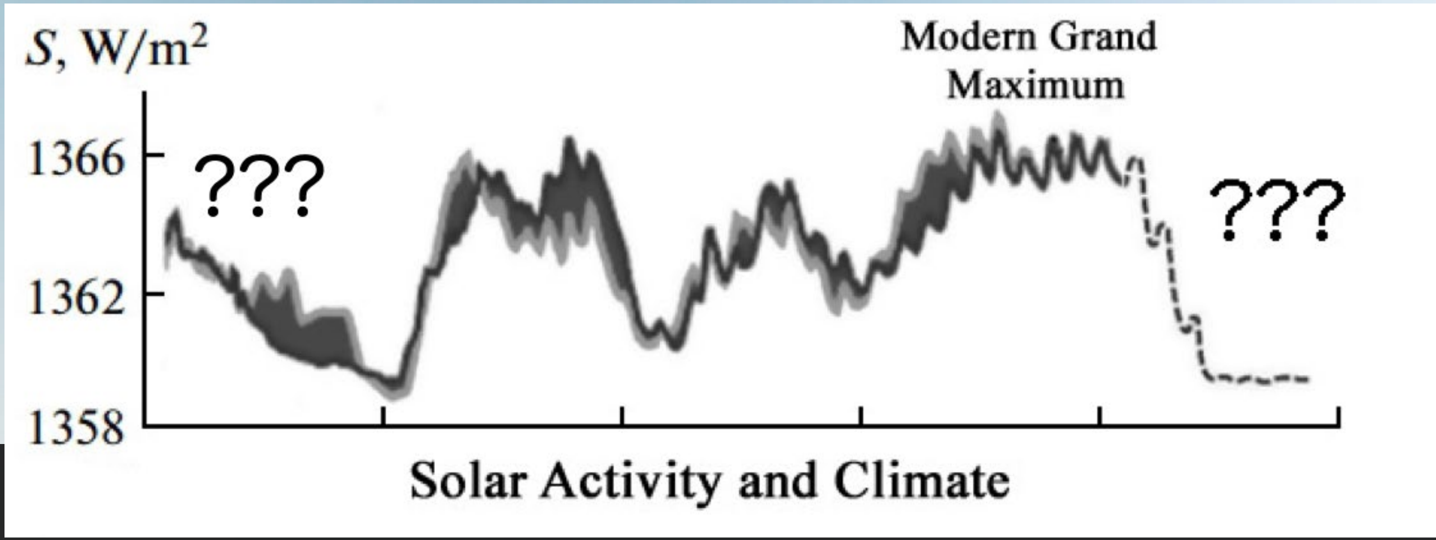

The next 5 decades under the Sun

and stars

Philip Judge, Ricky Egeland and Gerald Meehl ,
HAO and CGD

Jan, 2020

NCAR

High Altitude Observatory

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Climate sensitivity and Total Solar Irradiance

$$\Delta T_S \text{ (K)} = \lambda \, \Delta F \text{ (Wm}^{-2}\text{)}$$

$$\lambda \approx \tfrac{1}{4} \text{ (1-albedo)} \approx 0.8 \text{ K/Wm}^{-2}$$

IPCC

- The IPCC currently considers the Sun to be a minor player in recent century-long climate change, a consensus reached after several decades of multi-disciplinary research.

- AR5 (2013) report: "*All reconstructions rely on indirect proxies that inherently do not give consistent results. There are relatively large discrepancies...*

- These "results" are, in essence, *untestable extrapolations backwards in time*

- Here we ask,
  - can we find a *refutable, testable* source of ``hard data" to set limits on solar radiative forcing?
  - What can we expect over the next 5 decades?

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2001 IPCC

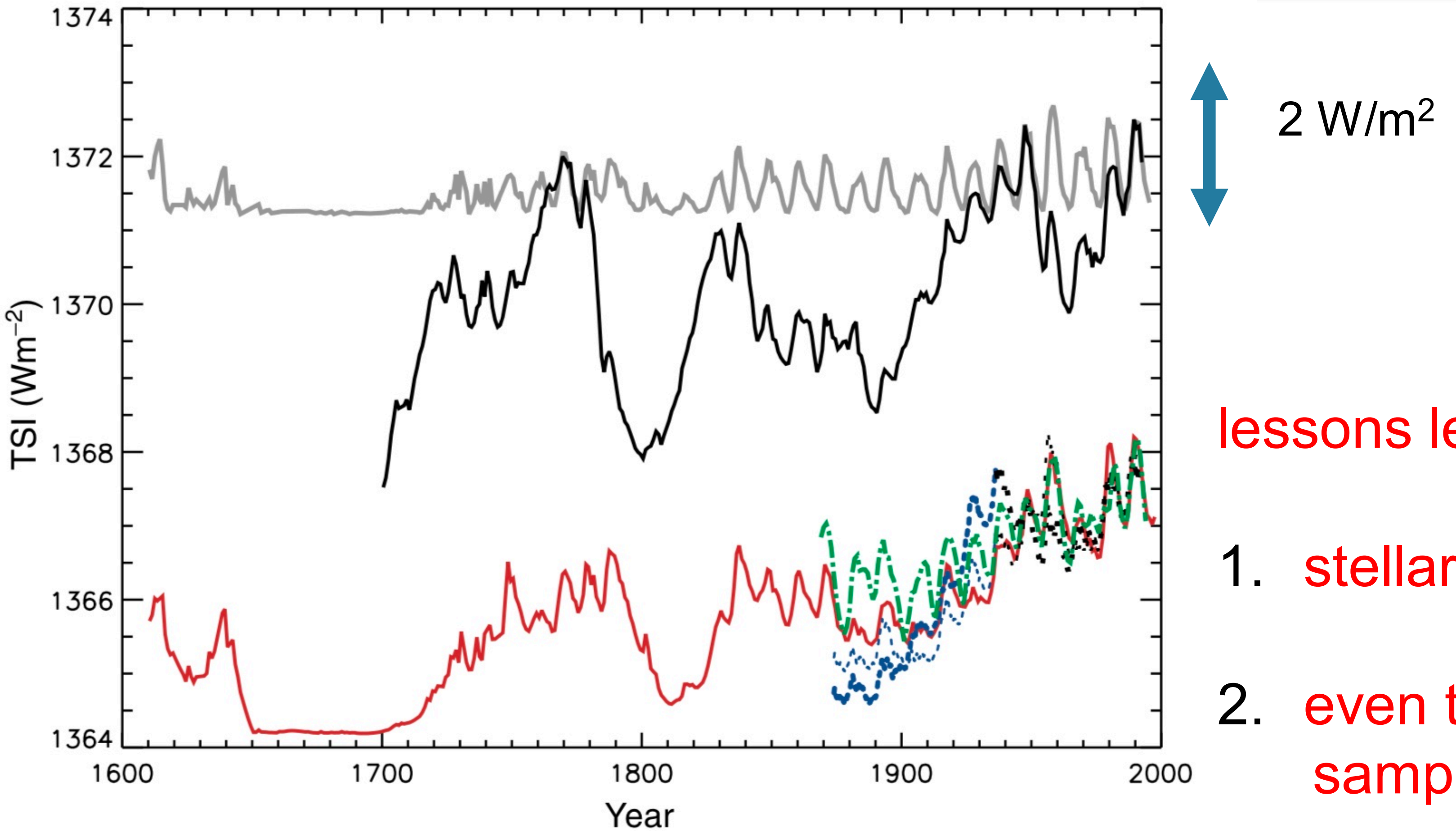

Figure 6.5: Reconstructions of total solar irradiance (TSI) by Lean *et al.* (1995, solid red curve), Hoyt and Schatten (1993, data updated by the authors to 1999, solid black curve), Solanki and Fligge (1998, dotted blue curves), and Lockwood and Stamper (1999, heavy dash-dot green curve); the grey curve shows group sunspot numbers (Hoyt and Schatten, 1998) scaled to Nimbus-7 observations for 1979 to 1993.

lessons learned:

1. stellar sample
2. even temporal sampling

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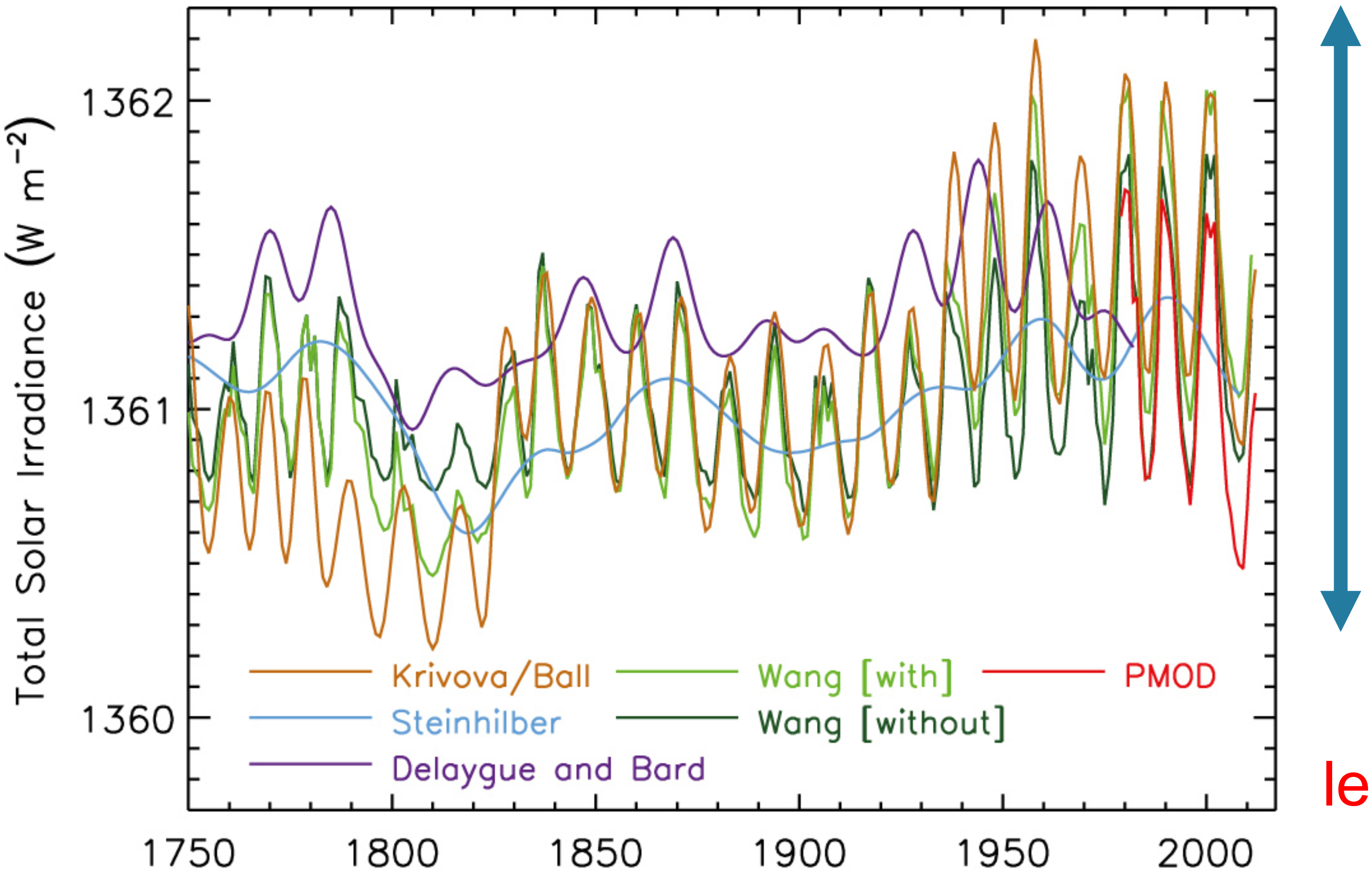
2013 IPCC AR5



lessons learned?

