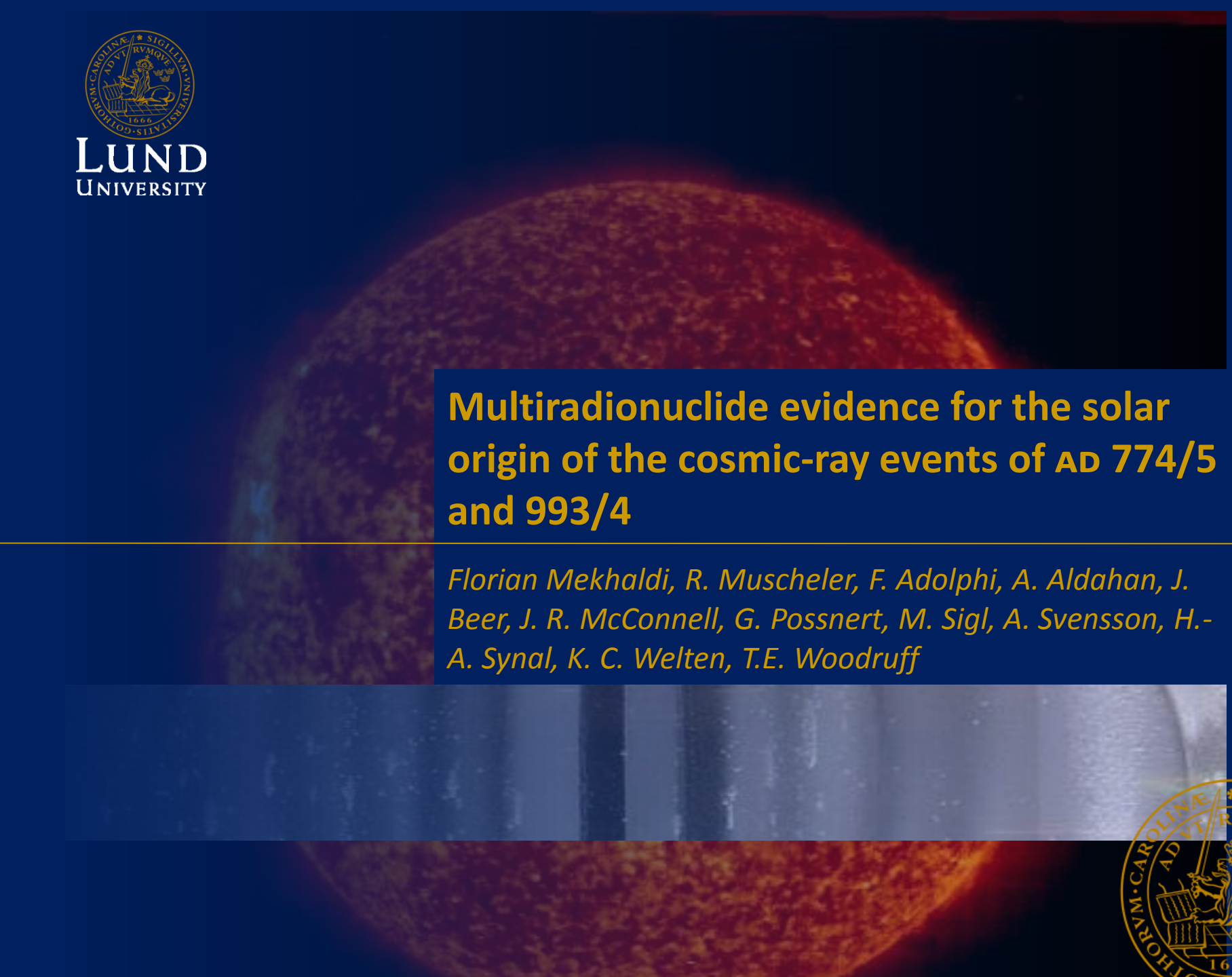
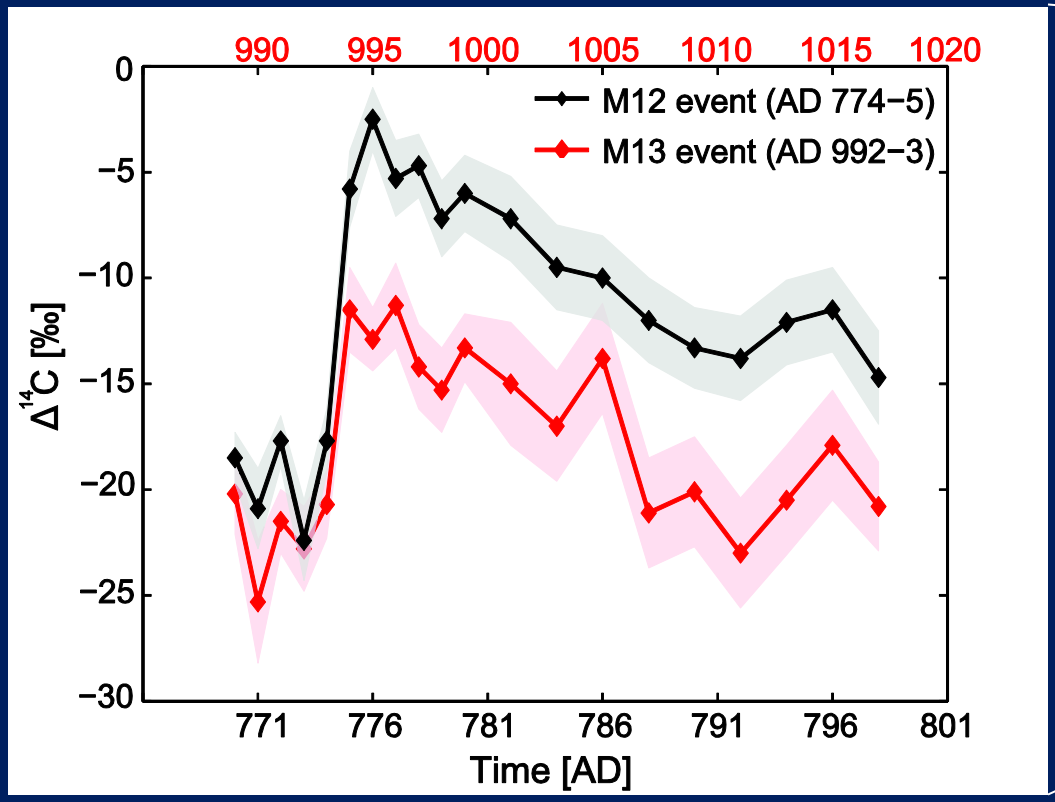


Multiradionuclide evidence for the solar origin of the cosmic-ray events of AD 774/5 and 993/4

Florian Mekhaldi, R. Muscheler, F. Adolphi, A. Aldahan, J. Beer, J. R. McConnell, G. Possnert, M. Sigl, A. Svensson, H.-A. Synal, K. C. Welten, T.E. Woodruff

