Wide field-of-view gamma-ray observatories

Christopher van Eldik • ECAP
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35+ years of ground-based gamma-ray observations

THE ASTROPHYSICAL JOURNAL, **342**:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

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ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

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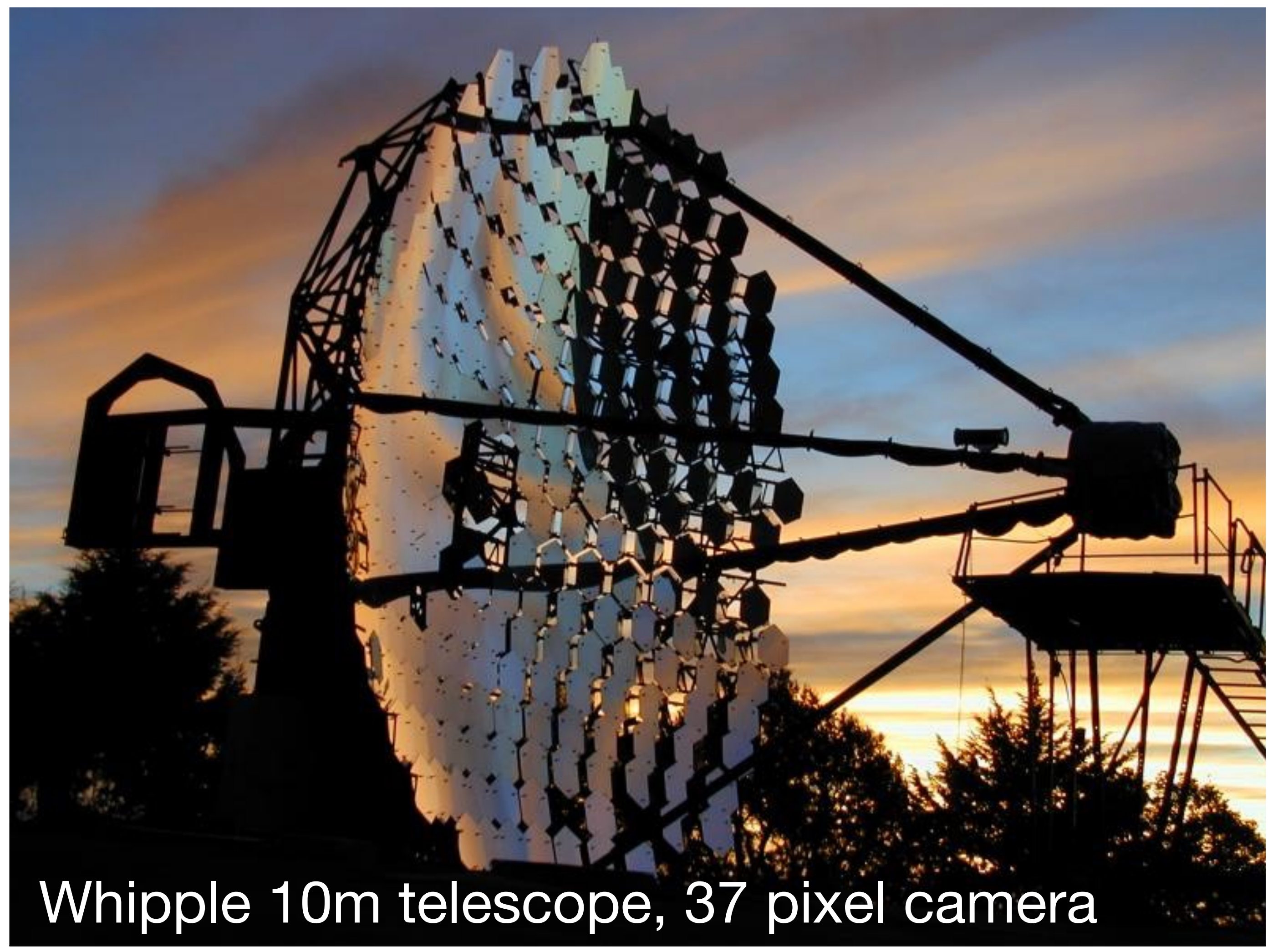
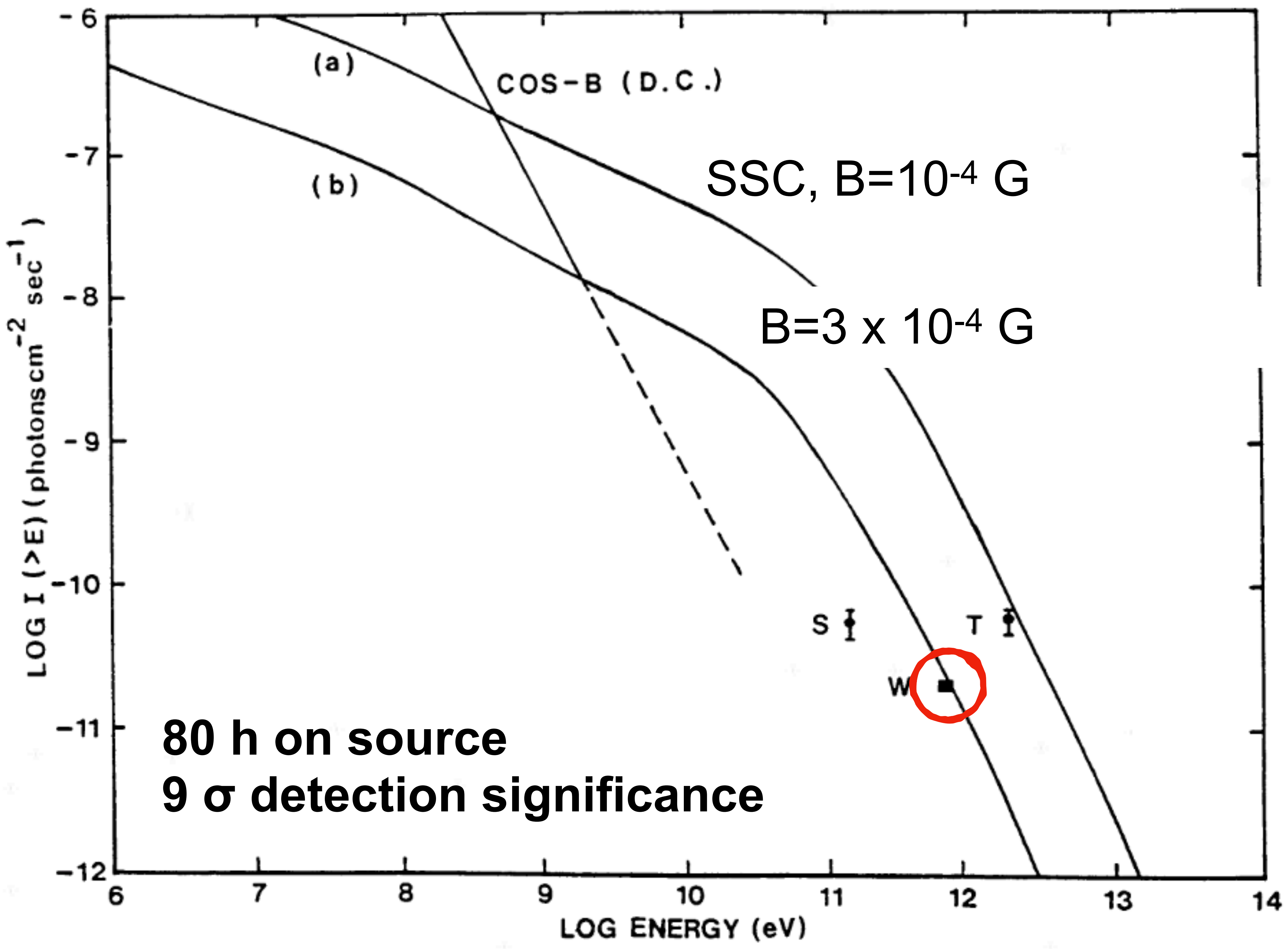
Weekes et al. (1989)



Whipple 10m telescope, 37 pixel camera



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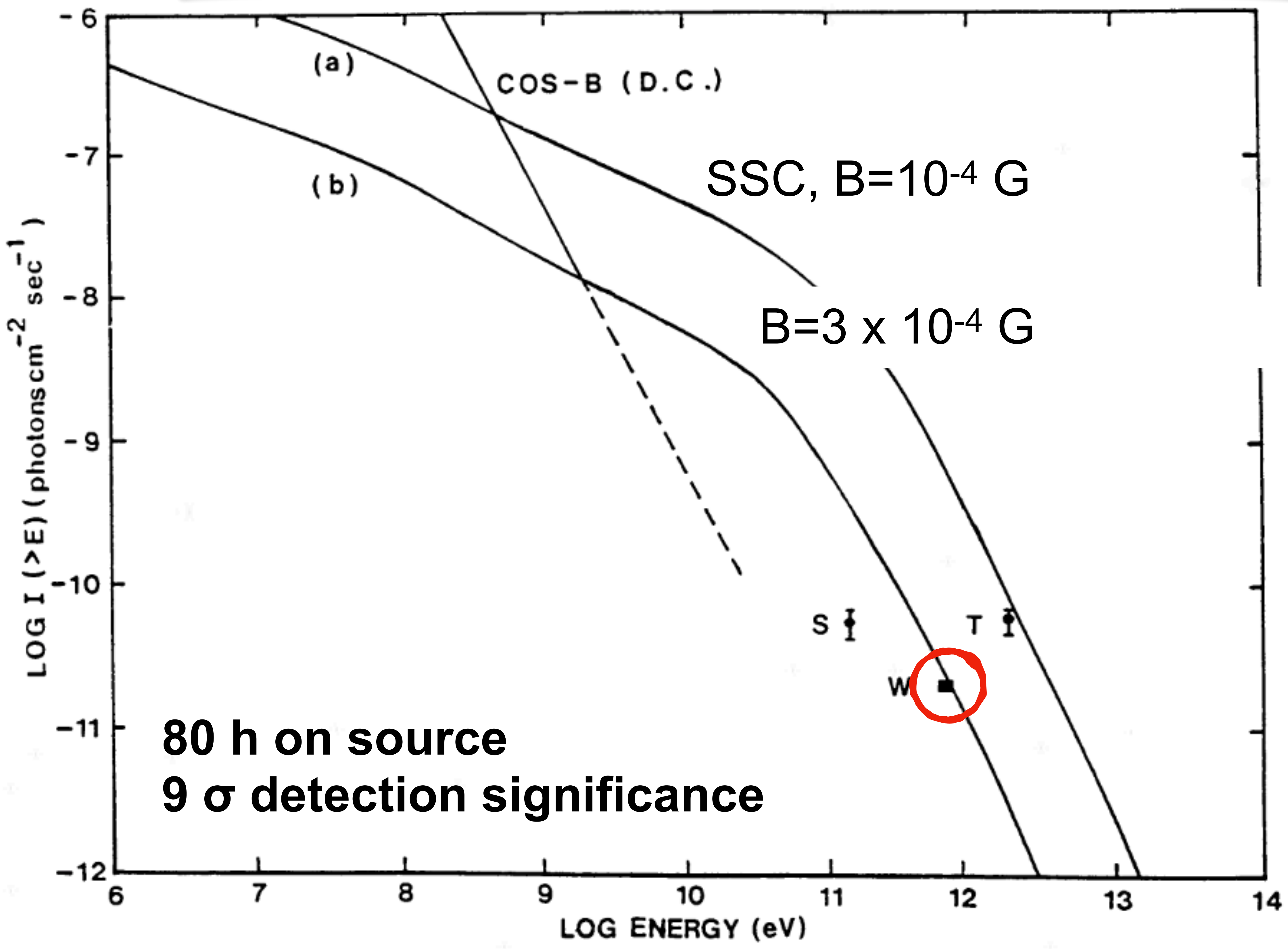
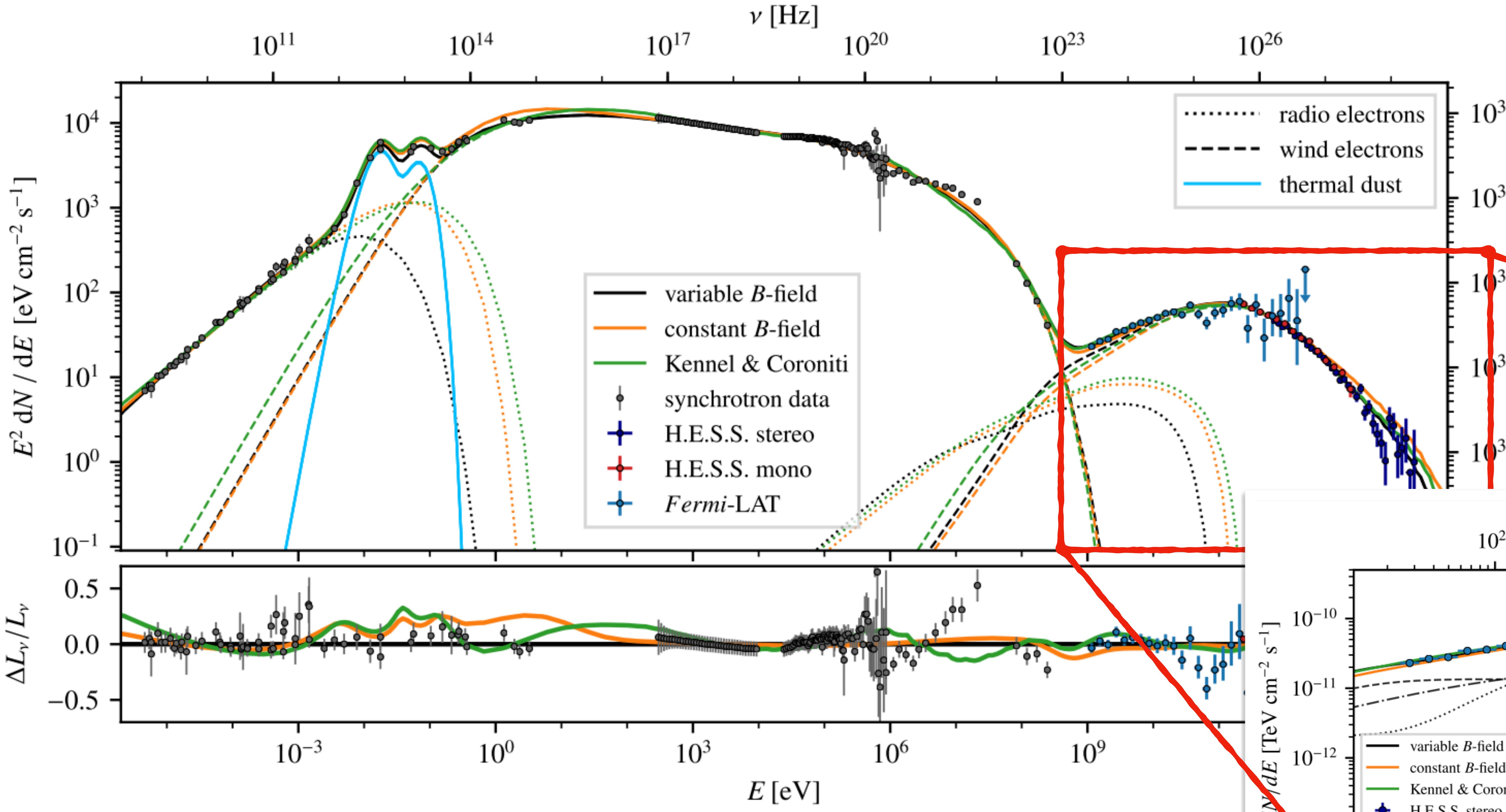
Weekes et al. (1989)

The existence of a steady source of TeV gamma rays has important consequences for the development of the field. For years significant improvements have been hampered by the absence of a standard candle which would act as a means to calibrate and test new techniques. Although weak, the Crab Nebula appears to have the stability necessary for this role. It will be of interest therefore to compare the results from other experiments when they devote time to the study of the steady emission from this source.

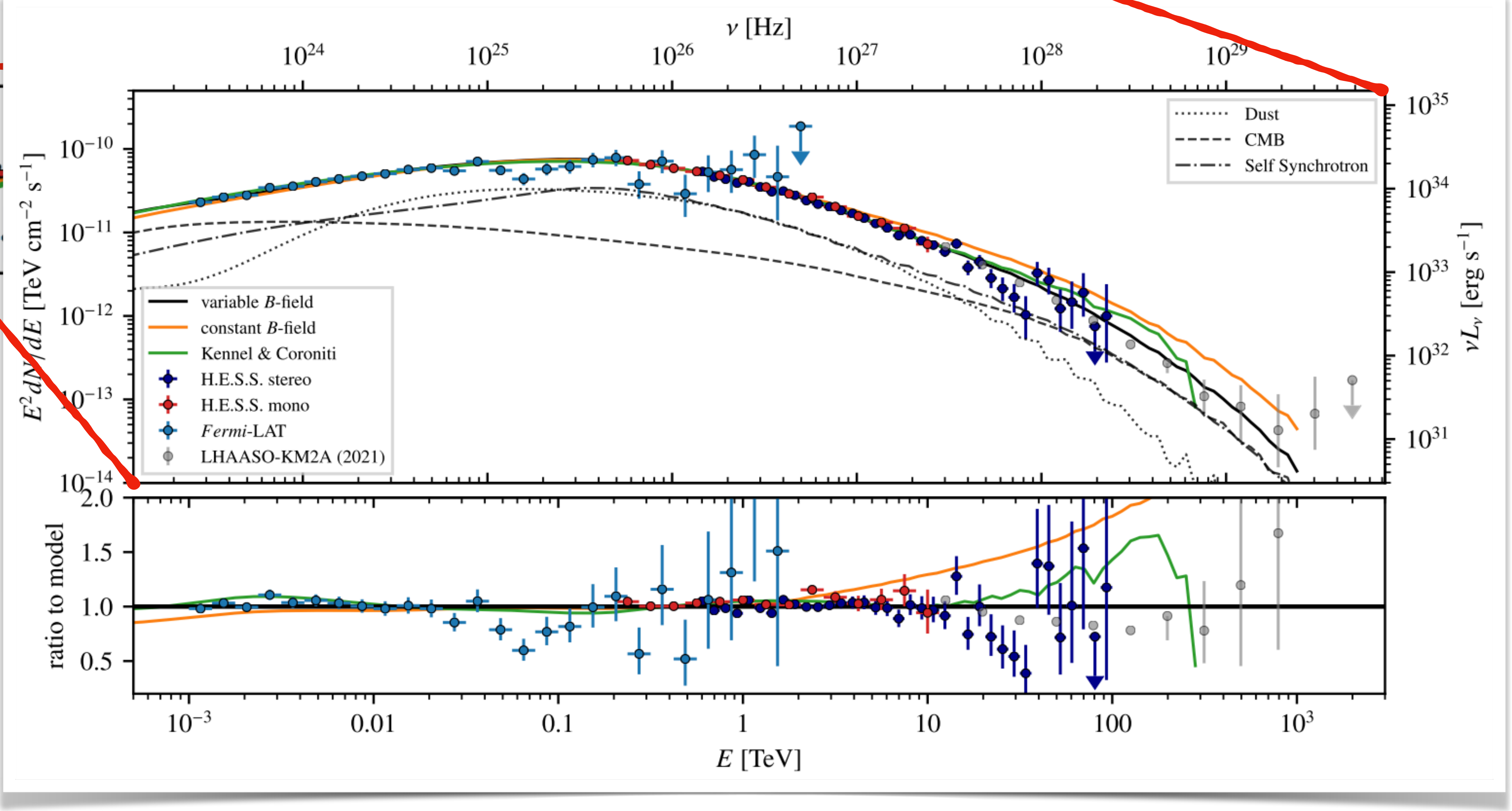


35+ years of ground-based gamma-ray observations



Parameter	variable B-field model	constant B-field model	Kennel & Coroniti
$\ln(n_{r,0})$	117.170	117.69	118.766
$\ln(\gamma_{r,\min})$	3.09 (fixed)	3.09 (fixed)	3.09 (fixed)
$\ln(\gamma_{r,\max})$	11.599	12.35	12.625
s_r	−1.5439	−1.649	−1.7419
ρ_r [″]	88.3	80.40	88.64
$\ln(n_{w,0})$	76.822	76.8315	−27.625
$\ln(\gamma_{w,\min})$	12.841	12.69	12.8366
$\ln(\gamma_{w,1})$	15.26	14.24	—
$\ln(\gamma_{w,2})$	19.197	19.35379	17.96
$\ln(\gamma_{w,\max})$	22.115	22.371	22.251
$\beta_{\min}$	2.8 (fixed)	2.8 (fixed)	2.8 (fixed)
$\beta_{\max}$	2 (fixed)	2 (fixed)	2 (fixed)
[illegible]	[illegible].117	−2.75	—
[illegible]	[illegible]3928	−3.1764	−2.8695
[illegible]	[illegible].782	−3.5118	−2.316
$\rho_{w,0}$ [″]	98.14	78.94	—
α_w	0.12544	0.11973	—
B_0 [μG]	256.4	126.39	—
r_s [″]	13.4 (fixed)	13.4 (fixed)	13.4 (fixed)
α	−0.4691	—	—
σ	—	—	0.021396
$\ln(L_{\text{spin-down}}$[erg/s])	—	—	88.716
$r_{\text{dust,in}}$ [pc]	0.55 (fixed)	0.55 (fixed)	0.55 (fixed)
$r_{\text{dust,out}}$ [pc]	1.53 (fixed)	1.53 (fixed)	1.53 (fixed)
$\log_{10}(M_1/M_\odot)$	−4.4 (fixed)	−4.4 (fixed)	−4.4 (fixed)
$\log_{10}(M_2/M_\odot)$	−1.2 (fixed)	−1.2 (fixed)	−1.2 (fixed)
T_1 [K]	149 (fixed)	149 (fixed)	149 (fixed)
T_2 [K]	39 (fixed)	39 (fixed)	39 (fixed)

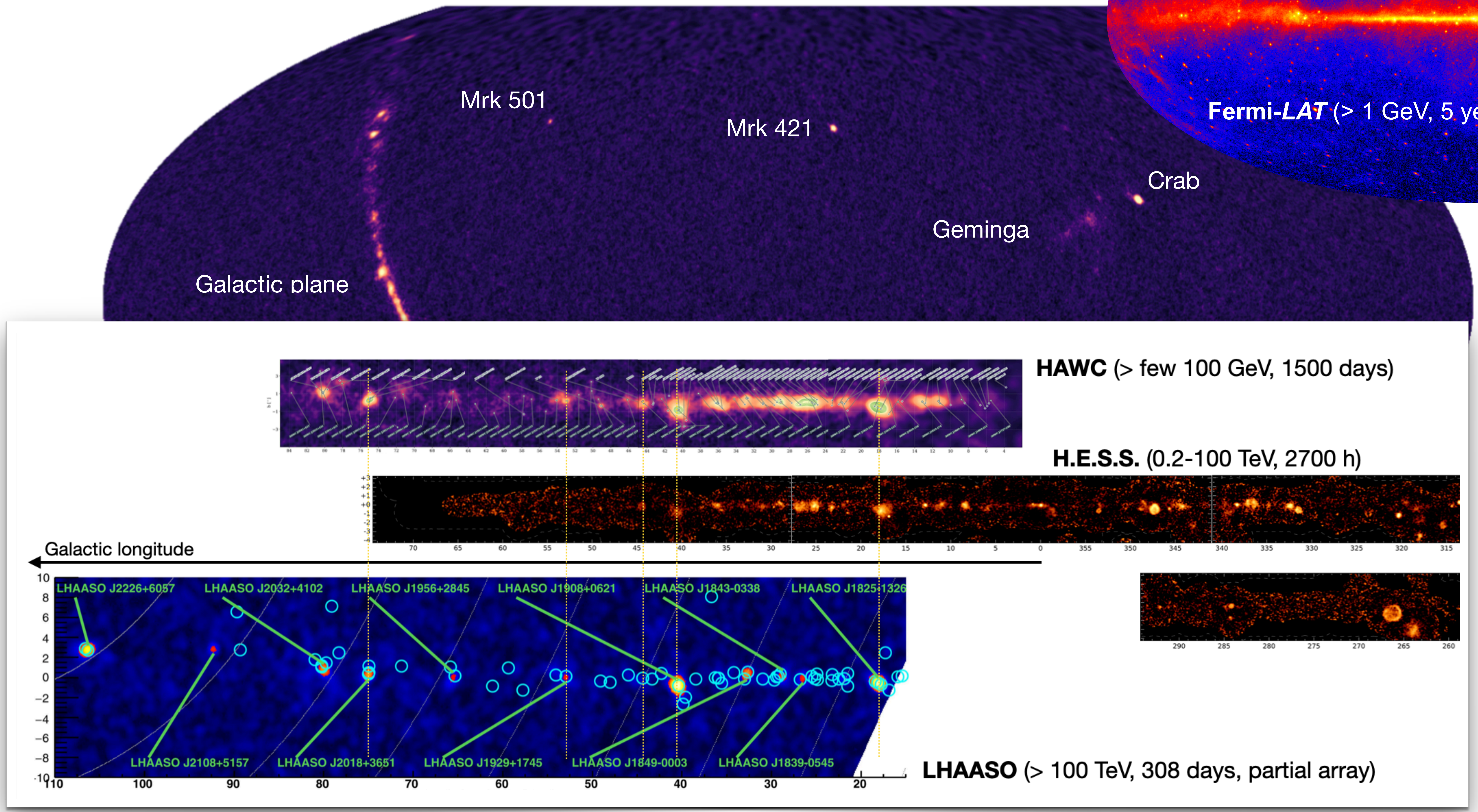
H.E.S.S. Coll. et al. (2024)

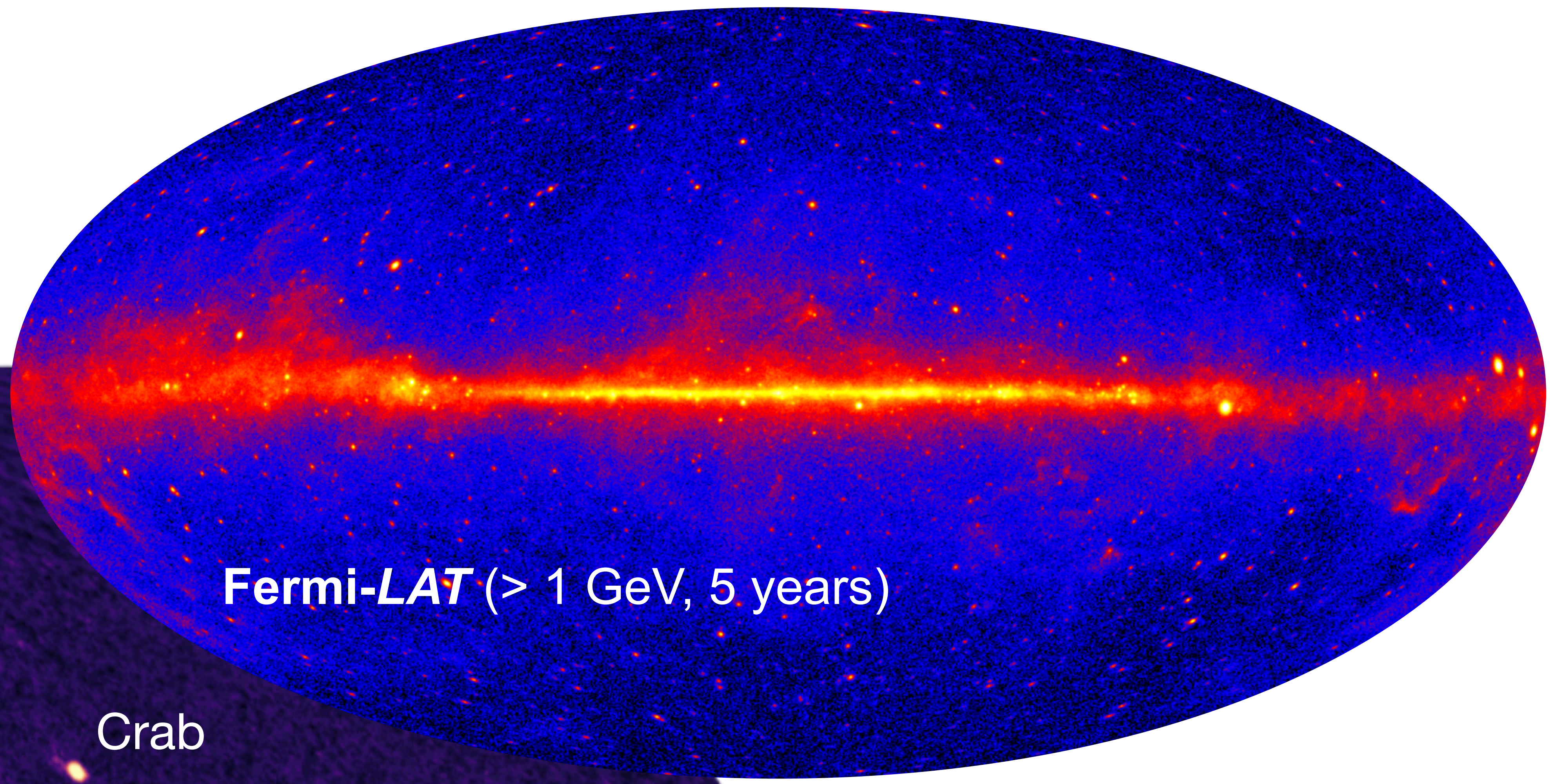


Crab nebula

- best-studied object at HE/VHE/UHE energies
- not quite a point source
- not quite a steady source
- a source of PeV gamma rays

Science case

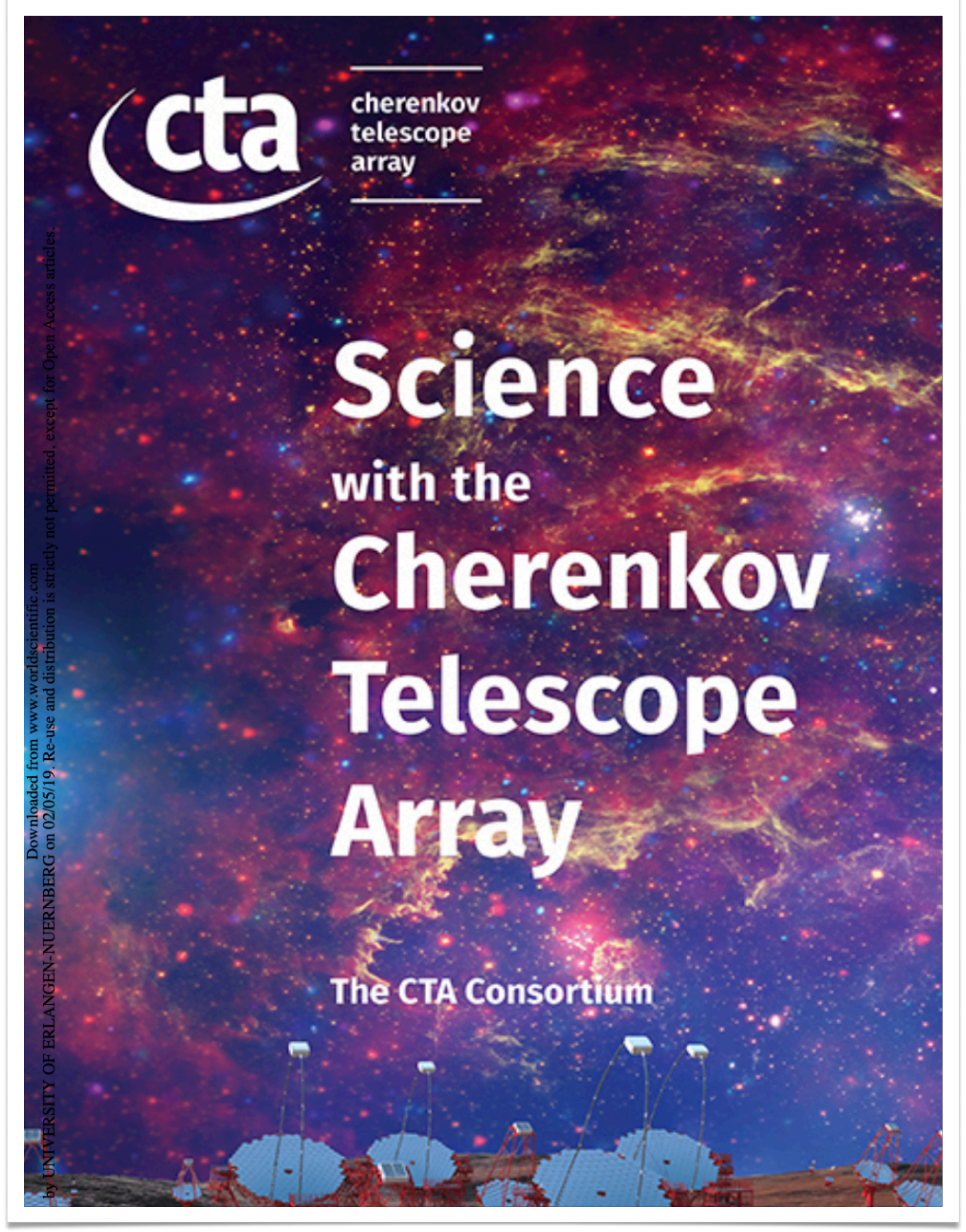




2023 census of non-thermal gamma-ray sky:

