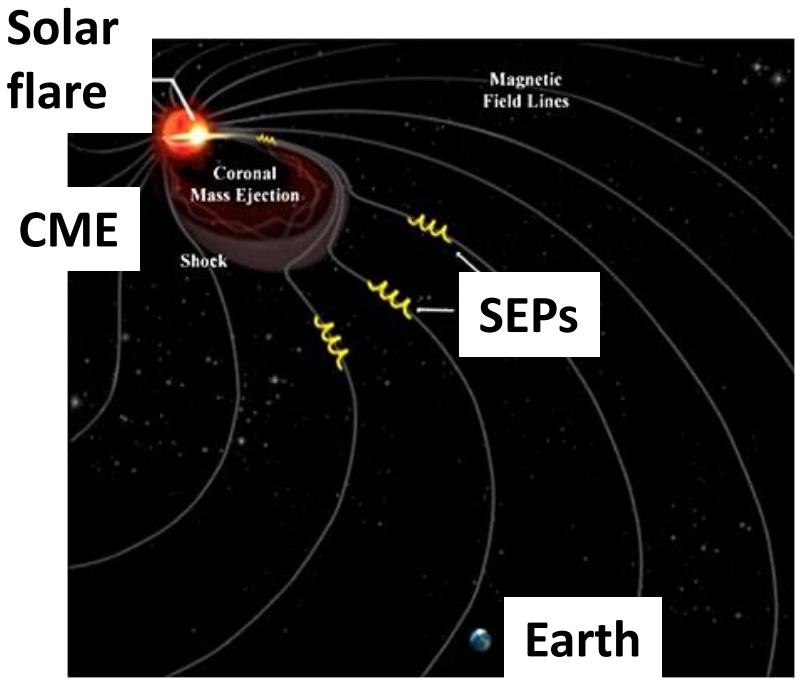
Cosmogenic Evidences for Past SEP Events

Fusa Miyake (ISEE, Nagoya University)

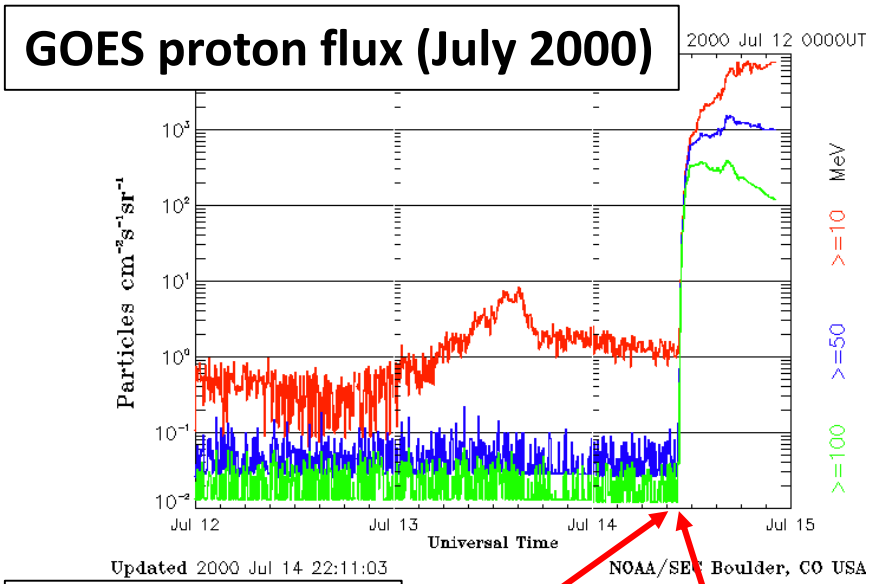
Collaboration with
K. Masuda, T. Nakamura, K. Kimura, M. Hakozaki, F. Tokanai, AJT Jull, IP Panyushkina, L. Wacker, T. Moriya, M. Takeyama, K. Horiuchi, Y. Motizuki, Y. Nakai, K. Takahashi, H. Motoyama, H. Matsuzaki

ICRC2019, Madison
31 July 2019

Solar Energetic Particles (SEPs)



http://spaceweather.uma.es/solarstorms.html



ESA/NASA

SEPs:

- originate from solar flares & CMEs
- Energy up to a few GeV or more

SEP events: observed as a sudden increase of SEP flux

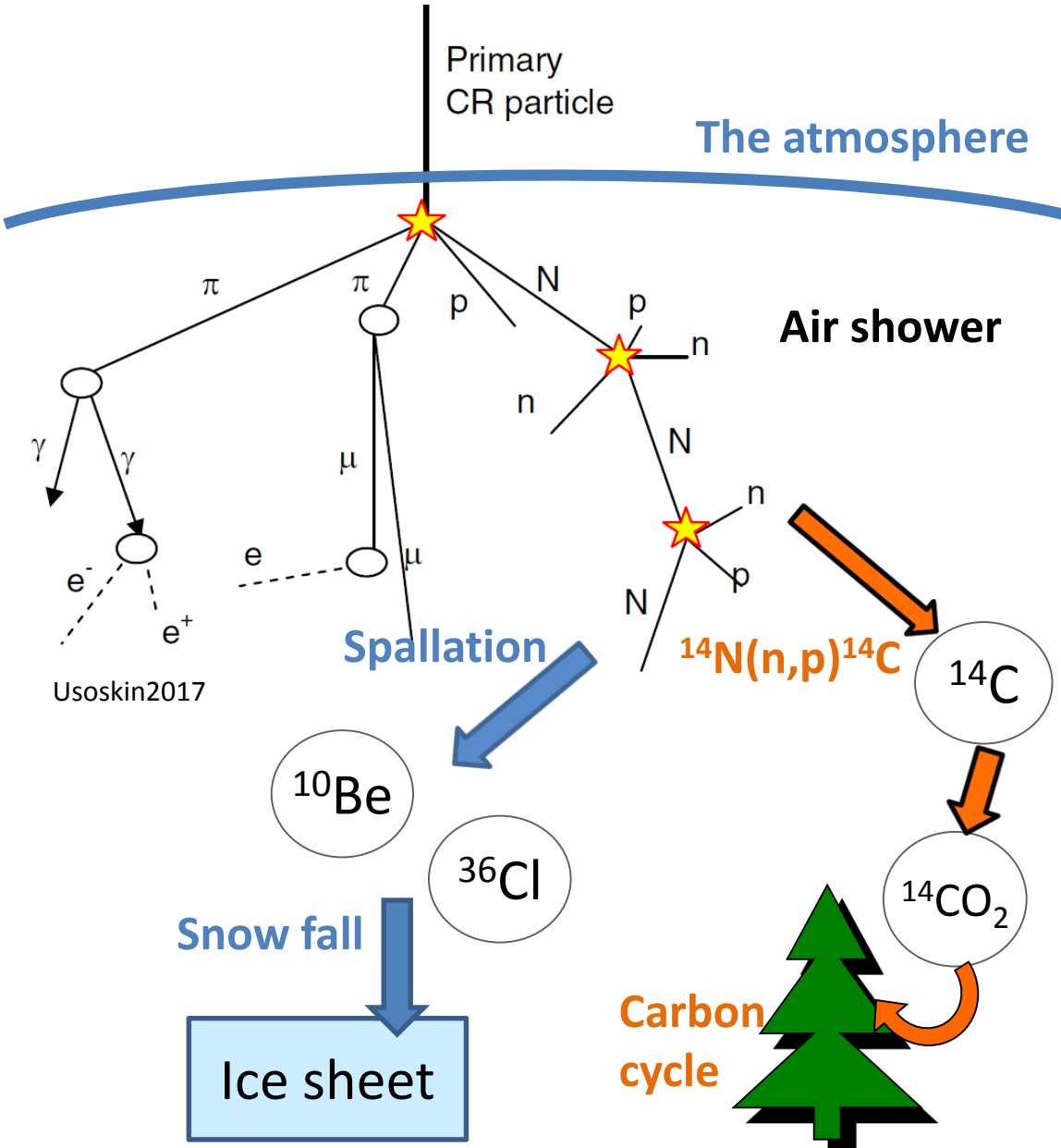
Study of SEP event for long-term

- SEPs observation
  - Satellite (~50 years): Direct observation
  - Ground detector, e.g. NM (~70 years): Indirect observation
    →Ground level enhancements (GLEs)
    →72 GLEs have been detected since 1942

- Longer-term characteristics of SEP events?
  - Occurrence rate of extreme SEP events?
  - Upper limit?

- Investigation of cosmogenic nuclides

Record of past cosmic ray intensity



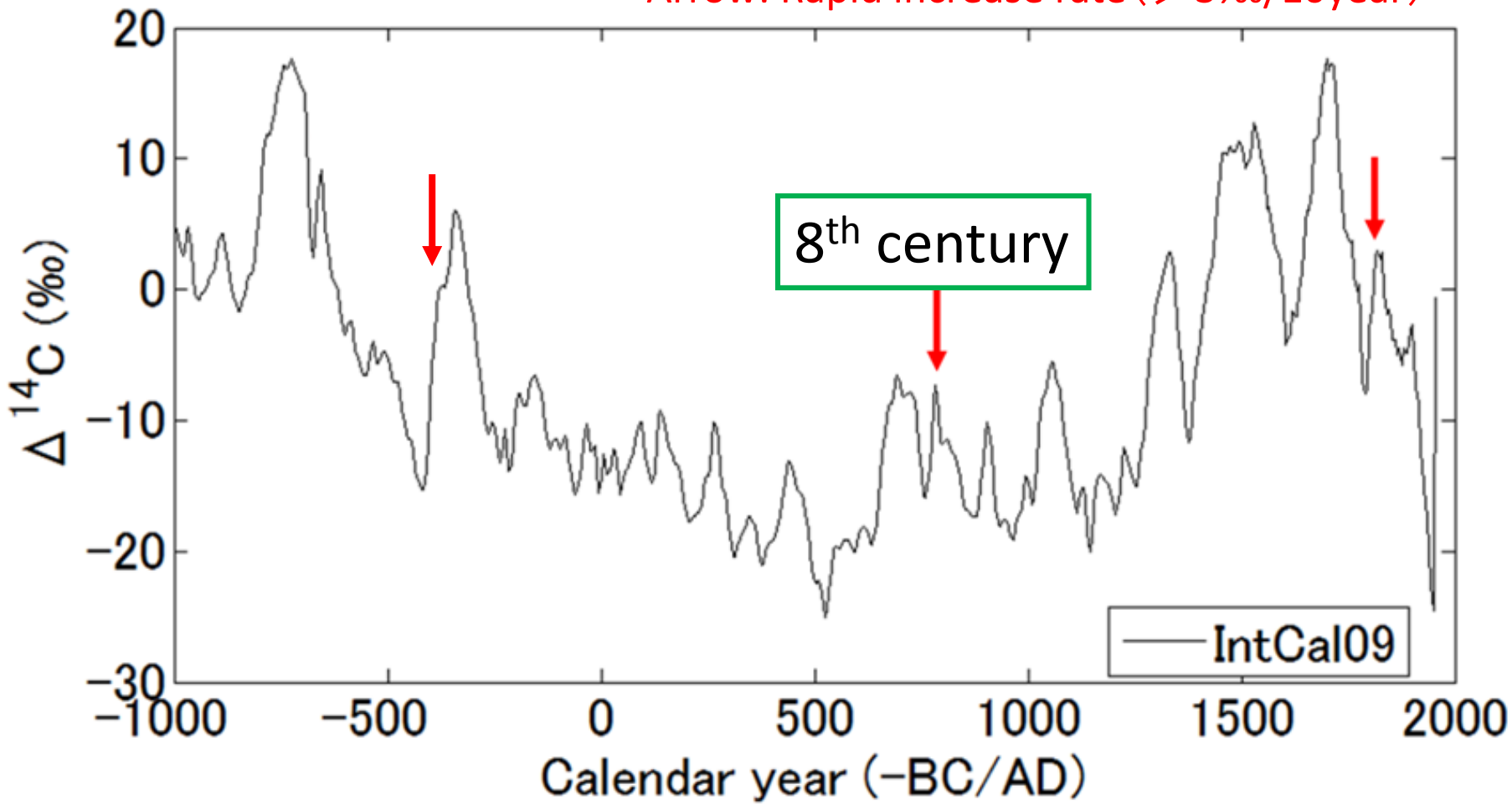
Cosmogenic nuclides
(^{14}C,^{10}Be, ^{36}Cl…)
>~10MeV primary CR

