PAN: Penetrating Particle Analyzer

In situ measurement instrument on the Lunar Orbital Platform-Gateway (formally DSG) or other planetary missions

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Solar Energetic Particles (SEP), Solar Modulation and Space Radiation: New Opportunities in the AMS-02 Era *#3*

April 23rd - 26th 2018, *Washington DC*

Presented at the ESA DSG Workshop, Dec. 5-6, 2017

DEEP SPACE GATEWAY

- Overview
- Opportunities
- Call for Ideas
- Workshop

PROSPECT

WORKSHOP: RESEARCH OPPORTUNITIES ON THE DEEP SPACE GATEWAY

In August 2017, the European Space Agency issued a Call for Ideas for Research Opportunities on the Deep Space Gateway. Submissions received in response to this Call will be presented and discussed at a workshop to be held at the European Space Research and Technology Centre (ESTEC), ESA's technical heart in Noordwijk, The Netherlands, on 5 and 6 December 2017.

23-Jan-2018 07:00 UT

Shortcut URL

http://exploration.esa.int/jump.cfm?oid=59377

Presented at the NASA DSG Workshop, Feb. 27 – Mar. 1, 2018

Meeting Location and Date

The Deep Space Gateway Science Workshop will be held February 27–March 1, 2018, in Denver, Colorado, at the Westin Denver International Airport Hotel.

NASA is sponsoring this three-day workshop to actively engage scientific communities in the early stages of determining the ways the gateway will be used to facilitate science. Attendance is by invitation only based on abstracts received, and invitations are expected to be sent mid-January 2018. We invite anyone interested in the science to be accomplished at the deep space gateway to submit an abstract for consideration.

COSPAR 2018

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PENETRATING PARTICLE ANALYZER (PAN)

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Geneva – Perugia – CERN – Prague – Huston – FHNW – IDEAS – ASI ...

Introduction

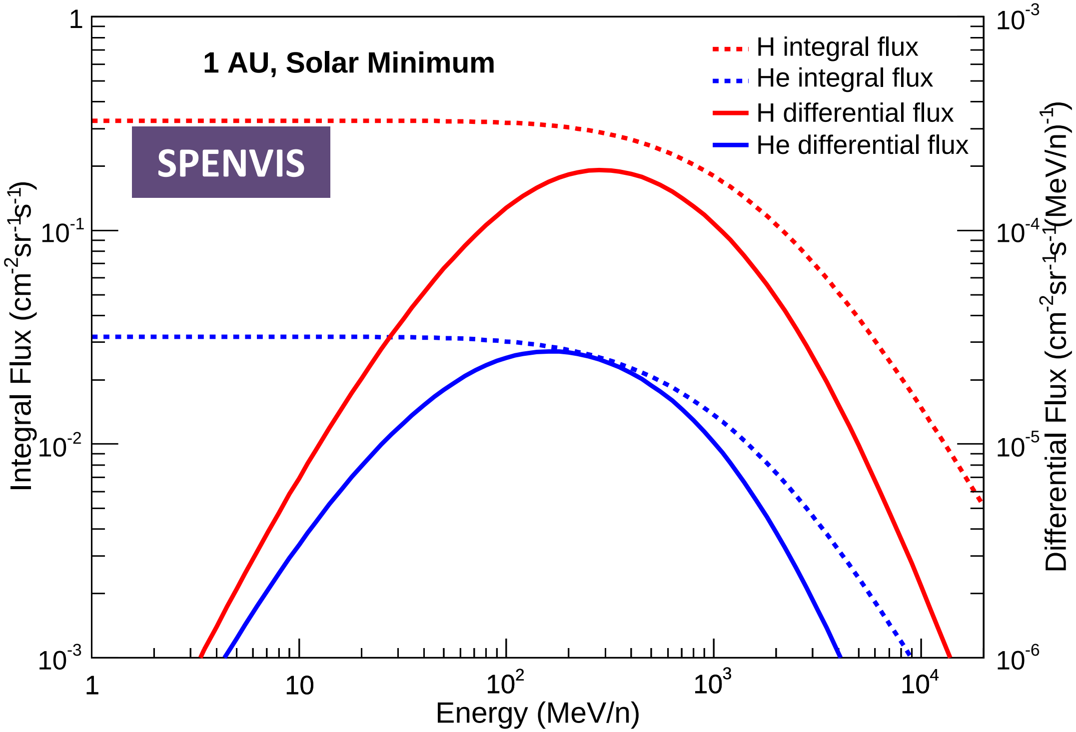
- PAN is a scientific instrument for deep space and interplanetary missions. It can precisely measure and monitor in real time the flux, composition, and direction of penetrating particles (> ~100 MeV/nucleon) in deep space.
- **Science goals: multi-disciplinary and cross-cutting**
  - *Cosmic ray physics*: fill an in situ observation gap of **galactic cosmic rays** (GCRs) in the GeV region in deep space, crucial for the understanding of the origin of the GCRs, and their interplay with solar activities.
  - *Solar physics*: provide precise information on **solar energetic particles** for studying the physical process of solar events, in particular those producing intensive flux of energetic particles.
  - Space weather: develop **space weather models** from the energetic particle perspective.
  - *Planetary science*: measure and monitor energetic particles to develop a full picture of the **radiation environment of a planet**, in particular as a **potential habitat.**
  - *Deep space travel*: Penetrating particles are difficult to shield. PAN can **monitor the flux and composition of penetrating particles during a space voyage**. PAN can become a standard on-board instrument for deep space travel.

