A signature of cosmic-ray increase in AD774-775 from tree rings in Japan

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LETTER

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A signature of cosmic-ray increase in AD 774–775 from tree rings in Japan

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Increases in ^{14}C concentrations in tree rings could be attributed to cosmic-ray events[1–7], as have increases in ^{10}Be and nitrate in ice cores[8,9]. The record of the past 3,000 years in the IntCal09 data set[10], which is a time series at 5-year intervals describing the ^{14}C content of trees over a period of approximately 10,000 years, shows three periods during which ^{14}C increased at a rate greater than 3‰ over 10 years. Two of these periods have been measured at high time resolution, but neither showed increases on a timescale of about 1 year (refs 11 and 12). Here we report ^{14}C measurements in annual rings of Japanese cedar trees from AD 750 to AD 820 (the remaining period), with 1- and 2-year resolution. We find a rapid increase of about 12‰ in the ^{14}C content from AD 774 to 775, which is about 20 times larger than the change attributed to ordinary solar modulation. When averaged over 10 years, the data are consistent with the decadal IntCal ^{14}C data from North American and European trees[13]. We argue that neither a solar flare nor a local supernova is likely to have been responsible.

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A signature of cosmic-ray increase in AD774-775 from tree rings in Japan

日本産樹木年輪中の西暦774-775年における宇宙線増加の痕跡

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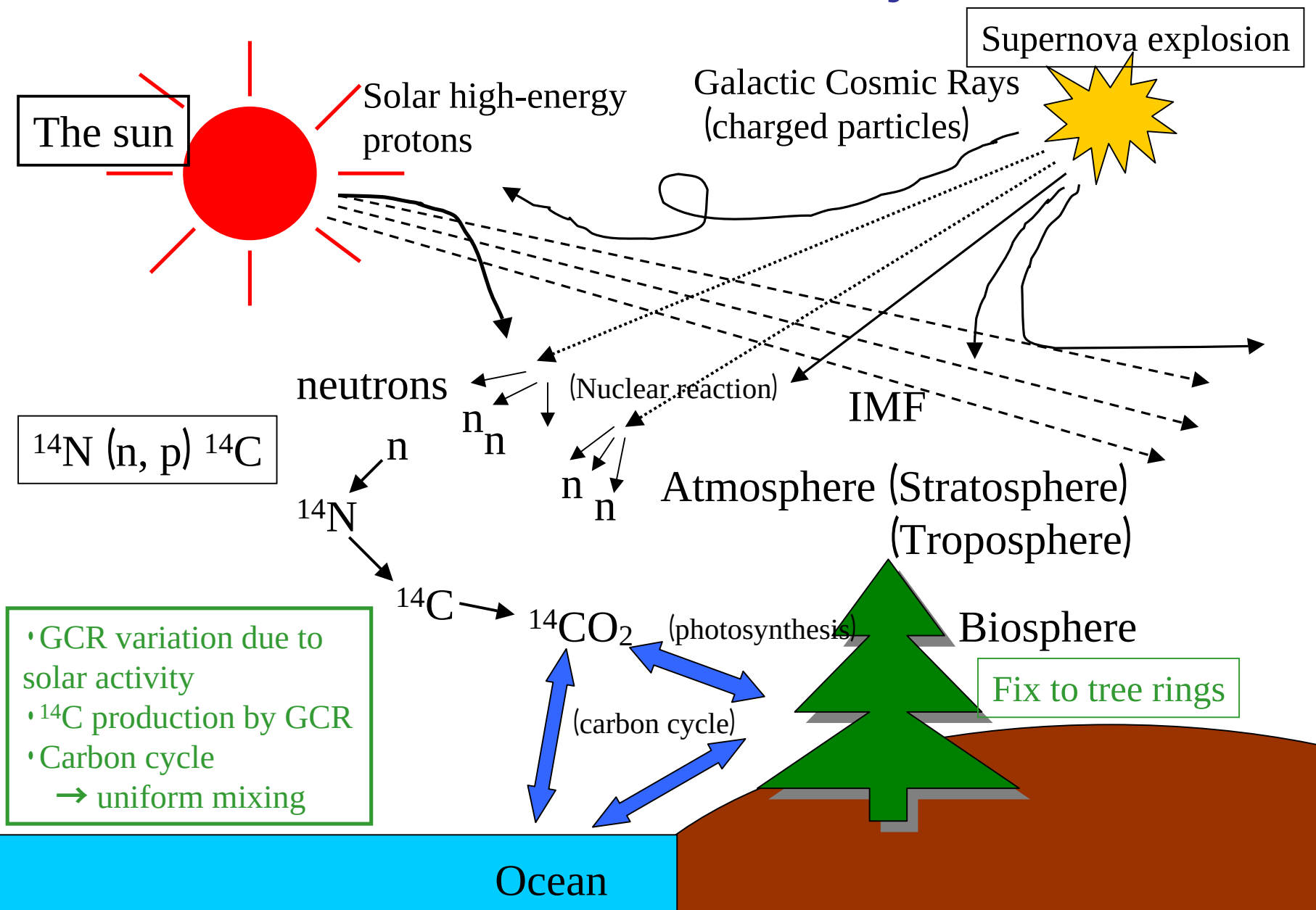
Meaning of ^{14}C measurement

- ^{14}C is produced by cosmic-rays in the upper atmosphere of the Earth. The cosmic-rays travels the heliosphere under the solar influence of interplanetary magnetic field. Therefore, the variation of ^{14}C content at a certain time in the past reflects the change of cosmic-ray intensity and therefore solar activity at the time.

Production of ^{14}C and carbon cycle



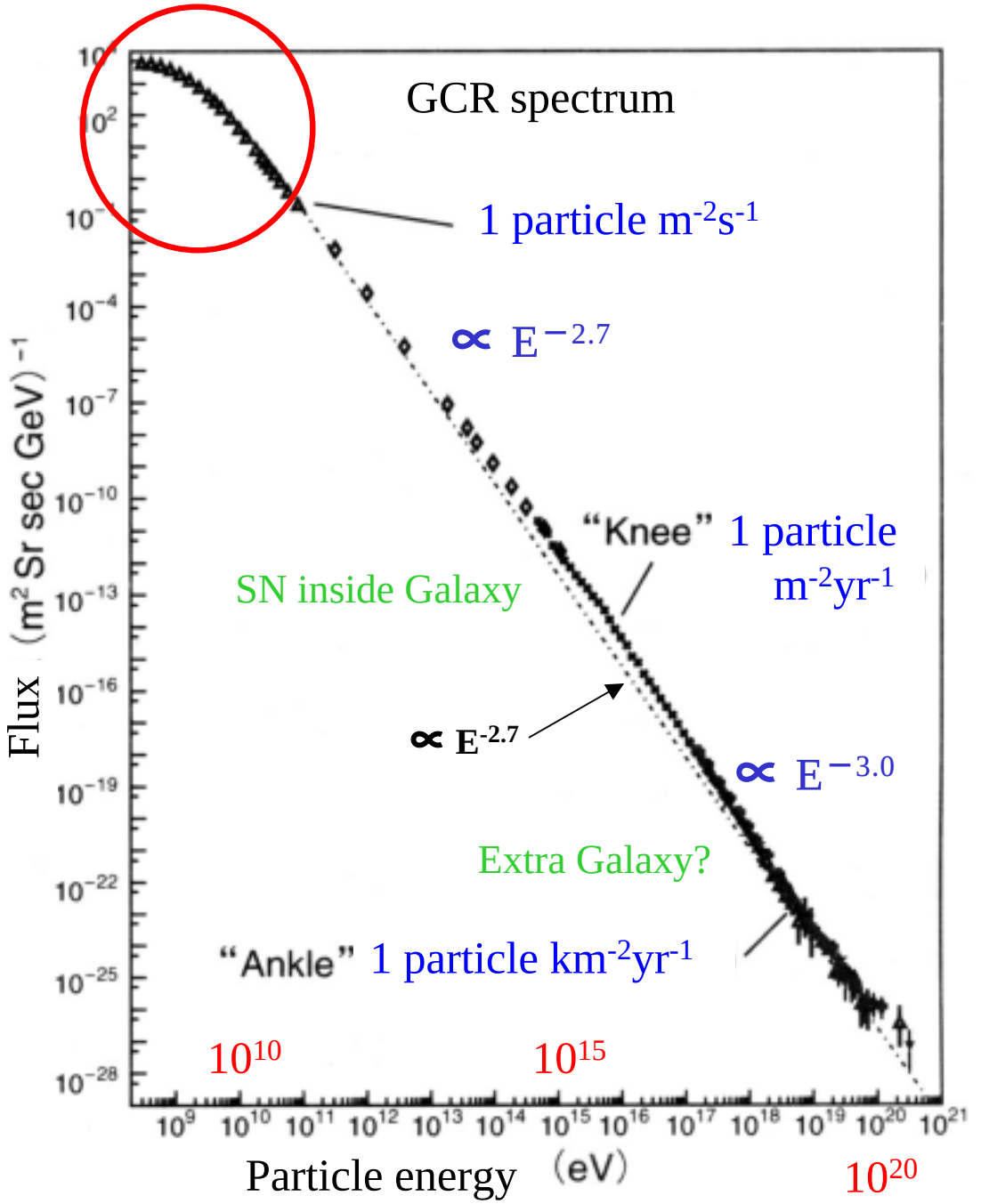
- GCR variation due to solar activity
- ^{14}C production by GCR
- Carbon cycle
  → uniform mixing

Energy spectrum of Galactic Cosmic Ray

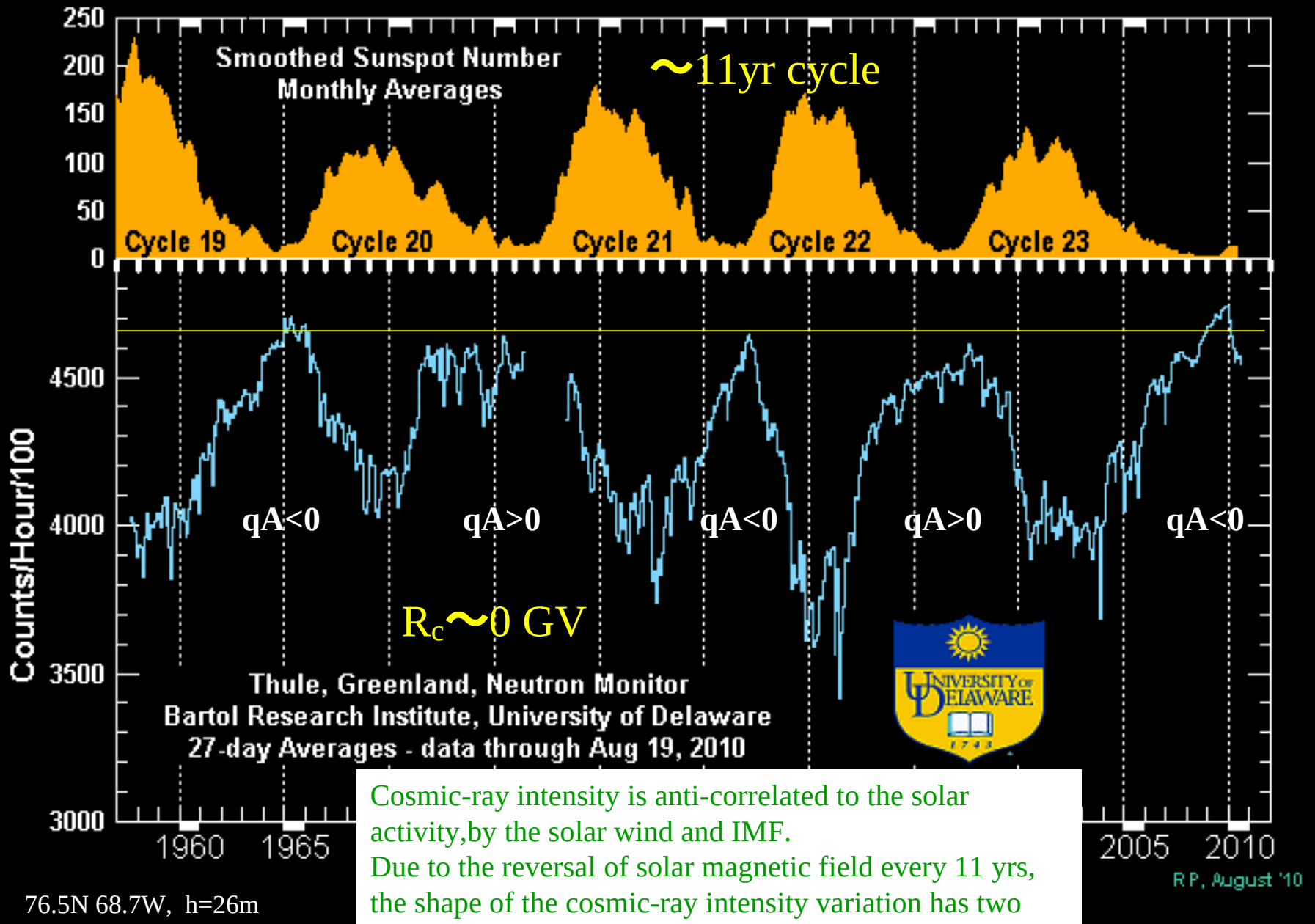
- -2.7th power of energy
- Knee $10^{15\text{-}16}$ eV
- Ankle $10^{18\text{-}19}$ eV
- Highest energy
  $> 10^{20}$ eV
  [10^{20} eV = 16 J = 4 cal]

- **Solar modulation**
  $< 10^{10}$ eV

- Only low energy CRs less than **10^{10} eV/n** are affected by solar activity



Thule (Greenland) Neutron Monitor 1957-2010



Cosmic-ray intensity is anti-correlated to the solar activity,by the solar wind and IMF.
Due to the reversal of solar magnetic field every 11 yrs, the shape of the cosmic-ray intensity variation has two

