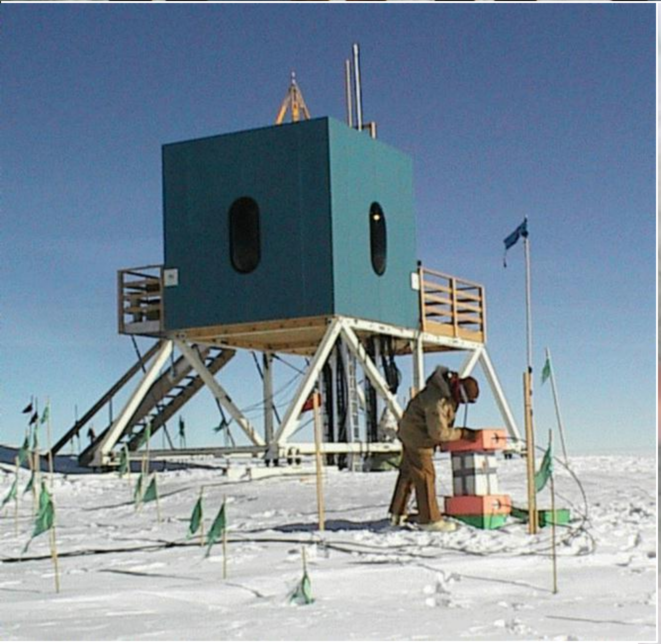
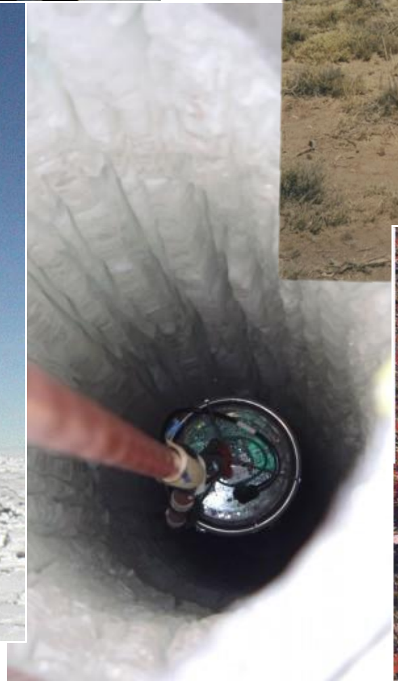
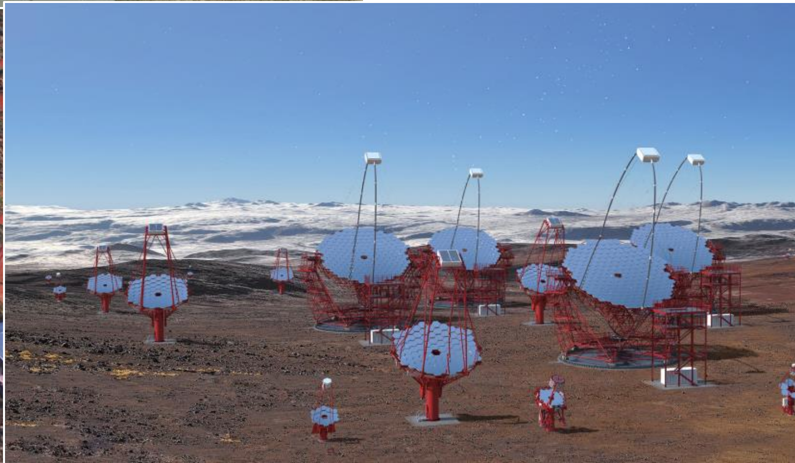
My Background

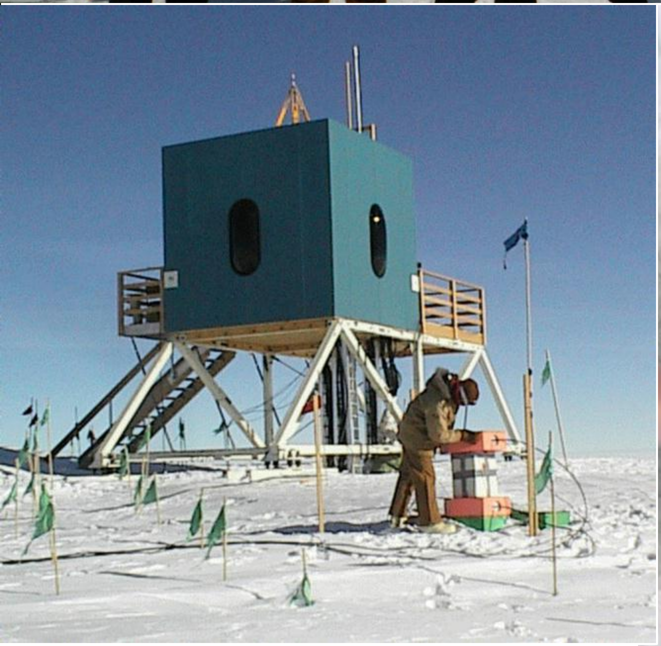


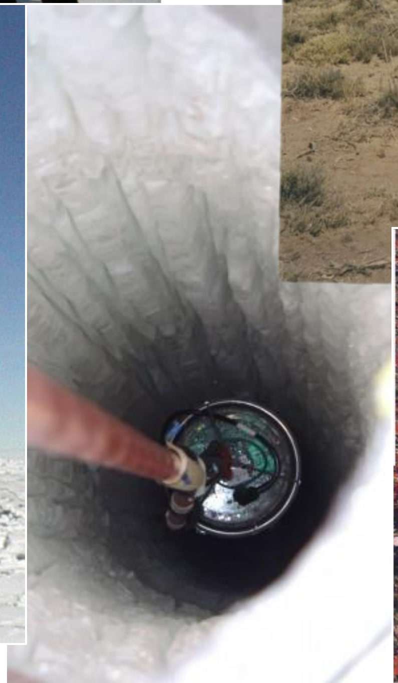


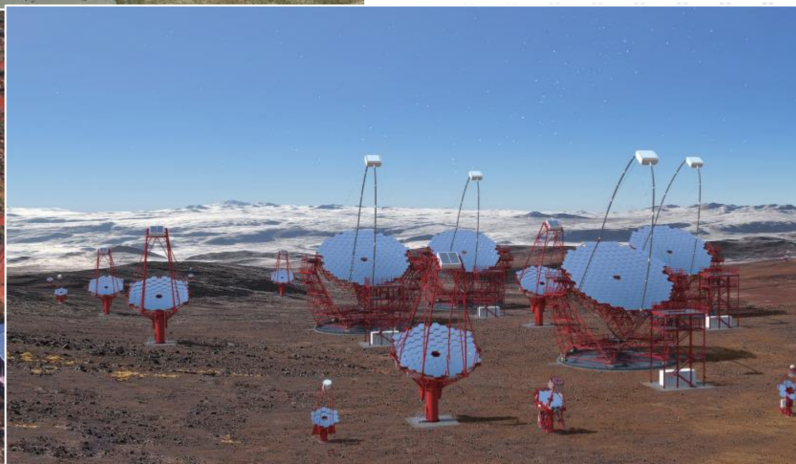


My Background

Jim







Observation of the Gamma Ray Sky from the ground:

the Air Shower array technique

Jim Hinton

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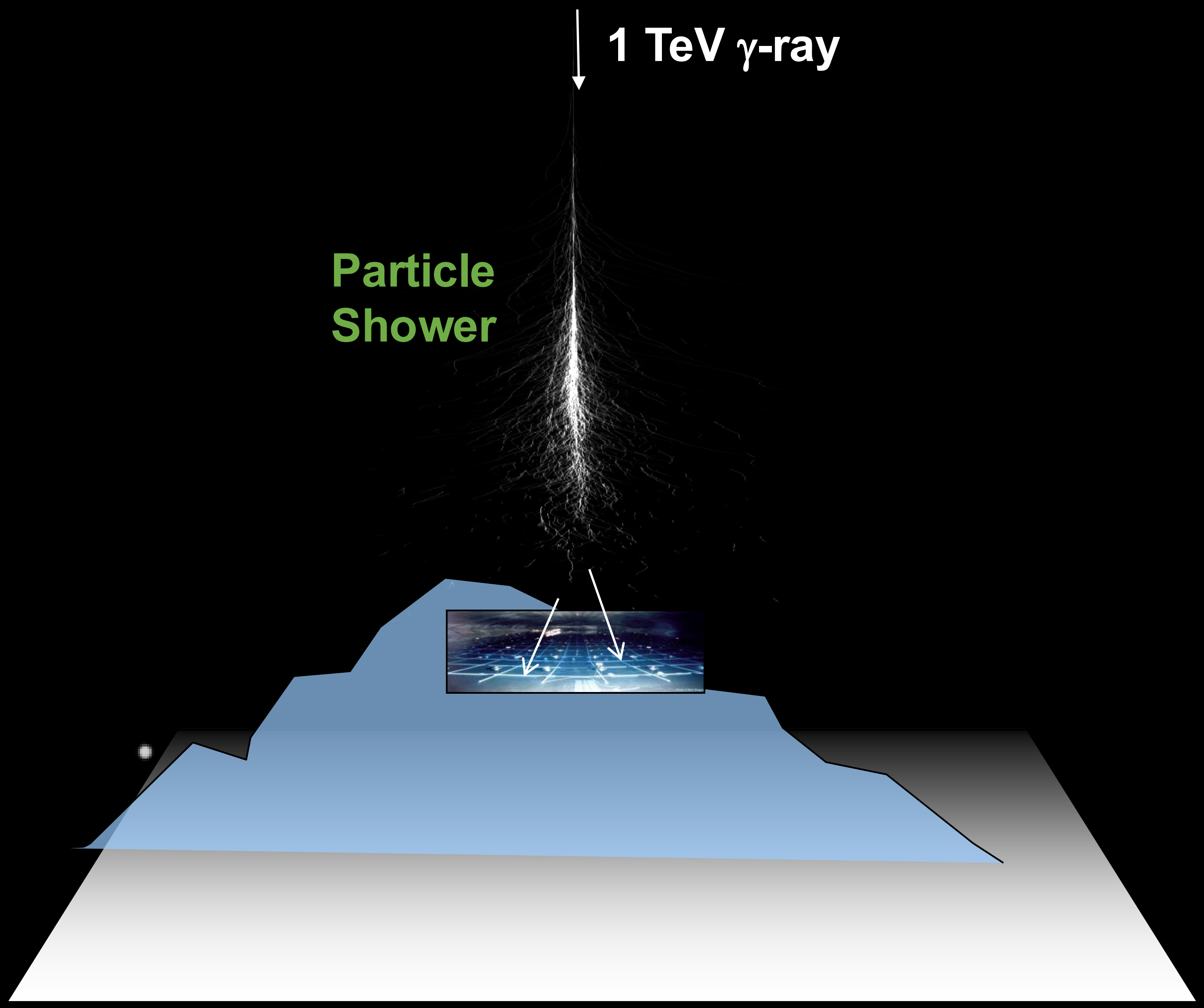
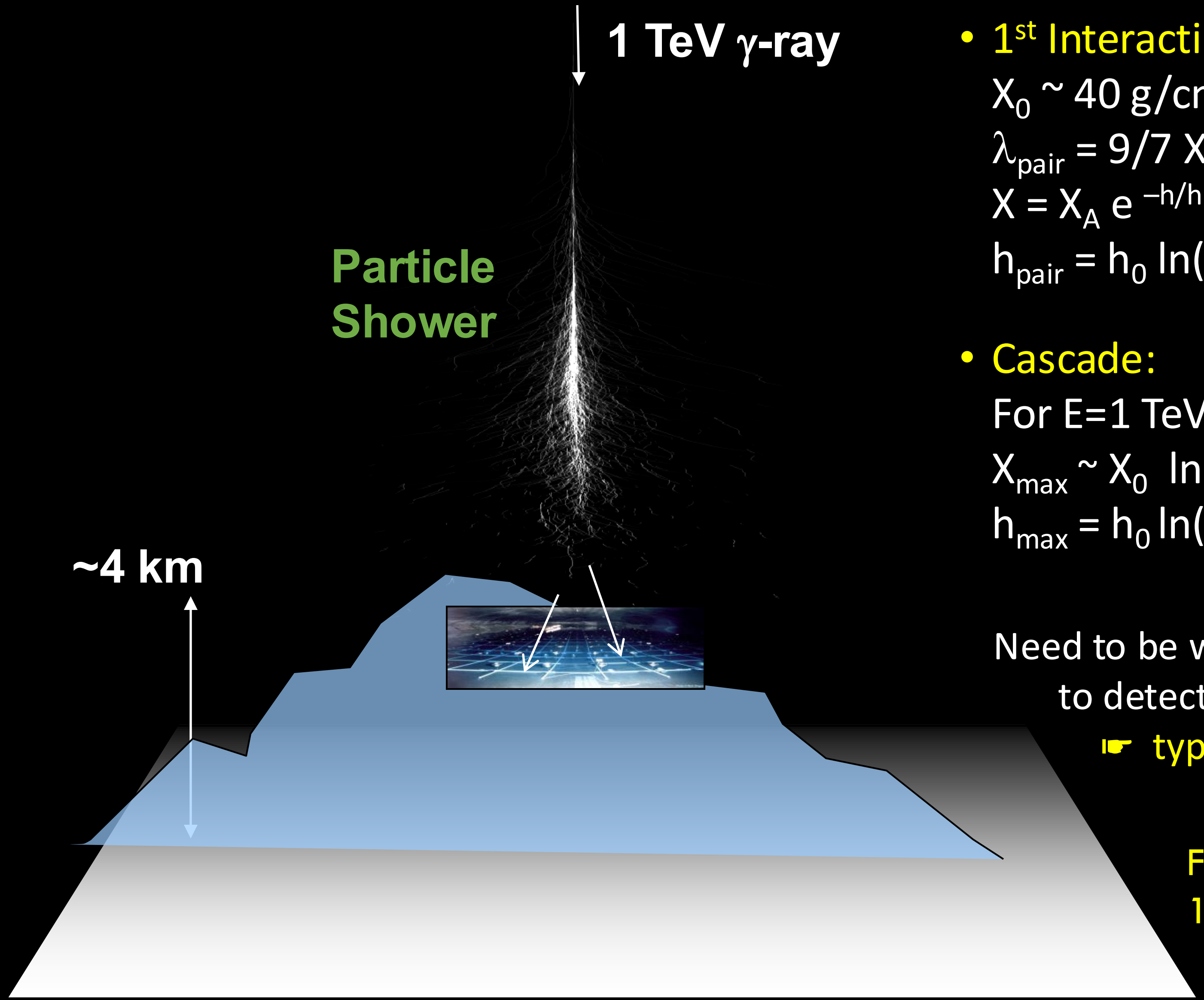
SEXTEN CENTER FOR ASTROPHYSICS RICCARDO GIACCONI

1st July 2025

Shower Particle Detection



Shower Particle Detection



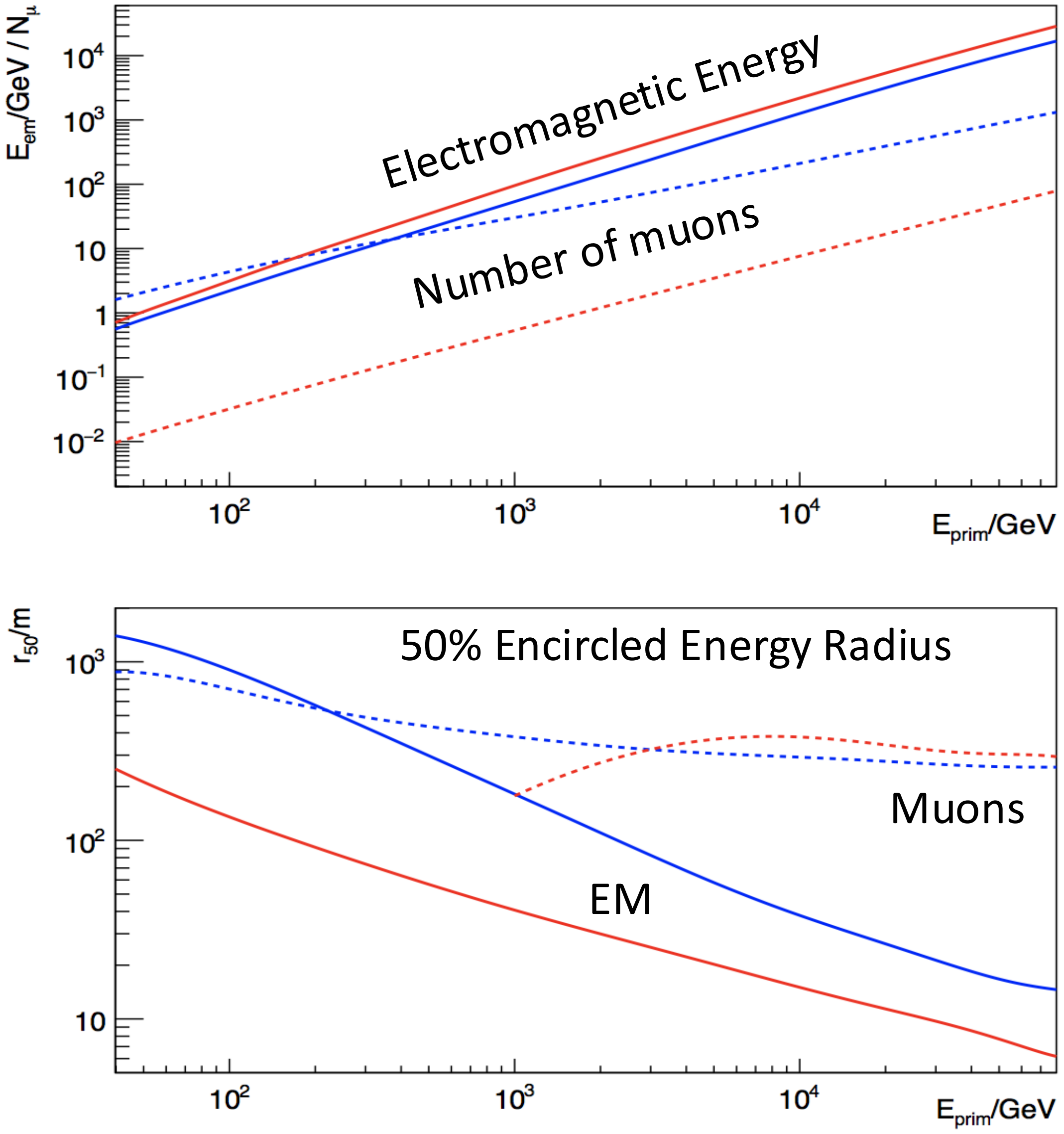
- 1st Interaction:
  $X_0 \sim 40$ g/cm^2
  $\lambda_{pair} = 9/7\ X_0 \sim 50$ g/cm^2
  $X = X_A\ e^{-h/h0}$ and $X_A \sim 10^3$ g/cm^2
  $h_{pair} = h_0 \ln(X_A/\lambda_{pair})$ ☛ 20 km

- Cascade:
  For E=1 TeV ($E_C \sim 80$ MeV)
  $X_{max} \sim X_0\ \ln(E/E_C) / \ln 2$
  $h_{max} = h_0 \ln(X_A/X_{max})$ ☛ 5 km

Need to be within a few X_0 of X_{max}
to detect particles directly
☛ typically >3 km alt.

