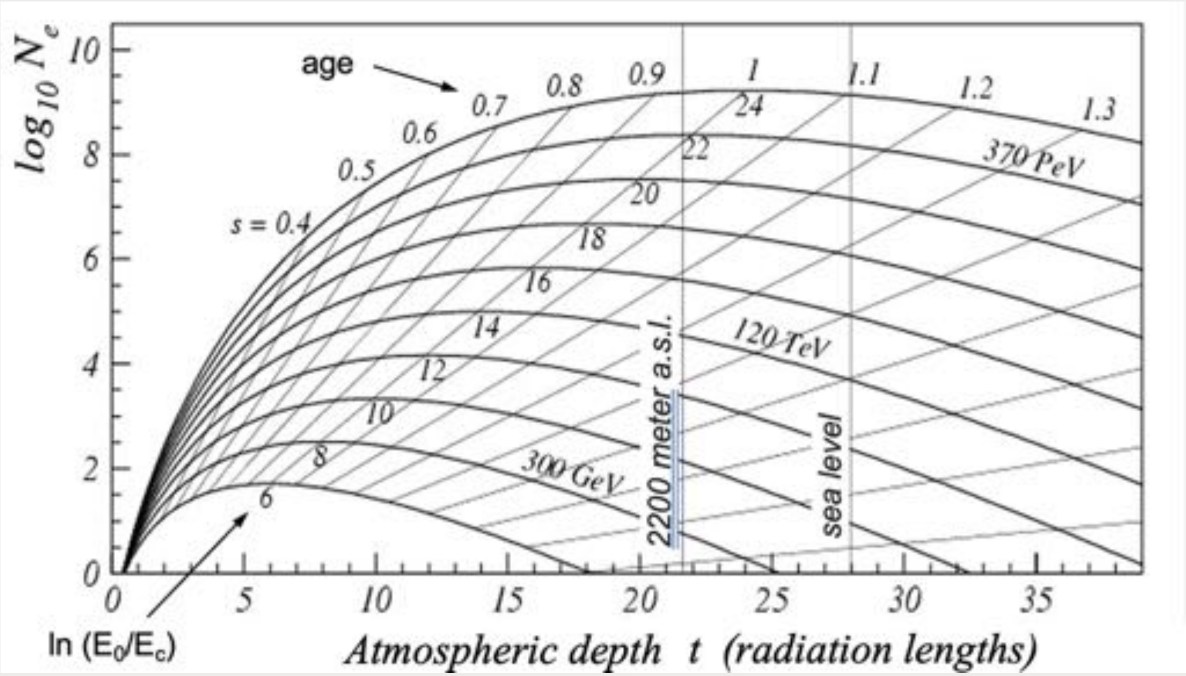
Cherenkov Radiation – light 'boom'



- 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

A model for Cherenkov emission

- Ingredients
  - *Model of the energy of primary electrons and positrons in the shower*
  - *Model of the medium* $v > c/n$



Air density

$$\rho(h) = \rho_0 \cdot e^{-\frac{h}{h_0}} \qquad h_0 = 7.1 \text{ km}$$

Refraction index

$$n = 1 + \eta_h = 1 + \eta_0 \cdot e^{-\frac{h}{h_0}}$$

$$\eta_0 = 2.9 \cdot 10^{-4}$$

at sea level

- Minimum energy for a charged particle to emit Cherenkov light

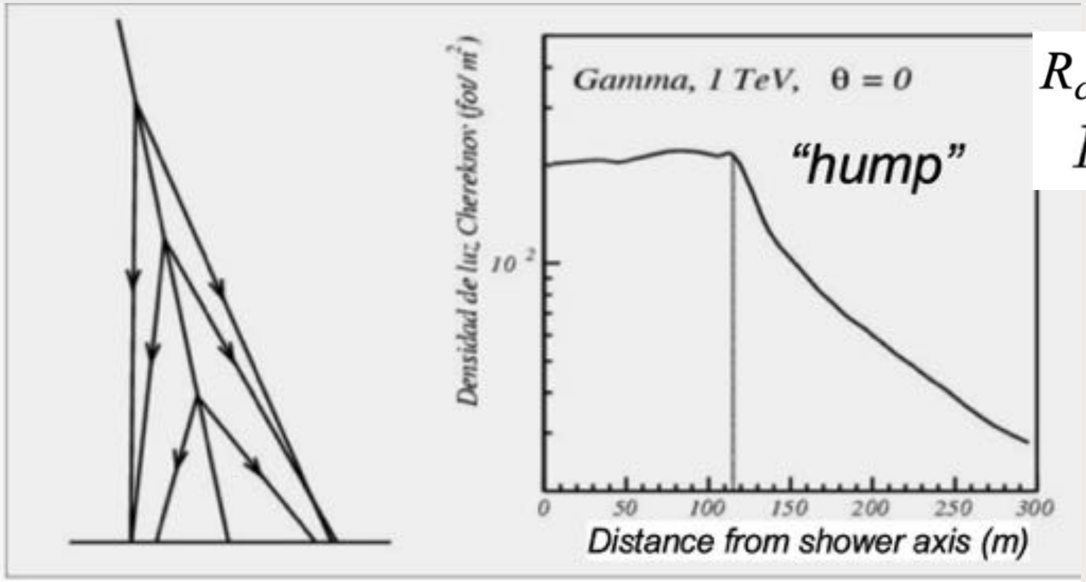
$$E_{min} = \frac{mc^2}{\sqrt{1-\beta^2}} > \frac{mc^2}{\sqrt{1-n^{-2}}} \sim \frac{mc^2}{\sqrt{2\eta_h}}$$

particle type	e±	μ±	p
$E_{thr.}$ @ sea level, GeV	0.021	4.4	38.9
@ 2 km a.s.l.	0.024	5.1	44.8
@ 10 km a.s.l.	0.043	8.9	78.6
@ 15 km a.s.l.	0.061	12.6	111.5

- Assuming $\beta \sim 1$ the Cherenkov angle

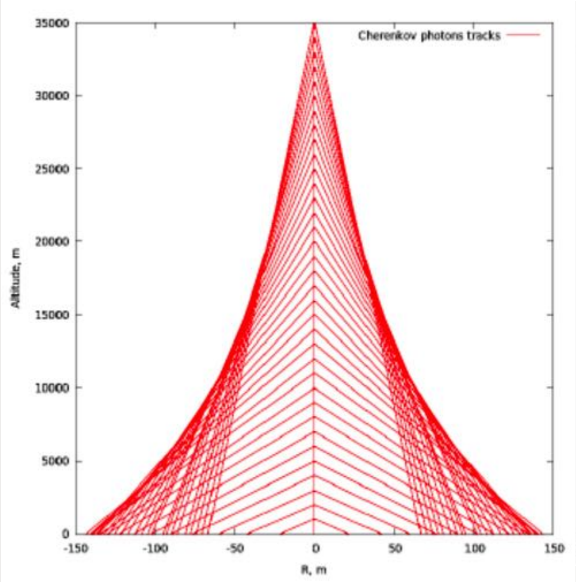
$$\cos(\vartheta_{max}) = \frac{1}{n} = \frac{1}{1+\eta_h} \sim 1 - \eta_h$$

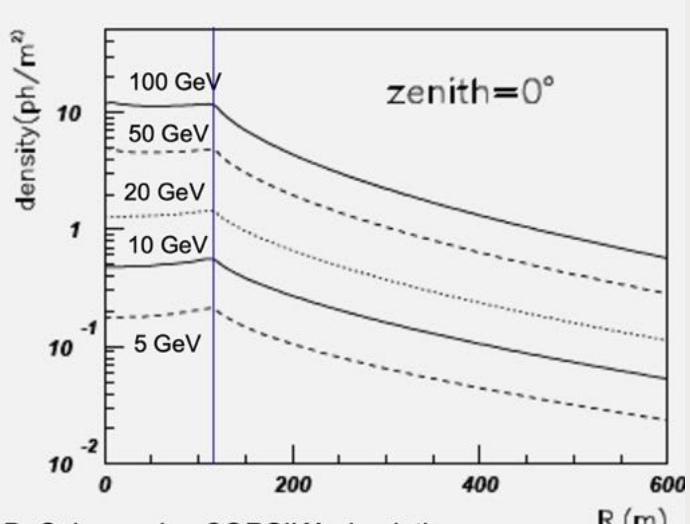
Lateral distribution



R_c: Distance from shower trajectory at which the C-photons hit the ground

$$R_c \equiv (h - h_{obs}) \cdot \tan\theta_{max} \quad \text{for } \beta = 1$$





D. Sobczynska, CORSIKA simulations

- Hump position depends only on observation altitude but not on energy

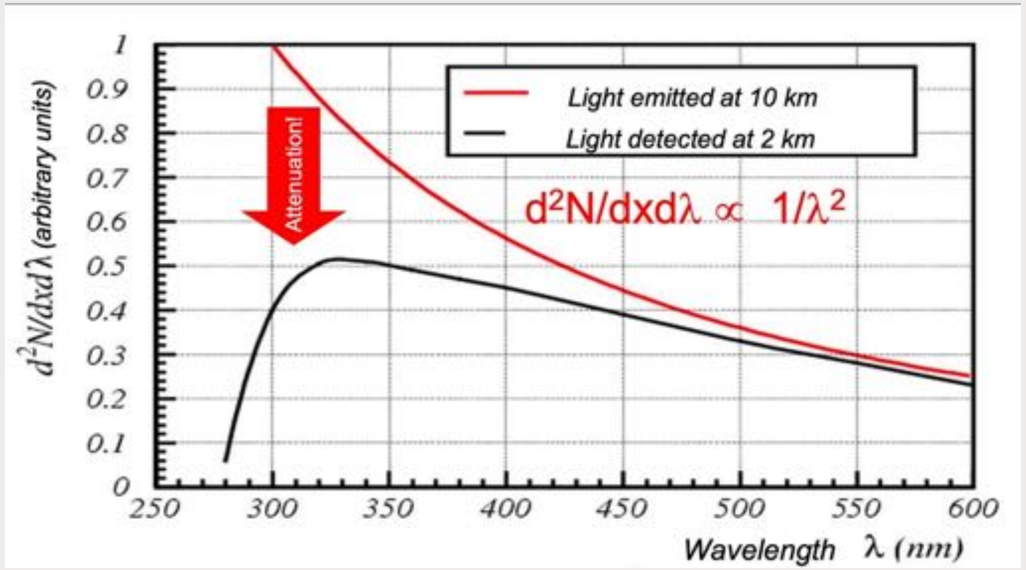
Photon yield and absorption

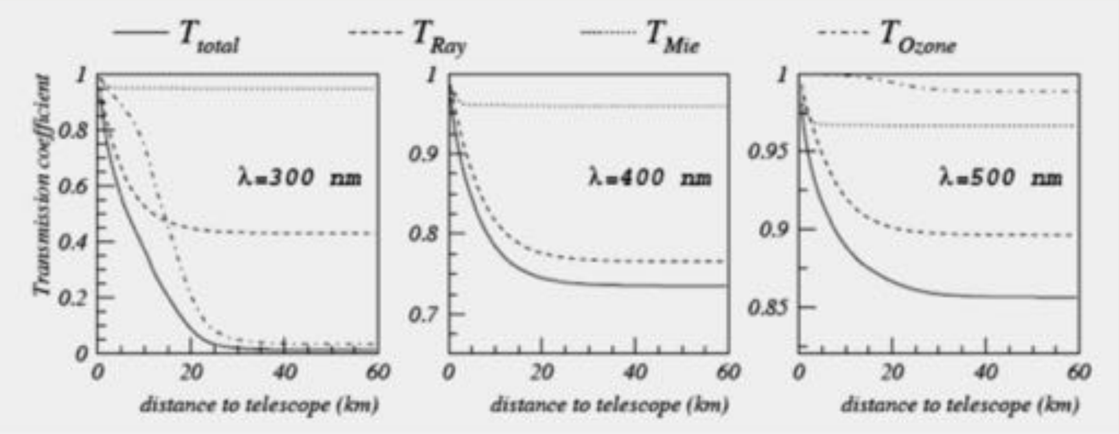
$$\frac{dN}{dx} = 2\pi\alpha \cdot \left(\frac{1}{\lambda_1} - \frac{1}{\lambda_2}\right) \cdot \left(1 - \frac{1}{\beta^2 n^2}\right)$$

Slanth depth, g/cm²	100	300	800	1036
Height a.s.l., km	16	10	2.2	0
Number of emitted C-photons/m	4.5	13	35	45

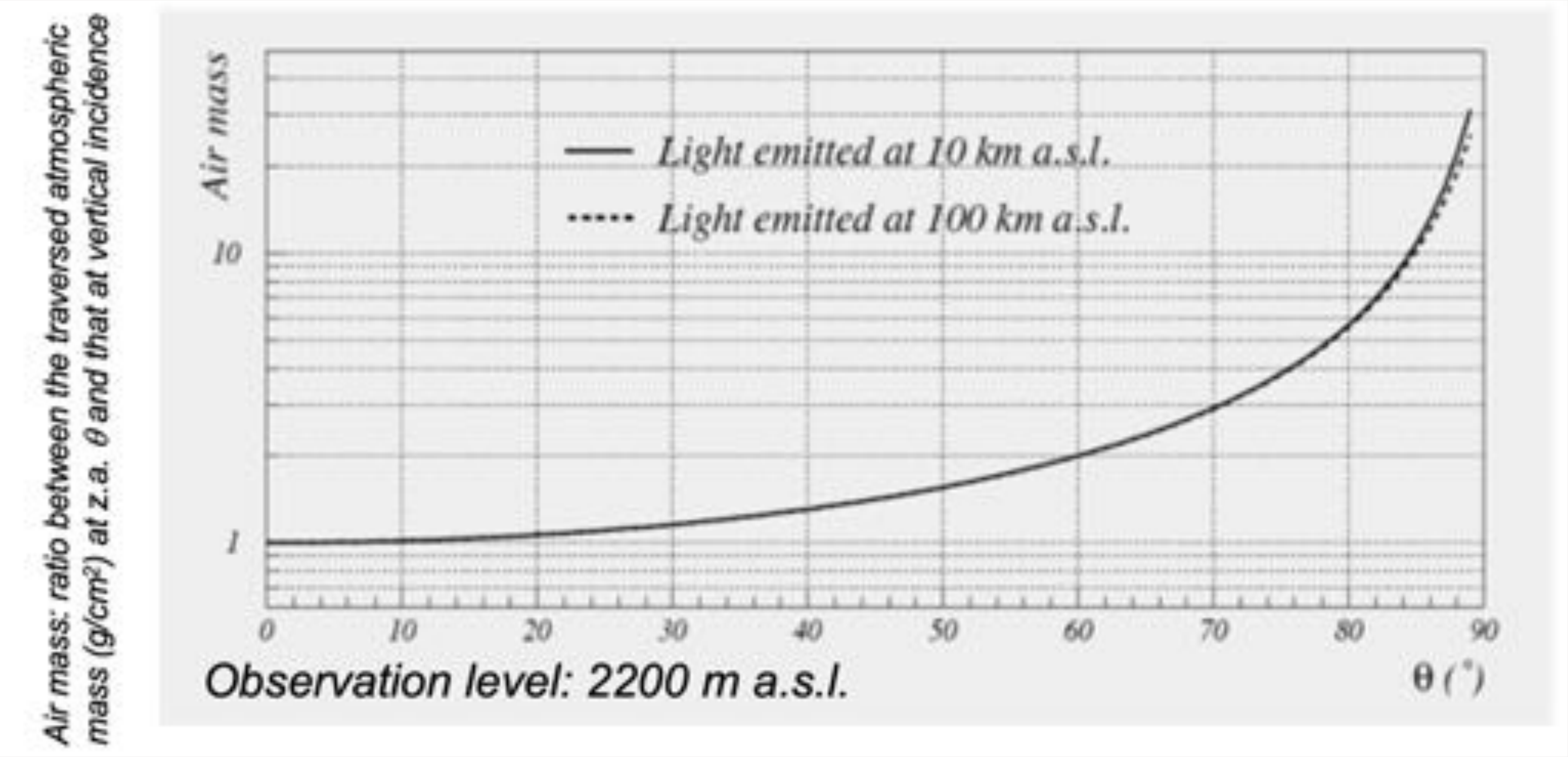
Image from low-energy showers (less particles) have lower density at ground

Peak in the UV-Blue (300nm)

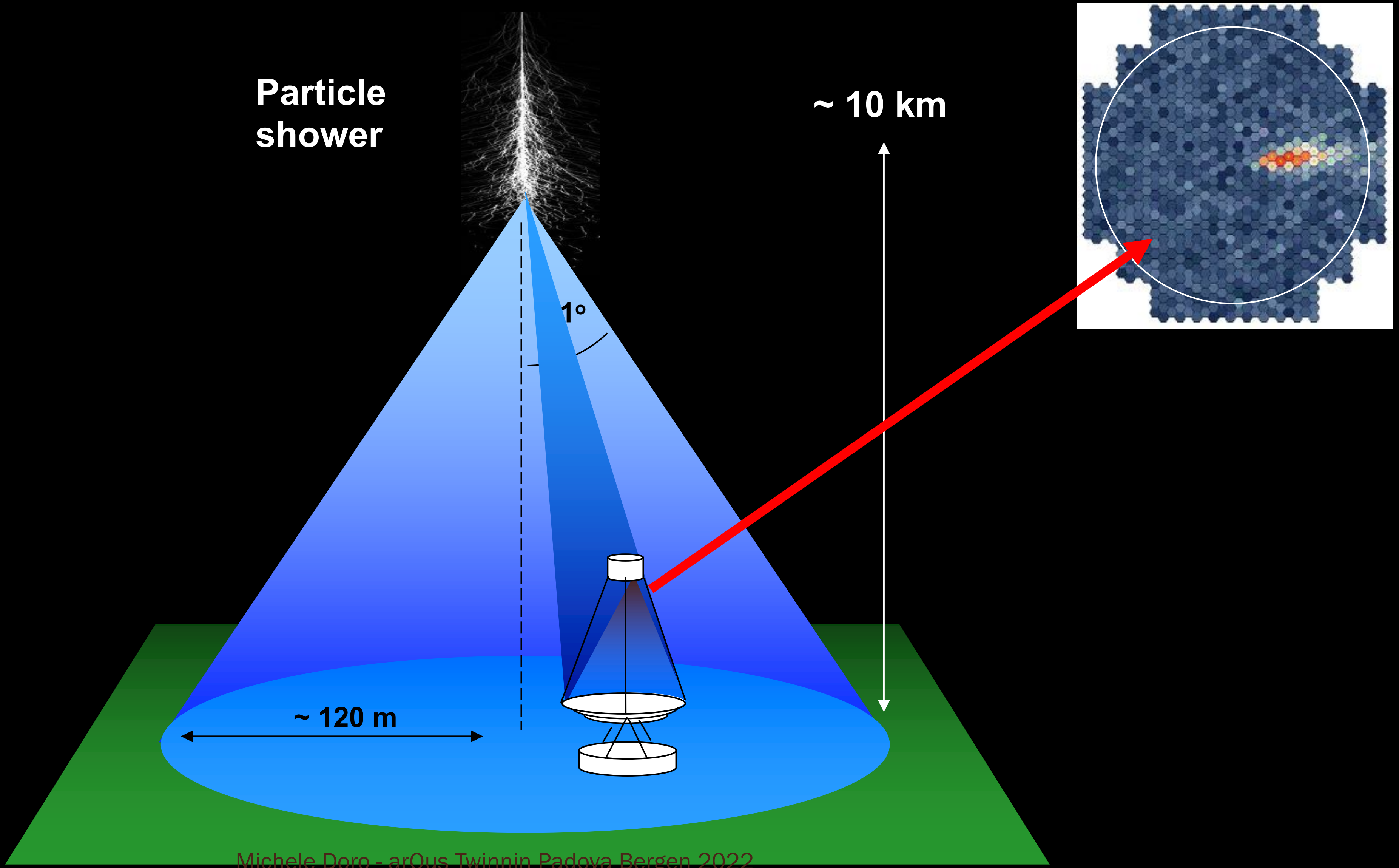


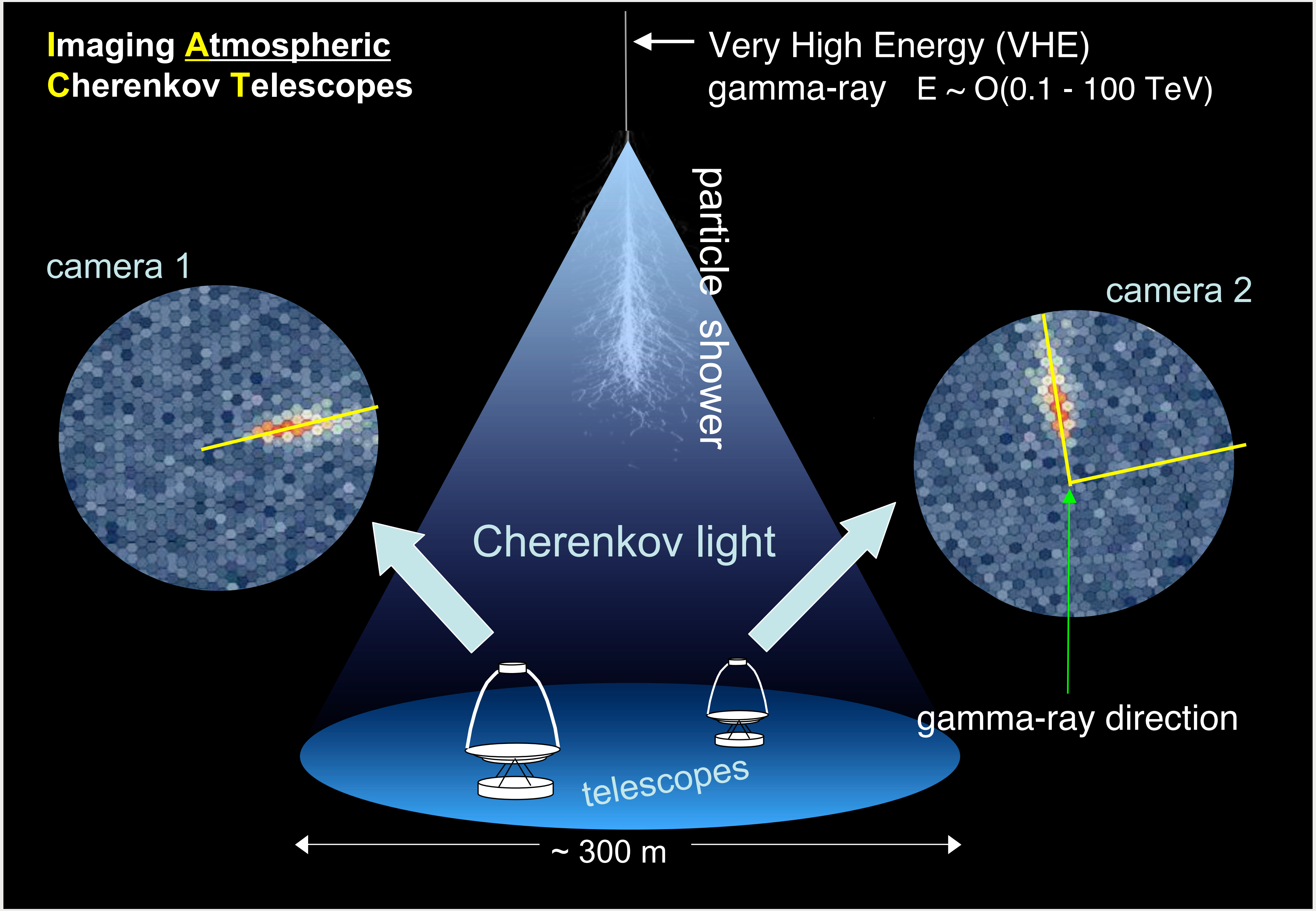


Attenuation in function of elevation



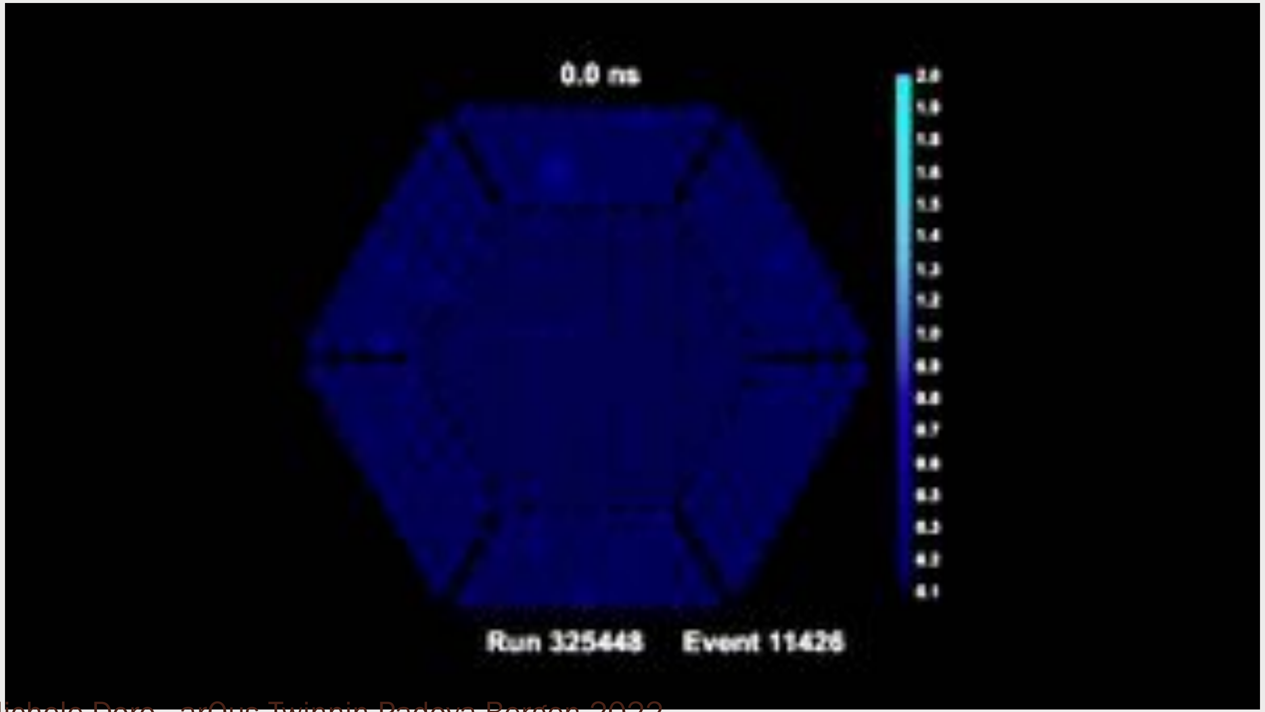
Detection of TeV gamma rays using Cherenkov telescopes




Imaging Atmospheric
Cherenkov Telescopes
Very High Energy (VHE)
gamma-ray E ~ O(0.1 - 100 TeV)
particle shower
camera 1
camera 2
Cherenkov light
gamma-ray direction
telescopes
~ 300 m

~1 picture/sec

2 x 10^9 pictures/sec!



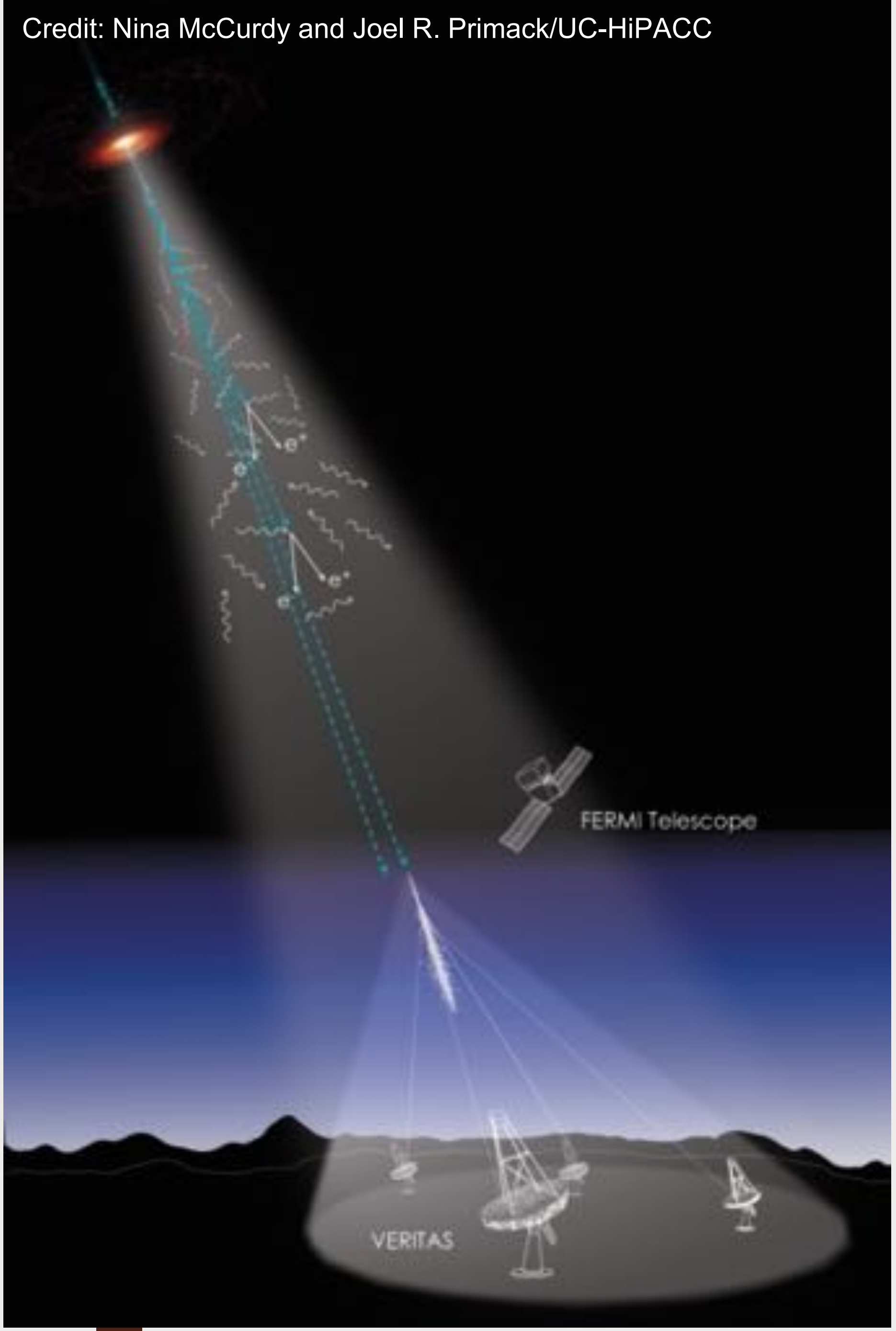
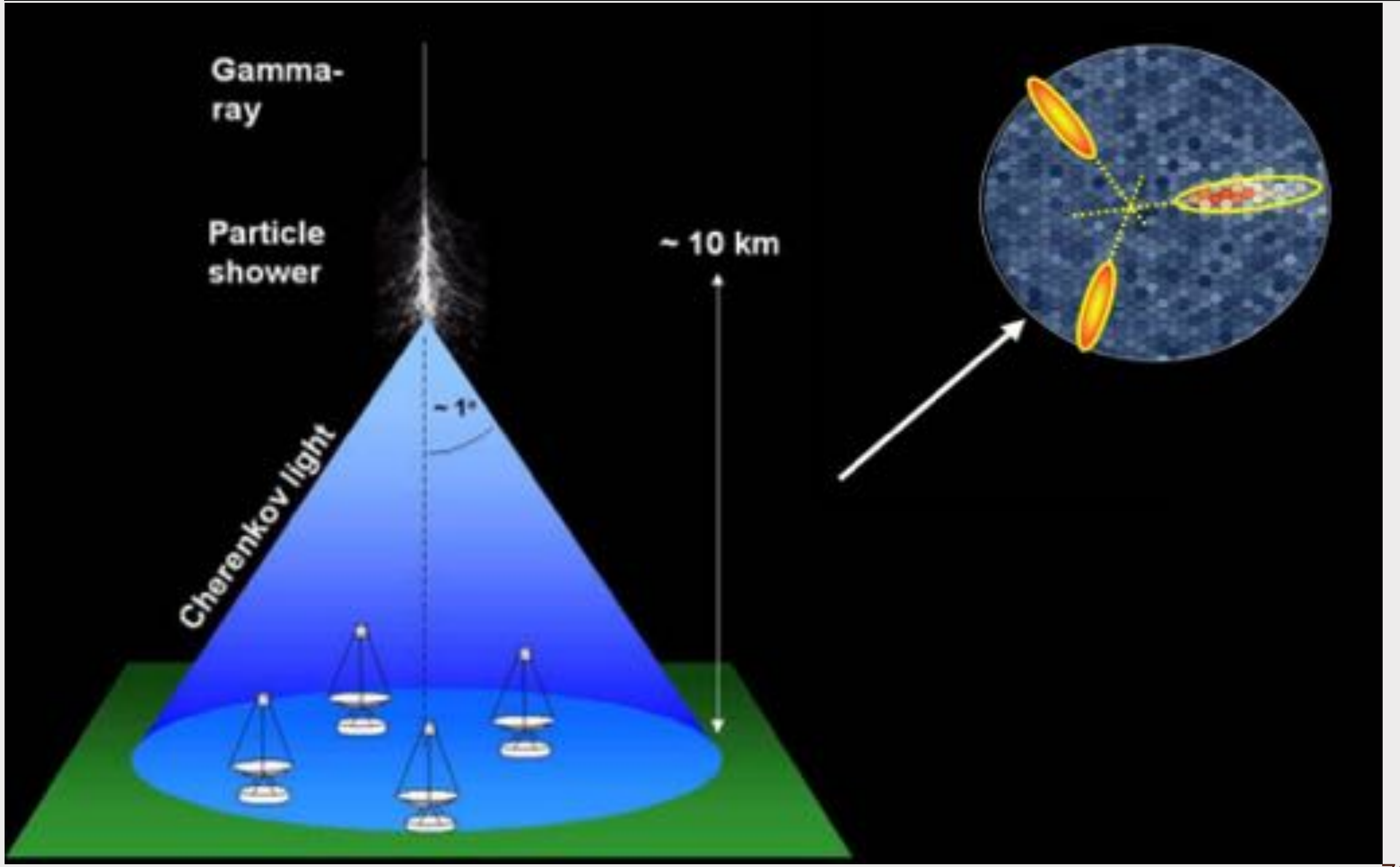


