Probing the Universe from the Tibetan Highland

Masato TAKITA (ICRR, Univ. of Tokyo)
For the Tibet ASγ Collaboration

@Utokyo New York Event, February 12, 2022
Online

Outline

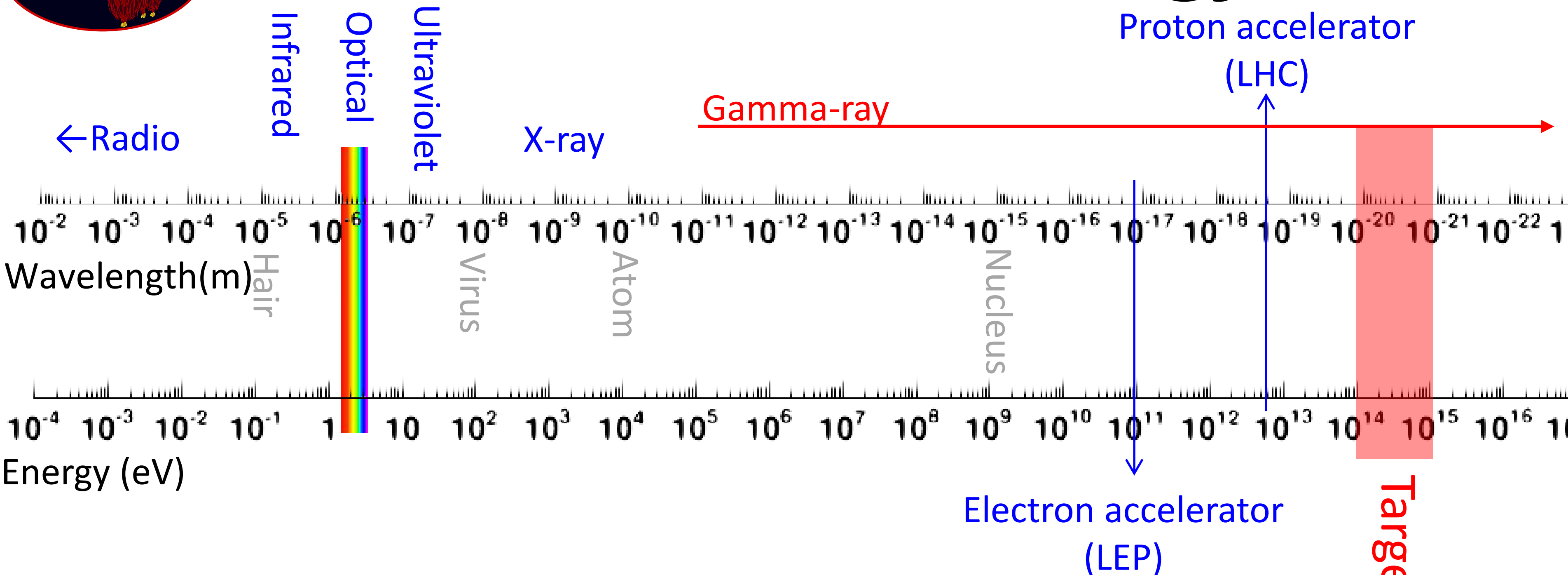
- Tibet ASγ Experiment (Multi-purpose)
- Gamma-ray Observation for cosmic-ray origin
- Sun Shadow Observation for solar magnetic field

Skipped in this talk are:

- Chemical composition in cosmic rays
- Tests of hadronic interaction models
- Cosmic-ray anisotropy measurement

- Summary

Observational Energy



The energy of electromagnetic waves is expressed in wavelengths.

Electron volt (eV): Unit of energy commonly used in particle physics.

10^{15} eV = 1 Peta electron volt (PeV)

→ 1000 trillion times more energetic than visible light!

Tibet ASγ Experiment

The Tibet ASγ Collaboration

Roughly 100 researchers

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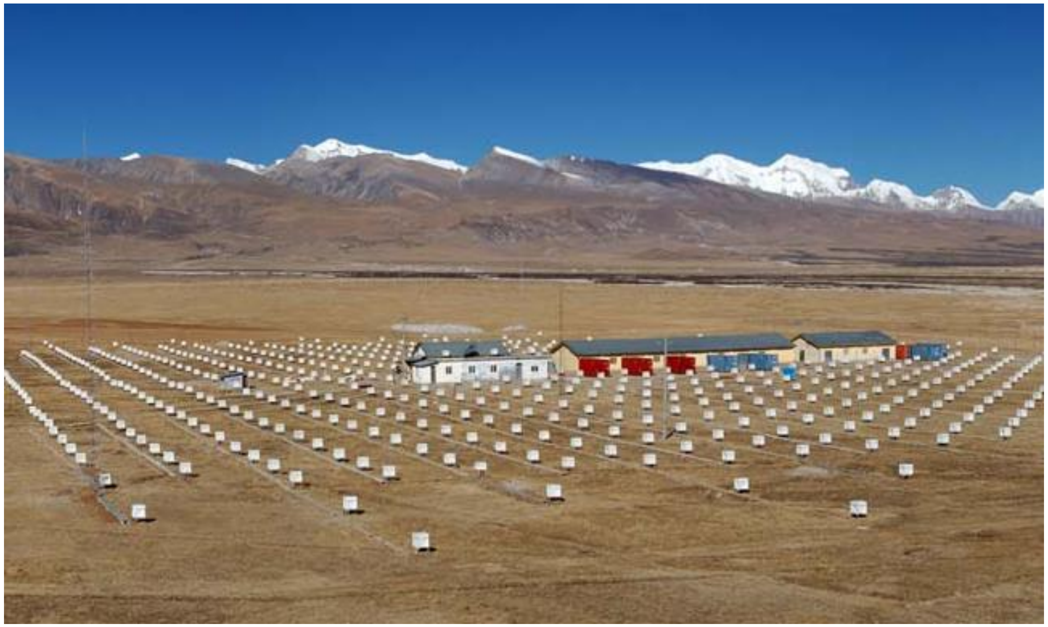
Tibet ASγ Experiment

Yangbajing, Tibet, China at the altitude of 4300m



Surface air shower array 65,700m^2 scintillation detectors

Observation regardless day and night with wide field of view.

Underground muon detectors 3400m^2 (Before filling water)

Low-cost large-area muon detector
→ utilize to discriminate gamma ray signals from cosmic ray background.

Key technology! in this study

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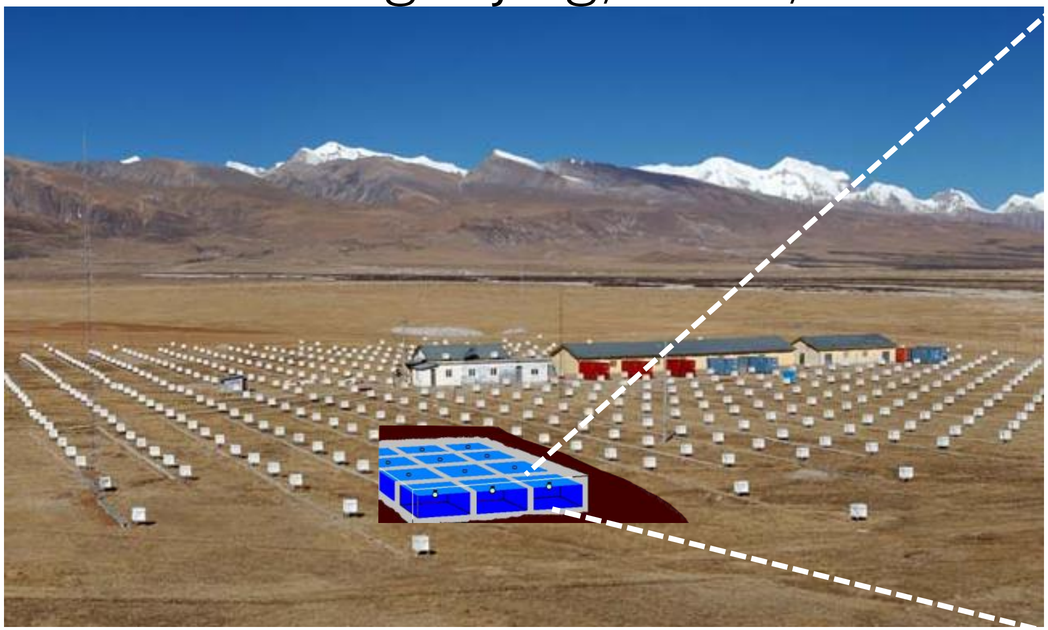

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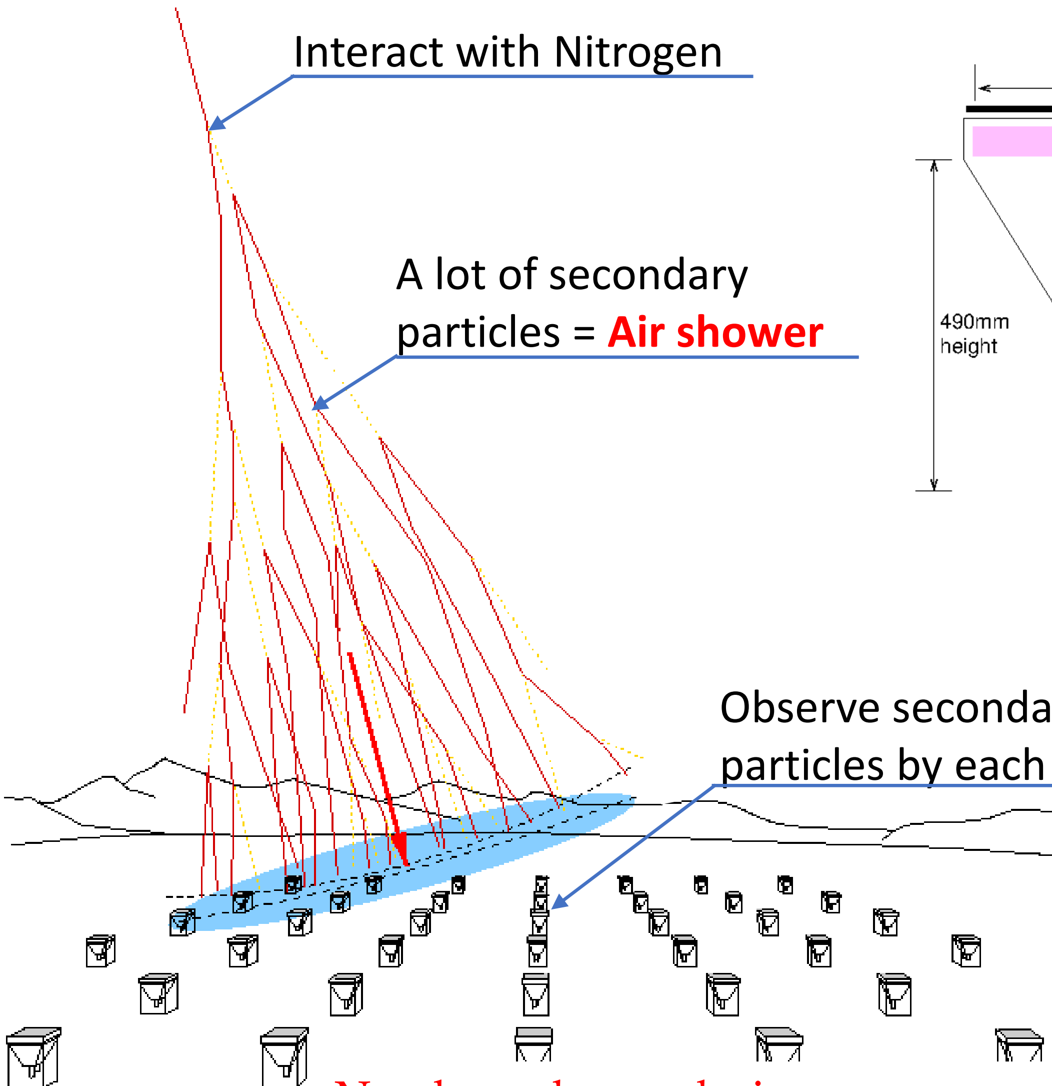
Detection Principle

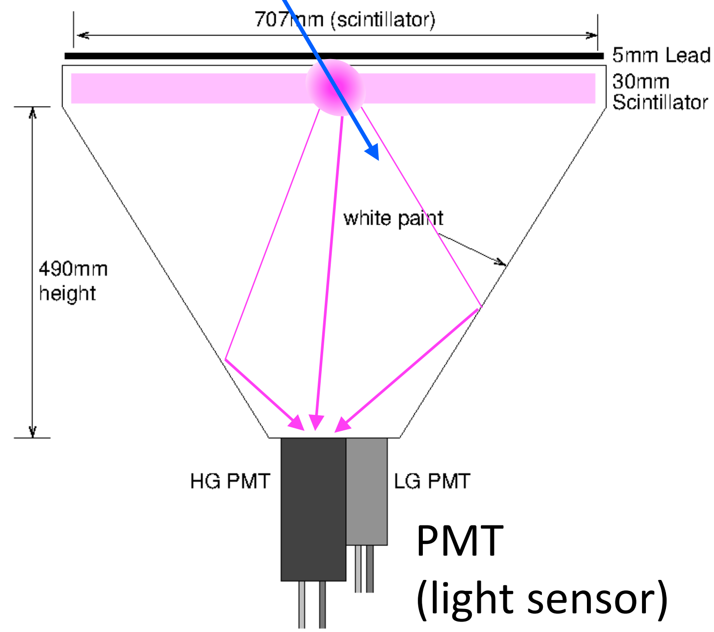
Gamma ray/Cosmic ray

Interact with Nitrogen

A lot of secondary particles = **Air shower**



Scintillator:
Emit fluorescence lights when particles pass it



PMT (light sensor)

Observe secondary particles by each detector

Determine the direction & energy of the gamma ray

- Angular resolution 0.2 deg
- Energy resolution 20% @0.1PeV

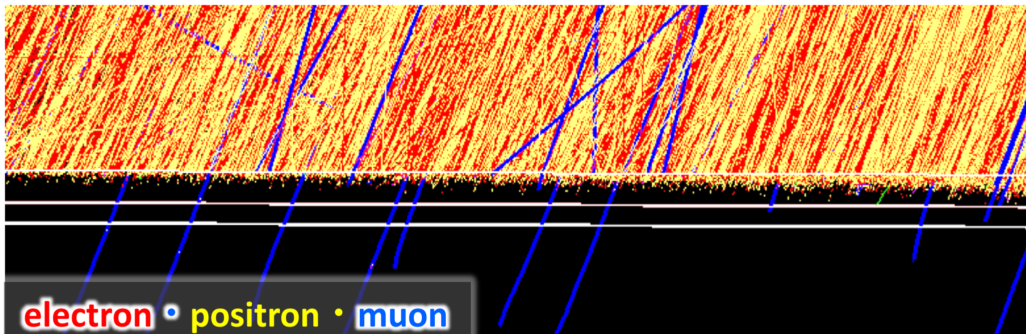
Need another technique to separate γ rays from cosmic rays.

Gamma-Ray Selection

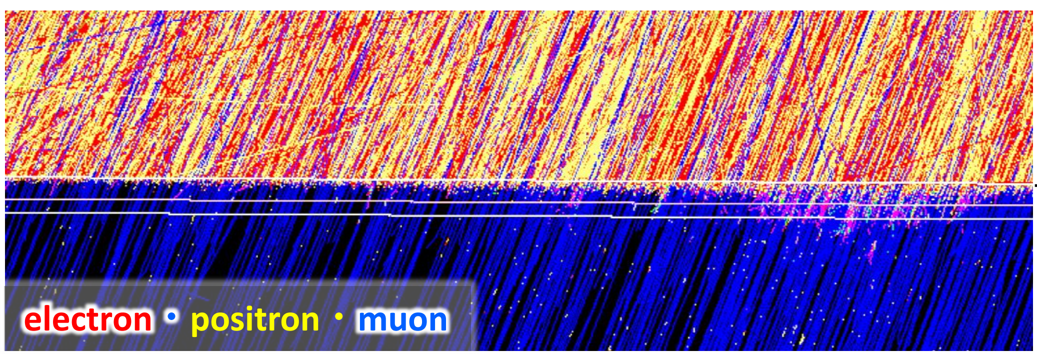
γ-ray → poor muons

Muons can penetrate underground

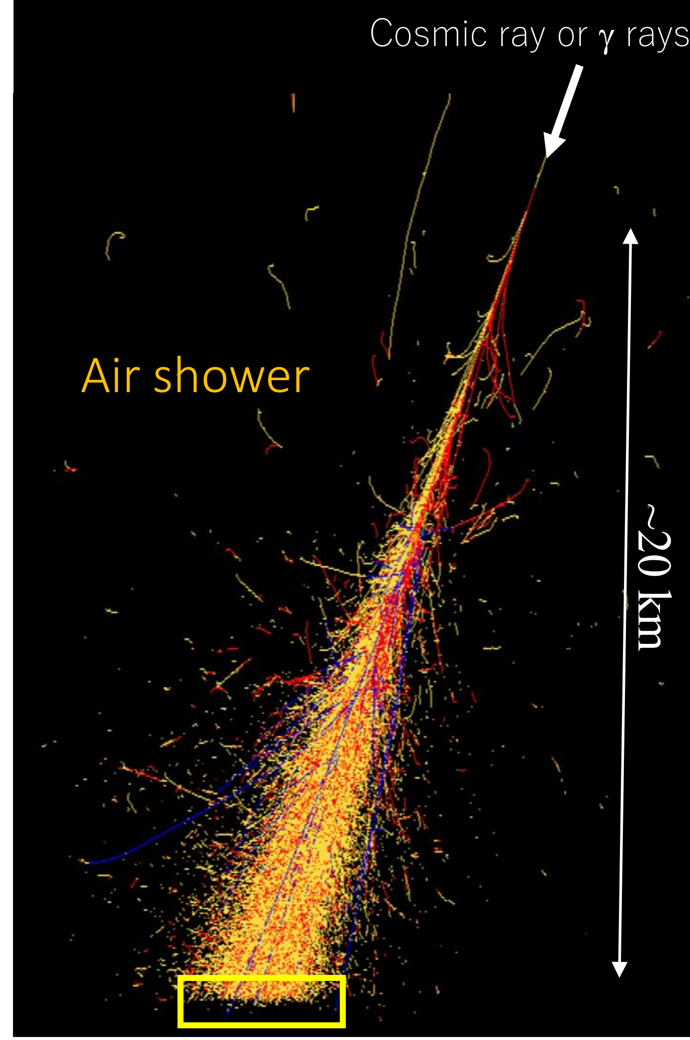
0.2PeV γ-ray



0.2PeV Cosmic ray (Noise)



