



Suprathermal and Energetic Particles; Their Interaction with Matter and Implications for (Human) Exploration

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Part I

Suprathermal and Energetic Particles

40 - 1^{re} 90. Sulfate Vitreux d'Ammoniac et de Potasse.
Papier noir. Cuir de l'Ammoniac.
Exposé au soleil le 27. et à la lune le 28. -
Vendredi le 1^{er} mars.

Ionization is a good measure of radioactivity.





Introduction

On a balloon flight in 1912 Victor Hess discovers 'Höhenstrahlung' at large heights. The degree of ionization increases with height! Millikan interprets it as cosmic or extraterrestrial radiation.



Image credit: NY Times

Level of radiation must increase with height.

Why? Is there a source of radiation out there?

What is this source?

What are the properties of this radiation?



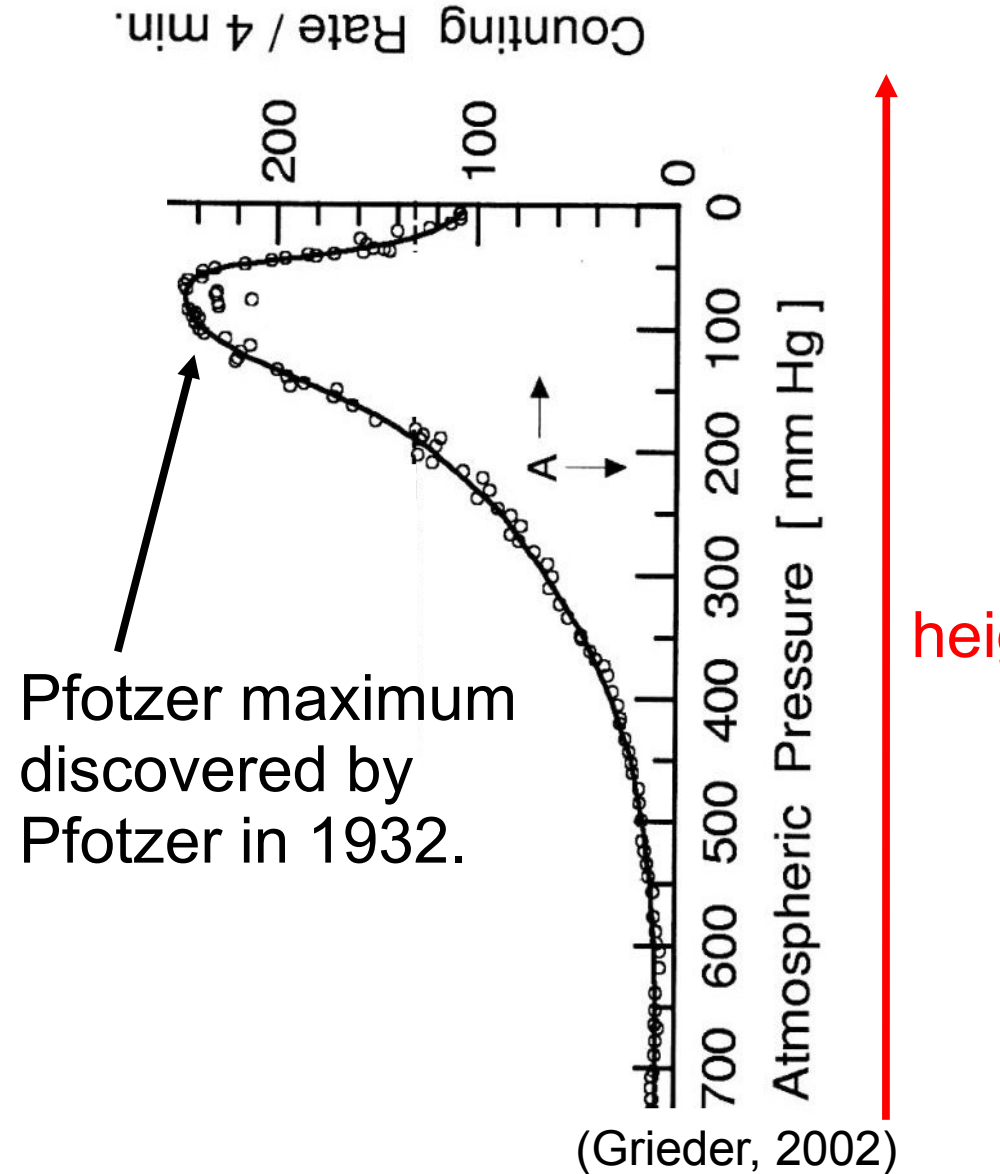
Why does ionization increase with height?

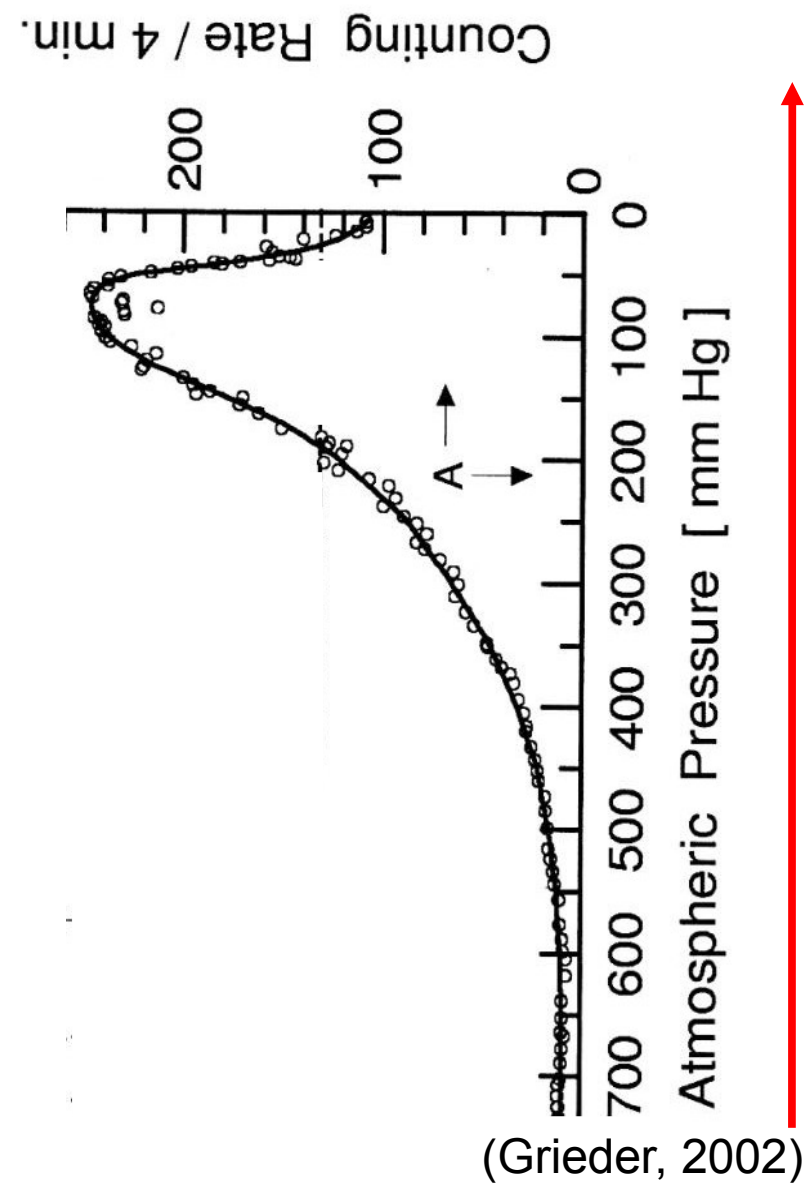
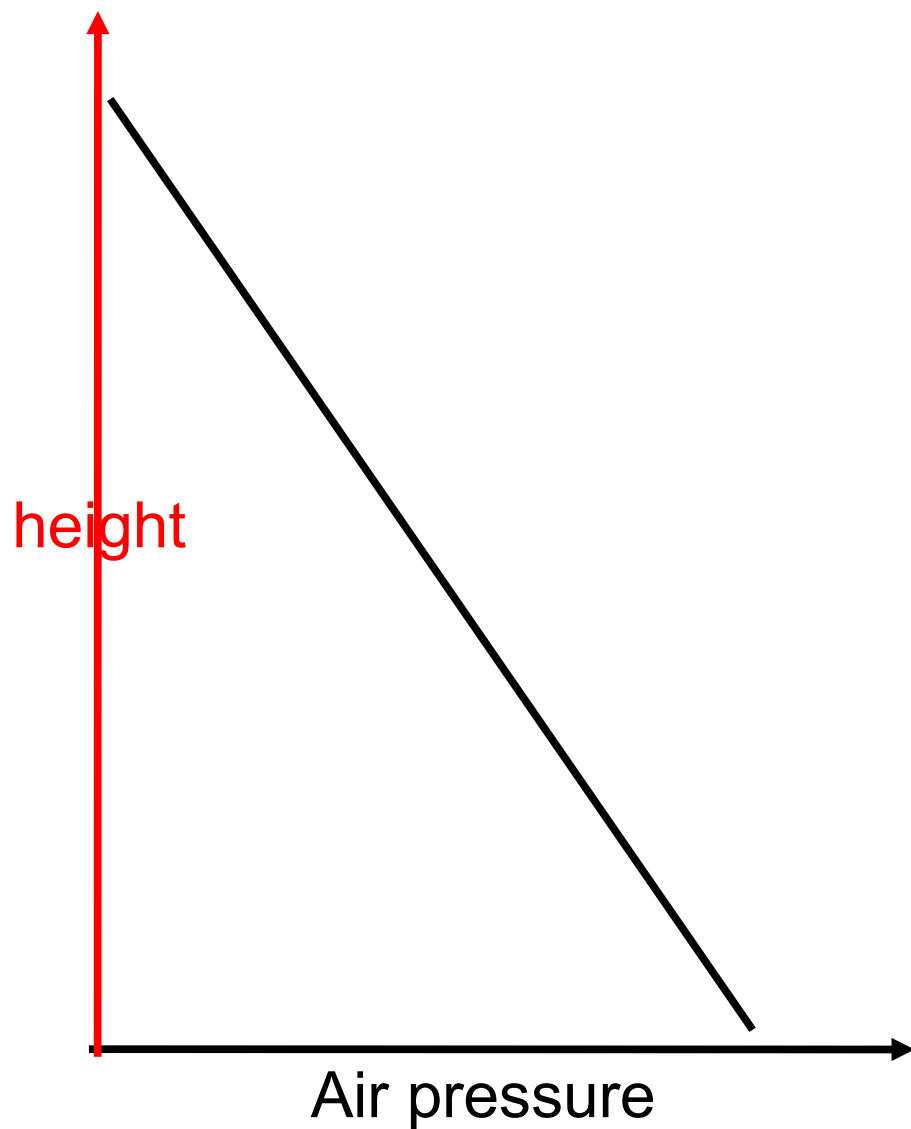
Measurements show count rate increases with height.

Air pressure decreases with height.

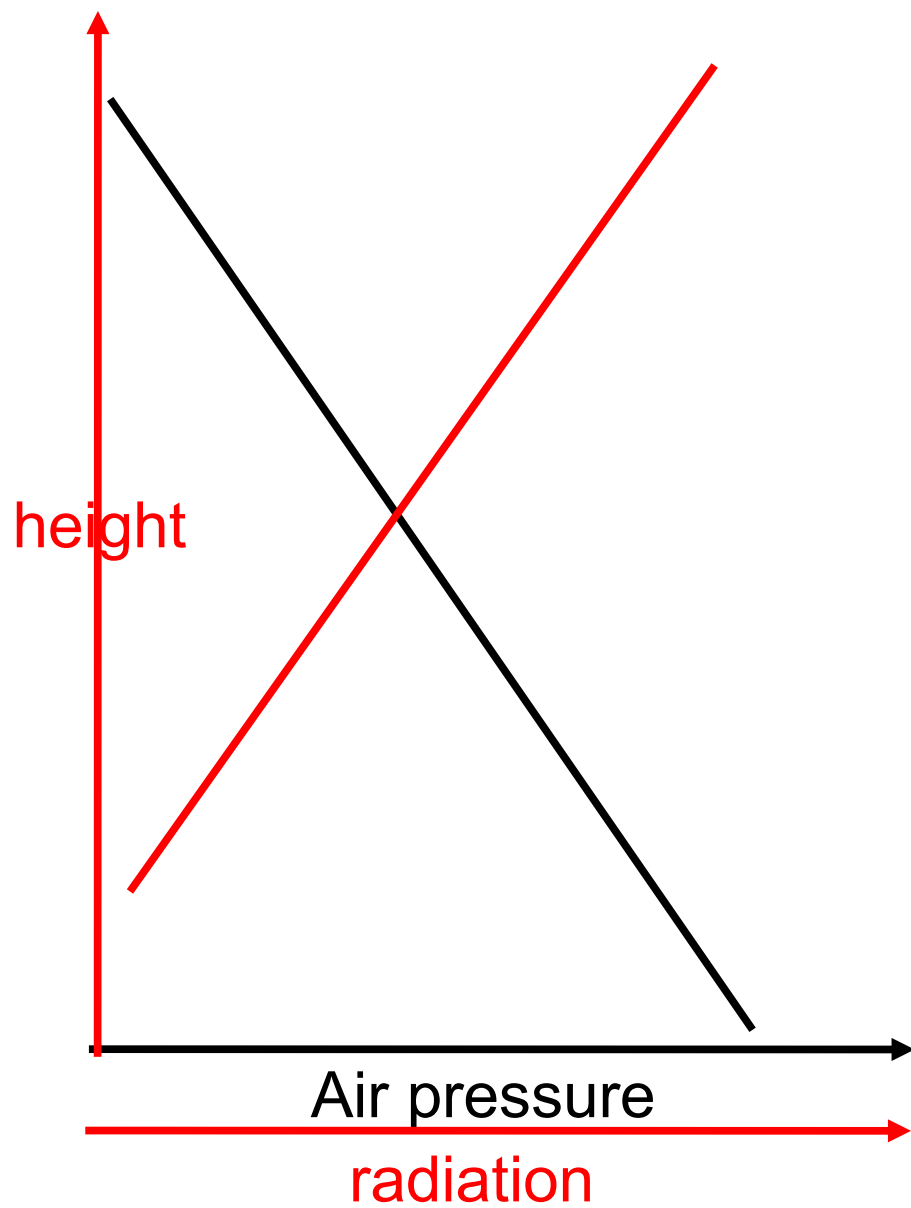
If Earth's radiation were ionizing, count rate should decrease with height because there is less air to ionize.

Can only be explained by ionizing agent coming in from outside the Earth ---> extraterrestrial origin!

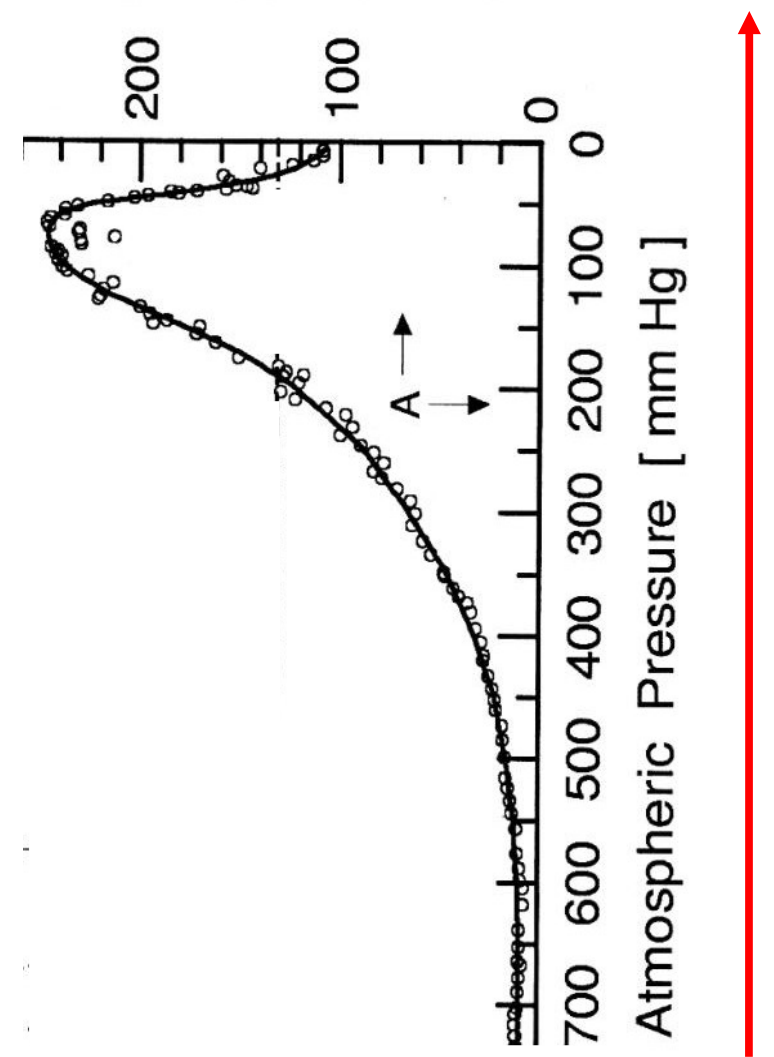




height



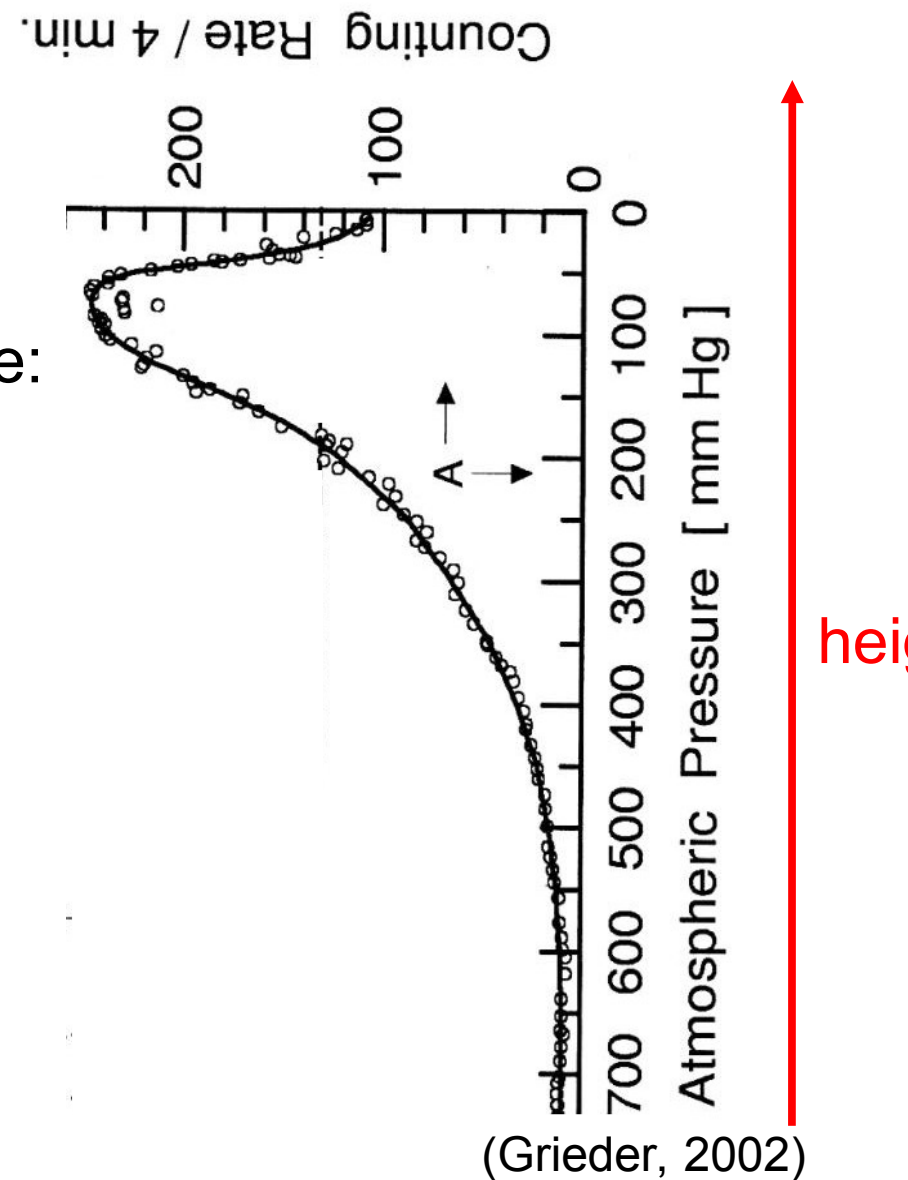
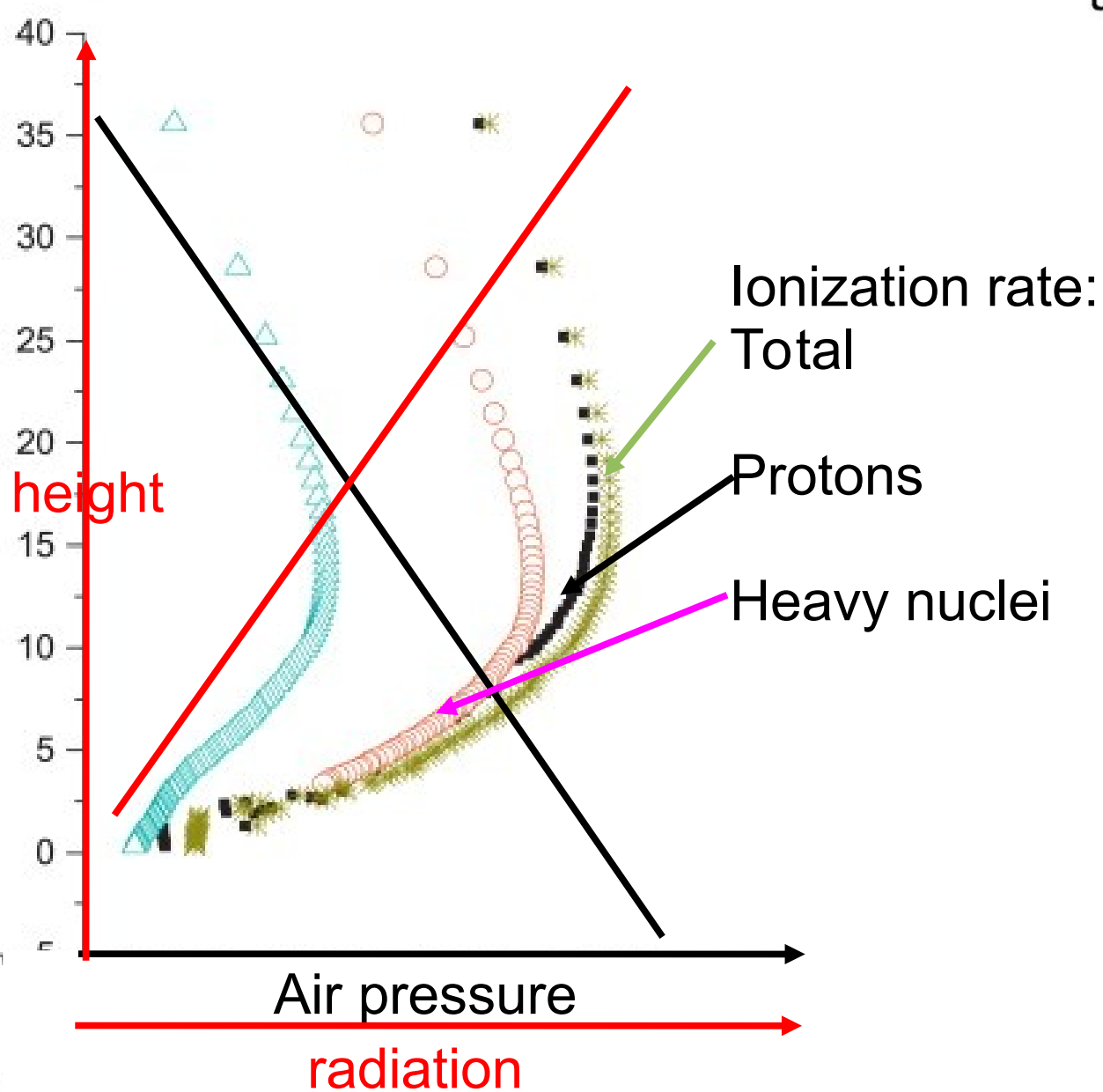
Counting Rate / 4 min.



(Grieder, 2002)

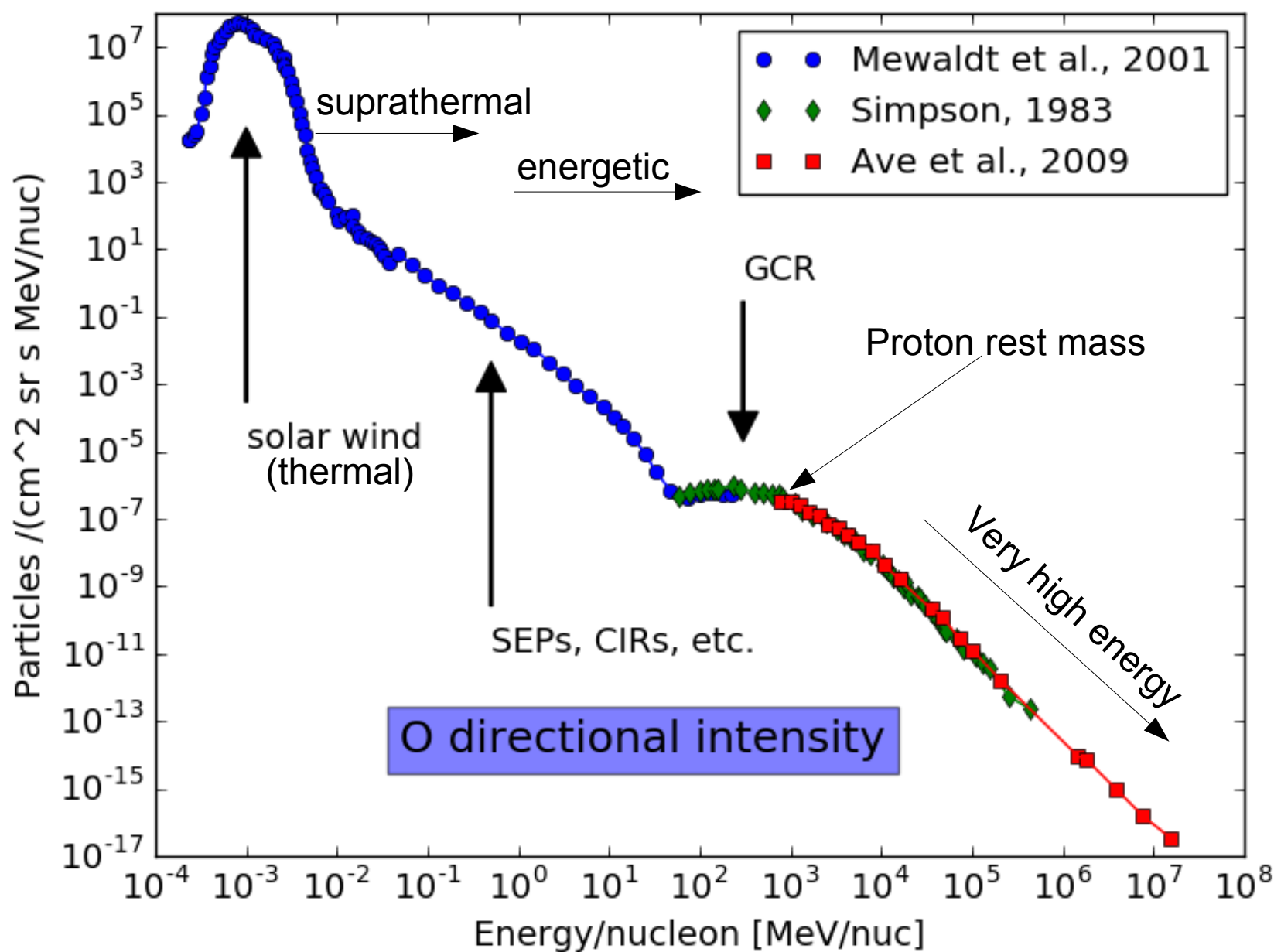


Formation of Pfozter Maximum

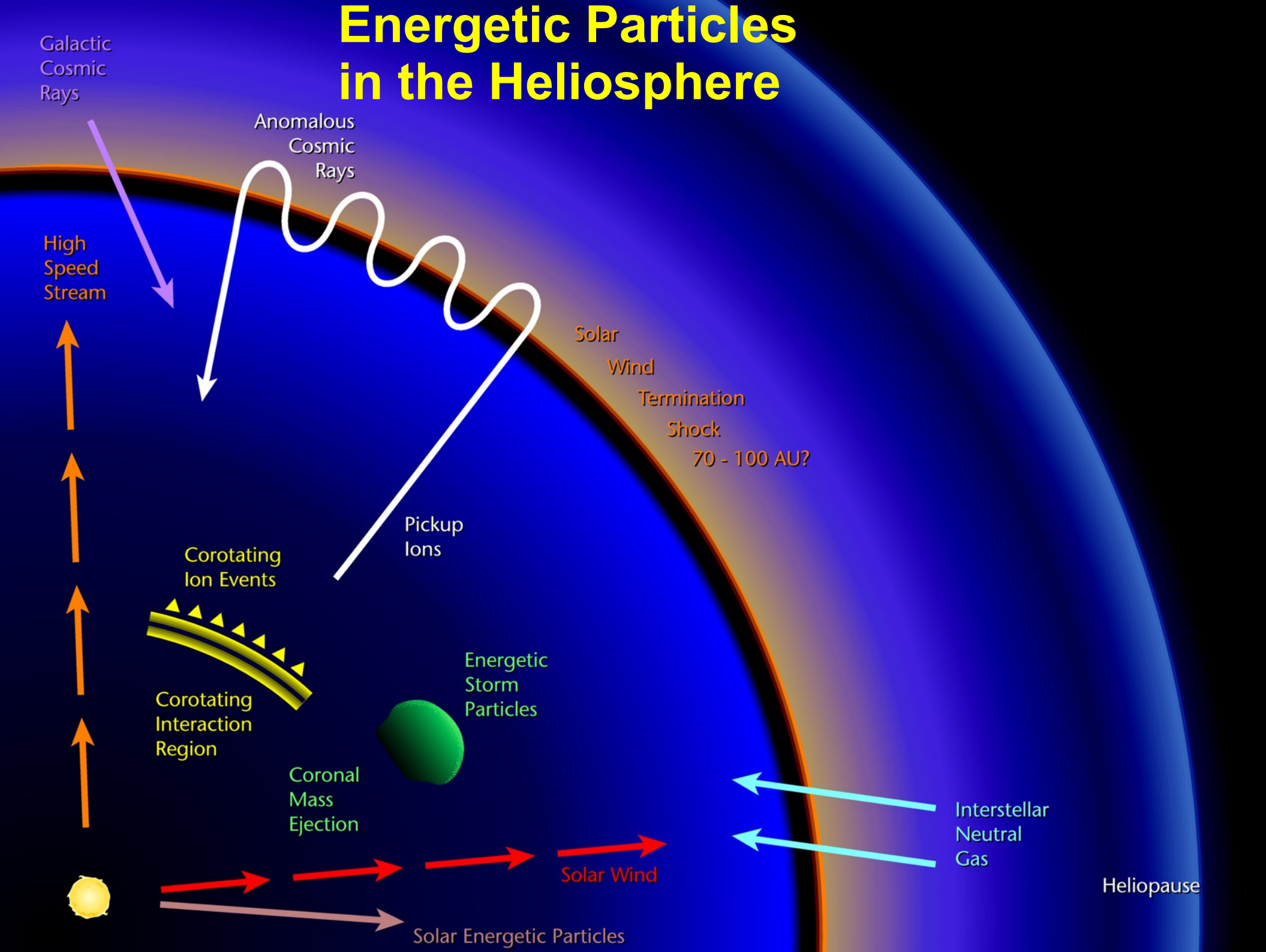


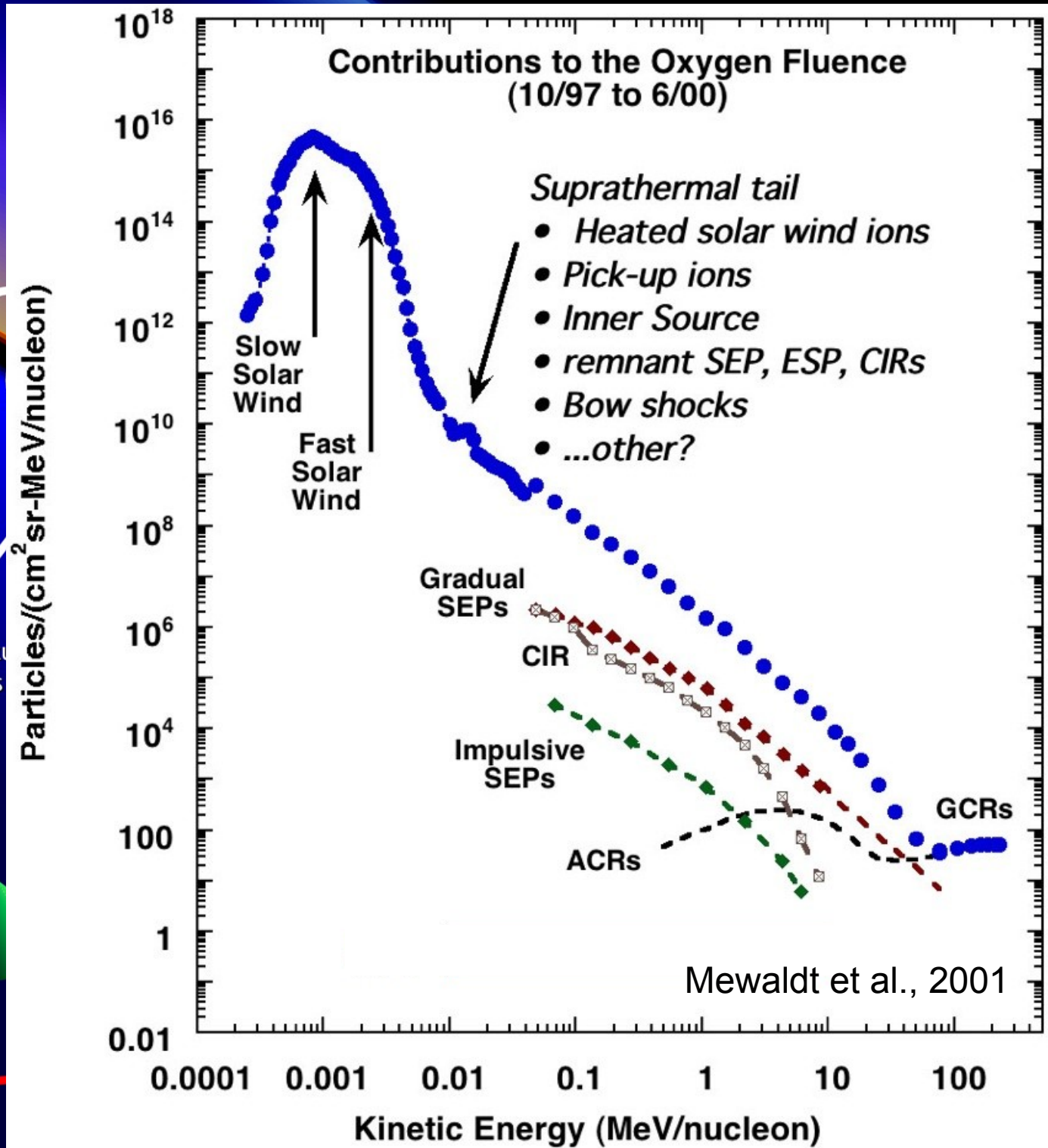
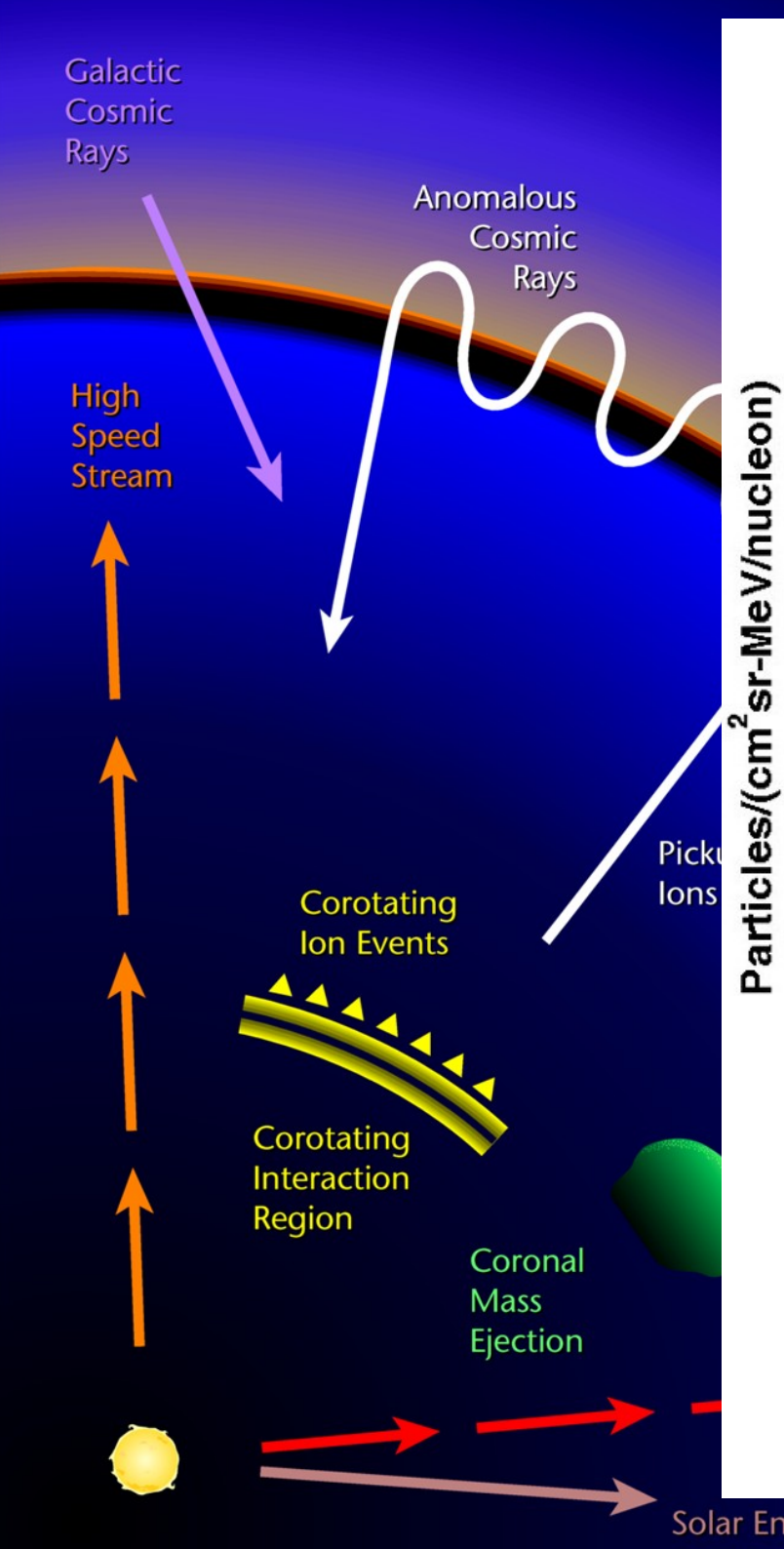


