Sun-as-a-star observations to characterize stellar active regions and universal atmospheric heating mechanism

Shin Toriumi

Japan Aerospace Exploration Agency (JAXA)

Space Climate 8 (September 20, 2022)

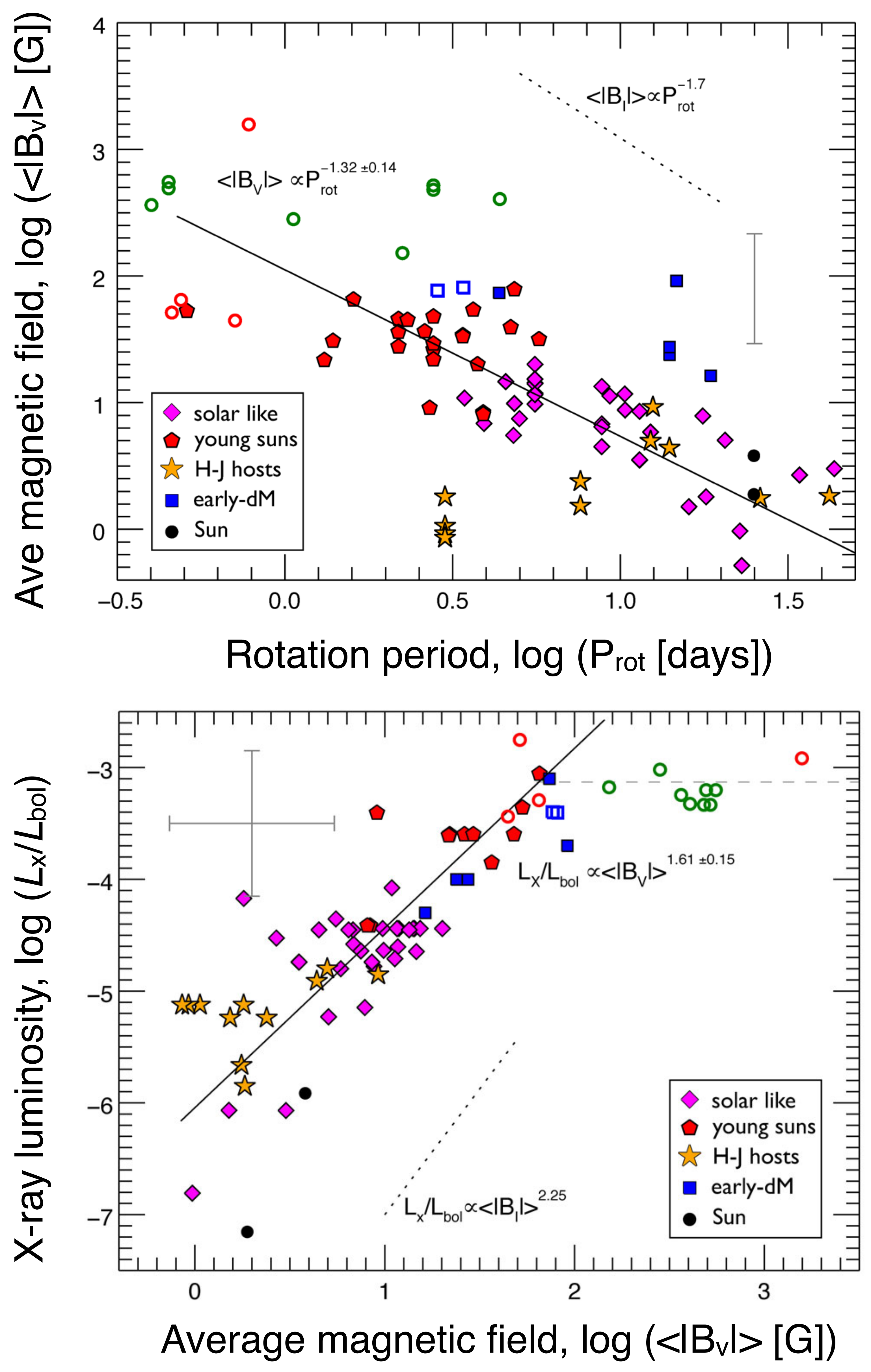
1. Introduction

Some importance of Sun-as-a-star studies

- On solar-like stars…

  Rotation speed — Mag field strength — X-ray luminosity
  (≒ **Rossby number**) (≒ **Total mag flux**)

  show strong correlations[1]



[Vidotto+ 2014]

[1: Skumanich 1972; Pizzolato+ 2003; Wright+ 2011; Vidotto+ 2014]

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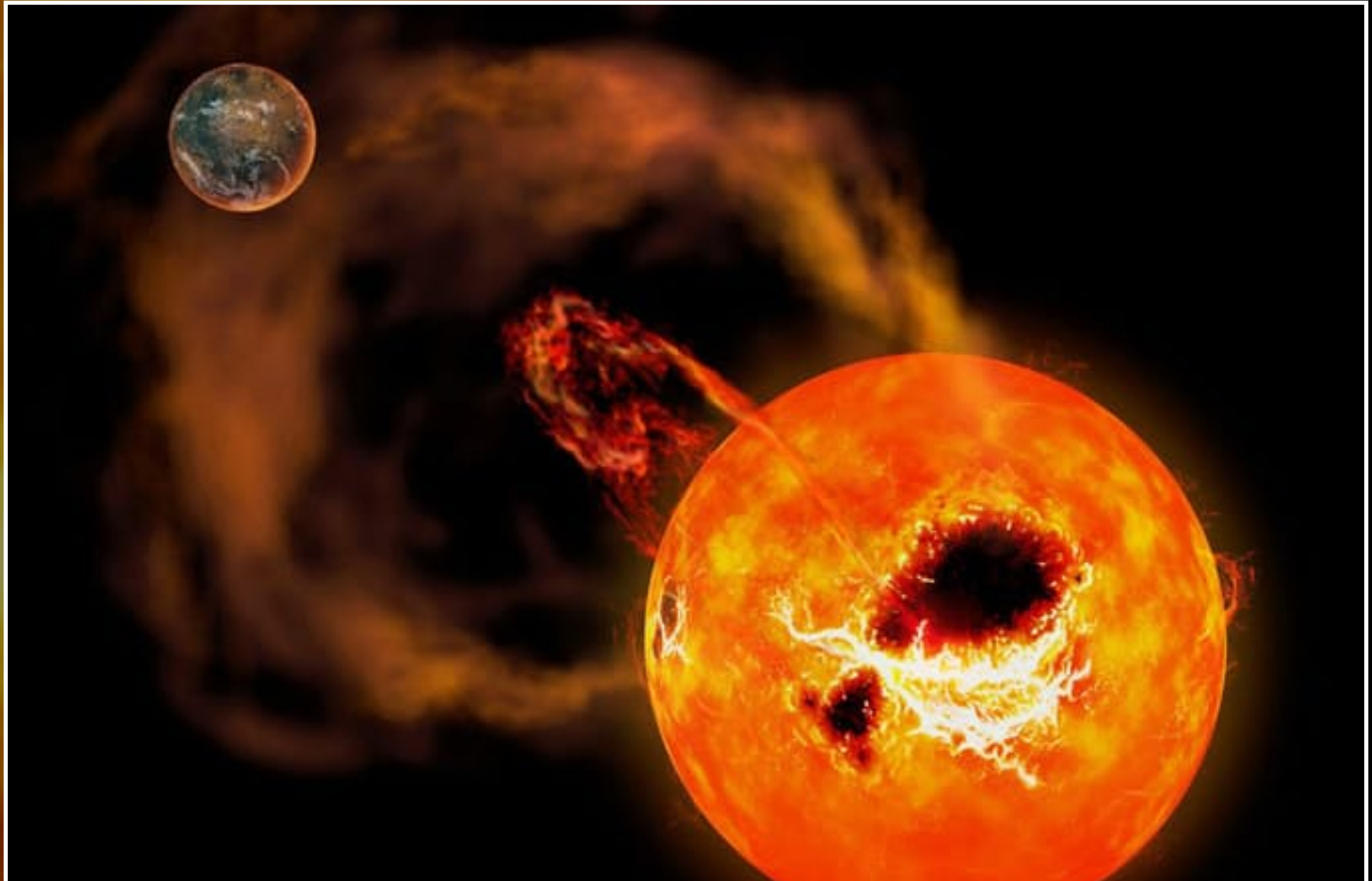
Flares & CMEs: Giant sunspots, huge flares and CMEs

⬇

How can we characterize stellar active regions?



Superflare on Sun-like stars

[1: Skumanich 1972; Pizzolato+ 2003; Wright+ 2011; Vidotto+ 2014]

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  (≒ **Rossby number**) (≒ **Total mag flux**)

  show strong correlations[1]

Flares & CMEs: Giant sunspots, huge flares and CMEs

↓

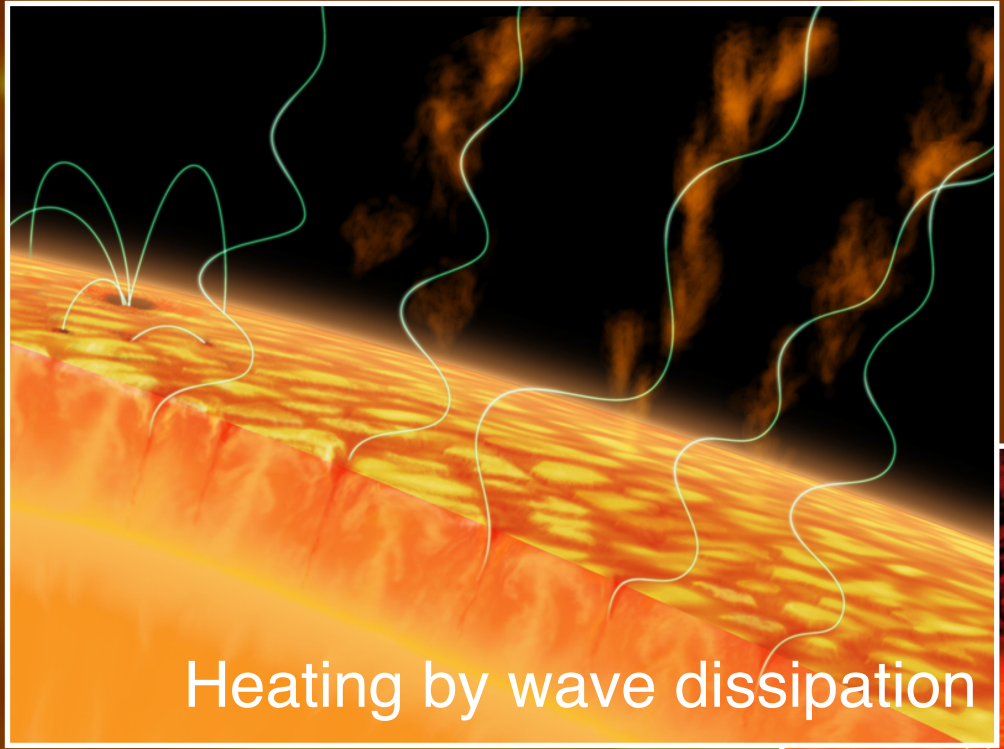
How can we characterize stellar active regions?

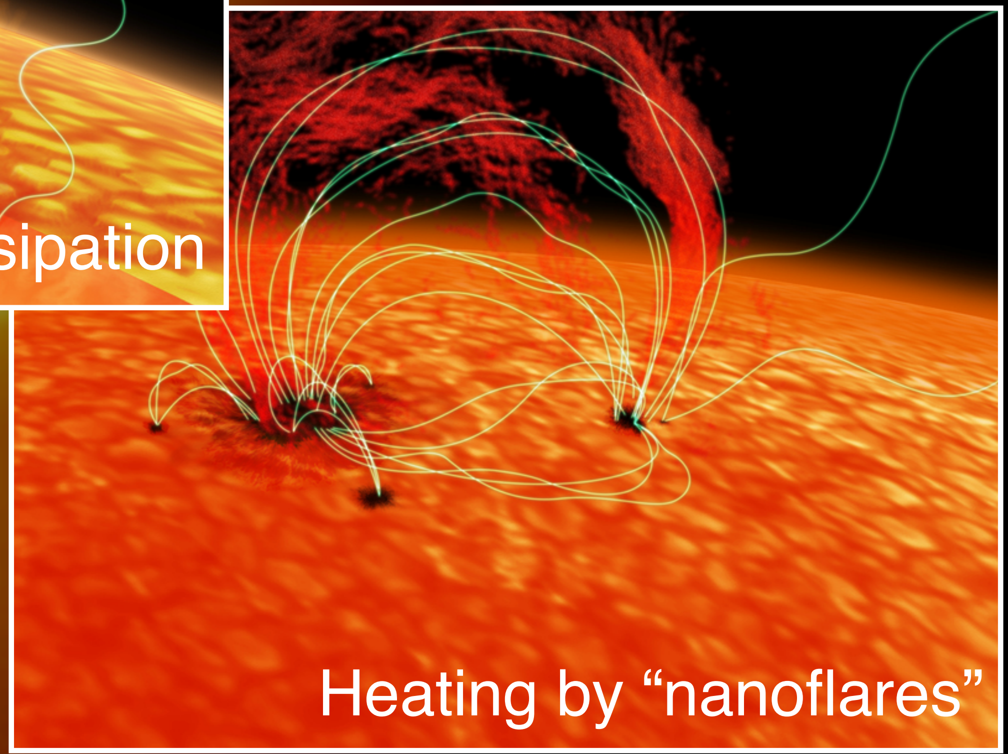
Extremely hot atmospheres: Strong XUV emission and winds

↓

Do solar-like stars share common heating mechanism?


Superflare on Sun-like stars


Heating by wave dissipation


Heating by “nanoflares”

[1: Skumanich 1972; Pizzolato+ 2003; Wright+ 2011; Vidotto+ 2014]

2. Characterization of Stellar ARs

[Toriumi et al. 2020]

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Sun-as-a-star Spectral Irradiance Observations of Transiting Active Regions

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Abstract

Major solar flares are prone to occur in active-region (AR) atmospheres associated with large, complex, dynamically evolving sunspots. This points to the importance of monitoring the evolution of starspots, not only in visible but also in ultraviolet (UV) and X-rays, in understanding the origin and occurrence of stellar flares. To this end, we perform spectral irradiance analysis on different types of transiting solar ARs by using a variety of full-disk synoptic observations. The target events are an isolated sunspot, spotless plage, and emerging flux in prolonged quiet-Sun conditions selected from the past decade. We find that the visible continuum and total solar irradiance become darkened when the spot is at the central meridian, whereas it is bright near the solar limb; UV bands sensitive to the chromosphere correlate well with the variation of total unsigned magnetic flux in the photosphere; amplitudes of extreme ultraviolet (EUV) and soft X-ray increase with the characteristic temperature, whose light curves are flat-topped due to their sensitivity to the optically thin corona; the transiting spotless plage does not show the darkening in the visible irradiance, while the emerging flux produces an asymmetry in all light curves about the central meridian. The multiwavelength Sun-as-a-star study described here indicates that the time lags between the coronal and photospheric light curves have the potential to probe the extent of coronal magnetic fields above the starspots. In addition, EUV wavelengths that are sensitive to temperatures just below 1 MK sometimes show antiphased variations, which may be used for diagnosing plasmas around starspots.

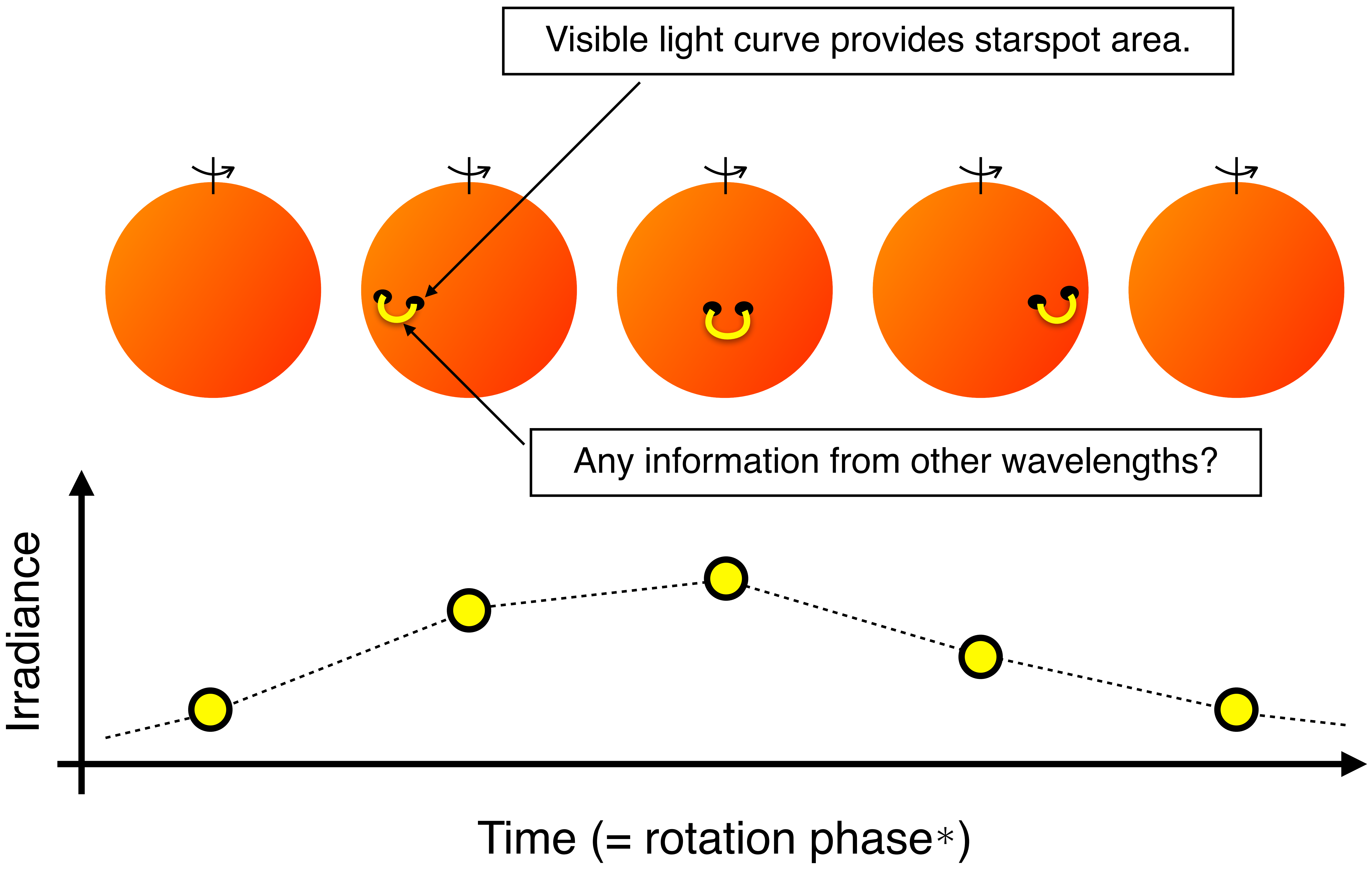
Unified Astronomy Thesaurus concepts: Solar spectral irradiance (1501); Sunspots (1653); Solar active regions (1974); Solar flares (1496); Solar analogs (1941); Starspots (1572); Stellar flares (1603); Time domain astronomy (2109)