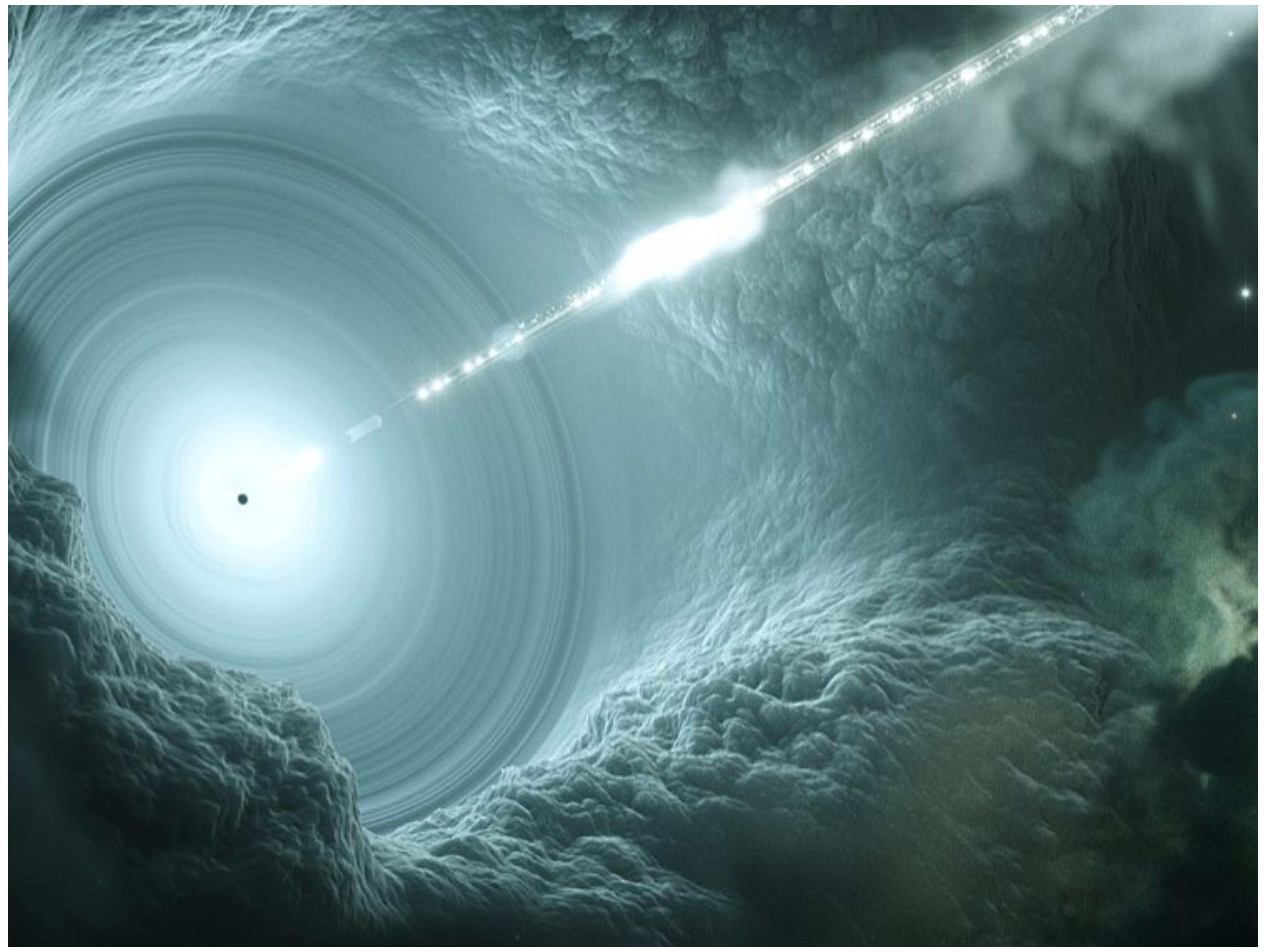
- 2700 sources > 50 MeV
- 250 sources > 1 TeV
- 40 sources > 100 TeV

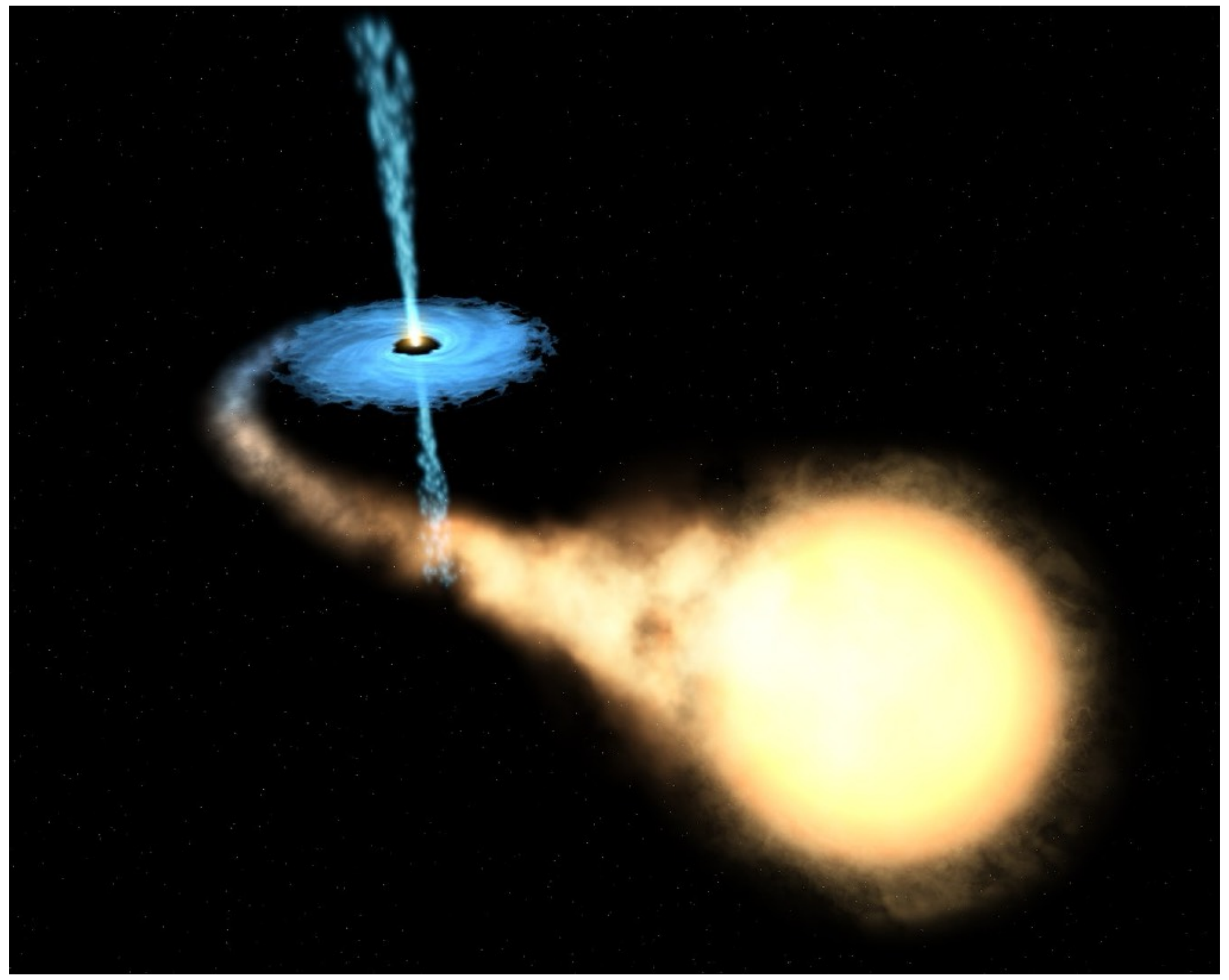
Science case

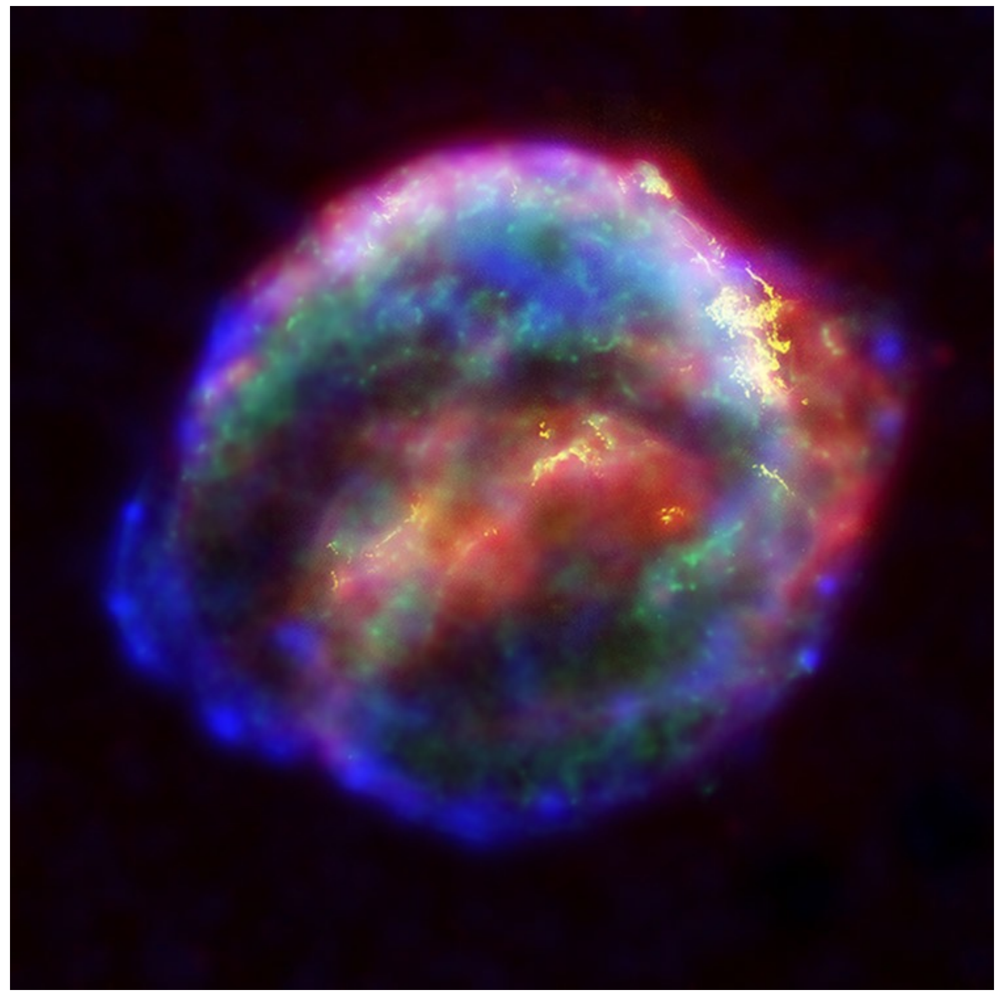


(Astrophysical) **key science questions:**

- **Where** are charged particles accelerated to ultrarelativistic energies?
- **How** do these sources function?
- **What** are the acceleration processes at play?
- **How** does particle transport into their environments work?
- **How** do particles feed back on their environment?
- **What** is their contribution to the cosmic ray population?
- **What** is the nature of dark matter?







Science case

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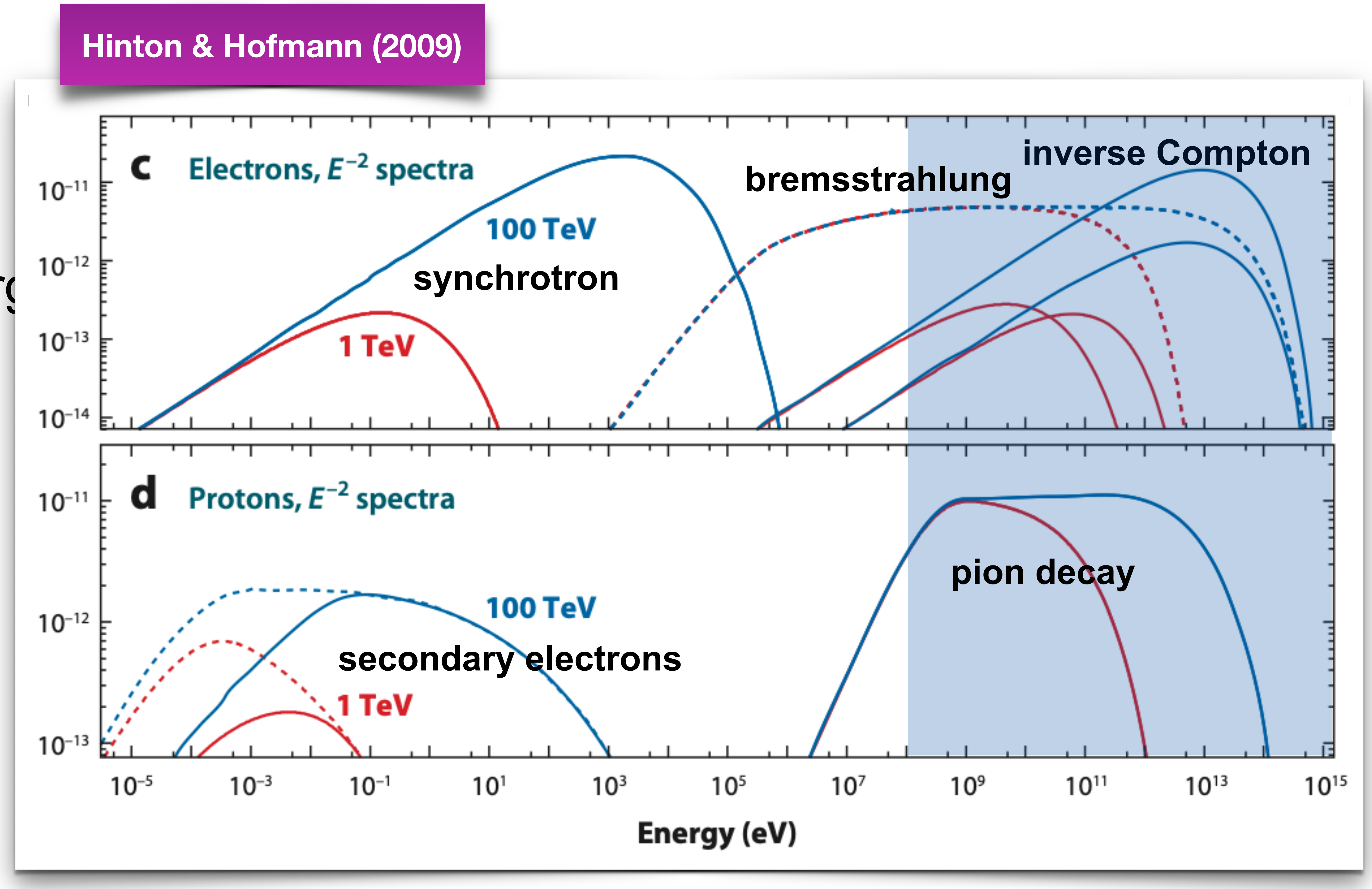
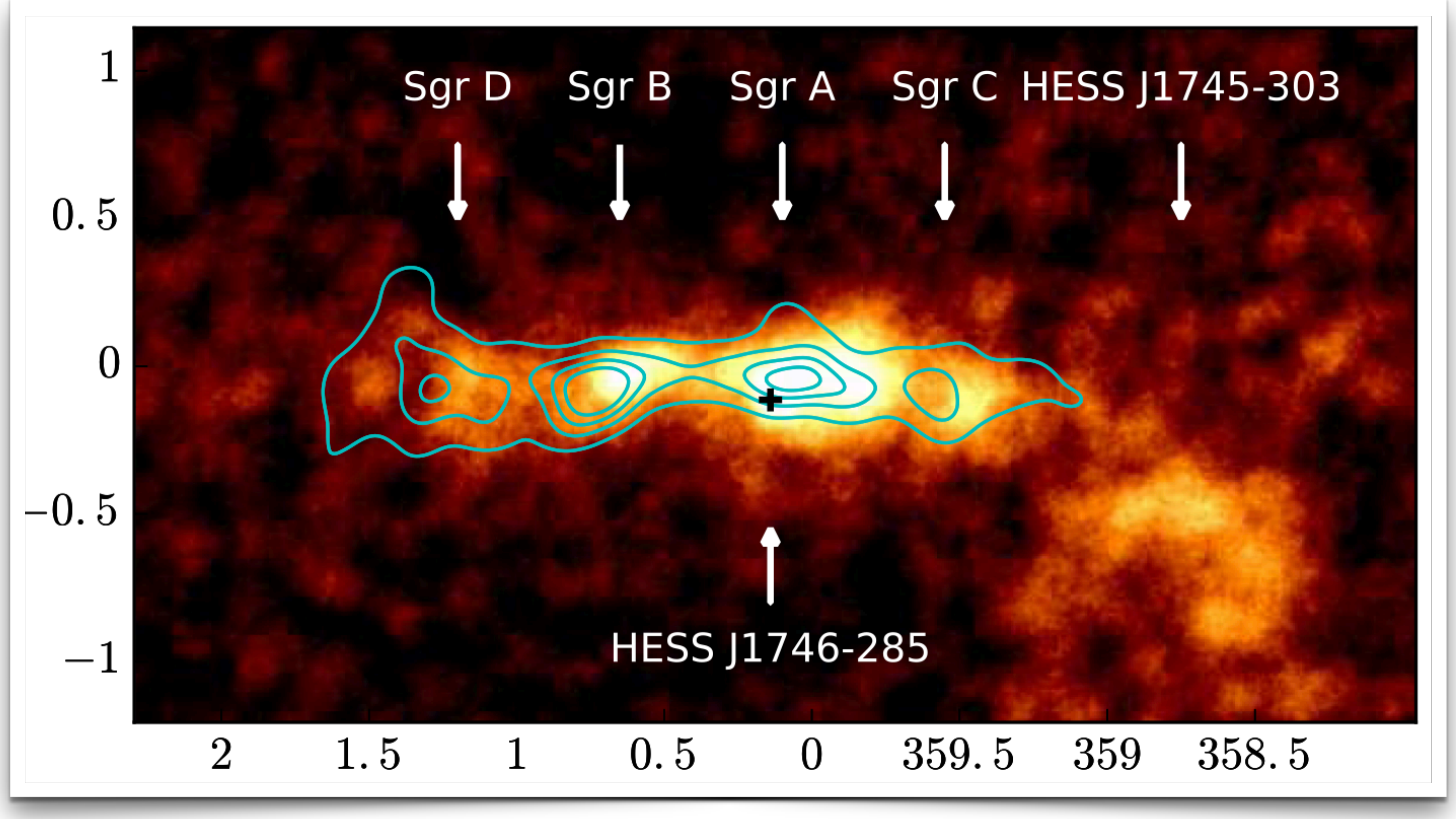




Gamma rays enable

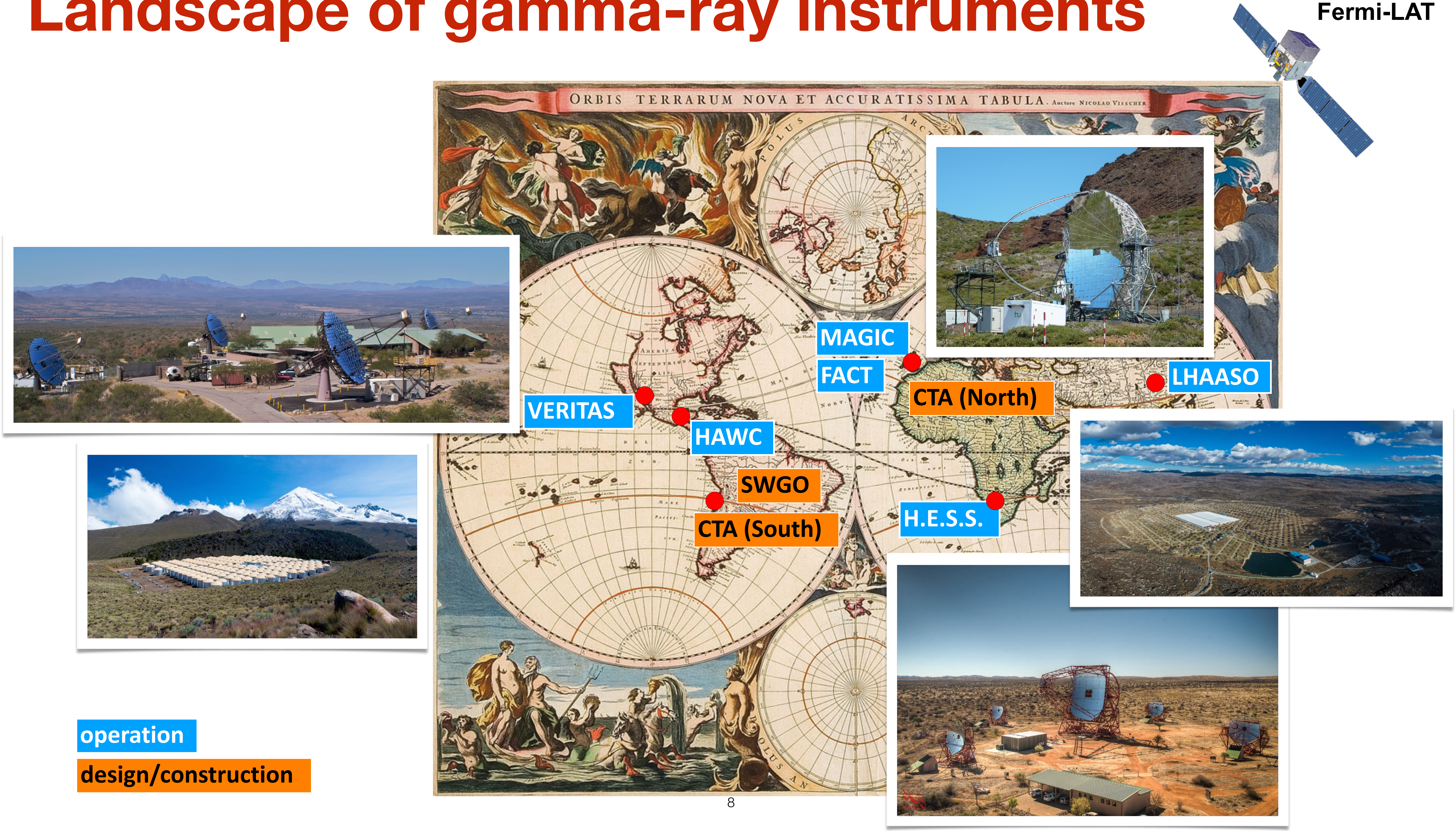
- access to non-thermal electrons (complementary to e.g. X-rays)
- unique access to non-thermal **proton/ion** populations

MWL/multi-messenger coverage often key:

- identification of dominant particle population
- understanding source physics through broad-band coverage

→ contemporaneous multi-instrument campaigns
→ ToO follow-ups

Landscape of gamma-ray instruments



operation

design/construction

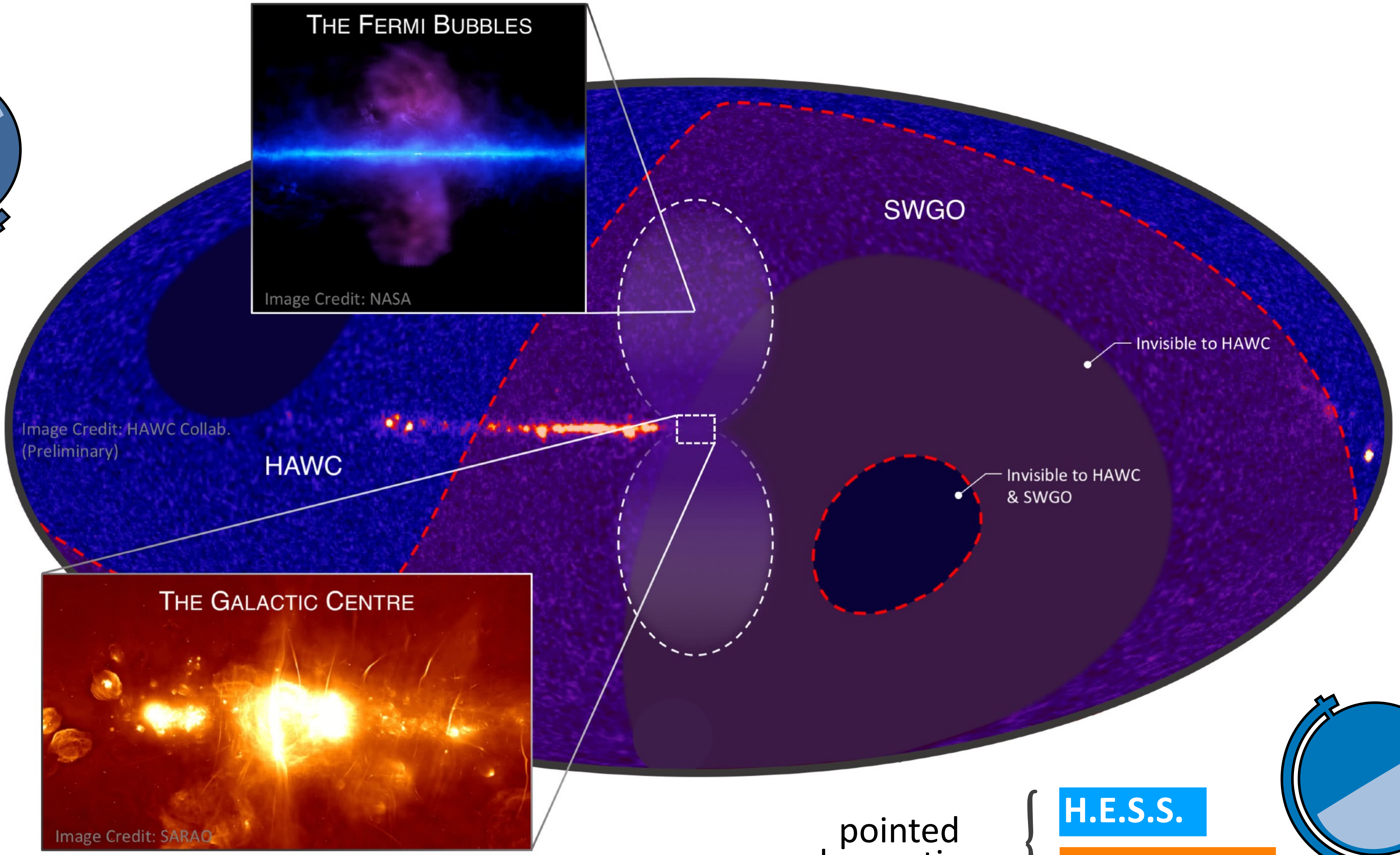
Instrument Complementarity: Hemispheres

pointed observations

- VERITAS
- MAGIC
- FACT
- CTA (North)

continuous survey

- HAWC
- LHAASO



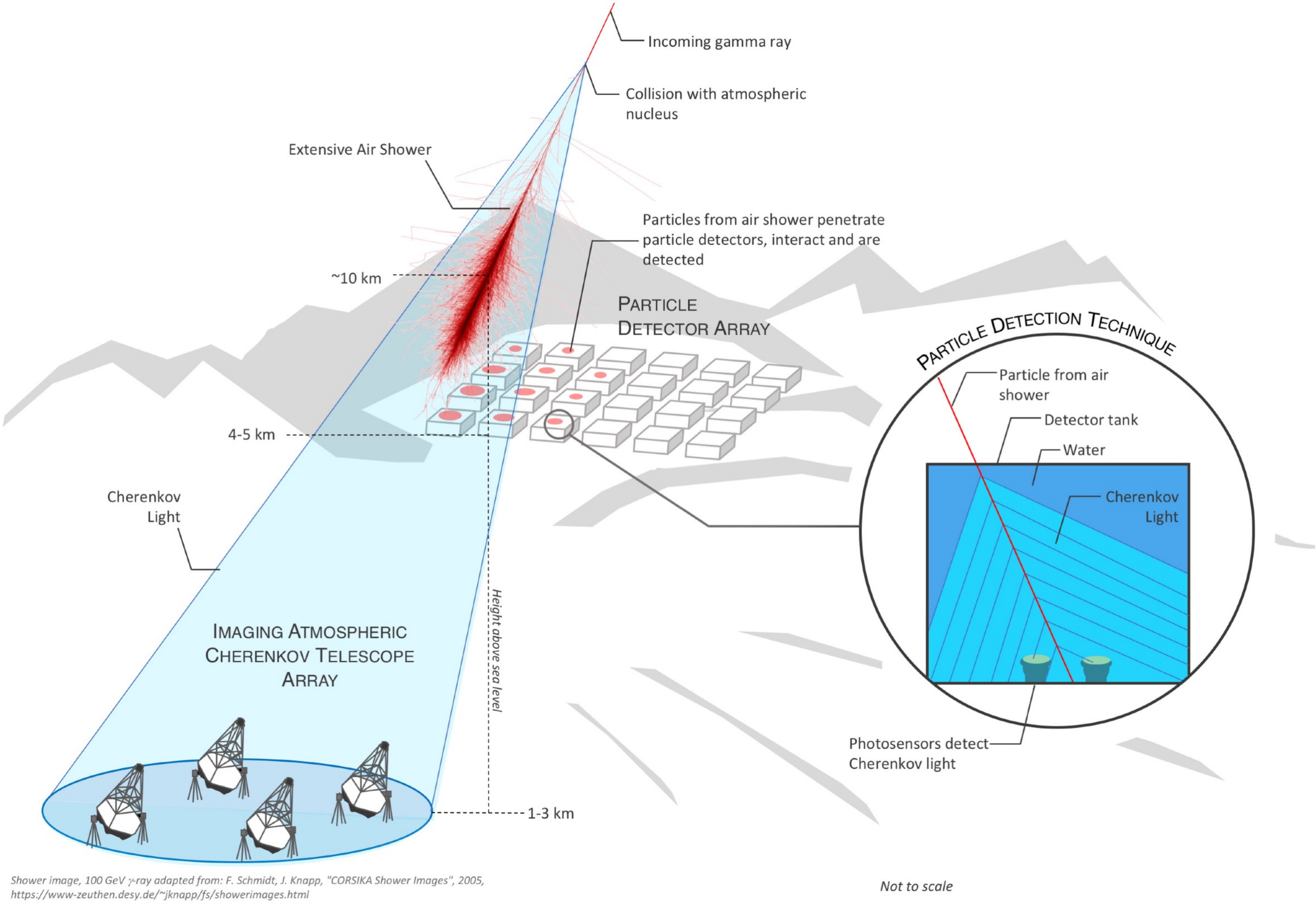
pointed observations

- H.E.S.S.
- CTA (South)

continuous survey

- SWGO

Instrument Complementarity: Detection technique



Imaging Atmospheric Cherenkov Telescopes:

- observations limited to clear nights
- comparatively small field of view
- excellent background rejection
- very good angular resolution
- very good energy resolution

VERITAS **MAGIC** **H.E.S.S.** **FACT**
CTA (North) **CTA (South)**

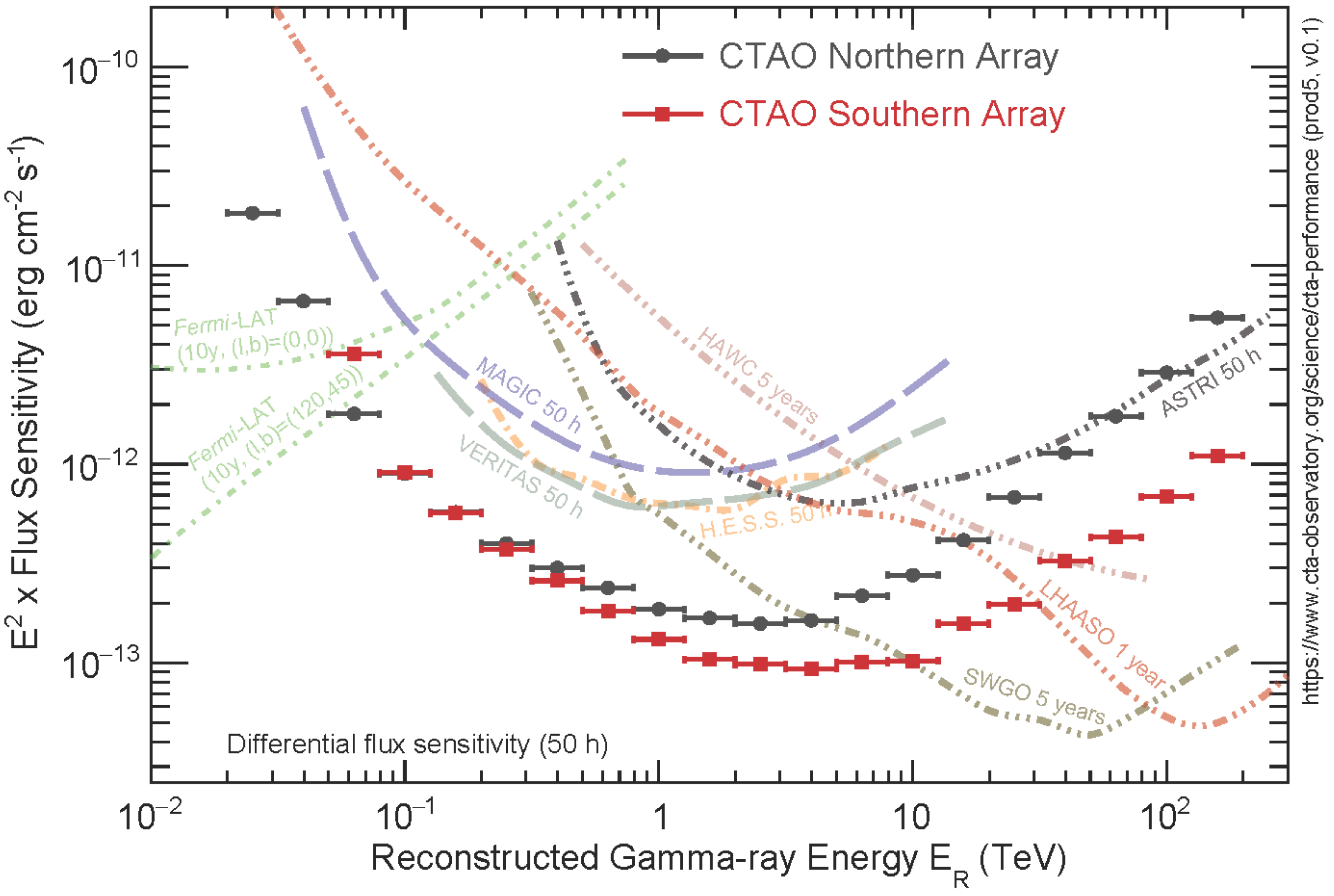
Particle Detector Arrays:

- 100% duty cycle
- very large field of view (15% sky)
- excellent background rejection
- good angular resolution
- good energy resolution