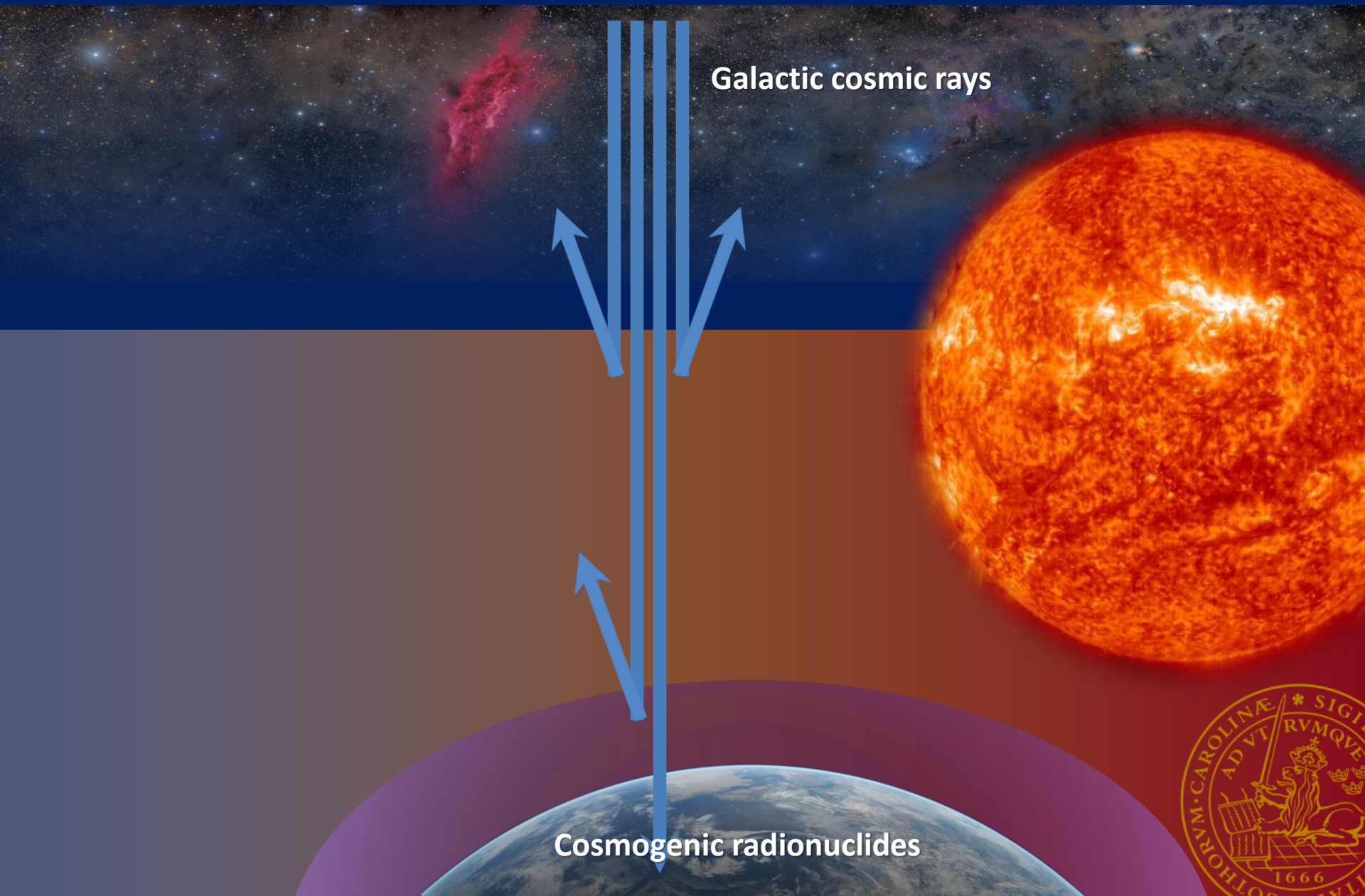
Premise

- **Peaks in radiocarbon concentration ($\Delta^{14}C$)** have been discovered which **are so large that they have been attributed to a large cosmic-ray event** – they were dated to AD 774/5 (and AD 993/4)
- The exact cause of the peaks has been under debate
- Here we present the **perspective offered by the additional radionuclides**(^{10}Be and ^{36}Cl) from ice cores

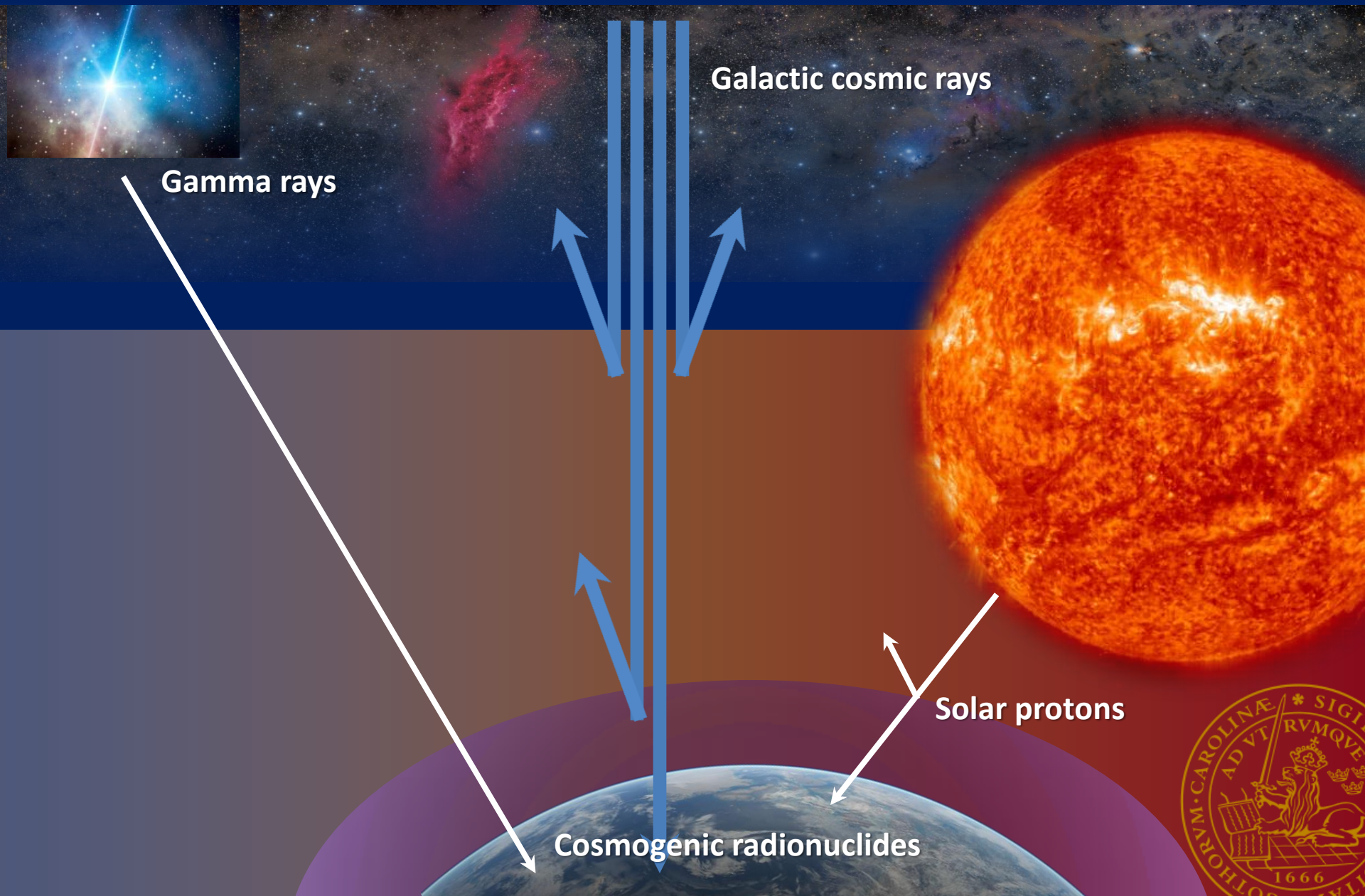


Miyake et al. 2012, 2013

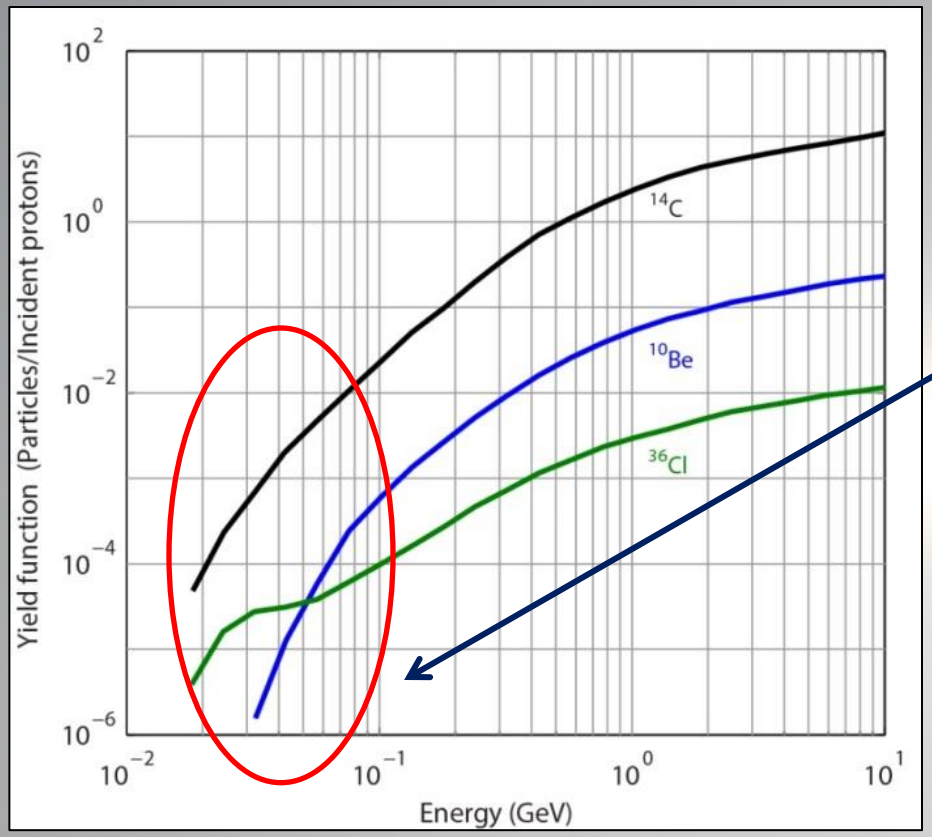
From cosmic rays to cosmogenic radionuclides