- Record of past
  --GCR intensities
  --extreme SEP event
- SEP event must appear as a sudden increase (<1 year) in cosmogenic data

Search for annual ^{14}C events（3,000 years）

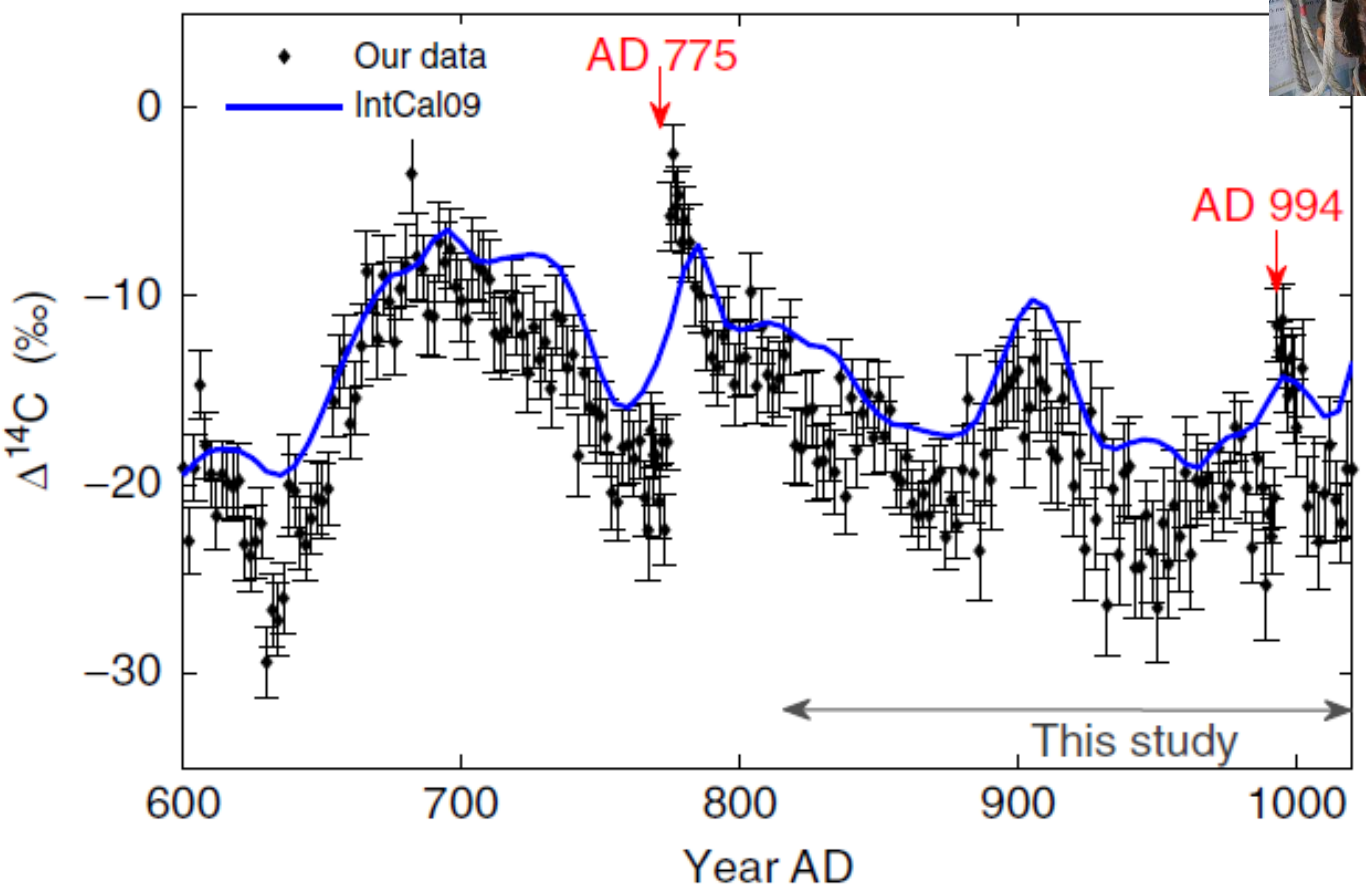
Look at IntCal Data (decadal res.: ~12,000 years)

Arrow: Rapid increase rate（＞3‰/10year）



Discovery of ^{14}C increase events

Japanese cedar

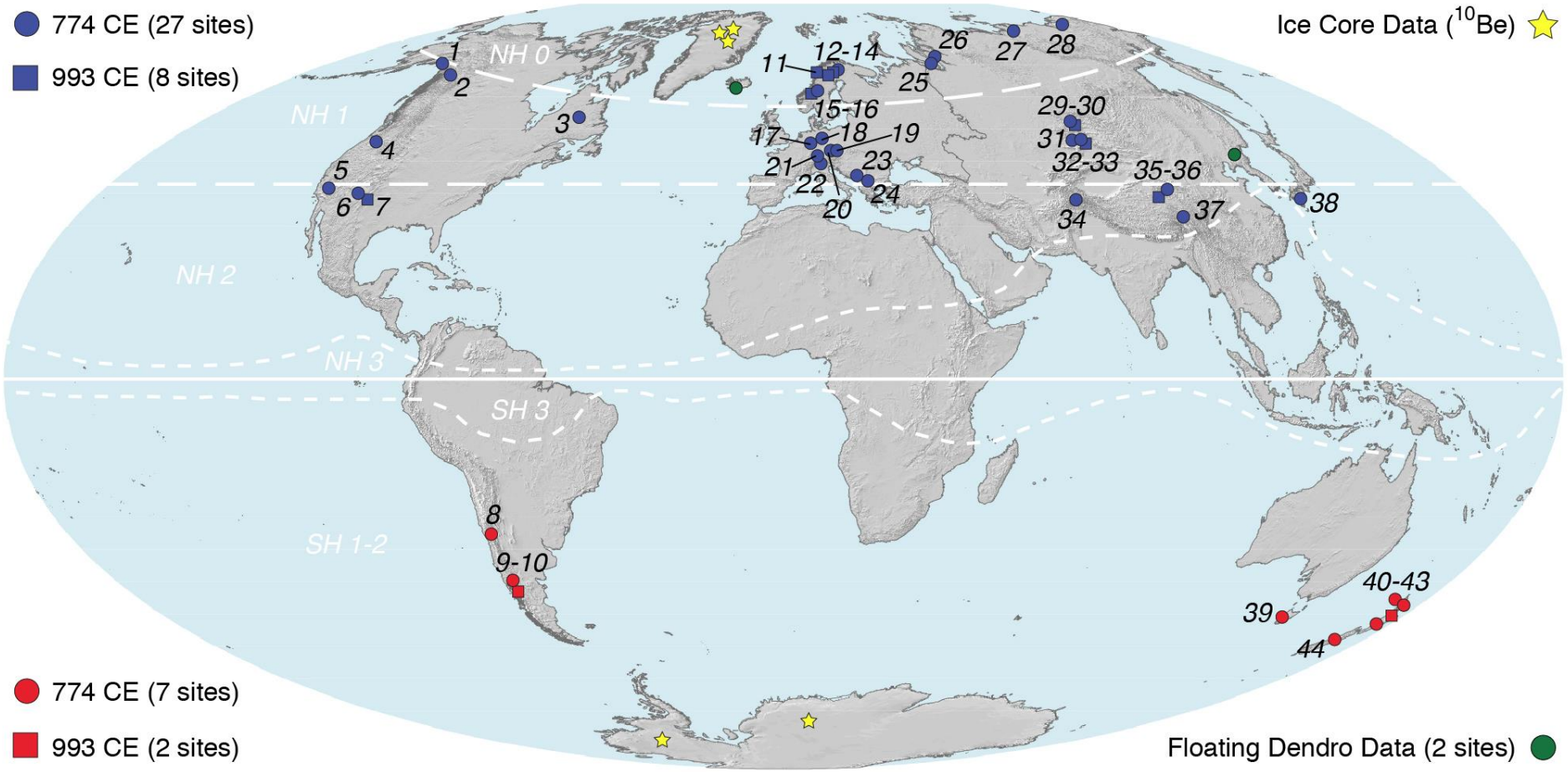


Miyake et al. 2013

- 774/775 CE event (Miyake+2012)
- 993/994 CE event (Miyake+ 2013)

  →Much larger increase against measurement errors and ordinary solar modulation

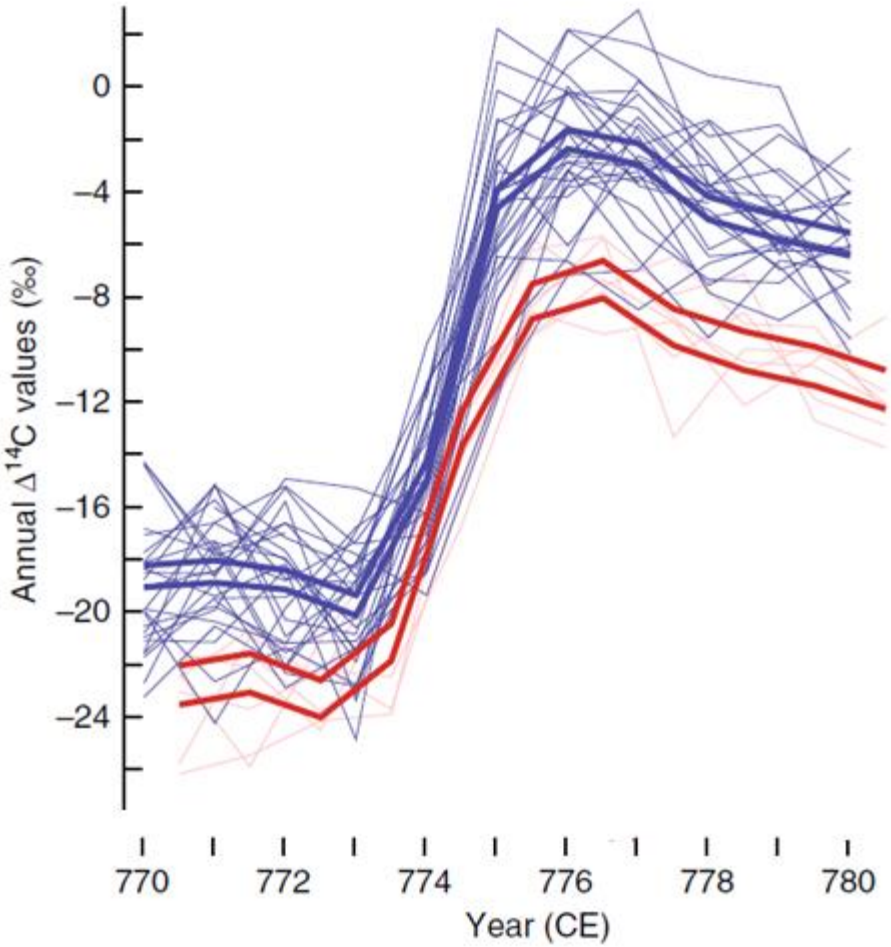
Worldwide confirmation of ^{14}C events



Büntgen *et al.* 2018

- 448 individual tree rings were measured at **ETH Zurich** (MICADAS) --27 species from both hemispheres