Supporting material: animations

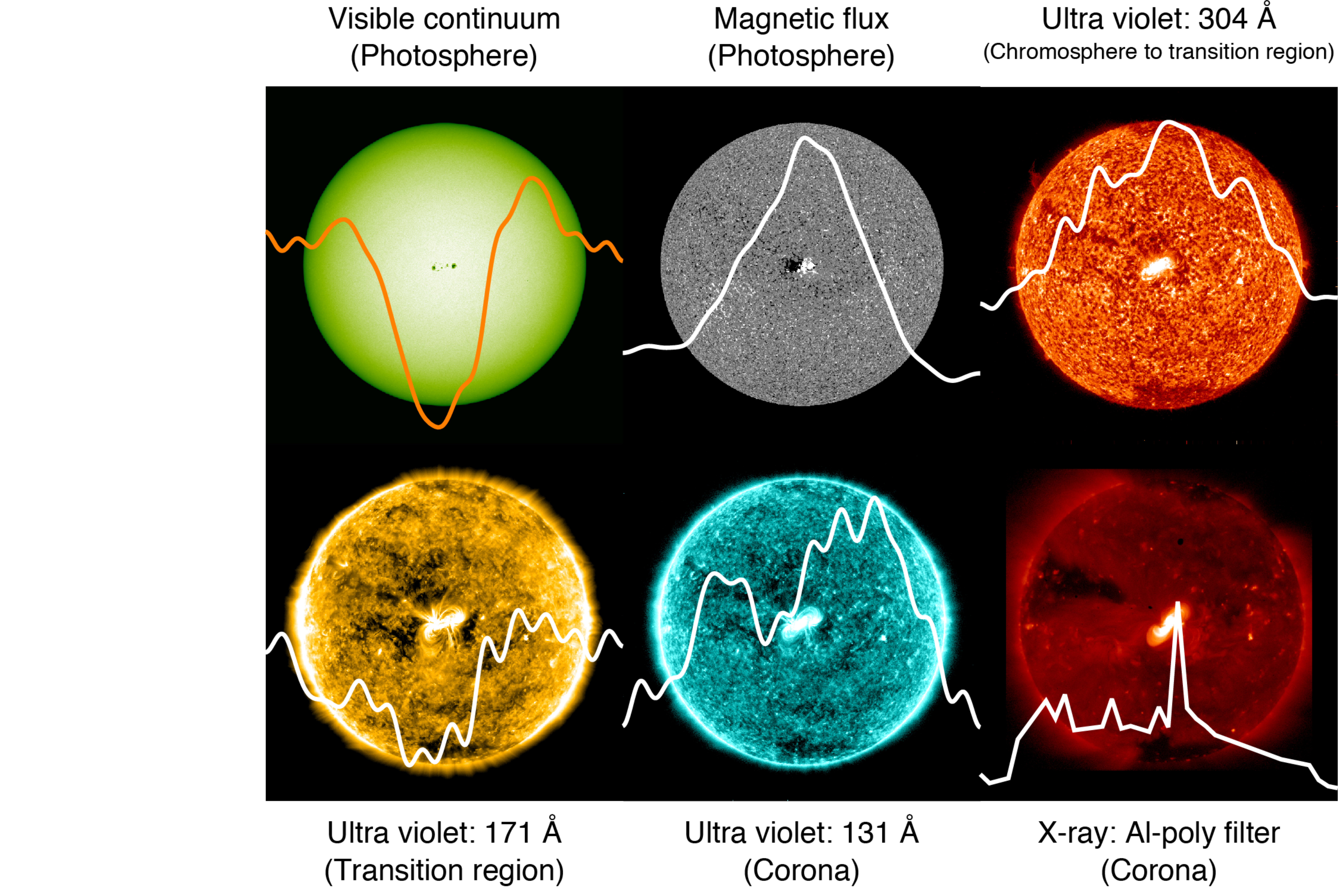
2. Characterization of Stellar ARs

- Sun-as-a-star light curves
  - Monitor starspots **not only in visible but also in UV and X-rays** to track atmospheric evolution
    → Test this possibility using solar data
  - Plot full-disk light curves in various wavelengths when **only a single sunspot group transits** across the solar disk in prolonged quiet-Sun conditions
  - Instruments
    - SDO/HMI: visible imaging, magnetic fields
    - SDO/AIA: UV and EUV imaging
    - Hinode/XRT: soft X-ray imaging
    - GOES/XRS: soft X-ray (no spatial res)
    - SORCE/TIM: total solar irradiance (no spatial res)

    → 14 wavelengths in total



[Toriumi et al. 2020]

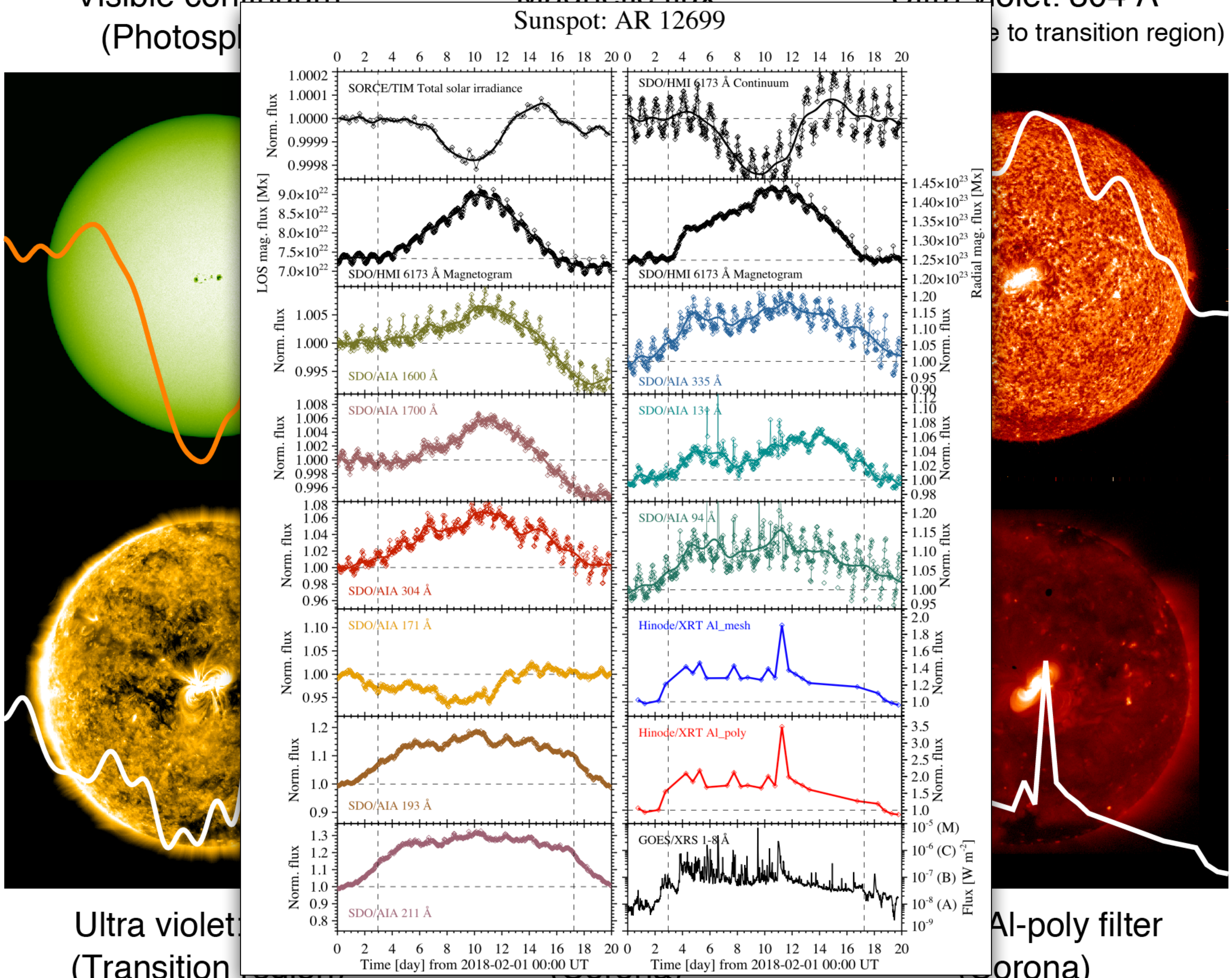


Visible continuum (Photosp

Magnetic flux

Ultra violet: 304 Å (…e to transition region)

[Toriumi et al. 2020]



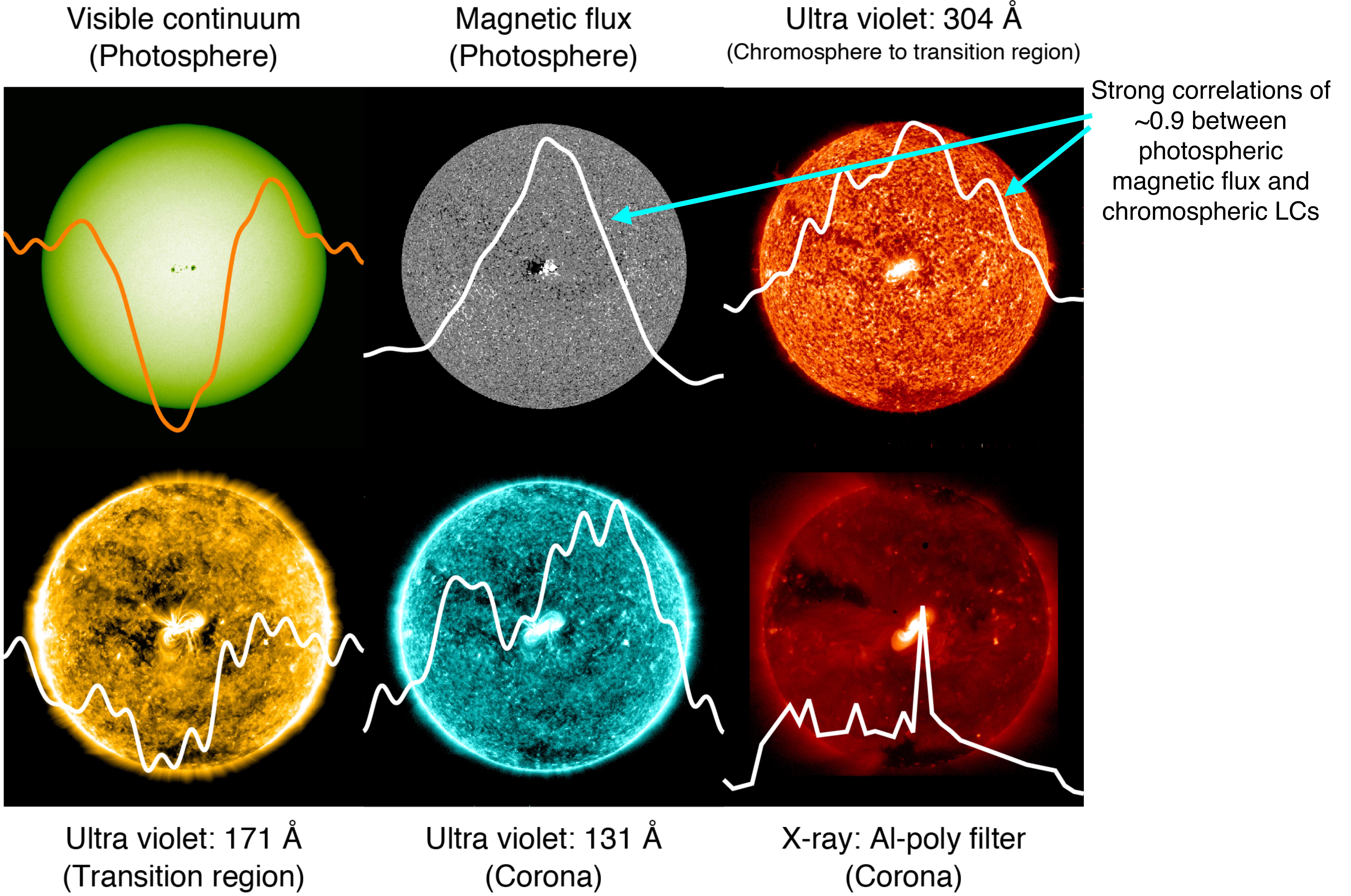
Ultra violet: (Transition region)

(Corona)

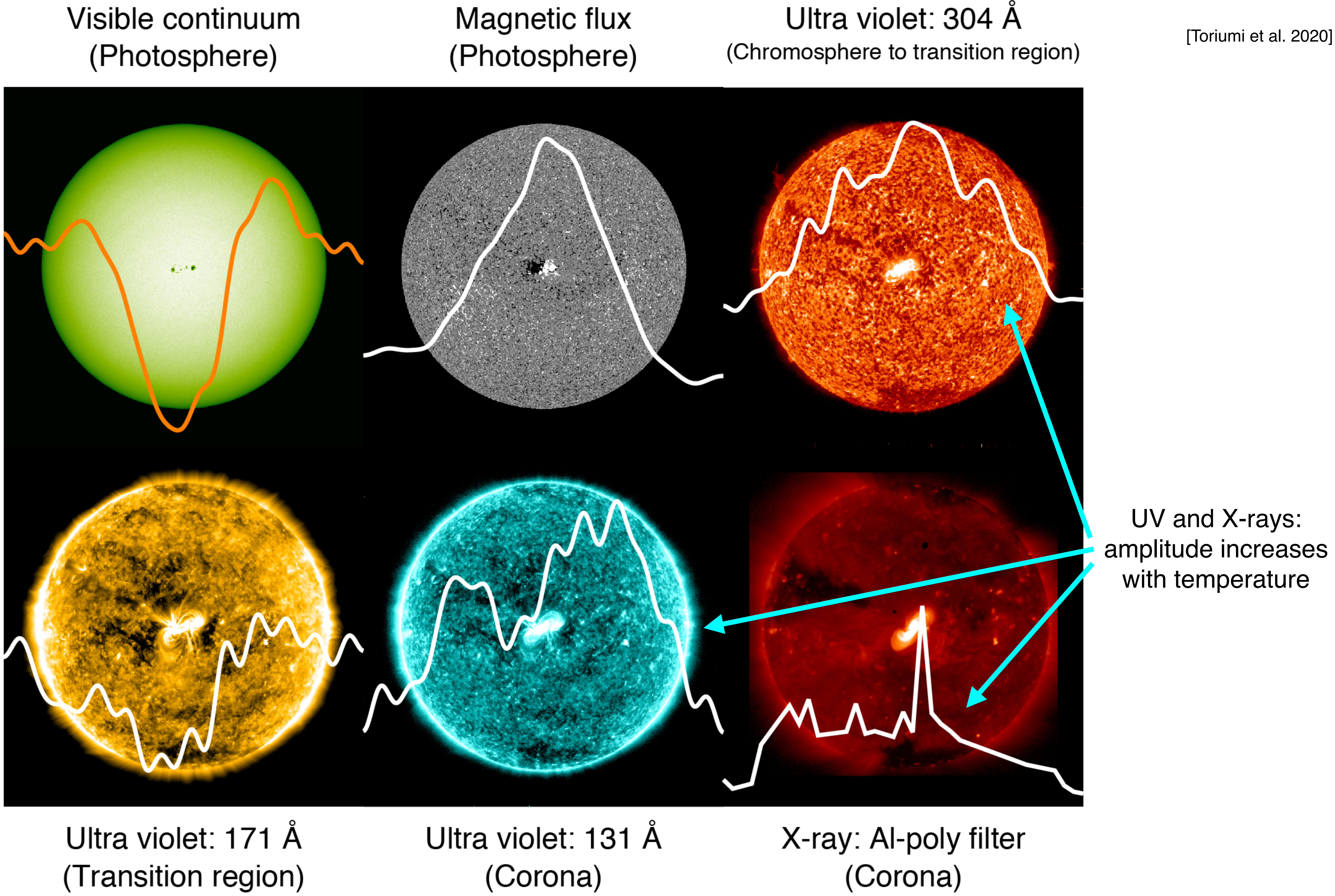
Al-poly filter (Corona)

Visible continuum
(Photosphere)
Magnetic flux
(Photosphere)
Ultra violet: 304 Å
(Chromosphere to transition region)
[Toriumi et al. 2020]
Ultra violet: 171 Å
(Transition region)
Ultra violet: 131 Å
(Corona)
X-ray: Al-poly filter
(Corona)


[Toriumi et al. 2020]
Visible continuum
(Photosphere)
Magnetic flux
(Photosphere)
Ultra violet: 304 Å
(Chromosphere to transition region)
"Shoulders": faculae are dominant
"Dip": sunspot is dark
Ultra violet: 171 Å
(Transition region)
Ultra violet: 131 Å
(Corona)
X-ray: Al-poly filter
(Corona)



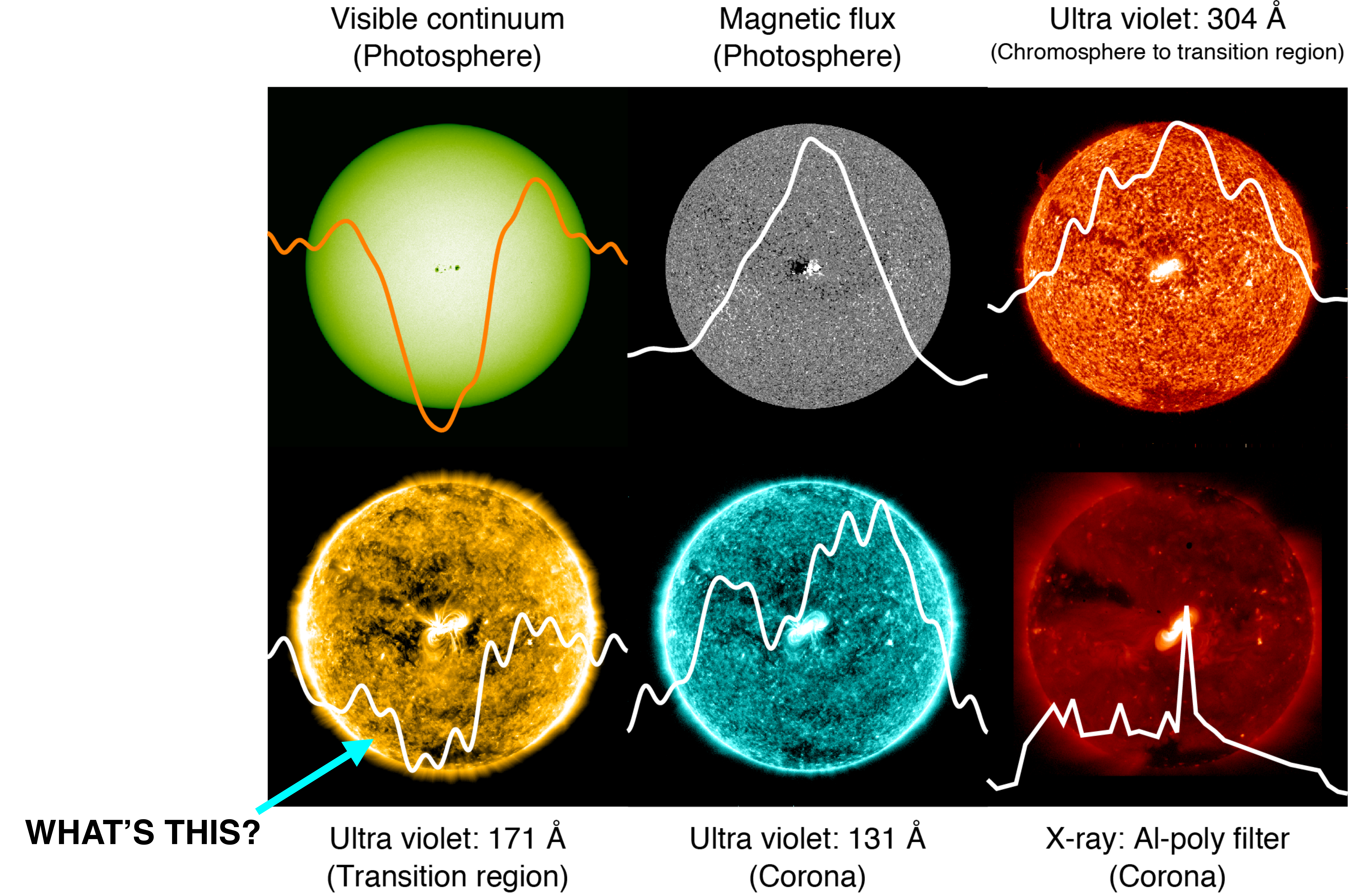
Visible continuum
(Photosphere)
Magnetic flux
(Photosphere)
Ultra violet: 304 Å
(Chromosphere to transition region)
Strong correlations of ~0.9 between photospheric magnetic flux and chromospheric LCs
Ultra violet: 171 Å
(Transition region)
Ultra violet: 131 Å
(Corona)
X-ray: Al-poly filter
(Corona)


Visible continuum
(Photosphere)
Magnetic flux
(Photosphere)
Ultra violet: 304 Å
(Chromosphere to transition region)
[Toriumi et al. 2020]
UV and X-rays:
amplitude increases
with temperature
Ultra violet: 171 Å
(Transition region)
Ultra violet: 131 Å
(Corona)
X-ray: Al-poly filter
(Corona)

[Toriumi et al. 2020]