From cosmic rays to cosmogenic radionuclides



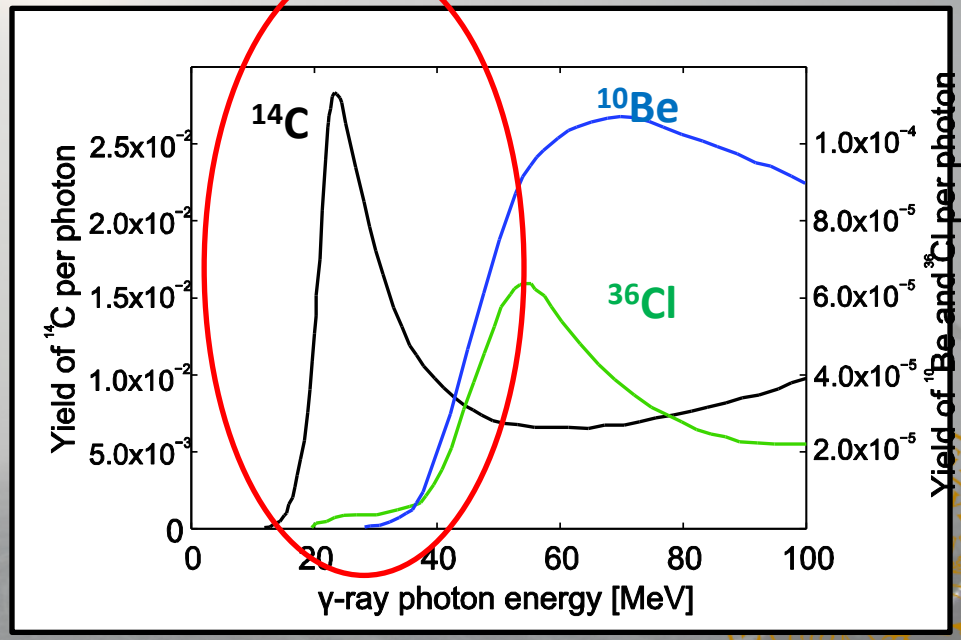
A multiradionuclide approach



Mekhaldi et al. (NCOMMS 2015)

Radionuclides have different sensitivities to different energies and to different particles

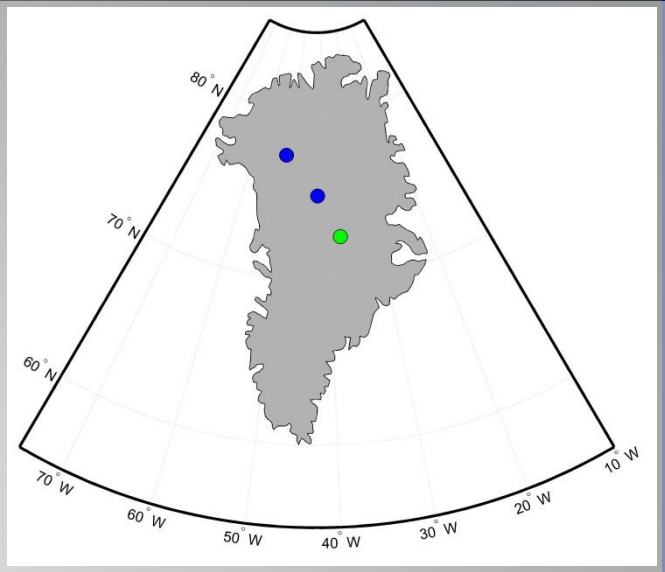
From Pavlov et al. (Mon. Not. R. Astron. 2013)

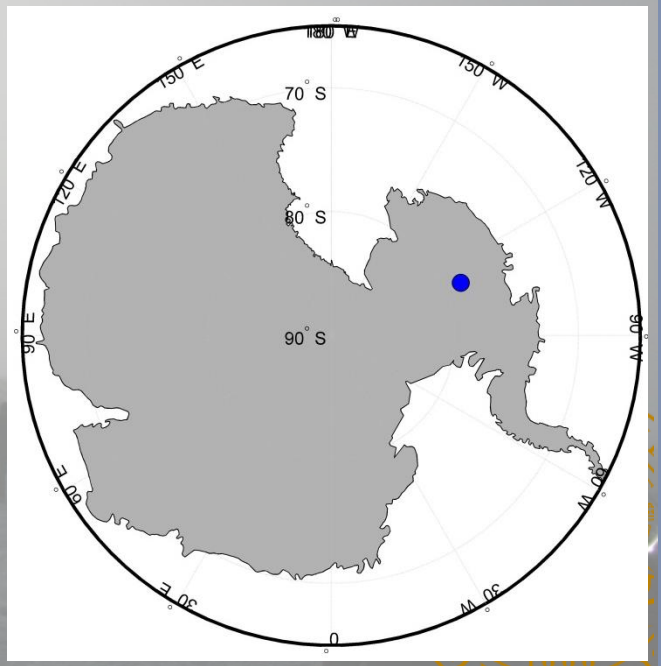


The NEEM ice core drilling camp in northern Greenland. Credit: Raimund Muscheler

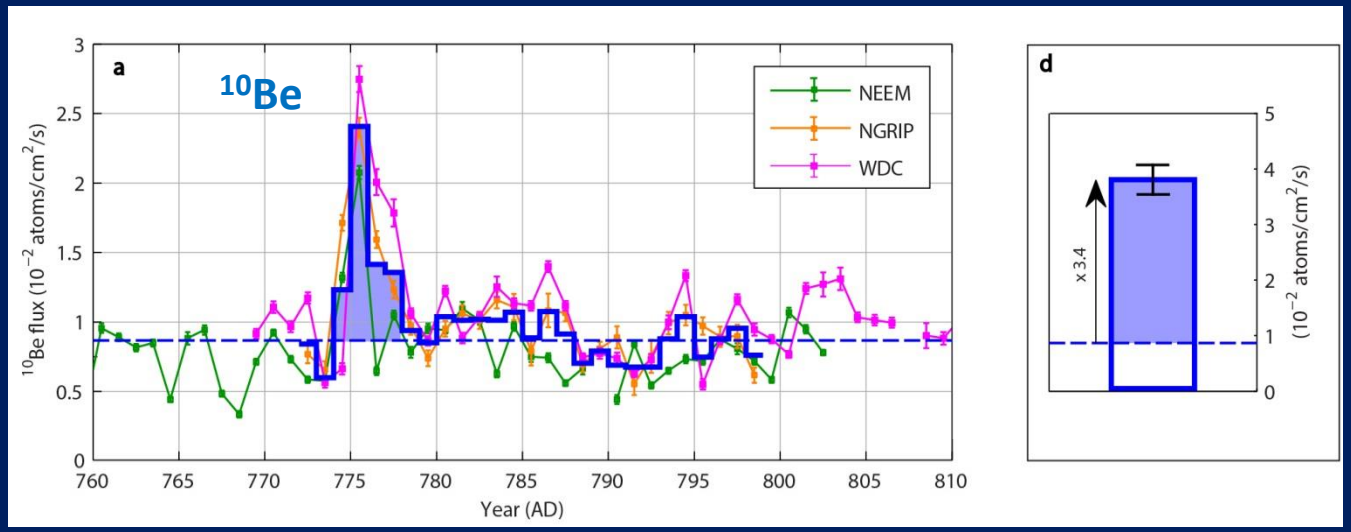
A multiradionuclide approach

- Newly measured ^{10}Be from the NGRIP and NEEM ice cores (Greenland) and the WAIS divide ice core (Antarctica)
- Available ^{36}Cl from the GRIP ice core (Greenland – resolution of only 5 years)
- Modeled ^{14}C prod. rates from Miyake et al. (2012, 2013) $\Delta^{14}C$ data





Mekhaldi et al. (NCOMMS 2015)



