

Particle Astrophysics

Harm Moraal

North-West University
Potchefstroom



NORTH-WEST UNIVERSITY
YUNIBESITHI YA BOKONE-BOPHIRIMA
NOORDWES-UNIVERSITEIT

SAIP Conference, 8 July 2014

Topics

- **South African astronomy**
- **Particle vs. photon astronomy**
- **Cosmic-ray spectra, composition**
- **Dark matter**
- **Neutrinos**
- **Cosmic-ray variations**
- **“Cosmic” rays from the sun**
- **Helioclimatology**

Particle vs. photon astrophysics

“The Skies” are explored through

- **Photons**

 - Radio

 - Microwave

 - Infrared

 - Optical

 - X-ray

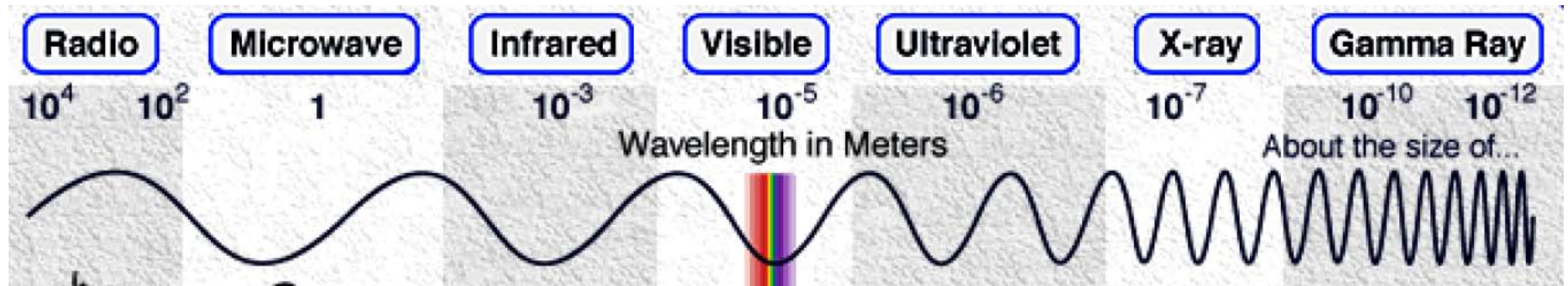
 - Gamma ray

- **Particles**

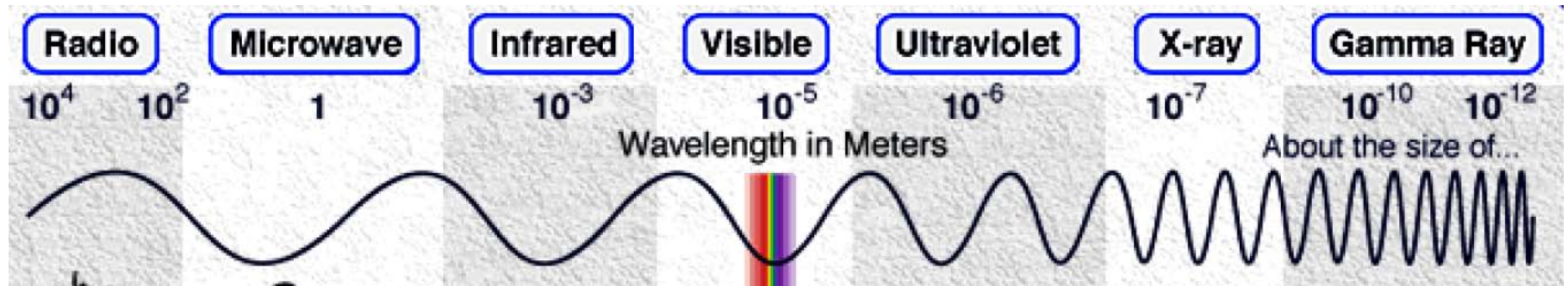
ASTRONOMY IN SOUTH AFRICA: A MULTI-WAVELENGTH LONG-TERM STRATEGIC PLAN

**Astronomy Desk Draft – version 1
28 May 2014**

Multiwavelength Astronomy



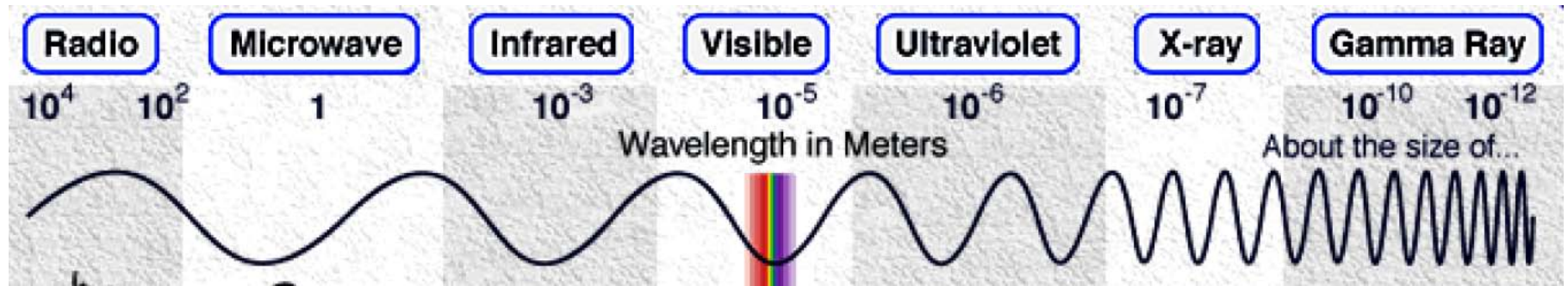
Multiwavelength Astronomy



SAAO & SALT



Multiwavelength Astronomy

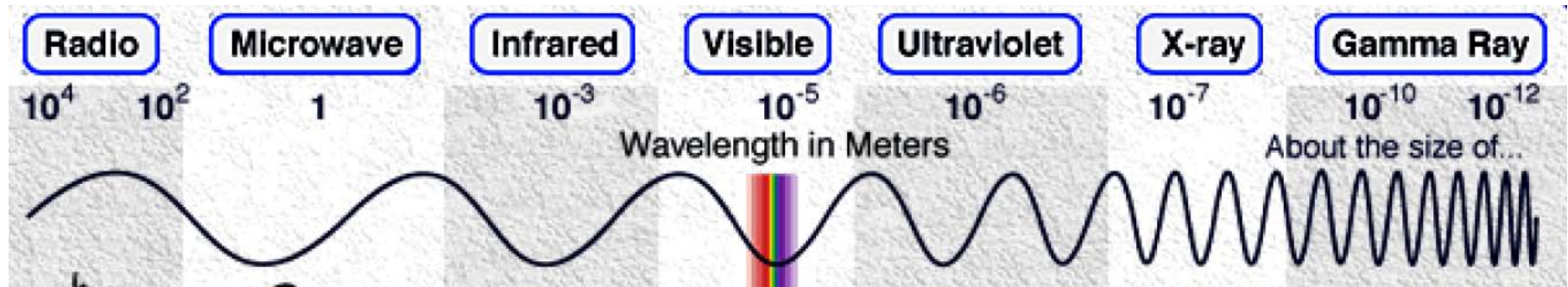


Hart RAO & KAT,
MeerKAT, SKA

SAAO & SALT



Multiwavelength Astronomy



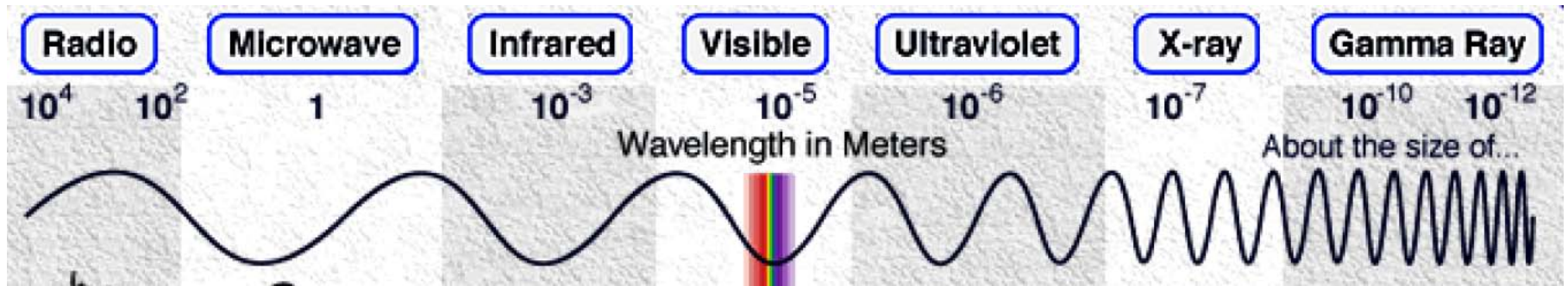
Hart RAO & KAT,
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SAAO & SALT

H.E.S.S.



Multiwavelength Astronomy



Hart RAO & KAT,
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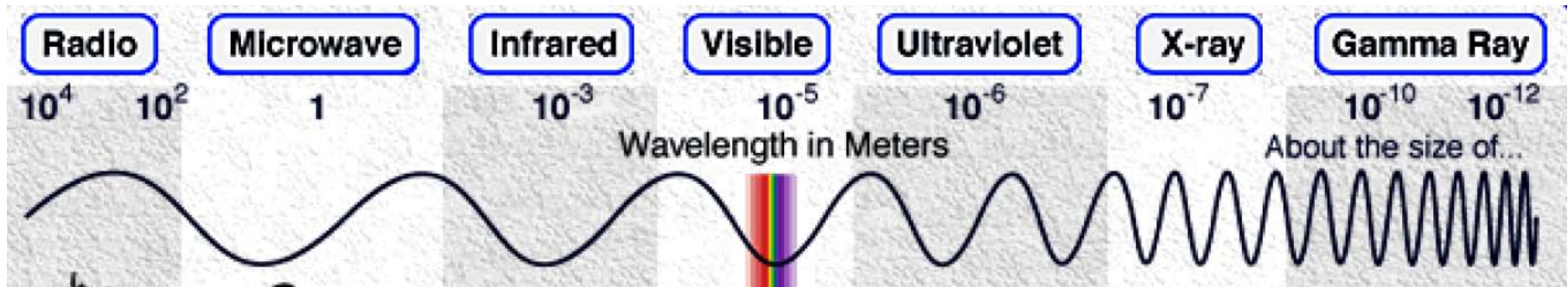
SAAO & SALT

H.E.S.S.



CTA, end 2014?

Multiwavelength Astronomy



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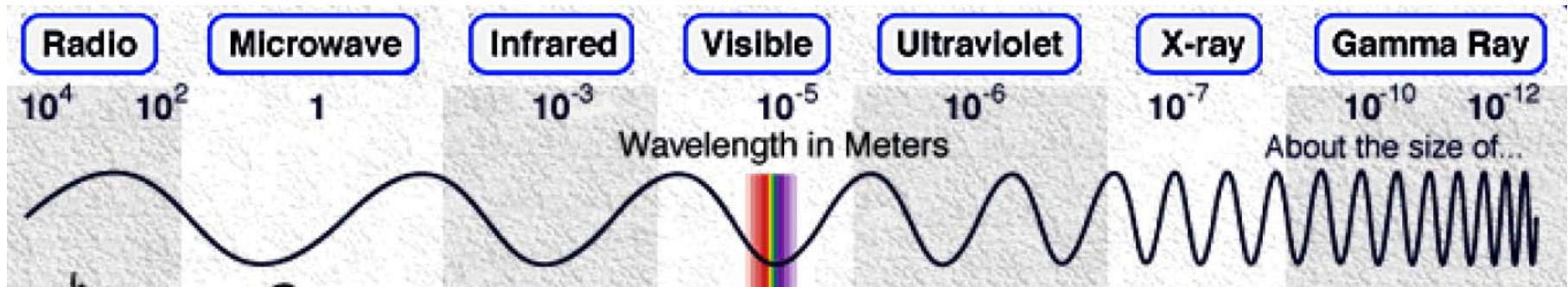


$< 10^{-3}$ eV

Energy = hc/λ
 ~ 1 eV

$> 10^9$ eV

Multiwavelength Astronomy



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SAAO & SALT

H.E.S.S

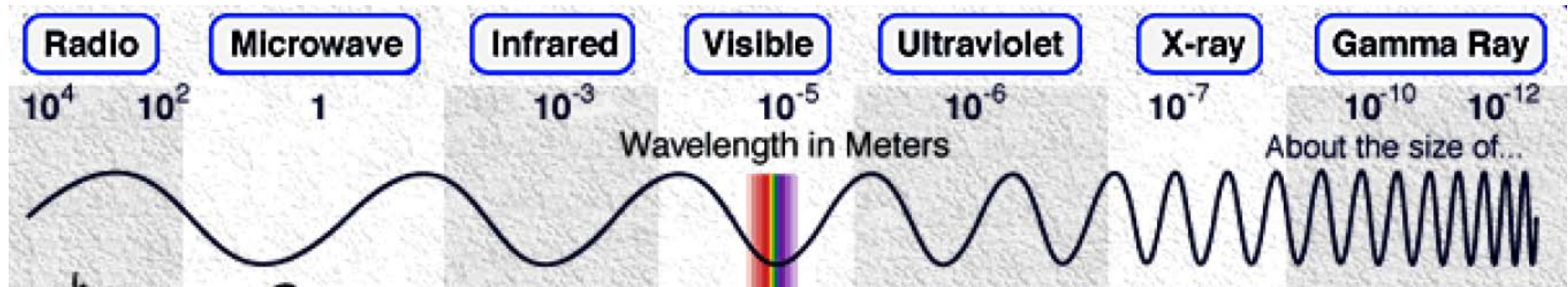


$< 10^{-3}$ eV
Rotations
and vibrations

Energy = hc/λ
 ~ 1 eV
Electronic jumps

$> 10^9$ eV
Nuclear
reactions

Multiwavelength Astronomy



Hart RAO & KAT,
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SAAO & SALT

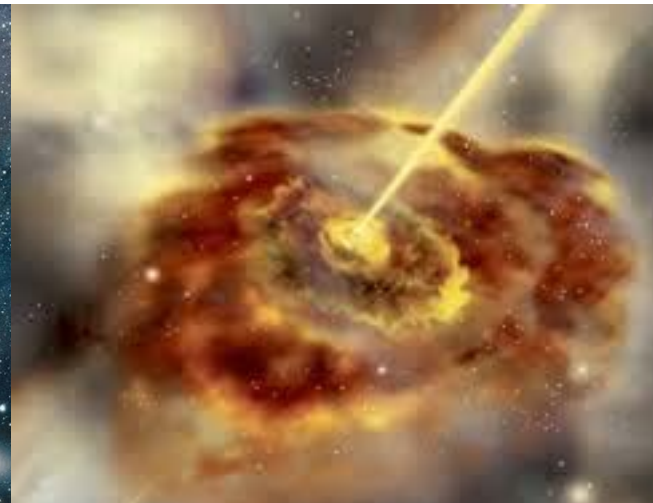
H.E.S.S



Horsehead nebula



Galaxy M31



Active Galactic Nucleus (guess)

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- “Cosmic” rays from the sun
- Helioclimatology

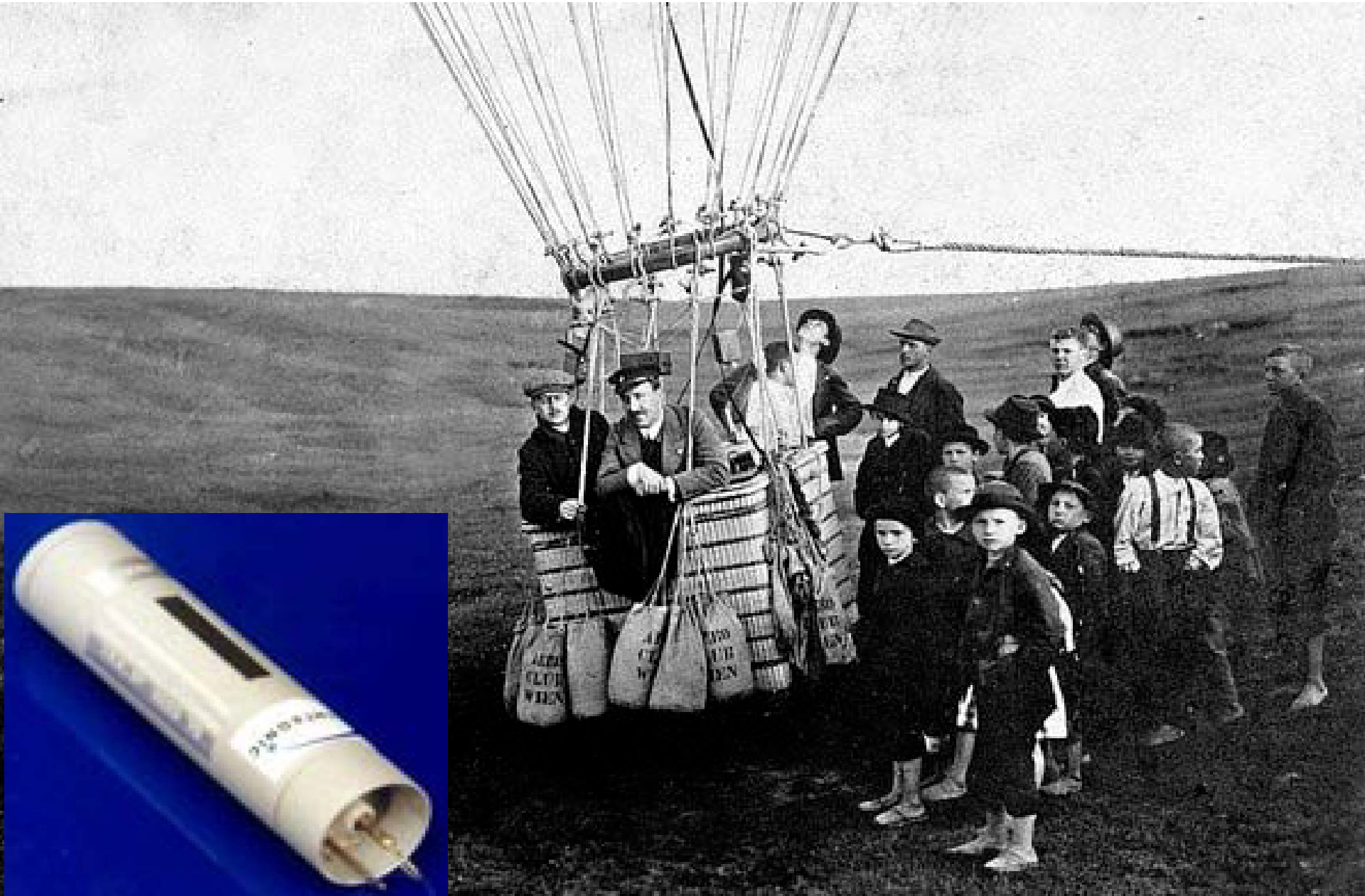
Cosmic rays

- Charged **particles** - 90% protons, 5% He nuclei, 3% heavier atomic nuclei, 2% electrons
- Characterised by very high energies (10^6 - 10^{20} eV)

Victor Hess, 7 August 1912



Victor Hess, 7 August 1912



Bad Saarow Railway Station – 100 years later



6 to 8 August 2012

Particle vs. Photon Astronomy

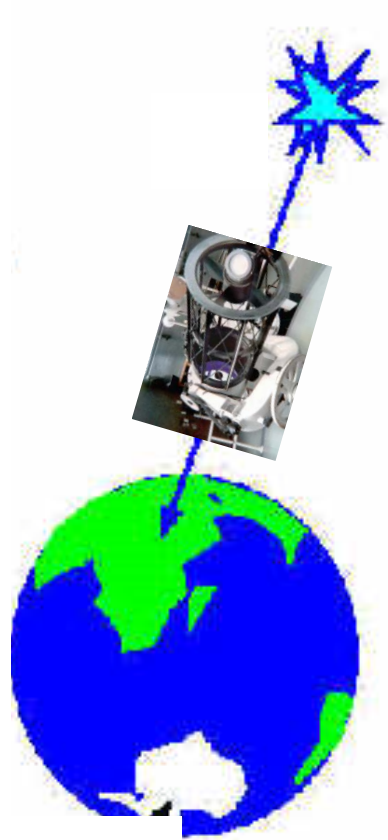


Photons

1. Where
2. How bright
3. Colour



Particle vs. Photon Astronomy



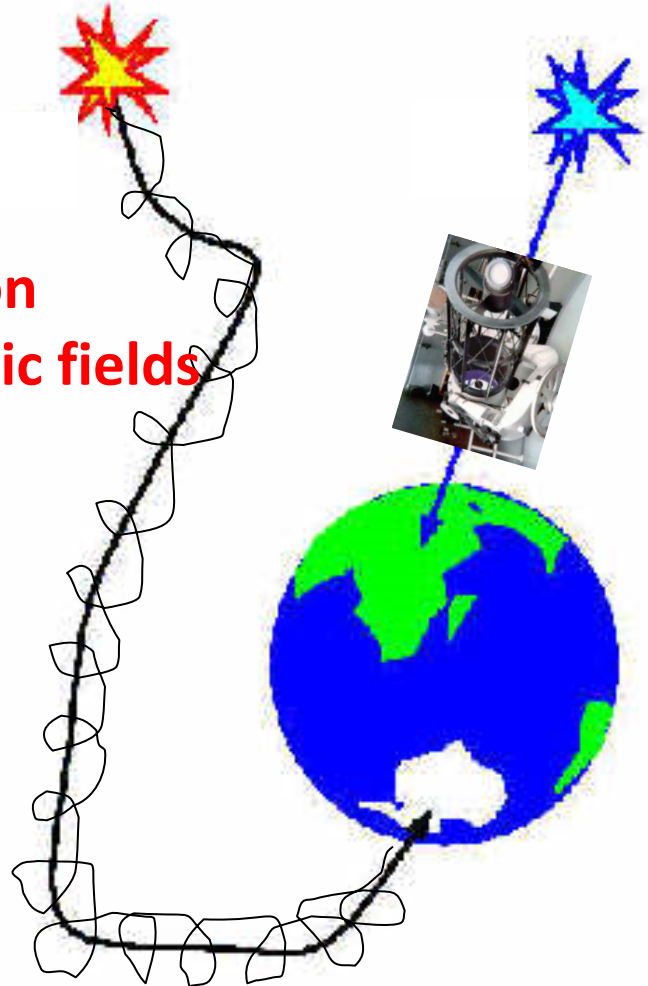
Photons

1. Where
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Particle vs. Photon Astronomy

Particles:
No such information
Because of magnetic fields

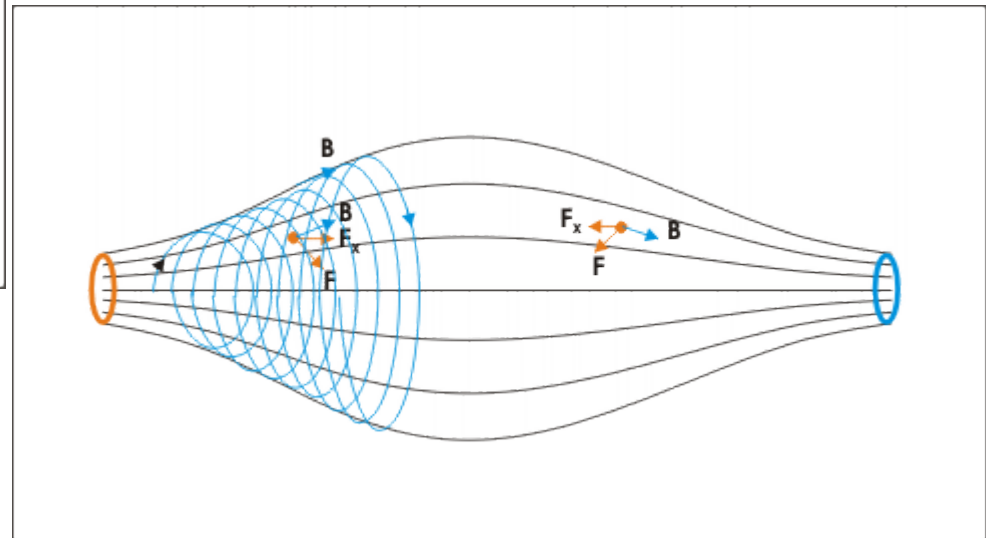
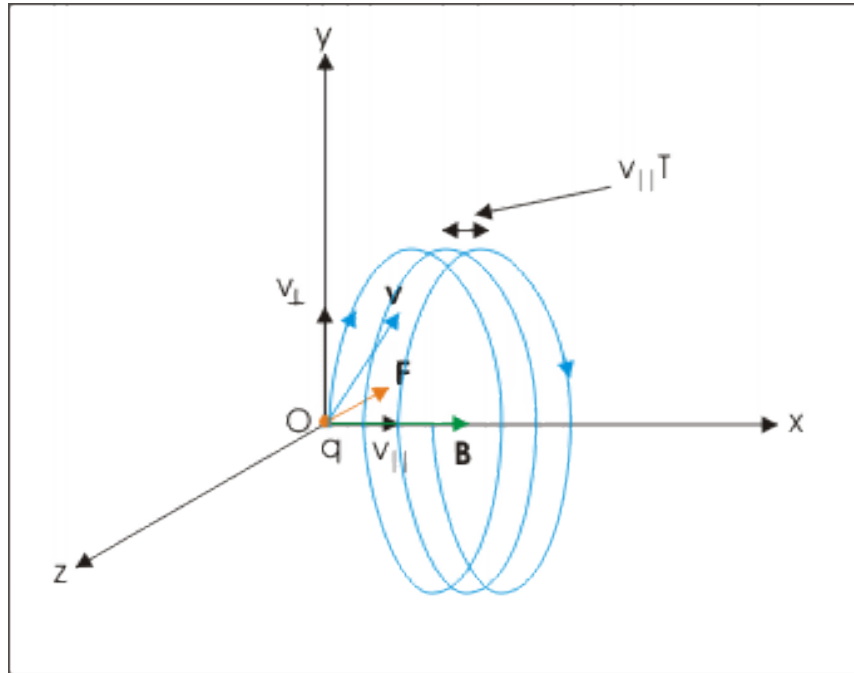


Photons

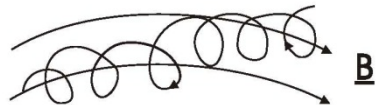
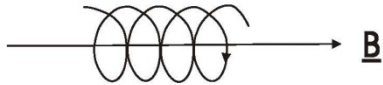
1. Where
2. How bright
3. Colour



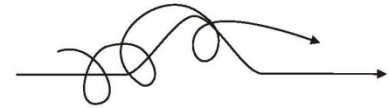
Charged particles spiral around magnetic field lines



Kinks in field cause scattering



This way?



Other way?

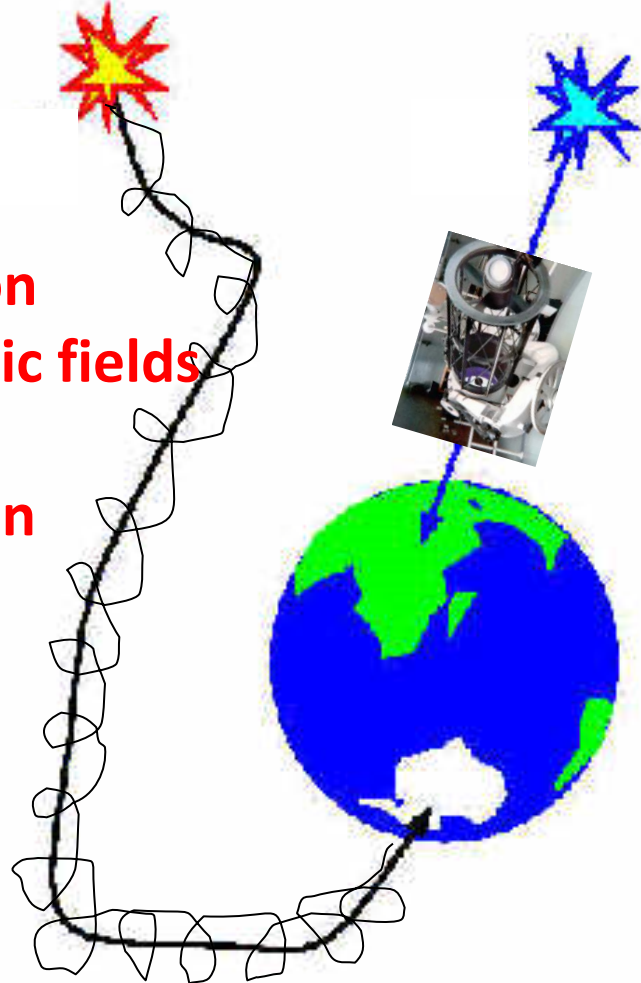


No way...? stuck

Particle vs. Photon Astronomy

Particles:
No such information
Because of magnetic fields

.....like a bead on an
elastic band



Photons

1. Where
2. How bright
3. Colour



Particle vs. Photon Astronomy



Photons

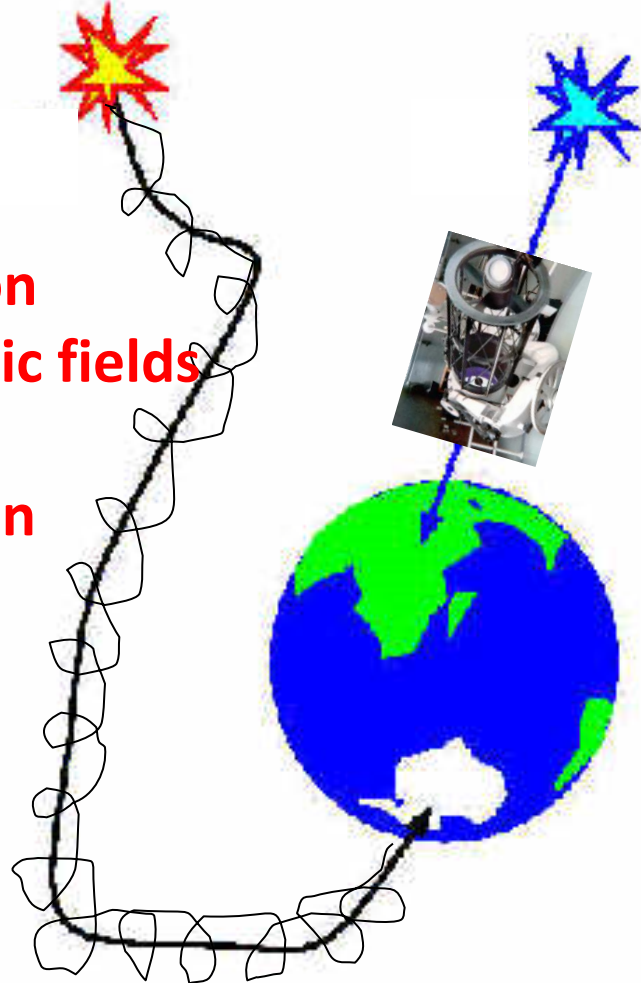
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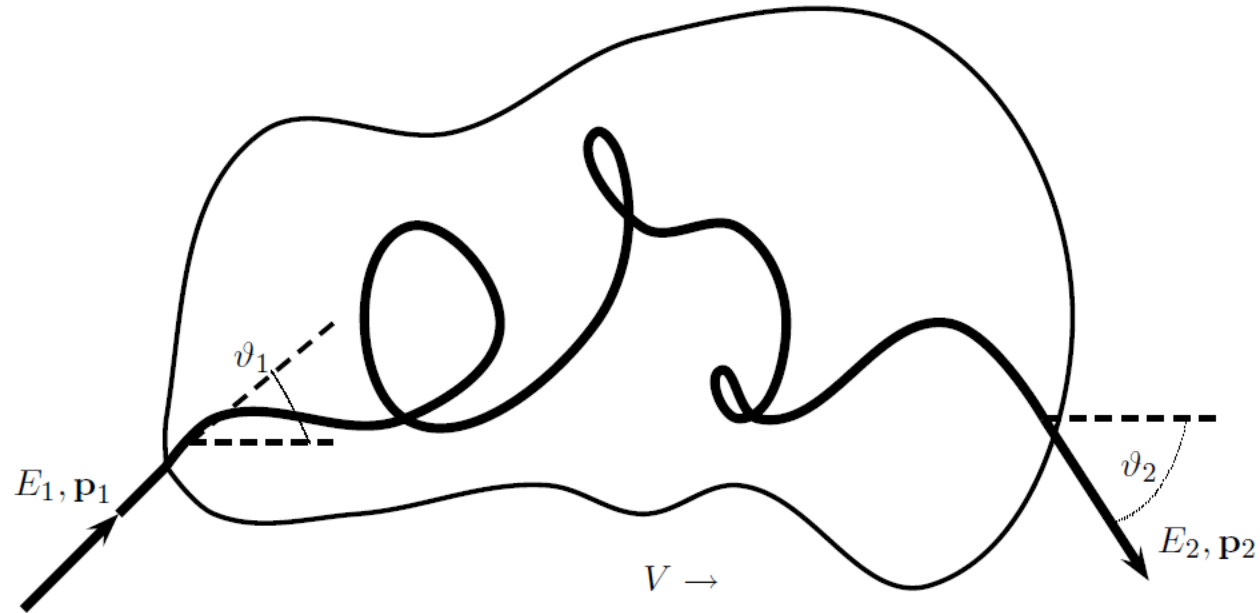


Photons

1. Where
2. How bright
3. Colour



Charged particles in magnetic fields

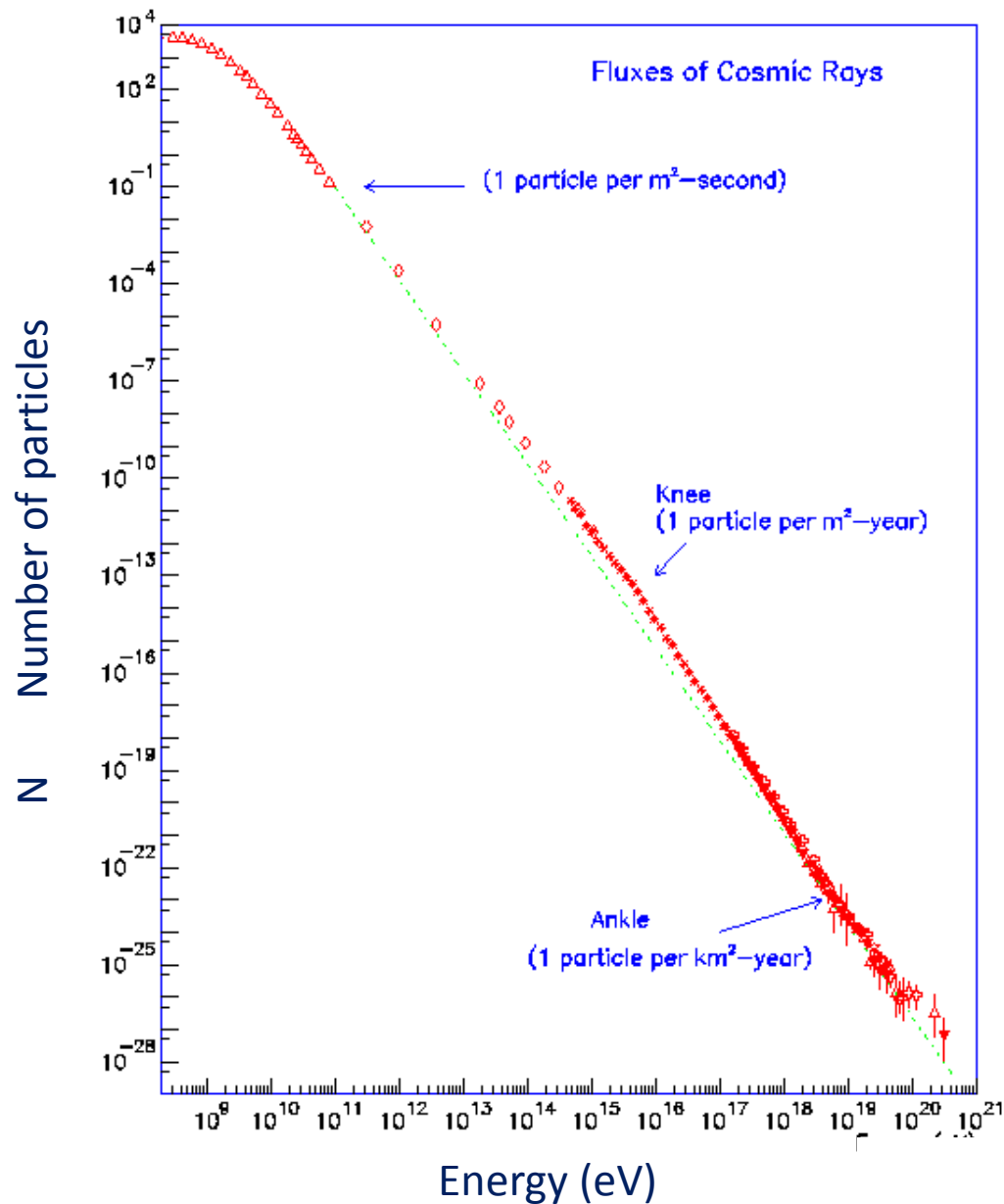


.... scattering $\longrightarrow$ isotropy

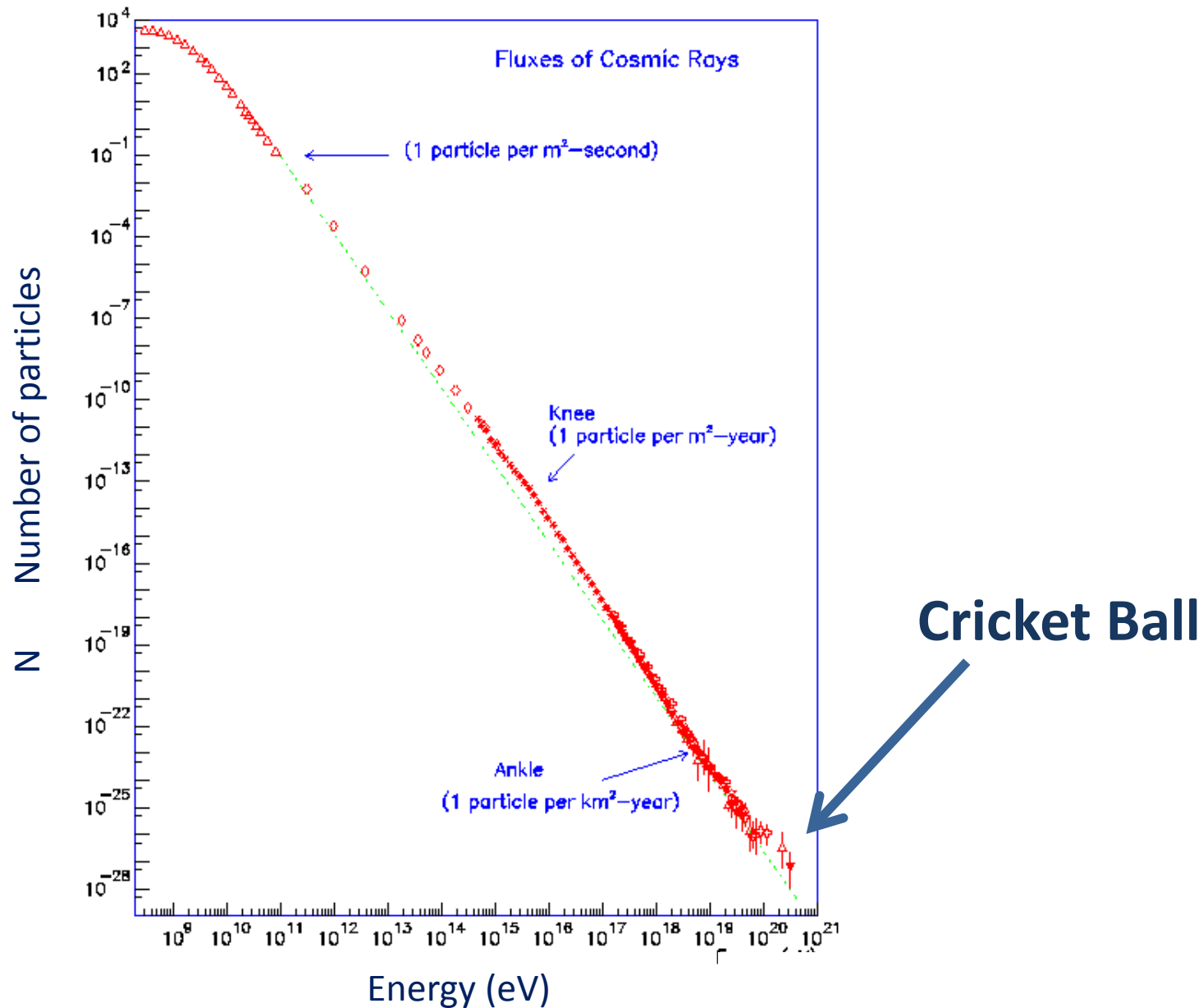
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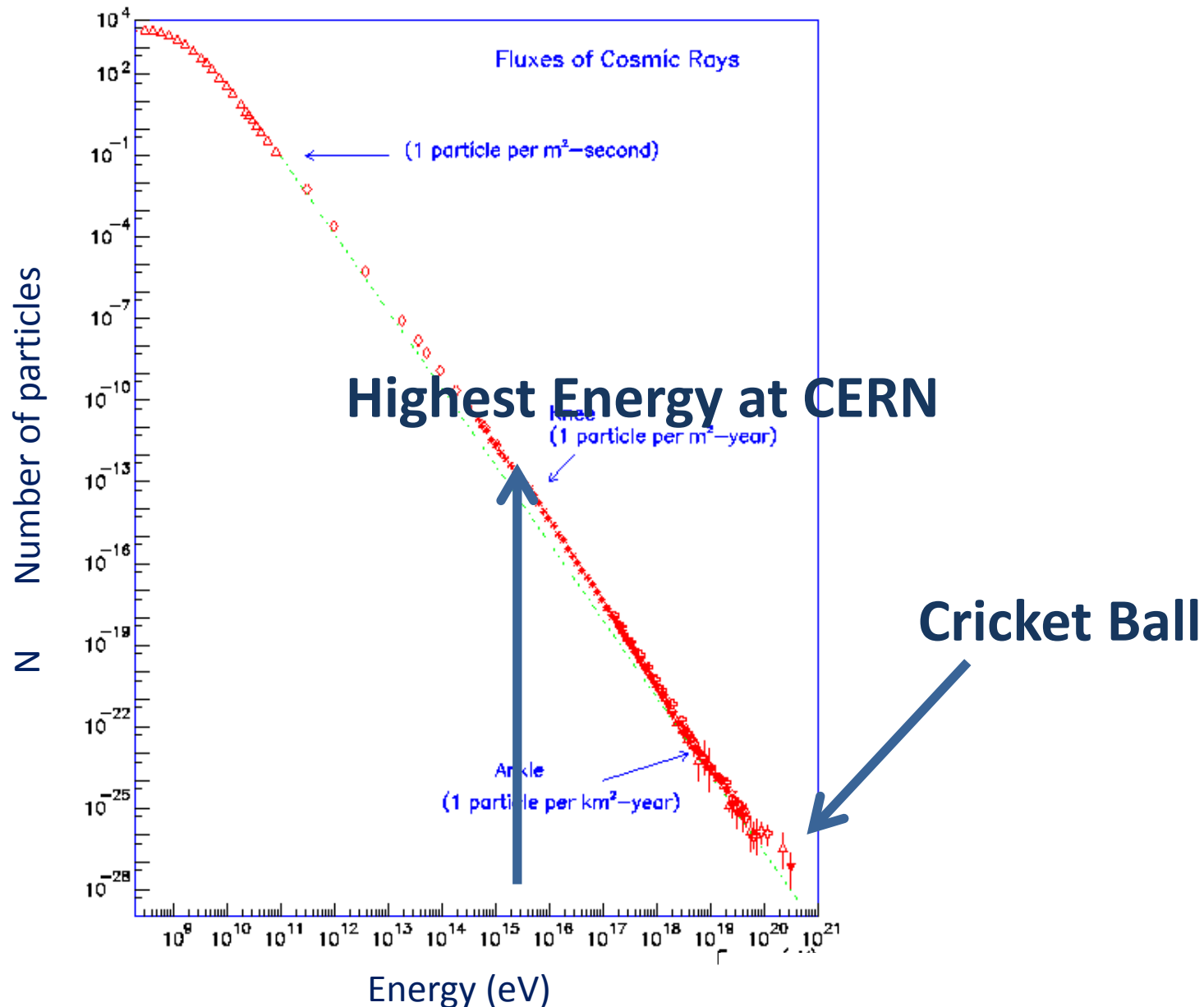
Cosmic ray spectrum



