Dependence of the Martian radiation environment on atmospheric depth: modeling and measurement

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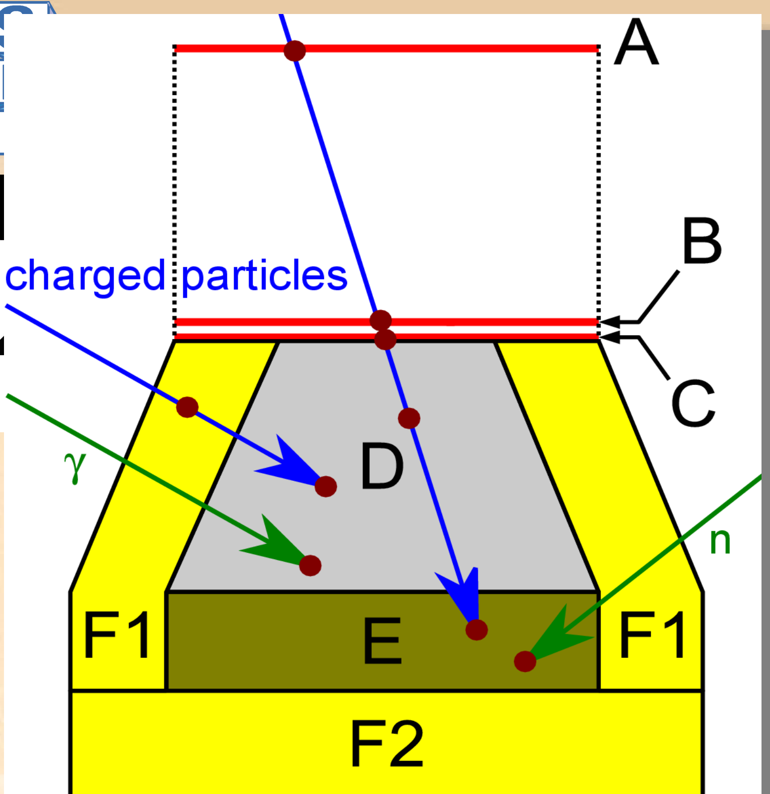
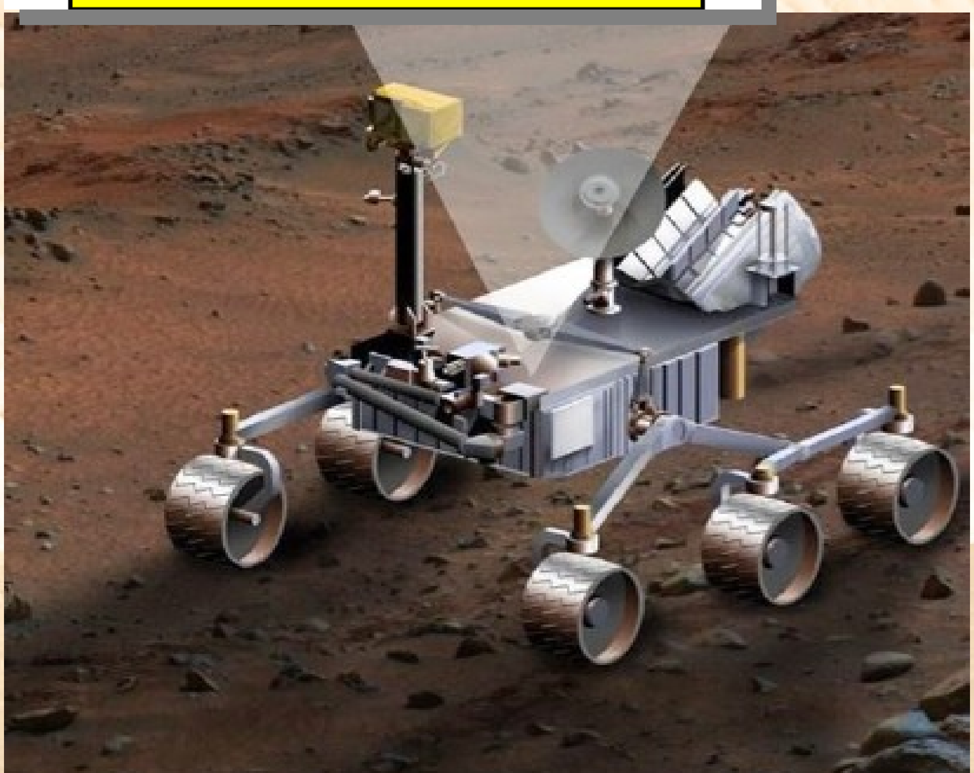
21st WRMISS

6–8 September 2016, ESTEC, Noordwijk

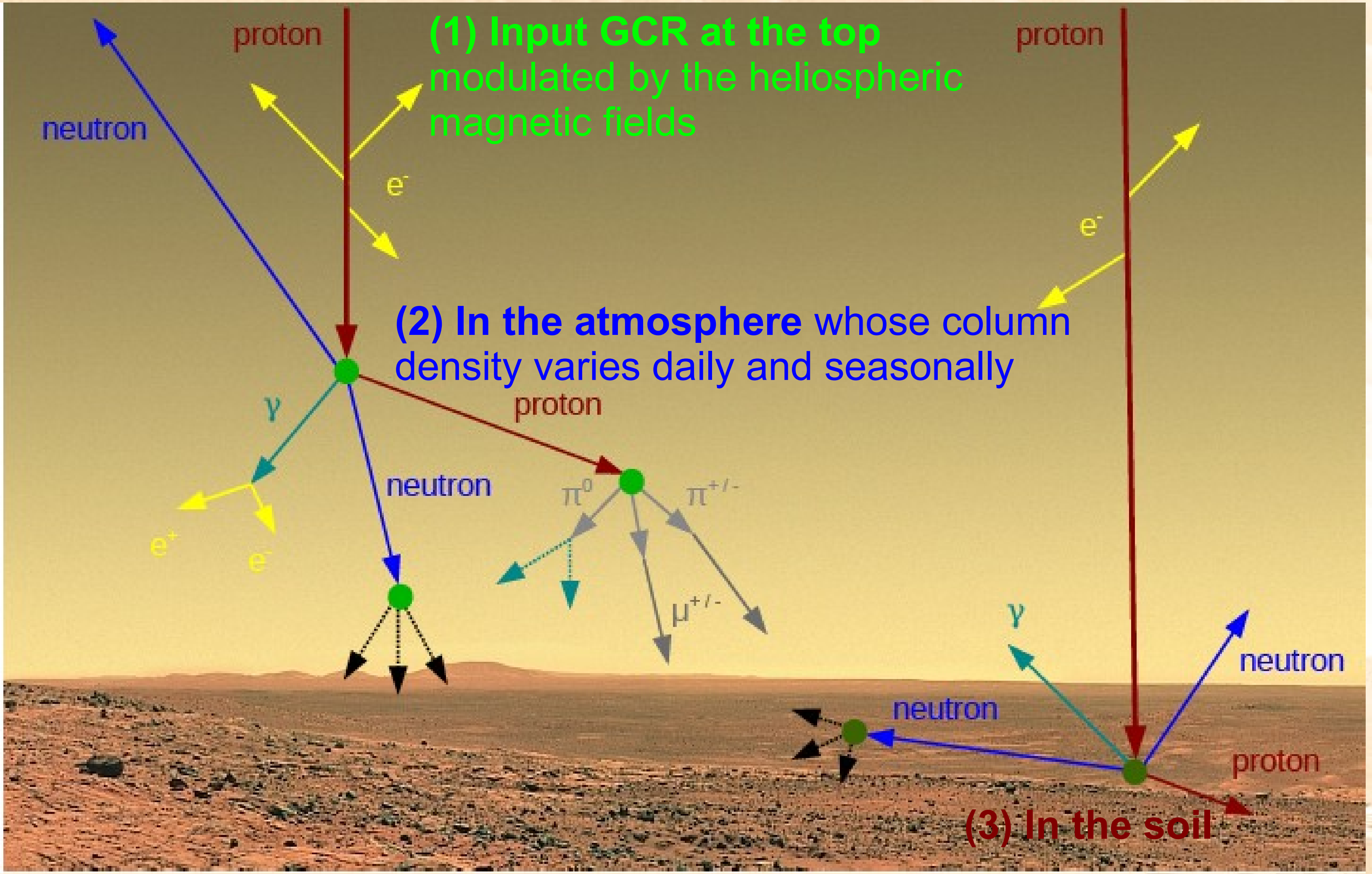




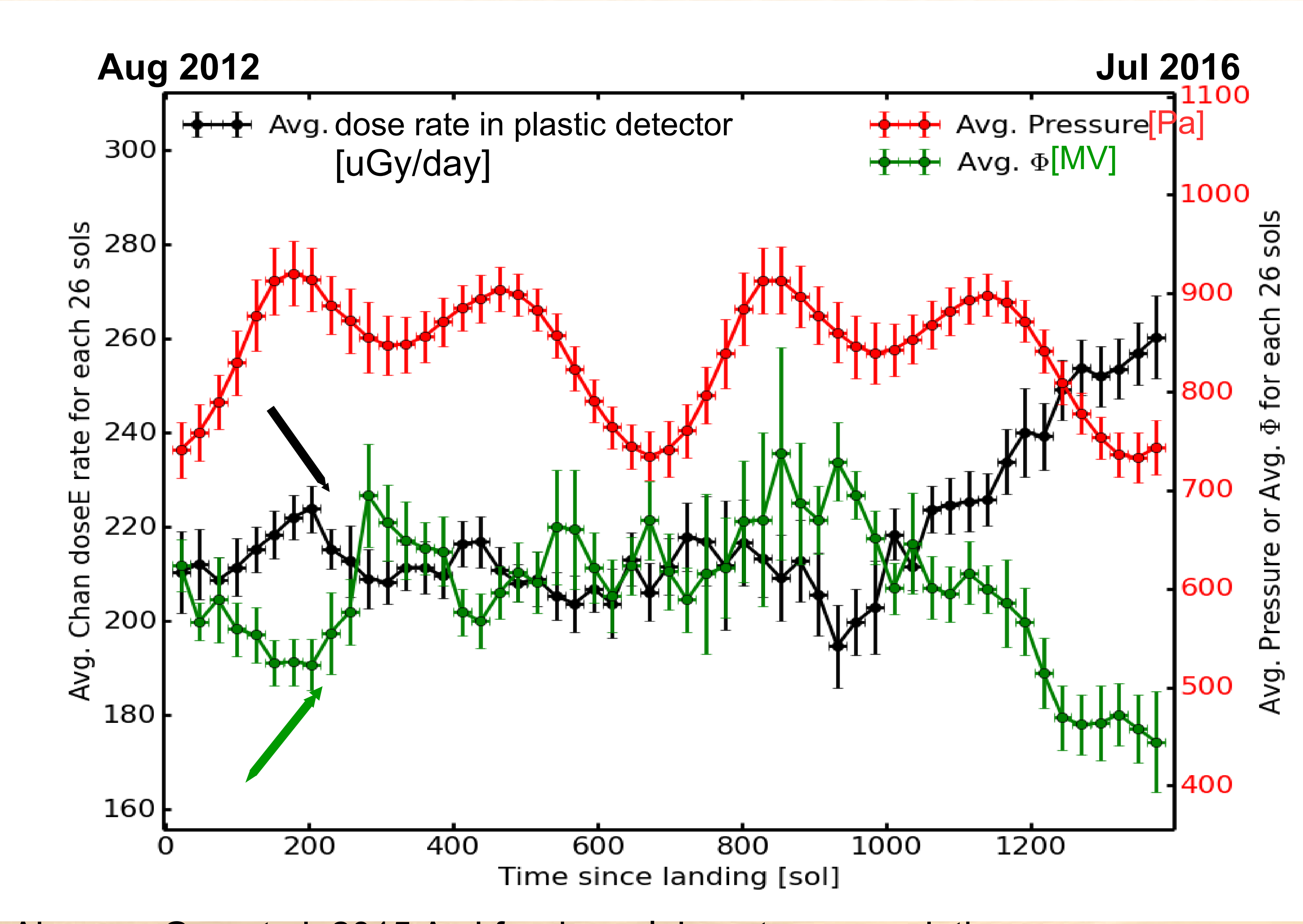
Radiation Assessment Detector (RAD) provides the **first** measurement for the **radiation environment on Mars**!

