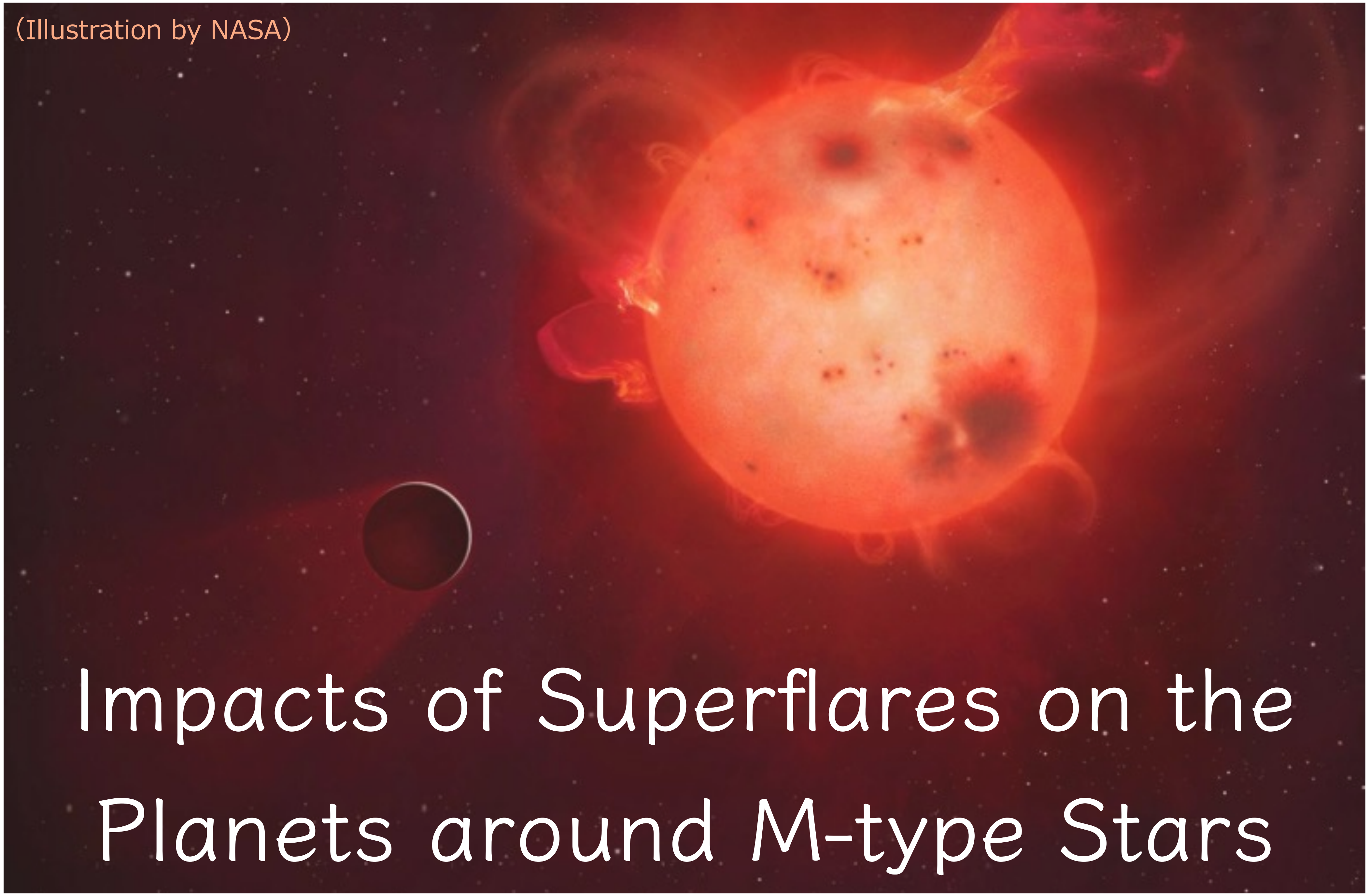
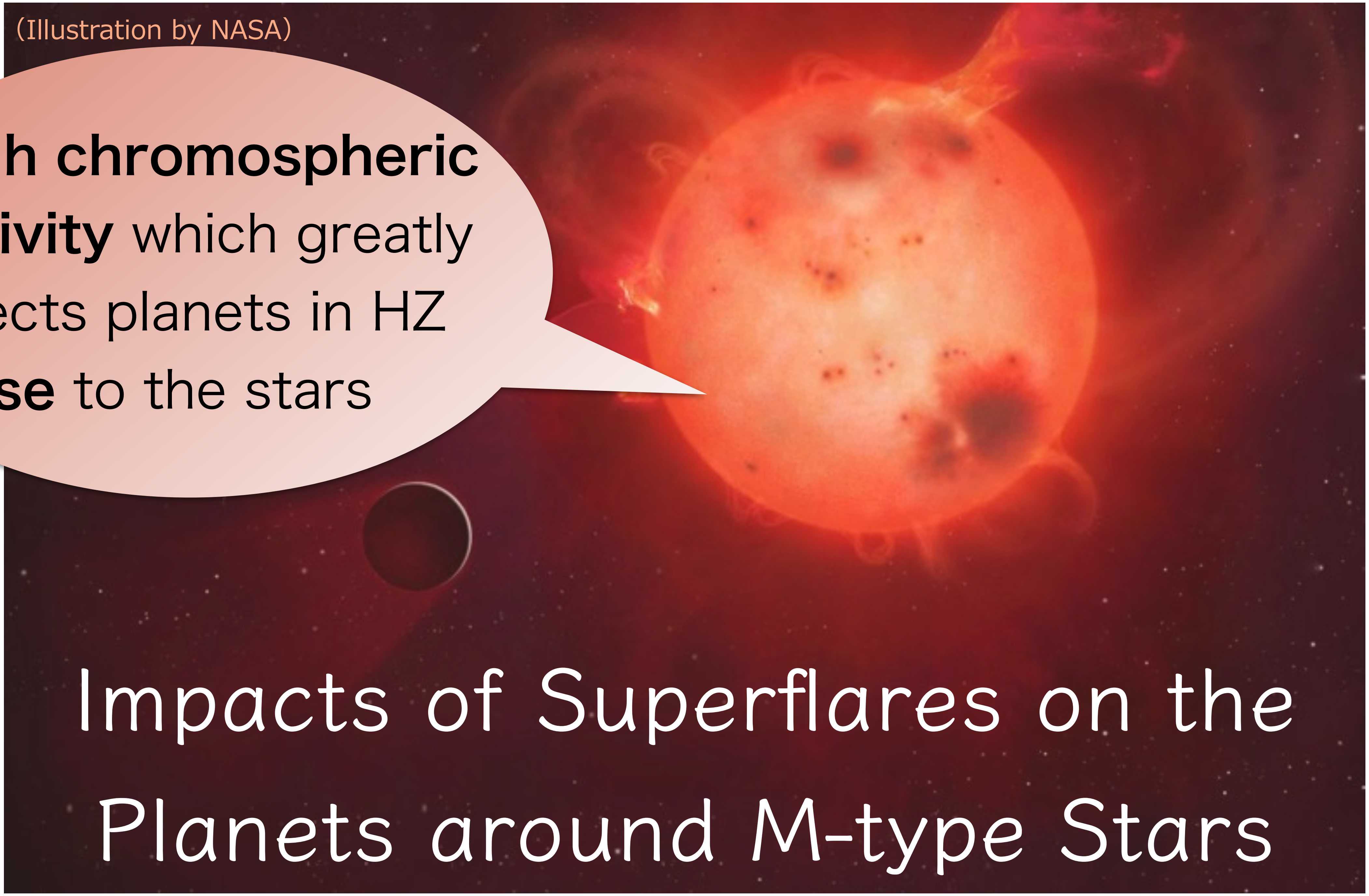

(Illustration by NASA)

Impacts of Superflares on the Planets around M-type Stars

Hiroyuki Ishikawa (Kyoto University)

Shota Notsu, Takanori Sasaki (Kyoto Univ.)

Mar 4, 2016 Superflare WS 2016 at Kyoto Univ.



(Illustration by NASA)

High chromospheric activity which greatly affects planets in HZ **close** to the stars

Impacts of Superflares on the Planets around M-type Stars

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Mar 4, 2016 Superflare WS 2016 at Kyoto Univ.

Previous Work

ASTROBIOLOGY
Volume 10, Number 7, 2010
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DOI: 10.1089/ast.2009.0376

The Effect of a Strong Stellar Flare on the Atmospheric Chemistry of an Earth-like Planet Orbiting an M Dwarf

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James Kasting,[4,*] and Suzanne Hawley[3]

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Segura et al., 2010

Method

- Observational data of the flare (**～10^{34} erg**) in 1985 from AD Leo (dM3e star)

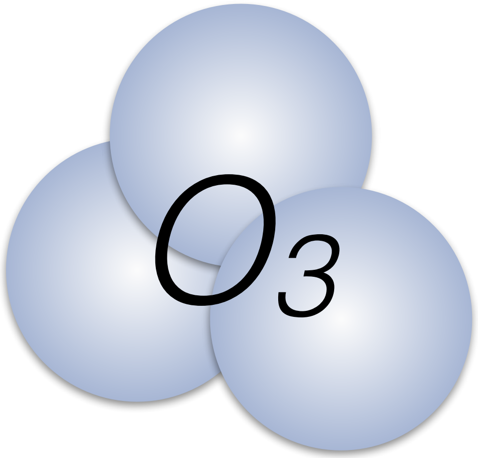
[Hawley & Pettersen, 1991]

- Investigated the impact of this flare on the atmosphere of **a hypothetical, Earth-like planet** (**with no magnetic field**) located **within habitable zone** (at 0.16 AU) of AD Leo,

using {
  a 1-D radiative-convective model
  a 1-D photochemical model

Segura et al., 2010

Ozone

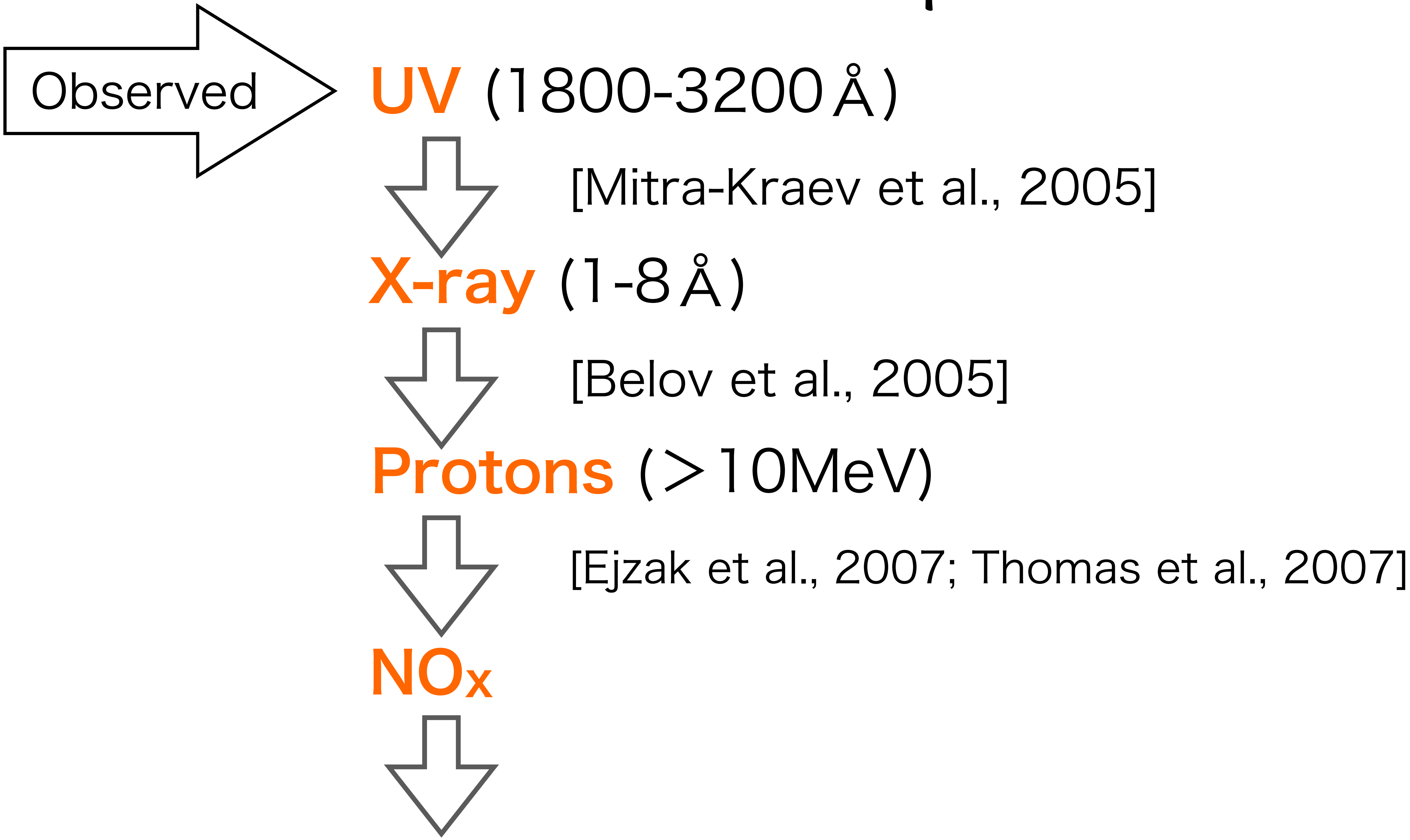


Ozone is important to search for extrasolar life because

- Ozone can **protect life** on the planetary surface from damaging UV radiation
- Ozone is one of the best compounds for extrasolar life **detection** via remote sensing
  ⇒ a promising “biosignature”