Figure of merits of current generation:

- FOV 5x5 deg
- 50 GeV- 100 TeV
- Eff.Area ~ 10^5-10^6 m^2
- Dark time: ~1000 h/year
- ~10-50 h source for detection
- ~0.1 angular resolution
- ~10-20% energy resolution

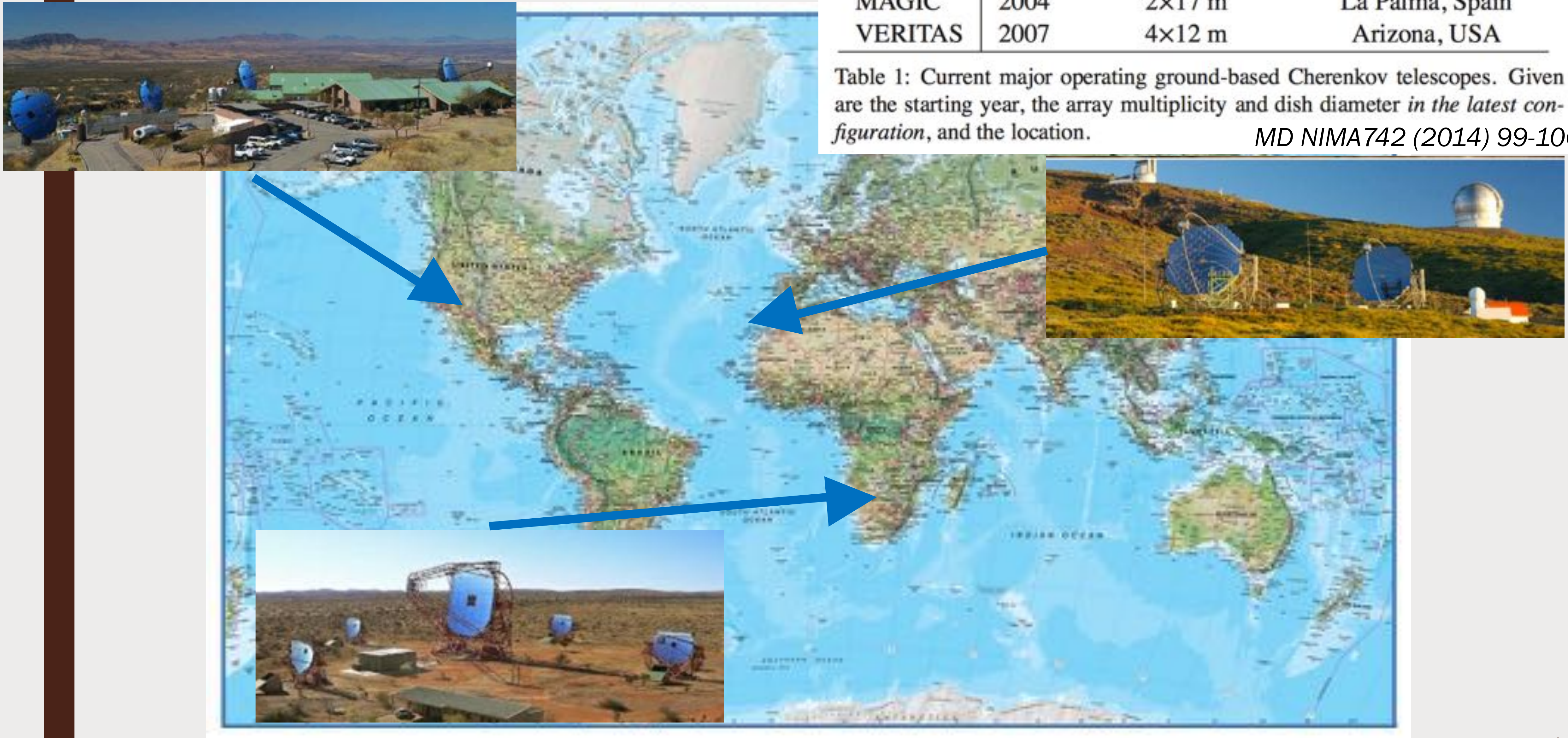


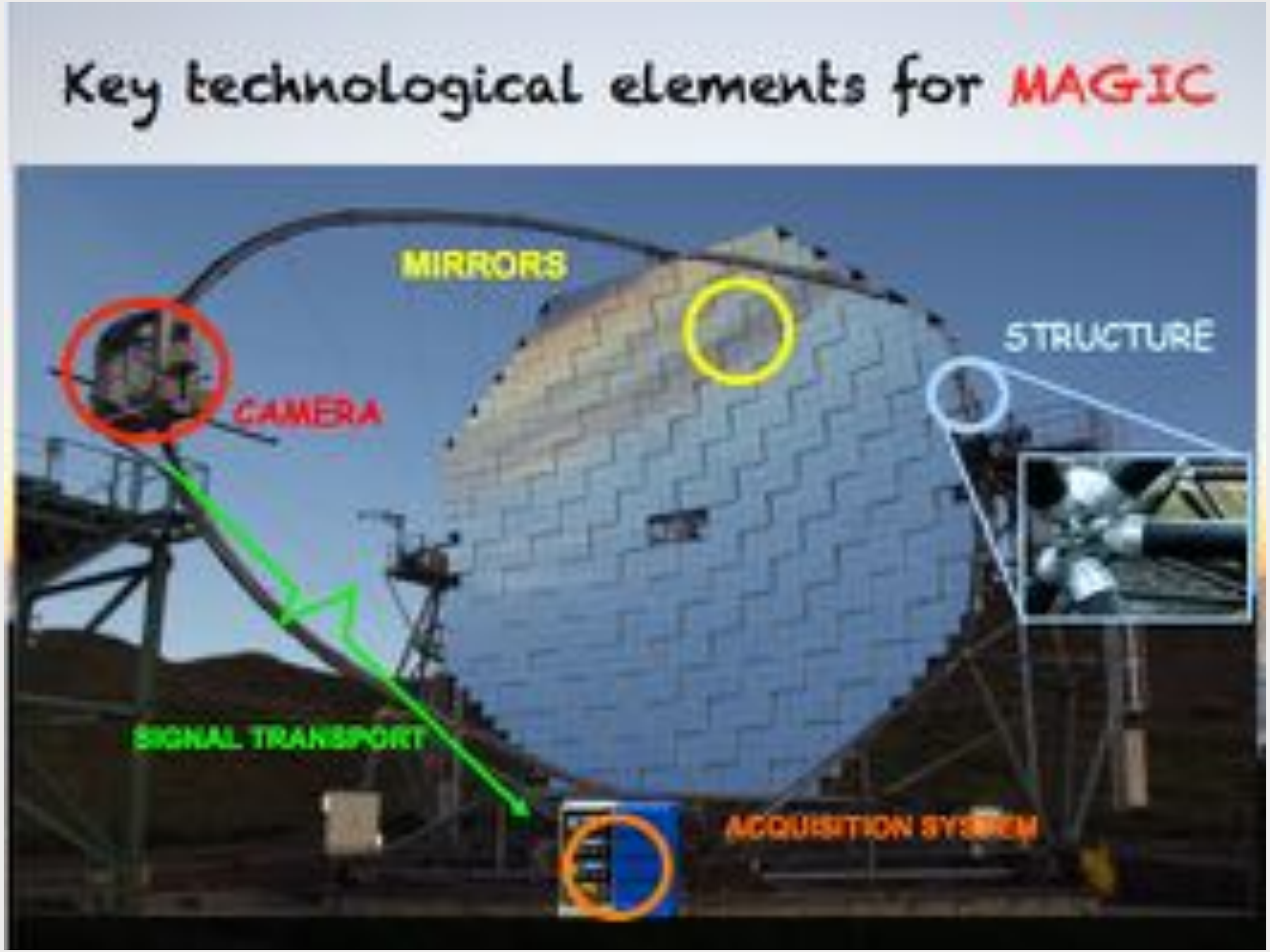
Current IACTs

IACT	Year	Nr. tels & diameter	Location
~~Whipple~~	~~1968~~	~~1×12 m~~	~~Arizona, USA~~
H.E.S.S.	2003	4×12 m+1×28 m	Gambserg, Namibia
MAGIC	2004	2×17 m	La Palma, Spain
VERITAS	2007	4×12 m	Arizona, USA

Table 1: Current major operating ground-based Cherenkov telescopes. Given are the starting year, the array multiplicity and dish diameter *in the latest configuration*, and the location.

MD NIMA742 (2014) 99-106



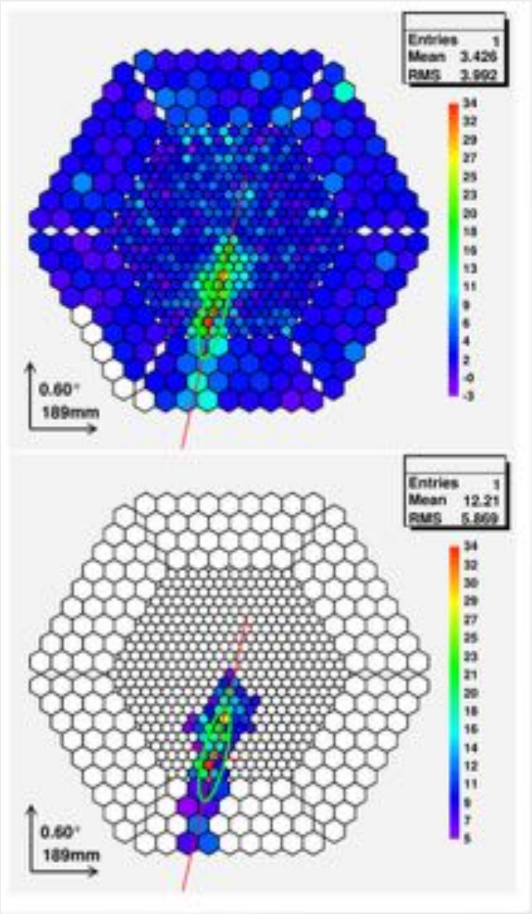

Key technological elements for MAGIC
MIRRORS
STRUCTURE
CAMERA
SIGNAL TRANSPORT
ACQUISITION

Events rate and selection

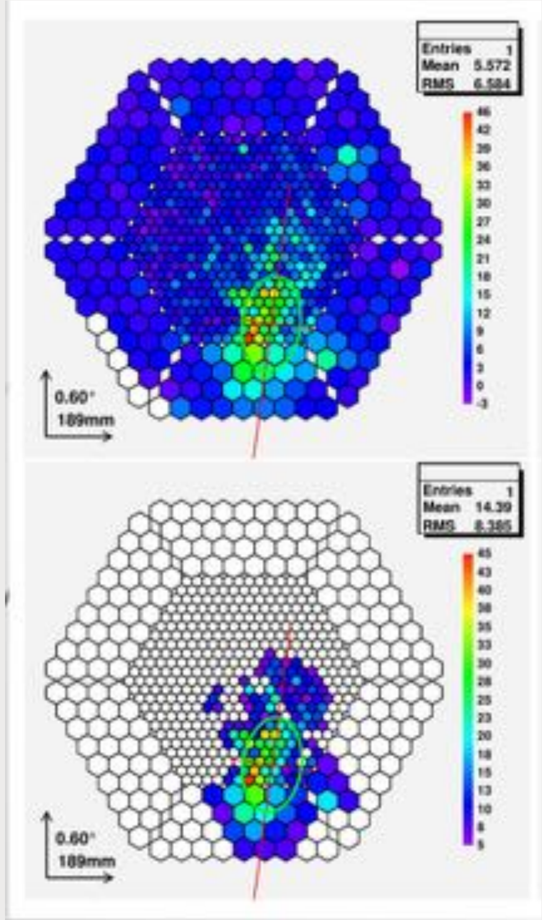
- During data-taking, e.g., MAGIC acquires **@ 200 Hz**. *These are mostly hadronic showers. Gamma-rays are less than 1/1000 of this rate.*
- During data reconstruction, **only 1/1000 hadronic events survive** (very energy dependent)

Events classes

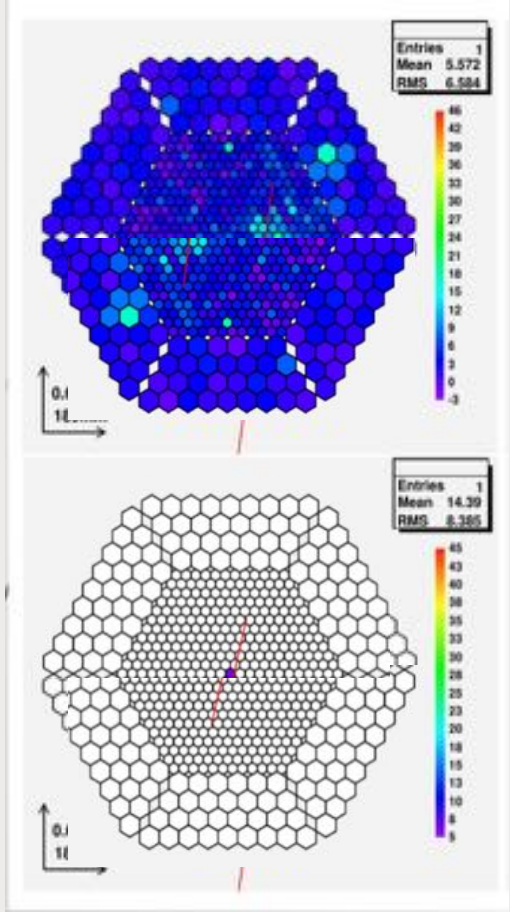
Gamma (the good)



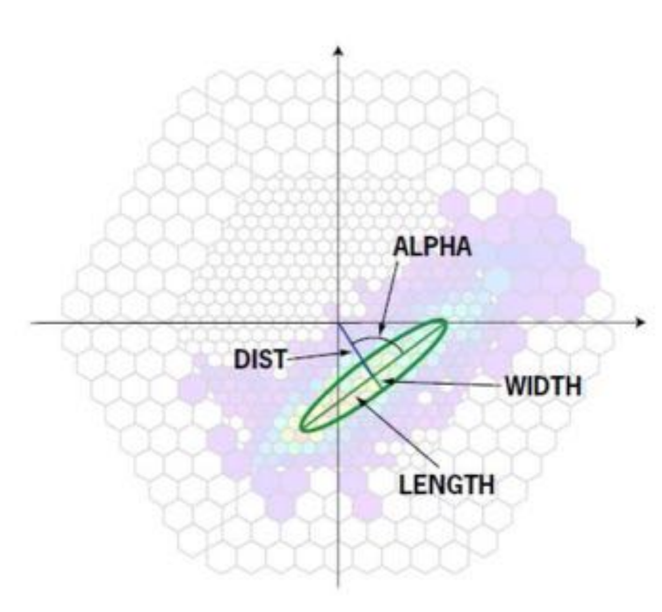
Hadron (the bad)



NSB (the ugly)



Event tagging

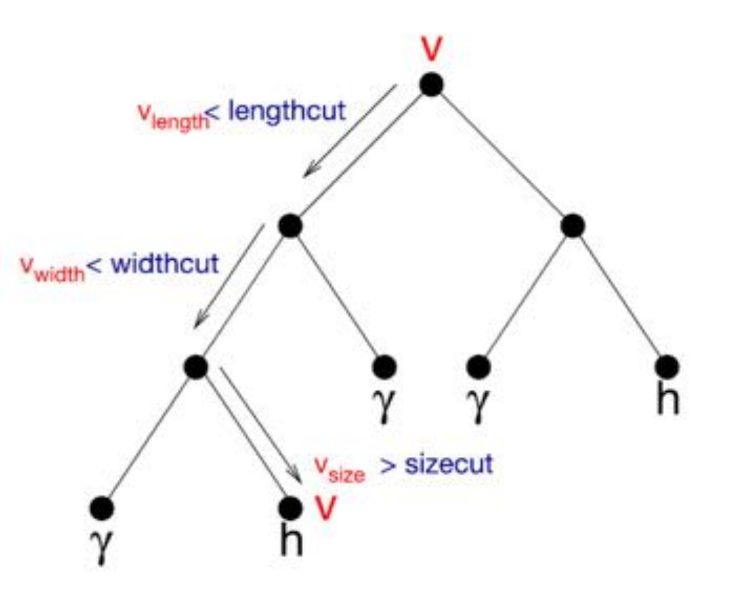


1

You "clean" the image and extract shape parameters

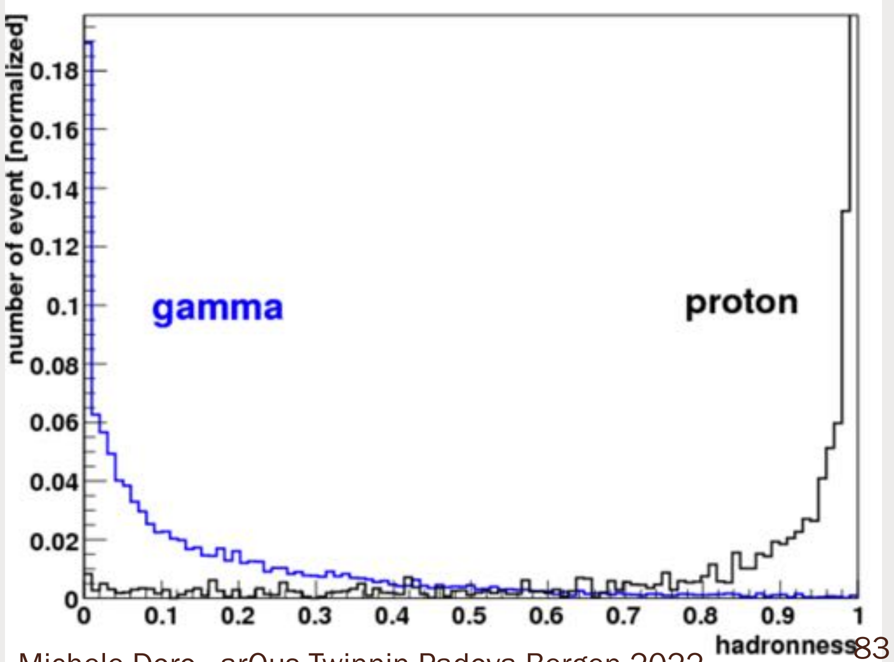
2

You make a Random Forest is a collection of decision trees, by comparing with Monte Carlo



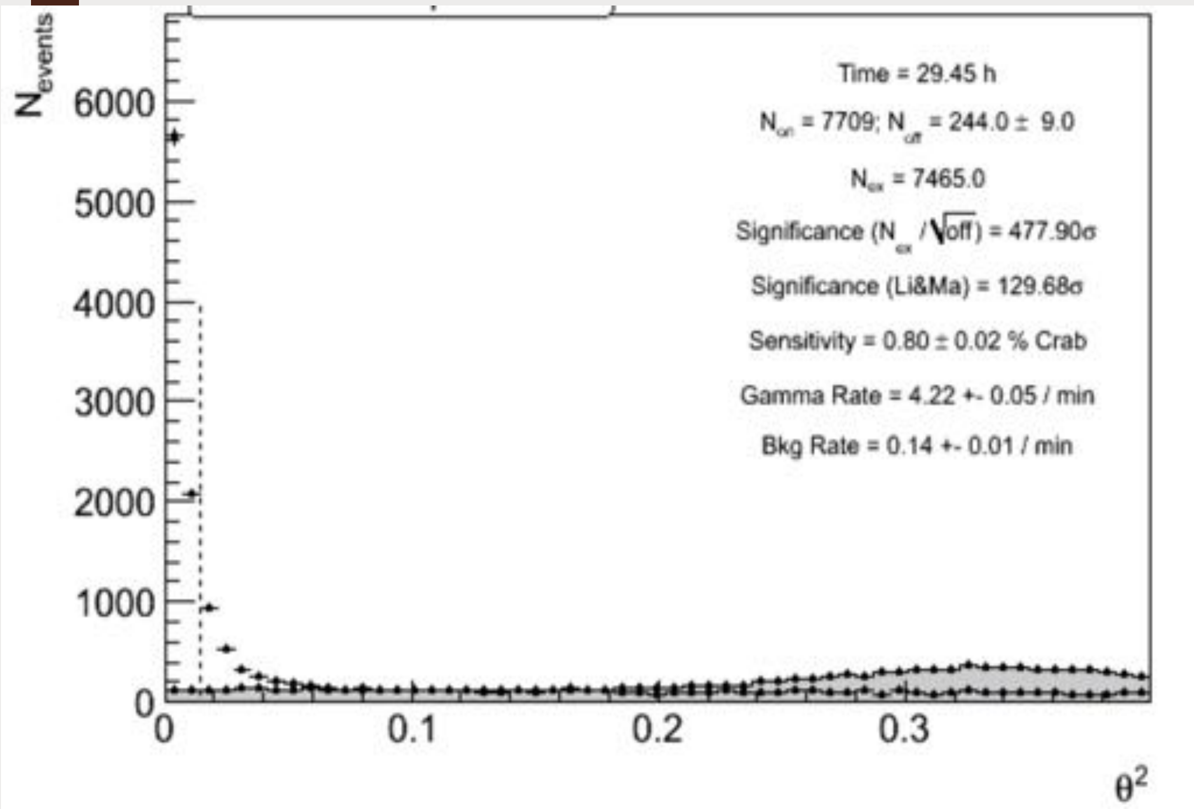
3

You have classified events according to "hadronness" and start to make cuts

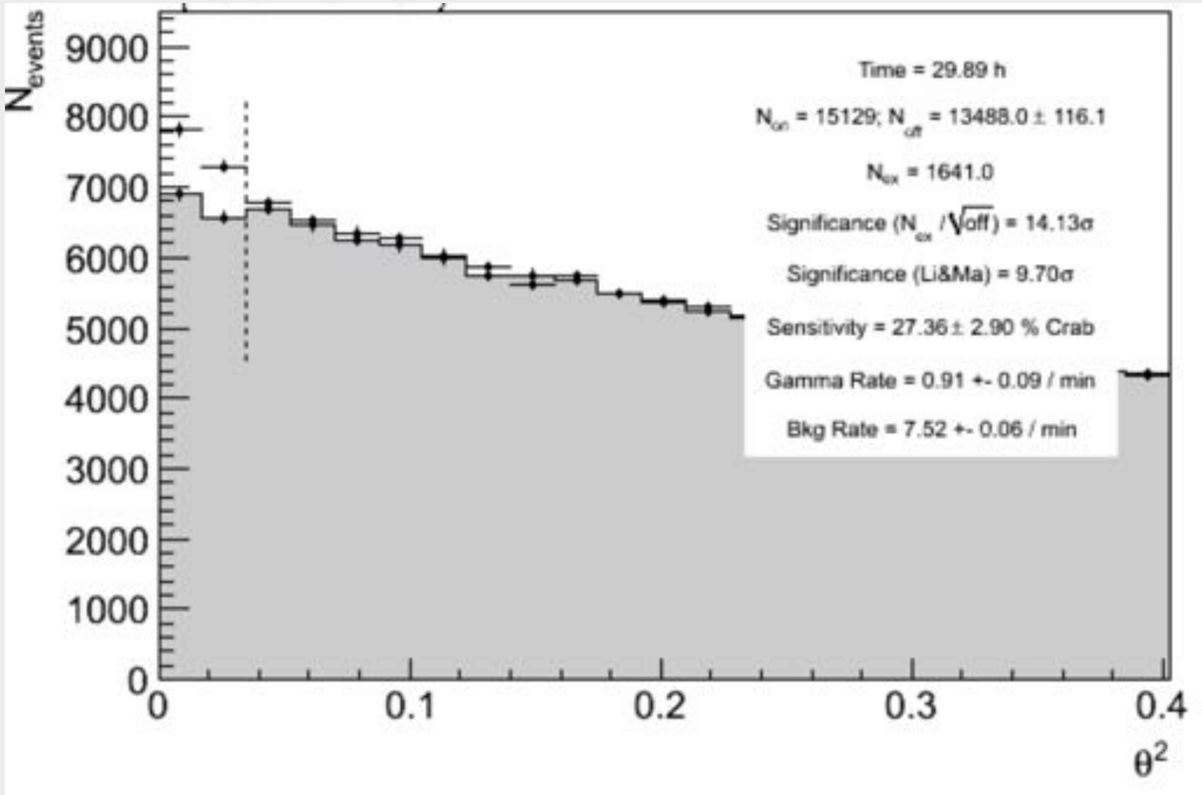


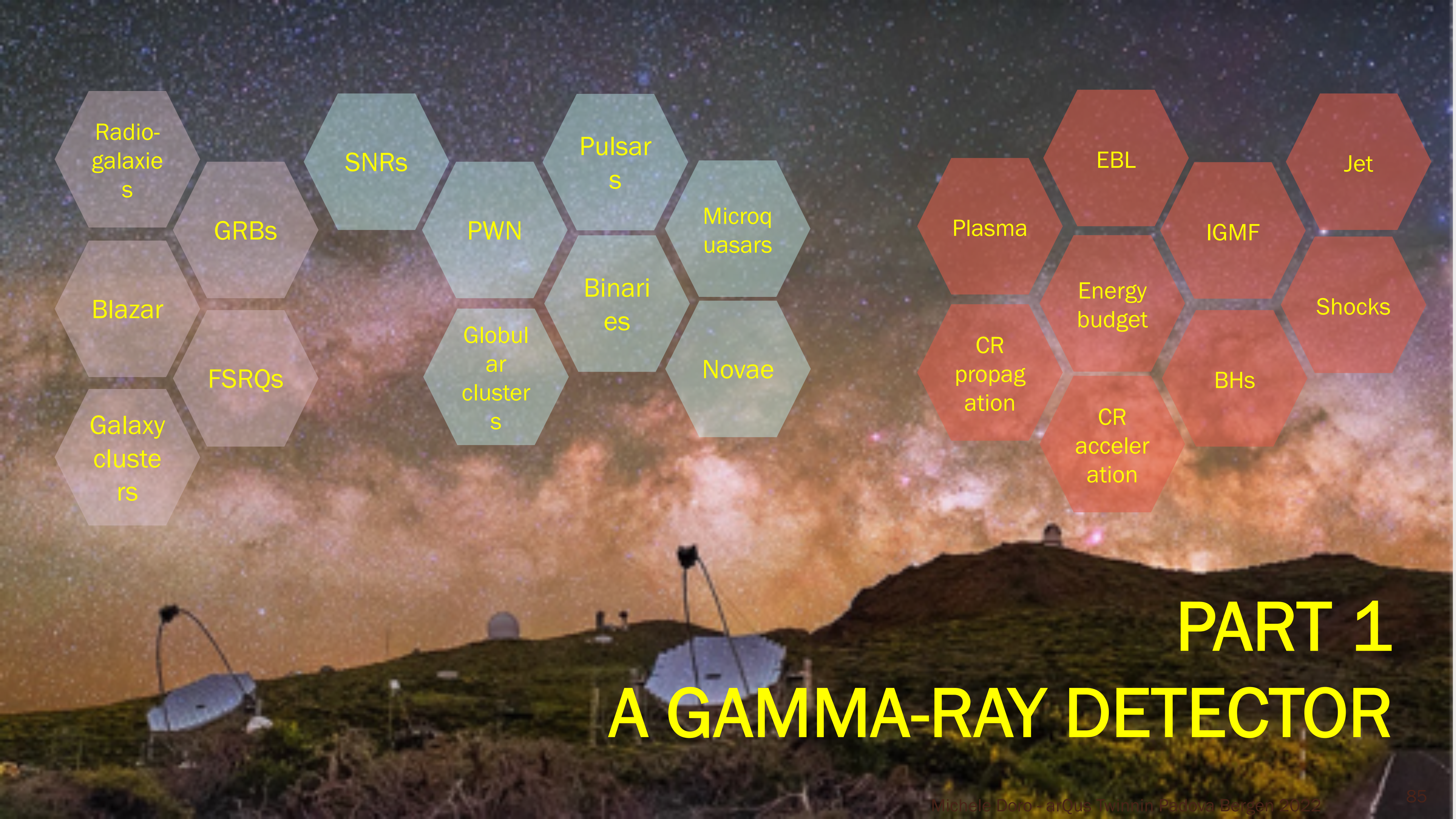
Some background survives

- Strong!