Field of view 1-2 sr
100% Duty Cycle

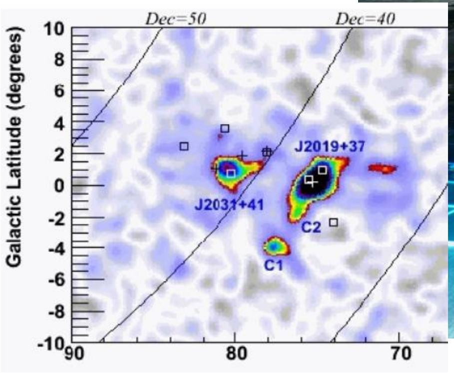
Ground-level Particles

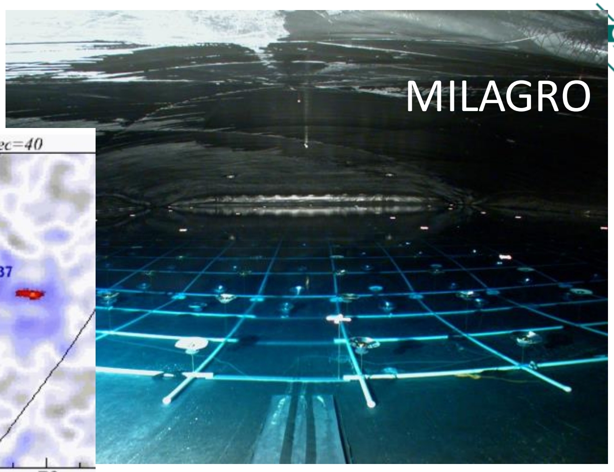


- Gamma and proton initiated showers at **5km altitude**
- 1 TeV gamma-ray brings 100 GeV of energy to the ground
  - Typical electron energy ~10 MeV
- 1 TeV proton on average 50 GeV EM + 30 muons
  - Typical energy of muons ~few GeV, with much bigger spread on ground

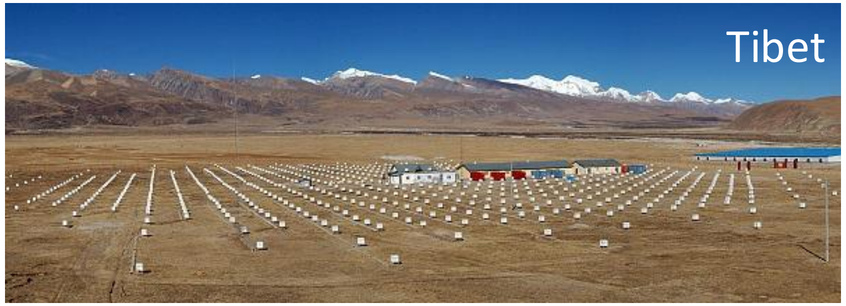
Ground-particle Detectors

MILAGRO: Cygnus Region





- 2.5 km ◉ MILAGRO – 2001-2008
- 4.1 km ◉ HAWC – 2015 -
- 4.3 km ◉ Tibet AS γ +ARGO – 1990s -
- 4.4 km ◉ LHAASO – 2021 -
- 4.8 km ◉ SWGO – 202X -

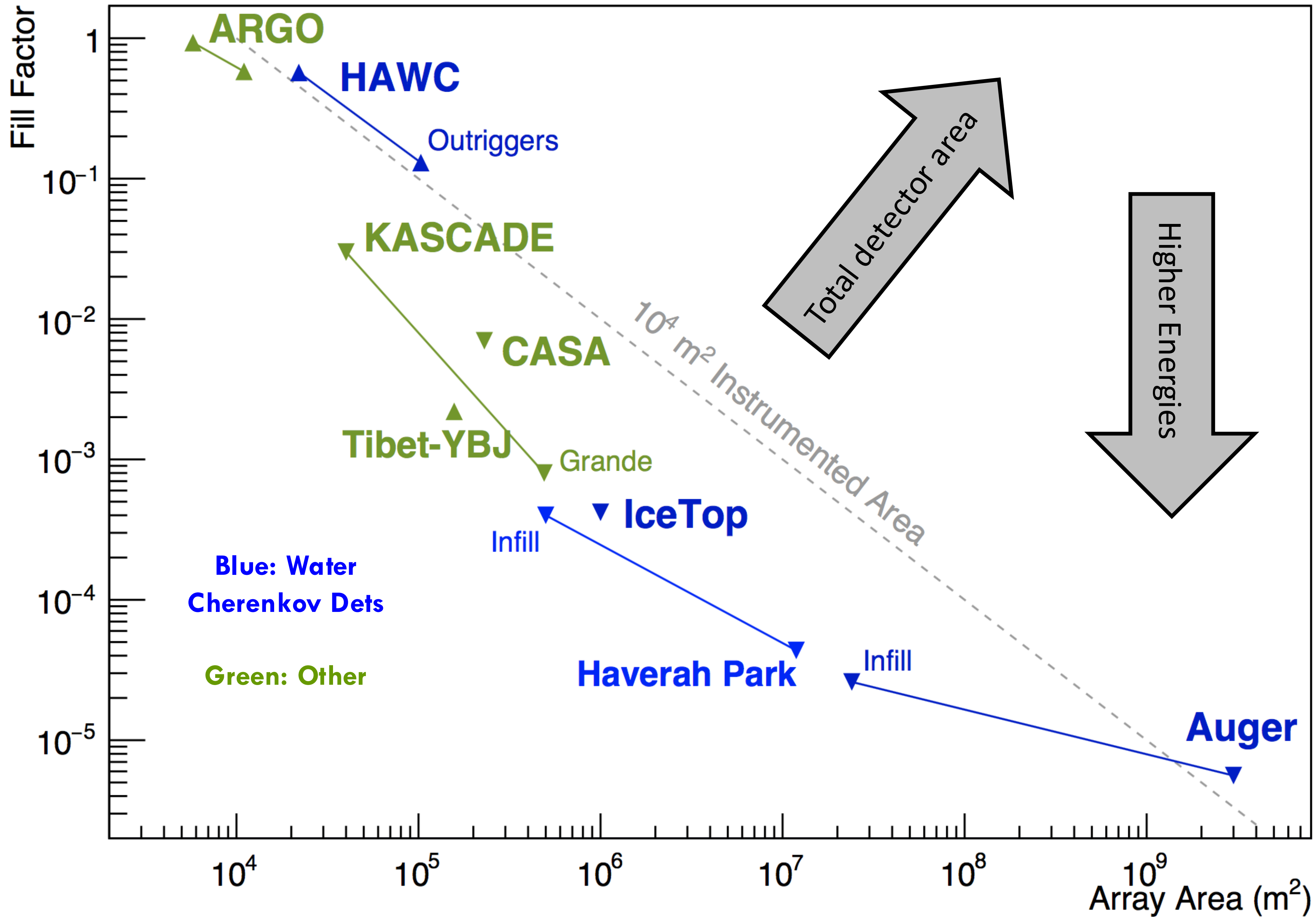


Drivers of performance:

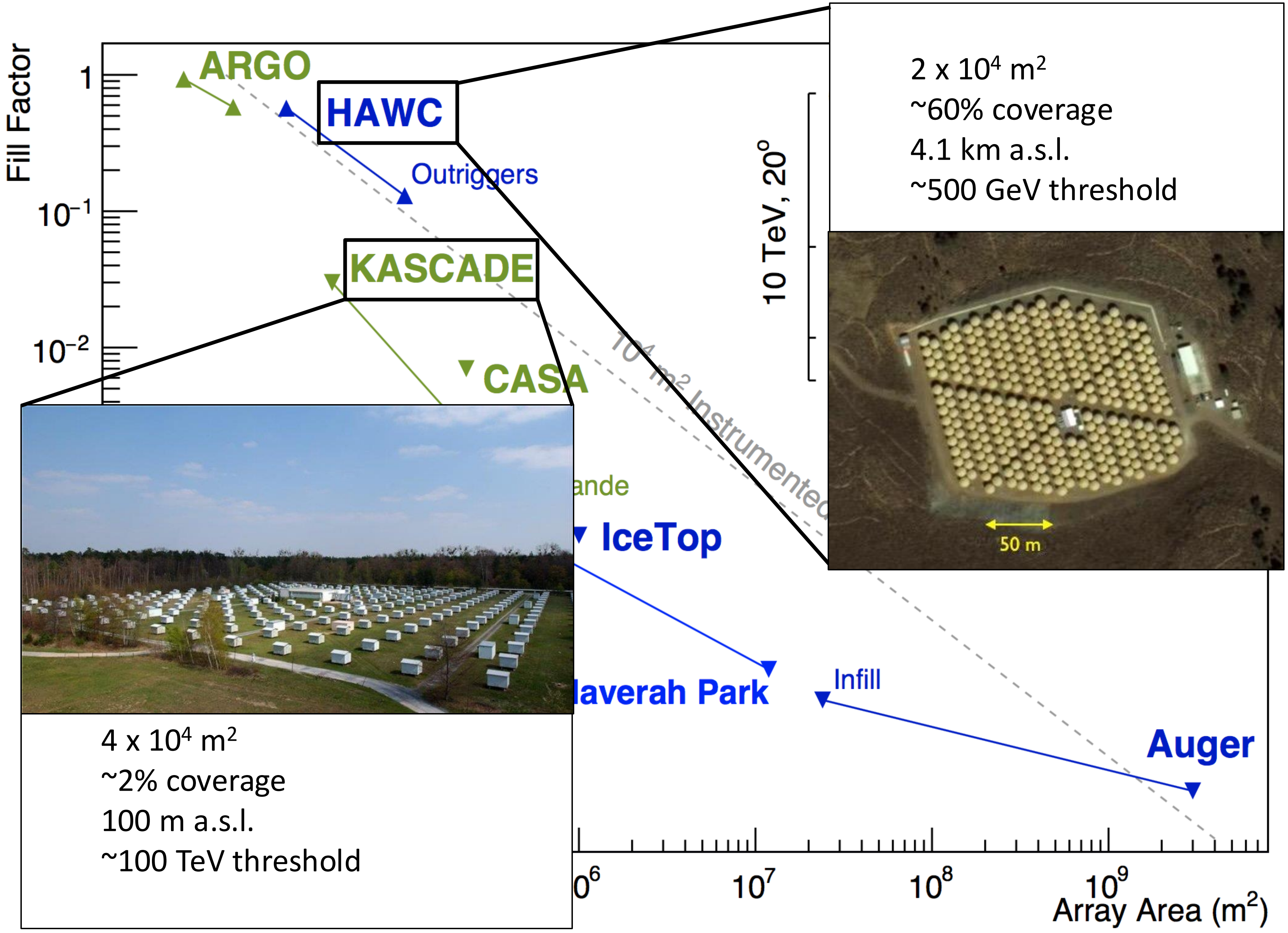
size, **fill factor** and **altitude** (move detector up to shower max)

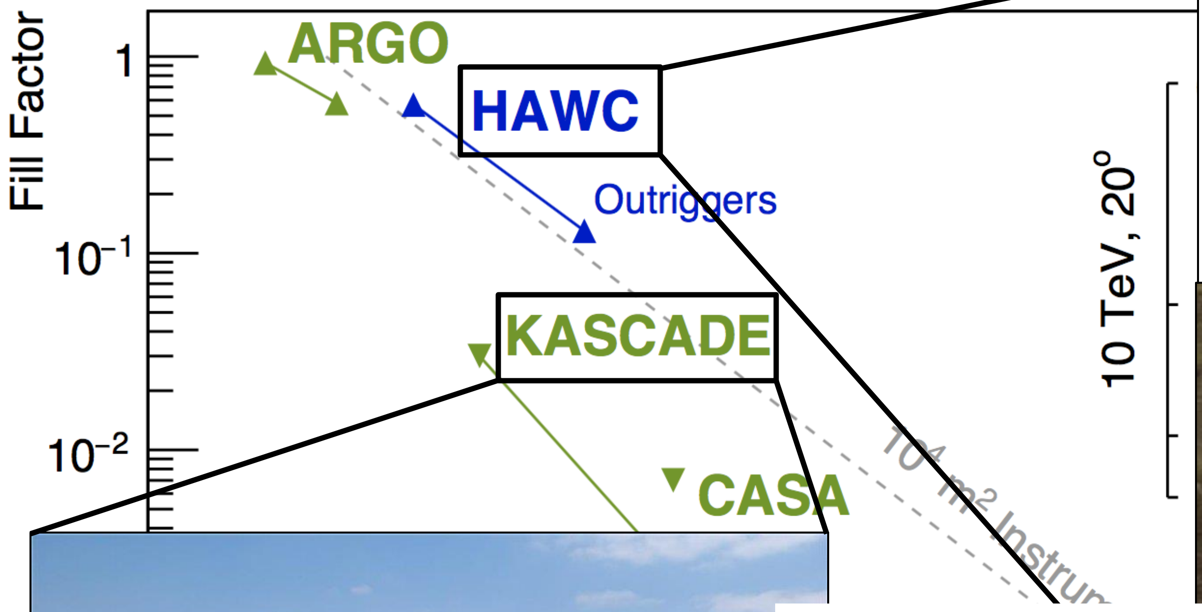
Increase altitude: MILAGRO → HAWC → SWGO
Increase also fill-factor and size: Tibet → LHAASO & SWGO

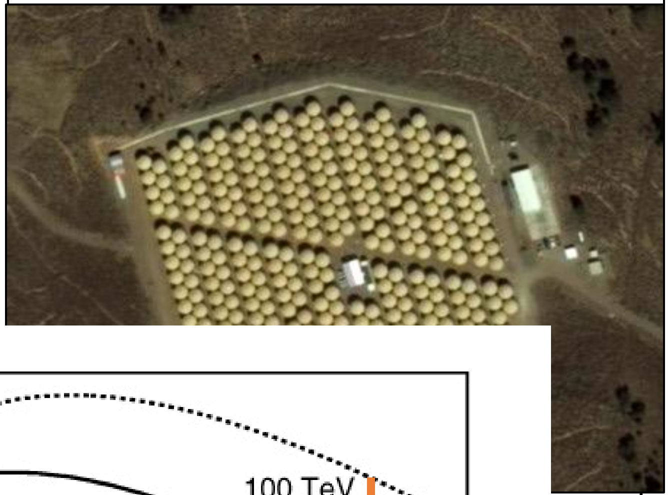
+ muon detection



Fill Factor
1
10−1
10−2
10−3
10−4
10−5
10⁴
10⁵
10⁶
10⁷
10⁸
10⁹
Array Area (m²)
ARGO
HAWC
Outriggers
KASCADE
CASA
Tibet-YBJ
Grande
IceTop
Infill
Haverah Park
Infill
Auger
10⁴ m² Instrumented Area
Total detector area
Higher Energies
Blue: Water
Cherenkov Dets
Green: Other

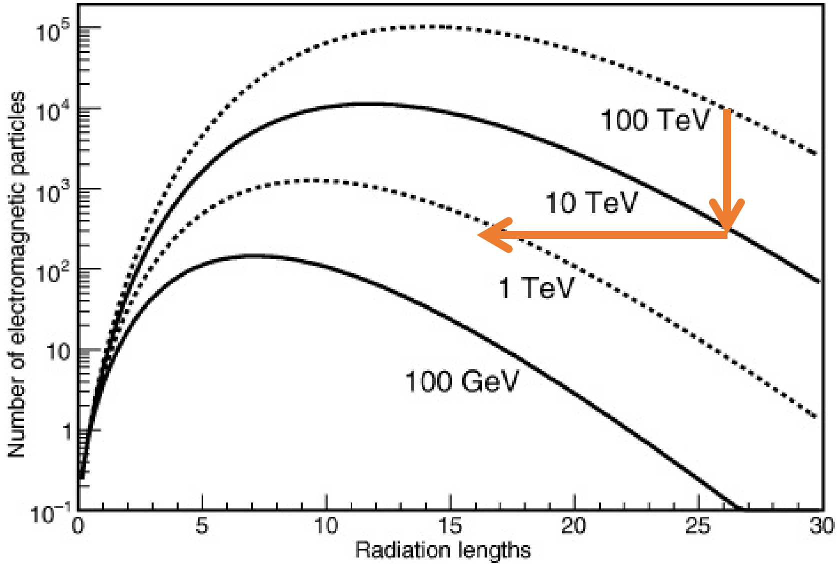

Fill Factor
1
10−1
10−2
ARGO
HAWC
Outriggers
KASCADE
CASA
ande
IceTop
laverah Park
Infill
Auger
10 TeV, 20°
10⁴ m² Instrumented
10⁶
10⁷
10⁸
10⁹
Array Area (m²)
2 x 10⁴ m²
~60% coverage
4.1 km a.s.l.
~500 GeV threshold
50 m
4 x 10⁴ m²
~2% coverage
100 m a.s.l.
~100 TeV threshold





2 x 10^4 m^2
~60% coverage
4.1 km a.s.l.
~500 GeV threshold

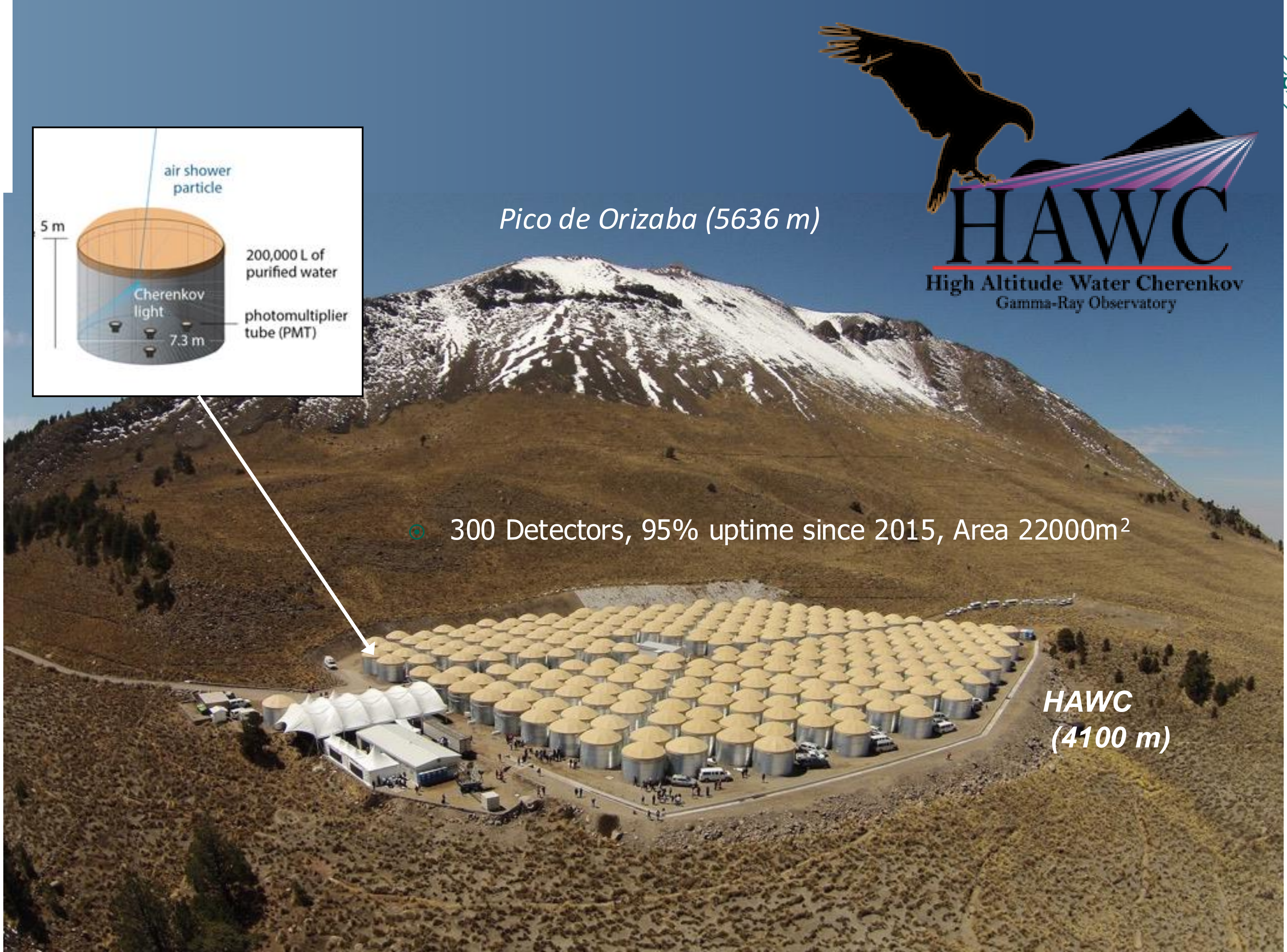
4 x 10^4 m^2
~2% coverage
100 m a.s.l.
~100 TeV threshold



