Solar modulations of MSL/RAD dose rate

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and the RAD/MSL team

WRMISS 2015, DLR, Germany

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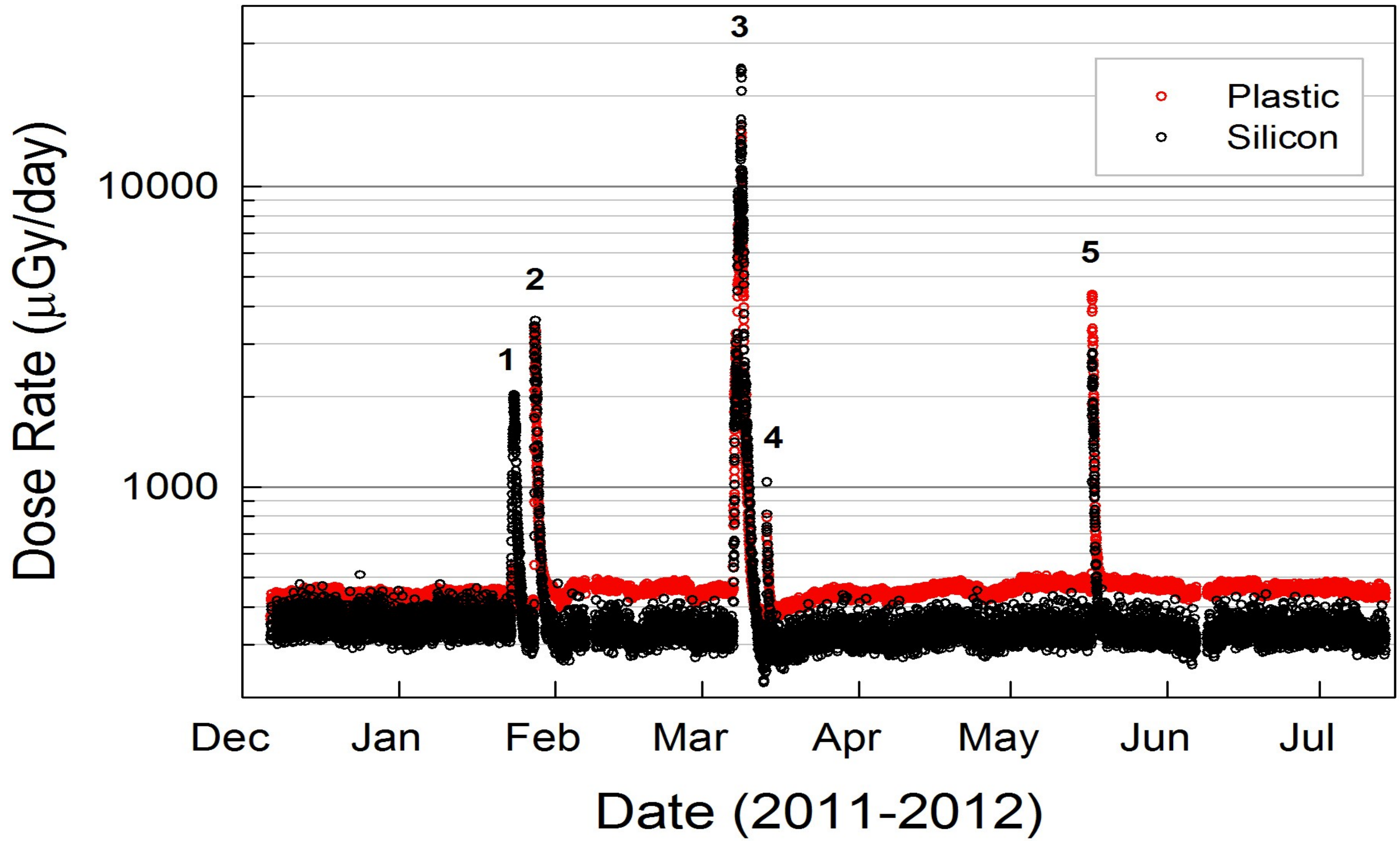
Measurement during the cruise

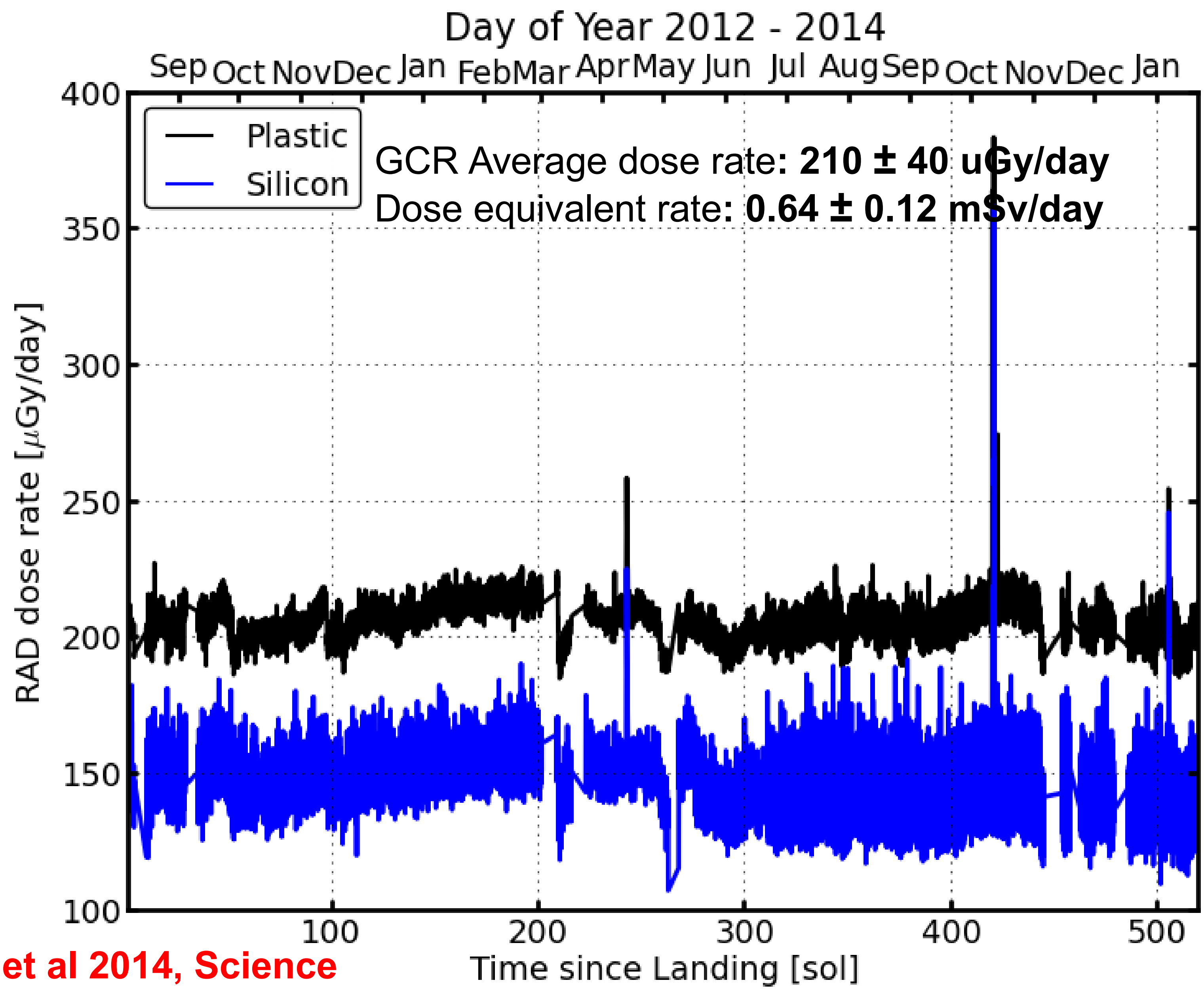
GCR Average dose rate: **480 ± 80 uGy/day**

Dose equivalent rate**: 1.84 ± 0.30 mSv/day**



Zeitlin et al 2013, Science

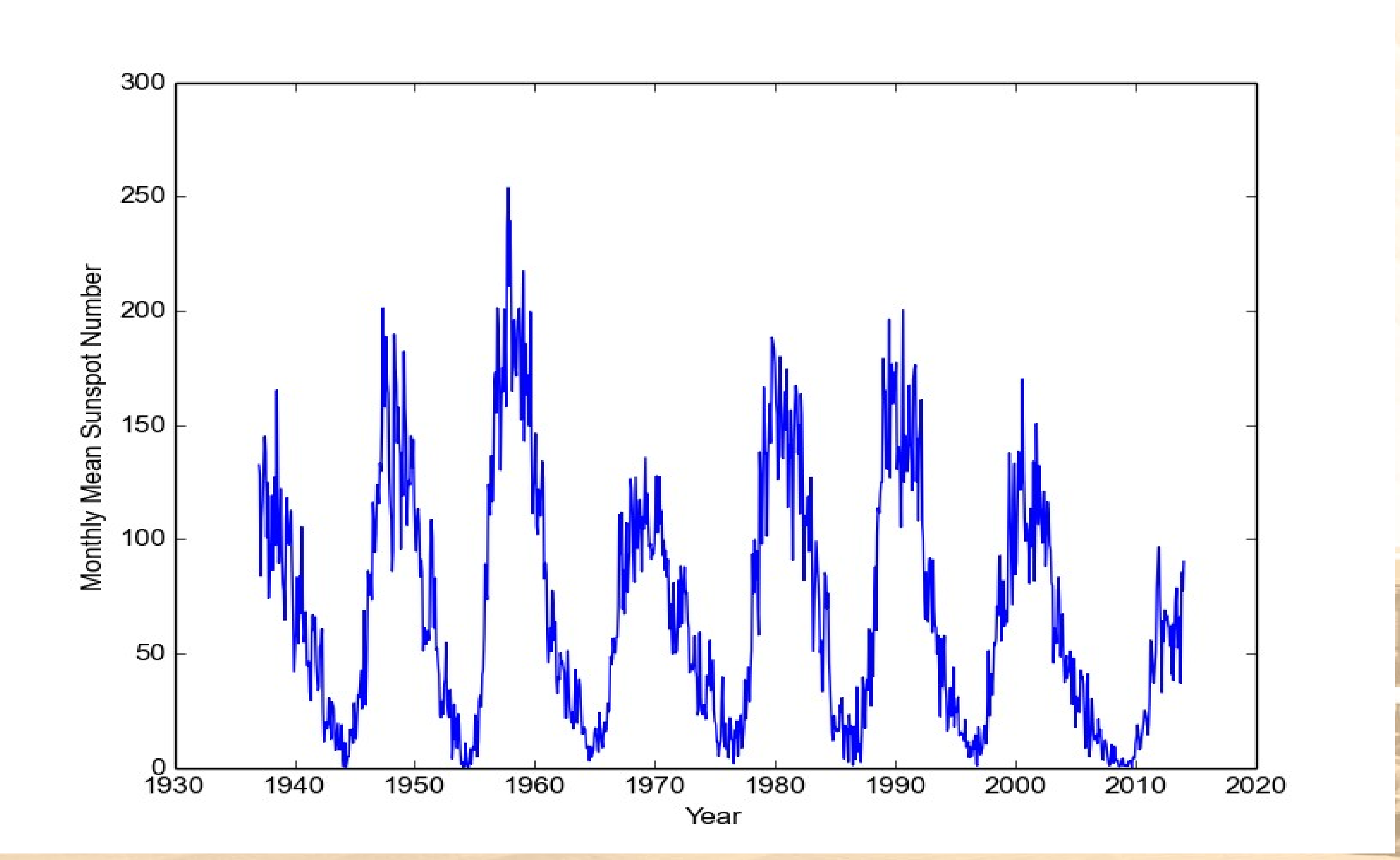
Measurement on the Martian surface



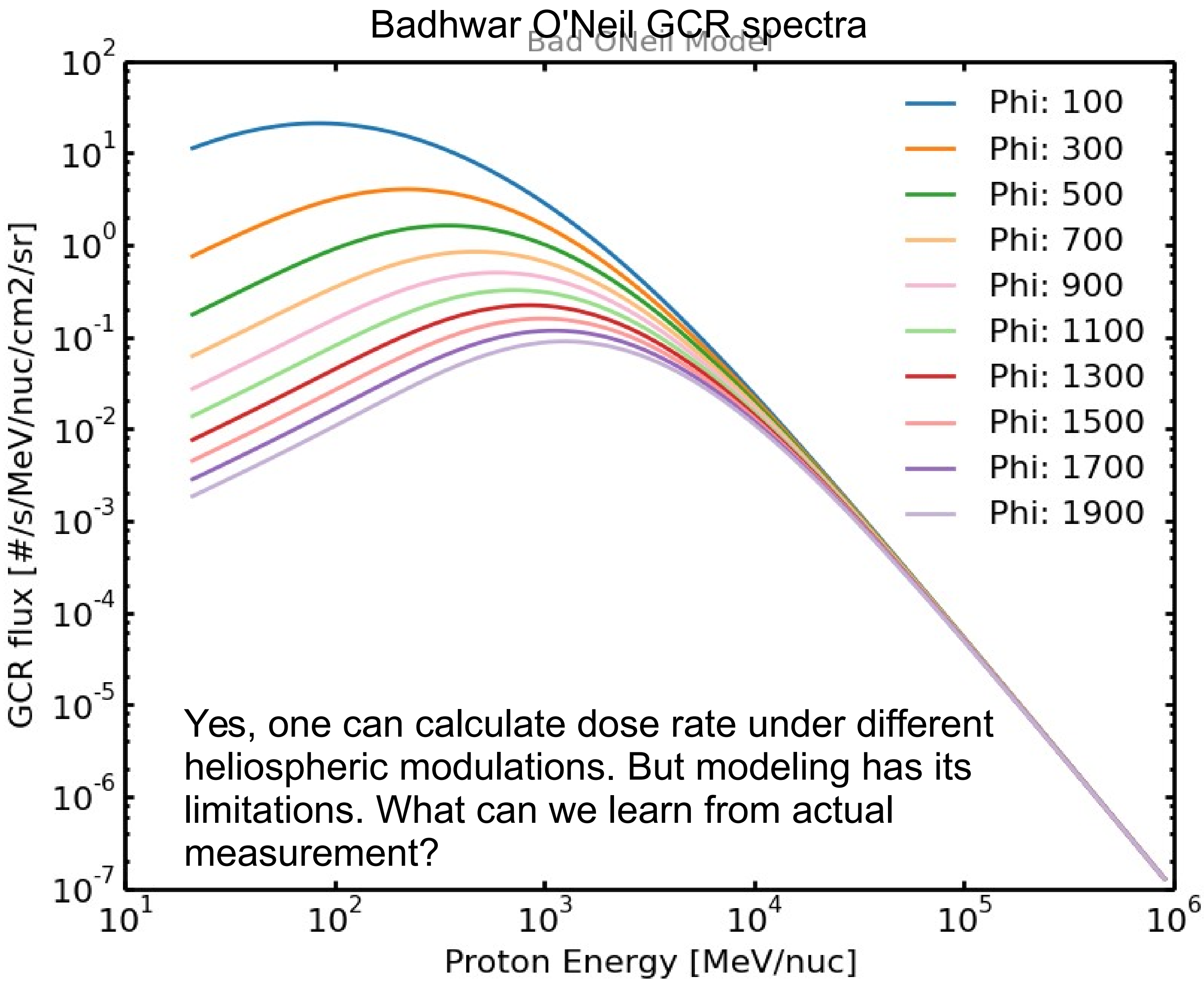
Hassler et al 2014, Science

Motivation of this work

Yes, the GCRs are constantly there. But their flux is not constant.
What we measure under the current modulation conditions may not be directly used to applied to future missions.