Worldwide confirmation_775 event

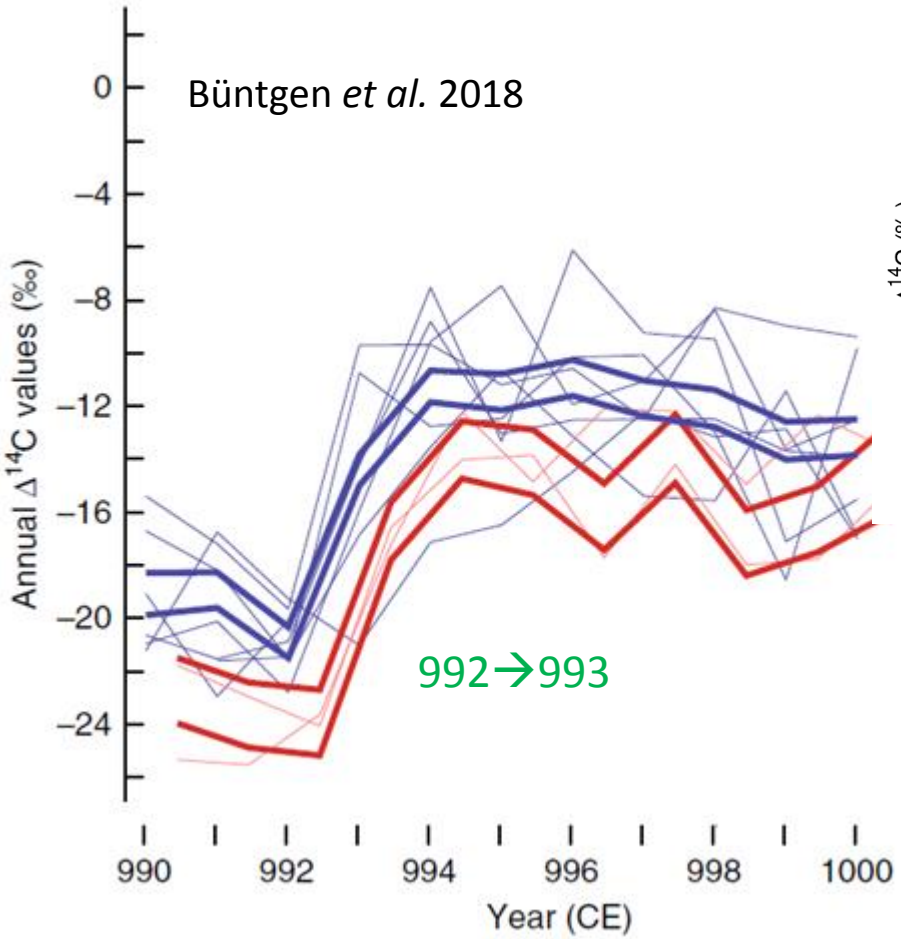


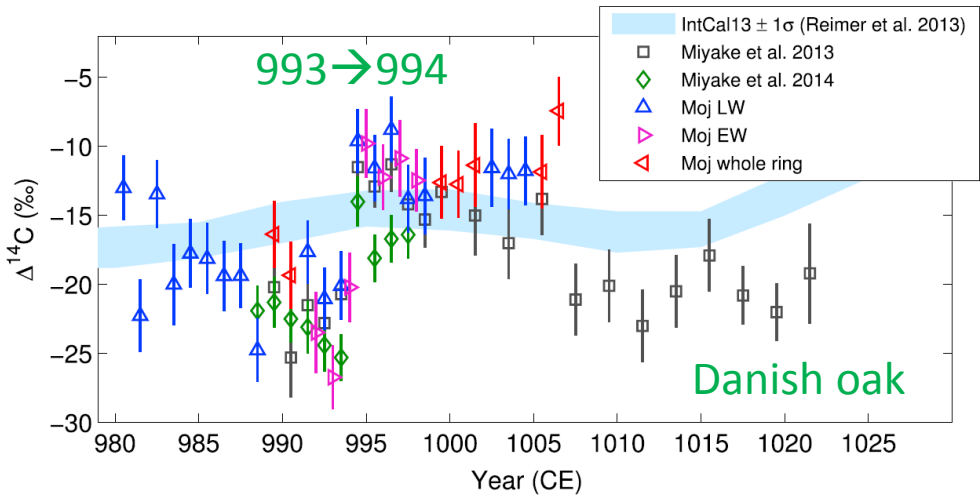
- 374 tree rings for 770-780 CE
- Blue: NH
- Red: SH
- Thick lines: standard uncertainties around hemispheric means

- **Increases were occurred in 774-776 CE**
- **Largest increase in 774-775 →consistent with our result**

Büntgen *et al.* 2018

Worldwide confirmation_993/994 event





Fogtmann-Schulz et al. 2017

- 110 tree rings for 990-1000 CE
- Blue: NH
- Red: SH
- Half increment of 775 event

- Most increases occurred in 992-993CE!?

Dendro problem?
Species difference?

- 993/994 event was confirmed as rapid ^{14}C increase
- Two ^{14}C events are reproduced in all over the world!!

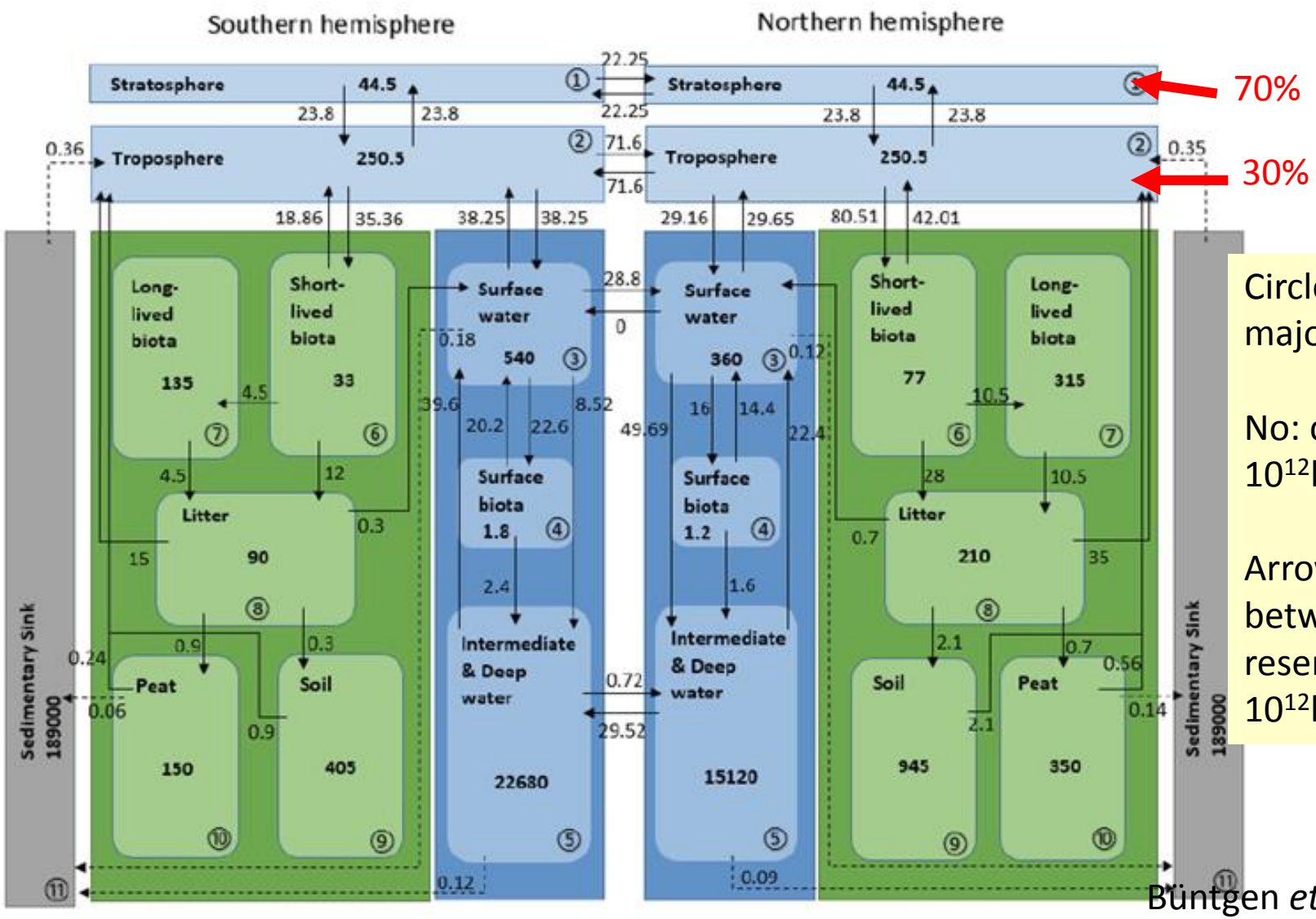
^{14}C data in tree ⇔ ^{14}C injection to the atmosphere

- Tree ring-based ^{14}C data
  - reflect tropospheric conditions during wood formation
  - **NOT** reflect ^{14}C production information

- Employ a global carbon cycle model to understand intra-annual course of the ^{14}C cycle
  - Box model

Global carbon 22-box model

Divide the world to several reservoirs (=boxes)