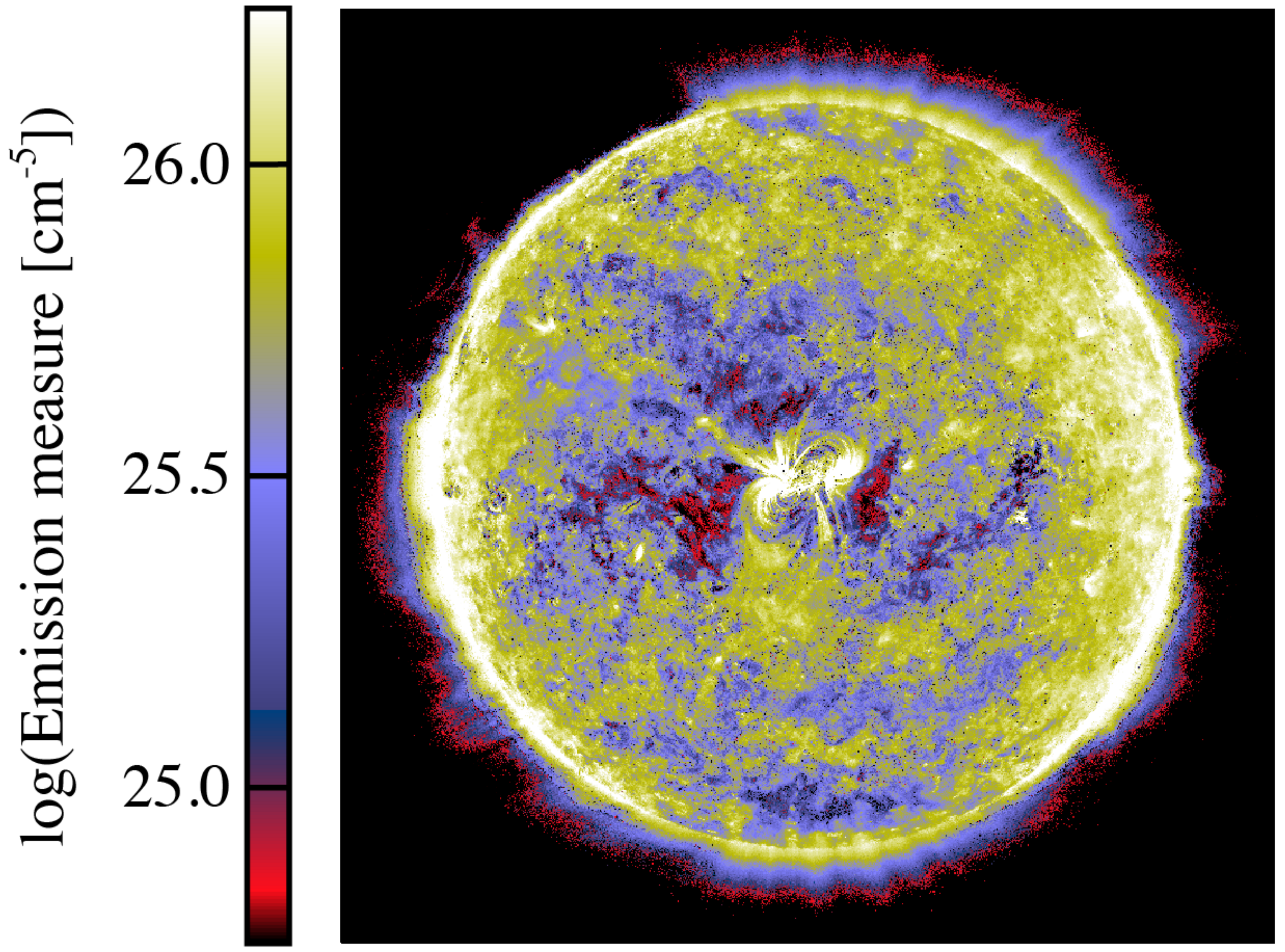

Visible continuum
(Photosphere)
Magnetic flux
(Photosphere)
Ultra violet: 304 Å
(Chromosphere to transition region)
Time lags due
to extended
coronal loops
Ultra violet: 171 Å
(Transition region)
Ultra violet: 131 Å
(Corona)
X-ray: Al-poly filter
(Corona)

[Toriumi et al. 2020]

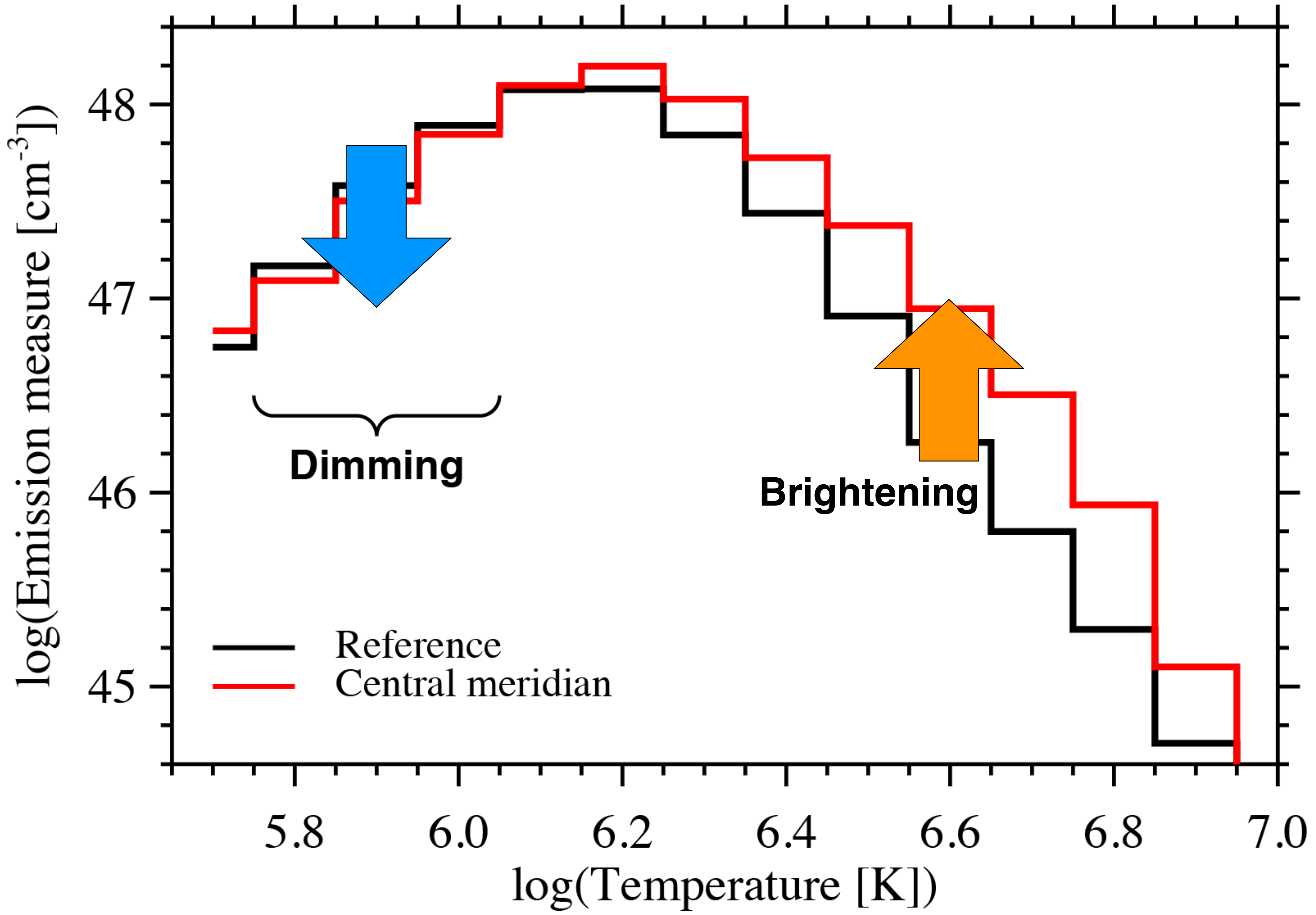


2. Characterization of Stellar ARs

- Differential Emission Measure inversion: $\mathrm{EM} = \int n_\mathrm{e}^2 \, dV$
  - Emission measure as a function of temperature



Emission measure: logT=[5.75, 6.05]



- EM of TR temperatures (0.6-0.8 MK) is reduced over a wide area around AR
- EM of coronal temperatures (>1.5 MK) is all increased

→ Significant heating of plasma, probably owing to AR, over ~40% of the solar disk over ~10 days

See also
- Kazachenko & Husdon (2020)
- Singh, Sterling, & Moore (2021)
- Payne & Sun (2021)

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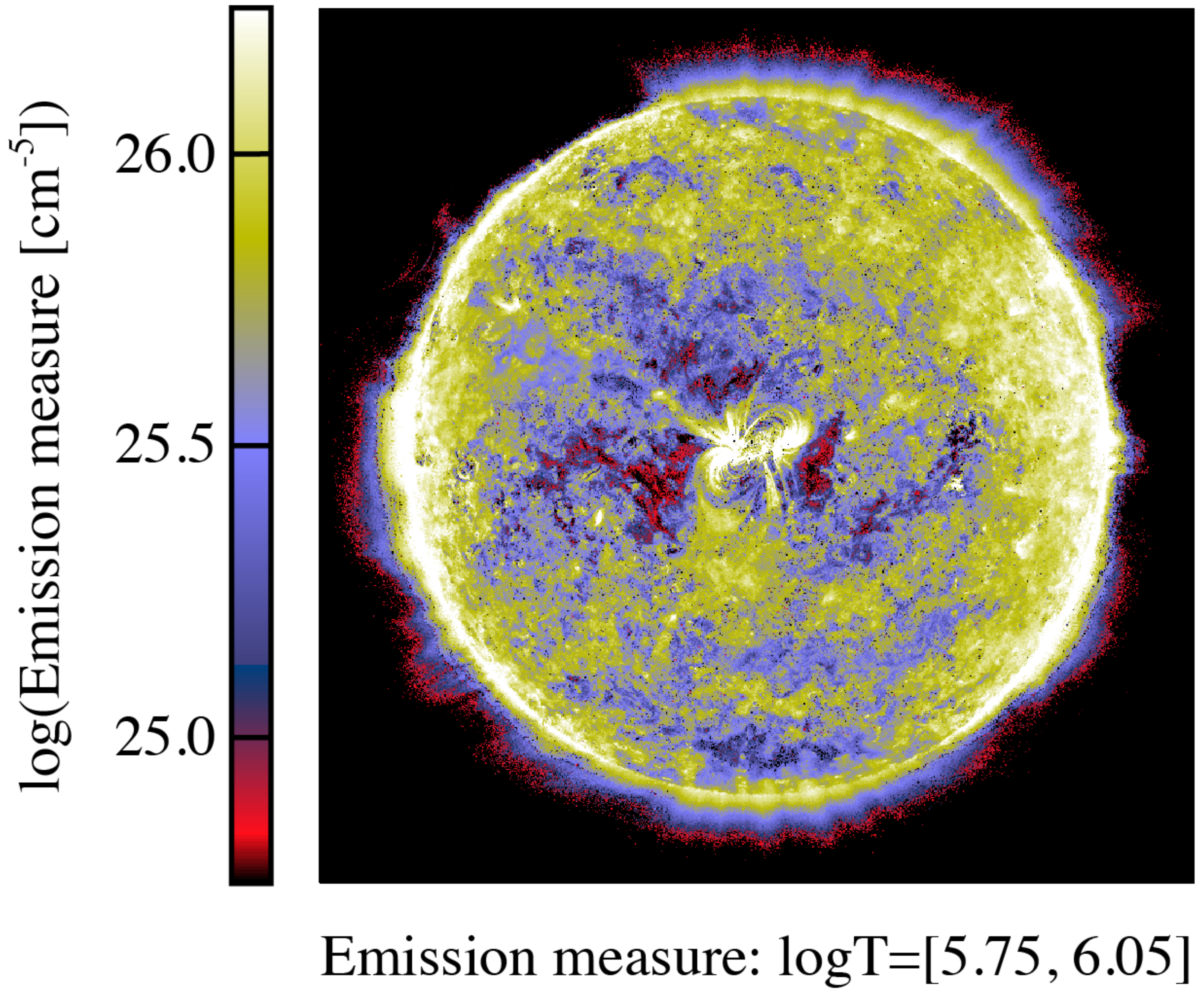

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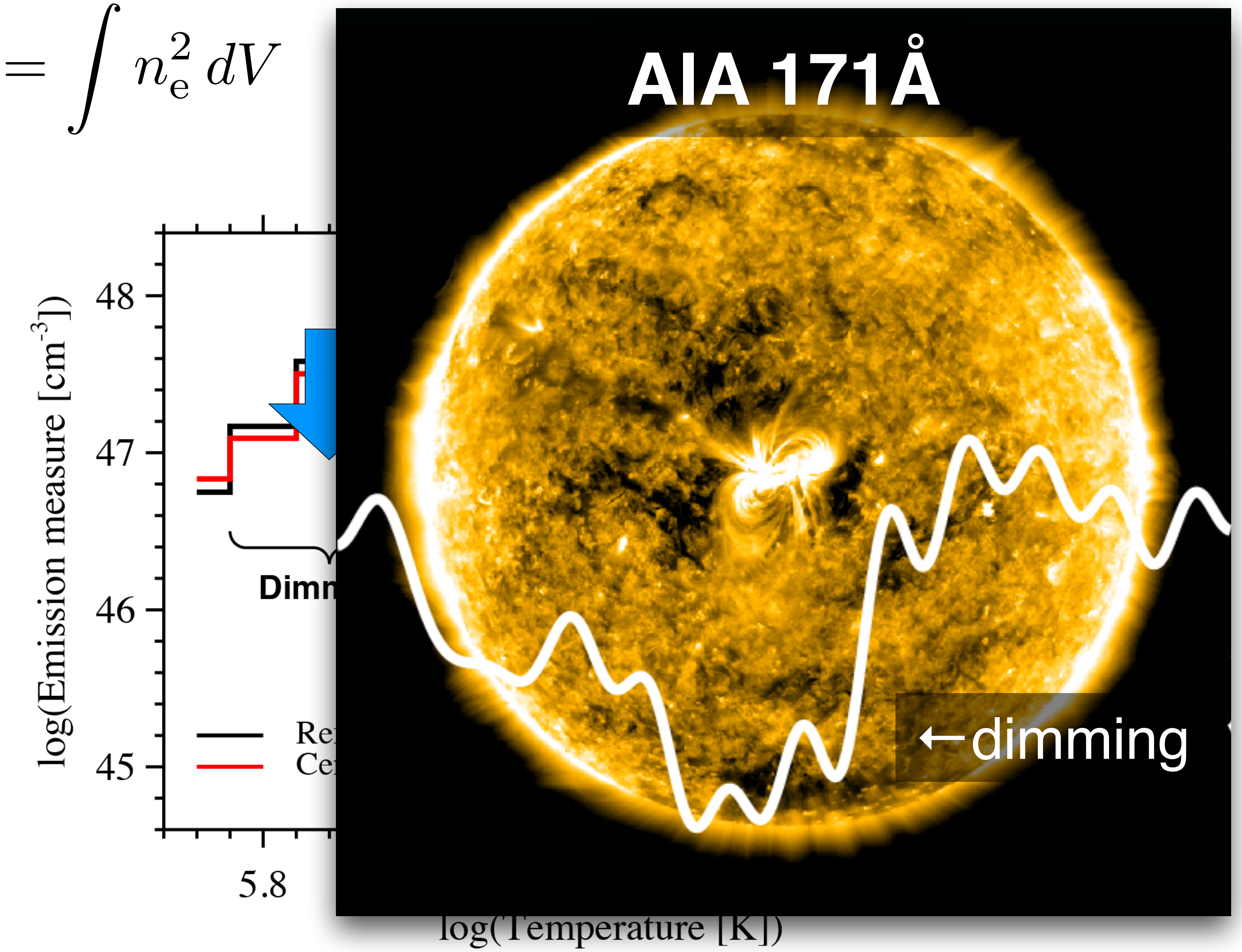

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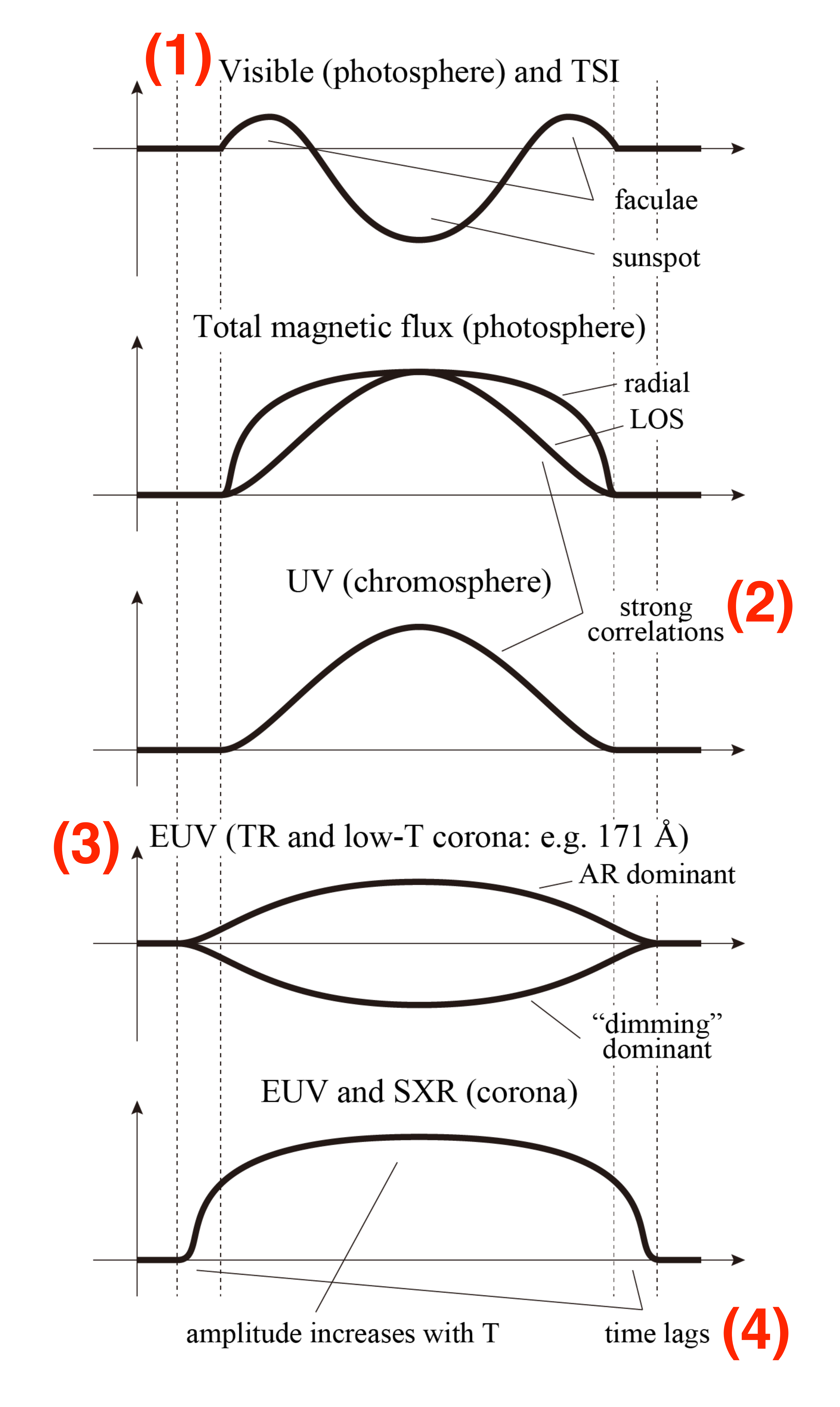
2. Characterization of Stellar ARs

- Possible "tools" for diagnosing stellar ARs
  - (1) **Visible** for starspot size and evolution
  - (2) **Near UV radiations** as the proxy for the total magnetic flux on the stellar surface (like Ca II monitoring)
  - (3) **Extreme UV sensitive to sub-MK** for diagnosing plasmas around starspots
  - (4) **Time lags between the coronal and photospheric curves** for the extension of coronal magnetic fields

Long-term, multi-wavelength monitoring of stars give us clues to understand AR evolutions



[Toriumi & Airapetian 2022]

3. Universality of Atmospheric Heating

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Universal Scaling Laws for Solar and Stellar Atmospheric Heating

