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Studies on Particle Energy and Directionality of the SAA Radiation Environment using the LIDAL detector

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26th WRMISS in Rome, 5 – 7 September 2023

ASI

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Space Radiation Environment

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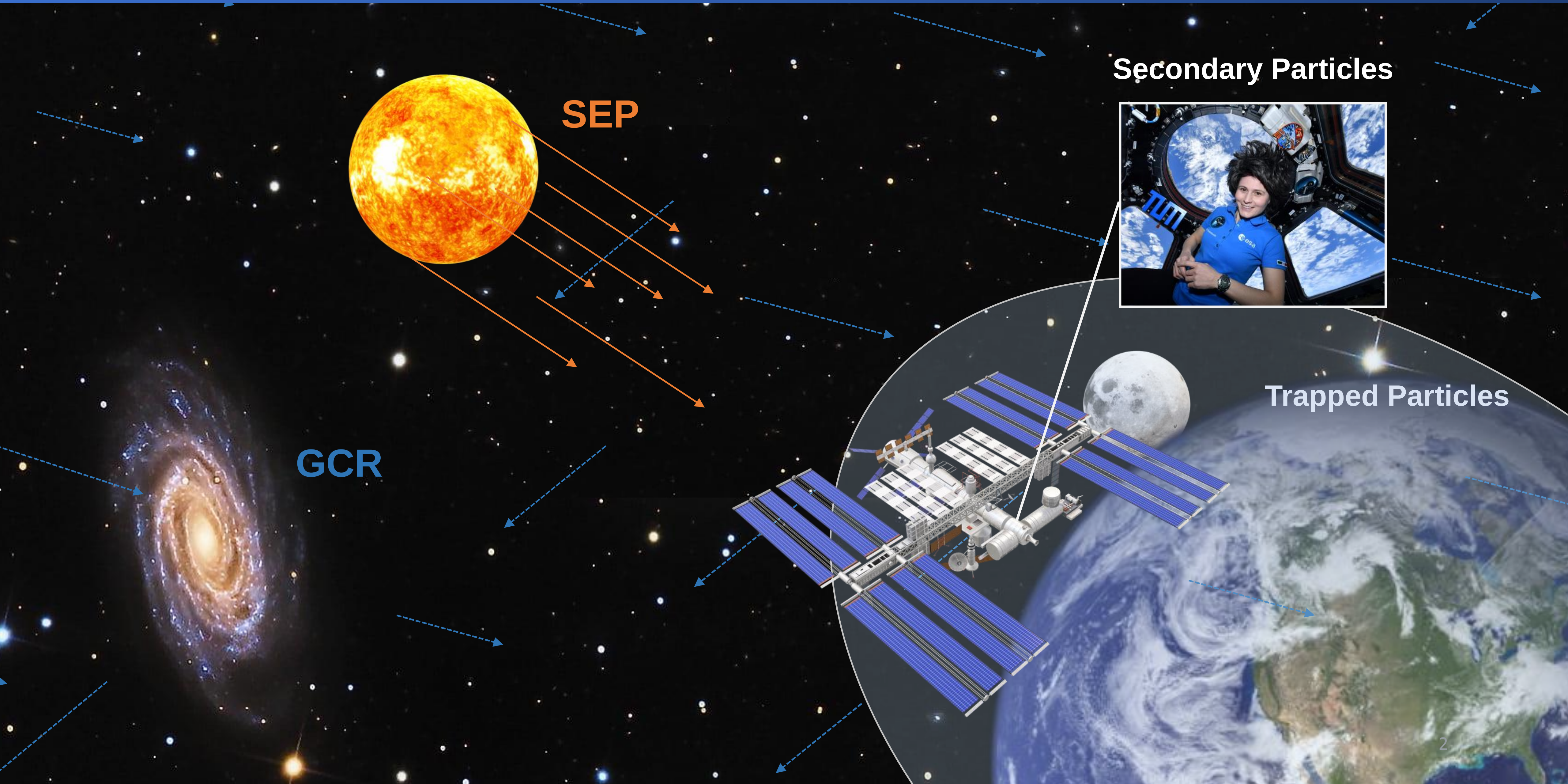
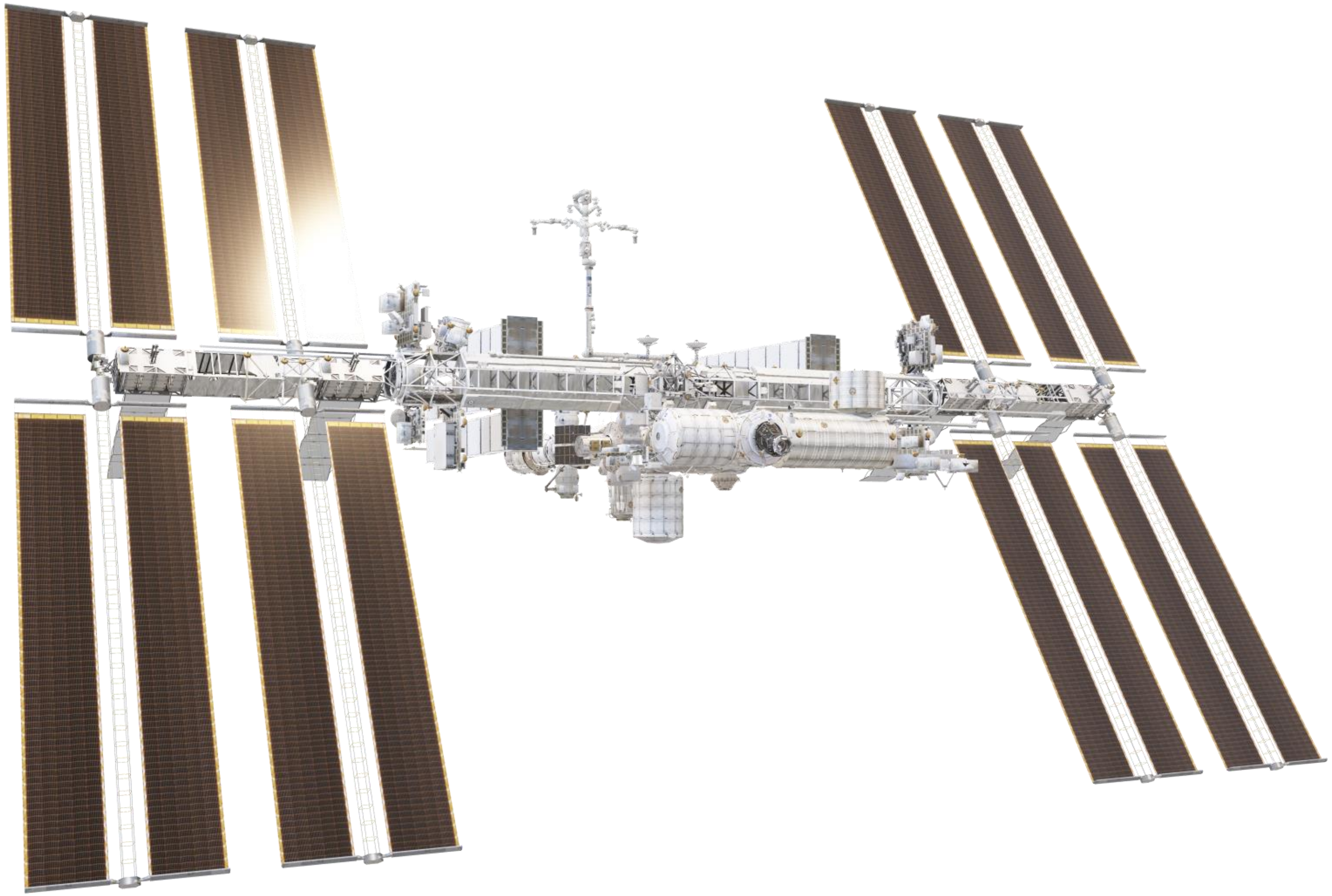
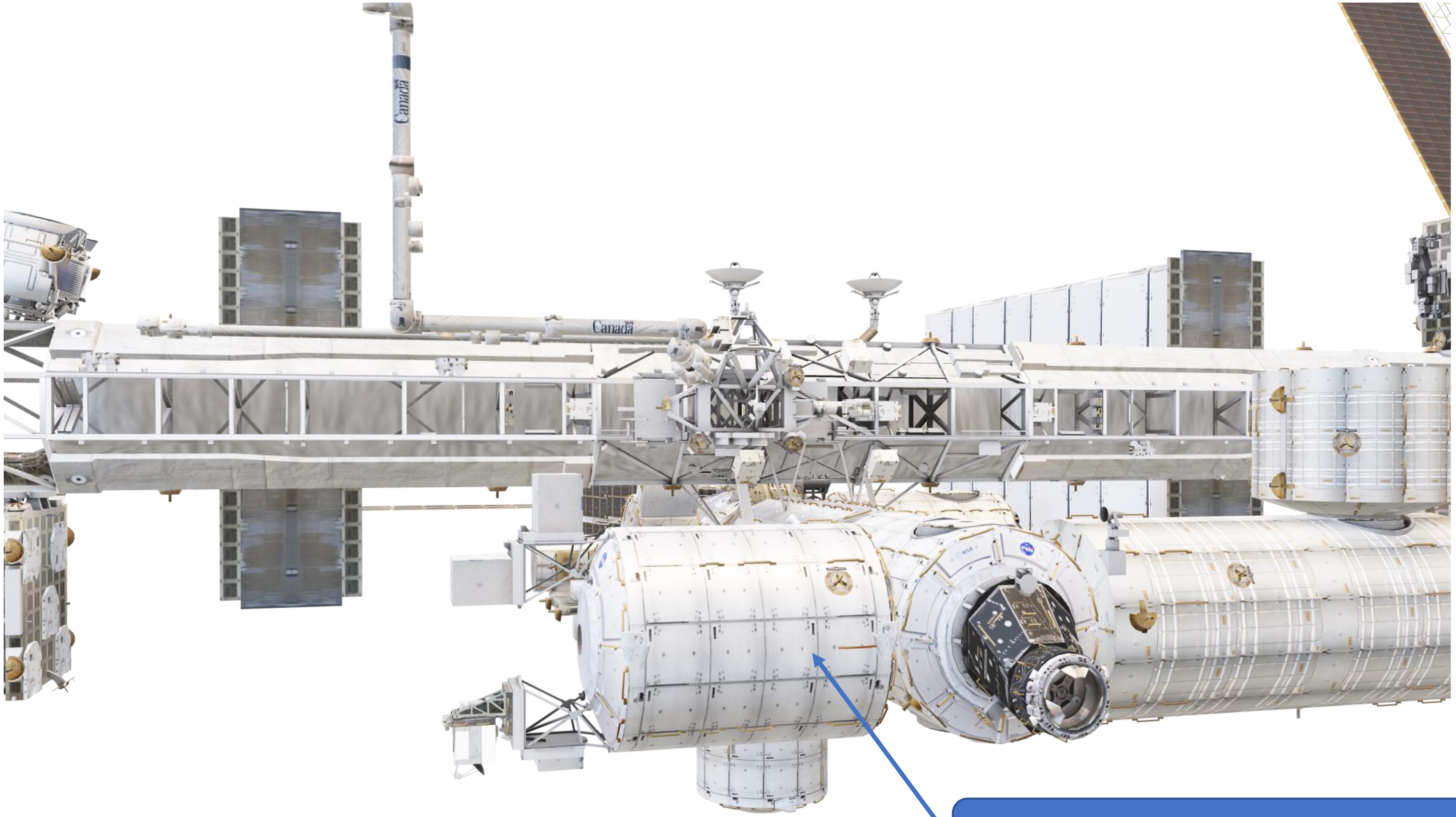