Sinnis 2009

ger

(m^2)



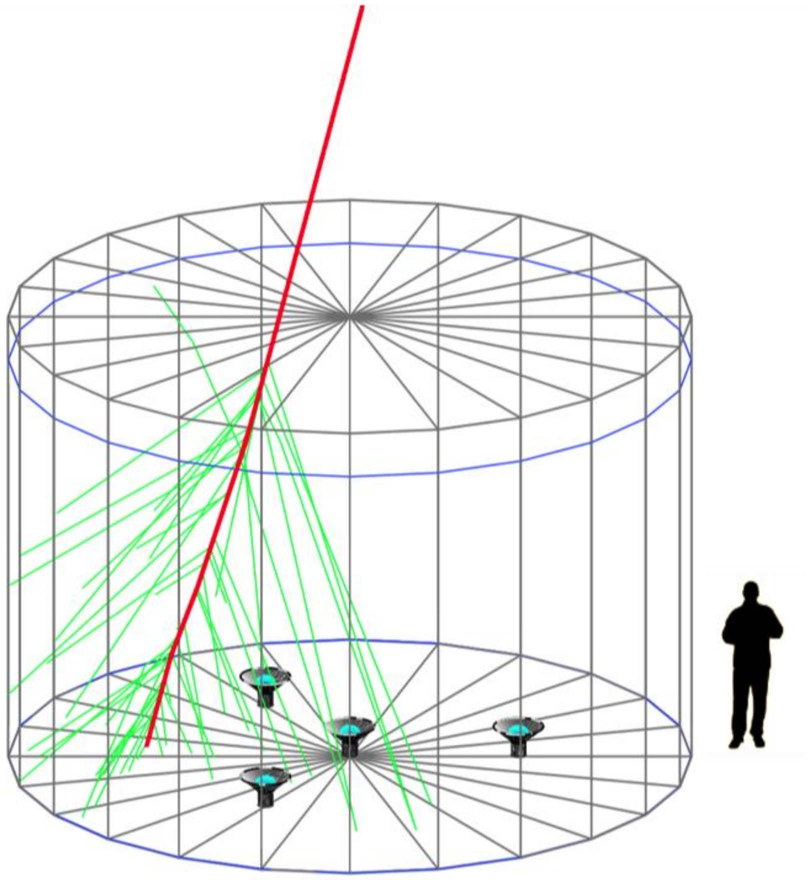
Pico de Orizaba (5636 m)

- 300 Detectors, 95% uptime since 2015, Area 22000m^2

HAWC (4100 m)

Detectors

$$\frac{d^2 N_c}{dx\, d\phi} = \frac{\alpha}{hc} \cdot \int_{\epsilon_1}^{\epsilon_2} \left(1 - \frac{1}{\beta_\mu^2(x) n^2(\epsilon, x)}\right) d\epsilon \ ,$$

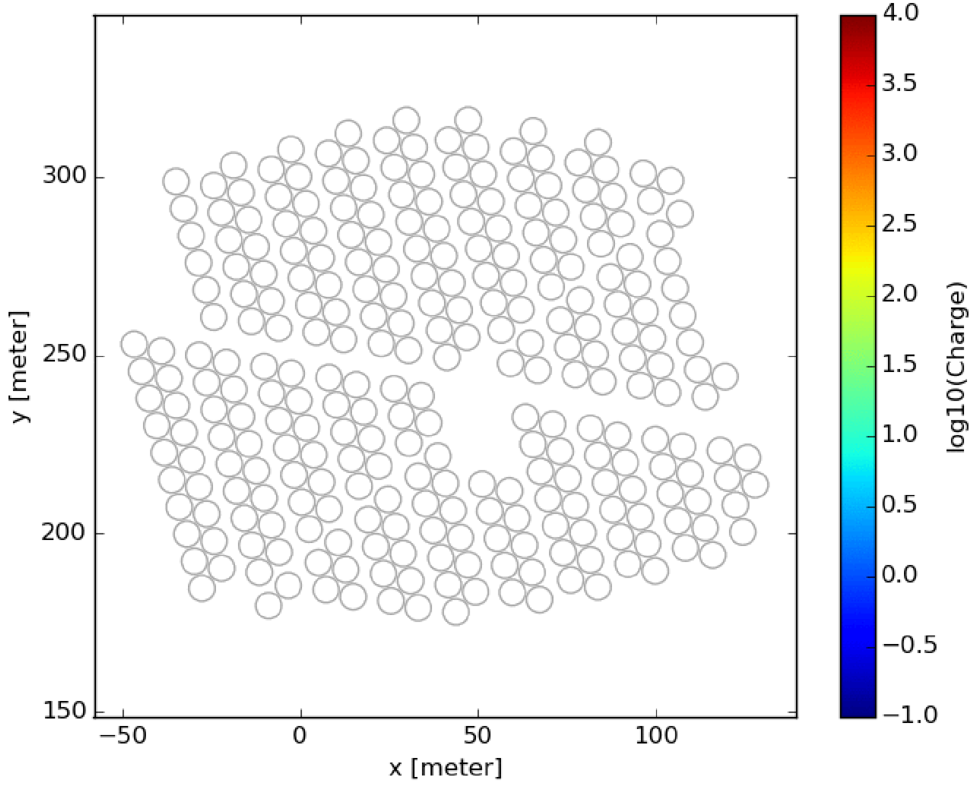


0.01% photosensitive area

5m deep, 7.3 m diameter

- 5m tank → 12 radiation lengths (X_0 ~ 40 g/cm^2)
  - Gamma conversion
  - EM showers near top of tank except for highest energy shower particles
- Muons
  - Pass through without interaction – long path length
- Cherenkov light
  - Angle: acos (1/n) ~ 41º
  - Yield: $(\Delta h\nu) 2\pi\alpha(1-1/n^2)/hc$ → 300 photons / cm

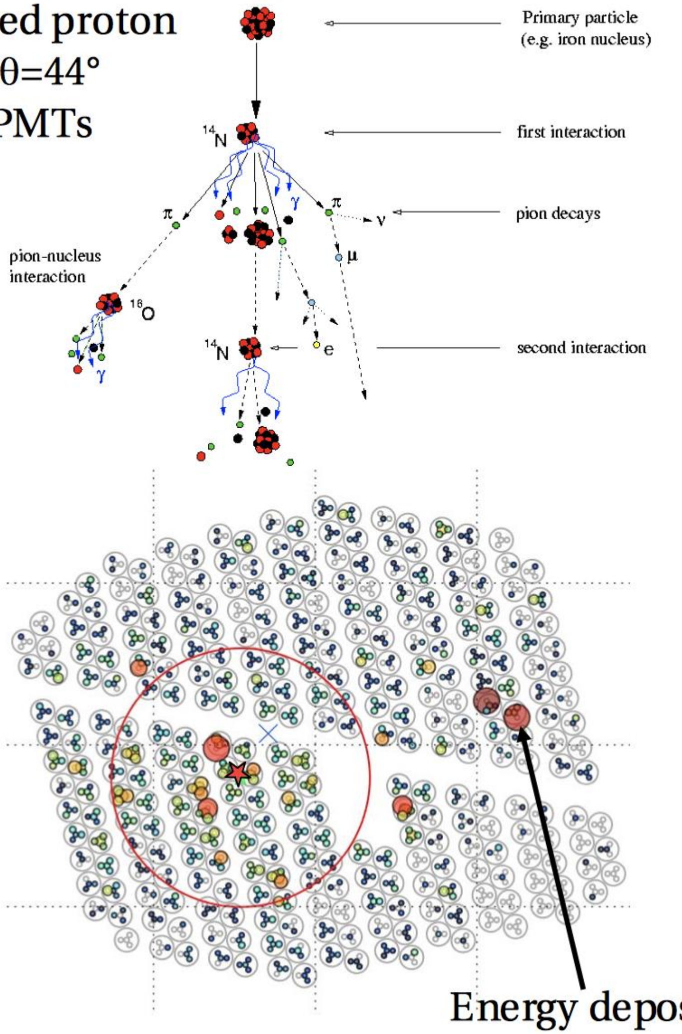
Events



- Direction from arrival times
  - time resolution ~ns over 100 m lever-arm → angular resolution ~(1 ns * c / 100 m) rad ~ 0.2º
- Energy?
  - More tricky – can measure ground-level size but big fluctuations doing to X_{max} differences / shower development
- Hadron Rejection?

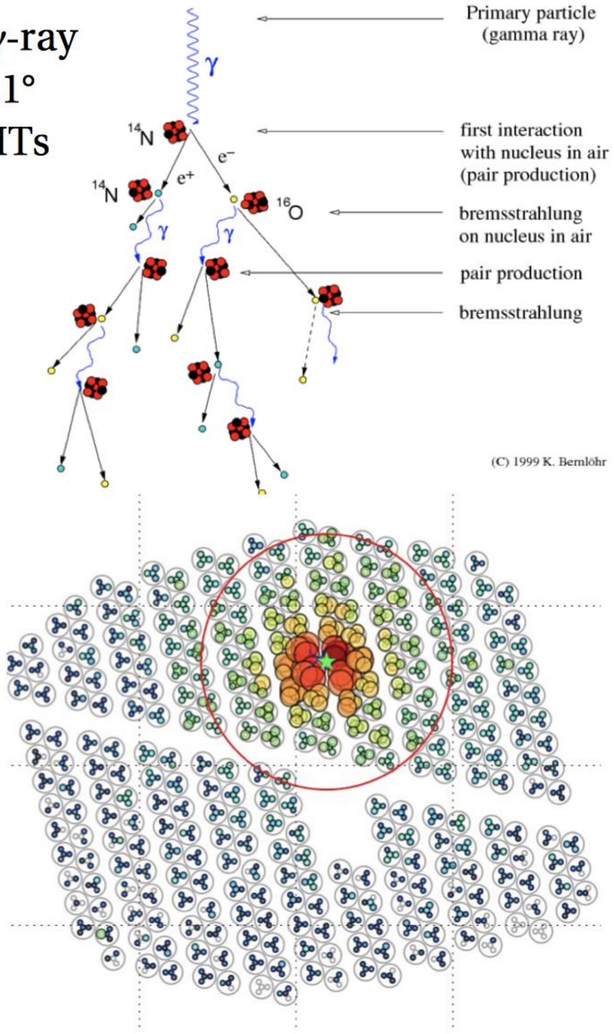
Gamma/Hadron Separation

Simulated proton
24 TeV, θ=44°
837 hit PMTs



Energy deposited
away from the core

Simulated γ-ray
21 TeV, θ=21°
1131 hit PMTs



HAWC Events RA/Dec.

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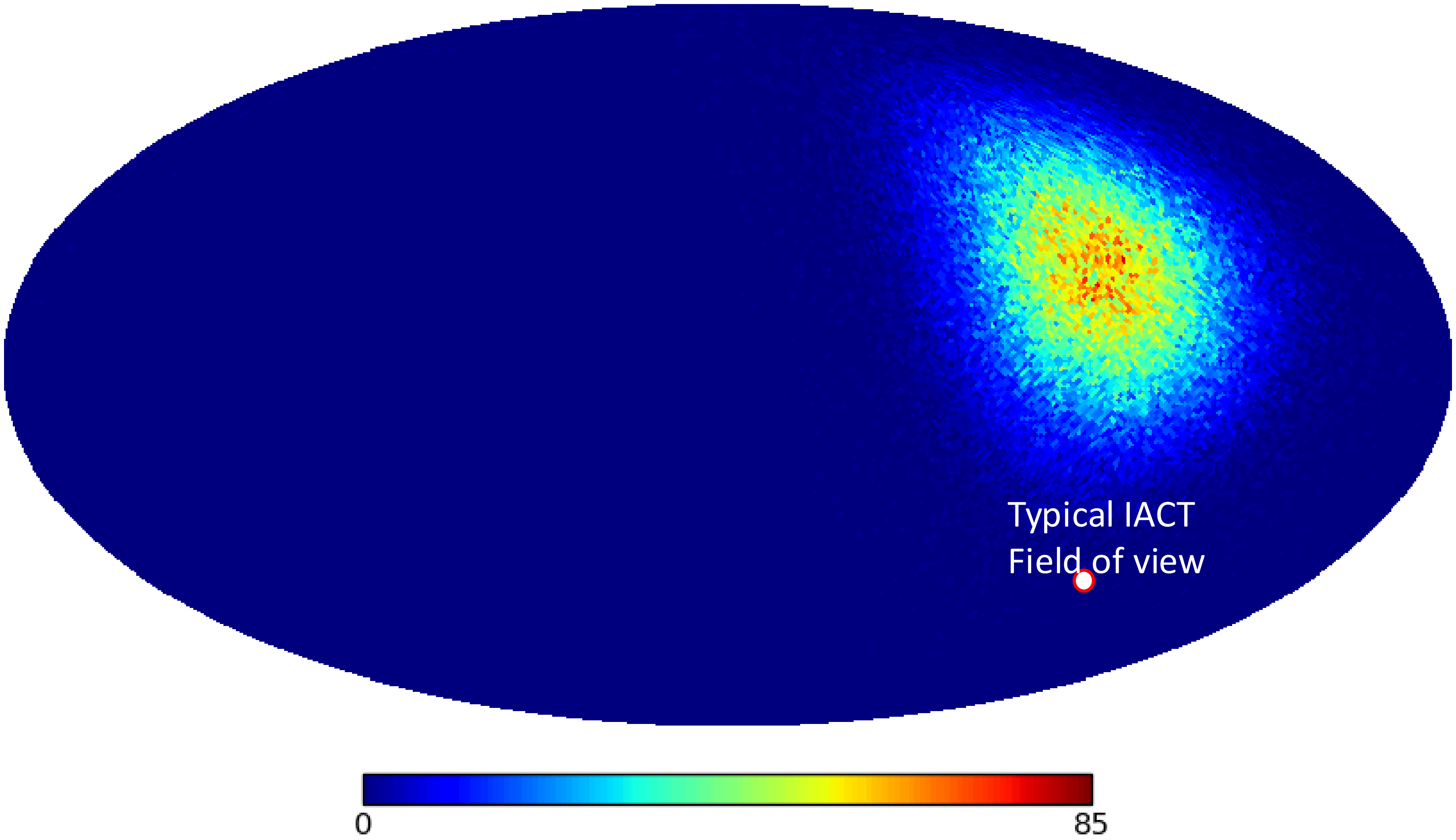
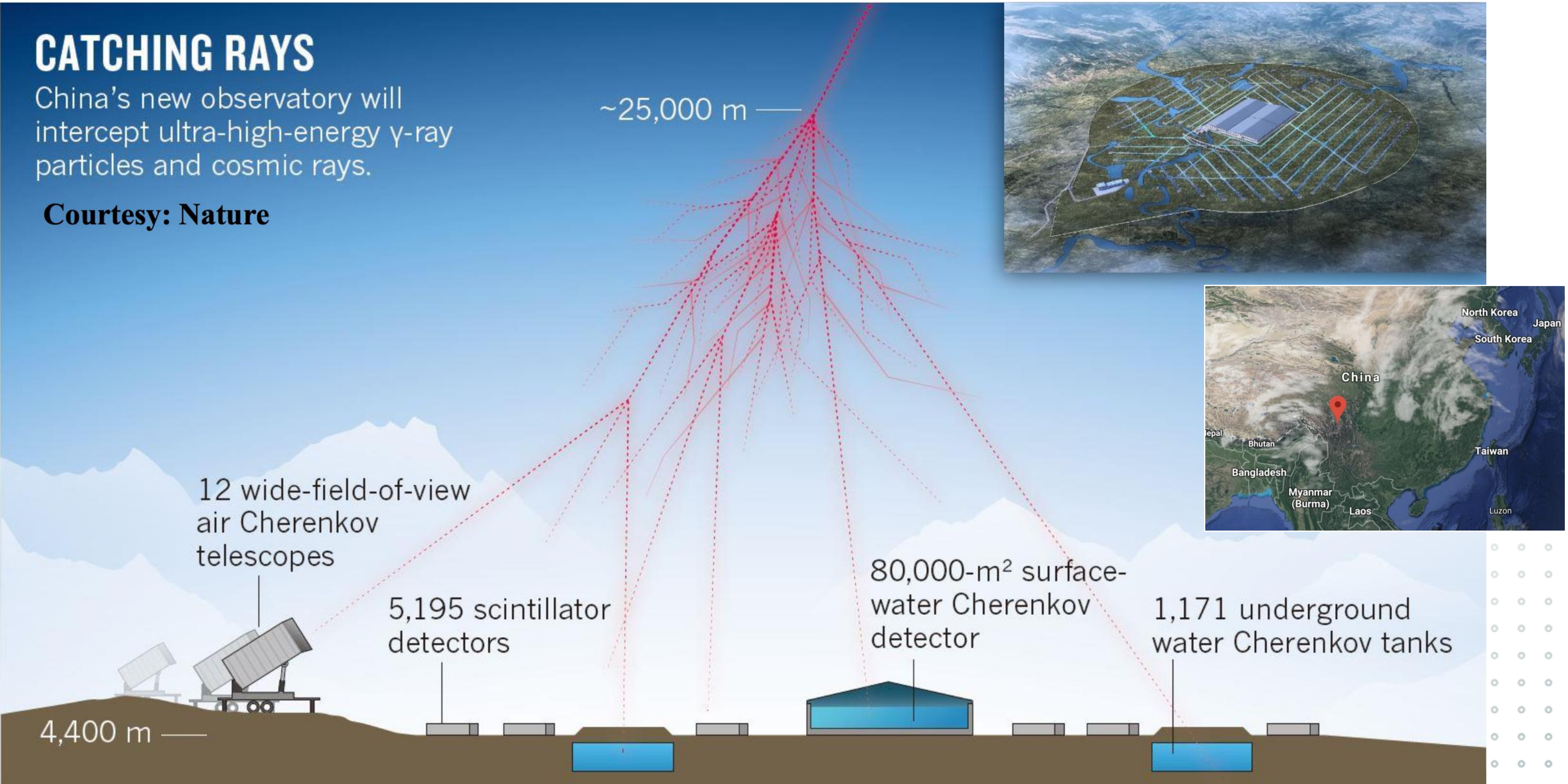