Nucleon production rate in the atmosphere

Masarik, 1999

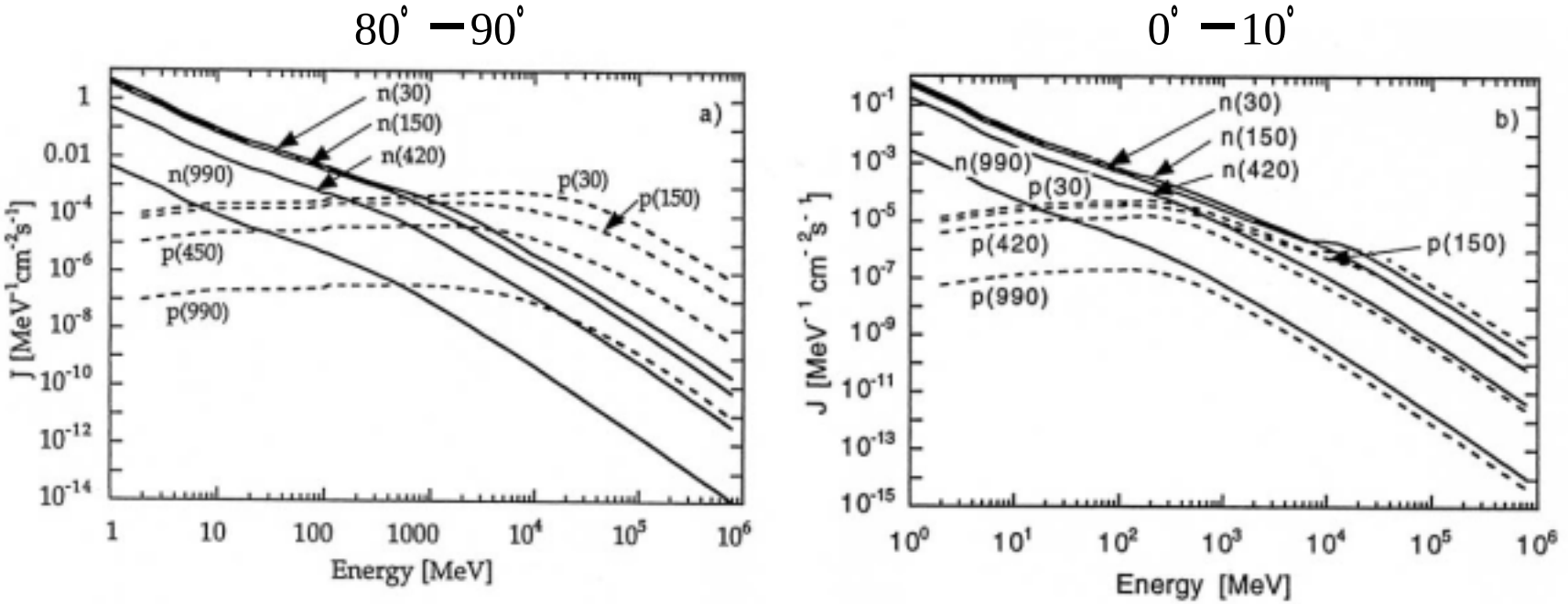


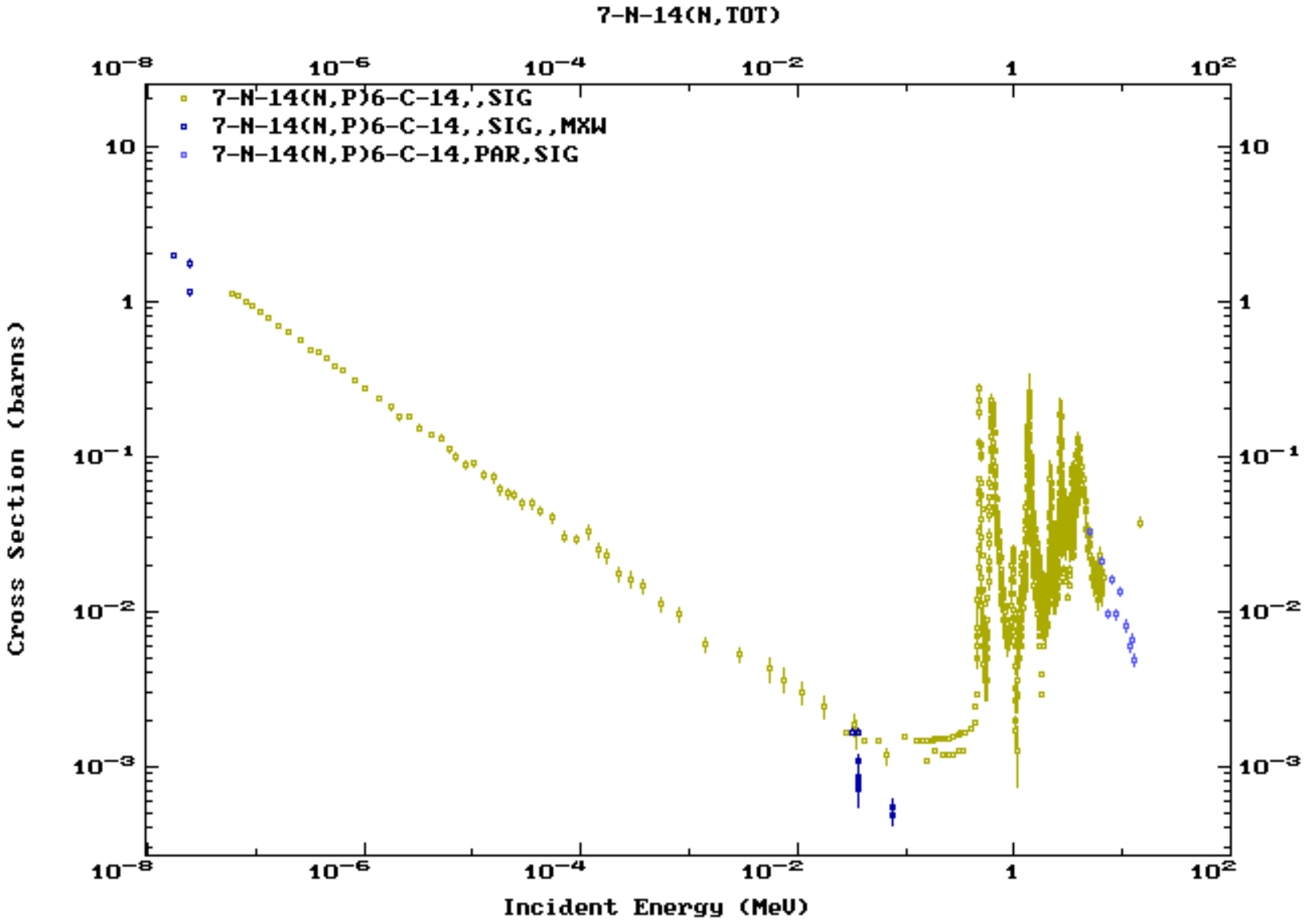
Figure 4. Differential neutron and proton fluxes in the Earth's atmosphere for the solar modulation parameter ϕ = 550 MeV, for four depths (30, 150, 420 and 990 g cm^{-2}) and for latitudes (a) 80° - 90°.and (b) 0° - 10°.

( ) is for atmospheric depth in g cm^{-2} .

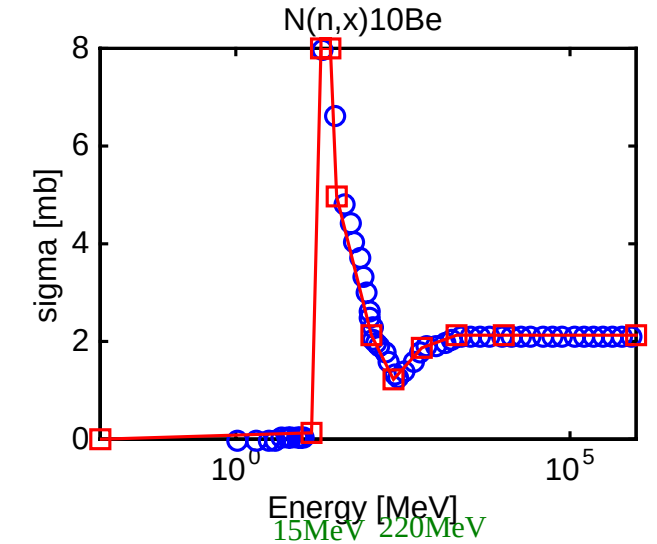
Modulation parameter for the solar activity ϕ is 550 MeV.

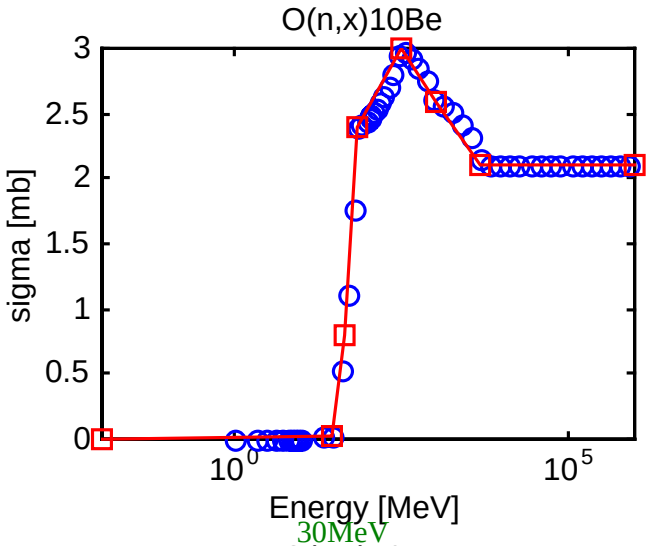
Calculation using GEANT+MCNP

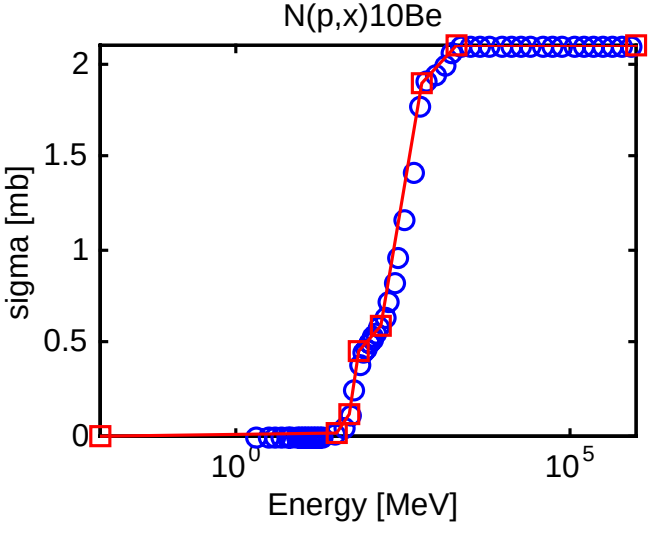
IAEA EXFOR ^{14}N (n, p) ^{14}C

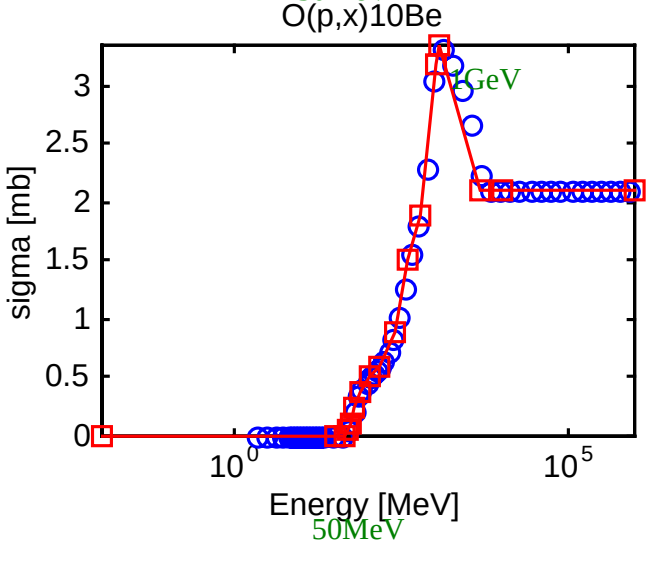


Cross section of ^{10}Be production (near threshold)





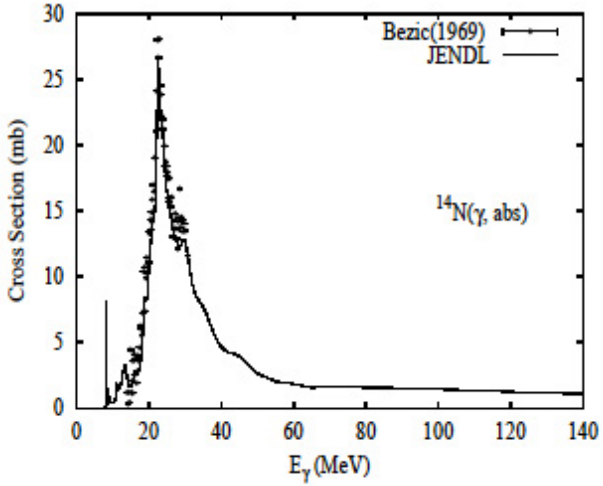


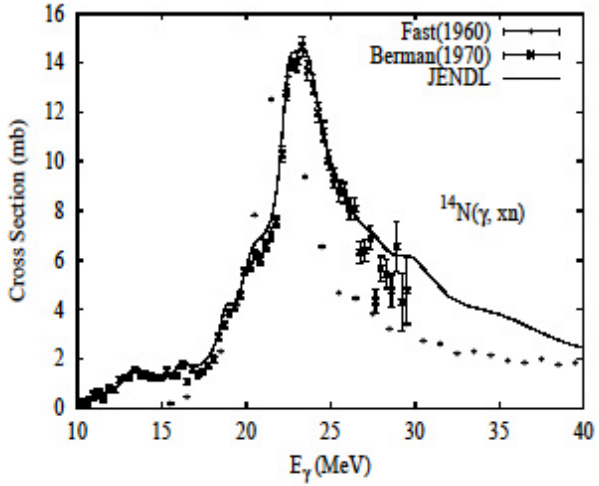


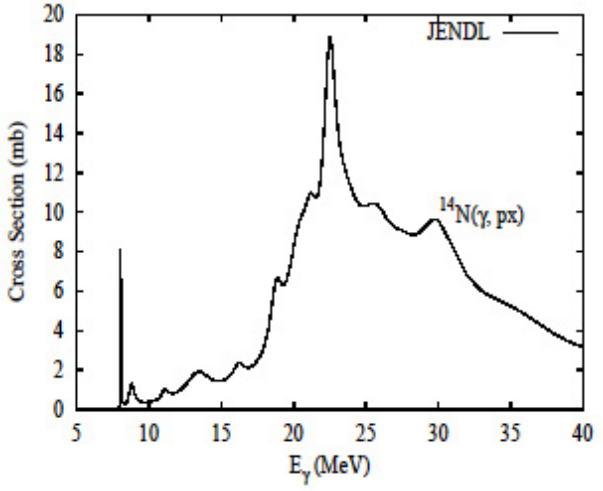
Red: experiment, Blue: calculation

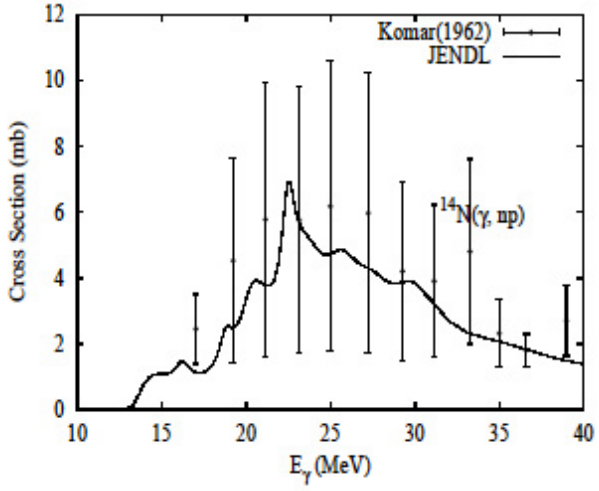
$\gamma + {}^{14}\mathrm{N}$

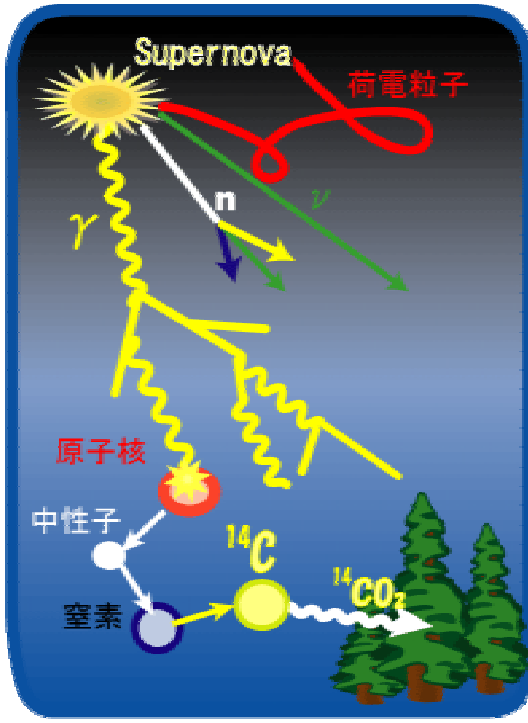
Abundance (%)	Threshold Energies (MeV)								
	γ,n	γ,p	γ,t	γ,He-3	γ,α	γ,2n	γ,np	γ,2p	γ,3n
99.63	10.55	7.55	22.74	20.74	11.61	30.62	12.50	25.08	46.24



