ASTR 421

Stellar Observations and Theory

Lecture 14
Pulsating & Variable Stars

Prof. James Davenport (UW)

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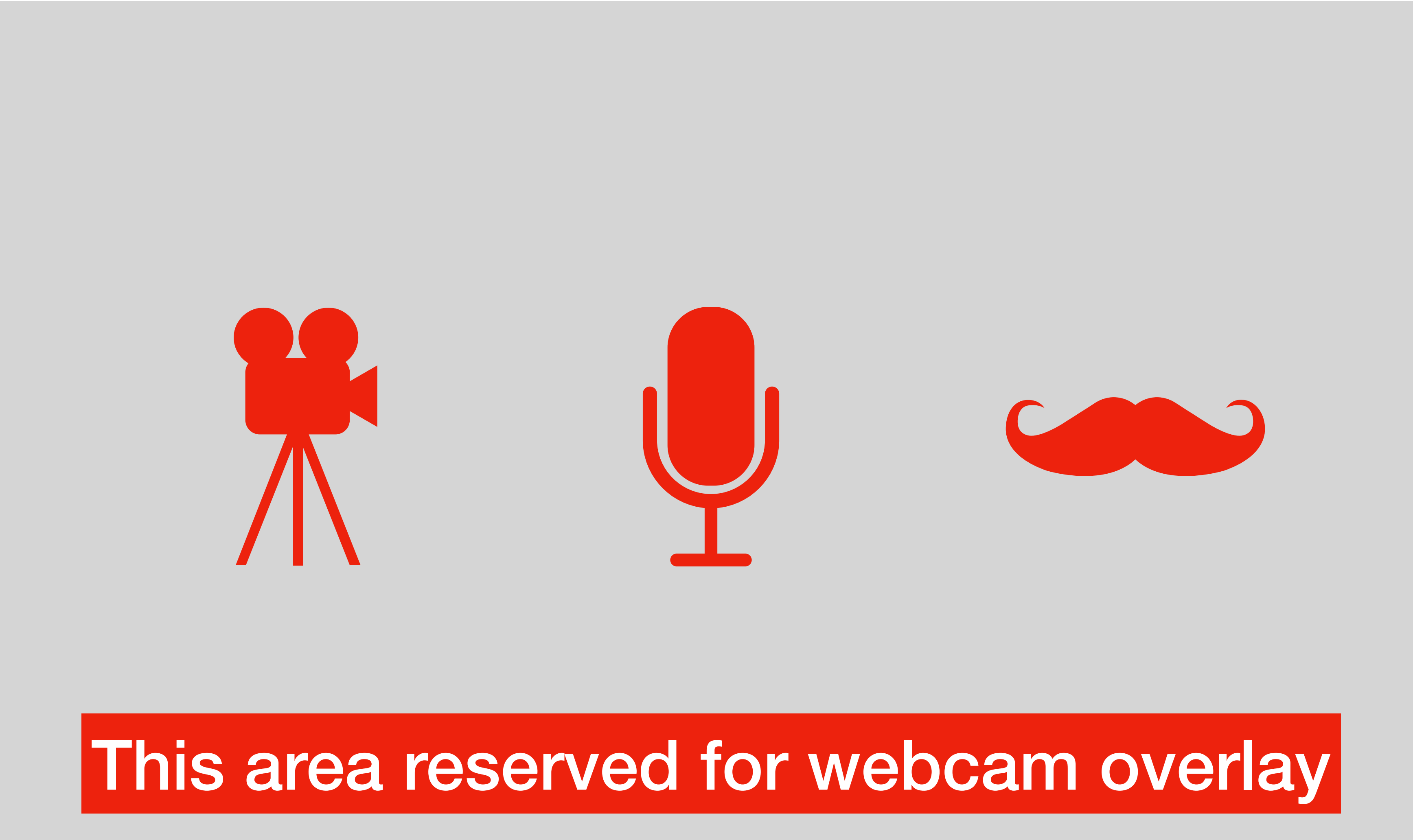
Today

- Why do stars vary their brightness?
- How do we study variable stars?
- (Some) Types of variable stars