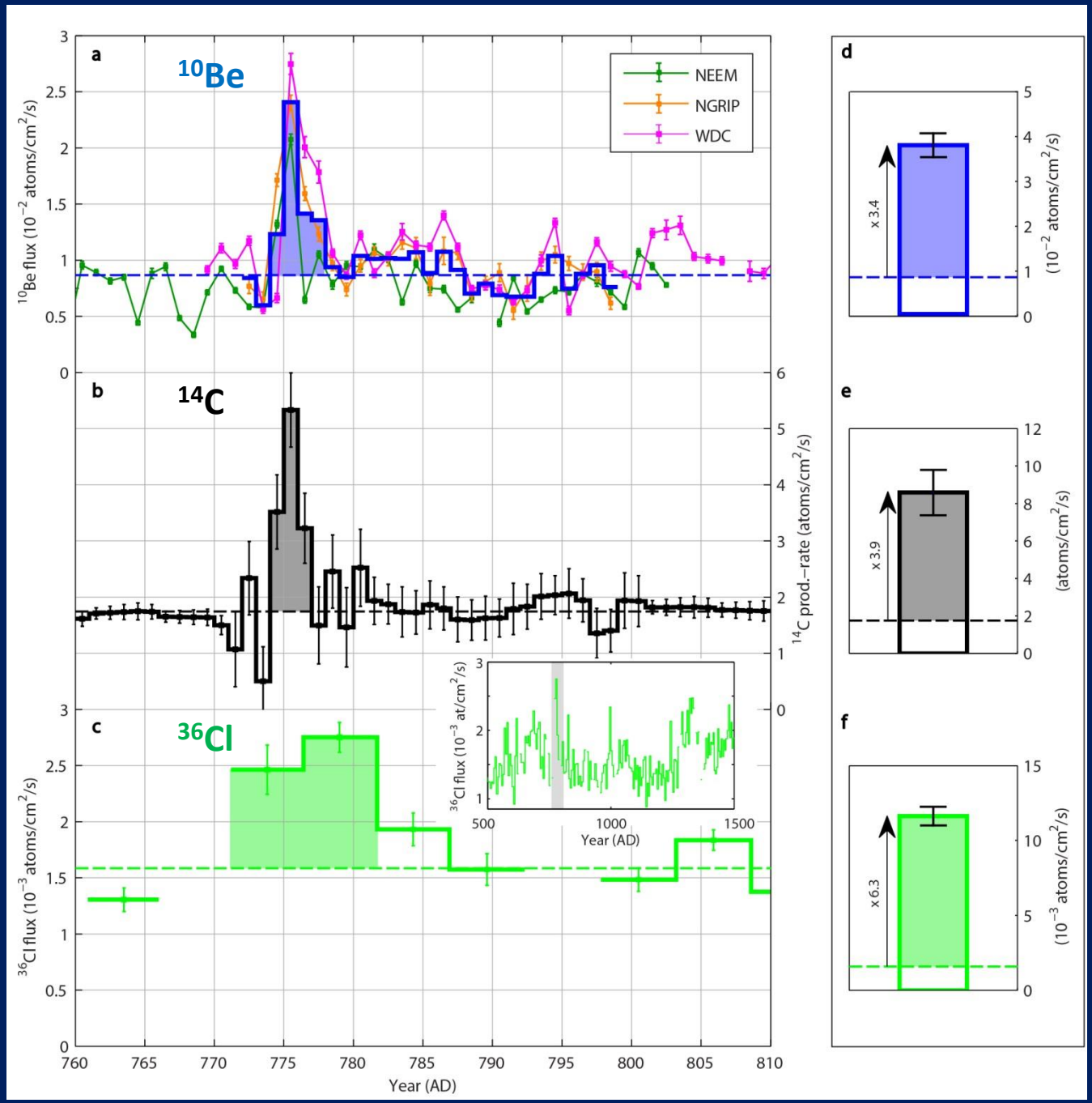
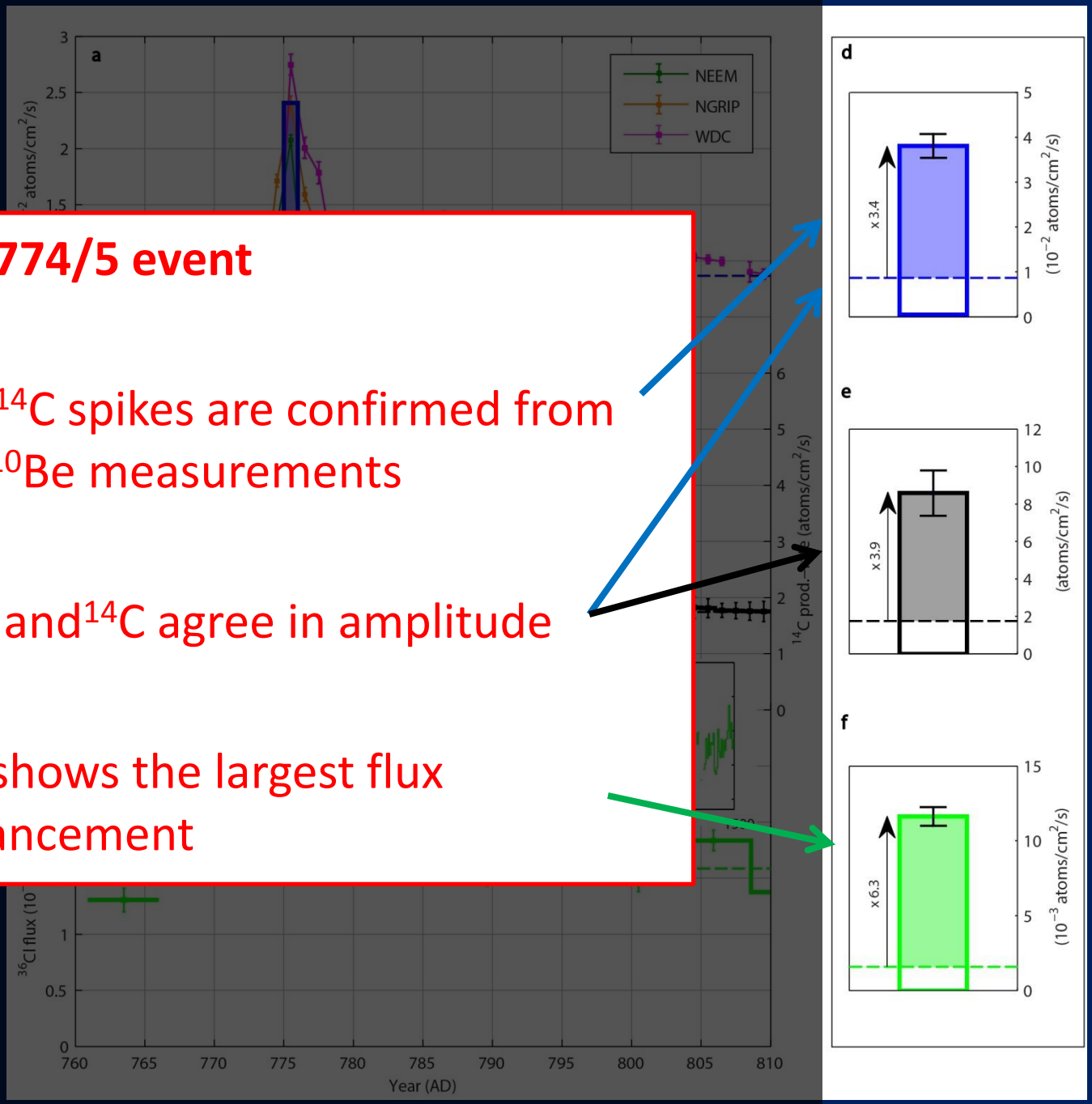


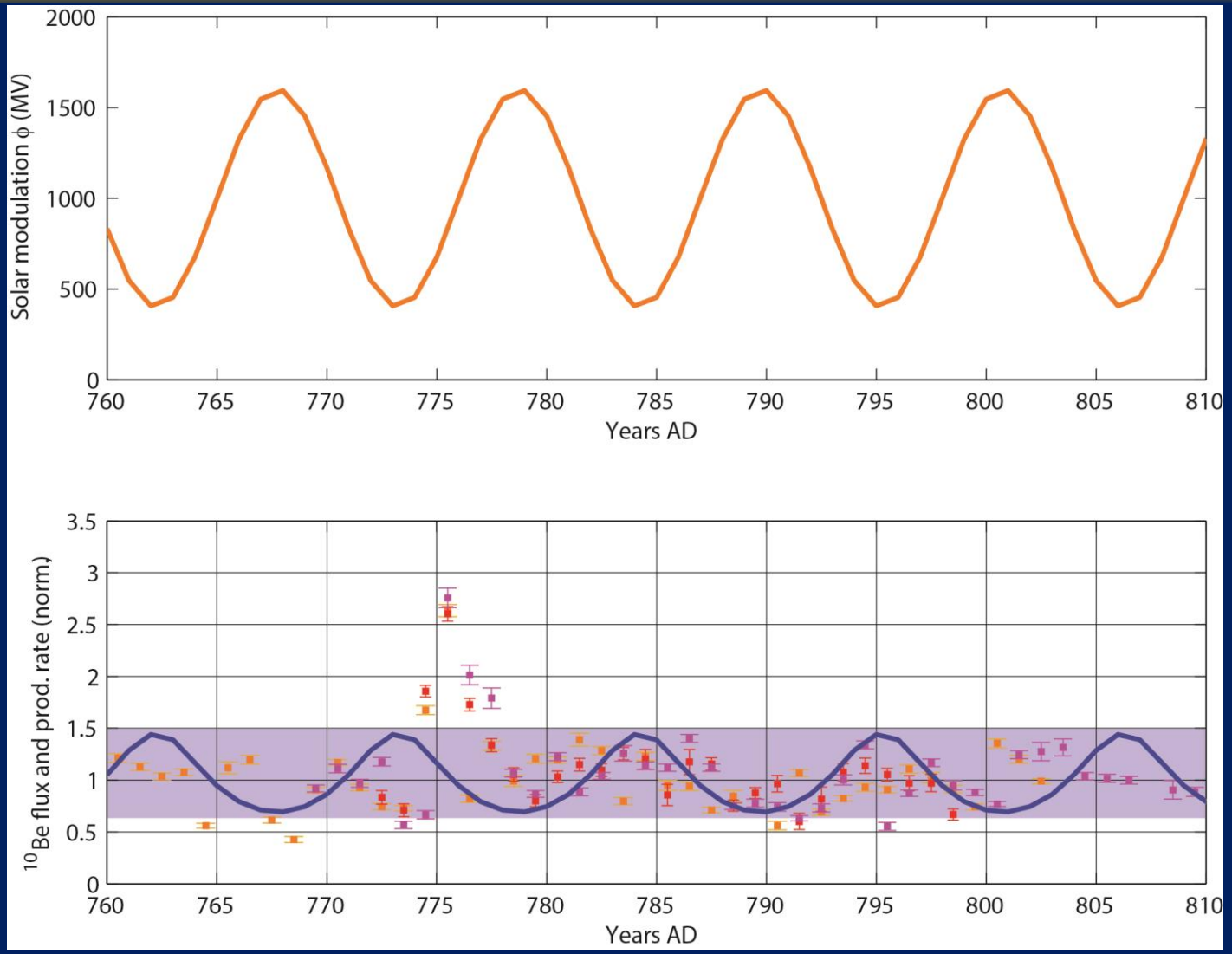
Fig 2. Mekhaldi et al. (NCOMMS 2015)



