Intrinsic Stellar Variability: Expulsions

The Variable Universe – Lecture 04
Fall Semester 2022

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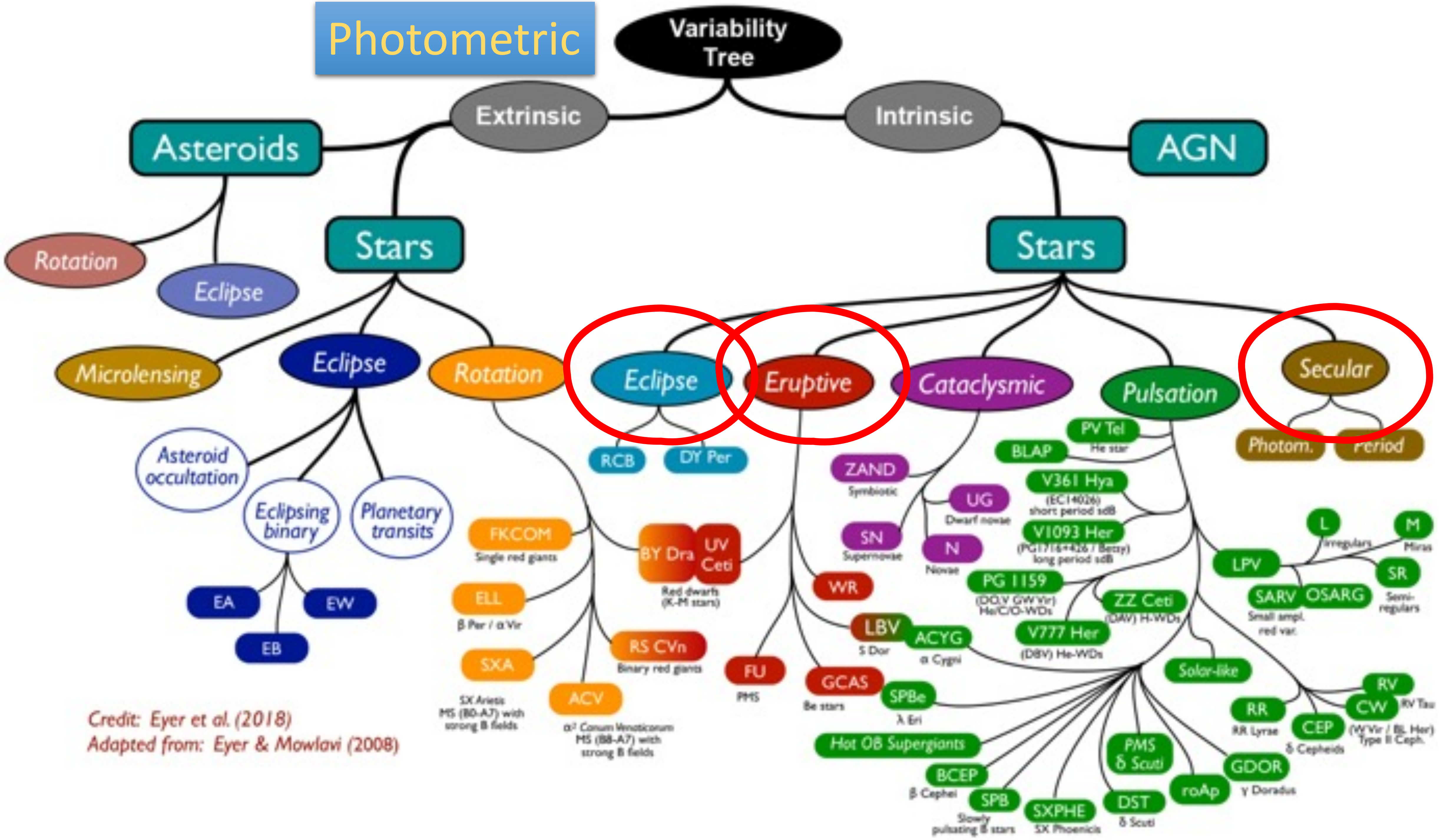
EPFL



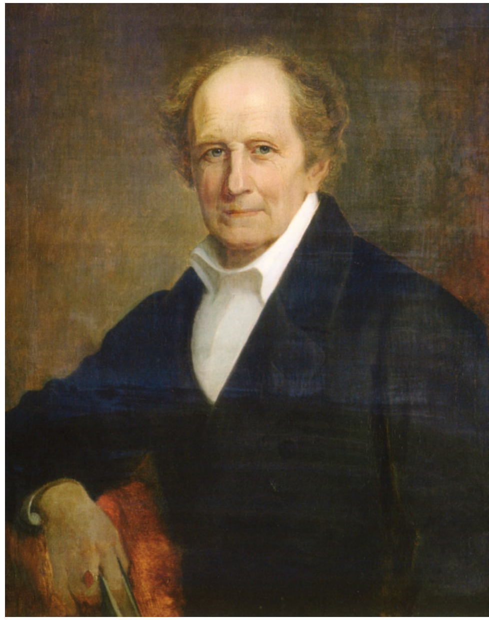
Photometric
Variability Tree
Extrinsic
Intrinsic
Asteroids
AGN
Rotation
Eclipse
Stars
Stars
Microlensing
Eclipse
Rotation
Eclipse
Eruptive
Cataclysmic
Pulsation
Secular
Asteroid occultation
Eclipsing binary
Planetary transits
EA
EW
EB
FKCOM
Single red giants
ELL
β Per / α Vir
SXA
SX Arietis MS (B0-A7) with strong B fields
ACV
α² Canum Venaticorum MS (B8-A7) with strong B fields
RS CVn
Binary red giants
BY Dra
UV Ceti
Red dwarfs (K-M stars)
RCB
DY Per
WR
LBV
S Dor
ACYG
α Cygni
FU
PMS
GCAS
Be stars
SPBe
λ Eri
Hot OB Supergiants
BCEP
β Cephei
SPB
Slowly pulsating B stars
SXPHE
SX Phoenicis
DST
δ Scuti
PMS δ Scuti
roAp
GDOR
γ Doradus
ZAND
Symbiotic
UG
Dwarf novae
SN
Supernovae
N
Novae
PV Tel
He star
BLAP
V361 Hya
short period sdB
V1093 Her
long period sdB
PG 1159
He/C/O-WDs
ZZ Ceti
(DAV) H-WDs
V777 Her
(DBV) He-WDs
Solar-like
LPV
L
Irregulars
M
Miras
SR
Semi-regulars
SARV
Small ampl. red var.
OSARG
RR
RR Lyrae
CEP
δ Cepheids
CW
(W Vir / BL Her) Type II Ceph.
RV
RV Tau
Photom.
Period
Credit: Eyer et al. (2018)
Adapted from: Eyer & Mowlavi (2008)

Variable star nomenclature

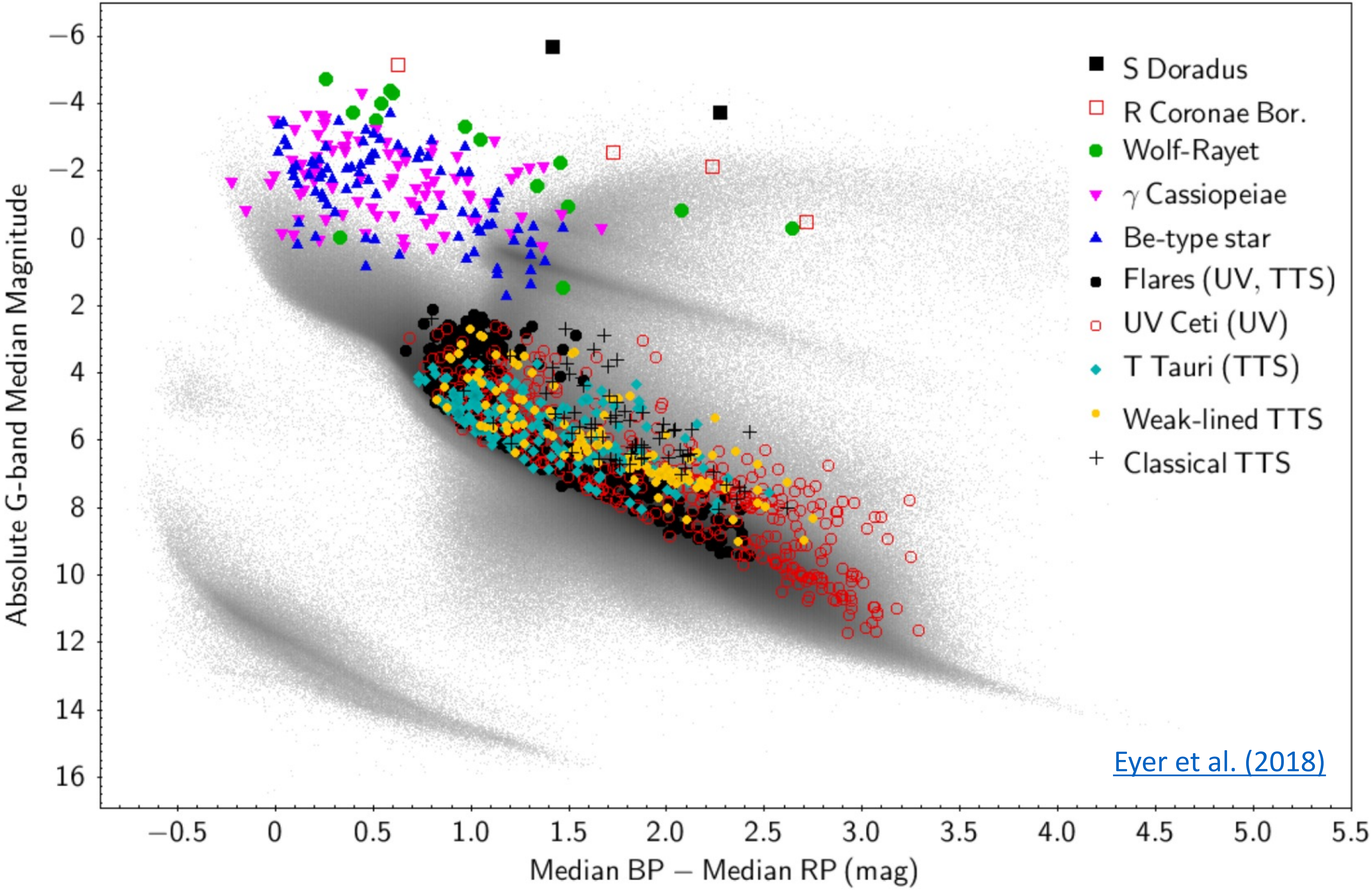
" I name R the star in the Virgin whose periodic variability was discovered in 1809 by Harding… I hope I will be forgiven for taking the liberty of designating by a letter a star which does not appear in the Bayer catalogue but it seems to me that owing to their originality, variable stars are entitled to claim such a distinction. To my mind, a particular name seems to be almost unavoidable to allow an easy identification of stars that are frequently mentioned. But in order to avoid confusion with the alphabetic designation of Bayer, I chose to use the last letters of the alphabet only and to write them in capitals… "

[Argelander (1855), AN 40, 361](#)
Translated by [CDS](#)

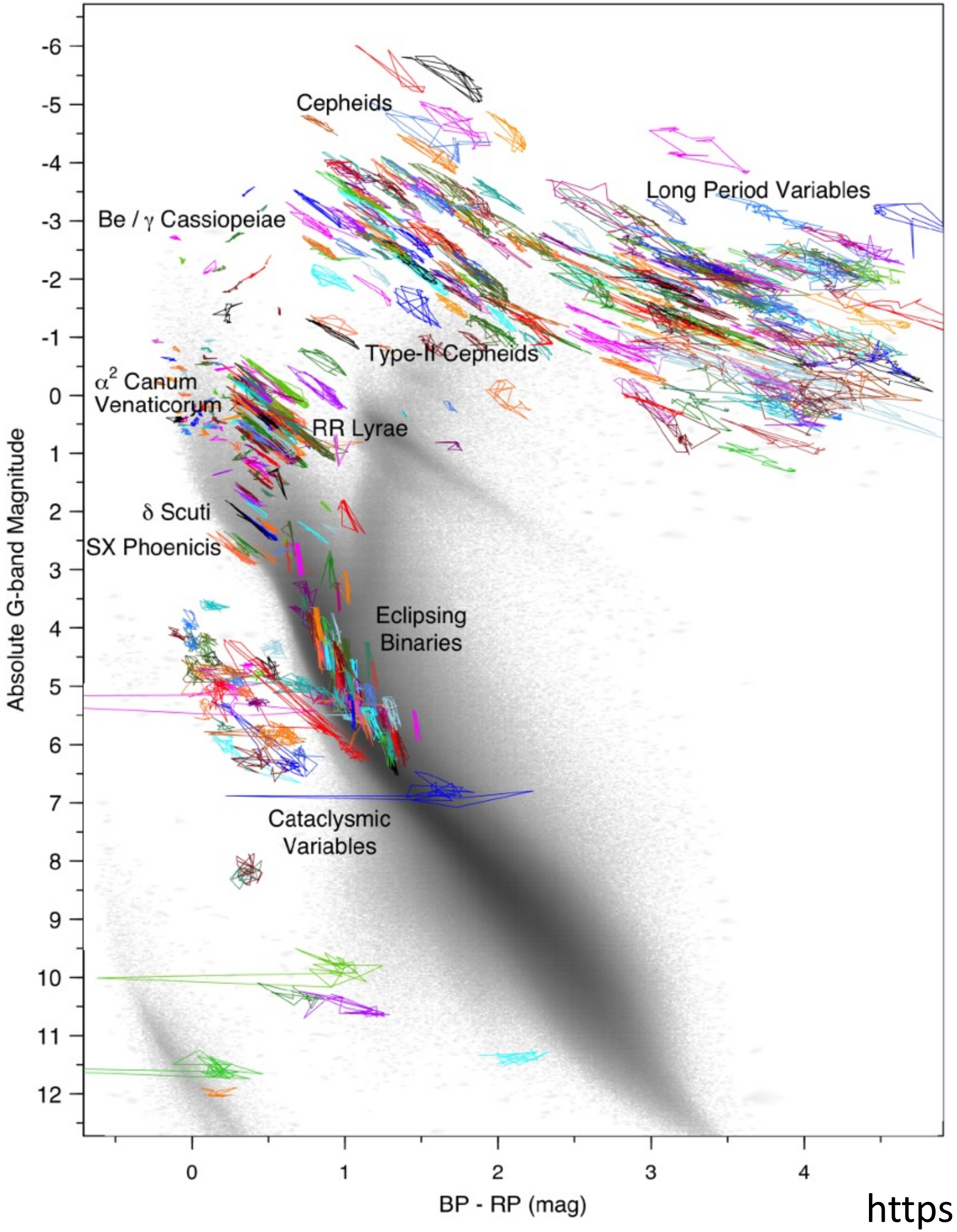
- Brightest stars go by
  - Arabic names, e.g. Aldebaran, Betelgeuse
  - Bayer designation: greek letters by brightness: α, β, e.g. δ Cep
  - Flamsteed designation: numbered by RA from West, e.g. 1 Tau, 2 Tau, …
- Argelander designation (1855)
  - Starts by letter 'R' -> 'Z' (e.g. R Mon): 9 stars
  - More variables: RR -> RZ, SS -> SZ, …, ZZ : 54 stars
  - Even more: AA -> AZ, BB -> BZ, …, QQ -> QZ : 334 stars
  - Oops… even more! V0335 Sgr onwards, e.g. V2430 Cyg
- Large surveys have rendered these naming schemes outdated
  - Some use coordinates: ASAS J184741-0654.4
  - Order of discovery in year, e.g. PTF11kly (SN2011fe)



Friedrich Wilhelm August Argelander



S Doradus
R Coronae Bor.
Wolf-Rayet
γ Cassiopeiae
Be-type star
Flares (UV, TTS)
UV Ceti (UV)
T Tauri (TTS)
Weak-lined TTS
Classical TTS
Absolute G-band Median Magnitude
Median BP − Median RP (mag)
−6
−4
−2
0
2
4
6
8
10
12
14
16
−0.5
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
Eyer et al. (2018)



Check out the animated version here:
https://www.cosmos.esa.int/web/gaia/gaiadr2_cu7