International Space Station

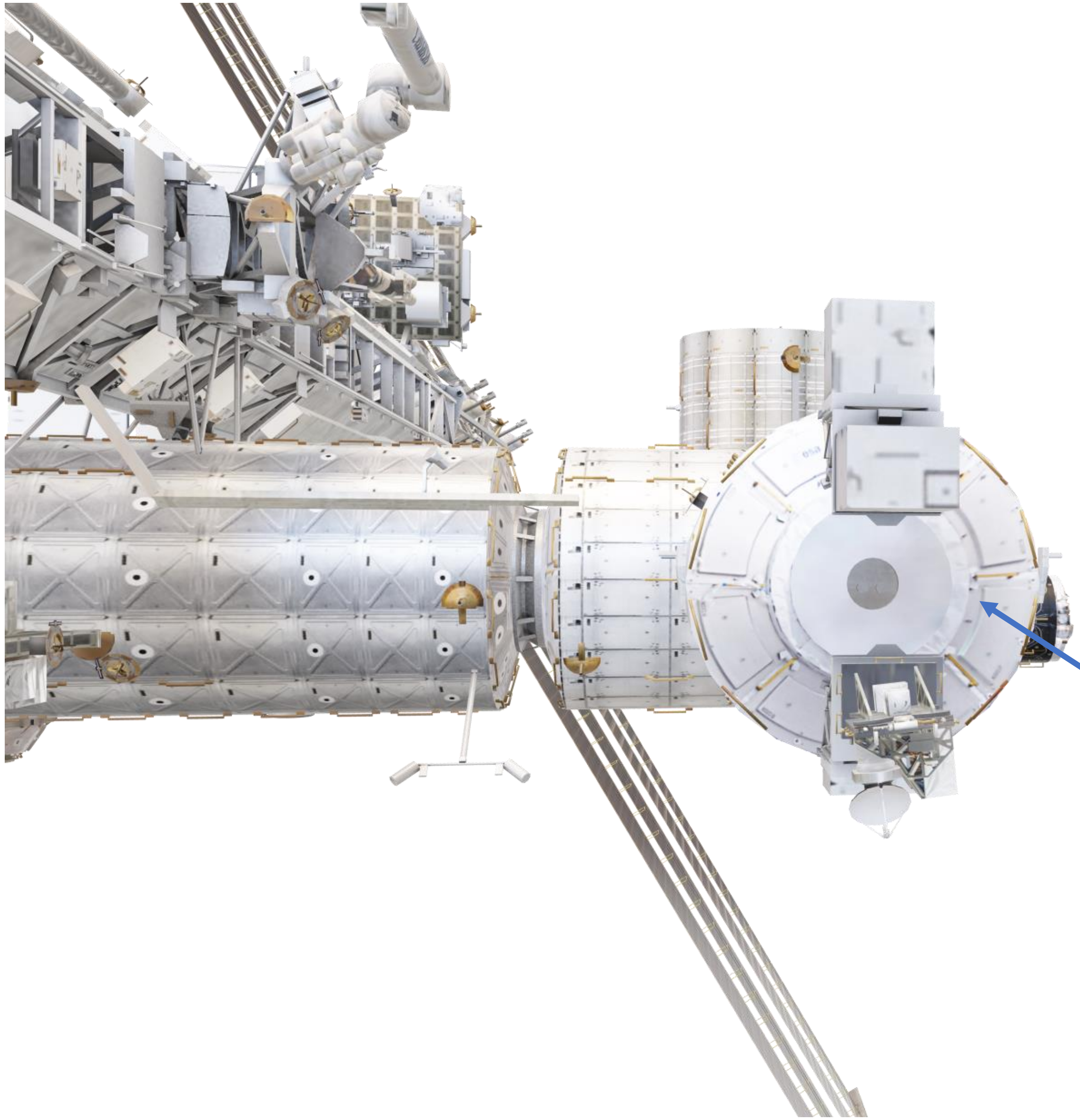


International Space Station



Columbus Module Front View

Columbus Module



Columbus Module Side View

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Columbus Module - Interior

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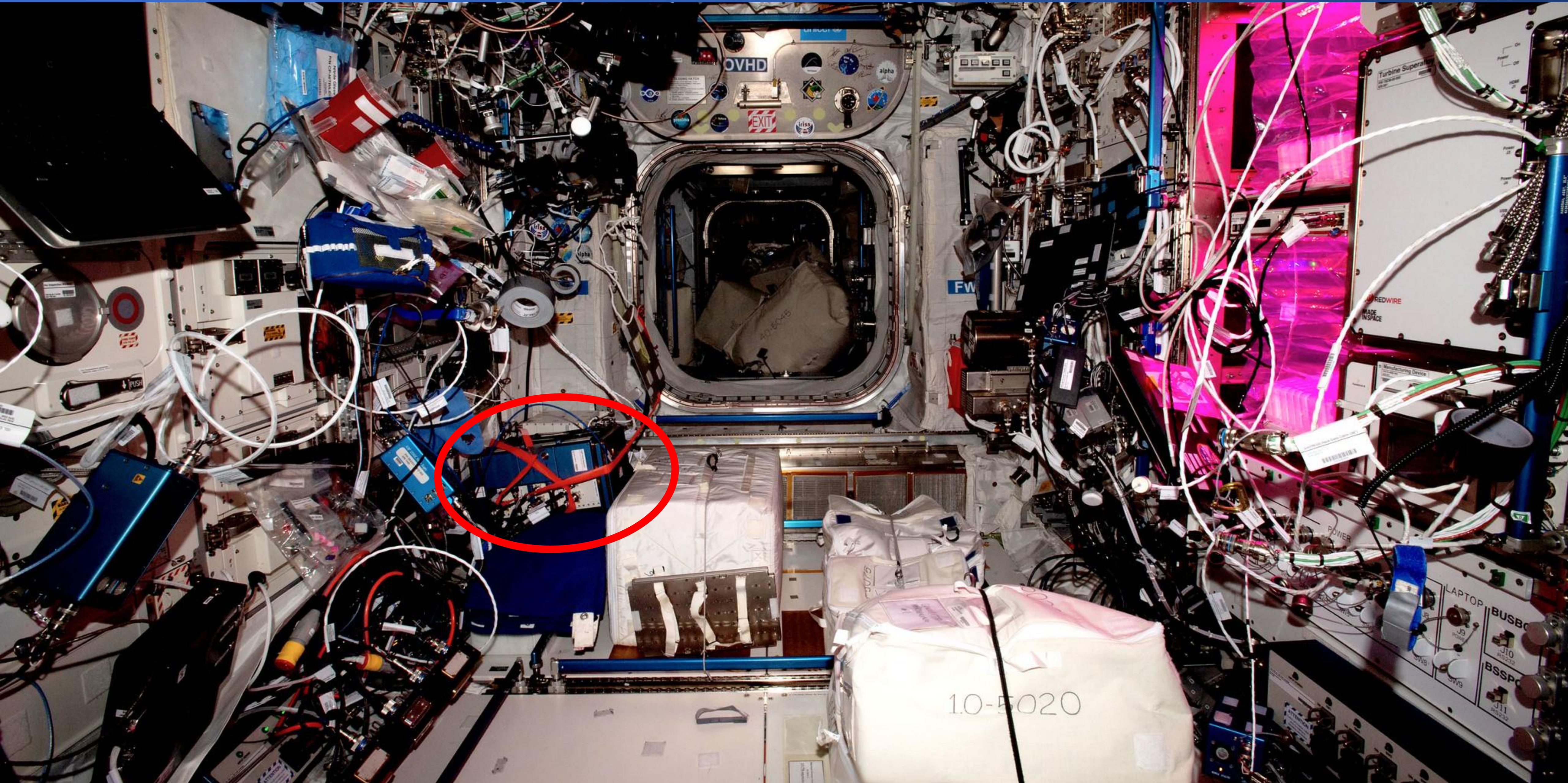
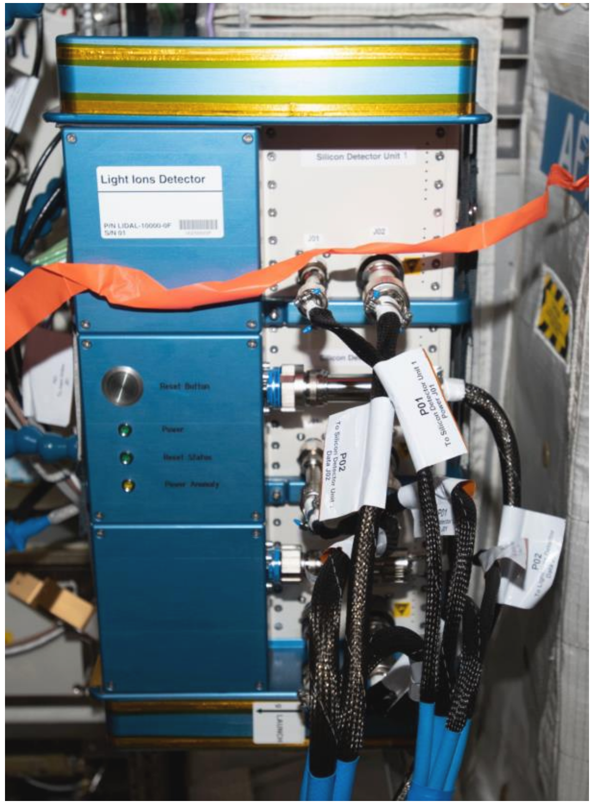
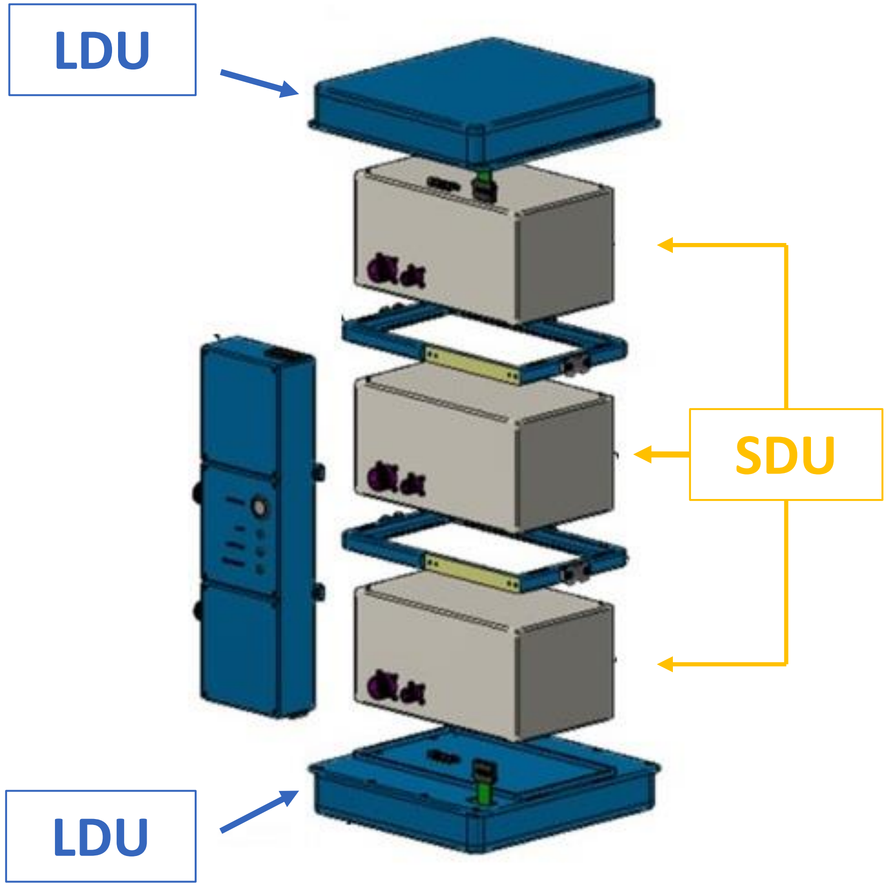


Light Ion Detector for ALtea (LIDAL)

Operative between January 2020 and, at least, 2024



LIDAL detector on board the ISS



Scheme of LIDAL system

SDU (ALtea Silicon Detector Unit)

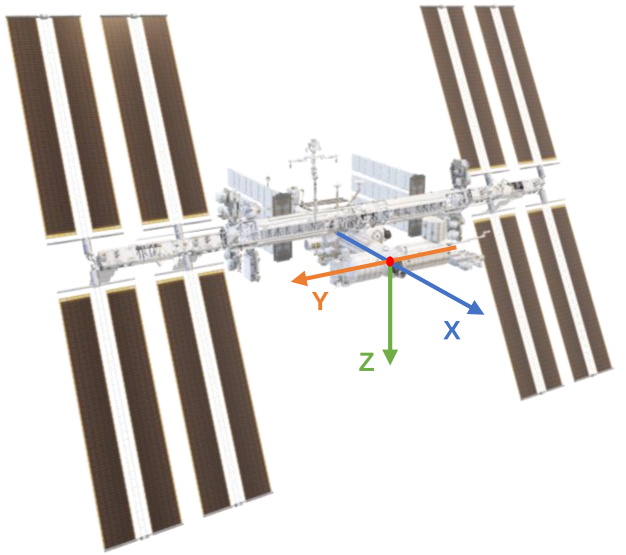
- 6 Silicon planes
- LET measure
- Particle tracking
- Self-trigger at 3 keV/µm

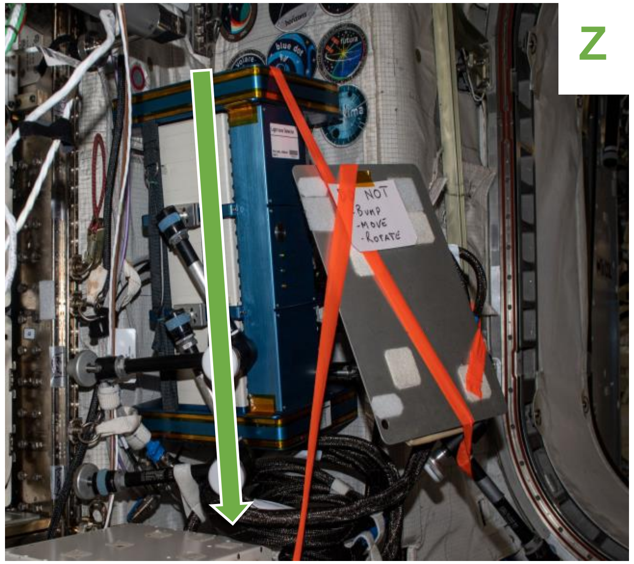
LDU (LID Detector Unit)

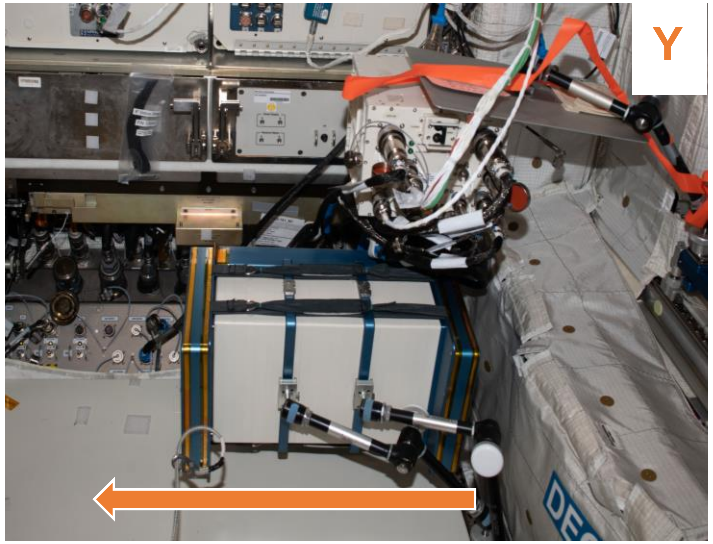
- 8 Plastic scintillators
- Time of Flight (70 ps) measure
- Particle tracking
- SDU under threshold measurements (2.3 keV/µm)

LIDAL System

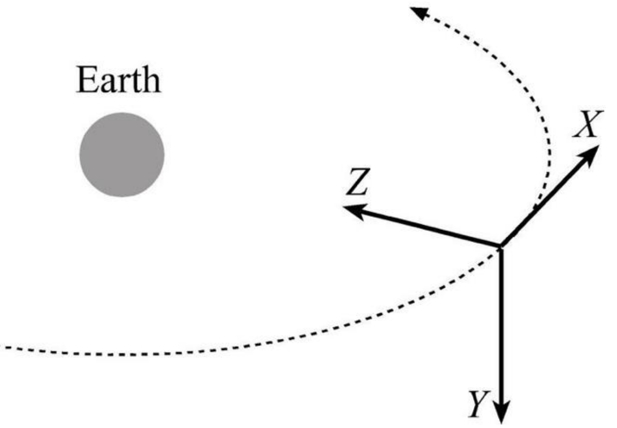
LIDAL along the 3 directions in the **Columbus** module

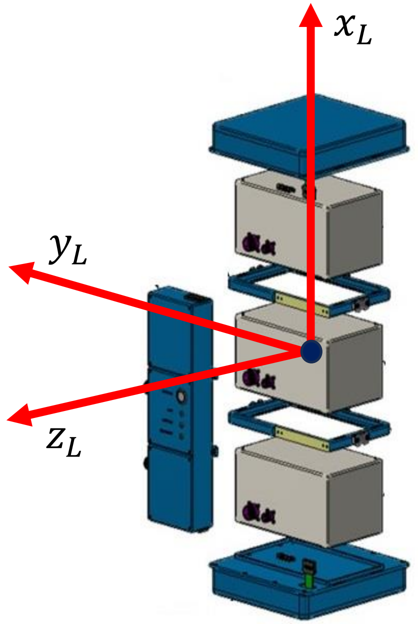






LVLH Reference Frame of the **ISS**





LIDAL Reference Frame

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LIDAL System

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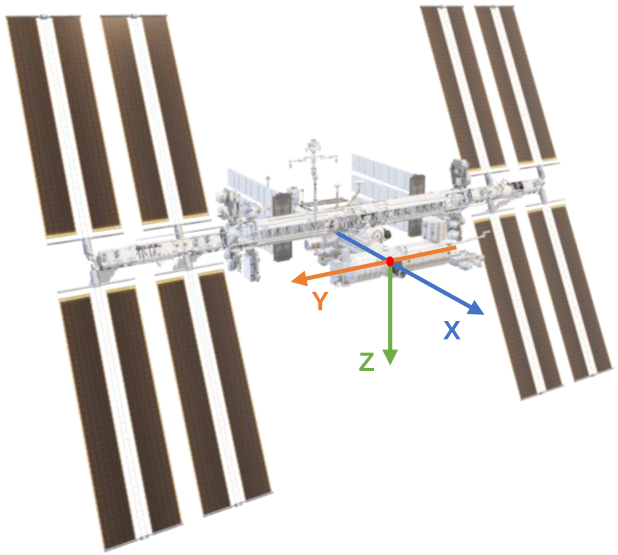
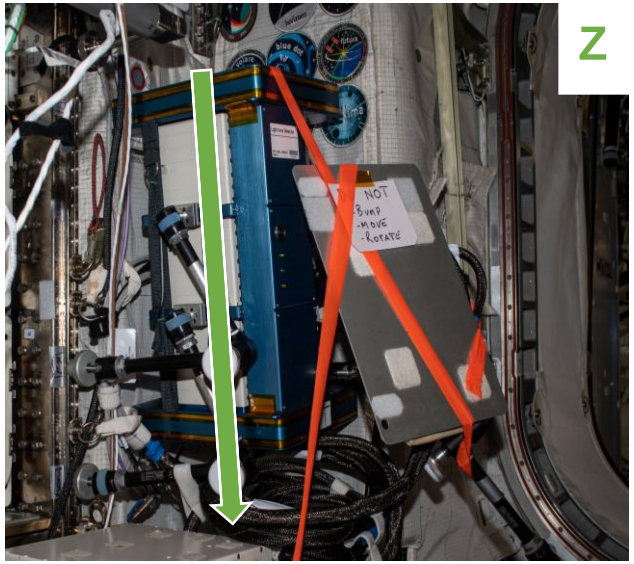
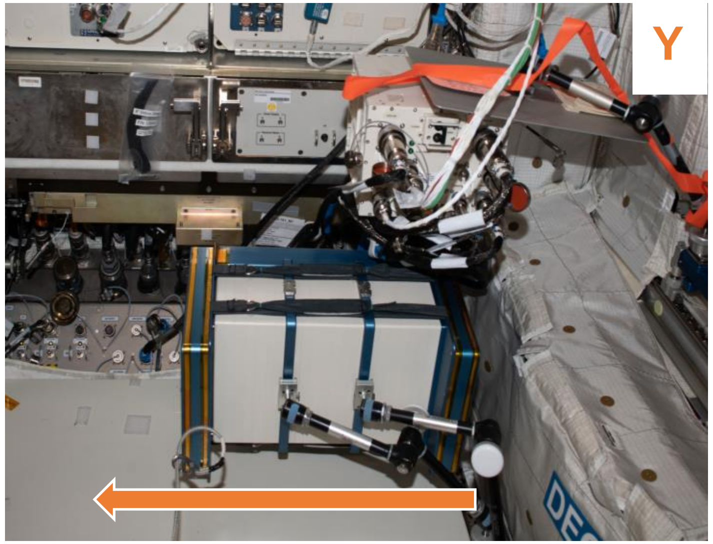
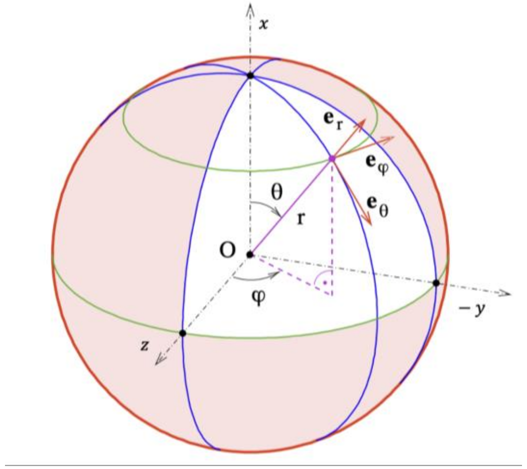
LIDAL along the 3 directions in the **Columbus** module

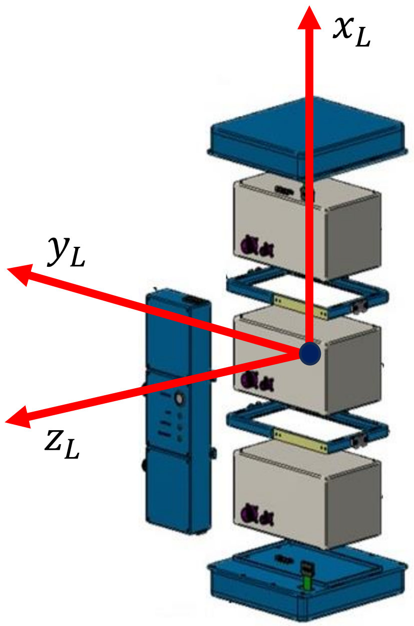






LIDAL polar coordinates Reference Frame





LIDAL Reference Frame

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LIDAL System

Geometrical characterization of the **LIDAL** system: Monte Carlo θ, ϕ distributions

