Cosmic Rays & Space Payload

(Our Dream …)

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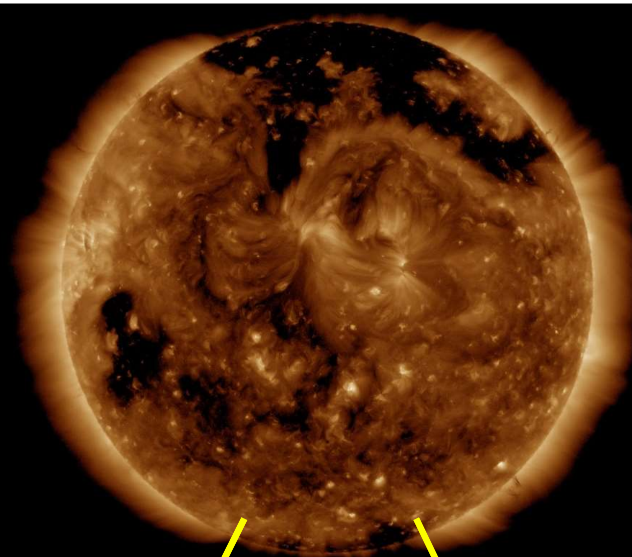
What are cosmic rays?

- Energetic particles and gamma rays from space
- Ordinary matter accelerated to high energies

  Ions ($^{1}H^{+}$, $^{4}He^{+2}$, $^{12}C^{+6}$, $^{16}O^{+8}$, ...), e^{-} , e^{+} … γ, μ^{+}, μ^{-}, n
- Earth's radiation environment … & hazards
- Key historical cause of biological mutations
- Used for hydrology, detection of nuclear material
- Source of many discoveries in particle physics, most recently neutrino oscillations
- Particle component of multimessenger astronomy

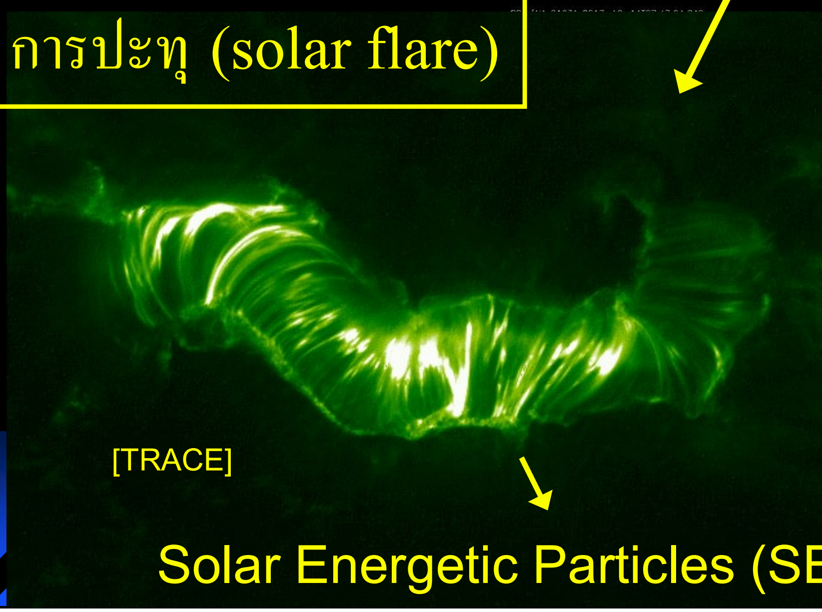
Image credit: www.invisiblemoose.com (WALTA group)

The Sun accumulates magnetic energy ...

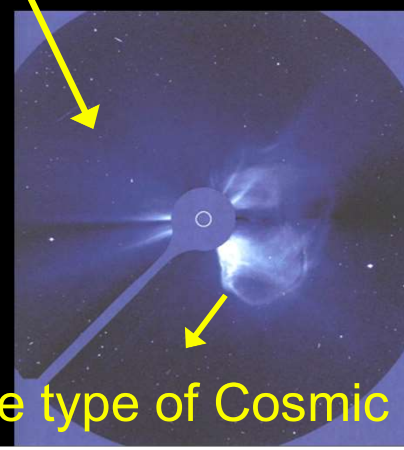


... which is released suddenly in solar storms!

การปะทุ (solar flare)

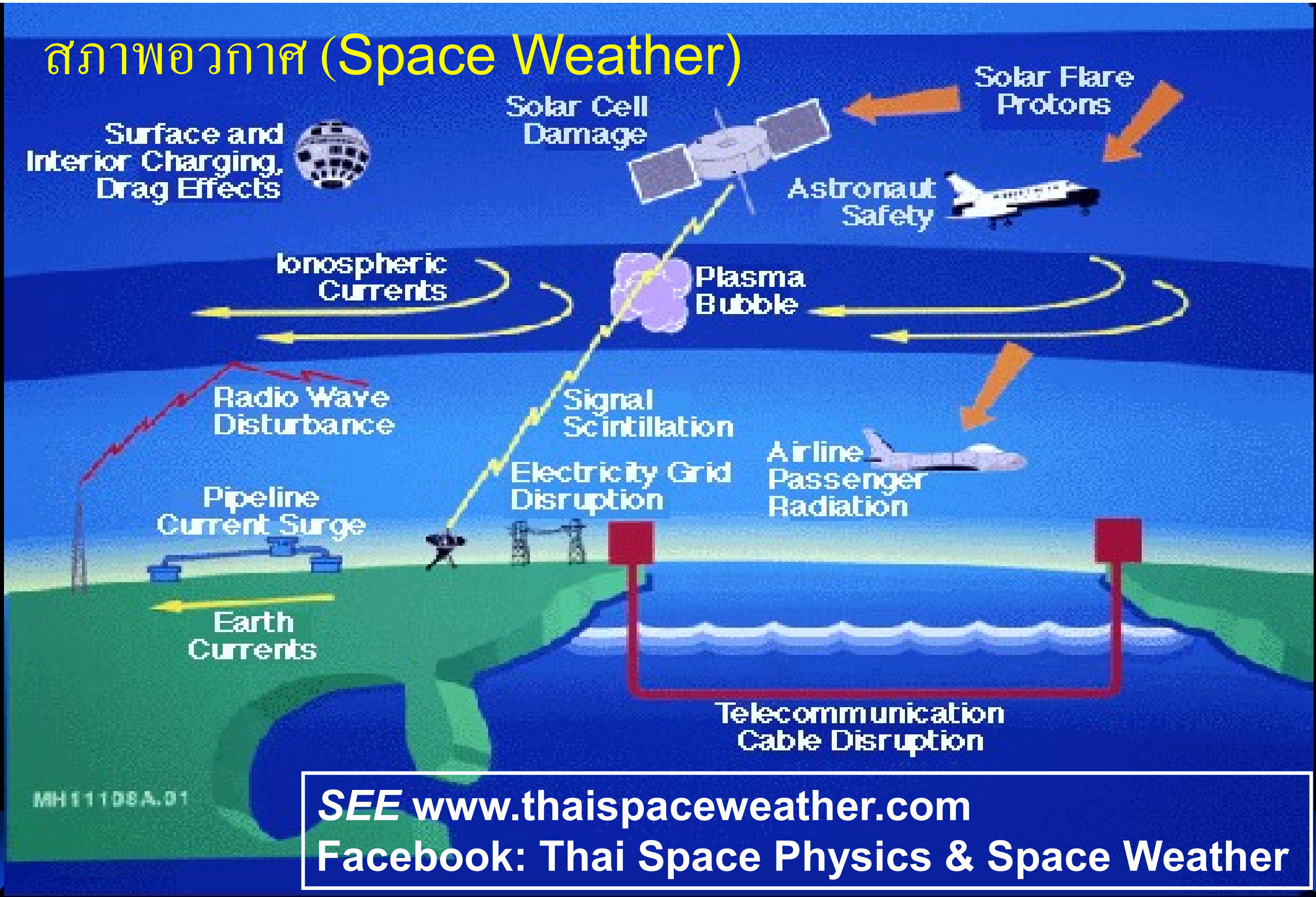


การปล่อยก้อนมวลจากโคโรนา (coronal mass ejection; CME)



Solar Energetic Particles (SEPs), one type of Cosmic Rays

สภาพอวกาศ (Space Weather)



SEE **www.thaispaceweather.com**
Facebook: Thai Space Physics & Space Weather

Image Credit: L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.

SPACE WEATHER EFFECTS
of fast solar wind and solar storms on human activity

- Prompt effects
  - Solar energetic particles, X-rays, EUV
  - Affect astronauts (on distant missions), satellites, ionosphere & GPS, potentially air passengers
- Delayed effects, after 1-4 days
  - CME or fast solar wind arrives at Earth
  - Possible geomagnetic storms (especially for $B_z<0$)
  - Satellite failures, induced currents, possible power outages

Energy loss of an energetic charged particle due to ionization of a medium

is the basis of most detection techniques, especially for energetic ions.

This is described by the Bethe (or Bethe-Bloch) formula (for intermediate *E*):

$$\left\langle -\frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 W_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right].$$

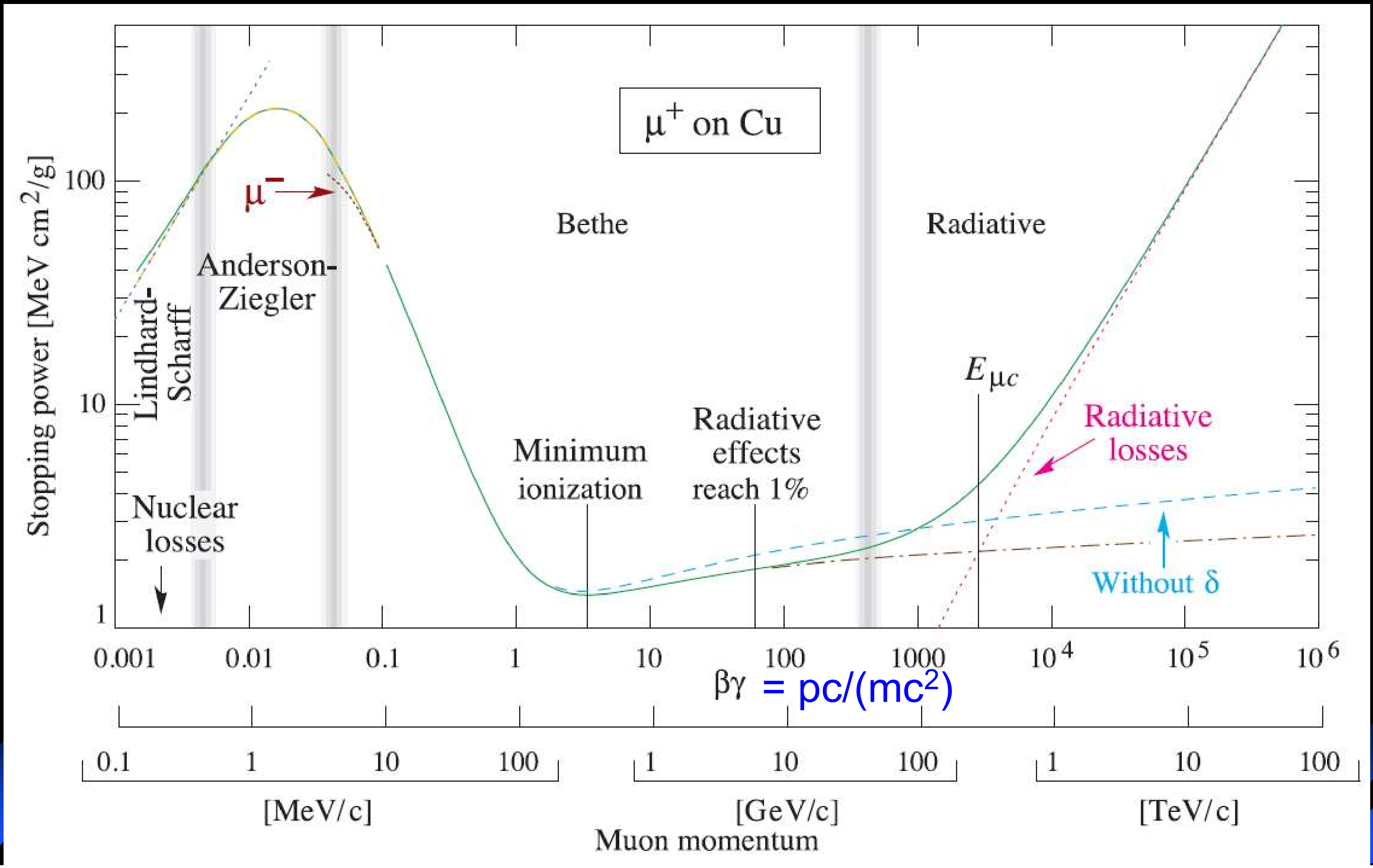
[from Review of Particle Properties, 2020 (34.2)]

Here $\beta = v/c$, γ, M, and z refer to the energetic particle; Z and A to the medium.
W_{max} = maximum energy transferred to an ionization electron,
I = mean ionization energy. δ is the density effect correction (Jackson 1975).

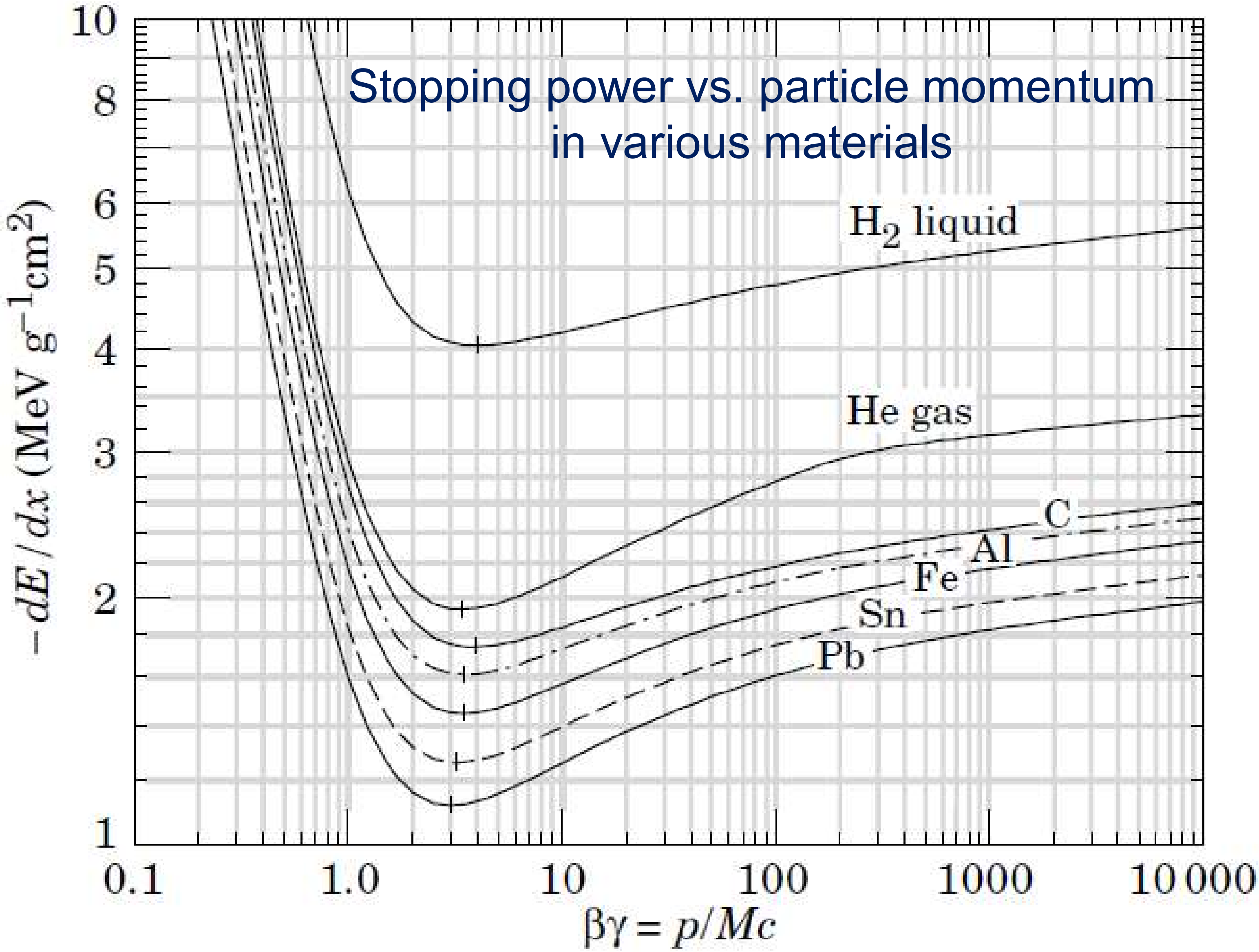
$$W_{\max} = \frac{2 m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}$$