Long-term average of the particle spectrum in the heliosphere



Energetic Particles in the Heliosphere







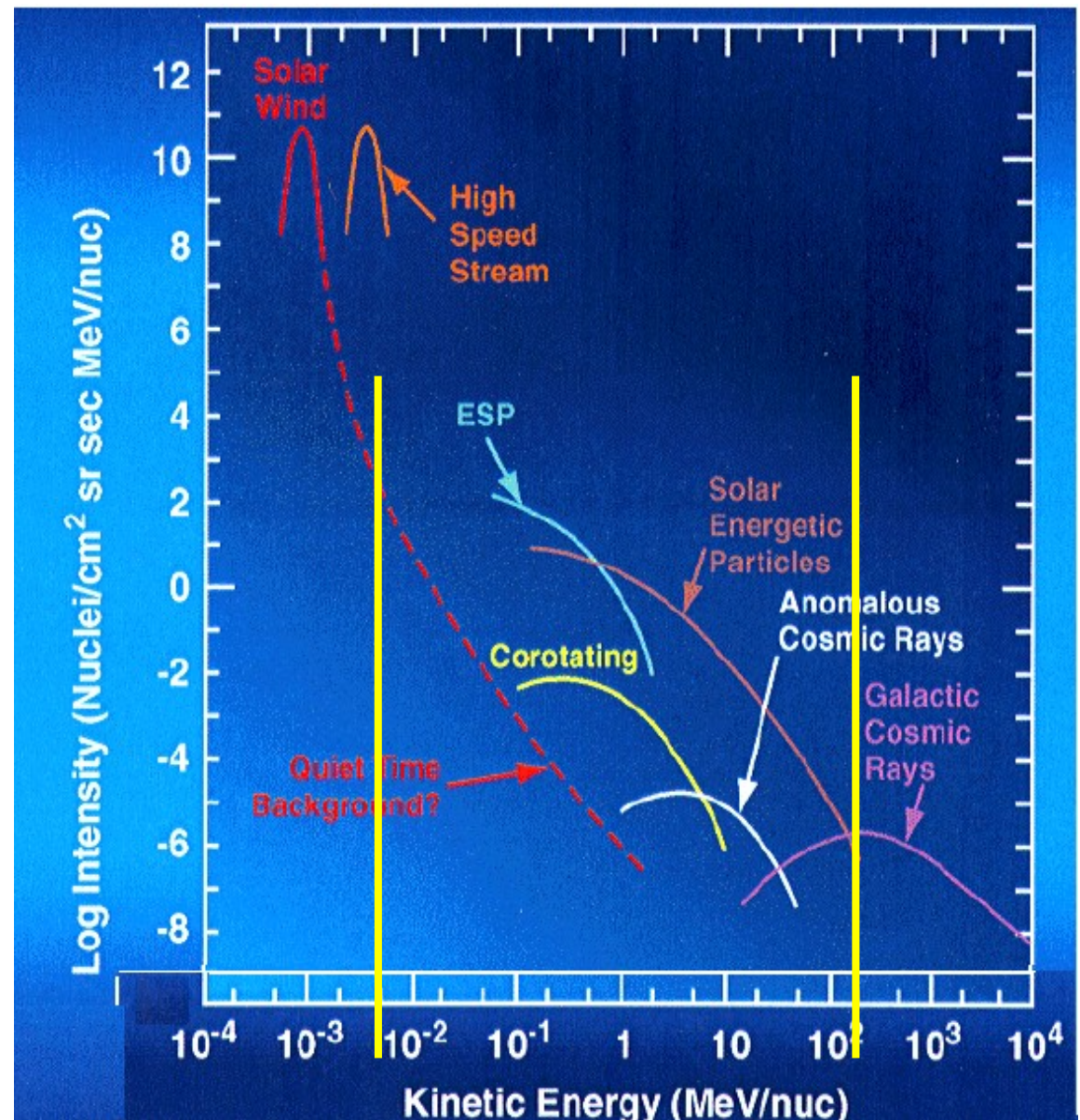
Energetic particles in the Heliosphere

Solar wind thermal particles:
protons, $E < 10$ keV
electrons, ~ 2 eV

Slowly varying Cosmic Rays:
 $\sim 1\text{ GeV} < E < 10$ PeV

Recurrent weak Co-rotating
Interaction Region (CIR)
events, ~ 27 -day periodicity:
 $E < \sim 10$ MeV

SEPs: protons, electrons, and
a small fraction of heavy ions:
 ~ 20 keV $< E < 2$ GeV





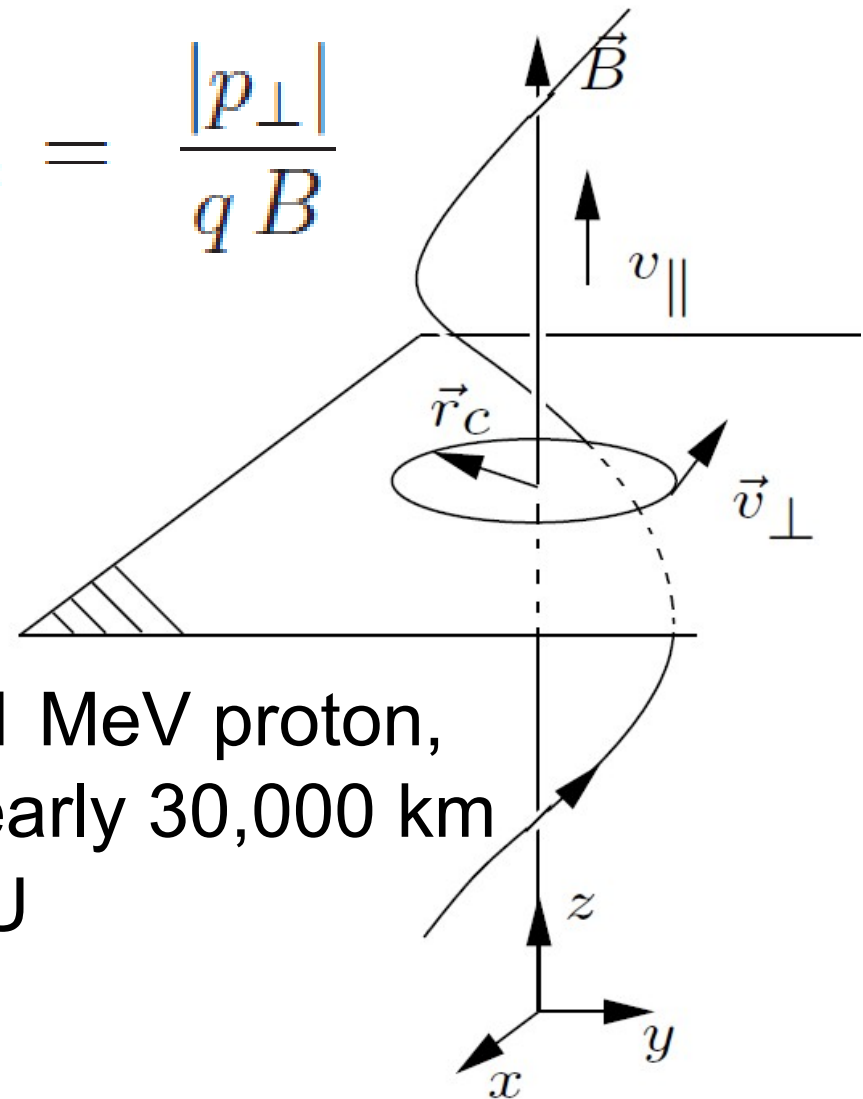
Some important points to remember

- Particles bound to B
- Gyro-radius, r_c
- Pitch angle α
- Gyrofrequency $\vec{\Omega} \doteq \frac{-q}{m\gamma} \vec{B}$
where

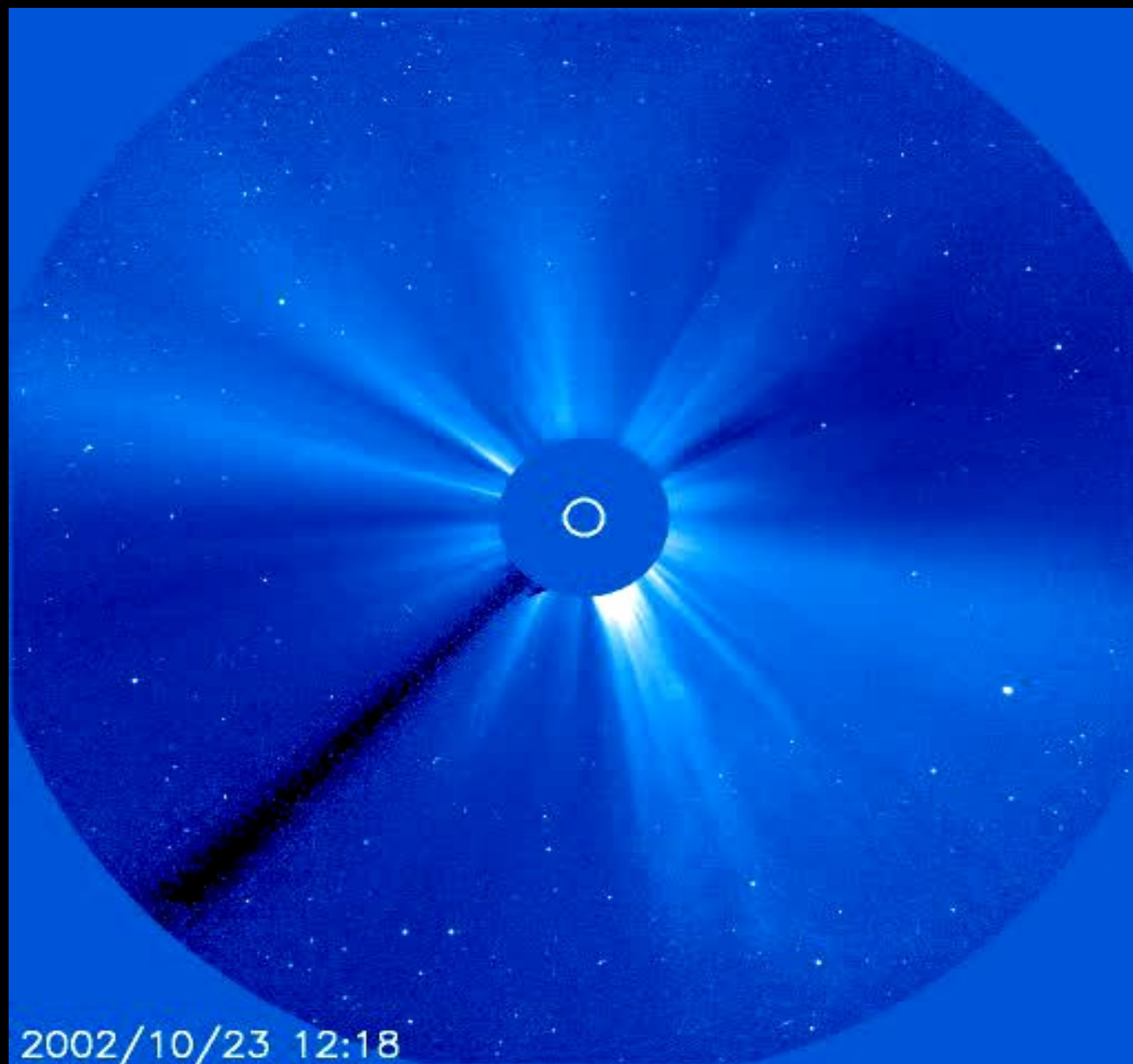
$$\gamma \doteq \frac{1}{\sqrt{1 - v^2 / c^2}}$$

- Rigidity $c B r_c = \frac{p c}{q}$

$$r_c = \frac{|p_{\perp}|}{q B}$$



For a 1 MeV proton,
 r_c is nearly 30,000 km
at 1 AU



2002/10/23 12:18



Solar Wind Primer:

Fast solar wind from coronal holes

Fairly uniform but strong turbulence, „young“ SW

Slow solar wind from unknown regions in streamer belt

Highly variable, dynamically „old“

Active regions, interchange reconnection, S-web

(Interplanetary) Coronal Mass ejections **(I)CMEs**

Highly variable but very low turbulence

Magnetic field structured as **Parker spiral**

Stream interaction regions develop as fast wind catches up with slow wind. Shocks develop beyond ~ 2 AU.

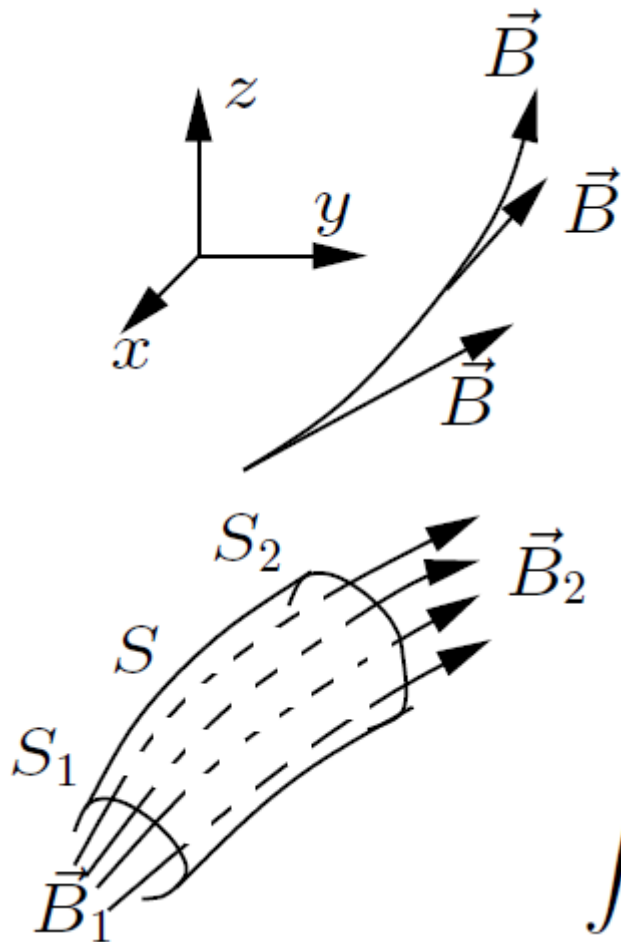


The Magnetic Field in the Solar Wind

We define a fieldline as an entity for which

$$\frac{dx}{B_x} = \frac{dy}{B_y} = \frac{dz}{B_z}$$

We define a flux tube as an entity for which the enclosed magnetic flux is conserved.



$$F_m = \int_S \vec{B} \cdot d\vec{S} = \text{const.} \quad (*)$$

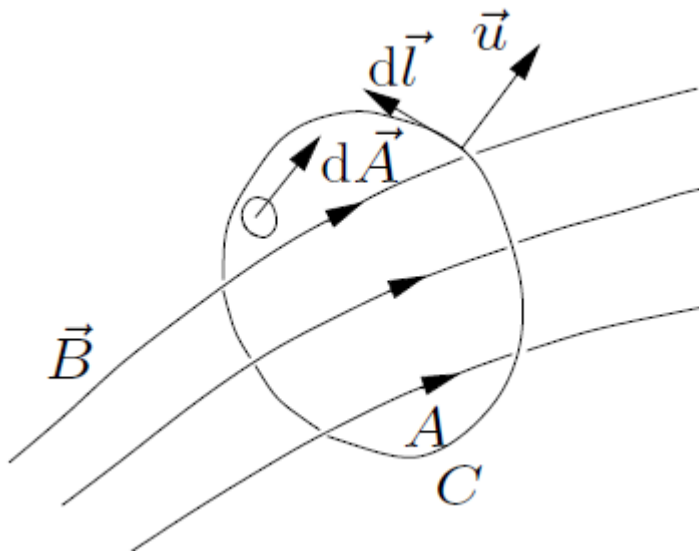
Because $\vec{B} \cdot d\vec{S} = 0$ for surface S,

$$\int_S \vec{B} \cdot d\vec{S} = \int_{S_1} \vec{B} \cdot d\vec{S} + \int_{S_2} \vec{B} \cdot d\vec{S},$$

But $\int_S \vec{B} \cdot d\vec{S} = \int_V \vec{\nabla} \cdot \vec{B} dV$, vanishes, which proves (*).



The Frozen-in Magnetic Field



For the well-conducting solar wind, the MHD induction equation,

$$\dot{\vec{B}} = \vec{\nabla} \times \vec{u} \times \vec{B} + \frac{1}{\mu_0 \sigma} \Delta \vec{B},$$

turns into

$$\dot{\vec{B}} = \vec{\nabla} \times \vec{u} \times \vec{B}, \text{ which means}$$

that the flux through C does not change.

There are two ways in which the flux through C could change:

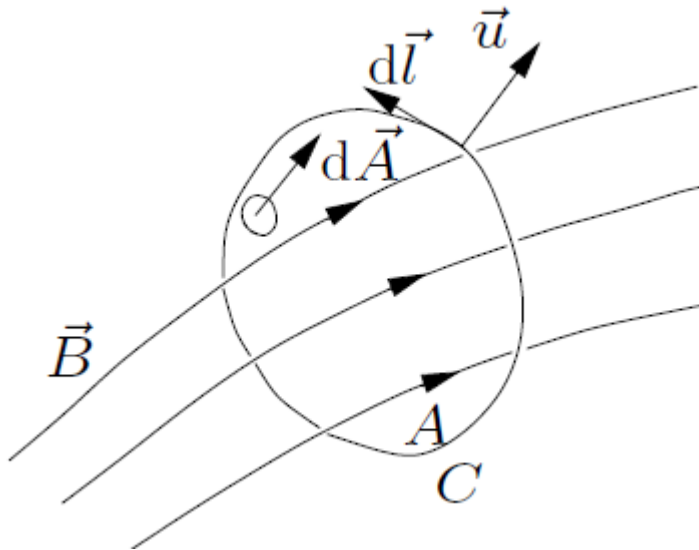
- The field, B, within C changes,
- The curve C moves with respect to B

For the first possibility we get

$$\dot{\vec{B}} \cdot d\vec{A} \xrightarrow{\text{Integration over A}} \int_A \partial_t \vec{B} \cdot d\vec{A}$$



The Frozen-in Magnetic Field II



For the second case, we consider the infinitesimal displacement of curve C. The infinitesimal change in the flux is

$$\vec{B} \cdot (\vec{u} \times d\vec{l})$$

The full change in flux is obtained by integration along C. Using the identity

$$A \cdot (B \times C) = (A \times B) \cdot C$$

we get

$$\frac{d}{dt} \int_A d\vec{A} \cdot \vec{B} = \int_A d\vec{A} \cdot \frac{\partial \vec{B}}{\partial t} - \oint_C d\vec{l} \cdot (\vec{u} \times \vec{B})$$

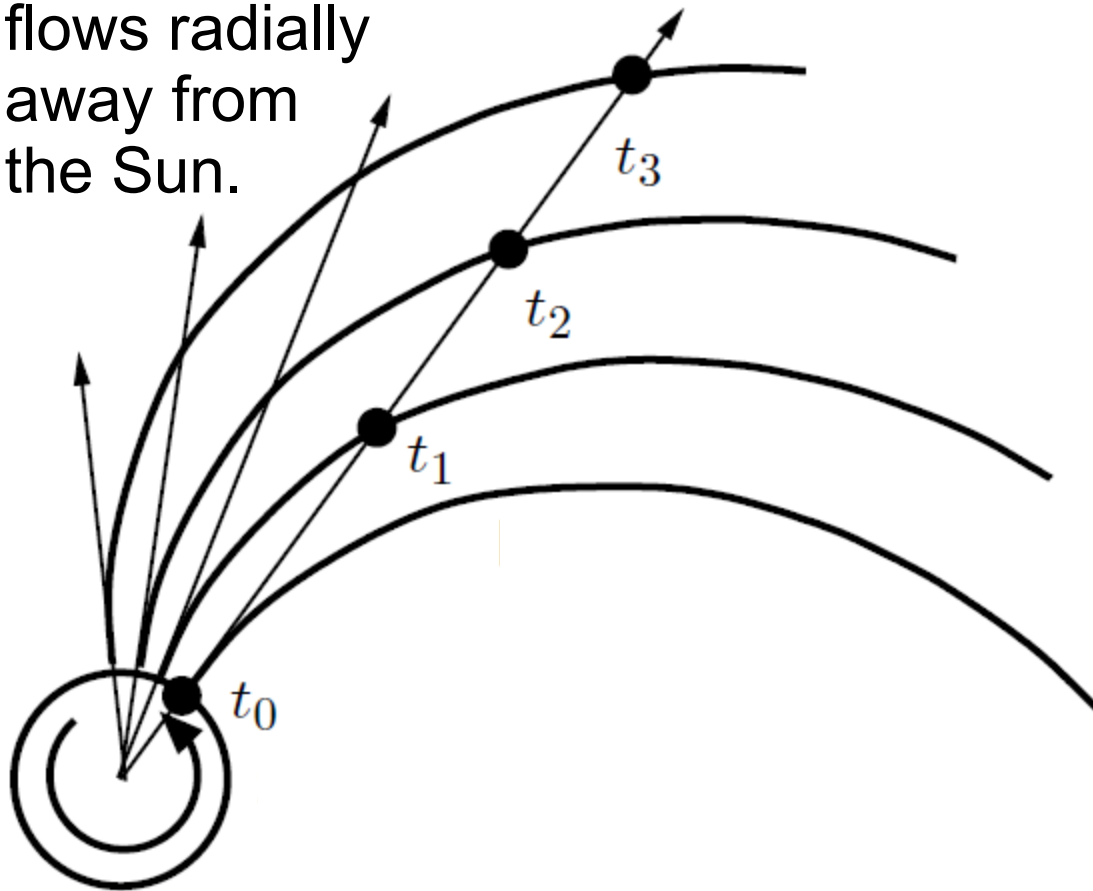
Using Stokes' theorem, we have the induction equation in integral, so

$$\frac{d}{dt} \int_A d\vec{A} \cdot \vec{B} = \int_A d\vec{A} \cdot \left(\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{u} \times \vec{B}) \right) = 0. \text{ QED}$$



The Heliospheric Magnetic Field

Solar wind
flows radially
away from
the Sun.



Radially expanding solar wind
pulls along the frozen-in
magnetic field.

This results in the formation
of an Archimedean spiral.

In honor of Eugene Parker
this is called the Parker spiral.



The Parker Spiral

Then the behavior of the heliospheric field is determined by the flow of the solar wind.
In a frame co-rotating with the Sun:

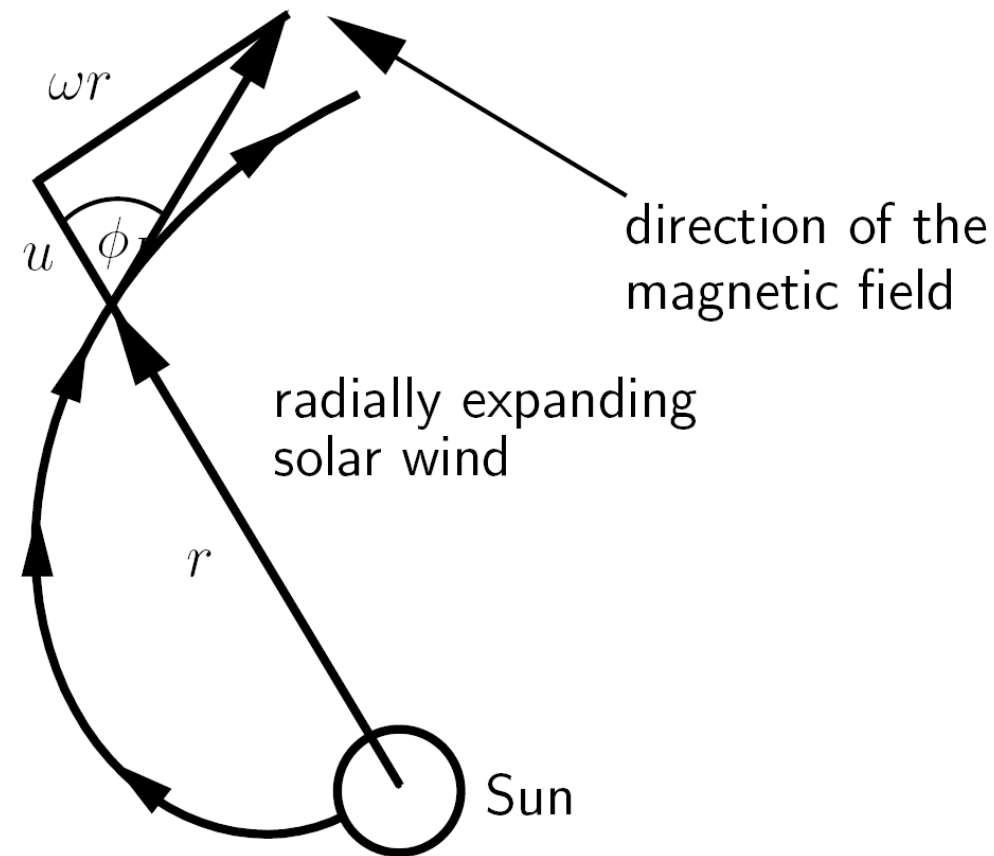
$$u_r = u,$$

$$u_\phi = -r\omega \sin \theta,$$

$$u_\theta = 0,$$

because the solar wind flows radially outwards from the Sun.

The so-called Parker-angle, ϕ_P , is the angle between the radial and the magnetic field directions.



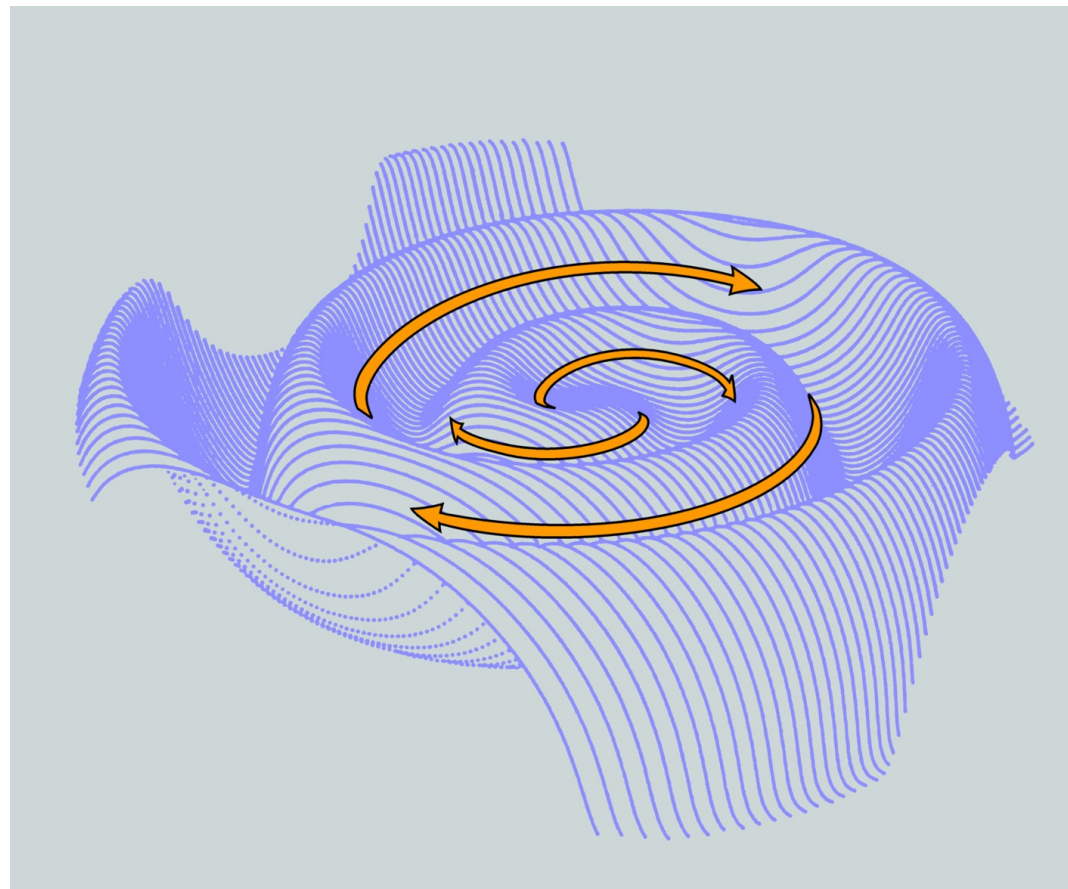
$$\cos^2 (\phi_P) = \frac{1}{1 + \left(\frac{\omega r \sin \theta}{u} \right)^2}$$

(typically about 45° at 1 AU)



The Heliospheric Current Sheet

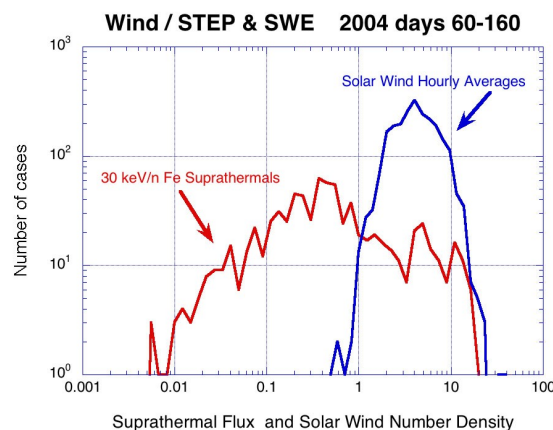
Because the Sun's rotation axis is inclined wrt. ecliptic, a warped current sheet forms. This was coined the „ballerina skirt“ by Alfvén.



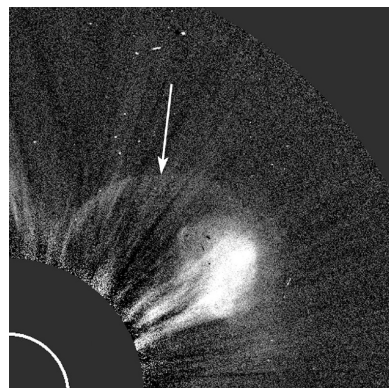


To be an energetic particle, you need to be:

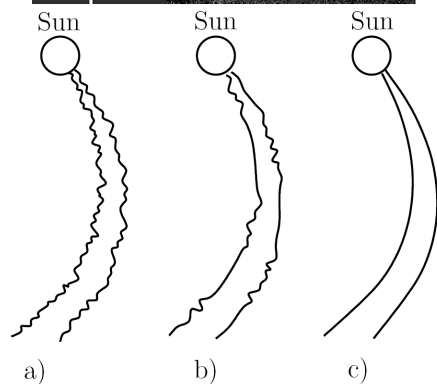
- injected

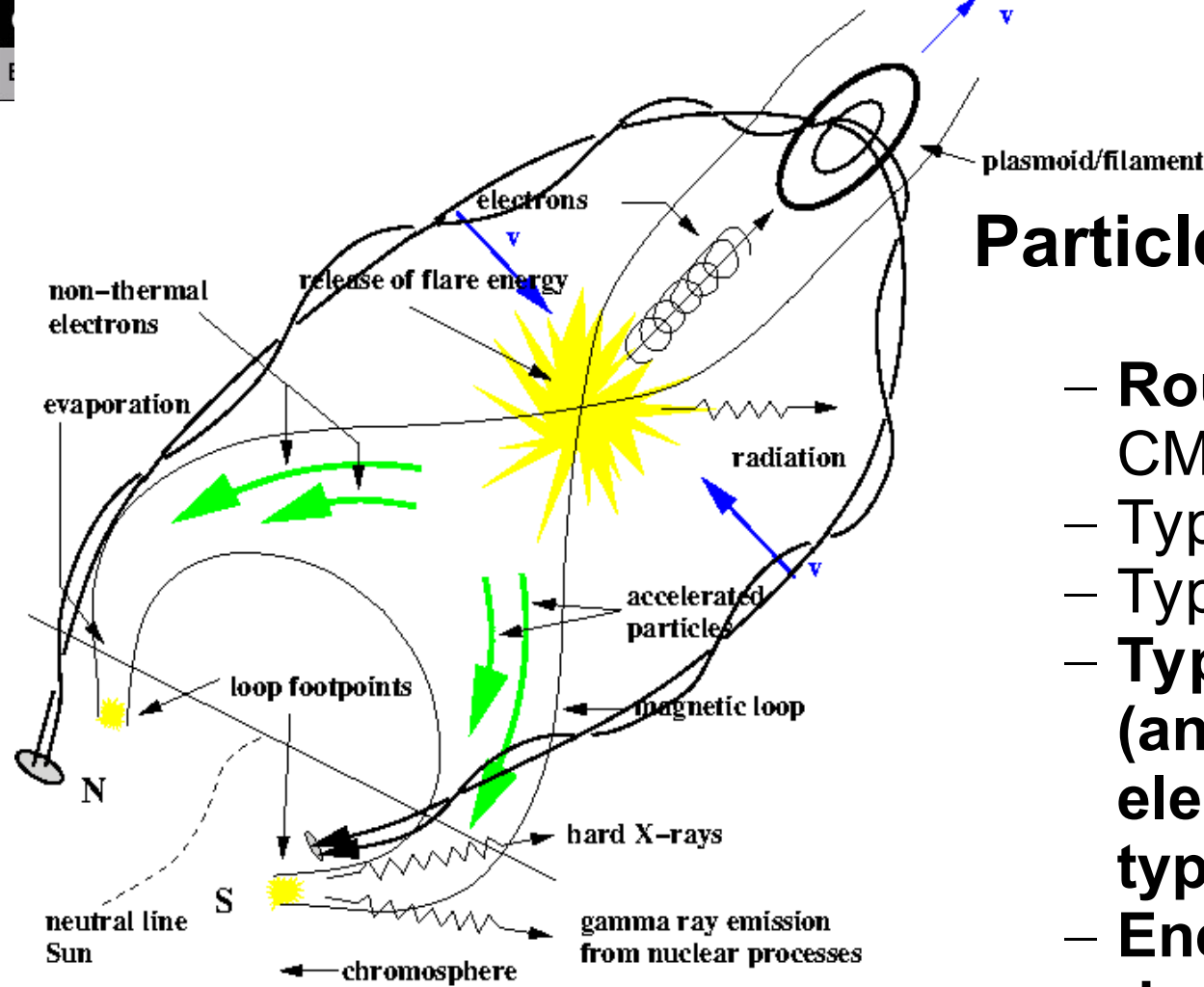
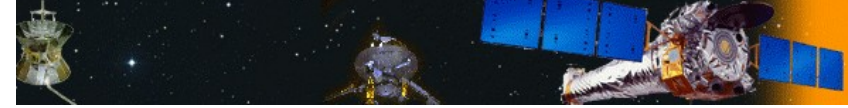


- accelerated



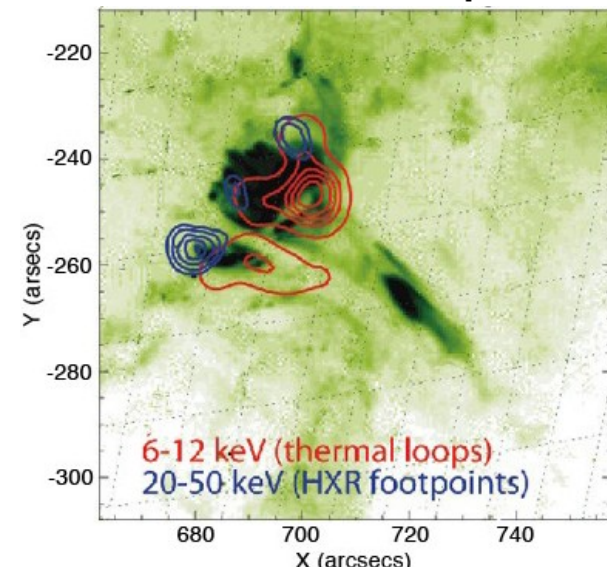
- transported



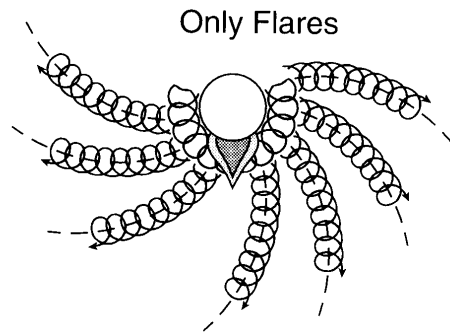


Particle acceleration in flares:

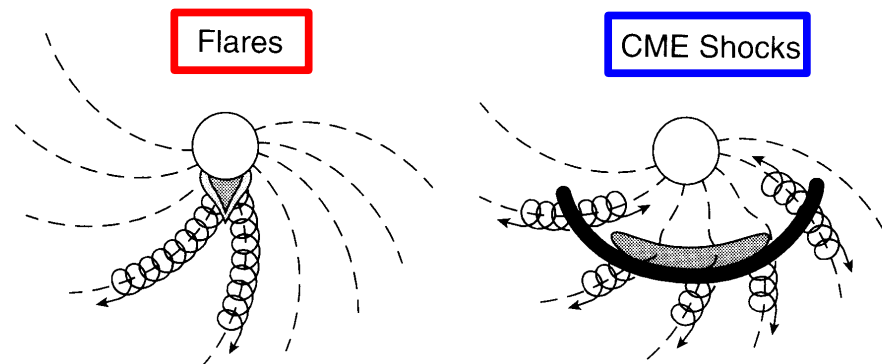
- **Rough** equipartition of flare and CME energy
- Typical duration 10 – 100 s
- Typical energy 10^{23} J
- **Typically between 1% - 10% (and up to 100%) of all electrons are accelerated to typically 100 keV**
- **Energetically these electrons dominate the plasma**
- Ions are also accelerated (and produce gamma rays)
- Occasionally, particles are accelerated to relativistic energies (GLEs).



