Particle Astrophysics

Harm Moraal

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Potchefstroom

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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

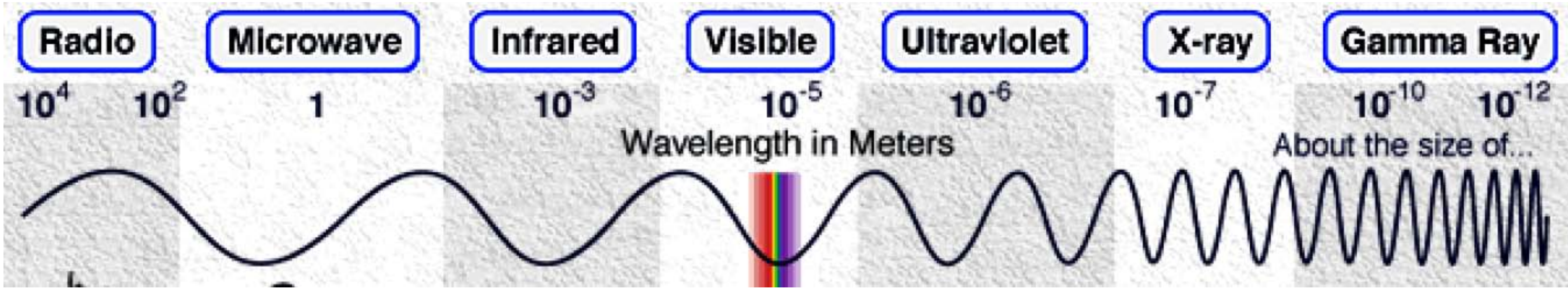
- **Photons**
  - Radio
  - Microwave
  - Infrared
  - Optical
  - X-ray
  - Gamma ray

- **Particles**

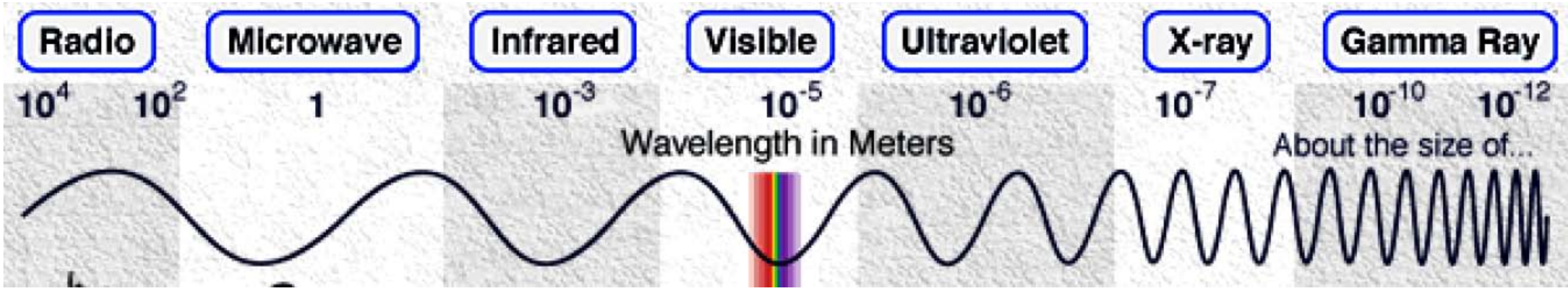
ASTRONOMY IN SOUTH AFRICA: A MULTI-WAVELENGTH LONG-TERM STRATEGIC PLAN

Astronomy Desk Draft – version 1
28 May 2014

Multiwavelength Astronomy



Multiwavelength Astronomy



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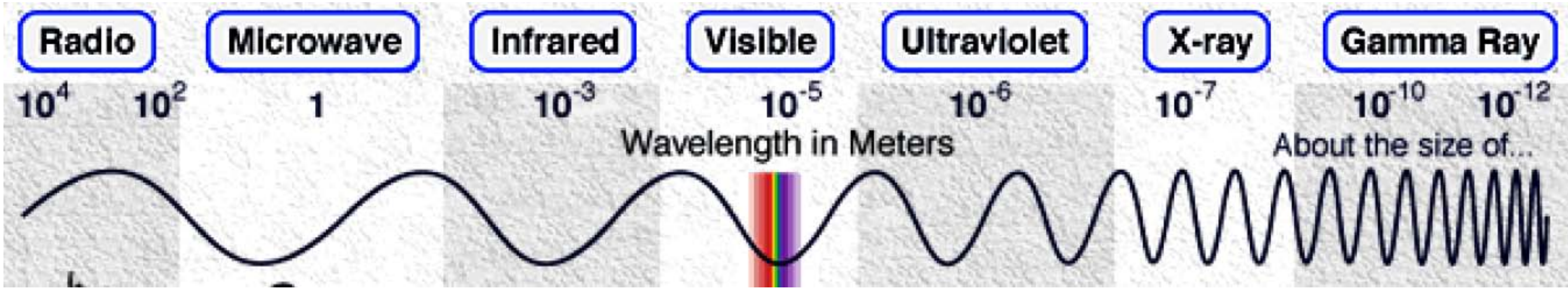
SAAO & SALT

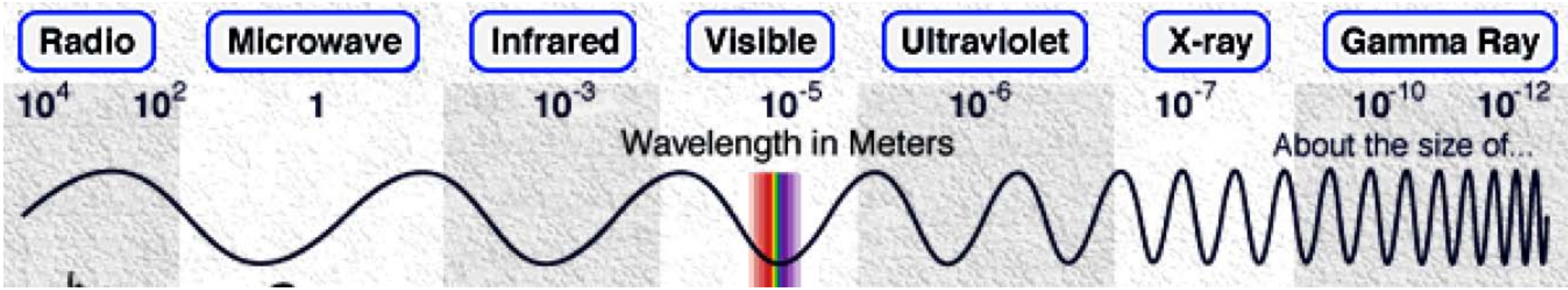
Multiwavelength Astronomy



Hart RAO & KAT, MeerKAT, SKA

SAAO & SALT

Multiwavelength Astronomy



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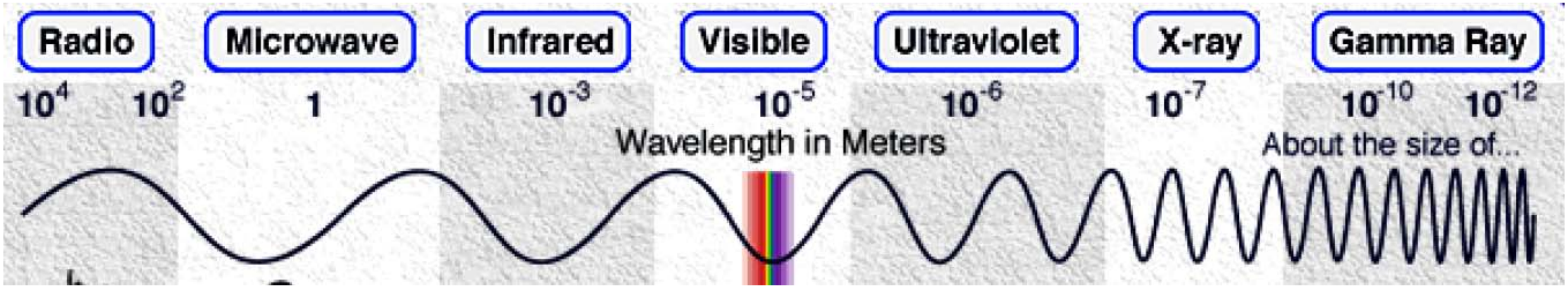
H.E.S.S

Multiwavelength Astronomy



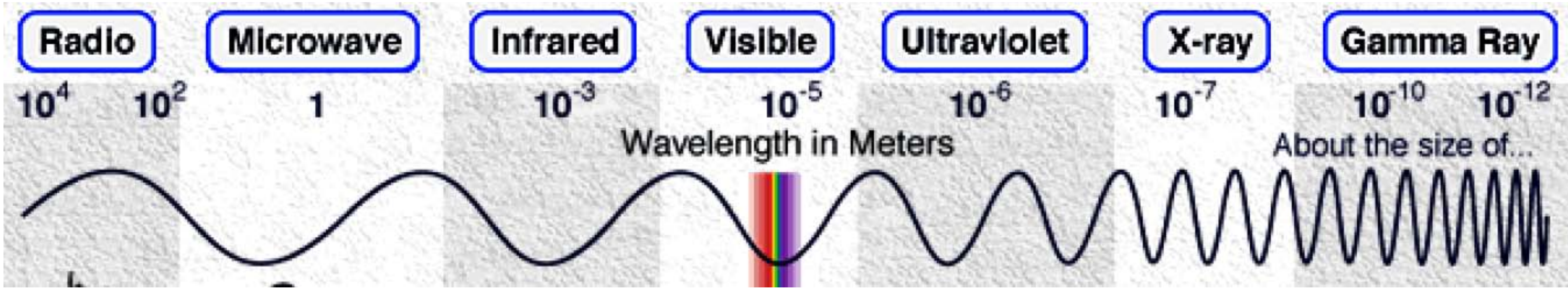
Hart RAO & KAT, MeerKAT, SKA

SAAO & SALT

H.E.S.S

CTA, end 2014?

Multiwavelength Astronomy



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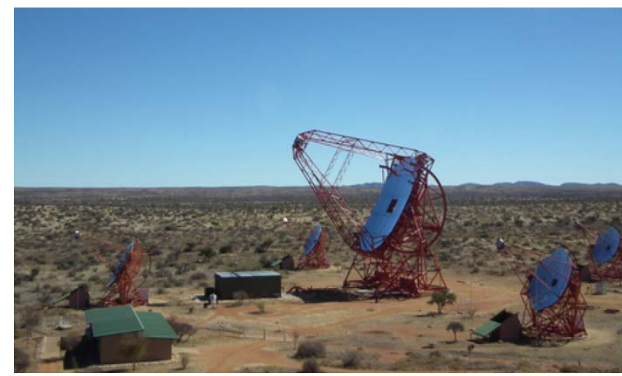


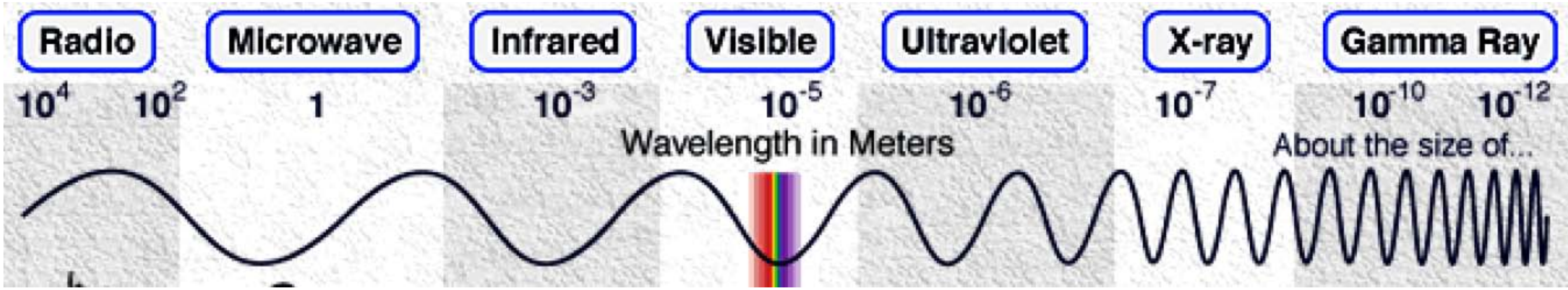
Energy $= hc/\lambda$

$< 10^{-3}$ eV

$\sim$ 1 eV

$> 10^{9}$ eV

Multiwavelength Astronomy



Hart RAO & KAT,
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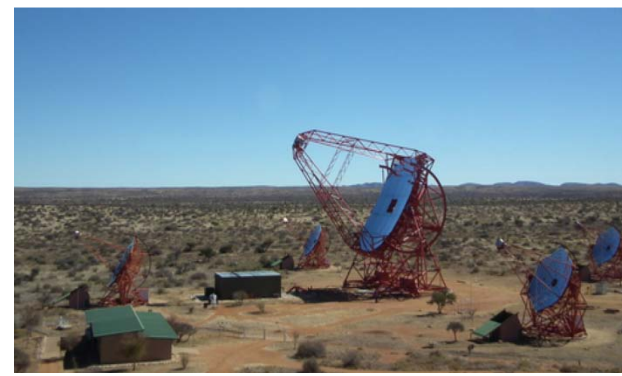


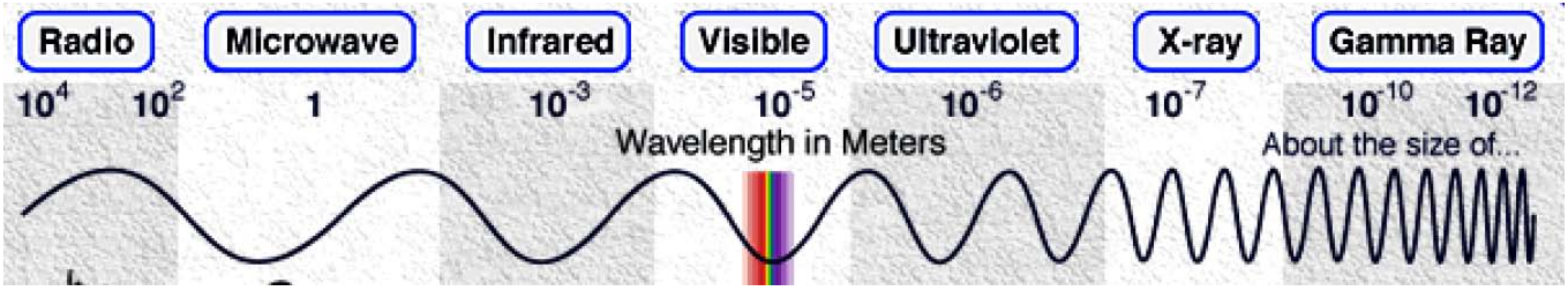
Energy = hc/λ

< 10^{-3} eV
Rotations
and vibrations

~ 1 eV
Electronic jumps

> 10^{9} eV
Nuclear
reactions

Multiwavelength Astronomy



Hart RAO & KAT, MeerKAT, SKA

SAAO & SALT

H.E.S.S

Horsehead nebula

Galaxy M31

Active Galactic Nucleus (guess)

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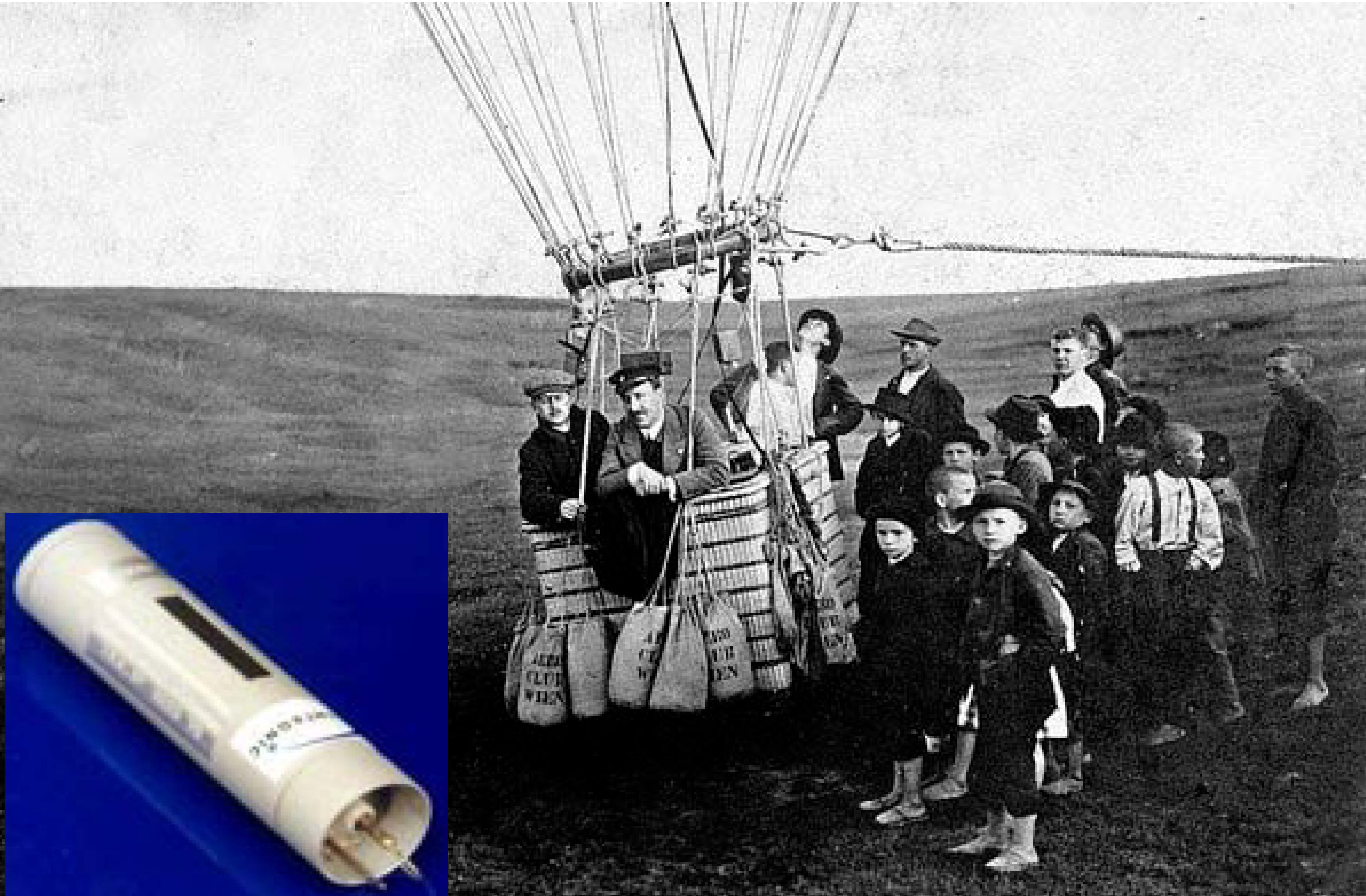
Cosmic rays

- 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



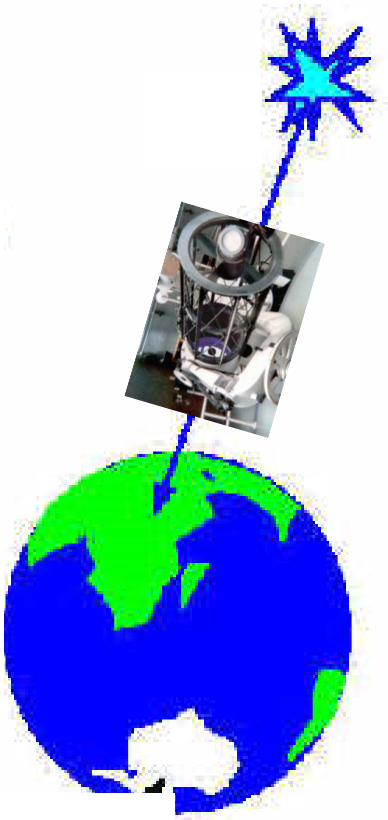
Bad Saarow Railway Station – 100 years later

Particle vs. Photon Astronomy

Photons

1. Where
2. How bright
3. Colour

Particle vs. Photon Astronomy

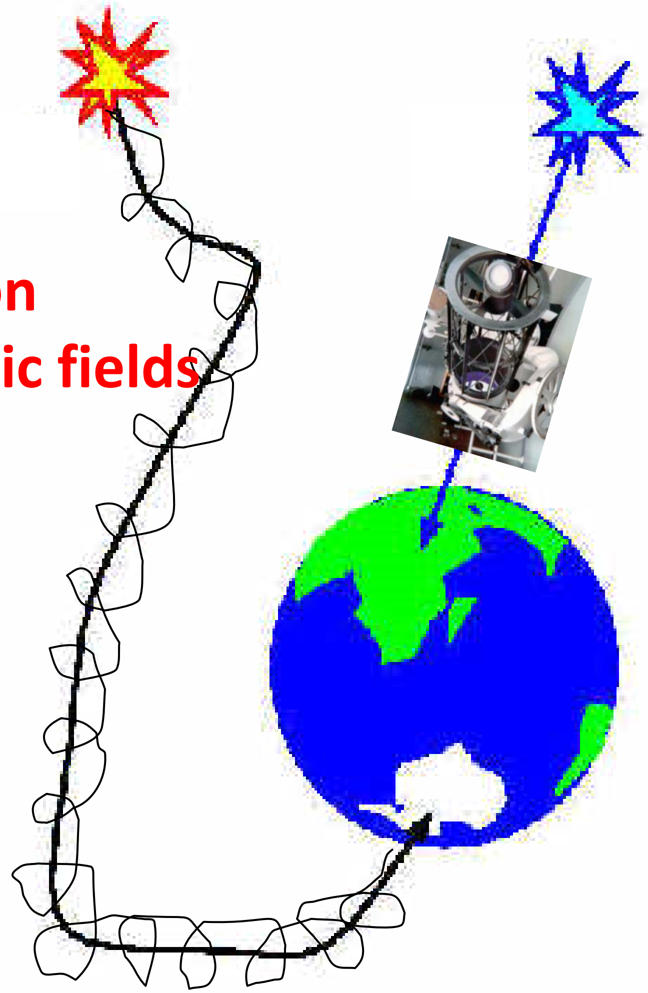


Photons

1. Where
2. How bright
3. Colour

Particle vs. Photon Astronomy

Particles:
No such information
Because of magnetic fields



Photons

1. Where
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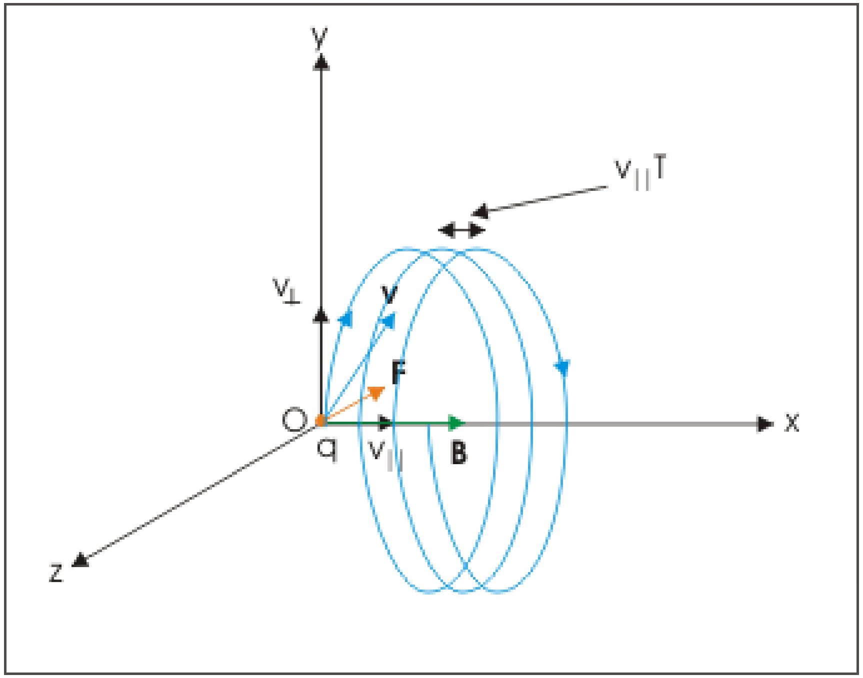
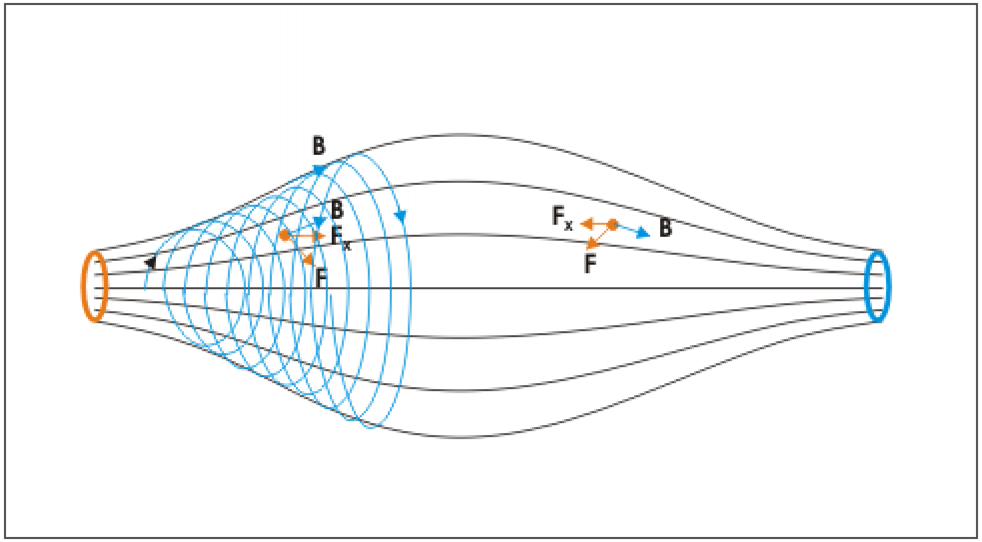
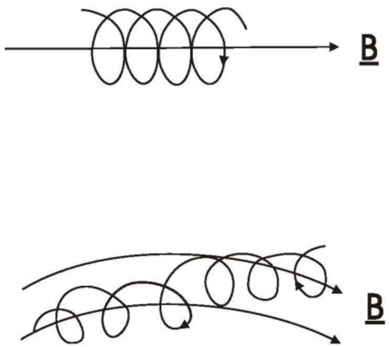
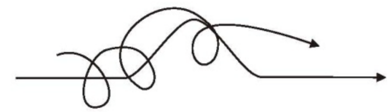
Charged particles spiral around magnetic field lines



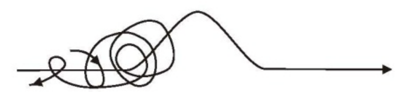


Kinks in field cause scattering





This way?



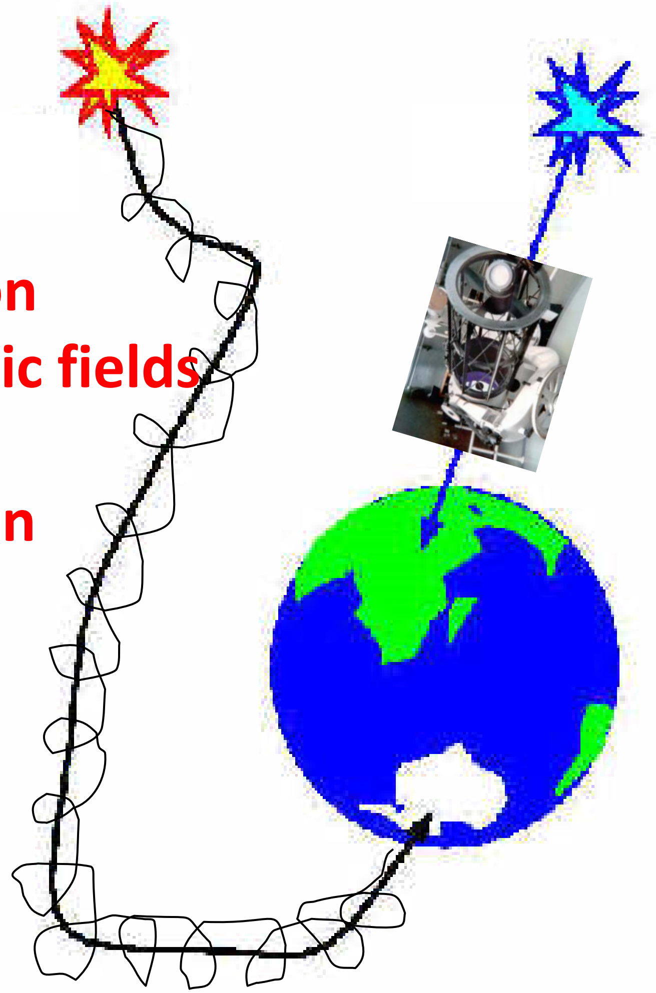
Other way?

No way…? stuck

Particle vs. Photon Astronomy

Particles:
No such information
Because of magnetic fields

……like a bead on an elastic band



Photons

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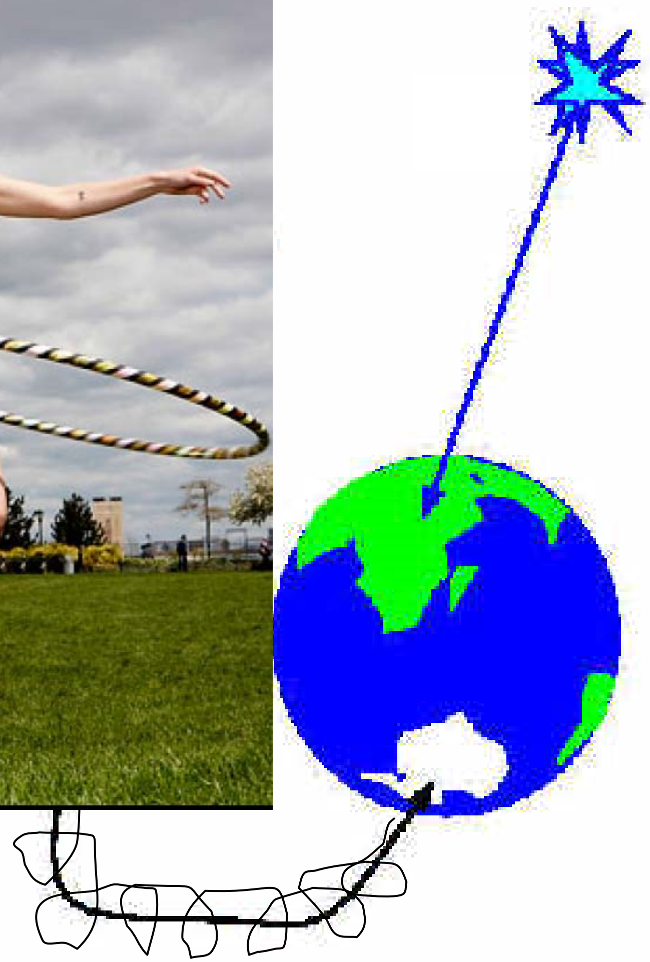
Particle vs. Photon Astronomy



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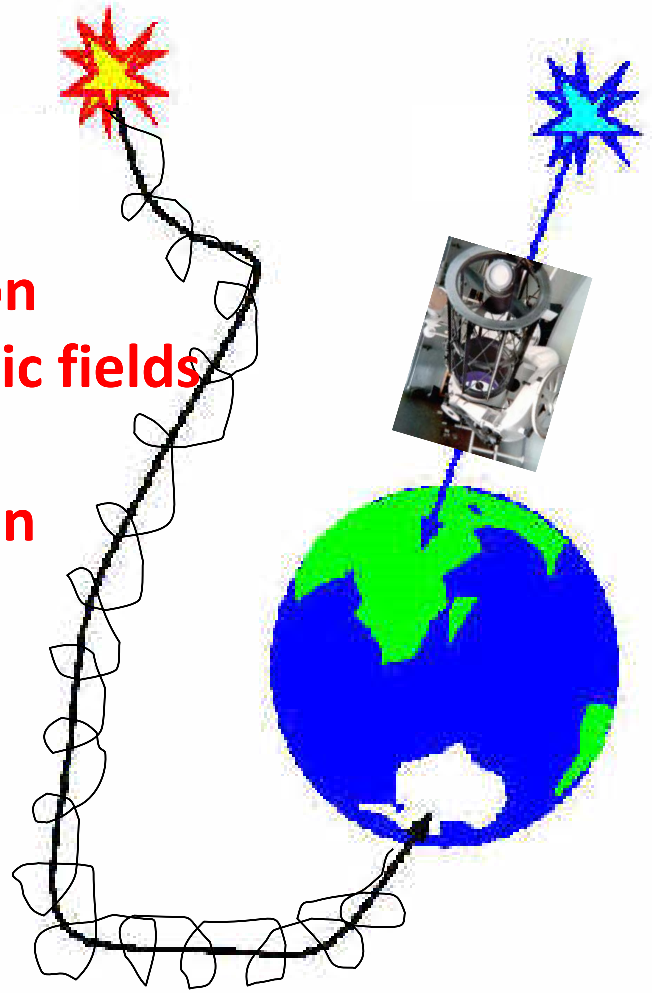
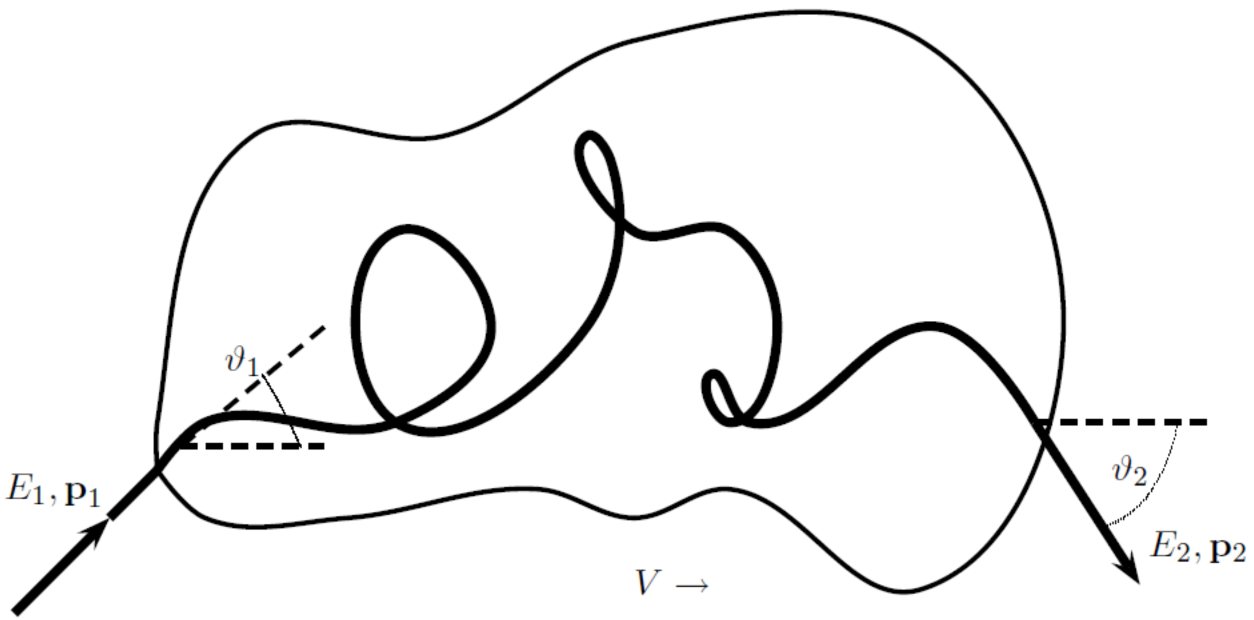


Photons

1. Where
2. How bright
3. Colour

Charged particles in magnetic fields



…. scattering ⟶ isotropy

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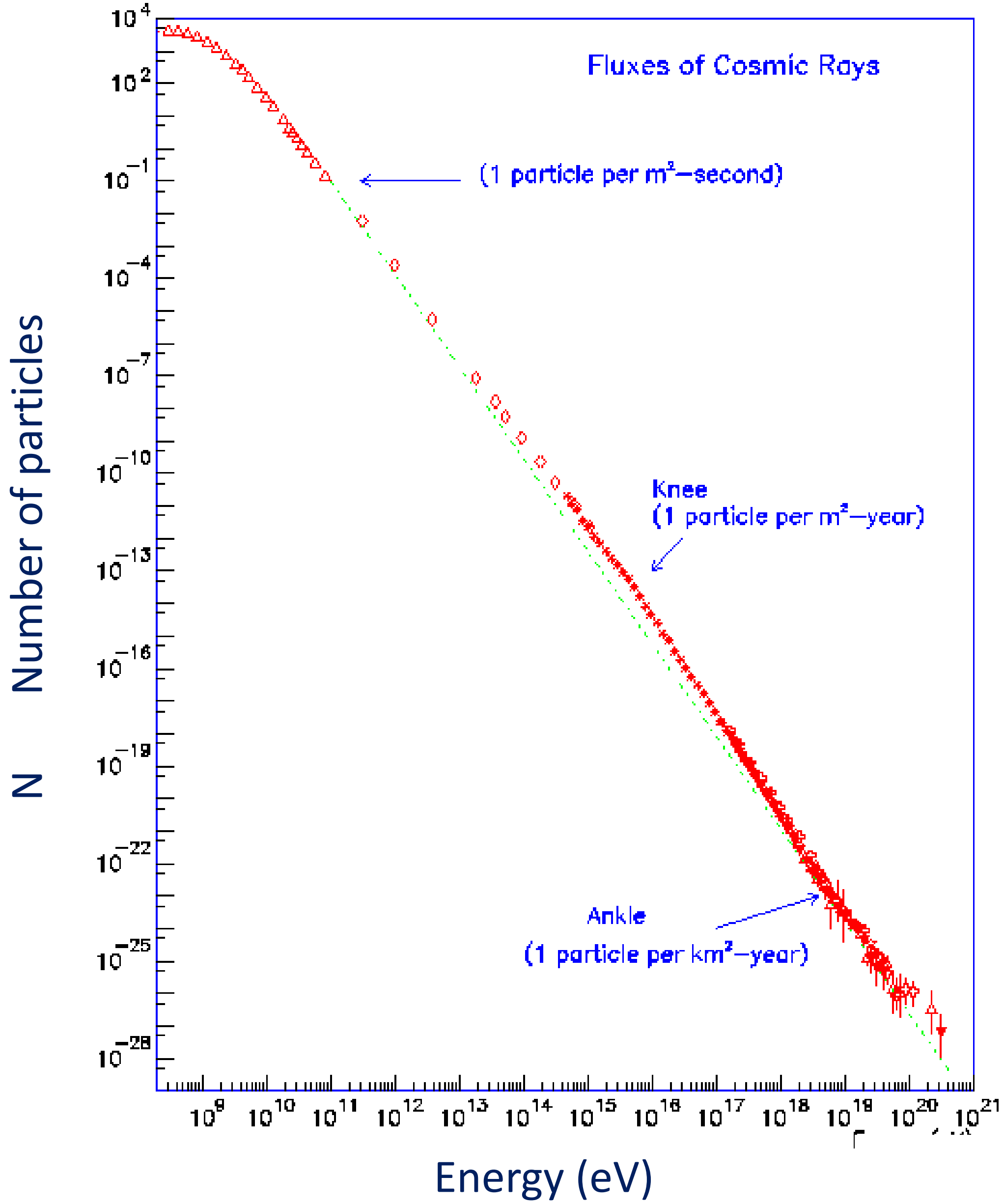
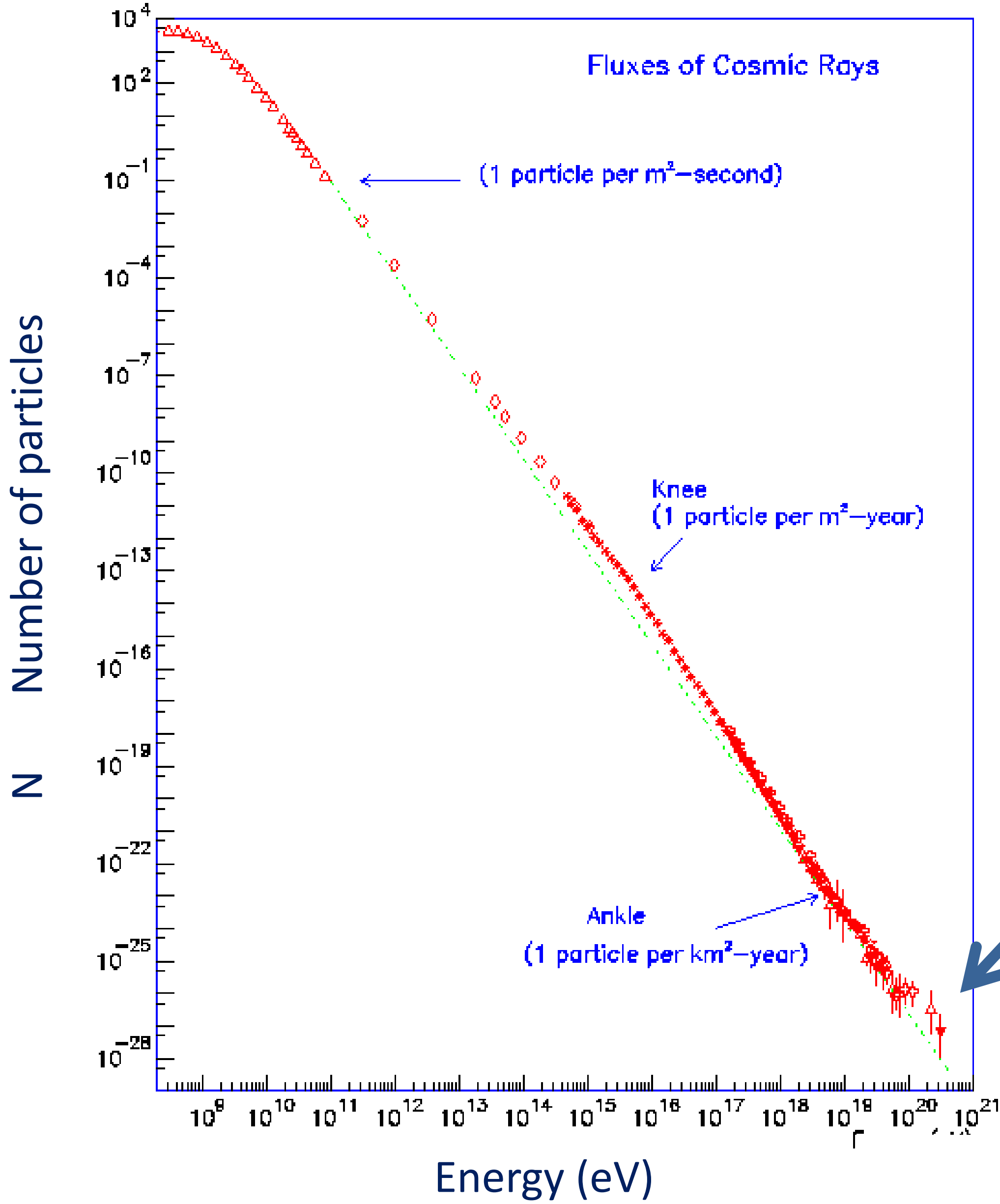
Cosmic ray spectrum

