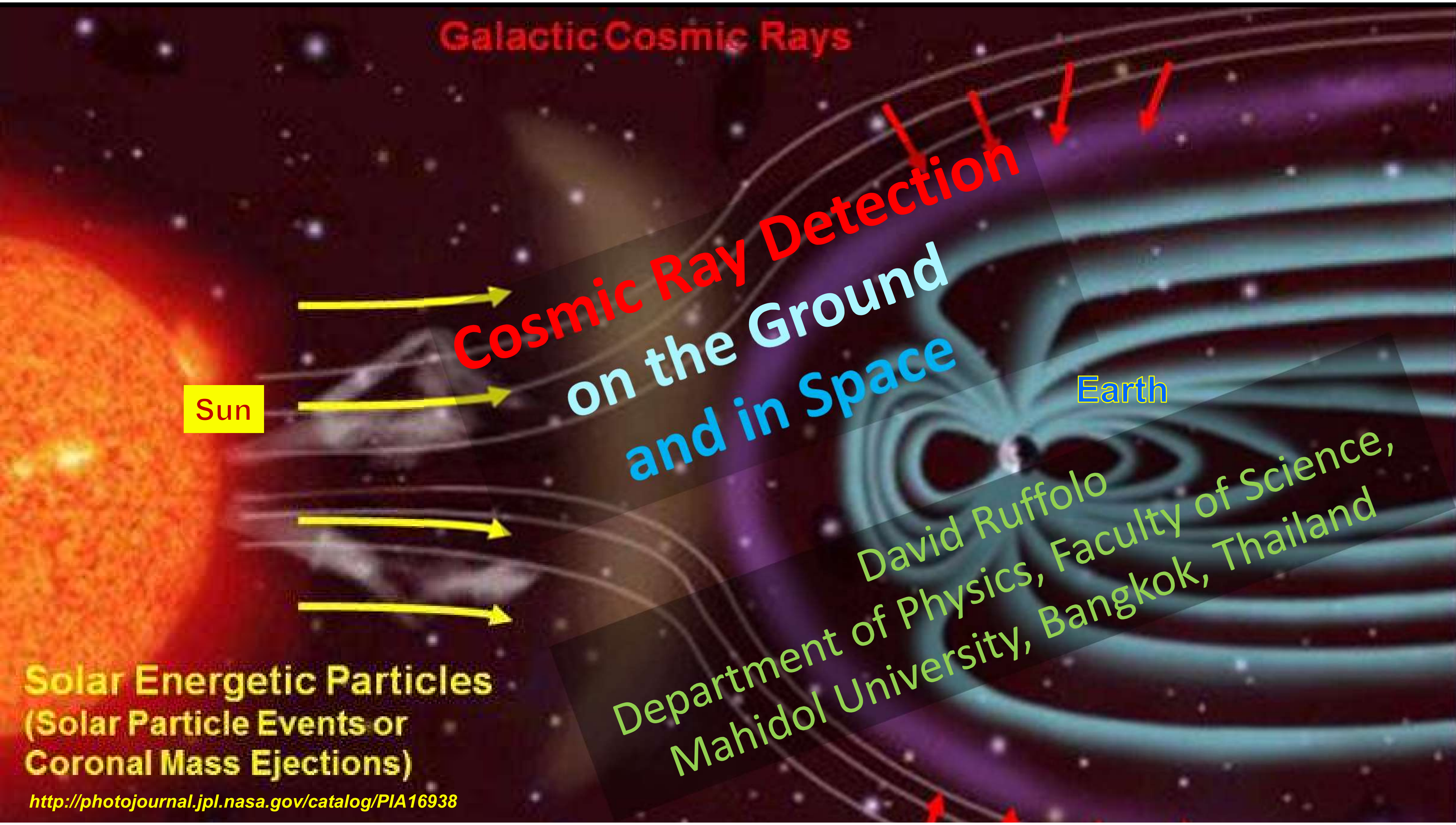
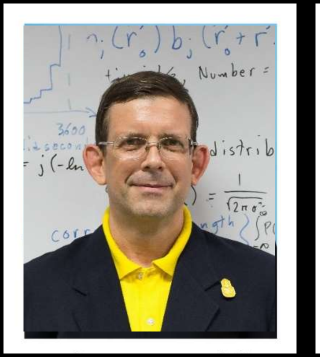


http://photojournal.jpl.nasa.gov/catalog/PIA16938

Cosmic Ray Detection on the Ground and in Space

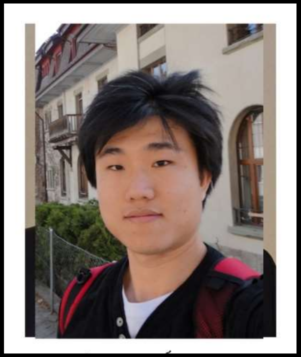
David Ruffolo
Department of Physics, Faculty of Science,
Mahidol University, Bangkok, Thailand

Faculty Members
Space Physics and Energetic Particles Group
Mahidol University, Bangkok, Thailand

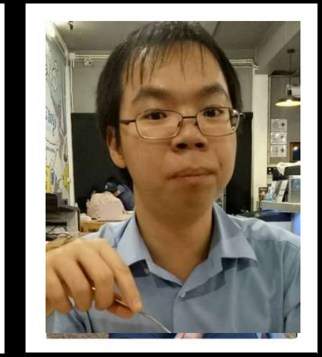


David Ruffolo

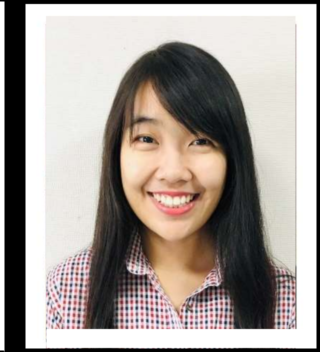
Alejandro Sáiz



Warit Mitthumsiri



Petchara Pattarakijwanich



Kullapha Chaiwongkhot

+ 2 postdoctoral researchers,
7 graduate students (4 Thai, 3 international),
several undergraduate & high school students

Space Physics at Mahidol University: Key Collaborations

Contact:
david.ruf@mahidol.ac.th

Thailand

- Chiang Mai U.
- Kasetsart U.
- NARIT
- PIM
- TMEC/NECTEC
- RMUTT
- Thammasat U.
- Chulalongkorn U.

Africa

- Northwest U., South Africa

USA

- U. Delaware
- Princeton U.
- NASA/Goddard
- U. Wisconsin River Falls
- Stanford U.
- U. Hawaii Manoa
- U. New Hampshire

Asia

- IHEP, CAS, China
- Purple Mountain Observatory, China
- Shinshu U., Japan
- Yamagata U., Japan

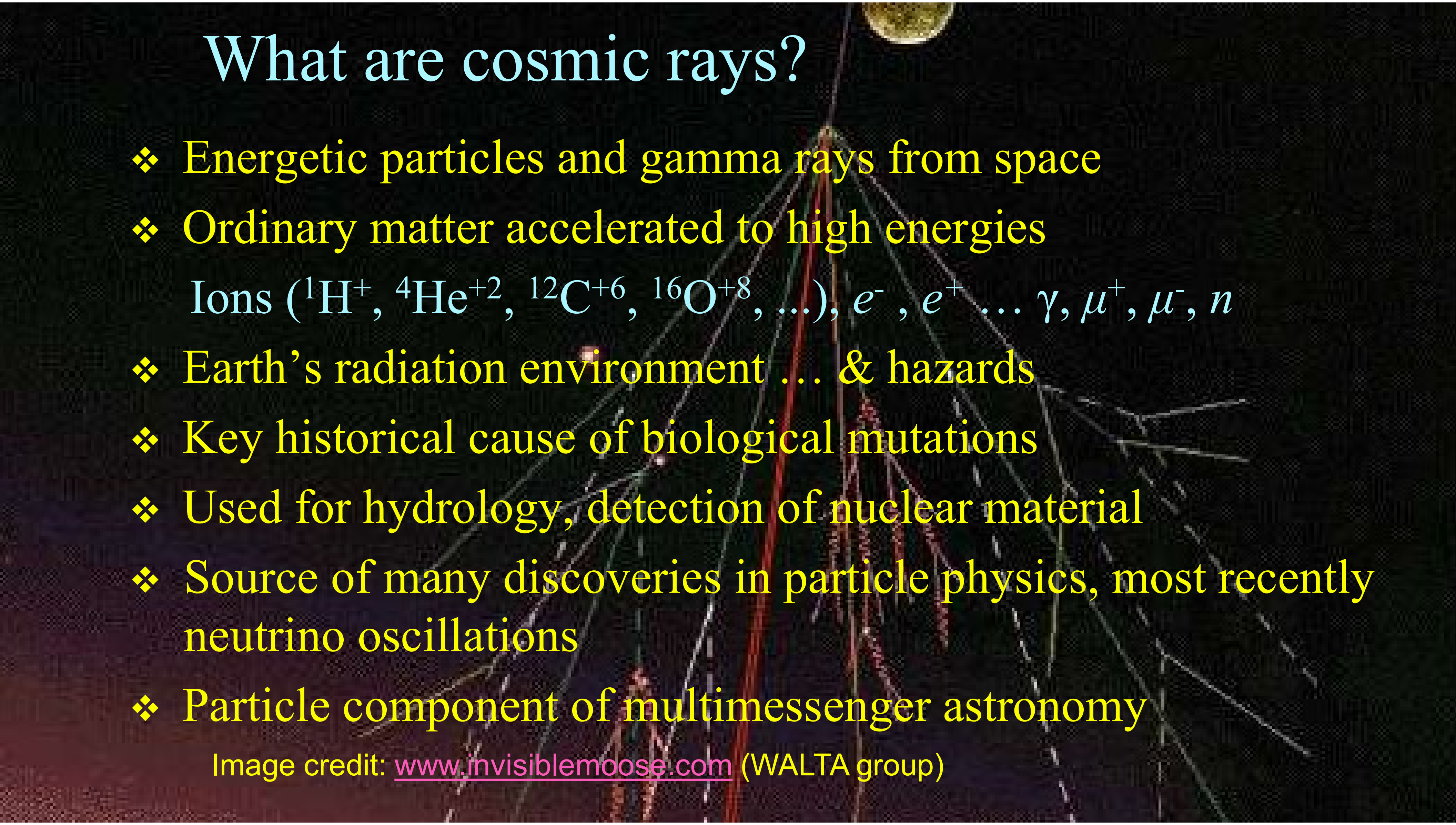
Europe

- IRAP, France
- UCL, UK

Australia/ New Zealand

- U. Tasmania
- Australian Antarctic Division
- Victoria U. Wellington

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)

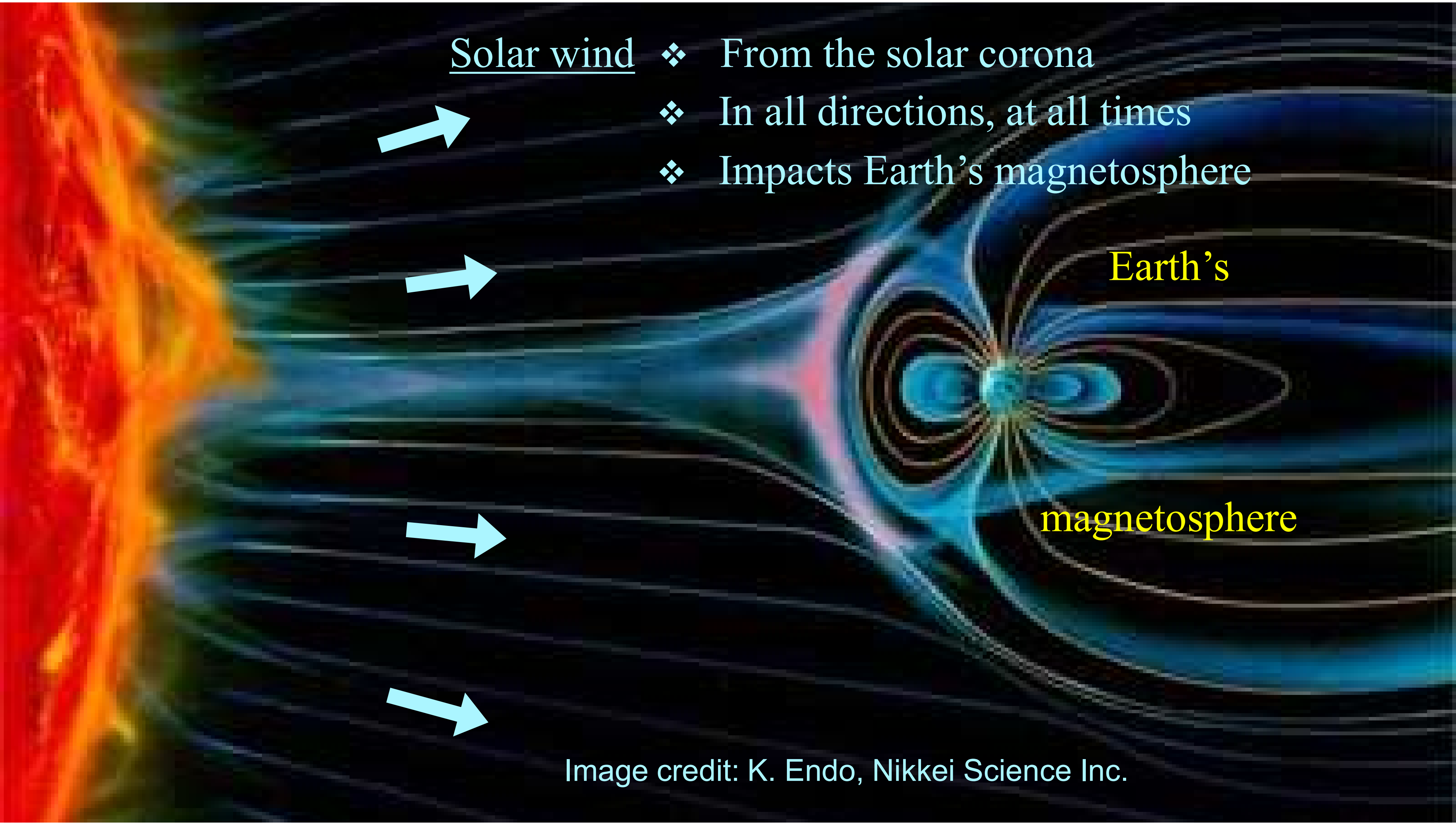
What is a plasma?

- A plasma is the "4th state" of matter (solid, liquid, gas, plasma)
- It is an ionized gas. For example

$$H \rightarrow H^+ + e^-$$

Atom → ion + electron(s)

- So a plasma is electrically conducting
- Most of the universe is filled with plasmas



Solar wind
- From the solar corona
- In all directions, at all times
- Impacts Earth's magnetosphere

Image credit: K. Endo, Nikkei Science Inc.