→ Underground muon detectors



Enlarged view

Gamma-ray Observation

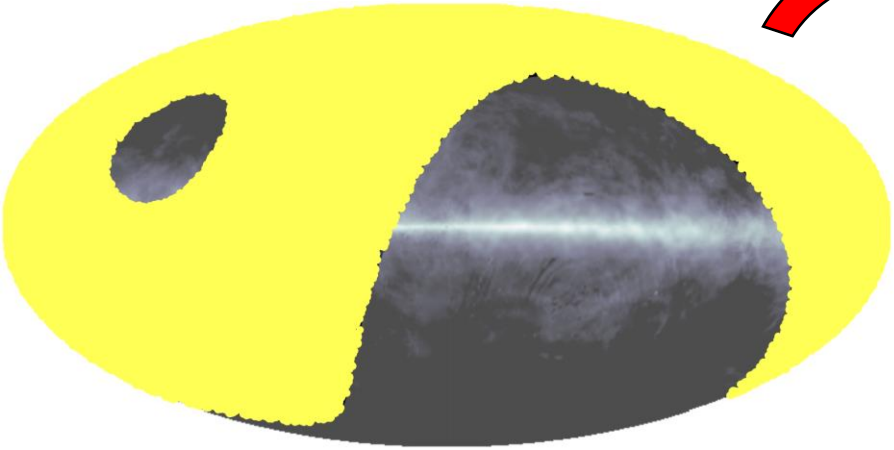
Cosmic-Ray Background Rejection

Look for a needle in a haystack
Expected cosmic-ray noise
= γ-ray signals x 100,000

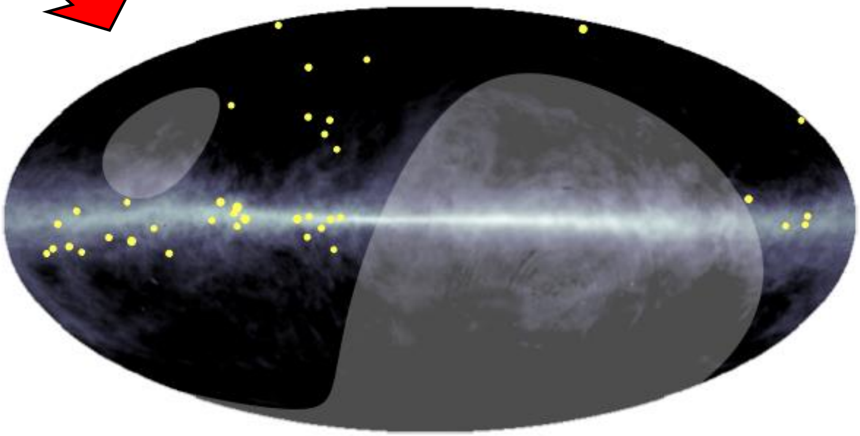
→ Selecting muon poor events measured by the underground detectors → Key technology!

Reducing cosmic-ray background noise to
one part per million @0.4 PeV

Before: ＞10 million events

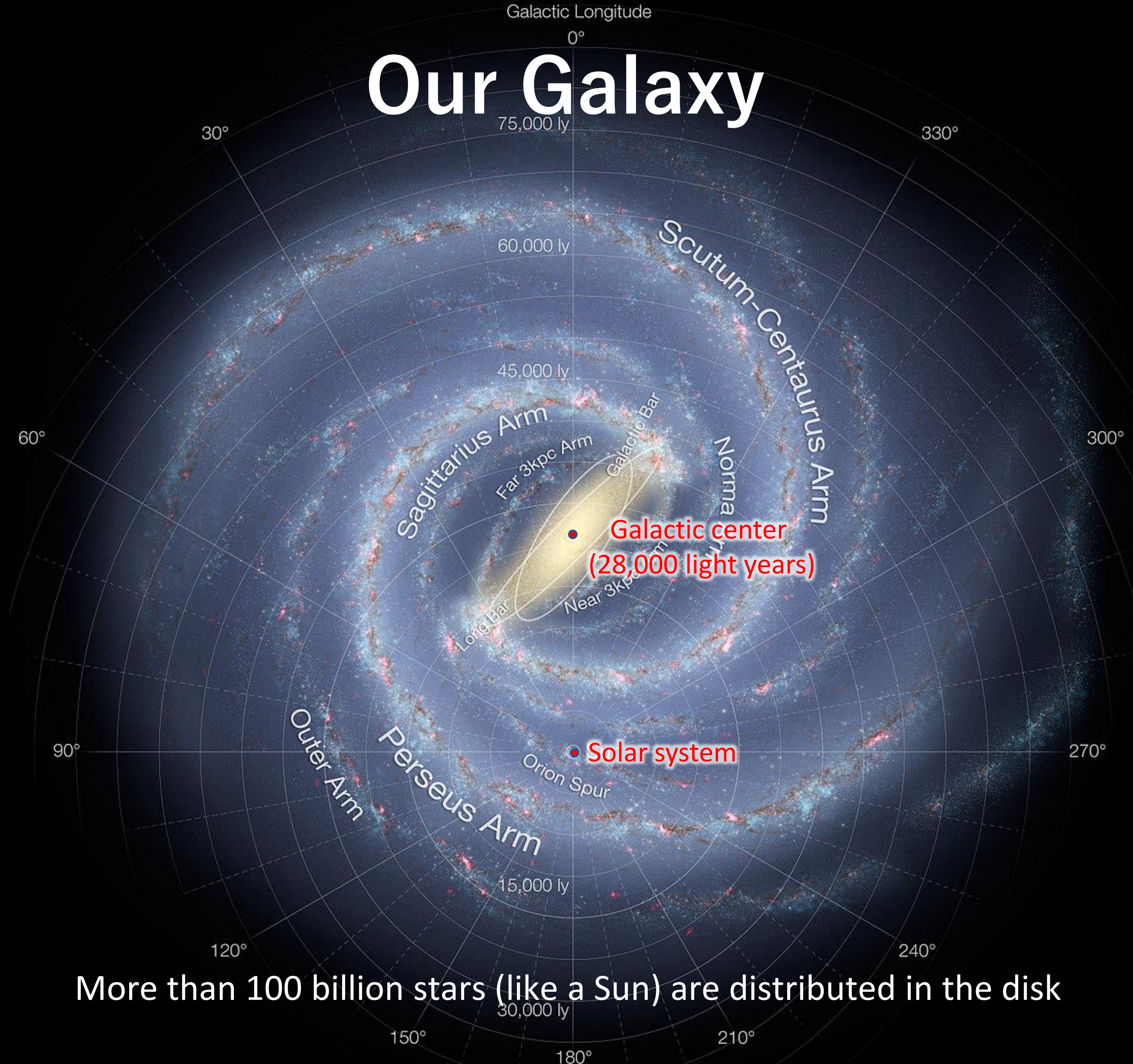


After rejection: 38 events



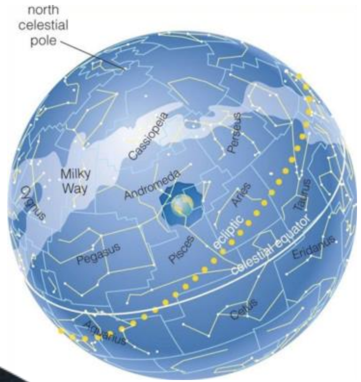
First Detection of 0.1-1 PeV gamma ray from the Milky Way

Our Galaxy

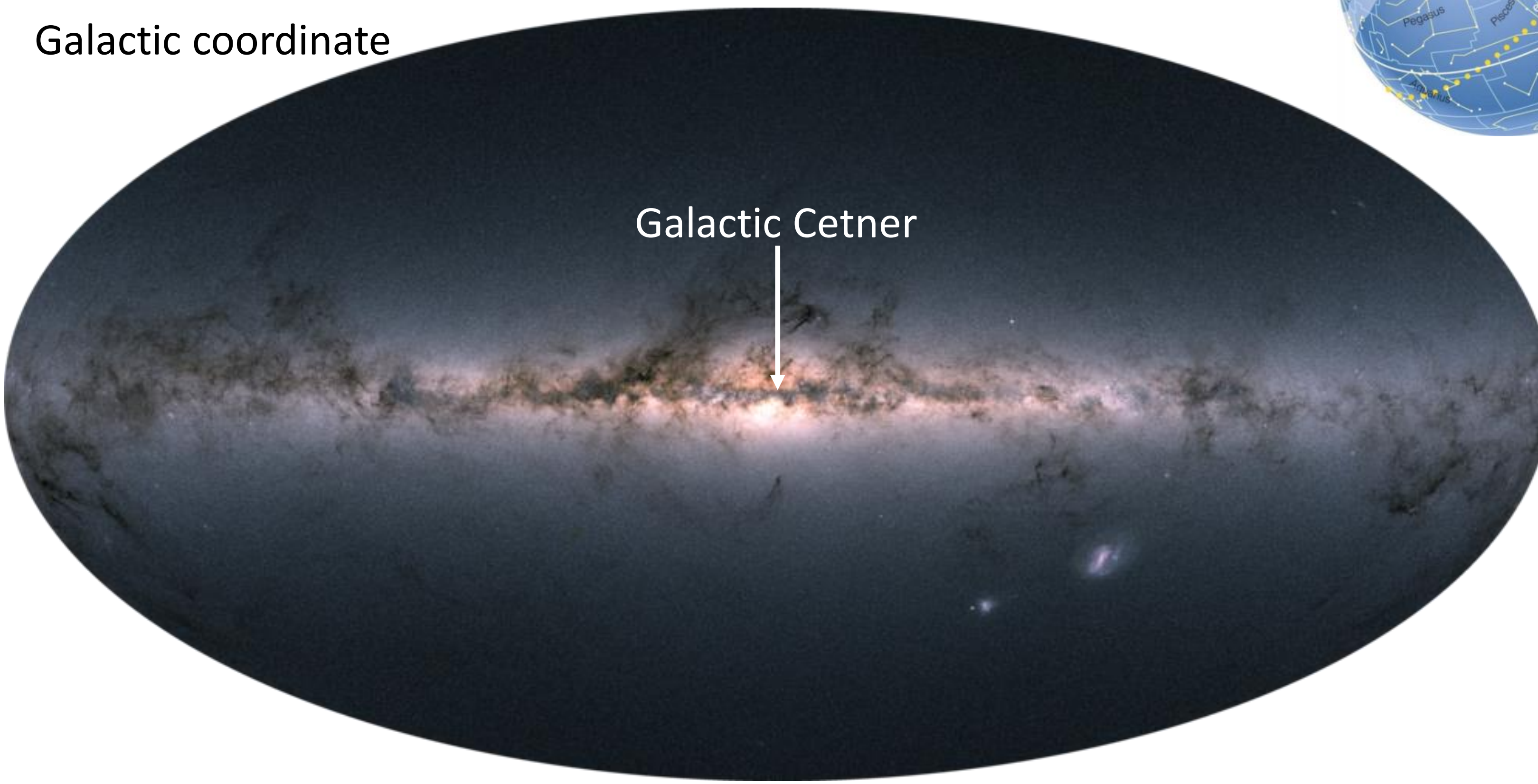


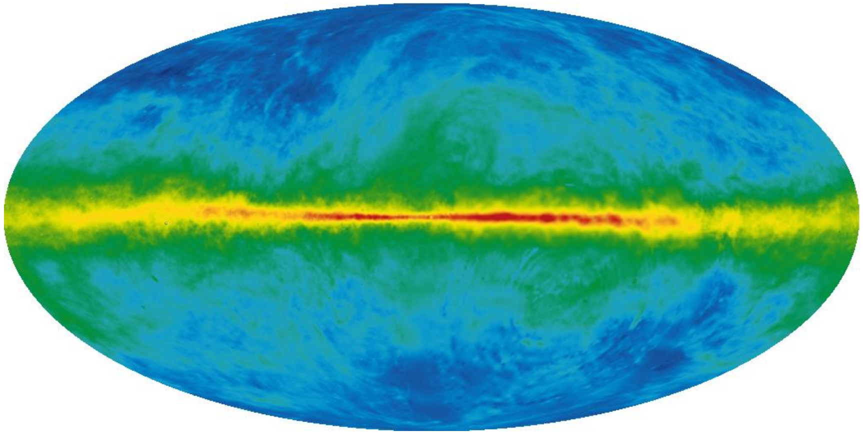
More than 100 billion stars (like a Sun) are distributed in the disk

Milky Way by Optical Observation



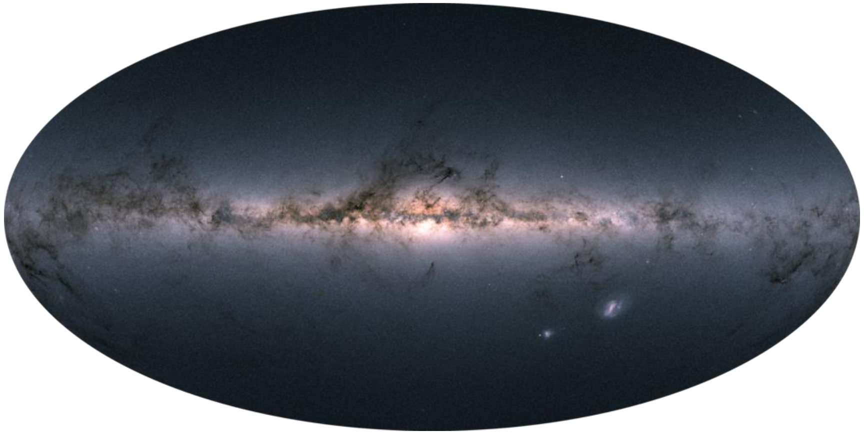
Galactic coordinate





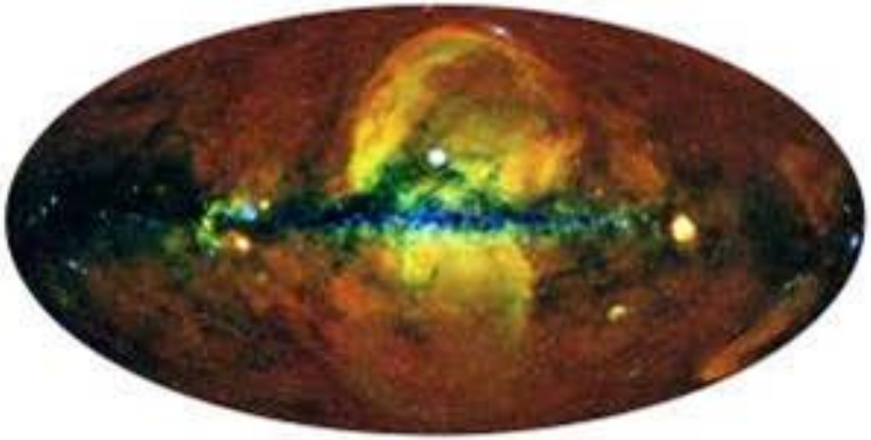
Radio: Atomic Hydrogens

Radio (21cm) HI Map
Hartmann et al. (1997)
Dickey & Lockman (1990)



Optical: Stars

Copyright: ESA/Gaia/DPAC



X-Ray：Hot plasma

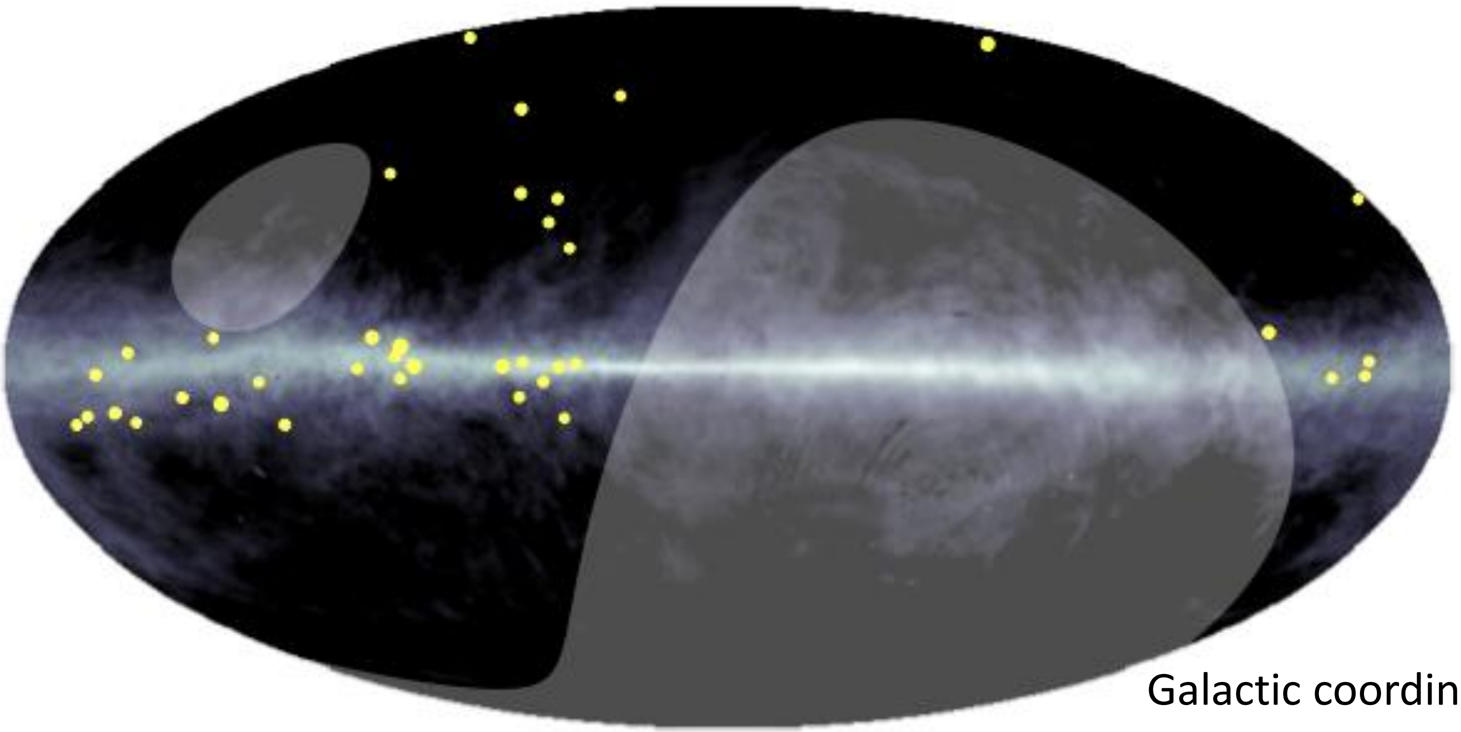
Copyright: eROSITA (MPE/IKI)

Highest Energy γ Rays from the Milky Way

23 ultra-high-energy gamma-ray events along the Milky Way!