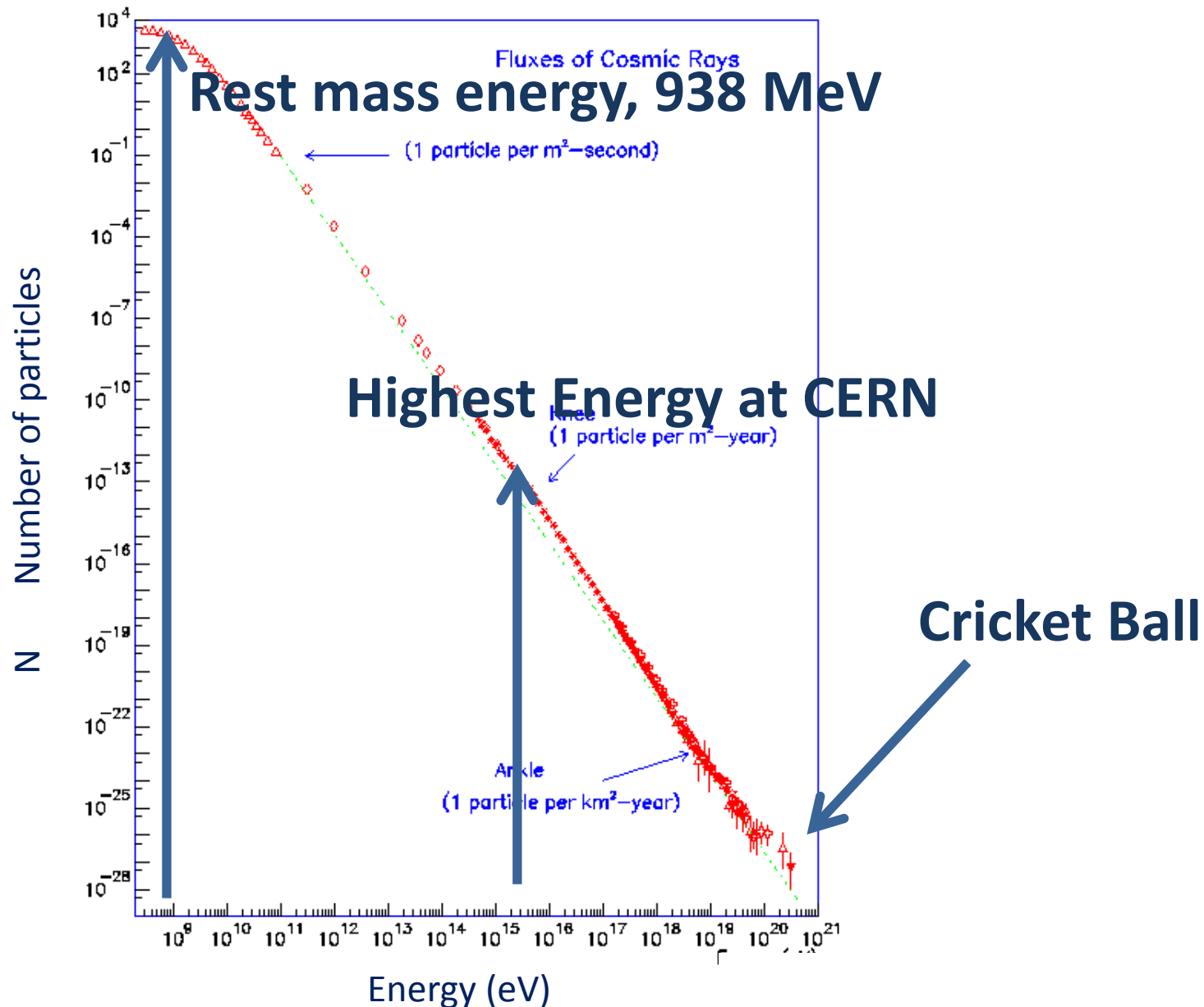
Cosmic-ray spectrum



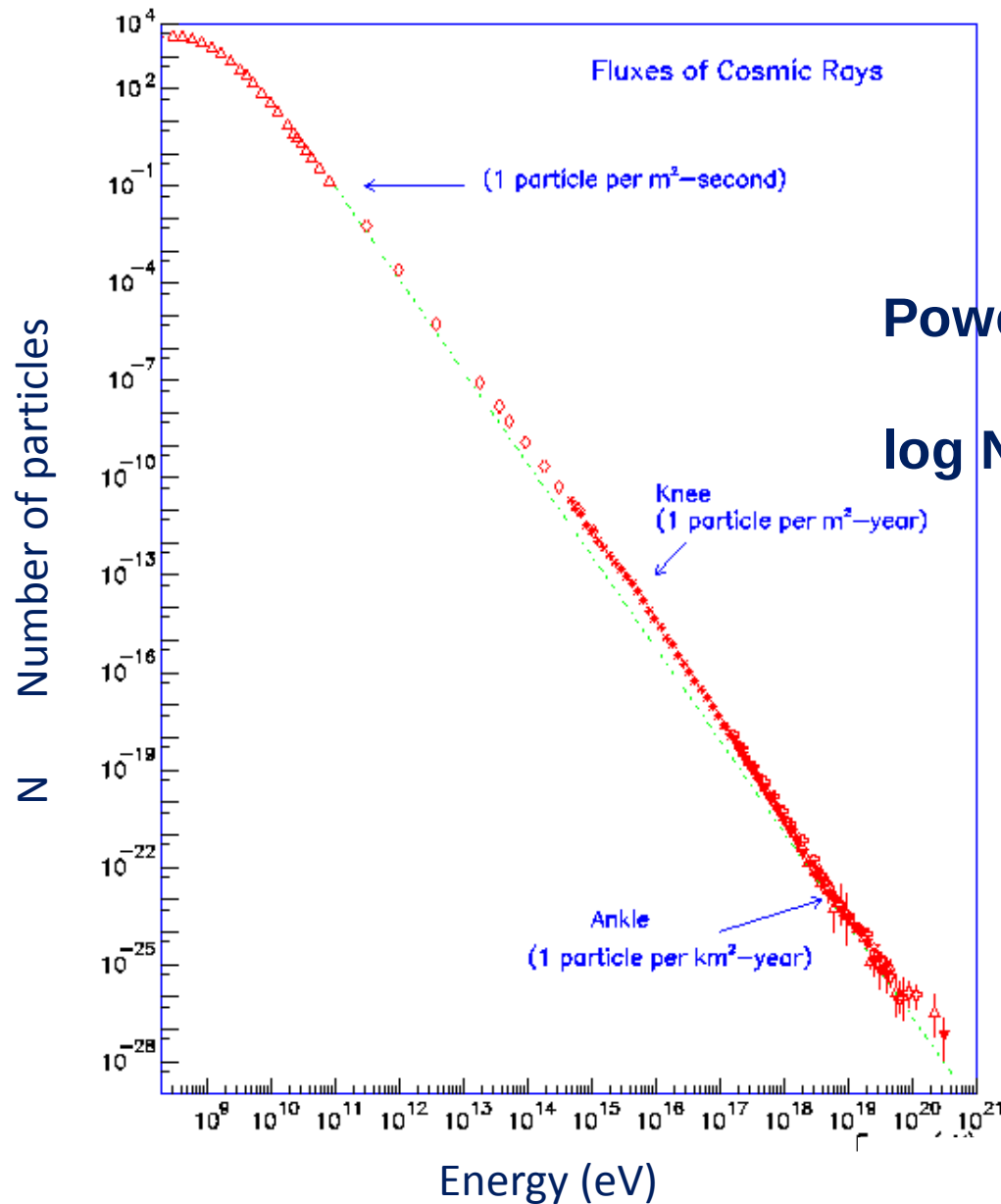
Cosmic-ray spectrum



Cosmic-ray spectrum



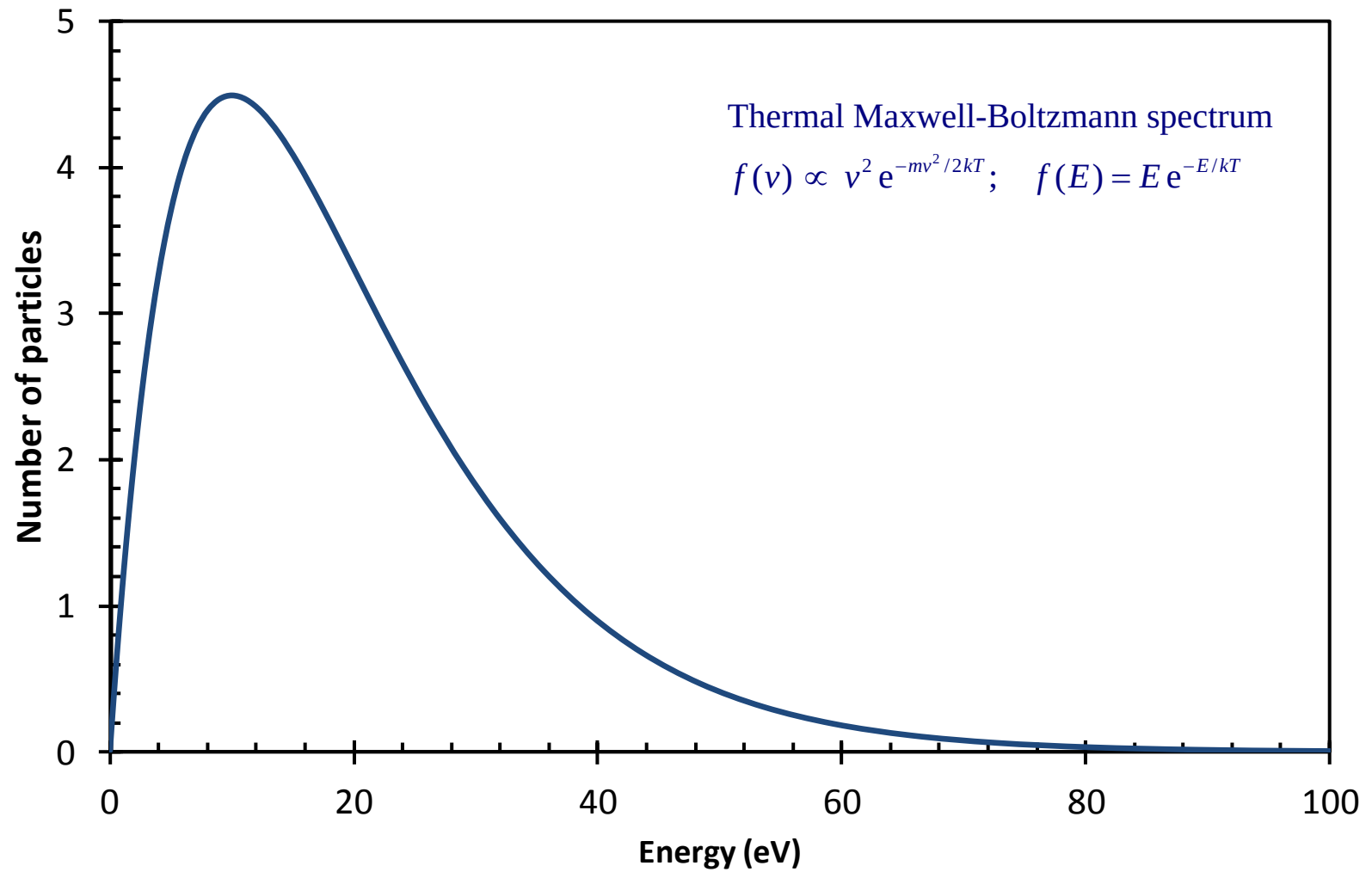
Cosmic ray spectrum



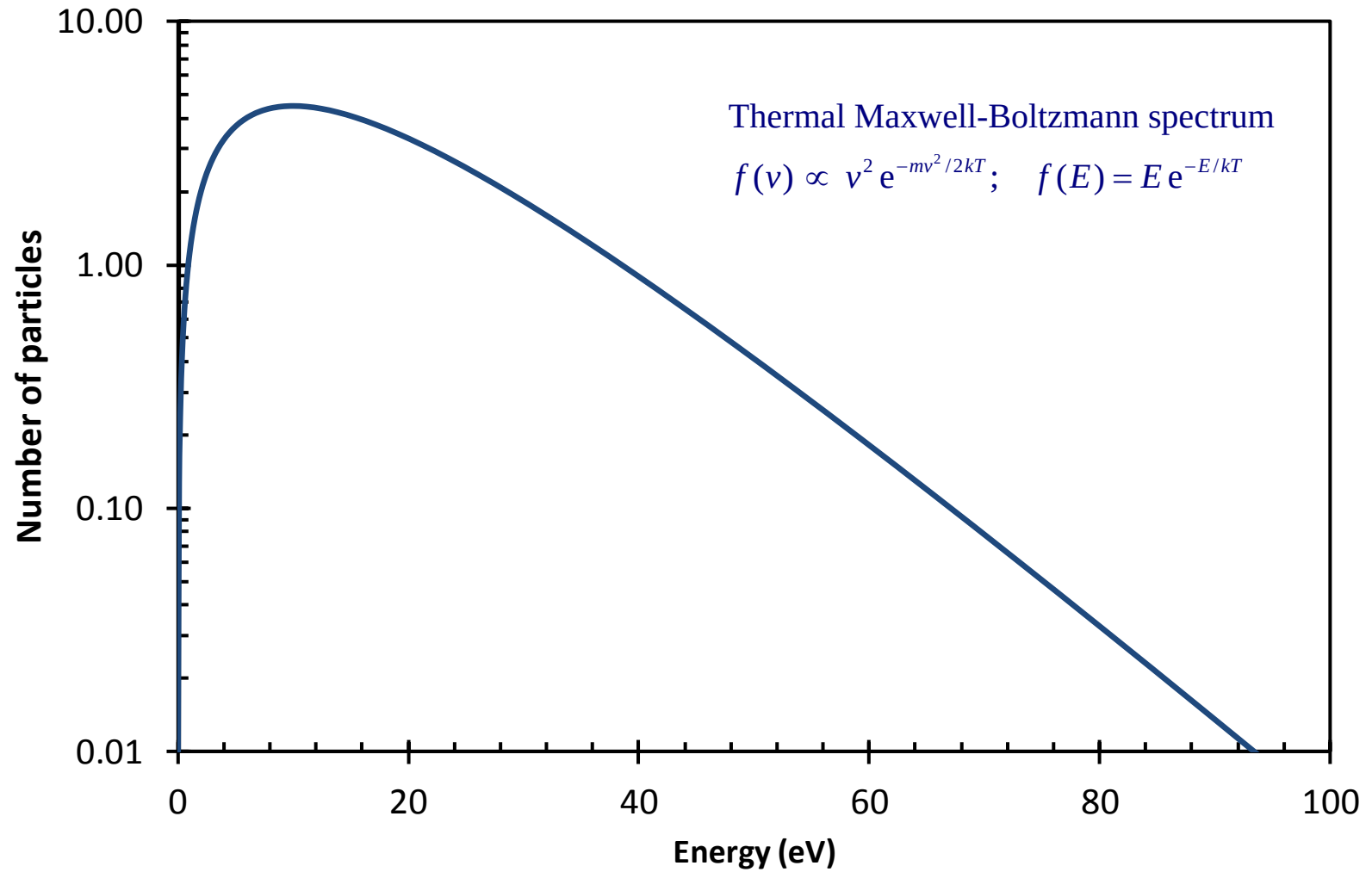
Power law: $N = a E^{-2.5}$

$\log N = -2.5 \log E + \log a$

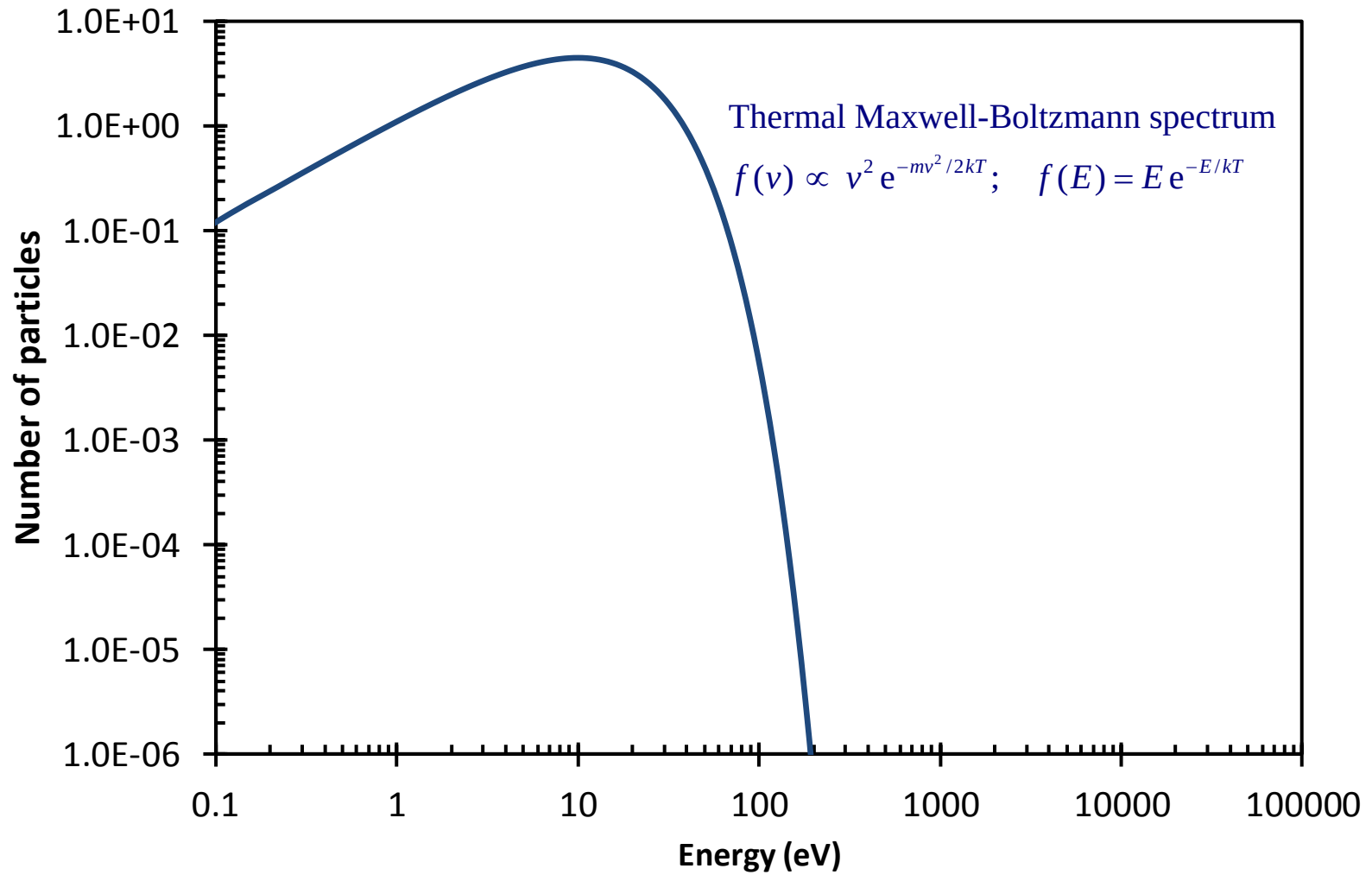
Cosmic-ray spectrum



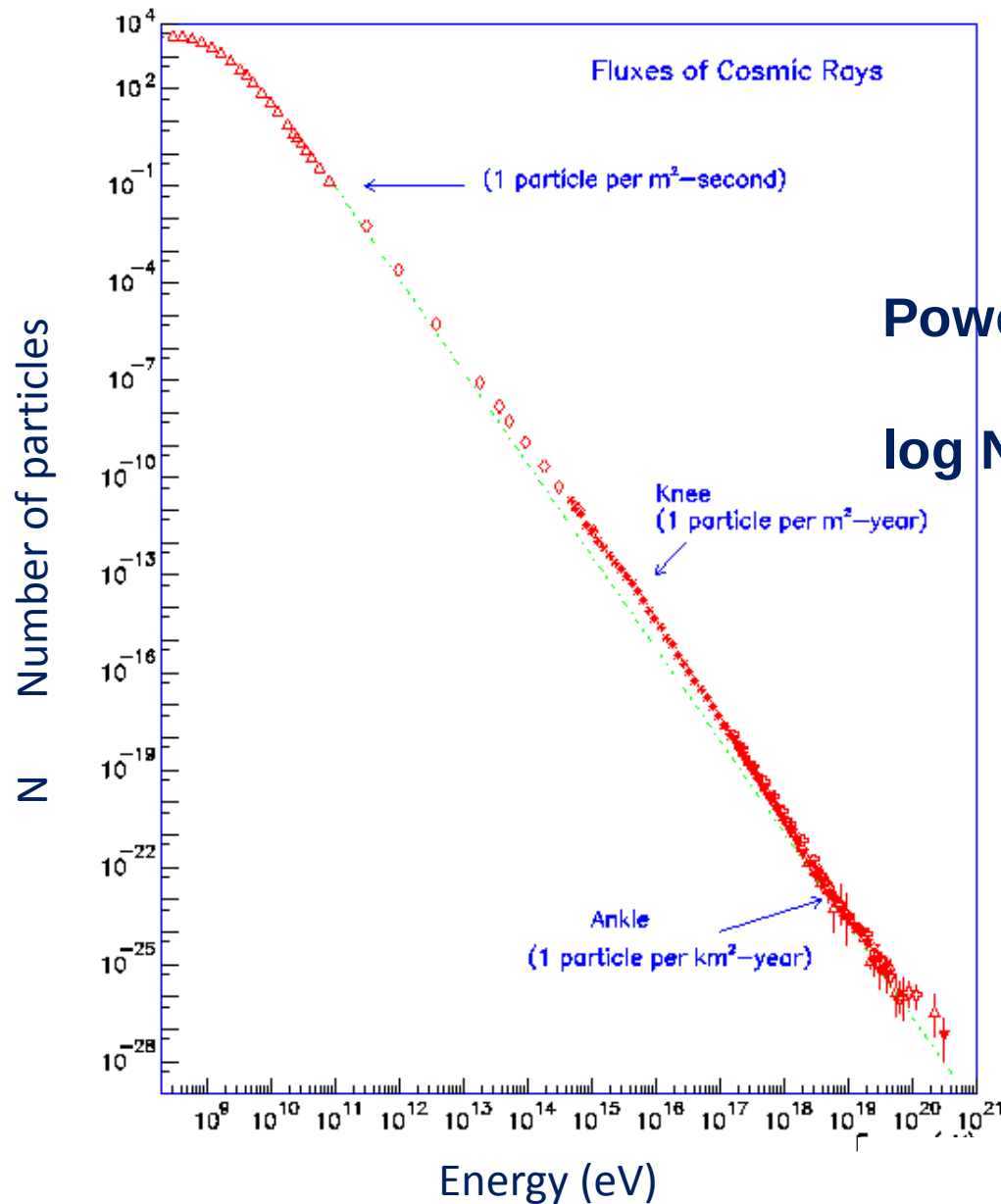
Cosmic-ray spectrum



Cosmic-ray spectrum



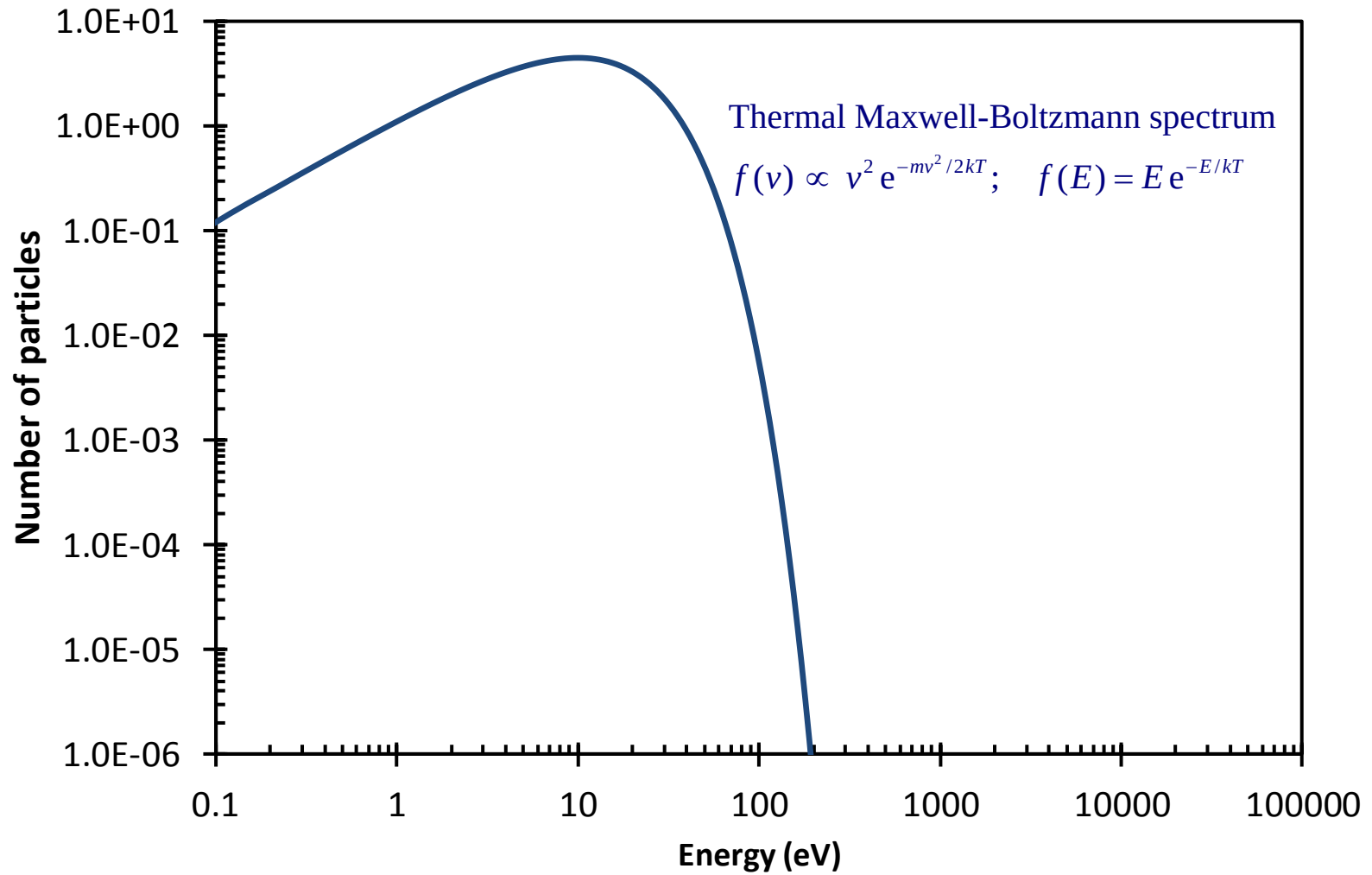
Cosmic ray spectrum



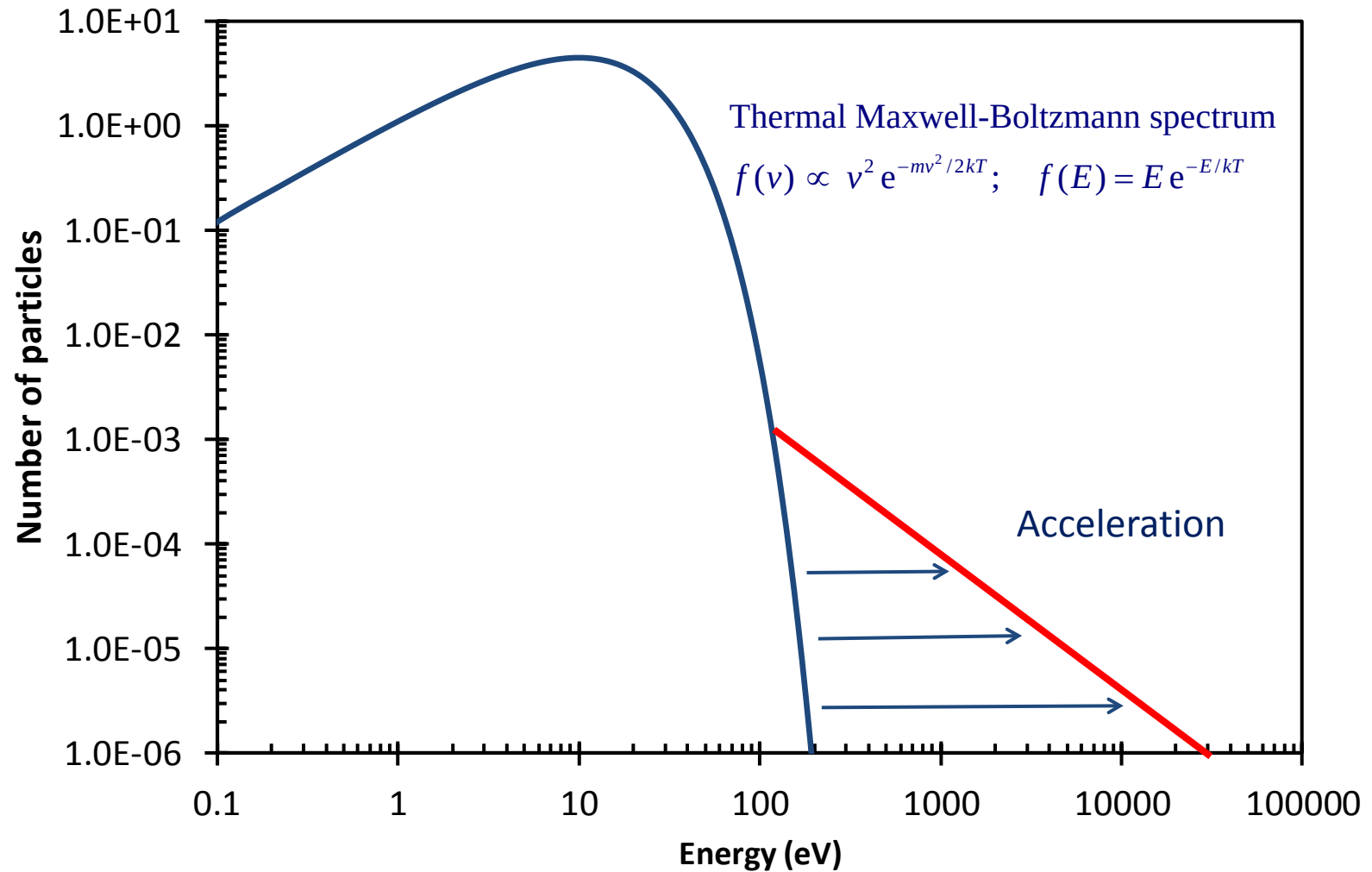
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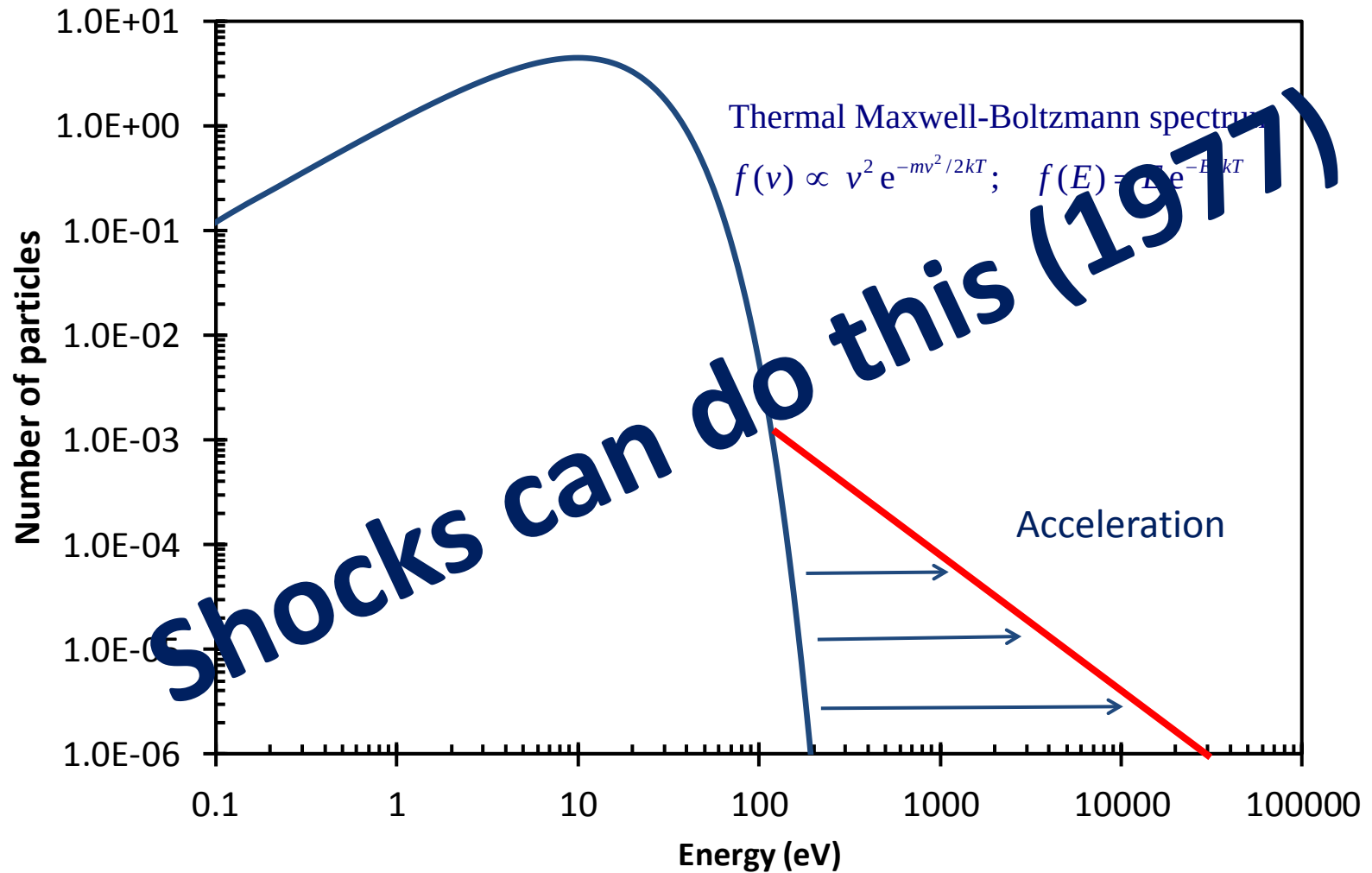
Cosmic-ray spectrum



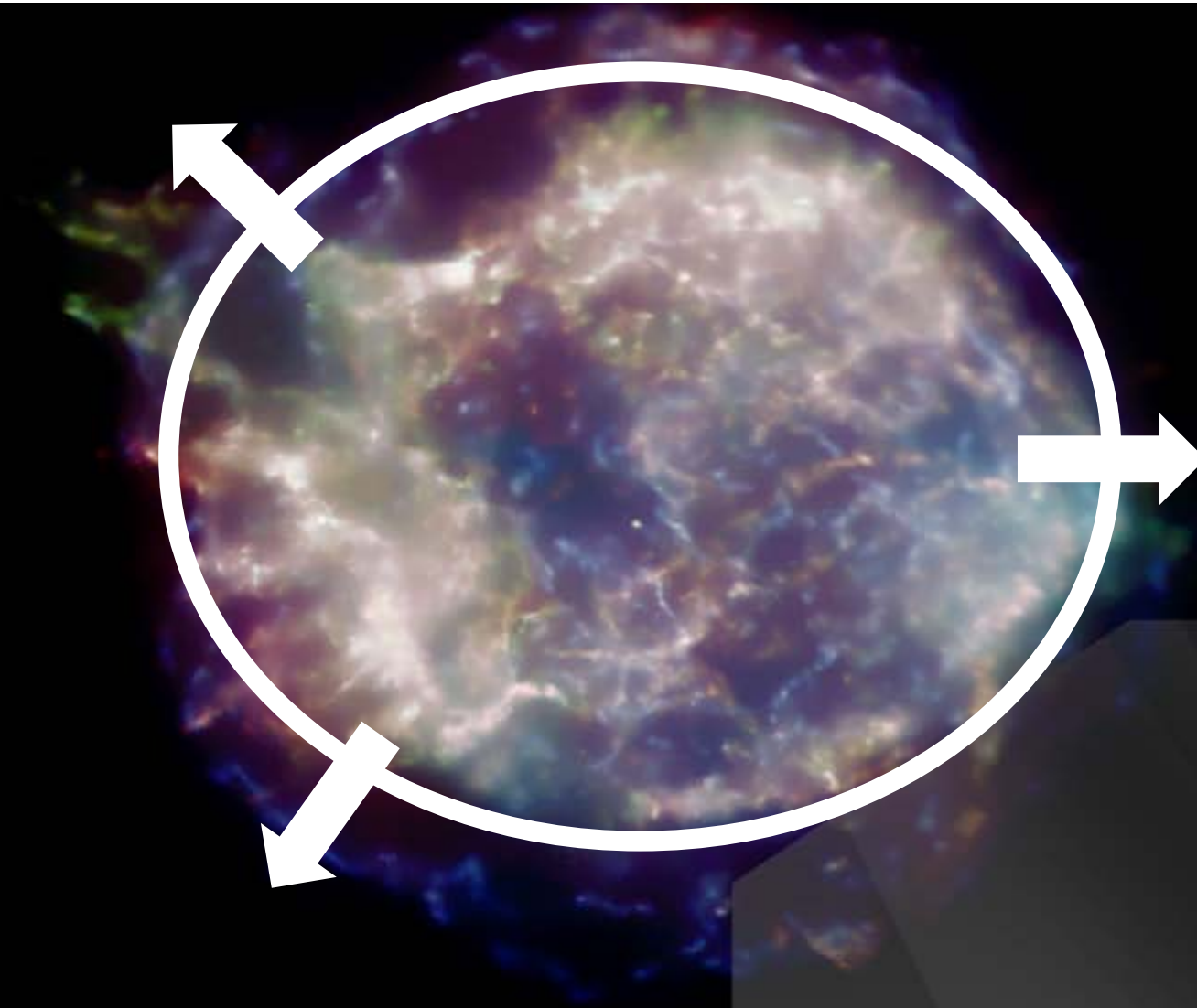
Cosmic-ray spectrum



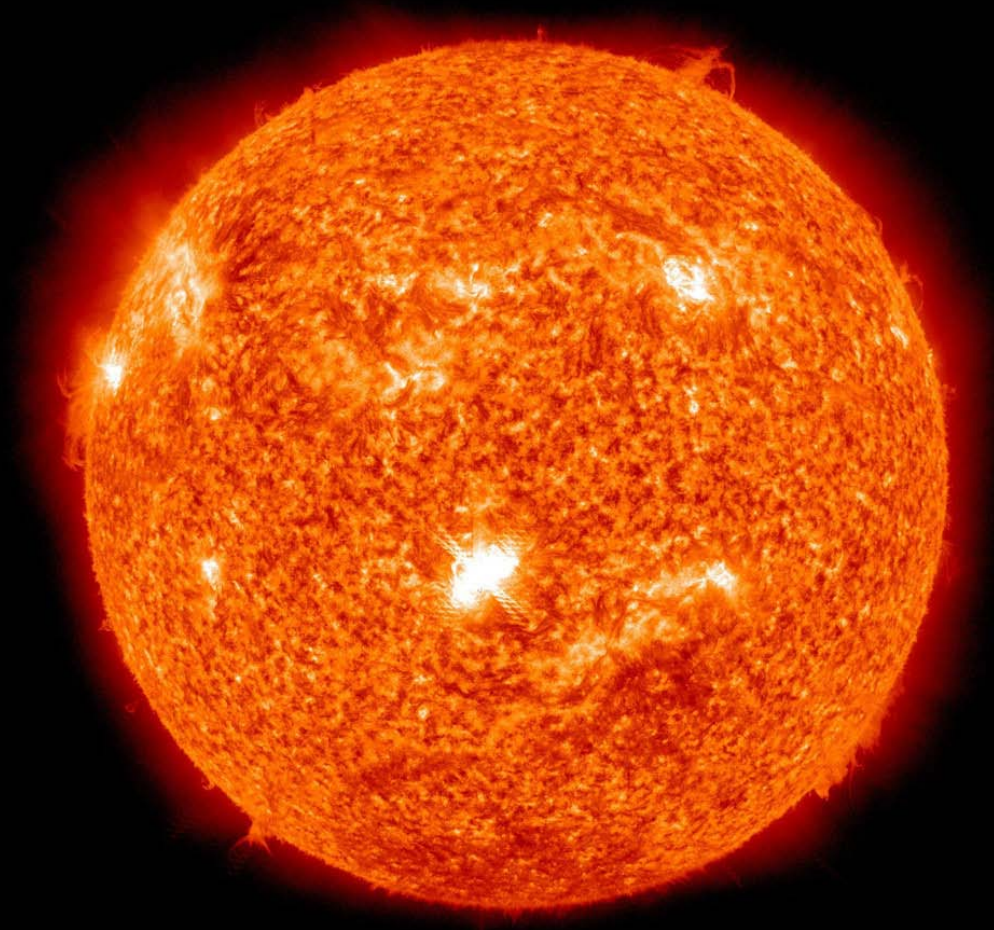
Cosmic-ray spectrum



Cassiopeia A in X-rays



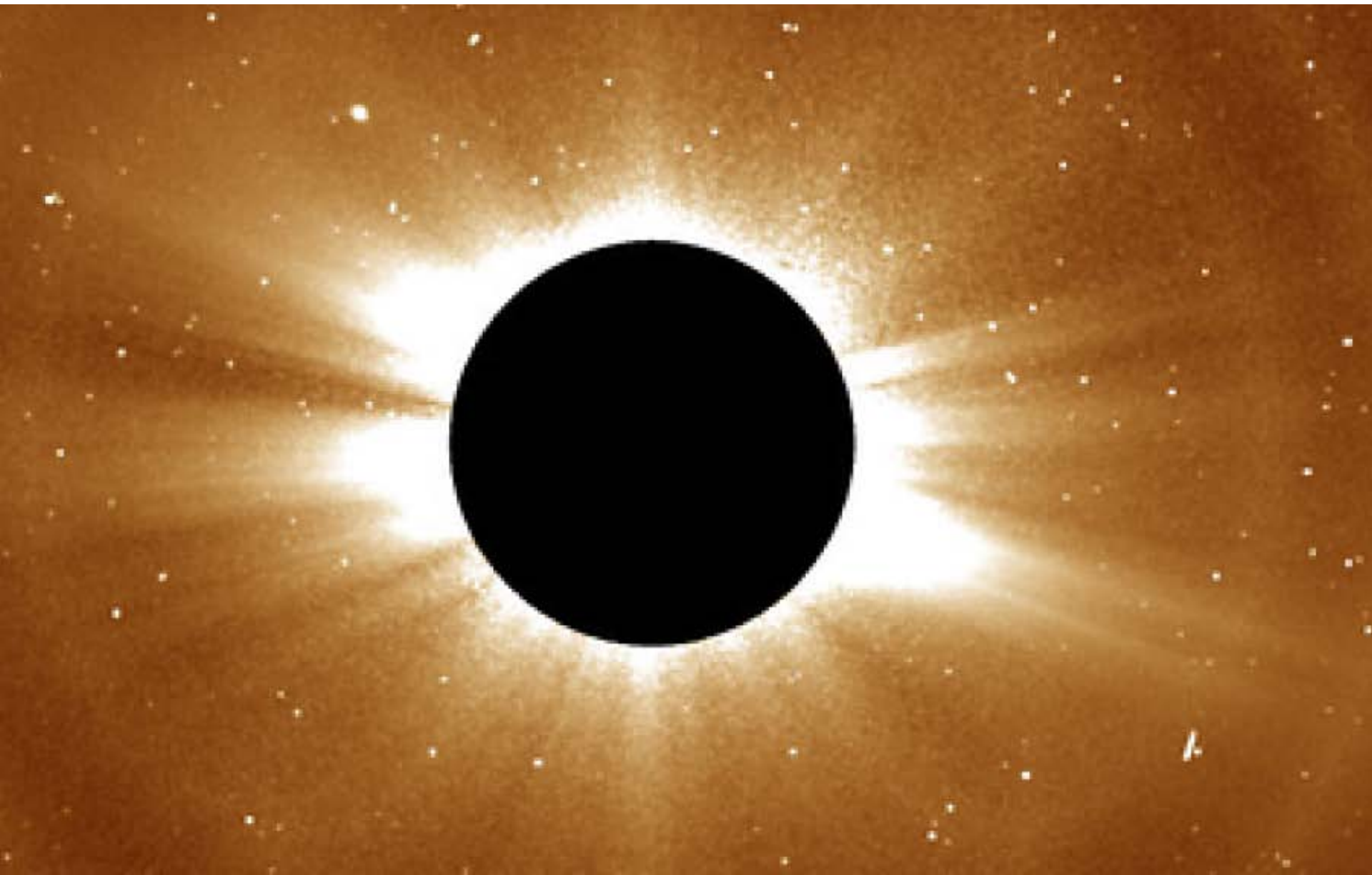
Solar Atmosphere



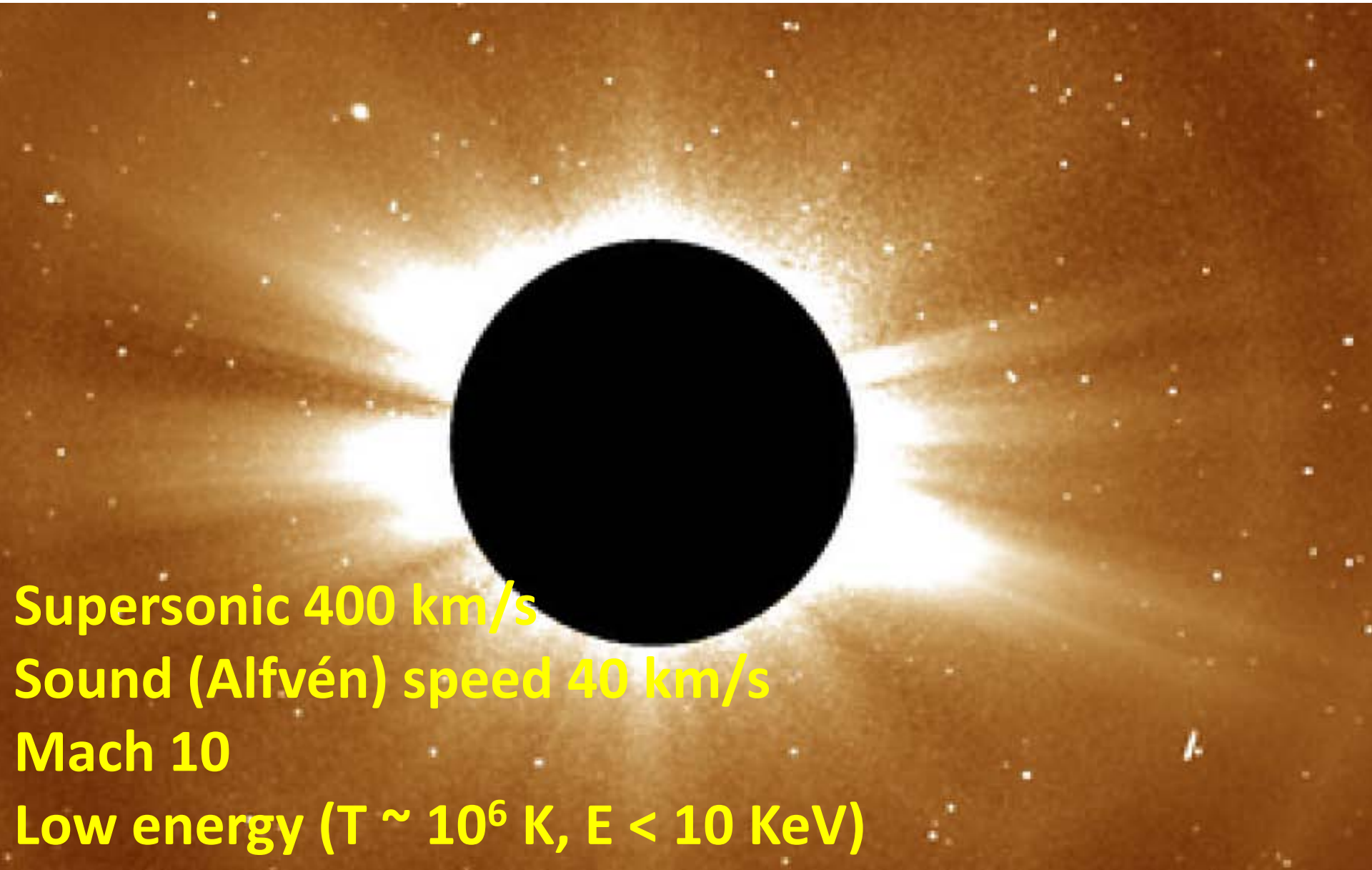
SDO/AIA 304 2011-02-13 17:36:45 UT

NASA

Solar Wind

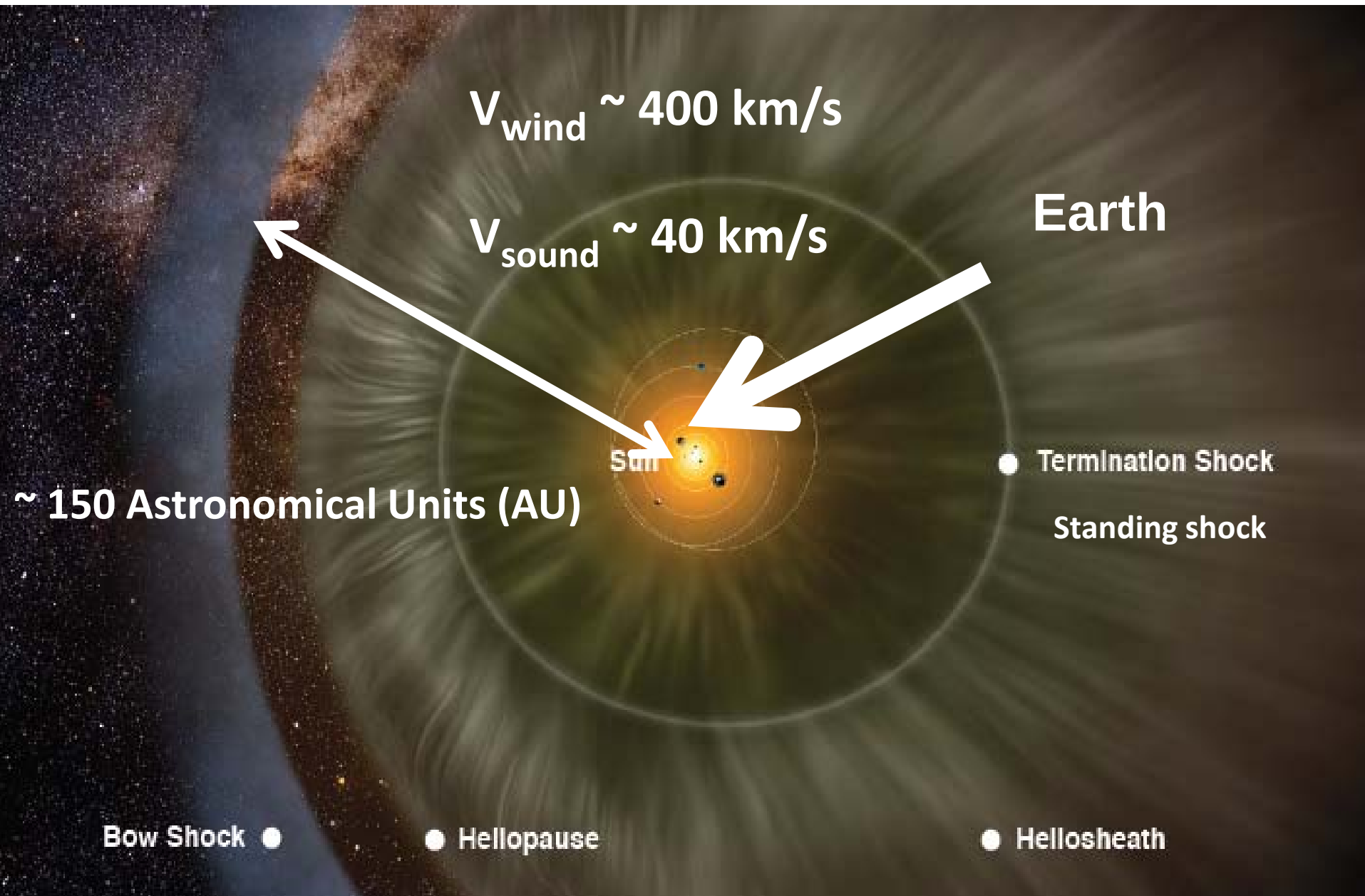


Solar Wind

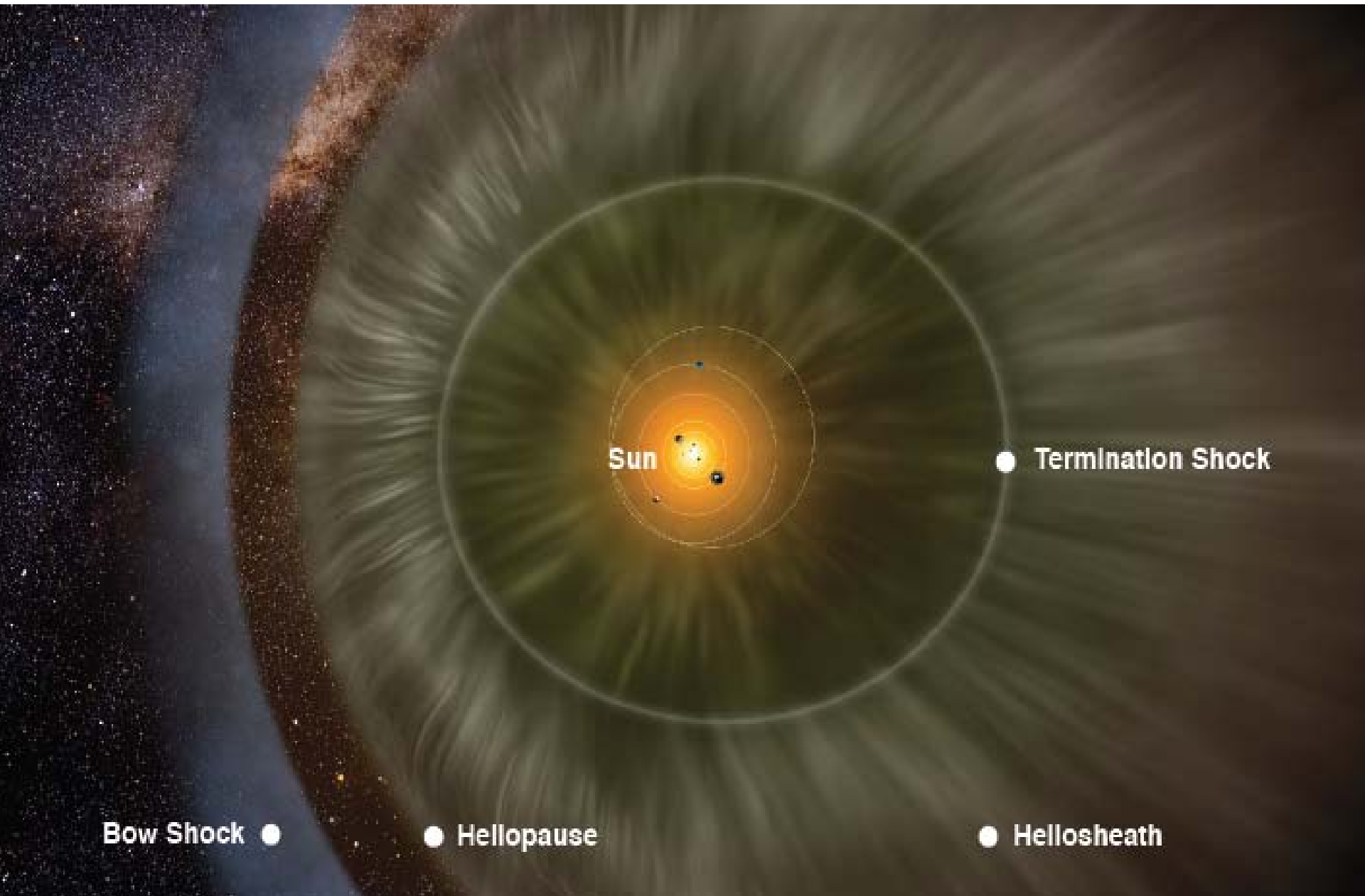


Supersonic 400 km/s
Sound (Alfvén) speed 40 km/s
Mach 10
Low energy ($T \sim 10^6$ K, $E < 10$ KeV)