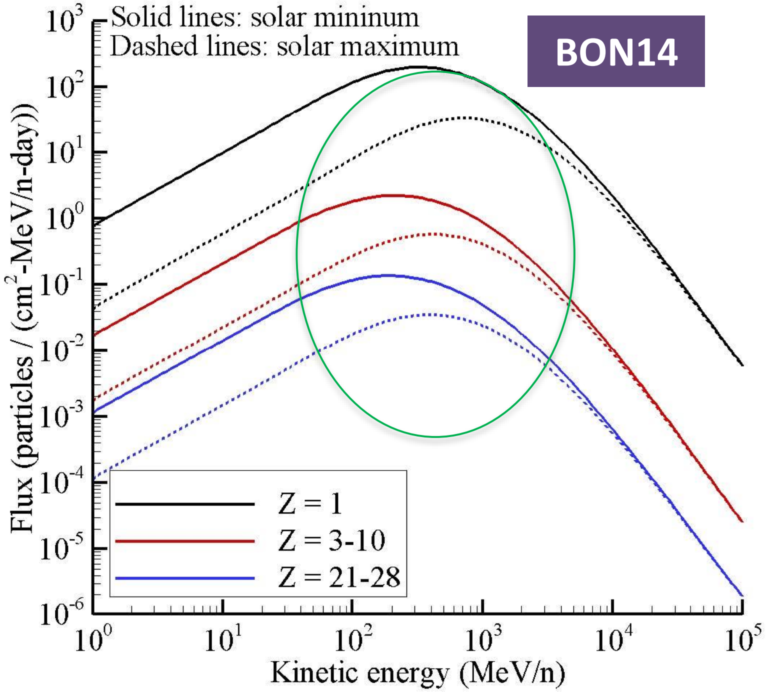
Radiation environment in deep space

- Plasma environment
  - Mainly low energy protons and electrons from solar wind
    - Unperturbed solar wind plasma (<10 keV)
  - Effectively stopped by multiplayer insulation (MLI) sheets (up to 100 keV)
- Particle radiation sources
  - Particles trapped in the Geomagnetic field
    - Negligible at DSG and beyond
  - Solar Energetic Particle (SEP)
    - Particles from solar eruptions (flare and Corona Mass Ejection)
    - Dominant at low energy (< 100 MeV), come in bursts
      - "GeV" Solar Particle Events rare but potentially damaging/dangerous
    - Main contributor to unshielded Total Ionization Doses (TID)
  - Galactic Cosmic Rays (GCR)
    - Dominant at high energy (> 100 MeV), peak at ~1 GeV/n
    - Modulated by solar activities
    - Has not been measured in situ in deep space in 100 MeV/n – 20 GeV/n
    - Important contributor to shielded TID for long missions

Galactic Cosmic Ray Flux at 1 AU

- Cosmic ray flux can be calculated with ESA's SPENVIS tool kit (or NASA's BON14)
  - Use ISO-15390 (Nymmik) standard model, at Solar Minimum (May 1996)





O'Neill, Golge, Slaba, NASA TP 218569, 2015

- Galactic cosmic ray flux in deep space modulated by solar activity
  - Variation ~x10 at 100 MeV
- Would be very useful to measure the solar modulation in the ~GeV region directly with the same instrument for a full solar cycle

Model and Data Comparison at 1 AU

- Many missions measure low energy cosmic ray flux up to ~100 MeV/n in deep space
  - IMP-8 (1973-2006), GEOS (since 1975), SOHO (since 1995), ACE (since 1997), …
  - ~GeV flux only measured by LEO/balloon missions using data near Earth at high altitude regions, not direct in deep space (close but not the same)

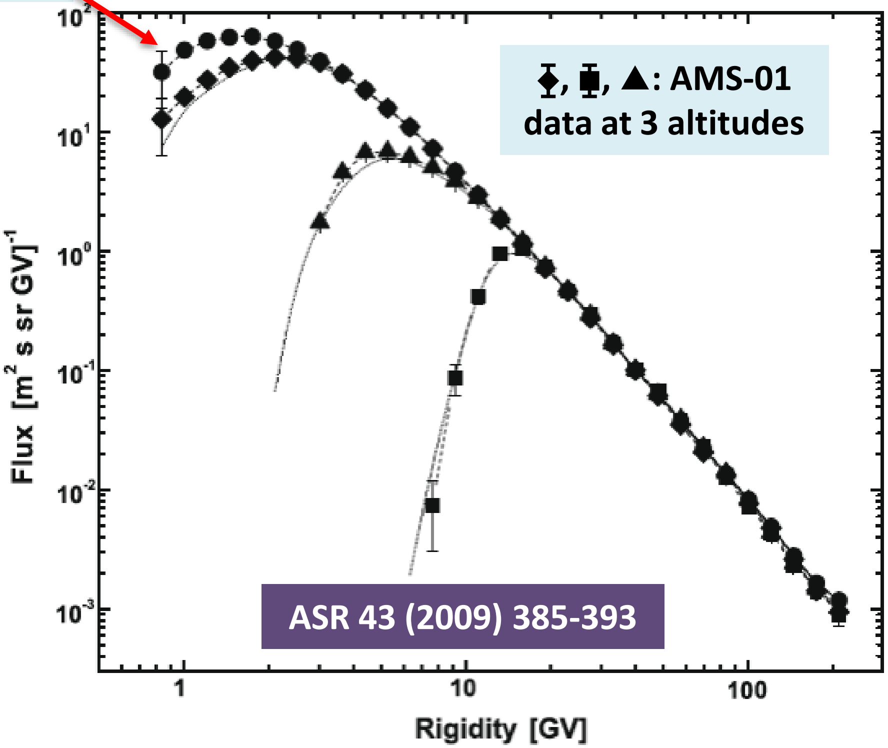
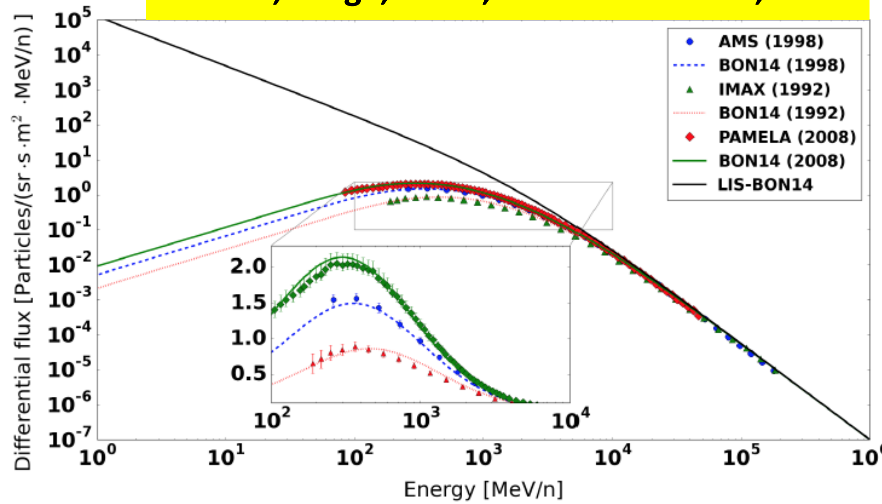


Fig. 3. Fluxes of He nuclei inside the magnetosphere. Values obtained using Eq. (4) (short-dots lines) are compared with AMS-01 data (symbols) for the three super-regions: SMa (squares), SMb (triangles) and SMc (diamonds). The full-circle data are those at 1 AU outside the magnetosphere.