The AD 774/5 event

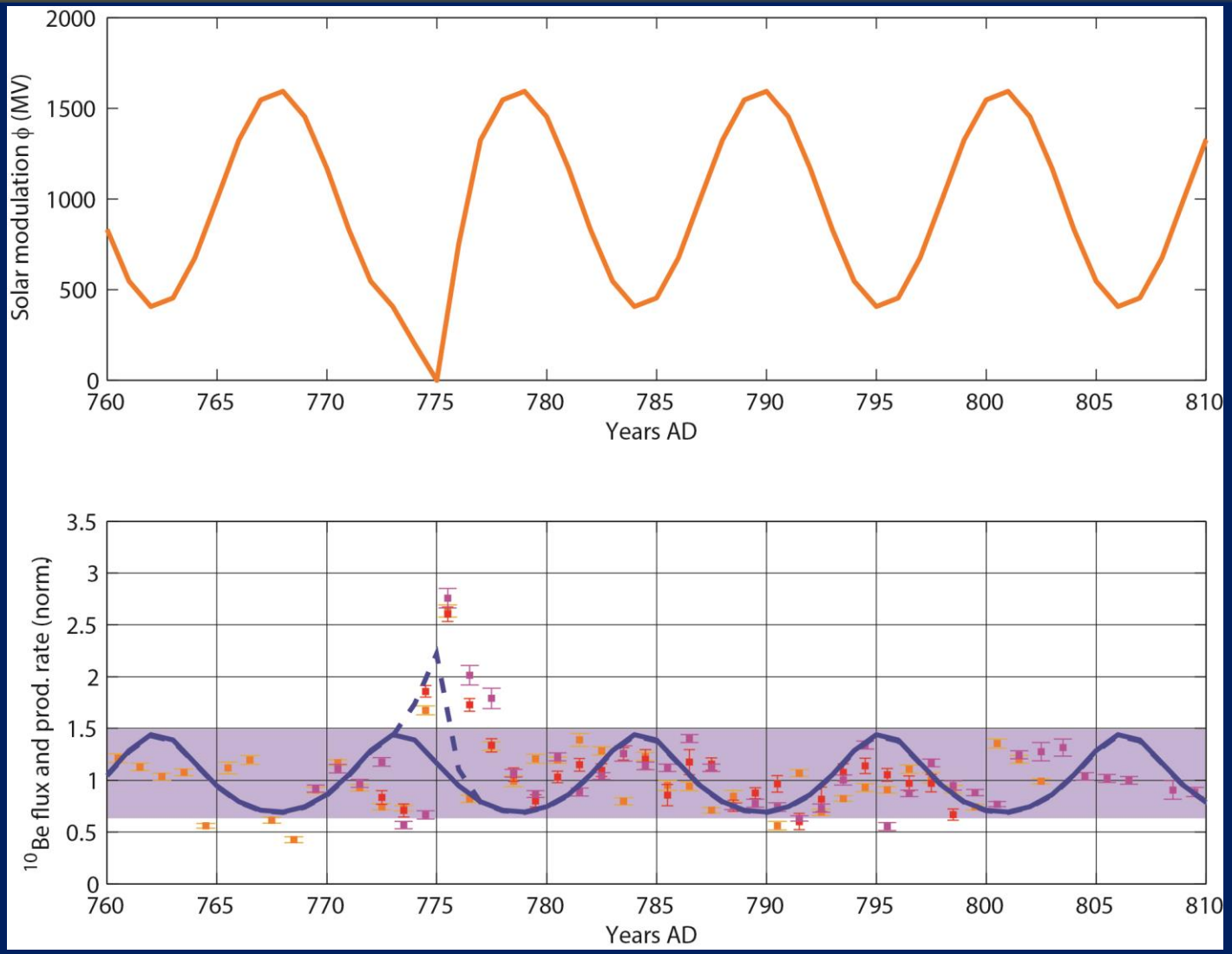
- The ^{14}C spikes are confirmed from our ^{10}Be measurements
- ^{10}Be and ^{14}C agree in amplitude
- ^{36}Cl shows the largest flux enhancement

Not solar modulation (*i.e.* rapid decrease in solar activity)



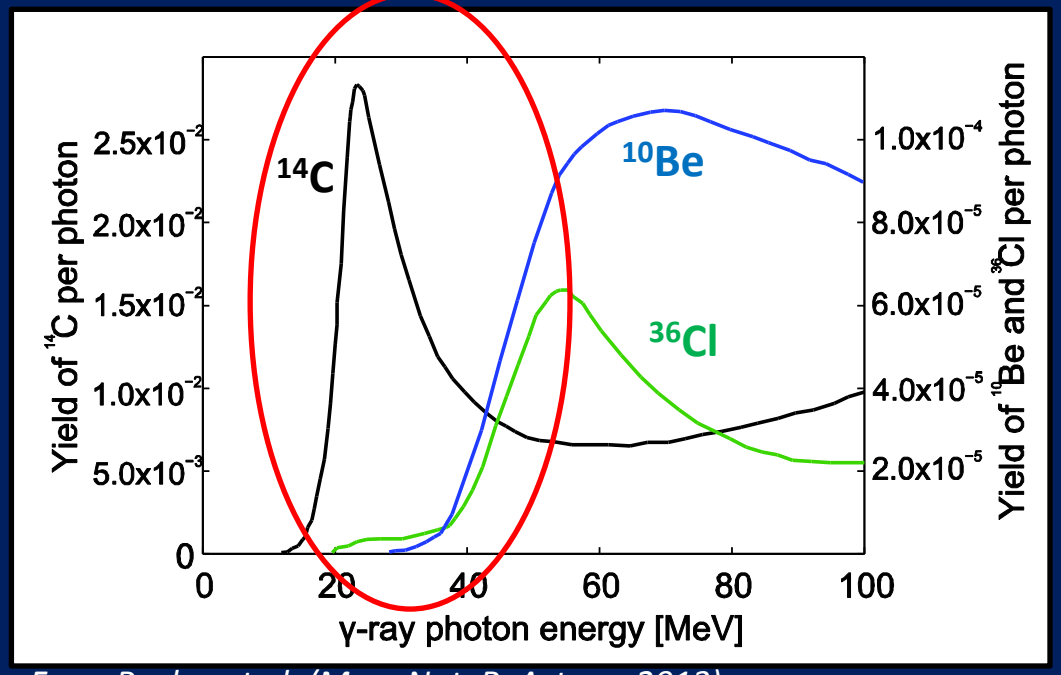
Solar activity can only account for the variability around the 'background level' of the peak.

Not solar modulation (*i.e.* rapid decrease in solar activity)

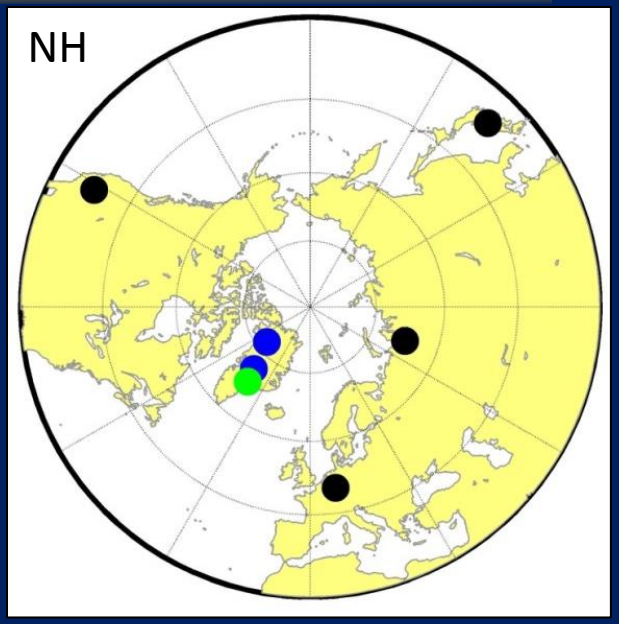


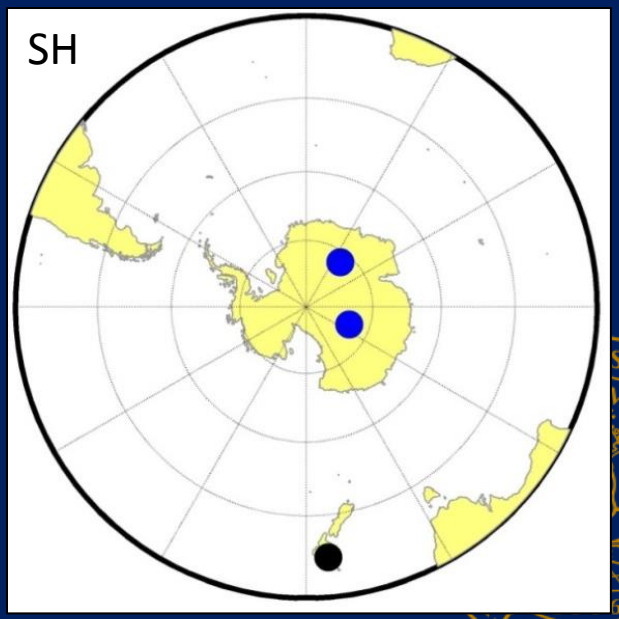
Solar activity can only account for the variability around the 'background level' of the peak.