Segura et al., 2010

Include the effect of protons



Observed

UV (1800-3200Å)

[Mitra-Kraev et al., 2005]

X-ray (1-8Å)

[Belov et al., 2005]

Protons (>10MeV)

[Ejzak et al., 2007; Thomas et al., 2007]

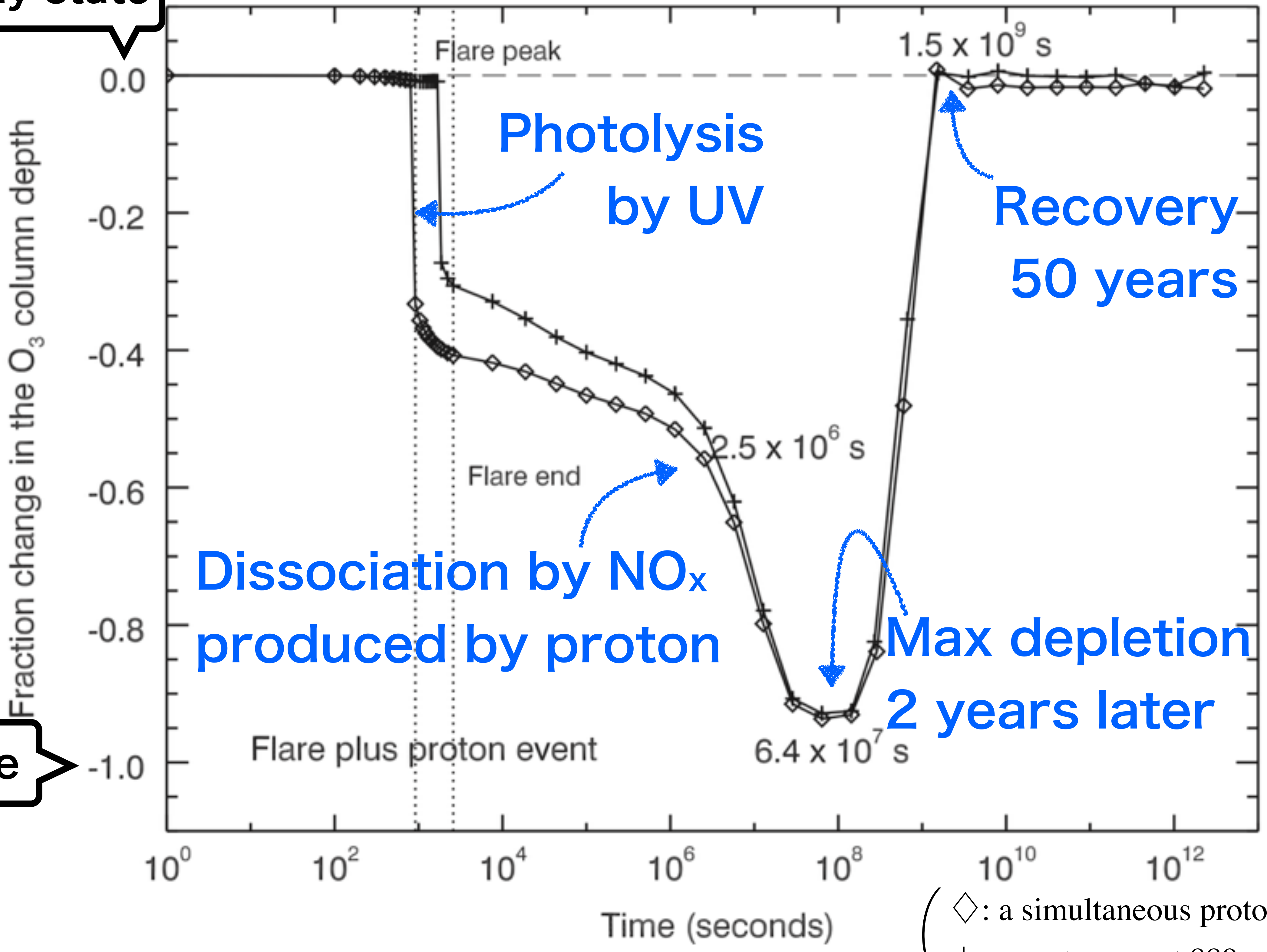
NO_x

Introduced this increase of NO_x

at the time when the flare peaks

Segura et al., 2010

Result



The steady state

No ozone

Photolysis by UV

Dissociation by NO_x produced by proton

Max depletion of 94% 2 years later

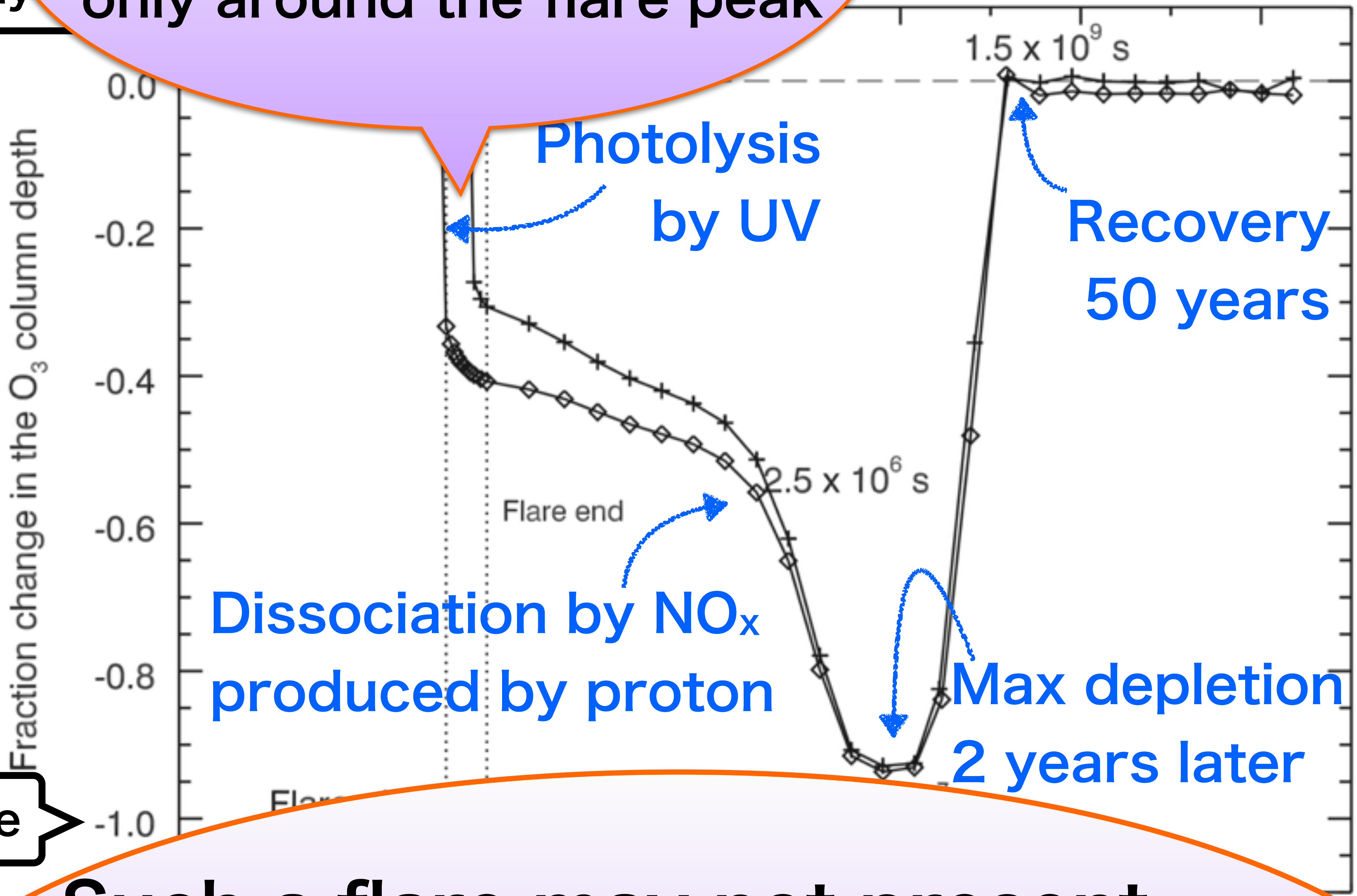
Recovery 50 years later

◇: a simultaneous proton event.
+: a proton event 889 s behind.

Segura

The steady

The significant UV increase takes place only around the flare peak



Photolysis by UV

Recovery 50 years later

Dissociation by NO_x produced by proton

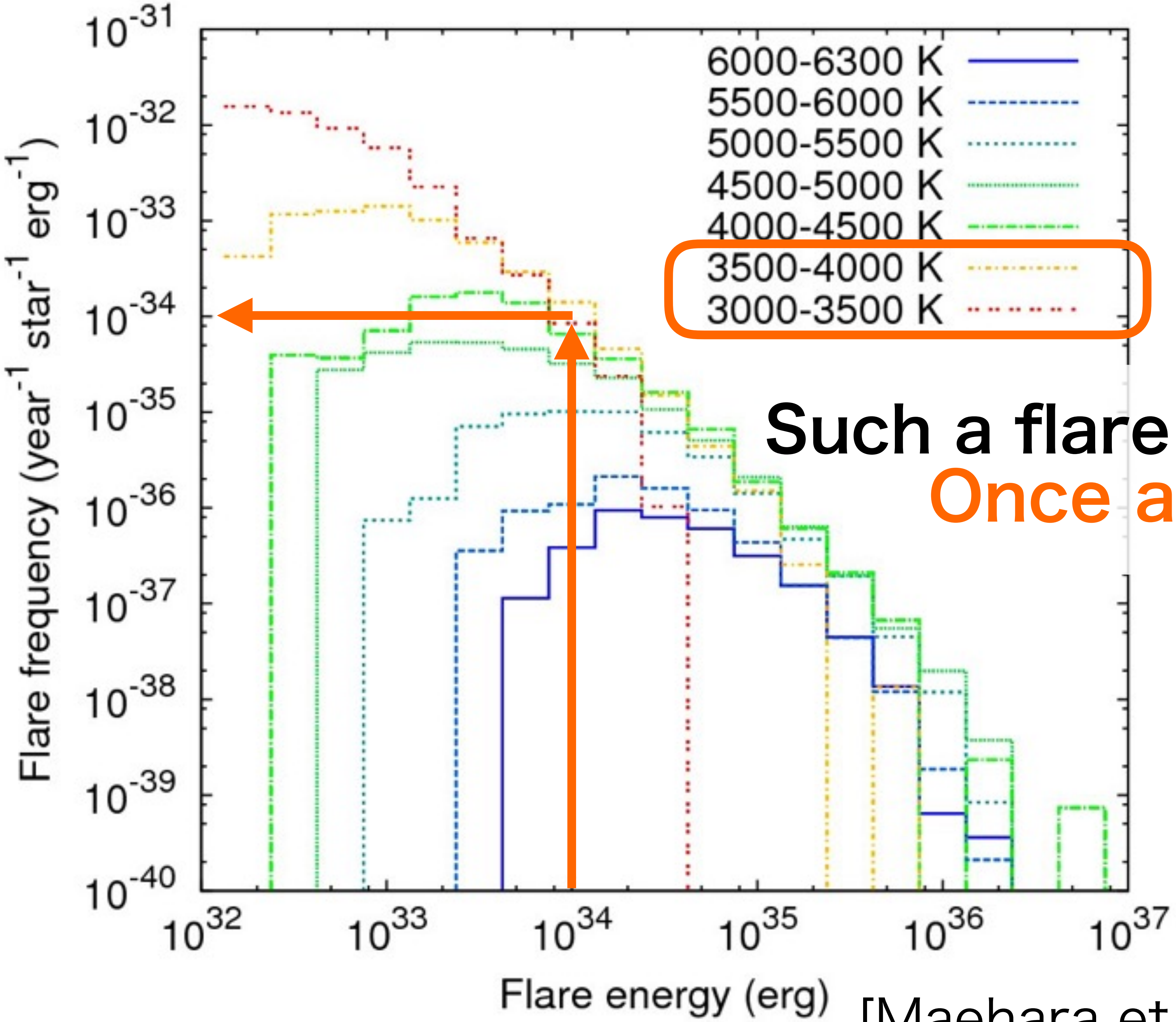
Max depletion of 94% 2 years later

No ozone

Such a flare may not present a direct hazard for the habitability

nt.