BON14: includes LEO/balloon data (AMS 1998, PAMELA, …)

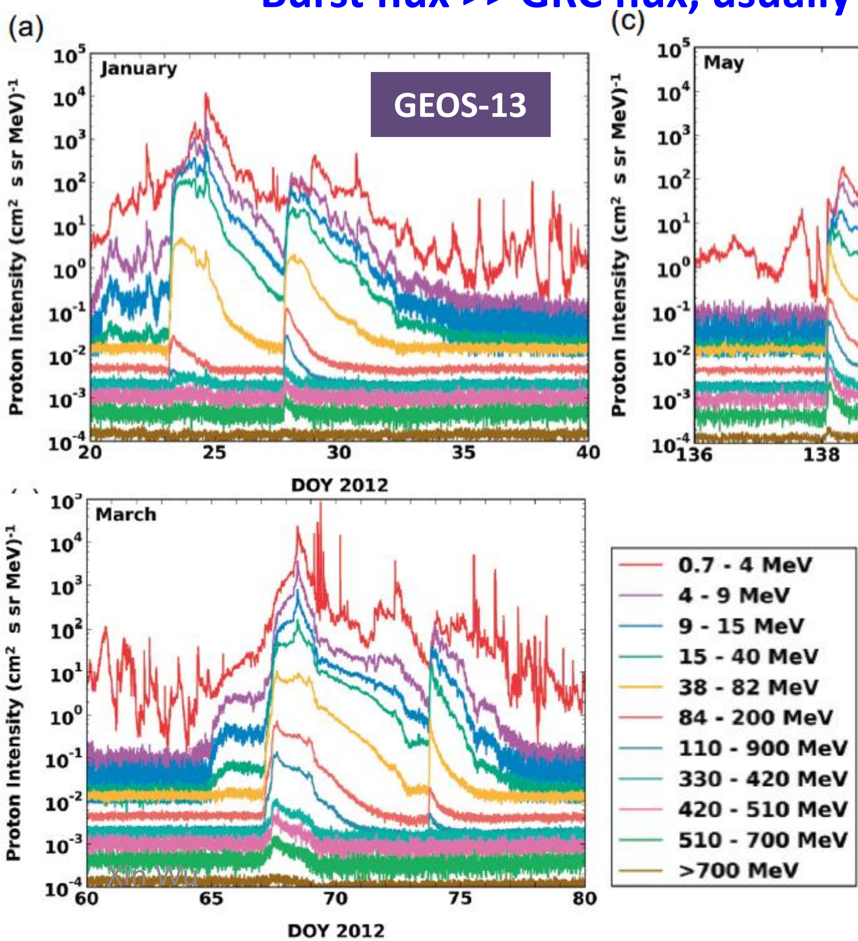
O'Neill, Golge, Slaba, NASA TP 218569, 2015

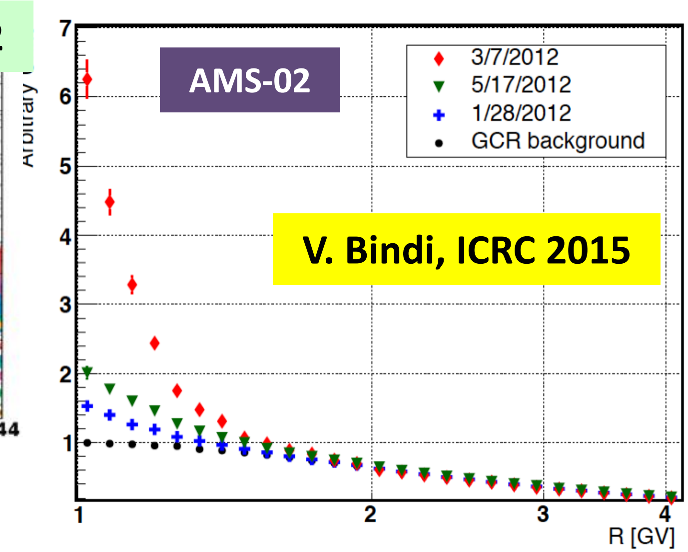


Direct measurements of GCR fluxes at 0.1-20 GeV can help to further improve the GCR interstellar and interplanetary models

Solar Particle Events (SPE)

- **SPE: solar events that produce SCR, also called Solar Radiation Storms**
  - **A few days at a time, a few per year on average (correlated to solar activity)**
  - **Definition: flux of protons at energies ≥ 10 MeV equals or exceeds 10 proton flux units (1 pfu = 1 particle $cm^{-2}s^{-1}sr^{-1}$)**
  - **Burst flux >> GRC flux, usually <100 MeV, with rare "GeV storms"**





- **Peak flux of proton >10 MeV can jump by a factor of 10^3-10^5, up to 10^5 pfu**
- **Normally much less for proton >100 MeV, but can jump to 1- 1000 pfu (SPE, no EVA)**

