International Cosmic Ray Conference
Madison, Wisconsin, USA
27 July 2019

Spectra of solar energetic particles and galactic cosmic rays over Myrs reconstructed using ^{26}Al from lunar rocks

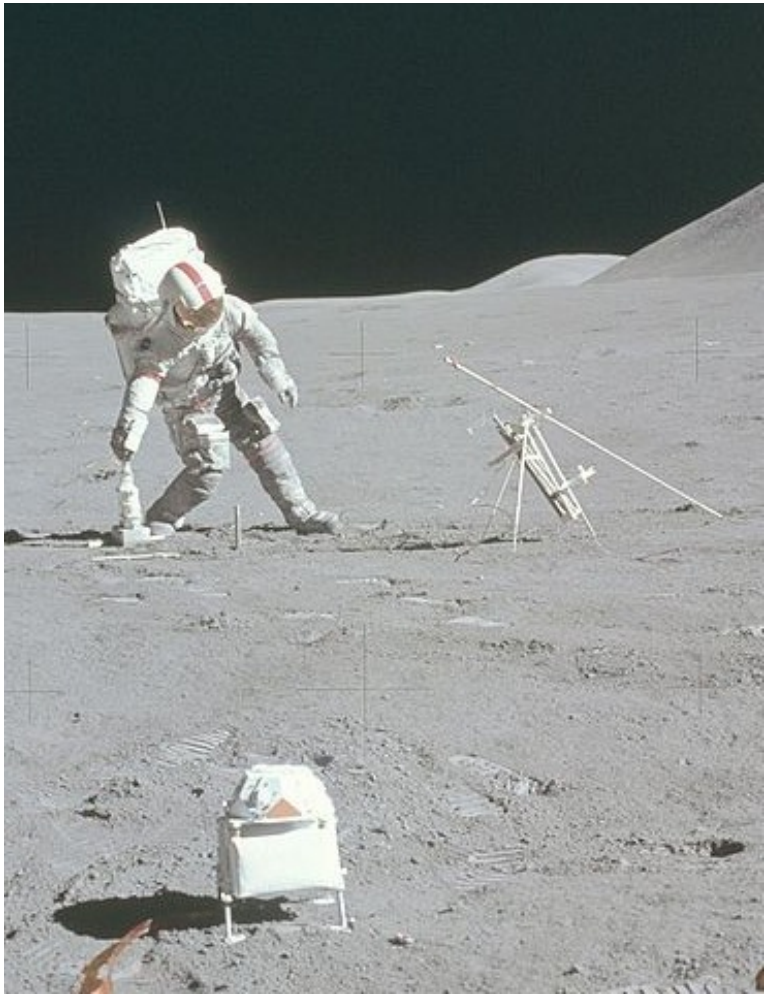
Stepan Poluianov[1]
G. Kovaltsov[2] and I. Usoskin[1]
1- Space climate research unit and
Sodankylä geophysical observatory,
University of Oulu, Finland
2- Ioffe physical-technical Institute, St. Petersburg, Russia

^{26}Al produced in situ at the Moon

- **Nuclides stay where they have been produced. No transport. No time resolution.**
- **Depth distribution of nuclides → information about the spectrum.**
- **Outside the magnetosphere → solar energetic particles significantly contribute to the total nuclide production.**

- **In this talk:**

  only Al-26 (lifetime 1.03 Myr).



(NASA, AS15-87-11847,cropped)

Lunar samples

- **Deep drill core 1500x (Apollo-15)**

  [Rancitelli et al., 1975, Nishiizumi et al., 1984]

  Al-26 meas. down to ~400 g/cm²

- **Lunar rock 64455 (Apollo-16)**

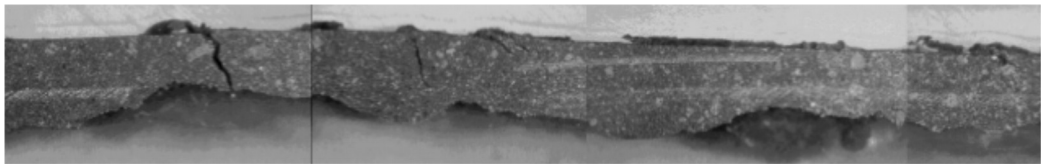
  [Nishiizumi et al., 2009]

  Al-26: 0.1-6 g/cm2

- **Lunar rock 74275 (Apollo-17)**

  [Fink et al., 1998]

  Al-26: 0.1-15.8 g/cm2



(Meyer, 2007; NASA S72-40132, S73-16018)