- Pulsating variables

- Read: BOB Ch 14



Part I

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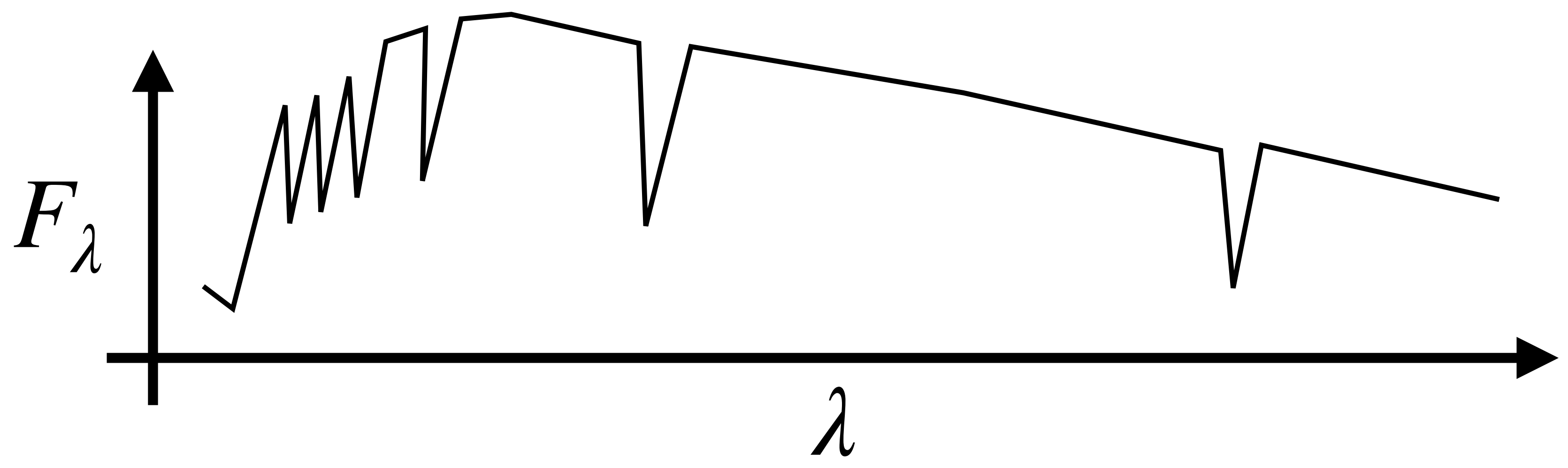
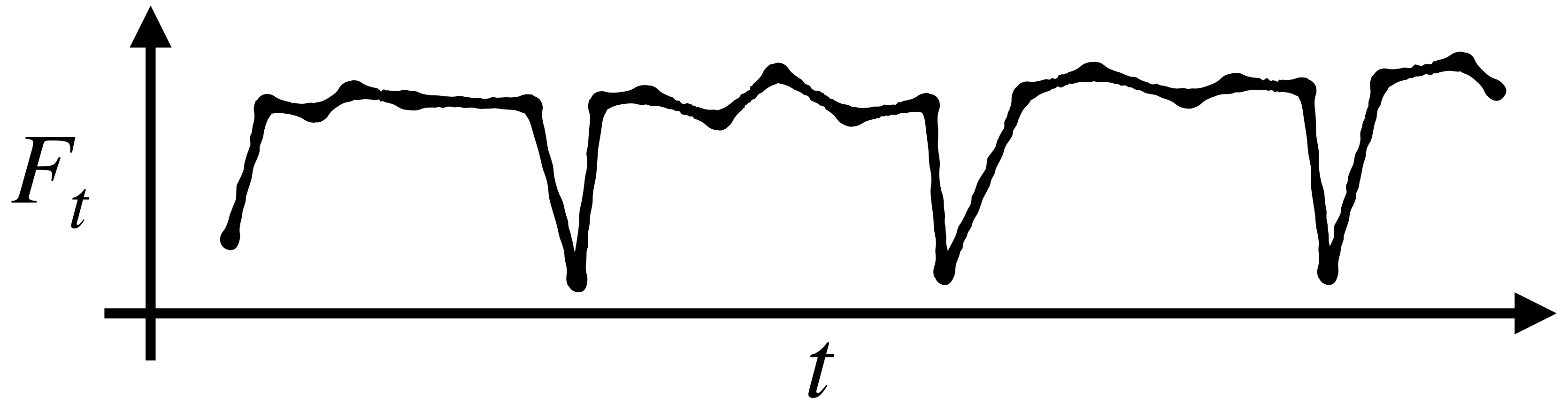
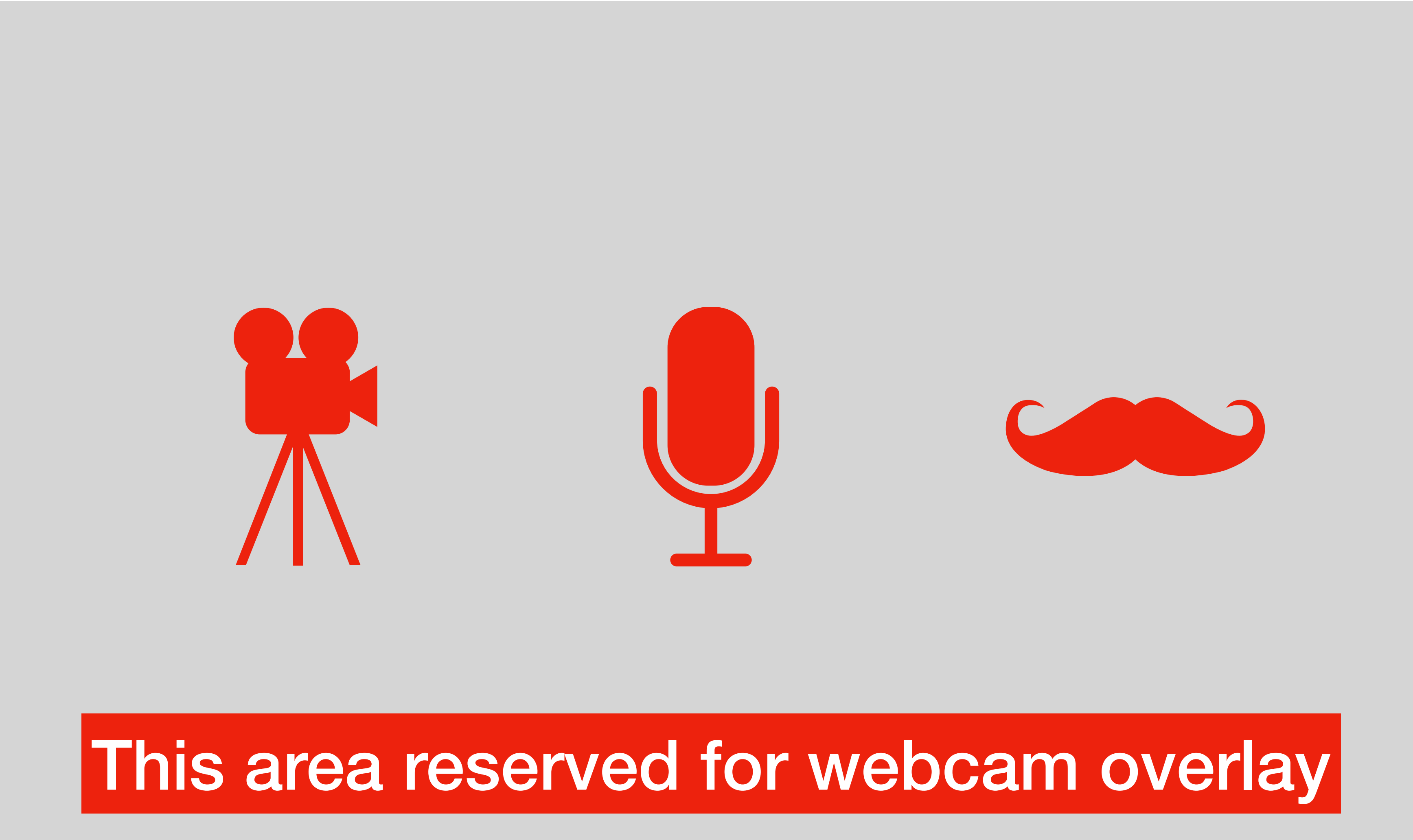
Why study brightness variations?