Circled no: major reservoir

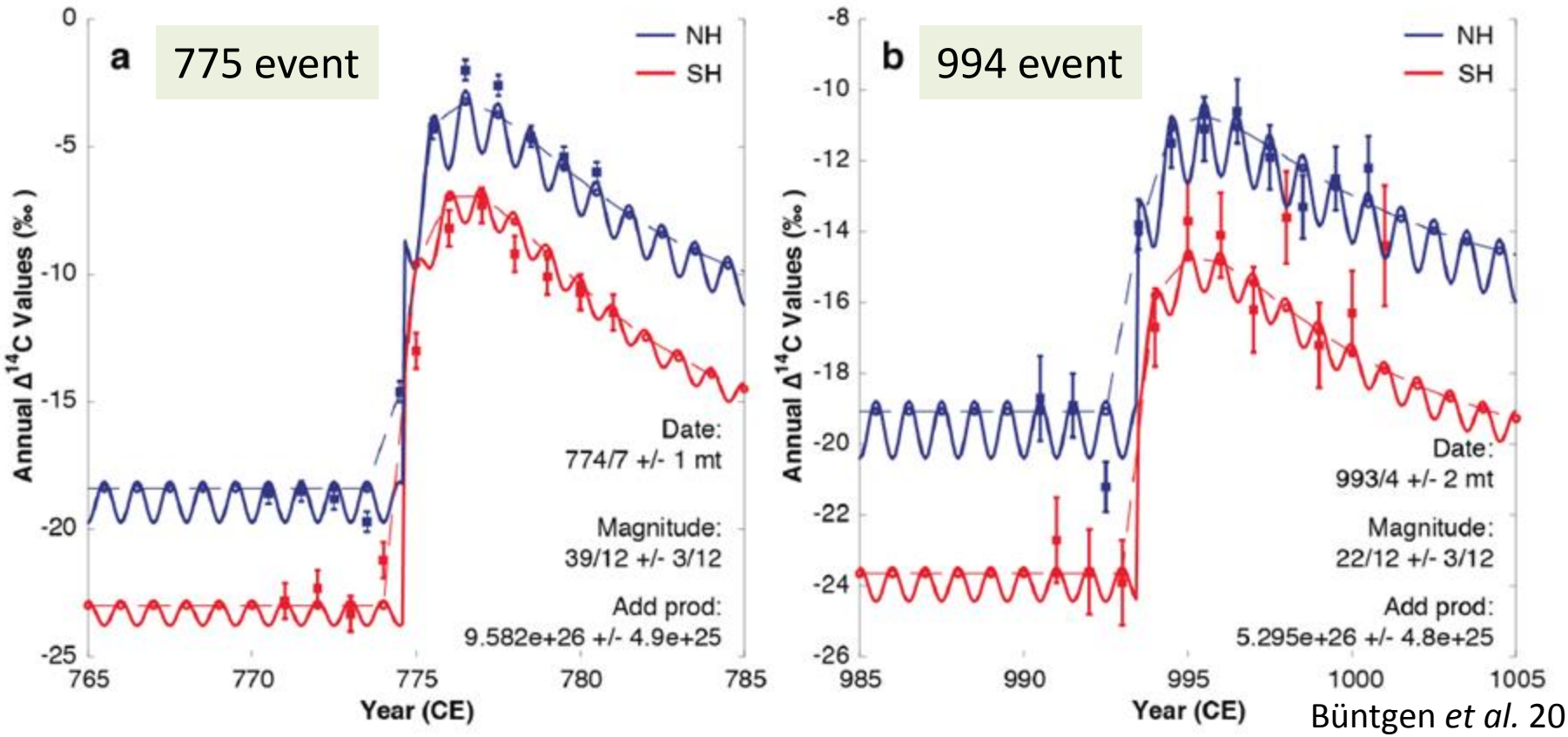
No: carbon mass 10^{12}kg

Arrow: flux between reservoir 10^{12}kg/yr

Büntgen *et al.* 2018

Box model simulation of ^{14}C events

- Fitting parameters: event start date, additional ^{14}C production



Büntgen *et al.* 2018

Event start date: July 774±1 month, April 993 ±2 months
Uusitalo et al. 2018: late spring to early summer in 774

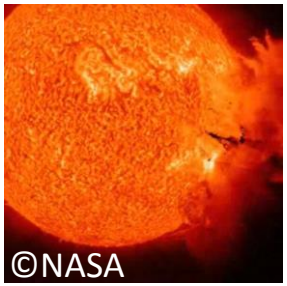
^{14}C production yield of 775 event

Reference	^{14}C production (atoms/cm^2)	Box model
Miyake+, 2012&2014	$(1.5 \pm 0.3) \times 10^8$	4-box
Usoskin+, 2013	$(1.3 \pm 0.2) \times 10^8$	6-box
Güttler+, 2015	2.1×10^8	11-box
Büntgen+, 2018	$(1.9 \pm 0.1) \times 10^8$	22-box

GCR ^{14}C yield : 6.2×10^7 atoms/cm^2/year
→775 event: 2-3 times larger than annual production by GCR!!

Origin of the events?

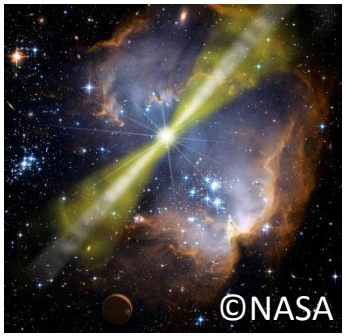
Emitting a lot of CRs & increasing CR intensities to the Earth



SEP event

Supernova

Gamma-ray burst

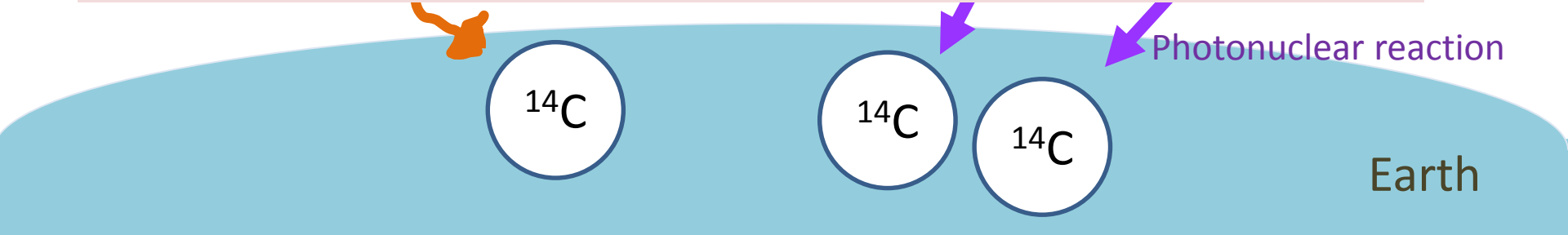


Protons…

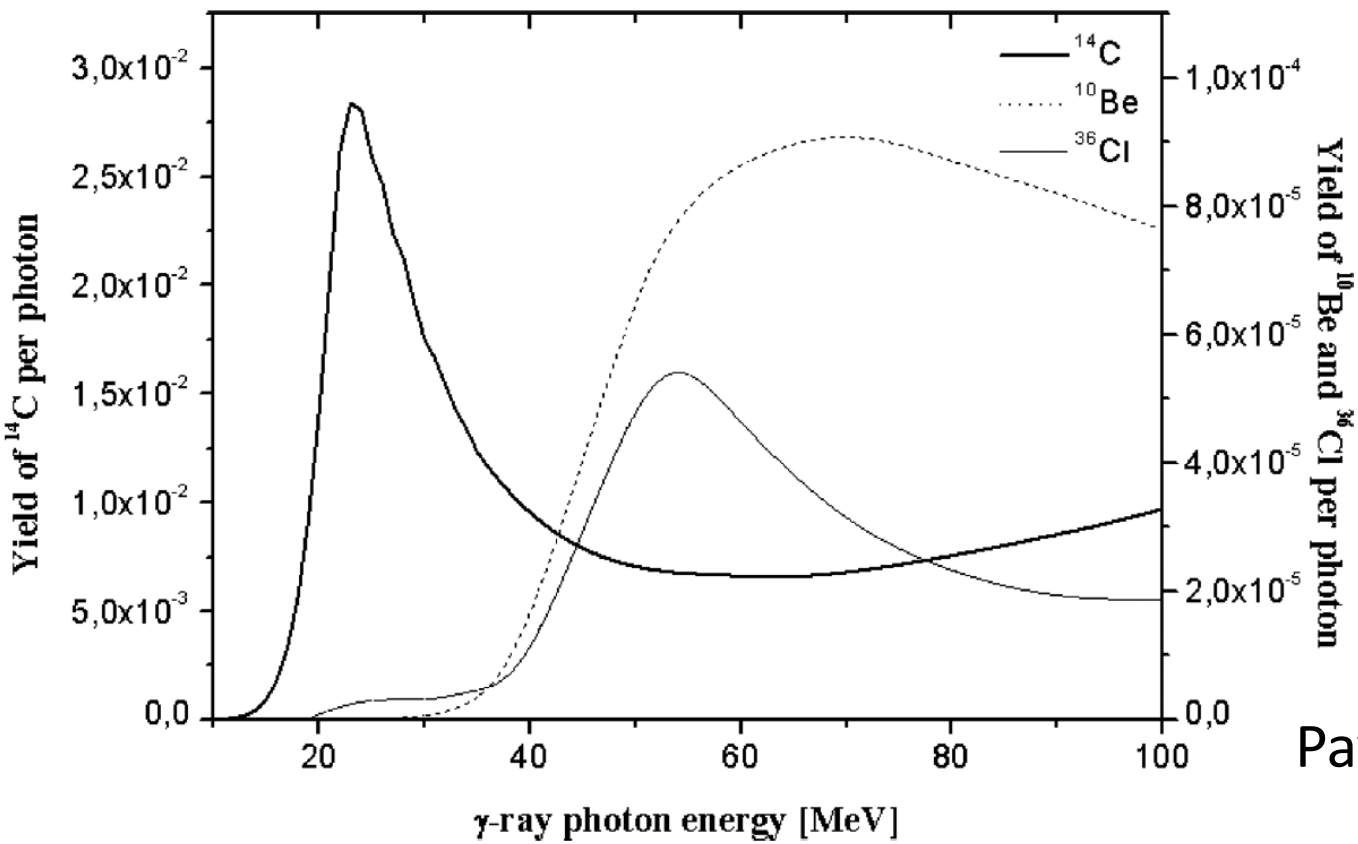
Gamma-rays

- These events can make detectable ^{14}C increase
- SEP (mostly proton) origin vs Gamma-ray origin??

Photonuclear reaction



To determine the cause__^{10}Be data



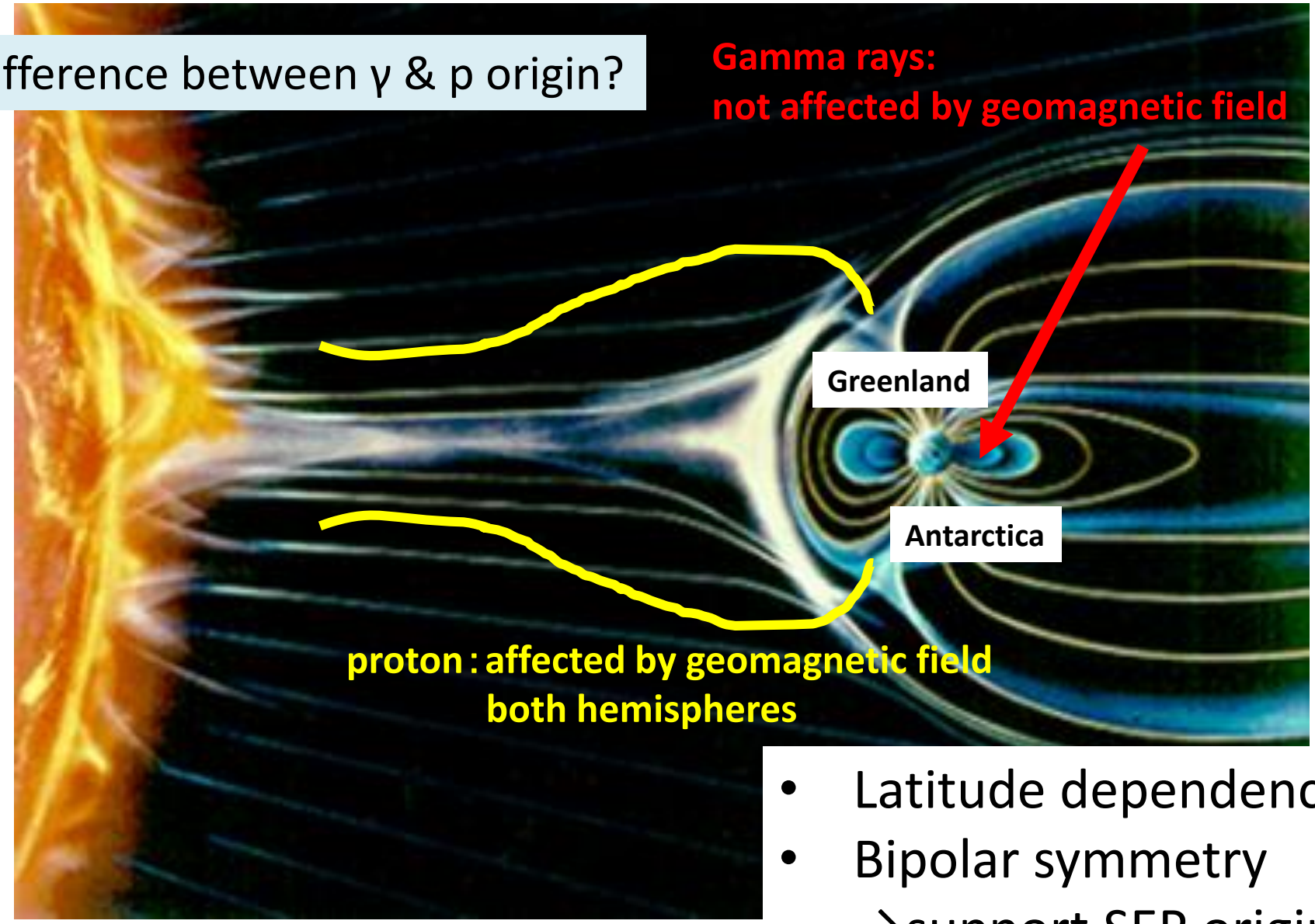
Pavlov et al. 2013

Energetic photon produces secondary neutrons →cosmogenic nuclides

- Production ratio ^{14}C/^{10}Be: different γ-ray and proton
  ^{14}C/^{10}Be:~400-800 (γ-ray events)⇔~50 (SEP)
- Detection of ^{10}Be Peak: **Not** GRB

Geomagnetic effects on cosmogenic nuclide data?