(2 years of data during period between 2014 and 2017)

The highest energy 0.957 PeV (~1 PeV) gamma ray is detected



0.4 – 1 PeV (sub-PeV) gamma rays

& Atomic hydrogen (HI) distribution

HI data available at https://lambda.gsfc.nasa.gov/product/foreground/fg_combnh_map.cfm

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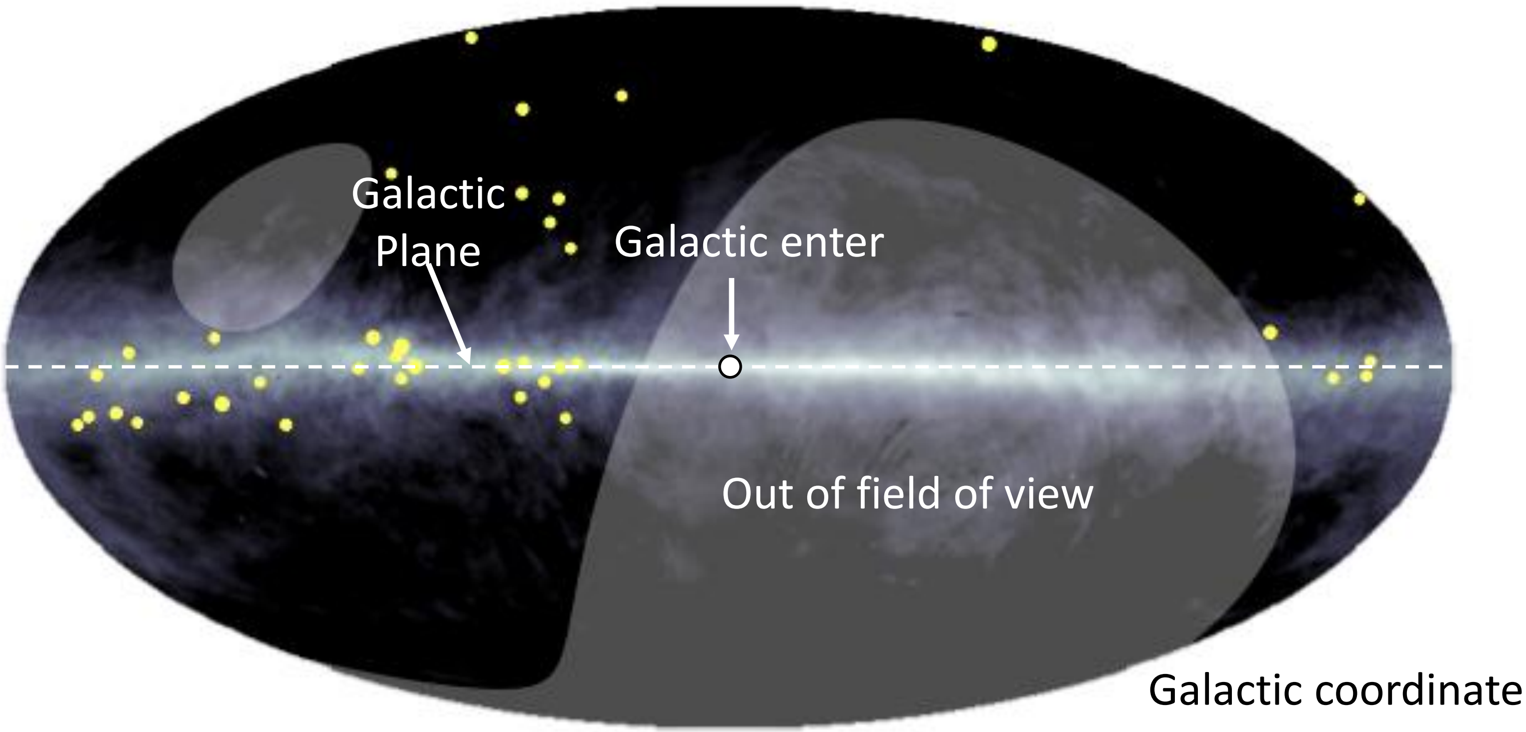

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→ Gamma rays from inside of our Galaxy

§ Scientific Interpretation

Cosmic rays were discovered by Victor Hess in 1912

(Novel prize in 1936)

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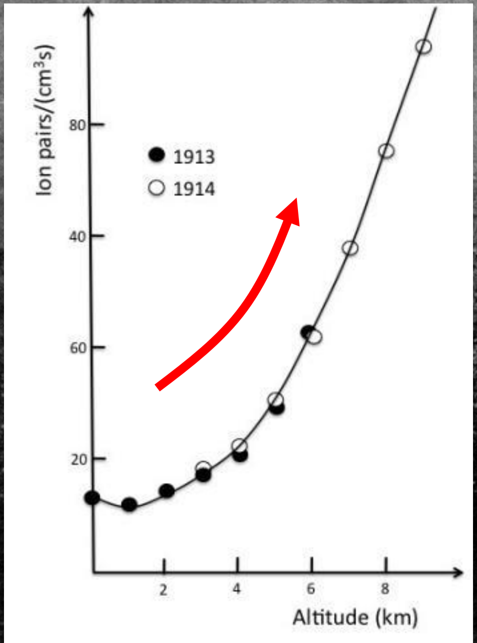
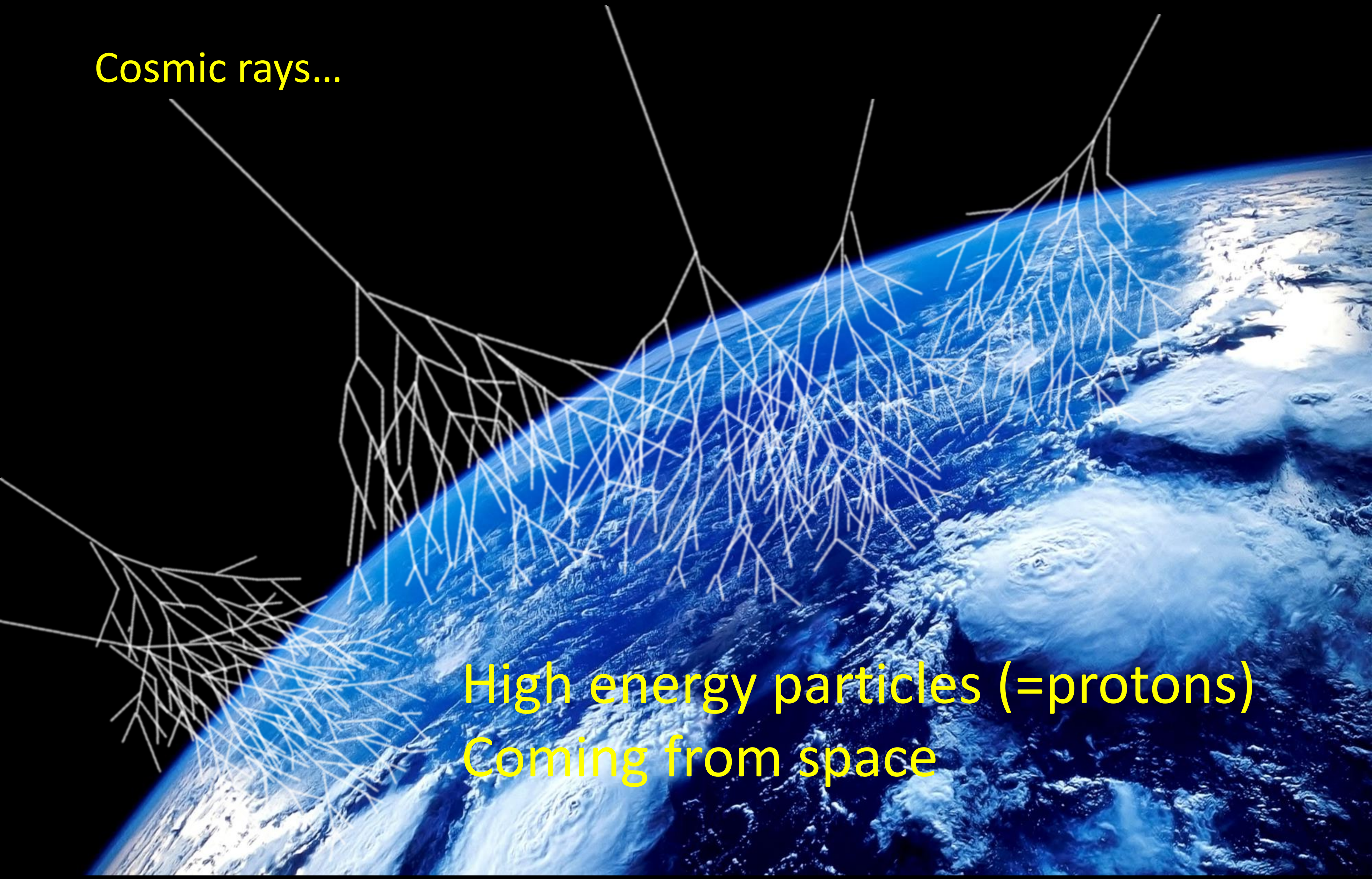


Cosmic rays…

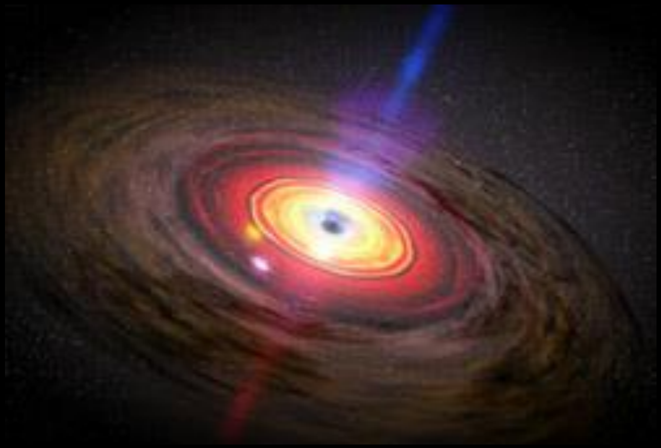


Cosmic rays…

Where do they come from?

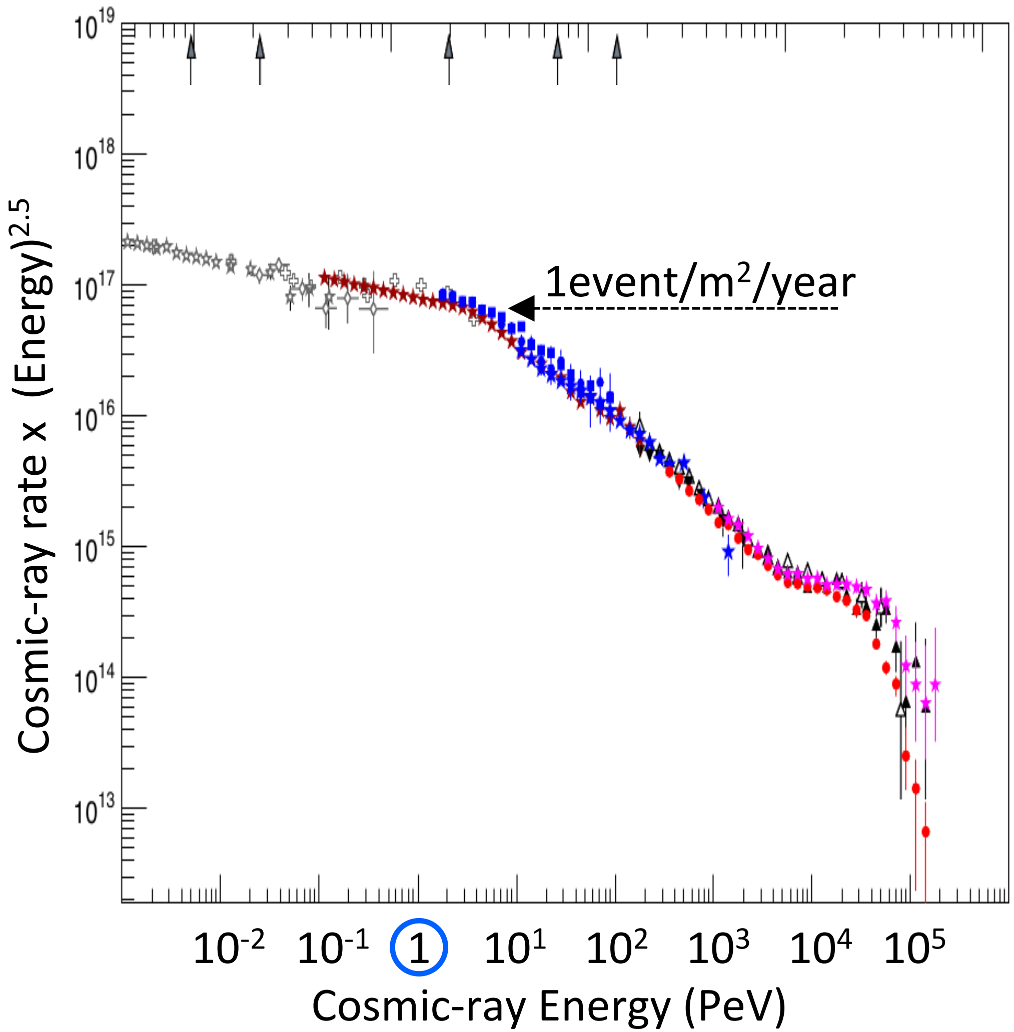
Sun

Supernova remnant?
(after star explosion)



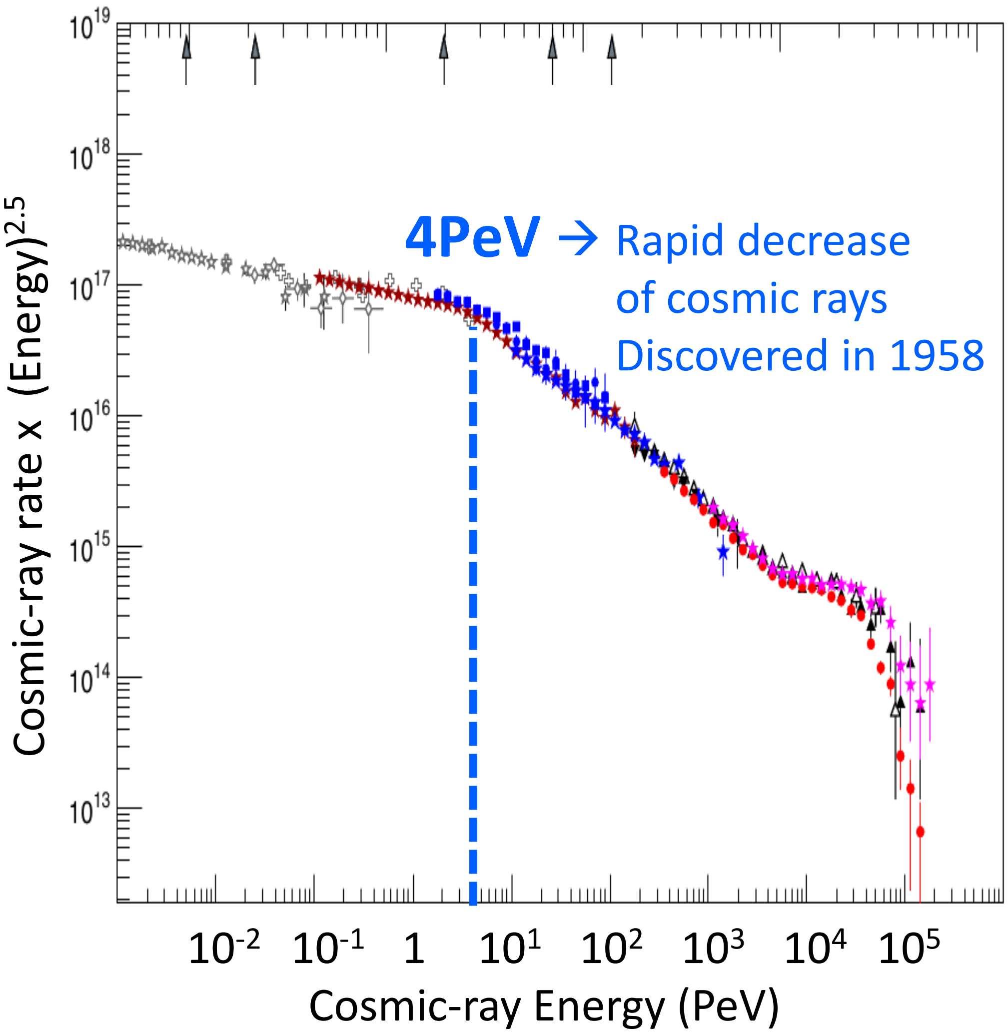
Active galaxy??
(massive blackhole)