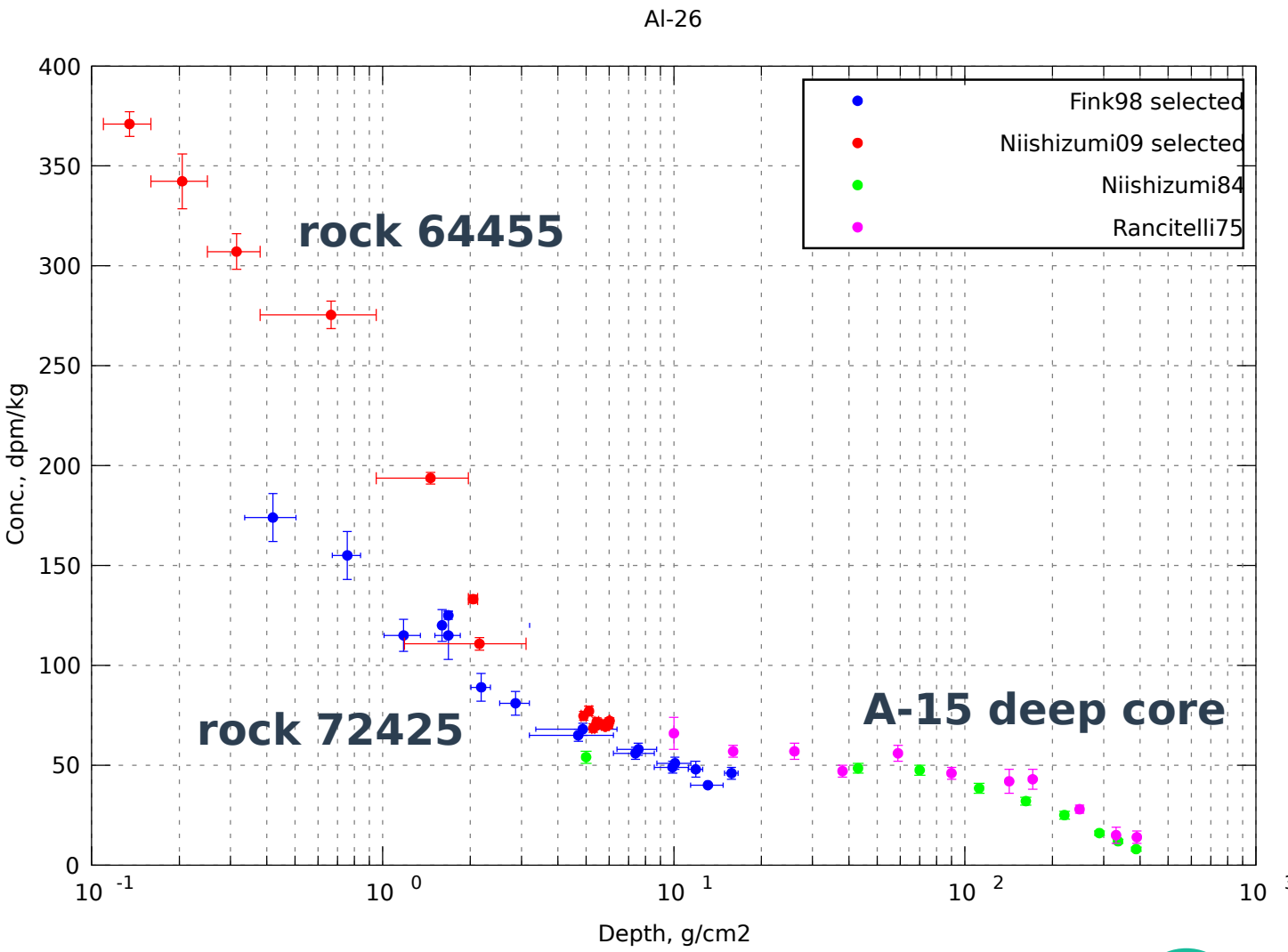
Measured depth profile

Al-26

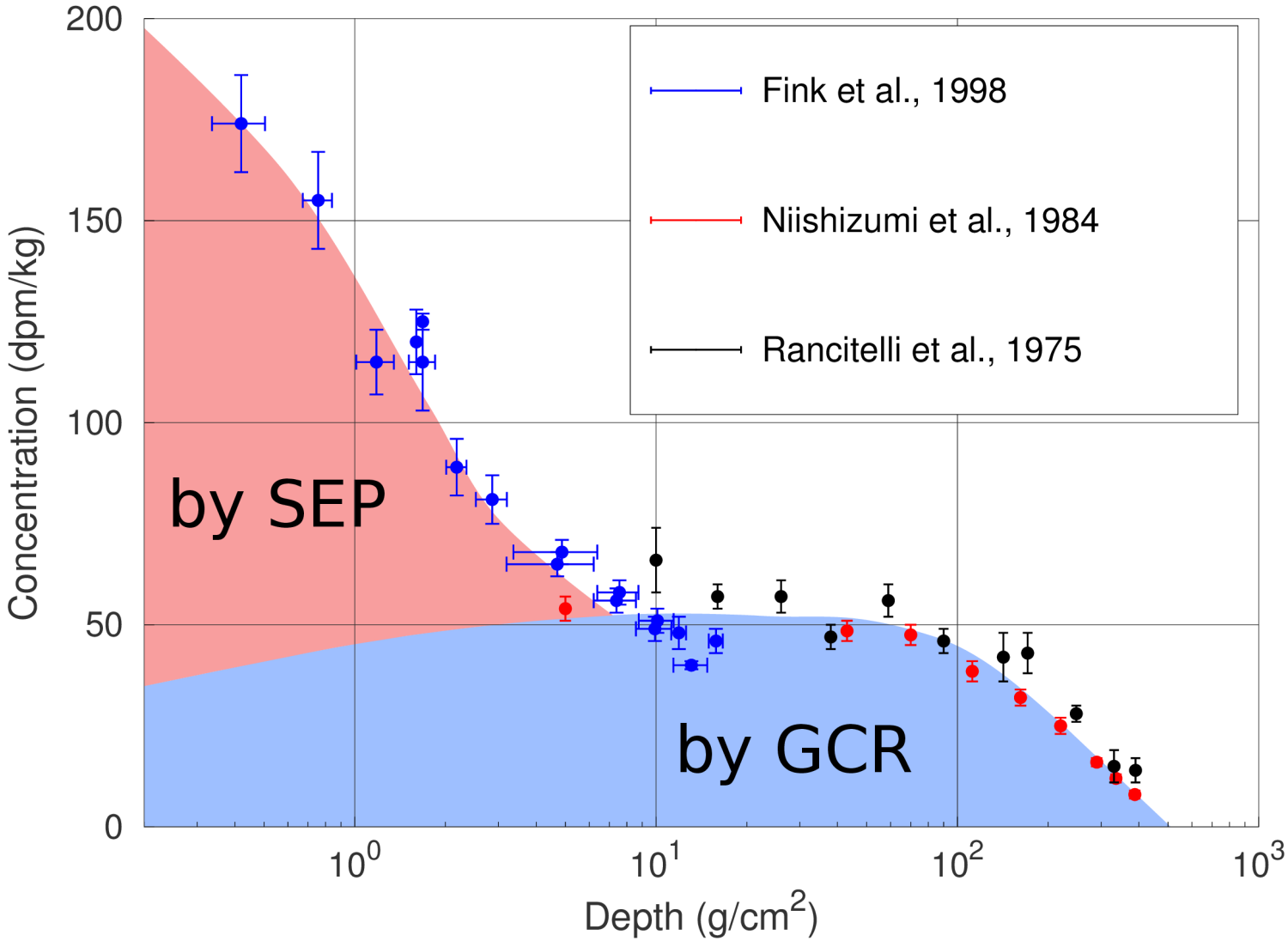
Fink98 – rock 72425

Ni09 – rock 64455

Ni84, R75 – deep drill core Apollo-15



GCR and SEP contributions



^{26}Al production model

- **Yield function approach – common model for GCR and SEP;**

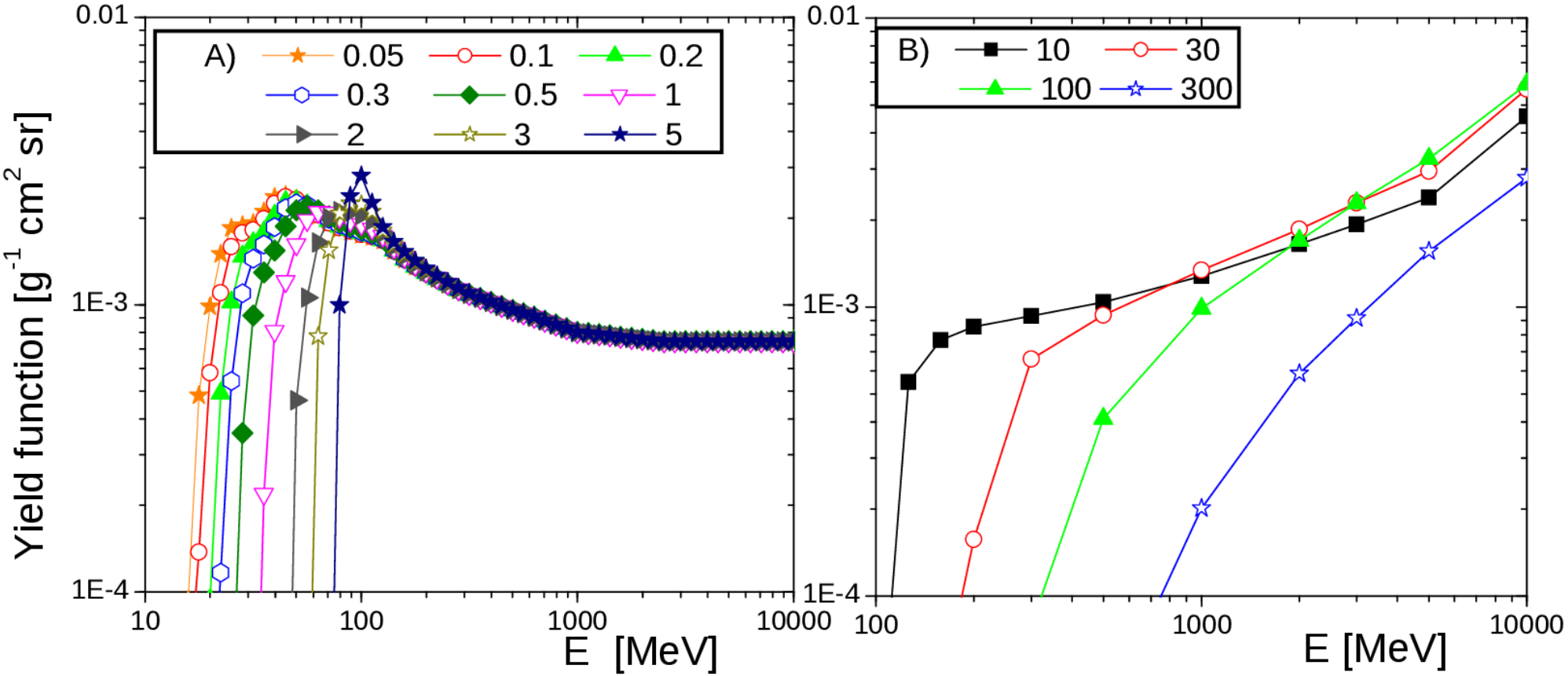
$$Q(h) = \sum_i \int Y_i(E,h) \cdot J_i(E) \cdot dE$$

- **Monte Carlo modelling of energetic particle transport in deep layers;**
- **Geant4.10 toolkit (QGSP + BIC + High-precision neutron model);**
