

MOONRAY: towards a cosmic radiation observatory on the Moon

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pressurized
habitat, control
room, labs,
workshop

unpressurized shed
with micrometeoroid
low-mass shield

MOONRAY site at
Lunar South Pole
(AI artist's view)

COSPAR 2024, July 13-21 – Busan, Korea

Direct detection of cosmic rays and γ rays

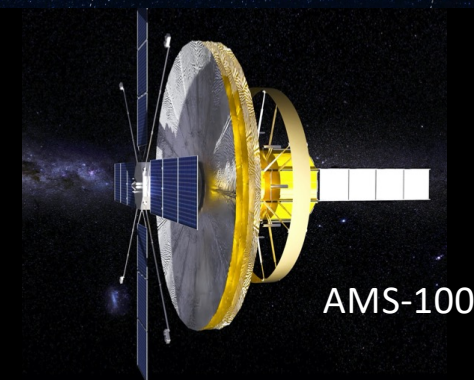
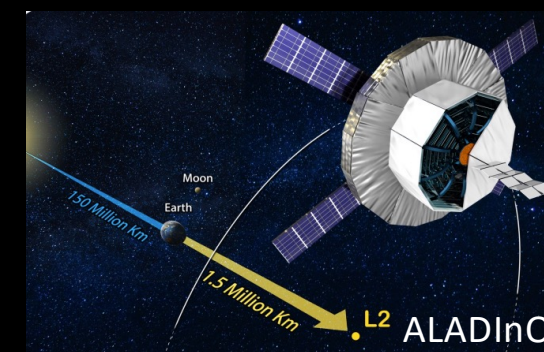
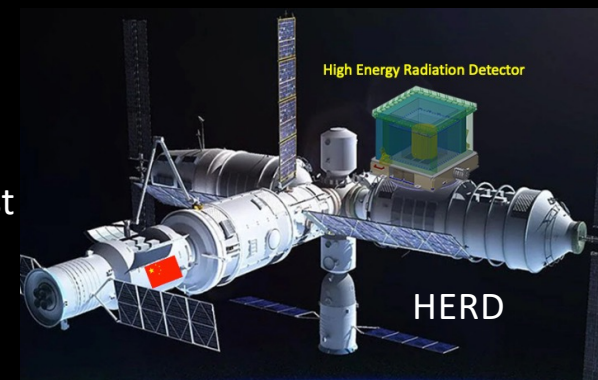
Instruments in Low Earth Orbit at present (or recent past)

Experiment	$e^\pm$ (present data)	e^+e^- (Energy range)	CR nuclei (Energy range)	charge Z	Gamma-ray	Site	Launch	Status
PAMELA	spectrometer	1-700 GeV (3 TeV with calorimeter)	1 GeV-1.2 TeV (extendable $\rightarrow$ 2TeV)	1-8	-	SAT	2006	ended
FERMI	no magnet	7 GeV – 2 TeV	50 GeV-1 TeV	1	20 MeV – 300 GeV GRB 8 KeV – 35 MeV	SAT	2008	operative
AMS-02	spectrometer	$e^+ < 2$ TeV $e^- < 3$ TeV (after upgrade)	1 GV-3 TV	1-28	1 GeV-1 TeV (calorimeter)	ISS	2011	operative
NUCLEON	no magnet	100 GeV-3 TeV	100 GeV-1 PeV	1-30	-	SAT	2014	ended
CALET	no magnet	1 GeV-20 TeV (extendable $\rightarrow$ 20TeV)	10 GeV-1 PeV	1-40	10 GeV-10 TeV GRB 7-20 MeV	ISS	2015	operative
DAMPE	no magnet	10 GeV-20 TeV	50 GeV-1 PeV	1-20	5 GeV-10 TeV	SAT	2015	operative
ISS-CREAM	no magnet	100 GeV-10 TeV	1 TeV-1 PeV	1-28	-	ISS	2017	ended

NEXT GENERATION (under study)

- A new generation of LARGE and VERY LARGE space instruments are being designed
- They are facing formidable challenges in terms of payload size, weight, power, and cost

Item	HERD (LEO)	ALADINO (L2)	AMS-100 (L2)
calorimeter depth for electrons	55 X_0	61 X_0	70 X_0
calorimeter depth for protons	3 λ_I	3.5 λ_I	4 λ_I
MDR	N/A	20 TV	100 TV
Acceptance (spectrometer + calorimeter)	N/A	$\sim 3 \text{ m}^2 \text{ sr}$	$\sim 20\text{-}30 \text{ m}^2 \text{ sr}$
Acceptance (calorimeter)	$\sim 2\text{-}3 \text{ m}^2 \text{ sr}$	$\sim 9 \text{ m}^2 \text{ sr}$	$\sim 20\text{-}30 \text{ m}^2 \text{ sr}$
# of channels	300 k	2.5 M	8 M
Weight	$\sim 4,000 \text{ kg}$	$\sim 6,000 \text{ kg}$	$\sim 40,000 \text{ kg}$
Power Consumption	$\sim 1.4 \text{ kW}$	$\sim 4 \text{ kW}$	$\sim 15 \text{ kW}$



Lunar South Pole

How about a "ground"
CR telescope on the
Moon ?

Henson crater
(88.5°S, 129.6°W)

*Other candidate sites
at Lunar South Pole:*

Sverdrup (88.5°S, 152.0°W)

Henson (88.5°S, 129.6°W)

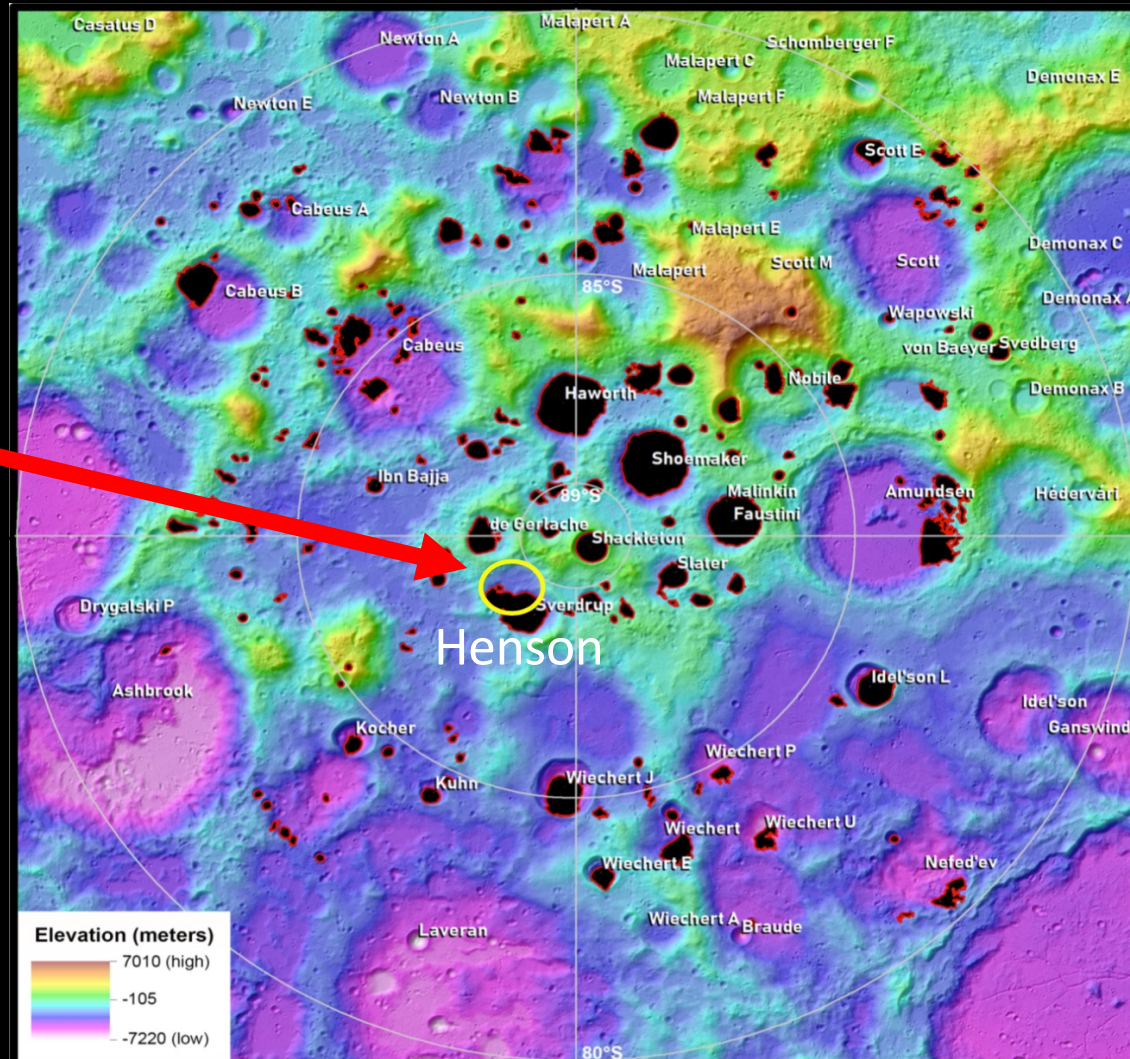
Shackleton (89.4°S, 129.4°E)

de Gerlache (88.5°S, 87.1°W)

Malapert Massif (85.8°S, 3.8°E)