- Weak

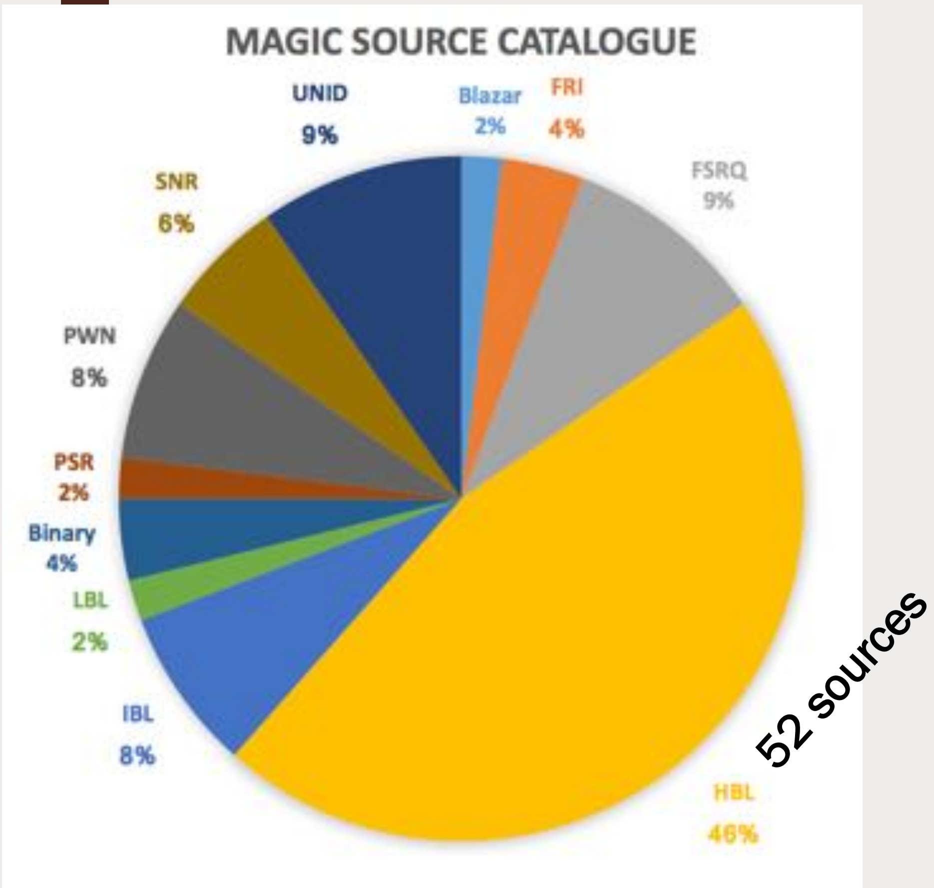


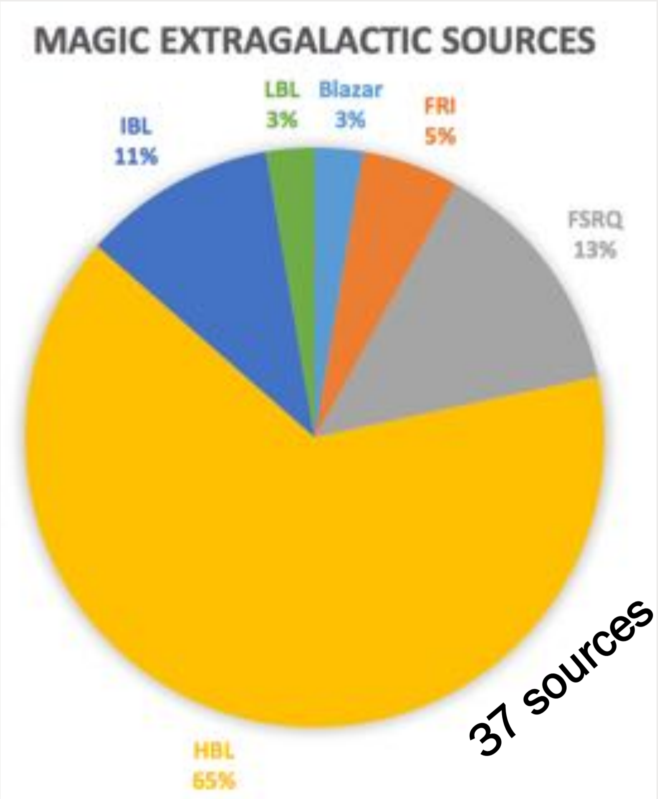


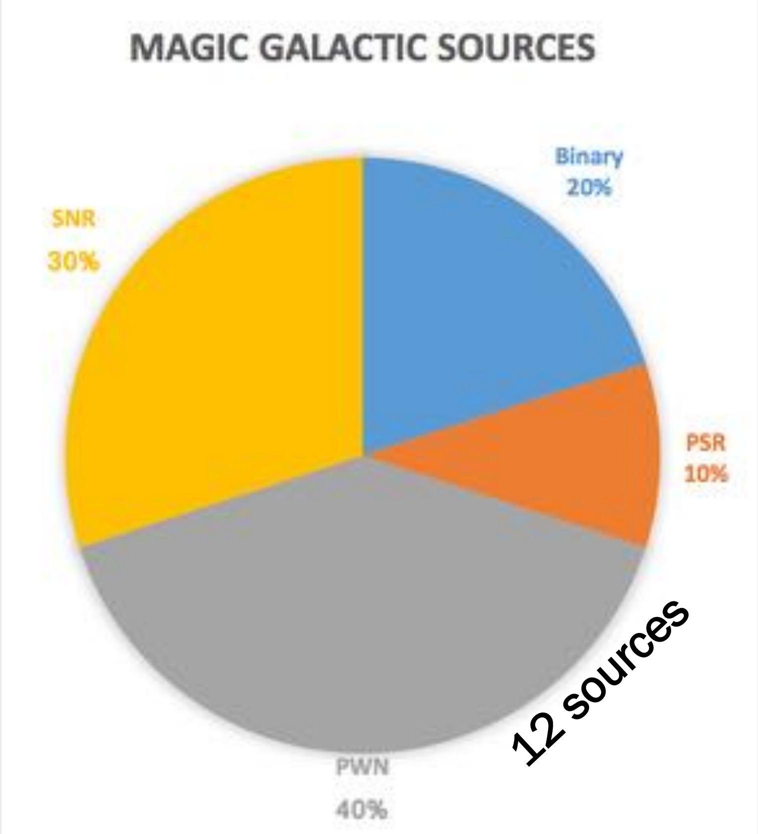
PART 1
A GAMMA-RAY DETECTOR

The MAGIC “catalogues”

From TeVCat 2.0 http://tevcat2.uchicago.edu



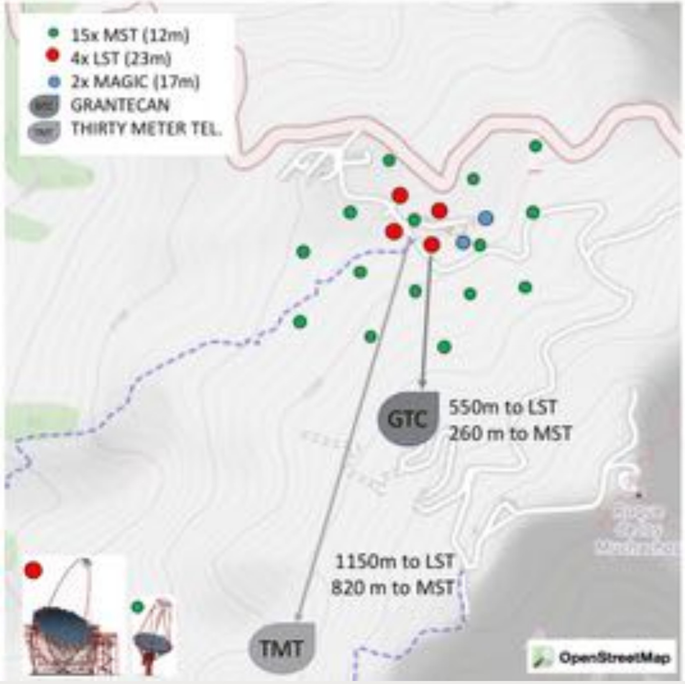


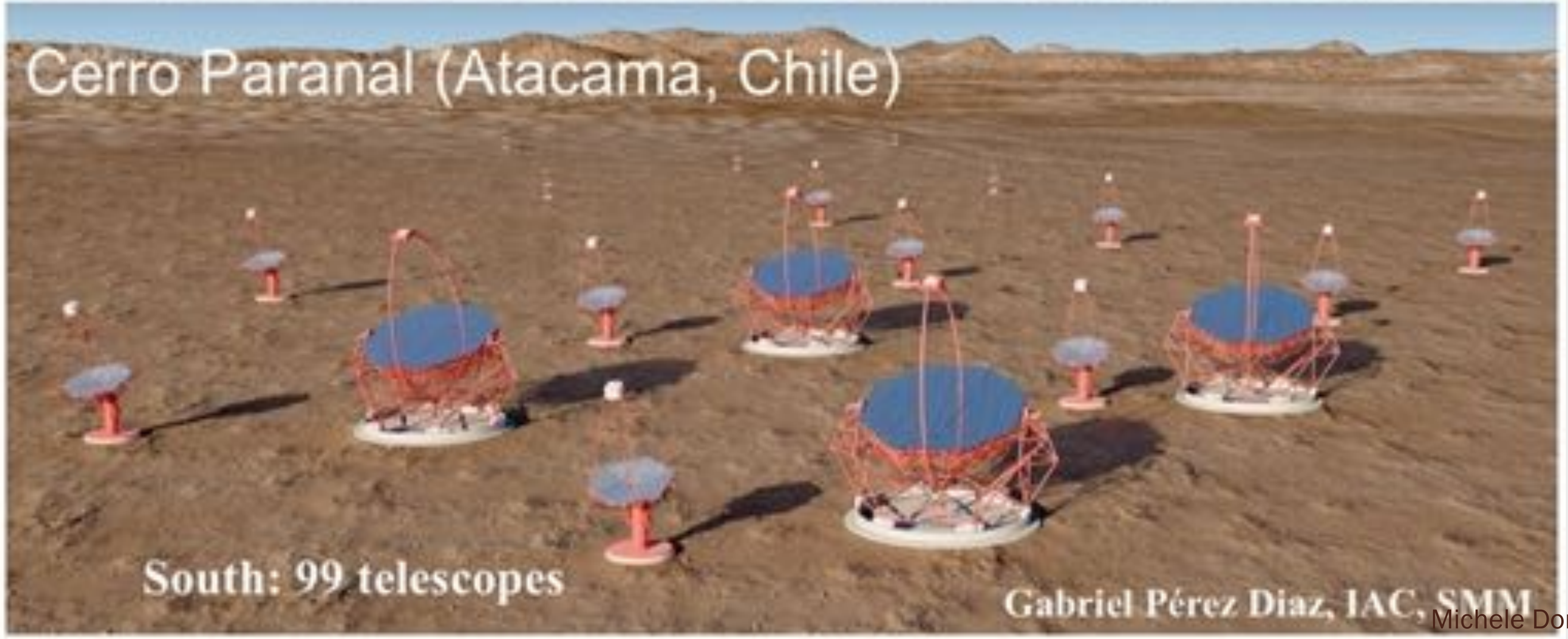


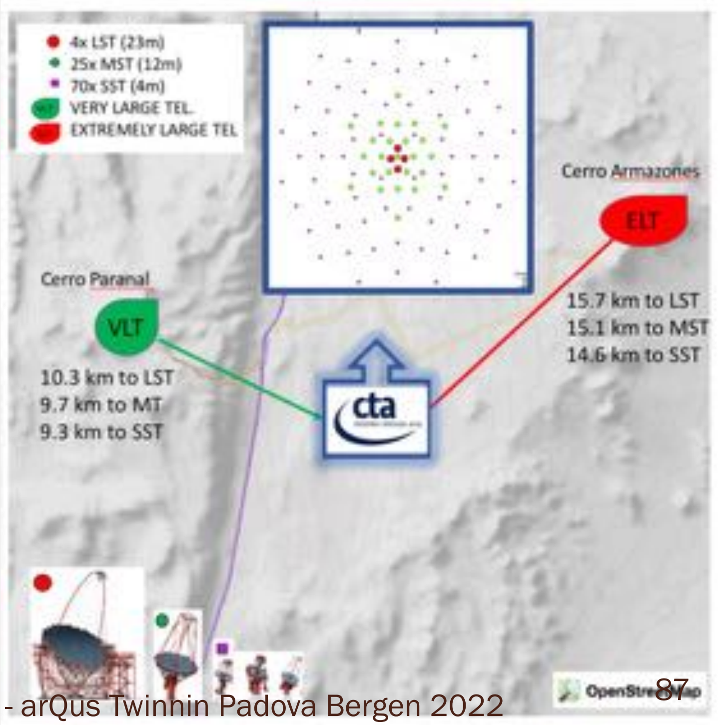
- Wide extragalactic and galactic catalogues
- MAGIC hunts the farthest objects due to lowest energy threshold

Two CTA arrays

M.Gaug, MD, MNRAS accepted 10.1093/mnras/sty2188→

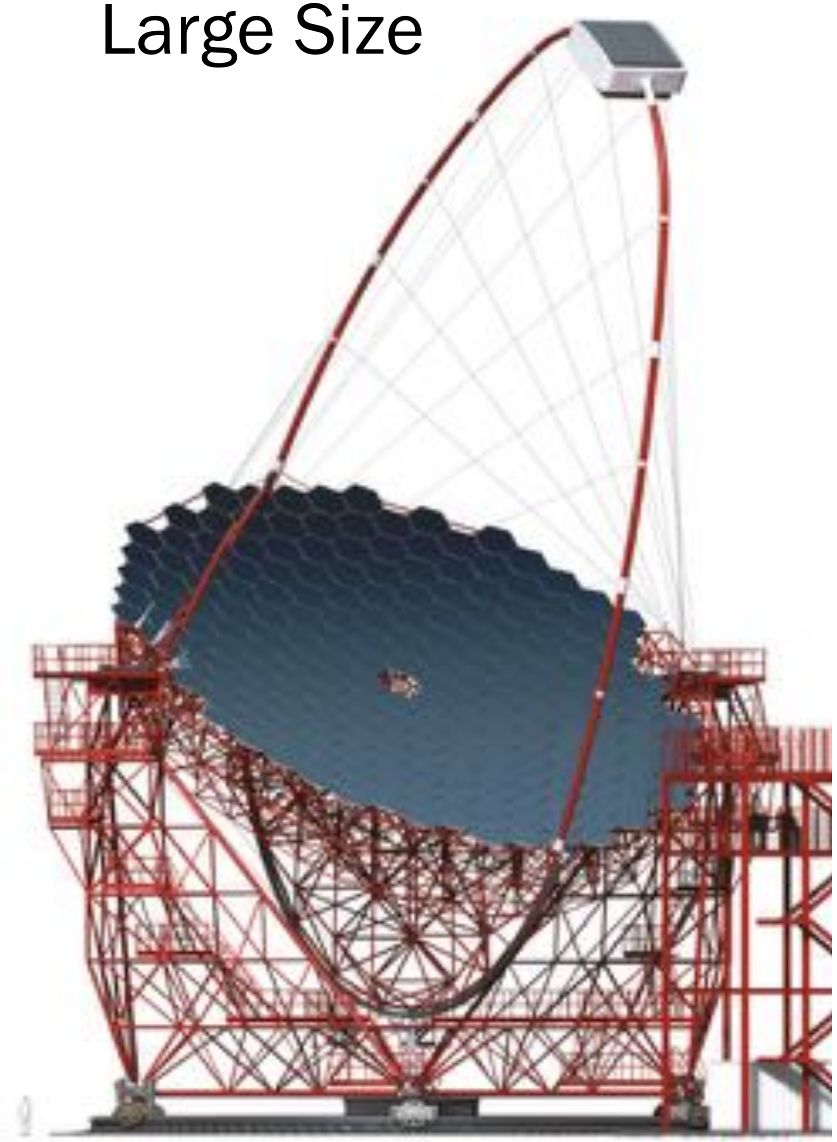






Three telescope sizes

Large Size

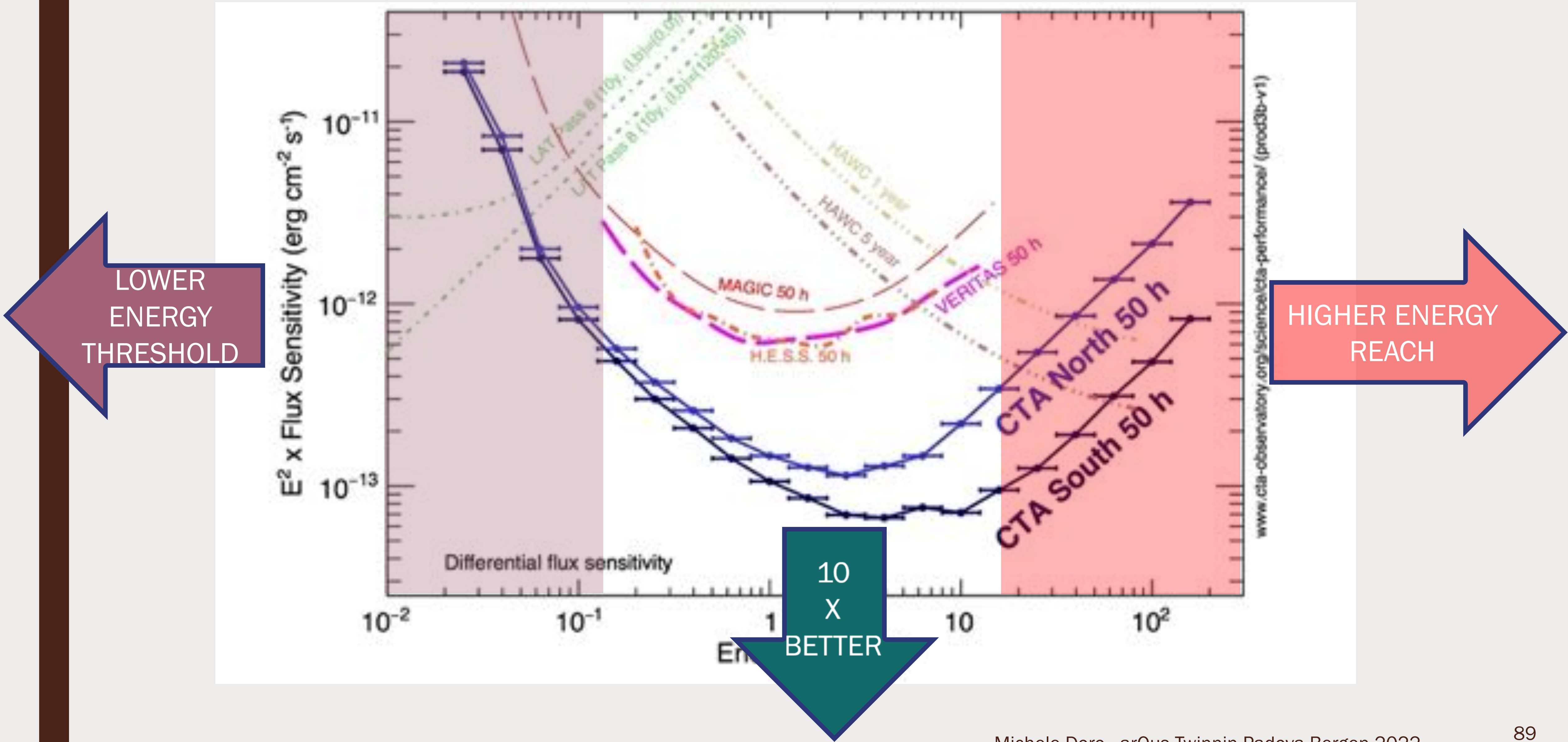


Medium Size

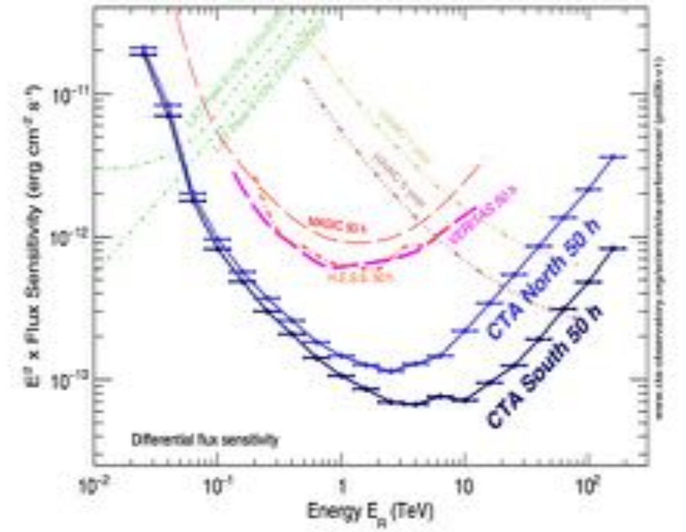
- 2017 Begin Pre-Construction
- 2022 Begin Operation
- 2022-25 Commissioning and Early Science
- 2024/5 Construction completion

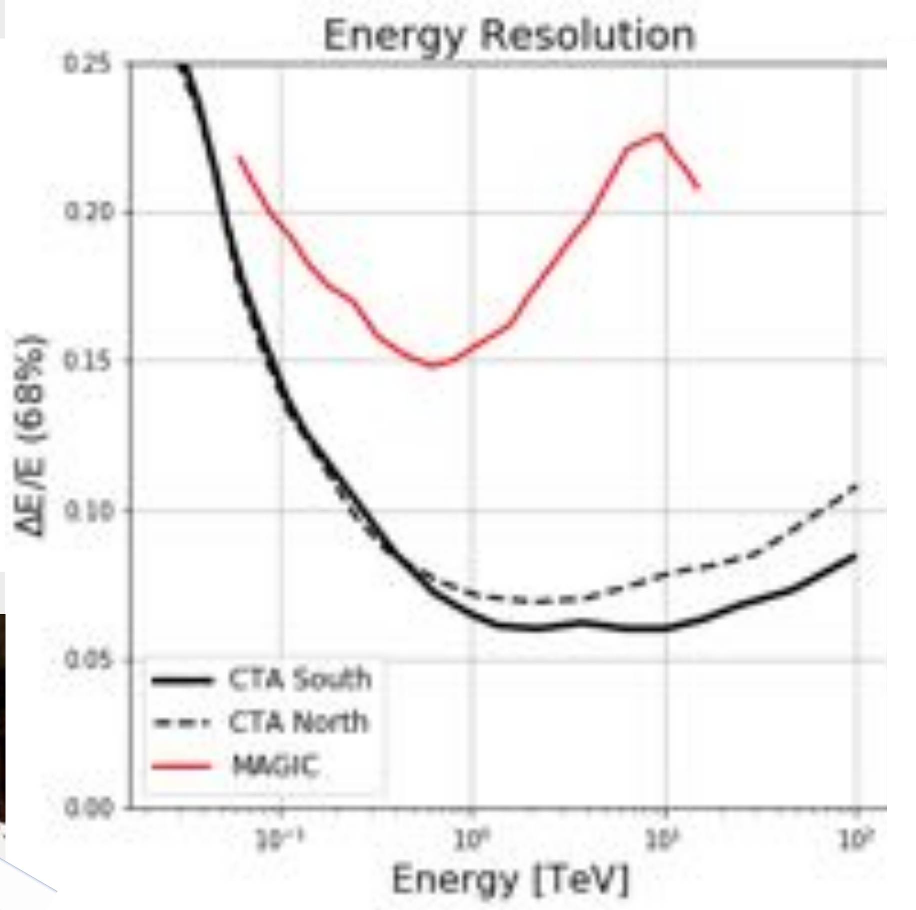
Small Size

A sensitivity leap

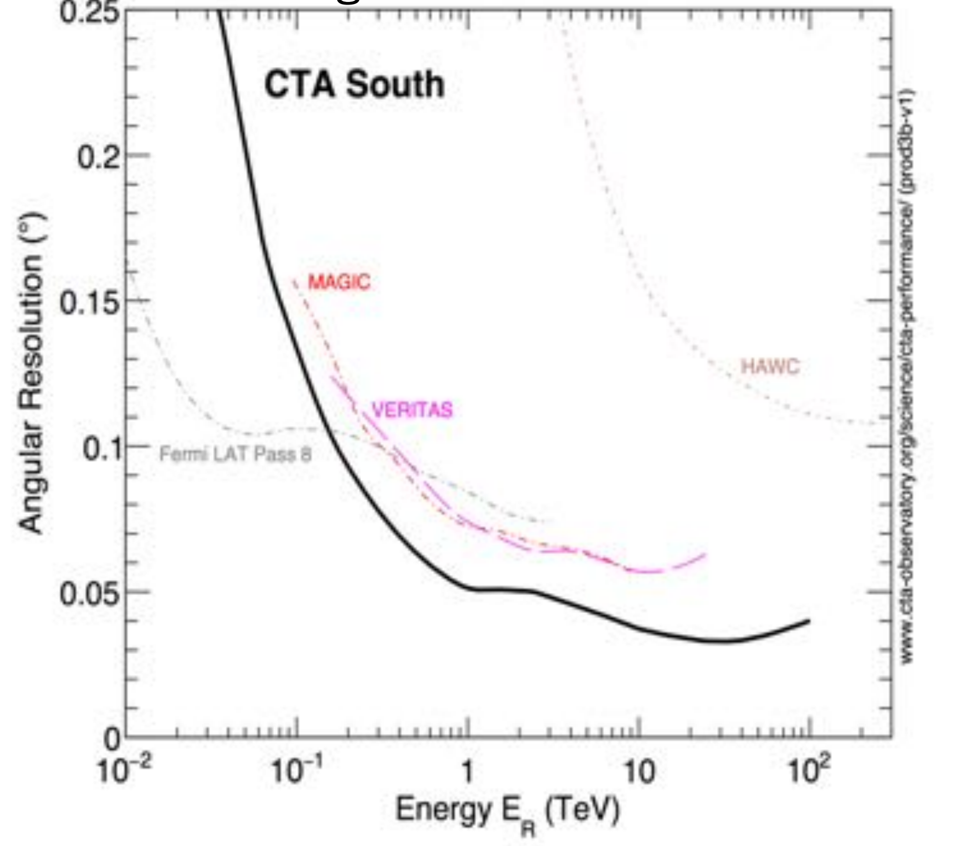


CTA energy and angular resolution





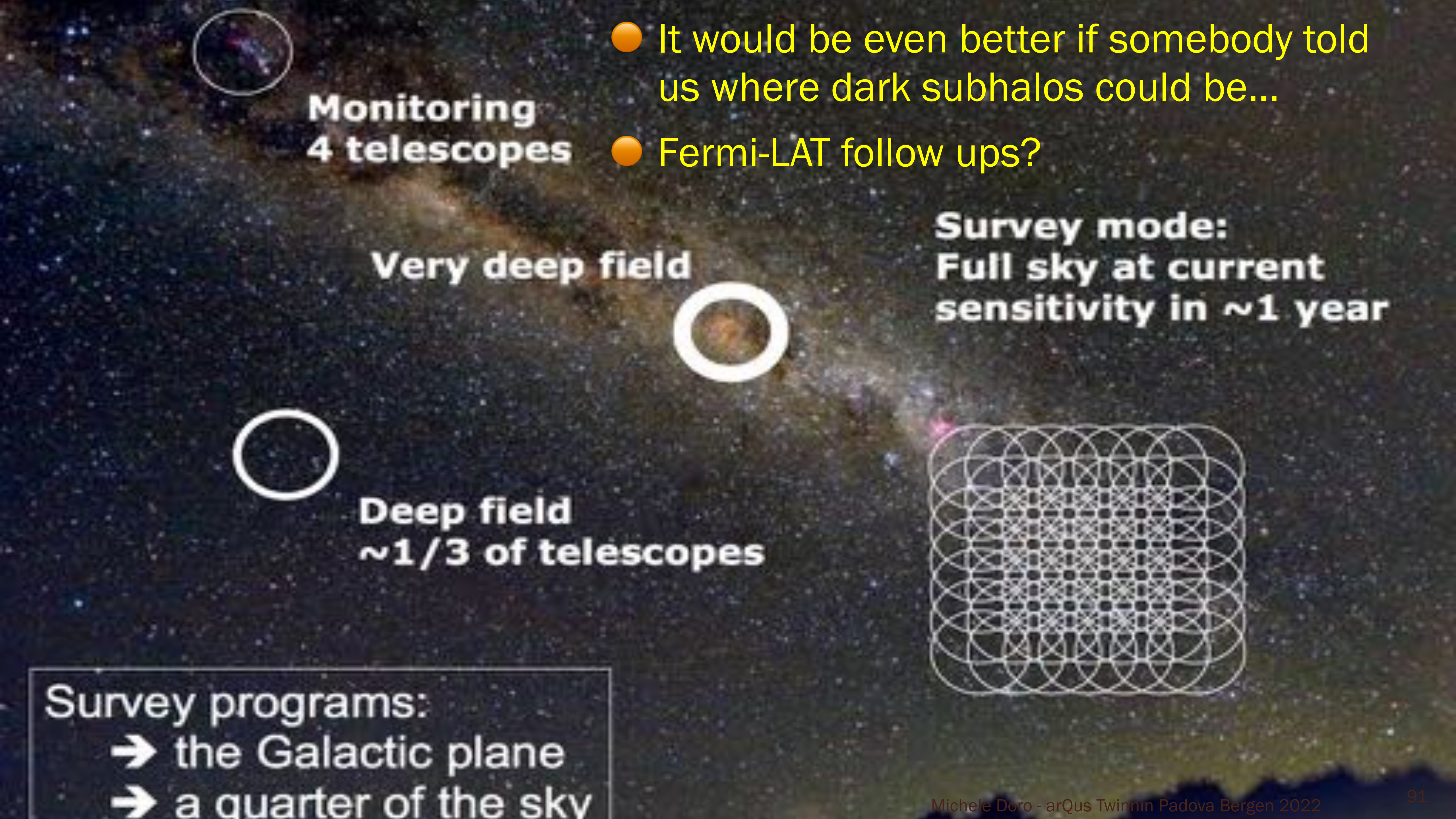
Angular resolution



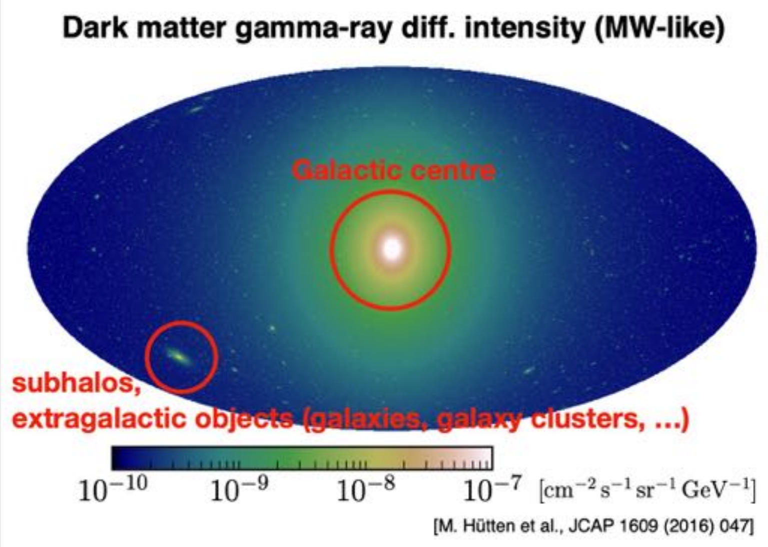
→spectral features

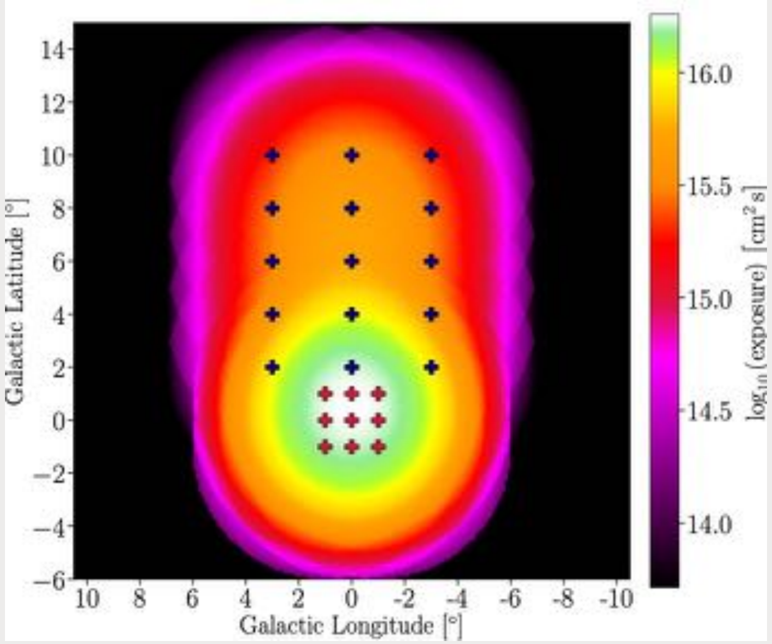
→ Morphology discrimination

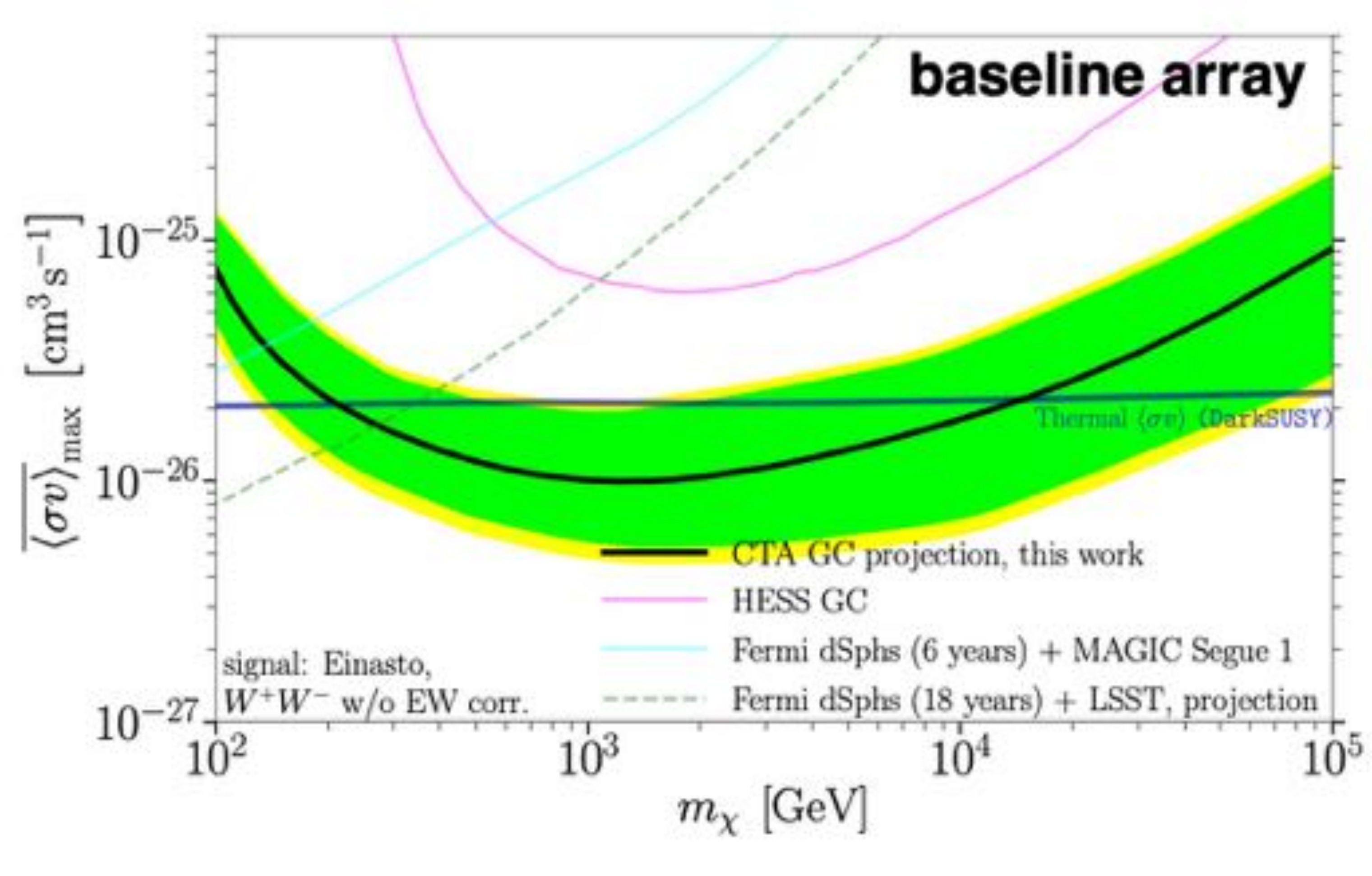
- It would be even better if somebody told us where dark subhalos could be…
- Fermi-LAT follow ups?