- RAD is an energetic particle detector designed to measure **galactic cosmic rays**, **solar energetic particles**, **secondary neutrons**, and other secondary particles.
- RAD contains six detectors, three of which (**A, B, and C**) are **silicon diodes** (each 300 micro meter thick) arranged as a telescope.
- The other three (**D, E, and F**) are **scintillators**.
  - **D**: 2.8 cm thick CSI
  - **E**: 1.8 cm thick hydrogen-rich plastic
  - **F**: 1.2 cm thick plastic; **anti-coincidence** for neutral particle detection.
- **Dose rates are measured in both silicon 'B detector' and plastic 'E detector'.**

Radiation environment at **the surface of Mars**



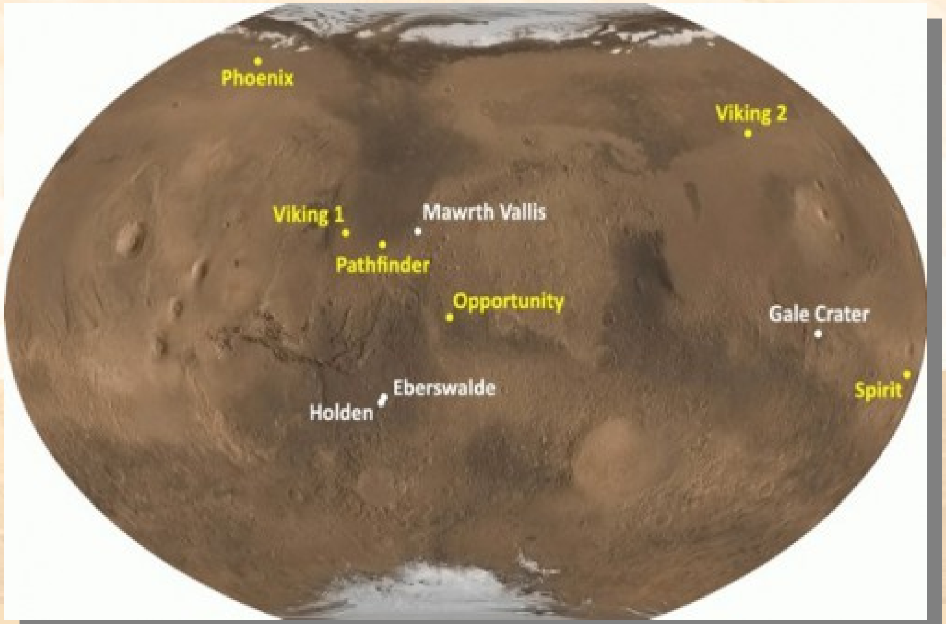
Dose rate, pressure and solar modulation

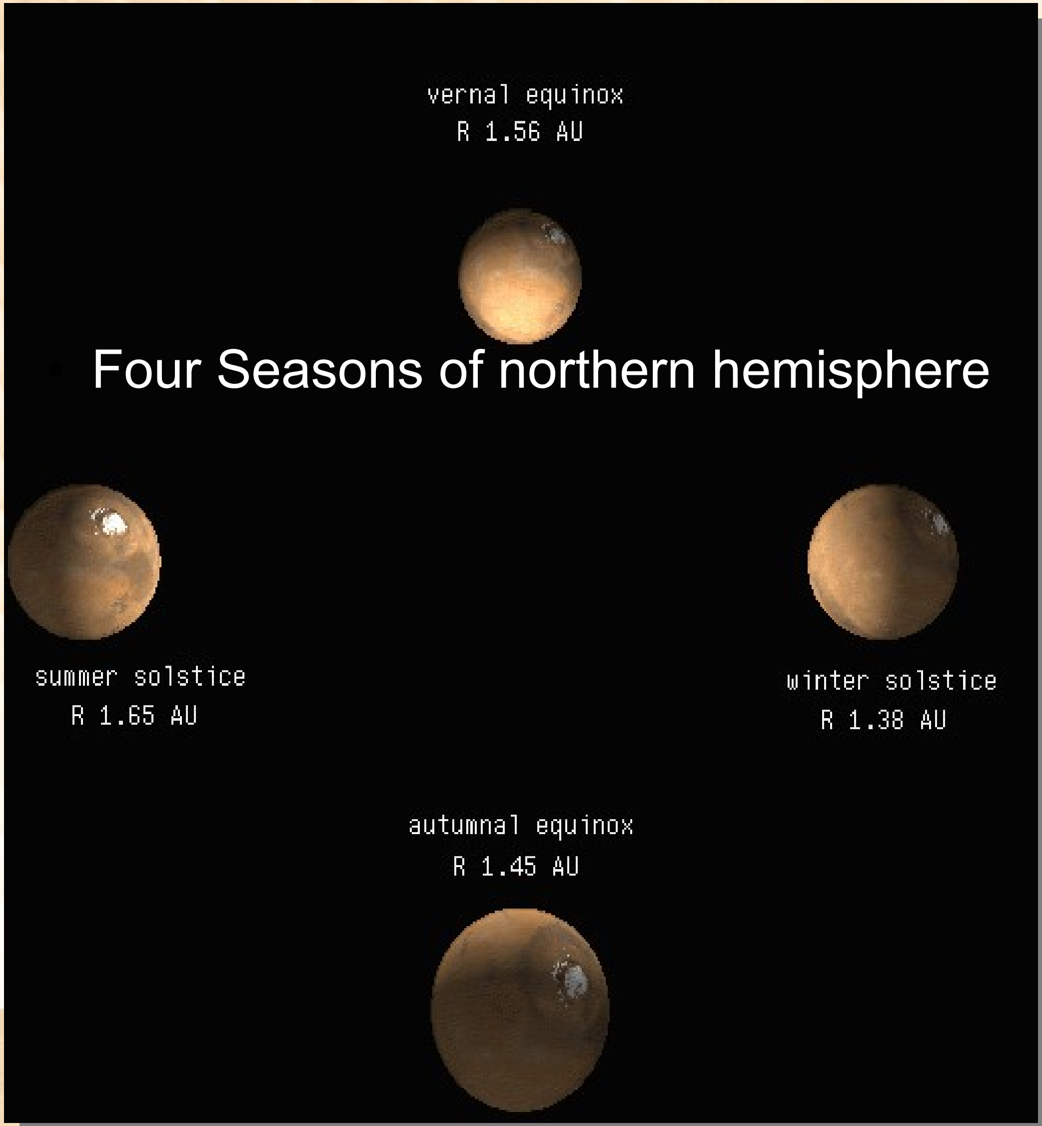


Also see Guo et al. 2015 ApJ for dose-Φ long-term correlation

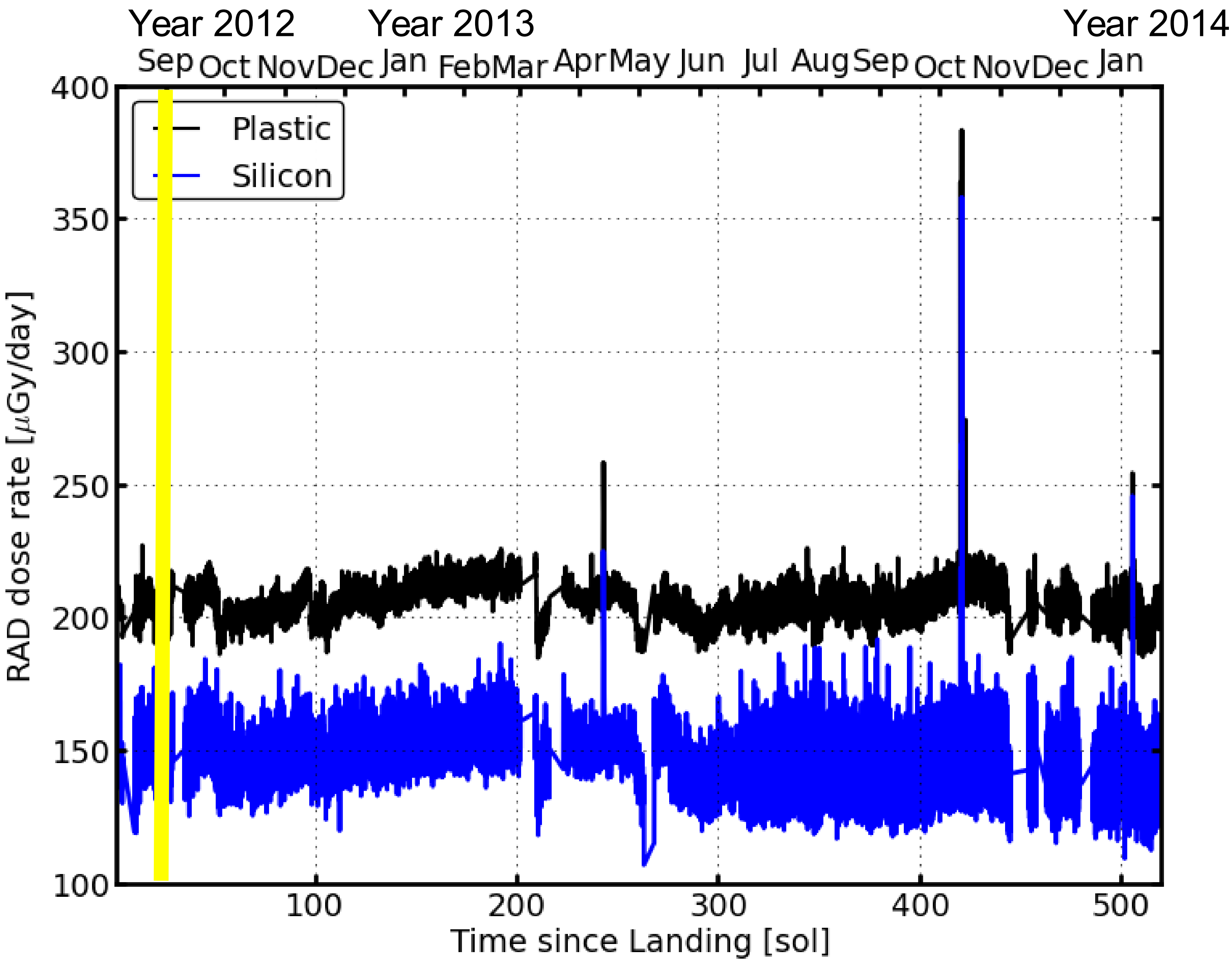
Seasonal pressure changes on Mars

- Seasonal conditions are reversed in the northern and southern hemispheres
- Seasonal pressure change is driven by the growing and shrinking of the polar caps (CO_2).
- Summer in the southern hemisphere is much warmer than summer in the northern hemisphere due to its closer distance to the Sun (high eccentricity orbit of Mars).
- The Atmospheric pressure is driven mainly by south polar caps changes