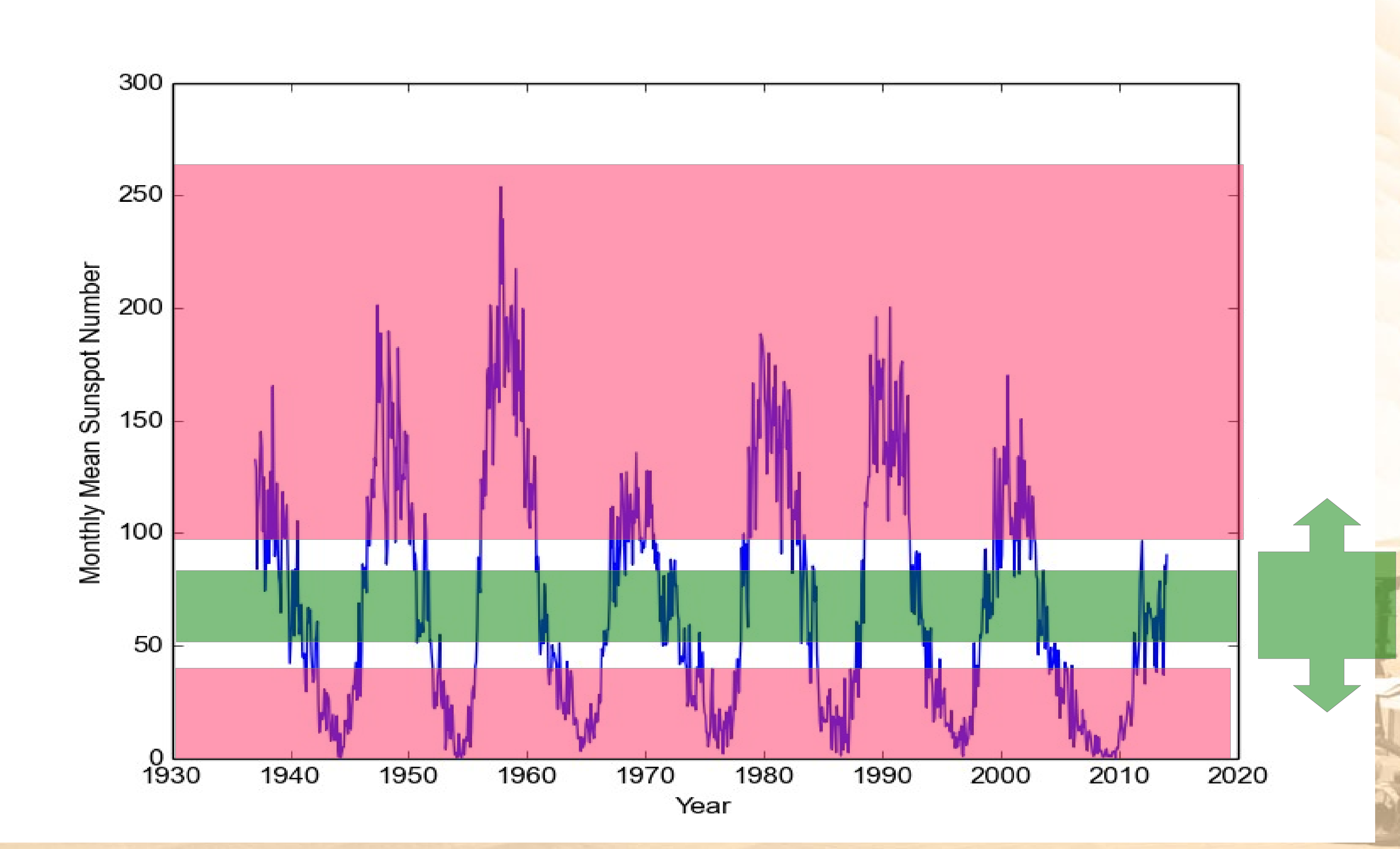
Solar Modulations of GCRs



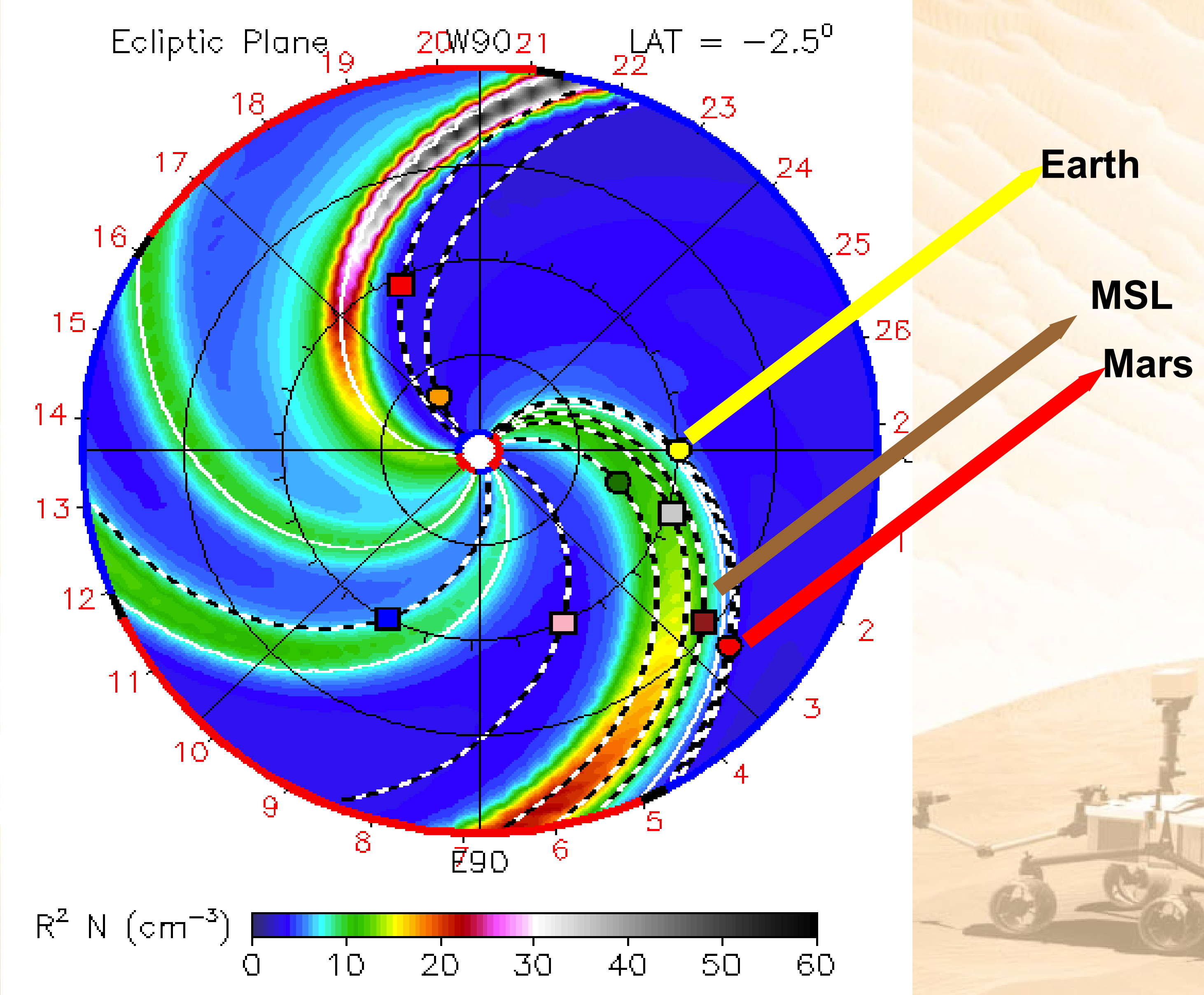
Yes, one can calculate dose rate under different heliospheric modulations. But modeling has its limitations. What can we learn from actual measurement?

Motivation of this work

We want to 'predict' the radiation environments under different modulation conditions using our measurements.



Cruise phase: magnetically well connected with Earth



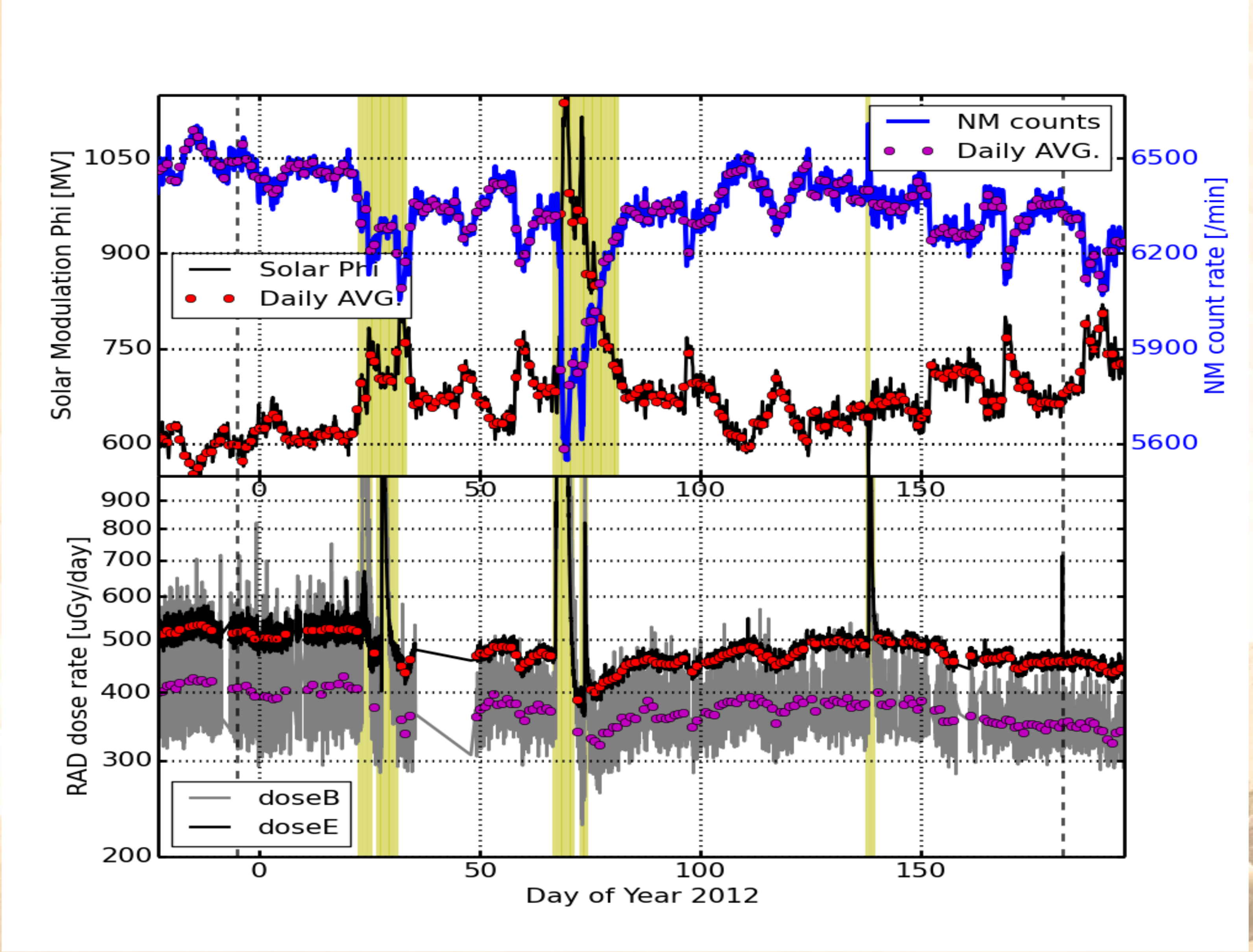
Cruise Phase
solar modulation and the dose rate

Solar modulation Φ is often measured by Neutron Monitors at Earth.

Regression correlation coefficient:

0.80 for silicon dose rate and Φ

0.77 for plastic dose rate and Φ



Guo et al 2015, A&A

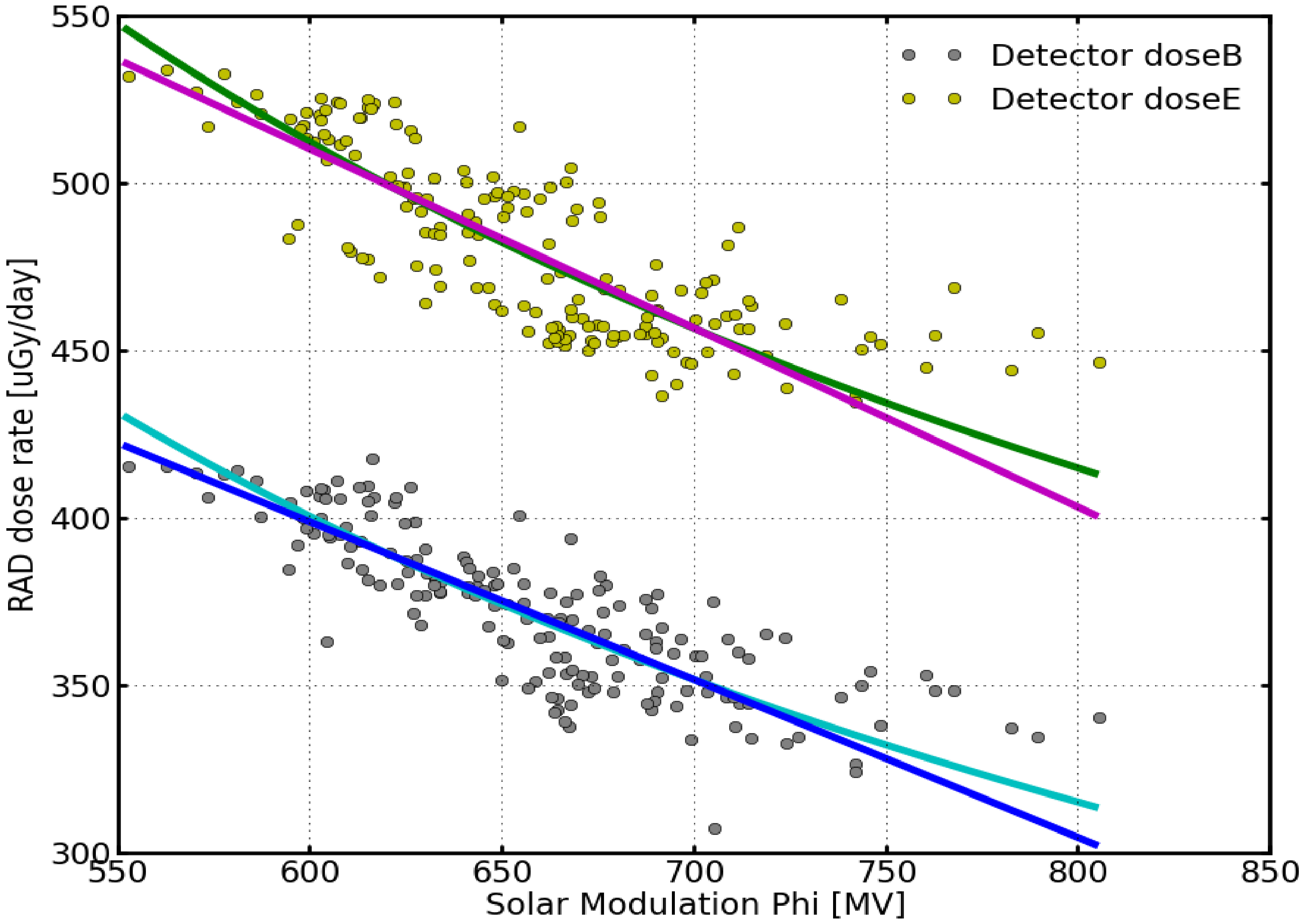
The data can be fitted well empirically in two ways