90°W

90°E

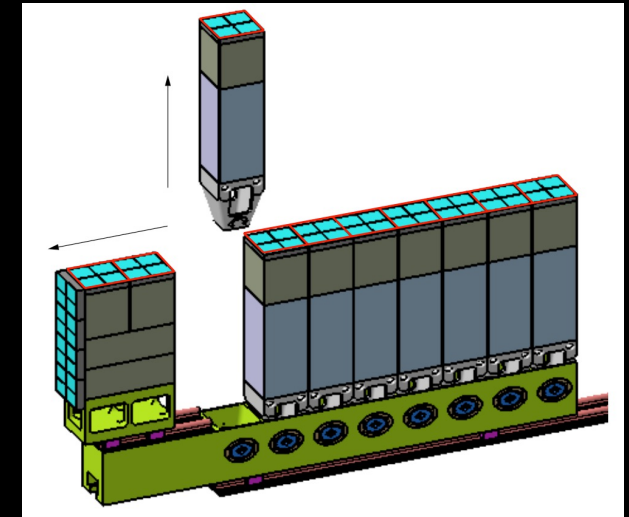


180°E

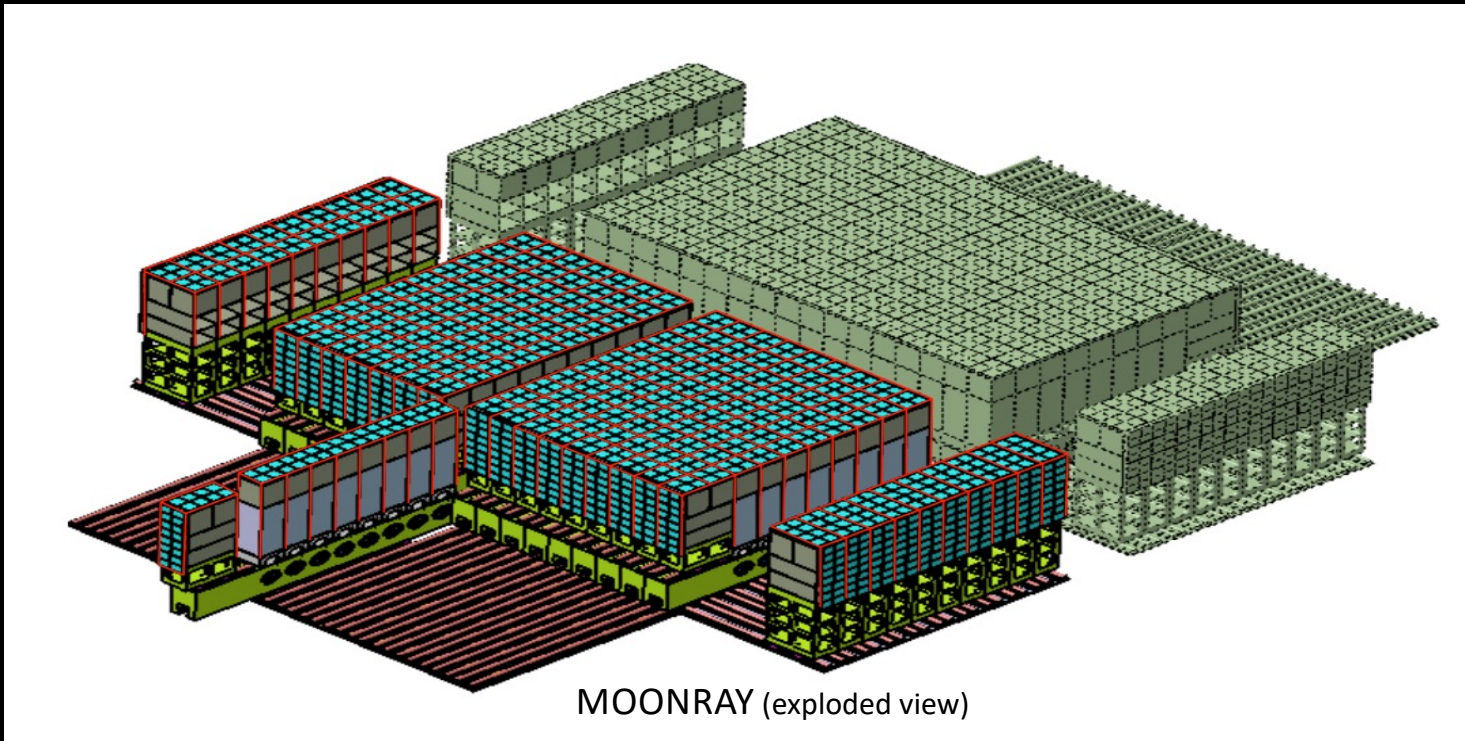
An instrument with $> 10 \text{ m}^2\text{sr}$ *effective acceptance*
 + order of magnitude larger *effective area* than FERMI
 => LARGE, HEAVY, POWER-HUNGRY

The KEY is MODULARITY: this is possible on the Moon

MOONRAY is designed as a closed packed array of towers



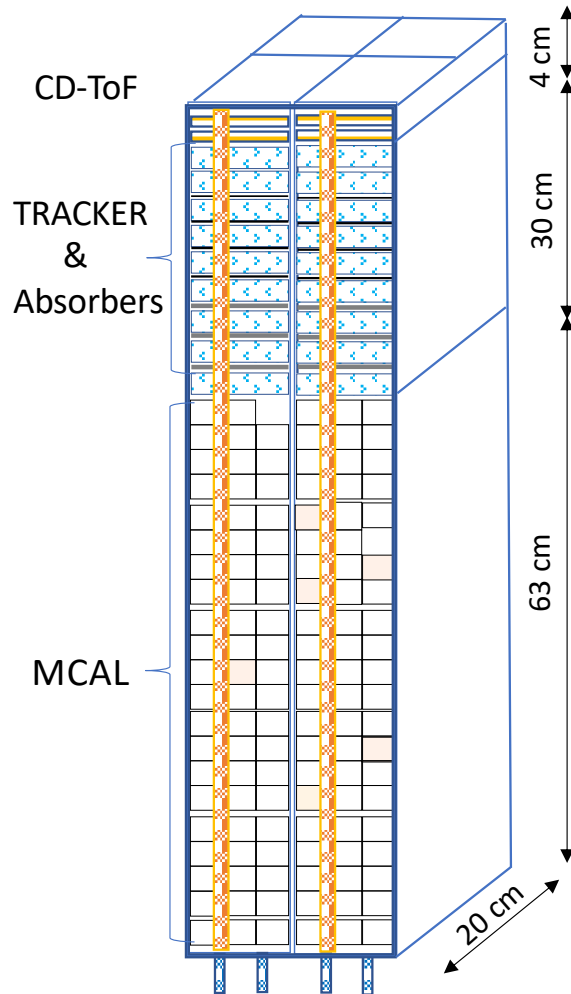
Showstoppers	spacecraft/ ISS in LEO	on the Moon
Power	severely limited (few KW)	👍 available for habitats and infrastructures
Volume	limited by spacecraft size (few m ³)	👍 instrument modules with limited volume (~0.2x0.2x1m ³)
Mass / launch	severely limited for single payload (few tons)	👍 instrument modules with limited mass (~200 Kg)
Temperature	radiators/heaters	👍 heaters + cold heat sink below regolith (insulator)
Observation time	< 10-20 yrs (typically)	👍 permanent installation: tens of years (in principle)
Installation	one go + commissioning	👍 progressive: multi-mission plan
Refurbishment	only possible with EVA on the ISS	👍 modules can be replaced/refurbished on site
Cost/kg	😓	😓😓



MOONRAY (exploded view)

- a LARGE array of fully independent modules (**towers**) with limited individual size and weight;
- gradual deployment of a progressively larger active volume over multiple space missions;
- collection of meaningful scientific data during the intermediate stages of the implementation;
- direct detection of charged cosmic rays and gamma rays above 1 GeV

MOONRAY TOWER - Concept



1 tower ~ 20cm x 20cm x 100 cm

Main Sub-detectors:

- ☐ ACD **Anti-Coincidence** Detector (not shown in this picture)
- ☐ CD-ToF **Charge Detector** and **Time-of-Flight**
- ☐ MT **Tracker** (Silicon Strip Detectors + absorbers)
- ☐ MCAL **Calorimeter** (homogeneous, 3D crystal array)

1 tower: ~20cm x 20cm x 100 cm (envelope)

MCAL: 6x6 crystals / layer

depth: 21 crystals => 63 cm ($55X_0$, 3λ)

1 tower: 6 x 6 x 21 = 756 crystals

tower mass dominated by MCAL: ~151.2 Kg (25.2 kg-moon) + tracker + W foils + r/o electronics + mechanics ~ **200 kg/tower (33.2 kg-moon)**

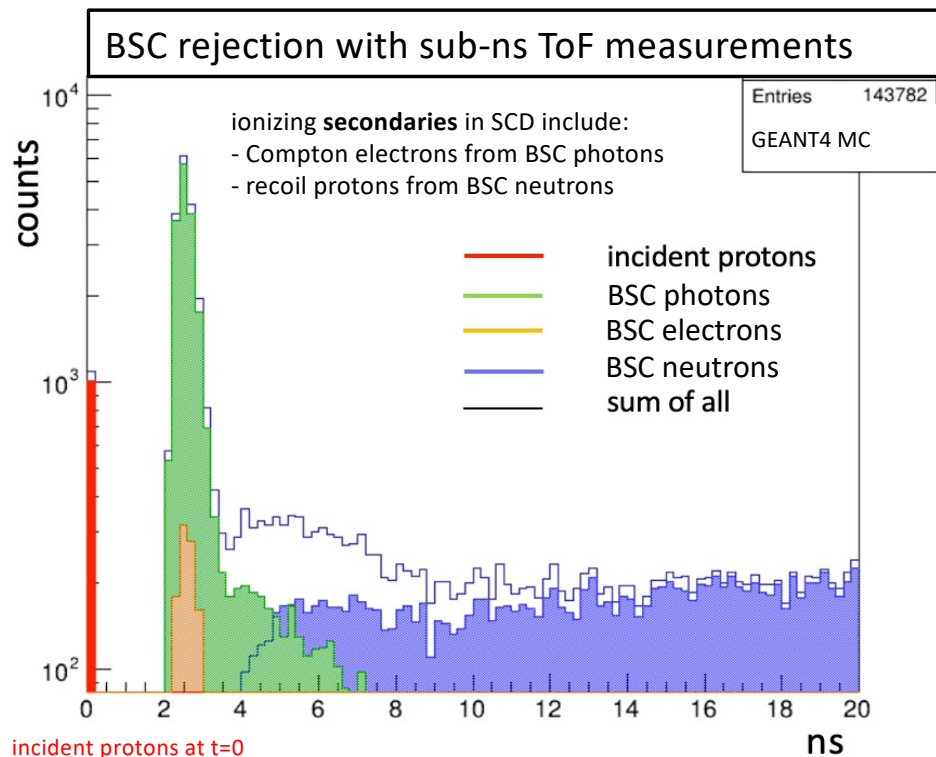
example: LYSO (Ce) 1 crystal: 3x3x3 cm³ 200gr

$\rho = 7.4 \text{ gr/cm}^3$ density

$\lambda = 21 \text{ cm}$ proton nuclear interaction length

$X_0 = 1.14 \text{ cm}$ radiation length

$R_M = 2.1 \text{ cm}$ Molière radius



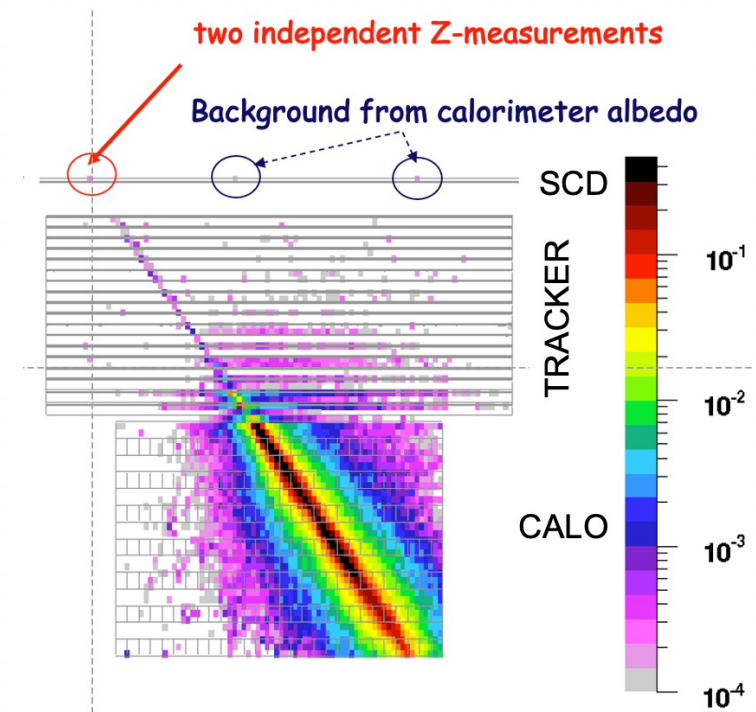
Arrival time (ns) of BSC from calorimeter on SCD with 30cm flight path