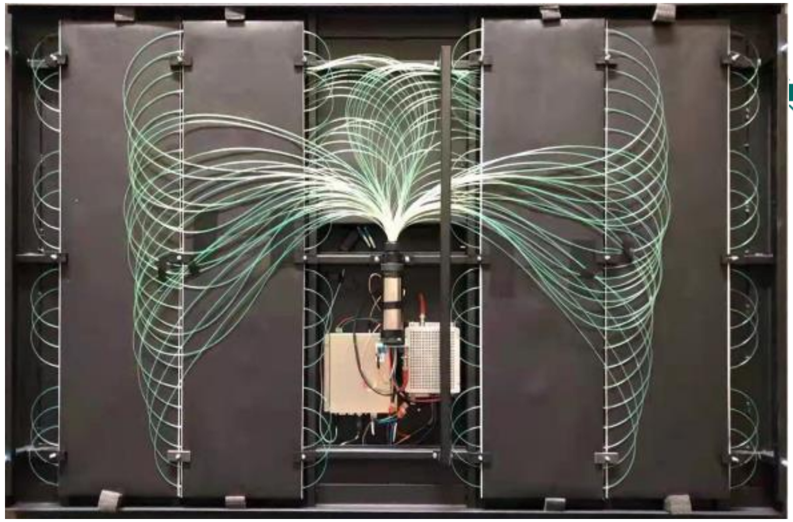
LHAASO

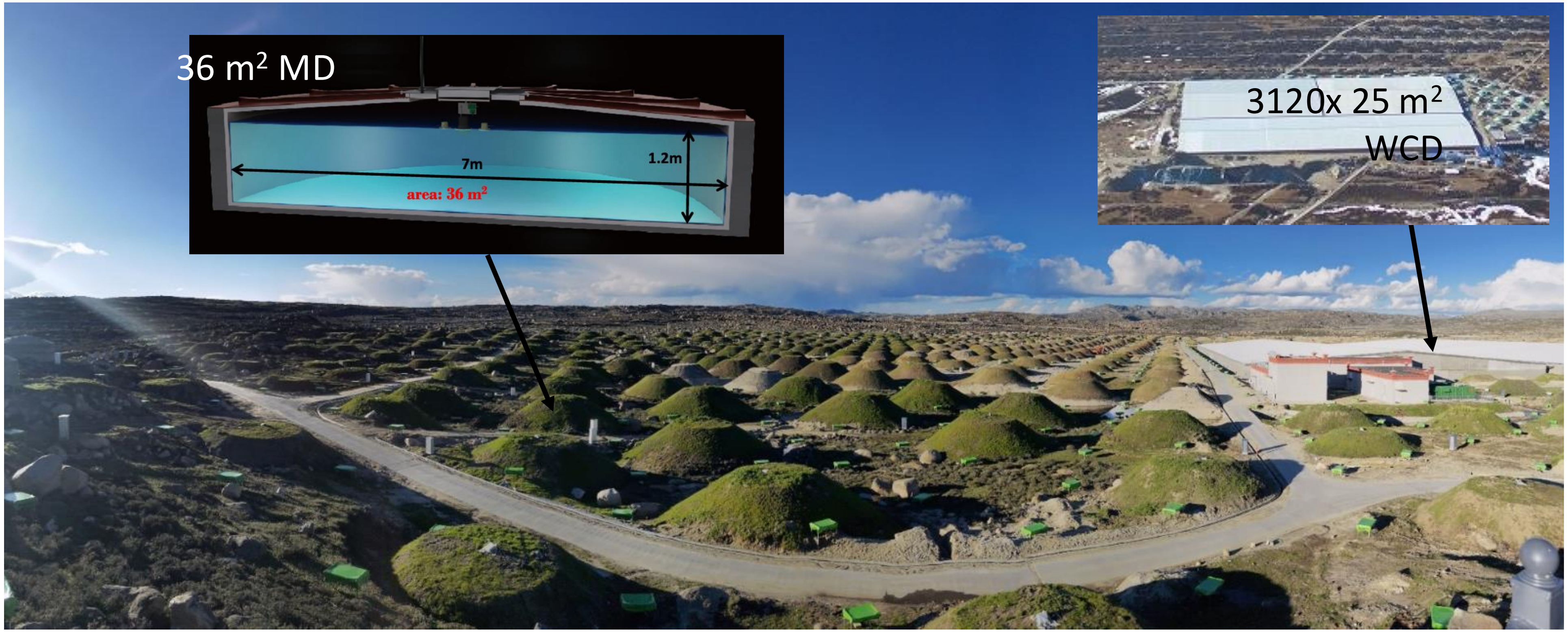

CATCHING RAYS
China's new observatory will intercept ultra-high-energy γ-ray particles and cosmic rays.
Courtesy: Nature
~25,000 m
12 wide-field-of-view air Cherenkov telescopes
5,195 scintillator detectors
80,000-m² surface-water Cherenkov detector
1,171 underground water Cherenkov tanks
4,400 m
North Korea
Japan
South Korea
China
Bhutan
Taiwan
Bangladesh
Myanmar (Burma)
Laos
Luzon

LHAASO

- Completed 2021
  - KM2A
    - ED scintillators, MD buried muon dets

1 m^2 ED
Green
Boxes
Below





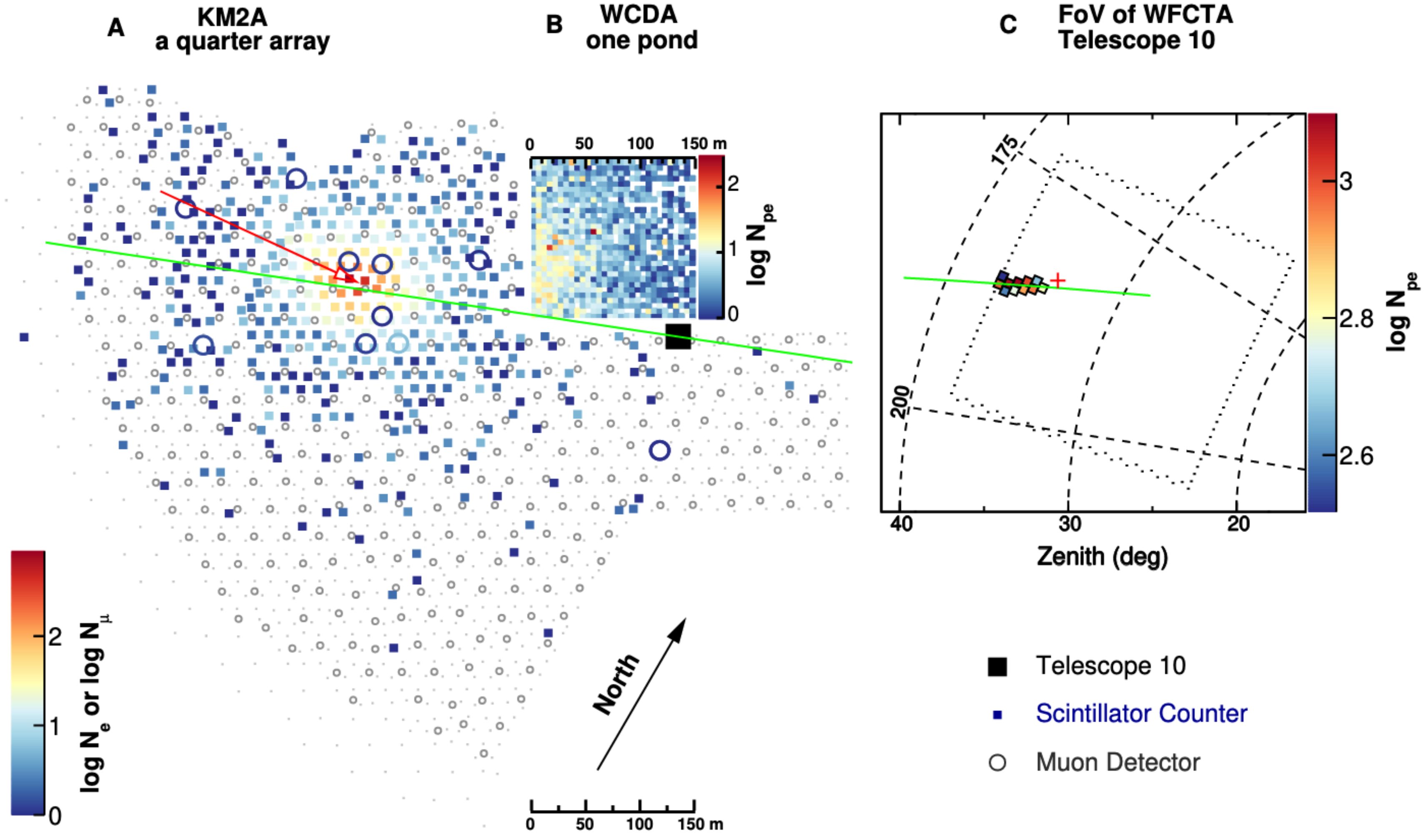


Figure 1: **The 0.88 PeV γ-ray event from the Crab recorded by the LHAASO detectors.** In panel A, squares indicate the scintillator counters of KM2A, colored according to the logarithm of number of detected particles N_e (color bar). The open circles indicate the 11 Muon Detectors of KM2A triggered by the shower. The position of the core is indicated by the red arrow, which is orientated in the arrival direction of the primary photon. The panel

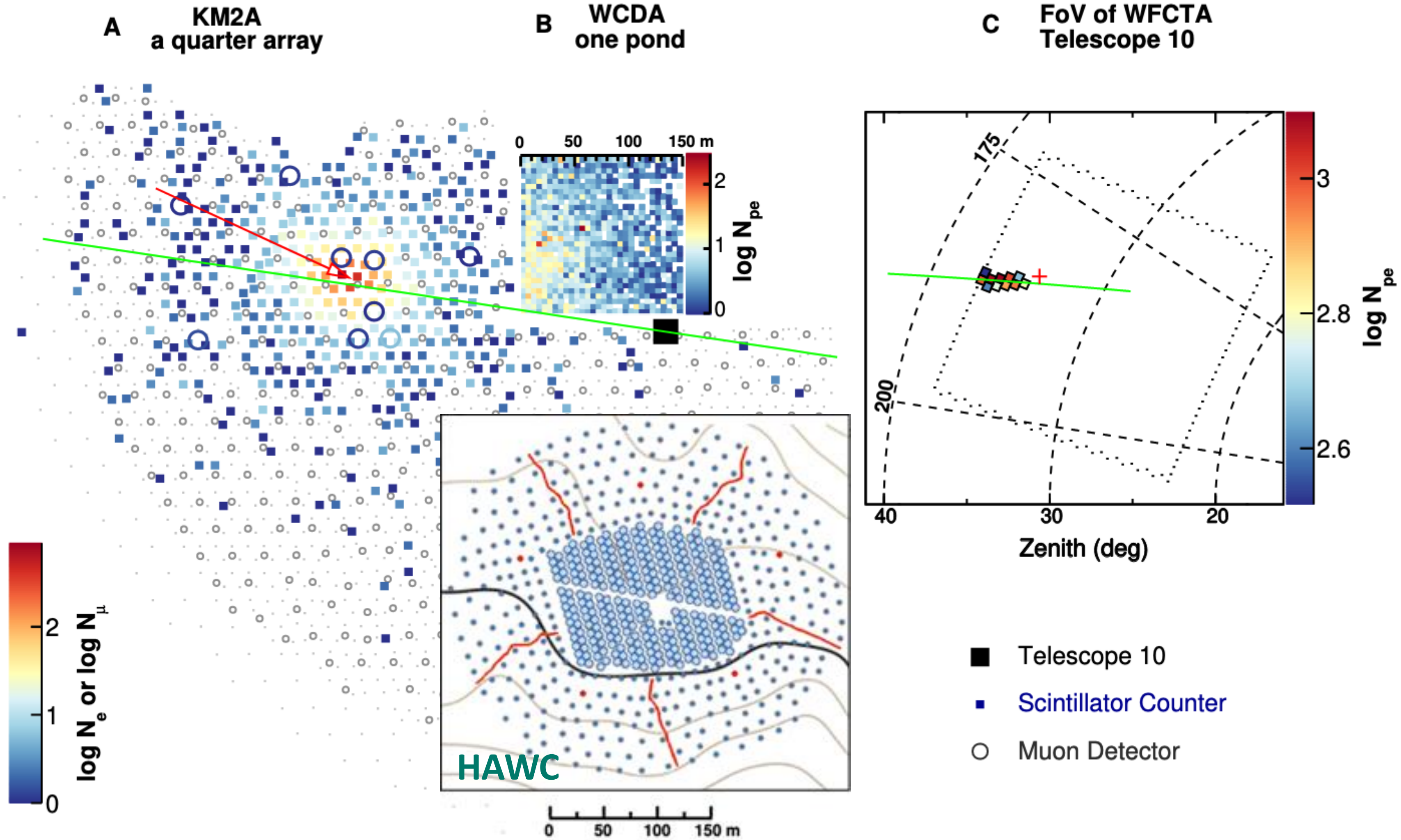


Figure 1: **The 0.88 PeV γ-ray event from the Crab recorded by the LHAASO detectors.** In panel A, squares indicate the scintillator counters of KM2A, colored according to the logarithm of number of detected particles N_e (color bar). The open circles indicate the 11 Muon Detectors of KM2A triggered by the shower. The position of the core is indicated by the red arrow, which is orientated in the arrival direction of the primary photon. The panel

Muon Counting

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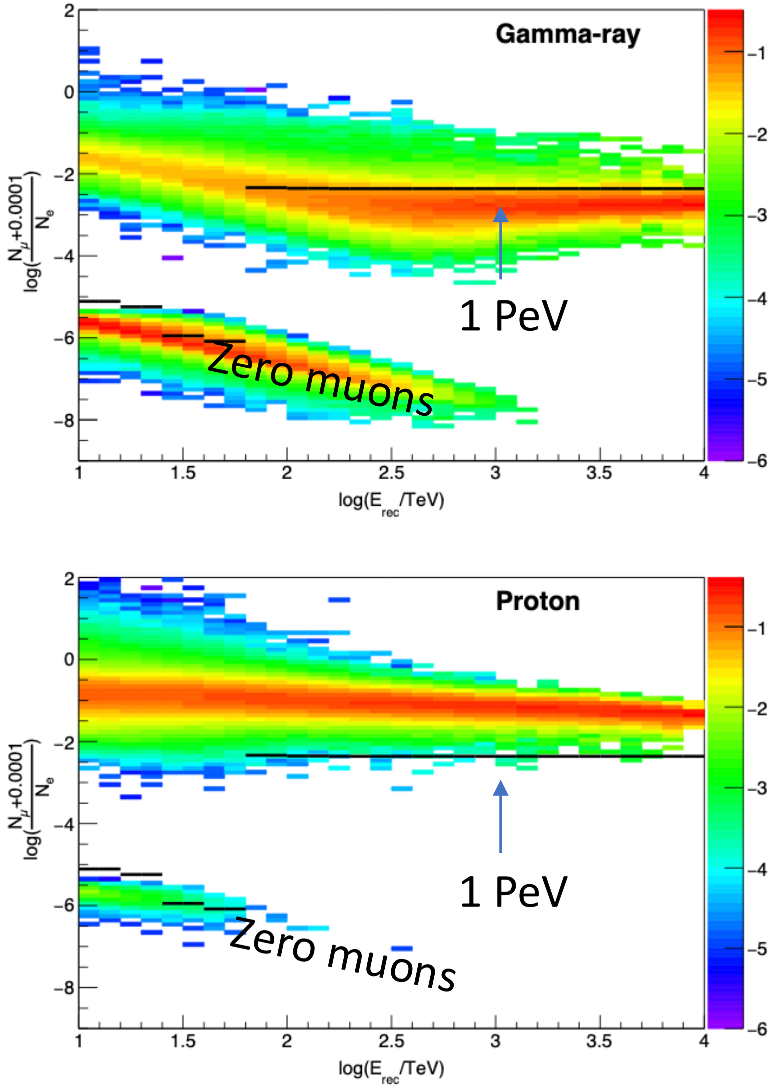
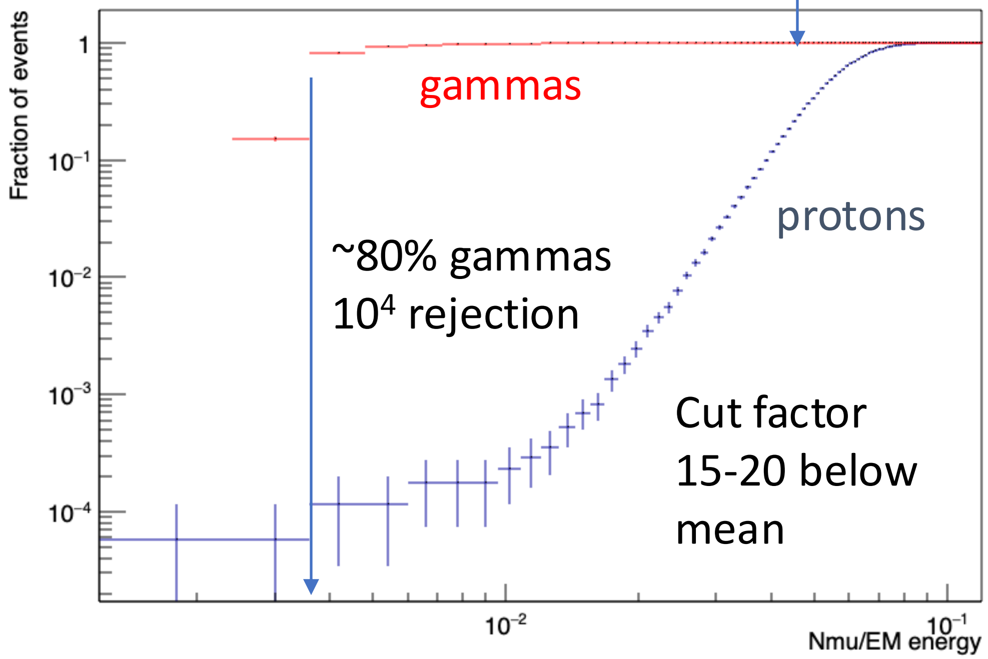


At 1 PeV

Proton mode

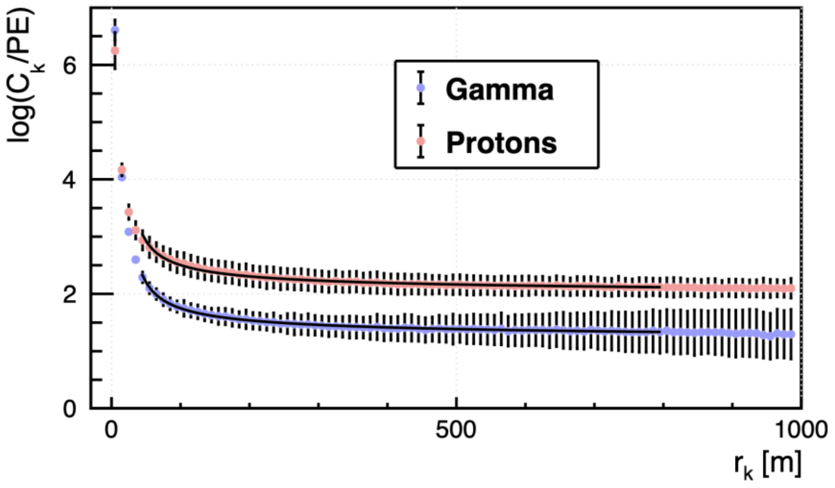


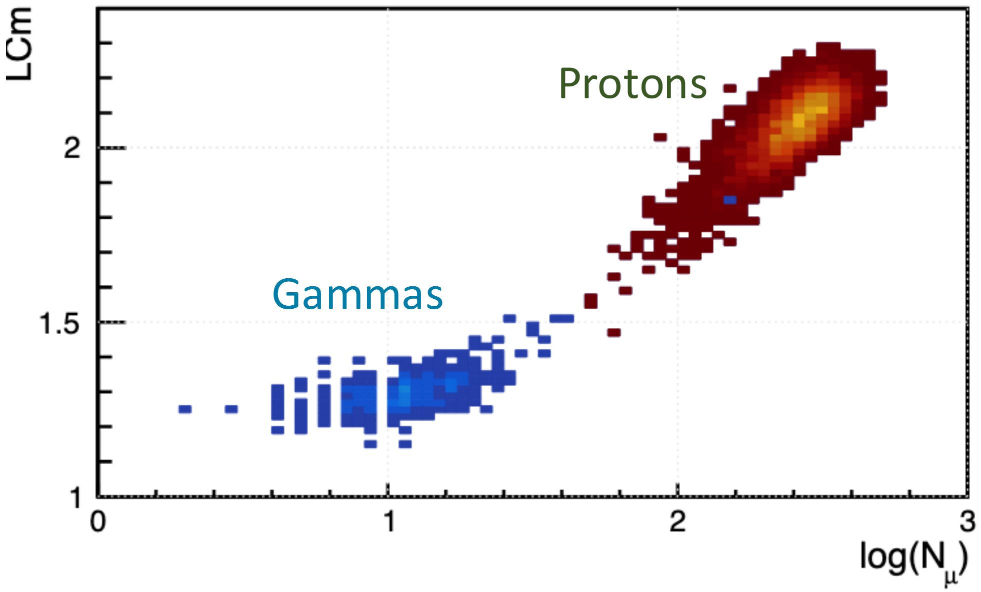
- Jim

- LHAASO

EM Fluctuations

Conceição et al arXiv 2204.12337





$$C_k = \frac{1}{2n_k(n_k-1)} \frac{1}{\langle S_k \rangle} \sum_{i=1}^{n_k-1} \sum_{j=i+1}^{n_k} (S_{ik} - S_{jk})^2$$

$$LCm \equiv \log\left(C_k\right)\big|_{r_k=r_m}$$

- LDF, sub-structure, azimuthal asymmetry
  - Sub-showers in hadronic showers produce additional fluctuations, closely correlated with muon number – tail of very gamma-like protons

Sensitivity?