Linear fit

$$D = \beta_0 + \beta_1 \phi,$$

Non-linear fit

$$D = \alpha_0 + \frac{\alpha_1}{\phi + \alpha_2}$$

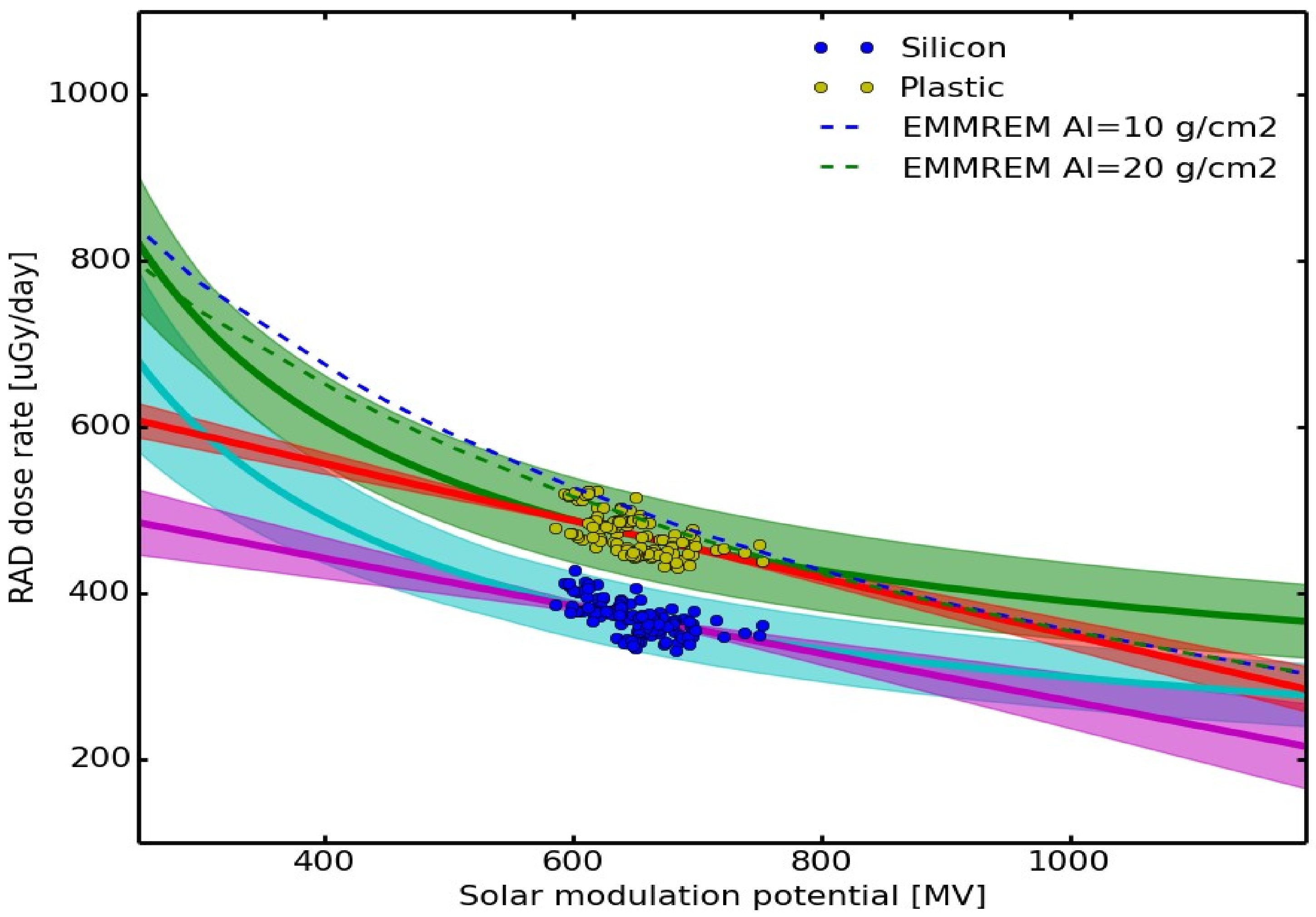


Fit the correlation between dose rate measurements and Phi

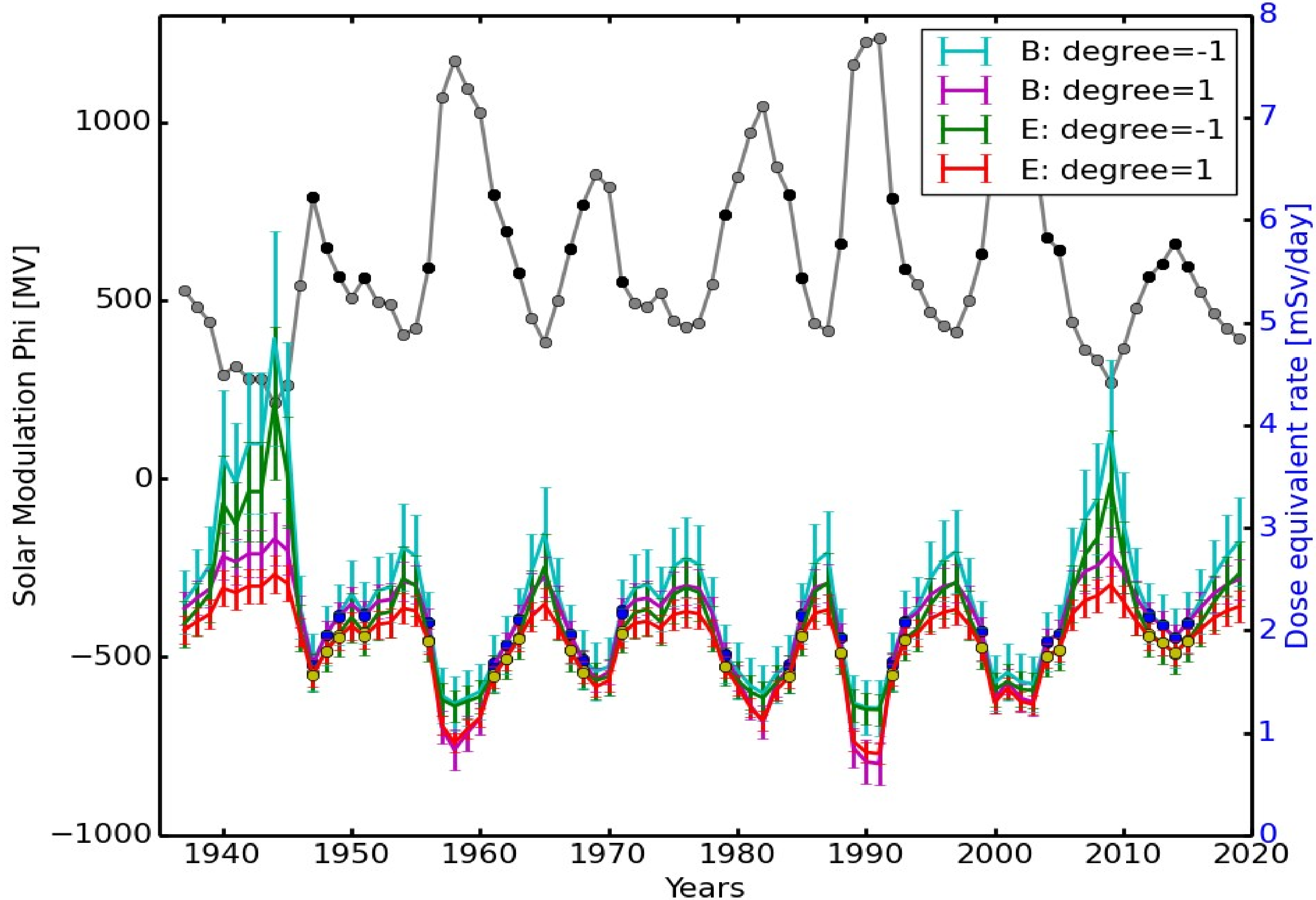
Linear:
$D = B0 + B1\ \Phi$

Silicon:
B1 = -0.39+- 0.07

Plastic:
B1 = -0.44+-0.04



'Predicted' dose equivalent rate during similar cruise missions under different solar modulation conditions

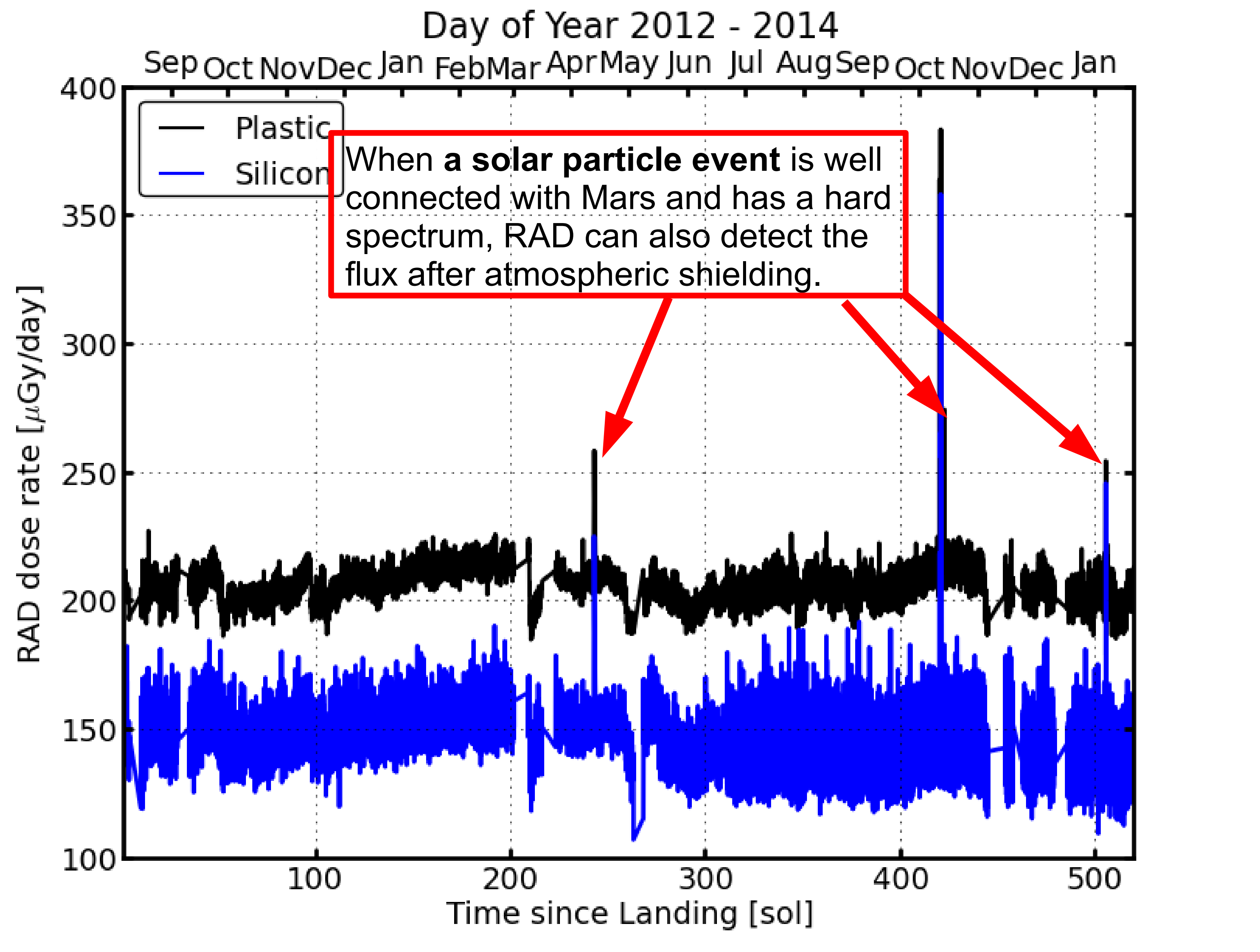


Guo et al 2015, A&A

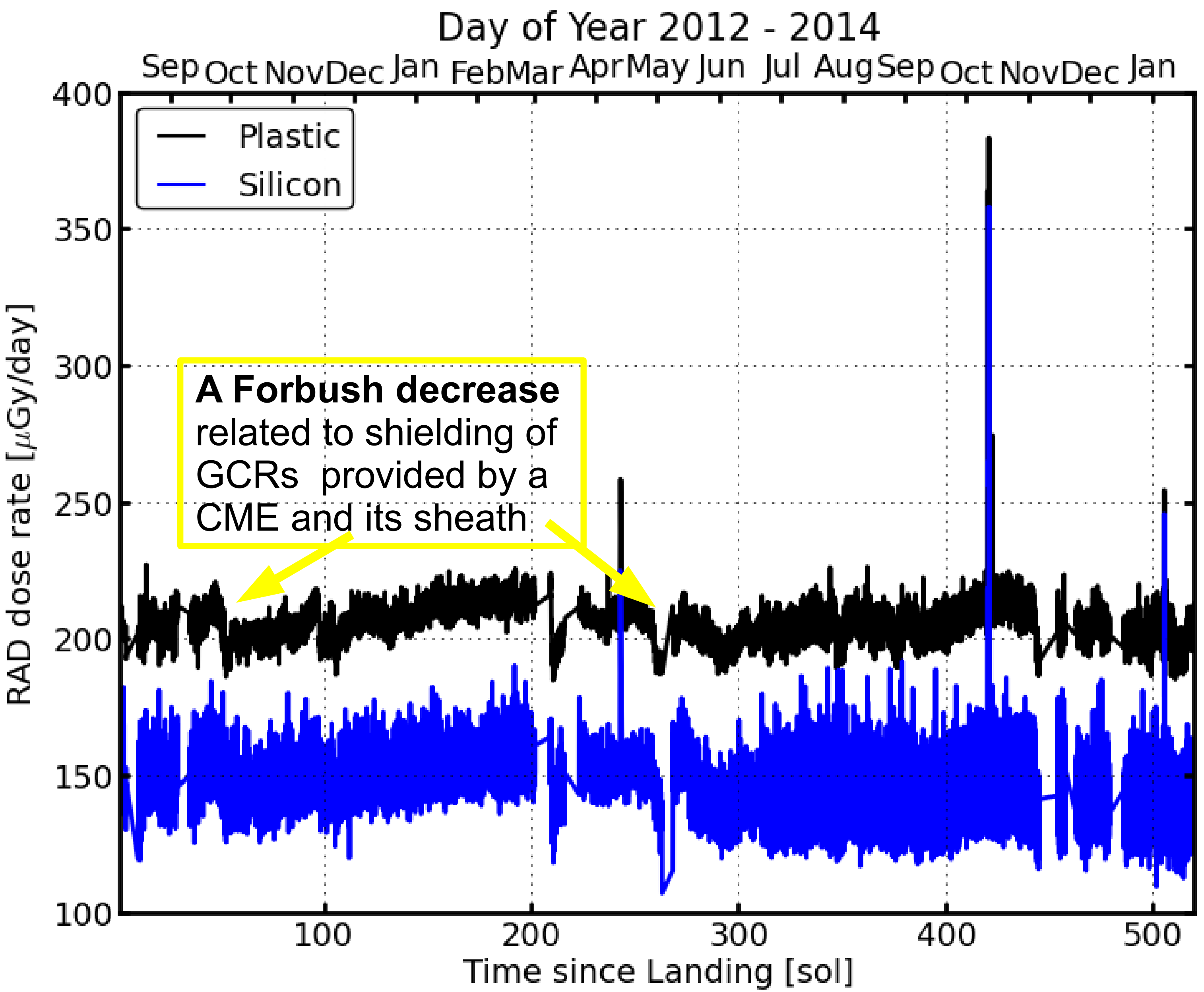
Discussions concerning future missions during the cruise

- The predicted dose equivalent rate during solar maximum conditions where Φ ~ 1200 MV was found to be as low as ≈ 0.5-1.5 mSv/day (as within the uncertainties of both models) which is considerably lower than the RAD cruise measurement 1.75 ± 0.30 mSv/day.
- The discrepancy of the two fitted models, as well as the extrapolation uncertainties, are significant at low solar modulation potentials and future measurements during solar minimum periods are necessary for improving the predictions at this range.
- Total mission GCR dose equivalent can be estimated:
  - Considering a similar shielding condition, assuming a 180-day one-way duration as a typical NASA's "Design Reference" Mars mission, we could estimate a crew taking a 360-day round trip to receive about **360 ± 180 mSv** from GCRs under a high solar modulation condition (solar maximum).
  - The fastest round trip with on-orbit staging and existing propulsion technologies has been estimated to be a 195-day trip (120 days out, 75 days back with an extra e.g., 14 days on the surface). This would result in an even smaller GCR-induced cruise dose equivalent during solar maximum: **195 ± 98 mSv**.
  - The MSL/RAD summed dose equivalent of the five observed SEPs is **24.7 mSv.** However, additional contributions of dose rate and dose equivalent rate by SEPs can differ significantly from our current measurements since the frequency and intensity of such events are highly variable.
  - These estimations are less than the safe upper limit for 30- to 60-years old, non-smoking females (600-1000 mSv) and males (800-1200 mSv) given by the NASA Central estimates of dose limits.