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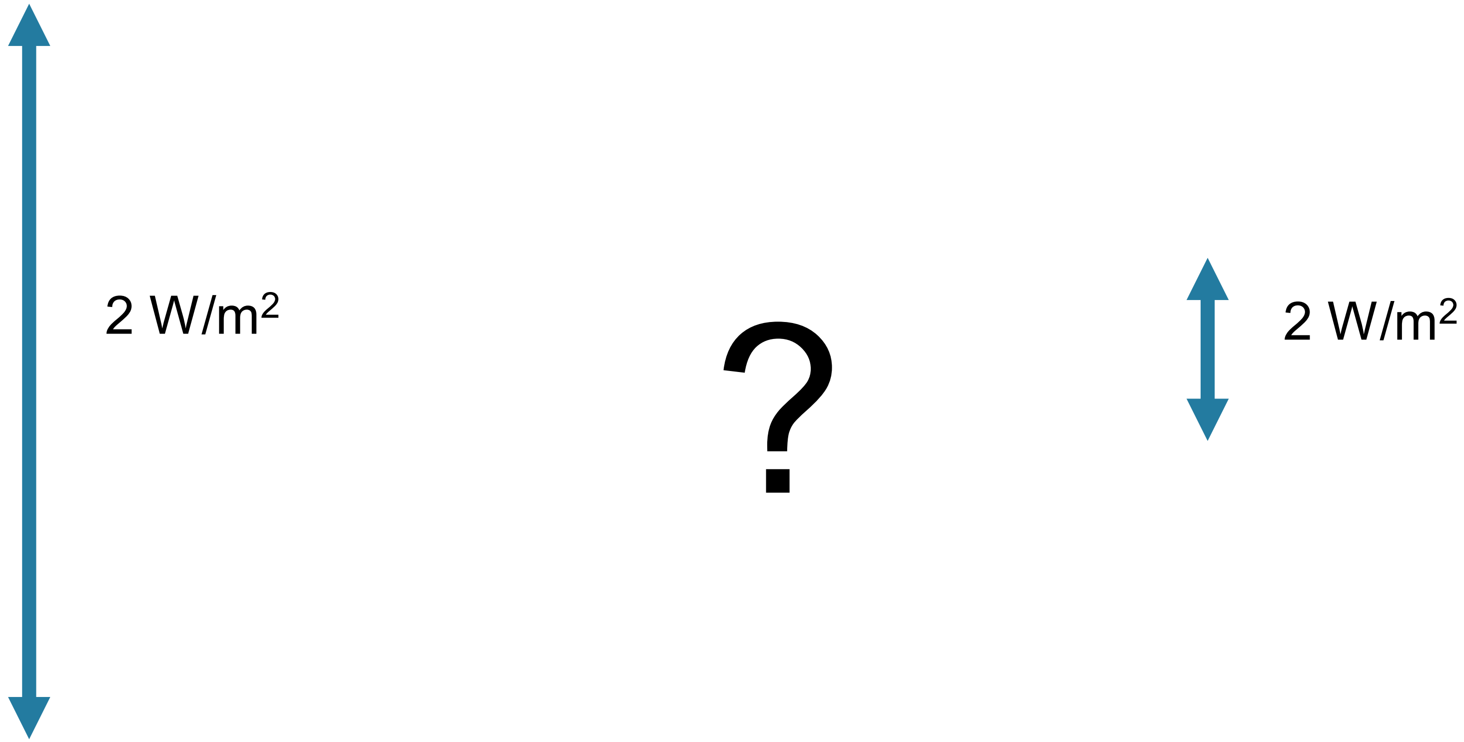
2021 IPCC AR6



Q: can we set credible limits on future solar irradiances?

- Time-scales of interest, ≥ ***decades***
- Historical solar data are ***insufficient*** for this task
- "Reconstructions" abound, all are ***untestable extrapolations***

- *=> Turn to the* ***stars – L. Boyd, G.W. Lockwood, G. Henry, J. Hall, R. Radick...***
- *milli-magnitude photometric precision:*

$$\Delta m_{BOL} = -2.5 \log_{10} e \ln[1 + \Delta F/F]$$
$$\approx 1.086 \Delta F/F, \qquad F\text{=irradiance}$$

individual stellar σ ≈ *0.0006 mag in b,y colors*

solar *cycle* $\Delta F/F$ ≈ *0.00073*
≈ *1 mmag in b,y colors (Radick et al 2018)*

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Patterns of Variation for the Sun and Sun-like Stars

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Abstract

We compare patterns of variation for the Sun and 72 Sun-like stars by combining total and spectral solar irradiance measurements between 2003 and 2017 from the *SORCE* satellite, Strömgren *b*, *y* stellar photometry between 1993 and 2017 from Fairborn Observatory, and solar and stellar chromospheric Ca II H+K emission observations between 1992 and 2016 from Lowell Observatory. The new data and their analysis strengthen the relationships found previously between chromospheric and brightness variability on the decadal timescale of the solar activity cycle. Both chromospheric H+K and photometric *b*, *y* variability among Sun-like stars are related to average chromospheric activity by power laws on this timescale. Young active stars become fainter as their H+K emission increases, and older, less active, more Sun-age stars tend to show a pattern of direct correlation between photometric and chromospheric emission variations. The directly correlated pattern between total solar irradiance and chromospheric Ca II emission variations shown by the Sun appears to extend also to variations in the Strömgren *b*, *y* portion of the solar spectrum. Although the Sun does not differ strongly from its stellar age and spectral class mates in the activity and variability characteristics that we have now studied for over three decades, it may be somewhat unusual in two respects: (1) its comparatively smooth, regular activity cycle, and (2) its rather low photometric brightness variation relative to its chromospheric activity level and variation, perhaps indicating that facular emission and sunspot darkening are especially well-balanced on the Sun.

The Astrophysical Journal, 855:75 (28pp), 2018 March 10

individual stellar $\sigma \approx$ 0.0006 mag in b,y colors

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Method and critical assumptions

1. The Sun is a typical star, stellar ensemble ≣ Sun in time

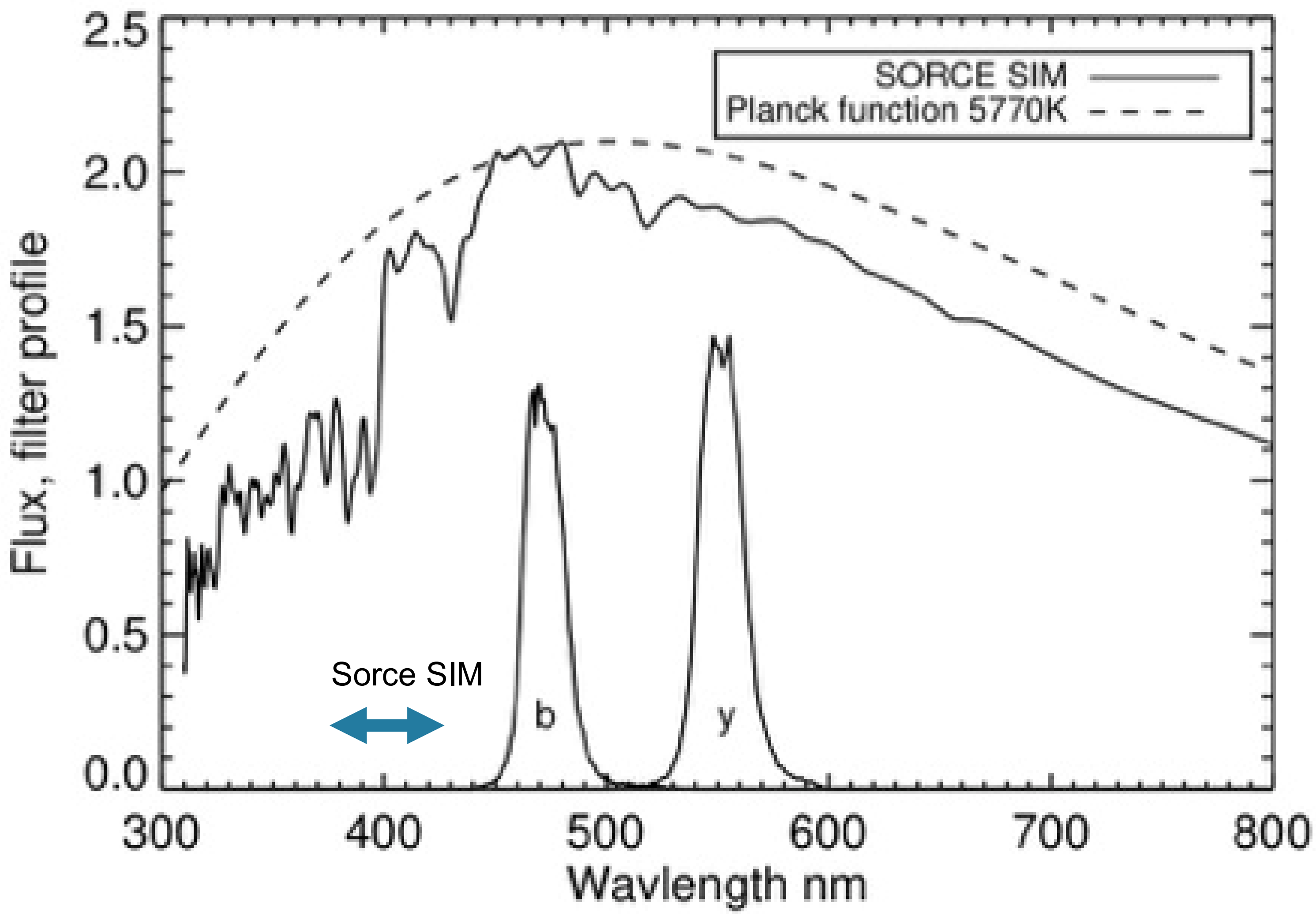
2. Variances are mostly captured in 2 decades of stellar data

3. Strömgren *b,y* colors are linearly proportional to irradiance

4. Sun's variations observed equator-on are not special
   (Schatten 1993 vs Knaack et al 2001)

unlike historical ``reconstructions'', all of these are refutable, and 2. improves with continued photometry

Precise photometry   Strömgren   b,y filters



Radick et al 2007:

$\Delta\ (b+y)/2 \approx 1.45\ \ \Delta F/F$

Sample selection is critical

Selection on Mass, luminosity, radius, metallicity, Prot, age, Ro

- Based on
  - S-indices, (Mt WIlson and SSS) and $R'_{HK.}$ (many authors)
  - Kepler photometry,
  - asteroseismology
  - “gyrochronology” (e.g. Melbom et al 2015)
  - spectroscopy
- Coupled with traditional work on
  - Convective turnover time (Noyes et al 2004)

- ``Sun-like”:
  - R'_{HK}
  - S index & photometry in-phase

- Reliable:
  - single star
  - good photometric comparisons (Henry)
  - use seasonal averages (cf. Baliunas & Jastrow 1990)

Table 1
The subset of stars analyzed

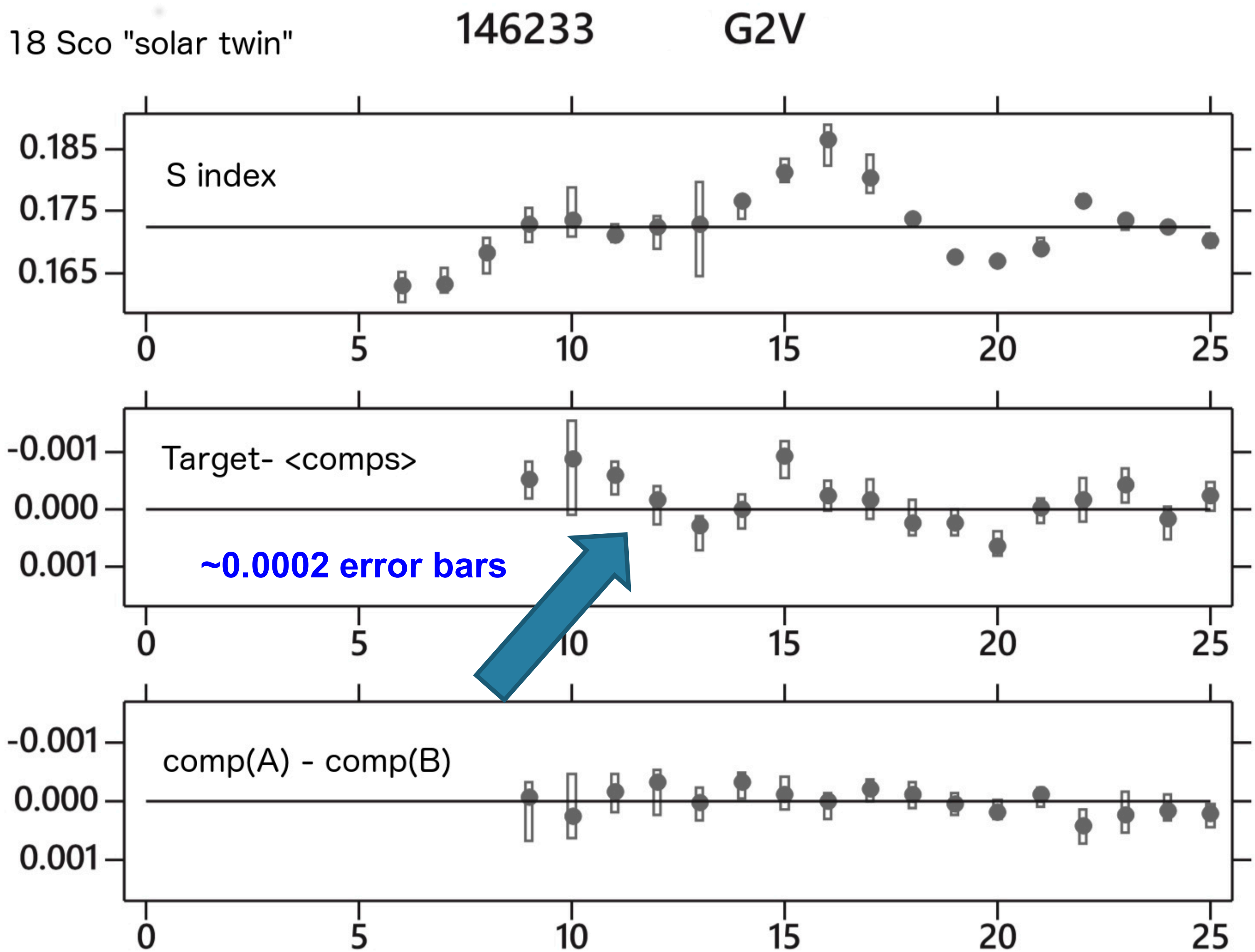
HD	Sp.	B-V	age (Gyr) low	up	p_{rot} days	var. type
*1461	G3VFe0.5	0.68	0.9	3.1	17.0	poor
10307	G1V	0.62	3.5	8.2		
13043	G2V	0.62	4.3	7.6	34.0	
*38858	G2V	0.64	3.2	7.5	40.0	
42618	G4V	0.64				
43587	G0V	0.61	4.45	5.49	20.3	flat
*50692	G0V	0.6	4.0	6.0	25.0	
*52711	G0V	0.59	4.9	9.7	30.0	
*95128	G1-VFe-0.5	0.61	6.03	6.03	30.0	
*101364	G5	0.65	3.5	3.5	23.0	
109358	G0V	0.58	5.3	7.1	28.0	
120066	G0V	0.59				
126053	G1.5V	0.63	5.49	5.49	35.0	poor?
141004	G0-V	0.6	5.8	6.7	25.8	long
143761	G0+VaFe	0.6	8.5	11.9	17.0	long
146233	G2Va	0.65	3.65	3.75	22.7	good
*157214	G0V	0.62	4.1	6.6	14.0	irr.
*159222	G1V	0.62	3.5	6.0	28.0	
*186408	G1.5Vb	0.62	6.7	7.3	23.8	flat
*186427	G3V	0.66	6.7	7.3	23.2	flat
*187923	G0V	0.65	8.1	9.5	31.0	
*197076	G5V	0.61	0.2	9.3	30.0	

Precise photometry Fairborn Obs. Henry, Boyd

Radick et al (2018)

nb

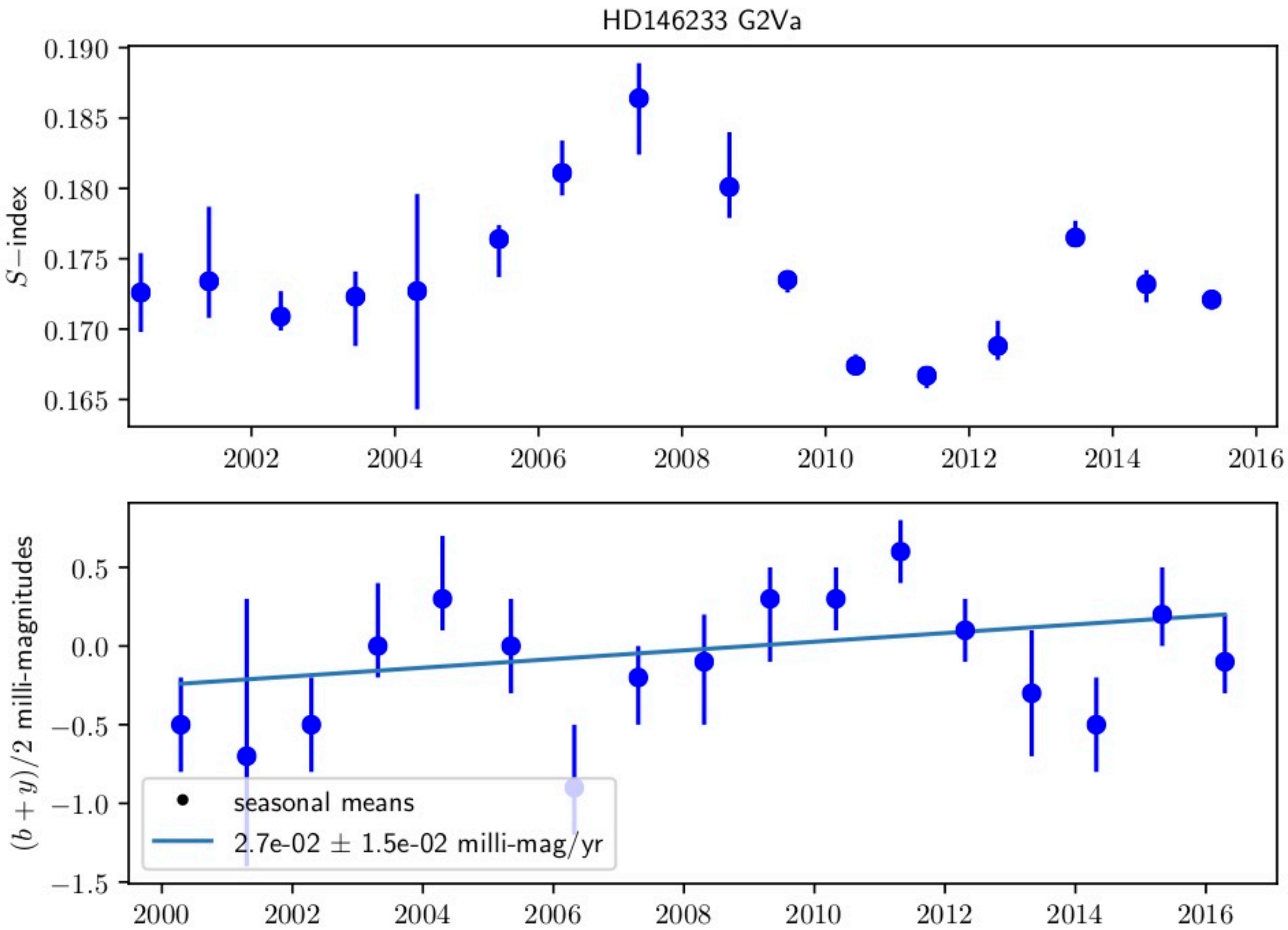
magnitudes



New analysis, SSS stellar sample Hall, Lockwood, Radick

Example:18 Scorpii "solar twin"