Flare stars

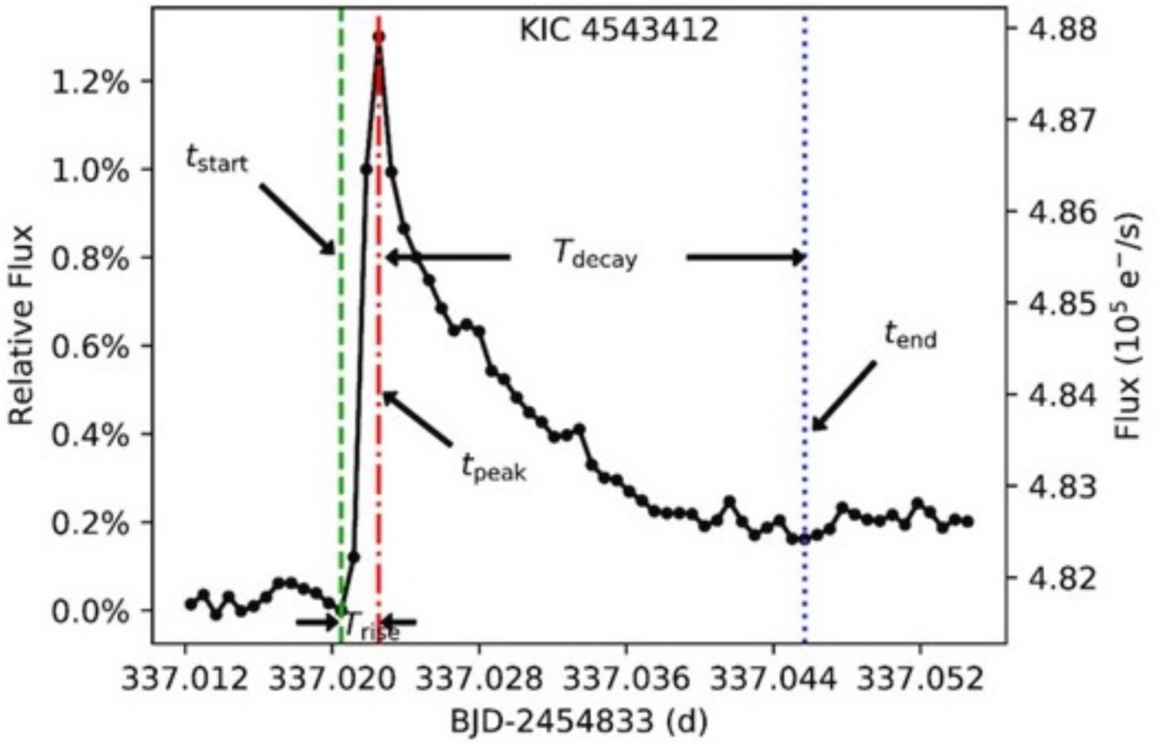
UV Ceti and RS Canum Ventaticorum stars

UV Ceti: single Main Sequence flare stars

Yan et al. (2021)

- Apparently single K-M dwarfs exhibiting flares
- Flares: rapid increases in brightness from X-rays & UV to radio
- Timescales: 5.9min (rise) and 22.6min (decay)
- Likely high-energy analogues of solar flares
- Cyclotron and synchrotron emission due to magnetic field reconnection events
- Hot coronae -> X-ray luminous (heated by B-fields)

Rise and decay times of 184 flare stars in Kepler

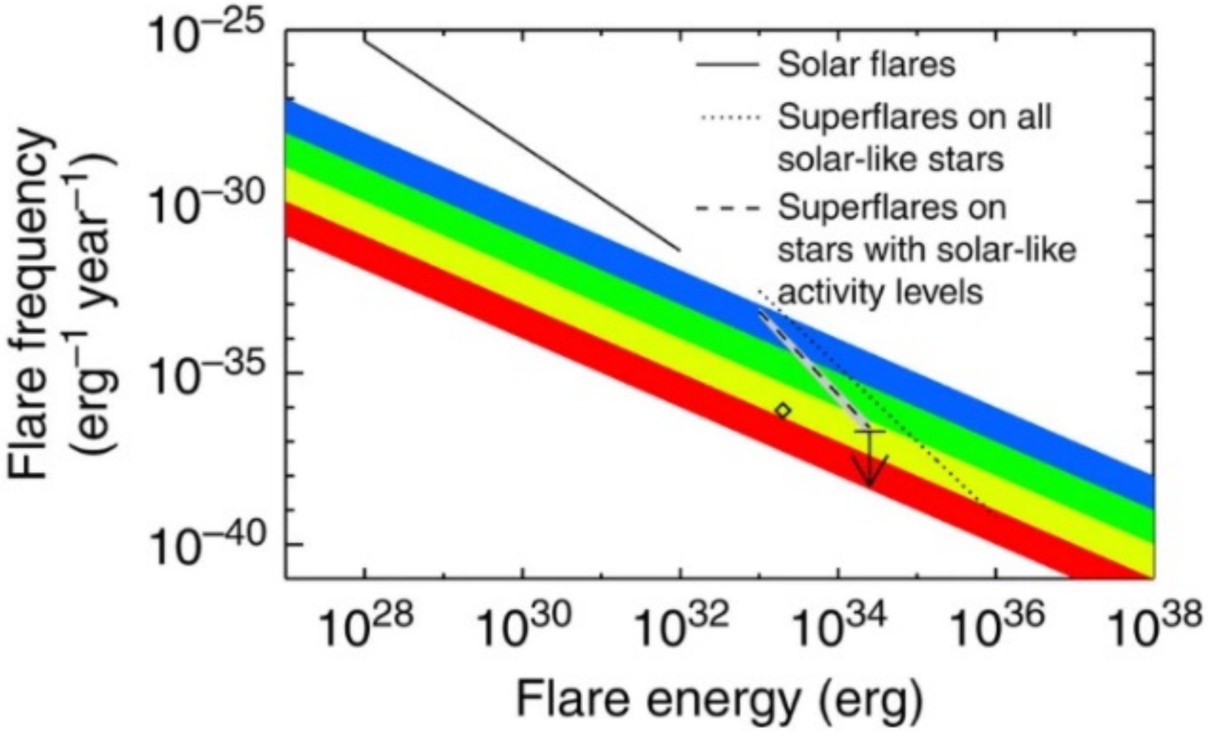


Superflares observed by Kepler

[Karoff et al. (2016)](#)

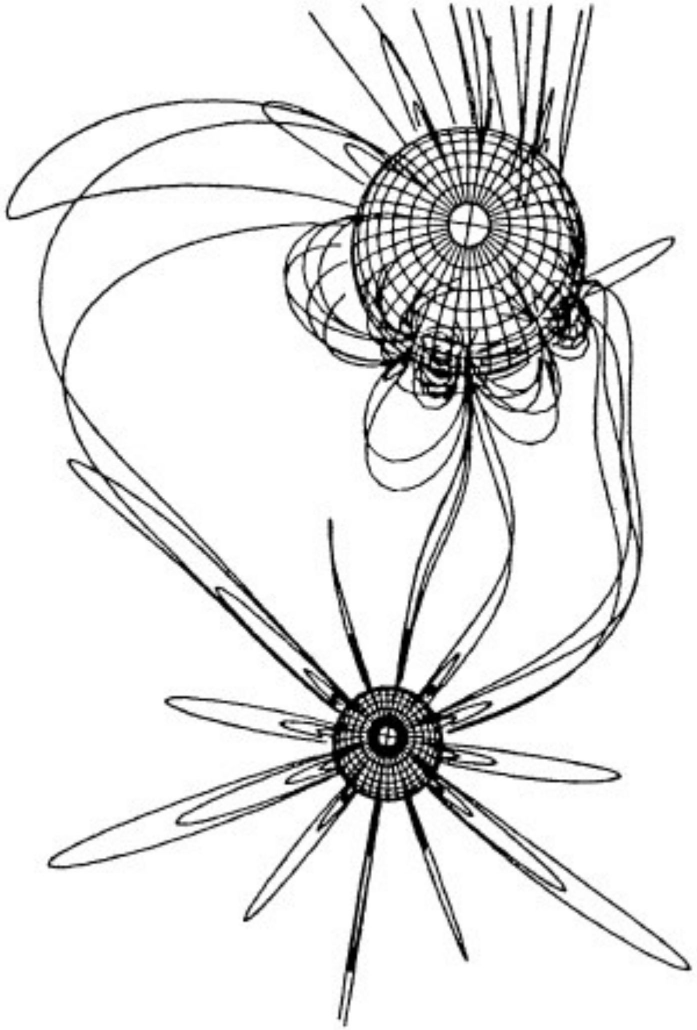
- Superflares: up to 10^6x Solar flare; only on spotted stars
- Most superflares on chromospherically active stars
- Some less active than Sun: Likely same mechanism
- Does the Sun superflare? Did it in the past? -> 14^C in Japanese tree rings indicate superflare E > 10^33erg in AD775

Figure 7: Comparison of occurrence rates of flares on the Sun and of superflares on solar-like stars.



RS CVn: magnetic activity-entangled binaries

- RS CVn discvoered by Lydia Ceraski in 1914
- Close detached binaries
- Tidally locked: orbital & rotational periods are identical
- Fast rotators (Prot < 20d) with spots (magnetic)
- High activity levels with chromospheric emission lines
- Excellent targets for Doppler Imaging and Zeeman Doppler Imaging

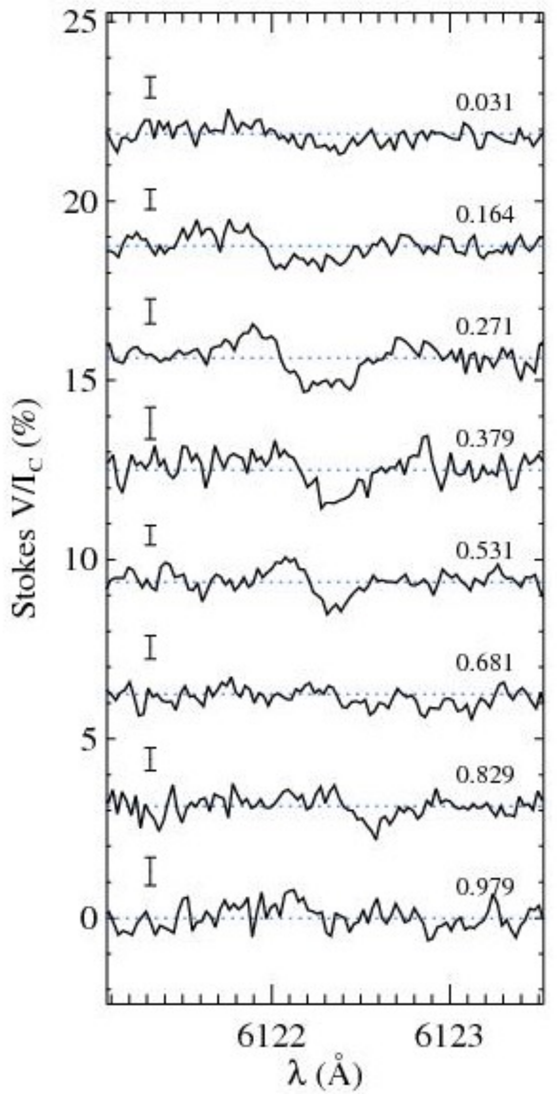


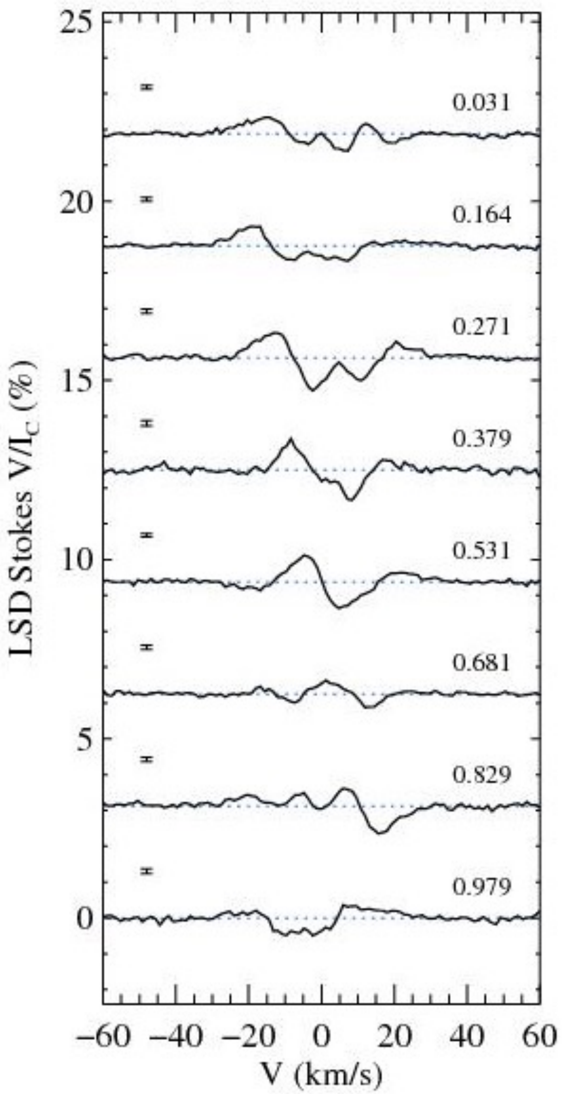
[Uchida & Sakurai (1985)]

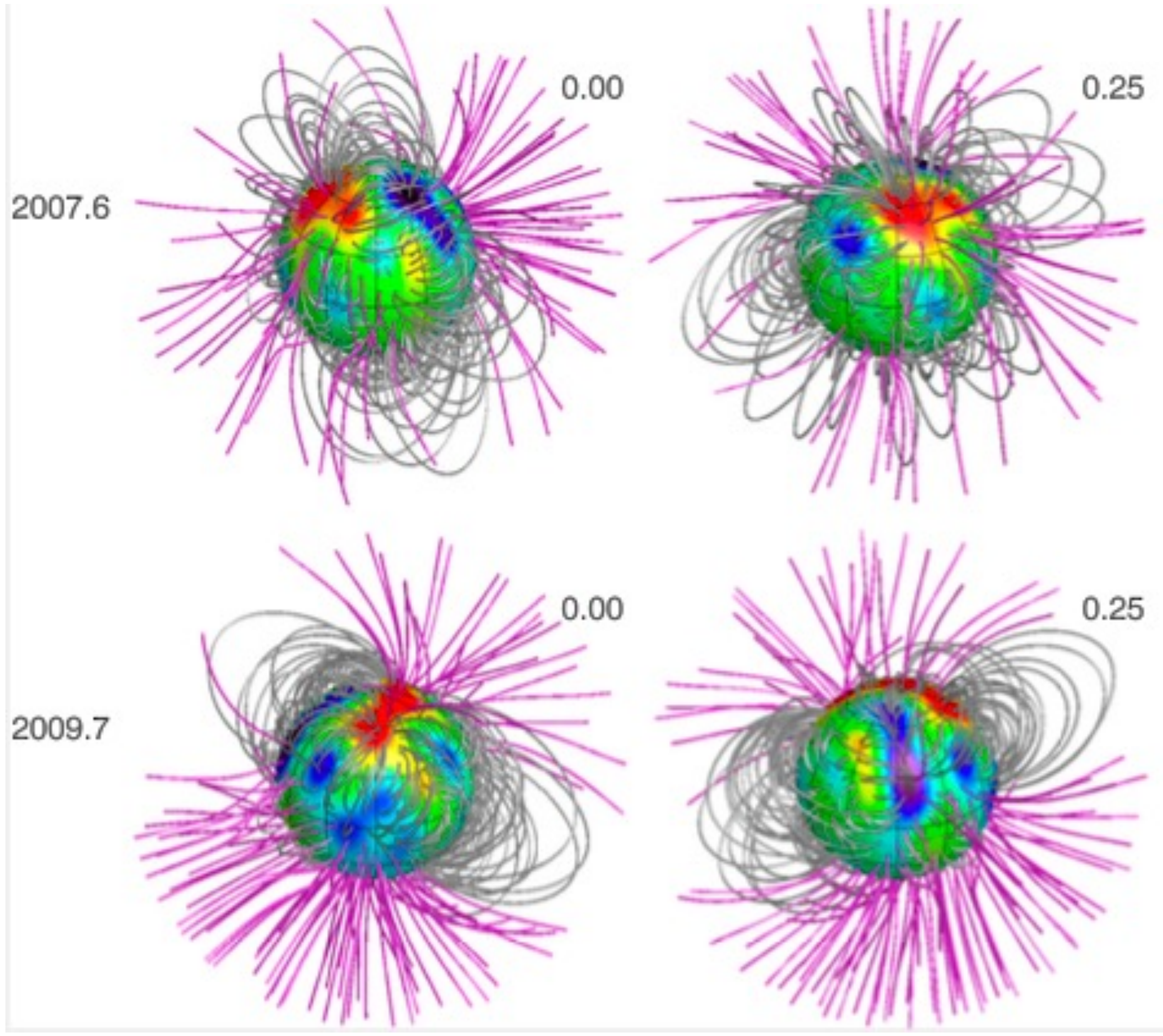
Zeeman Doppler Imaging of RS CVn Star II Peg

[Kochukhov et al. (2012)](#)

K2IV + M0-M3V (SB1)