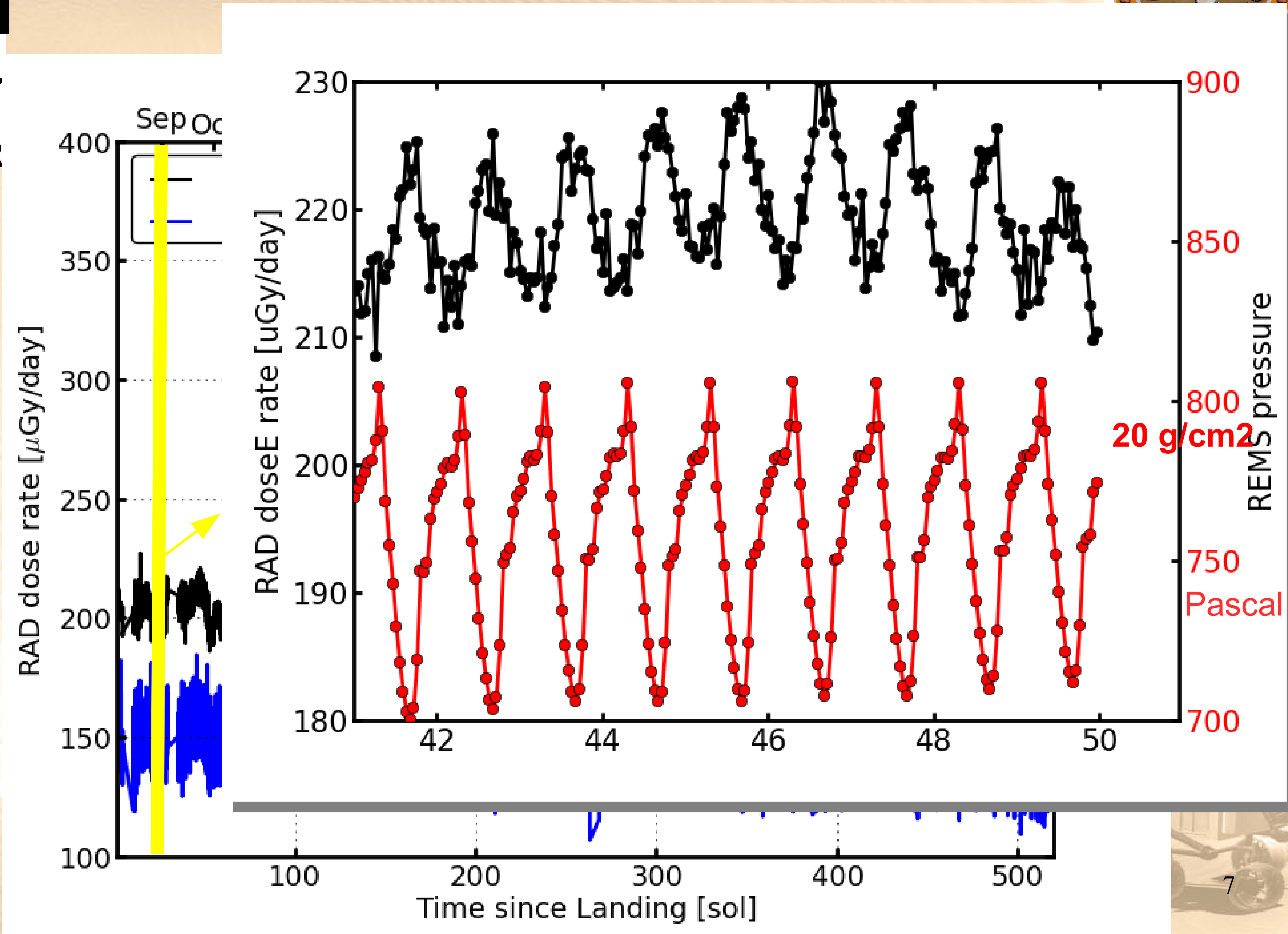




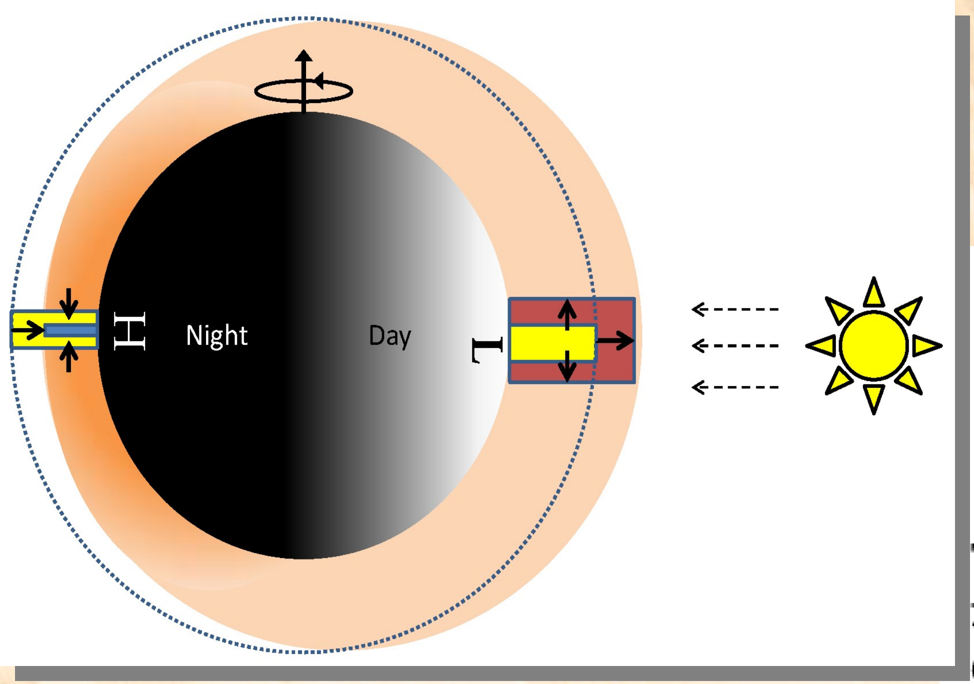
How does the atmosphere affect the dose rate?