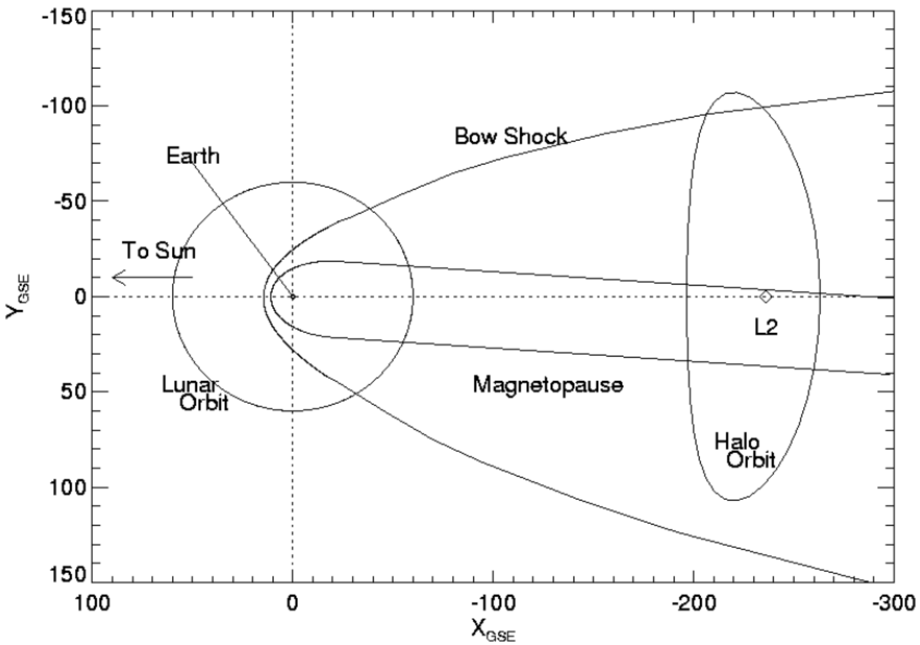
NOAA SPE Scale

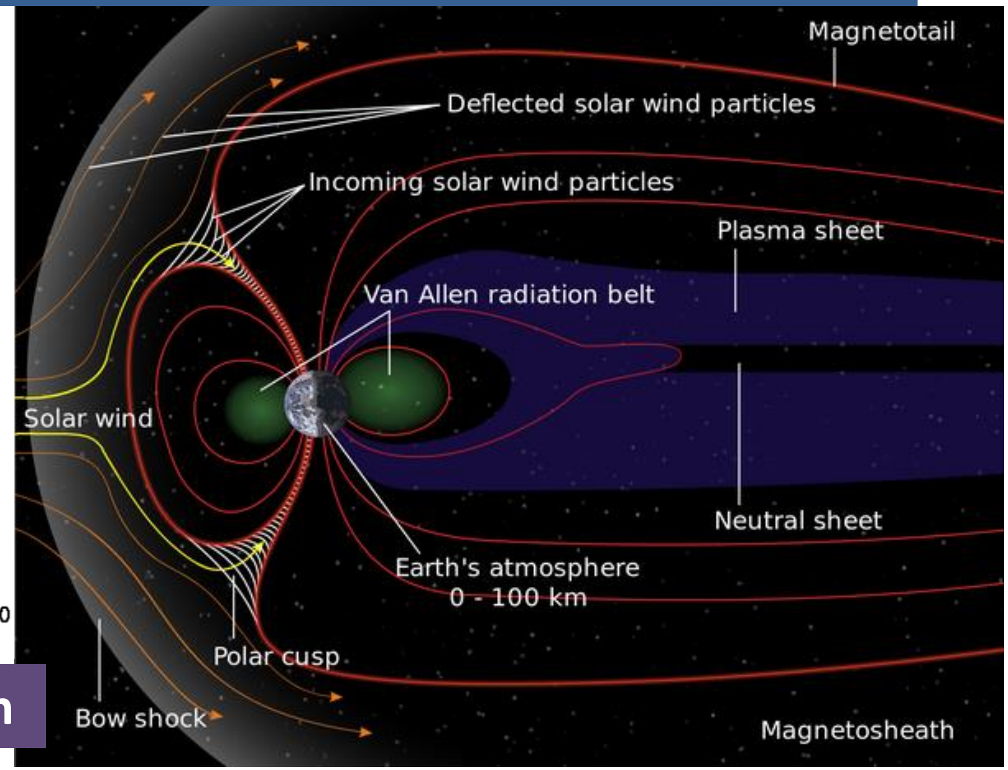
Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk. *** Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** Satellite operations: infrequent single-event upsets possible. Other systems: effects on HF propagation through the polar regions, and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·$ster^{-1}$·cm^{-2} Based on this measure, but other physical measures are also considered.
** These events can last more than one day.
*** High energy particle (>100 MeV) are a better indicator of radiation risk to passenger and crews. Pregnant women are particularly susceptible.

- **SPE scale defined with level of >10 MeV ion flux**
  - **10^5 pfu: Extreme, fewer than 1 per cycle**
  - **10^4 pfu: Severe, 3 per cycle**
  - **10^3 pfu: Strong, 10 per cycle**
  - **10^2 pfu: Moderate, 25 per cycle**
  - **10^1 pfu: Minor, 50 per cycle (correlated with solar activity, 14 in 2012)**

Earth's Magnetosphere and the Moon Orbit

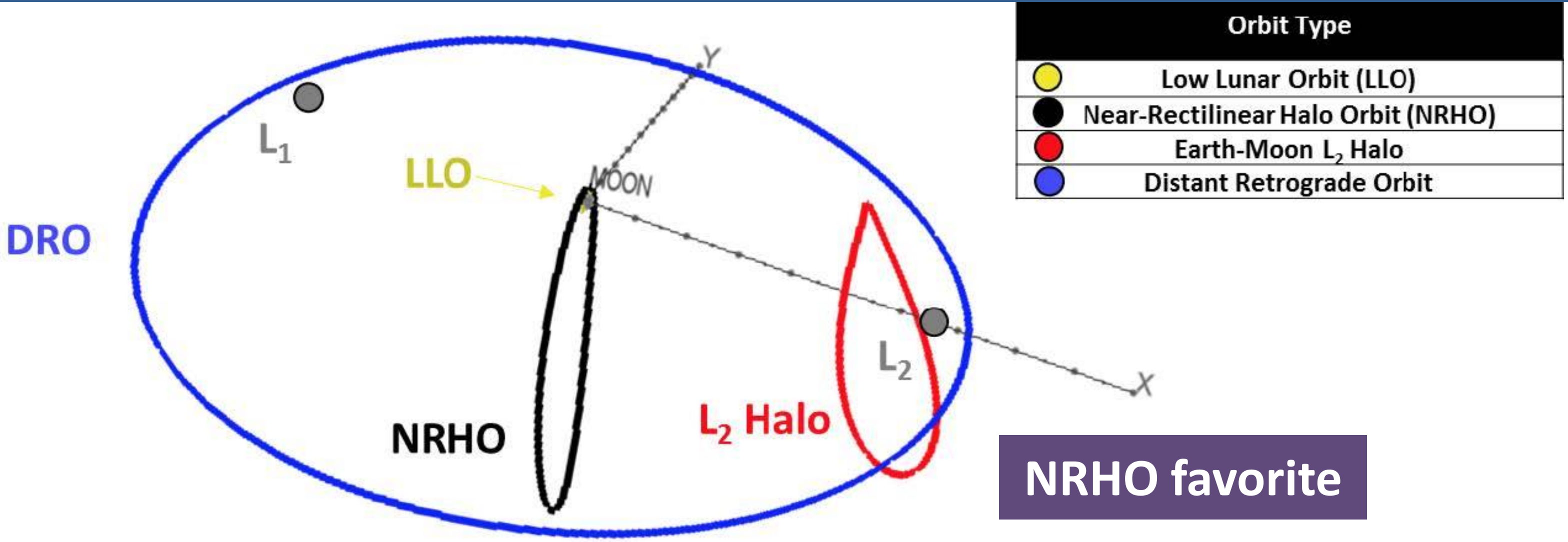




Moon in the magnetotail ~6days/month

- **R_E = 6371 km**
- **Outer Van Allen belt outer edge: 66,000 km (~10 R_E)**
- **Distance to Bow Shock nose: 90,000 km (~15 R_E)**
- **Average distance Earth-Moon : 385,000 km (~60 R_E)**
- **Sun-Earth L1/L2 (ACE/Planck orbit): 1.5×10^6 km (~235 R_E)**