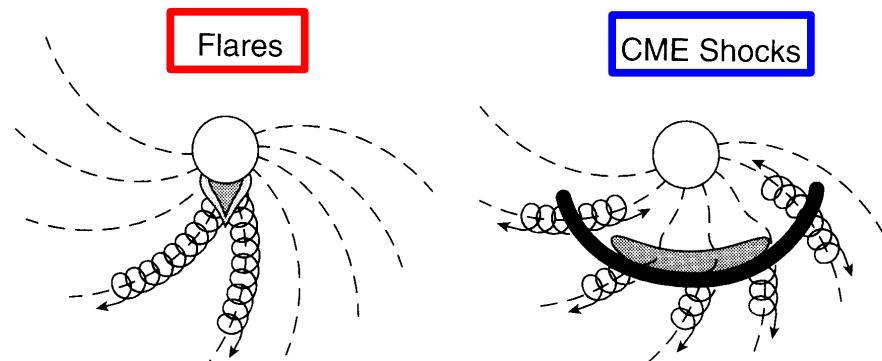
Old Picture:



~~Old~~ new
New Picture:

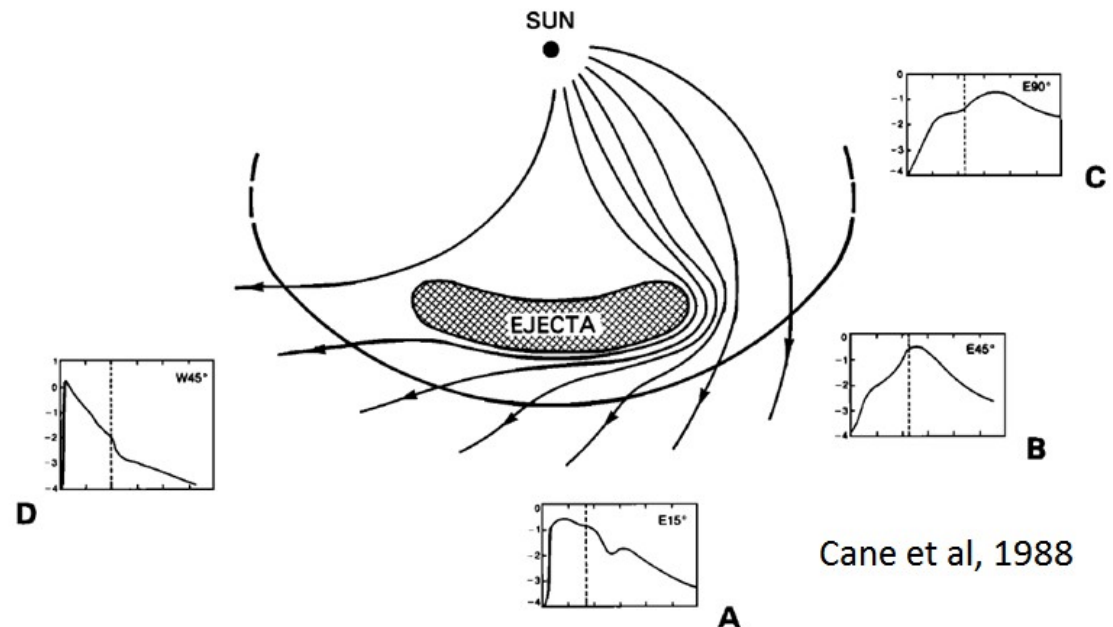


New Picture:



But flares don't rule (alone)!

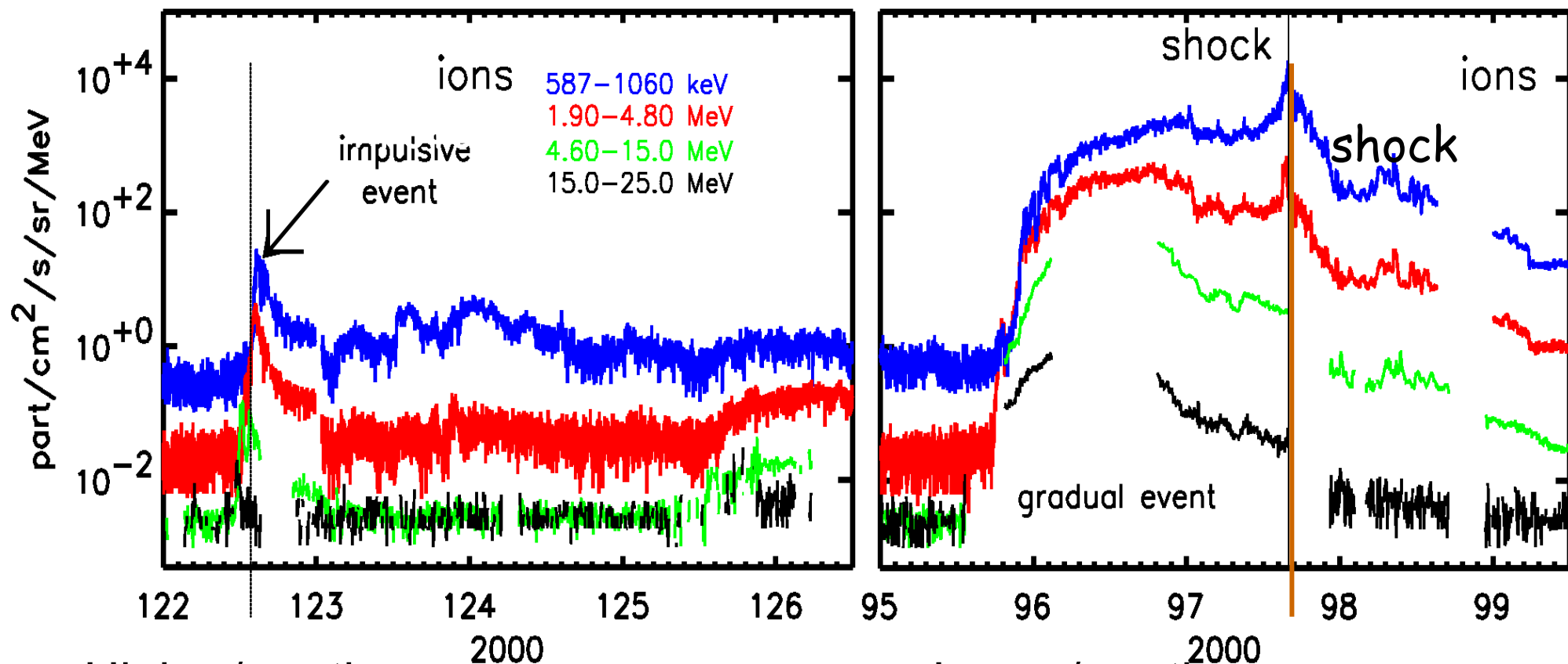
CME-driven shocks play an important role in accelerating particles.



Life is more complicated:
Flares can contribute to shock-accelerated particles. Exact role is current research topic.



Impulsive and Gradual Events

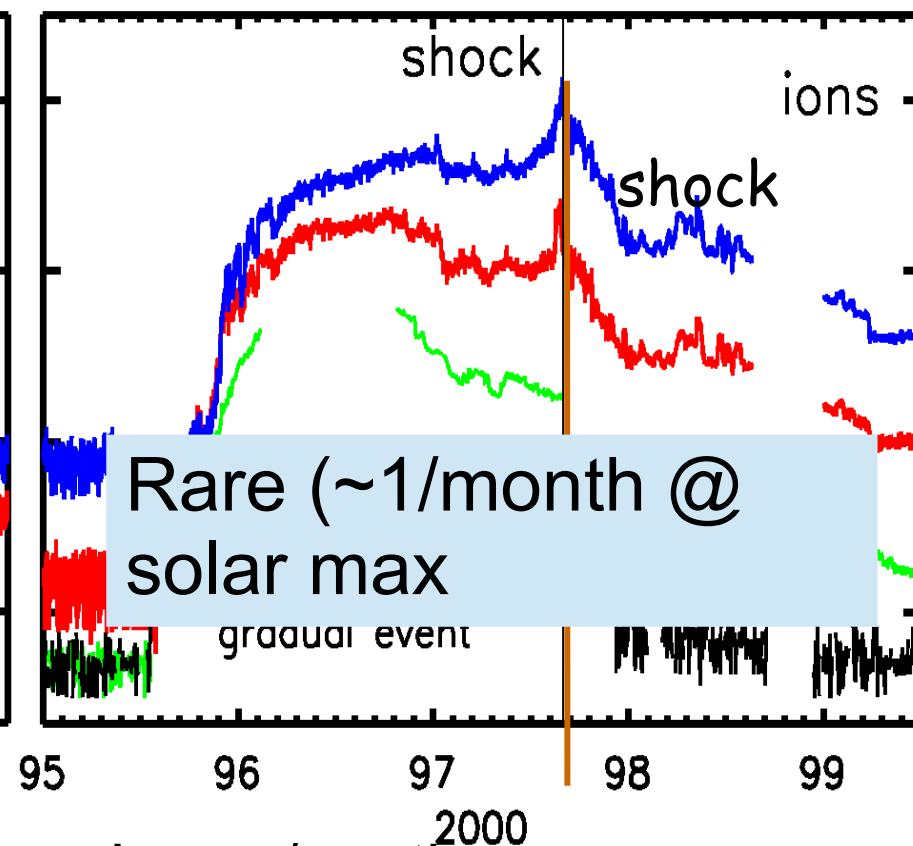
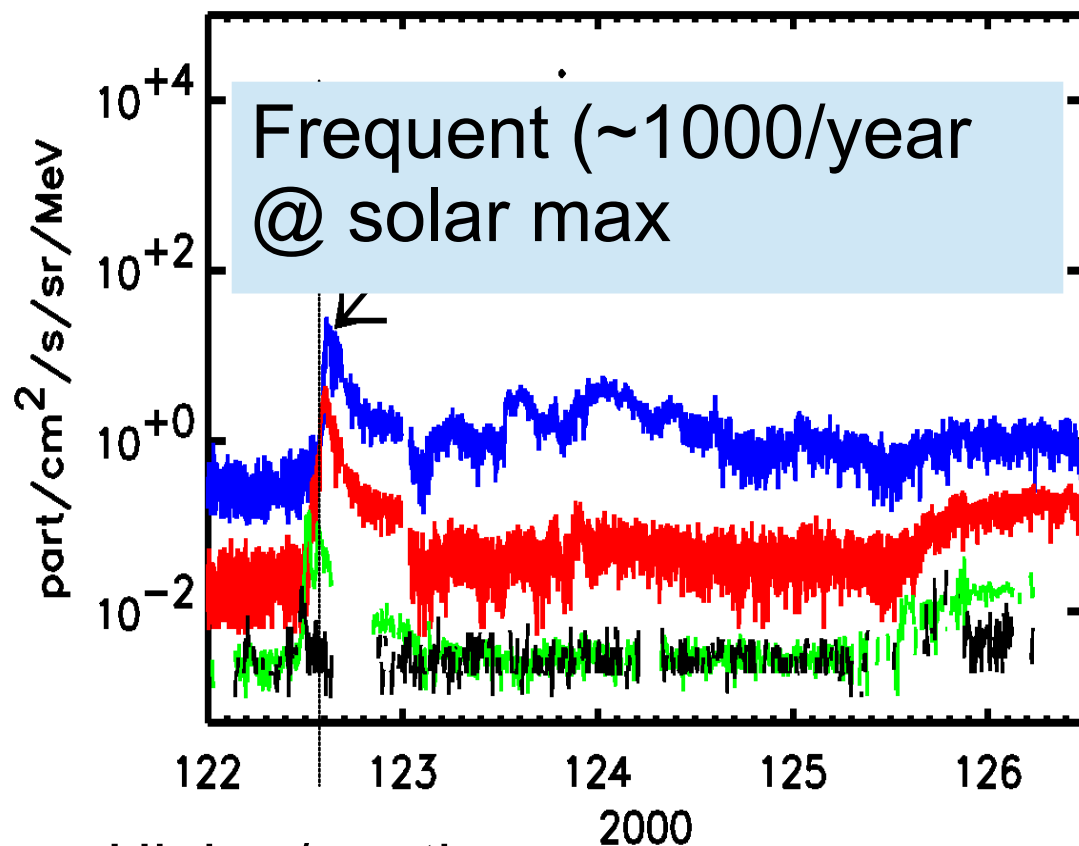


- High e/p ratio
- Mainly low-energy e & p
- Enhanced ³He, α/p, and heavy ions
- High <Q>
- Narrow (~30° longitude)
- Type III radio bursts

- Low e/p ratio,
- variable composition and <Q>
- Rather wide (~100° longitude)
- Large flares and CMEs
- Accelerated by CME shocks



Impulsive and Gradual Events



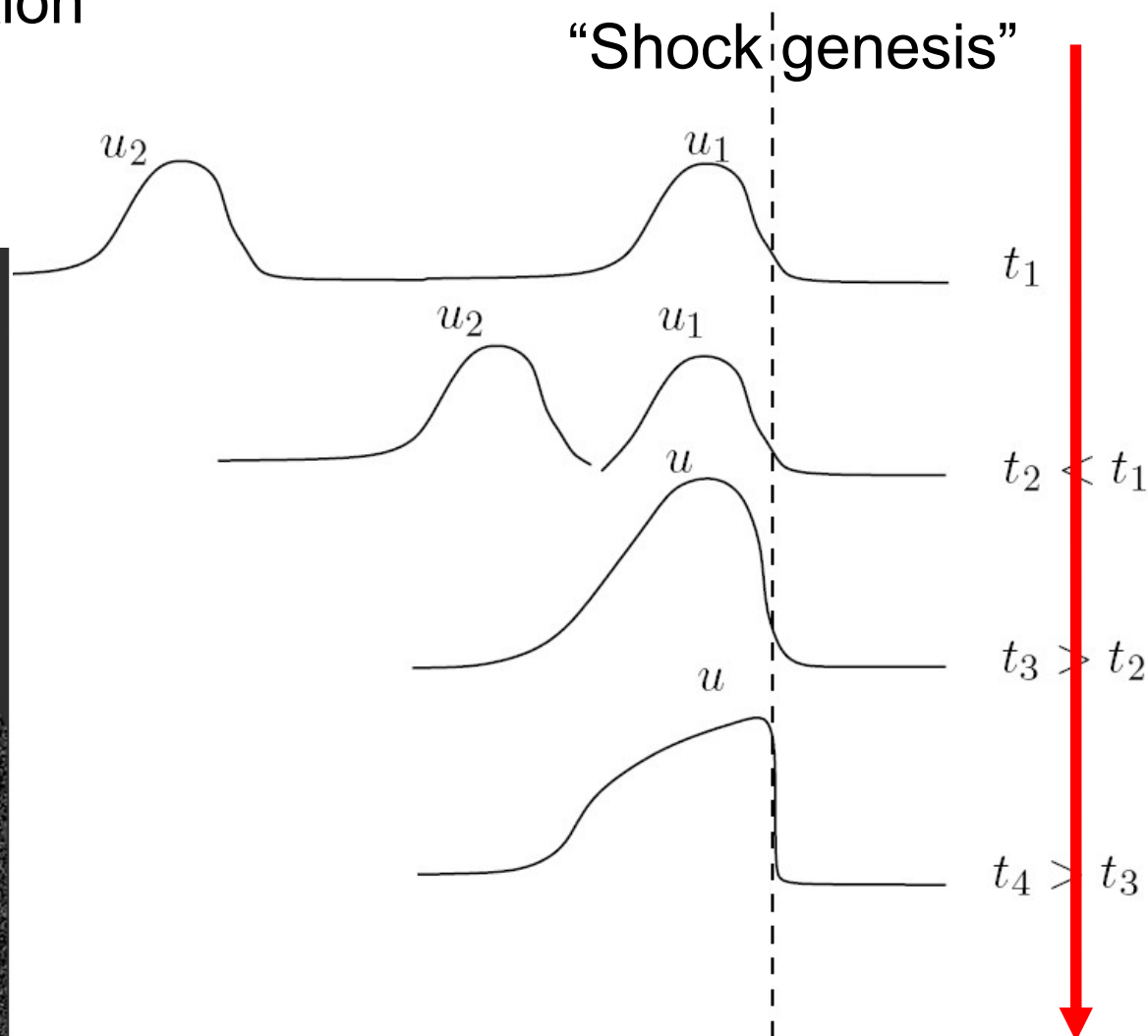
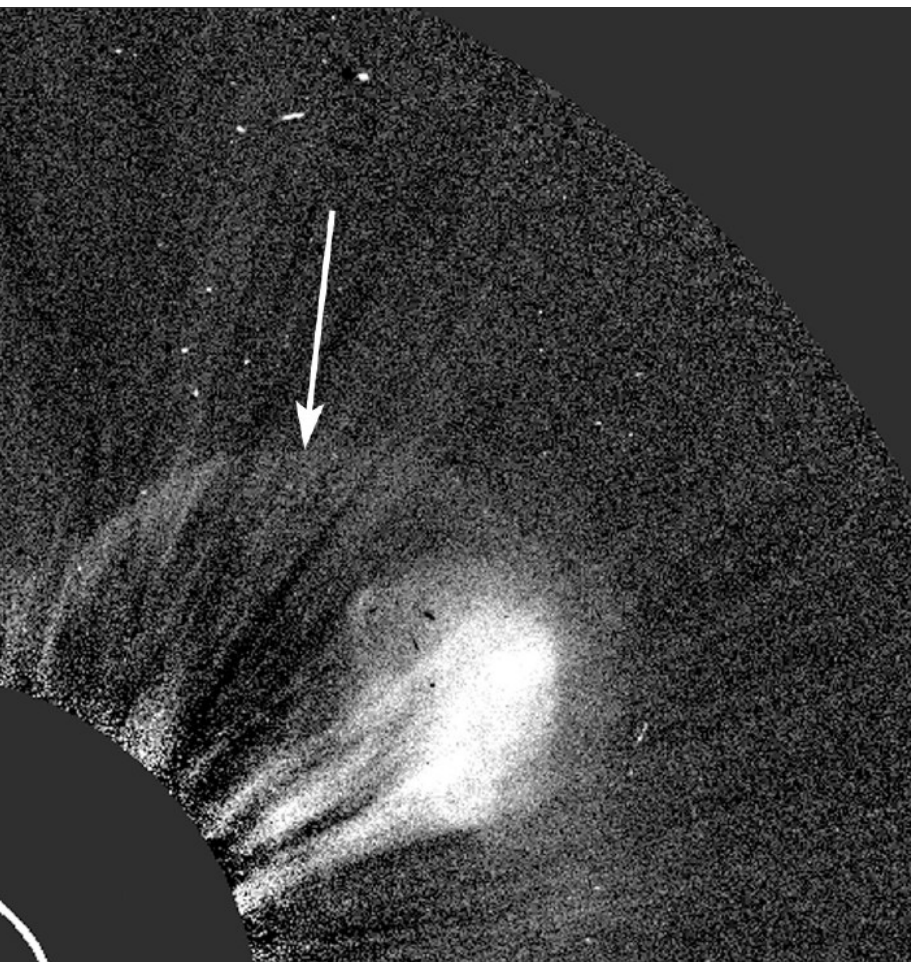
- High e/p ratio
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- variable composition and <Q>
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Shock Acceleration - A more organized way of accelerating particles?

- a.) diffusive shock-acceleration
- b.) shock-drift acceleration





Shock or diffusive (Fermi 2) acceleration

Turbulent structures
moving towards you

stepwise acceleration
via turbulent motions

Some particles gain energy in every reflection
(Fermi acceleration)

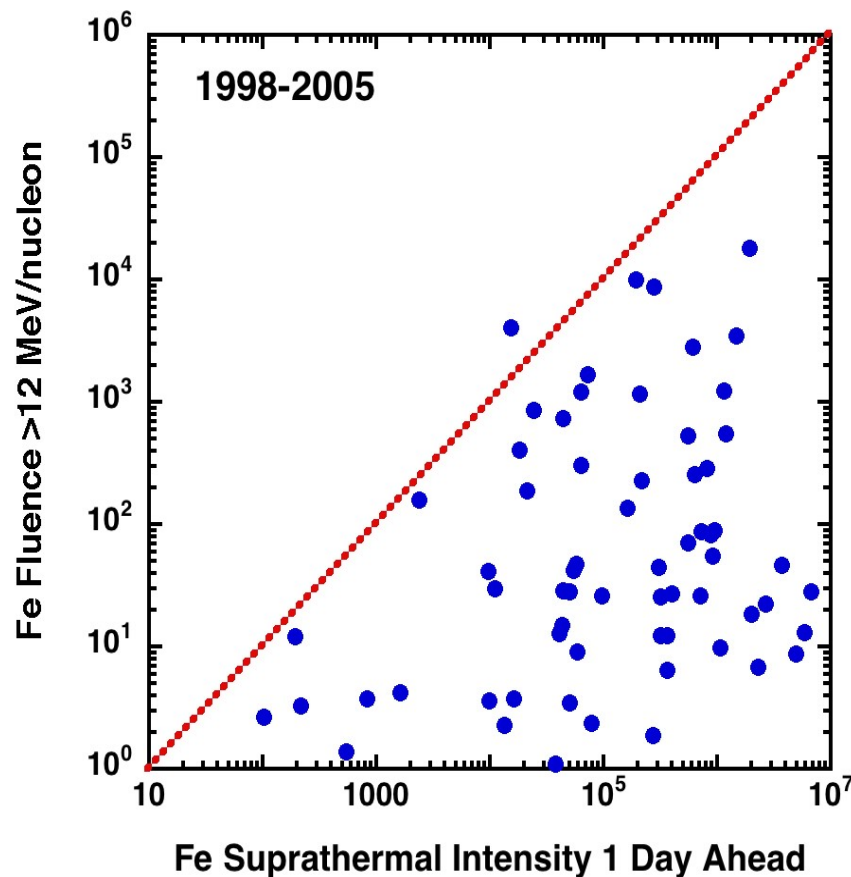
Shock (in fact, any location
with converging turbulence)

This scenario ultimately
leads to the observed
power-law distribution
in energy. If the shock is
large enough, it can
explain large events.

Turbulent structures
moving towards you



Role of suprathermal seed population?



- Diffusive Shock Acceleration, but:
 - Origins of seed populations
 - Proton-amplified waves and turbulence
 - Acceleration efficiencies of CME shocks
 - Shock geometry & variations
- CME shock acceleration efficiencies highly variable

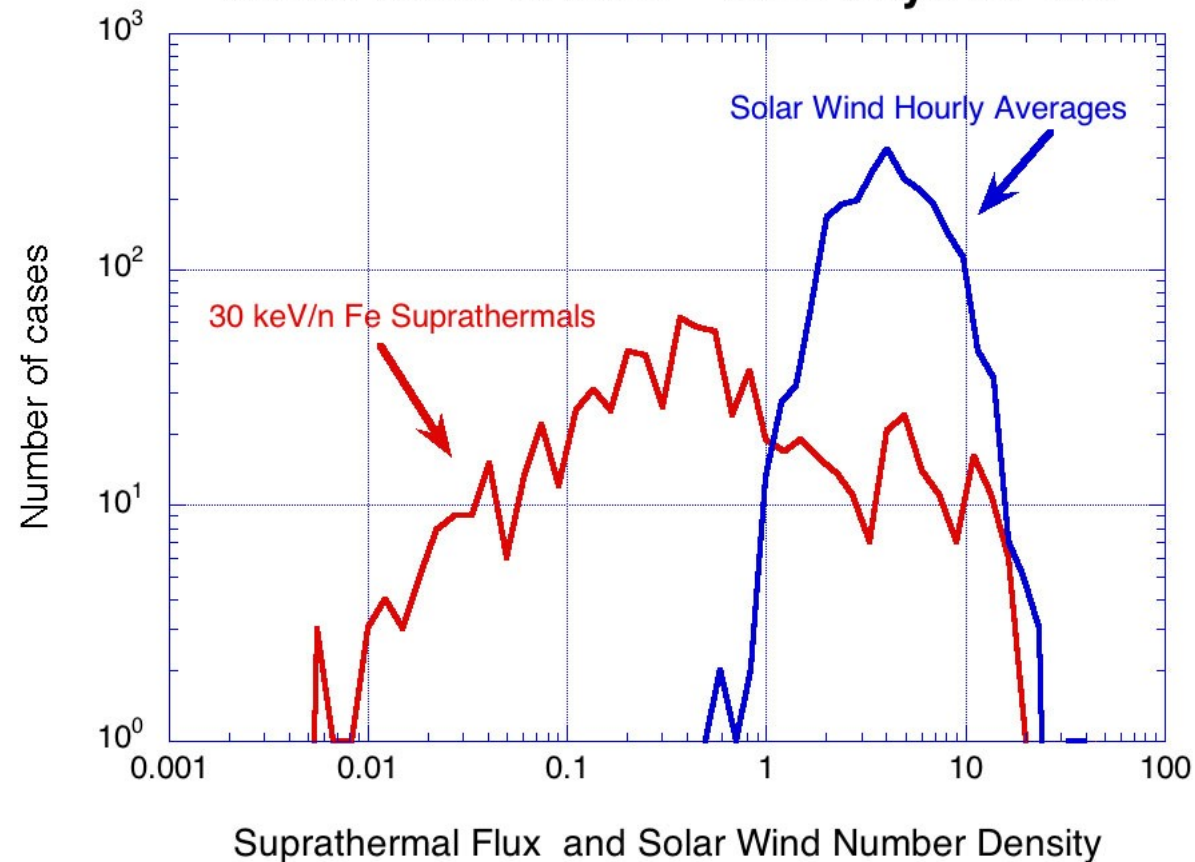
→ **Need near Sun data to resolve different effects and mechanisms**

How does the suprathermal particle population through which a shock moves influence the resulting intensity of energetic particles that are accelerated?



Immense variability in suprathermal heavy ion flux

Wind / STEP & SWE 2004 days 60-160



Peak intensities in shock events vary over a range of $\sim 10^4$

- not explained by CME speed
- not explained by shock acceleration models
- not explained by solar wind number density which does not change nearly as much

(Mason et al., 2005)



Suprathermal particles present most of the time

Flare suprathermals

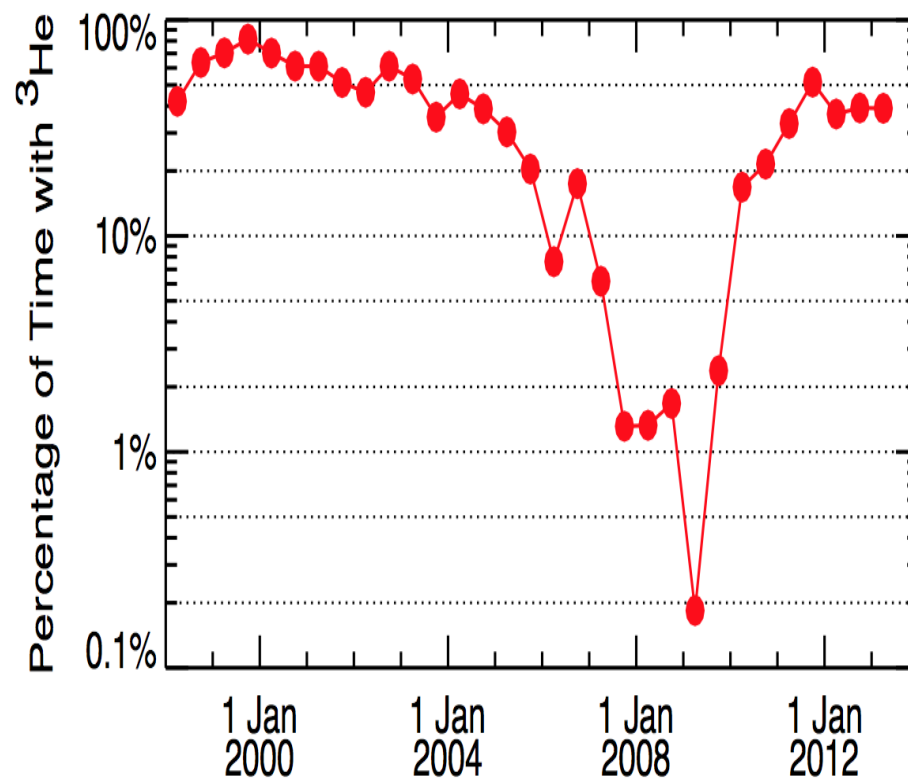
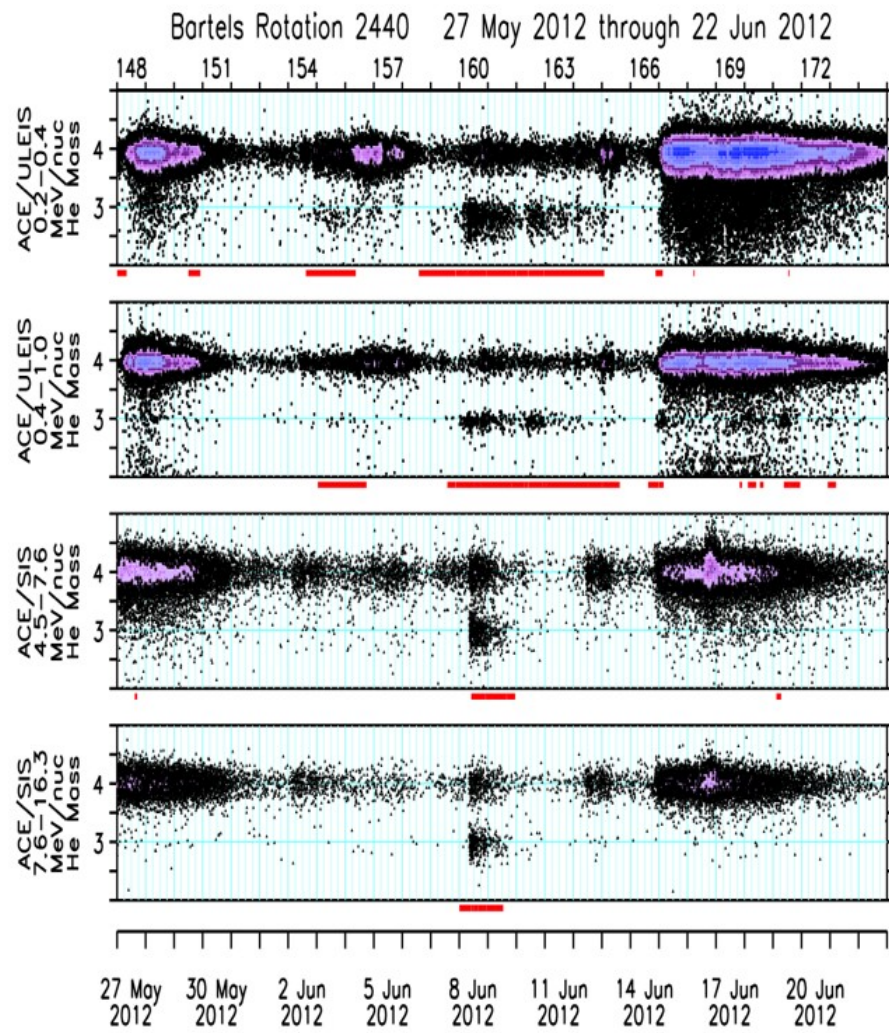


Figure 2. Average percentage of time that ^3He was detected at ACE during each 6-month period from the start of 1998 through mid-2013. All four of the energy intervals illustrated in Fig. 1 were used in identifying times when ^3He was present.

(Wiedenbeck et al., 2014)



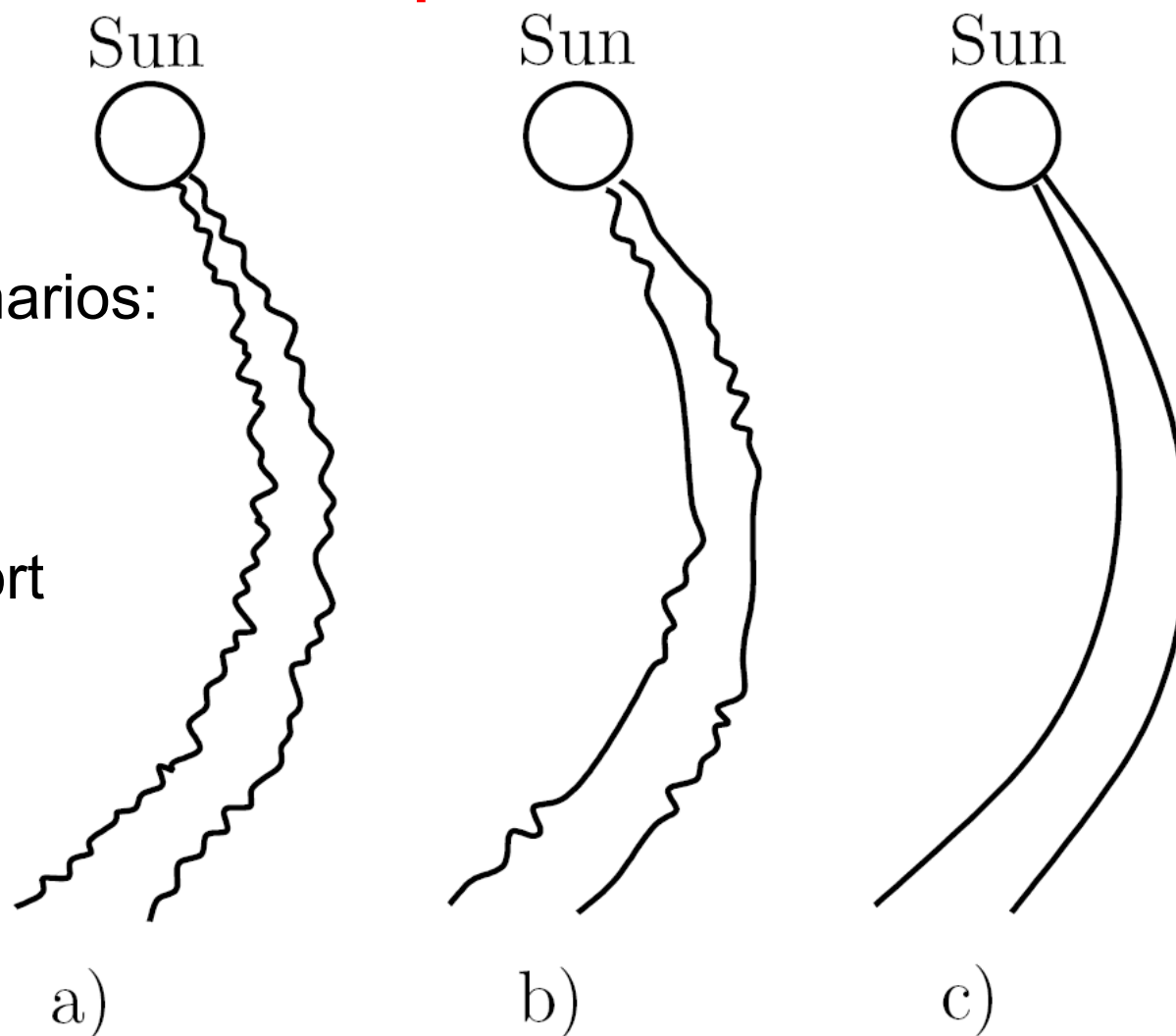
Once accelerated, particles get away, but continue to be scattered, a process called **transport**

Three different scenarios:

a) diffusive

b) focused - transport

c) scatter free



Timing studies are best done with scatter-free events. They can be recognized by beam-like pitch-angle distributions.