Not a gamma-ray burst



From Pavlov et al. (Mon. Not. R. Astron. 2013)

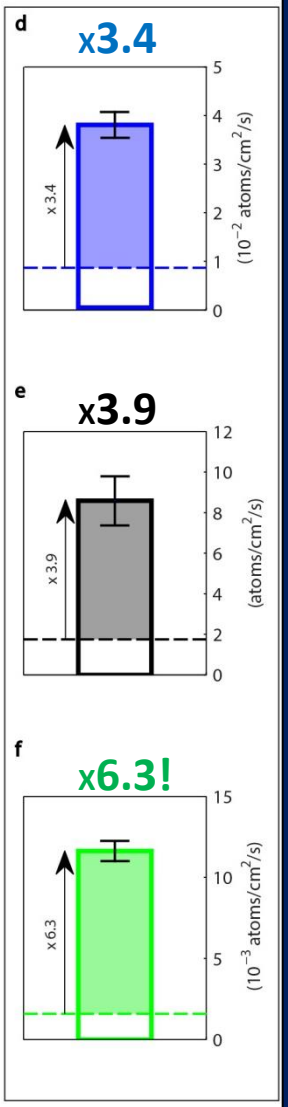




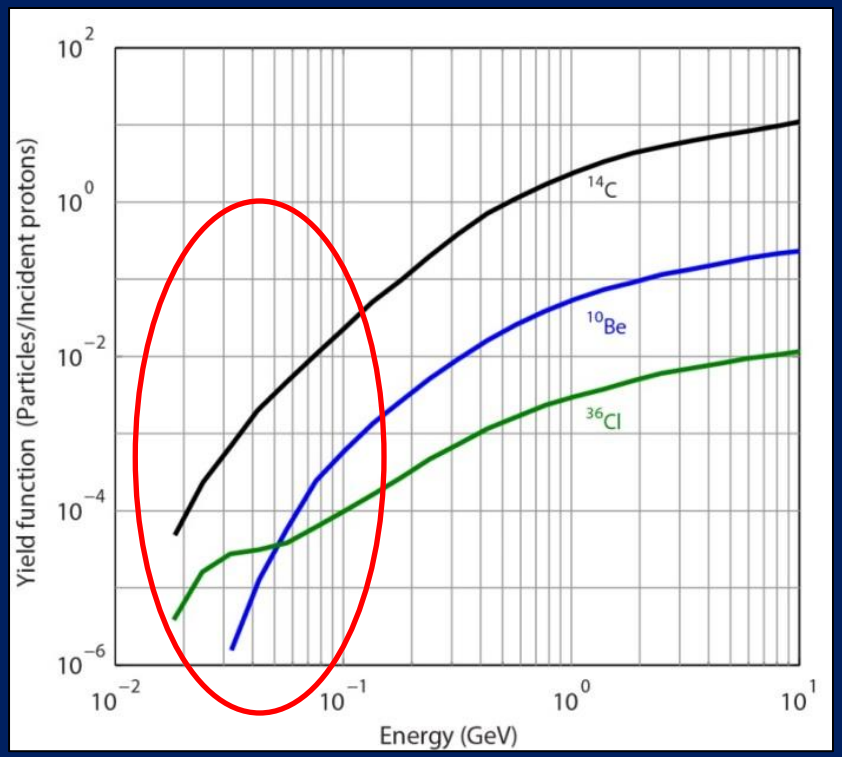
- **GRBs can produce ^{14}C but** should **not lead to peaks in ^{10}Be and/or ^{36}Cl**

- **A GRB would not** be expected to **impact radionuclide production** (and deposition) **in both hemispheres** – not affected by Earth's magnetic field

The signature of exceptional SPE(s)

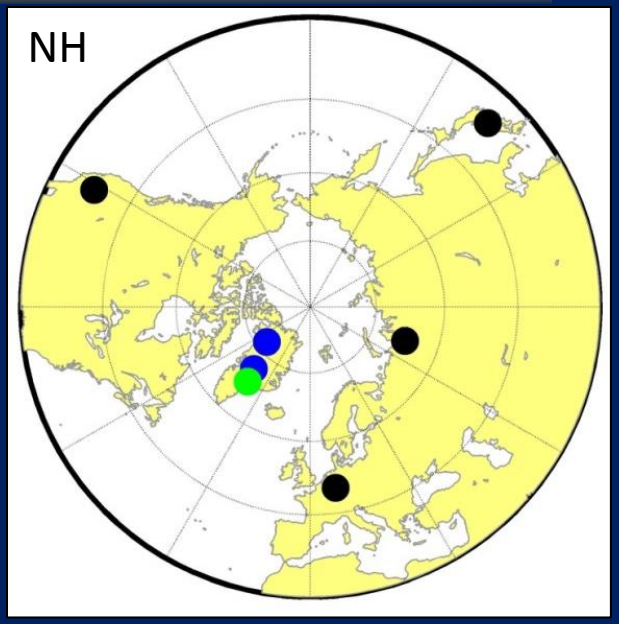


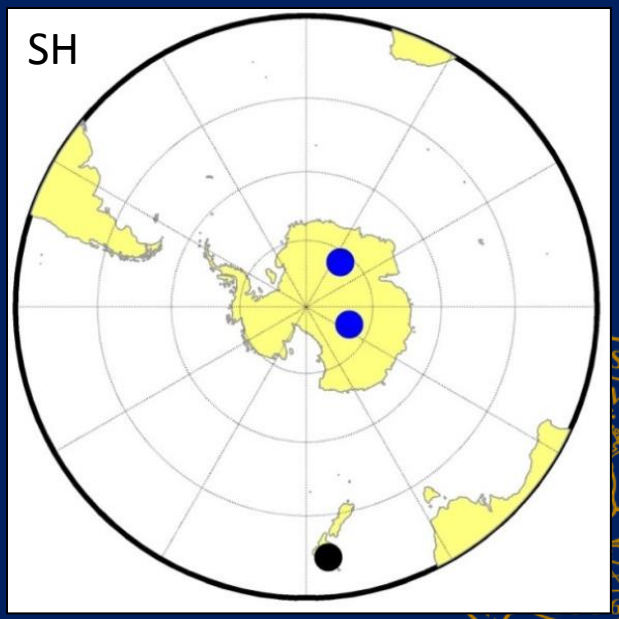
Production of radionuclides by solar protons



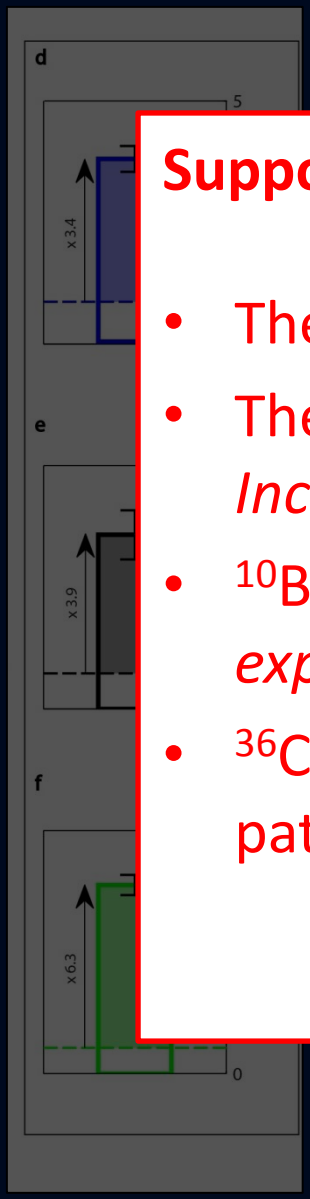
Peak measured in ^{10}Be, ^{14}C, and ^{36}Cl for the AD 775 event