LIDAL

LID

Sensitive Area: 128 cm^2

Length: 49 cm

Field Of View (FOV): ~20°

GF: 13.5 cm^2 sr

Detectable Energy (Min): 100 MeV/n

+

ALtea

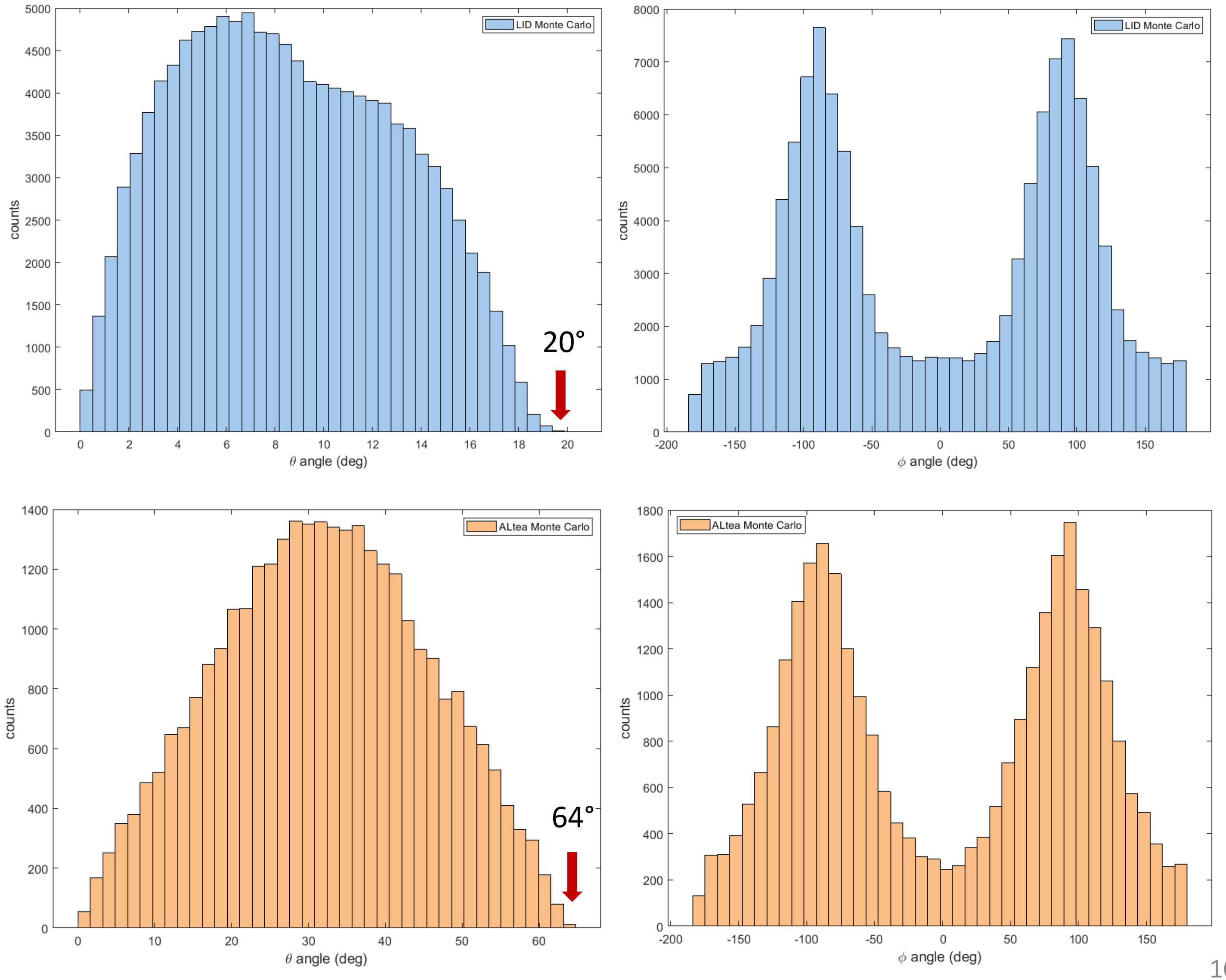
Sensitive Area: 128 cm^2

Length: 8.2 – 35.8 cm

Field Of View (FOV): ~64° – 27°

GF: 230 – 27 cm^2 sr

Detectable Energy (Min): 40 MeV/n



LIDAL System

Detector **angular efficiency** (*fraction of the impinging flux detected at that angle*):

$$\eta(\theta,\phi) = \frac{n_{\mathrm{MC}}(\theta,\phi)}{\max(n_{\mathrm{MC}})} \in [0,1]$$

where $\mathrm{n_{MC}}(\theta,\phi)$ is the number of particles impinging on the detector (isotropic and homogeneous source)

Geometrical Factor of each angular sector (*quantity independent of the incoming flux*):

$$\mathrm{GF}(\theta,\phi) = \frac{\eta(\theta,\phi)}{\sum_{\theta,\phi}\eta(\theta,\phi)} \cdot \mathrm{GF_{tot}}$$

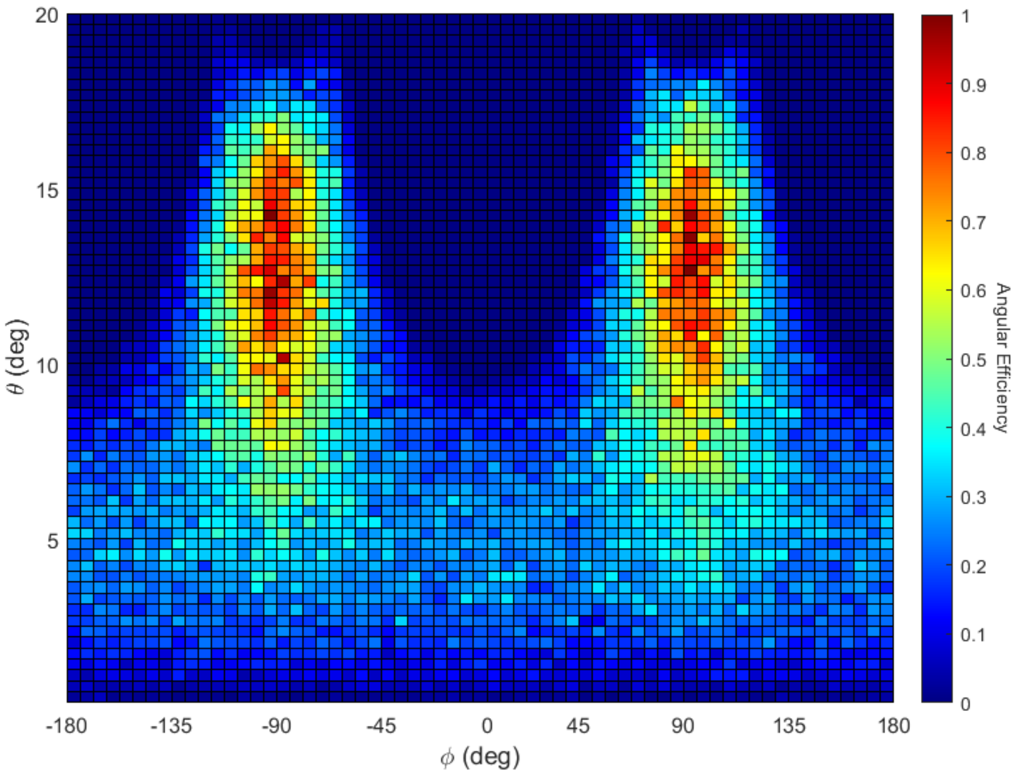
where the detector $\mathrm{GF_{tot}}$ is calculated using the Sullivan formula (vd. *Sullivan, 1971*)

Flux distribution (*for any incoming flux knowing* $\eta(\theta,\phi)$ *from the MC simulation*) [p/cm^2 s sr]:

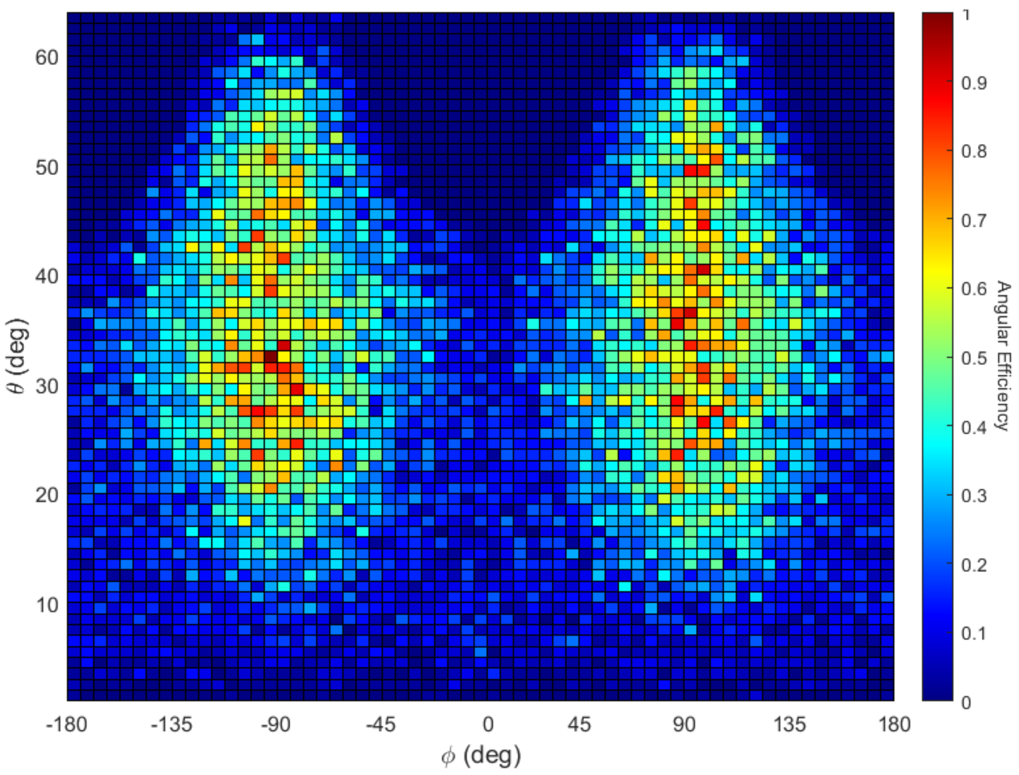
$$\Phi(\theta,\phi) = \frac{n(\theta,\phi)}{t \cdot \mathrm{GF}(\theta,\phi)}$$

LIDAL System

LID angular efficiency, $\eta(\theta,\phi)$, for Monte Carlo isotropic distribution



ALtea angular efficiency, $\eta(\theta,\phi)$, for Monte Carlo isotropic distribution



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Scientific Problem: the SAA

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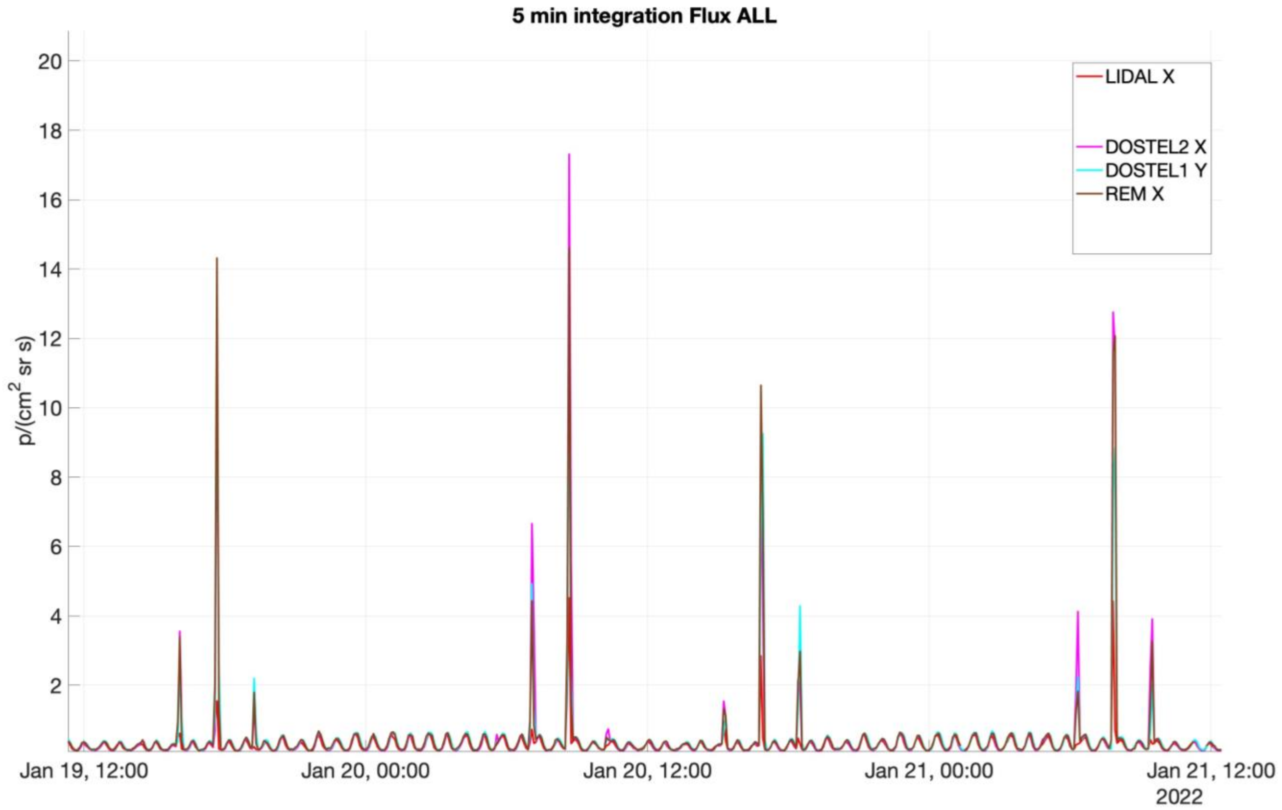
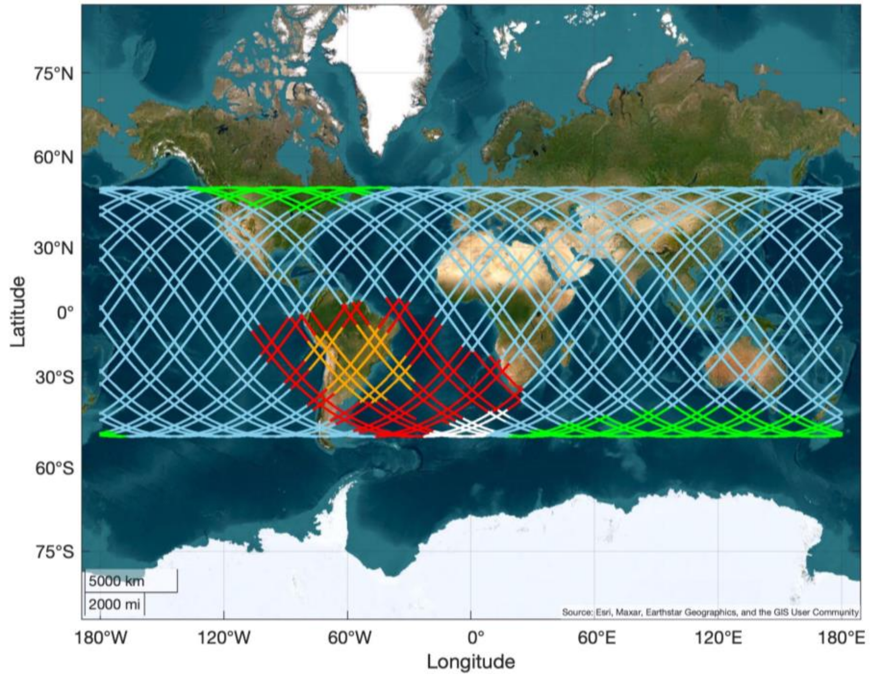
LID measures a lower **SAA** particle flux in respect to REM and DOSTEL



WHY?

LID-REM (DOSTEL) SAA Peaks Ratio (@ fixed direction) $\sim 27 \pm 5\%$

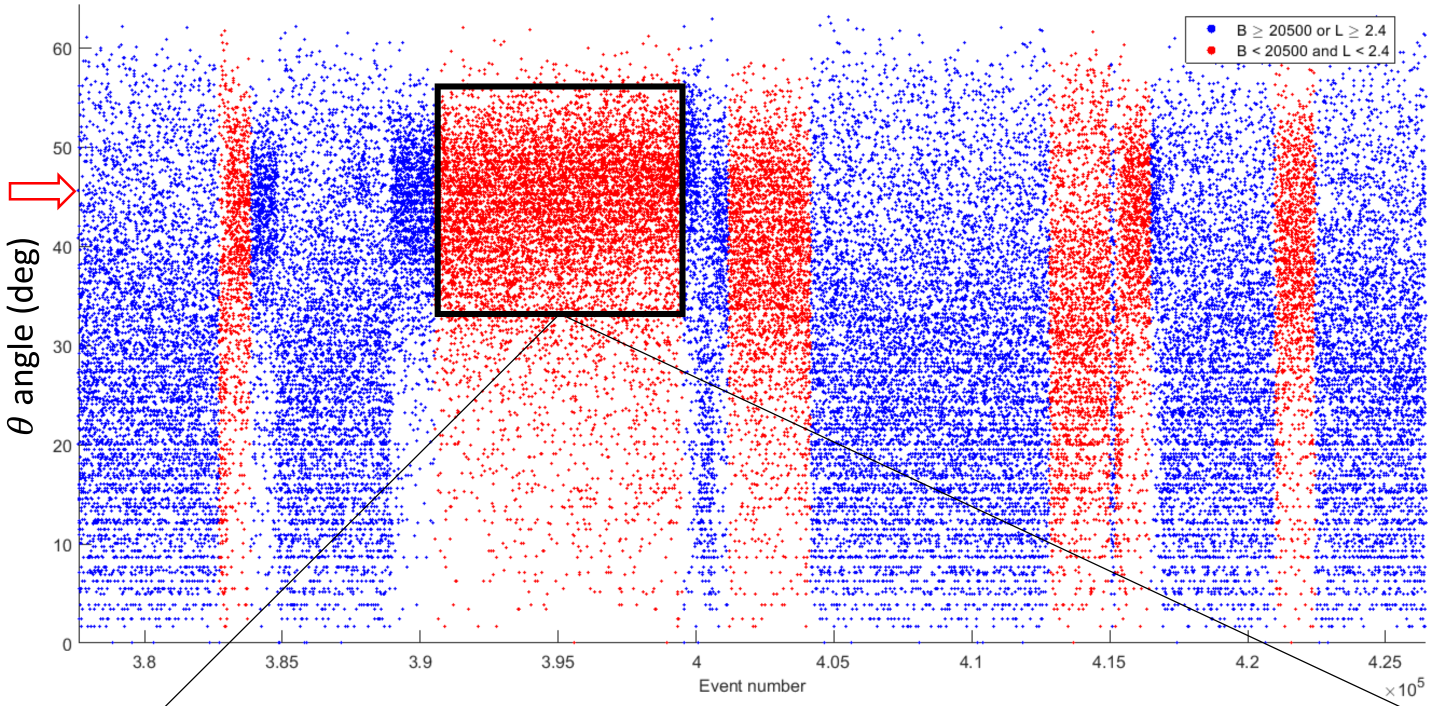
Geographical selections



- Low Latitude ($L < 1.5,\ B \geq 23.5\ \mu T$)
- High Latitude ($L > 3,\ \text{Any B}$)
- Inner SAA ($L < 2.4,\ B < 20.5\ \mu T$)
- Extended SAA ($L < 2.4,\ B < 23.5\ \mu T$)