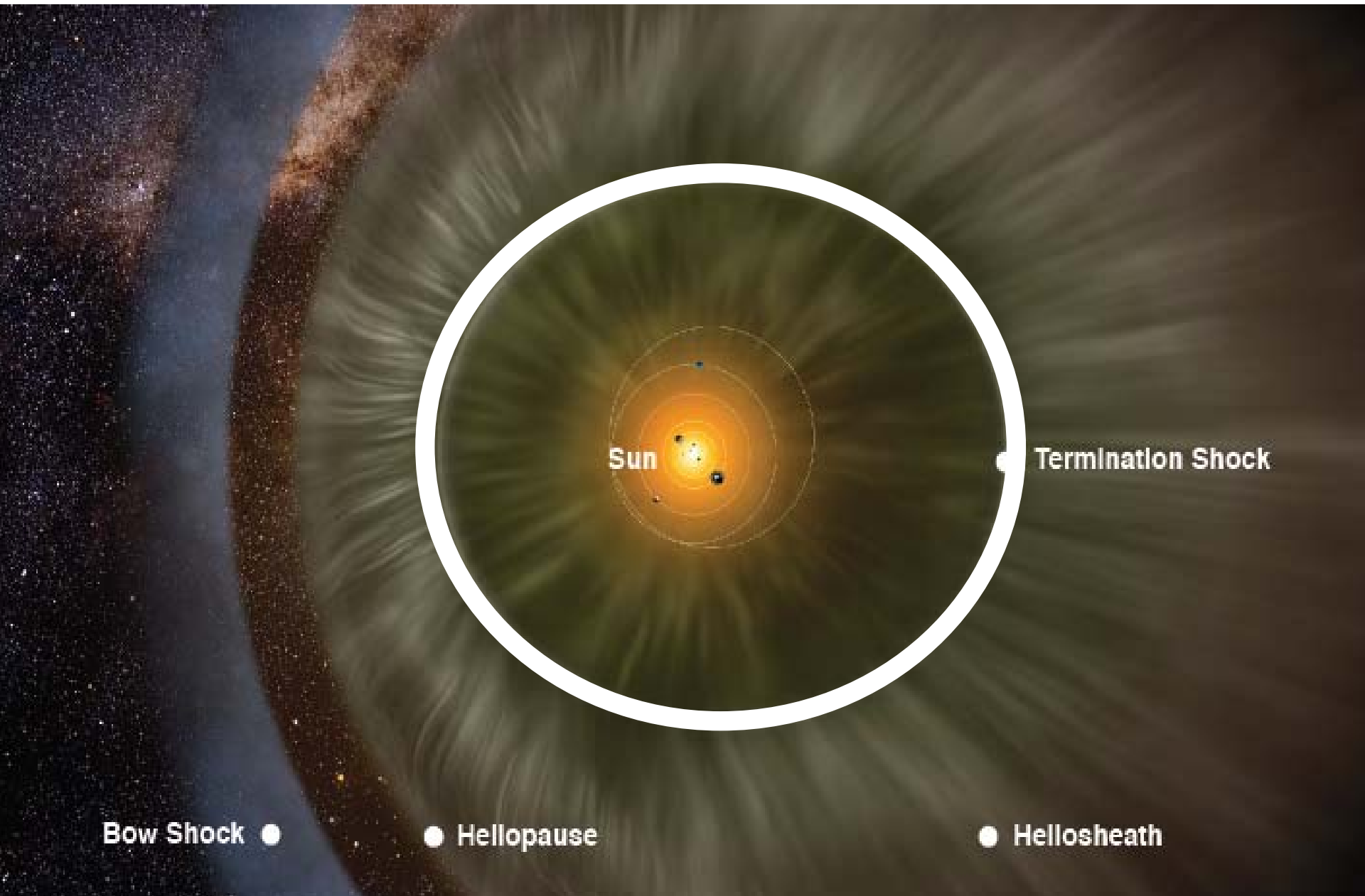
The Heliosphere



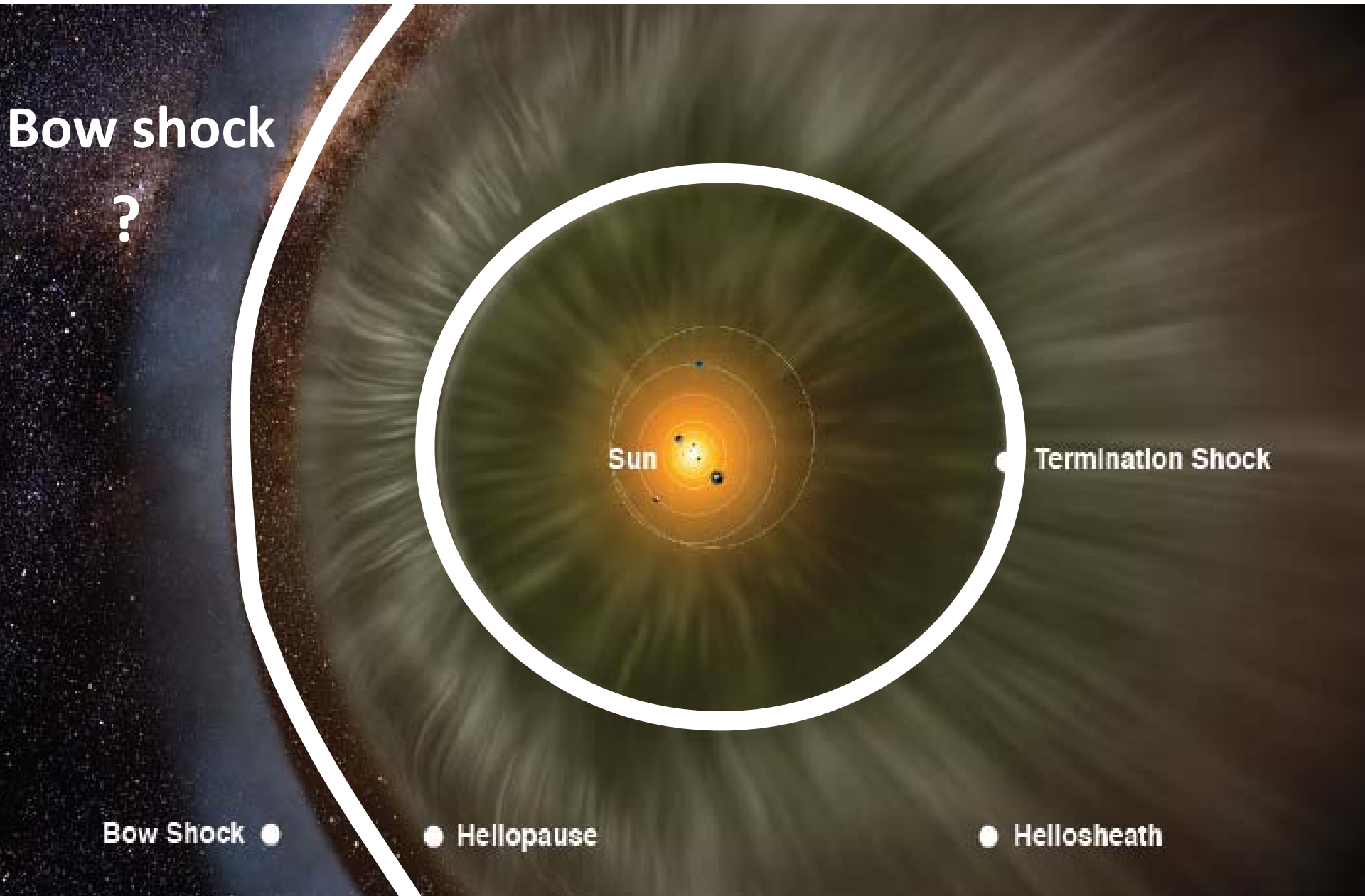
The Heliosphere



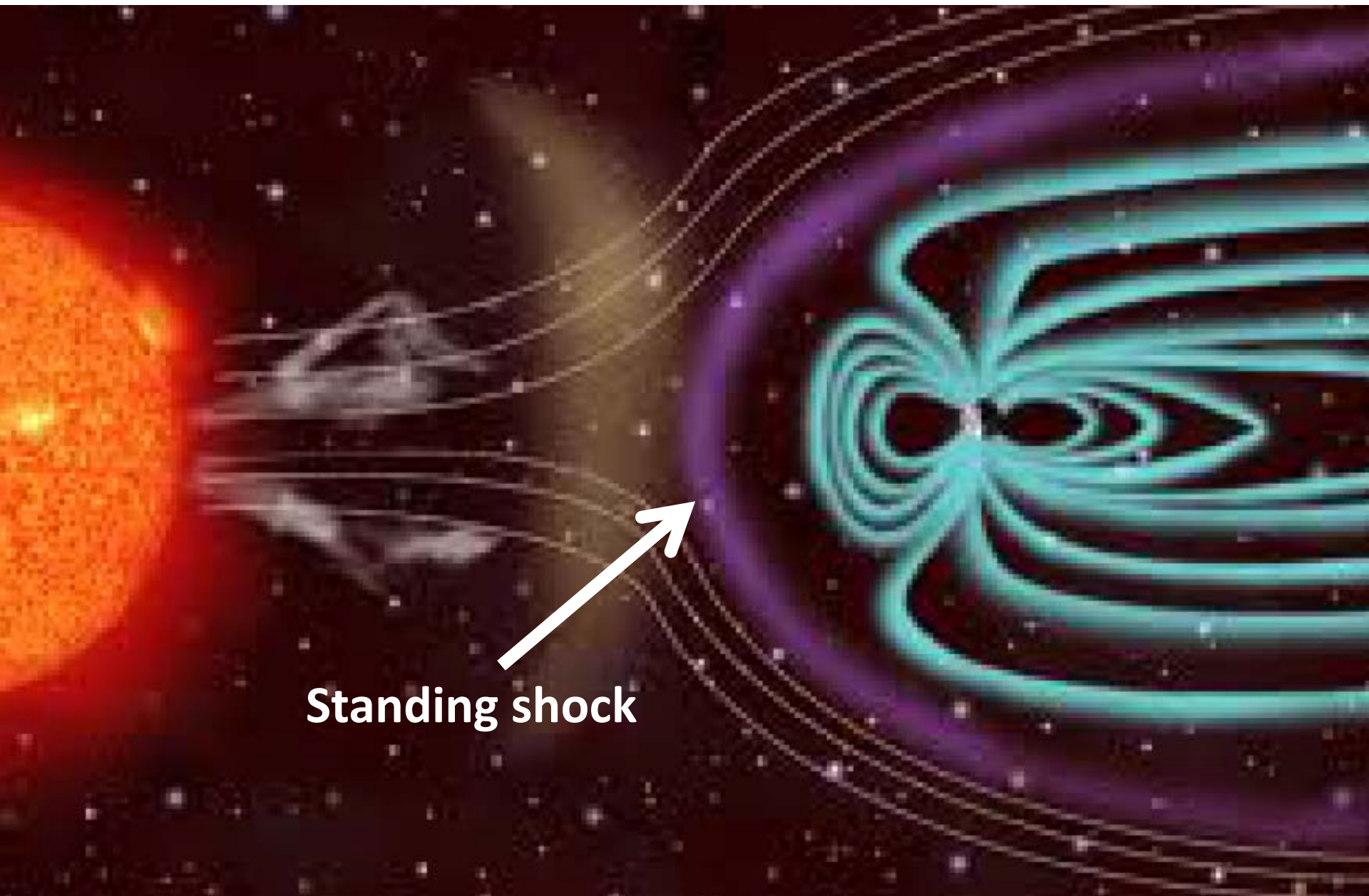
The Heliosphere



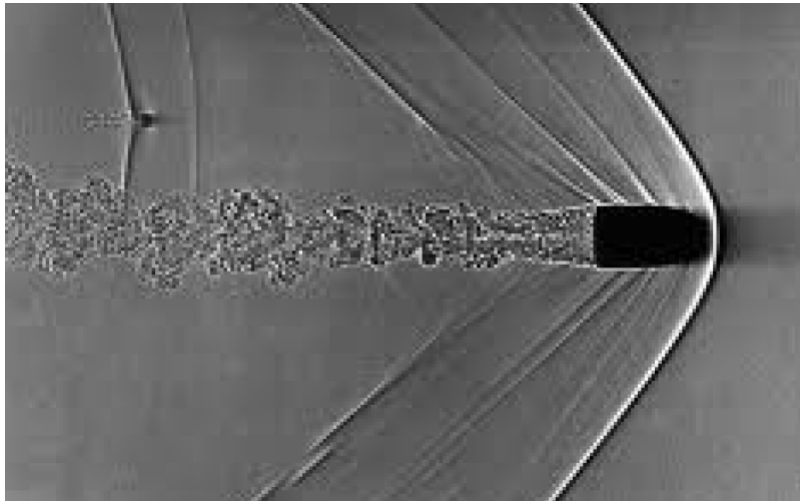
The Heliosphere



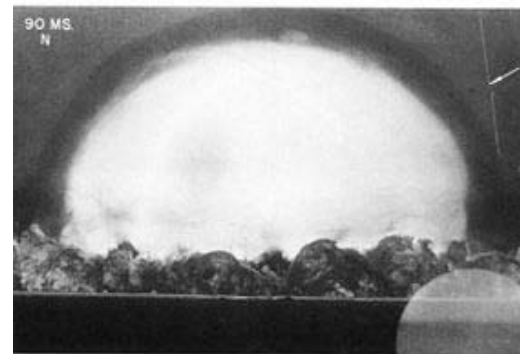
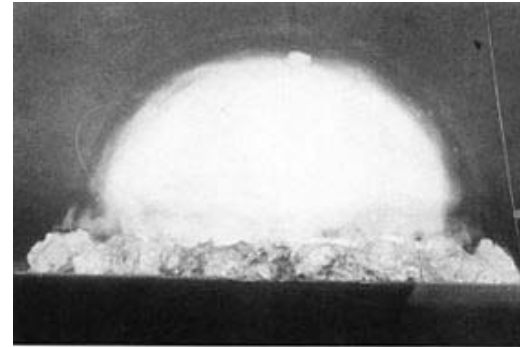
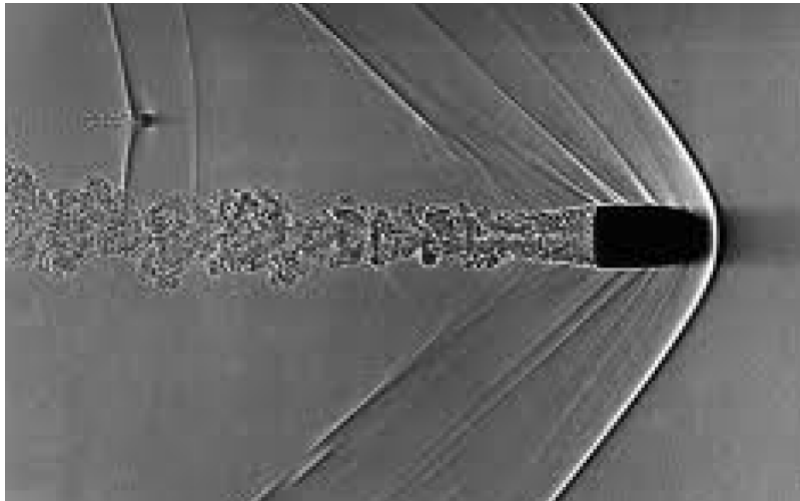
Geomagnetic field



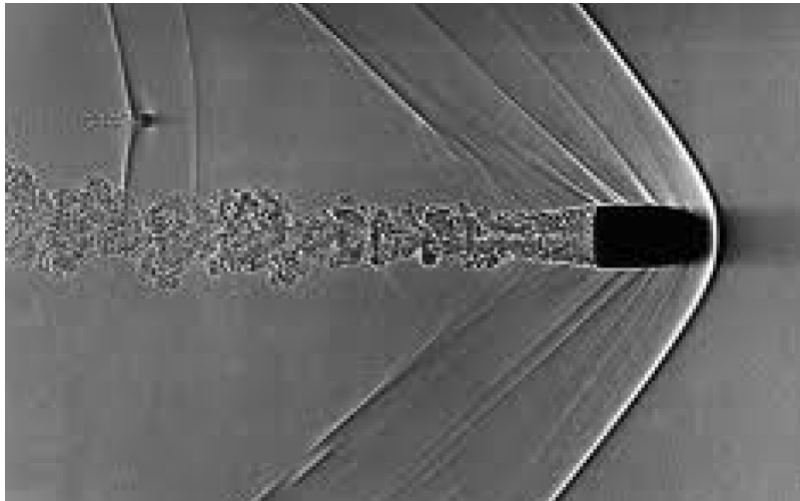
Moving shocks



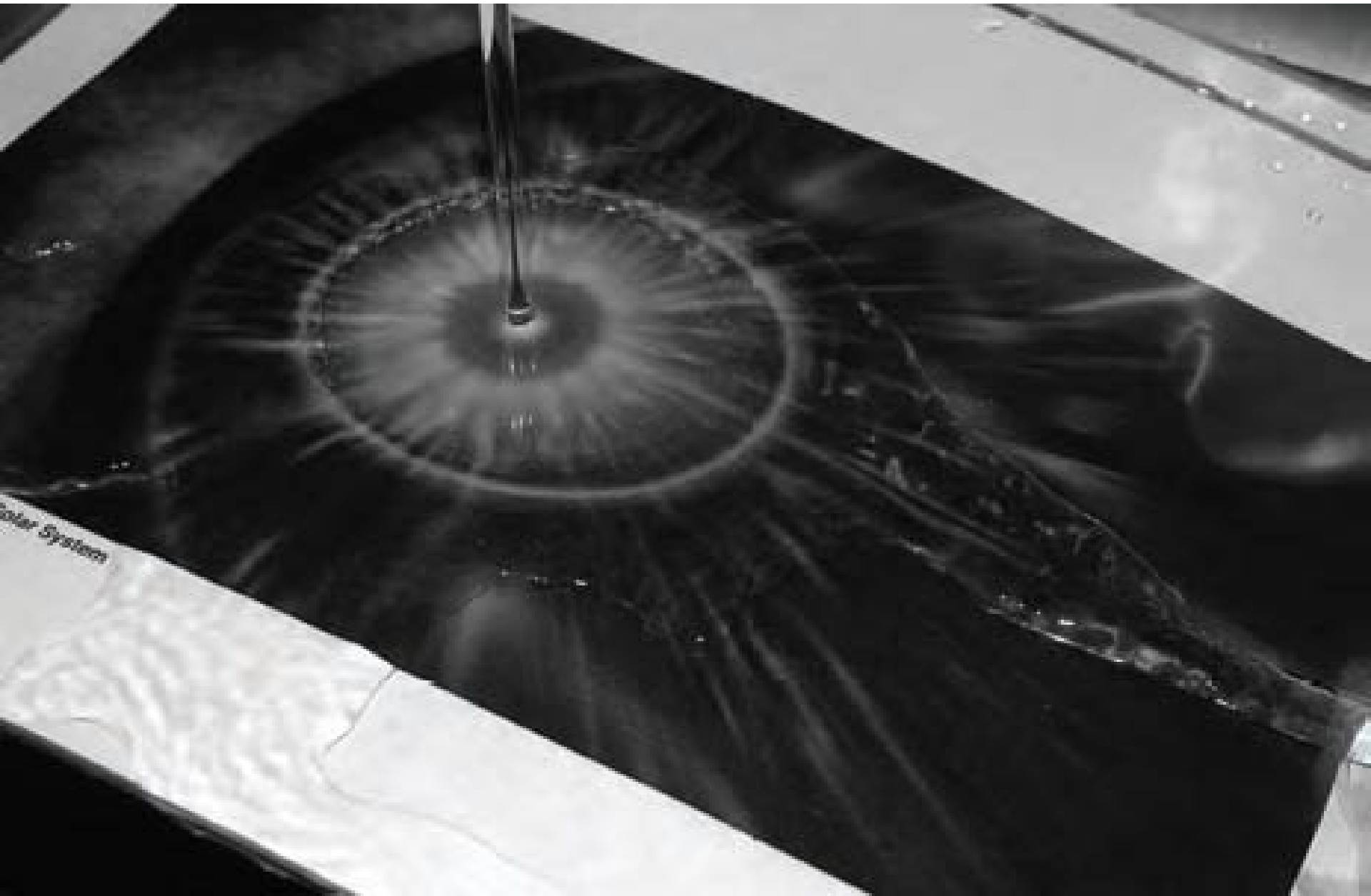
Moving shocks



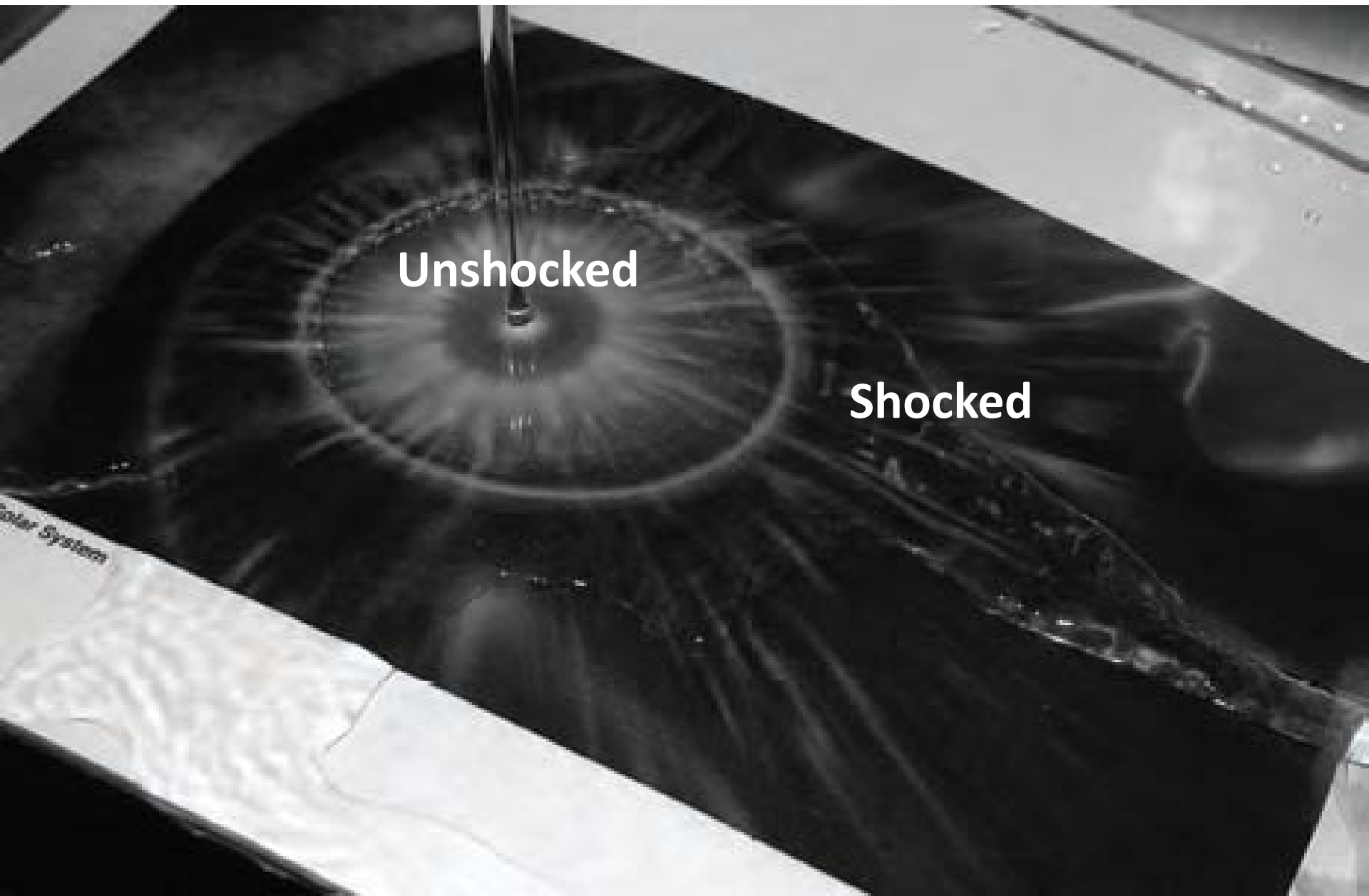
Moving shocks



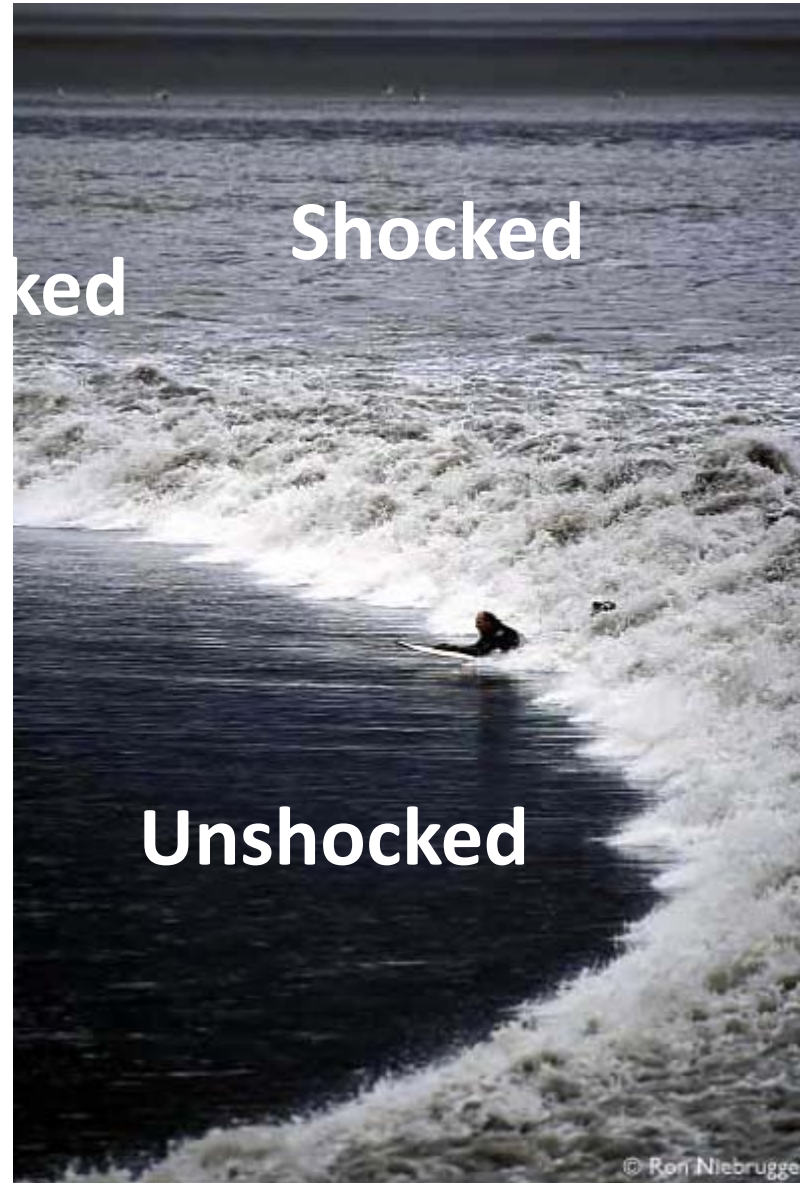
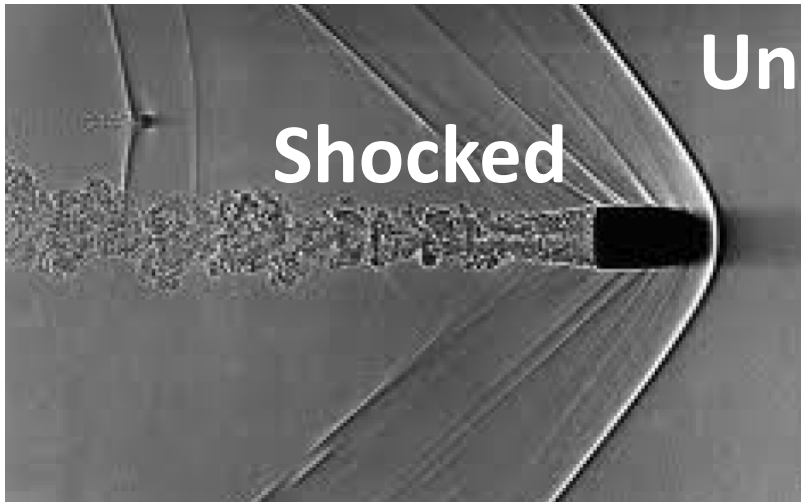
The kitchen sink (standing shock)



Stationary shock; kitchen sink



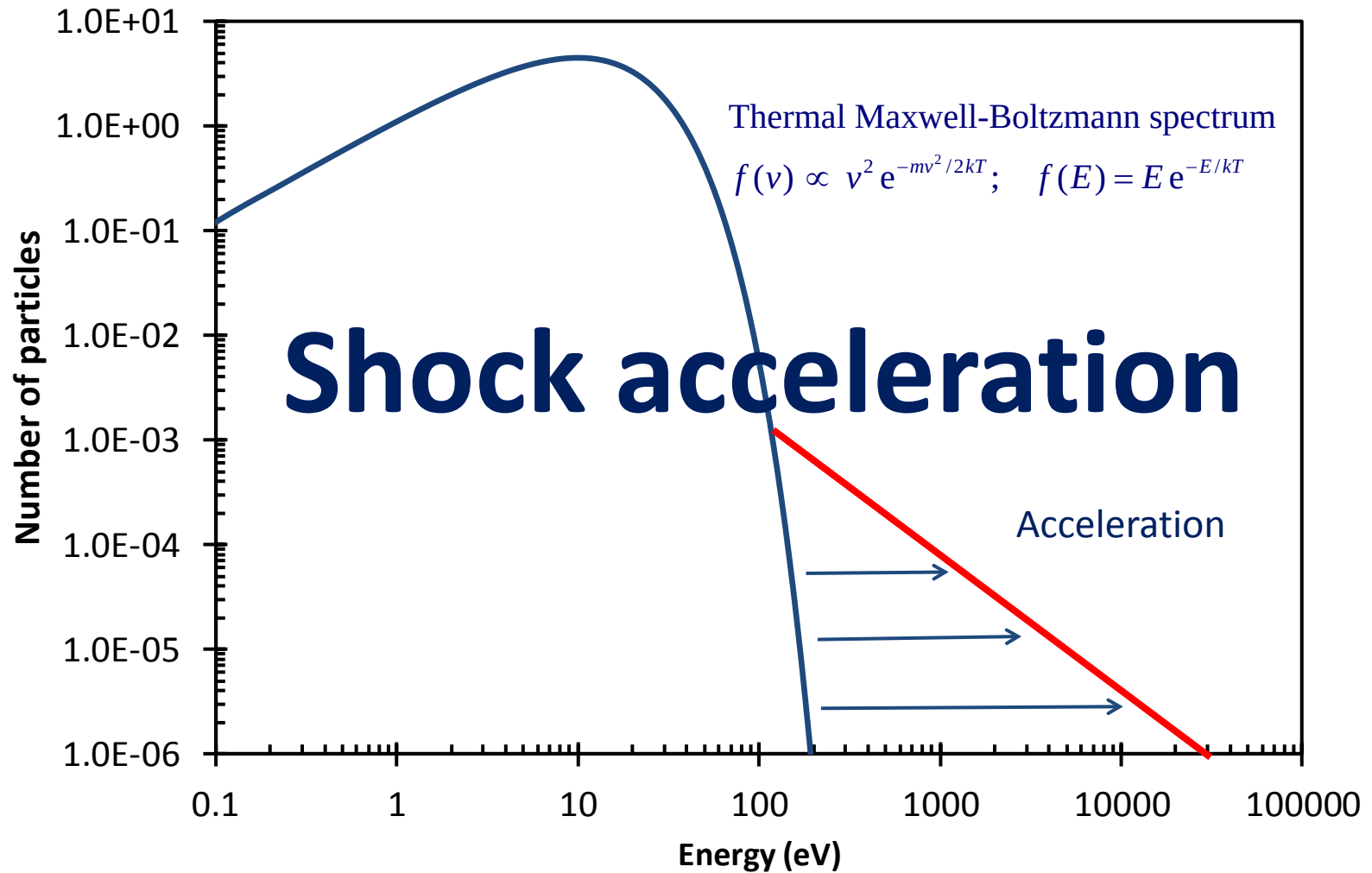
Moving shocks



Shock

- **A flow is supersonic (super Alfvénic) when it is faster than the particles can interact with each other**
- **This supersonic flow can only become subsonic through a shock transition**

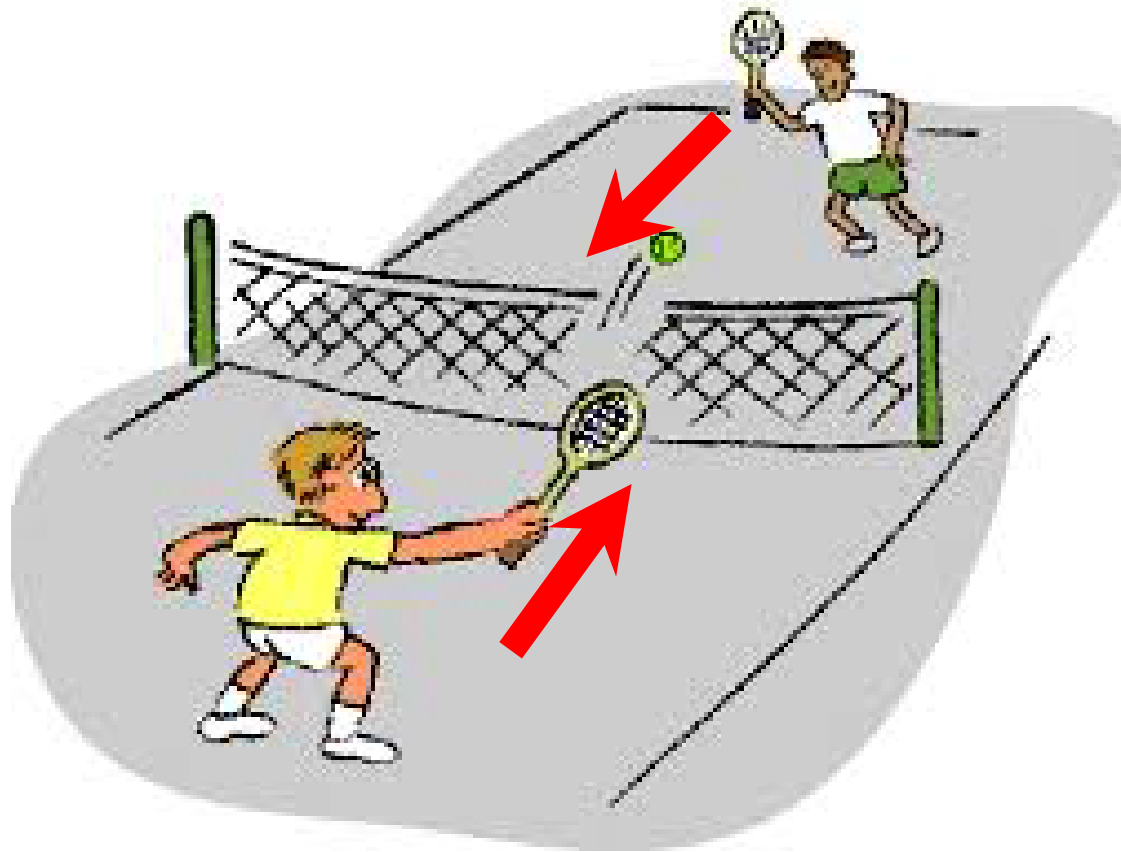
Cosmic-ray spectrum



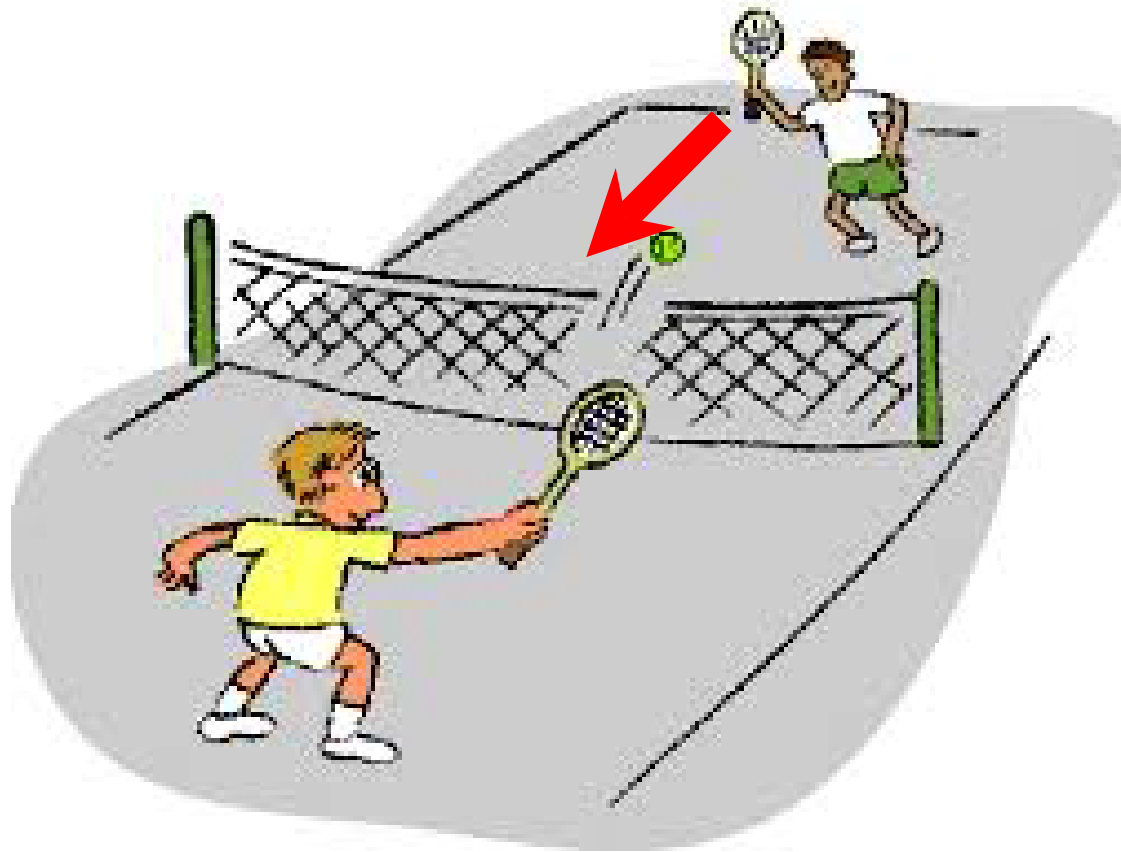
Acceleration



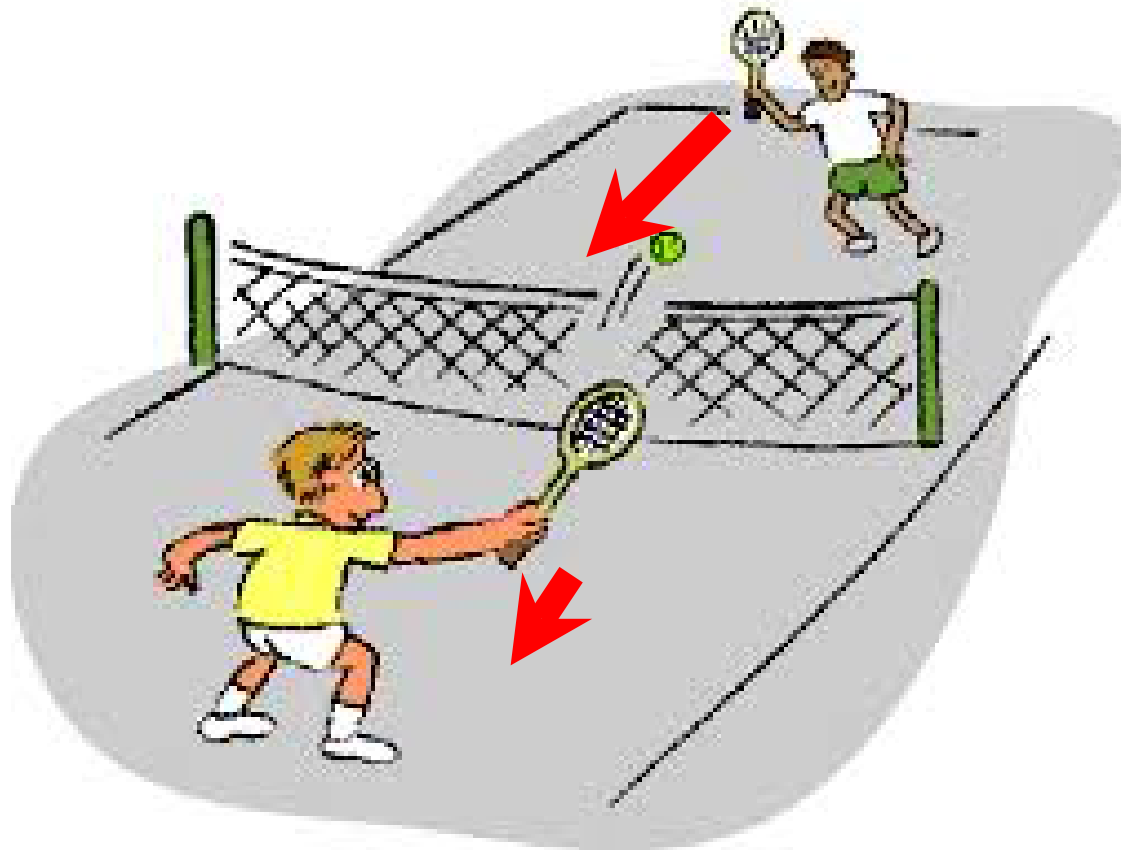
Acceleration



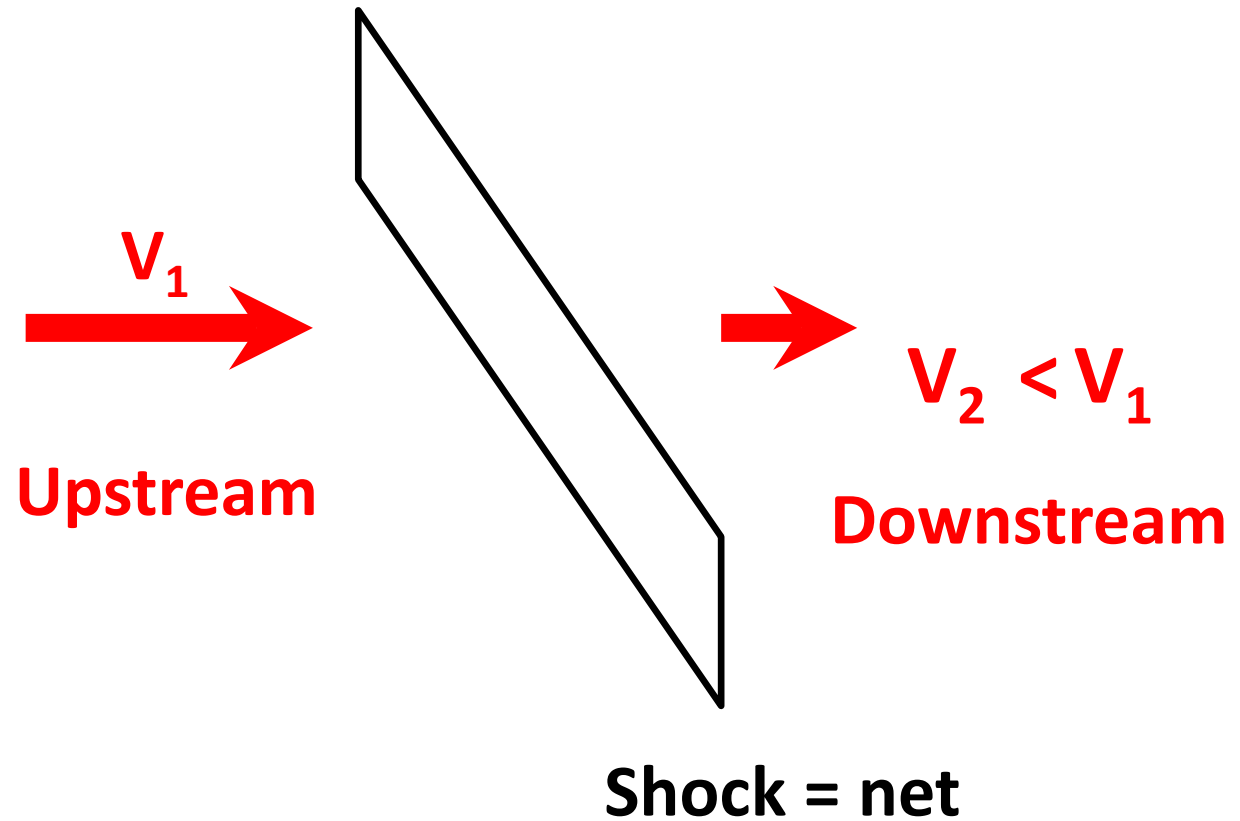
Acceleration



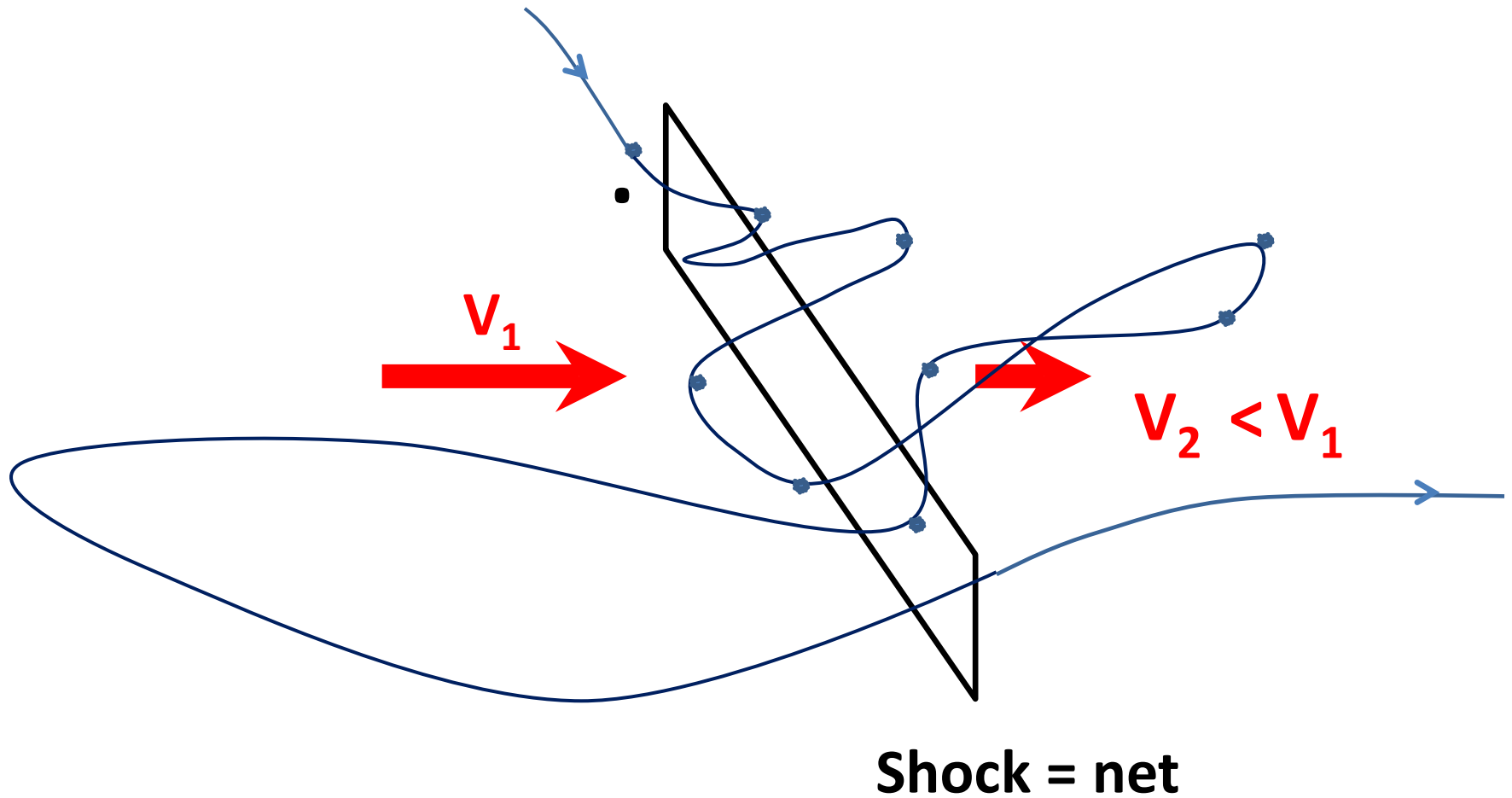
Acceleration



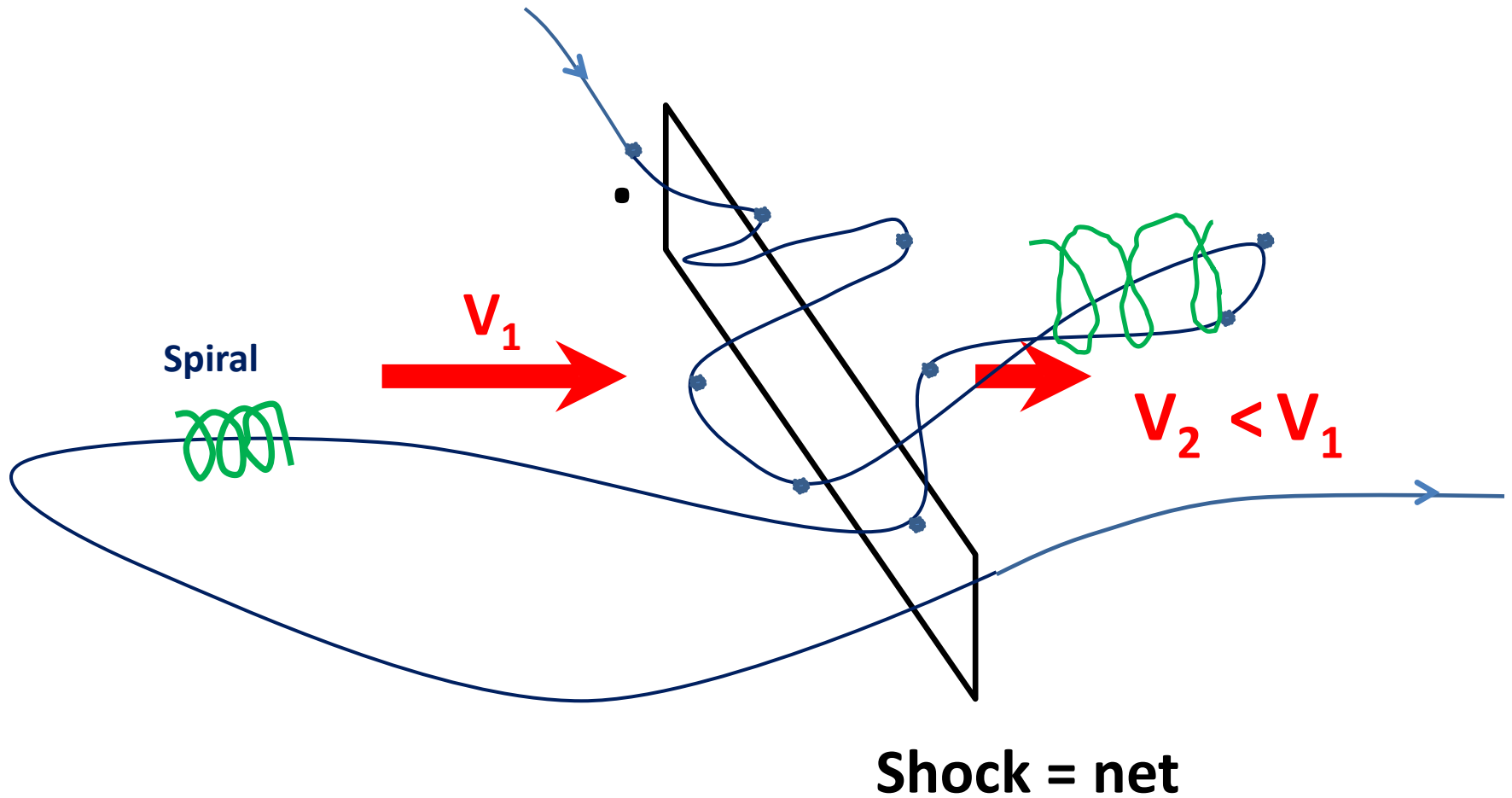
Acceleration



Acceleration



Acceleration



Cosmic-ray spectrum

Diffusive shock acceleration (1977)

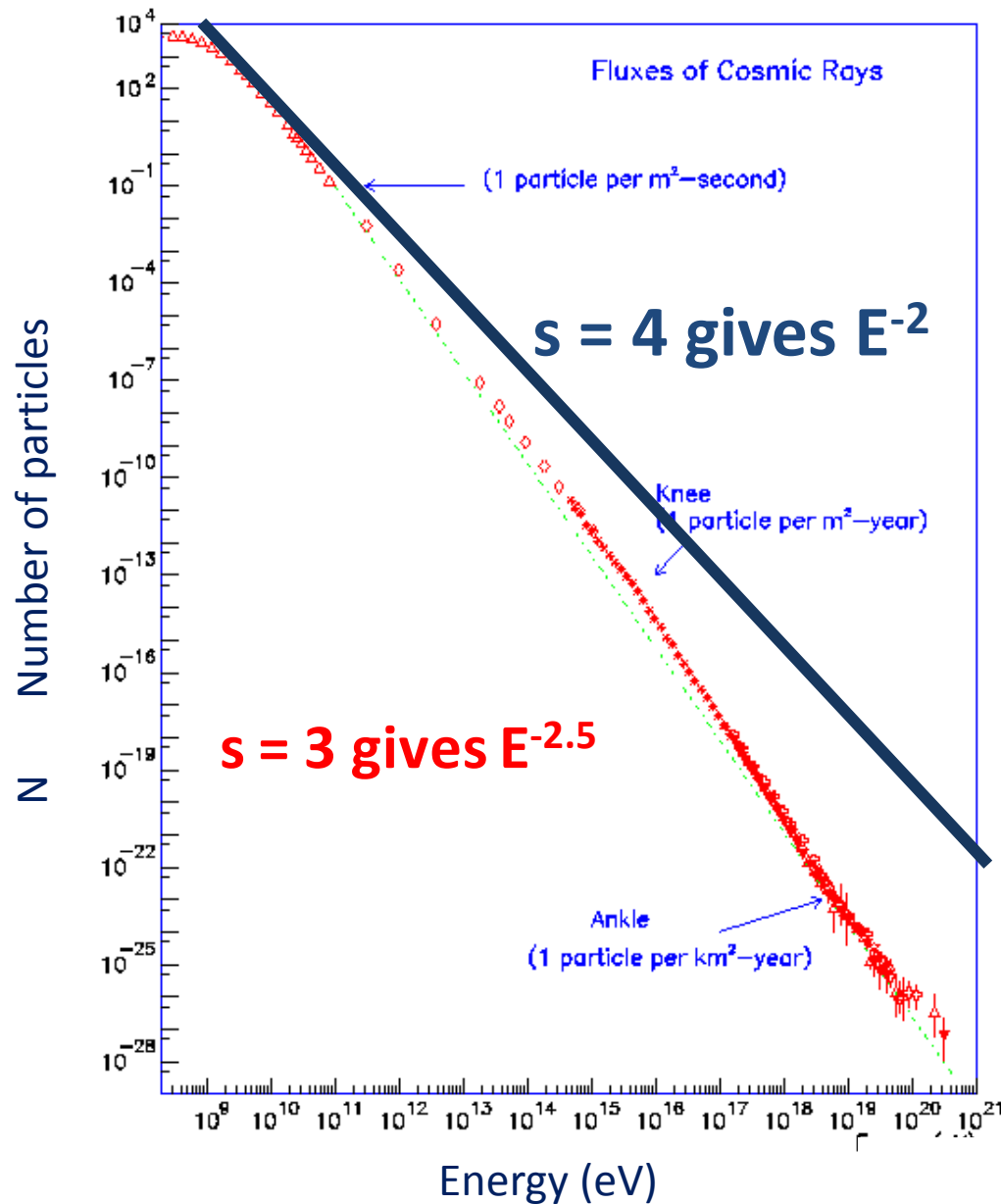
$$n(E) = aE^{\frac{2+s}{1-s}}$$

where $s = \frac{V_1}{V_2} = \frac{\rho_2}{\rho_1}$ = compression ratio

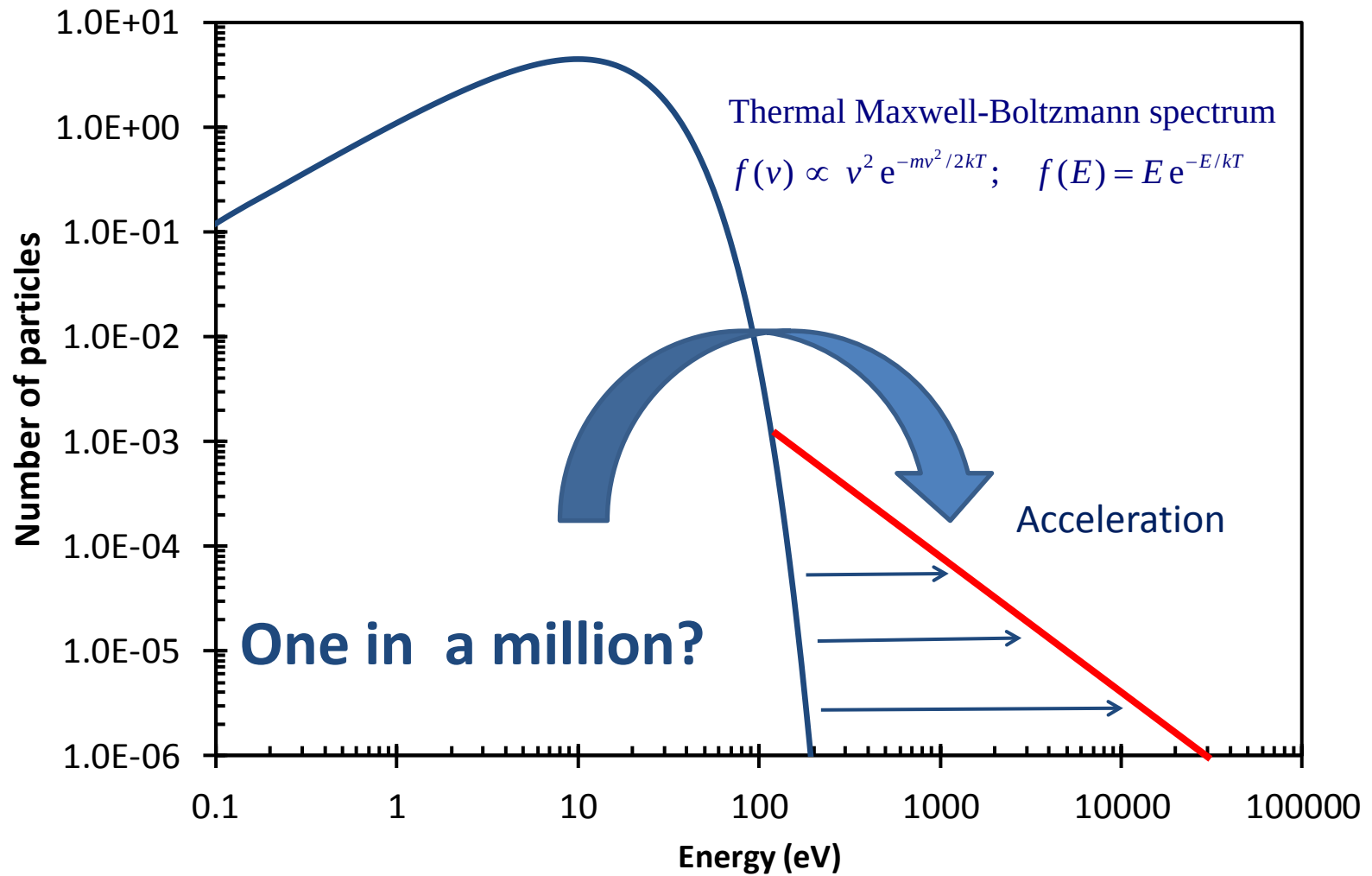
Maximum $s = 4$ (this follows from fluid dynamics);