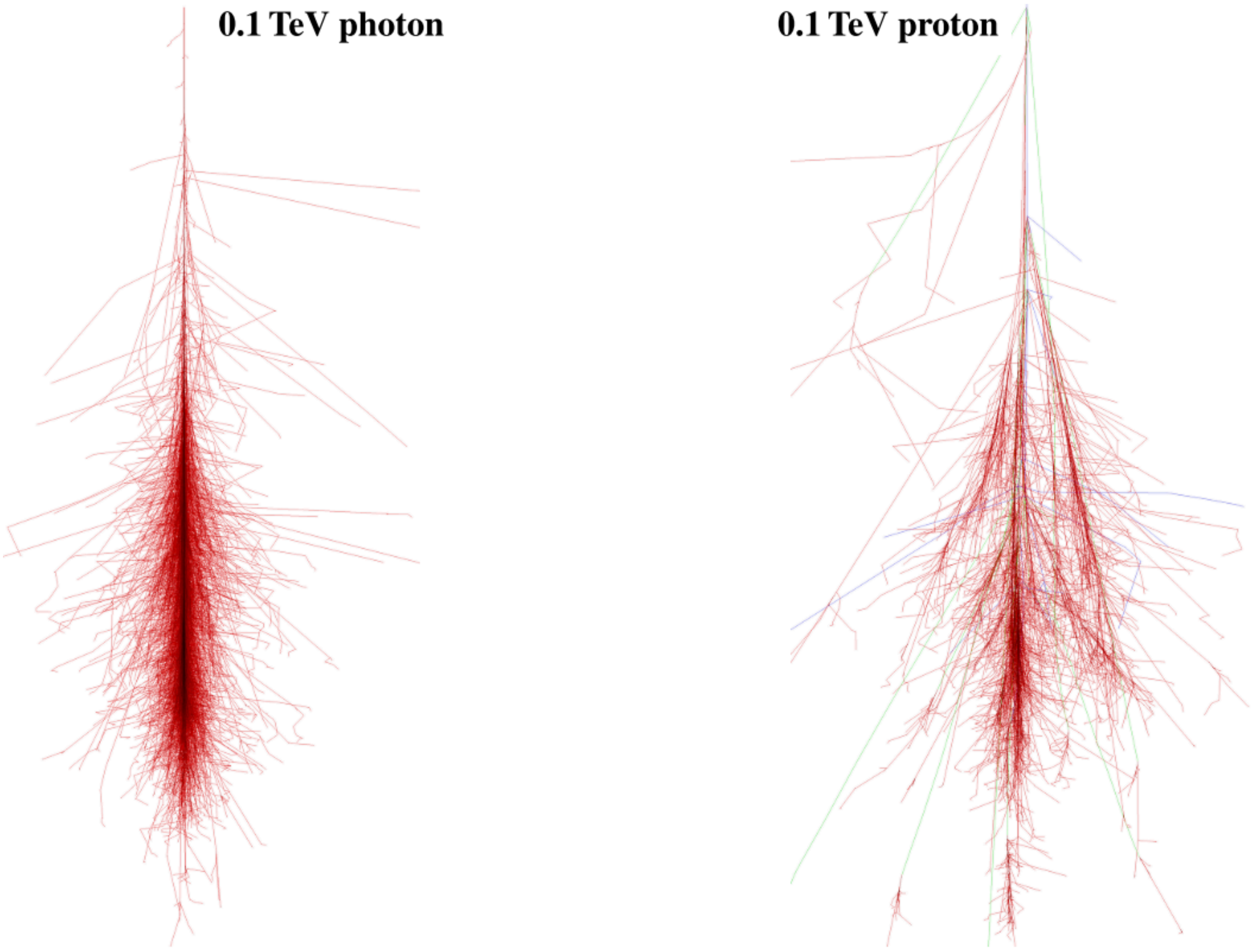
HAWC **LHAASO**
SWGO

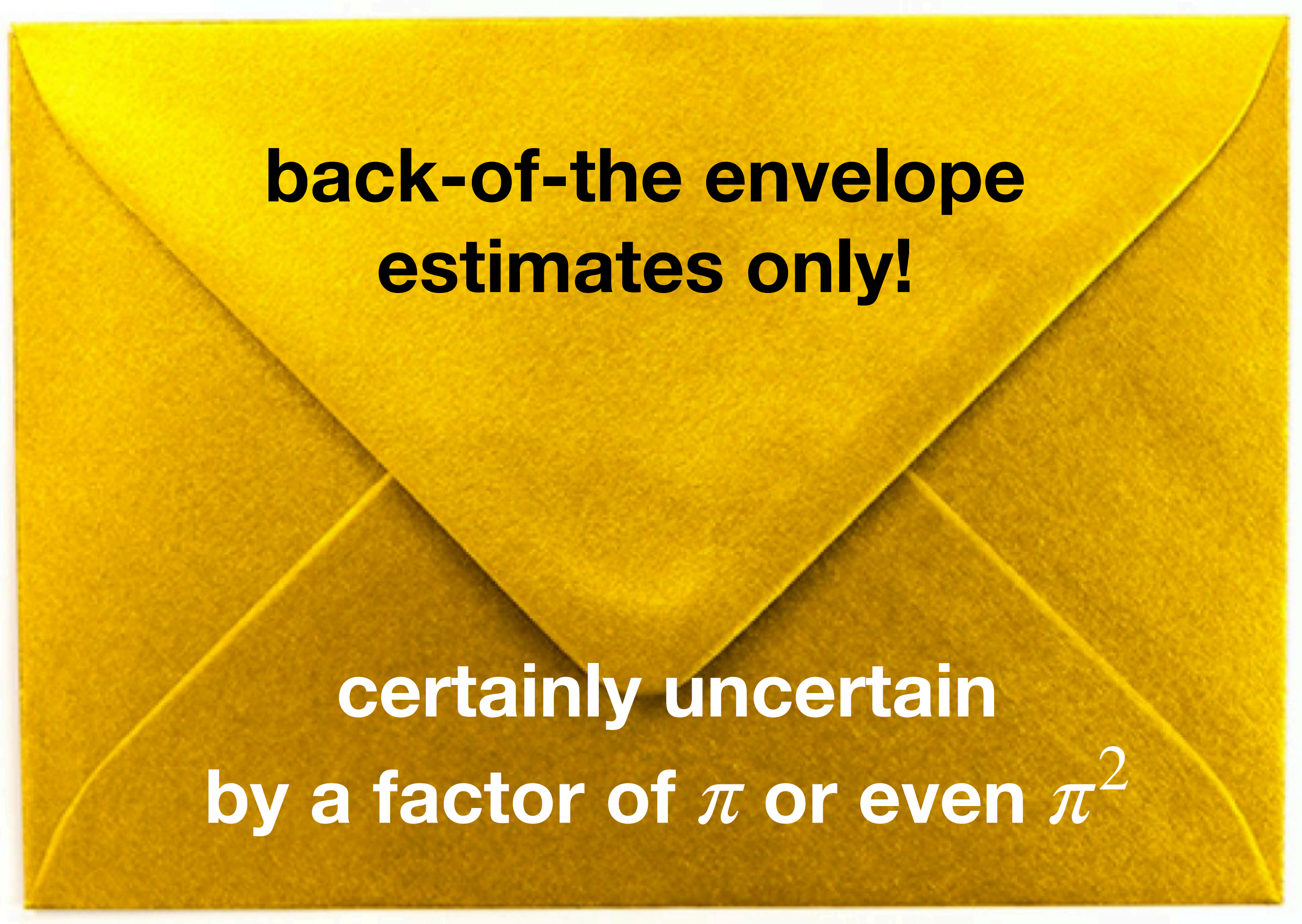
particle detector arrays are complementary to pointed instruments!

Instrument Complementarity: Sensitivity



Where and how to build a particle detector array





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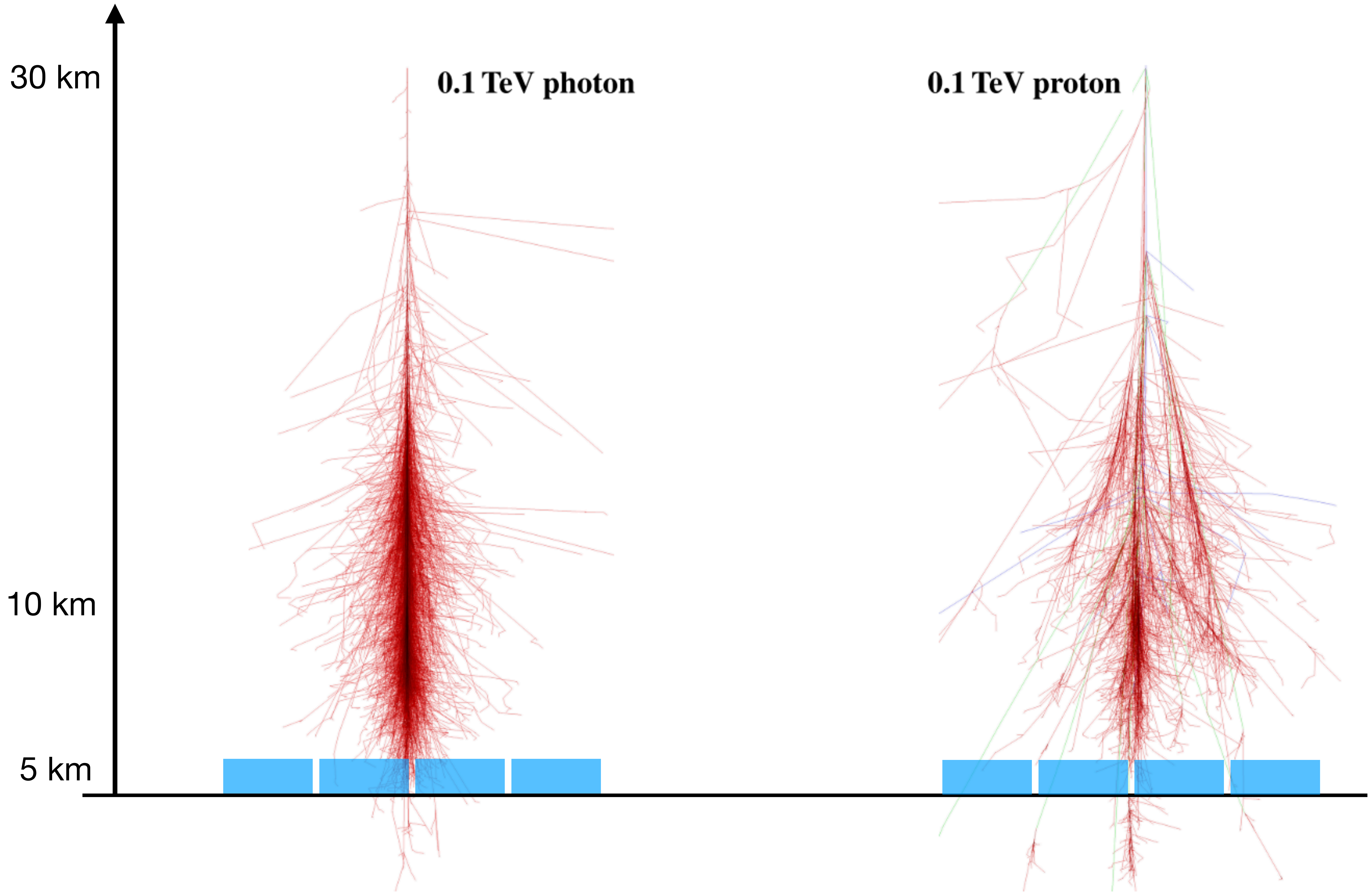
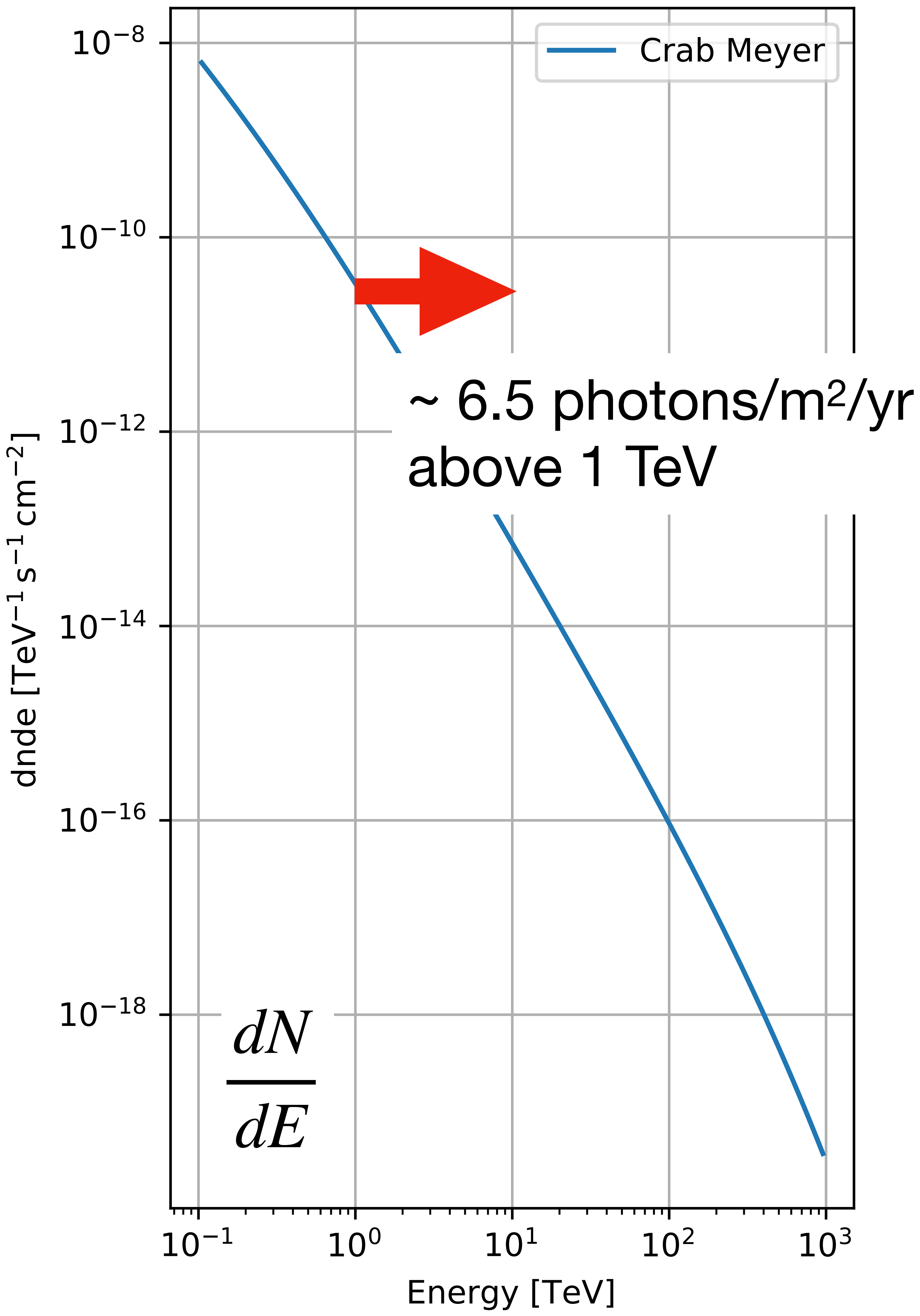


Particle detector arrays take **sample** of shower particles at fixed height

- gamma-ray flux at > 1 TeV energies small
  → huge collection area required
- must be placed “within” shower
  → high altitudes needed (4-5 km)
- access only tiny slice of shower
  → disadvantage compared to IACTs, fluorescence detectors
- must fight large CR background
  → use “patchiness” of shower footprint
  → dedicated muon detectors

How big of a detector?



The Crab is indeed one of the strongest steady VHE gamma-ray sources.

But…

$$N(>E) = t \cdot \int_E^\infty \frac{dN}{dE} \cdot A_{\mathrm{det}}(E)\ dE \sim 23$$

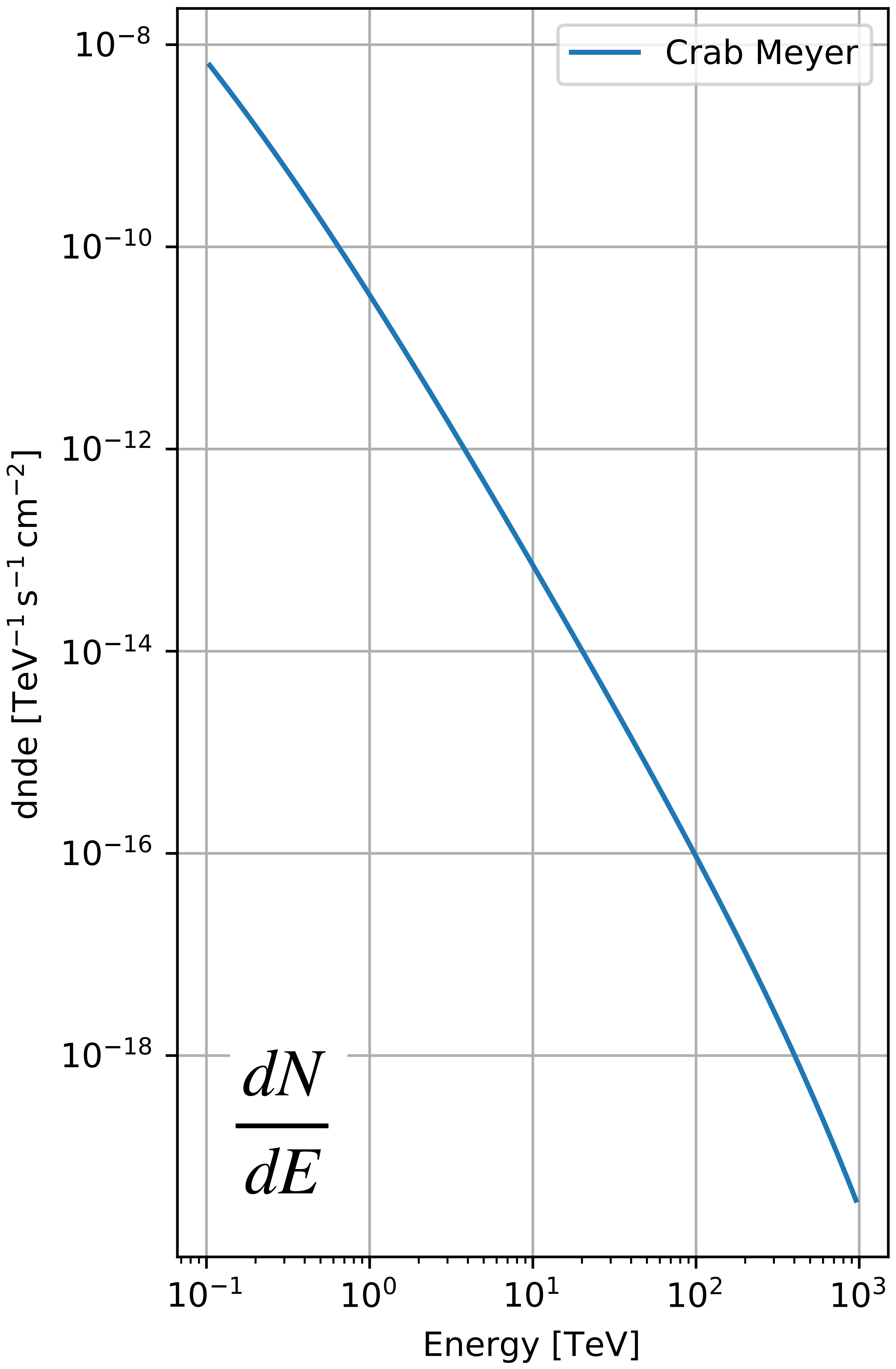
E: $1\ \mathrm{TeV}$

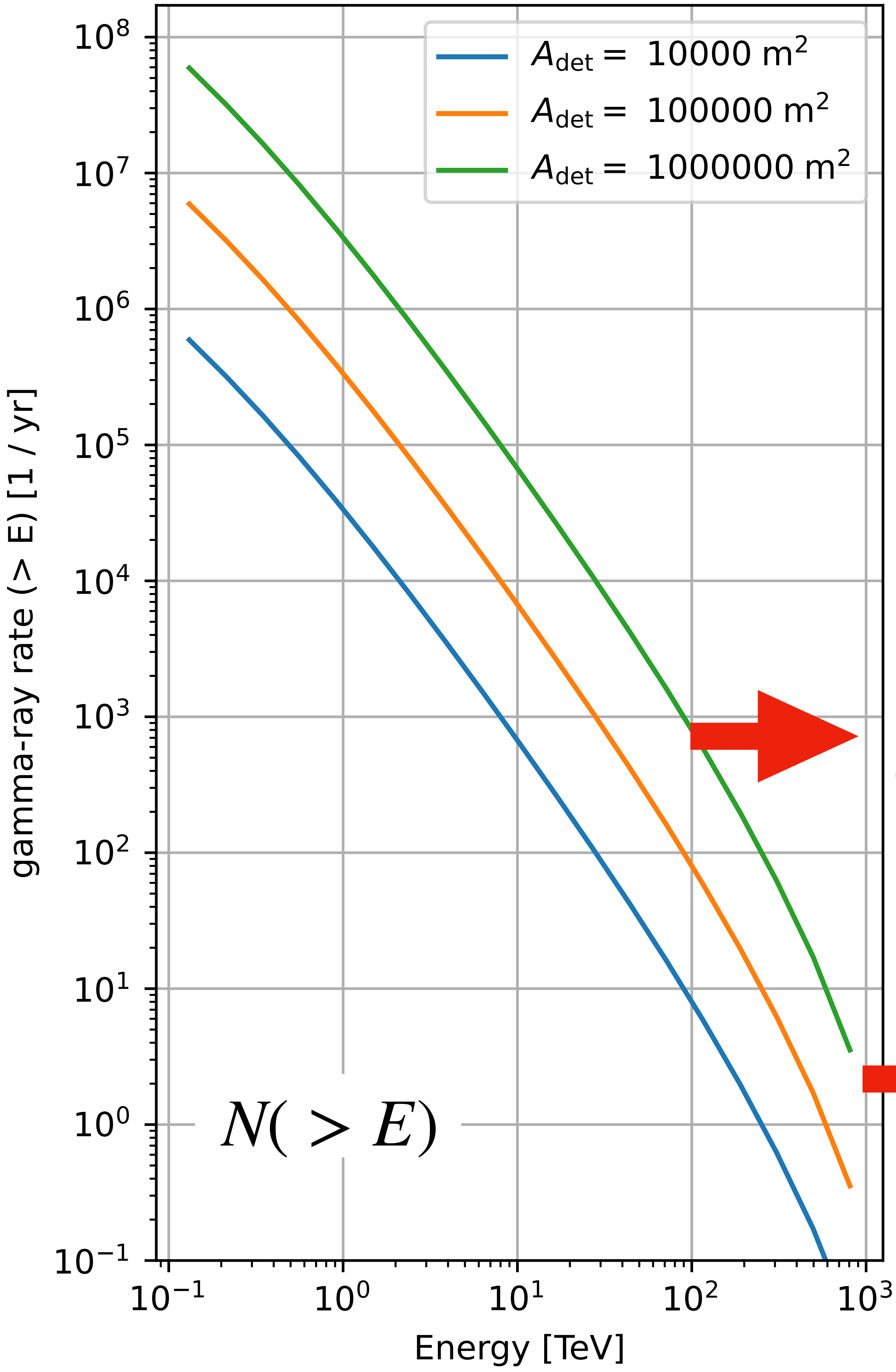
t: $3.5 \cdot \pi \cdot 10^7\ \mathrm{s}$

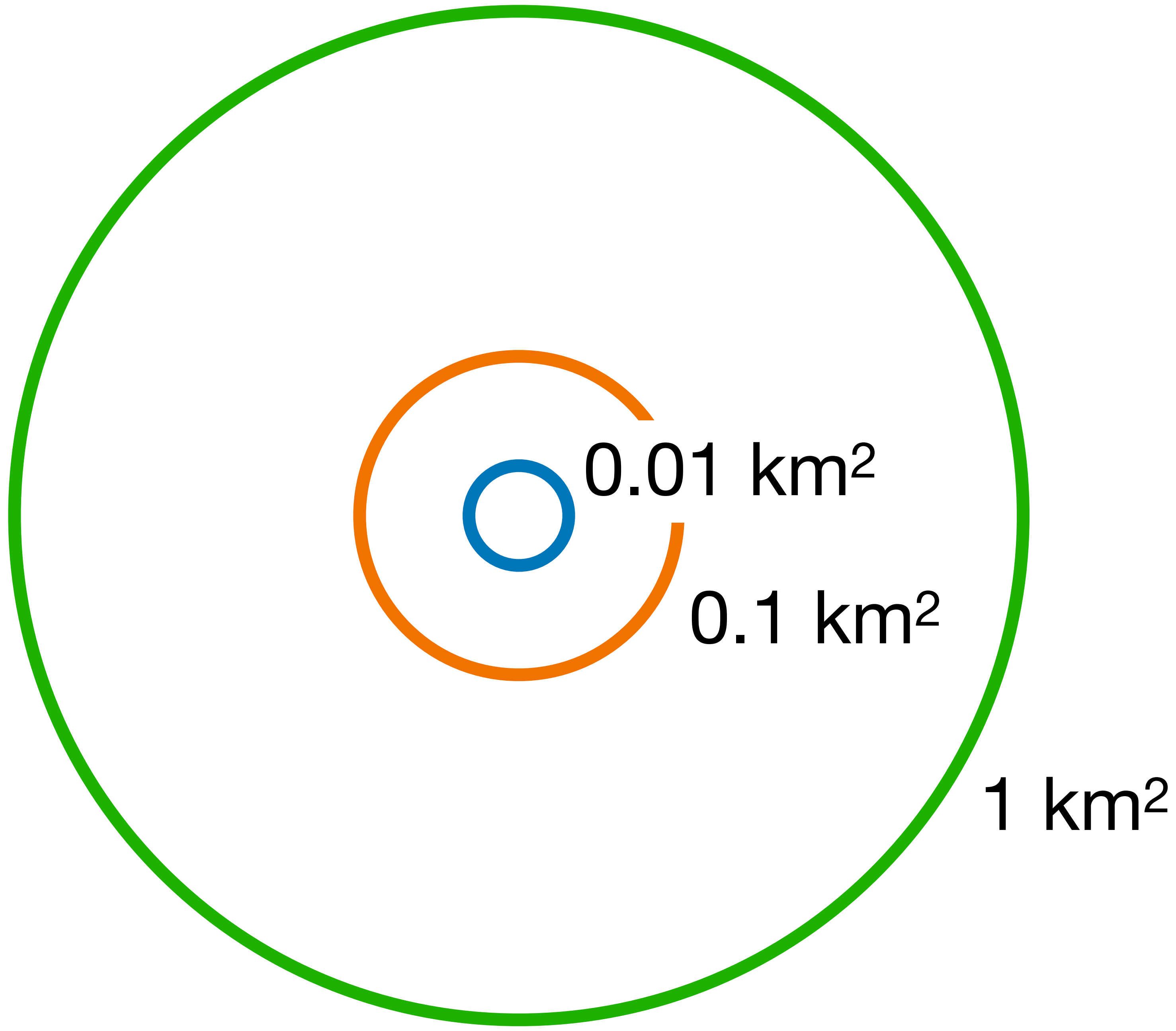
A_{det}: $1\ \mathrm{m}^2$

We need a pretty big detector. Or PhDs will take a bit longer.

How big of a detector?





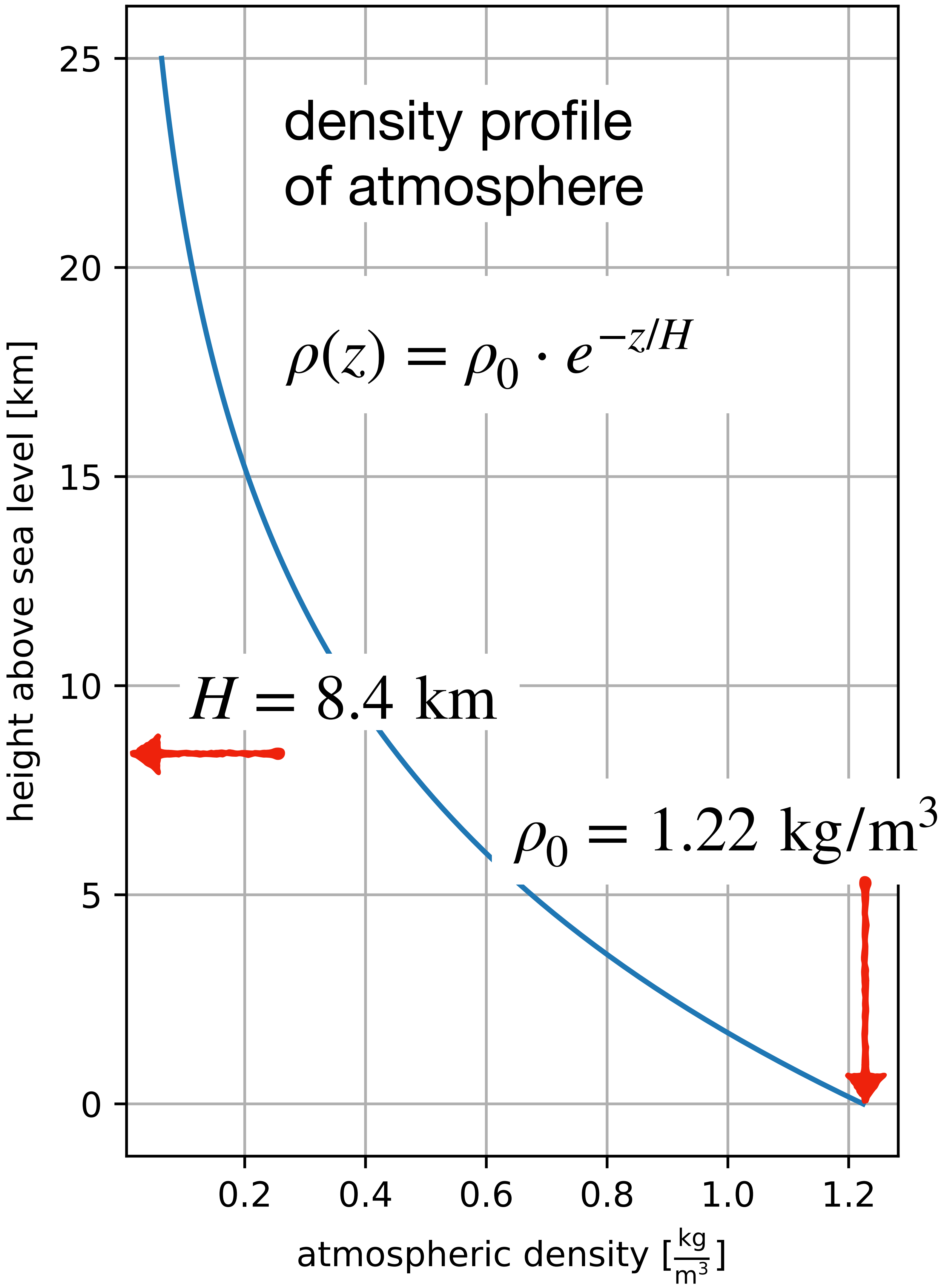


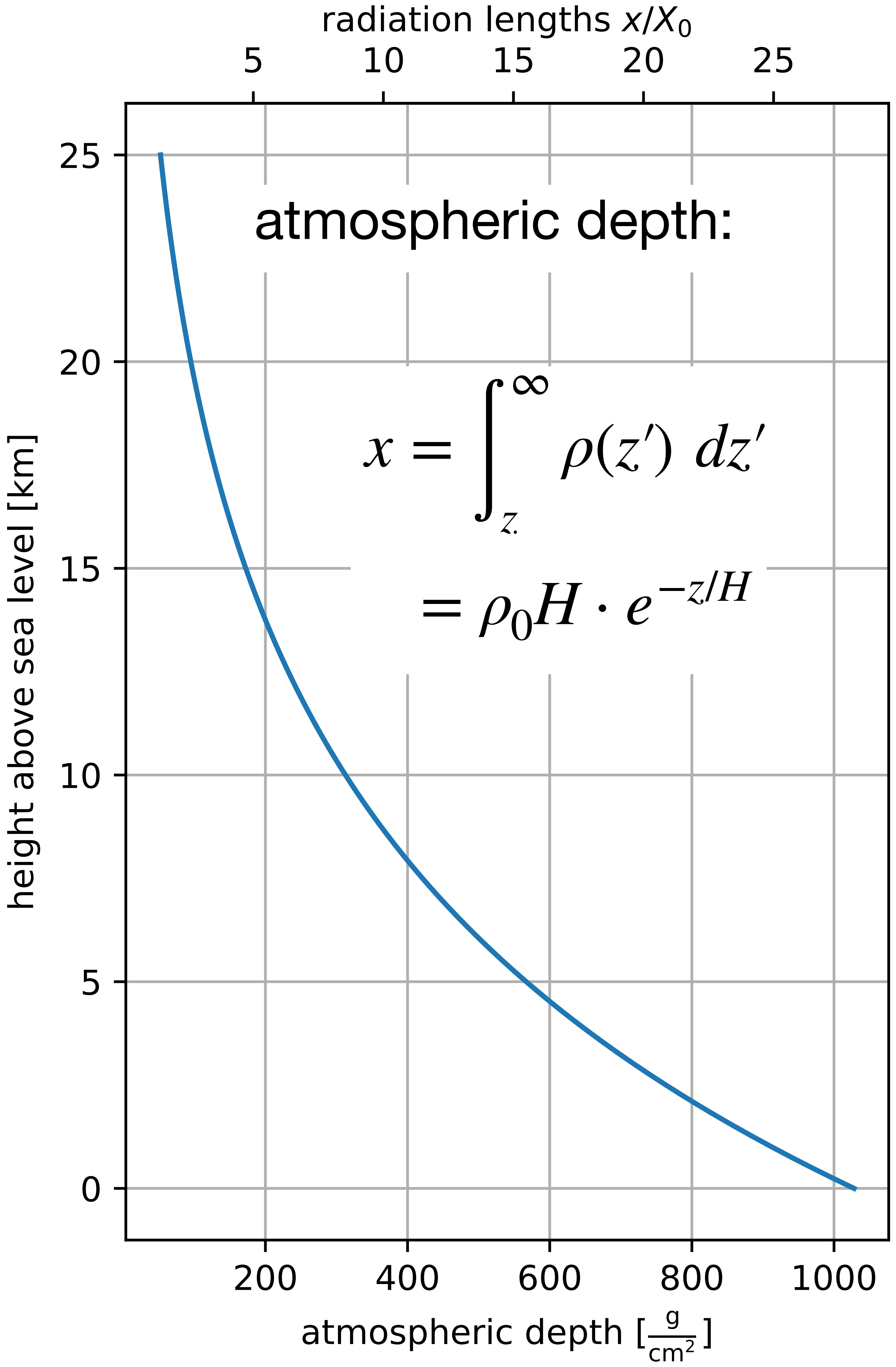
800 photons/yr above 100 TeV for km^2-sized detector

few photons/yr above 1 PeV for km^2-sized detector

To access UHE (>100 TeV) gamma rays, we need a really big detector.