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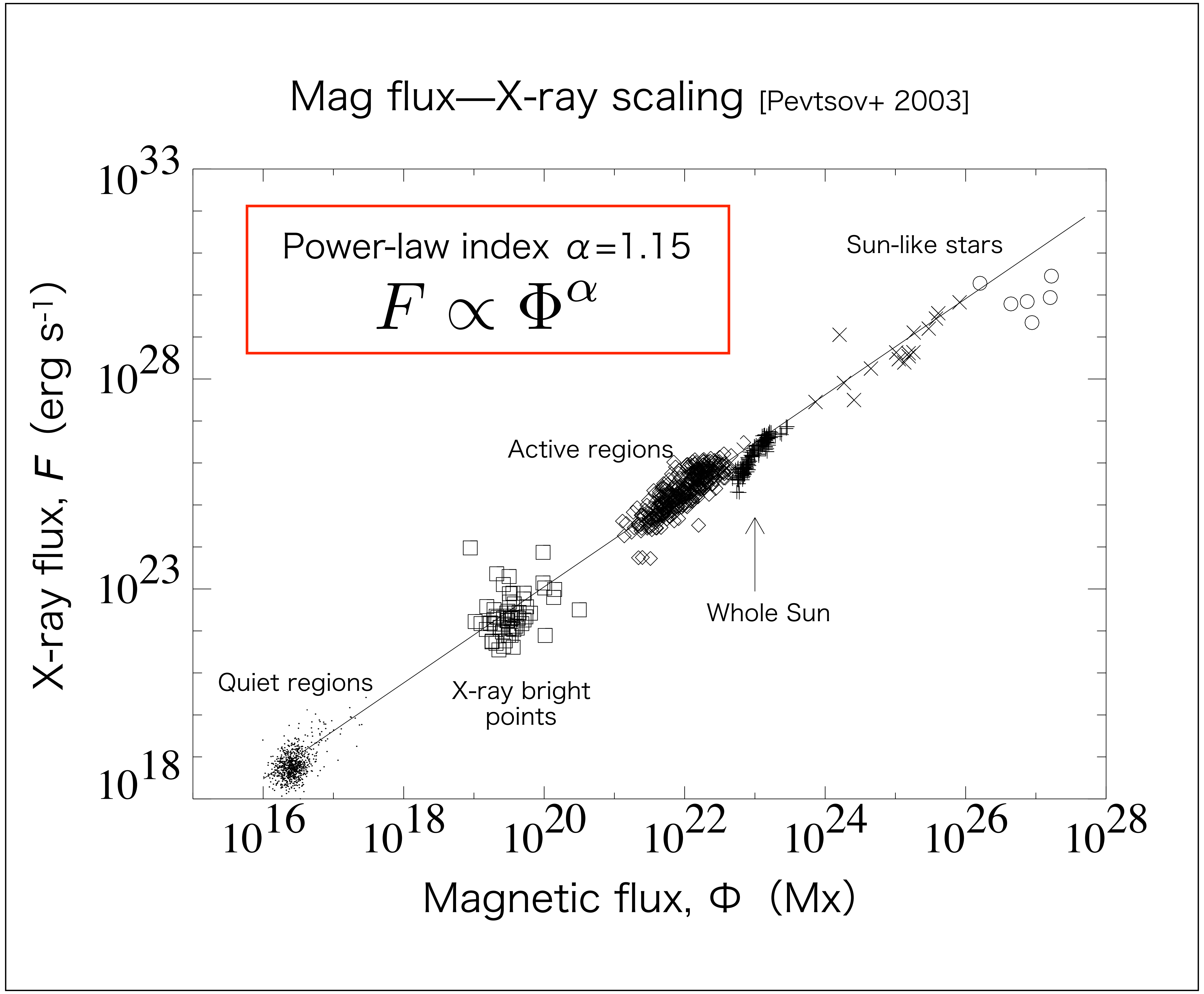
Abstract

The Sun and Sun-like stars commonly host multimillion-kelvin coronae and 10,000 K chromospheres. These extremely hot gases generate X-ray and extreme ultraviolet emissions that may impact the erosion and chemistry of (exo)planetary atmospheres, influencing the climate and conditions for habitability. However, the mechanism of coronal and chromospheric heating is still poorly understood. While the magnetic field most probably plays a key role in driving and transporting energy from the stellar surface upwards, it is not clear whether the atmospheric heating mechanisms of the Sun and active Sun-like stars can be described in a unified manner. To this end, we report on a systematic survey of the responses of solar and stellar atmospheres to surface magnetic flux over a wide range of temperatures. By analyzing 10 years of multiwavelength synoptic observations of the Sun, we reveal that the irradiance and magnetic flux show power-law relations with an exponent decreasing from above unity to below as the temperature decreases from the corona to the chromosphere. Moreover, this trend indicating the efficiency of atmospheric heating can be extended to Sun-like stars. We also discover that the power-law exponent depends on the solar cycle, becoming smallest at maximum activity, probably due to the saturation of atmospheric heating. Our study provides observational evidence that the mechanism of atmospheric heating is universal among the Sun and Sun-like stars, regardless of age or activity.

Unified Astronomy Thesaurus concepts: G dwarf stars (556); Solar analogs (1941); Stellar coronae (305); Stellar chromospheres (230); Stellar magnetic fields (1610); Solar coronal heating (1989); Solar chromospheric heating (1987); Solar magnetic fields (1503)

[Toriumi & Airapetian 2022]

3. Universality of Atmospheric Heating



- Previous studies
  - X-ray luminosity has a uniform scaling relationship with a power-law index of $\alpha \simeq 1.15$
  - One of the key results of JAXA's Yohkoh satellite
  - Barometer for efficiency of coronal heating in regard to surface magnetic flux[1]

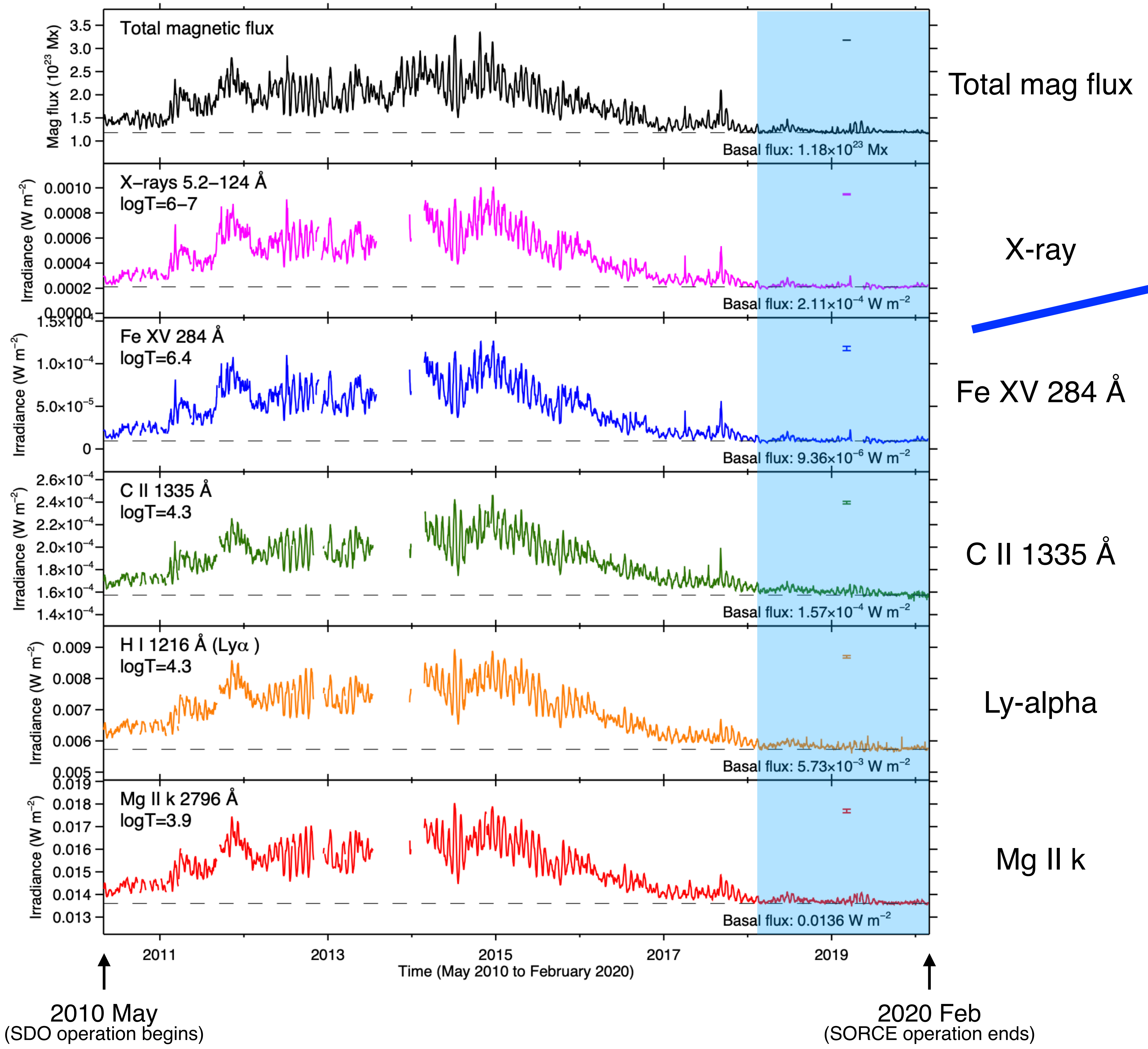
- What about in other lines (= temperatures)? [2]
  - Analysis of Sun-as-a-star synoptic data over 10 yr
  - X-ray, EUV, UV, optical, and radio
  - corresponding to corona (logT=6-7) to chromosphere (logT=4)
  - Compare scaling with stellar data

[1: Fisher+ 1998; Pevtsov+ 2003; Vidotto+ 2014; Reiners+ 2022]
[2: Skumanich 1975; Schrijver+ 1989; Rutten+ 1991; Loukitcheva+ 2009; Barczynski+ 2018]

3. Universality of Atmospheric Heating

- Solar synoptic data over 10 yr

Total magnetic flux and representative emission lines



- Calculate basal flux and residual
  - Basal fluxes are defined as medians of data from Mar 2019 to Feb 2020 with following criteria
    - Sunspot number = 0
    - Total sunspot area = 0
    - Magnetic flux < 5th percentile of all time

Residual = Light curve – Basal flux

- Basal flux: background heating
- Residual: heating due to magnetic elements

Total radial unsigned magnetic flux
- daily value
- generated from four full-disk line-of-sight magnetograms per day

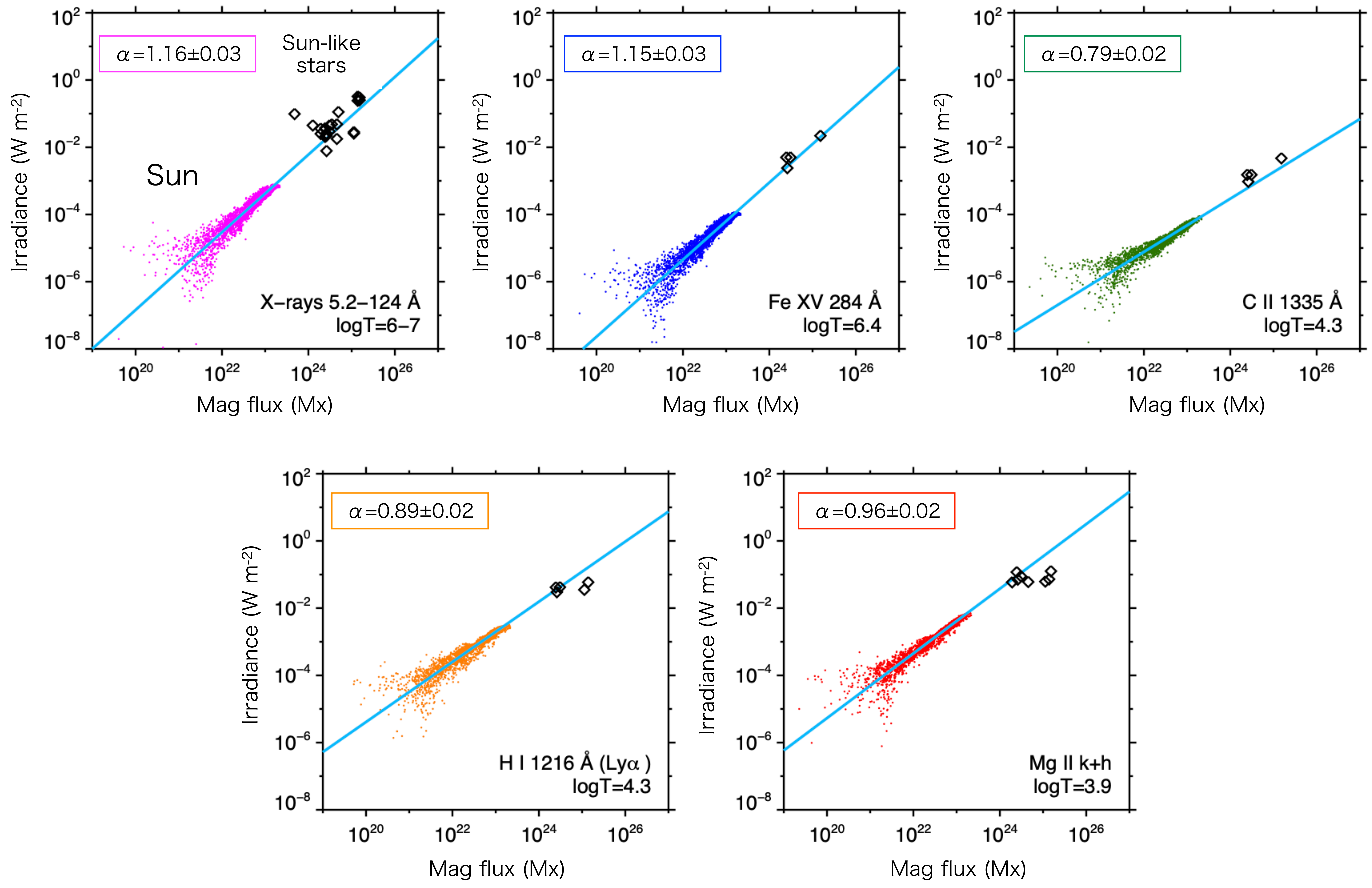
16 spectral lines/bands
- daily value
- X-ray to radio
- logT=3.8—7

Line centers and widths adopted from Ayres (2021)

[Toriumi & Airapetian 2022]

3. Universality of Atmospheric Heating

Mag flux—multi-line proportionality $F \propto \Phi^{\alpha}$



- Solar data
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  - Other lines also show power-law scalings, although the α values are smaller for cooler temperatures
- Stellar data
  - Mainly G-dwarfs with ages from 50 Myr to 4.5 Gyr
  - Total magnetic flux based on Kochukhov et al. (2020)
  - Irradiance from published data
- Comparison of Sun and stars
  - Stellar data points are located at extensions of solar scaling laws for all spectral lines (= all temperatures)

✓ Heating mechanism is universal among the Sun and stars, regardless of age or activity

3. Universality of Atmospheric Heating

[Toriumi & Airapetian 2022]

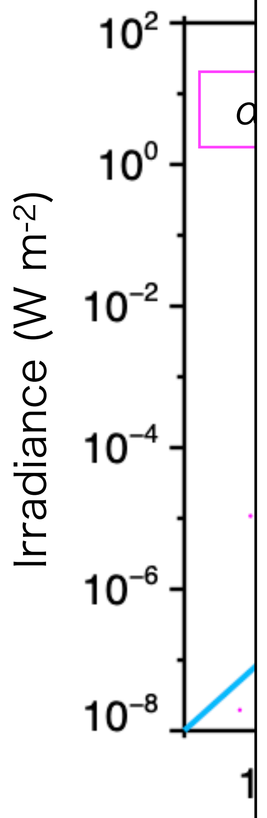

Table 3
Characteristics of the Sun-like Stars

HD (1)	Name (2)	Sp. Type (3)	$T_{\rm eff}$ (K) (4)	log g (5)	Age (Myr) (6)	$P_{\rm rot}$ (days) (7)	R ($R_\odot$) (8)	Φ (Mx) (9)	X-rays 5.2–124 Å (W m^{-2}) (10)	Fe XV 284 Å (W m^{-2}) (11)	C II 1335 Å (W m^{-2}) (12)	Lyα (W m^{-2}) (13)	Mg II k+h (W m^{-2}) (14)
1835	BE Cet	G3V	5837	4.47	600	7.78	1.00	4.55×10^{24}	4.80×10^{-2}, 1.78×10^{-2}	…	…	…	6.04×10^{-2}
20630	κ^1 Cet	G5V	5742	4.49	600	9.3	0.95	2.61×10^{24}	2.19×10^{-2}, 2.56×10^{-2}	2.40×10^{-3}	9.50×10^{-4}	3.01×10^{-2}	7.09×10^{-2}
39587	χ^1 Ori	G0V	5882	4.34	500	4.83	1.05	2.47×10^{24}	3.48×10^{-2}, 3.73×10^{-2}	5.00×10^{-3}	1.52×10^{-3}	4.16×10^{-2}	1.18×10^{-1}
56124		G0V	5848	4.46	4500	18	1.01	4.78×10^{23}	9.79×10^{-2}	…	…	…	…
72905	π^1 Uma	G1.5V	5873	4.44	500	4.9	0.95	3.08×10^{24}	4.48×10^{-2}, 2.96×10^{-2}	5.00×10^{-3}	1.52×10^{-3}	4.22×10^{-2}	8.93×10^{-2}
73350	V401 Hya	G5V	5802	4.48	510	12.3	0.98	2.43×10^{24}	2.05×10^{-2}	…	…	…	…
76151		G3V	5790	4.55	3600	20.5	1.00	2.62×10^{24}	7.78×10^{-3}	…	…	…	…
82558	LQ Hya	K1V	5000	4.00	50	1.601	0.71	1.39×10^{25}	3.24×10^{-1}, 2.43×10^{-1}	…	…	5.91×10^{-2}	7.27×10^{-2}
129333	EK Dra	G1.5V	5845	4.47	120	2.606	0.97	1.52×10^{25}	3.03×10^{-1}, 2.52×10^{-1}	2.20×10^{-2}	4.70×10^{-3}	…	1.26×10^{-1}
131156	ξ Boo A	G7V	5570	4.65	200	6.4	0.83	1.13×10^{25}	2.58×10^{-2}, 2.83×10^{-2}	…	…	3.53×10^{-2}	6.19×10^{-2}
166435		G1IV	5843	4.44	3800	3.43	0.99	4.94×10^{24}	1.12×10^{-1}	…	…	…	…
175726		G0V	5998	4.41	500	3.92	1.06	1.26×10^{24}	4.48×10^{-2}	…	…	…	…
190771		G2V	5834	4.44	2700	8.8	1.01	3.48×10^{24}	4.80×10^{-2}	…	…	…	…
206860	HN Peg	G0V	5974	4.47	260	4.55	1.04	1.92×10^{24}	3.56×10^{-2}, 2.52×10^{-2}	…	…	…	5.90×10^{-2}
Sun	(mean)	G2V	5777	4.44	4600	25.4	1.00	1.73×10^{23}	4.24×10^{-4}	4.12×10^{-5}	1.84×10^{-4}	6.77×10^{-3}	2.55×10^{-2}
	(median)							1.67×10^{23}	3.87×10^{-4}	3.59×10^{-5}	1.82×10^{-4}	6.69×10^{-3}	2.52×10^{-2}
	(max)							3.35×10^{23}	1.01×10^{-3}	1.27×10^{-4}	2.46×10^{-4}	8.94×10^{-3}	3.06×10^{-2}
	(min)							1.16×10^{23}	1.85×10^{-4}	5.68×10^{-6}	1.52×10^{-4}	5.60×10^{-3}	2.32×10^{-2}

Note. The HD number, name, spectral type, effective temperature, surface gravity, age, rotation period, and radius of the stars are shown in Columns 1–8. Column 9 shows the total hemispheric magnetic flux estimated based on the Zeeman broadening of the spectral lines. Columns 10–14 show the irradiances of X-ray 5.2–124 Å, Fe XV 284 Å, C II 1334.5 + 1335.7 Å, Lyα, and Mg II k+h (combined) in the literature, all converted to the values at 1 au from the stars. For X-rays, multiple observations are shown (if they exist).

References. Turon et al. (1993), Valenti & Fischer (2005), McDonald et al. (2012), Gonzalez et al. (2010), Cole et al. (2015), Allende Prieto & Lambert (1999), Vidotto et al. (2014), Rosén et al. (2016), Oláh et al. (2016), See et al. (2019), Kochukhov et al. (2020), Telleschi et al. (2005), Ribas et al. (2005), Takeda et al. (2007), Wood & Linsky (2010), Güdel et al. (1997), Wood et al. (2005), Schmitt et al. (1990), Dorren & Guinan (1994).