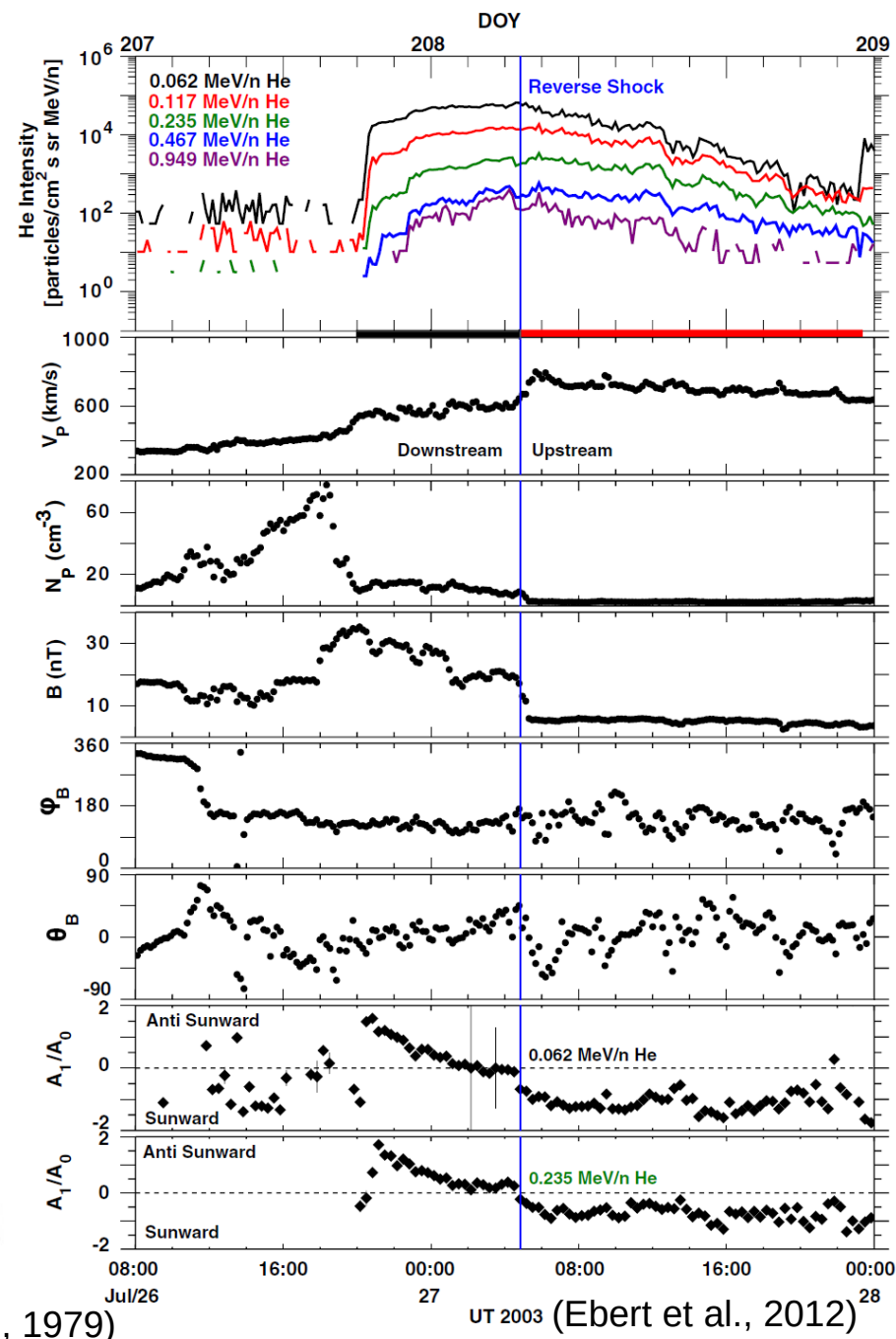
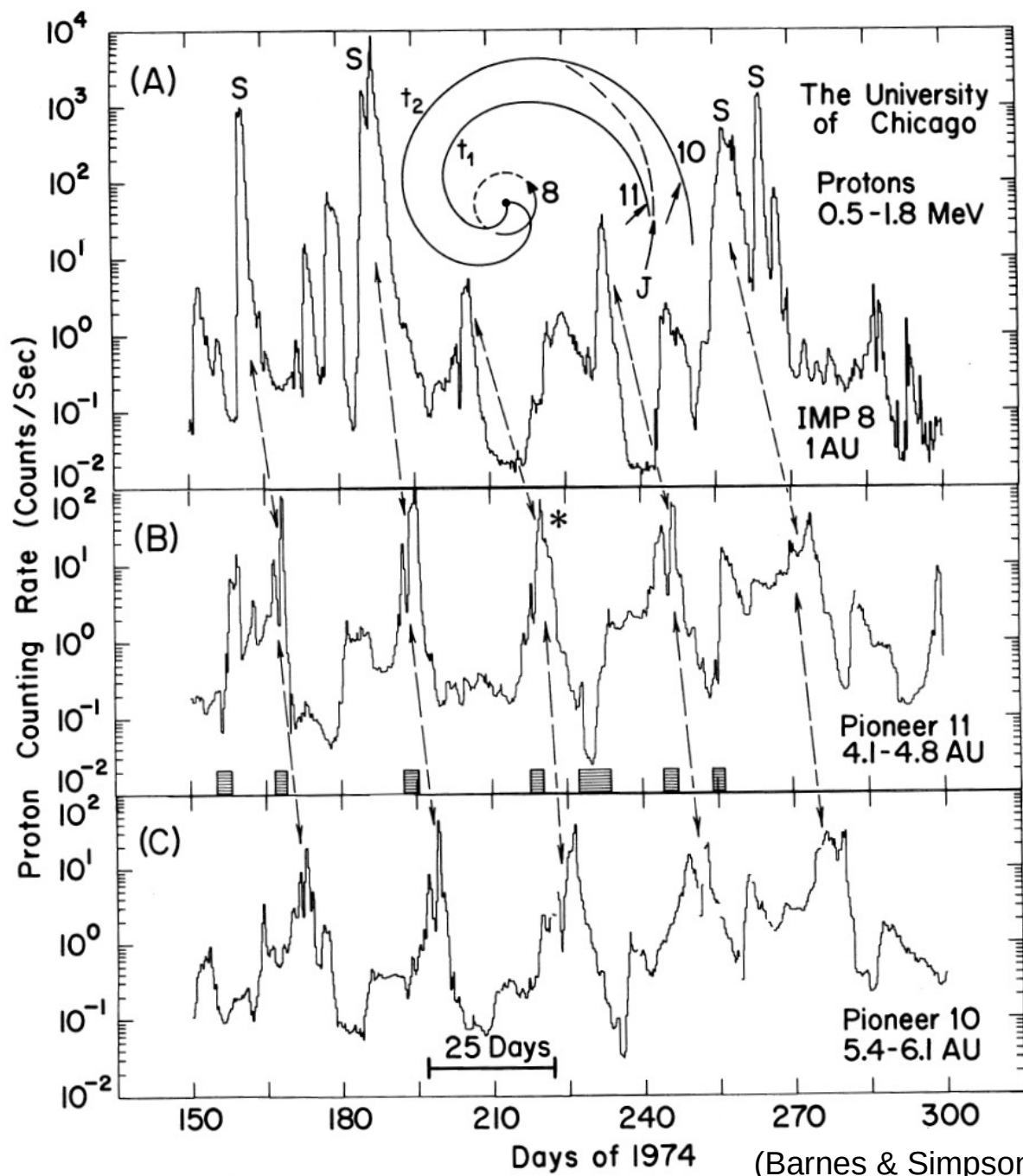


The particle transport equation

$$\begin{aligned}
 \frac{\partial F(t, \mu, r, p)}{\partial t} = & -\cos \psi \frac{\partial}{\partial r} \\
 & \times \left\{ \left[v\mu + \left(1 - \mu^2 \frac{v^2}{c^2} \right) v_{\text{sw}} \sec \psi \right] F(t, \mu, r, p) \right\} && \text{Streaming + Convection} \\
 & - \frac{\partial}{\partial \mu} \left\{ \left[\frac{v}{2L(r)} \left(1 + \mu \frac{v_{\text{sw}}}{v} \sec \psi - \mu \frac{v_{\text{sw}} v}{c^2} \sec \psi \right) \right. \right. \\
 & \left. \left. + v_{\text{sw}} \left(\cos \psi \frac{d}{dr} \sec \psi \right) \mu \right] (1 - \mu^2) F(t, \mu, r, p) \right\} && \text{Focusing} \\
 & + \frac{\partial}{\partial \mu} \left\{ D_{\mu\mu} \frac{\partial}{\partial \mu} \left[\left(1 - \mu \frac{v_{\text{sw}} v}{c^2} \sec \psi \right) F(t, \mu, r, p) \right] \right\} && \text{Differential convection} \\
 & + \frac{\partial}{\partial p} \left\{ p v_{\text{sw}} \left[\frac{\sec \psi}{2L(r)} (1 - \mu^2) + \cos \psi \frac{d}{dr} (\sec \psi) \mu^2 \right] \right. \\
 & \left. \times F(t, \mu, r, p) \right\} + G(t, \mu, r, p), && \text{Pitch-angle scattering} \\
 & && \text{Adiabatic deceleration} \\
 & && \text{Source term}
 \end{aligned} \tag{1}$$

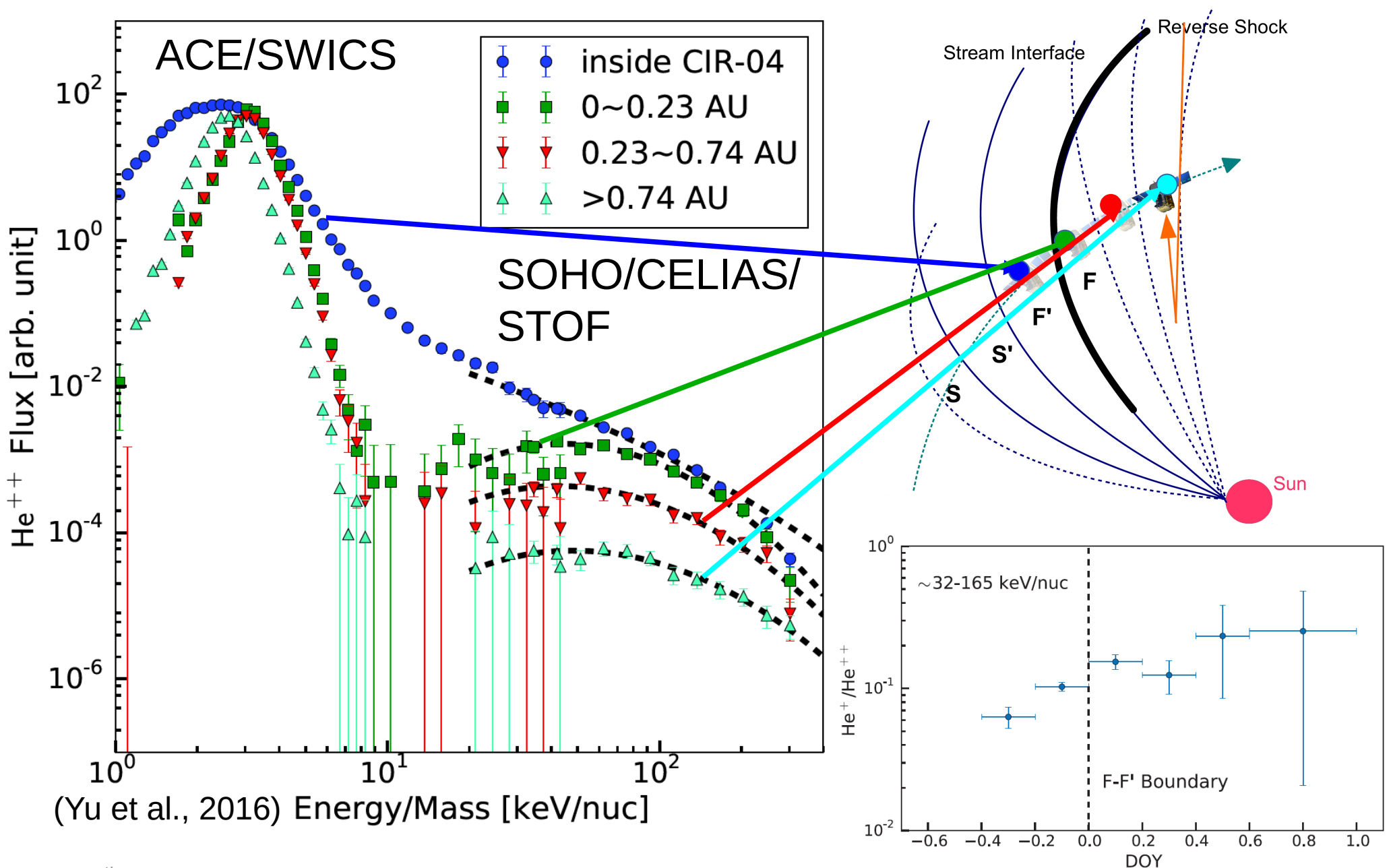


Pristine shock acceleration at CIRs?





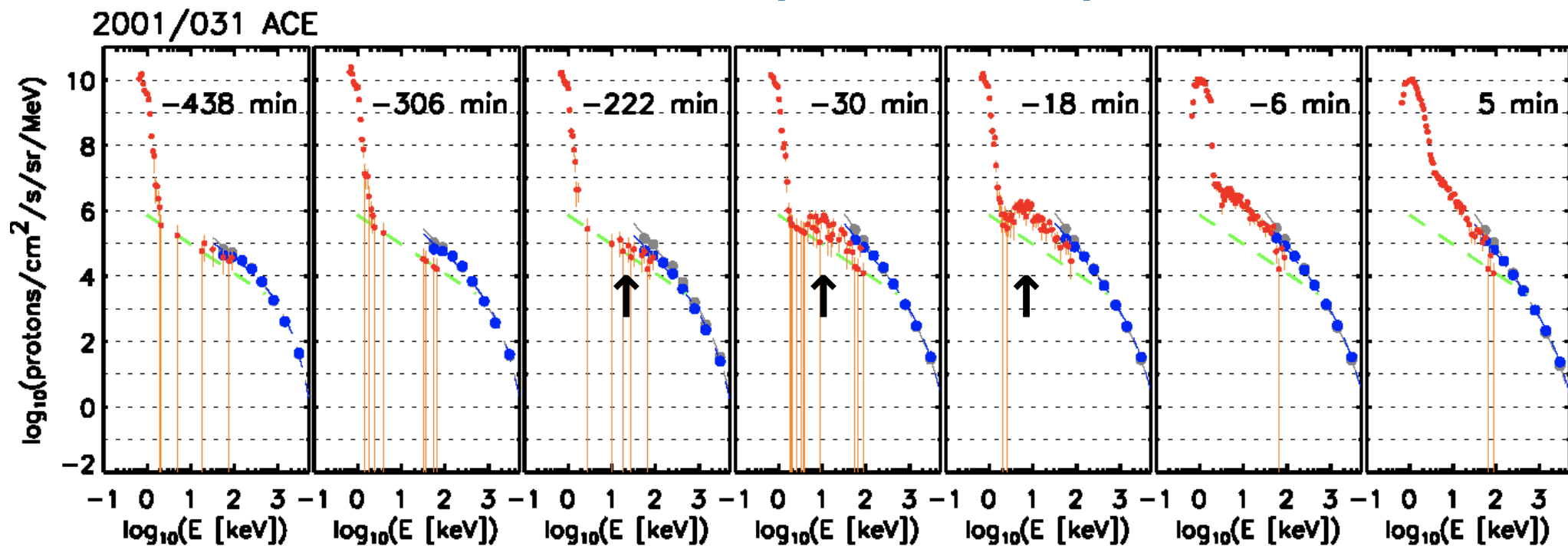
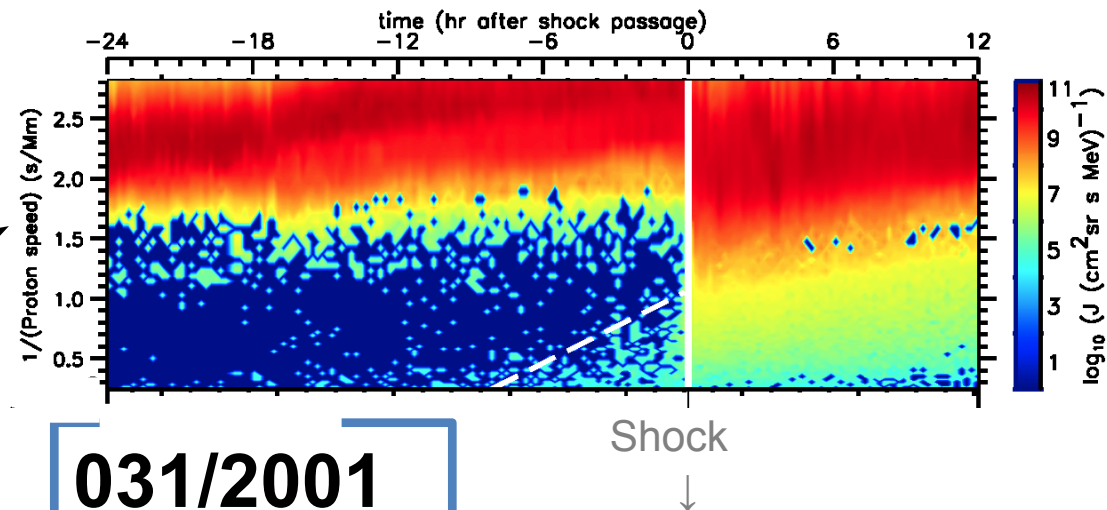
Suprathermal He^{++} at CIRs





Not unexpectedly, we observe similar behavior at CME-driven, transient shocks.

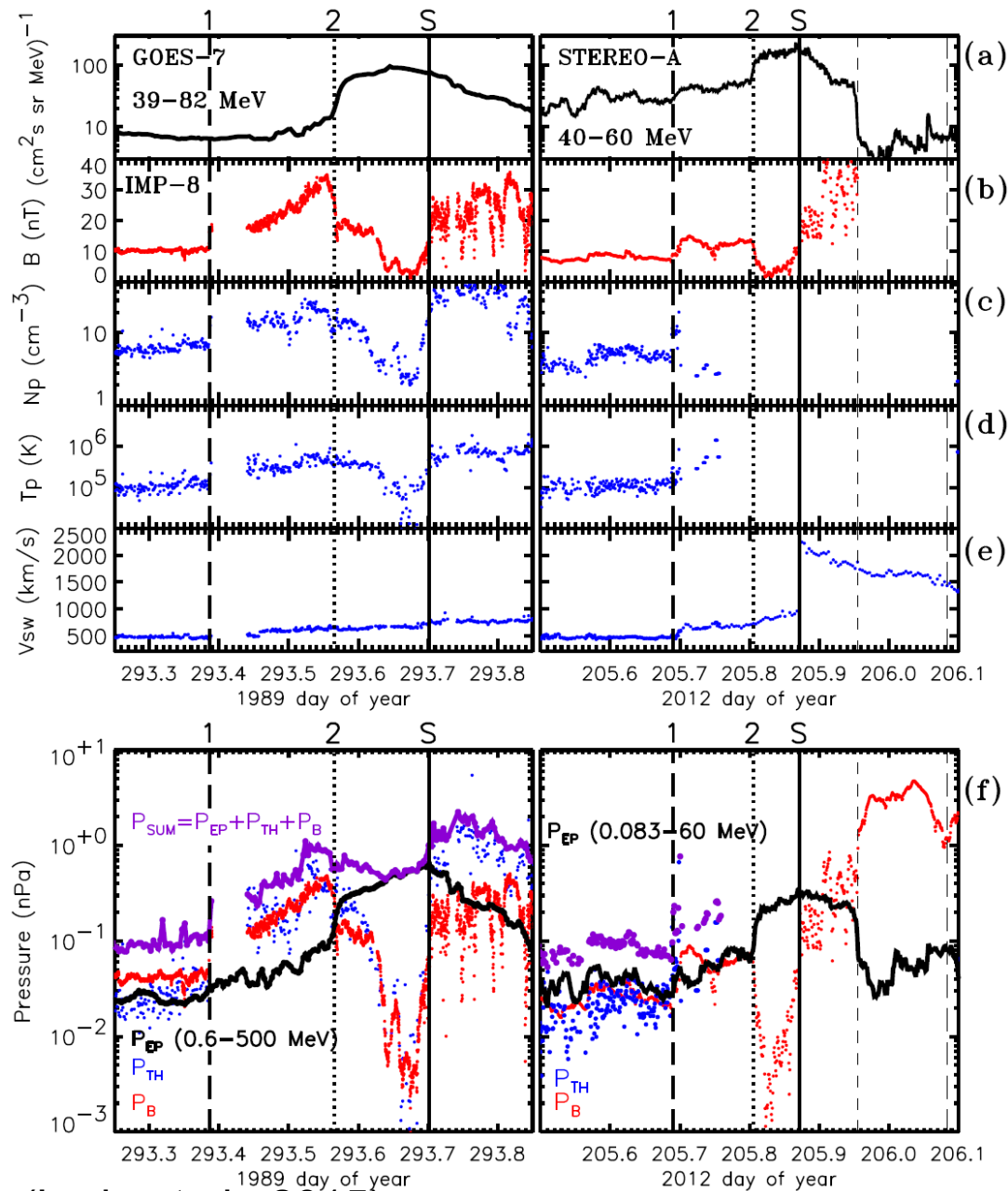
$$\frac{1}{v_{\text{ion}}} [\text{s/Mm}]$$



(Lario, et al.)



Substantial pressure in energetic particles



Lario et al., 2015, studied periods of elevated energetic particle intensities in which pressure of > 83 keV protons is larger than thermal or magnetic pressure.

Such periods are not rare.

Energetic particles often matter for shock dynamics.

Energetic particle pressure should be accounted for when computing shock parameters.

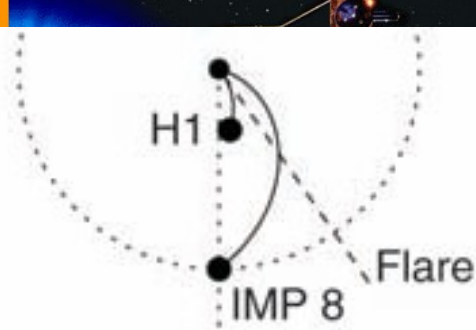
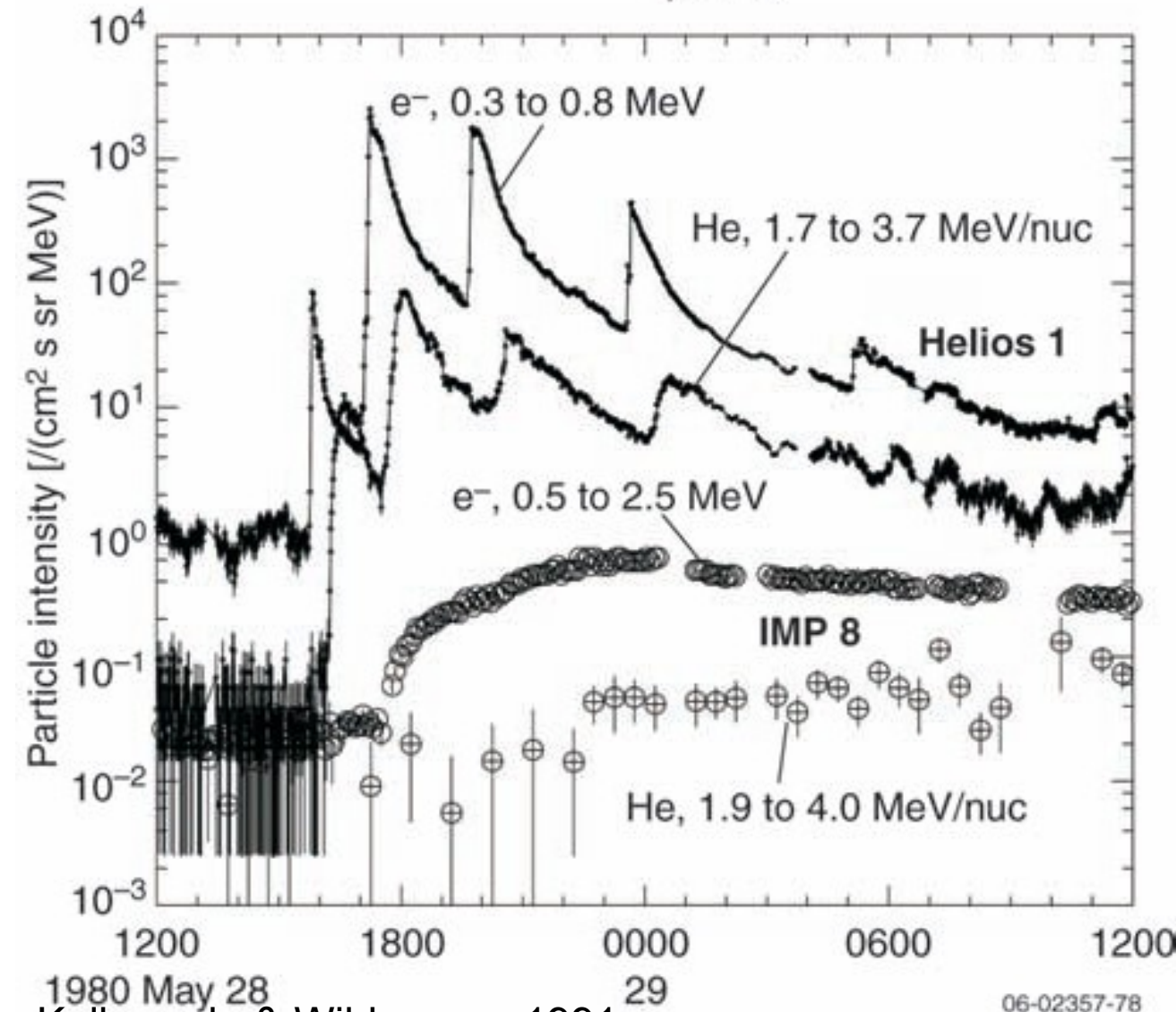


Illustration of the effect of transport on particles

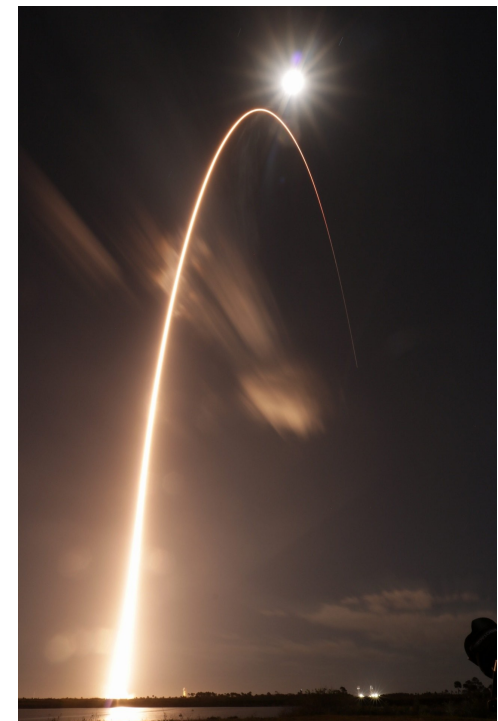
Solar Orbiter & PSP can disentangle transport effects from injection effects.



1980 May 28
Kallenrode & Wibberenz, 1991

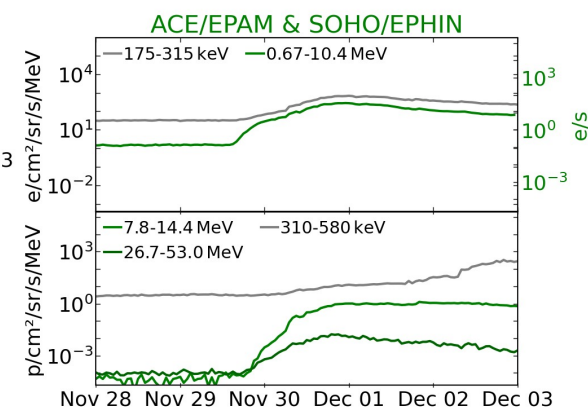
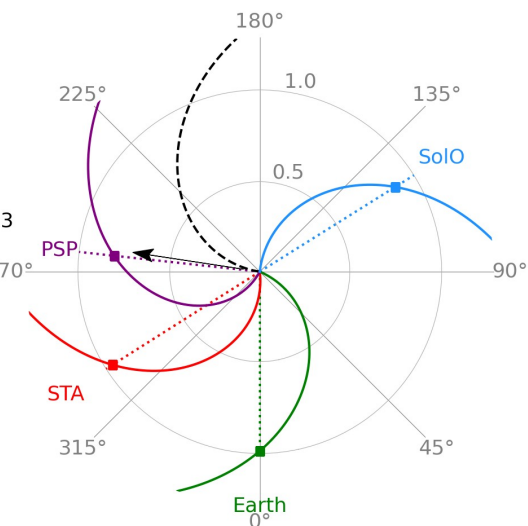
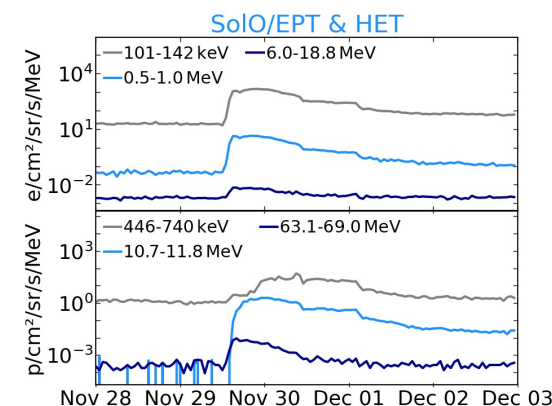
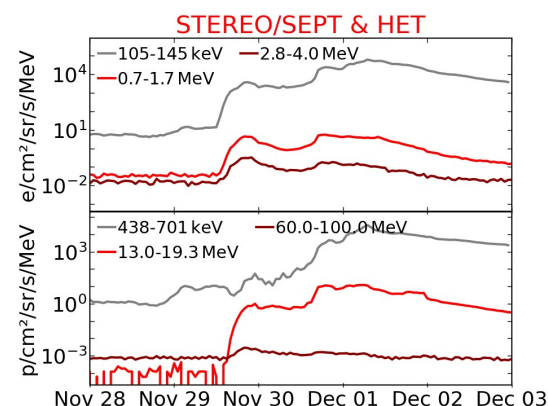
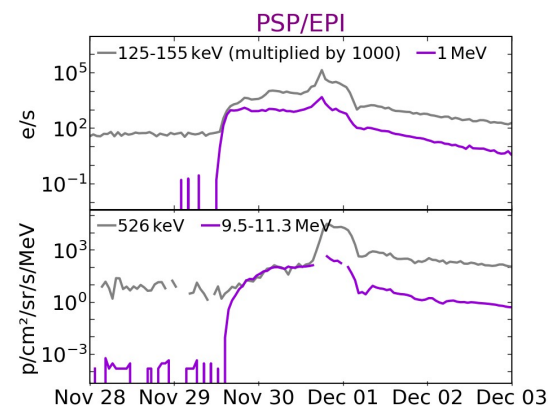
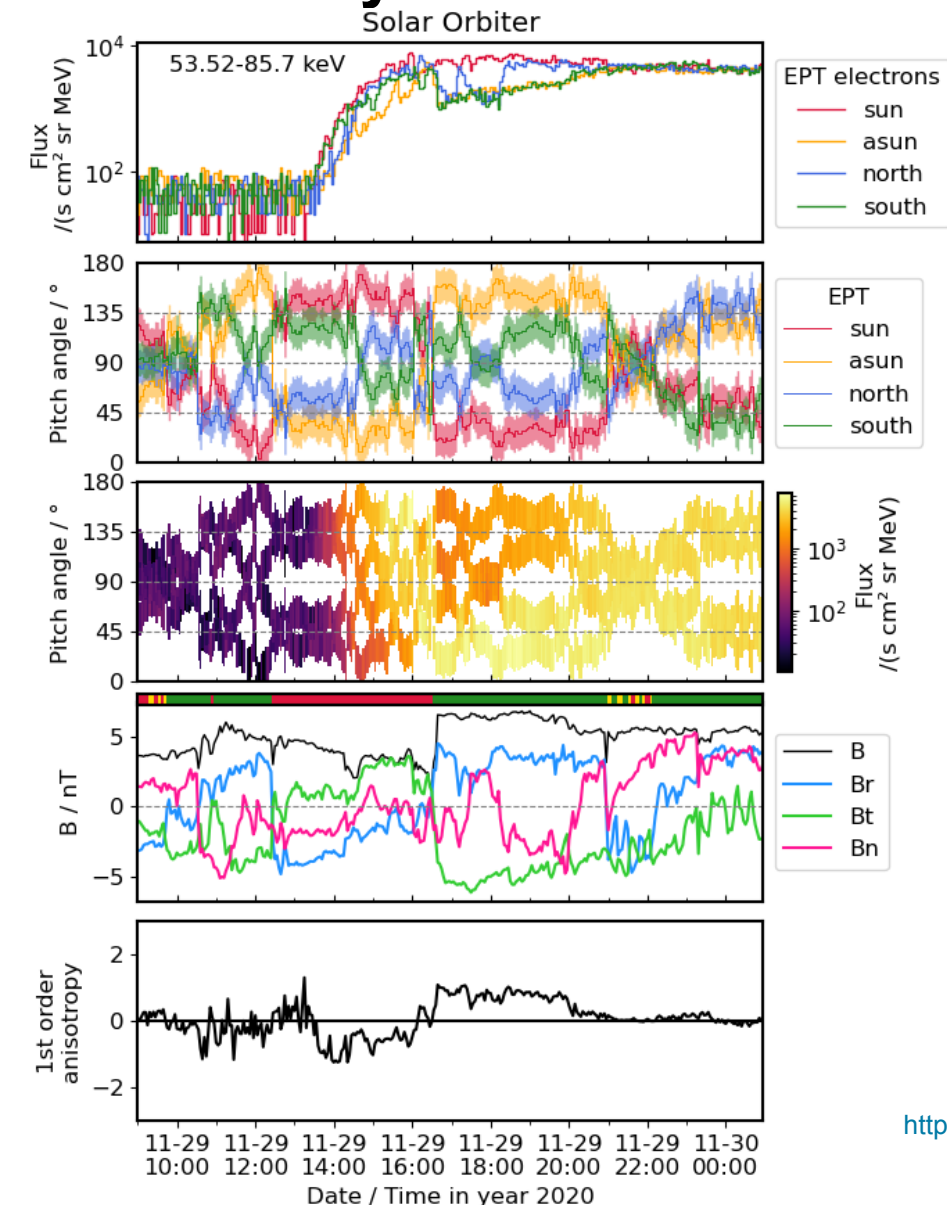
July 29, 2021

USTC summer school, rfws/cau





The first wide-spread energetic particle event observed by Solar Orbiter on 2020 November 29



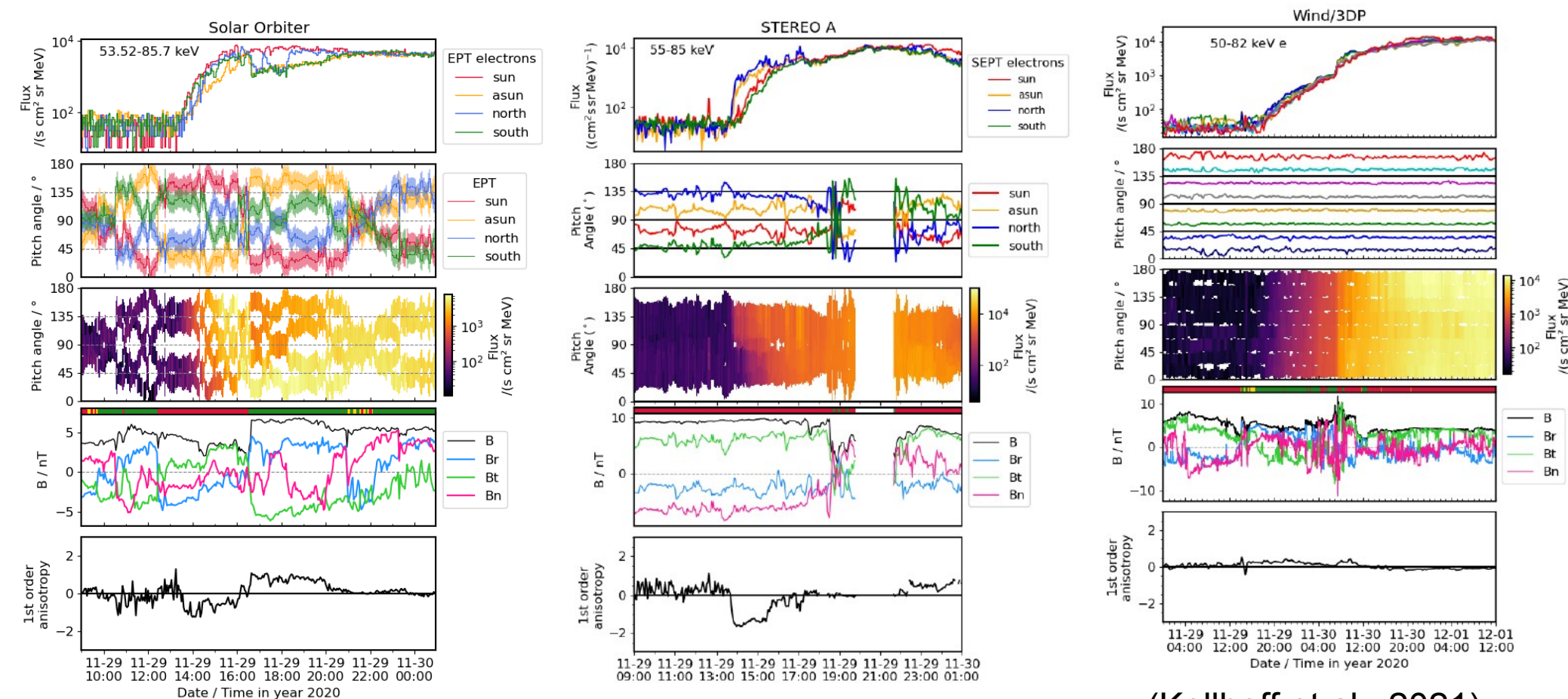
(Kollhoff et al., 2021)

<https://doi.org/10.1051/0004-6361/202140937>



The first wide-spread energetic particle event observed by Solar Orbiter on 2020 November 29

Anisotropic onset at wide separations!