Hence $n(E) = aE^{-2}$

Cosmic-ray spectrum

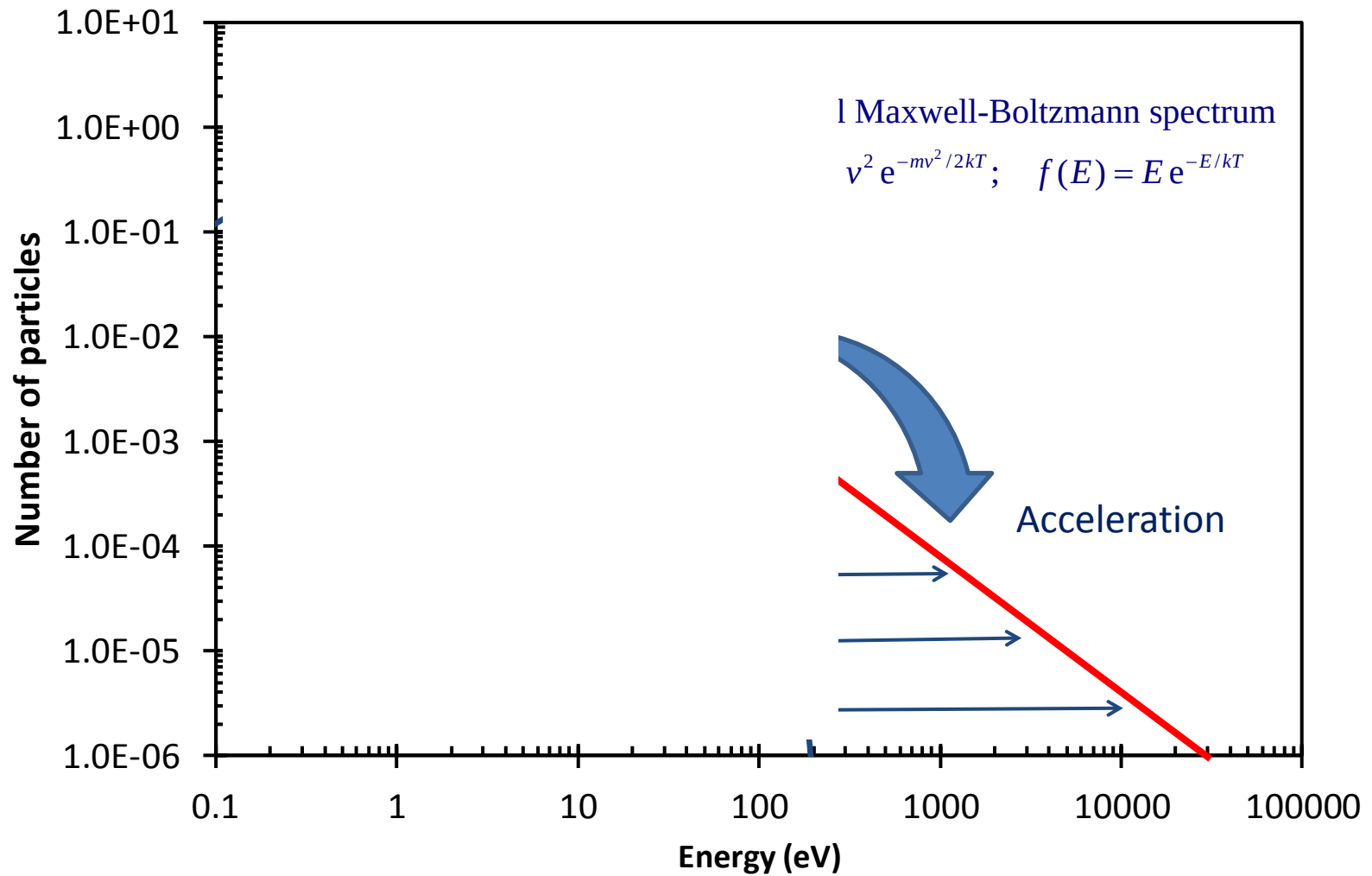


Cosmic-ray spectrum



Shock or Fermi acceleration

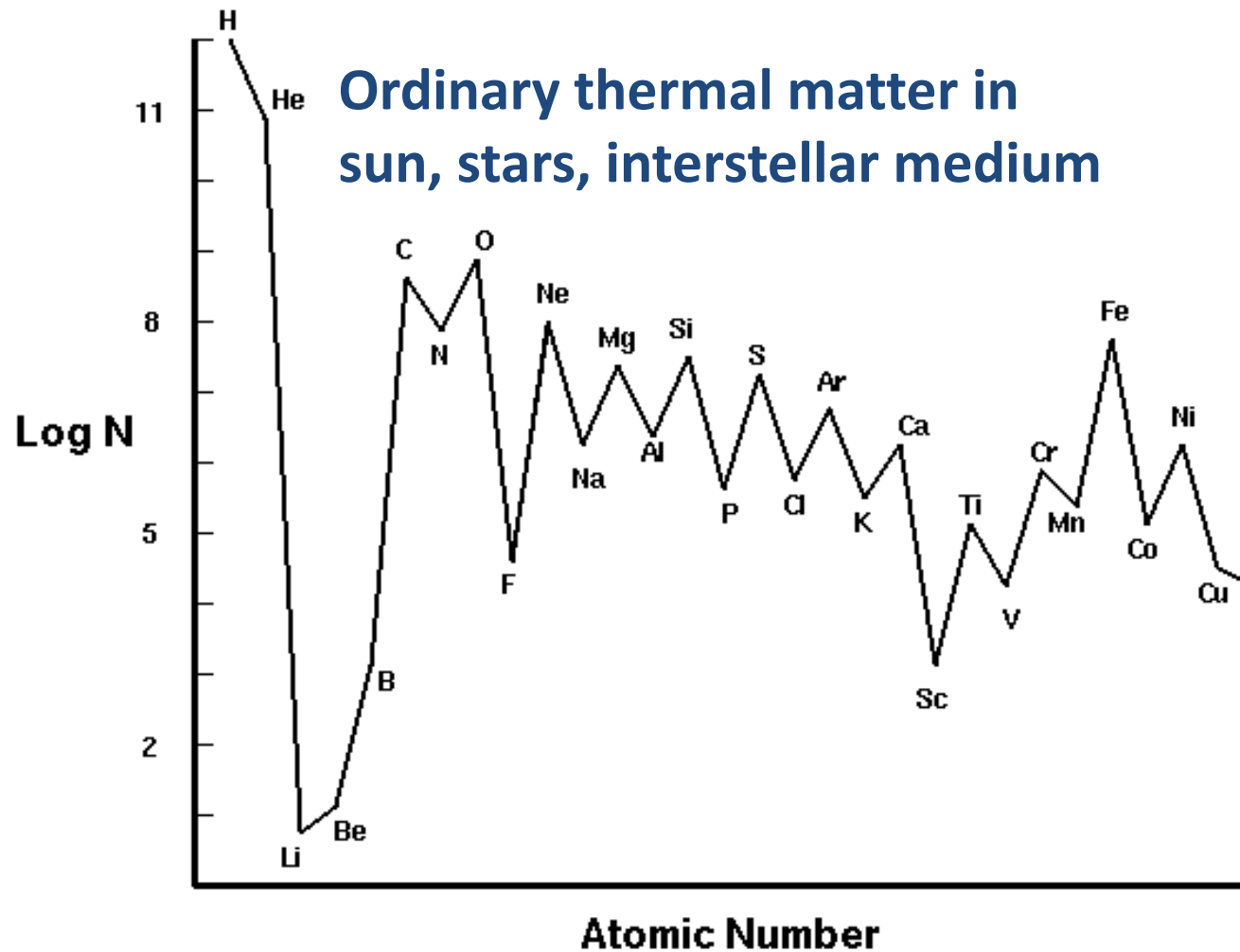
Cosmic-ray spectrum



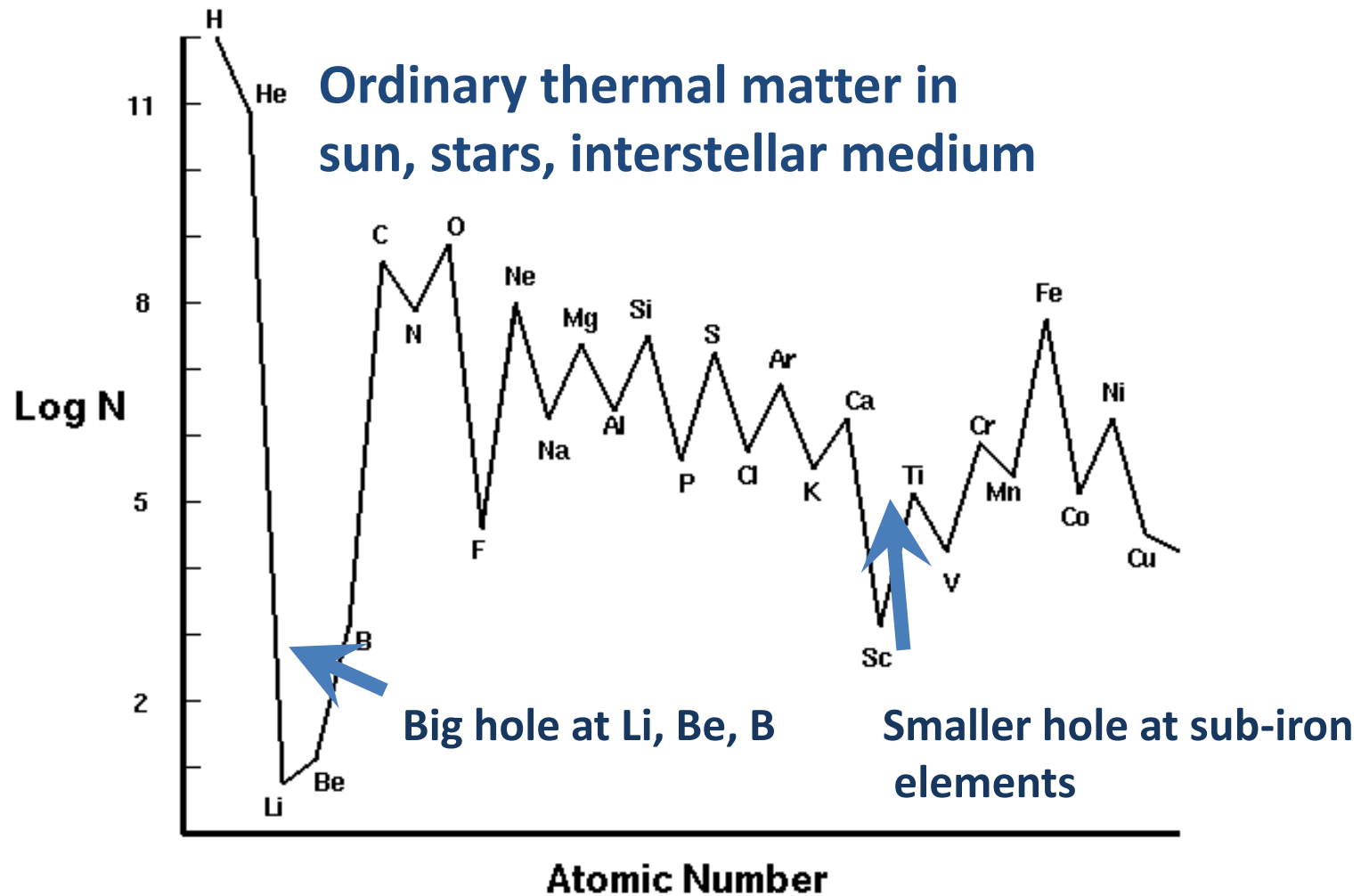
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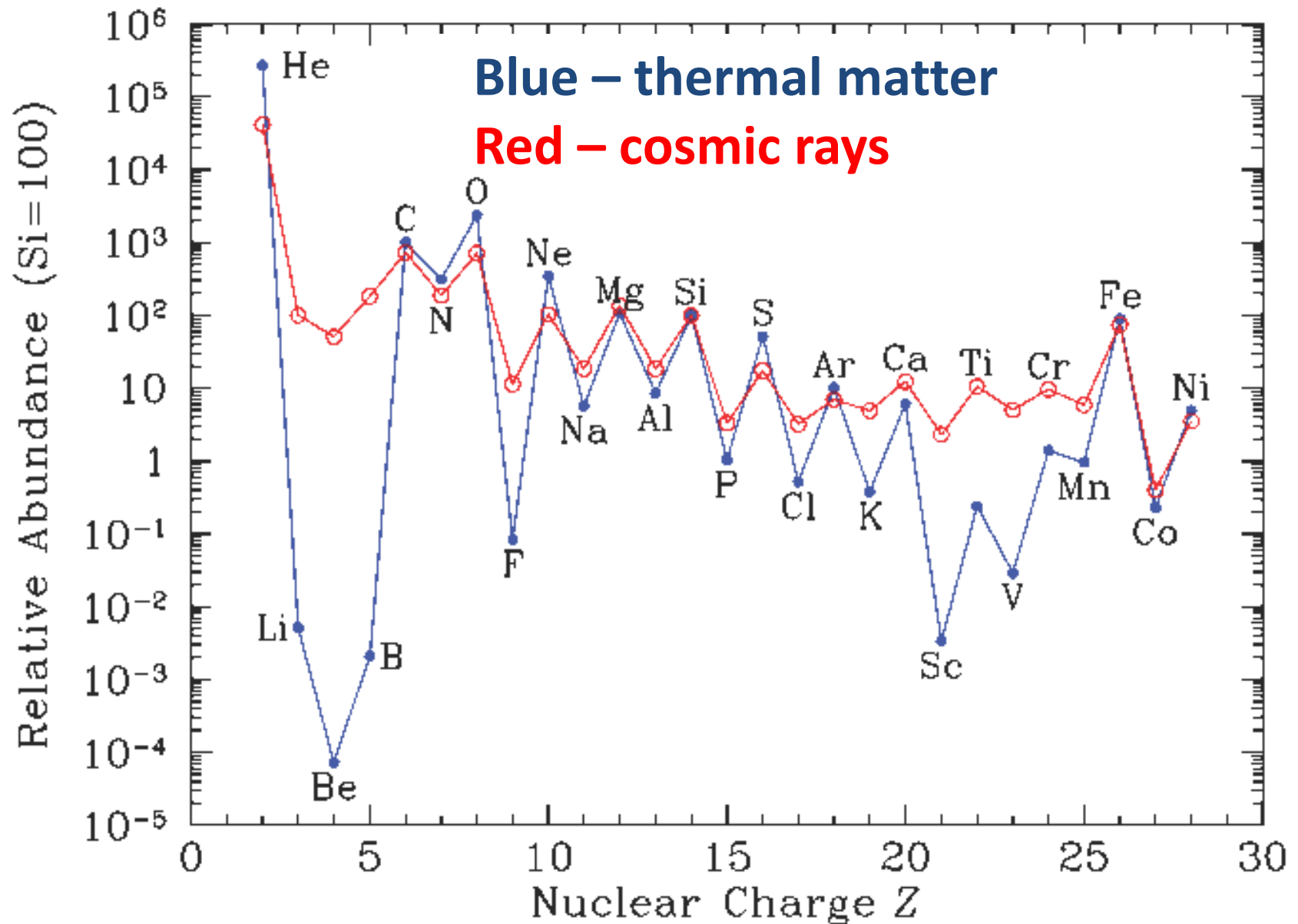
Cosmic-ray Composition



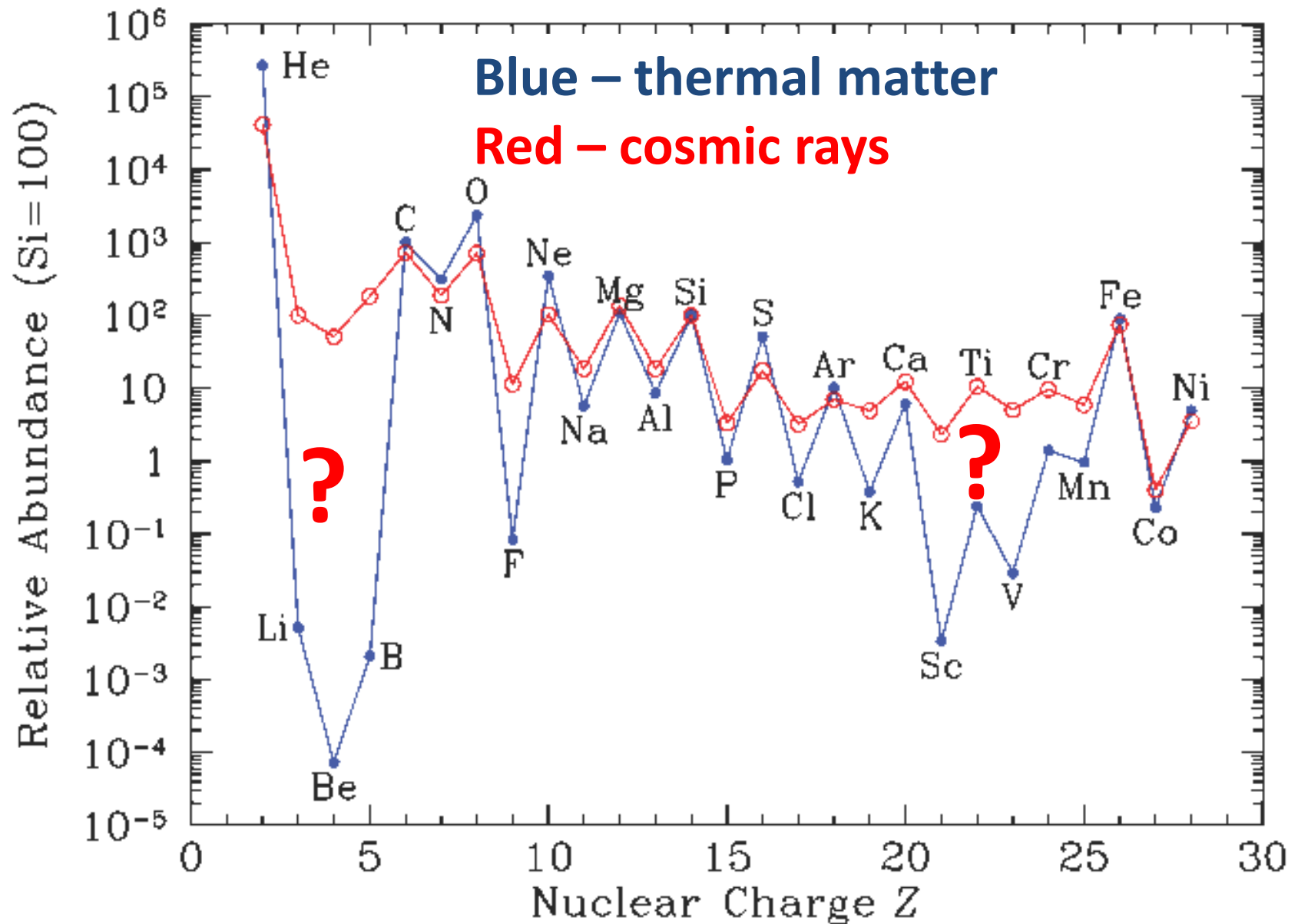
Cosmic-ray Composition



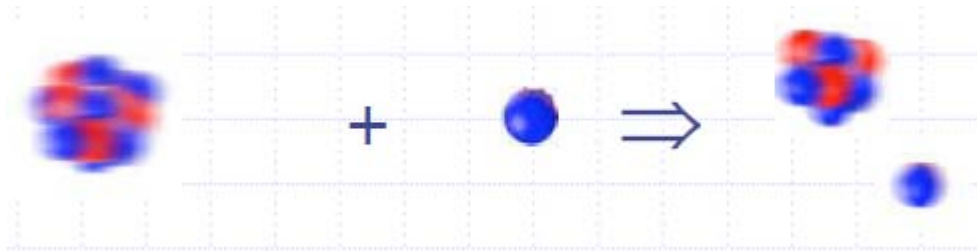
Cosmic-ray Composition



Cosmic-ray Composition



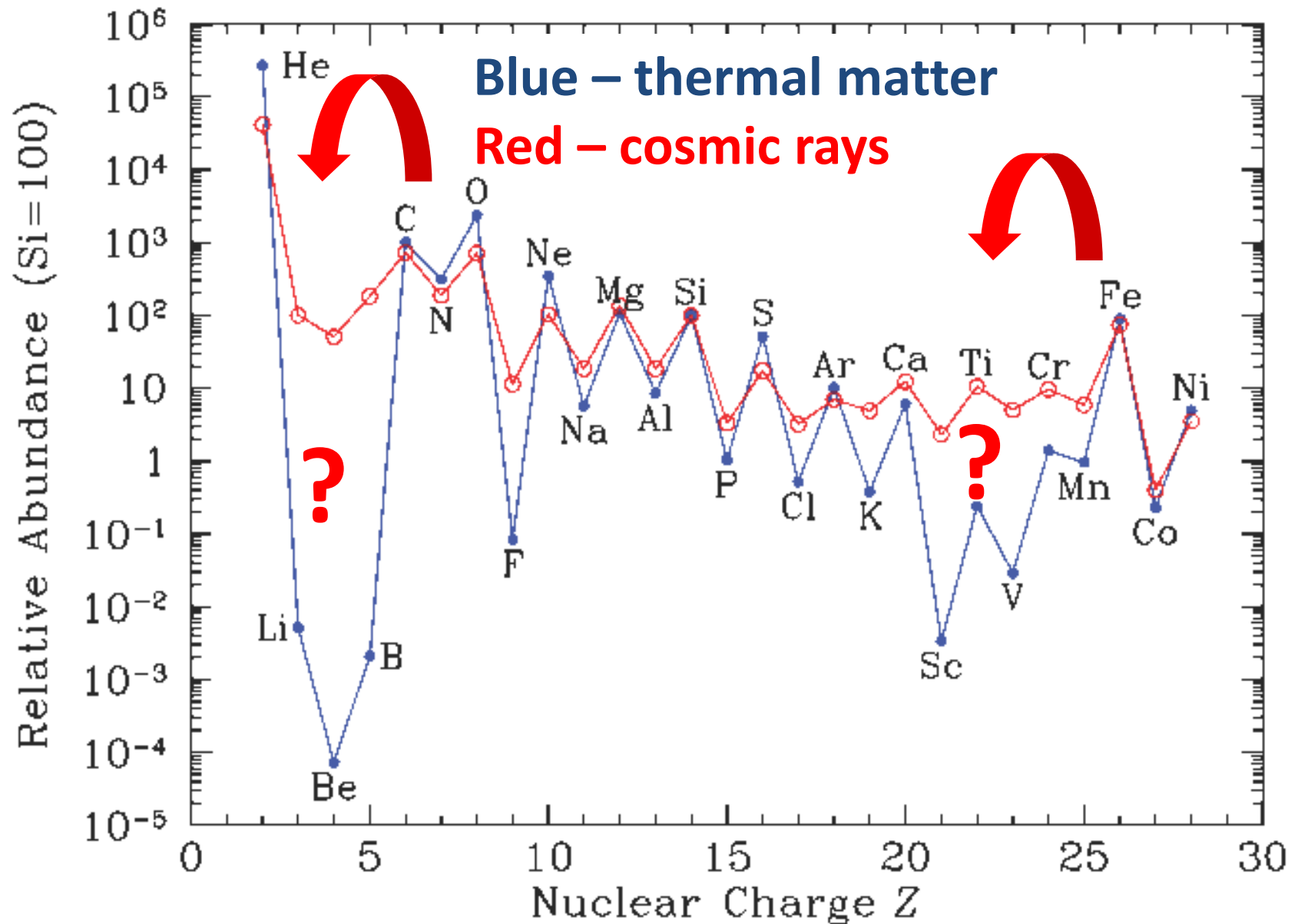
Cosmic-ray Composition



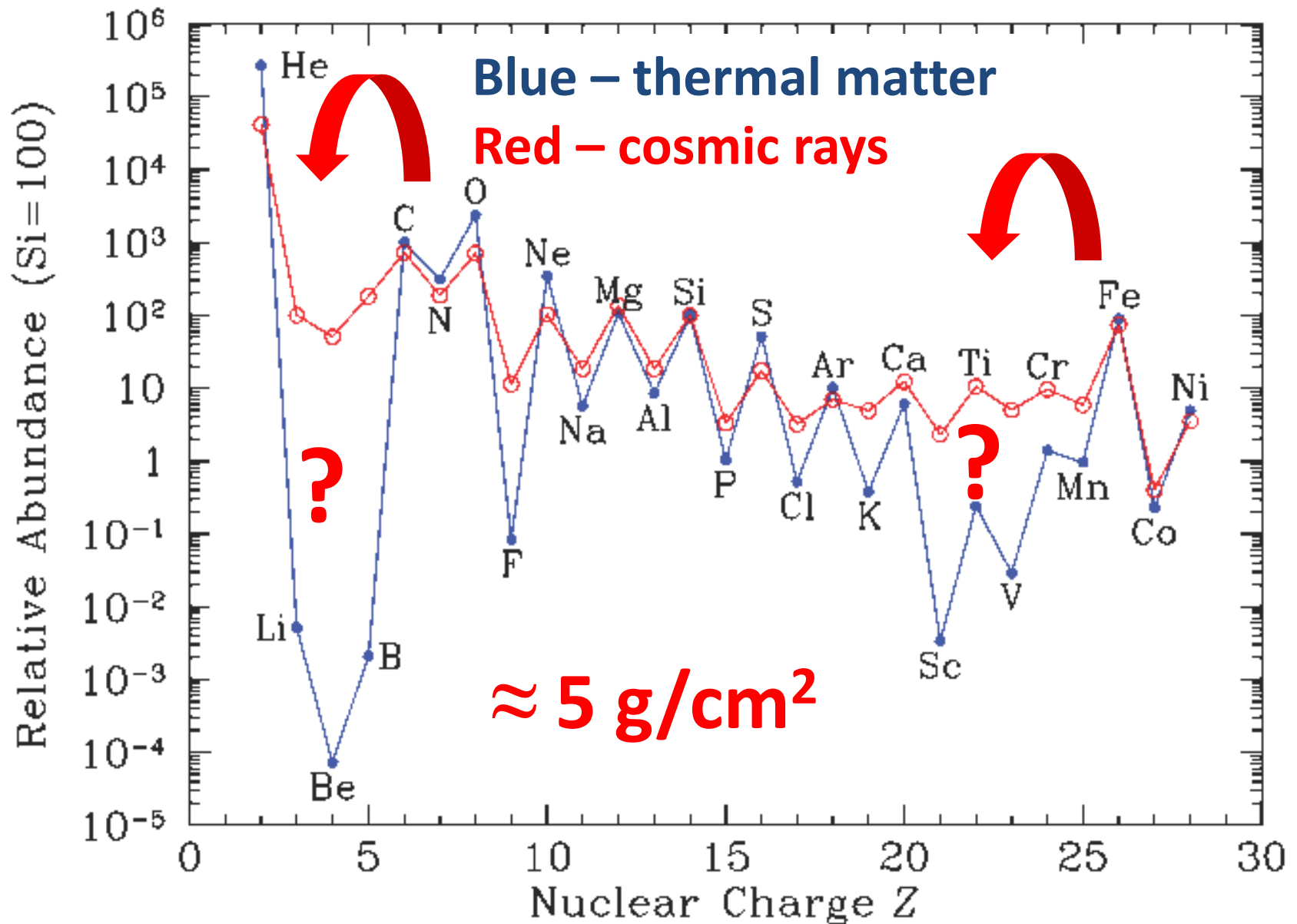
Nuclear spallation of cosmic rays

Cosmic ray C,N,O + thermal particles $\longrightarrow$ Li, Be, B

Cosmic-ray Composition

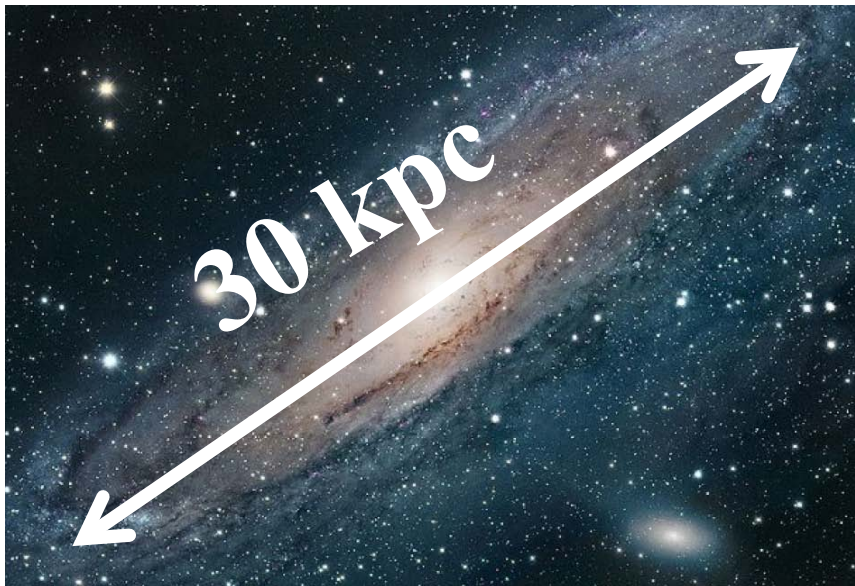


Cosmic-ray Composition



Cosmic-ray Composition

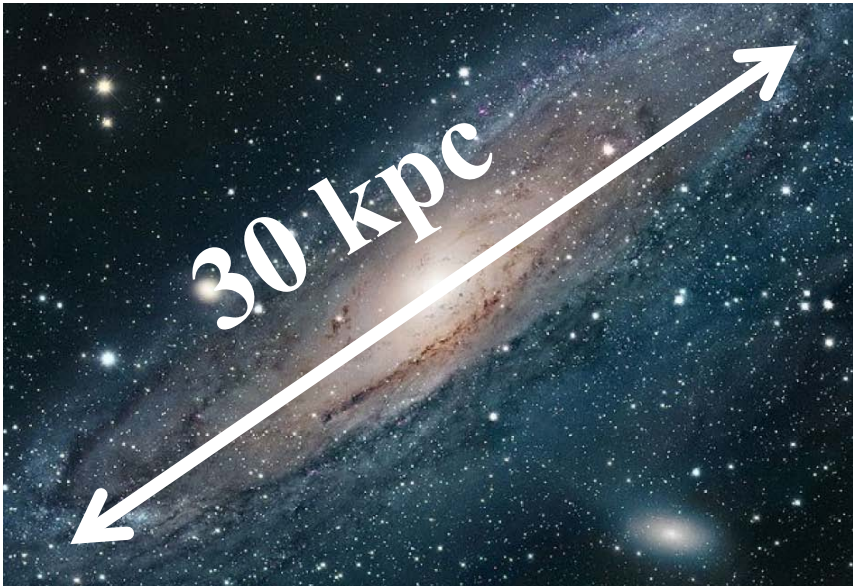
$$\frac{5 \text{ g}}{\text{cm}^2} \times \frac{1 \text{ cm}^3}{\text{proton}} \times \frac{1 \text{ proton}}{1,6 \times 10^{-24} \text{ g}} = 3 \times 10^{24} \text{ cm} = 1 \text{ Mpc}$$



➡ Cosmic rays are extragalactic

Cosmic-ray Composition

$$\frac{5 \text{ g}}{\text{cm}^2} \times \frac{1 \text{ cm}^3}{\text{proton}} \times \frac{1 \text{ proton}}{1,6 \times 10^{-24} \text{ g}} = 3 \times 10^{24} \text{ cm} = 1 \text{ Mpc}$$



~~Cosmic rays are extragalactic~~

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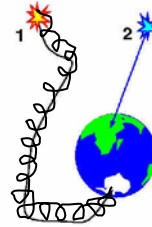


➡ ~~Cosmic rays are extragalactic~~

Galactic:
Most probably supernova blast
wave shocks

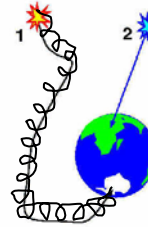
Status after 102 years

- Can't see through mist



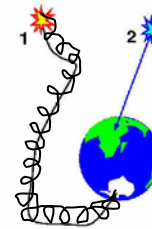
Status after 102 years

- Can't see through mist
- Look at gammas instead (since ~ 1980)



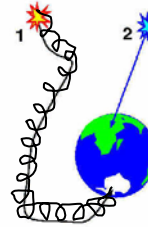
Status after 102 years

- Can't see through mist
- Look at gammas instead (since ~ 1980)
- Indeed SNRs glow



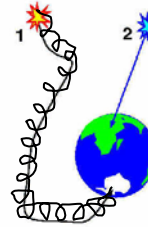
Status after 102 years

- Can't see through mist
- Look at gammas instead (since ~ 1980)
- Indeed SNRs glow
- Protons or electrons?

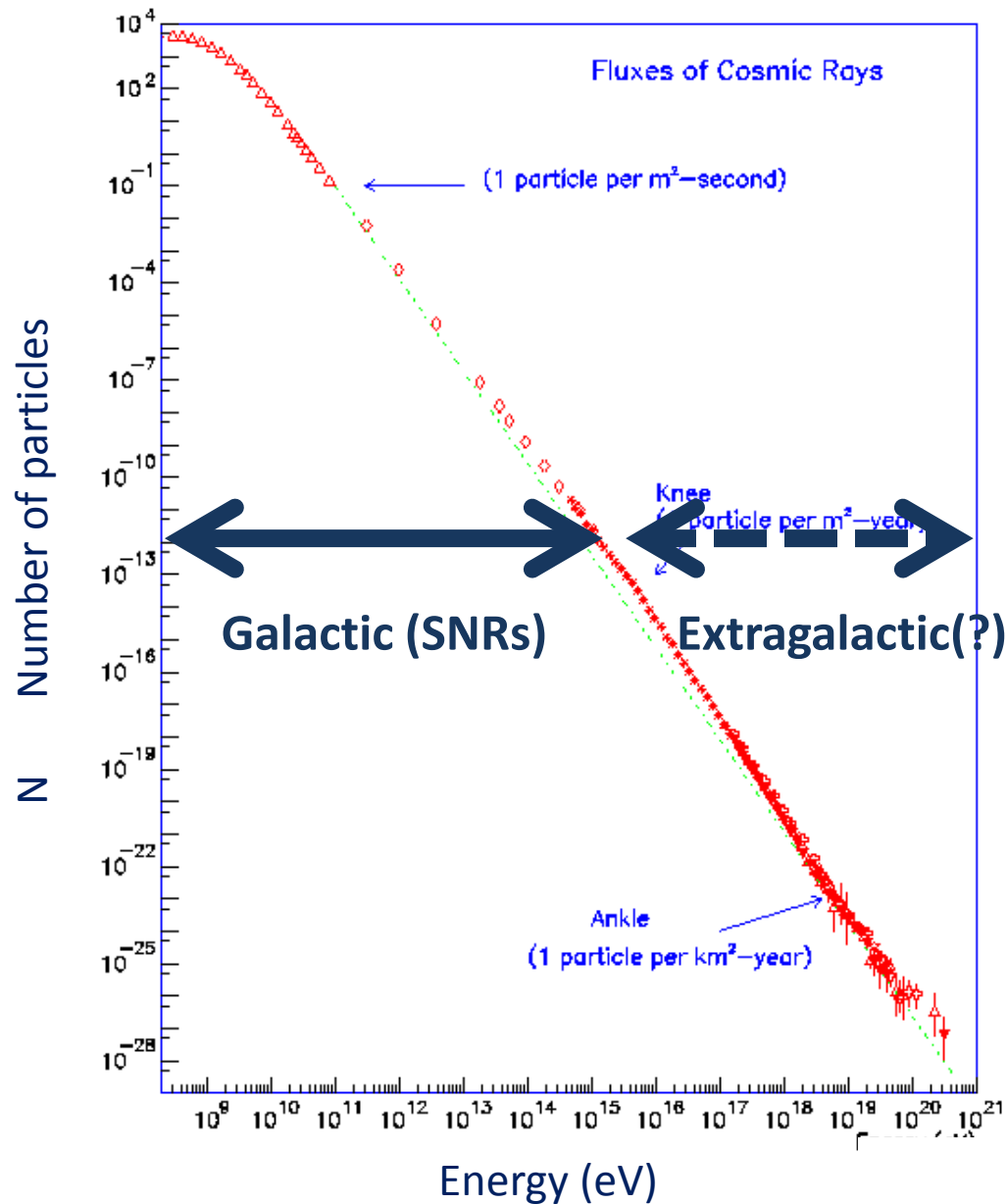


Status after 102 years

- Can't see through mist
- Look at gammas instead (since ~ 1980)
- Indeed SNRs glow
- Protons or electrons?
- Fermi space telescope 14 Feb. 2013, SNR IC443 – indeed protons!

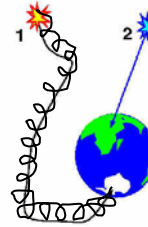


Status after 102 years



Status after 102 years

- Can't see through mist
- Look at gammas instead (since ~ 1980)
- Indeed SNRs glow
- Protons or electrons?
- Fermi space telescope 14 Feb. 2013, SNR IC443 – indeed protons!
- Particle *and* photon astronomy



Why are cosmic rays important?

- **Only one in a million of interstellar gas**
- **But millions of times more energy**

Why are cosmic rays important?

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- But millions of times more energy
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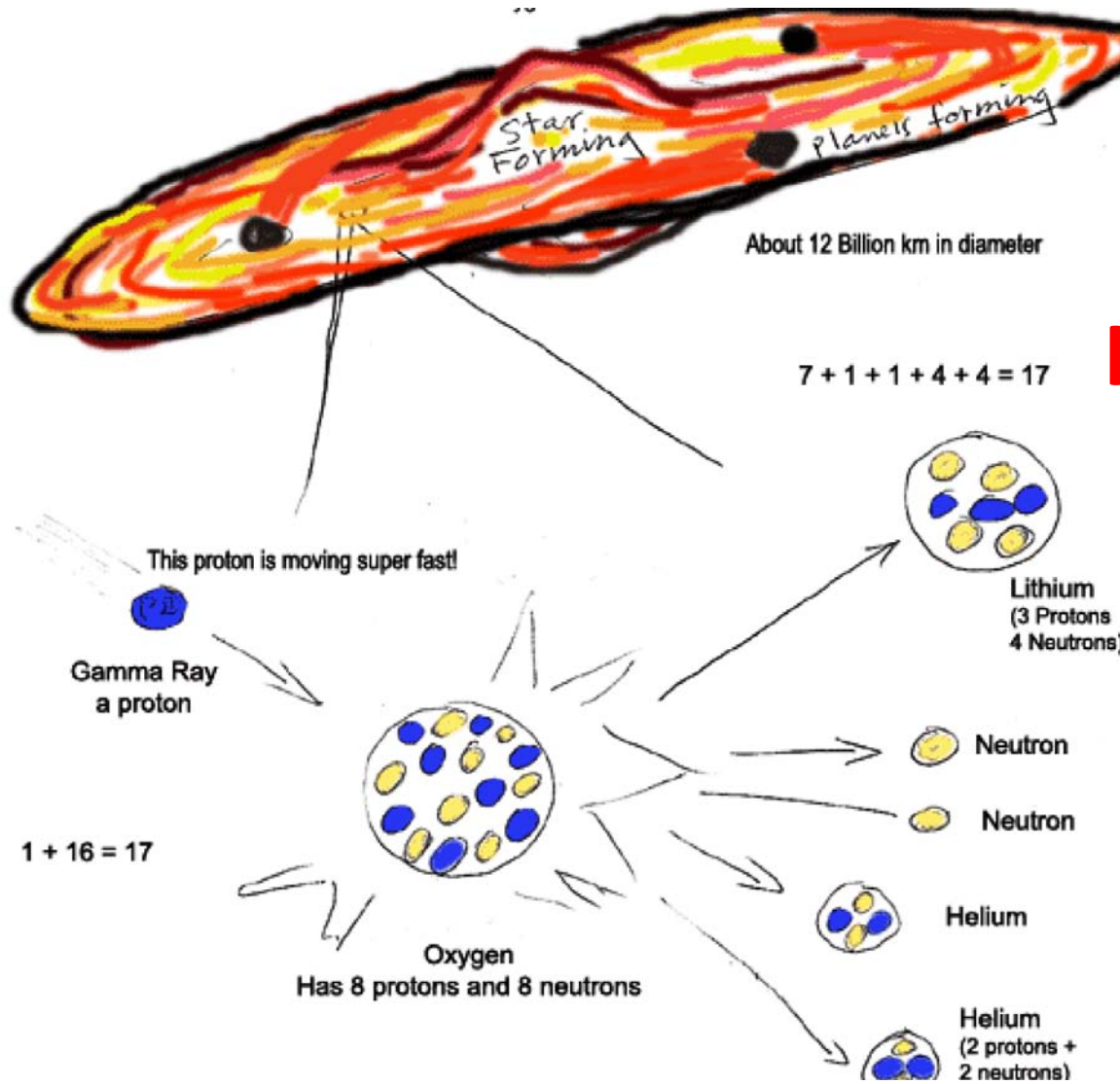
Why are cosmic rays important?

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 $\approx$ interstellar matter $\approx$ cosmic rays $\approx$ **1 eV/cm³**

Why are cosmic rays important?

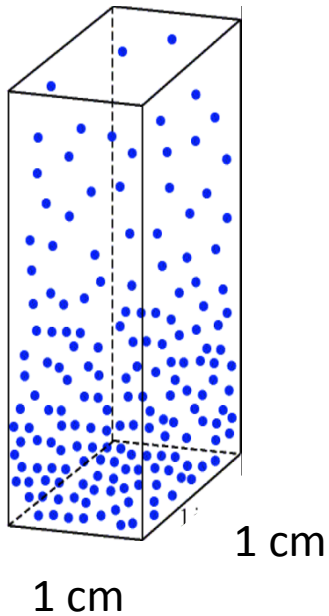
- Only one in a million of interstellar gas
- But millions of times more energy
- Thus their speed is c (for energies $> 10^9$ eV)
- Equipartition of energy: light $\approx$ magnetic field $\approx$ interstellar matter $\approx$ cosmic rays $\approx 1 \text{ eV/cm}^3$
- Cosmic rays are young:
d = 1 Mpc at $c = 3 \cdot 10^8 \text{ m/s}$ implies $\sim 10^7$ years

Cosmic-ray Composition



How much (little)
is 5 g/cm^2?

The atmosphere

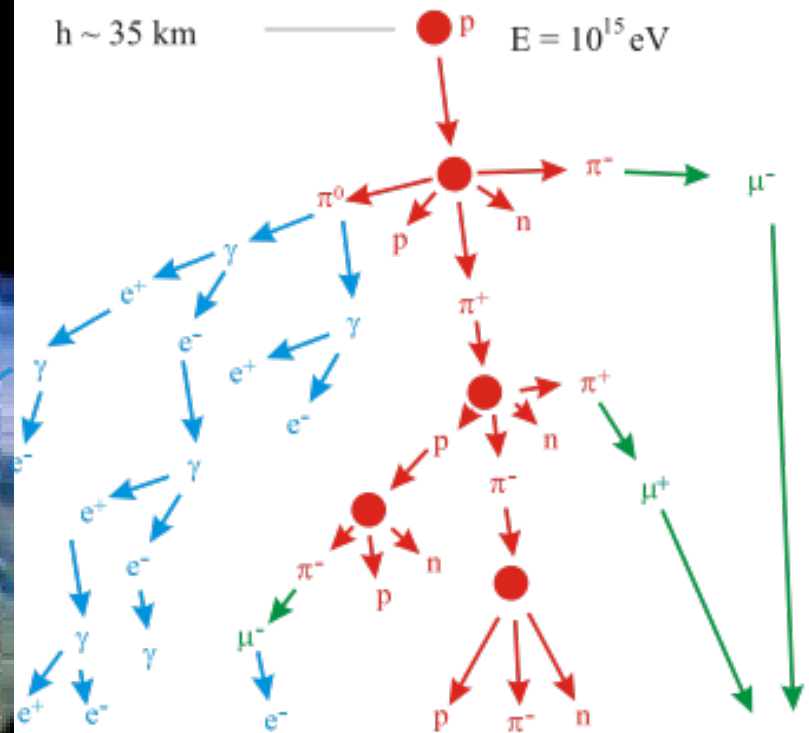
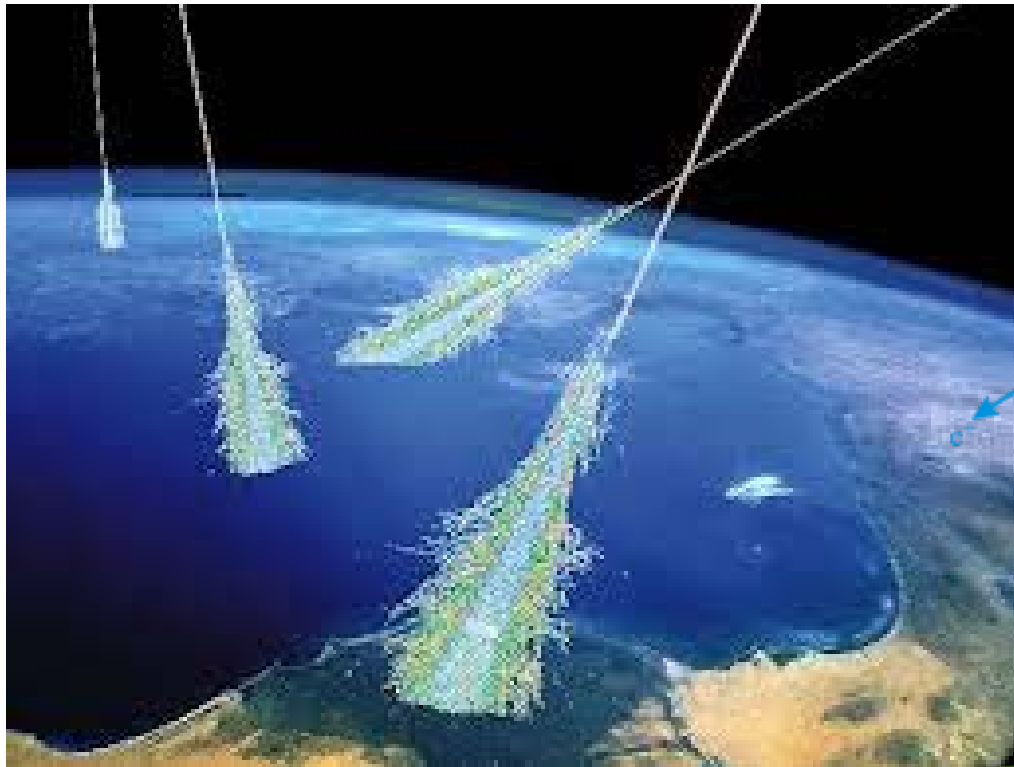


How much (little) is 5 g cm^{-2} ?