Cosmic Ray Rate & Energies



- Wide energy range
- Main component is proton
- Rate decreases to 1/100 when energy is 10 times higher

Cosmic Ray Rate & Energies



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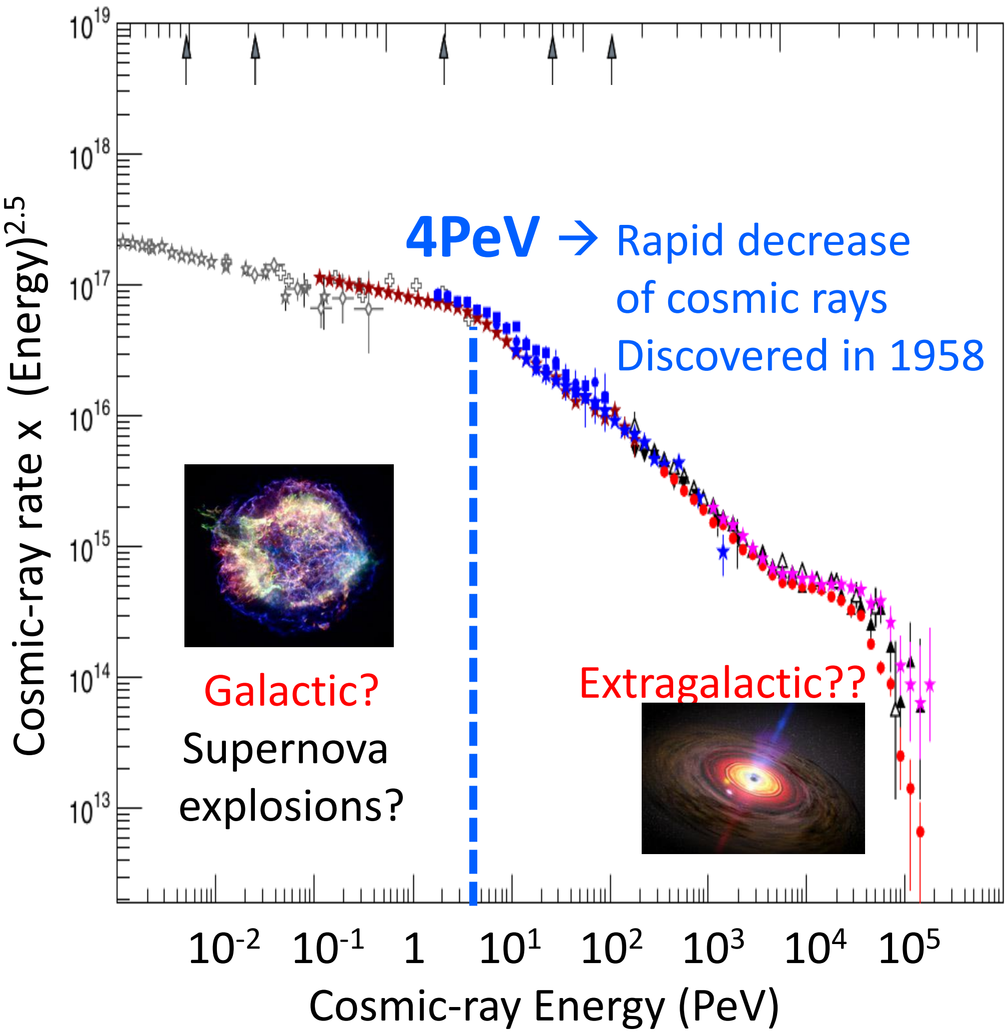
Cosmic Ray Rate & Energies



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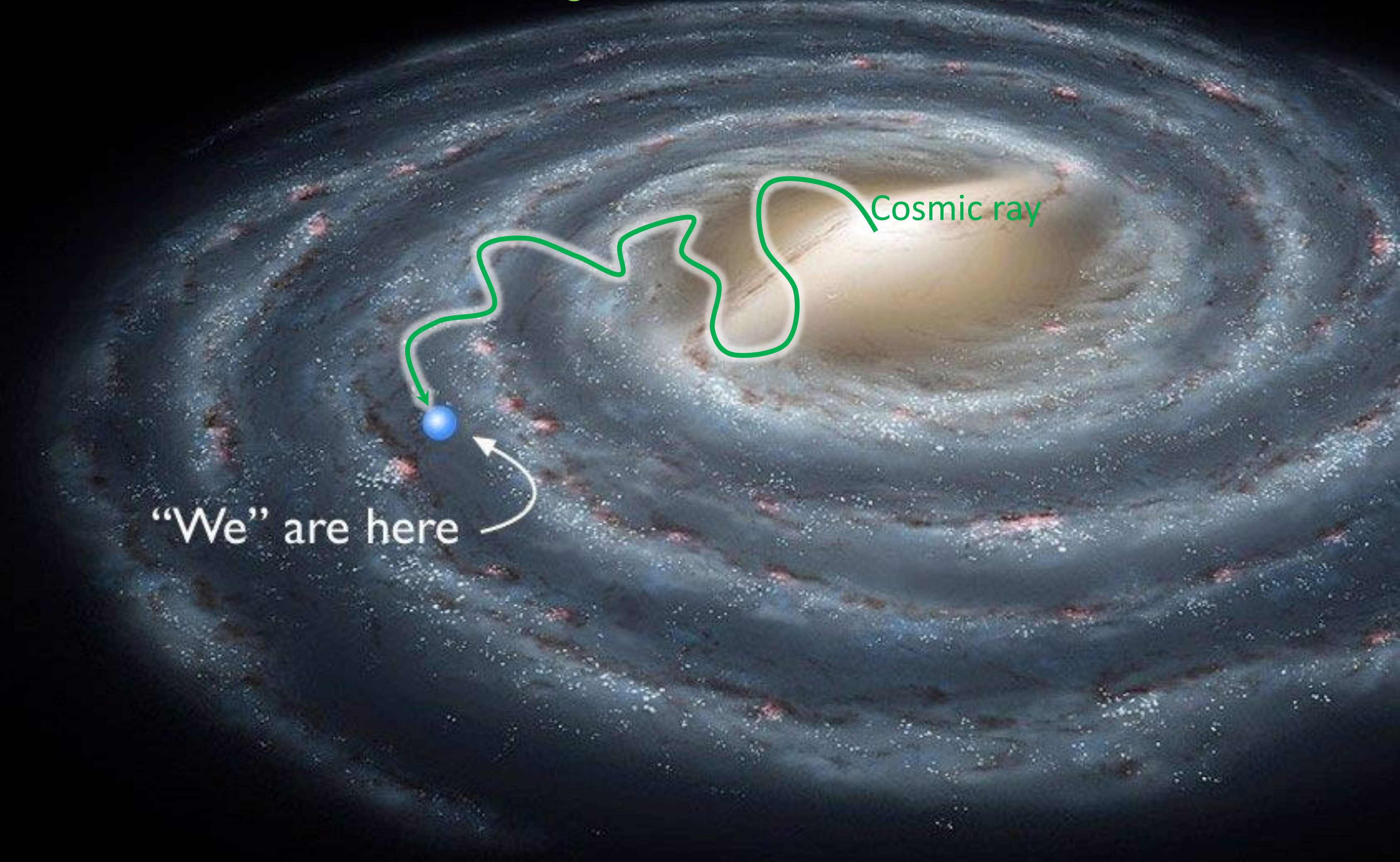
- Main component is proton
- Rate decreases to 1/100 when energy is 10 times higher

As an open question, Did/Do "PeVatrons" really exist in our Galaxy?

PeVatron: Cosmic superaccelerators accelerating CR to Peta electron volt

Cosmic rays with electric charge are bent by
the magnetic field in the universe, and lose their directions



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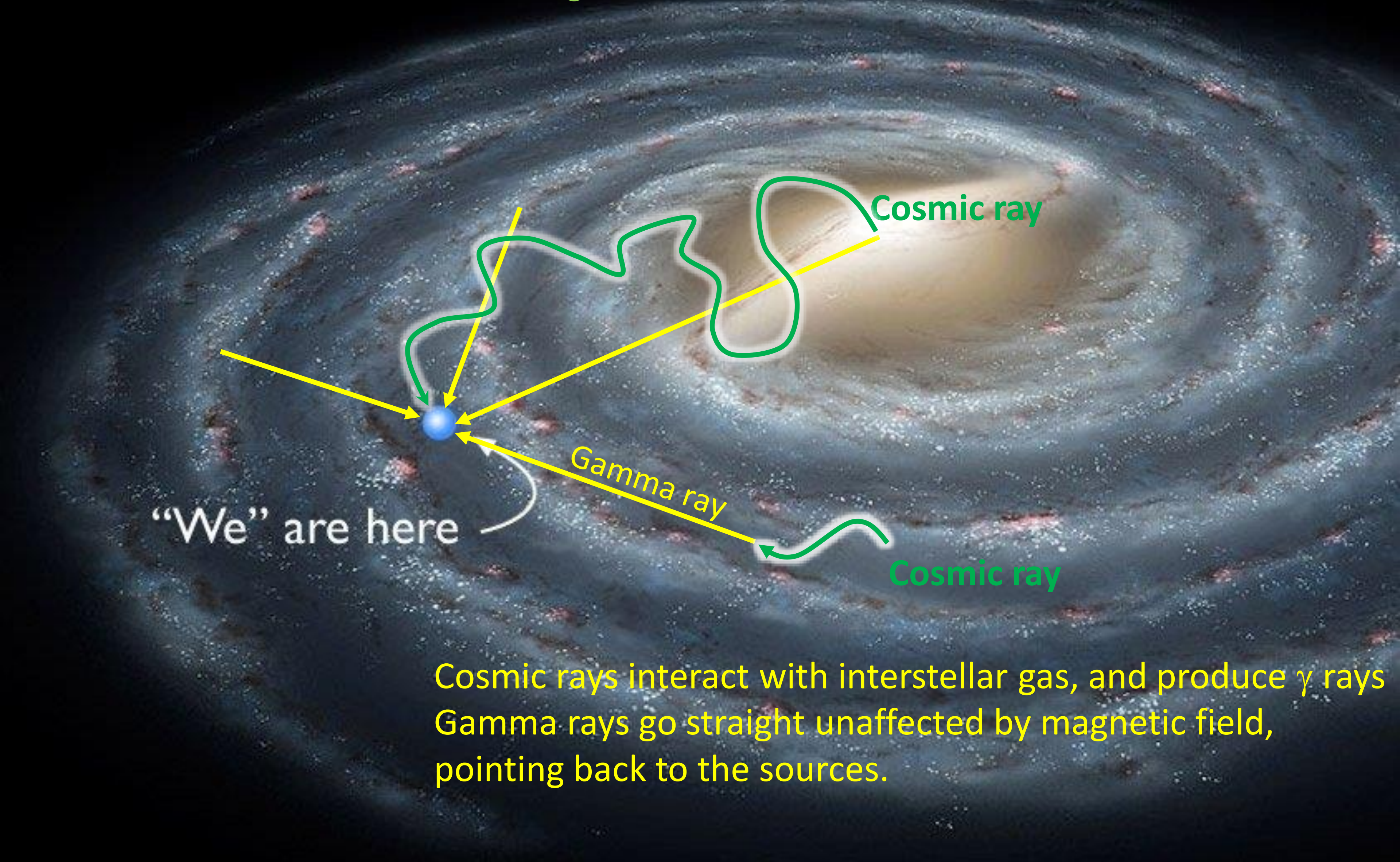


Cosmic rays interact with interstellar gas, and produce γ rays
Gamma rays go straight unaffected by magnetic field,
pointing back to the sources.

History of Cosmic-Ray Physics

1912 Discovery of cosmic rays (Hess)

1934 Supernova hypothesis as cosmic-ray origin (Baade & Zwicky)

1949 Acceleration theory of cosmic rays (E. Fermi)

1958 Discovery of rapid decrease in cosmic-ray flux (Kulikov & Khristiansen)
→ Cosmic rays below a few PeV are/were produced in our Galaxy? = PeVatrons

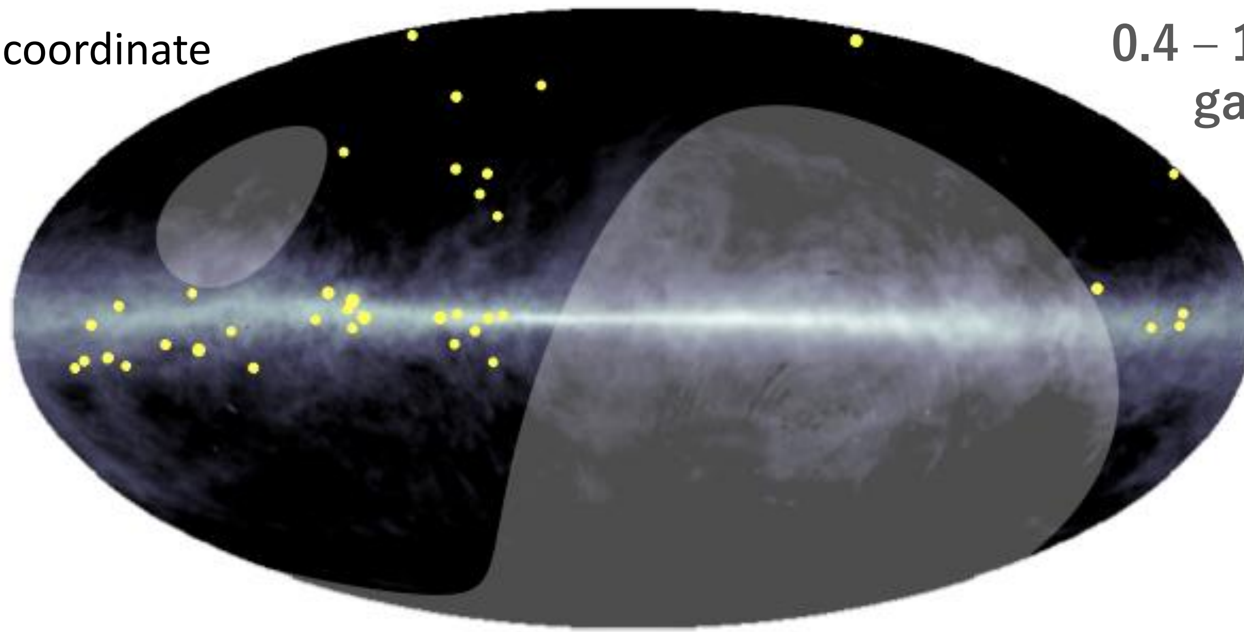
1970s-1990s Detection of γ rays from Milky Way (OSO-3, SAS-2, COS-B, EGRET)
→ 1/10000th PeV γ rays induced by cosmic rays in our Galaxy

2013 Detection of 1/1000th PeV γ rays induced by cosmic rays in SNR
(Fermi-LAT satellite + Ground γ-ray telescope)

Despite exhaustive searches for **PeVatrons** over last 20 years, researchers have no conclusive evidence yet.
→ A mystery for 60 years in cosmic-ray physics

Scientific Interpretation

Galactic coordinate

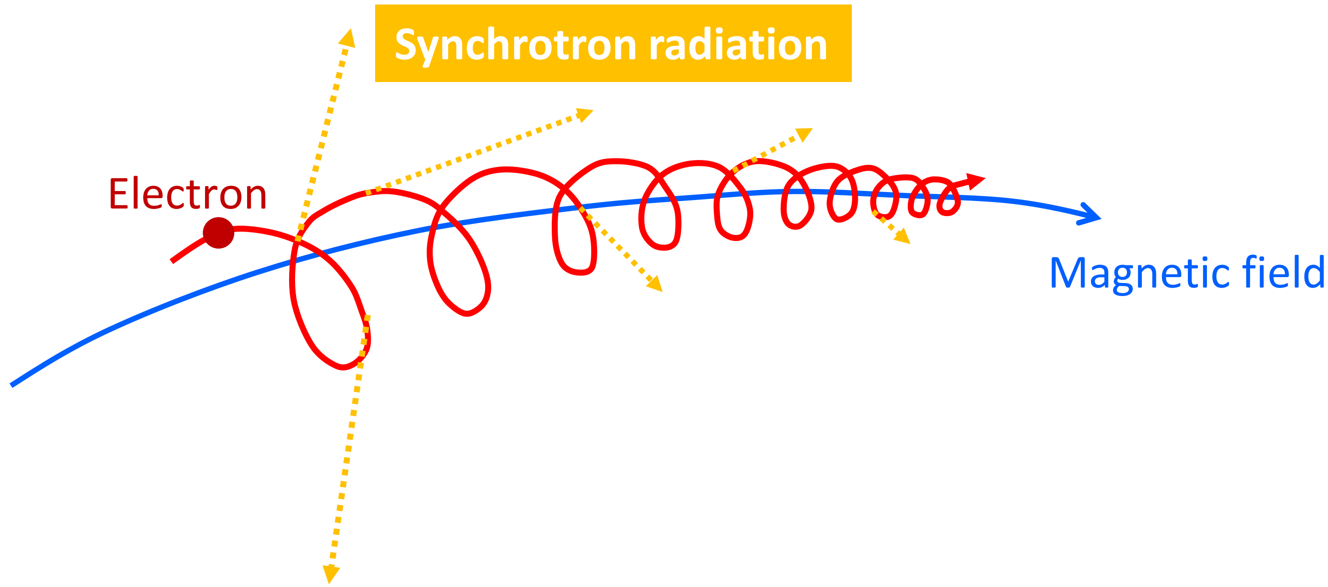


0.4 – 1 PeV
gamma rays

✓ Highest-energy gamma rays, including one Peta-electron-volt, are discovered to be spread out along the Milky Way, rather from known gamma-ray objects.

→ Gamma rays coming directly from the objects are difficult to identify cosmic-ray proton origin, since they could be gamma rays produced by collisions of "electrons" with photons.

Electron origin? vs Proton origin?