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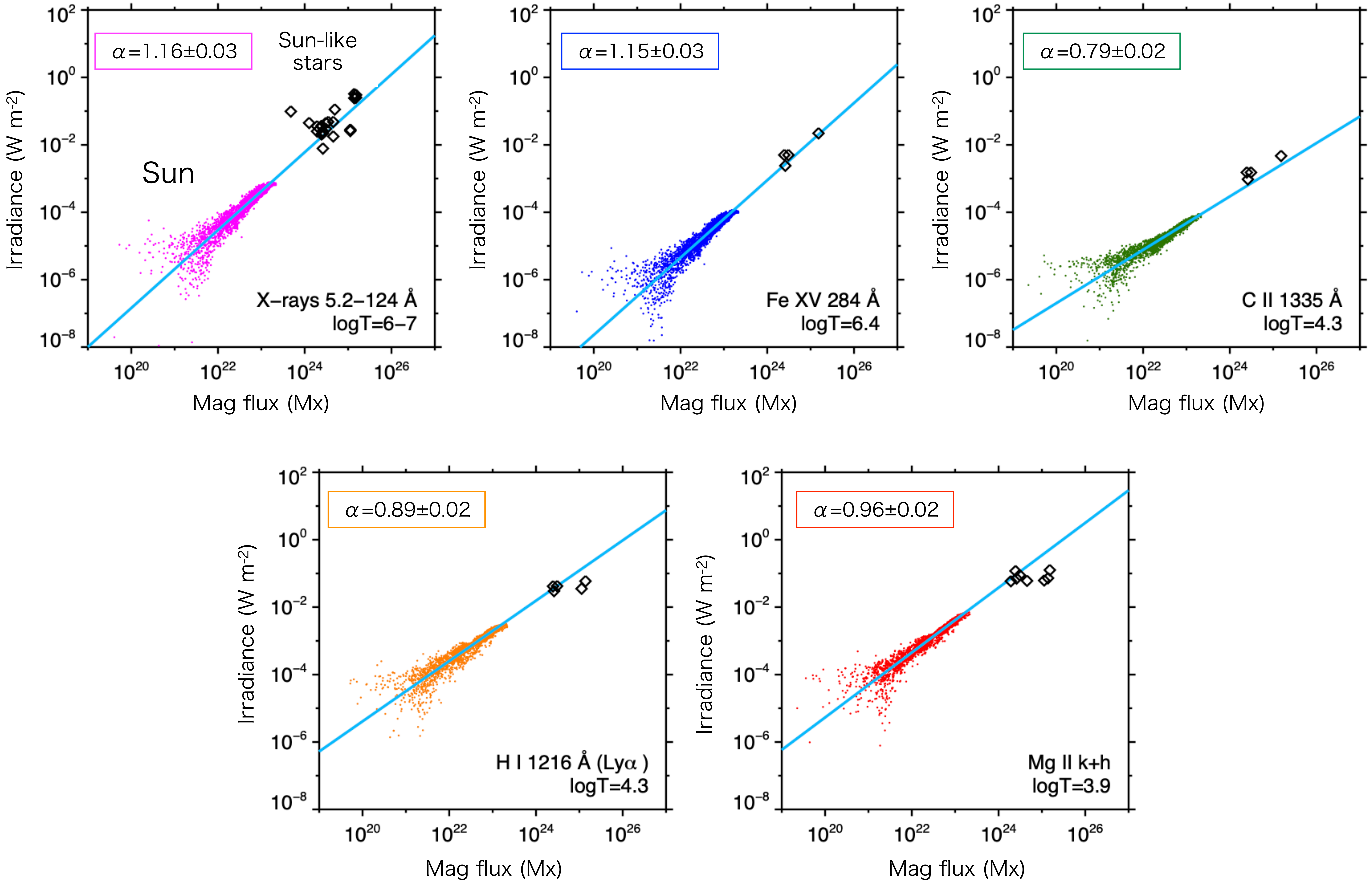
[Toriumi & Airapetian 2022]

3. Universality of Atmospheric Heating

Mag flux—multi-line proportionality $F \propto \Phi^{\alpha}$



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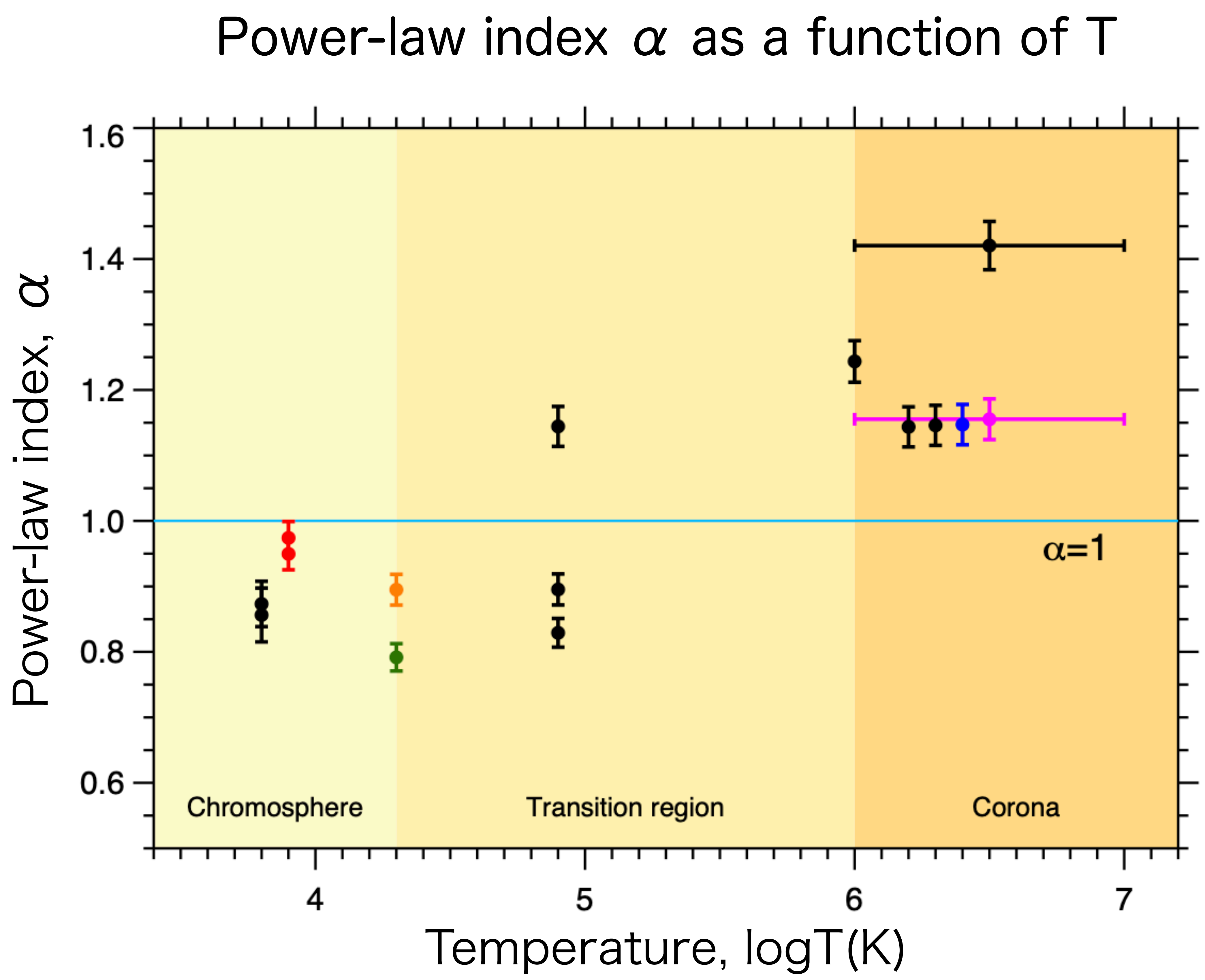
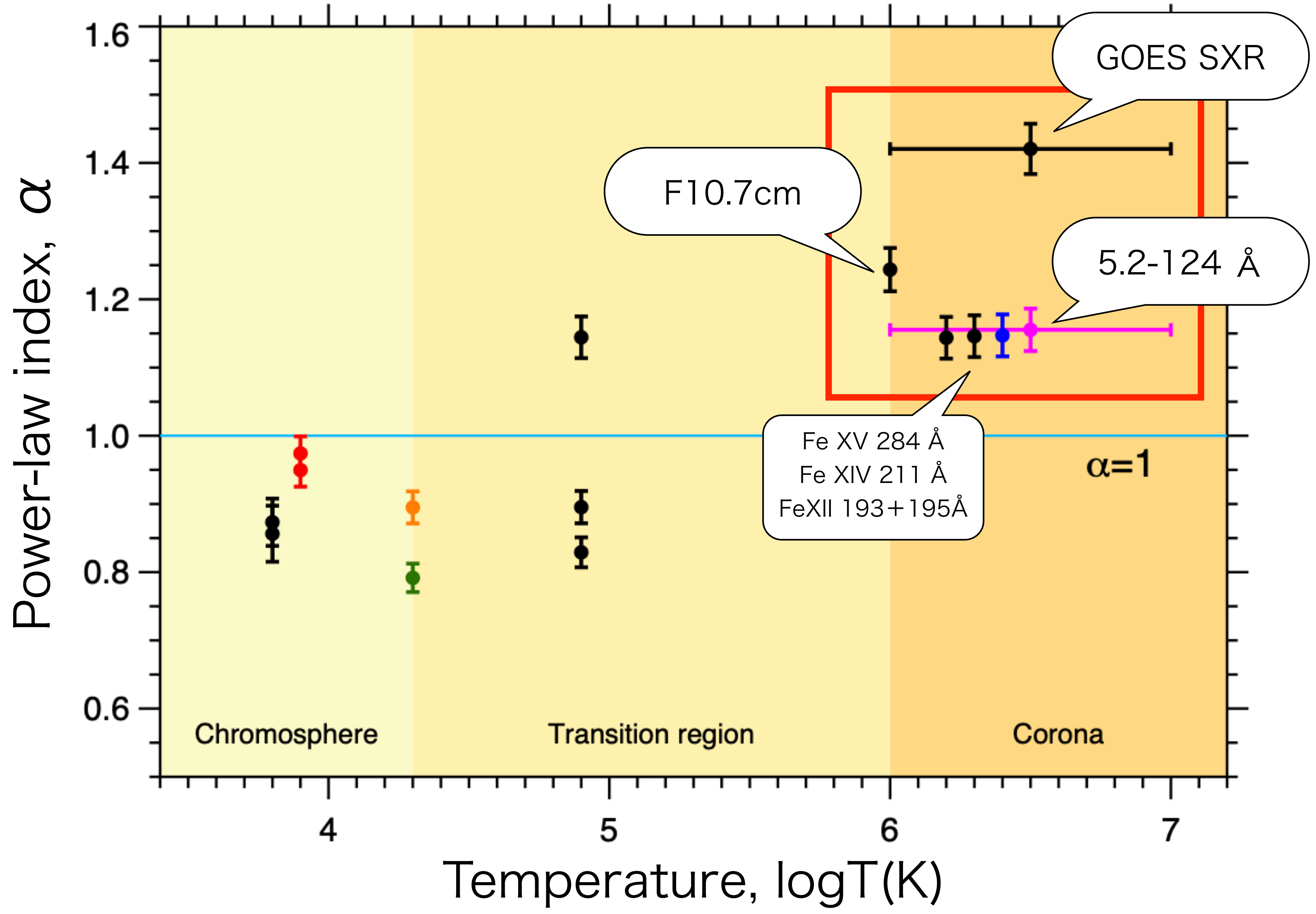


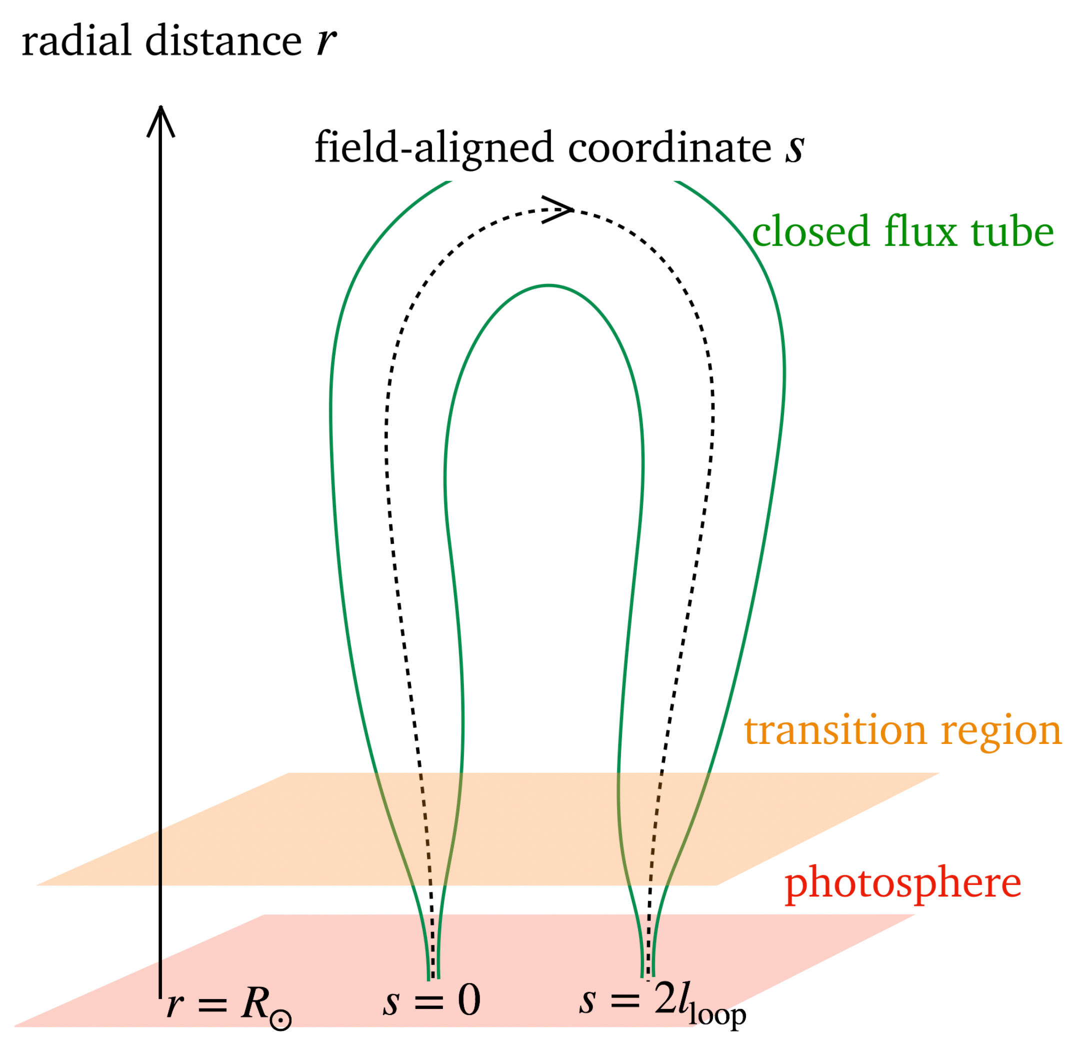
[Toriumi & Airapetian 2022]

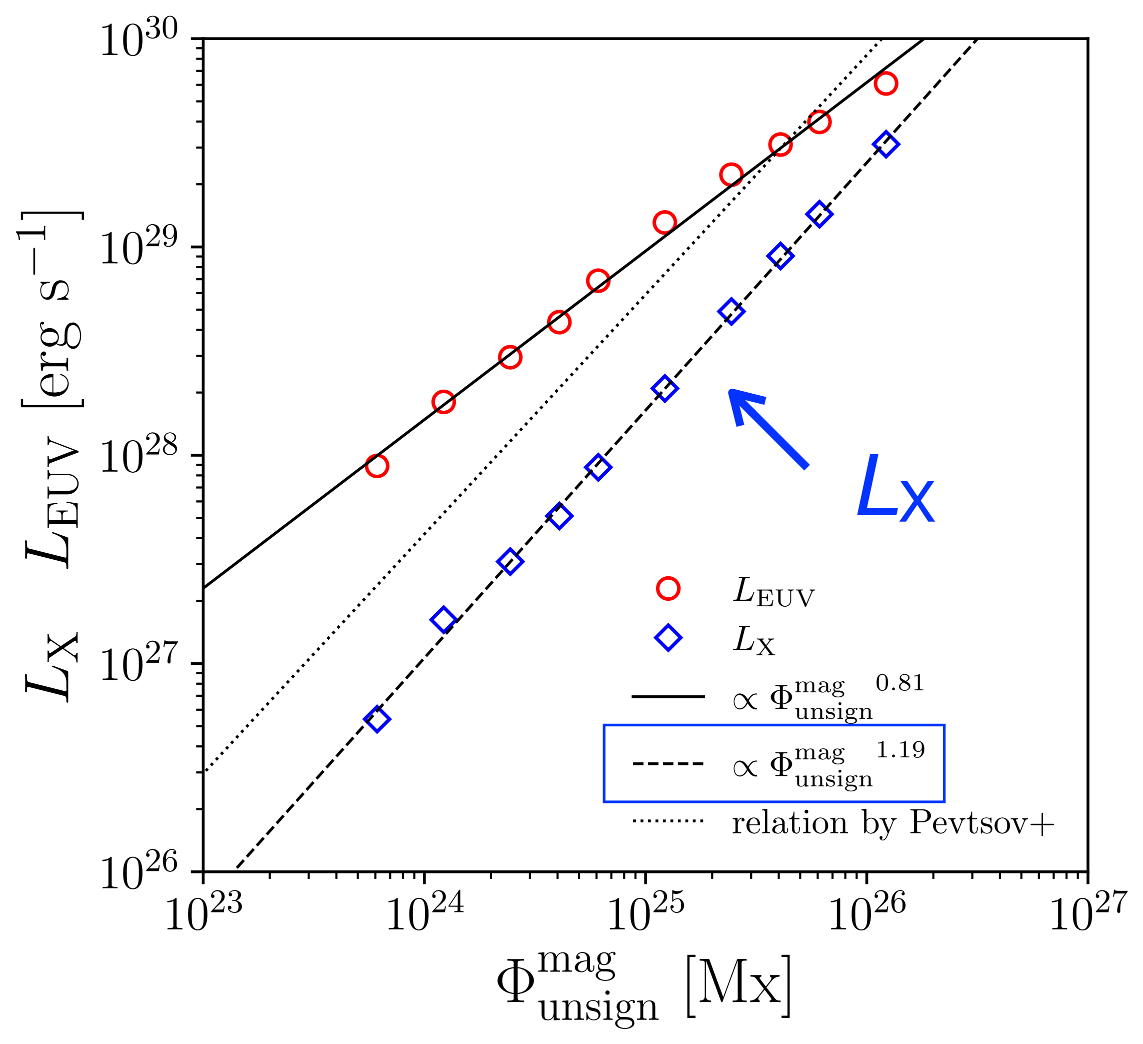
3. Universality of Atmospheric Heating

Power-law index α as a function of T



- Corona: logT > 6
  - Not only X-rays but also other coronal proxies consistently show α >1
  - Explained by theoretical and numerical models [Zhuleku et al. 2020; also Fisher+1998; Takasao+ 2020]