nb milli-magnitudes

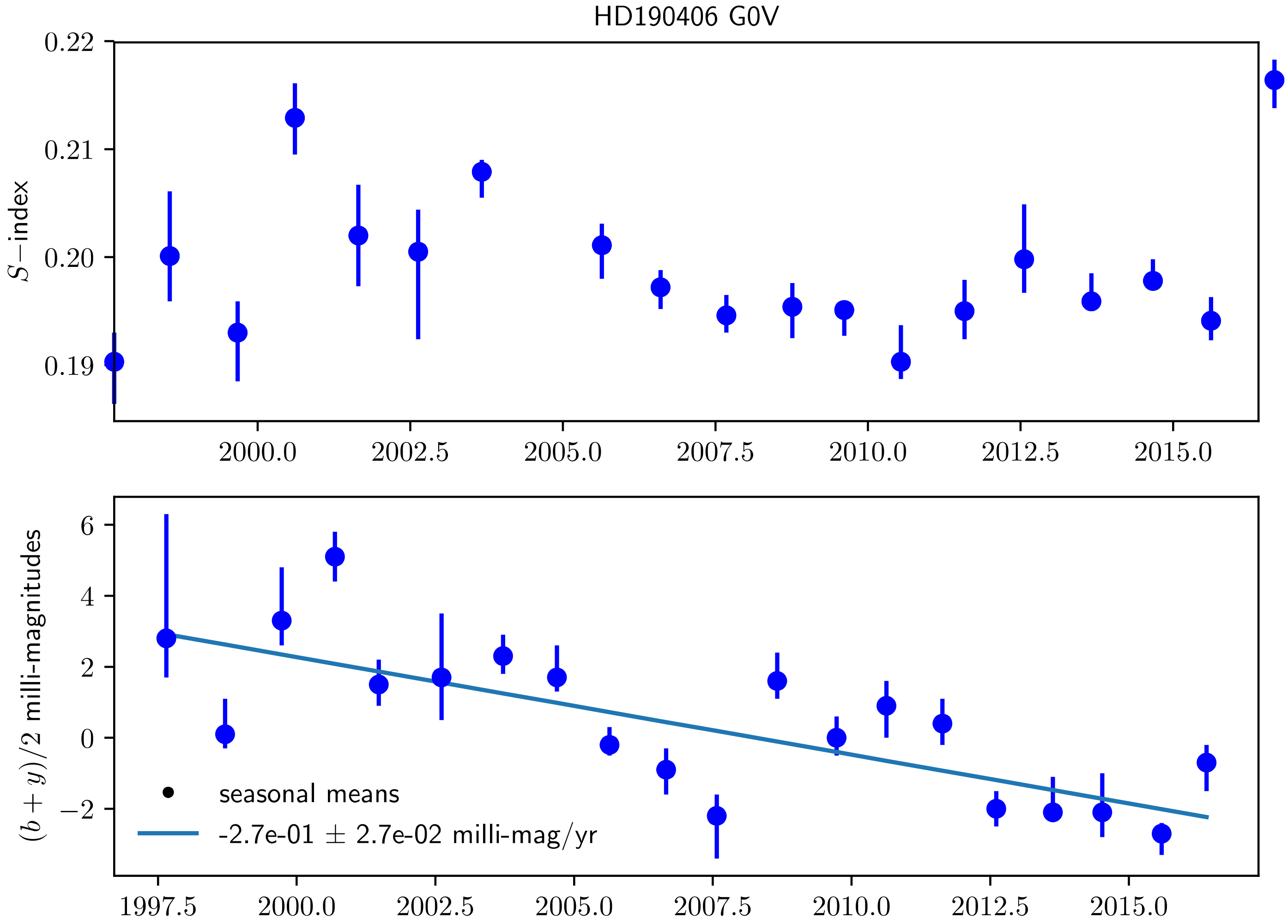


Seek secular changes in photometry

tory

New analysis, SSS stellar sample Hall, Lockwood, Radick

Example: HD 190406 a rapid secular change

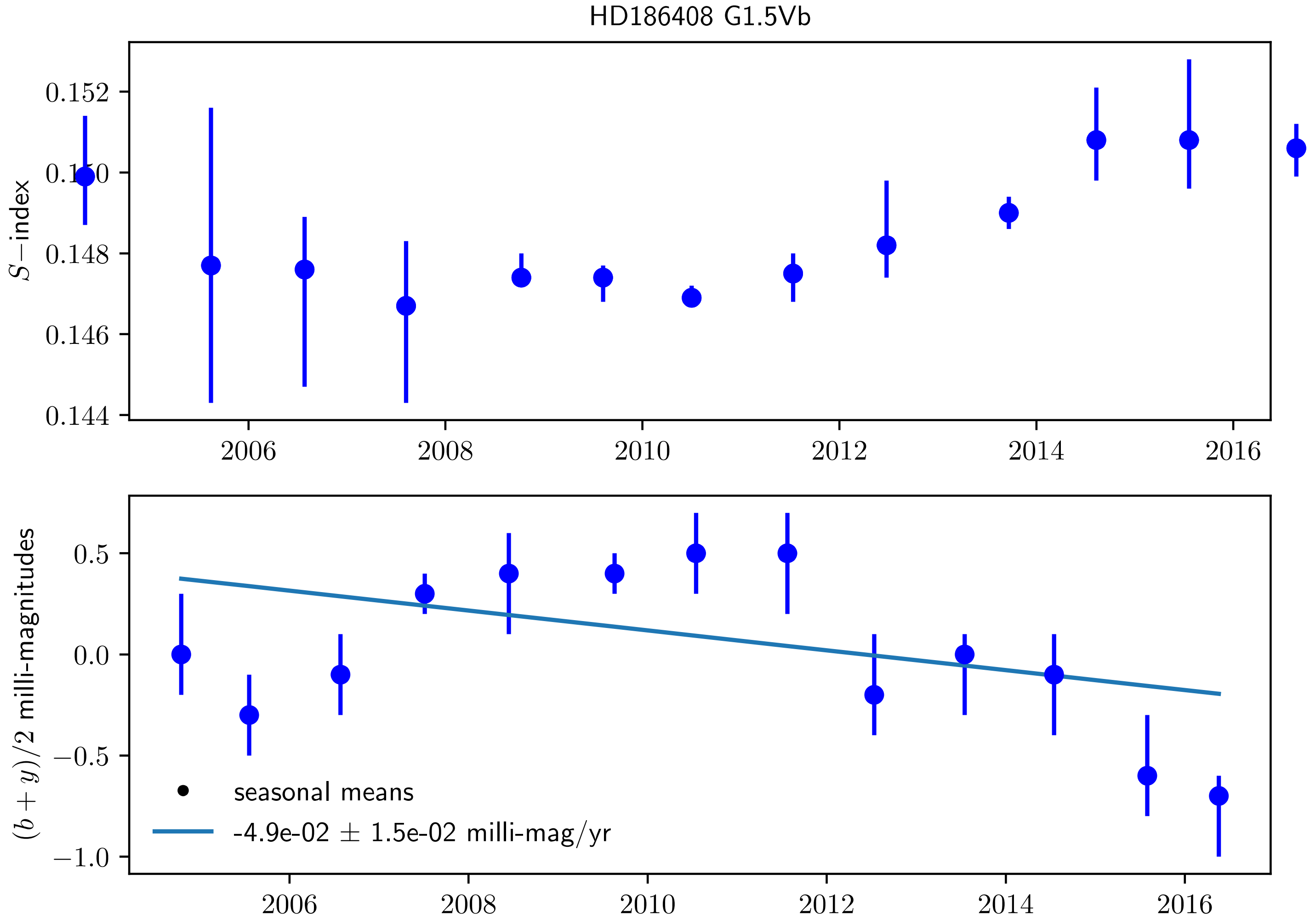


Young star 15 Sge age=2.5 Gyr

ervatory

New analysis, SSS stellar sample Hall, Lockwood, Radick

Example: HD 186408



Old star 16 Cyg A, age=7 Gyr

Ensemble results.

Table 2
Derived stellar properties

HD	dis.	Ro	$\log R'_{HK}$	τ	Gradient		
				yr	$\log g_i(\tau)$ mag/yr	sign	$\log \sigma_i$ mag/yr
1461	0.68	1.8	-5.04	17.99	-5.55	[illegible]	0.89
10307	0.61		-5.01	19.89	-4.54	+	0.10
13043	0.92	3.3	-5.01	15.02	-4.97	−	0.41
38858	0.29	3.5	-4.89	18.96	-4.81	−	0.23
42618	0.25		-4.96	14.98	-4.79	−	0.31
43587	0.71	2.6	-4.99	16.06	-4.[illegible]	+	0.13
146233	0.15	1.9	-4.95	16.0	-4.56	+	0.19
157214	0.53	1.37	-5.01	14.58	-4.46	+	0.18
159222	0.25	2.7	-4.89	17.54	-4.31	+	0.14
186408	0.88	1.89	-5.07	11.59	-4.31	−	0.12
186427	0.65	1.9	-5.04	11.59	-4.80	+	0.32
187923	1.01	2.6	-5.05	16.58	-4.05	−	0.11
197076	0.34	3.0	-4.89	15.58	-3.96	+	0.11

Critical

"dis." = weighted Euclidian distance of star from solar

with an ensemble mean gradient

$$\langle G(\tau) \rangle \approx -6 \pm 19 \text{ micro} - \text{magnitudes per year.}$$