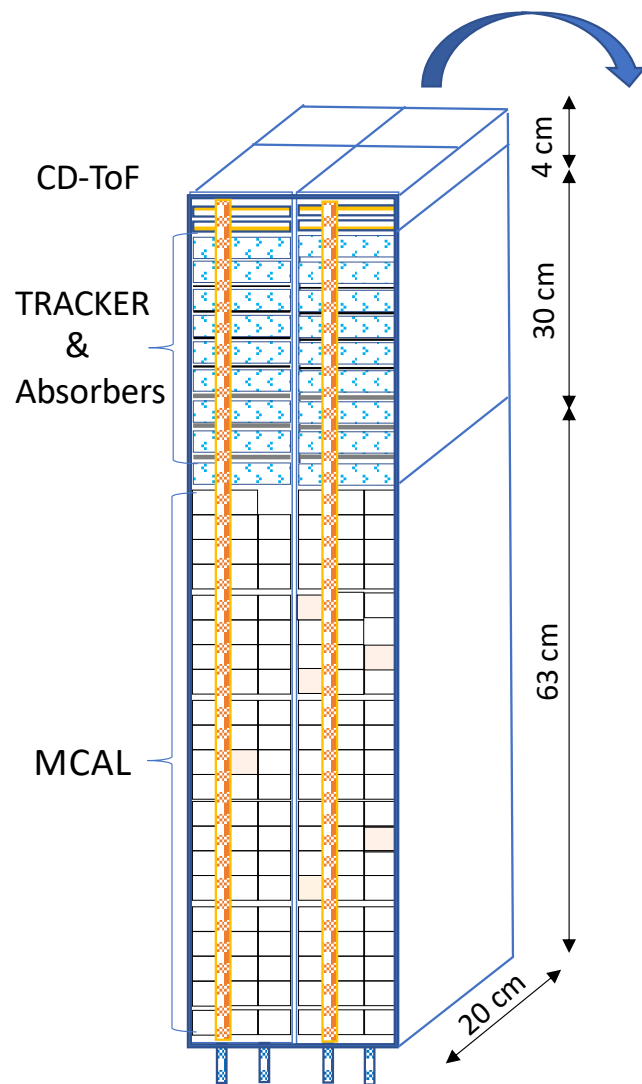
- large dynamic range > 1000 m.i.p
- 100 ps time resolution
- LGADS with large pixels (**3mm x 3mm**) to cover large $O(m^2)$ sensitive area
- independent TRACKER for fine track resolution
- challenging power budget < 150 W/m²
- modest Rad Hardness required in space < 10¹¹ 1 MeV neq

CHD-ToF

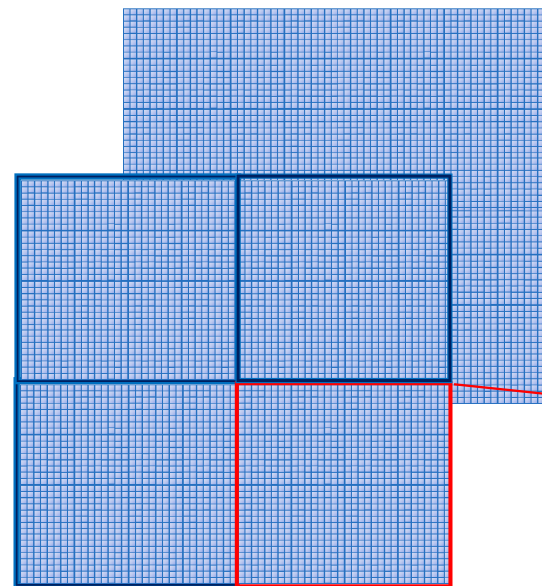
CHARGE IDENTIFICATION of cosmic-ray ions with charge $1 \leq Z \leq 30$ via multiple $dE/dx \propto Z^2$ in a pixelated sub-ns **Charge-ToF detector** (SCD)

Backscattering (BSC) from calorimeter generates fake hits in SCD and tracker, degrading charge-ID as energy increases.





1 tower ~ 20cm x 20cm x 97 cm



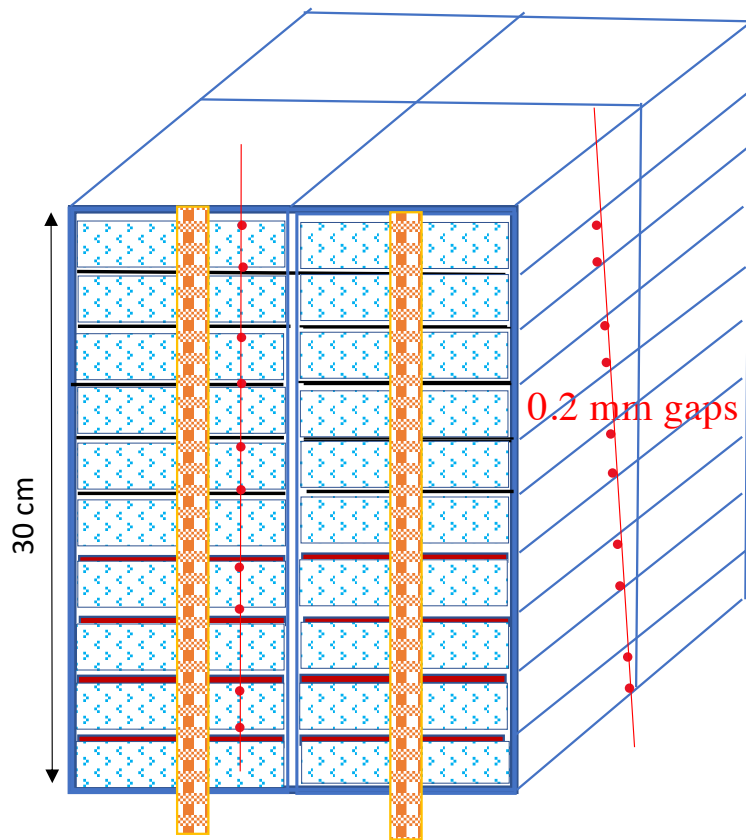
target: 100 ps
flight path ≥ 30 cm

CHD-ToF

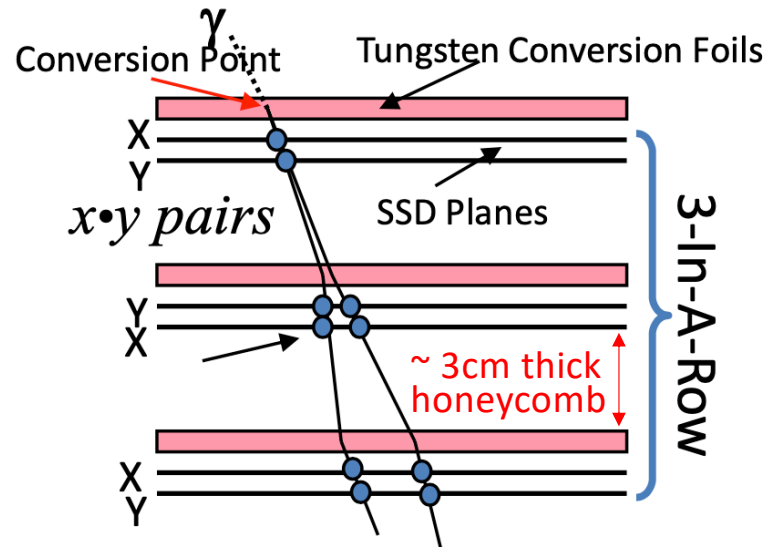
two layers of 2 x 2 tiles of LGAD arrays
3mm x 3mm LGADs
4096 LGADS / tower



TILE (9.6 cm x 9.6 cm): 256 FE ASICs
1 ASIC / 4 LGADs = 1024 LGADs



TRACKER



- Very similar to FERMI
- **Silicon Strip Detectors (SSD)**
8.95x8.95cm², 400 μm thick
pitch = 228μm
384 strips/ SSD

e[±] pair Opening Angle

$$\theta_{Open} \approx \frac{4m_e}{E_\gamma}$$

100 MeV $\Theta \sim 17$ mrad

1 GeV $\Theta \sim 1.7$ mrad = 0.1°

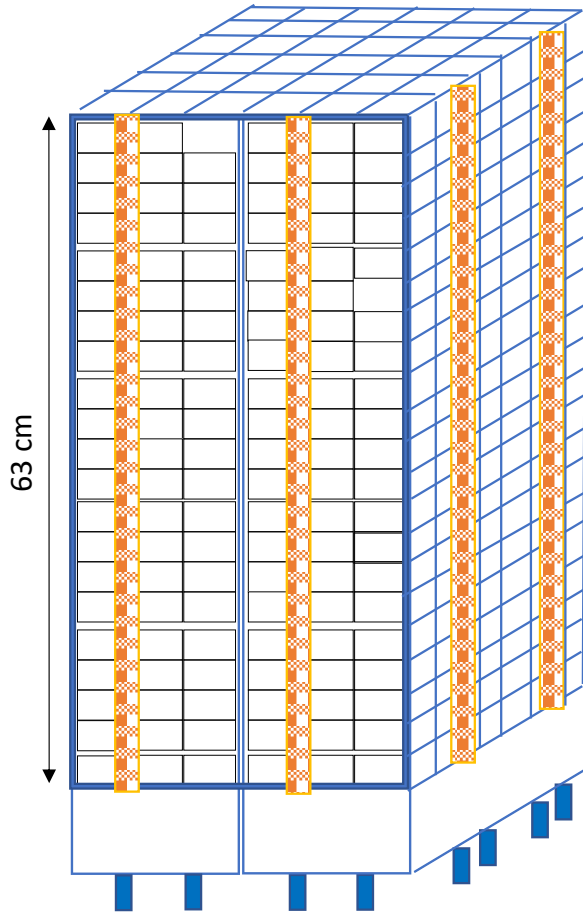
1 TeV $\Theta \sim 1.7$ μrad

=> above 1 GeV the e[±] pair appears as a SINGLE track

absorber	rad. length	volume/tile	absorber weight (g)
4 x 0.03cm W foils	0.12 X ₀	10x10x0.01 = 1 cm ³	77.2
4 x 0.18cm W foils	0.72 X ₀	10x10x0.072 = 7.2 cm ³	556
TOTAL	0.84 X ₀		633

MOONRAY absorbers
(100% W: 19.3 gr/cm³)

CALORIMETER (MCAL)



- Homogeneous calorimeter: 3D crystal array
- A good choice is LYSO crystals, though expensive
- Alternative solutions: BGO, CsI or Inhomogeneous calorimeter