Potential DSG Orbits

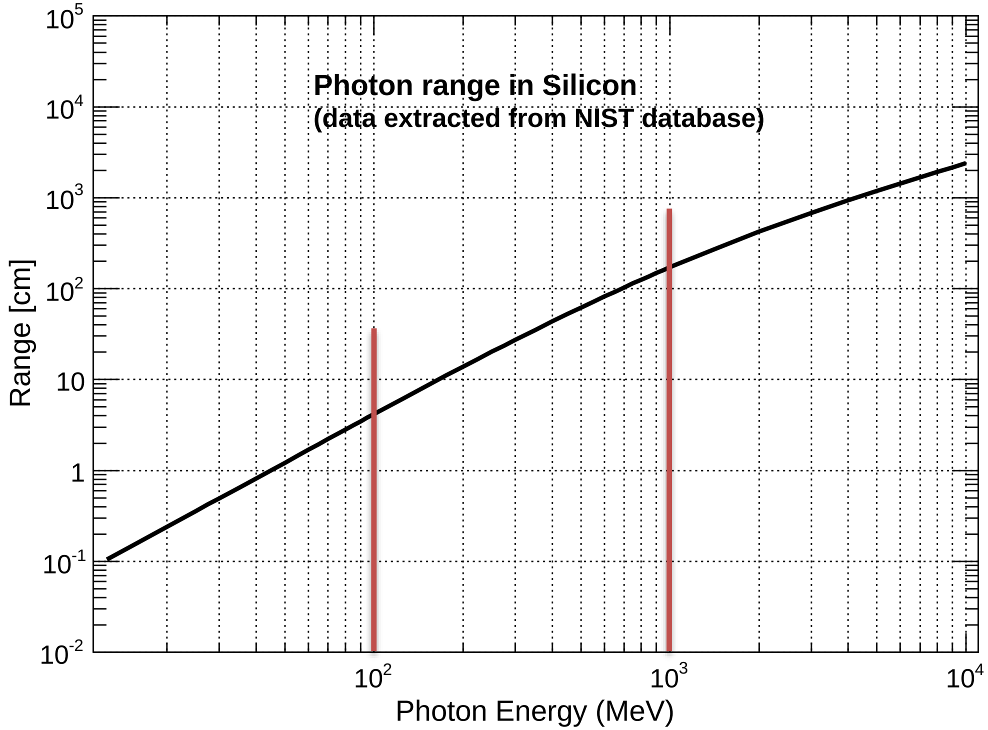


NRHO favorite

Orbit	Property	Value
Near Rectilinear Halo Orbit	Period	6-8 days
	Orbits around	Moon
	Distance to lunar surface	Approx. 2,000 to 75,000 km
	Inclination	Approx. 90°
	Earth visibility	Constant
Earth-Moon L_2 Halo Orbit	Period	8-14 days
	Orbits around	Earth-Moon 2nd Lagrange point
	Distance to Moon	60,000 km
	Earth visibility	Constant

Challenge of measuring GeV protons

- Energy of GeV protons cannot be measured by the ΔE – E method used for low E
  - Only ~4 cm Si to stop 100 MeV protons, but 170 cm Si to stop 1 GeV protons
  - Nuclear interaction length of Si = 46.52 cm ⇒ even with 170 cm of Si, more likely to produce a hadronic shower before losing all the energy by dE/dx
    - If use a calorimeter ⇒ too thick, bad resolution (typically 30-40%)

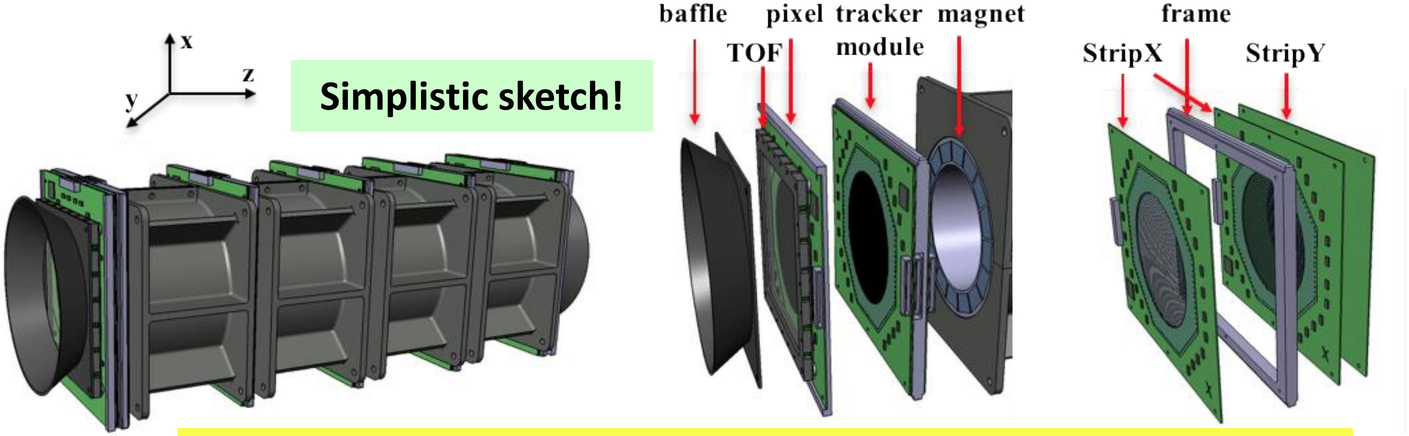


Solution: use magnetic spectrometer to measure rigidity, then infer the momentum and energy with independently measured Z