The estimate is consistent with a value of zero,

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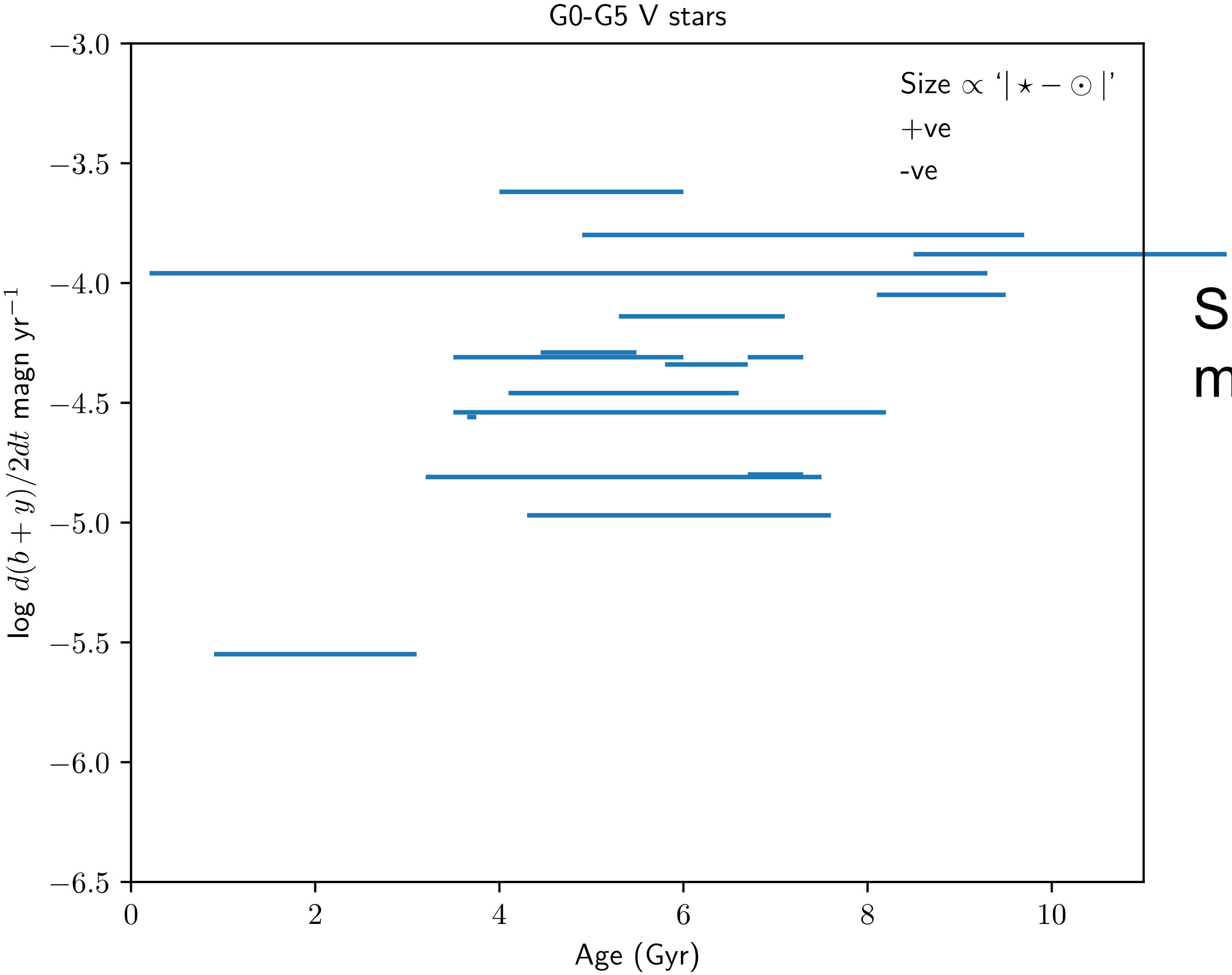
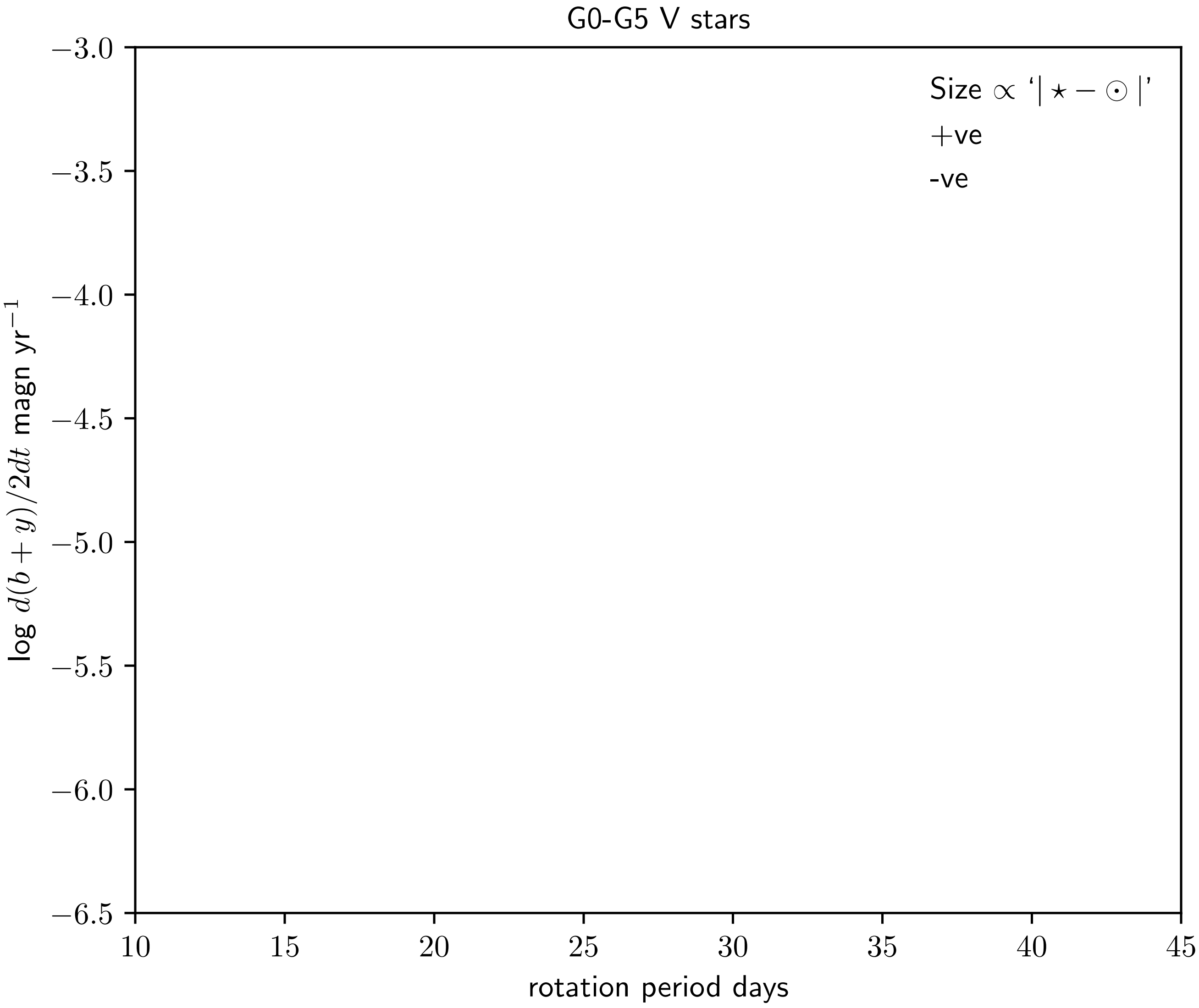
Ensemble results. Photometric gradient vs age



Smaller circle = more Sun-like

Ensemble results. Photometric gradient vs rotation period



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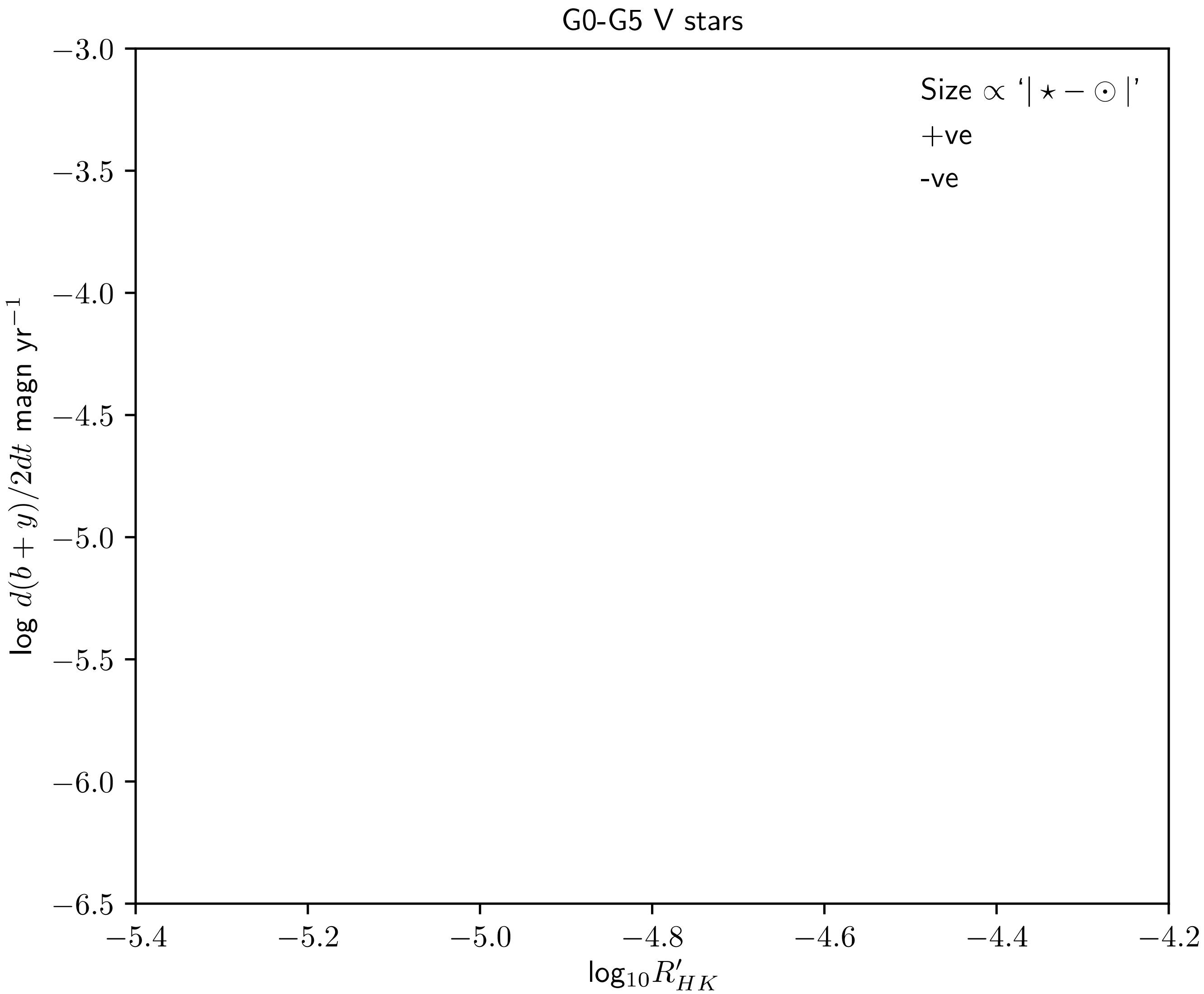
Ensemble results. Photometric gradient vs R'HK



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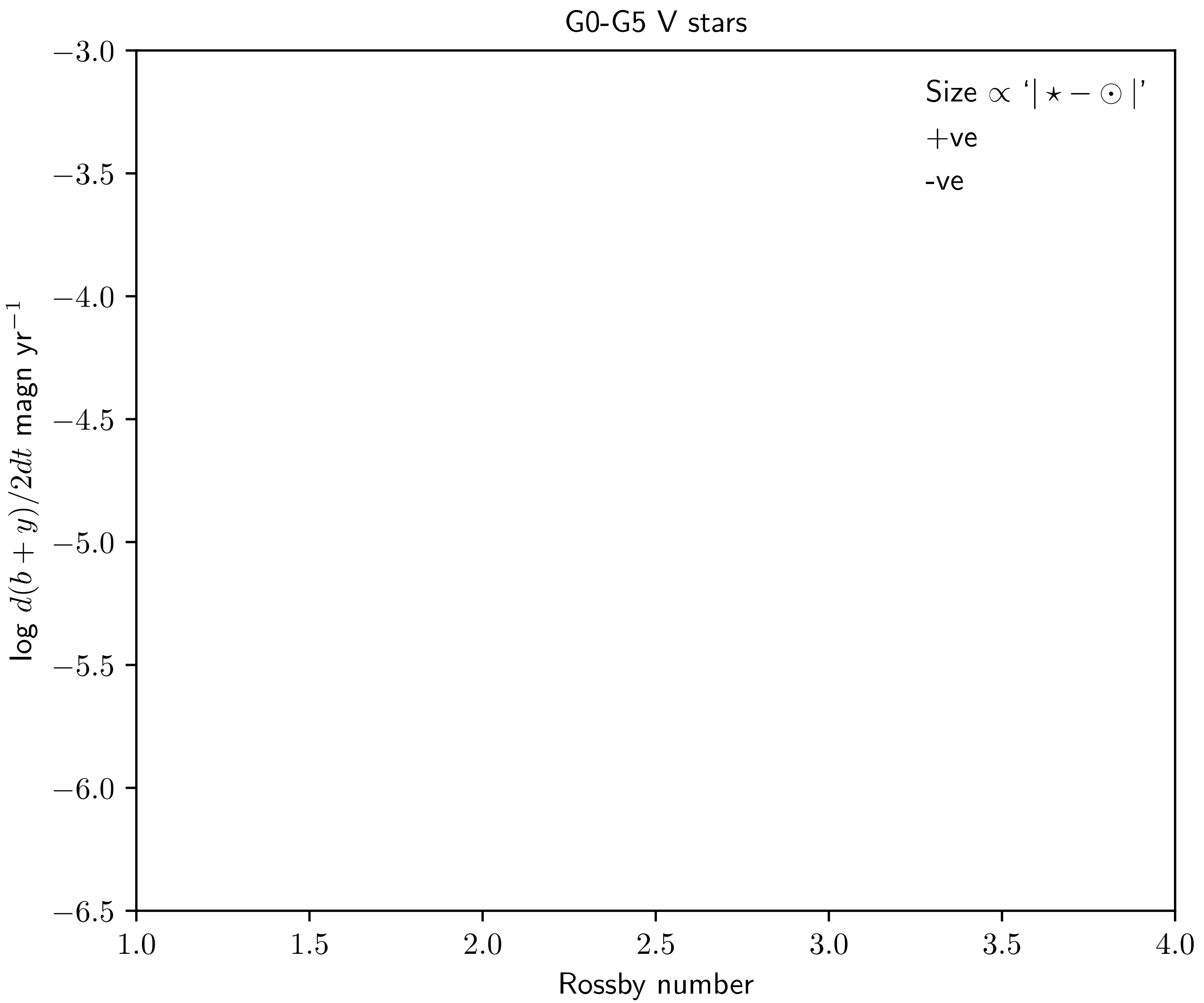
Results. Photometric gradient vs Ro