1 Atmosphere = $100 \text{ kPa} = 10^5 \text{ N/m}^2 = 10^4 \text{ kg/m}^2 = 1000 \text{ g/cm}^2$

200 x

Cosmic-ray showers



$N = 10^6$
 $N(e) = 18\%$
 $N(\gamma) = 18\%$
 $N(p, n, \pi) = 0,3\%$
 $N(\mu) = 1,7\%$

Topics

- South African astronomy
- Particle vs. photon astronomy
- Cosmic-ray spectra, composition
- **Dark matter**
- Neutrinos
- Cosmic-ray variations
- “Cosmic” rays from the sun
- Helioclimatology

Dark matter

Spiral Galaxy NGC 4414



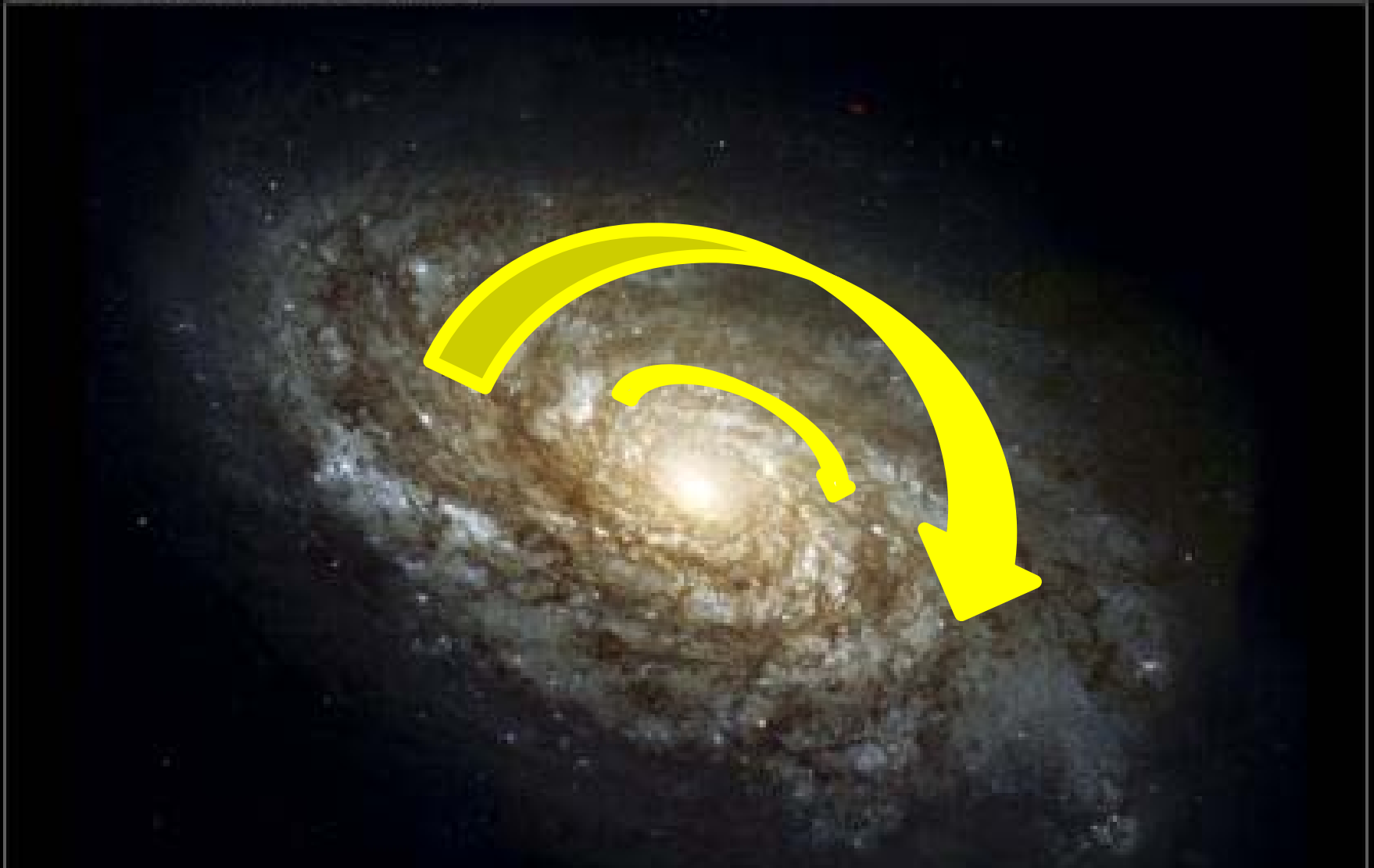
Dark matter

Spiral Galaxy NGC 4414



Dark matter

Spiral Galaxy NGC 4414



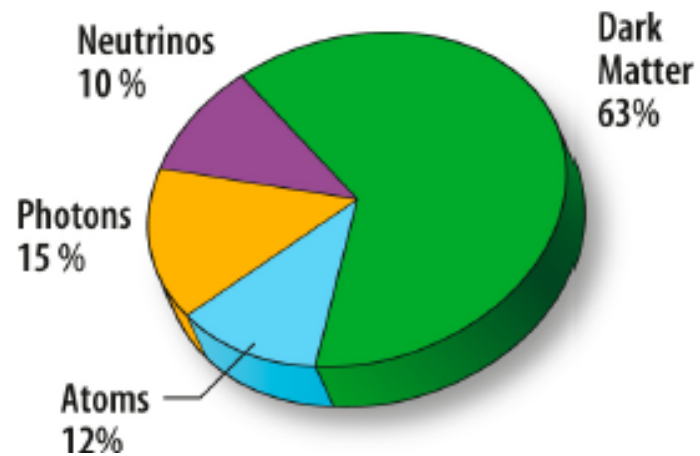
Dark matter



Gravitational Lens in Abell 2218

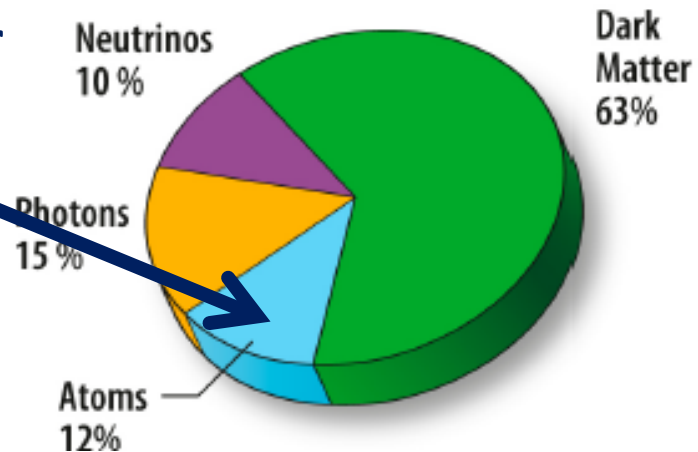
HST · WFPC2

Dark matter

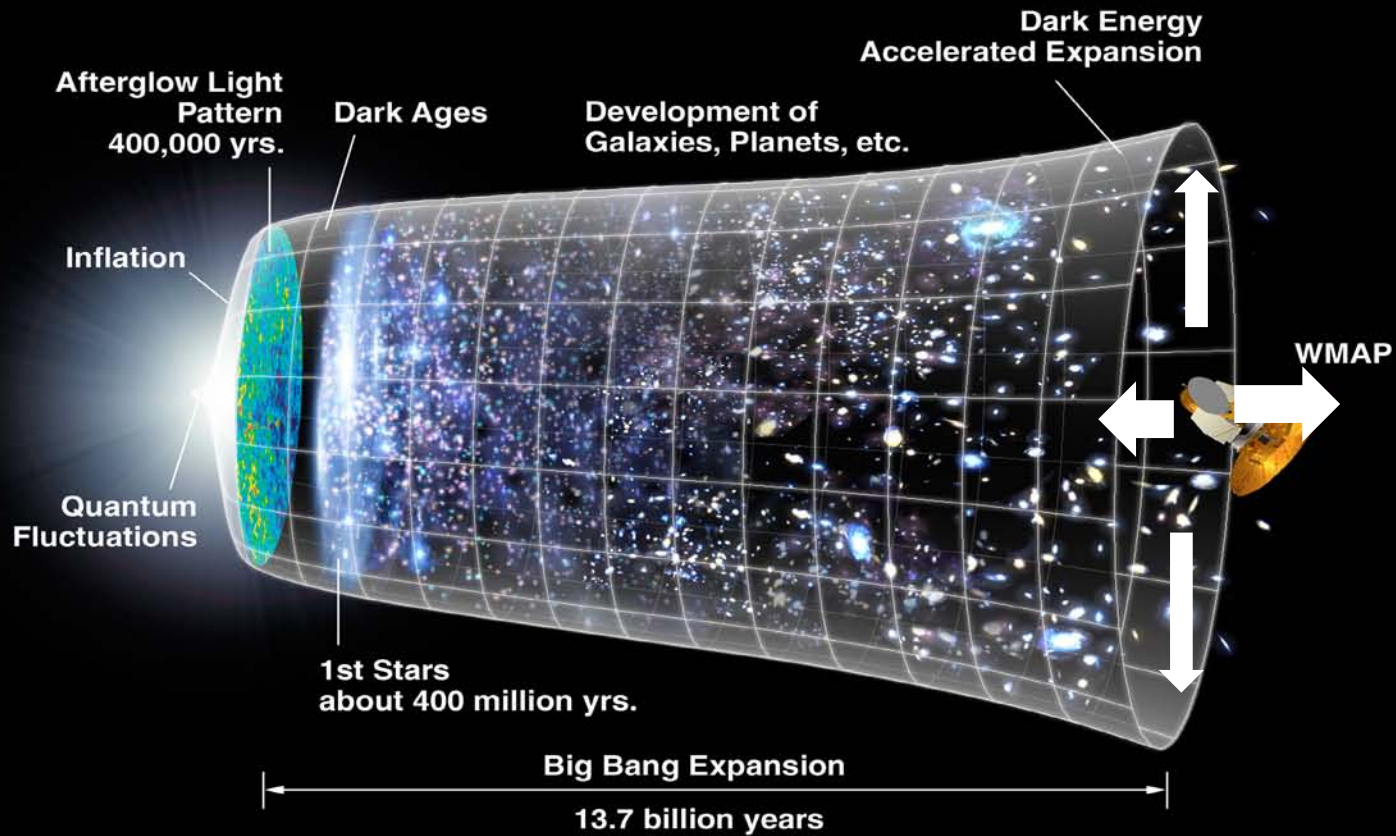


Dark matter

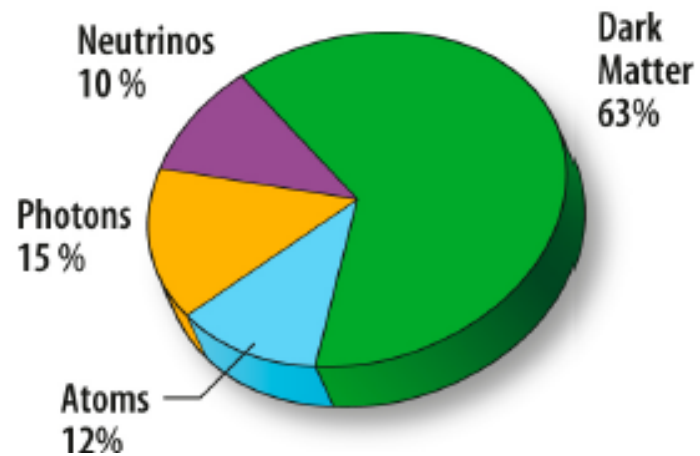
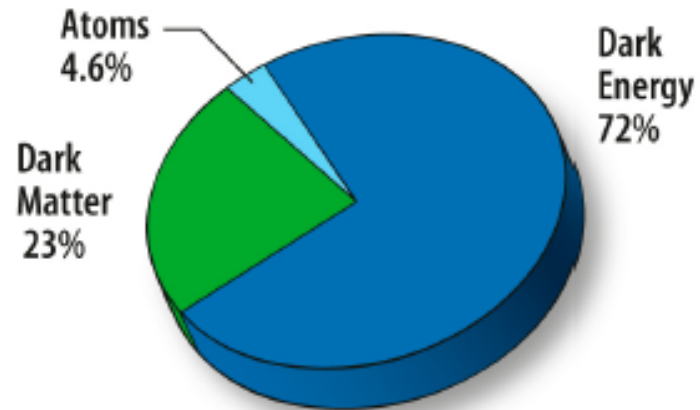
- > 90% in stars
- < 10% interstellar matter



Dark Energy



Dark matter-energy



Topics

- South African astronomy
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- Cosmic-ray variations
- “Cosmic” rays from the sun
- Helioclimatology

Neutrino Astronomy

- Postulated: Pauli 1930

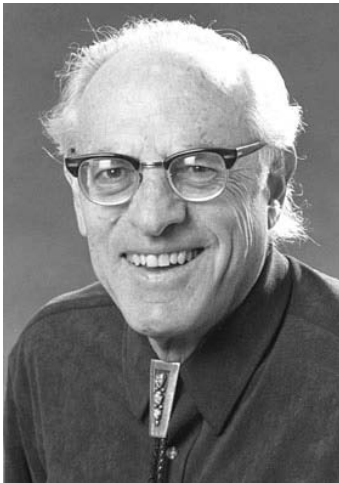
$$n \rightarrow p^+ + e^- + \nu$$

Neutrino Astronomy

- Postulated: Pauli 1930



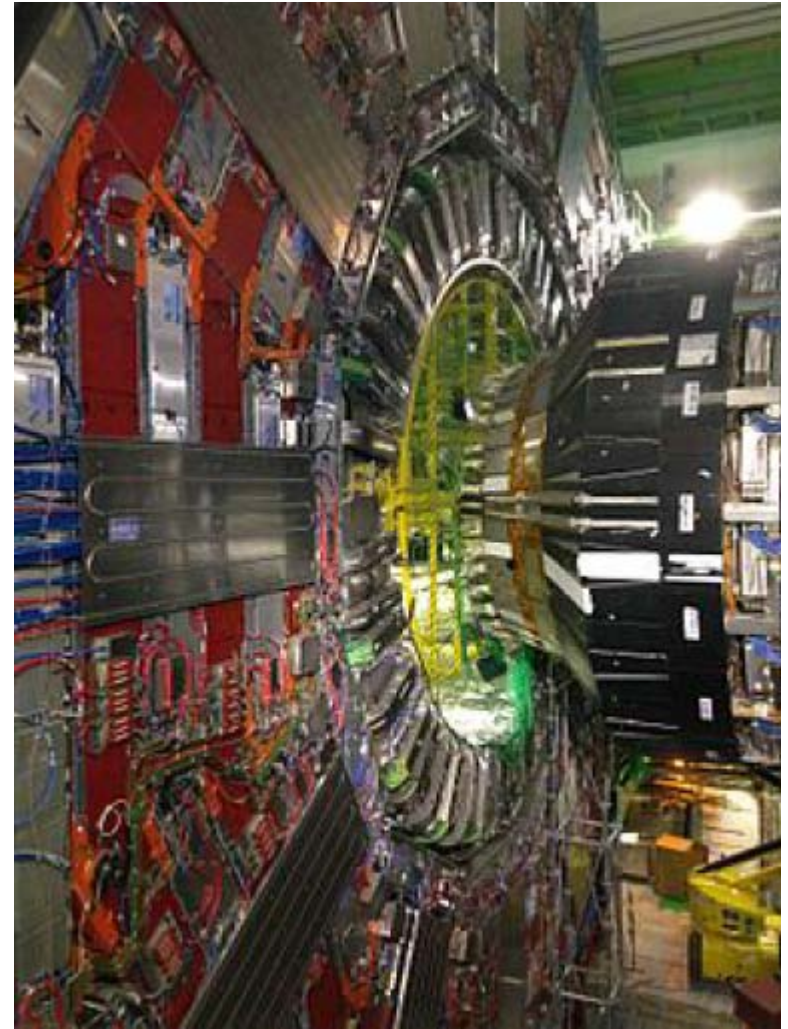
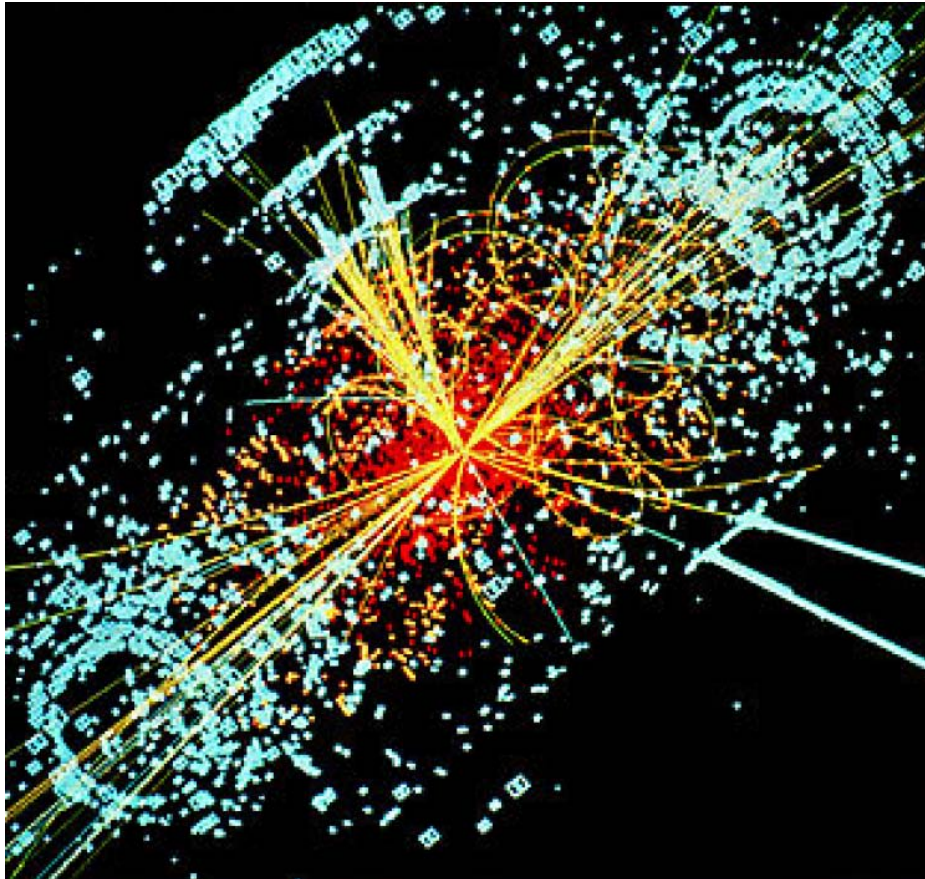
- Detected: 20 July 1956



Frederick Reines
& Clyde Cowan

Neutrino Astronomy

Neutrino event in LHC, CERN

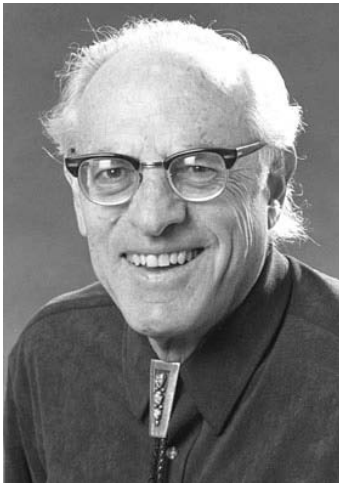


Neutrino Astronomy

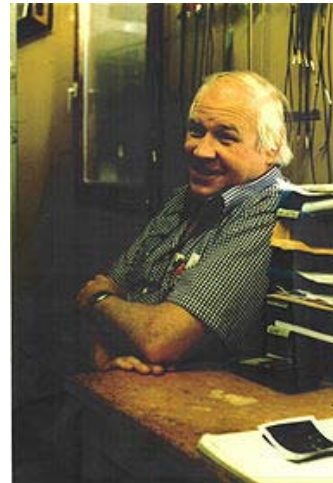
- Postulated: Pauli 1930



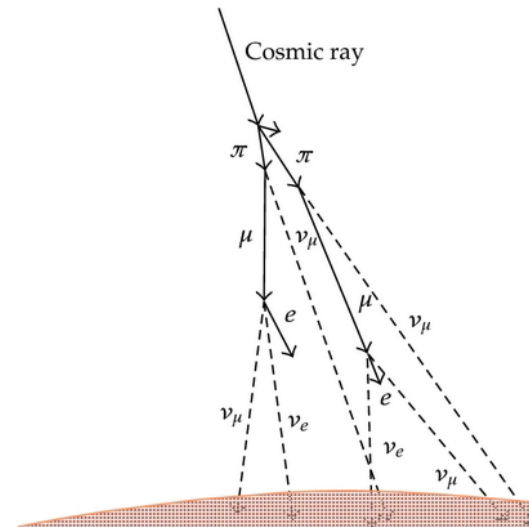
- Detected: 20 July 1956
- In nature: August 1965 (ERPM, Boksburg)



Frederick Reines
& Clyde Cowan



Friedel Sellschop
(WITS)



Neutrino Astronomy

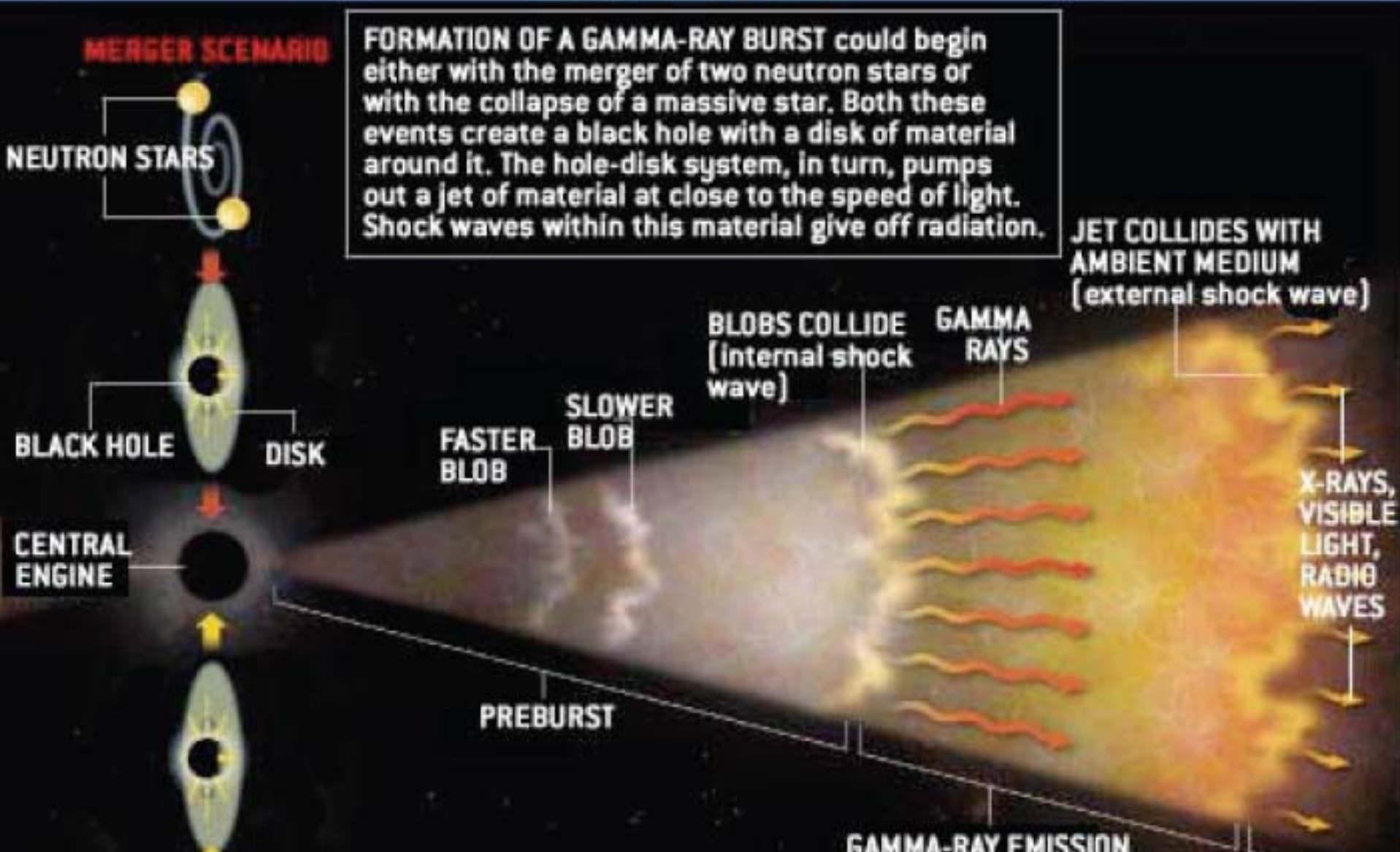
- Postulated: Pauli 1930



- Detected: 20 July 1956
- In nature: August 1965 (ERPM, Boksburg)
- Astrophysical importance: non-interacting

Neutrino Astronomy

BURSTING OUT



Neutrino Astronomy

- Postulated: Pauli 1930



- Detected: 20 July 1956
- In nature: August 1965 (ERPM, Boksburg)
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Neutrinos $\longrightarrow$ muons $\longrightarrow$ Cherenkov light
electrons
tauons

Neutrino Astronomy

- Postulated: Pauli 1930



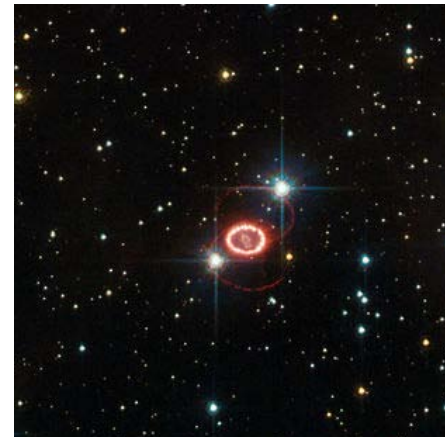
- Detected: 20 July 1956
- In nature: August 1965 (ERPM, Boksburg)
- From sun: Homestake, since 1970
----- 6.5×10^{10} per cm^2 per second

Neutrino Astronomy

- Postulated: Pauli 1930



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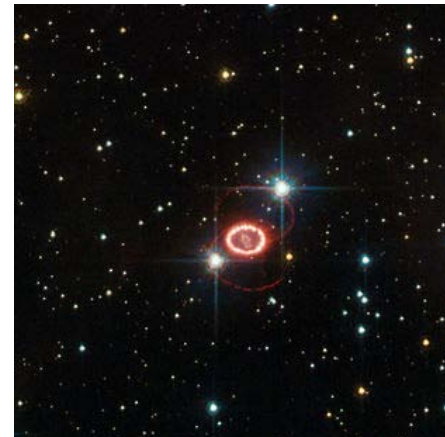


Neutrino Astronomy

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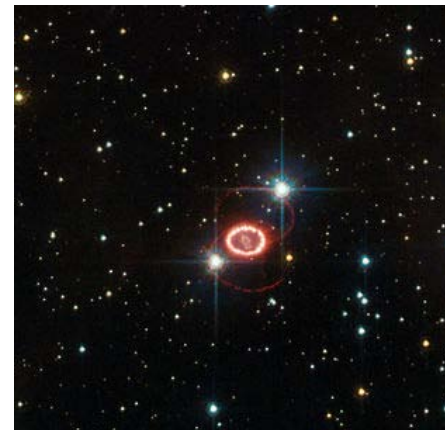


Neutrino Astronomy

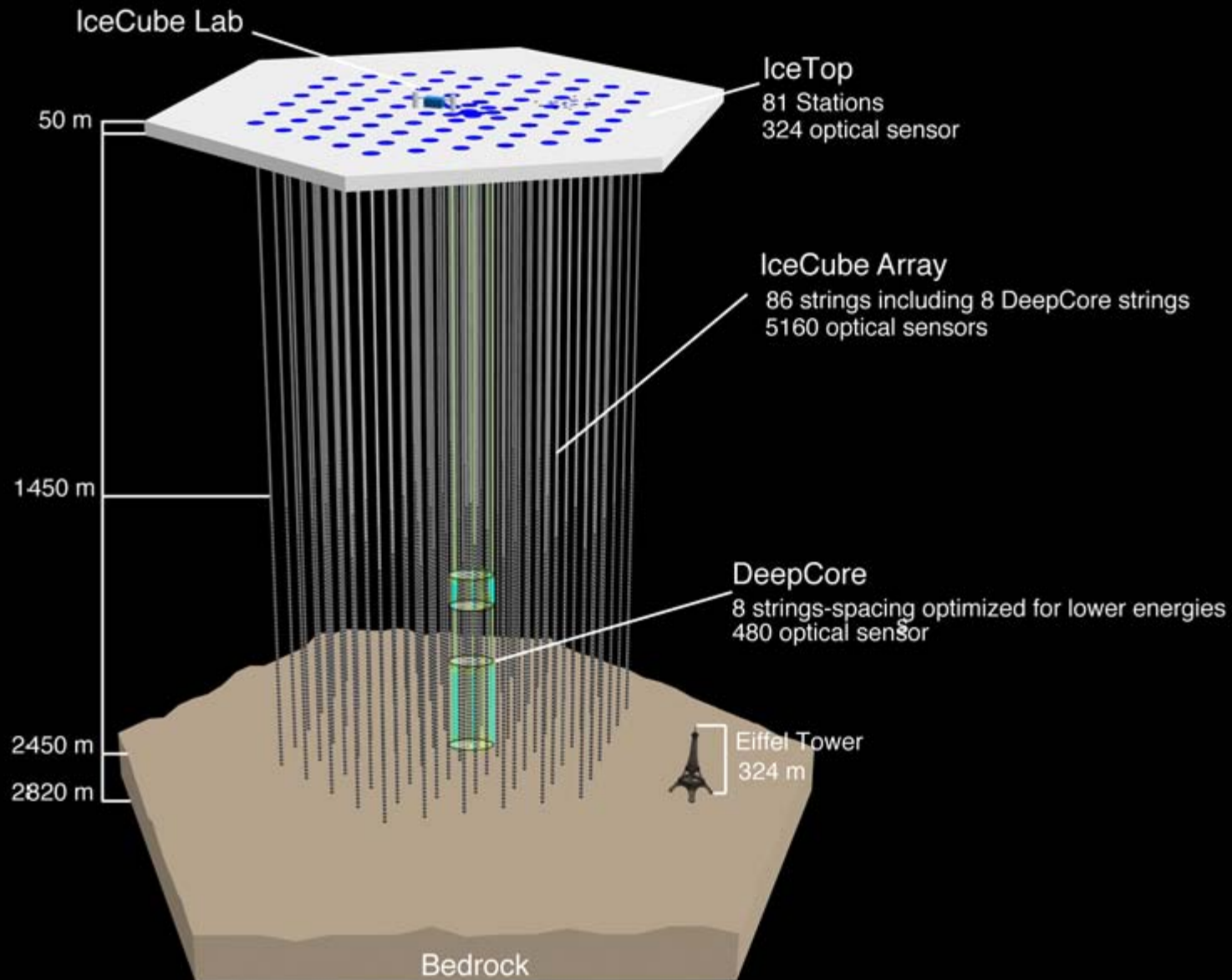
- Postulated: Pauli 1930



- Detected: 20 July 1956
- In nature: August 1965 (ERPM, Boksburg)
- Astrophysical importance: non-interacting
- From sun: Homestake, since 1970
- Supernova 1987A: 24(!) neutrinos seen
- IceCube



Neutrino Astronomy – Ice Cube

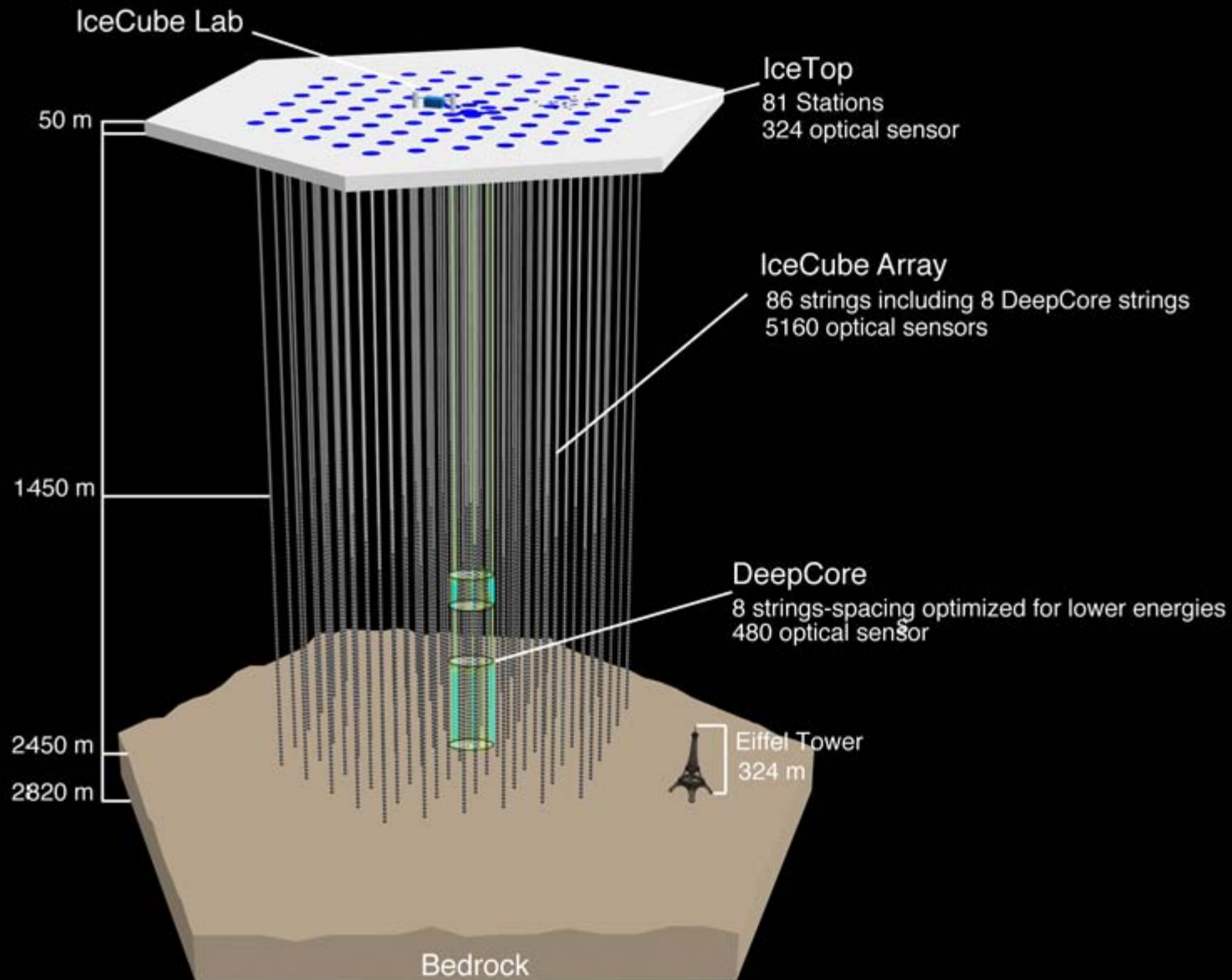


Neutrino Astronomy – Ice Cube

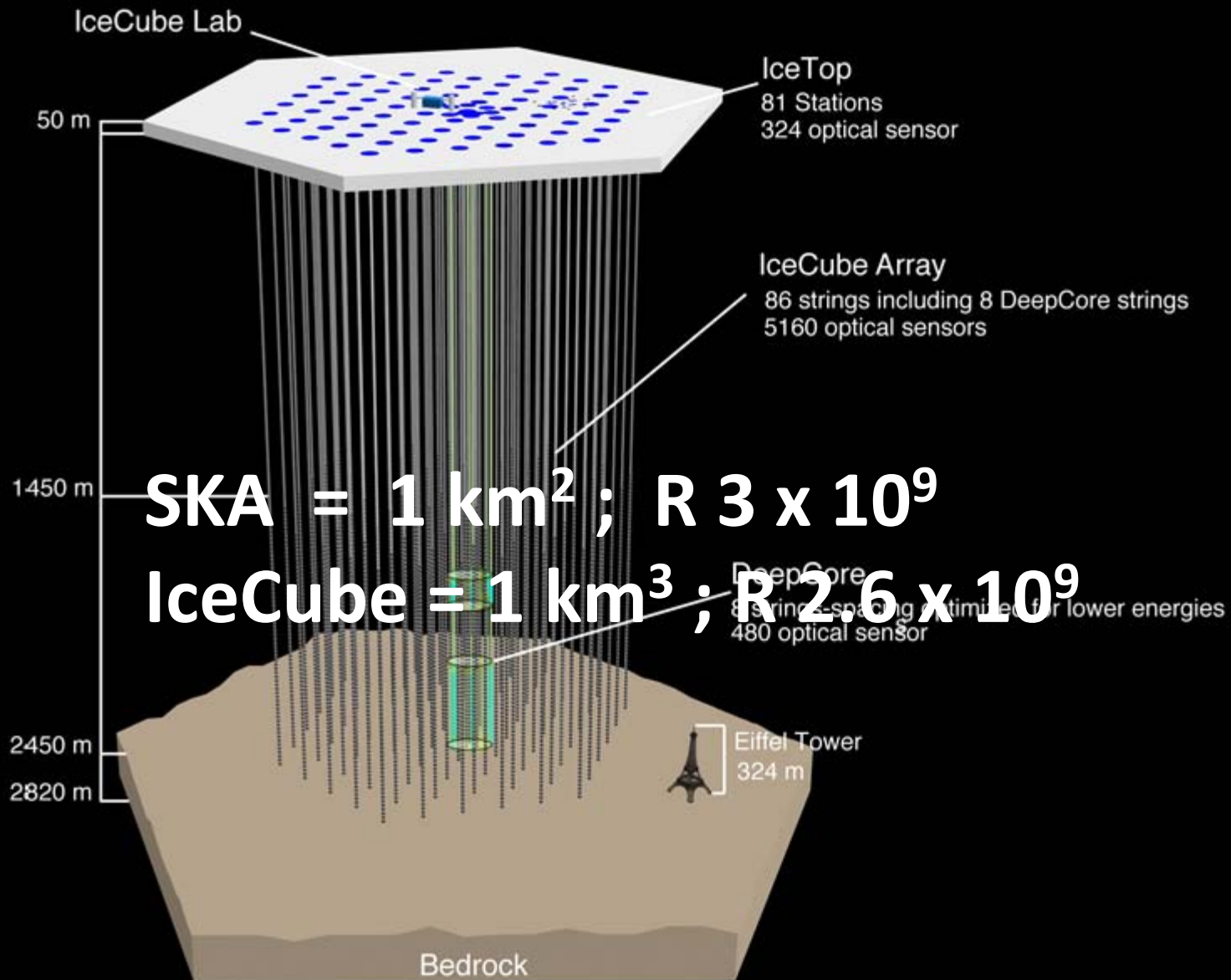
Amundsen-Scott South Pole Station



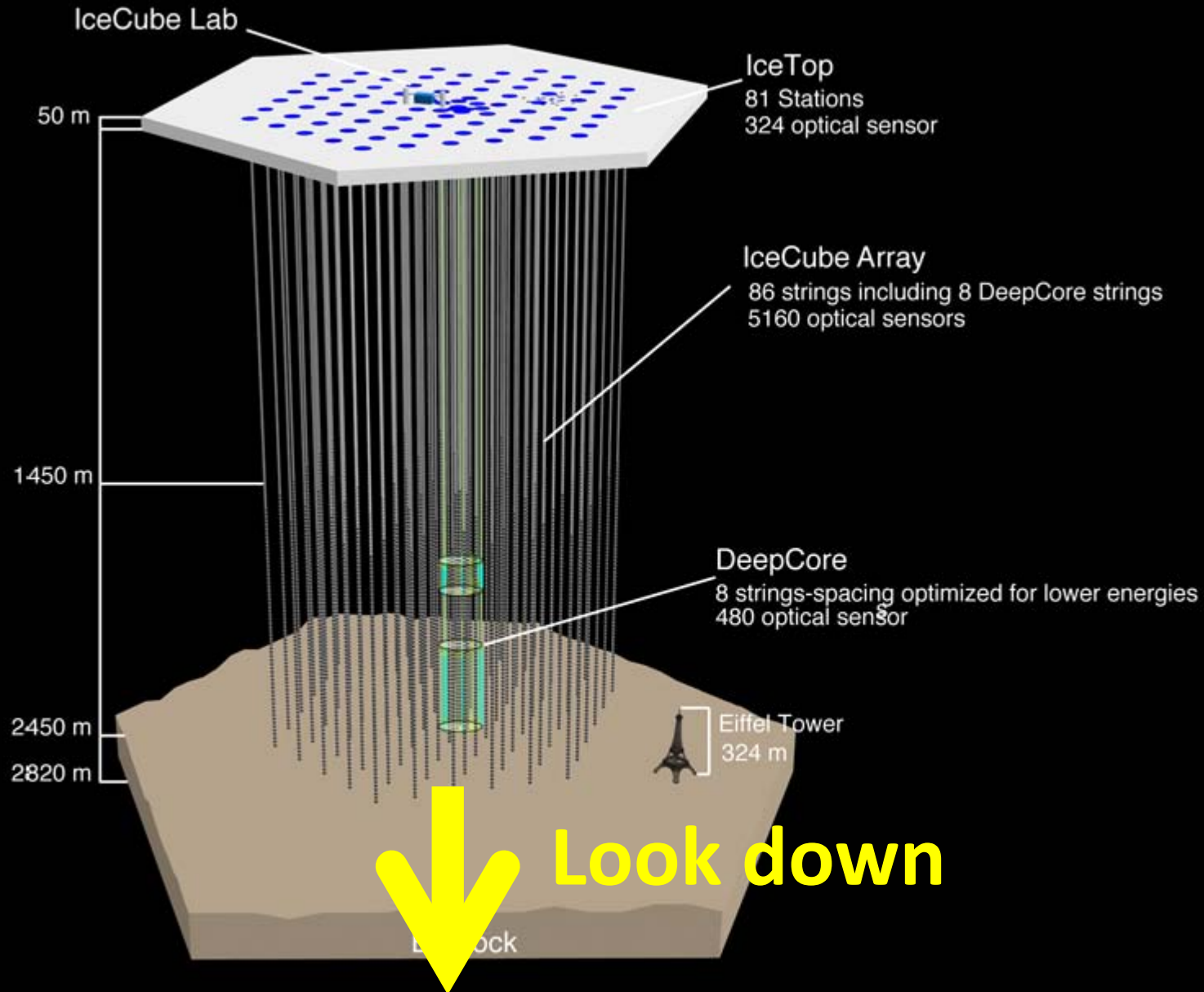
Neutrino Astronomy – Ice Cube



Neutrino Astronomy – Ice Cube



Neutrino Astronomy – Ice Cube



Neutrino Astronomy

- Postulated: Pauli 1930



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- From sun: Homestake, since 1970
- Supernova 1987A: 24(!) neutrinos seen
- Bert and Ernie: 15 May 2013
> 10^{15} eV

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- Detected: 20 July 1956
- In nature: August 1965 (ERPM, Boksburg)
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Names

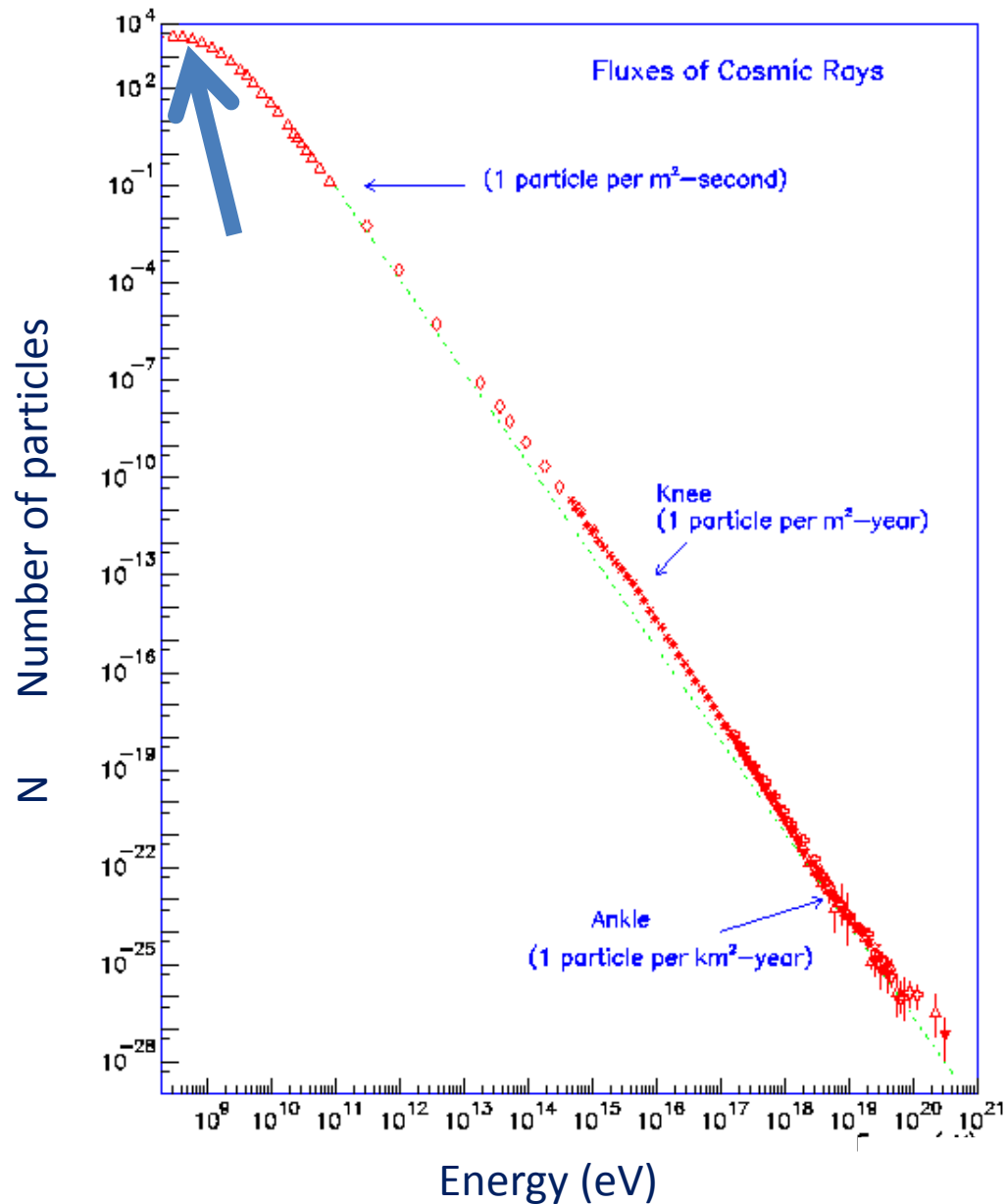
Particle Astrophysics

Astroparticle Physics

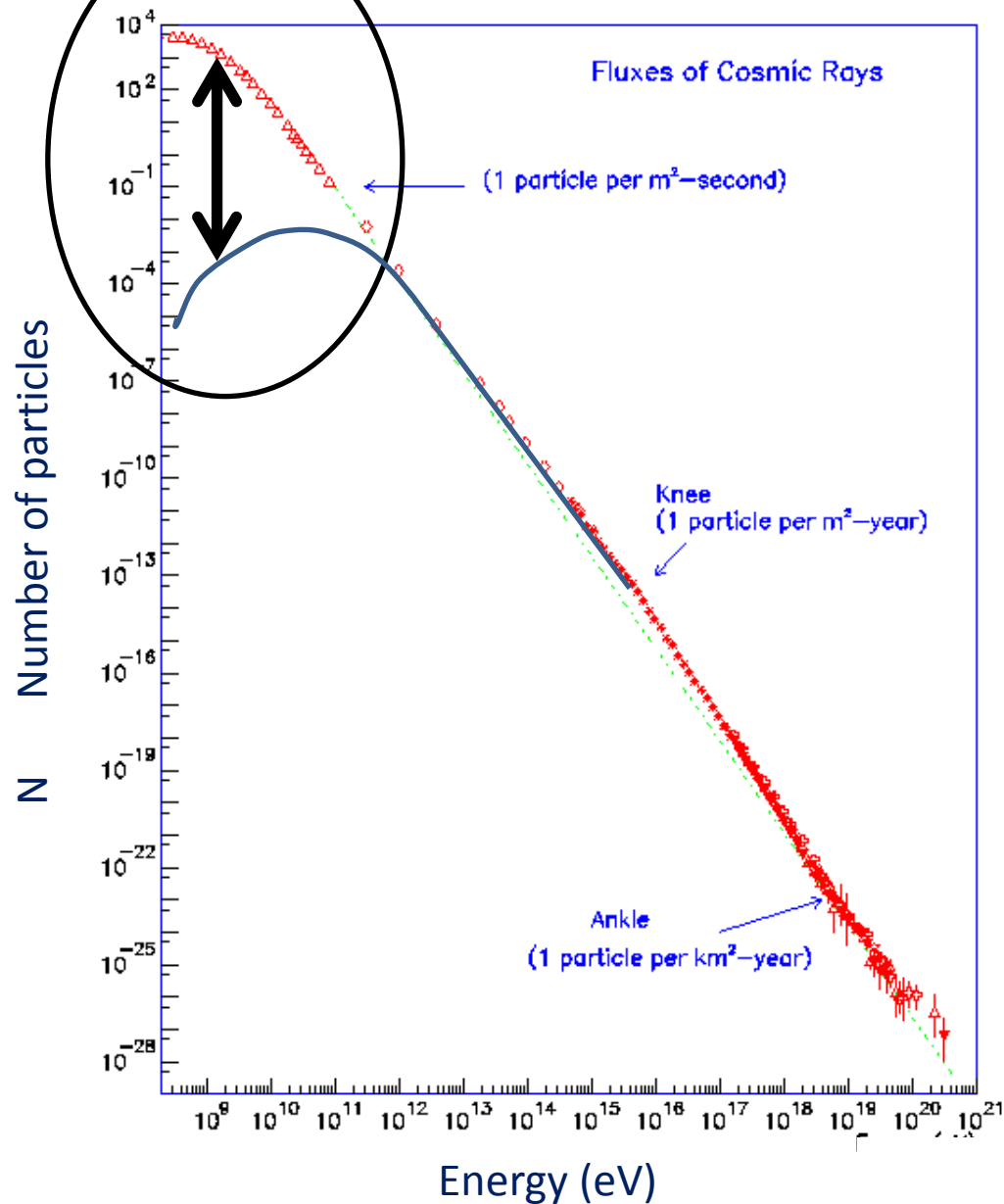
Topics

- South African astronomy
- Particle vs. photon astronomy
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- Dark matter
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- **Cosmic-ray variations**
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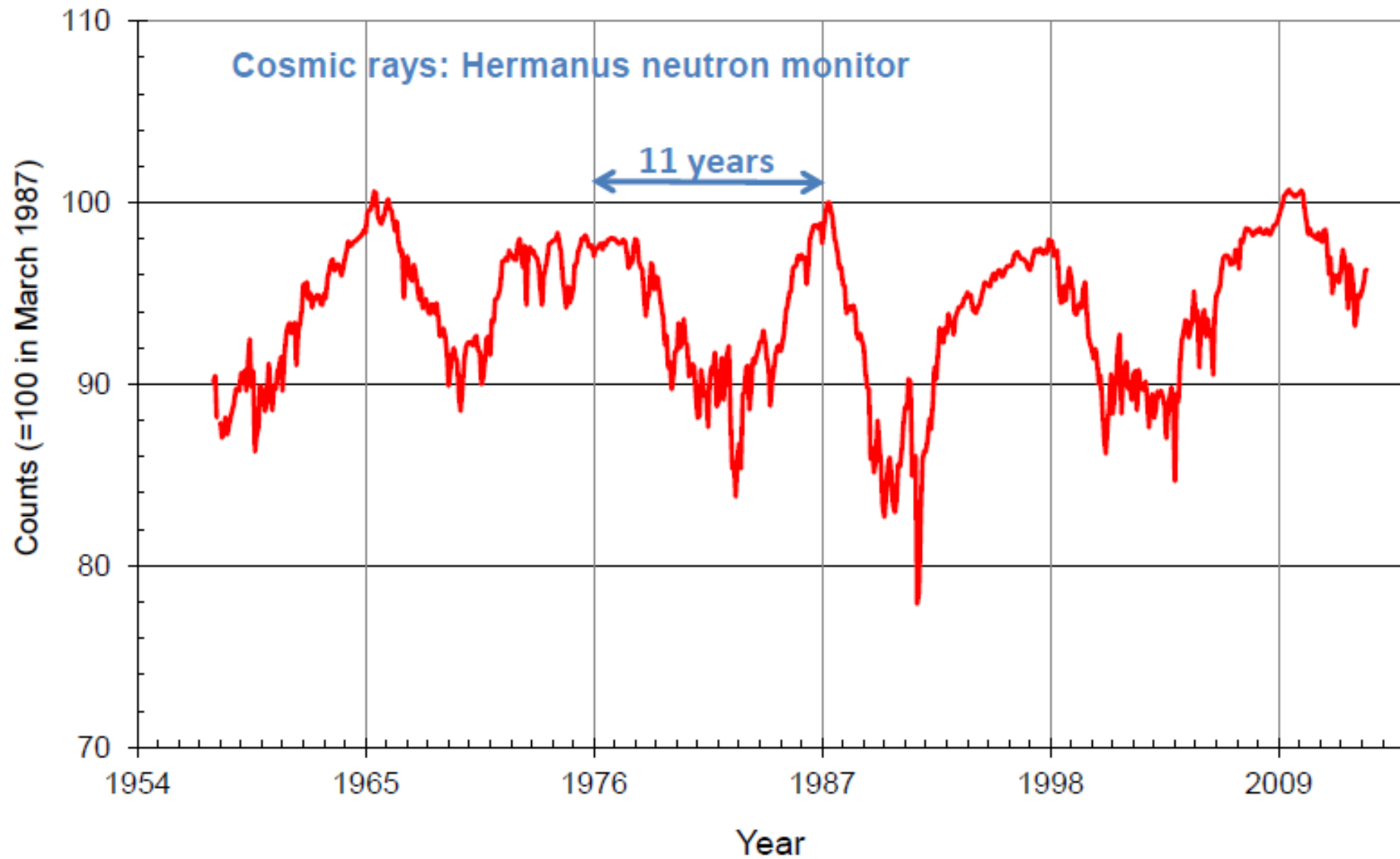
Cosmic ray spectrum