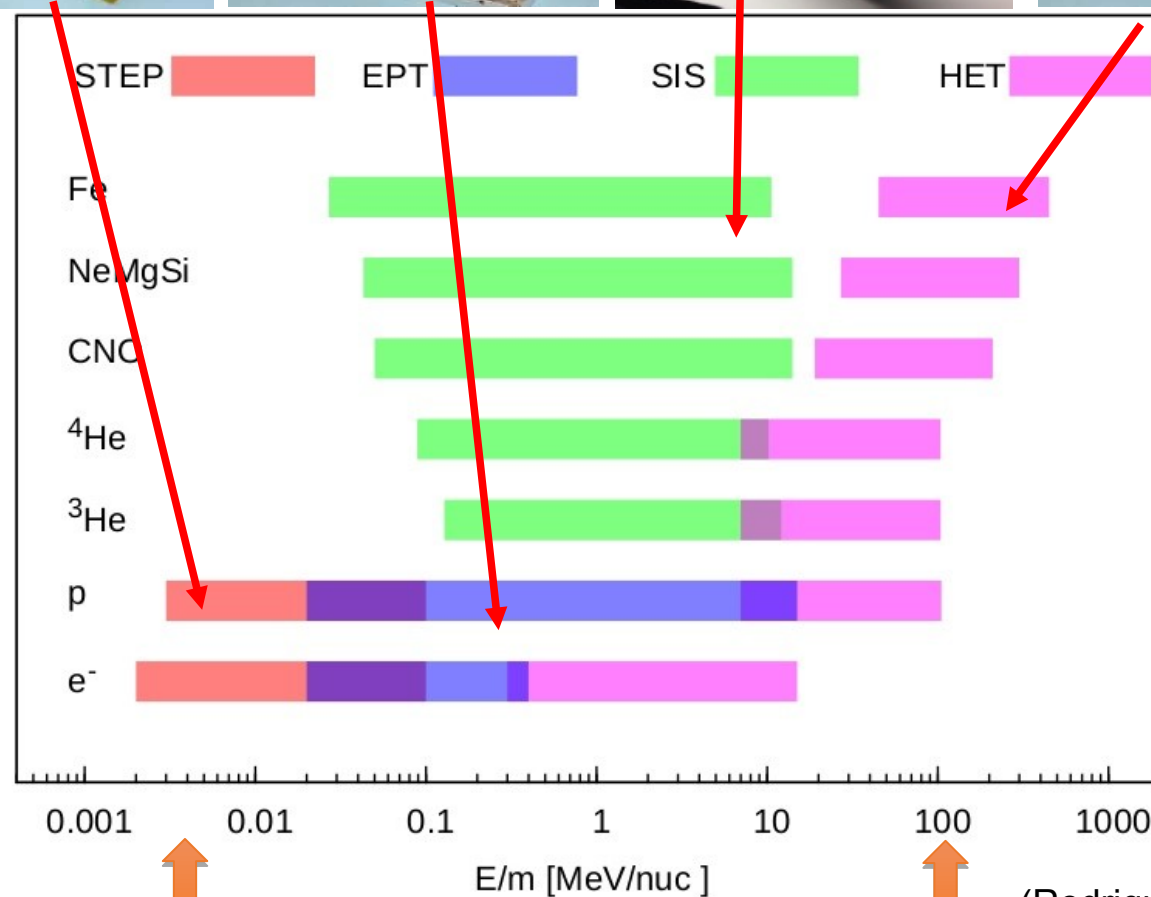
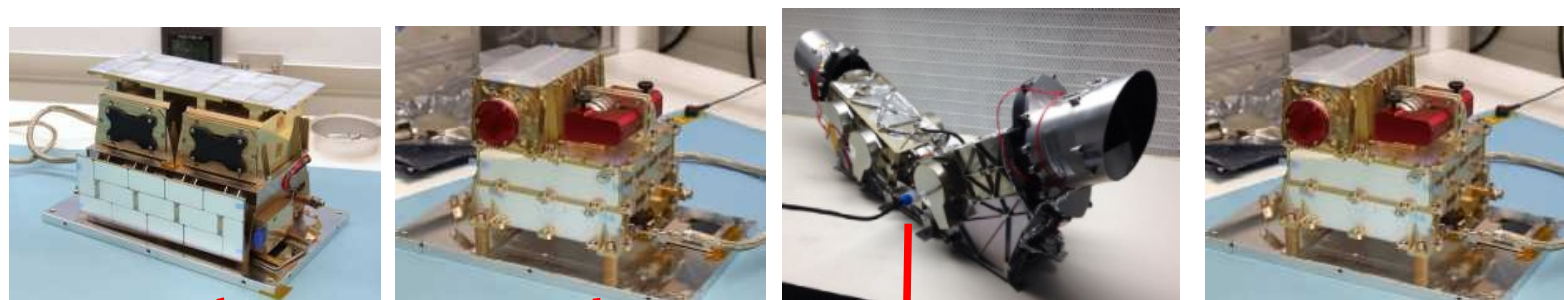


<https://doi.org/10.1051/0004-6361/202140937>

(Kollhoff et al., 2021)



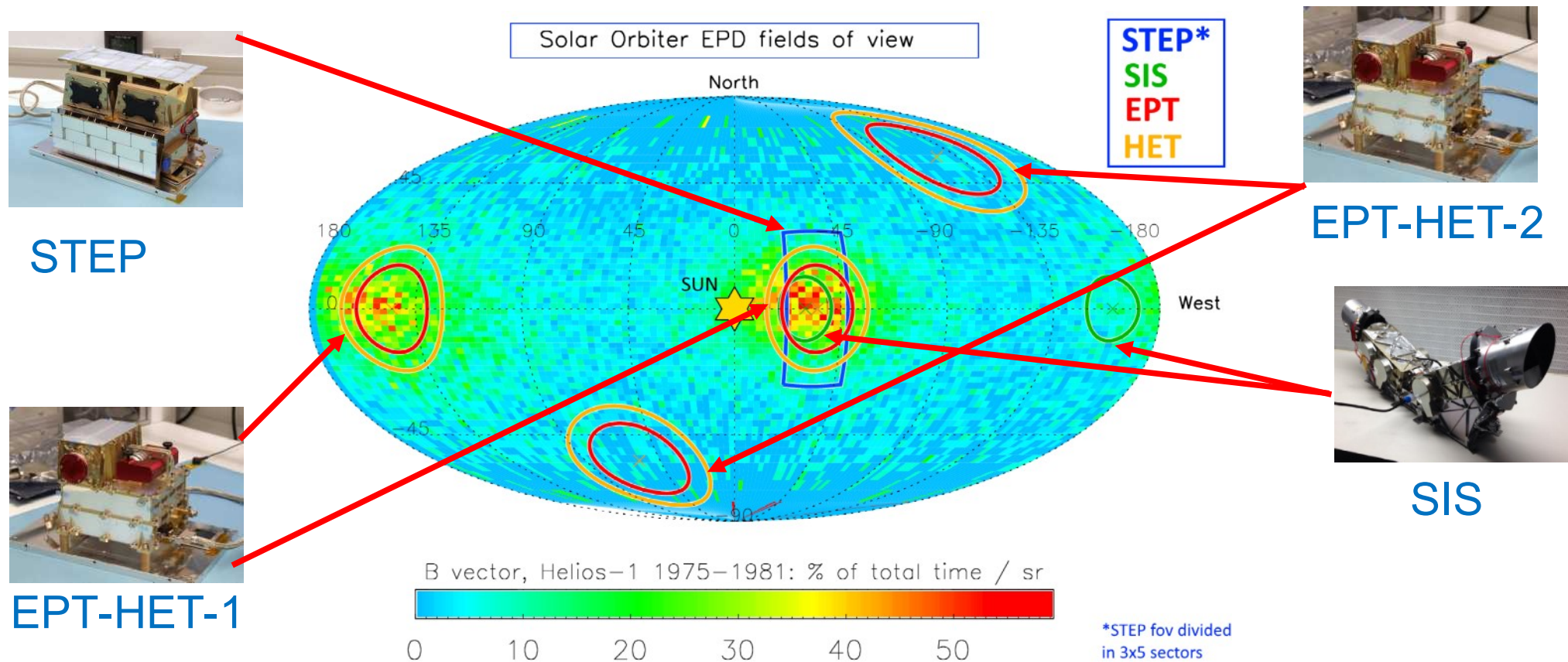
EPD on Solar Orbiter covers a wide range of energies (energy/nuc)



(Rodriguez-Pacheco et al., 2020,
Wimmer-Schweingruber et al., 2021)



EPD on Solar Orbiter has different viewing directions to provide adequate pitch-angle distributions.



(Rodriguez-Pacheco et al., 2020,
Wimmer-Schweingruber et al., 2021)



Measuring suprathermal ions

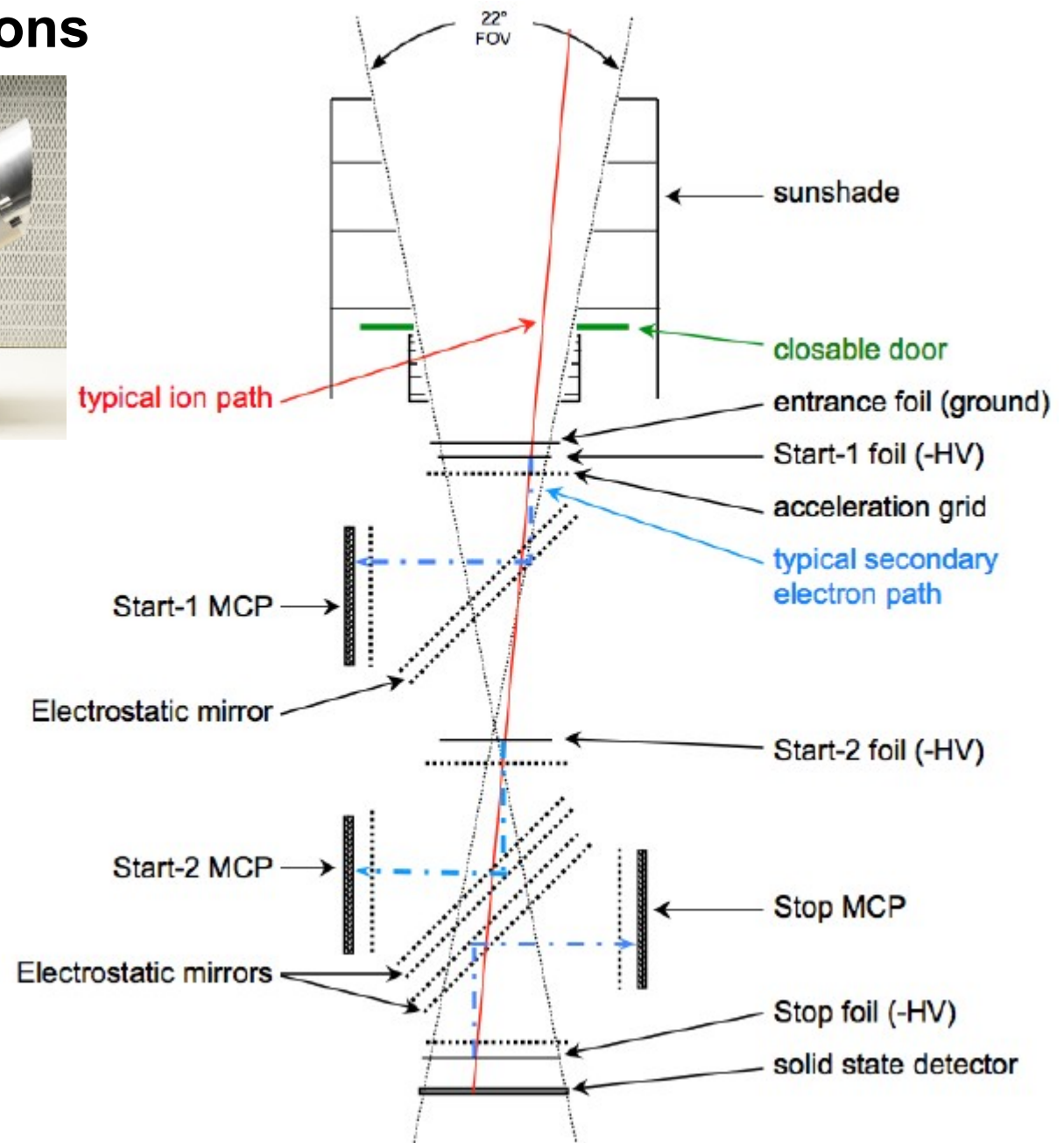


(Rodriguez-Pacheco et al., 2020)

SIS on Solar Orbiter
Measures:

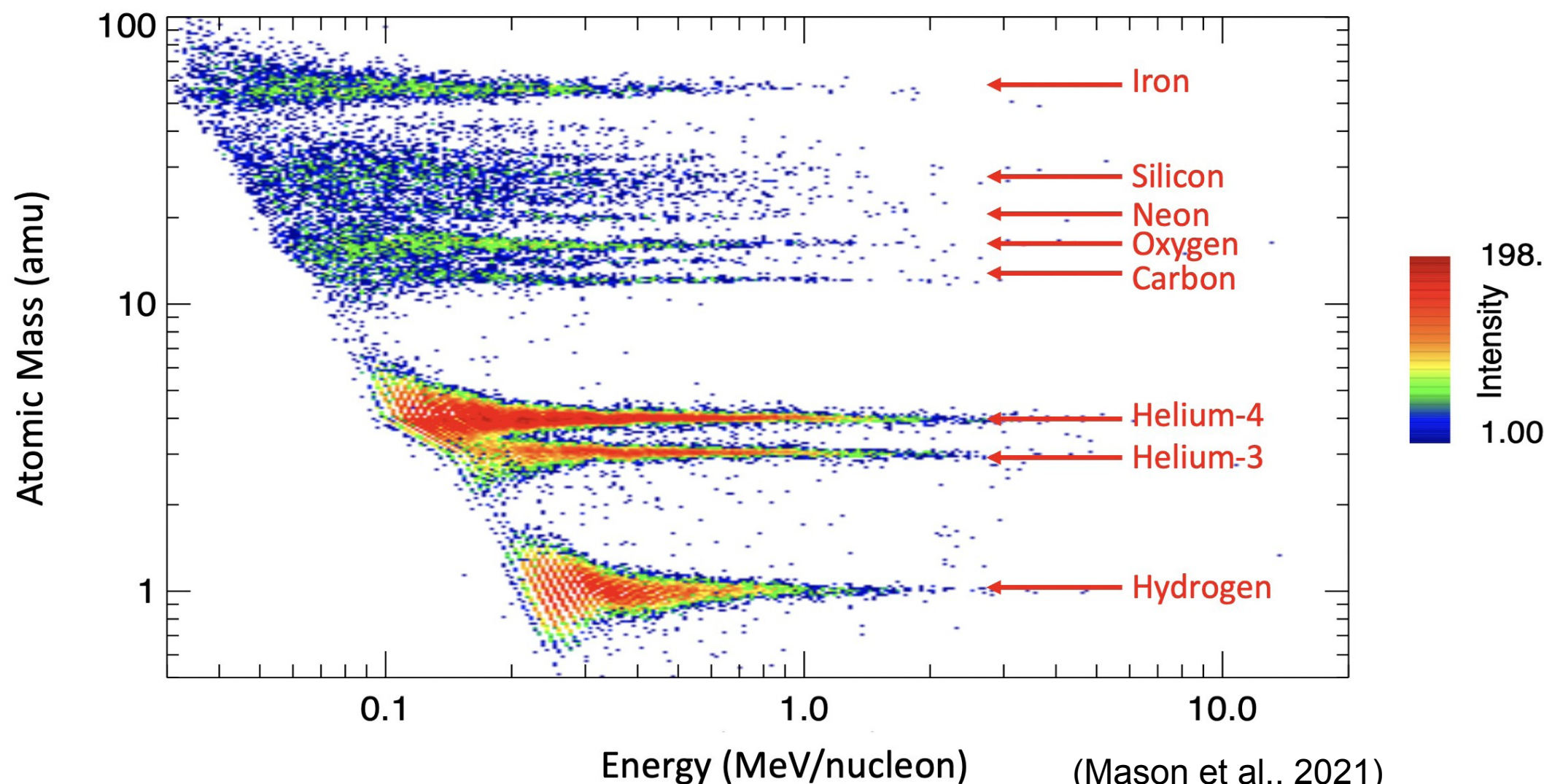
- multiple ToF
- total energy

Excellent ToF resolution
allows isotope separation!





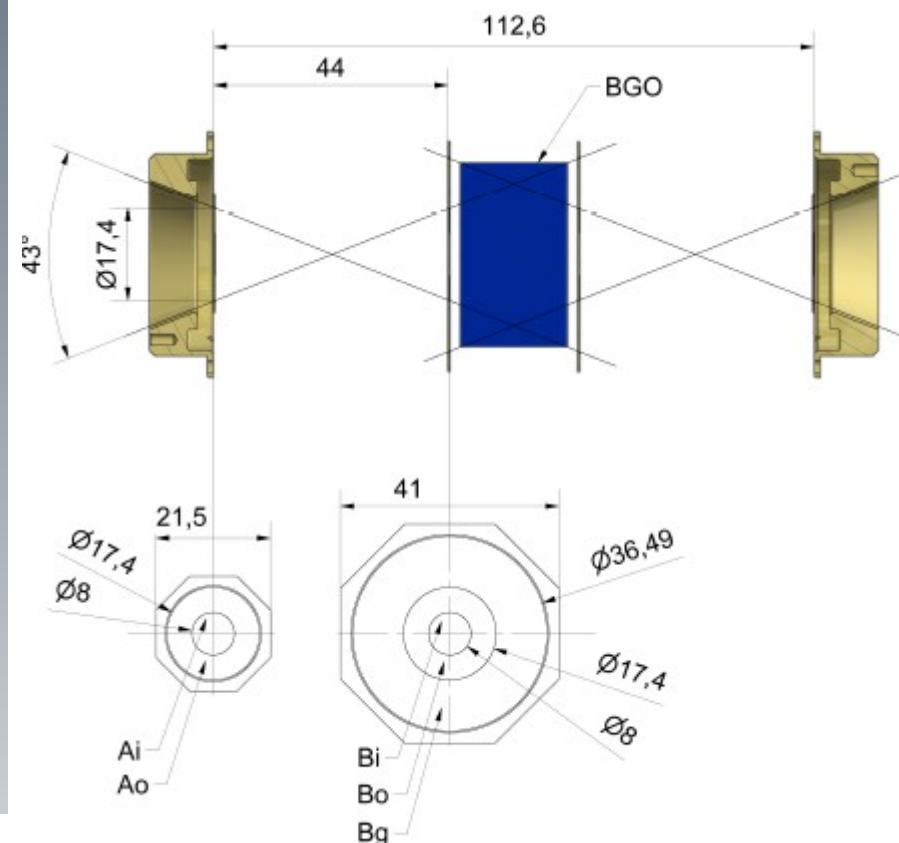
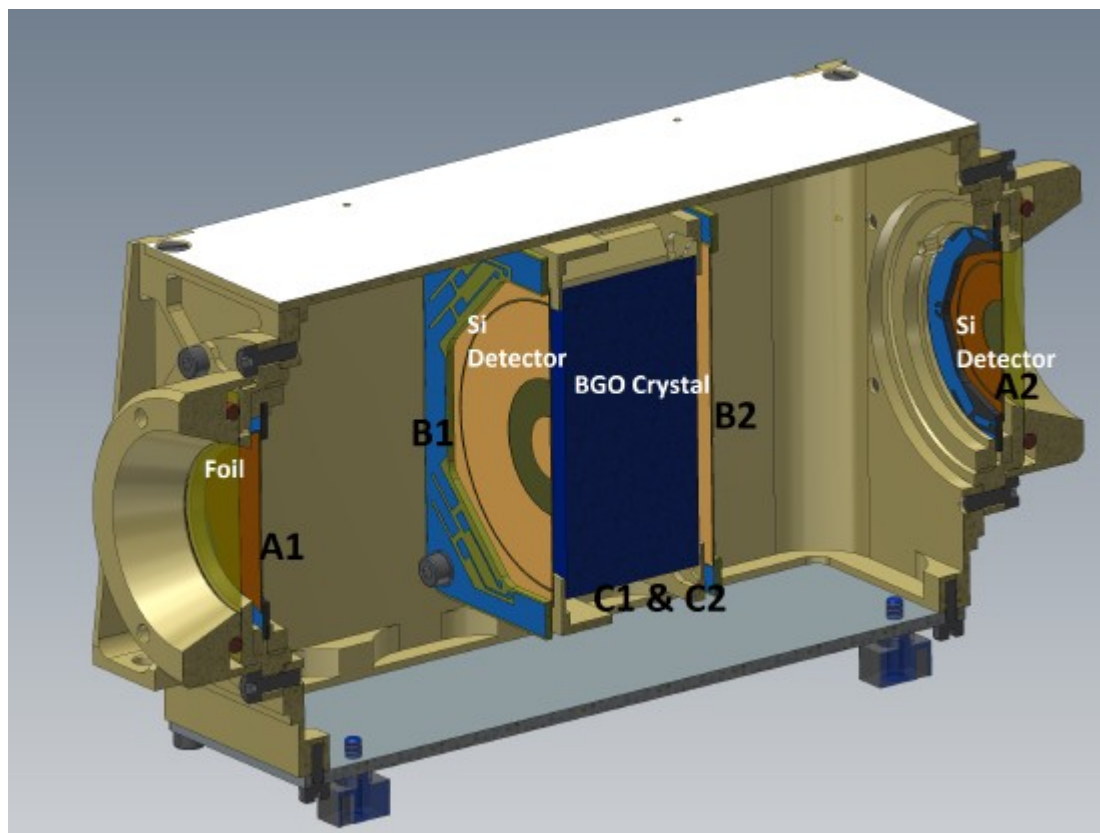
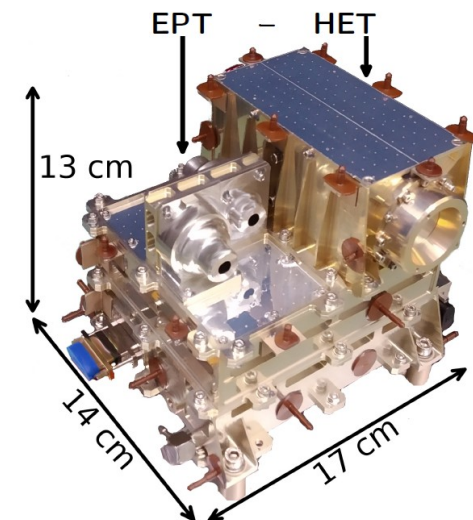
Elemental and isotopic resolution of SIS





Measuring high-energy ions & electrons: The High-Energy Telescope (HET)

Multiple dE/dx vs. total E measurement allows
element and isotope resolution



(Rodriguez-Pacheco et al., 2020)

July 29, 2021

USTC summer school, rws/cau

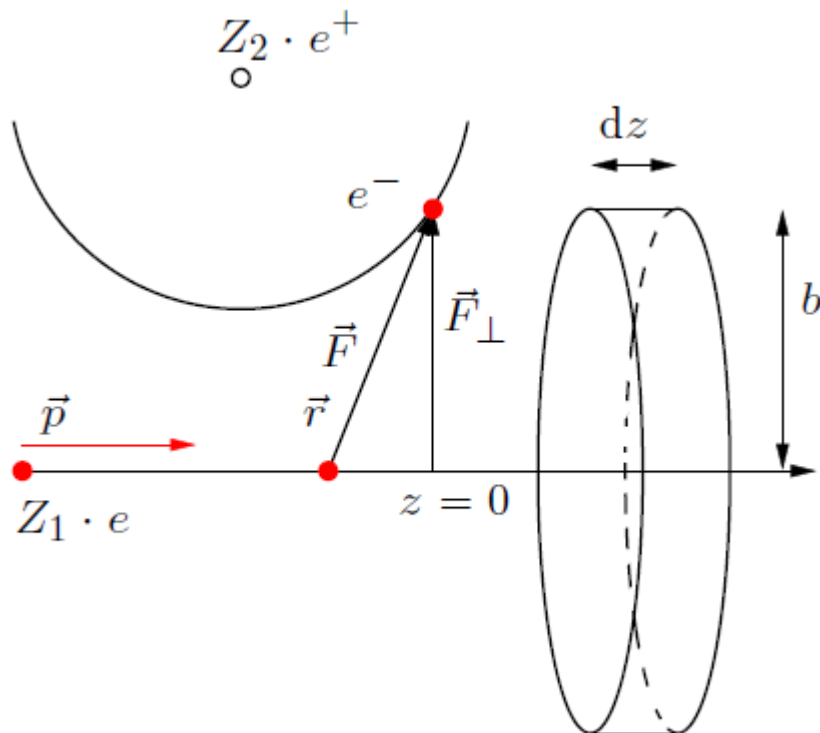


Interaction of charged radiation with matter

- „Ionizing radiation“:
 - Collisions with electrons
- Other interactions (not necessarily ionizing):
 - Collisions with nuclei
 - Nuclear reactions
 - Excitation of phonons

Reactions need to be described by cross sections, but some analytic approximations are sometimes helpful. The most important is the one by Bethe, Bloch, Lindhard, and Schjott.

Interaction of charged radiation with matter



Force on electron is

$$\vec{F} = \frac{Z_1 e^2}{4\pi\epsilon_0(z^2 + b^2)} \frac{\vec{r}}{r}.$$

Momentum transfer is:

$$\begin{aligned}\Delta p &= \int_{-\infty}^{+\infty} F dt = \int_{-\infty}^{+\infty} F_{\perp} dt \\ &= \frac{1}{v} \int_{-\infty}^{+\infty} F_{\perp} dz = \frac{e}{v} \int_{-\infty}^{+\infty} E_{\perp} dz.\end{aligned}$$

Use Gauß' law $\int_A \vec{E} \cdot d\vec{A} = 2\pi b \int E_{\perp} dz = Q/\epsilon_0 = Z_1 e/\epsilon_0.$

and obtain momentum
and energy transfer.

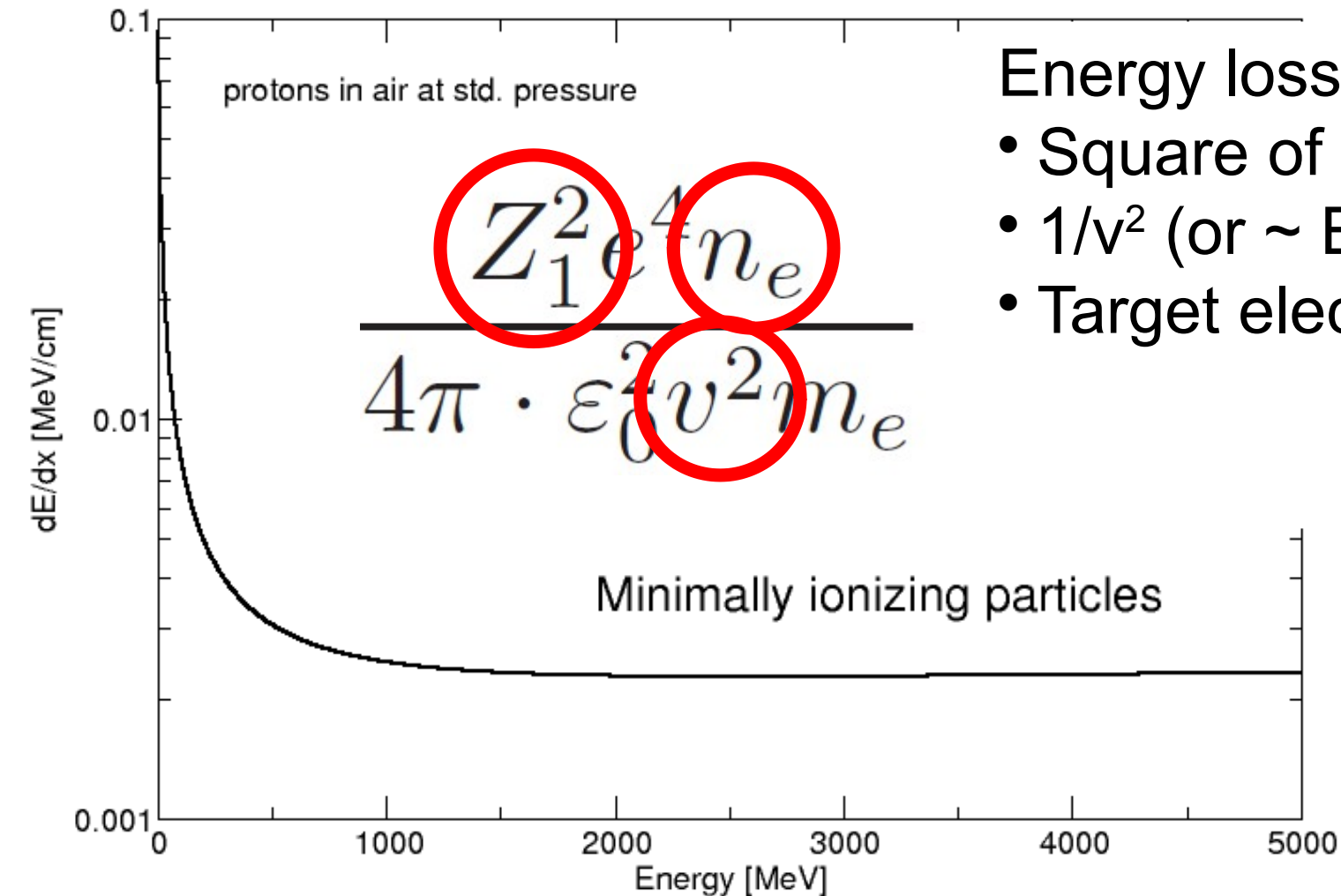
$$\Delta p = \frac{1}{2\pi\epsilon_0} \cdot \frac{Z_1 e^2}{vb},$$

$$\Delta\epsilon = \frac{\Delta p^2}{2m_e} = \frac{1}{8\pi^2\epsilon_0^2 m_e} \cdot \left(\frac{Z_1 e^2}{vb}\right)^2. \quad 47$$



Ionizing energy loss of charged particles in matter: Bethe-Bloch

$$\frac{dE}{dx} = -\frac{Z_1^2 e^4 n_e}{4\pi \cdot \varepsilon_0^2 v^2 m_e} \cdot \left[\ln \left(\frac{2m_e v^2}{\langle E_B \rangle} \right) - \ln(1 - \beta^2) - \beta^2 \right], \text{ where } \beta = v/c.$$



Energy loss goes with:

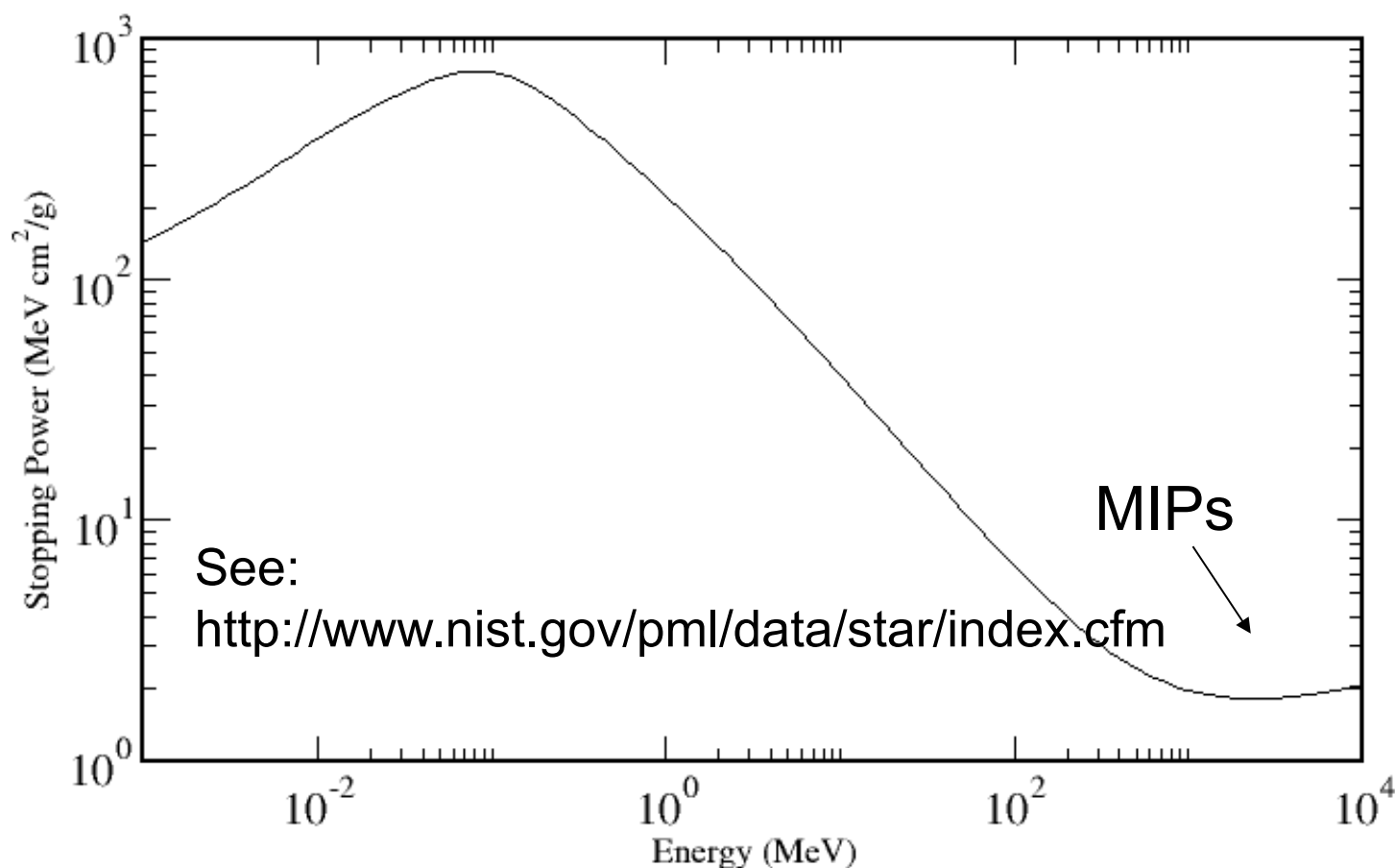
- Square of projectile charge
- $1/v^2$ (or $\sim E/m$) of projectile
- Target electron density



Ionizing energy loss of charged particles in matter: Bethe-Bloch

$$\frac{dE}{dx} = -\frac{Z_1^2 e^4 n_e}{4\pi \cdot \varepsilon_0^2 v^2 m_e} \cdot \left[\ln \left(\frac{2m_e v^2}{\langle E_B \rangle} \right) - \ln(1 - \beta^2) - \beta^2 \right], \text{ where } \beta = v/c.$$

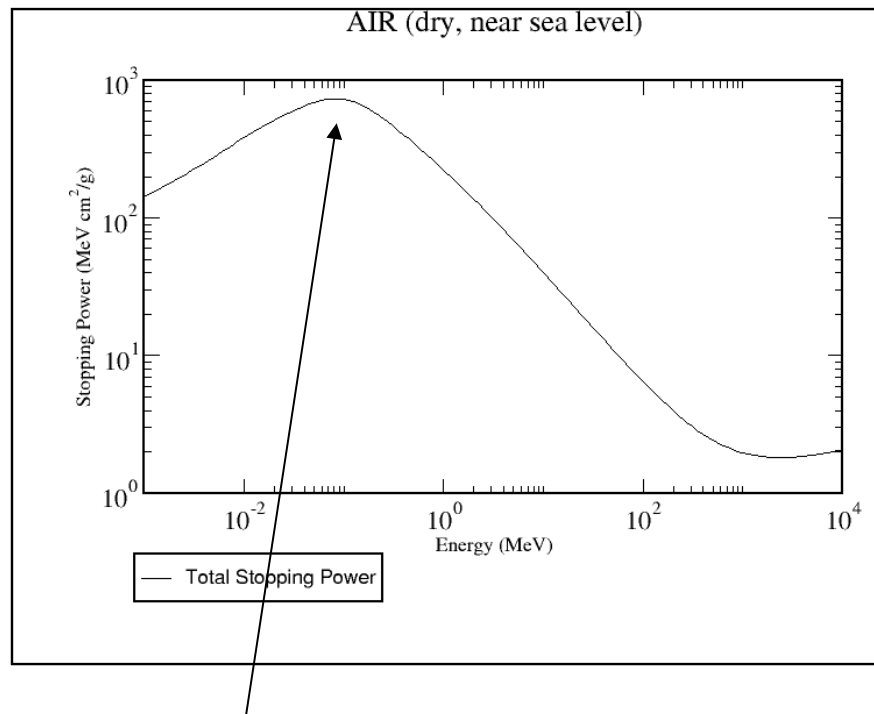
AIR (dry, near sea level)



You can calculate the stopping power at NIST for all sorts of combinations of projectile and target materials.



Energy loss of charged particles in matter



So energy loss is given as MeV/(g/cm²).

What does that mean?

Multiply by density, $\rho = \text{g/cm}^3$ to obtain

dE/dx in units of MeV/cm.