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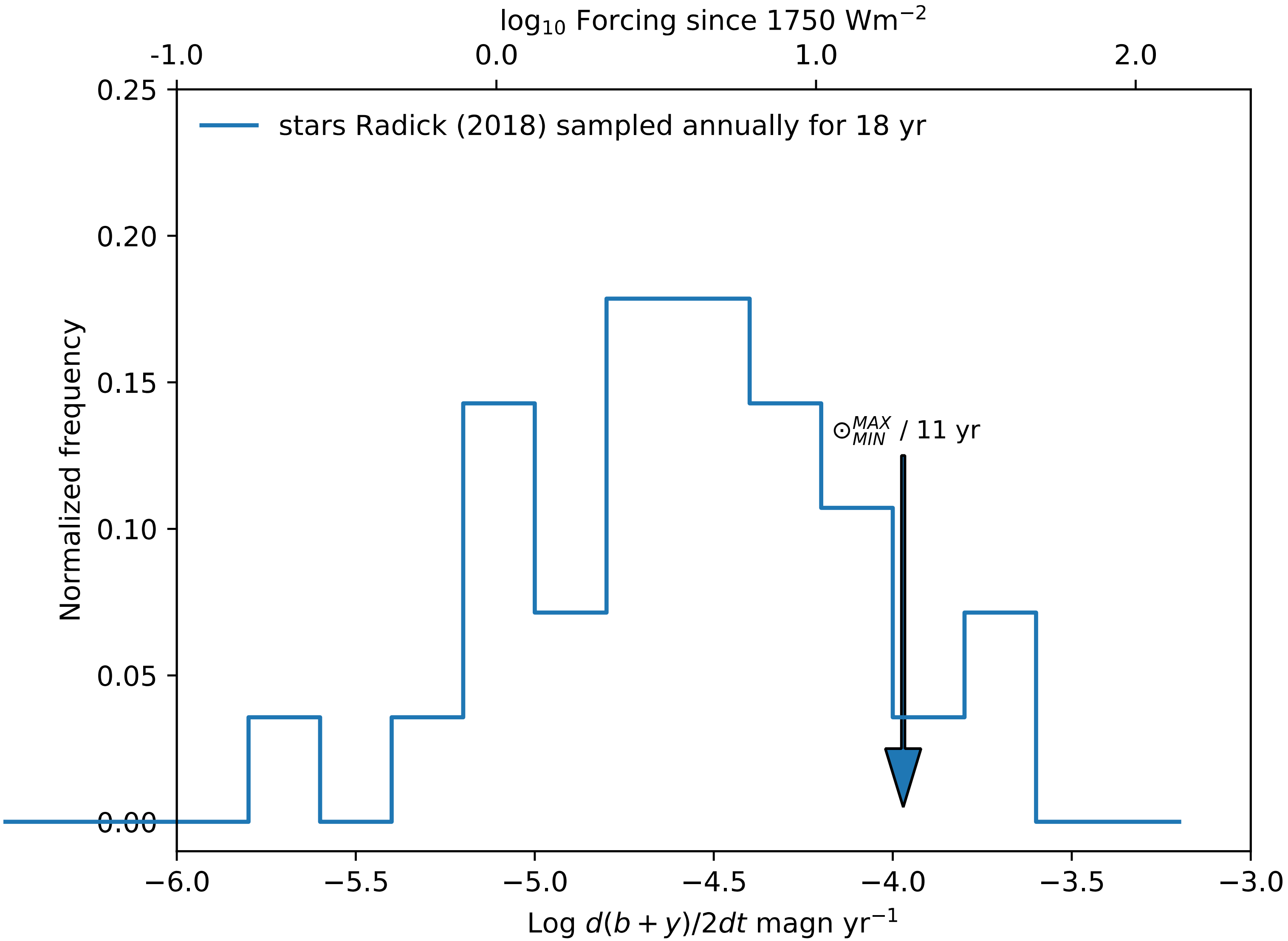
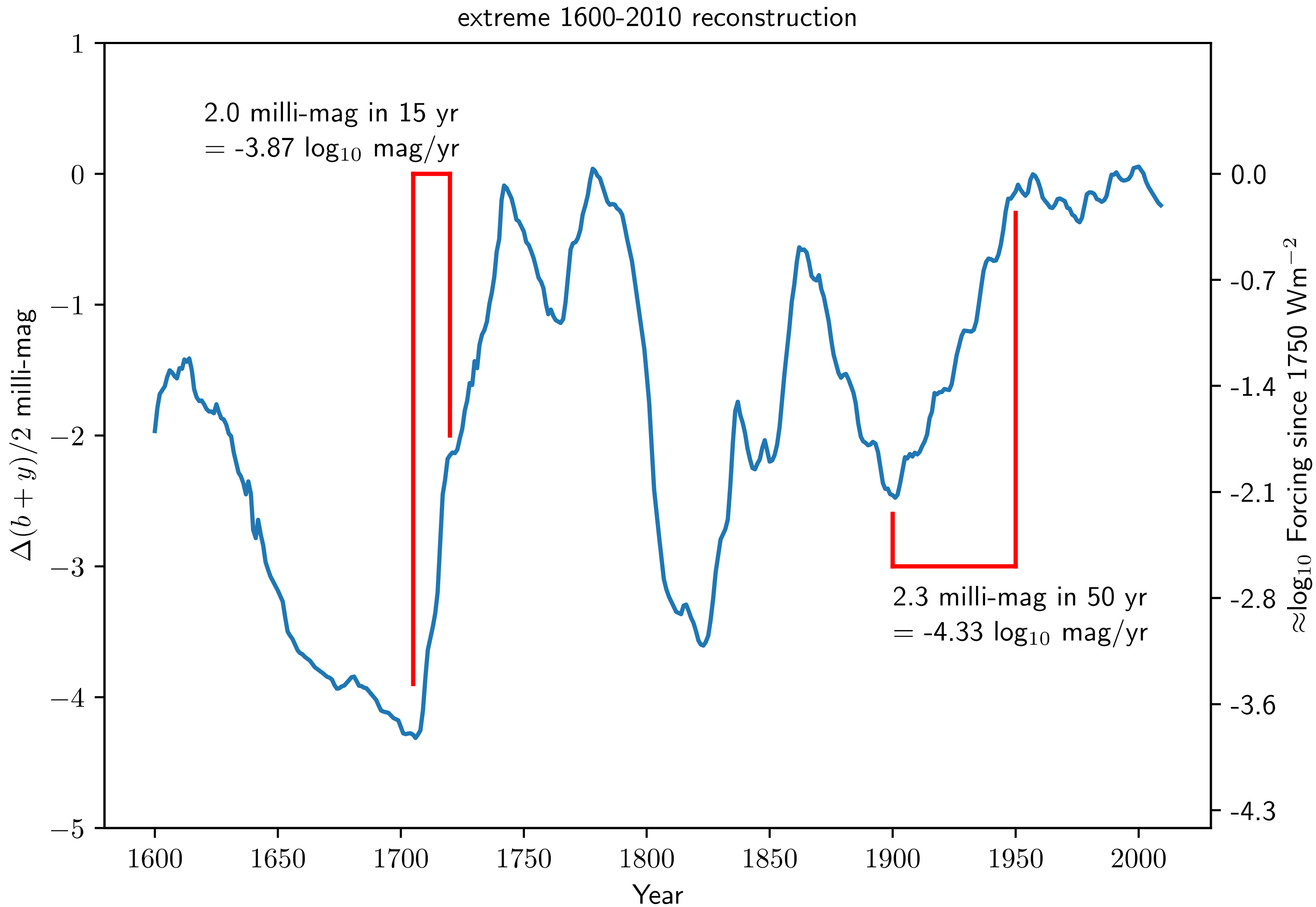
Histogram of results