K/A	$4\pi N_A r_e^2 m_e c^2/A$	0.307 075 MeV g^{-1} cm^2 for A = 1 g mol^{-1}
r_e	Classical electron radius $e^2/4\pi\epsilon_0 m_e c^2$	2.817 940 325(28) fm

Stopping power vs. particle momentum



Stopping power vs. particle momentum in various materials

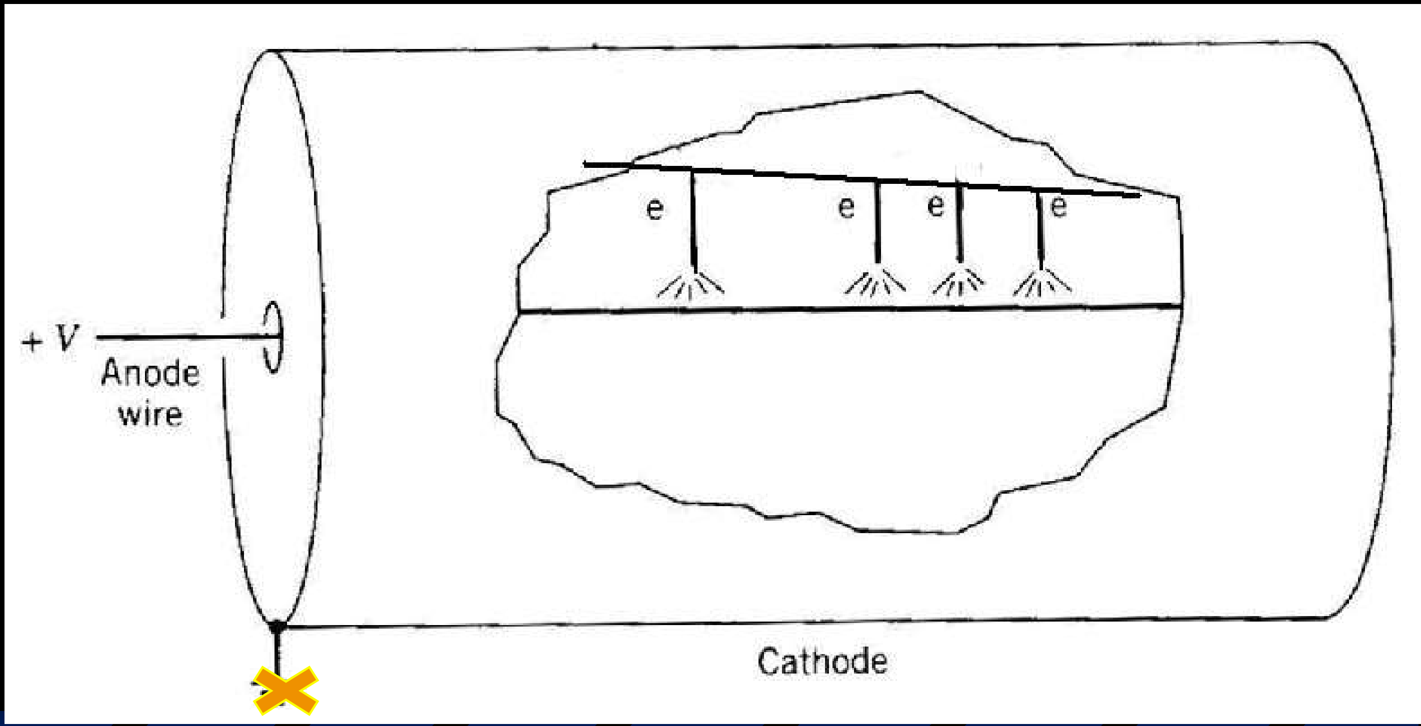


A proportional counter measures the ionization energy loss due to passage of charged particles.

Yellow: Voltages used in our neutron monitors

-2800 V

0 V, signal measured here



Picture modified from

Krane, K.S. *Introductory Nuclear Physics*. John Wiley & Son, 1988, page 205

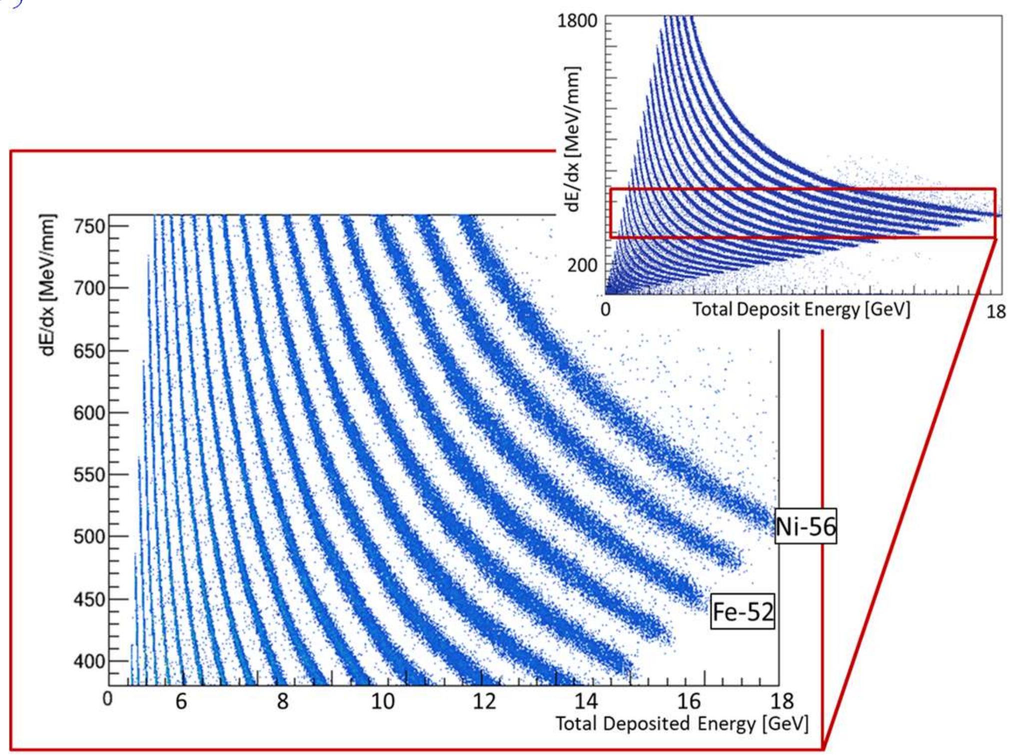
For moderately relativistic charged particles, -dE/d$x \propto z^2/v^2$ and $E \approx (1/2)mv^2$.
Consider using multiple detector layers, including

- thin layers that measure $\Delta E = |\mathrm{d}E/\mathrm{d}x|\ \Delta x$
- a thick layer where the particle stops, which measures E.

Multiplying the two,

$$\Delta E \times E \propto (z^2/v^2)\ mv^2 \propto z^2 m$$

This is the ΔE vs. E technique for identifying particle species.

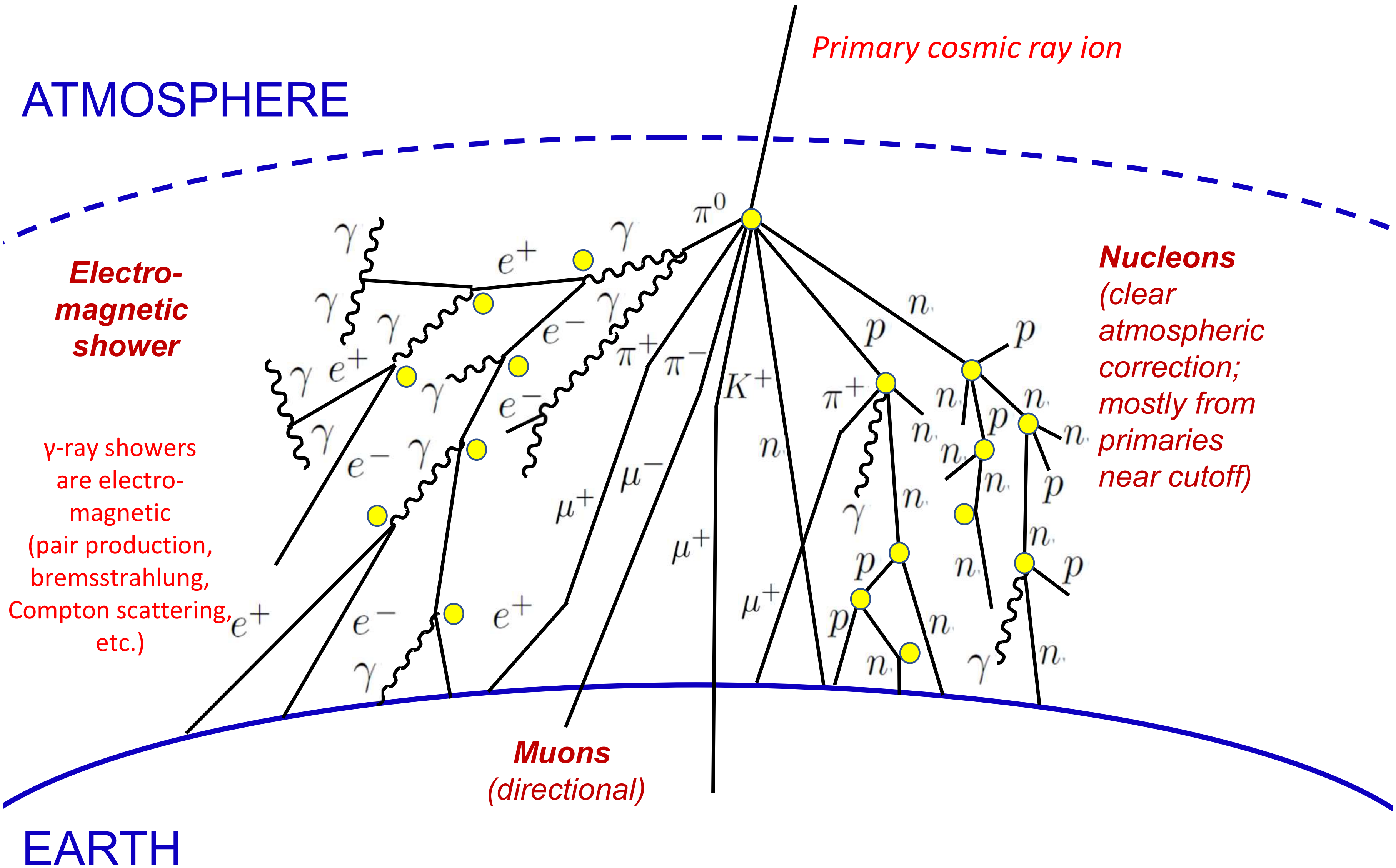


GEANT4 simulation by Dr. Kullapha Chaiwongkhot

For ions, z=Z and $m \propto A$ are discrete:

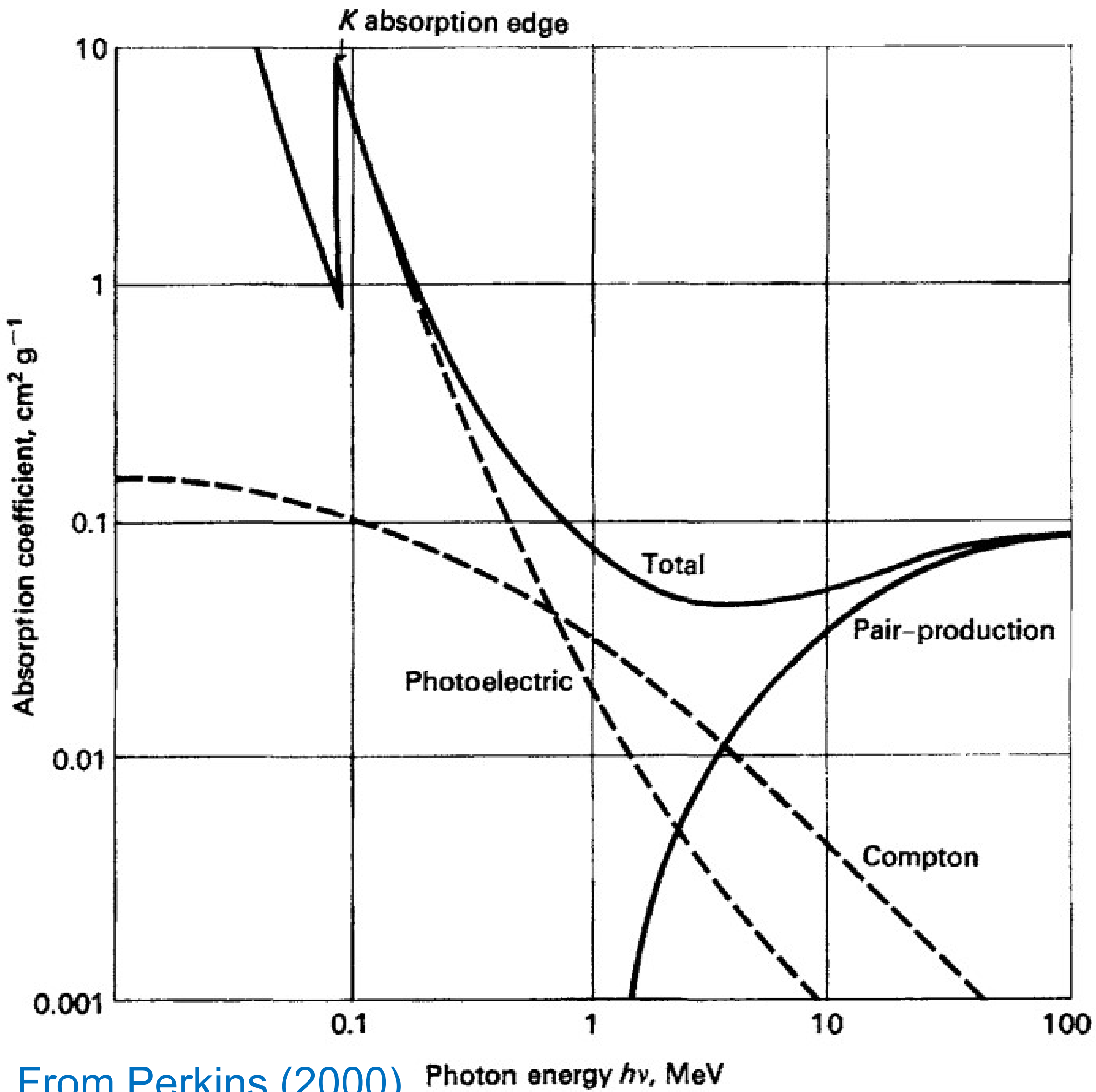
Isotope	Z	A	Z^2A
^{1}H	1	1	1
^{2}H	1	2	2
^{3}He	2	3	12
^{4}He	2	4	16

…



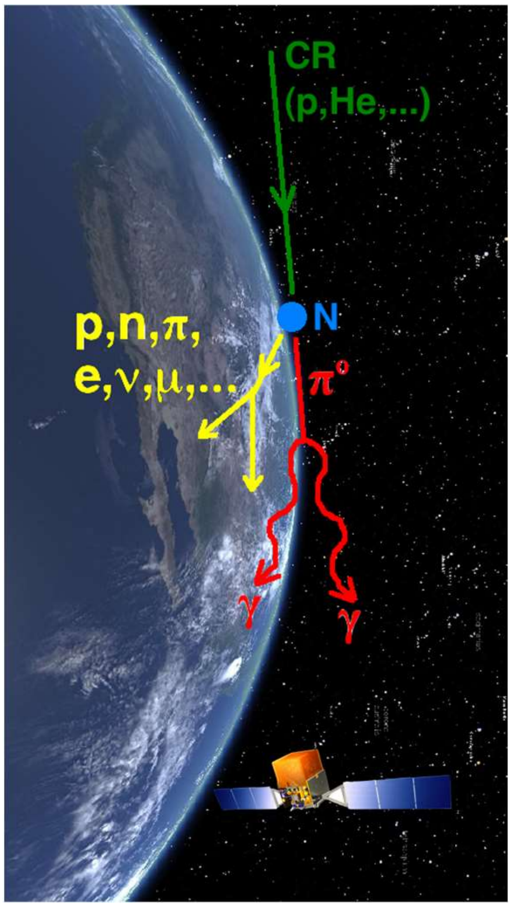
ATMOSPHERE
Primary cosmic ray ion
Electro-magnetic shower
γ-ray showers are electro-magnetic (pair production, bremsstrahlung, Compton scattering, etc.)
Nucleons (clear atmospheric correction; mostly from primaries near cutoff)
Muons (directional)
EARTH