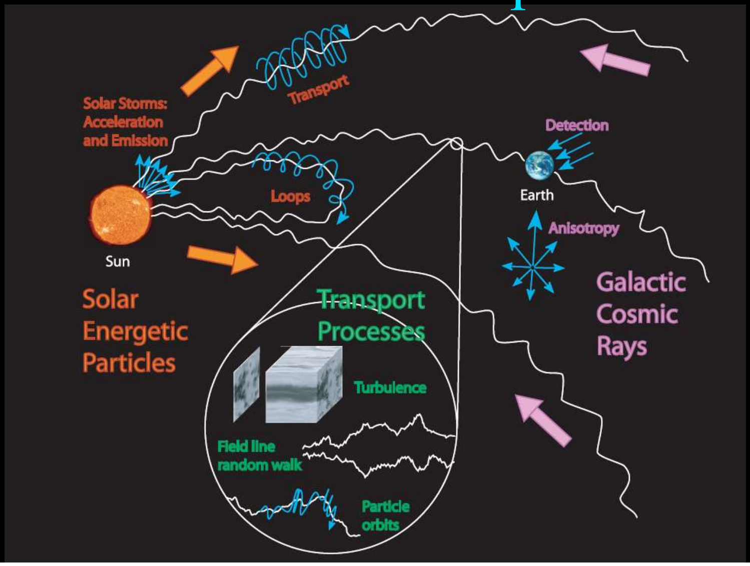
Space Plasma Physics & Cosmic Rays

Space plasma processes accelerate cosmic rays …

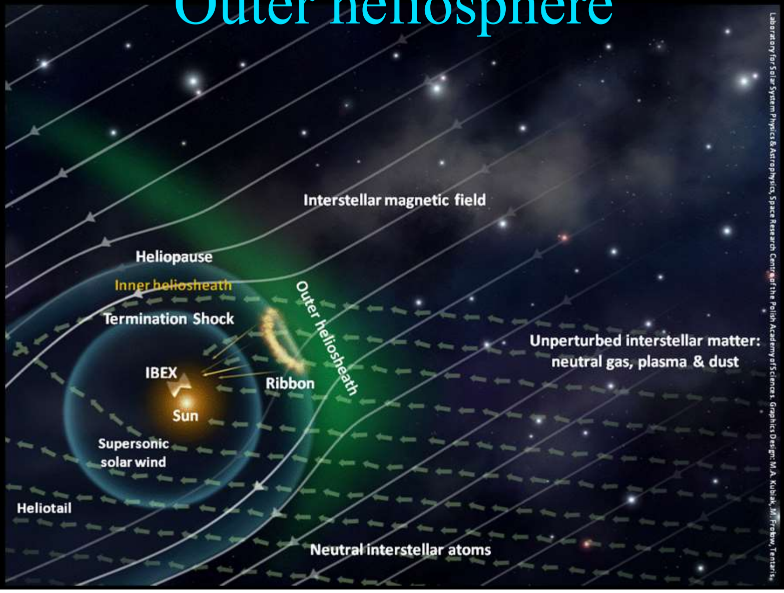
… and govern their transport …

… so cosmic rays provide remote sensing of plasma conditions throughout the heliosphere

Inner heliosphere



Outer heliosphere



Laboratory for Solar System Physics & Astrophysics, Space Research Centre of the Polish Academy of Sciences. Graphics Design: M.A. Kubiak, M. Frołow, Tentaris

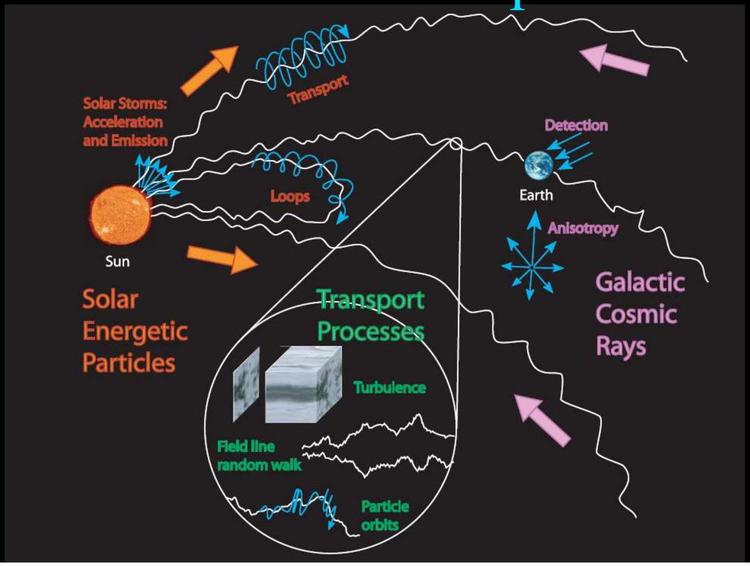
Space Plasma Physics & Cosmic Rays

Key sources of cosmic rays for Earth's radiation environment:

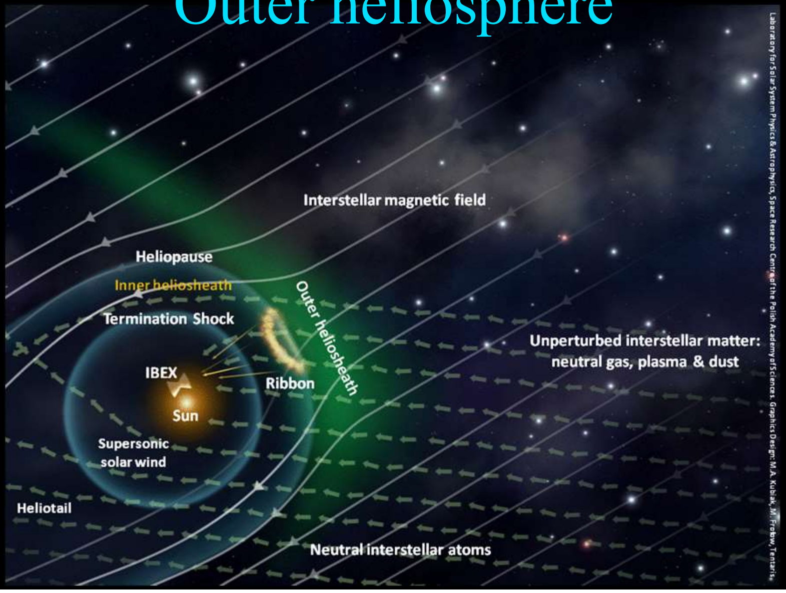
- From solar storms (solar energetic particles)
- From supernova explosions (Galactic cosmic rays)

IN BOTH CASES, TIME VARIATIONS ARE DUE TO OUR SUN

Inner heliosphere



Outer heliosphere



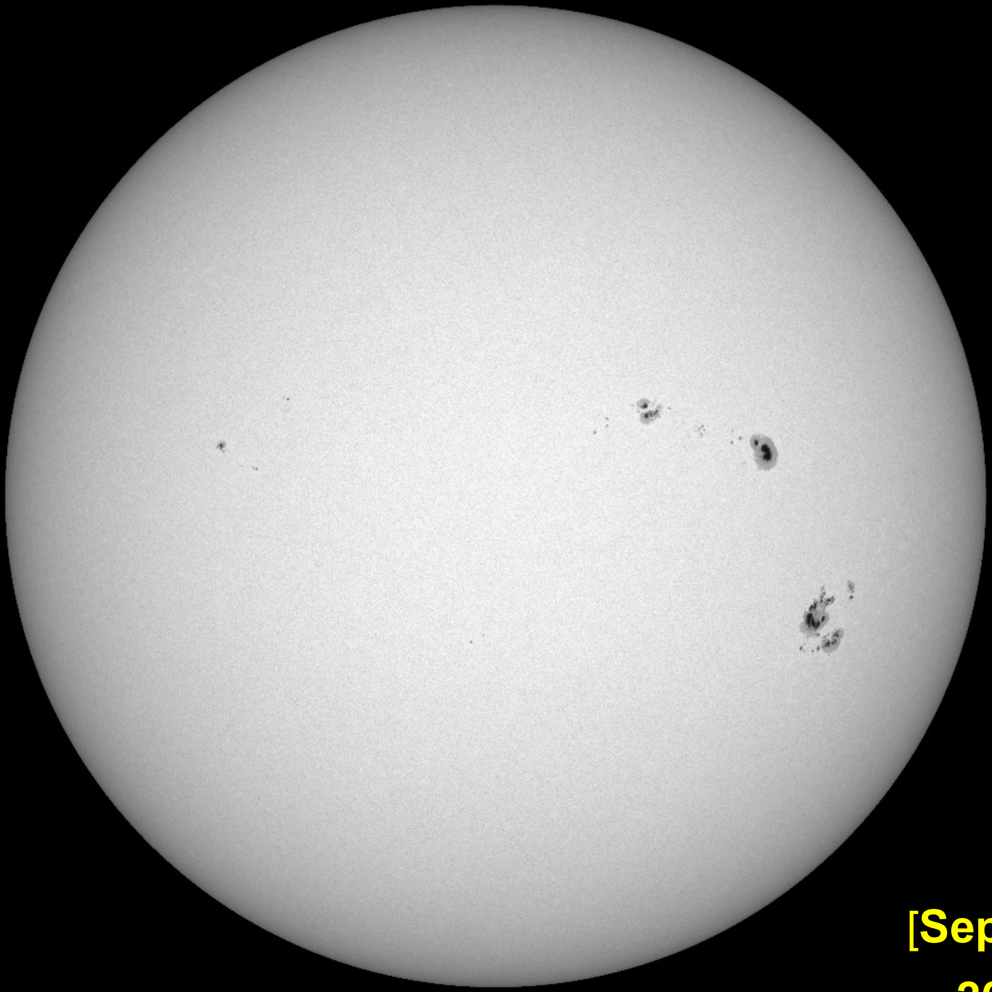
Laboratory for Solar System Physics & Astrophysics, Space Research Centre of the Polish Academy of Sciences. Graphics Design: M.A. Kubiak, M. Frołow, Tentaris.

The surface of the Sun (called the photosphere)

- Sunspots are where intense magnetic fields exit or enter the photosphere.
- Lower brightness (lower T)
- Large sunspot number every 11 years (more or less)
- Solar maximum ~ 2000, 2014
  & soon
- Solar minimum ~ 2008, 2019

Photosphere has T=6000 K …

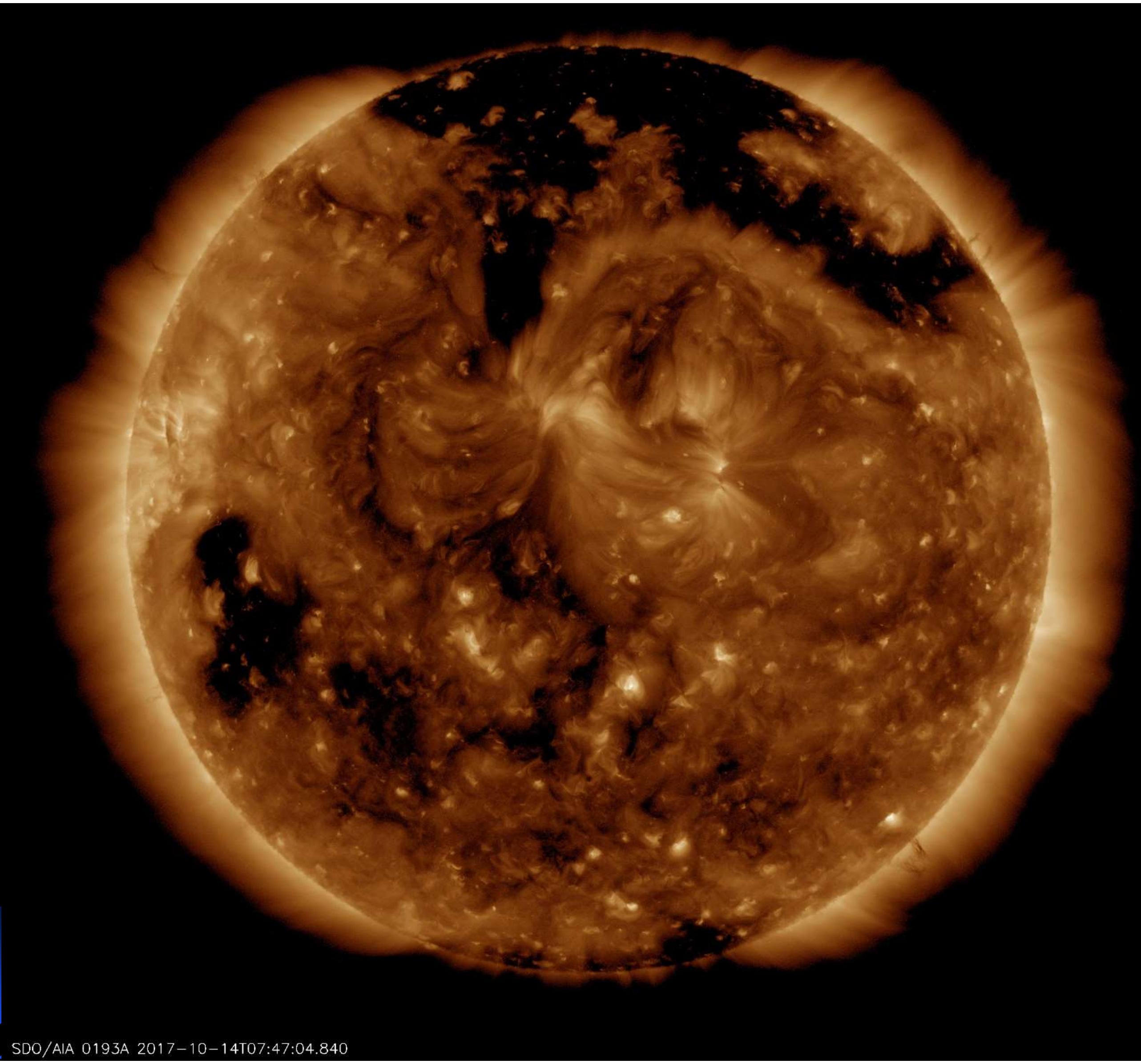
… Sunspots have T=4000 K



[Sep. 6, 2017]

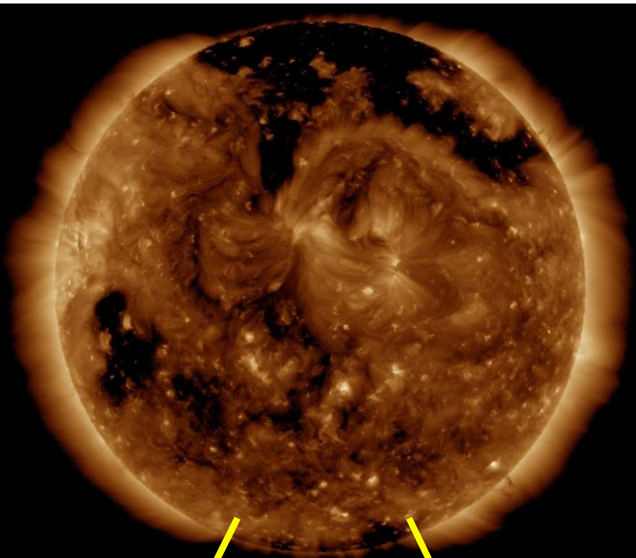
SDO/HMI Continuum 2017–09–06T23:34:19.300

Full-disk image of the Sun in EUV (extreme ultraviolet) radiation



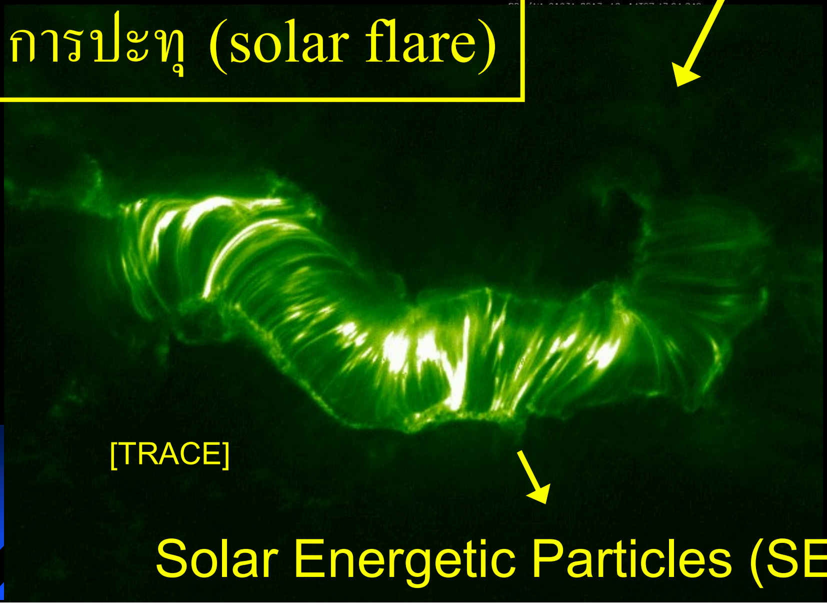
[SDO 195 Å image on October 14, 2017]

The Sun accumulates magnetic energy ...