Stars and an extreme reconstruction



Shapiro et al 2011

Stars and an extreme reconstruction

Persistent characteristic of this reconstruction

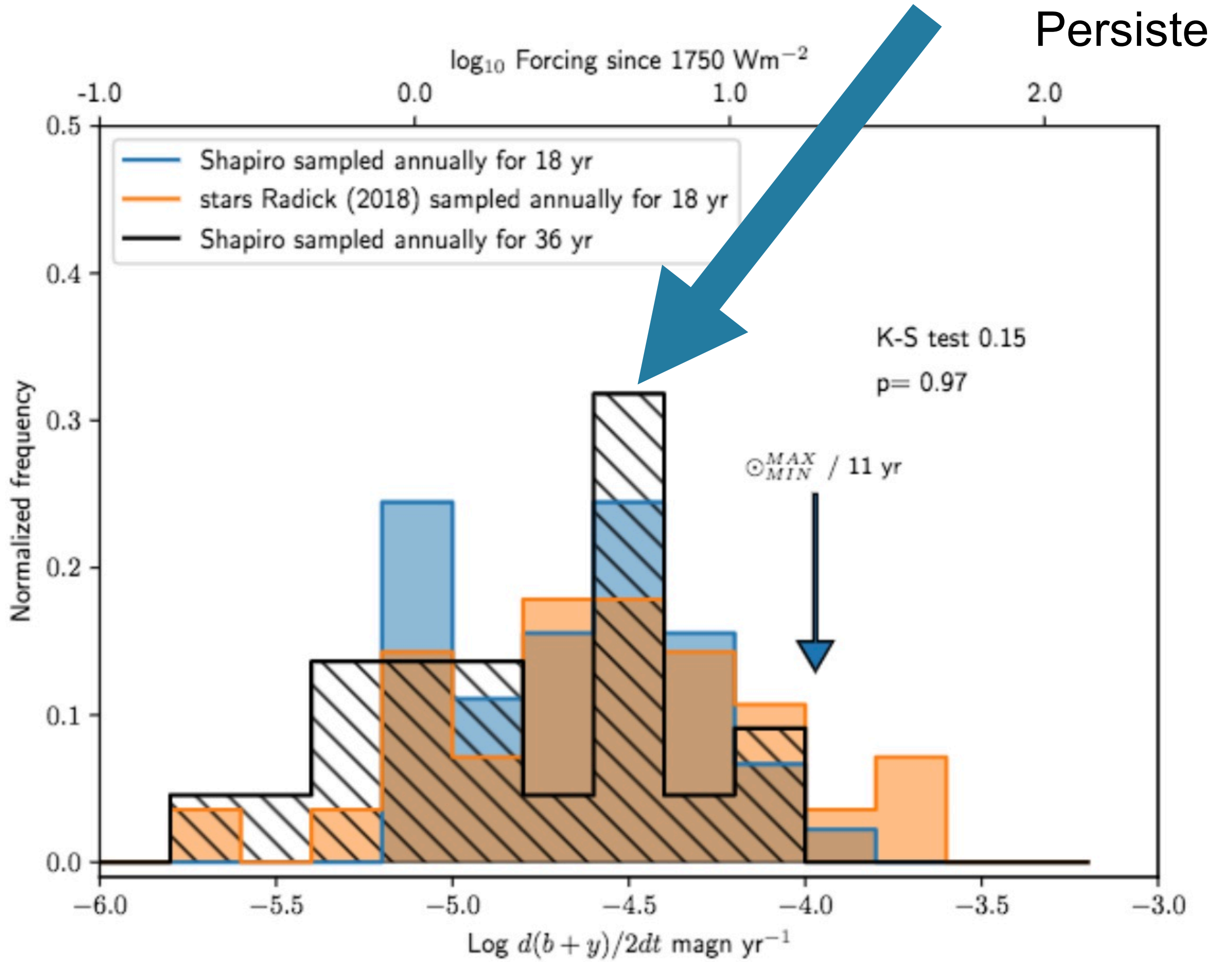


Figure 6. The distributions of stars according to their derived secular slope ($d(b+y)/2dt$) is shown along with distributions drawn from time-series extracted from the computations. All three distributions are compatible with being drawn from the same underlying distribution according to the Kolmogorov-Smirnoff test. Statistics

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Bottom line from Sun -like stars

with an ensemble mean gradient

$$\langle G(\tau)\rangle \approx -6{\pm}19 \text{ micro} - \text{magnitudes per year}$$

$$\Delta F(\tau)_{\odot} \approx -1.5{\pm}4.5 \text{ W m}^{-2} \text{ since 1750,} \qquad (2)$$

where we have used $G = (1.55 \pm 0.37)\Delta F/F$ to convert from milli-magnitudes to irradiance changes ΔF in W m^{-2} (Radick et al. 2018) for an average irradiance of $F = 1361$ W m^{-2}. The important figure here is the range of the slope from the uncertainties of ± 4.5 W m^{-2}.

climate forcing since 1750 due to anthropogenic effects, which is estimated by the IPCC (Myhre et al. 2013) to be

$$\Delta F_{AG} \approx 1.1 \text{ to } 3.3 \text{ W m}^{-2} \text{ since 1750.} \qquad (3)$$

Bottom line from Sun -like stars

In 5 decades the solar radiative forcing will be

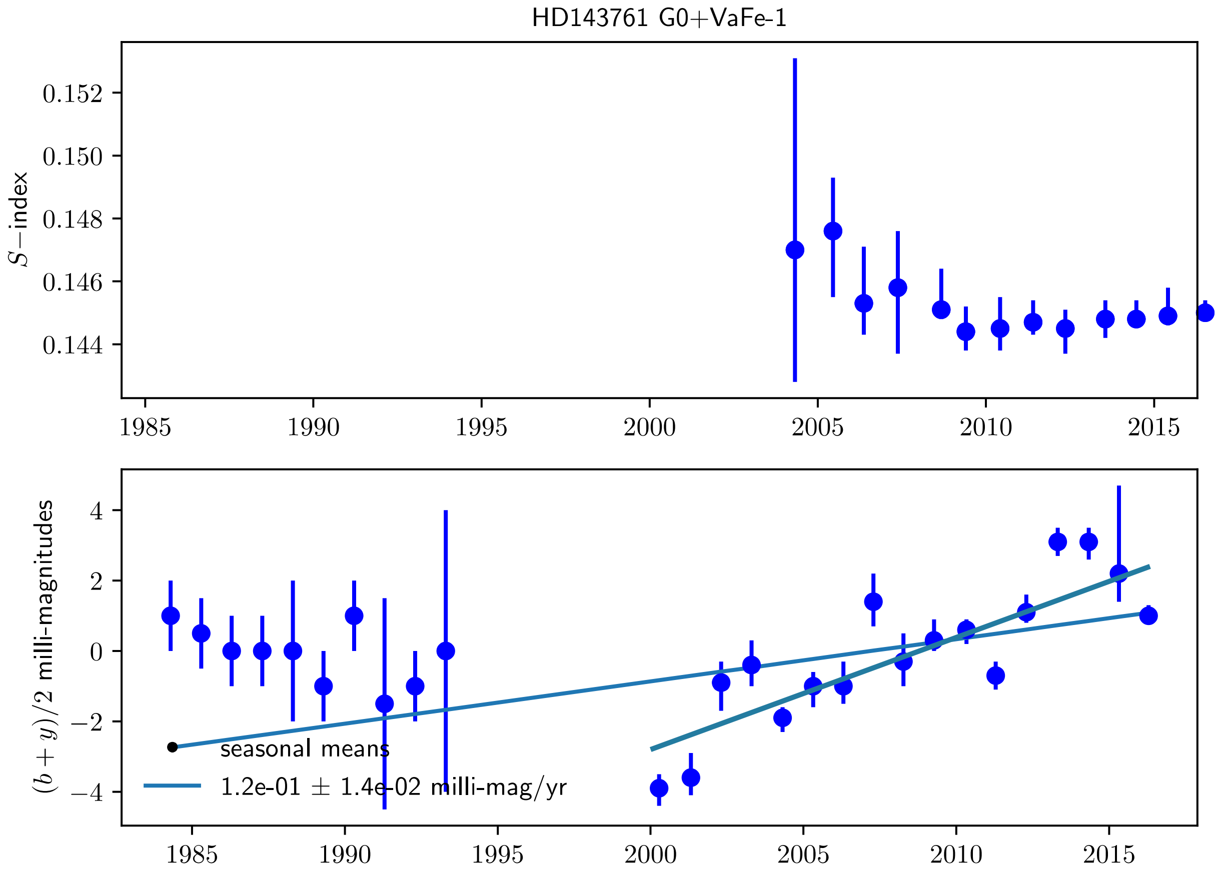
$$-0.85 < \Delta F < +0.85 \quad W\,m^{-2}$$

- or -

$$-0.7 < \Delta T_{\oplus} < +0.7 \; K$$

We expect these limits to get smaller as stars are observed for longer periods, maybe a factor of 2 in 18 years or so

Longer time series will yield tighter constraints



Moves from 0.3 to 0.12 milli-mag / yr
in going from 10 to 30 year time series

Reminder: critical assumptions

1. The Sun is a typical star

2. Variances are mostly captured in 2 decades of data

3. Strömgren *b,y* colors are linearly proportional to Irradiance

4. Sun's variations observed equator-on are not special
   (Schatten 1993 vs Knaack et al 2001)

unlike historical ``reconstructions'', all of these are refutable
and 2. becomes less important with continued photometry

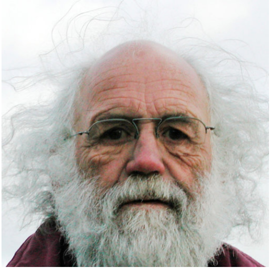
Conclusions

Secular changes in the brightness of Sun-like stars typically produce (±1**σ**, 68% probability)

± 0.85 W/m^2 of radiative forcing in 5 decades

based only on 16 years of data, versus

+ 2 W/m^2 anthropogenic forcing in 5 decades (Lean, Jan 30 2020)

Urgent need for **continued automated photometry** , including perhaps a "Geosphere" (Judge & Egeland 2014 MNRAS, refereed by )

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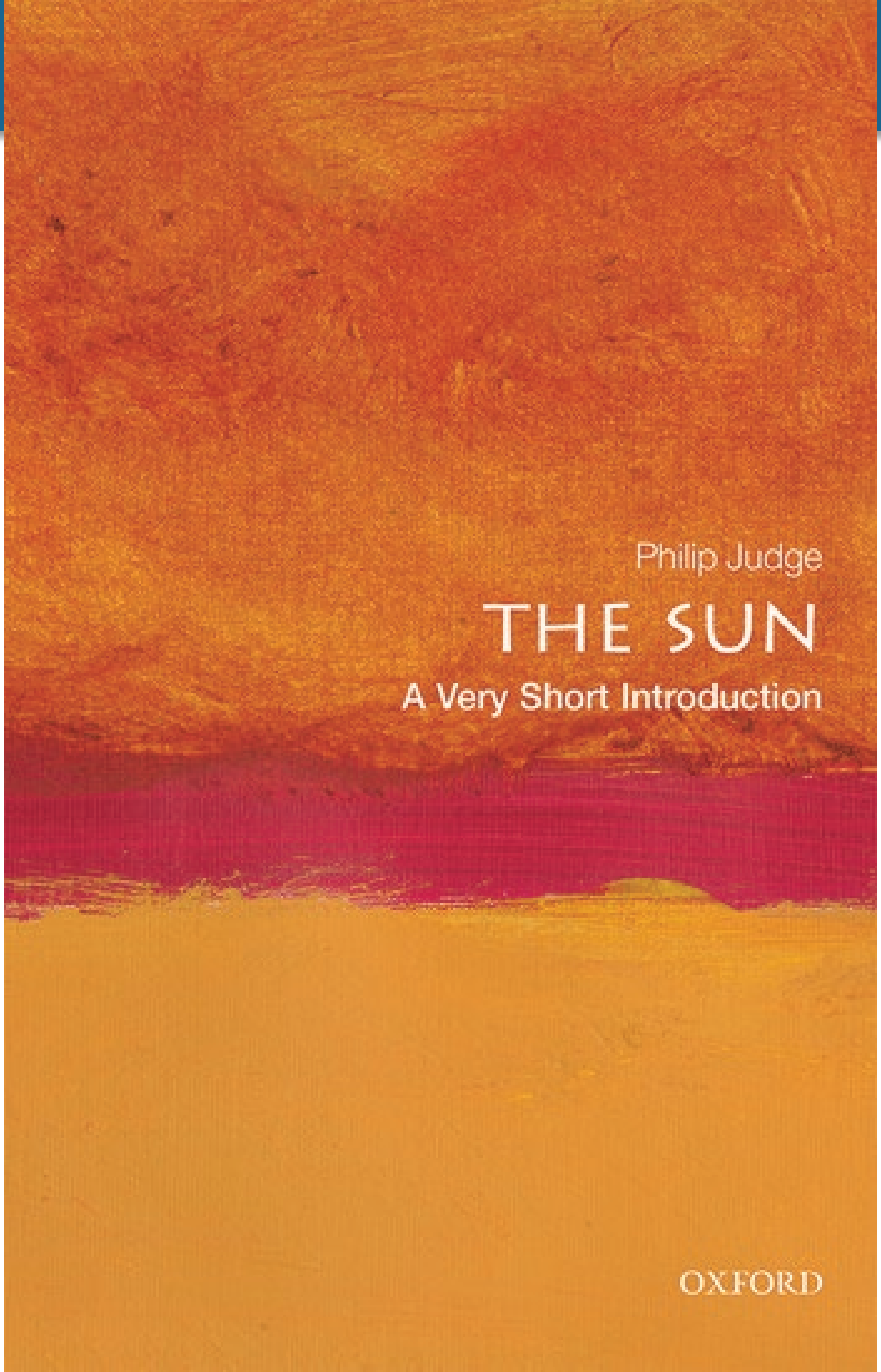
Shameless commerce