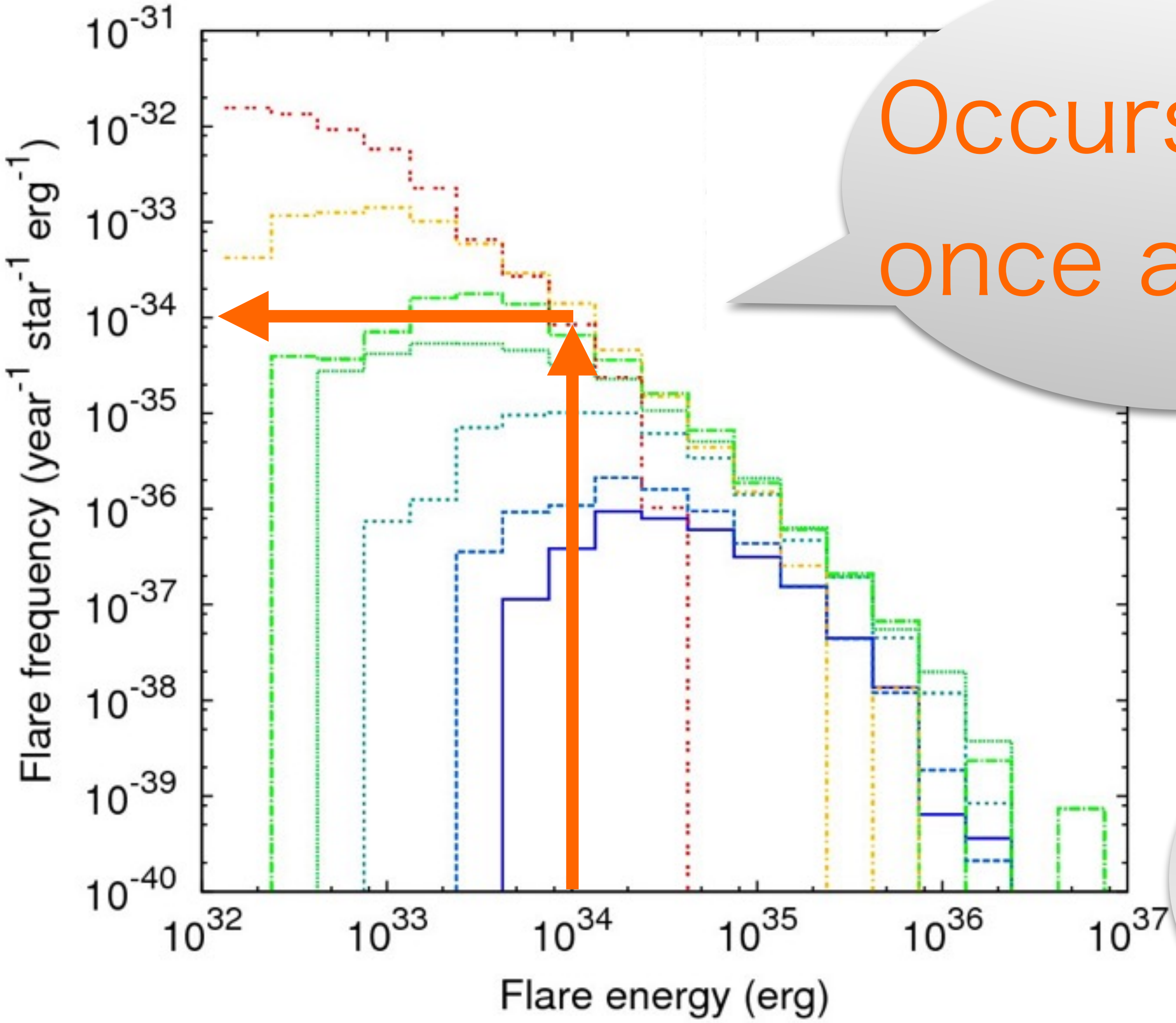
Estimation of Frequency



Such a flare occurs
Once a year !

[Maehara et al., in prep]

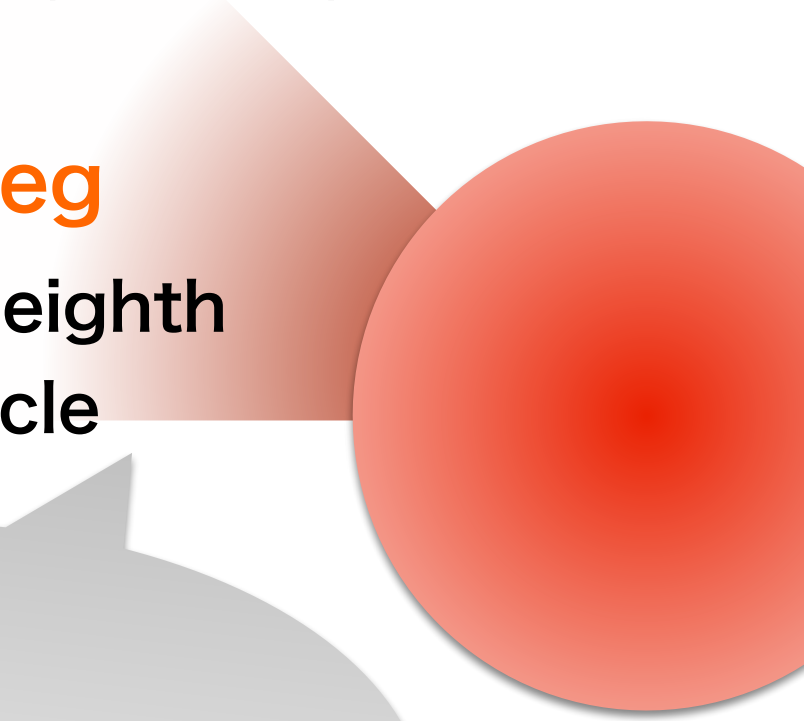
Estimation of Frequency



Occurs about once a year

[Maehara et al., in prep]

[Gopalswamy et al., 2009]



44 deg

～ One-eighth of a circle

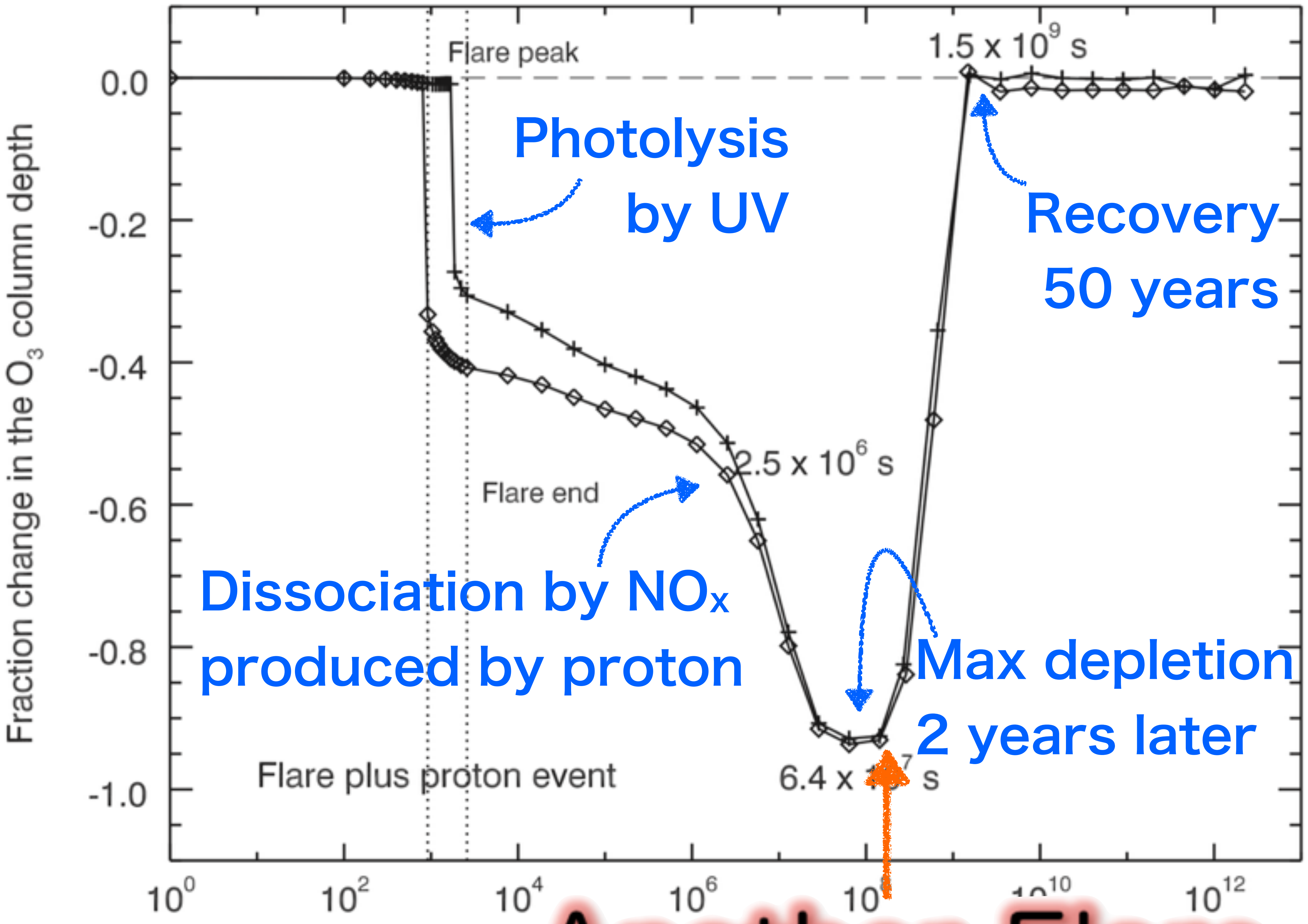
Hit more than once every ten flares

⇨ Planets orbiting M dwarfs encounter the protons with 10^{34} erg flares over **Once a Decade !!**

(the frequency rises when a large starspot appears.)