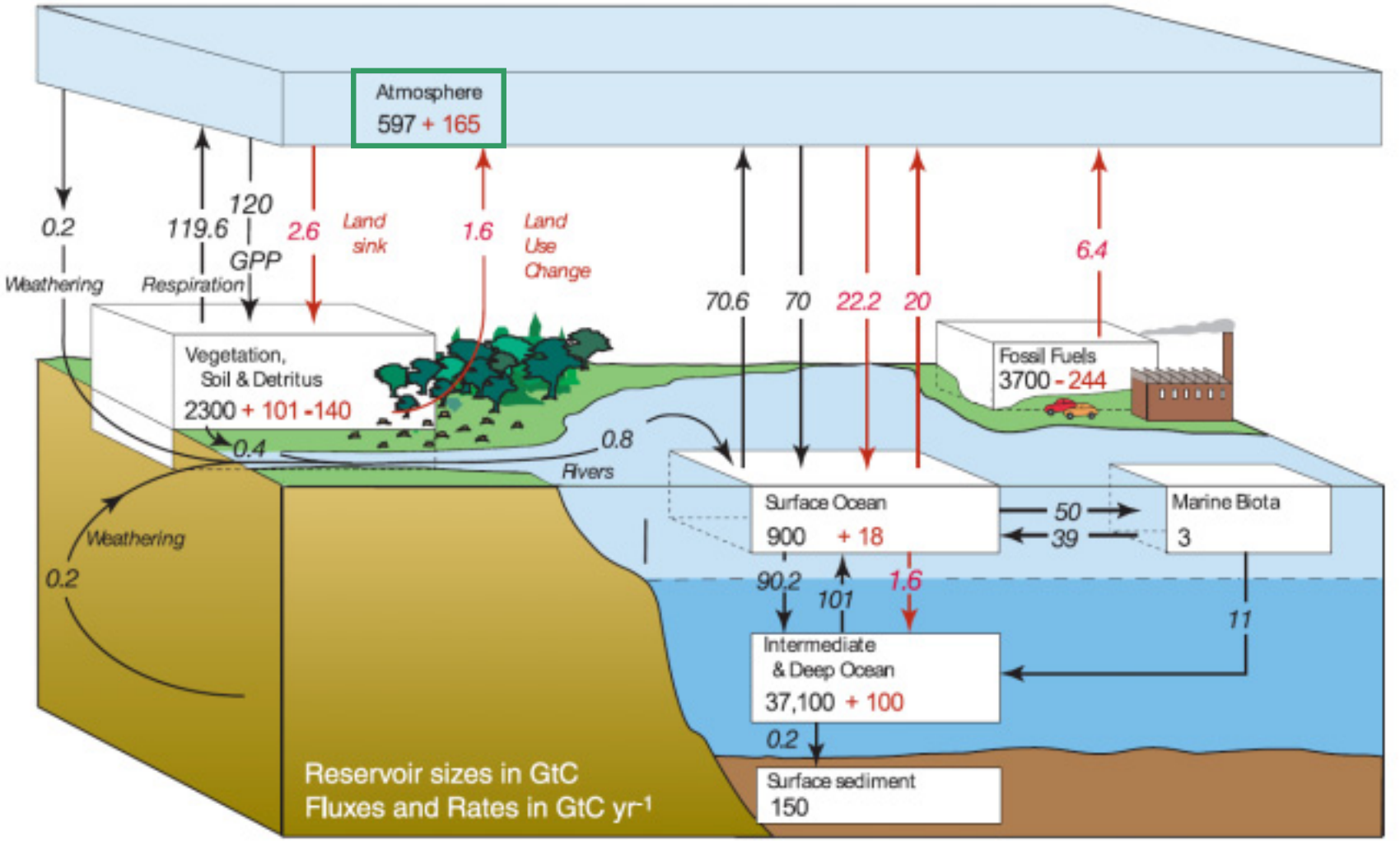








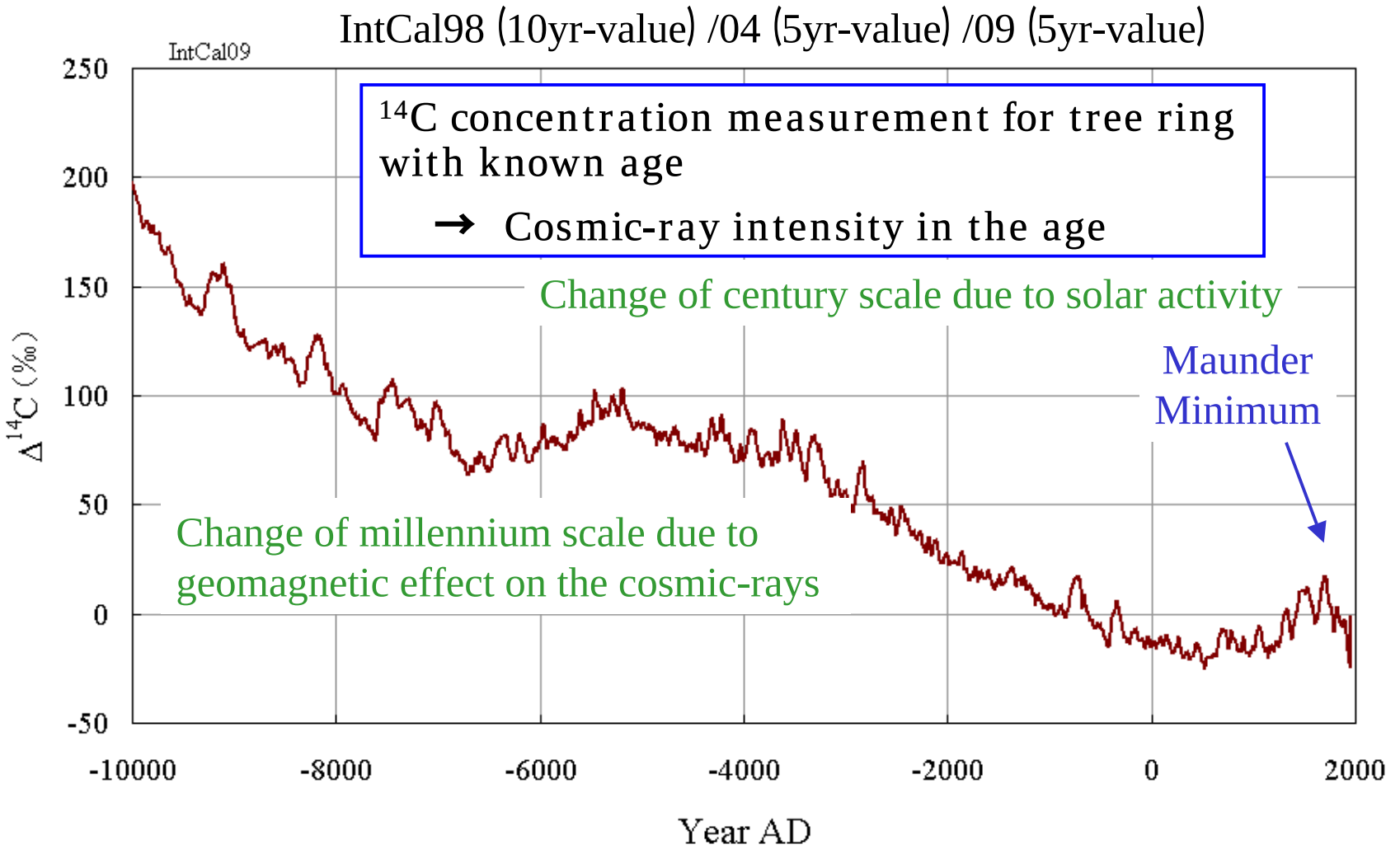
Global carbon cycle and reservoir



Atmospheric ^{14}C moves to ocean and plant and changes are damped and delayed

IPCC2007

IntCal09 calibration curve for ^{14}C in the past 12,000 years

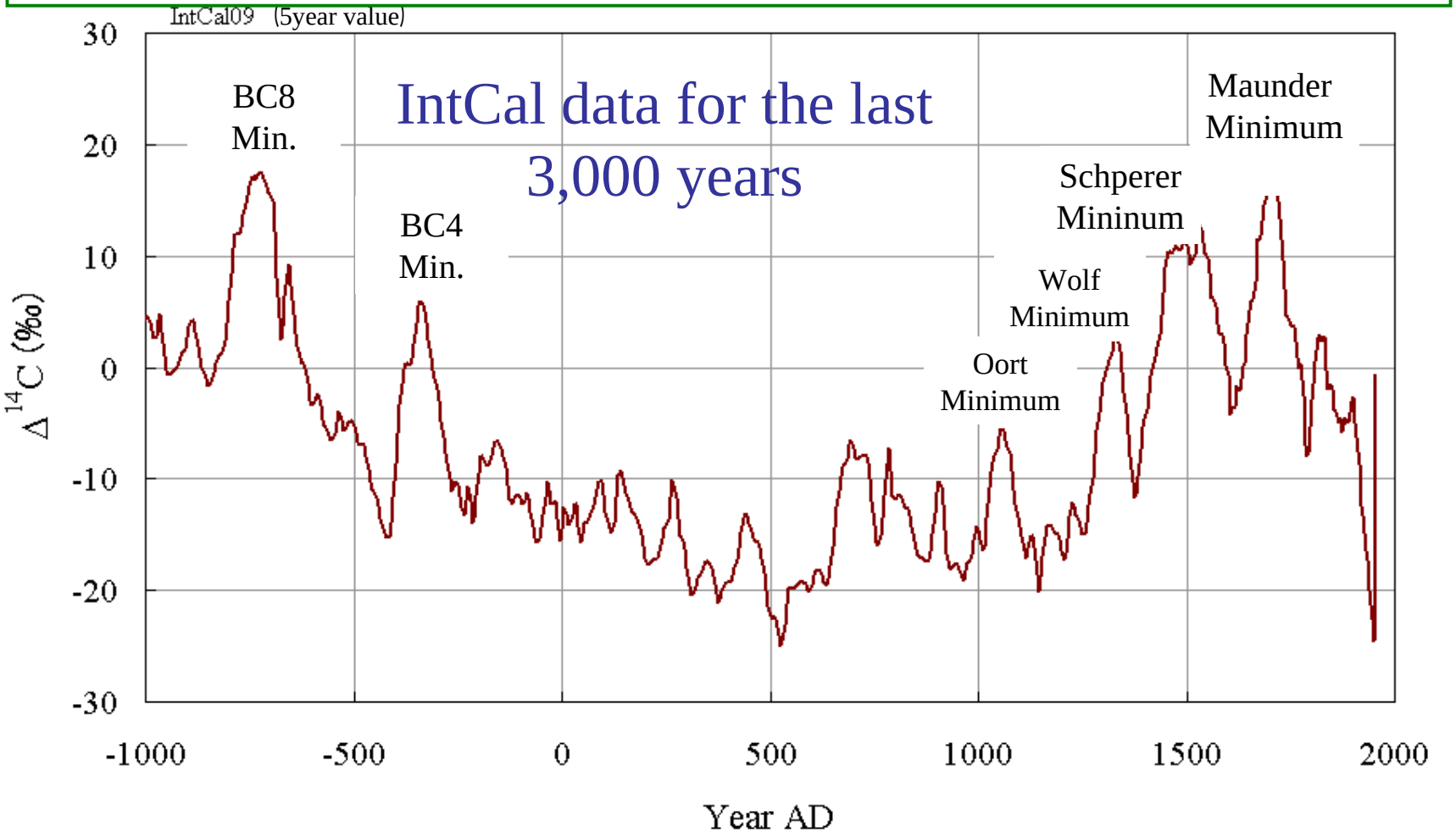


AD775 event

F. Miyake *et al.*

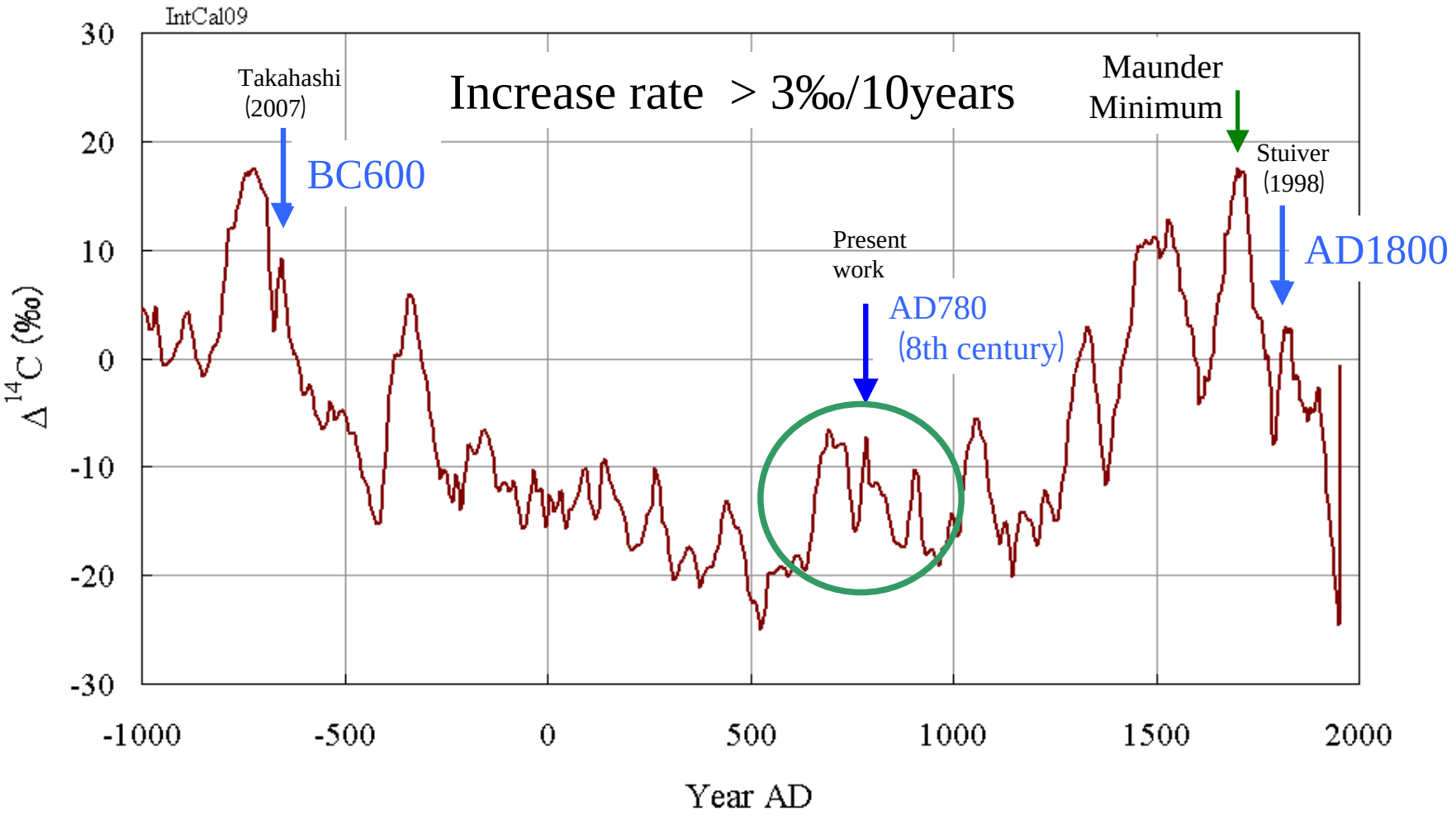
Nature 486 (2012) 240-242

Present study： To search for and investigate rapid increase of ^{14}C content and clarify the change of cosmic-ray environment for the past 3,000 years



Rapid increase in ^{14}C for the past 3,000 years

(three rapid increases (blue arrows) → done for the two)



Tree ring sample from the 8th century

Measured samples (single-year ring)

Tree-A Yakusugi (Nagoya Univ.)