Surface data: First time on Mars!



The first 500 Sols of dose rate data



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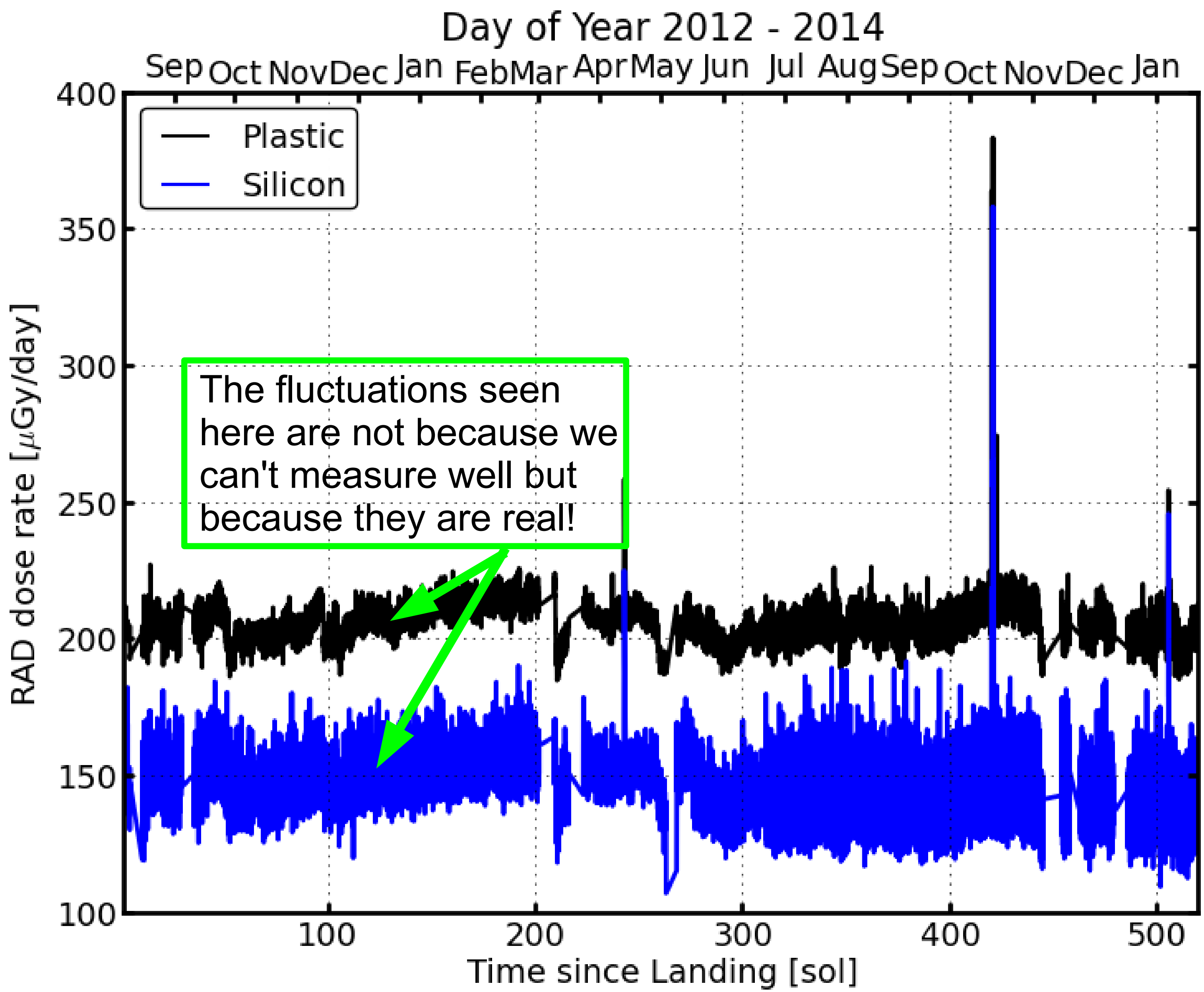

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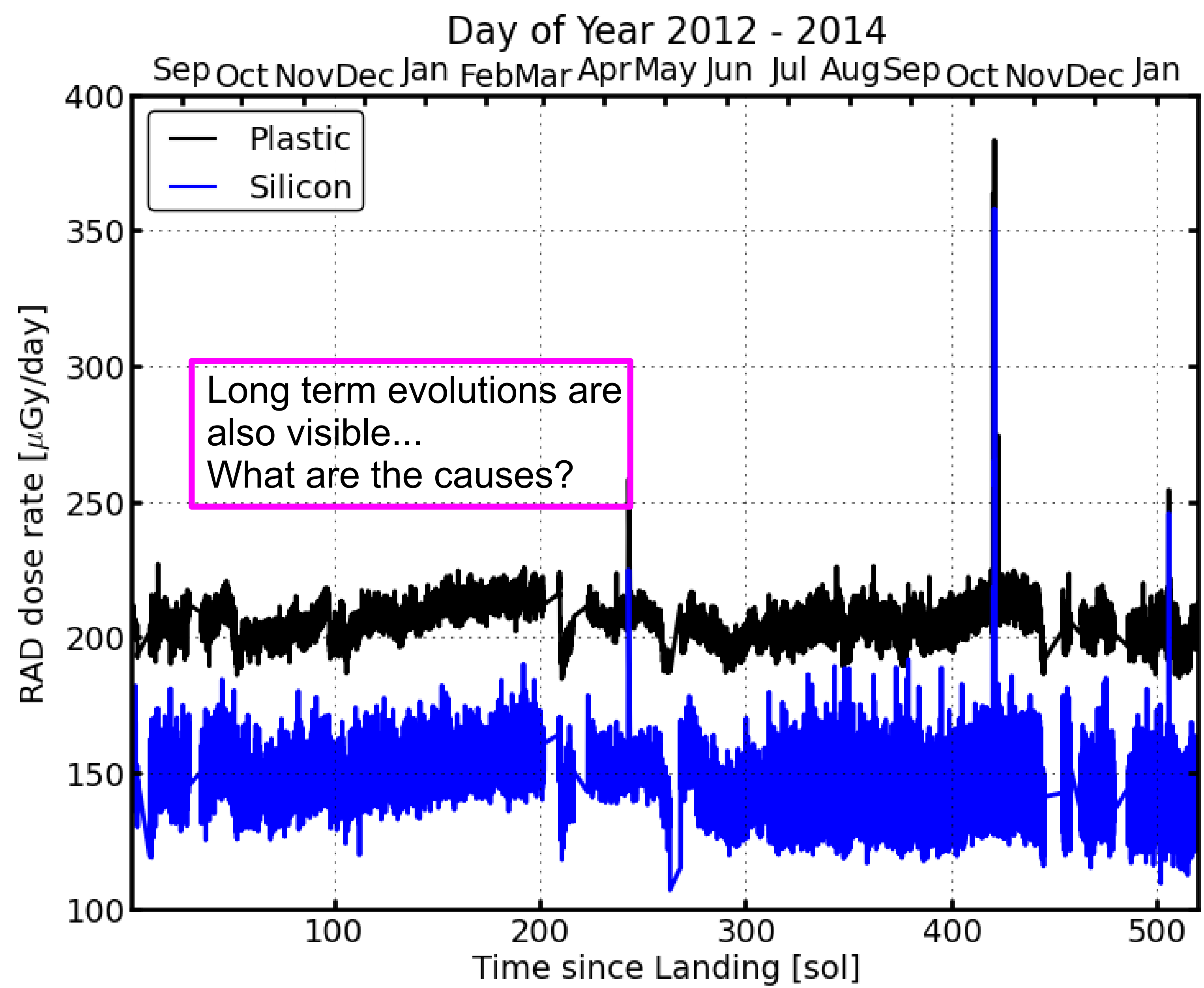
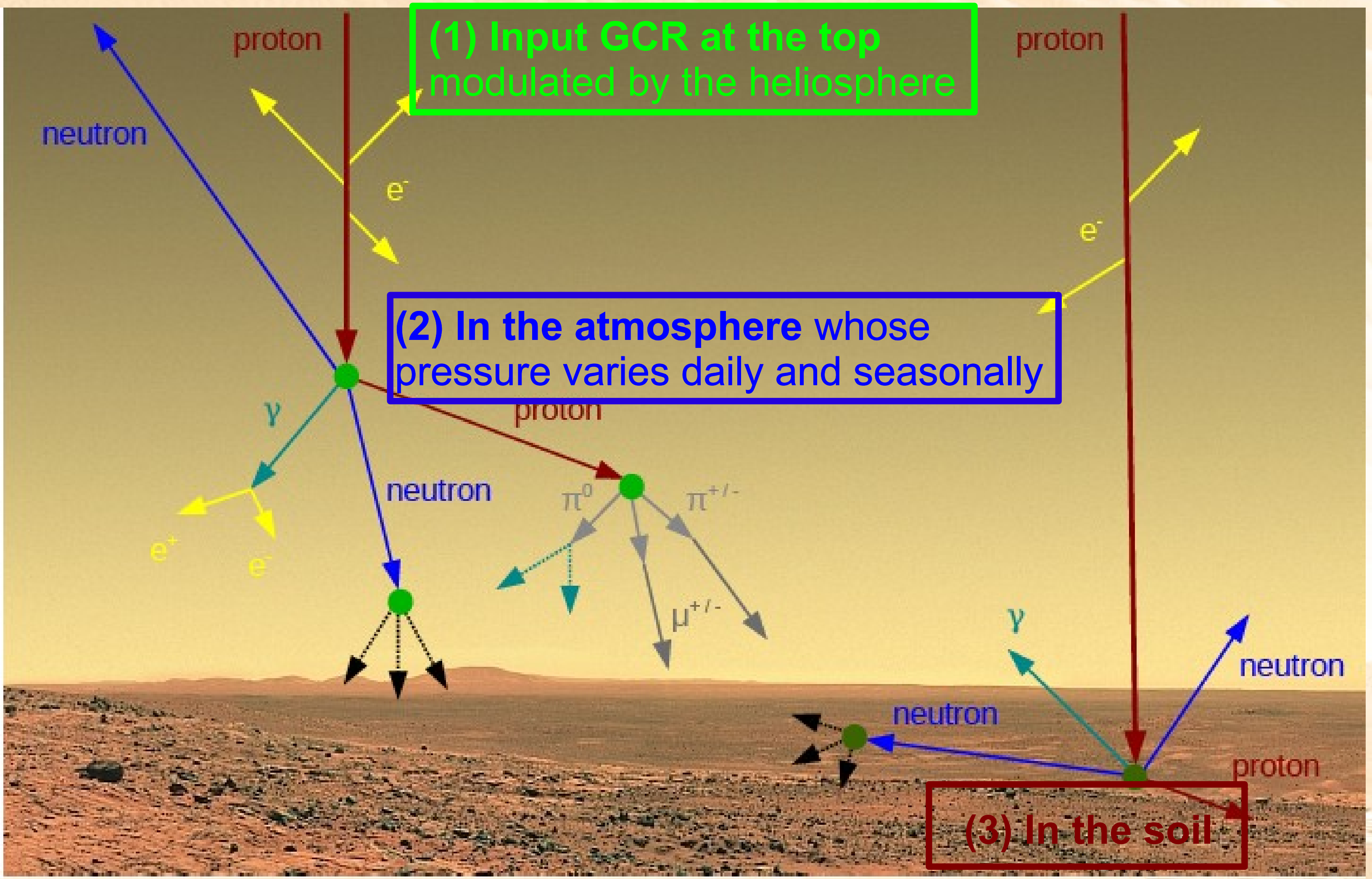


Particle fluxes on **the surface of Mars**



Plot from Ehresmann et al 2011

Variations of surface particle spectra → variations of surface dose rates

$$\boxed{D(\Phi, P)} = \sum_j \int_{\epsilon_{min}}^{\epsilon_{max}} \int_0^{\infty} \lambda_j(E, \epsilon) \boxed{F_j(\Phi, P, E)} \, dE \, d\epsilon / m$$

- Surface particle fluxes and corresponding dose rates are affected by solar modulation potential Φ and atmospheric pressure P.
  - When pressure is higher and shielding is stronger, dose rates decrease.
  - When solar magnetic potentials are higher, more GCRs are shielded away and dose rates are lower.
- Excluding SEPs, RAD measured dose rates are affected by three major influences concurrently and continuously:
  - Day and night fluctuations of the atmosphere column mass
  - Seasonal changes of the atmospheric density
  - Modulations of the heliospheric magnetic fields as well as the rotation of the Sun (~27 days)