- **Analytical at shallow depths.**

- **Appropriate chem. compositions, geometries, errosion rates for each of the samples;**
- **Individual yield func. for incident protons and α-particles;**
- **Cross-sections: Nishiizumi et al., 2009; Reedy, 2007; Tatischeff et al., 2006; Reedy, 2013;**
- **The pion contribution is included (Li et al., 2017).**

^{26}Al yield function

Sample 64455, depths in g/cm2



Galactic cosmic ray fit

X^2-fit into Apollo-15 long core data

The result:

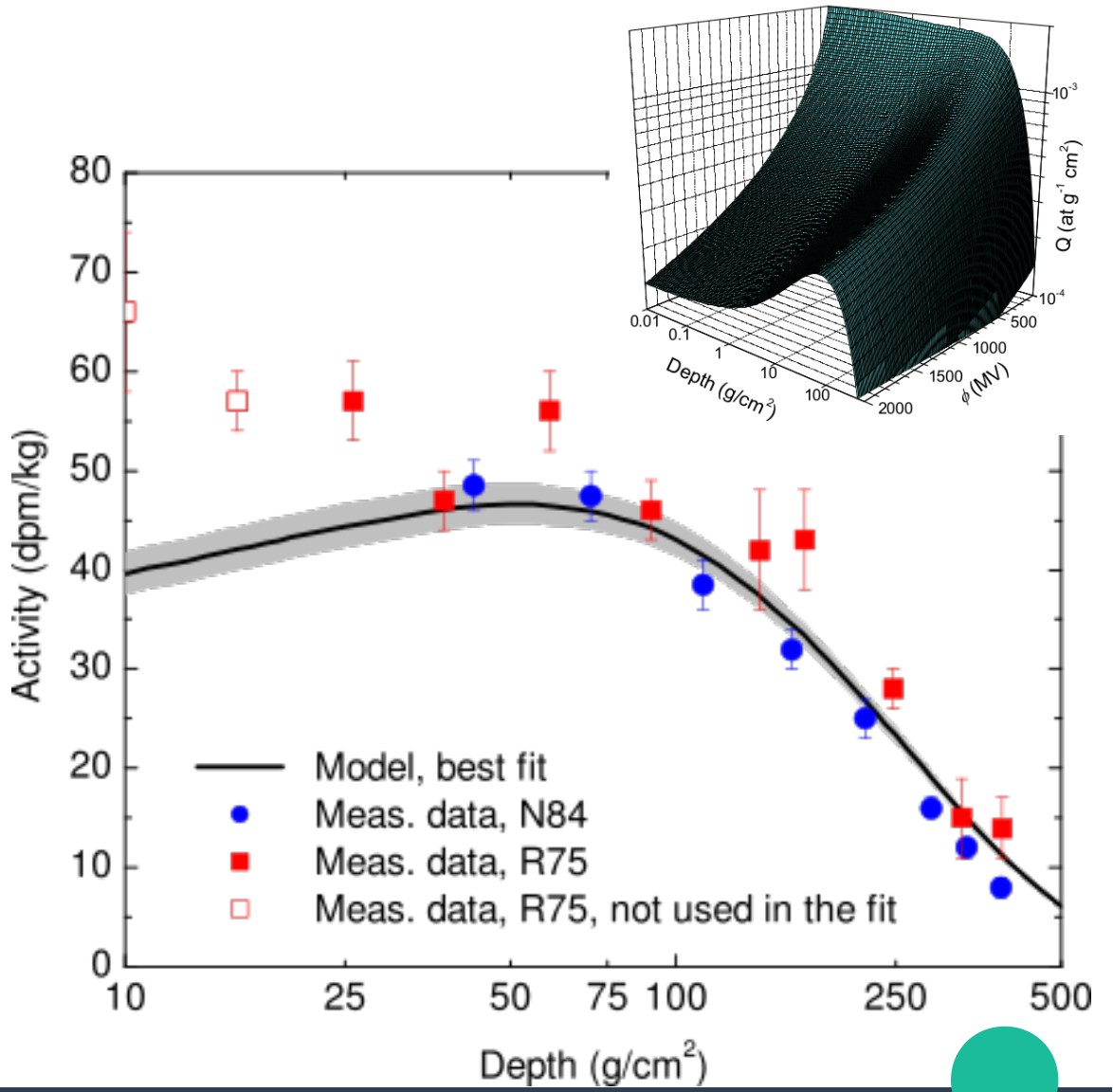
Mean modulation potential φ=496±40 MV on the Myr time scale