- Spectroscopy (F_λ) is expensive, especially in time!



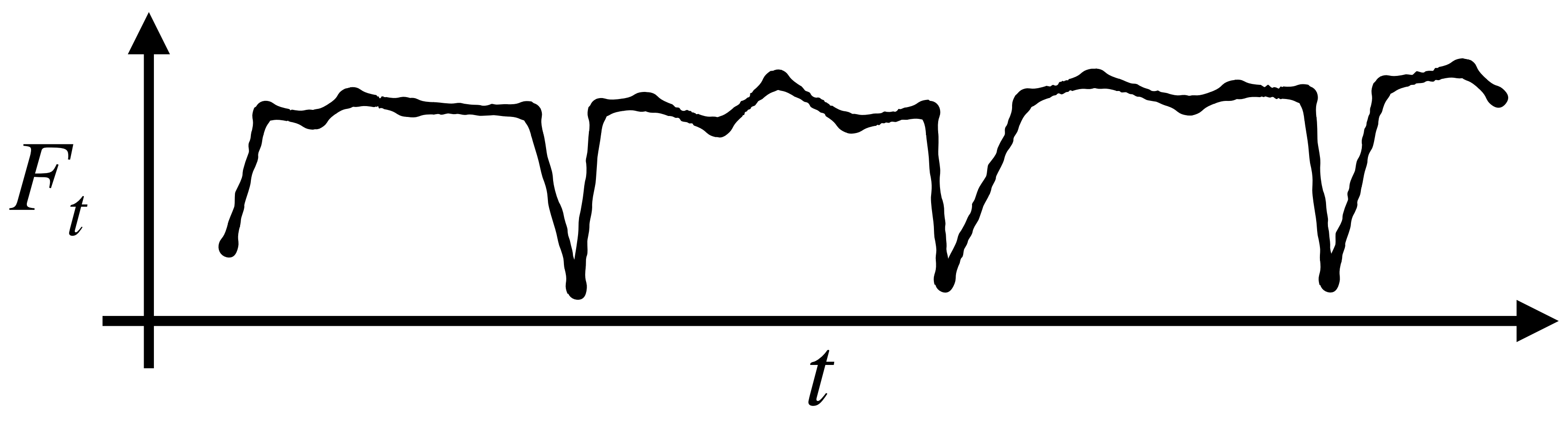
- Time-domain information (AKA light curves, AKA time series) (F_t) can be gathered for MANY stars simultaneously, and with smaller telescopes, gives us a "power spectrum"





Why study brightness variations?

- Power spectrum maybe *not quite* as informative as wavelength spectrum, but it's close… and we're STILL learning to read it!
    - Very active area(s) of research
    - (IMO) we're in the middle of a massive leap forward in studying stars with time-series!
- Time series reveal unique properties (taken with spectra is super combo!)



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Why study brightness variations?

- We get data for “free” from other programs
    - Transiting exoplanet surveys (e.g. Kepler, TESS, KELT)
    - SNe or cosmologically-focused surveys (e.g. ZTF, LSST)
    - Astrometry missions (HIPPARCOS, Gaia)
- *Many* other “time-domain” surveys, primarily in optical & NIR
    - e.g. ASAS-SN, Evryscope, WISE, VVV
        - Lots of places to go check for data!