SAA Data Analysis

***θ* angle** of the particles as measured by **ALtea** in the Full Orbit region along the Z direction

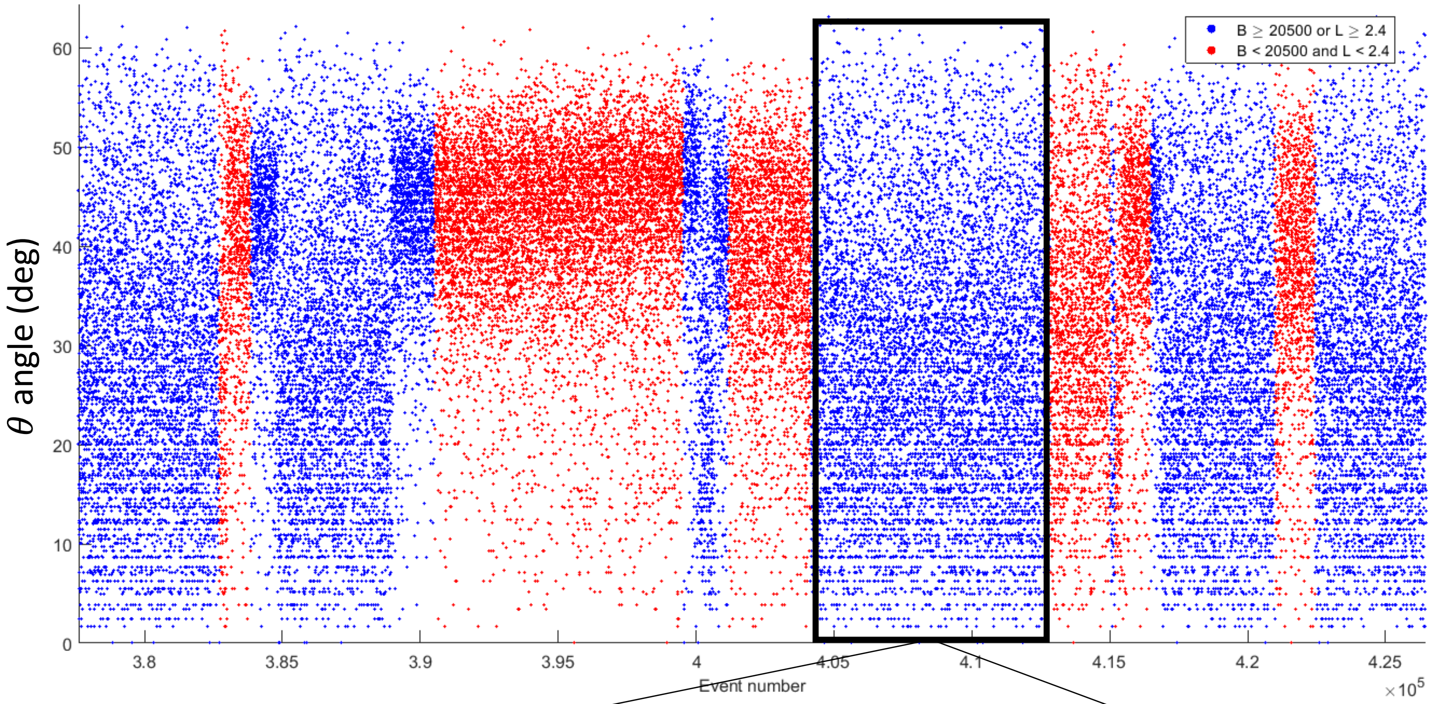


Blue dots: Full Orbit w/o inner SAA
Red dots: Inner SAA

SAA particles exhibit a certain **directionality** (Well-known phenomenon!)

SAA Data Analysis

$\boldsymbol{\theta}$ **angle** of the particles as measured by **ALtea** in the Full Orbit region along the Z direction



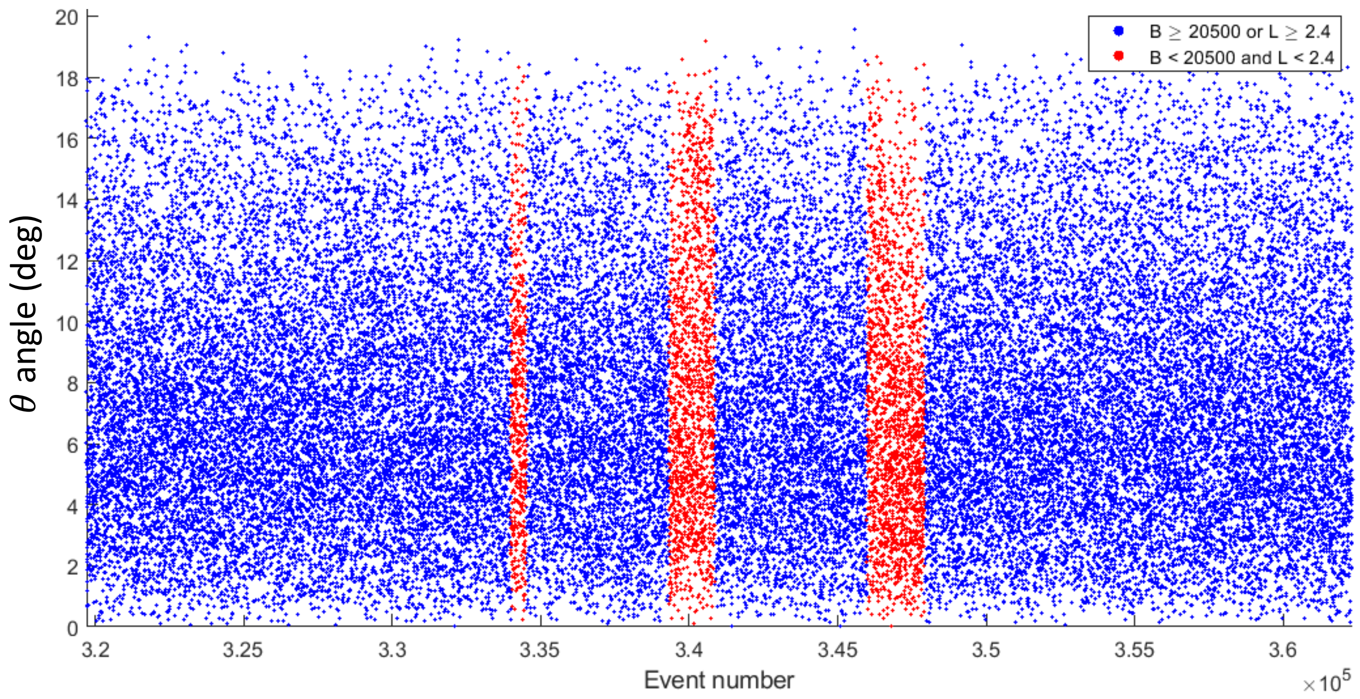
Blue dots: Full Orbit w/o inner SAA

Red dots: Inner SAA

Conversely, GCR particles exhibit an **isotropic** behaviour

SAA Data Analysis

θ angle of the particles as measured by **LID** in the Full Orbit region along the Z direction

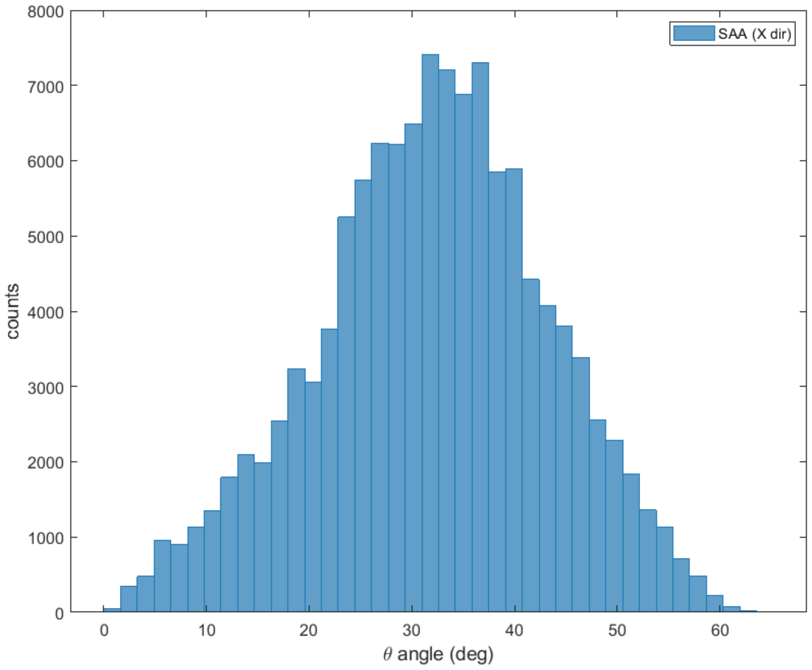


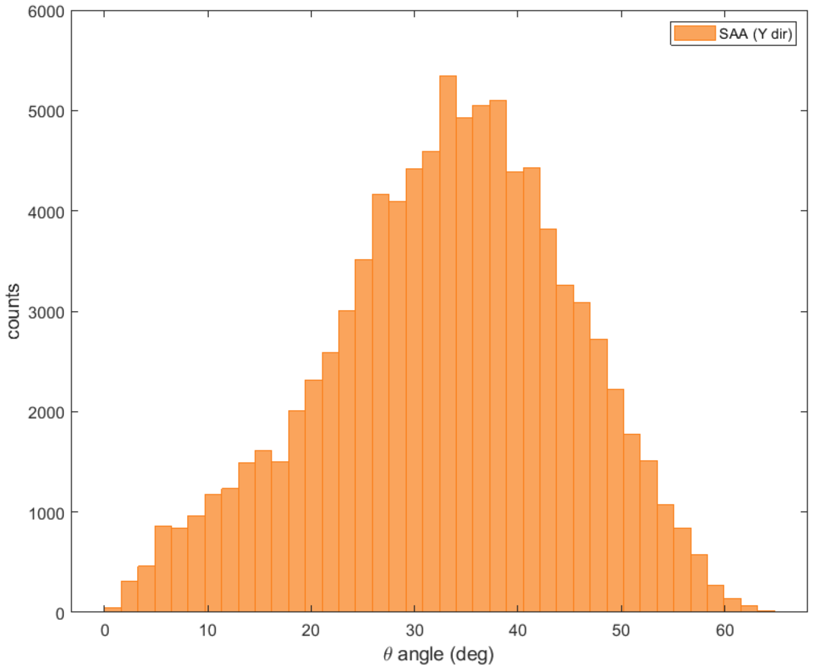
Blue dots: Full Orbit w/o inner SAA
Red dots: Inner SAA

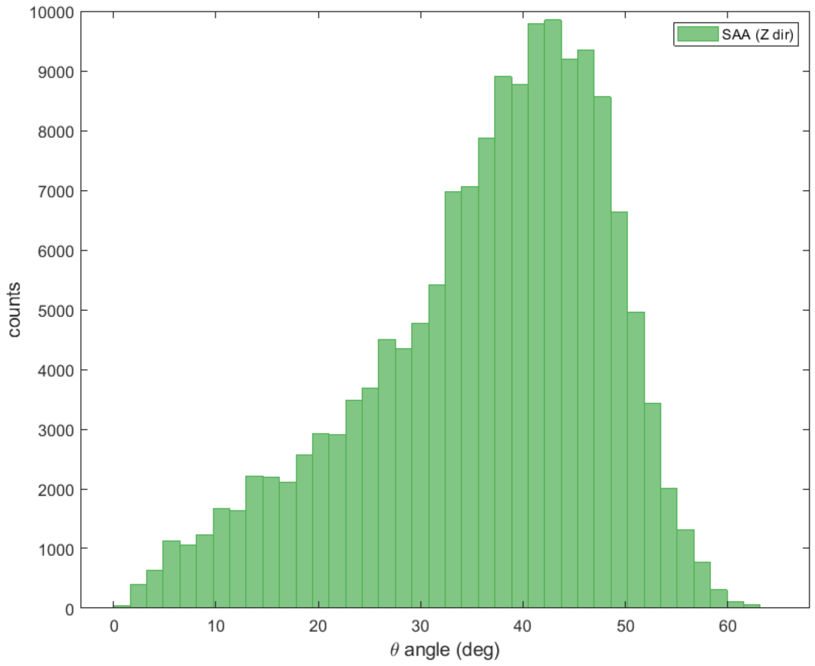
In this case, the *particles do not appear to have a preferred direction*, and **no distinction** can be made between the **SAA** and **GCR** populations, at least in angular terms

SAA Data Analysis

ALtea $\boldsymbol{\theta}$ distributions along the X, Y, Z directions in the LIDAL reference frame



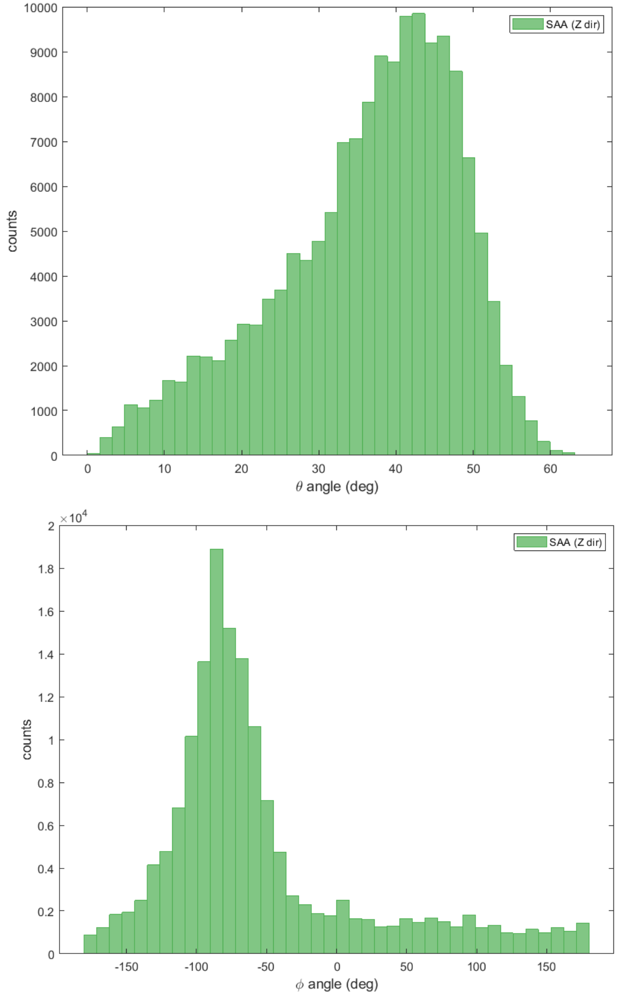




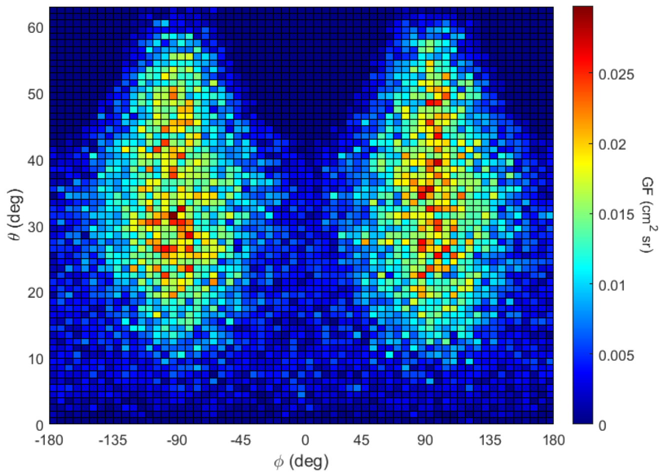
Asymmetry in the $\boldsymbol{\theta}$ distributions of SAA particles if compared to the Monte Carlo one for an isotropic radiation field

SAA Data Analysis – $\Phi(\theta,\phi)$

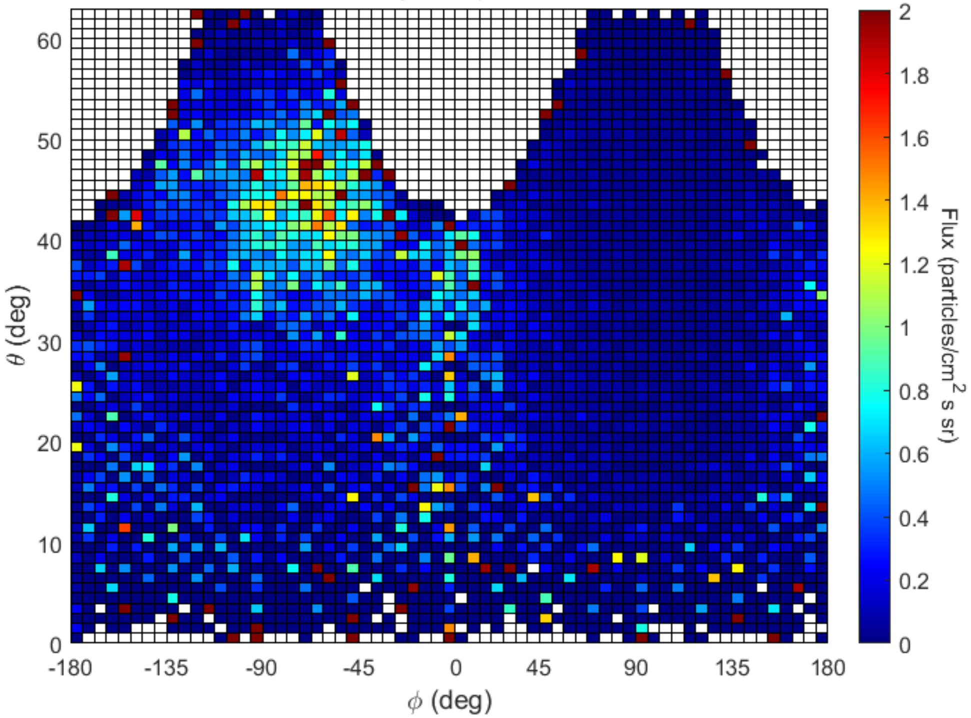
ALtea (and **LID**) data normalization (the detector features are not involved anymore!) and particle flux, $\Phi(\theta,\phi)$, in the SAA