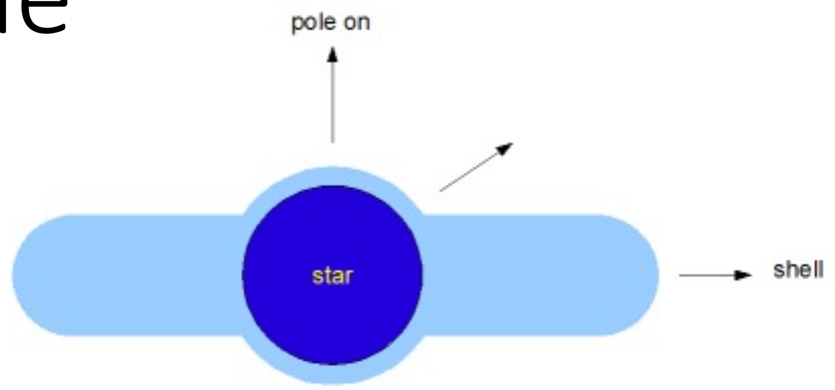


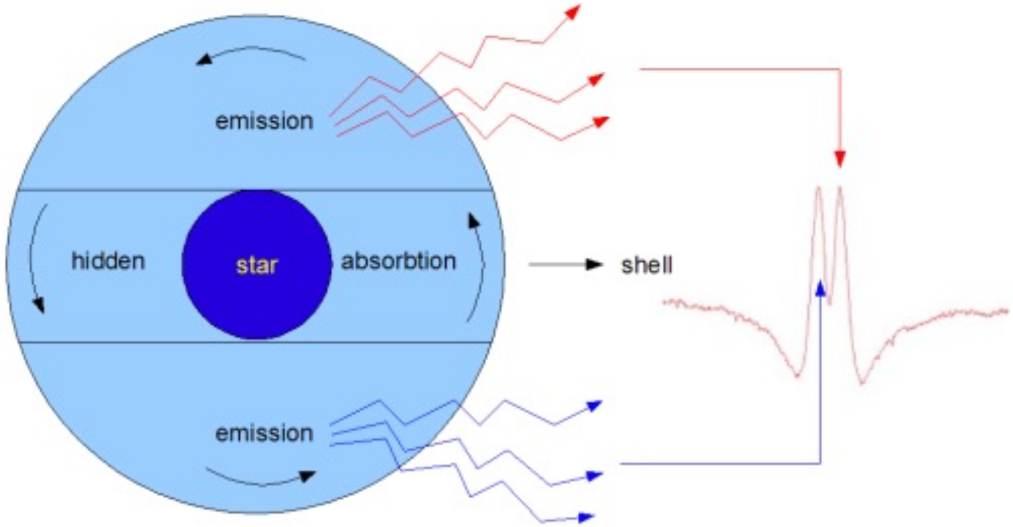
Be stars

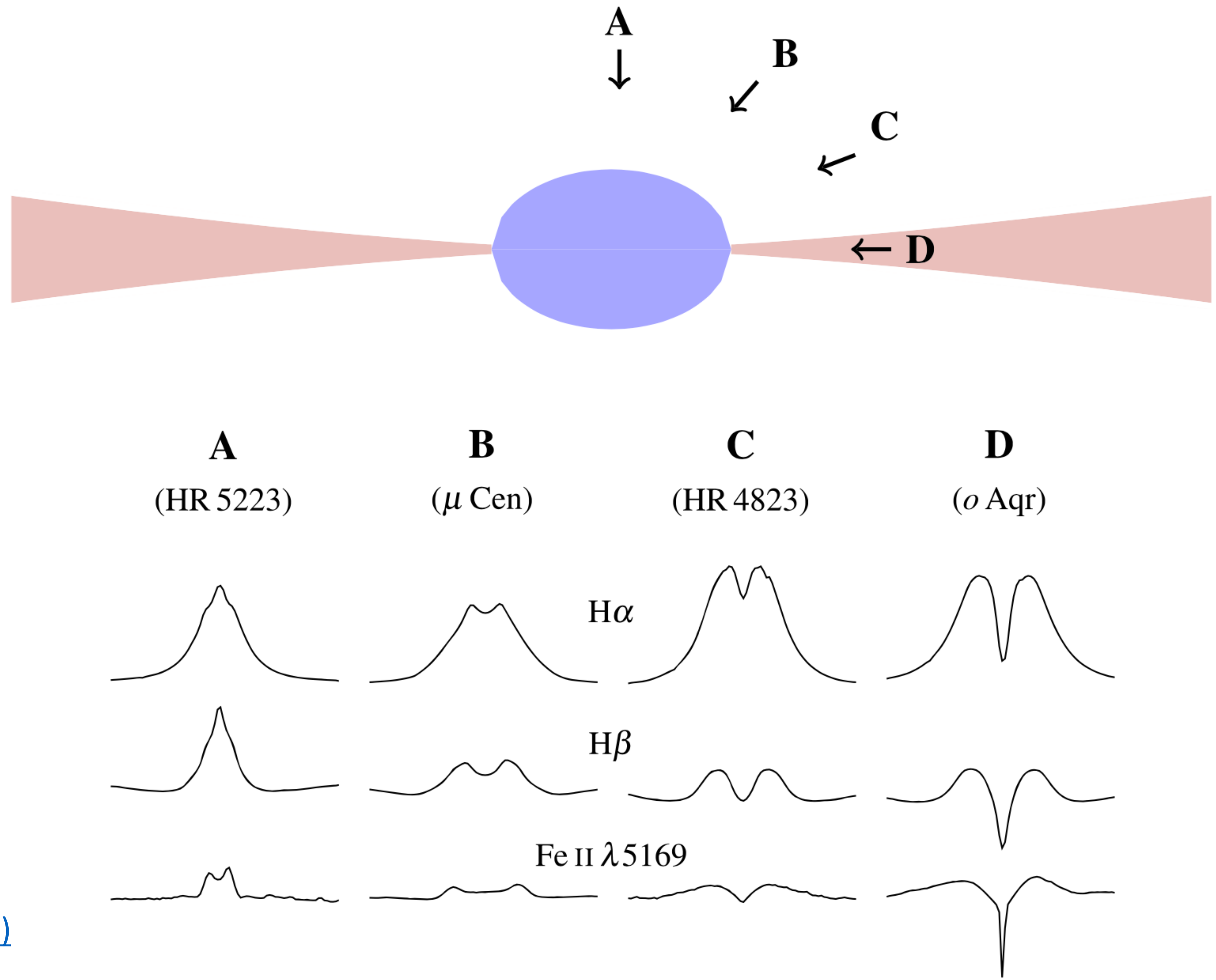
B-type Main Sequence stars showing emission

Classical Be stars: γ Cassiopeiae

- Non-supergiant B-stars
- (Transient) Balmer emission feature(s)
- First observed in 1866 in γ Cas
- Brightest specimen: Achenar (α Eridani)
- Fast rotation
- Photometric and spectroscopic variability
- multiperiodic
- Periods range from 0.4d to 3d
- Light curves can be reminiscent of mild nova outbursts



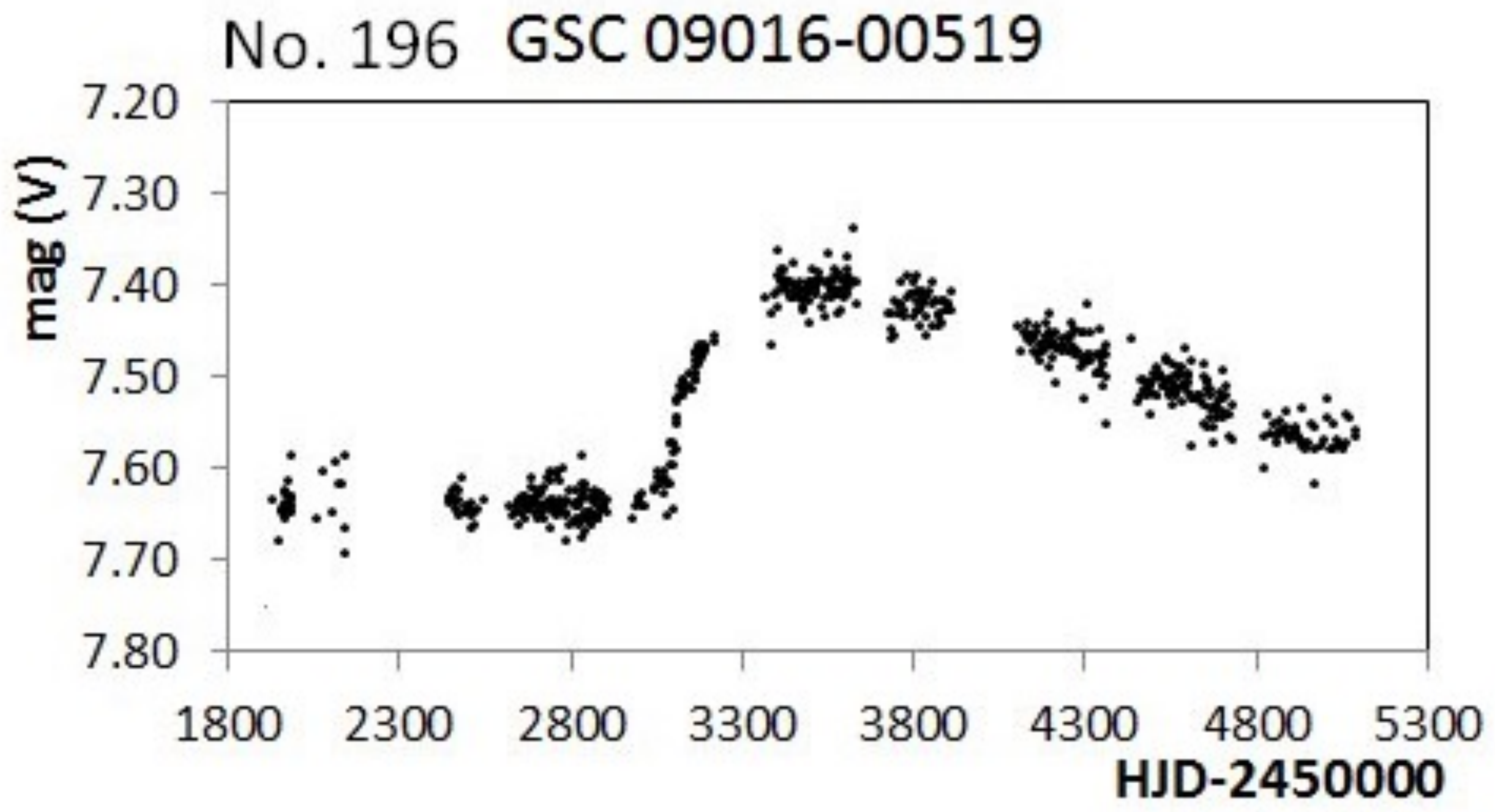




Rivinus et al. (2013)

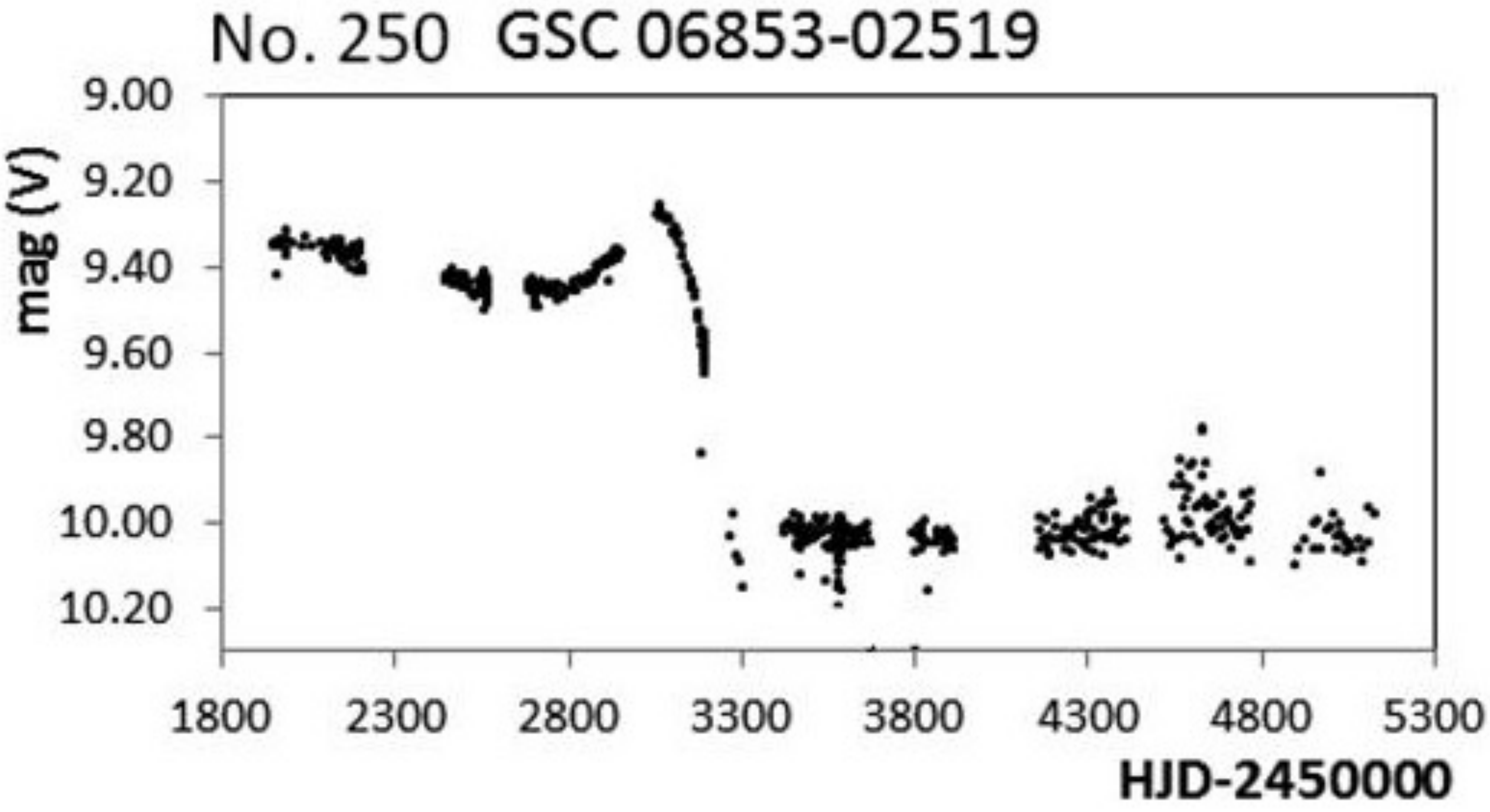
Classical Be stars: long-term outbursts

Bernhard et al. (2018)



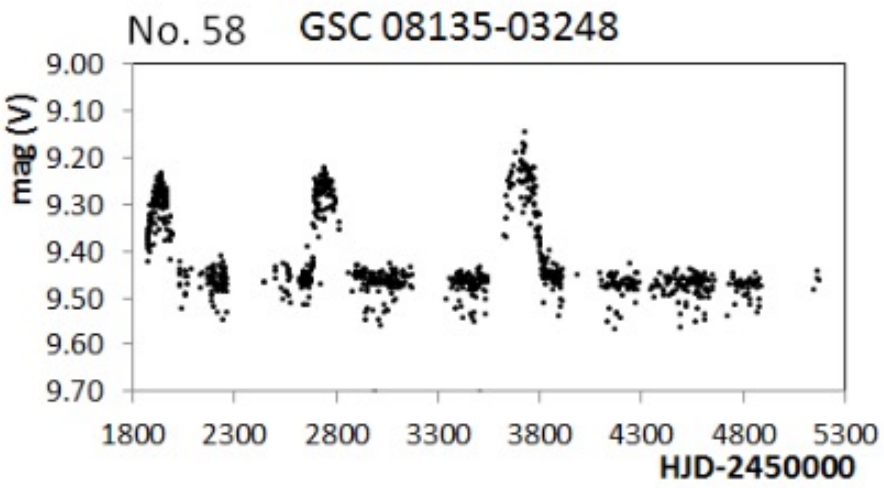
Classical Be stars: long-term negative outbursts

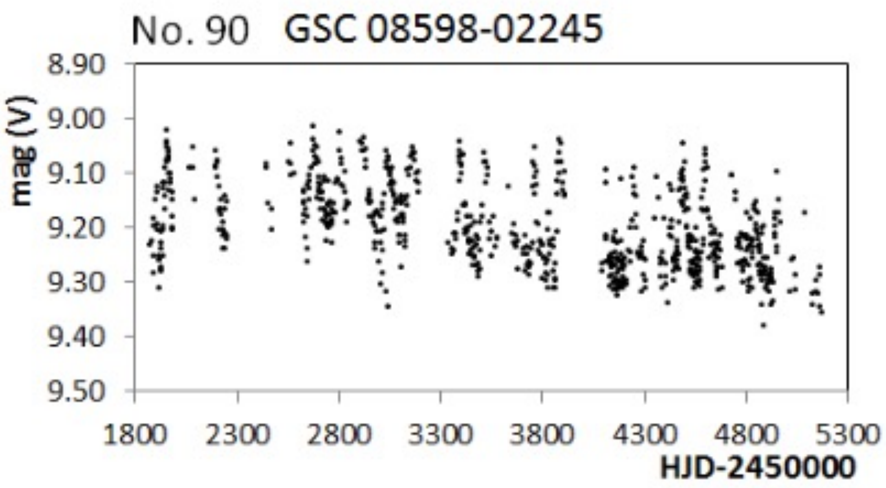
Bernhard et al. (2018)