PAN Instrument proposal to LOP-G

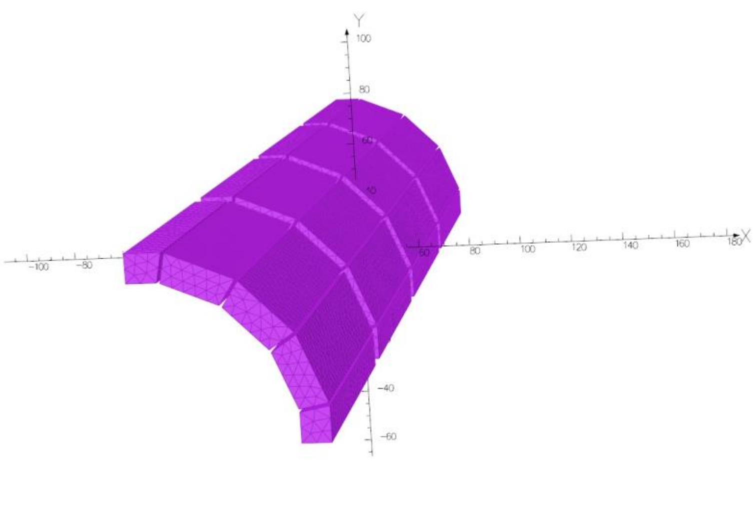
- **Light weight (20 kg) low power (20 W) spectrometer with permanent magnet**

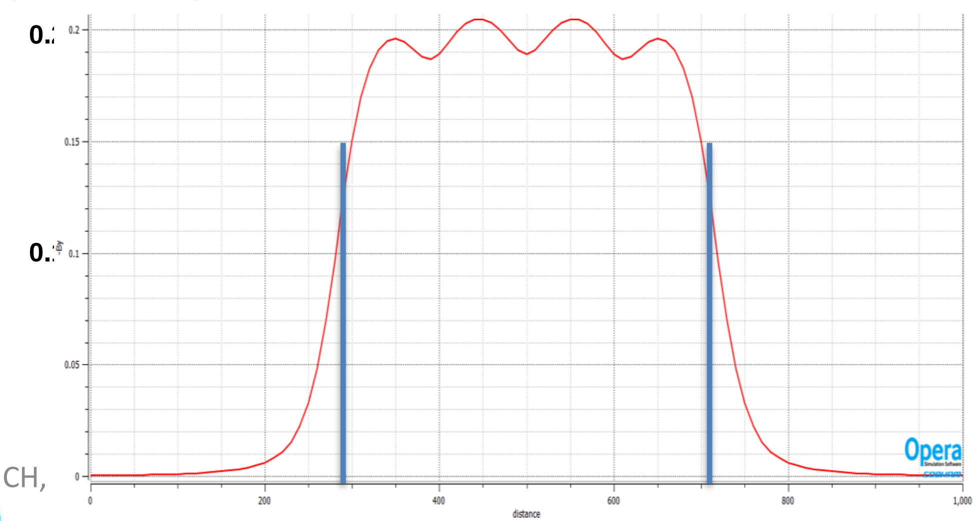
Simplistic sketch!



Measure particles coming in from both ends (symmetric)

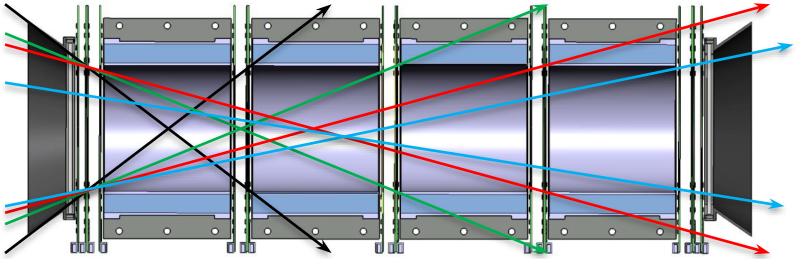
- **4 Halbach permanent magnet sectors, each ϕ = 10 cm, L = 10 cm, provide a dipole magnetic field of ~0.2 Tesla, total weight ~11 kg**

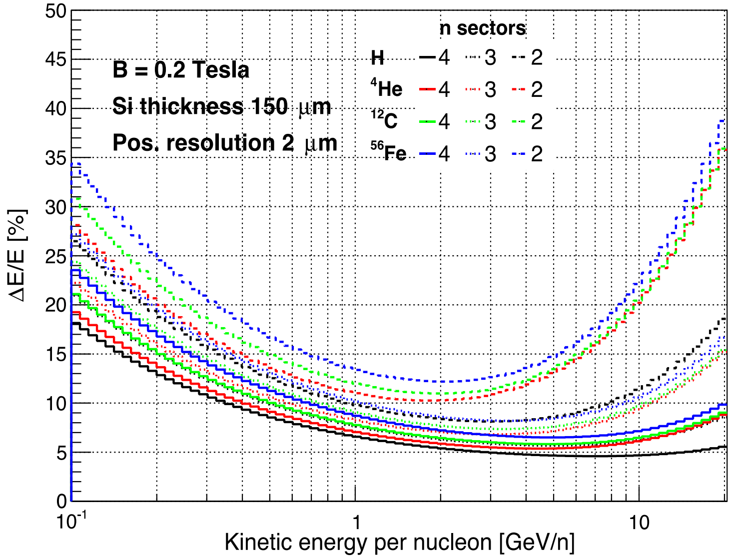


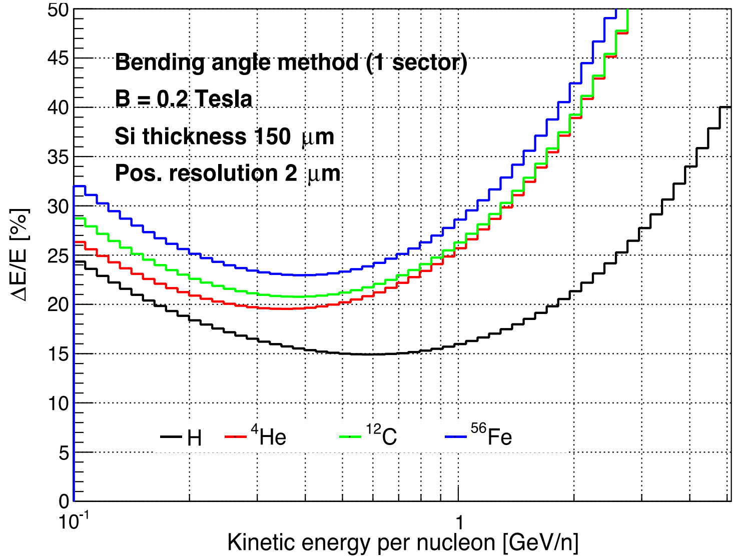


PAN measurement principle

- **Measure momentum by both radius and bending angle, to have large acceptance**
  - **GF: ~32, 10, 5, 3 cm^2sr (x2 for isotropic sources), for crossing 1, 2, 3, 4 sectors**
  - **Open angle 25, 33, 47, 80°**