Series 1: AD750-820 every-other-year

Series 2: AD774-780 every year

Tree-B Yakusugi (Fukushima Univ.)

Series 3: AD770-779 every year

Measurement of ^{14}C concentration

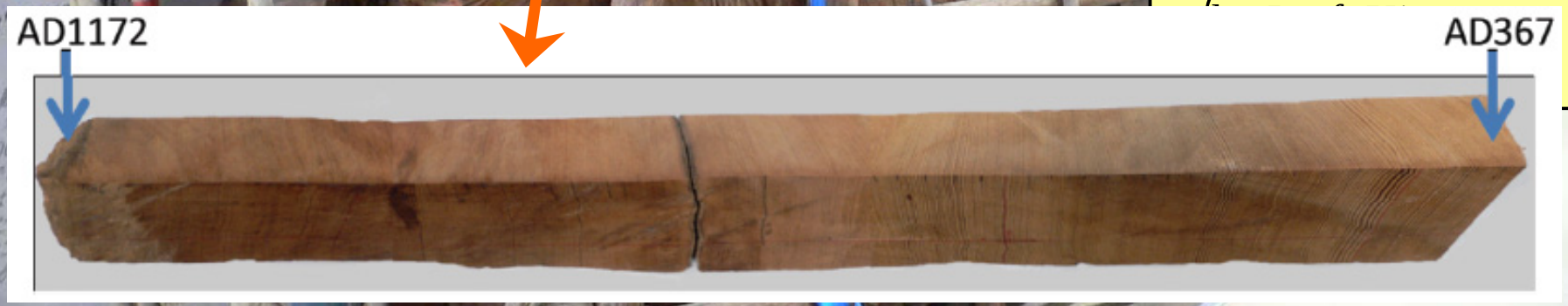
Accelerator mass spectrometer (AMS)

@Center for Chronological Research, Nagoya Univ.

Yakusugi: Long-lived Japanese cedar tree, which grew in Yaku Island of southern Japan

Yakusugi

- Daiameter 1.9 m
- Thickness 30 cm
- Tree age 1900 years
- Remaining rings
  AD97-1551
- Growing place:
  Ishizuka, Kamiyaku-cho, Yaku Island
- Cut in AD1956
- Transported to Nagoya in AD1995
- Dating:
  Dendrochronology

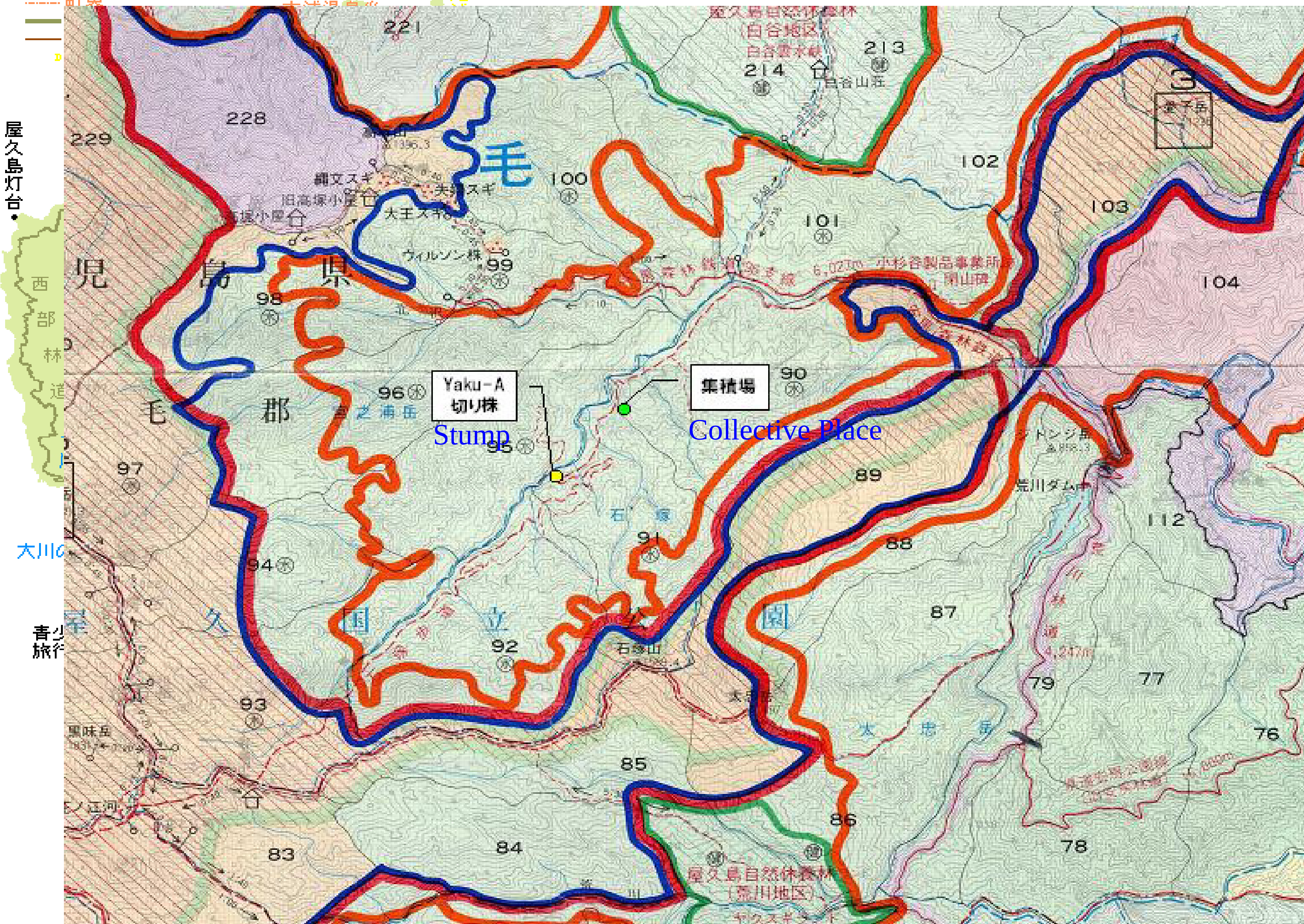


Growing place of the Yakusugi

Ishizuka, Kamiyaku-cho, Yaku Island

Dec. 2004

Yaku Island



Yaku-A
切り株
Stump
集積場
Collective Place
屋久島灯台
縄文スギ
大王スギ
ウィルソン株
毛
児
島
県
郡
国
立
公
園
屋久島自然休養林
白谷地区
荒川地区
白谷山荘
荒川ダム
石塚山
大川の
青少
旅行
西
部
林
道
221
228
229
213
214
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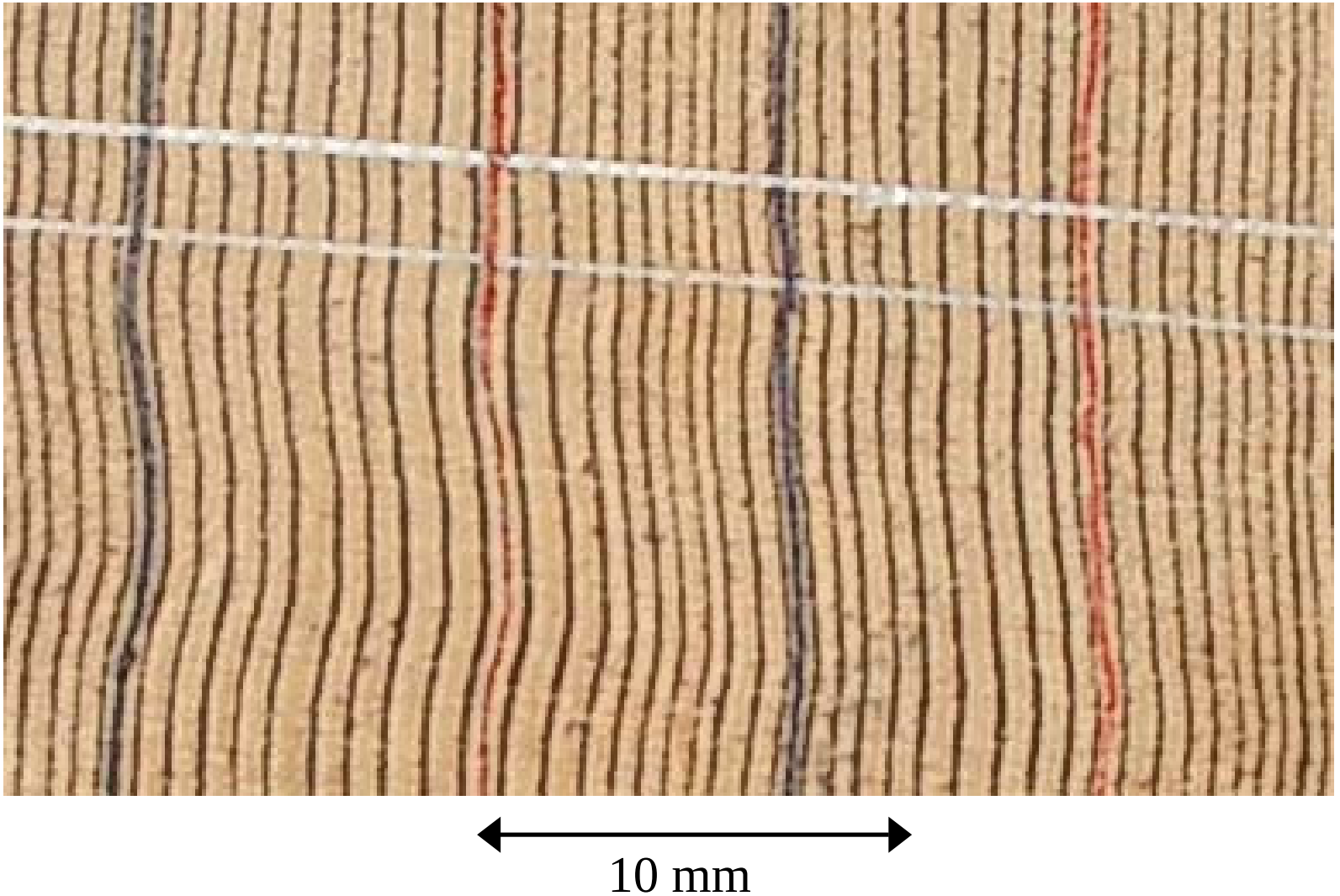
112
3

Stump of the Yakusugi used for this study

Disk of the Yakusugi (identical disk)

Ring pattern of the Yakusugi



Sample preparation
(by F. Miyake)
@^{14}C lab., STEL

Measured samples

← Cutting out of each ring

Acid・alkali treatments
Removal of lignin
Extraction of cellulose
Conversion to CO_2

← CO_2 purification
(Vacuum and cryogenic trap)

Reduction to graphite
Target for AMS

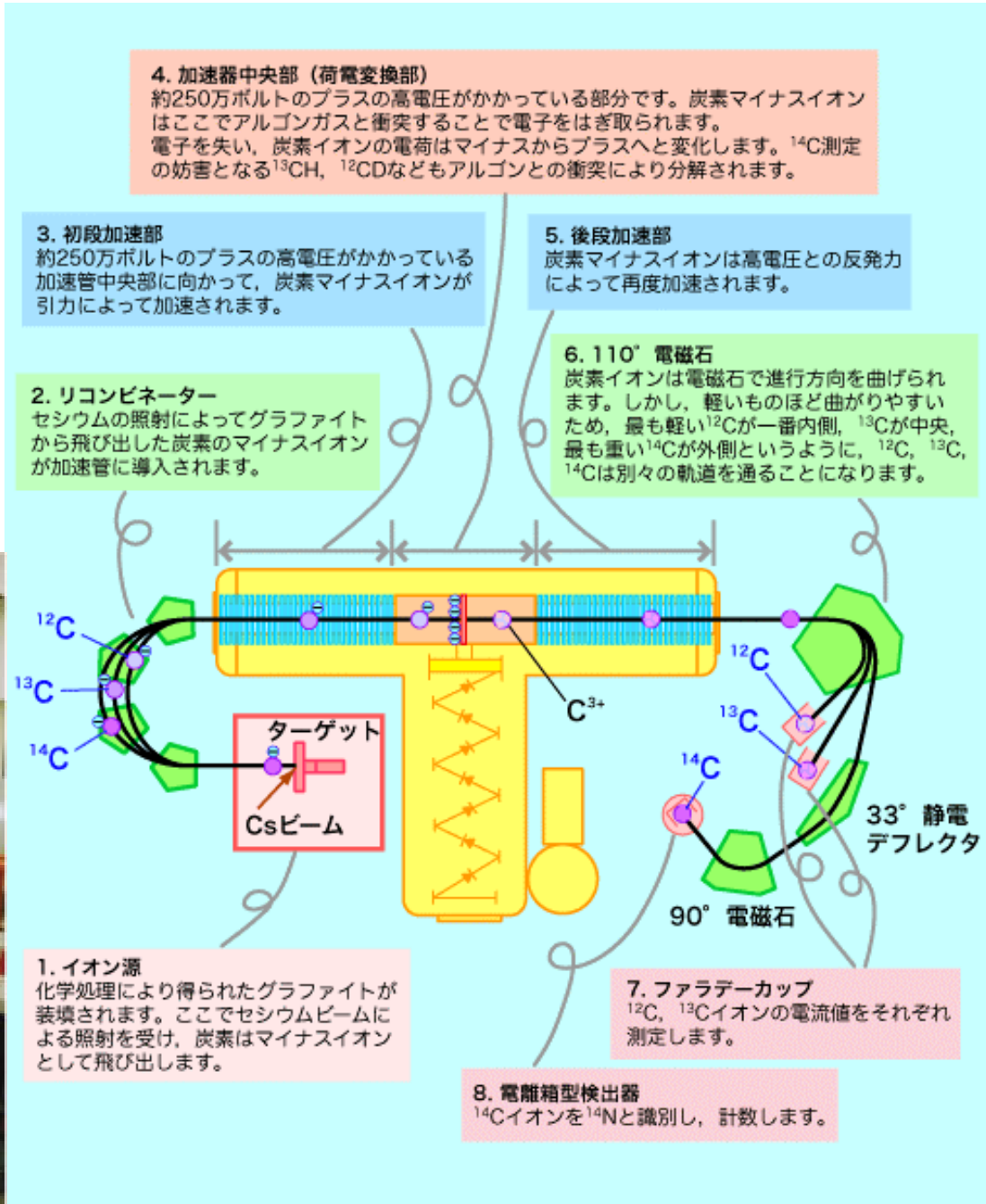
年測センターHPより

Accelerator mass spectrometer (AMS)