LYSO (Ce) 1 crystal: $3 \times 3 \times 3 \text{ cm}^3$ 200gr

$\rho = 7.4 \text{ gr/cm}^3$ density

$\lambda = 21 \text{ cm}$ proton nuclear interaction length

$X_0 = 1.14 \text{ cm}$ radiation length

$R_M = 2.1 \text{ cm}$ Molière radius

1 crystal: $3 \text{ cm} \times 3 \text{ cm} \times 3 \text{ cm}$

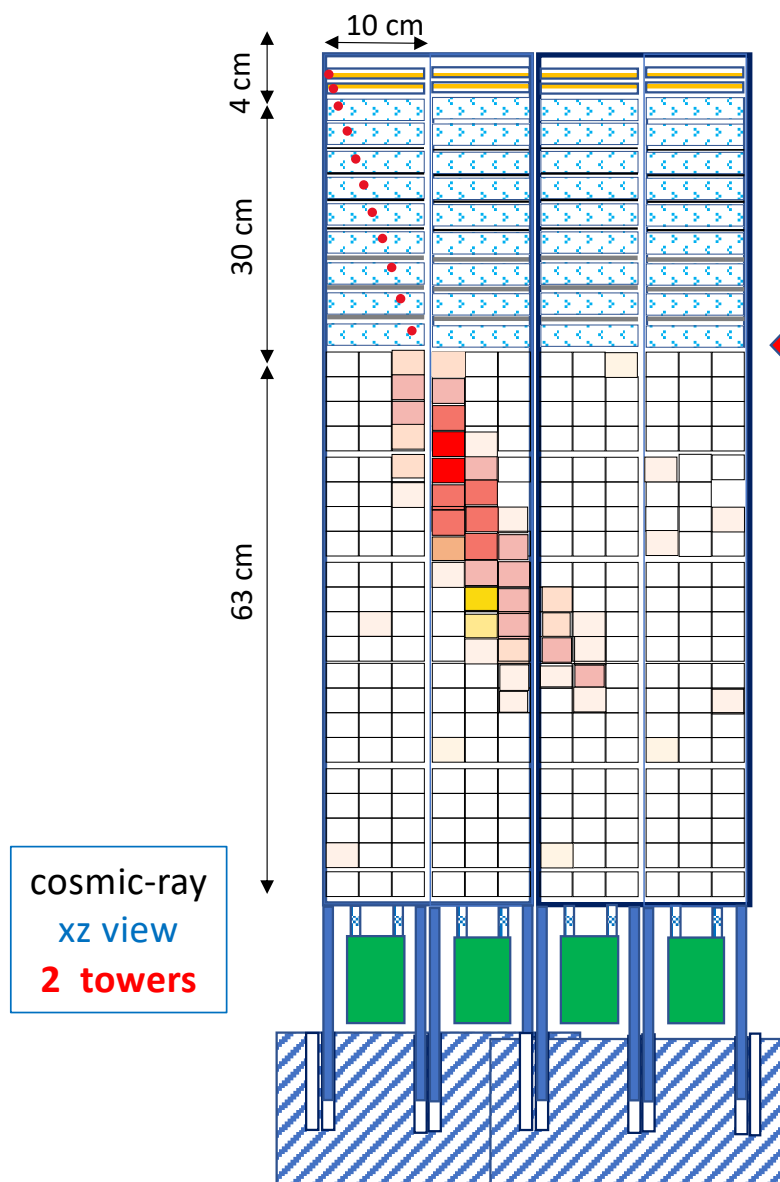
1 layer: 6×6 crystals $\Rightarrow 18 \text{ cm} \times 18 \text{ cm}$

depth: 21 crystals $\Rightarrow 63 \text{ cm}$ ($55X_0, 3\lambda$)

1 tower: $6 \times 6 \times 21 = 756$ crystals

151.2 Kg (25.2 kg-moon)

- Huge dynamic range (10^6) covered with a pair of small/large area PDs/crystal
- Direct optical coupling and/or via clear fibers (trigger)
- possibility to adapt the CD-ToF ASIC (3 ranges): under study
- possibility of dual readout with embedded Cherenkov cubes: under study

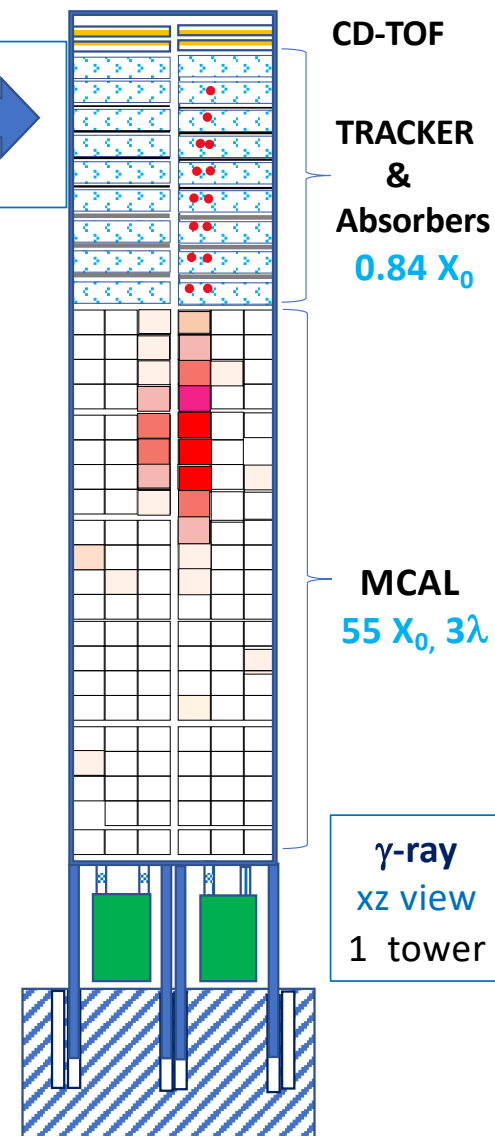


Artist's view of a 50 MeV photon
converting into an $e^\pm$ pair in one tower
(above 1 GeV the $e^\pm$ pair appears as a SINGLE track)

Artist's view of an electron shower
propagating into two adjacent towers

Modularization into slim towers calls for a
minimization of the inter-tower gap and of the
passive materials in the tower sidewalls.

In FERMI-LAT: the distance from the SSD
detector edge in one module to the detector
edge in the adjacent tower is only **15.9 mm**.
That includes the 2.5 mm gap between modules
and the 1.5mm thickness of each of the two
carbon-composite sidewalls.



LATERAL WALLS: (CD-ToF and Tracker modules)

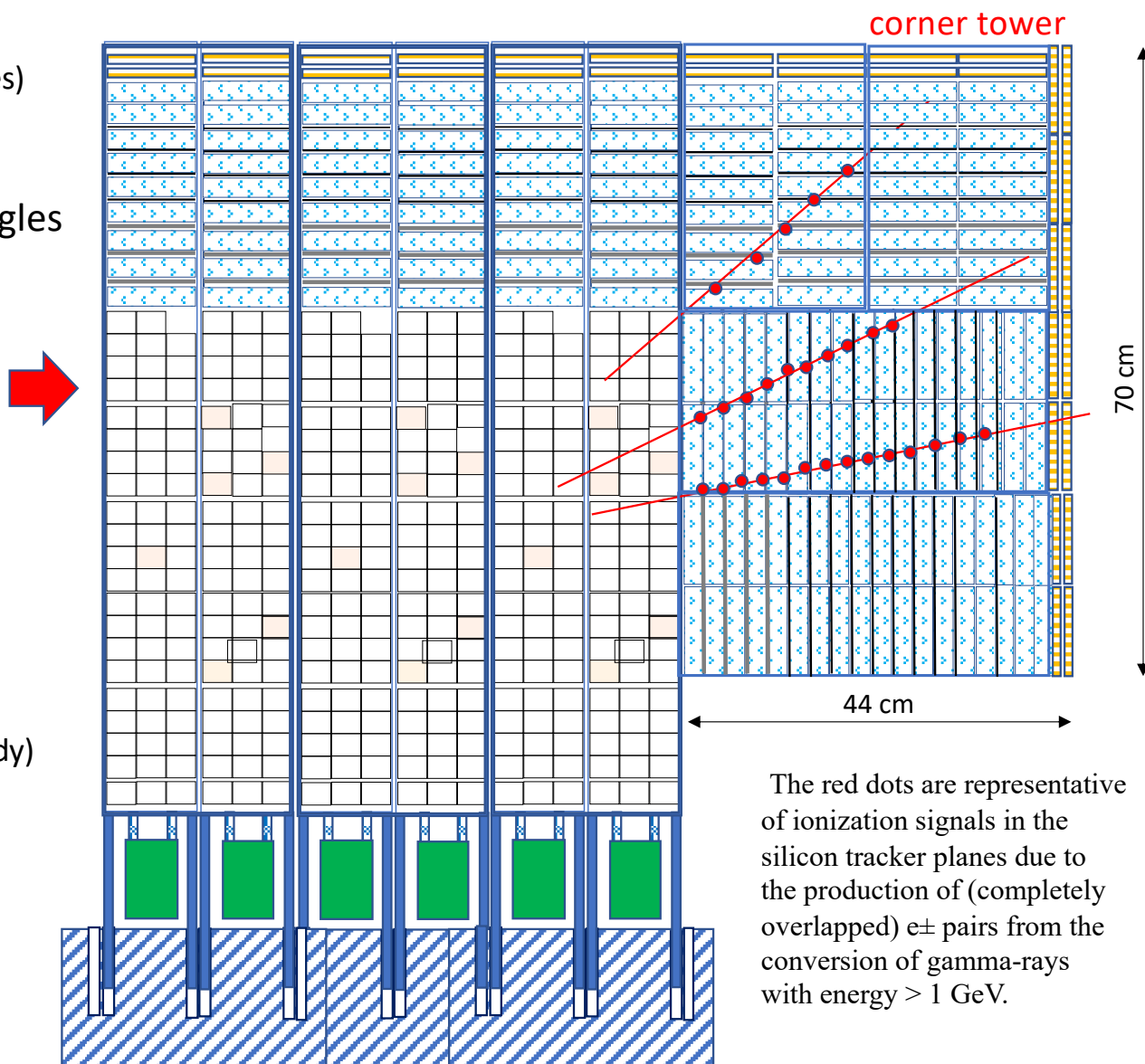
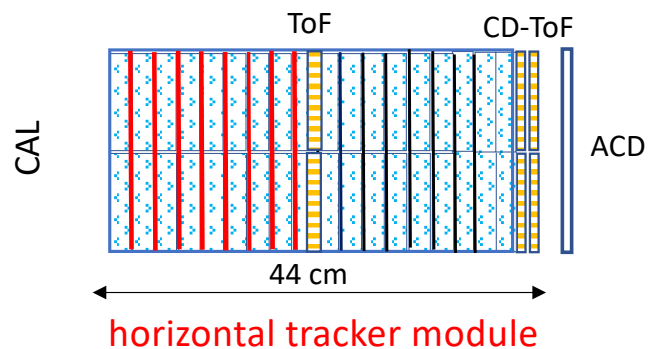
increase the acceptance

γ -ray detection down to small elevation angles

Artist's concept: cross-section of one of the "lateral walls" and its interface to a group of three towers of the central "core" of the telescope.
ACD paddles are not shown.