For comparison:

Holocene (the last 11 000 years) φ=449±70 MV

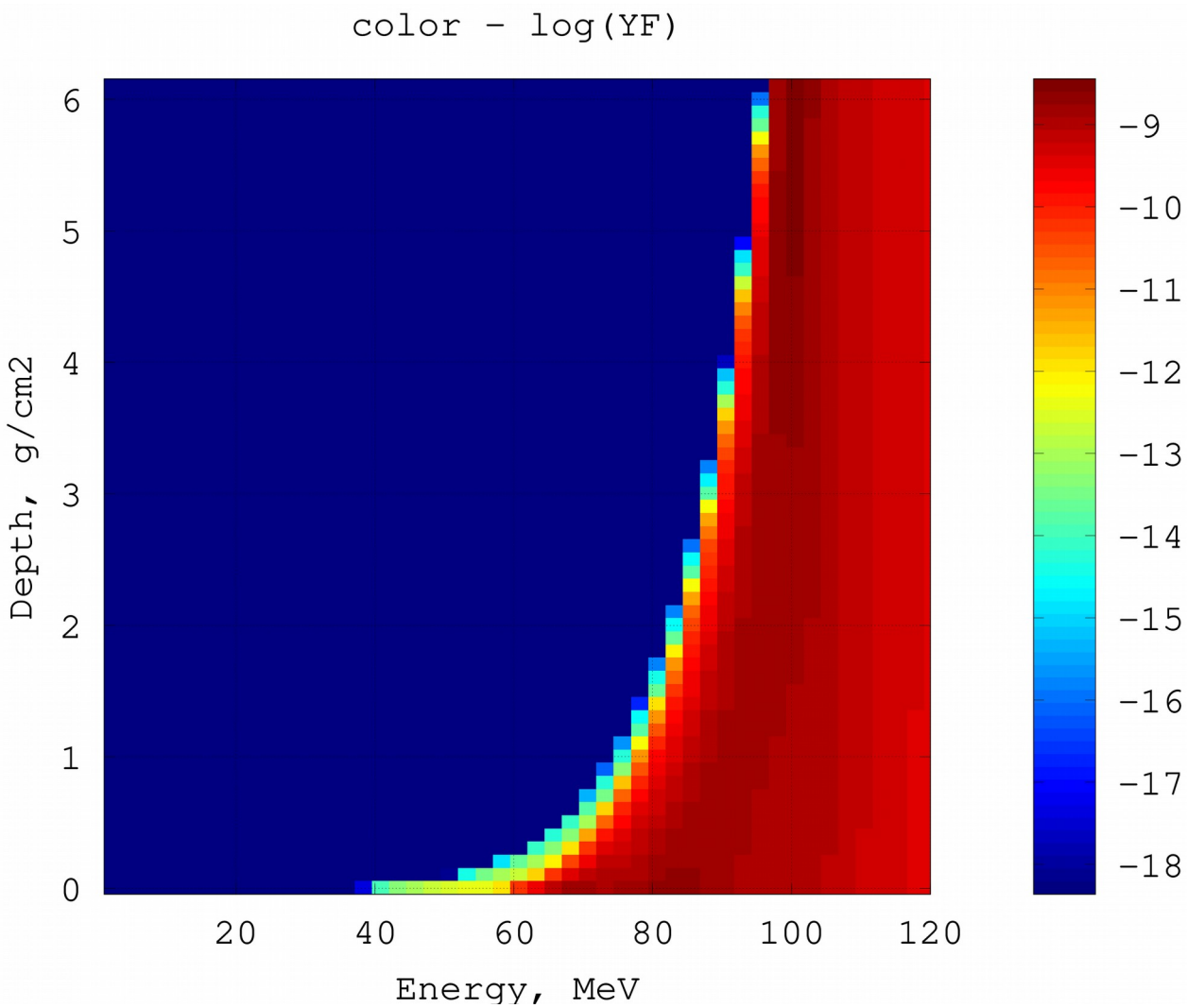
Modern Grand maximum φ=660±20 MV

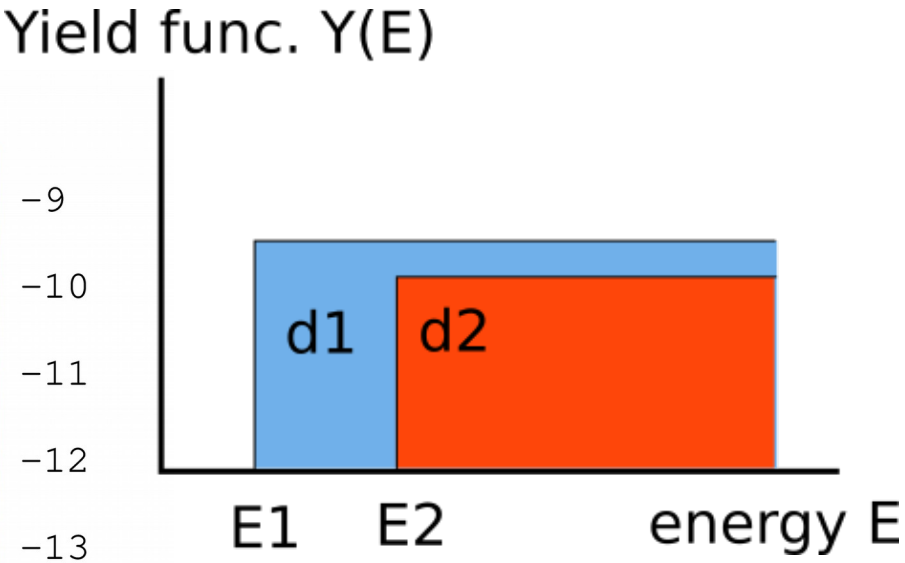
(all φ for LIS Vos&Potgieter2015)