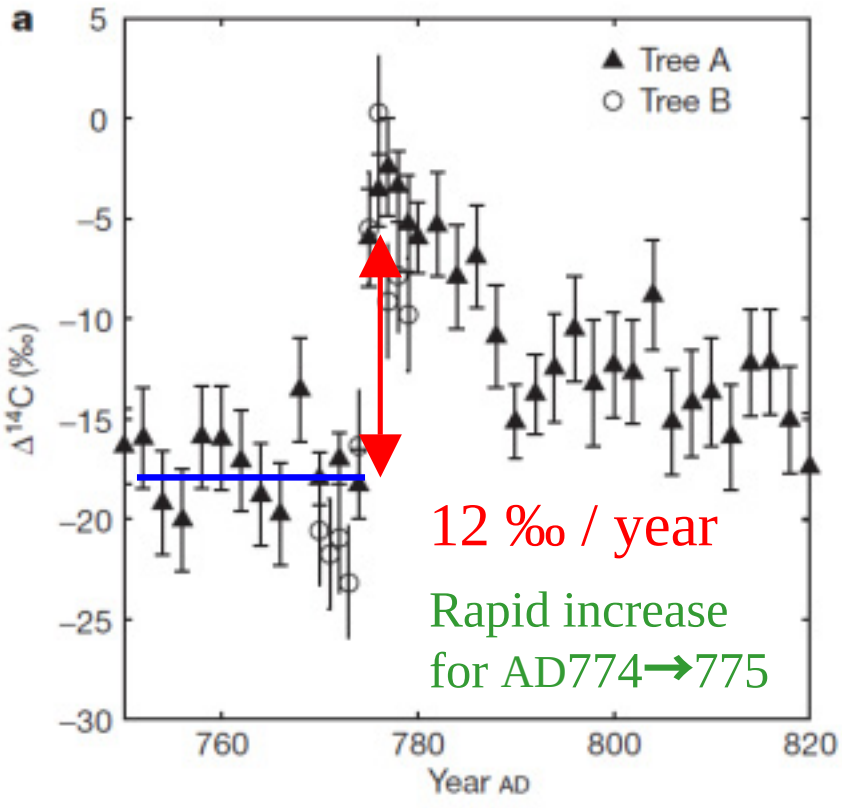
Center for Chronological Research

Comparing with the standards sample, express $^{14}C/^{12}C$ ratio as $\Delta^{14}C$ (‰)

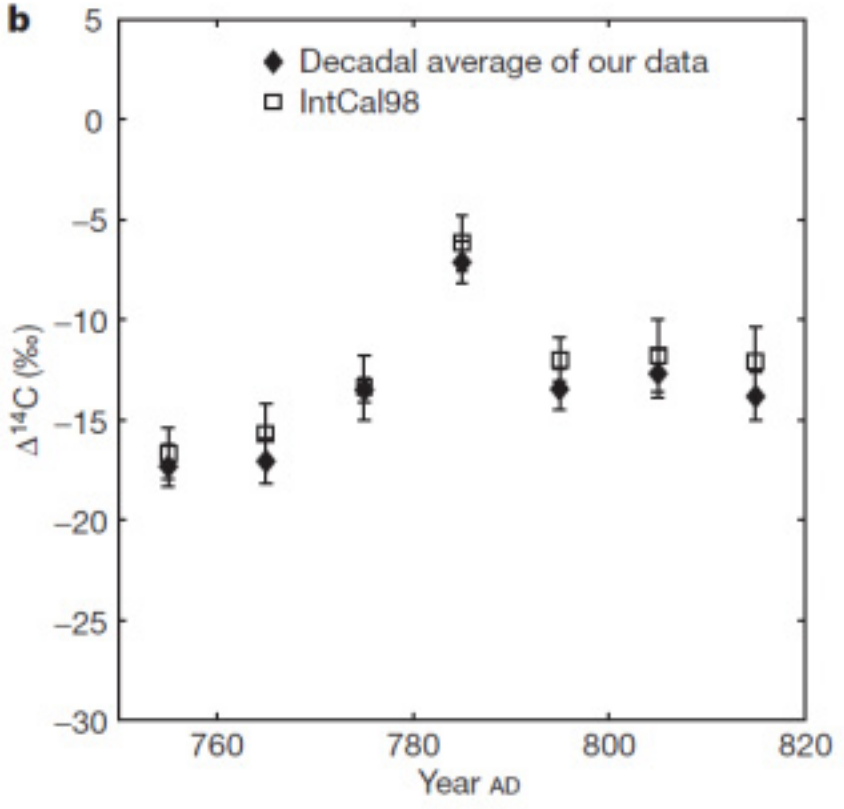
[Single measurement error ～2.6‰]



Result：^{14}C increase（single year, decadal）

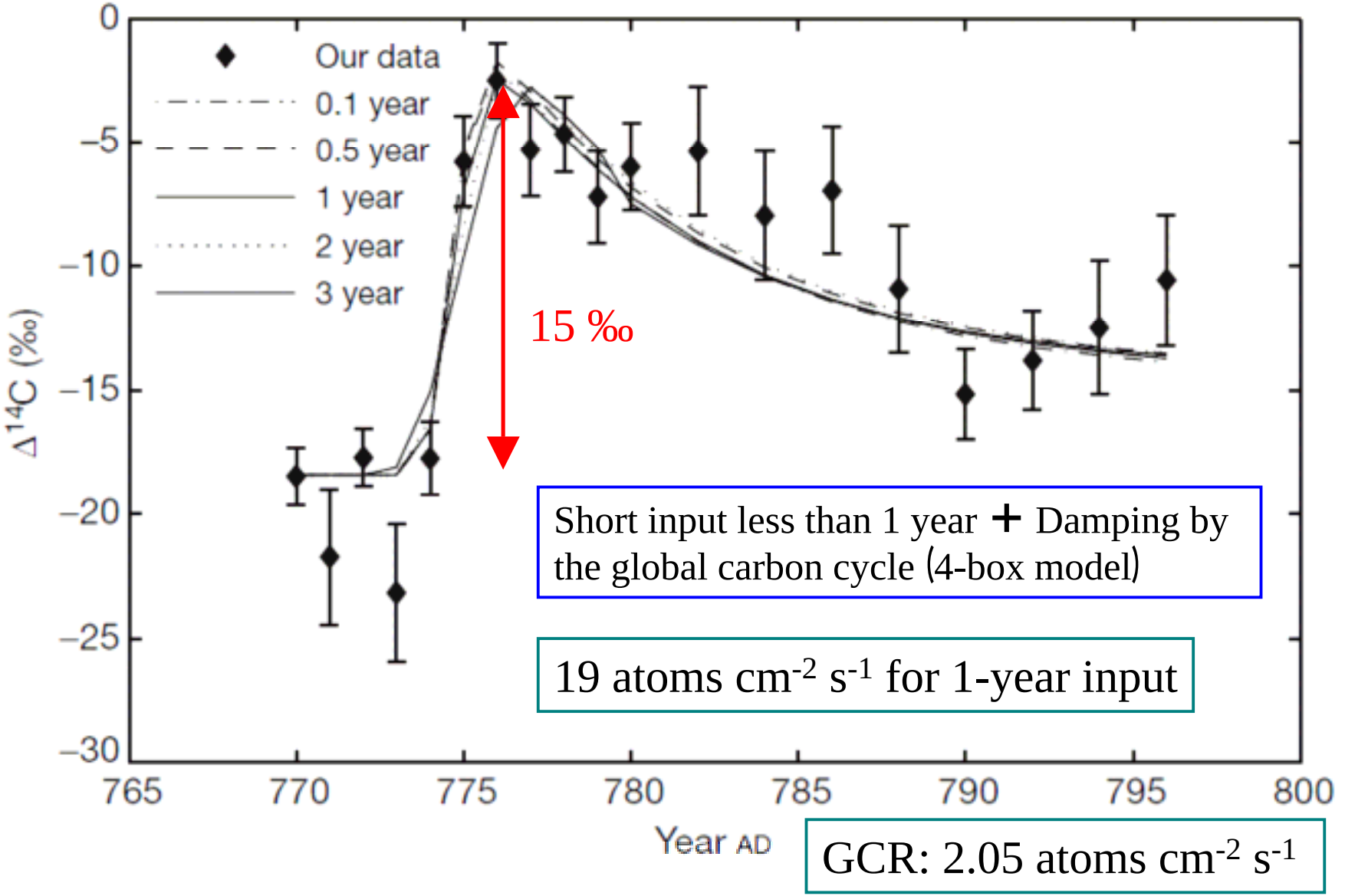


a) Variation of ^{14}C concentration
（1-2 year value）



b) Variation of ^{14}C concentration
（decadal mean） and
comparison with IntCal

Response of ^{14}C content for input period of cosmic rays

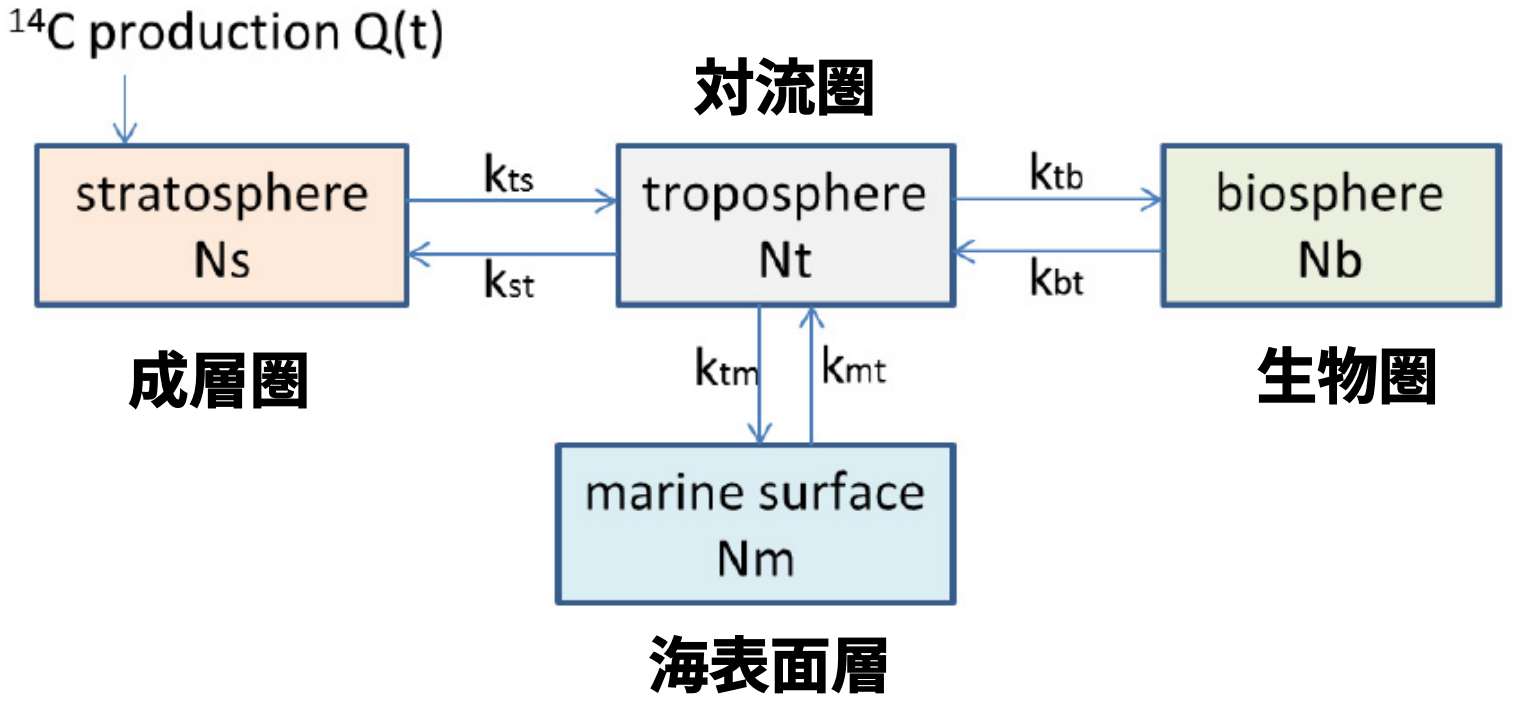


Short input less than 1 year + Damping by the global carbon cycle (4-box model)

19 atoms cm^{-2} s^{-1} for 1-year input

GCR: 2.05 atoms cm^{-2} s^{-1}

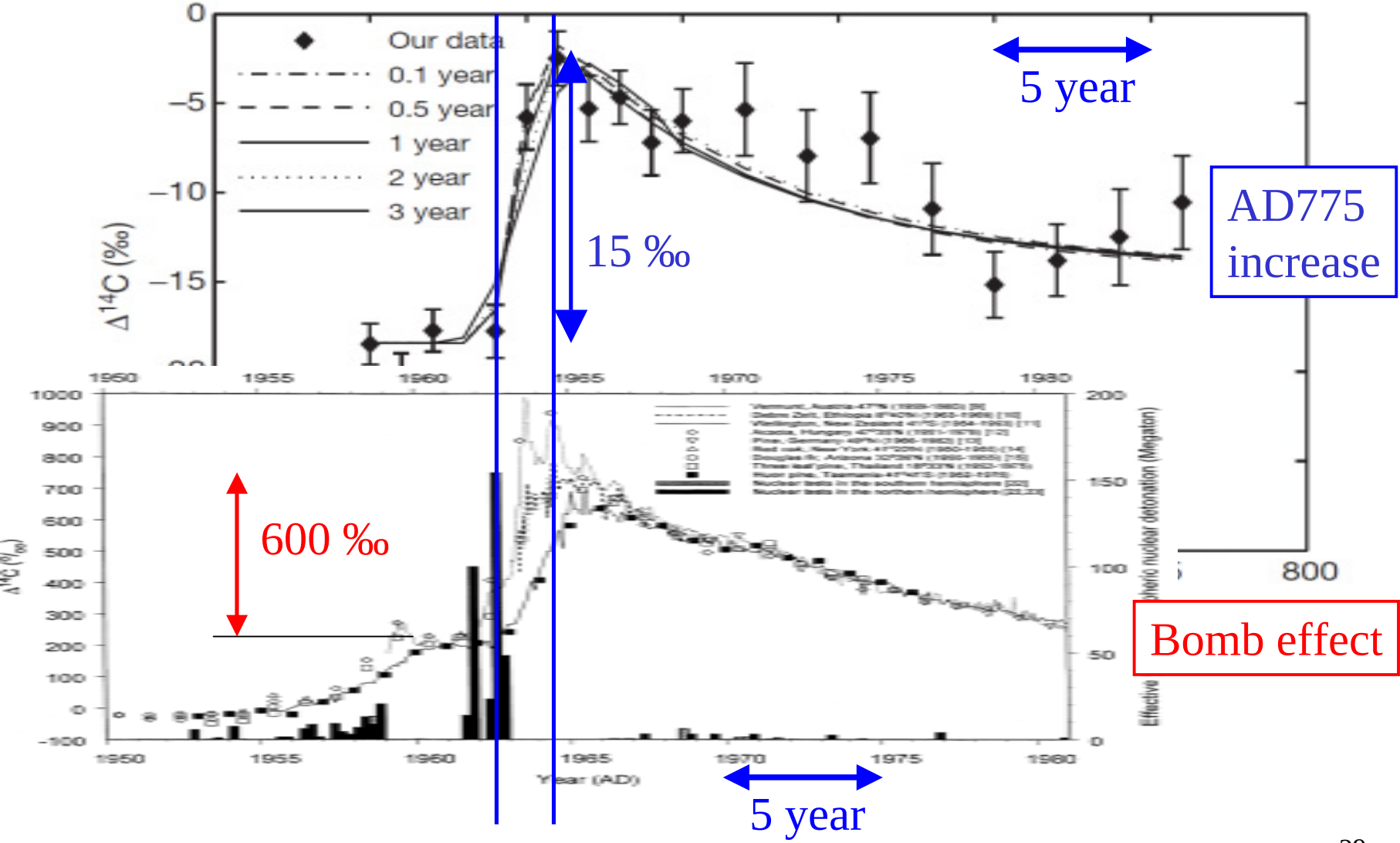
A model of the global carbon cycle (4-box model)



k_{ts} =1/3 [1/yr], k_{tb} =1/23 [1/yr], k_{tm} =1/11 [1/yr],
N_s/N_a = 0.15, N_t/N_a = 0.85, N_b/N_a = 2.52, N_m/N_a = 2,
$N_a = N_t + N_s$.