June 2020

focus on physical processes

for the interested public



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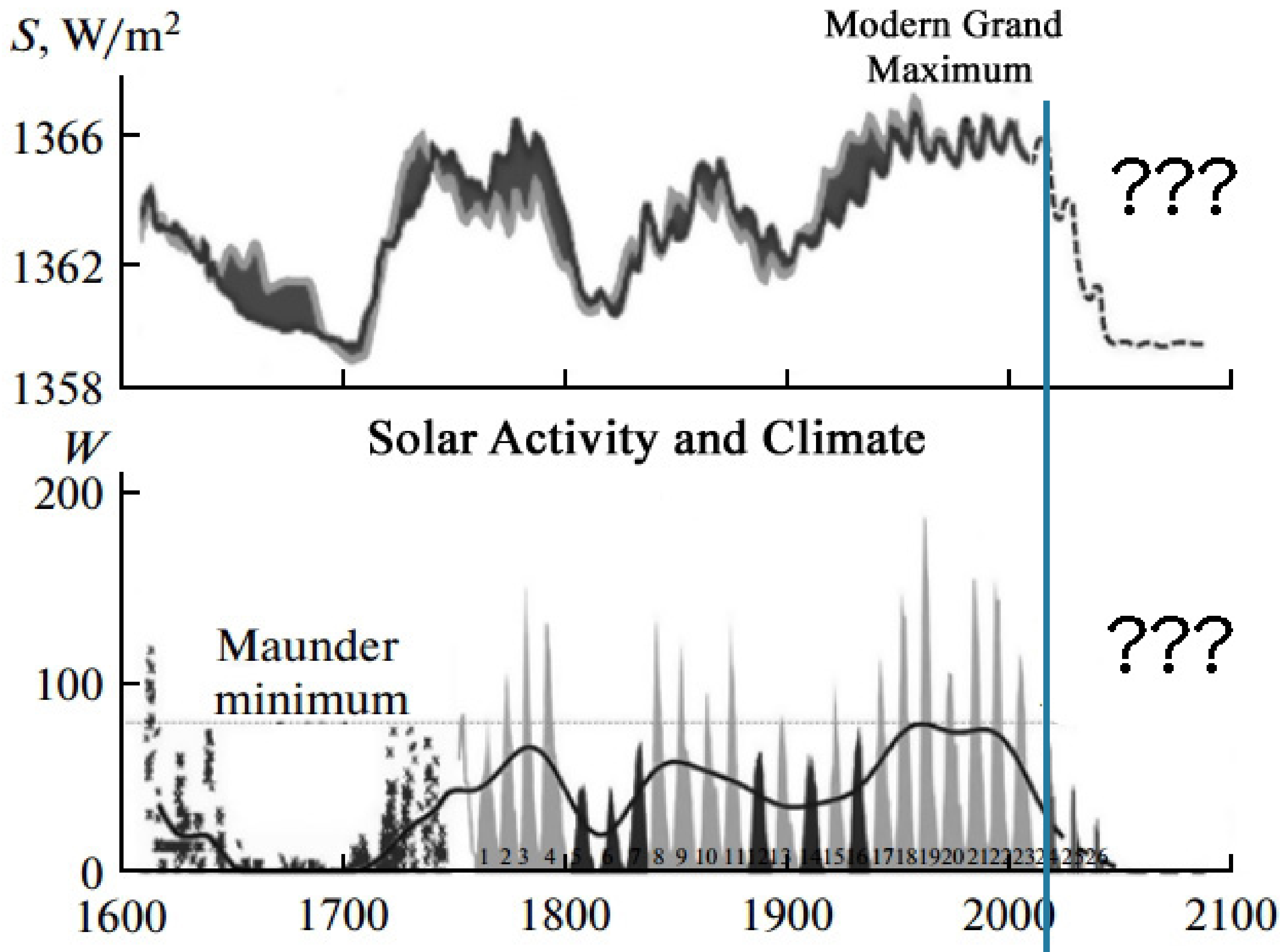
- EXTRA SLIDES

Q: can we set credible limits on future solar irradiances?

(Don't believe this amplitude...) {

but ***why?***



Abdussamatov, 2012

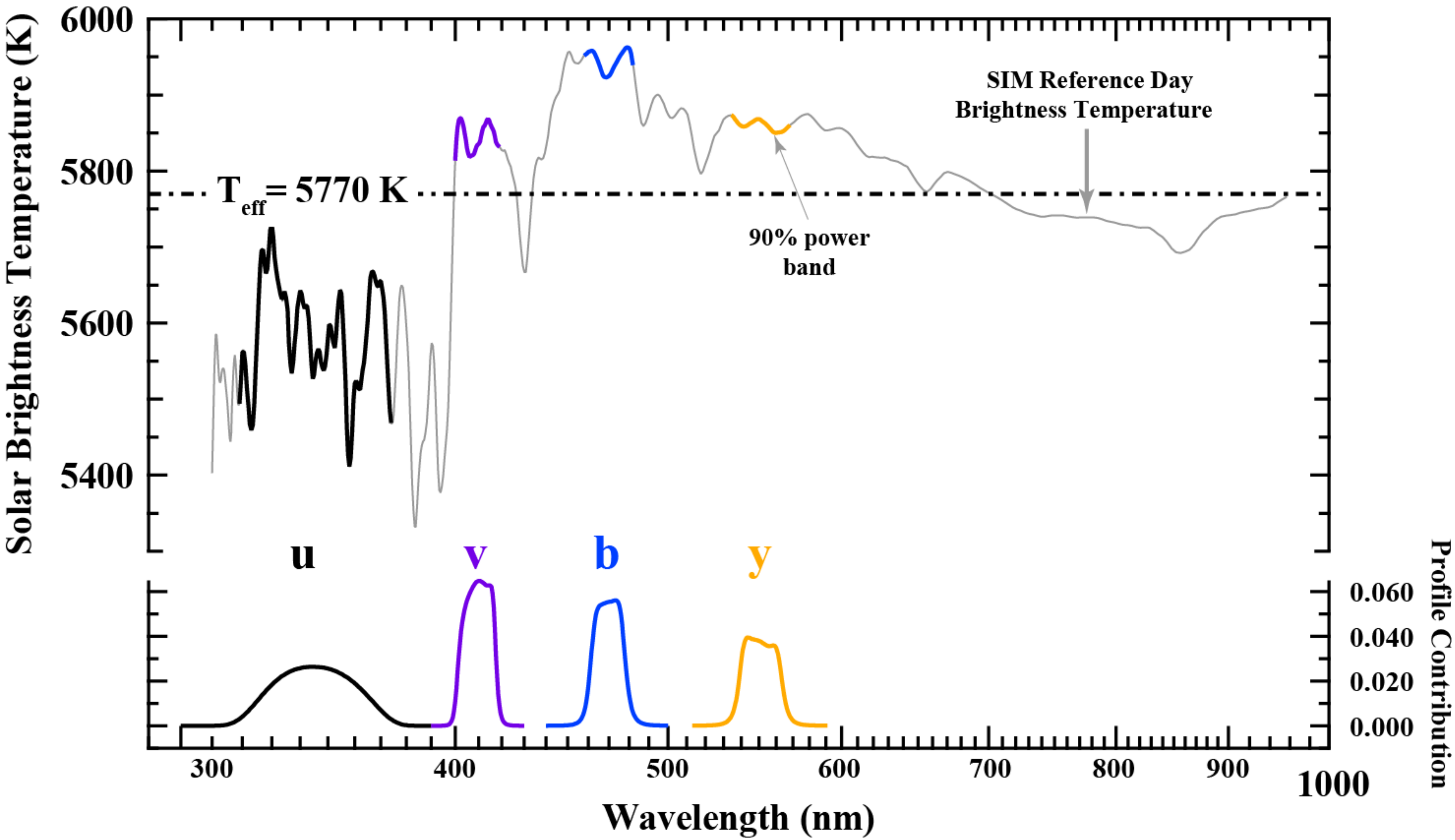
How "typical" is the Sun among the stars?

- A question asked for many years
- Not many stars in a parametric "volume element"
  - dAge, dTeff, dFe/H, dmass, dradius,...
- Sun shows +ve correlation of visible and Ca II emission typical of older, slower-rotating stars

- However:
- Cycle is the most regular of all ☆ (Egeland 2017)
  - similar to K stars
- Radick et al 2018:

"its rather low photometric brightness variation relative to its chromospheric activity level and variation, perhaps indicate that facular emission and sunspot darkening are especially well-balanced on the Sun".

J. Harder 2014: Strömgren Filters wrt Brightness Temperature



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Q: can we set credible limits on future solar irradiances?

*"According to the IPCC (2013), solar forcing is extremely small and cannot induce the estimated 1.0–1.5 °C since the LIA. However, **thesolar radiative forcing is quite uncertain because from 1700 to 2000 the proposed historical total solar irradiance reconstructions vary greatly from a minimum of 0.5 W/m2 to a maximum of about 6 W/m2** (cf..: Hoyt and Schatten 1993; Wang et al. 2005; Shapiro et al. 2011).*

Mazzarella and Scafetta 2018

$0.017\ W/m^2/yr$ and other numbers

- Max $_\odot$ - Min $_\odot$. / 4 yr => $0.25\ W/m^2/yr$
- Min1996 $_\odot$ - Min2008 $_\odot$. / 12 yr => $0.08\ W/m^2/yr$
- Modern max $_\odot$ - Maunder min $_\odot$ => $0.018\ W/m^2/yr$ (*Shapiro et al. reconstruction**).

*Extreme but well-defined case: $\Delta F = 6\ Wm^{-2}$ (1600-today)

Recent advances

- Precise stellar photometry from Fairborn Observatory (Boyd, Henry)
  - Automated Photometric Telescopes (APT)
  - milli-magnitude precision
  - 1993 onwards (so far 17 yr span, note: Solar cycle 11yr)

- New analyses from

  - Egeland (2018) Ph. D. Thesis, Montana State University:
    "Long-Term Variability of the Sun in the Context of Solar-Analog Stars"

  - Radick, W. Lockwood, Henry, Hall, Pevtsov ApJ 2018
  - *"Patterns of Variation for the Sun and Sun-like Stars"*