Ideal integral spectrometer

Al-26 yield function for protons





Ideal int. spectrometer – the response is proportional to the integral flux

A(d) → F(>E*)

d → E*

Effective energy and converstion coefficient

Int. particle flux:

$F(>E^*(d)) = K(d) \cdot A_{meas}(d)$

Conversion coef. $K = F_{model}(>E^*) / A_{model}(d)$,

Effective energy E^*

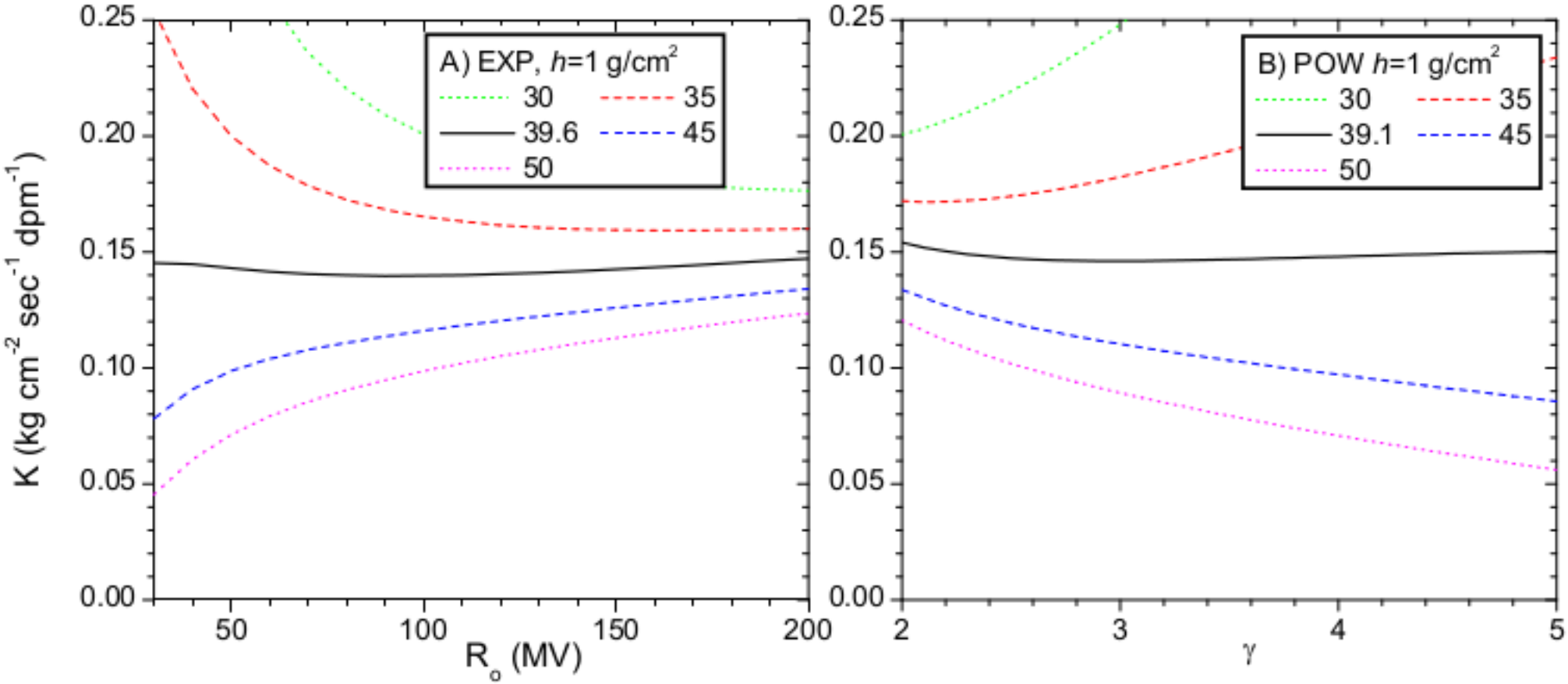
SEP int. spectra:

EXP: $F_{model} = F_{0\ EXP} \cdot \exp(-R/R_0)$

POW: $F_{model} = F_{0\ POW} \cdot E^{-\gamma}$

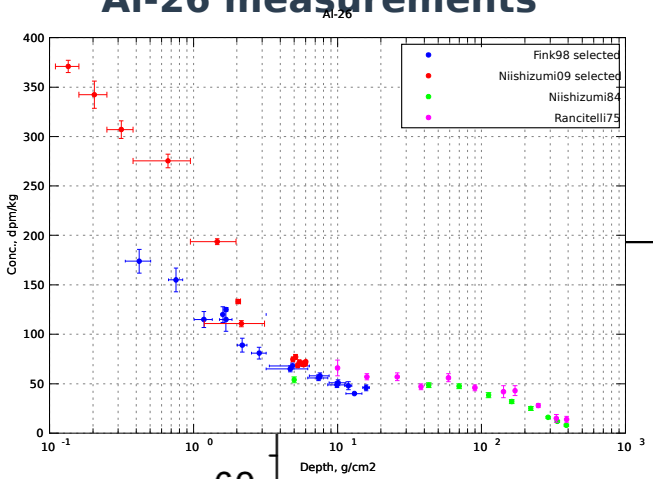
Effective energy and converstion coefficient