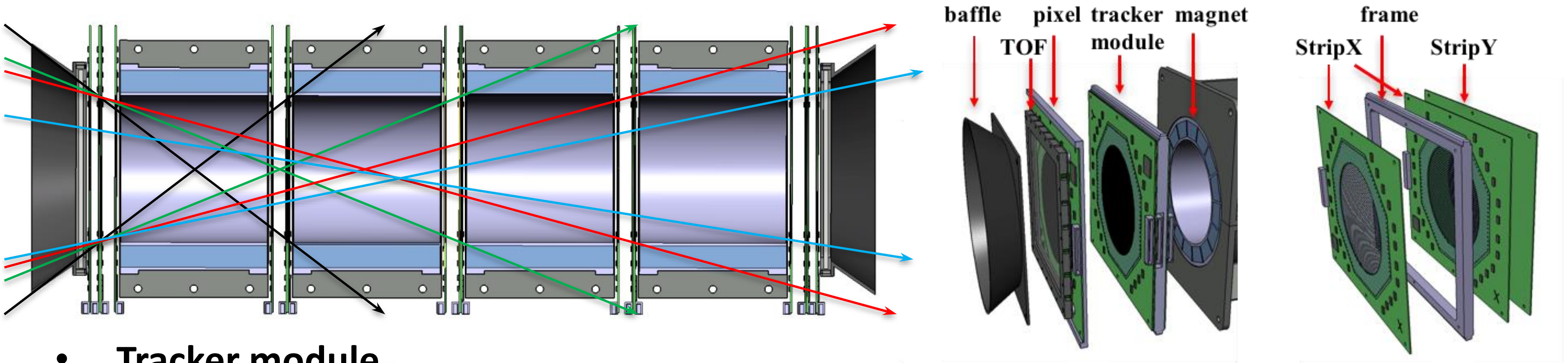




- **Energy resolution <10% for protons of 0.4 – 20 GeV for 4-sector acceptance**
  - **<20% for protons of 0.2 – 2 GeV for 1-sector acceptance**

PAN detector modules

- **5 tracker modules, 2 TOF modules, 2 pixel modules**



- **Tracker module**
  - 2 StripX: 25 µm readout pitch, 150 µm thick, **2 µm resolution**, to measure both bending radius and bending angle, 40k channels, total power budget 8W
  - 1 stripY: 500 µm readout pitch, 150 µm thick, high dynamic range ASIC for Z = 1 – 26, trigger signal, time stamp (<100 ps resolution), 1k channels, total ~1 W
- **TOF module**
  - 3 mm thick scintillator, read out on all sides by SiPM: trigger, particle counter (max. ~10 MHz), charge measurement (Z = 1 -26), time (<100 ps), total ~1 W
- **Pixel module**
  - Avoid measurement degradation for high rate solar events
  - Issue to be resolved: total (static) power consumption ~2-4 W, for ~190 cm^2

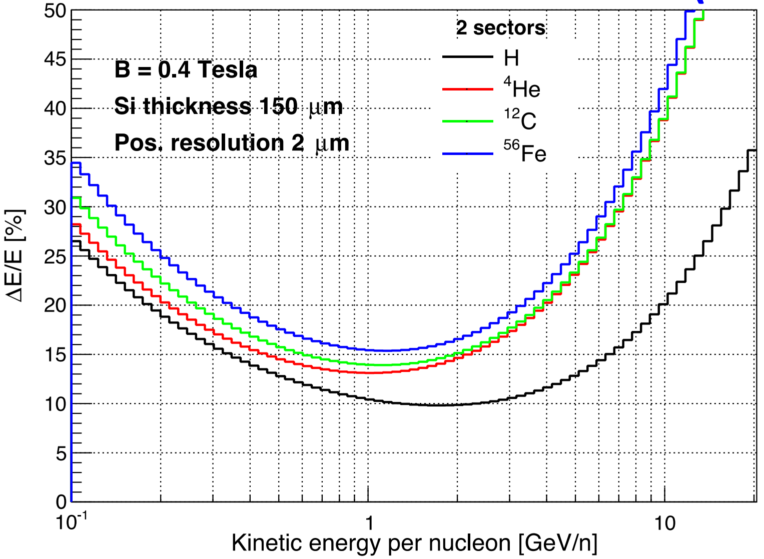
Role of the pixel detector

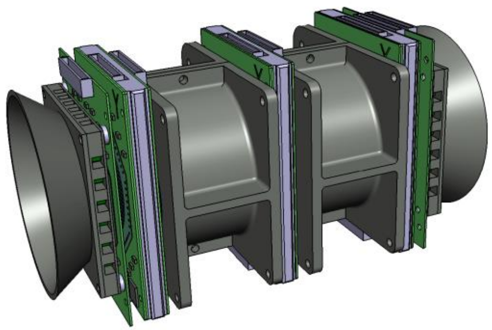
The key of the PAN design is to optimize resource utilization for both long term low rate (GCR) and short term high rate (SEP) operation

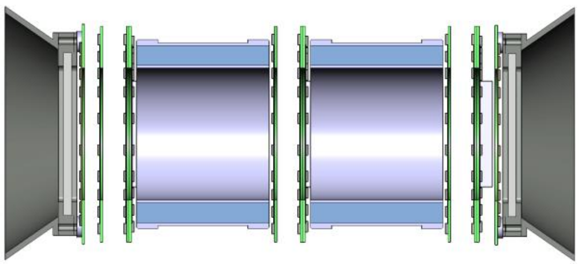
- At high rate (S5 SEP events)
  - Improve measurement of triggered events: TOF pileup and Si layer multi-hits
    - Pixel, no pileup: provide unambiguous charge and 3d points
  - Non-triggered pixel hits, ~2.4 MHz
    - Pixel is working "standalone", so energy information limited, but at least can provide an integrate flux measurement for >20 MeV
  - Requirement: up to 5-10 MHz (~95 cm^2) → ~1.5-3 Hz/pixel
- At lower rate (up to S4 SEP events)
  - 1 extra 3d point
    - With 4-10 μm position resolution, improve energy resolution
    - With ~100 μm position resolution, help pattern recognition
  - 1 extra charge measurement
    - At least for lower Z, effective limit to be investigated