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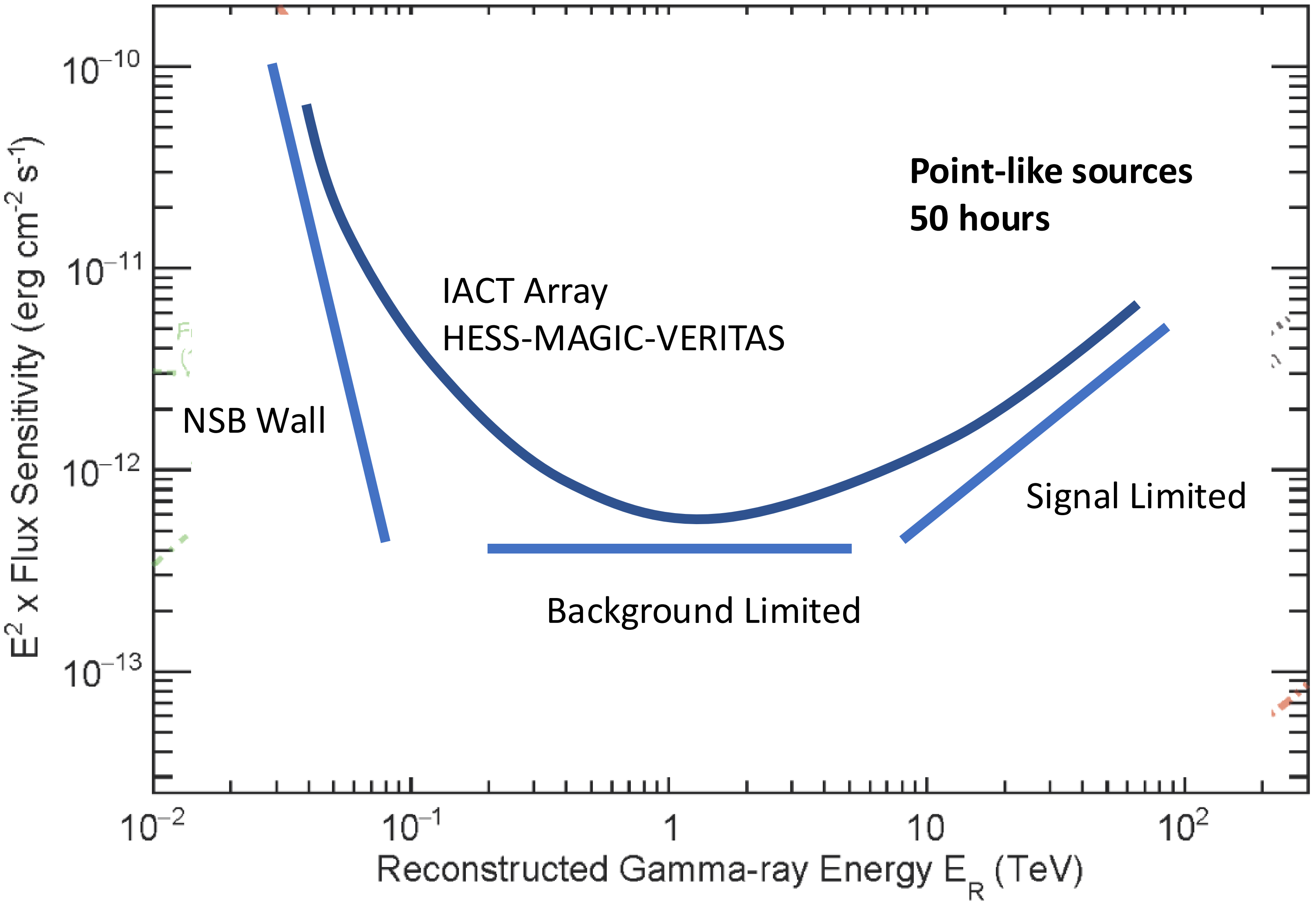

Sensitivity?

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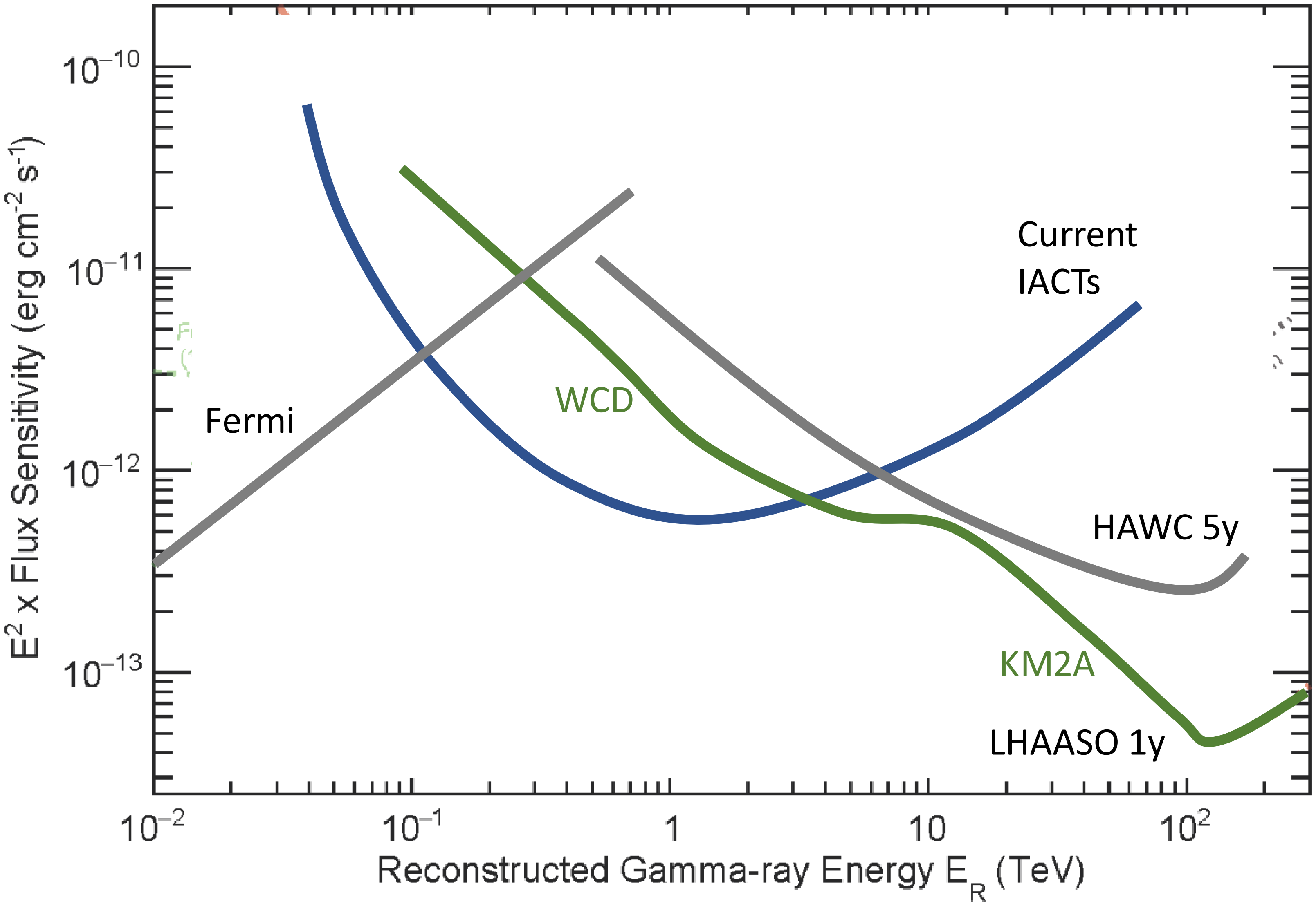
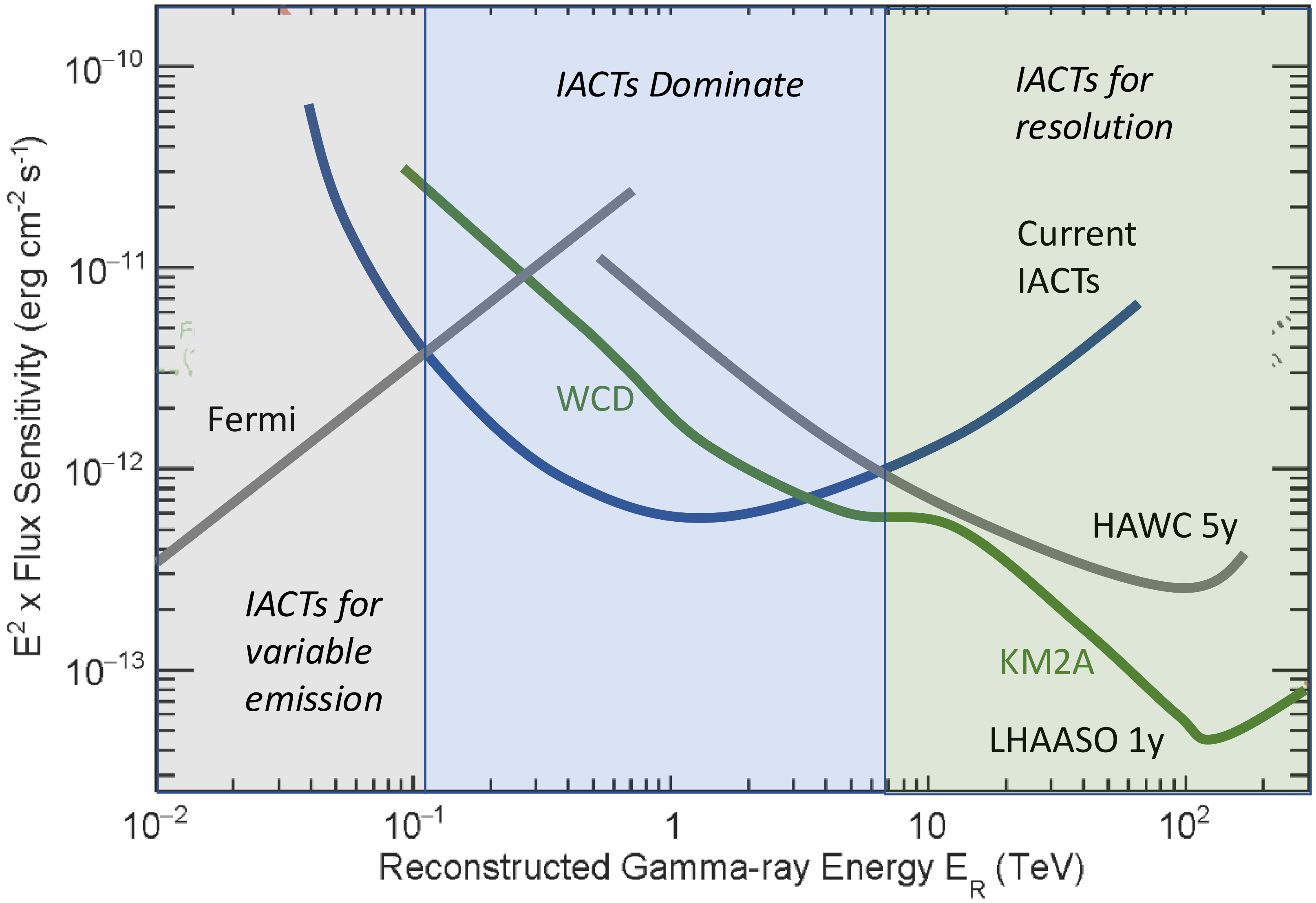


Sensitivity?



Resolution?

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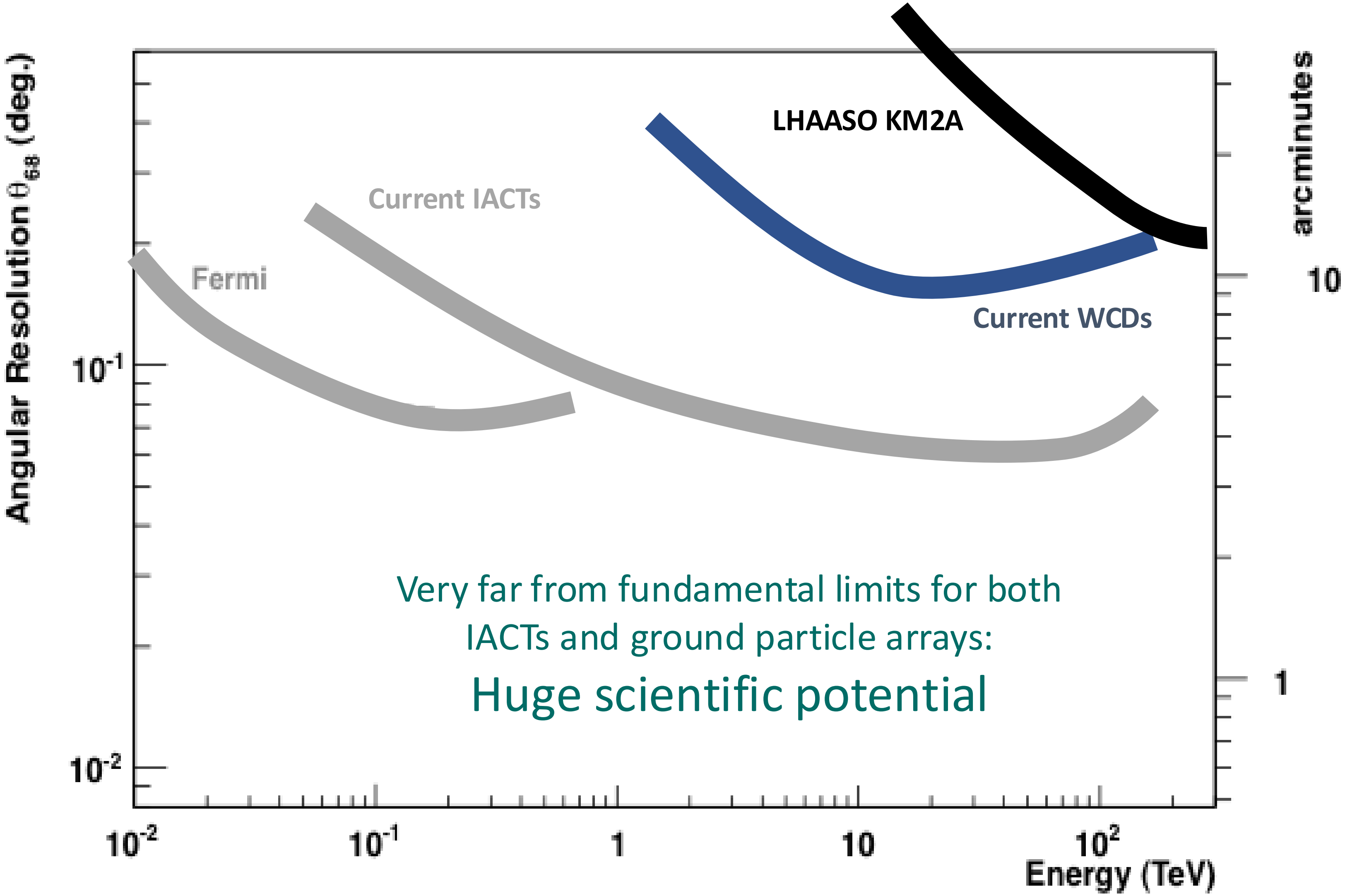


Very far from fundamental limits for both IACTs and ground particle arrays:

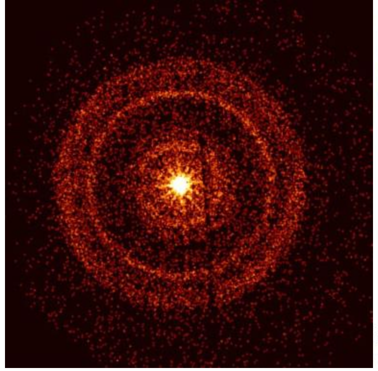
Huge scientific potential

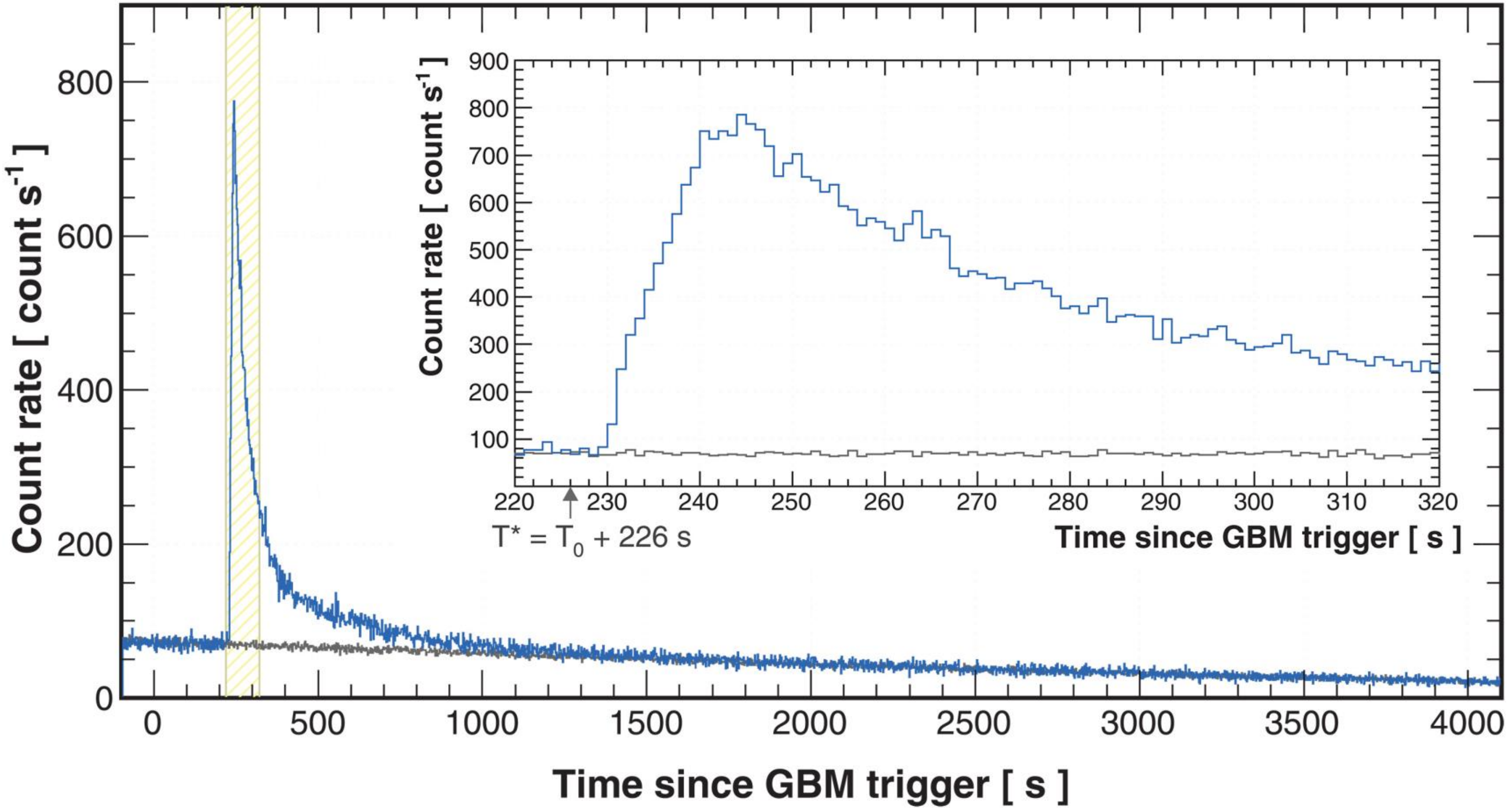
Fill factor is critical for resolution

LHAASO scintillators <1%

Discoveries?

e.g. GRB 221009A





Cao et al, Science 2023

- z = 0.1505, photons up to (reconstructed) energy of **18 TeV**

Discoveries?