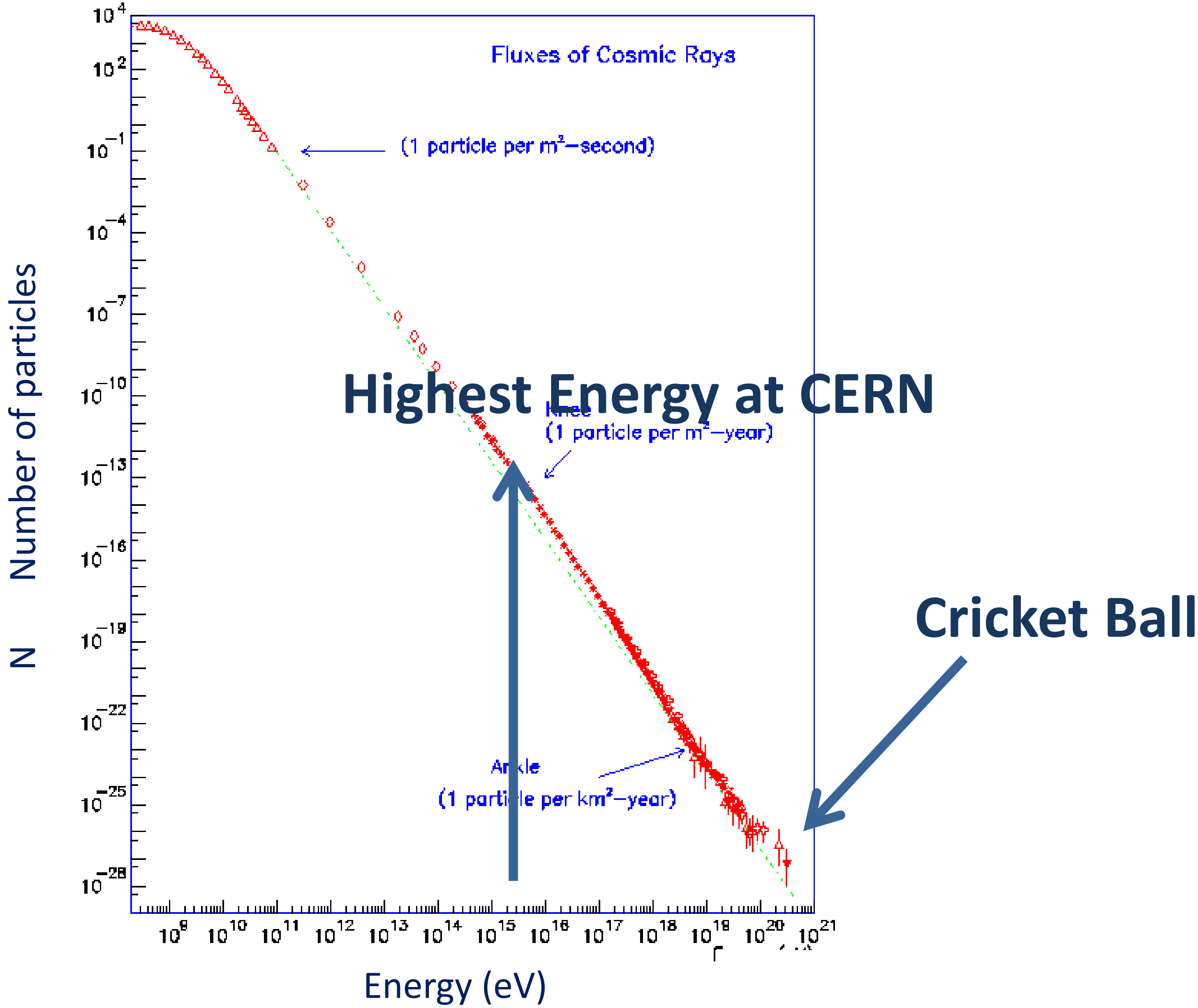


Cosmic-ray spectrum

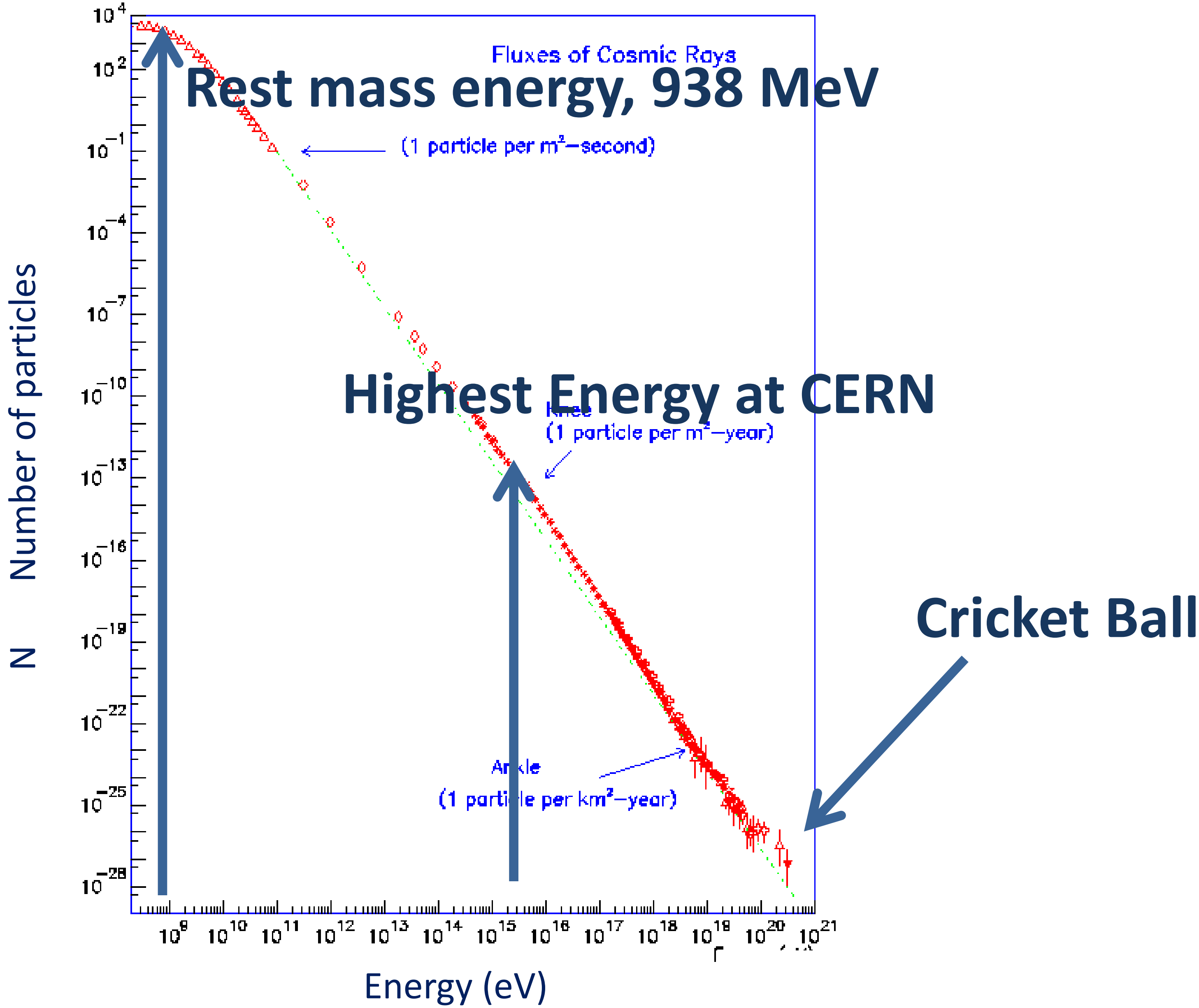


Cricket Ball

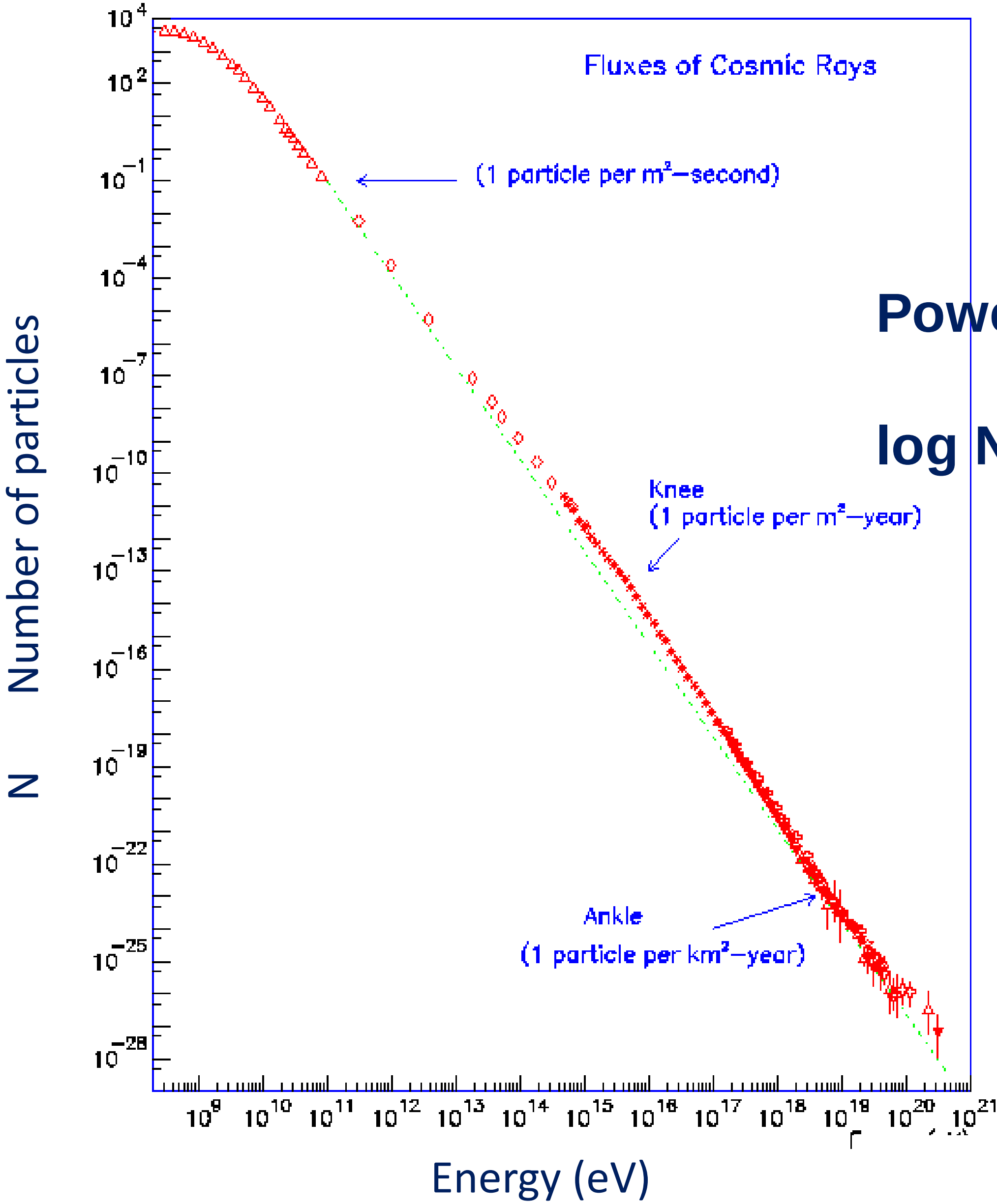
Cosmic-ray spectrum



Cosmic-ray spectrum



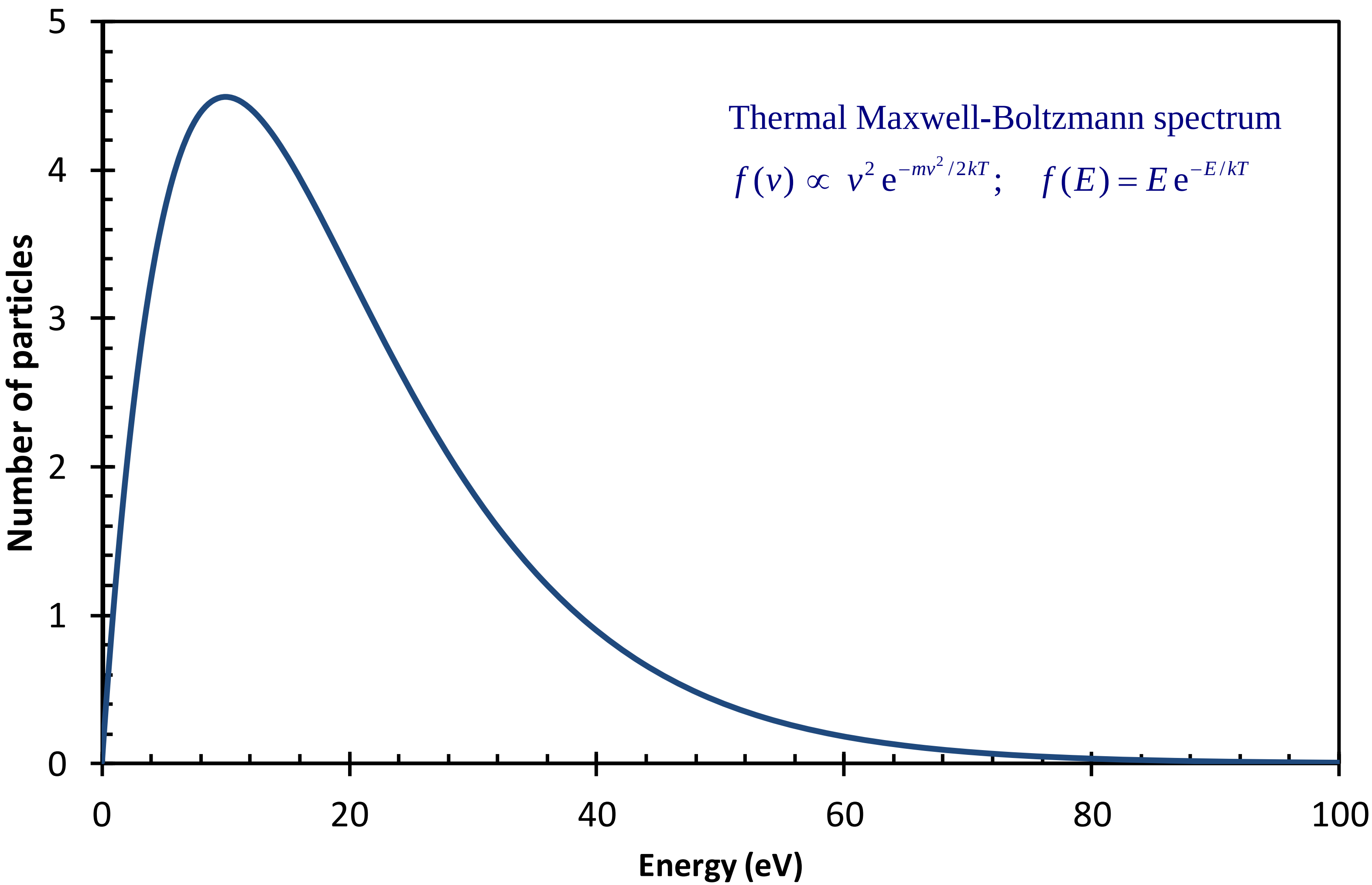
Cosmic ray spectrum



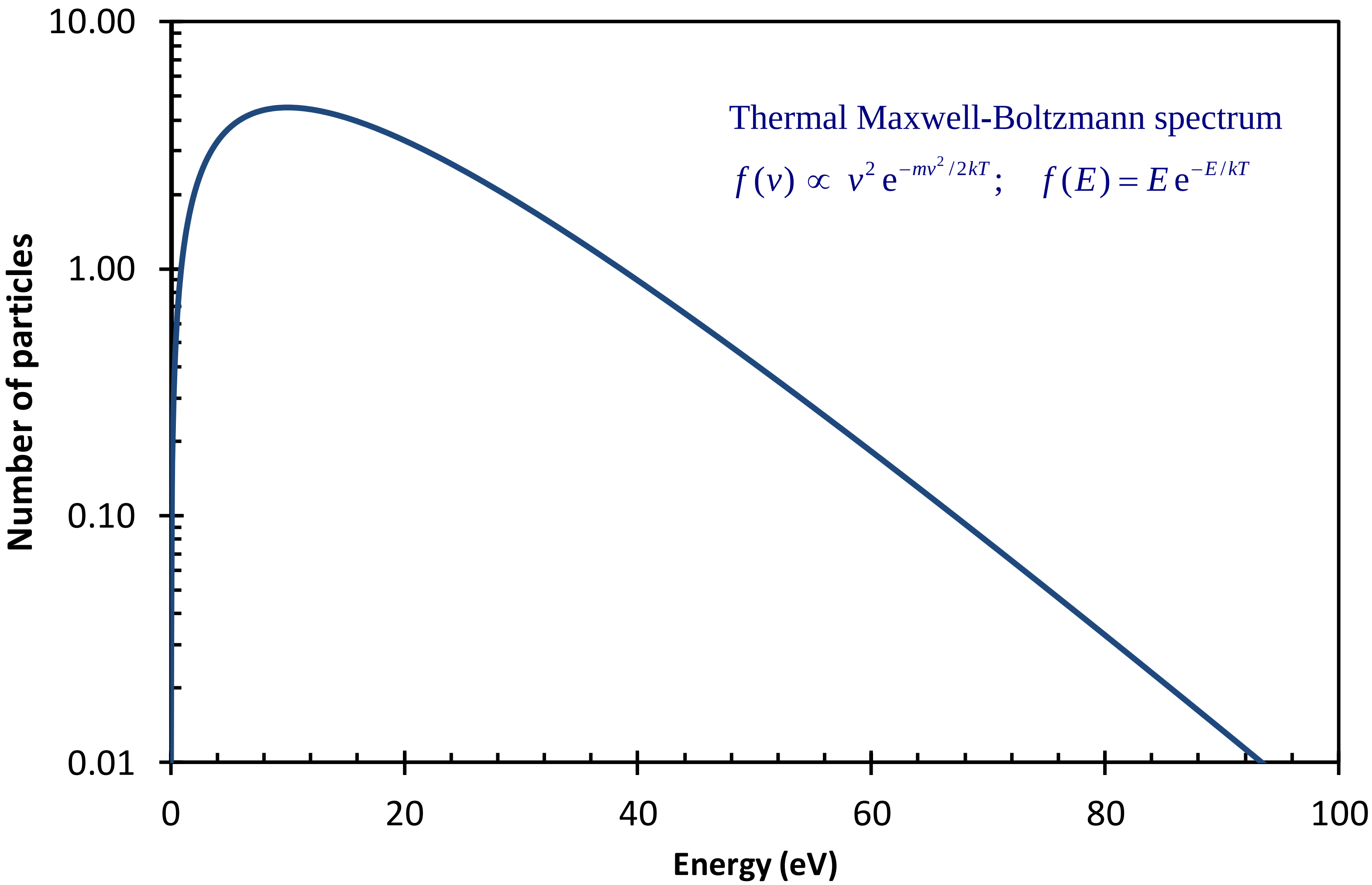
Power law: $N = a E^{-2.5}$

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

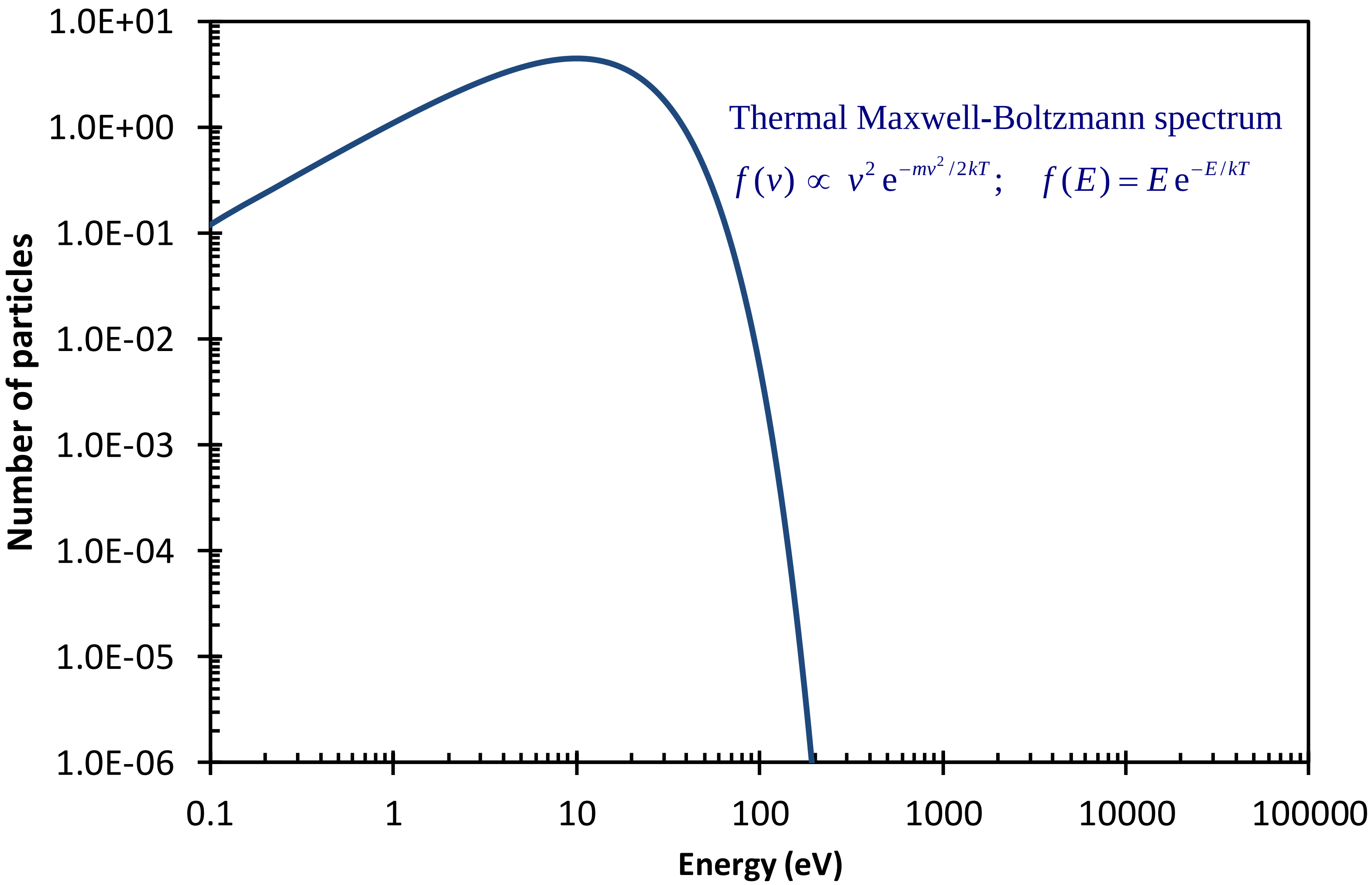
Cosmic-ray spectrum



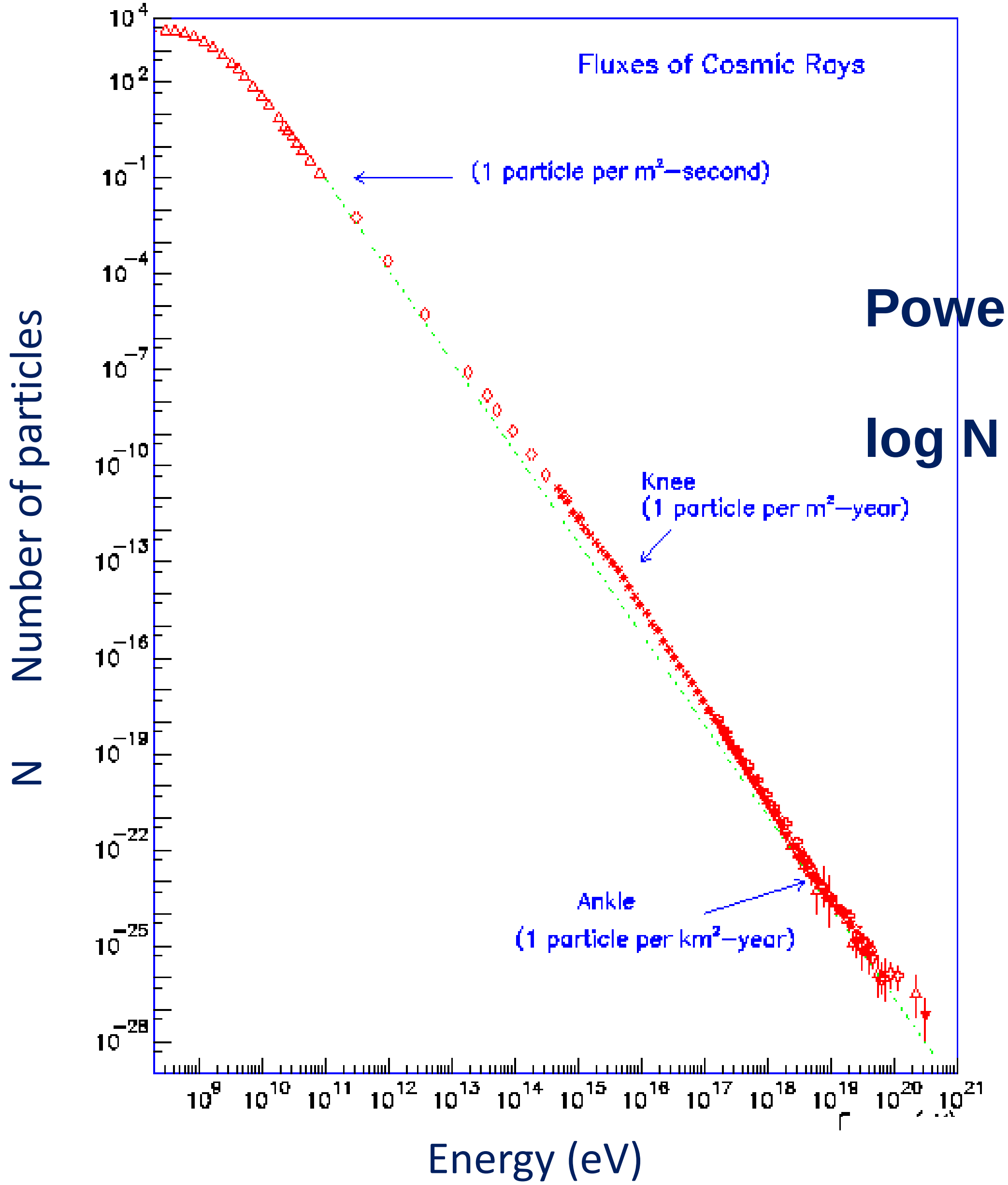
Cosmic-ray spectrum



Cosmic-ray spectrum



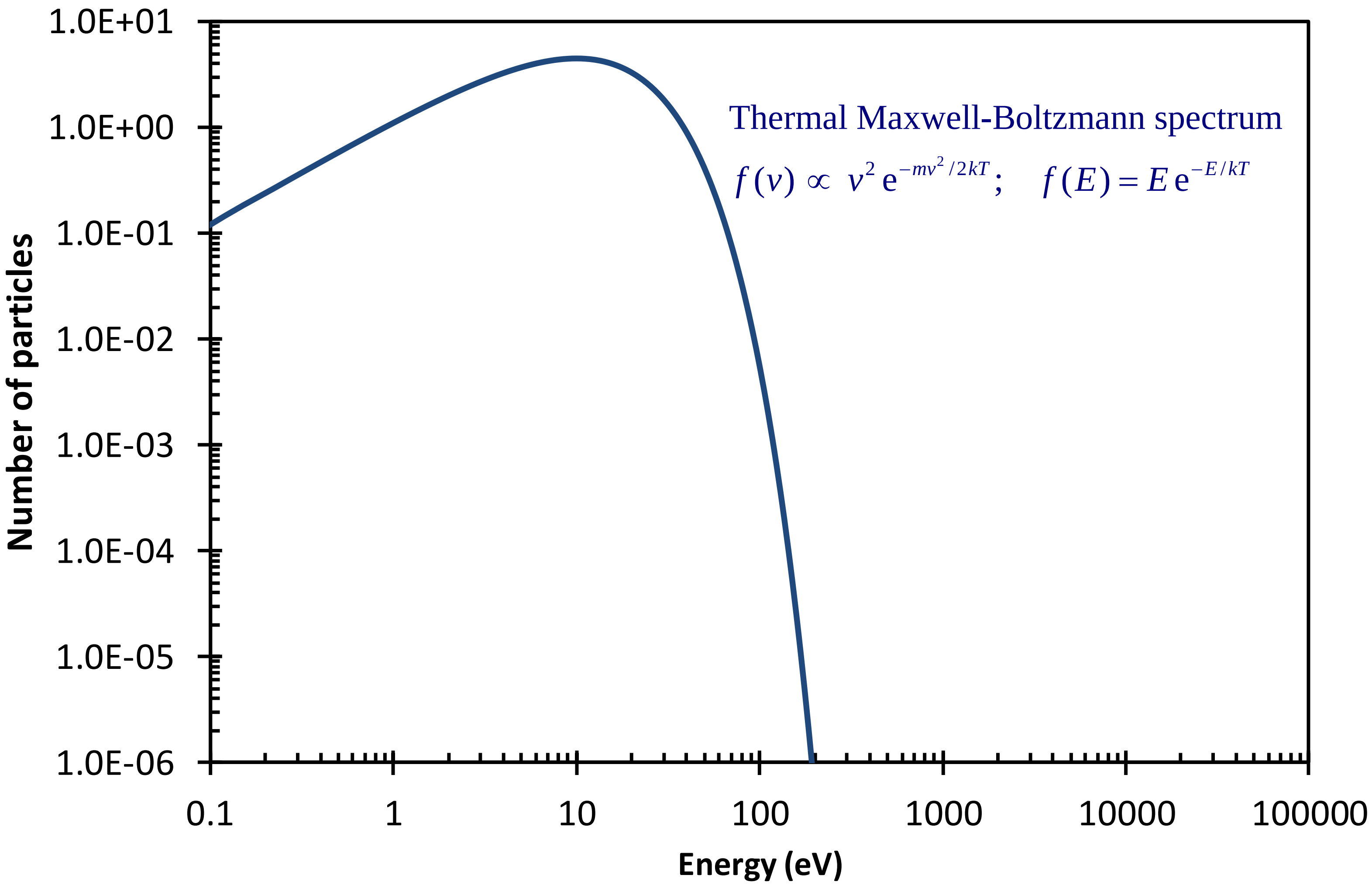
Cosmic ray spectrum



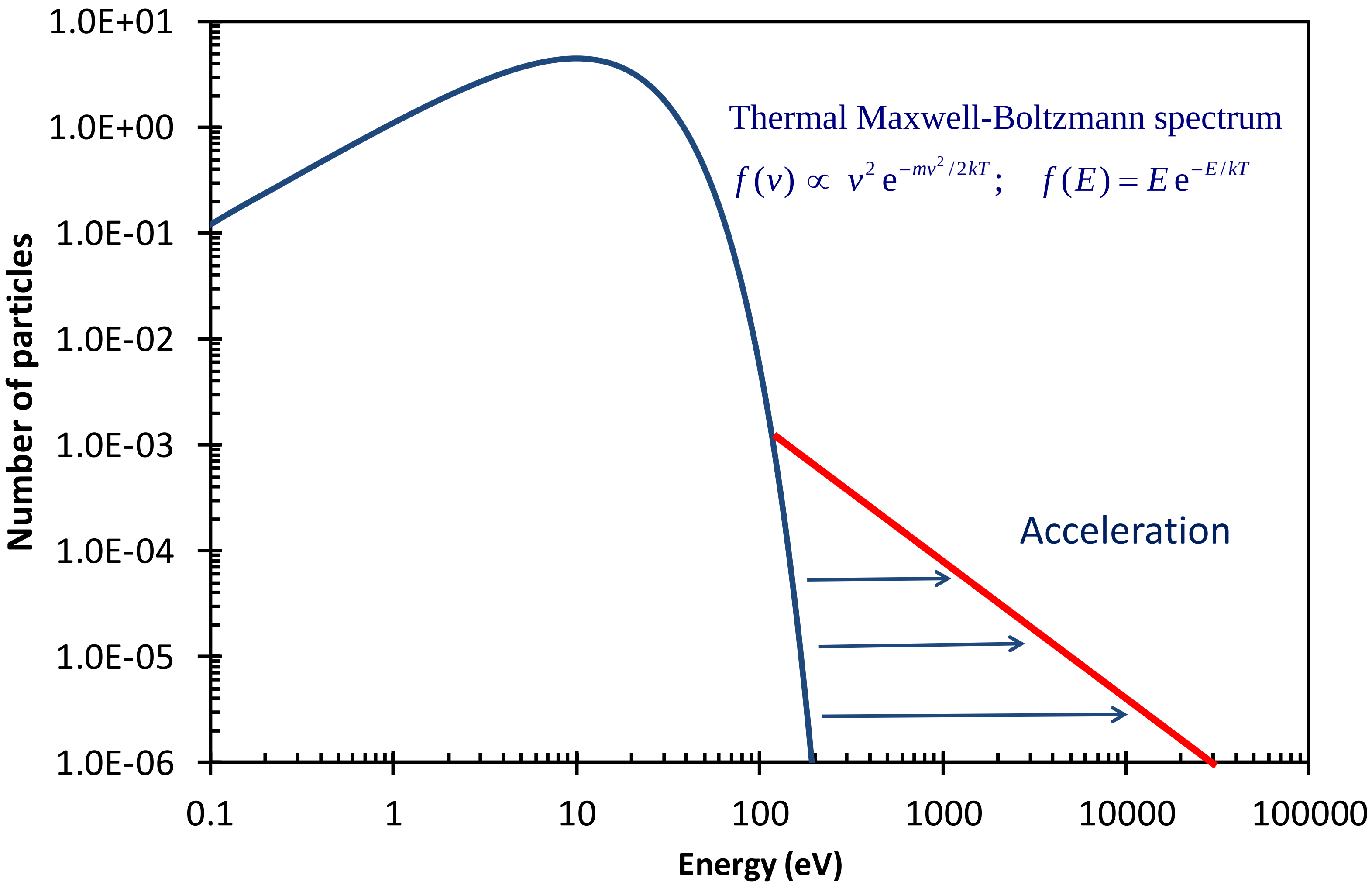
Power law: N =a $E^{-2.5}$

log N = -2.5 log E + log a

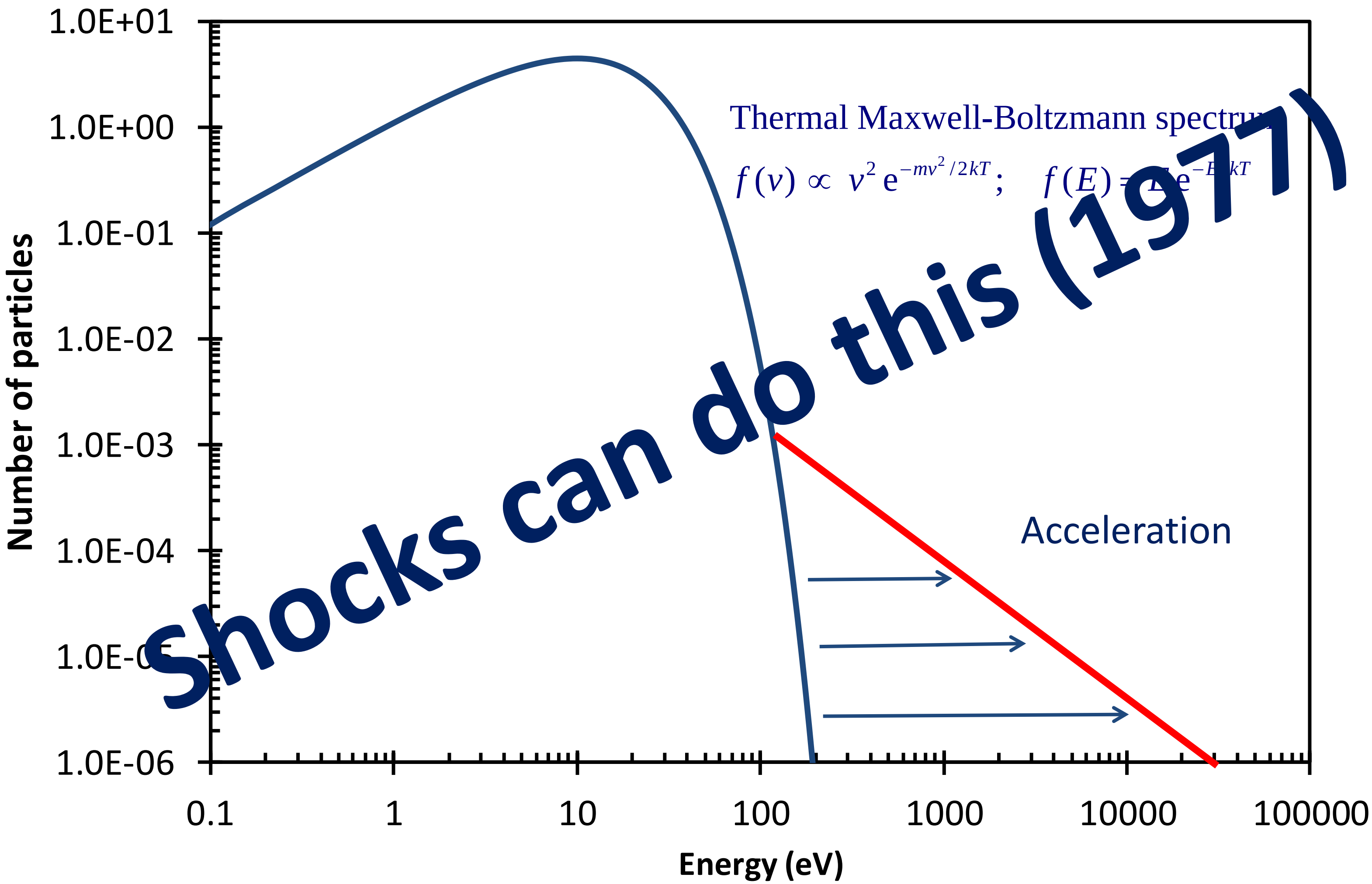
Cosmic-ray spectrum



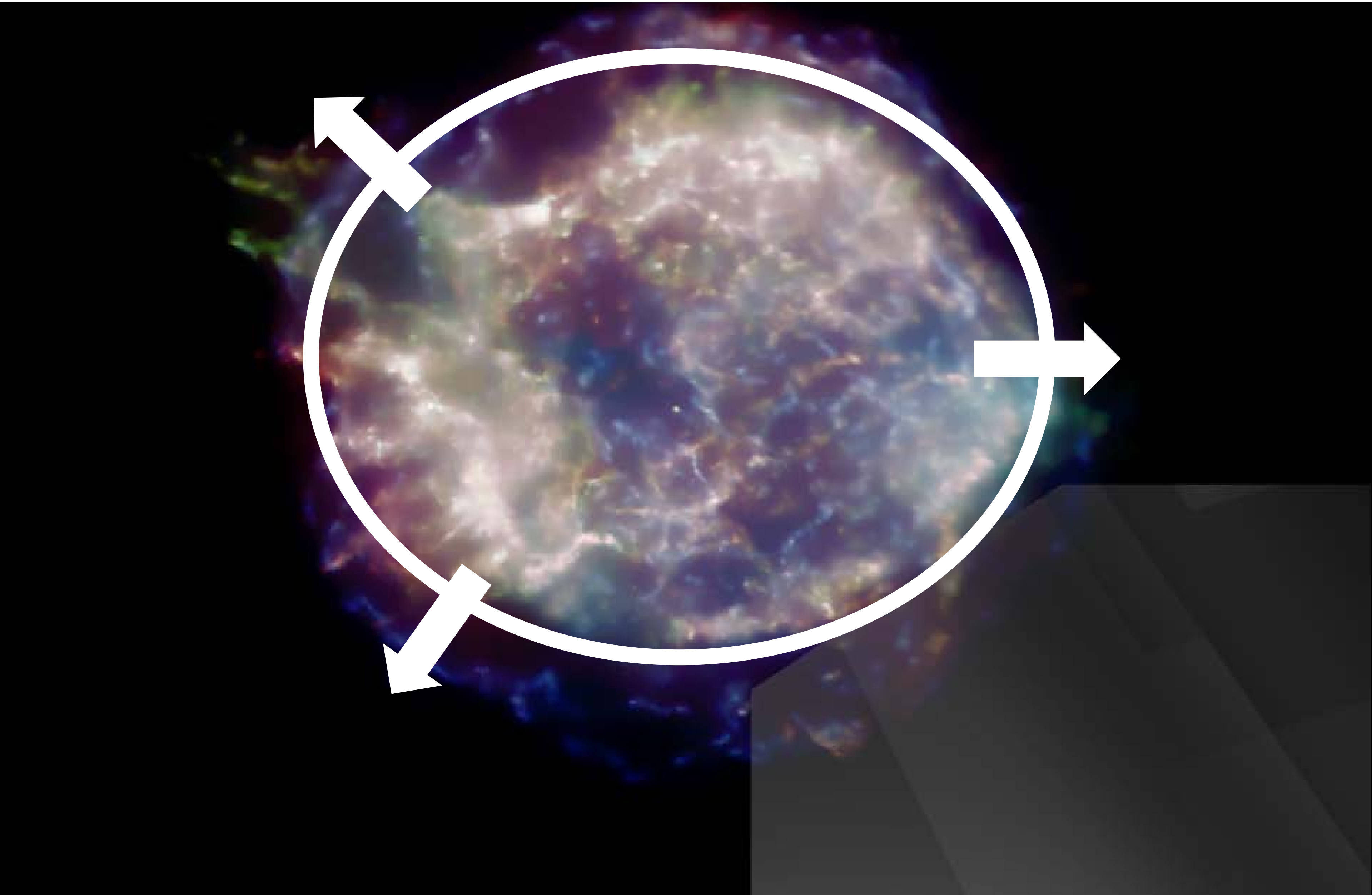
Cosmic-ray spectrum



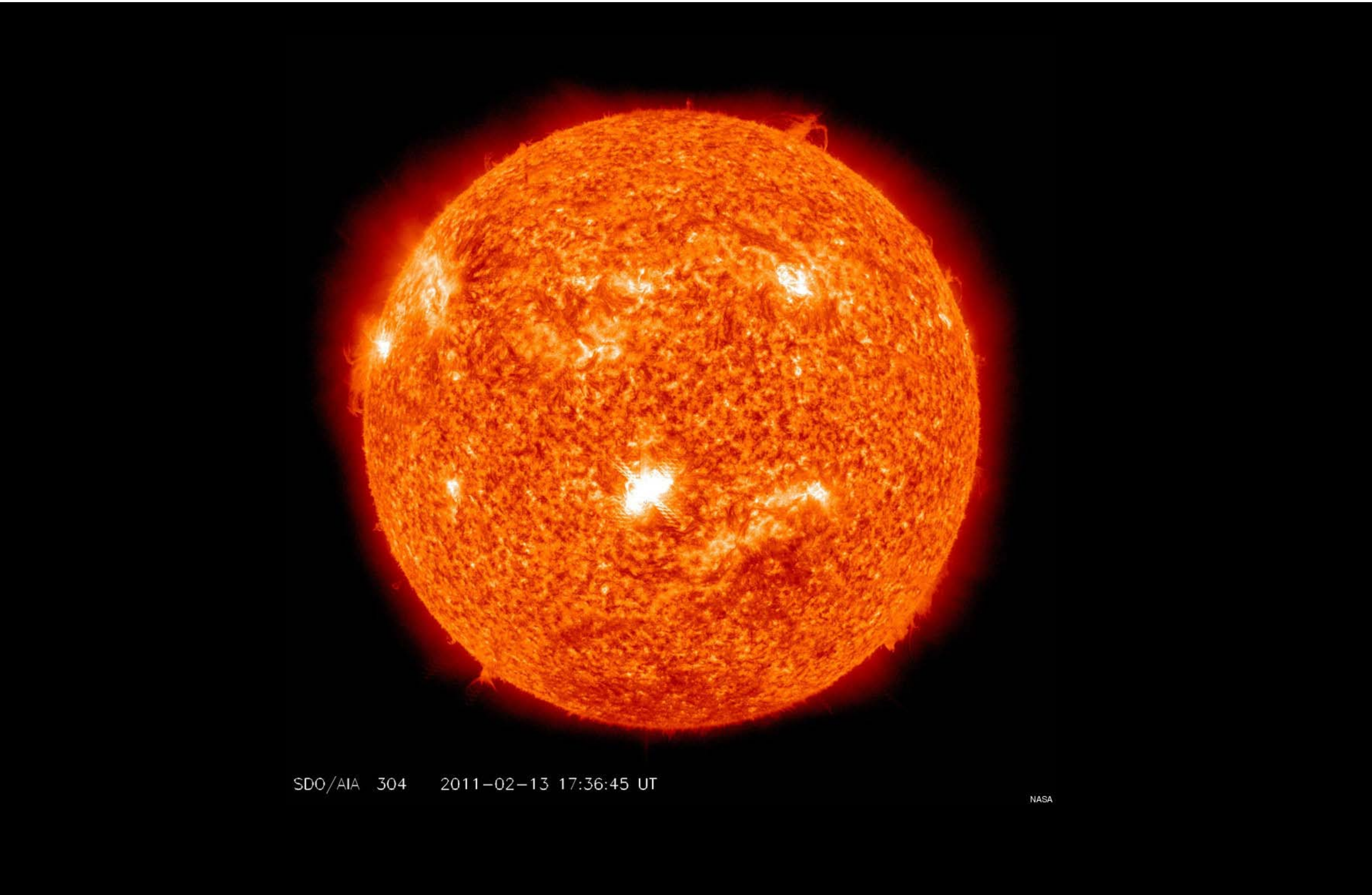
Cosmic-ray spectrum



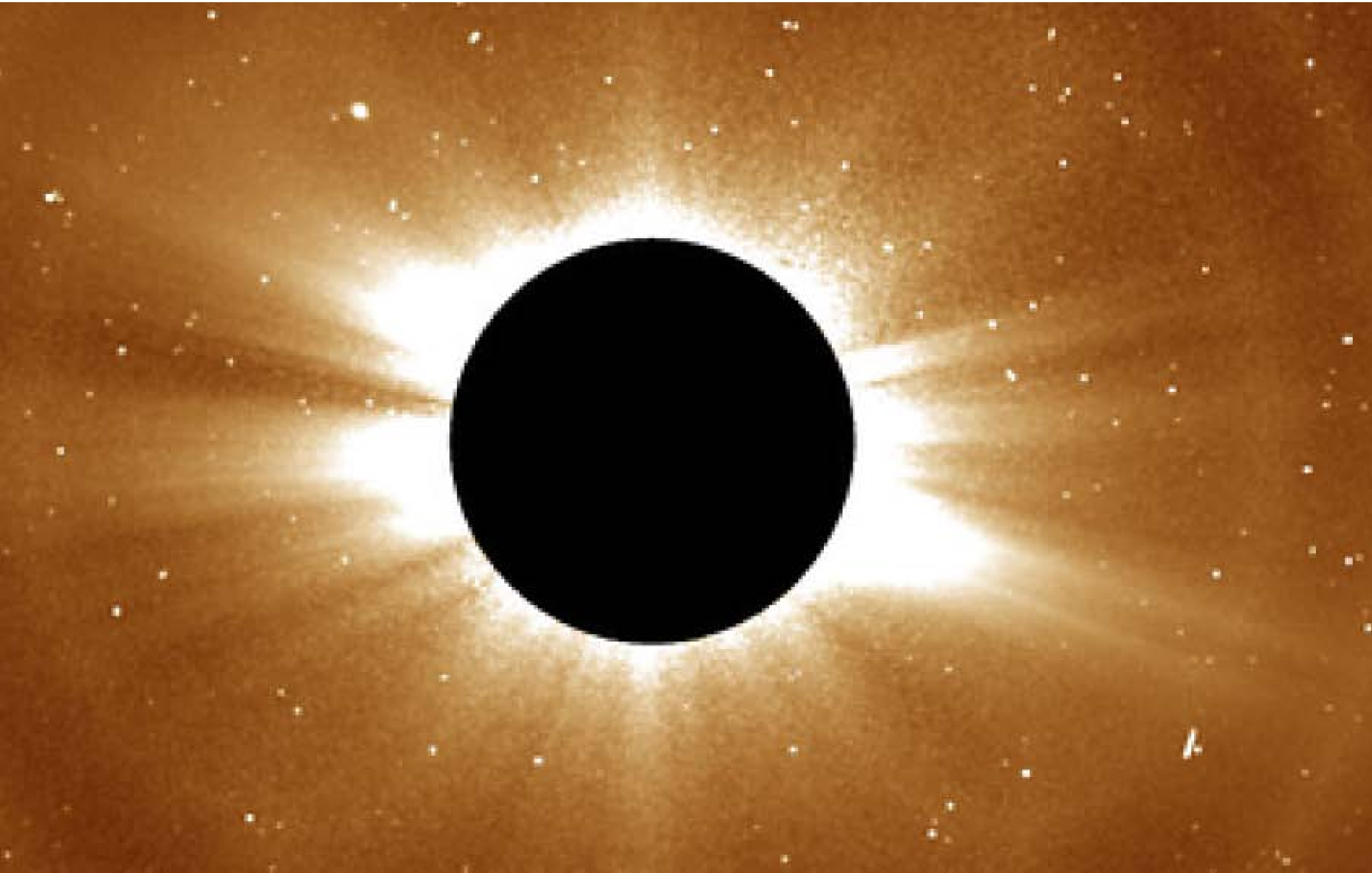
Cassiopeia A in X-rays



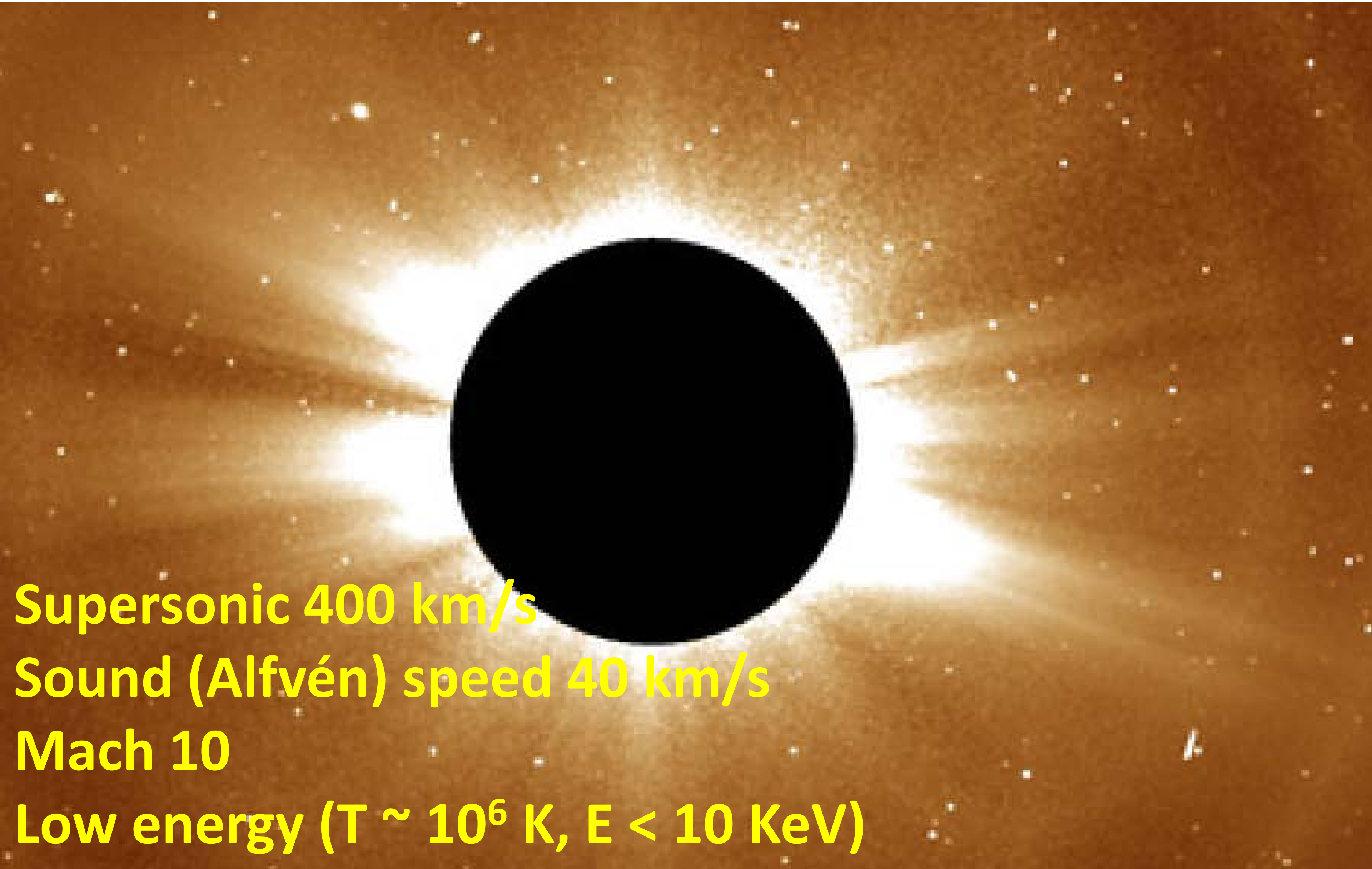
Solar Atmosphere



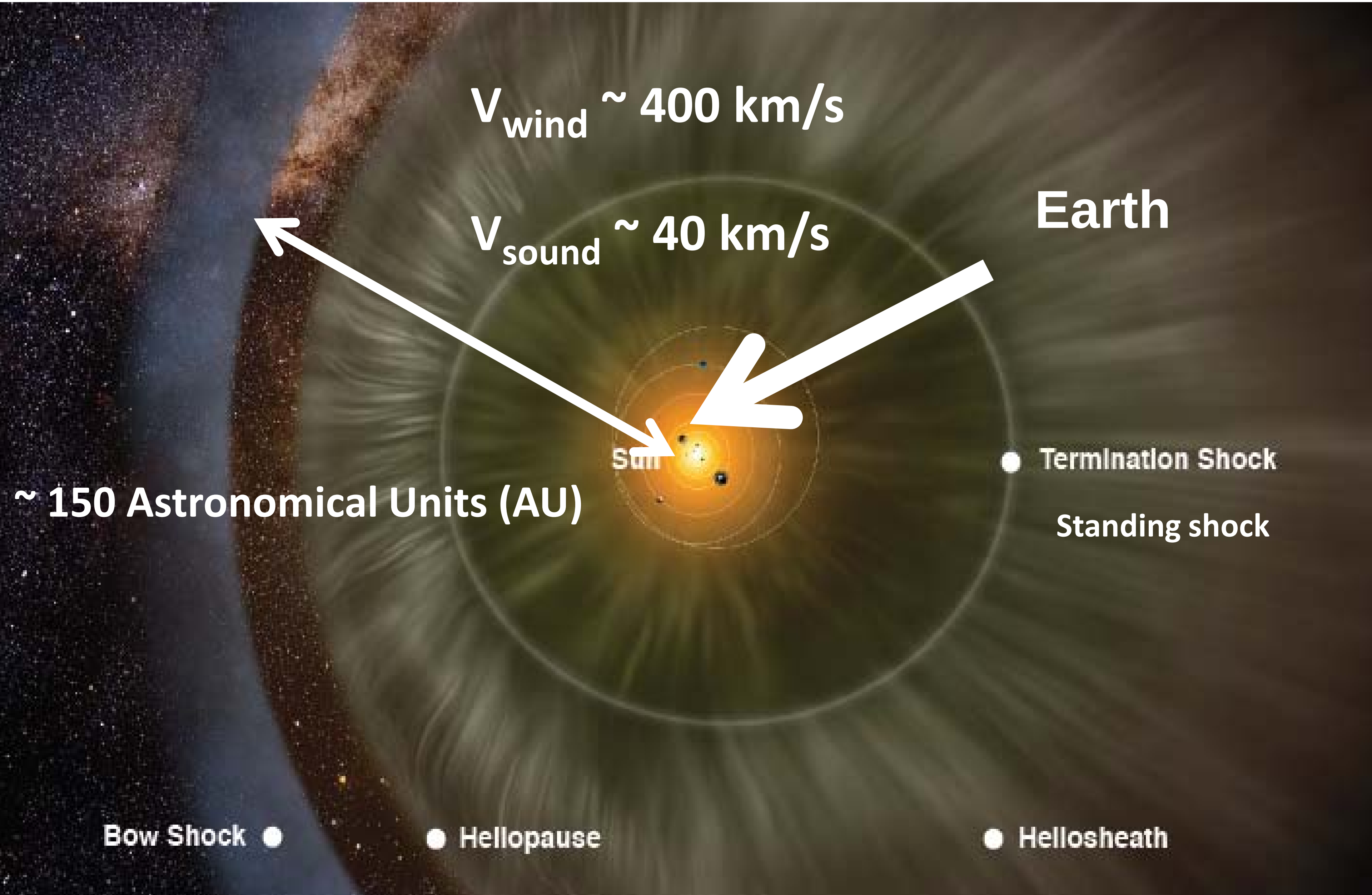
Solar Wind



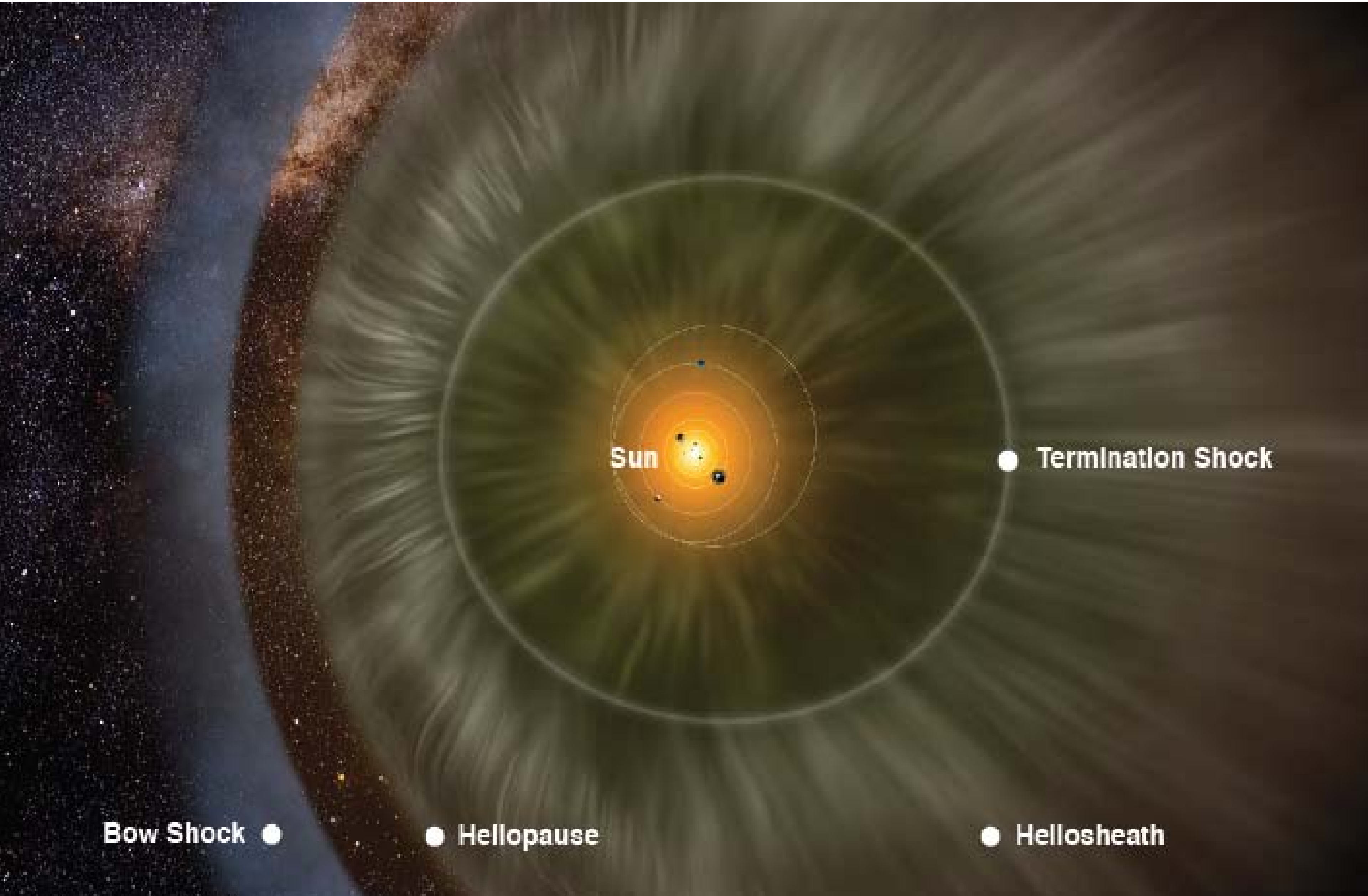
Solar Wind


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

The Heliosphere



The Heliosphere



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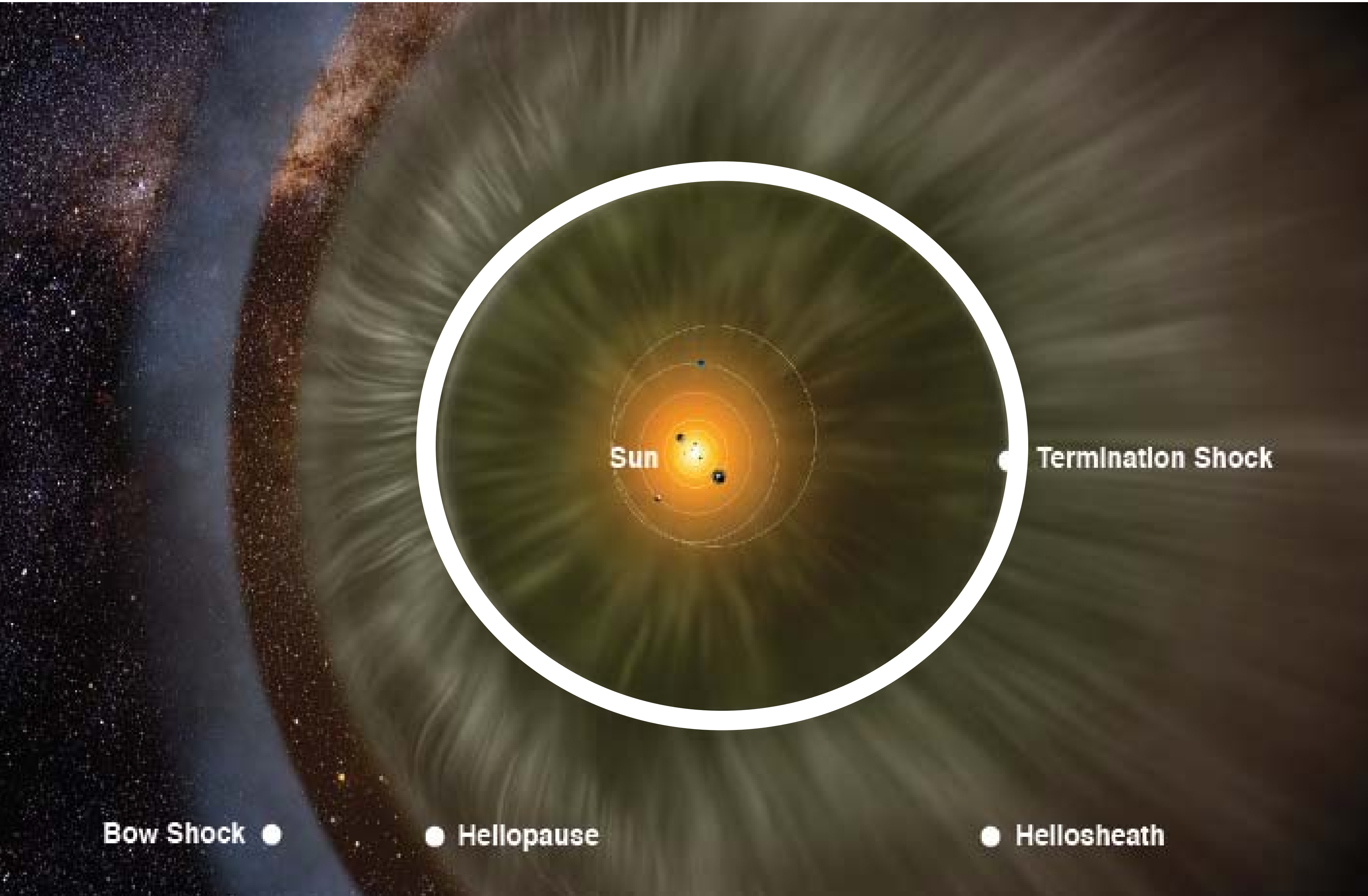