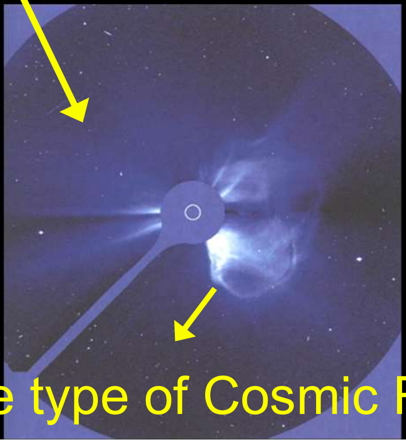
... which is released suddenly in solar storms!

การปะทุ (solar flare)



[TRACE]

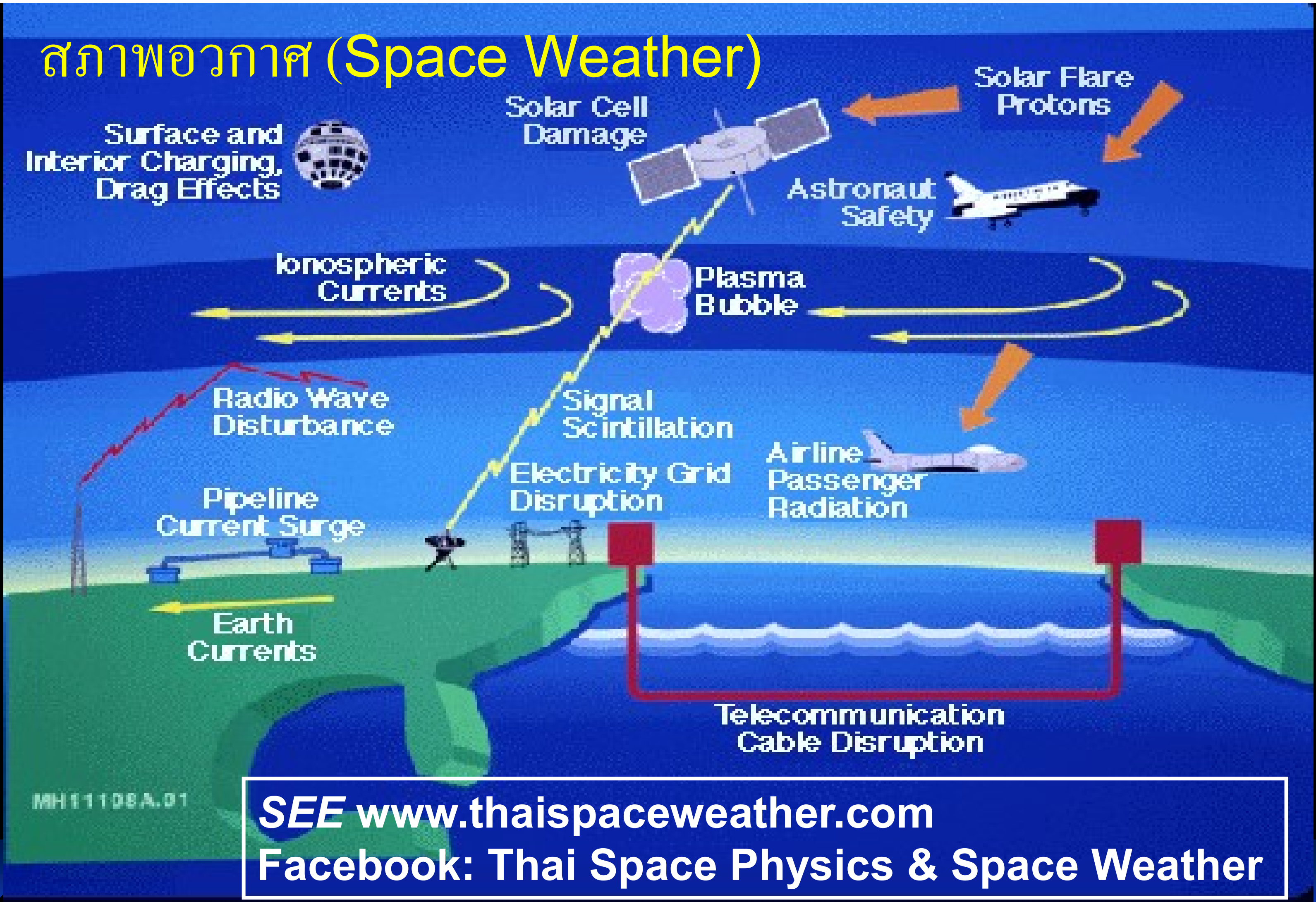
การปล่อยก้อนมวลจากโคโรนา (coronal mass ejection; CME)



[SOHO]

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

สภาพอวกาศ (Space Weather)

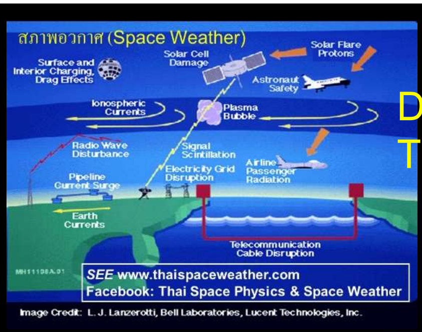


SEE **www.thaispaceweather.com**

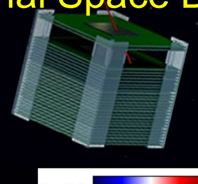
Facebook: Thai Space Physics & Space Weather

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

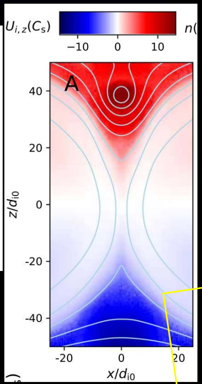
Overview of Our Research



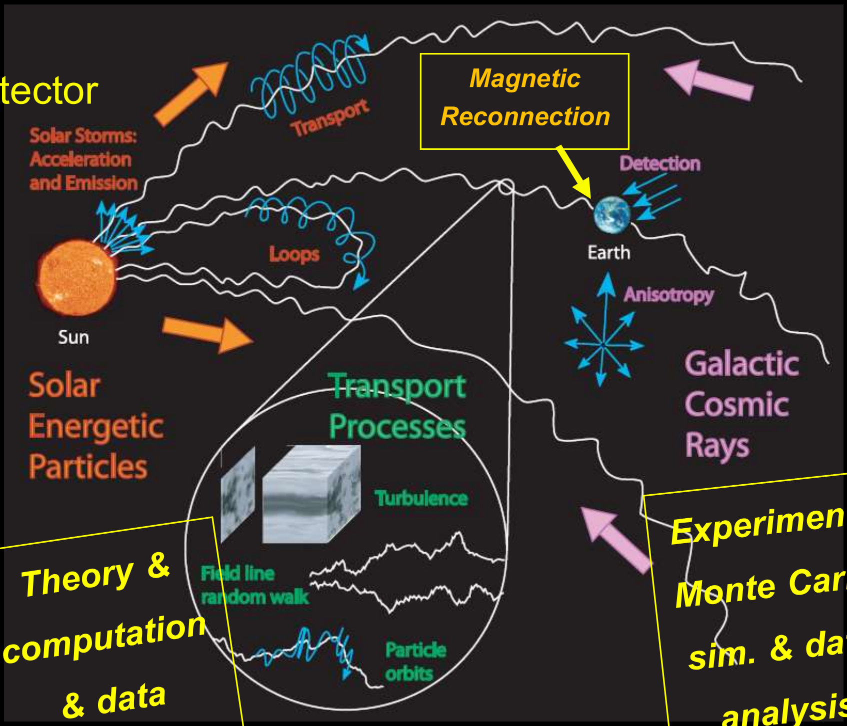
Developing a Thai Space Detector



$$
\begin{aligned}
\frac{\partial F(t,\mu,z,p)}{\partial t} = &-\frac{\partial}{\partial z}\mu v F(t,\mu,z,p) \\
&-\frac{\partial}{\partial z}\left(1-\mu^2\frac{v^2}{c^2}\right)v_{\mathrm{sw}}\sec\psi F(t,\mu,z,p) \\
&-\frac{\partial}{\partial \mu}\frac{v}{2L(z)}\left[1+\mu\frac{v_{\mathrm{sw}}}{v}\sec\psi-\mu\frac{v_{\mathrm{sw}}v}{c^2}\sec\psi\right](1-\mu^2)F(t,\mu,z,p) \\
&+\frac{\partial}{\partial \mu}v_{\mathrm{sw}}\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu(1-\mu^2)F(t,\mu,z,p) \\
&+\frac{\partial}{\partial \mu}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial \mu}\left(1-\mu\frac{v_{\mathrm{sw}}v}{c^2}\sec\psi\right)F(t,\mu,z,p) \\
&+\frac{\partial}{\partial p}pv_{\mathrm{sw}}\left[\frac{\sec\psi}{2L(z)}(1-\mu^2)+\cos\psi\frac{d}{dr}(\sec\psi)\mu^2\right]F(t,\mu,z,p)\,.
\end{aligned}
$$



Plasma Simulation

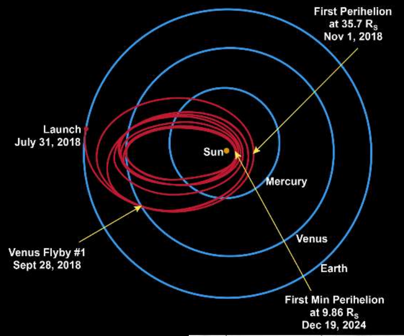


Theory & computation & data analysis

Experiment, Monte Carlo sim. & data analysis

Participating in LHAASO (China)

Operating the Princess Sirindhorn Neutron Monitor at Doi Inthanon



Analyzing Parker Solar Probe data

Upgrading & Operating Cosmic Ray Detectors at Mawson Station (Antarctica)

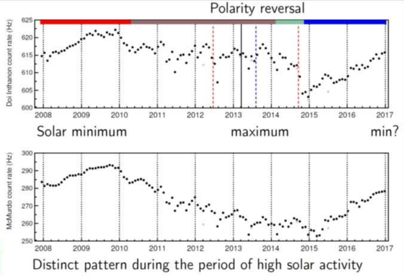
Solar Modulation over the 11-year solar cycle

- Distinct pattern of solar modulation at high cutoff rigidity Mangeard+18 At solar max. (high tilt angle), high-rigidity modulation tracks magnetic field, as if diffusion short-circuits drift along heliospheric current sheet.

Doi Inthanon: Geomagnetic cutoff ≈ 17 GV

McMurdo: Geomagnetic cutoff ≈ 0 GV, atmospheric cutoff ~ 1 GV

David Ruffolo, Mahid



Distinct pattern during the period of high solar activity

Some of you may be wondering …

Why study cosmic rays in Thailand?

Short answer:

- **I love to study cosmic rays, and**
- **I love Thailand!**

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

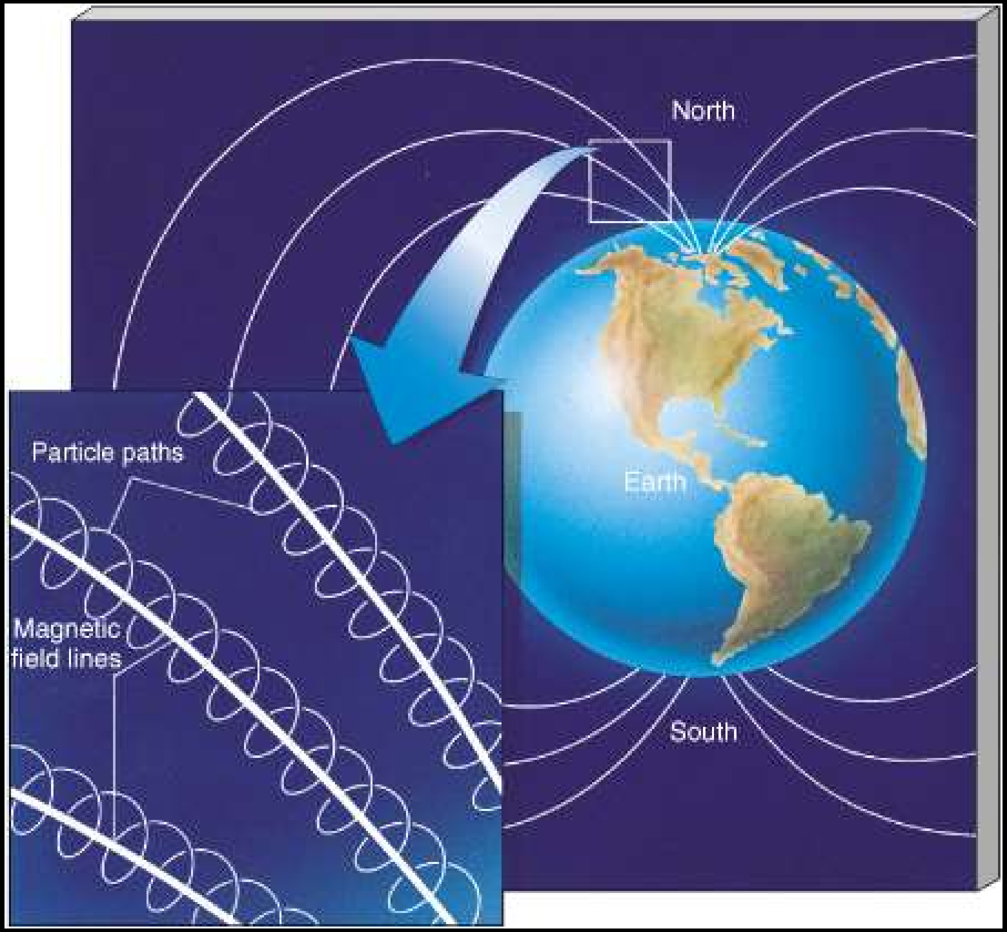
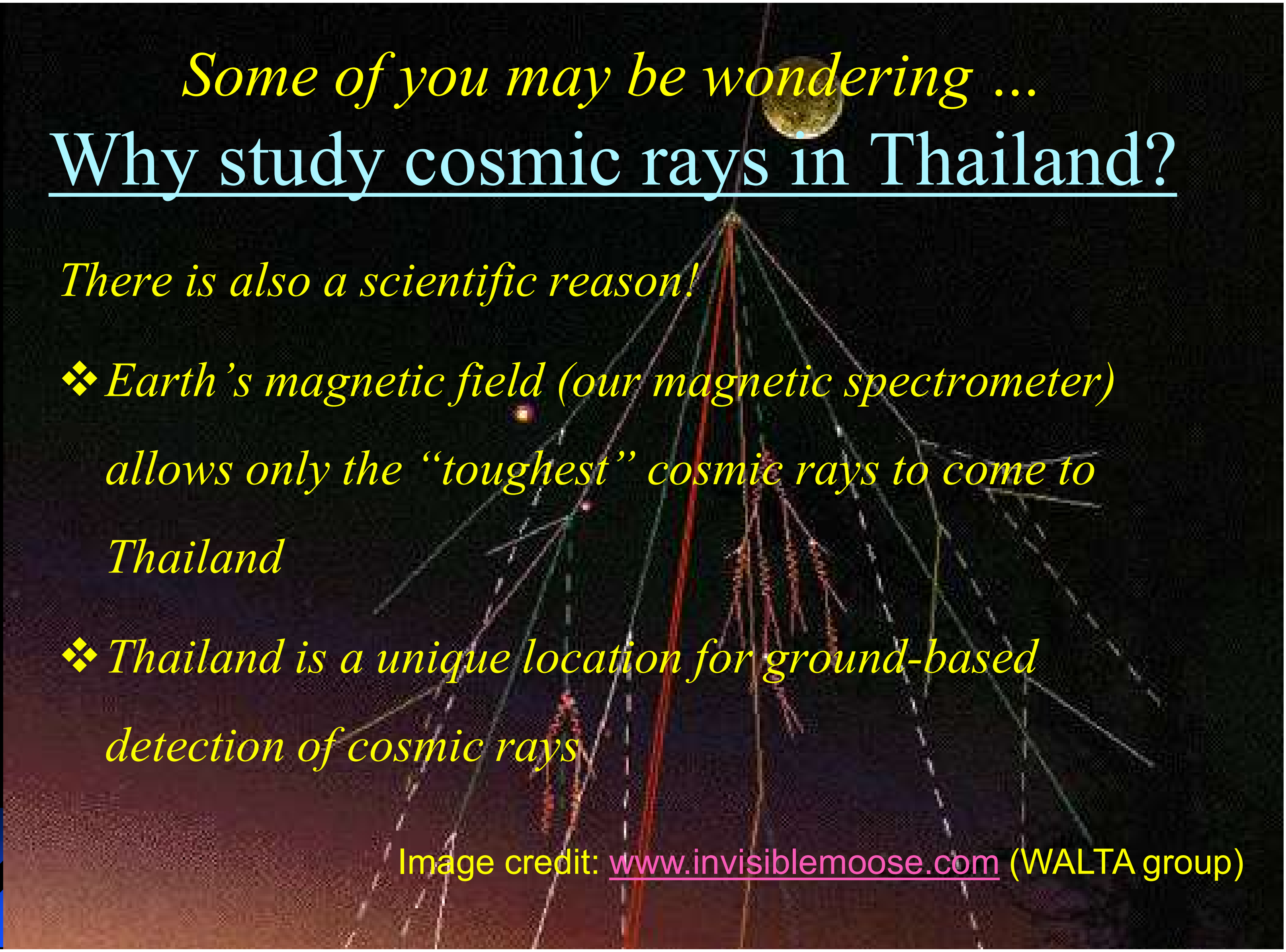


Image credit: http://astronomy.nju.edu.cn/~lixd/GA/AT4/AT407/HTML/AT40705.htm



Some of you may be wondering …

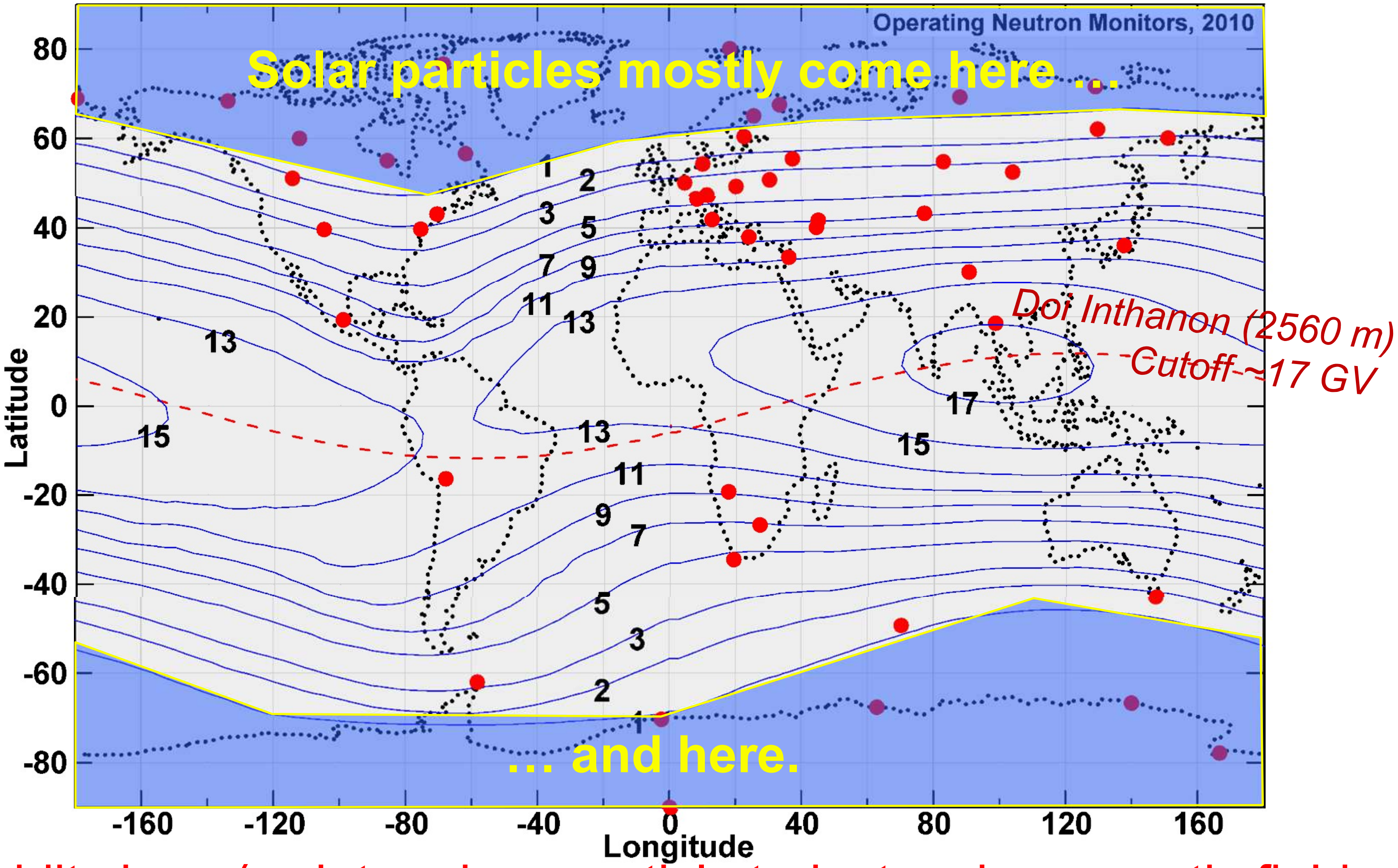
Why study cosmic rays in Thailand?

There is also a scientific reason!

- ❖ *Earth's magnetic field (our magnetic spectrometer) allows only the "toughest" cosmic rays to come to Thailand*
- ❖ *Thailand is a unique location for ground-based detection of cosmic rays*

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

Locations of neutron monitors and their cutoff rigidities in GV.



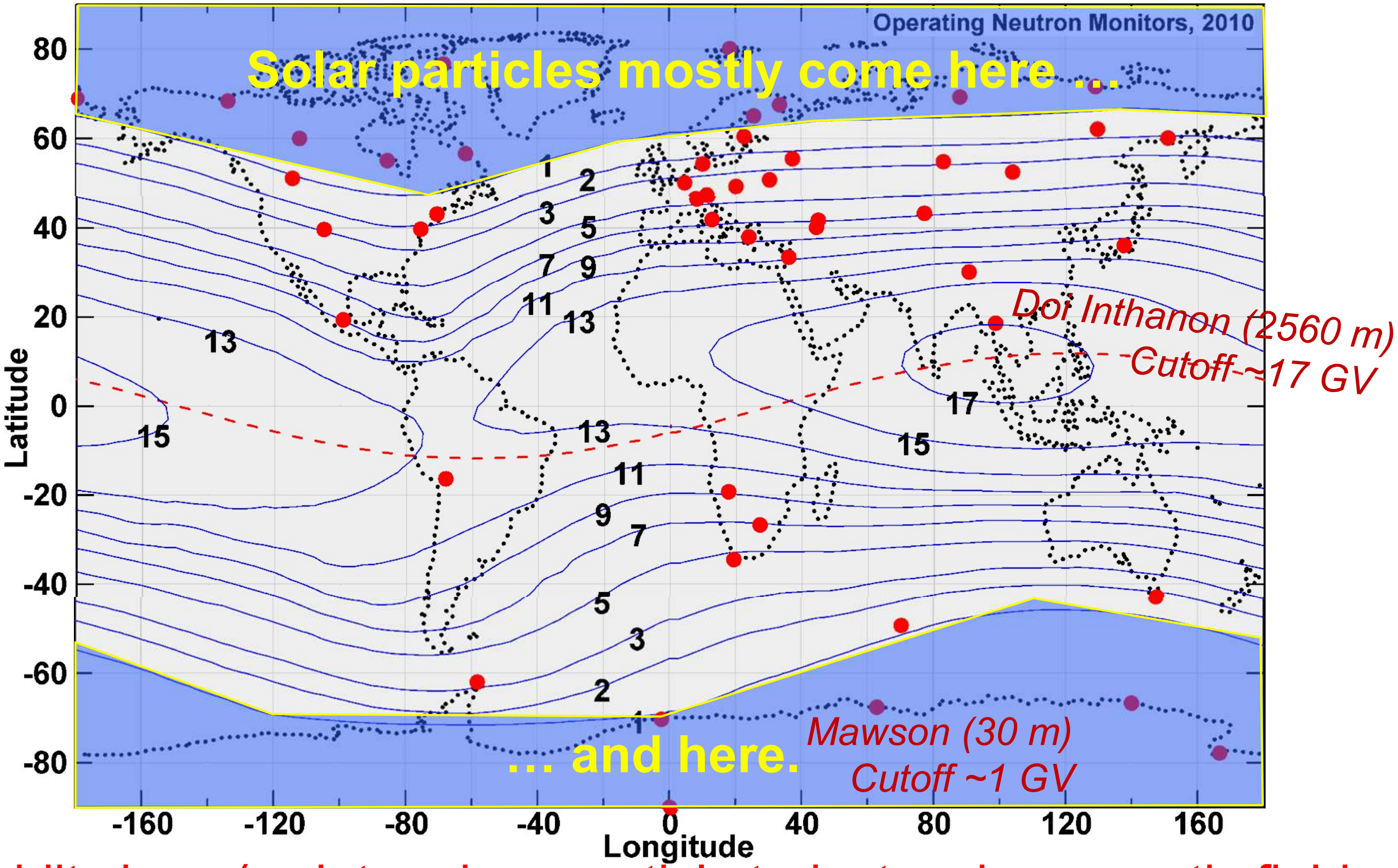
Solar particles mostly come here …

… and here.

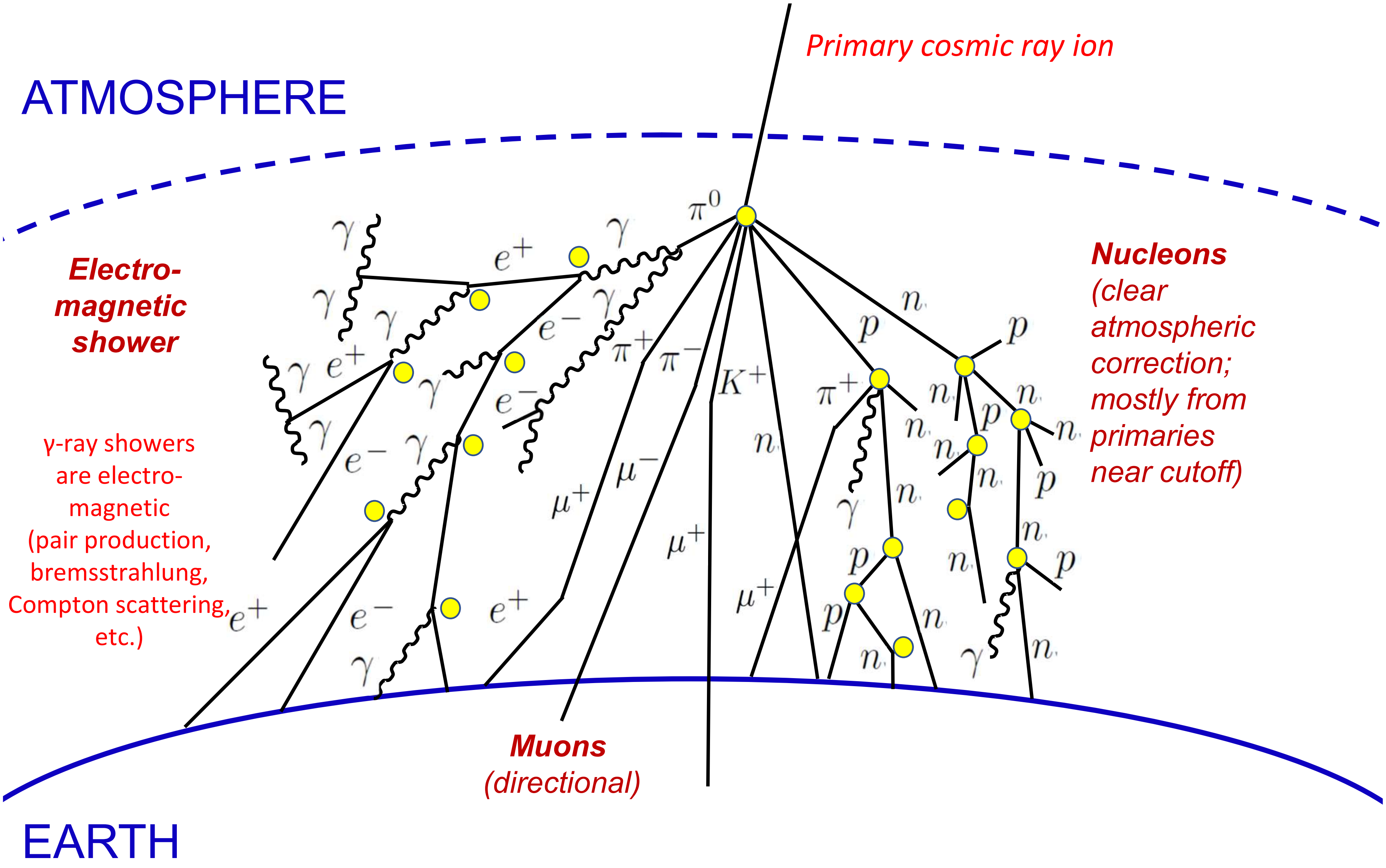
Doi Inthanon (2560 m)
Cutoff ~17 GV

Rigidity is *pc/q,* determines particle trajectory in magnetic field

Locations of neutron monitors and their cutoff rigidities in GV.