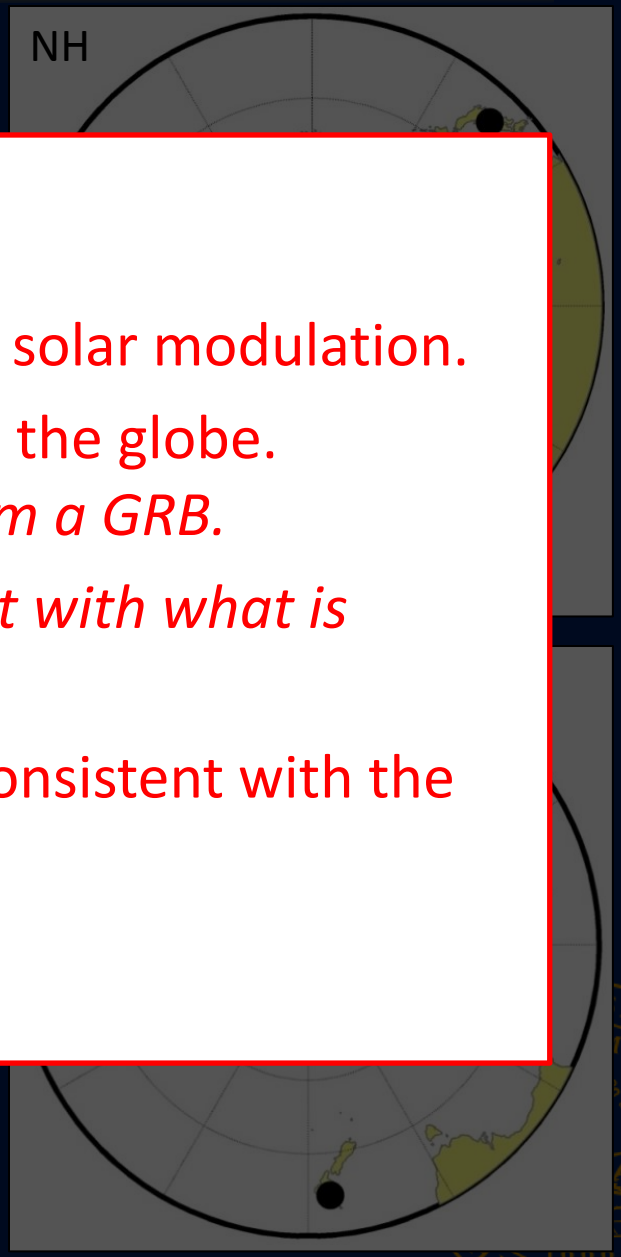
The peaks have been measured all over the globe!





The signature of exceptional SPE(s)

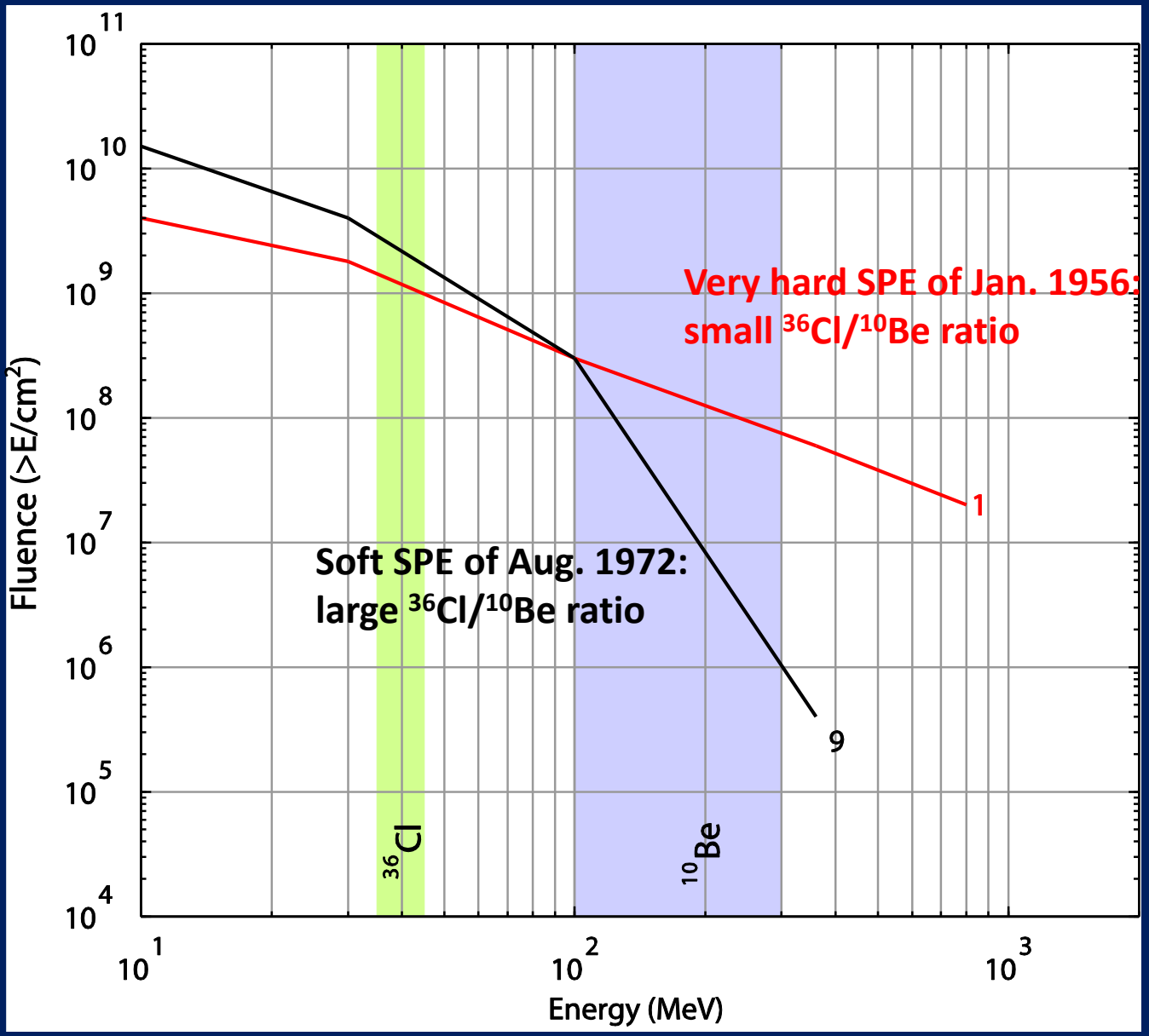




Supporting a (or several) SPE(s):

- The ^{10}Be peaks clearly stand out from solar modulation.
- The peaks are measurable throughout the globe. *Inconsistent with what is expected from a GRB.*
- ^{10}Be enhancement. *Again, inconsistent with what is expected from a GRB.*
- ^{36}Cl enhancement is largest which is consistent with the pattern *expected from solar protons.*

Relationship between $^{36}Cl/^{10}Be$ ratios and spectral hardness



Modified from Mekhaldi et al. (NCOMMS 2015)

Relationship between $^{36}Cl/^{10}Be$ ratios and spectral hardness

A very hard energy spectrum!

Table 2 | Relative $^{36}Cl/^{10}Be$ ratios.

	Solar proton event	Relative $^{36}Cl/^{10}Be$ ratio
1	23 February 1956	1.2
2	20 January 2005	1.5
	AD 774/5	1.8± 0.2
	AD 993/4	2.1± 0.4
3	29 September 1989	2.5
4	29 October 2003	3
5	14 July 2000	3.5
6	19 October 1989	3.6
7	10 July 1959	4
8	12 November 1960	4
9	04 August 1972	6
10	04 November 2001	6

The ratios are based on computations of the annual mean production of ^{10}Be and ^{36}Cl by 10 large solar proton events between 1956 and 2005 (ref. 35). The ratios calculated in this study for the AD 774/5 and 993/4 events are also included. The table is sorted by ascending ratios.