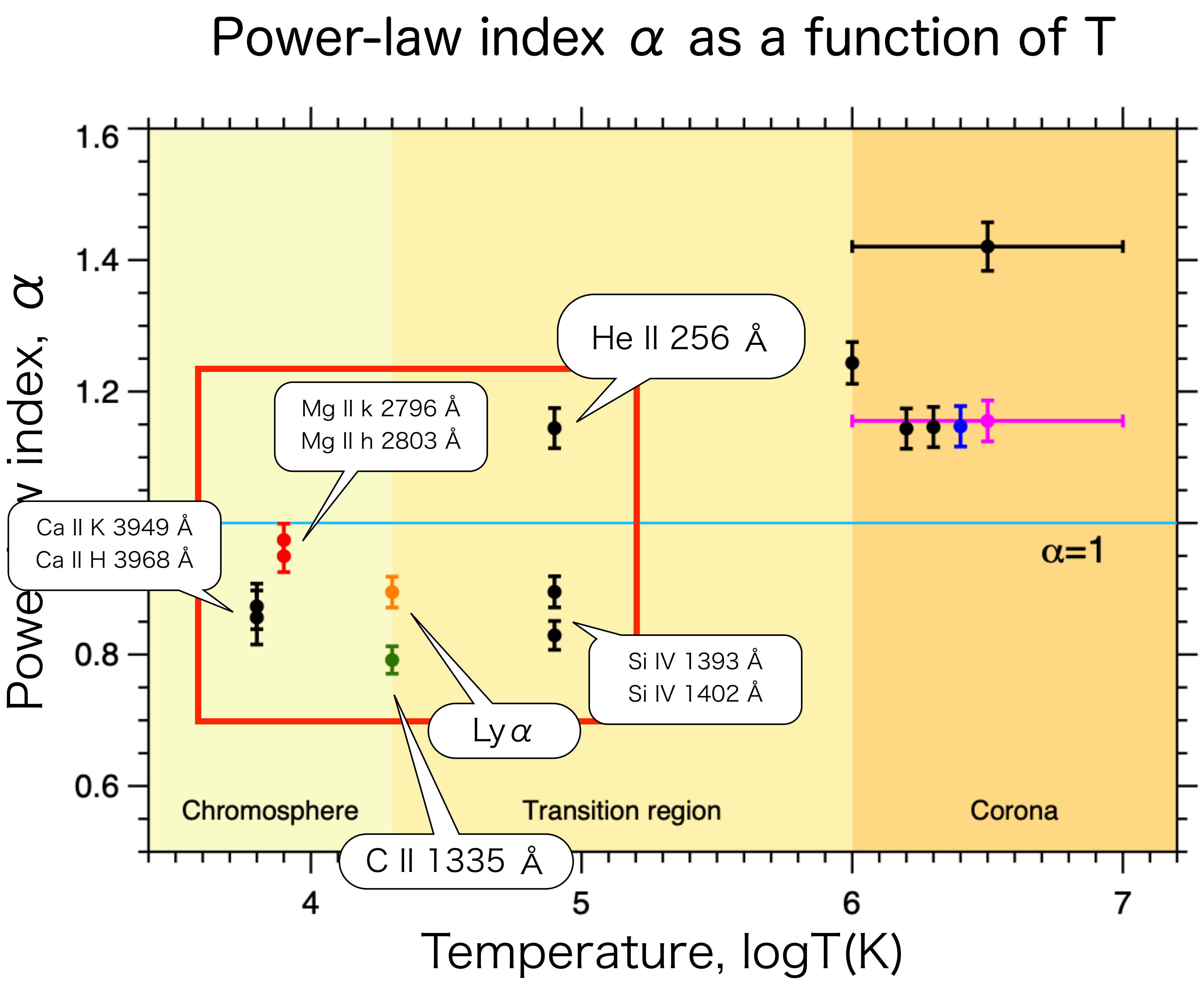




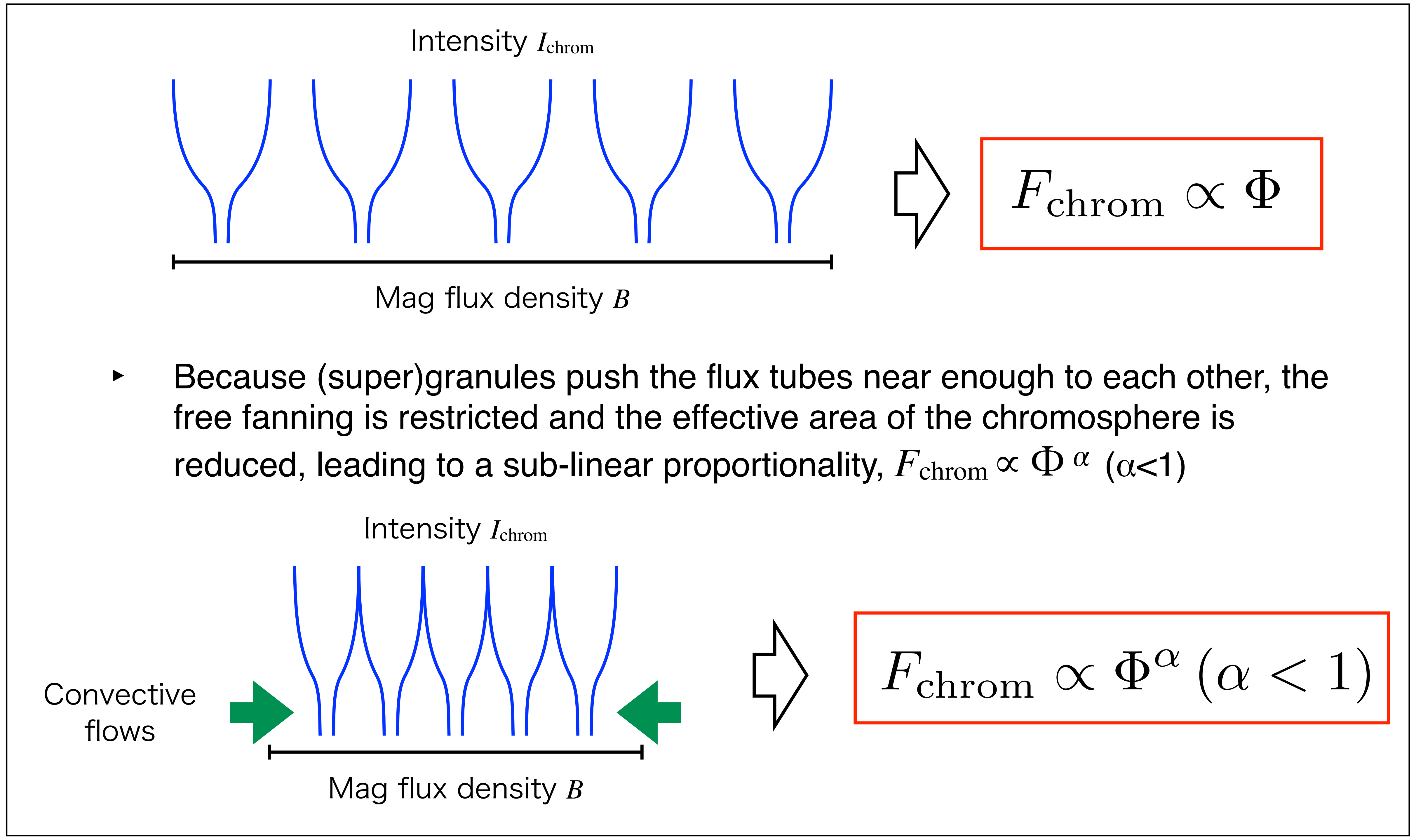
[Shoda & Takasao 2020]

[Toriumi & Airapetian 2022]

3. Universality of Atmospheric Heating



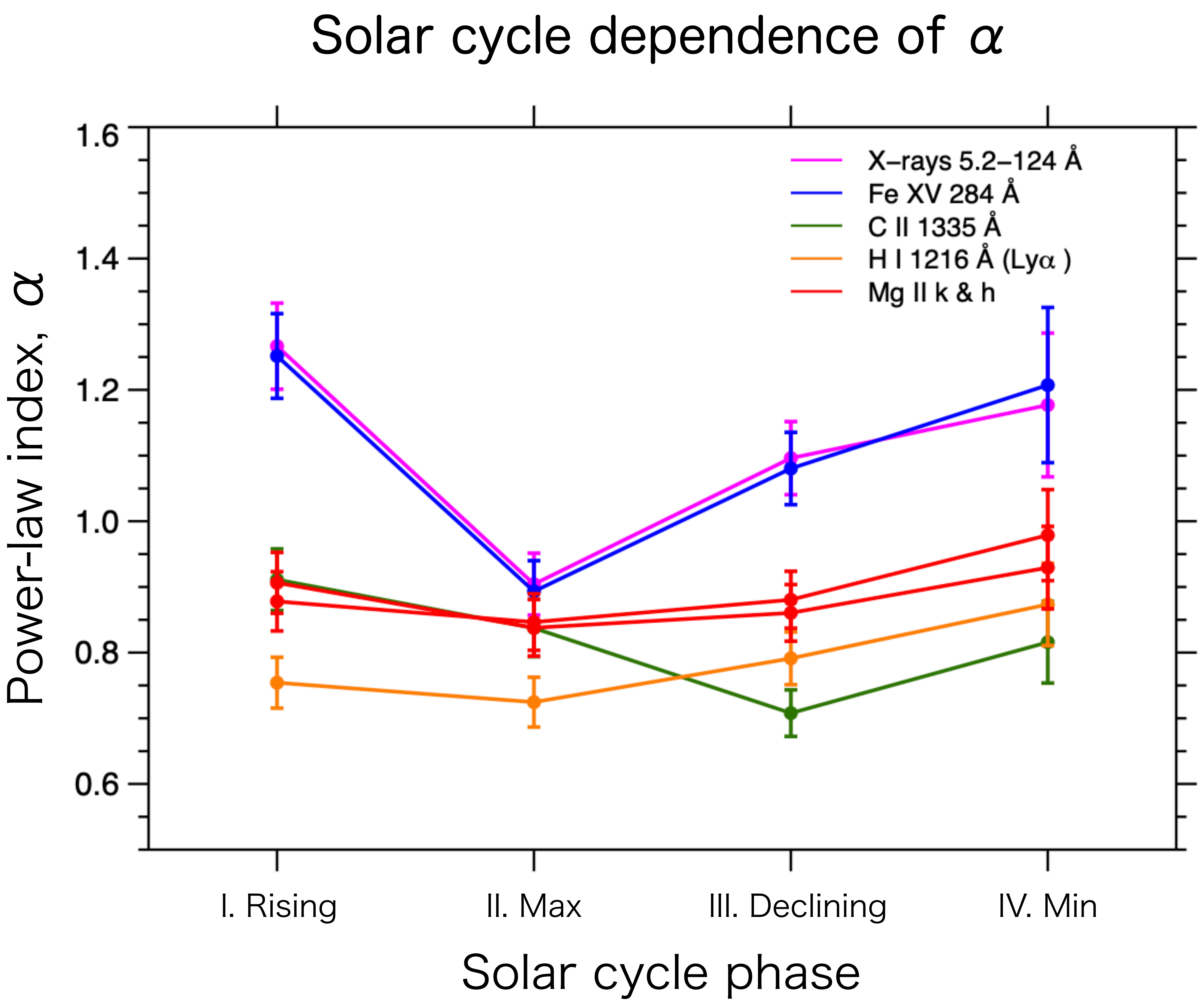
- TR to chromosphere: logT < 6
  - Power-law exponents fall below unity, α <1, indicating that the efficiency of chromospheric heating is weaker than the corona
  - In line with the previous studies [Skumanich et al. 1975; Schrijver et al. 1989; Loukitcheva et al. 2009; Barczynski et al. 2018]
  - Geometrical model by Schrijver et al. (1989) :



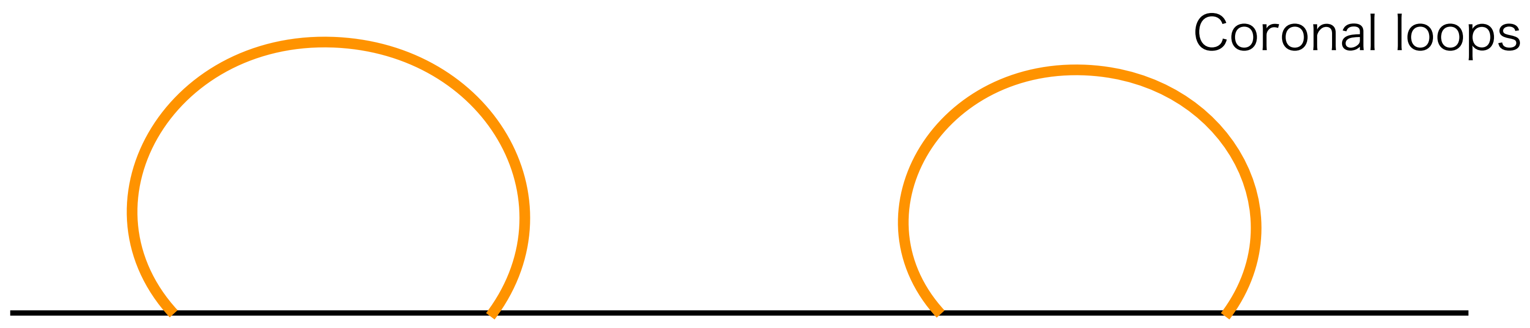
- Flux tube expansion is also a key for Alfven wave reflection [Cranmer & van Ballegooijen 2005]
- May require numerical modeling to understand why α<1

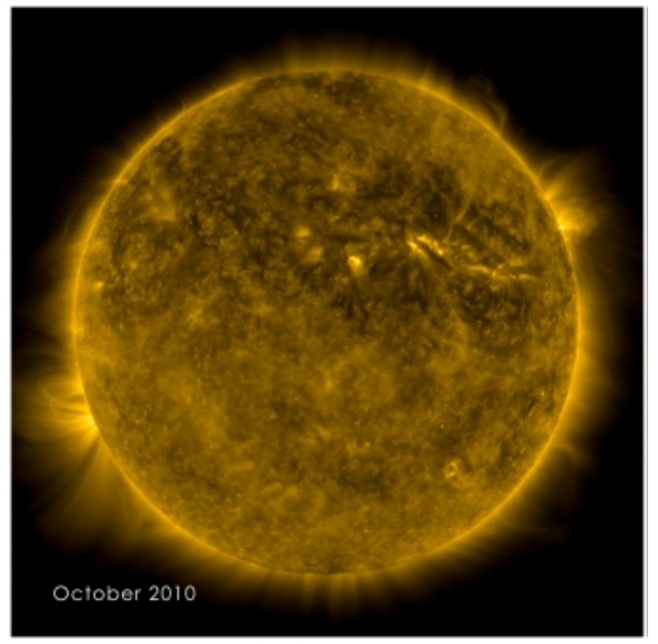
[Toriumi & Airapetian 2022]

3. Universality of Atmospheric Heating

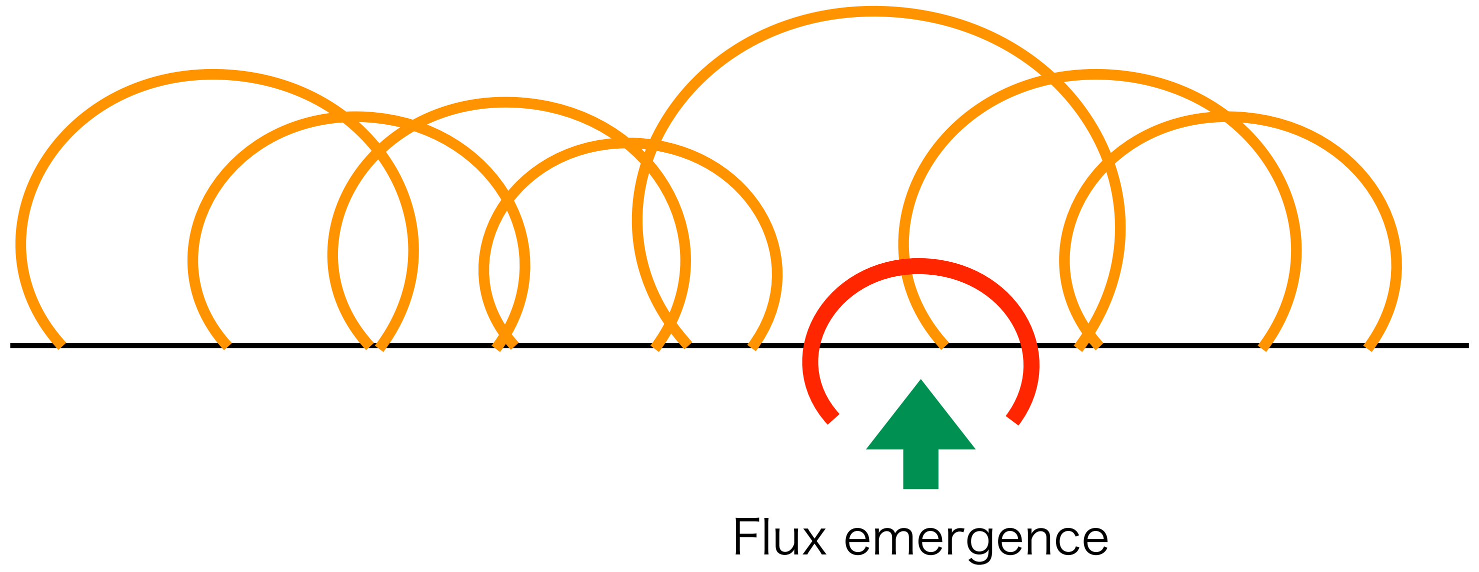


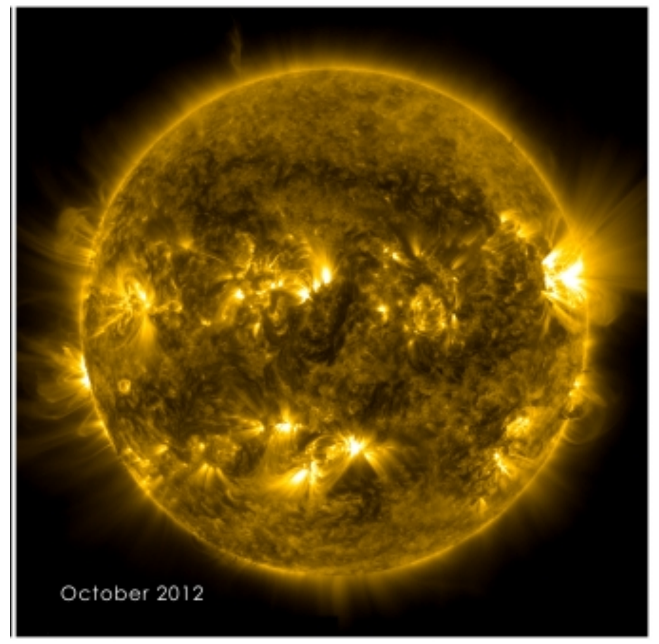
- α is smallest at solar maximum
  - At minimum, the Sun has few active regions.





  - At maximum, the Sun is filled with magnetic fluxes and loops. Therefore, the atmosphere is not effectively heated any more even if the new mag flux is supplied to the surface via flux emergence.

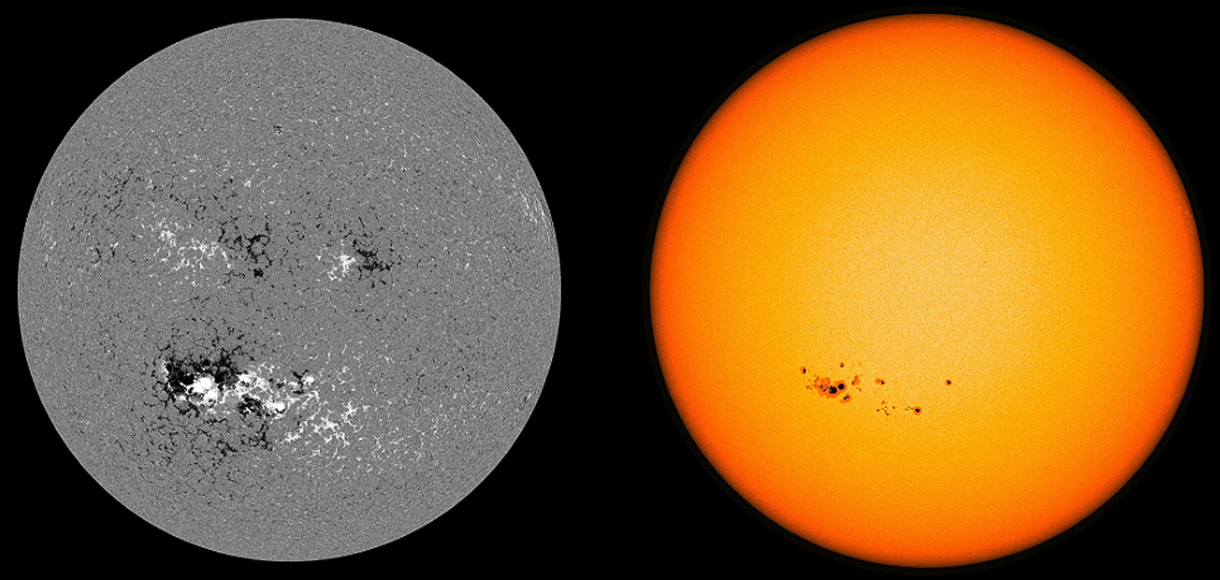




- Requires global effect in numerical modeling?