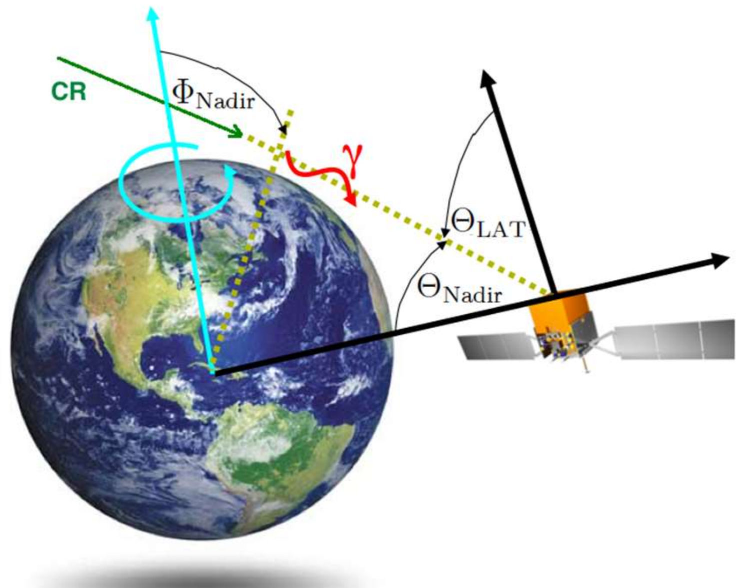
Energy loss (or destruction) of γ-rays



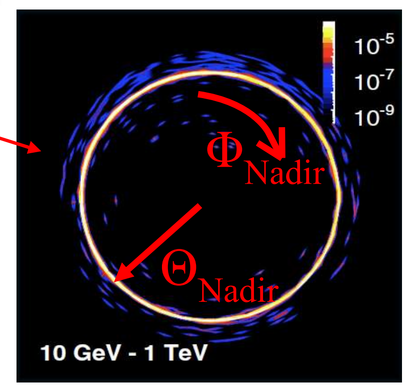
From Perkins (2000)

CR-Induced γ-Ray Emission from Earth's Atmosphere (Warit Mitthumsiri)





- **How Earth "looks" in γ-rays**
- **Physical limb at $\Theta_{nadir} = 67°$**
- **γ-ray emission peaks at $\Theta_{nadir} = 68.1°$**



TSC
Thai Space Consortium

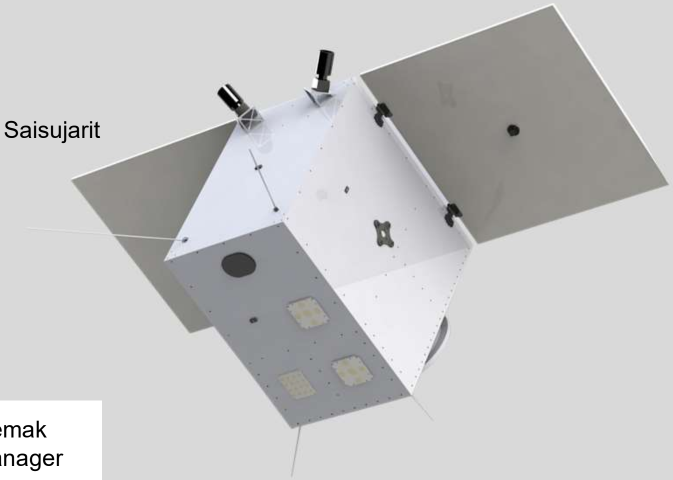
Scientific and Research Satellite TSC-1

KMUTNB

Dr. Phongsathorn Saisujarit
Project manager

NARIT

Phongsakorn Meemak
Deputy project manager



- Microsatellite Mass:~100 Kg.
- SSO orbit at 500 - 600 Km.
- Main Payload equipment :
  - Hyperspectral Imaging Camera 30 m GSD
  - Minor Payload equipment: Space Weather
    Design, integrate and test in Thailand
- Ground station at NARIT and GISTDA
- Data sending: X-band, S-band , UHF
- Data receiving: S-band , VHF

STR&Thermal (NARIT, NSTDA)

Anuphong
Chinphat
Chanoknun

EPS (NSTDA, NARIT, GISTDA)

Methawin
Nipitchon

C&DH (NARIT, GISTDA)

Noppakao

COMMU (NARIT)

Sathit

ADCS (NARIT, KMUTNB)

Paksarun
Wirachai

AIT (NARIT)

Narumit

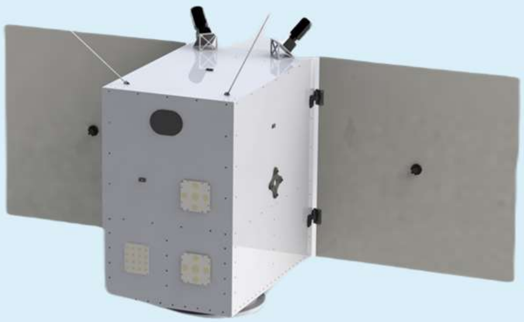
Technical Advisory Team
HSI Payload (NARIT)

MU
SW Payload

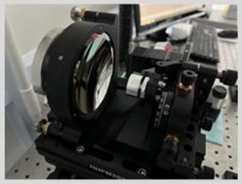
Project Coordinator
Procurement
Engineer (NARIT)

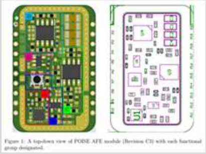
Current Challenges and Opportunities in Space Technologies for human capacity building

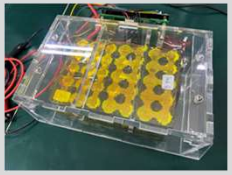
Satellite Subsystem Engineering Adaptation in Related Field

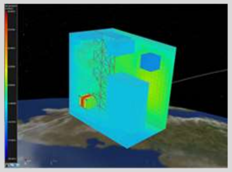


TSC-1 Scientific Satellite



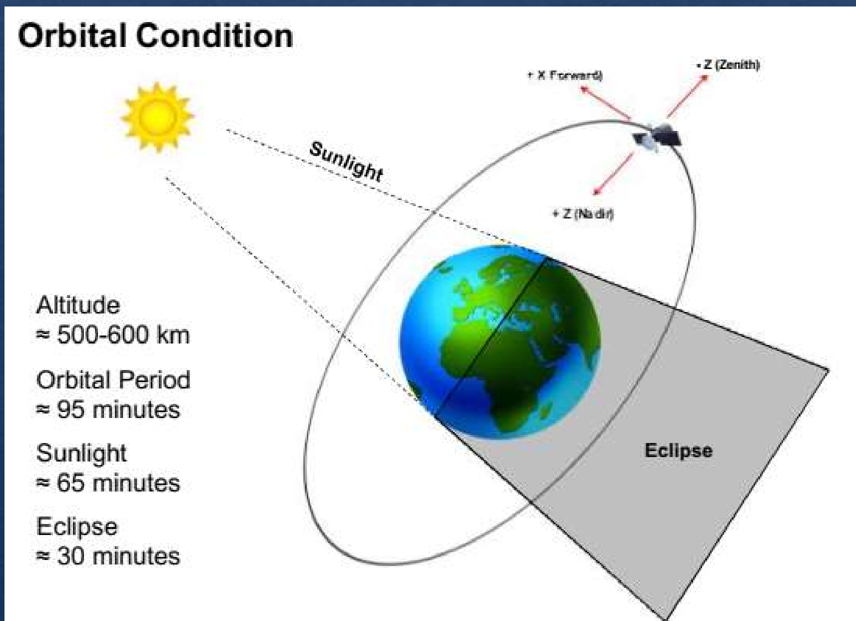






TSC Thai Space Consortium

TSC 1



System Requirement

Titles	Requirement
Dimension	TSC-1 dimension shall be 1m x 1m x 1m.
Weight	TSC-1 weight shall not exceed 100 kg.
Altitude	TSC-1 altitude shall be 500 – 600 km.
Inclination	TSC-1 inclination shall be a sun synchronous orbit at 98 degree.
Lifetime	TSC-1 lifetime shall be at least 3 years of satellite operations.
Coverage Area	TSC-1 mission shall provide Thailand's coverage area.

Missions:
- Hyperspectral Imaging Payload
- **Space Weather Payload**

A Satellite Detector Development:

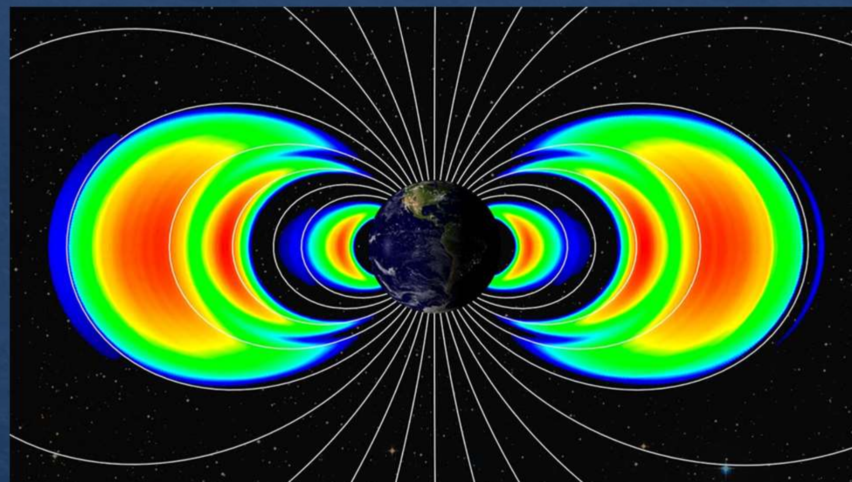
POiSE

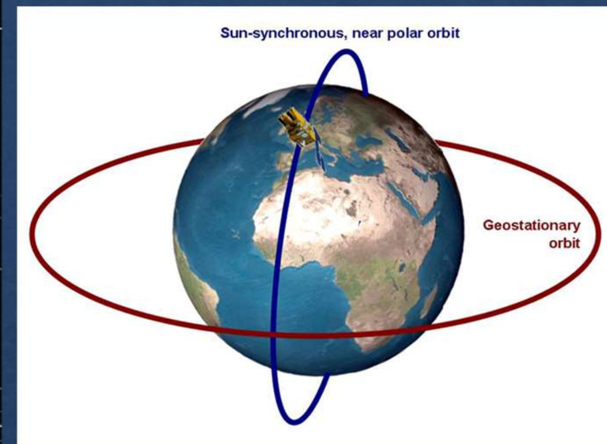
Polar
Orbiting
Ion
Spectrometer
Experiment

By POiS(ons)E

POiSE

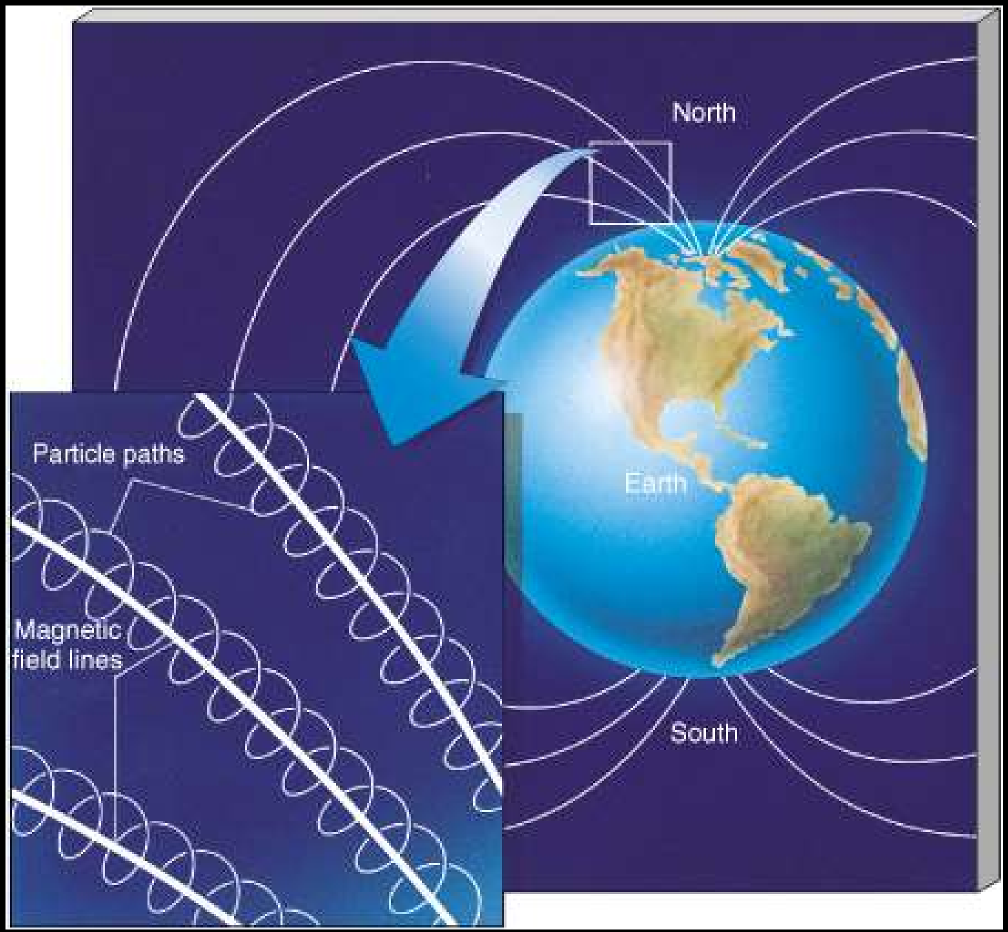
(Polar Orbiting Ion Spectrometer Experiment)





- **Short-term plan (TSC-1):**
  Detection of radiation belt & solar energetic ions of various elements, providing warning of space weather effects and determining charge states via deflection in Earth's magnetic field
  - **Warning function will reproduce some capabilities of other nations**
  - **Charge state measurements of ions ~10 MeV/n were performed over 1992-2004, and are not currently available from any other instruments**
  - **Charge state information is scientifically important (see Ruffolo 1997)**

Low-energy cosmic rays only reach Earth's polar regions; higher energy is needed to penetrate equatorial B field



The trajectory in a magnetic field depends on *pc/q* … so by measuring the magnetic latitude at which ions of a known element and energy are observed, we can infer their charge state *Q*.

Galactic cosmic rays are fully stripped ($Q = Z$), but solar energetic particles can have $Q < Z$.

Image credit: http://astronomy.nju.edu.cn/~lixd/GA/AT4/AT407/HTML/AT40705.htm

THE ASTROPHYSICAL JOURNAL, 481:L119–L122, 1997 June 1

CHARGE STATES OF SOLAR COSMIC RAYS AND CONSTRAINTS ON ACCELERATION TIMES AND CORONAL TRANSPORT

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Received 1996 December 3; accepted 1997 March 10

ABSTRACT

We examine effects on the charge states of energetic ions associated with gradual solar flares due to shock heating and stripping at high ion velocities. Recent measurements of the mean charges of various elements after the flares of 1992 October 30 and 1992 November 2 allow one to place limits on the product of the electron density times the acceleration or coronal residence time. In particular, any residence in coronal loops must be for less than 0.03 s, which rules out models of coronal transport in loops, such as the "birdcage" model. The results do not contradict models of shock acceleration of energetic ions from coronal plasma at various solar longitudes.