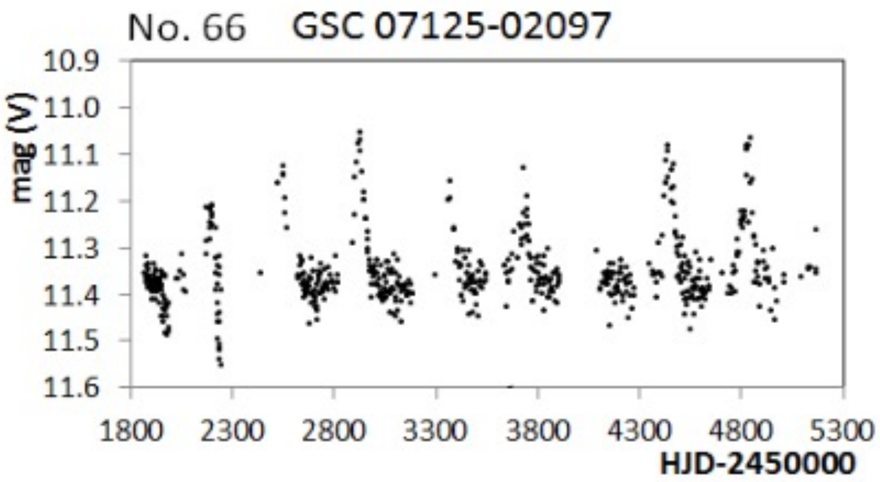


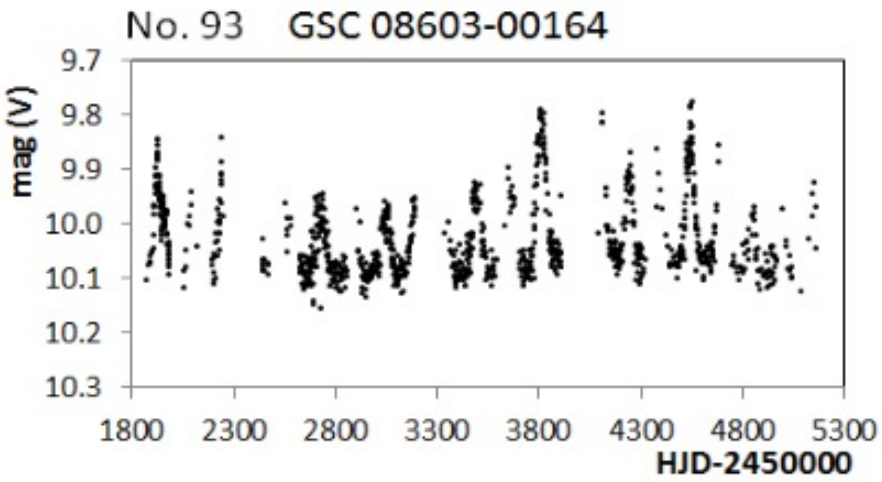
Classical Be stars: recurring outbursts

Bernhard et al. (2018)



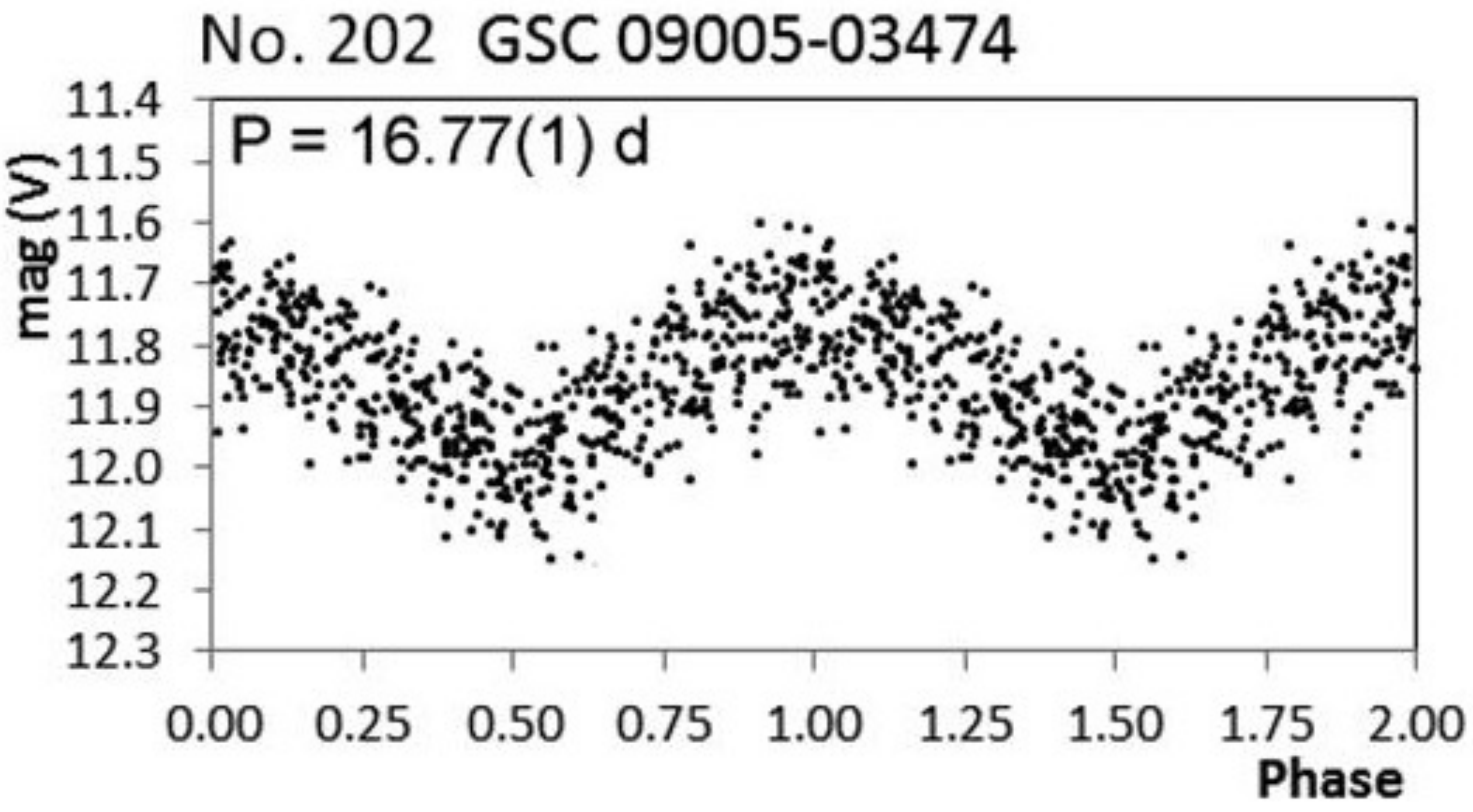






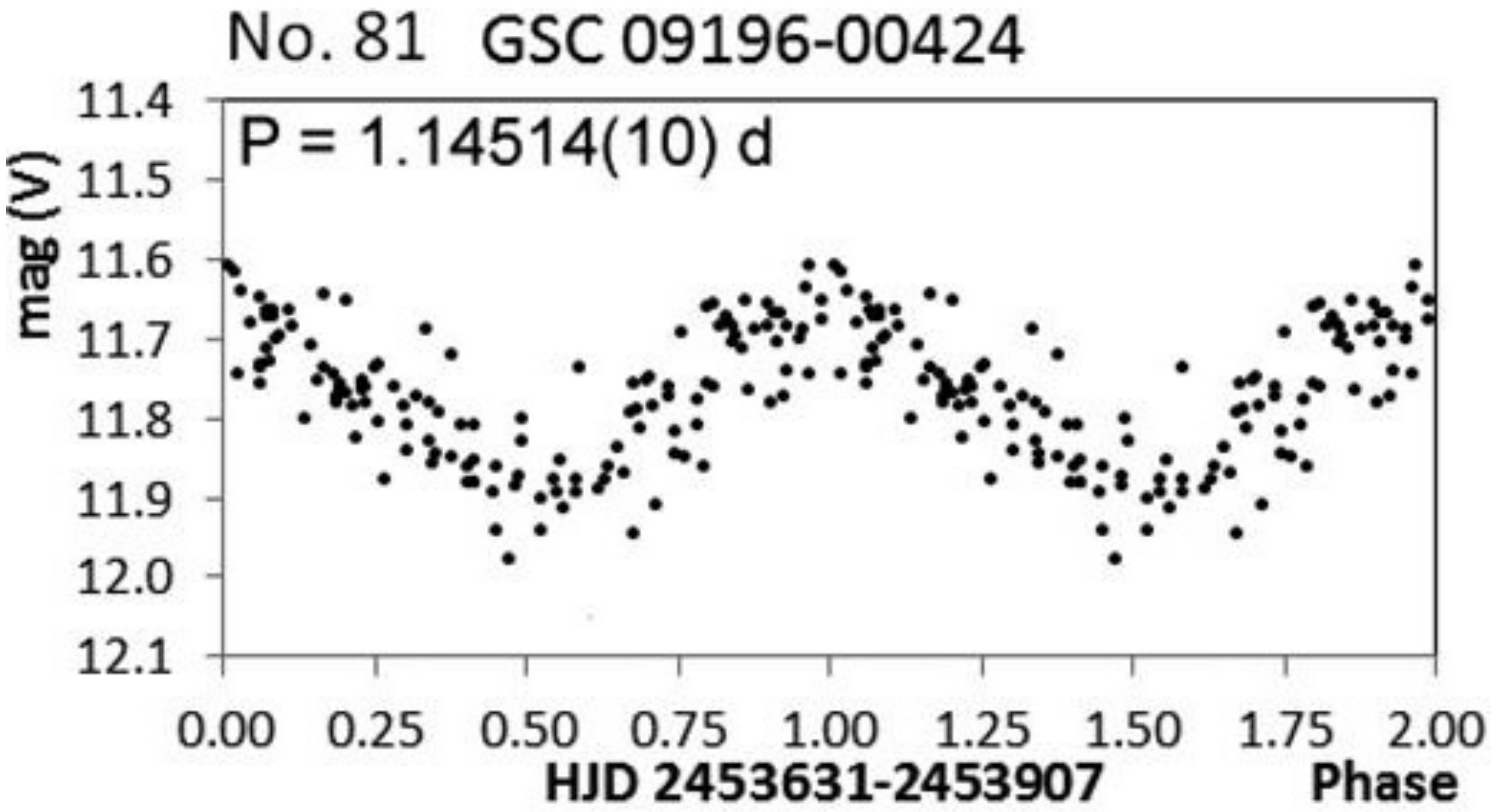
Classical Be stars: intermediate periodic variability

Bernhard et al. (2018)



Classical Be stars: short-periodic variability

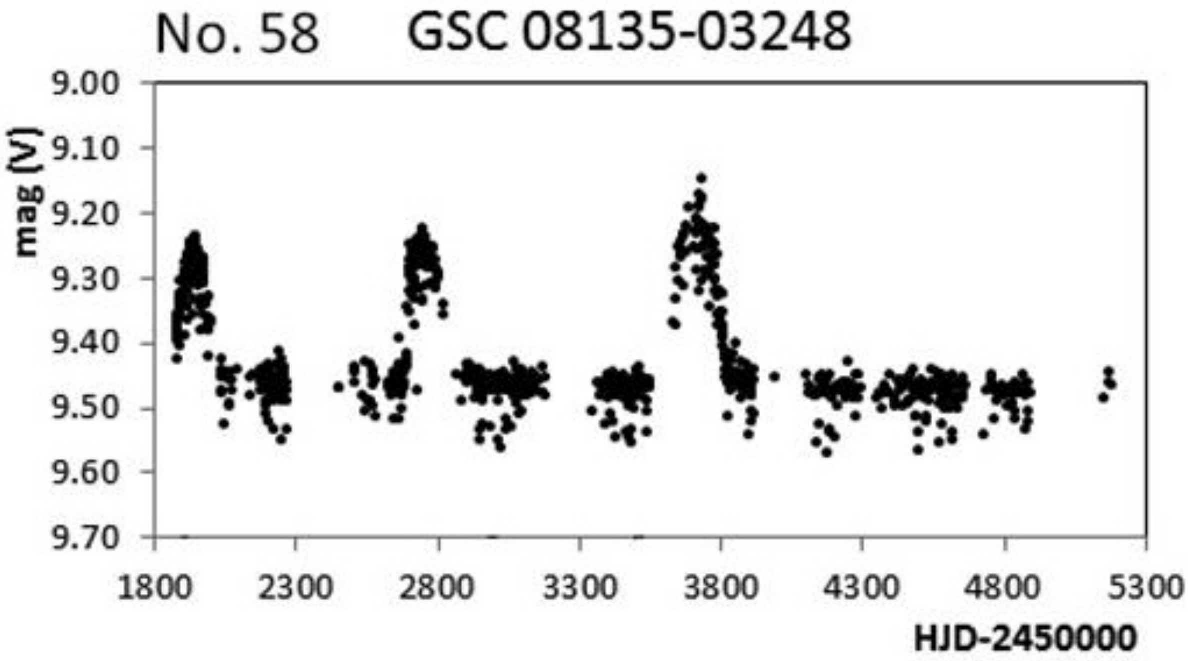
[Bernhard et al. (2018)](#)

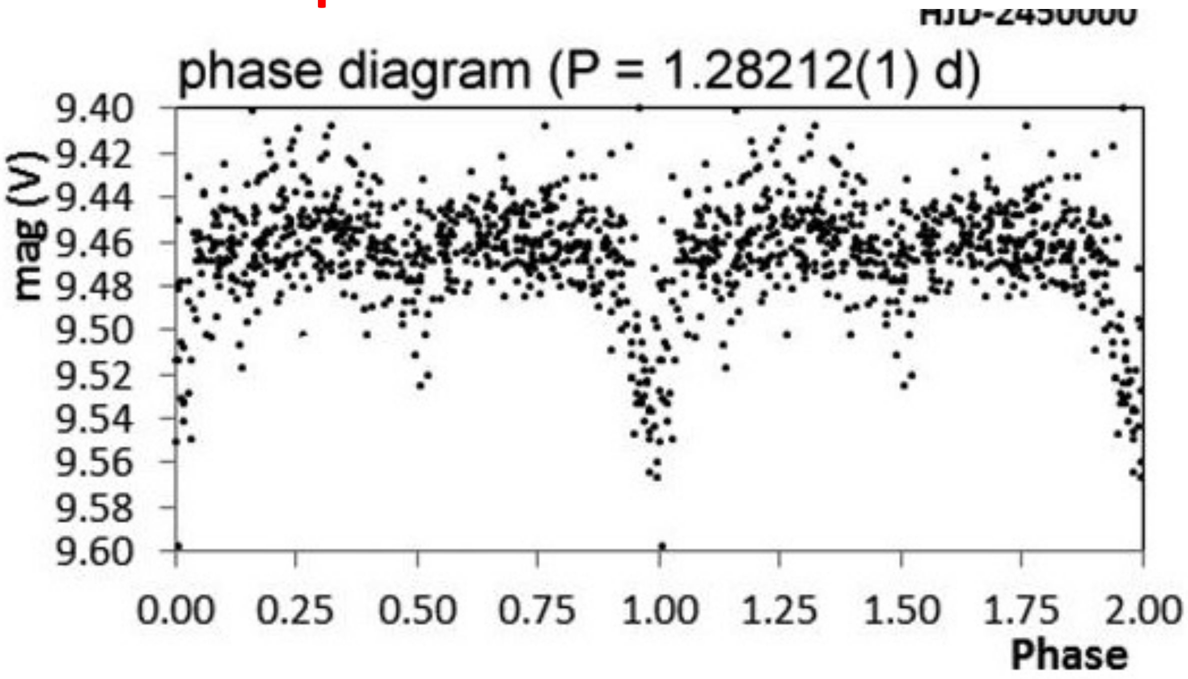


Classical Be stars: can show multiple effects

Bernhard et al. (2018)

Eclipses!