$\mathrm{GF}(\theta,\phi)$



$\Phi(\theta,\phi)$ SAA **Z dir**



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SAA Data Analysis – $\Phi(\theta, \phi)$

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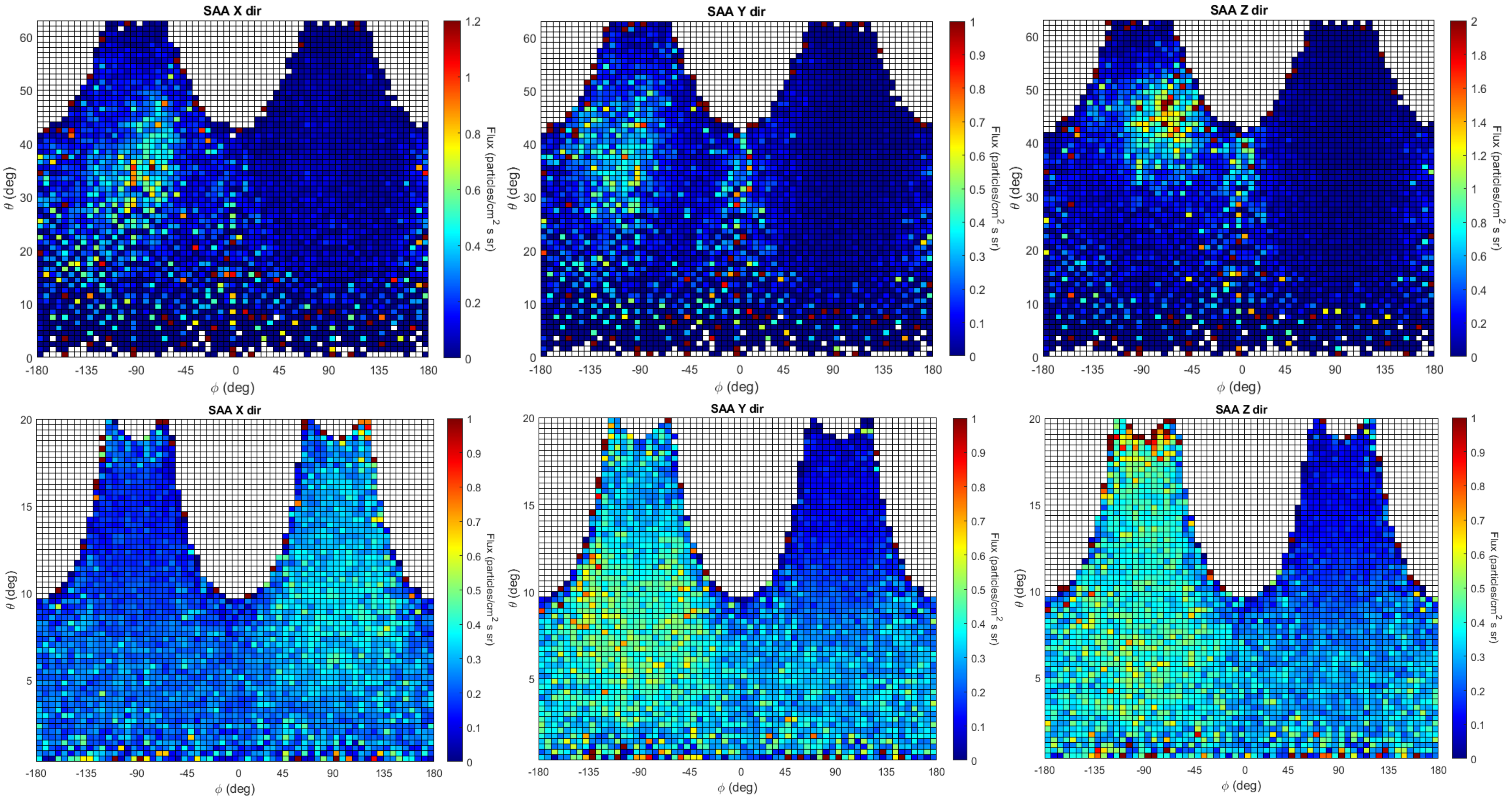
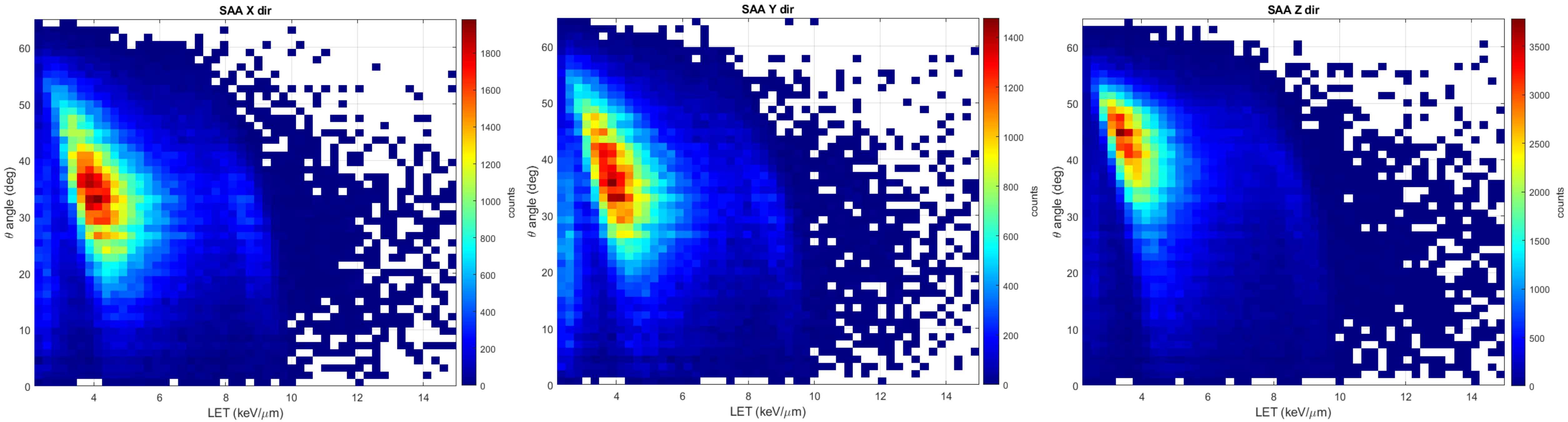
ALtea

LID



SAA Data Analysis

(θ, LET) ALtea particle histograms along the 3 directions

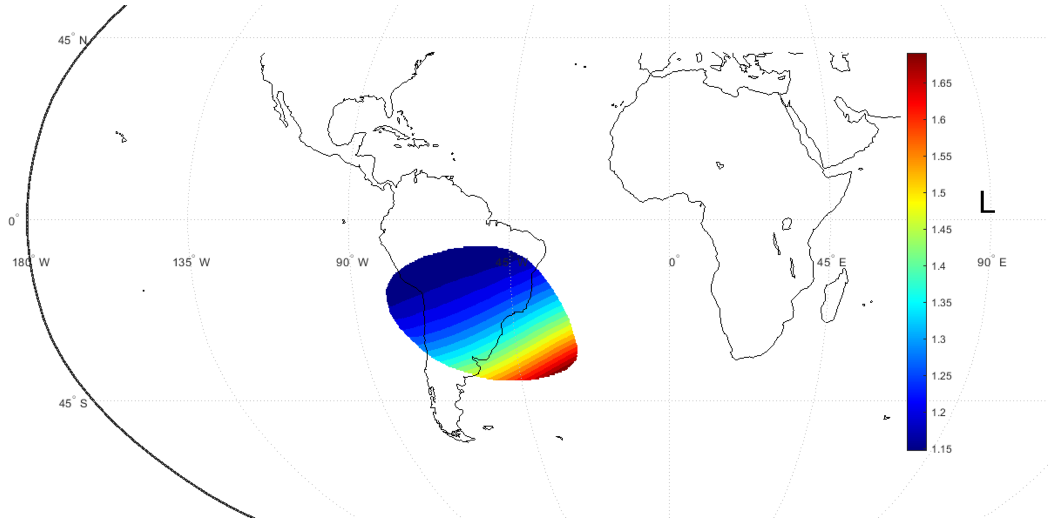


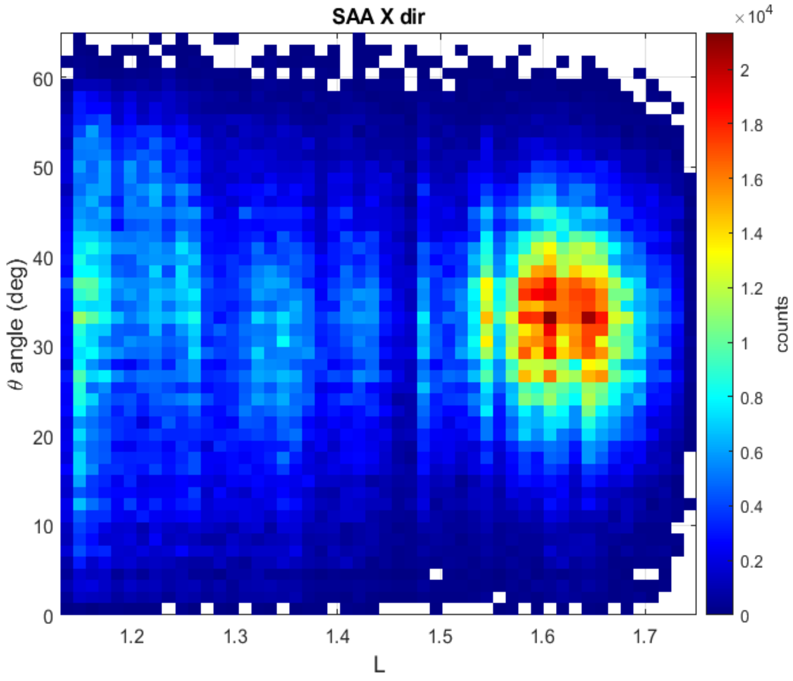
- In the SAA region, particles with $\mathrm{LET} < 15\,\frac{\mathrm{keV}}{\mu\mathrm{m}}$ corresponds to *protons* with kinetic energies comprises between ~40 MeV and ~100 MeV.
- In each direction, peaks of the θ distribution are due to low-LET protons ($\mathrm{LET} \lesssim 5\,\frac{\mathrm{keV}}{\mu\mathrm{m}}$)

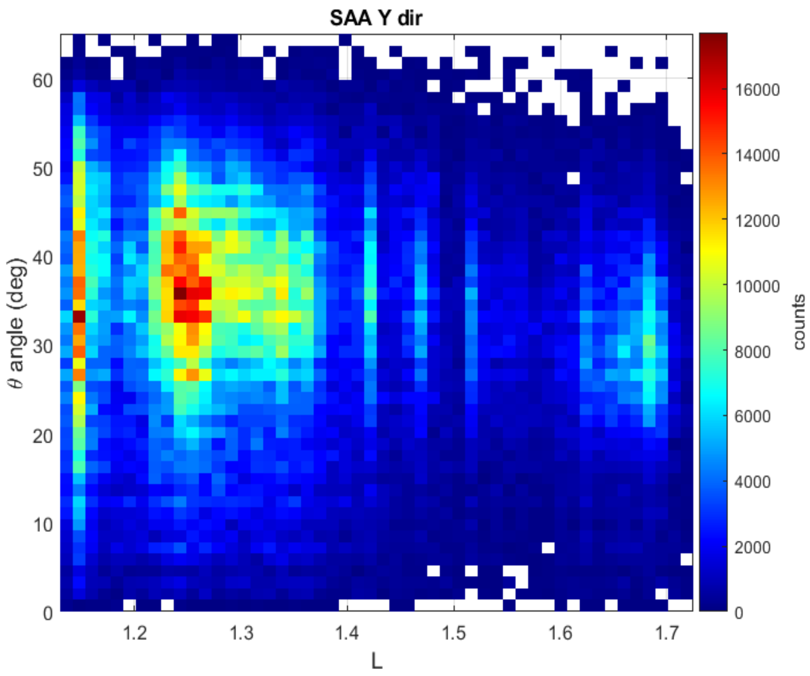
SAA Data Analysis

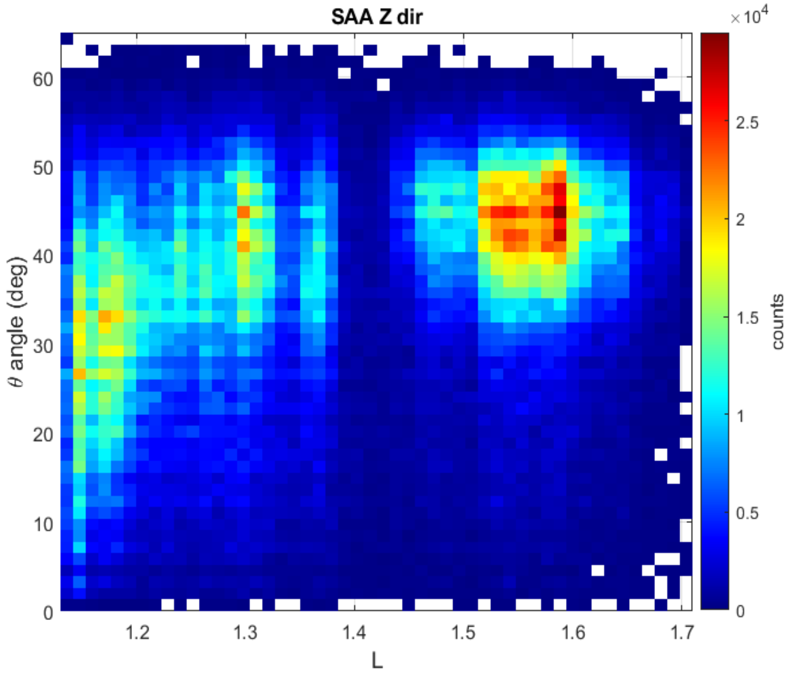
($\boldsymbol{\theta}$, L) **ALtea** particle histograms along the 3 directions

- The (θ, L) distribution exhibit characteristic patterns as the direction varies
- There seems to be a *relationship* between the detection direction and θ as well as the detection direction and L-parameter