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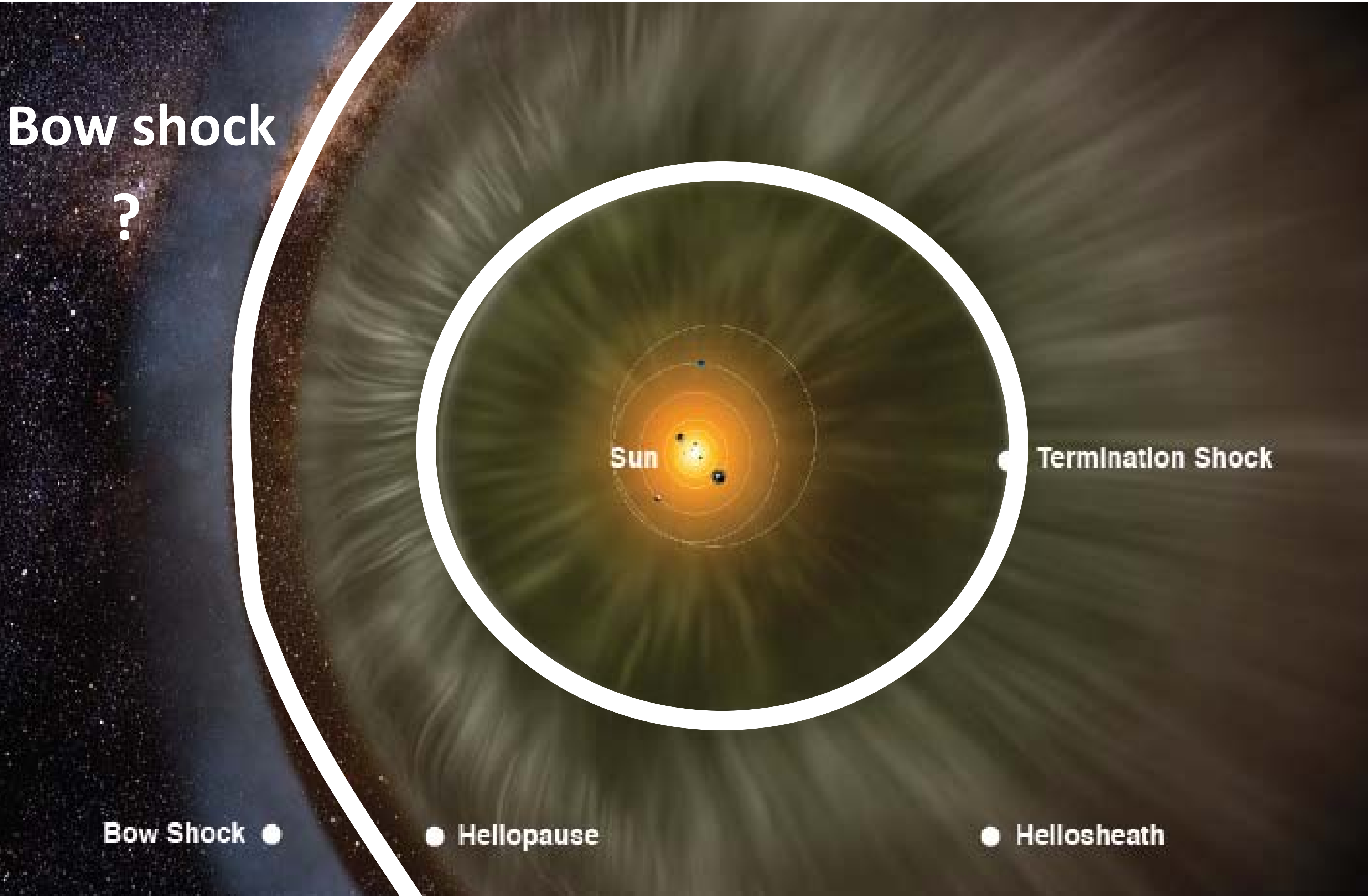
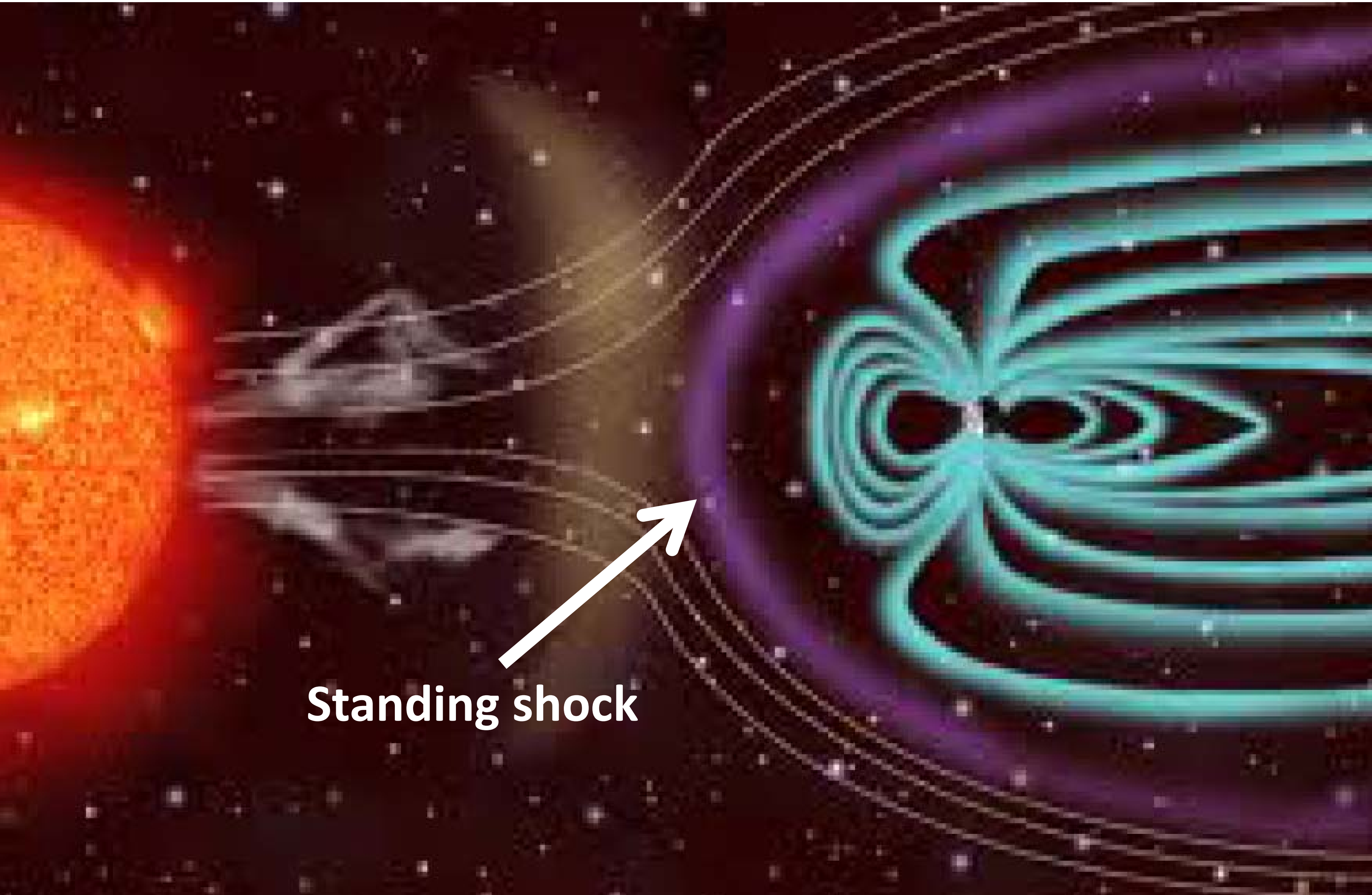
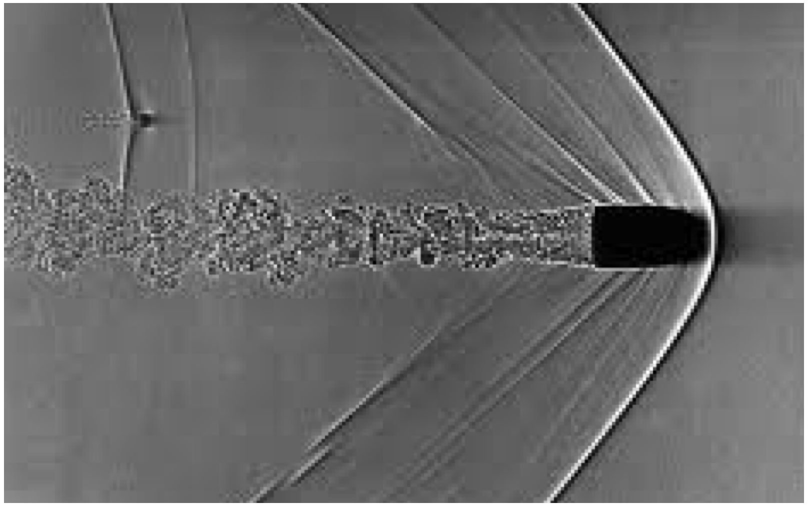


Geomagnetic field



Moving shocks



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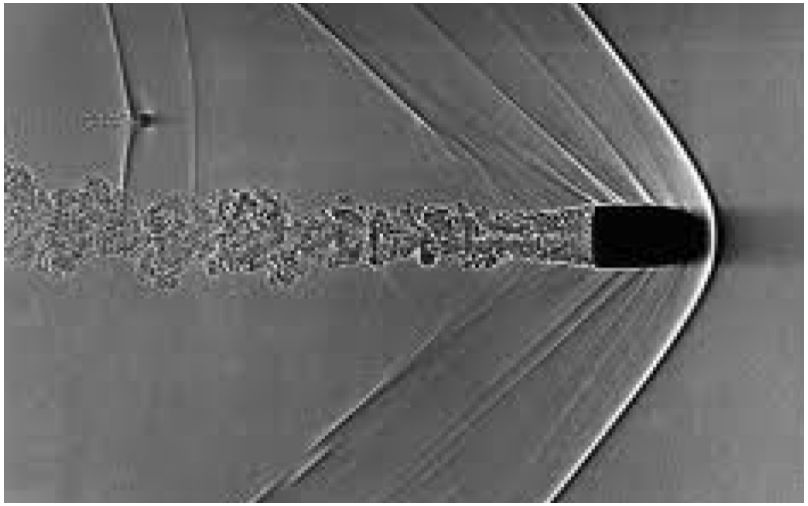

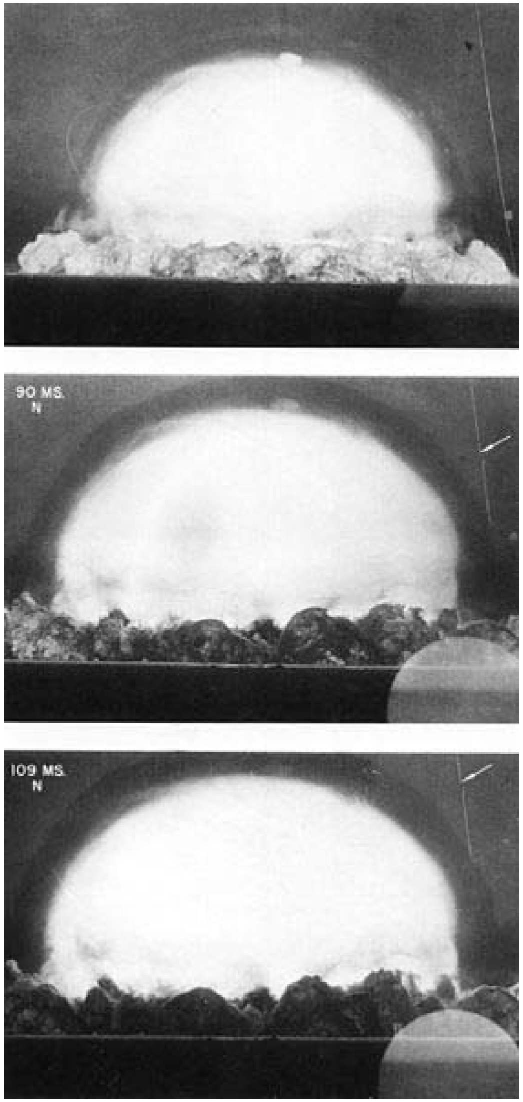

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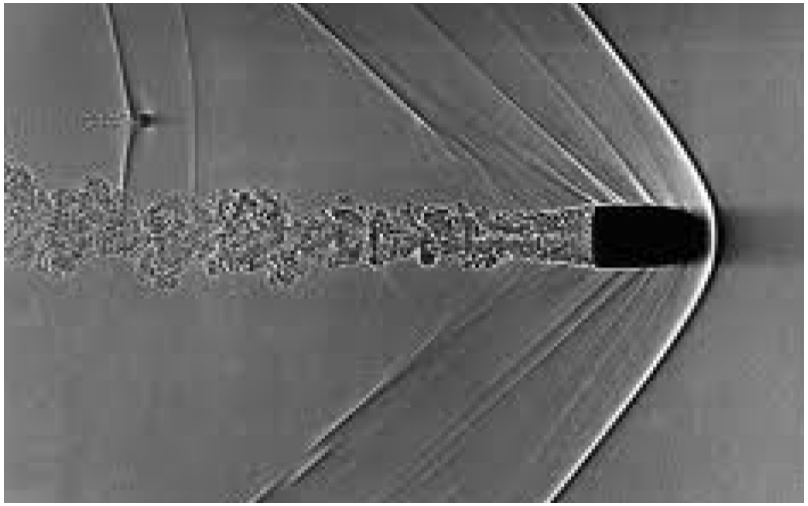
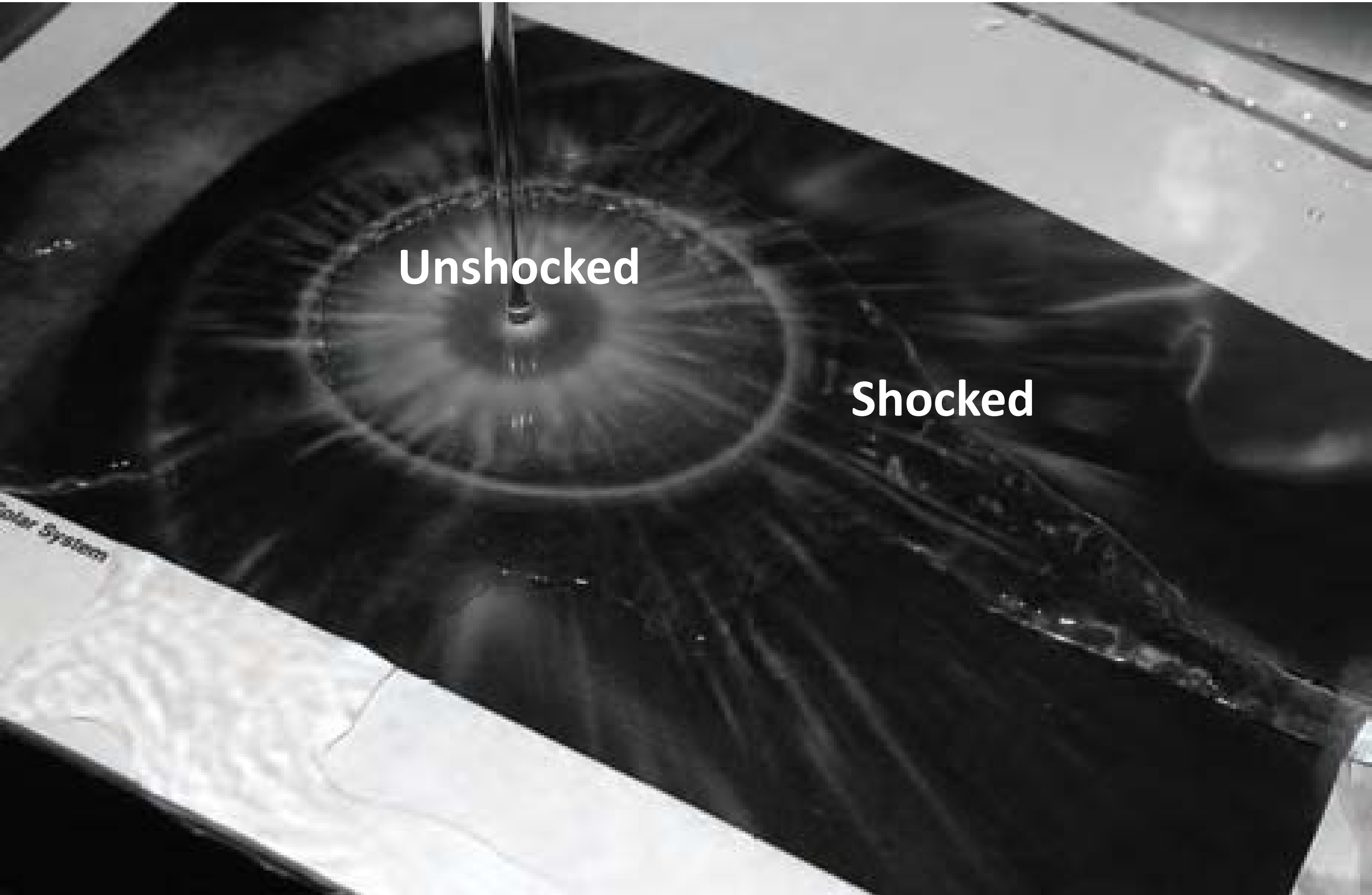


The kitchen sink (standing shock)

Stationary shock; kitchen sink



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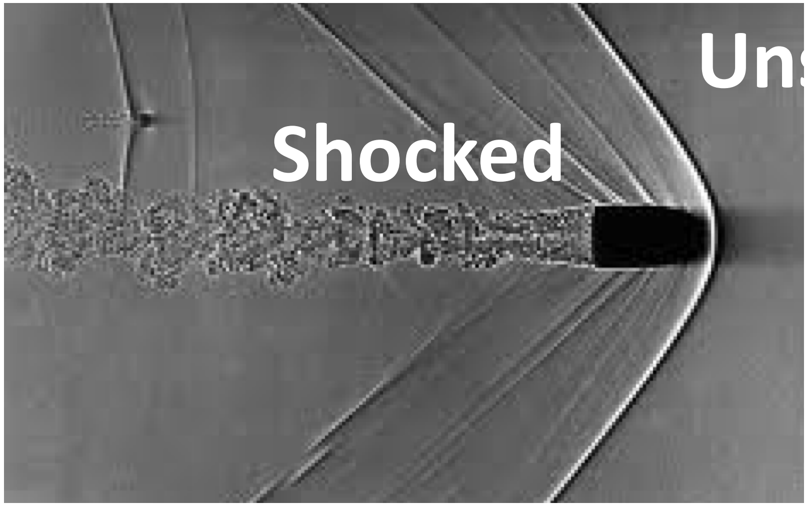
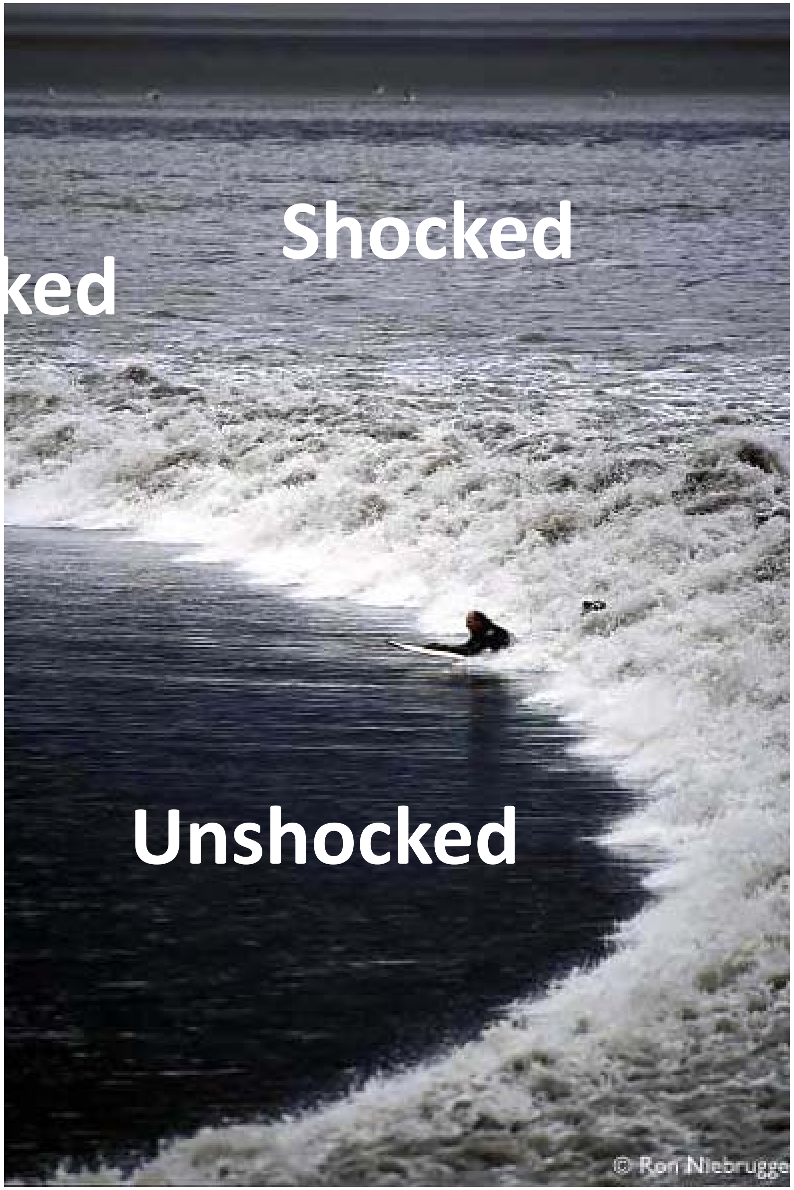
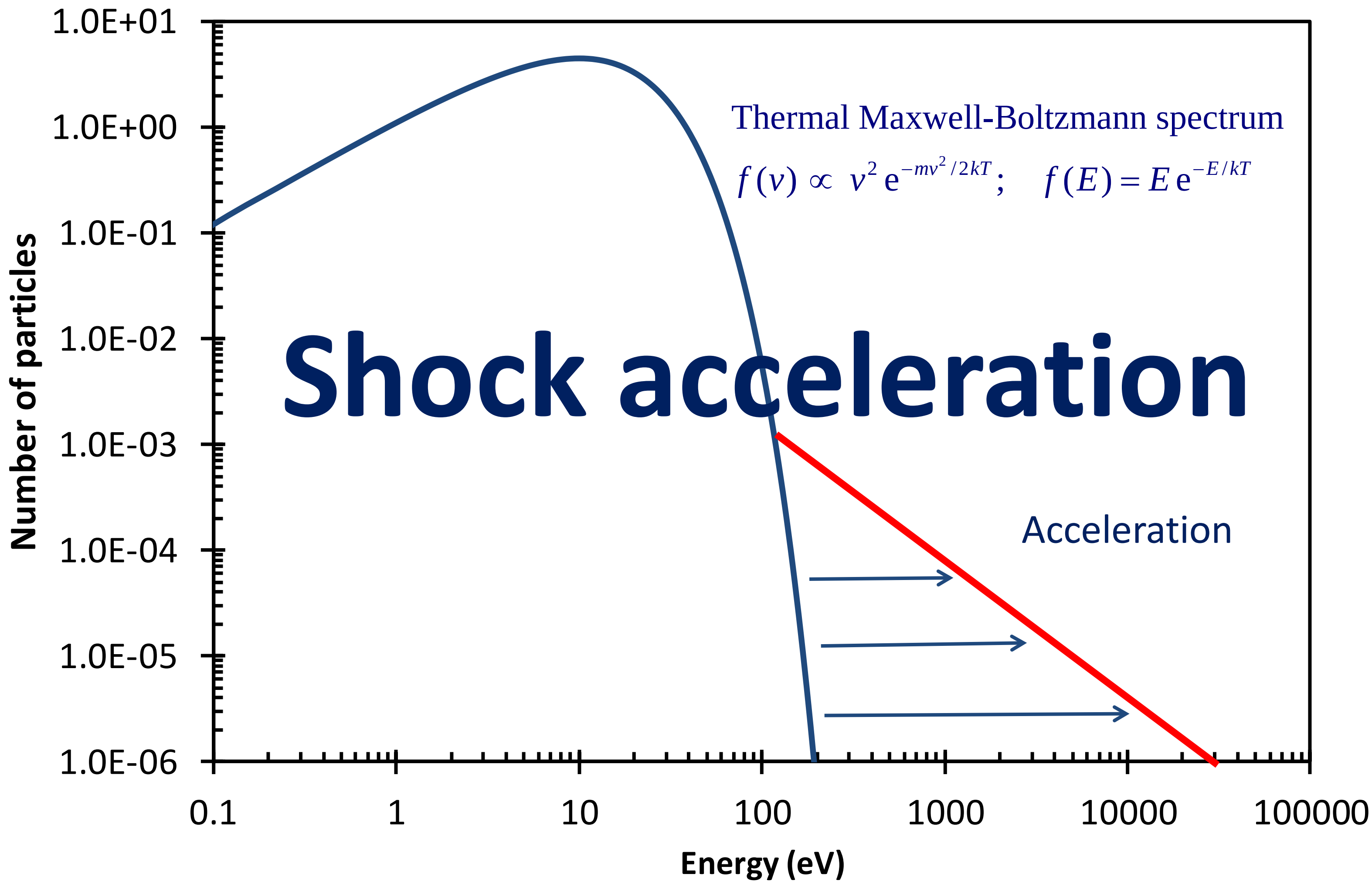




Shock

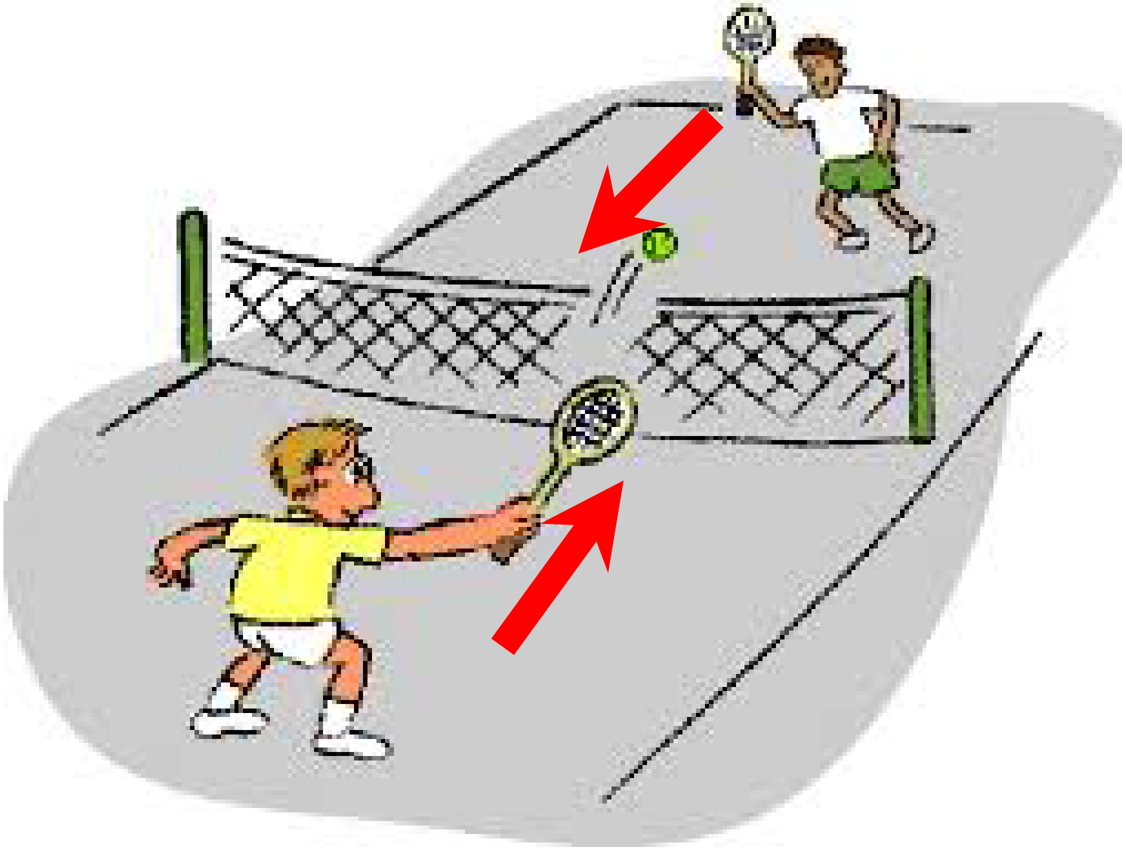
- A flow is supersonic (super Alfvénic) when it is faster than the particles can interact with each other
- This supersonic flow can only become subsonic through a shock transition

Cosmic-ray spectrum



Acceleration

Acceleration



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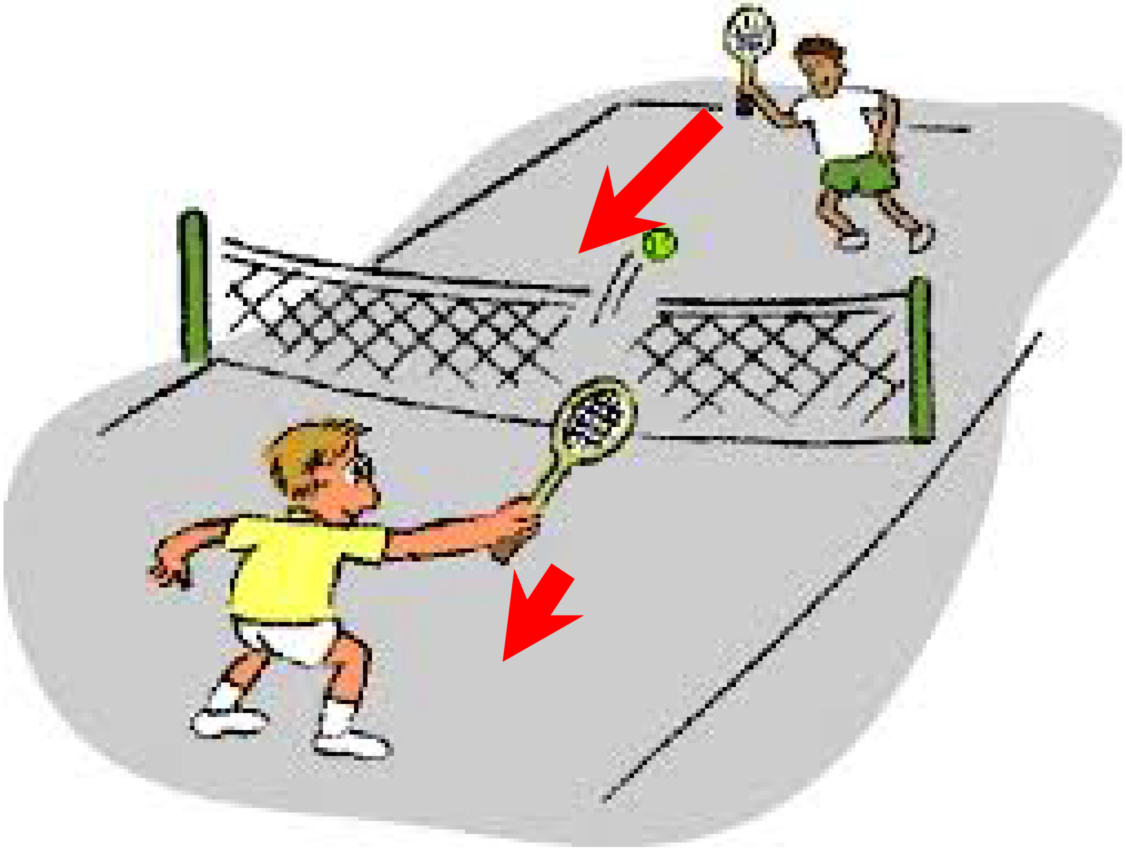

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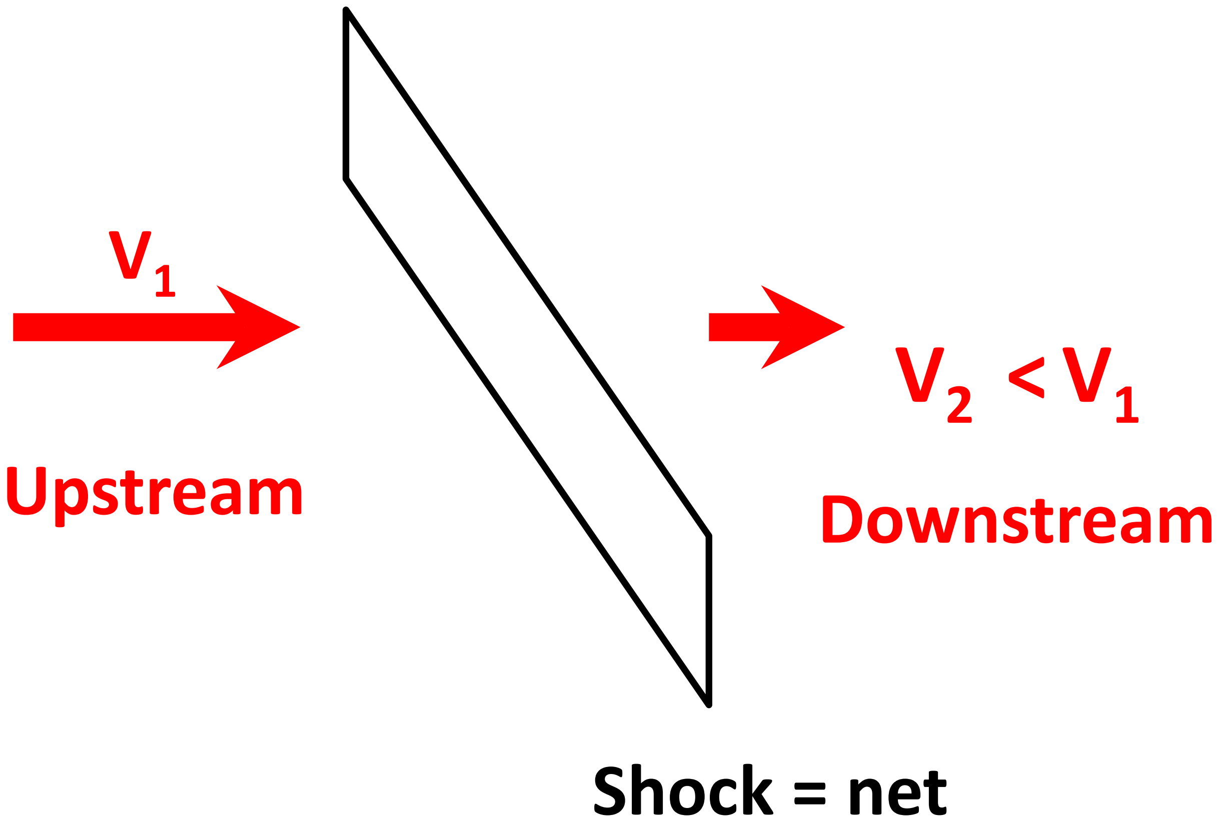

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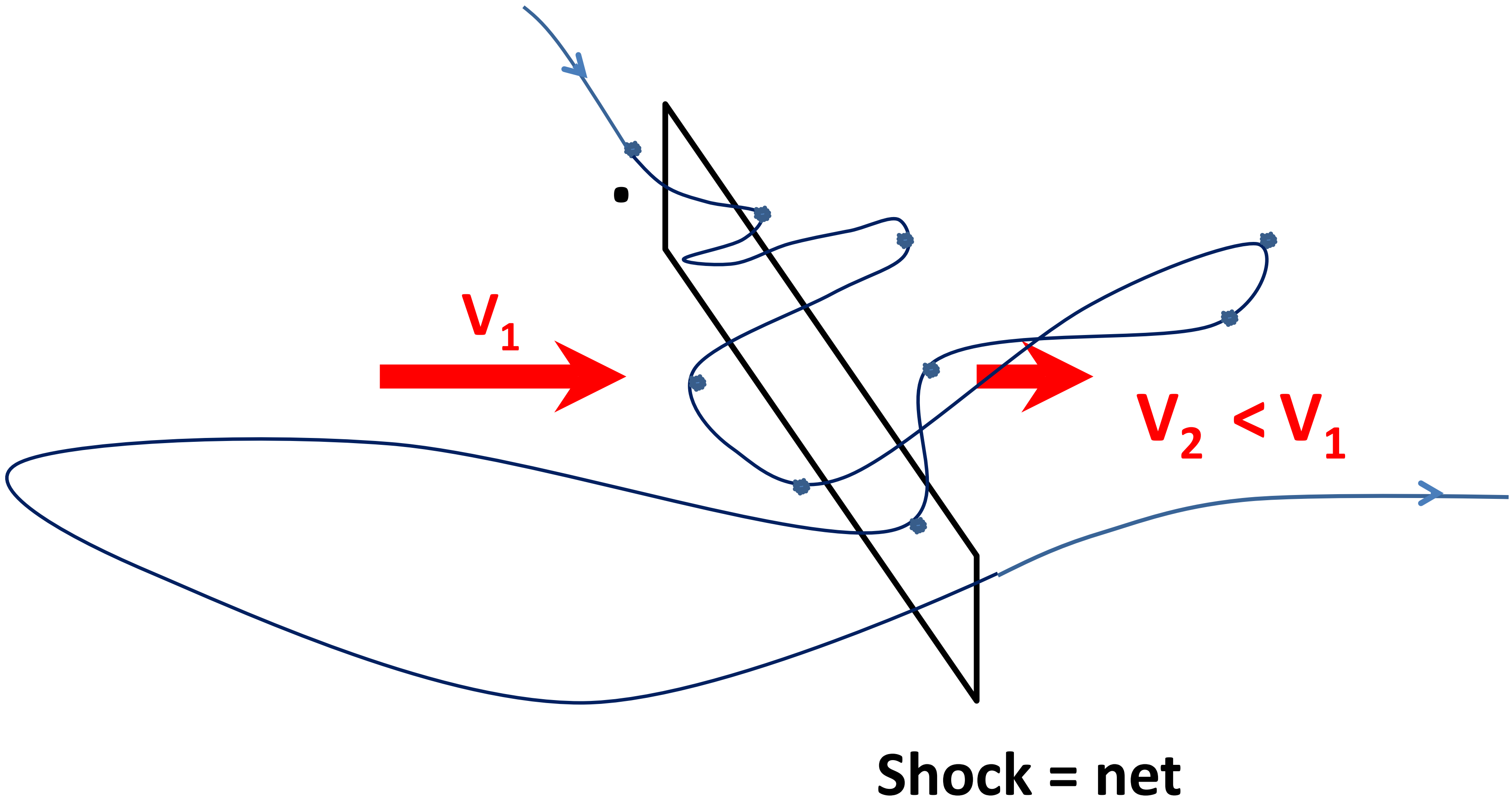

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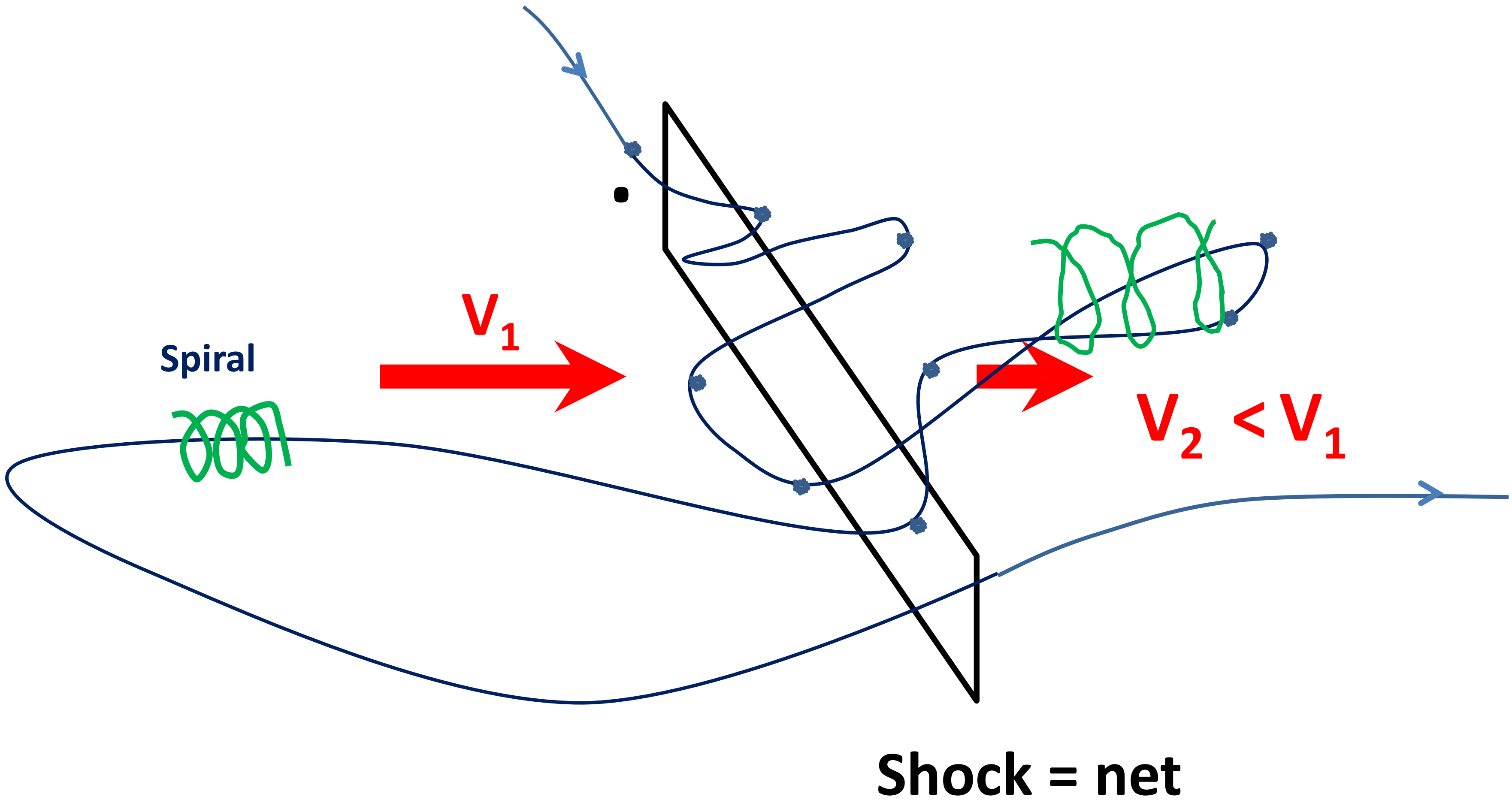


Cosmic-ray spectrum

Diffusive shock acceleration (1977)

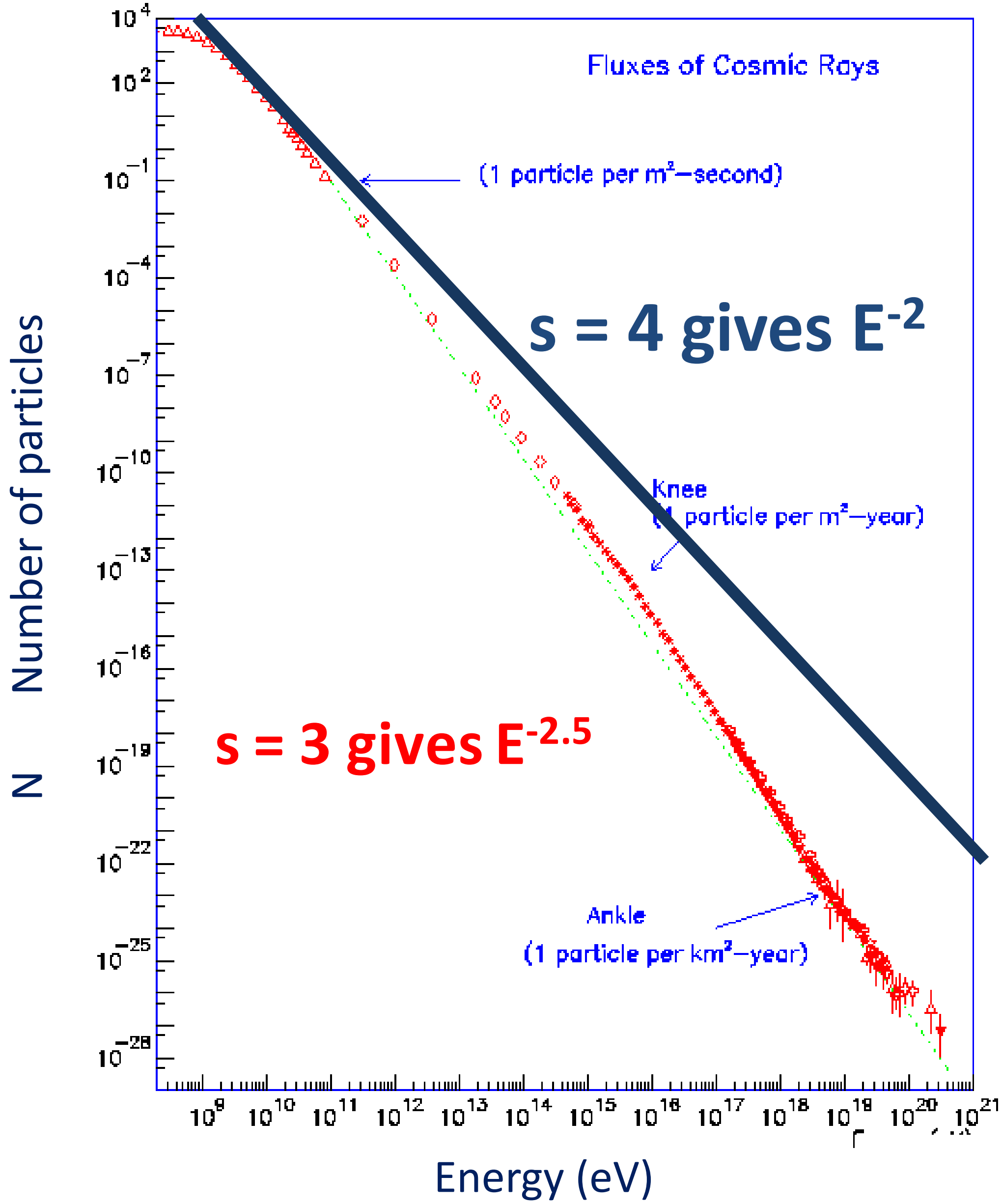
$$n(E) = aE^{\frac{2+s}{1-s}}$$

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

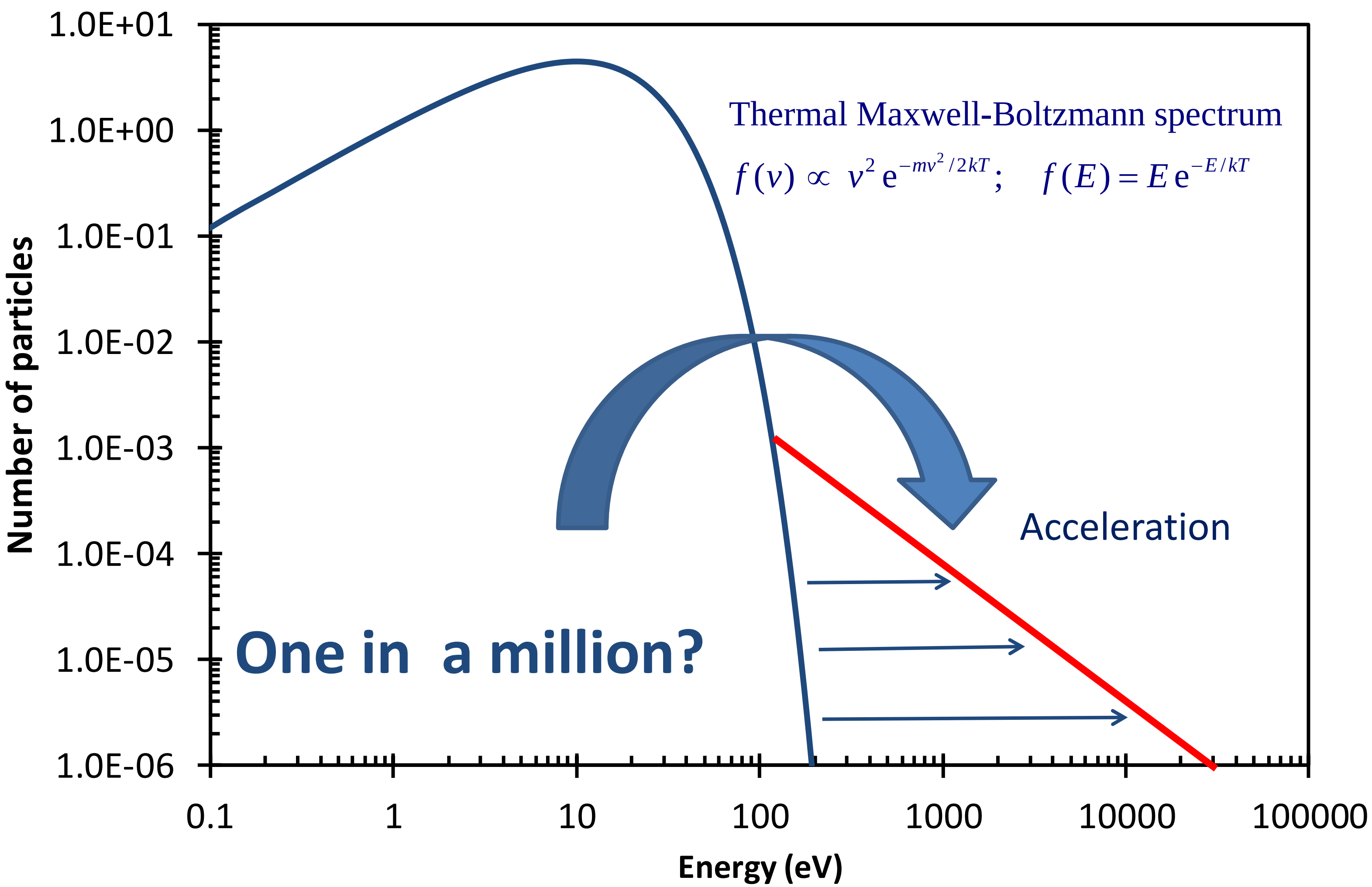
Maximum $s = 4$ (this follows from fluid dynamics);