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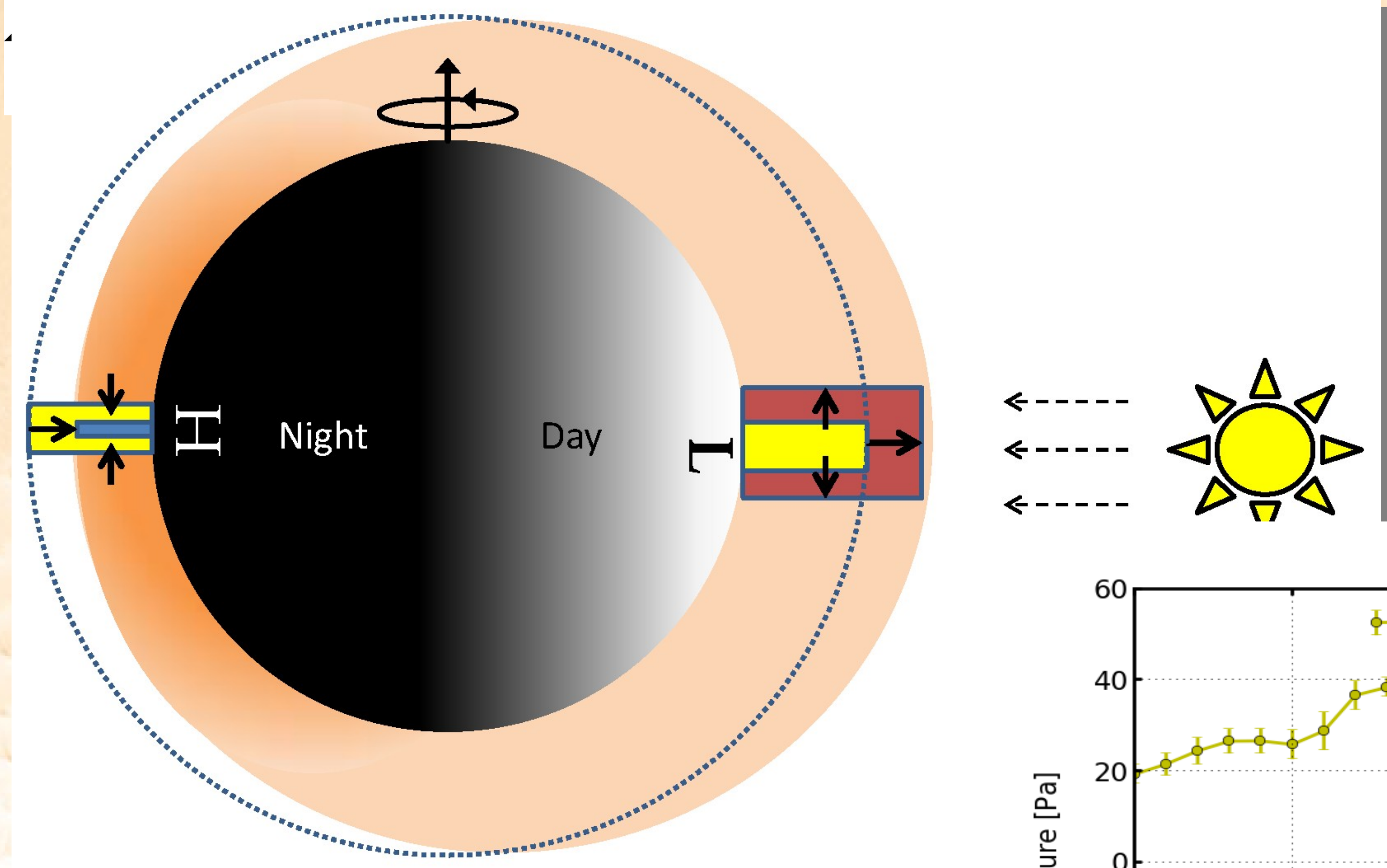
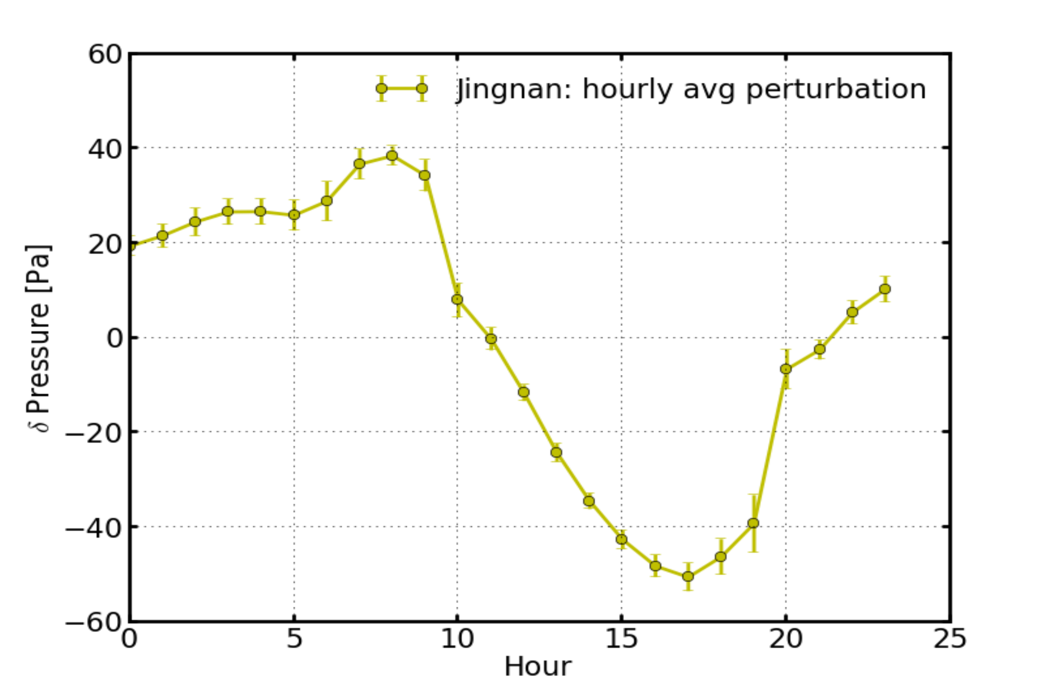
Diurnal Variations of Pressure: Column Mass Changes Due to Thermal Tide

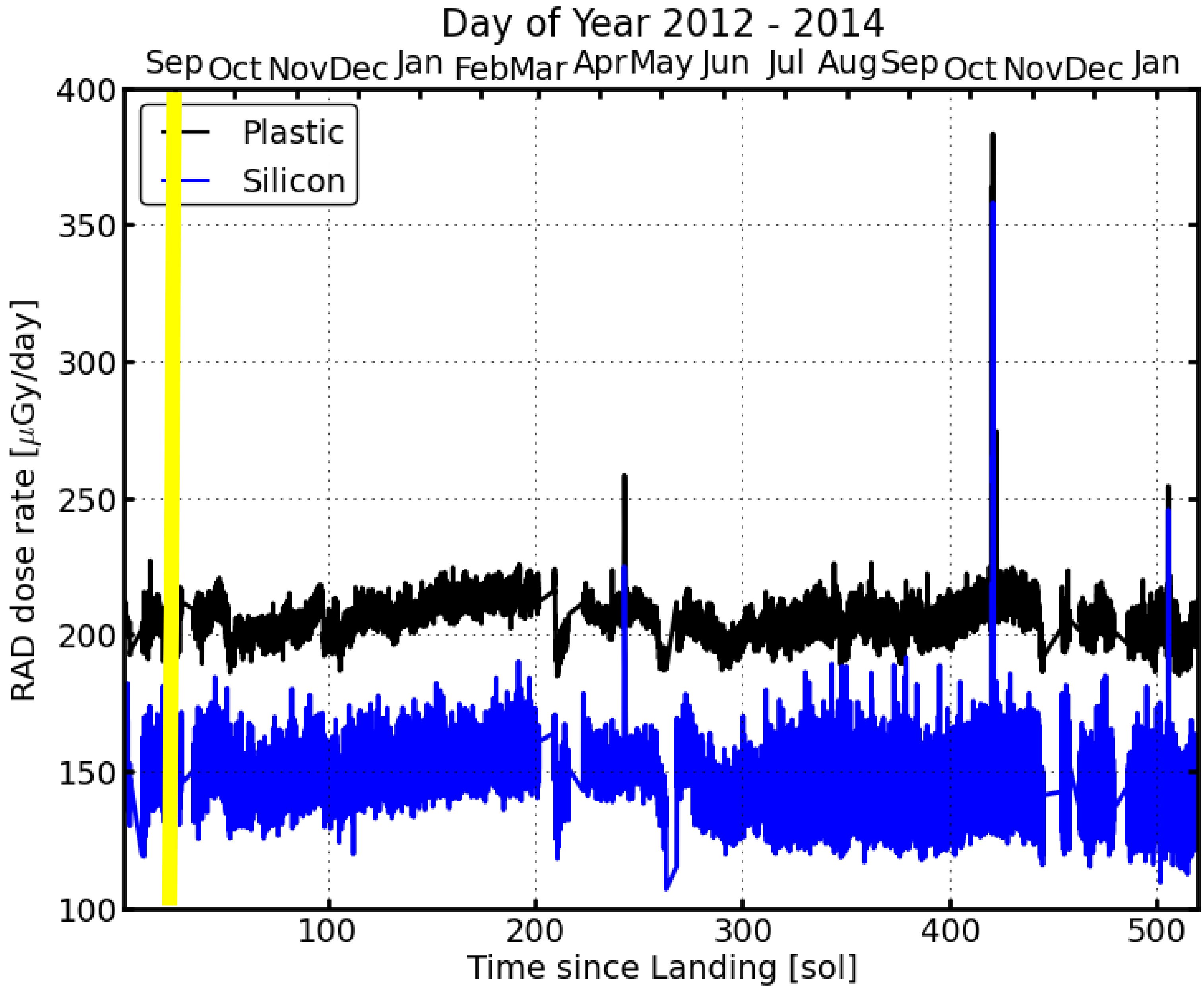




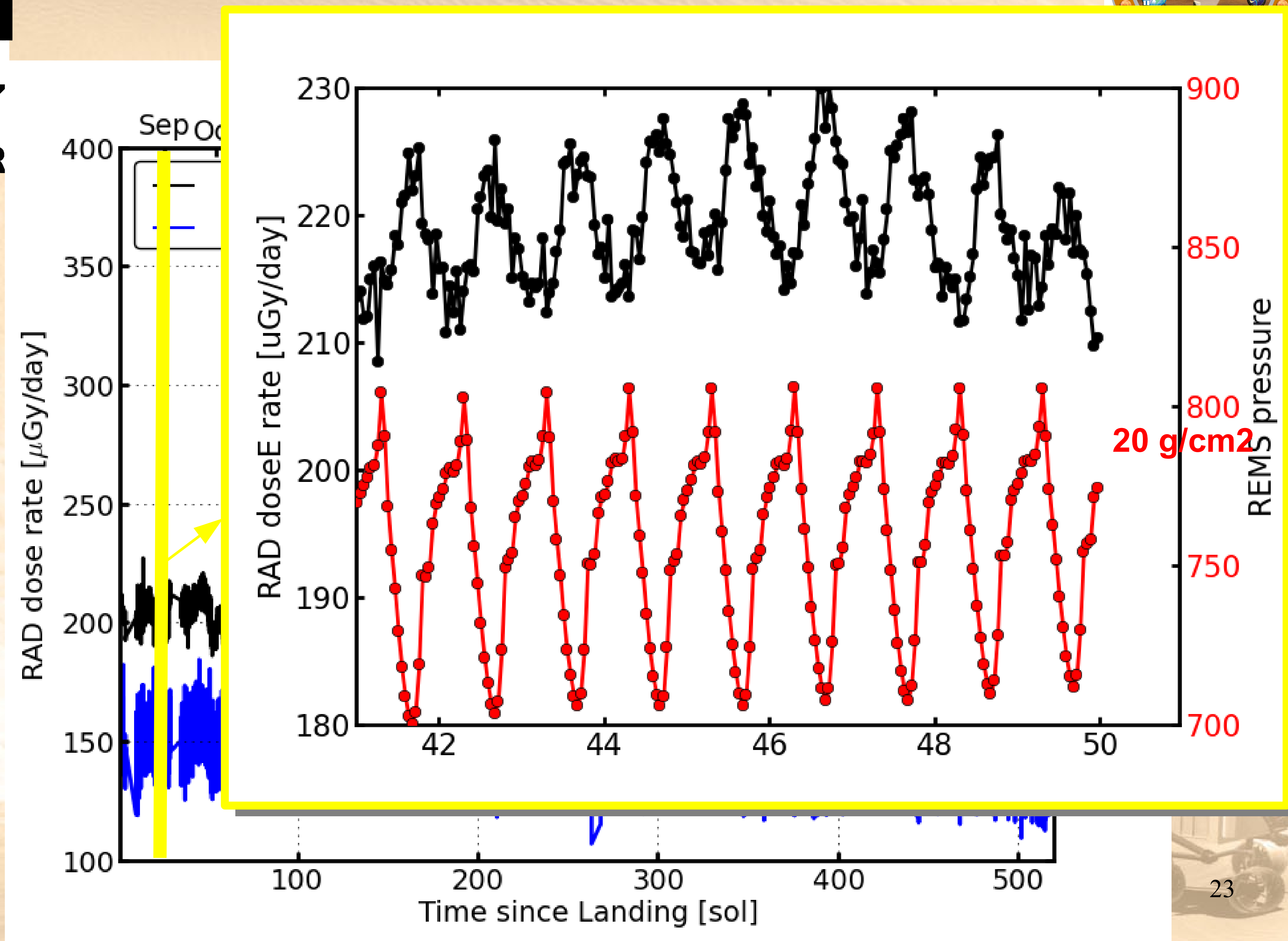
Rafkin et al. 2014

Crater circulations amplify the tide, leading to a stronger effect.

Let's take a zoom-in look of the diurnal variations



For example, dose and pressure during sol 40-50



Anti-correlation between dose rate and pressure

The derived relationship between pressure [Pa] and dose rate [uGy/day] variations is:

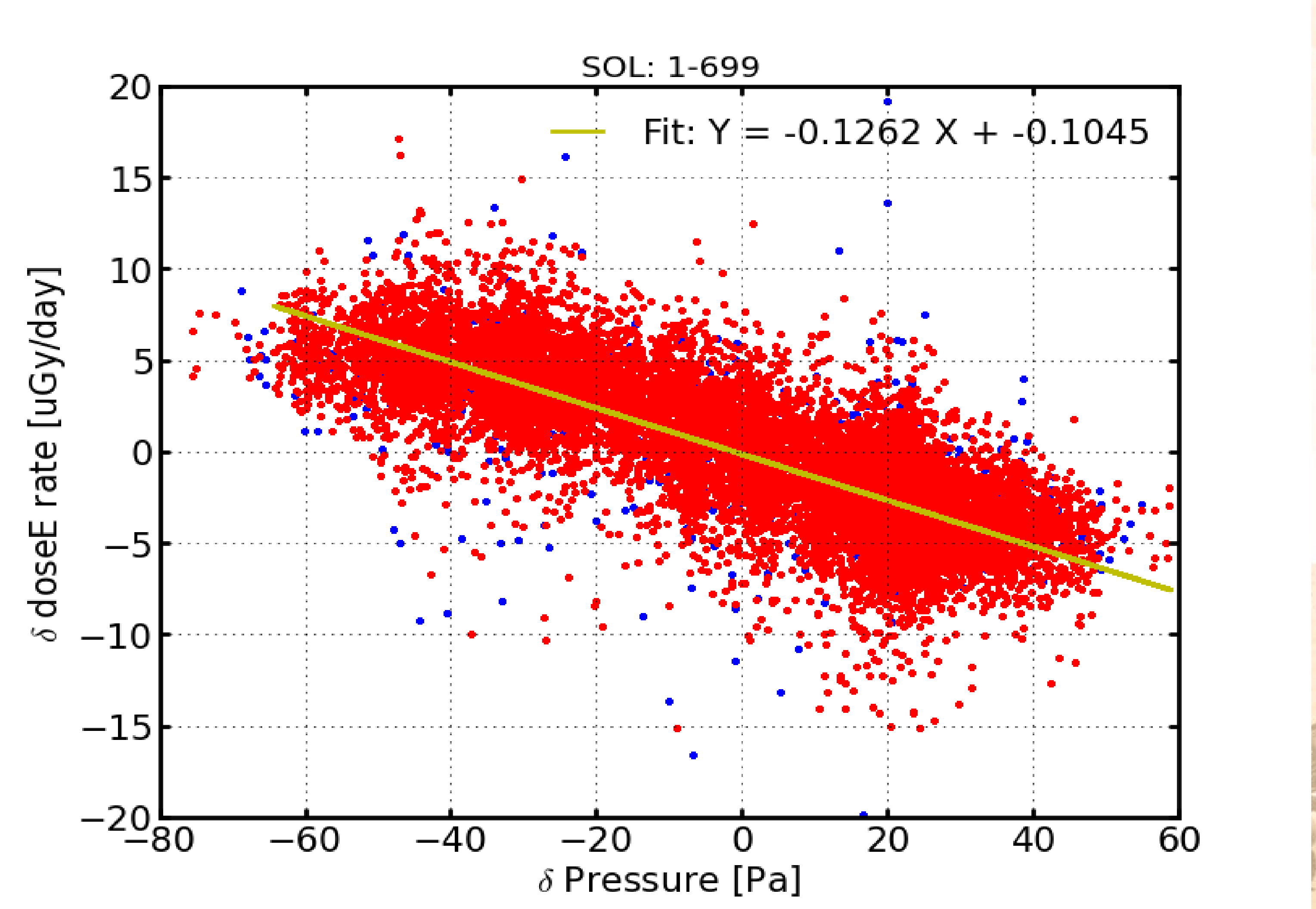
$$\delta \bar{D}_h = \kappa_d \times \delta \bar{P}_h$$

Fitted:Kappa=0.13

The perturbation analysis isolate the pressure effect.