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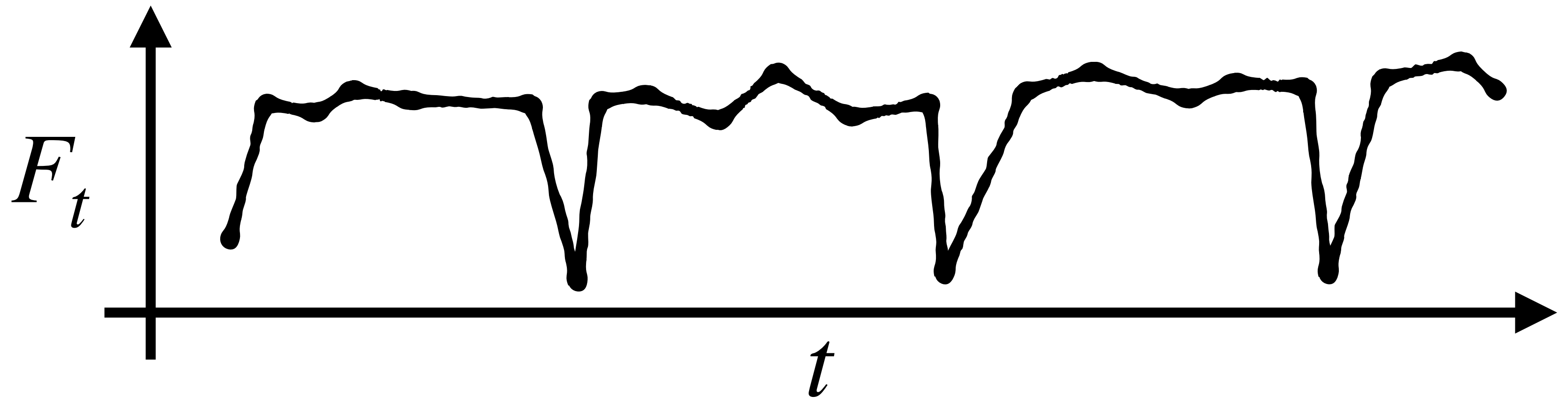
What causes stars to vary in brightness?

*Not an exhaustive list…



- Broadly, variability is due to either:
- **Intrinsic changes from the star**
  - variations of the stellar spectrum (or "spectral energy distribution", SED)
  - Eruptions, transient events, pulsations, accretion, dust formation, spots…
- **Extrinsic changes, along the line of sight**
  - Physical blocking/occulting of light, by a wide variety of objects!
    - Occasionally blocking star & *adding* flux (e.g. lensing)

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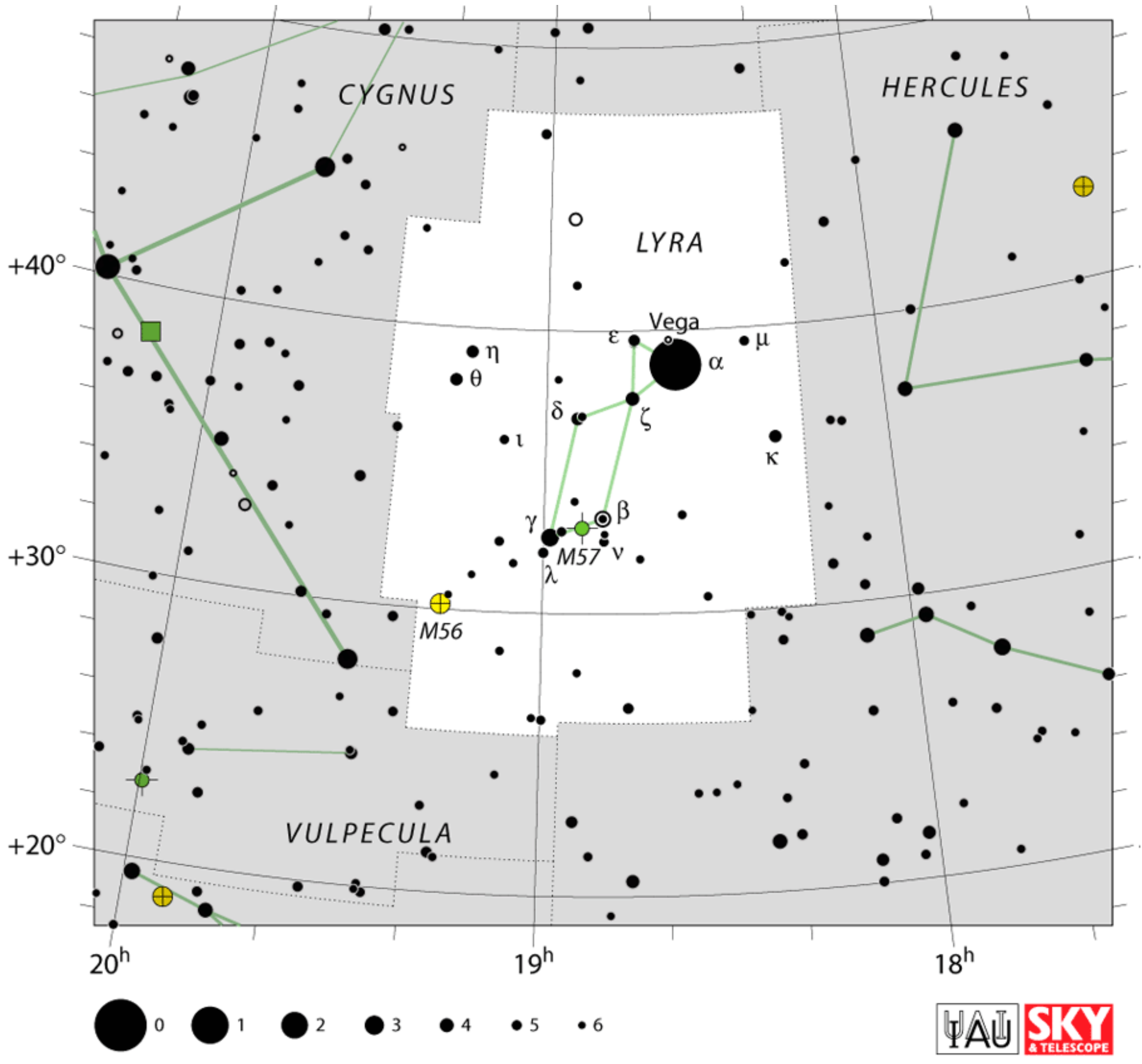
Aside: Variable Star Designations