CTA and dark matter







gammapy.org/cta.html

Apps | Lavoro | Projects | Didattica | Social | Utilities | Personale | Links | Reading List | URL Short INFN

Gammapy News About CTA Contact Team Contribute Documentation

CTA

Introduction

The Cherenkov Telescope Array (CTA) is the next generation ground-based observatory for gamma-ray astronomy at very-high energies. Gammapy is a prototype for the CTA science tools (see 2017arXiv170901751D).

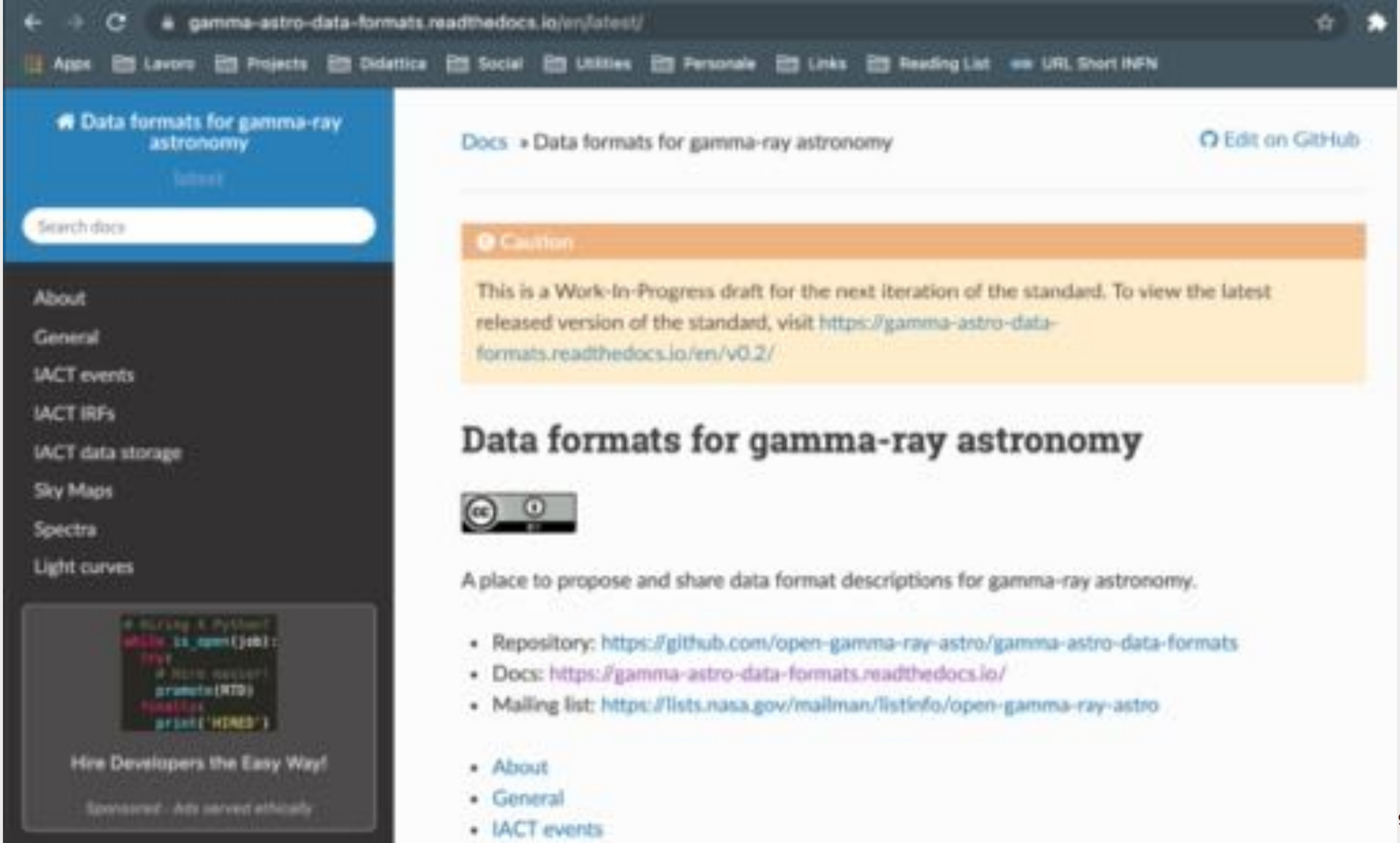
This page provides a little bit of information and links to useful resources concerning simulation and analysis of CTA data with Gammapy. Most of the pages we link to here require a CTA user account to access the information.

Getting started

To learn how to use Gammapy for CTA analysis, use the Gammapy tutorials. We suggest you do the "Getting started with Gammapy" one first, and then continue with "CTA first data challenge (1DC) with Gammapy" and "CTA data analysis with Gammapy" and finally the "CTA 2D source fitting with Sherpa".

If you have questions, please post on the Gammapy CTA mailing list or contact the Gammapy coordination committee (see Gammapy contacts page)

Please note that Gammapy is a very young project and is under heavy development. At the moment we are participating in the CTA first data challenge, fixing issues and adding new functionality for CTA.


gamma-astro-data-formats.readthedocs.io/en/latest/
Apps Lavoro Projects Didattica Social Utilities Personale Links Reading List URL Short INFN
Data formats for gamma-ray astronomy
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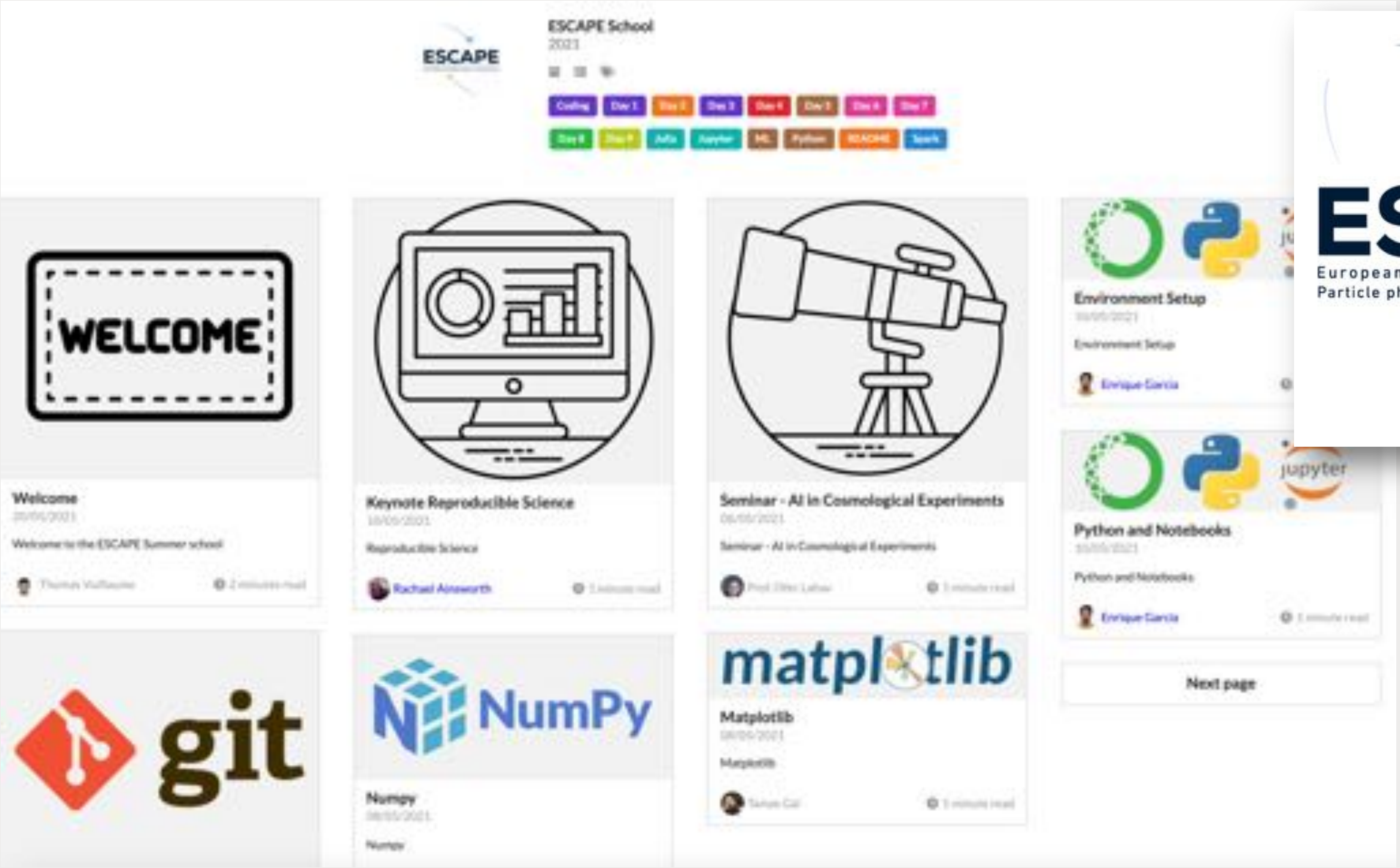
Search docs
About
General
IACT events
IACT IRFs
IACT data storage
Sky Maps
Spectra
Light curves
Hire Developers the Easy Way!
Sponsored · Ads served ethically
Docs » Data formats for gamma-ray astronomy
Edit on GitHub
Caution
This is a Work-In-Progress draft for the next iteration of the standard. To view the latest released version of the standard, visit https://gamma-astro-data-formats.readthedocs.io/en/v0.2/
Data formats for gamma-ray astronomy
A place to propose and share data format descriptions for gamma-ray astronomy.
• Repository: https://github.com/open-gamma-ray-astro/gamma-astro-data-formats
• Docs: https://gamma-astro-data-formats.readthedocs.io/
• Mailing list: https://lists.nasa.gov/mailman/listinfo/open-gamma-ray-astro
• About
• General
• IACT events

Last week - ESCAPE

https://escape2020.github.io/school2021/

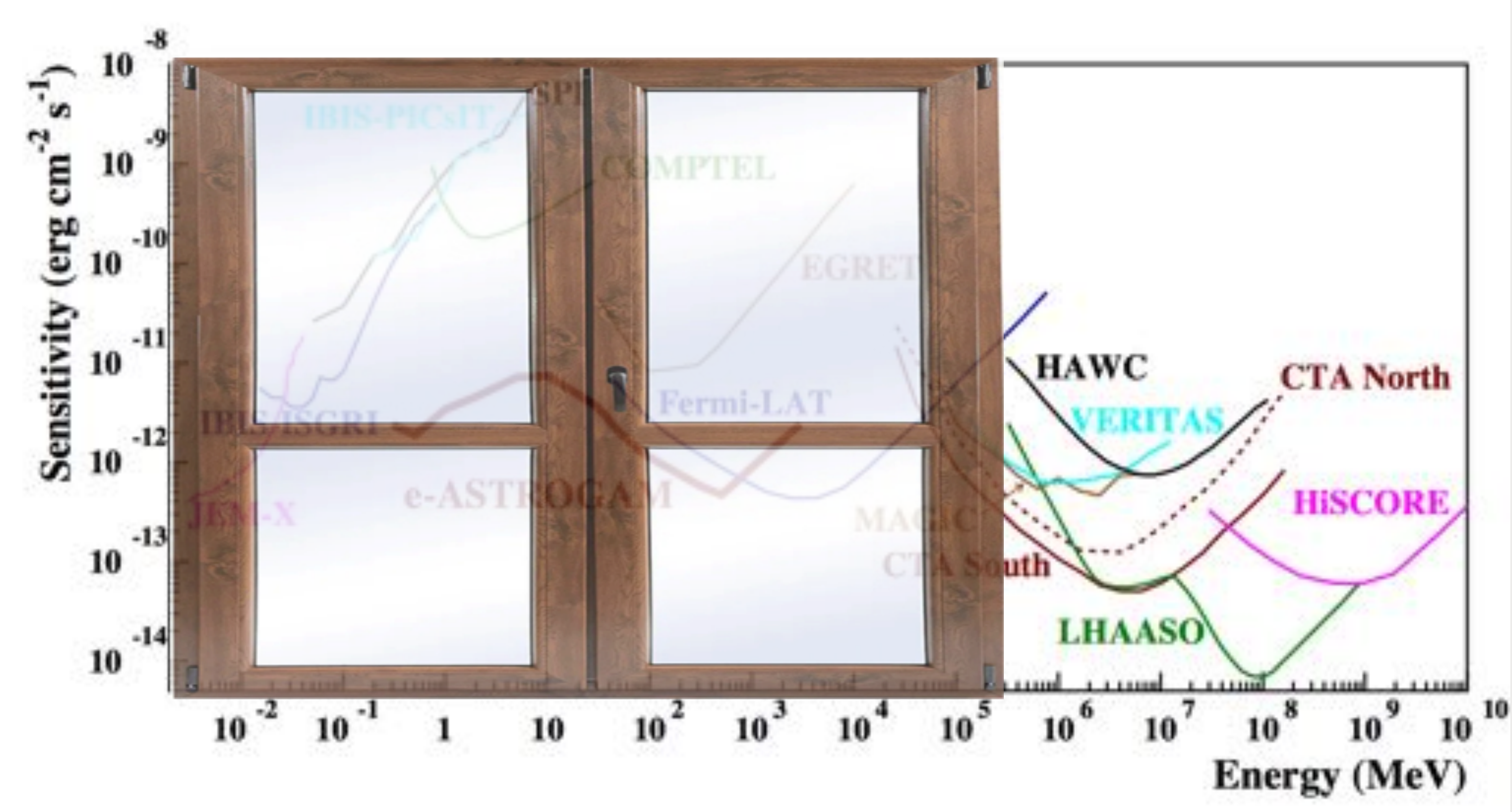


ESCAPE
European Science Cluster of Astronomy & Particle physics ESFRI research Infrastructures

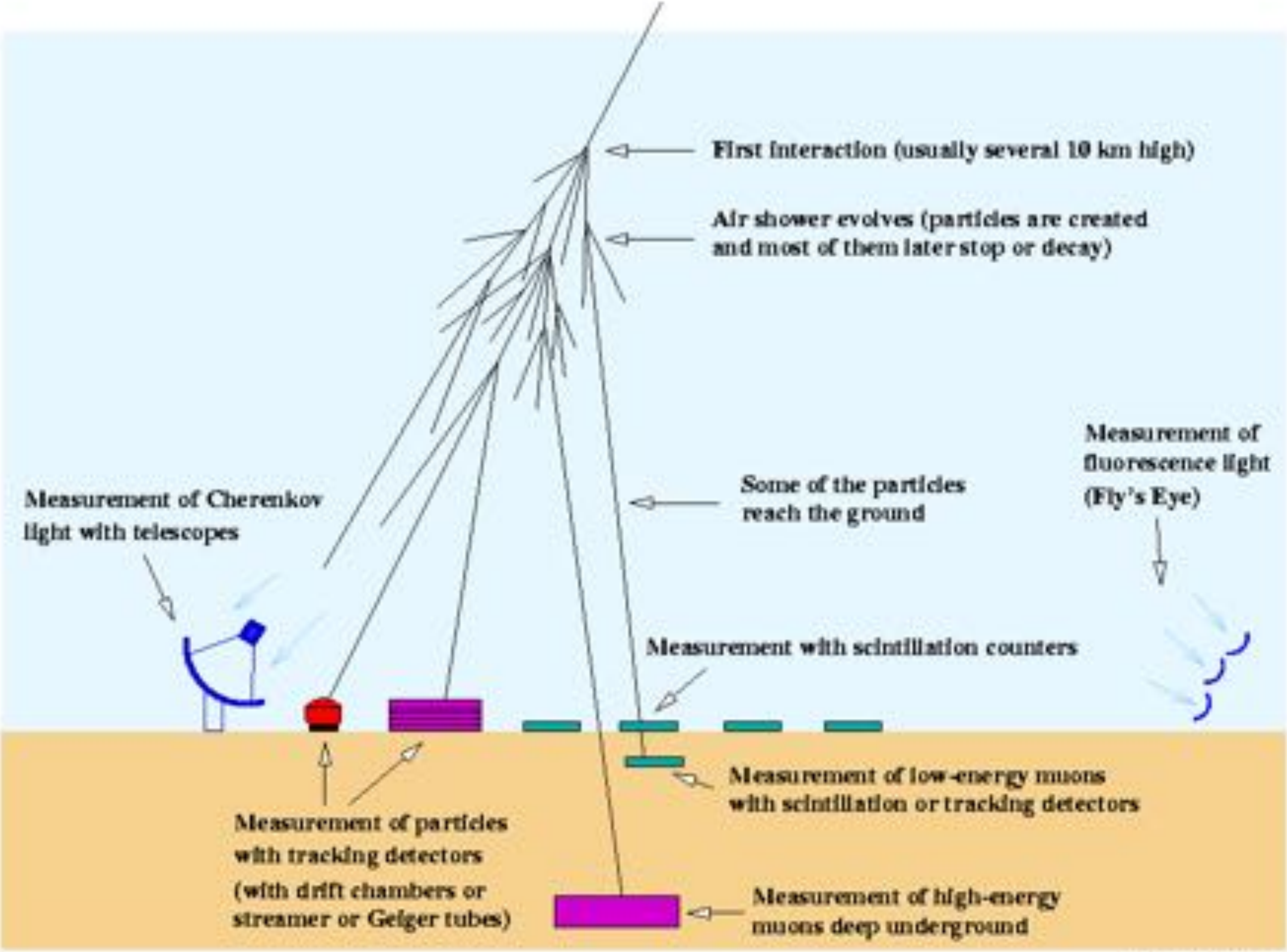
GROUND-TEV-WIDE FOV

SHOWER FRONT

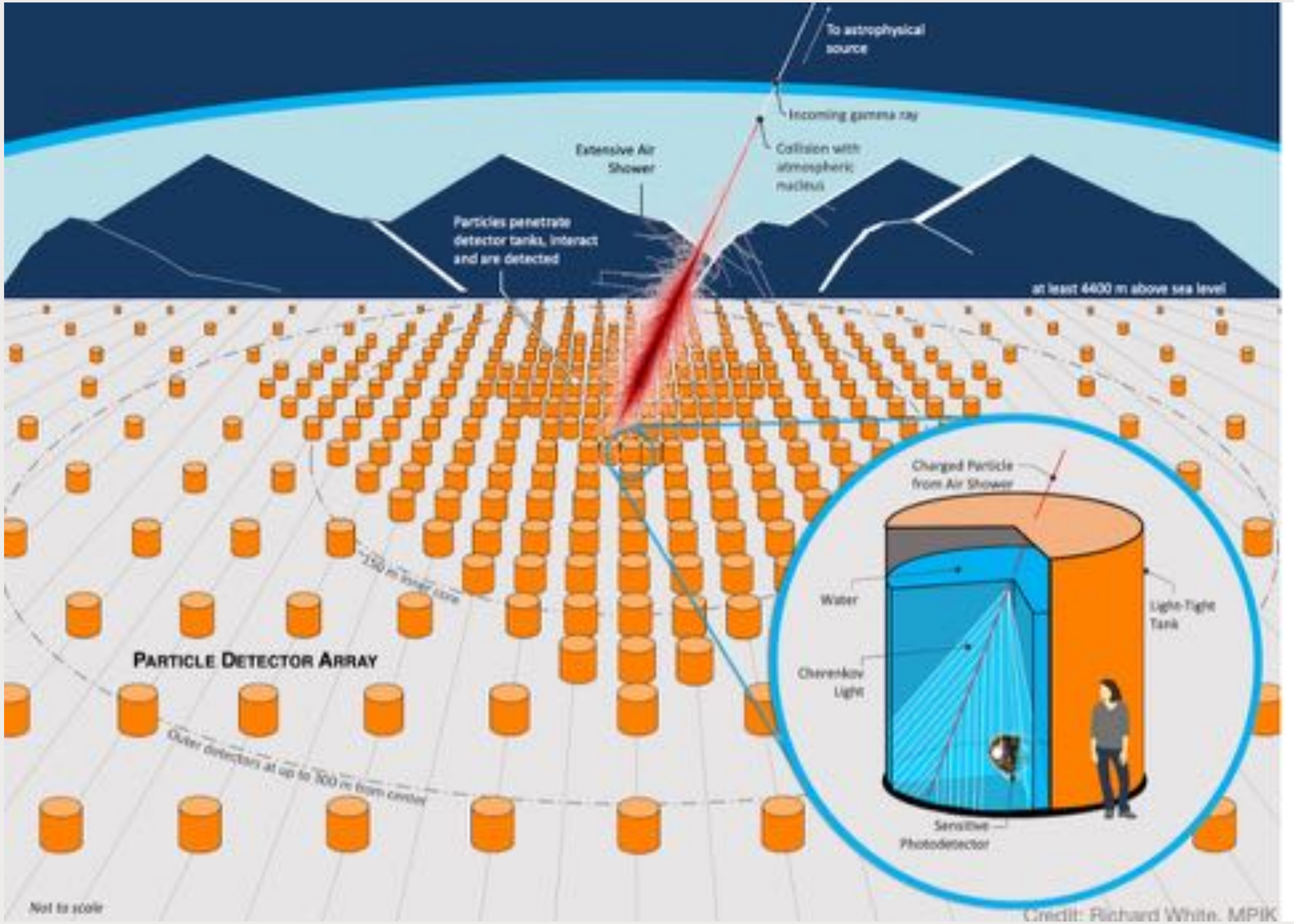
Where are we



Sensitivity (erg cm^{-2} s^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
HAWC
CTA North
VERITAS
HiSCORE
CTA South
LHAASO
10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9} 10^{10}
Energy (MeV)

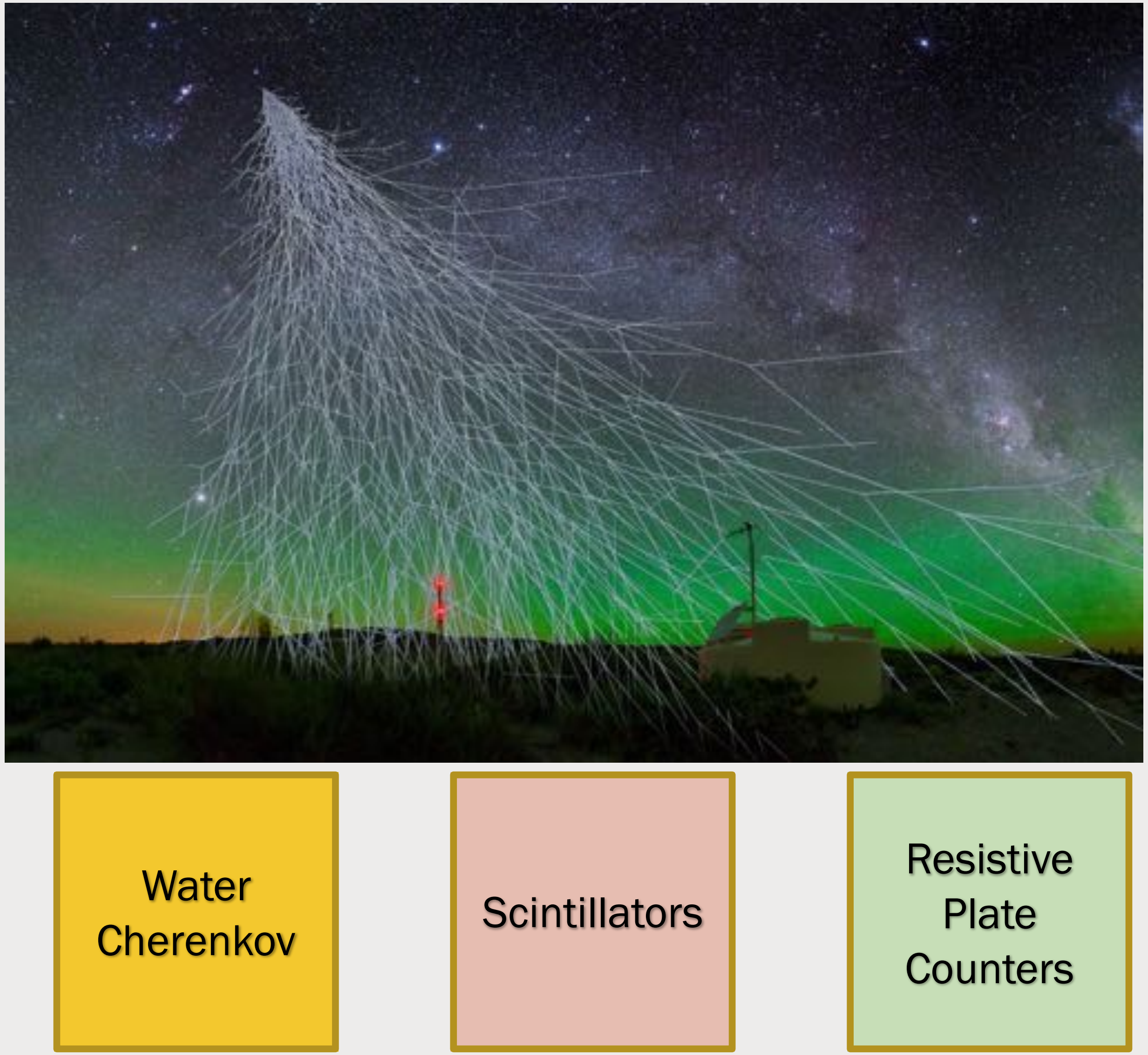

First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Some of the particles reach the ground
Measurement of fluorescence light (Fly's Eye)
Measurement of Cherenkov light with telescopes
Measurement with scintillation counters
Measurement of low-energy muons with scintillation or tracking detectors
Measurement of particles with tracking detectors (with drift chambers or streamer or Geiger tubes)
Measurement of high-energy muons deep underground

Particle detectors



- Detection of charged shower constituents through several instruments
  $e^{+}, e^{-}, \mu, (\gamma)$
- Large arrays
- Higher altitudes
- All-day duty cycle
- Wide FOV
- TeV+ threshold

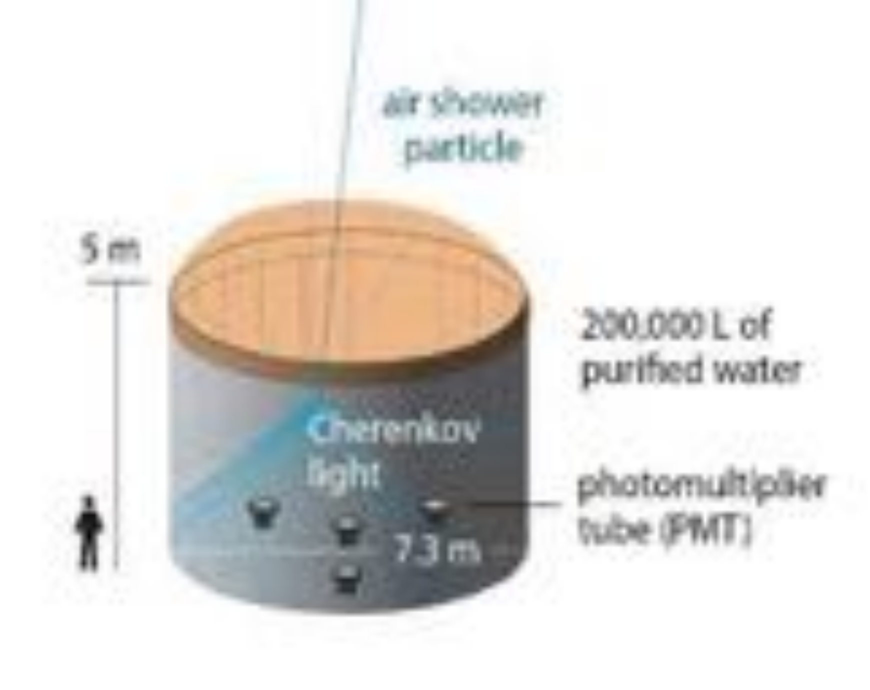
What detectors?



- Charged particle detectors
  - *Water Cherenkov (in tank, manmade or natural water pond)*
  - *Scintillator units*
  - *Resistive Plate Counters*
- To separate electrons from muons one can consider specific 'muon-only' detectors
  - *Shielding with thick material allows $\gamma, e^{\pm}$ absorption*

Water Cherenkov (tank,pond)

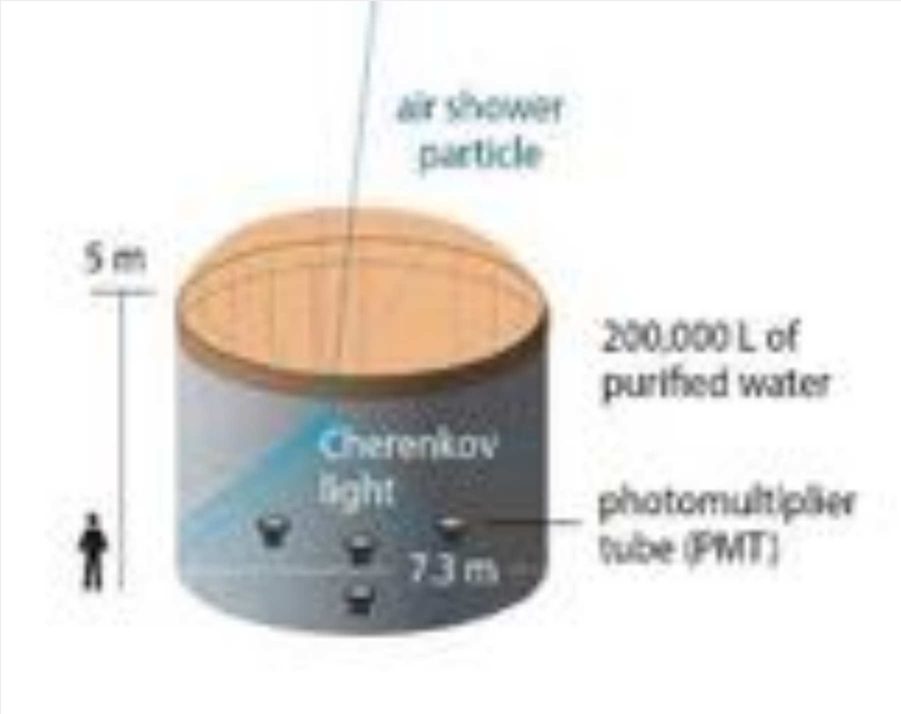
- Water: n = 1.33;
  θ_{max} = 41.2°
  for $e^{\pm}$ E_{thr} = 775 KeV
  for $\mu^{\pm}$ E_{thr} = 160 MeV
  $N_{photons/mm}$ = 36 for λ in (300 – 600) nm



- In water charged particles emit Cherenkov light
  - *Wider angle than in atmosphere*
- Needs
  - *Purified water, few m depth*
  - *Insulated tank*
  - *Few light sensors*
- Can be done in solid materials
- Exp: Milagro, HAWC, LHAASO (also Auger)

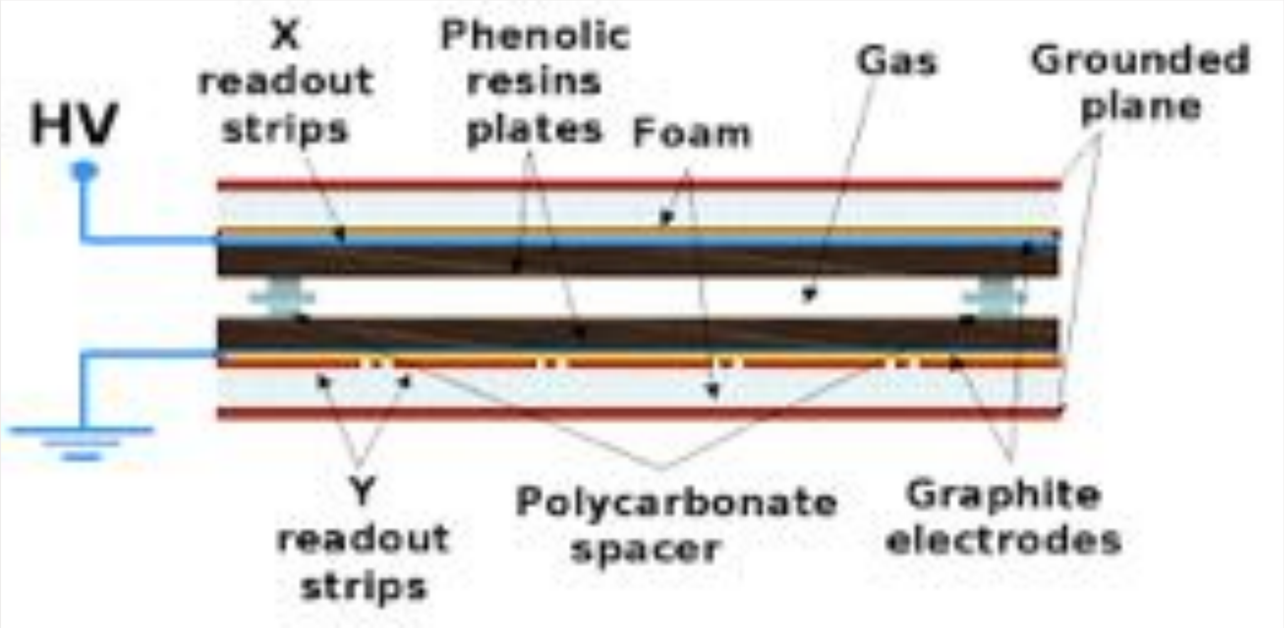
- Plexiglas: n = 1.50;
  θ_{max} = 48.2°
  for $e^{\pm}$ E_{thr} = 686 KeV
  for $\mu^{\pm}$ E_{thr} = 142 MeV
  $N_{photons/mm}$ = 46 for λ in (300 – 600) nm