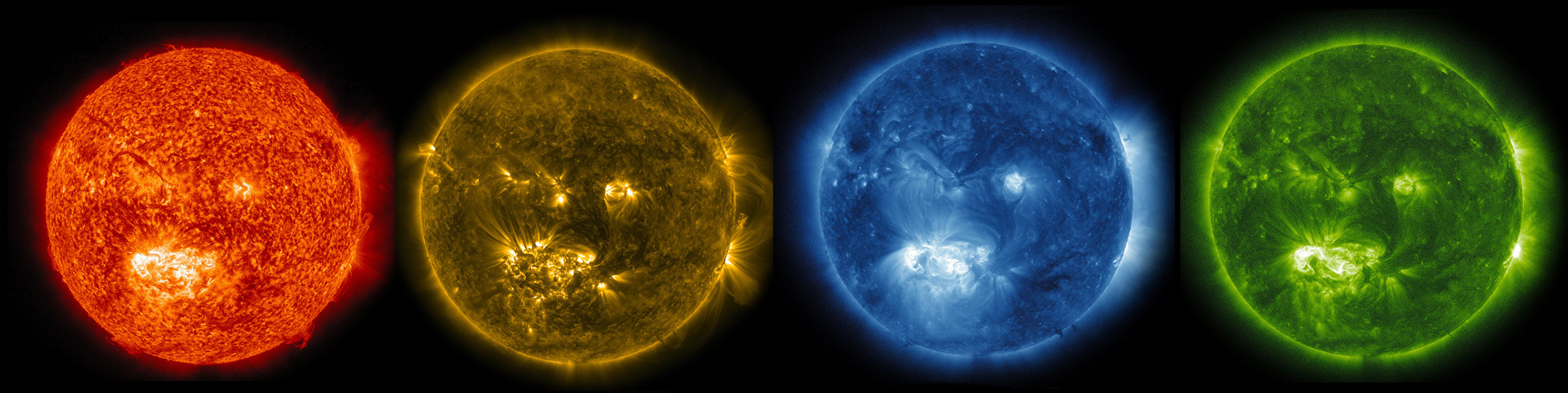
[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated



Activity proxy

- Radial magnetic flux



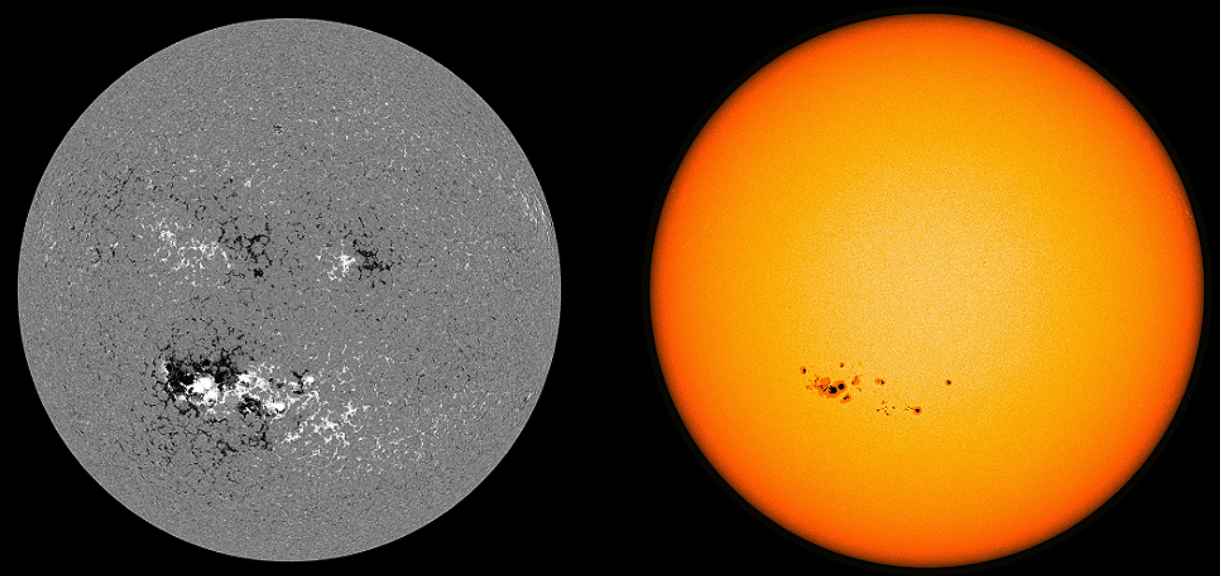
Irradiance (3.8 < logT < 7)

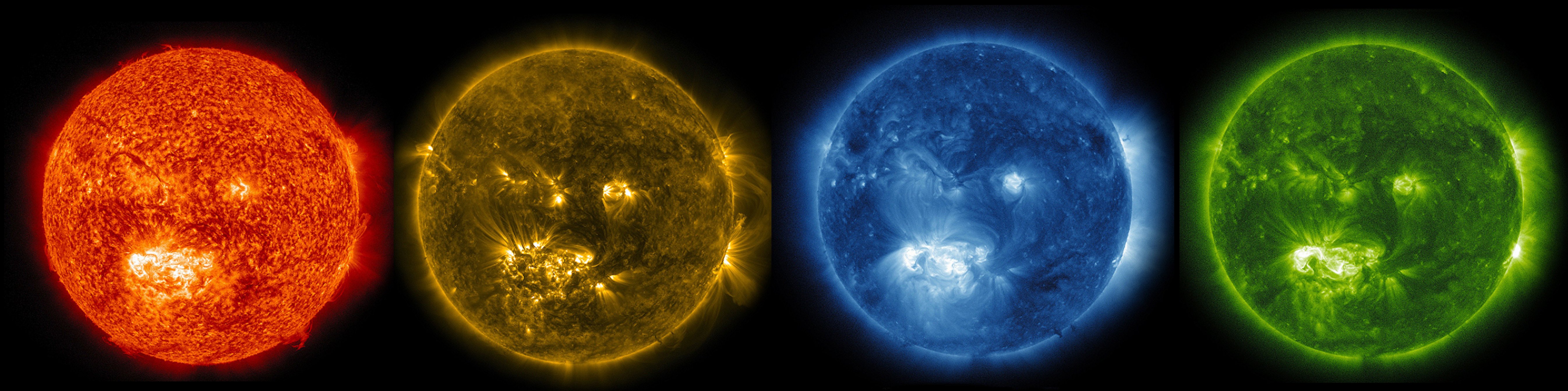
- X-rays 1–8 Å
- X-rays 5.2–124 Å
- Fe XV 284 Å
- Fe XIV 211 Å
- Fe XII 193+195 Å
- F10.7 cm radio
- He II 256 Å + blends
- Si IV 1393 Å
- Si IV 1402 Å
- C II 1335 Å
- H I 1216 Å (Lyα)
- Mg II k 2796 Å
- Mg II h 2803 Å
- Ca II K 3934 Å
- Ca II H 3968 Å
- H I 6563 Å (Hα)

Catalog of power-law index

[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated





Activity proxy

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Catalog of power-law index

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- Fe X 174 Å
- Fe XI 180 Å
- F10.7cm radio
- Fe IX 171 Å
- N V 1238 Å
- N V 1242 Å
- C IV 1548 Å
- C IV 1551 Å
- C III 1175 Å
- He II 256 Å +blends
- He II 304 Å
- Si IV 1393 Å
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- Si III 1206 Å
- He I 10830 Å
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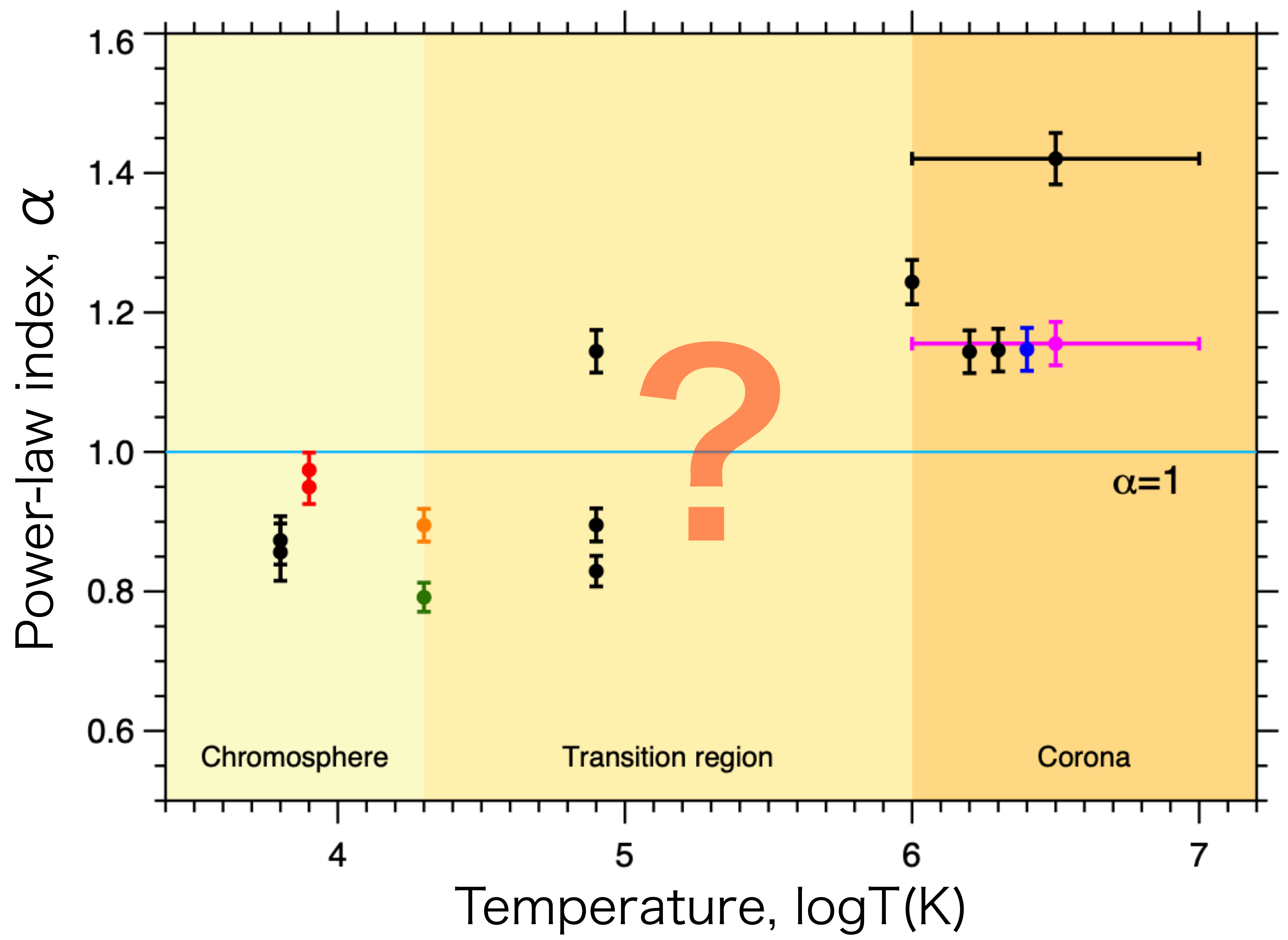
[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated

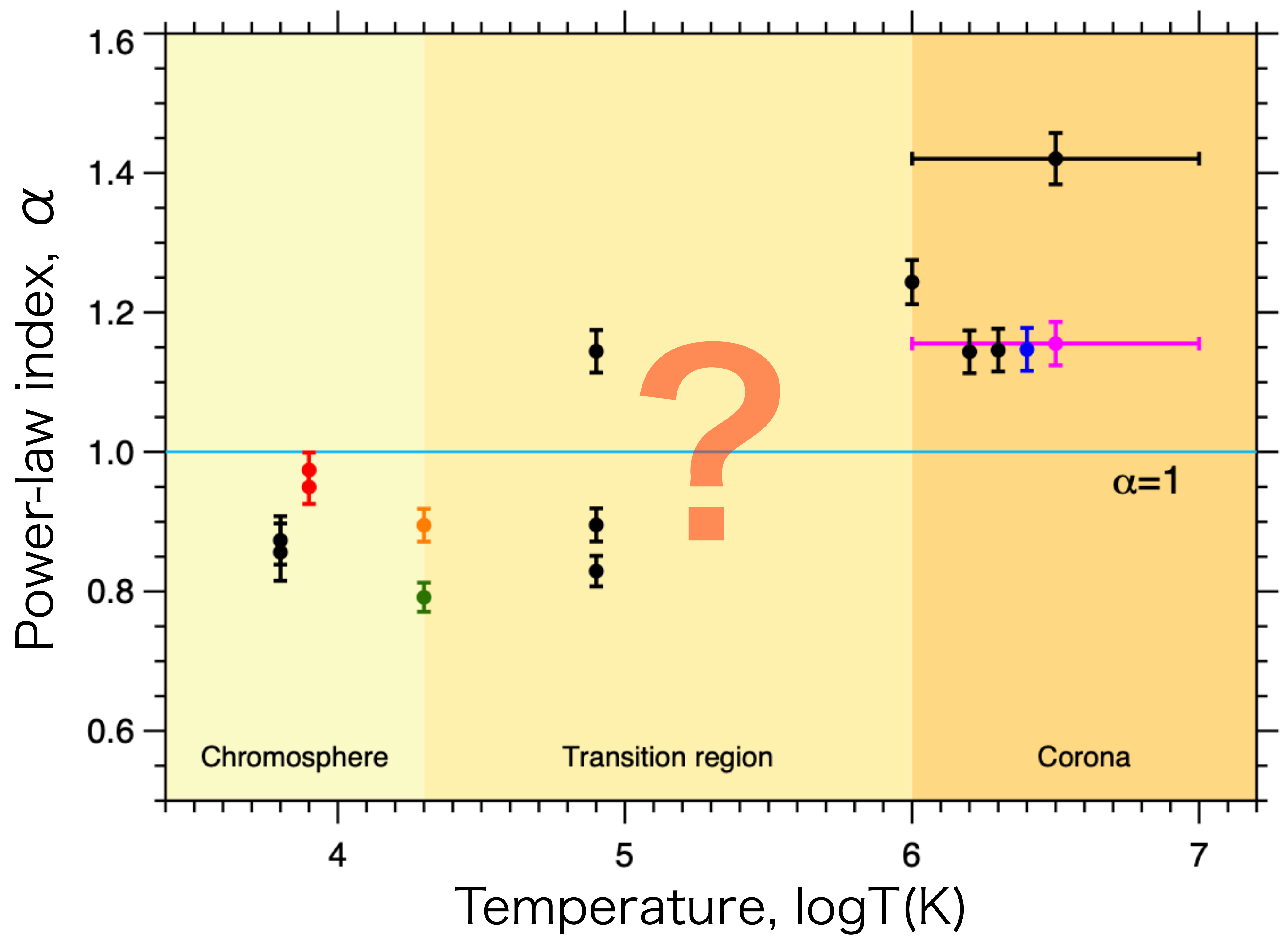
Previous result



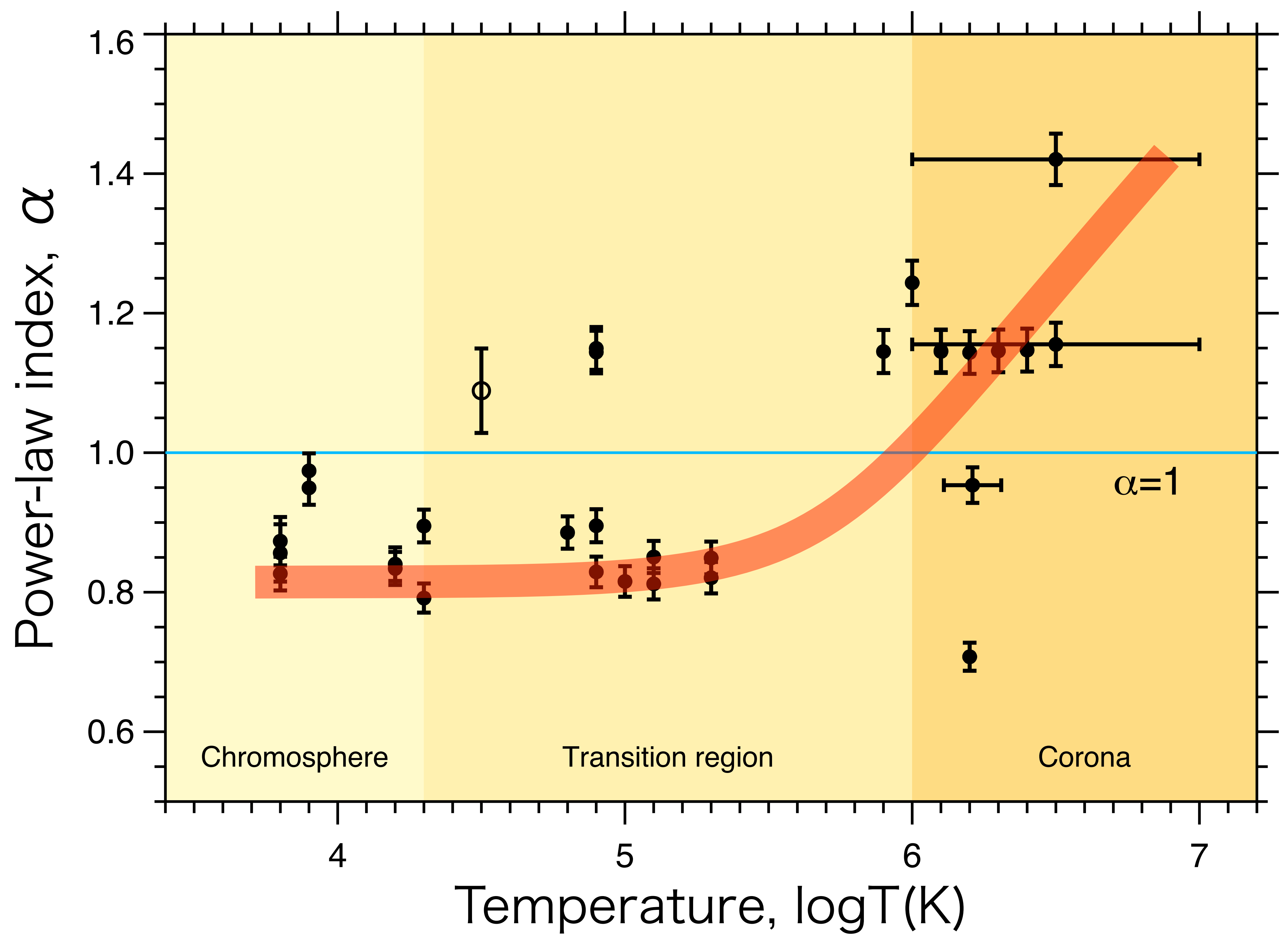
[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated

Previous result



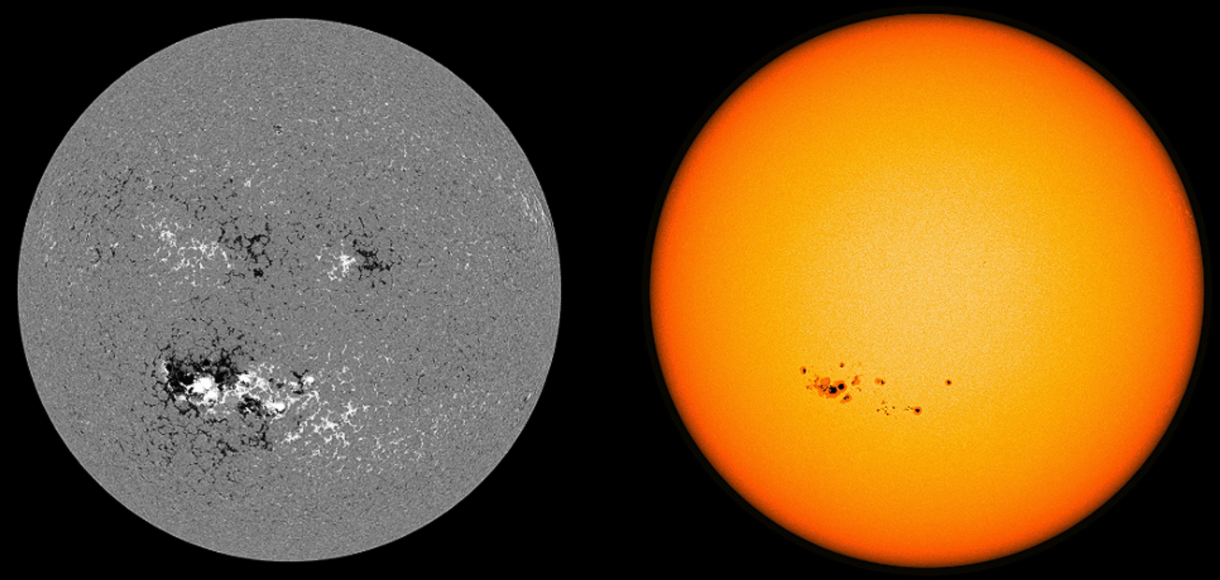
Updated catalog: line number increased

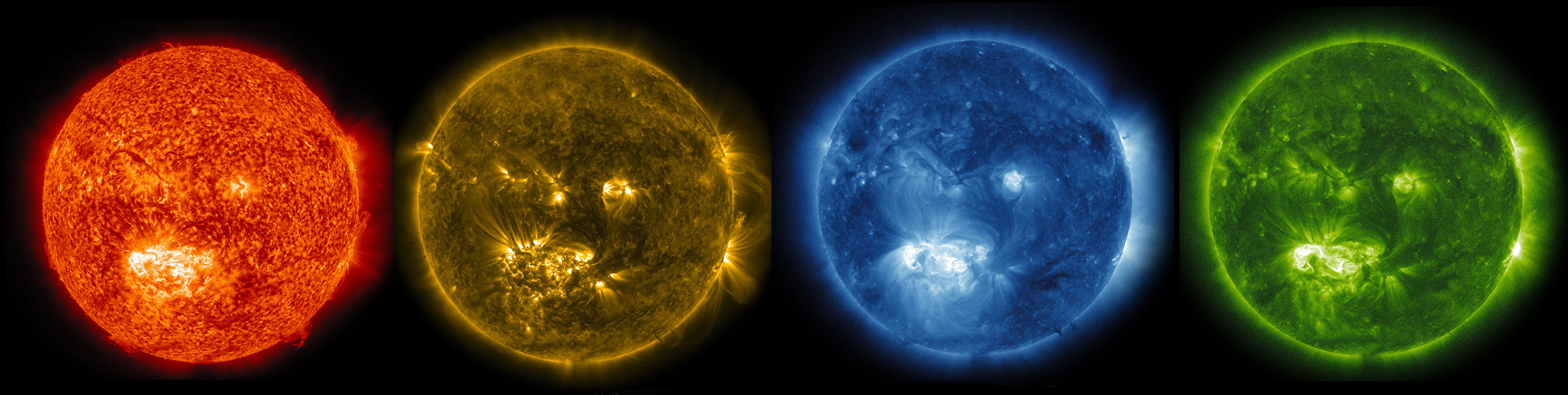


✓ Similarity of heating efficiencies (mechanisms) of transition region and chromosphere