Segura et al., 2010

UV & Protons



Photolysis by UV

Recovery 50 years later

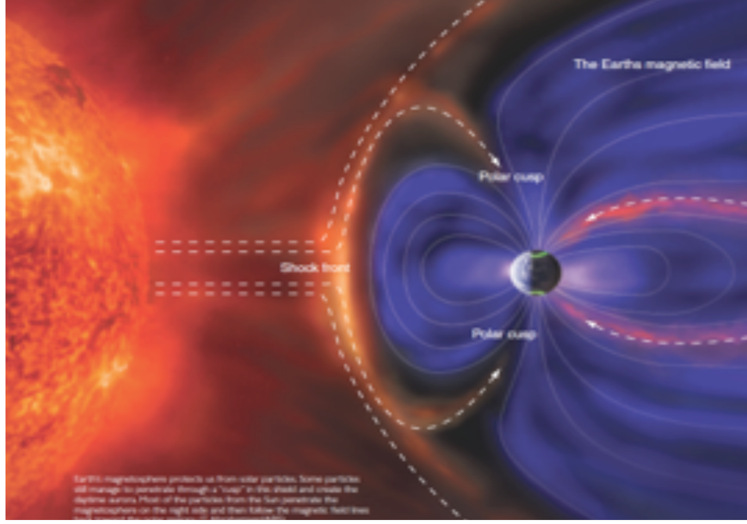
Dissociation by NO_x produced by proton

Max depletion of 94%, 2 years later

Another Flare

Segura et al., 2010

An Important Remaining Issue ⇒ Magnetic Field

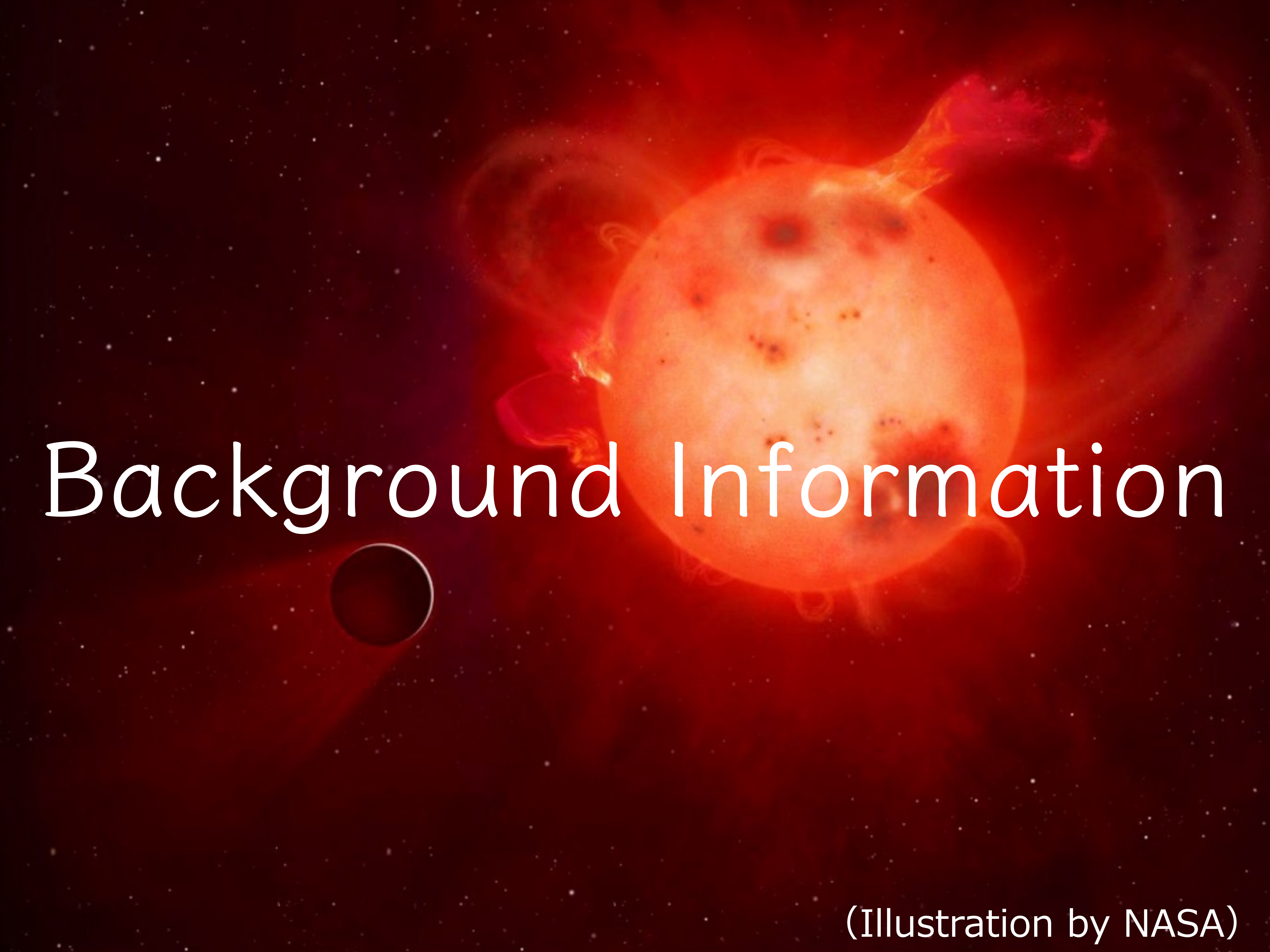


- A magnetic field allows the entrance of protons **only through the poles.**
  ⇒ If the planet has a magnetic field, the depletion may become smaller and the predicted recovery time may shorten. (e.g. Thomas et al., 2007)

- **2-D** or **3-D** model is required to calculate those factors in detail for the planet with a magnetic field.

Summary

- **M dwarfs** are often regarded as **the primary targets** in the search for habitable planets.
- However, there are some complications including the high chromospheric activity which leads to **large and frequent flares**.
- Such a flare causes the ozone depletion of **94%** in the atmosphere of the planet with no magnetic field and recovery takes about **50 years**.
- Taking into account **the high frequency** of the flare production, **the ozone must be destructed constantly** so that it could not exist in the atmosphere on the planets in the habitable zones of M-type stars.
- **Magnetic fields** should be considered with 2-D or 3-D models.



Background Information

(Illustration by NASA)

Disadvantages
of Targeting M Dwarfs for Habitable Planets

- M dwarfs often have high **chromospheric activity** which greatly affects planets in HZ close to the stars
- **Large starspots** lower the accuracy of the transit method or the Doppler method (→e.g., Omiya-san's talk)
- High possibility to be **tidally locked**
- Many planets around M dwarfs are surrounded by **H/He envelopes** which make the planets uninhabitable

…etc.

⇨ Are these planets really "habitable"?

Segura et al., 2010

Hawley and Pettersen, 1991

The Flare from AD Leonis

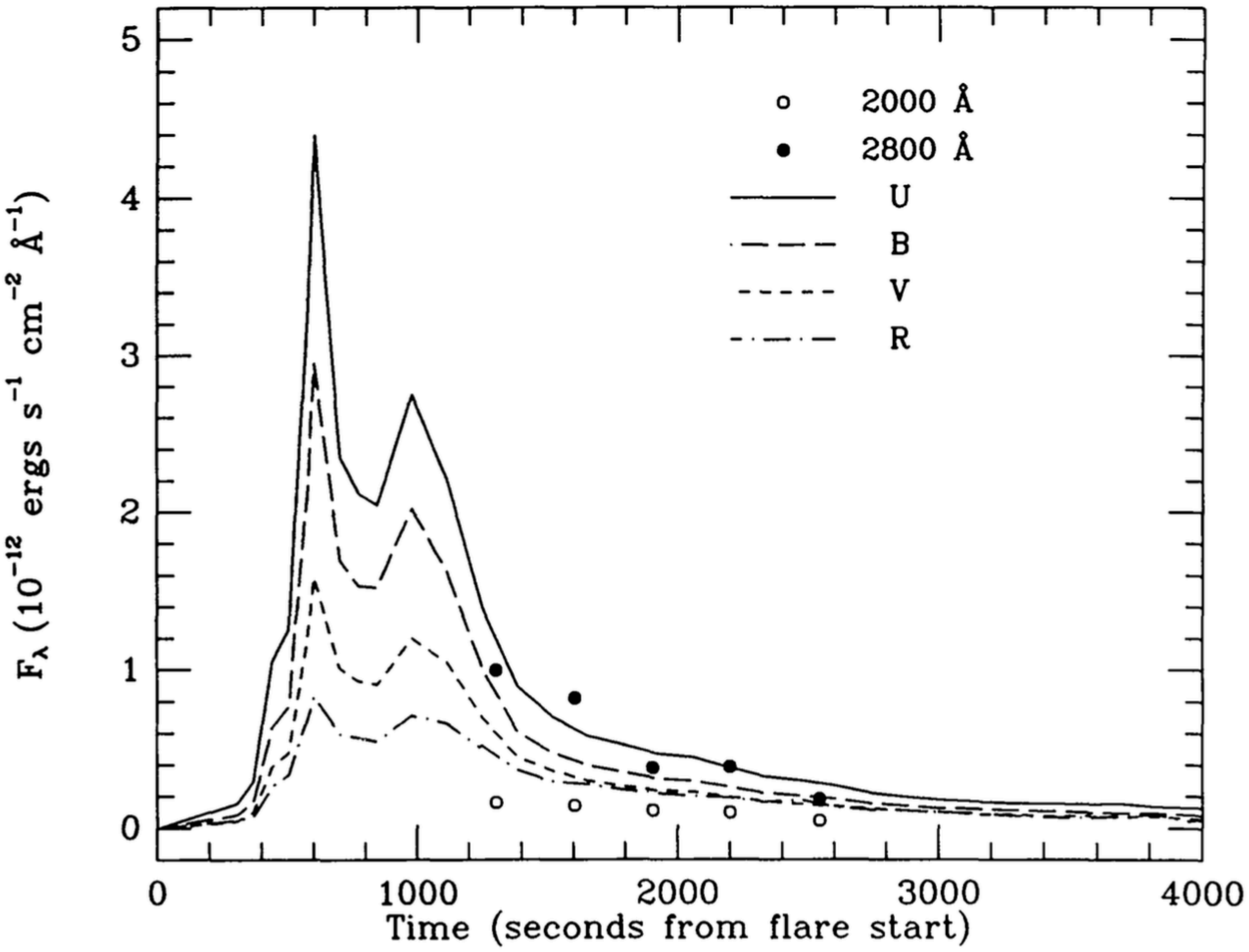
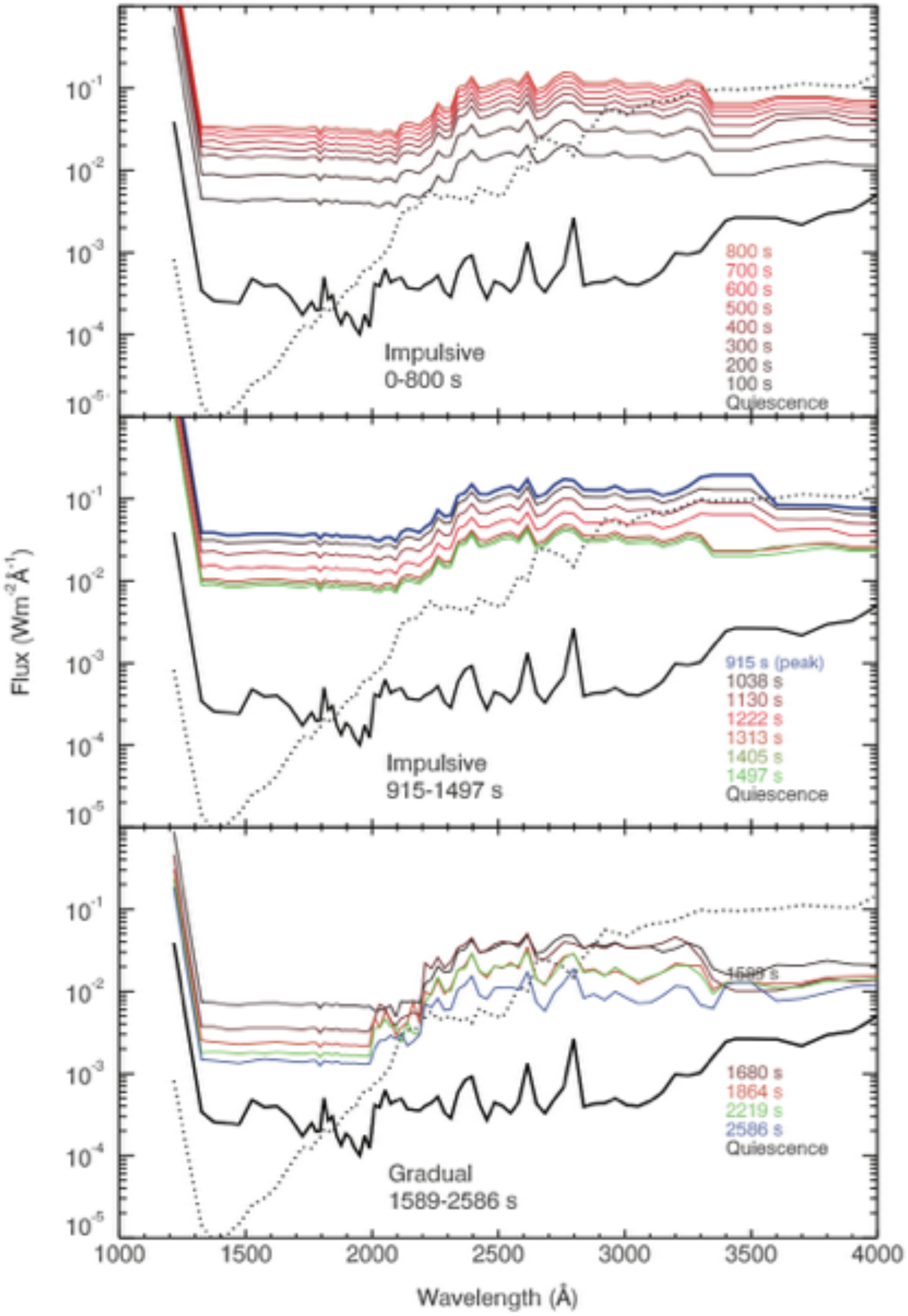


FIG. 1.—Flare light curves as measured in *U*, *B*, *V*, and *R*. F_λ, the monochromatic continuum flux in each filter, is plotted against time. The continuum F_λ at two ultraviolet wavelengths measured in the *IUE* LWP spectra are also shown. Zero on the time axis corresponds to 04:40 UT, the flare start time.