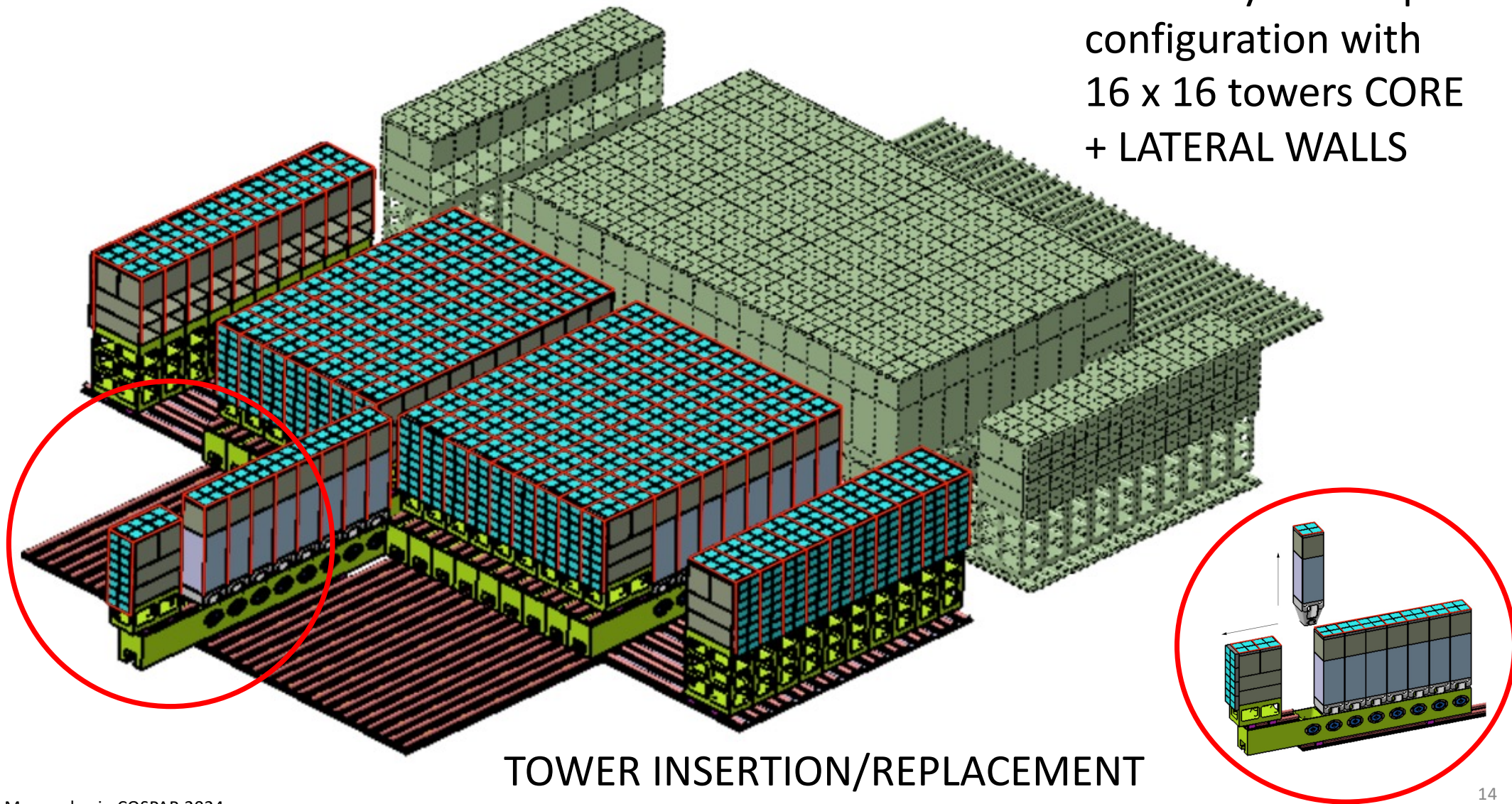
Two different **tracker module types**:

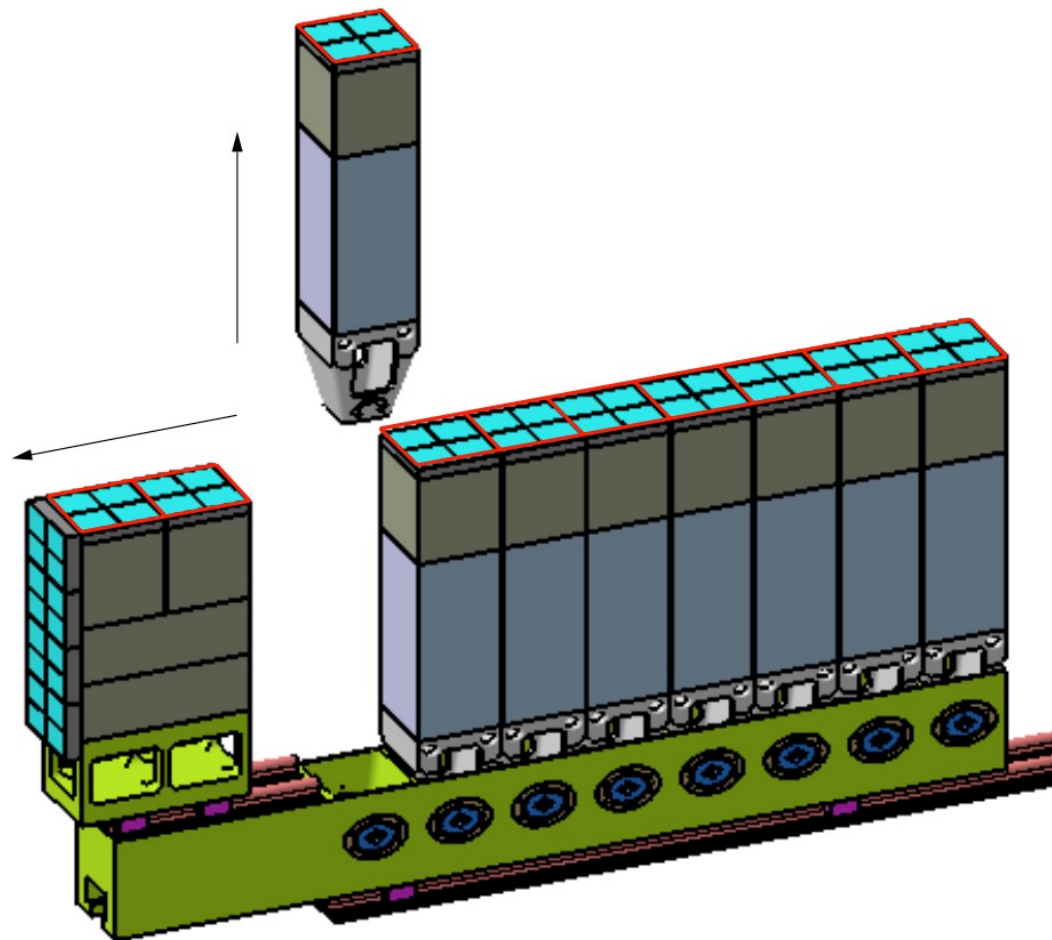
- "short" (~ 30 cm) for vertical and "corner" modules
- "long" (~ 44 cm) for horizontal tracker modules with 8 thick (tot $=1.4 X_0$) + 8 thin **W absorbers** ($0.24 X_0$)
- possibility to insert a ToF in the middle to improve the rejection of BSC in the tracker layers (under study)



Marrocchesi - COSPAR 2024

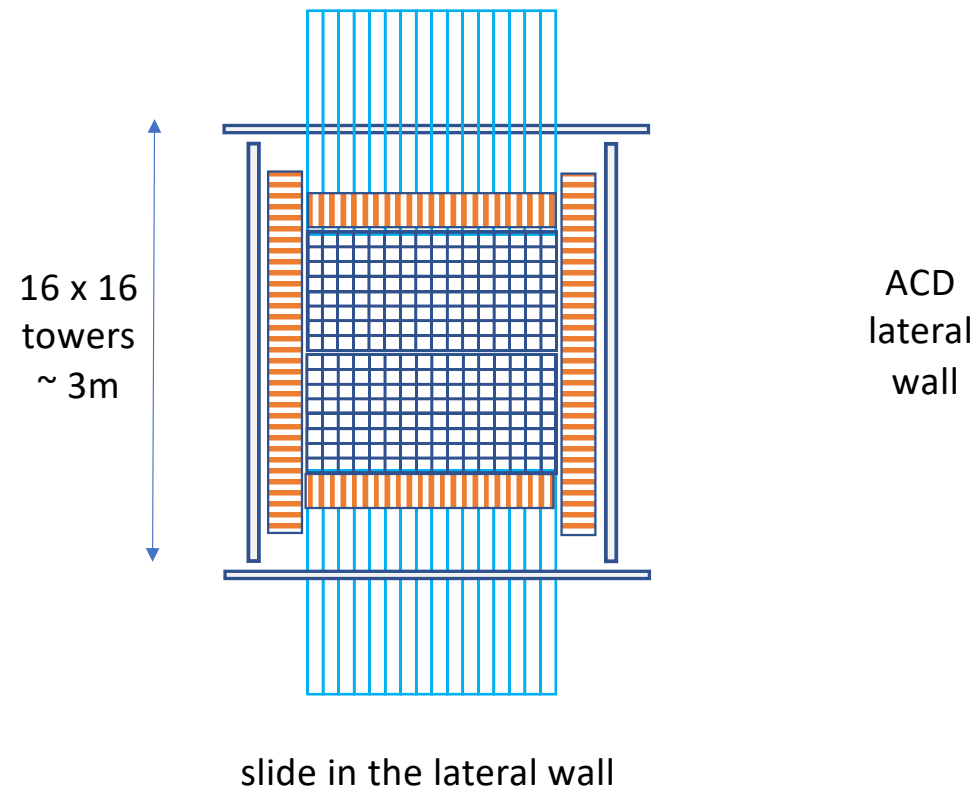
MoonRay telescope
configuration with
16 x 16 towers CORE
+ LATERAL WALLS