Air: $1\text{kg/m}^3 = 1\text{mg/cm}^3$

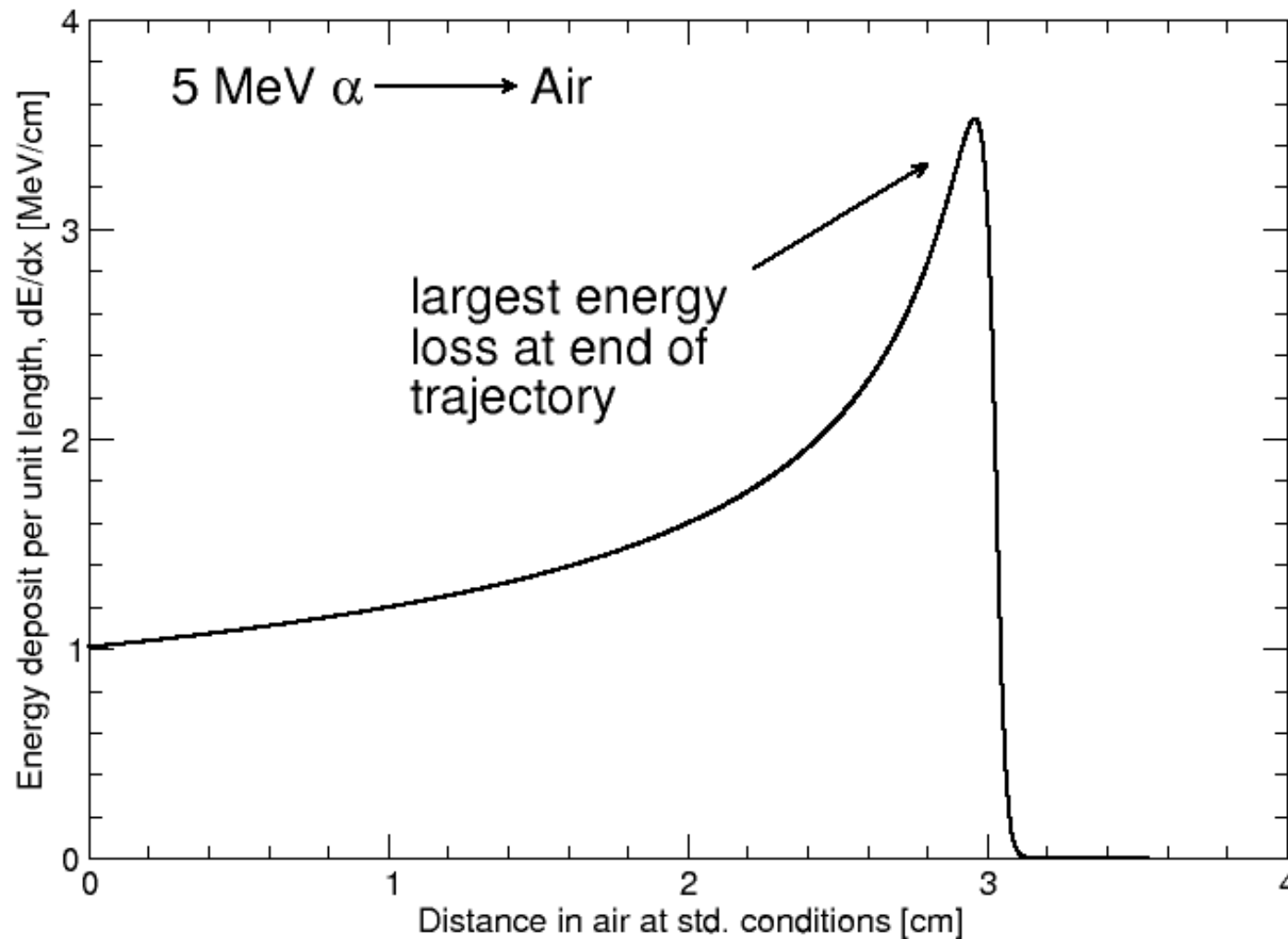
So $10^3 \text{ MeV}/(\text{g}/\text{cm}^2) = 1 \text{ MeV}/\text{cm}$. Compare this to binding energy of N_2 molecules of 15.6 eV. In fact, ions will also loose energy to nuclei, so 37 eV is the correct number to be used for $\langle E_B \rangle$.

Ionizing radiation ionizes air!



Energy loss of charged particles in matter: Deposition profile – The Bragg Peak

$$\frac{dE}{dx} = -\frac{Z_1^2 e^4 n_e}{4\pi \cdot \varepsilon_0^2 v^2 m_e} \cdot \left[\ln \left(\frac{2m_e v^2}{\langle E_B \rangle} \right) - \ln(1 - \beta^2) - \beta^2 \right], \text{ where } \beta = v/c.$$

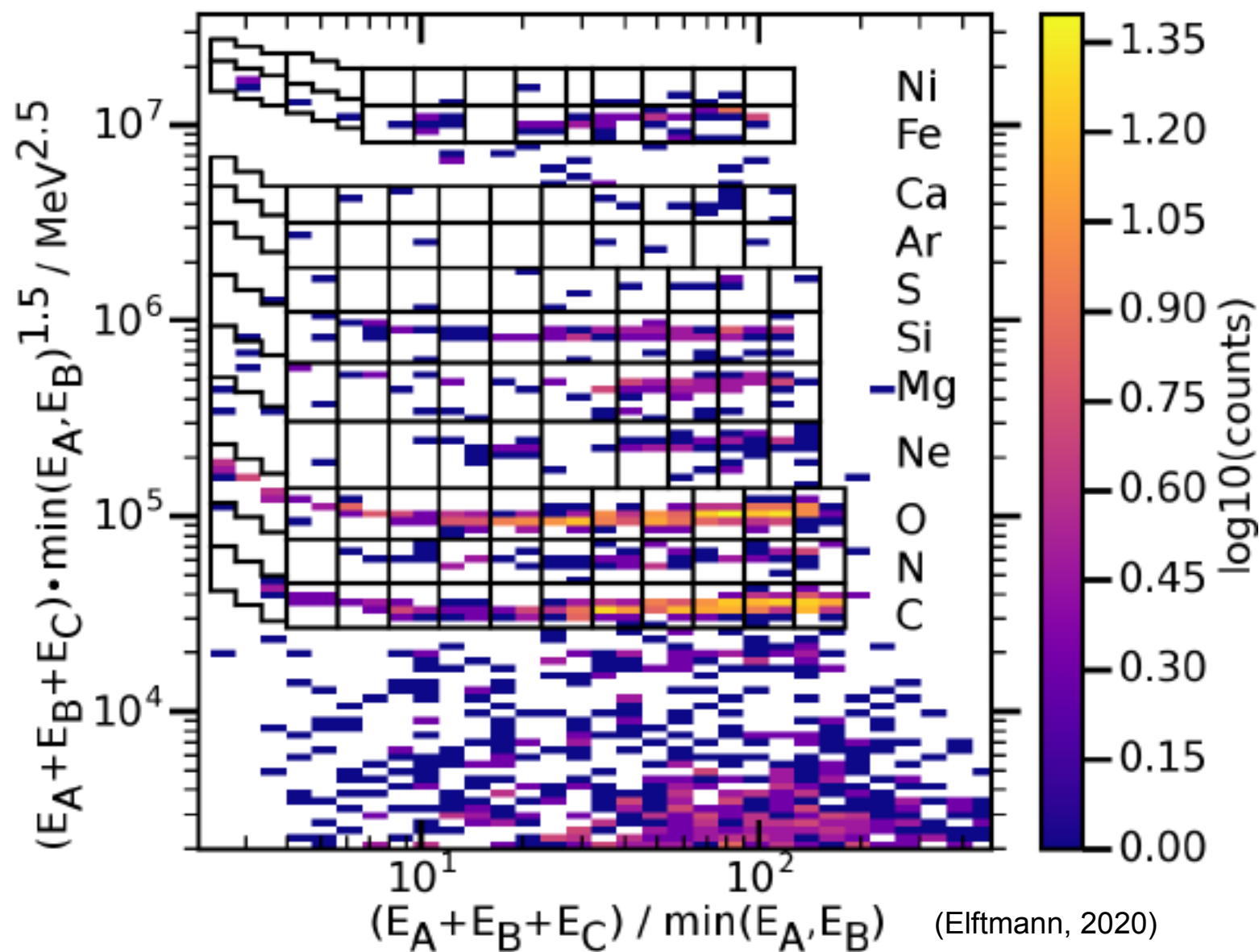


Because a particle loses more energy when it has less energy, it loses most of its energy at the end of its trajectory.

5 MeV α particle only penetrates few cm of air.

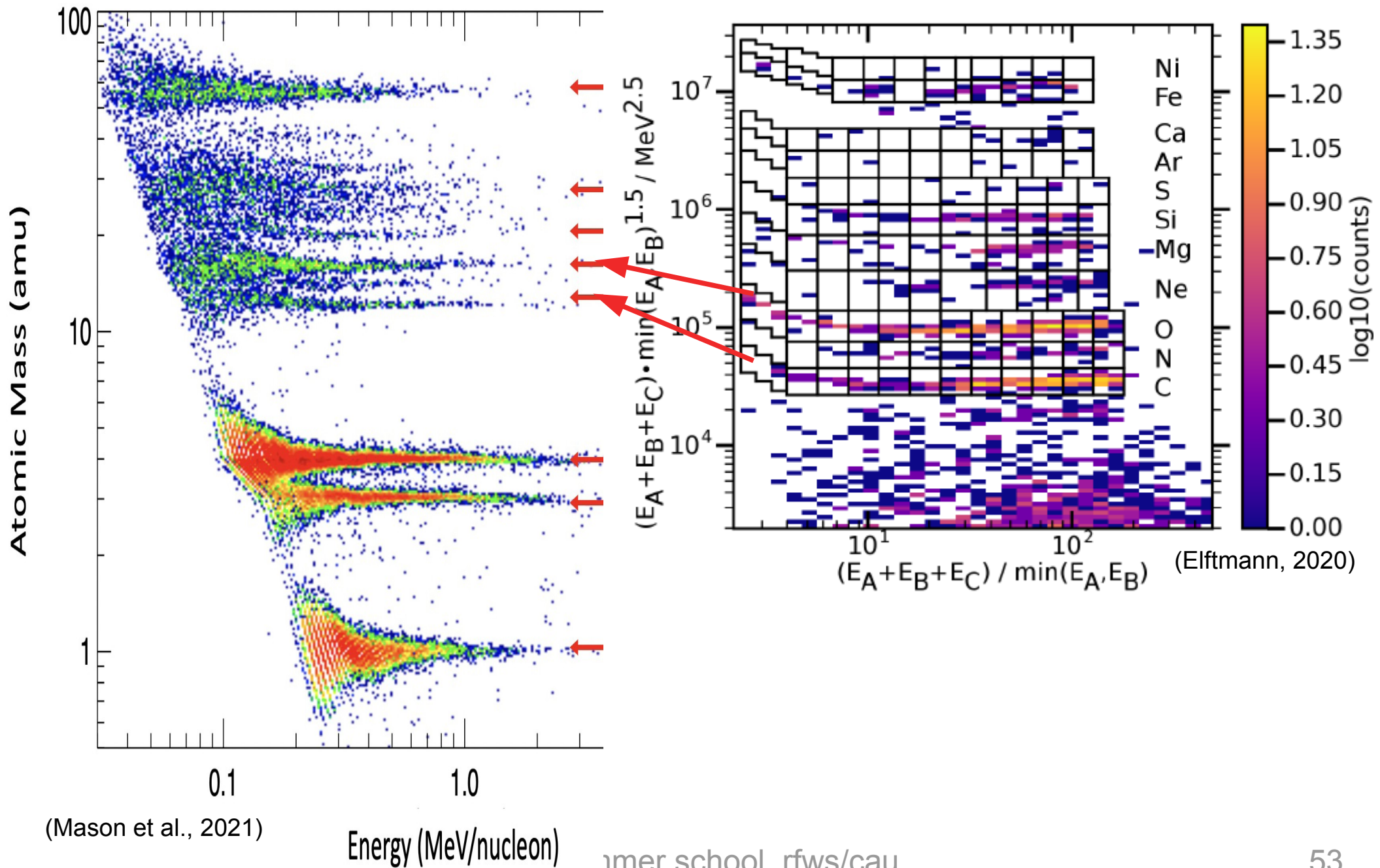


Elemental and isotopic resolution of HET



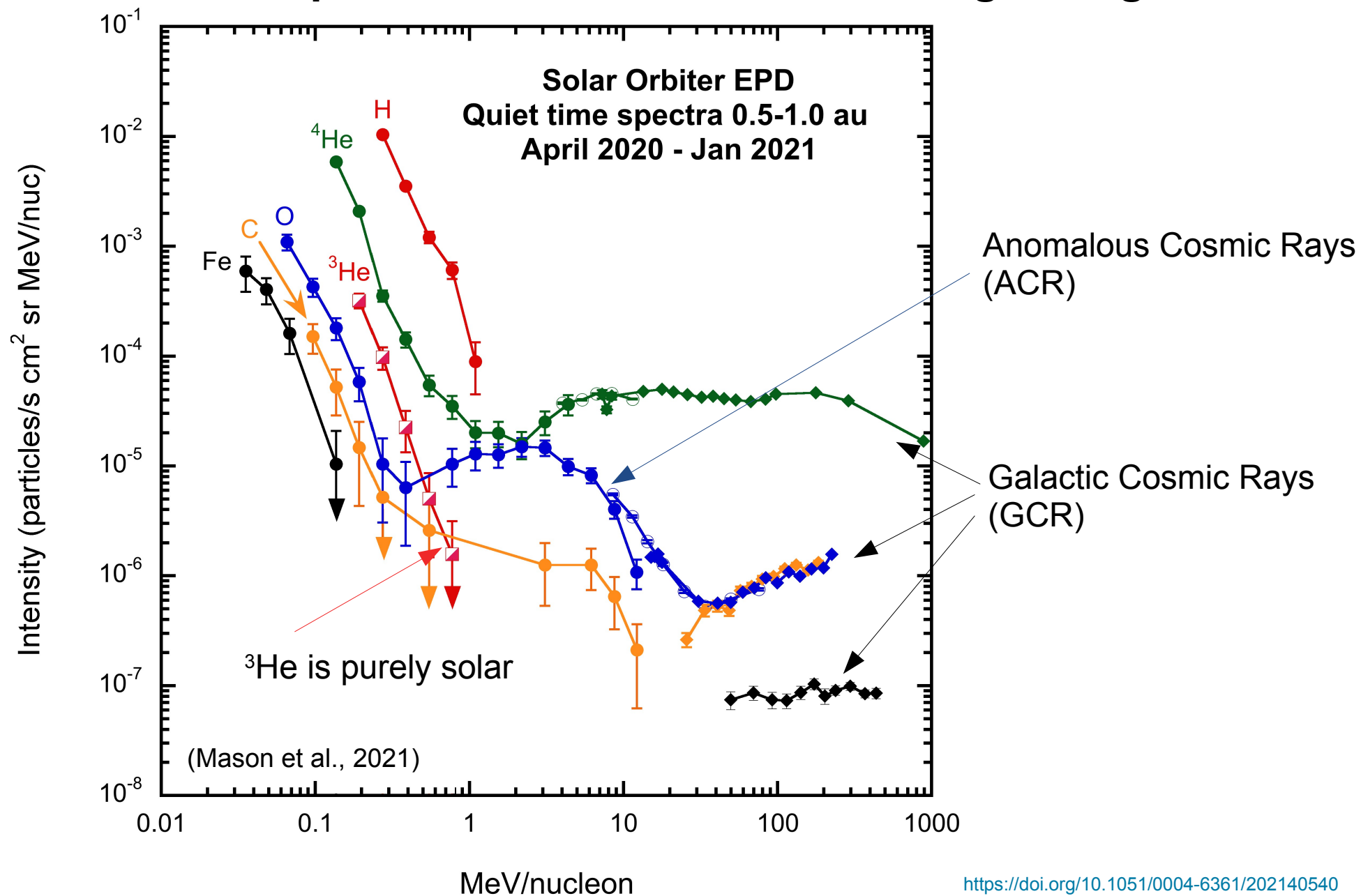


Elemental and isotopic resolution of SIS & HET





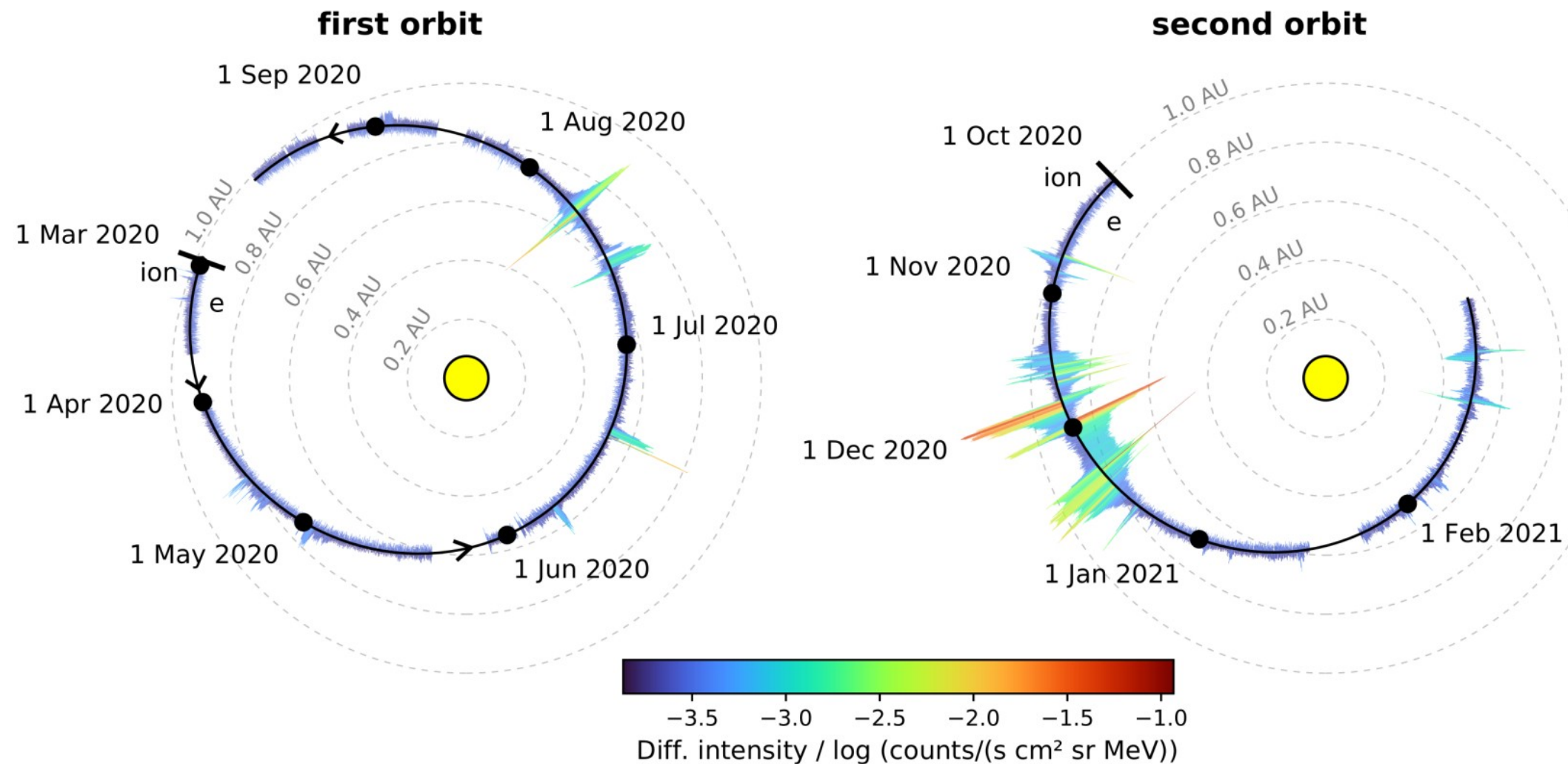
Combined spectra from SIS and HET show good agreement



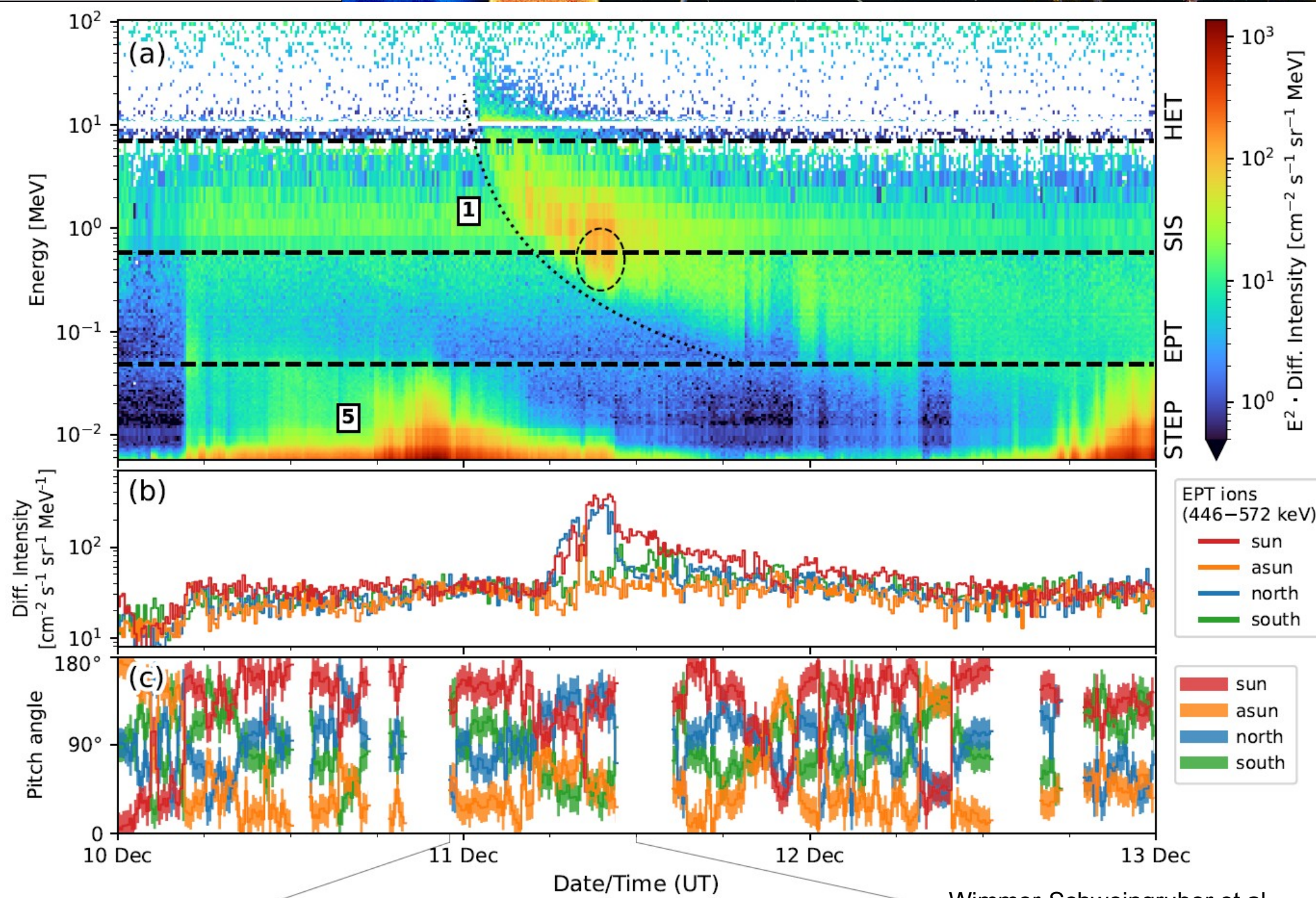
<https://doi.org/10.1051/0004-6361/202140540>



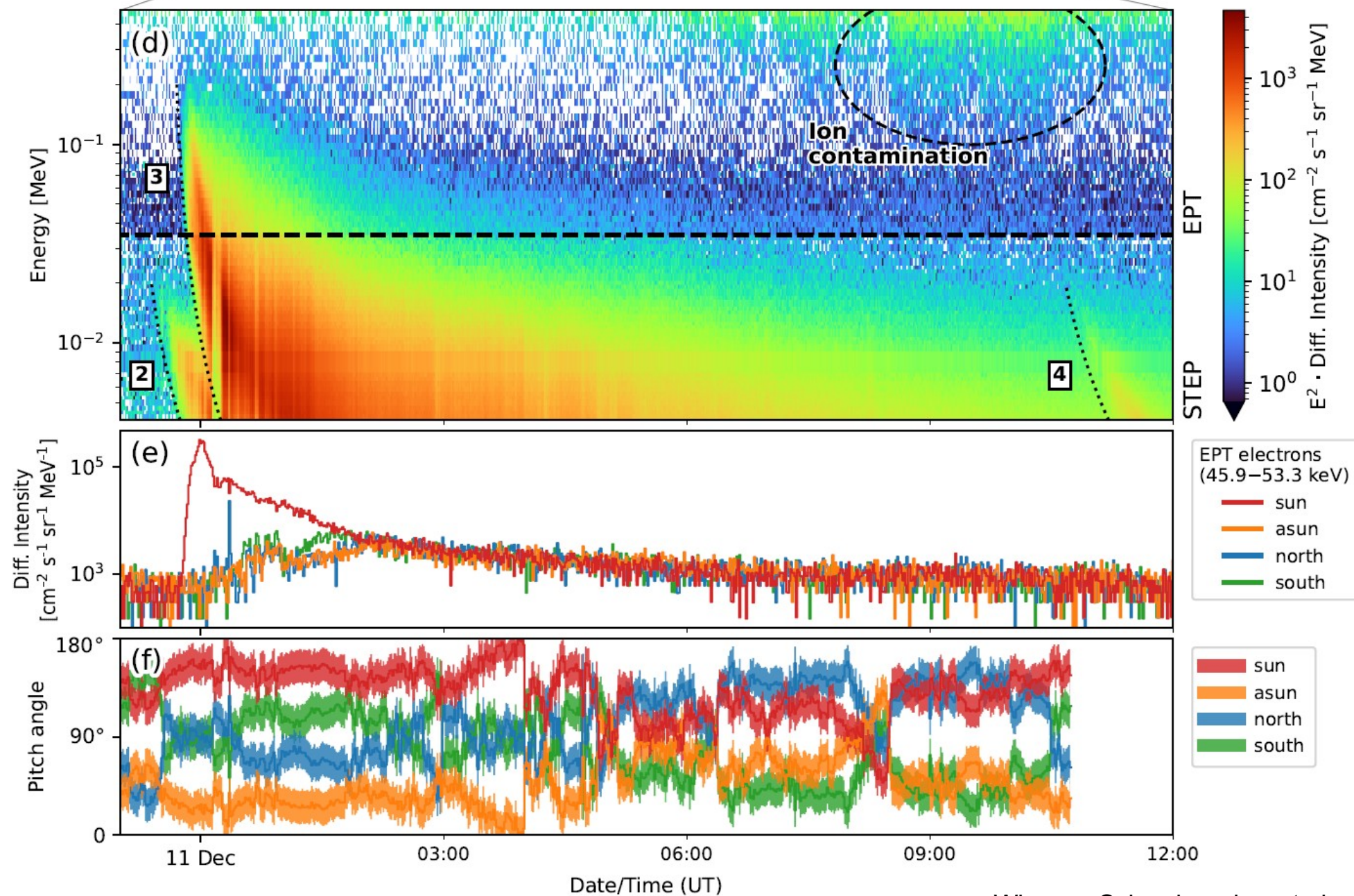
The first year of energetic particle measurements in the inner heliosphere with Solar Orbiter's Energetic Particle Detector



Wimmer-Schweingruber et al.,
2021, A&A accepted



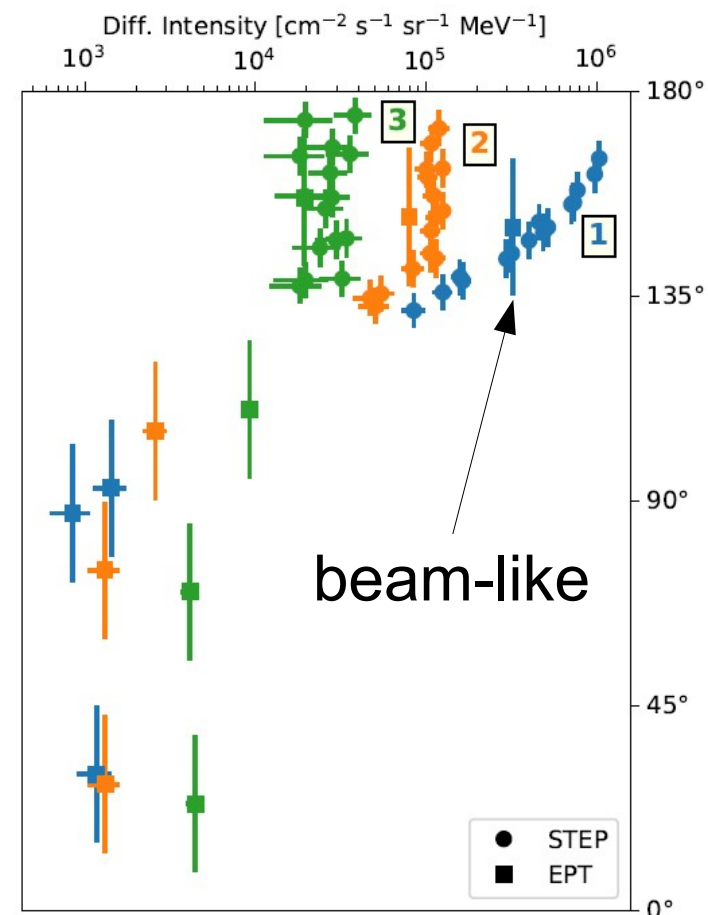
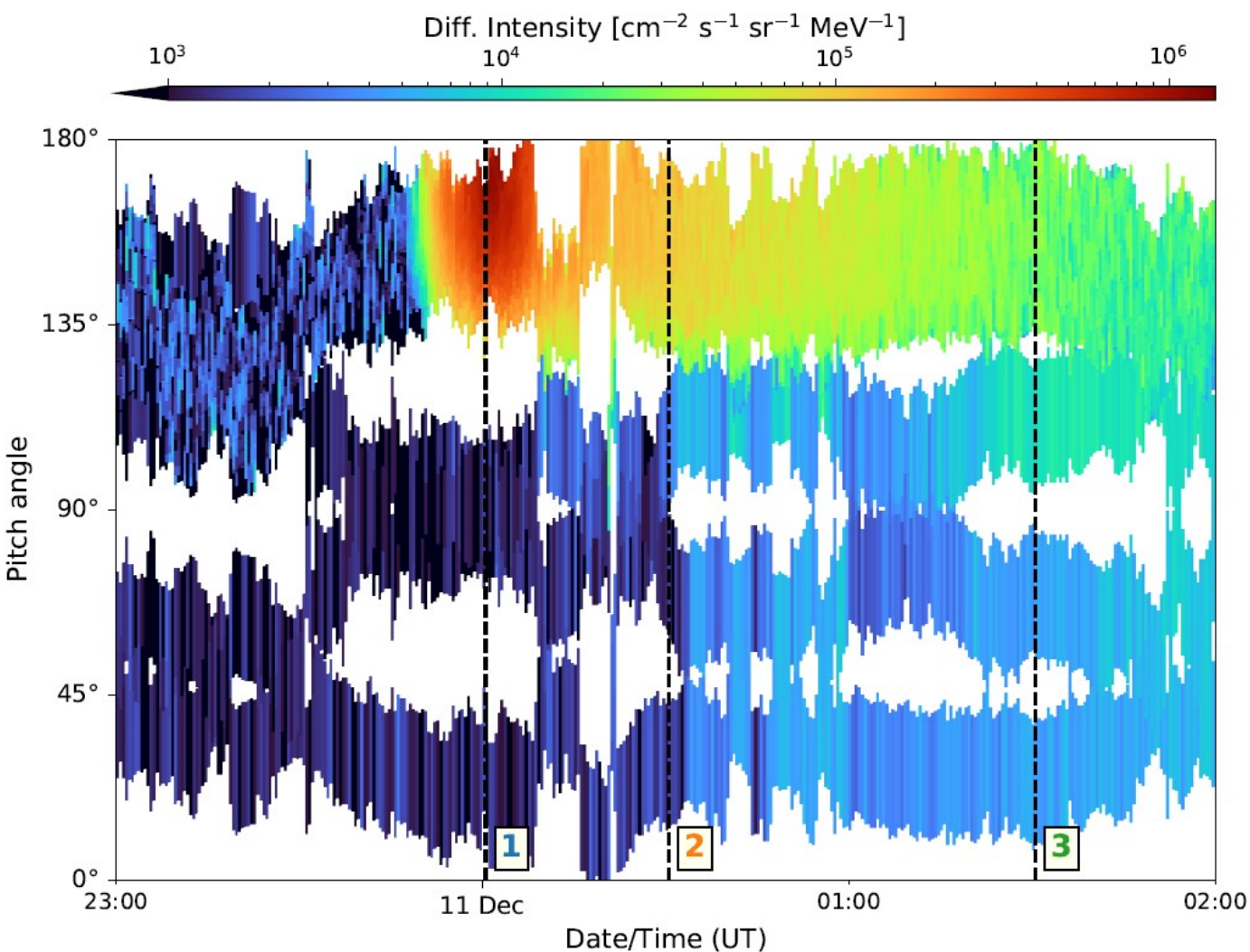
Wimmer-Schweingruber et al.,
2021, A&A accepted



Wimmer-Schweingruber et al.,
2021, A&A accepted



Electron pitch-angle distribution for the December 2020 event.

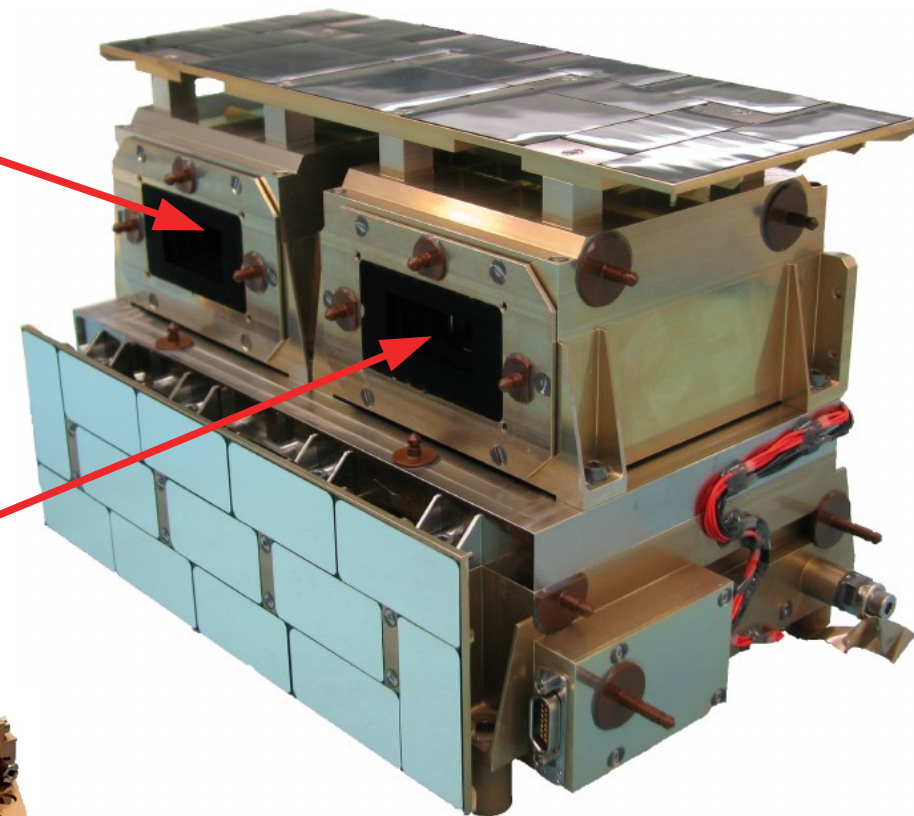


Wimmer-Schweingruber et al.,
2021, A&A accepted

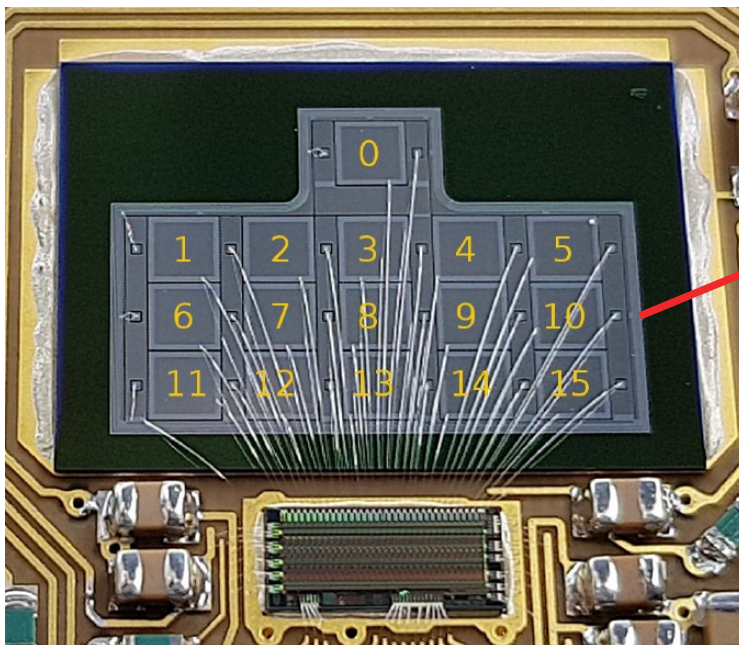
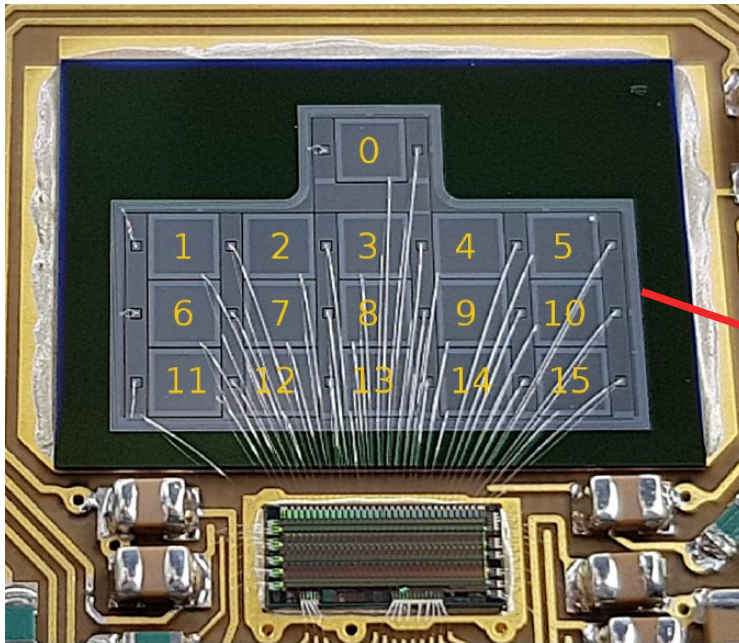
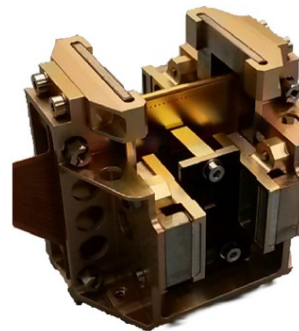