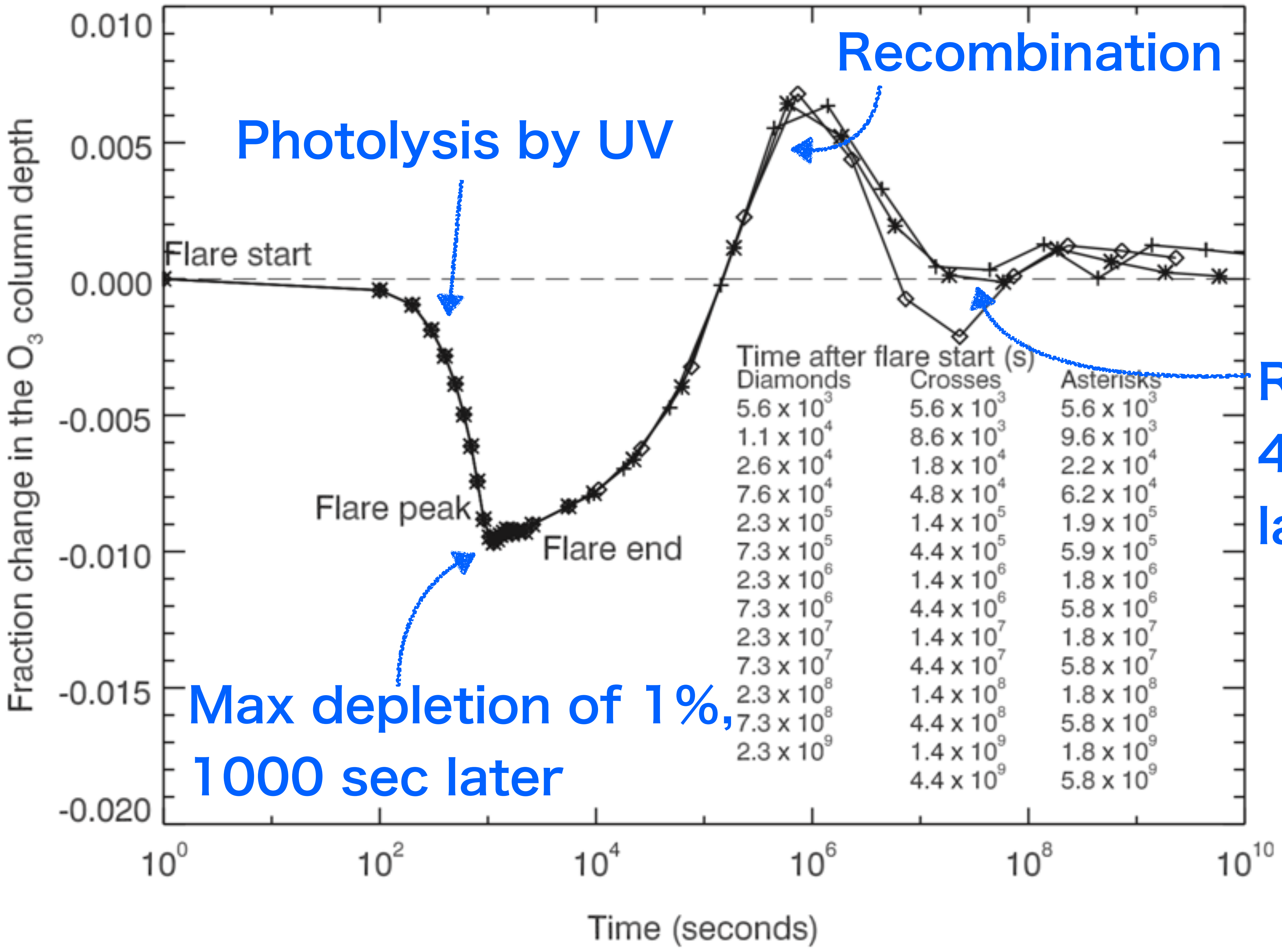
Segura et al., 2010

Input Data of the Flare



Segura et al., 2010

UV only (no proton)



Time after flare start (s)

Diamonds	Crosses	Asterisks
5.6×10^3	5.6×10^3	5.6×10^3
1.1×10^4	8.6×10^3	9.6×10^3
2.6×10^4	1.8×10^4	2.2×10^4
7.6×10^4	4.8×10^4	6.2×10^4
2.3×10^5	1.4×10^5	1.9×10^5
7.3×10^5	4.4×10^5	5.9×10^5
2.3×10^6	1.4×10^6	1.8×10^6
7.3×10^6	4.4×10^6	5.8×10^6
2.3×10^7	1.4×10^7	1.8×10^7
7.3×10^7	4.4×10^7	5.8×10^7
2.3×10^8	1.4×10^8	1.8×10^8
7.3×10^8	4.4×10^8	5.8×10^8
2.3×10^9	1.4×10^9	1.8×10^9
	4.4×10^9	5.8×10^9

Photolysis by UV

Recombination

Max depletion of 1%,
1000 sec later

Recovery
4 months
later

Segura et al., 2010

Estimate the Proton Flux

- The **proton** flux can be **estimated** from the **X-ray** intensity(1-8Å) of the same flare. [Belov et al., 2005]

$$I_{\mathrm{p}}(>10\ \mathrm{MeV}) = (4.8 \pm 1.3) \times 10^{7}\ I_{x}^{1.14 \pm 0.14}$$

- The **X-ray** luminosity also can be **derived** from the **UV** energy density. [Mitra-Kraev et al., 2005]

$$\mathscr{L}_{x} = 10^{-4.4}\,\mathscr{E}_{\mathrm{UV1}}^{1.08} \quad (2450\text{-}3200\text{Å})$$

$$\mathscr{L}_{x} = 10^{-15}\,\mathscr{E}_{\mathrm{UV2}}^{1.4} \quad (1800\text{-}2250\text{Å})$$

Segura et al., 2010

Scale the NO_x Production

- The production of **nitrogen oxides** is proportinal to the proton fluence [Ejzak et al., 2007; Thomas et al., 2007]

- **Estimate** nitrogen oxide production based on this relation

using the data of the NOx production for the Carrington Event calculated by **Rodger et al., 2008**

- Introduce this increase in the number density of NO_x at the peak of the flare (915 s)

Fig.7 in Rodger et al., 2008

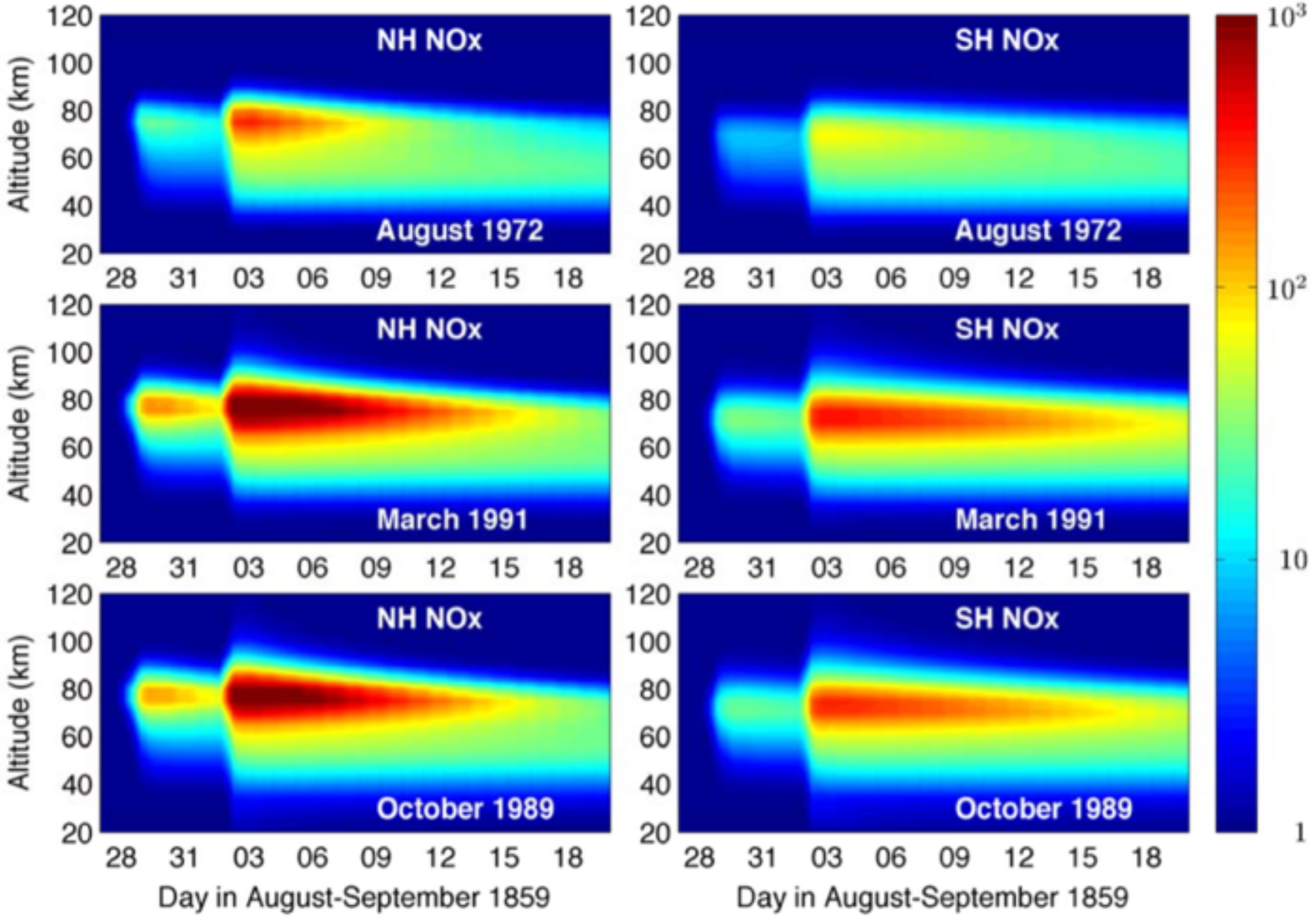
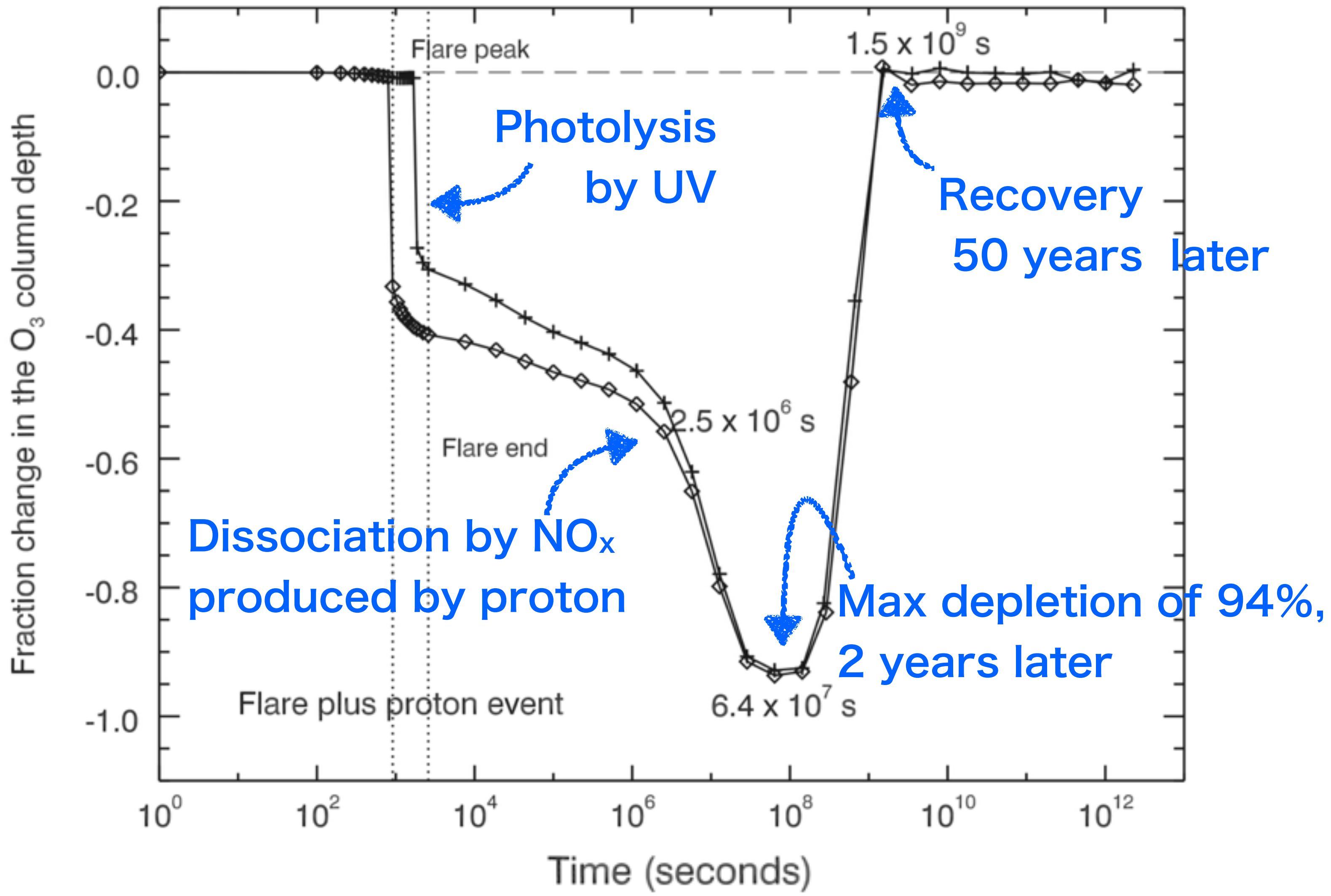


Figure 7. SPE-driven changes in odd nitrogen (NO_x) determined from the SIC model for the varying SPE spectra, and show as the ratio to the control run (Figure 3). The left panels are for the northern hemisphere, while the right are the southern hemisphere. [See the online version for the color version of this figure].