[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated





Activity proxy

- Radial magnetic flux

Catalog of power-law index

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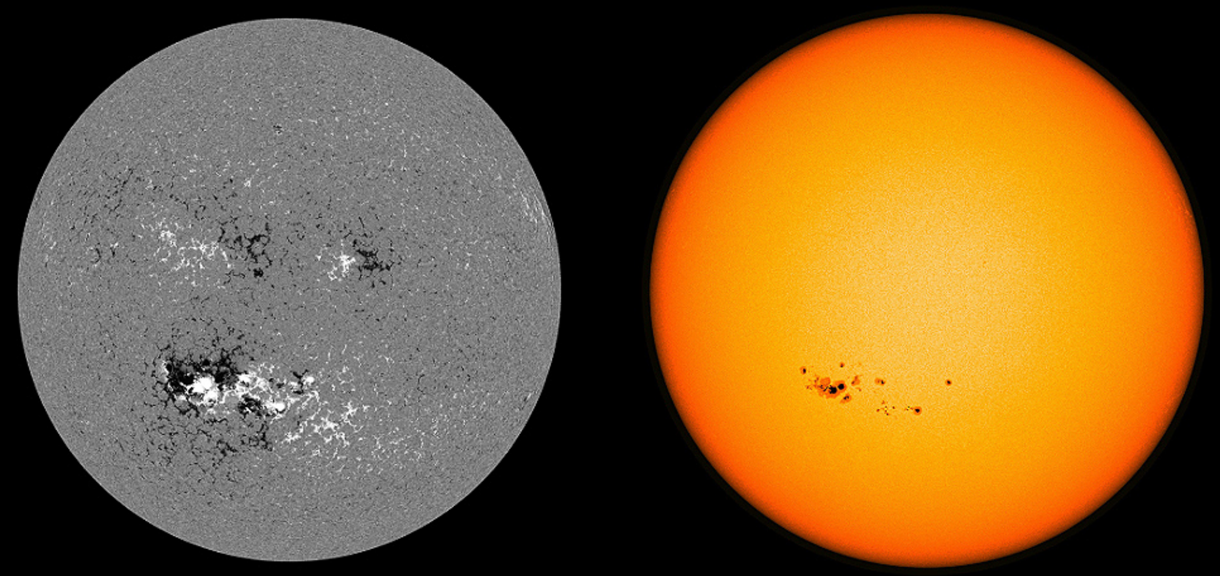
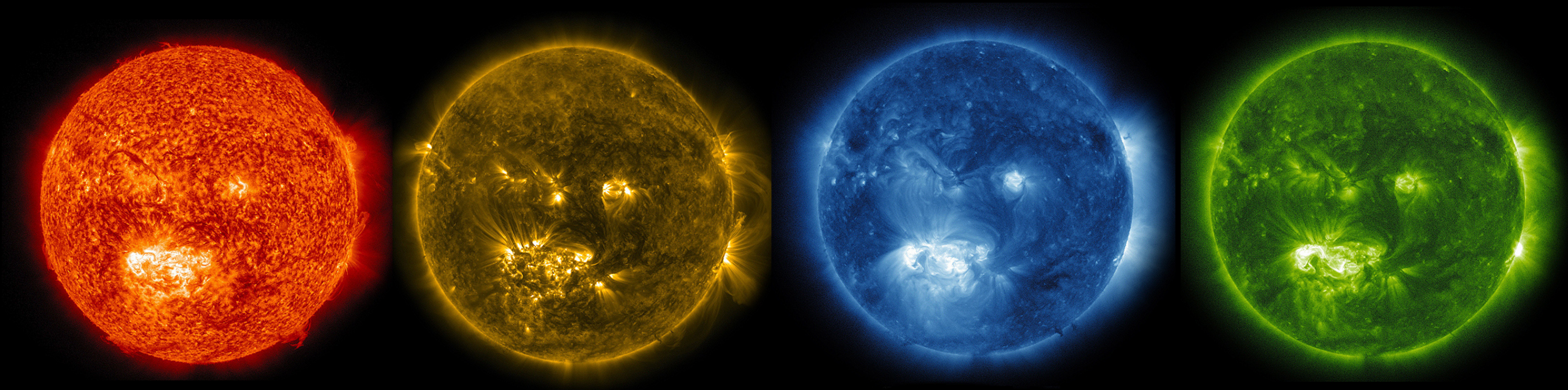
[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated





Activity proxy

- Radial magnetic flux
- LOS magnetic flux
- Sunspot number
- Sunspot area
- F10.7 cm radio

Catalog of power-law index

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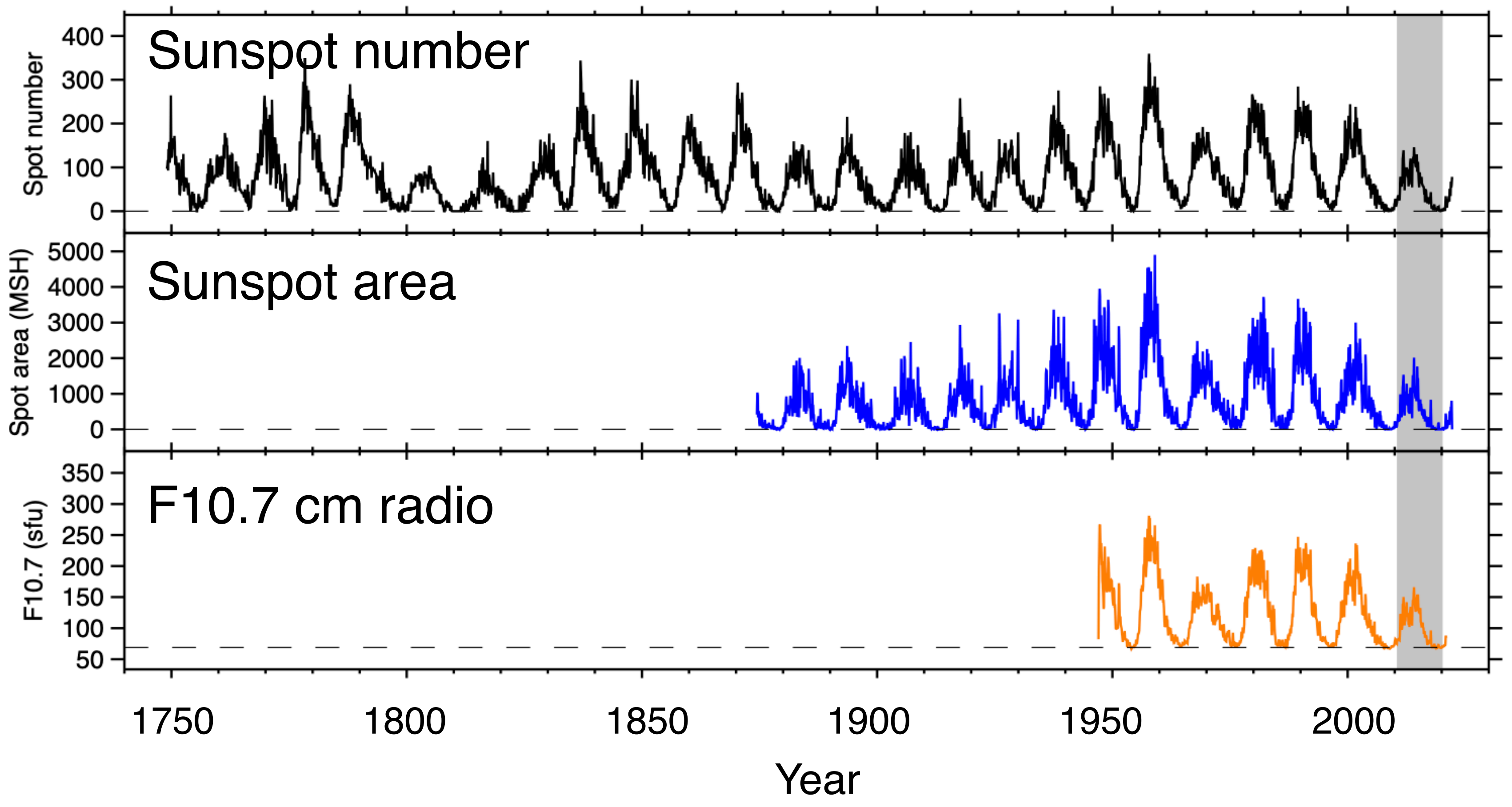
[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated

Historical solar observations



Catalog of α

$$F^{\rm line}(t) = 10^{\beta}\left[P(t) - P_0\right]^{\alpha} + F_0^{\rm line}$$

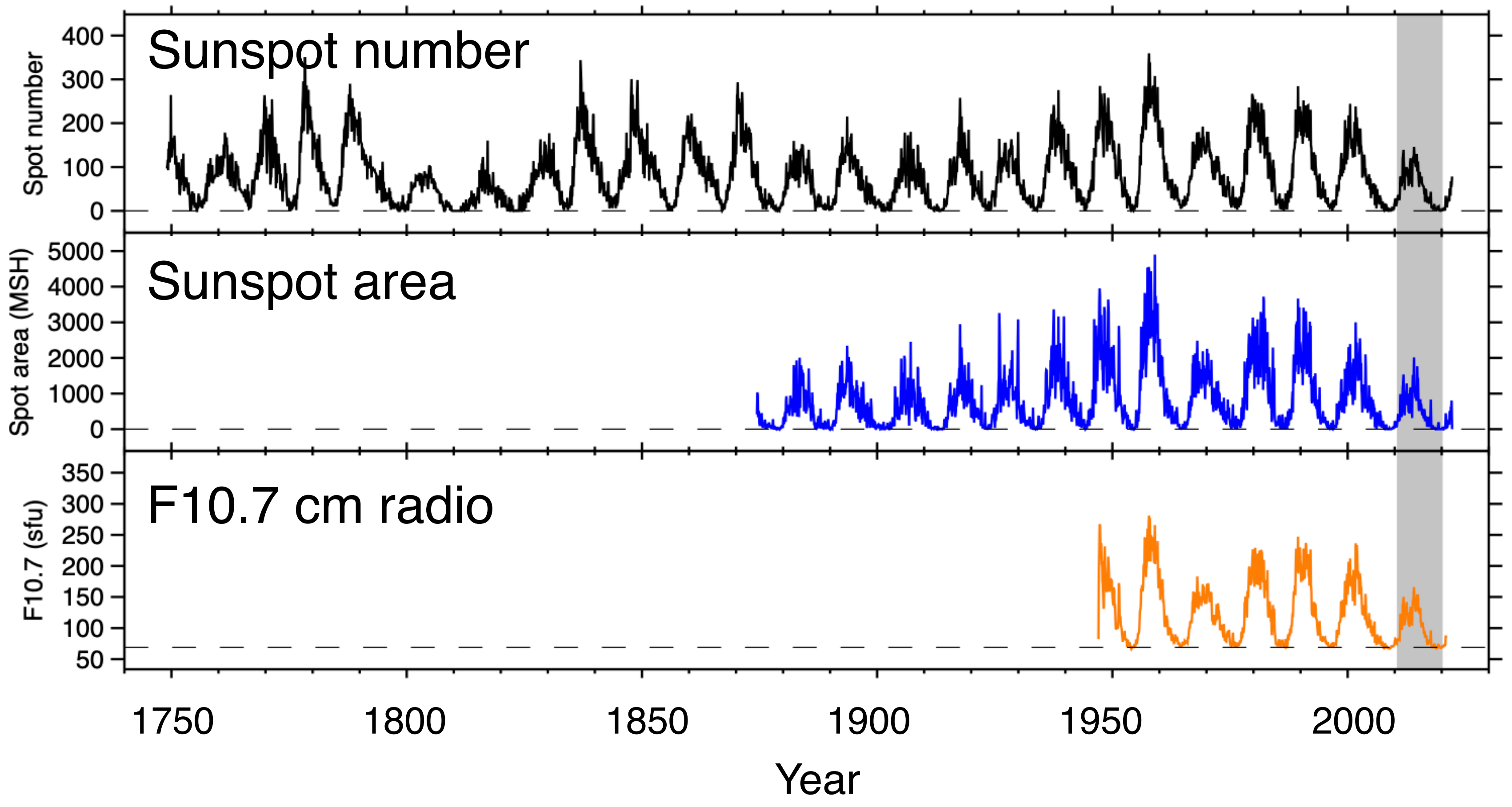
Irradiances can be reconstructed from

- Historical solar observations
- Stellar observations
- Surface flux transport simulations
- Dynamo models
- etc.

[Toriumi et al. ApJS, accepted]

3. Universality of Atmospheric Heating: Catalog Updated

Historical solar observations



Catalog of α

$$F^{\text{line}}(t) = 10^{\beta}\,[P(t) - P_0]^{\alpha} + F_0^{\text{line}}$$

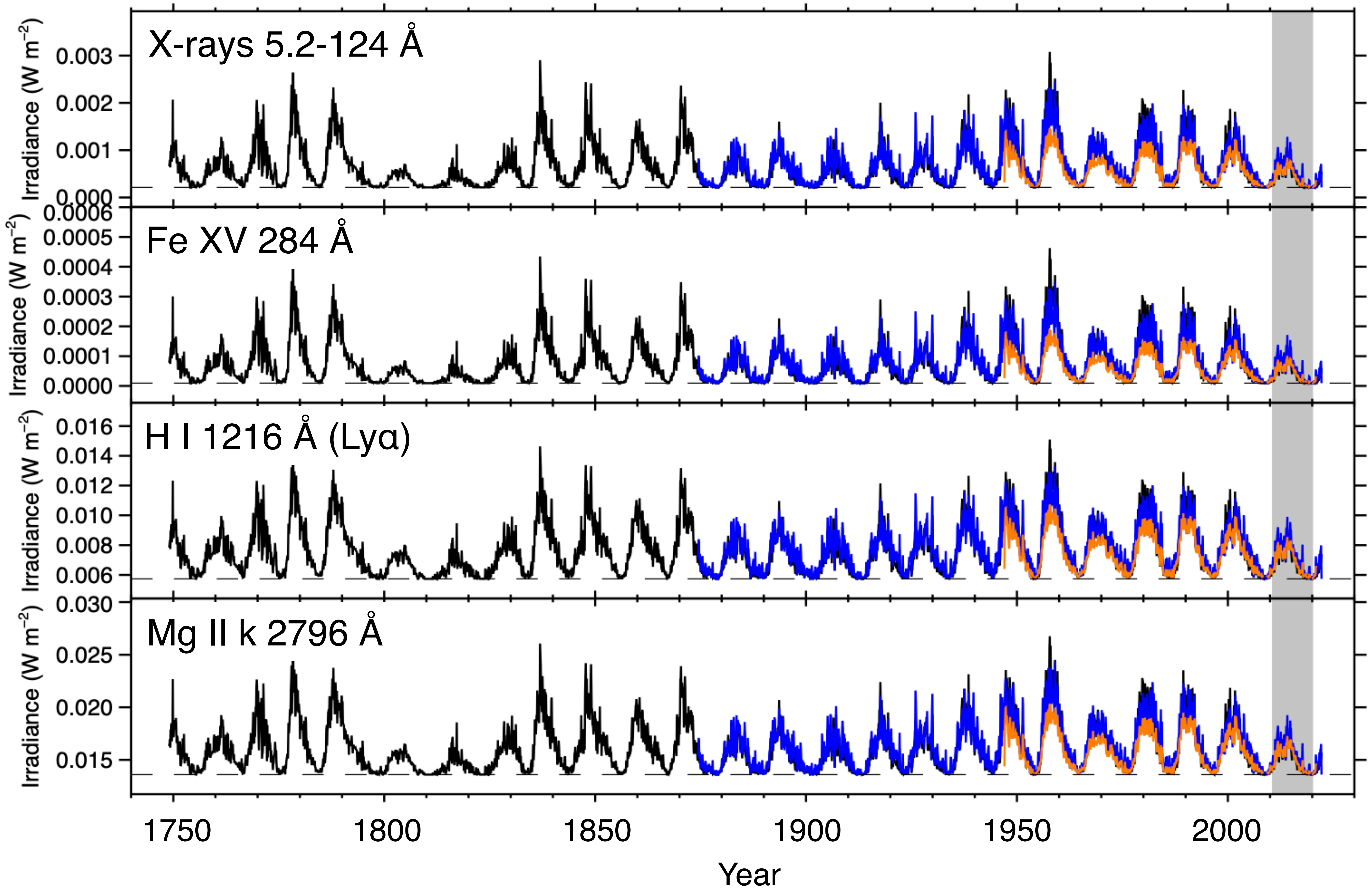
Irradiances can be reconstructed from

- Historical solar observations
- Stellar observations
- Surface flux transport simulations
- Dynamo models
- etc.

Pros: Relative differences between the proxies are less than 20% 👍

Cons: Scalings are measured only for the “very weak” cycle 24 👎

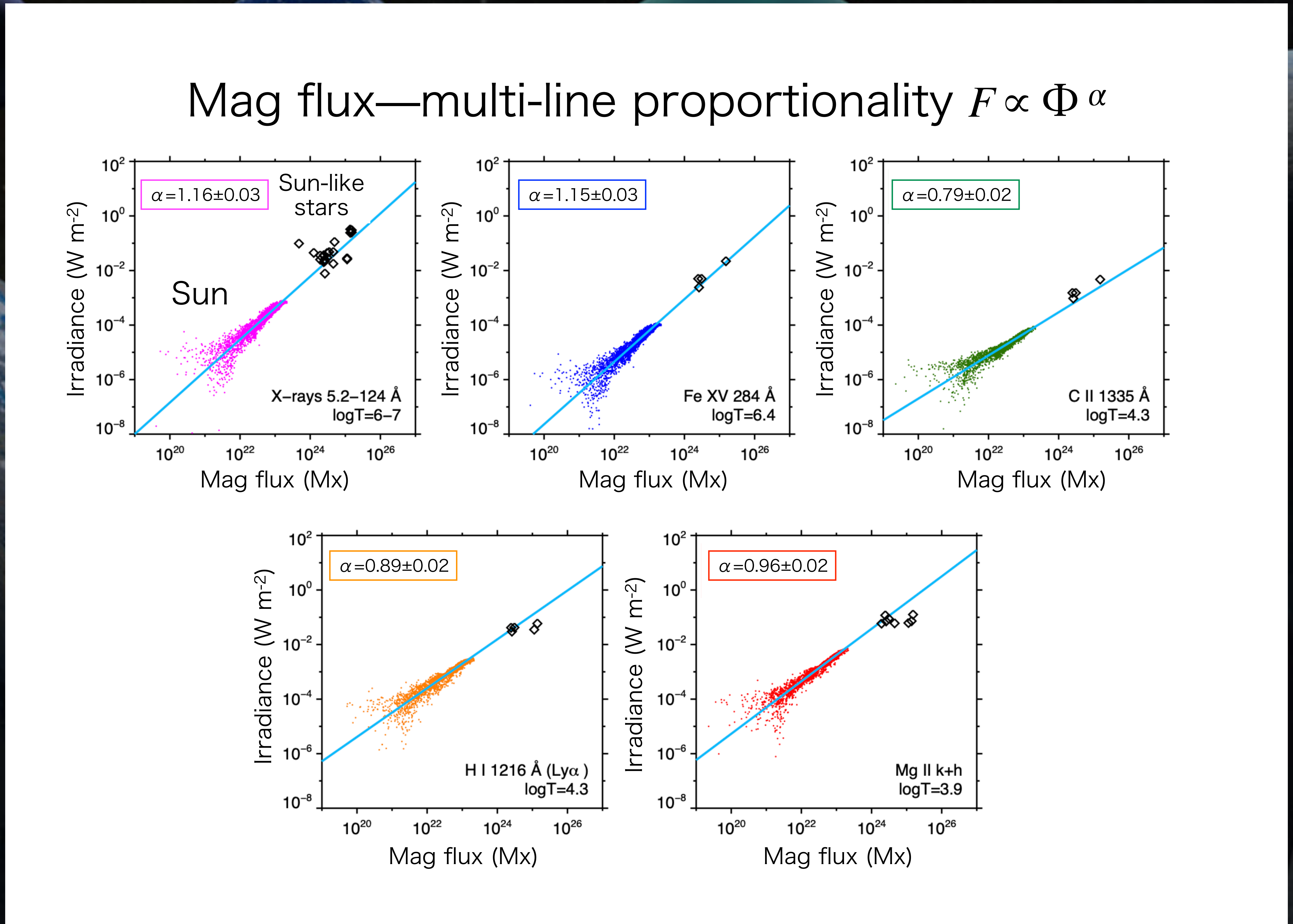
Sample reconstructed irradiances over centuries



✓ New catalog provides means to empirically synthesize line irradiances

4. Summary and Discussion

- Characterization of stellar ARs
  - Test idea using Sun-as-a-star data
  - Long-term, multi-wavelength monitoring of stars may provide means to track AR evolutions
- Universal atmospheric heating
  - Comparison of scaling laws $F \propto \Phi^{\alpha}$ between the Sun and Sun-like stars with ages from 50 Myr to 4.5 Gyr
  - The heating mechanism is universal among the Sun and Sun-like stars, regardless of age or activity
  - Updated catalog of power-law index can be used for reconstruction of line irradiances from various proxy data



Toriumi et al. 2020, ApJ, 902, 36
Toriumi & Airapetian 2022, ApJ, 927, 179
Toriumi et al. 2022, ApJS, accepted

Thank you for your attention

Send feedback to toriumi.shin@jaxa.jp