Subject headings: acceleration of particles — Sun: corona — Sun: flares — Sun: particle emission

TABLE 1

MEAN CHARGES DUE TO SHOCK HEATING[a]

			$T_d = 7 \times 10^6$ K		$T_d = 1.5 \times 10^7$ K	
ELEMENT	MEASURED[b]	$T_d = T_u$	$nt = 1 \times 10^{10}$	$nt = 2 \times 10^{10}$	$nt = 5 \times 10^9$	$nt = 1 \times 10^{10}$
N..........	6.47 ± 0.20	5.82	6.09	6.28	6.12	6.33
O..........	6.95 ± 0.20	6.20	6.42	6.60	6.48	6.71
Ne	8.53 ± 0.27	7.99	8.05	8.10	8.10	8.19
Mg........	10.30 ± 0.34	9.86	9.95	9.99	9.97	10.03
Si..........	10.54 ± 0.37	9.65	10.65	*11.14*	10.64	*11.15*
S	10.84 ± 0.44	9.19	10.71	*11.42*	10.76	*11.57*
Ar.........	10.08 ± 0.91	9.54	*11.02*	*11.81*	*11.13*	*12.05*
Ca.........	11.46 ± 0.49	10.35	11.48	*12.18*	11.66	*12.52*
Fe.........	15.18 ± 0.73	10.39	12.68	13.09	12.64	13.19
Ni.........	12.62 ± 1.30	9.32	12.70	13.76	12.52	13.92

NOTE.—Units of *nt* are cm^{-3} s.

[a] Calculated assuming that ions spend equal times at $T_u = 1.5 \times 10^6$ K and at T_d. Italicized values are those in excess of the measured values plus one standard deviation.

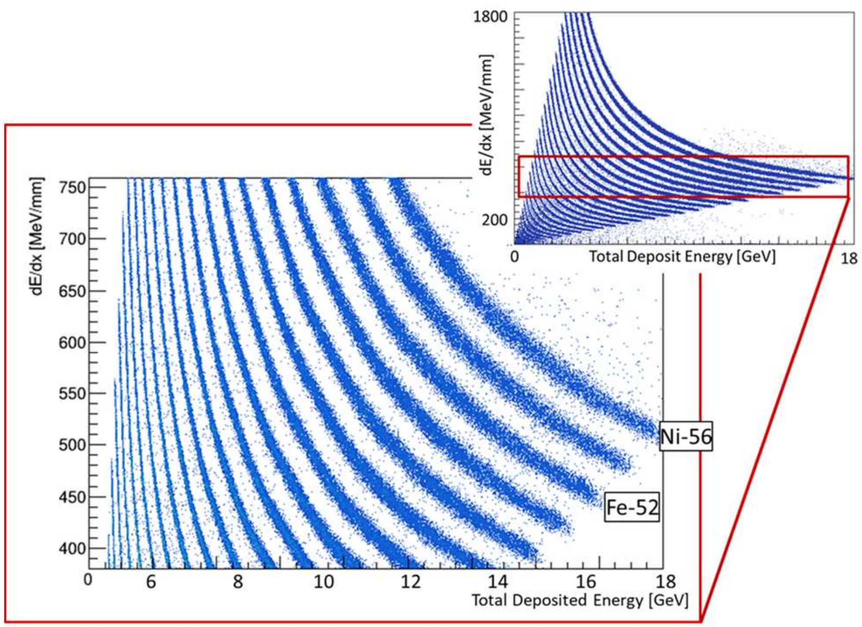
[b] Leske et al. 1995.

Previous work in Thailand analyzed measurements by SAMPEX/MAST of charge states of solar energetic ions at tens of MeV/n. These were inconsistent with an origin deep inside the solar atmosphere, supporting the idea of acceleration at interplanetary shocks.

POiSe = Polar Orbiting Ion Spectrometer Experiment (for TSC-1)

(Polar Orbiting Ion Spectrometer Experiment)

- Inspired by *SAMPEX/MAST* mission during 1992-2004
- From He to Ni (Z = 2 to 28), Energy range : ~ 15MeV/nuc - ~200MeV/nuc
- Silicon based detectors for ions identification by **ΔE – E Technique**



David Ruffolo, Mahido… versity

Position sensitive detector:

2 Double-sided silicon-based detector (Mirion)

dE-detector: Silicon-based

- 4 PINs (TMEC)
- 4 PIPs (Mirion)

E-detector:

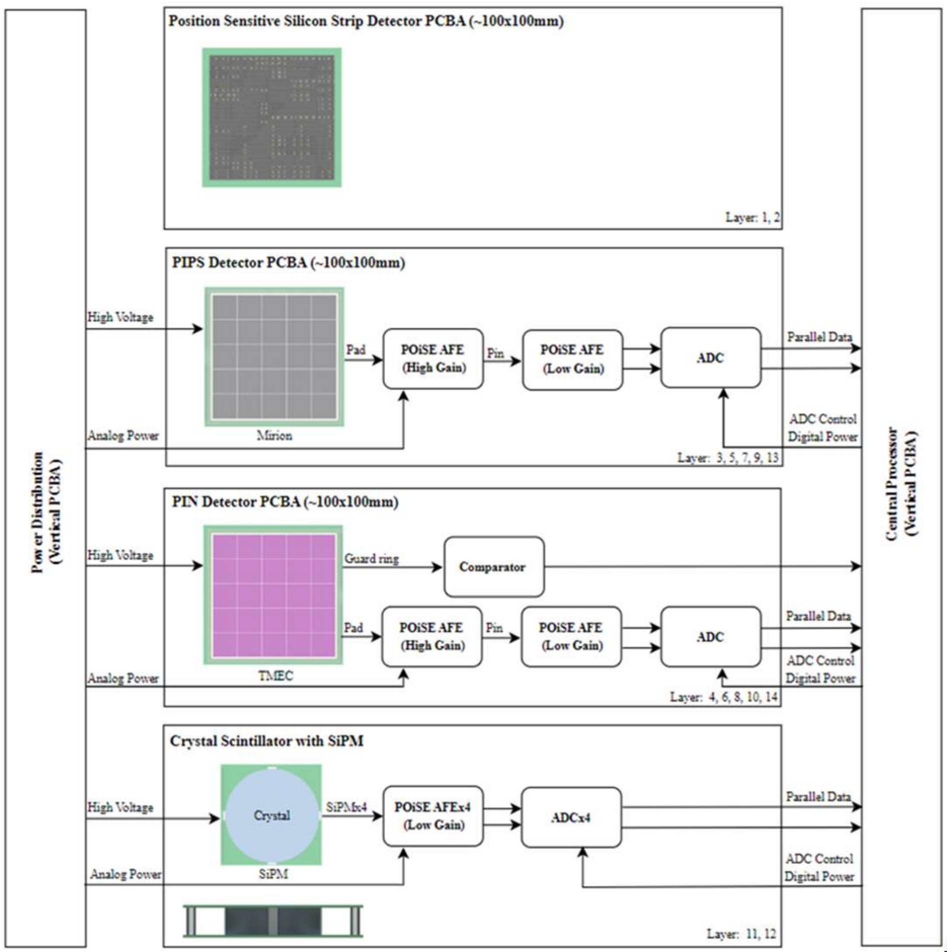
1 CsI(Tl) Scintillator + 4 SiPMs

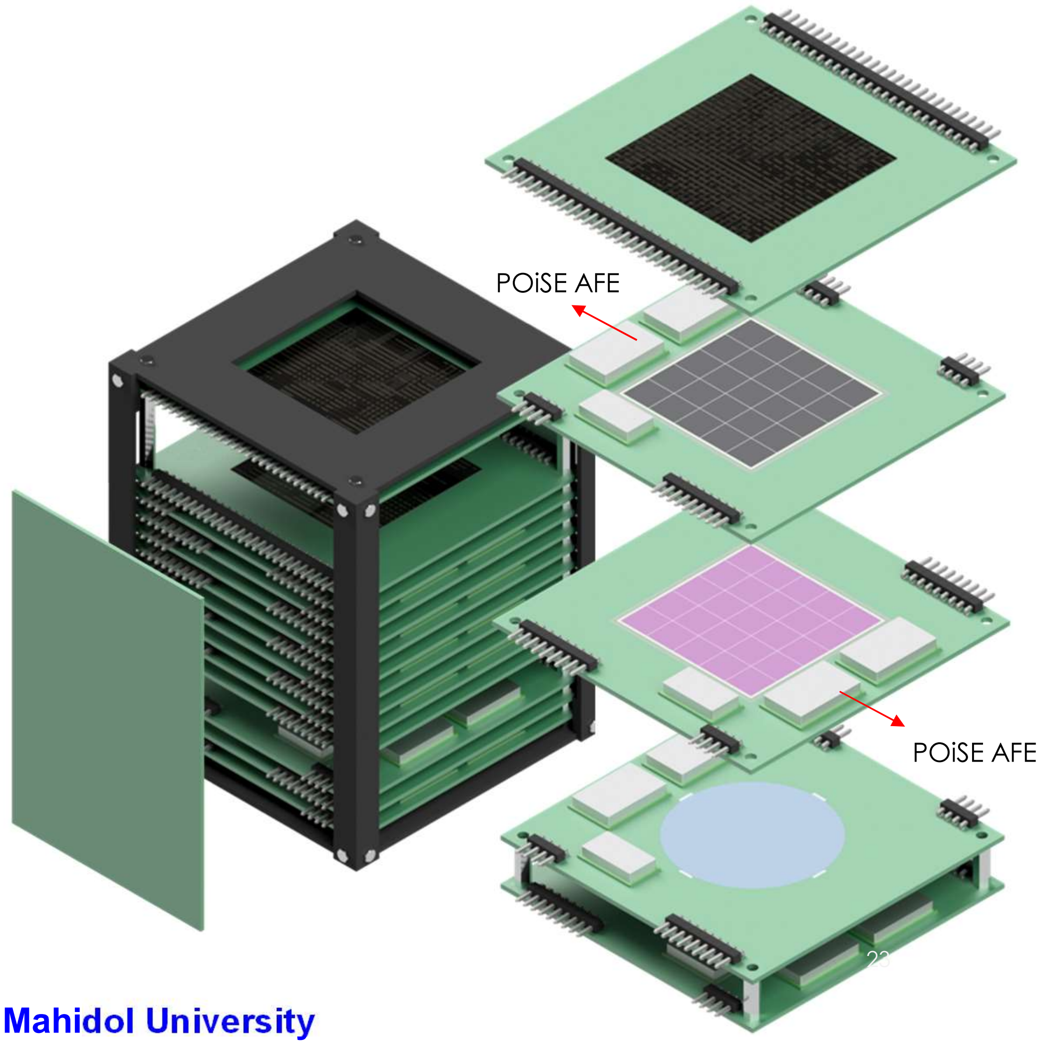
Veto-detector: Silicon-based

- 1 PIN (TMEC)
- 1 PIP (Mirion)

Overview of POiSE readout electronics

1st design of the electronics interface inside our payload



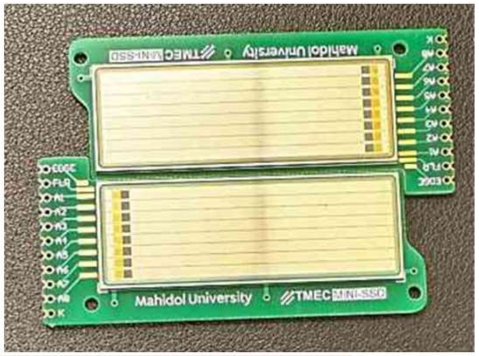


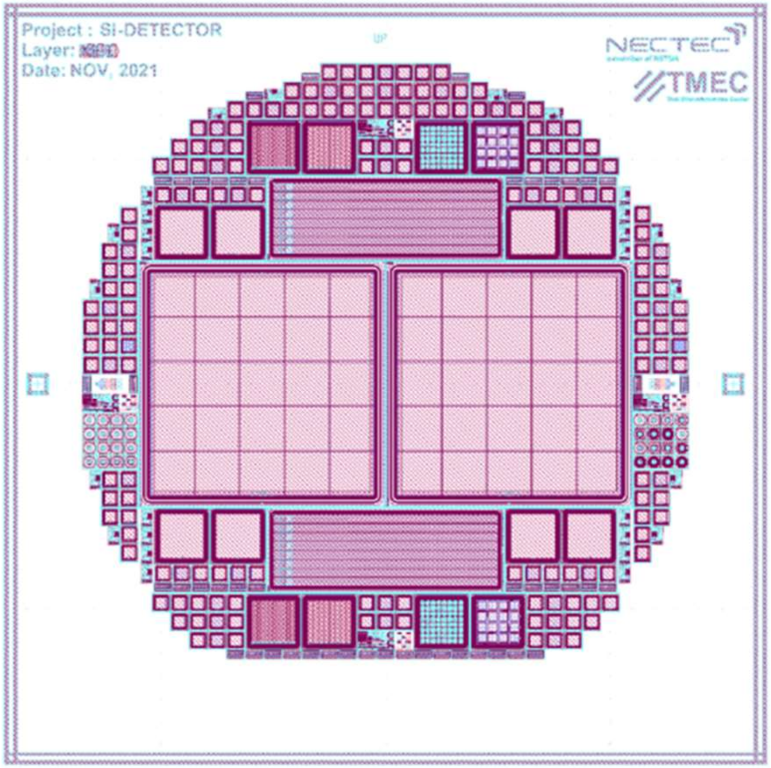
, Mahidol University

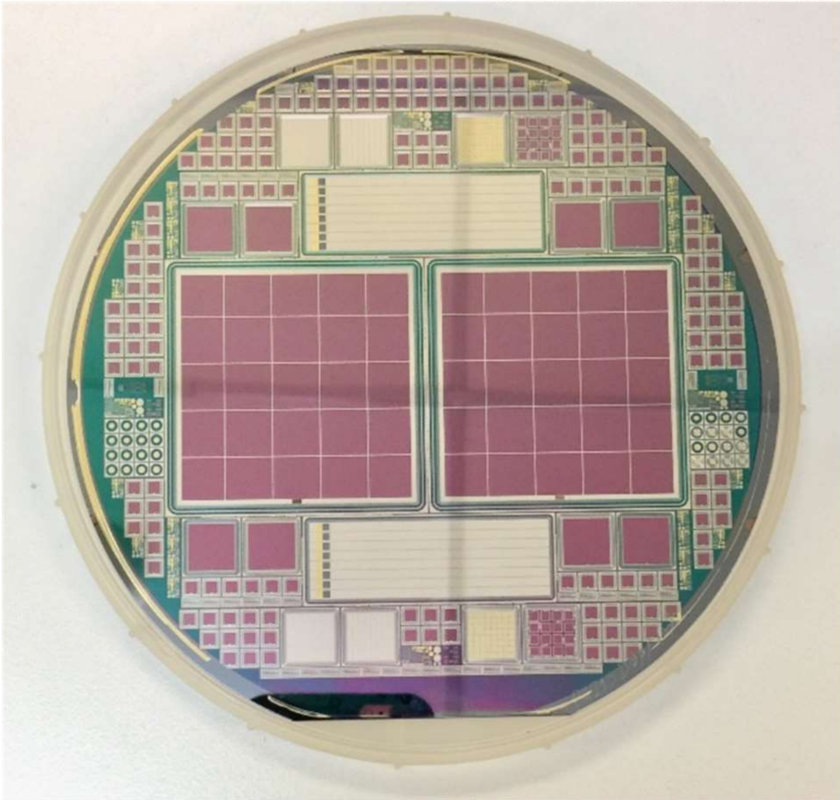
POISE
(Polar Orbiting Ion Spectrometer Experiment)