Single tanks or segmented ponds



- HAWC, SWGO
- Milagro, LHAASO

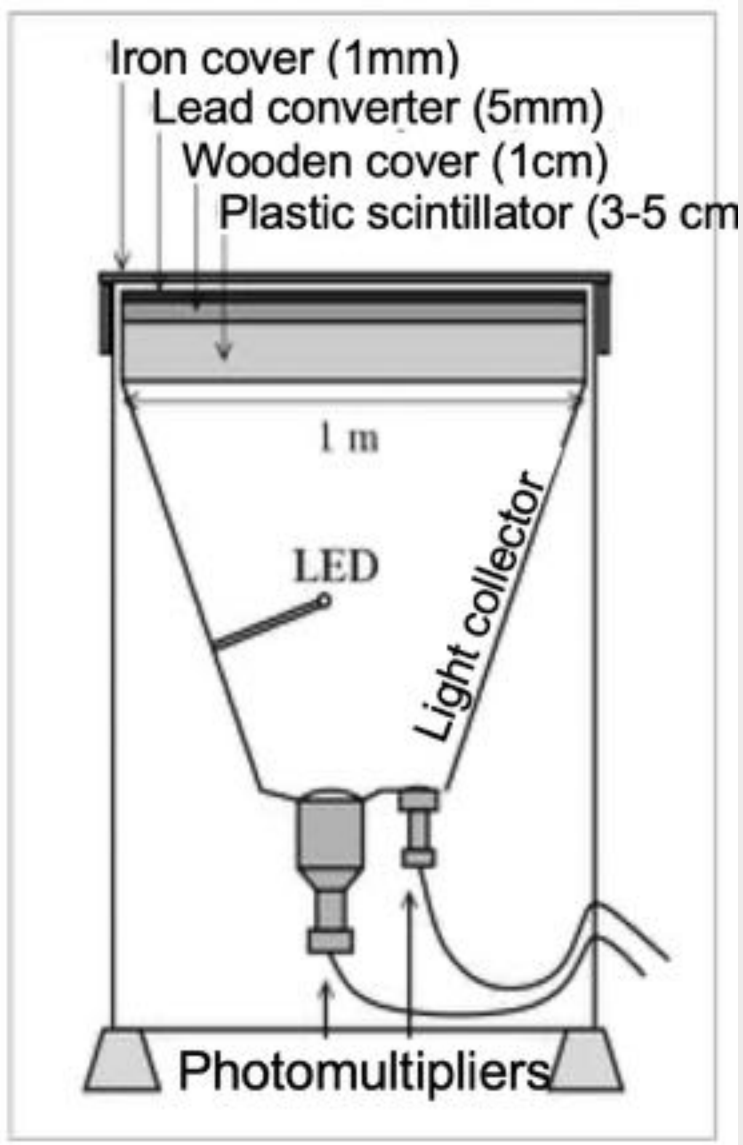
Resistive Plate Counter



- ARGO-YBJ

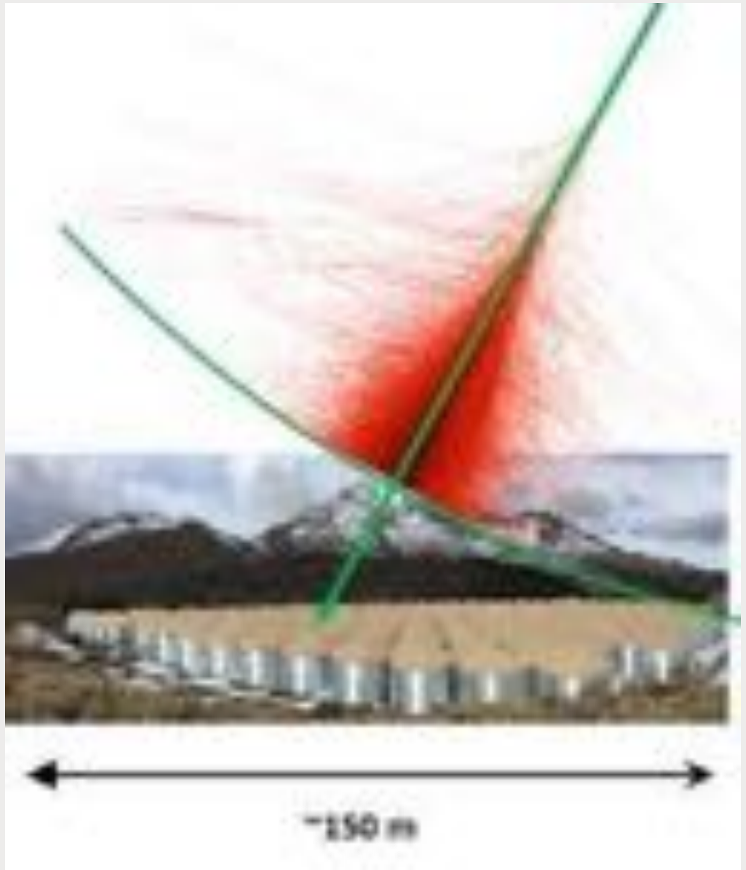
- Needs:
  - *Chamber filled with Argon gas*
  - *HV*
  - *Charged particle ionize*
  - *Readout strips allows for very accurate*
  - *Spatial resolution*
  - *Temporal resolution*
- Experiments: Argo-YBJ
- Not a calorimetric measurement

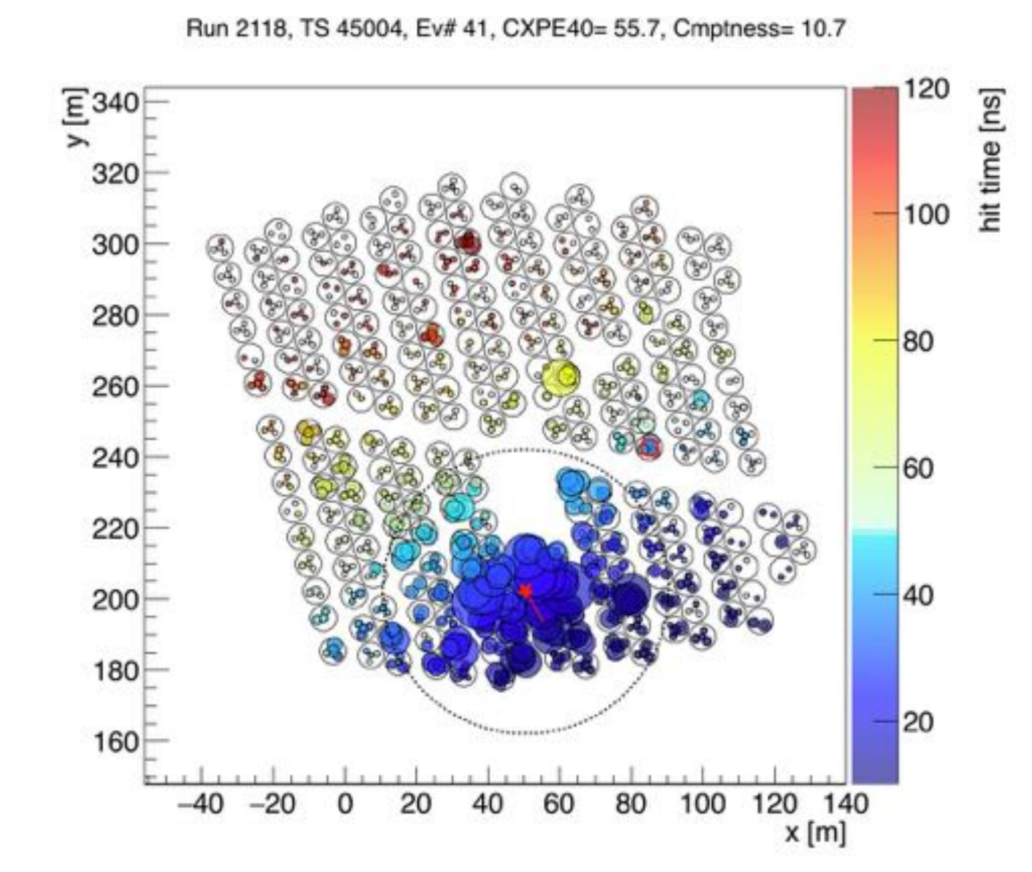
Scintillators



- Needs
  - *Wide area scintillator*
  - *Light collector+photsensors*
- Experiments: HEGRA, LHAASO

Shower core-temporal reconstruction

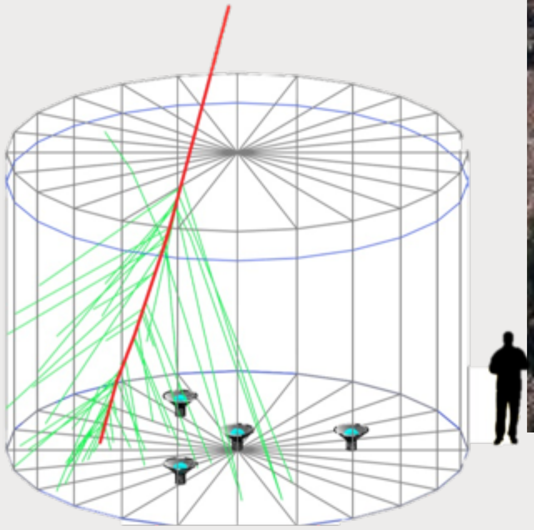


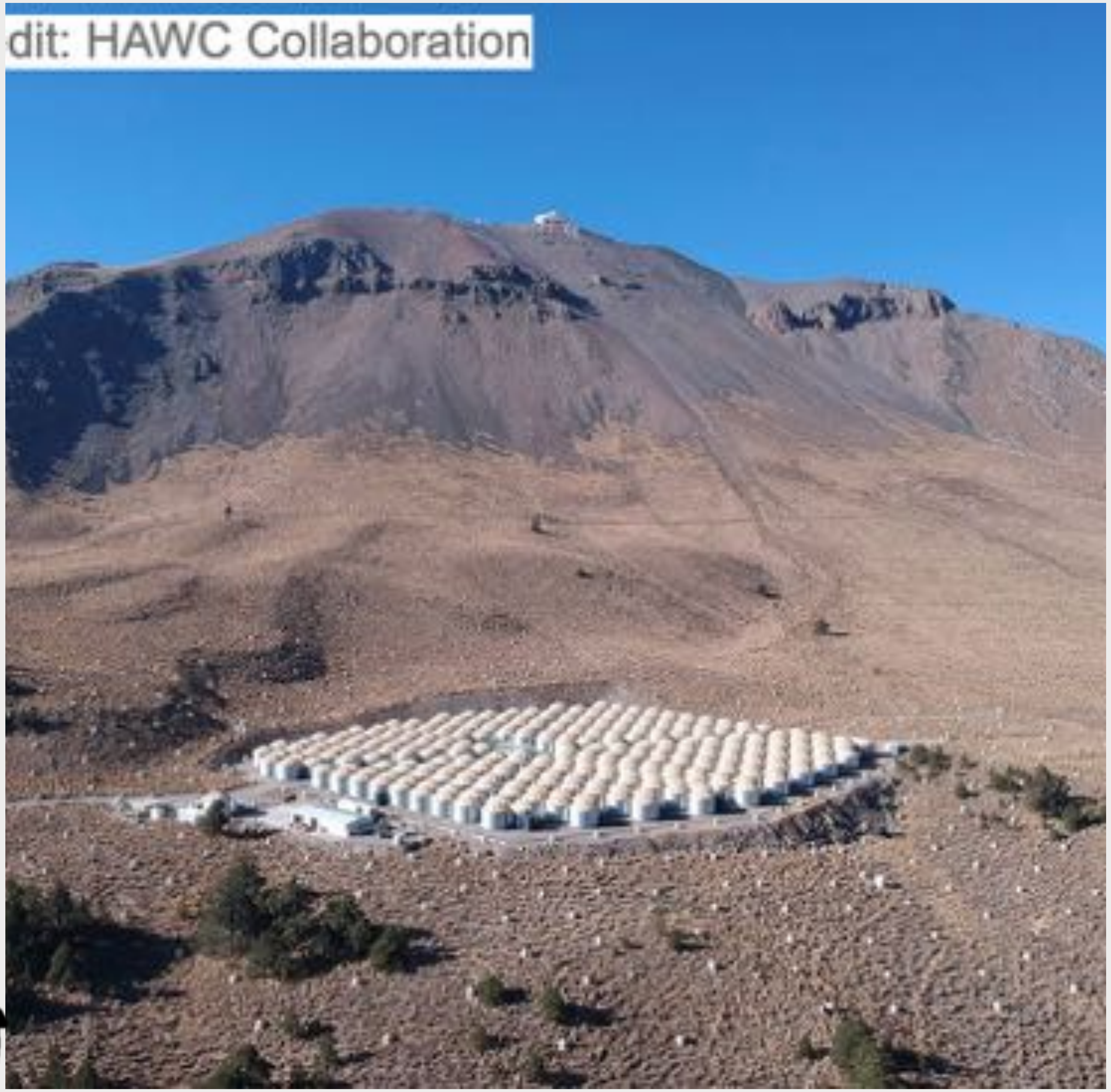


- Need a model for temporal evolution (ns)
- Shower core location and evolution

HAWC

- Location: Puebla, Mexico, 4100 m asl
- Collaboration: US+Mexico (mostly), 120 scientists
- Operating: 2016+
- Technique:
  - *Inner 300 water Cherenkov tanks 7m d, 4.5m h*
    - 4 PMTs / tank
  - *Outer sparse 350 tanks 1.65m h*
    - 1 PMT / tank





LHAASO

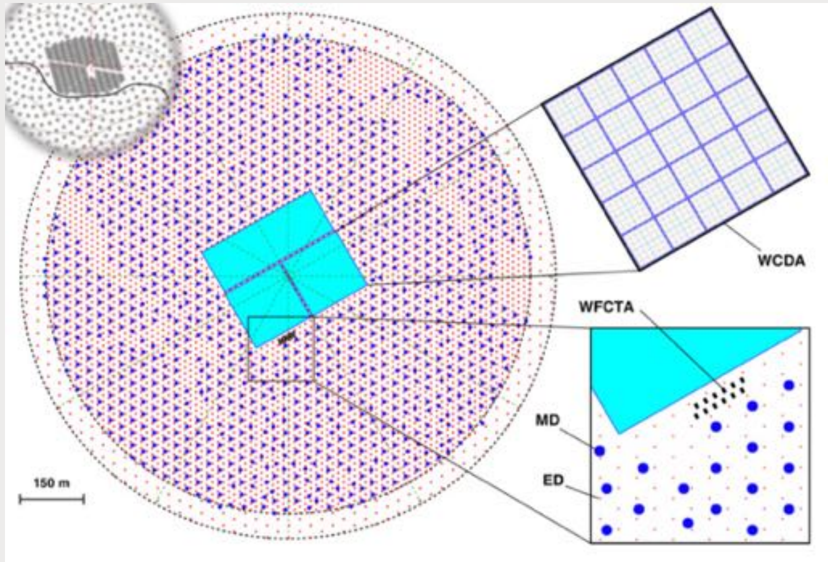
- Location: Sichuan, China, 4410 m a.s.l.
- Collaboration: China
- Operating: 2020+

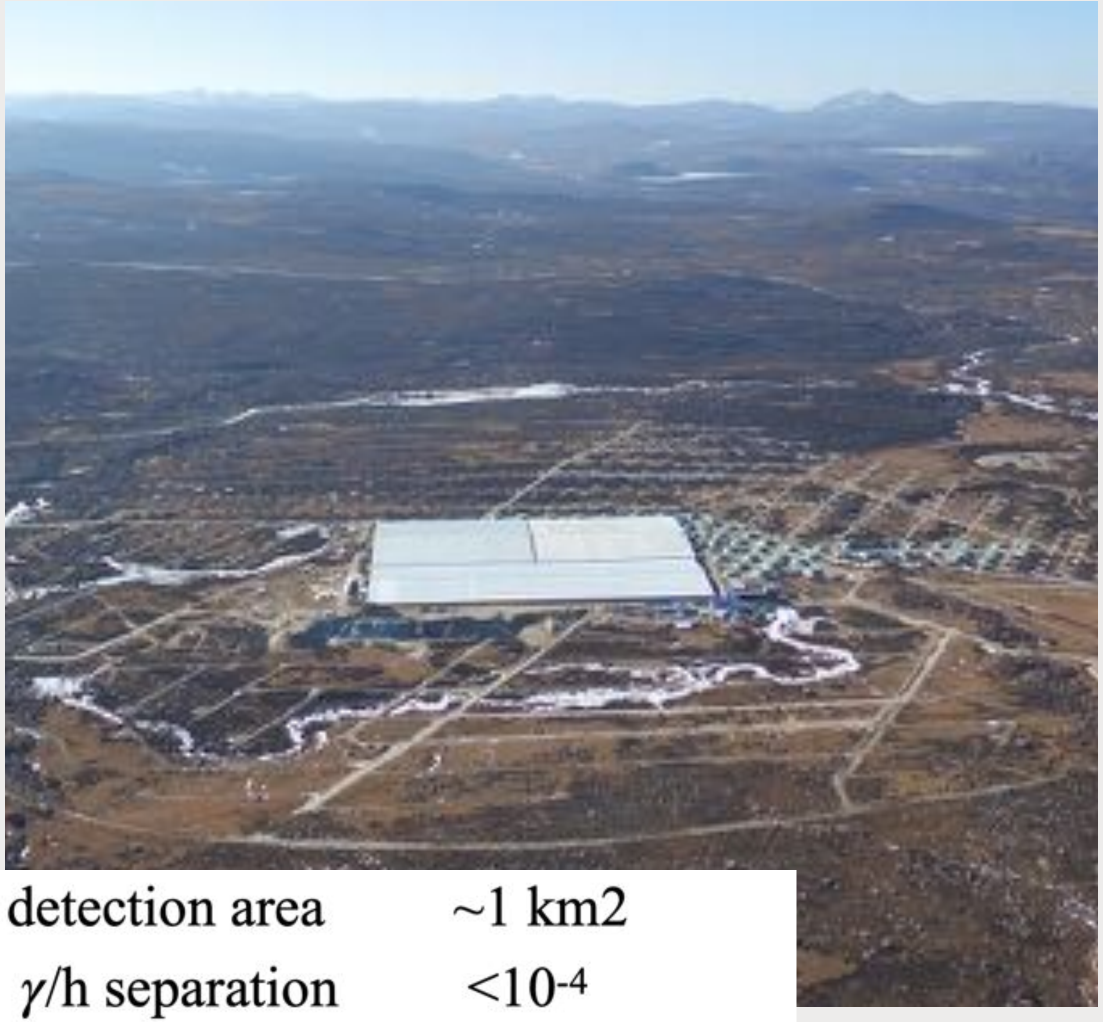
5195 Scintillators
- 1 m² each
- 15 m spacing

1171 Muon Detectors
- 36 m² each
- 30 m spacing

3000 Water Cherenkov Cells
- 25 m² each

12 Wide Field Cherenkov Telescopes





detection area	~1 km2
γ/h separation	$<10^{-4}$
large FoV	~1 ster
exposure time	~2000 h/yr
good PSF	~15 arcmin
energy resolution.	~15%

Article | Published: 17 May 2021

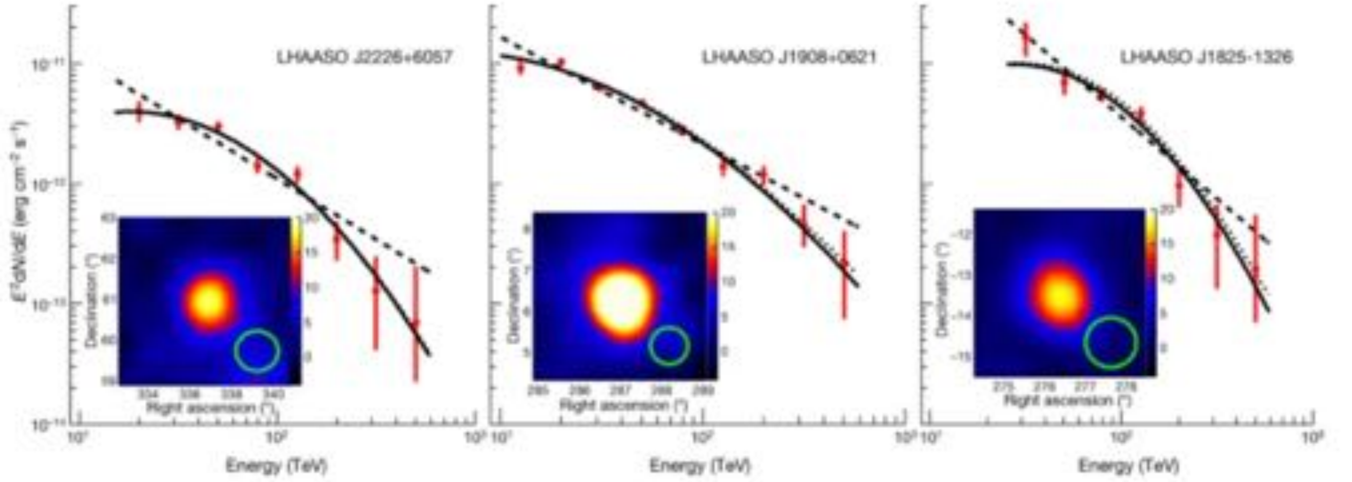
Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

Zhen Cao, F. A. Aharonian, [...]X. Zuo

Nature **594**, 33–36 (2021) | Cite this article

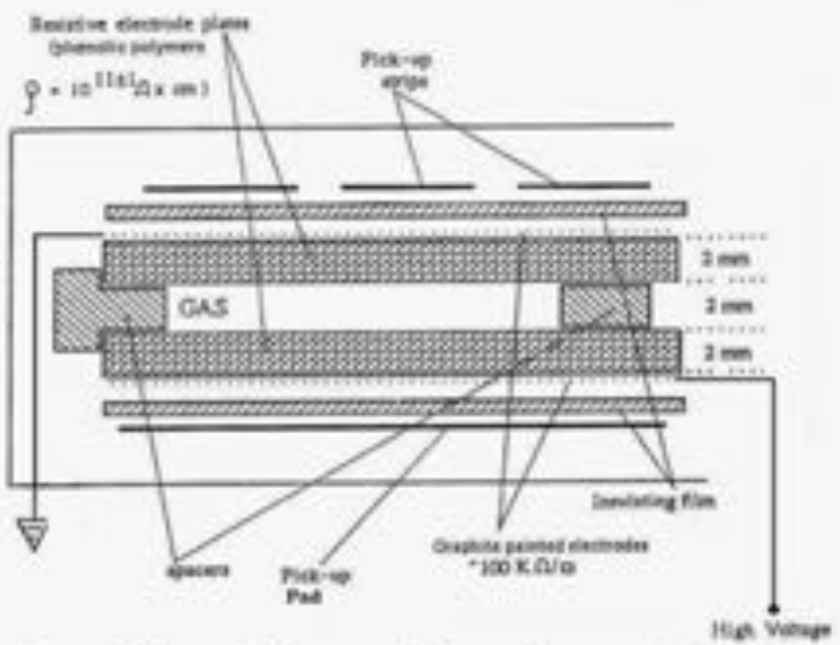
Source name	RA (°)	dec. (°)	Significance above 100 TeV (×σ)	E_{max} (PeV)	Flux at 100 TeV (CU)
LHAASO J0534+2202	83.55	22.05	17.8	0.88 ± 0.11	1.00(0.14)
LHAASO J1825-1326	276.45	−13.45	16.4	0.42 ± 0.16	3.57(0.52)
LHAASO J1839-0545	279.95	−5.75	7.7	0.21 ± 0.05	0.70(0.18)
LHAASO J1843-0338	280.75	−3.65	8.5	$0.26_{-0.10}^{+0.16}$	0.73(0.17)
LHAASO J1849-0003	282.35	−0.05	10.4	0.35 ± 0.07	0.74(0.15)
LHAASO J1908+0621	287.05	6.35	17.2	0.44 ± 0.05	1.36(0.18)
LHAASO J1929+1745	292.25	17.75	7.4	$0.71_{-0.07}^{+0.16}$	0.38(0.09)
LHAASO J1956+2845	299.05	28.75	7.4	0.42 ± 0.03	0.41(0.09)
LHAASO J2018+3651	304.75	36.85	10.4	0.27 ± 0.02	0.50(0.10)
LHAASO J2032+4102	308.05	41.05	10.5	1.42 ± 0.13	0.54(0.10)
LHAASO J2108+5157	317.15	51.95	8.3	0.43 ± 0.05	0.38(0.09)
LHAASO J2226+6057	336.75	60.95	13.6	0.57 ± 0.19	1.05(0.16)

Fig. 1: Spectral energy distributions and significance maps.

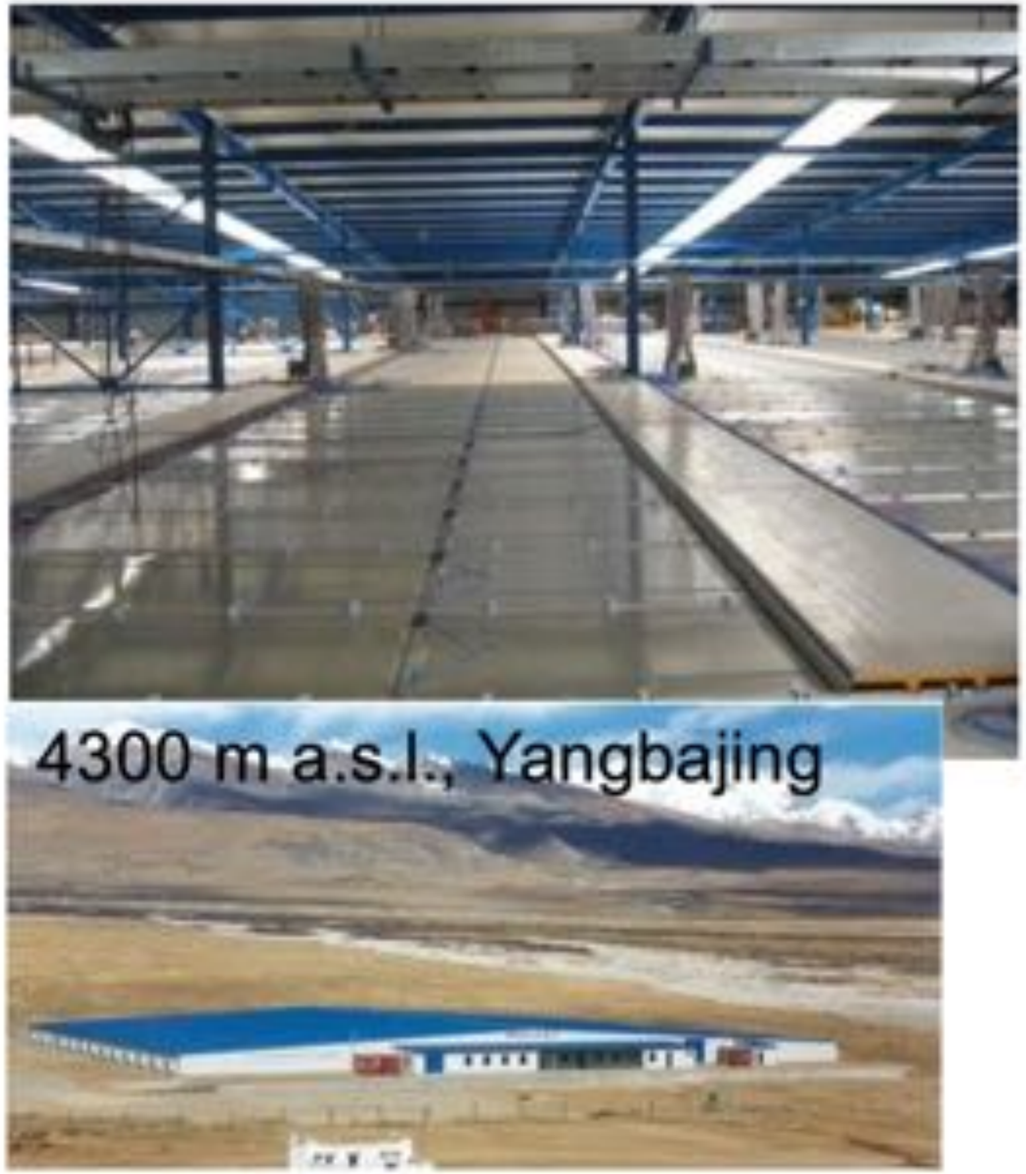


ARGO-YBJ

Going further down in E: better coverage of the detection area

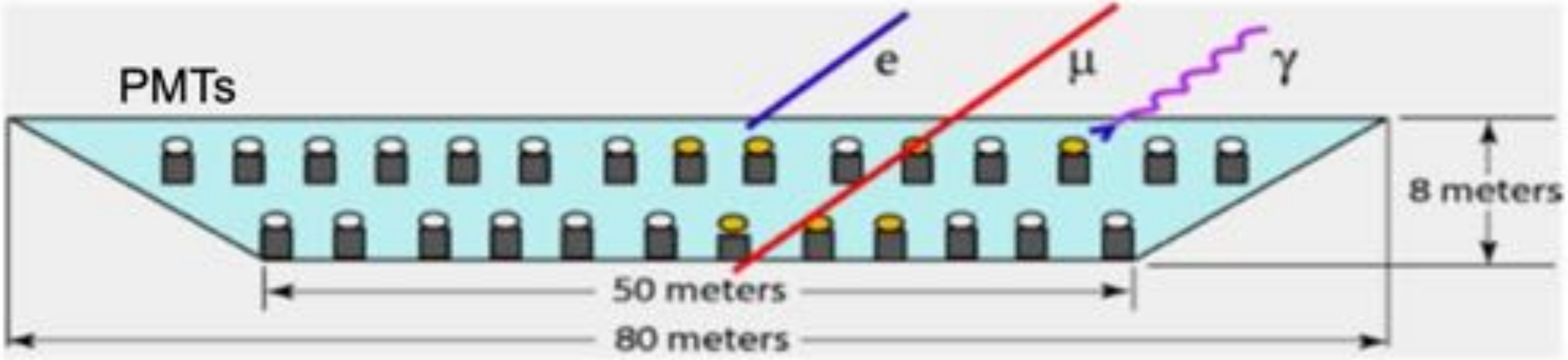


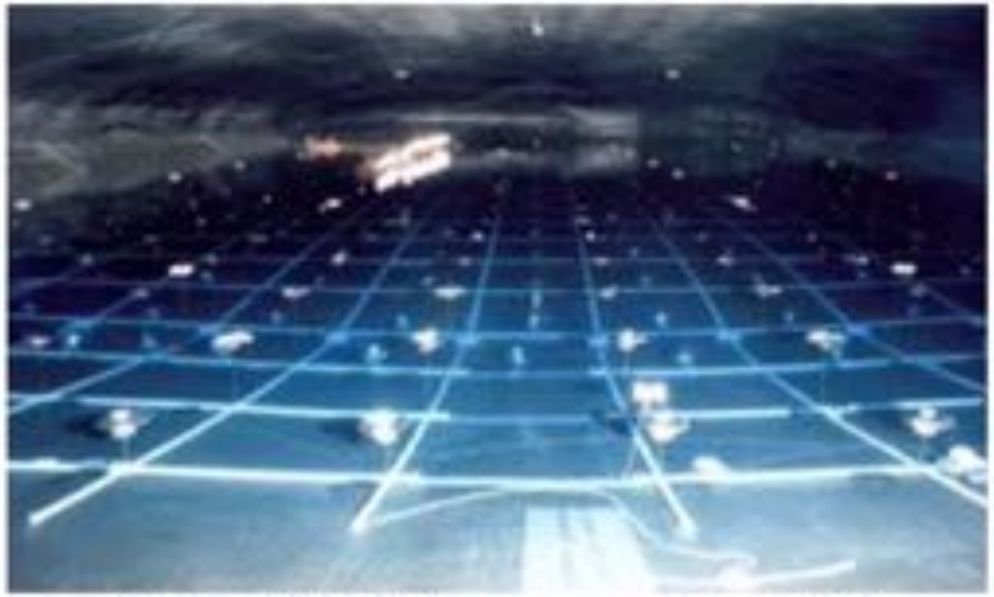
Resistive Plate Chambers (RPCs) are gaseous ionisation detectors with parallel resistive electrodes
Good time and spatial resolution