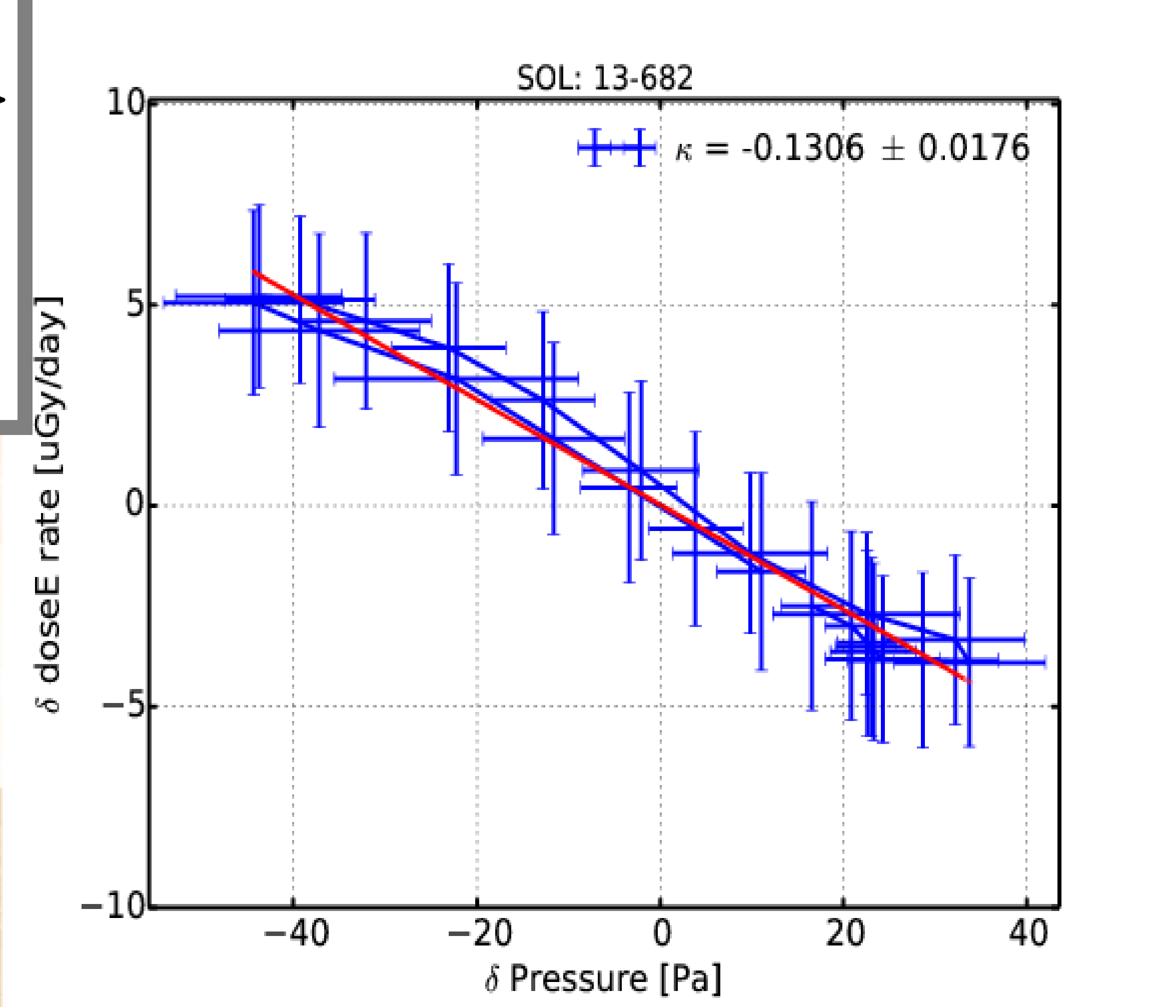


Zoom-in: dose and pressure during sol 40-50



Anti-correlation of the surface pressure and dose rate

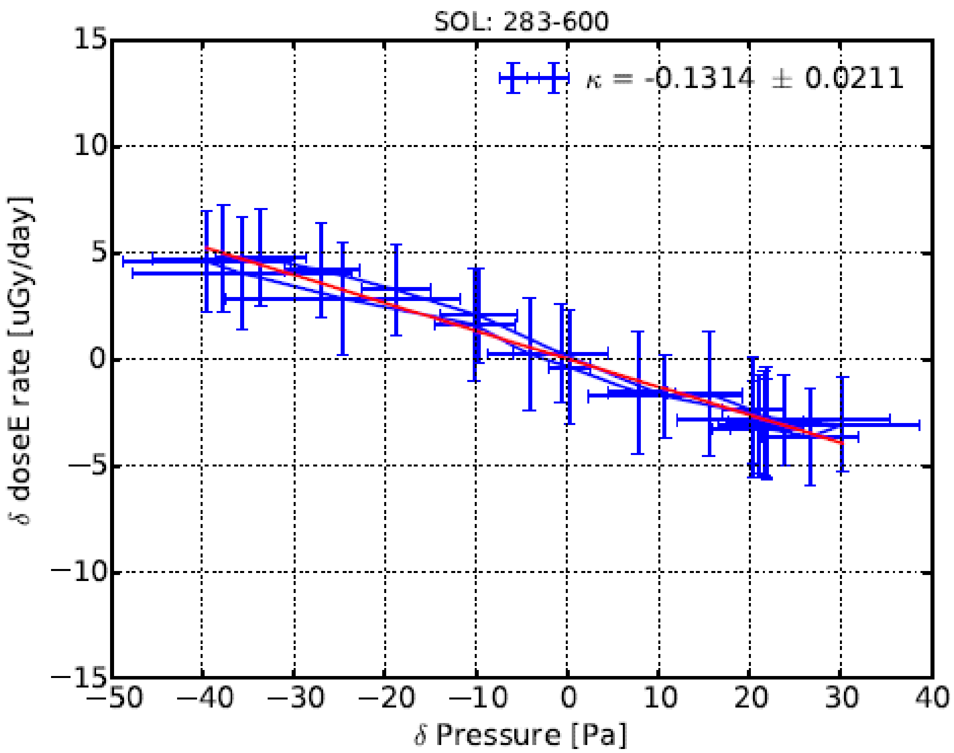




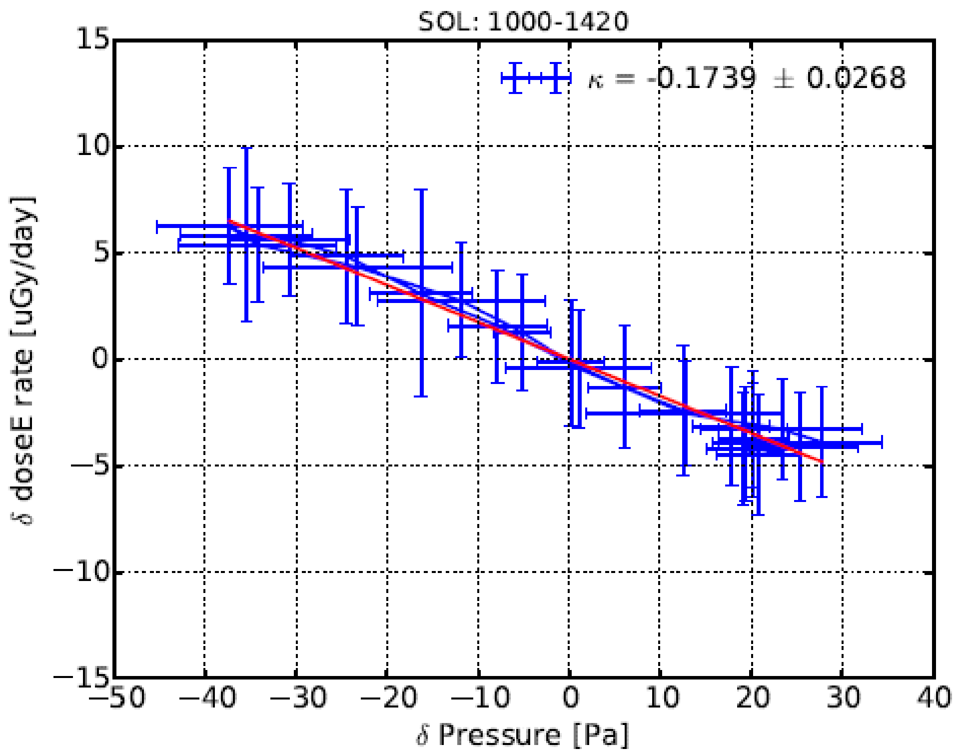
Left: Diurnal Variations of surface pressure due to column mass changes caused by the thermal tide.

Right: **The isolated (where solar modulation effect is reduced to minimum) pressure-dose rate correlation** of the diurnal oscillations of the hourly-binned data.
(Rafkin et al 2014, Guo et al 2015)

This effect is not constant:
Why + How does it change?



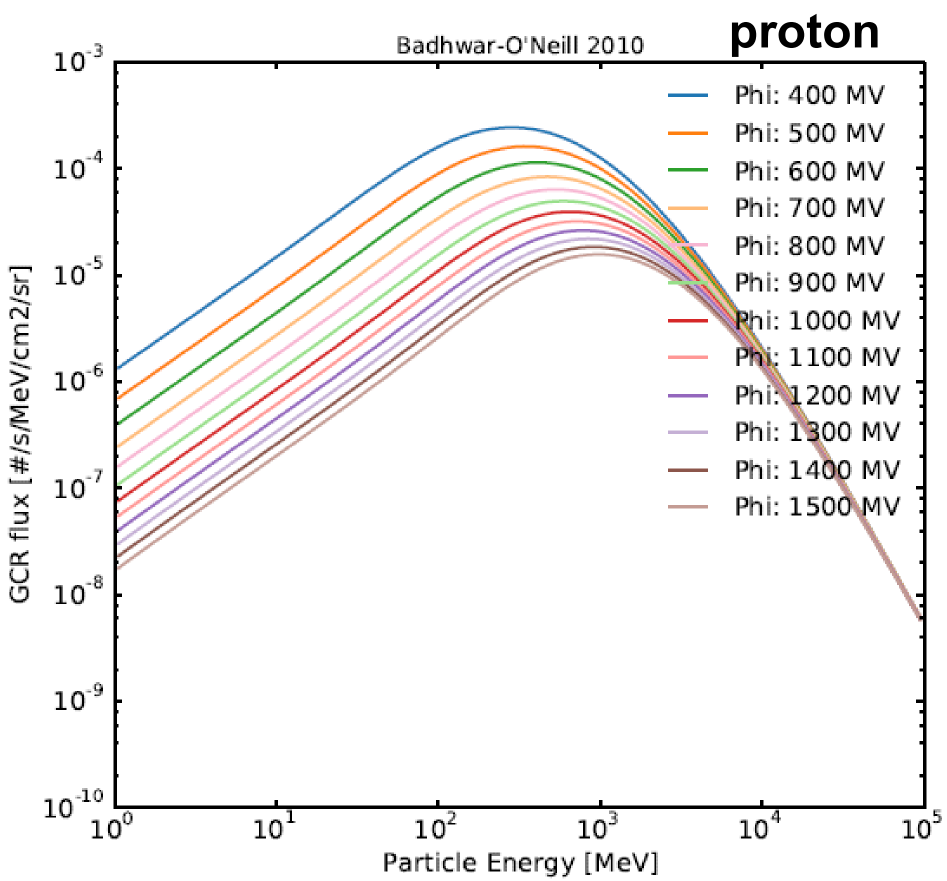
(a) plastic detector, $\bar{\Phi}$ = 578 MV

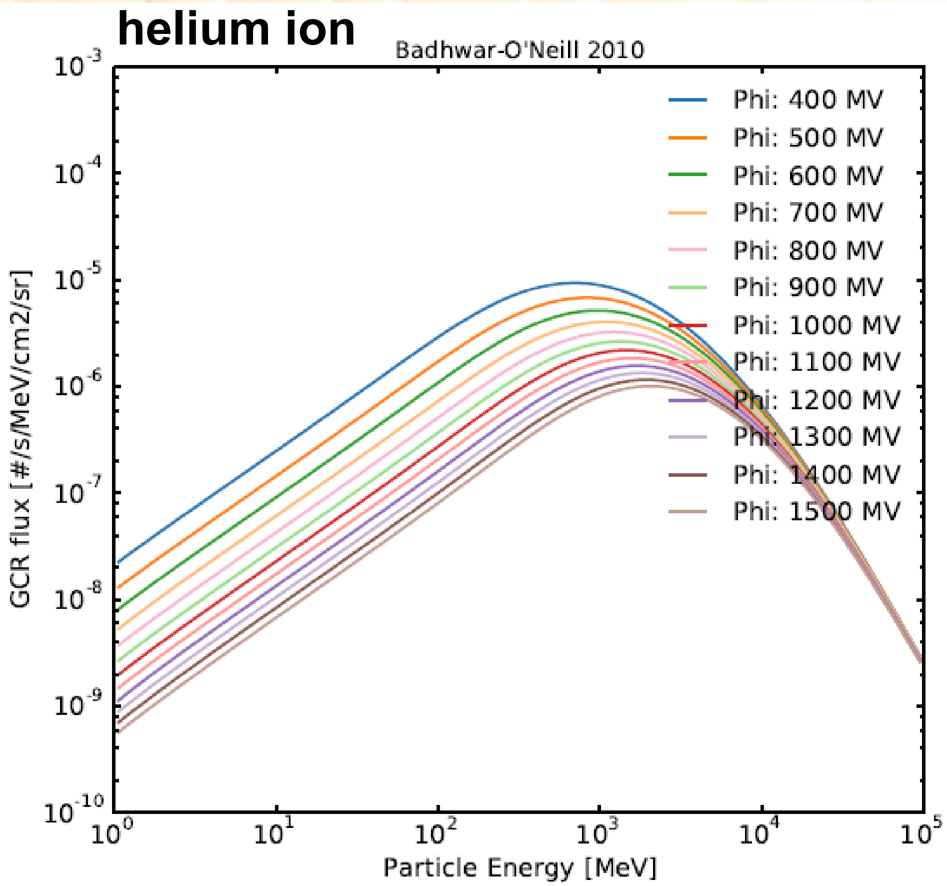


(b) plastic detector, $\bar{\Phi}$ = 489 MV

Model the atmospheric effect using HZETRN2015 (1)

- GCR model used:
  - Badhwar-O'Neill 2010 (BON2010) model
  - Z from 1 to 28
  - Φ from 400 to 1500 MV



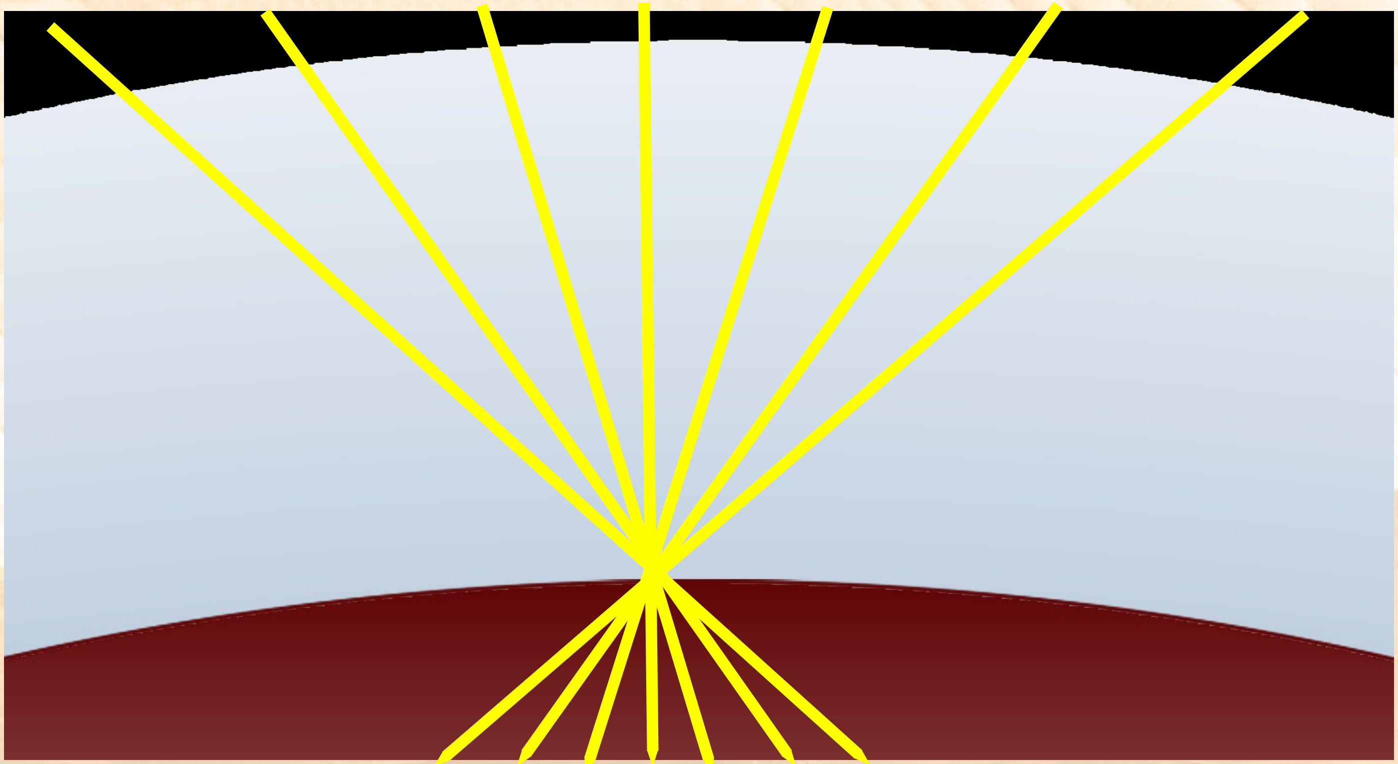


Model the atmospheric effect using HZETRN2015 (2)