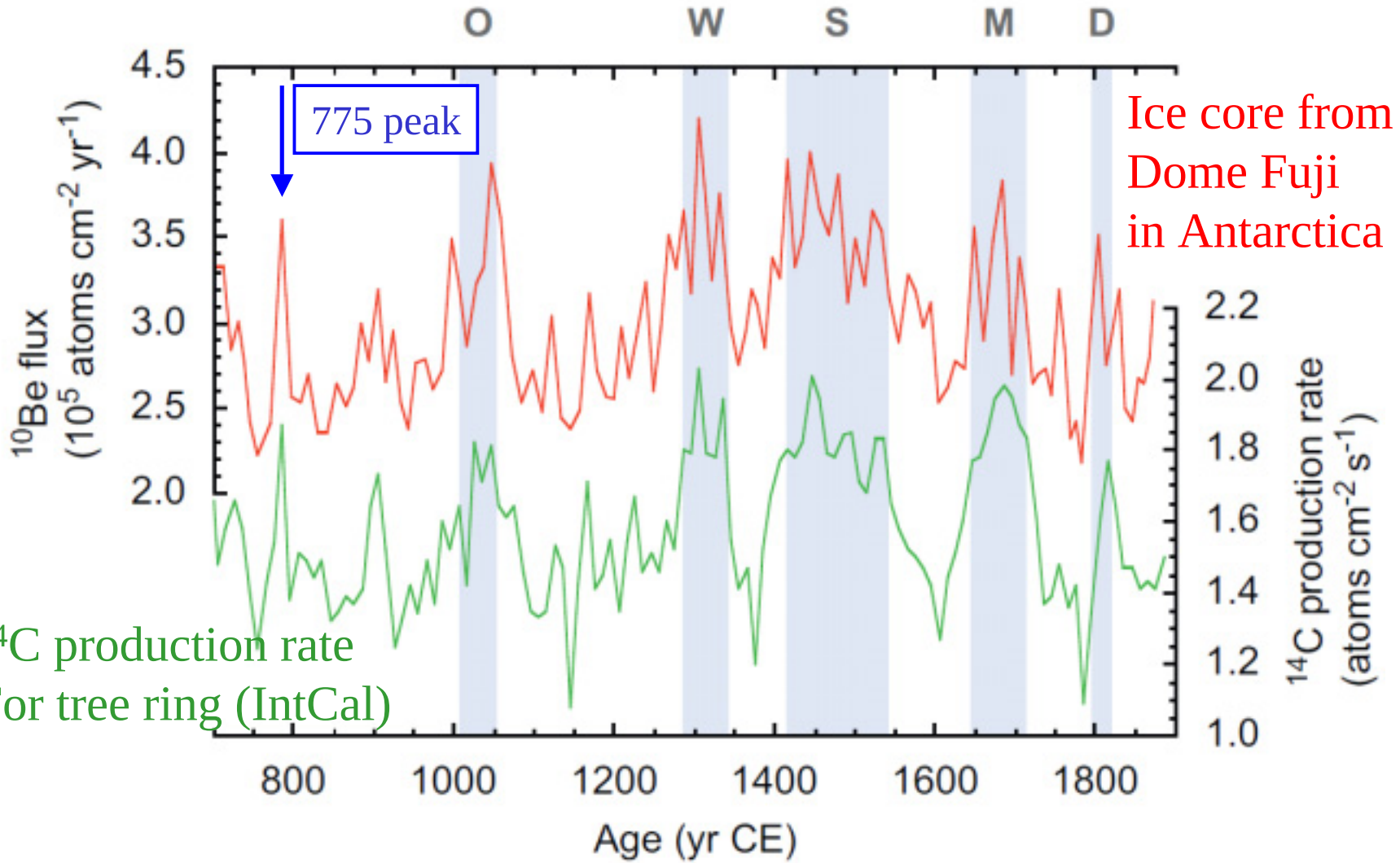
Nakamura, 1987

Comparison with Bomb effect

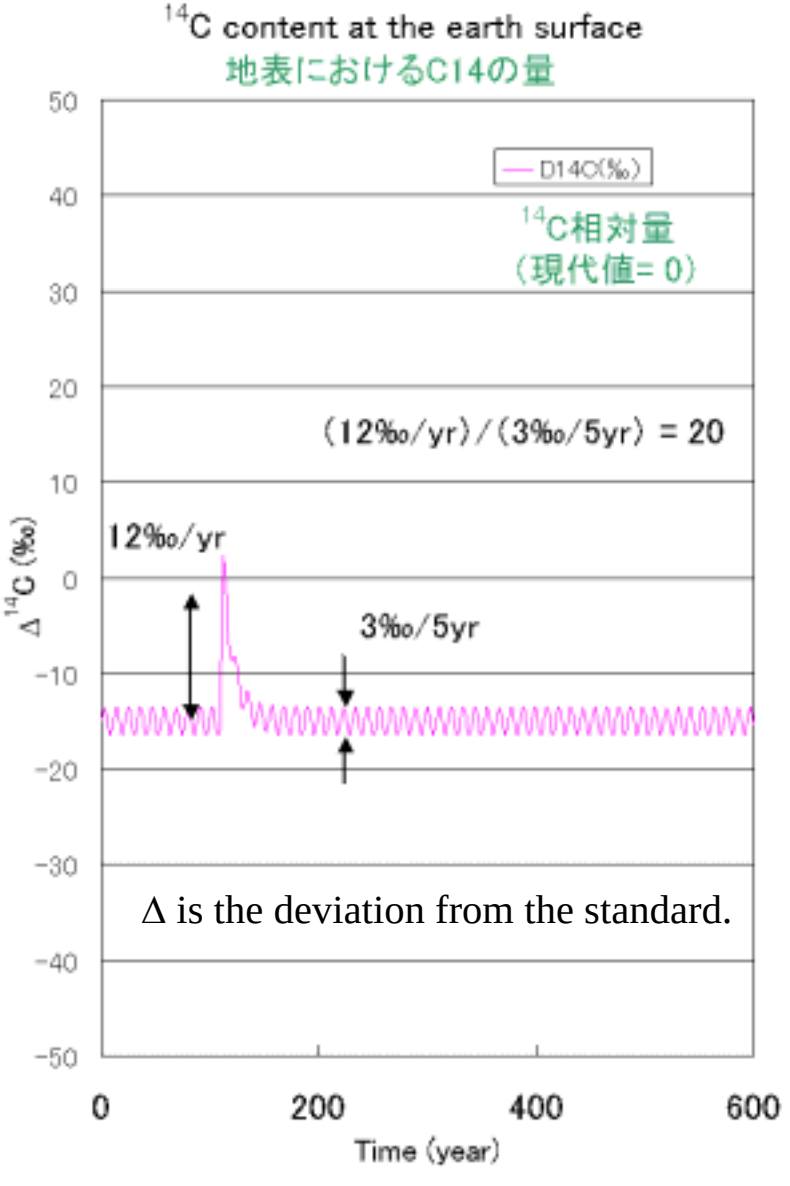


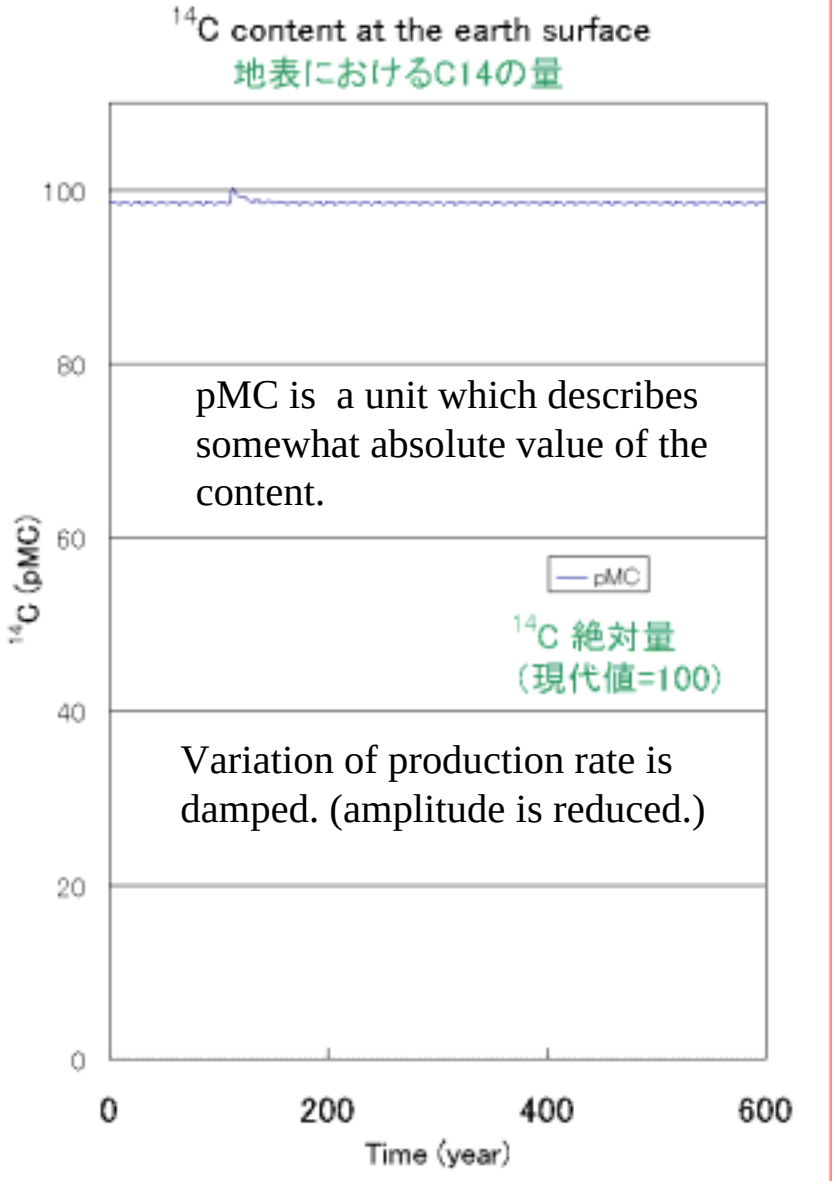
Decadal ^{10}Be record

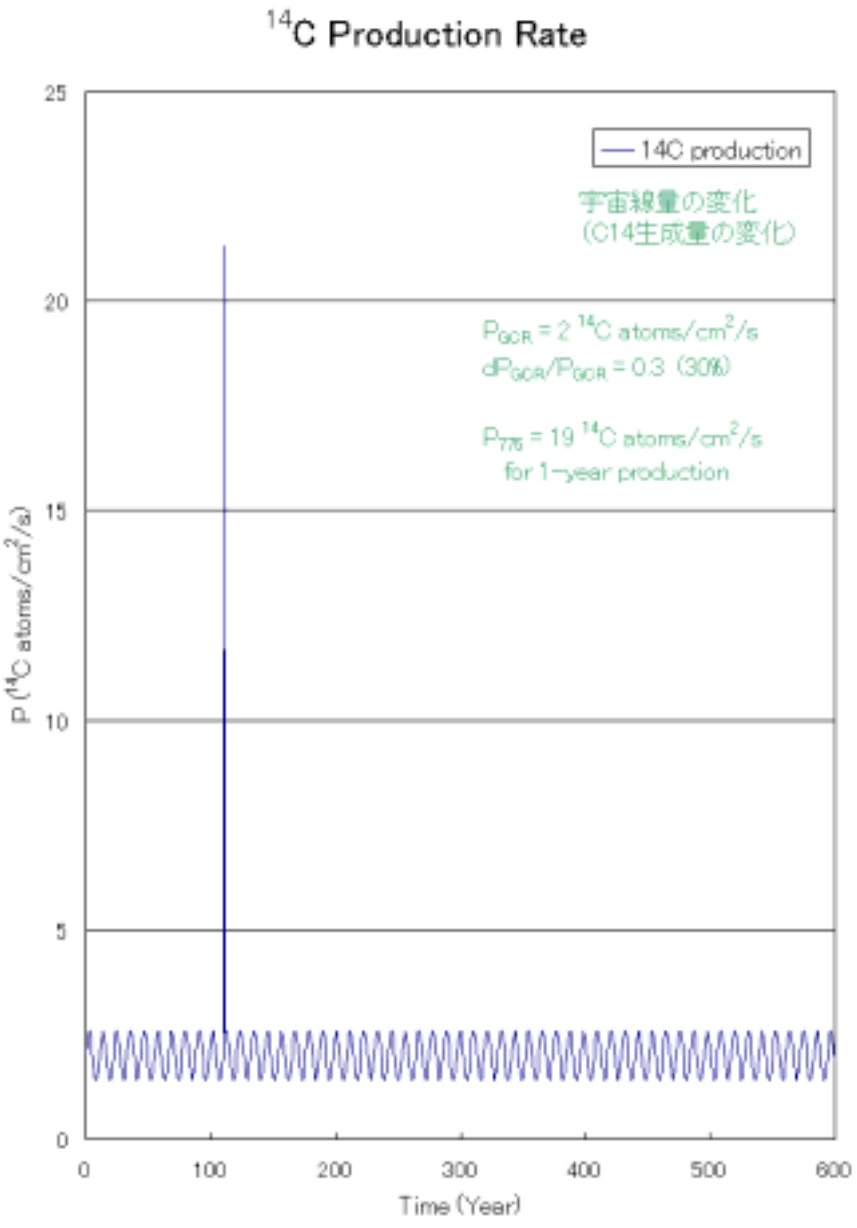
Horiuchi, 2008



$\Delta^{14}C$ and pMC expressions of ^{14}C model data







Production rate of ^{14}C

Average production rate of ^{14}C by galactic cosmic rays:
2 atoms/cm^2/s

Variation of ^{14}C production rate due to the 11-year solar cycle:
30%

^{14}C production rate in AD775 event for 1-year continuous input:
19 atoms/cm^2/s (10 times the normal)

If the continuance time of the event is shorter, ^{14}C production rate is larger.