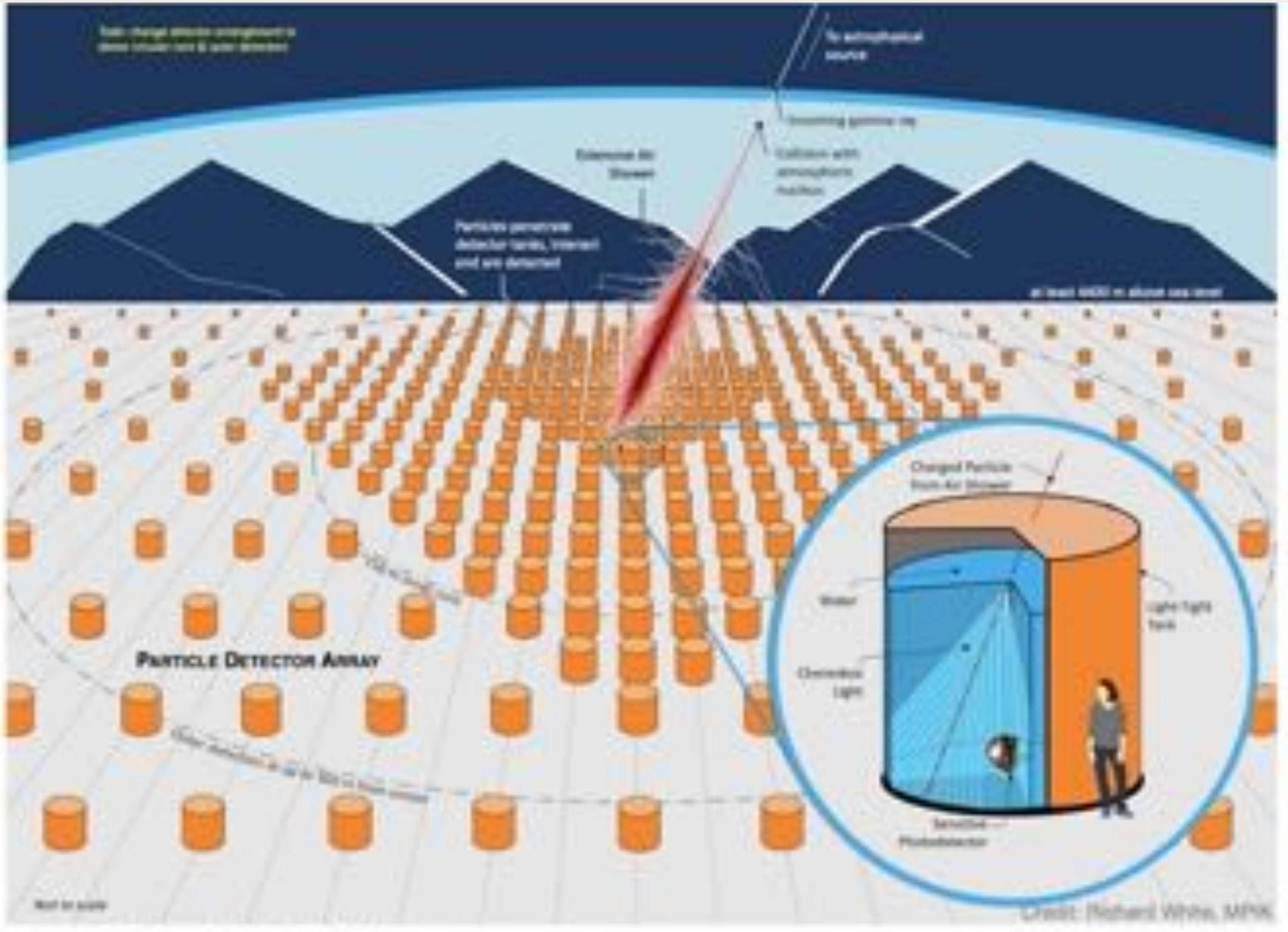
MILAGRO (moved to → HAWC)

Achieves full coverage in a different way: Cherenkov light emission in water



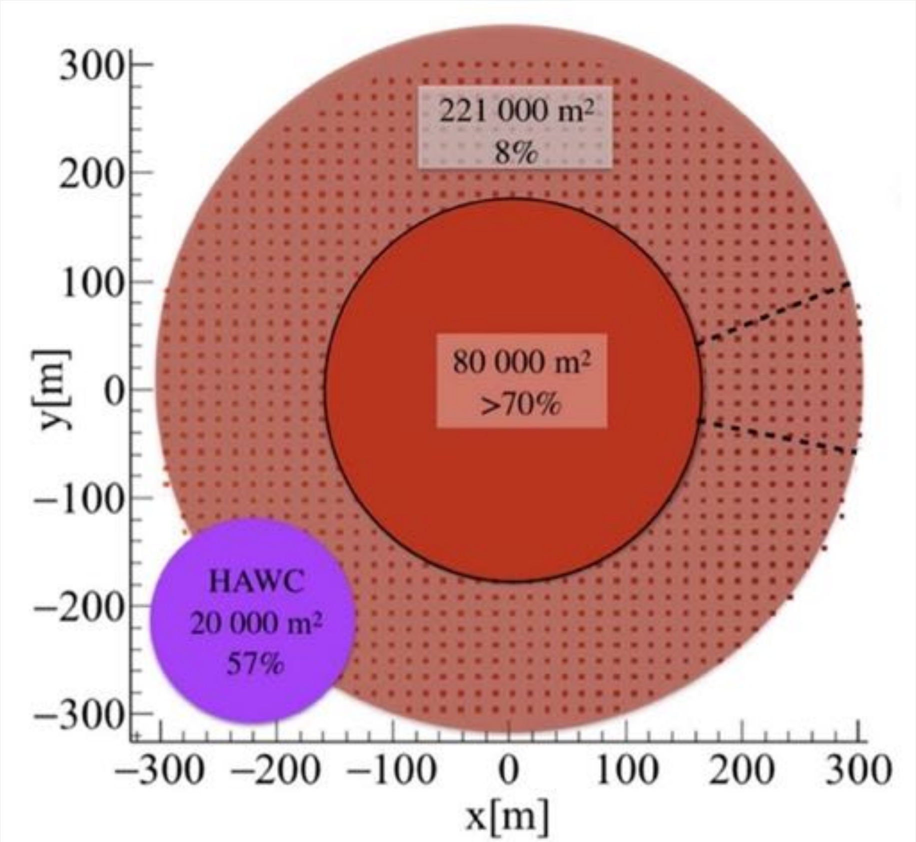


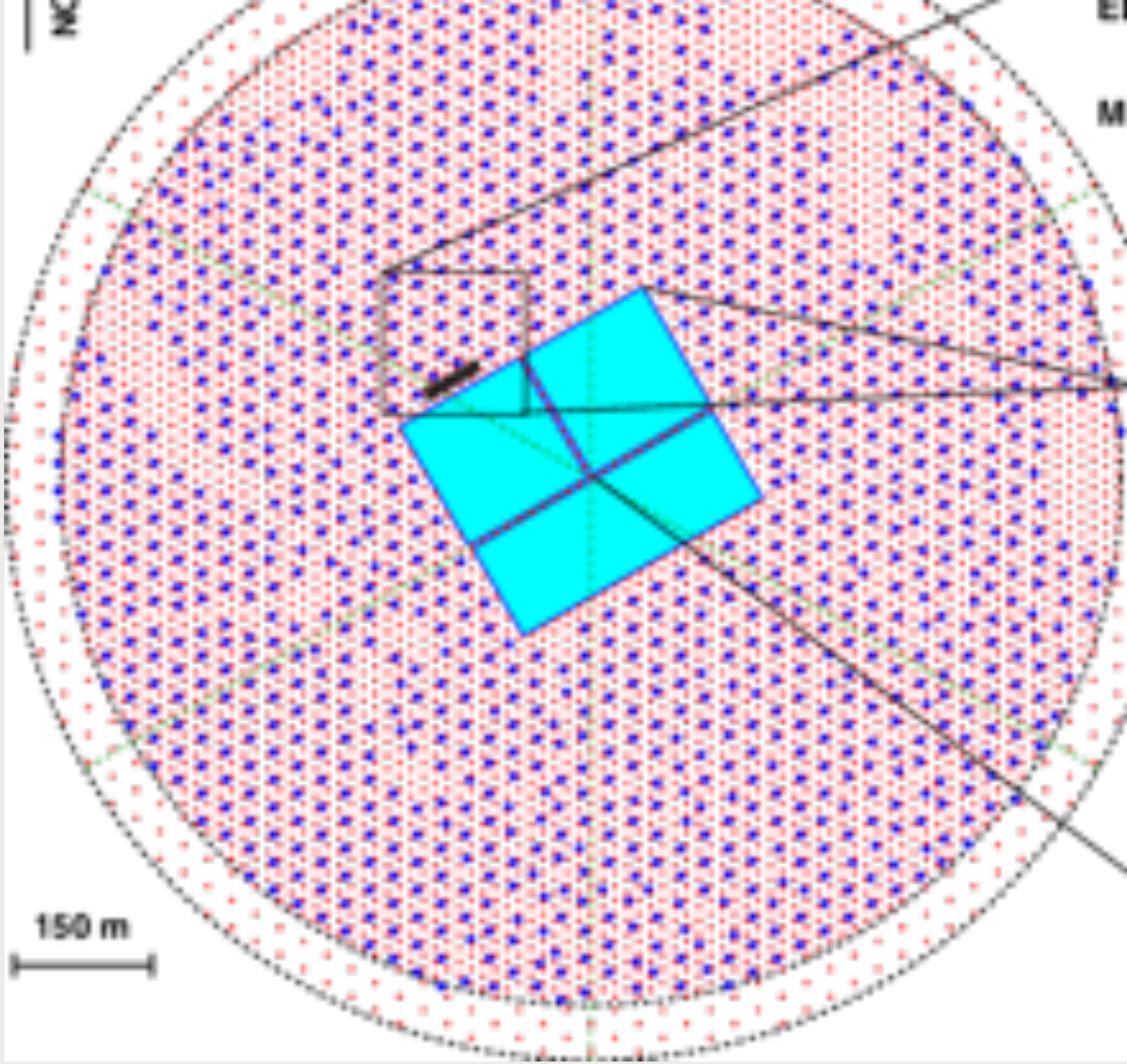
Southern Wide-Field gamma-ray observatory



- A shower-front detector of TeV gamma rays to be located in South America
- 100^{+} GeV – 100^{+} TeV
- Built on experience of HAWC, Milagro, Auger + MAGIC, CTA,

SWGO

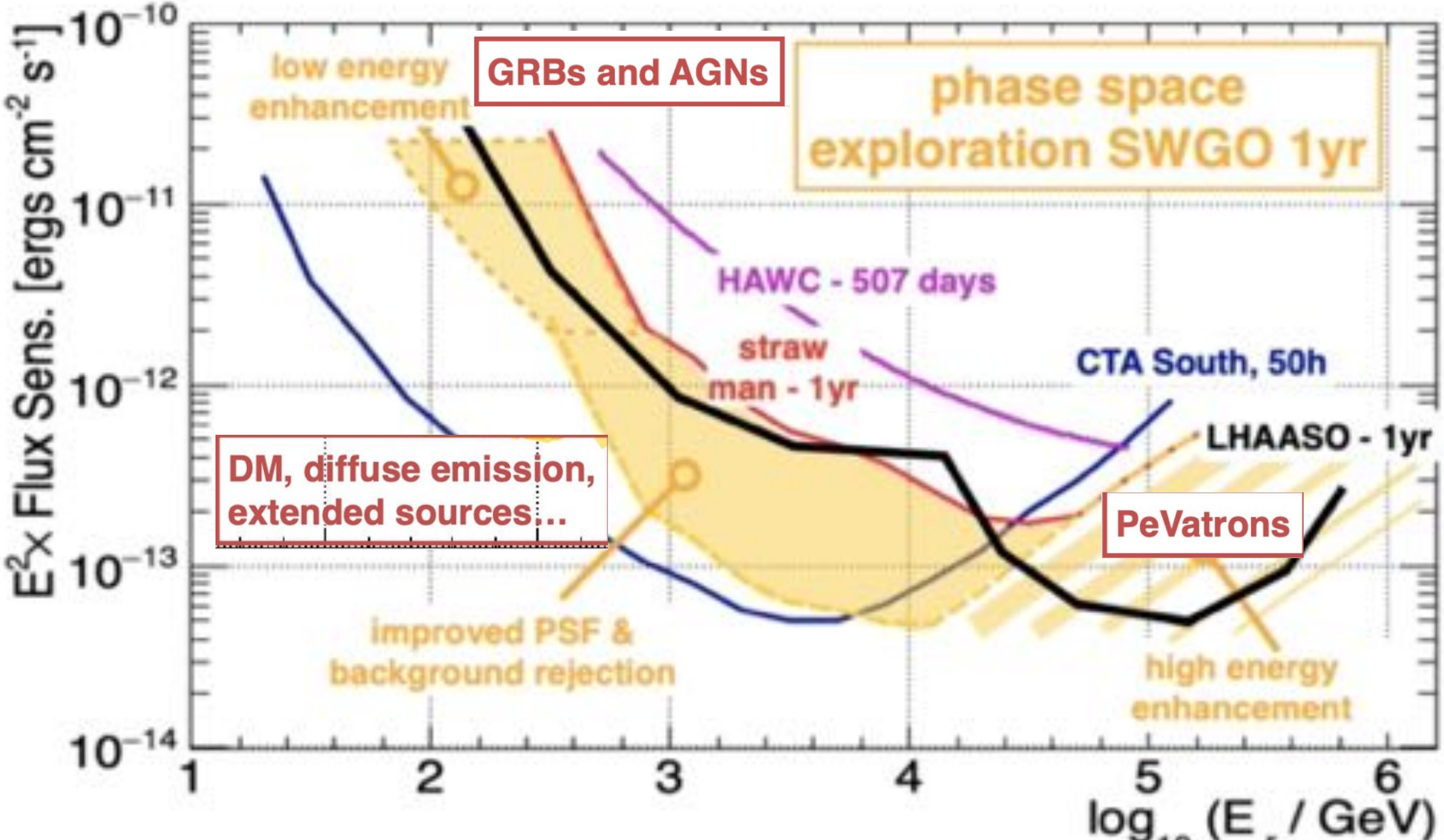

221 000 m²
8%
80 000 m²
>70%
HAWC
20 000 m²
57%
y[m]
x[m]
300
200
100
0
−100
−200
−300
−300 −200 −100 0 100 200 300


150 m

…brought up in South America in 201x

Country	Site Name	Latitude	Altitude [m a.s.l]
Argentina	Alto Tocomar	S 24.195; W 66.510	4,430
	Cerro Vecar	S 24.185; W 66.475	4,800
Bolivia	Chacaltaya	16.23 S	4,740
Chile	Pajonales	22.57 S	4,600
	Pampa La Bola	22.56 S	4,770
Peru	Imata	15,50 S	4,450
	Yanque	15.44 S	4,800
	Sibinacocha	13.51 S	4,900

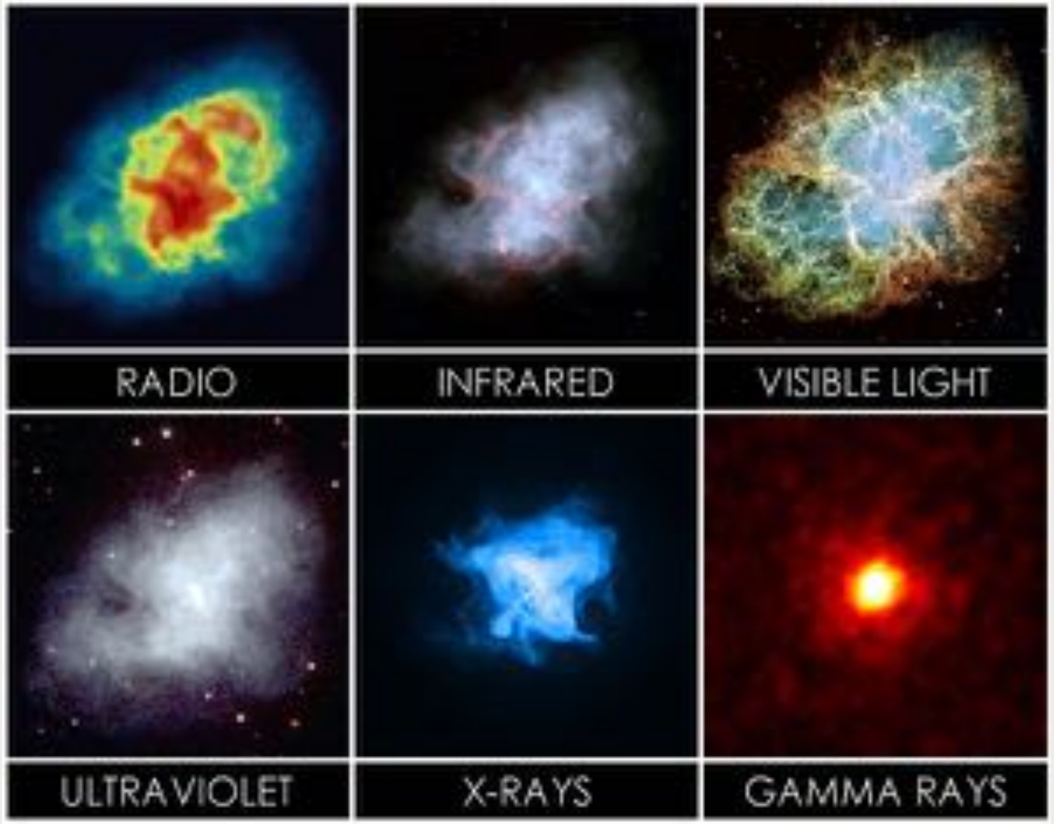
- MD site working group coordinator 2019-21

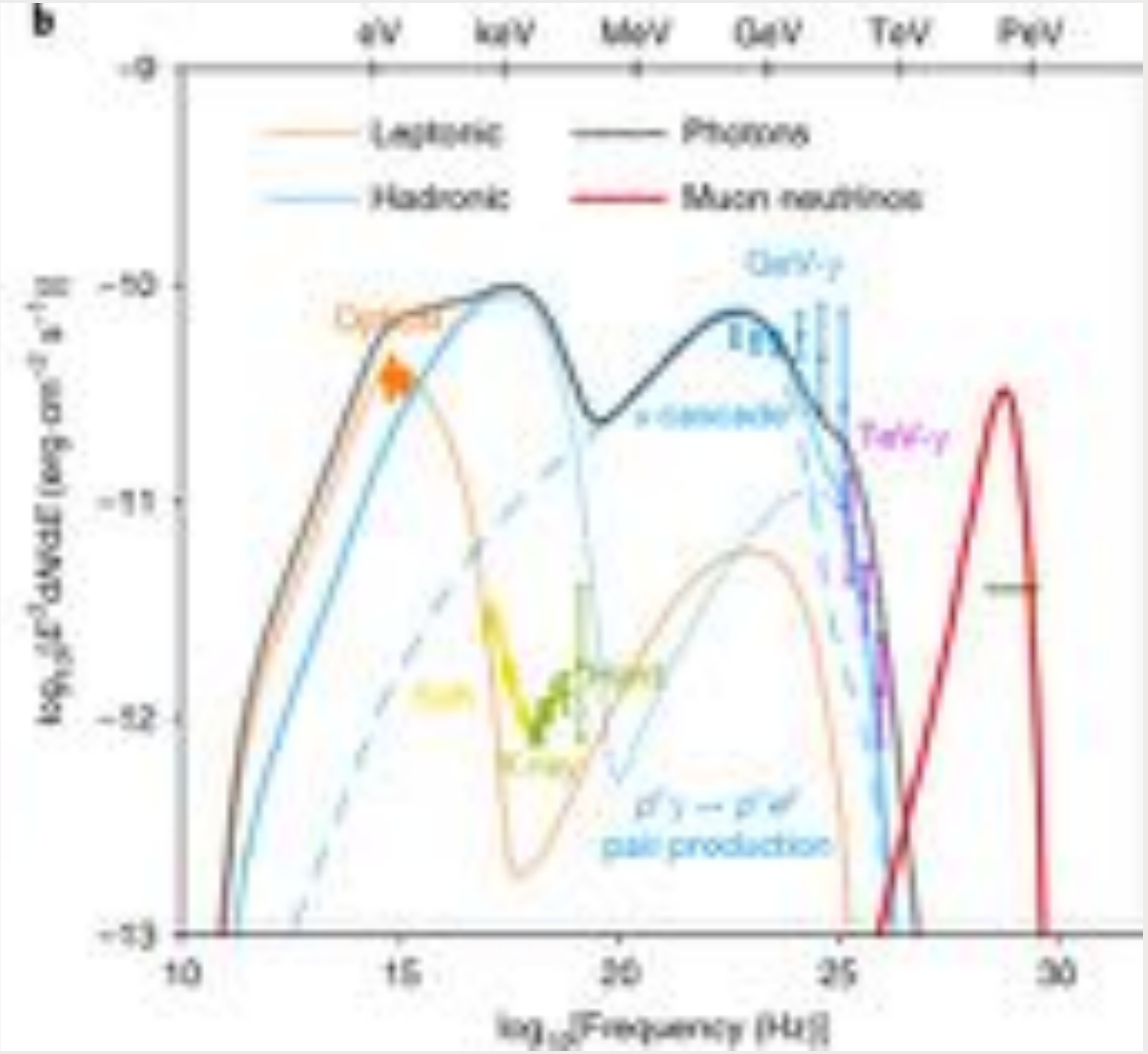


GRBs and AGNs
low energy enhancement
phase space exploration SWGO 1yr
HAWC - 507 days
straw man - 1yr
CTA South, 50h
LHAASO - 1yr
DM, diffuse emission, extended sources...
PeVatrons
improved PSF & background rejection
high energy enhancement
E²× Flux Sens. [ergs cm⁻² s⁻¹]
log₁₀ (E / GeV)

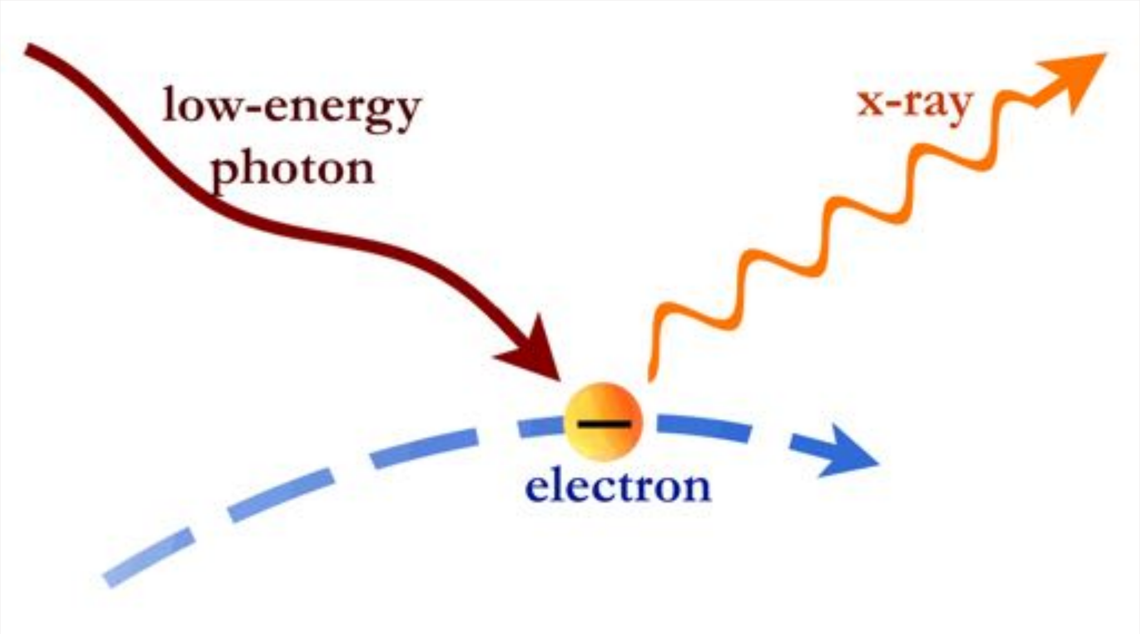
CONCLUSIONS

Multi-messenger

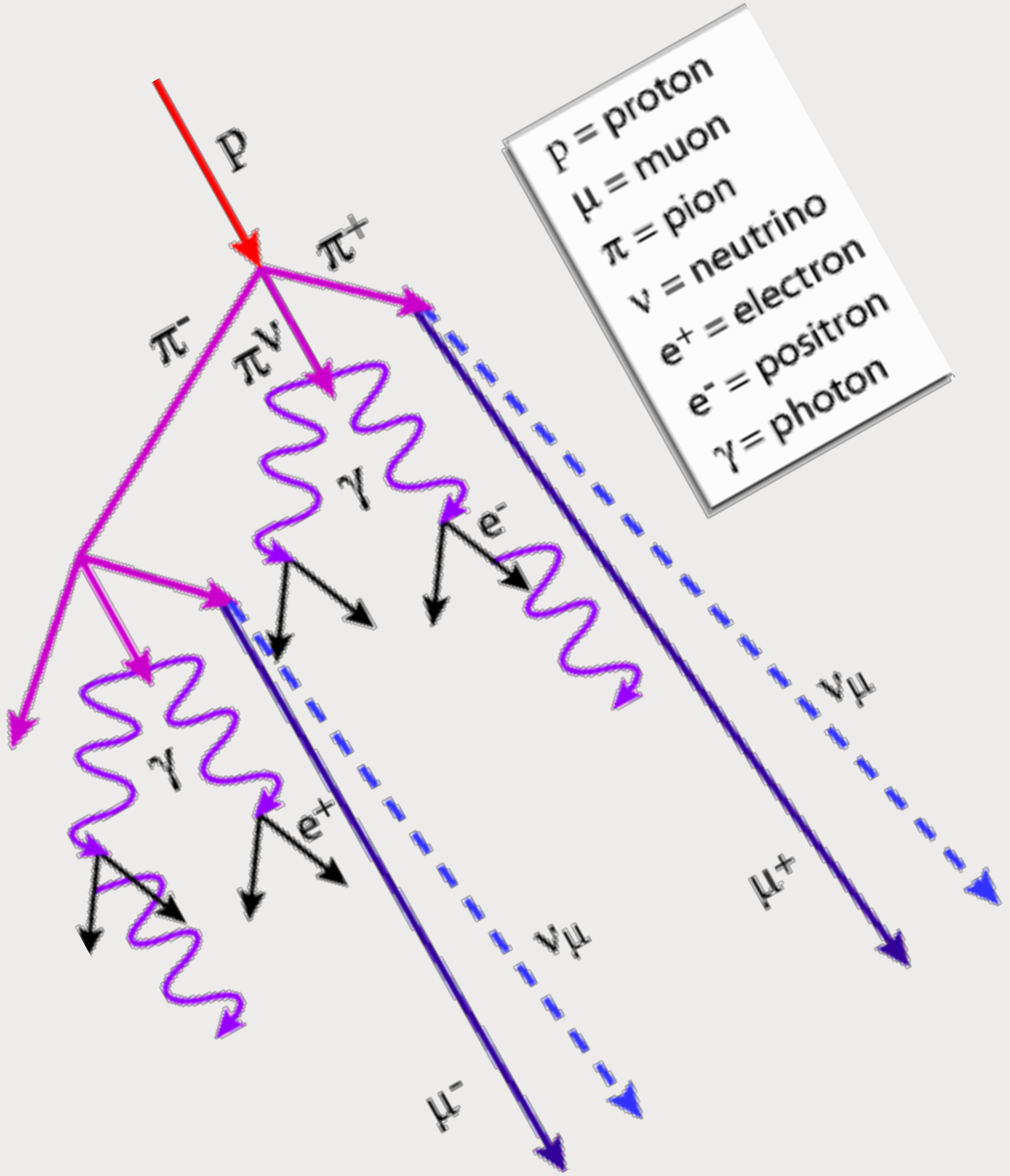




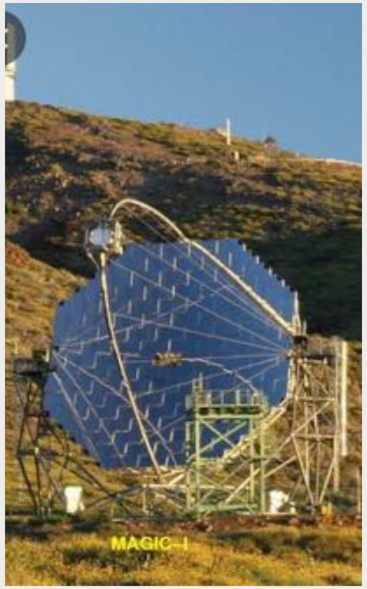
Gamma-rays

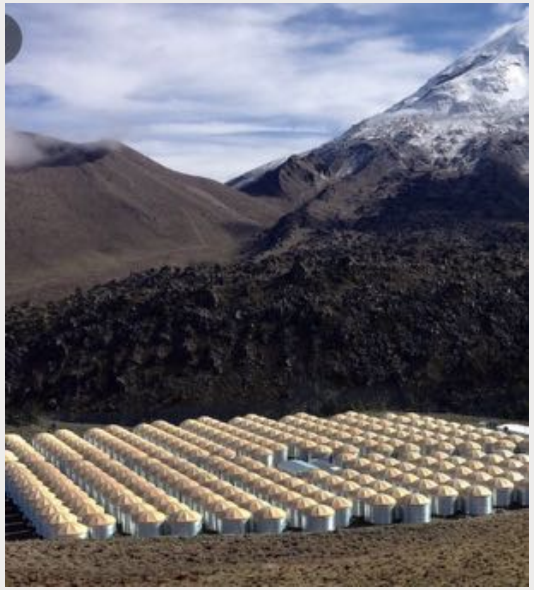


- Probes of astrophysics
- Probes of cosmic-ray physics
- Probes of fundamental physics



Experiments





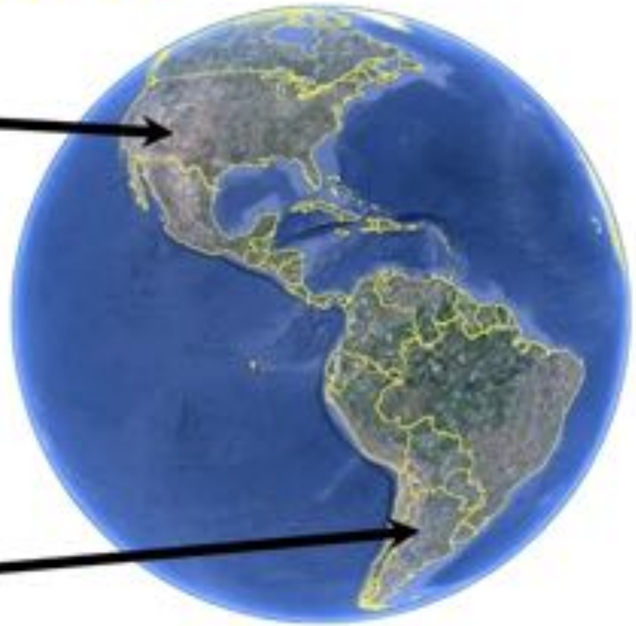
- Pick yours and
  - *Know the instrument details in details!*
  - *Know the software (contact members if needed)*
  - *Consider building an experiment, so much fun!*

Good bye and thanks!