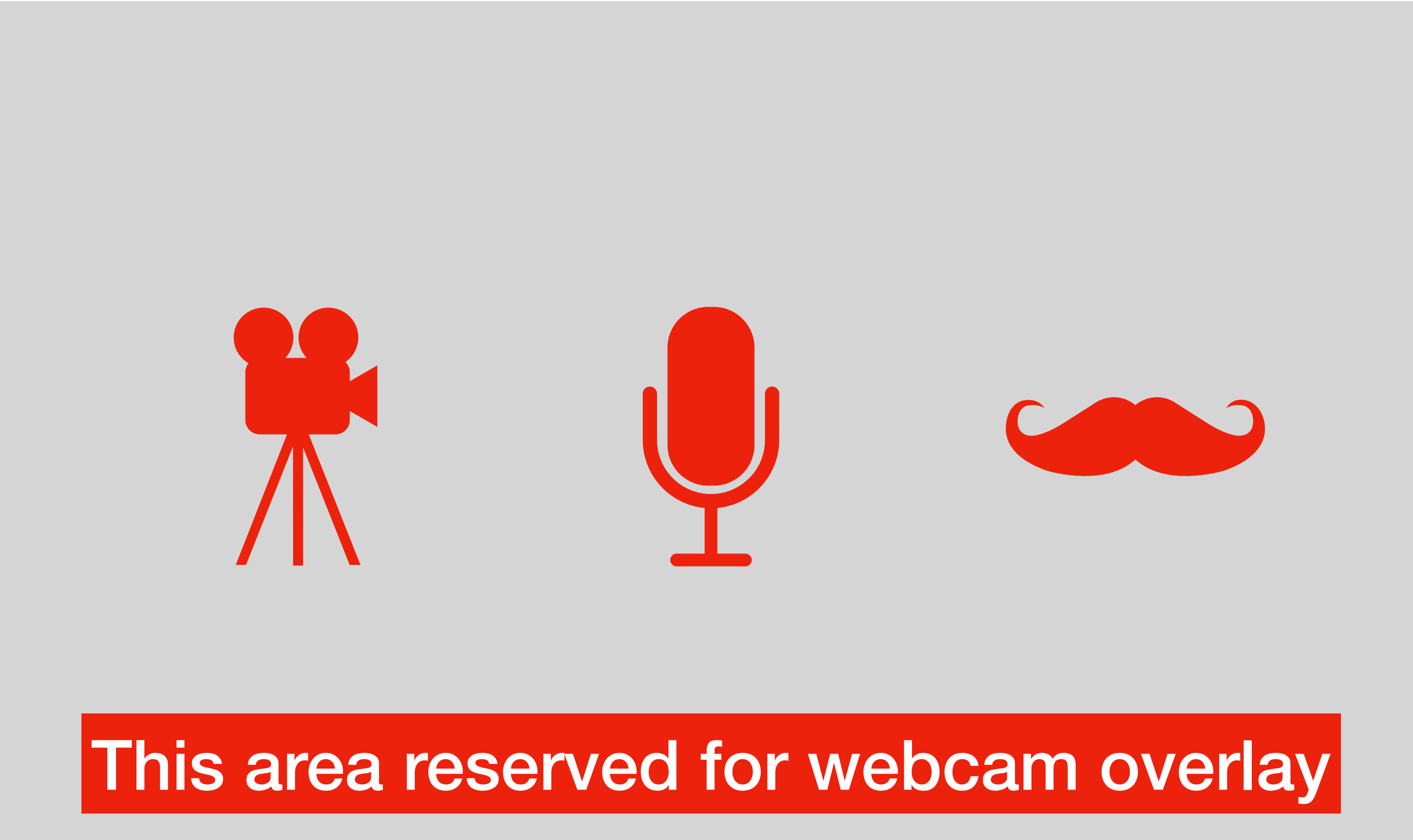


https://en.wikipedia.org/wiki/Variable_star_designation

- A very historical topic…
  - **New types of variable stars are named after the first star discovered in that class (the “prototypical” star)**
  - Named based on the brightness ordering of stars within constellations…