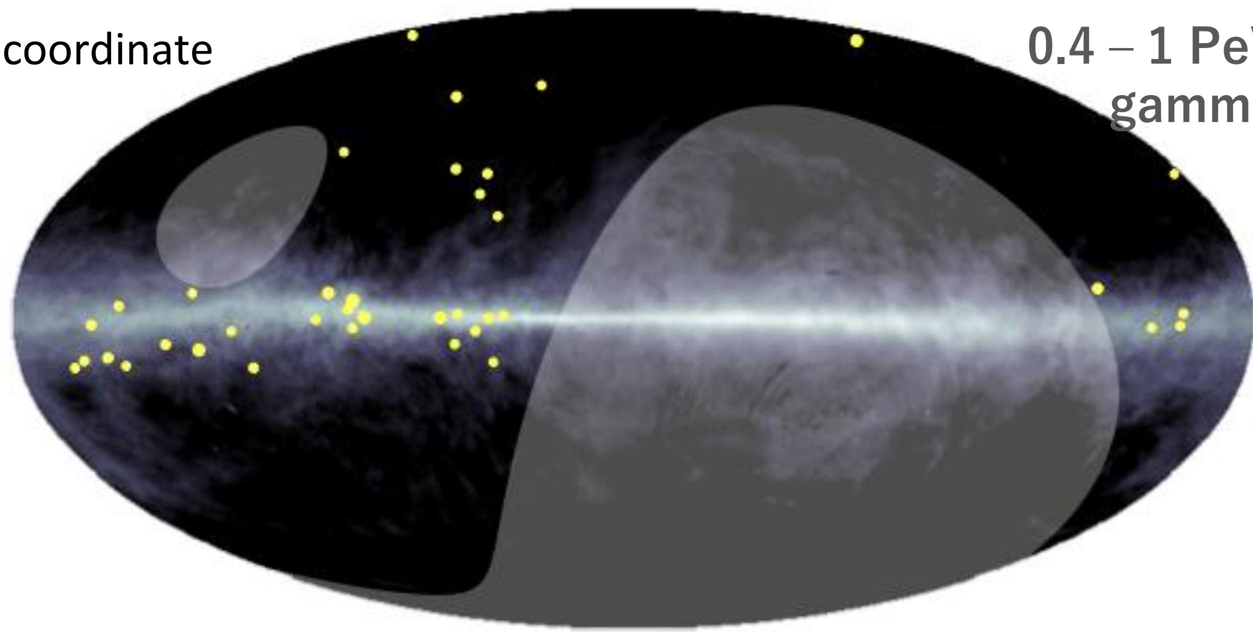


✓ Gamma rays are coming isolated from known gamma-ray sources.
→ **Electrons** lose their energy quickly, so they **should stay near the object**.
→ **Protons** don't lose energy and **can escape farther from the object**.

Electron origin? vs Proton origin?

Galactic coordinate

0.4 – 1 PeV gamma rays



- ✓ Gamma rays are coming isolated from known gamma-ray sources.
  - → **Electrons** lose their energy quickly, so they **should stay near the object**.
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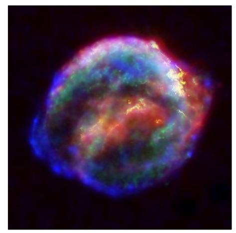
Strong evidence for sub-PeV γ rays induced by cosmic rays

PeVatrons & Cosmic-Ray Pool

Supernova (SN) explosion occurs every 30 years in our Galaxy



In SN remnants, cosmic rays are accelerated within 10,000 years after explosion → "PeVatron"

Cosmic rays has been trapped by galactic magnetic field more than a few million years, forming cosmic-ray pool
= Accumulated for 100,000 SN explosions

Cosmic rays in galactic magnetic field
3 – 30 PeV

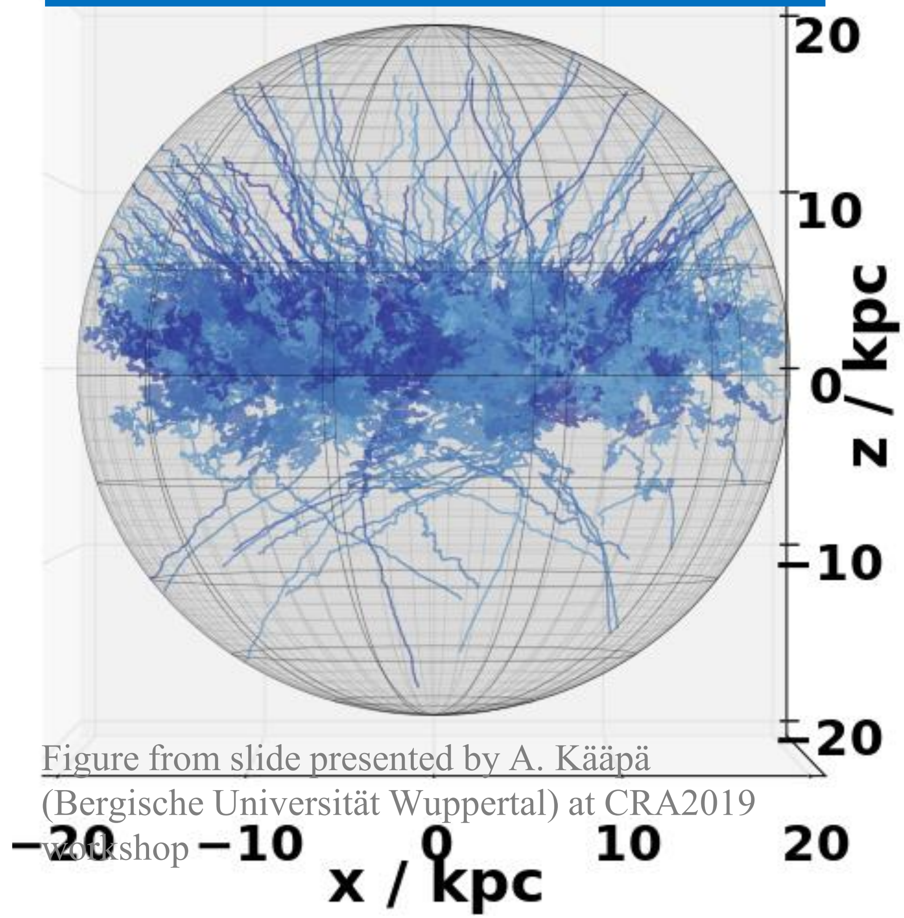
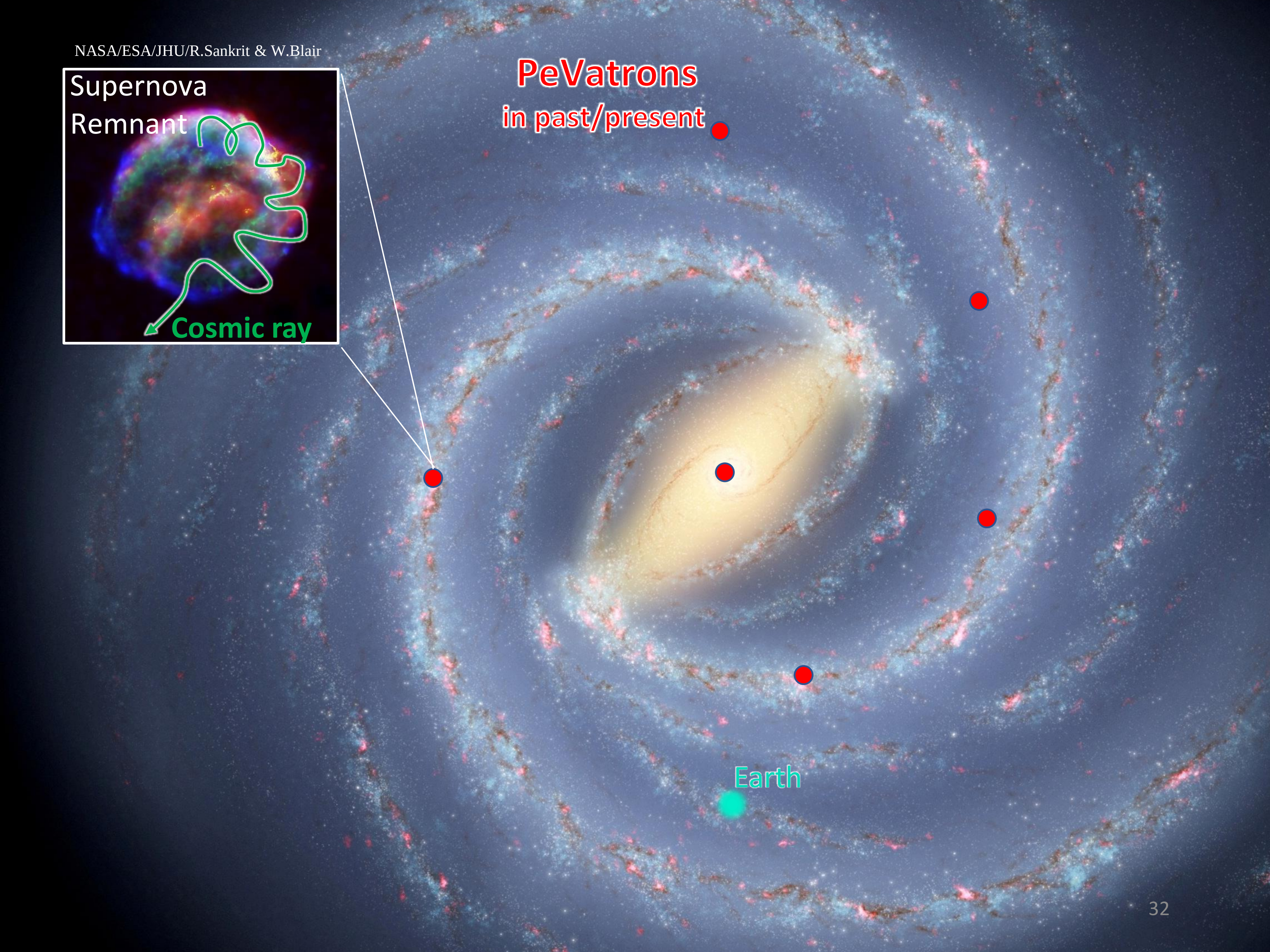
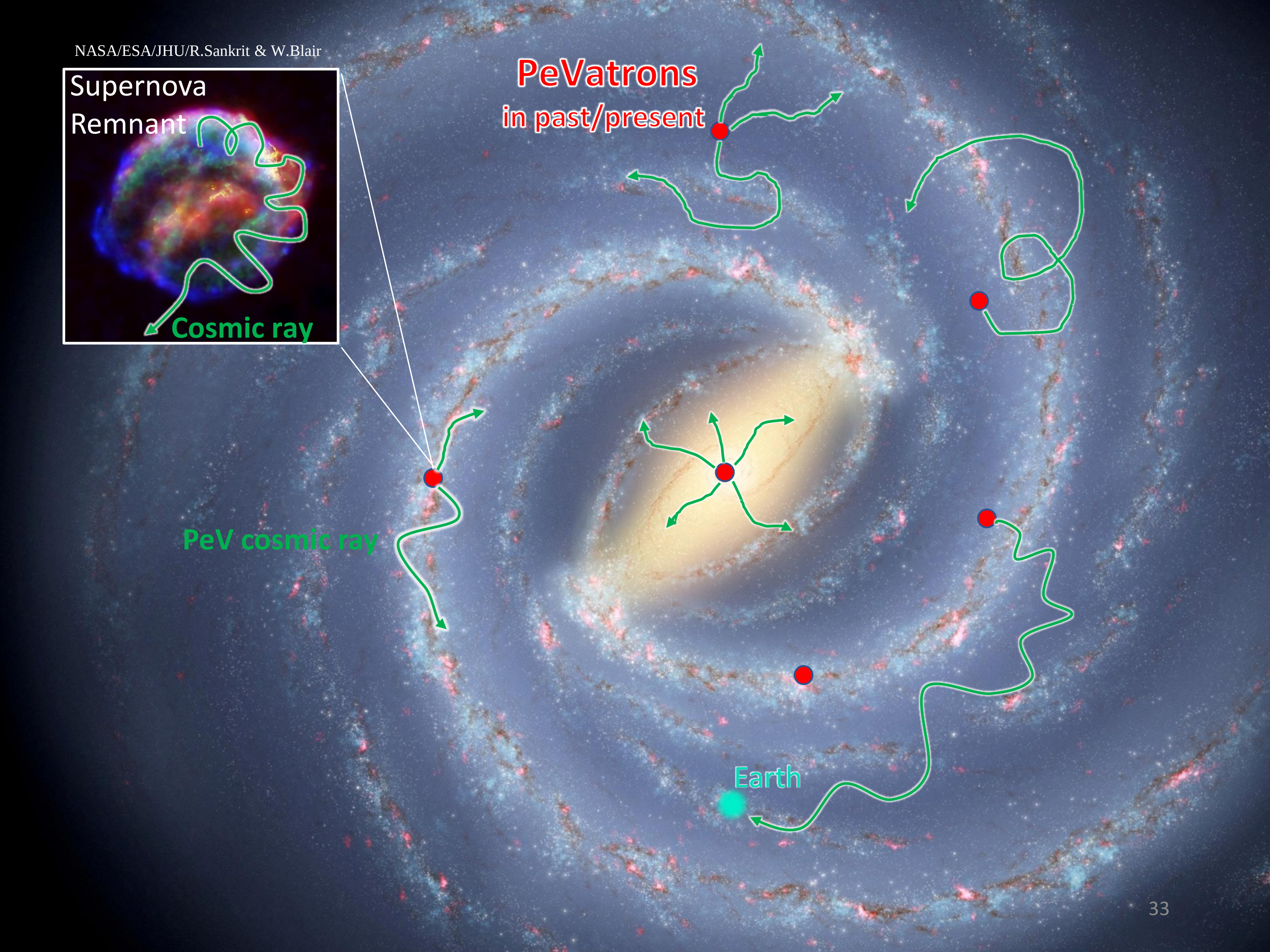


Figure from slide presented by A. Kääpä (Bergische Universität Wuppertal) at CRA2019 workshop


NASA/ESA/JHU/R.Sankrit & W.Blair
Supernova
Remnant
Cosmic ray
PeVatrons
in past/present
Earth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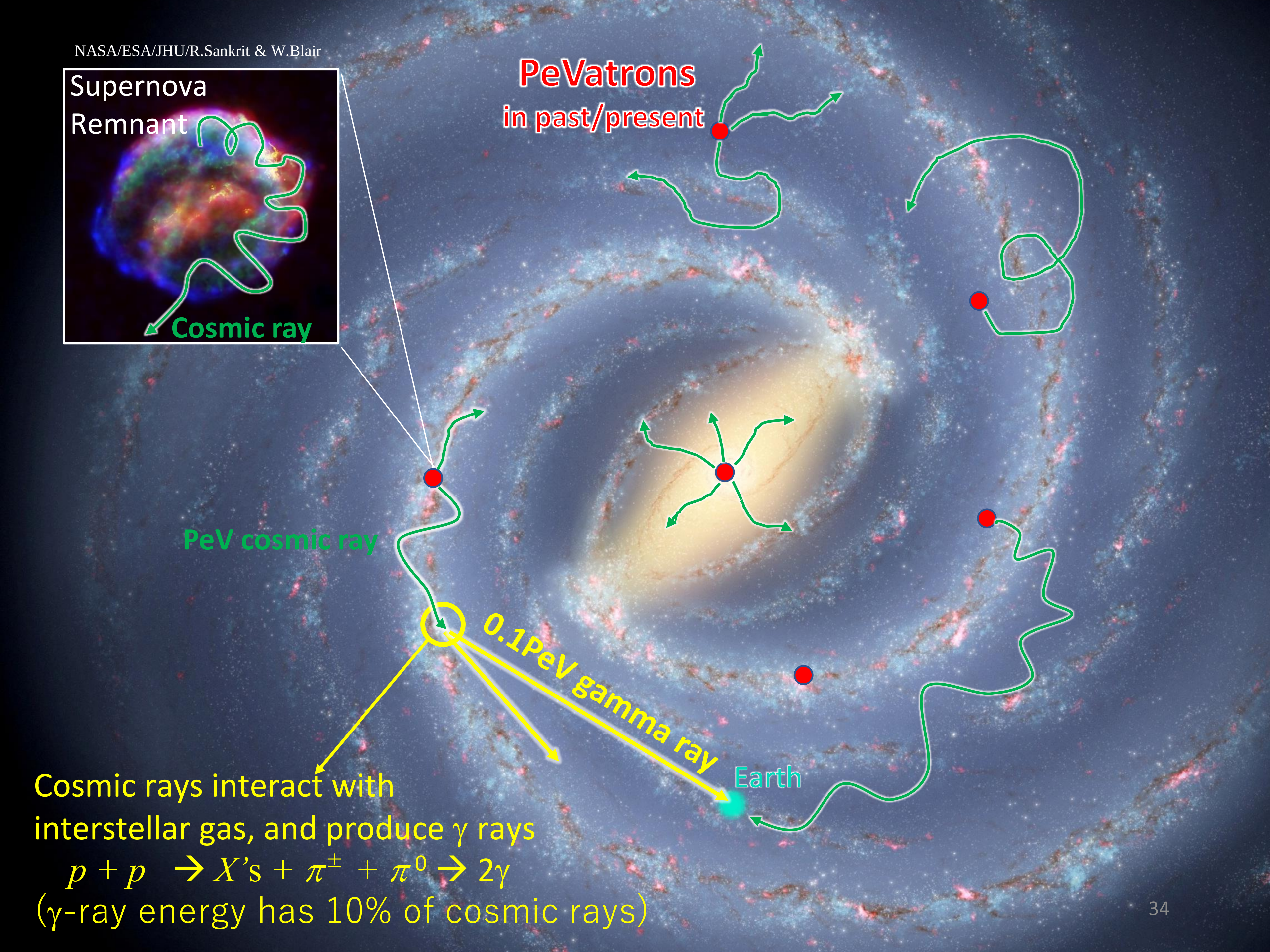
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Supernova Remnant
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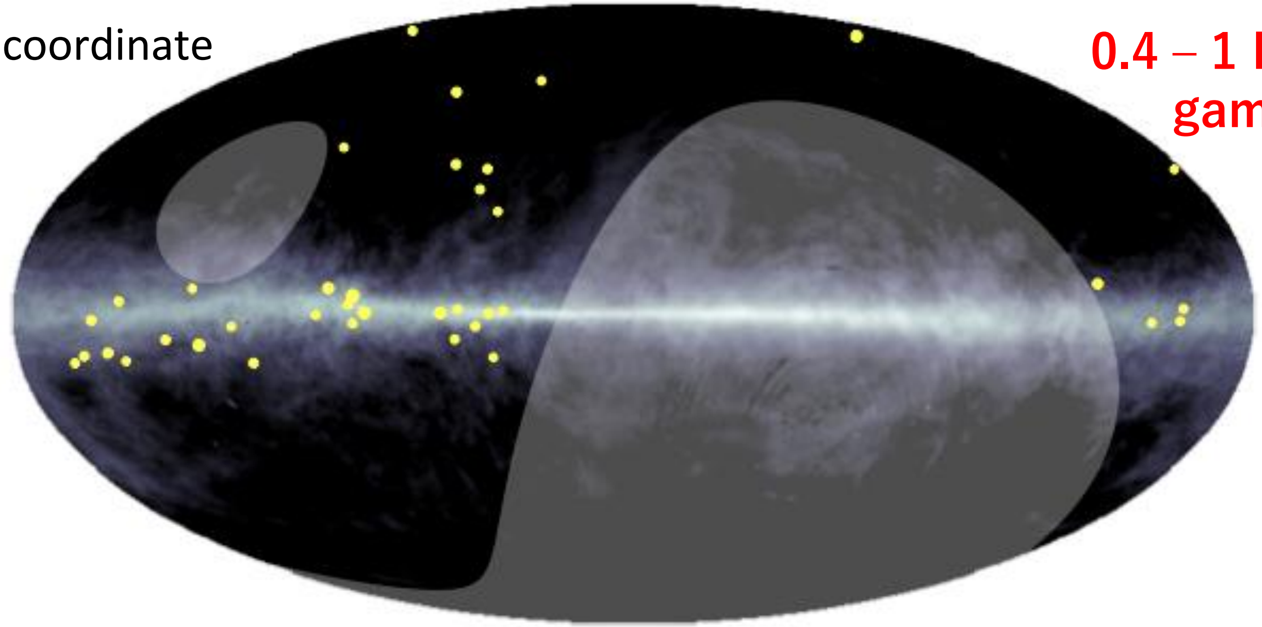
PeV cosmic ray
0.1PeV gamma ray
Earth
Cosmic rays interact with interstellar gas, and produce γ rays
$p + p \rightarrow X\text{'s} + \pi^{\pm} + \pi^{0} \rightarrow 2\gamma$
(γ-ray energy has 10% of cosmic rays)