E_hs = the averaged data in each hour at certain Sol
E_s = total average of all hours at certain Sol

P_hs = E_hs – E_s
the perturbation in each hour at certain Sol are plotted as red dots



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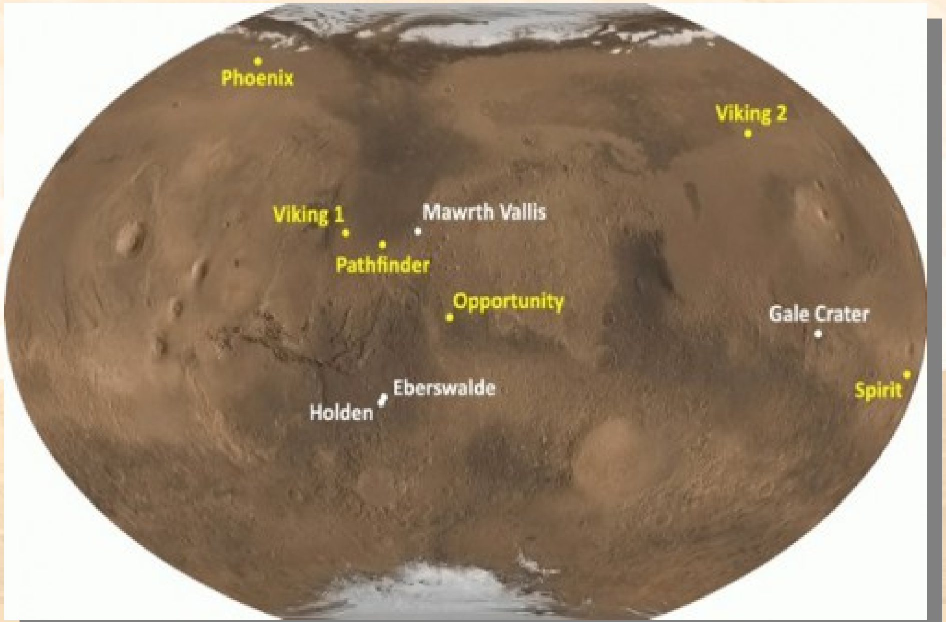
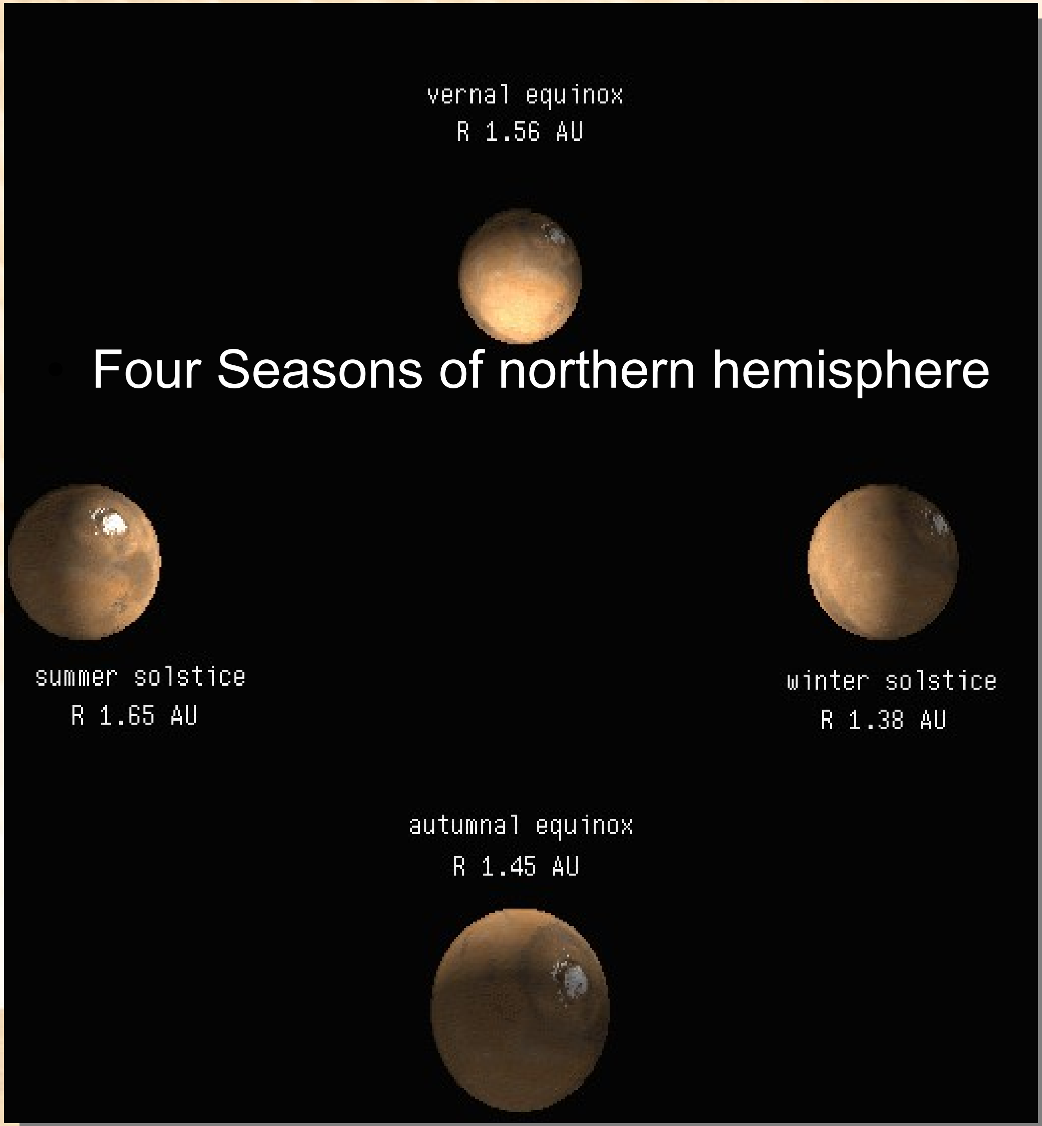
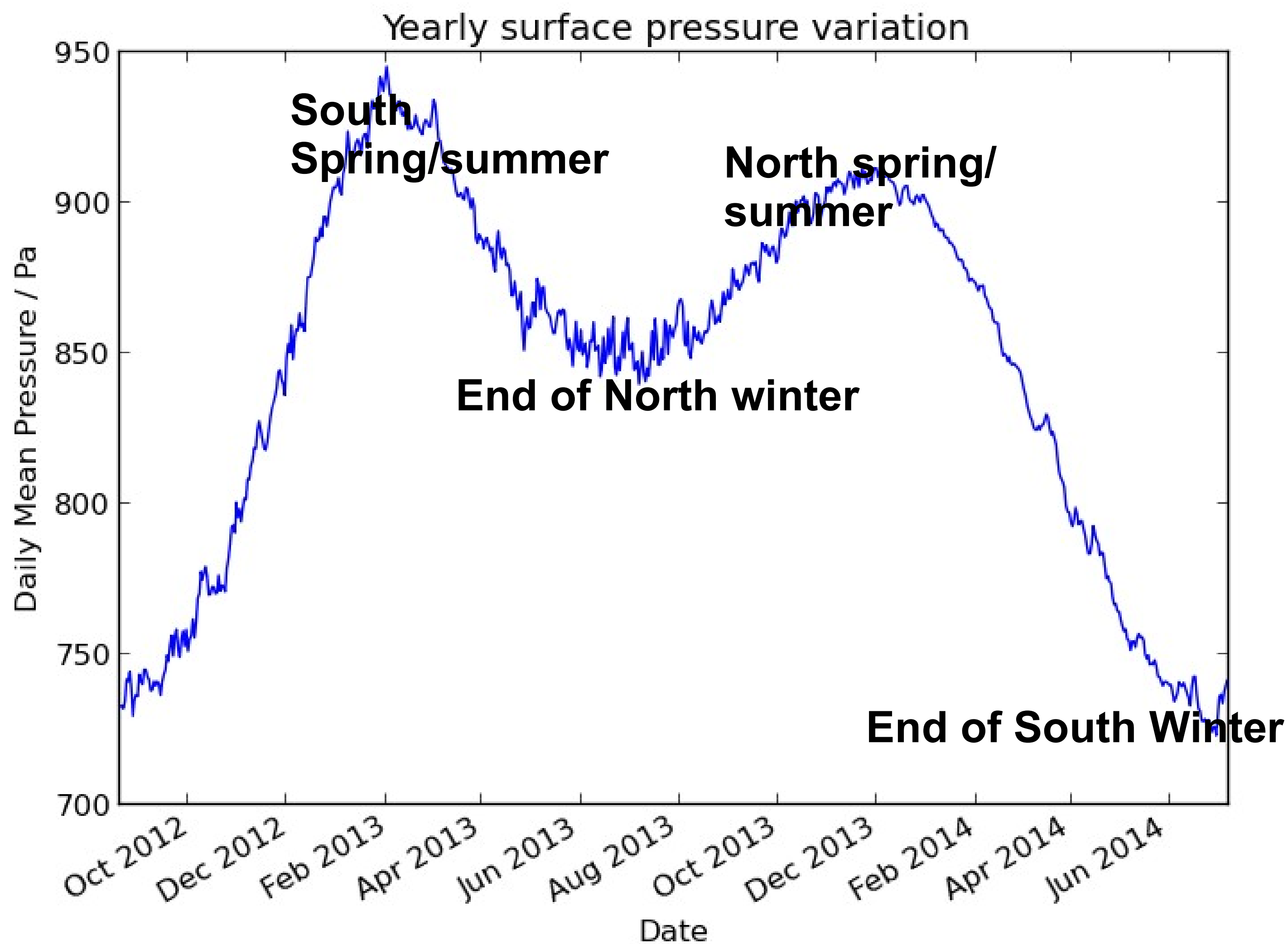
Seasonal pressure changes on Mars

- Seasonal conditions are reversed in the northern and southern hemispheres
- Seasonal pressure change is driven by the growing and shrinking of the polar caps (CO2).
- 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



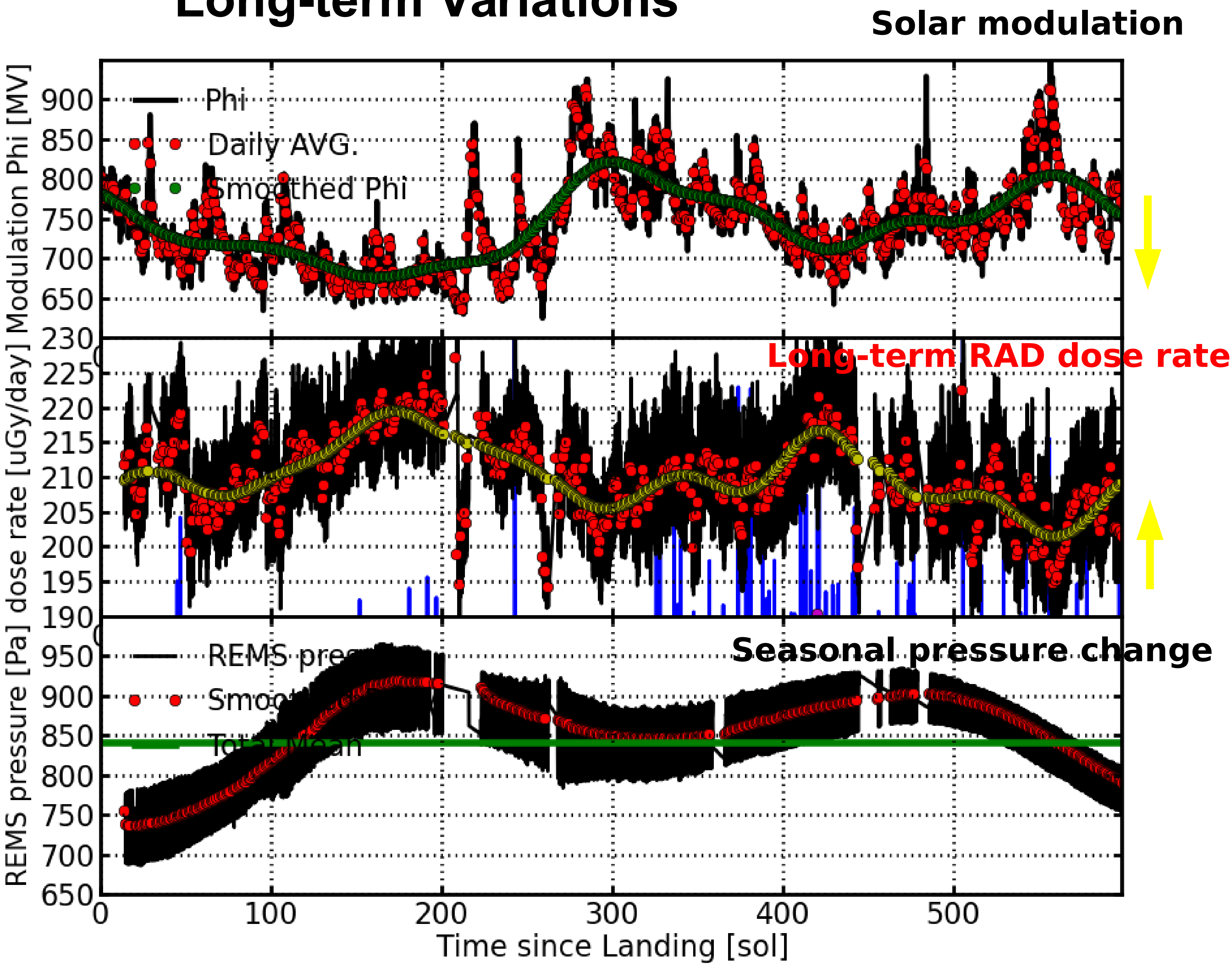


Pressure Changes over a Martian Year (687 earth days)



Data provided by Martian Atmospheric data base

Long-term Variations



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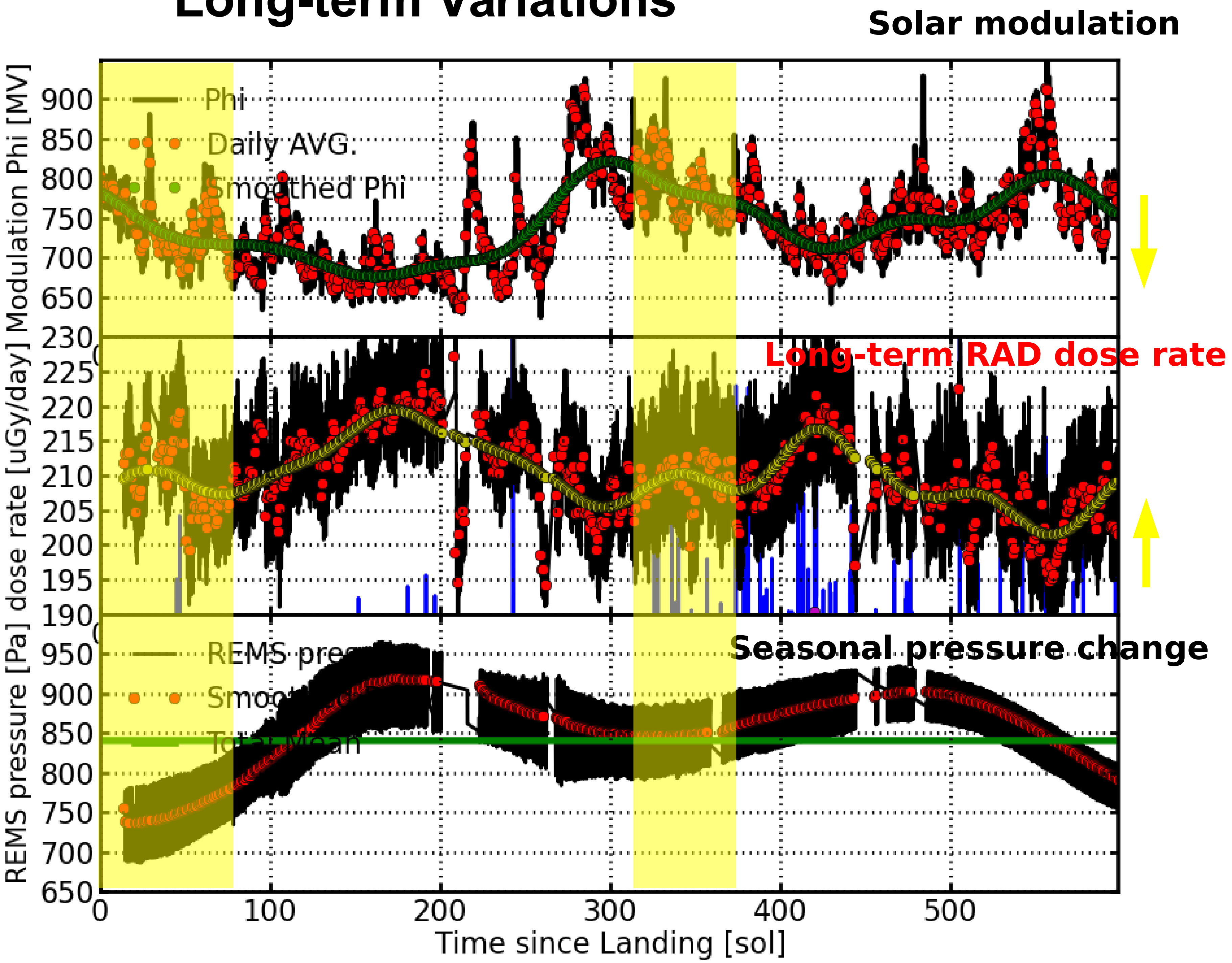