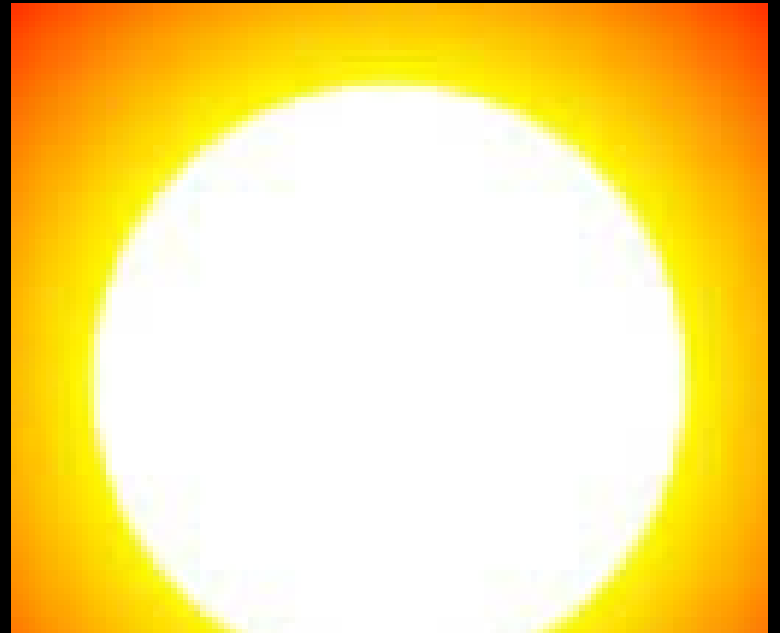
Cosmic ray spectrum



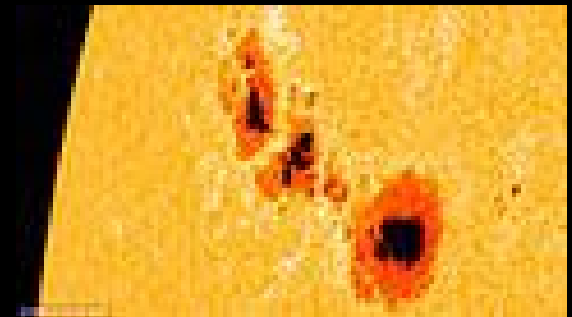
Cosmic-ray counts



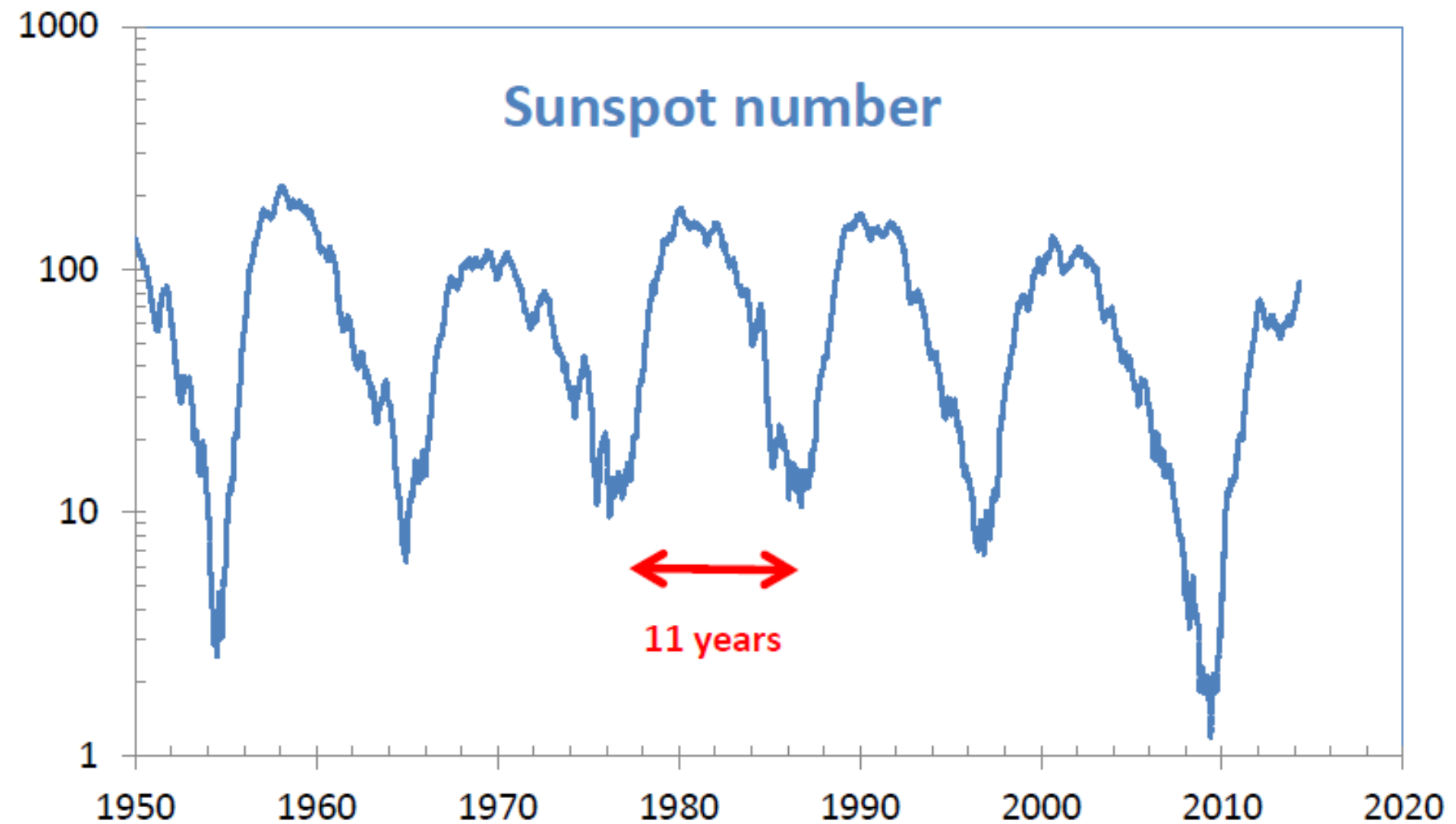
The Sun



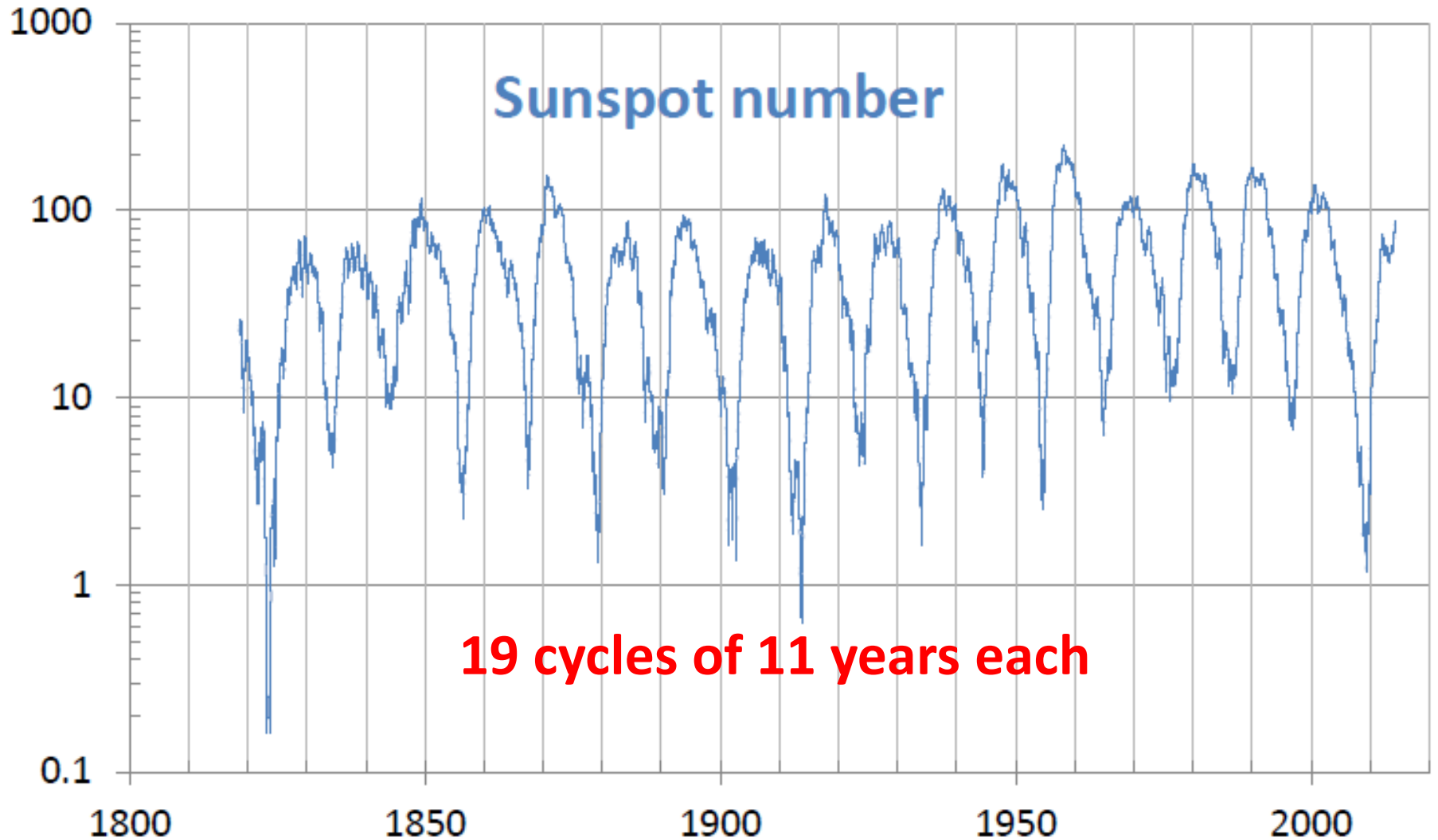
Sunspots



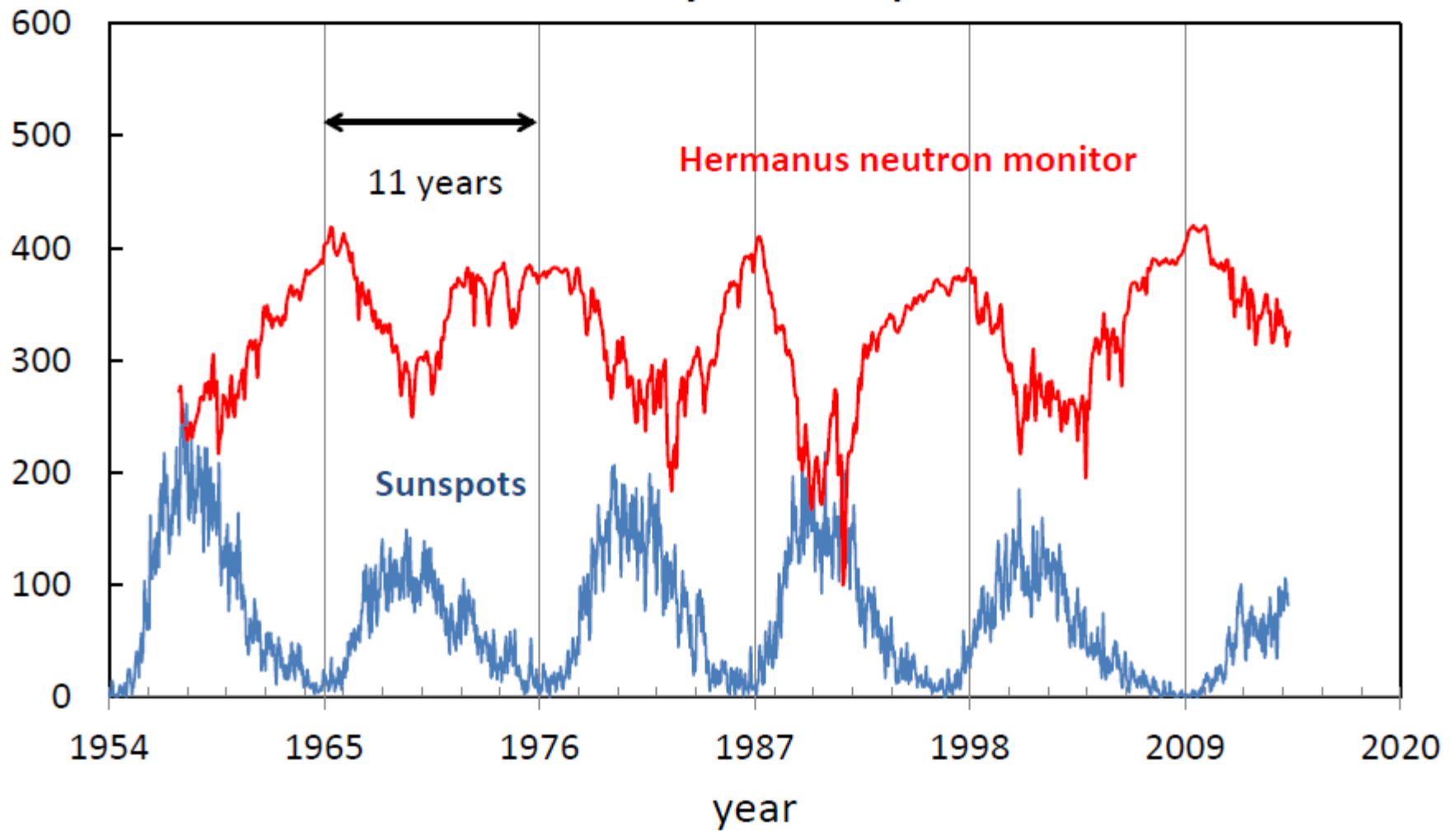
Sunspots



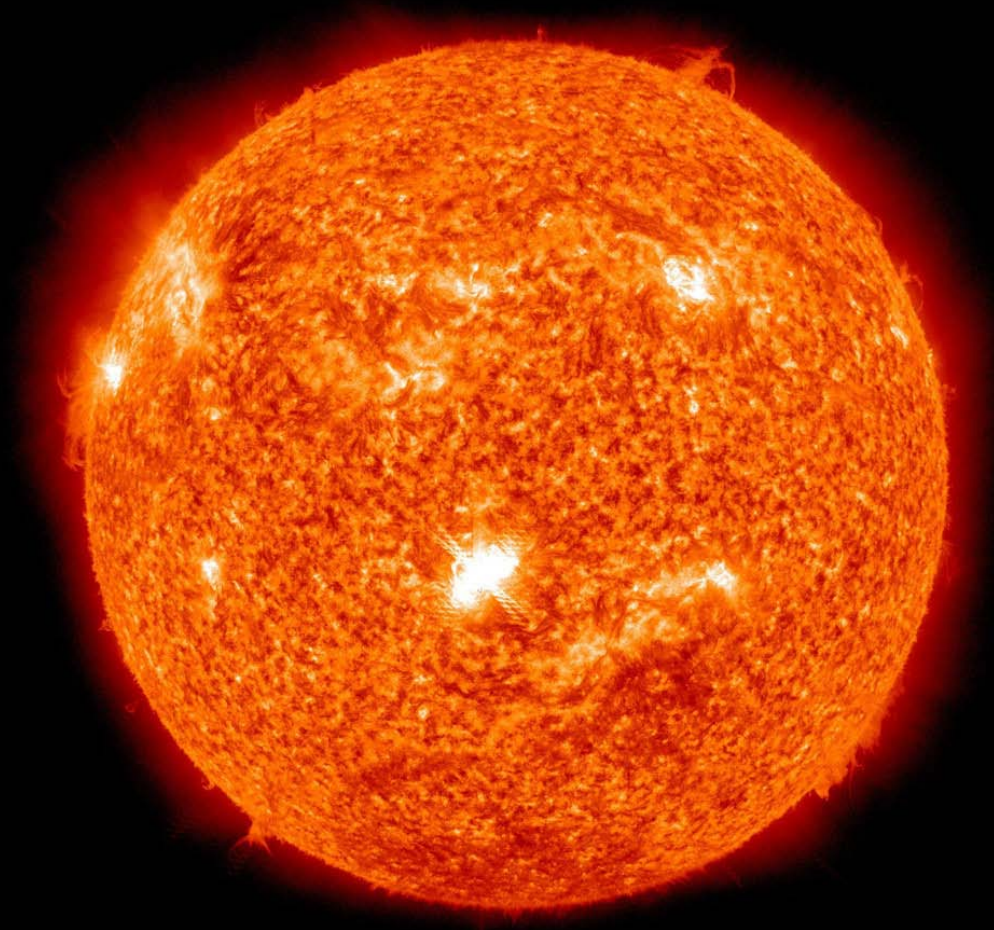
Sunspots since 1818



Cosmic rays and sunspots



Solar Atmosphere



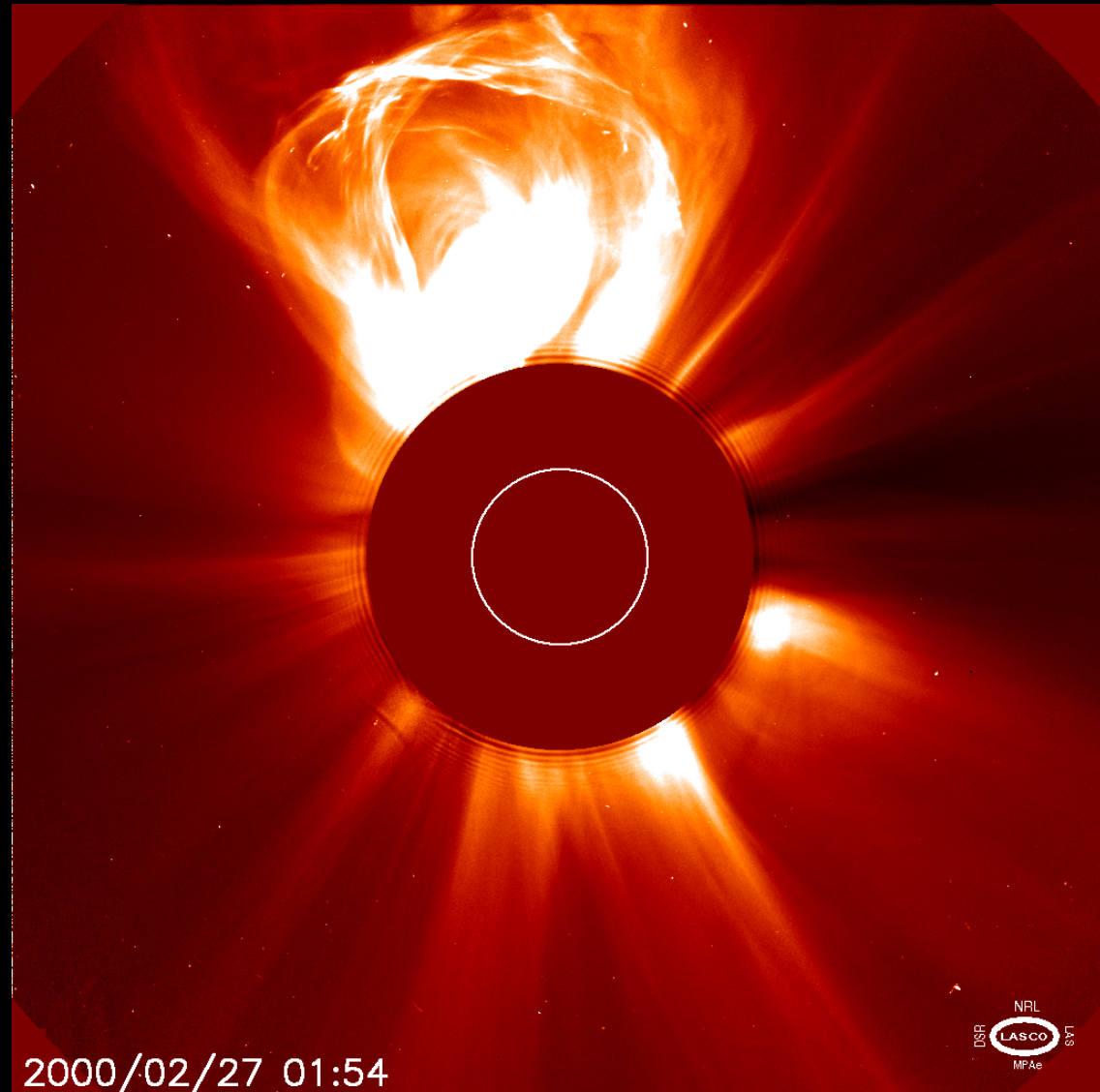
SDO/AIA 304 2011-02-13 17:36:45 UT

NASA

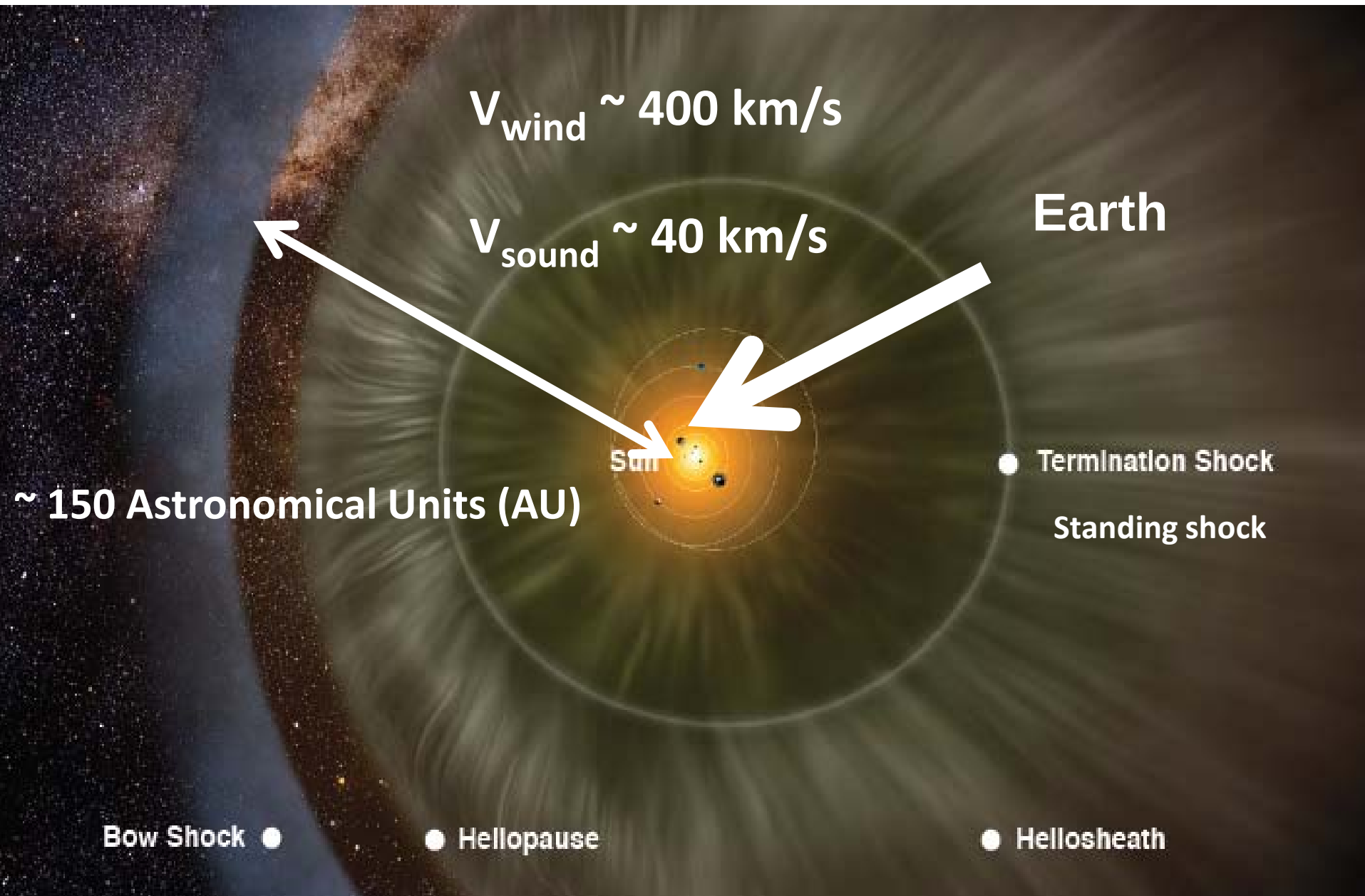
Solar Flare



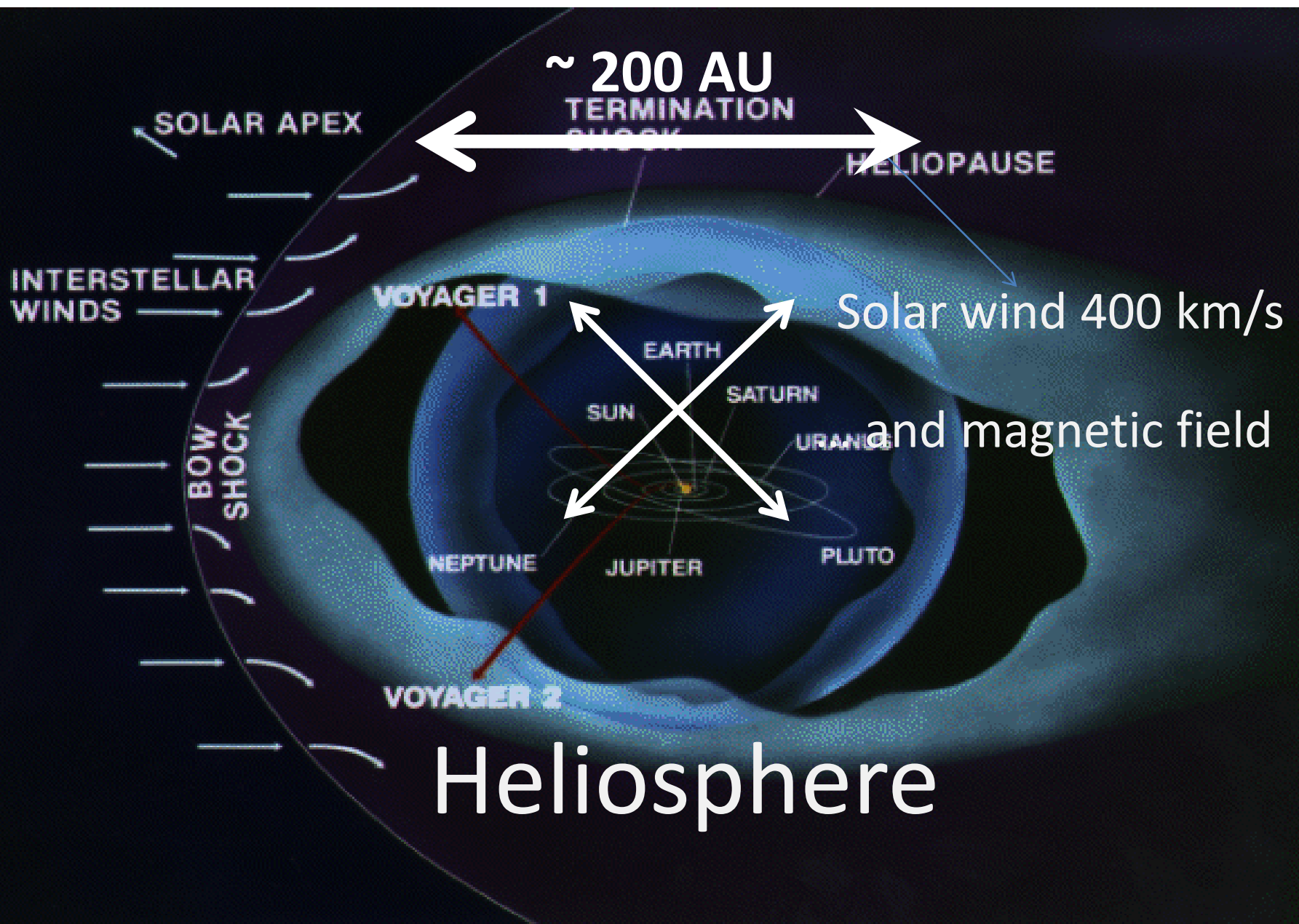
Solar wind and Coronal Mass Ejection



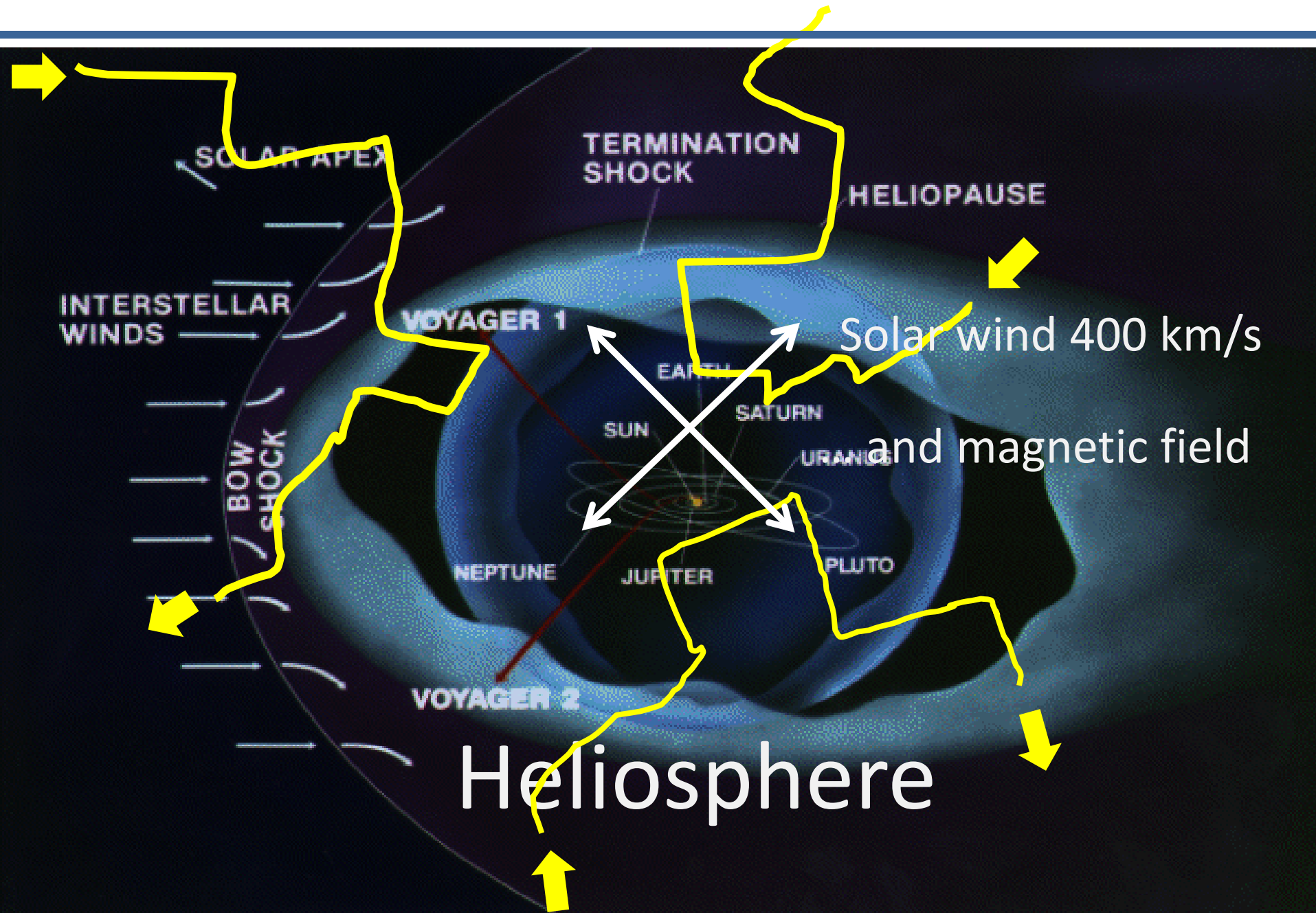
The Solar Wind and Heliosphere



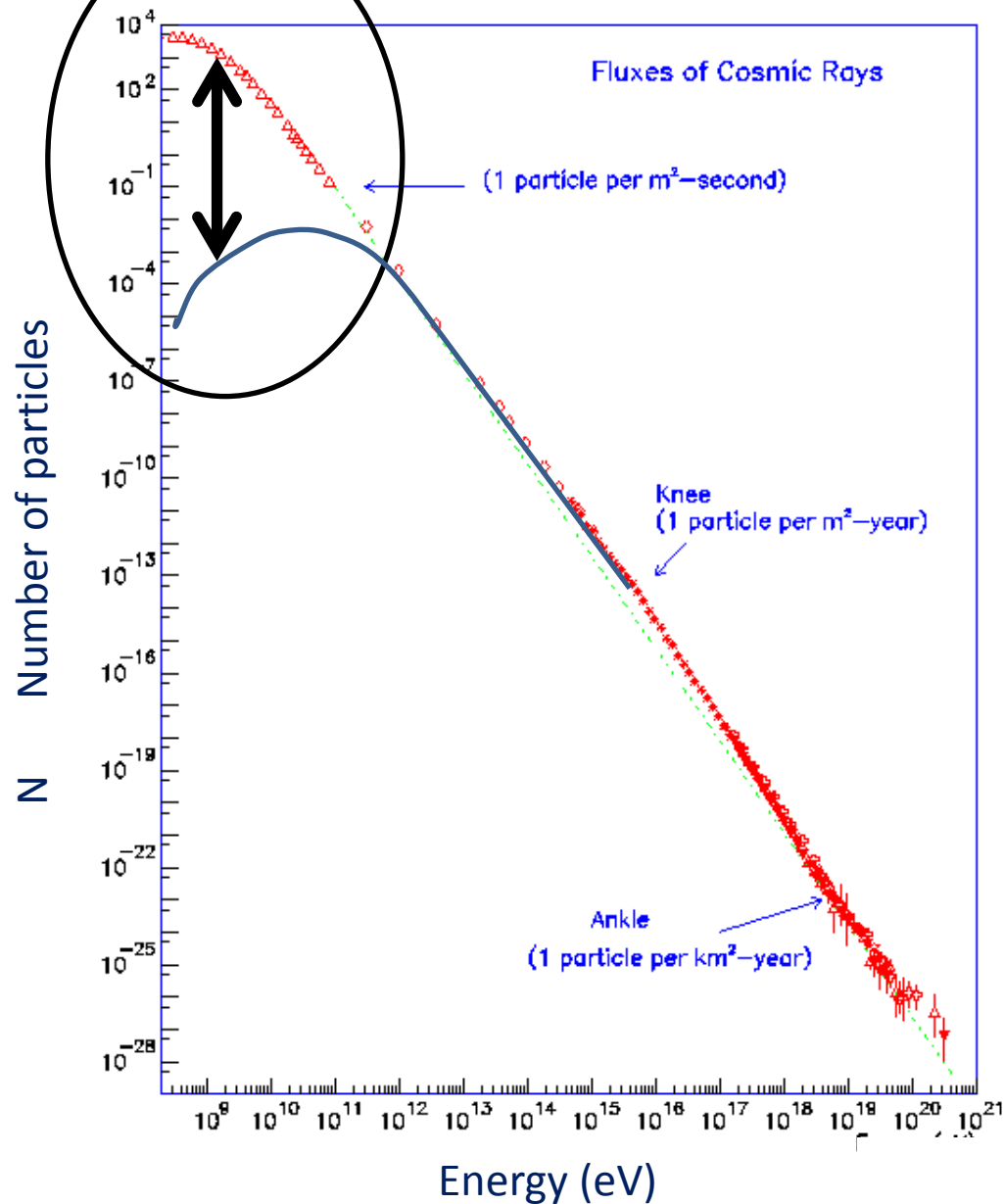
Cosmic rays in the heliosphere



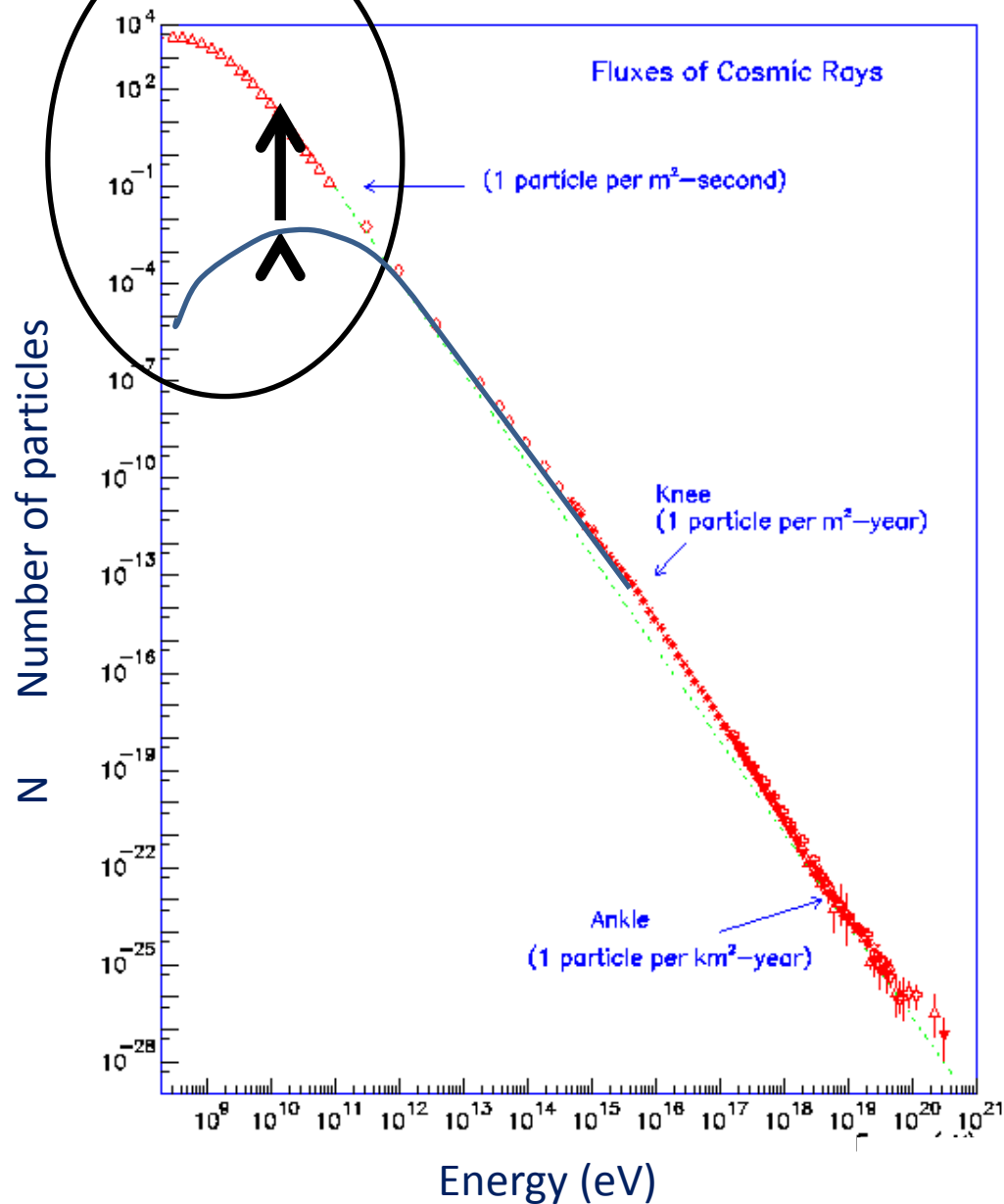
Cosmic rays in the heliosphere



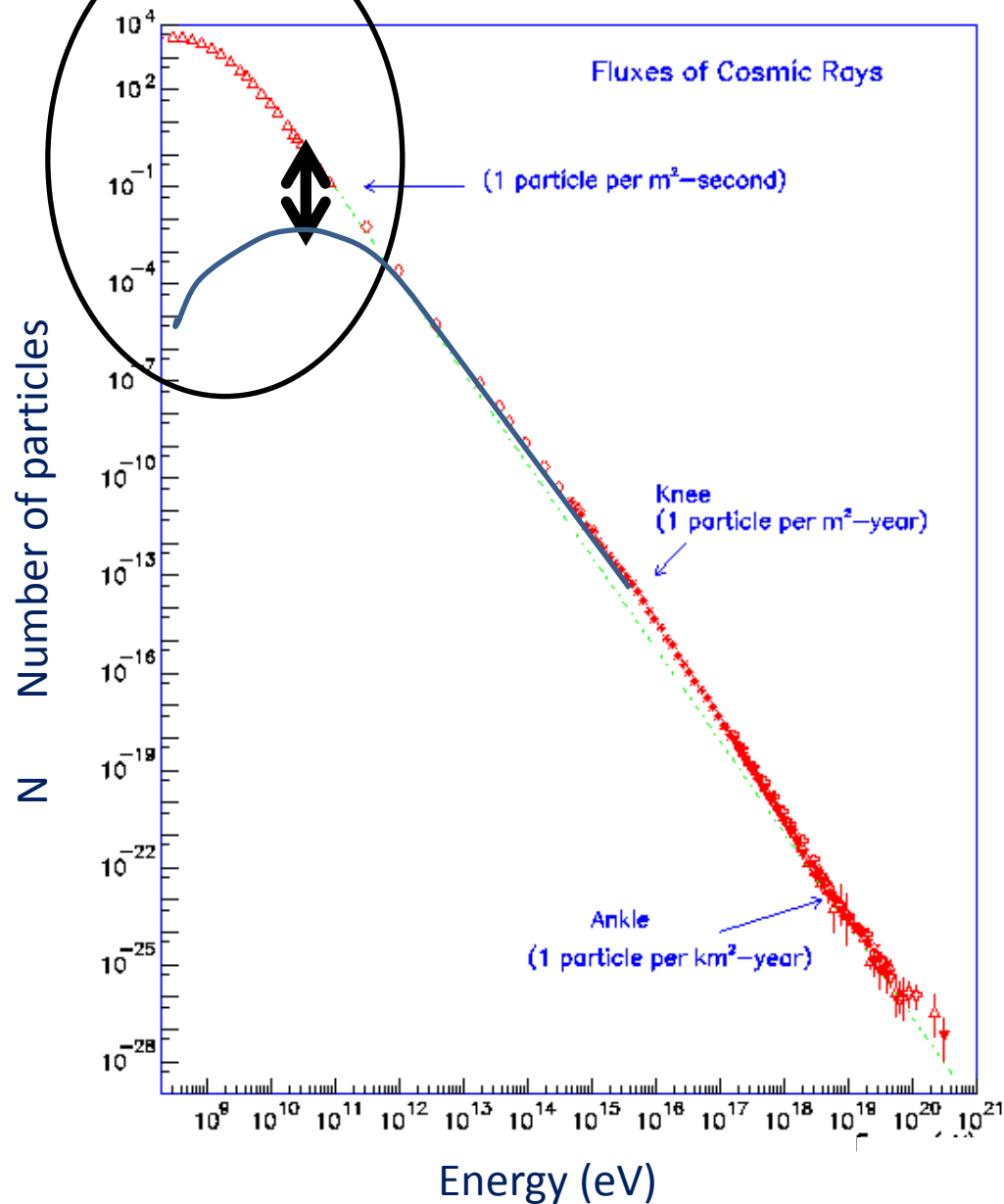
Cosmic ray spectrum



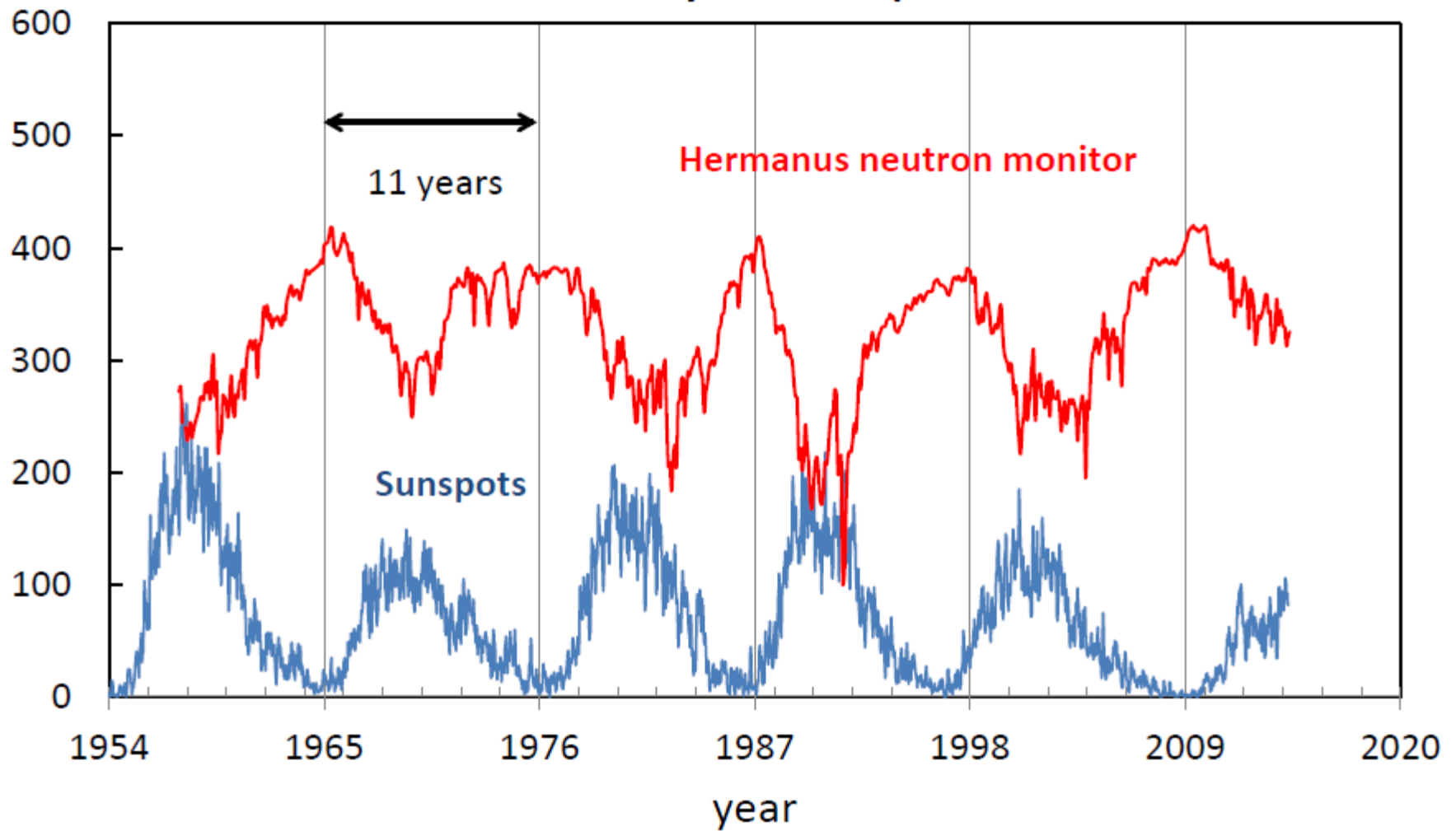
Cosmic ray spectrum



Cosmic ray spectrum



Cosmic rays and sunspots



The Voyager Mission – launched 1977

Voyager 1
130 AU

Voyager 2

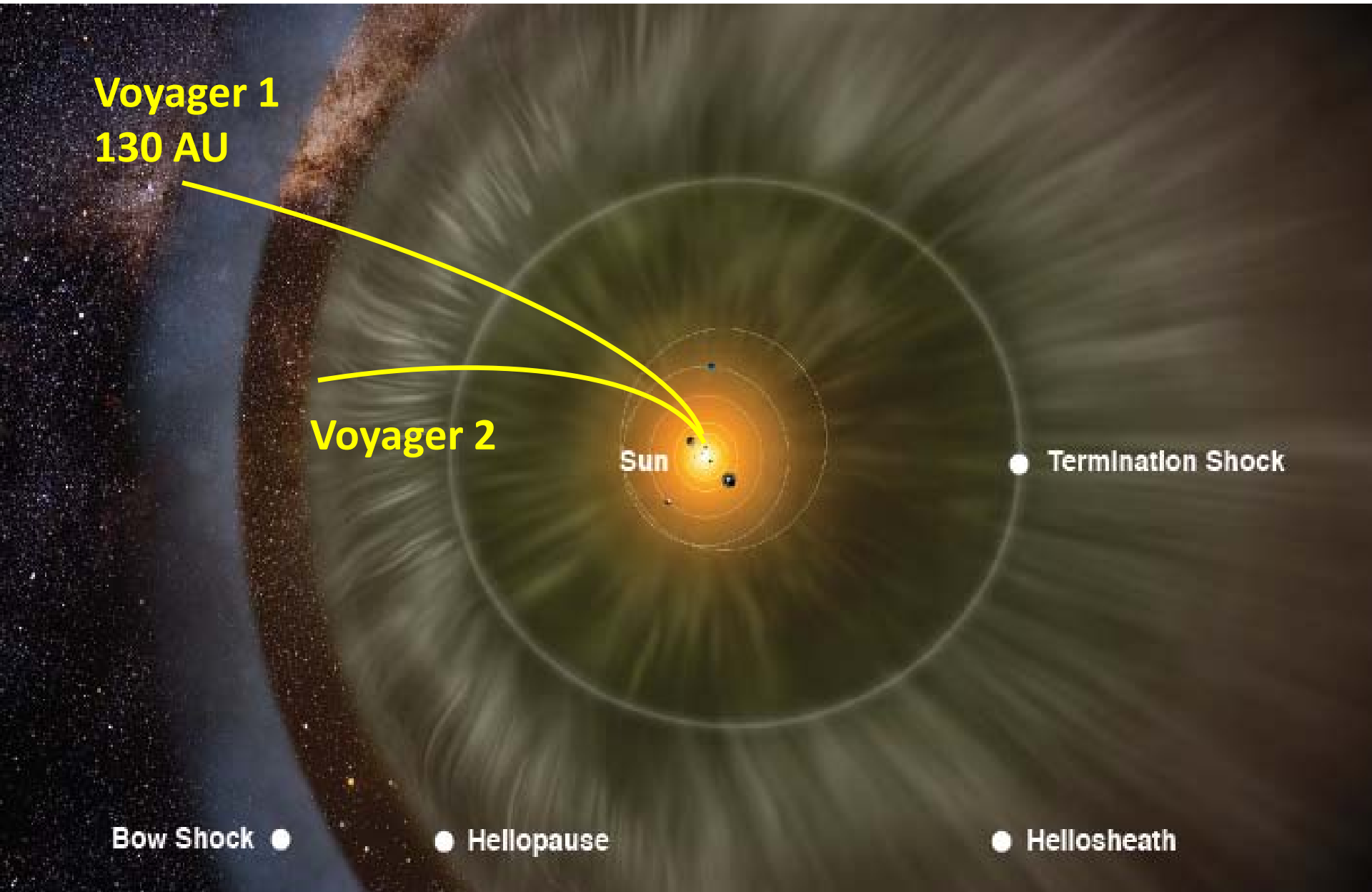
Sun

● Termination Shock

Bow Shock ●

● Heliosheath

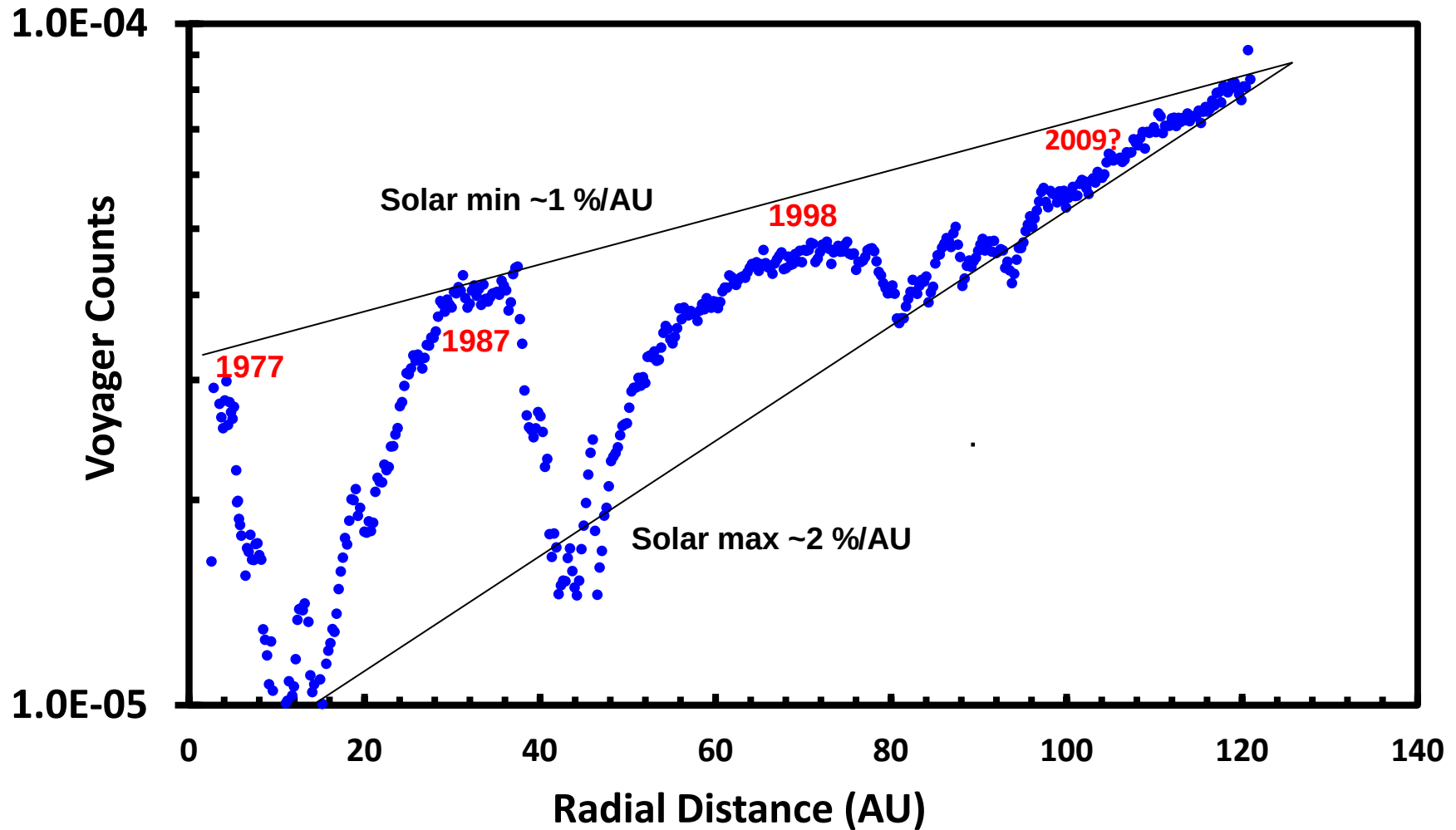
● Heliosheath



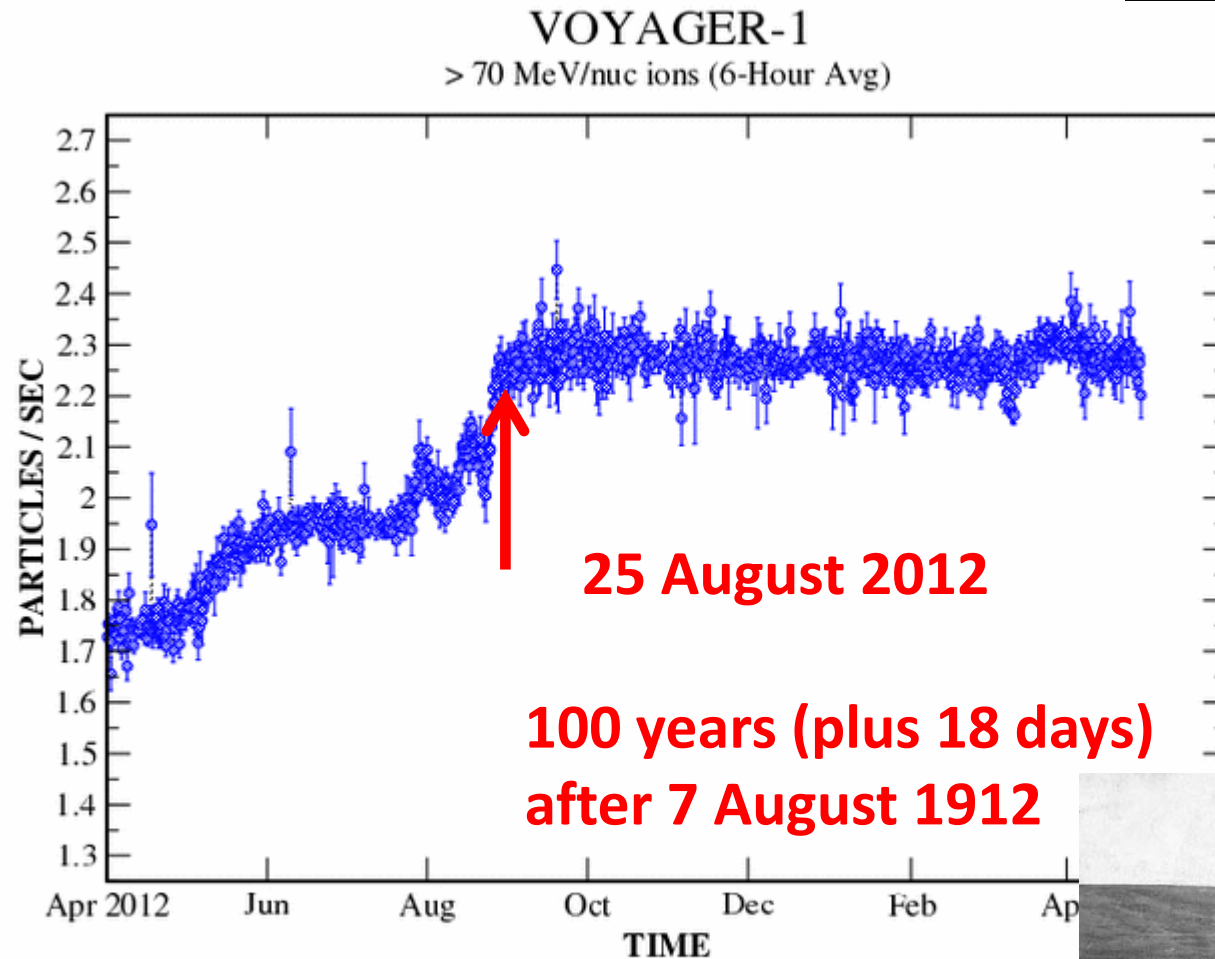
The Voyager Mission



265 MeV/n He Voyager 1 Counts



The Voyager Mission



Humanity's farthest journey

Voyager 1
130 AU

Voyager 2

Sun

Bow Shock ●

● Hellopause

● Hellosheath

National Aeronautics and Space Administration



Date: April 28, 2011

Time: 1–2:00 p.m.