EXP: $F = F_0 \cdot \exp(-R/R_0)$ **POW: $F = F_0 \cdot E^{-\gamma}$**



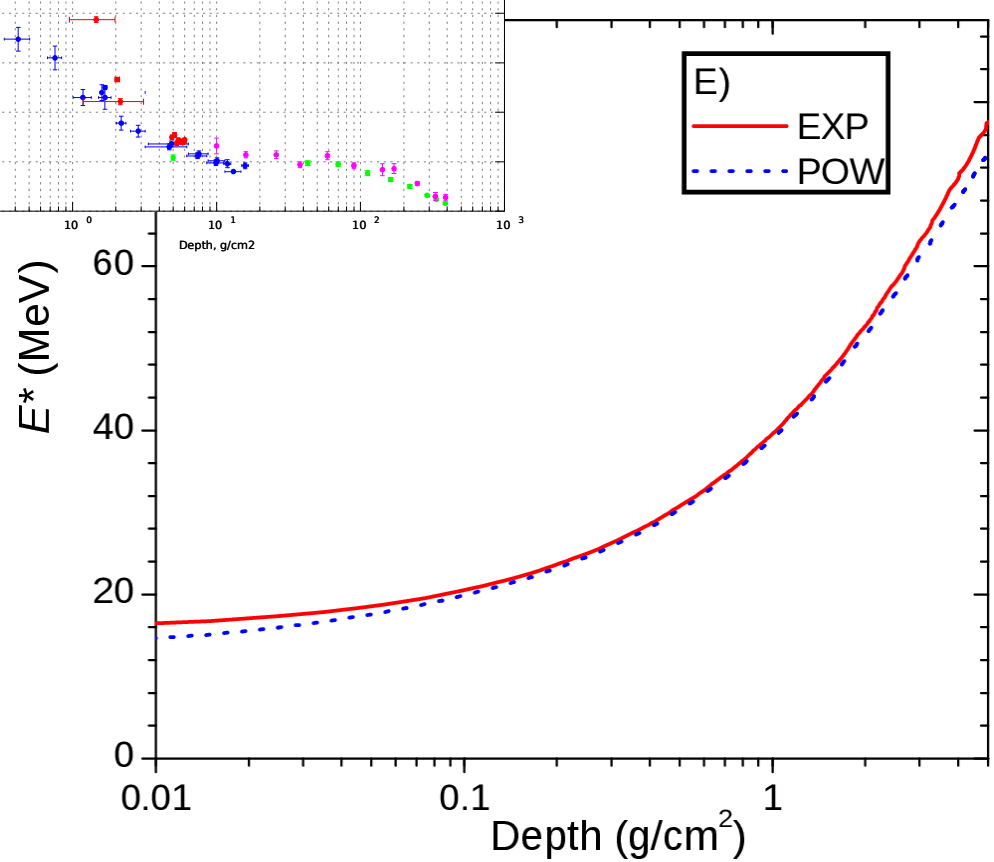
Effective energy and converstion coefficient