Rigidity is *pc/q,* determines particle trajectory in magnetic field



Primary cosmic ray ion

Electro-magnetic shower

γ-ray showers are electro-magnetic (pair production, bremsstrahlung, Compton scattering, etc.)

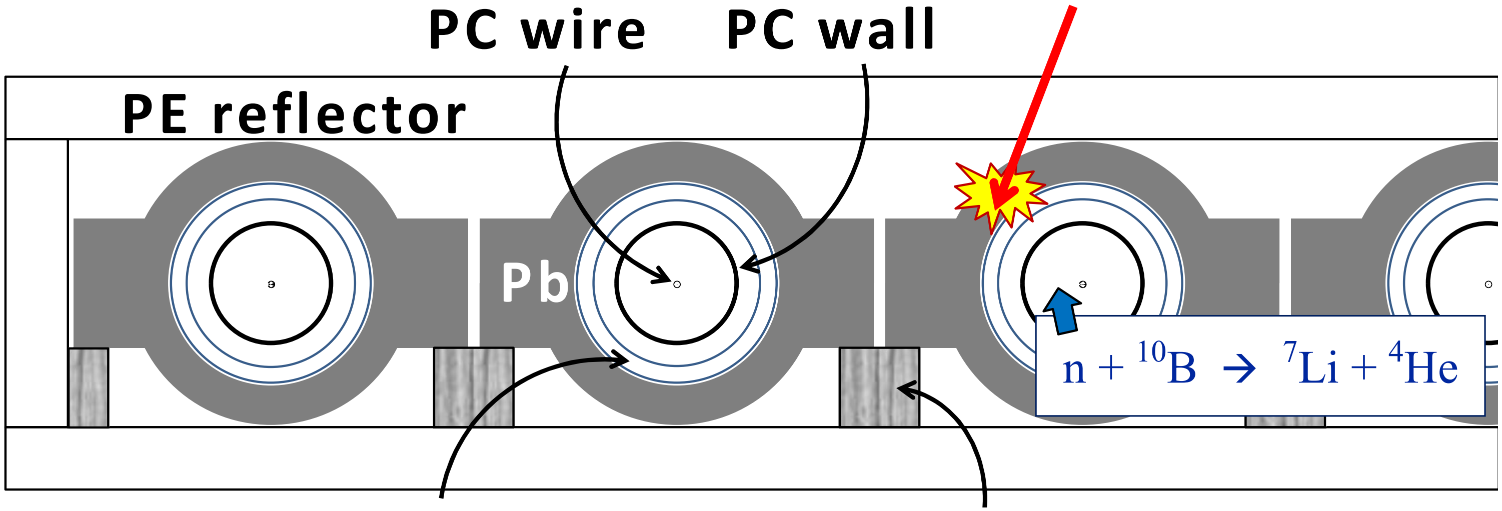
Nucleons *(clear atmospheric correction; mostly from primaries near cutoff)*

Muons *(directional)*

Princess Sirindhorn Neutron Monitor

(18 counters, NM-64 design)

PC= $^{10}BF_3$ proportional counter



Atmospheric secondary particle (usually a neutron)

PC wire

PC wall

PE reflector

Pb

$n + {}^{10}B \rightarrow {}^{7}Li + {}^{4}He$

PE moderator
(PE=polyethylene)

Wood

[Ruffolo+16]

Provides accurate count rate, related to cosmic ray flux in space. Altitude is extremely important, so at Thailand’s highest peak …


อากาศโยธิน
2007 2 27

[Ruffolo+16]


Princess Sirindhorn Neutron Monitor

Opening ceremony, January 21, 2008

Random number generation based on arrival times of neutrons from cosmic-ray showers

Kanin Aungskunsiri,[1,*] David Ruffolo,[2] Kruawan Wongpanya,[1] Sakdinan Jantarachote,[1]
Pongpun Punpetch,[1] Achara Seripienlert,[3] Alejandro Sáiz,[2] and Waraporn Nuntiyakul[4]
[1]*National Electronics and Computer Technology Center, Pathum Thani 12120, Thailand*
[2]*Department of Physics, Faculty of Science, Mahidol University, Bangkok 10400, Thailand*
[3]*National Astronomical Research Institute of Thailand, Chiang Mai 50180, Thailand*
[4]*Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai 50200, Thailand*
(Dated: February 15, 2024)

(submitted to Physical Review Applied)

Randomness is indispensable in modern technology for various crucial aspects like data privacy, secure communications, algorithm robustness, and simulations. We demonstrate the potential to realize an entropy source from the arrival times of neutrons produced in the atmosphere by cosmic ray showers and detected by a ground-based neutron monitor. The data on neutron detections recorded by the Princess Sirindhorn Neutron Monitor are converted into uniformly random distribution outputs at an extraction ratio of 13 bits per single detection event. These derived outputs achieve nearly full entropy rates and successfully pass the statistical randomness validation according to the U.S. National Institute of Standards and Technology (NIST) Special Publication 800-22 test suite, with no repeating patterns detected from an autocorrelation analysis. Cosmic rays serve as a readily non-deterministic source for random key generation through minimal yet real-time processing, making them suitable for use as a supplementary resource to strengthen the security of both space- and ground-based applications.

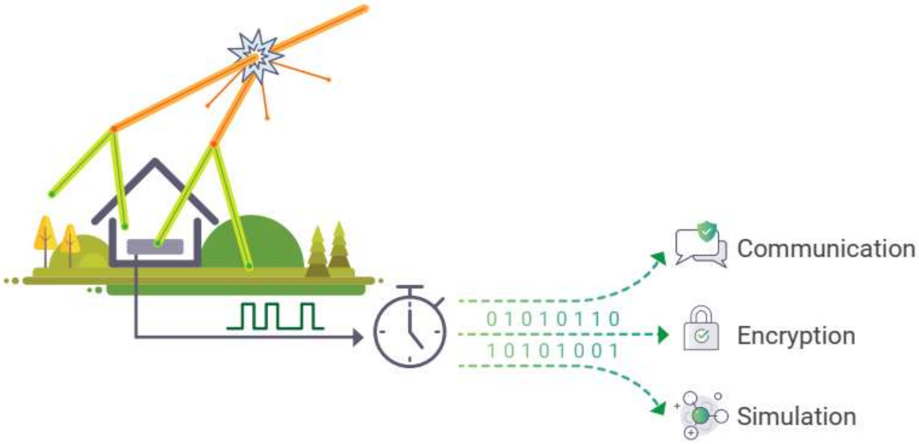


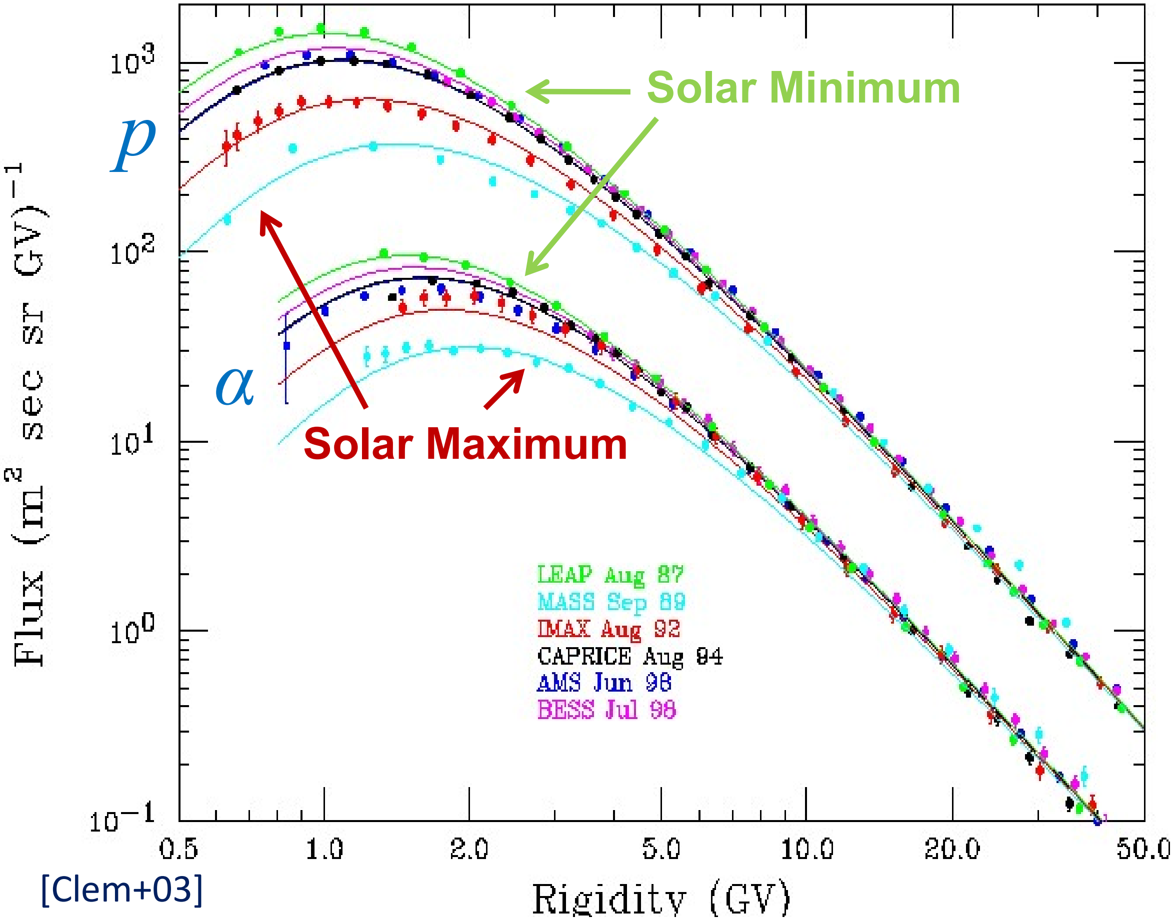
TABLE I. NIST SP800-22 test results for a 160,000,000-bit sequence collected from the generated random outputs. The criteria to pass this test suite with a significance level of 0.01 require that both the P-values-total and the calculated proportions for each of the 15 sub-methods must reach a minimum threshold of 0.0001 and 0.96, respectively.

Method	P-values-total	Proportion	Result
1. Frequency	0.345 449	0.9941	Pass
2. Block Frequency	0.656 634	0.9941	Pass
3. Runs	0.850 337	0.9941	Pass
4. Longest Run	0.828 826	0.9882	Pass
5. Rank	0.196 260	0.9882	Pass
6. Fast Fourier Transform	0.073 701	0.9941	Pass
7. Overlapping Template	0.120 119	0.9941	Pass
8. Universal	0.306 892	0.9882	Pass
9. Linear Complexity	0.527 860	0.9941	Pass
10. Approximate Entropy	0.708 280	0.9941	Pass
11. Non-overlapping Template	0.411 287	0.9914	Pass
12. Serial	0.361 111	0.9970	Pass
13. Cumulative Sums	0.637 119	0.9941	Pass
14. Random Excursions	0.296 780	0.9848	Pass
15. Random Excursions Variant	0.408 578	0.9777	Pass

Solar Effects on Galactic Cosmic Rays

- 11/22-year solar cycle: solar modulation (during solar maximum, Galactic cosmic rays “blown out”) [Mangeard+18]
- 27-day synodic variations: as Sun rotates, Earth feels fast or slow solar wind, faster wind blows out cosmic rays [Yeeram+14]
- 1-day diurnal variations: as Earth rotates, we sample particles from different directions, measure anisotropy [Yeeram+14, Buatthaisong+22]
- Solar storms: Galactic cosmic ray flux decreases (“Forbush decreases”) as blown out by solar storms [Tortermpun+18, Munakata+22]

Solar modulation: Energy (or rigidity) spectrum
of Galactic cosmic rays varies with the solar cycle.

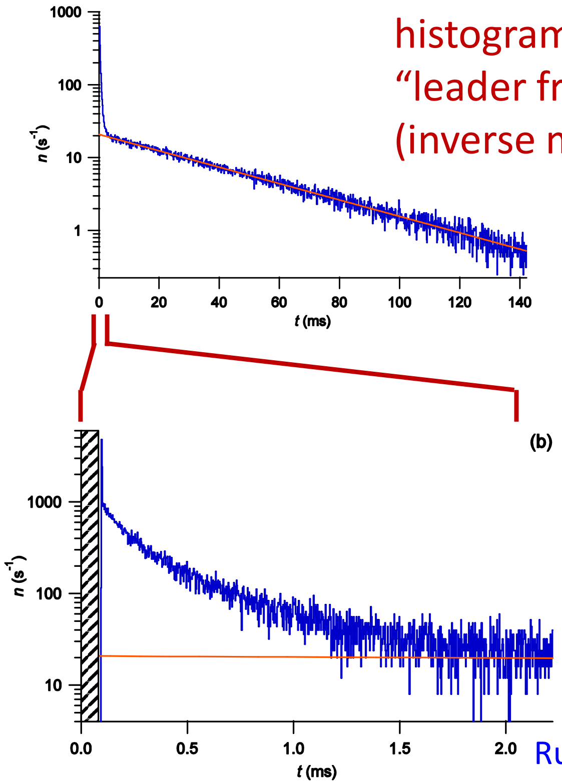


[Clem+03]

Usually, any "rolling" (count rate decrease) occurs with hardening of spectral index. Does the spectrum "roll" & "unroll" in the same way?

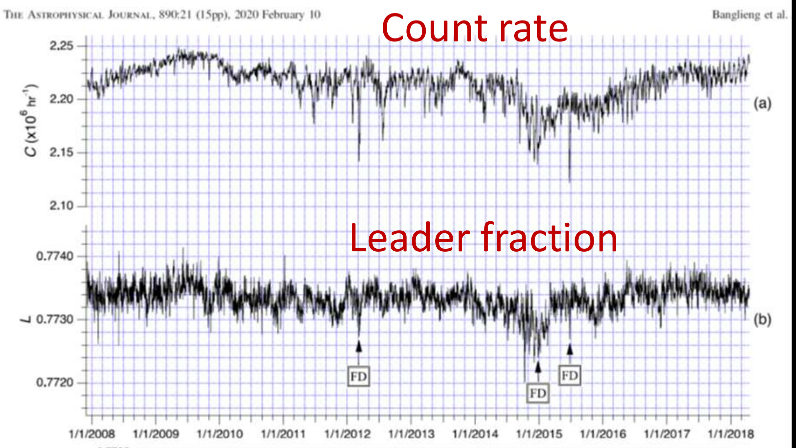
- ❖ Measuring spectral variations at a single NM station using neutron time-delay distributions Banglieng+20

Implemented at Doi Inthanon, NM at highest cutoff, so extends the "reach" of worldwide NM network.