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

Cosmic-ray spectrum

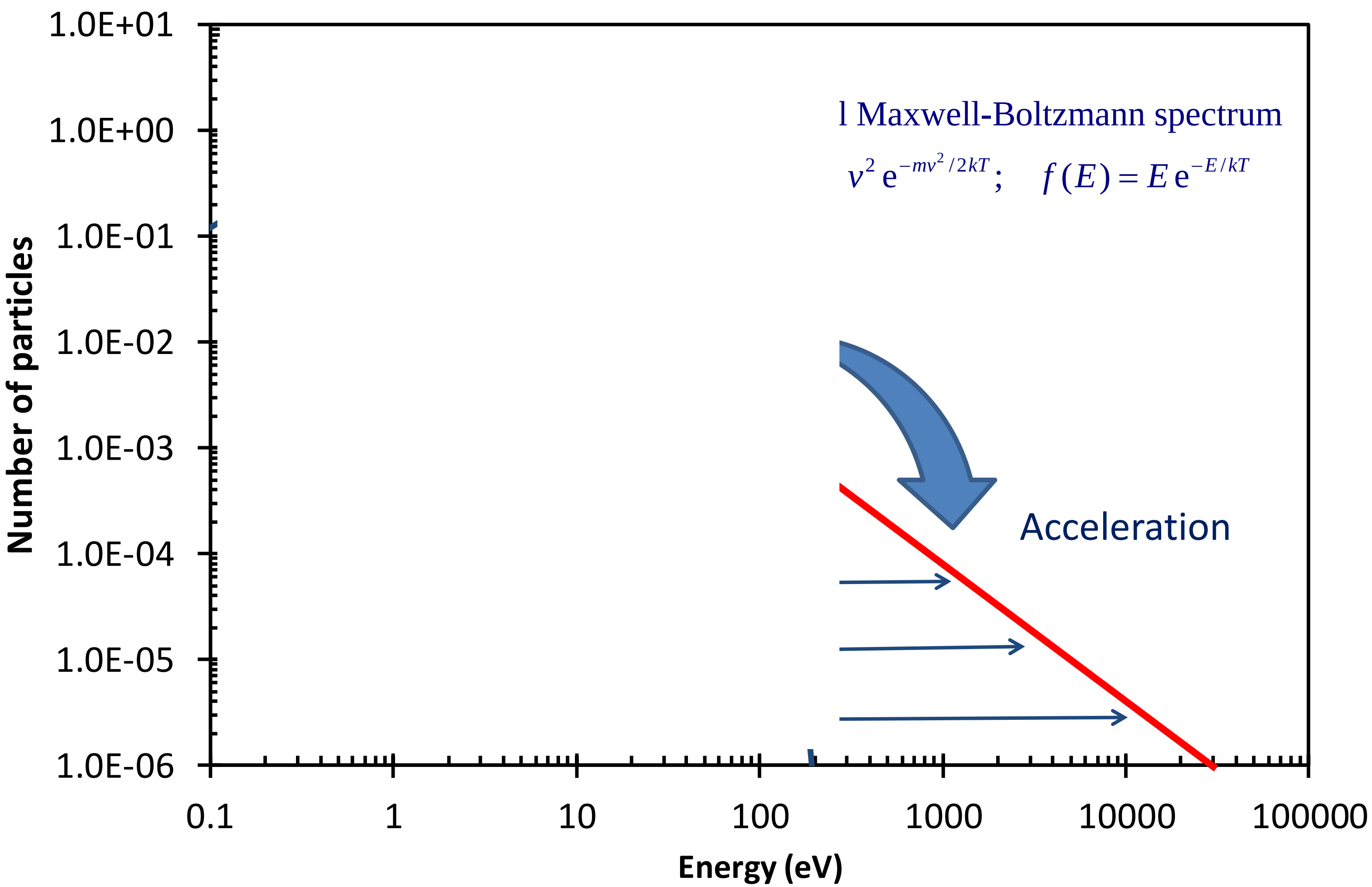


Cosmic-ray spectrum



Shock or Fermi acceleration

Cosmic-ray spectrum



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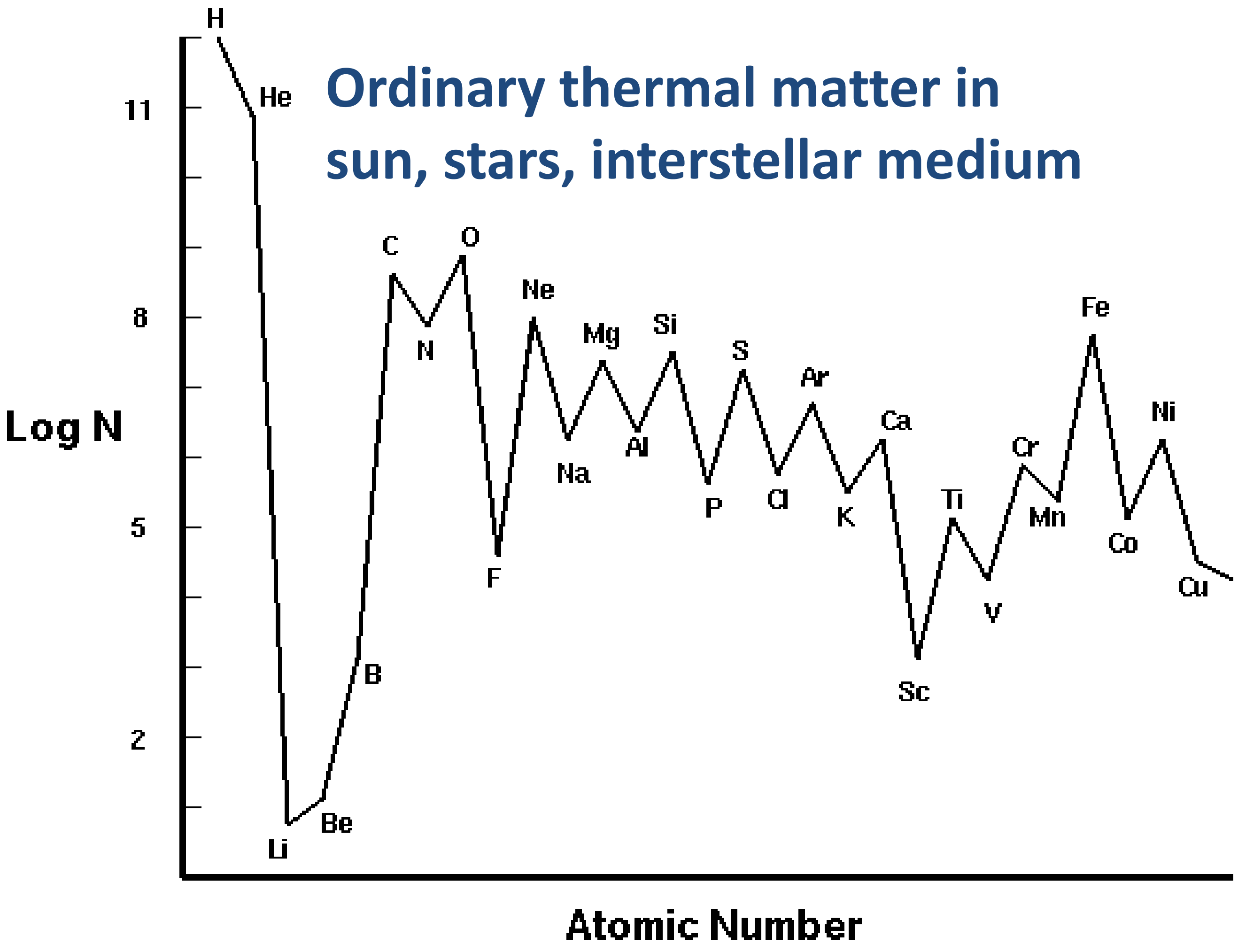
Cosmic-ray Composition



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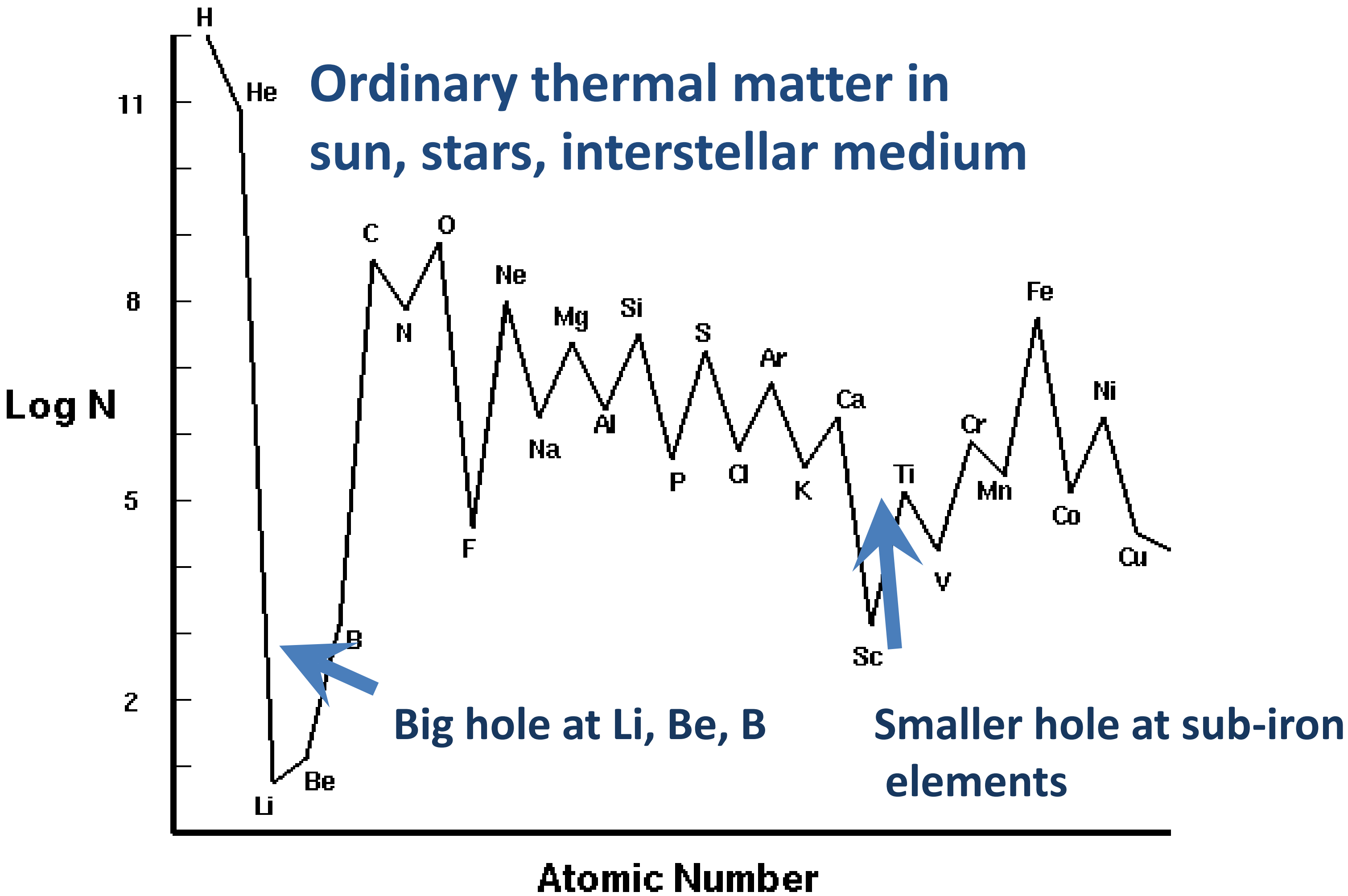
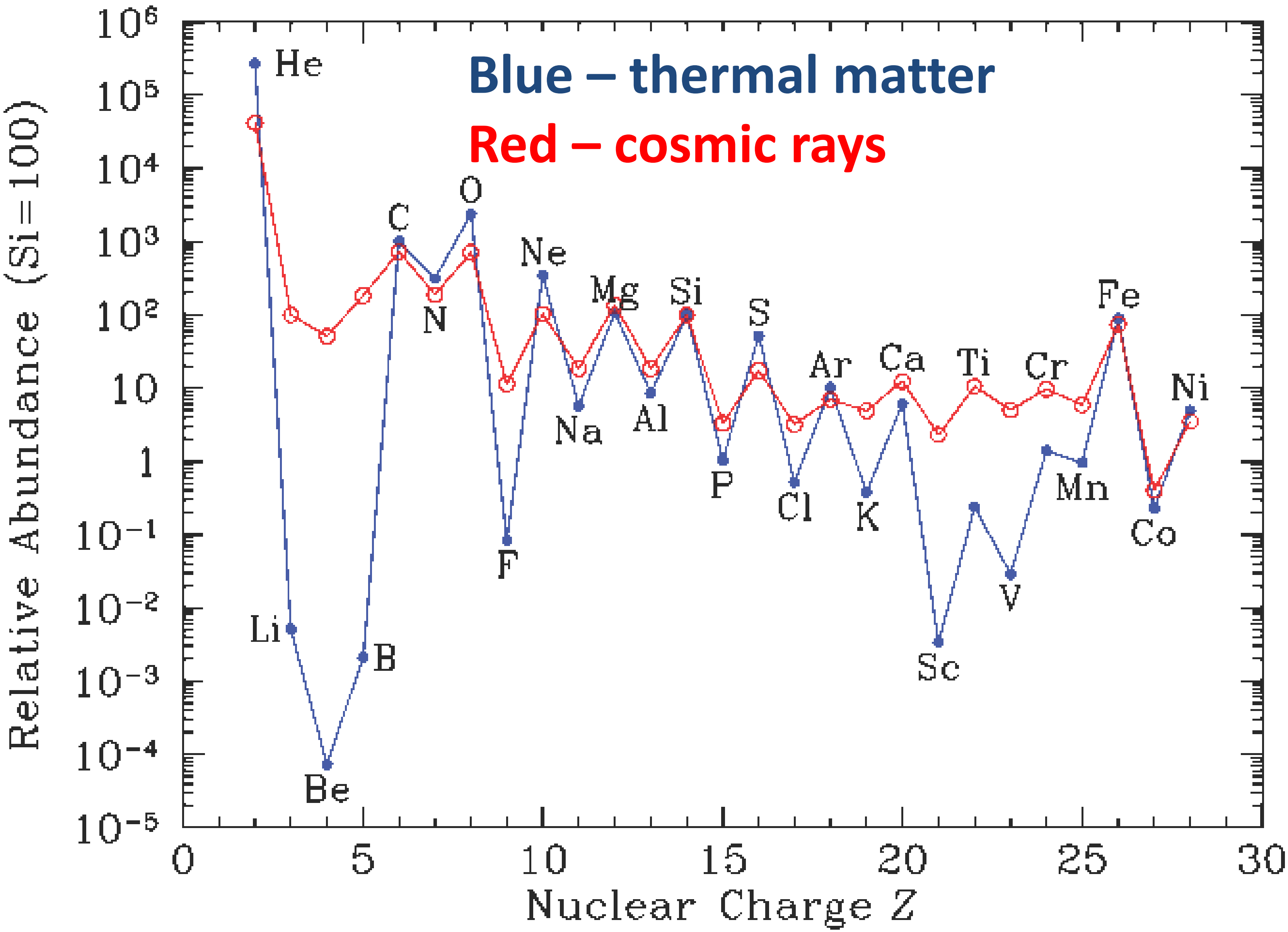
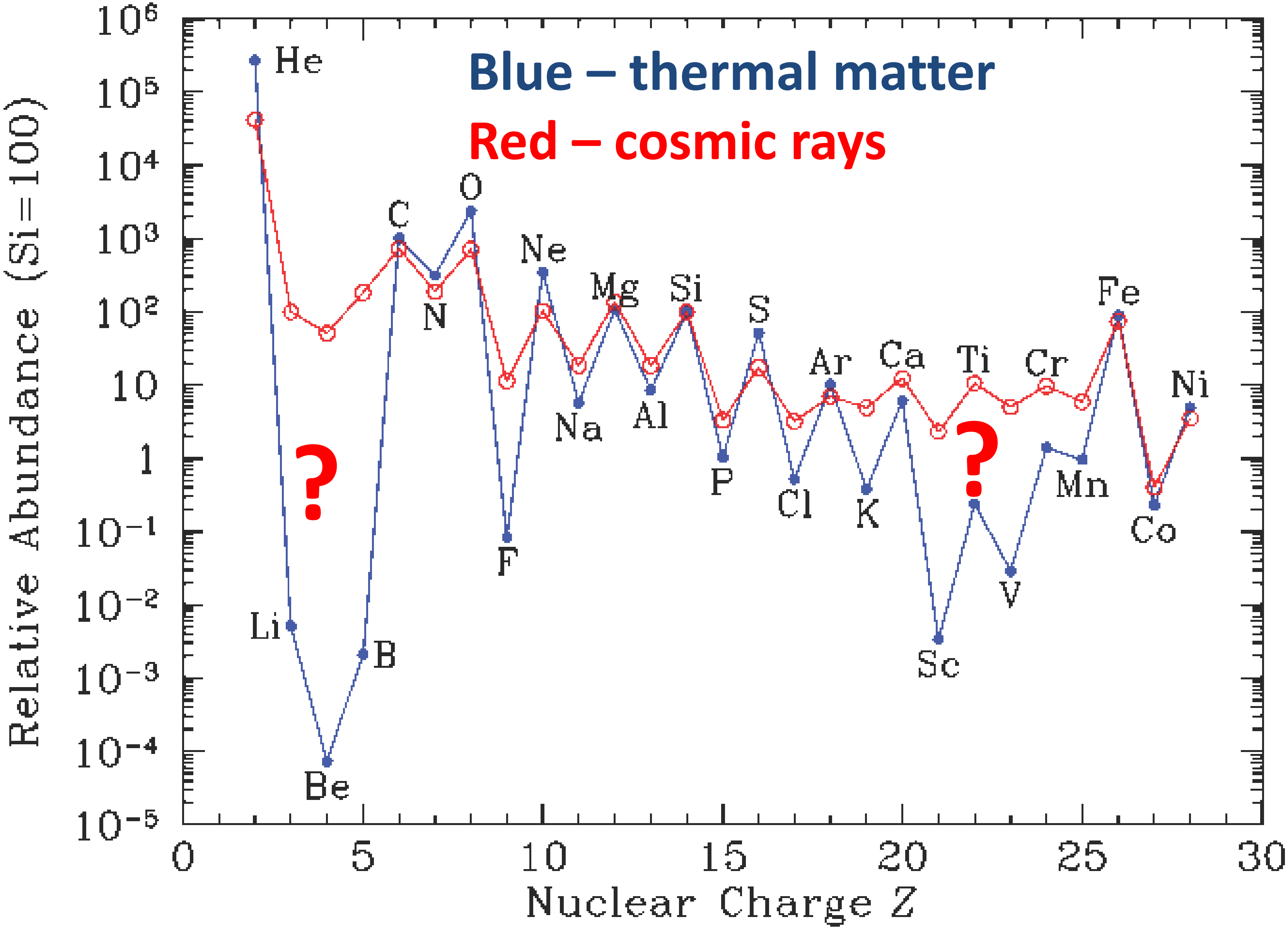


Cosmic-ray Composition



Cosmic-ray Composition



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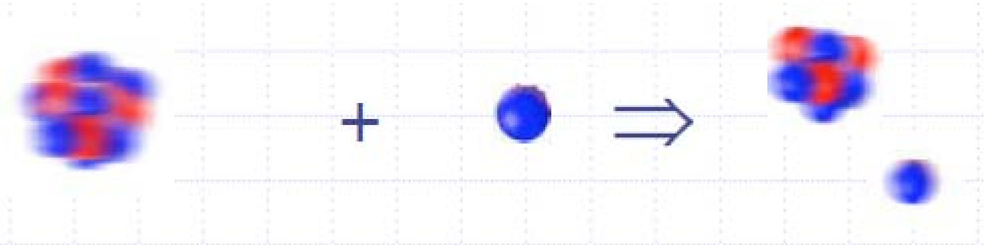
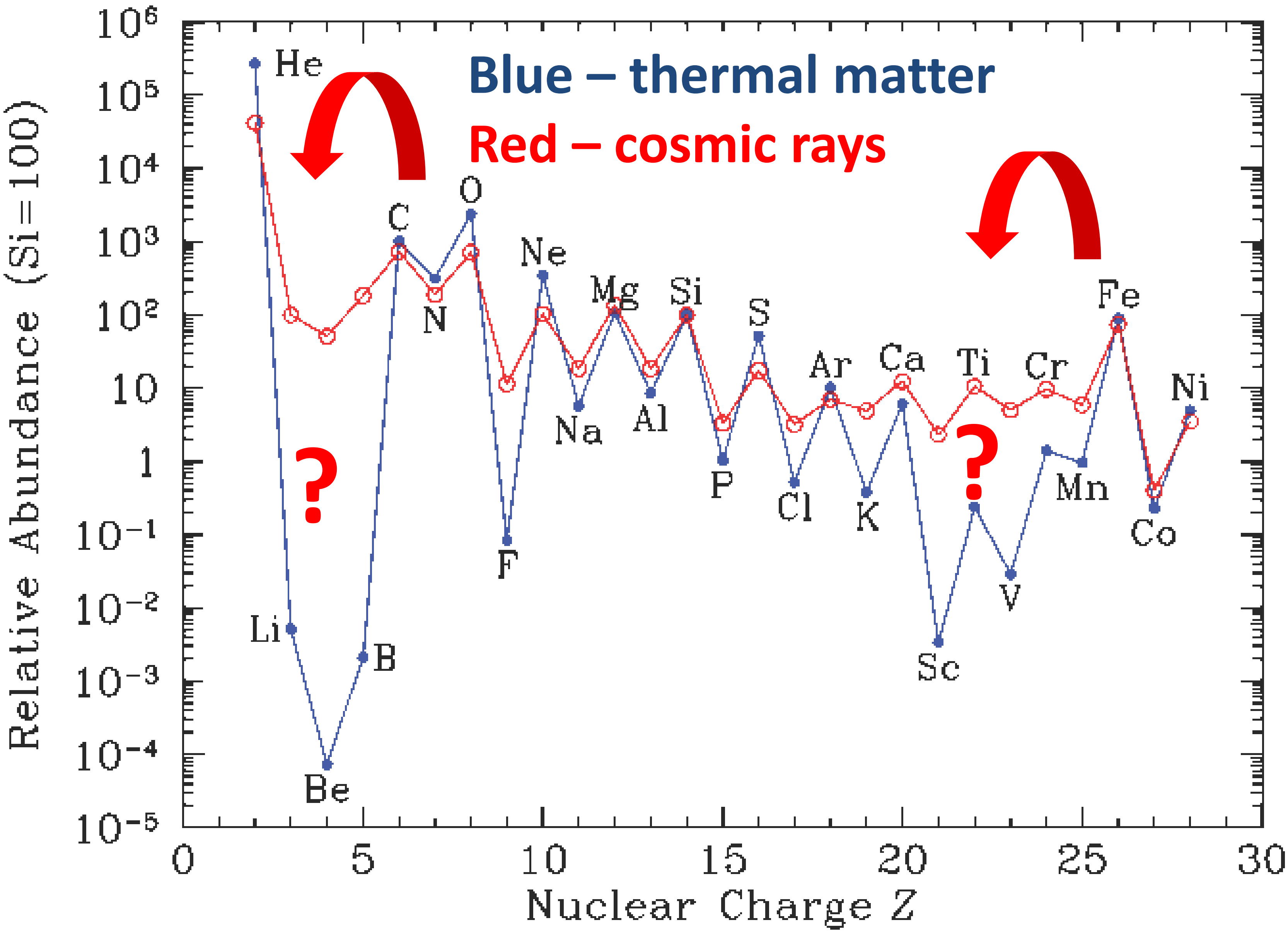


Nuclear spallation of cosmic rays

Cosmic ray C,N,O + thermal particles ➡ Li, Be, B

Cosmic-ray Composition



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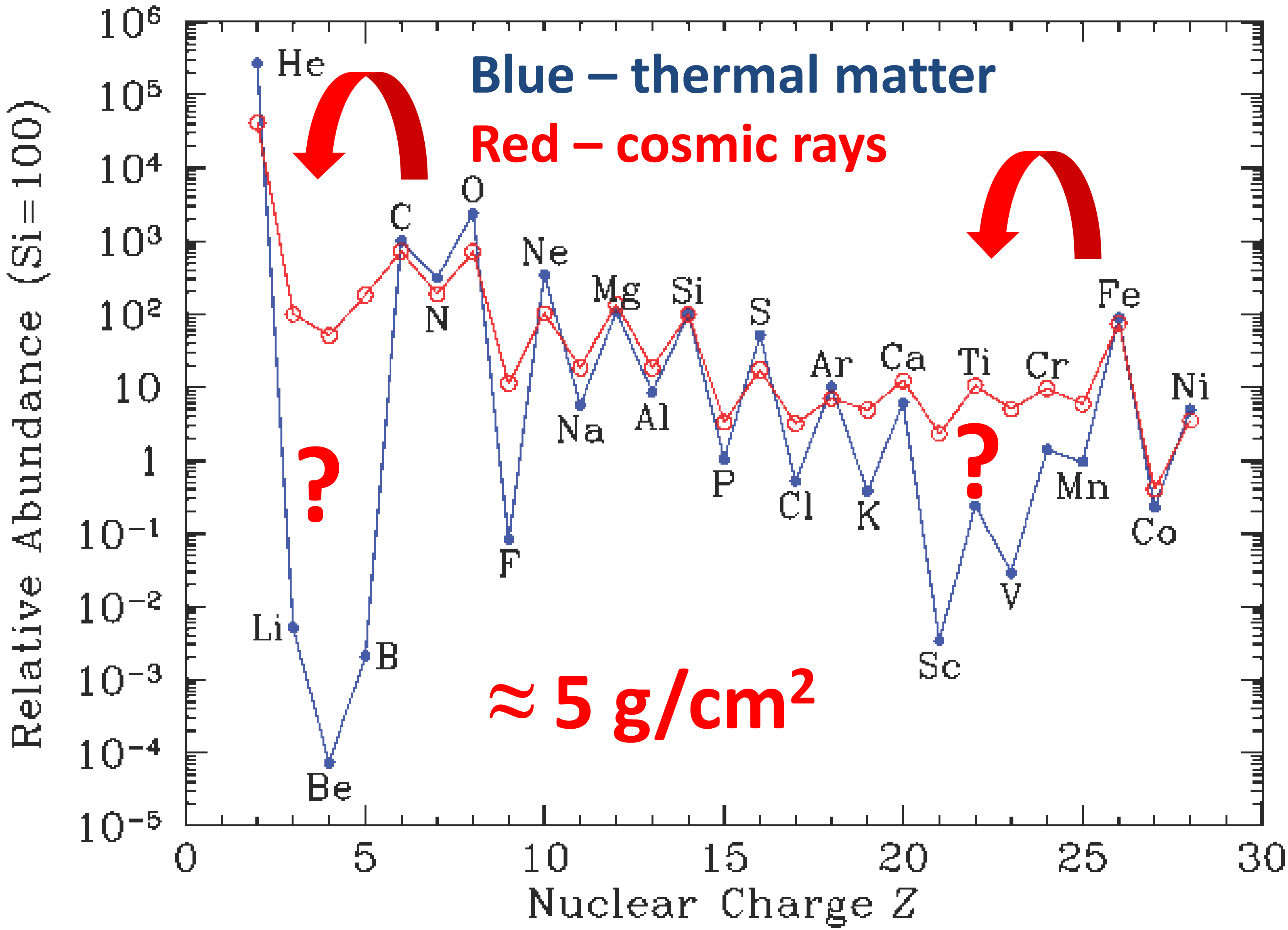
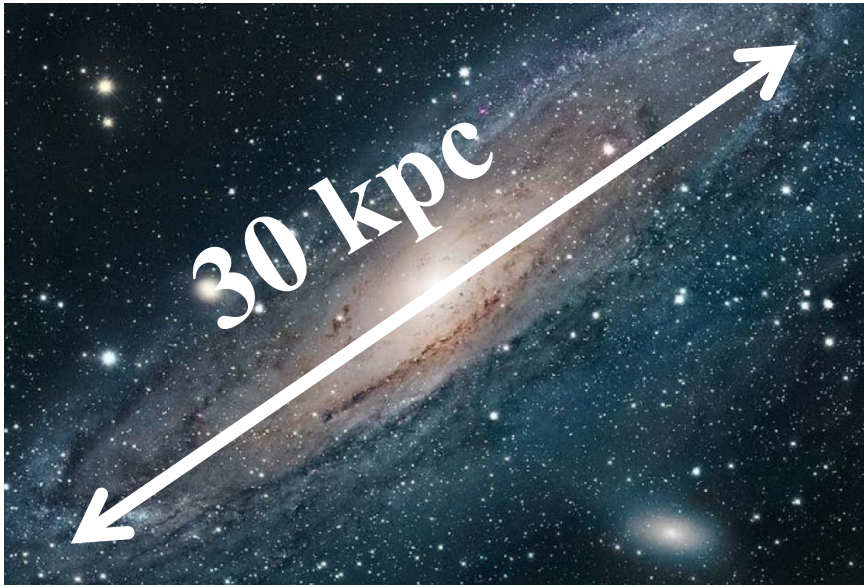


Cosmic-ray Composition

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



Cosmic rays are extragalactic

Cosmic-ray Composition

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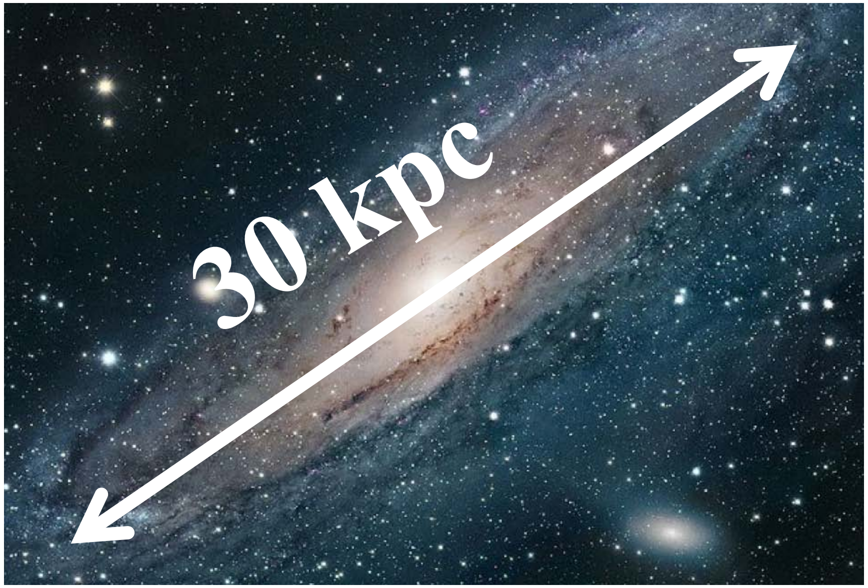

→ ~~**Cosmic rays are extragalactic**~~

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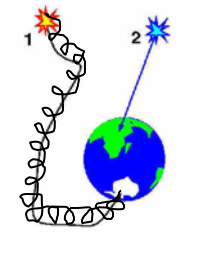
➡ ~~Cosmic rays are extragalactic~~

Galactic:
Most probably supernova blast wave shocks

Status after 102 years

- Can't see through mist



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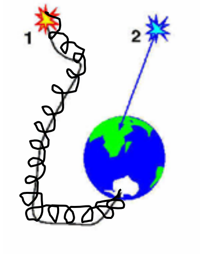

- Look at gammas instead (since ~ 1980)

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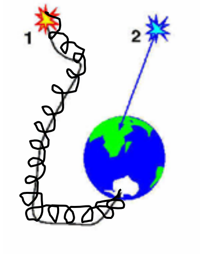

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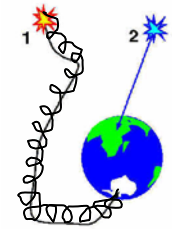

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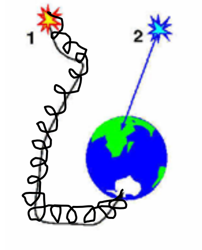

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- Fermi space telescope 14 Feb. 2013, SNR IC443 – indeed protons!

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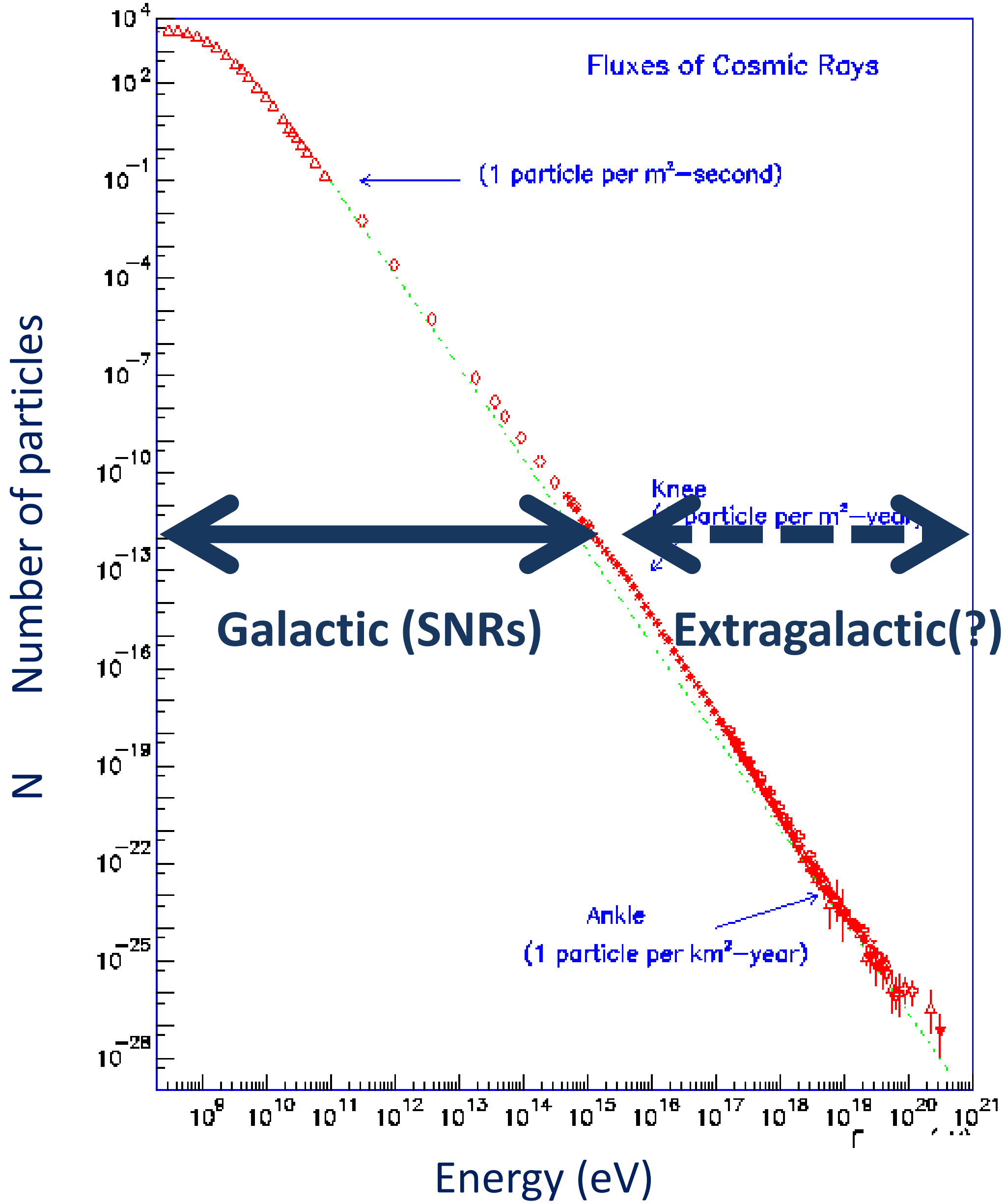

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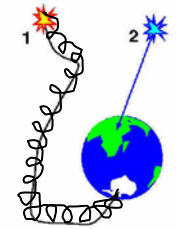

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- Particle *and* photon astronomy

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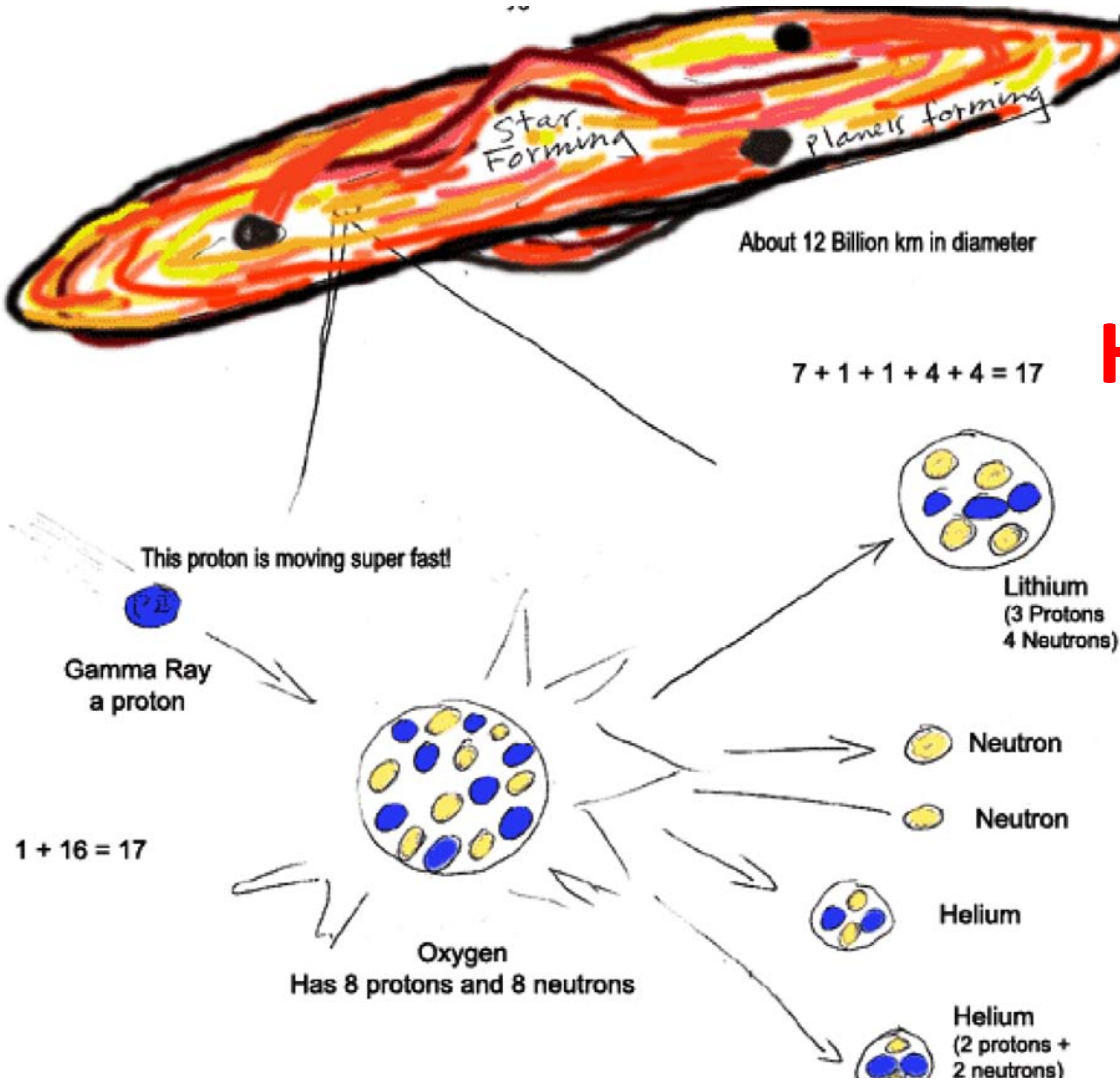
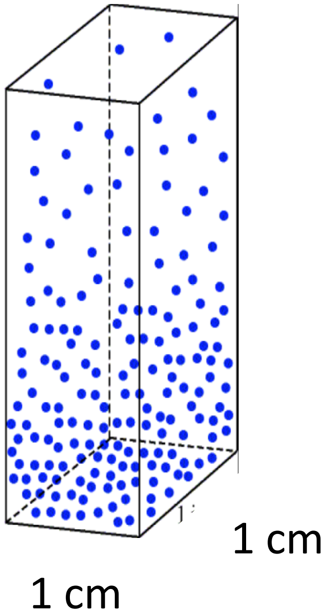
- Thus their speed is c (for energies > 10^9 eV)
- Equipartition of energy: light ≈ magnetic field ≈ interstellar matter ≈ cosmic rays ≈ **1 eV/cm^3**
- Cosmic rays are young:
  d =1 Mpc at c = 3.10^8 m/s implies ~ **10^7 years**

Cosmic-ray Composition



How much (little) is 5 g/cm^2……?

The atmosphere

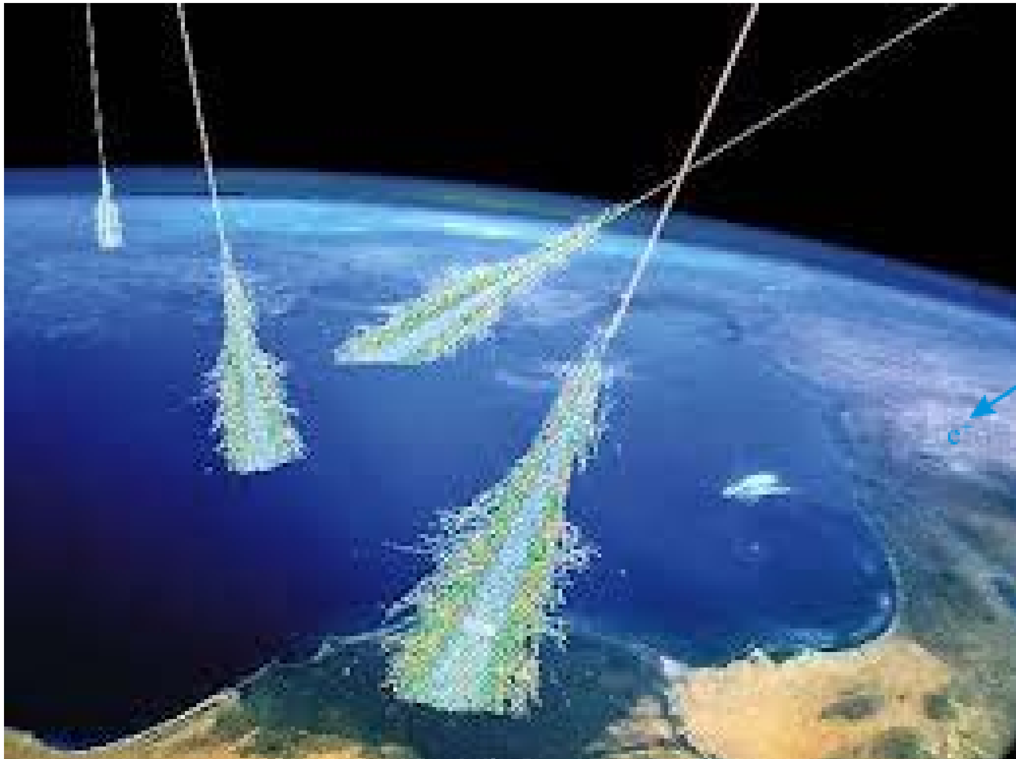


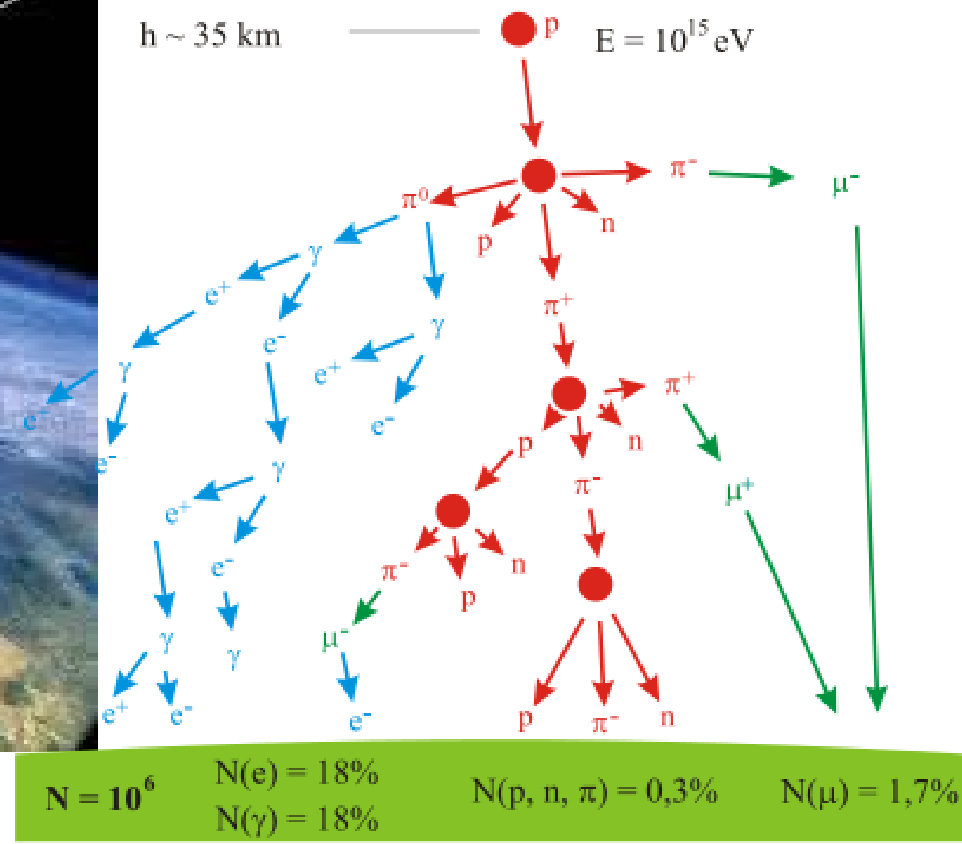
How much (little) is 5 g cm^{-2}?

1 Atmosphere = 100 kPa = 10^5 N/m^2 = 10^4 kg/m^2 = 1000 g/cm^2

200 x

Cosmic-ray showers

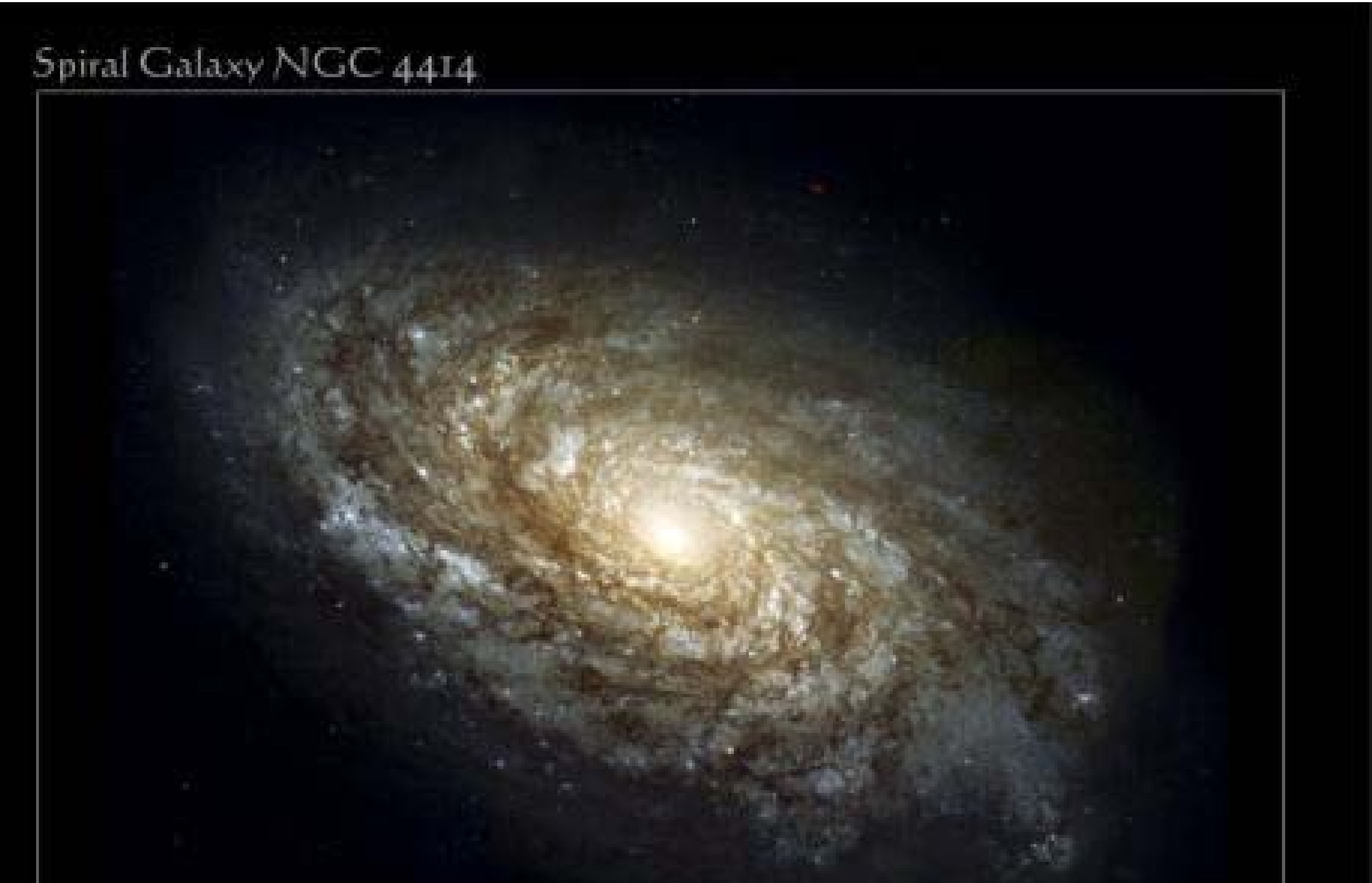




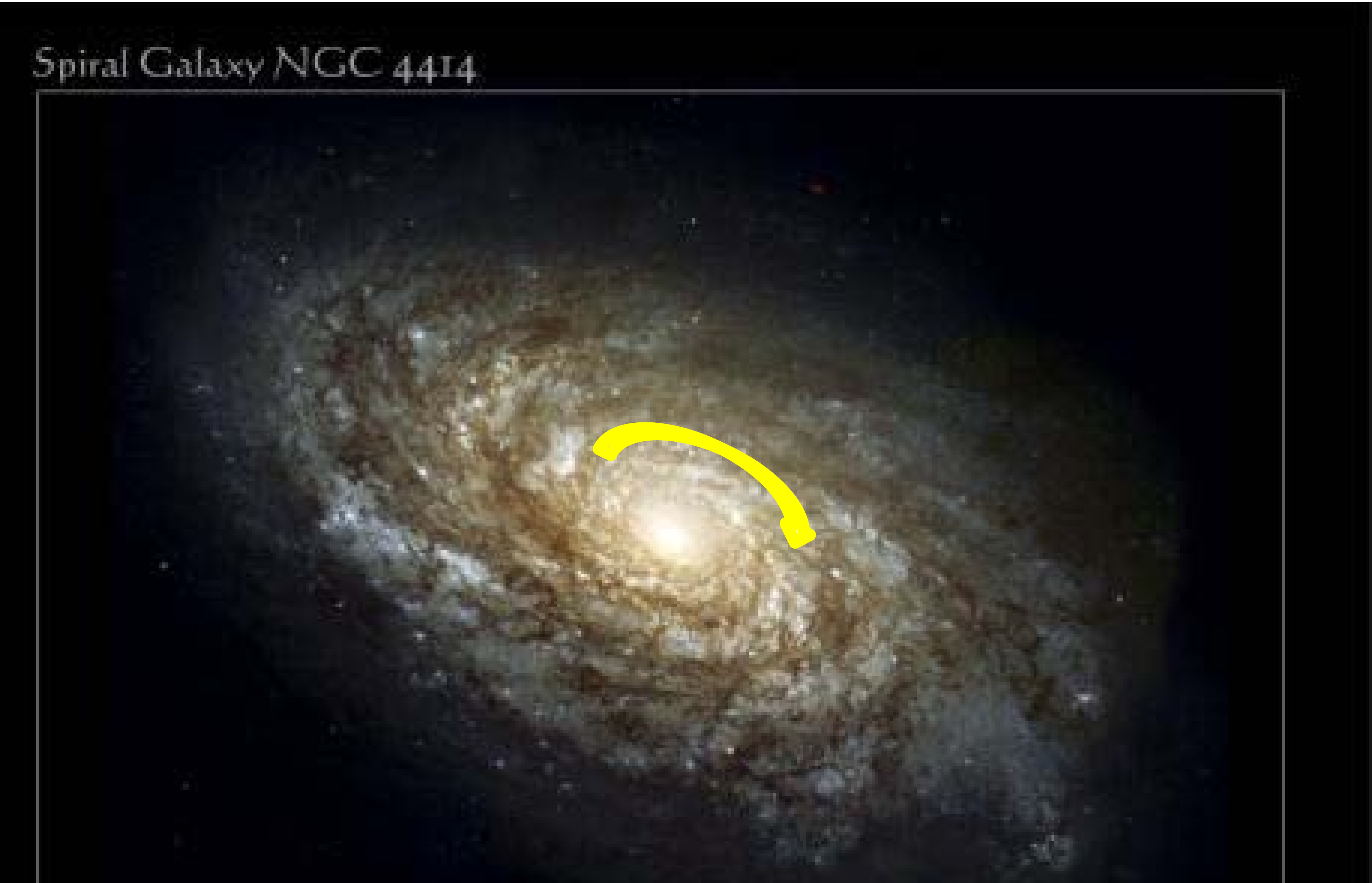
Topics

- 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



Dark matter



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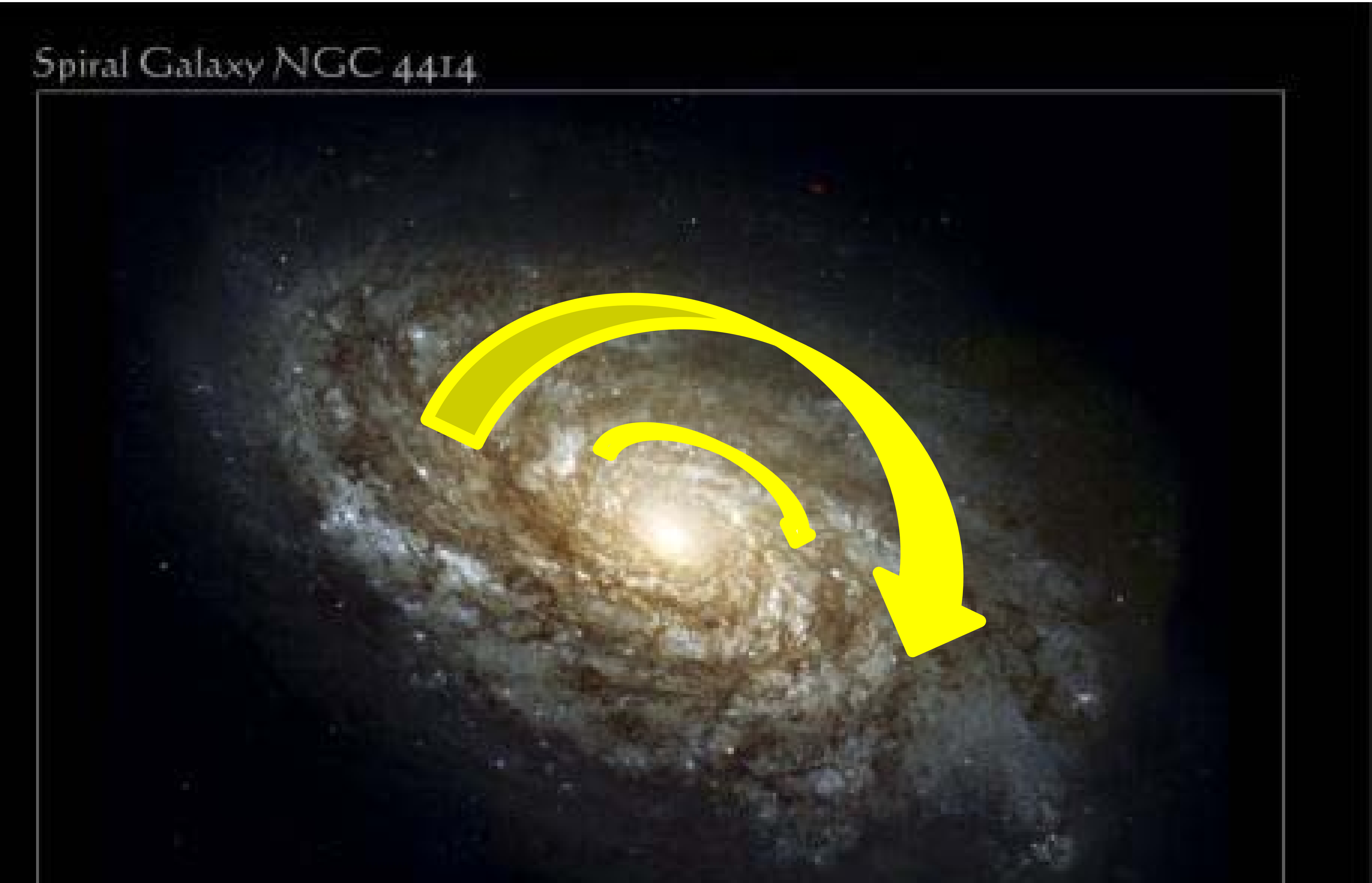