Statistics for Be star variability

Bernhard et al. (2018)

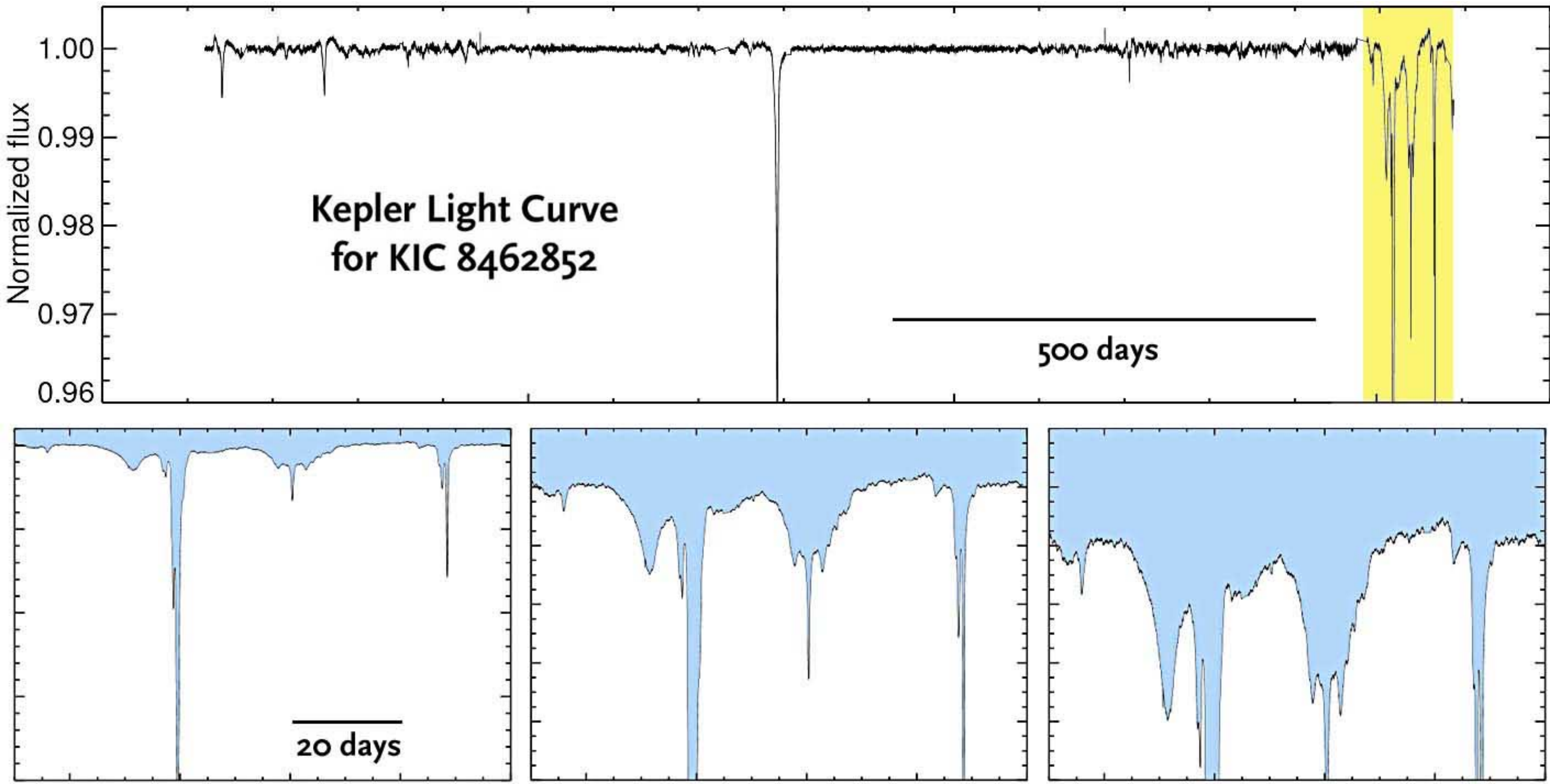
- 73 +/- 5% show variability on some timescale
- Long-term variations: 36 +/- 6 %
- Intermediate timescales: 1 +/- 1%
- Short-term non-radial pulsations: 6 +/- 3%
- Surprise: 24 +/- 6 % show semiregular or periodic outbursts
- Early-type Be stars more frequently burst than mid- or late-type Be-stars [not fraction of bursters, but frequency of bursts in bursters]
- Mean amplitude decreases from early- to late-type Be stars
- Median rising time: 28.5d, median falling time: 51d

What causes Be star phenomenon?

Balona & Ozuyar 2020

- Canonical: mass-loss from star aided by pulsation and rapid rotation
- Requires stars to rotate near critical velocity
- As a group, Be stars rotate fast, but not excessively
- TESS observations tend to differ from this picture
- Are there spots??
- Balona et al. argue for magnetic activity
- Flares difficult to see against bright hot star
- Magnetic reconnection rapid enough to explain phenomenon?

“Negative” variability



Kepler Light Curve
for KIC 8462852
Normalized flux
1.00
0.99
0.98
0.97
0.96
500 days
20 days

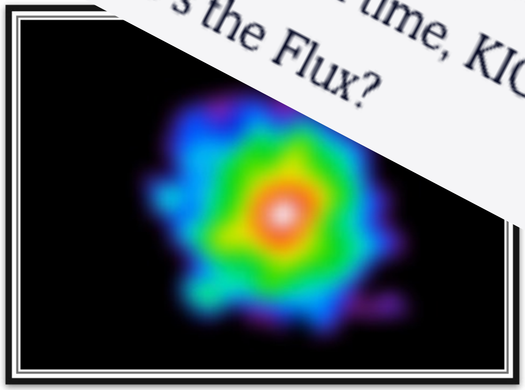
www.wherestheflux.com

Help astronomers get the data they need to unravel one of the biggest mysteries of all time, KIC 8462852 --- Where's the Flux?

This is the official page for research related to the most mysterious star in our Galaxy.

The star KIC 8462852 is also known as Tabby's Star, or the WTF star for "Where's the Flux?".

Curious for more data?



News and Updates

December 04, 2018

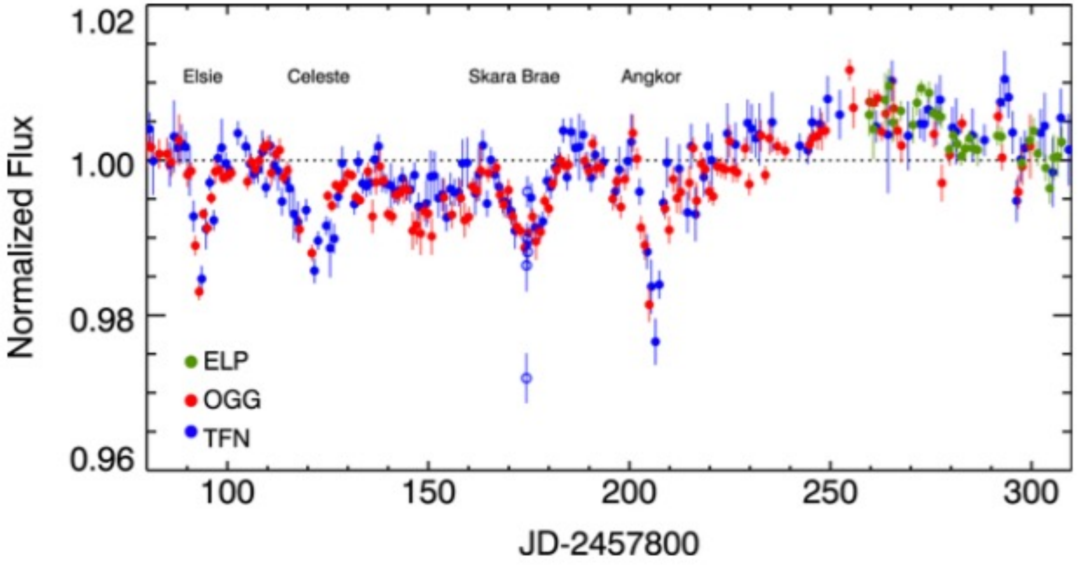
Community training on data an... ...s Cumbres Education Program

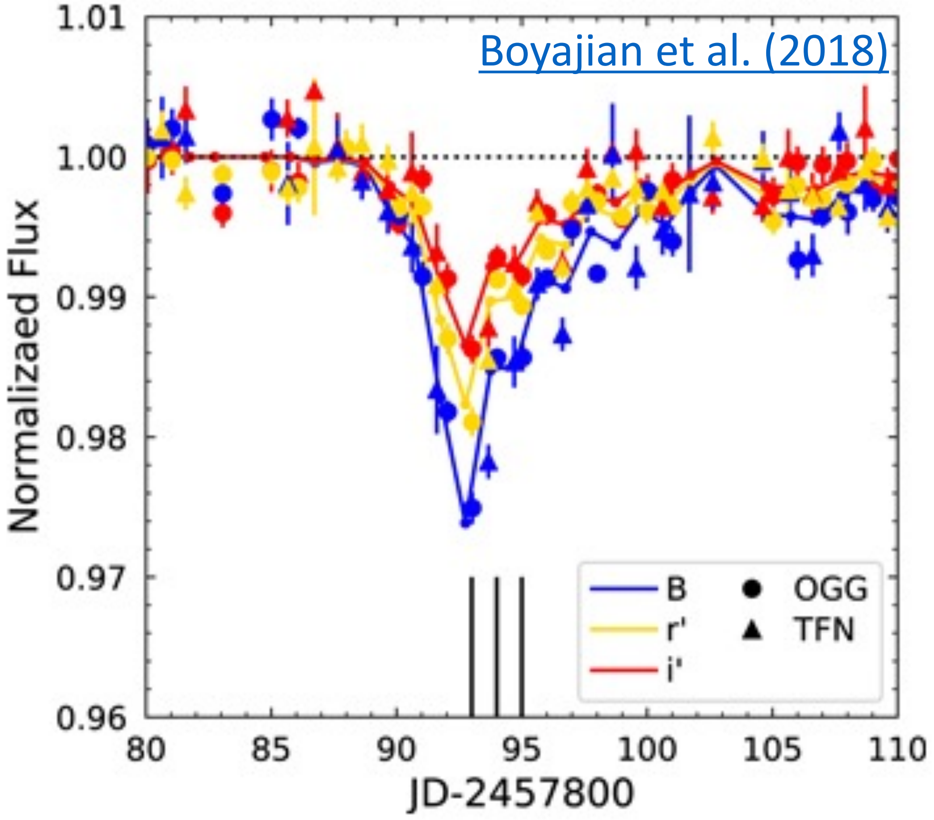
We are new partners in the LC... ...use reddit as a communal gathering place to teach the public how to build a light curve using astronomical image... ...for details!

The most mysterious star in the Galaxy

KIC 8462852 – ”Boyajian’s star”

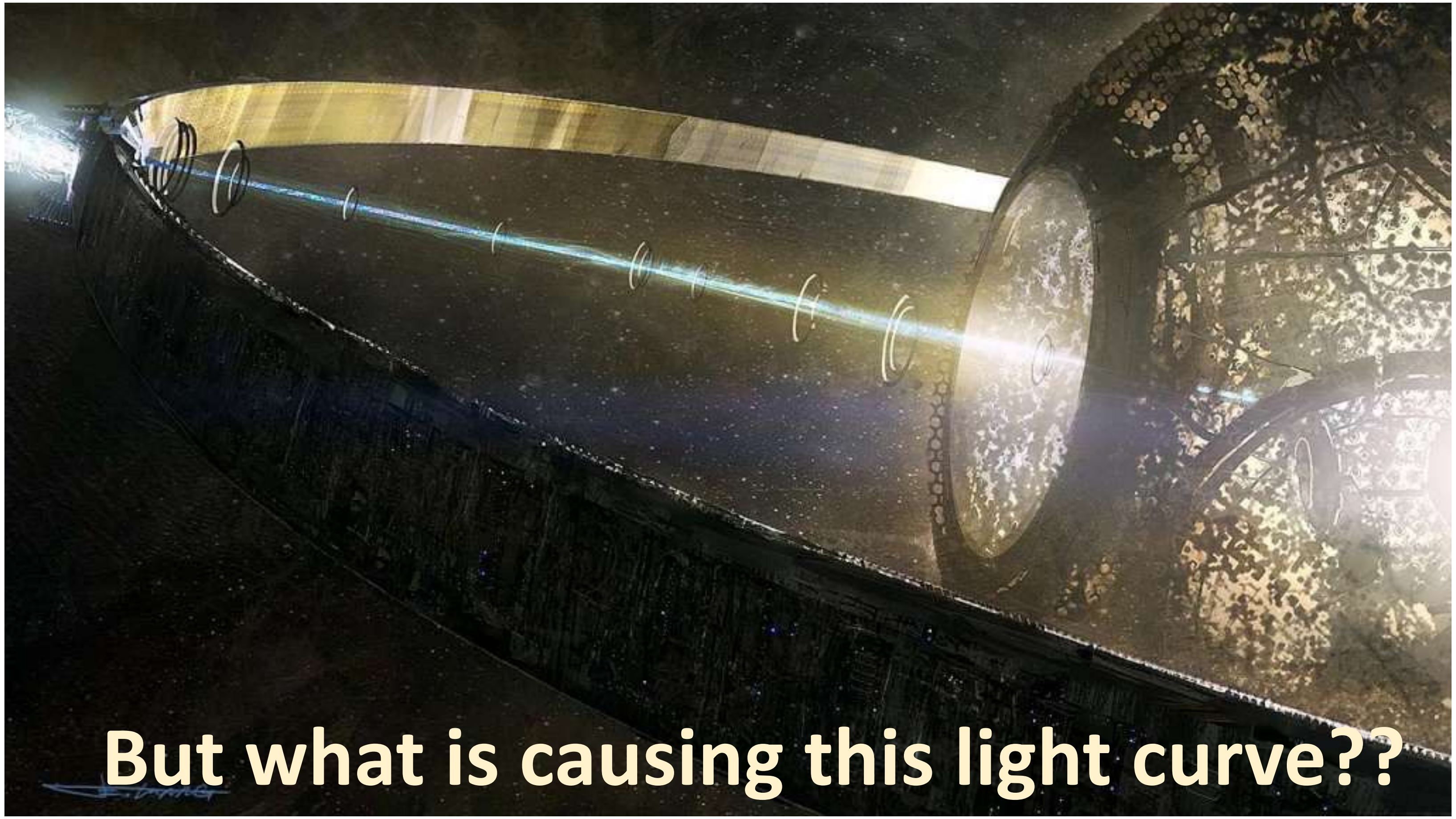
- Irregular intensity dips of up to a few percent
- Kepler light curve provides exquisite detail
- Crowdfunded telescope project to study one star (~100,000 USD)
- Visual binary recently discovered (~800 au, [Pearce et al. 2021])
- Spectroscopy, polarimetry, interferometry, many-year monitoring
- So, what’s happening?





Interesting Forbes article summarzing recent results

This is NOT what's happening!



Conceptually simple, specifically tricky: dust!

[Hitchcock et al. 2019](#)

- Chromatic dips
- Irregular variability
- RV search: no signal
- Interferometry & spectropolarimetry : nothing special
- Hitchcock et al. (2019) multiband monitoring identifies dusty origin
- A cautionary tale of blowing things out of proportion
- Still an interesting star to study because origin of dust is unclear
- Possibly a more common feature? Exocomets?

Secular evolution

Seeing stellar evolution happen on human timescales

Sakurai’s object – V4334 Sgr

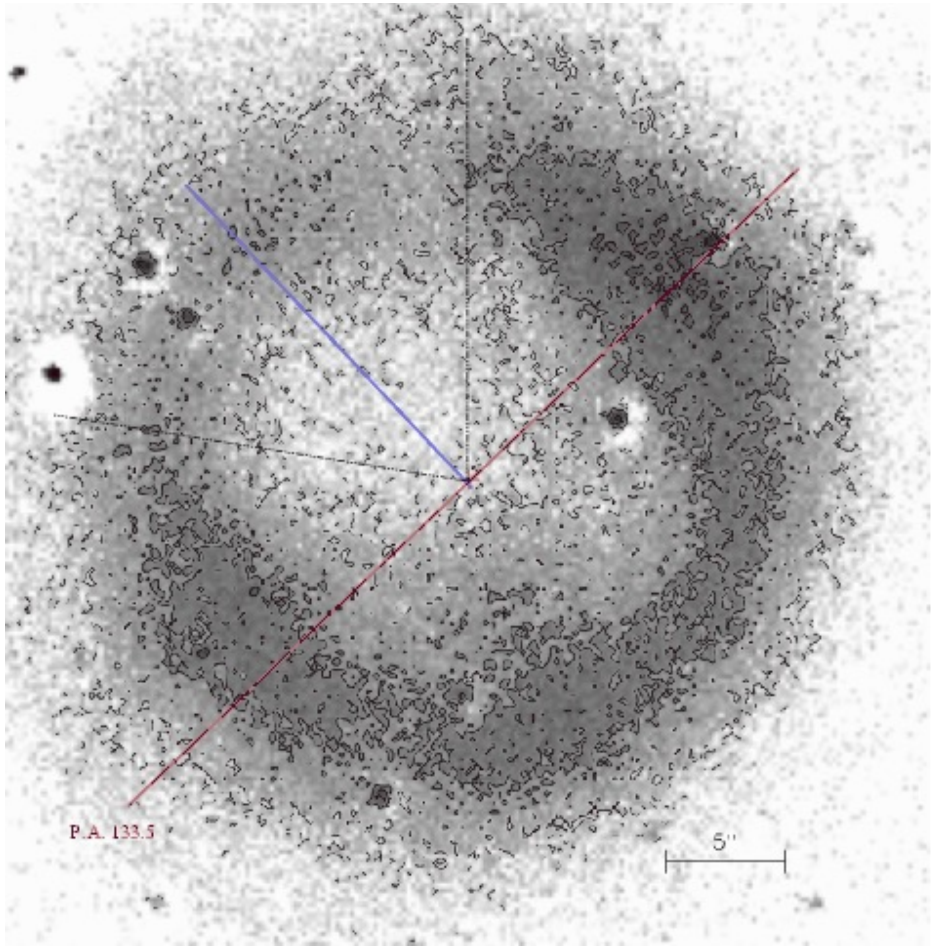
Evans et al. (2020)

- Discovery by amateur Yukio Sakurai (1995) with 300mm f/2.8 lens on Fuji G400 film
- Originally reported as a nova
- Spectrum like early G or F supergiant, reddened, no emission
- Central star of old planetary nebula (post-WD)
- Extreme mass-loss events & disk
- Nowadays: prototype Very Late Thermal Pulse (VLTP) object
- Rare! One object per decade in Galaxy!