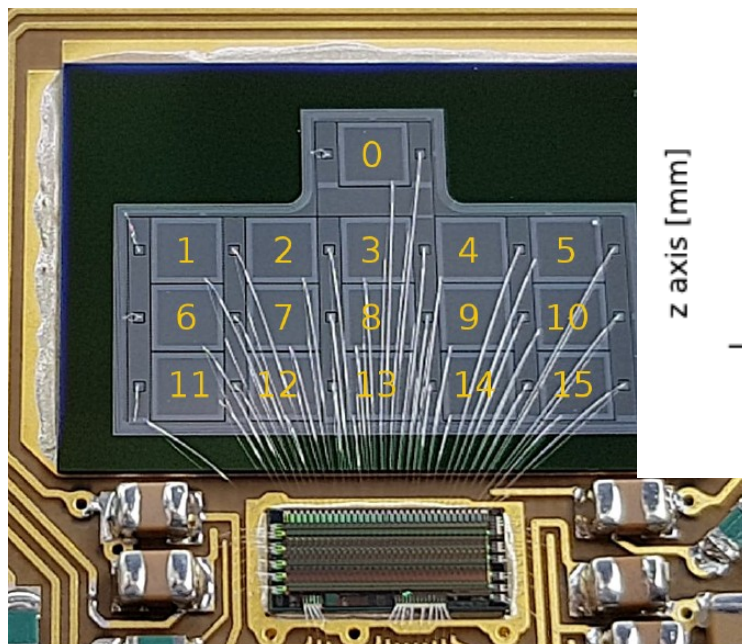
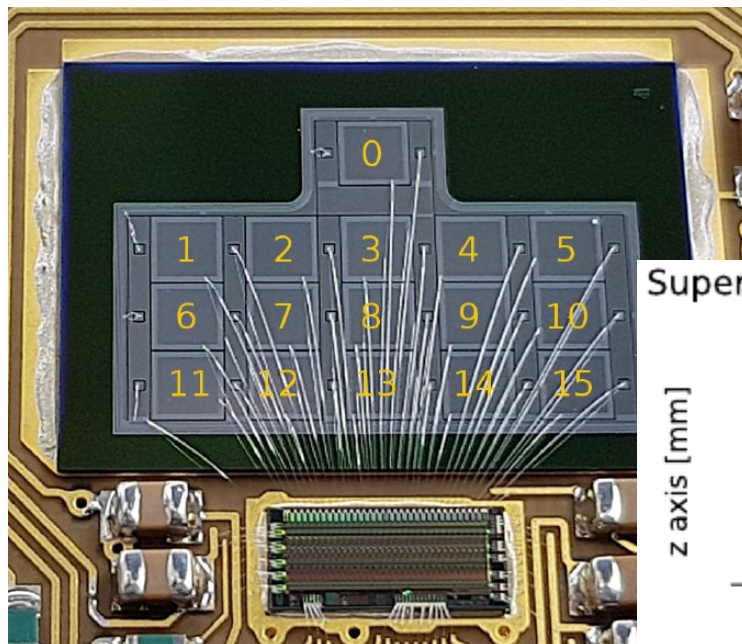
SupraThermal Electrons & Protons (STEP)

Integral channel:
Measures electrons & ions



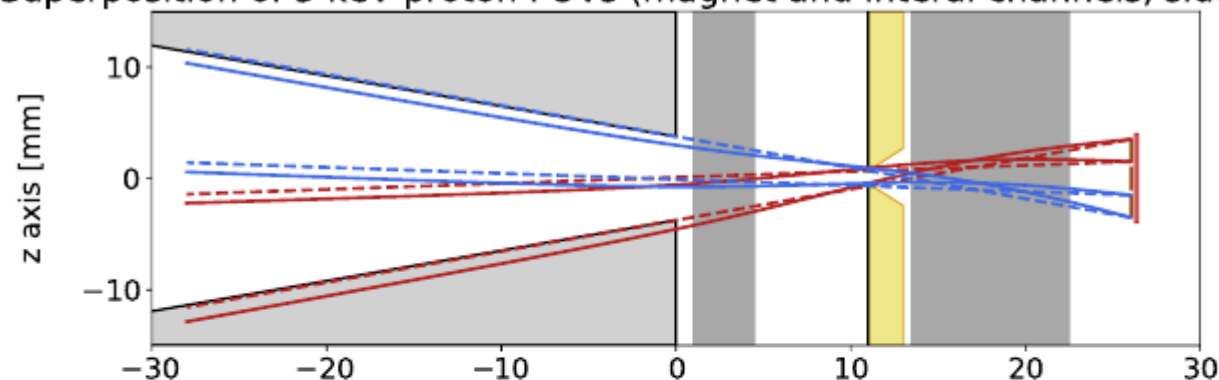
Magnet channel:
Deflects electrons,
measures ions



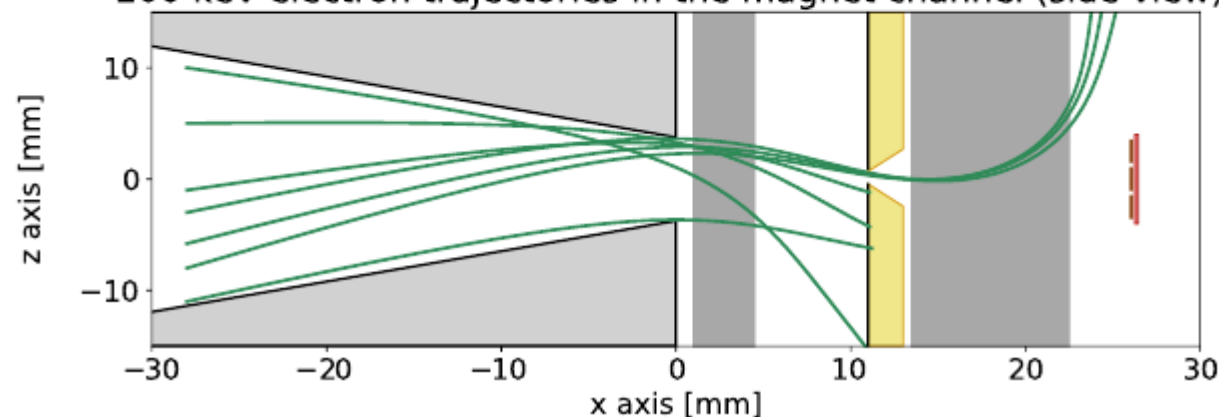


Integral channel:
Measures electrons & ions

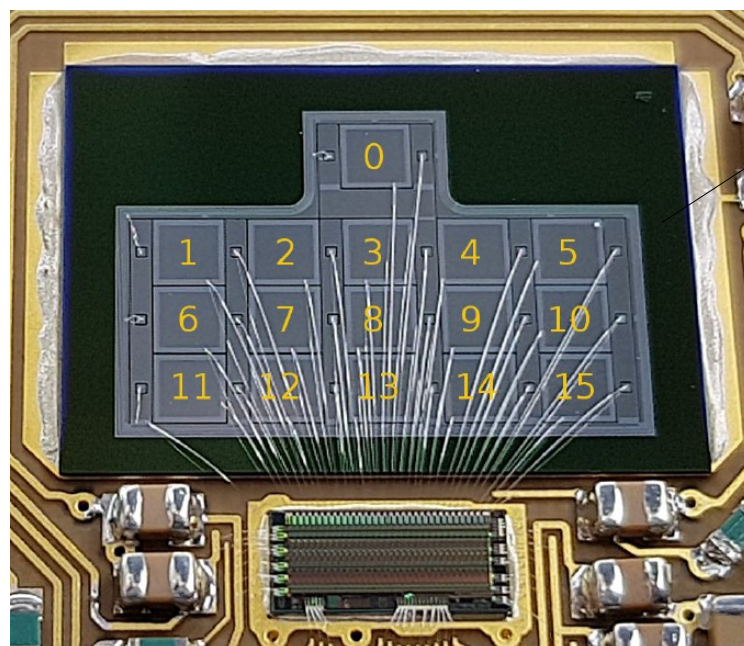
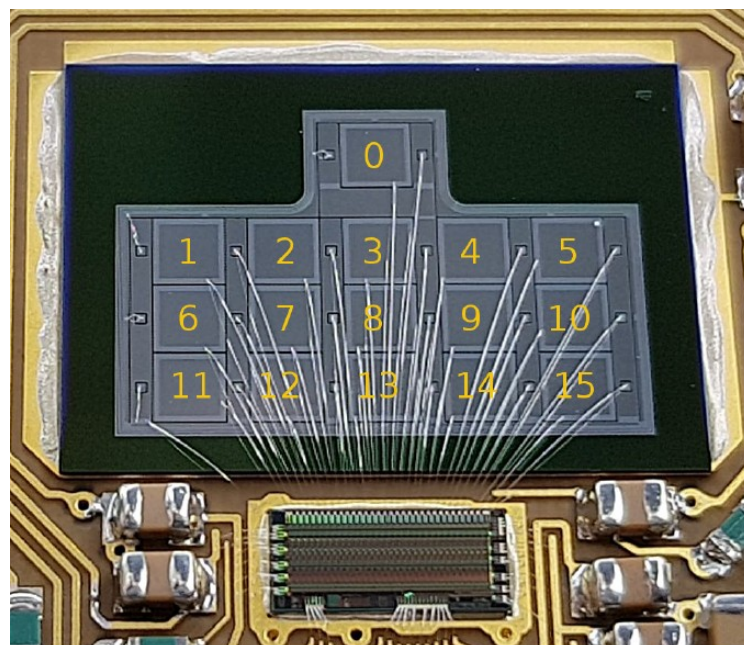
Superposition of 5 keV proton FOVs (magnet and interal channels, side view)



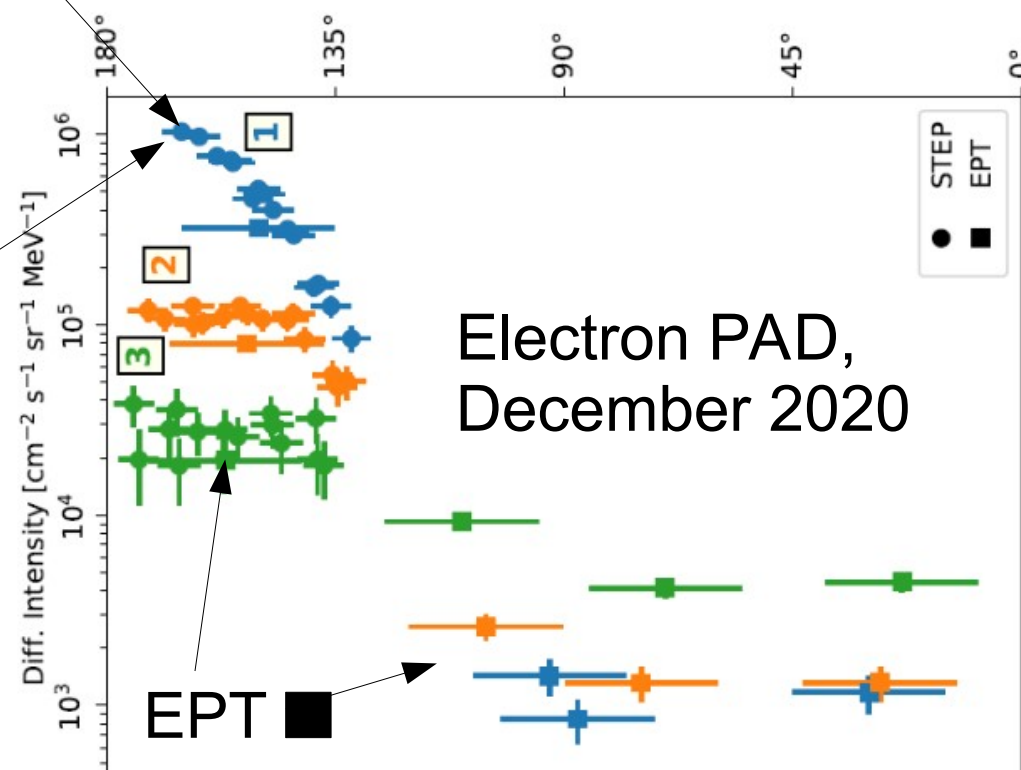
200 keV electron trajectories in the magnet channel (side view)



Magnet channel:
Deflects electrons,
measures ions



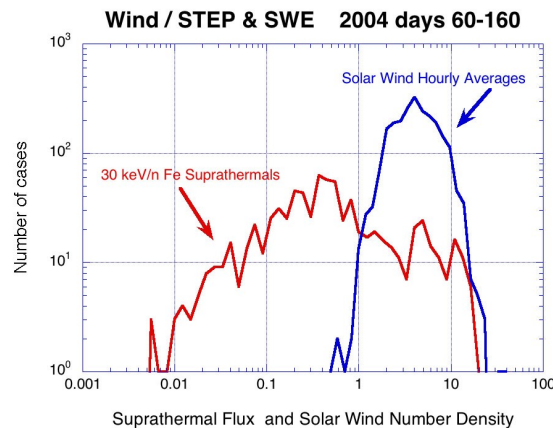
Integral channel:
Measures electrons & ions
Magnet channel:
Deflects electrons,
measures ions
„Int – Mag = electrons“



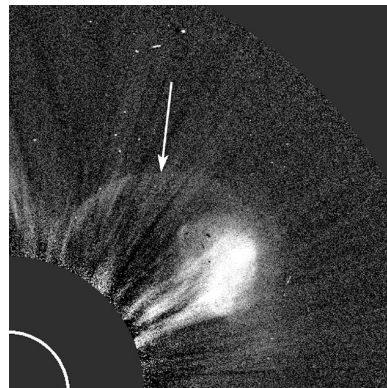


Summary suprathermal & energetic particles:

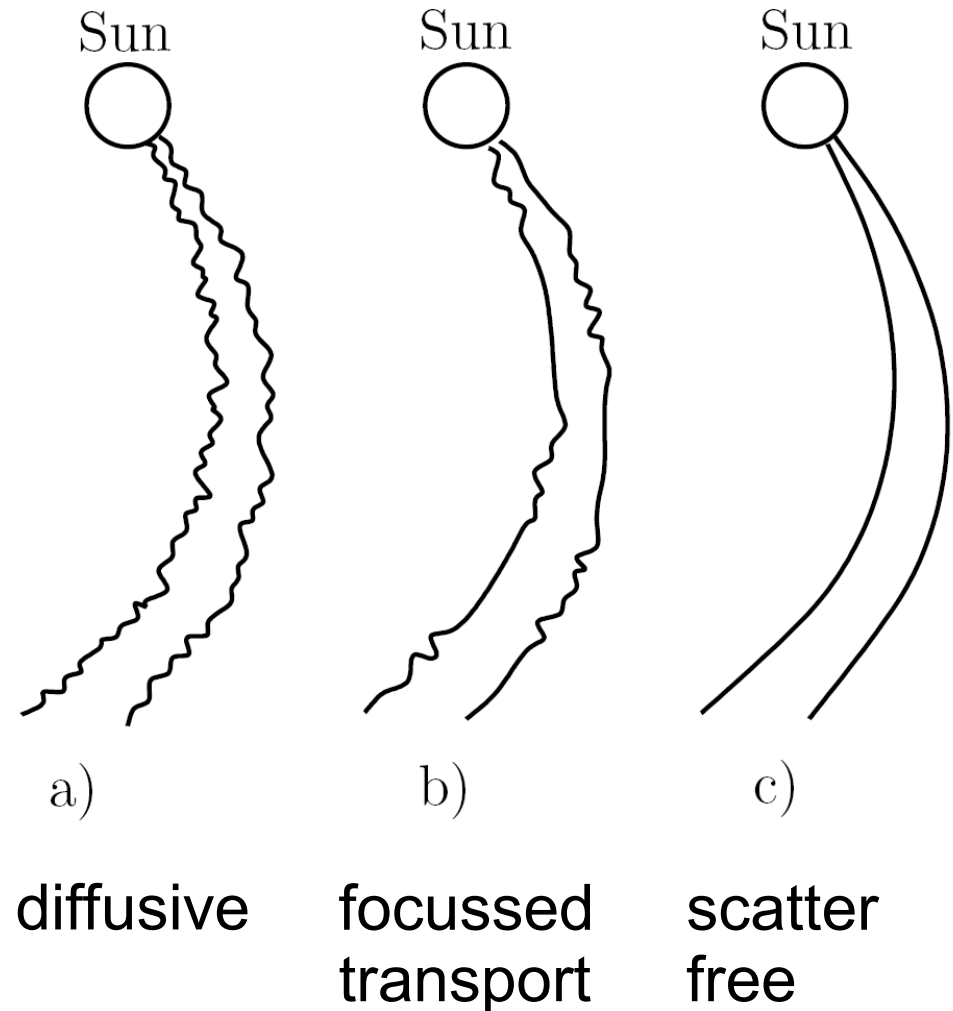
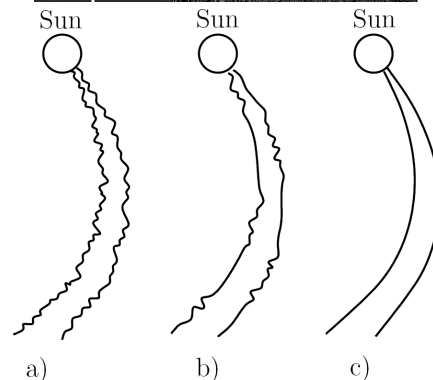
- injection



- acceleration



- transport





Part II

Interaction with Matter

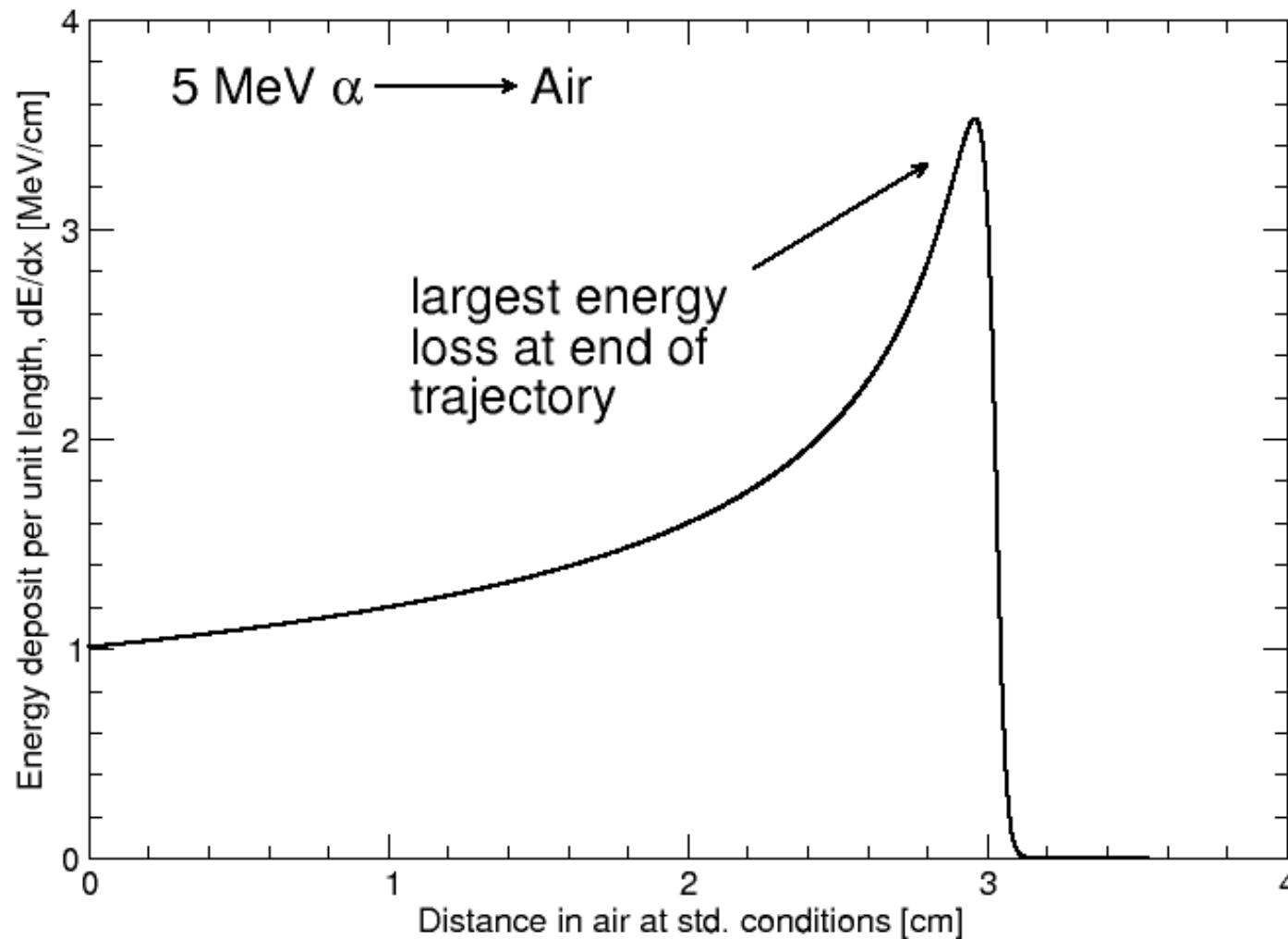
—

Implications for Exploration!



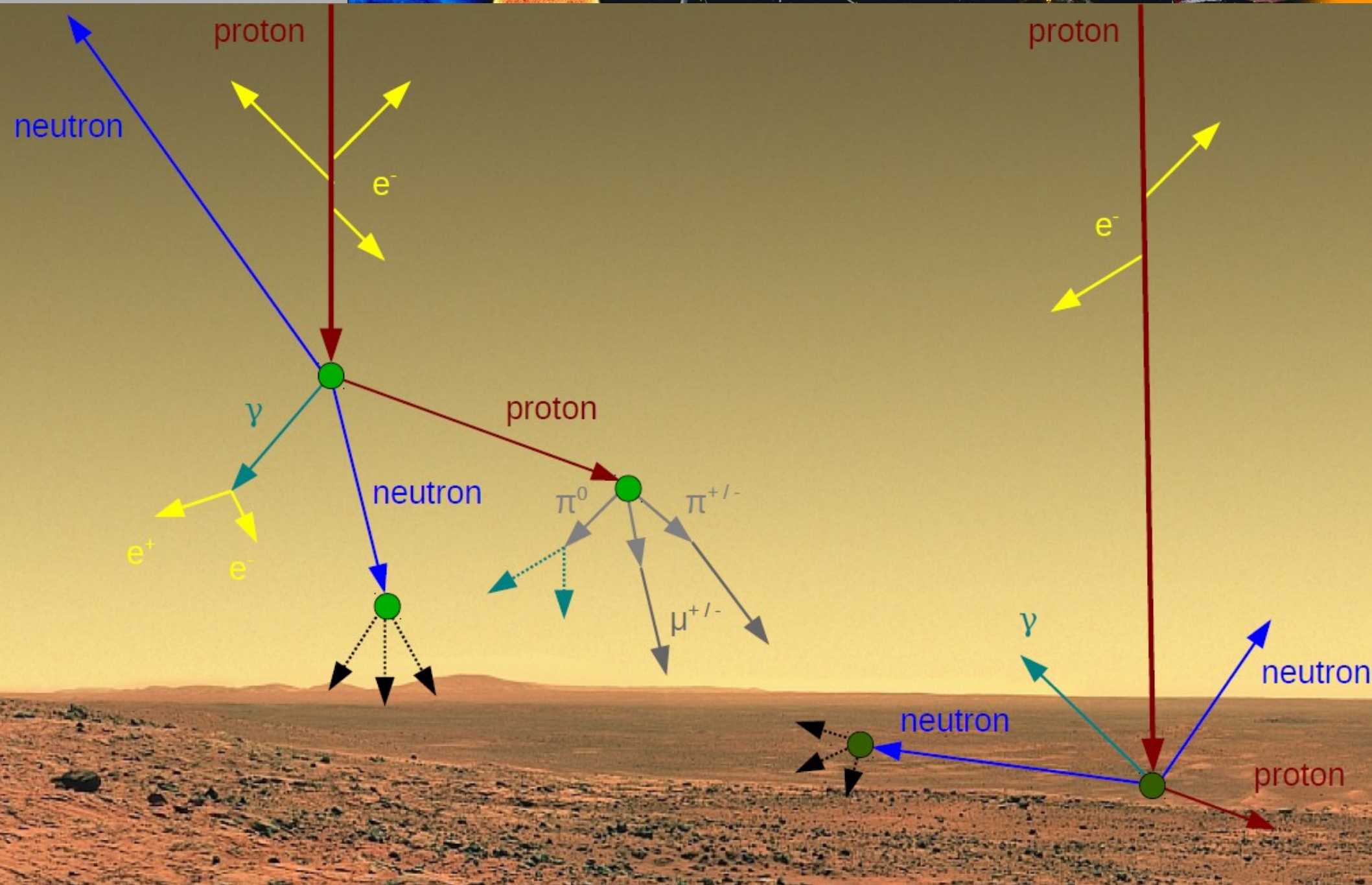
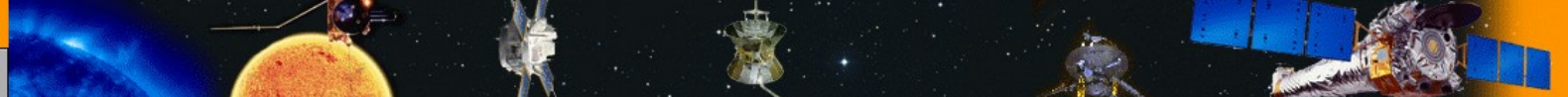
Energy loss of charged particles in matter: Deposition profile – The Bragg Peak

$$\frac{dE}{dx} = -\frac{Z_1^2 e^4 n_e}{4\pi \cdot \varepsilon_0^2 v^2 m_e} \cdot \left[\ln \left(\frac{2m_e v^2}{\langle E_B \rangle} \right) - \ln(1 - \beta^2) - \beta^2 \right], \text{ where } \beta = v/c.$$

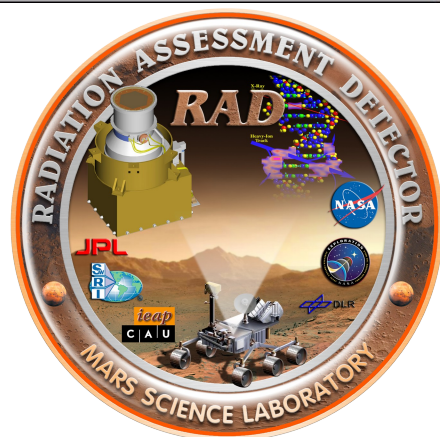
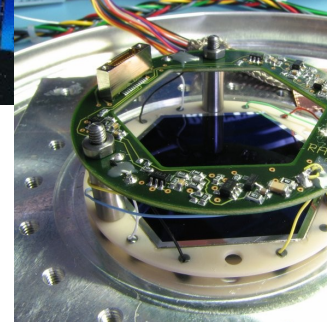


Because a particle loses more energy when it has less energy, it loses most of its energy at the end of its trajectory.

5 MeV α particle only penetrates few cm of air.



Secondary radiation (neutrals!) plays an important role! (Ehresmann, 2011)

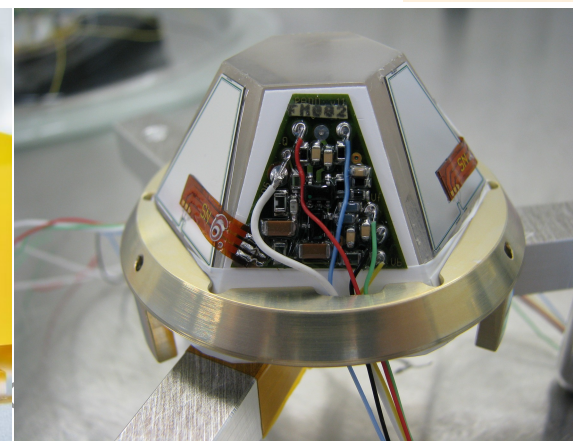
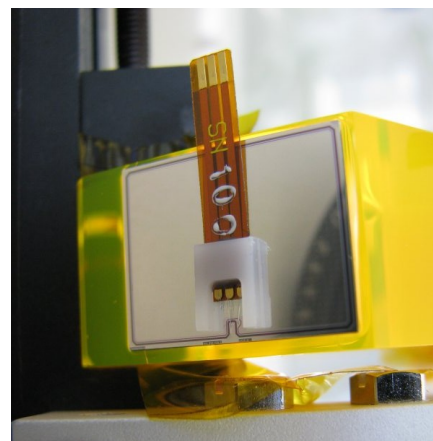
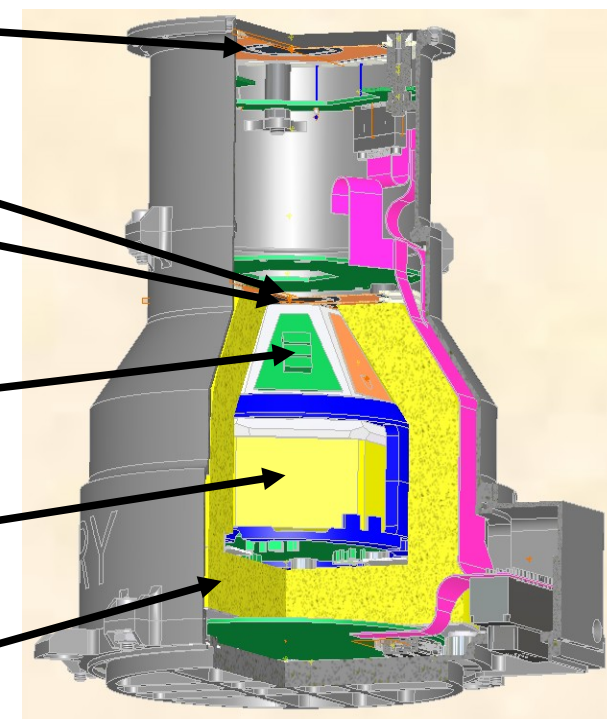
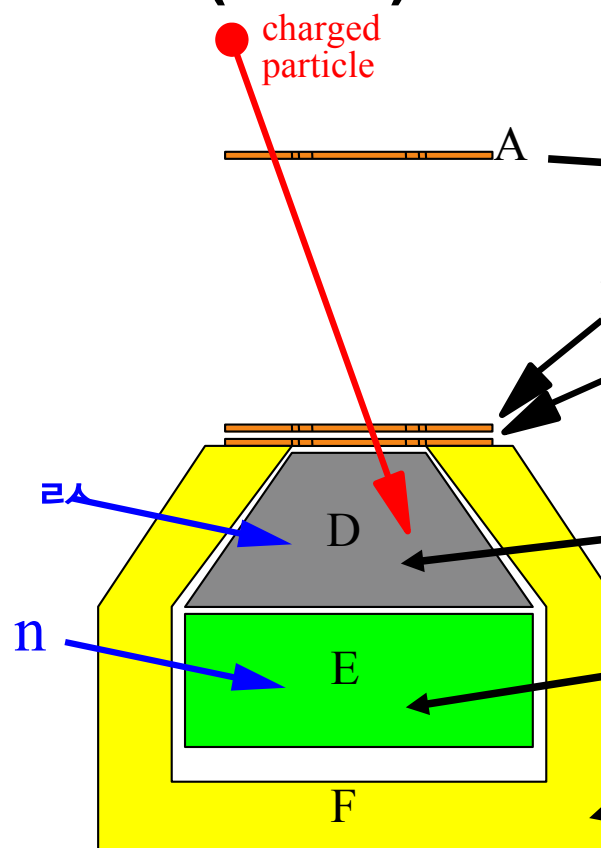


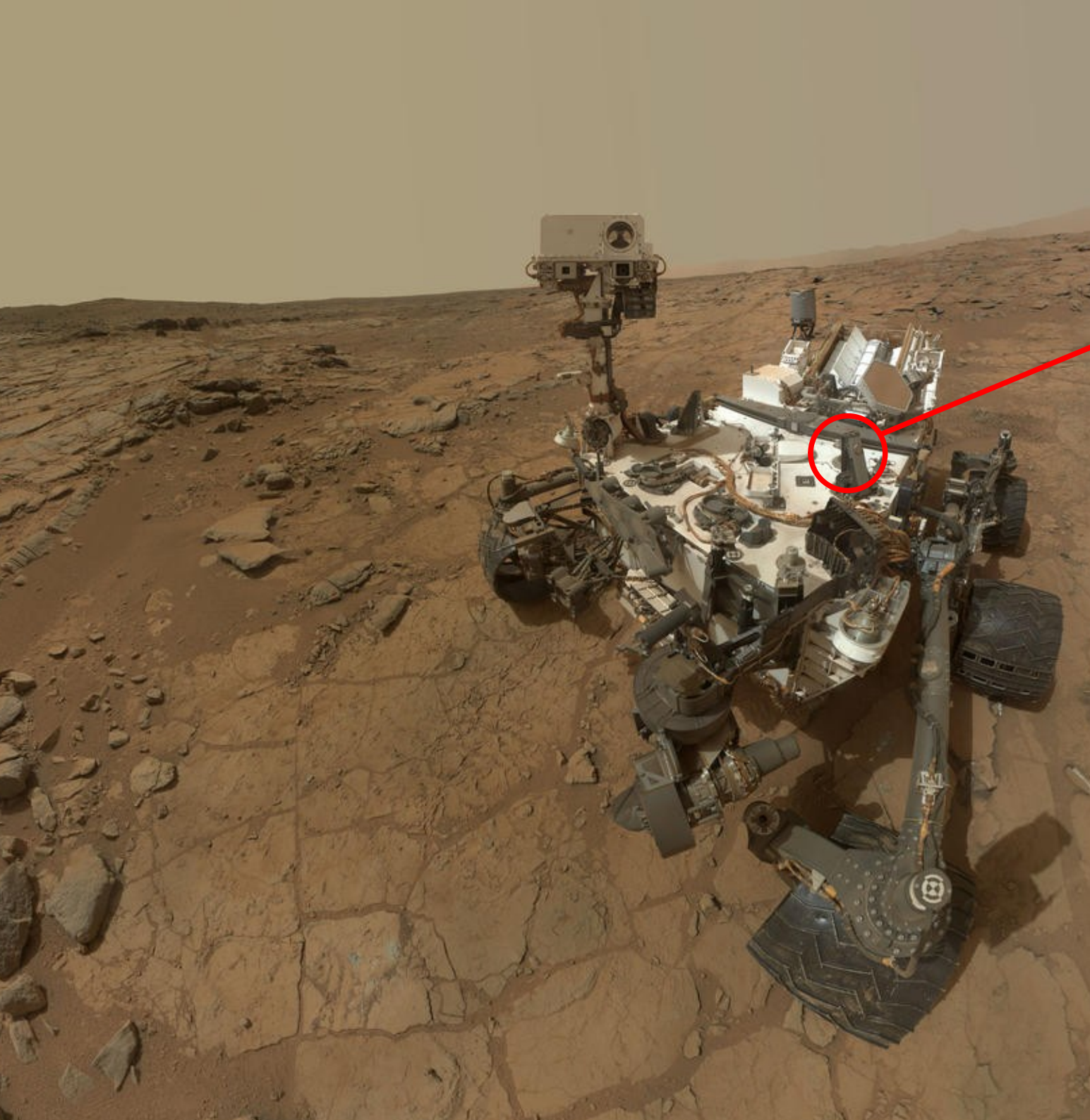
MSL's Radiation Assessment Detector (RAD)

Solution:

Requirements:

- Charged particles ($1 < Z < 27$) up to 100 MeV/nuc
- Neutral particles (n , γ) up to 100 MeV
- LET
- Composition
- Time series
- Autonomous operations







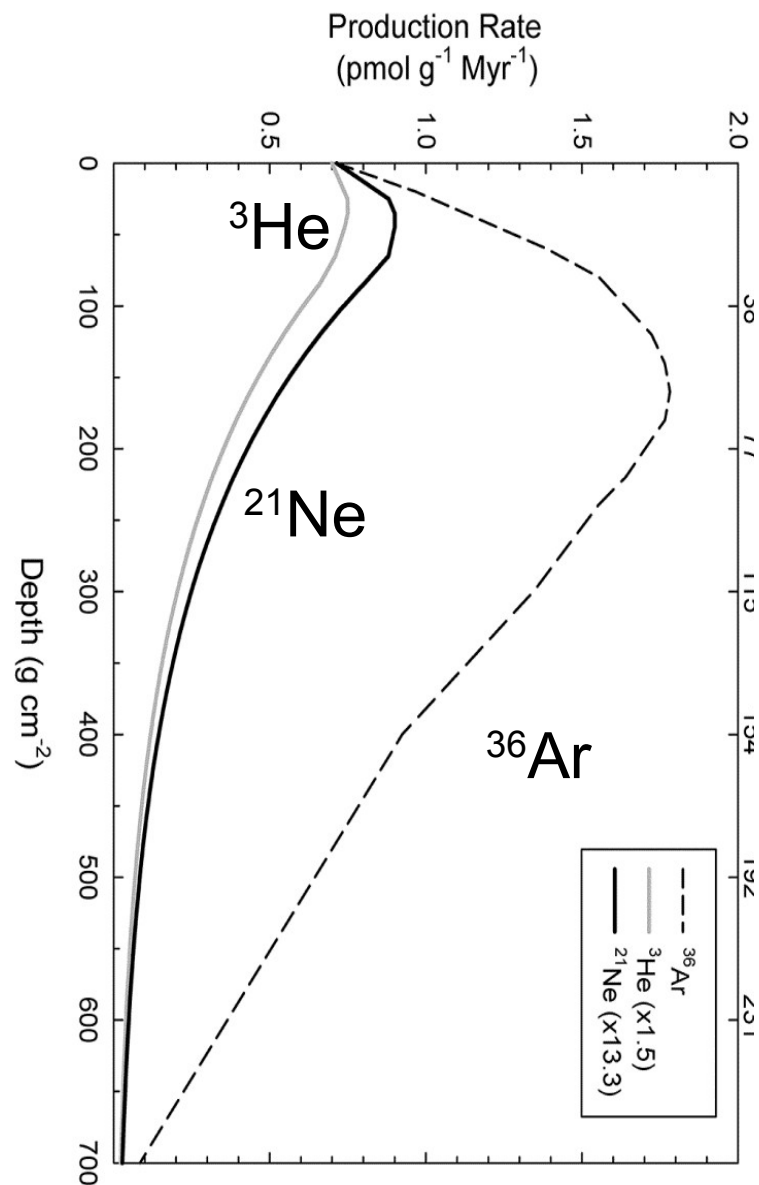


Age determination with cosmogenic isotopes

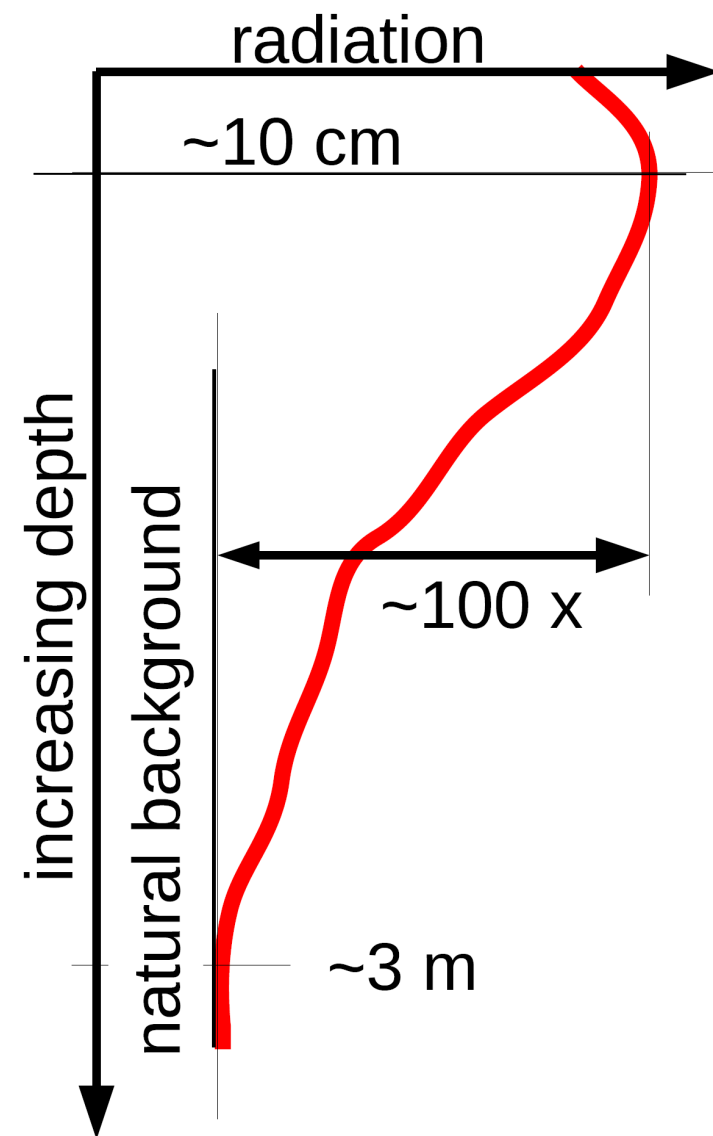
Nuclear reactions lead to creation of cosmogenic isotopes (here ^3He , ^{21}Ne , ^{36}Ar)

Their (relative) abundance is an indicator for the exposure age.