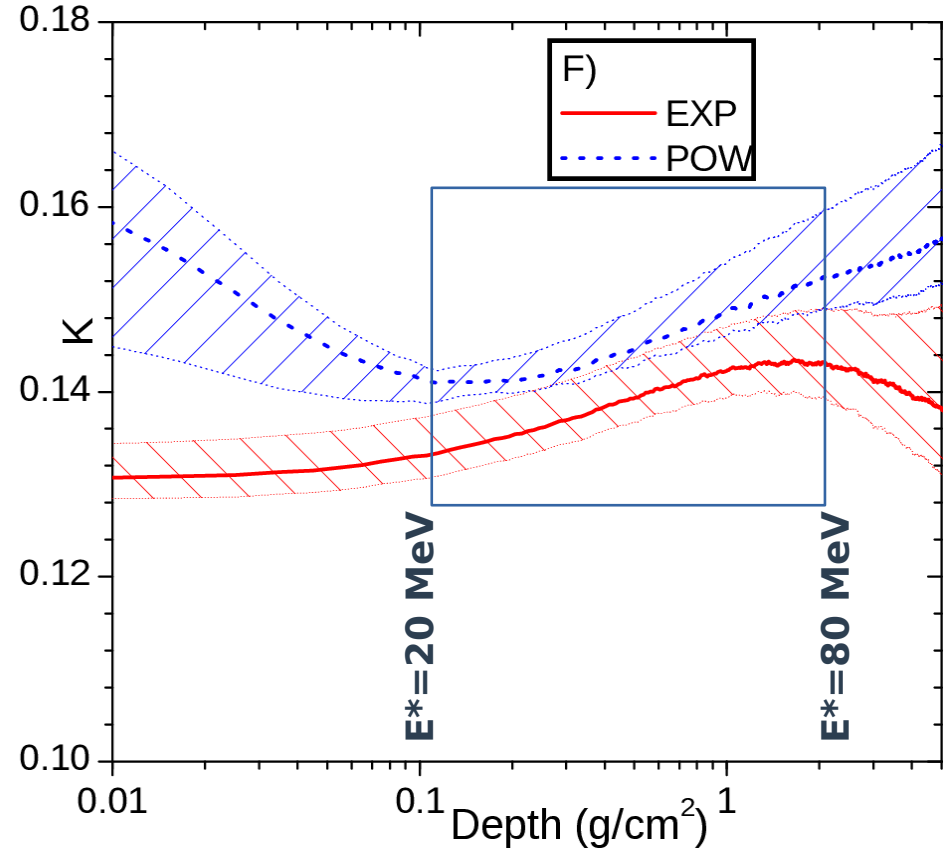
Al-26 measurements



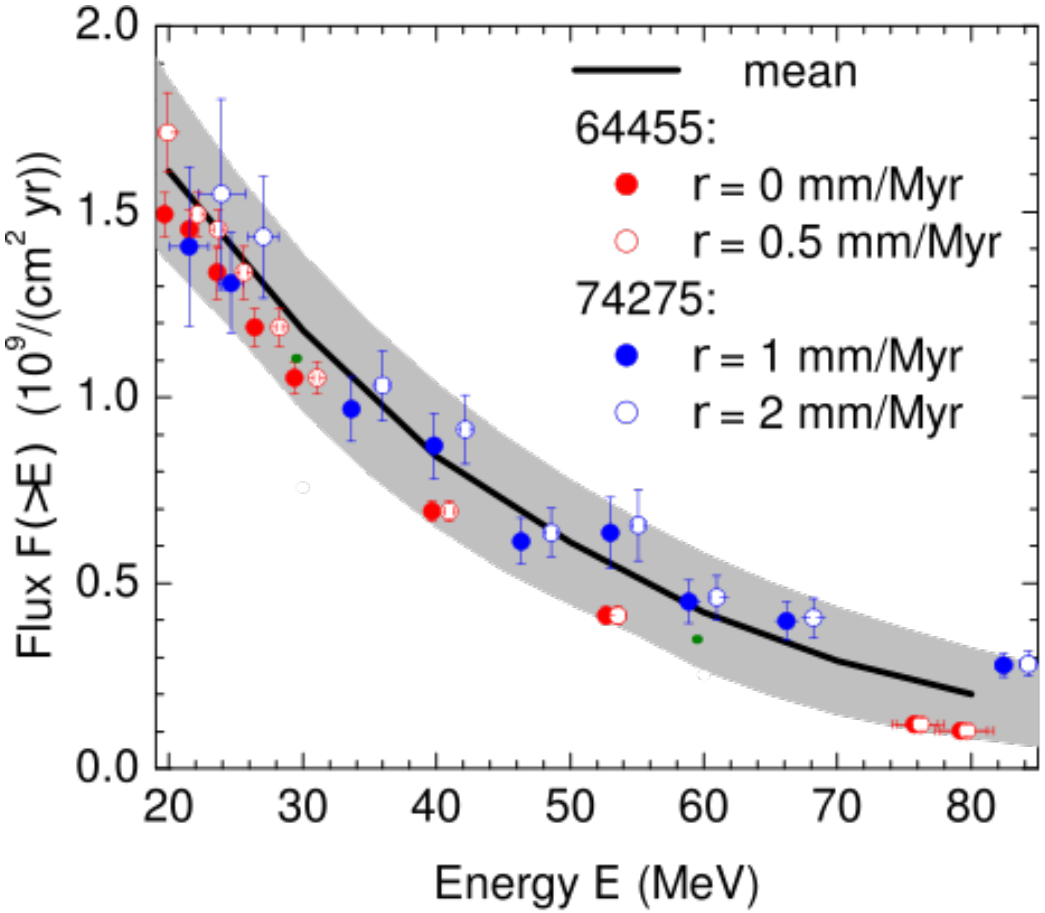
$$F(>E^*(d)) = K(d)\cdot A_{meas}(d)$$

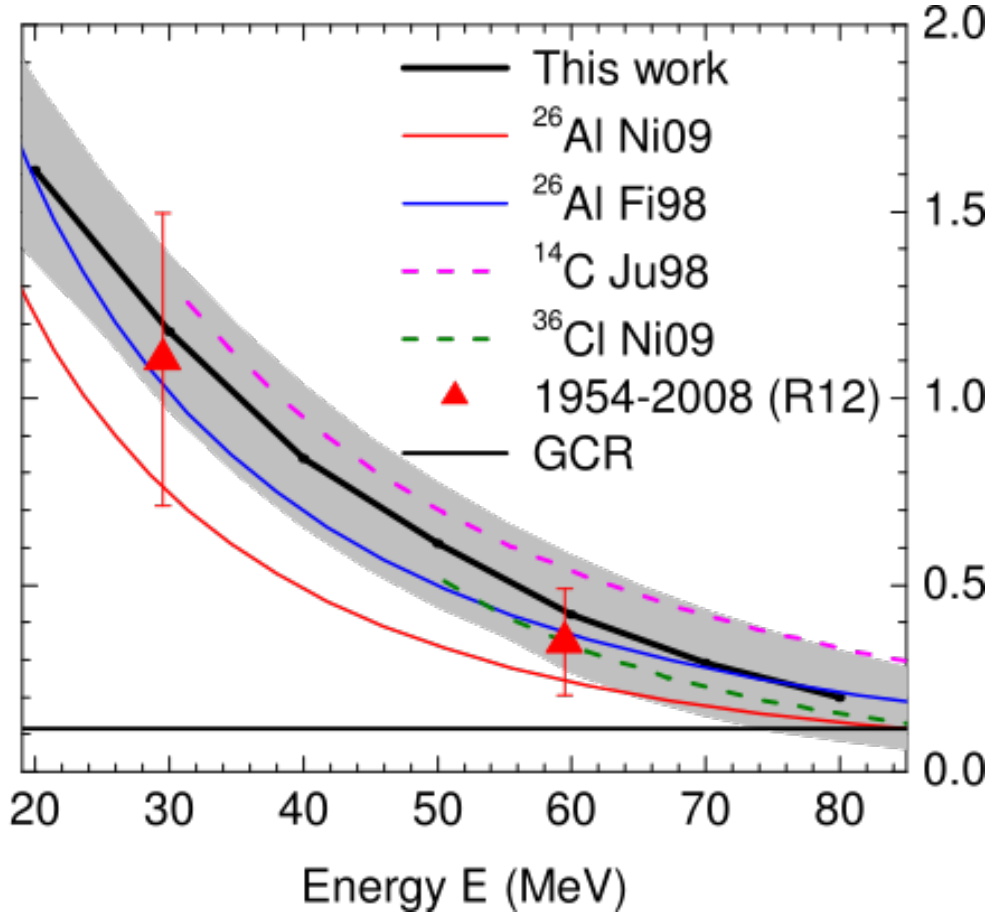
Al-26 as an integral spectrometer. Parameters.