Sakurai's object: observational landscape

Hinkle & Joyce (2014)

- Planetary Nebula: central star had reached top of WD cooling sequence: Teff ~ 100,000K (Kerber et al. 1999)
- PN spectrum and central star RVs match
- Brightened from 16 mag to 12.4 mag from 06/94 to 02/96
- Teff dropped by 2000K in 400d in 96/97
- 05/96 to 10/96: drop in hydrogen abundance by 0.7dex
- Early 1997: spectrum consistent with cool carbon star
- 1998: fading events that look like R CrB stars

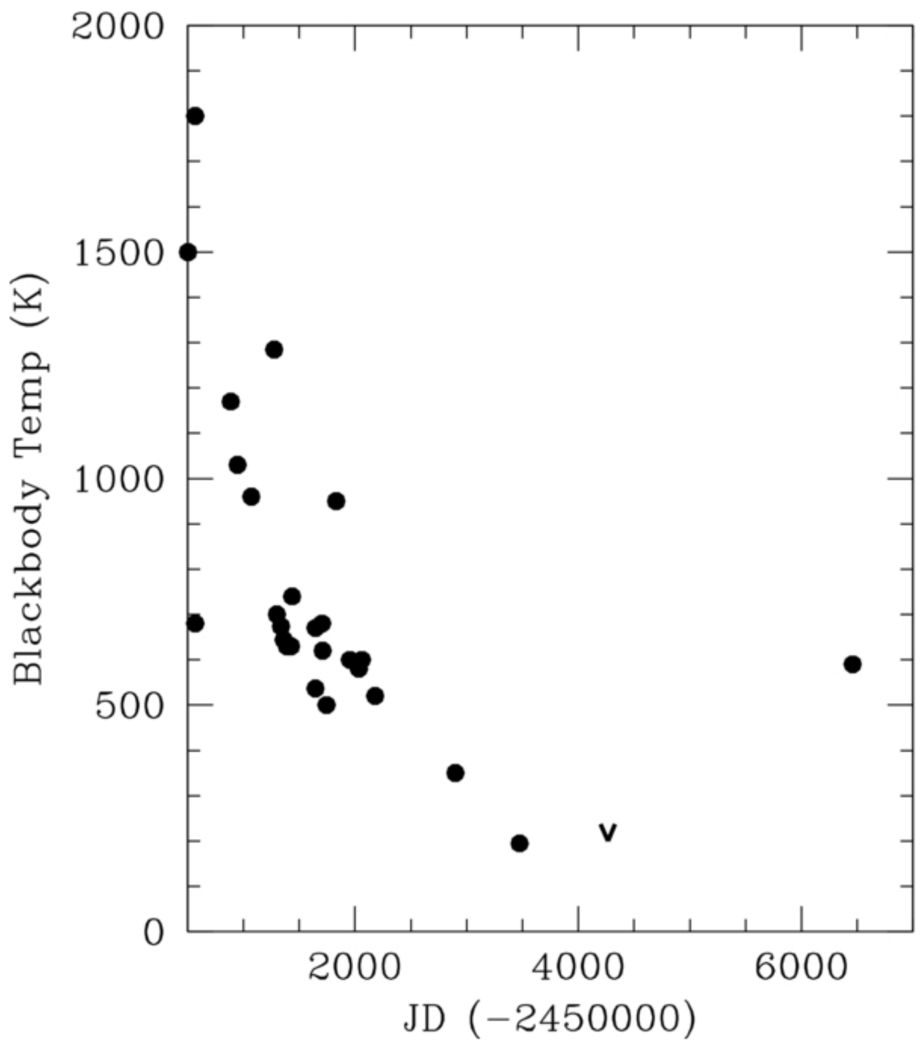


Chesneau et al. (2009)

Sakurai's object: observational landscape

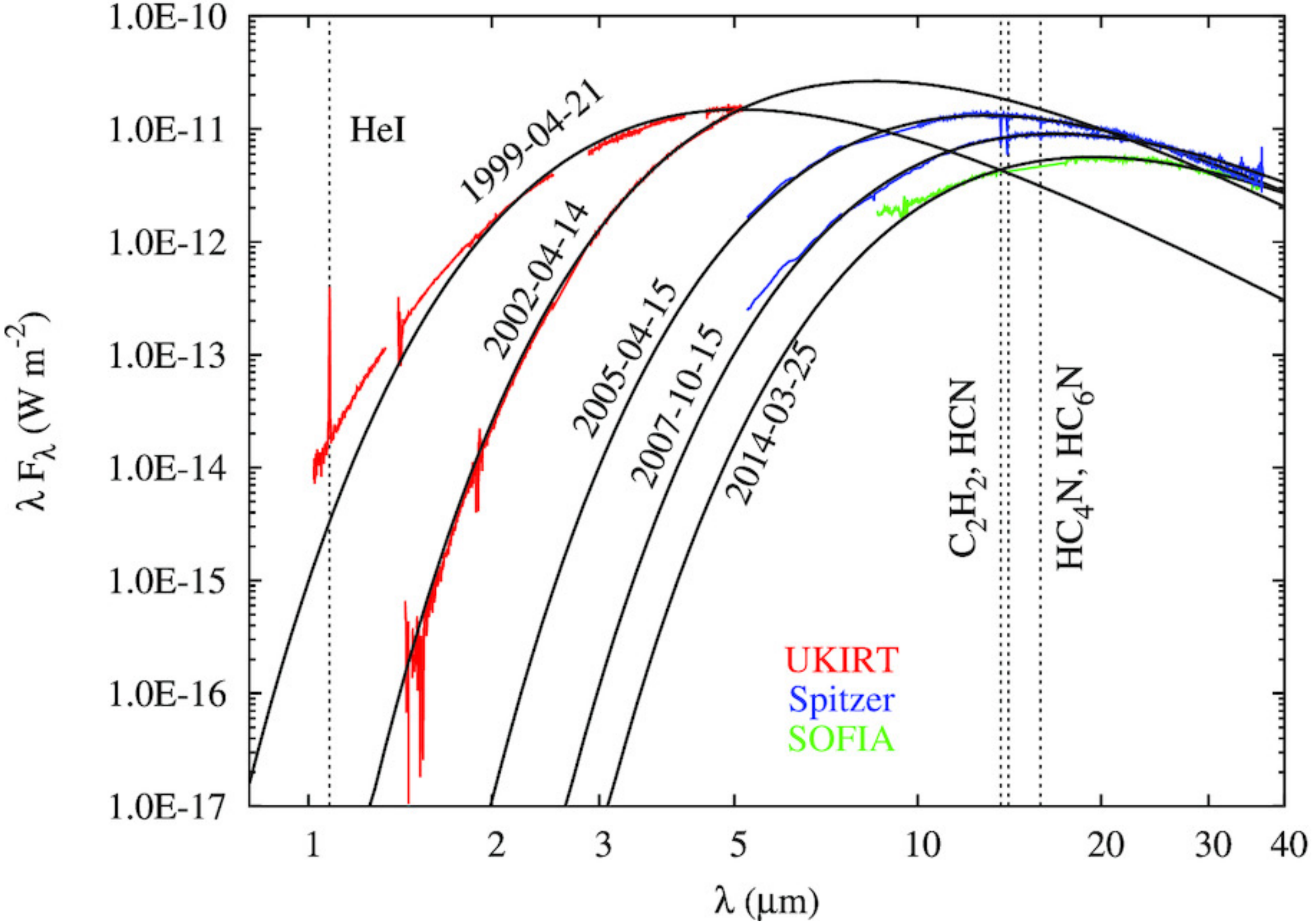
Hinkle & Joyce (2014)

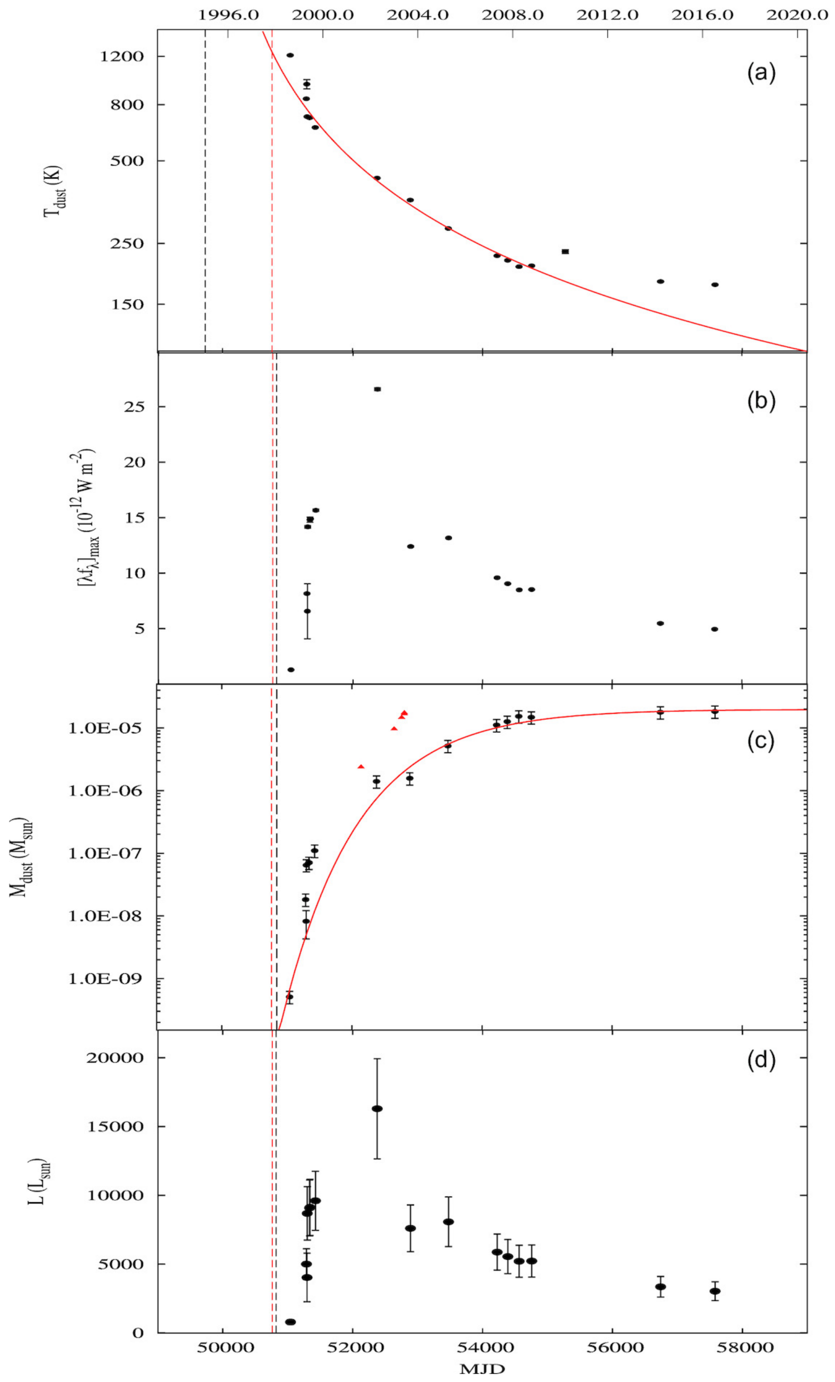
- 1997: Dust production as close 7 Rstar above photosphere
- By 1999: not detectable at optical wavelengths
- 08/2000: HST shows no star < 24.2 mag in V-band
- Far IR: Dust shell as cool as 180-210K in 2005
- By 2007: total ejected mass ca 10^-4 Msol



Dust evolution in V4334 Sgr

Evans et al. (2020)

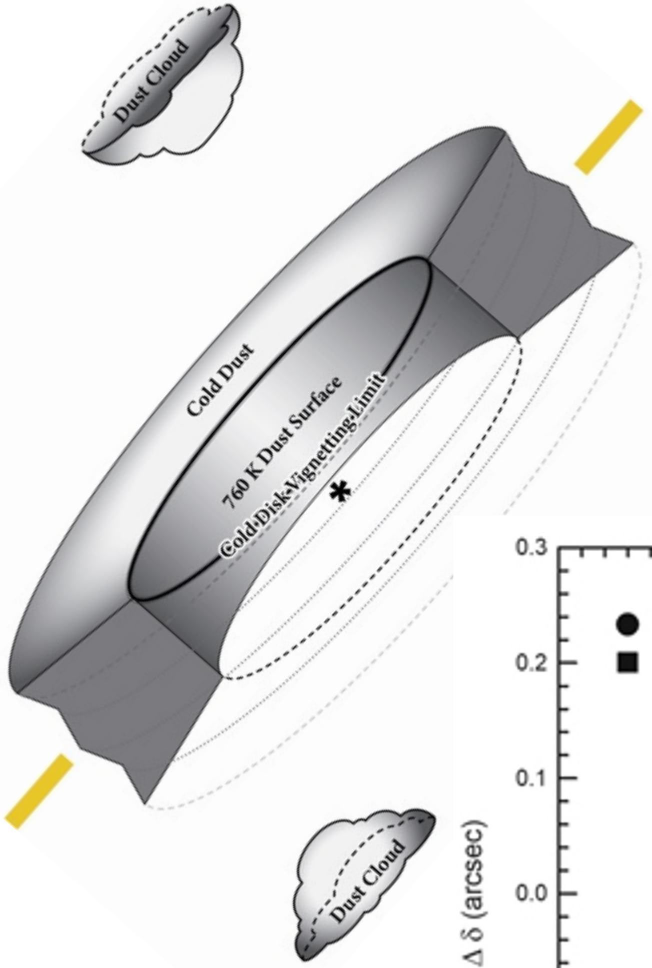


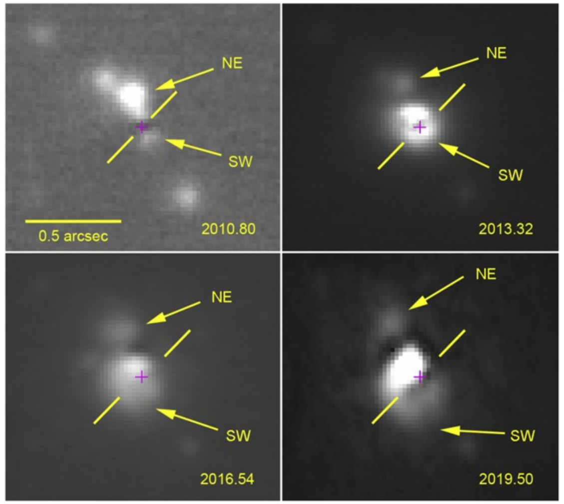


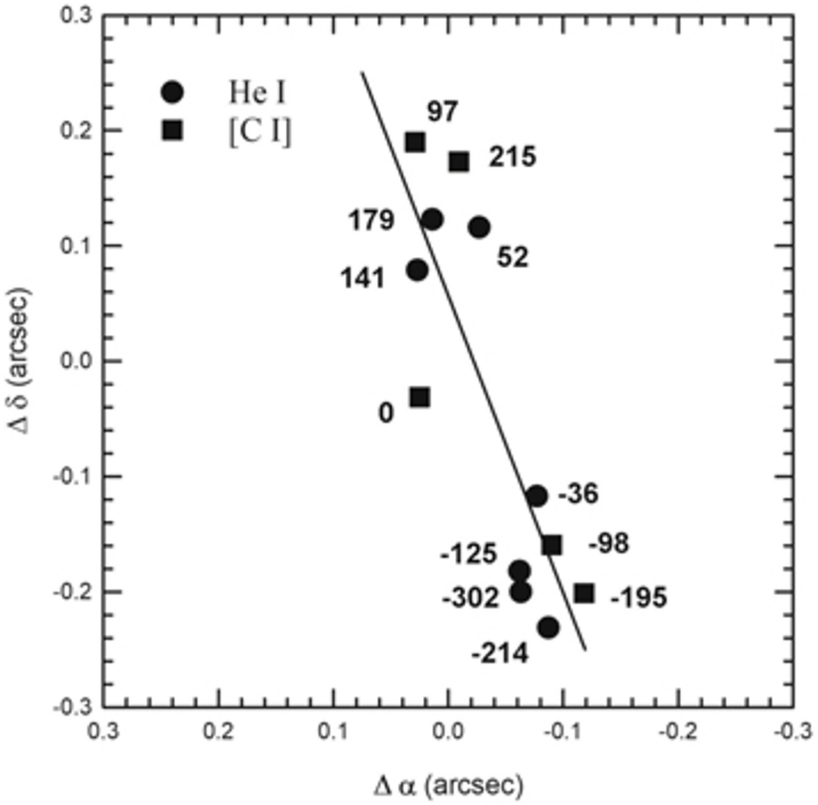
Latest update

[Hinkle et al. 2020](#)