At what altitude?





atmospheric depth x:

column density that a vertically incident particle traverses in the atmosphere

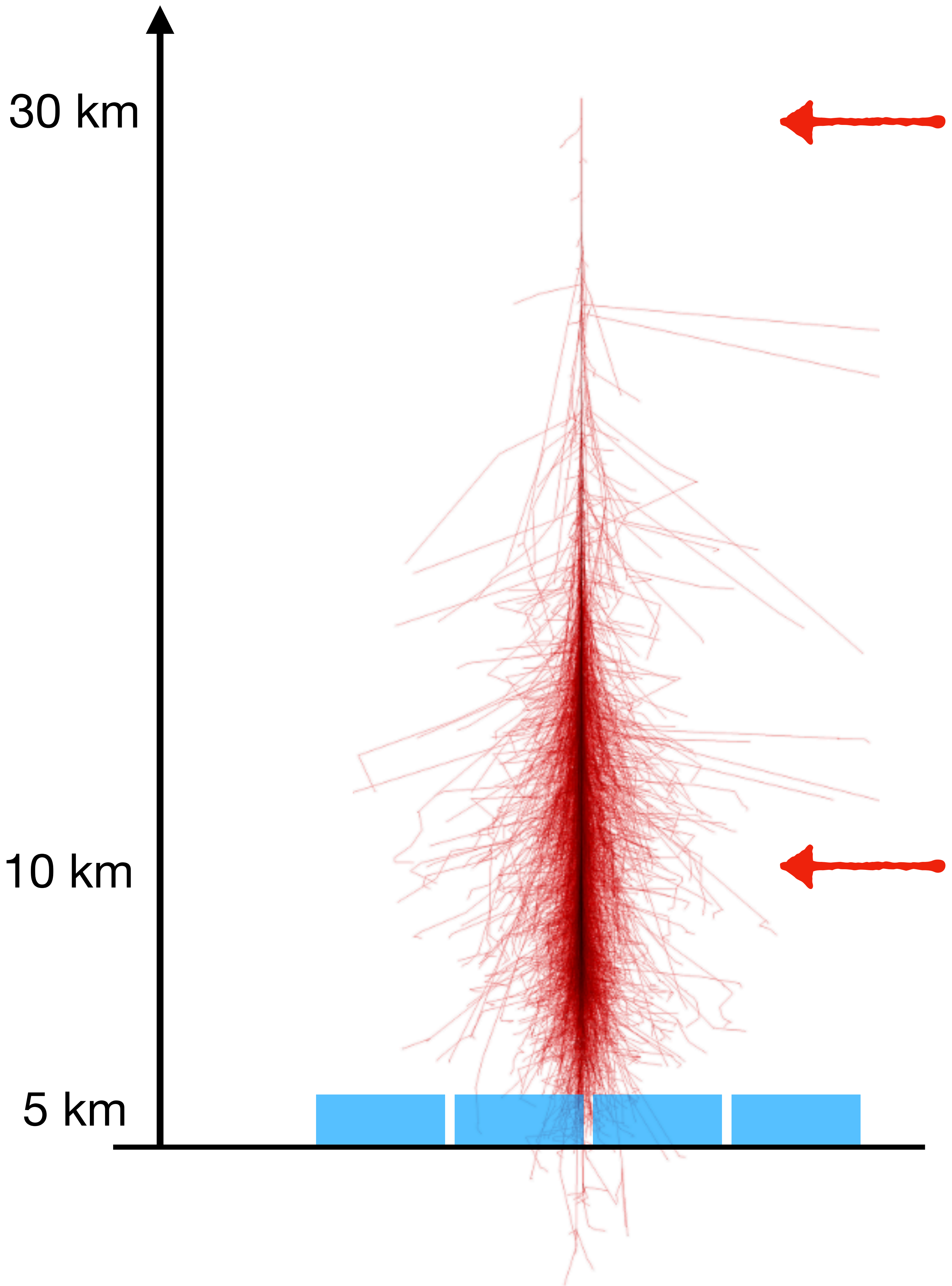
radiation length X_0:

distance over which an electron looses all but 1/e of its energy through bremsstrahlung

for air, $X_0 = 36.6\ \mathrm{g/cm^2}$

→ thickness of atmosphere is ~28 radiation lengths

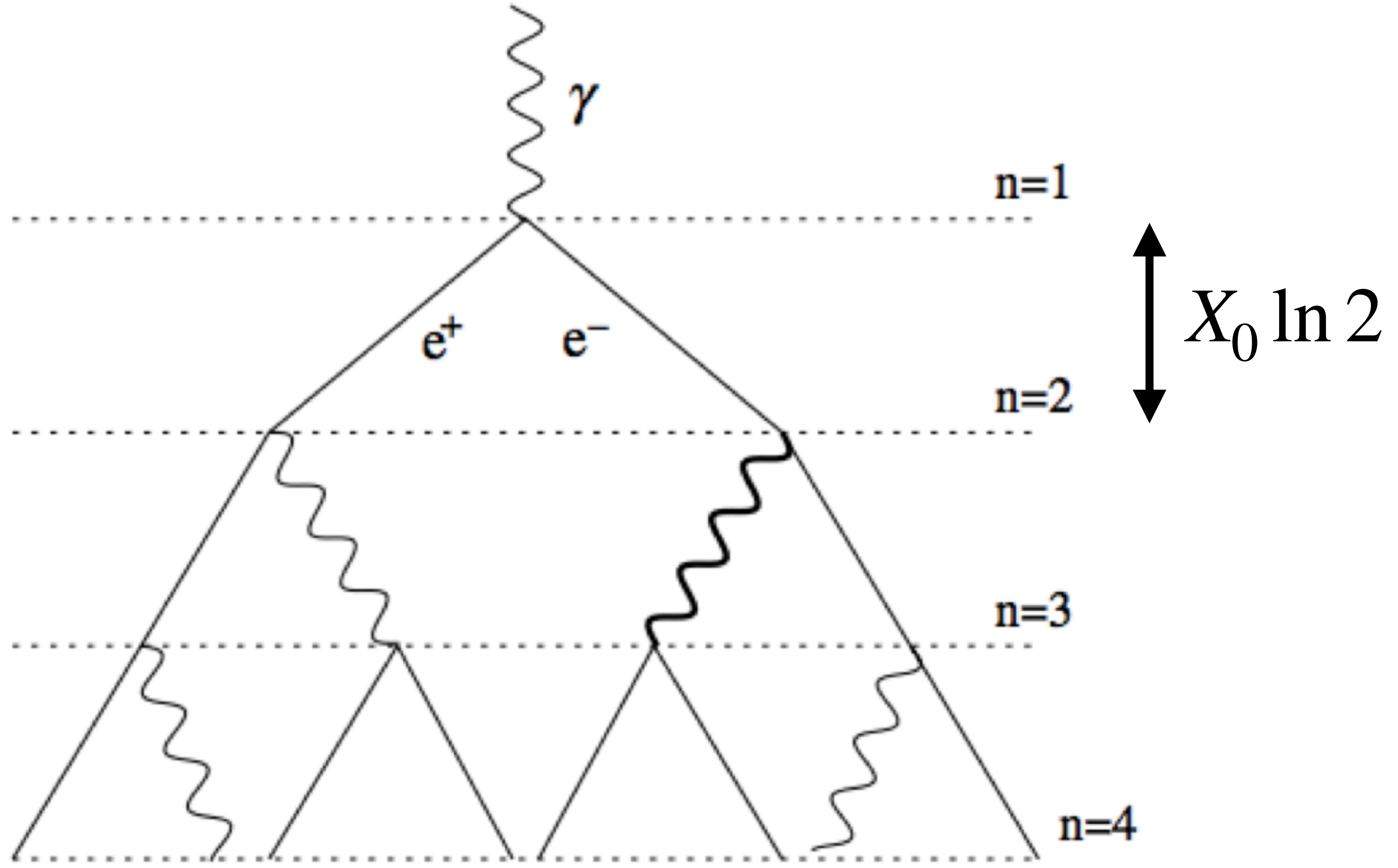
At what altitude?



height of first interaction

shower maximum $X_{\max}$

Heitler's simple toy model:



$\rightarrow X_{\max} = X_0 \ln(E/E_c)$

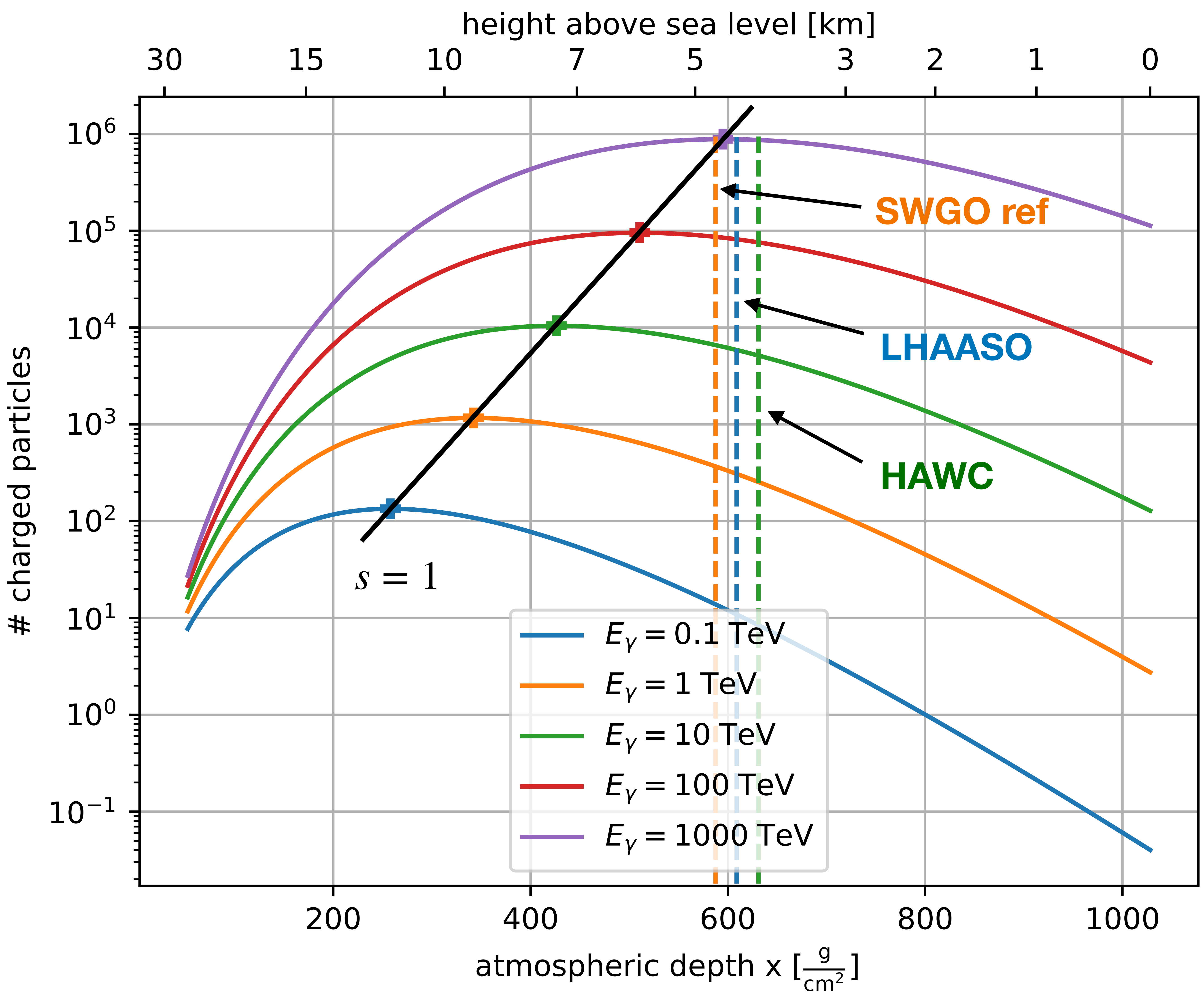
$\rightarrow N_{\max} \sim E$

$E_c = 87$ MeV

basis for

- choice of detector altitude
- measurement of primary energy

At what altitude?



let's look in more detail!

number of electrons as function of atmospheric depth:

$$N(x,E) = \frac{0.31}{\sqrt{\ln(E/E_c)}} \cdot e^{\frac{x}{X_0}\cdot(1-\frac{3}{2}\cdot\ln s)}$$

Greisen (1956)

"shower age"

$$s = \frac{3}{1 + 2\ln(E/E_c)\cdot(X_0/x)}$$

→ any real detector will always be located in the tail of the shower

→ to reach sub-TeV threshold, must go close to 5 km altitude

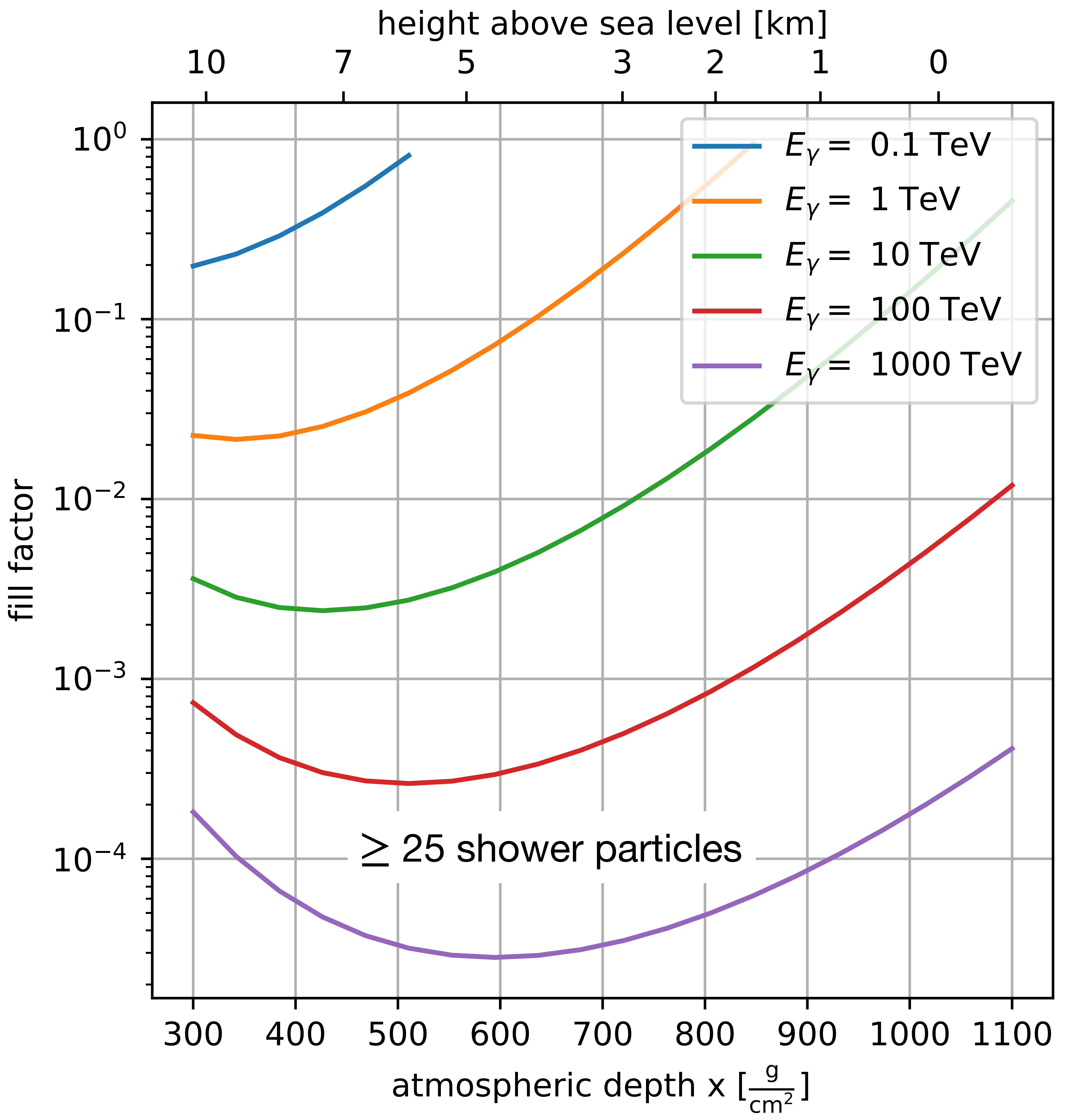
→ additionally, significant fluctuations due to stochasticity of first interaction height

The role of the fill factor

Energy threshold depends on

- **altitude**
  the higher the altitude, the more shower particles at ground level
- **fill factor** (=fraction of instrumented array area)
  the higher the fill factor, the more shower particles can be detected

here: assume ≥ 25 shower particles must cross active part of the detector



Energy threshold vs. effective area

Energy threshold depends on

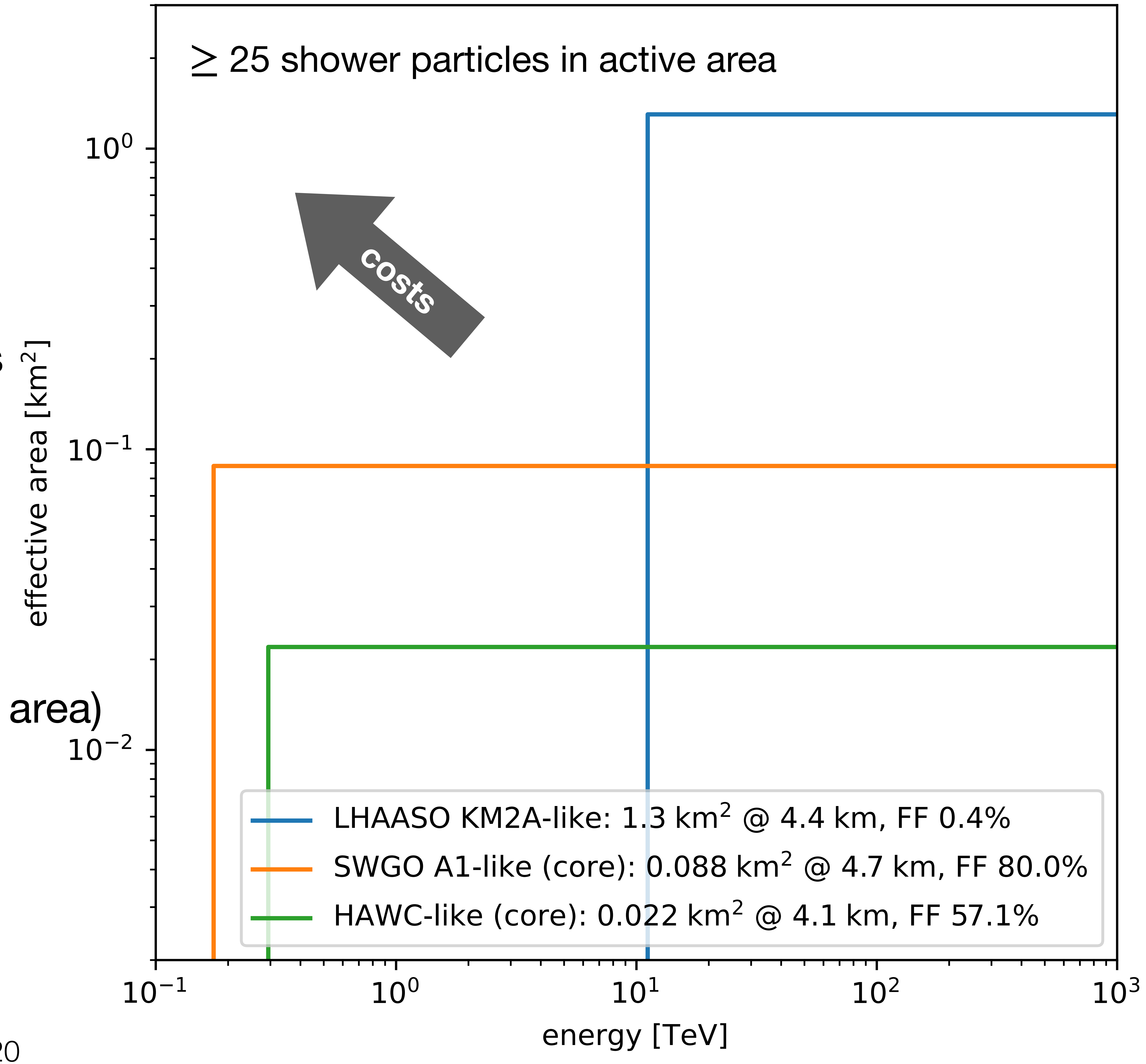
- **altitude**
  the higher the altitude, the more shower particles at ground level
- **fill factor** (=fraction of instrumented array area)
  the higher the fill factor, the more shower particles can be detected

here: assume $\geq$ 25 shower particles must cross active part of the detector

for **fixed costs**, must always balance

- access to even higher energies (increase effective area)
- wish for low energy threshold (increase fill factor)

→ **typical approach**:
core detector w/ dense instrumentation
+ outer detector w/ sparse instrumentation



Shower fluctuations and shower footprint

(1) shower development is **stochastic process:**

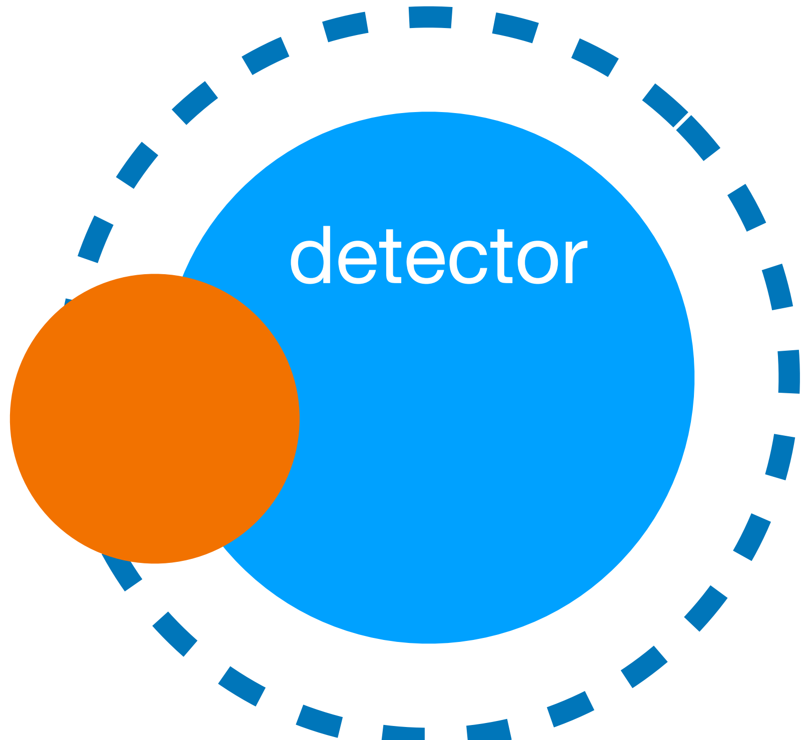
- **significant variation** in first interaction height
- variations in shower development

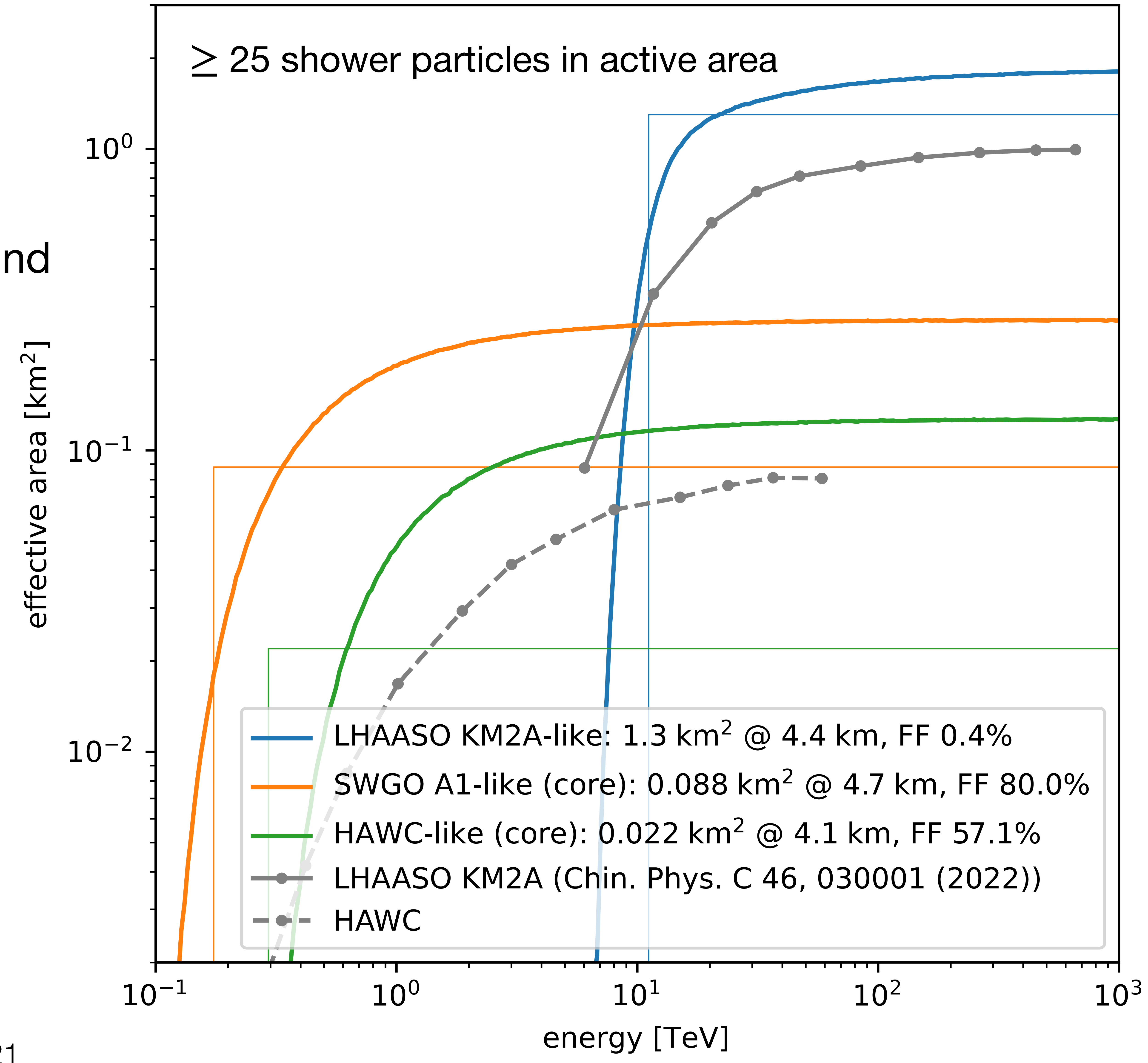
→ **large fluctuations** in number of particles on ground for showers of same primary energy
→ smooth onset of trigger threshold

(2) shower footprint on ground has **extent of several 100 m**:

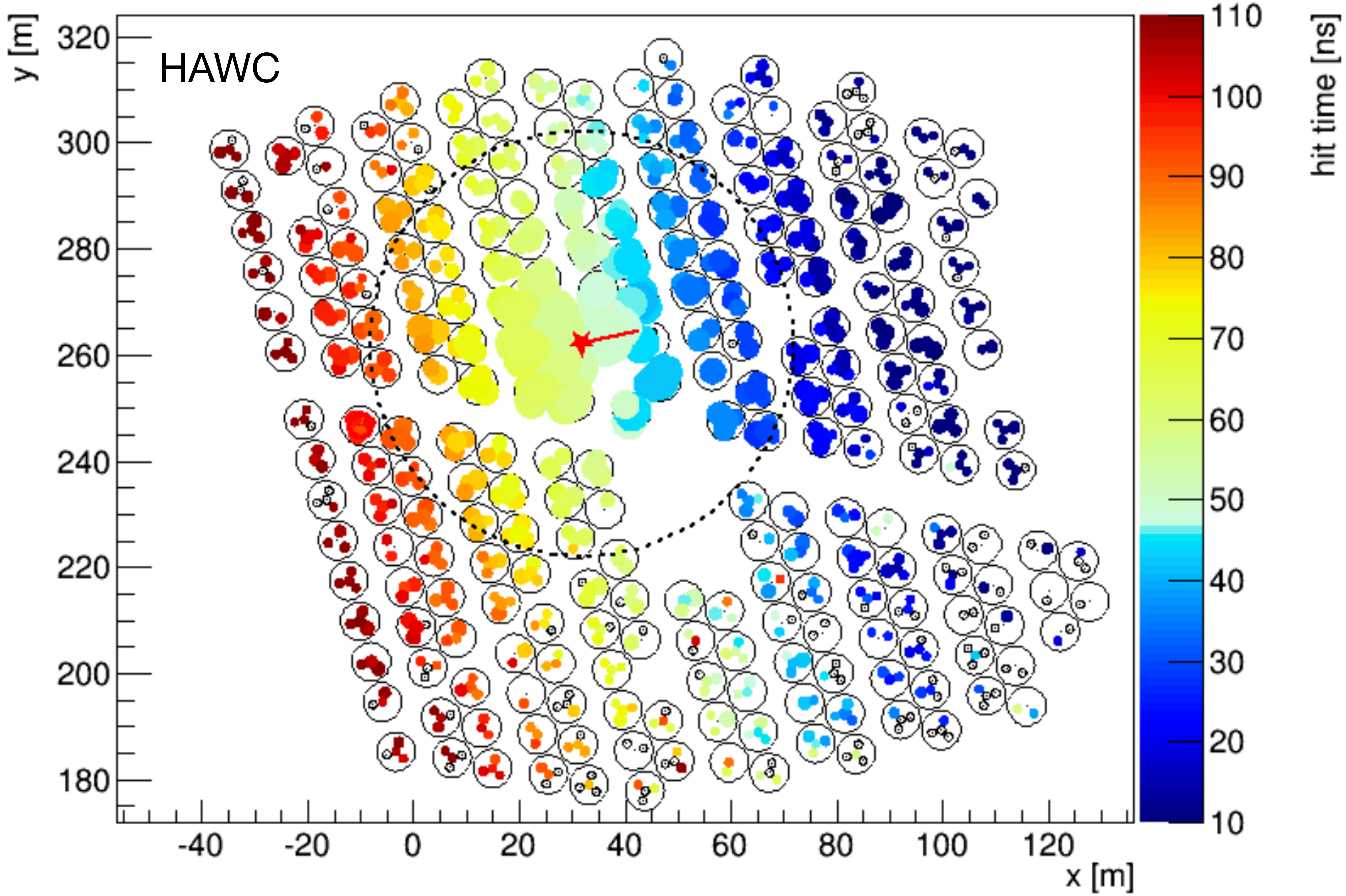
- can trigger showers even if impact point not within array

→ **significant increase** in detection area for smaller arrays





Direction reconstruction



based on **arrival time distribution** of shower particles

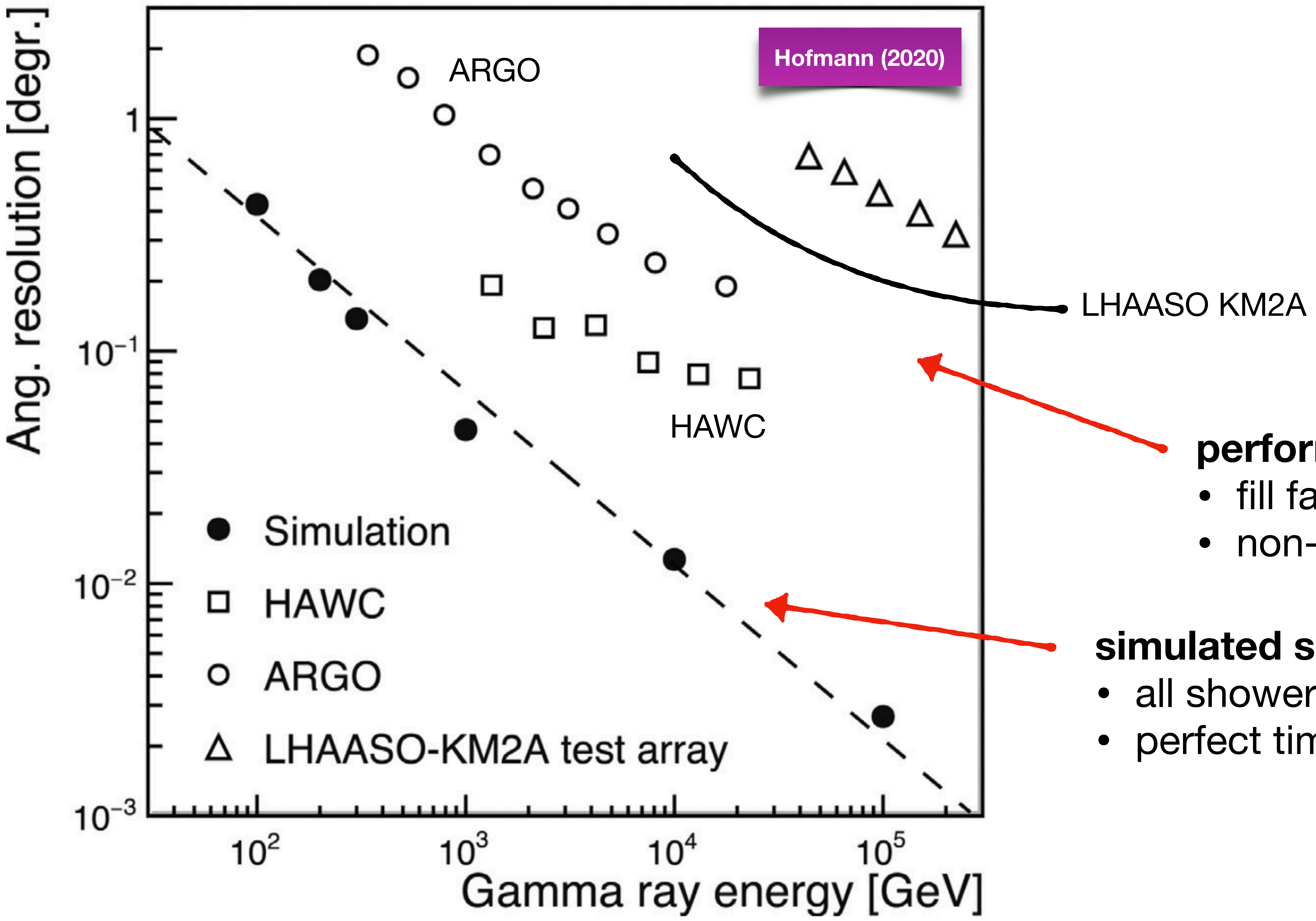
- width of distribution in shower plane only some 10 ns

→ precise **relative timing** (resolution) and **absolute timing** (pointing) is key

- more particles provide more information

→ resolution will improve with **gamma-ray energy**, **altitude** and **fill factor**