Ruffolo+16

From time-delay histograms … infer "leader fraction" (inverse multiplicity)

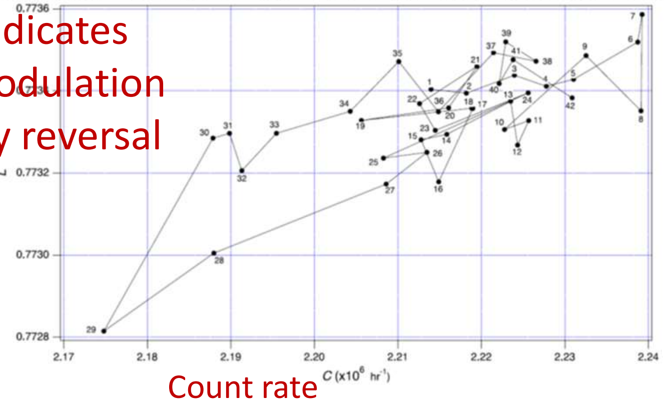

The Astrophysical Journal, 890:21 (15pp), 2020 February 10

Banglieng et al.

Count rate

Leader fraction

Hysteresis indicates change in modulation after polarity reversal

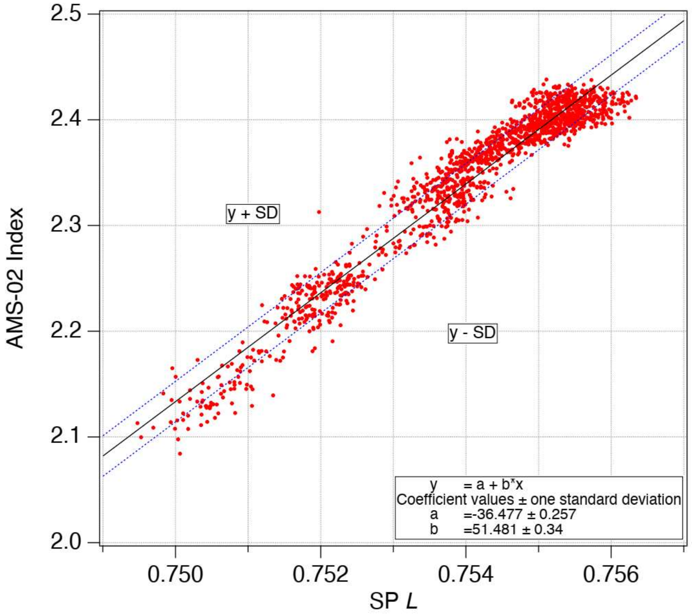


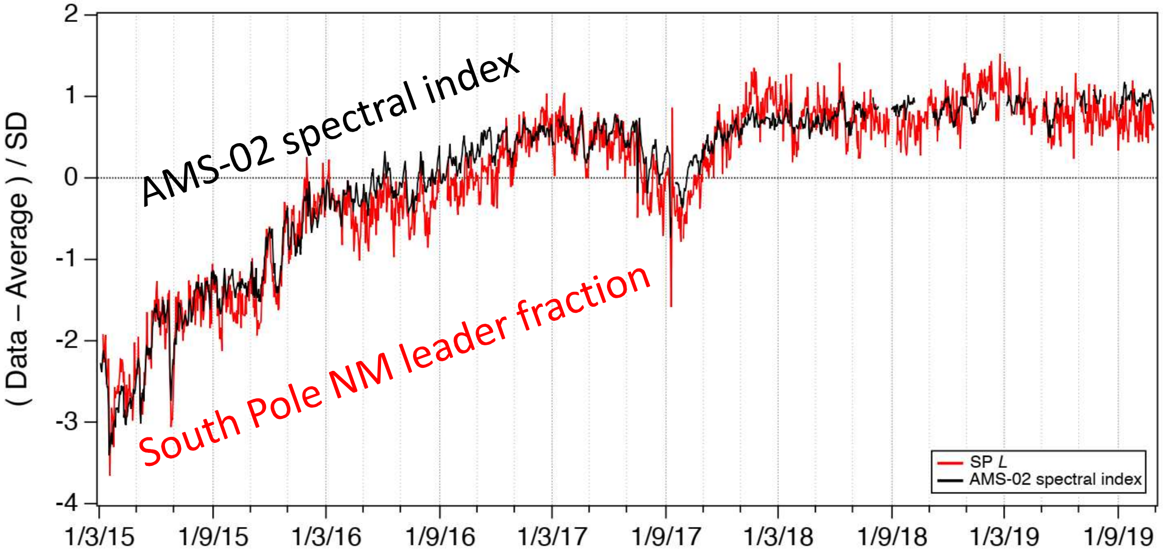
Leader fraction

Count rate

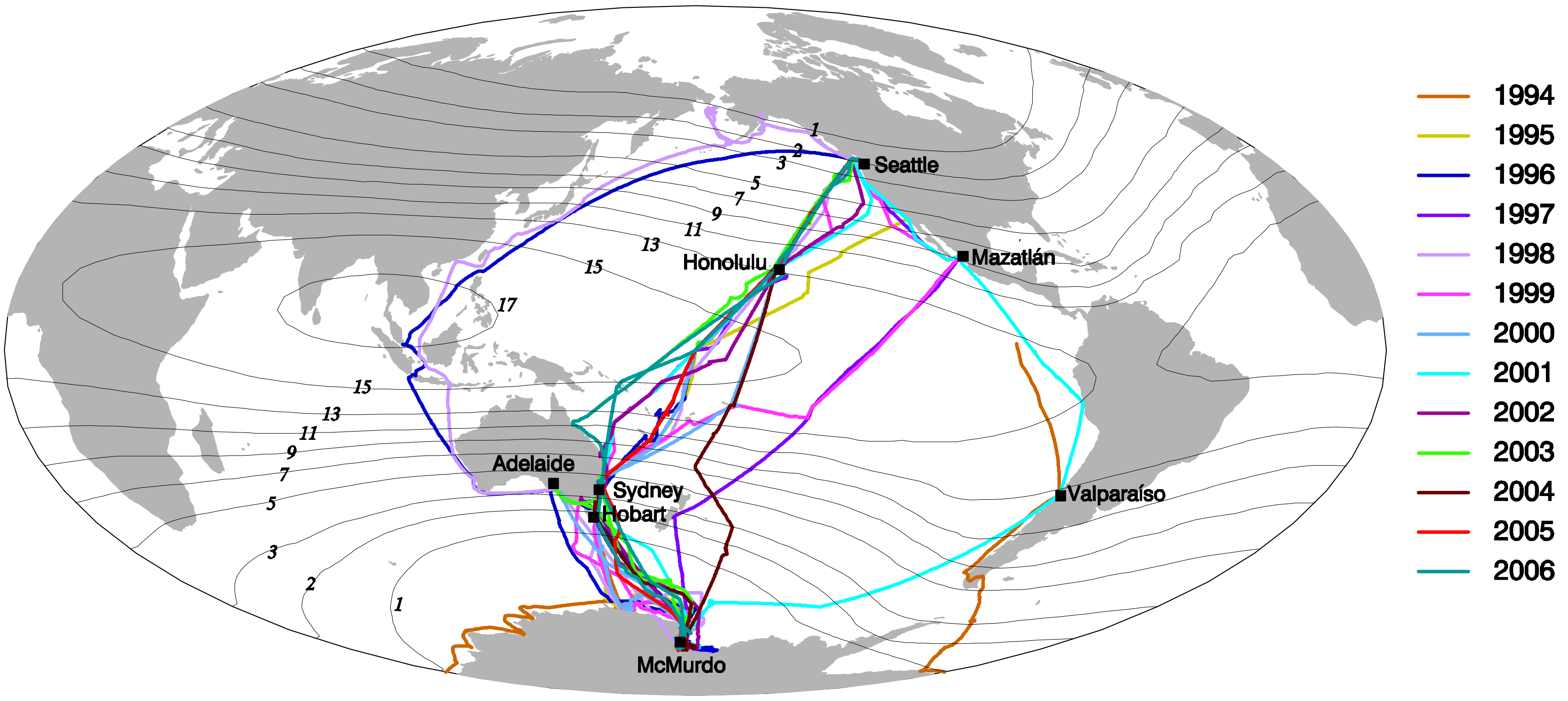
At high cutoff rigidity (~17 GV), variation in the spectral index is not precisely measured by spacecraft.

At low cutoff rigidity (~1 GV), we use AMS-02 data to calibrate the leader fraction from Antarctic NMs, to provide long-term ground-based measurements of the Galactic cosmic ray spectrum based on individual stations. Daily spectral power-law index can be measured with absolute uncertainty of ±0.02.



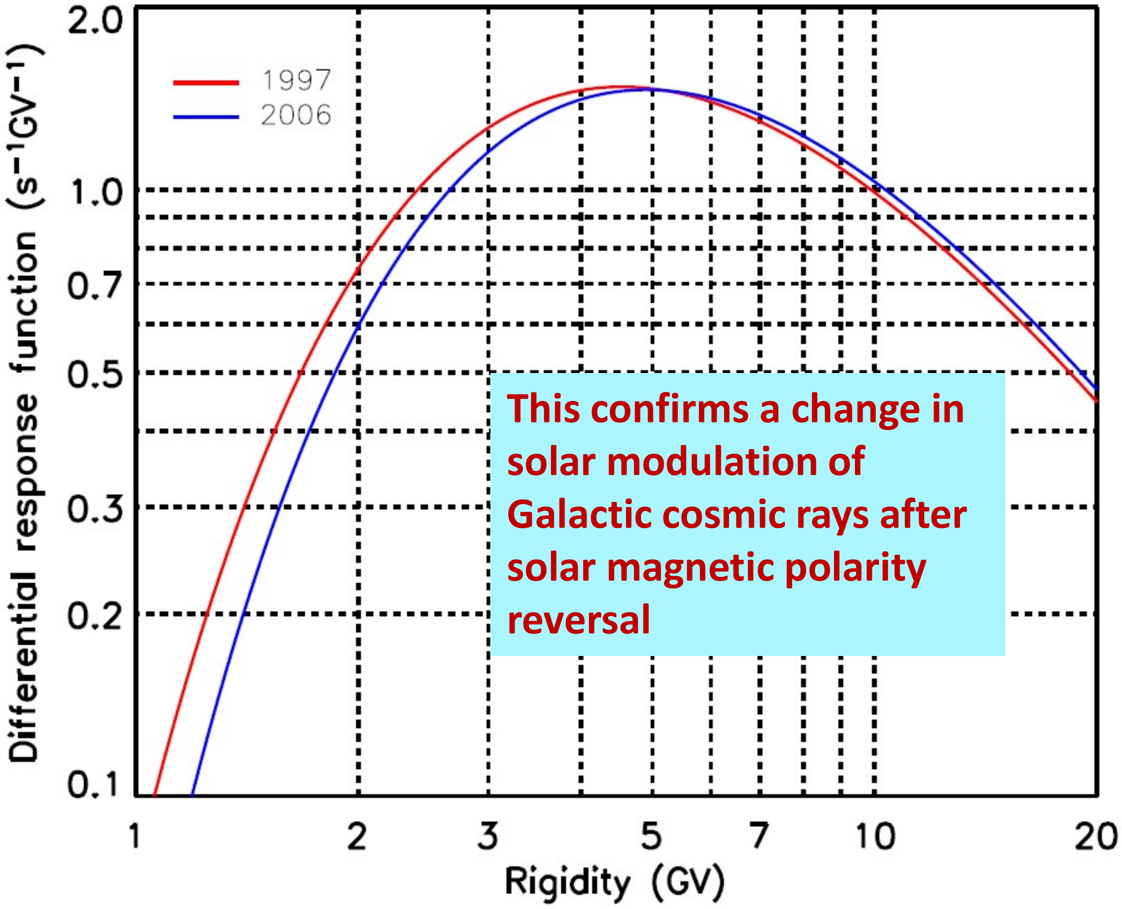


Cosmic ray spectrum: Analyzing data from the 1994-2007 American-Australian latitude surveys (Analysis led by Waraporn Nuntiyakul)



[Nuntiyakul+14; see also Nuntiyakul+18, Nuntiyakul+20, Poopakun+23]

Crossover in spectra for opposite solar magnetic polarity (near sunspot minimum)



This confirms a change in solar modulation of Galactic cosmic rays after solar magnetic polarity reversal

[Nuntiyakul+14]

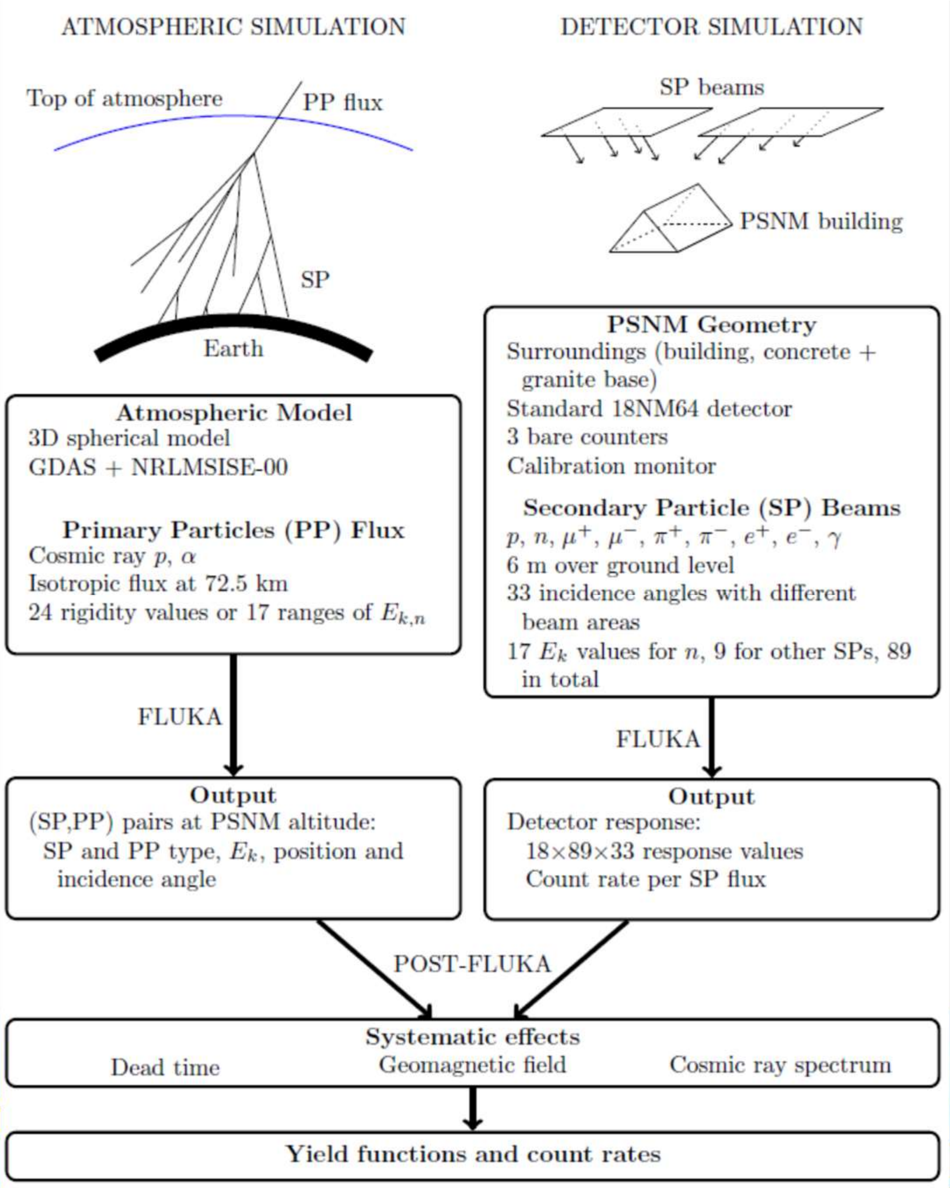
“Changvan” portable neutron monitor

This has measured the cosmic ray flux during two sea voyages between China and Antarctica in 2019-2020.