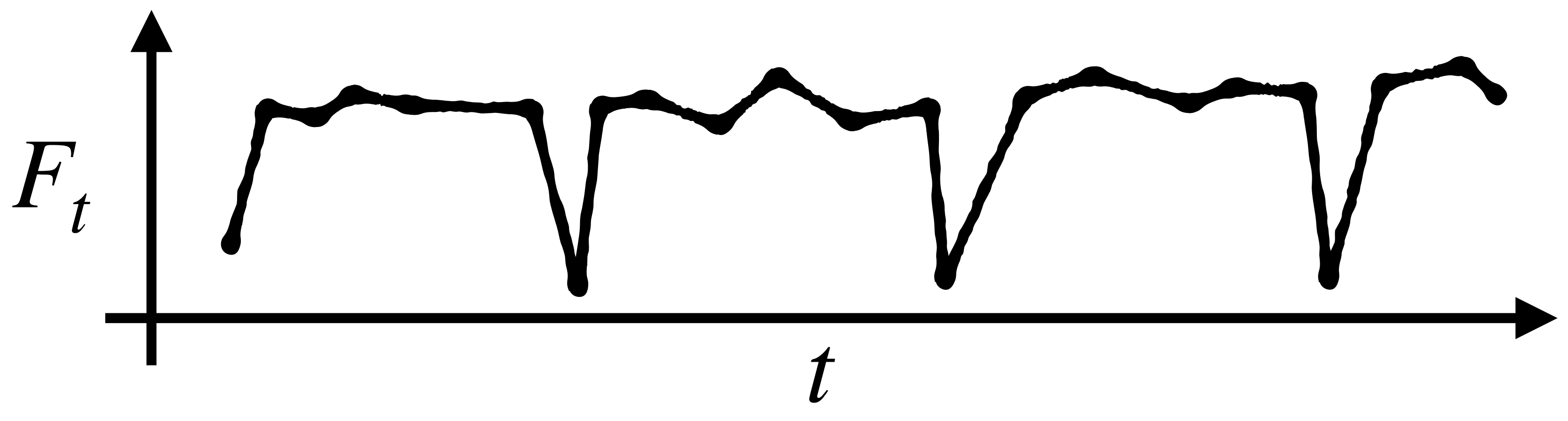
https://www.iau.org/public/themes/constellations/

  - e.g. α Lyrae (aka VEGA), β Lyrae… (“Bayer designation”)
  - When you run out of Greek letters, you switch to letter combos (R - Z, then RR…. Up to ZZ)
  - And then at some point just just *V# Constellation*
  - **This is confusing and inconsistent!**



Variability: Connecting *Timescales* to Stars

- Our goal is to connect the **variations in brightness** (& maybe λ) to physical processes or **properties of the star**.
- Stars can (& often do) change at all timescales: seconds-minutes-hours-days-years-centuries… Gyr.
- The *observable* parameters for a given process:
  - The timescale (t) of the process
  - The amplitude (ΔF) of the resulting variation
  - Both *can* be λ dependent, but especially ΔF_λ