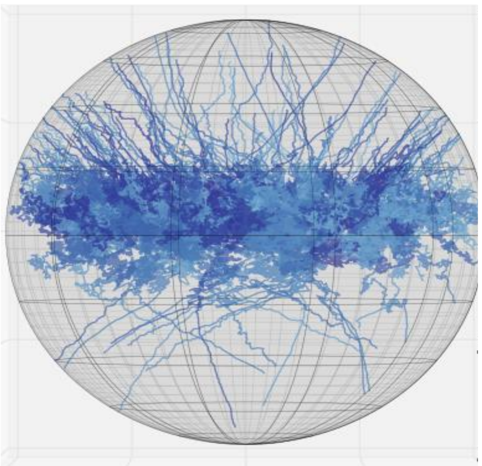
Scientific Interpretation



- ✓ This is the first compelling evidence for existence of PeVatrons, in the past and/or present Galaxy, which accelerate protons up to the Peta electron volt (PeV) region.

Scientific Interpretation

High-energy
cosmic rays



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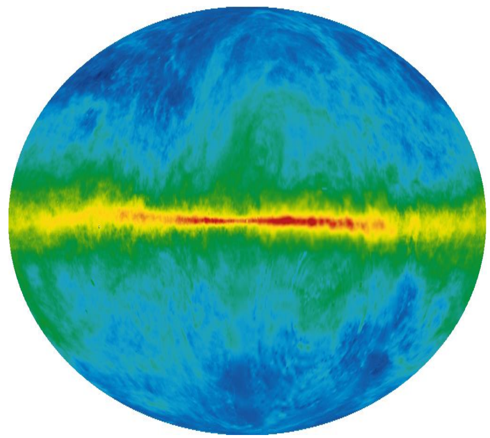
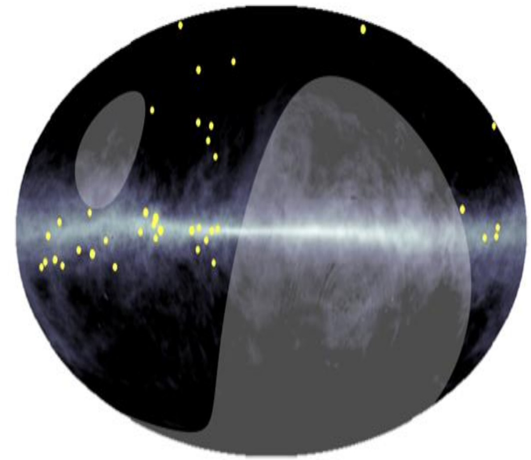
Interstellar
matter



Radio (21cm) HI Map
Hartmann et al. (1997)
Dickey & Lockman (1990)

=

High-energy
gamma rays

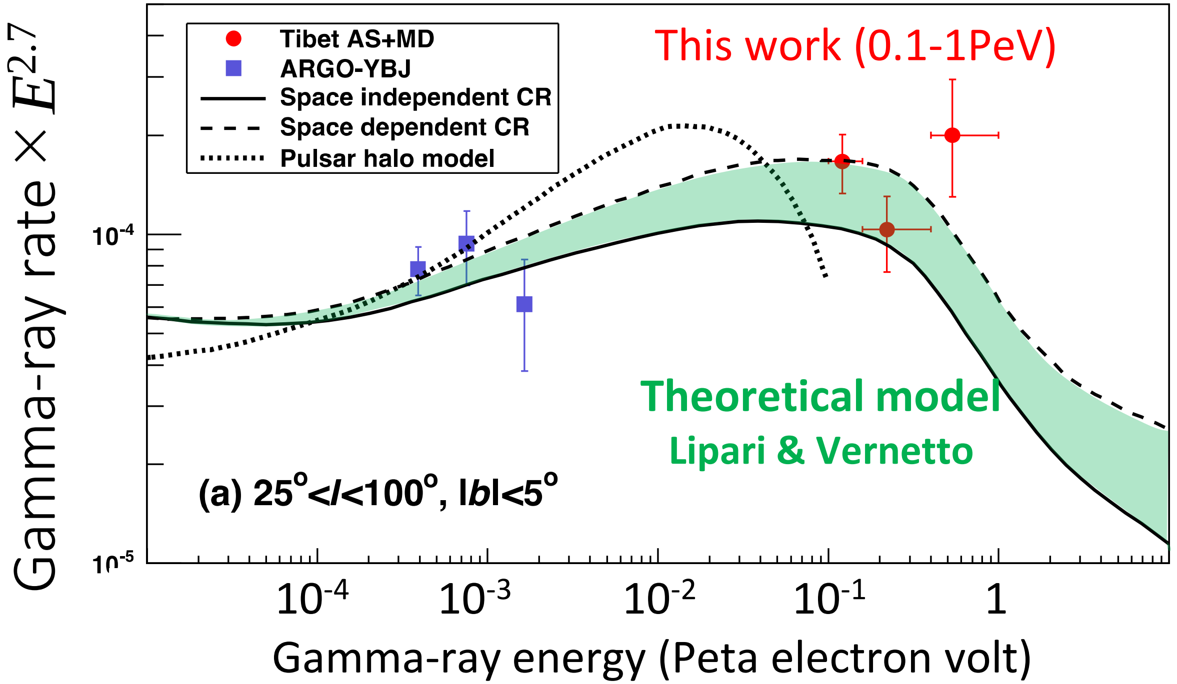


This Work

- ✓ This work proves a theoretical model that cosmic rays produced by PeVatrons are trapped in the Galactic magnetic field for millions of years, forming a pool of cosmic rays.

Scientific Interpretation

The measured γ-ray rates are consistent with the expected one from cosmic-ray pool scenario assuming the cosmic-ray rate observed on Earth.



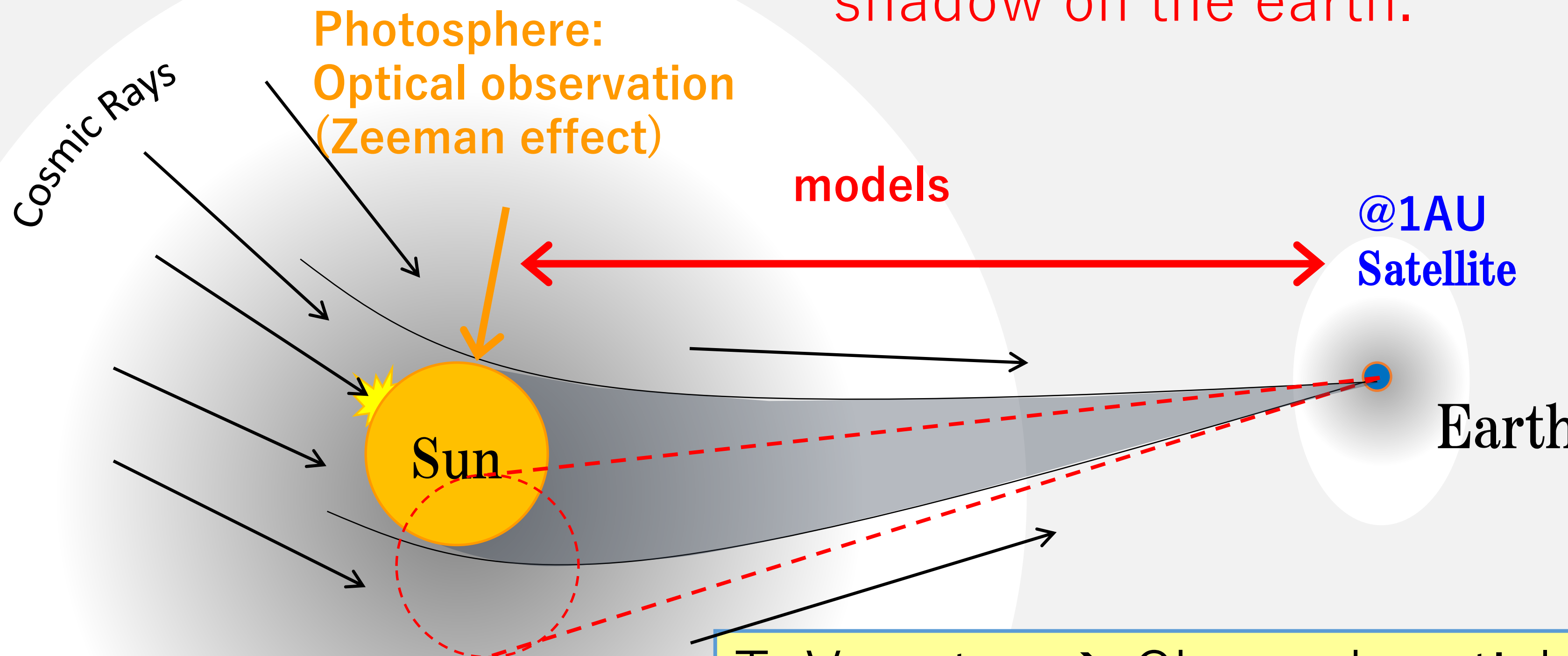
✓ It is verified that all the high-energy cosmic rays propagated to Earth can be explained by the cosmic-ray pool produced by Pevatrons in the past/present Galaxy.

Sun Shadow Observation

Sun Shadow

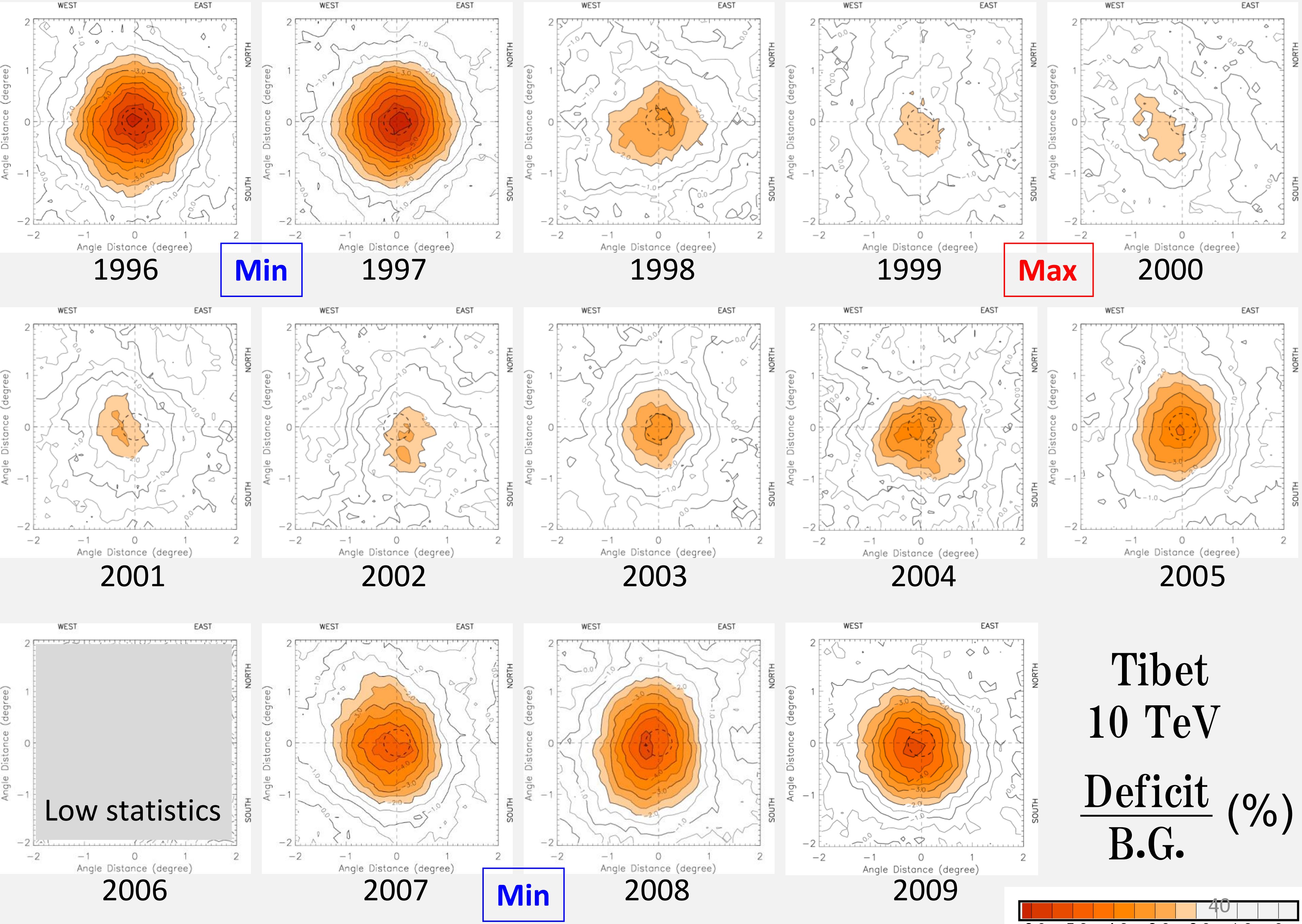
Sun Shadow

Sun blocks VHE cosmic rays, and cast the cosmic-ray shadow on the earth.



TeV proton → Charged particle
Gyroradius
$\sim$7.4AU (B=30μG near the earth)
$\sim 0.16R_\odot$(B=300mG near the sun)

→ Sun shadow provides unique method to probe solar MFs experimentally.