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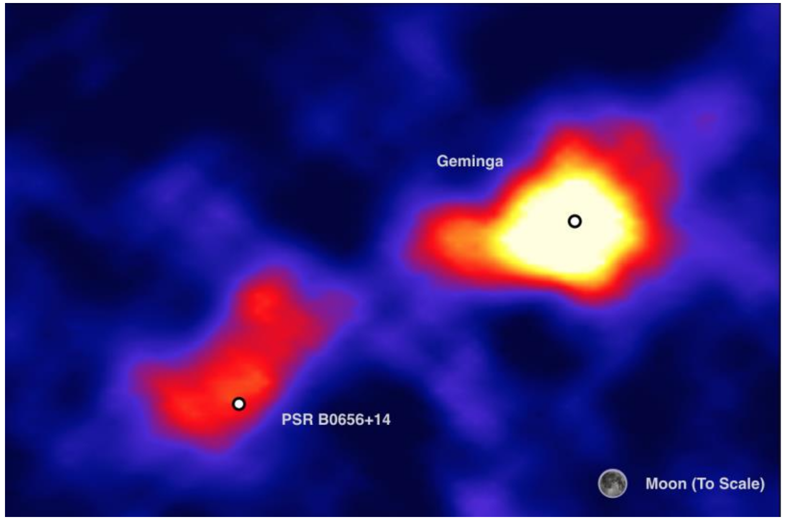
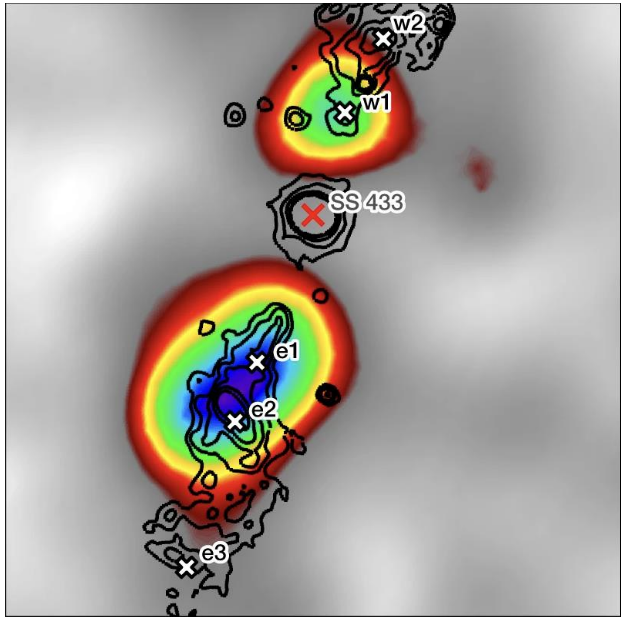
- Very large-scale sources
  - e.g. The ‘halos’ of Geminga and Monogem

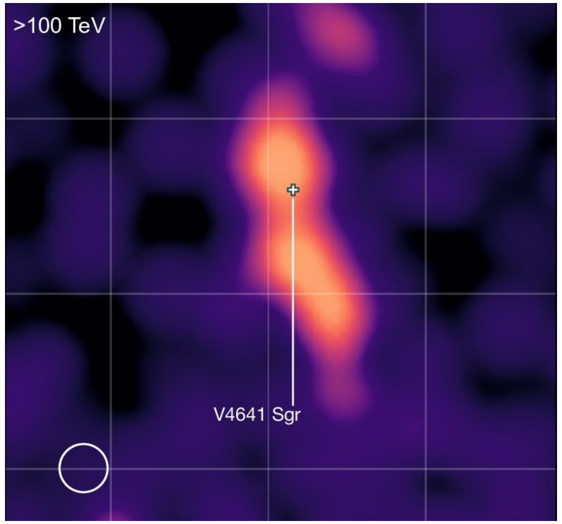


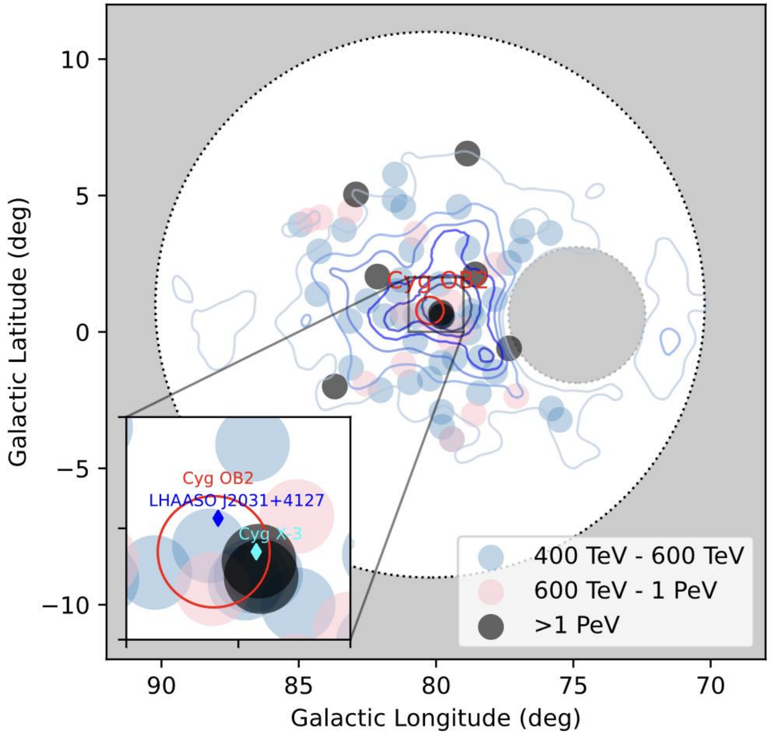
- Emission in to a new energy domain – in particular with LHAASO
  - PeV emission from Galactic Accelerators – e.g. Cygnus ‘bubble’

- Very hard spectrum sources
  - e.g. SS 433 ‘lobes’

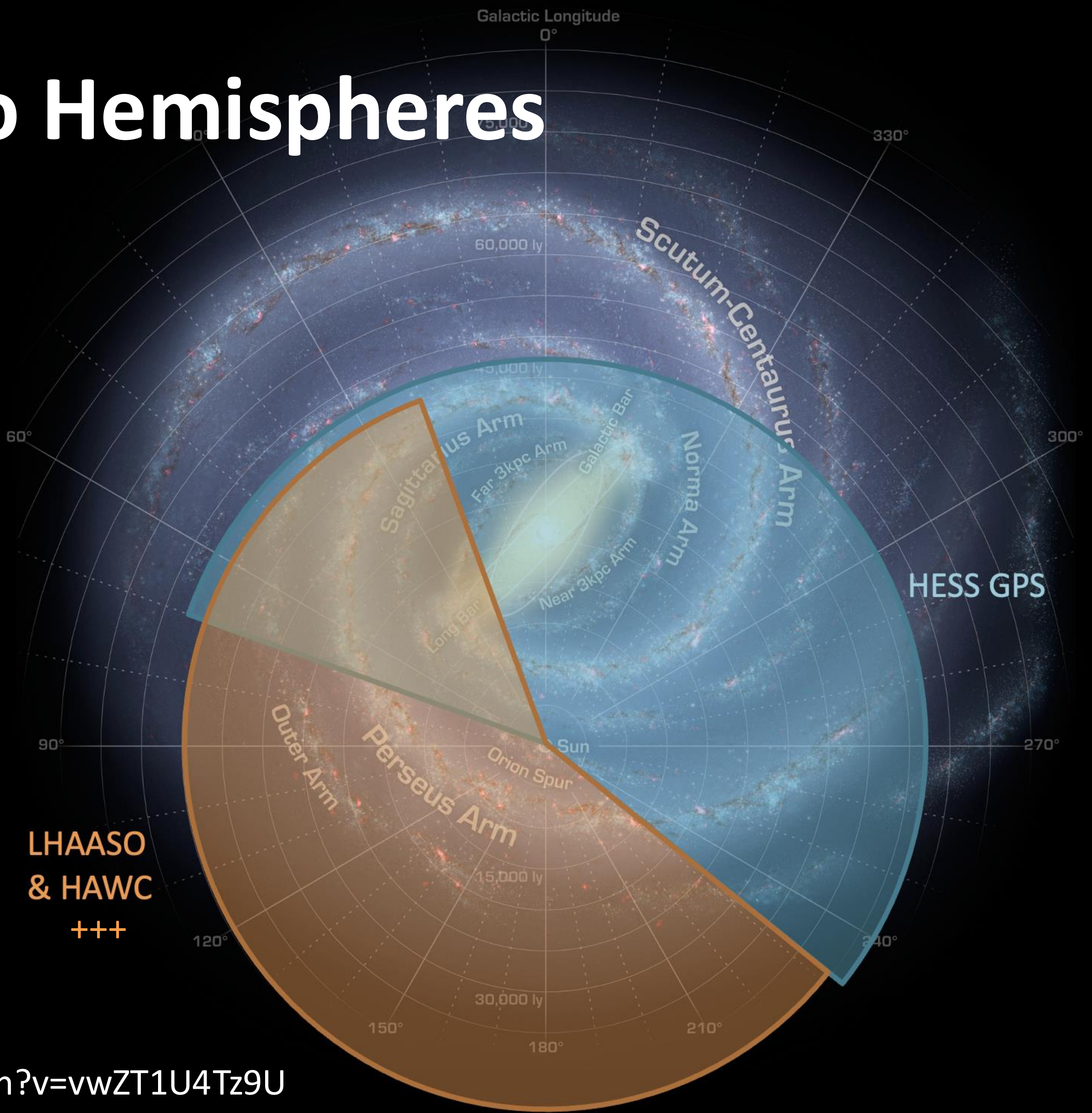


- Off-plane Galactic objects
  - e.g. V4647 Sgr





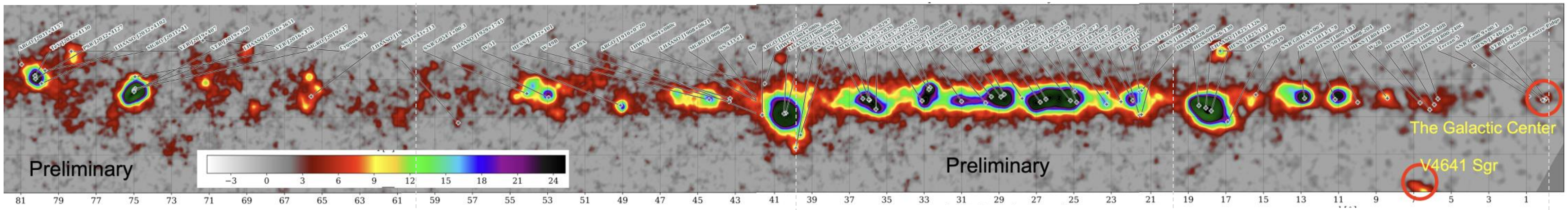
A Tale of Two Hemispheres



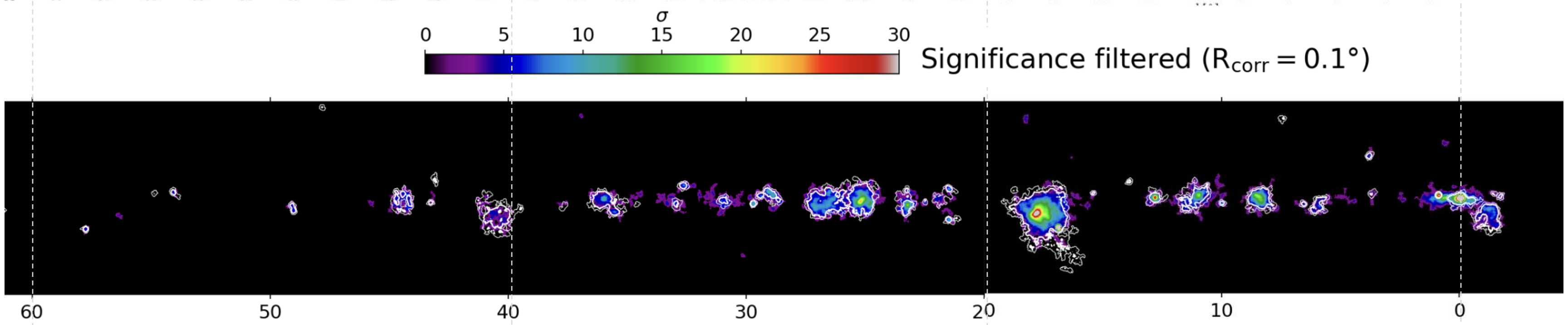
NASA/JPL-Caltech/R. Hurt

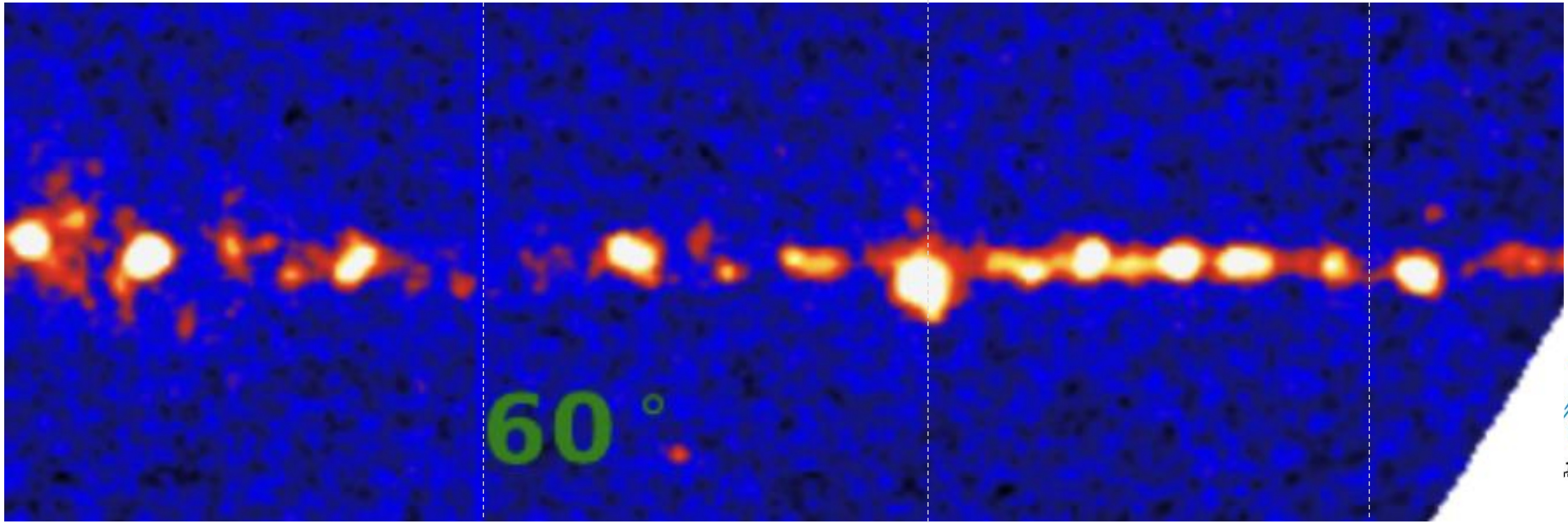
https://www.youtube.com/watch?v=vwZT1U4Tz9U

+ Pass 5 prelim. Goodman Gamma2022

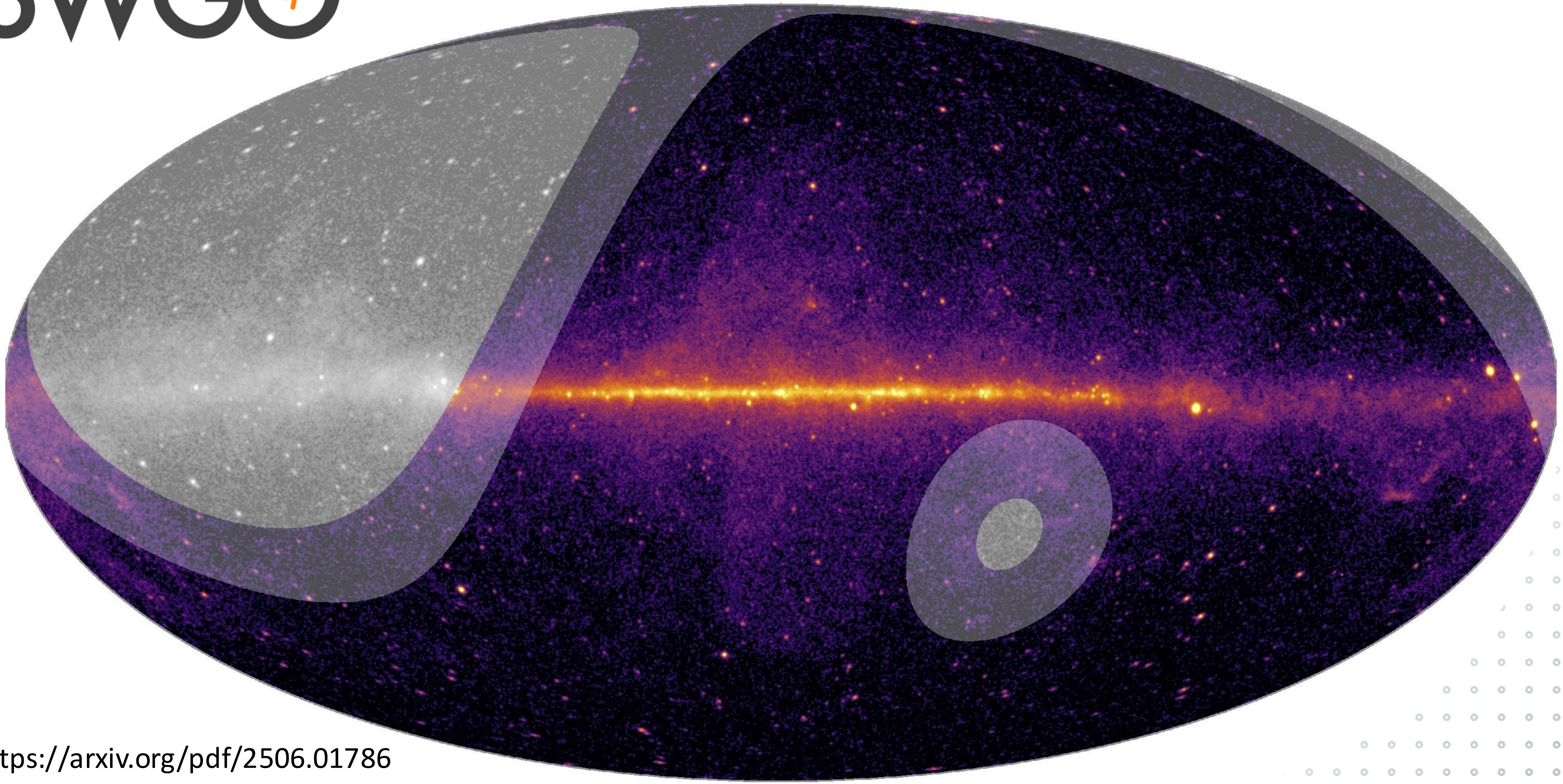


+ Updated HESS GPS (Remy et al ICRC 2023)