Direction reconstruction - the ultimate limits



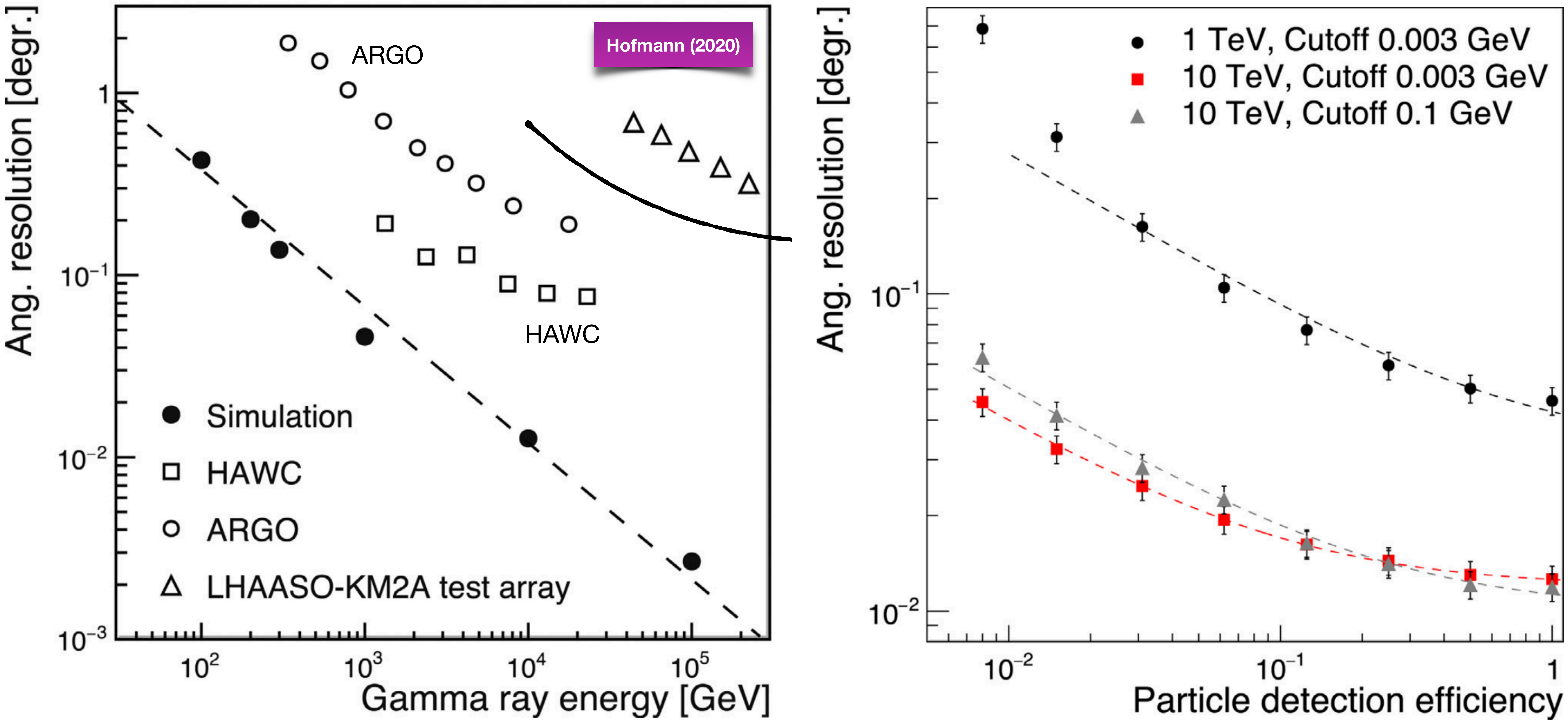
performance of current instruments

- fill factor < 1
- non-zero timing resolution

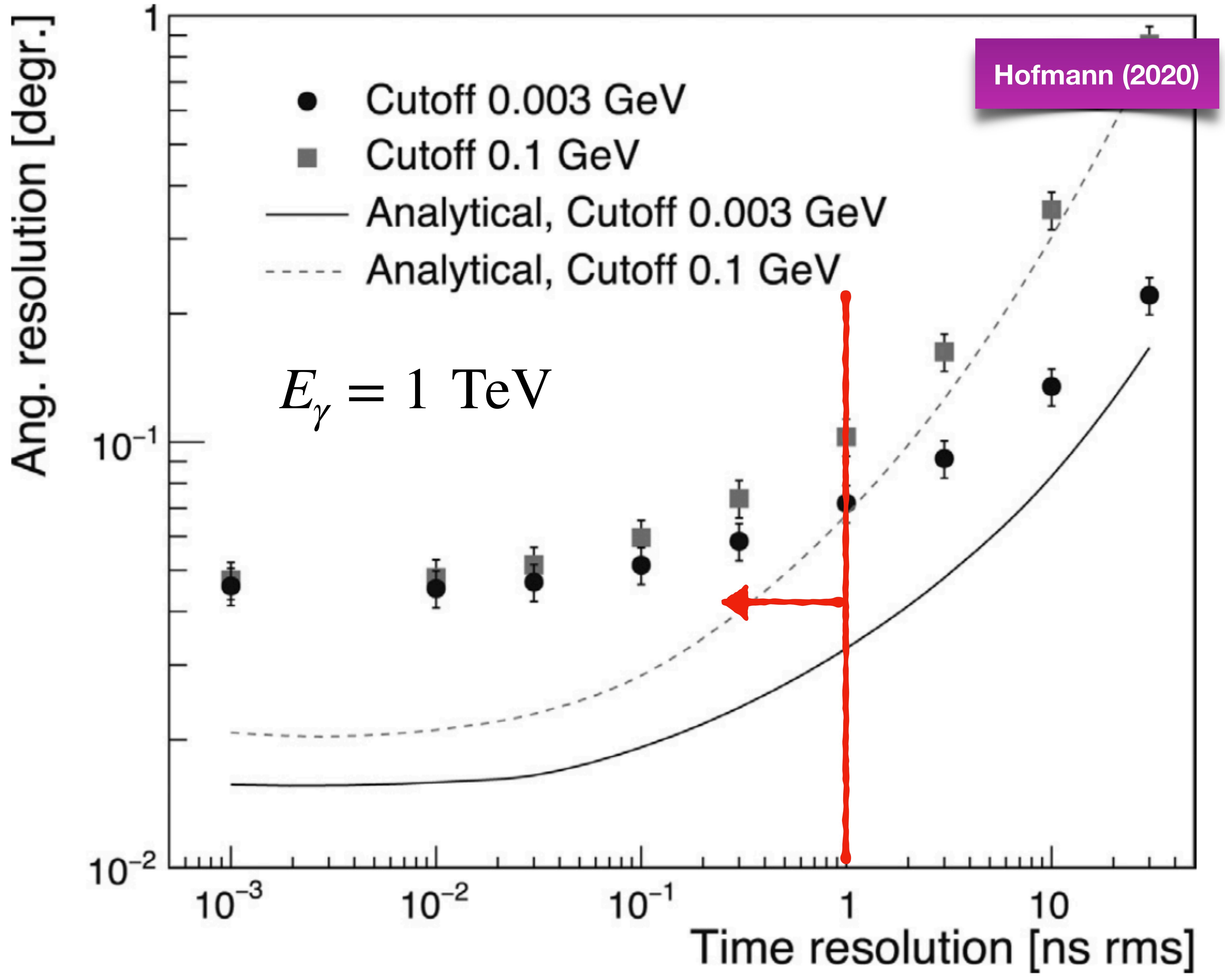
simulated site @ 5 km

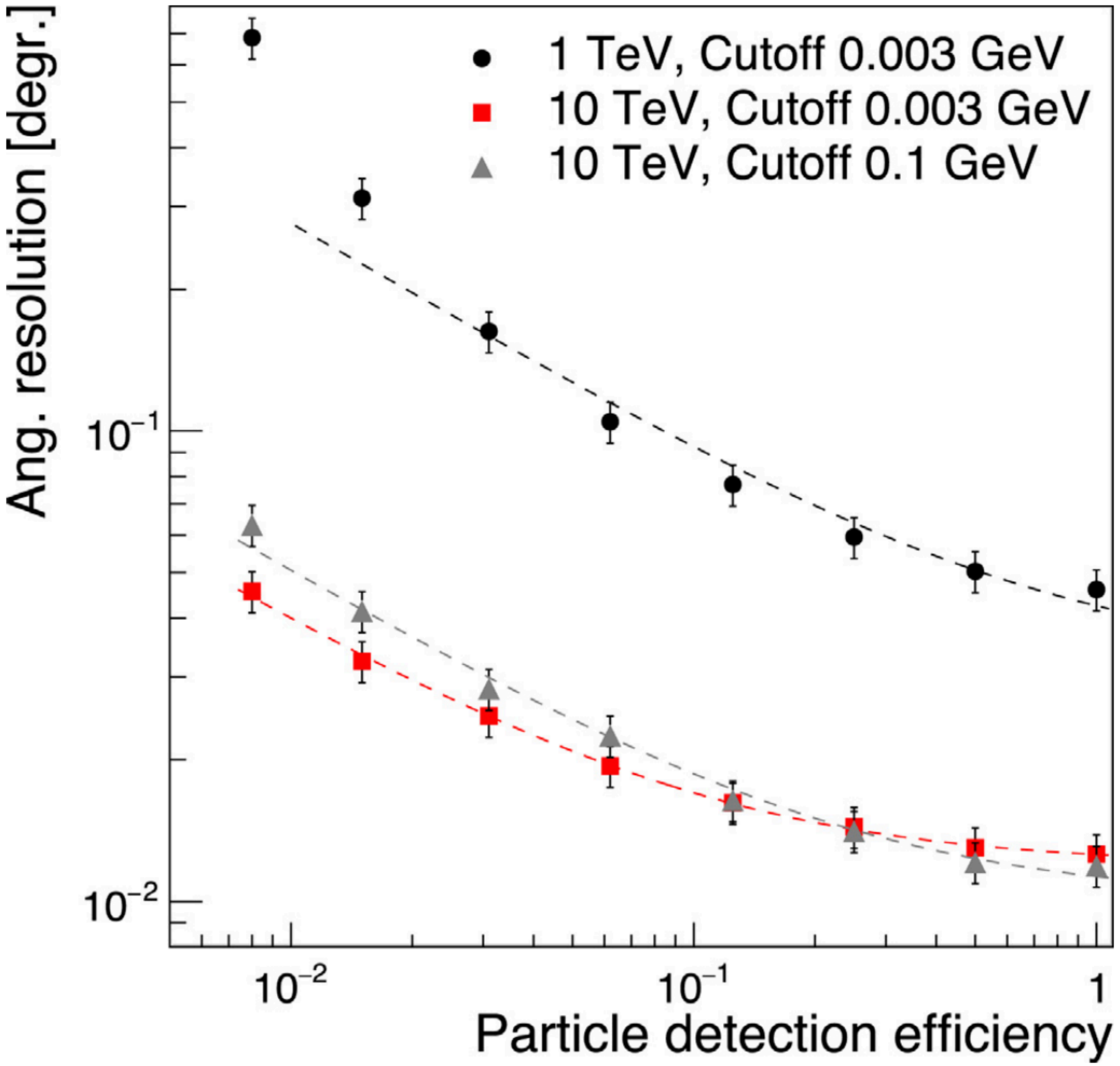
- all shower particles registered
- perfect timing

Direction reconstruction - fill factor



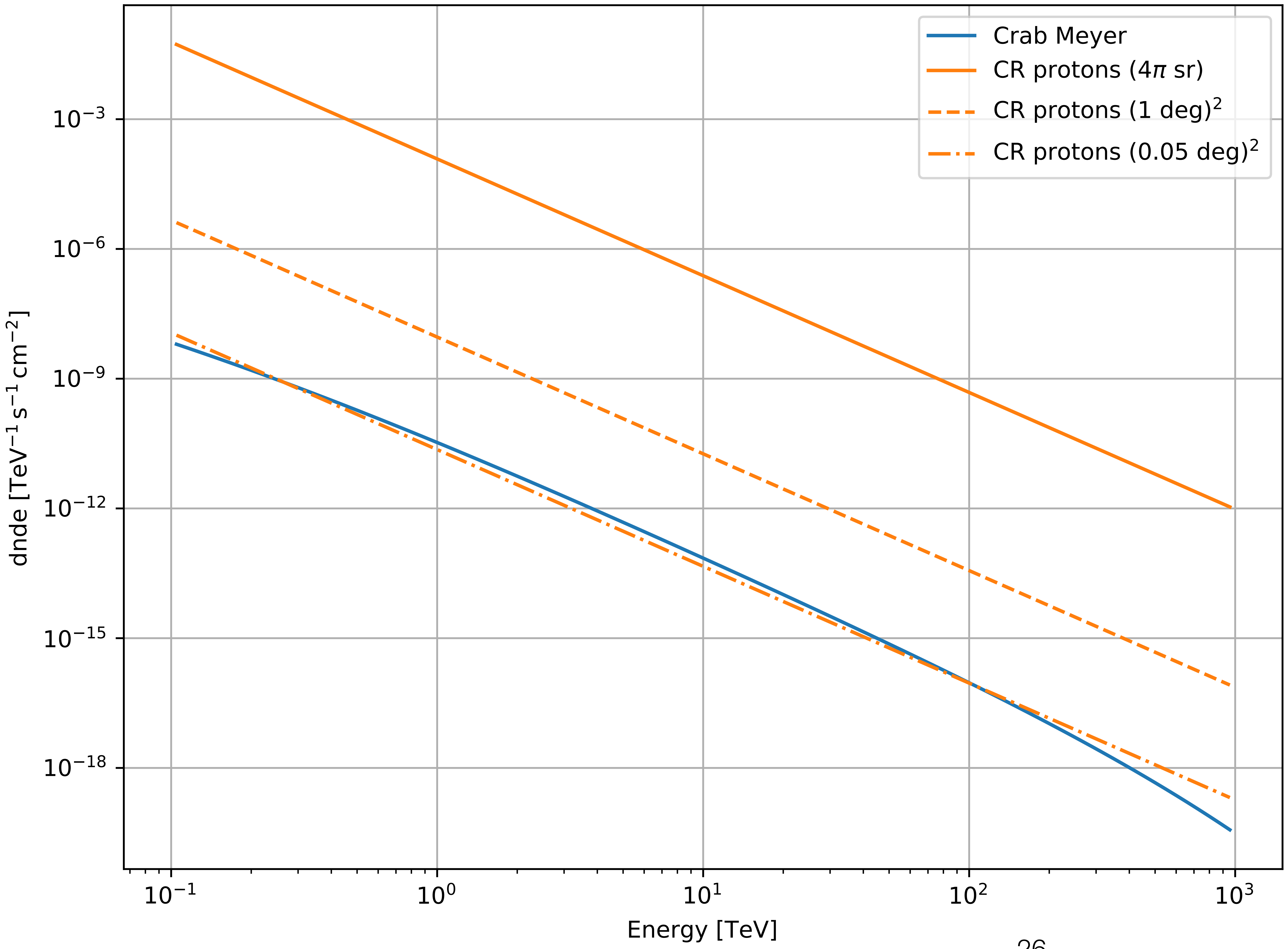
Direction reconstruction - time resolution

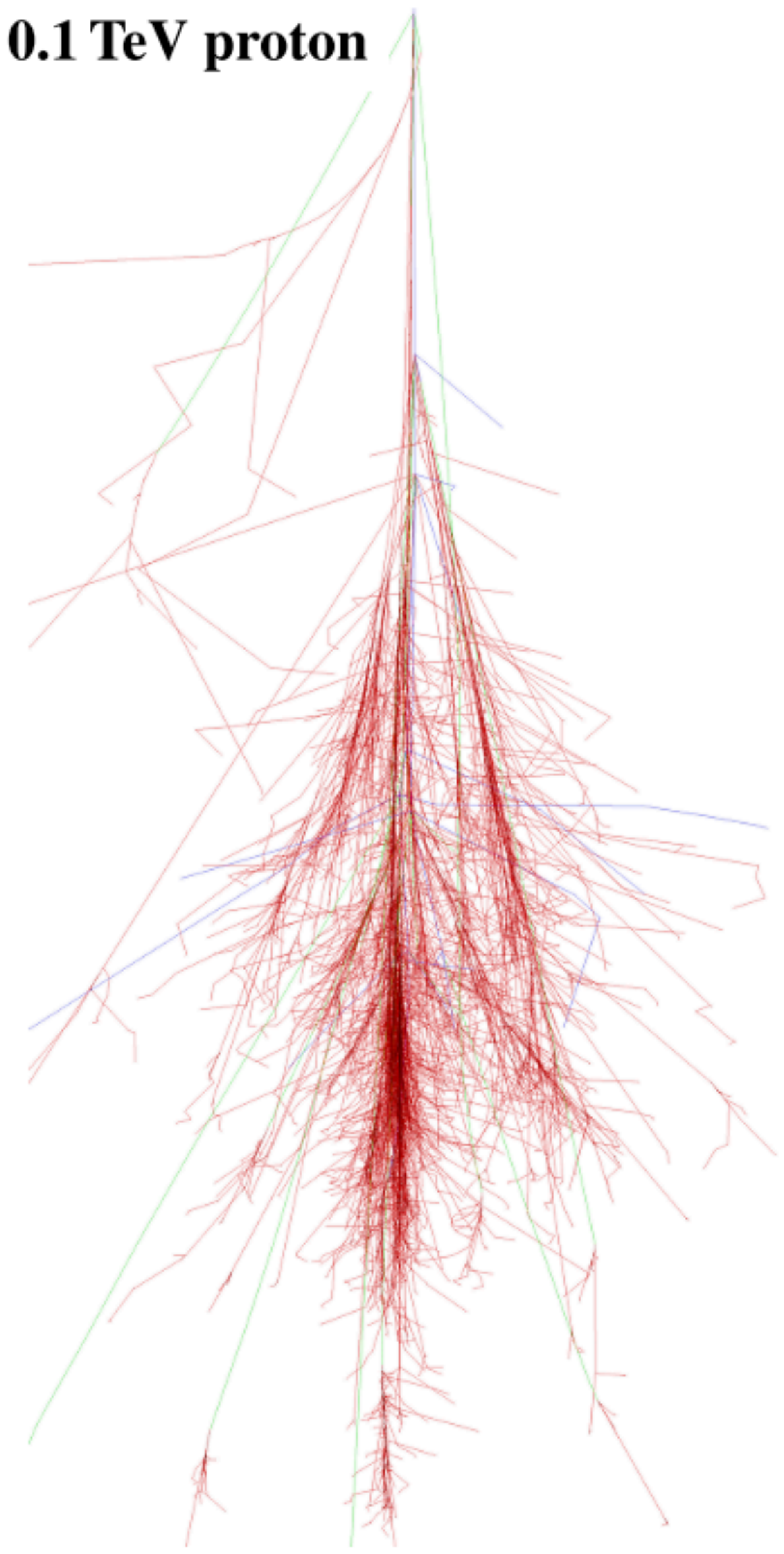




sub-1 ns time resolution desirable
→ implications for detector unit size and detector type

Background!



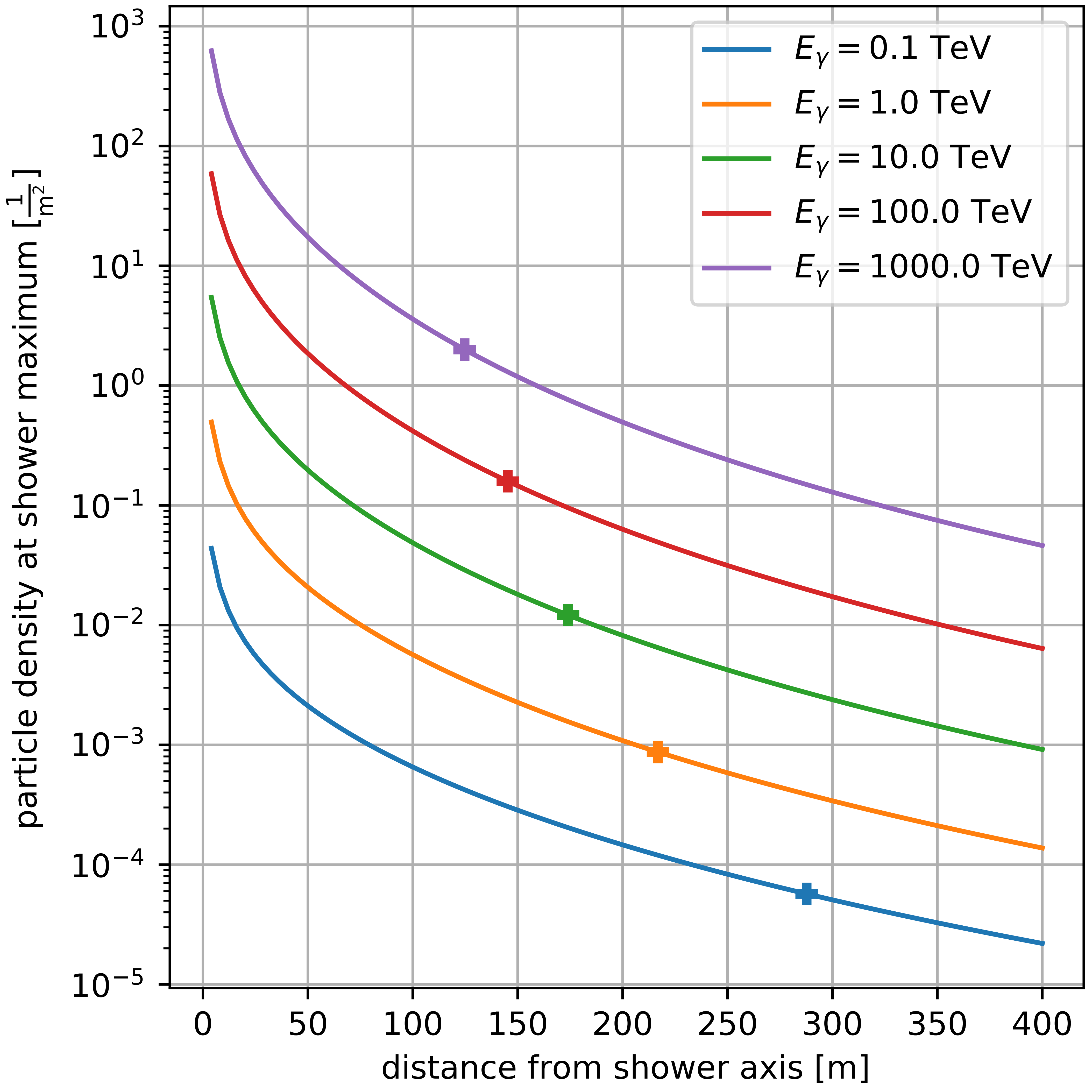


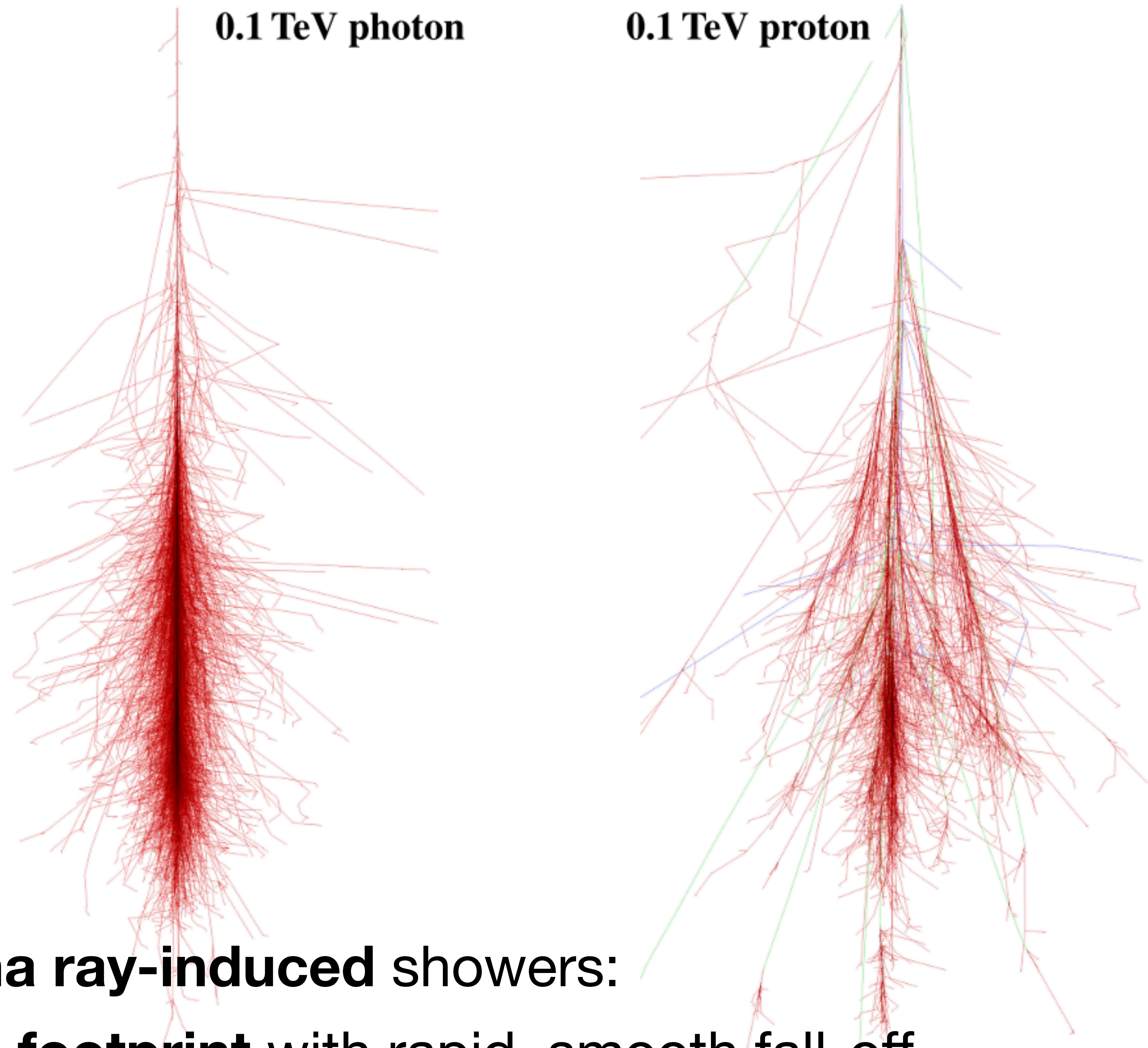
may want to suppress cosmic rays by several orders of magnitude.

→ measure lateral “patchiness” of shower footprint

→ dedicated measurement of muon content

EM vs. hadronic showers





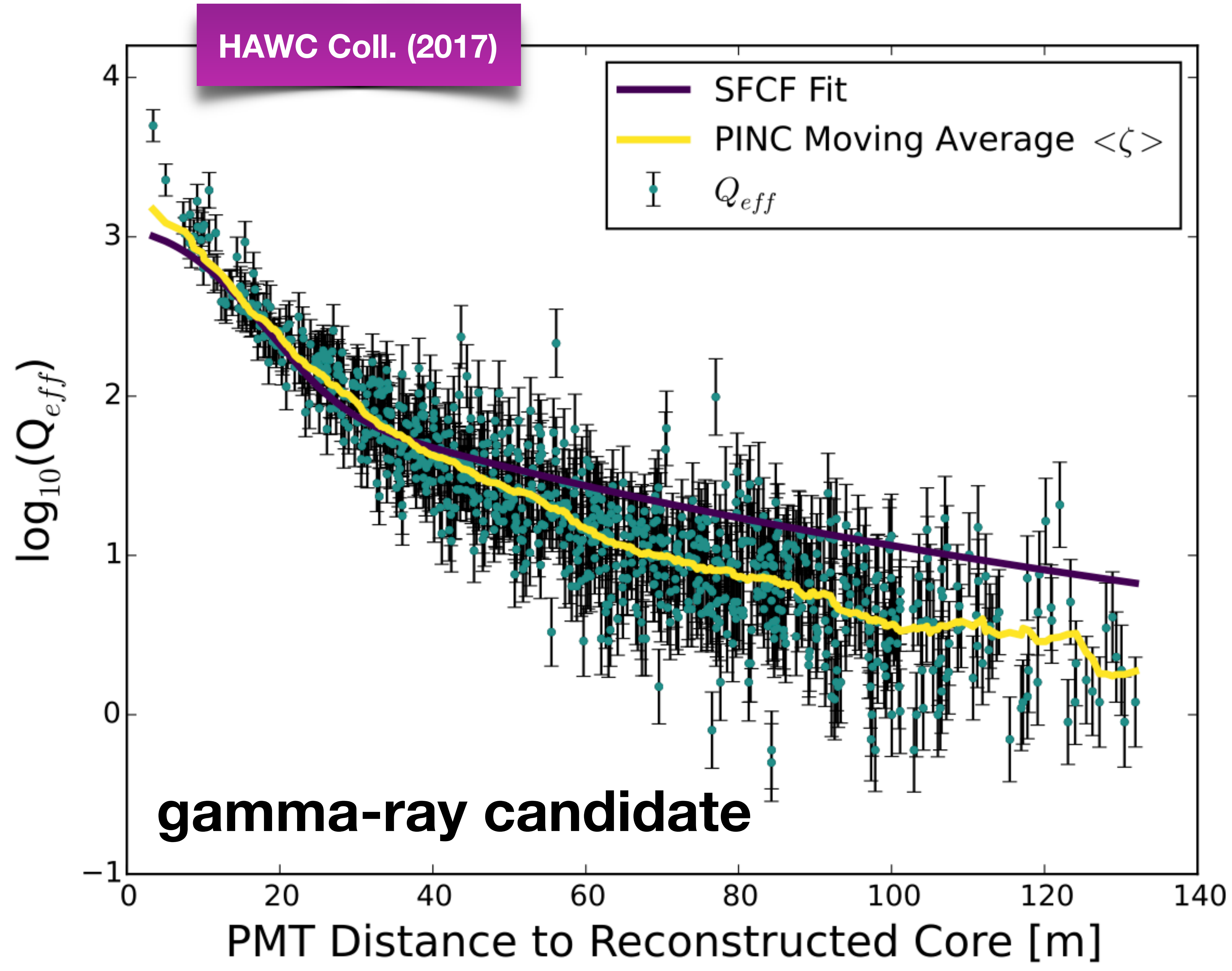
gamma ray-induced showers:

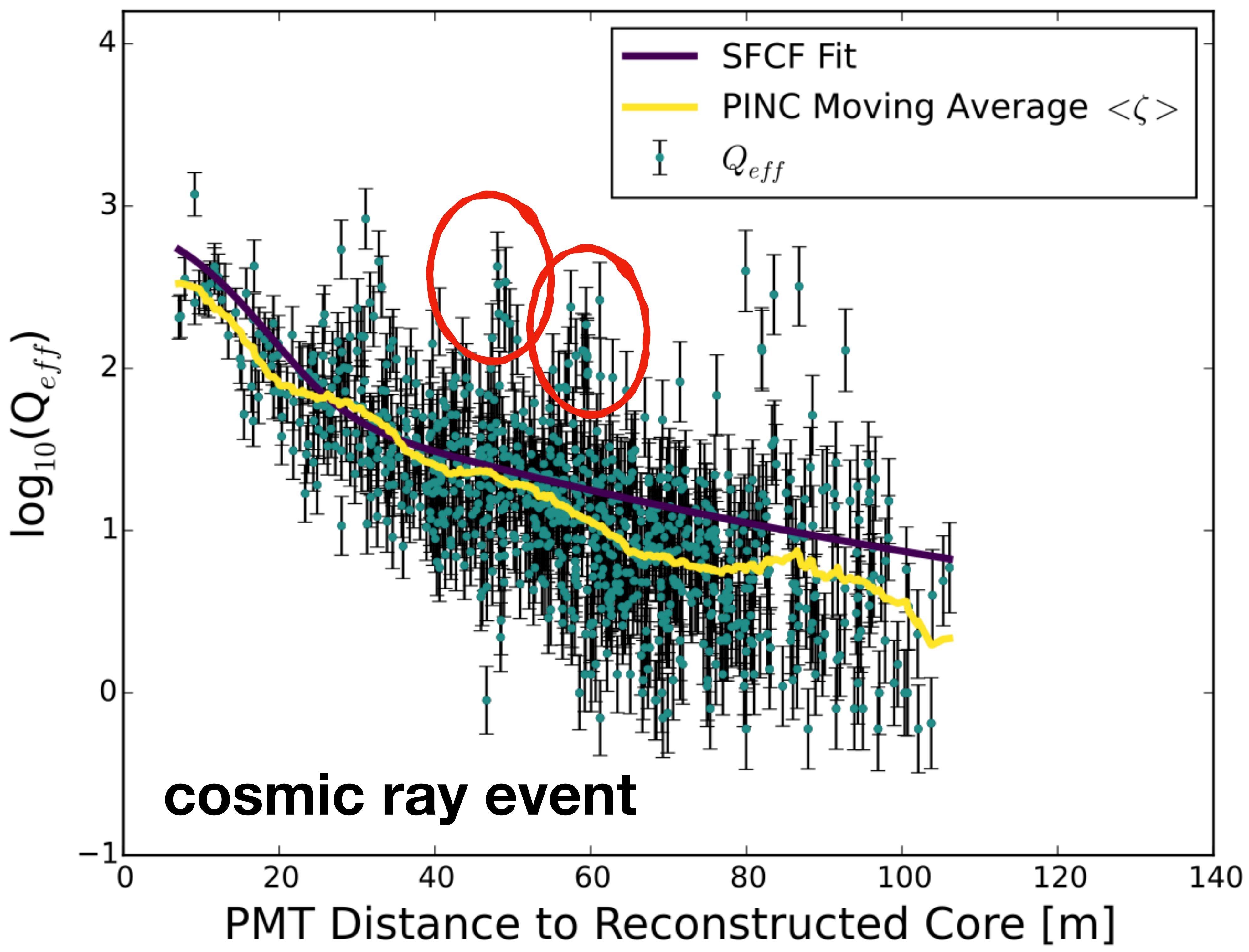
- **slim footprint** with rapid, smooth fall-off from the shower core

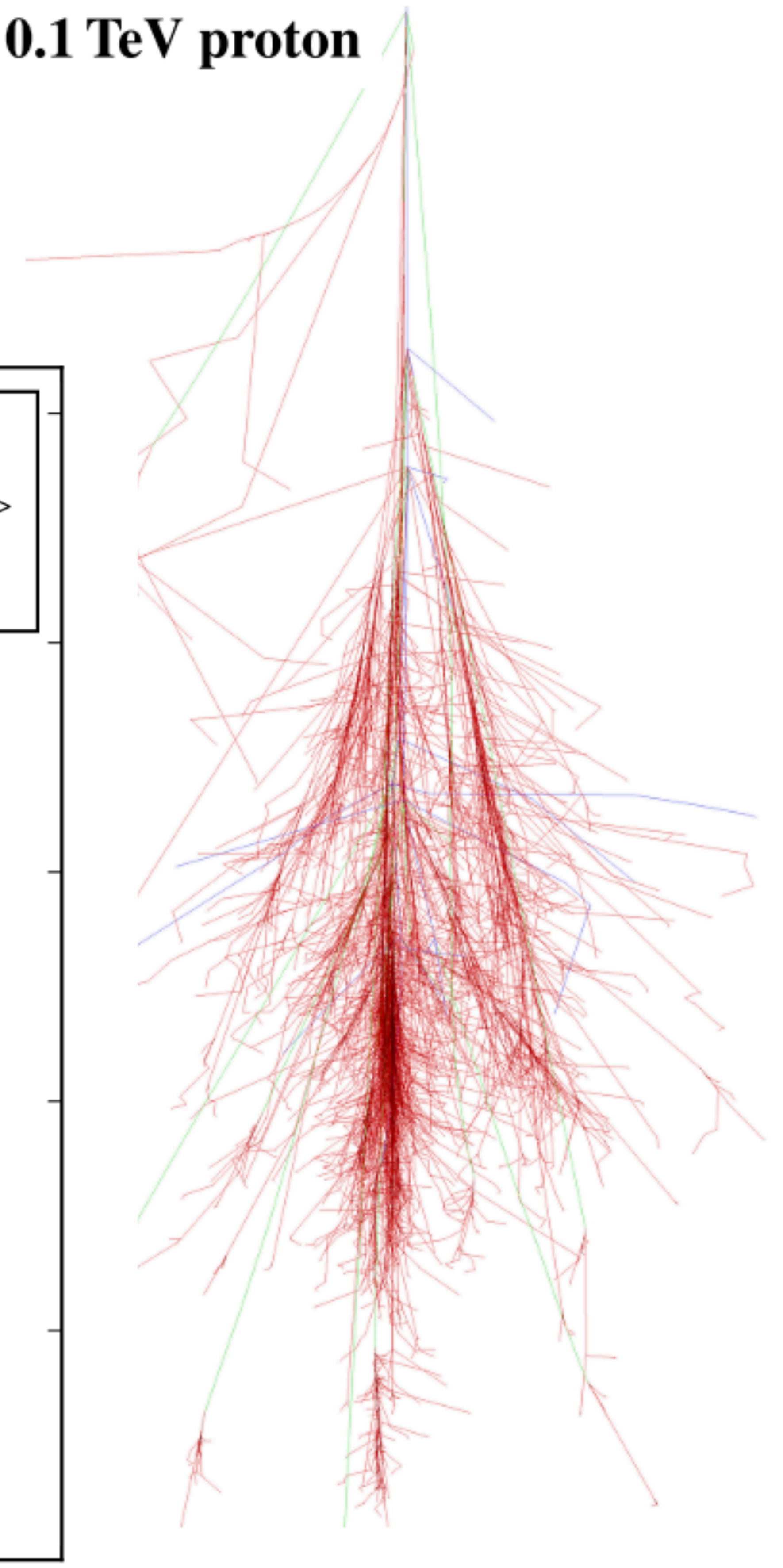
cosmic ray-induced showers:

- **patchy** footprint due to hadronic fragments/muons with large transverse momentum
- prominent **muon component** at ground

HAWC - compactness and PINCness

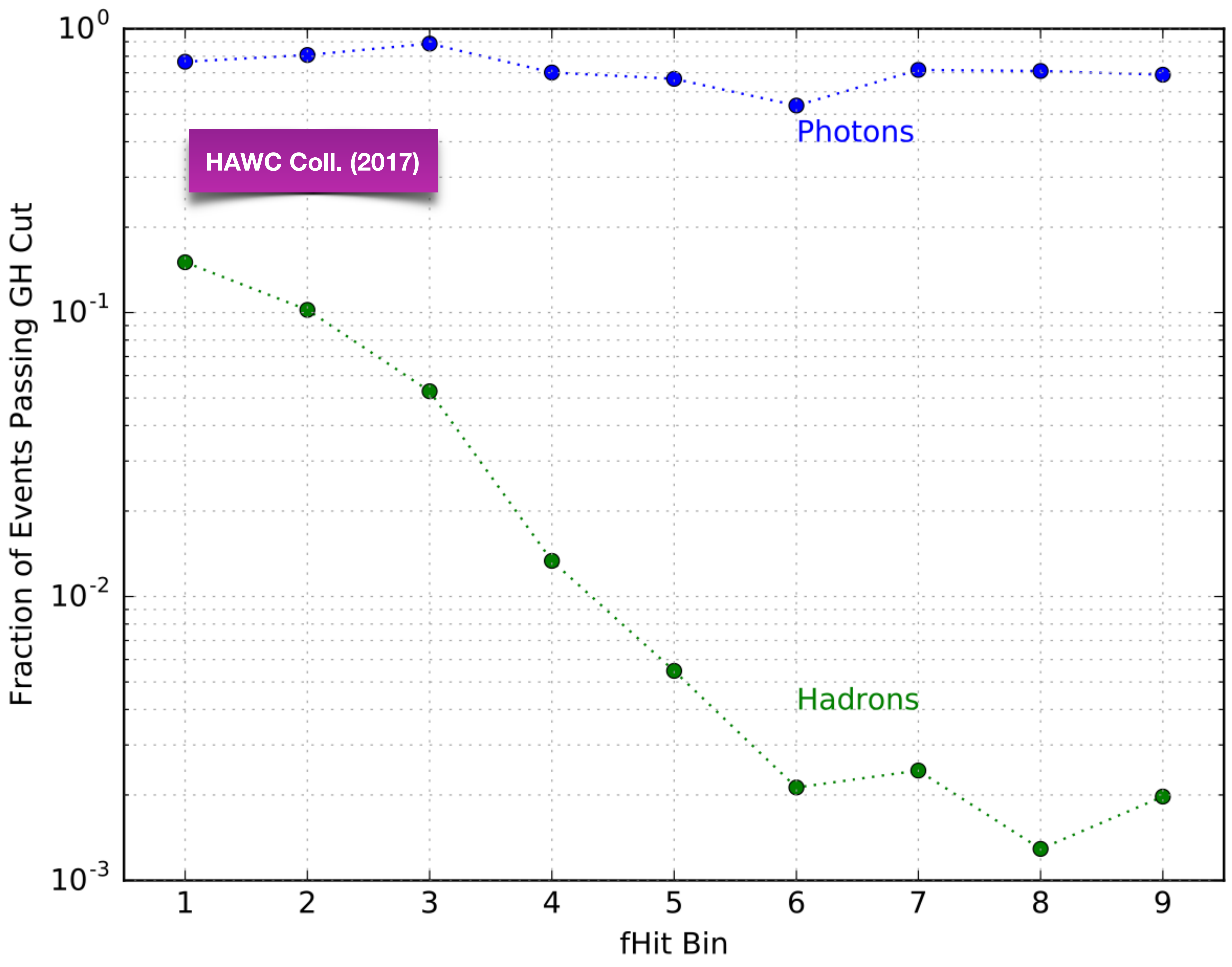




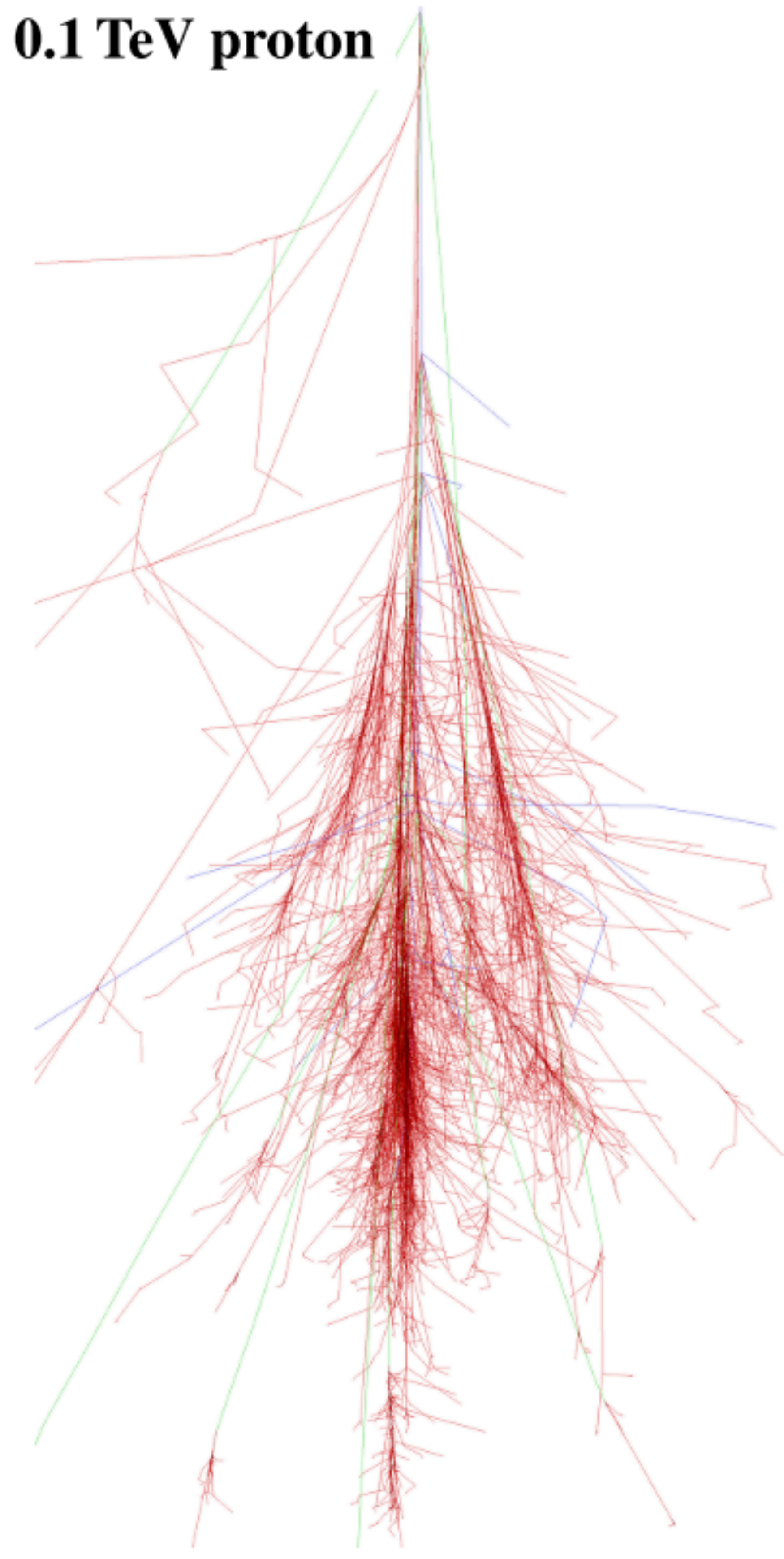


separating variables based on deviation from smoothness of lateral shower profile
→ used either as "box cuts" or in ML approach

HAWC - compactness and PINCness



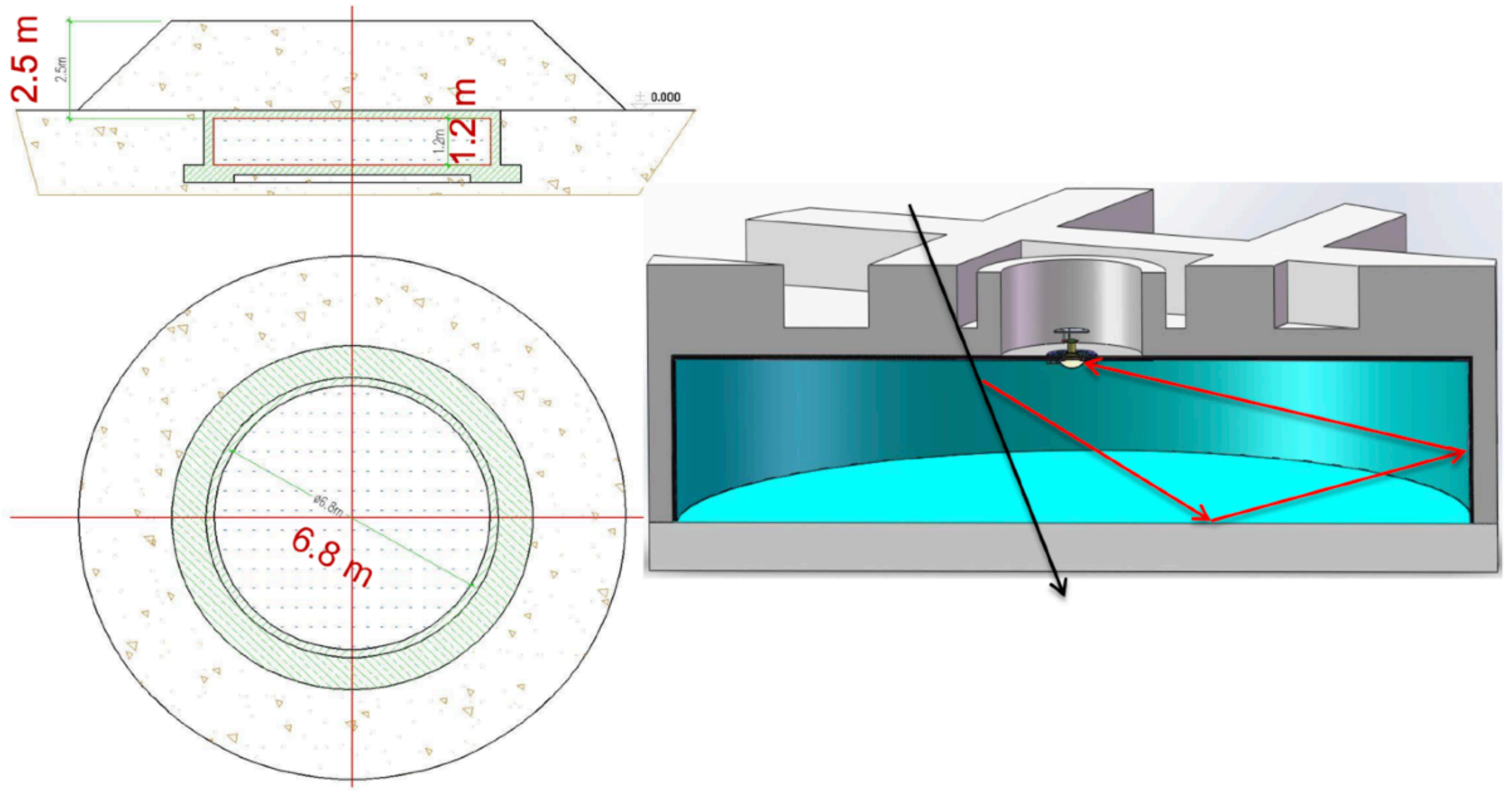
“reconstructed energy”



cosmic ray suppression:
almost 3 orders of magnitude at highest energies

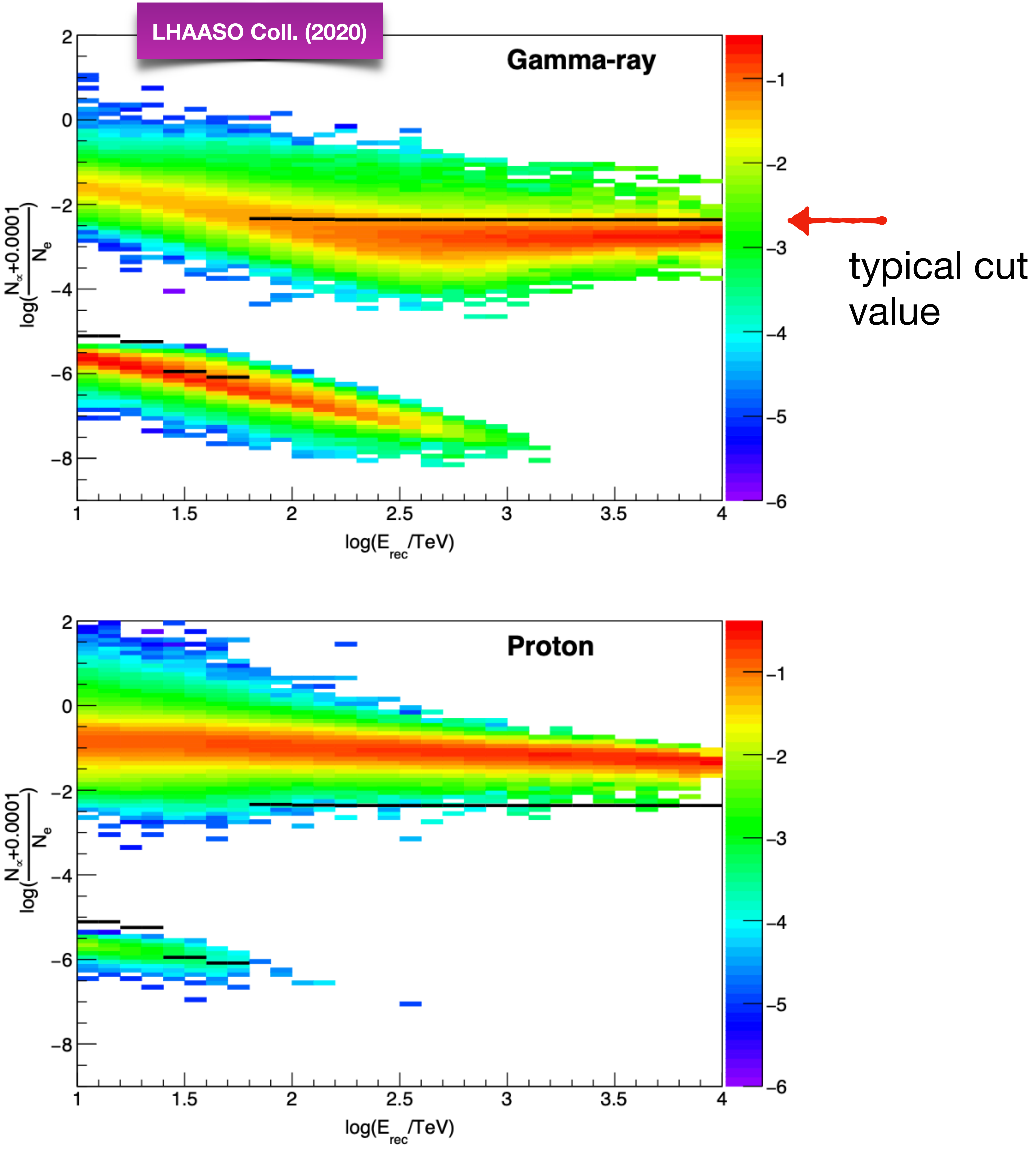
LHAASO KM2A

- **electromagnetic detectors**:
  ~ 5000 lead-covered scintillation counters
- **muon detectors:**
  ~ 1200 water-Cherenkov detectors
  buried under 2.5 m of soil

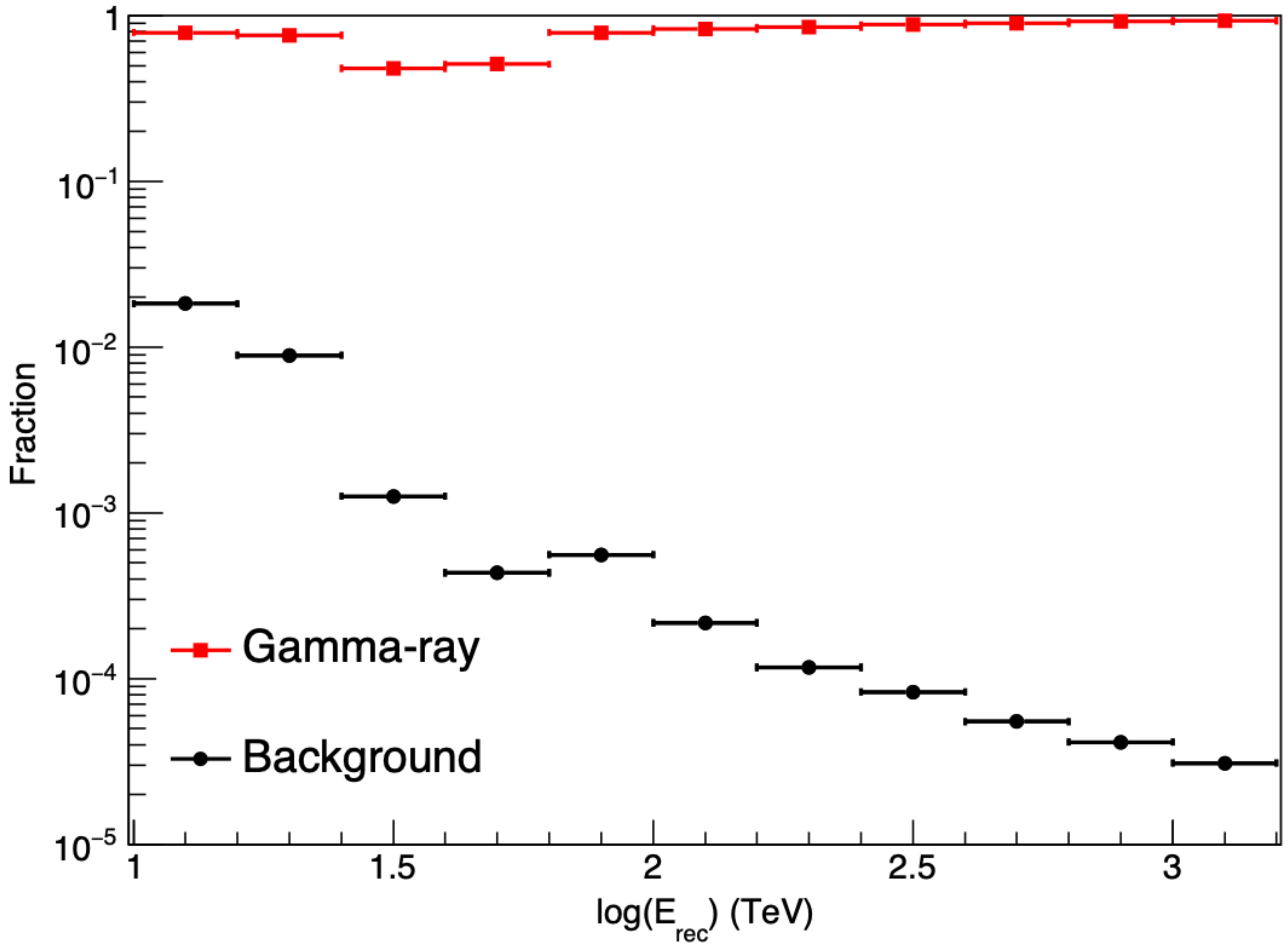


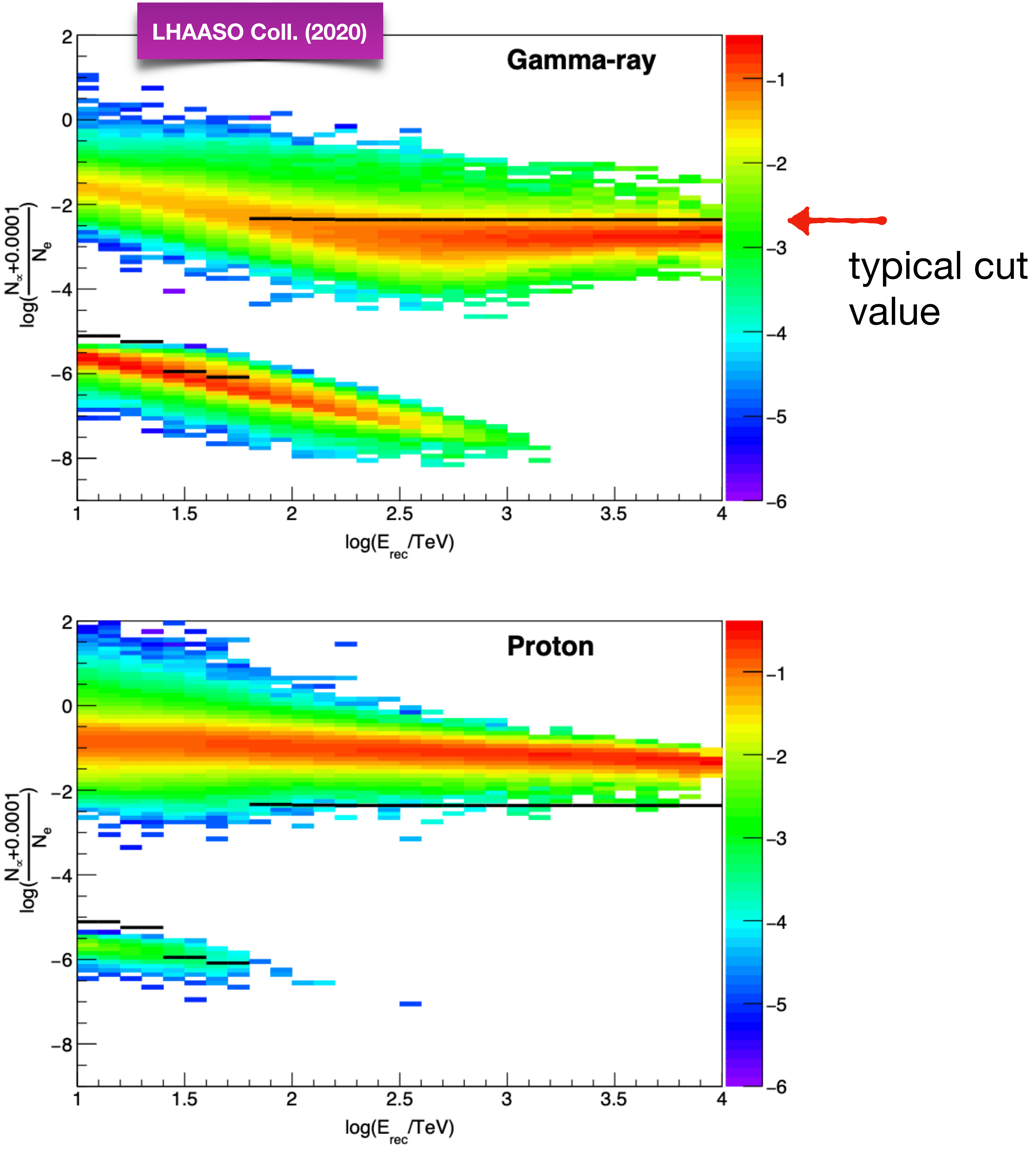
→ simultaneous measurement of electromagnetic and muonic content of each shower

→ separating variable is $R = \log\left(\frac{N_\mu + 0.0001}{N_e}\right)$



LHAASO KM2A



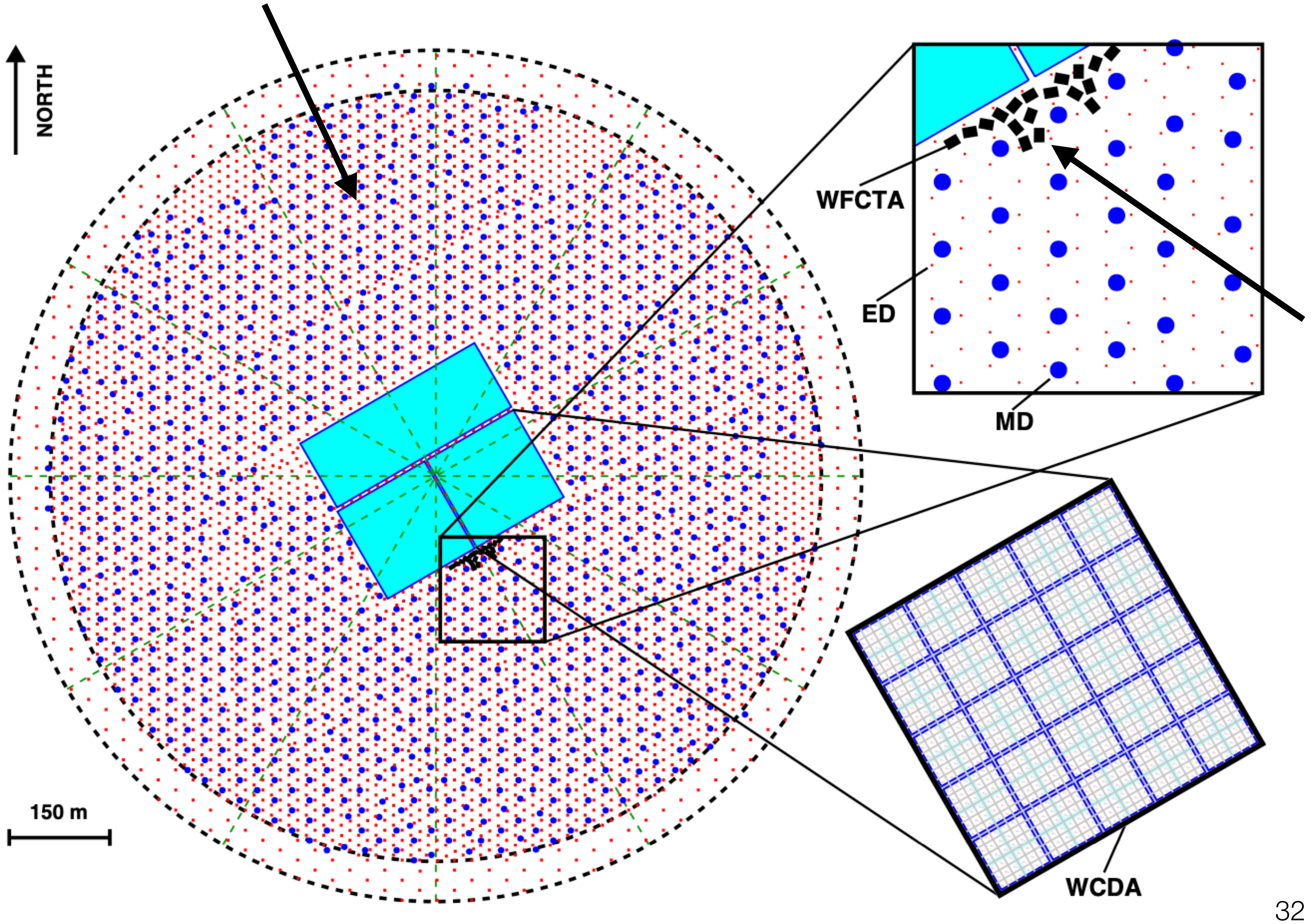


→ **excellent suppression** of up to $5 \cdot 10^{-5}$ even with partially completed array

LHAASO: a hybrid gamma- and cosmic-ray detector

- located in Sichuan, China, 4400 m a.s.l.
- full operation since 2021
- gamma-ray energy range ~100 GeV → ≲1 EeV

Kilometer Squared Array
~5000 scintillators, ~1200 muon counters



Wide Field Cherenkov Telescope Array
18 imaging Cherenkov telescopes

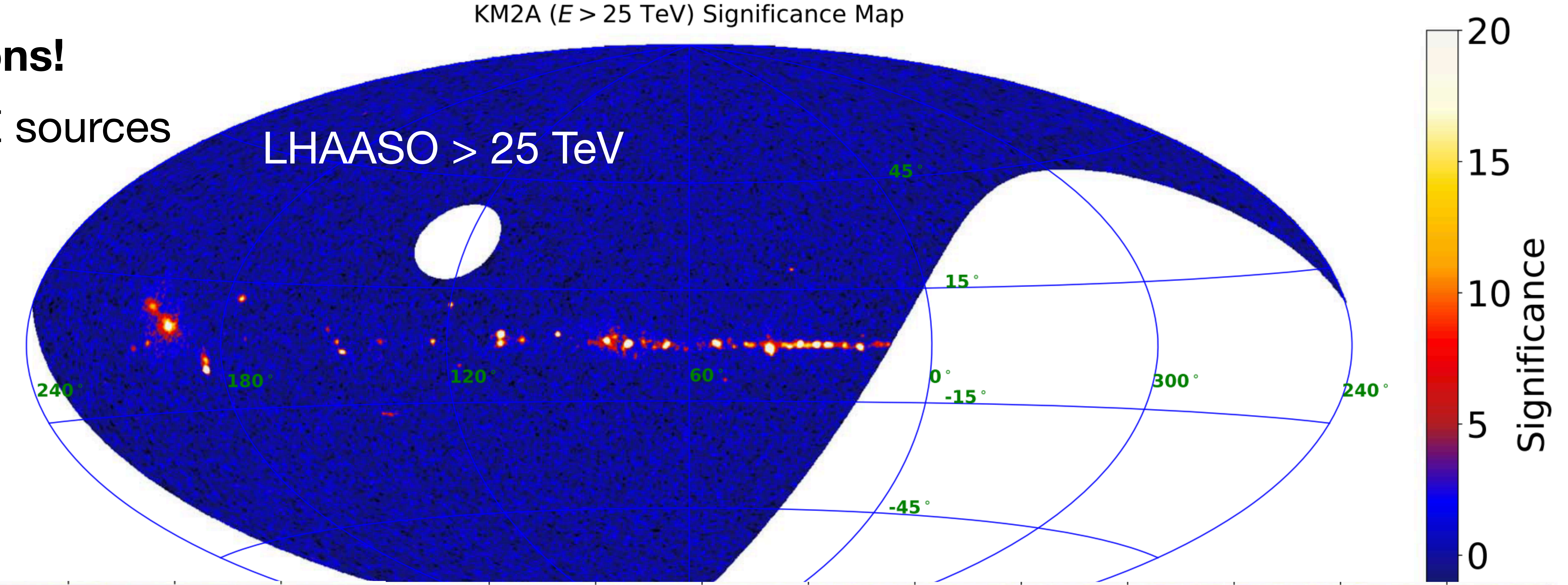
Water Cherenkov Detector Array
78.000 m^2 of segmented water pond

LHAASO: opening the PeV gamma-ray sky

- since 2020, **43 sources of > 100 TeV (UHE)** gamma rays detected
- maximum photon energy: **1.4 PeV**
- in total, 90 gamma ray sources above 1 TeV

→ **Milky Way populated by PeVatrons!**

- almost all sources adjacent to VHE sources
- almost all in vicinity of
  - energetic pulsars/SNRs
  - star forming regions

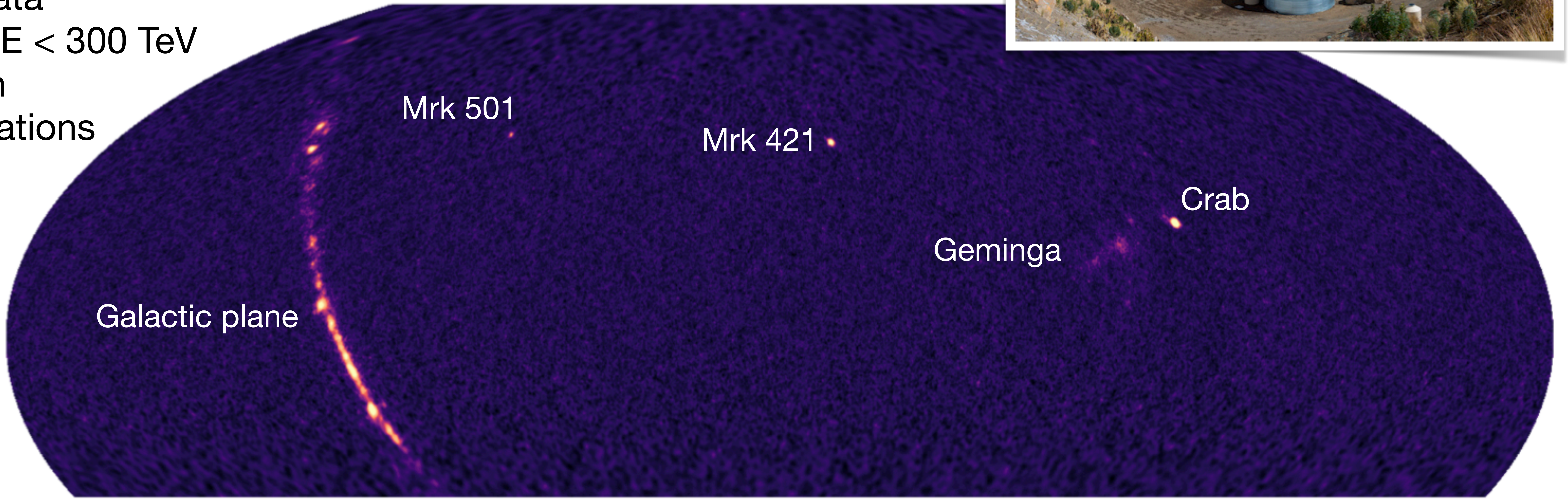


LHAASO Coll. (2024)

The HAWC gamma-ray sky

3HWC catalog:

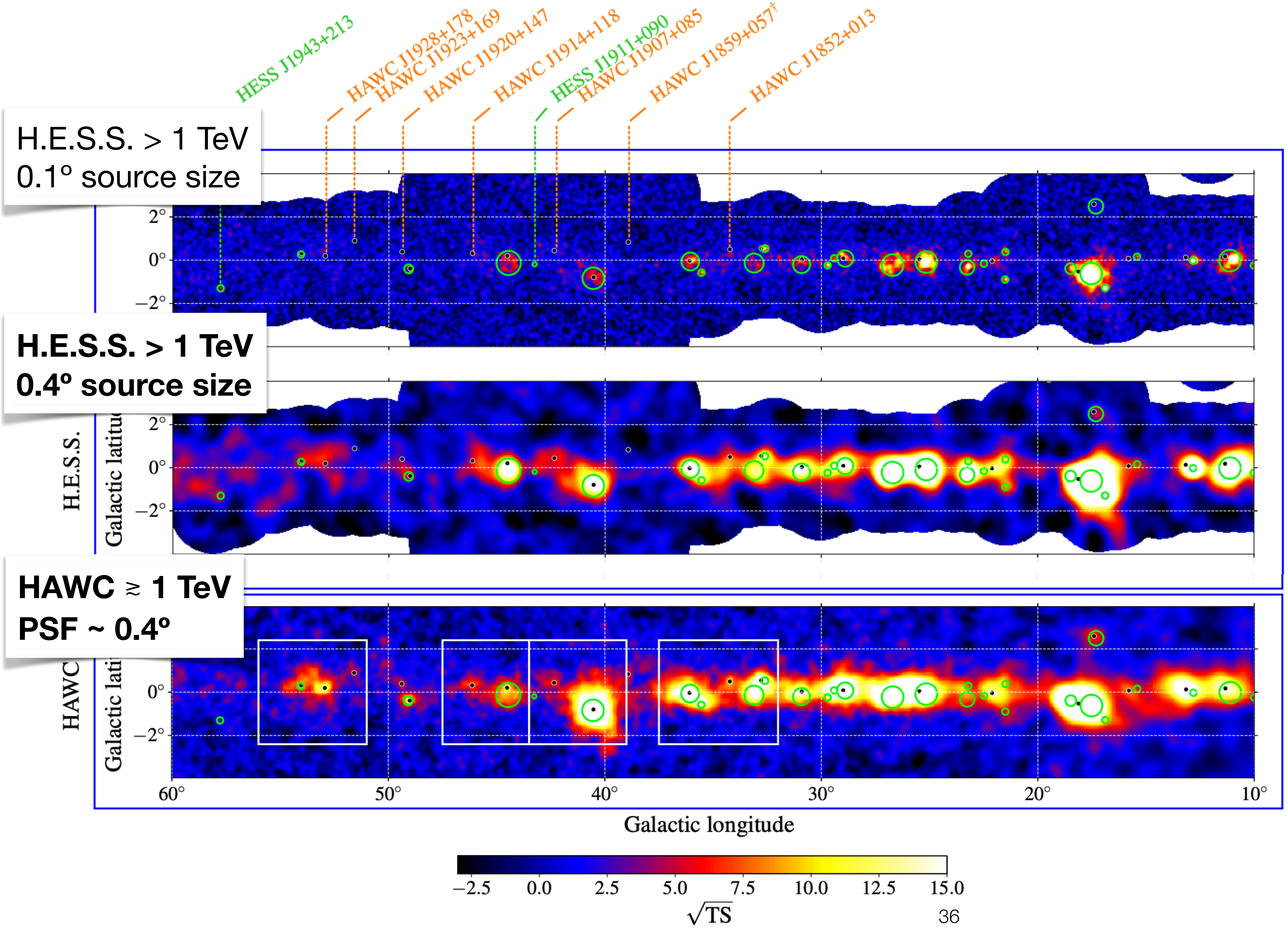
- 1500 days of data
- few 100 GeV < E < 300 TeV
- 65 sources with ~45 TeV associations



HAWC Coll. (2020)

The Galactic Plane from 100 GeV to > 1 PeV

The H.E.S.S.-HAWC Sky



First survey comparison using consistent analysis methods:

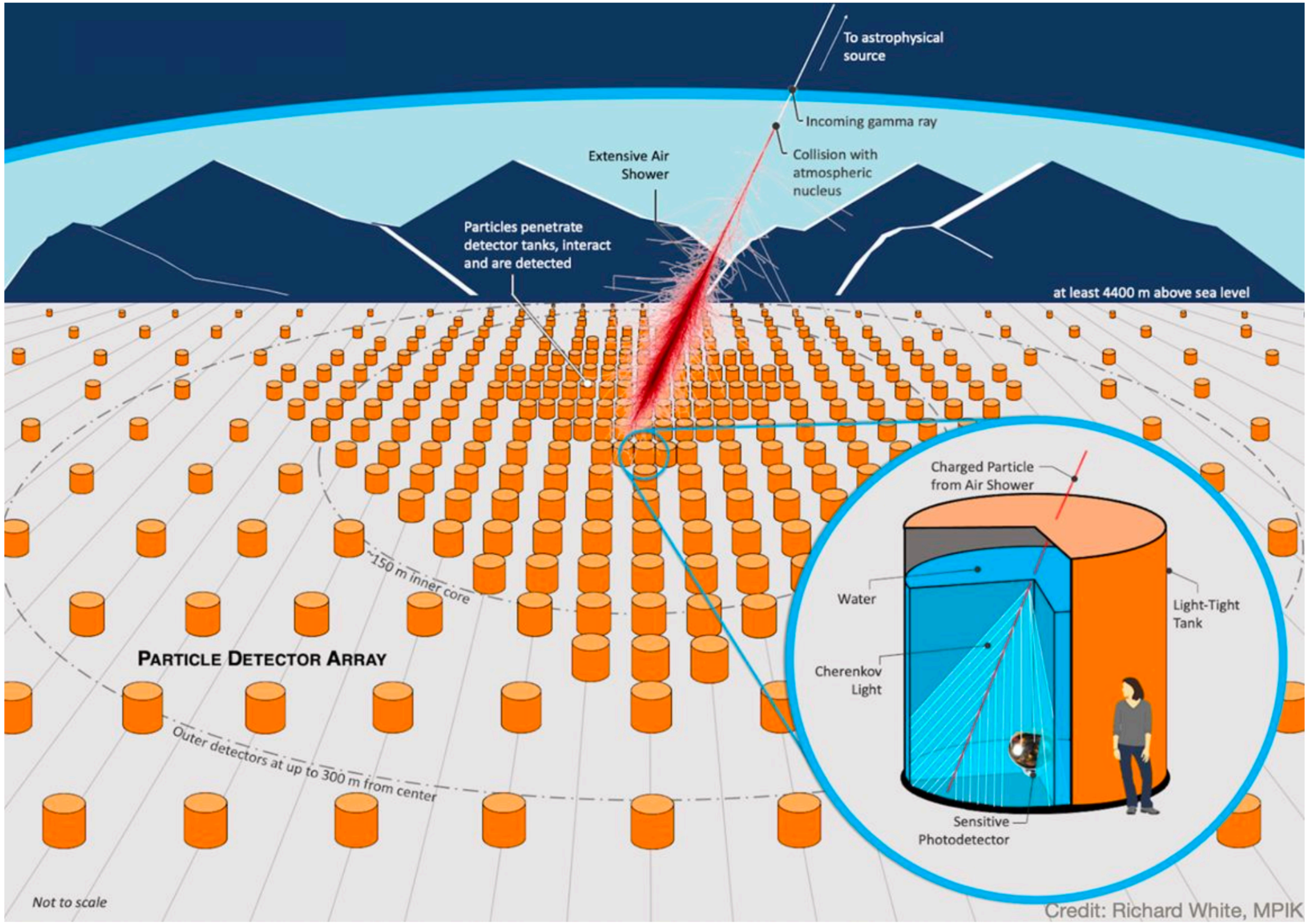
- similar energy range (> 1 TeV)
- similar angular resolution (0.4°)
- similar background modelling

→ **strikingly similar maps**

→ **four new extended H.E.S.S. sources found**

H.E.S.S. & HAWC Coll. ApJ (2021)

SWGO: surveying the southern sky

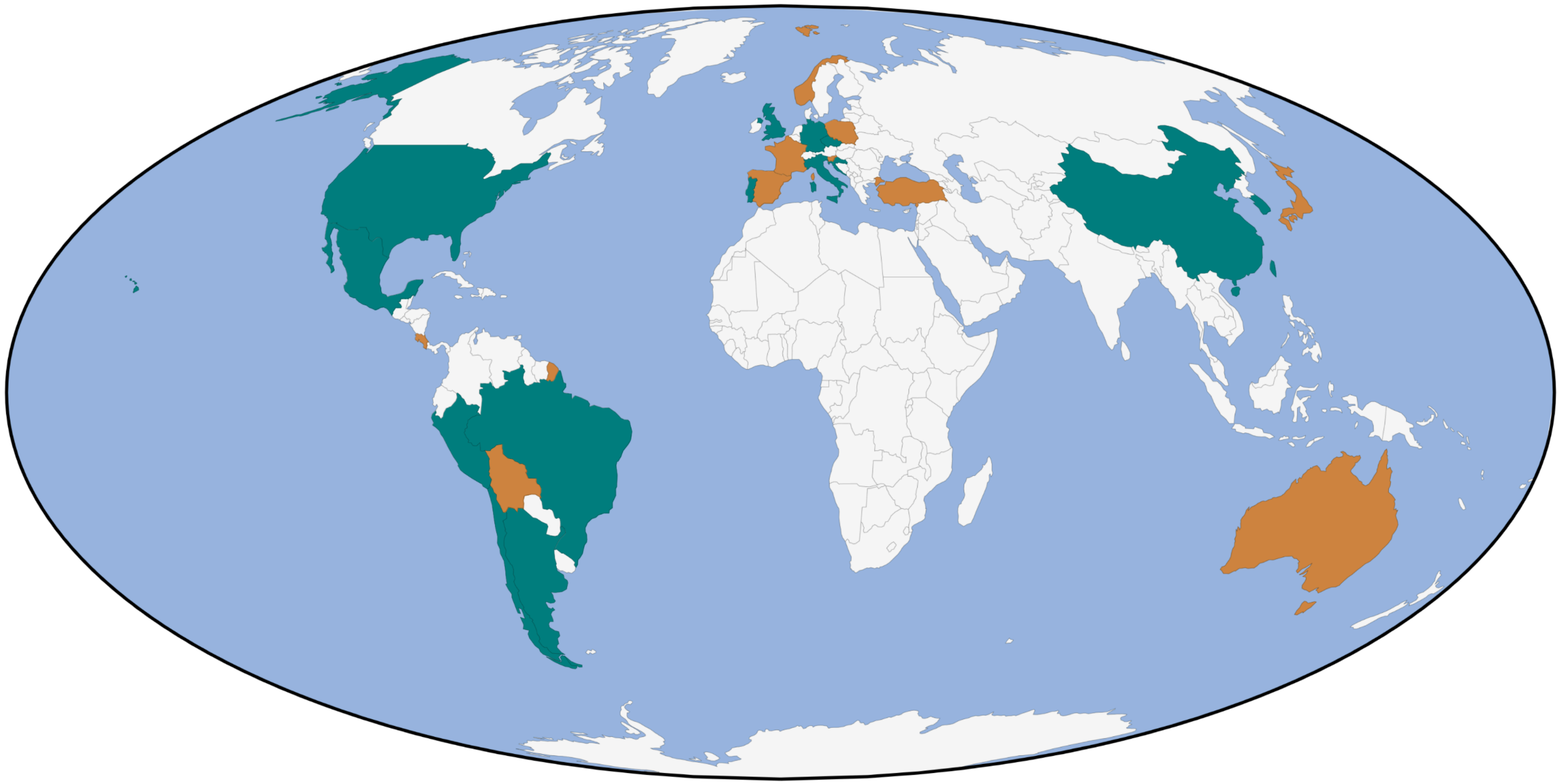


Collaboration towards realising **gamma-ray observatory** in **Latin America**

- **core energy range**: 100s of GeV - 100s of TeV
- large field-of-view, large duty cycle
- considerably larger than HAWC
- primarily based on water Cherenkov detectors

SWGO
The Southern Wide-field Gamma-ray Observatory

SWGO: surveying the southern sky



Collaboration towards realising **gamma-ray observatory** in **Latin America**

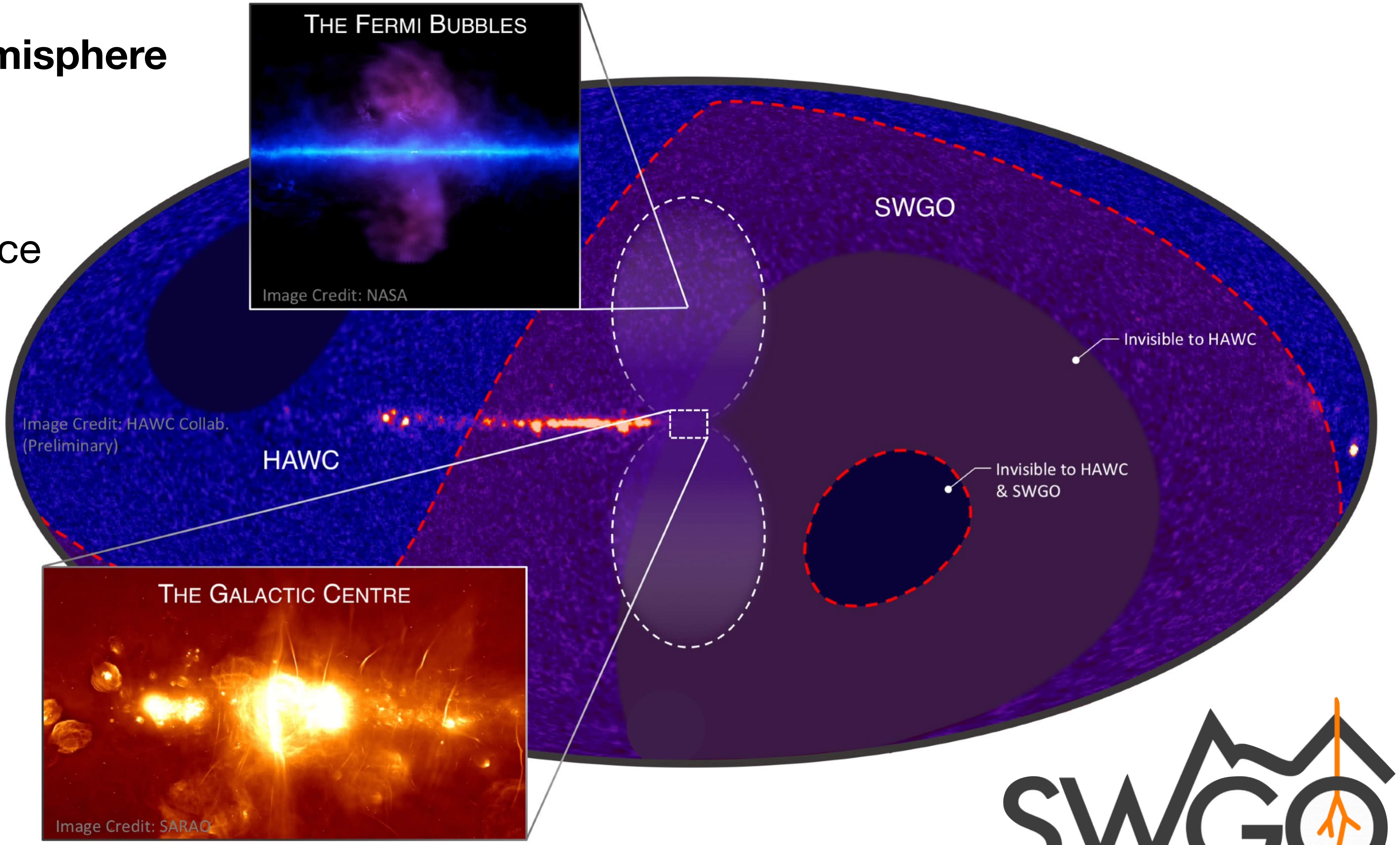
- **core energy range**: 100s of GeV - 100s of TeV
- large field-of-view, large duty cycle
- considerably larger than HAWC
- primarily based on water Cherenkov detectors

> 70 institutes in 14 countries + supporting scientists

SWGO
The Southern Wide-field Gamma-ray Observatory

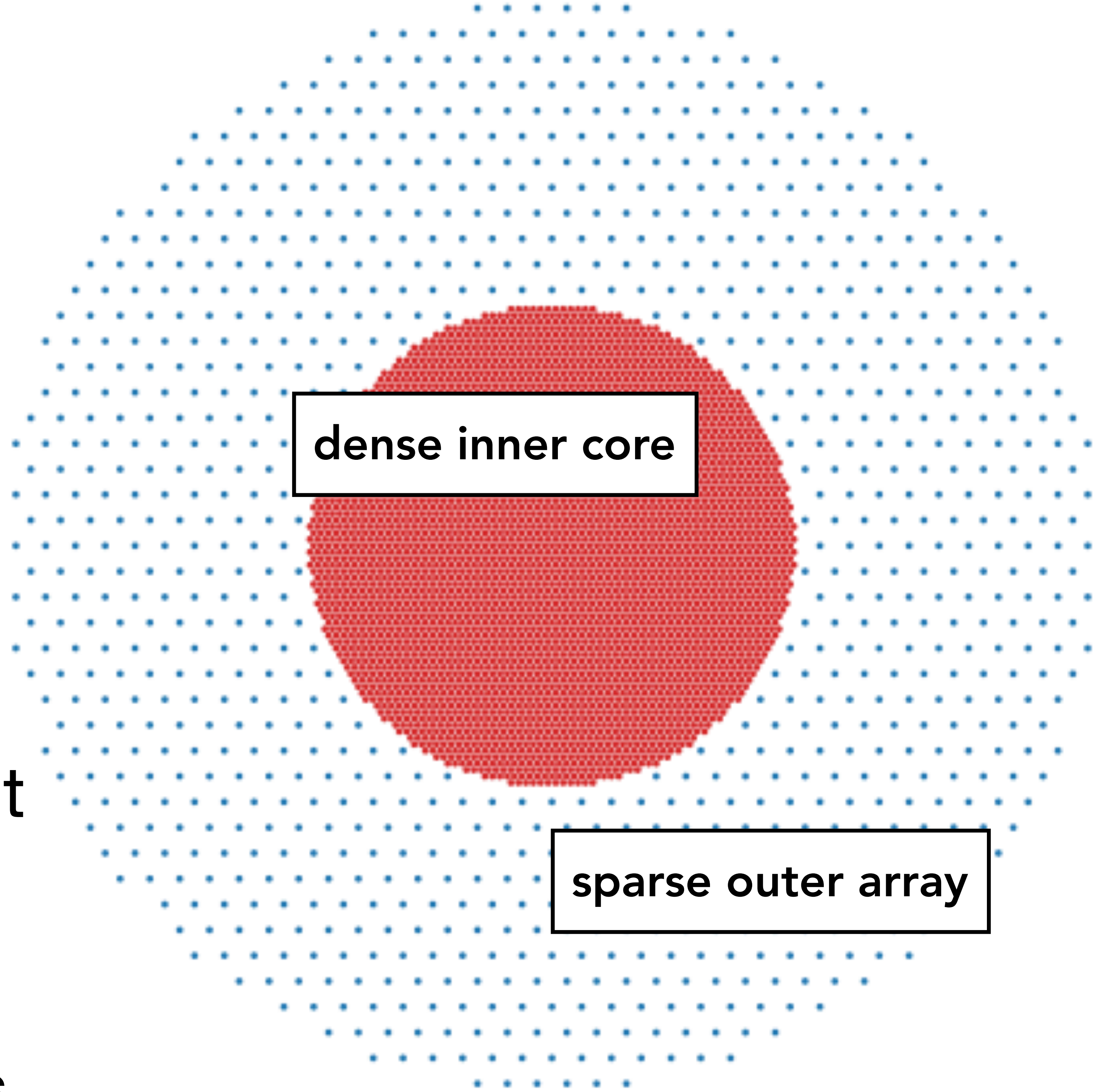
SWGO: surveying the southern sky

- **SWGO:** access to **southern hemisphere**
  - inner Galaxy
  - Galactic Centre region
  - Fermi bubbles
  - unexplored extragalactic space
- ideally suited to **complement CTA-South**

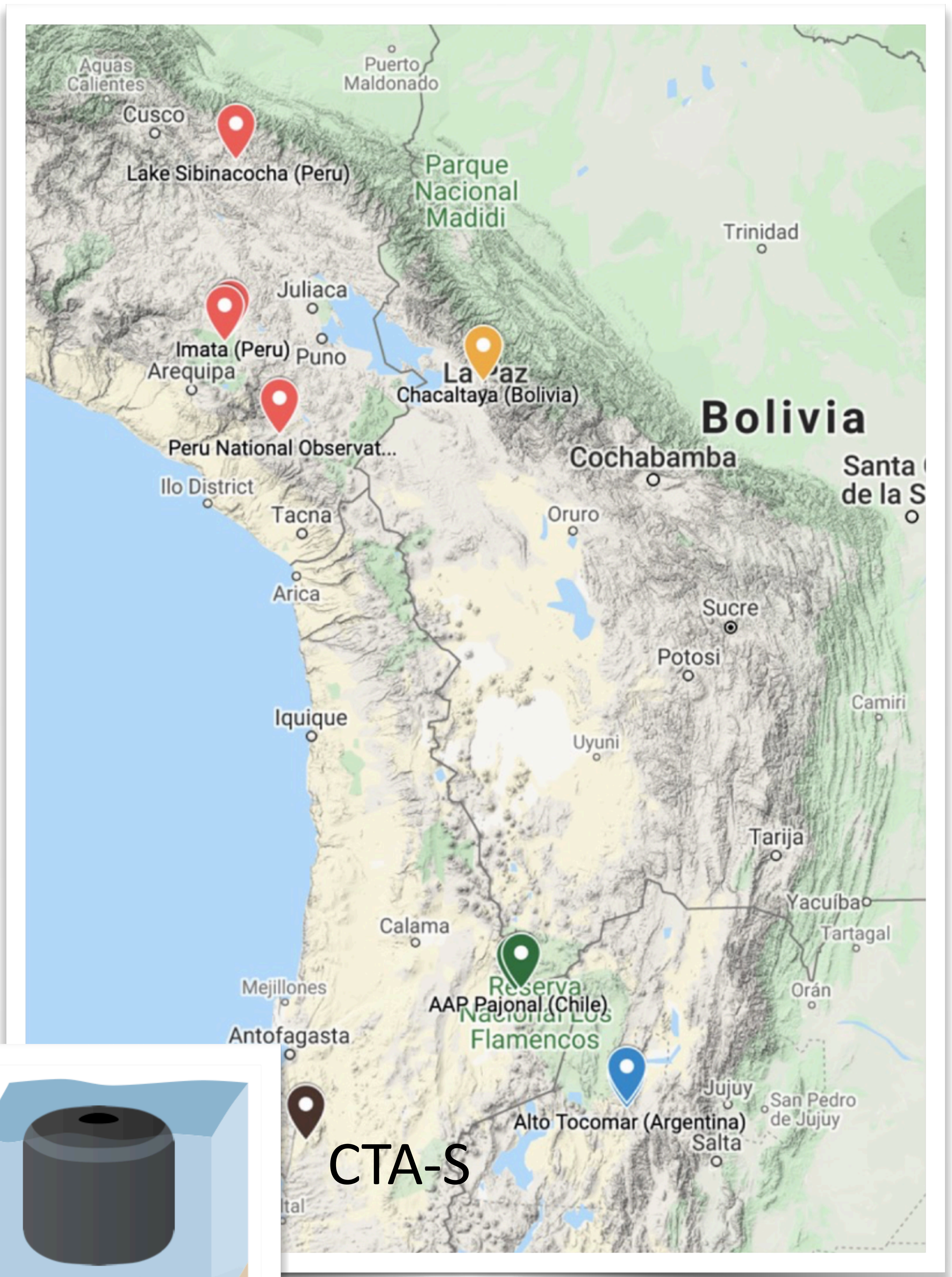


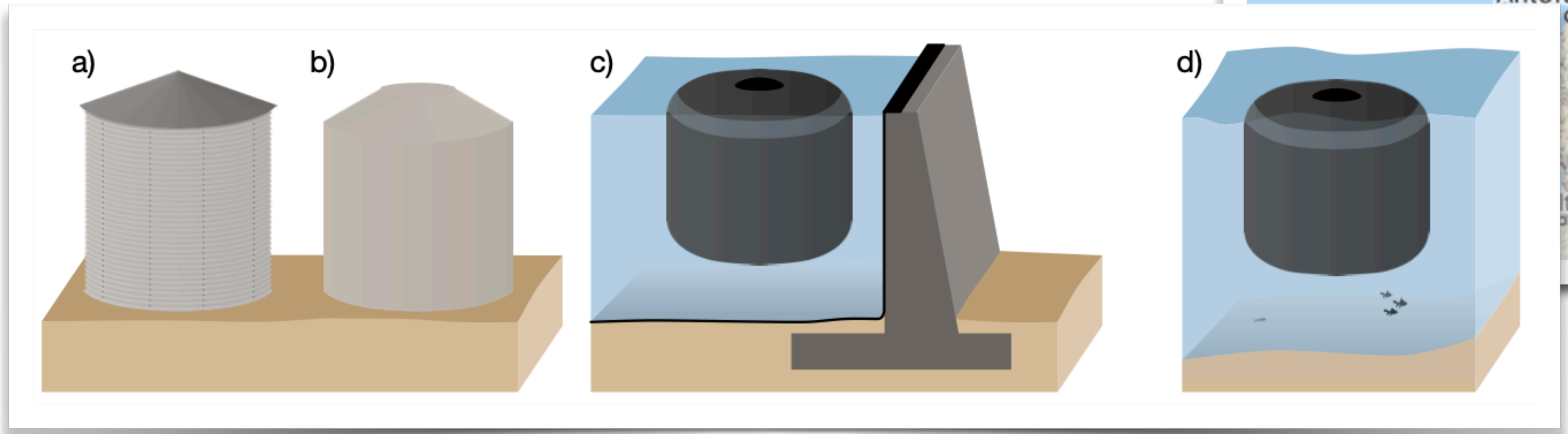
The Southern Wide-field Gamma-ray Observatory

SWGO: baseline design and site options

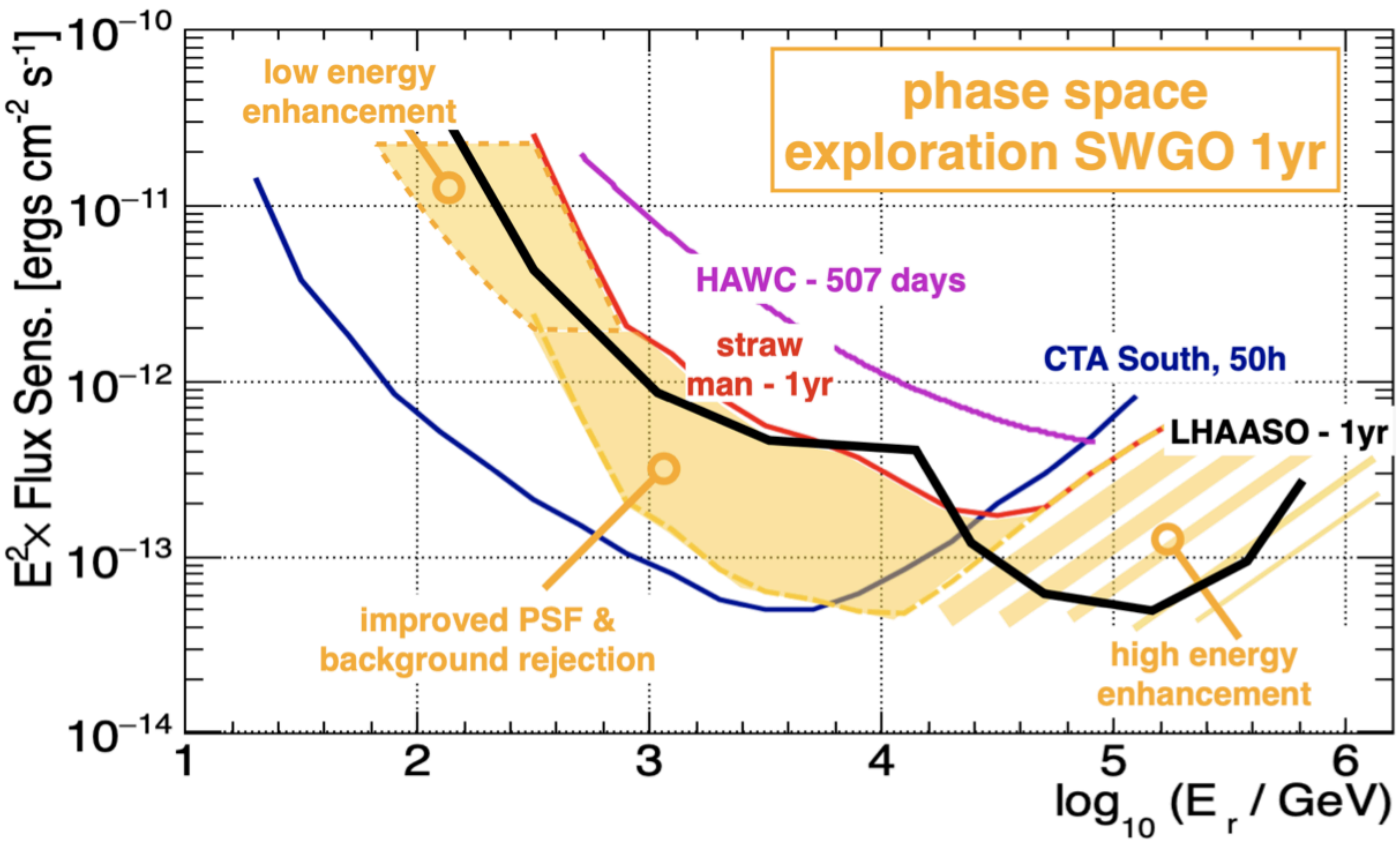


- **dense inner core** & **sparse outer array**
- quite possibly ~km^2 footprint
- **various tank designs**/ deployment options
- shortlist of **4 excellent sites** > 4700 m altitude identified (+ backup sites)





SWGO performance: sensitivity

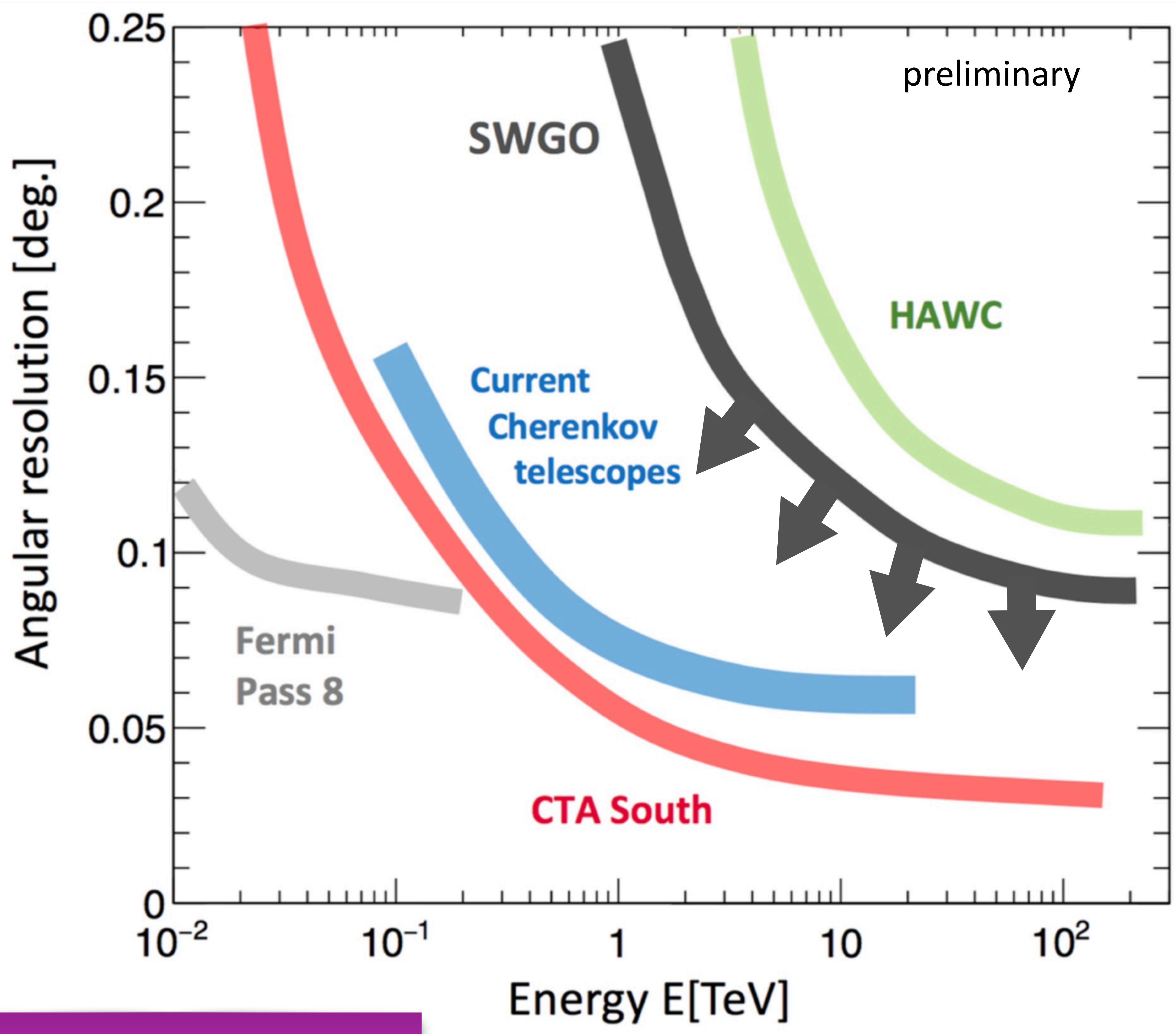


Hinton et al. (SWGO Coll.) ICRC 2021

simple "straw man" model (scaled from HAWC):

- **~competitive** to CTA / LHAASO in core energy range
- **optimisation** towards low and/ or high energies possible
- **upgrade** possibility through staged construction
- performance of various realistic **candidate configurations** being analysed