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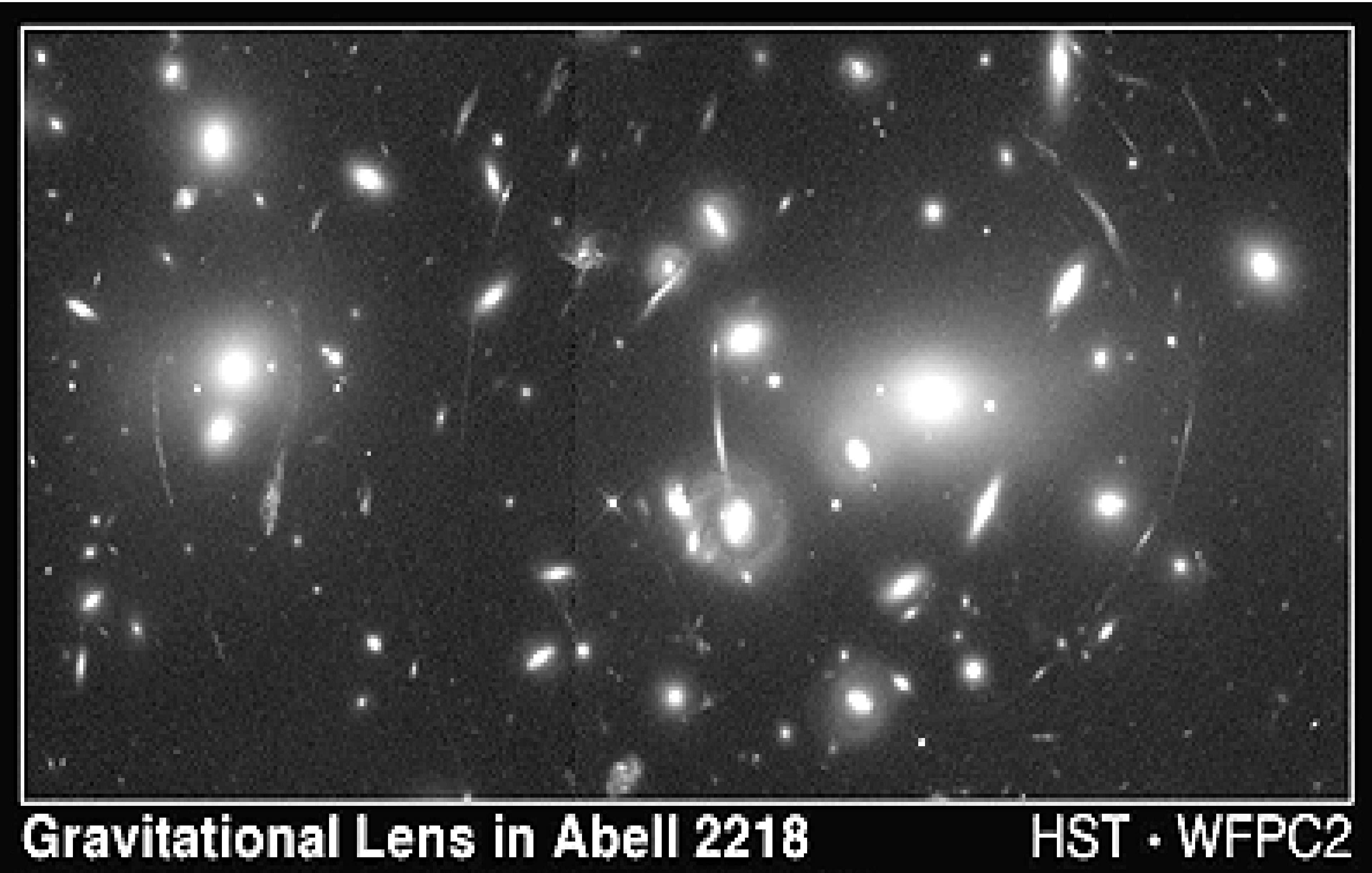

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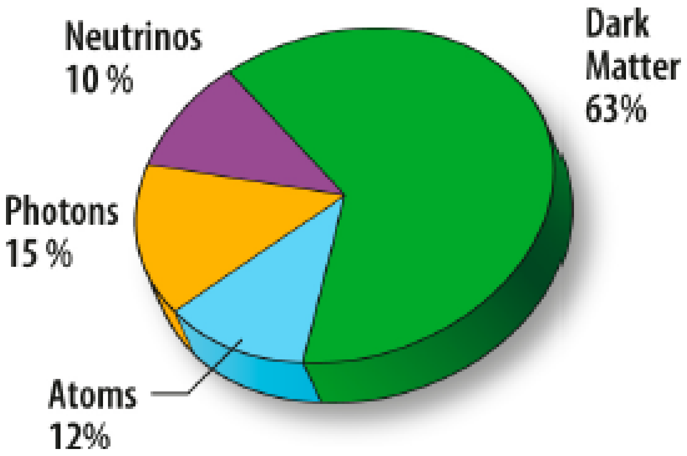
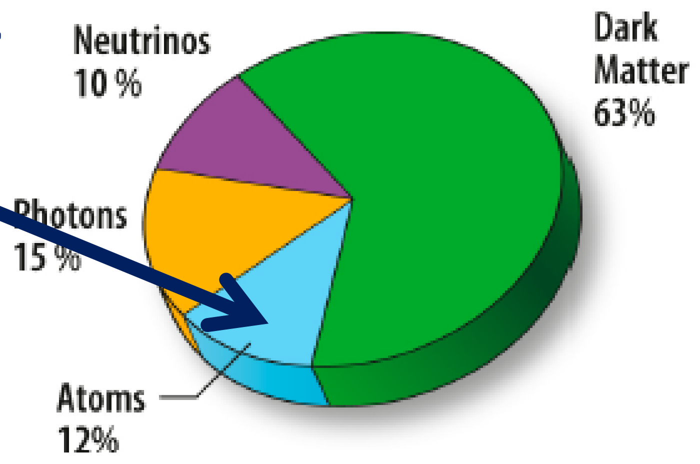
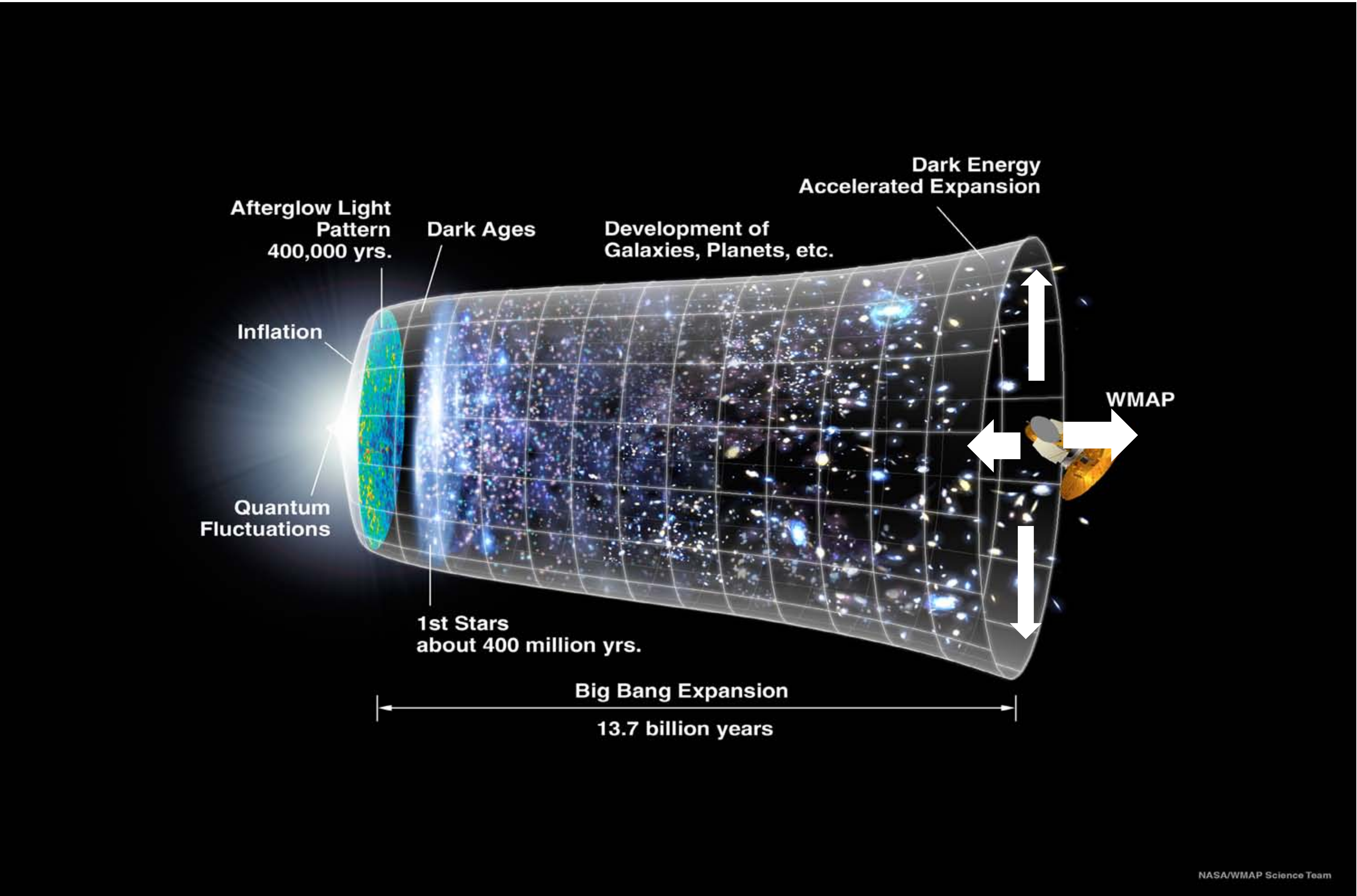


Dark matter

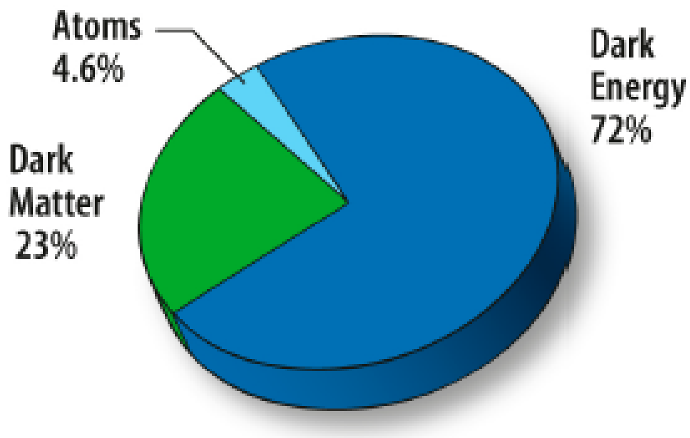
- > 90% in stars
- < 10% interstellar matter

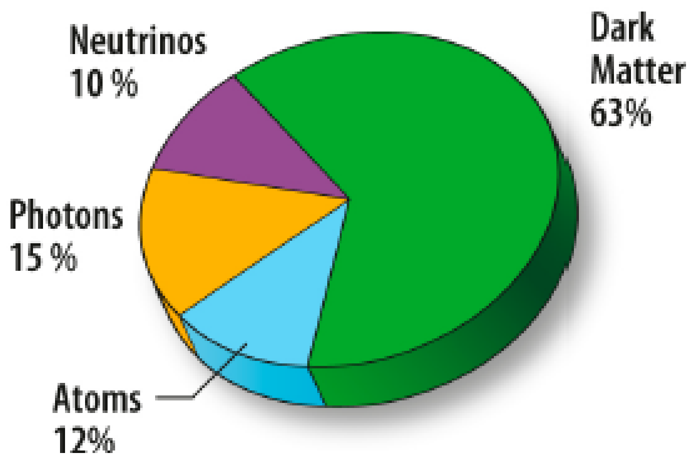


Dark Energy


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

Dark matter-energy





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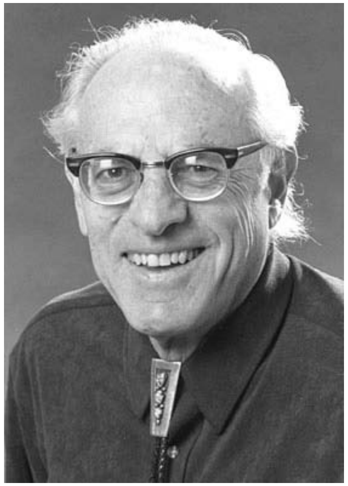
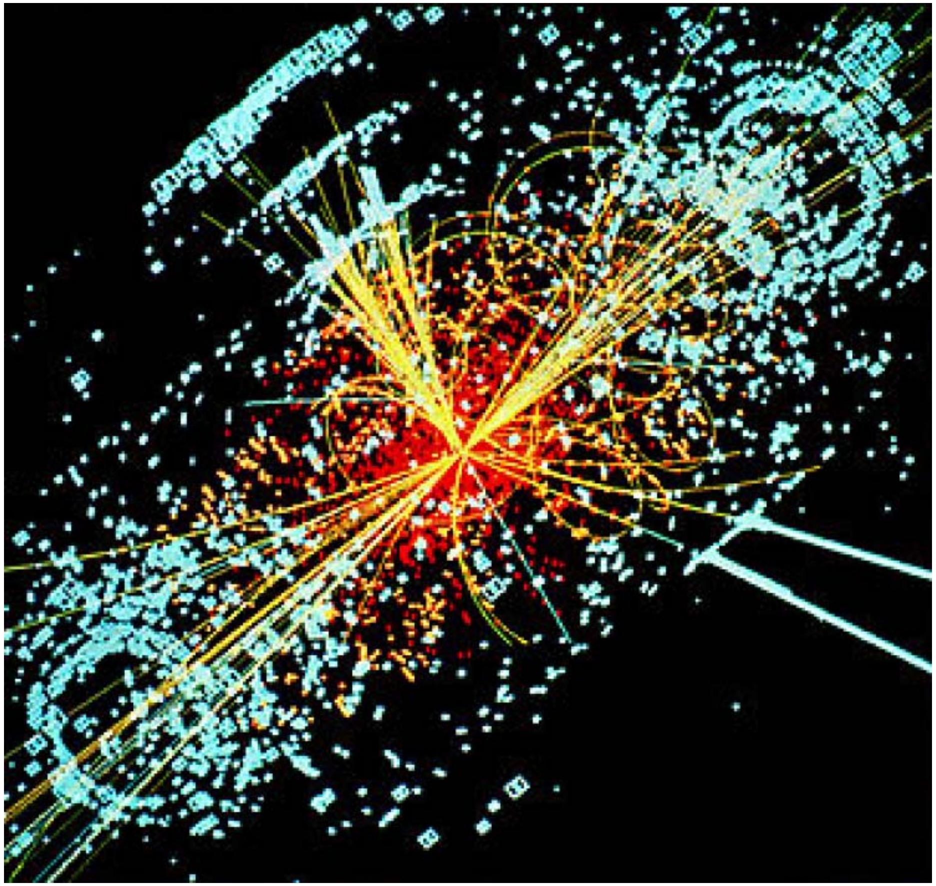


Frederick Reines
& Clyde Cowan

Neutrino Astronomy

Neutrino event in LHC, CERN



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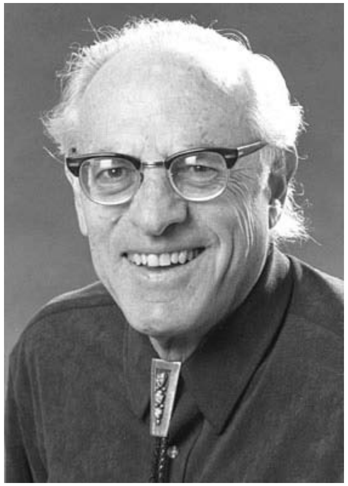

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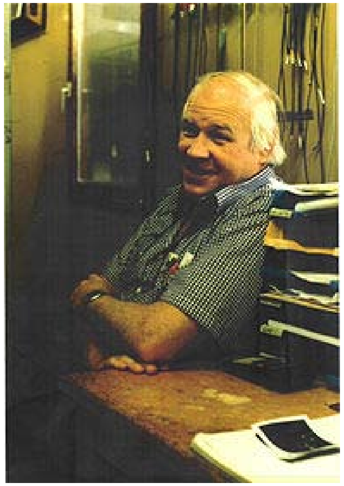
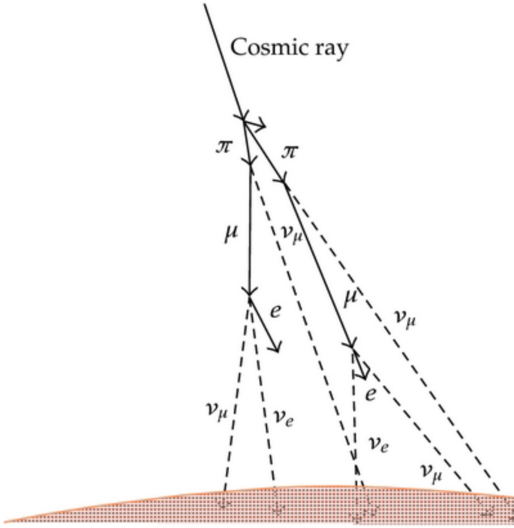


Friedel Sellschop (WITS)



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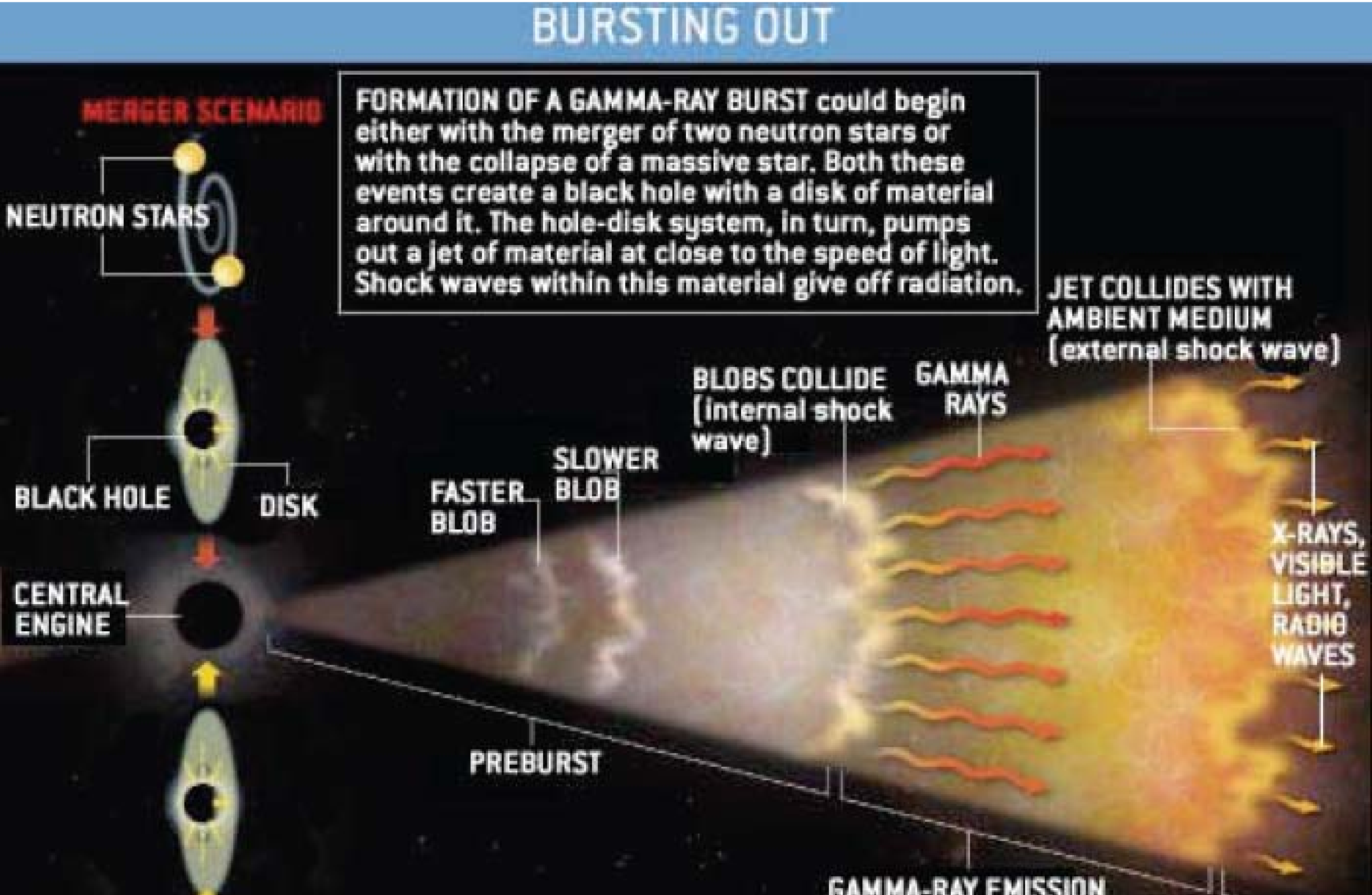

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Neutrinos ⟶ muons, electrons, tauons ⟶ Cherenkov light

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  ----- 6.5×10^{10} per cm^2 per second

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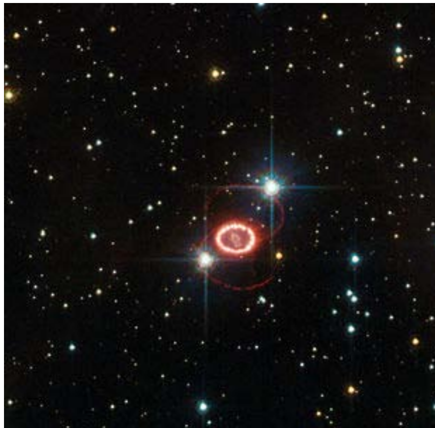
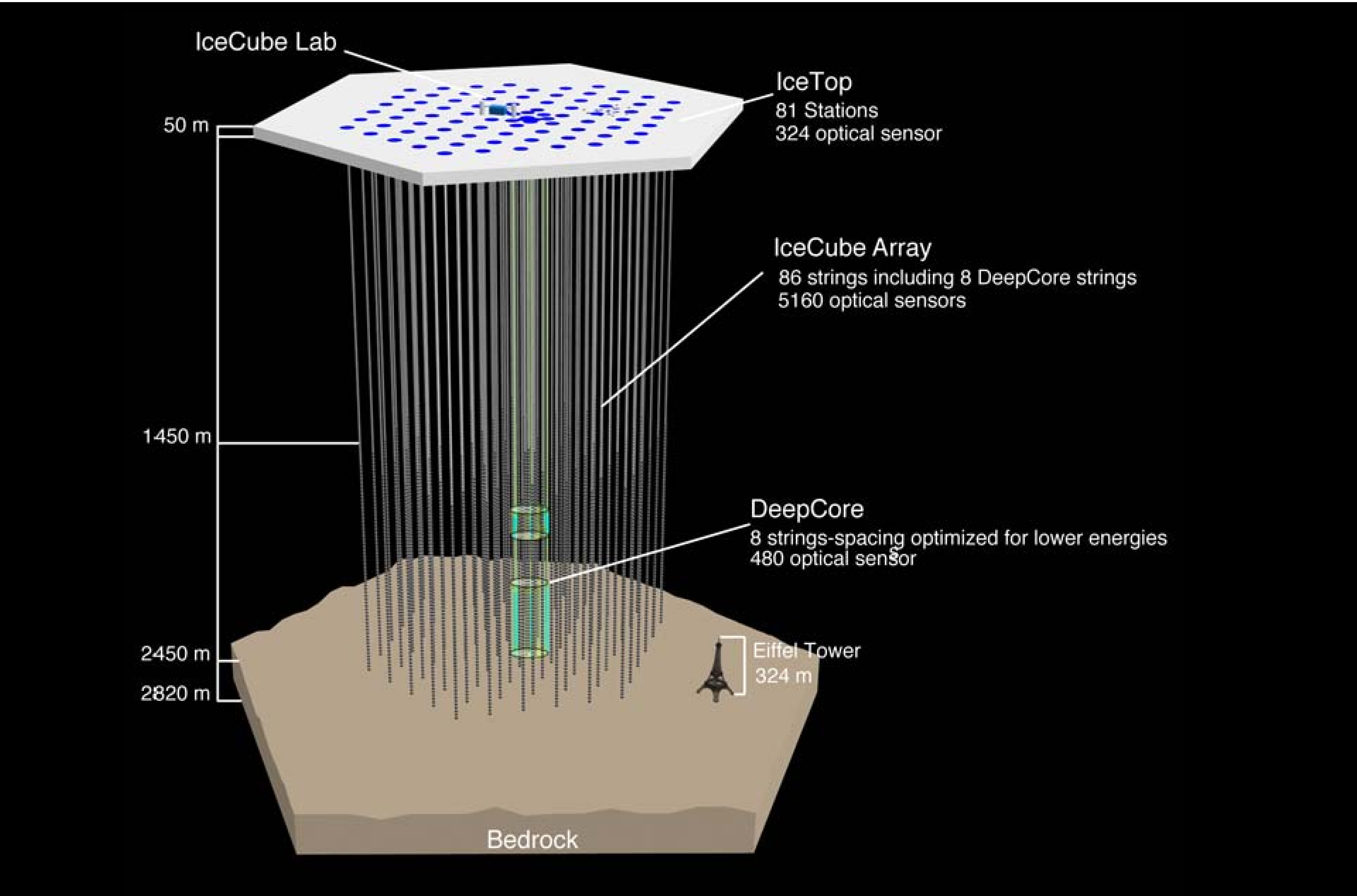


Neutrino Astronomy – Ice Cube



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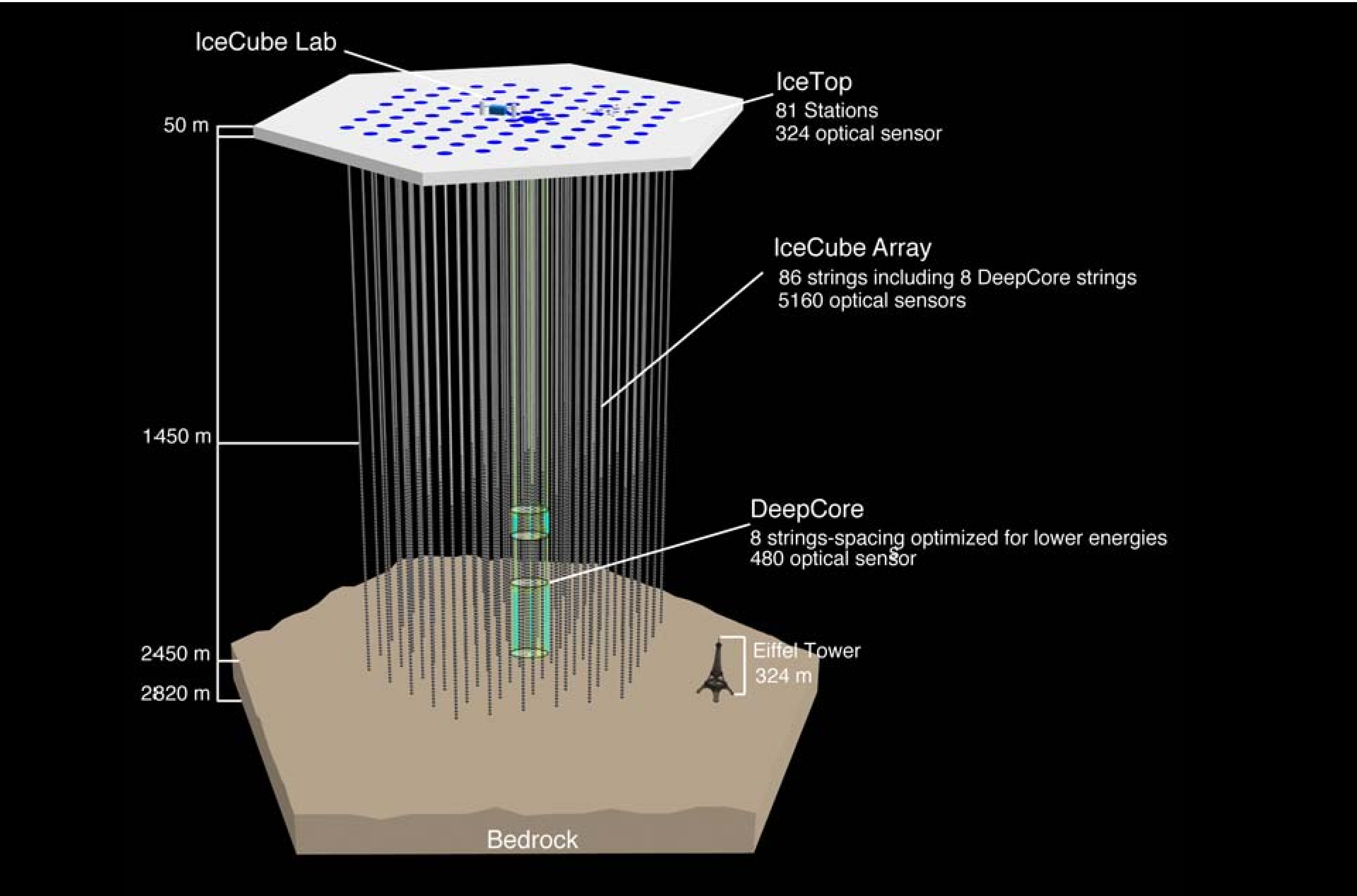

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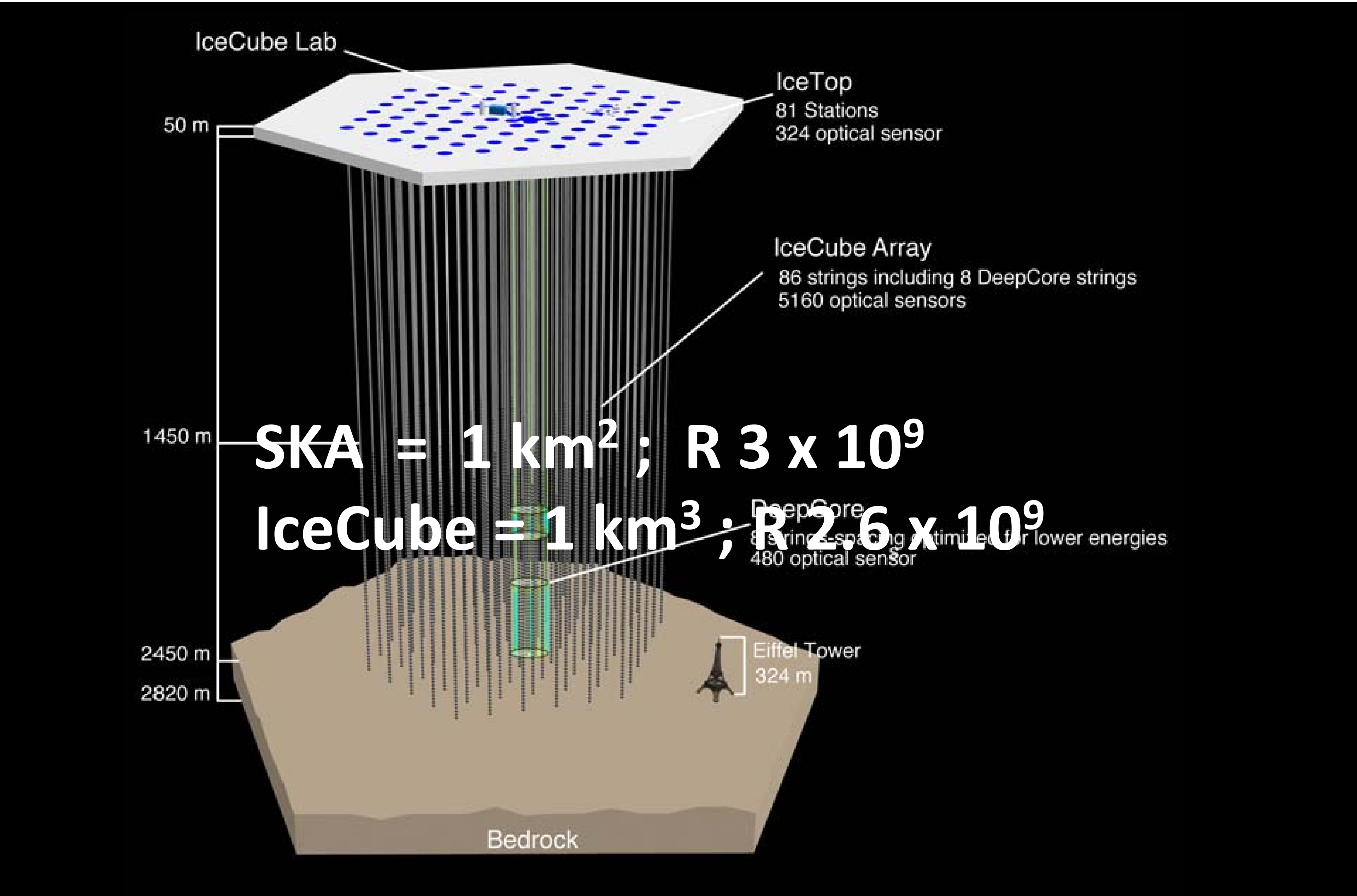
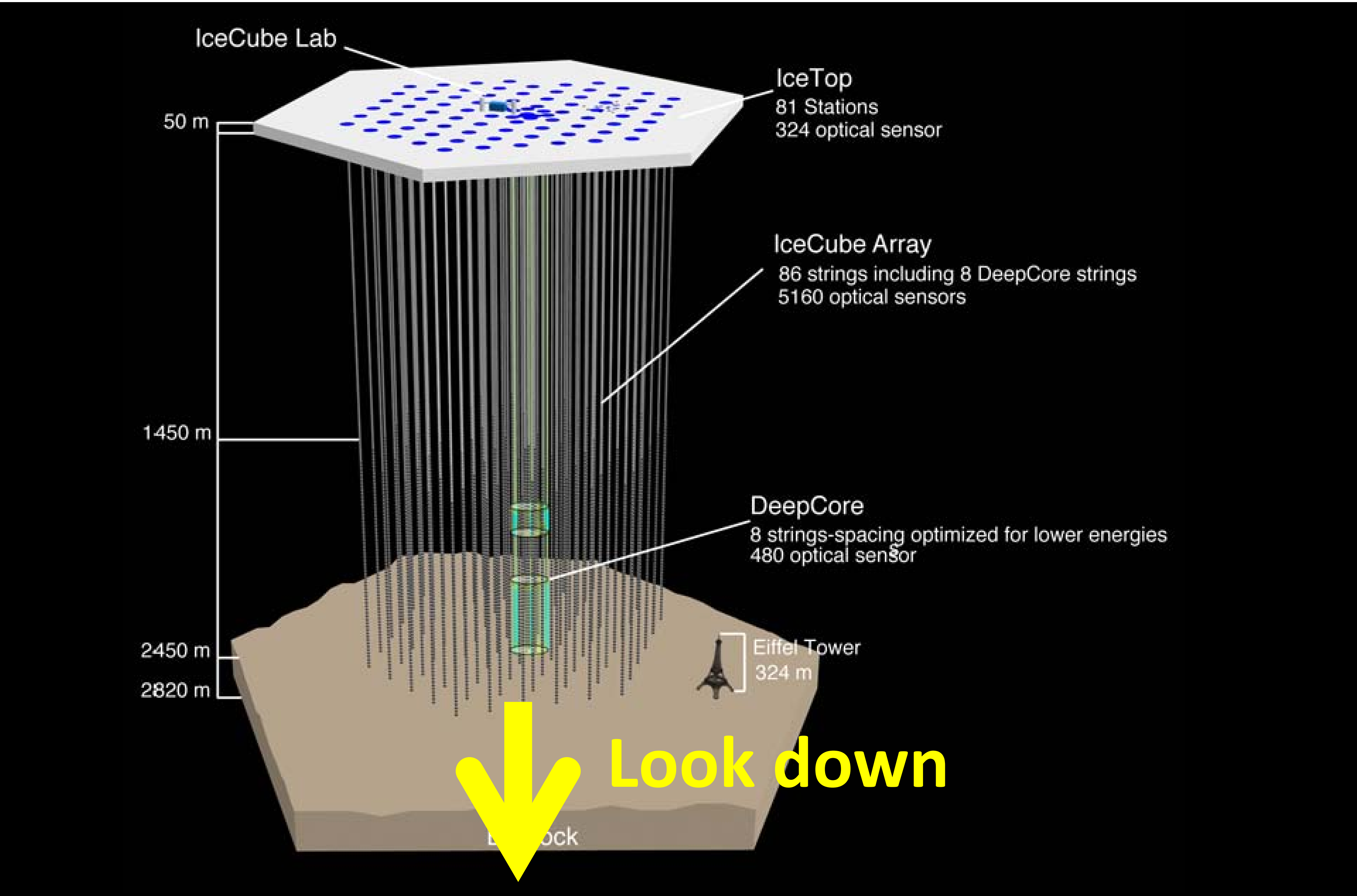


SKA = 1 km^2 ; R 3 x 10^9

IceCube = 1 km^3 ; R 2.6 x 10^9

Neutrino Astronomy – Ice Cube



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  $> 10^{15}$ eV

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Names

Particle Astrophysics

Astroparticle Physics

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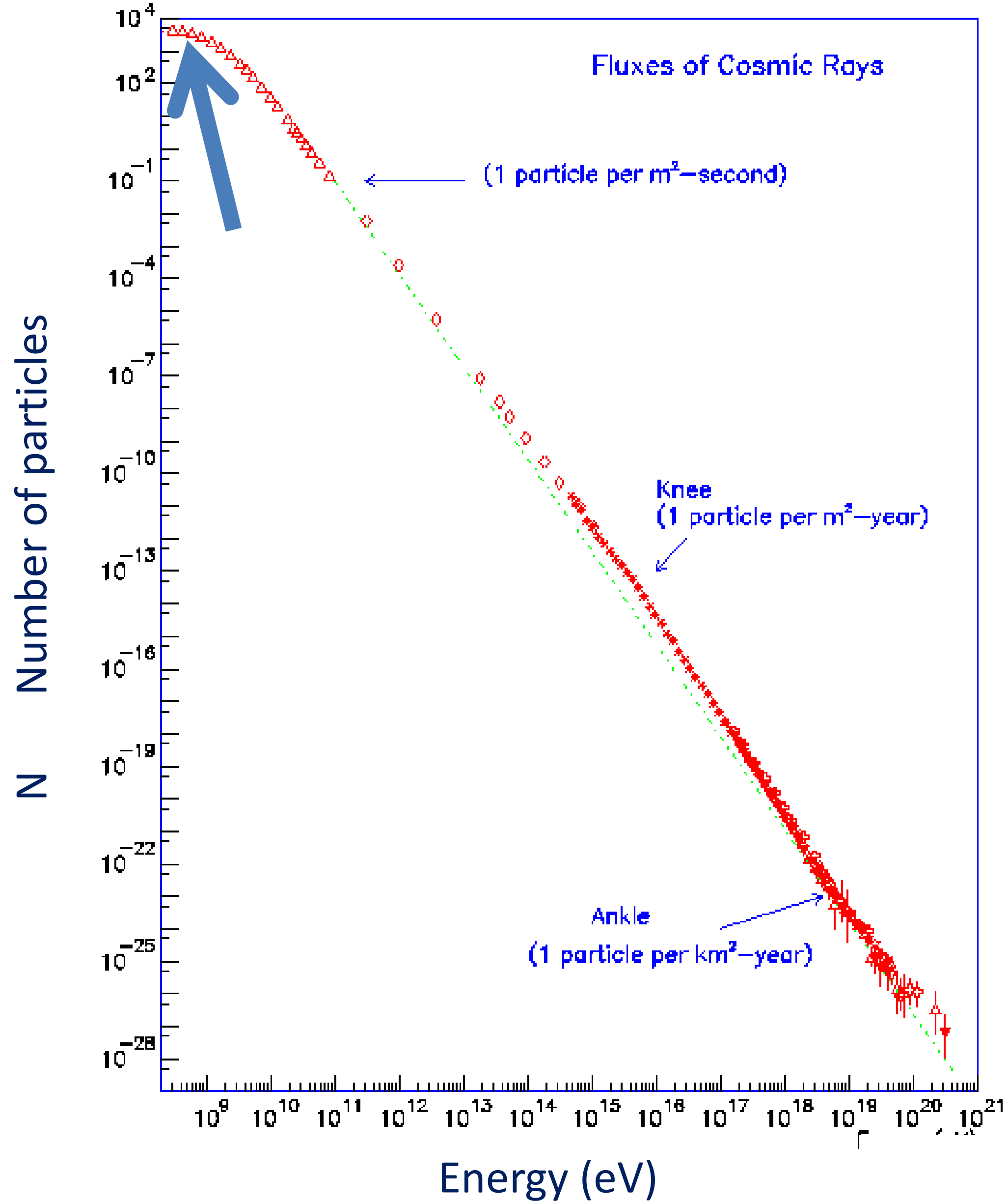
Cosmic ray spectrum



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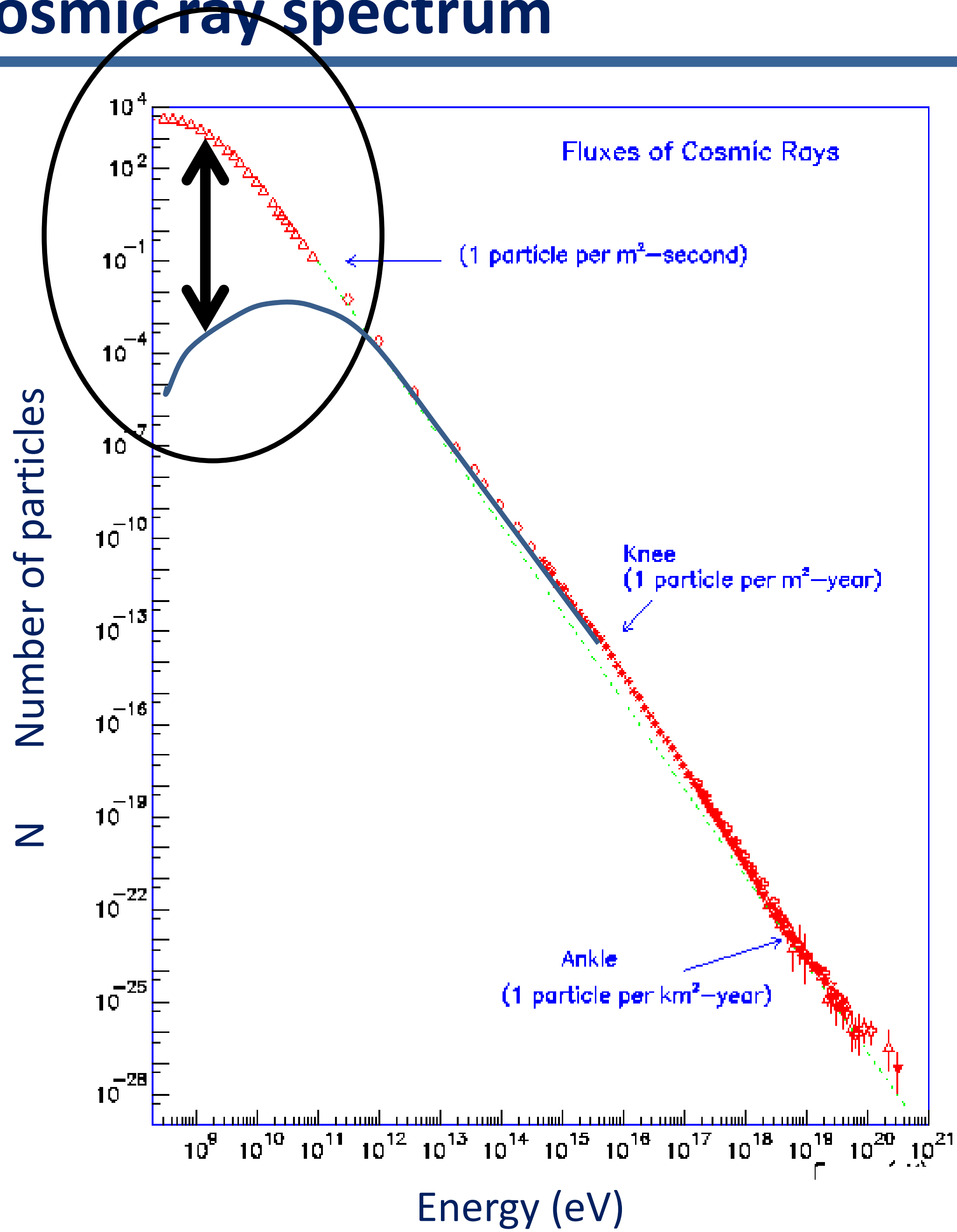
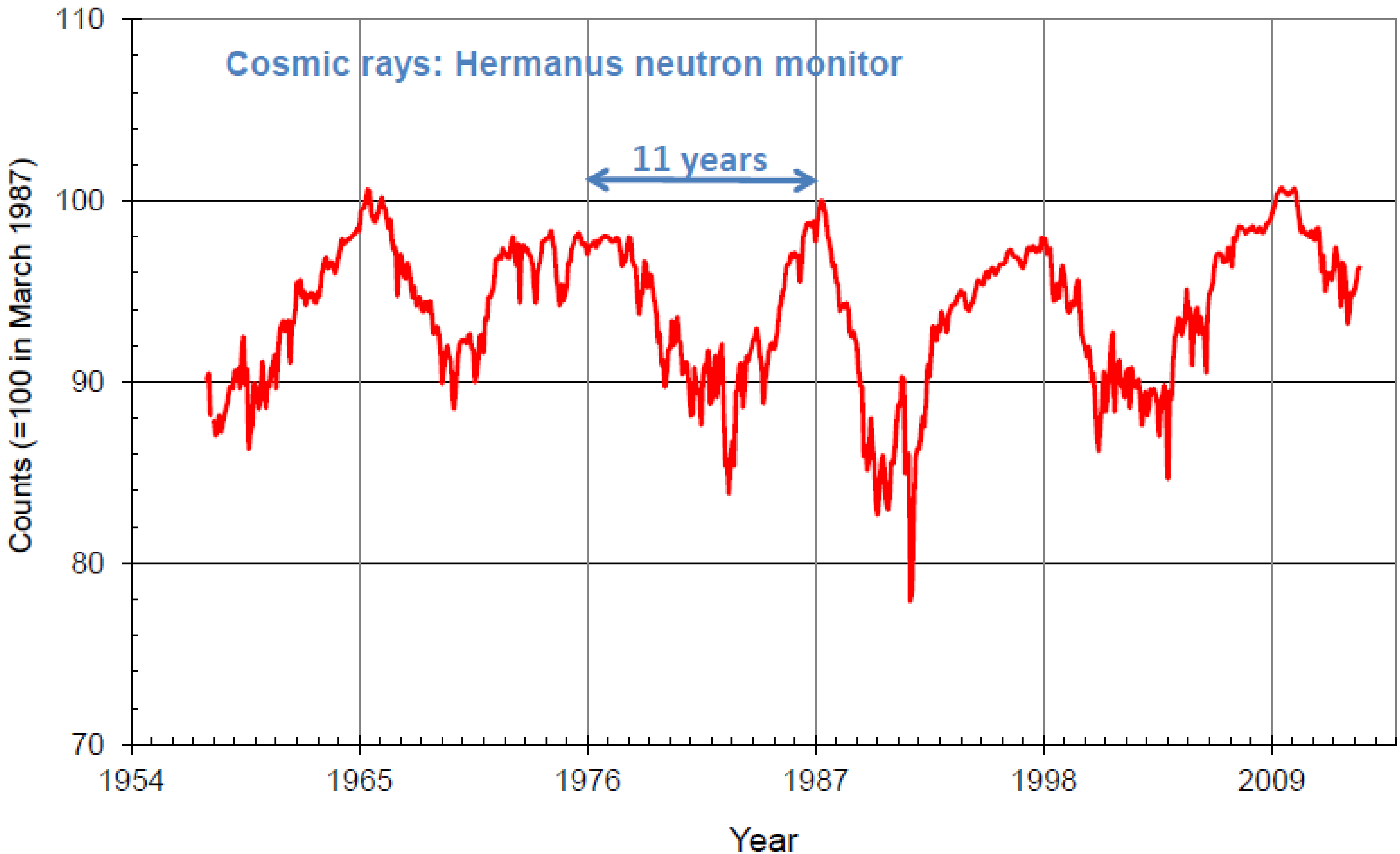
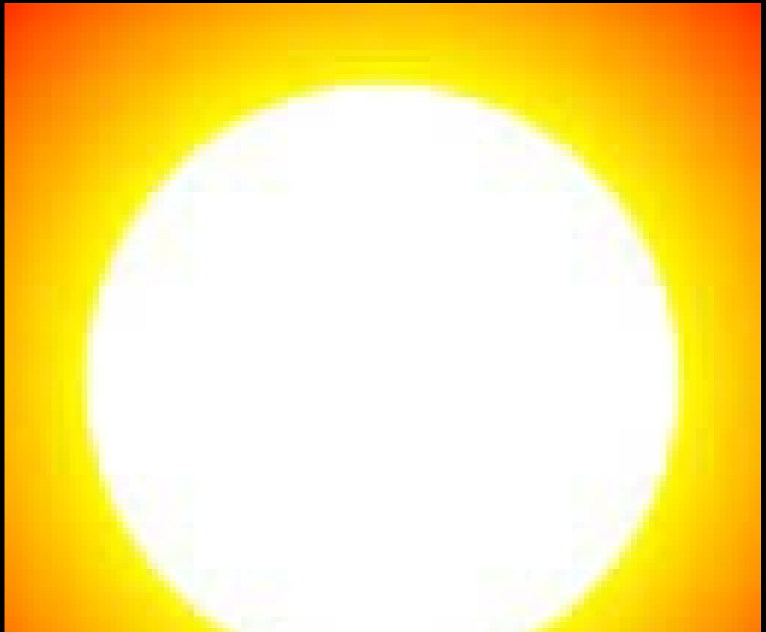