Currently on a Korean ship!

Neutron monitor detection of Galactic cosmic rays

We have developed
state-of-the-art
Monte Carlo (FLUKA) modeling
of Galactic cosmic ray primary
particle (PP) interactions in the
atmosphere to make secondary
particles (SP) …
followed by modeling SP
interactions in the neutron monitor
[Mangeard+16a,b]



Atmospheric Model
3D spherical model
GDAS + NRLMSISE-00

Primary Particles (PP) Flux
Cosmic ray p, α
Isotropic flux at 72.5 km
24 rigidity values or 17 ranges of $E_{k,n}$

PSNM Geometry
Surroundings (building, concrete + granite base)
Standard 18NM64 detector
3 bare counters
Calibration monitor

Secondary Particle (SP) Beams
p, n, μ^+, μ^-, π^+, π^-, e^+, e^-, γ
6 m over ground level
33 incidence angles with different beam areas
17 E_k values for n, 9 for other SPs, 89 in total

Output
(SP,PP) pairs at PSNM altitude:
SP and PP type, E_k, position and incidence angle

Output
Detector response:
$18 \times 89 \times 33$ response values
Count rate per SP flux

Systematic effects
Dead time
Geomagnetic field
Cosmic ray spectrum

Yield functions and count rates

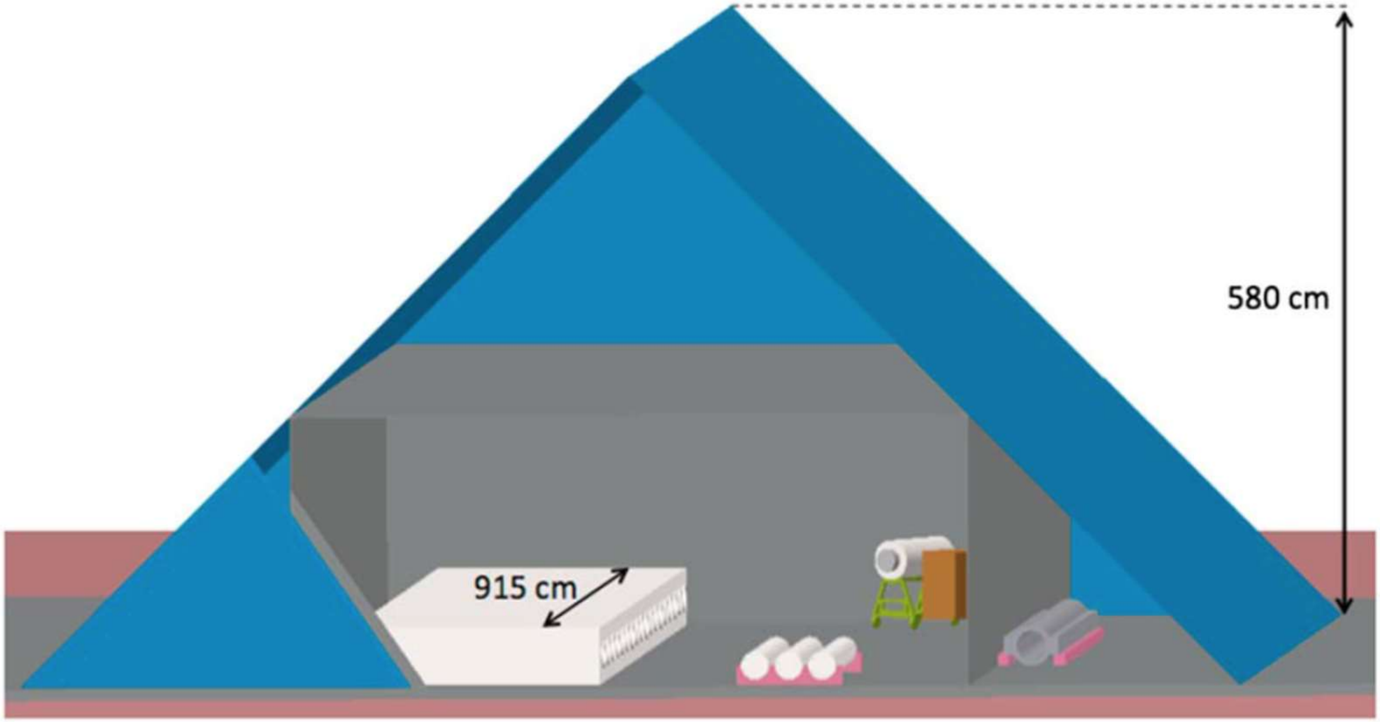
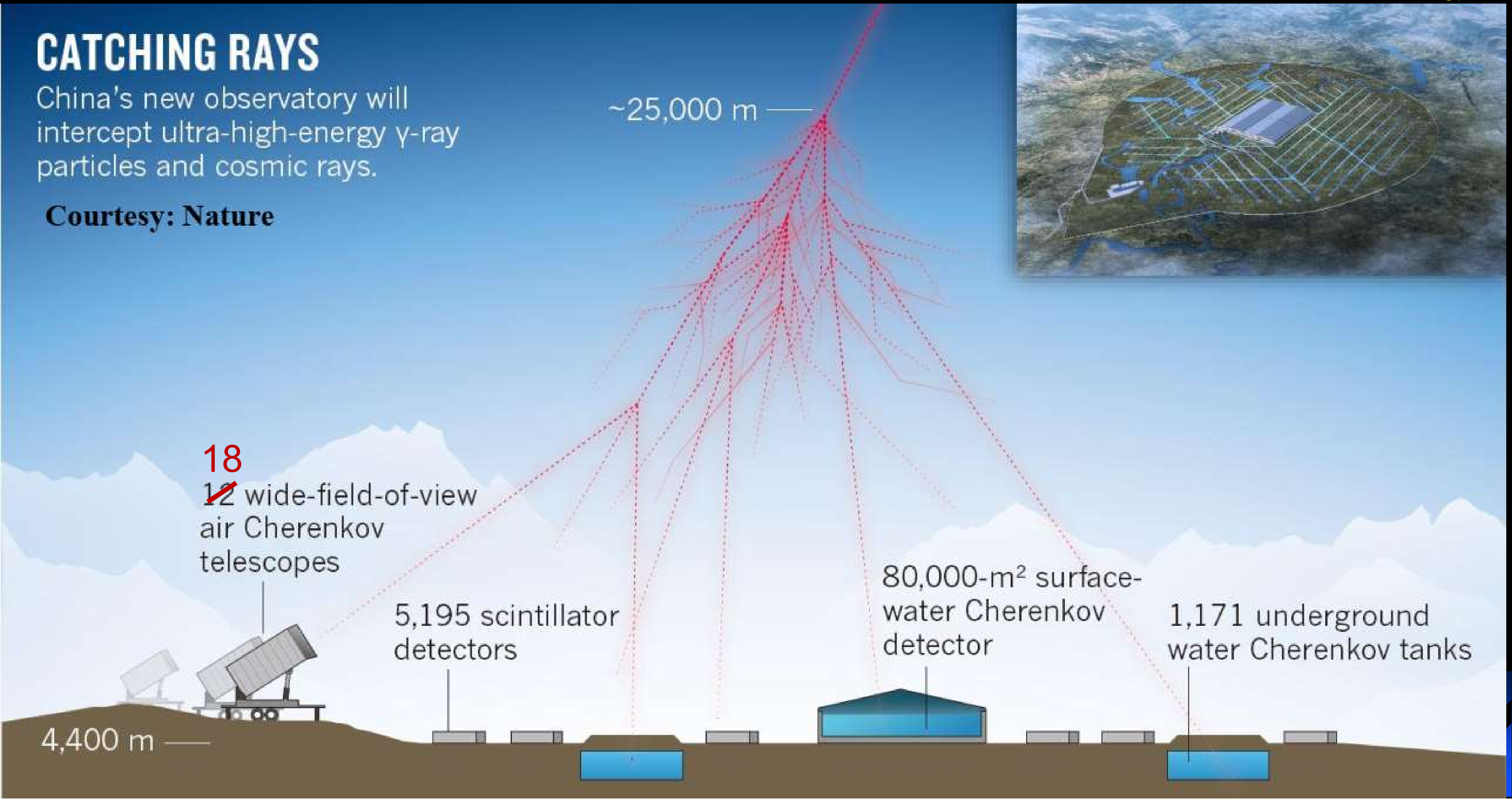


Figure 2. Illustration of the geometry for Monte Carlo simulations of the calibrator inside the PSNM building at Doi Inthanon, Thailand. This cutaway view removes most of the east wall. The calibrator (white cylinder at right) was operated inside the station during June 2010. The 18-tube NM64 neutron monitor (left) and three bare neutron counter tubes (front) have been operating there since 2007. Spare lead rings are kept in a storage room to the right. [Aiemsa-ad+15]

Our "galaxy cluster" (21 nodes, 320 cores)

Large **H**igh **A**ltitude **A**ir **S**hower **O**bservatory (LHAASO) in Sichuan, China at 4410 m altitude



CATCHING RAYS

China's new observatory will intercept ultra-high-energy γ-ray particles and cosmic rays.

Courtesy: Nature

~25,000 m

18

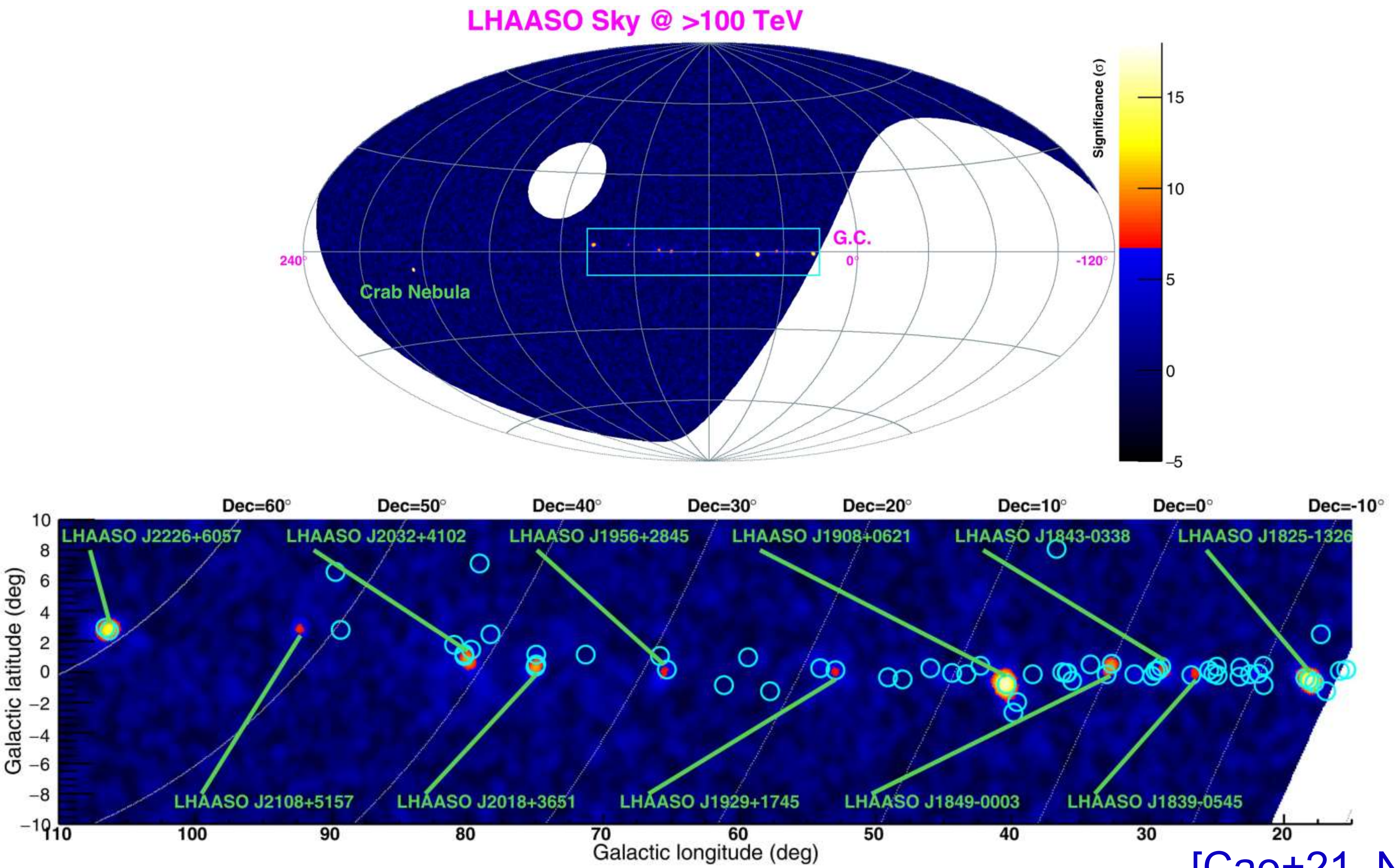
~~12~~ wide-field-of-view air Cherenkov telescopes

5,195 scintillator detectors

80,000-m² surface-water Cherenkov detector

1,171 underground water Cherenkov tanks

4,400 m

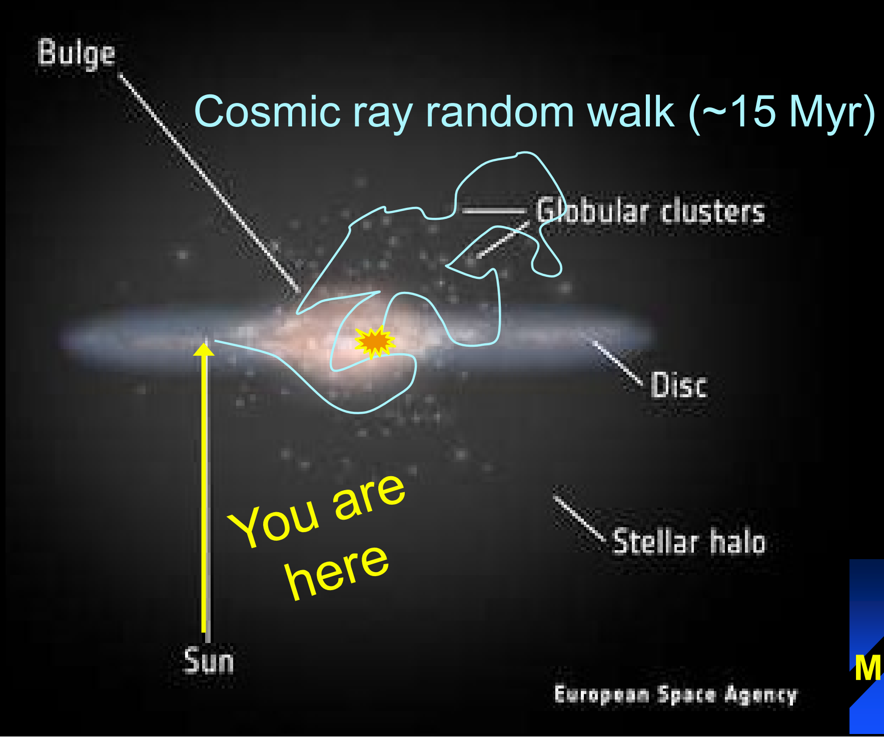


[Cao+21, Nature]

Extended Data Fig. 4 | LHAASO sky map at energies above 100 TeV. The circles indicate the positions of known very-high-energy γ-ray sources.