- 2009: IR interferometry : optically thick disk (40 +/- 6 au), highly inclined
- SEDs show cold ~200K and hot ~760K dust
- Hot dust very low mass fraction, dominates NIR but won't shape nebula
- Hot dust likely associated with shock heating inner disk wall & clouds by fast wind
- Disk of cold dust with bright nothern polar hole
- NIR imaging: clouds moving radially away from point source





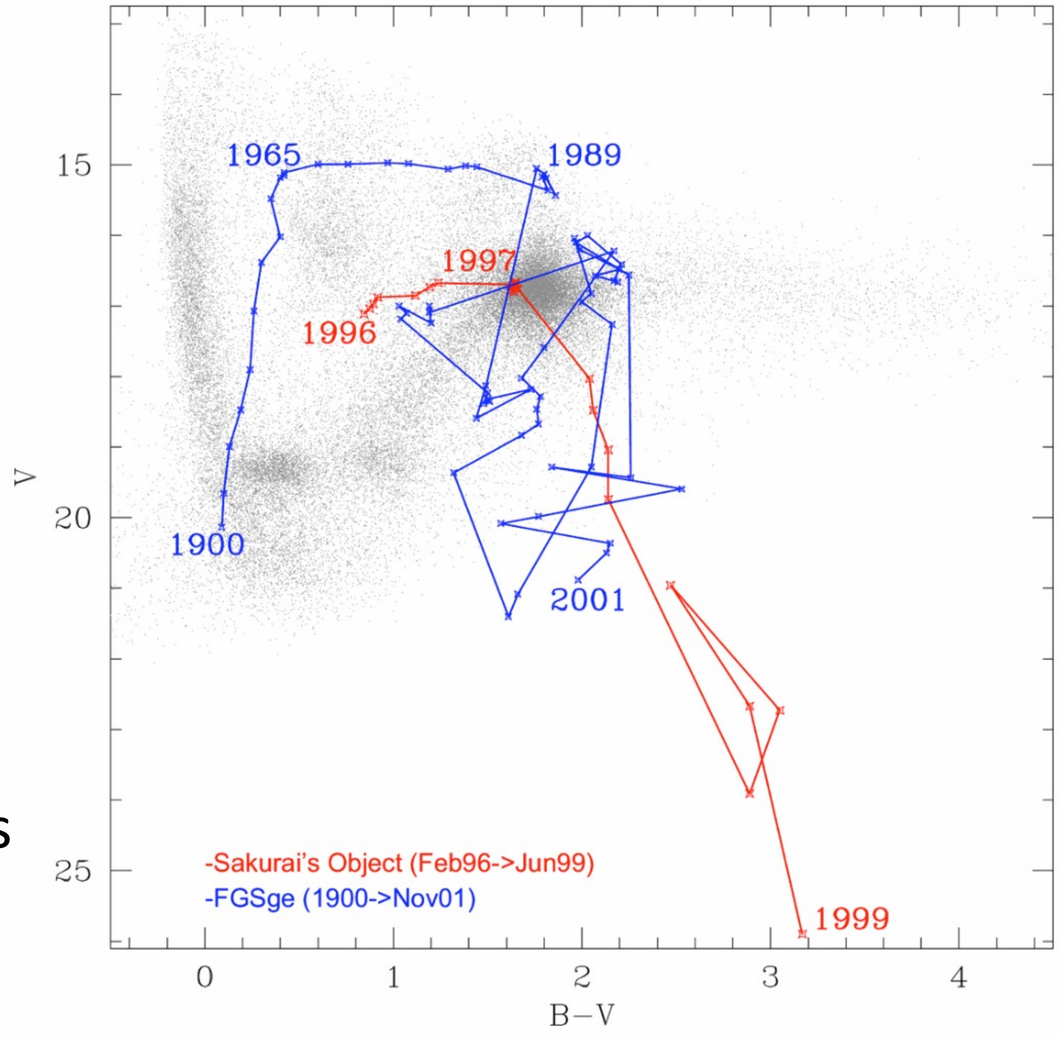


Is there a population of these?

Spano et al. (2009)
https://arxiv.org/pdf/0907.4090

Lawlor & MacDonald (2002)

- Sakurai: first return to AGB?
  - Post-AGB helium flash on 6-yr timescale
- FG Sge: second return to AGB?
  - Late-thermal pulse object (Jeffery & Schönberner 2006)
- V605 Aql: best analog to Sakurai's object, older twin? Clayton et al. 2013
- Different in timescale: Sakurai super fast, FG Sge is slower (120 yr of born-again behavior)
- "Born-again" or Very Late Thermal Pulse stars
- May be up to 10-15% of late AGB stars

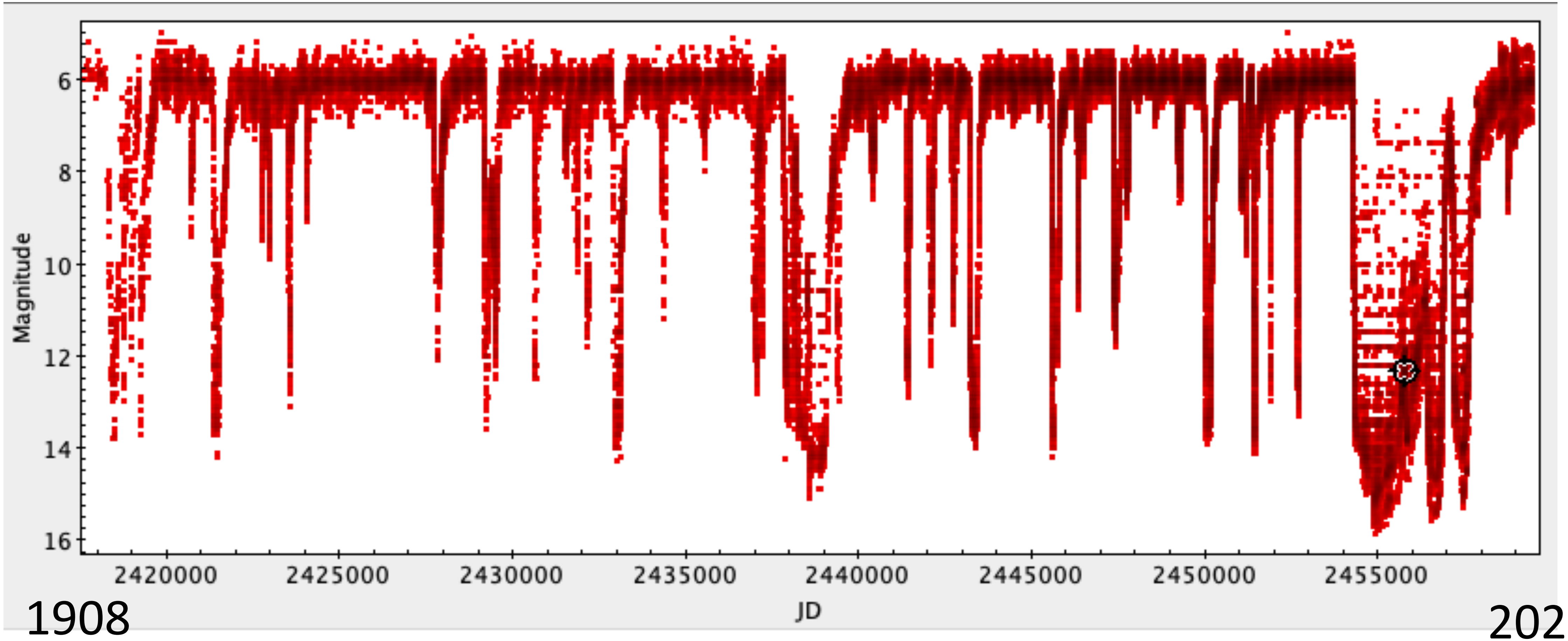


R Coronae Borealis

The most impressive cases of negative variability

R CrB stars

A dimming by 9+ mag: 5000 times fainter!



1908

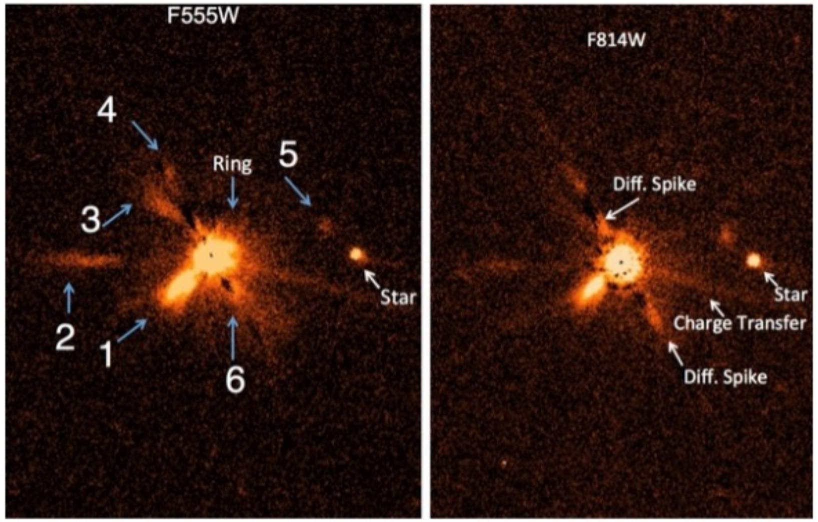
2021

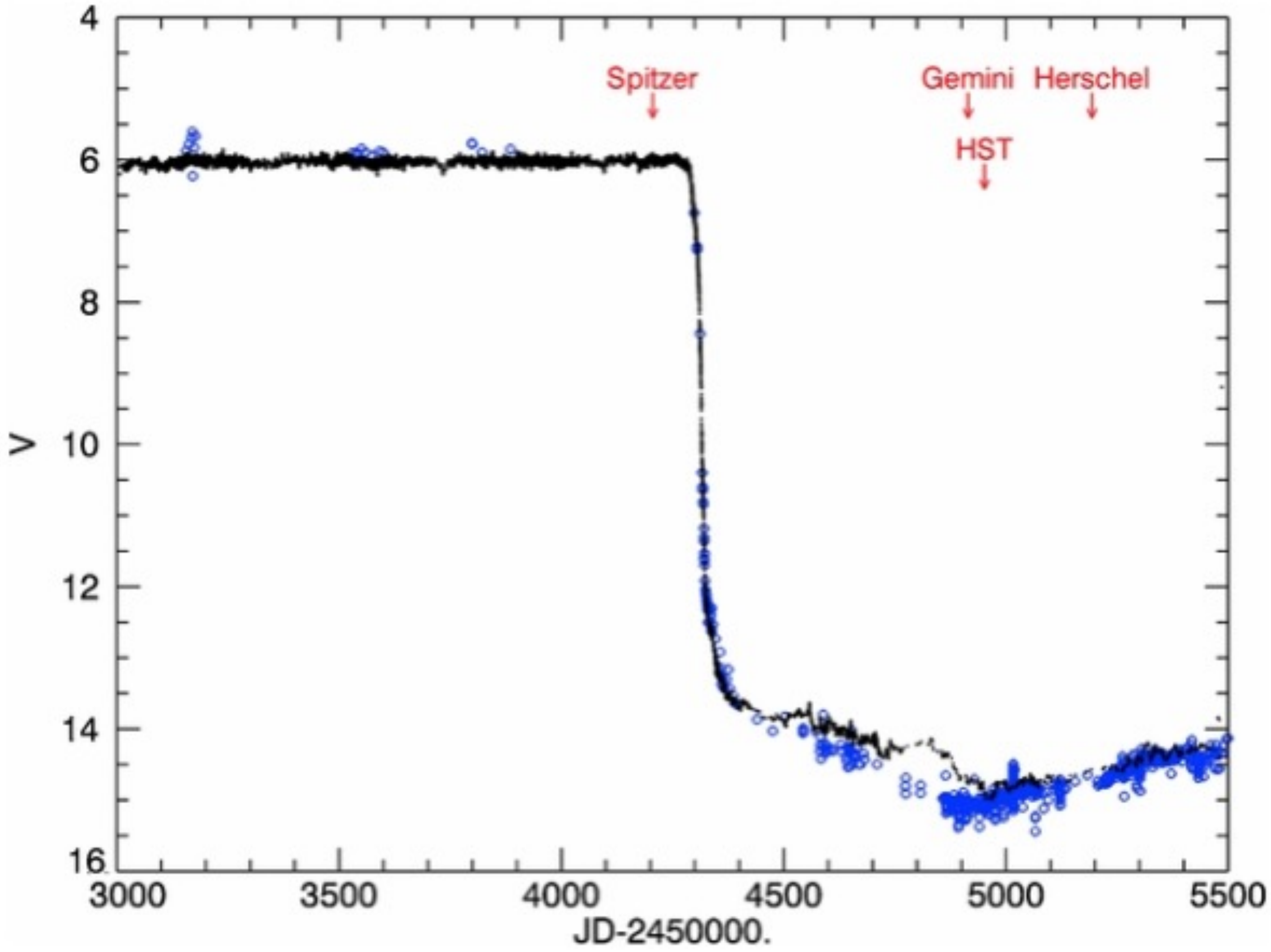
https://www.aavso.org/data-download

R Coronae Borealis

[Clayton et al. (2011)](#)

- Images before and during event: natural coronagraph!
- Cometary knots detected within a few 1000 au of star



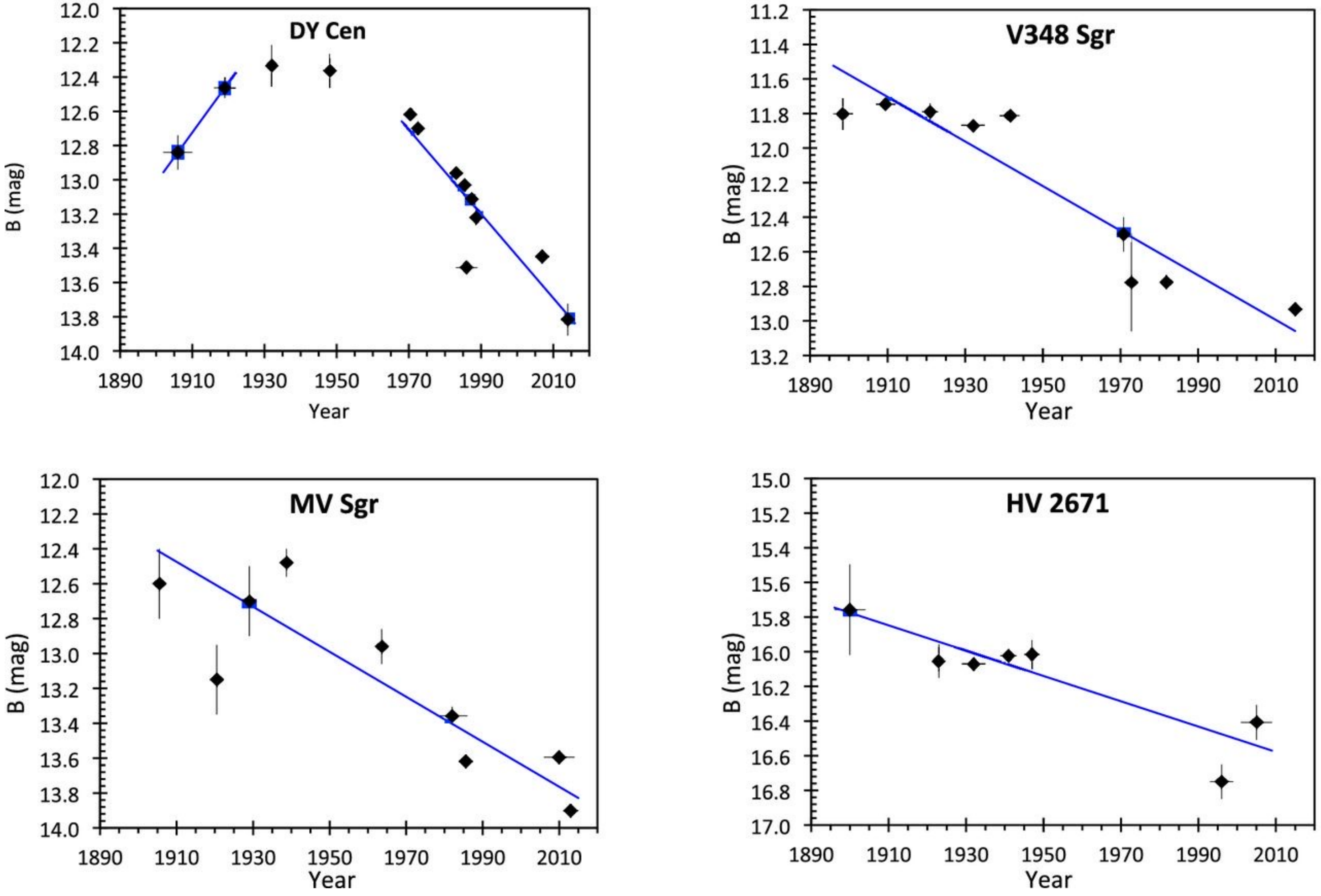


HST/WFPC2 F555W (left) and F814W (right) images with a PSF removed from the position of R CrB. White arrows indicate instrumental features and the companion star. Blue arrows indicate real nebular structures around R CrB. The angular distance between R CrB, which lies in the center of the images, and the faint star to the west is ~3''. The cometary knots are numbered.