- Nuclear Physics Models
  - Heavy ion collisions
    - NUCFRG3 abrasion/ablation model with electromagnet dissociation (EMD) and light ion coalescence [Adamczyk et al. 2012]
  - Light ions and neutrons
    - Simplified parametric representation of Bertini/Ranft results for nucleons [Wilson et al. 1991]
    - Parametric representation of quantum multiple scattering fragmentation (QMSFRG) model for light ions [Cucinotta et al. 1993]
  - Others:
    - Combination of Badhwar and Thermal models for π+- production [Werneth et al. 2013]
    - Parameterization for π0 production and decay [Kafexhiu et al. 2014]
    - Electron, positron, gamma cross section parameterizations from NIST and EGS [Nealy et al. 2010]

Model the atmospheric effect using HZETRN2015 (3)

- **Ray-by-ray transport procedure implemented**
  - Transport performed along large number of rays covering full 4π
  - Density profile along any direction can be determined if the vertical profile is known
  - Transport through atmosphere (sphere) and 300 g/cm2 (1.75 m) of regolith for each ray
  - Bi-directional transport used along each ray to include neutron backscatter



MCD Atmosphere
- De Angelis et al., 2004
- 95% CO_2
- 2.7% N_2
- 1.6% Ar
- Trace amounts of O_2 and CO

Regolith
- McKenna-Lawlor, 2012
- 51.2% SiO_2
- 9.3% Fe_2O_3
- 7.4% H_2O
- 32.1% $Al_2MgCaNa_2K_2O_7$
- Ends up being ~47% O and 24% Si

Model the atmospheric effect using HZETRN2015 (4)

Particles transported over energies between 1 keV/n and 1 TeV/n.
Particles with type j have the flux **F(E)** defined as particle density in the energy space.
Particle dose and dose equivalent are computed from the integrals.

$$D(\Phi,\sigma) = \sum_{j} \sum_{area}^{geo} \iint_{0}^{\infty} \lambda_j(E,\epsilon) F_j(\Phi,\sigma,E)\, dE\, d\epsilon / m.$$

MeV/kg/sec → uGy/day

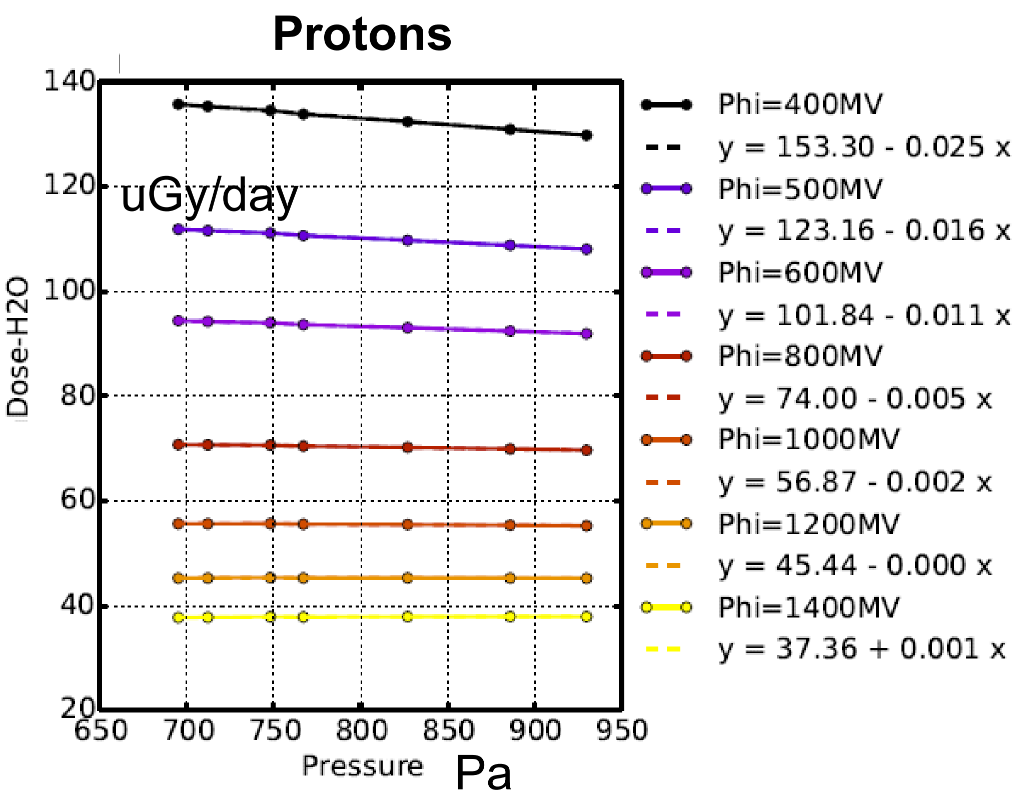
The surface particle fluxes generated from the models include all primaries and secondaries in both forward and backward directions.

This energy transfer process, included as a yield factor, can be estimated using e.g. Bethe-Bloch Ansatz for charged particles. Neutron dose is defined as inelastic reaction products and recoils with Z>2 produced by neutron-nucleus collisions. The recoil protons by neutron-hydrogen elastic collisions scored separately.

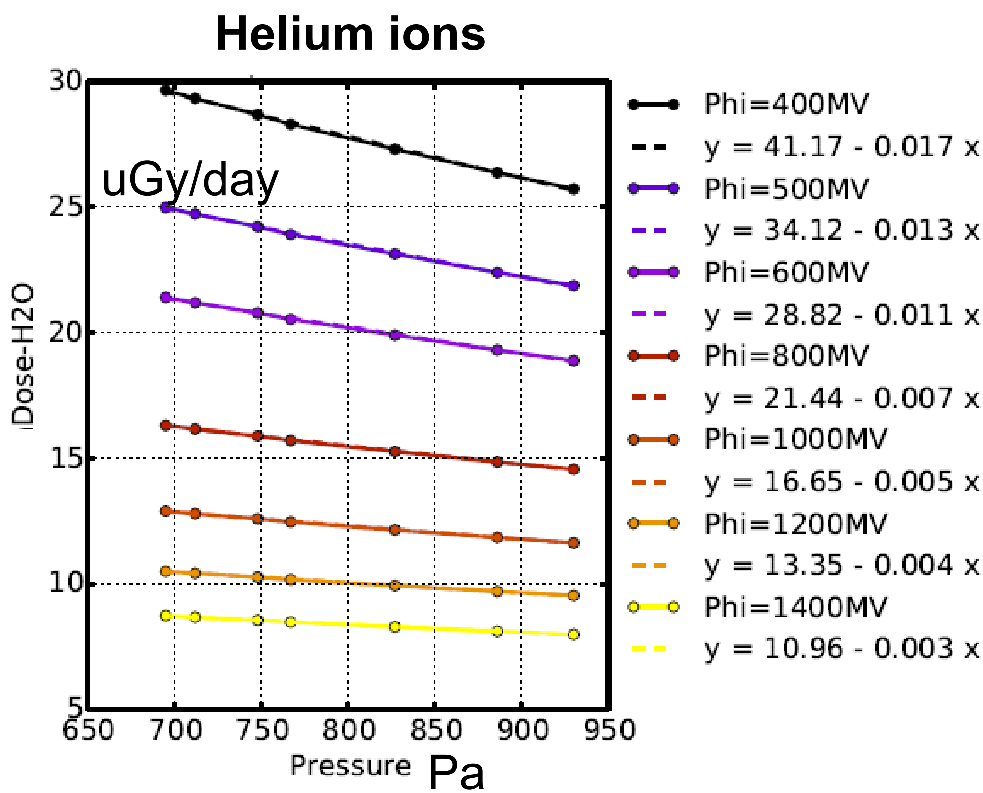
Model the atmospheric effect using HZETRN2015 (5)

- Φ ranges form 400 to 1500 MV.
- Total surface column depth σ changes between σ=18.9g/cm2 (~700 Pa) and σ=25.7 (~950 Pa) g/cm2 which correspond to the range of pressures of different seasons at Gale crater.
- For each above setup (certain Φ and surface σ), there are 5 virtual detectors in the model: on the surface and at elevations of 4, 8, 12, 16 g/cm2.
- The resulting dose rates in different cases are studied based on the above 2D parameter space: Φ and column depth σ.

HZETRN results of surface dose rate in water: induced from protons (left) and helium ions (right)