Mini.PAN for planetary missions

- Smaller device for in-situ radiation measurement and monitoring, not for cosmic ray or solar physics
  - 2 Halbach permanent magnet sectors, each ϕ = 5 cm, L = 5 cm, provide a dipole magnetic field of ~0.4 Tesla, magnet weight ~2 kg, total < 5 kg
  - GF: ~6.3 or 2.1 cm^{2}sr (x2 for isotropic sources, for crossing 1 or 2 sectors







Can be simplified further with only one-side sensitive

- Energy resolution <20% for p of 0.2 – 10 GeV for 2-sector acceptance
- Energy resolution for 1-sector acceptance same as PAN (<20% for protons of 0.2 – 2 GeV)
  - Shorter sector length compensated by stronger B field

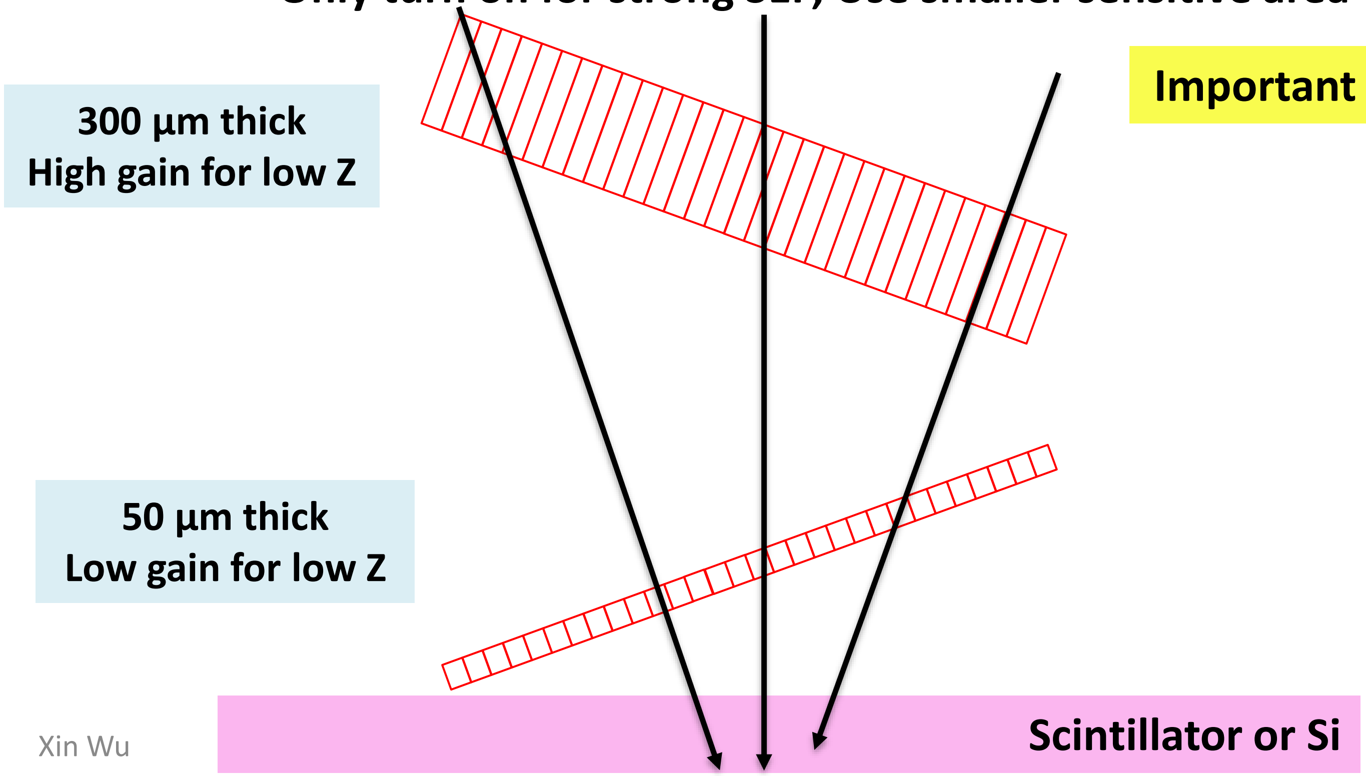
Can add a few layers of Si detectors to measure 10 MeV – 20 MeV with the classical ΔE –E method (~2.4 mm of Si) ⇒ full range energetic particle monitor

Can also use pixel detector if power allows

Pixel as low energy "Add-on"

- Add small pixel detectors before TOF to measure flux of 10-20 MeV, without dead-time, up to very high rate → cover the full range from 10 MeV – 20 GeV, and Z = 1 – 26, in strongest SEP event with one instrument !
  - Use dE/dx – E method: dE/dx by pixel, E by Scintillator (or silicon)
  - 2 layers, thick-thin, tilted, to ensure good direction and Z measurement
  - Mitigation for power consumption
    - Only turn on for strong SEP, Use smaller sensitive area

Important to have large DNR



Conclusion

- **Direct measurements of penetrating particles (100 MeV/n – 20 GeV/n) in deep space are important**
  - **New window for for cosmic ray physics and solar physics**
  - **Unique input to space weather modeling and forecasting**
  - **Indispensable for human deep space missions**
  - **Important for planetary exploration**
- **Magnetic spectrometer is the most suitable measurement technique in this range**
  - **Basic principle and technologies demonstrated by PAMELA and AMS-02**
  - **High precision strip detector and high rate low power active pixel detectors are becoming available**
- **PAN is suitable for LOP-G or medium to large solar missions, while mini.PAN is suitable for planetary exploration missions**
- **PAN and mini.PAN can be easily extended to cover the full range of energetic particles (10 MeV – 20 GeV)**

With the growing interests of space agencies on space weather, deep space exploration and human space travel, it seems there is a real opportunity for an instrument like PAN to be realized in the near future!

Thanks you for your attention!