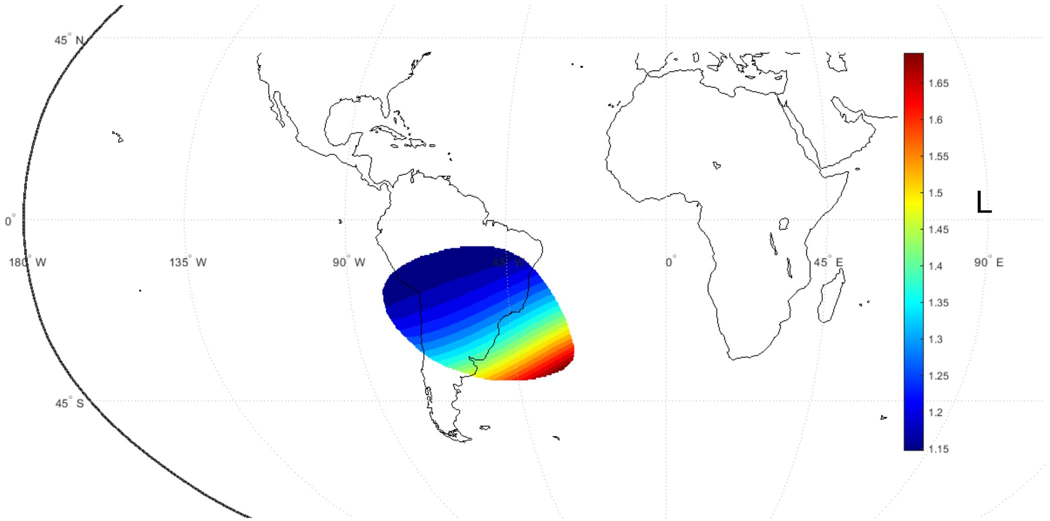


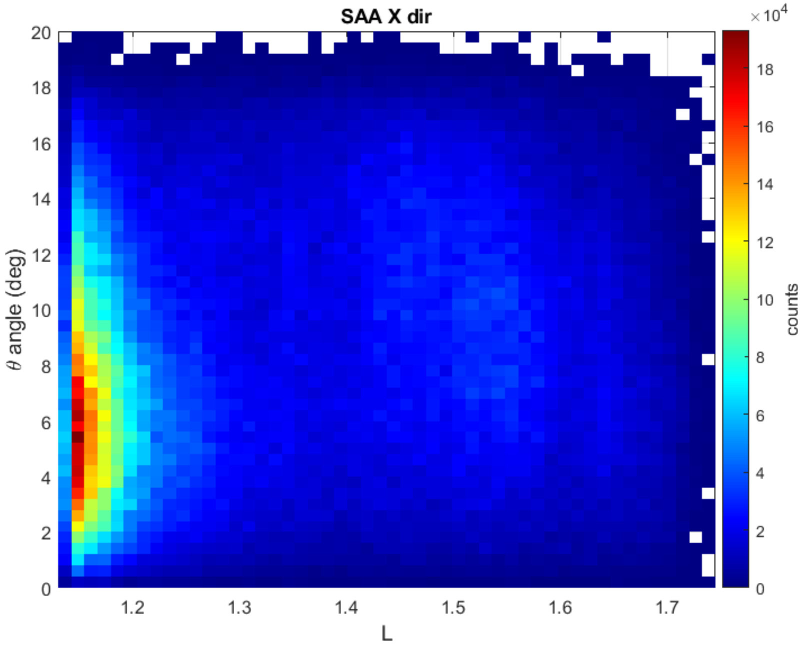


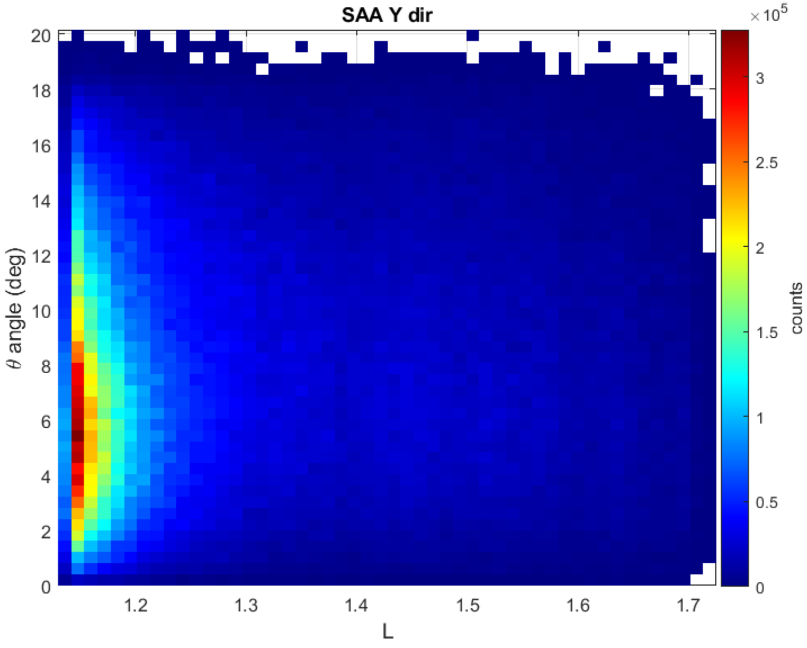
SAA Data Analysis

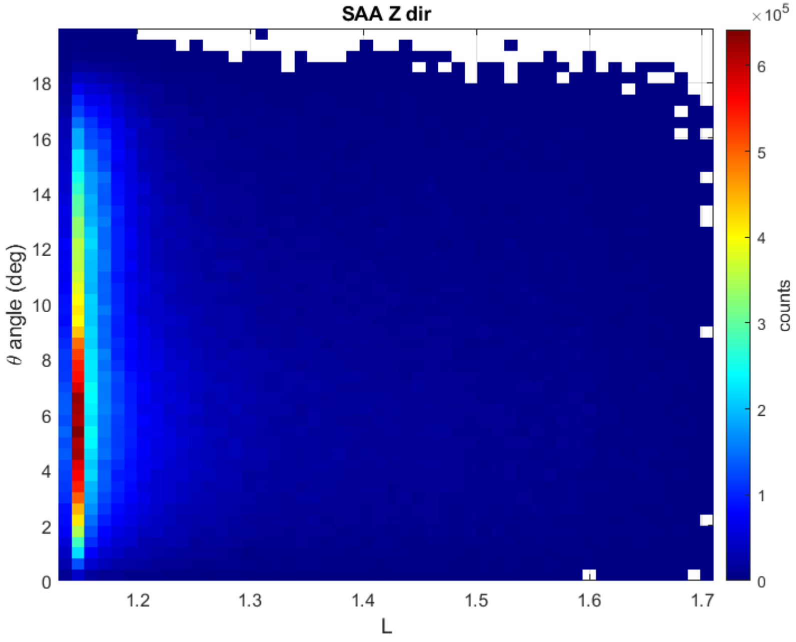
($\boldsymbol{\theta}$, L) LID particle histograms along the 3 directions

- Peaks of θ distribution are for L < 1.2, near the **equatorial region**







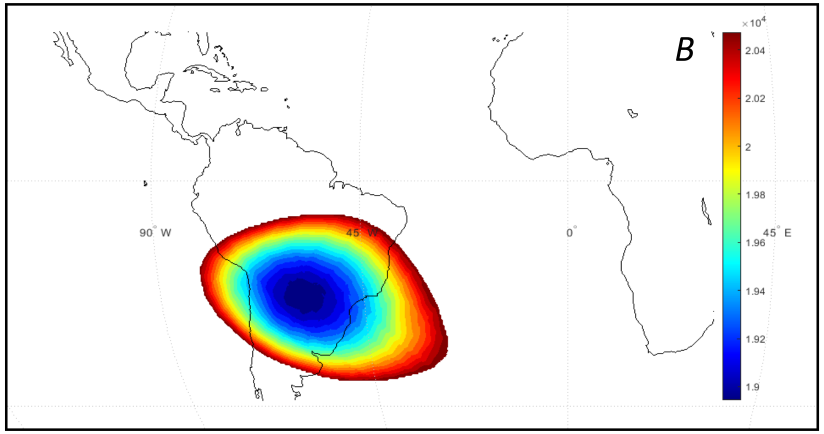


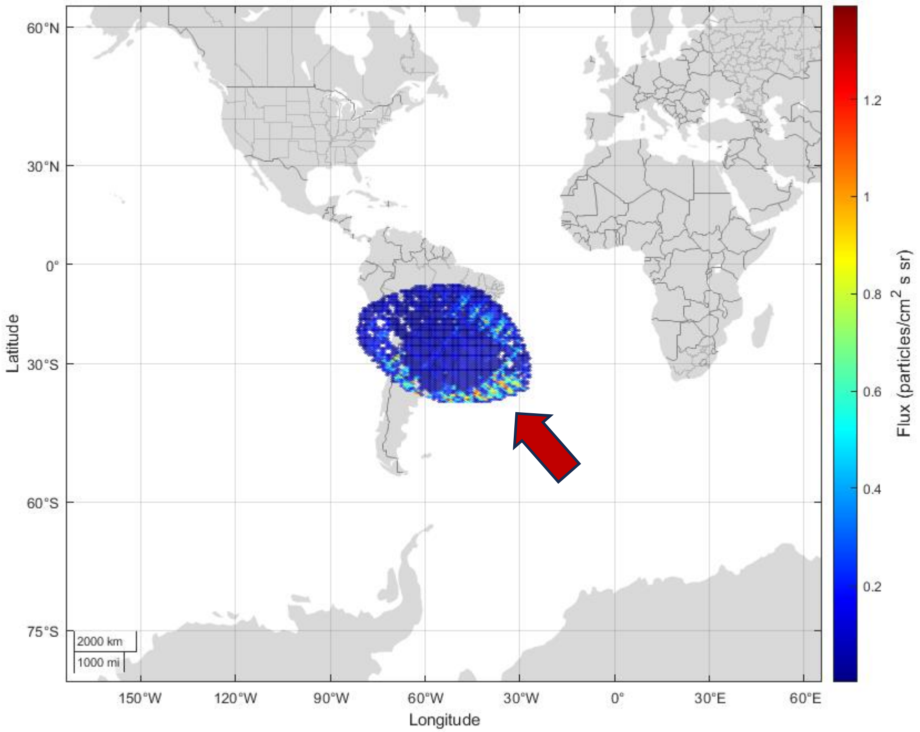
SAA Data Analysis – Flux Plots

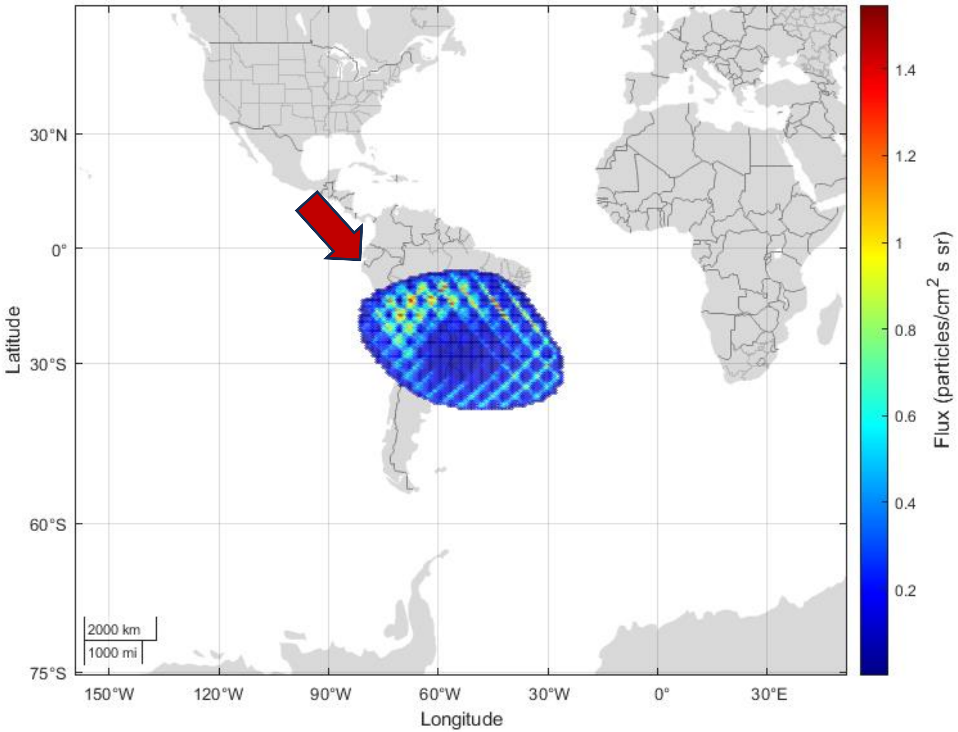
ALtea (left) and **LID** (right) particle flux takes on a doughnut-shaped structure

ALtea measures a higher flux in the southern part of the SAA, while **LID** measures it in the northern part.

Are **ALtea** and **LID** measuring the *same* particle population? Let's see it!







SAA Data Analysis – θ Plots

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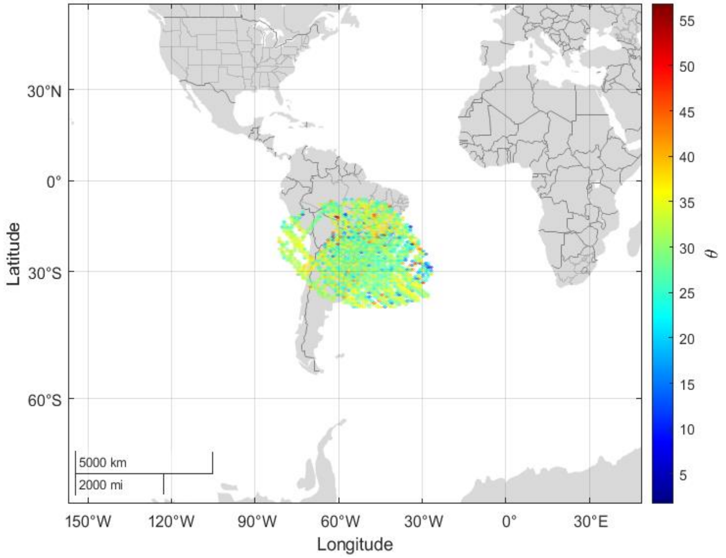
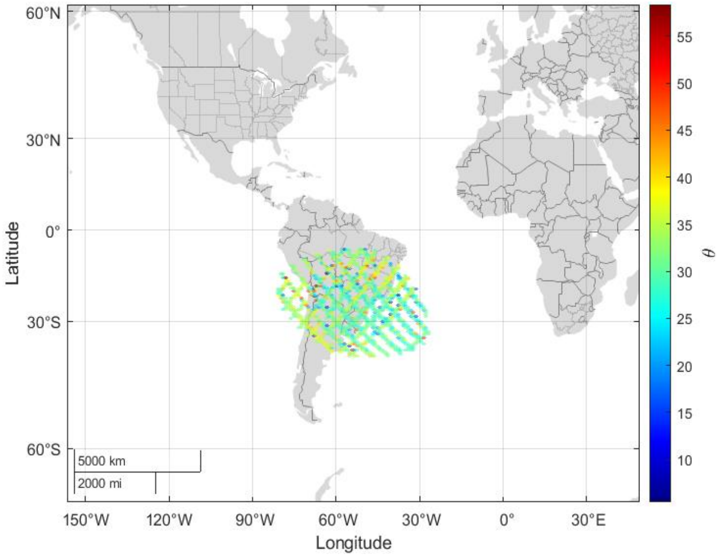
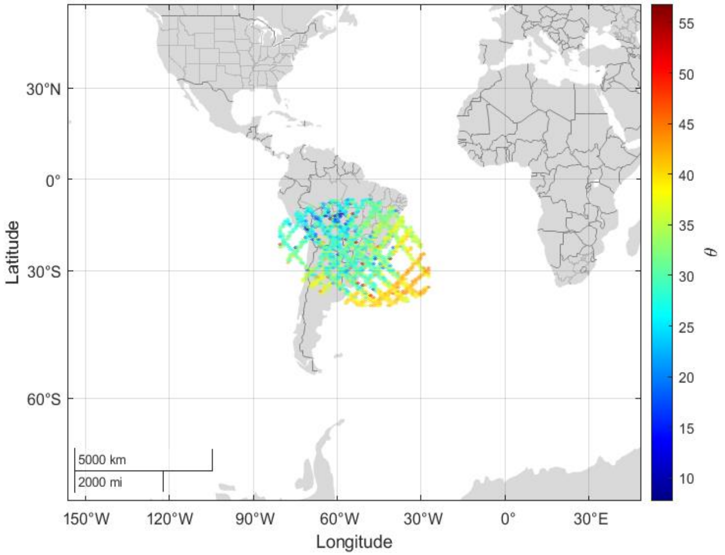
ALtea



SAA X dir

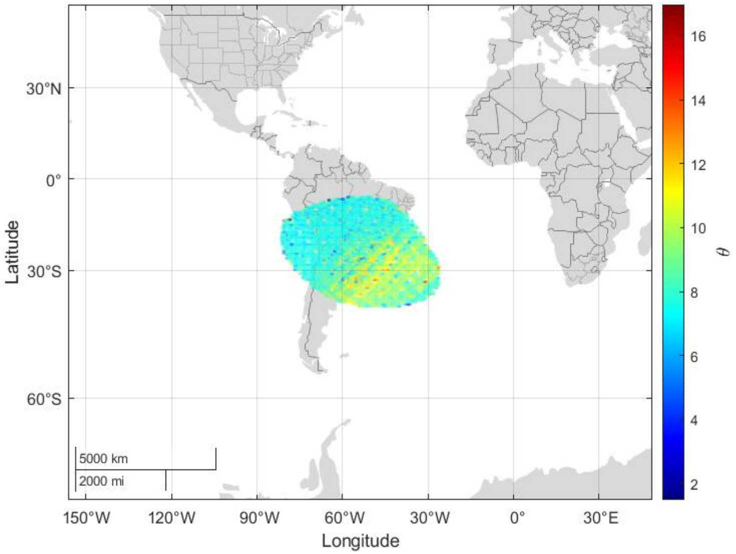


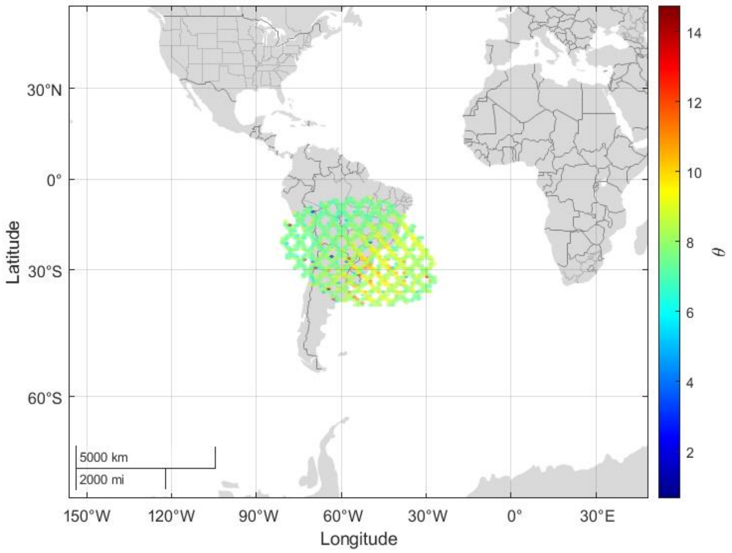
SAA Y dir

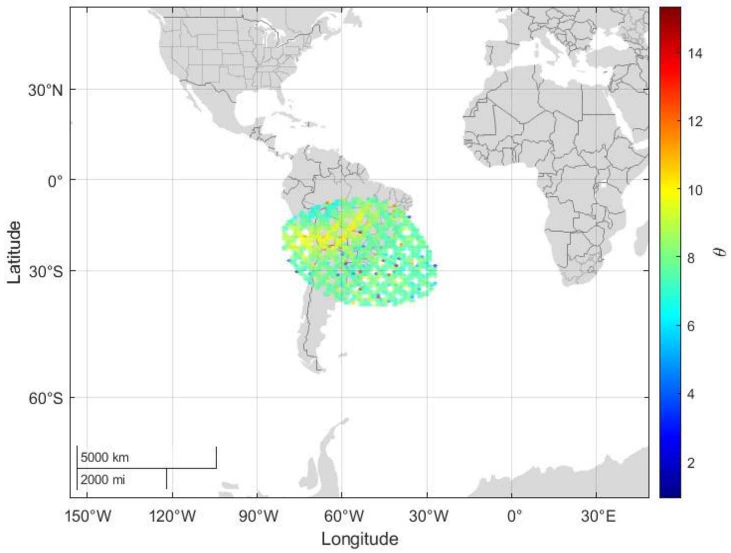


SAA Z dir

LID







SAA Data Analysis

Geometrical constraints: **LID** can only see a portion of the particles detectable by **ALtea**