BACKUP

COSMIC RAY DETECTORS

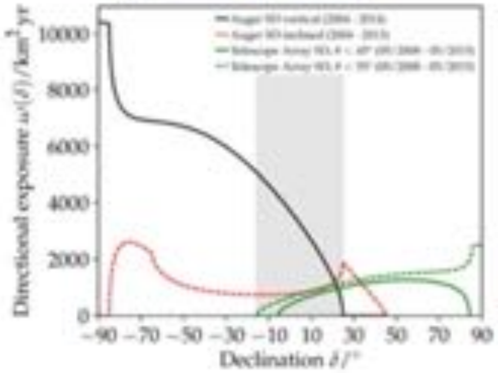
Earth Observatories



Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

Together full sky coverage



Auger:
- 6.7 x 10^4 km^2 sr yr (spectrum)
- 9 x 10^4 km^2 sr yr (anisotropy)

TA:
- 8.1 x 10^3 km^2 sr yr (spectrum)
- 8.6 x 10^3 km^2 sr yr (anisotropy)

30

The Pierre Auger Observatory

South Hemisphere

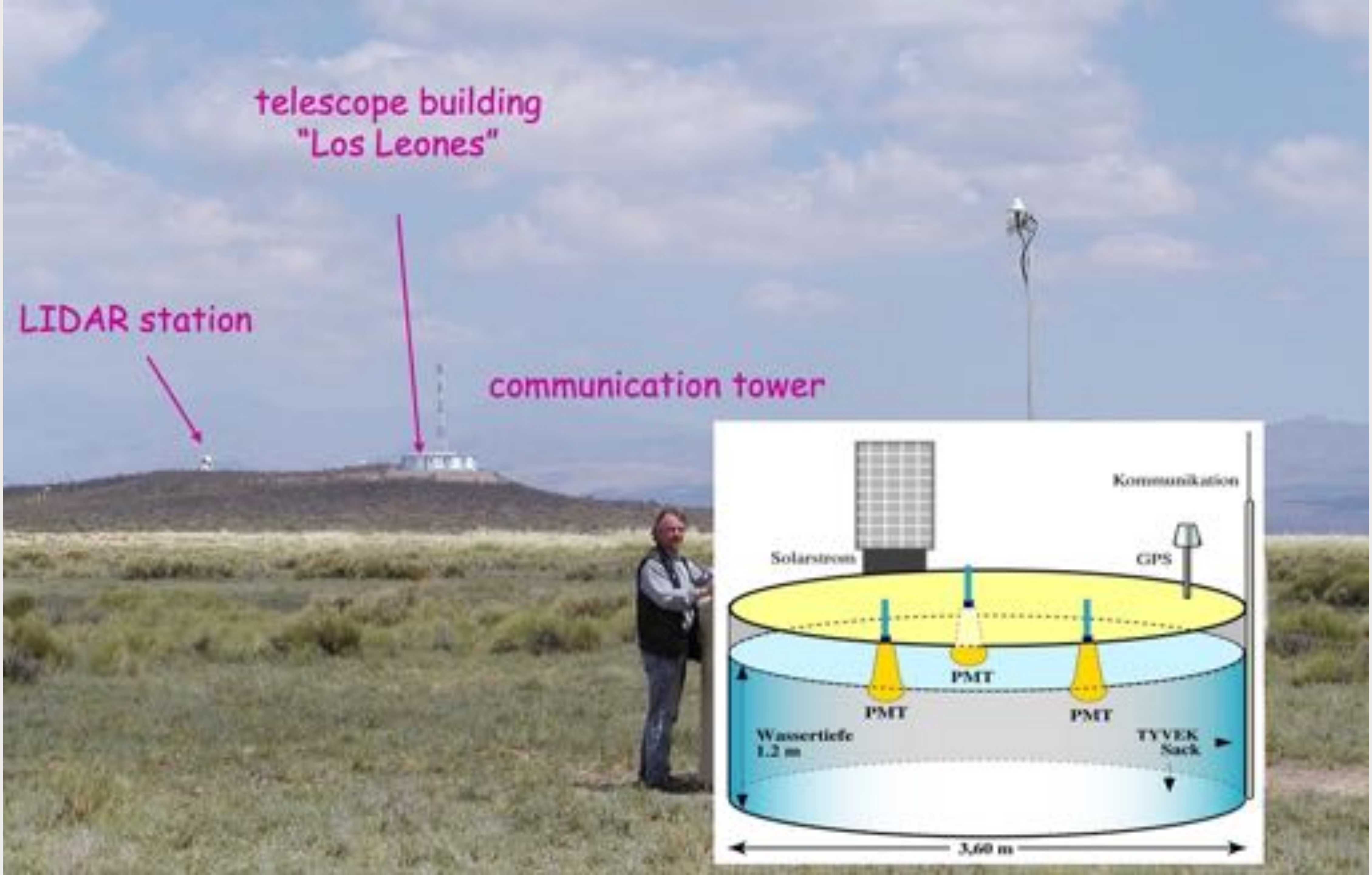
Area ~ 3000 km2

24 fluorescence telescopes

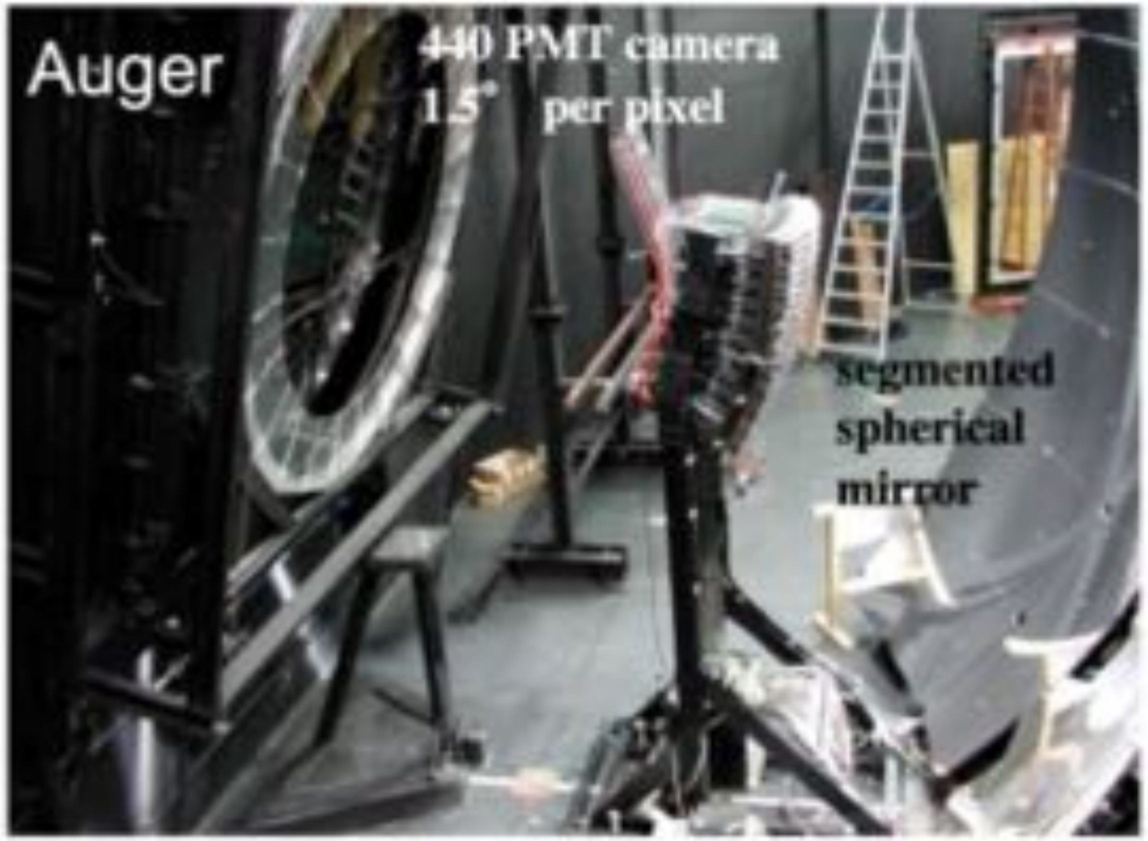
1600 water Cerenkov detectors

Malargüe, Argentina

Nov 2009


telescope building
"Los Leones"
LIDAR station
communication tower
Kommunikation
Solarstrom
GPS
PMT
PMT
PMT
Wassertiefe
1.2 m
TYVEK
Sack
3,60 m

Fluorescence detectors



HiRes

Due to the low intensity of fluorescence light, these instruments are only sensitive to showers of $E > 10^{18}$ eV

Too high a threshold for γ-ray astronomy! (but good for CR studies)

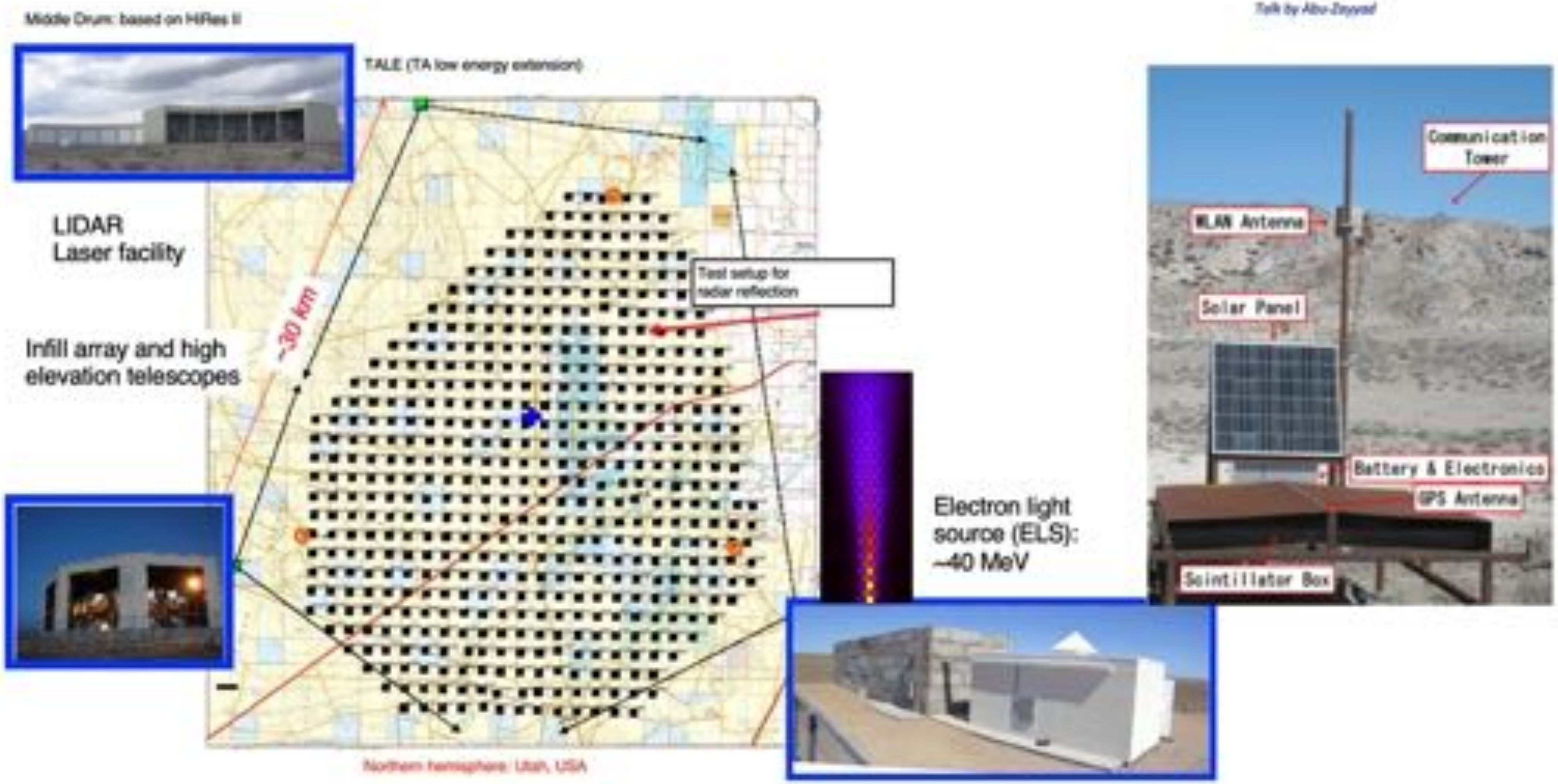
Telescope Array (TA)

Area ~ 680 km^2

3 fluorescence telescopes

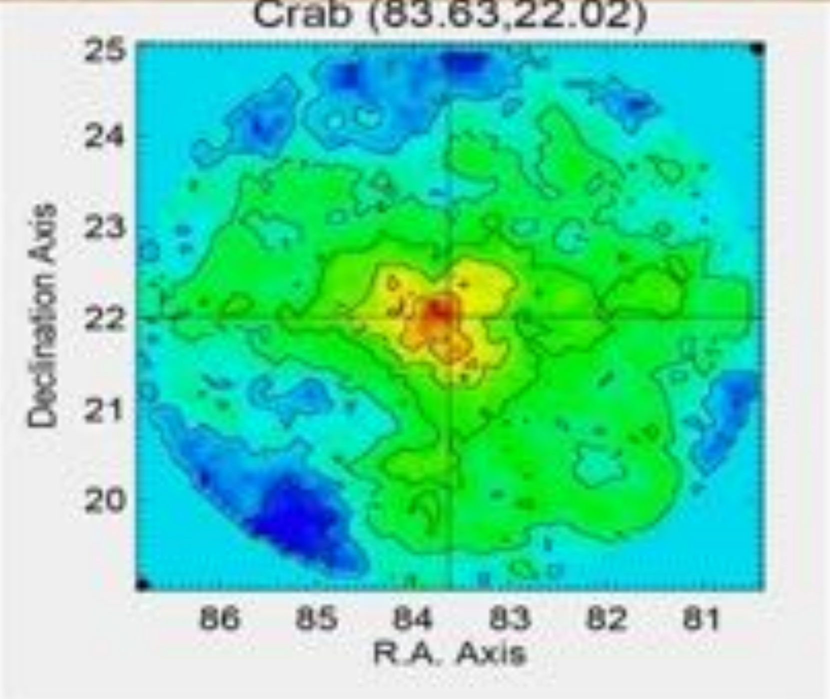
507 double-Layer scintillators

Talk by Abu-Zayyad

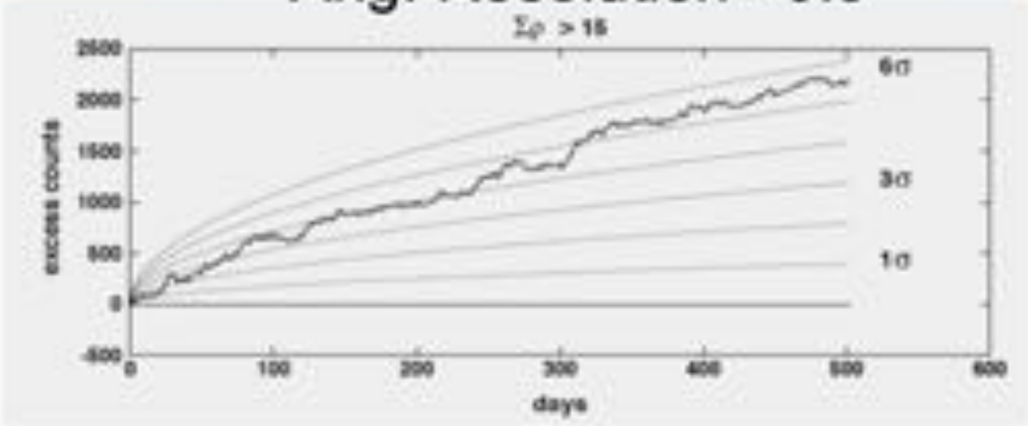


Tibet Air Shower array

4300 m a.s.l., Yangbajing

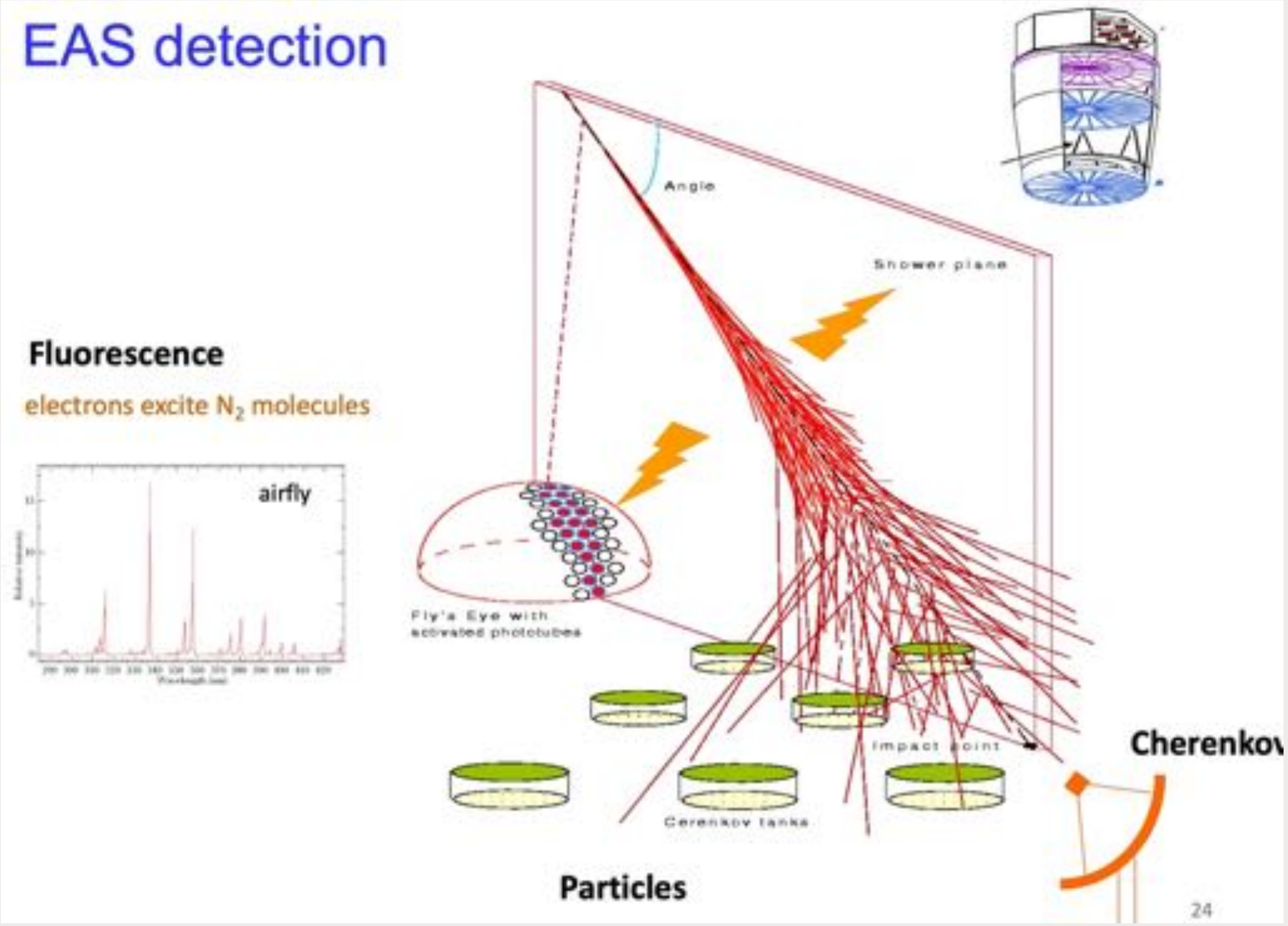


Ang. Resolution ~0.9°

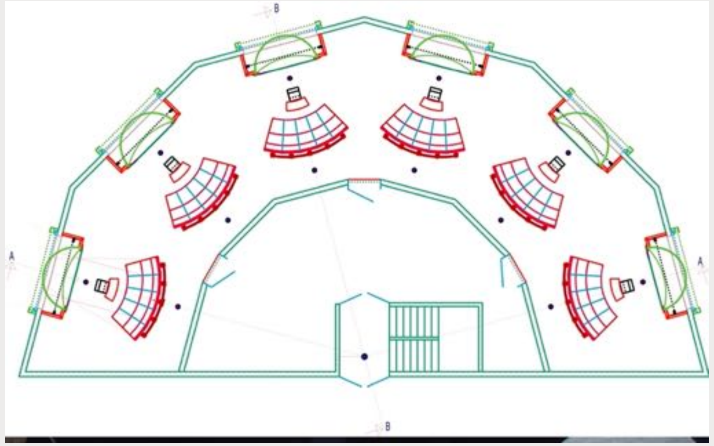


1999: Crab detection above 3 TeV (5.5 σ) in 500 days

FLUORESCENCE- (FROM CR)

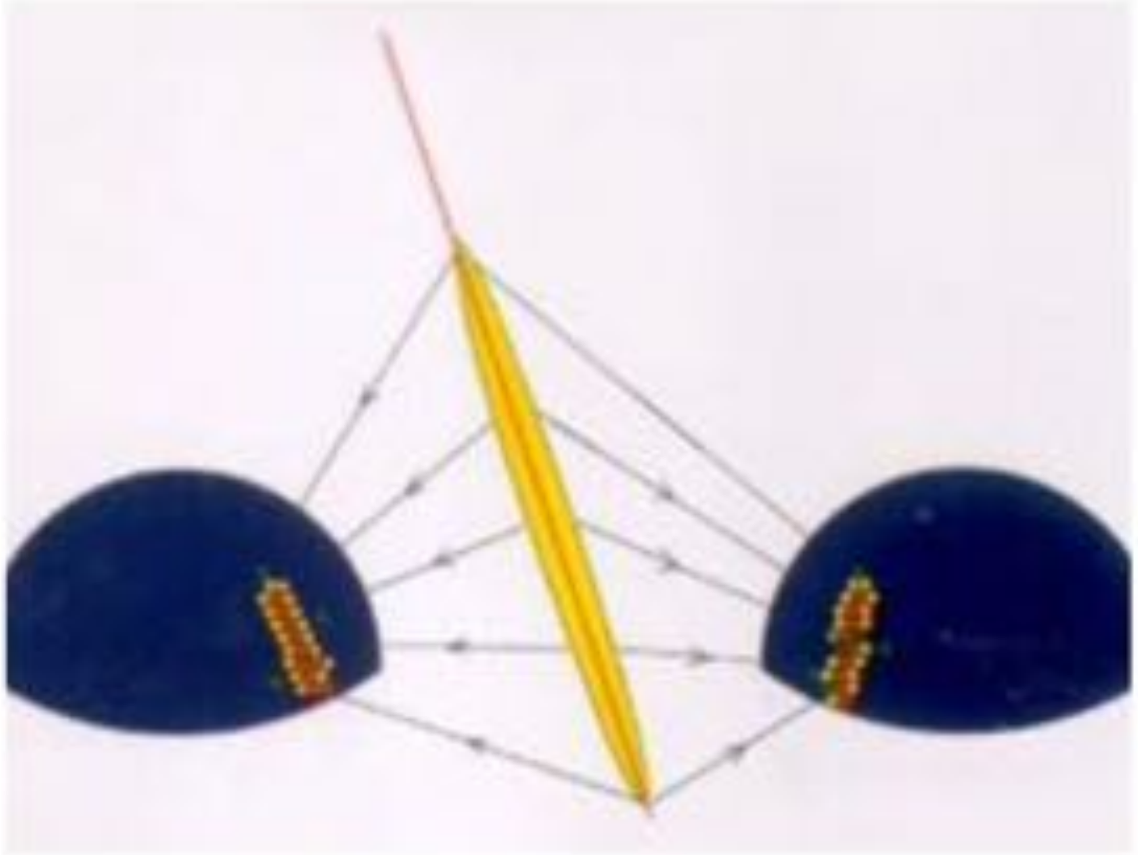

EAS detection
Angle
Shower plane
Fluorescence
electrons excite N_2 molecules
airfly
Fly's Eye with activated phototubes
Impact point
Cherenkov
Cerenkov tanks
Particles
24

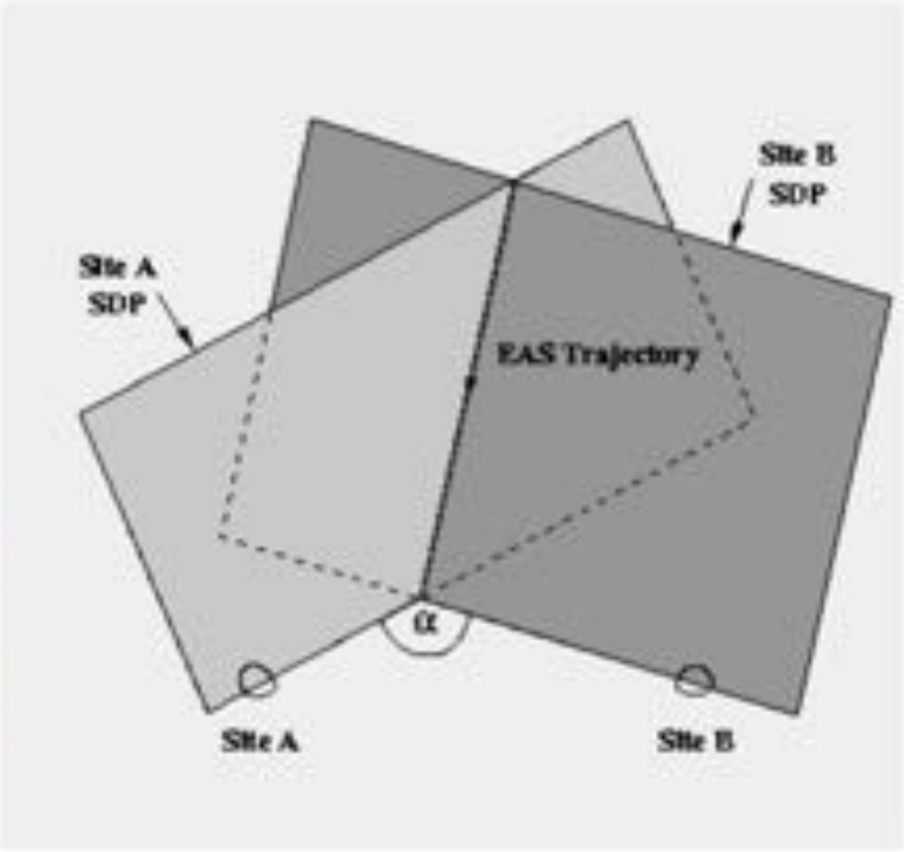

Fly's eye



Fluorescence detectors

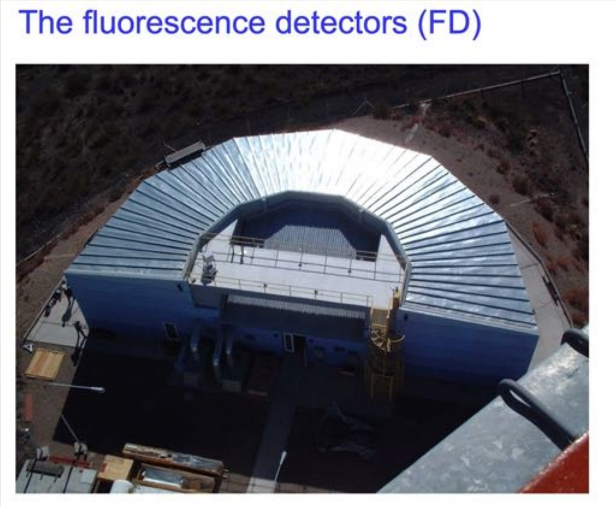
Stereo observations: better determination of shower direction and impact point

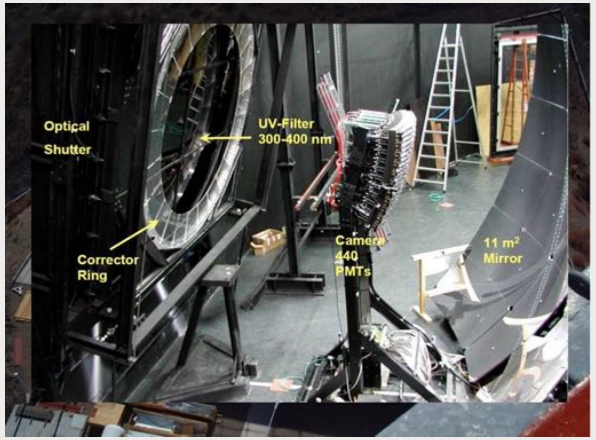




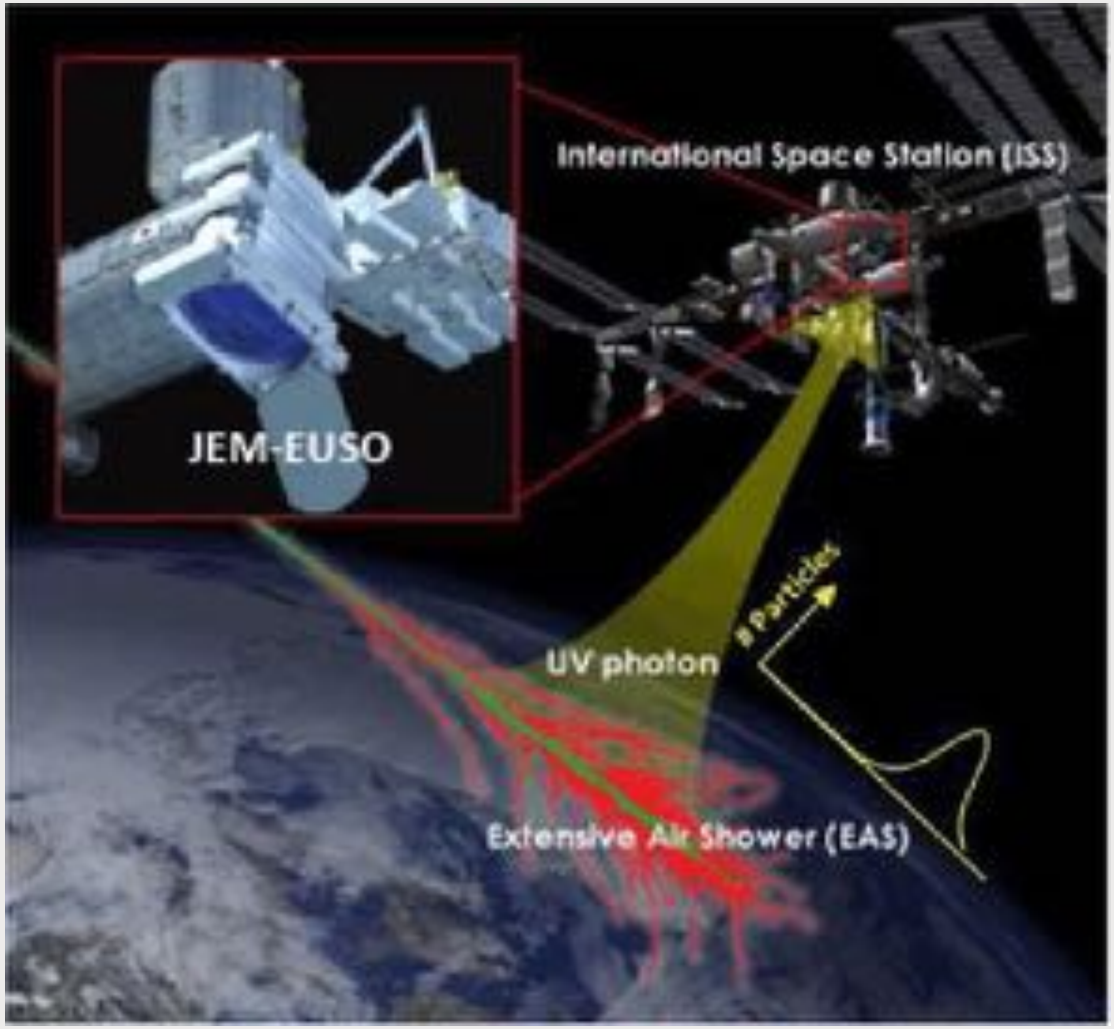
At the highest energies (EeV)

- Auger, Telescope Array





Fluorescence from space



- JEM-EUSO planned mission

HISTORY

Ground-based γ-ray astronomy in the World

Experiment	Type	Location	Altitude	Specifications
~~CACTUS~~	~~AC-Sampling~~	~~Barstow, USA~~	~~640 m~~	~~144 x 42 m^2~~
~~CANGAROO-III~~	~~AC-Imaging~~	~~Woomera, Australia~~	~~165 m~~	~~4 x 78 m^2~~
HESS	AC-Imaging	Gamsberg, Namibia	1800 m	4 x 110 m^2
MAGIC	AC-Imaging	La Palma, Spain	2250 m	1 x 226 m^2
PACT	AC-Sampling	Pachmarhi, India	1075 m	25 x 4.5 m^2
~~SHALON~~	~~AC-Imaging~~	~~Tien Shan, Kazakhstan~~	~~3338 m~~	~~1 x 11 m^2~~
~~STACEE~~	~~AC-Sampling~~	~~Albuquerque, USA~~	~~1700 m~~	~~64 x 37 m^2~~
TACTIC	AC-Imaging	Mt. Abu, India	1400 m	1 x 9.5 m^2
VERITAS	AC-Imaging	Mt. Hopkins, USA	1275 m	2 x 110 m^2
~~Whipple~~	~~AC-Imaging~~	~~Mt. Hopkins, USA~~	~~2250 m~~	~~1 x 78 m^2~~
ARGO-YBJ	Air Shower	Yangbajing, Tibet	4300 m	4000 m^2
GRAPES-III	Air Shower	Ooty, India	2200 m	288 x 1 m^2
~~Milagro~~	~~Air Shower~~	~~Los Alamos, USA~~	~~2630 m~~	~~4800 m^2~~
Tibet	Air Shower	Yangbajing, Tibet	4300 m	761 x 0.5 m^2
		LHAASO	4400	~1 km²