Difference between γ & p origin?

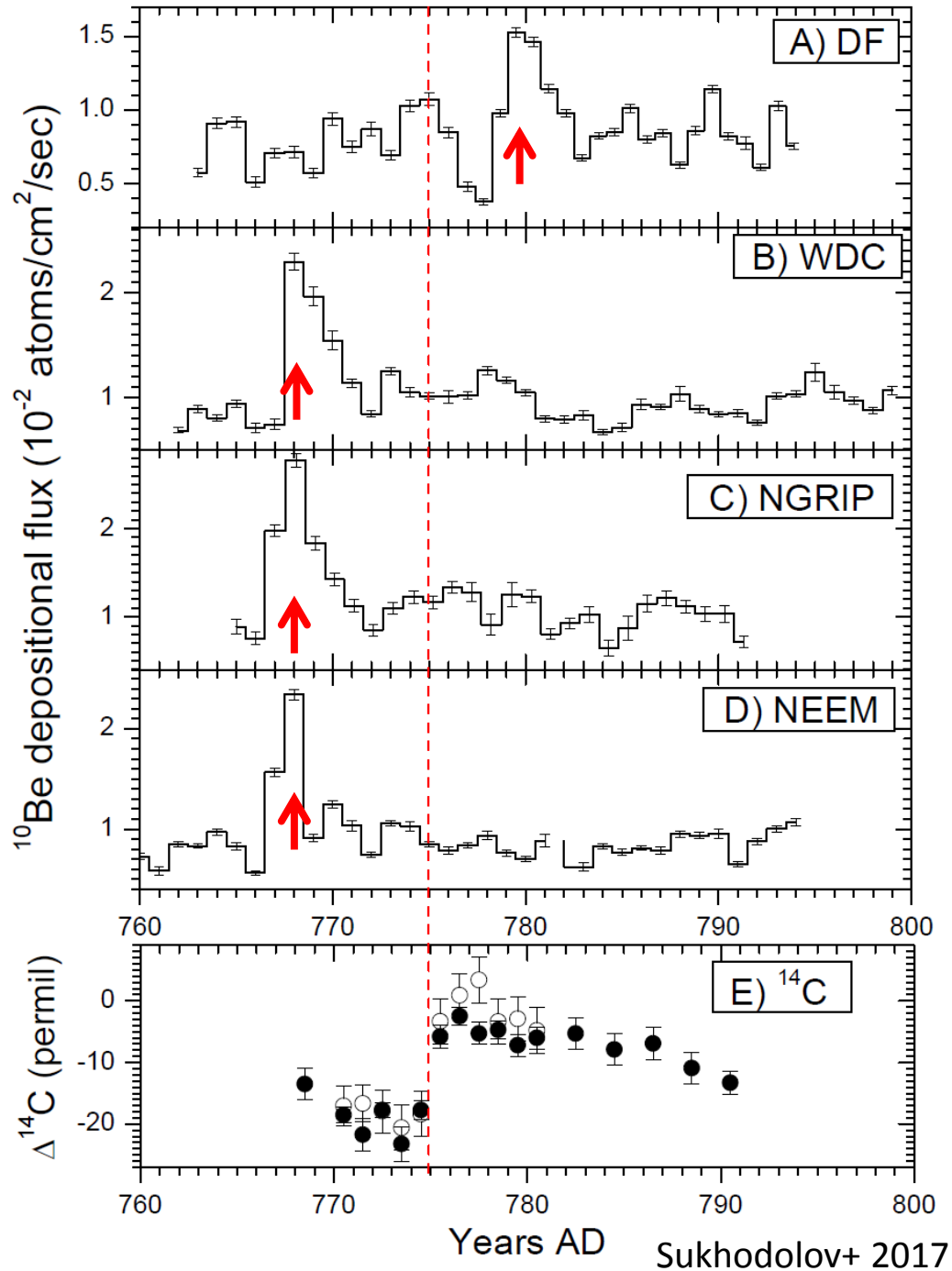


- Latitude dependence
- Bipolar symmetry
  →support SEP origin

Quasi-annual ^{10}Be data

- Dome Fuji ice core, Antarctica
- WDC (Antarctica)
- NGRIP, NEEM TUNU (Greenland)
  Sigl+2015, Mekhaldi+2015

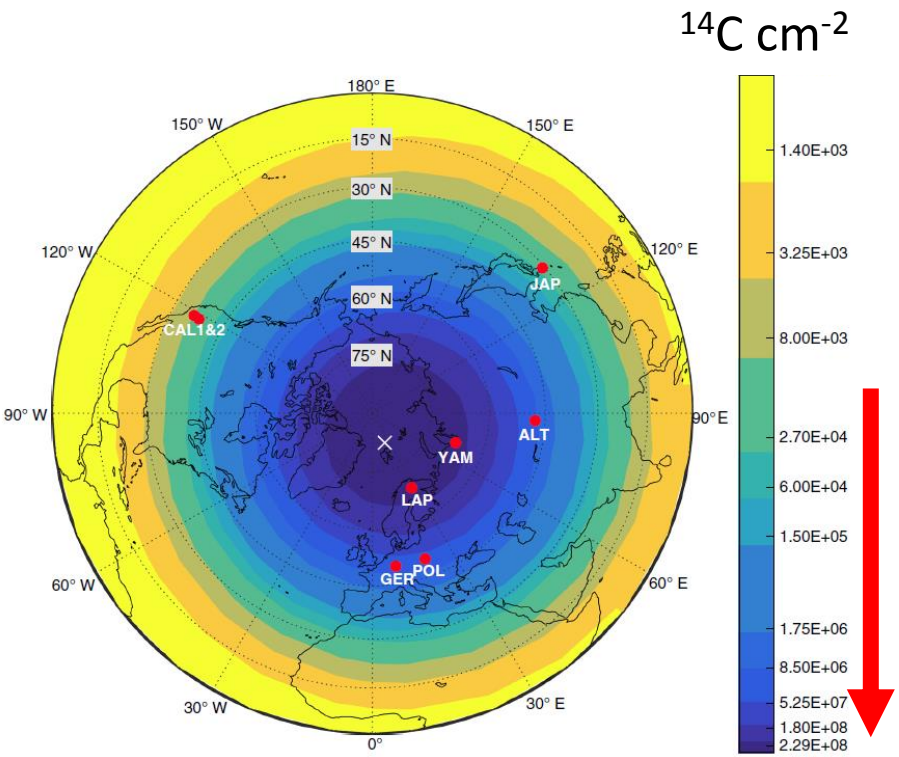
- Clear ^{10}Be peaks
- Bipolar symmetry
  →also 994 event



Sukhodolov+ 2017

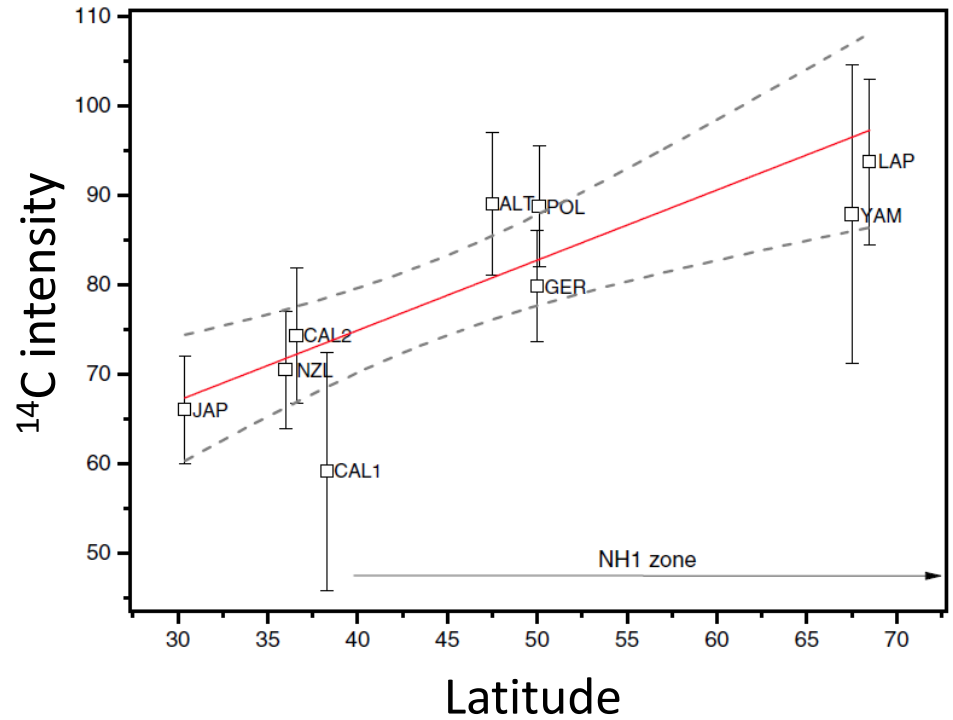
Latitude dependence

Uusitalo et al. 2018



Strong SEP event 1956 case

Increase Number of ^{14}C



- Significant latitude dependence
  →affected by geomagnetic field
  →Solar origin
- Büntgen et al. 2018 also showed latitude dependence

Origin of the ^{14}C events?

- Existence of ^{10}Be peaks deny gamma-ray origin

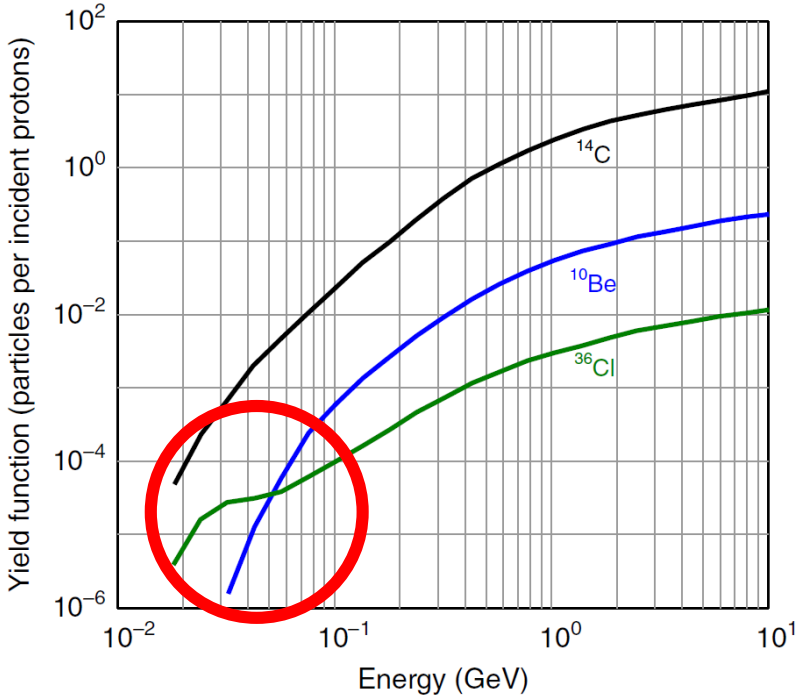
- Latitude dependence in ^{14}C
- Bipolar symmetry: ^{10}Be & ^{14}C peak in both hemispheres