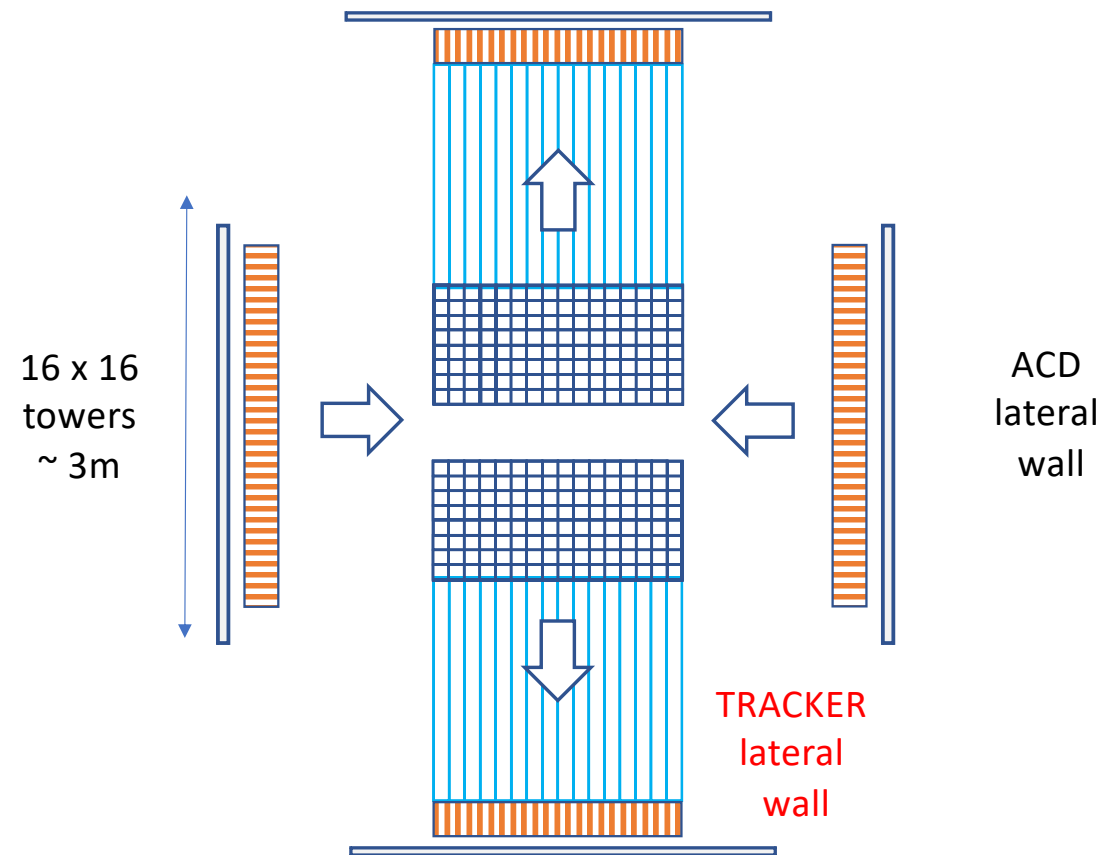


TOWER INSERTION/REPLACEMENT

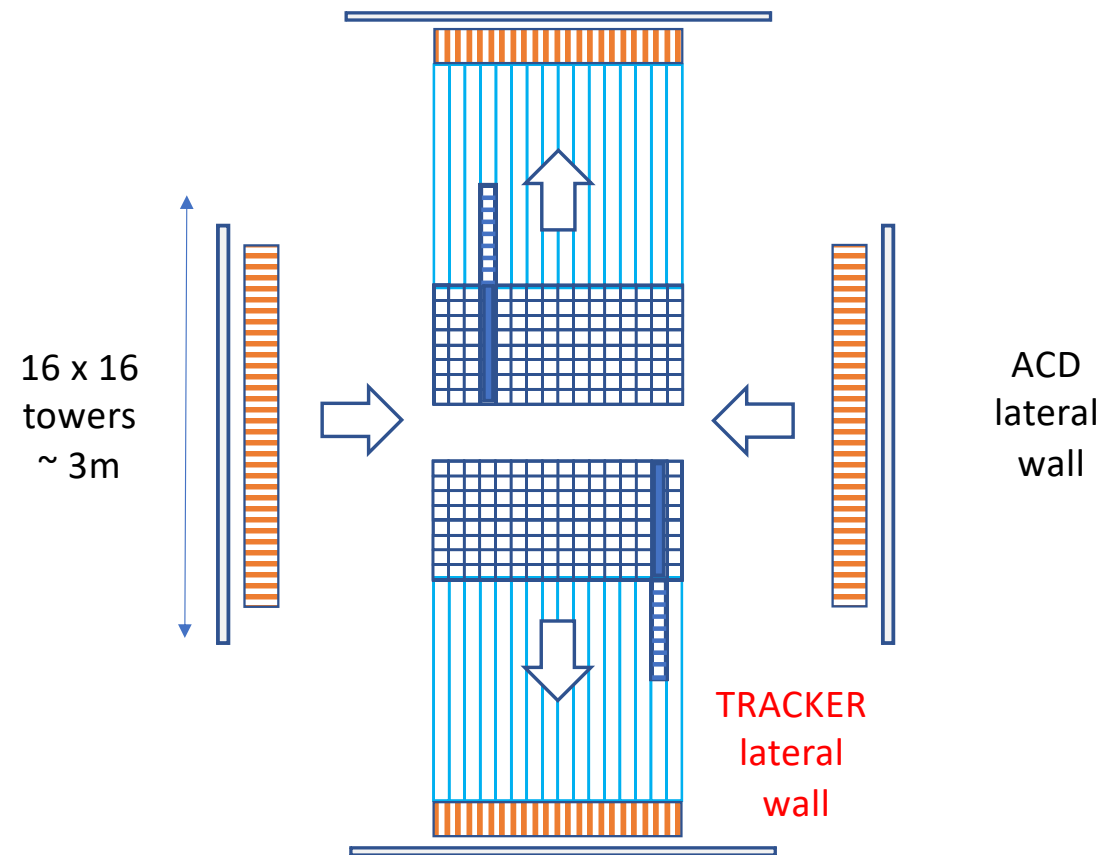
TOP VIEW



TOP VIEW



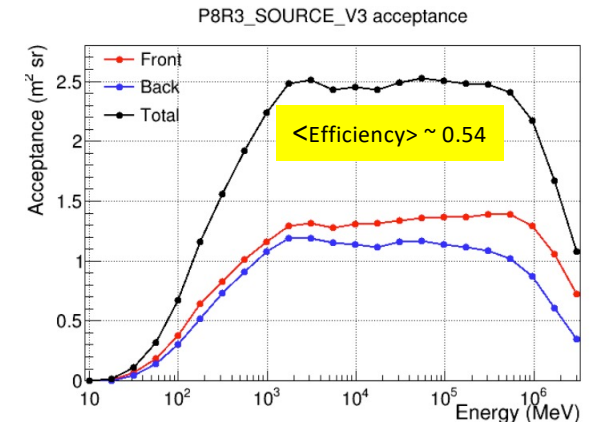
TOP VIEW



MOONRAY – Effective Geometric Factor (preliminary estimate)

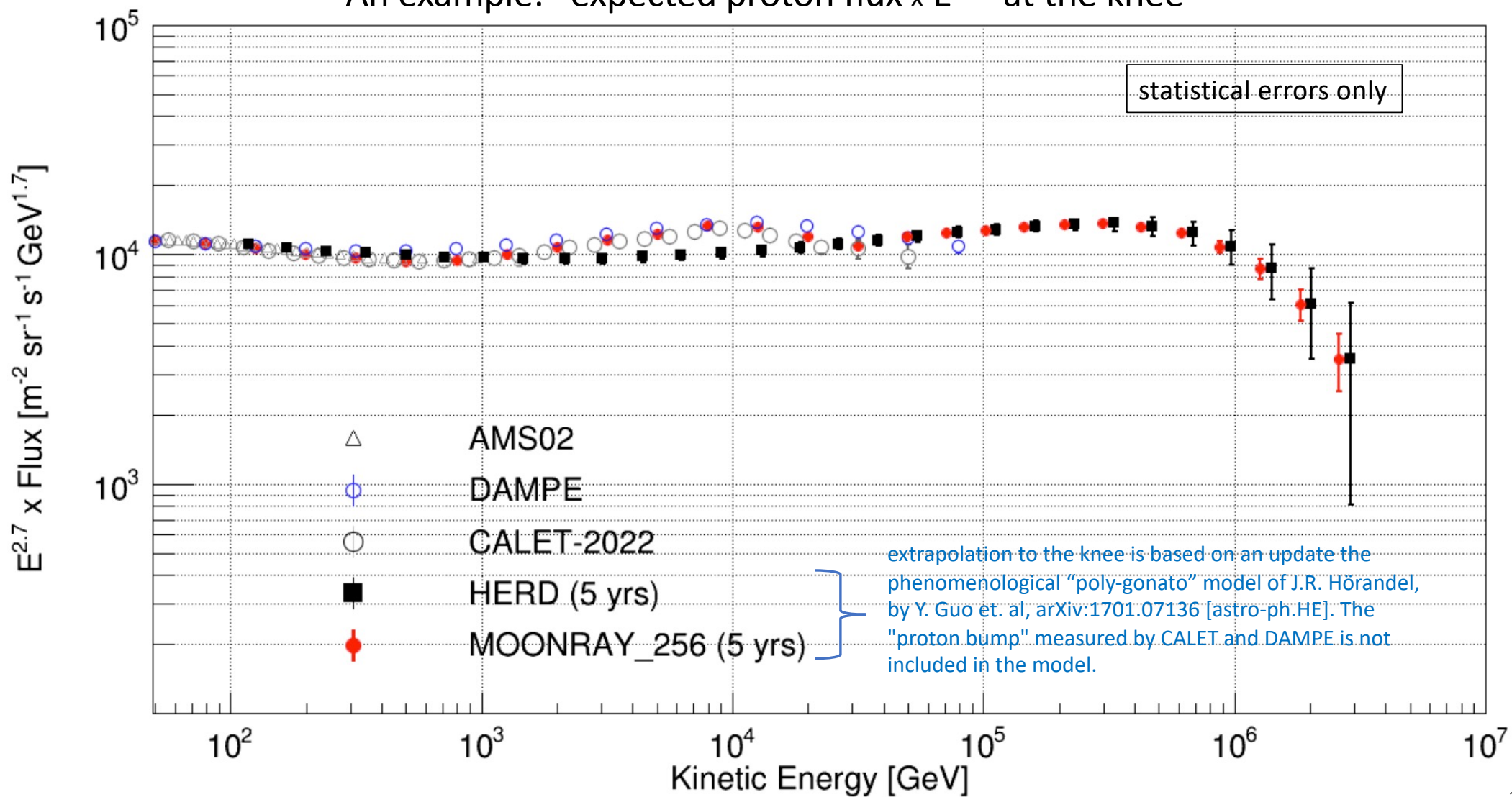
MOONRAY-100 10x10 towers	2x2x1 m ³	GF (m ² sr) (proton/electron)	GF _{eff} ^(a) (m ² sr) proton 100 TeV 55X ₀	GF _{eff} ^(a) (m ² sr) electron 100 TeV 30X ₀
TOP-DOWN (TD)	2x2	6.5/7.6	3.5	4.1
LATERAL (4 LT)	2x0.7	4.6/5.5	2.5	3.0
TOTAL (TD + 4 LT)		11.1/13.1	6.0	7.1

MOONRAY-256 10x10 towers	3.2x3.2x1 m ³	GF (m ² sr) (proton/electron)	GF _{eff} ^(a) (m ² sr) proton 100 TeV 55X ₀	GF _{eff} ^(a) (m ² sr) electron 100 TeV 30X ₀
TOP-DOWN (TD)	3.2x3.2	20.9/22.4	11.3	12.1
LATERAL (4 LT)	3.2x0.7	6.5/7.1	3.5	3.8
TOTAL (TD + 4 LT)		27.4/29.5	14.8	15.9



for comparison: **FERMI-LAT**
Effective GF = **2.5** m² sr (on axis)

An example: expected proton flux $\times E^{2.7}$ at the knee



A non-exhaustive list of physics targets for MOONRAY



VHE charged cosmic-rays:

- exploration of the "knee" with direct measurements (up to 10 PeV)
- **precision** assessment of p, He fluxes in the multi-TeV region;
- **precision measurements** of the fluxes and relative abundances of individual elements (primaries and secondaries);
- study of TeV electrons+positrons aiming at the identification of their sources;
- measurements of anisotropies;
- comparative studies of anomalous spectral features;
- abundances of ultra-heavy nuclei with $Z > 30$.

VHE gamma-rays:

- *continuous* detection of sources in the **Southern Sky**;
- identification of some of the FERMI unassociated γ -ray sources;
- study of "Hot Spots" in UHECR and in neutrinos (identified by AUGER and ICECUBE, respectively);
- study of the complex structure of the Galactic Centre (GC);
- search of PeVatrons;
- observations leading to improved models of diffuse emission;
- search for narrow γ -ray spectral peaks as possible signatures of DM annihilation.