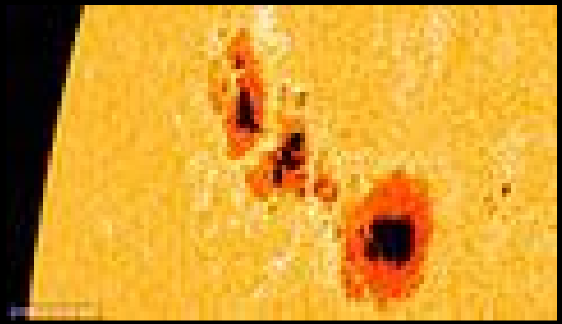
Cosmic-ray counts



The Sun



Sunspots



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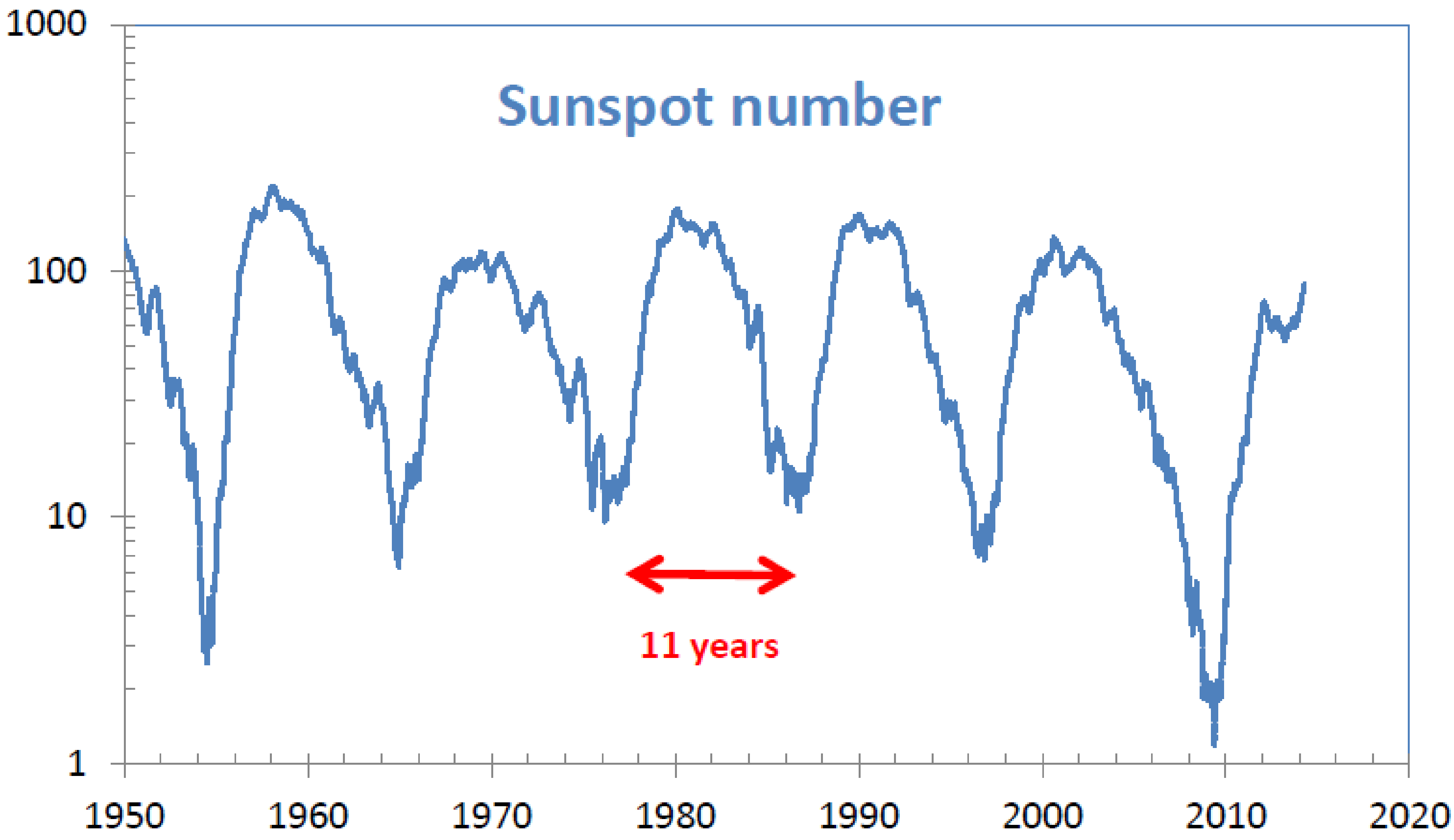
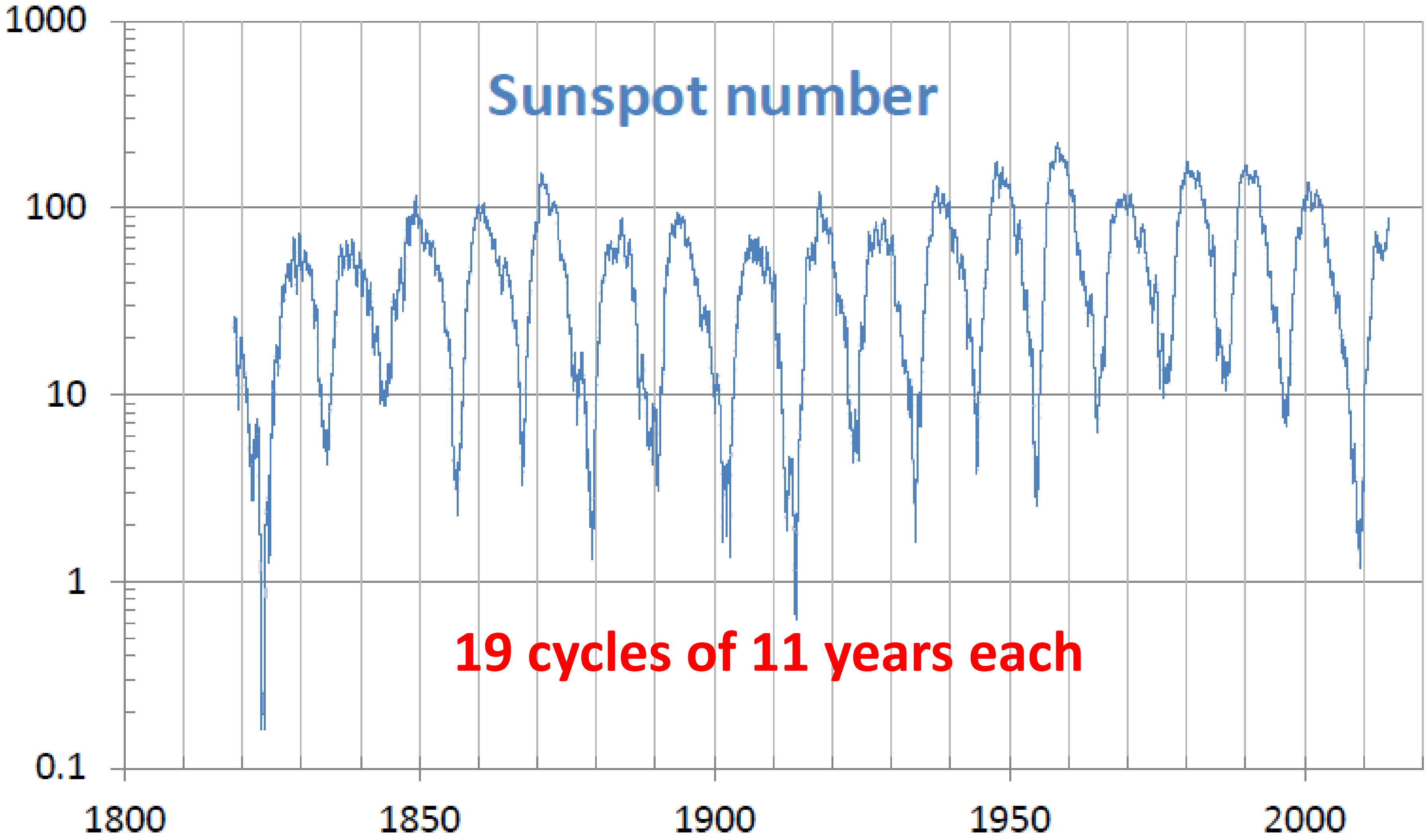
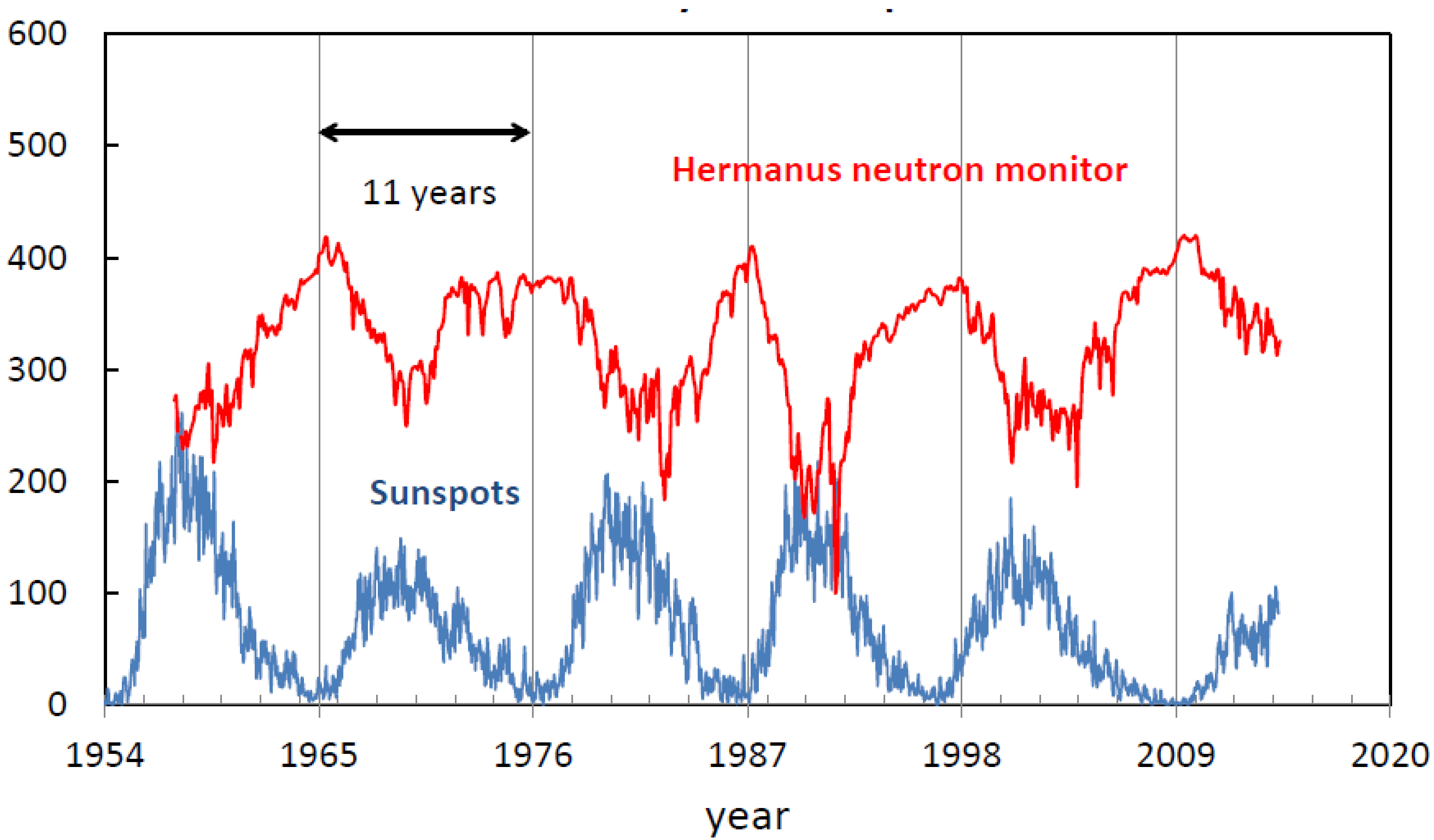


Sunspot number
1000
100
10
1
1950
1960
1970
1980
1990
2000
2010
2020
11 years

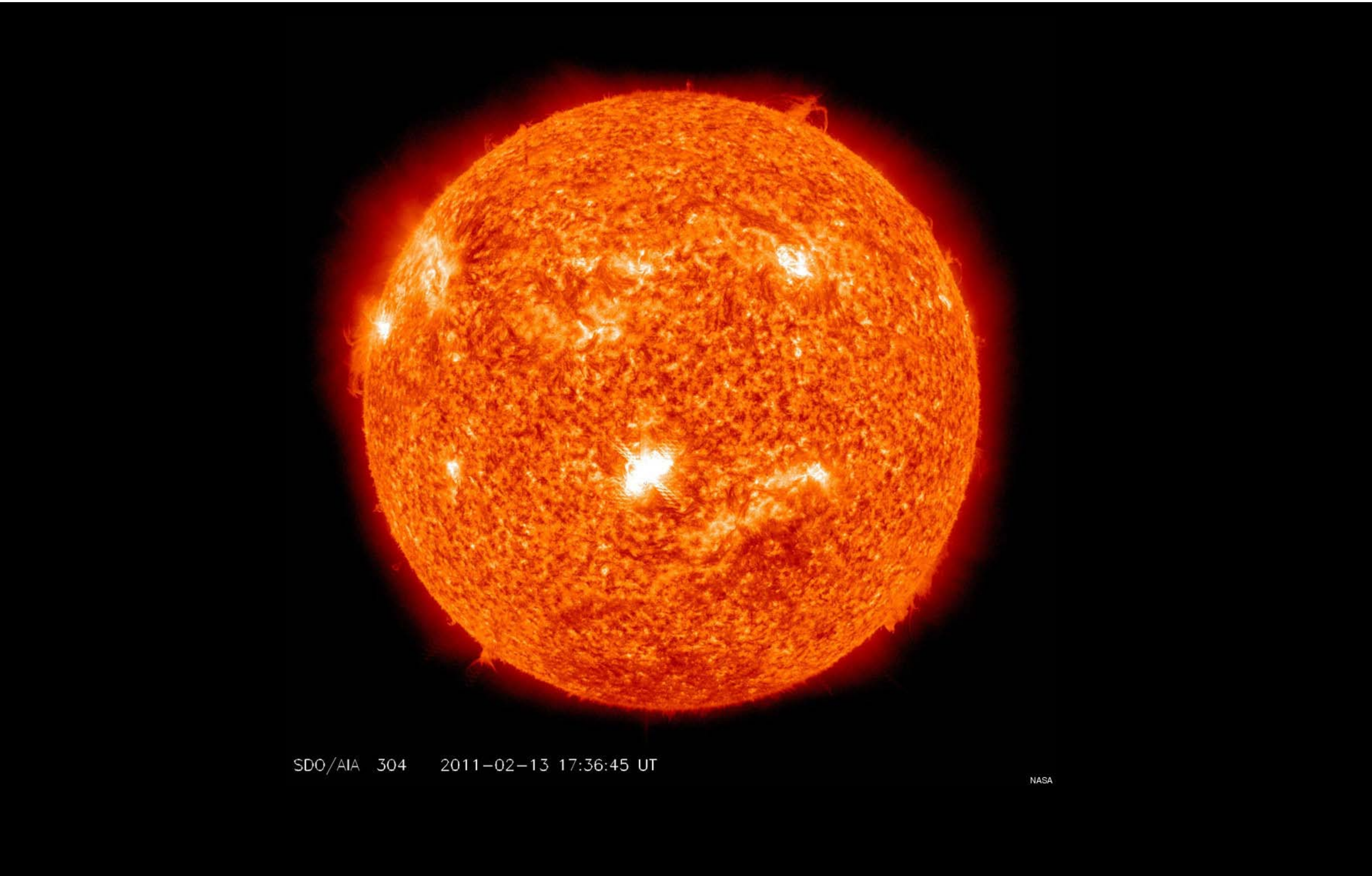
Sunspots since 1818



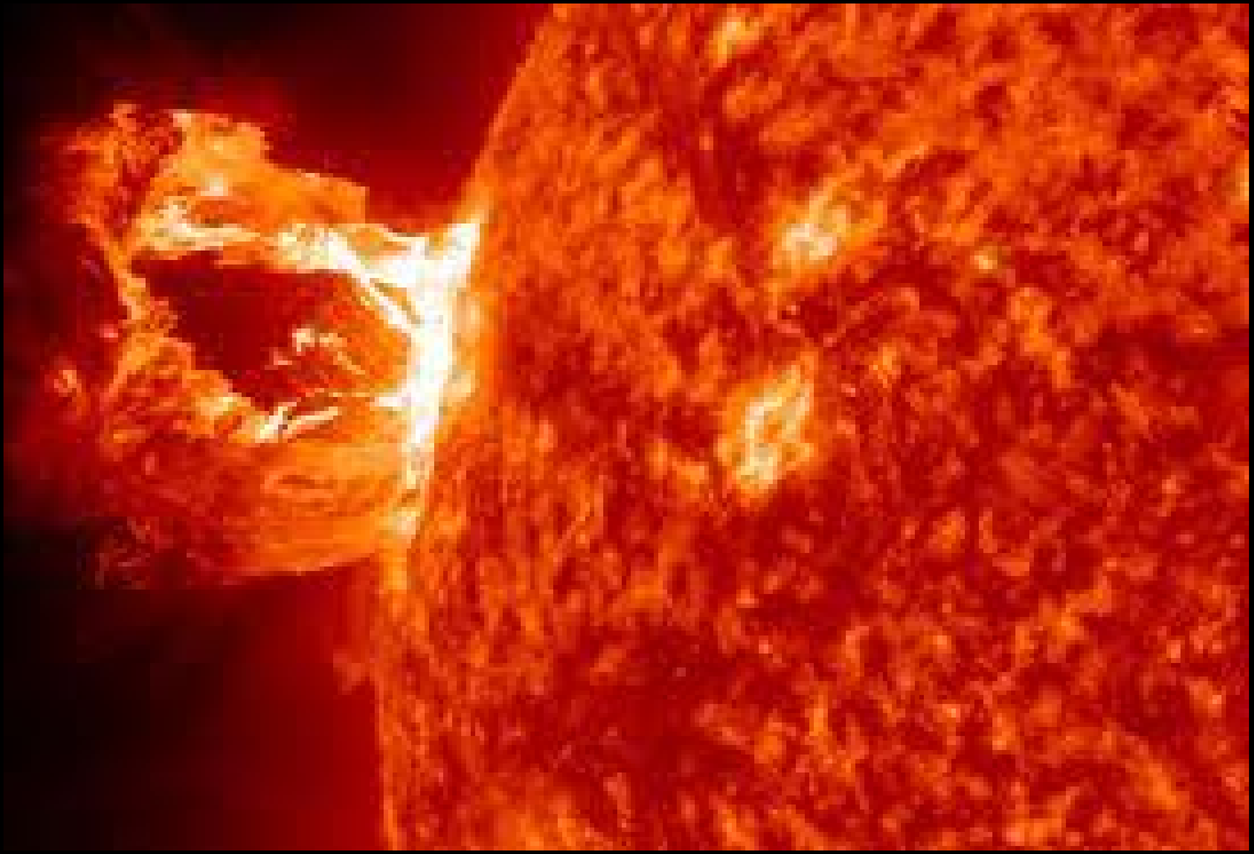
Cosmic rays and sunspots



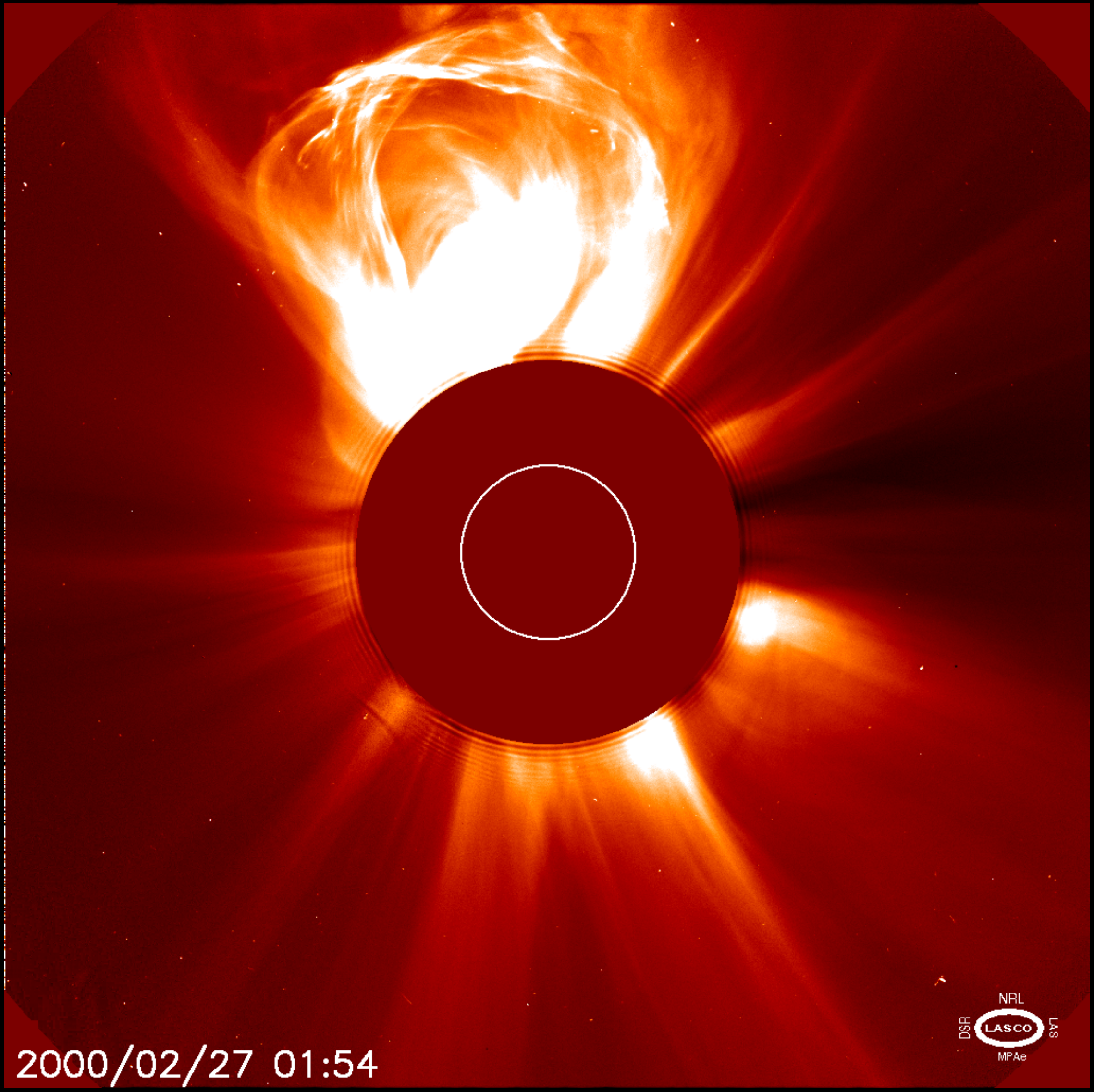
Solar Atmosphere



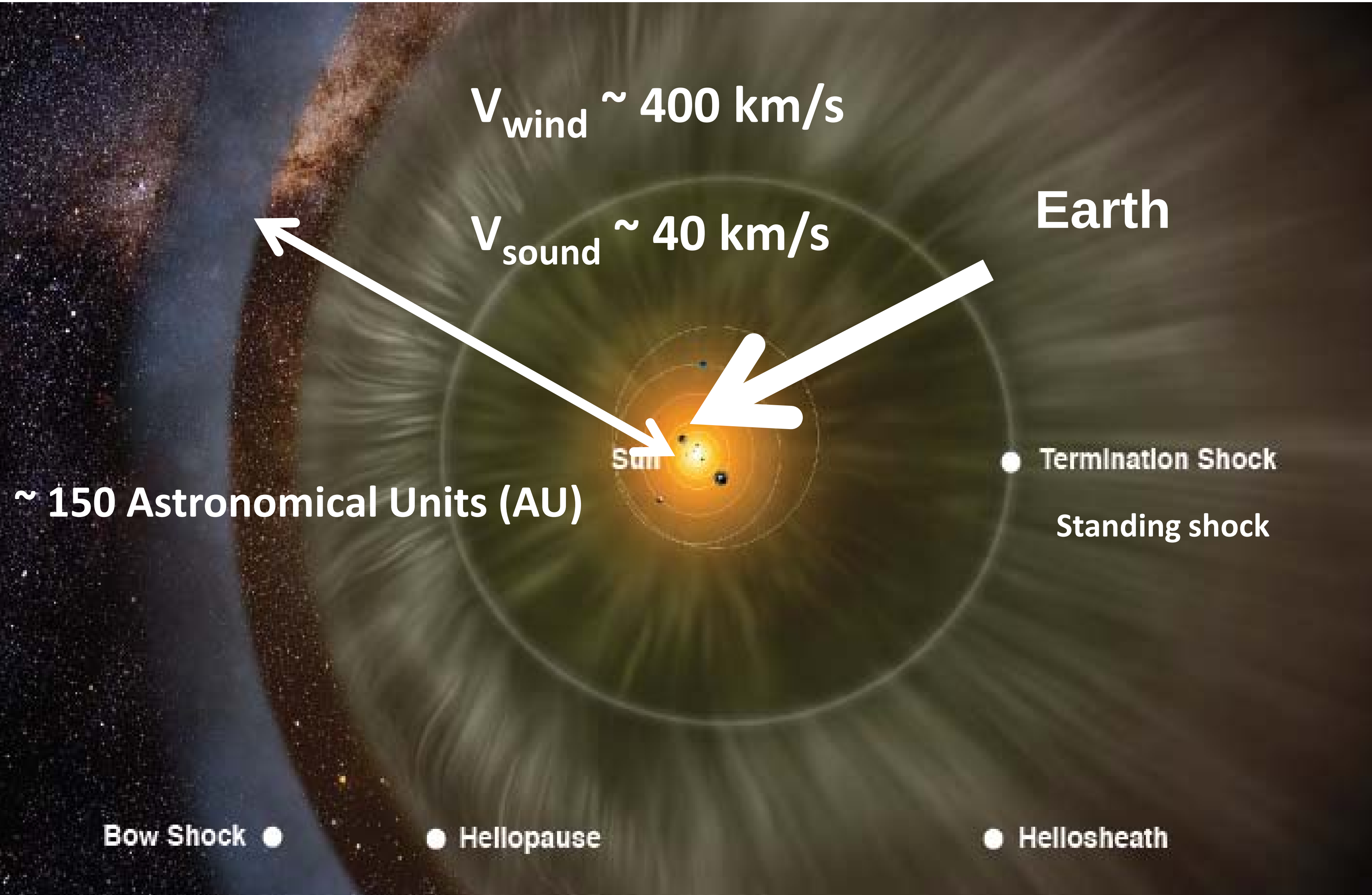
Solar Flare



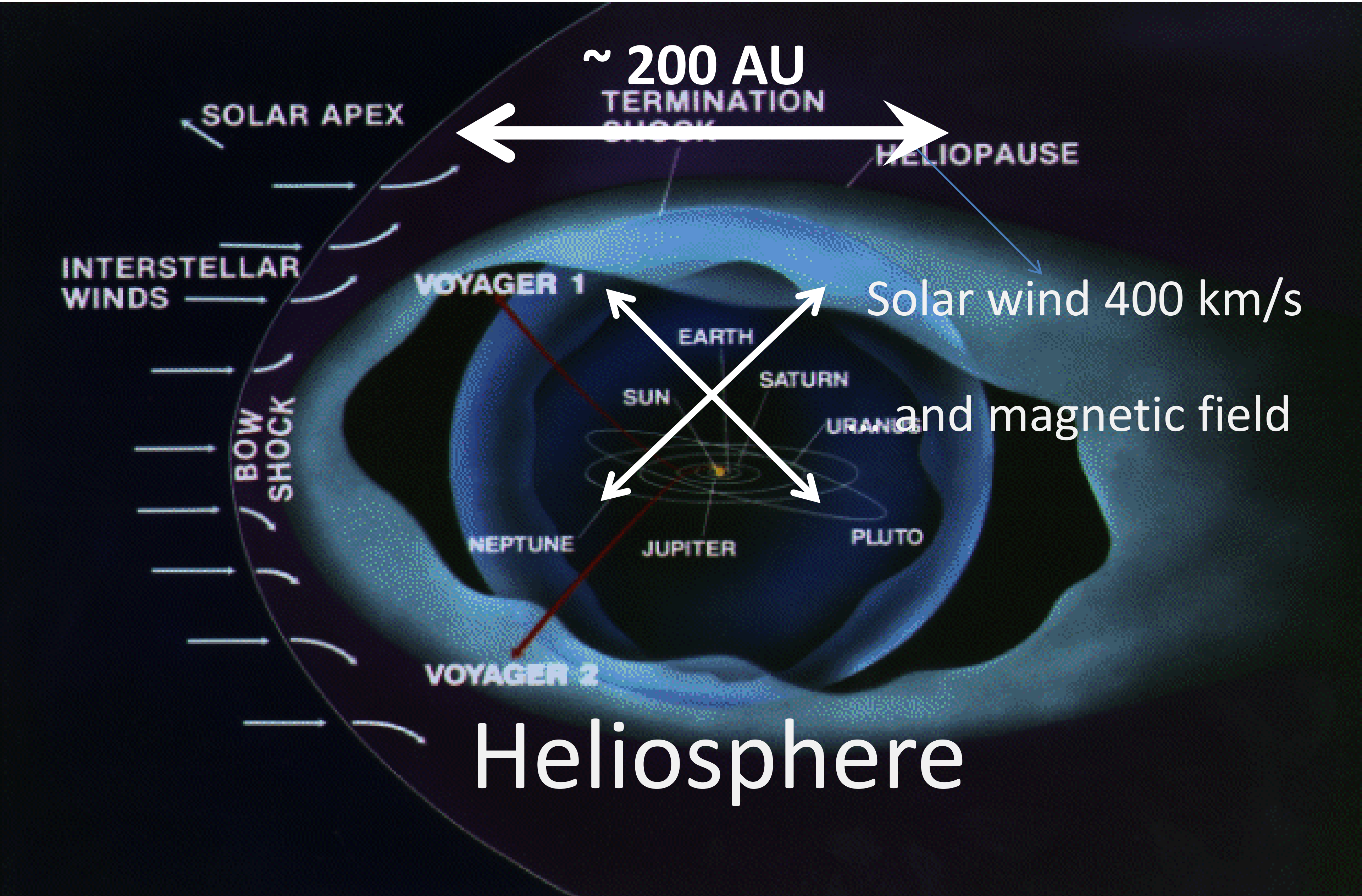
Solar wind and Coronal Mass Ejection



The Solar Wind and Heliosphere



Cosmic rays in the heliosphere



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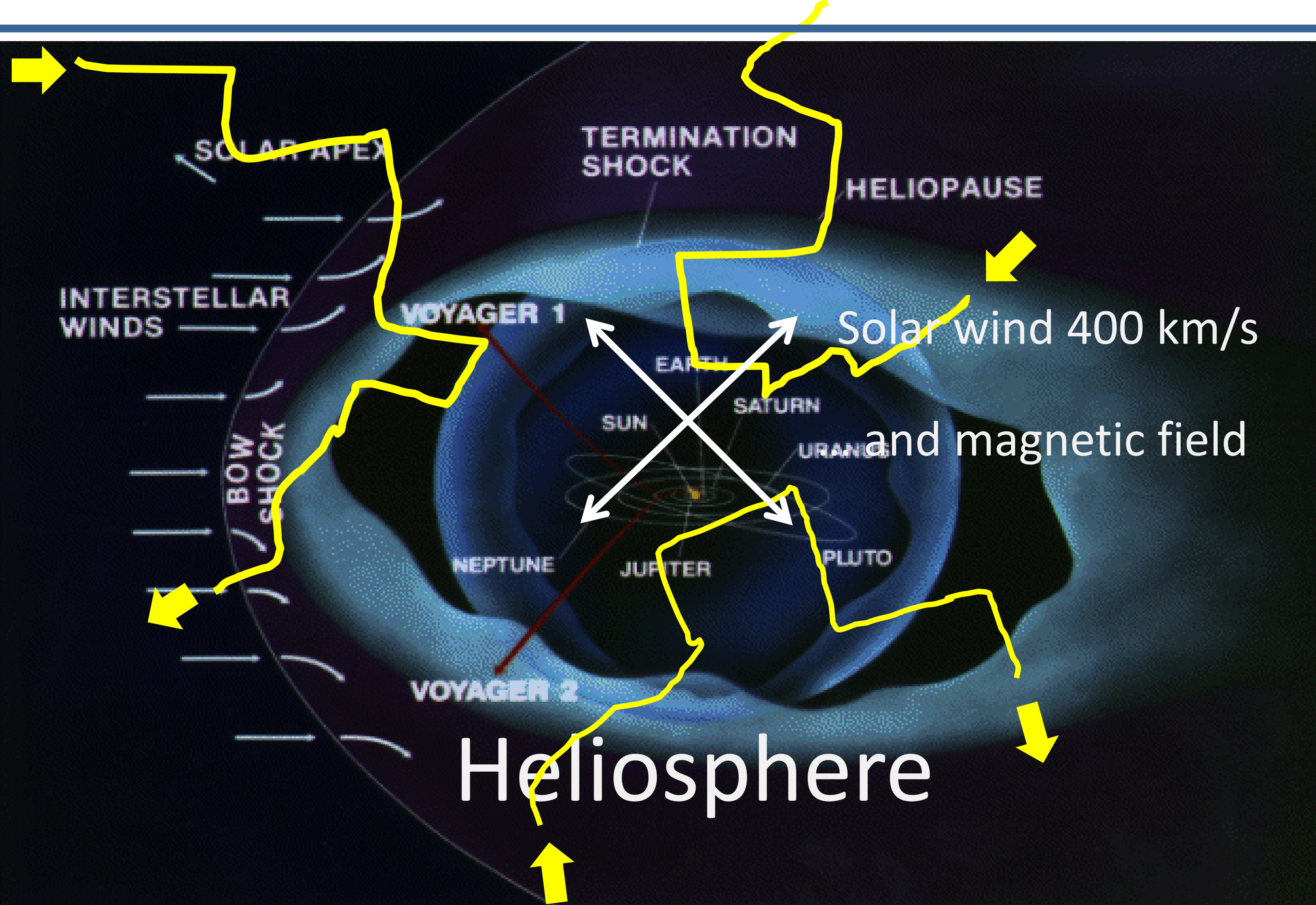
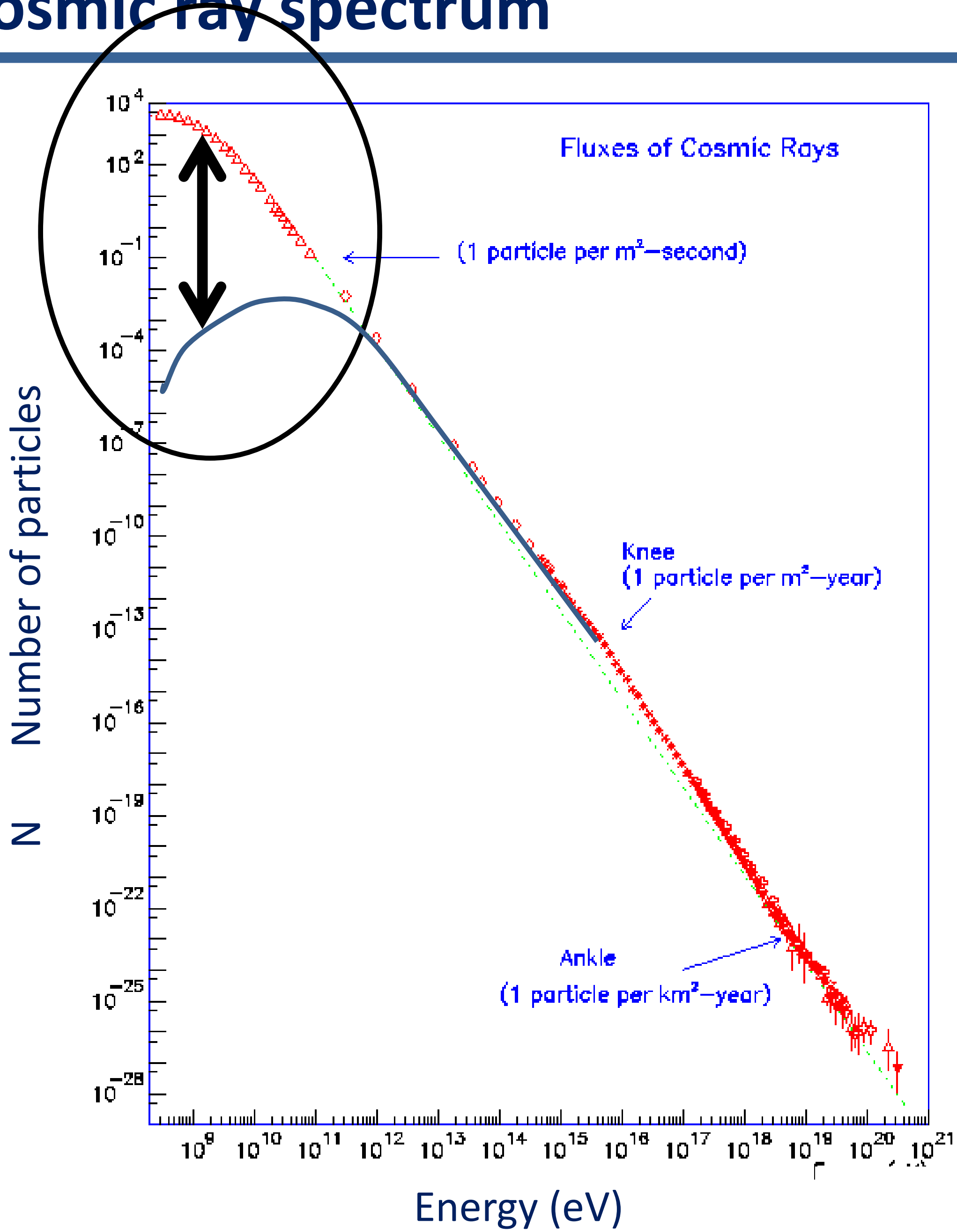
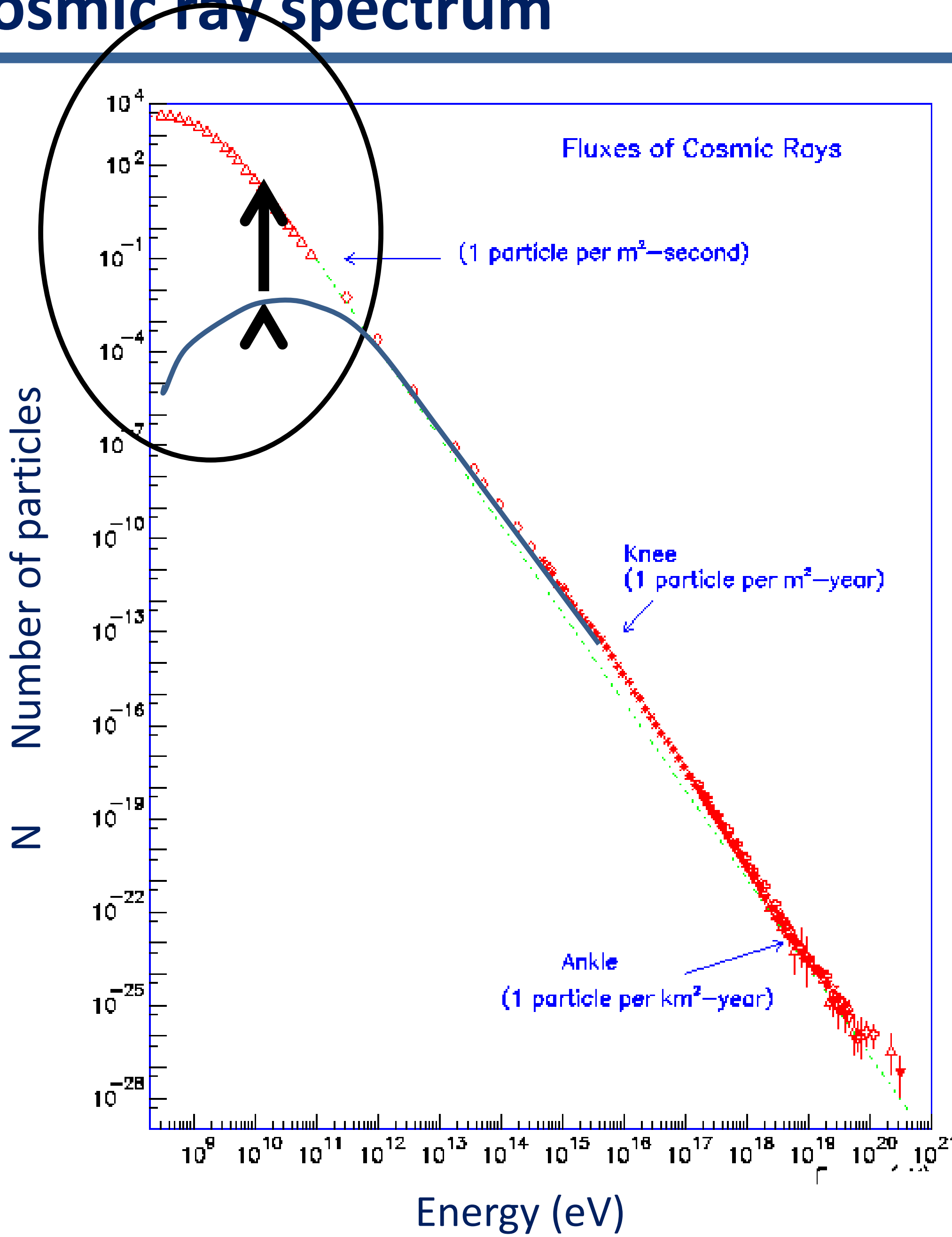


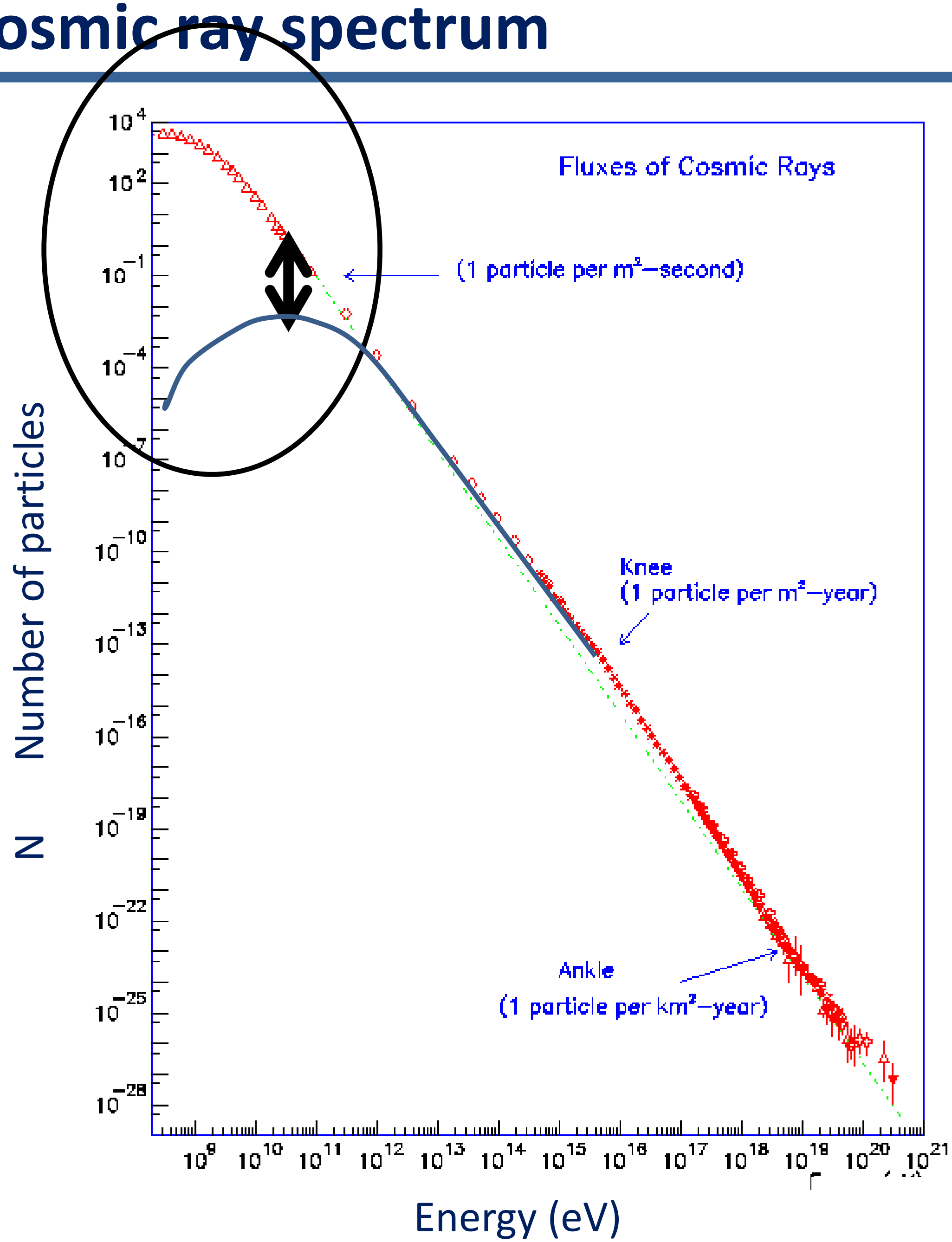
Cosmic ray spectrum



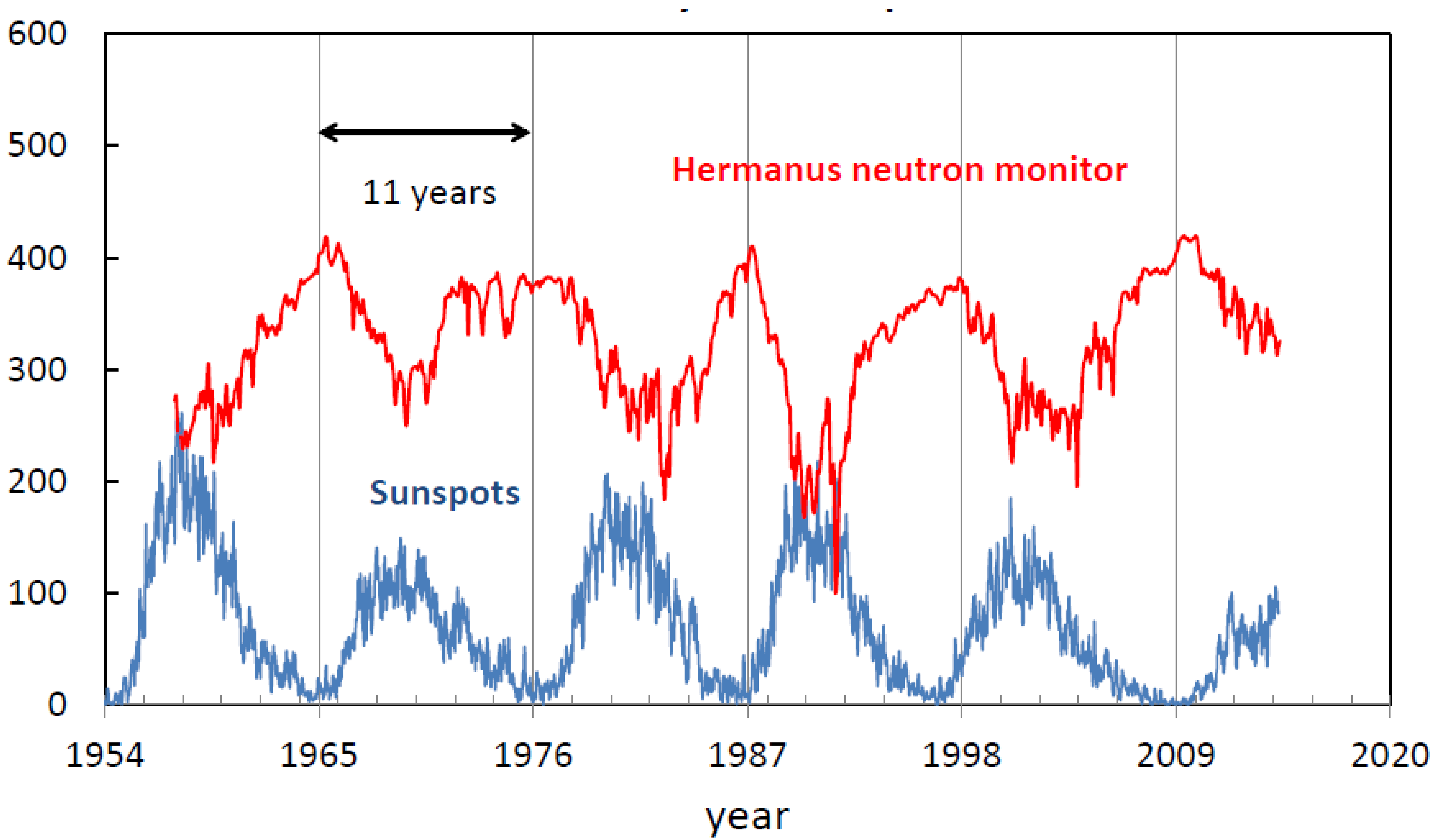
Cosmic ray spectrum



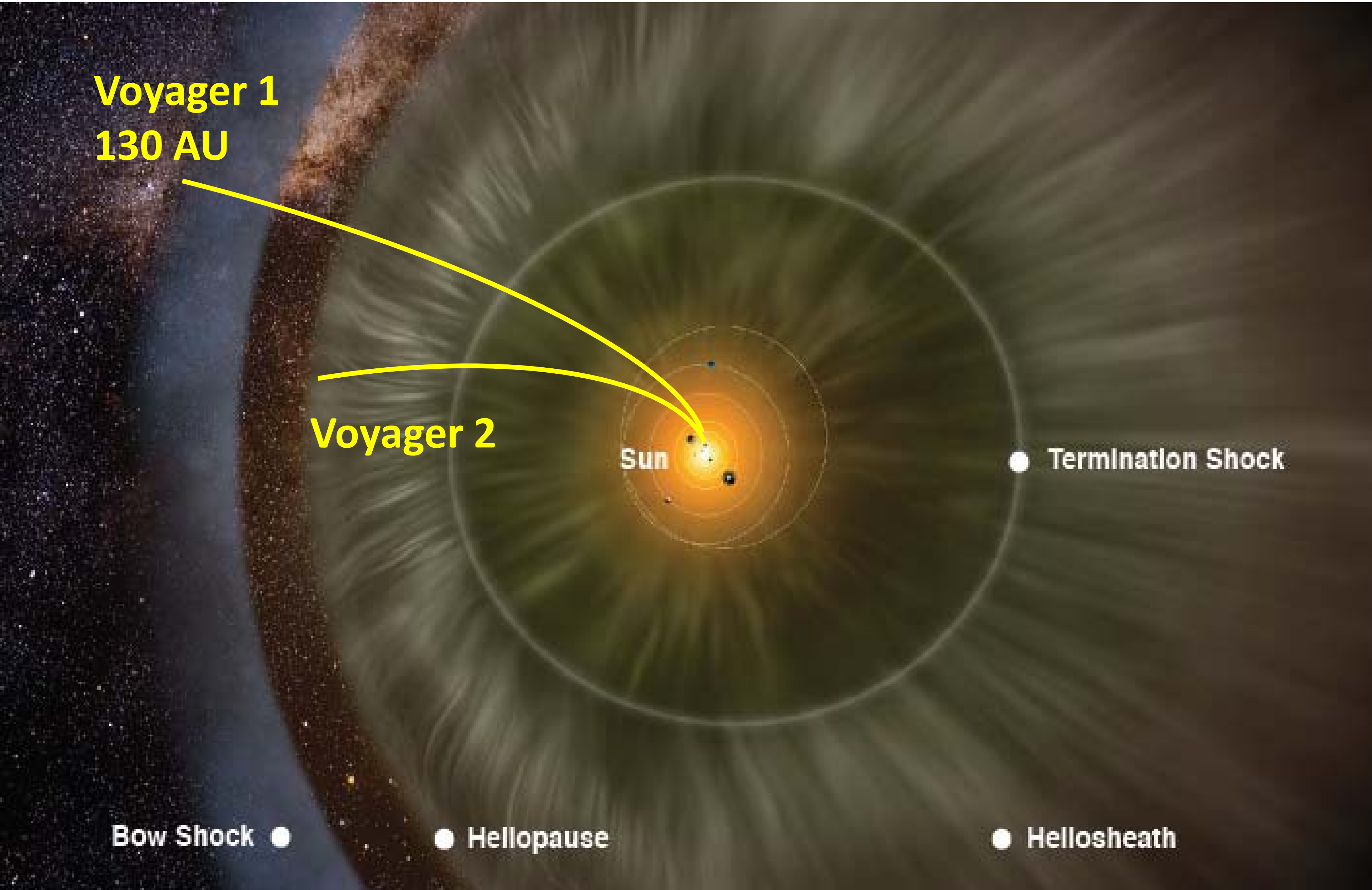
Cosmic ray spectrum



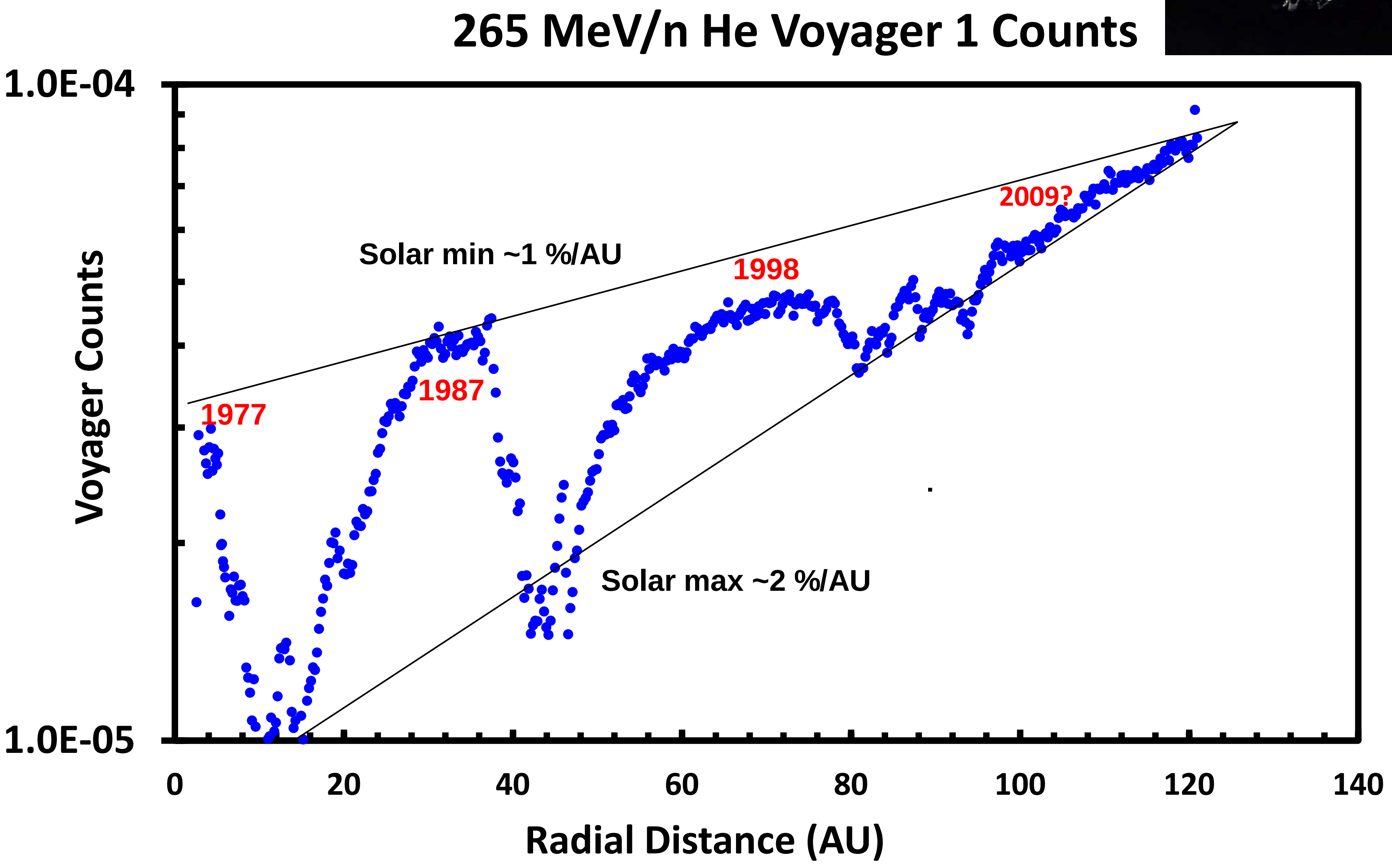
Cosmic rays and sunspots



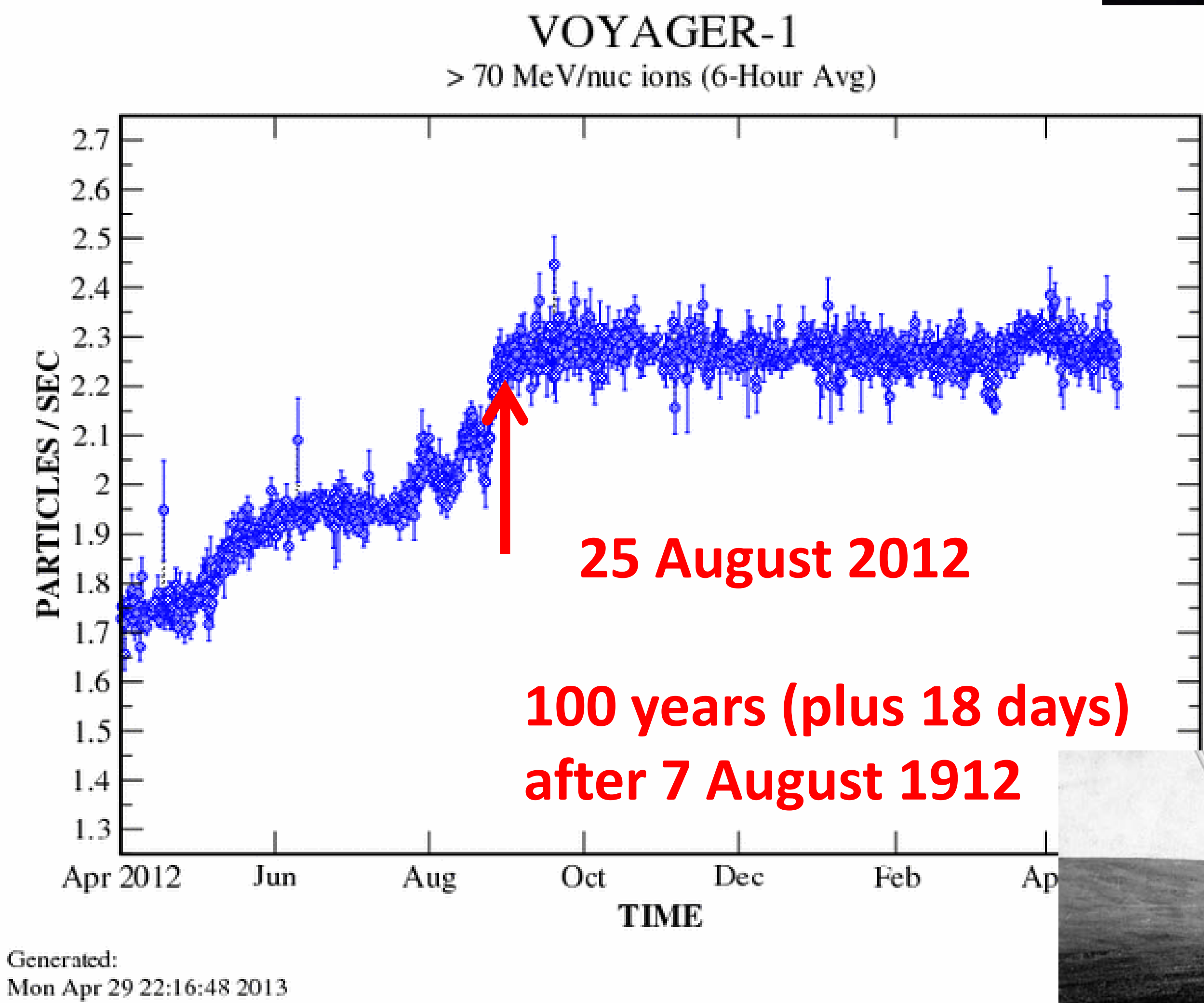
The Voyager Mission – launched 1977



The Voyager Mission



The Voyager Mission



25 August 2012

100 years (plus 18 days)
after 7 August 1912

Humanity's farthest journey

Theory

Three forms of the Transport Equation

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

or, in terms of f

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

or, slightly manipulated

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

Too difficult to solve analytically …..