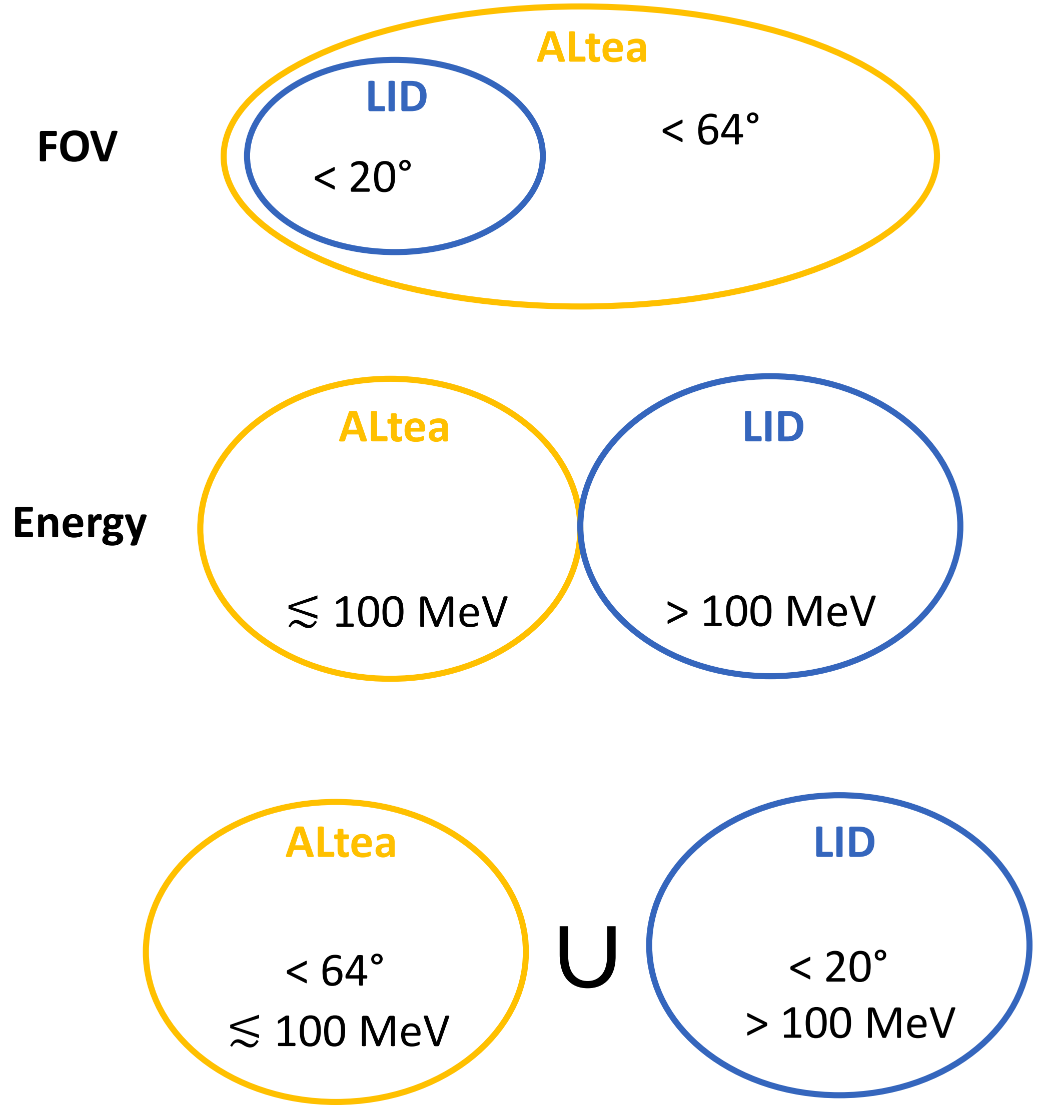
Energy constraints: **LID** is *never* a subset of **ALtea**

- ALtea can detect low-Z particles (such as H and He) with impinging energies ranging from 40 MeV to about 100 MeV (for protons)
- LID is capable of measuring low-Z particles with energies spanning from 100 MeV up to several GeV

Then…

In the SAA region (mainly low-Z and low-energy particles) LID and ALtea represent *disjoint sets*.

LID and ALtea combined data can offer a comphrensive overview of the SAA radiation field.



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SAA Data Analysis – Energy Plots

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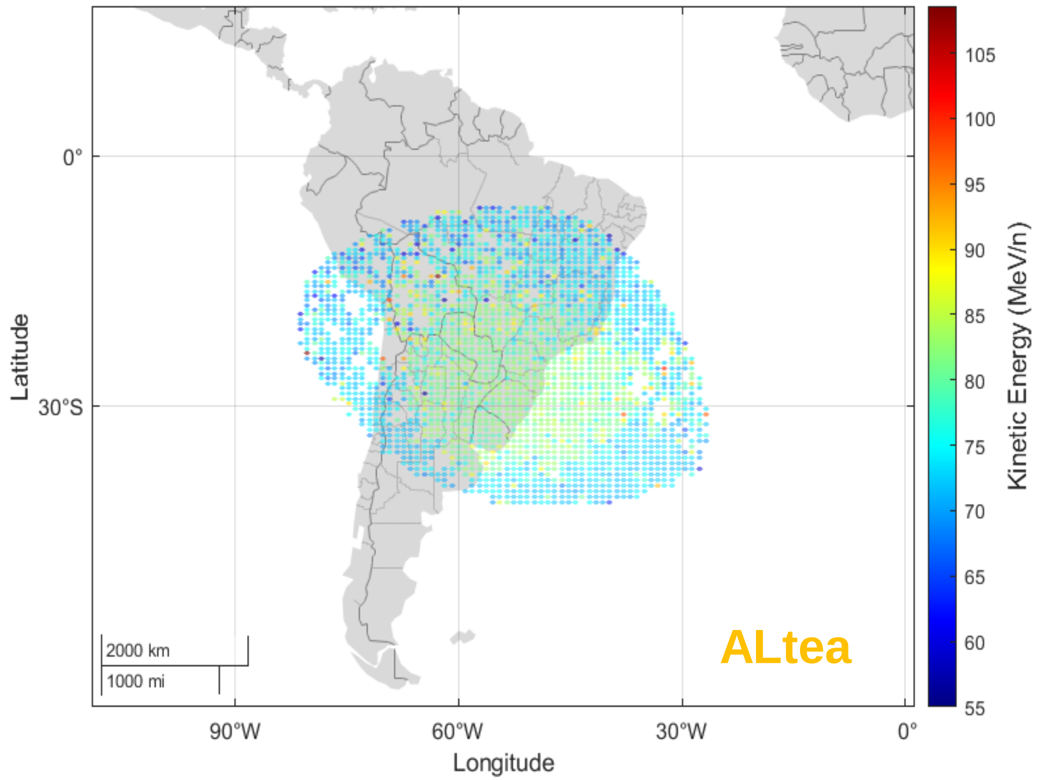
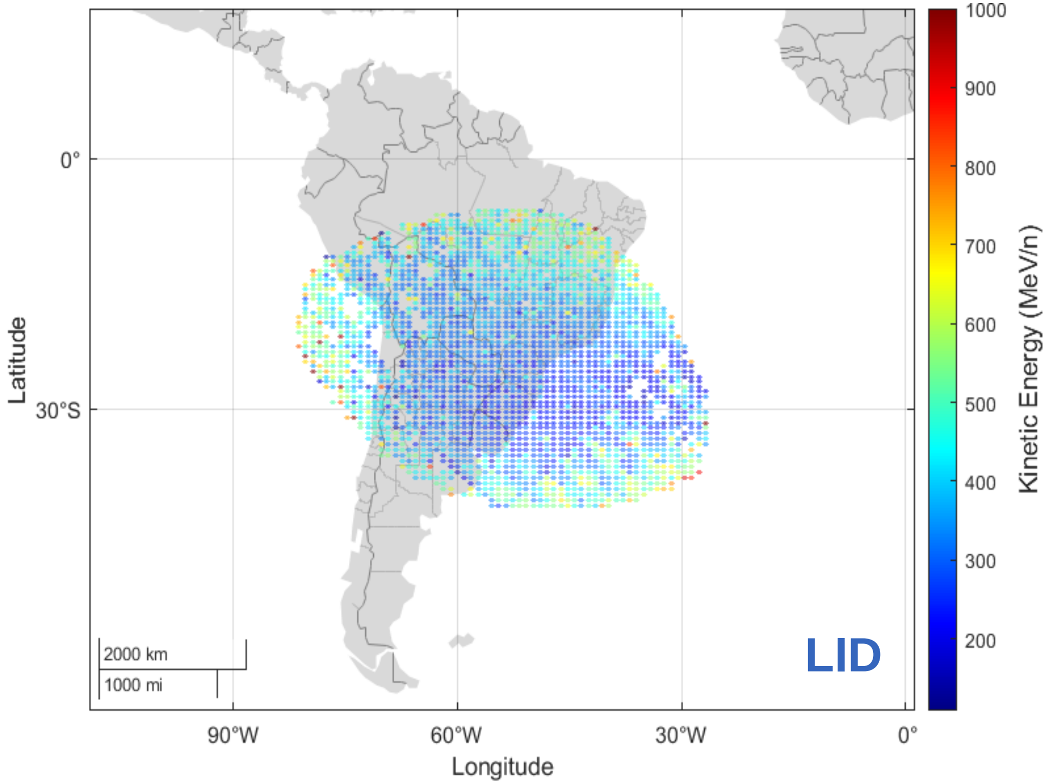
ALtea and LID measure two distinct particle populations as kinetic energy plots reveal!

- ALtea protons with lower energy (< 75 MeV/n) tend to form a ***circular halo*** along the outer edge of the SAA, while protons with higher energy tend to be located in the ***core*** of the SAA
- LID lower-energy (< 400 MeV/n) protons tend to be located in the ***core*** of the SAA, while protons with higher energy along the ***outer edge***.



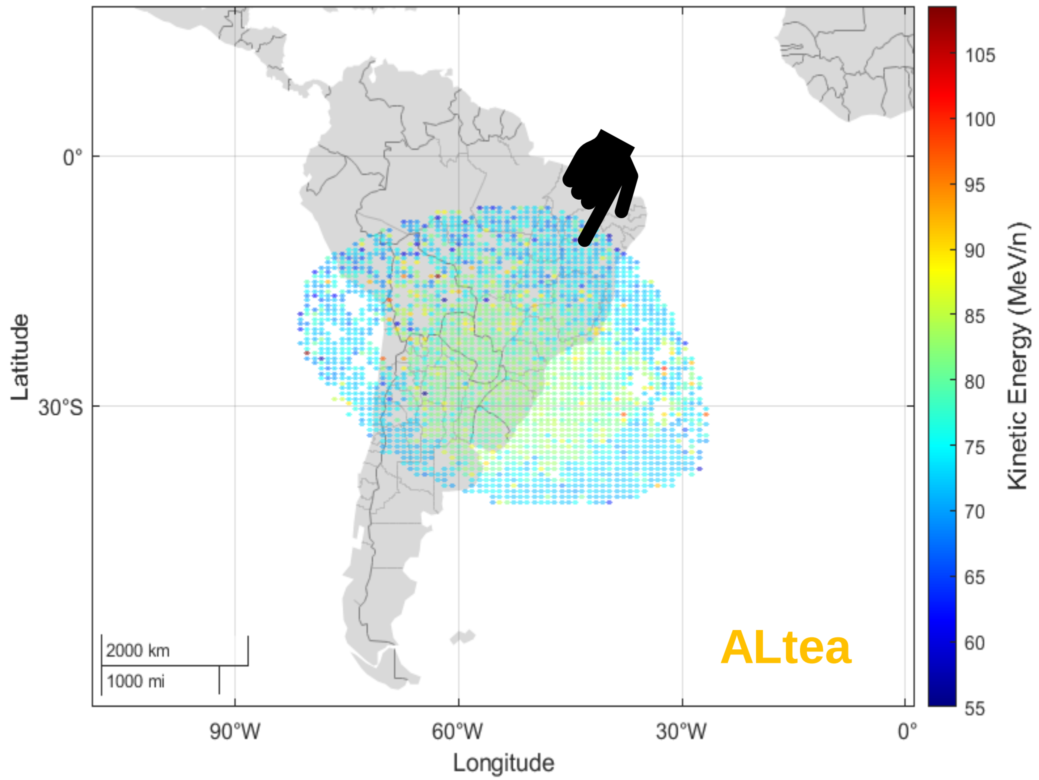


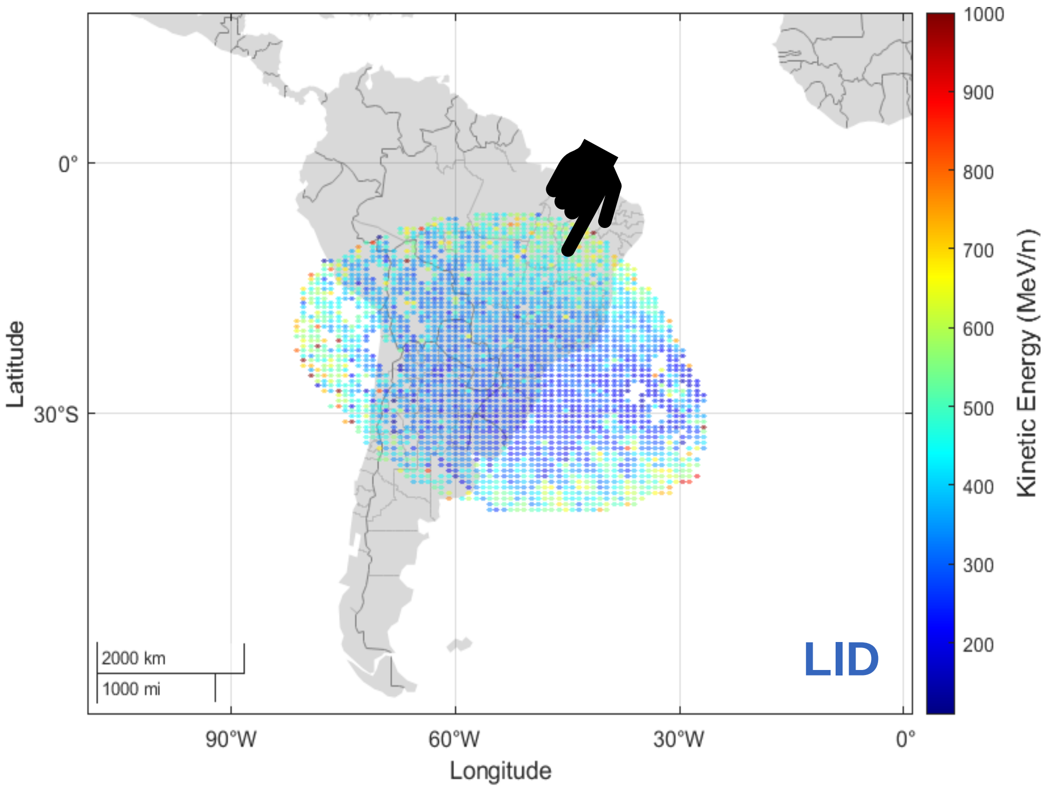
SAA Data Analysis – Energy Plots

What are these energy plots telling us?

- In the core of the SAA, **ALtea** and **LID** measure <u>two distinct portions of the same energy spectrum</u>

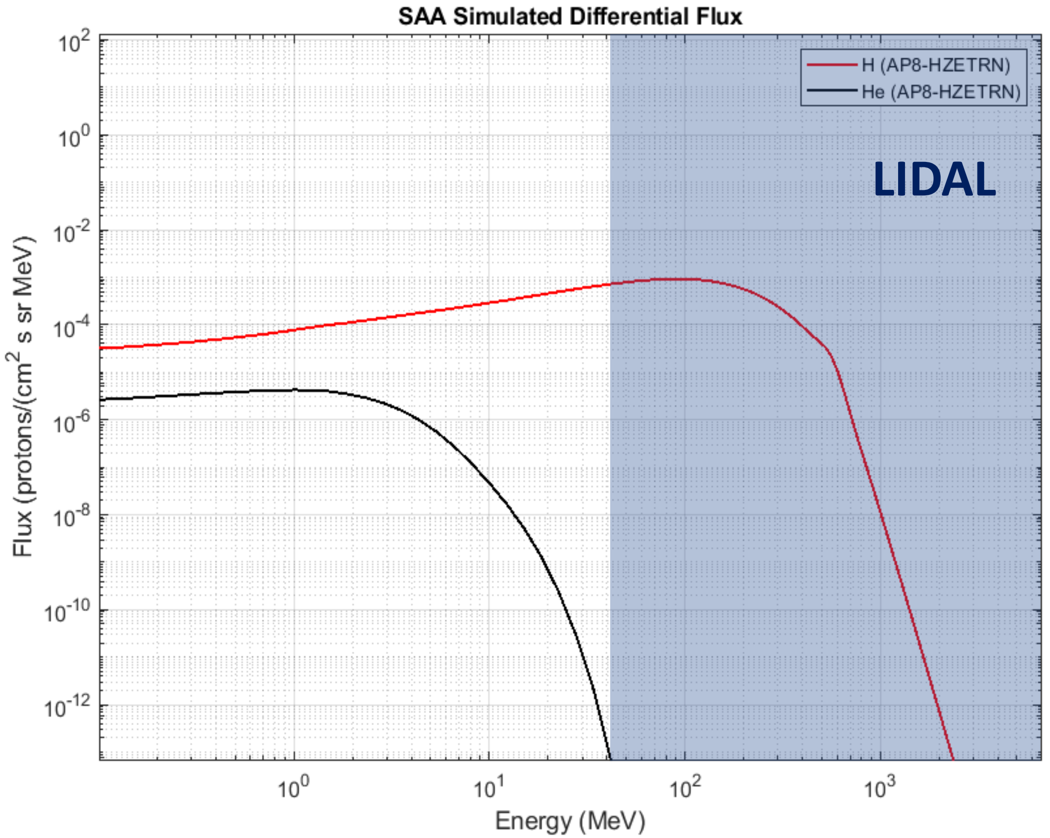
What can be said about the particles populating the circular halo?