+ 1[st] LHAASO Catalogue : KM2A

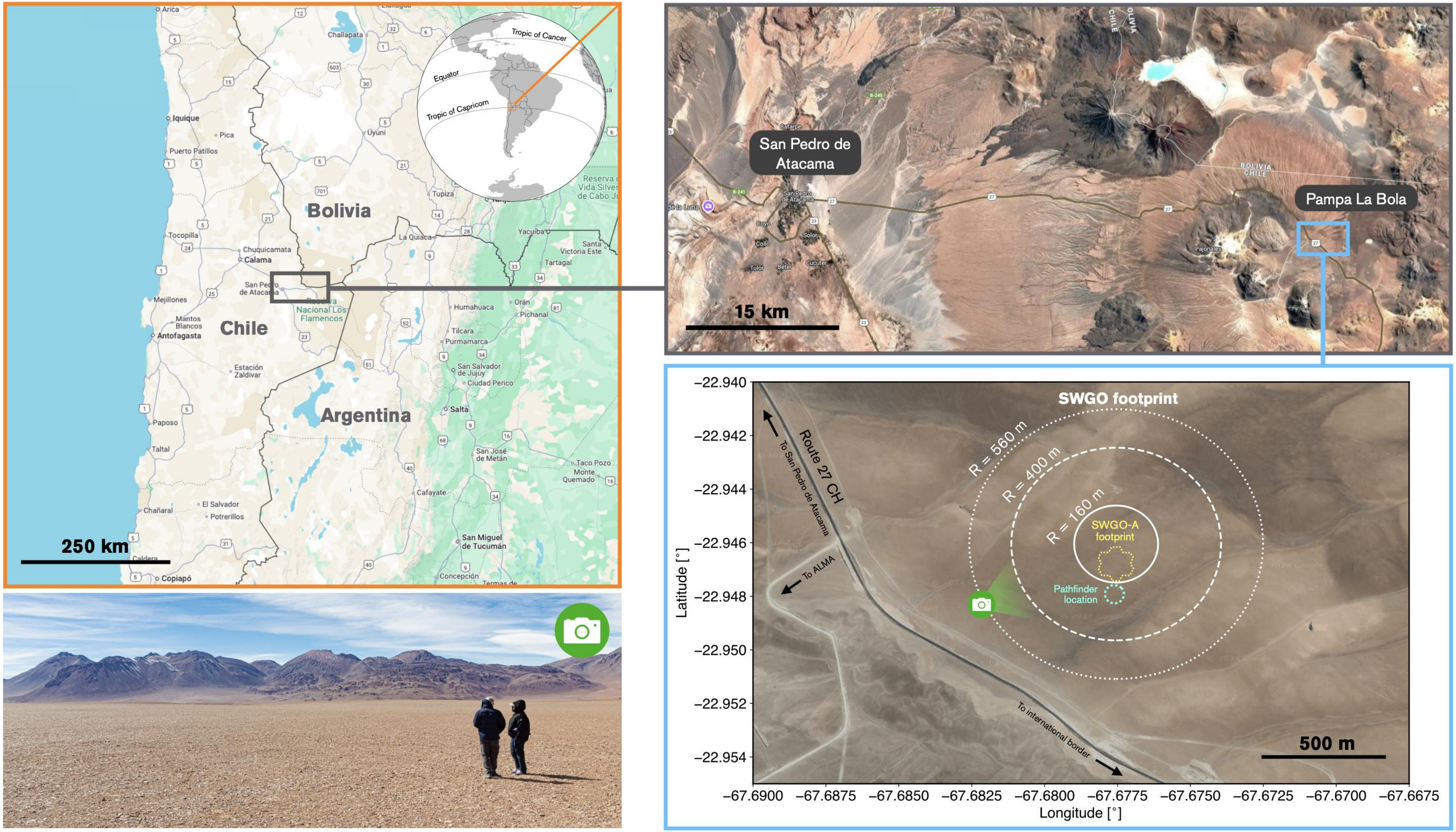


https://arxiv.org/pdf/2506.01786

The SWGO Collaboration

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

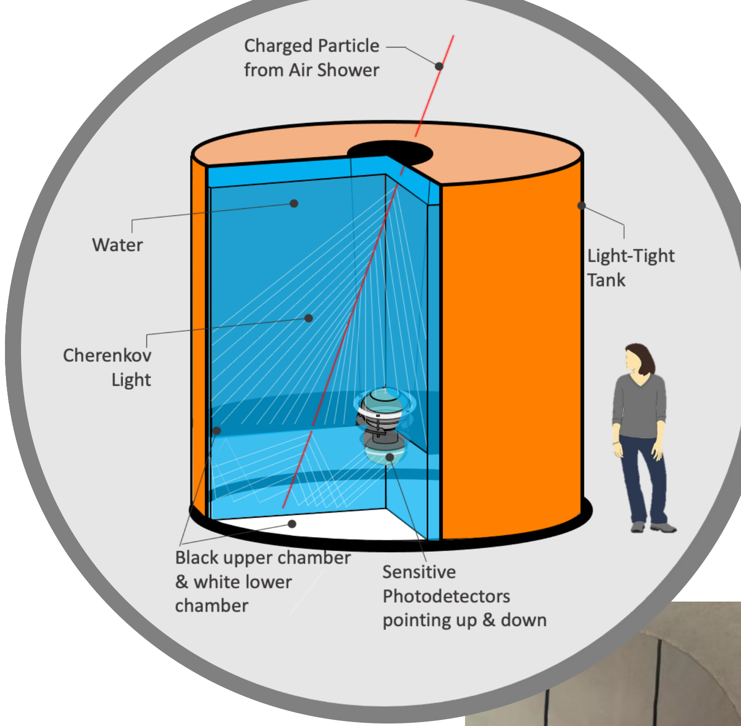
SWGO members and guests at the site of the project, Pampa La Bola
(12th Collaboration Meeting, San Pedro de Atacama, 5-9 May, 2025)

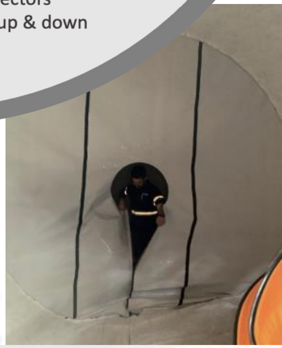


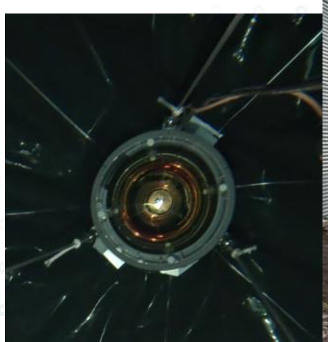
Tropic of Cancer
Equator
Tropic of Capricorn
Bolivia
Chile
Argentina
Arica
Iquique
Pica
Puerto Patillos
Tocopilla
Chuquicamata
Calama
San Pedro de Atacama
Reserva Nacional Los Flamencos
Mejillones
Mantos Blancos
Antofagasta
Estación Zaldivar
Paposo
Taltal
Chañaral
El Salvador
Potrerillos
Caldera
Copiapó
Challapata
Uyuni
Tupiza
La Quiaca
Yacuiba
Tartagal
Humahuaca
Orán
Pichanal
Tilcara
Purmamarca
San Salvador de Jujuy
Ciudad Perico
Salta
San José de Metán
Cafayate
San Miguel de Tucumán
Concepción
Taco Pozo
Monte Quemado
250 km
San Pedro de Atacama
Pampa La Bola
BOLIVIA CHILE
15 km
SWGO footprint
R = 560 m
R = 400 m
R = 160 m
SWGO-A footprint
Pathfinder location
Route 27 CH
To San Pedro de Atacama
To ALMA
To international border
500 m
Latitude [°]
Longitude [°]
−22.940
−22.942
−22.944
−22.946
−22.948
−22.950
−22.952
−22.954
−67.6900
−67.6875
−67.6850
−67.6825
−67.6800
−67.6775
−67.6750
−67.6725
−67.6700
−67.6675

SWGO Status

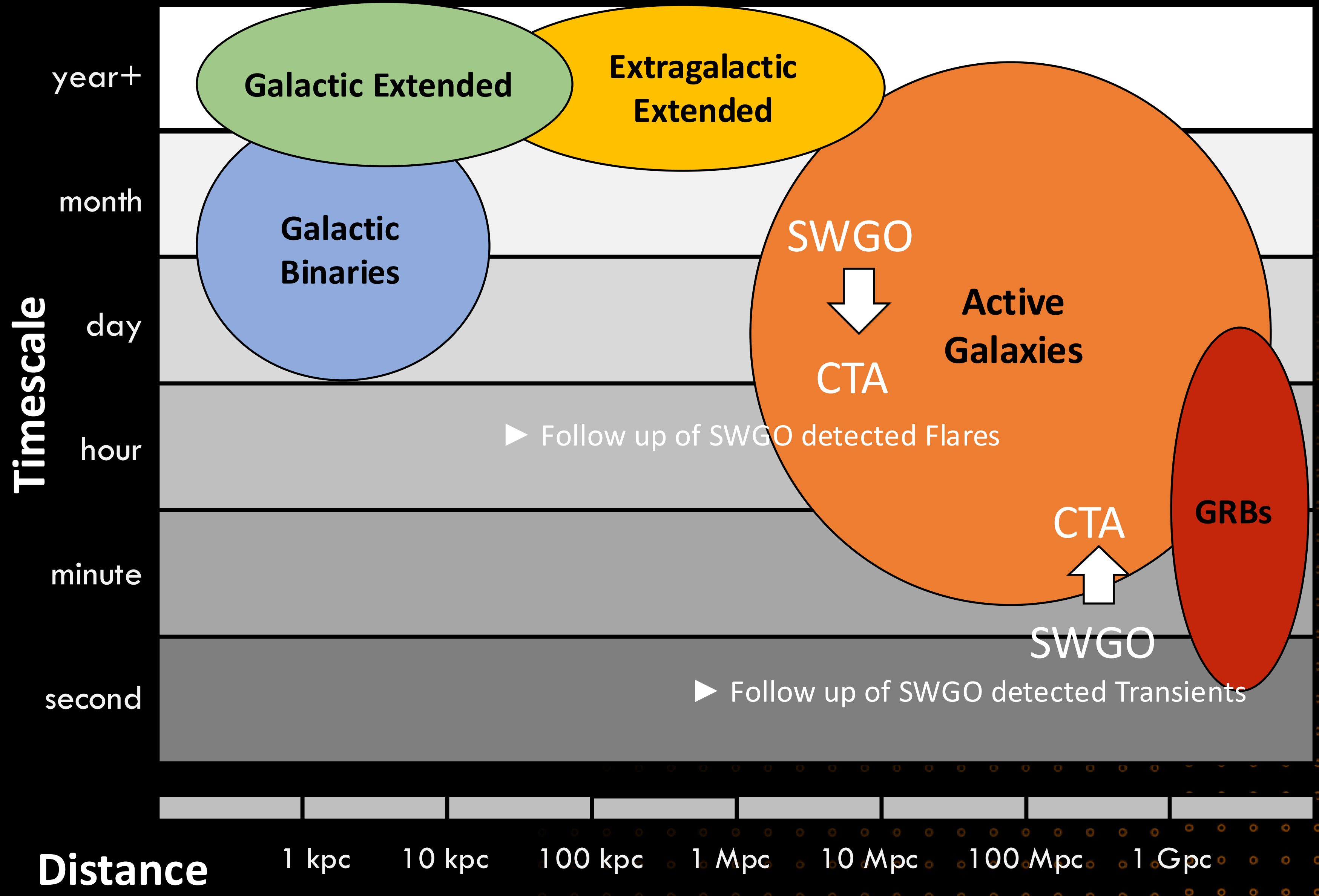
- Rapidly reaching end of R&D phase
  - Aim for small # of WCDs on site early in 2026
    - The Pathfinder
  - Major funding applications submitted / in prep.
    - Submitted: SWGO-A proposal to NSF
- Narrowing down the phase space towards baseline:
  - Zoned array: inner FF > 50%, outer to ~1 km^2 scale (“A4”)
  - Inner array - dual layer WCD 5.2 m diameter, 4 m deep
  - Outer array – WCD design still open
- Excellent γ/h separation from dual layer approach







SWGO ➡ CTA ▶ Follow up of SWGO detected Galactic Sources



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SWGO

CTAO

Transients: GRBs

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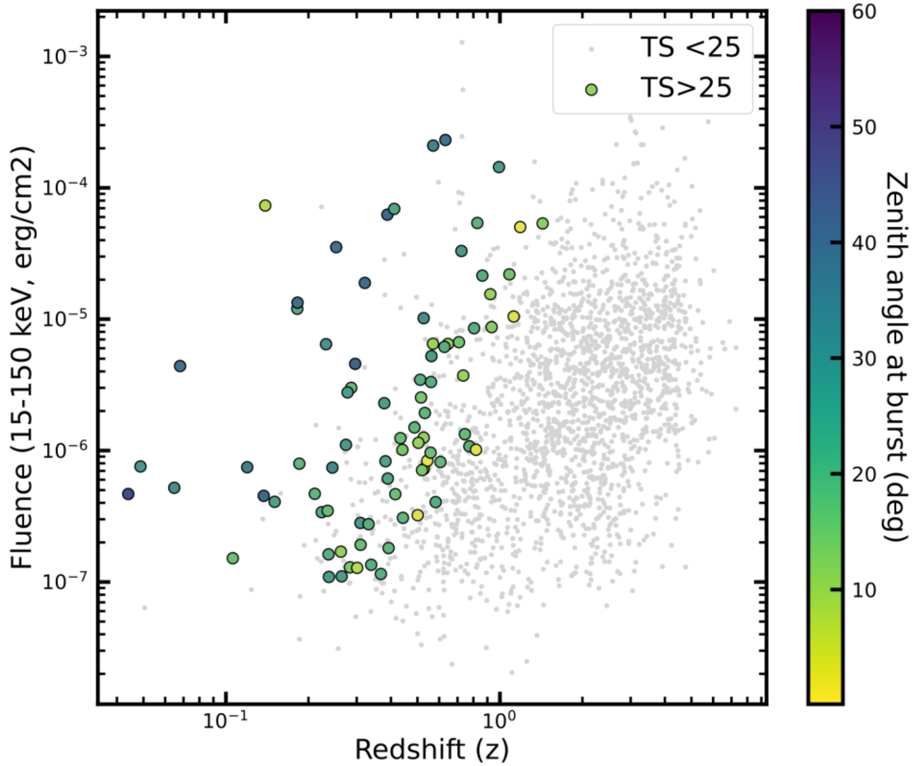
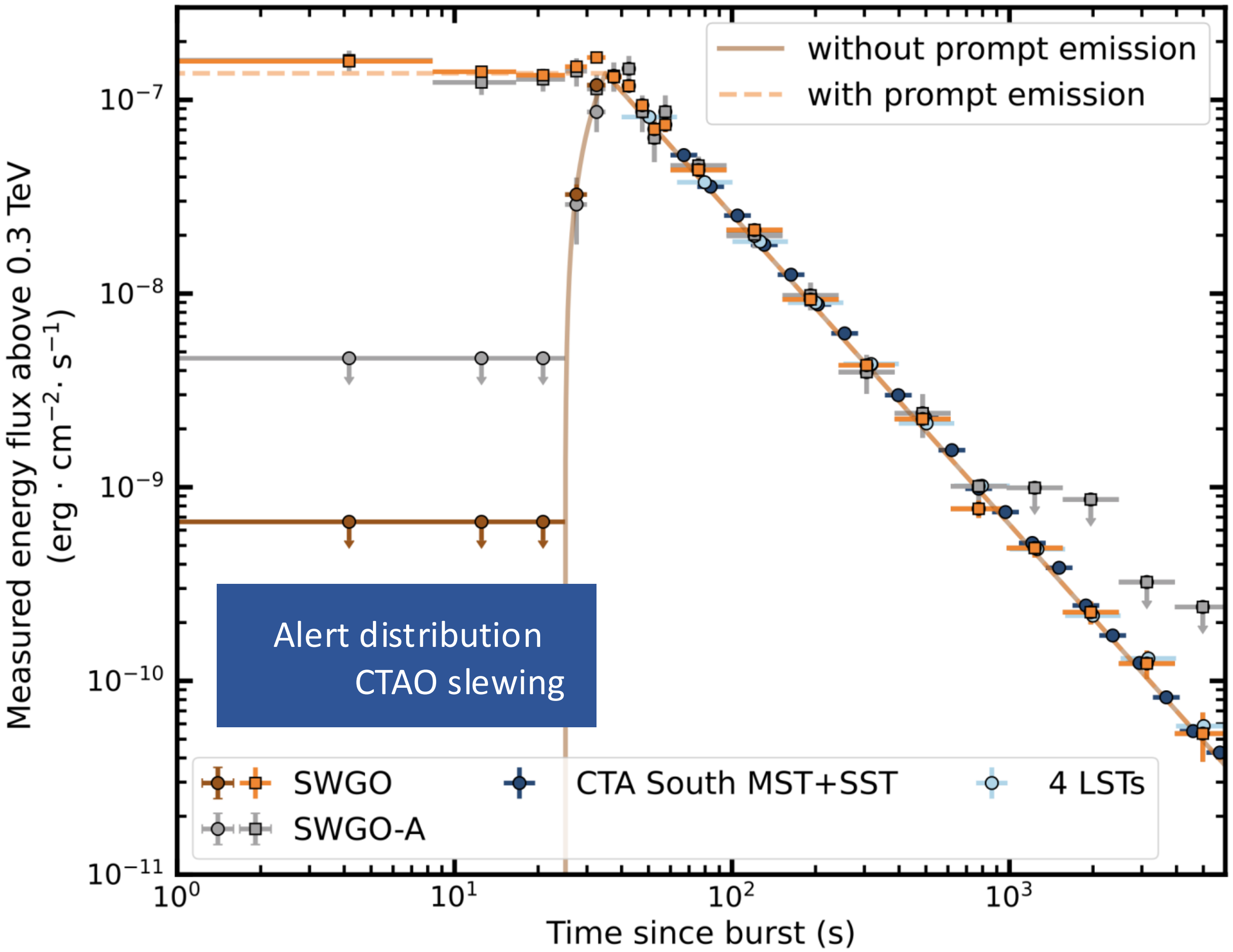
- Prompt phase observations
  - SWGO+CTAO observations to cover full light-curve !