Cosmic-ray diffusion tensor

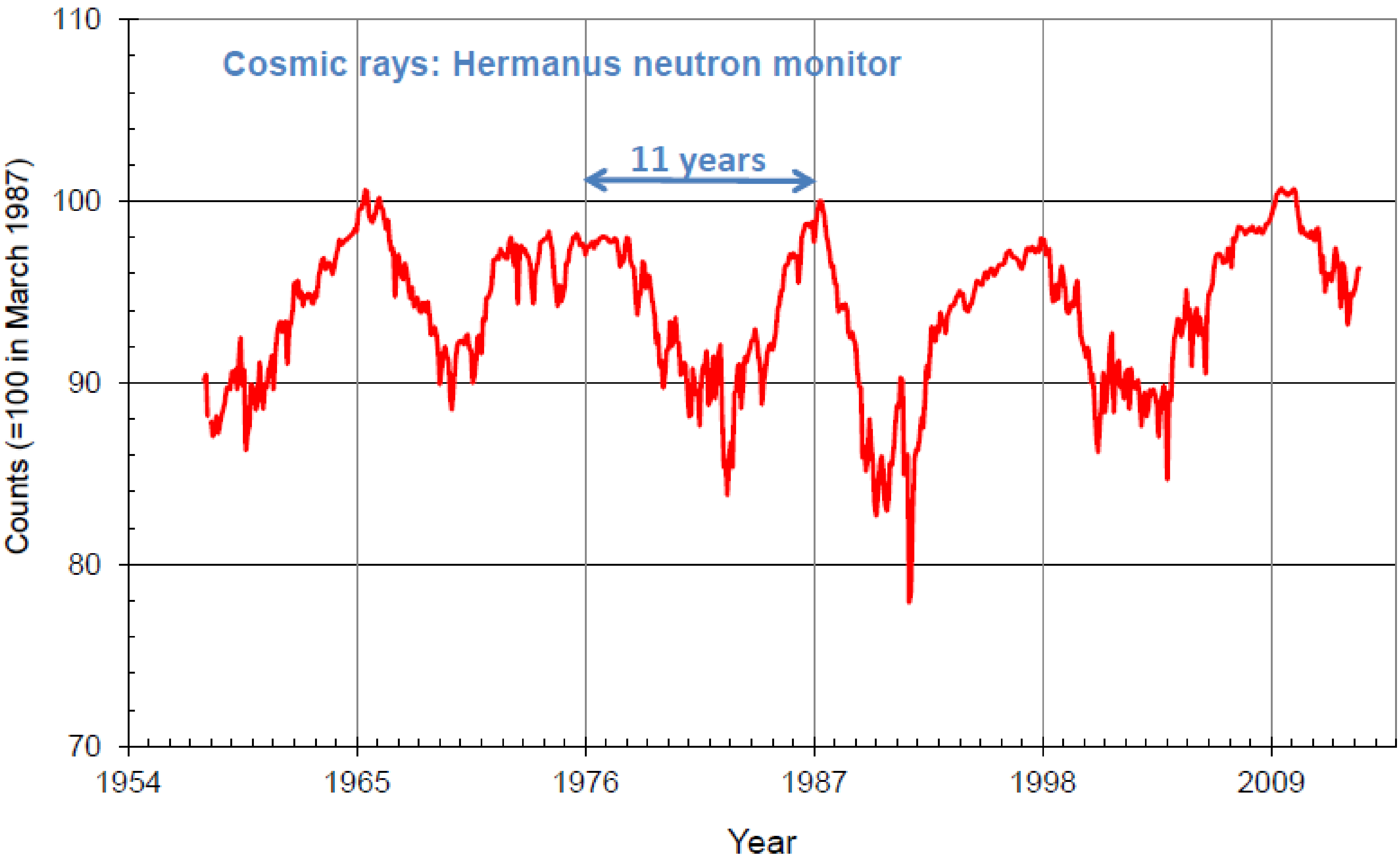
$$\mathbf{K} = \begin{pmatrix} \kappa_{\|} & 0 & 0 \\ 0 & \kappa_{\perp} & \kappa_T \\ 0 & -\kappa_T & \kappa_{\perp} \end{pmatrix}$$

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

- How do the solar wind and the heliopsheric magnetic field have to look to explain the observed cosmic-ray intensity variations?

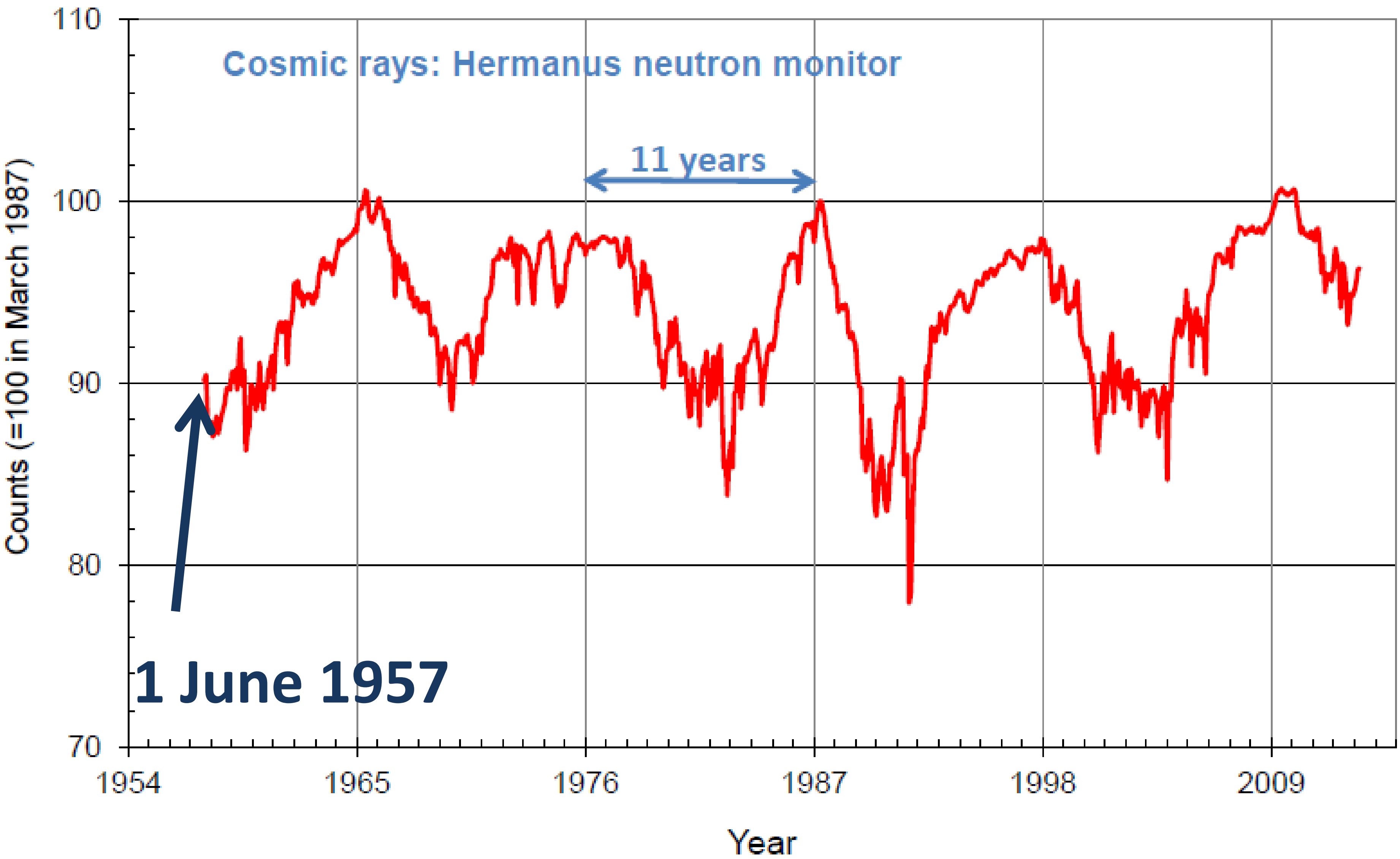
- Does this agree with what we observe of the solar wind and heliospheric magnetic field?

Experimental work



Hermanus neutron monitor

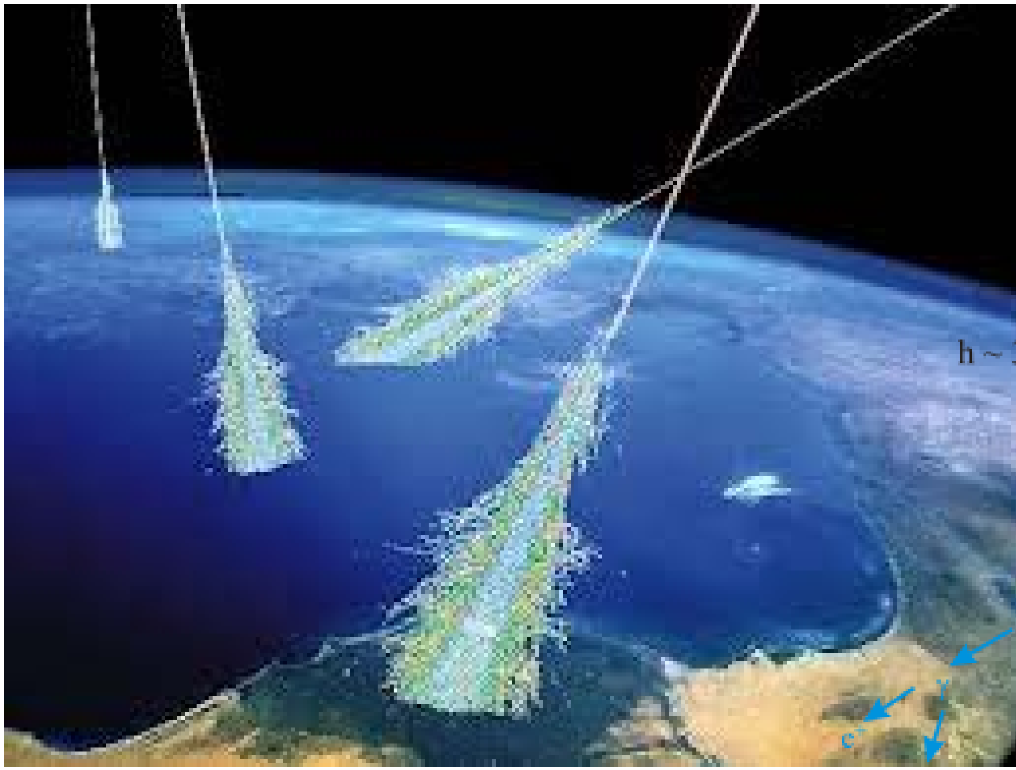
Experimental work

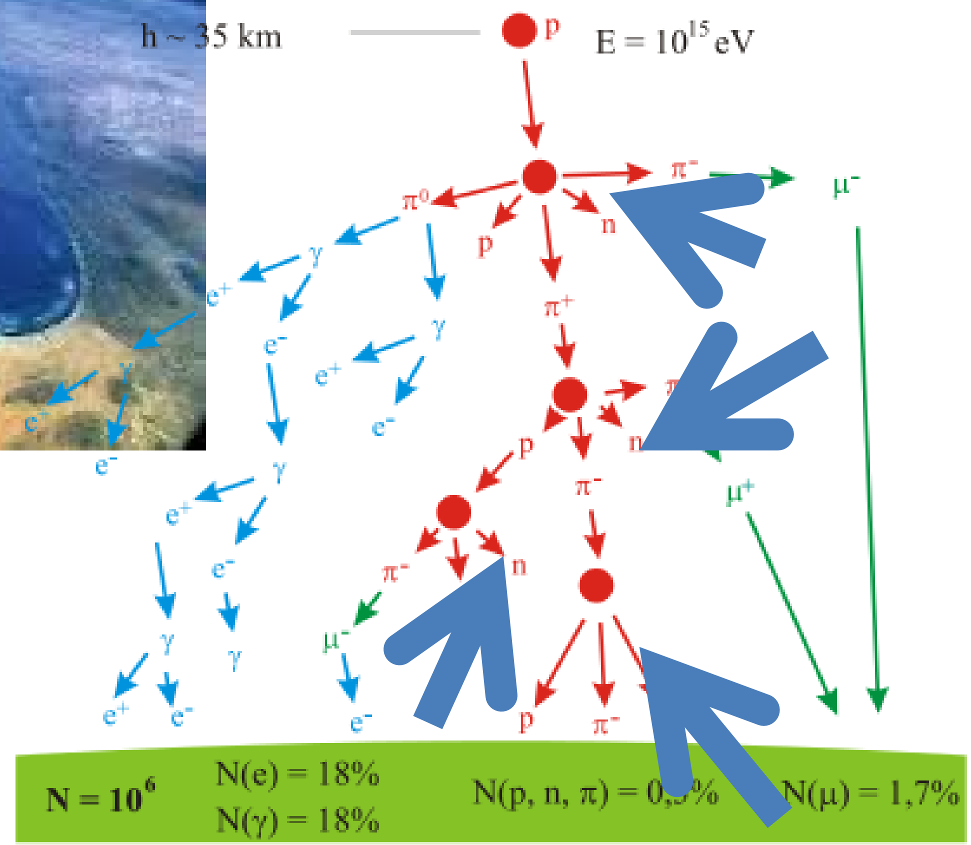


Sanae

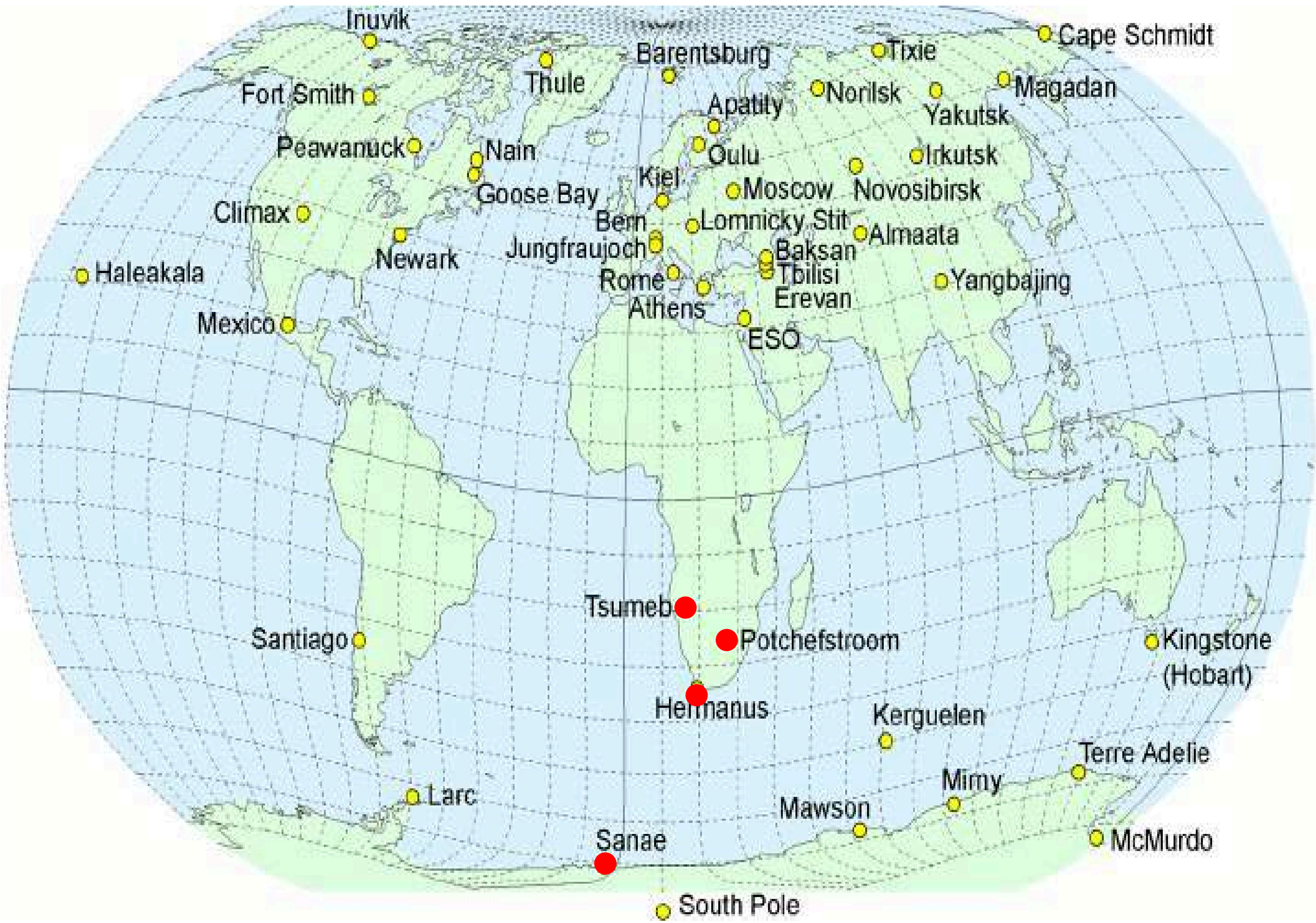
Sanae Neutron Monitor

Neutron monitors – sensitive to the neutrons

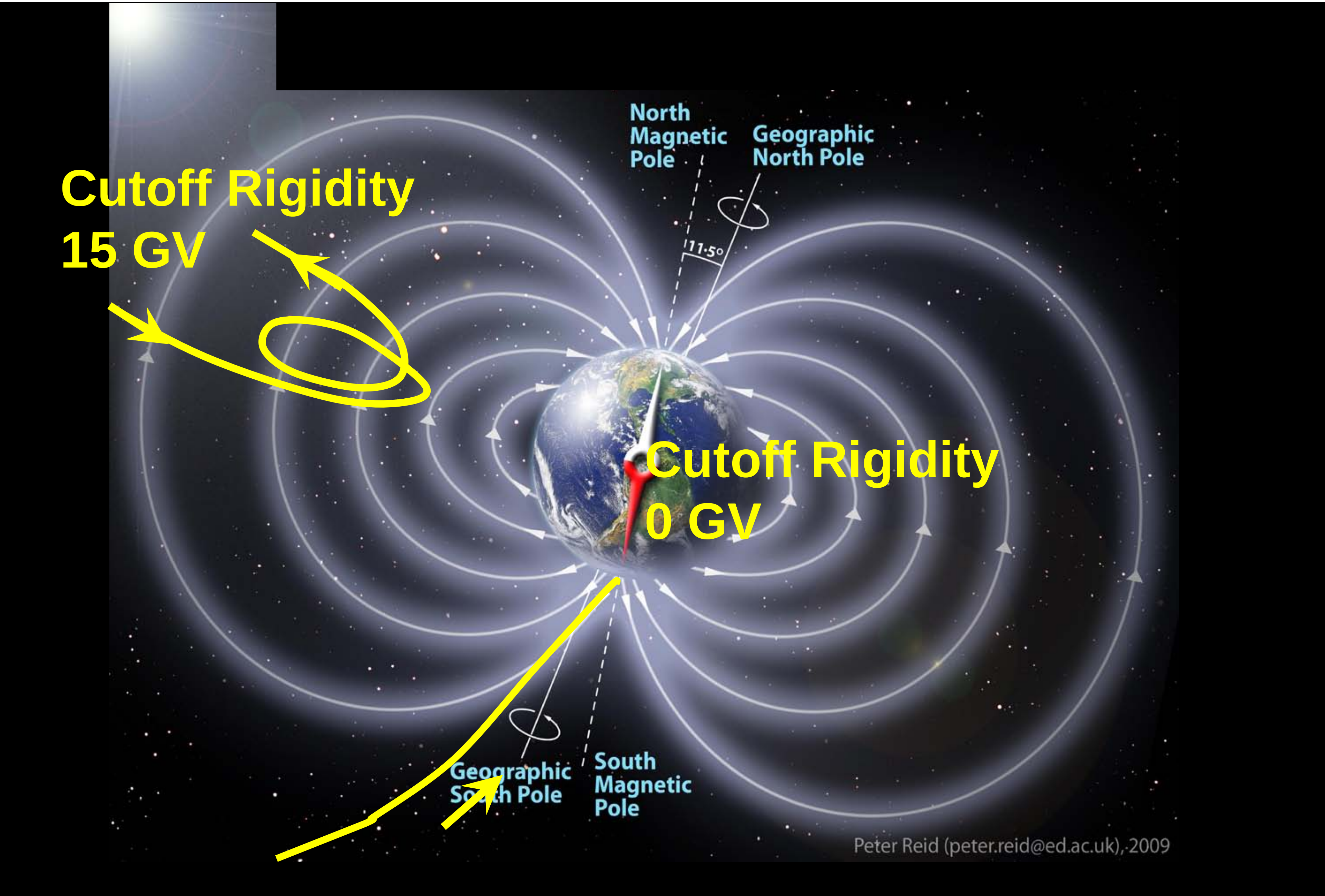




Neutron monitor network



The poles are better



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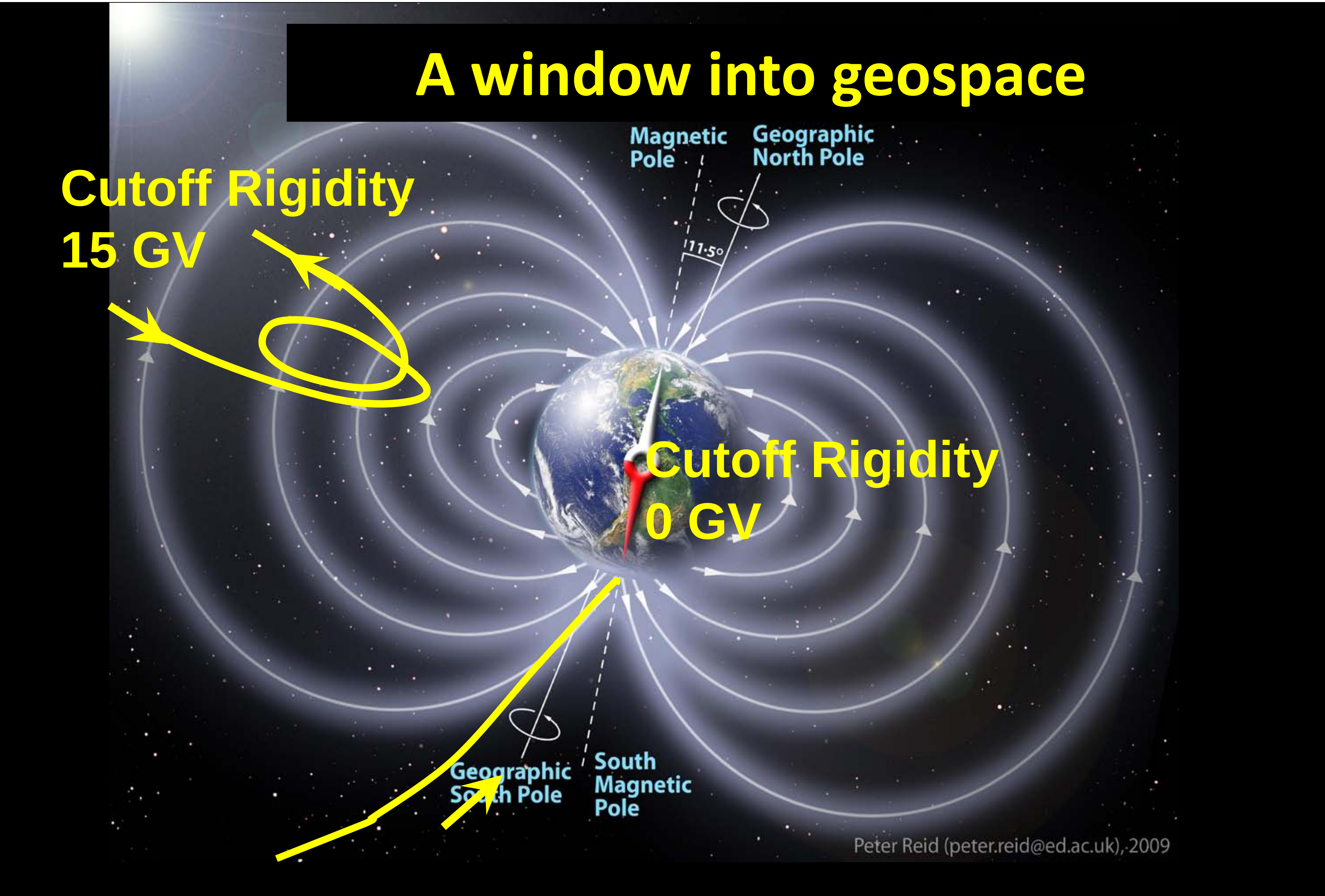
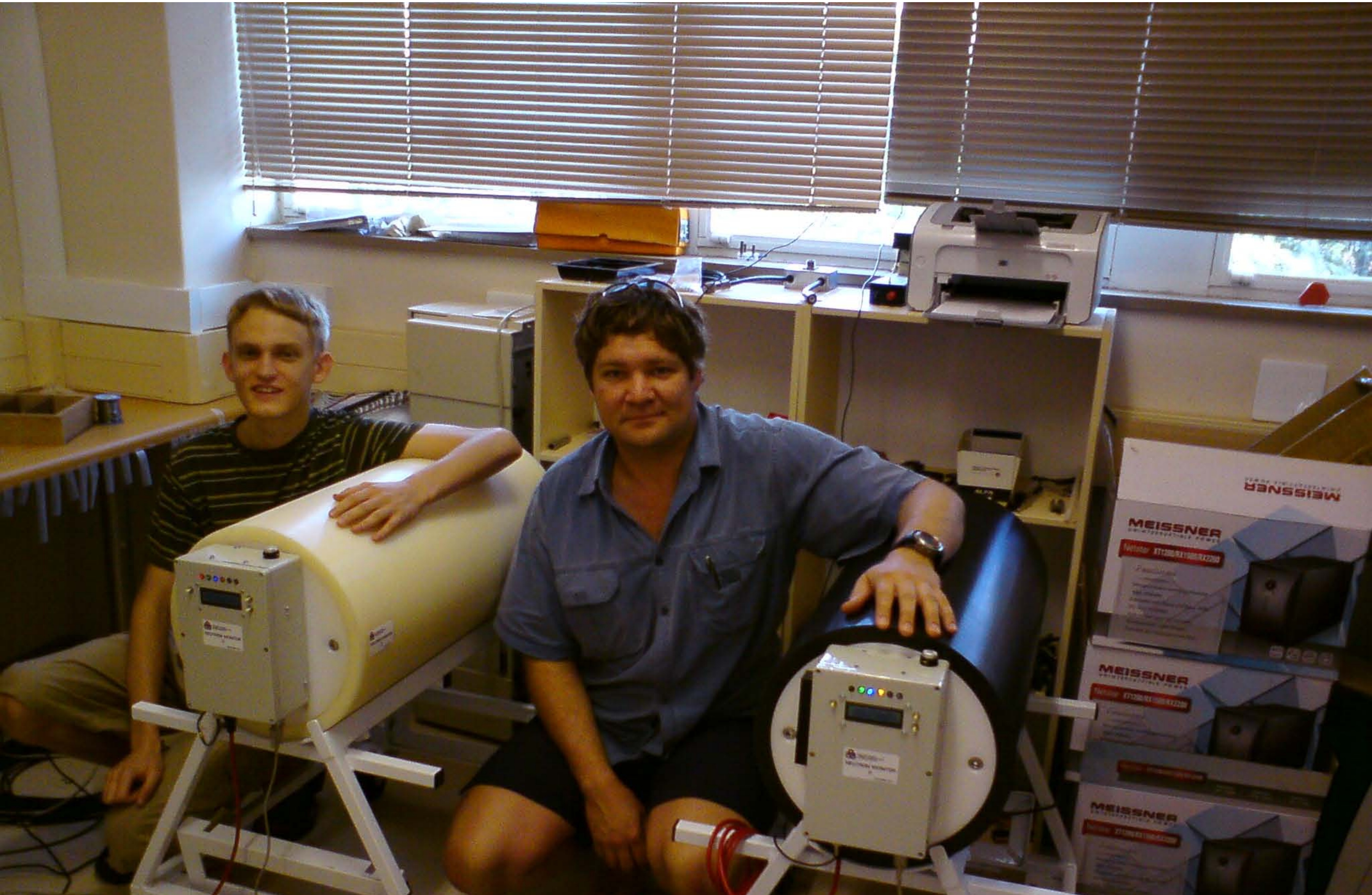
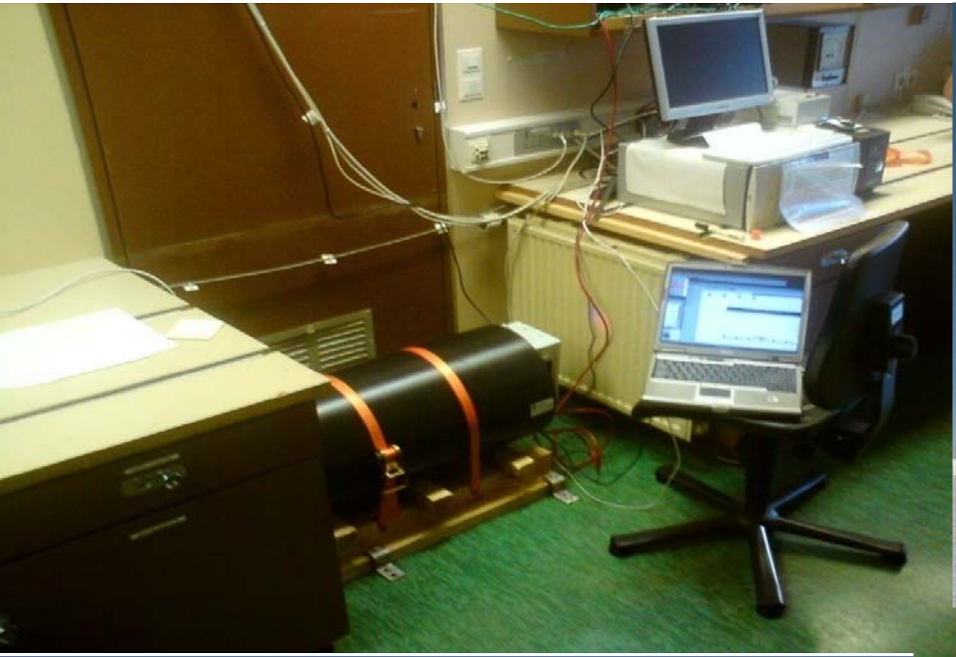


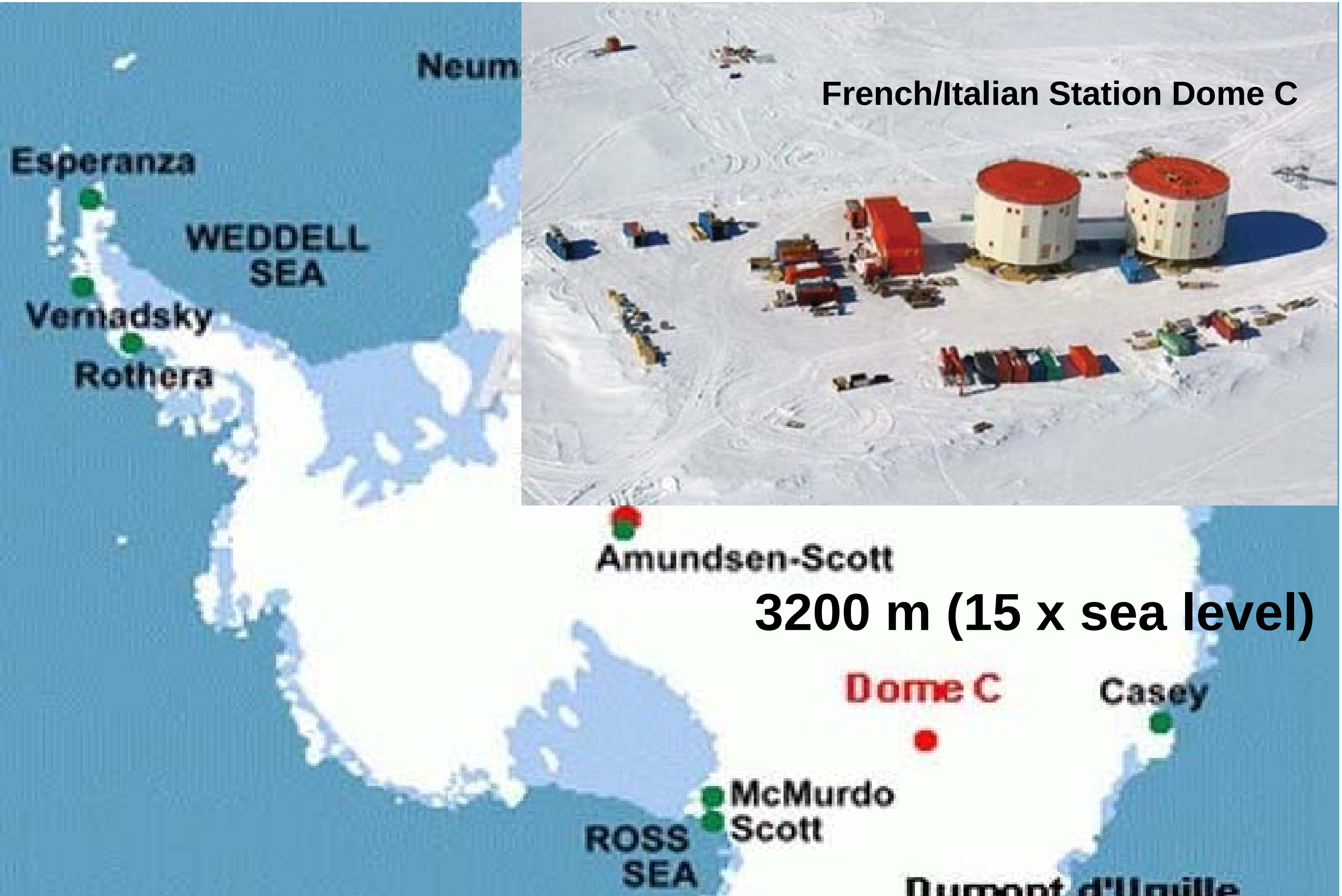
Mini neutron monitors



Mini neutron monitors



Mini neutron monitors



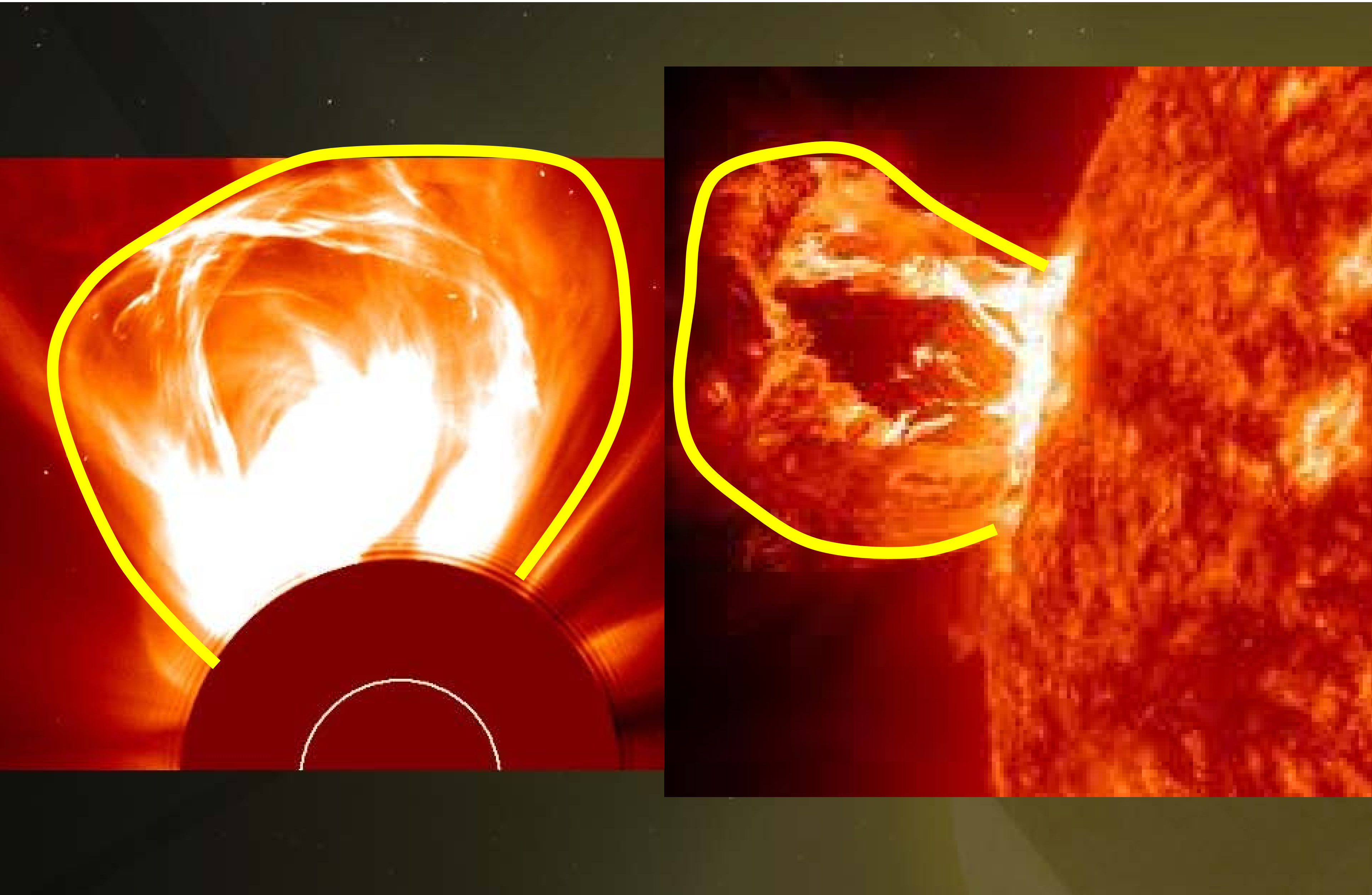
Mini neutron monitors

Sierra Negra, Mexico, 4200 m

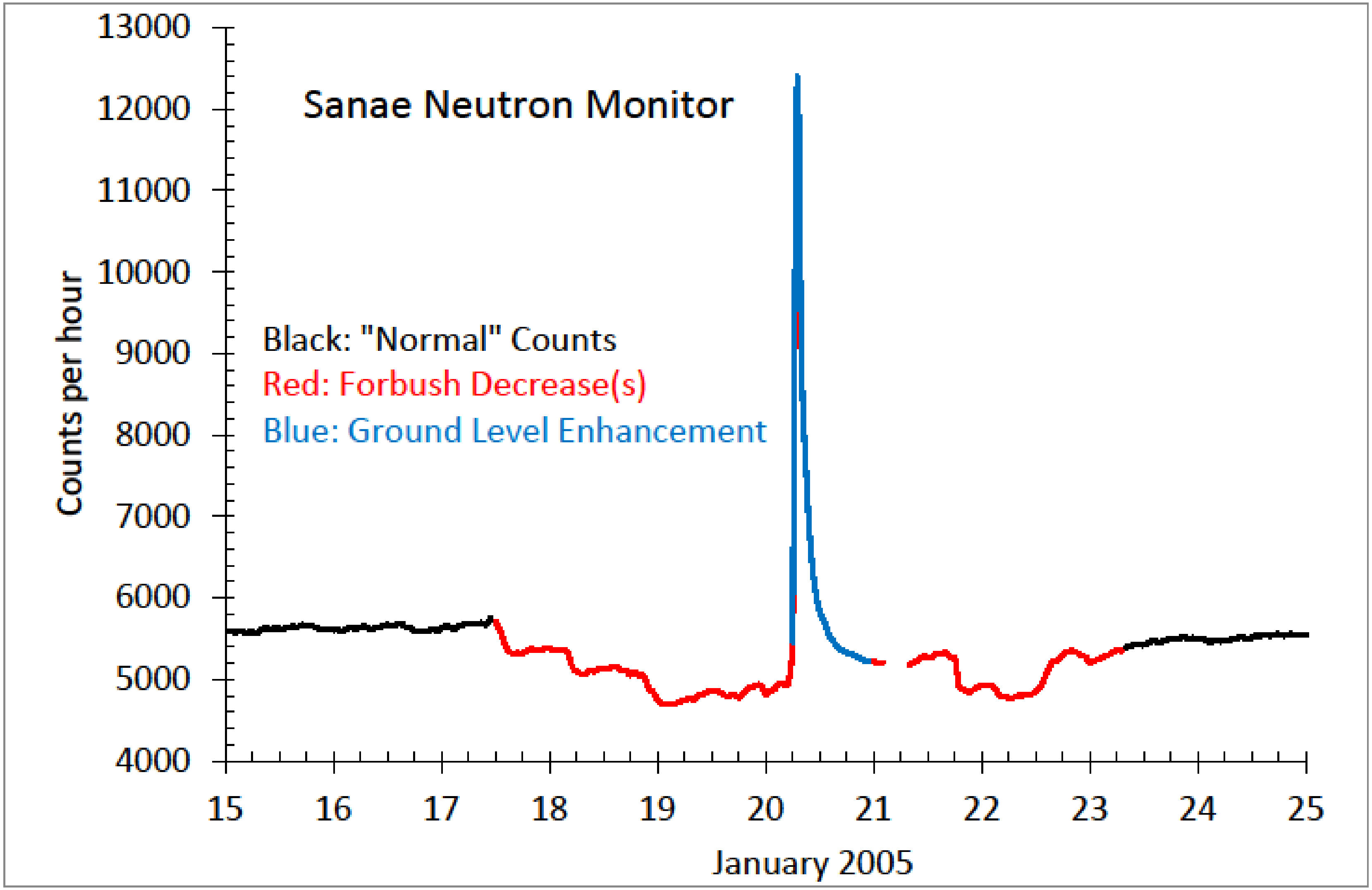
Topics

- South African astronomy
- Particle vs. photon astronomy
- Cosmic-ray spectra, composition
- Dark matter
- Neutrinos
- Cosmic-ray variations
- “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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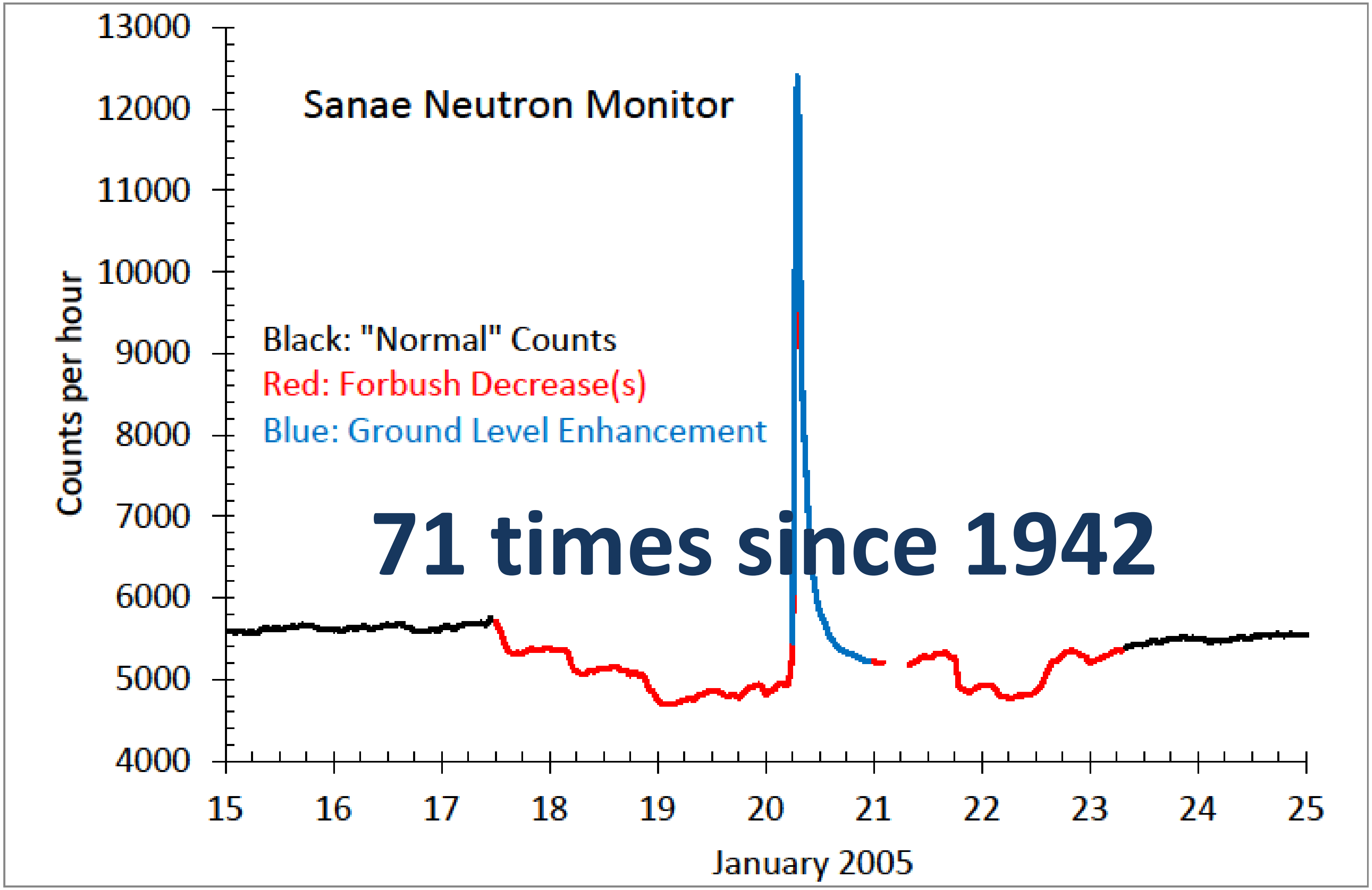

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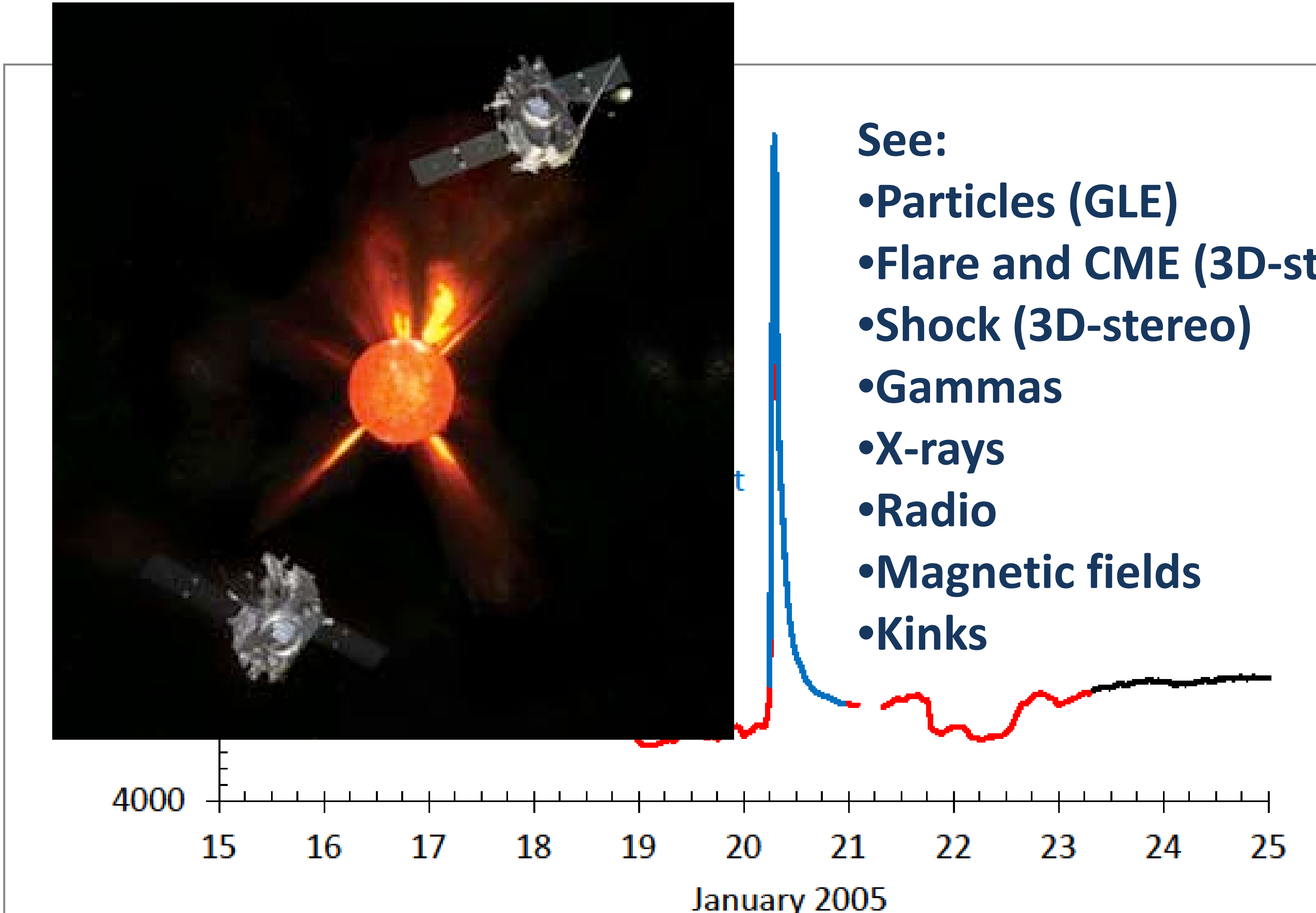
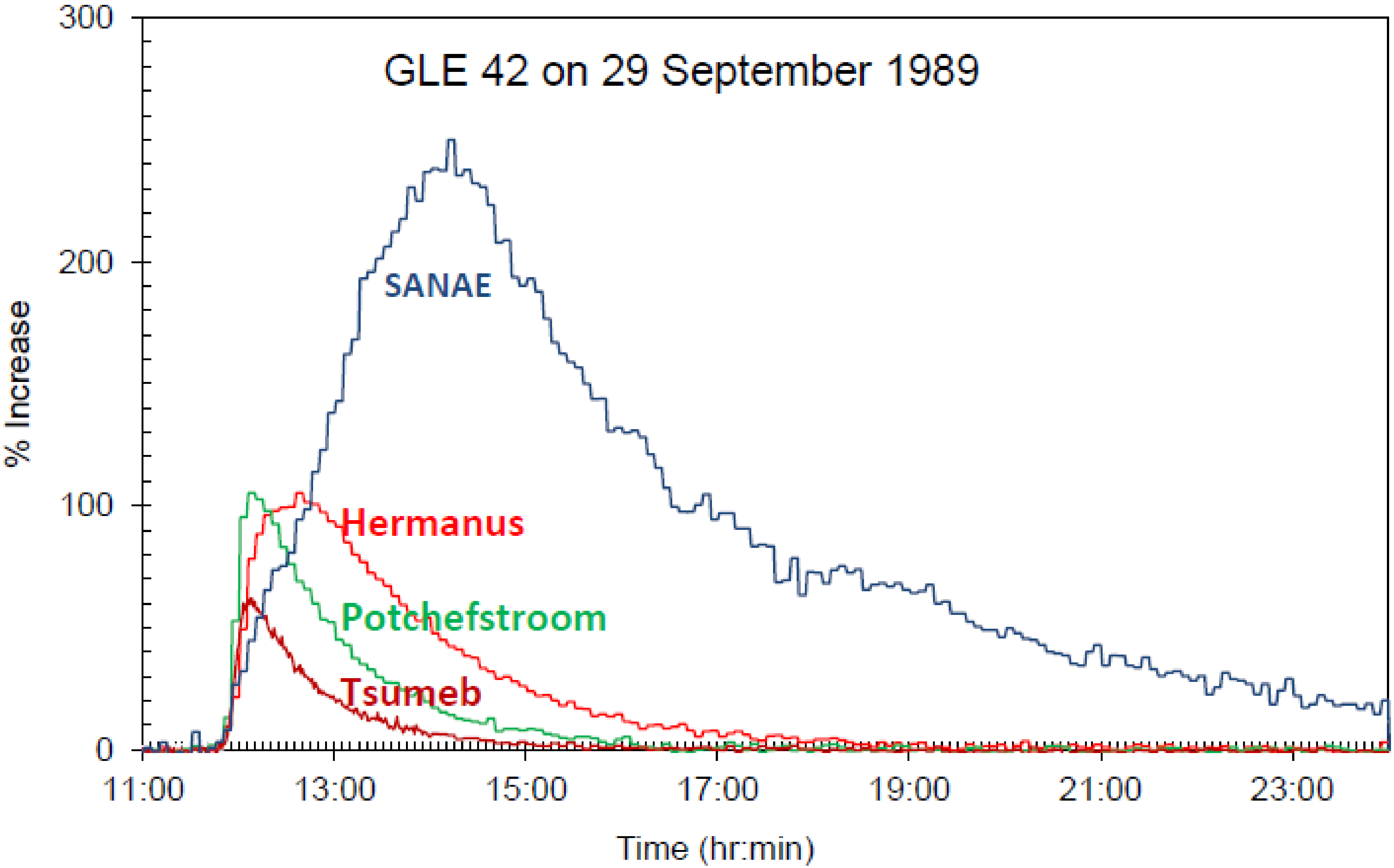


See:
- Particles (GLE)
- Flare and CME (3D-stereo)
- Shock (3D-stereo)
- Gammas
- X-rays
- Radio
- Magnetic fields
- Kinks

The Window into Geospace…..