SWGO performance: angular resolution



Engel et al. (SWGO Coll.) SNOWMASS 2022

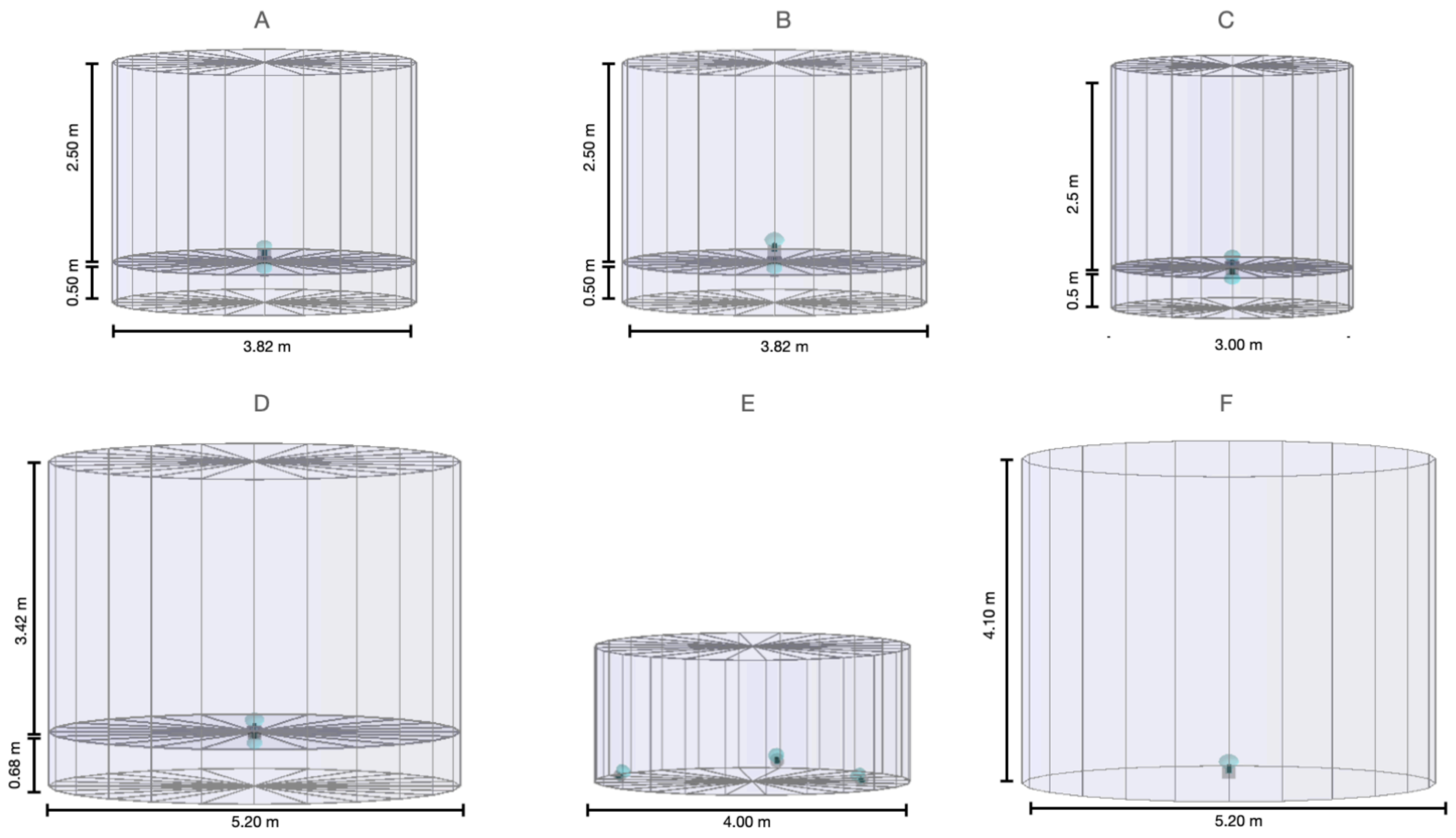
from “straw man” model:

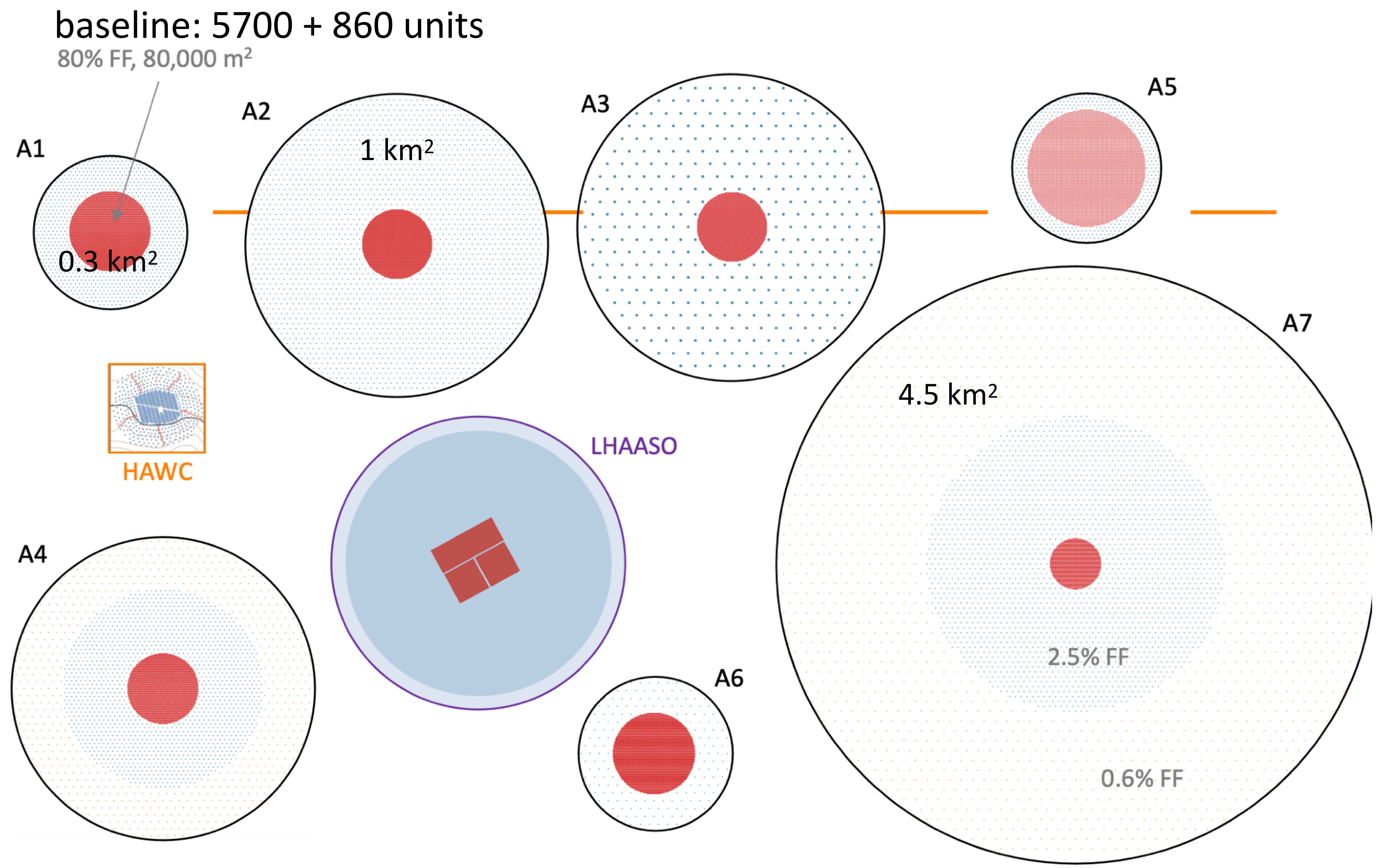
- **0.2º - 0.1º** in core energy range
  → **modest** compared to CTA
- **SWGO** ideal for
  - (transient) source hunting
  - detection of very extended emission
  - monitoring of variable objects
- can trigger CTA for detailed studies

SWGO array optimisation

performance comparison of
- different array layouts
- different unit designs

at **equal nominal cost**
- to be completed as we speak

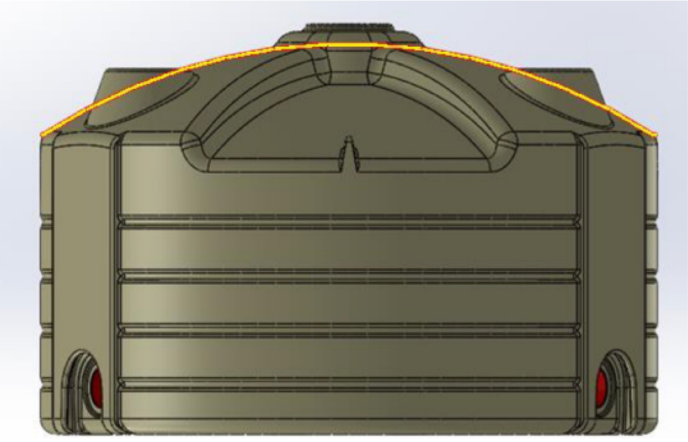




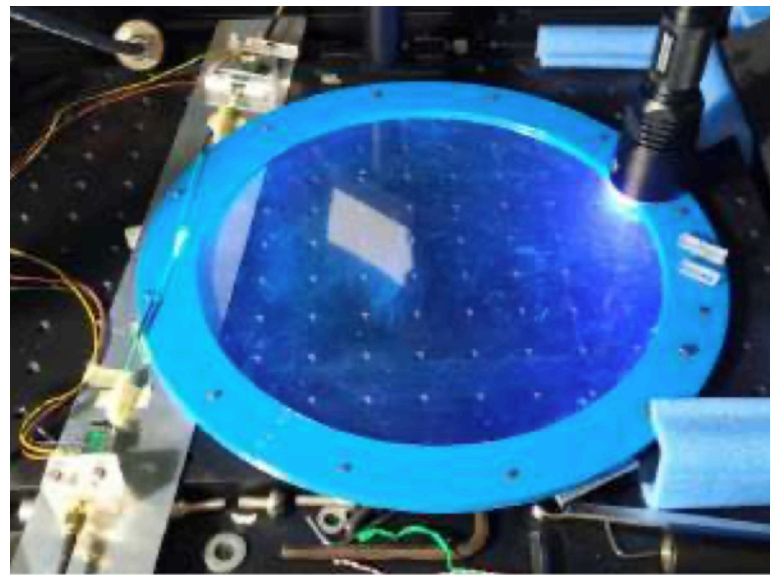
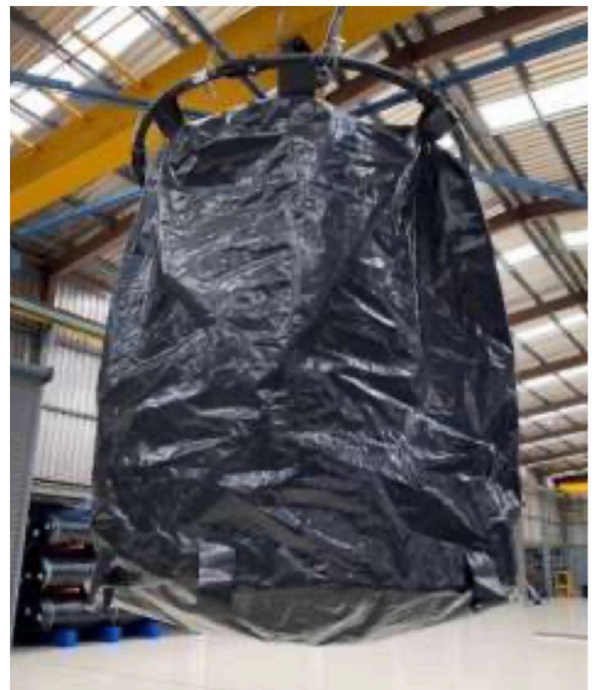
results to be applied to key science cases using well-defined science benchmarks for final **design choice**

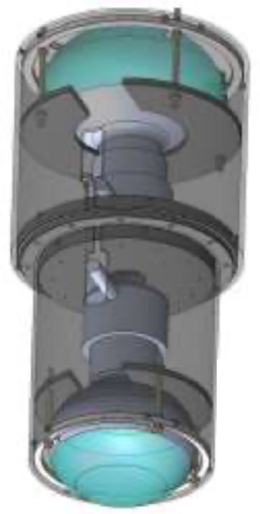
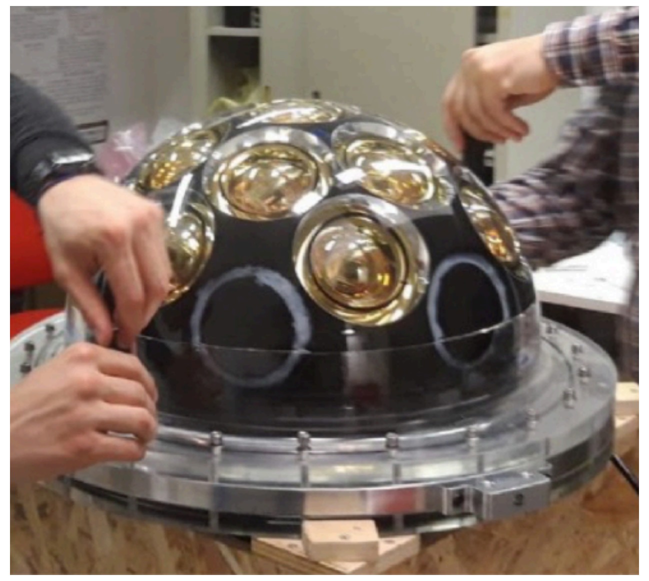
Prototyping SWGO

- WCD mechanics
  - Water container
    - Tank (bladders)
    - Open pond (bladders)
    - Closed pond (curtains)
    - Lake (bladders)
  - Segmentation
    - Double-layer
    - None
- Photodetectors
  - Detector
    - Large-area PMT
    - SiPM array
    - Multi-sensor
    - Distributed sensors
  - Light guide
    - None
    - Winston cone
    - WLS plate or fibres
- Electronics chain
  - Photodetector supply
    - Active base
    - Multi-channel HV
  - Digitiser
    - High-rate sampling
    - Medium-rate sampling + TDC
    - Time-over-threshold (ToT)
  - Clock distribution
    - White Rabbit
    - RapCal

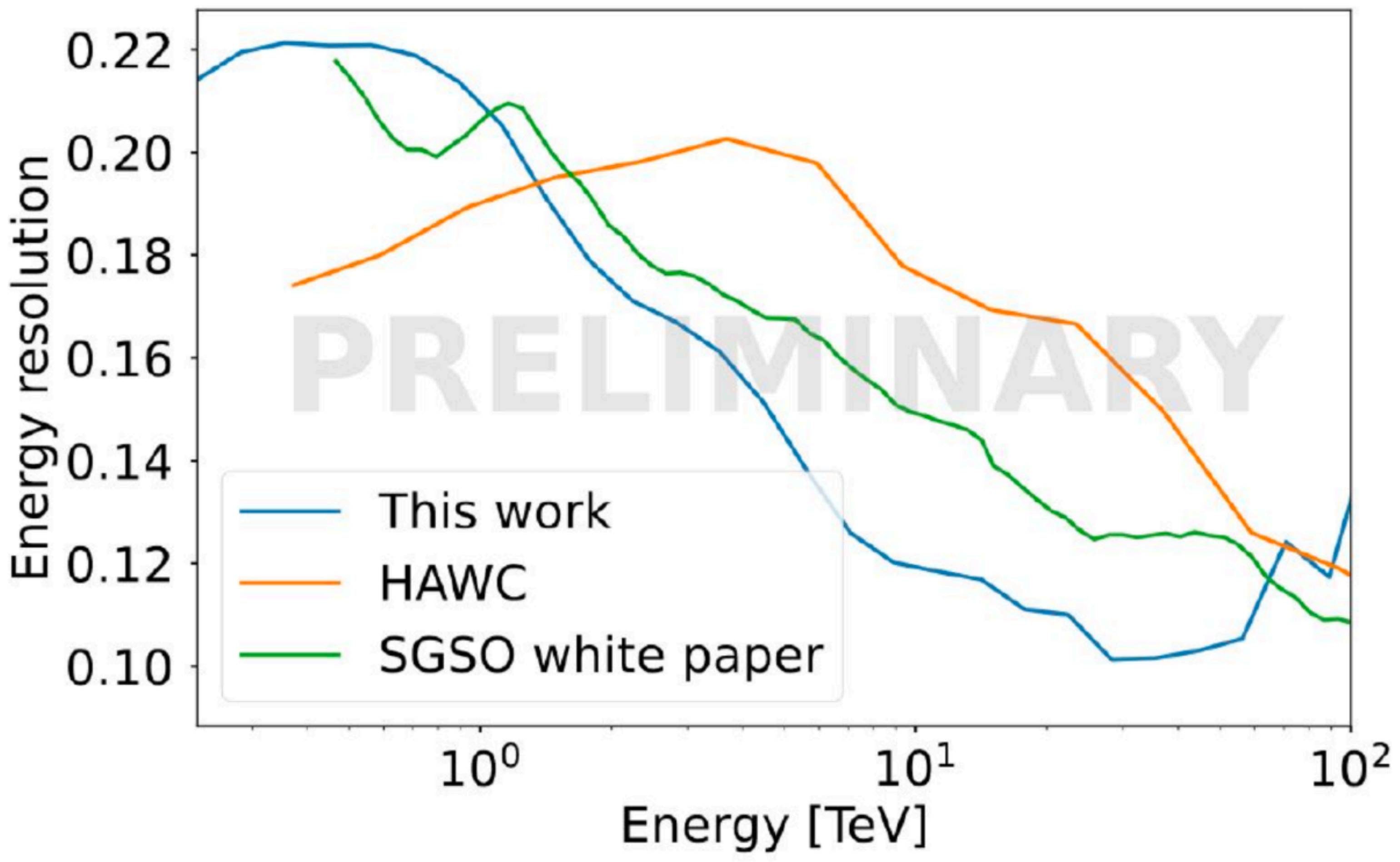




Working towards **baseline design**
as reference for alternative solutions

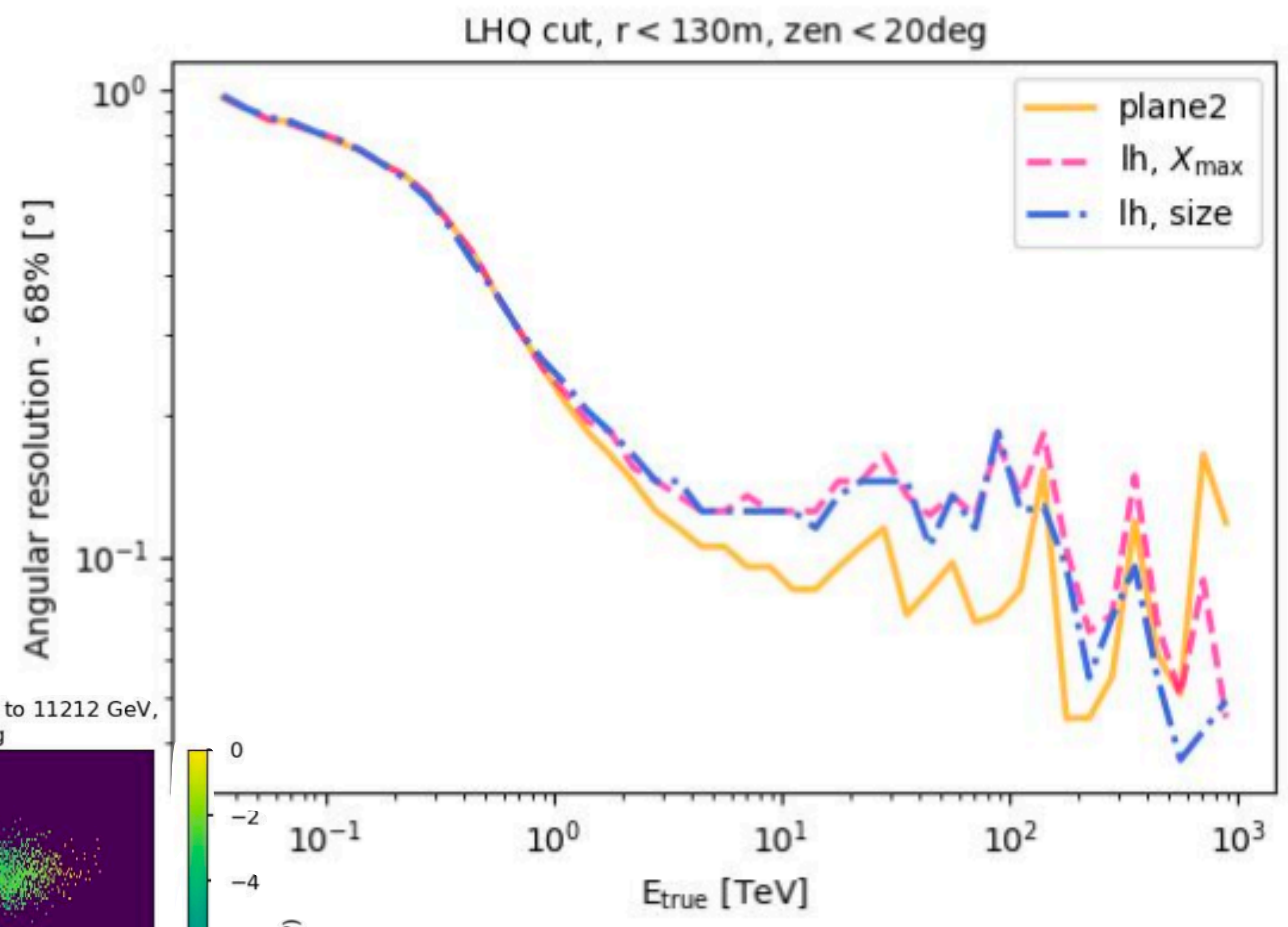



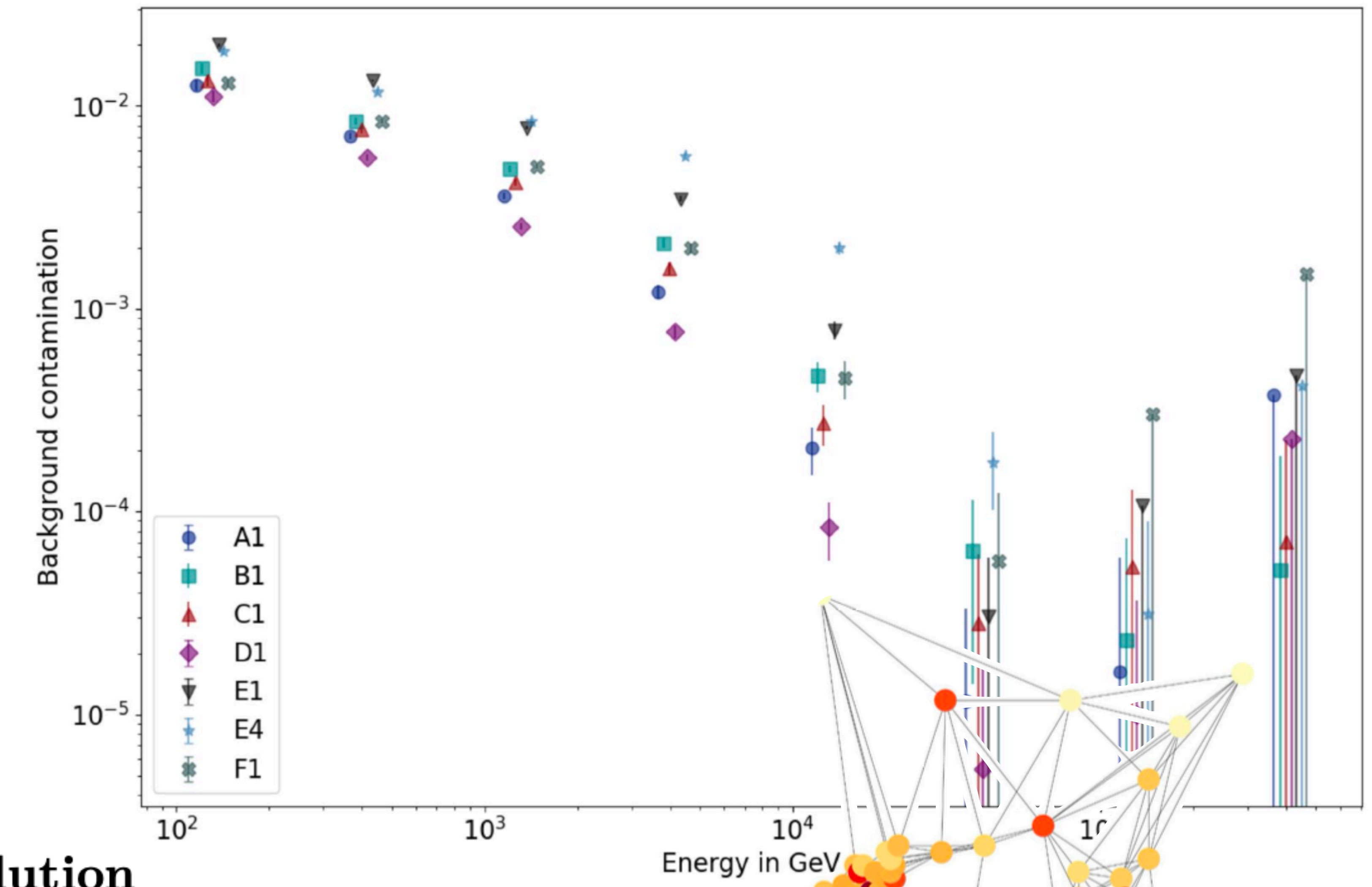




A few ECAP contributions to SWGO

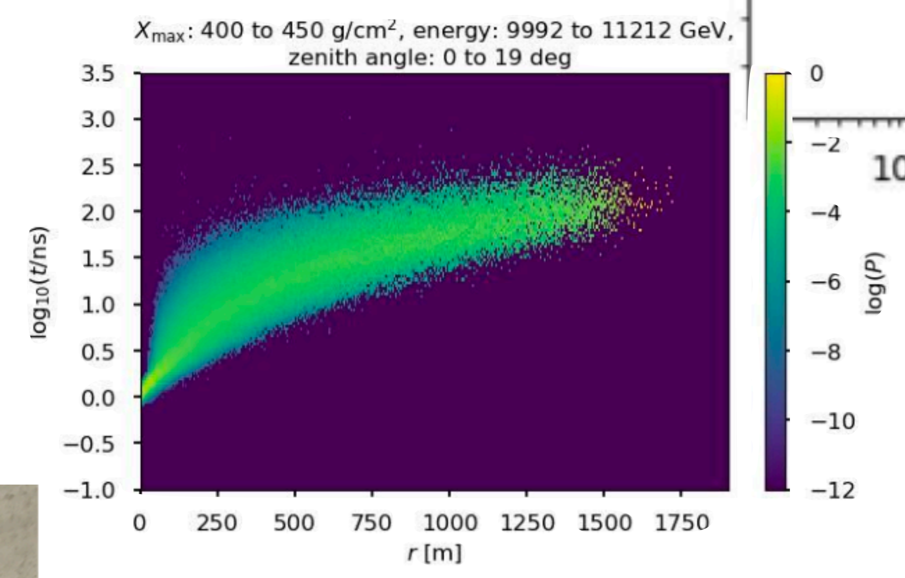


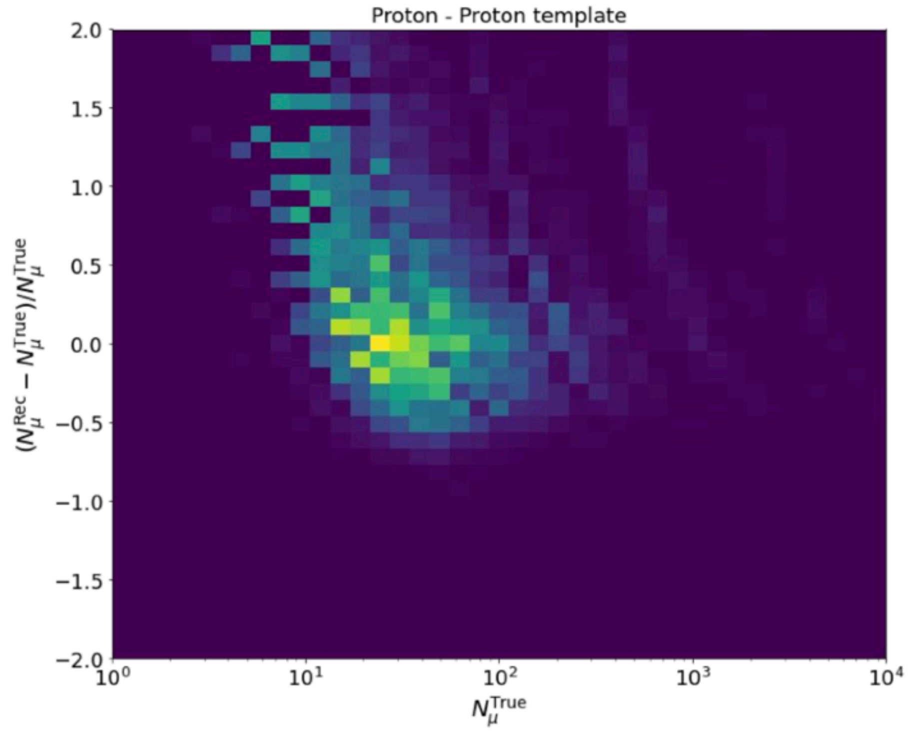
template fitting, graph neural networks and transformer networks for energy & direction reconstruction and gamma-hadron separation

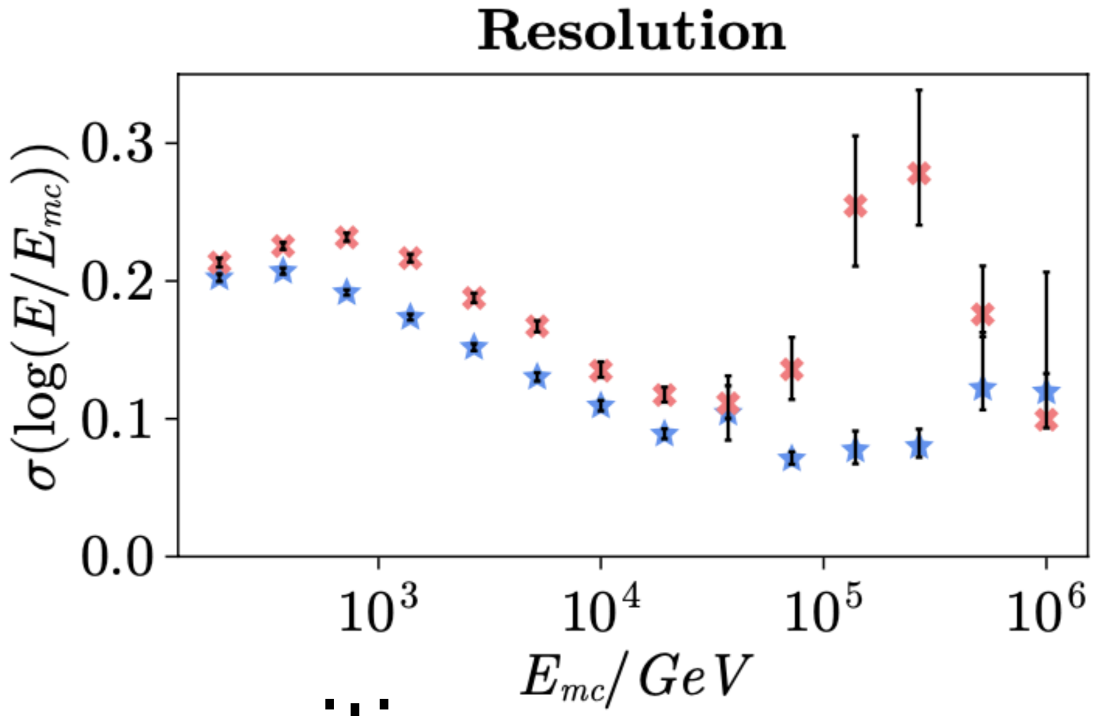




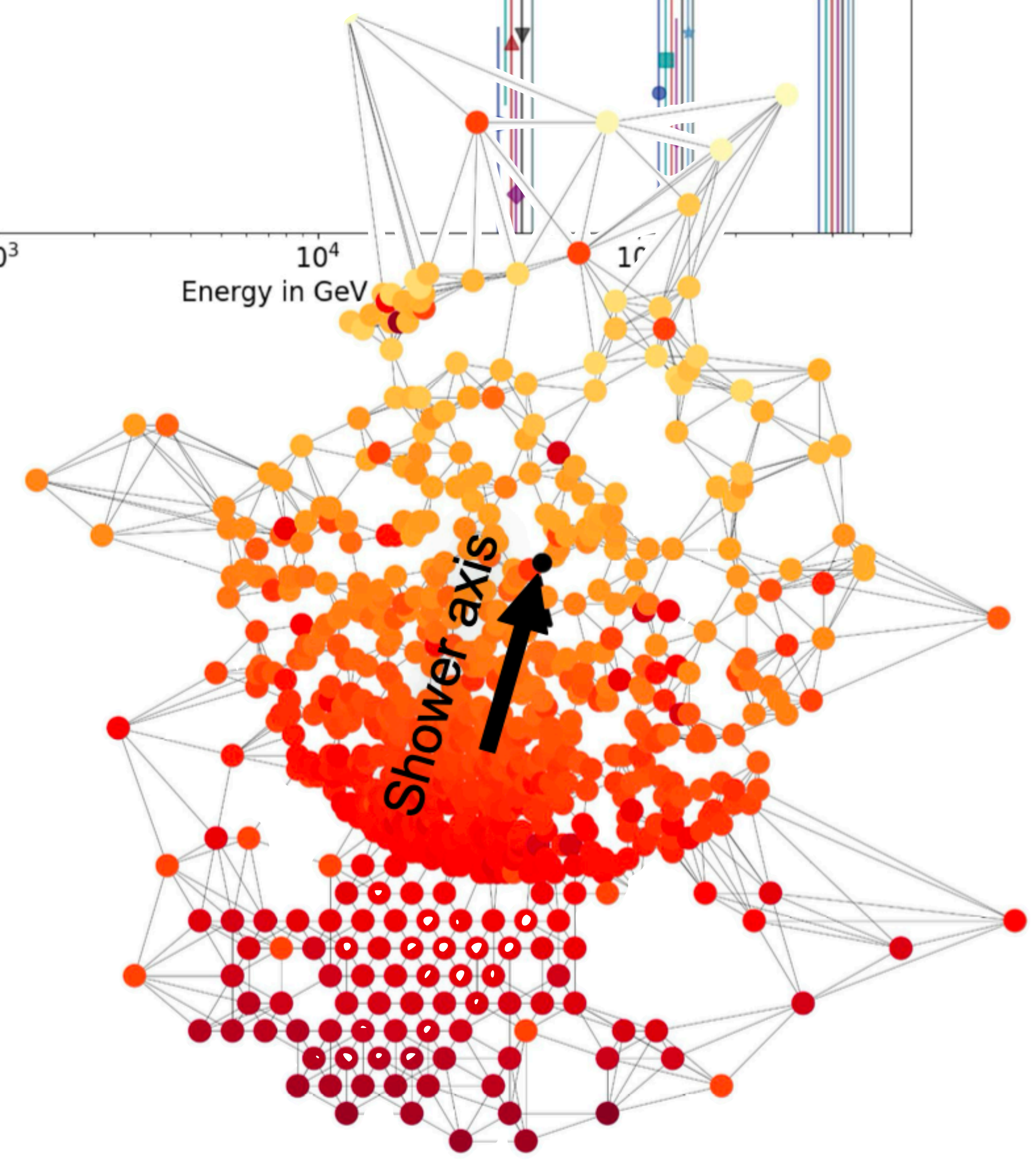
re-using
Antares-PMTs
for SWGO







CR composition
extended sources
diffuse emission…



SWGO project milestones

SWGO R&D Phase Milestones			Timeline
M1	R&D Phase Plan Established	✔	~ Q1 2020
M2	Science Benchmarks Defined	✔	
M3	Reference Configuration & Options Defined	✔	
M4	Site Shortlist Complete	✔	
M5	Candidate Configurations Defined	✔	
M6	Performance of Candidate Configurations Evaluated		~ Q2 2024
M7	Preferred Site Identified		
M8	Design Finalised		
M9	Construction & Operation Proposal Complete		~ Q3 2025

- **R&D phase** (till Q3/2025): follow well-defined set of milestones towards construction proposal
- **Preparatory phase** (till ~2027): detailed construction planning, engineering array on final site
- **Construction & operation phase:** 2027++

Summary

- Particle detector arrays work.
- They keep providing beautiful results since almost a decade.
- **Let's complement the existing ones by building SWGO.**