WEST
EAST
NORTH
SOUTH
Angle Distance (degree)
1996
Min
1997
1998
1999
Max
2000
2001
2002
2003
2004
2005
2006
Low statistics
2007
Min
2008
2009
Tibet
10 TeV
Deficit / B.G. (%)
−6.0 −5.0 −4.0 −3.0 −2.0 −1.0 0

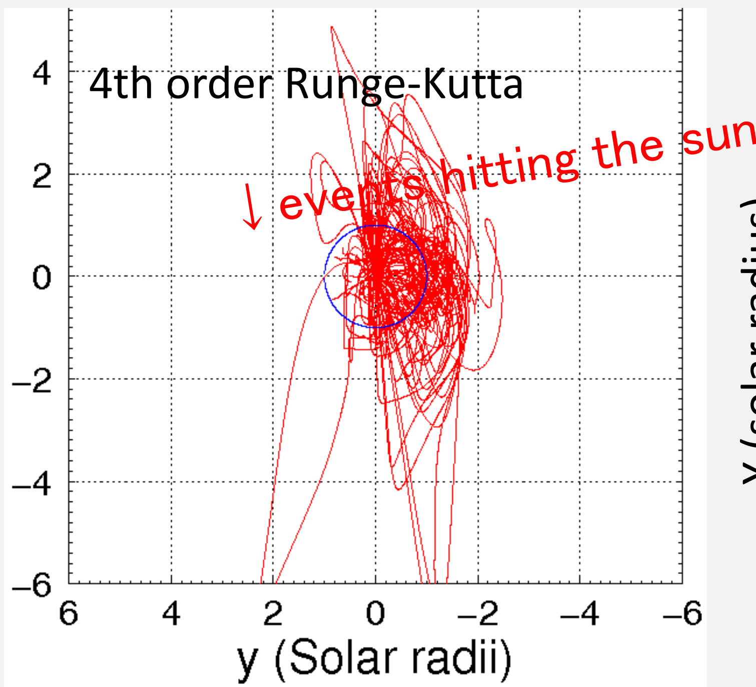
MC Simulation of Sun Shadow

- Anti-particles are shot back to the Sun from the Earth assuming CR spectra, compositions, detector responses

- Particle trajectories are traced assuming the solar MFs between the Sun and the Earth

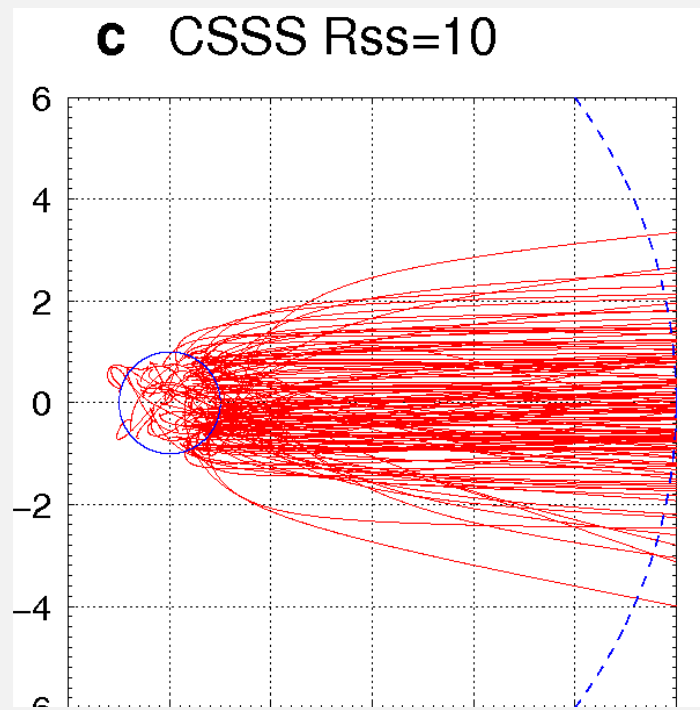
-> Events hitting the sun reconstruct the Sun shadow

Z (solar radius)



X (solar radius)

Y (solar radius)



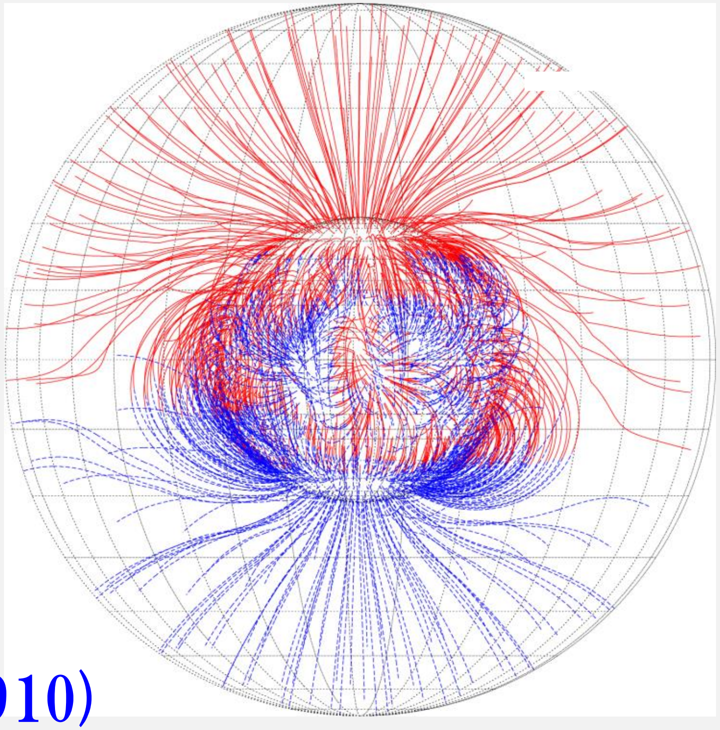
X (solar radius)

Time Dependent Coronal MF

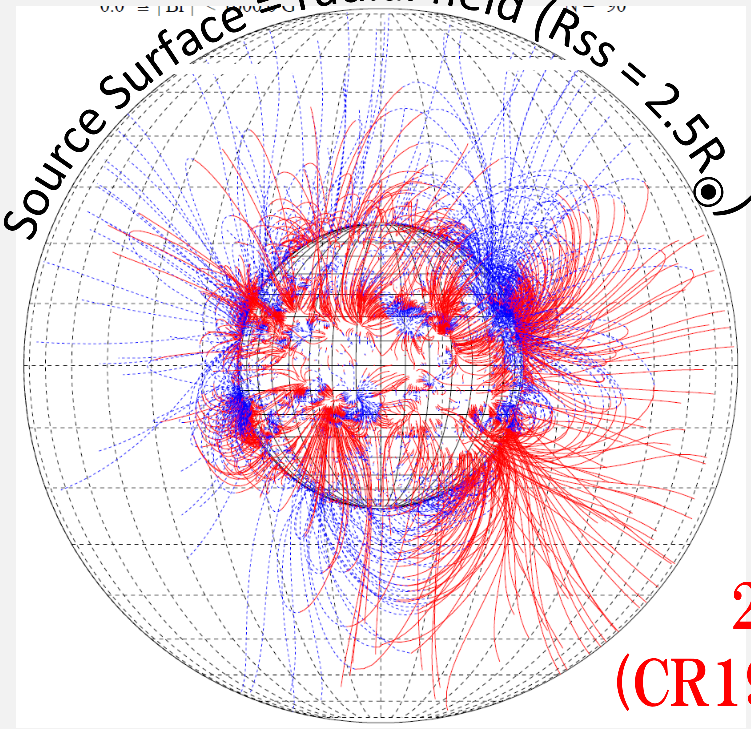
Corona -> potential field models ***(PSSS and CSSS)***
Extrapolated from the photospheric MFs measured by Kitt Peak (KPVT/SOLIS) in each Carrington rotation (~27 days)

IMF -> Parker spiral model with latitude dependence of the solar wind velocity taken into account.

Geomag.-> Dipole model



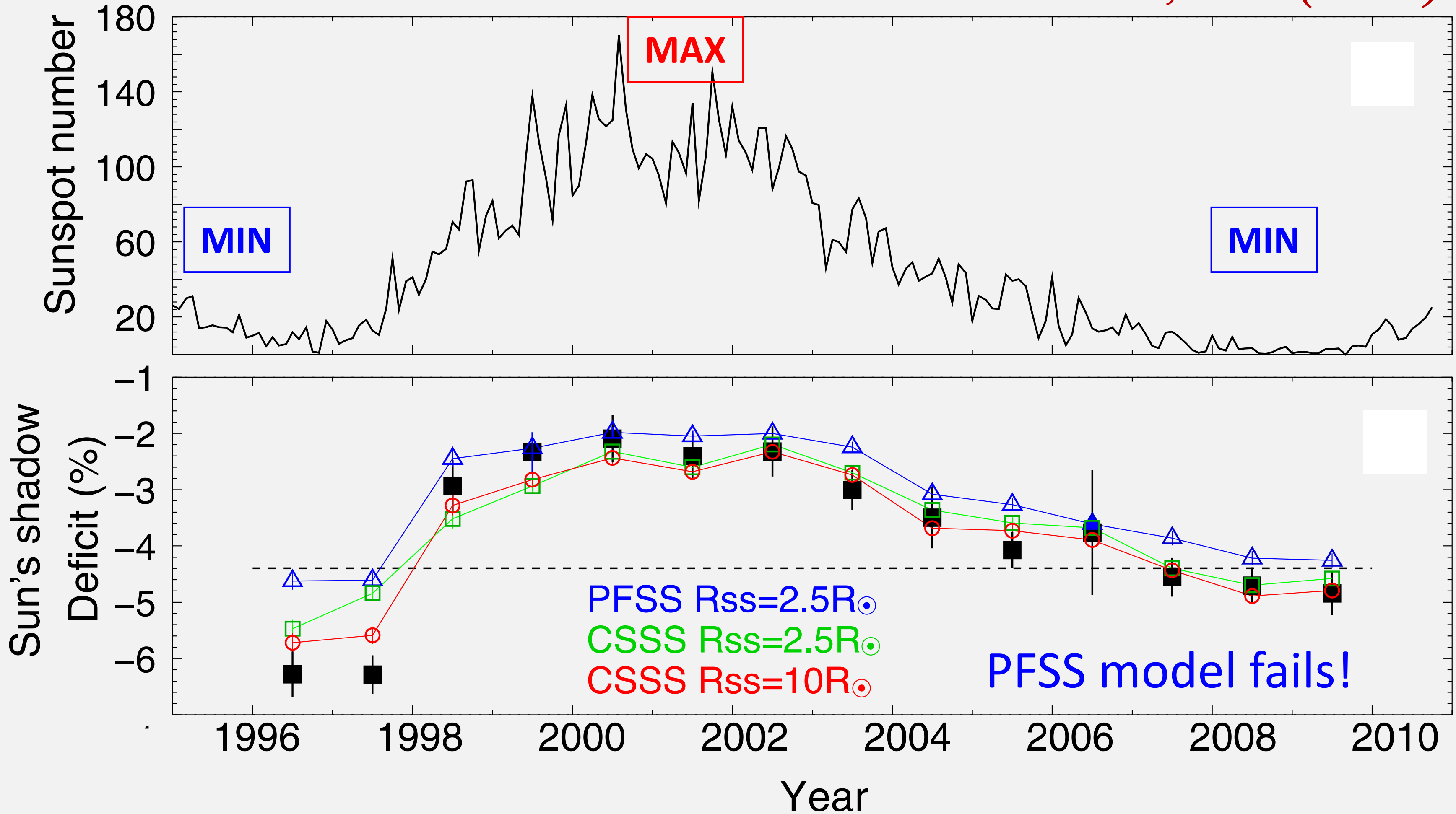
1996 (CR1910)



2001 (CR1978)

Evaluation Solar MF models

Amenomori et al, PRL (2013)



- ✓ Discovery of a clear anti-correlation of the deficits
- ✓ First demonstration to evaluate the coronal MF models

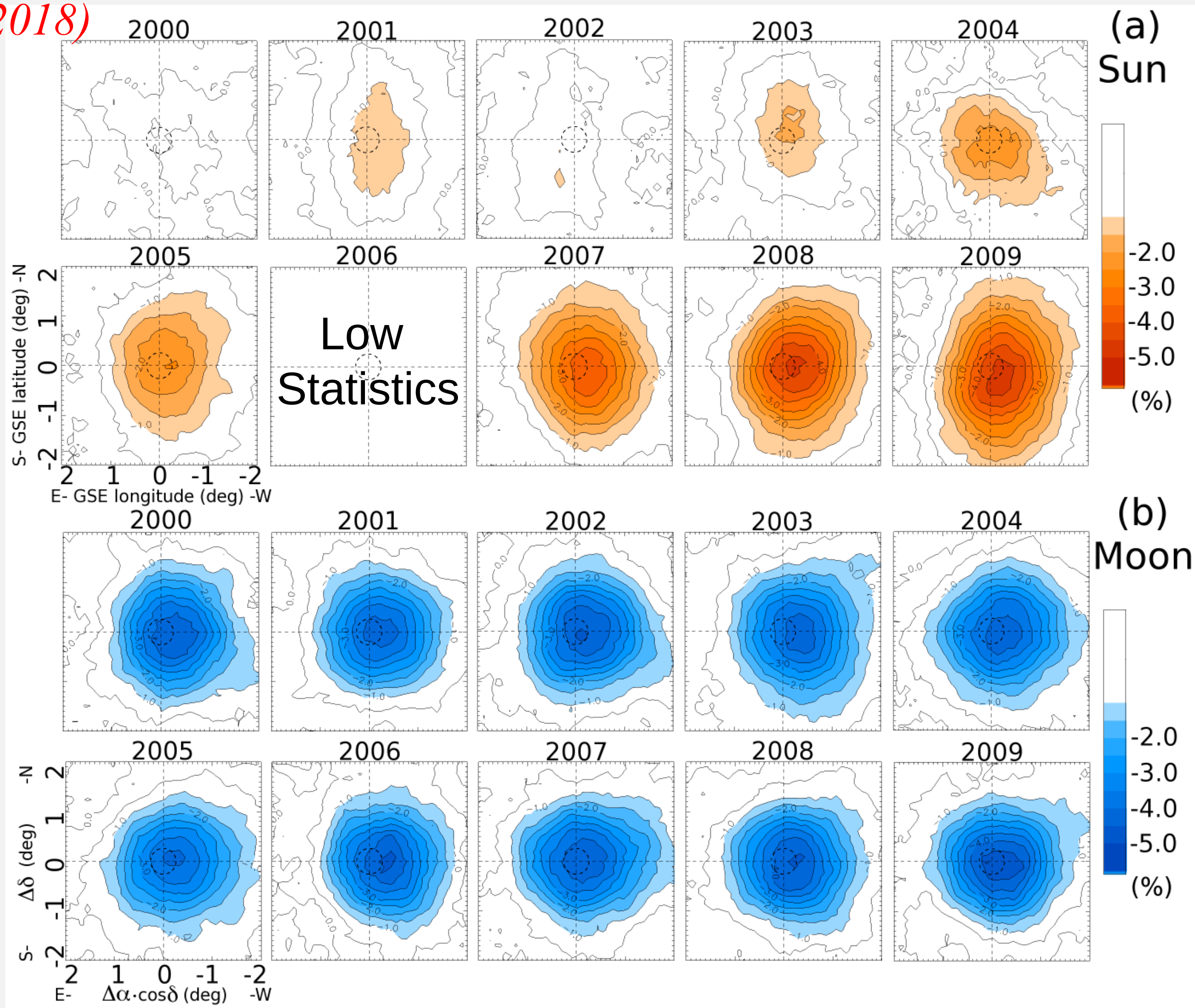
→ A clear solar-cycle variation of the deficits
CRs are scattered by solar magnetic field.

Amenomori et al., ApJ, 860,13 (2018)

Sun

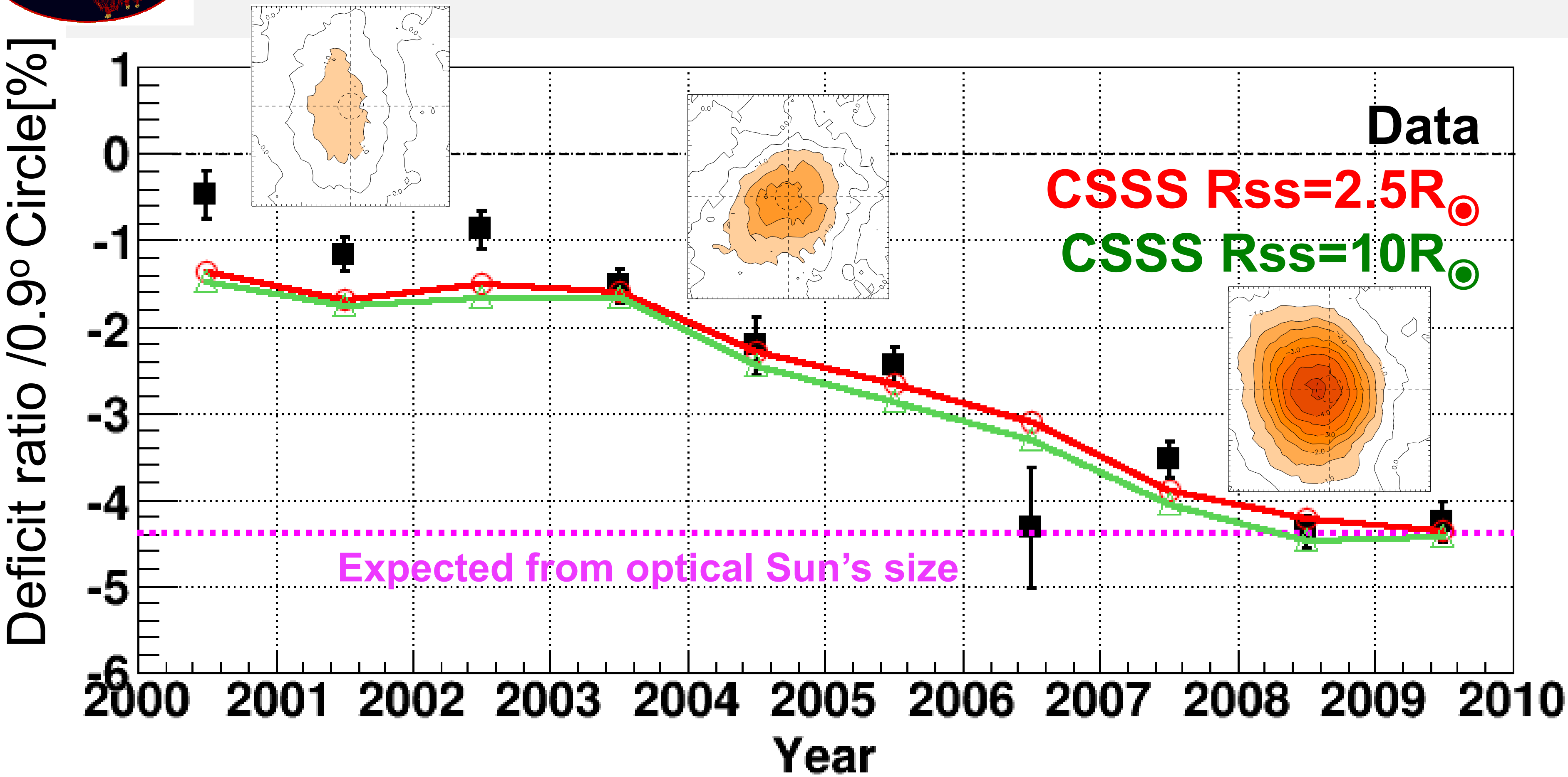
2000-2009
Tibet-III
(>3TeV)

Moon



→ Shift westward by geomagnetic field
Detector stability calibration

Deficit – Obs/MC **All Data** - 3 TeV



χ^2 test :

χ^2 / dof = 32.1 / 10 (3.4σ)

χ^2 / dof = 46.9 / 10 (4.8σ)