NASA HQ Auditorium
300 E Street S.W.
Washington, D.C. 20546

Speakers:

Ed Stone

Voyager Project Scientist
Professor of Physics
California Institute of Technology

Ann Druyan

Creative Director,
Voyager Interstellar Message Project
Carl Sagan's Co-Writer and Widow

Suzanne Dodd

Voyager Project Manager
Jet Propulsion Laboratory

Merav Opher

Voyager Guest Investigator and
Assistant Professor of Astronomy
Boston University

NASA SCIENCE UPDATE

The Voyager Spacecraft Humanity's Farthest Journey

You're invited...

Experience firsthand:

- The story of how a unique idea became scientific legend
- The exotic region of space Voyagers are exploring right now and where they're going
- The cosmic context: What it means to leave our sun's sphere of influence behind
- The vision of sending a message from Earth to possible life elsewhere in the galaxy
- The enduring science impact on our imaginations, education and future exploration

You are invited to hear the story of the 33-year journey of NASA's twin Voyager spacecraft to the edge of our solar system, where they are approximately 10 billion miles away from our sun. The Voyagers are currently exploring an uncharted region located far beyond the planets we now know...a region that forms the outer boundary of the solar bubble. In a few years, humanity's farthest explorer will transition into the medium between stars—known as interstellar space.



www.nasa.gov

Theory

Three forms of the Transport Equation

$$\frac{\partial U}{\partial t} + \nabla \cdot (\mathbf{V}U - \mathbf{K} \cdot \nabla U) - \frac{1}{3}(\nabla \cdot \mathbf{V}) \frac{\partial}{\partial p}(pU) = 0$$

or, in terms of f

$$\frac{\partial f}{\partial t} + \nabla \cdot (\mathbf{V}f - \mathbf{K} \cdot \nabla f) - \frac{1}{3p^2}(\nabla \cdot \mathbf{V}) \frac{\partial}{\partial p}(p^3 f) = 0$$

or, slightly manipulated

$$\frac{\partial f}{\partial t} + \mathbf{V} \cdot \nabla f - \nabla \cdot (\mathbf{K} \cdot \nabla f) - \frac{1}{3p^2}(\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln p} = 0$$

Too difficult to solve analytically

Cosmic Rays in the Heliosphere

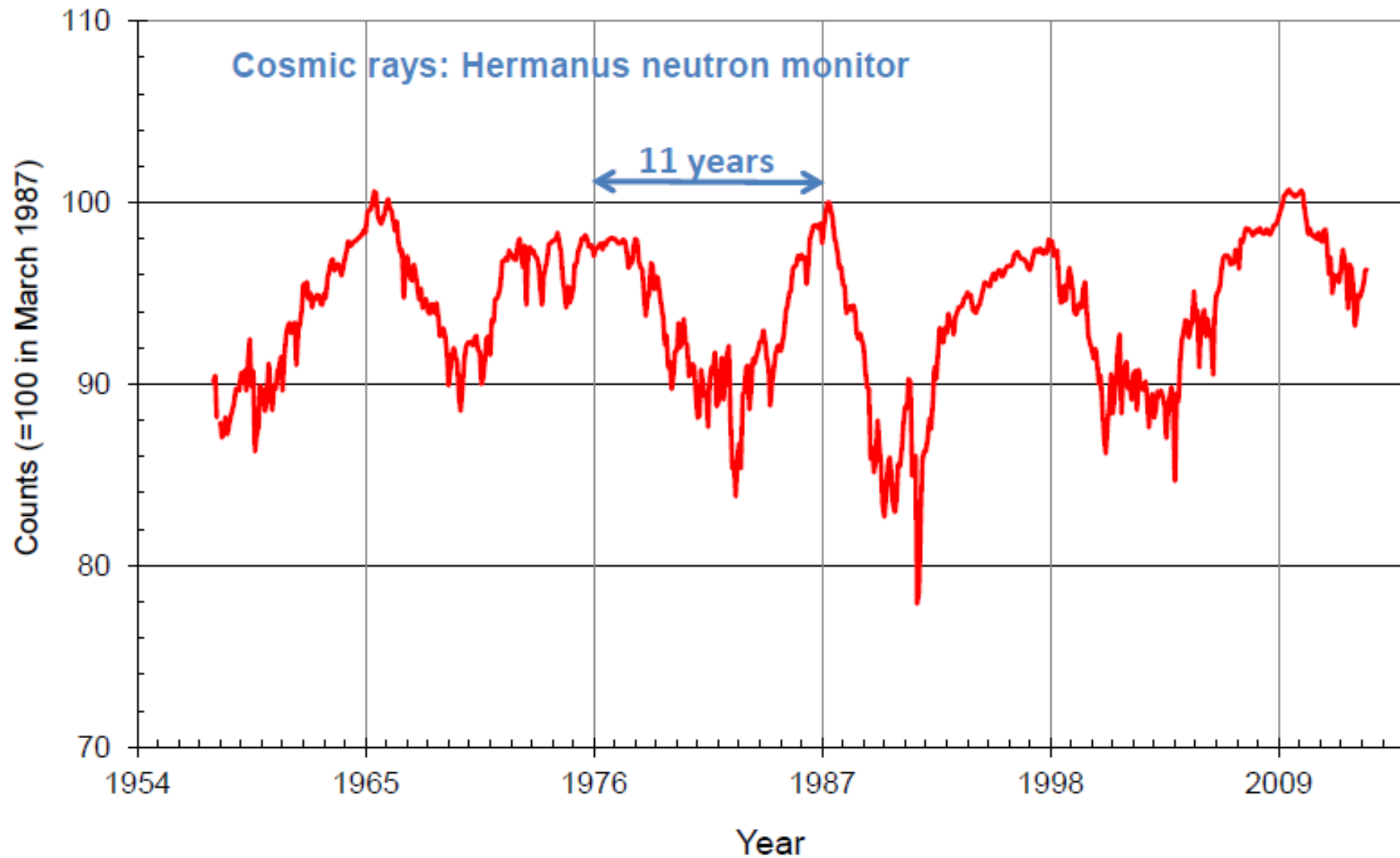
Cosmic-ray diffusion tensor

$$\mathbf{K} = \begin{pmatrix} \kappa_{\parallel} & 0 & 0 \\ 0 & \kappa_{\perp} & \kappa_T \\ 0 & -\kappa_T & \kappa_{\perp} \end{pmatrix}$$

each $\kappa_i = \kappa_i(\mathbf{r}, P, t)$

- How do the solar wind and the heliospheric magnetic field have to look to explain the observed cosmic-ray intensity variations?
- Does this agree with what we observe of the solar wind and heliospheric magnetic field?

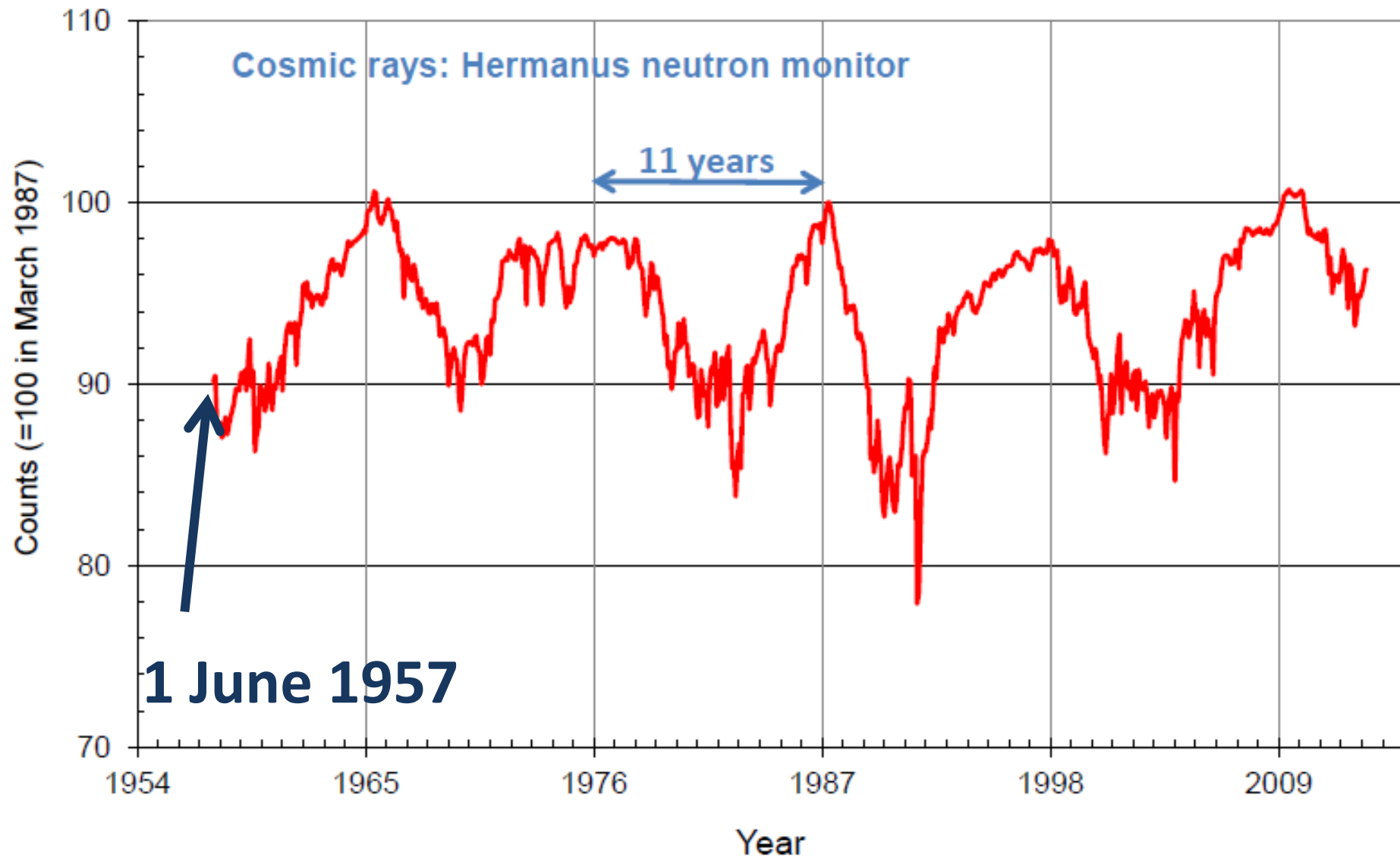
Experimental work



Hermanus neutron monitor



Experimental work



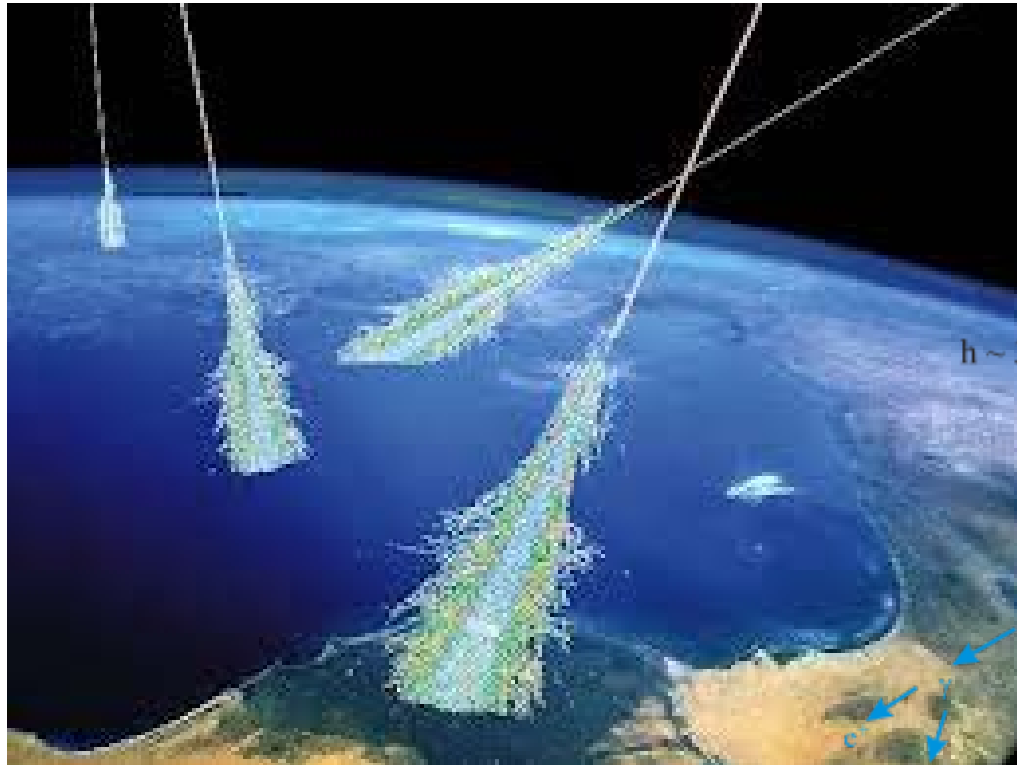
Sanae



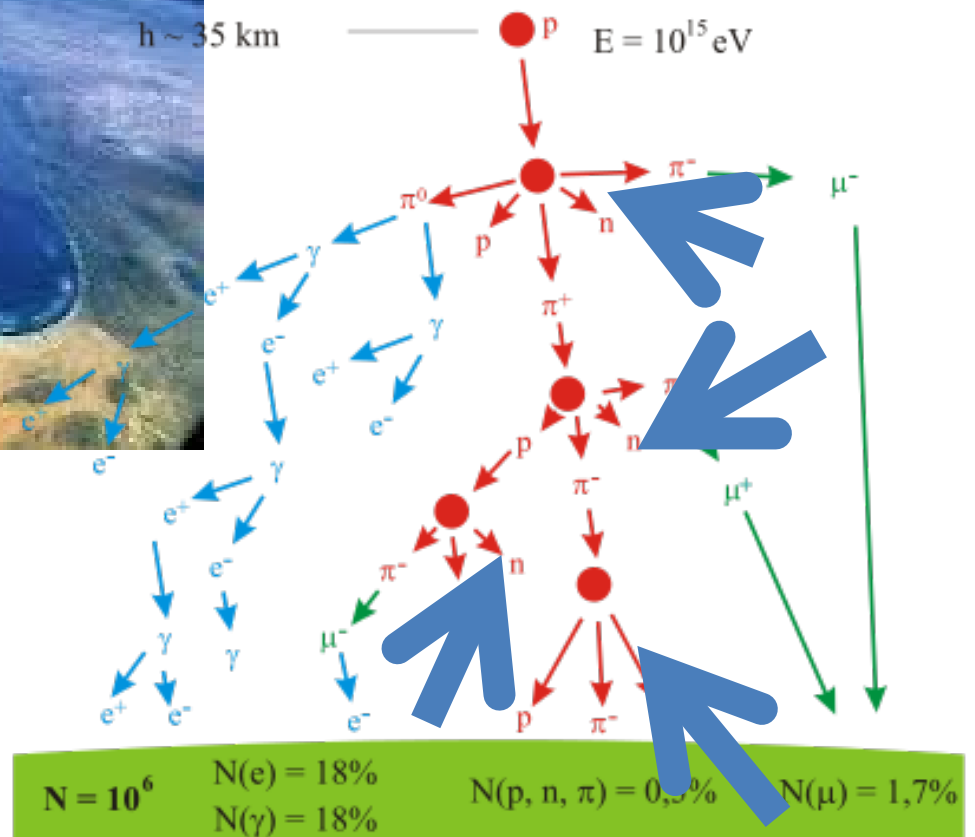
Sanae Neutron Monitor



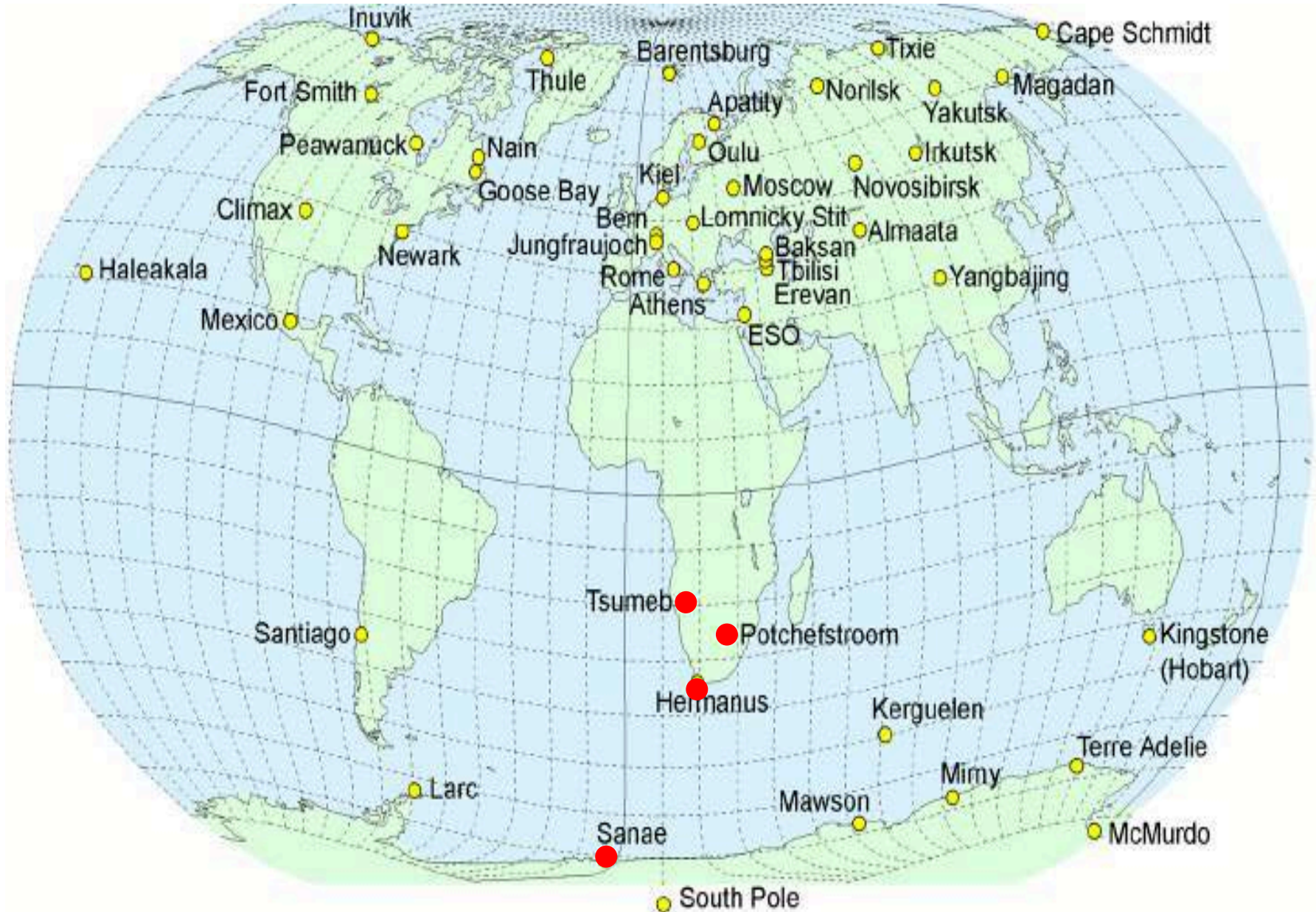
Neutron monitors – sensitive to the neutrons



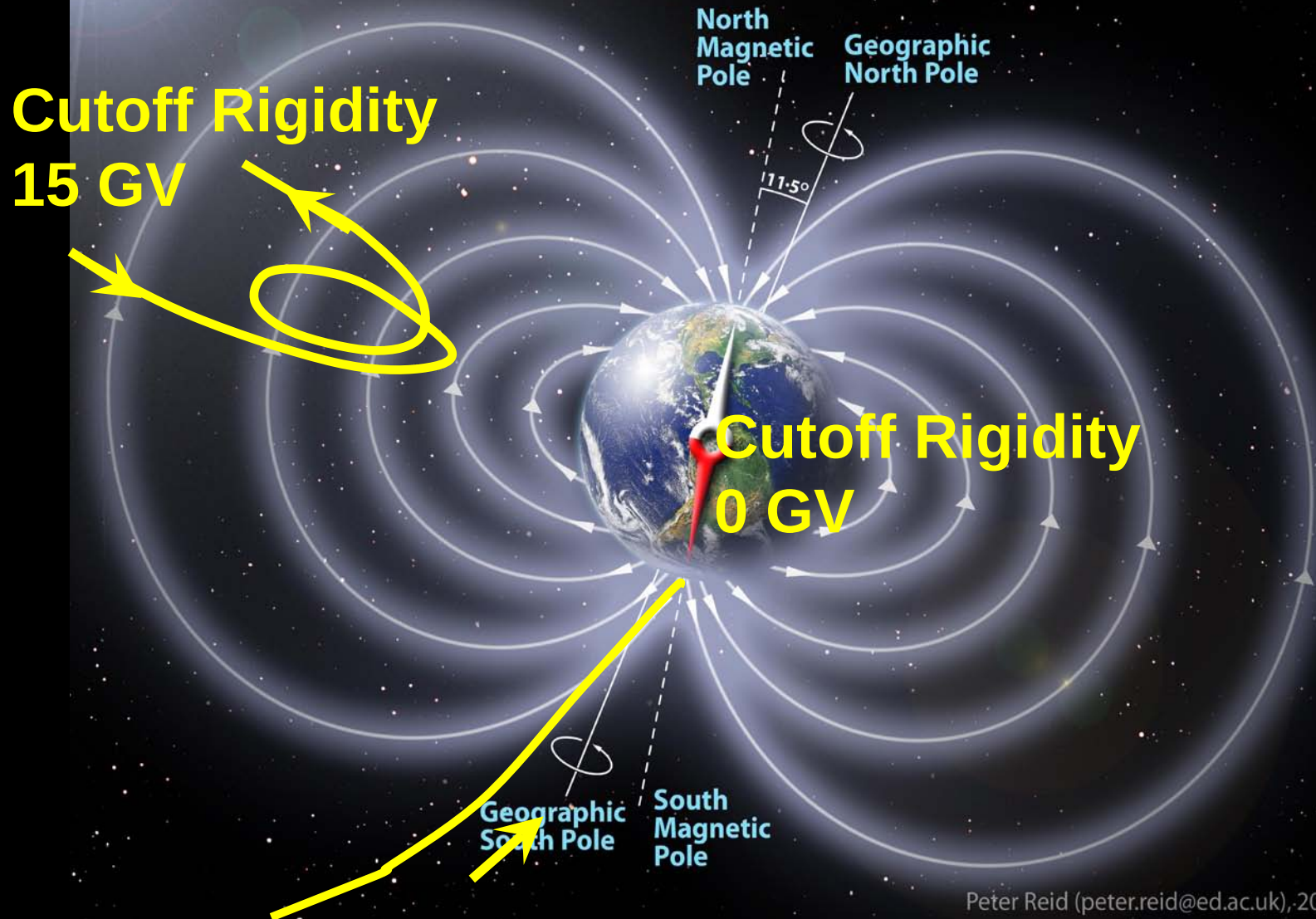
$h \sim 35 \text{ km}$



Neutron monitor network



The poles are better



The poles are better

A window into geospace

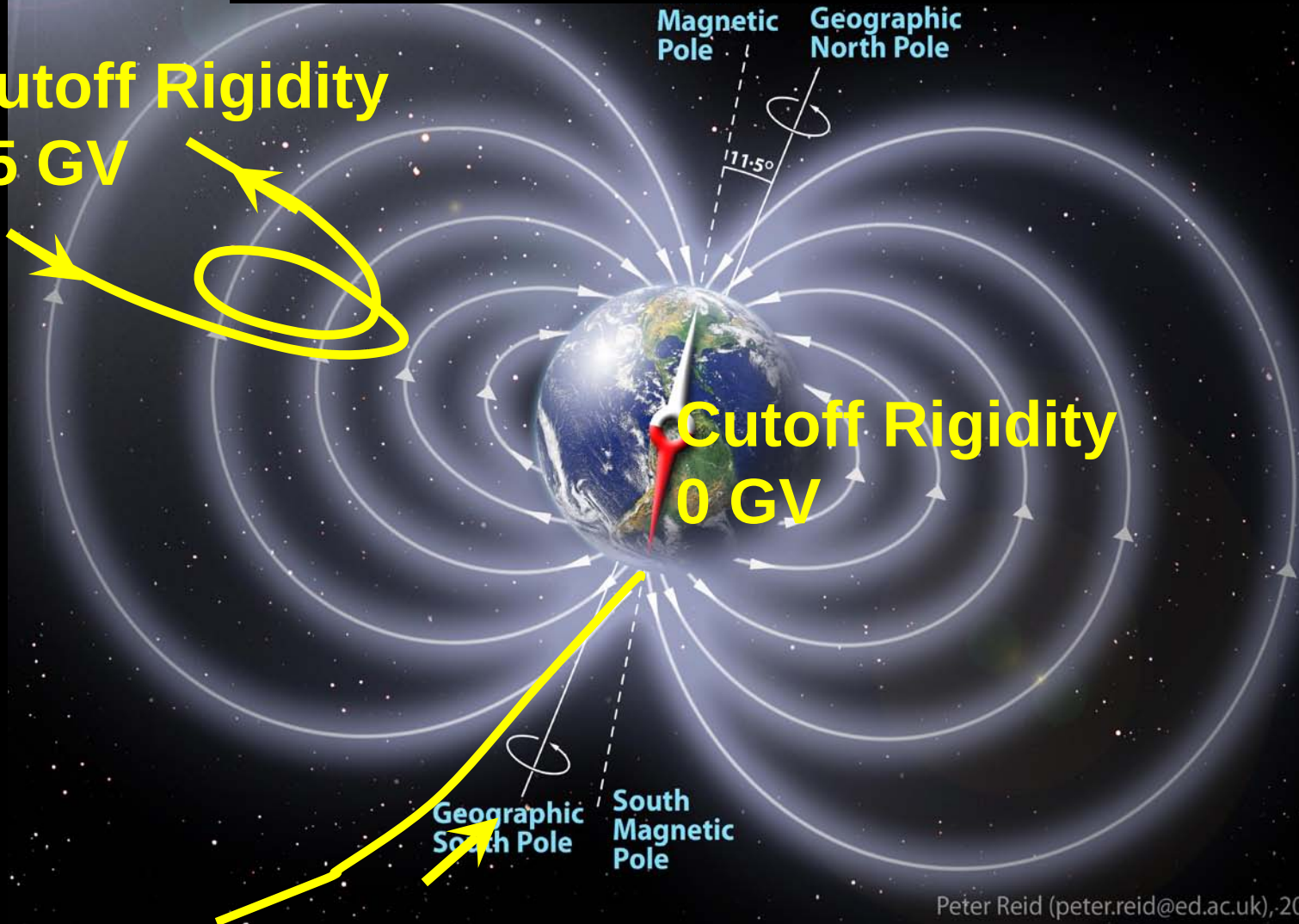
Cutoff Rigidity
15 GV

Magnetic Pole
Geographic North Pole

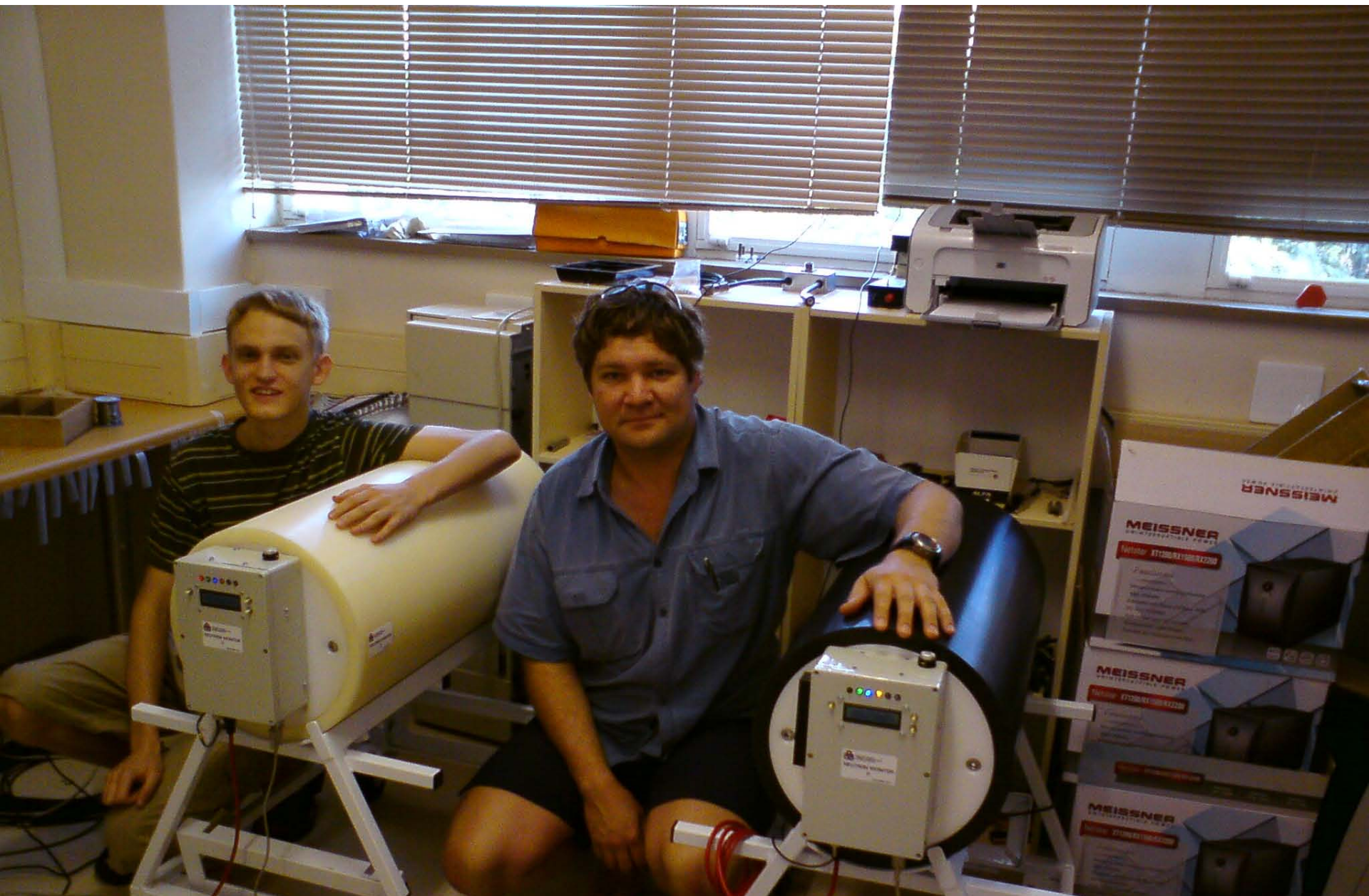
11.5°

Cutoff Rigidity
0 GV

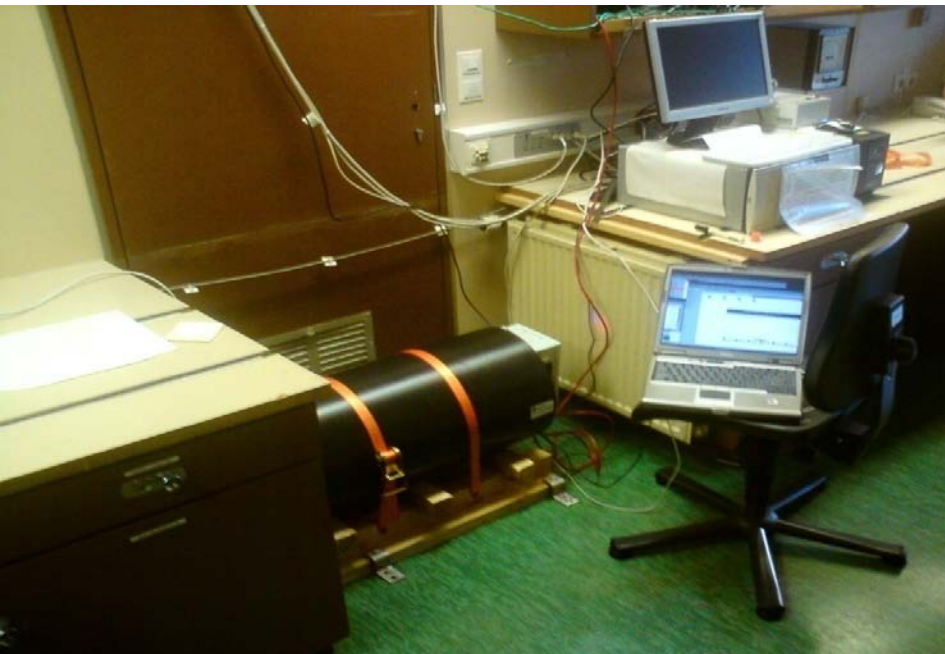
Geographic South Pole
South Magnetic Pole



Mini neutron monitors



Mini neutron monitors



Mini neutron monitors



French/Italian Station Dome C

Amundsen-Scott

3200 m (15 x sea level)

Dome C

Casey

McMurdo
Scott

ROSS
SEA

Dumont d'Urville

Mini neutron monitors

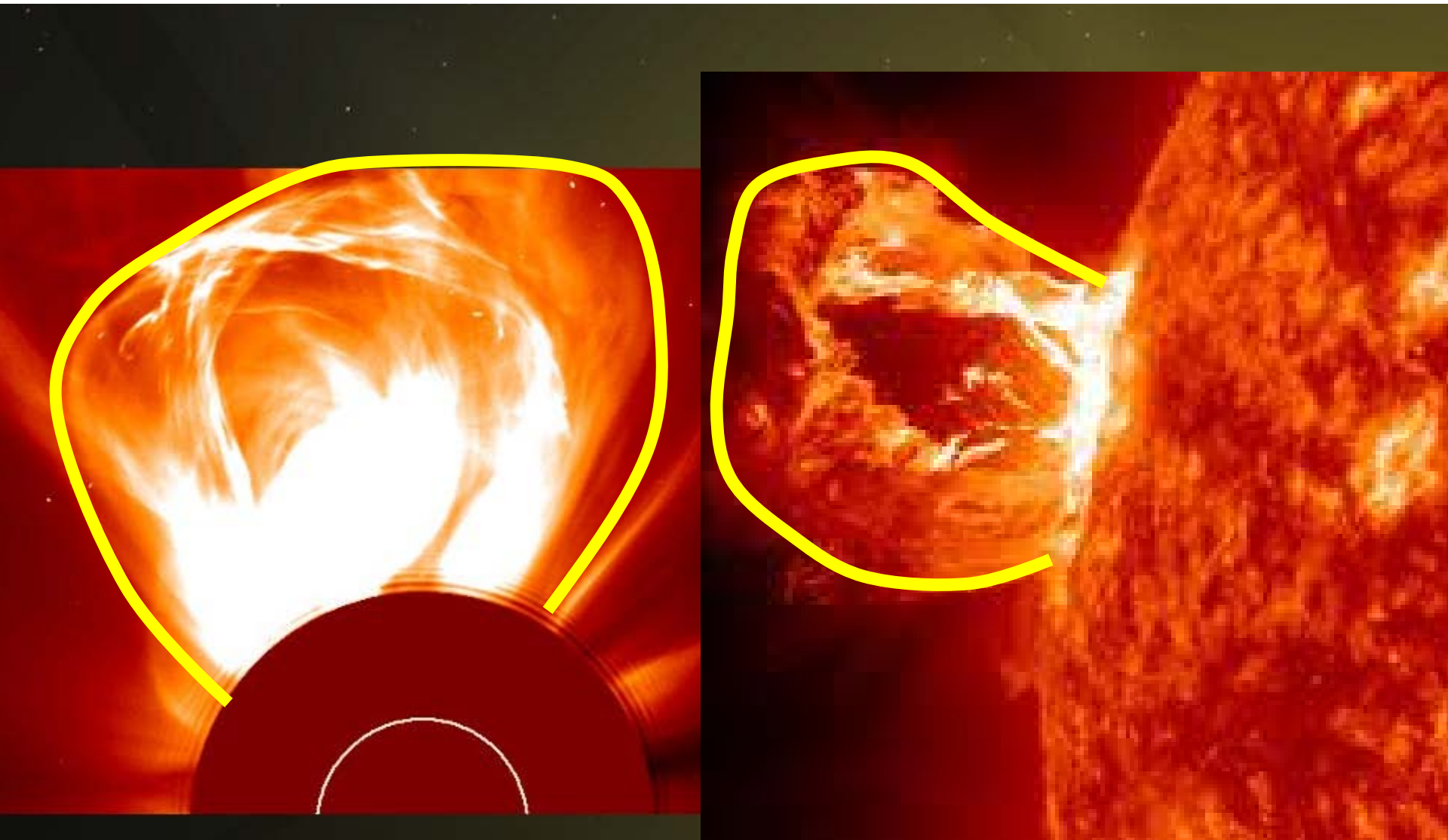
Sierra Negra, Mexico, 4200 m



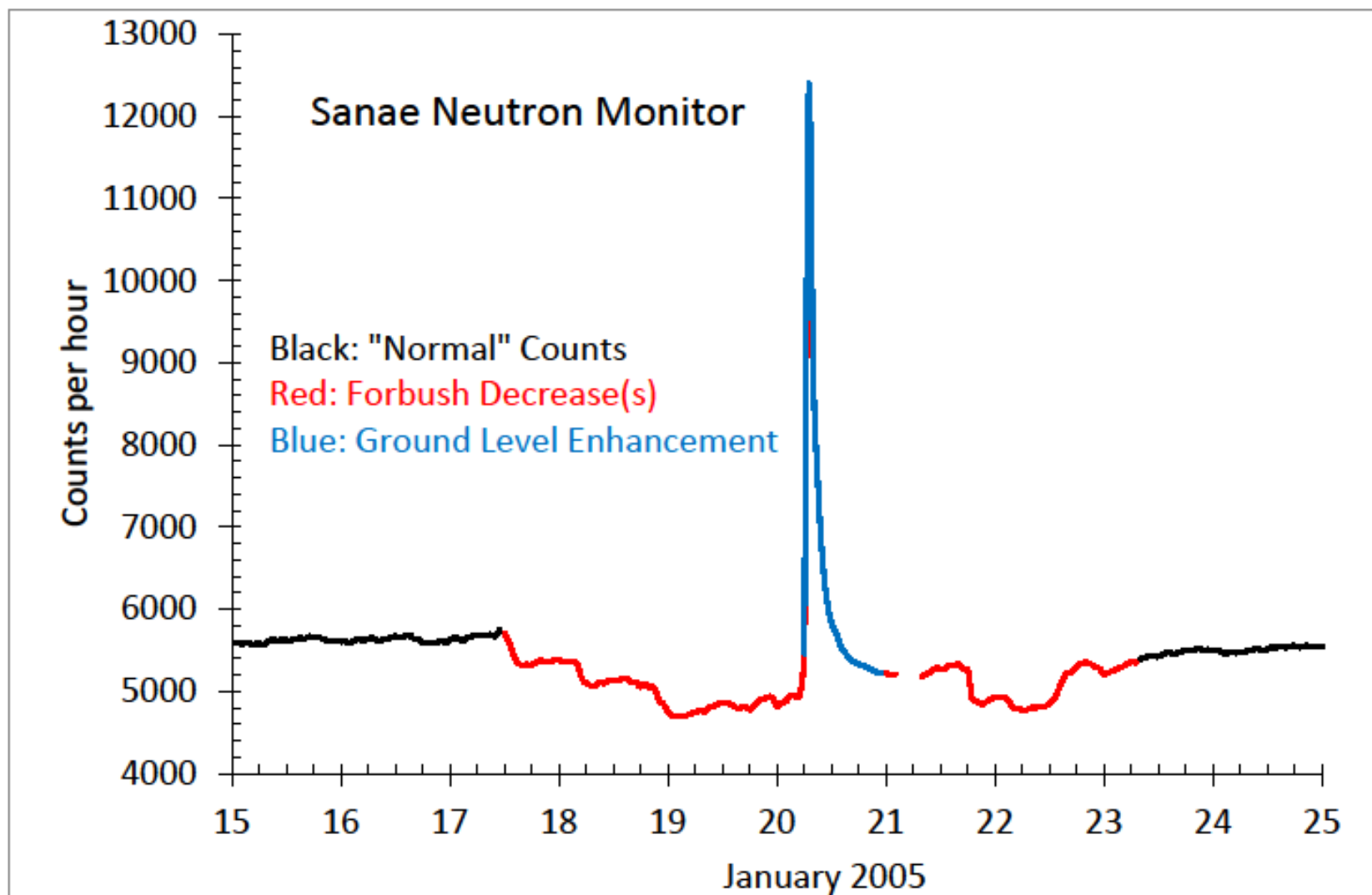
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- “Cosmic” rays from the sun
- Helioclimatology

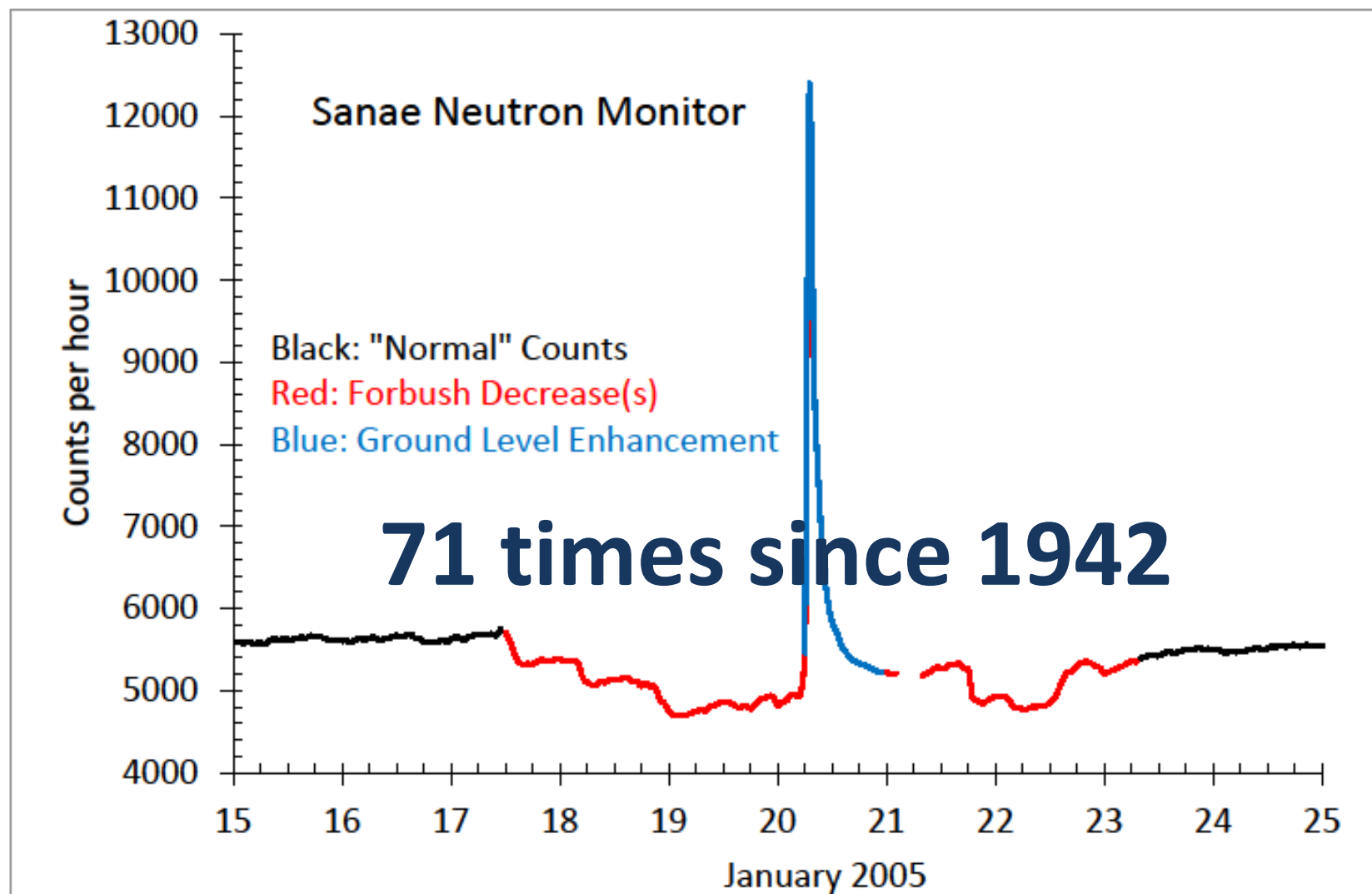
Solar flare and coronal mass ejection - shocks



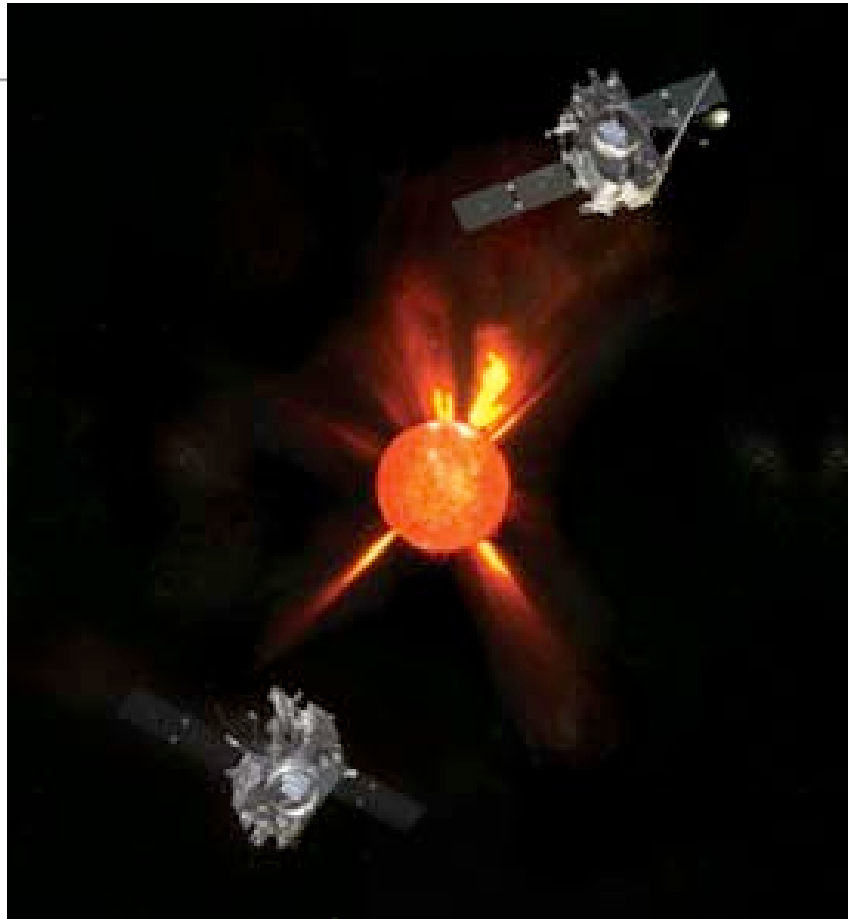
Ground-level Enhancement (GLE) = "cosmic" rays from sun



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Ground-level Enhancement (GLE) = "cosmic" rays from sun



See:

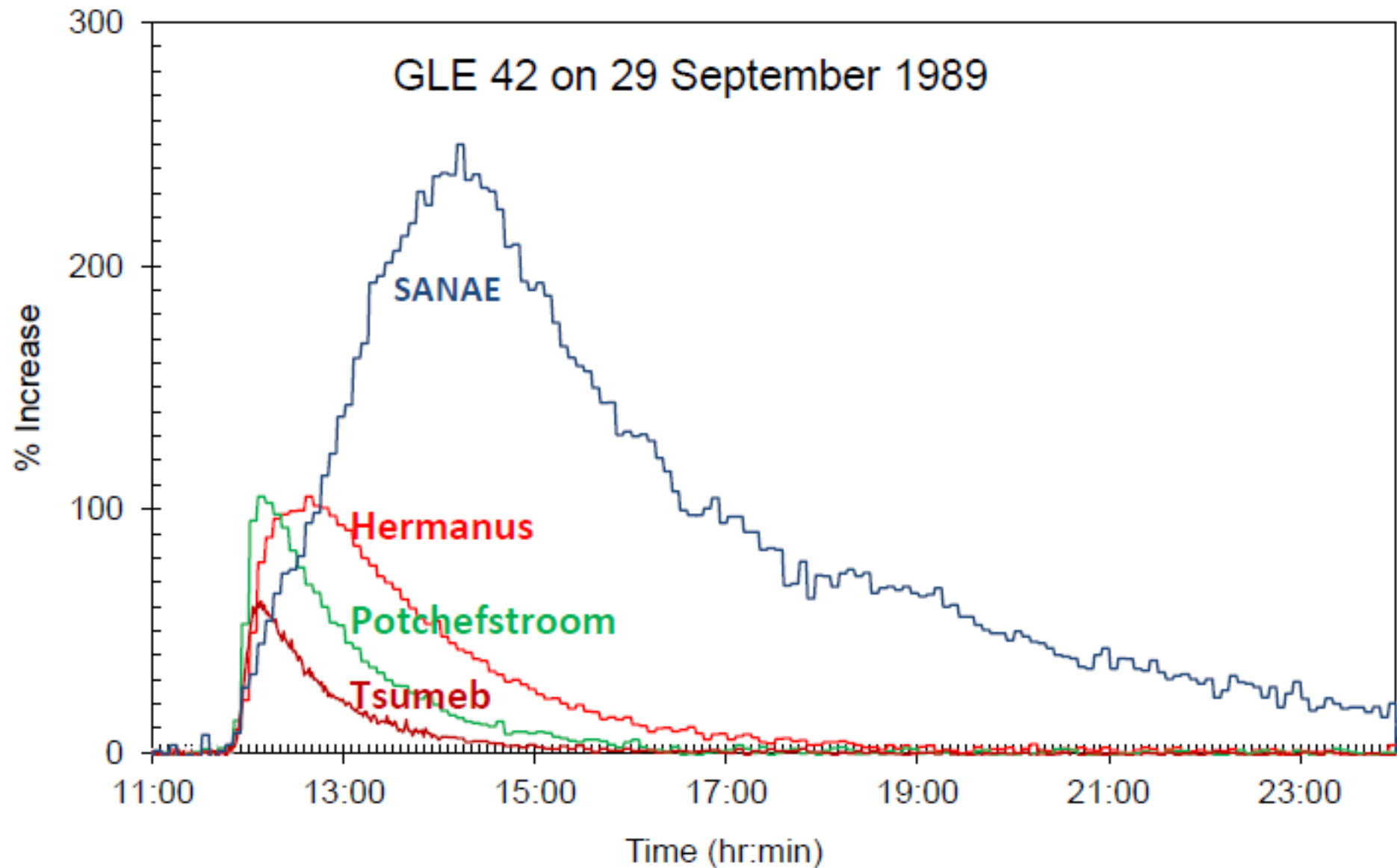
- Particles (GLE)
- Flare and CME (3D-stereo)
- Shock (3D-stereo)
- Gammas
- X-rays
- Radio
- Magnetic fields
- Kinks

4000

15 16 17 18 19 20 21 22 23 24 25

January 2005

The Window into Geospace.....