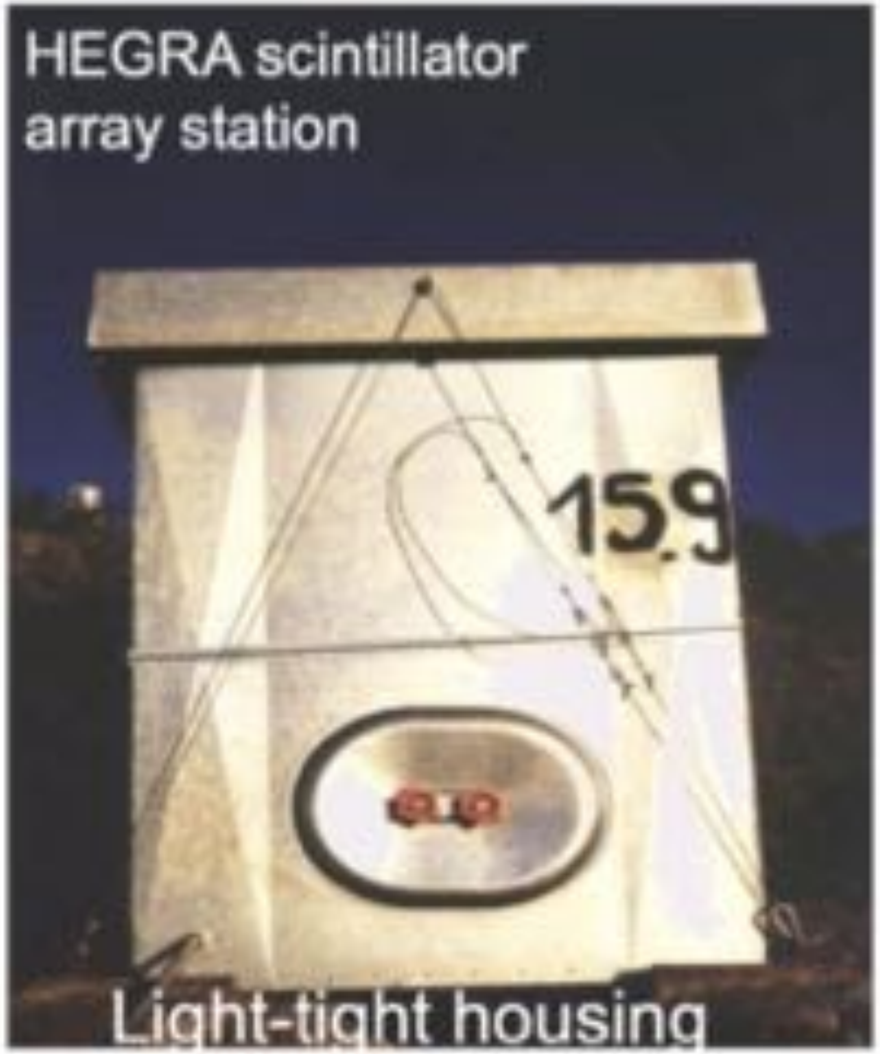
Rene Ong, 2005

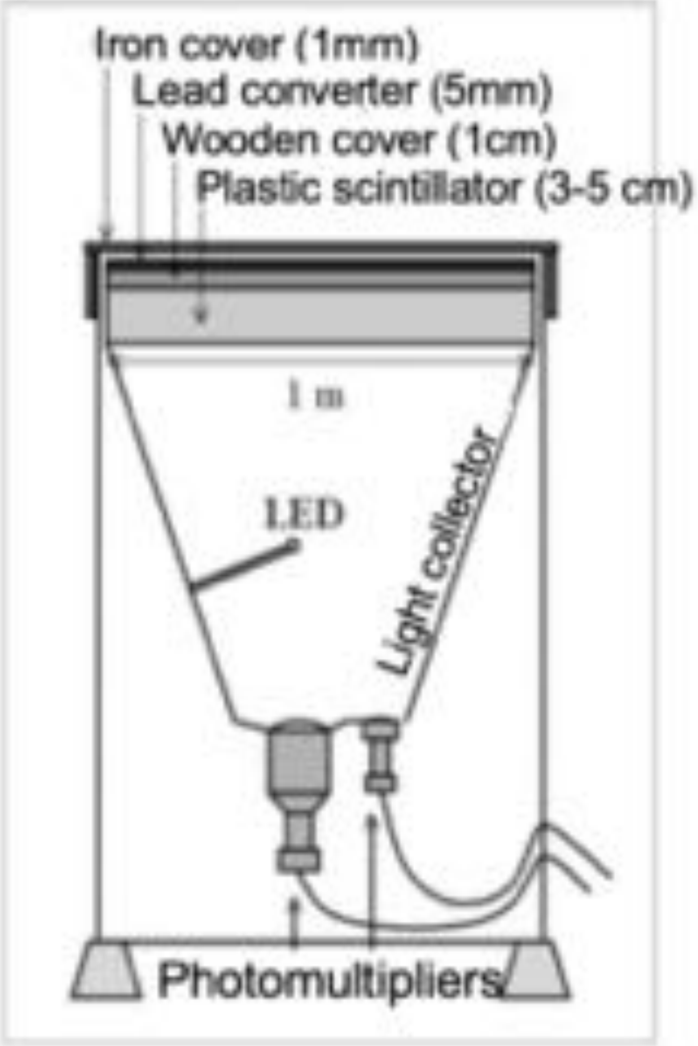
The HEGRA scintillator array

HEGRA (High Energy Gamma Ray Array)

ORM, 2200 m a.s.l. 1991 - 2000, $E_{thresh,\gamma} \approx 25$ TeV

Typical AS array detector station: Scintillator + PMT(s)



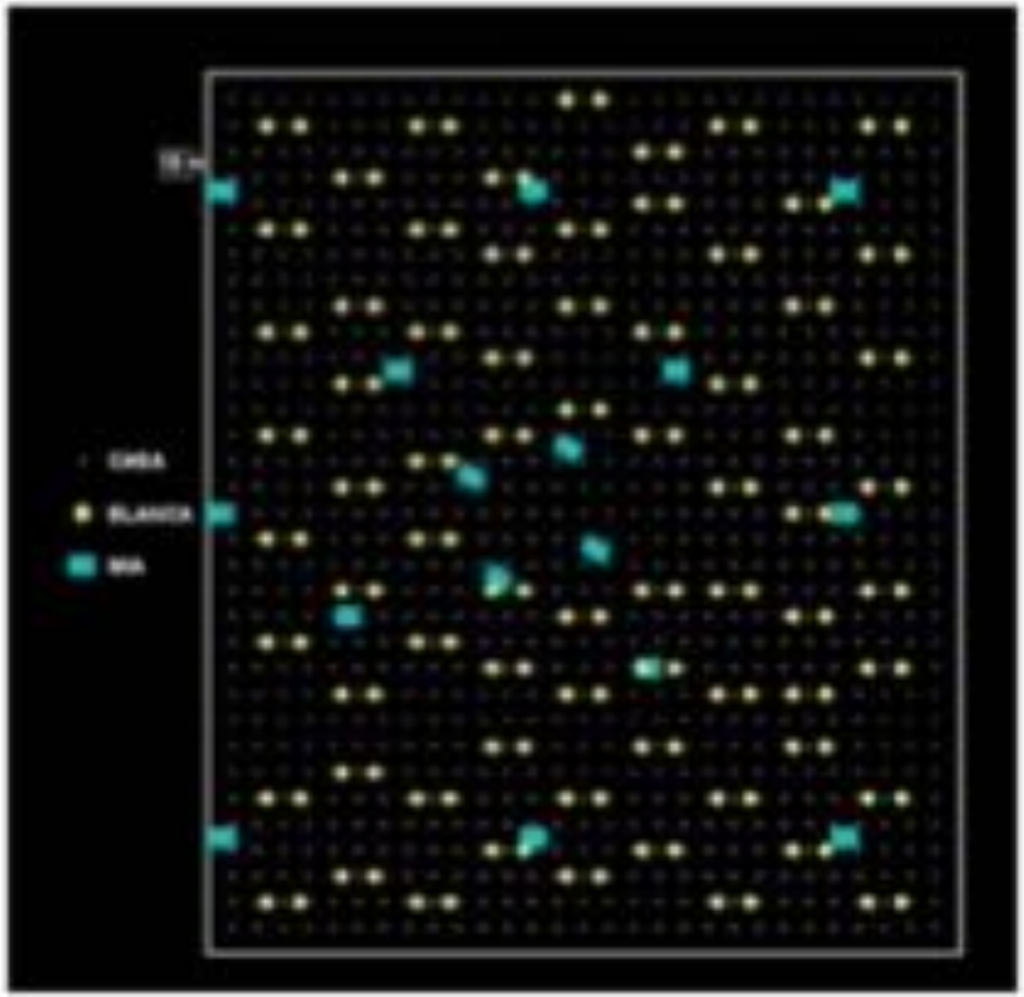


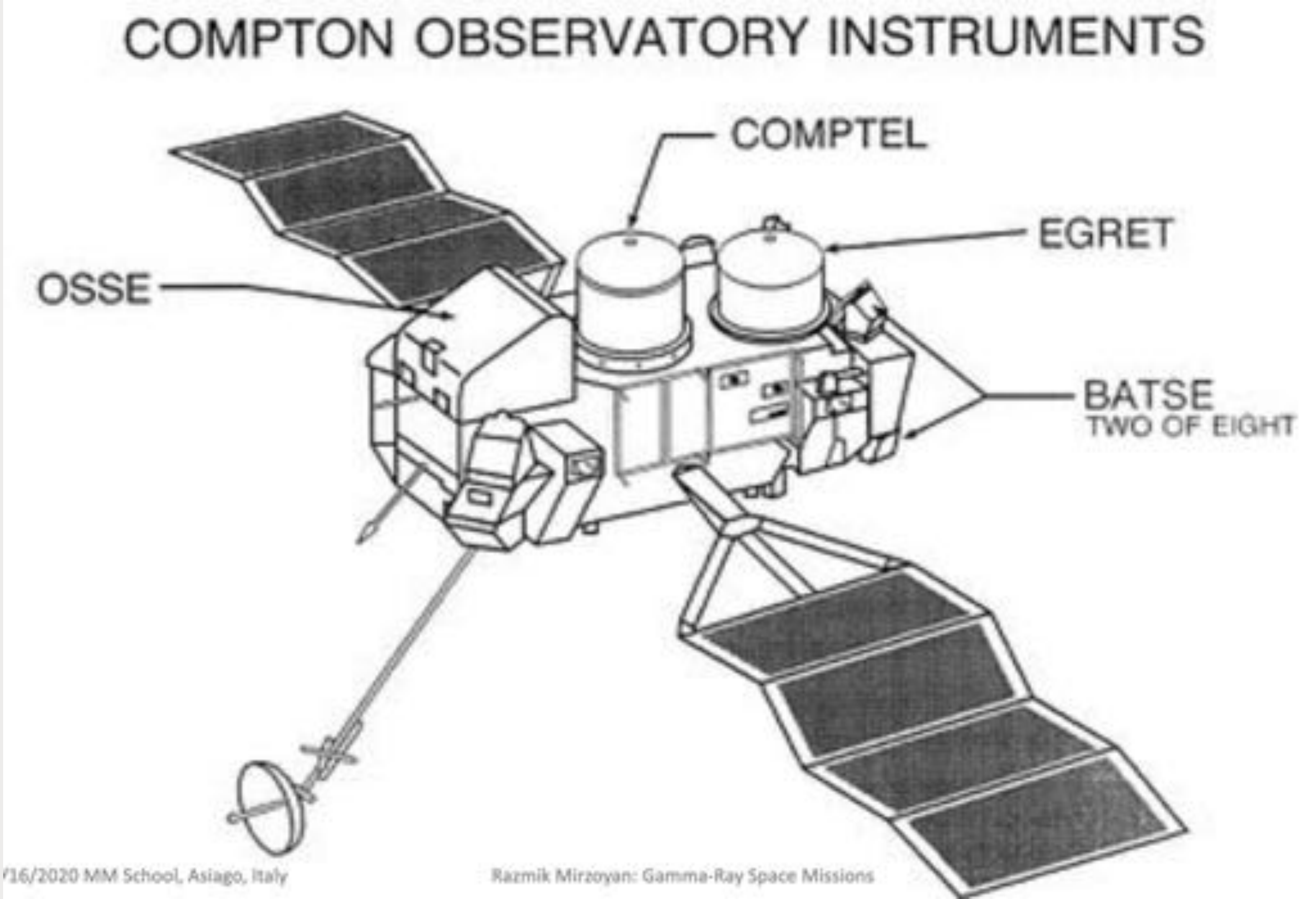
Measured light ∝ number of charged particles.

Led converter (~1 R.L.) to turn γ's into detectable $e^{\pm}$ pairs

CASA-MIA

Ground array - Chicago Air Shower Array (Dugway, Utah)

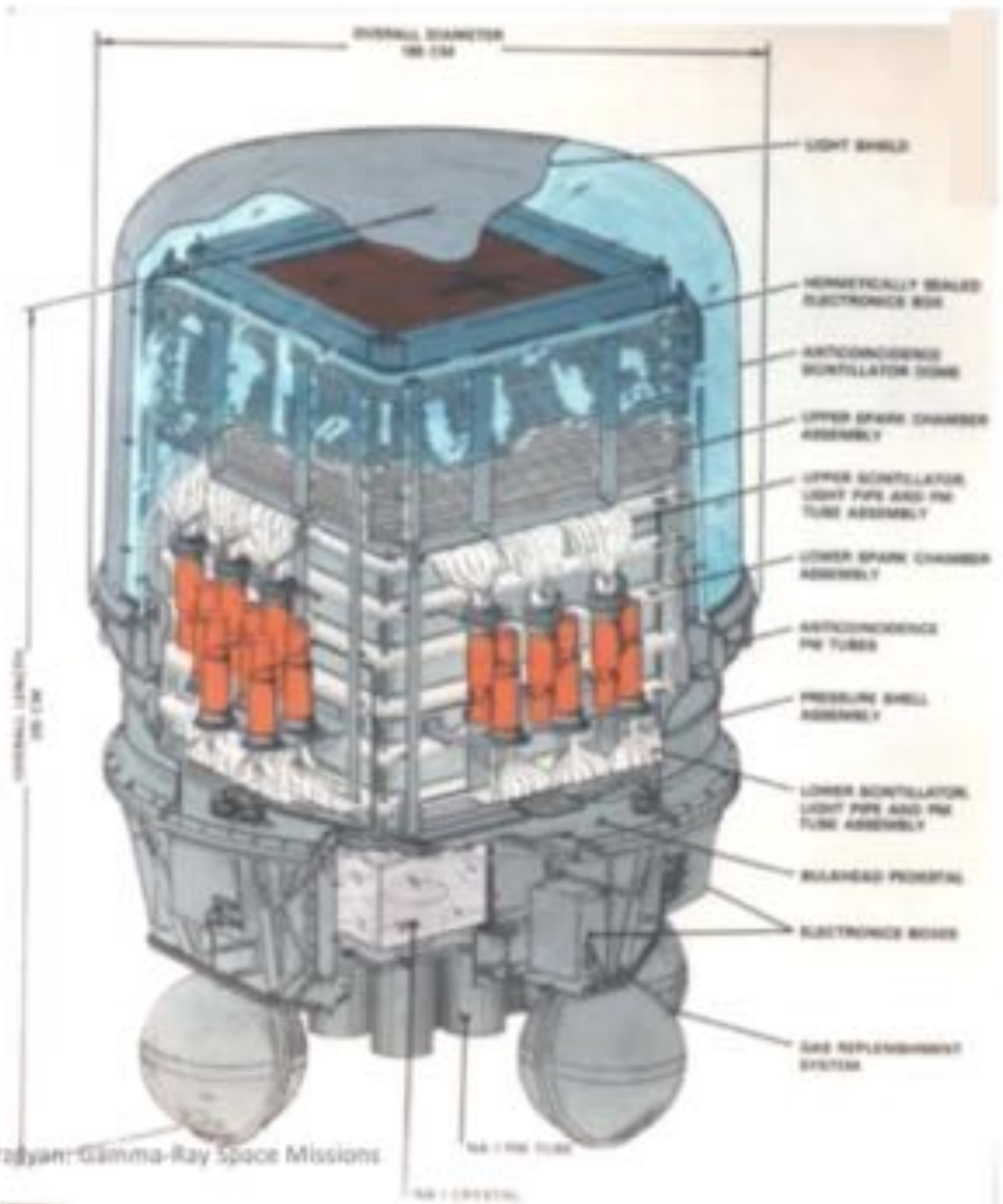


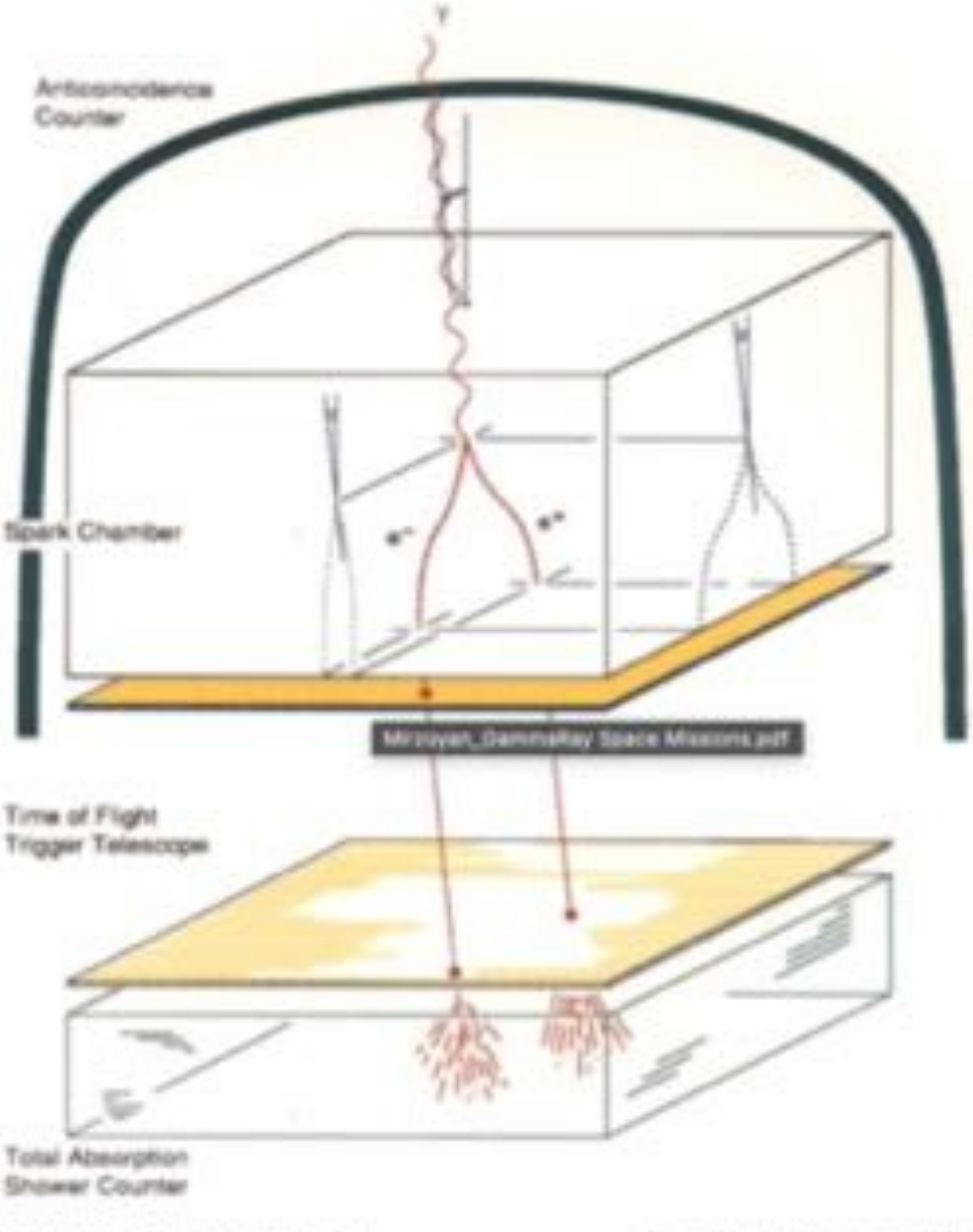

COMPTON OBSERVATORY INSTRUMENTS
COMPTEL
EGRET
OSSE
BATSE
TWO OF EIGHT

EGRET:the detector

Energy range:	20 MeV - 30 GeV
Weight:	1820 Kg
Power:	160 W
Field of view:	0. 5 sr
Dead Time:	100 ms
Effective Area (@1GeV)	1200 cm^2
Angular resolution (@100MeV)	5.8°

Sensitivity	0.1 GeV	$5x10^{-8}$
for point	1 GeV	$1x10^{-8}$
sources	10 GeV	$2x10^{-8}$
(ph cm^{-2} s^{-1})*		



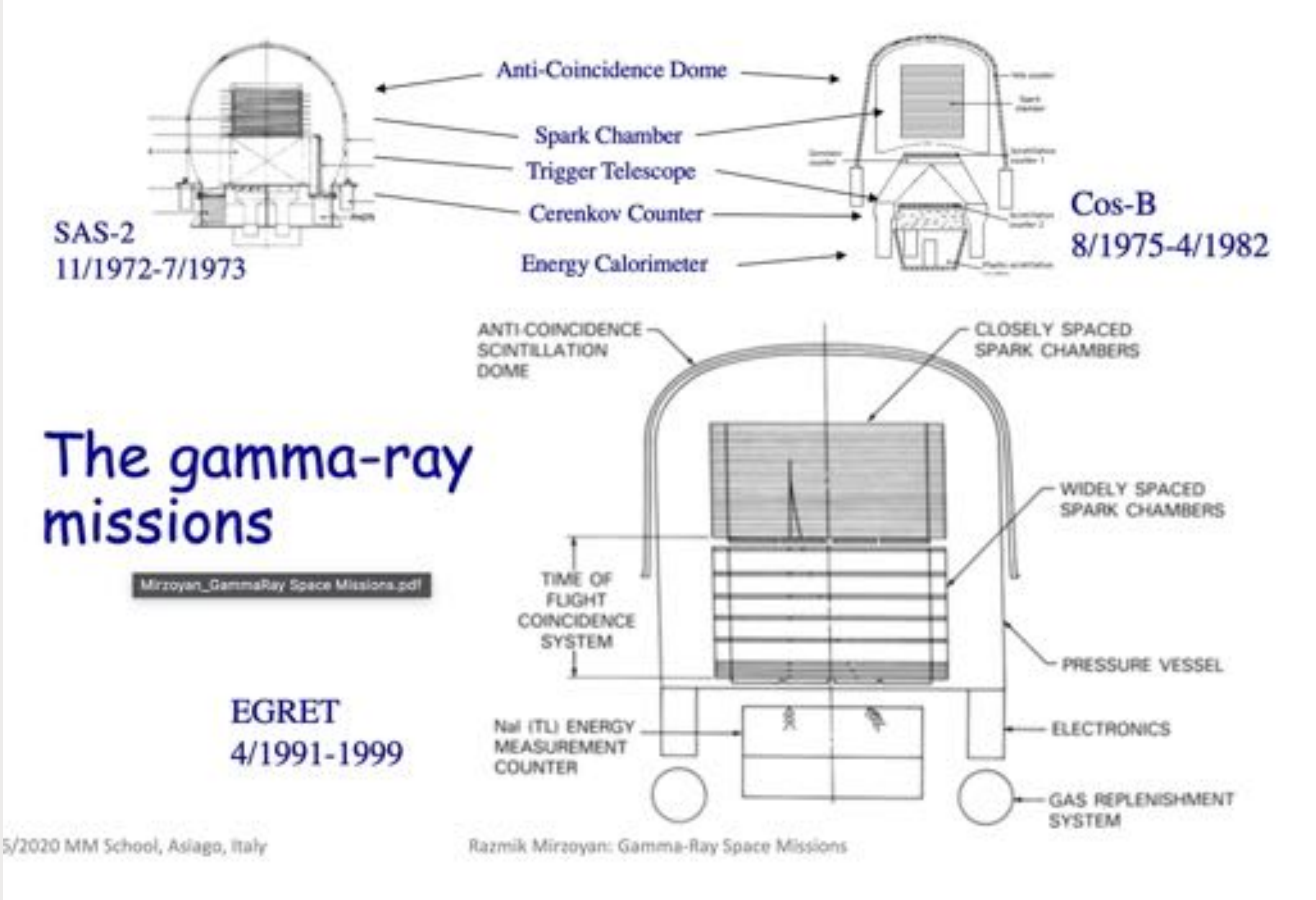


EGRET: Principle of Detection of High Energy Gamma Rays

EGRET – Principle of gamma ray detection

A γray which enters the top of the EGRET instrument will pass undetected through the **large anticoincidence scintillator** surrounding the spark chamber and has a probability 33% of converting into an electron positron pair in one of the **thin tantalum (Ta) sheets** interleaved between the **28 closely spaced spark chambers** in the upper portion of the instrument.

Below the conversion stack are **two 4 x 4 arrays of plastic scintillation** detector tiles spaced 60 cm apart which register the passage of charged particles. If the timeofflight delay indicates a downward moving particle which passed through a valid combination of upper and lower scintillator tiles, and the anticoincidence system has not been triggered by a charged particle, the track information is recorded digitally. In this manner, a three dimensional picture of the path of the electronpositron pair is measured. **The energy deposition** in the NaI(Tl) Total absorption Shower Counter (TASC) located directly below the lower array of plastic scintillators is used to estimate the photon energy.

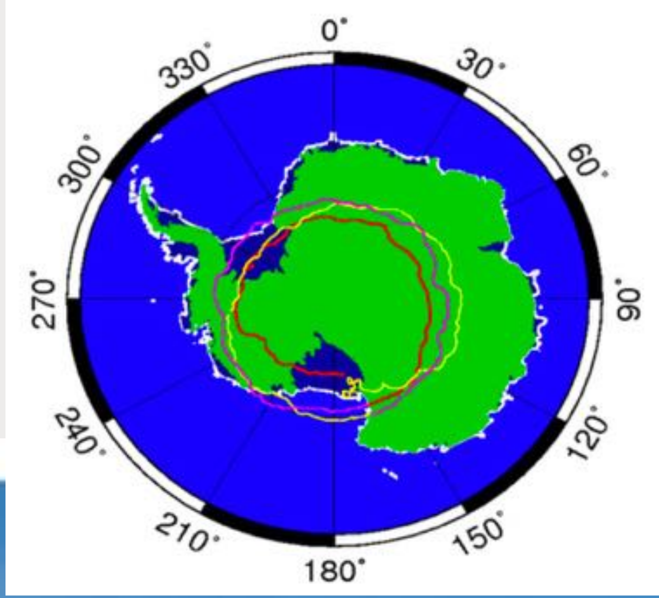

Anti-Coincidence Dome
Spark Chamber
Trigger Telescope
Cerenkov Counter
Energy Calorimeter
SAS-2
11/1972-7/1973
Cos-B
8/1975-4/1982
The gamma-ray missions
Mirzoyan_GammaRay Space Missions.pdf
ANTI-COINCIDENCE SCINTILLATION DOME
CLOSELY SPACED SPARK CHAMBERS
WIDELY SPACED SPARK CHAMBERS
TIME OF FLIGHT COINCIDENCE SYSTEM
PRESSURE VESSEL
NaI (TL) ENERGY MEASUREMENT COUNTER
ELECTRONICS
GAS REPLENISHMENT SYSTEM
EGRET
4/1991-1999
5/2020 MM School, Asiago, Italy
Razmik Mirzoyan: Gamma-Ray Space Missions

The Pioneer Trevor Weekes and his 10m Ø Whipple telescope gave birth to γ-ray astrophysics: 9σ from Crab Nebula in 1988 !

„If a telescope can within a few s evaporate a solid piece of steel, it can also measure gamma rays“ ;-)

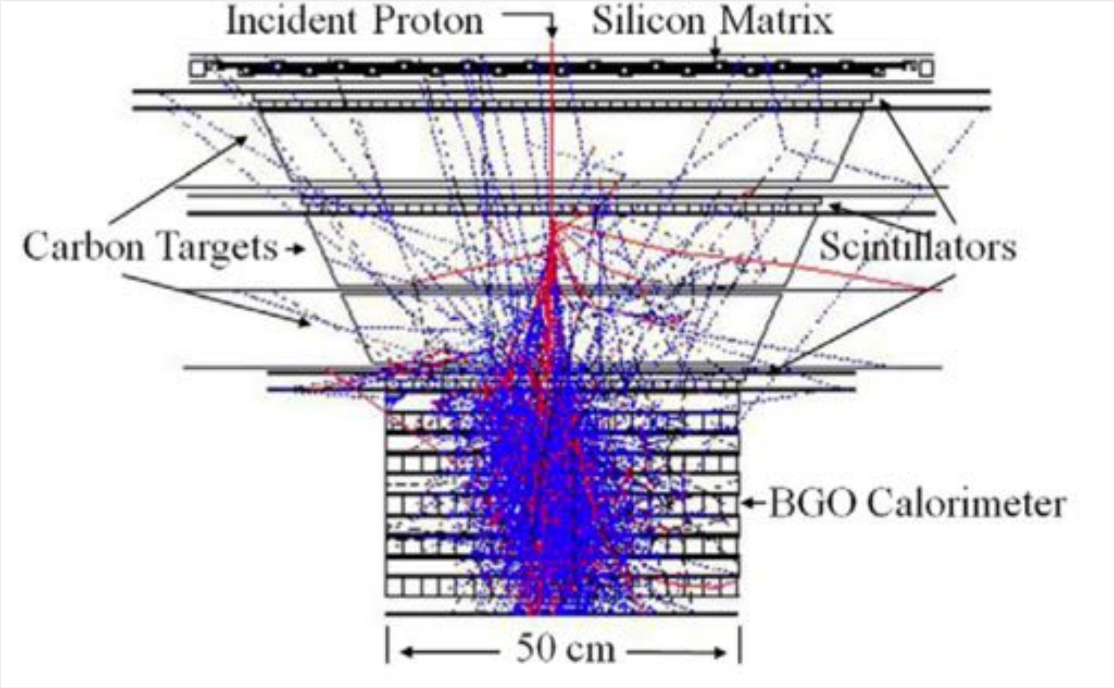
The 1st telescope (of 5 planned) we´ve built: 1989

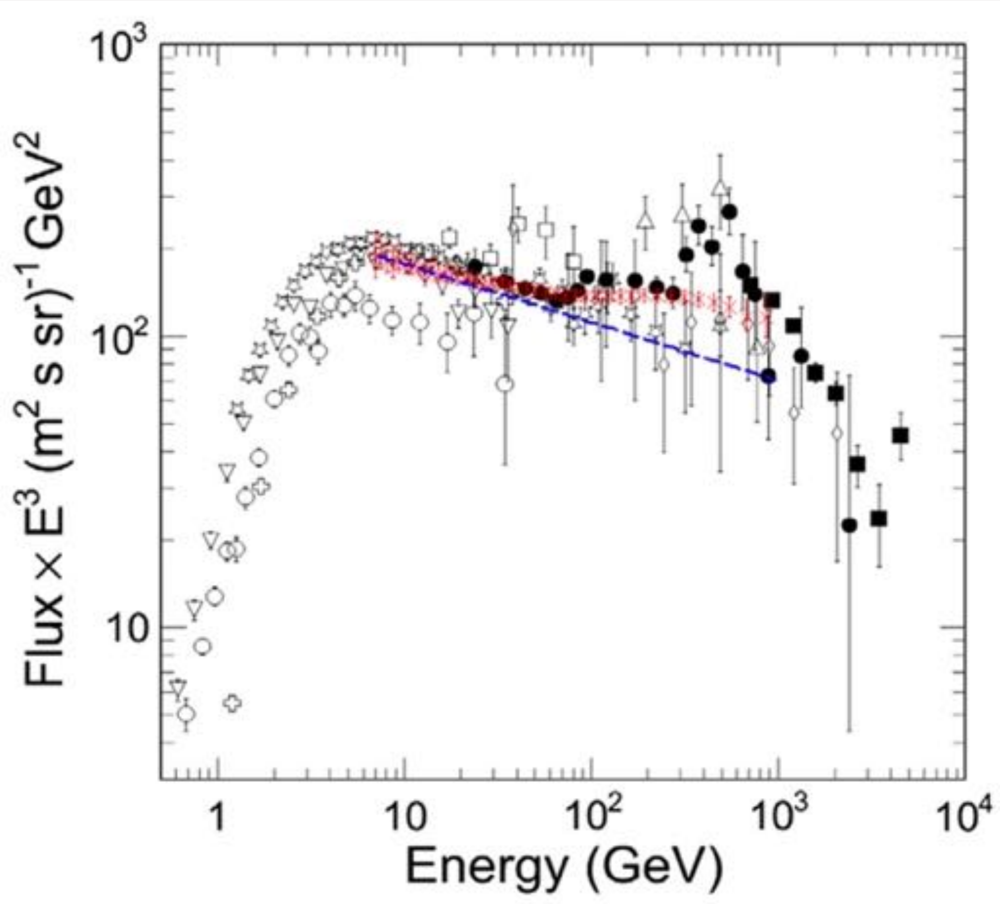
BALOONS



- currently limited to □1015 eV
- incident particles are identified element-by-element with excellent charge resolution.
- A challenge of balloon-borne experiments is that the detectors must be large enough to collect adequate statistics,

e.g. ATIC





- currently limited to 10^{15} eV
- incident particles are identified element-by-element with excellent charge resolution.
- A challenge of balloon-borne experiments is that the detectors must be large enough to collect adequate statistics,

Astroparticle Physics 39–40 (2012) 76–87

Table 1
Comparison of balloon borne experiments for high-energy cosmic ray measurements.

Instrument	Energy measurement technique	Charge range and resolution	Flight duration	Atmospheric depth[a] (g/cm^2)	Effective exposure (m^2-sr-days)	Observed number of protons >6 TeV
ATIC	Calorimeter (0.75 λ_I, 18 X_0)	$1 \leq Z \leq 28$ $\Delta Z = 0.3$	~48 days	4.3 (7.9)	5	~720
TRACER[a]	TRD	$8 \leq Z \leq 28$ $\Delta Z = 0.3$ (O) 0.5 (Fe) $3 < Z \leq 28$ $\Delta Z = 0.3$ (O) 0.5 (Fe)	~10 days ~4 days	3.9 (9.2)	50 20	None
CREAM	Calorimeter (0.5 λ_I, 20 X_0)	$1 \leq Z \leq 28$ $\Delta Z = 0.2$	~160 days	3.9 (6.8)	48	>5000
	TRD	$3 < Z \leq 28$ $\Delta Z = 0.2$	~42 days	3.9(7.9)	55	None
JACEE	Emulsion (~0.05 λ_I, ~4 X_0)	$1 \leq Z \leq 28$ Charge group	~60 days (1436 m^2 hr)	5.3 (28)	~10 (644 m^2 hr)	656
RUNJOB	Emulsion (~0.2 λ_I, ~4 X_0)	$1 \leq Z \leq 28$ Charge group	~60 days (575 m^2 hr)	10 (48)	6 (p); 24 (>C)	Close to JACEE

[a] The average vertical depth is shown with the maximum depth considering the angle acceptance in parentheses.

- BESS, CAPRICE, HEAT, GAPS, TRACER, HEAO, JACEE