Segura et al., 2010

Result



Photolysis by UV

Recovery 50 years later

Dissociation by NO_x produced by proton

Max depletion of 94%, 2 years later

The lower ozone concentrations produced by the flare may still be detectable by missions such as Terrestrial Planet Finder or Darwin, given that an ozone column depth as low as **$3 * 10^{17}$ cm ^{2}** produces a potentially detectable feature in the mid-IR planetary spectrum (**Table 1, Fig. 13a in Segura et al., 2003**).

At the maximum depletion, the O3 column depth was **$1.1*10^{18}$ cm ^{2}**. This is 15 times lower than the initial O3 column depth for the AD Leo planet and 7.5 times lower than the O3 column depth cal- culated for present Earth by our model.

Segura et al., 2010

Change of the UV Flux

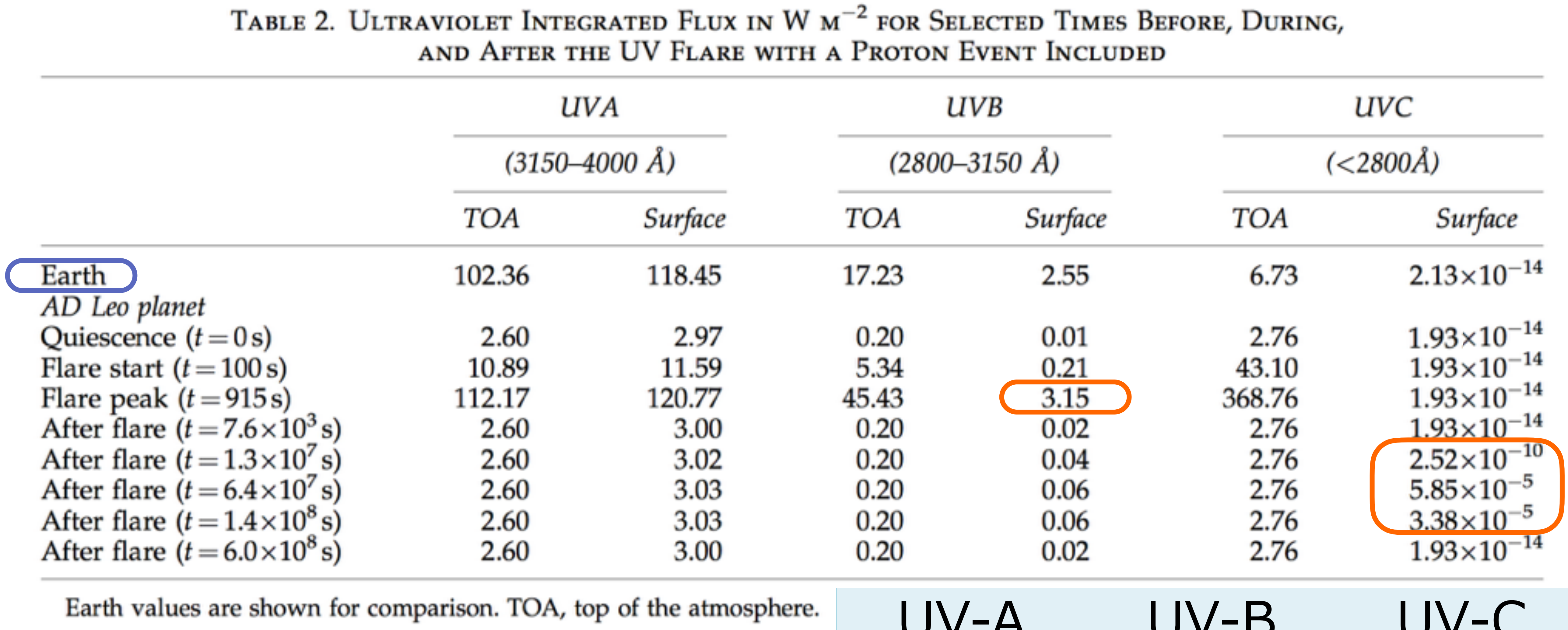


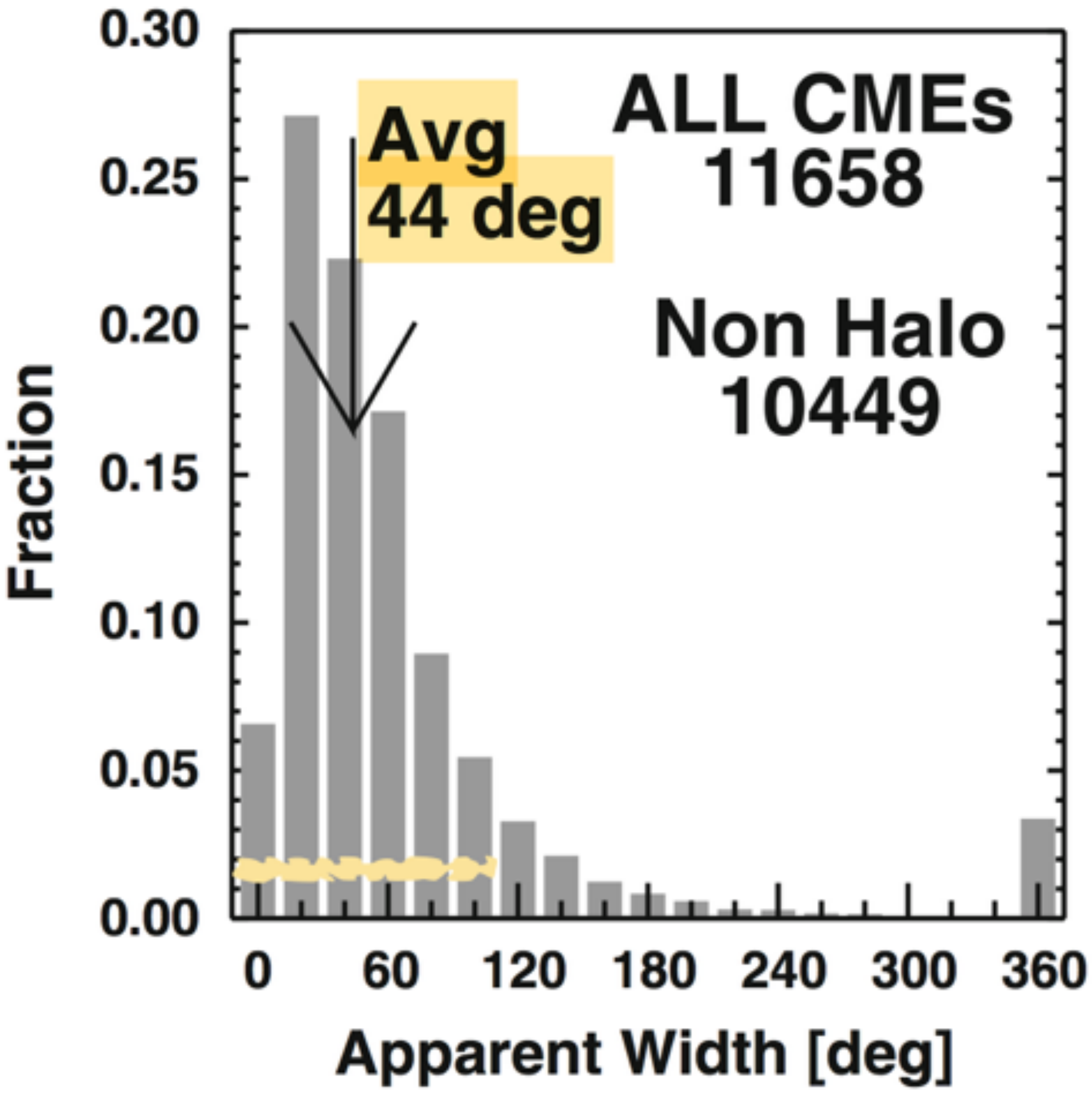
TABLE 2. ULTRAVIOLET INTEGRATED FLUX IN W M^{-2} FOR SELECTED TIMES BEFORE, DURING, AND AFTER THE UV FLARE WITH A PROTON EVENT INCLUDED

	UVA		*UVB*		*UVC*	
	(3150–4000 Å)		*(2800–3150 Å)*		*(<2800Å)*	
	TOA	*Surface*	*TOA*	*Surface*	*TOA*	*Surface*
Earth	102.36	118.45	17.23	2.55	6.73	2.13×10^{-14}
AD Leo planet						
Quiescence ($t=0$ s)	2.60	2.97	0.20	0.01	2.76	1.93×10^{-14}
Flare start ($t=100$ s)	10.89	11.59	5.34	0.21	43.10	1.93×10^{-14}
Flare peak ($t=915$ s)	112.17	120.77	45.43	3.15	368.76	1.93×10^{-14}
After flare ($t=7.6\times10^{3}$ s)	2.60	3.00	0.20	0.02	2.76	1.93×10^{-14}
After flare ($t=1.3\times10^{7}$ s)	2.60	3.02	0.20	0.04	2.76	2.52×10^{-10}
After flare ($t=6.4\times10^{7}$ s)	2.60	3.03	0.20	0.06	2.76	5.85×10^{-5}
After flare ($t=1.4\times10^{8}$ s)	2.60	3.03	0.20	0.06	2.76	3.38×10^{-5}
After flare ($t=6.0\times10^{8}$ s)	2.60	3.00	0.20	0.02	2.76	1.93×10^{-14}

Earth values are shown for comparison. TOA, top of the atmosphere.

UV-A	UV-B	UV-C
3150-4000 Å	2800-3150 Å	<2800 Å
Safer than B or C by the factor of a hundred	A bit dangerous	More dangerous !!