PINs

TMEC
Thai Microelectronics Center



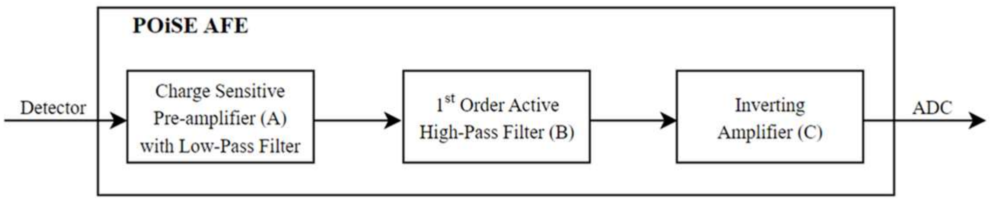


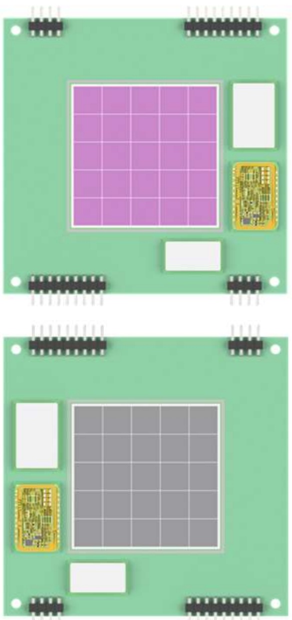


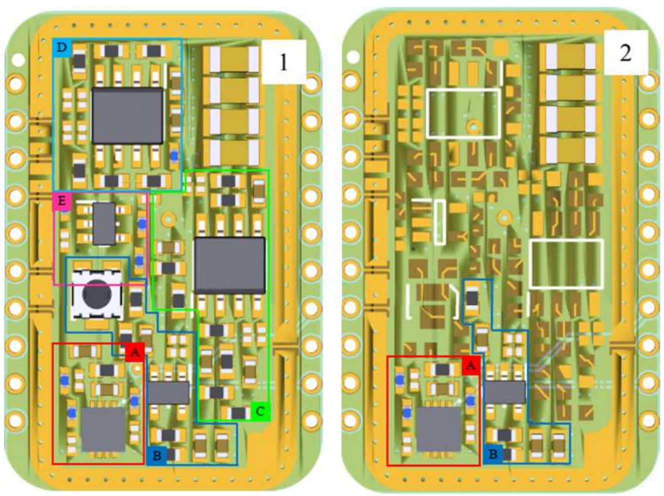
Sunruthai Burom

POiSE Analog Front-End

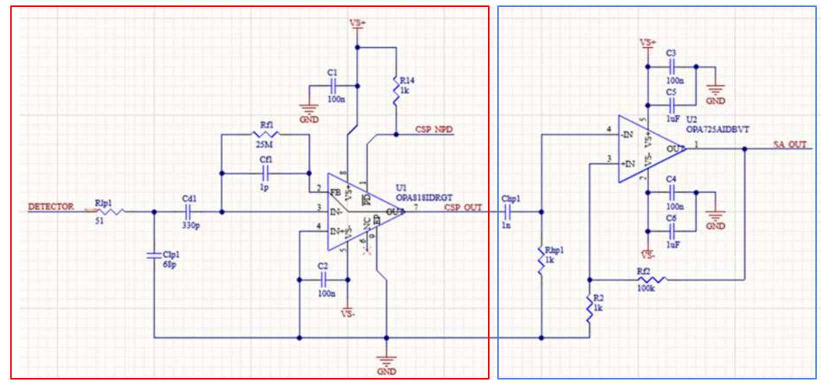
POiSE Analog Front-End module or **POiSE AFE** module for PINS/PIPs comprises three functional parts:







A top-down view of POiSE AFE module with each functional group designated.
[1] is revision C3 [2] is revision D (latest)

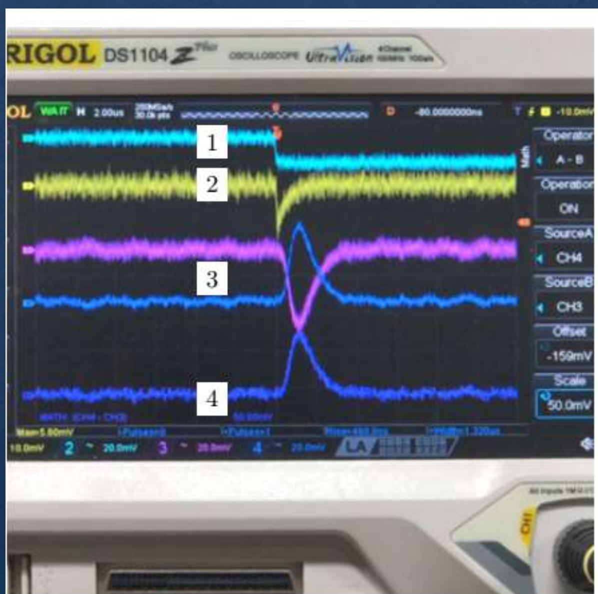


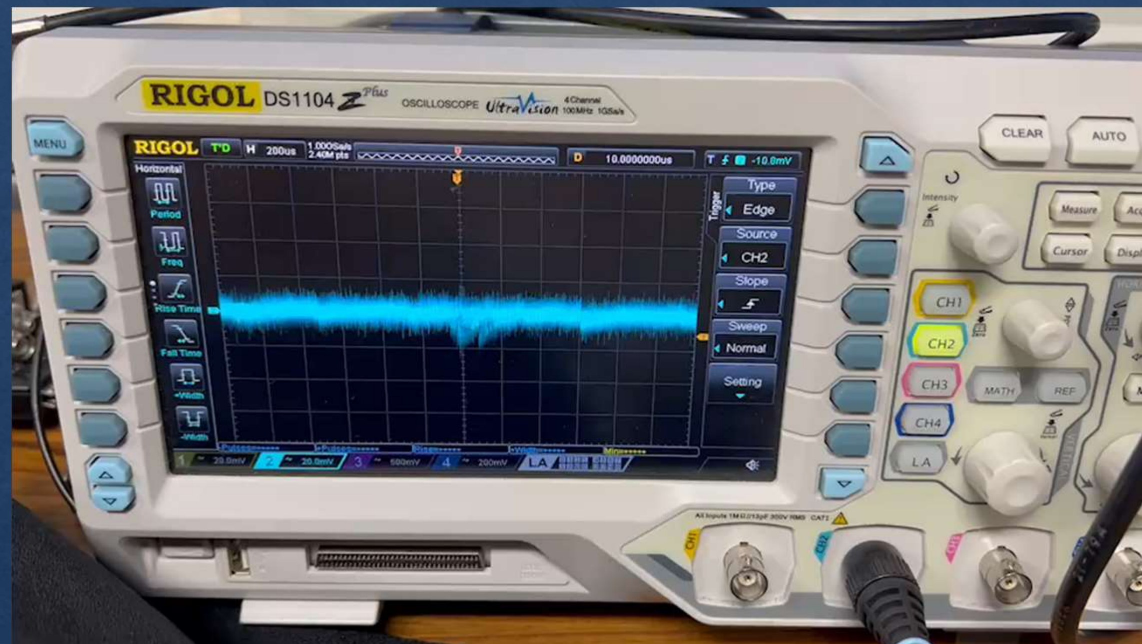
POiSE AFE revision D,yellow is a CSP output pulse, blue is shaping amplifier output pulse

POiSe

AFE

Analog Front-End

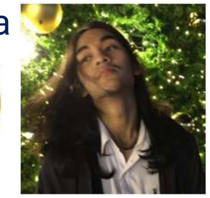


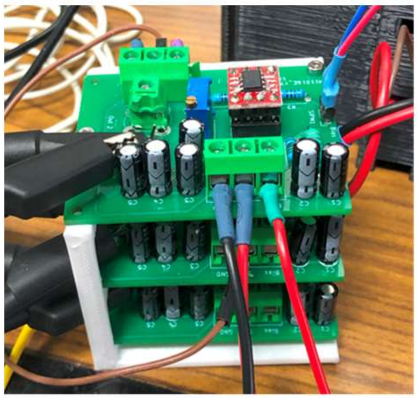


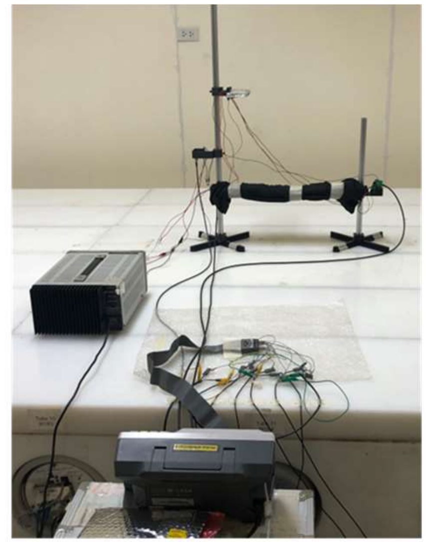
An example of a pulse created by a β particle from its source. (1) is a long-tail pulse created by the CSP. (2) is a triangle pulse from the output of the high-pass filter. (3) is a differential signal created when (2) passes through the fourth-order low-pass filter and the fully-differential amplifier. (4) is the resulting single-ended output, which has width of around 2.5 μs

POiSE Analog Front-End (AFE)

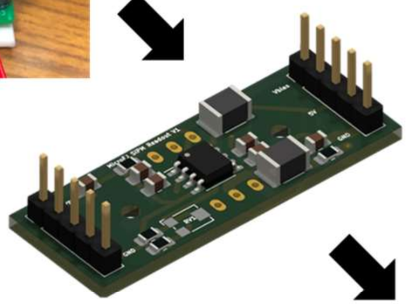
Koth Amratisha

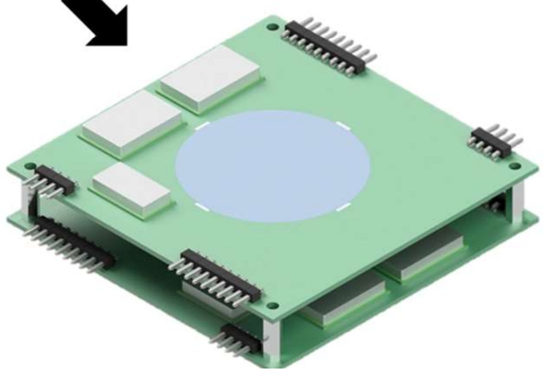






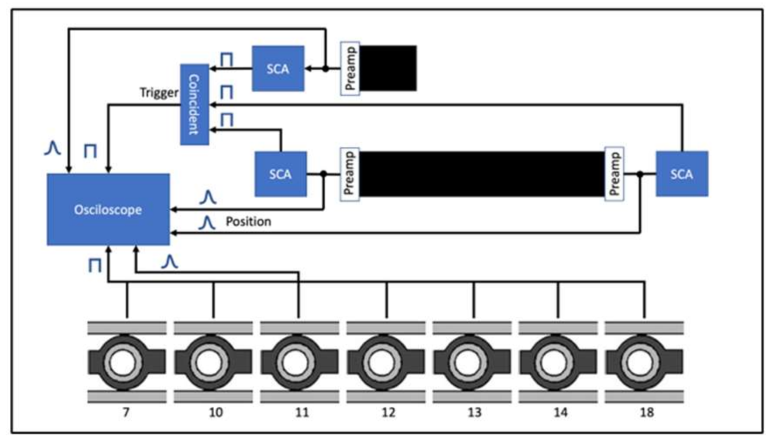
POiSE AFE module for SiPM and CsI(TI)





K. Amratisha, et al, ***Neutron Propagation Time Distribution Measured by Various Neutron Monitor Counters Relative to Direction-Tracked Charged Atmospheric Secondaries***, 2023ICRC, proceeding.

Tube	Tube 11	Tube 12
7	-4	-5
10	-1	-2
11	0	-1
12	1	0
13	2	1
14	3	2
18	7	6



Testing the Space Weather Payload

Kunlanan Puprasit

Radiation sources

The prototype detectors can differentiate particle energies → Comparing the response of the prototype detector with the commercial detector

Ion accelerator

To calibrate signal pulse height and deposited energy

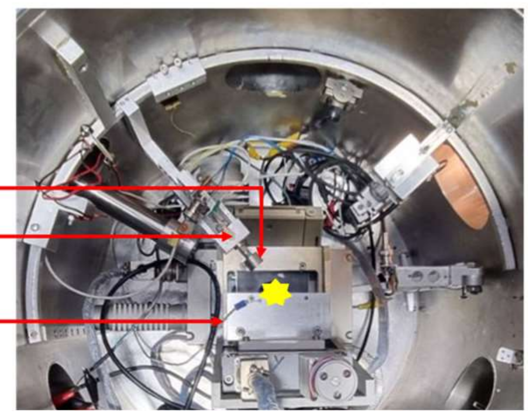
RBS stands for Rutherford BackScattering

a nuclear scattering technique used to study the composition and structure of materials at the atomic level by measuring the energy and angle of the backscattered ions.