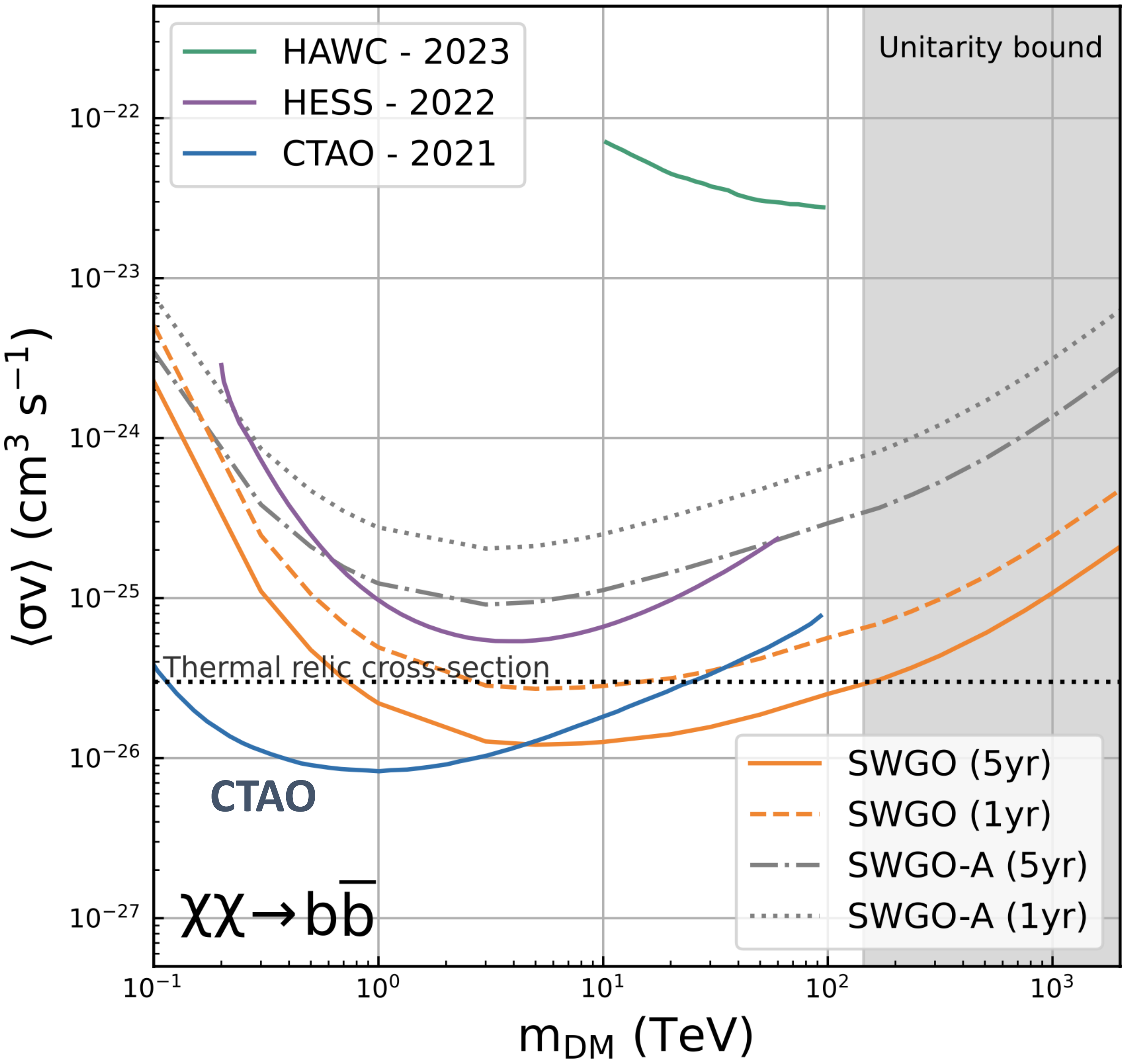




Detection rate O(1 per year)

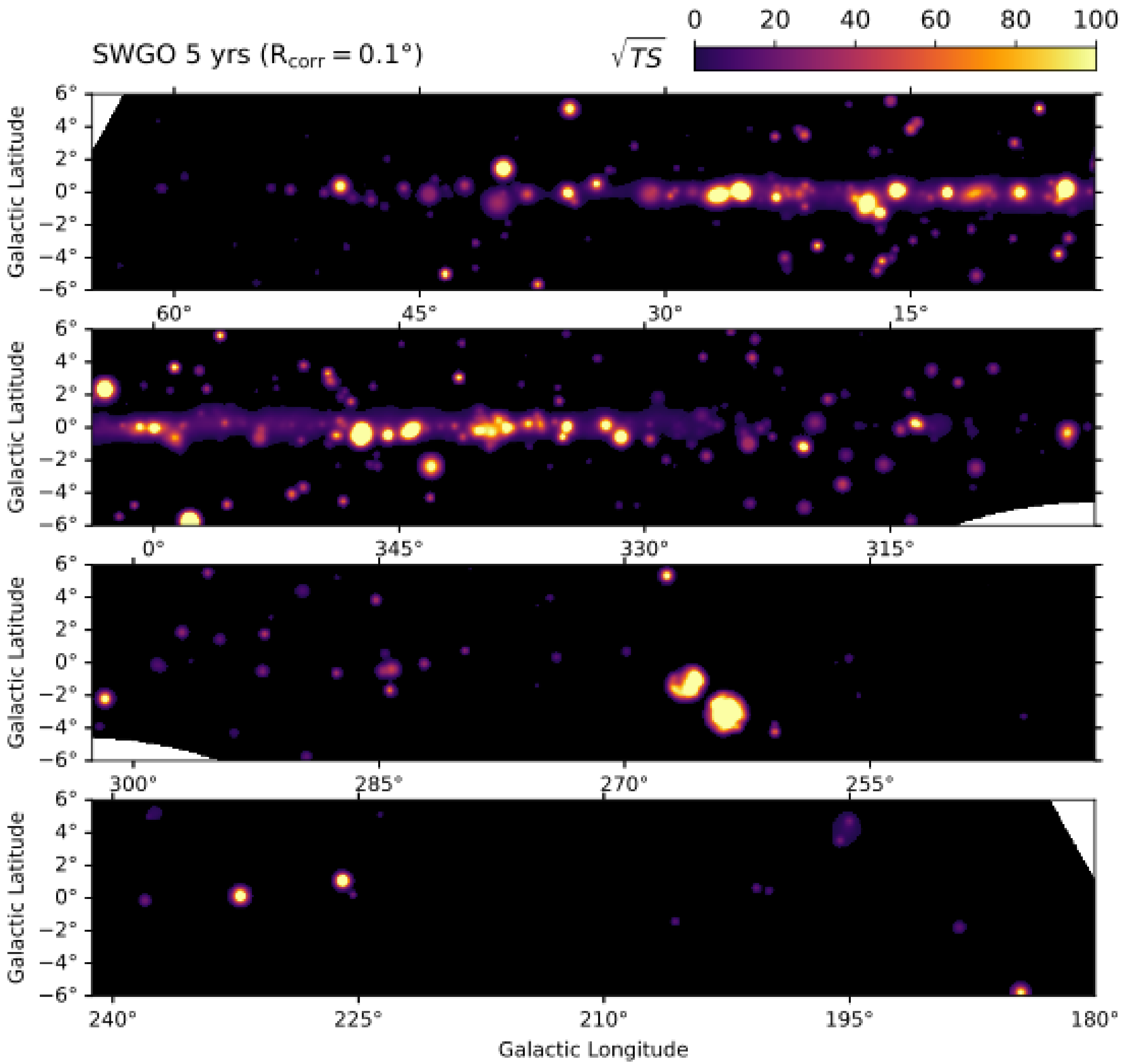
Dark Matter

- WIMPs as a Thermal Relic of the Big Bank
  - Still a strong DM candidate
- Indirect detection with gammas reaching critical sensitivity for Gal. Centre
  - SWGO advantages: wide field, BG systematics, higher energies
  - Again CTAO+SWGO extremely powerful



And a lot more…

- Simulated Galactic Plane Observation with SWGO
  - Use CTAO pop. Model
    - 499 CTA dets
    - 461 detections in SWGO FoV
    - SWGO 5 years: 487
  - Very similar source statistics
    - Strong complementarity in terms c E-range and source scale
    - CTAO resolution key to disentangl



Summary

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- Ground particle arrays are powerful tools for high energy astrophysics and astroparticle physics. Particular advantages:
  - Large exposure and excellent background rejection at UHE
    - Highest sensitivity at >100 TeV
  - Very large-scale diffuse emission
    - Very large Field-of-view
    - Very low systematics from background subtraction
  - Prompt observations of transients
    - Observing the whole overhead sky all the time
- Combination with IACT arrays very effective
- Exciting progress towards SWGO!
  - Joint CTAO/SWGO science very promising

Job Opportunities !

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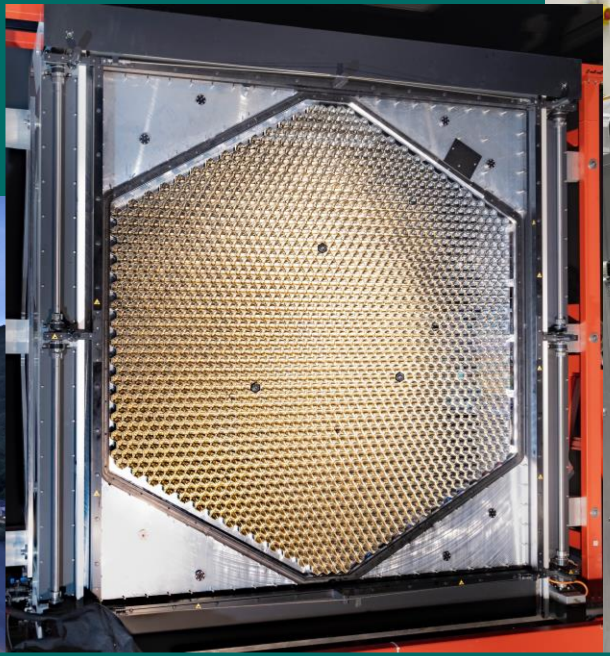
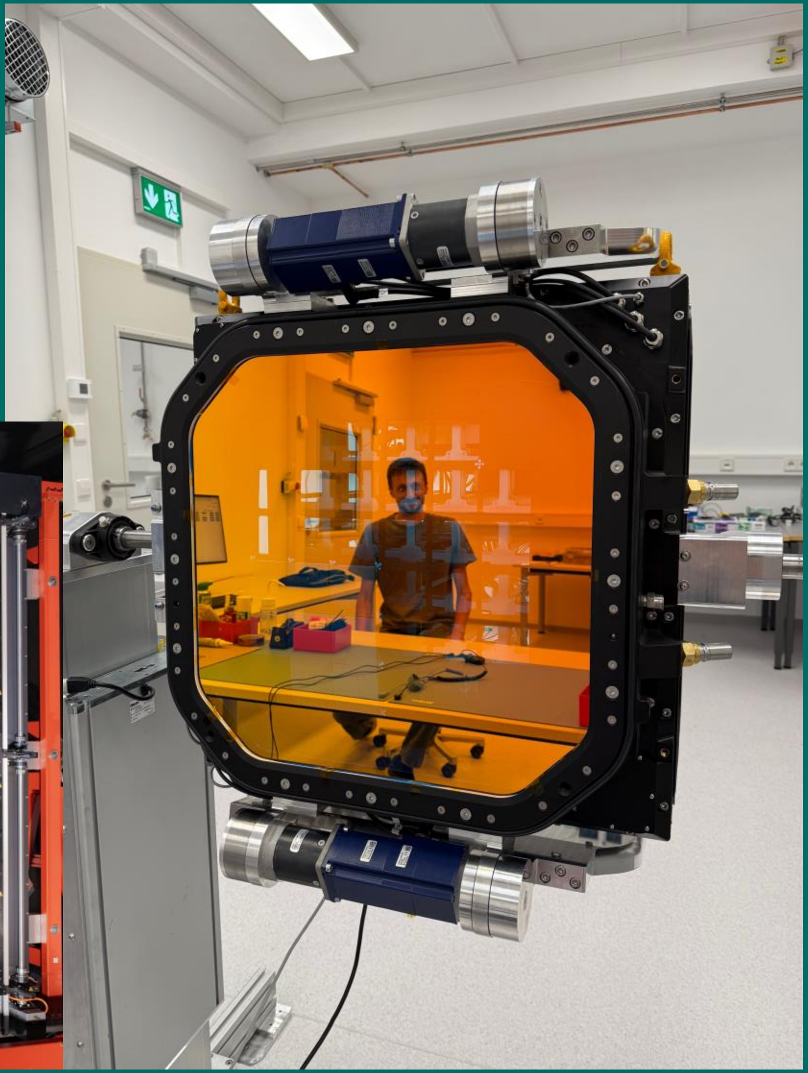
MPIK (in Heidelberg, Germany) is looking for new PhD Students and Post docs

- To work on CTAO and SWGO

Talk to me at the coffee break!





Questions?

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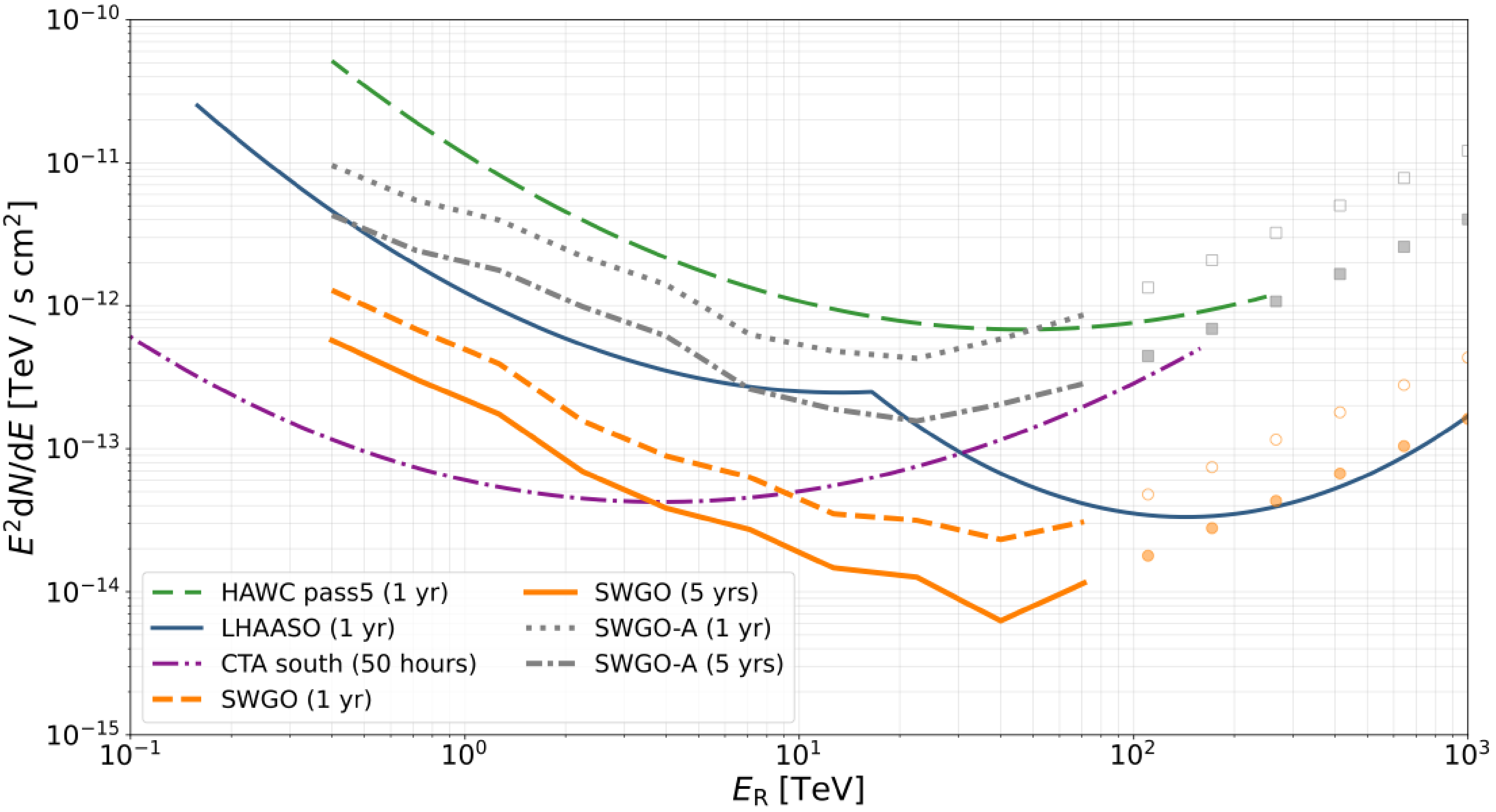
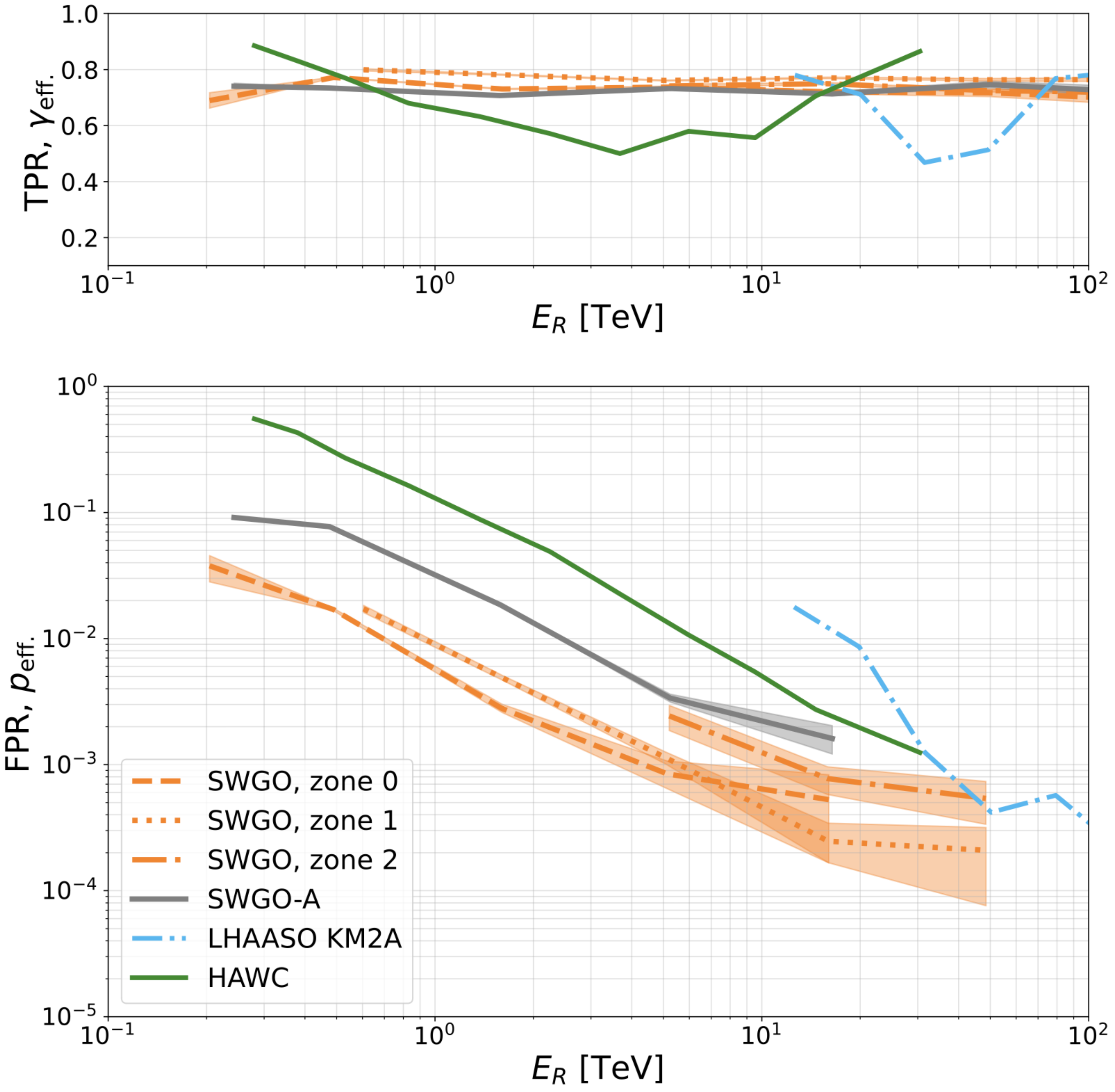


- Caveat – not fully realistic at low E (overlapping showers)

BG Rejection



Angular Resolution

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