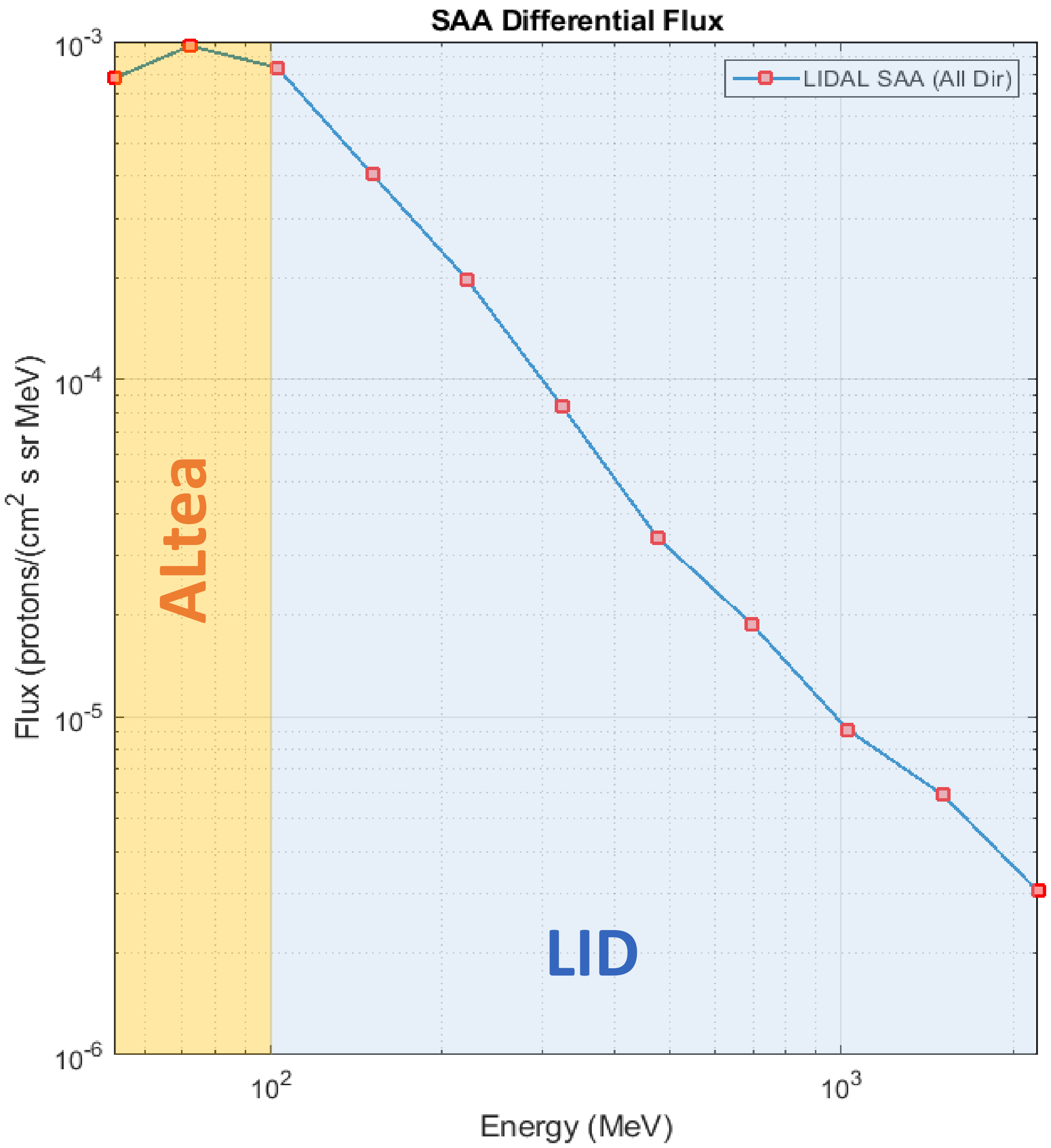


SAA Data Analysis – Energy Spectrum

Transported (HZETRN) Flux (AP8MIN) inside the ISS under 40 g/cm² of Al shielding material



- The SAA radiation field inside the ISS mainly consists of protons with energies up to 600-700 MeV (above this energy the flux is very low!)
- He ions contribution to flux is negligible



SAA Data Analysis – Energy Spectrum

TOR VERGATA UNIVERSITY OF ROME

HSERLAB Human Space Exploration Radiation LAB

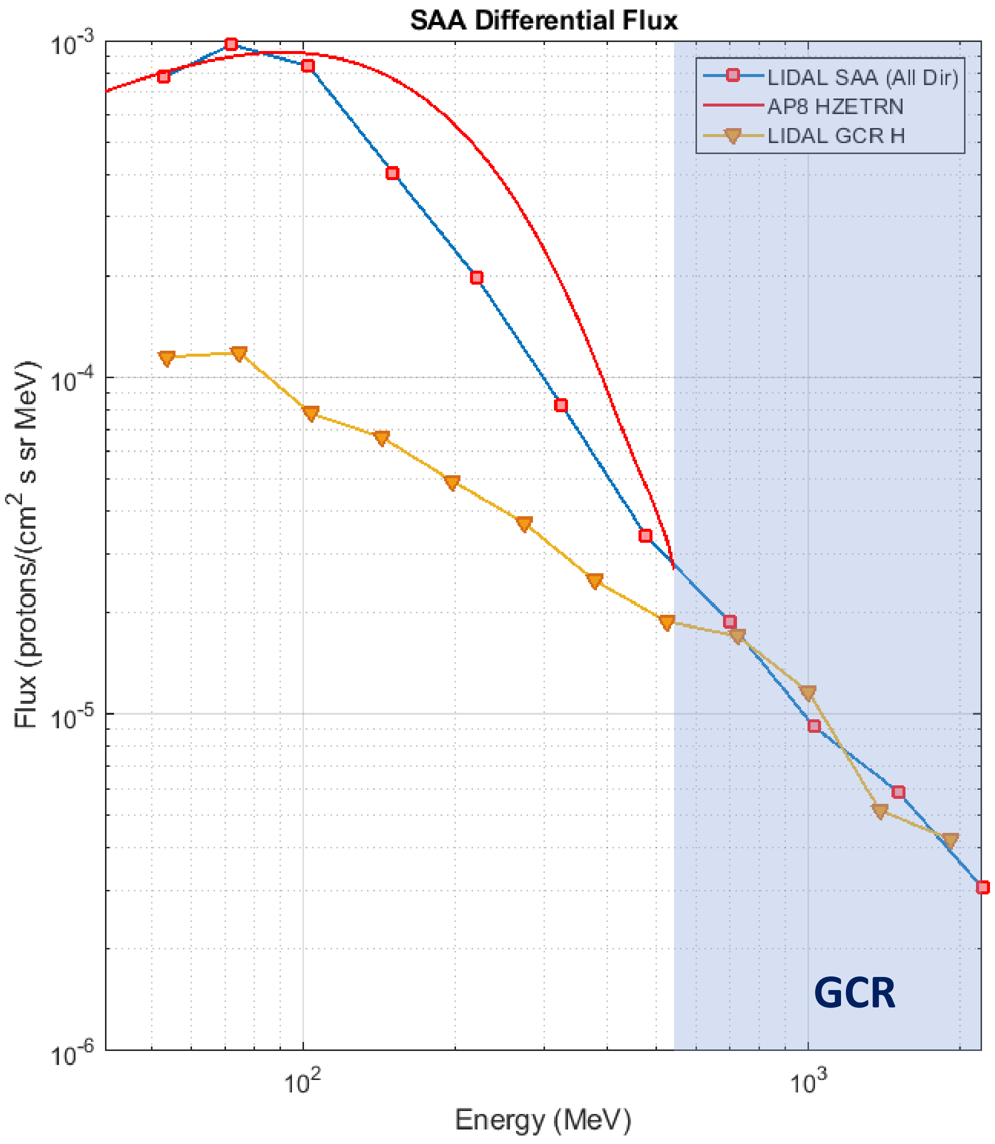
A possible answer…

- Low-energy protons (~75 MeV) populate the SAA circular halo as measured by **ALtea**
- High-energy GCR particles populate the SAA outer edge as measured by **LID**

- Above 500 MeV, the GCR component becomes predominant being the SAA spectrum ~ GCR proton spectrum

- Below the 500 MeV-threshold, although the GCR component is present, its flux contributes only minimally to the overall SAA spectrum (at very low energy the GCR flux is one order of magnitude lower than that of SAA particles)

ALtea and **LID** features provide the first SAA particle energy spectrum within a space habitat



Pitch Angle, α

The pitch angle is the angle between the velocity vector of a charged particle and the local magnetic field vector at its position.

The **pitch angle** is given by the equation:

$$\alpha = \mathrm{acos}\left(\frac{\vec{v}\cdot\vec{B}}{(|\vec{v}||\vec{B}|)}\right)$$

where:

- α is the pitch angle (in radians).
- $\vec{v}$ is the velocity vector of the charged particle.
- $\vec{B}$ is the magnetic field vector at the particle's position.

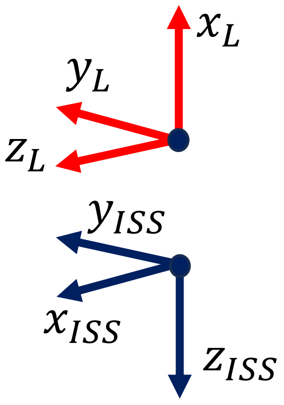
➢ The pitch angle can vary from 0° (particle moving parallel to the magnetic field lines) to 180° (particle moving antiparallel to the magnetic field lines).

➢ All **stably-trapped ions** have a pitch angle of about 90°

Pitch Angle, α

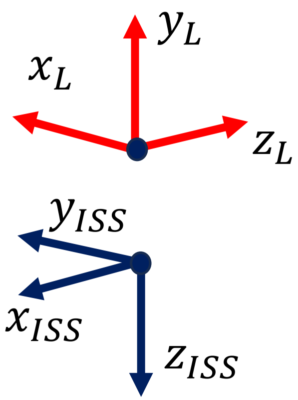
A transformation between the LIDAL reference frame and the ISS one has to be made for each LIDAL orientation along the three ISS axes.

LIDAL Z dir



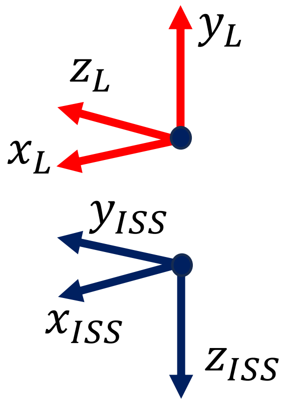
$$R_Z = \begin{bmatrix} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{bmatrix}$$

LIDAL Y dir

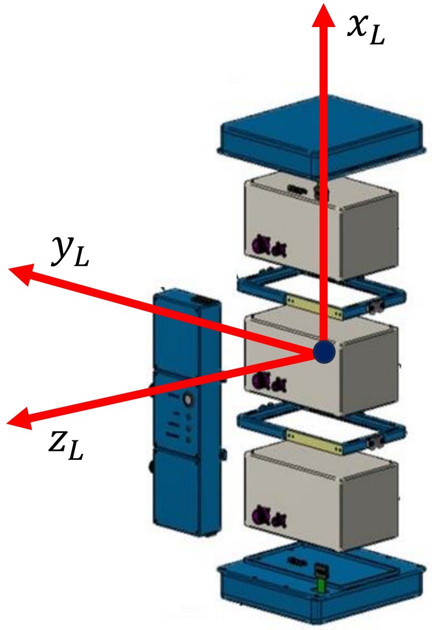


$$R_Y = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & -1 \\ -1 & 0 & 0 \end{bmatrix}$$

LIDAL X dir

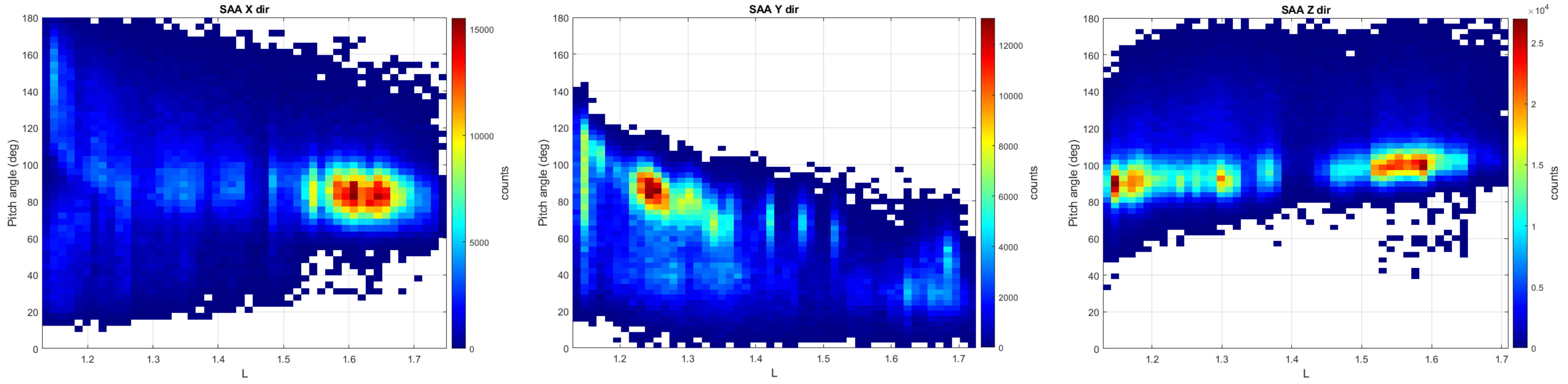


$$R_X = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & -1 \\ 0 & 1 & 0 \end{bmatrix}$$

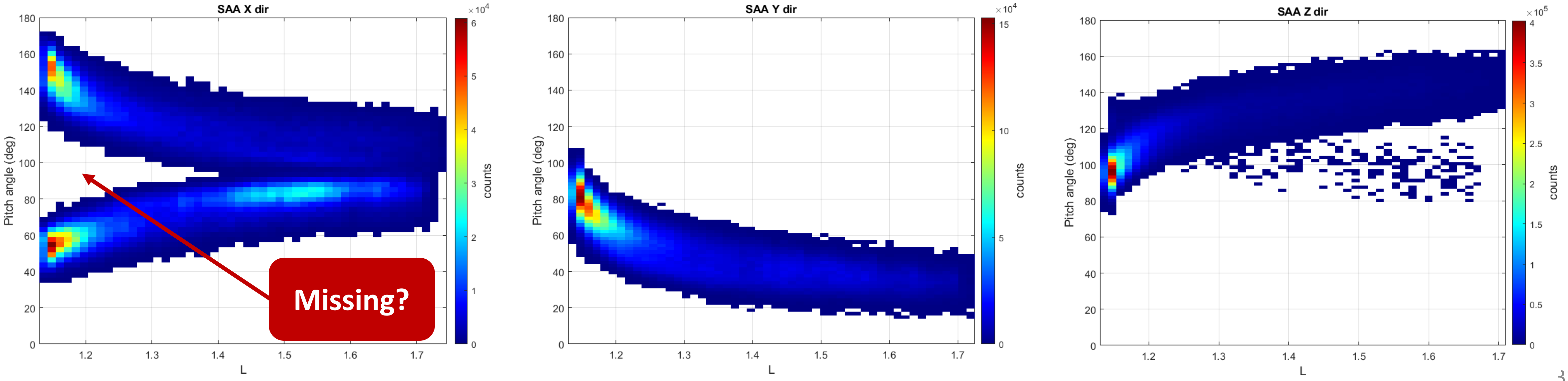


Pitch Angle, α

ALtea

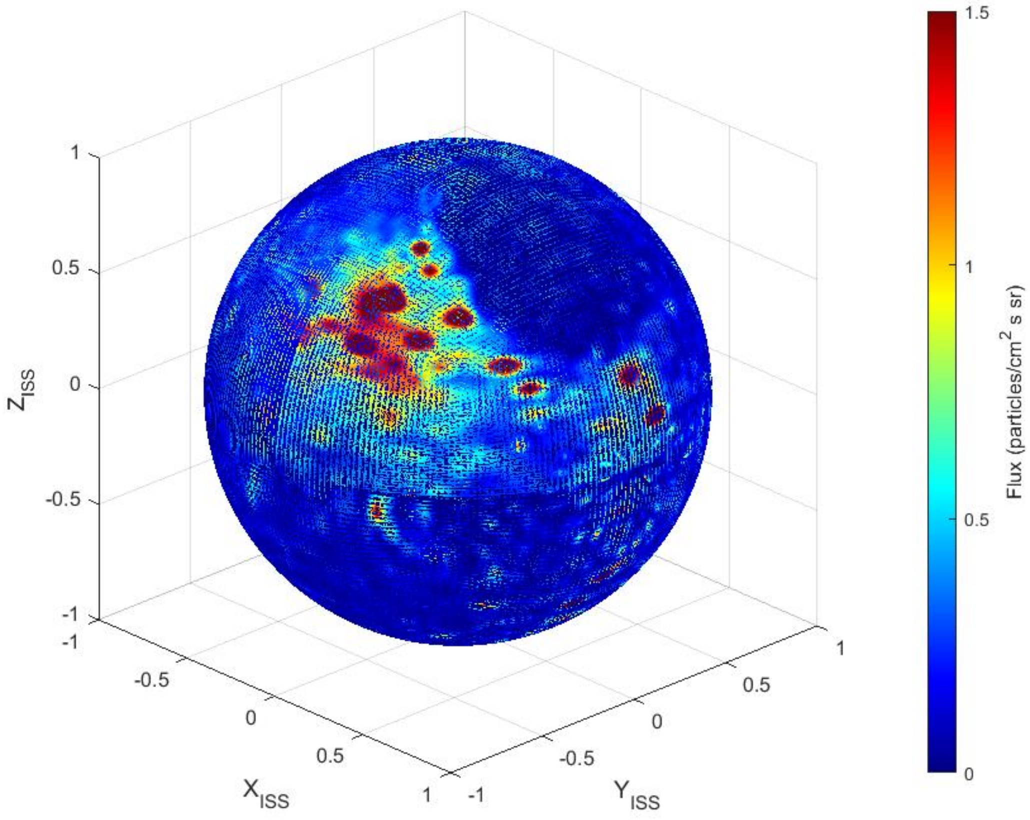


LID



Conclusions

- LIDAL can operate as a **dual detector**
- Understanding why LID fluxes are lower than DOSTEL’s and REM’s
- SAA radiation field directionality characterization
- LIDAL can provide information on different particle populations within the SAA geomagnetic region.
- First SAA particle kinetic energy spectrum within a space habitat



SAA flux **anisotropy** within the ISS habitat as measured by ALtea

THANK YOU FOR THE ATTENTION!

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