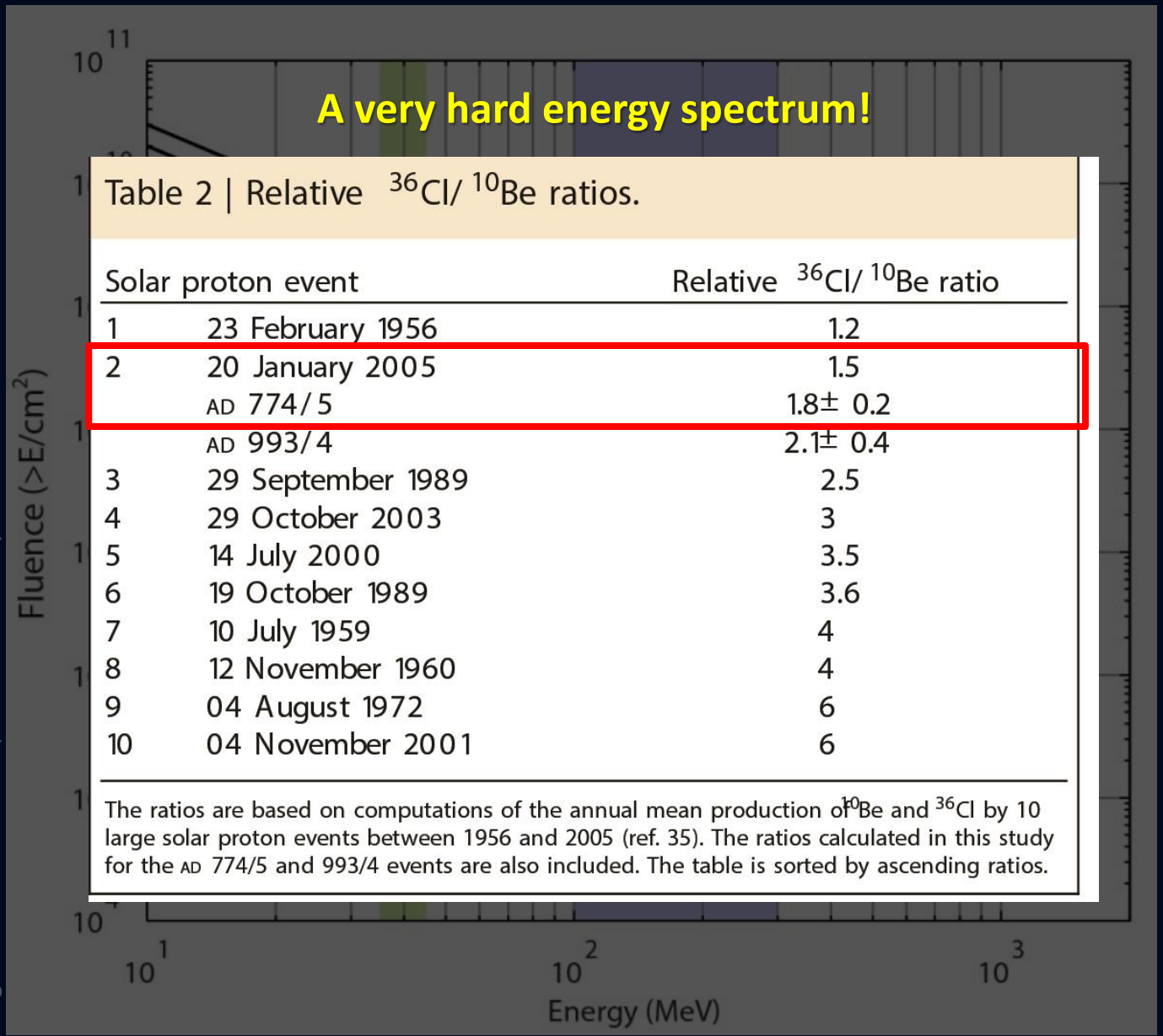
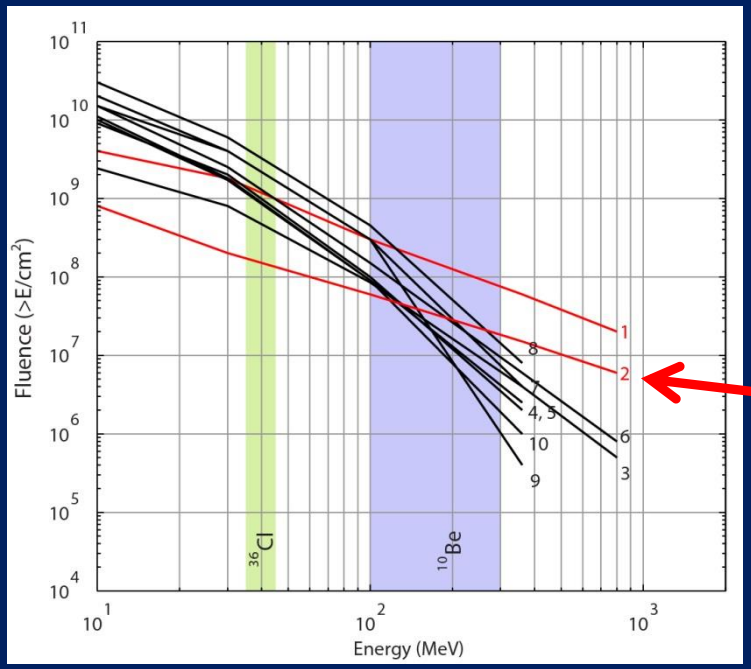


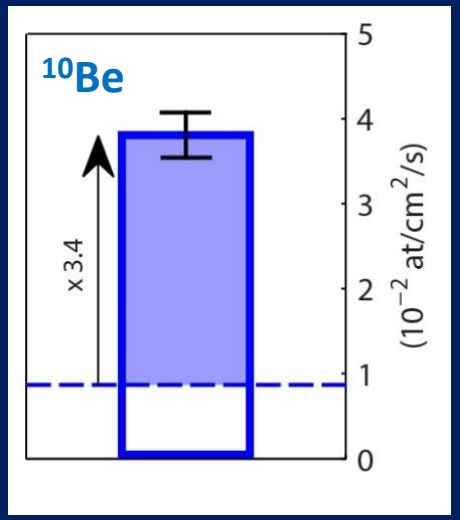
Fig 4. Mekhaldi et al. (NCOMMS 2015)

Estimating a possible fluence > 30 MeV



(2) SPE05

AD 774/5



- We know how much 10Be has increased to due the SPE of Jan. 2005 (Webber et al. 2007)
- We then simply scale up the fluence spectrum of SPE05 to explain the ^{10}Be increase measured for the AD 775 event
- We accordingly find a F_{30} of **2.82 ± 0.25 x 10^{10} protons/cm²** !
  *(**1.02 ± 0.21 x 10^{10} protons/cm²** for the AD 993/4 event)*

The AD 775 SPE(s) was larger than anything ever measured so far!

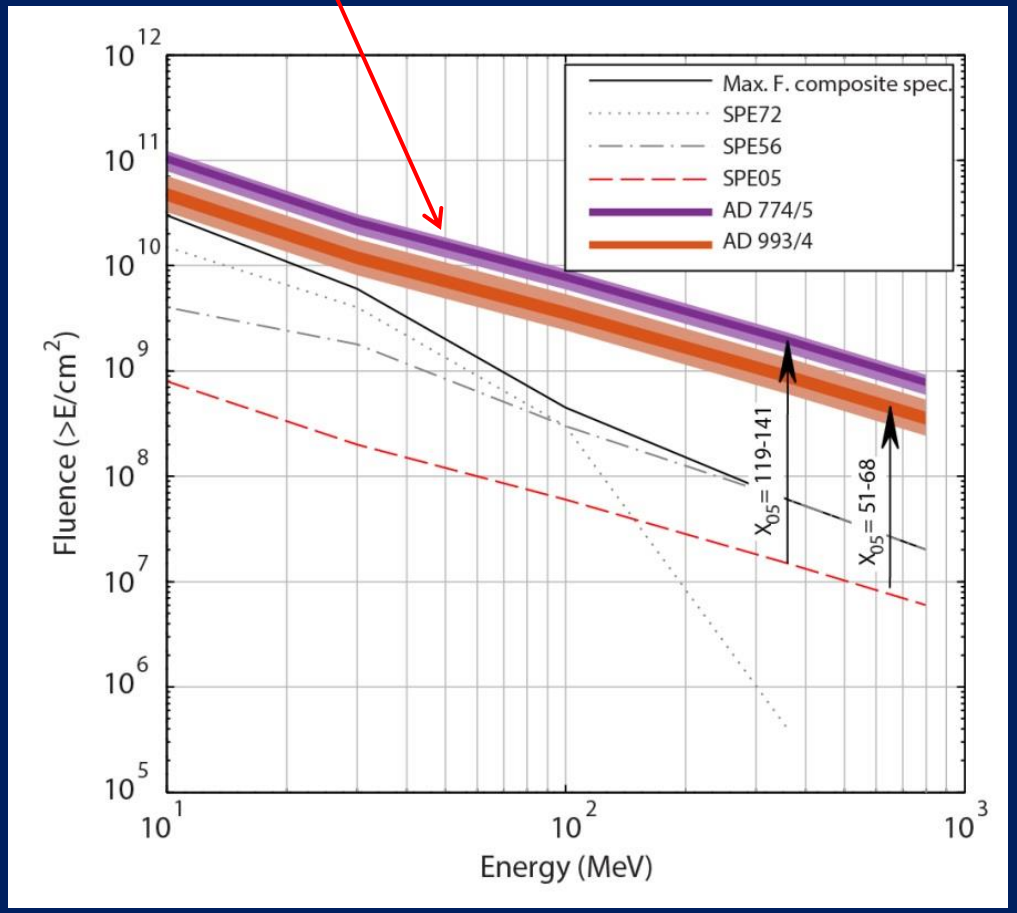


Fig 5. Mekhaldi et al. (NCOMMS 2015)

- The ^{10}Be, ^{14}C, and ^{36}Cl peaks are in full agreement with **SPEs as the cause of the AD 774/5 and 993/4 events**
- Using ^{36}Cl/^{10}Be ratios, we can estimate a probable spectral hardness for the events
- The SPE(s) of AD 774/5 and 993/4 had a **very hard energy spectrum**
- Based on the induced production of ^{10}Be and ^{14}C, we estimate **a possible fluence > 30 MeV in the order of 2 x 10^{10} protons/cm^2**
- This would make the AD 775 event **stronger than any SPE measured** during the instrumental era

Thanks // Kiitos