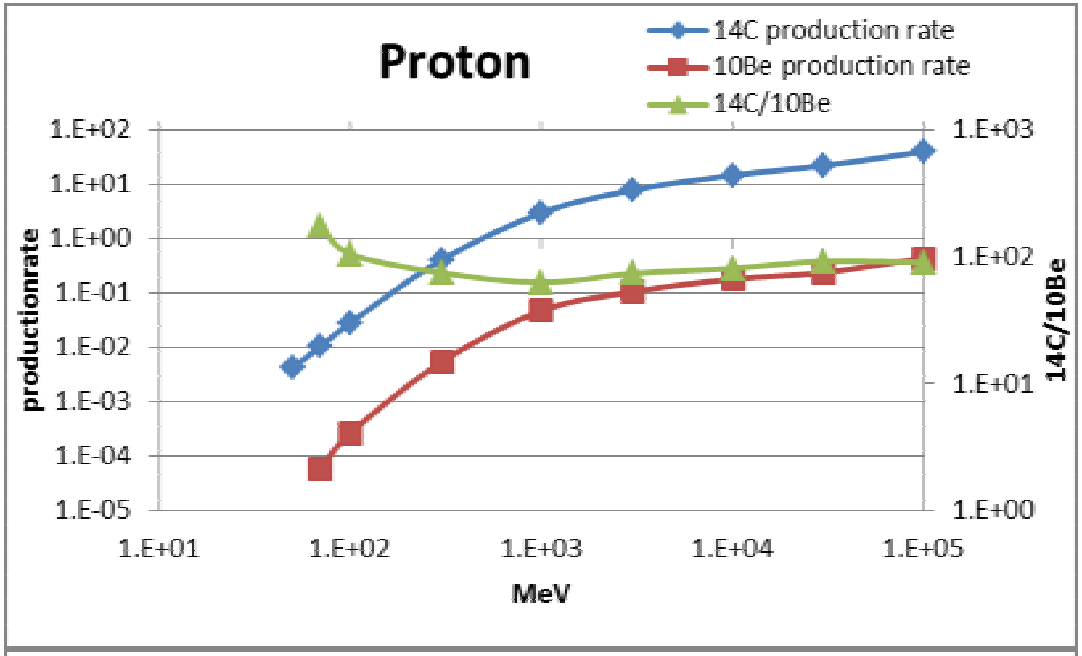
Characteristics of ^{14}C increase in the 8th century

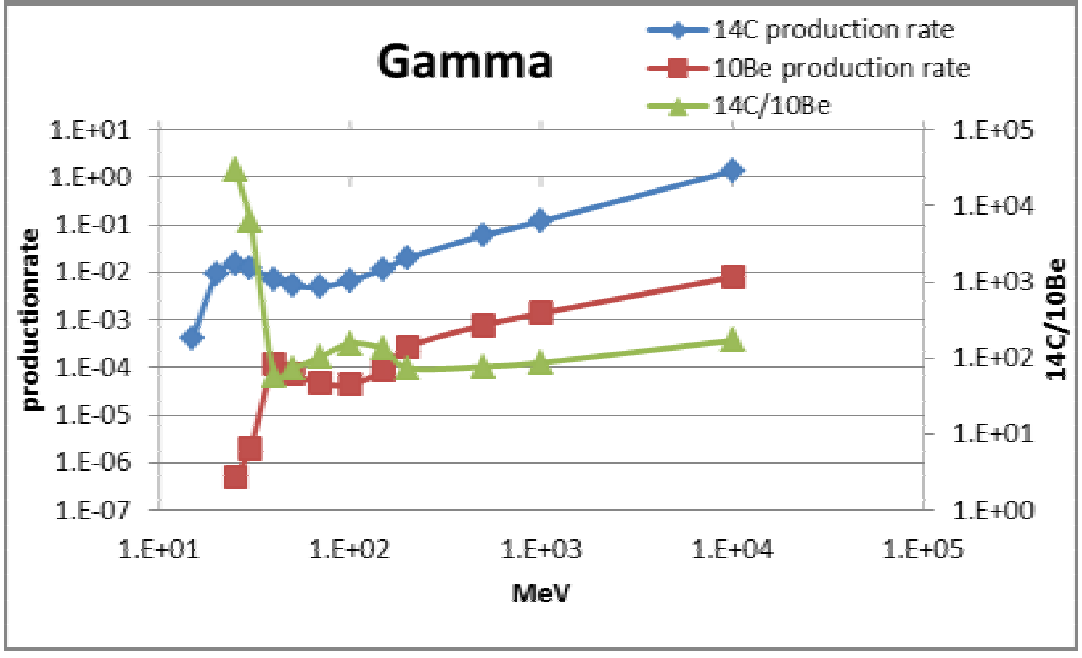
- ^{14}C concentration increased by 12‰ within 1 year, and then decayed slowly.
- The increase was 20 times larger than the variation due to normal solar activity change.
- $\Delta^{14}C$ value averaged over 10 years agrees with the decadal IntCal data by American and European samples.
- It also agrees with decadal ^{10}Be data from Antarctic ice core.
- Model analysis revels that ^{14}C were produced in the rate of 19 atoms cm^{-2} s^{-1} and reduced by the global carbon cycle.

→ The global increase of cosmic rays occurred due to an extraterrestrial high-energy phenomenon in a short duration less than 1 year.

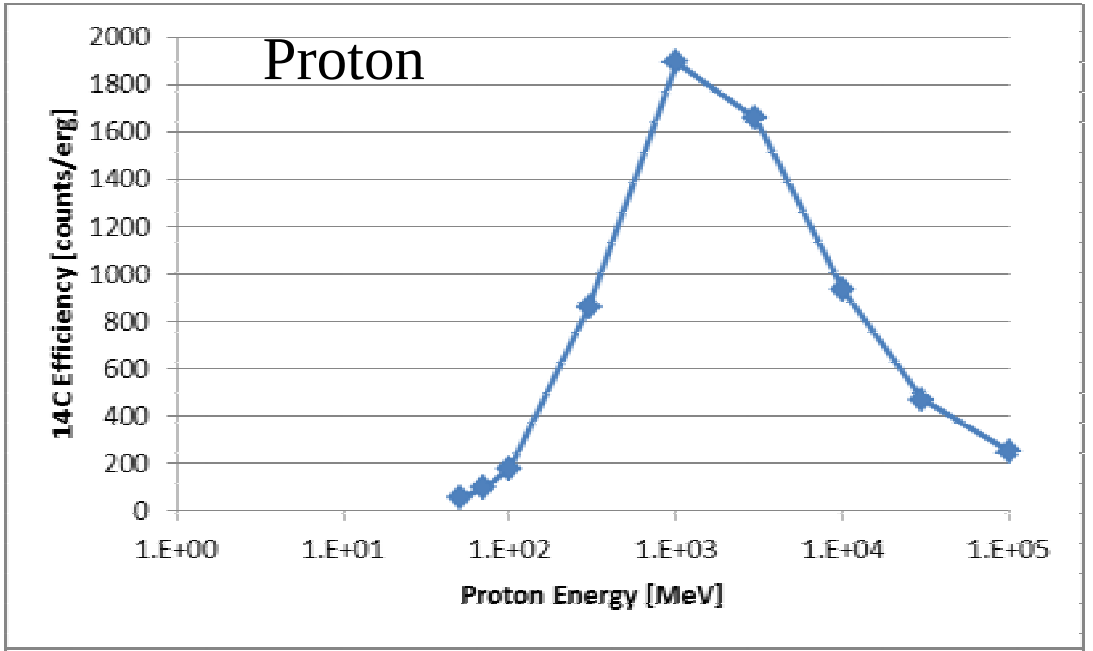
Cause: Supernova explosion (gamma-ray emission), Solar superflare (release of high-energy protons), etc.

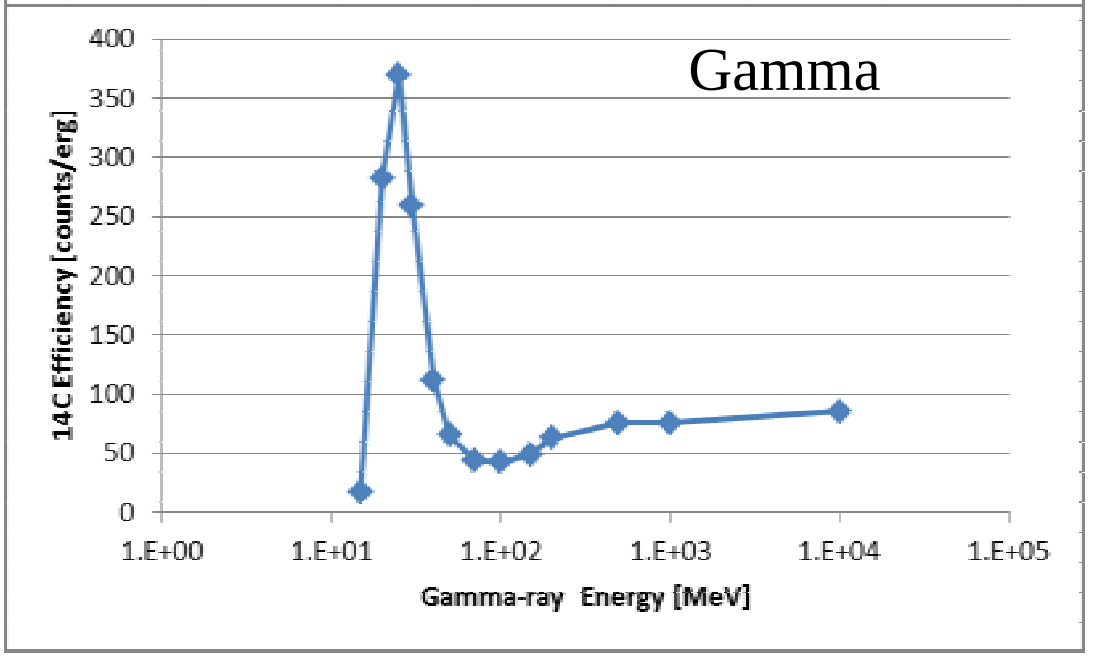
- Simulation was performed what amount of ^{14}C is produced in the earth's atmosphere by gamma-rays (or protons).





Production rate of nuclides as a function of incident energy (^{14}C and ^{10}Be, atoms/incident particle) and their ratio





^{14}C production efficiency per unit incident energy (atoms/erg) for proton and gamma-ray incidence

Estimation of total cosmic-ray energy corresponding to the 15‰ increase

- The 15‰ increase of ^{14}C corresponds to 13.5 kg of ^{14}C as compared with the total ^{14}C amount in the earth's atmosphere (= total carbon amount 750Gt*1.2*10^{-12} = 900 kg).
- The number of ^{14}C corresponds to 13.5kg is 6*10^{26} atoms
- Assuming the energy spectrum of gamma-rays as $\propto E^{-2.5}$,, ^{14}C production by gamma-rays is 120 atoms/erg and the total gamma-ray energy reaching the earth should be 7*10^{24} erg.
- Assuming the energy spectrum of solar protons as $\propto \exp(-R/R_0)$ with R_0 = 78MV and taking into account the geomagnetic cut-off, ^{14}C production by protons is 10 atoms/erg and the total proton energy reaching the earth should be 8*10^{25} erg.

Supernova hypothesis

- The total gamma-ray energy reaching the earth is $7*10^{24}$ erg.
- Assuming the distance from the earth and SN as 2kpc and isotropic emission, the total energy emitted from the supernova is estimated to be 3×10^{51} erg.
- Total emitted energy from normal supernova explosion is around 10^{51} erg. Assuming that 1 % of it is gamma-rays, 1049 erg can be emitted as gamma-rays.
- Although present event gives an energy 100 times larger than the normal one, for the smaller distance of one tenth of 2kpc, the total gamma-ray energy would be 3×10^{49} erg and almost the same as the normal ones.

Problems

- There seems not to exist historical records of supernova in AD775.
  - No historical record for SNR CasA (wave) and Vela Jr.(^{44}Ti γ)
  - Vela Jr.: d～several 100 pc, age = 10^3～10^4 year (possible SN775 ?)
- Near and young supernova should be written in records ?

List of young supernovae

Table 1. Supernovae and remnants from 200 BC to 1800 AD

Strom, 1994

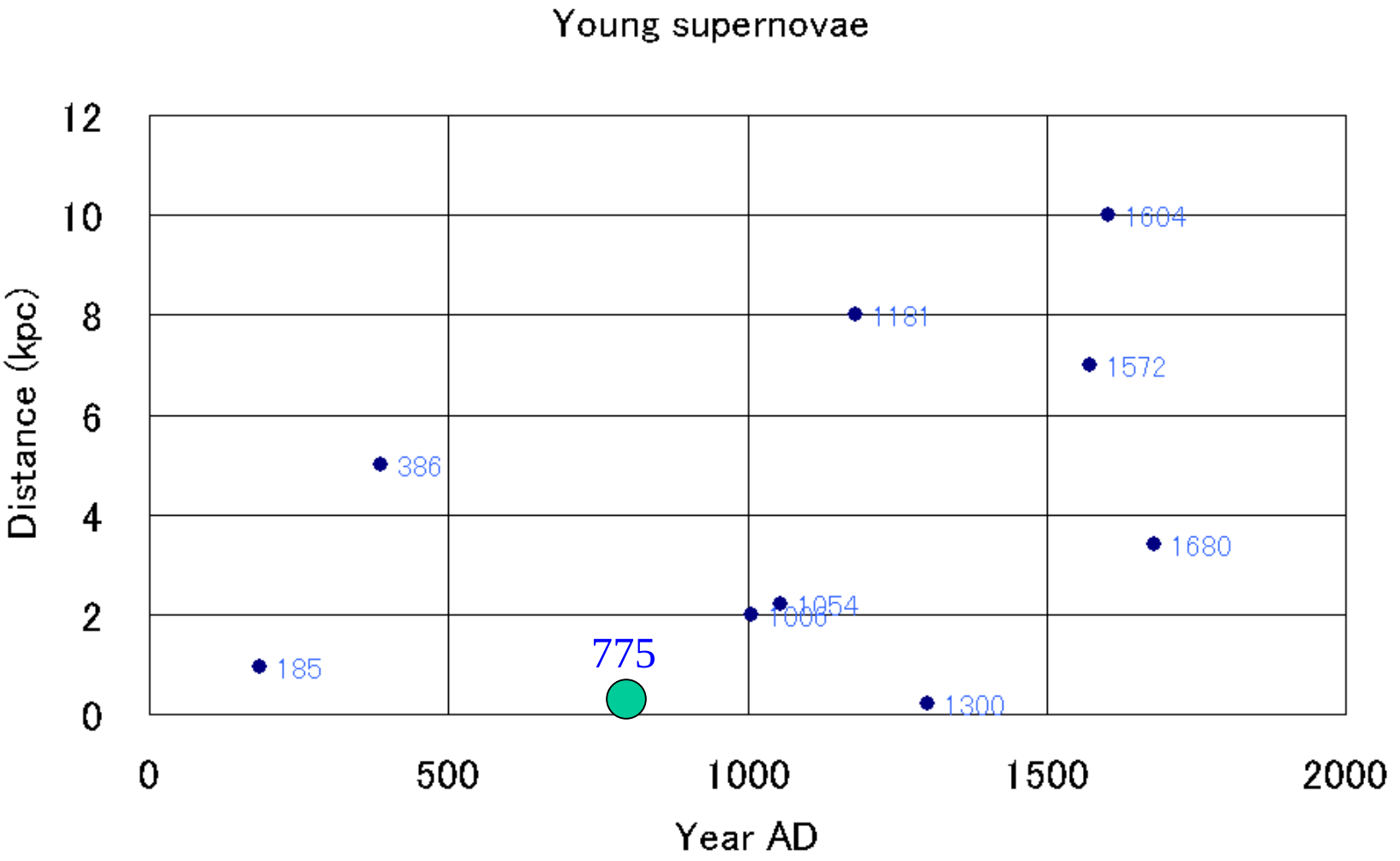
Year of SN	Land*	Duration (d)	Remnant	d (kpc)	D (pc)	b (°)	z (pc)	Age (yr)	Basis for young†
1604 AD	C,K	330	Kepler	4.4	4.1	+6.8	525	375	v,D
386 AD	C	90	G 11.2−0.3	5	5.8	−0.3	26	1595	D
§	—	—	Cas A	2.8	4.1	−2.1	103	315	v,D
1572 AD	C,K	480	Tycho	2.3	5.6	+1.4	56	410	v,D
1181 AD	C,J	185	3C 58	2.6	6.8	+3.1	141	800	v,D
1054 AD	C,J	540	Crab	2	4.1	−5.8	203	930	v,D,P
—	—	—	G 292.0+1.8	3.6	12.6	+1.8	113	—	v,D
185 AD	C	≥ 140	MSH 14−63	0.95	12.4	−2.3	38	1795	v,D
1006 AD	C,J,K?	240	PKS 1459−41	1.4	12.2	+14.6	365	975	v,D
—	—	—	RCW 103	3.3	8.6	−0.4	23	—	v,D,(P)
393 AD	C	210	RX J1713.7-3946 *	—	—	$\lesssim 5$	—	—	—