MOONRAY: Effective Area for gamma-ray detection (on axis) – preliminary estimate

MOONRAY-100 10x10 towers (2m x 2m x 1m)	SSD Tiles	ϵ_{conv}	$\langle\epsilon\rangle_{\text{cuts}}$	Area _{eff} (m ²)
TOP-DOWN tiles (TD)	400	0.57	0.7	1.3
LATERAL tiles (LT)	4x80	0.81	0.7	1.6
CORNER tiles (CT)	4x80	0.57	0.7	1.0
TOTAL (TD + 4 LT + 4 CT)	1040			3.9

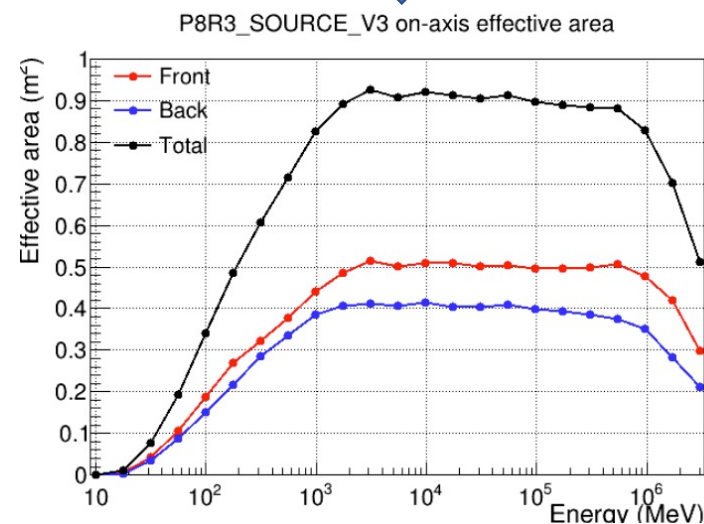
MOONRAY-256 16x16 towers (3.2m x 3.2m x 1m)	SSD Tiles	ϵ_{conv}	$\langle\epsilon\rangle_{\text{cuts}}$	Area _{eff} (m ²)
TOP-DOWN tiles (TD)	1024	0.57	0.7	3.3
LATERAL tiles (LT)	4x128	0.81	0.7	2.6
CORNER tiles (CT)	4x128	0.57	0.7	1.6
TOTAL (TD + 4 LT + 4 CT)	2048			7.5

for comparison:

FERMI-LAT (1.75m x 1.75m x 0.72m):

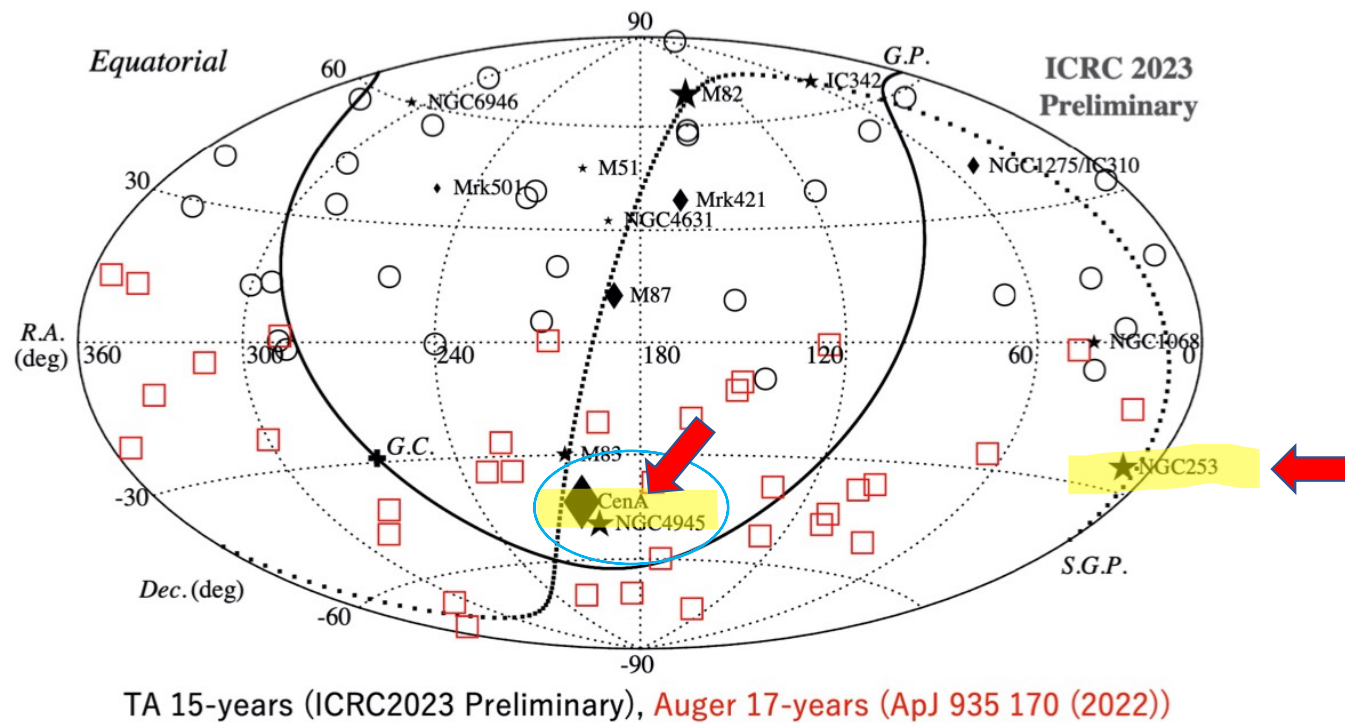
SSD sensitive area = 2.05 m²

=> **effective area = 0.9 m²** (on axis)

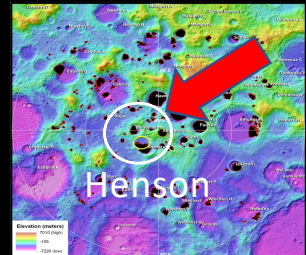
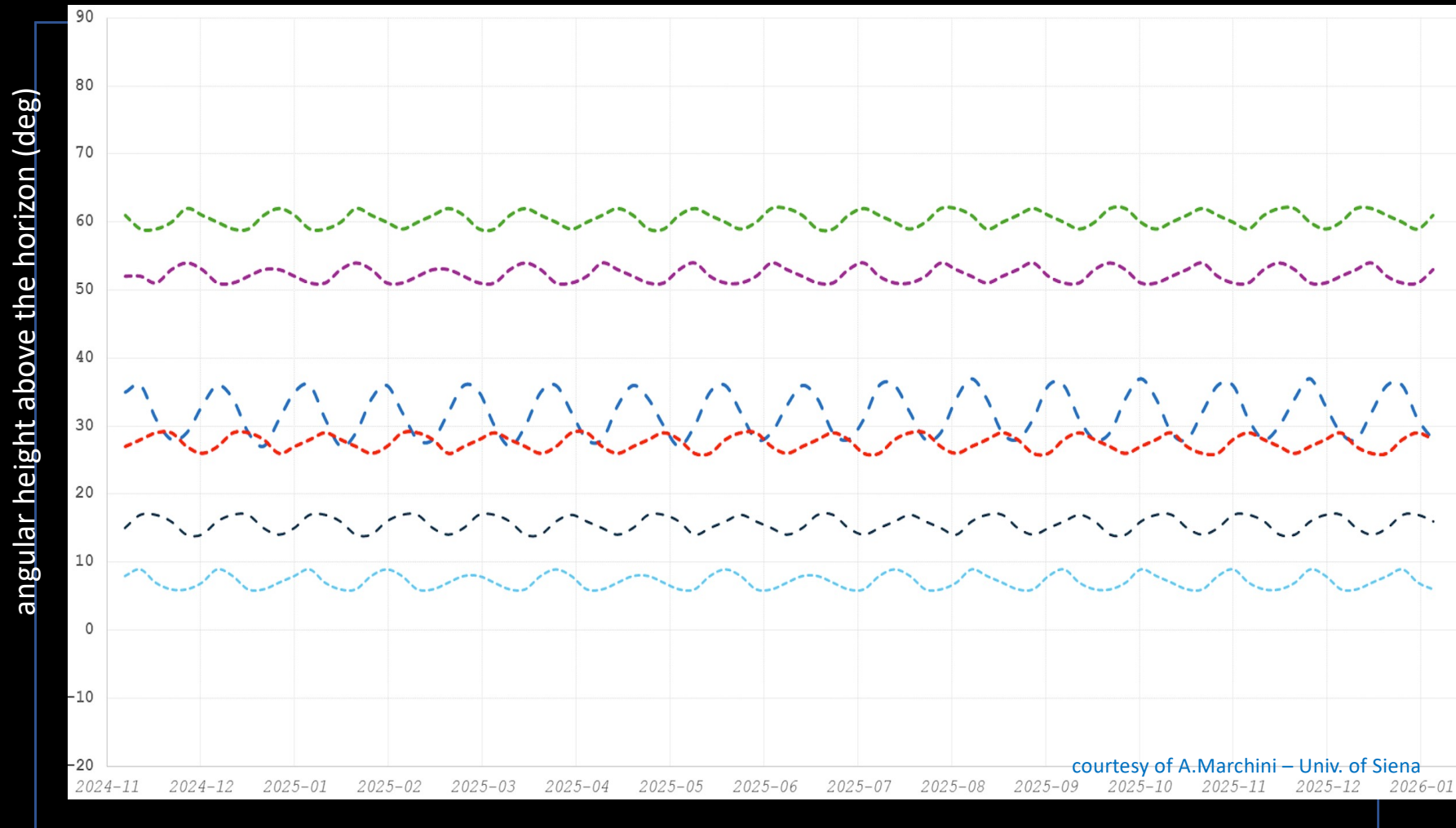


a factor ~8 larger than FERMI-LAT
+ on source duty cycle ~ 6 times larger

Chasing potentially interesting gamma-ray sources near the UHECR "Hot Spots"



Annual visibility at candidate site close to Henson crater (Moon South Pole@ 88.5°S, 129.6°W)