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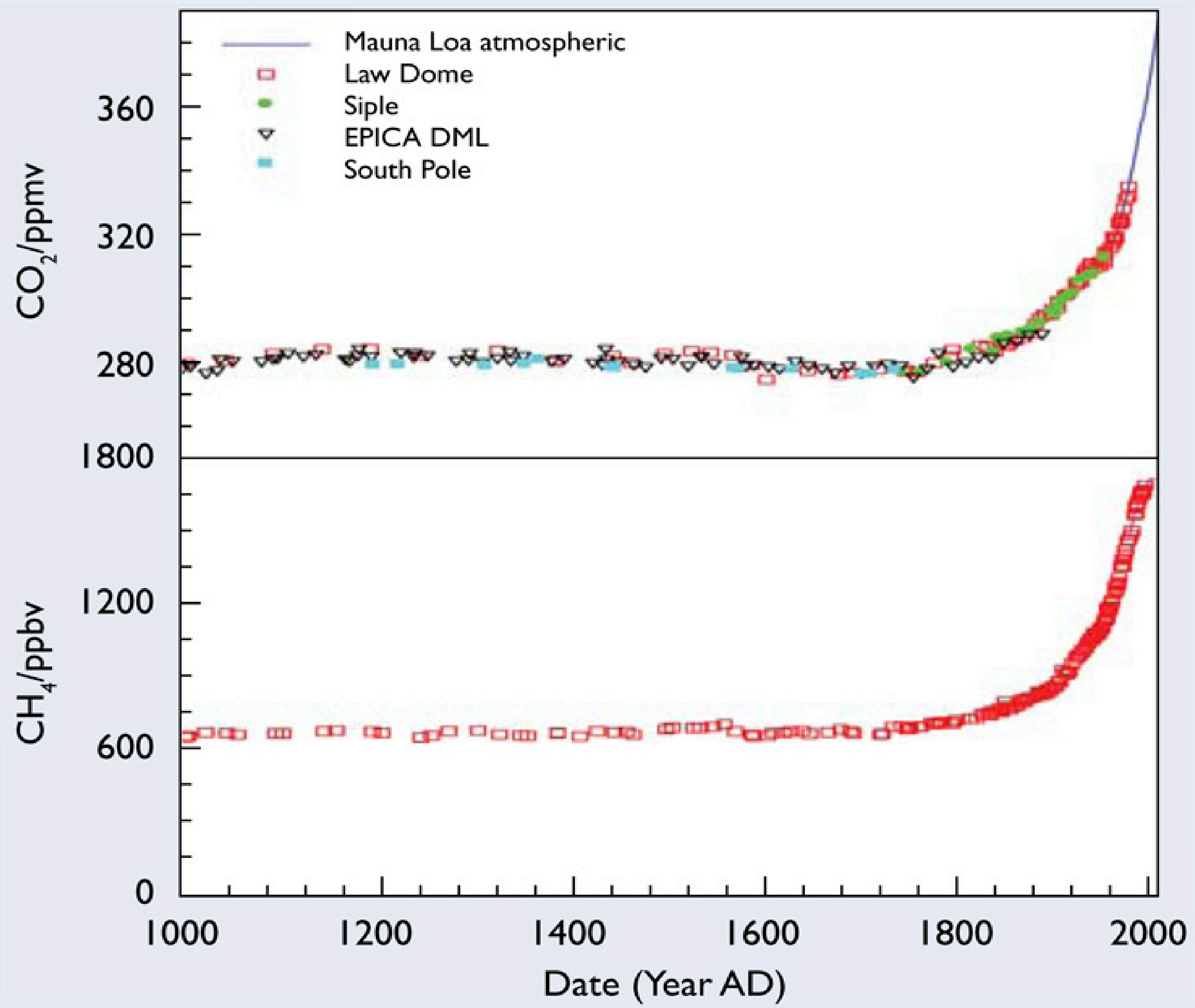
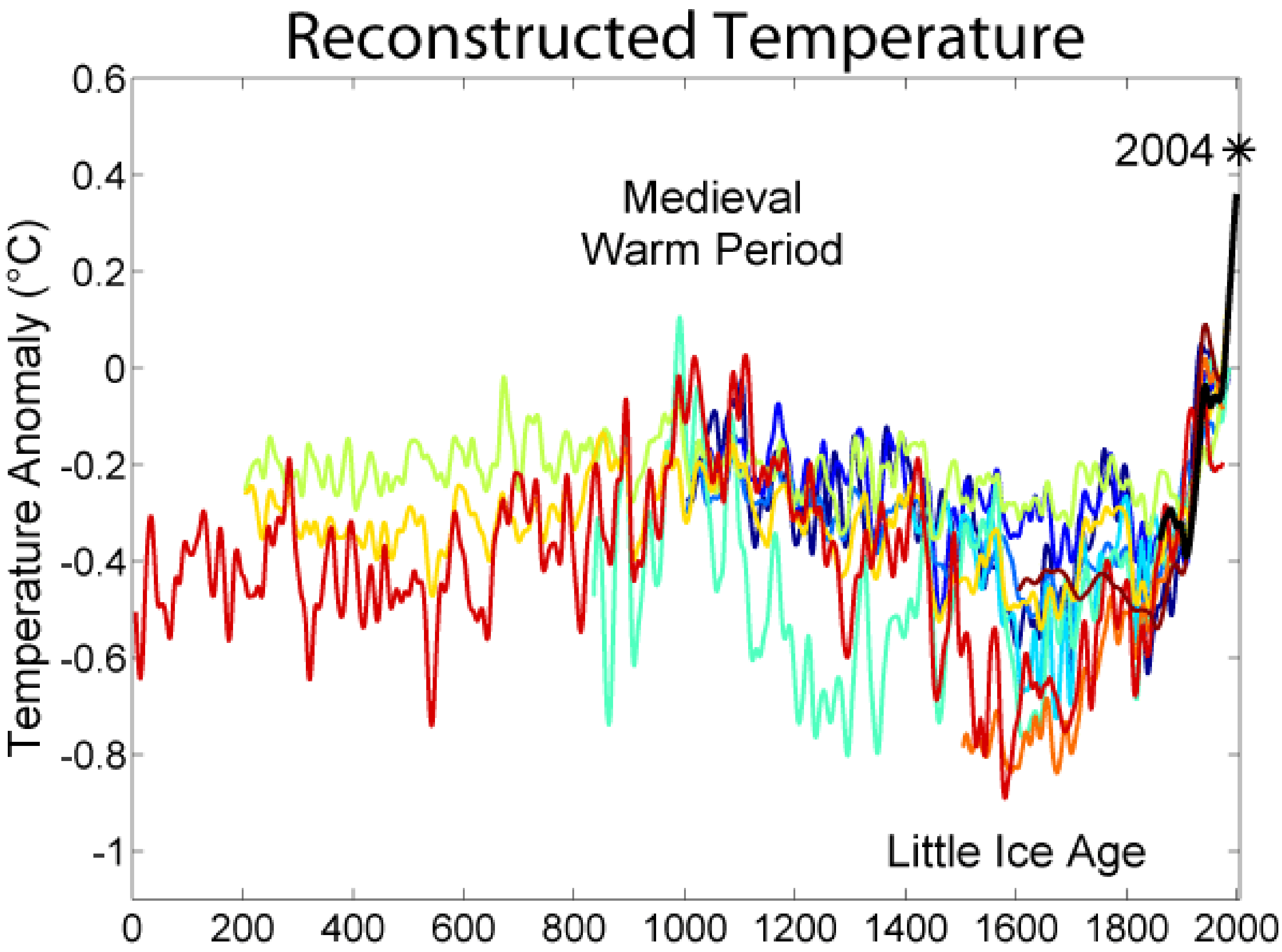
- Cosmic-ray variations
- "Cosmic" rays from the sun
- Helioclimatology → Geoclimatology

Climate change

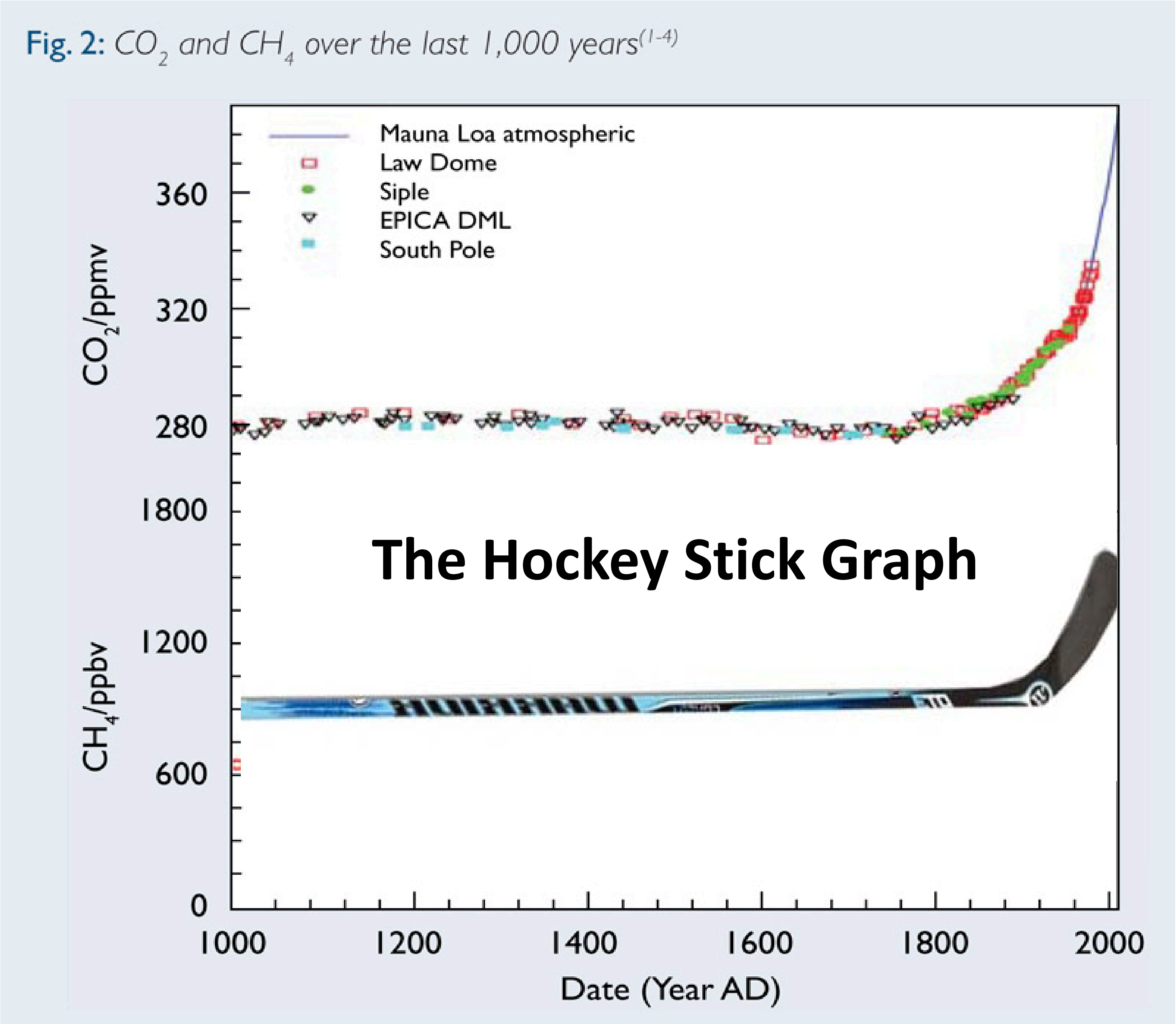
Fig. 2: *CO_2 and CH_4 over the last 1,000 years*[1-4]



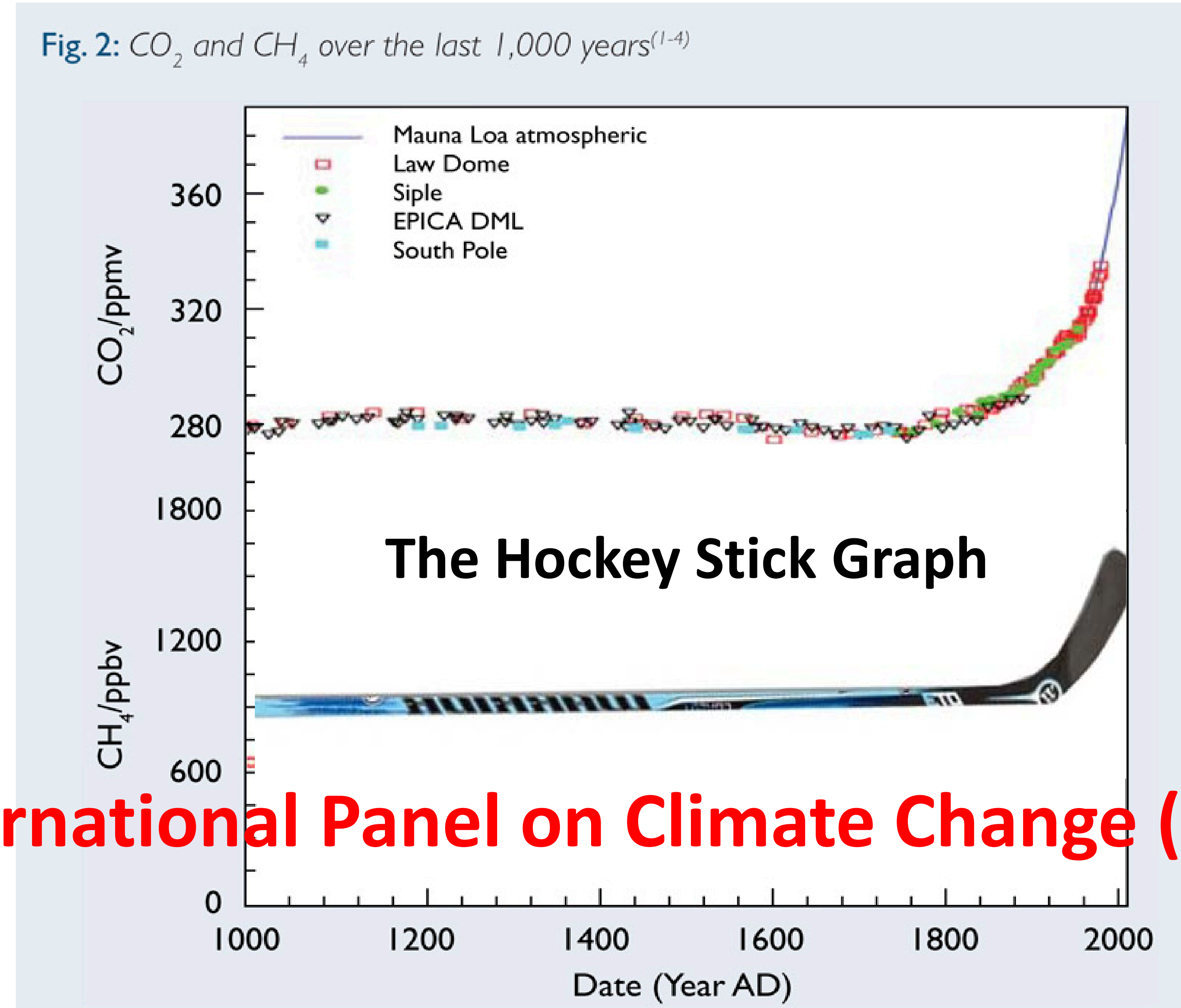
Climate change



Climate change

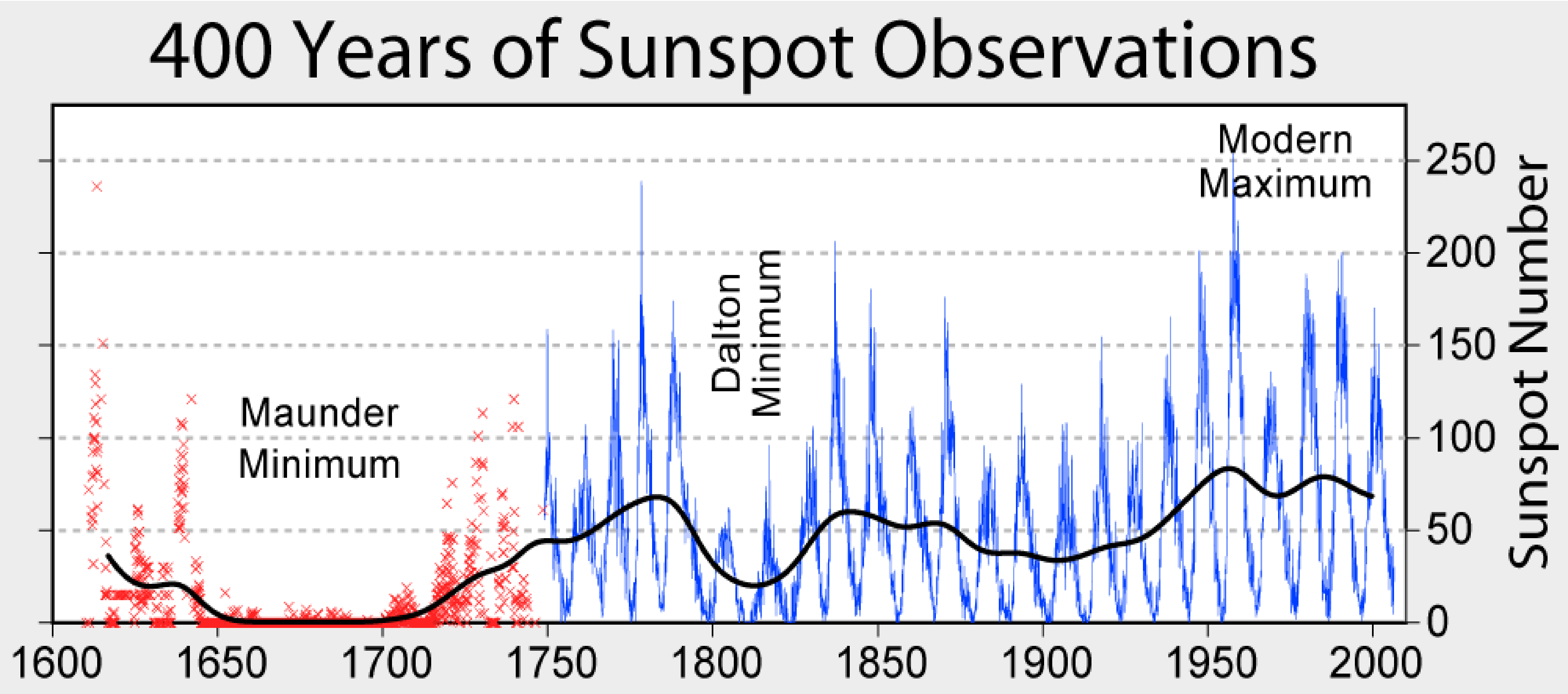


Climate change

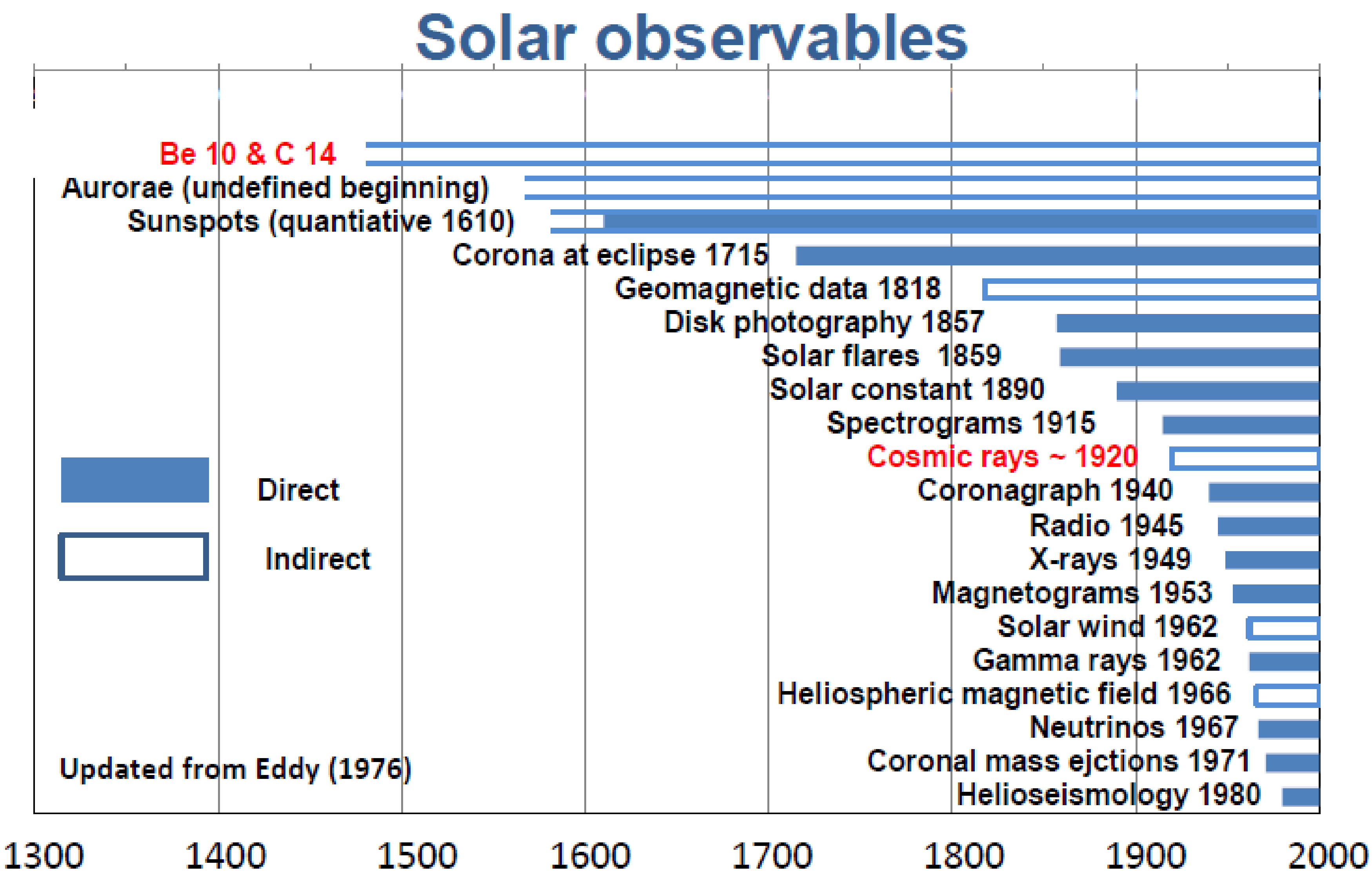


International Panel on Climate Change (IPCC)

Climate change



History of the Sun



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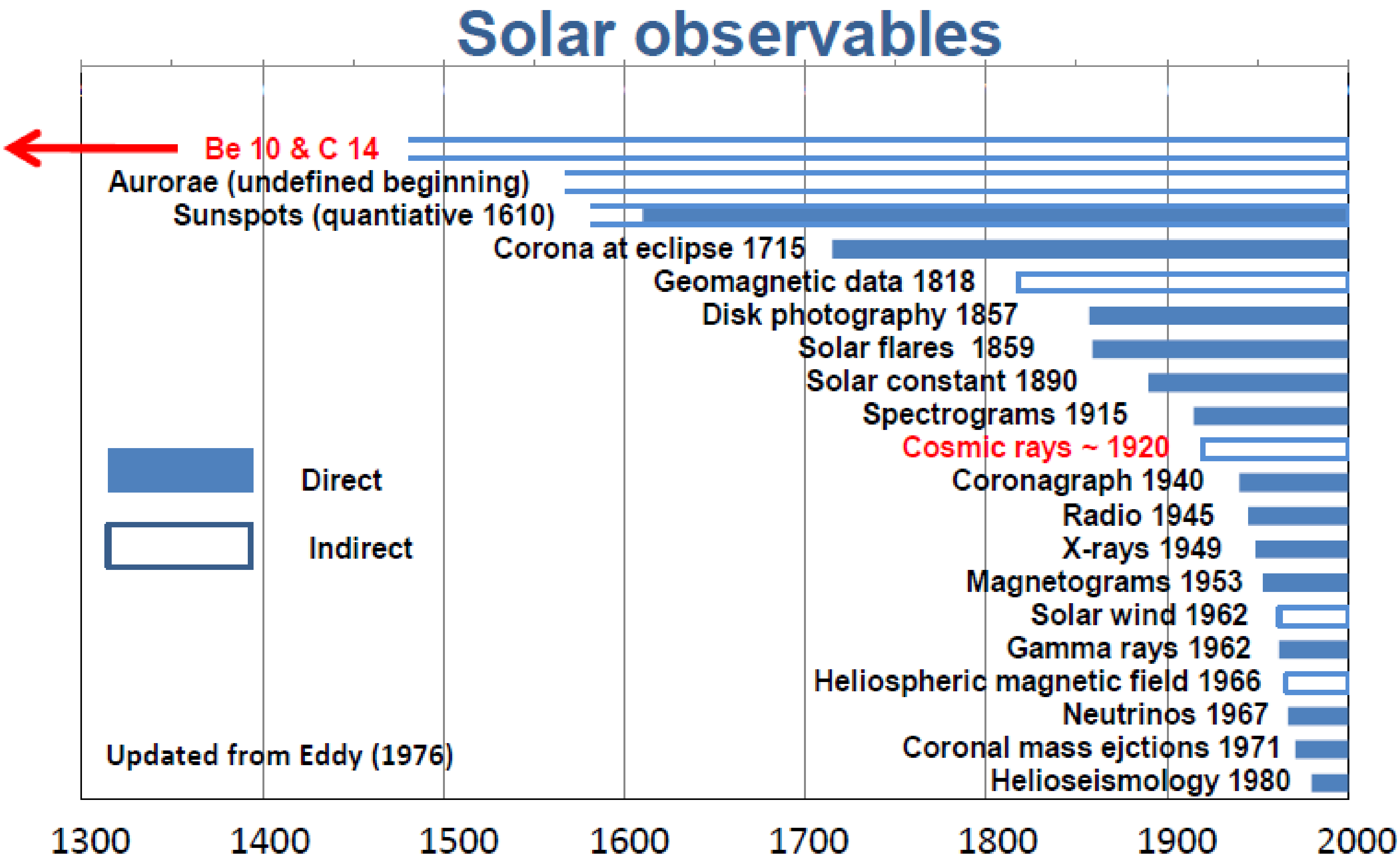
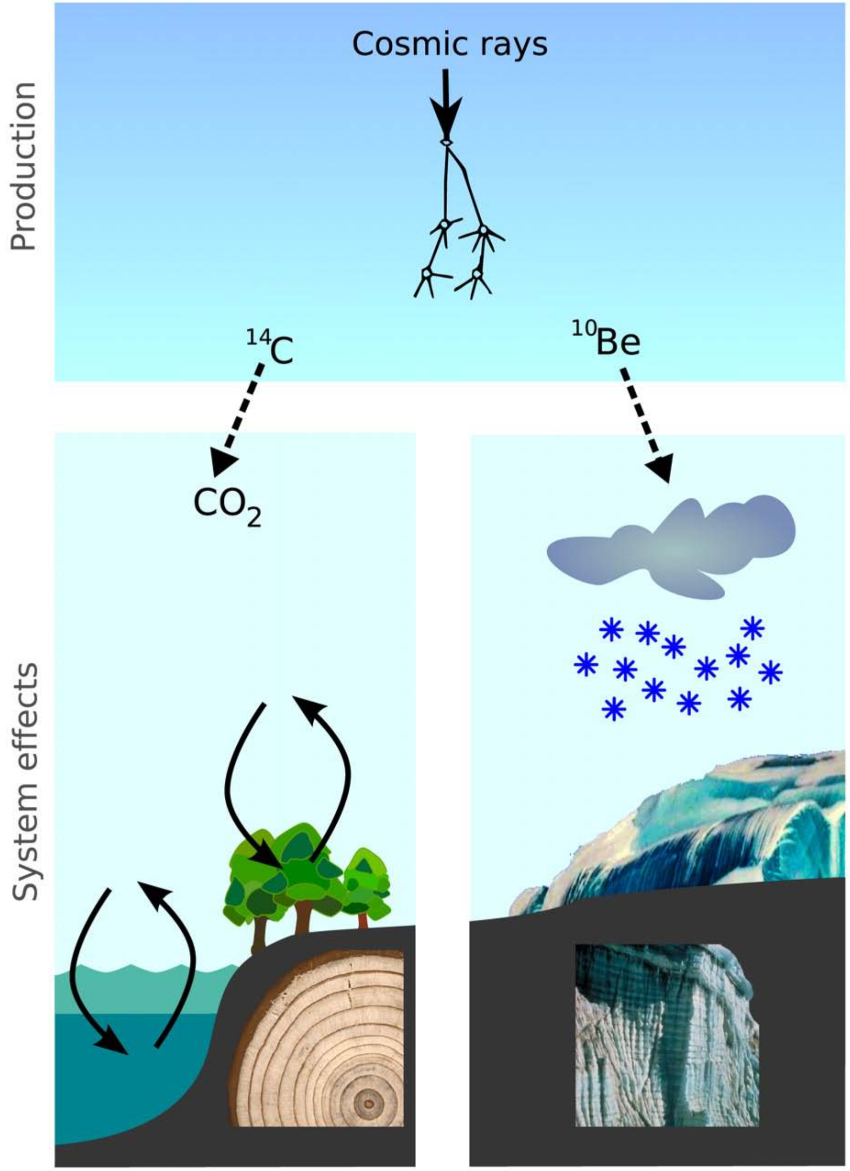
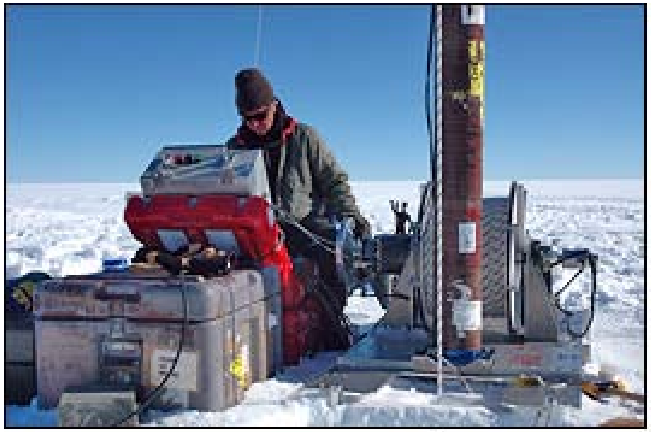


Paleo-cosmic rays: ^{14}C and ^{10}Be

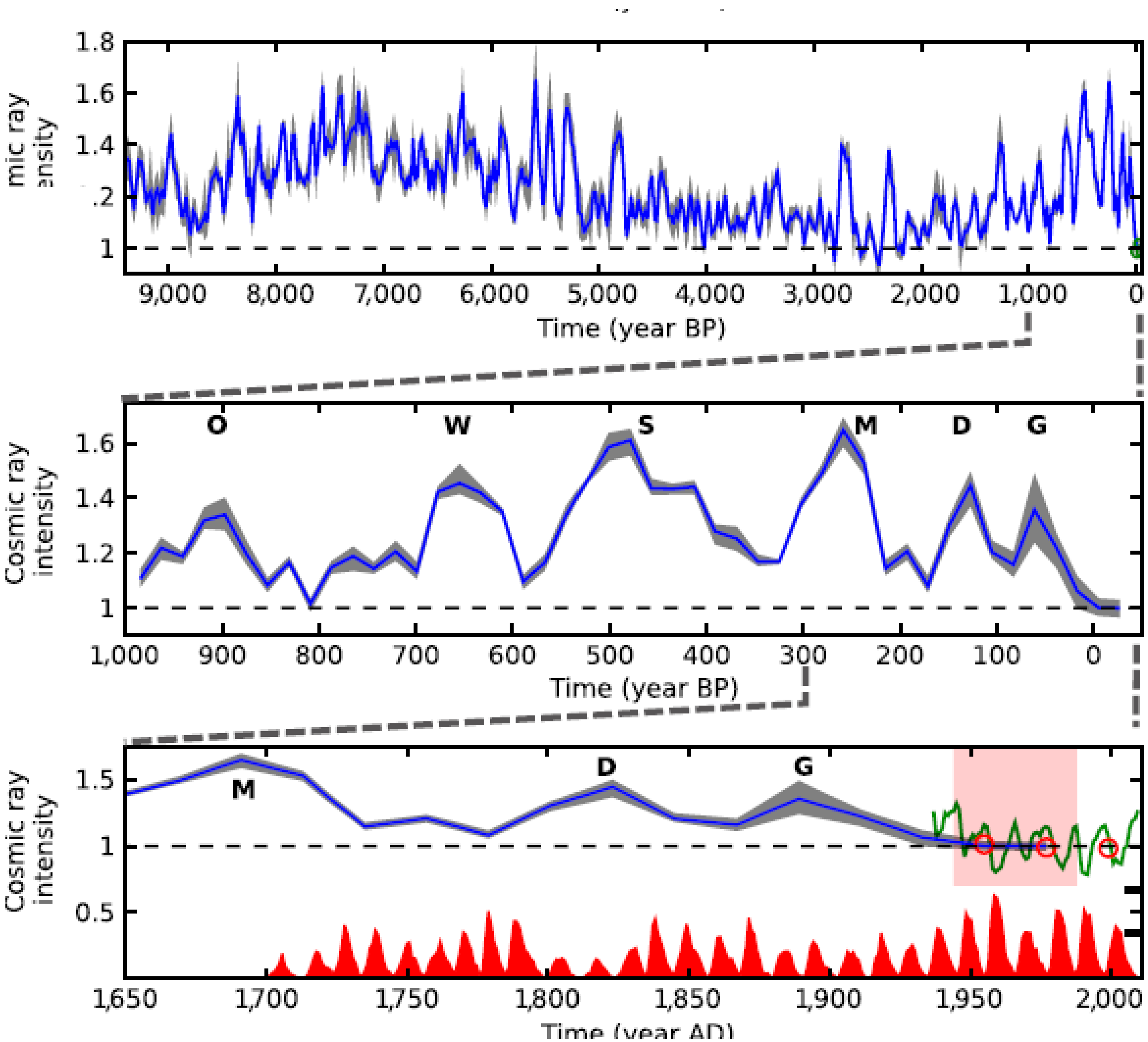


Paleo-cosmic rays: ^{10}Be





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



Steinhilber et al. (2012)

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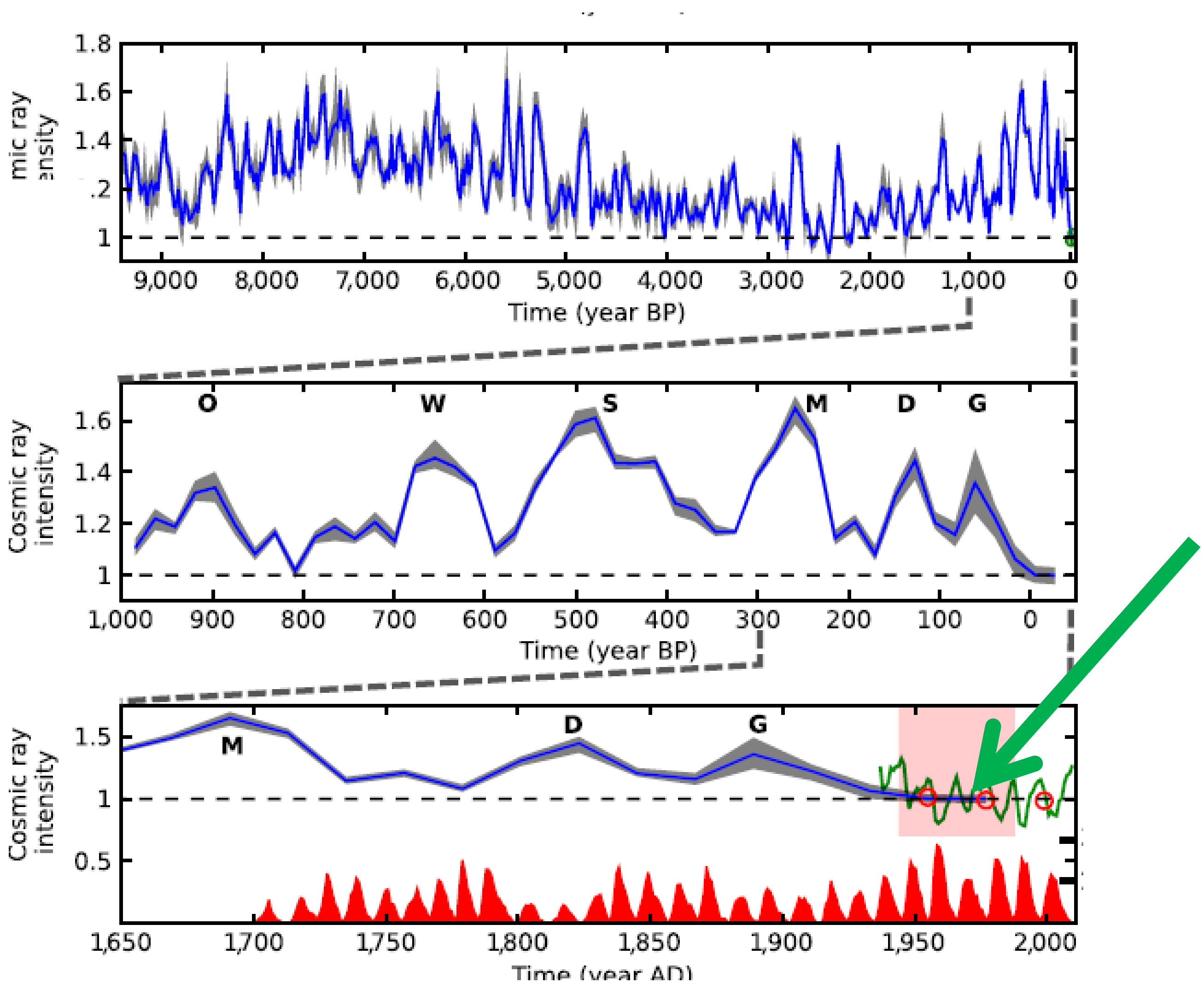

Steinhilber et al. (2012)

Paleo-cosmic rays: ^{10}Be

Ice shelf in Queen Maud Land

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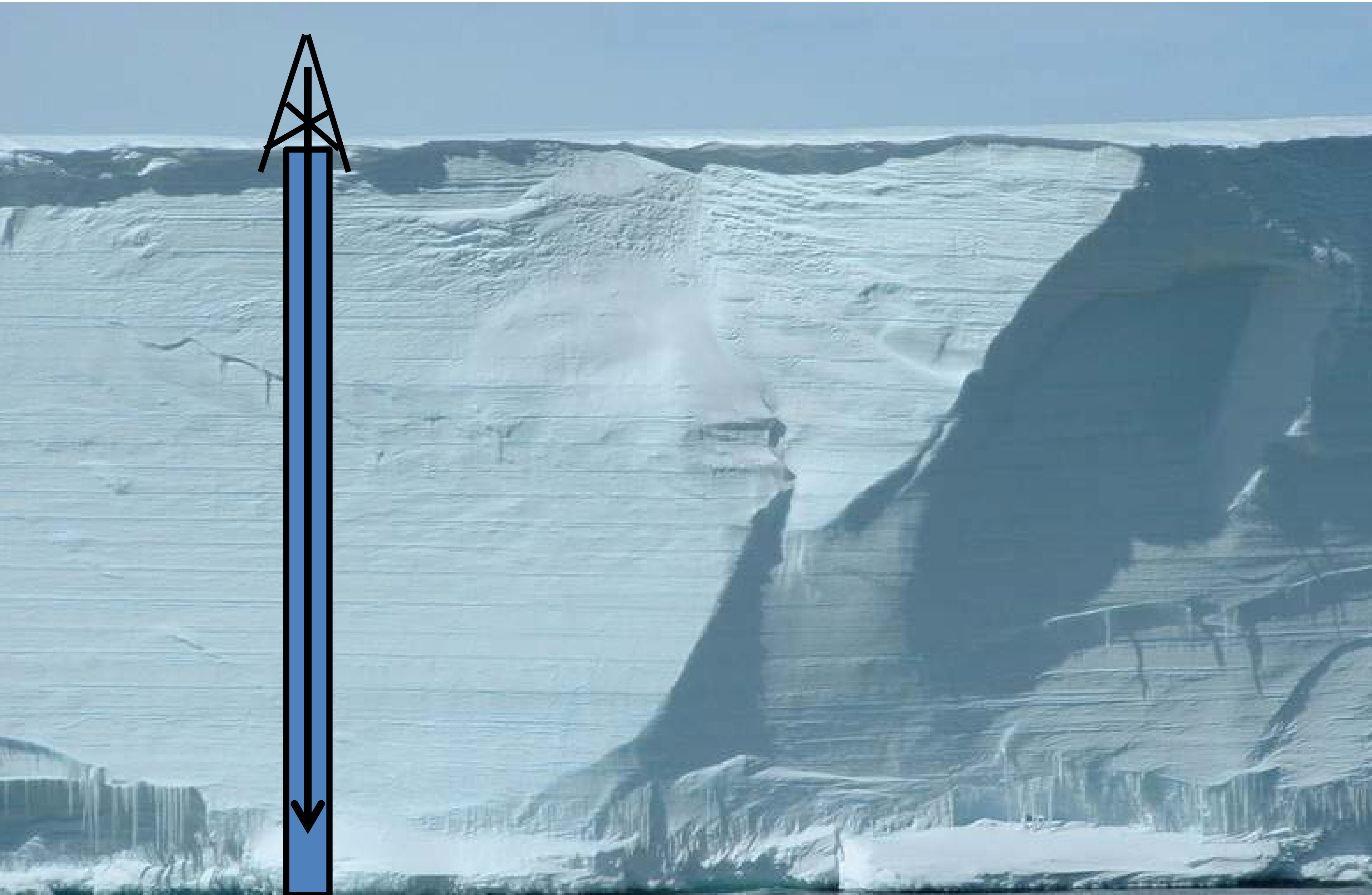
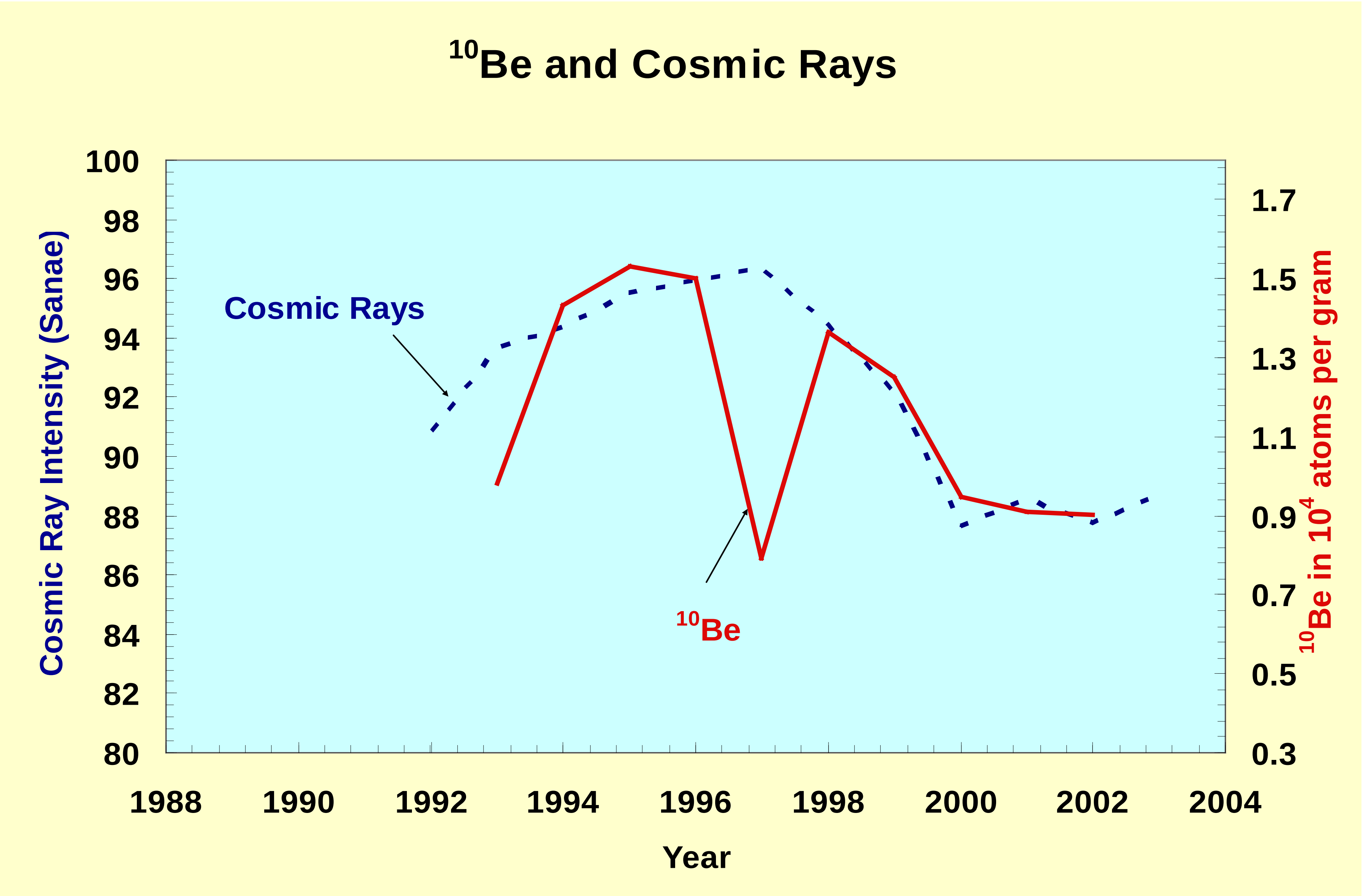
Shallow drilling ……. ~ 60 years deep

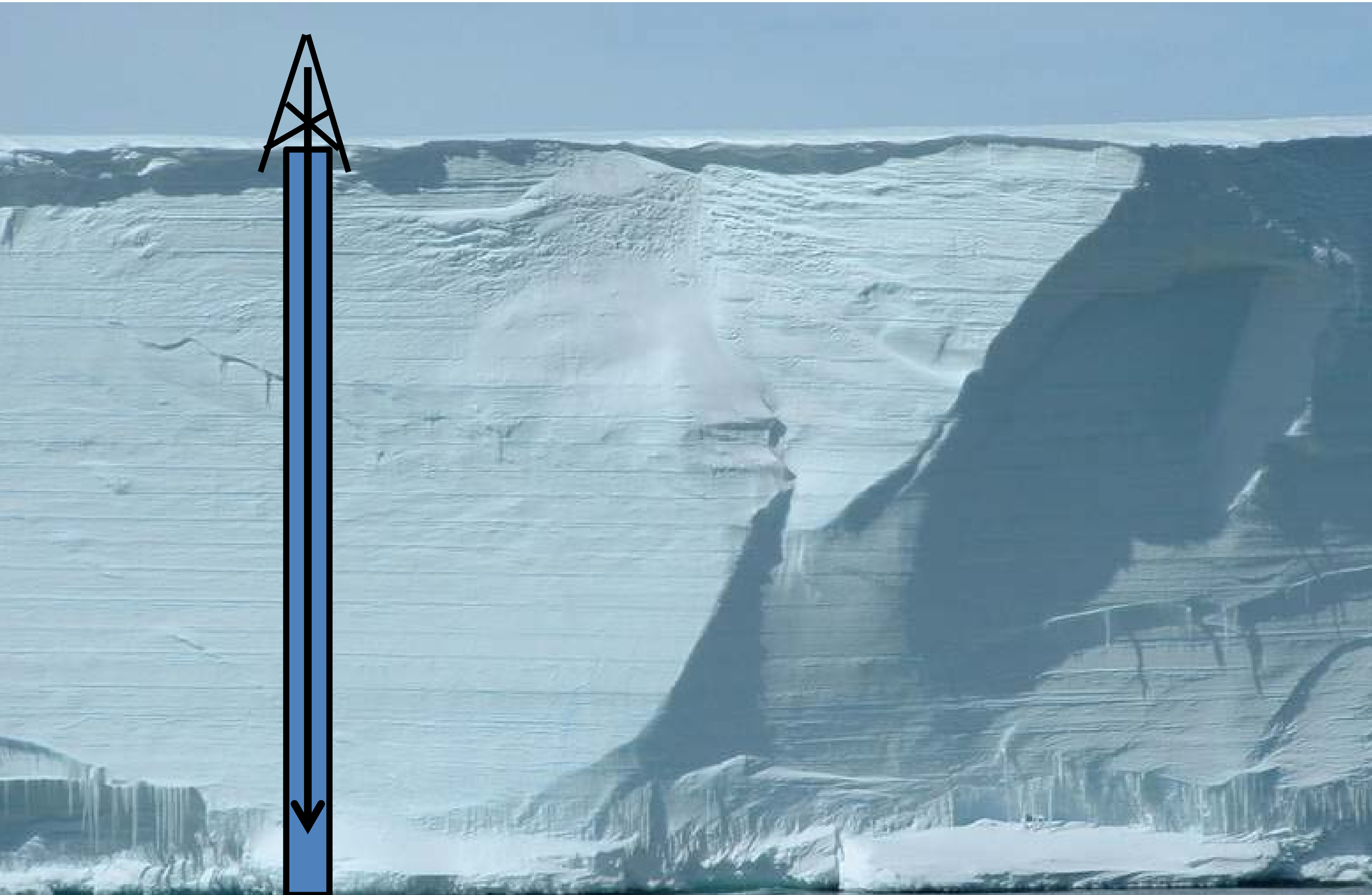


Pilot Project 2006

Pilot project 2006



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
- Particle Astronomy after 102 years:
  - 25 August 2012 – longest journey ever completed
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Acknowledgements

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  the South African National Antarctic Programme
  for over 50 years.

- NASA/Wikipedia