Gamma rays from cosmic rays in our Galaxy:

1. Acceleration (origin: where, how?)
   - *e*+, *e*- (leptons)
   - *p* & other ions (hadrons)
2. Transport (propagation)



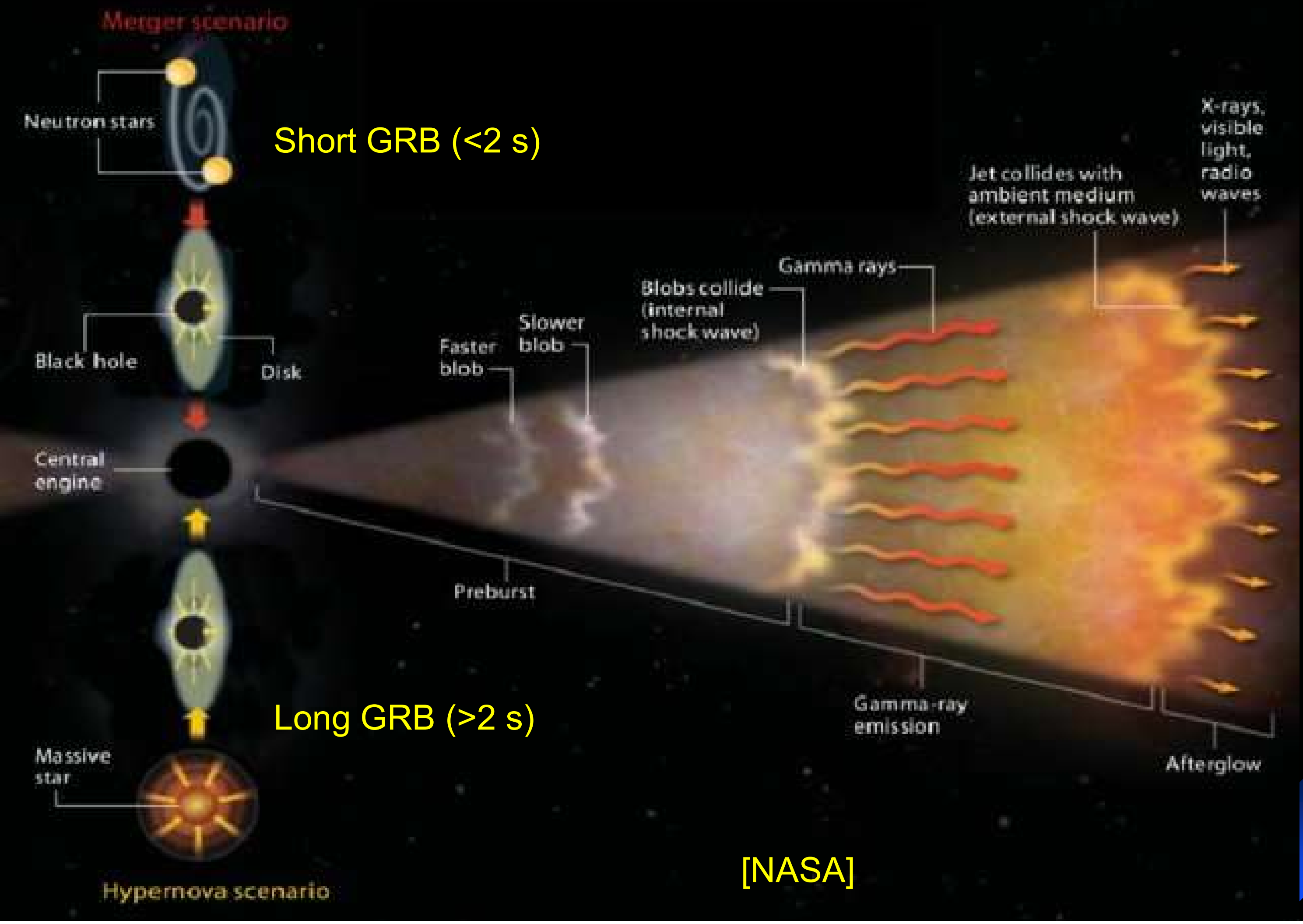
3. Interactions
   - leptons: electromagnetic cascade

     (e+, e-, γ)
   - hadronic cascade:

     $\pi+, \pi- \Rightarrow \mu, \nu$

     $\pi^0 \Rightarrow 2\gamma$

Gamma ray burst GRB221009A: Brightest Of All Time (BOAT)



Short GRB (<2 s)

Long GRB (>2 s)

[NASA]

- ❖ Estimated to occur once every 10,000 years!
- ❖ LHAASO has continuous coverage (no pointing needed)
- ❖ Luckily, this GRB was high in the sky
- ❖ First ever observation of TeV afterglow onset …
- ❖ Recent publication in *Science*

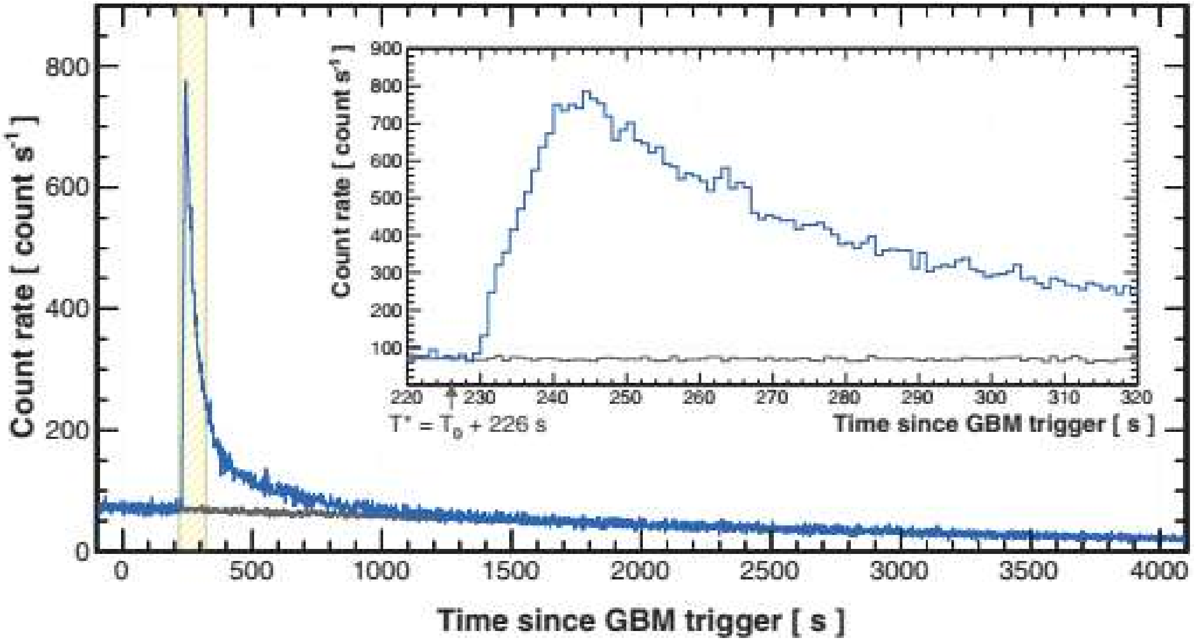
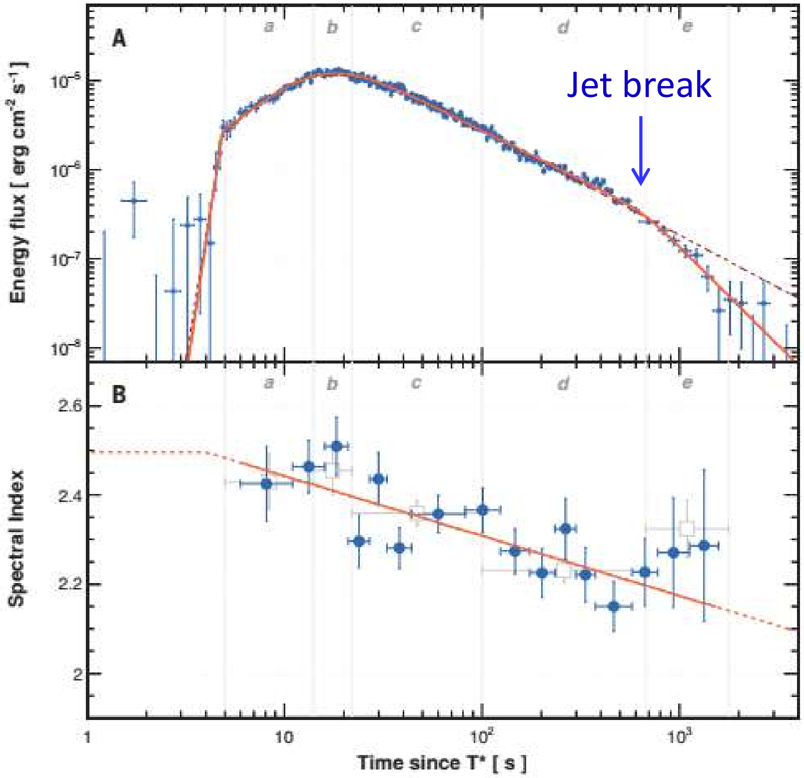


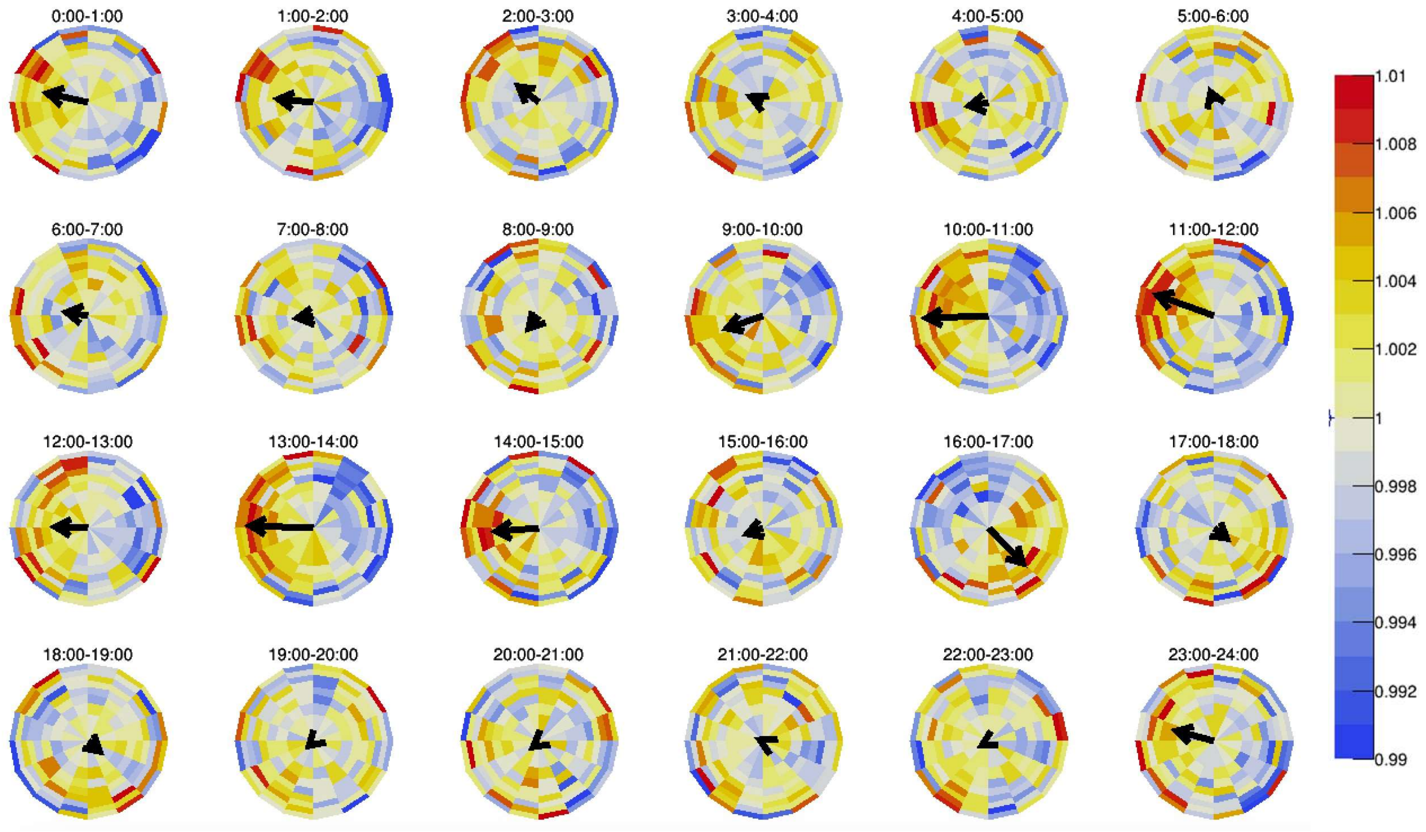
Fig. 1. Count rate light curve of GRB 221009A observed by LHAASO-WCDA. The energy range of photons observed is ~0.2 to 7 TeV. The inset panel shows a zoomed-in view of the light curve during 220 to 320 s (yellow shaded zone) after the GBM trigger (T_0), with the arrow indicating the reference time $T^* = T_0 + 226$ s for our light curve analysis (see text). Blue histograms are the data, and black histograms are the estimated background.



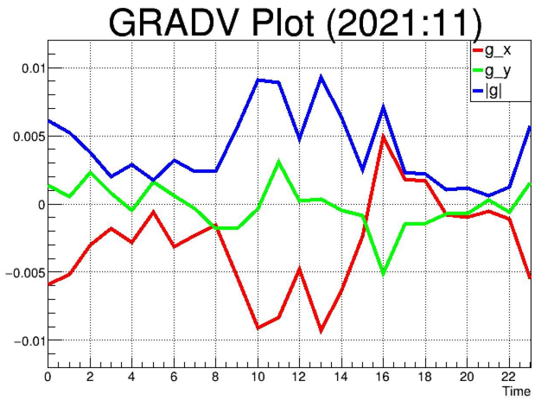
[Cao+23, Science]

- From time profile, conclude that environment had constant density (not a wind)
- Earliest ever detection of a jet break, indicates beam angle <1 degree
- Extreme beaming explains extreme brightness

First Observation of Transient Large Scale Anisotropy >150 GeV



- Around the time of ICME arrival, midday on 2021 Nov 4, there was a marked enhancement in the anisotropy and the gradient magnitude



Hourly WCDA skymaps centered at the zenith direction, out to a zenith angle of 45 degrees (outer circle), for $60 < N_{hit} < 100$ for each hour UT of 2021 Nov 4

Space physics and energetic particles group, alumni, friends, & family, 2017