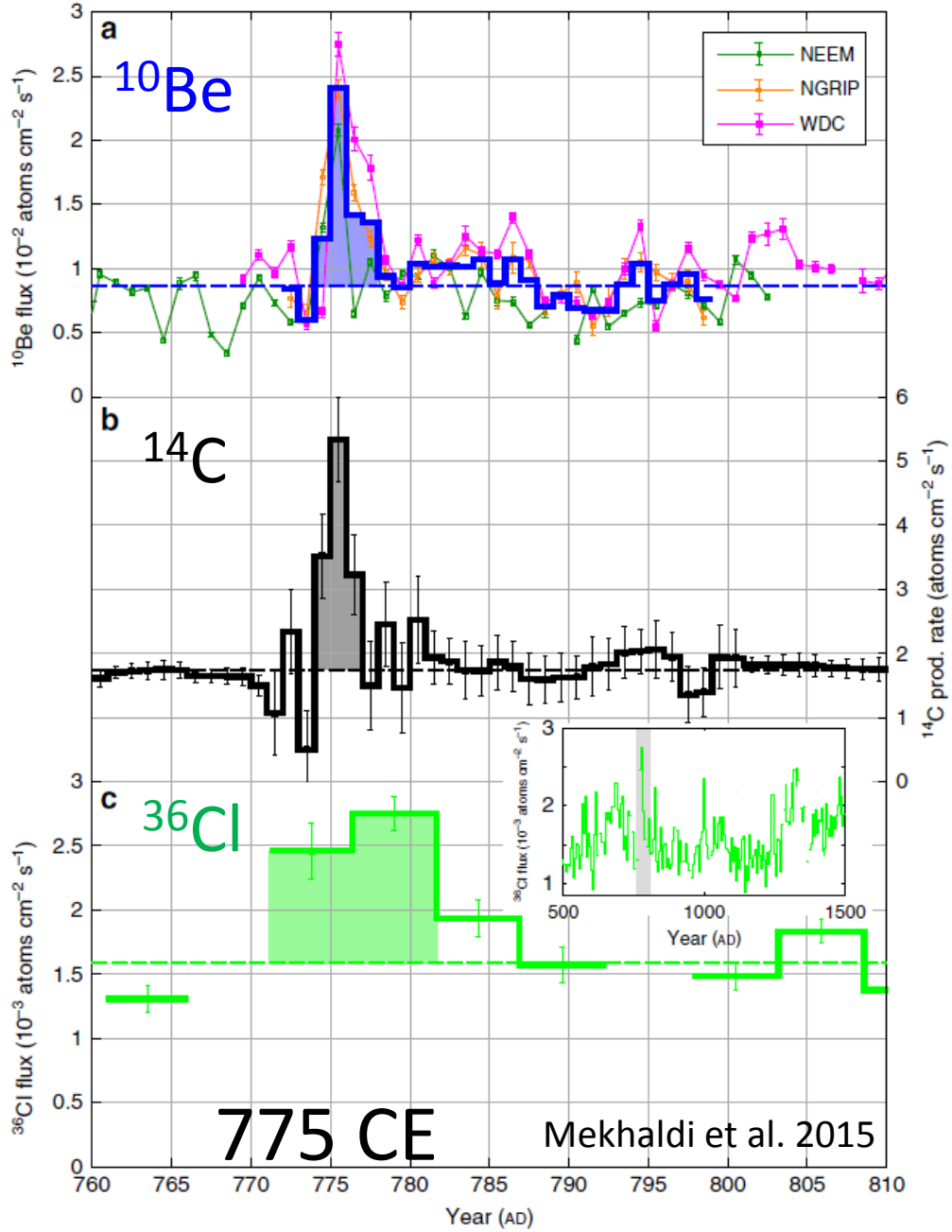
- No supernova remnants found

- Origin: **extreme SEP events!!**

Energy spectrum: $^{36}Cl/^{10}Be$

Mekhaldi et al. 2015





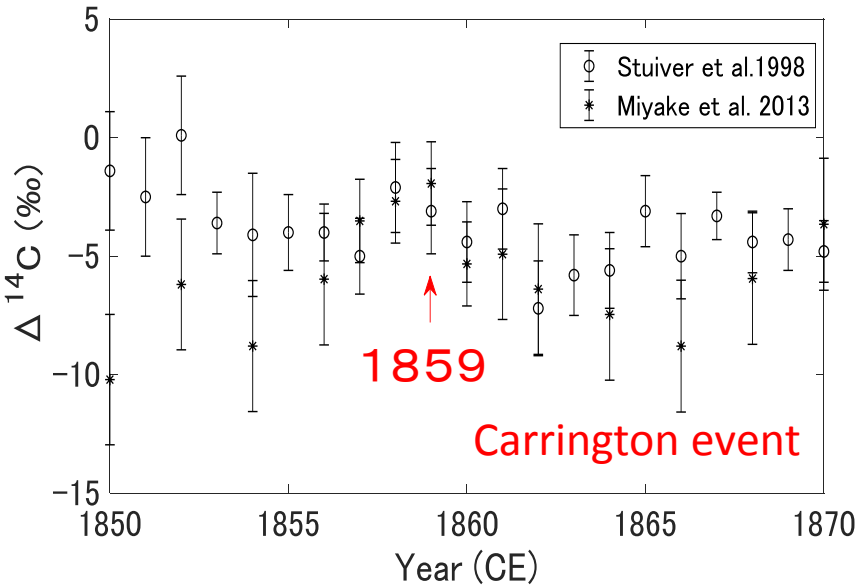
$^{36}Cl/^{10}Be$: Low(~2)

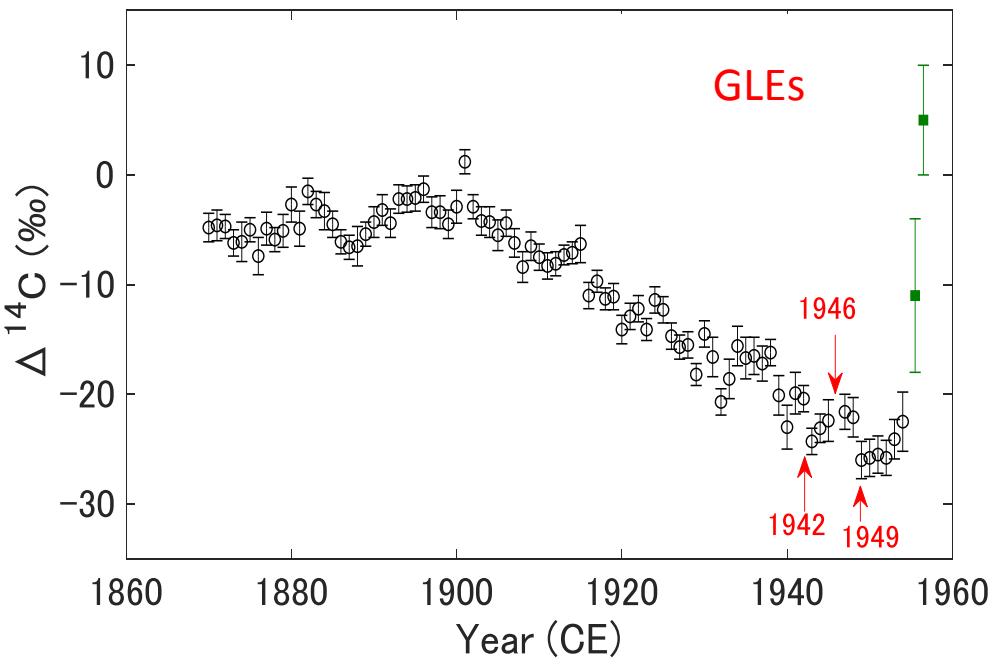
→Both 775 & 993/994 events

→Comparable to hardest energy spectrum detected so far

Event scale?

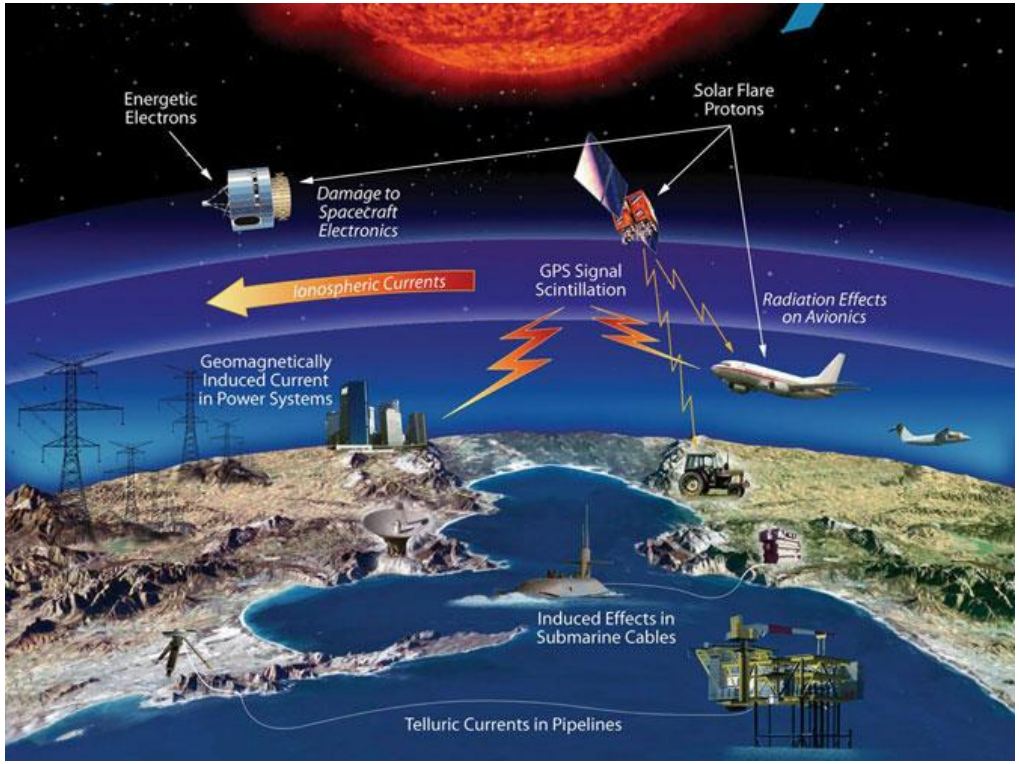
- Energy spectrum assuming SEP events in 1956
  →25~50 × SPE56
  Usoskin et al. 2013





- No ^{14}C increase in
  -- Carrington event
  -- recorded GLEs
- 775 event
  → >10 × largest SPE on record

Occurrence rate of extreme SEP events?