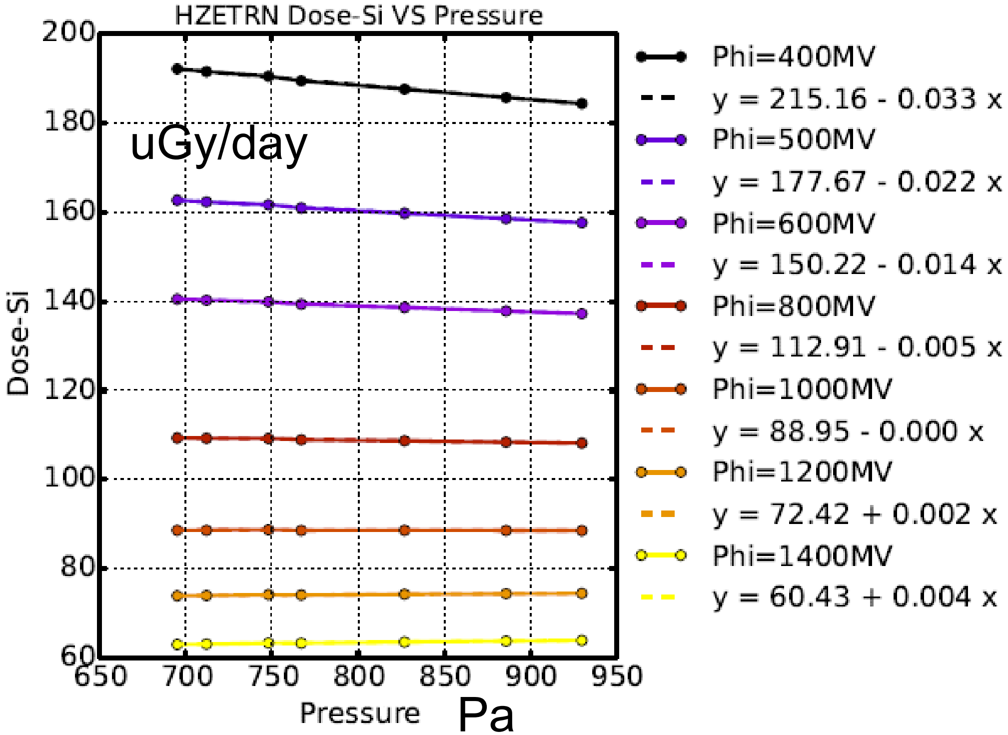
(c) surface dose rate from protons



(d) surface dose rate from helium ions

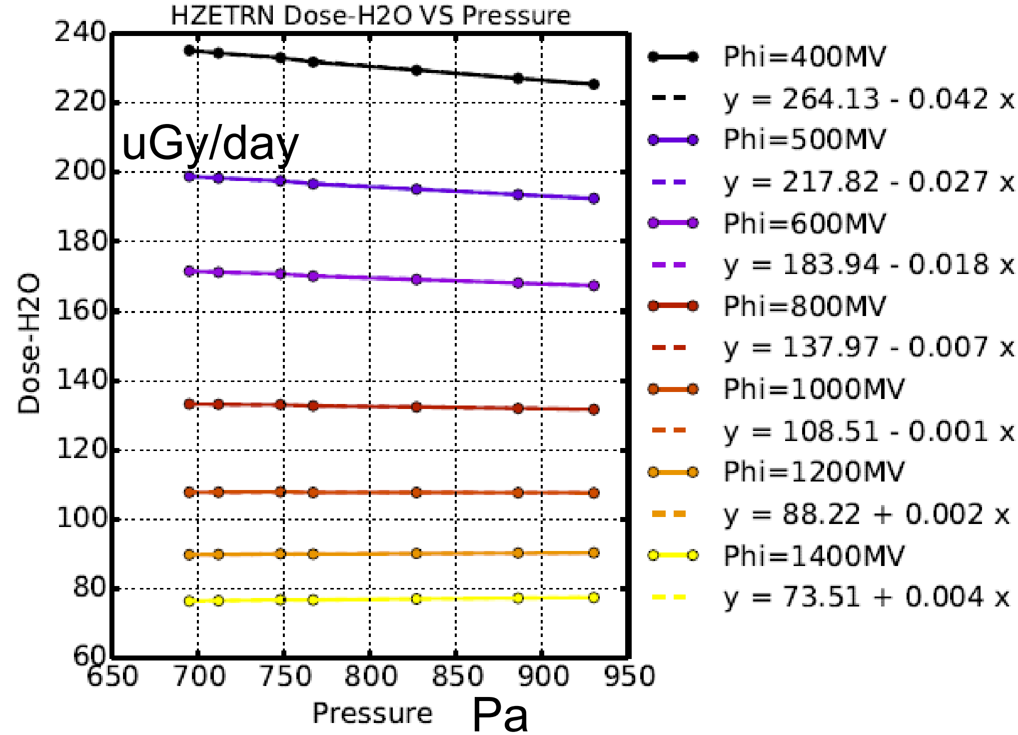
HZETRN results of surface dose rates

Silicon



(a) total surface dose rate in silicon

Water



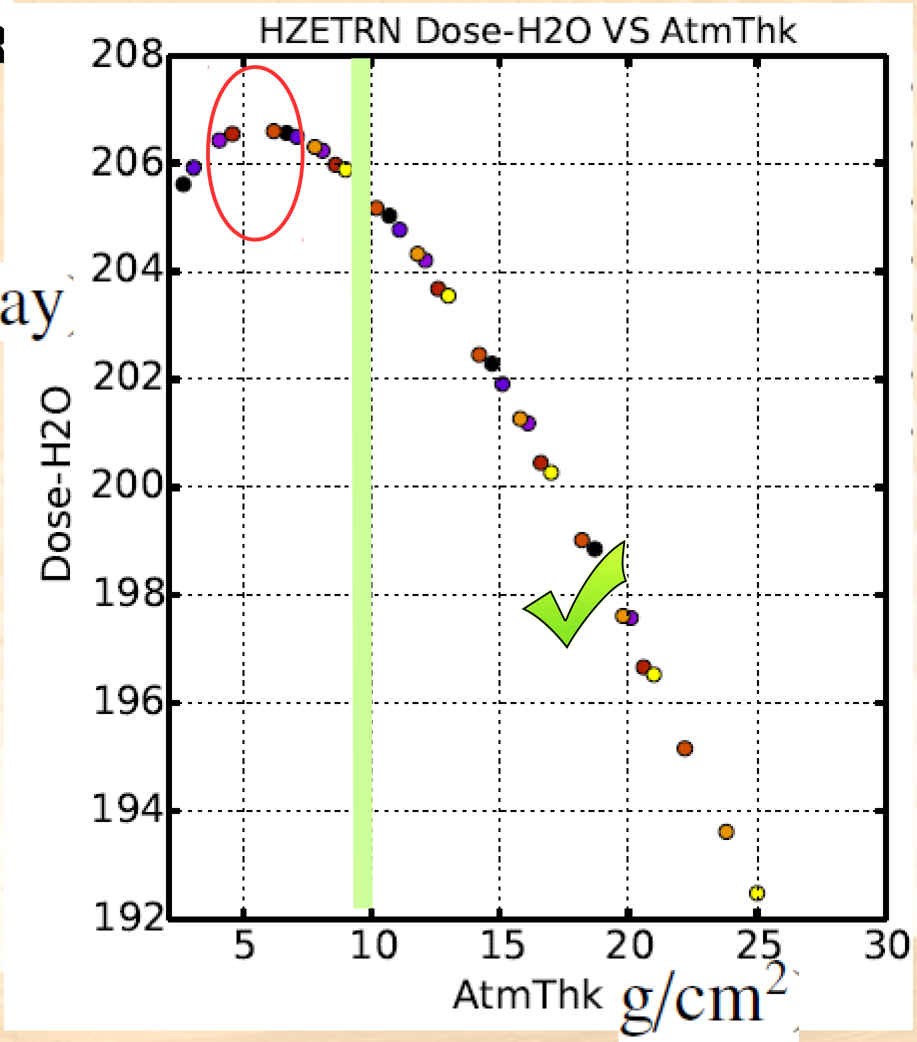
(b) total surface dose rate in water

- The modeled surface dose rate anti-correlates with the surface pressure as Φ <= ~800 MV.
- This anti-correlation decreases as Φ increases and even vanishes at Φ >= 1000 MV.

- This is because at large Φ values, the primary GCR fluxes are more strongly modulated by the heliospheric magnetic fields, especially at lower energy ranges where particles are more easily shielded by the atmosphere and are more responsible for the anti-correlation.
- **Can we extrapolate this anti-correlation of the pressure and surface dose rate to the top of the atmosphere?**

Can we extrapolate this anti-correlation to the top of the atmosphere? – **Not really**

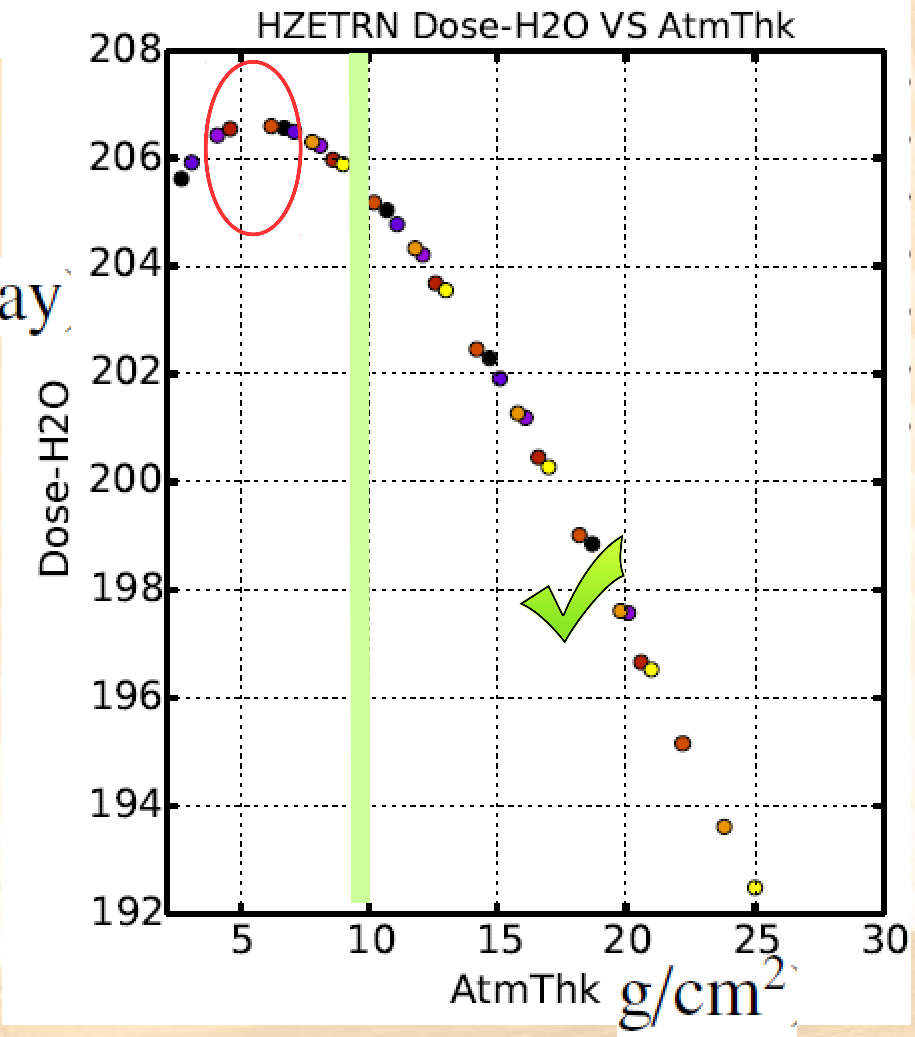
e.g, Φ = 500 MV



- The anti-correlation between column depth and dose rate can only be extrapolated to the dose peak ('dose-Pfotzer-maximum') at high altitudes of the atmosphere.
- At altitudes above the dose peak, dose rate increases as column depth increases. At deeper altitudes, dose rate anti-correlates with the column depth.