Estimation of Frequency

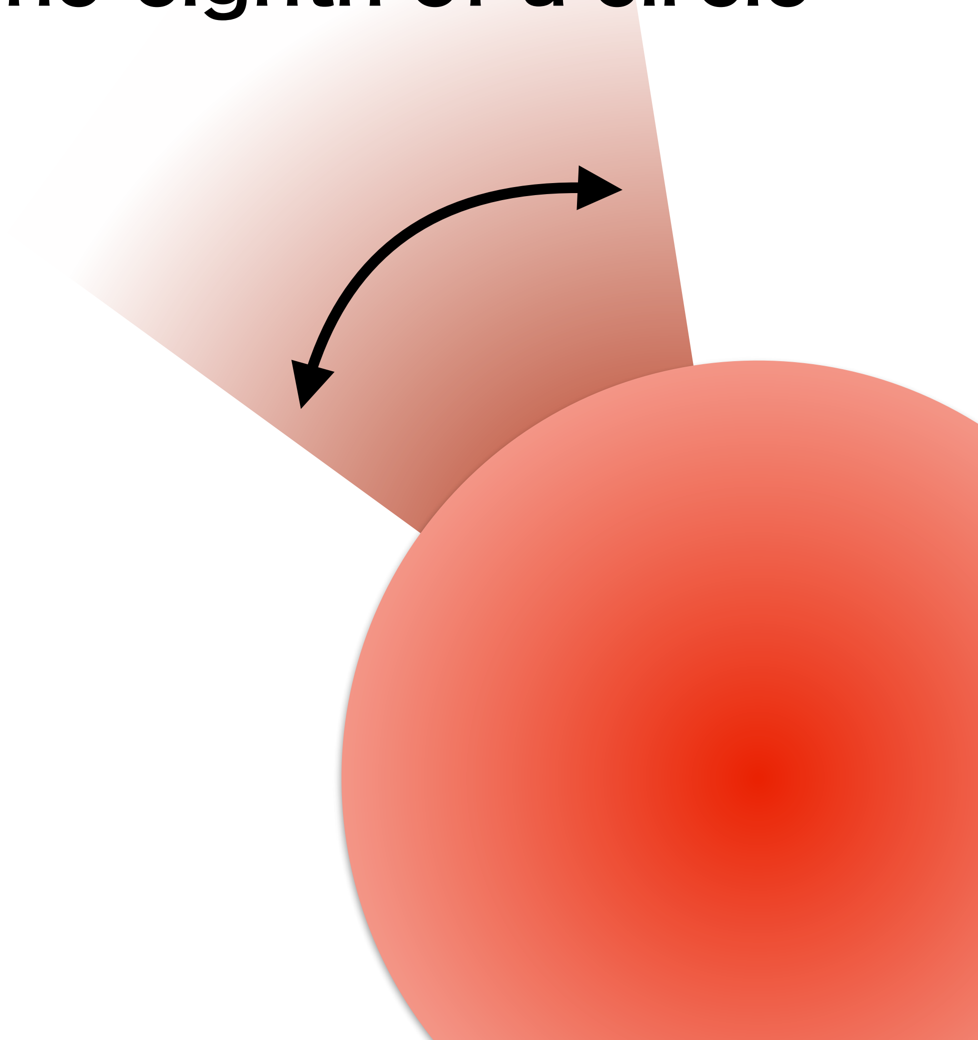


[Gopalswamy et al., 2009]

Hit more than once every ten flares

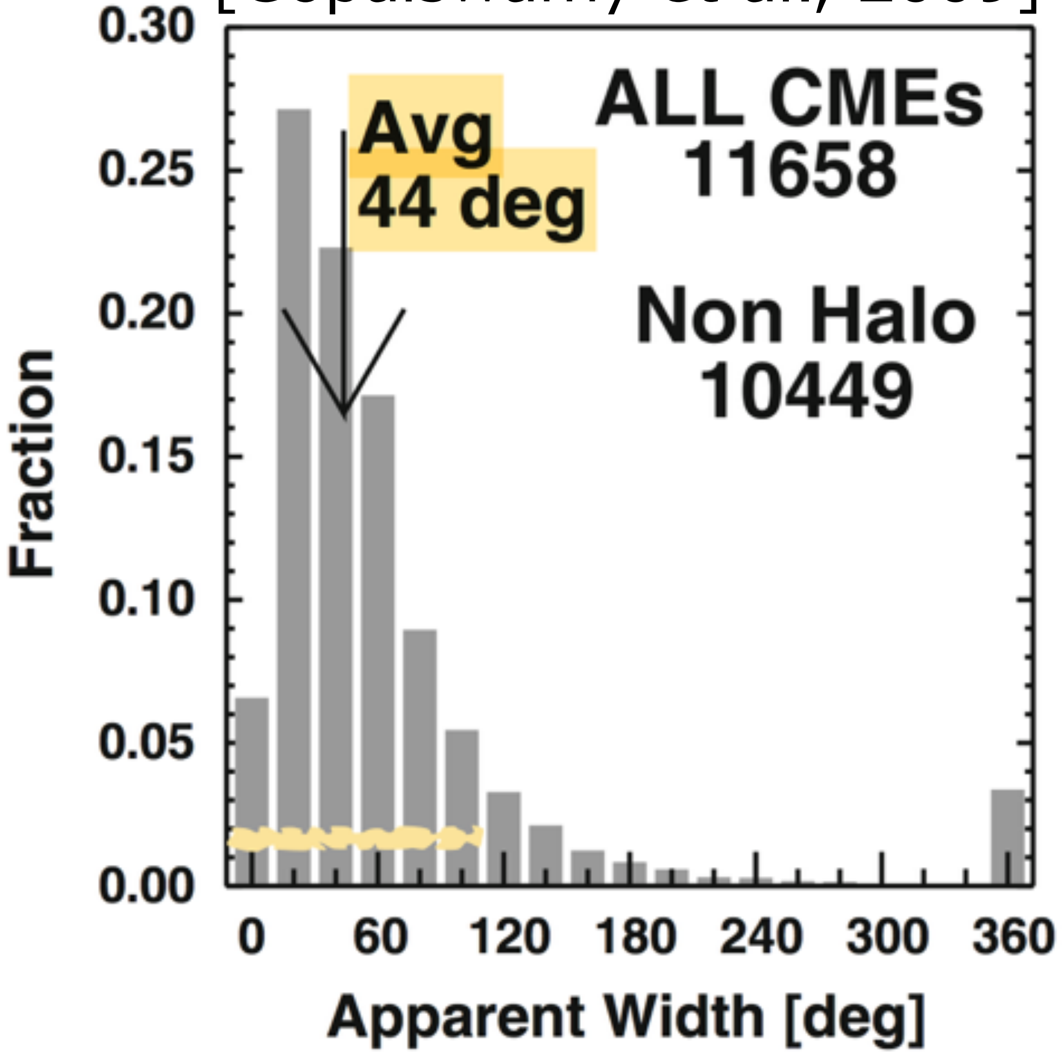
44 deg

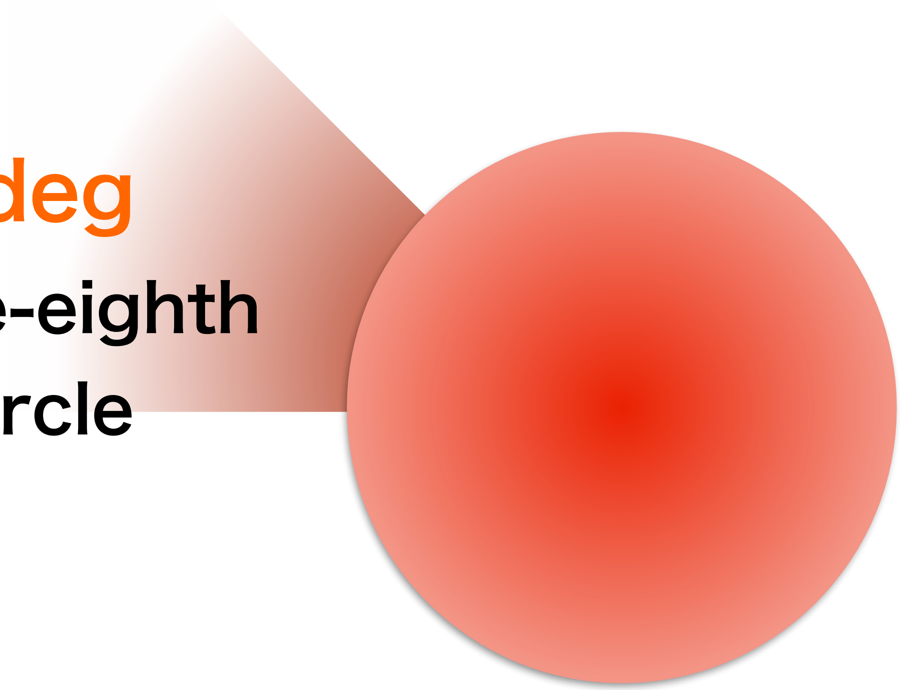
～ **One-eighth of a circle**



Estimation of Frequency

[Gopalswamy et al., 2009]

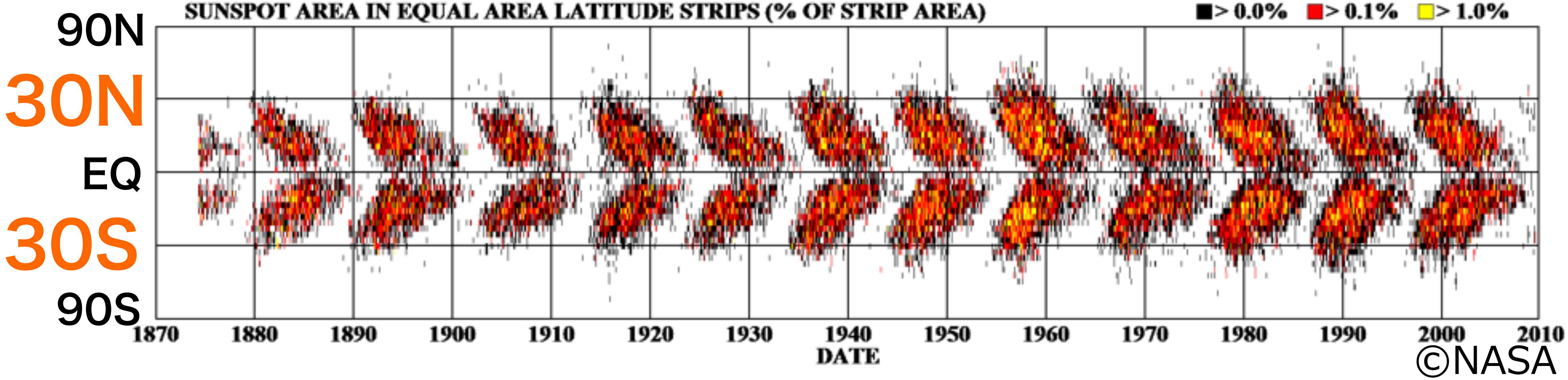




44 deg

～ One-eighth of a circle

Planetary orbits is in the **equatorial plane** of the star around which **flares occur**



©NASA

Gopalswamy *et al.*, 2009

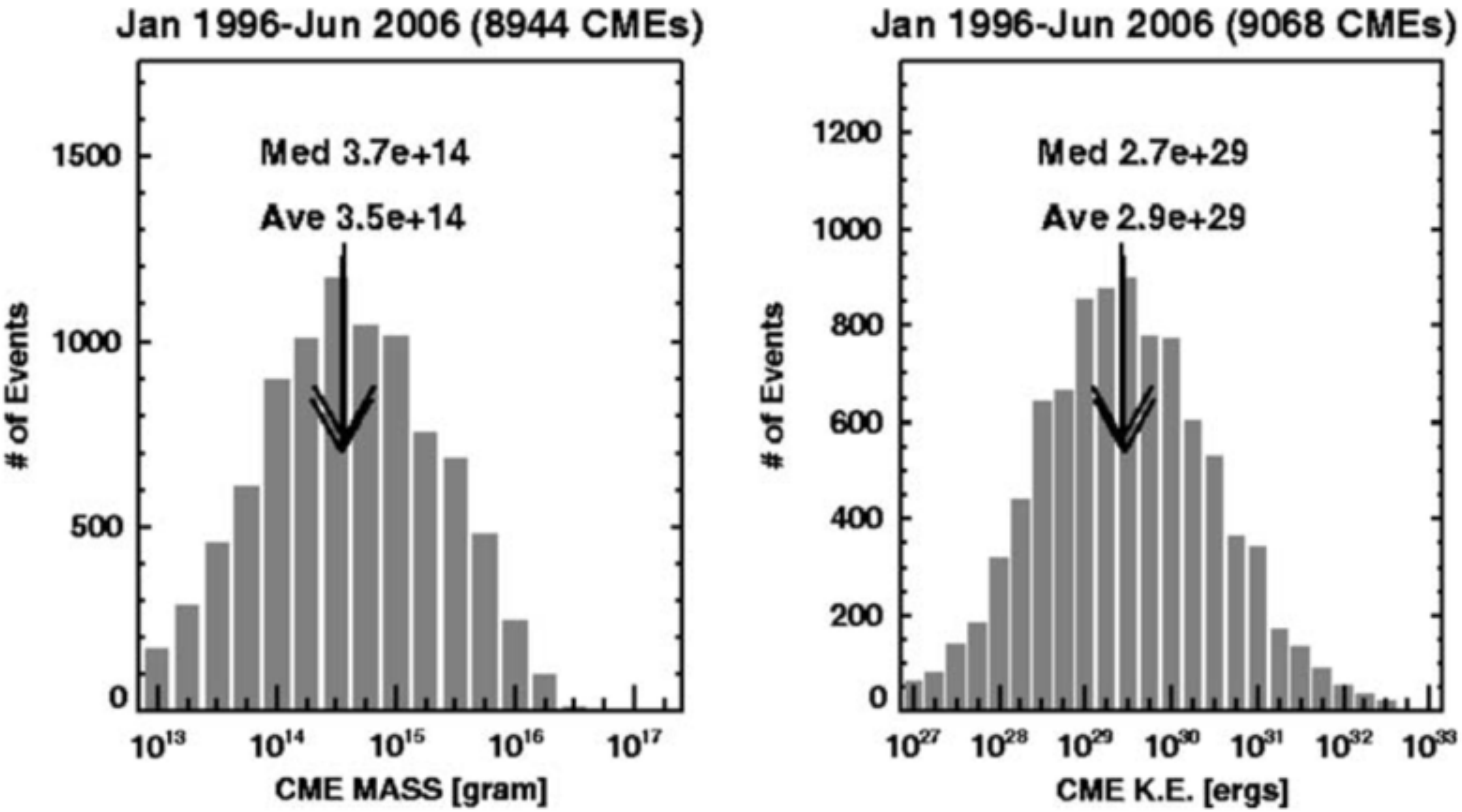


Fig. 11 Distributions of CME mass and kinetic energy of all CMEs for which mass and speed measurements were possible. The average (Ave) and median (Med) values of the distributions are shown on the plots