©NASA

SPE shown in ^{14}C data might affect heavy damage on modern society

--effect of energetic particles

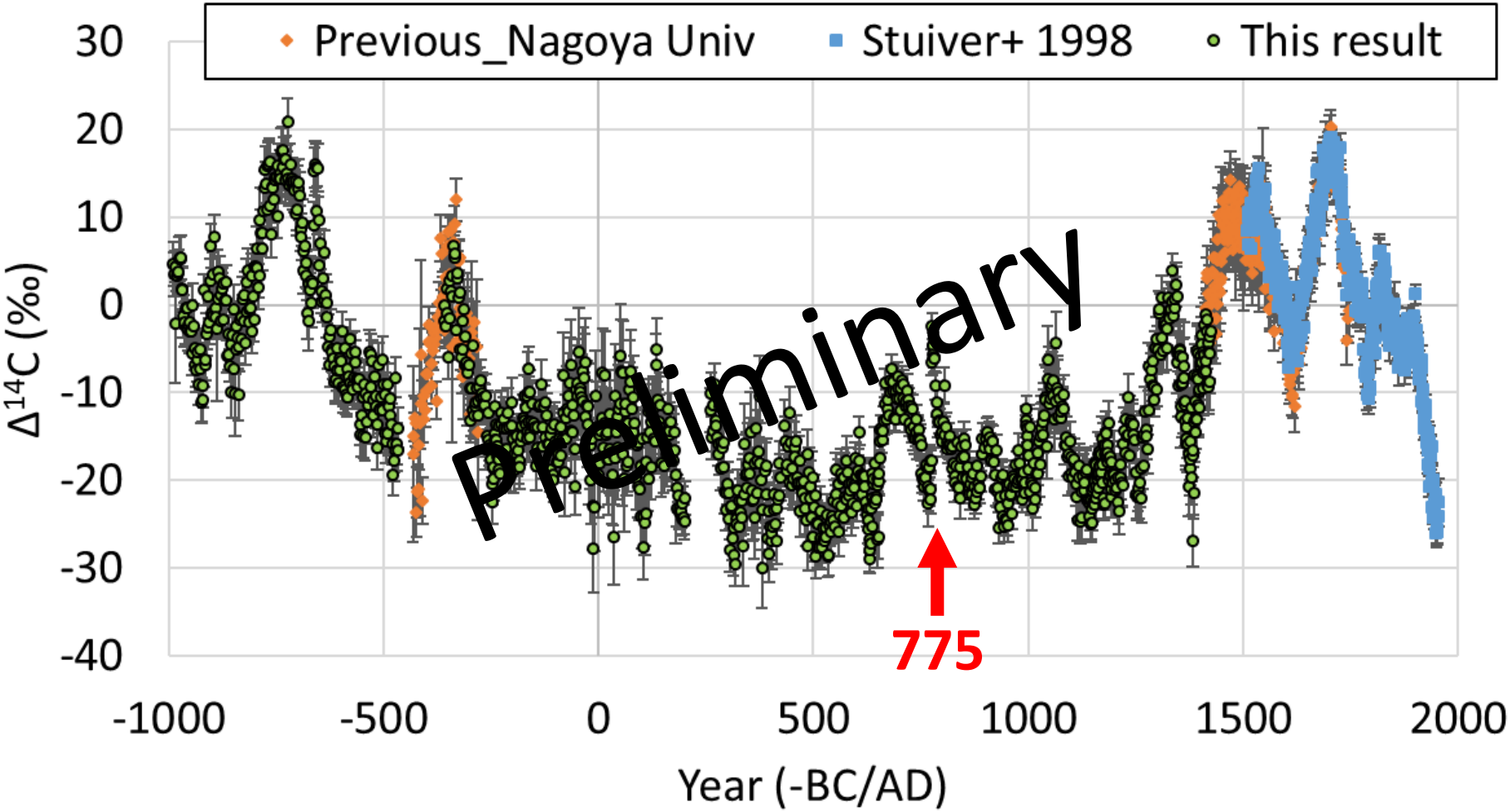
--accompanied geomagnetic storm

→large blackout, communication failure, ……

- Occurrence rate?
- We have annual ^{14}C data for limited period

→extended measurement period to past 3000 years

Further search for ^{14}C increase events



- Obtained annual ^{14}C data for most of last 3000 years
- 775 event: the largest for this period!!
- Average error: 2.8‰

Event detection

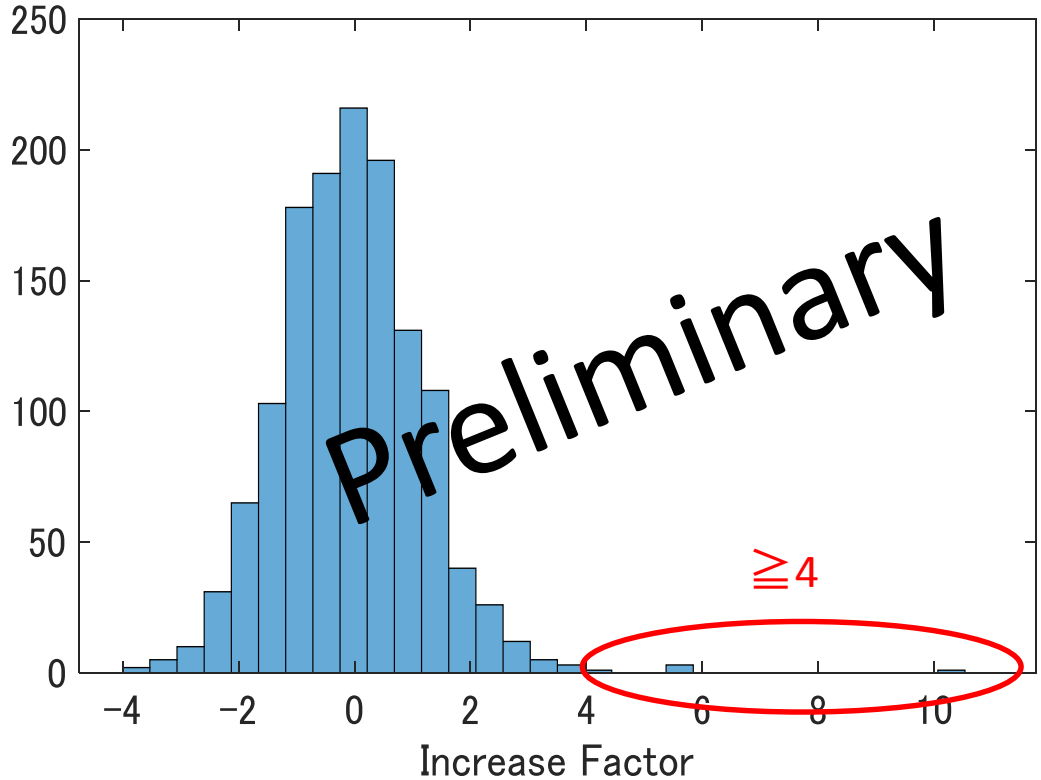
- Errors ≦3‰ →continuous data for ~2200 years
- [ave(1,2)-ave(3,4)]/ave(error)

  Increase Factor (IF) 1,2,3,4: continuous $\Delta^{14}C$ values

  →Detection of a gap in ^{14}C data & eliminating outlier cases

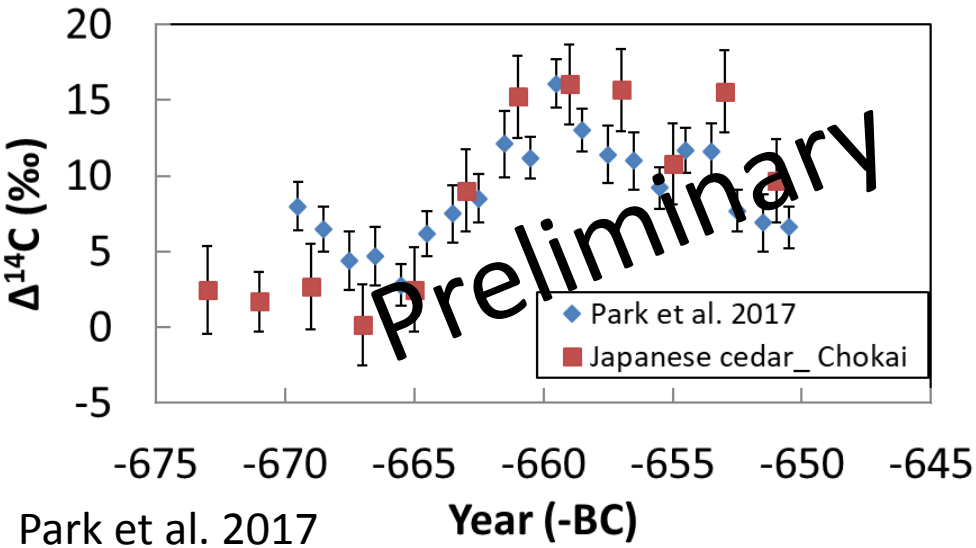
- Criteria: IF ≧4
- Detected events in descending order
  1. AD 775 event: IF 10
  2. AD 994 event: IF 5
  3. 660 BC: IF 4