Explanations

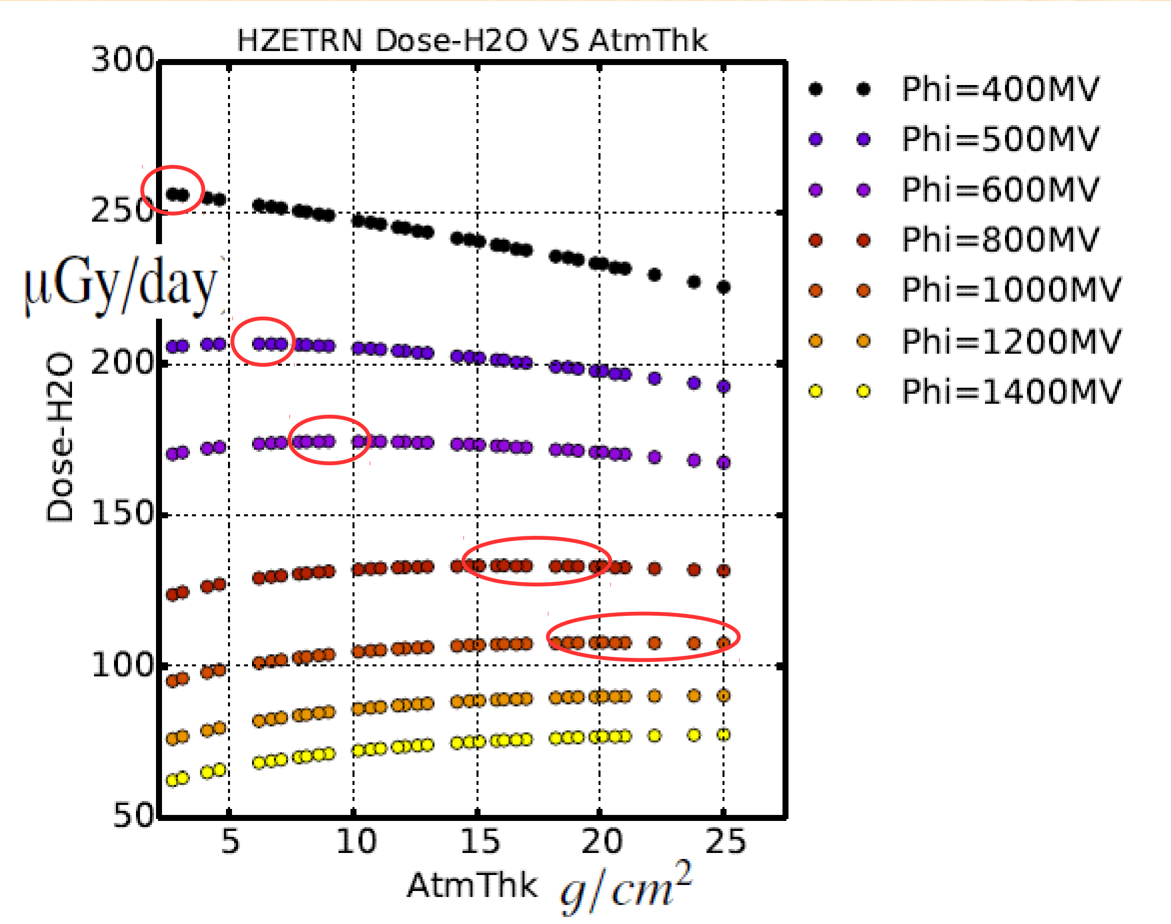
e.g, Φ = 500 MV



- At small atmospheric depths, the lower-energy protons and high-charge primaries contributes to the total dose rate significantly.
- As the depth grows, these primary particles are shielded and their flux decreases.
- Meantime, secondaries are being generated from high energy ions to lower-energy lower-charged particles.
- The contributed dose rate by the high-charge primaries decreases and by the low-charge secondaries increases. The resulting decrease/increase of the accumulated dose rate is a net-gain result of the above process.

- How does this change as solar modulation changes? And **where is the dose peak at e.g. Φ=1000?**

Where is the dose peak for Φ = 1000? – Near the surface

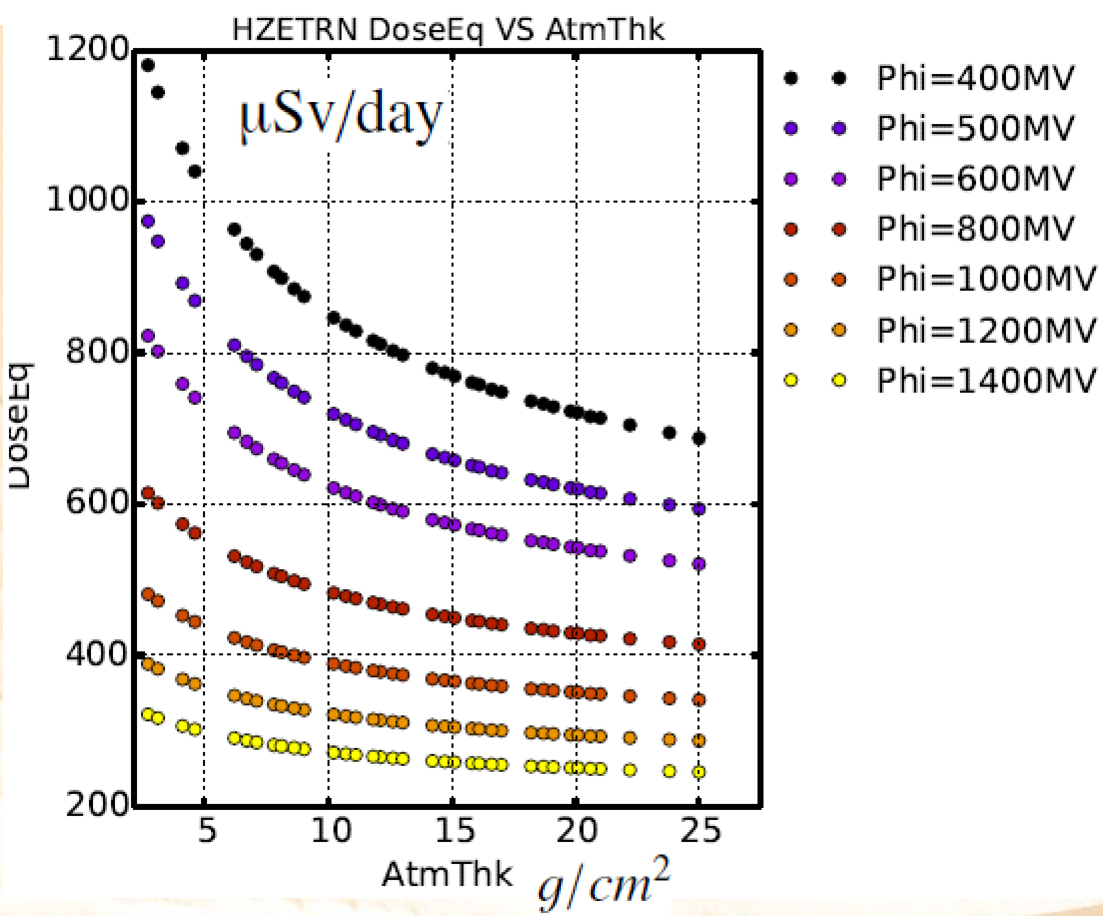


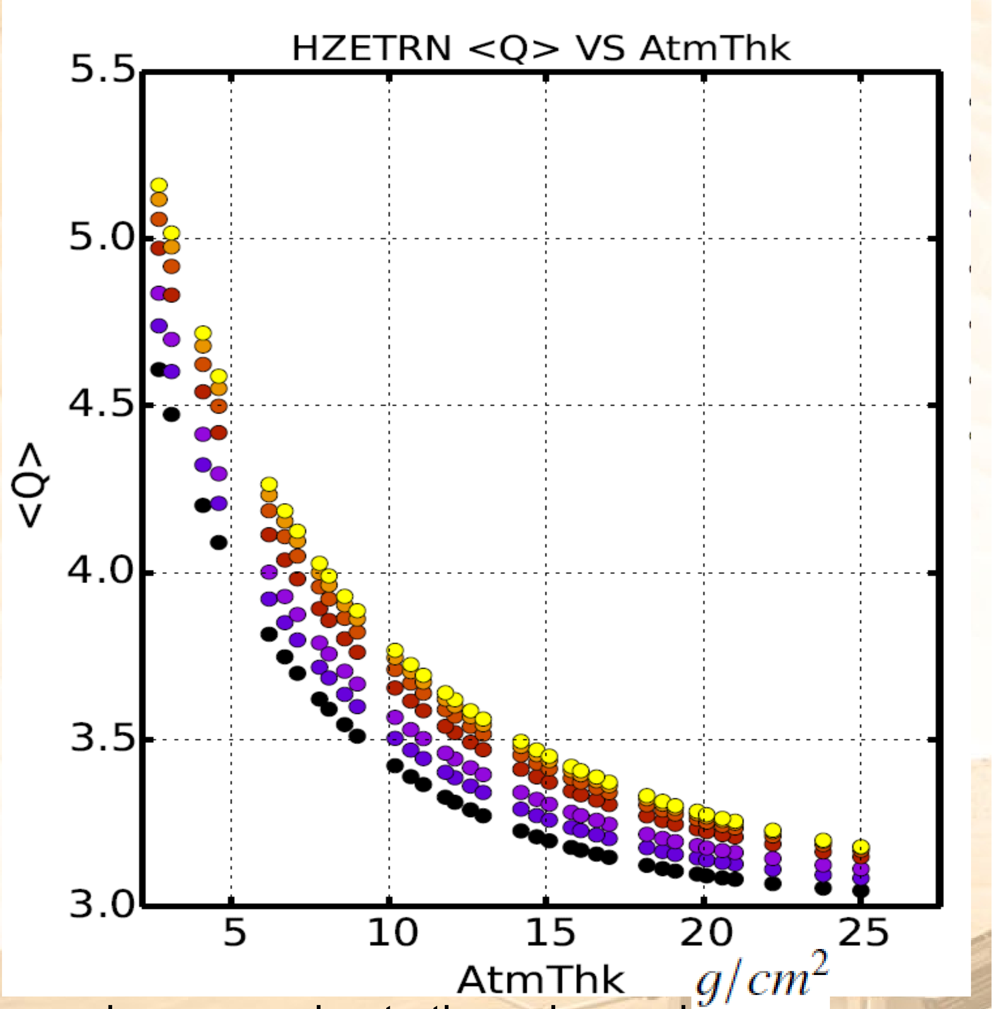
- For large Φ values (→ 1000 MV), the dose peak may be on/below the surface.
- For very strong solar modulation, the anti-correlation vanishes and dose rate generally slightly increases as column depth σ increases.

- This is because for larger Φ, there are fewer low-energy GCRs and the generation of secondaries from high-charge high-energy particles in the atmosphere dominates the contributions to dose rate.