Vela
PSR B1259-63

Centaurus A
NGC 253

TXS 0506+056

Sgr A*

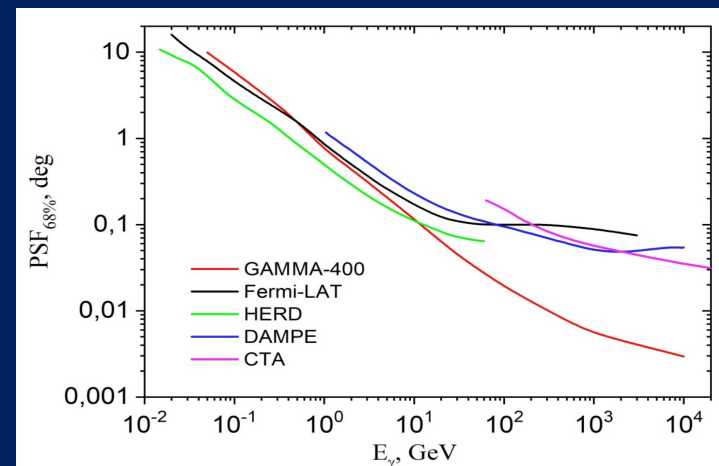
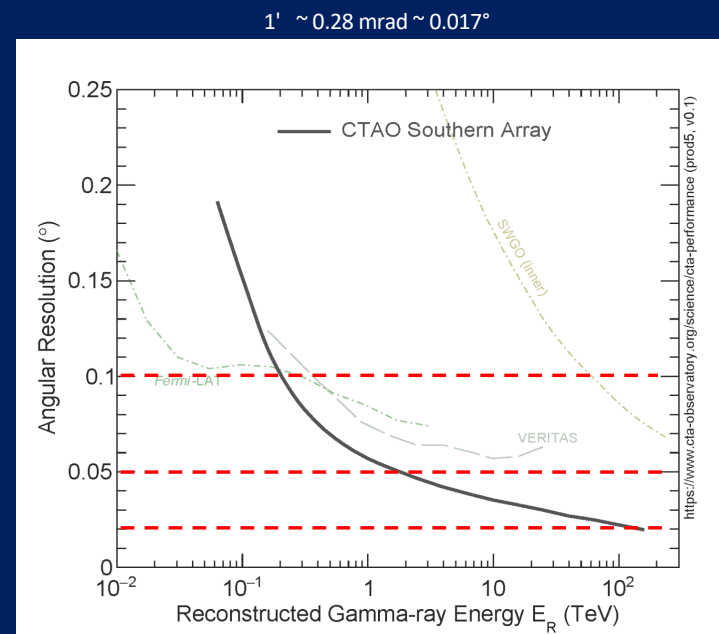
Angular Resolution & PSF

	100 GeV	1 TeV	100 TeV
FERMI	0.1°	0.08°	
CALET	0.1°	0.08°	
HERD	0.1°	0.05°	
MOONRAY	0.1°	0.05°	
CTAO South	0.15°	0.05°	0.02°
LHAASO	0.5°	0.2°	0.05°

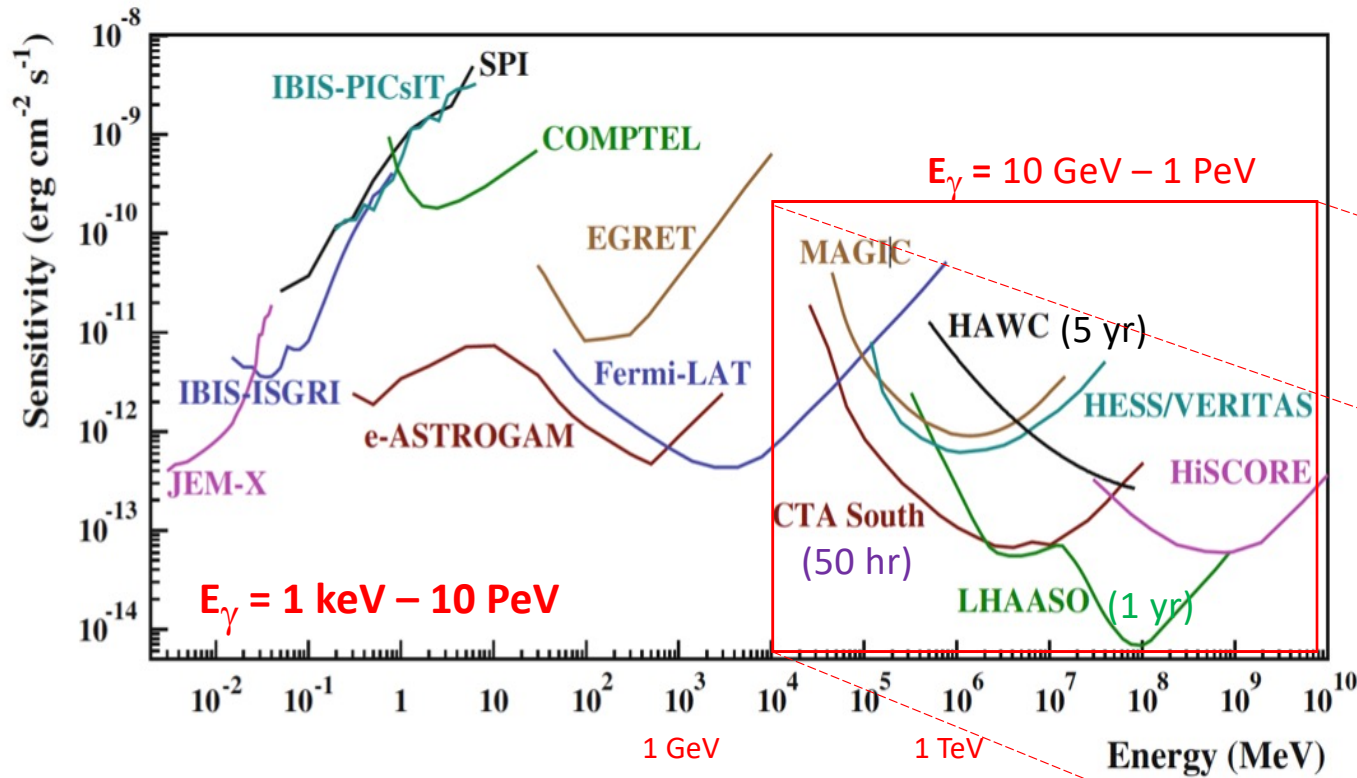
Energy resolution

MOONRAY: 1-2% for electrons above 10 GeV
(FERMI-LAT: 5-10% > 10 GeV)

~ 30% for protons
scales as $A^{-1/2}$ for nuclei



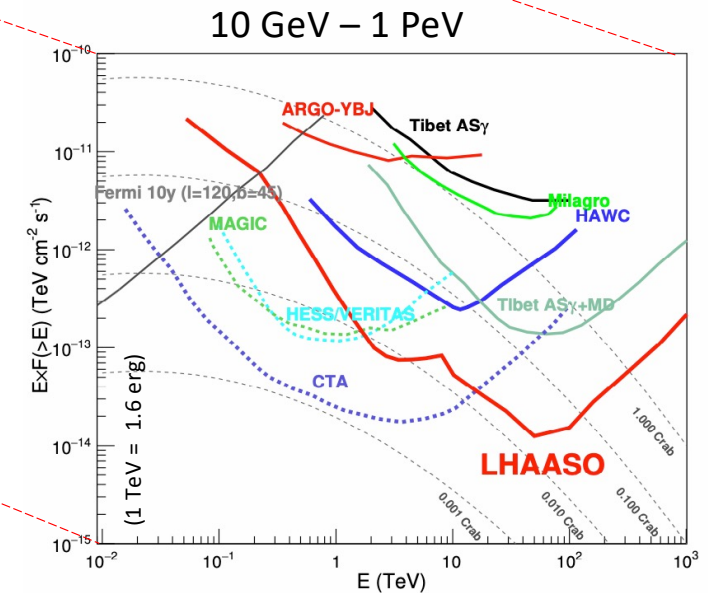
Observation of gamma-ray sources: Integral Sensitivity (5σ)



A. De Angelis, M.Mallamaci arXiv:1805.05642v3 [astro-ph.HE]

reference: FERMI-LAT Sensitivity @ 100 GeV
for short term observations (1 year) $\sim 10^{-11}$ erg cm $^{-2}$ s $^{-1}$

$S/B^{1/2} > 5\sigma$
with diffuse background
 $B = 1.5 \cdot 10^{-5}$ cm $^{-2}$ s $^{-1}$



Zhen Cao, et. al., Annu.Rev.Nucl.Part.S Vol. 73:341-363 (2023)

Source sensitivity

	FERMI	MOONRAY_100	MOONRAY_256	HERD	CTAO-South
Duty Cycle	15% ^(a)	>95%	>95%	80-90%	10-15%
A_{eff} (m ²) ^(b) @ 100 GeV	0.9	3.9	7.5	TBC ^(c)	tens –hundreds ^(d)
Angular resolution @ 100 GeV	0.1°	0.1° - 0.14°	0.1° - 0.14°	0.1°	0.15°
Energy resolution @ 100 GeV	5-10%	1-2%	1-2%	1-2%	20-25%
ST Sensitivity ^(e) (erg cm ⁻² s ⁻¹) @ 100 GeV	~10 ⁻¹¹	~10 ⁻¹²	~5x10 ⁻¹³	^(c) ~10 ⁻¹²	2x10 ⁻¹³ - 2x10 ⁻¹⁴
LT Sensitivity ^(f) (erg cm ⁻² s ⁻¹) @ 100 GeV	~10 ⁻¹²	~10 ⁻¹³	~5x10 ⁻¹⁴	^(c) ~2x10 ⁻¹³	
Sensitivity gain vs FERMI @ 100 GeV	1	10.9	21	^(c) O(10)	O(10-10 ²)

^(a) FERMI-LAT duty cycle for on-source observations: 11%-17% in all-sky survey mode

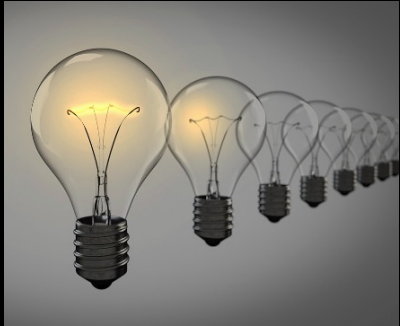
^(b) $A_{\text{eff}} = A_{\text{sens}} \times \text{Efficiency}$

^(c) depends on the final HERD configuration. Expected to increase with energy and reach several m² at around 1 TeV.

^(d) tens of m² at around 100 GeV (Large-Sized Telescopes), hundreds of m² at around 1 TeV (Medium-Sized Telescopes)

^(e) estimated for **short term (ST)** observations (1 year) as $S/B^{1/2} > 5 \sigma$ with diffuse background $B = 1.5 \cdot 10^{-5} \text{ cm}^{-2} \text{ s}^{-1}$

^(f) estimated for **long term (LT)** observations (10 years)



POWER CONSUMPTION (1st order estimate)

INSTRUMENT ONLY

	power/chn (mW)	total chns M_100/M_256	MOONRAY_100 (W)	MOONRAY_256 (W)
CHD-TOF	2.0	0.81M/2.0M	1640	4198
TRACKER	0.18	1.38M/3.5M	250	640
MCAL (756/tower)	0.28	75.6K/193.5K	210	542
Tot Instrument Power (W)			2100	5380
TRIGGER (estimate)			24	61
Power Supply (estimate)			176	450
TOTAL			2300	5891

FIRST-ORDER ESTIMATE < 6kW (instrument) + THERMAL CONTROL (heaters, etc...)

Conclusions:

MOONRAY is a proposed *modular* telescope at the South Pole of the Moon:

VHE cosmic rays:

- up to 256 towers (3.2 m x 3.2 m x 1m) + 4 lateral walls
- Geometric Factor: $\sim 30 \text{ m}^2\text{sr}$
- Effective Acceptance: up to $16 \text{ m}^2\text{sr}$
- can explore the knee up to 10 PeV

VHE gamma rays:

- Effective Area: $\sim 8 \times \text{FERMI-LAT}$
- Duty Cycle $> 95\%$
- can study γ -ray sources down to a few degrees above the horizon

more details can be found in the paper:

[P. S. Marrocchesi, Astroparticle Physics 152 \(2023\) 102879](#)