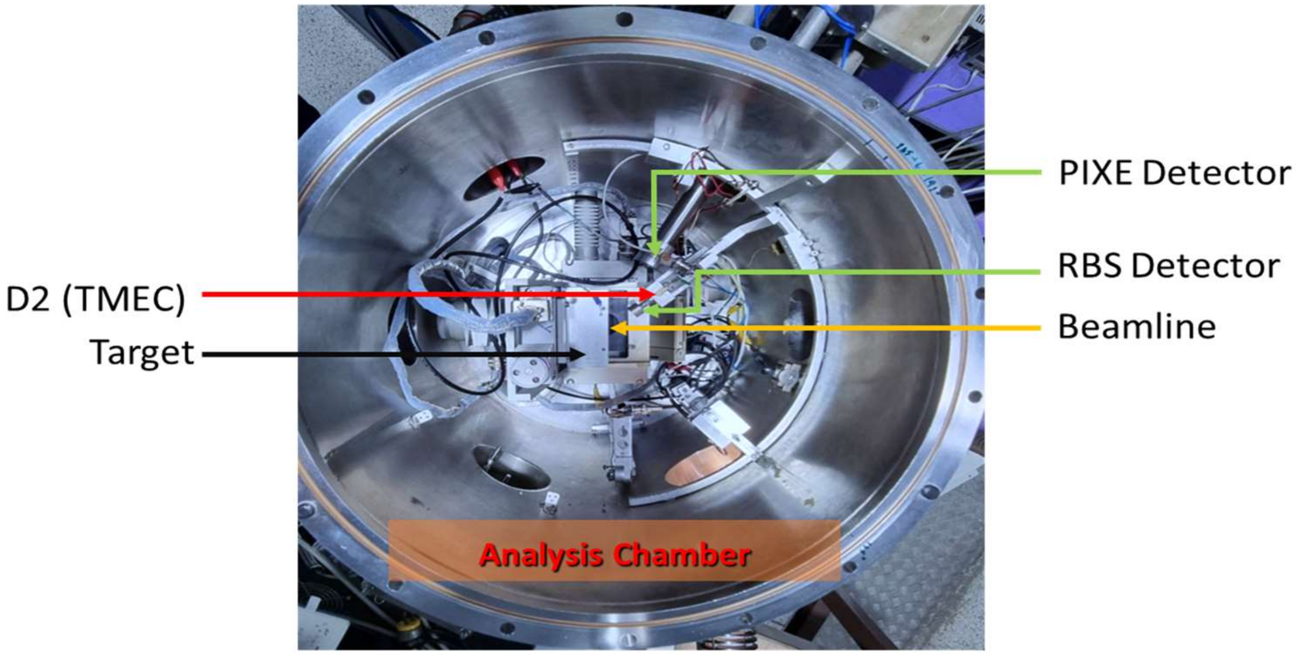
RBS detector

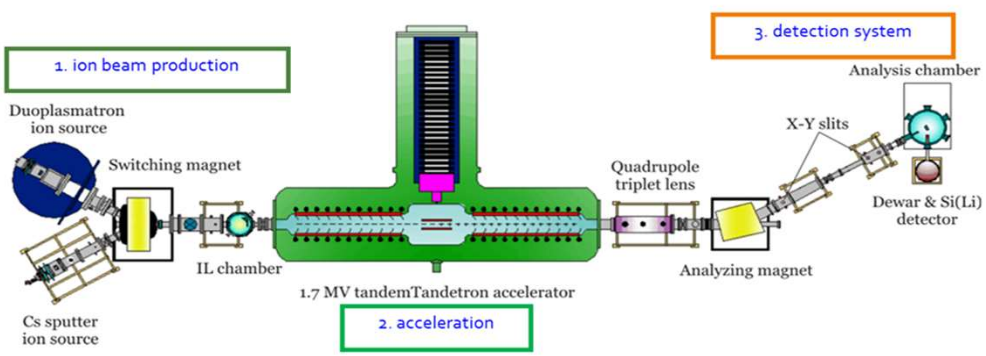
Prototype detector

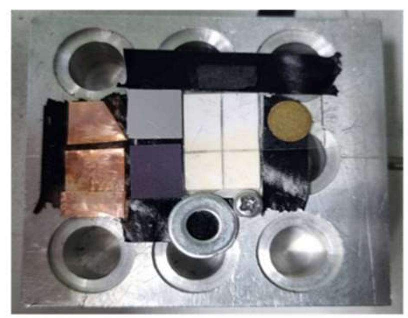
Sample Holder



Ion accelerator test

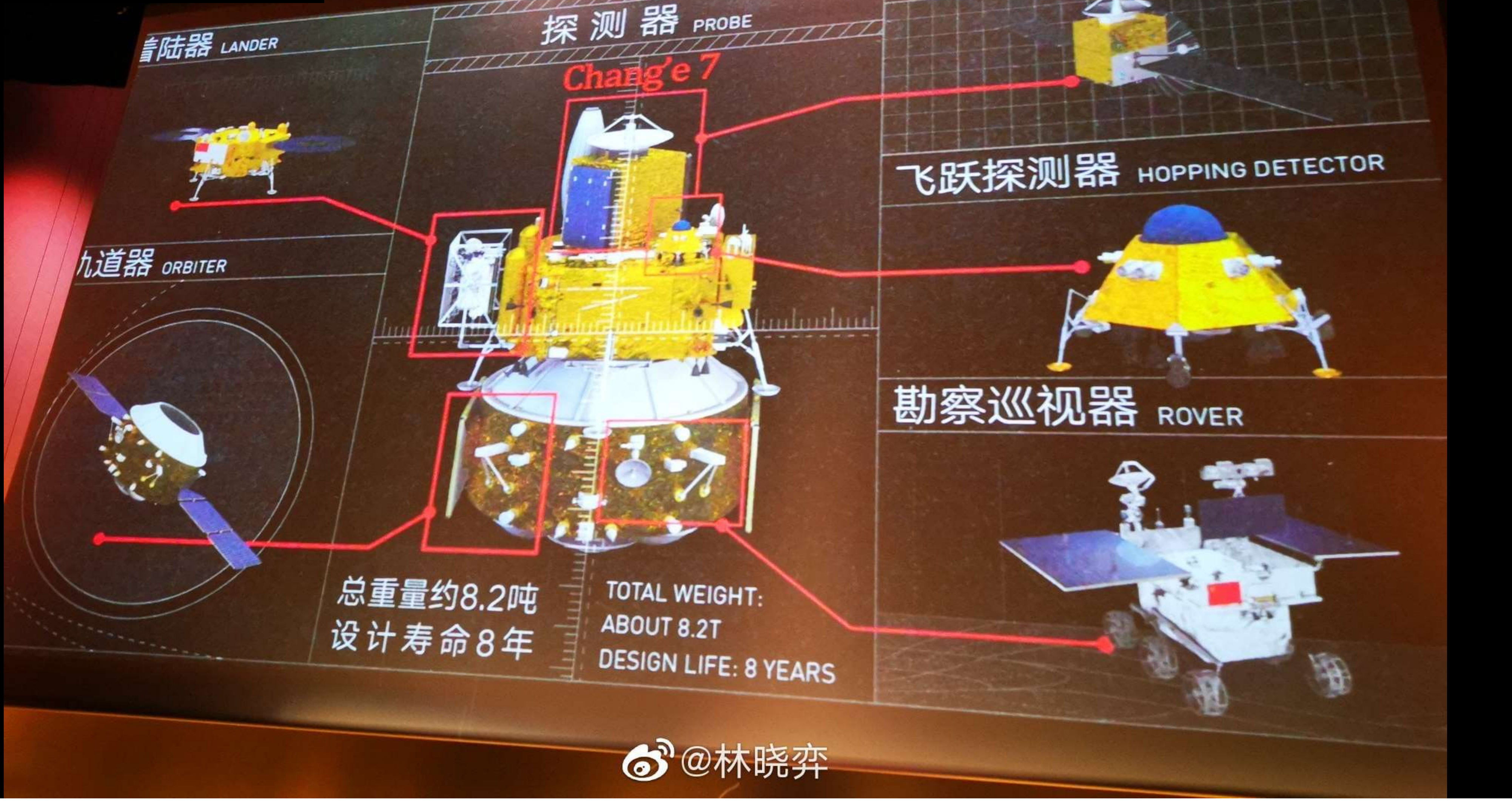






Cu, Au, Si, Al, Fe, C

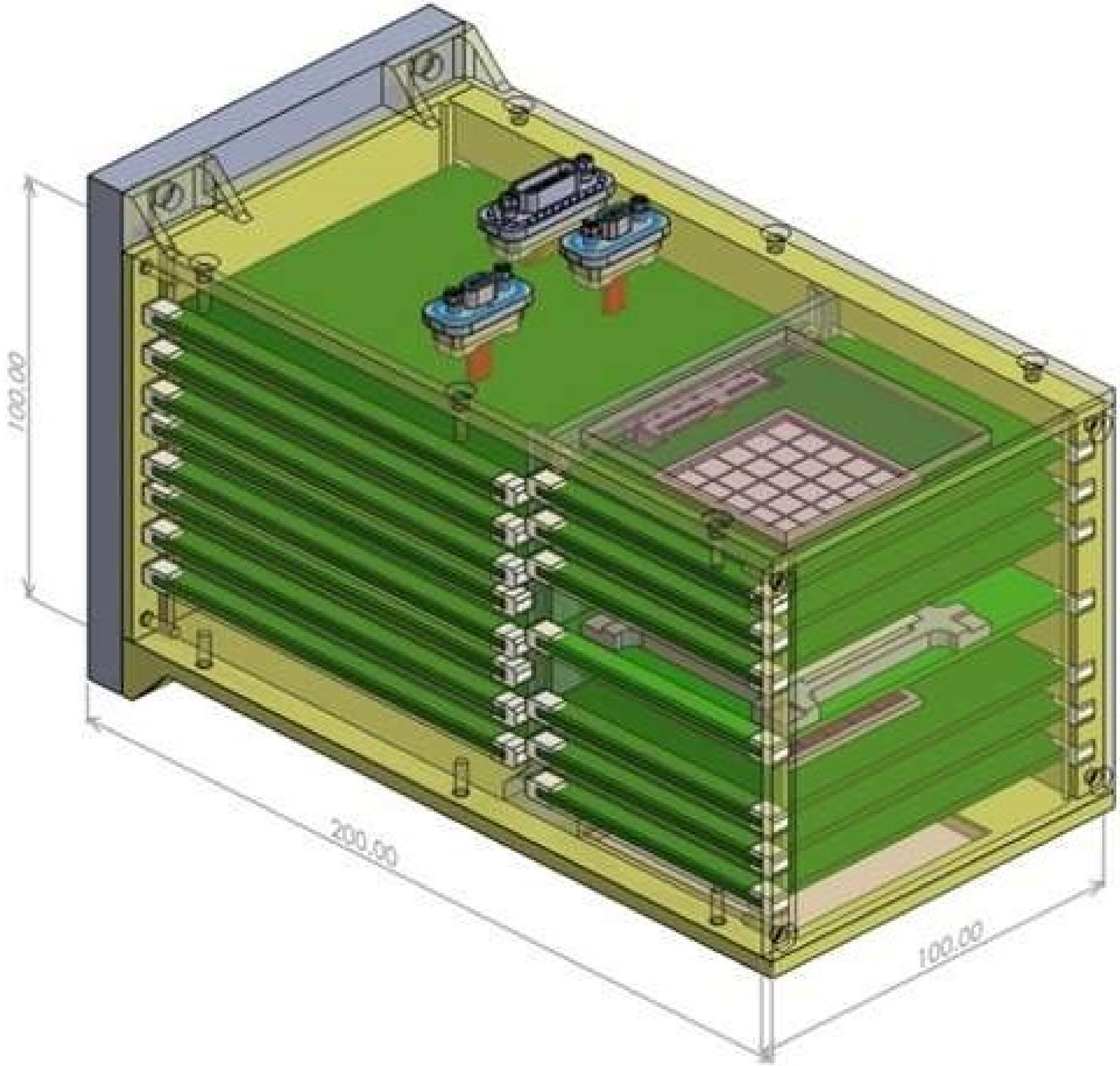
Chang'e 7: Helping to set up the International Lunar Research Station



MATCH

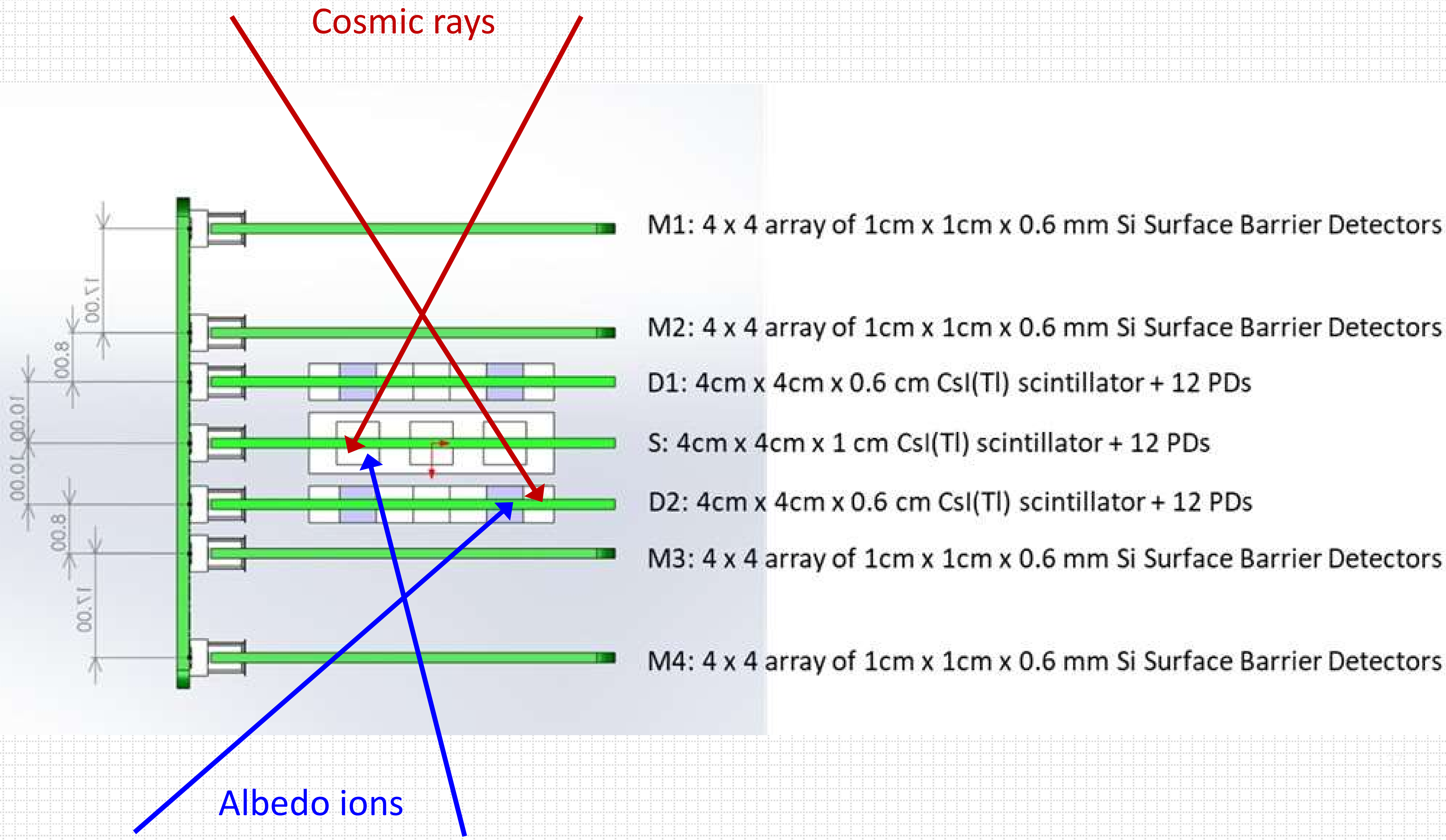
Moon-
Aiming
Thai-
Chinese
Hodoscope

A candidate mission for **Chang'E-7**, Lunar Research Station Project (ILRS), CNSA



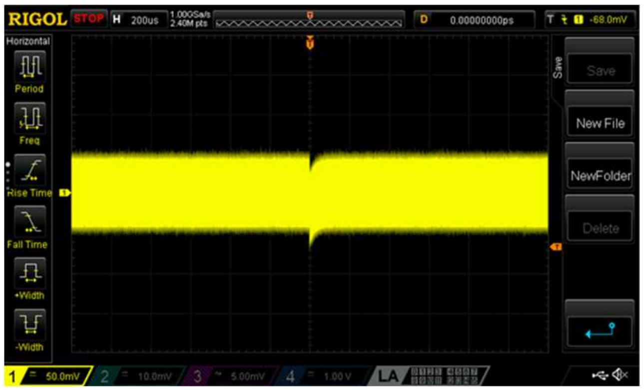
Detector Design

(inside the stack of detectors)

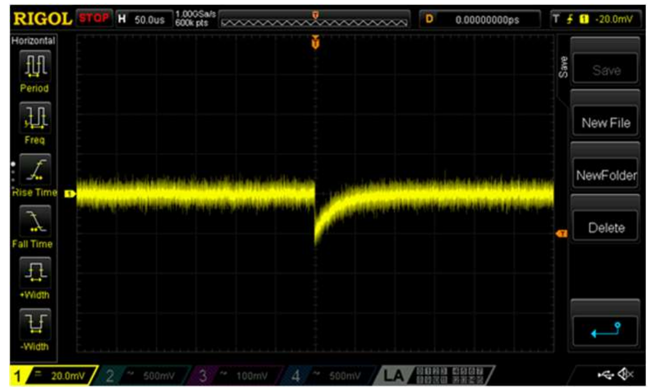

Cosmic rays
M1: 4 x 4 array of 1cm x 1cm x 0.6 mm Si Surface Barrier Detectors
M2: 4 x 4 array of 1cm x 1cm x 0.6 mm Si Surface Barrier Detectors
D1: 4cm x 4cm x 0.6 cm CsI(Tl) scintillator + 12 PDs
S: 4cm x 4cm x 1 cm CsI(Tl) scintillator + 12 PDs
D2: 4cm x 4cm x 0.6 cm CsI(Tl) scintillator + 12 PDs
M3: 4 x 4 array of 1cm x 1cm x 0.6 mm Si Surface Barrier Detectors
M4: 4 x 4 array of 1cm x 1cm x 0.6 mm Si Surface Barrier Detectors
Albedo ions

Background noise reduction

An example of a pulse of a alpha particle from Am-241 (~5.4MeV) before and after applied 45 MHz low pass filter.



A CSP output pulse from POiSE AFE revision C3.



A CSP output pulse from POiSE AFE revision D.

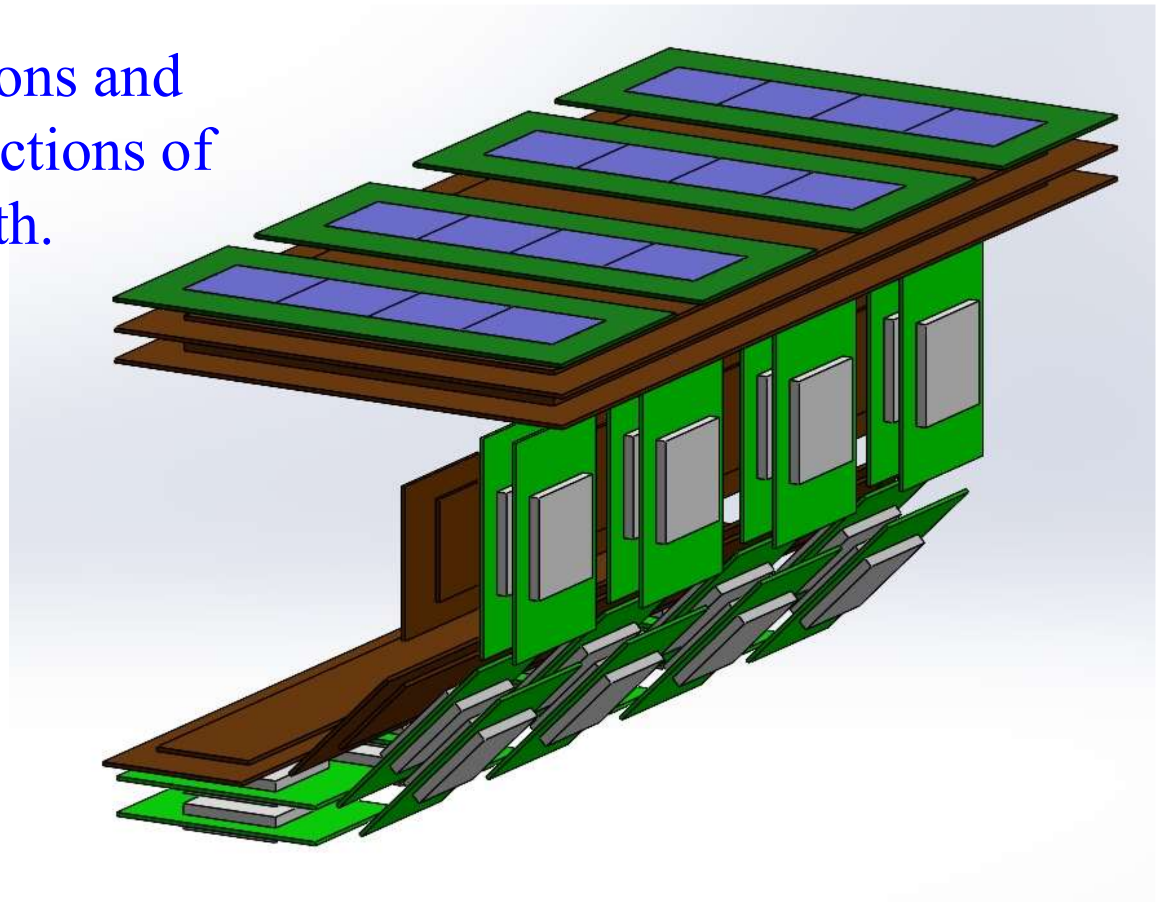
POiSE AFE revision D,yellow is a CSP output pulse, blue is shaping amplifier output pulse.