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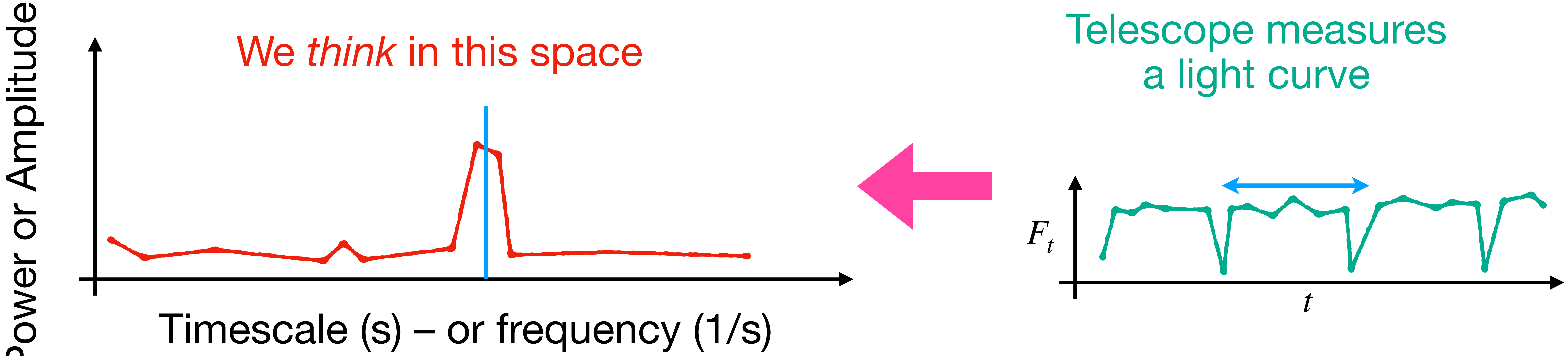
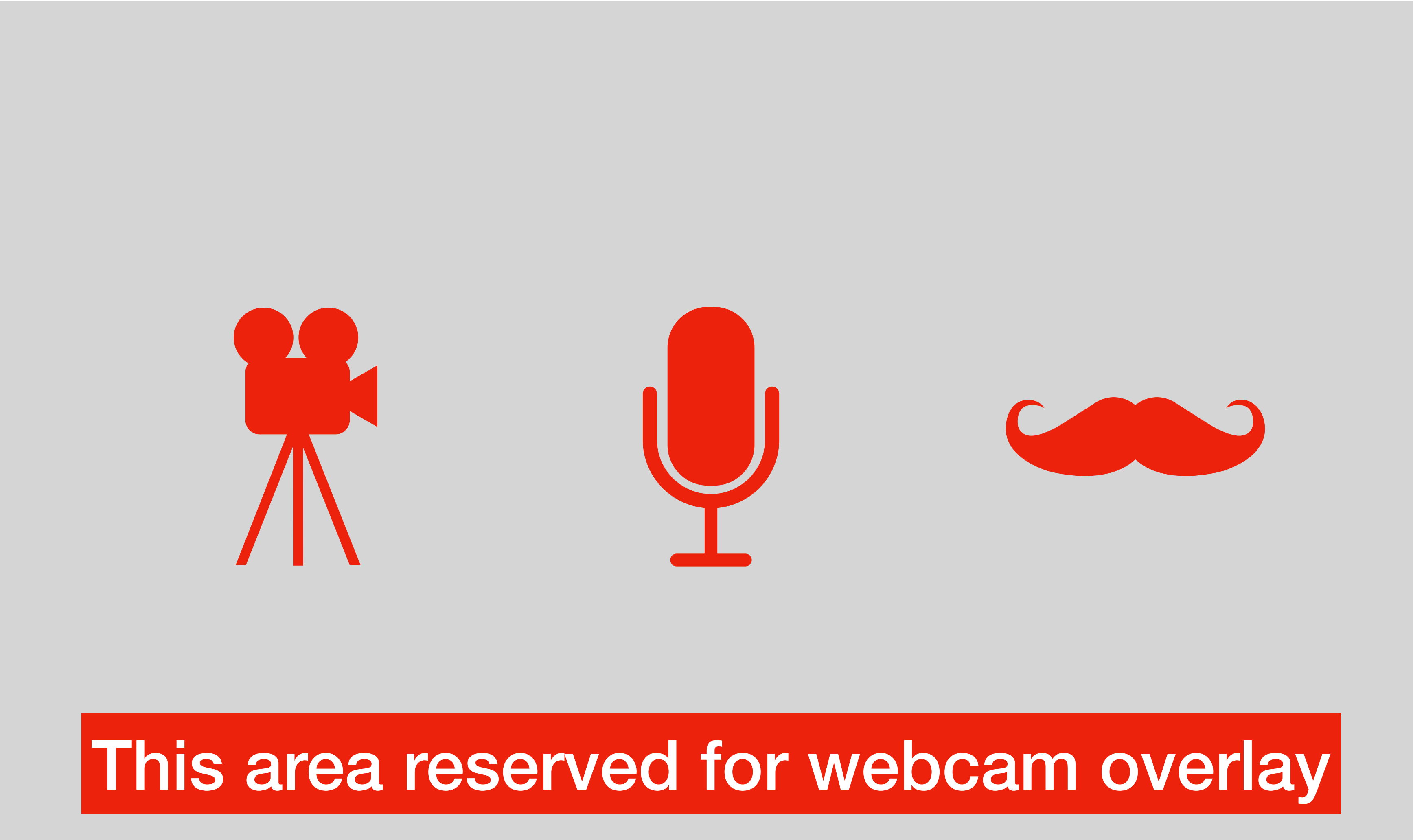
Variability: Connecting *Timescales* to Stars