Sheepbed was exposed for only 80 ± 30 million years!



(Farley et al., Science, 2013)



Ionizing radiation breaks chemical bonds and produces radicals and oxidants.





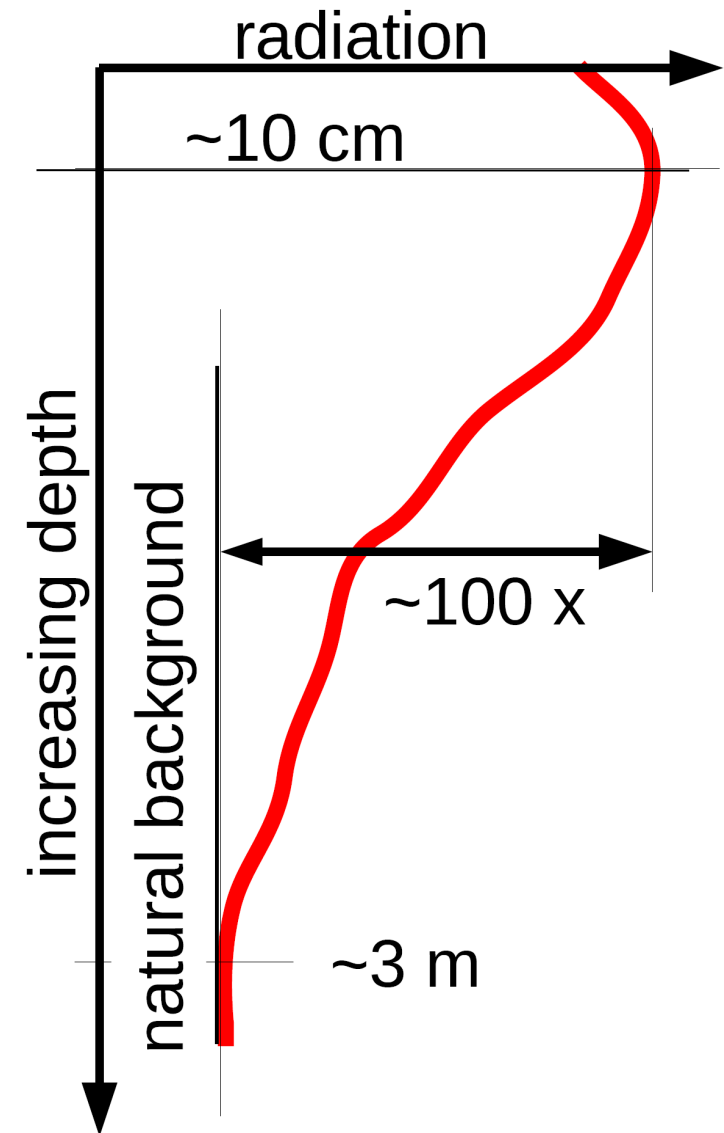
How long could organic molecules survive ionizing radiation environment?

Previous models: 50 – 150 mGy/y
RAD measurements: 76 mGy/y

Organic molecules are efficiently destroyed at a depth of 4-5 cm. In 650 million years only 1/1000 survives.

How many after 3.8 Gy?

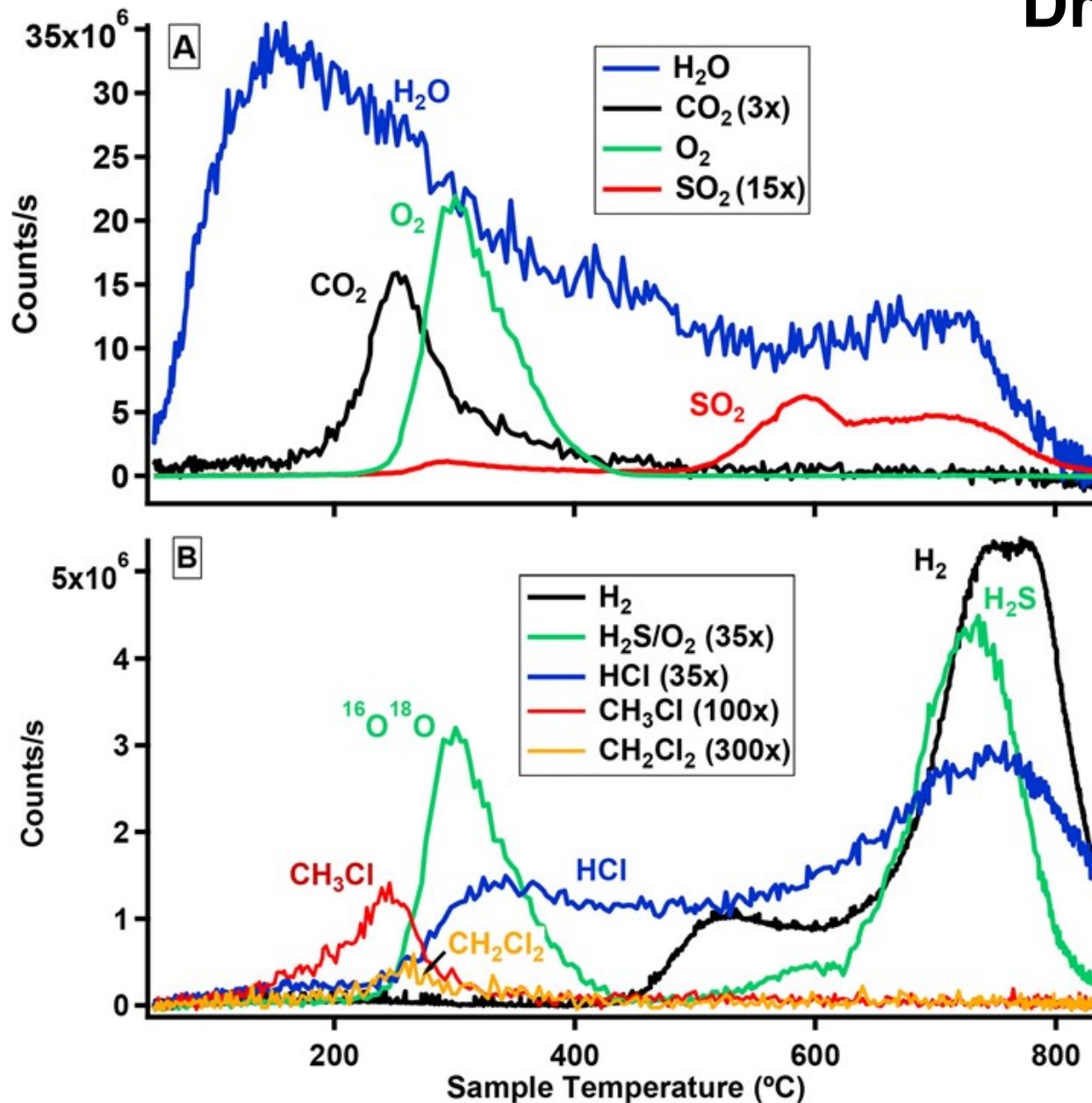
=> Half of the organics should still be around if the soil were only exposed for 65 million years.





Drill results from SAM

Measurements show that the drilled mudstone contained carbon, nitrogen, oxygen, and sulfur. These elements are needed for life to form.



	SURFACE HABITATS		DEEP HABITATS				
	Shallow water		Trapped oceans			Top oceans	
	The Earth	Mars	Ganymede	Callisto	Titan	Europa	Enceladus
Liquid Water	●	●	●	●	●	●	●
Stable Environment	●	●	●	●	●	●	●
Essential elements	●	●	●	●	●	●	●
Chemical Energy	●	●	●	●	●	●	●

(Ming et al., Science, 2013)

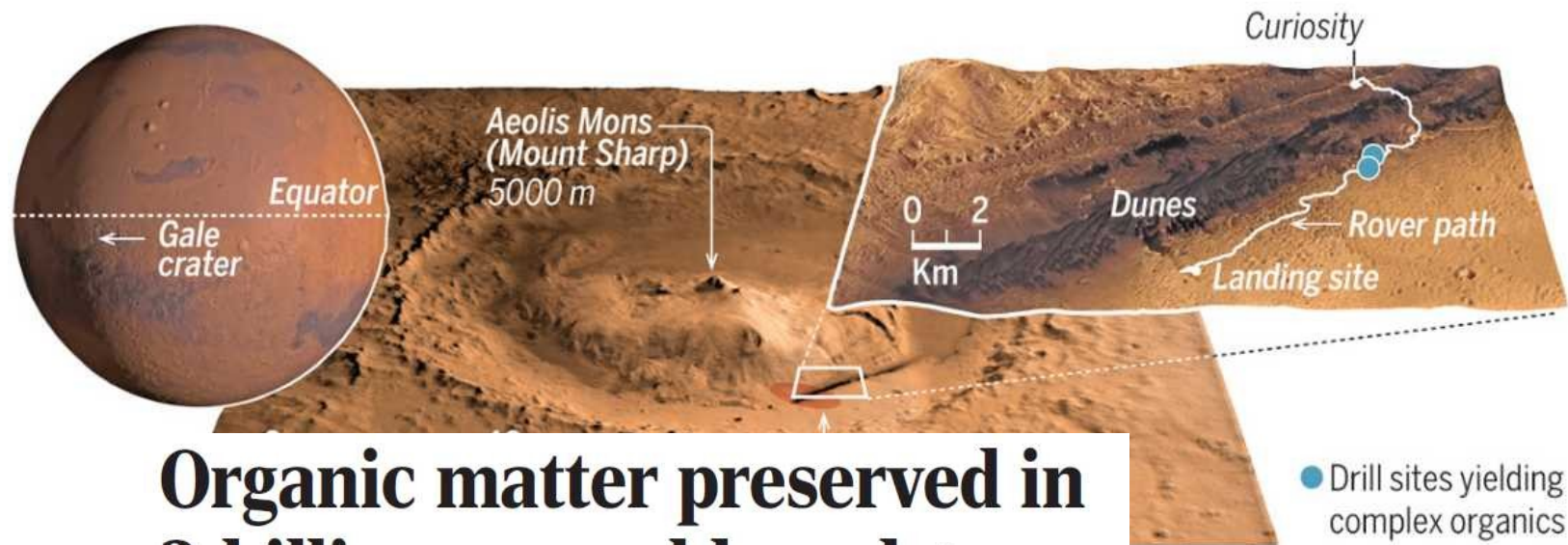


PLANETARY SCIENCE



NASA Curiosity rover hits organic pay dirt on Mars

Carbon molecules in rocks from ancient lakebed resemble kerogen, a “goopy” fossil fuel building block on Earth

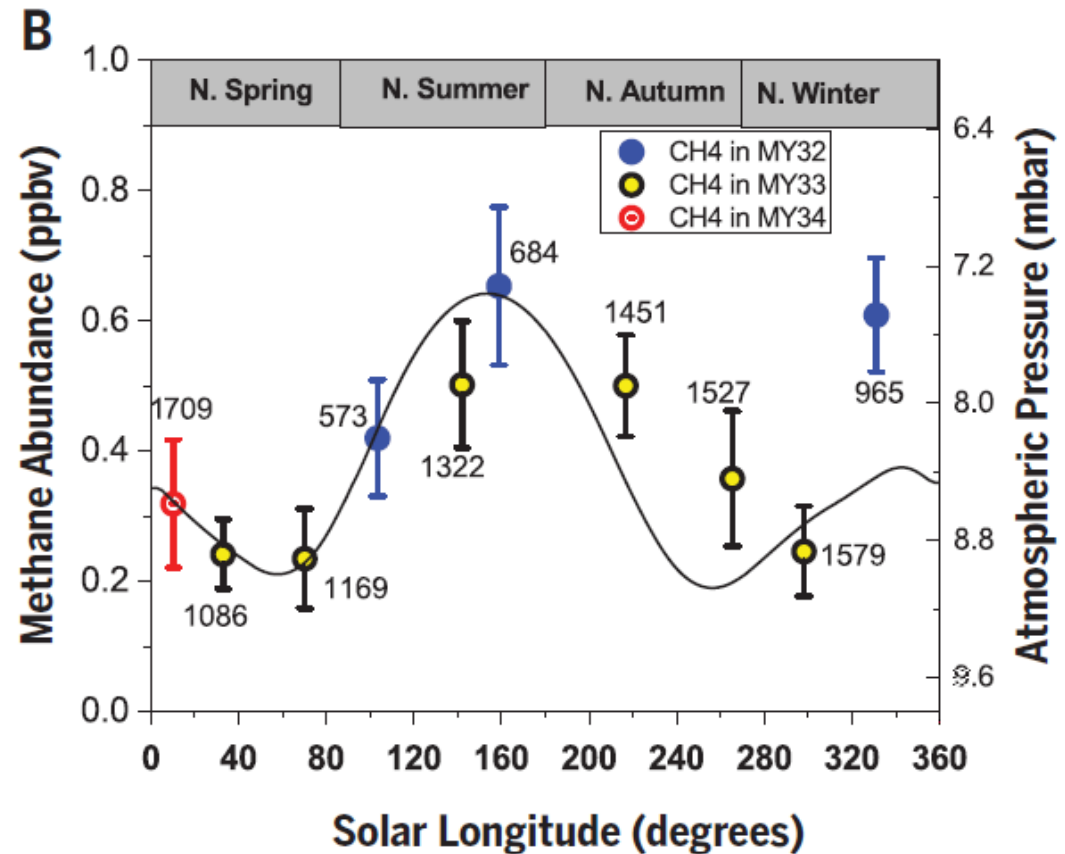
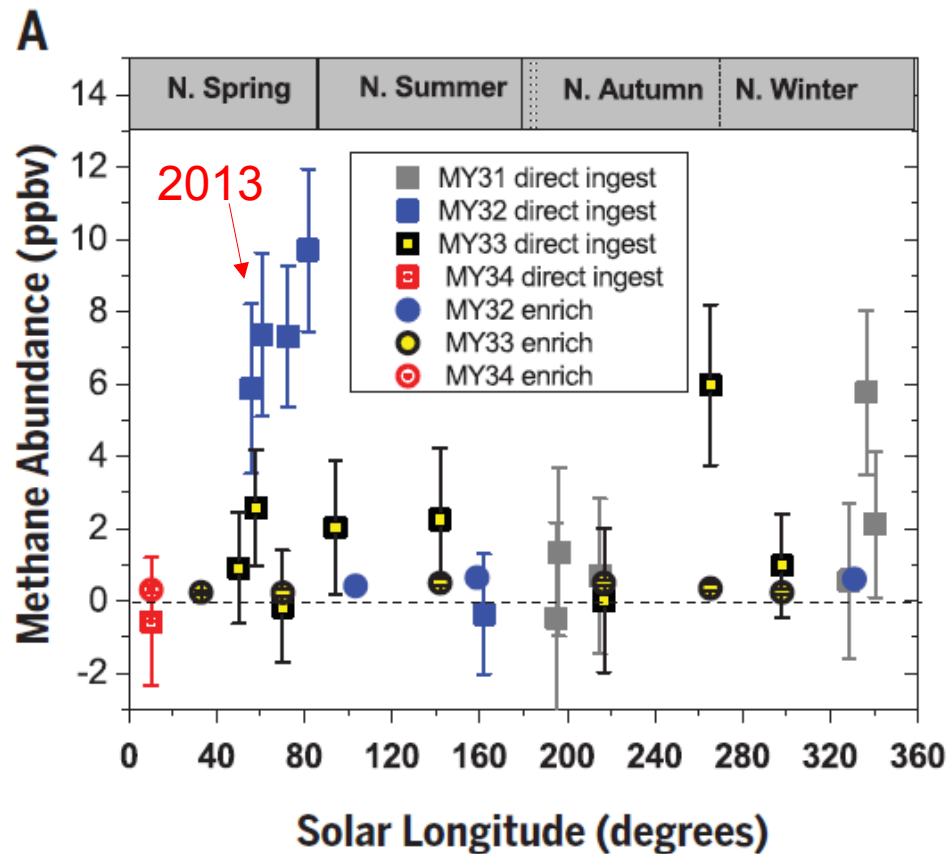


**Organic matter preserved in
3-billion-year-old mudstones
at Gale crater, Mars**

Eigenbrode et al. Science 2018;360:1096



Detection of Methane (CH_4) on Mars



(Webster et al., 2018)

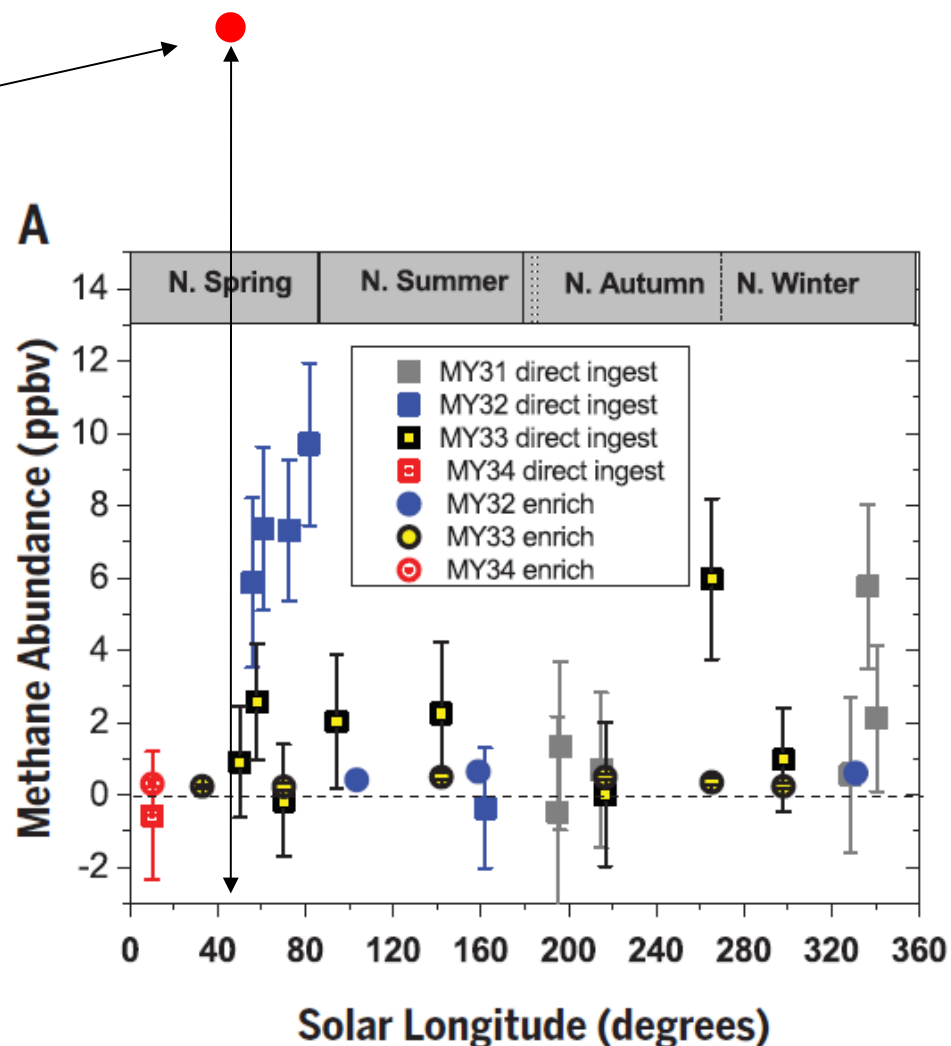
Methane had been detected by Formisano et al. (2004) with ESA's Mars Express. CH_4 was seen again in-situ by SAM on MSL in 2013. CH_4 background varies seasonally (Webster et al., 2018)



Detection of Methane (CH_4) on Mars – again!

- MSL-Measurements of 2013 were confirmed by MEX
- **MSL/TLS measured 21 ppbv CH_4 on June 19, 2019**
- MEX was above Gale crater at that time
- Why is CH_4 so variable on Mars?

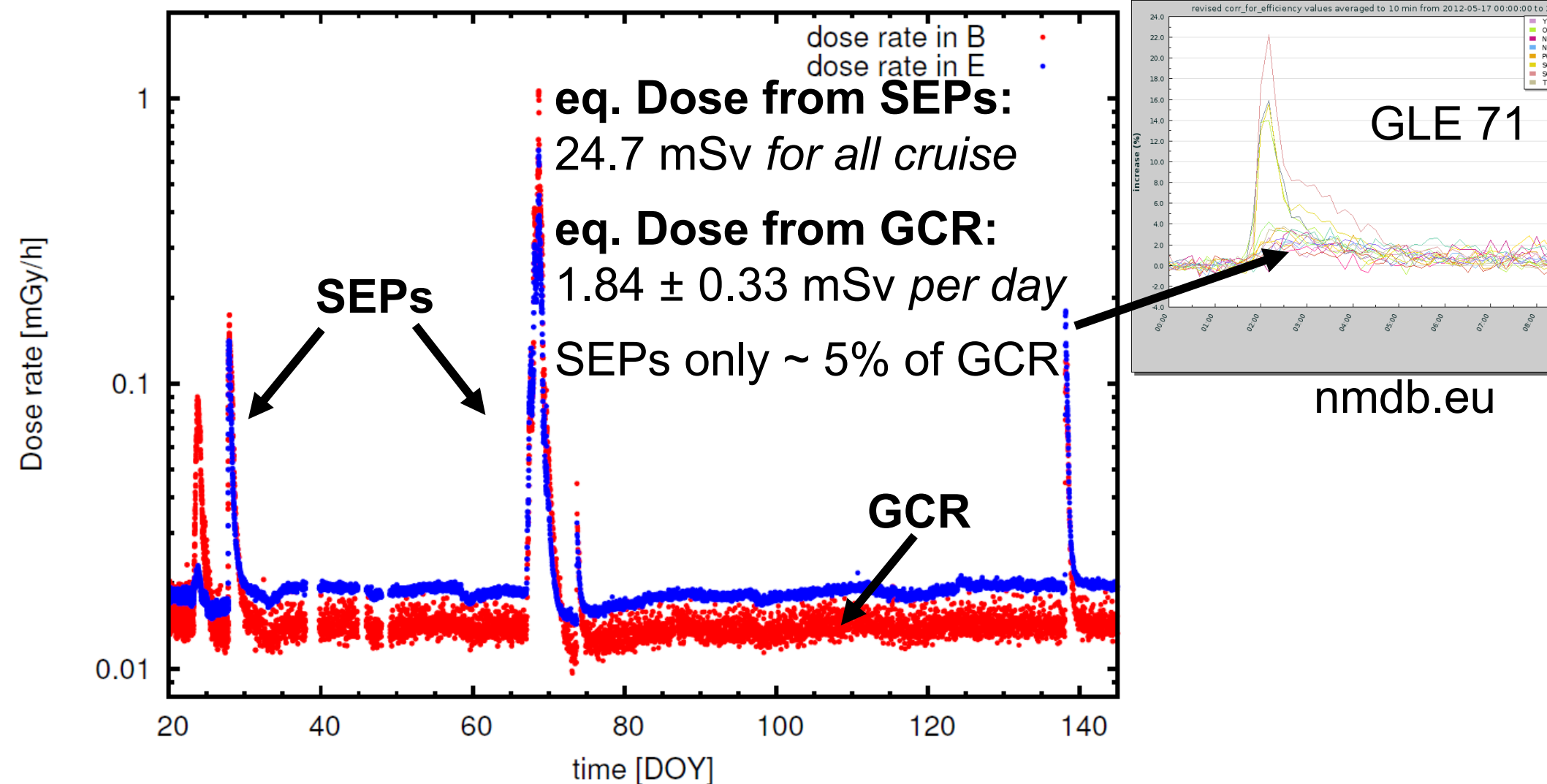
For comparison: On Earth the CH_4 concentration in pre-industrial times was ~ 700 ppbv, today (2019) it is 1866 ppbv.





Back to radiation:

Summary of solar particle events seen by MSL/RAD during cruise



GCR dominates radiation exposure during RAD's cruise



Risks Assessments for all DRM*s (Jan 2015)

Human Spaceflight Risks	In Mission Risk - Operations						Post Mission Risk - Long Term Health					
Human Spaceflight Risks 01/12/15	Low Earth Orbit	Low Earth Orbit	Deep Space Sortie	Lunar Visit/Habitation	Deep Space Journey/Habitation	Planetary	Low Earth Orbit	Low Earth Orbit	Deep Space Sortie	Lunar Visit/Habitation	Deep Space Journey/Habitation	Planetary
	6 Months	12 Months	30 Days	1 year	1 Year	3 years	6 Months	12 Months	30 Days	1 year	1 Year	3 years
VIIP	A	A	A	A	RM	RM	A	A	A	A	RM	RM
Renal Stone Formation	A	A	A	A	RM	RM	RM	RM	RM	RM	RM	RM
Inadequate food and nutrition	A	A	A	A	RM	RM	A	A	A	A	A	RM
Risk of Space Radiation Exposure	A	A	A	A	A	A	A	A	A	RM	RM	RM
Medications Long Term Storage	A	A	A	A	A	RM	A	A	A	A	A	RM
Acute and Chronic Carbon Dioxide	A	A	A	A	RM	RM	A	A	A	A	A	A
inflight Medical Conditions	A	A	A	RM	RM	RM	A	A	A	A	RM	RM
Cognitive or Behavioral Conditions	A	A	A	A	RM	RM	A	A	A	RM	RM	RM
Risk of Bone Fracture	A	A	A	A	A	A	A	A	A	A	A	RM
Team Performance Decrements#	A	A	A	A	RM	RM	A	A	A	A	A	A
Reduced Muscle Mass, Strength	A	A	A	A	A	RM	A	A	A	A	A	A
Reduced Aerobic Capacity	A	A	A	A	A	RM	A	A	A	A	A	A
Sensorimotor Alterations	A	A	A	A	A	RM	A	A	A	A	A	RM
Human-System Interaction Design#	A	A	A	RM	RM	RM	A	A	A	A	A	A
Injury from Dynamic Loads	A	A	RM	RM	RM	RM	A	A	RM	RM	RM	RM
Sleep Loss	A	A	A	A	RM	RM	A	A	A	A	RM	RM
Altered Immune Response	A	A	A	A	RM	RM	A	A	A	A	A	RM
Celestial Dust Exposure	N/A	N/A	A	TBD	TBD	TBD	N/A	N/A	A	TBD	TBD	TBD
Host-Microorganism Interactions	A	A	A	A	RM	RM	A	A	A	A	A	RM
Injury due to EVA Operations	A	A	A	RM	A	RM	A	A	A	RM	RM	RM
Decompression Sickness	A	A	A	A	RM	A	A	A	A	RM	A	RM
Toxic Exposure	A	A	A	A	A	A	A	A	A	A	A	A
Hypobaric Hypoxia	A	A	A	A	A	A	A	A	A	A	A	A
Space Adaptation Back Pain	A	A	A	A	A	A	N/A	N/A	N/A	N/A	N/A	N/A
Urinary Retention	A	A	A	A	A	A	A	A	A	A	A	A
Hearing Loss Related to Spaceflight	A	A	A	A	A	A	A	A	A	A	A	A
Orthostatic Intolerance	A	A	A	A	A	A	A	A	A	A	A	A
Injury from Sunlight Exposure - retired	A	A	A	A	A	A	A	A	A	A	A	A
Risk of electrical shock - Retired	A	A	A	A	A	A	A	A	A	A	A	A

A - Accepted RM- Requires Mitigation

Green - controlled

Yellow - partially controlled

Red - uncontrolled

* Design Reference Mission



Summary of radiation exposure seen by MSL/RAD during cruise

Quantity	value	Estimated variability	Two 180-day legs return trip
RAD cruise measurement SEPs	24.7 mSv (5% of all)	Orders of magnitude	?
RAD cruise measurement GCR	1.84 mSv/d	0.33 mSv/d ± 20%	= 662 ± 108 mSv ± 20%
6-month stay of astronaut on ISS	75-90 mSv/(a/2)	20%	150-180 mSv
Radiation worker limit (ICRP)	20 mSv/a	n/a	
Average exposure of normal population	4 mSv/a	Wide range, radon!	
Allowable additional exposure norm. pop.	1 mSv/a	n/a	



Summary of radiation exposure for a manned mission to Mars based on MSL/RAD measurements

Radiation exposure on a
mission to Mars:

Cruise: 662 +/- 108 mSv

Mars: 320 +/- 50 mSv

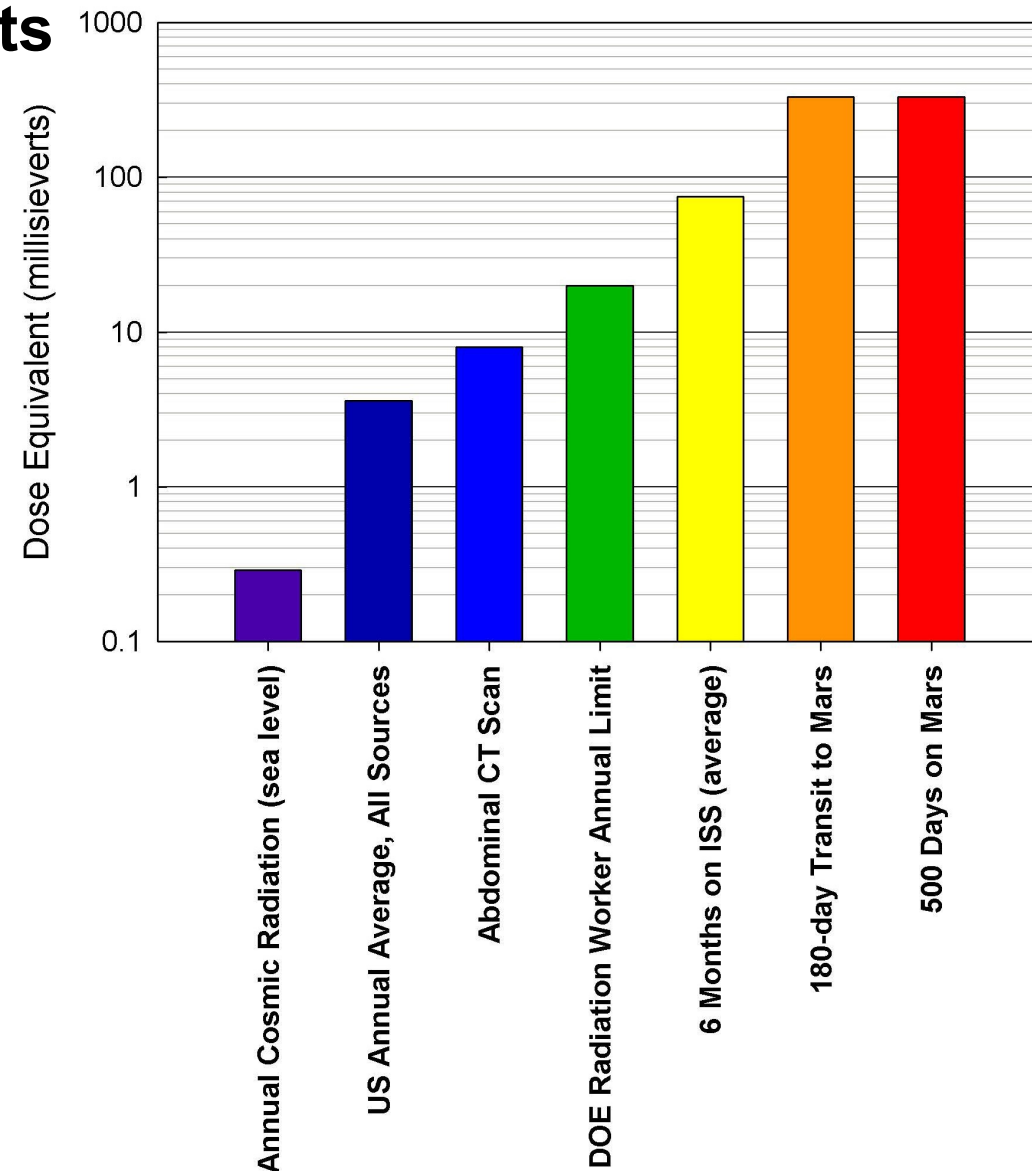
Total ~ 1000 mSv

For comparison:

6 months ISS: 75-90 mSv

radiation worker: 20 mSv/y

CT-scan: 8 mSv

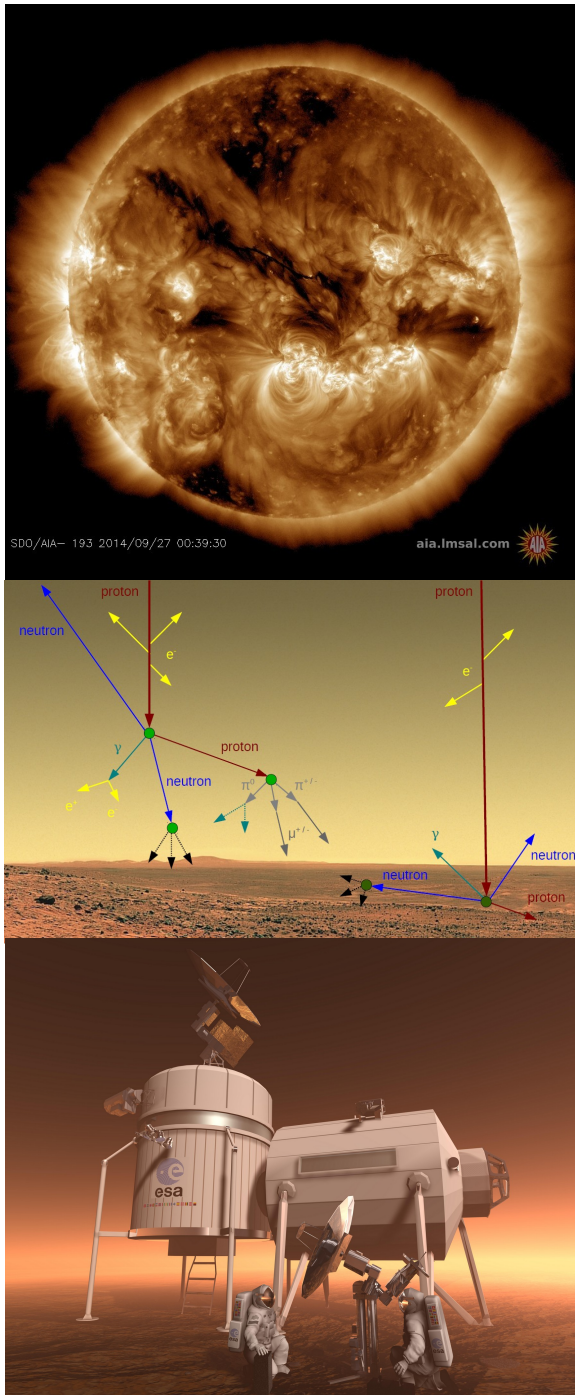


(Zeitlin et al., Science, 2013)



Implications for human exploration

- Particle radiation is complex!
- Space weather predictions are still very difficult
- Large variability (solar, heliospheric, seasonal, diurnal)
- Secondary radiation important (n/ γ)
- Where should we live on Moon & Mars?
- Implications for non-terrestrial life? Exo-, astrobiology?





Conclusions:

Space radiation is influenced by a number of factors:

- solar corona
- solar wind
- transport phenomena
- heliosphere

Space radiation is important to

- understand the history of the solar system
- understand the habitability of (exo-) planets and moons
- prepare for human exploration of the solar system

謝謝