3 events/ ~2,200 years



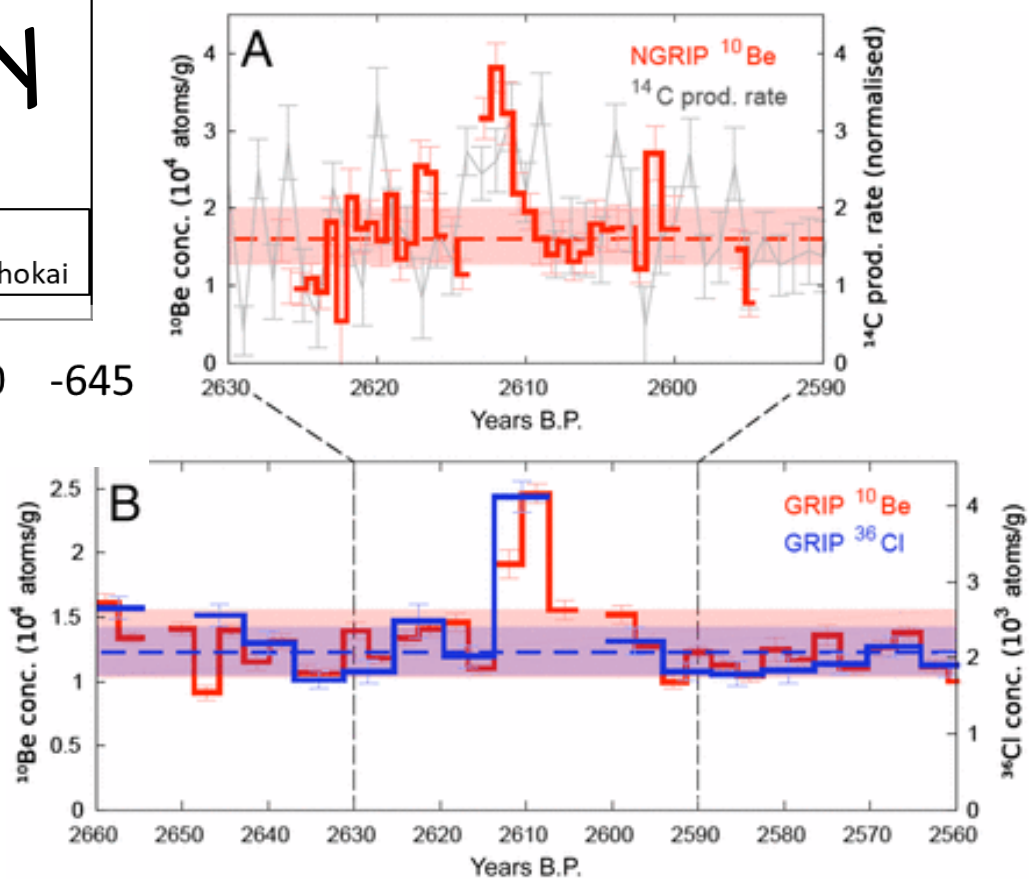
The third event: ~660 BC

^{14}C increase over 3-4 years



Park et al. 2017

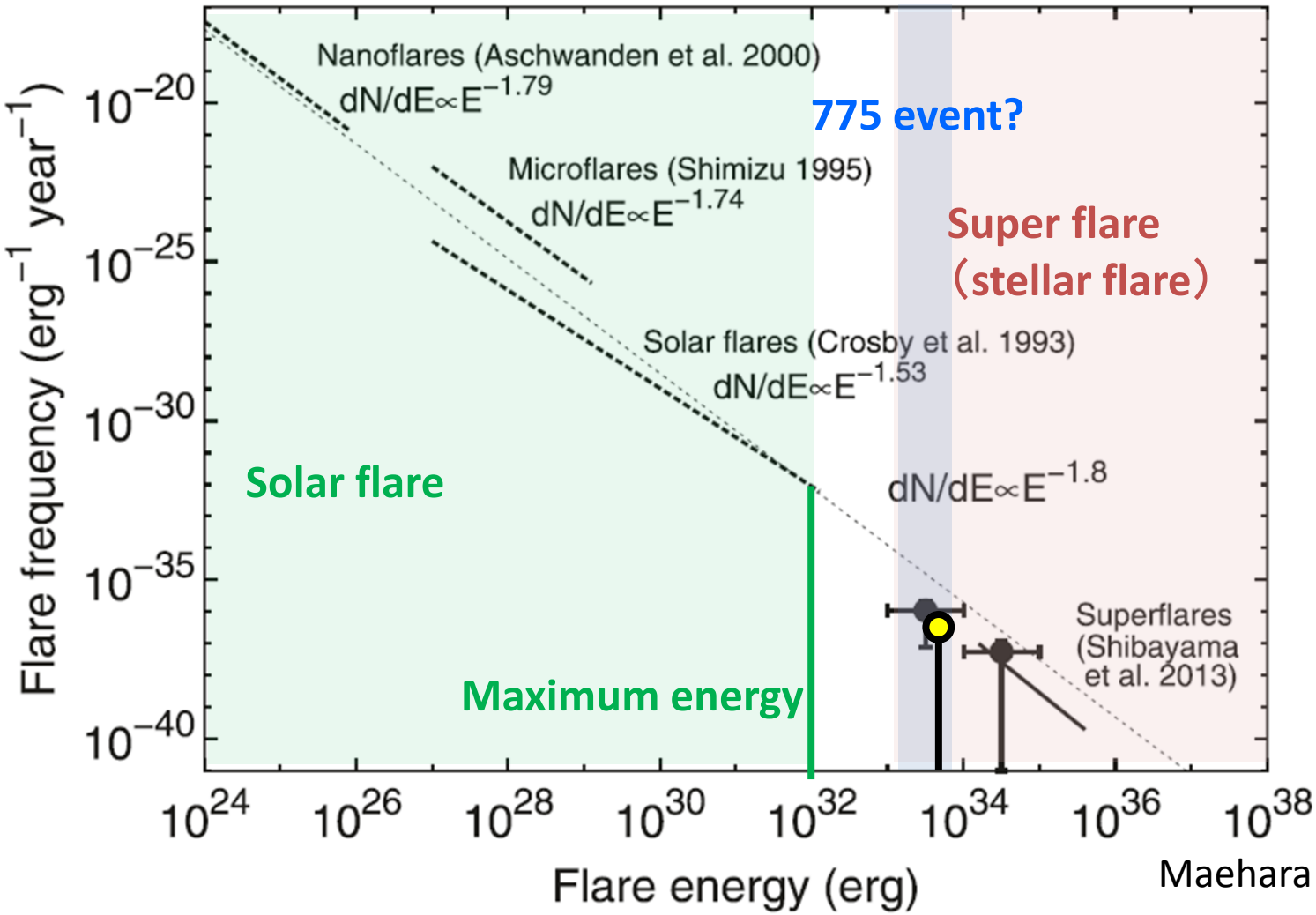
Clear ^{10}Be & ^{36}Cl increases (Greenland ice cores)



- Explained by SEP event (hard energy spectrum)
- Longer increase time of ^{14}C data reflects several SEP events?

O'Hare et al. 2019

Occurrence rate & energy distribution of solar flare



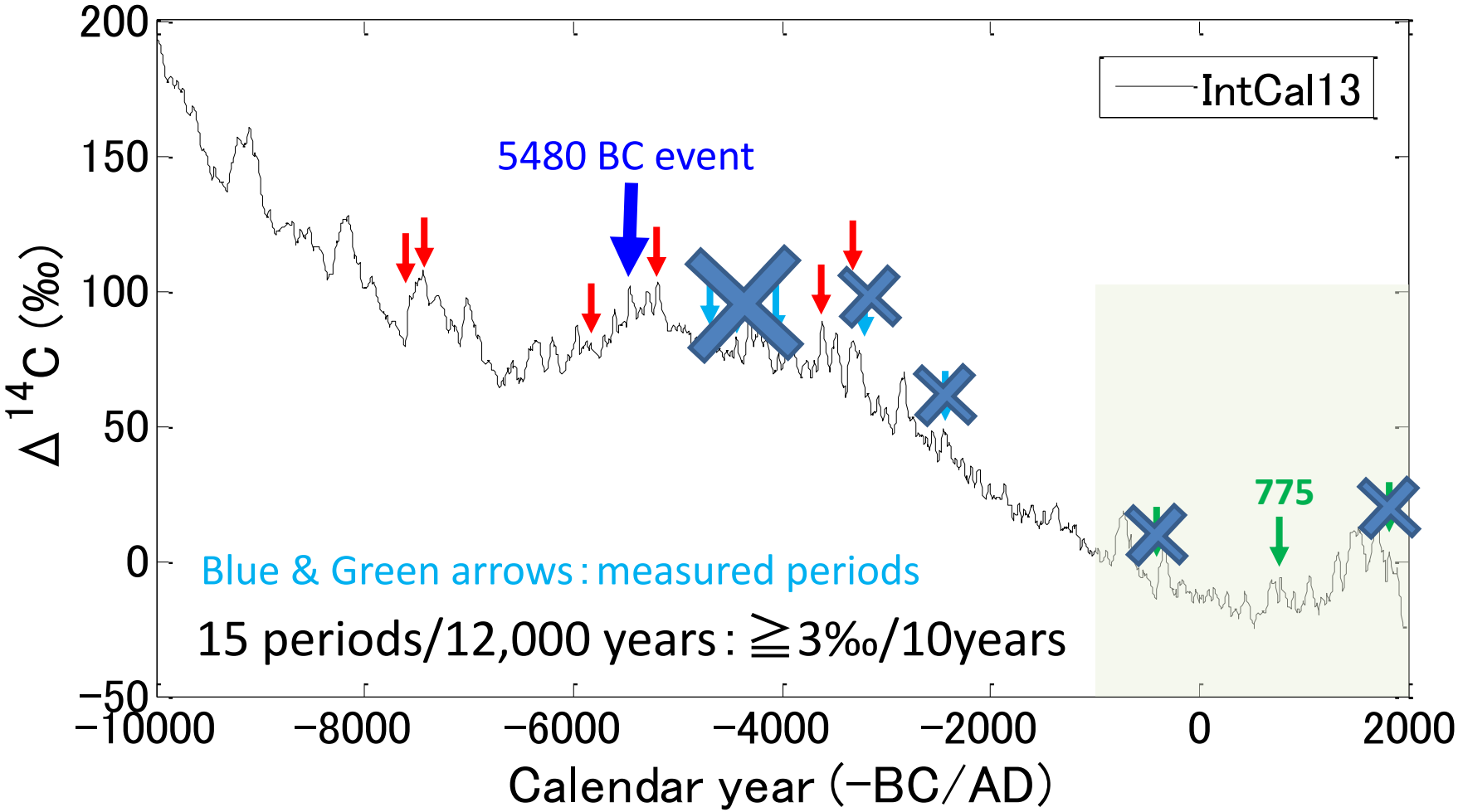
Maehara et al. 2015

- Assumptions:
  - Flare scale of detected SEP events: ~50 × maximum solar flare (10^{32} erg)
  - Event rate: 3/2200 years

Survey for longer periods:

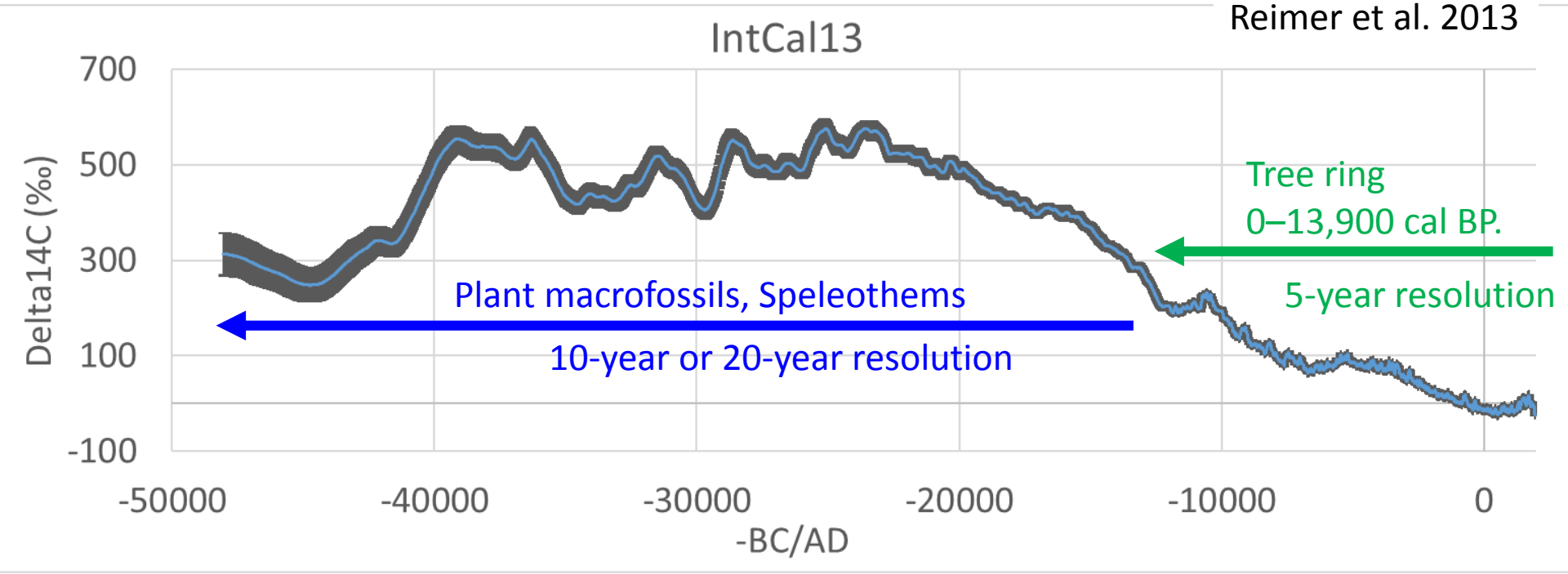
1. Holocene: largest event comparable to 775 event
2. Past ~50,000 years

Search for the largest event ~775 event



- 9 periods/15 periods ---> Annual measurement
- **7 periods are not rapid changes→775 event: Rare & The largest**
- 5480 BC event: 20‰ increase/10years (Miyake+2017)

How about past 50,000 years?



- Before 13900 cal BP: resolution and data condition is not same as tree rings →Difficult to directly compare with tree-ring dataset
- Increase rate (point-point) before 13,900 cal BP: <5‰/20years
  →maximum annual increase: ~100‰ <10 × 775 event
- Future investigation using cosmogenic nuclides with high precision

Summary

- Continuous ^{14}C data for most of the past 3000 years
- The 775 event is the largest /~3,000years (even /12,000 years?)
- Occurrence rate of ^{14}C events ~3/2200 years
- Longer increase event(s):
  Relate to several SPEs occurred in a few years?
  →Further confirmations (e.g. high-res. ^{10}Be&^{36}Cl measurement)

Future work

- Collect more ^{14}C data to define more accurate occurrence rate
  →More accurate occurrence rate (~775 event scale)
- Detection of smaller scale events
- More study for the 775 event (event scale, energy spectrum…)
- SEP event vs solar flare (also geomagnetic storm)?