Topics

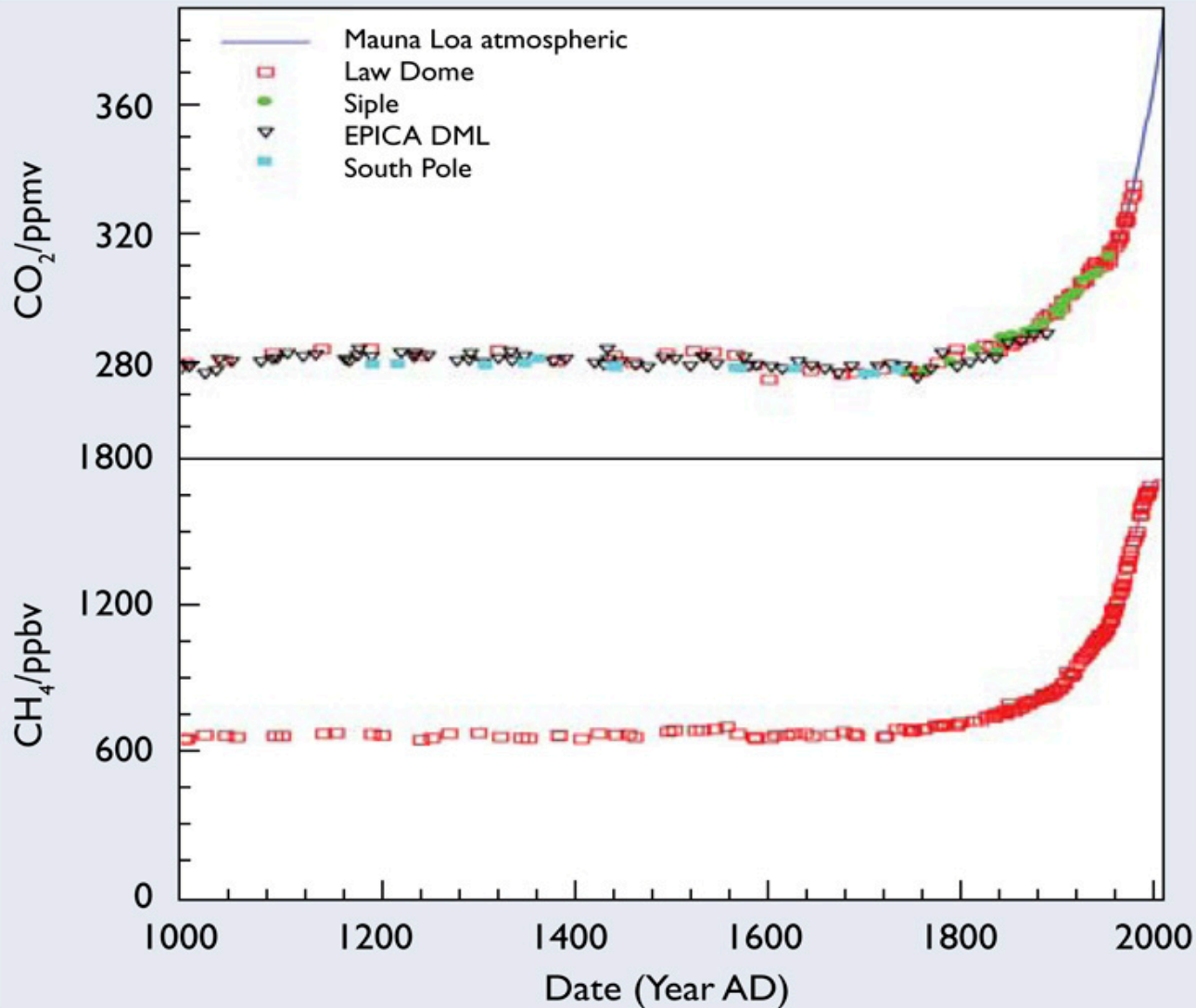
- South African astronomy
- Particle vs. photon astronomy
- Cosmic-ray spectra, composition
- Dark matter
- Neutrinos
- Cosmic-ray variations
- “Cosmic” rays from the sun
- **Helioclimatology**

Topics

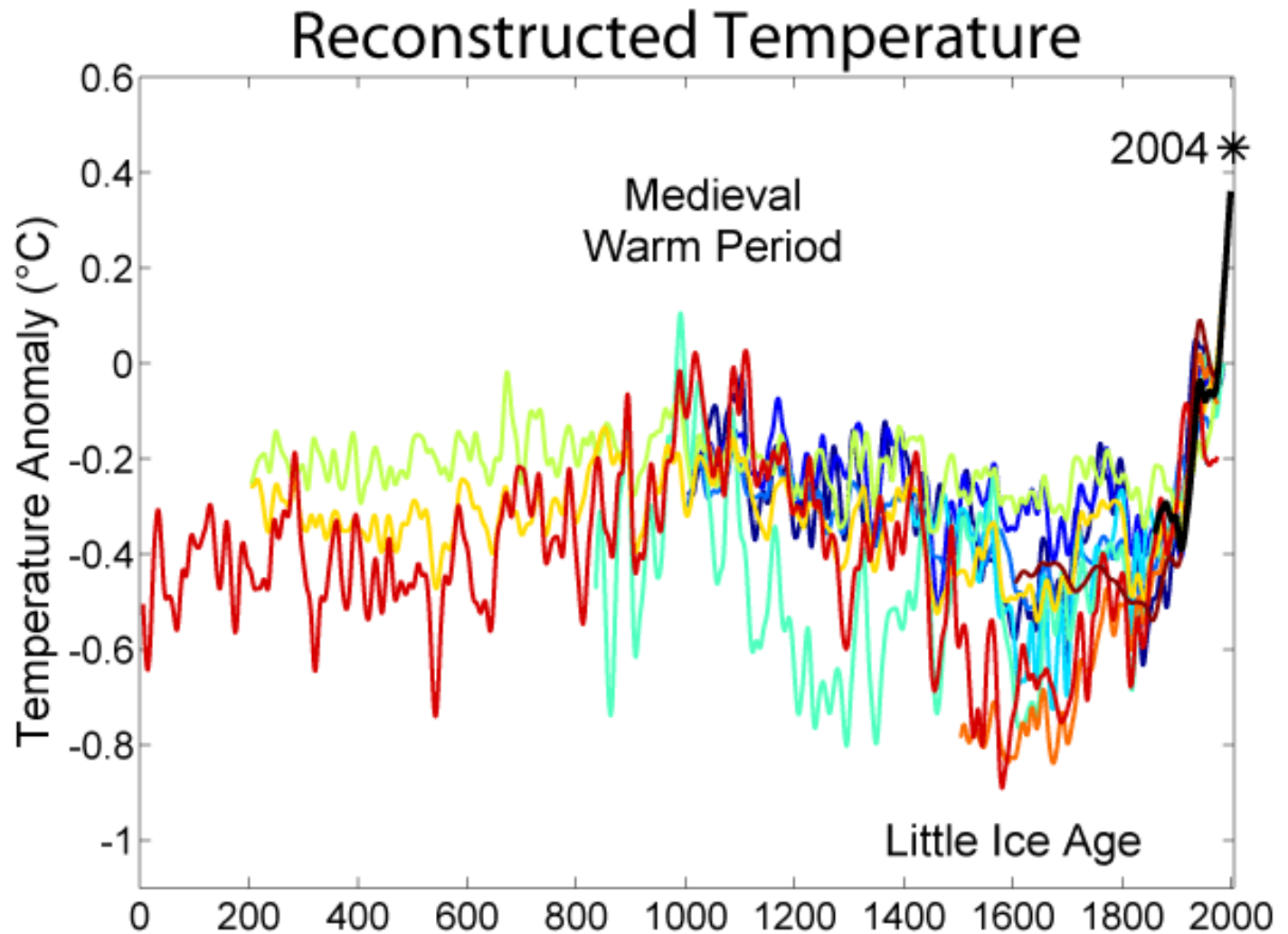
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- Helioclimatology ➡ Geoclimatology

Climate change

Fig. 2: CO_2 and CH_4 over the last 1,000 years⁽¹⁻⁴⁾

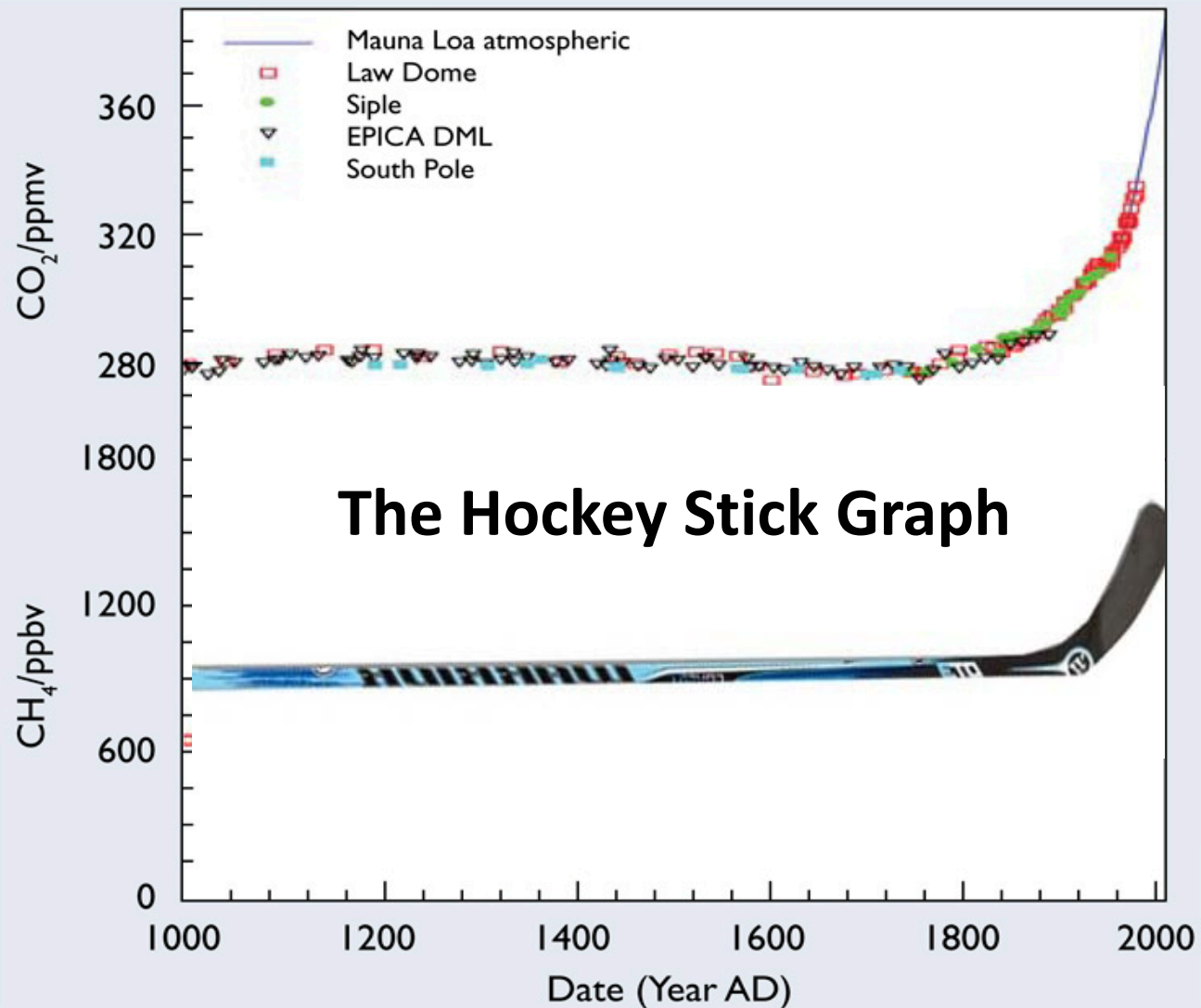


Climate change



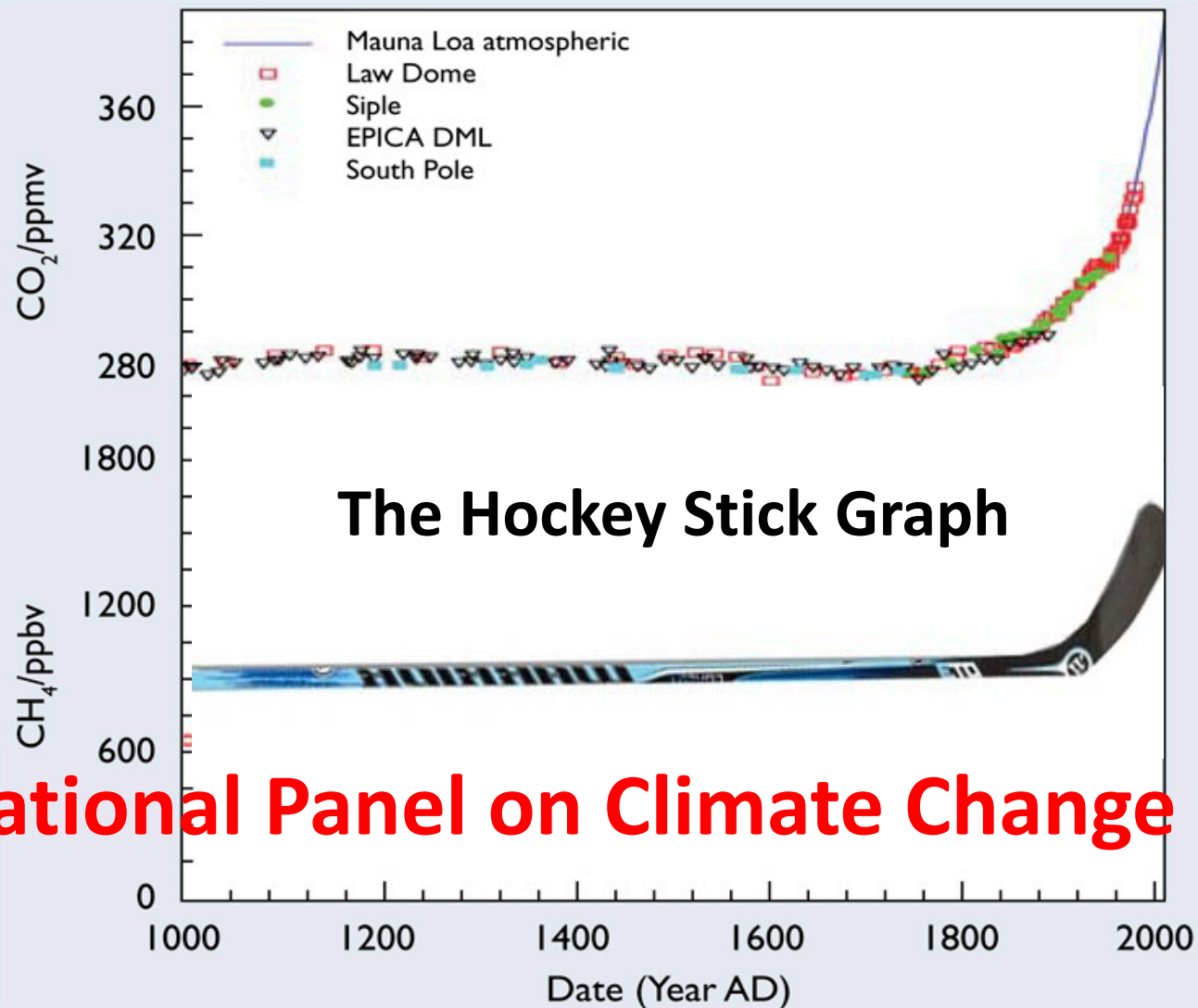
Climate change

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Climate change

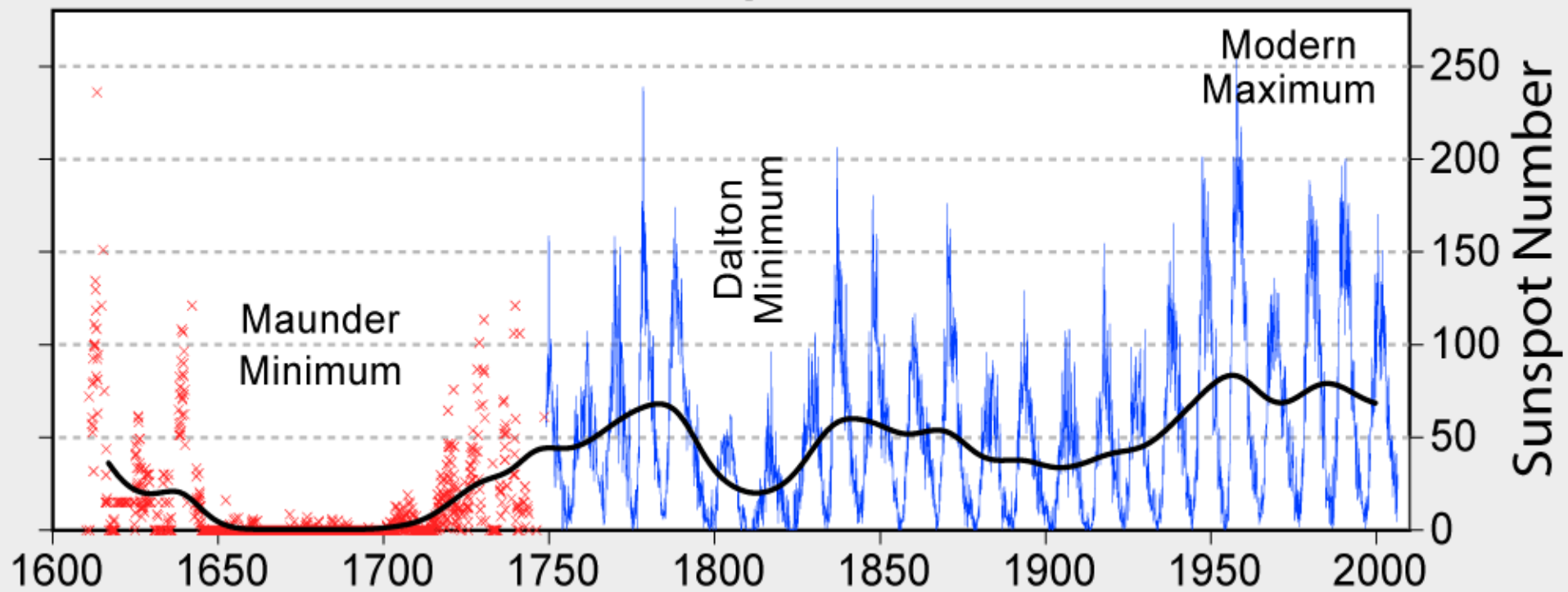
Fig. 2: CO_2 and CH_4 over the last 1,000 years⁽¹⁻⁴⁾



International Panel on Climate Change (IPCC)

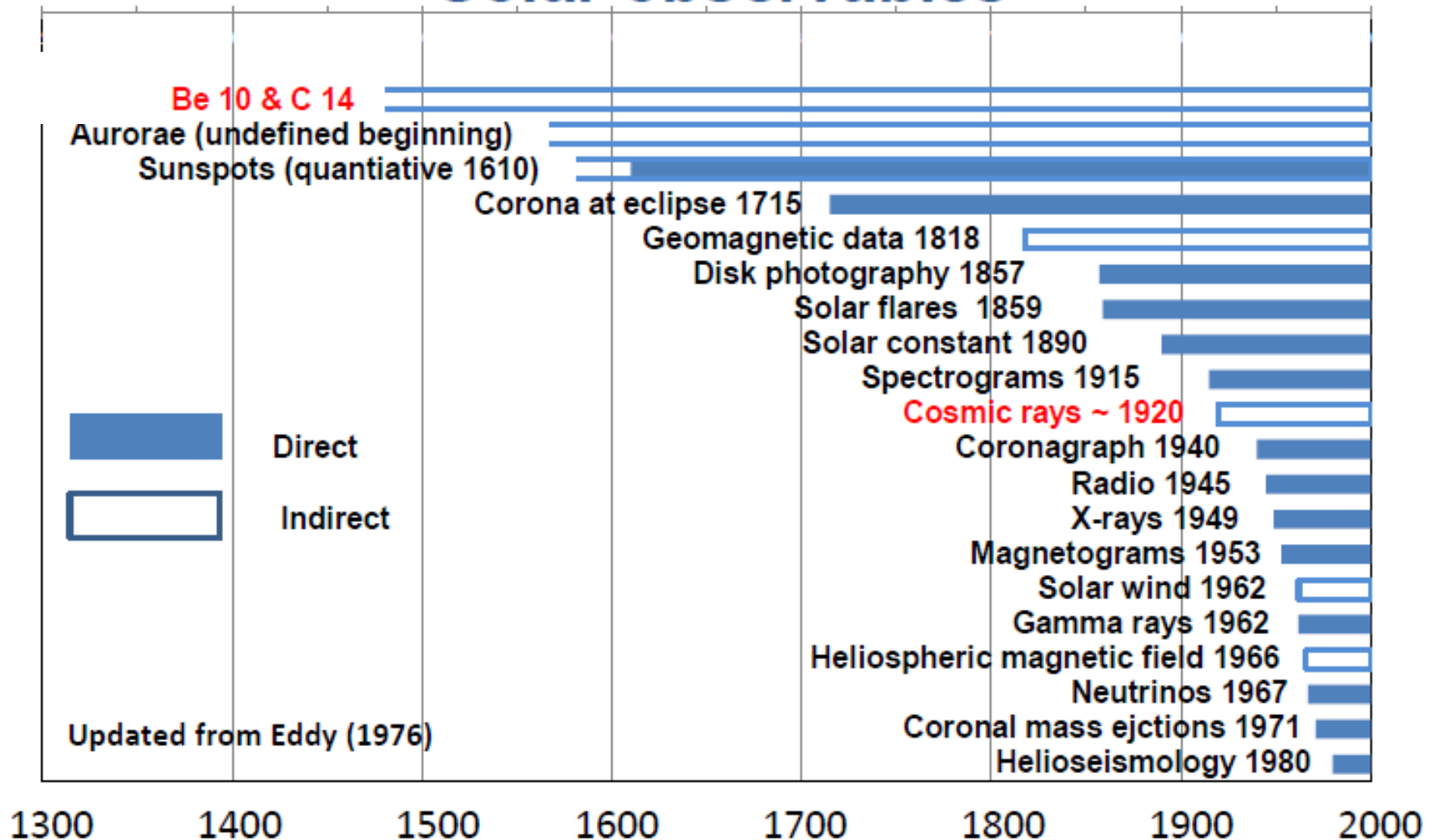
Climate change

400 Years of Sunspot Observations



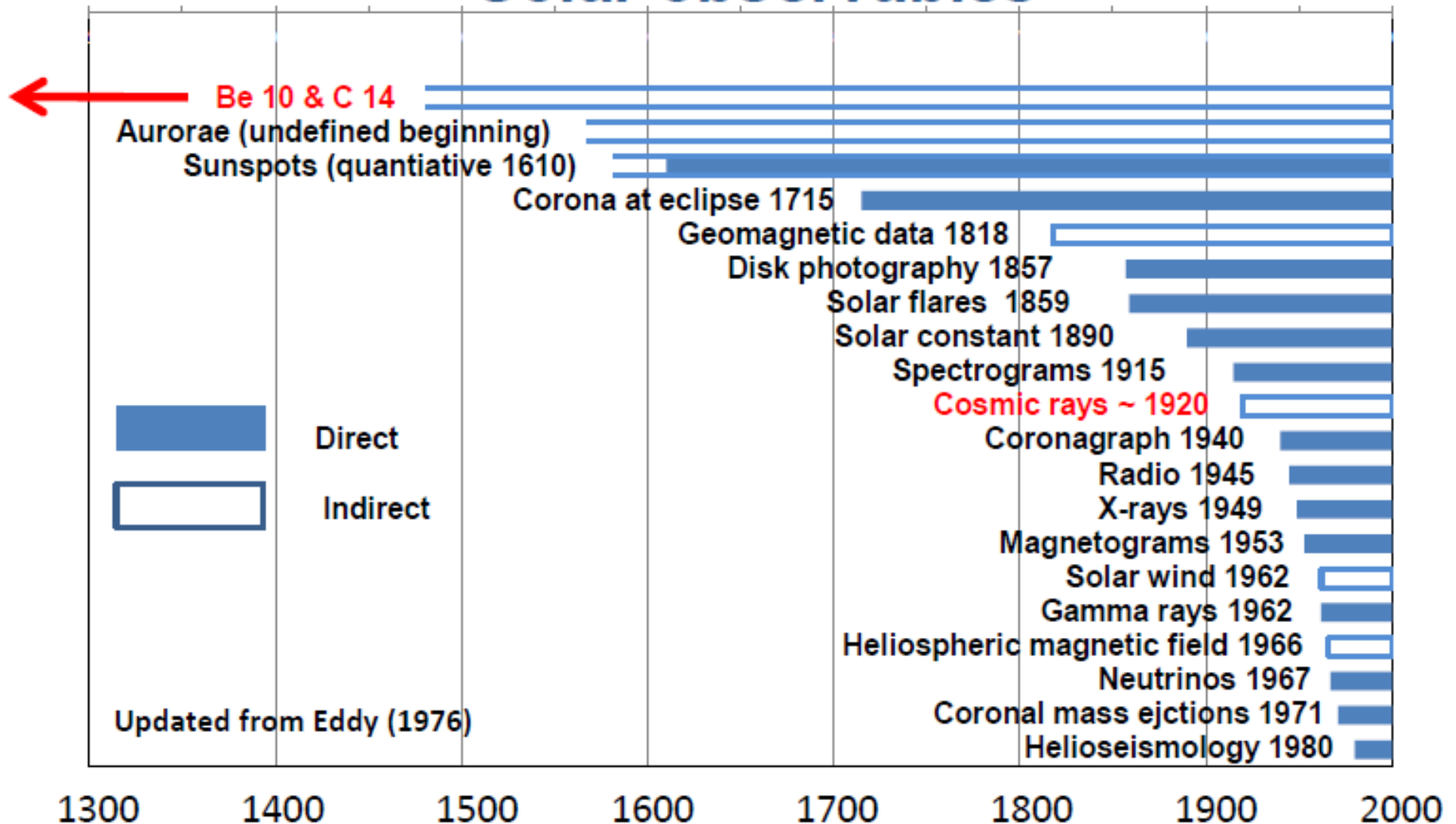
History of the Sun

Solar observables

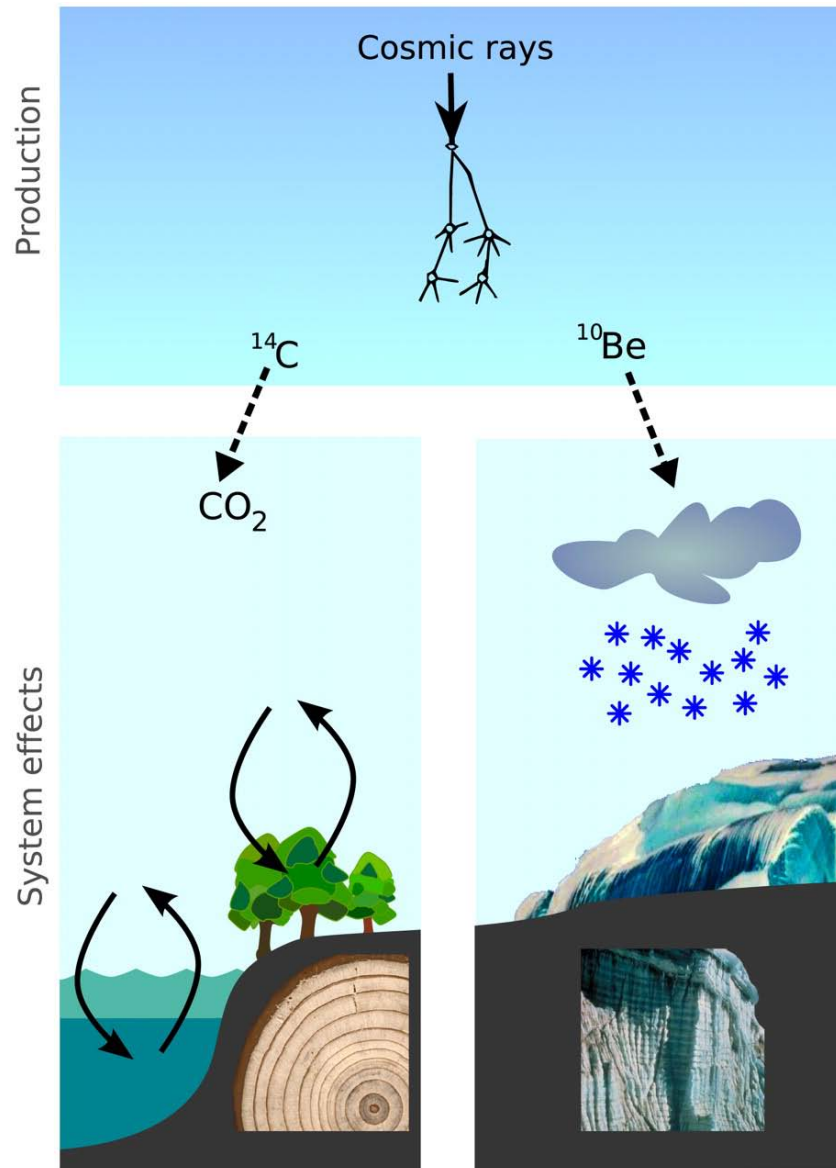


History of the Sun

Solar observables



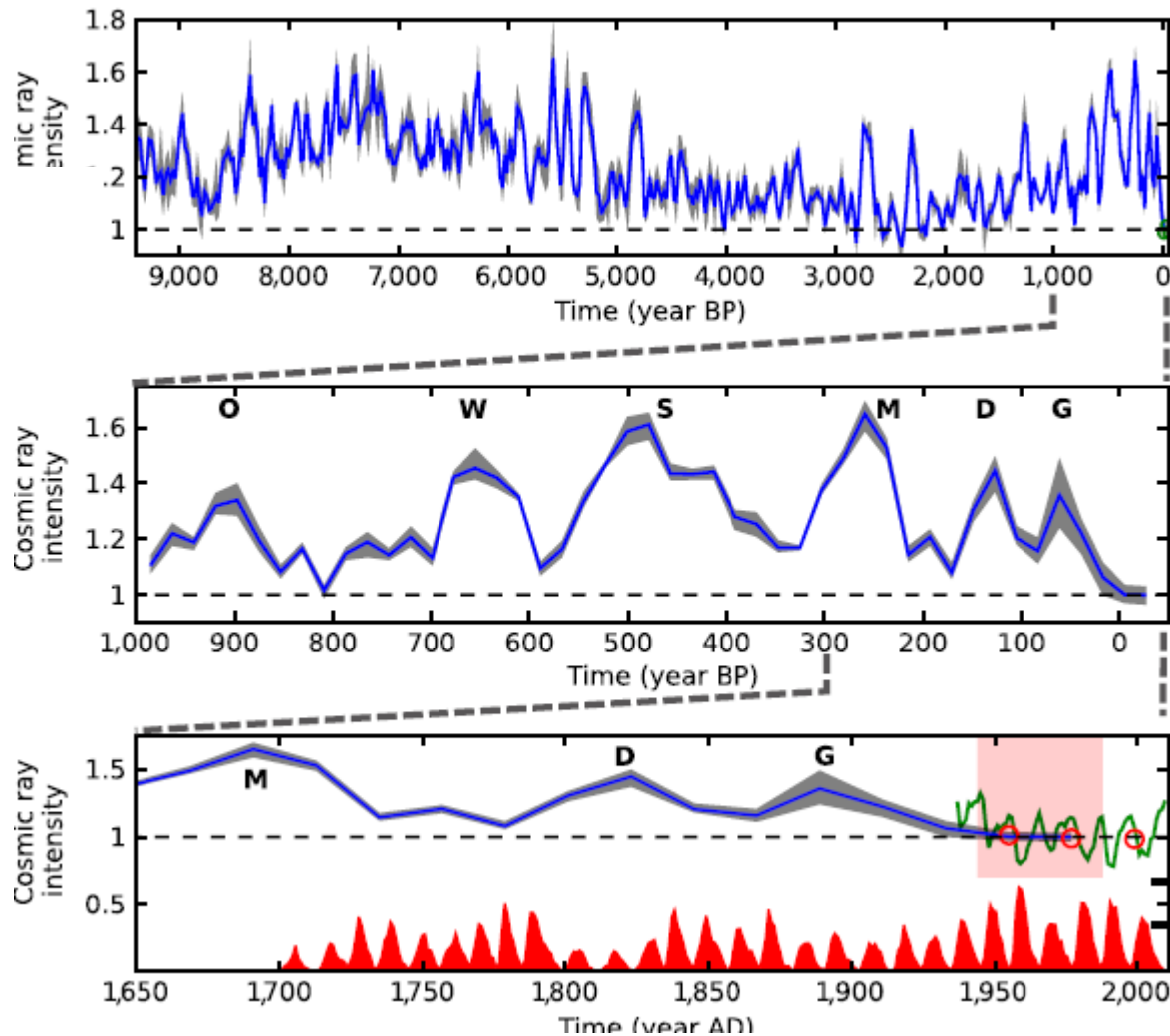
Paleo-cosmic rays: ^{14}C and ^{10}Be



Paleo-cosmic rays: ^{10}Be

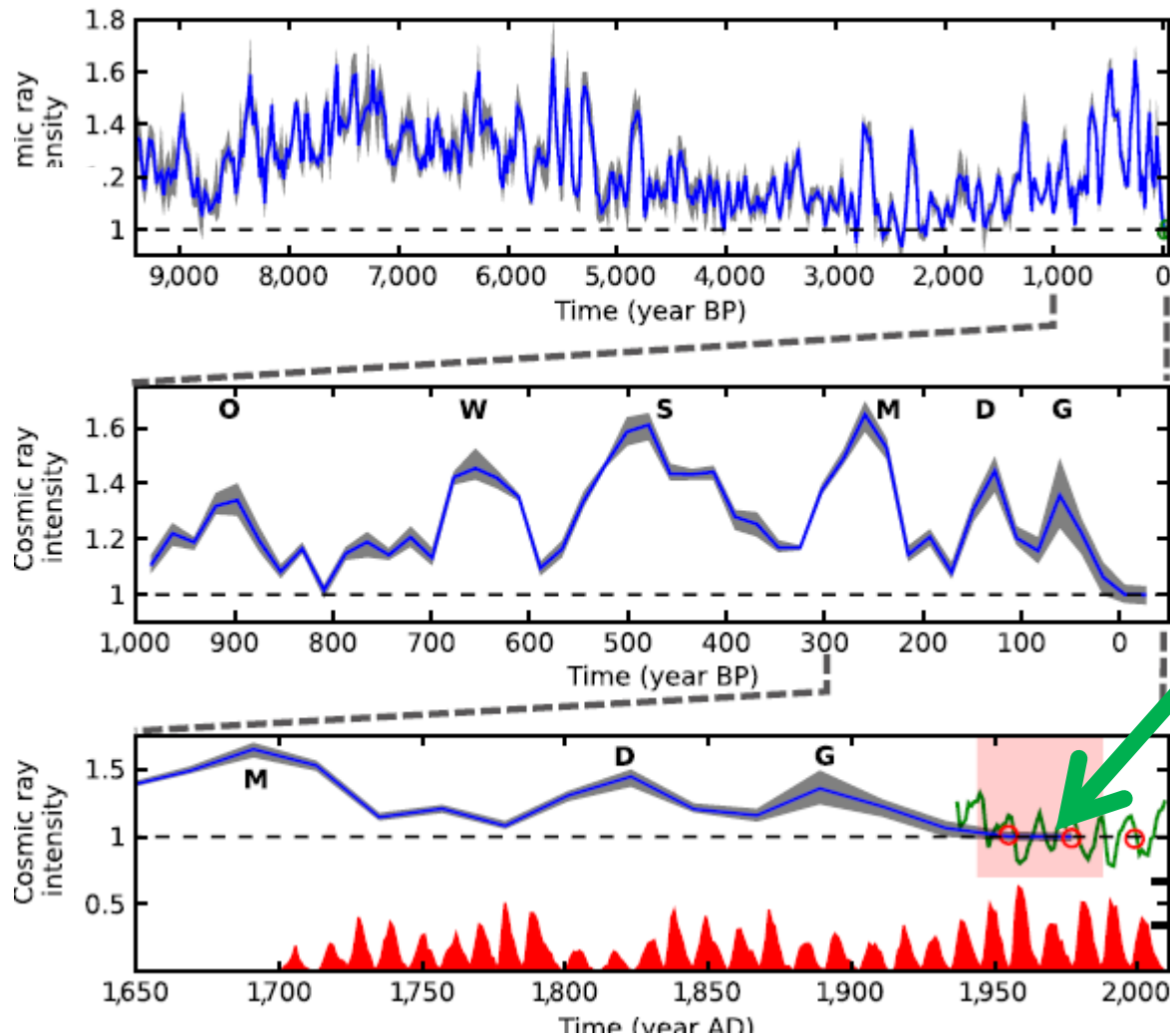


^{10}Be in polar ice ... Earth's neutron monitor



Steinhilber et al. (2012)

^{10}Be in polar ice ... Earth's neutron monitor



Steinhilber et al. (2012)

Paleo-cosmic rays: ^{10}Be



Ice shelf in Queen Maud Land



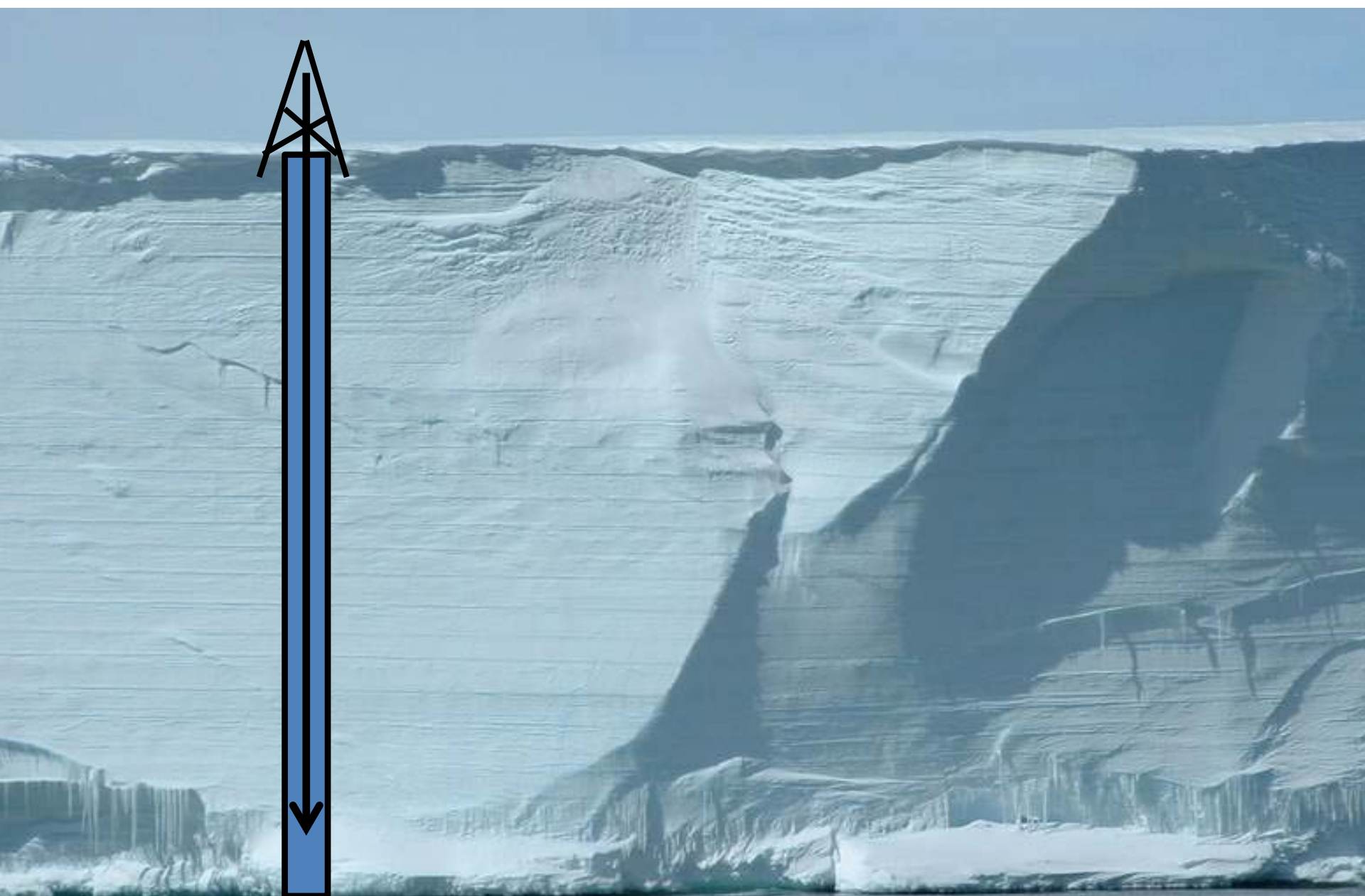
Ice shelf in Queen Maud Land



Ice shelf in Queen Maud Land



Shallow drilling ~ 60 years deep

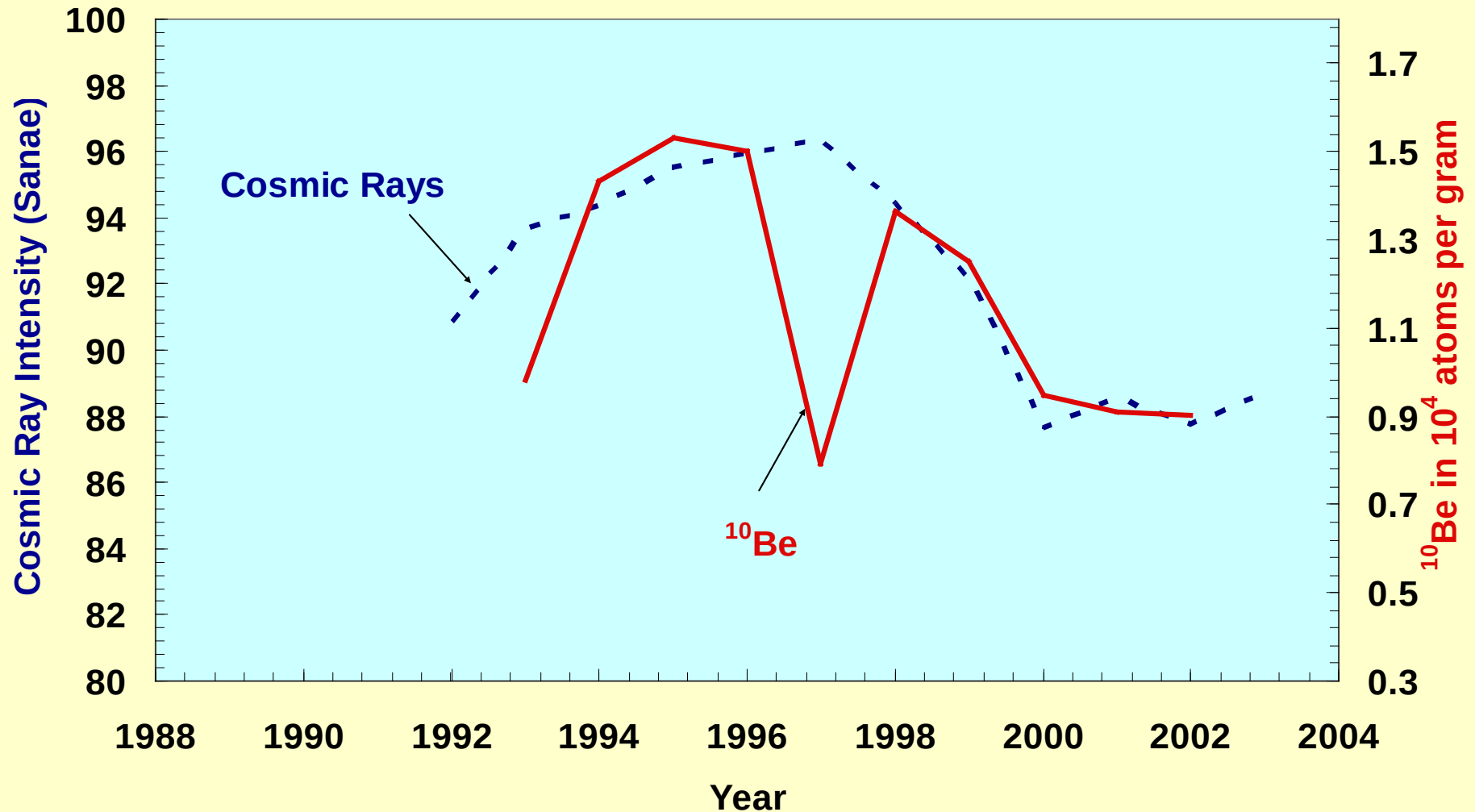


Pilot Project 2006

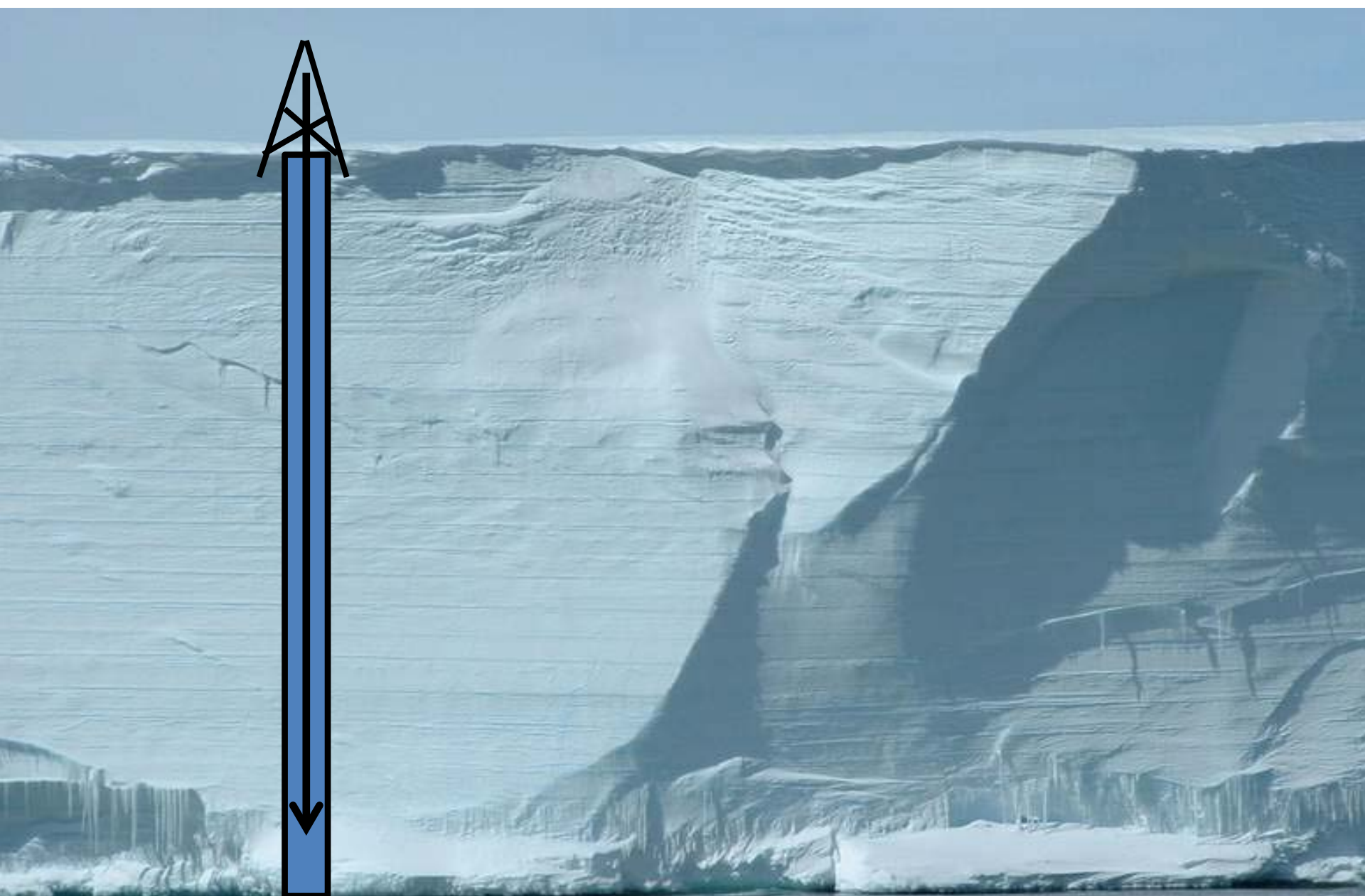


Pilot project 2006

^{10}Be and Cosmic Rays



Shallow drilling ~ 60 years deep



- **Particle Astronomy after 102 years:**
 - 25 August 2012 – longest journey ever completed
 - 14 February 2013 – SNRs *do* produce CR protons
 - 15 May 2013 – two true cosmological neutrinos seen

South African Astronomy

- **Radio Astronomy**
- **Optical Astronomy**
- **Gamma-ray Astronomy**
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the South African National Antarctic Programme
for over 50 years.**
- **NASA/Wikipedia**