*only stat. error

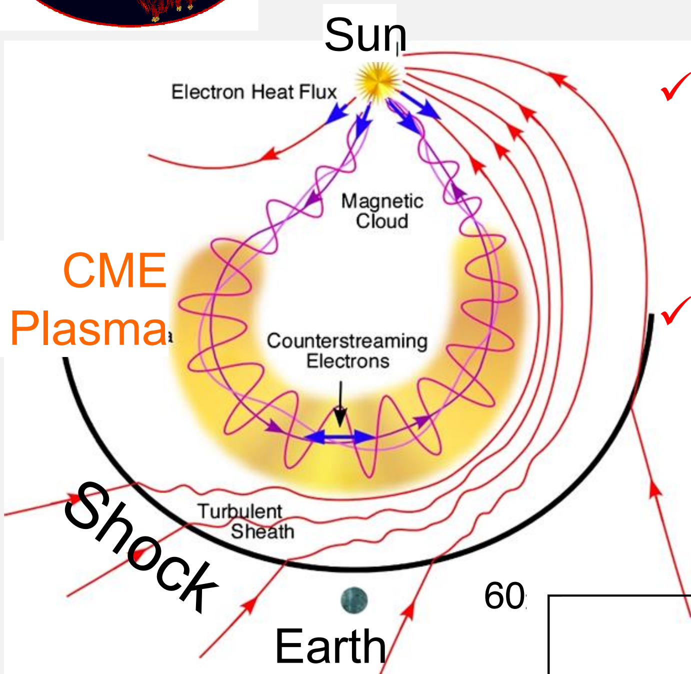
CSSS does not reproduce well at the solar maximum

Influence of CMEs?

http://www.srl.caltech.edu/ACE/ASC/DATA/level3/icmetable2.htm

CME Catalog

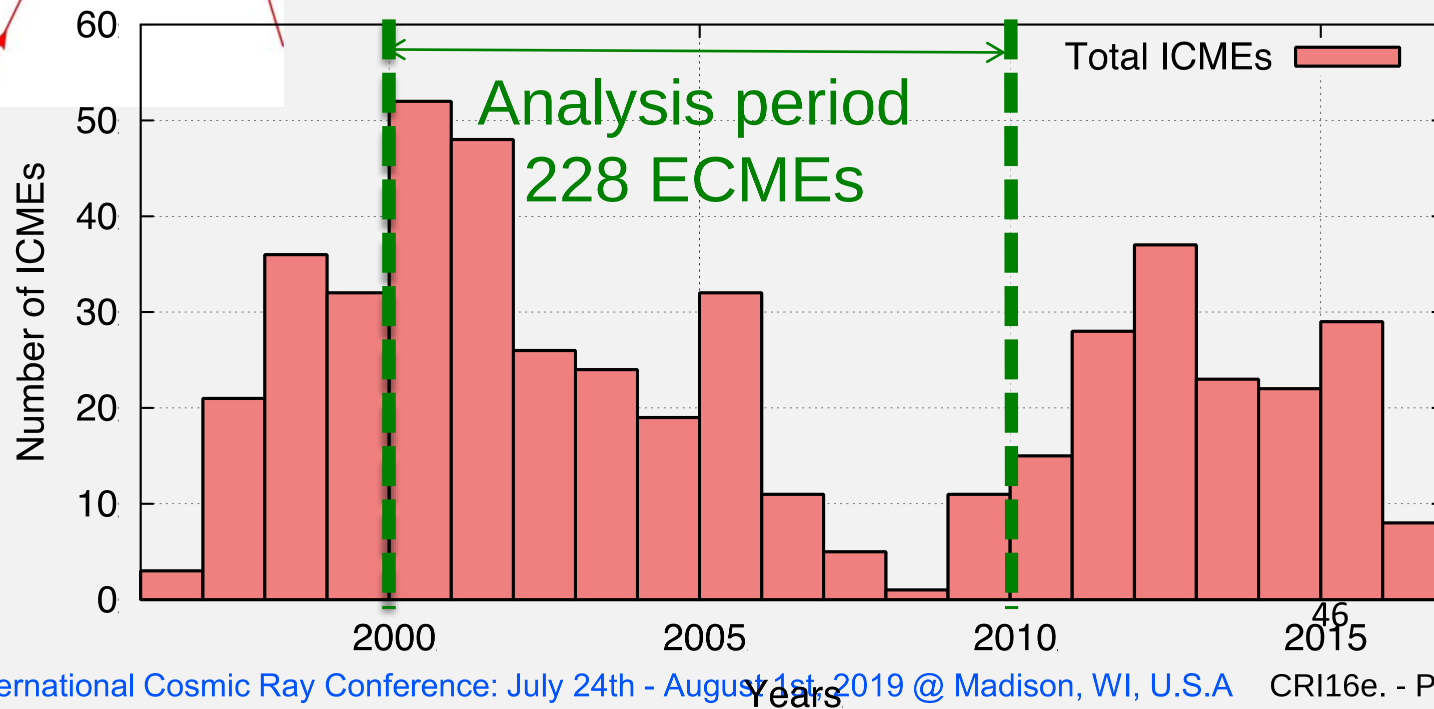
Richardson & Cane, Solar Phys (2010)



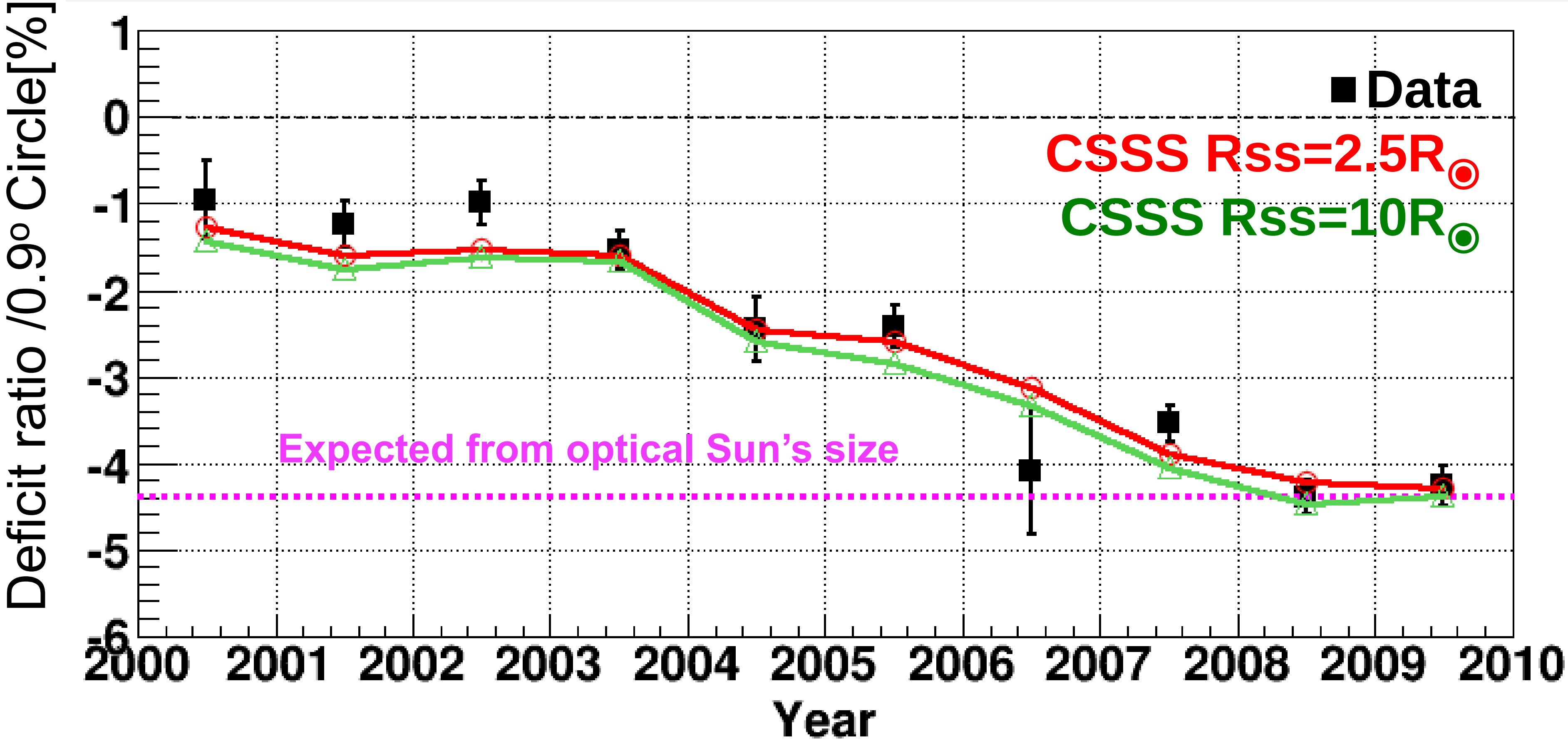
✓ Richardson & Cane Catalog
- CME plasma information observed at the earth
- Only Earth-directed CMEs (ECMEs) are listed

✓ Exclude transit periods of ECMEs from the analysis
- ECME start is the eruption time at the Sun
- ECME end is plasma end at the earth.
- ECME transit period is ~4 ± 1 days

Coronal
Mass
Ejection



Deficit – Obs/MC **Excluding ECMEs** - 3 TeV



χ^2 test :

χ^2 / dof = 12.2 / 10 (0.6σ

χ^2 / dof = 21.0 / 10 (2.0σ

*only stat. error

Exclude ECMEs → CSSS works

First evidence for influence of ECMEs on the Sun shadow at 3 TeV

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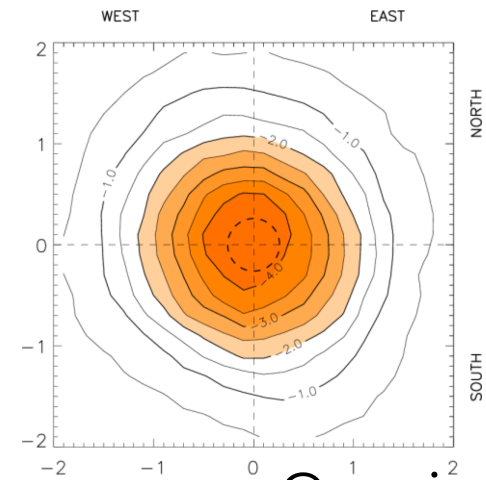
Forecast of CME-> Space Weather

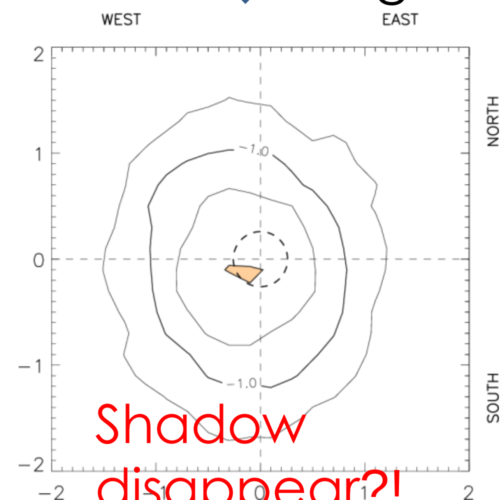
Magnetic Field between Sun and Earth is indirectly observed by cosmic rays!

CME takes ~4days from Sun to Earth.
→vs. Cosmic Rays takes ~ 8min.
The Sun Shadow could forecast space weather in principle!

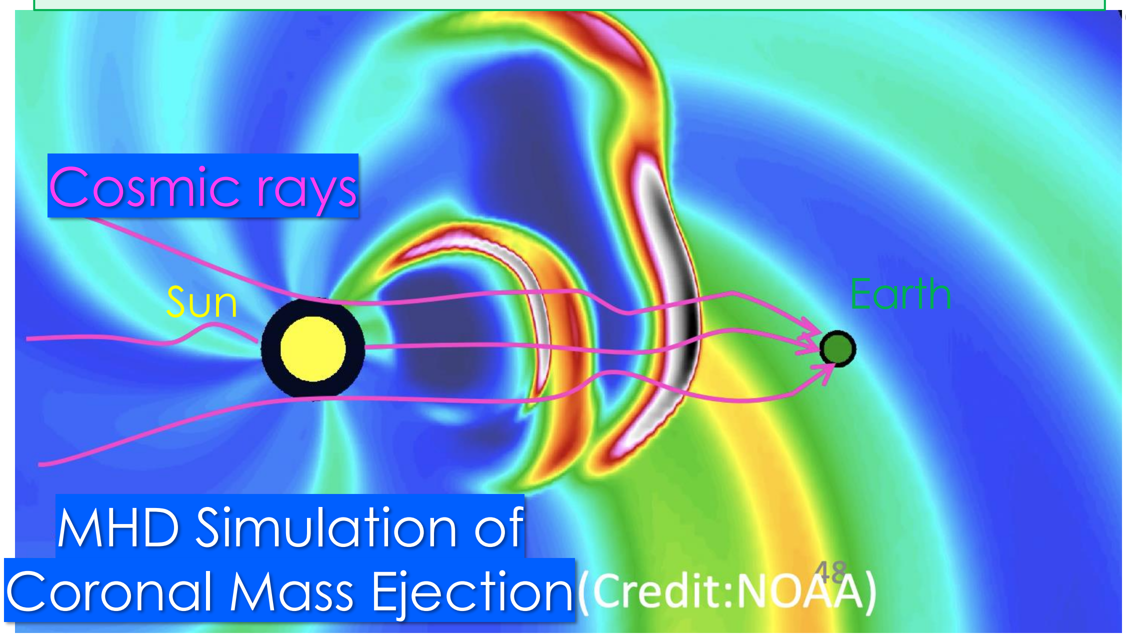


CME occurs！

Cosmic rays scattered by magnetic field



Shadow disappear?!



MHD Simulation of Coronal Mass Ejection(Credit:NOAA)

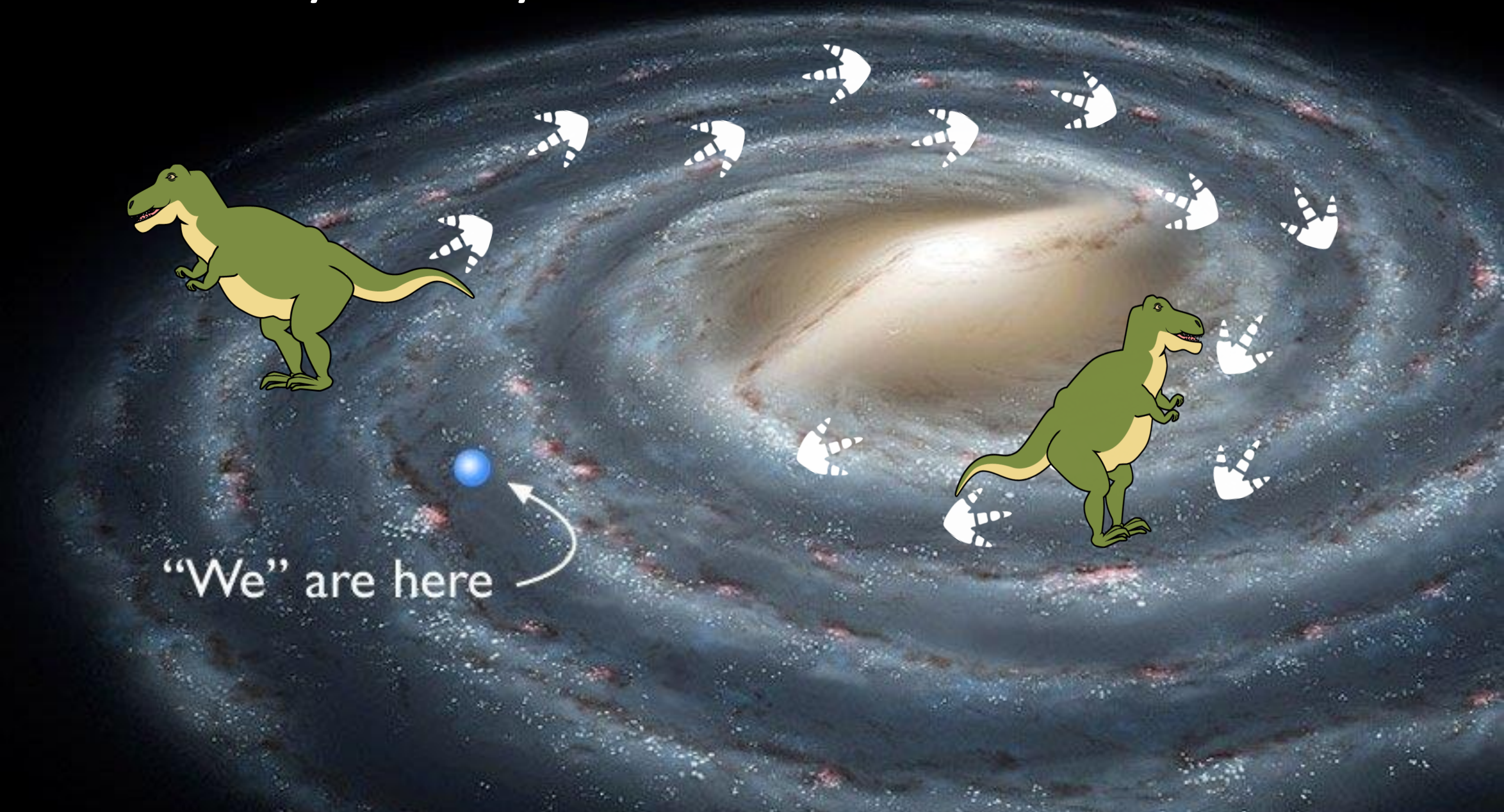
Summary

We are Unraveling 60-Year-Old Mystery of Cosmic Ray Origin,

- ✓ Highest energy sub-PeV (0.1-1 PeV) gamma rays from the Milky Way galaxy
- ✓ Conclusive evidence for existence of PeVatrons in past/present Milky Way galaxy
- ✓ Experimental evidence for the theoretical model of high-energy "cosmic-ray pool" in the Milky Way galaxy.

The Sun shadow in Cosmic Rays could forecast Space Weather.

Thank you for your attention!



Dinosaur = PeVatron

Footprints = sub-PeV γ rays