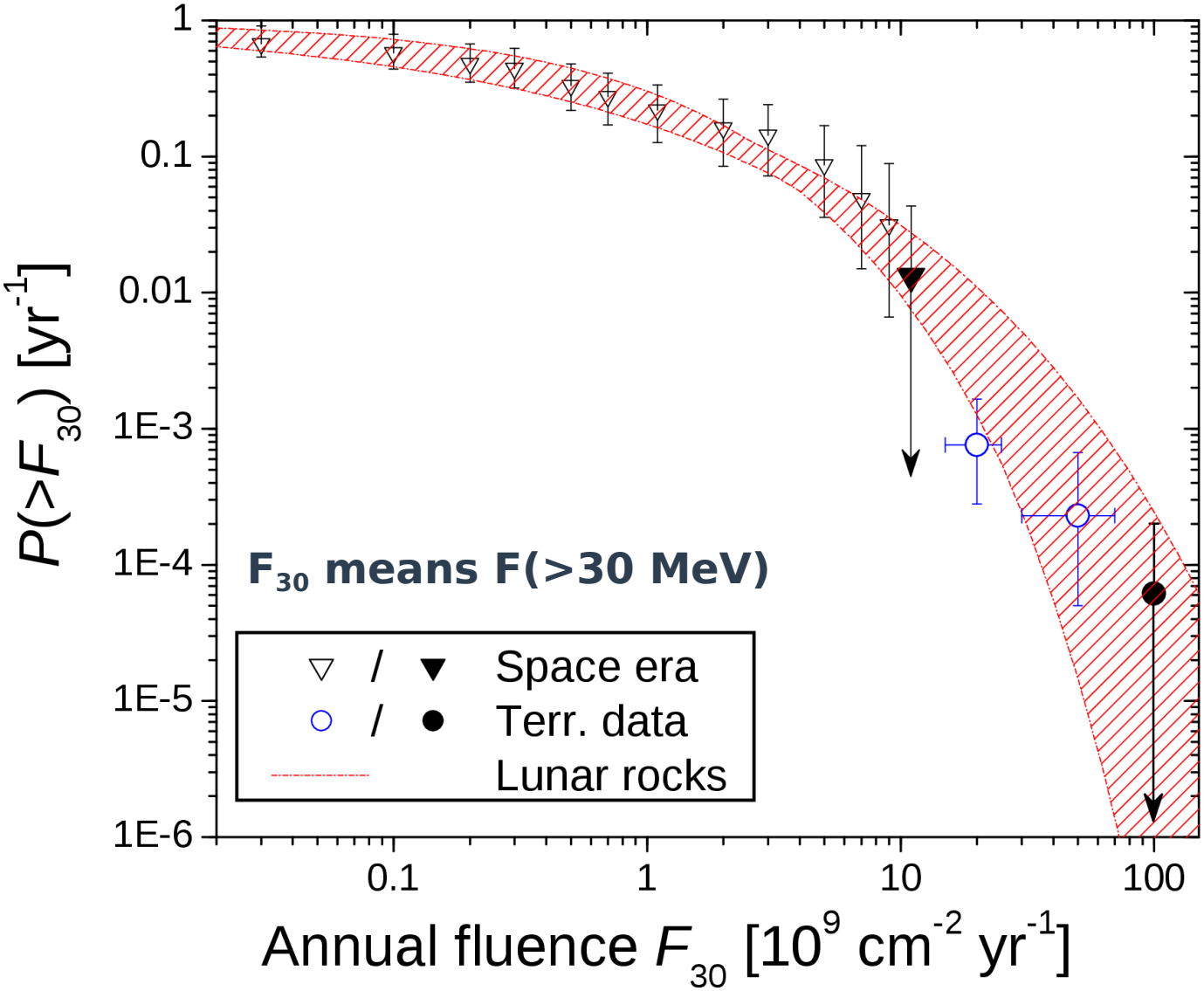


Reconstructed SEP int. flux F(>E) at the Myr time scale





SEP occurance probability distribution



Summary

Al-26 in Apollo-15 lunar deep-drill core:

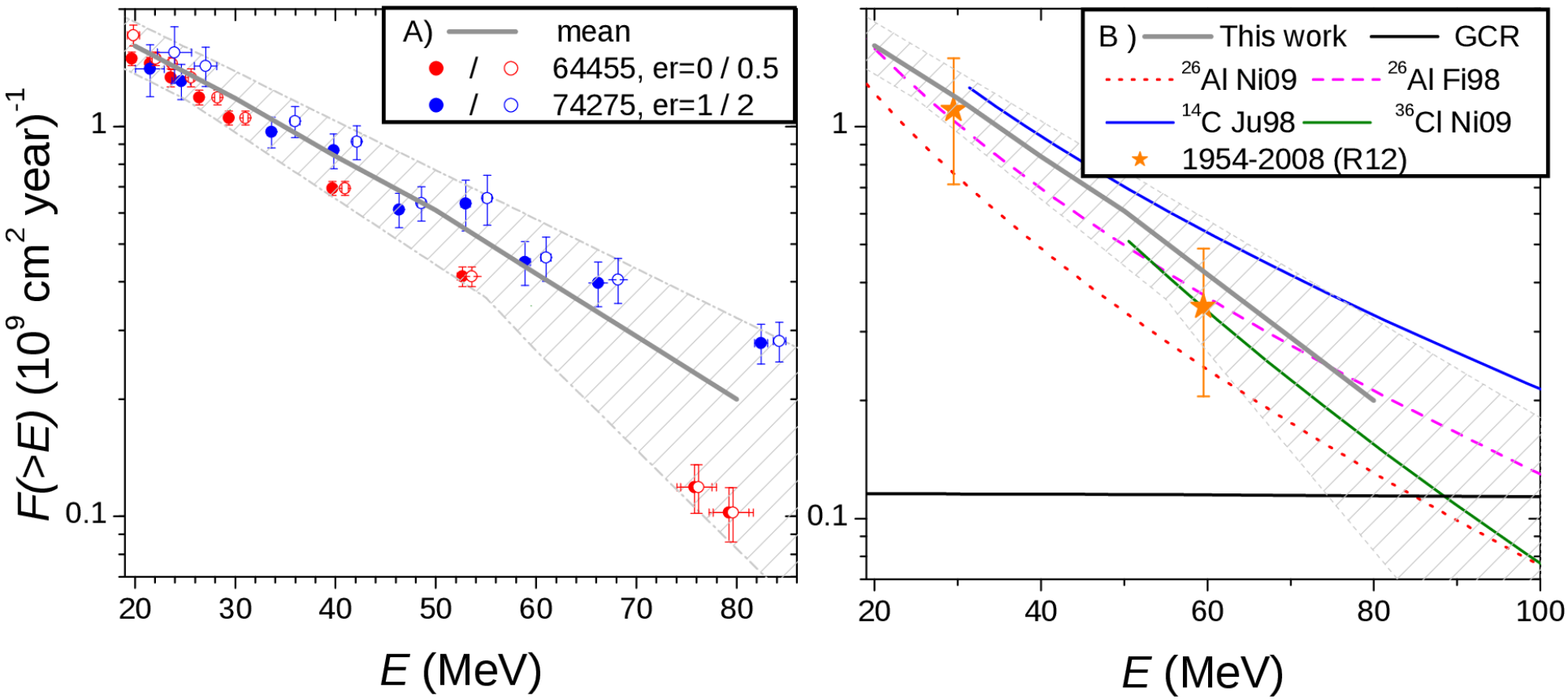
- **The average modulation potential is estimated as φ=496±40 MV on the Myr time scale.**
- **It is close to the Holocene value 449±70 MV and lower than one for the Modern Grand maximum (660±20 MV).**

Al-26 in lunar samples 64455 and 74275:

- **SEP integral spectrum F(>E) reconstruced without any a-priori asumptions on its shape in the range 20-80 MeV.**
- **SEP flux on the Myr time scale is comparable with one over the last several decates.**
- **SEP occurance probability: no expected events with annual fluence >30 MeV above 10^{11} part./(cm^2 yr) on the Myr time scale.**

Thank you!

Reconstructed SEP int. flux F(>E) at the Myr time scale



Reconstruction of the Al-26 content