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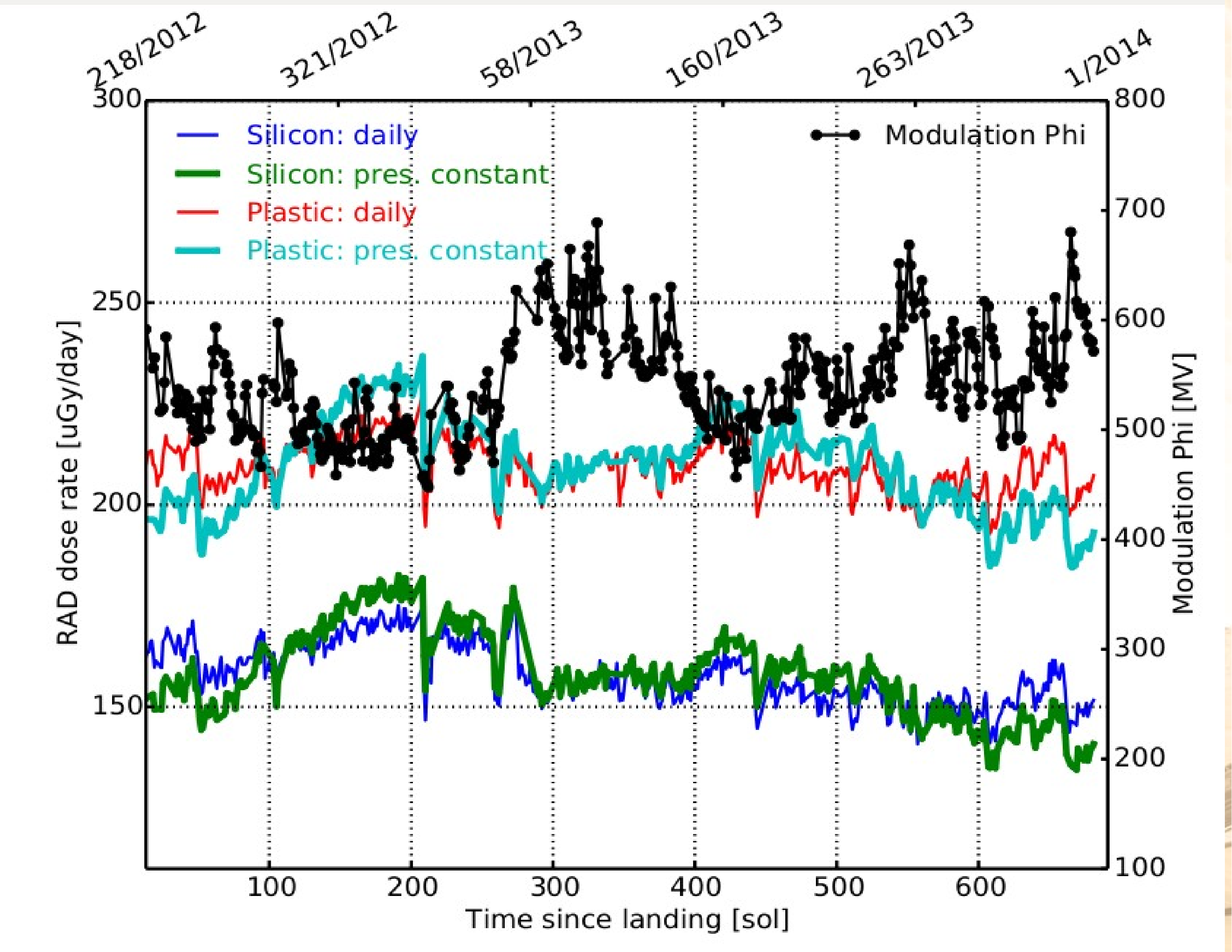
Subtract longterm pressure effect

→ 'Pure' Solar Modulation effect

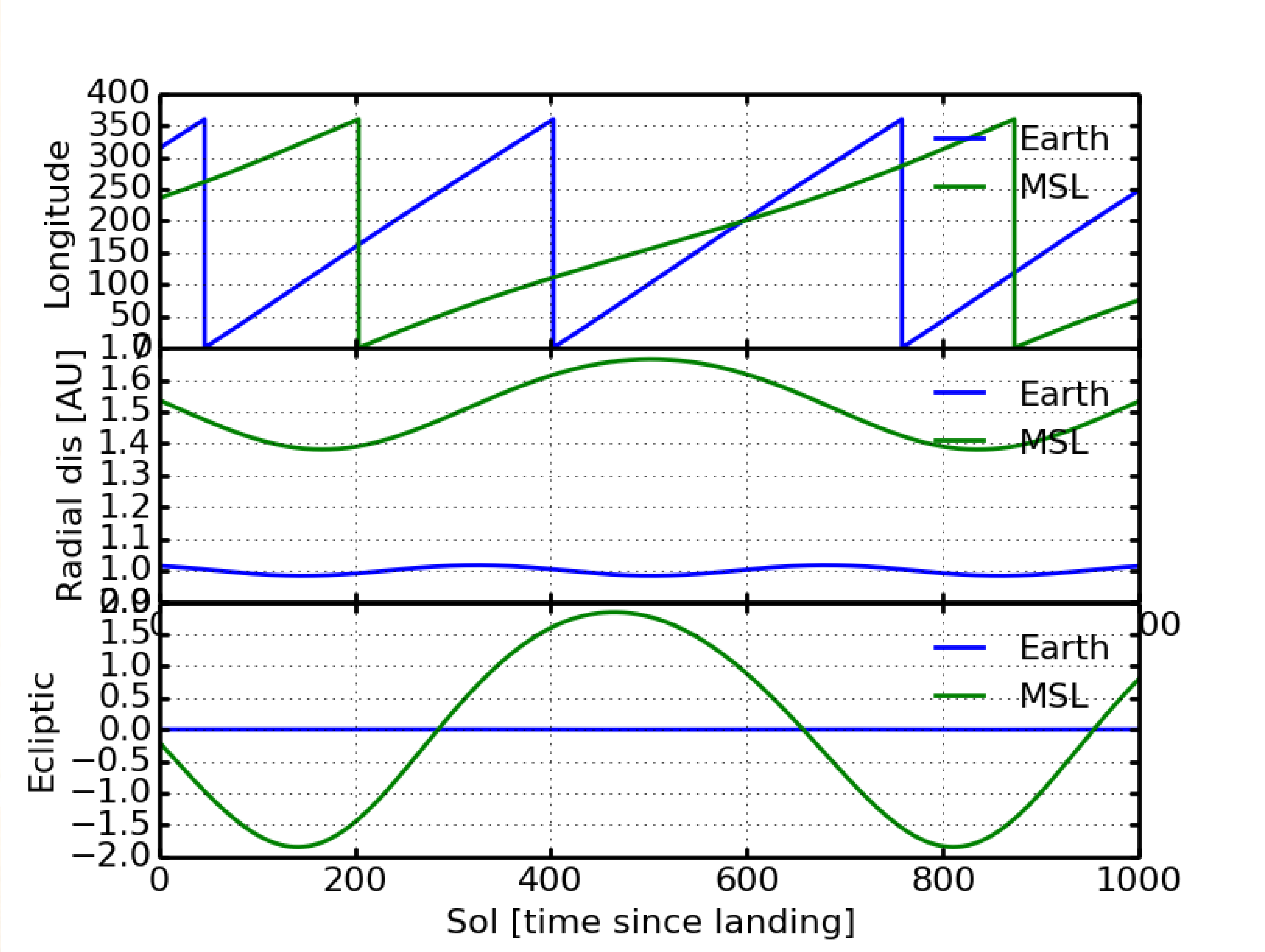
- Assume that the pressure is constant at its average, 840 Pa, we can subtract the contributions of dose rate changes led by seasonal pressure variations

- The corrected silicon and plastic dose rates without pressure influences are shown in cyan and green colors.



Guo et al 2015b, ApJ

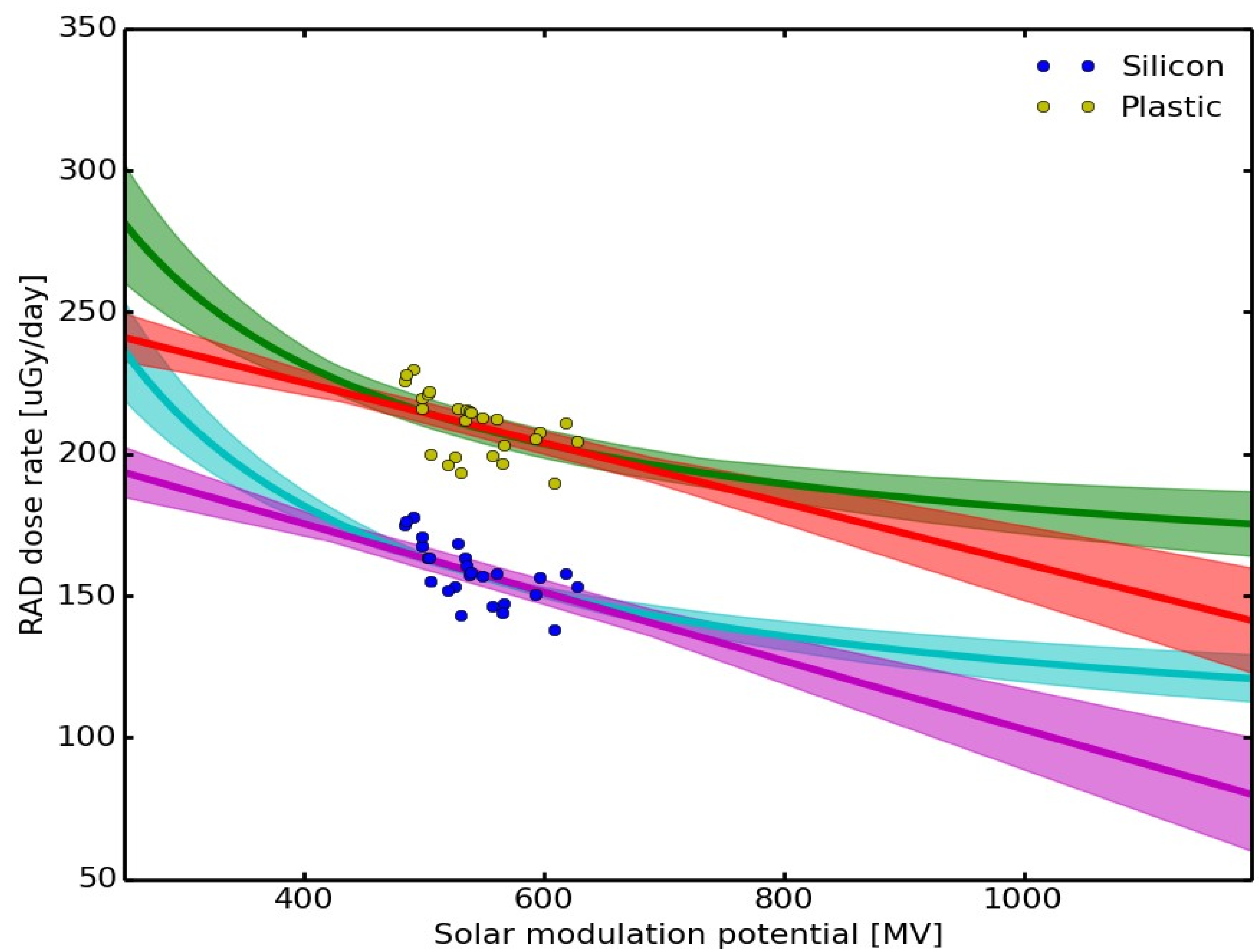
But the longitudinal separation of the two planets are significant



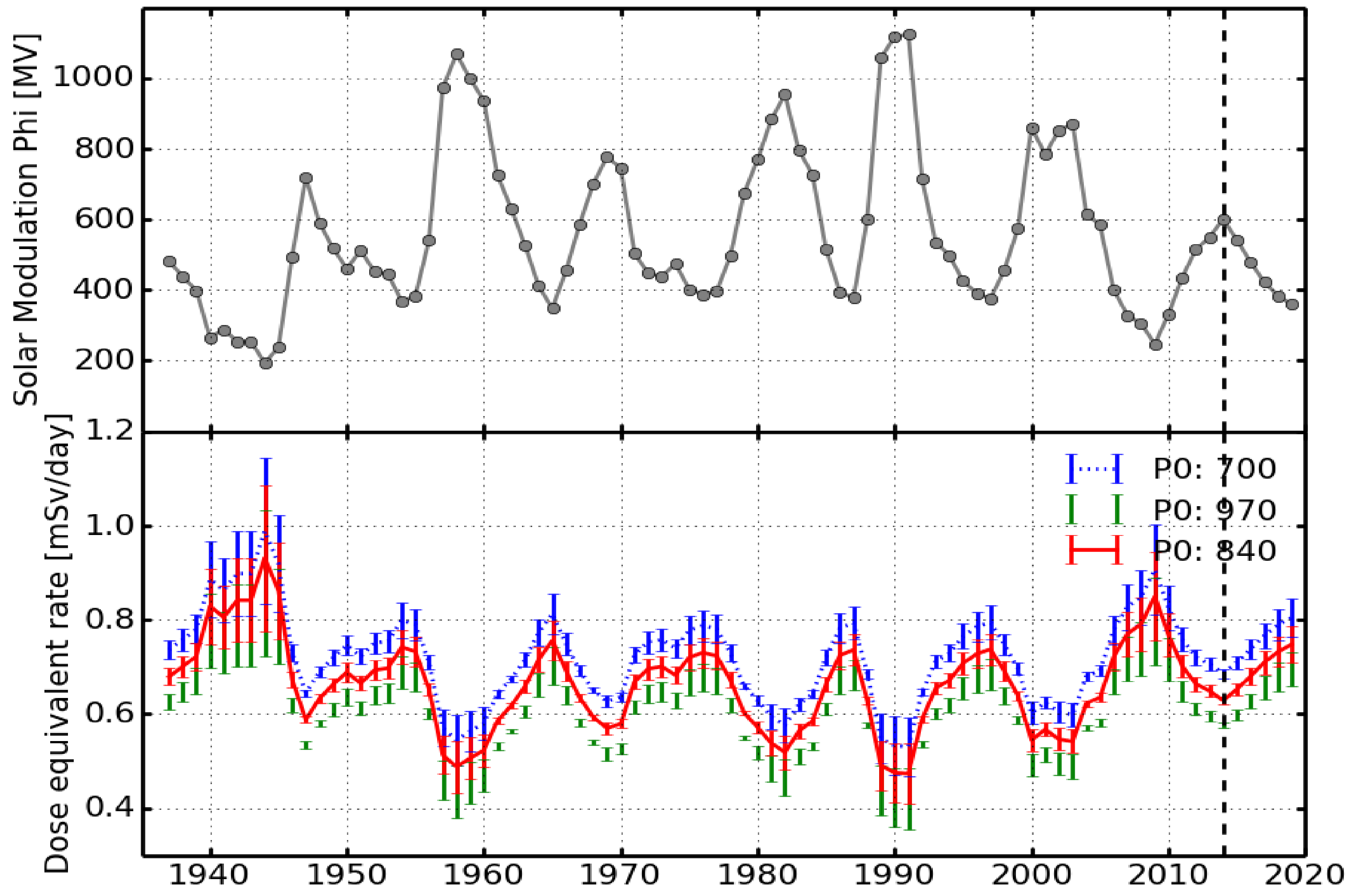
Correlate and fit solar modulation potential with pressure-constant dose rate