*20% of CMEs may not have been detected by LASCO because they are either masked by the occulting disk or they are back-sided. (Yashiro+, 2005)

Lower Energy Flares are More Frequent

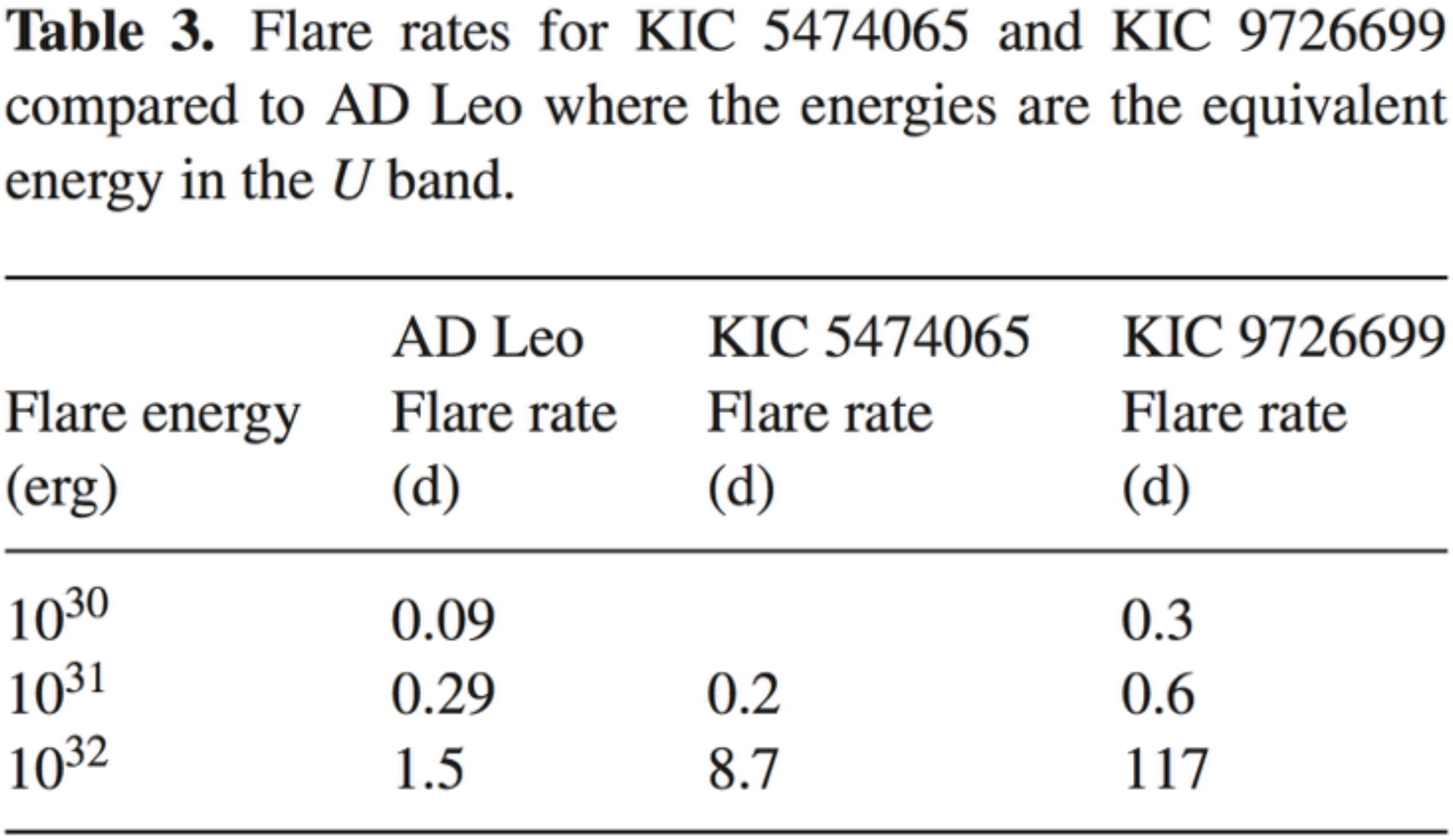


Table 3. Flare rates for KIC 5474065 and KIC 9726699 compared to AD Leo where the energies are the equivalent energy in the *U* band.

Flare energy (erg)	AD Leo Flare rate (d)	KIC 5474065 Flare rate (d)	KIC 9726699 Flare rate (d)
10^{30}	0.09		0.3
10^{31}	0.29	0.2	0.6
10^{32}	1.5	8.7	117

[Ramsay et al., 2013]

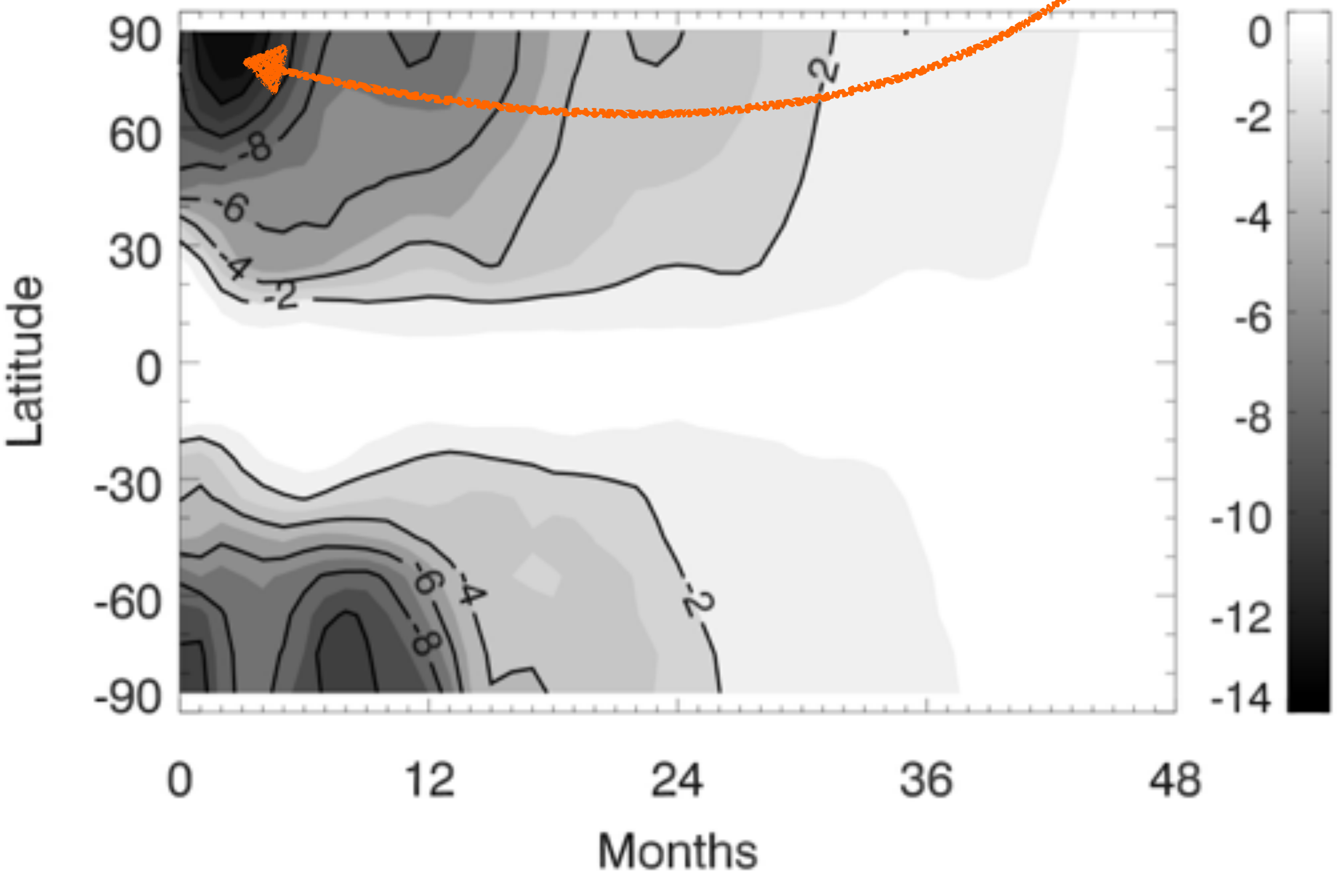
- When the energy of flares becomes **~10 times** smaller, its frequency becomes **~10 times**

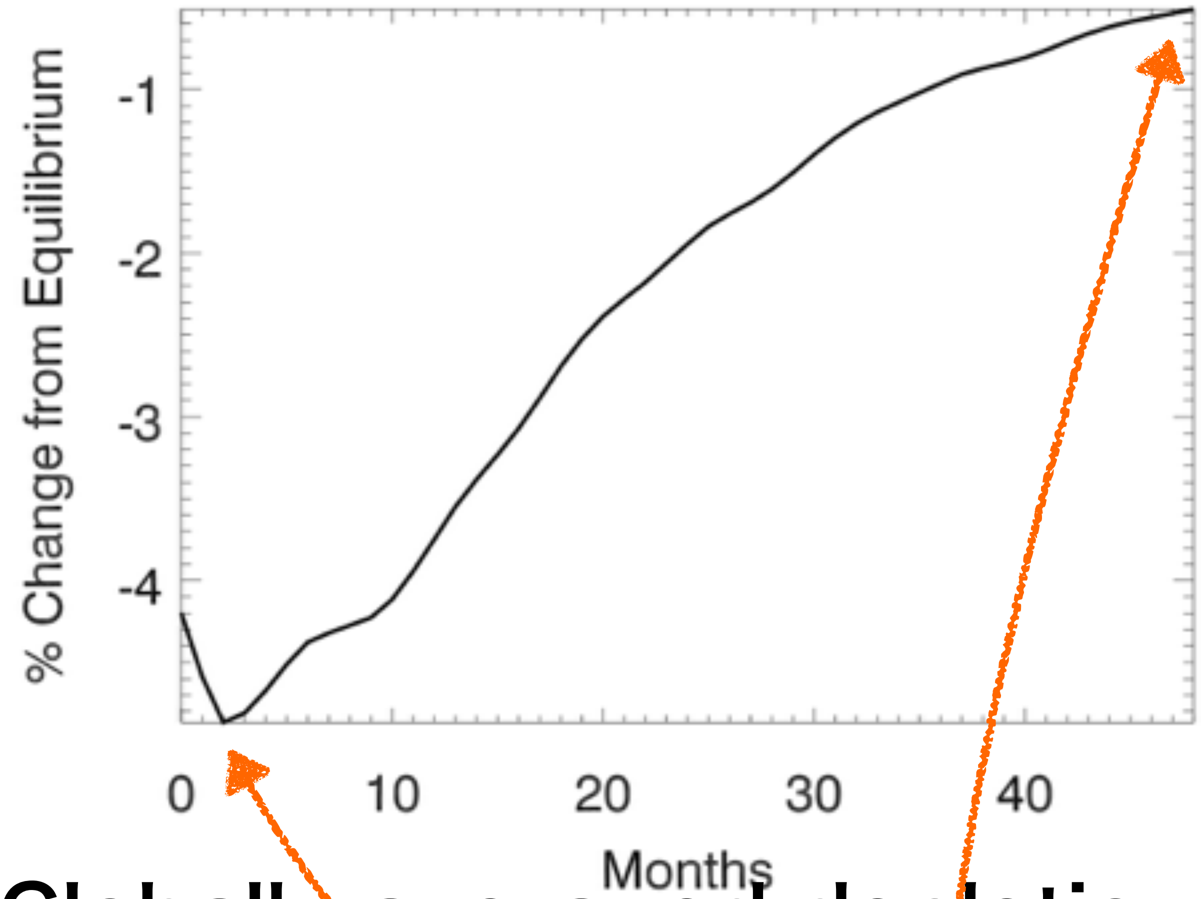
Segura et al., 2010

The Earth with a Magnetic Field

Thomas et al. (2007) simulated the effect of Carrington event of the Sun on the Earth with 2-D and 3-D models.

The maximum ozone depletion at high latitudes reaches 14%





Globally averaged depletion reaches only 5% and predicted recovery time is about 4 years