Burrows, 2000

Table 1 Supernovae that have exploded in our Galaxy and the Large Magellanic Cloud within the last millennium

Supernova	Year (AD)	Distance (kpc)	Peak visual magnitude
SN1006	1006	2.0	−9.0
Crab	1054	2.2	−4.0
SN1181	1181	8.0	?
RX J0852-4642	~1300	~0.2	?
Tycho	1572	7.0	−4.0
Kepler	1604	10.0	−3.0
Cas A	~1680	3.4	~6.0?
SN1987A	1987	50 ± 5	3.0

Year of historical record and estimated distance



Solar high-energy proton hypothesis

- The total proton energy reaching the earth should be $8*10^{25}$ erg.
- Assuming the isotropic emission, the energy emitted from the sun is 2×10^{35} erg.
- Emitted energy from normal flares is 10^{29-32} erg.
  - Large flare as 1000 times (Superflare)

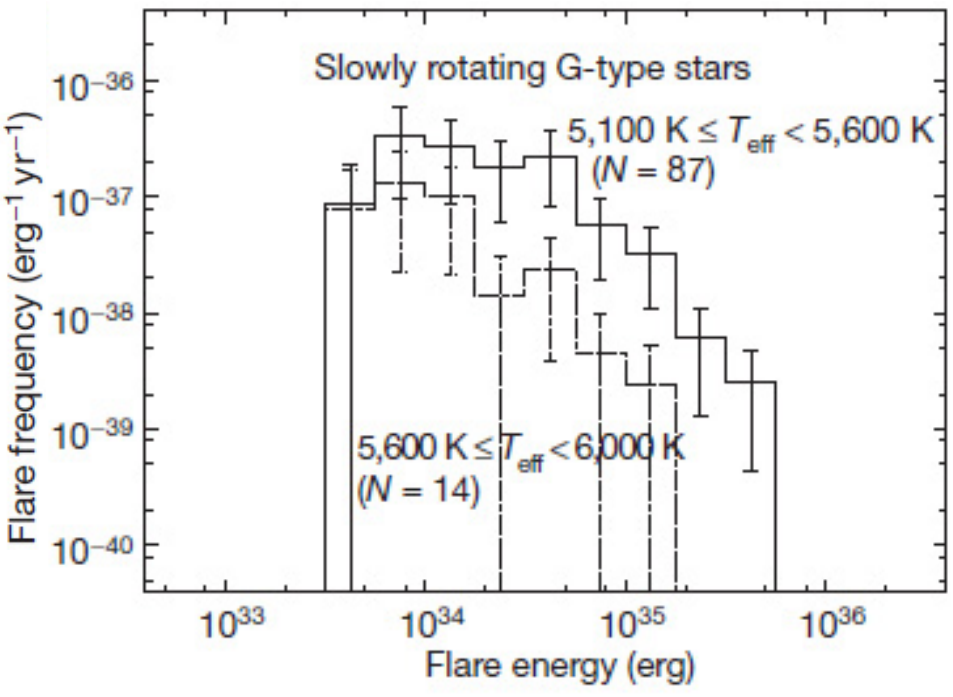
How about the possibilities that such a large flare occur in our system? ……A theory says superflares do not occur in our sun because it needs a hot Jupiter.

- Now, superflares are possible in the Sun. (Maehara et al., 2012)

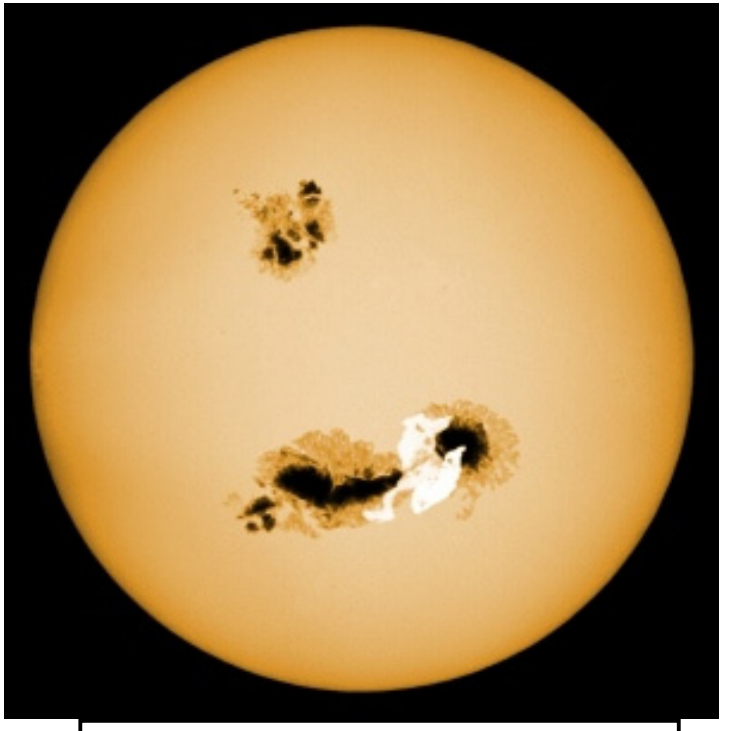
- Estimation of effect of protons on human being and environment
- Effect of UV radiation
- Necessary to investigate on change of global environment

Frequency of superflares

Superflares on solar-type stars
Maehara et al., *Nature* 11063 (2012)



From data analysis of the Kepler satellite



From the normal sunspot image…

For solar-type stars (G-type in main sequence with rotation period more than 10 days and surface temperature of 5600-6000K),
probability of superflare with 10^{34} erg is once in 800 years,
probability of superflare with 10^{35} erg is once in 3000 years.

Summary

- We have studied cosmic-ray events and solar activity in the past by measuring 14C contents in tree rings with 1-2 year time resolution.
- A rapid increase of 14C concentration in the atmosphere from AD774 to 775 was found.
- The increasing rate is 20 times larger than the variation due to the normal solar activity. It is the largest increase in cosmic-ray intensity at least in the last 3,000 years.
- For the cause of increase, high-energy extraterrestrial phenomena is considered, such as

  (1) nearby supernova explosion with gamma-ray emission,

  (2) Solar superflare accompanied by high-energy protons,

  but their possibilities are not so high in our present knowledge.
- Annual data on ^{10}Be, nitrate, etc. and historical record (documentations, environment changes) are necessary.

Clue to an ancient cosmic-ray event?

- It is tempting to speculate that the ancient text of the *Anglo-Saxon Chronicle* might offer a clue to the cause of the mysterious, dramatic cosmic-ray event in ad 774 (F. Miyake *et al. Nature* **486,** 240–242; 2012).
- A chronicle entry for the same year (see go.nature.com/wwkw5j) hints at the presence of a supernova largely hidden behind a dust cloud, which would scatter and absorb all light bar a trickle of red. The resulting supernova remnant would be invisible.
- The entry notes: "**This year also appeared in the heavens a red crucifix, after sunset**; the Mercians and the men of Kent fought at Otford; and wonderful serpents were seen in the land of the South-Saxons."
  - **Jonathon Allen** *University of California, Santa Cruz, California, USA. jokallen@ucsc.edu*

More medieval clues to cosmic-ray event

- Gary W. Gibbons & Marcus C. Werner

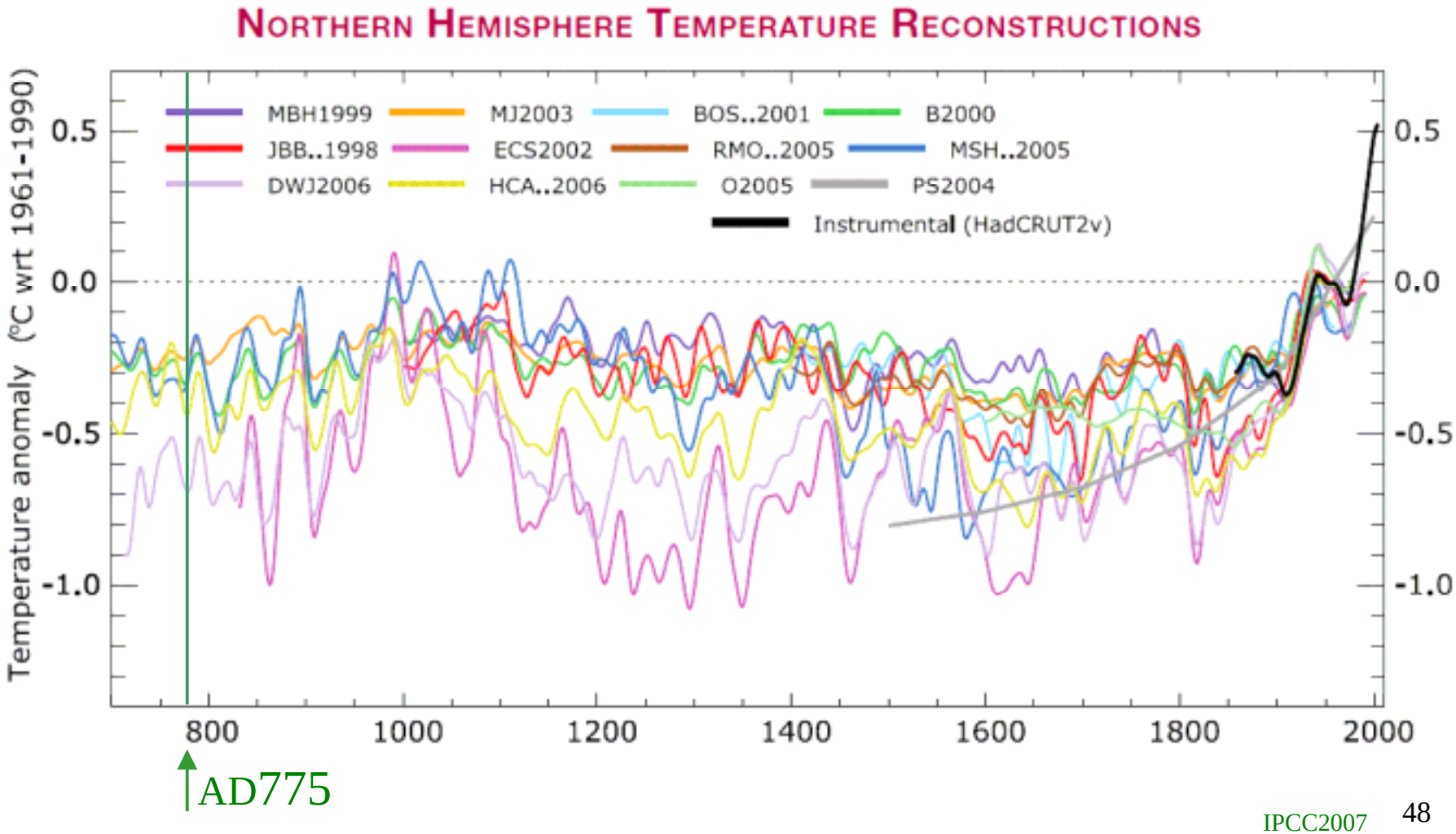
  Nature 487, 432 (26 July 2012) doi:10.1038/487432c
- Jonathon Allen quotes an entry in the *Anglo-Saxon Chronicle* that might account for the increased cosmic-ray flux in AD 774–775 (*Nature* 486, 473; 2012). Other medieval texts recall another celestial phenomenon from around the same time, which may or may not be pertinent.
- In the context of Charlemagne's campaign against the Saxons, the annals of the monastery of Lorsch, Germany (*Annales Laurissenses*), mention an image witnessed in AD 776 as "**two shields burning with red colour and moving above the church itself**". The *Chronicon* of Sigebert of Gembloux notes that "when the Saxons besieged the castle of Heresburch, the glory of God appeared to all, surely as two shields burning with the colour of blood and making certain motions through the air, as if at war". The phenomenon seems to have been observed during the day, suggesting that it was very bright if indeed it was a cosmic event.
- The *Anglo-Saxon Chronicle* also describes a heavenly red crucifix, a colour that is a traditional motif of battlerelated portents. The date disparity between the shield sighting and the AD 774–775 event might be explained by an extended period of auroral activity. Also, the *Anglo-Saxon Chronicle* entry is linked to the Battle of Otford, thought to have occurred in AD 776.

Daniel Baker
a space physicist at the University of Colorado's Laboratory
for Atmospheric and Space Physics in Boulder, Colorado, says

- Flares are sometimes associated with coronal mass ejections (CMEs) — huge eruptions of magnetically charged plasma from the Sun's atmosphere that send streams of charged particles towards Earth. It might be possible for CMEs to be accompanied by conditions in which an unusual number of protons are accelerated to super-high energies, even without the flare itself being "ridiculously strong".
- We know much more these days about how important proton acceleration is at the shock fronts that precede CME structures as they propagate towards Earth, I would like to think about whether a strong CME moving directly towards Earth could have produced the intense proton population that impacted Earth's atmosphere.

Auroras are seen when bursts of charged particles hit Earth's atmosphere — but there is no record of these occurring at the same time as the ^{14}C increase.

Temperature variation for the past 1,300 years



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