- Data have been binned into each 26-sols in order to smooth out the solar rotation effect and the heliospheric longitudinal discrepancies between Earth and Mars.
-

Linear parameter:
B1 = -0.12 (silicon); -0.11 (plastic)



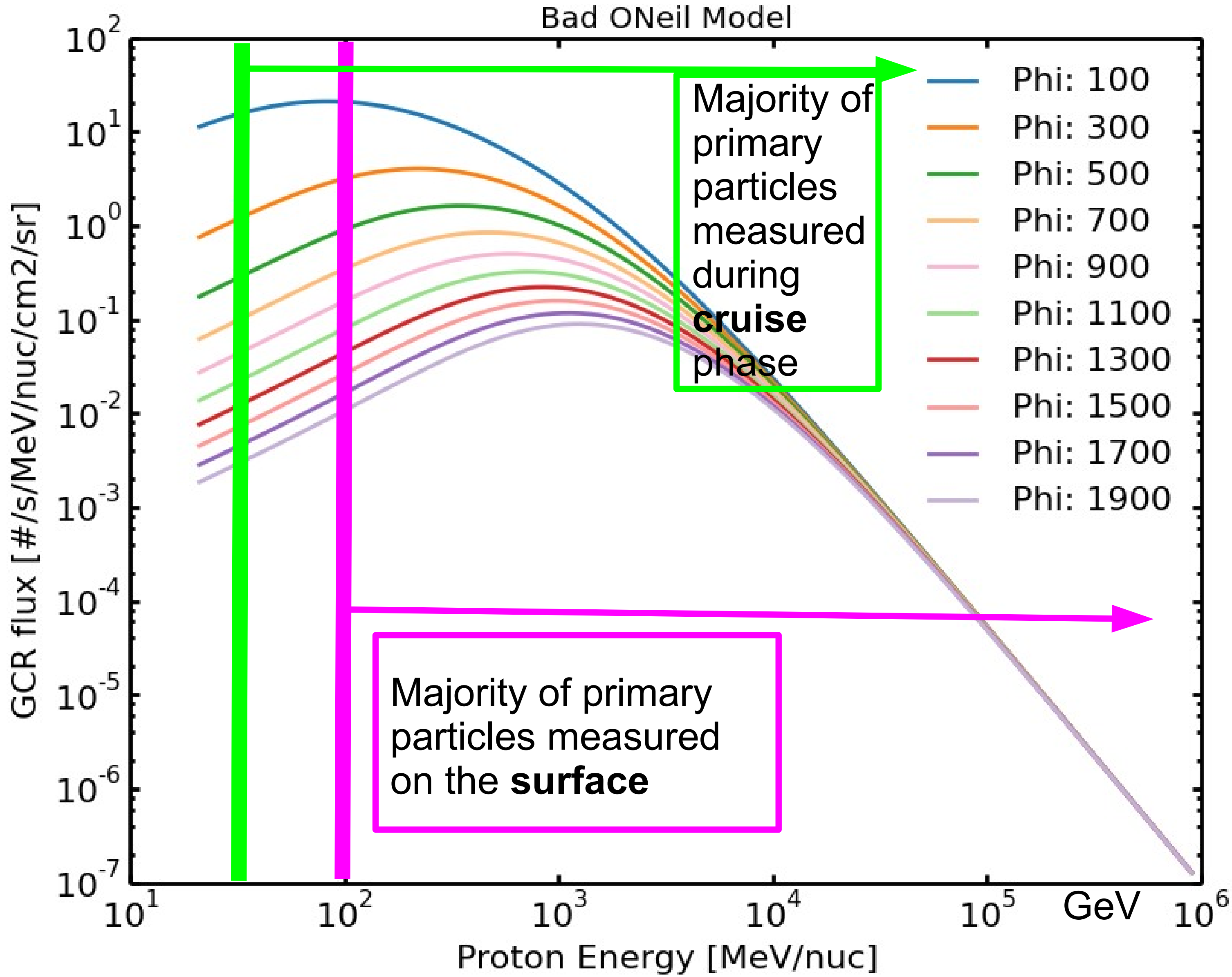
Prediction of GCR radiation during other solar modulation and pressure conditions



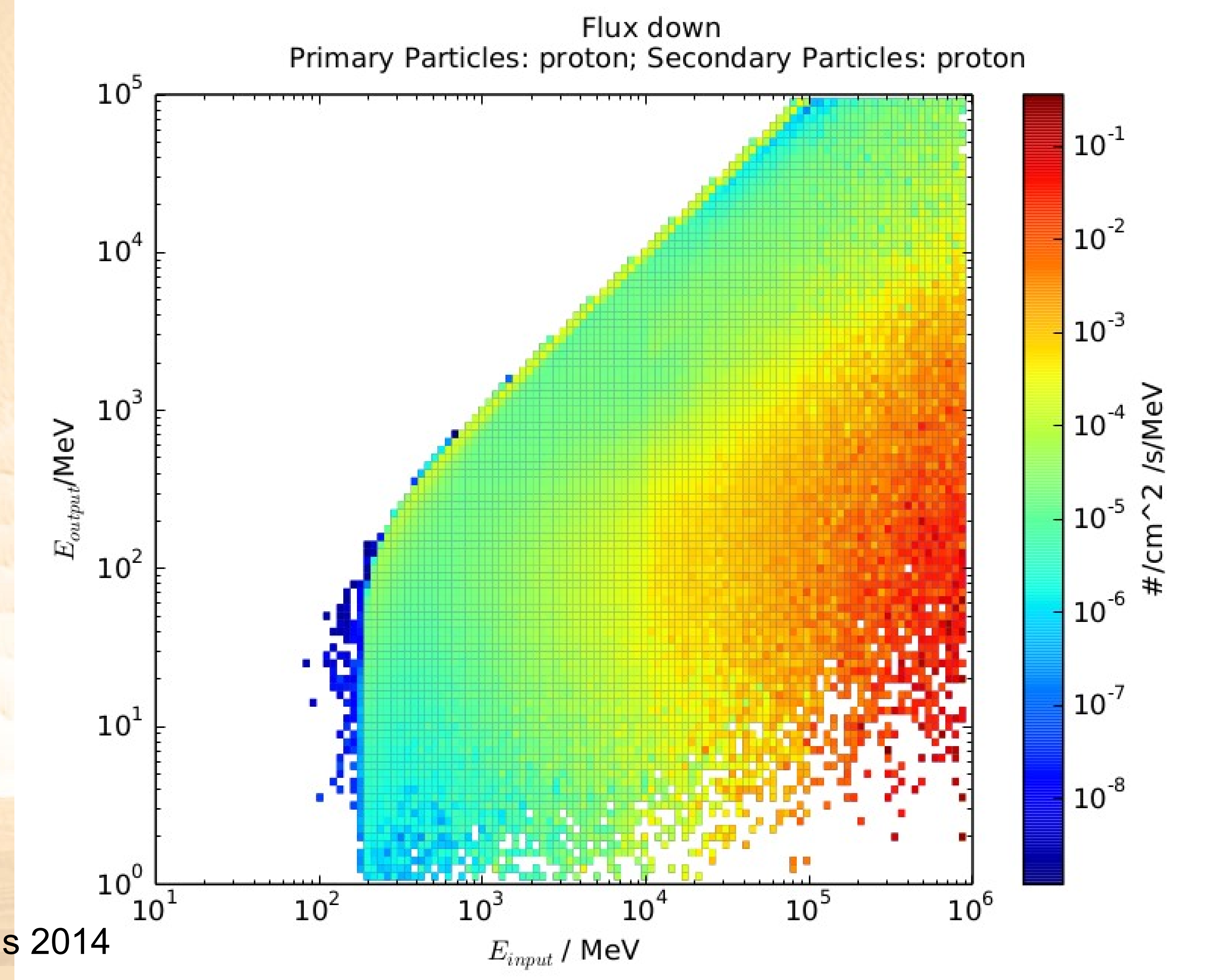
Guo et al 2015b, ApJ

D = B0 + B1 Φ:

Linear dependence B1 obtained from surface measurements are less than that from the cruise phase

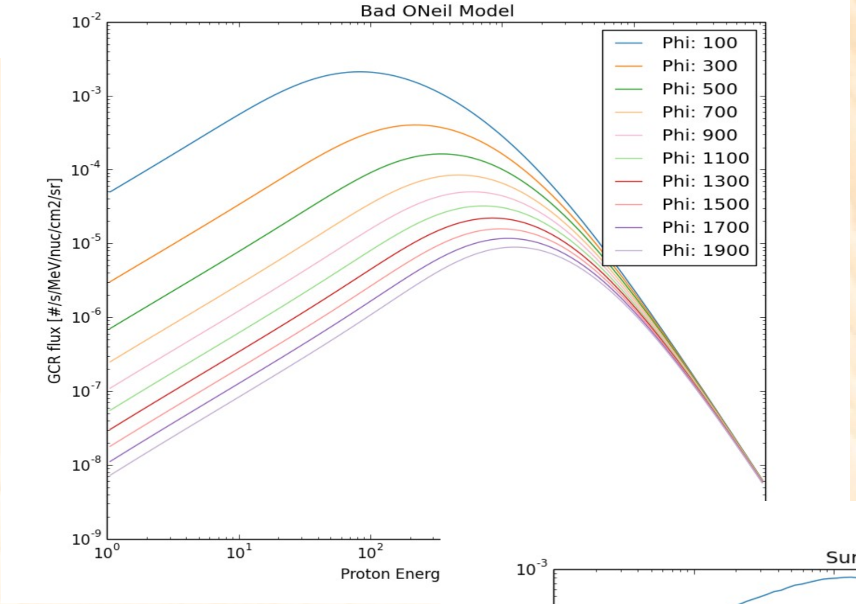


PLANETOCOSMICS (GEANT4) simulations e.g., Primary protons → secondary protons



Krauss thesis 2014

Input spectra through atmosphere → Surface spectra



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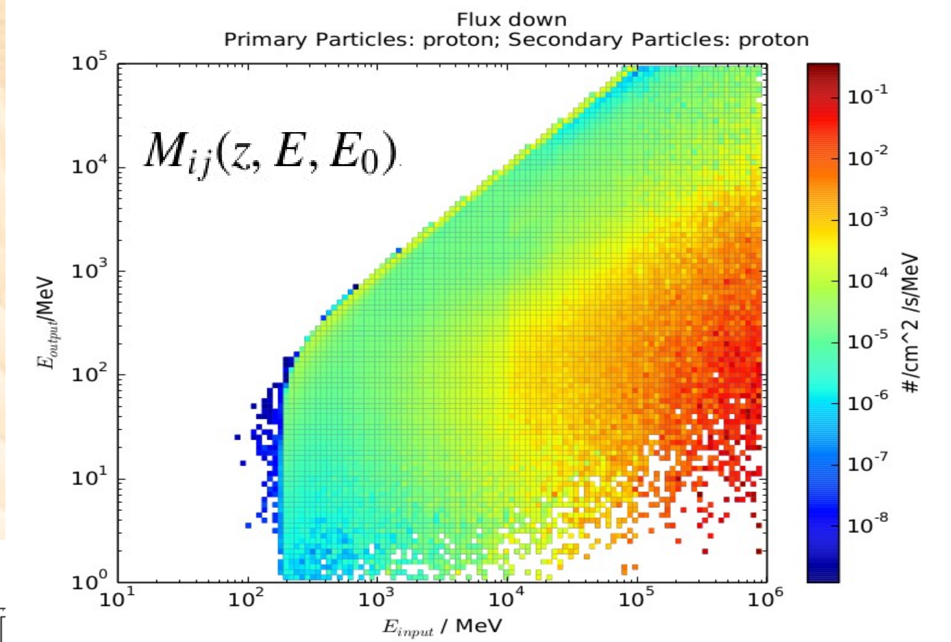

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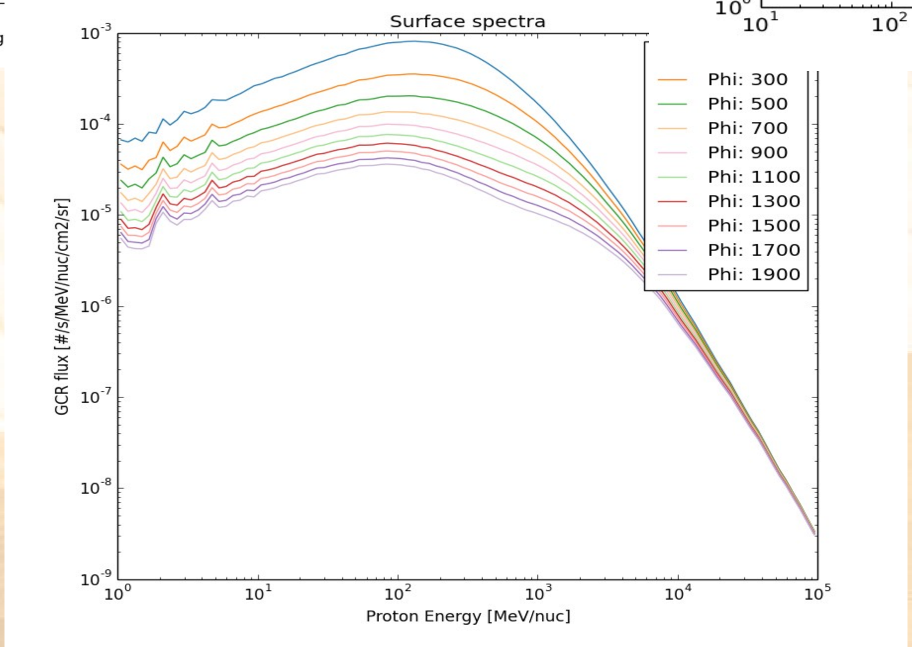

Discussions

$$D(\Phi, p) = D_{01} + \kappa P + \beta\Phi,$$

- Both models have assumed the independent effect of pressure and Φ on dose rates. However, this may be modified when pressure and Φ change over wider ranges than have been observed to date:
  - a much thinner atmosphere will allow more lower-energy particles to reach the surface which experience stronger modulation (e.g., bigger |β| in the linear model). Therefore, for significant pressure changes, β should be a function of P, i.e., β(P)
  - much stronger solar modulation (bigger Φ) would lead to a larger fraction of high-energy particles in the GCR flux and these energetic particles are less affected by the atmosphere (smaller |κ|); when pressure is much higher and the surface atmospheric depth is closer to the Pfotzer maximum, most primary particles are shielded while more secondary particles are generated and this may result in a decreased shielding effect; therefore the dependence of dose rate on pressure may be modified as P and Φ change substantially, i.e., κ = κ(P, Φ)
  - both the linear and non-linear models are empirical and derived from measurements; despite the robustness of the fitting of the actual data, the extrapolation is highly uncertain and a complete model requires measurements over the full range of solar conditions.

Guo et al 2015b, ApJ

We would also like to thank

- MSL/REMS Team
- OULU Neutron Monitor
- WDC-SILSO (Sunspot Index and Long-term Solar Observations)