Proposal for Chang'E-8 Lander and Rover:

Assessing Lunar Ion-Generated Neutrons (ALIGN)

to detect both downward cosmic ions and albedo neutrons produced by interactions of those ions in the lunar regolith.

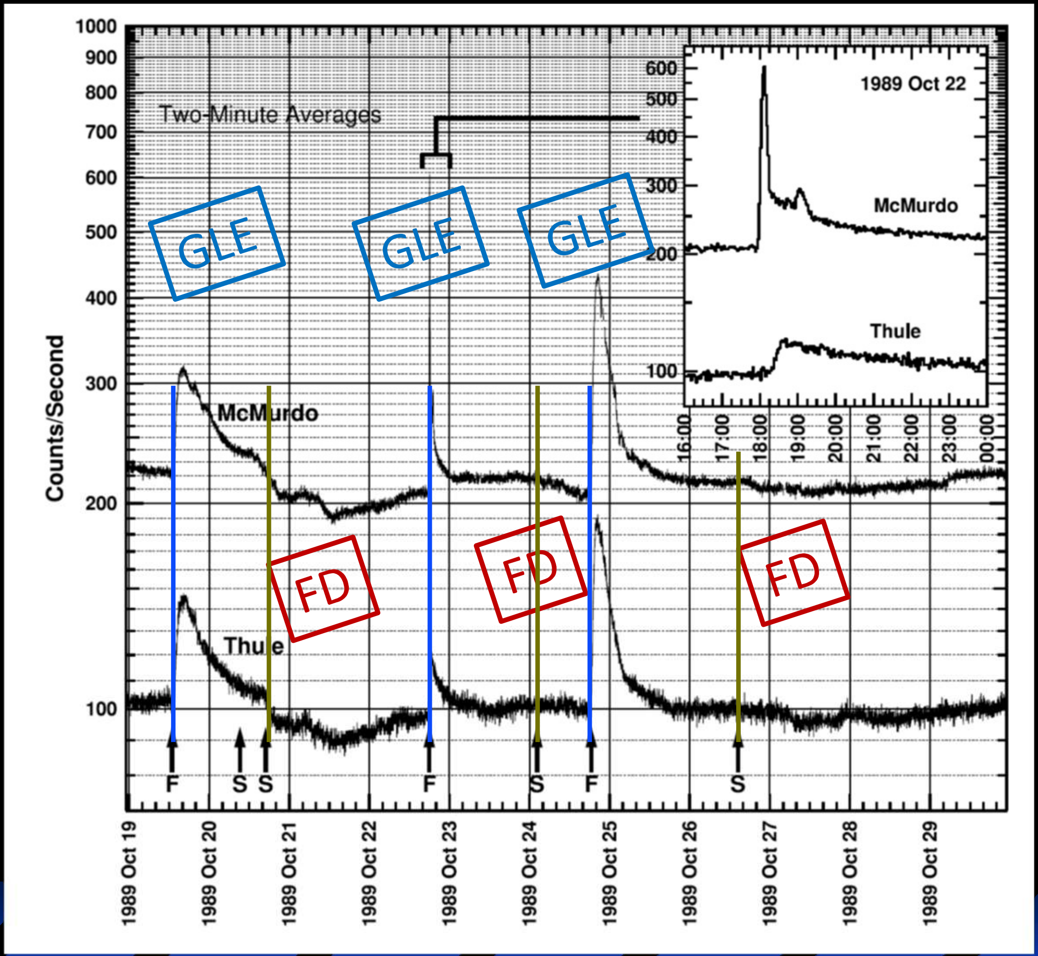
(Let's hope the lander doesn't land upside-down like the recent Japanese Moon lander!)



Earliest warning of an ongoing solar radiation storm: Relativistic solar protons can be detected as Ground Level Enhancements (GLE)

- Ground-level neutron monitors always observe Galactic cosmic rays.
- About 15 times per solar cycle, a solar event produces such a high proton flux above ~ 400 MeV that a temporary Ground Level Enhancement of solar energetic particles (SEPs) is seen in addition to the GCR background.
- The solar particle spectrum is softer (steeper) than GCR spectrum, so GLE is usually seen up to at most a few GeV.

Ground Level Enhancements (GLEs)



Ruffolo+06

A neutron monitor usually sees Galactic cosmic rays, but occasionally a solar storm produces enough relativistic particles to be seen above the GCR background – a GLE.

A Forbush decrease (FD) is a decrease in GCR after passage of a CME-driven shock.

Simulation of interplanetary transport

- Specify magnetic field configuration
- Solve PDE ⇨
- Runs in a few minutes [Nutaro+01]

Fitting SEP data

- Simultaneous fit to intensity vs. time
  anisotropy vs. time
- Optimal piecewise linear injection (least squares)
- Optimal scattering mean free path, λ [Ruffolo+98]
- Optimal magnetic configuration [Bieber+02]

Relativistic Solar Particles

Precision modeling of solar particle data

$$\frac{\partial F(t,\mu,z,p)}{\partial t} = -\frac{\partial}{\partial z}\mu v F(t,\mu,z,p) \qquad \text{(streaming)}$$

$$-\frac{\partial}{\partial z}\left(1-\mu^2\frac{v^2}{c^2}\right)v_{sw}\sec\psi F(t,\mu,z,p) \qquad \text{(convection)}$$

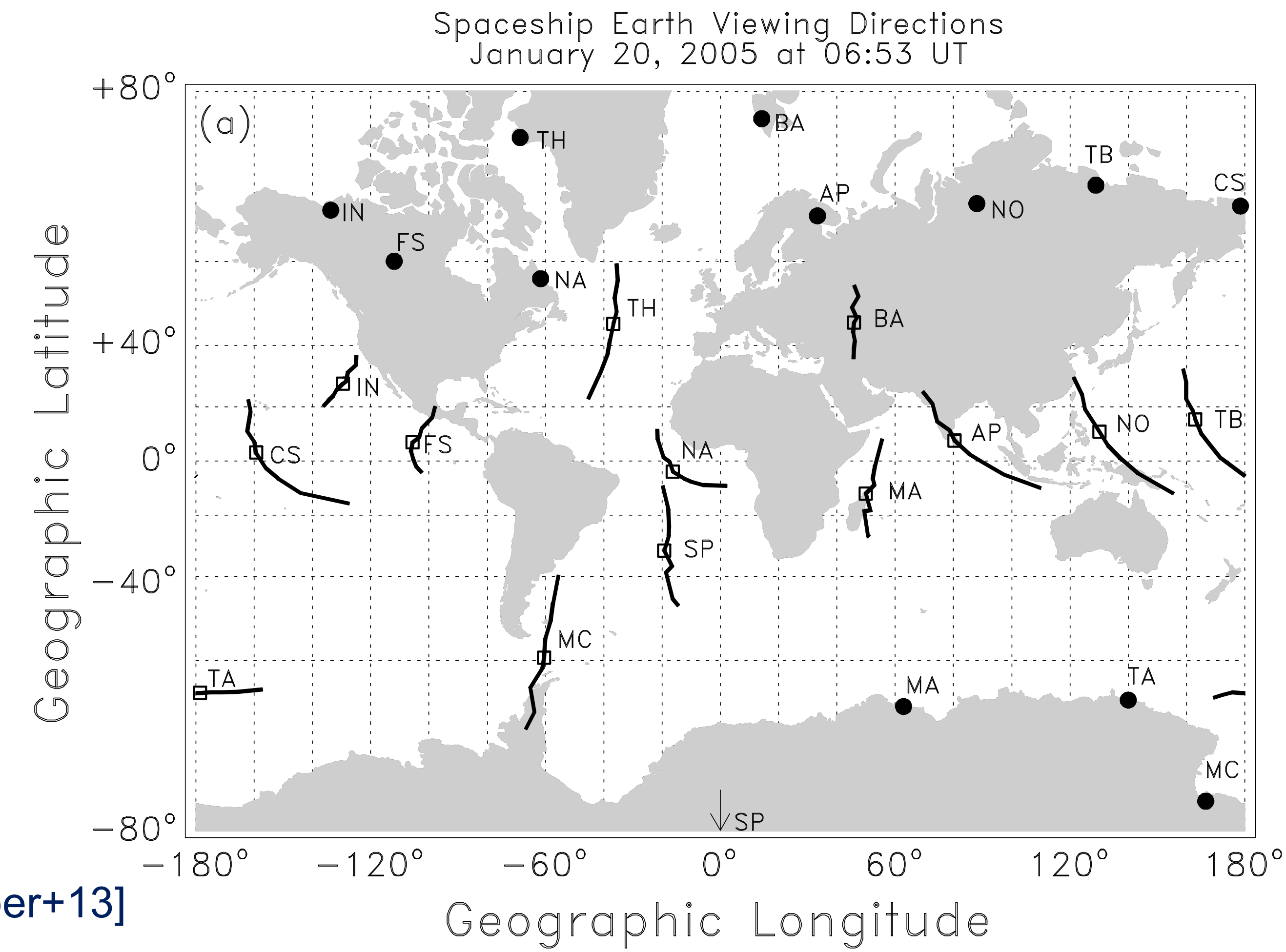
$$-\frac{\partial}{\partial \mu}\frac{v}{2L(z)}\left[1+\mu\frac{v_{sw}}{v}\sec\psi-\mu\frac{v_{sw}v}{c^2}\sec\psi\right](1-\mu^2)F(t,\mu,z,p) \qquad \text{(focusing)}$$

$$+\frac{\partial}{\partial \mu}v_{sw}\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu(1-\mu^2)F(t,\mu,z,p) \qquad \text{(differential convection)}$$

$$+\frac{\partial}{\partial \mu}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial \mu}\left(1-\mu\frac{v_{sw}v}{c^2}\sec\psi\right)F(t,\mu,z,p) \qquad \text{(scattering)}$$

$$+\frac{\partial}{\partial p}pv_{sw}\left[\frac{\sec\psi}{2L(z)}(1-\mu^2)+\cos\psi\frac{d}{dr}(\sec\psi)\mu^2\right]F(t,\mu,z,p)\,. \qquad \text{(deceleration)} \quad (11)$$

Pitch-angle transport equation [Ruffolo95]



[Bieber+13]

STATION CODES

FS: Fort Smith, Canada

TH: Thule, Greenland

MC: McMurdo, Antarctica

NA: Nain, Canada

SP: South Pole, Antarctica

BA: Barentsburg, Norway

MA: Mawson, Antarctica

AP: Apatity, Russia

NO: Norilsk, Russia

TB: Tixie Bay, Russia

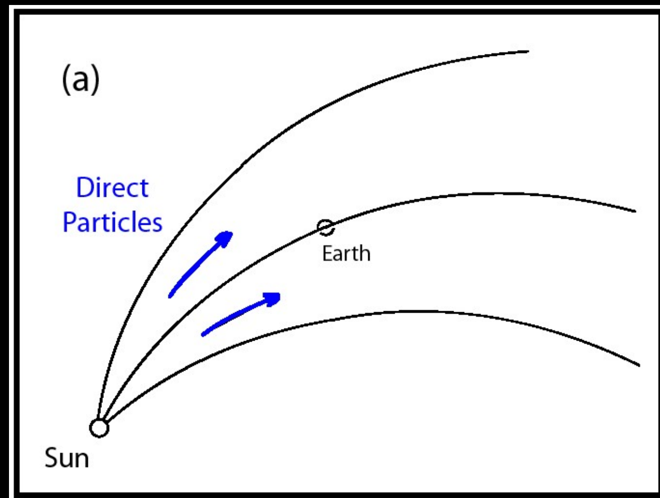
CS: Cape Schmidt, Russia

IN: Inuvik, Canada

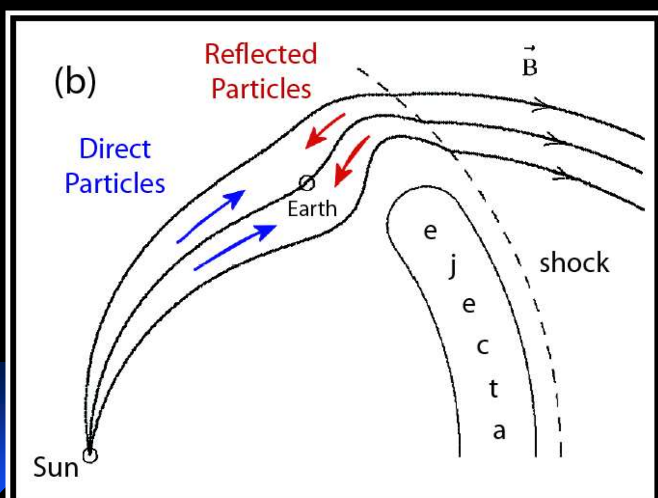
Squares show the asymptotic viewing direction of a median energy (1.4 GeV) solar cosmic ray. Lines encompass the central 80% of detector energy response, extending from the direction of a 0.5 GeV particle to that of a 4.6 GeV particle. Directions of nominal inward ("O") and outward ("X") Parker spiral also shown.