All hot RCB stars are fading by 1-3 mag/century

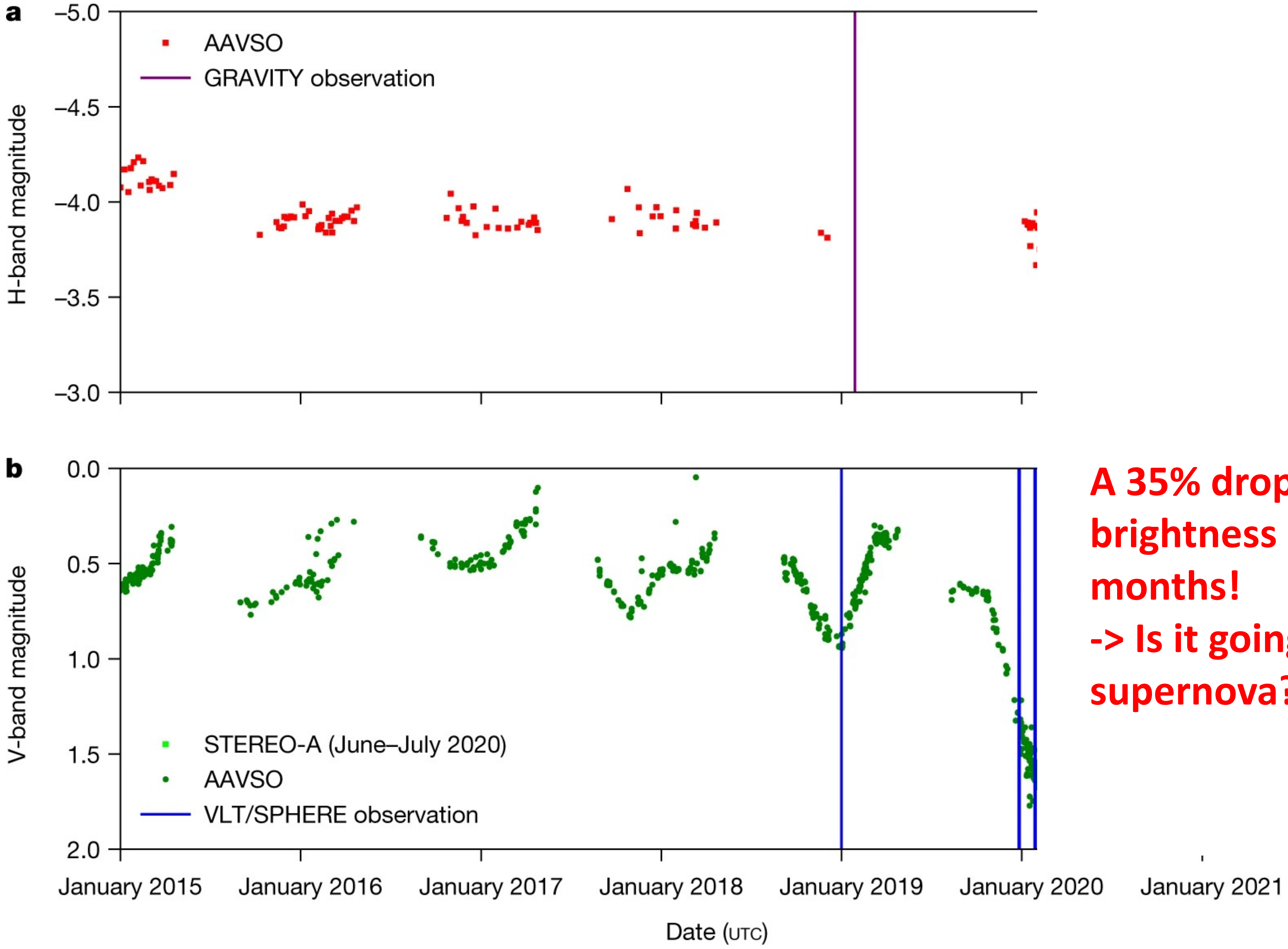
[Schaefer 2016]

- 100yr baselines thanks to photographic plates (DASCH)
- Indicates that star is moving to hotter temperature at fixed luminosity in HRD



The Great Dimming of Betelgeuse

Special Session 22 at European Astronomical Society Meeting 2021

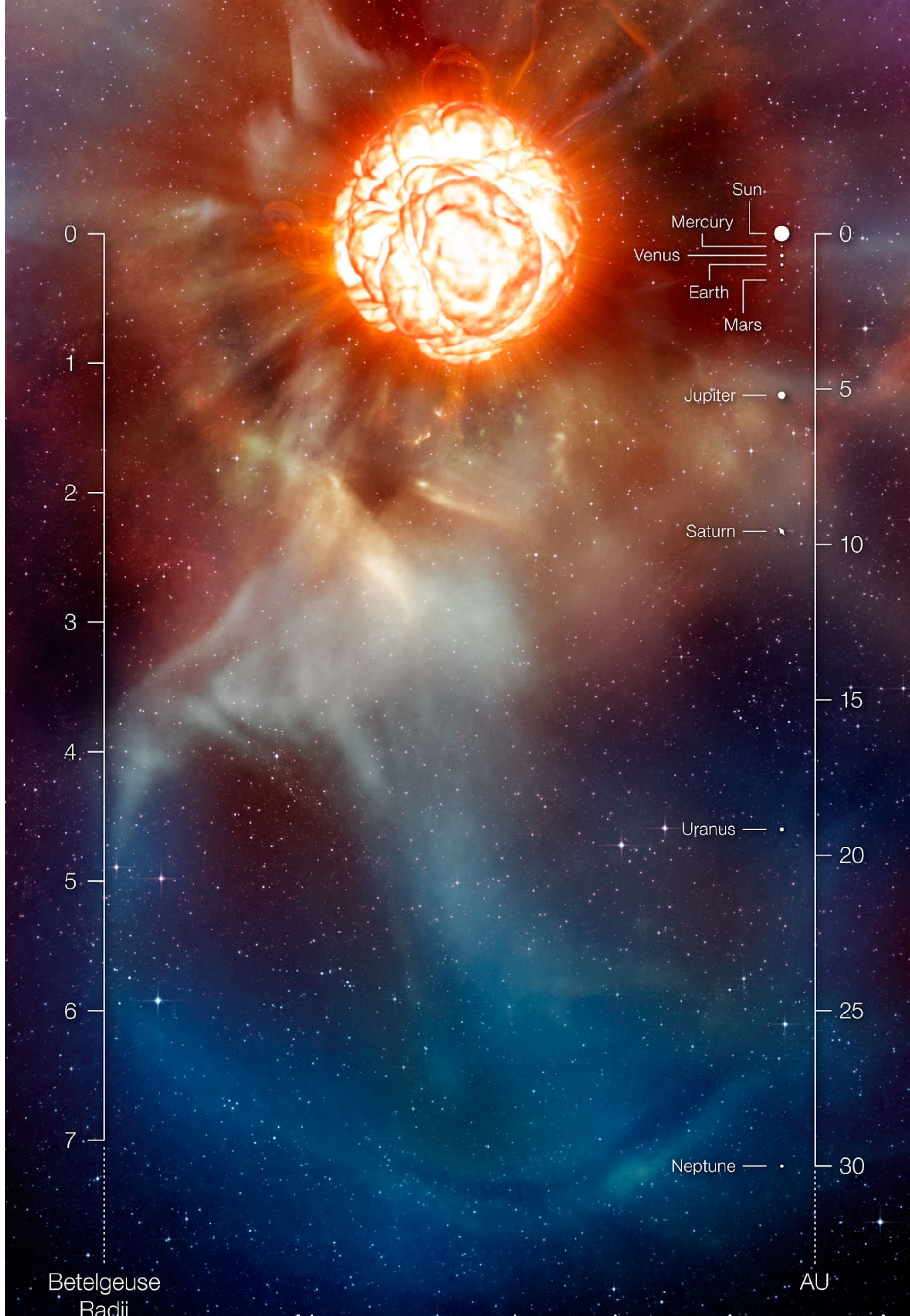


A 35% drop in brightness in a few months!
-> Is it going supernova???

ıtargès et al. (2021)

Context and Relevance

- Red Supergiants like Betelgeuse (ca. 20 Msun) are progenitors of core-collapse supernovae
- Formation channels for neutron stars and stellar-mass black holes detected by LIGO/VIRGO
- CC-SNe important for chemical enrichment of ISM
- Betelgeuse has R = 900 Rsun => nearly the size of Jupiter’s orbit
- Diluted outer layers feature pulsations and just a few enormous convective cells and huge plume of material spanning size of Solar system



https://www.eso.org/public/images/eso0927d/

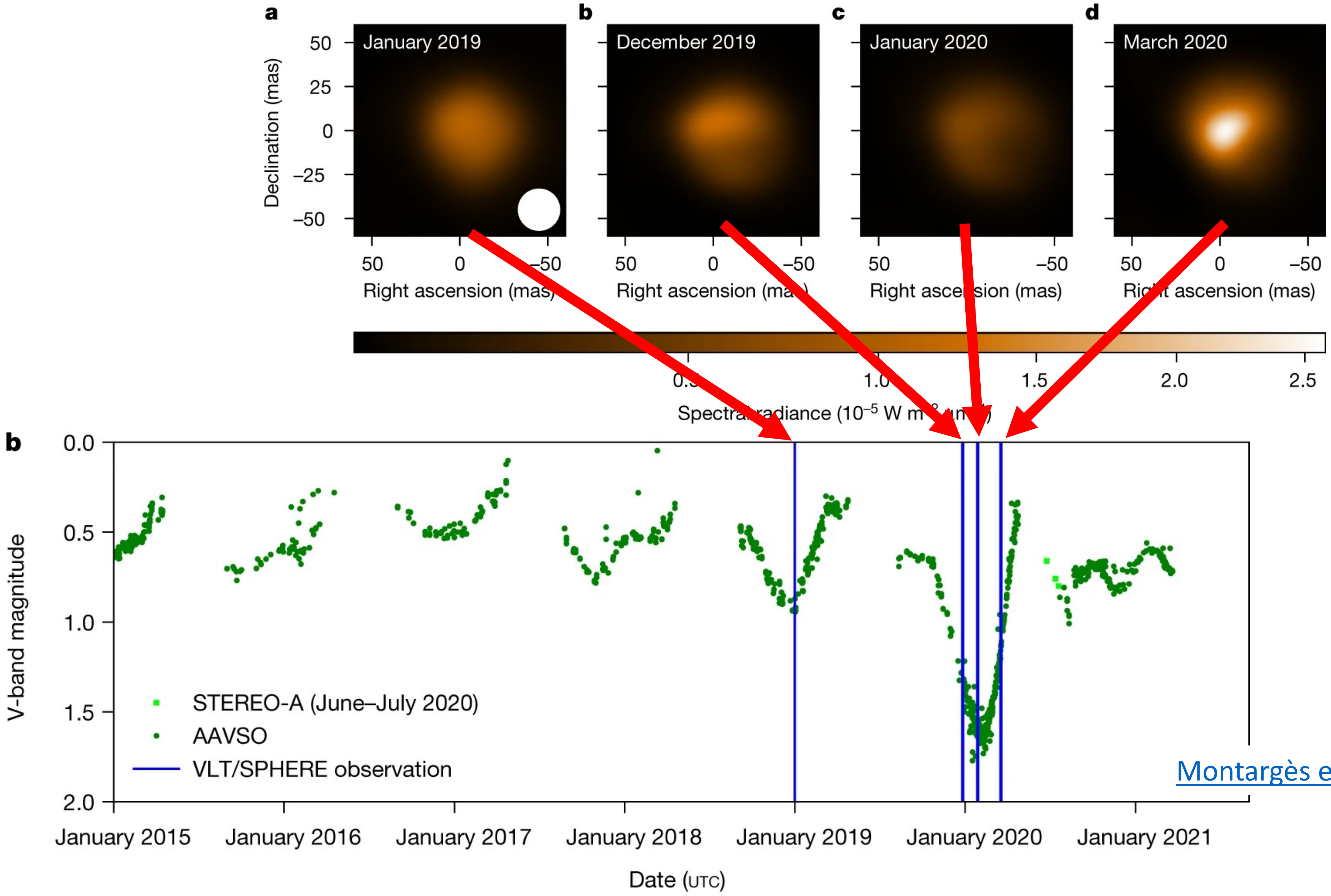
Actual resolution of ESO press release image

https://www.eso.org/public/images/eso0927d/

Potential scenarios

- (local) decrease in Teff
- Occultation by newly formed dust
- ~~Occultation by dust transiting star~~
- Change in angular diameter

Rejected because clump should change quadrant before and after deepest dimming
-> Observations Jan & March 2020 show dark area remained in SW quadrant



[Montargès et al. (2021)]

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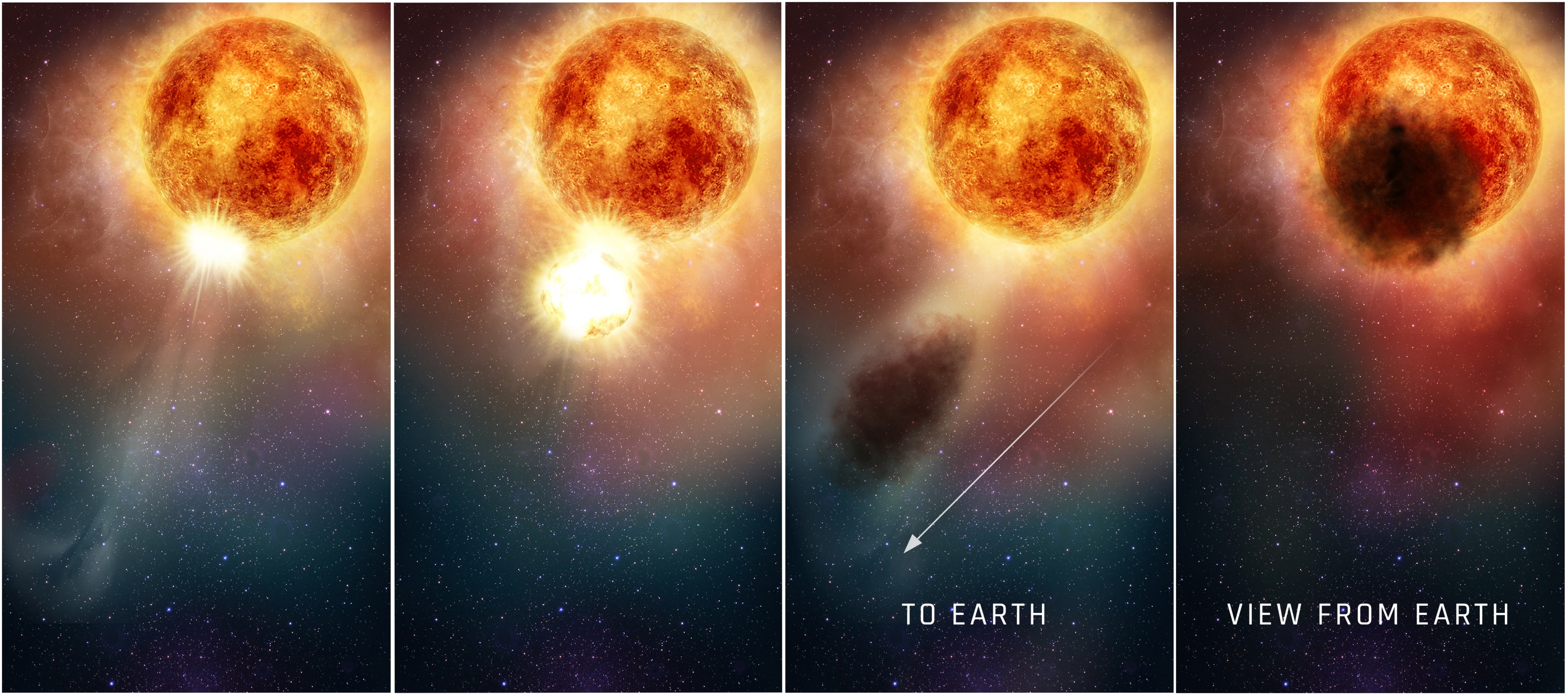
Rejected by measured angular diameters:
42.61 ± 0.05 mas (Jan 2019)
42.11 ± 0.05 mas (Feb 2020)
-> 30% change (12+ mas) required to explain flux variation in visible

Dupree et al. 2020; https://iopscience.iop.org/article/10.3847/1538-4357/aba516



https://www.nasa.gov/feature/goddard/2020/hubble-finds-that-betelgeuses-mysterious-dimming-is-due-to-a-traumatic-outburst

Explanation by Montargès et al. (2021)

- Combination of pulsation and cool convection spot
- Cooled local environment rapidly forms dust
- Localized, southern, dust cloud blocked light temporarily
- Mass loss generally: gaseous & due to stellar winds (10^-6 - 10^-7 Msun/yr)
- Here: clumpy, erratic & sudden mass loss events
- Hugely important for understanding mass loss in stars
- CC-SNe may still happen, but we don’t know when

Questions?