- **This effect is much more visible in the dose equivalent rate!**

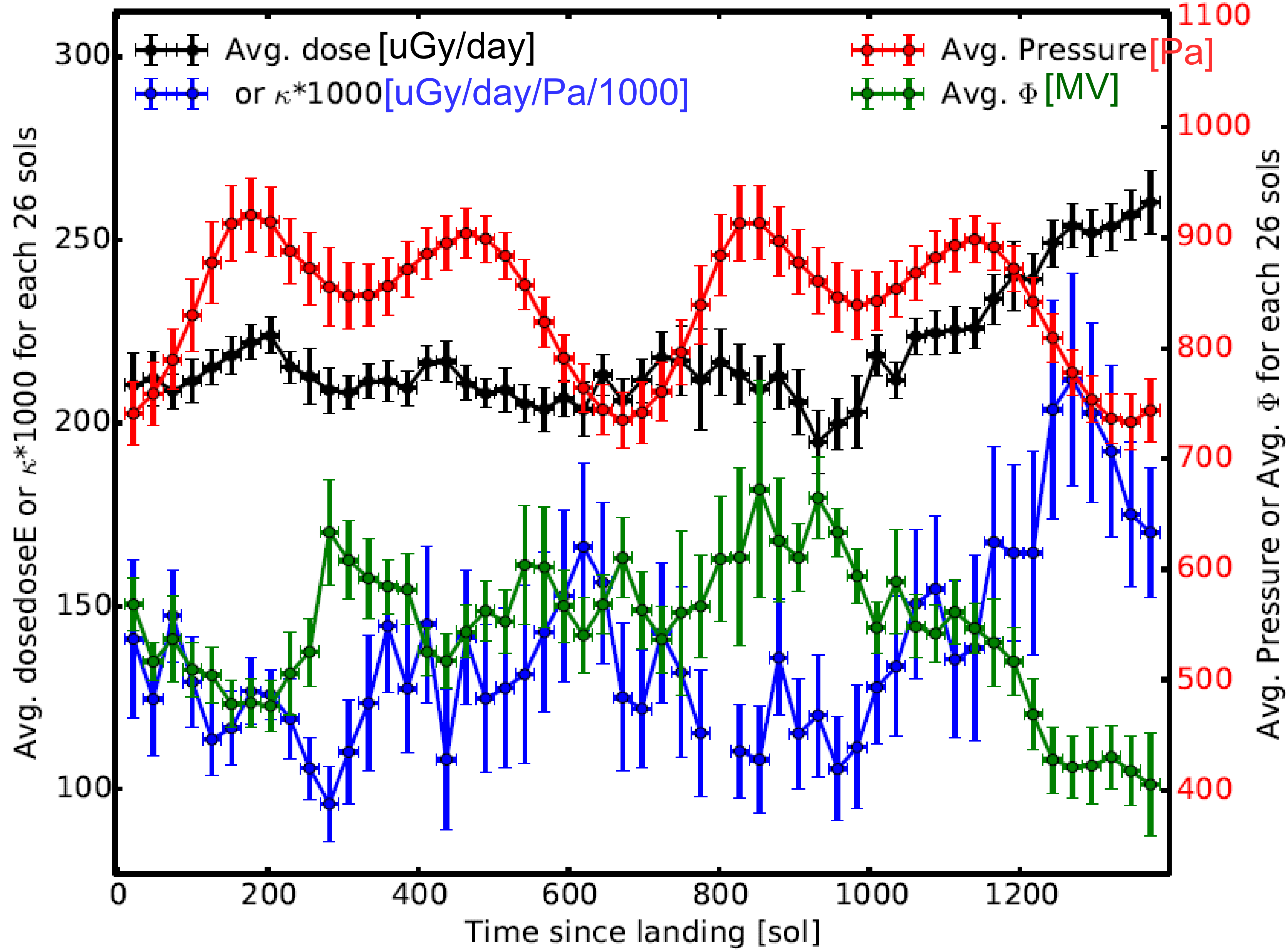
Dose equivalent rate and <Q> versus column depth



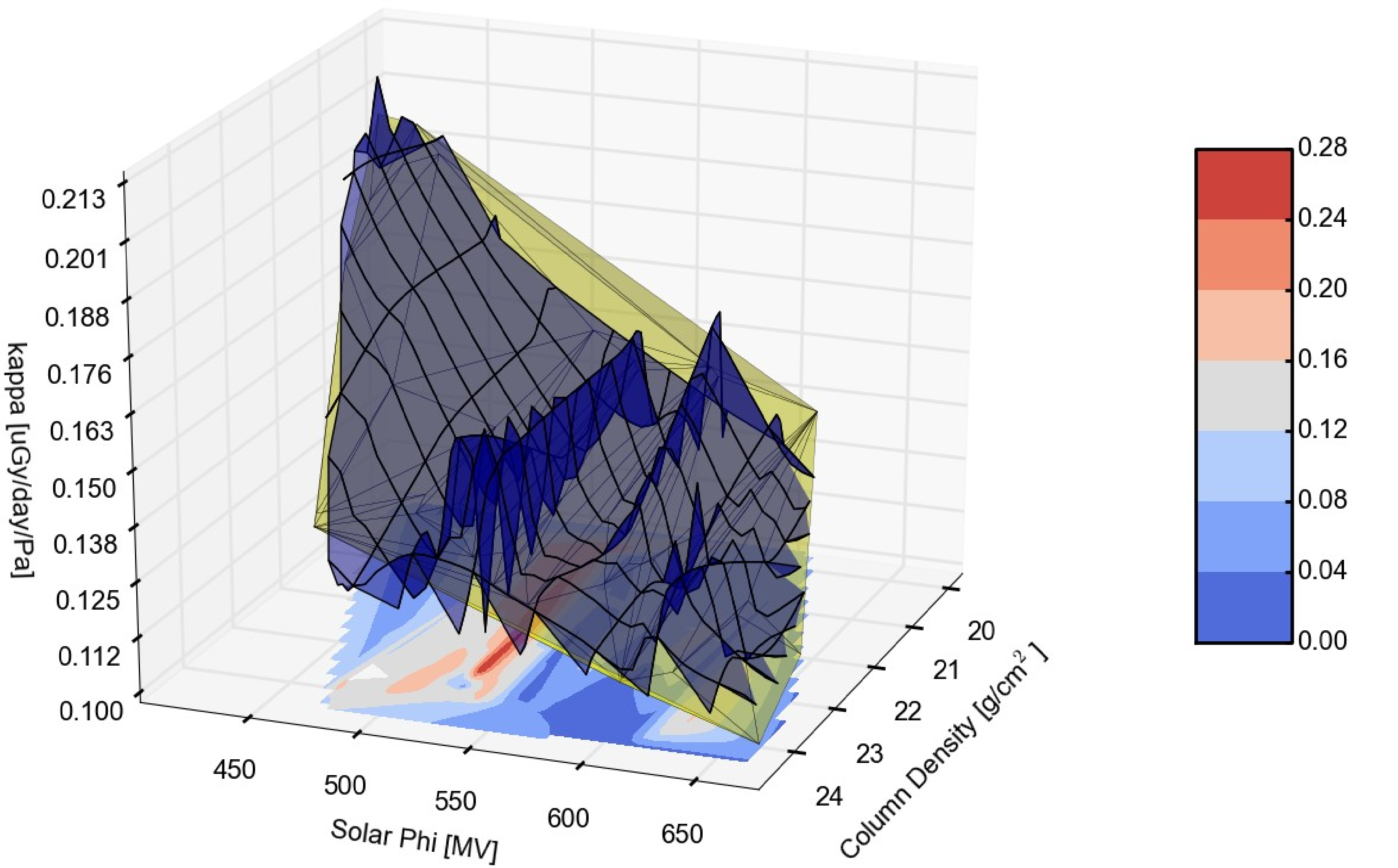


- The dose equivalent rate and <Q> always decreases as σ increases due to the enhanced fragmentation of heavy ions (stronger for higher Z particles).

RAD dose data, pressure, kappa and modulation potential Φ for each 26-sols



As solar modulation increases, the pressure-dose correlation decreases



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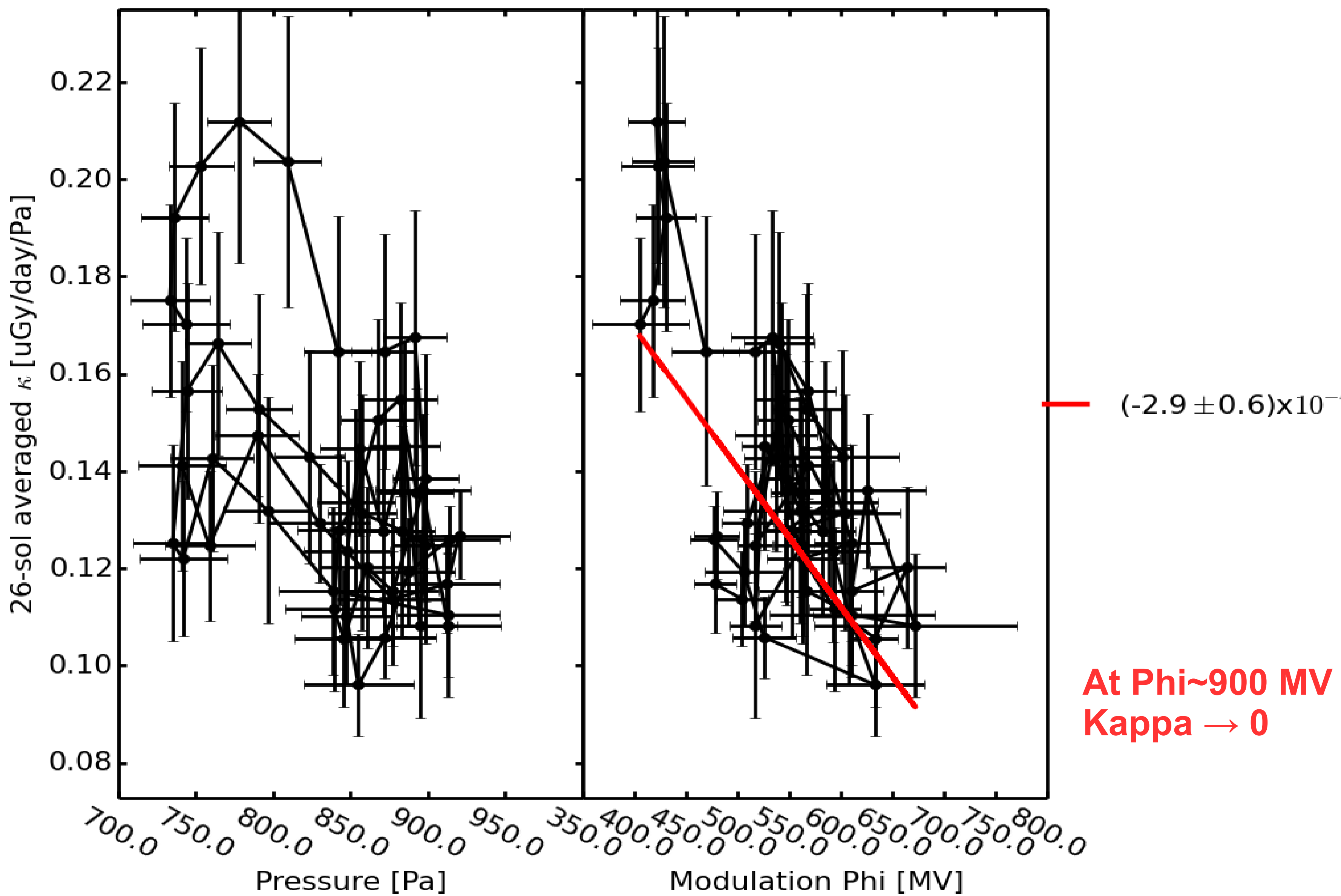

At Phi~900 MV
Kappa → 0

Summary and discussion

- The GCR-induced surface dose rate variation is driven by both the solar modulation and the change (both daily and seasonly) of Martian atmospheric depth σ.
- In the long-term, the solar modulation has a much stronger effect on the dose rate variations.
- The surface dose rate is anti-correlated with the surface pressure (or σ) for Φ <~ 900 MV, as shown by the model and indicated by the measurement.
- As suggested by modeled results, this dose-depth anti-correlation could be extrapolated to the top of the atmosphere only at weak solar modulation conditions (Φ<=400MV).
- For future human exploration to planet Mars during solar minimum periods (worst-case scenario and maybe the case in next decades), it is important to take into consideration of the atmospheric shielding effect.
  - Based on the RAD measurements, a first-order estimation at Φ=200 MV would result in ~ 55.5 uGy/day of dose rate **difference** between 700 Pa and 950 Pa seasonal pressure conditions at Gale crater.
  - This suggests that it would be perhaps better to avoid the minimum pressure season of the southern hemisphere late winter caused by the southern CO2 ice cap reaching its maximal extent.
- As Φ increases, the dose-depth anti-correlation weakens. And this effect vanishes when Φ >~ 900 MV. This is due to the lack of lower-energy particles which are more affected by the atmospheric shielding.
- For very big Φ at solar maximum, a deeper atmosphere may be even enhancing the total dose rate resulting in a slightly positive correlation. This needs to be tested by data collected at solar maximum conditions.