Magnetic Configurations

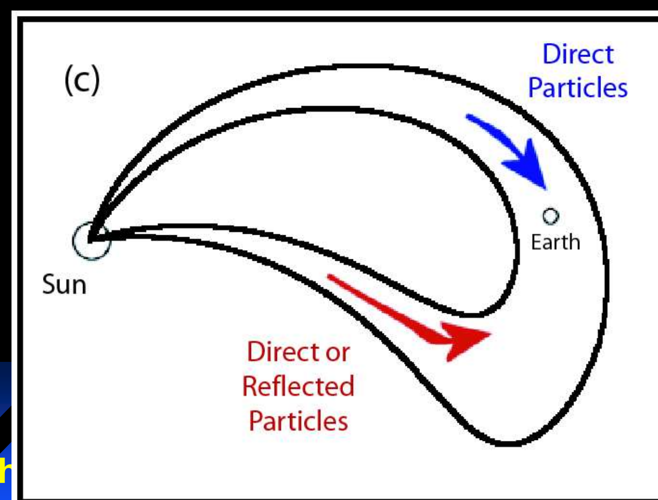
Spiral →



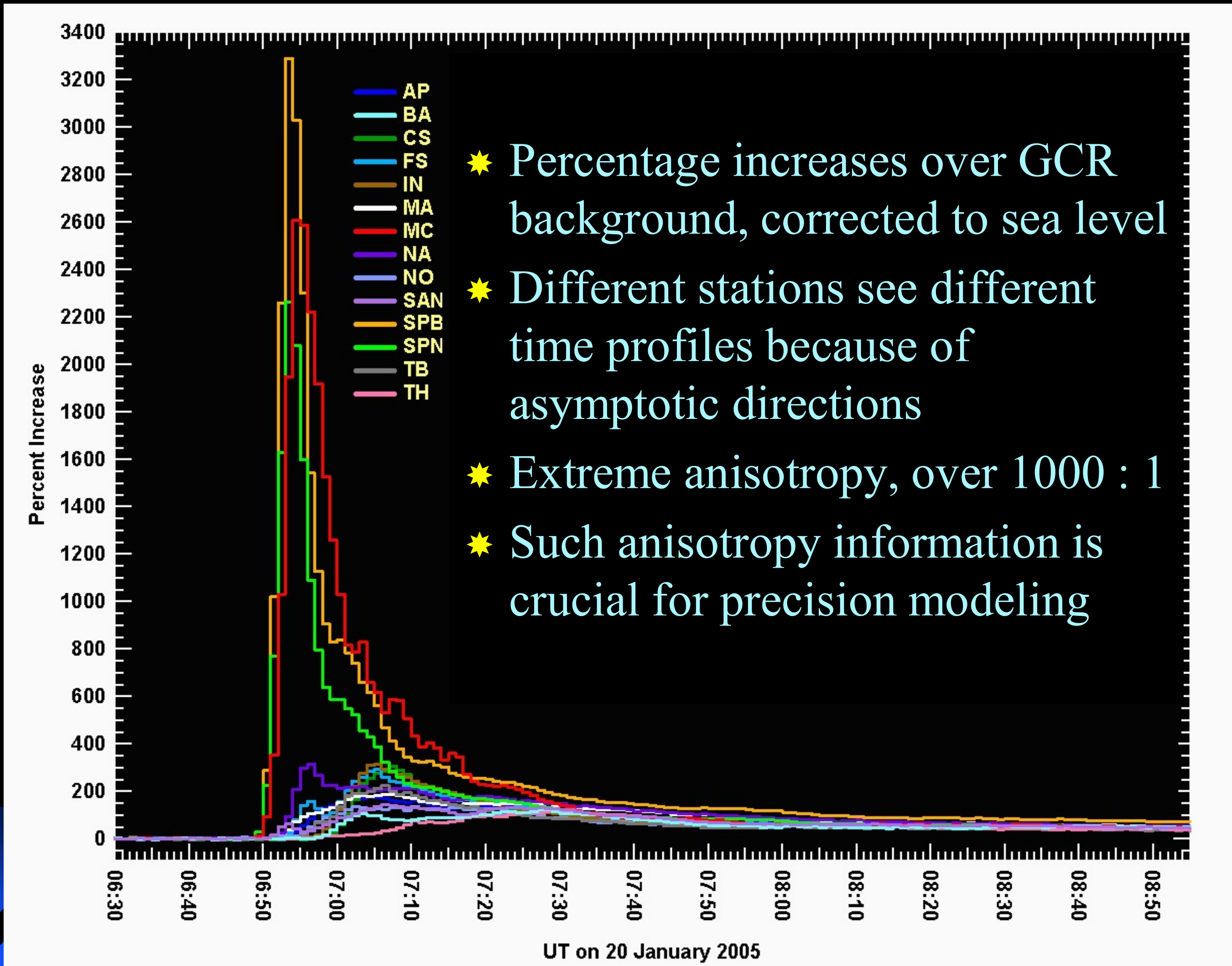
Bottleneck
2000 July 14
[Bieber+02]



Loop
1989 Oct 22
[Ruffolo+06]



Jan. 20, 2005: Largest GLE in 50 years



- Percentage increases over GCR background, corrected to sea level
- Different stations see different time profiles because of asymptotic directions
- Extreme anisotropy, over 1000 : 1
- Such anisotropy information is crucial for precision modeling

Solar injection timing: For two previous events, supports origin of relativistic solar protons from CME-driven shock, not from flare

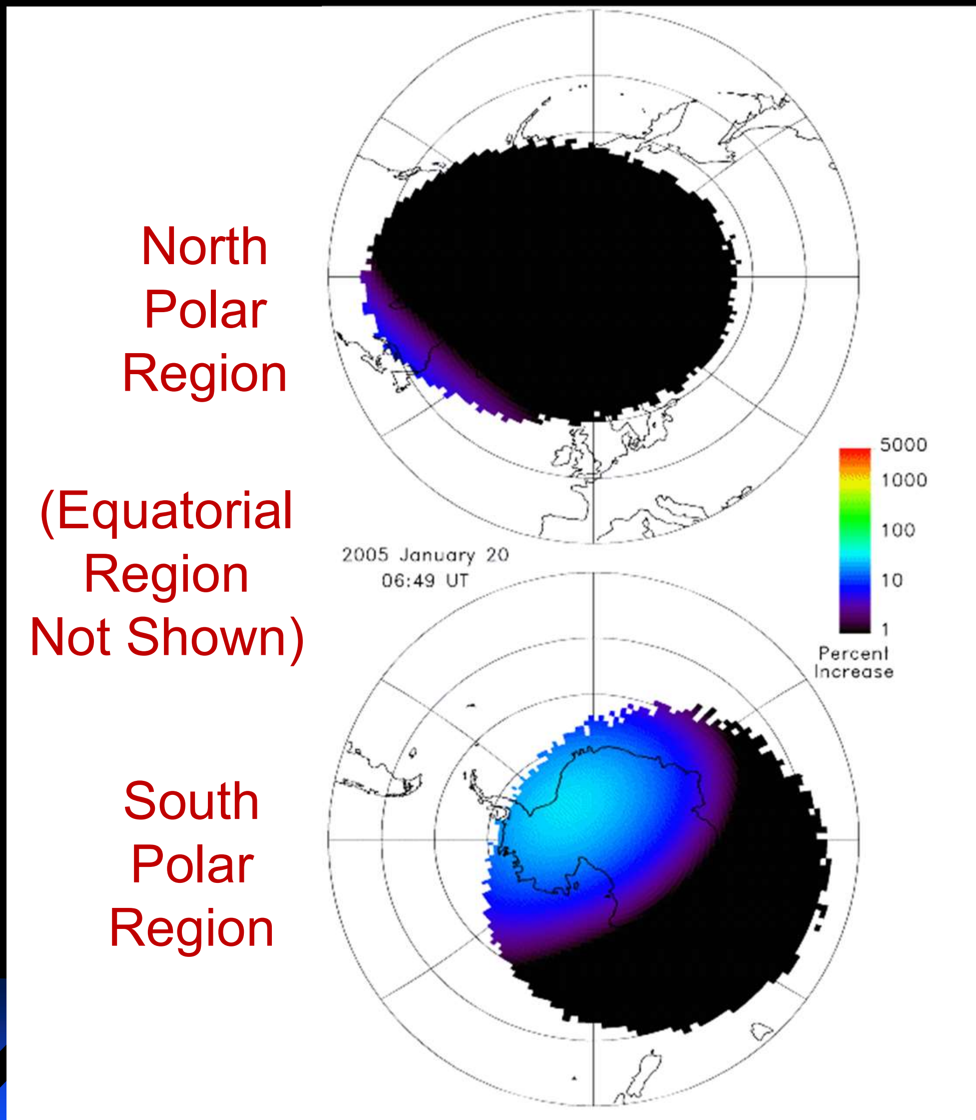
(2005 Jan 20 was complex, harder to interpret)

Timing of various emissions from three major solar events

EMISSION	APR. 15, 2001			OCT. 28, 2003			JAN. 20, 2005		
	START	PEAK	END	START	PEAK	END	START	PEAK	END
Relativistic Protons	**13:42**	13:48		**11:03**	11:41		**06:40**	06:43	
FLARE: Soft X-rays	13:11	**13:42**	13:47	10:52*	**11:02**	11:16	06:28	**06:53**	07:18
FLARE: H-alpha	13:28	**13:41**	15:27	09:53*	**11:57**	14:12	06:33	**06:38**	08:46
FLARE: Type III radio burst	13:36		13:38	-		-	06:37		06:53
CME: CME liftoff*	*13:31*			*10:58*			*06:25*		
CME: Type II radio burst	13:40		13:47	10:54		11:03	06:36		06:52
CME: Type IV radio burst	13:44		14:57	10:25		15:23	06:35		16:51

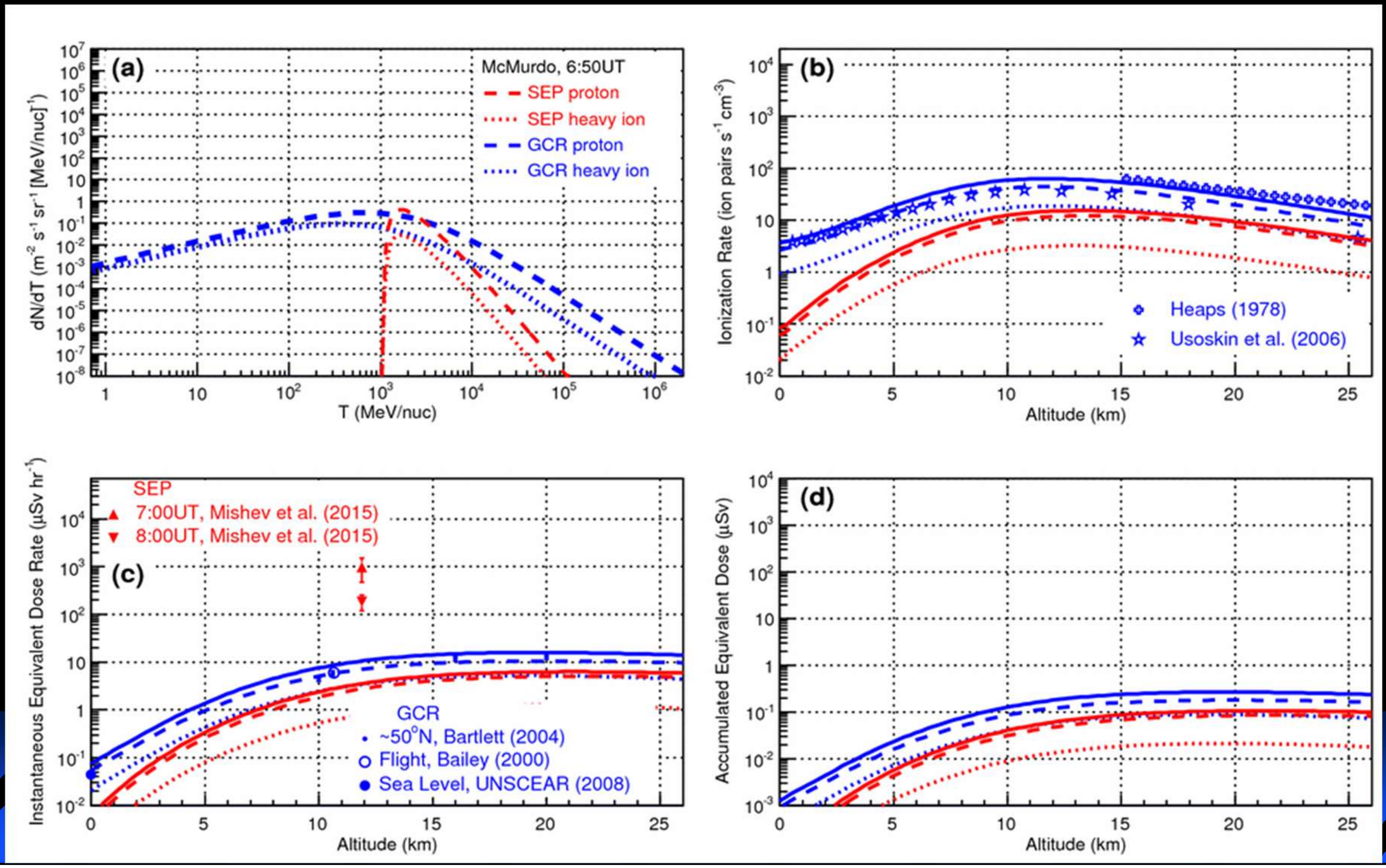
* Quadratic fits, systematic uncertainty of a few minutes ** Sudden onset of intense emission

[Bieber+05]



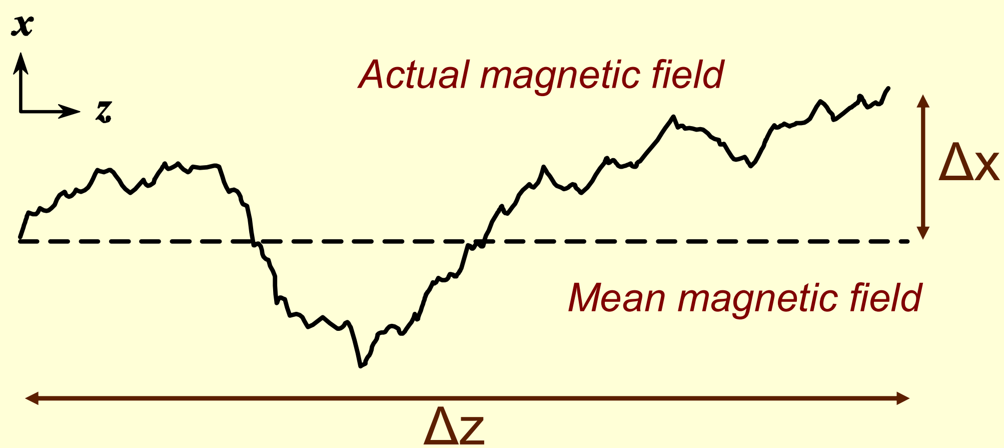
For radiation dose in Earth's atmosphere, particle anisotropy can be a major factor in SEP events

2005 Jan 20: เหตุการณ์พายุสุริยะที่กระทบบรรยากาศโลก (ชั่วคราว)
[Mitthumsiri et al. 2017]



Space Plasma Physics
Random Walk of Field Lines and Energetic Particles in Magnetic Turbulence

- Physics ideas
- Analytic calculations
- Computer simulations

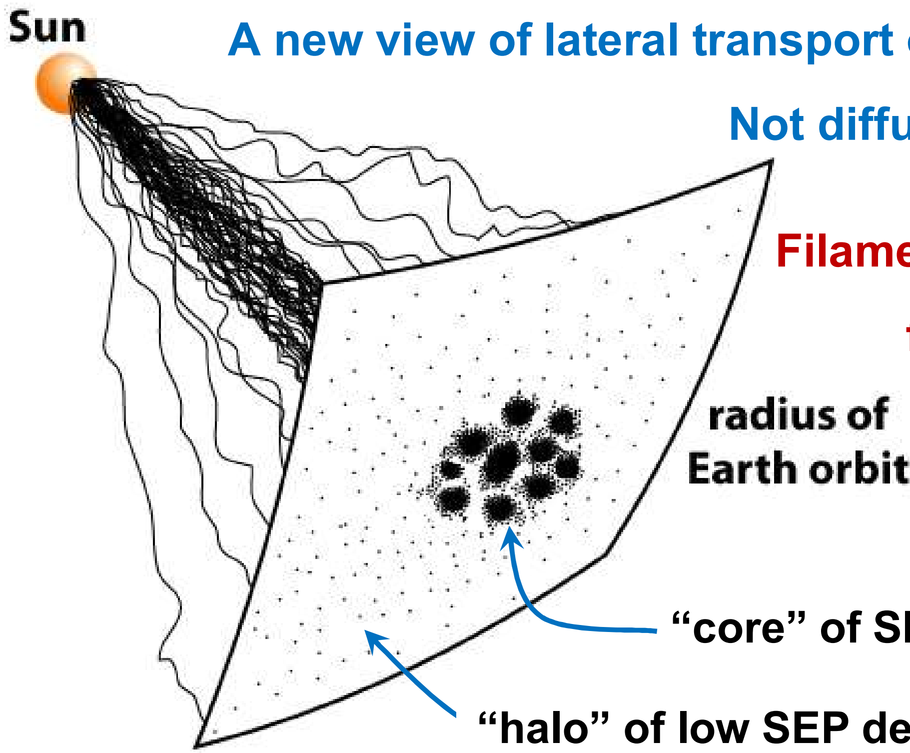


$\langle \Delta x \rangle = 0$

$\langle \Delta x^2 \rangle = 2\ D\ \Delta z$

A new view of lateral transport of field lines and particles:

Not diffusive during initial transport.



Filamentary magnetic connectivity from a narrow source region naturally arises from turbulence model.

[Ruffolo+03; details of the process have been worked out by Chuychai+05; Chuychai+07; Tooprakai+07; Seripienlert+10;
predictions for Parker Solar Probe & Solar Orbiter Missions by Tooprakai+16]

Recent & ongoing work:

- Study of path lengths of field lines & particles [Chhiber+21, Sonsrettee+ submitted],
- Observations by Parker Solar Probe as close as 0.11 AU from the Sun [to be presented at COSPAR2024]


Scientists are invited to
Study cosmic rays in Thailand!
Mahidol University can and has supported:
❖**Graduate students**
❖**Postdoctoral researchers (new position in July)**
❖**Visiting scientists for 2 to 6 months**
Thank you for your attention!