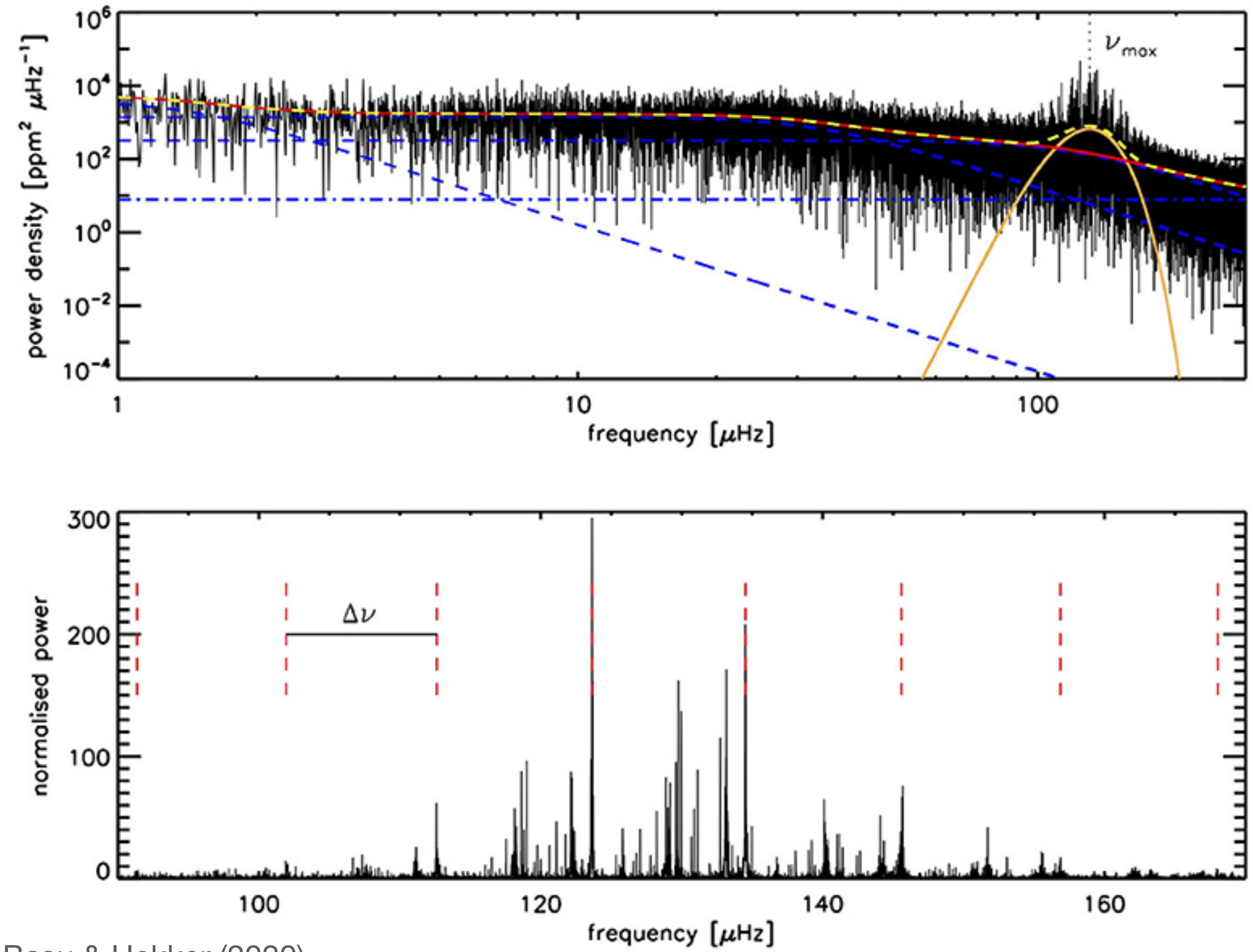


Remember your friend the Fourier Transform,
and it's handy pal the FFT
(and *many* other ways to do related transformations)



Power spectra

Sometimes: Power spectral density (PSD)
See also: Periodogram



Basu & Hekker (2020)

- Need thousands of brightness measurements, high precision, over a wide range of timescales
- Can be used for both intrinsic and extrinsic variability sources (simultaneously even!)

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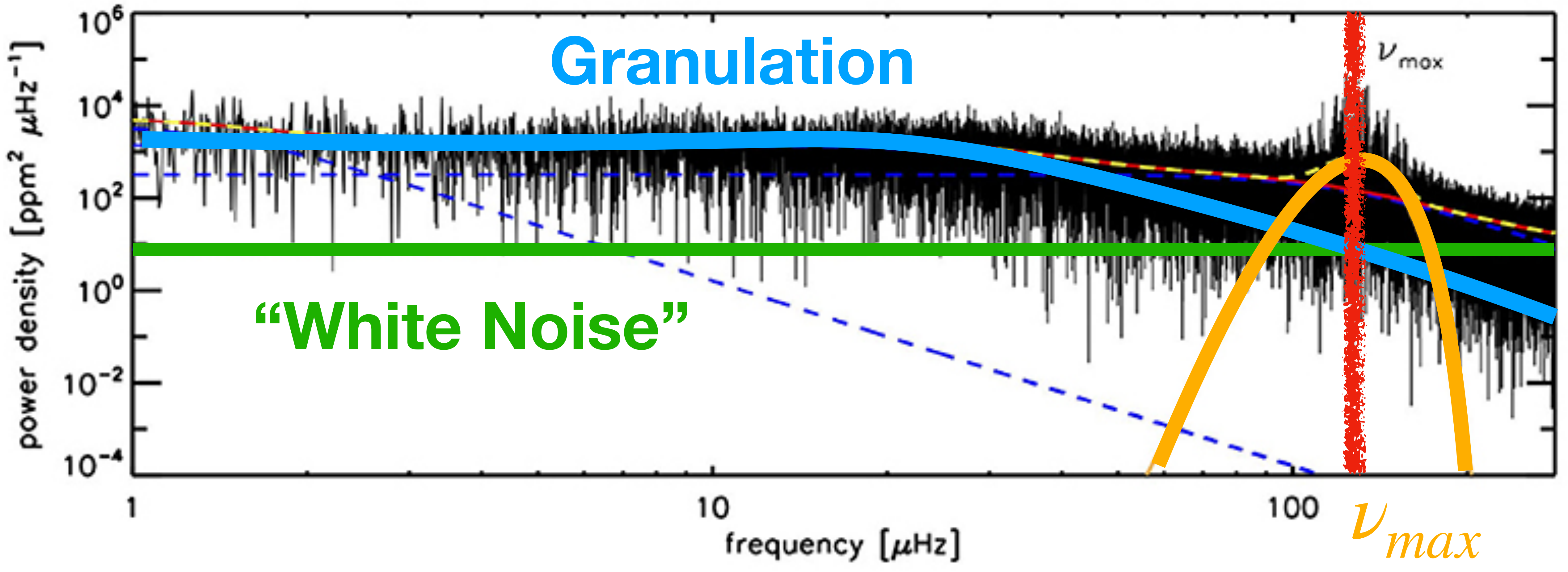
Power spectra

Sometimes: Power spectral density (PSD)
See also: Periodogram

Compare to classical spectra



- Need thousands of brightness measurements, high precision, over a wide range of timescales
- Can be used for both intrinsic and extrinsic variability sources (simultaneously even!)

- Can measure **specific frequencies** or periods (think about lines)

  or **general shapes** (think about continuum)

Basu & Hekker (2020)

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Let’s explore some types of variability!

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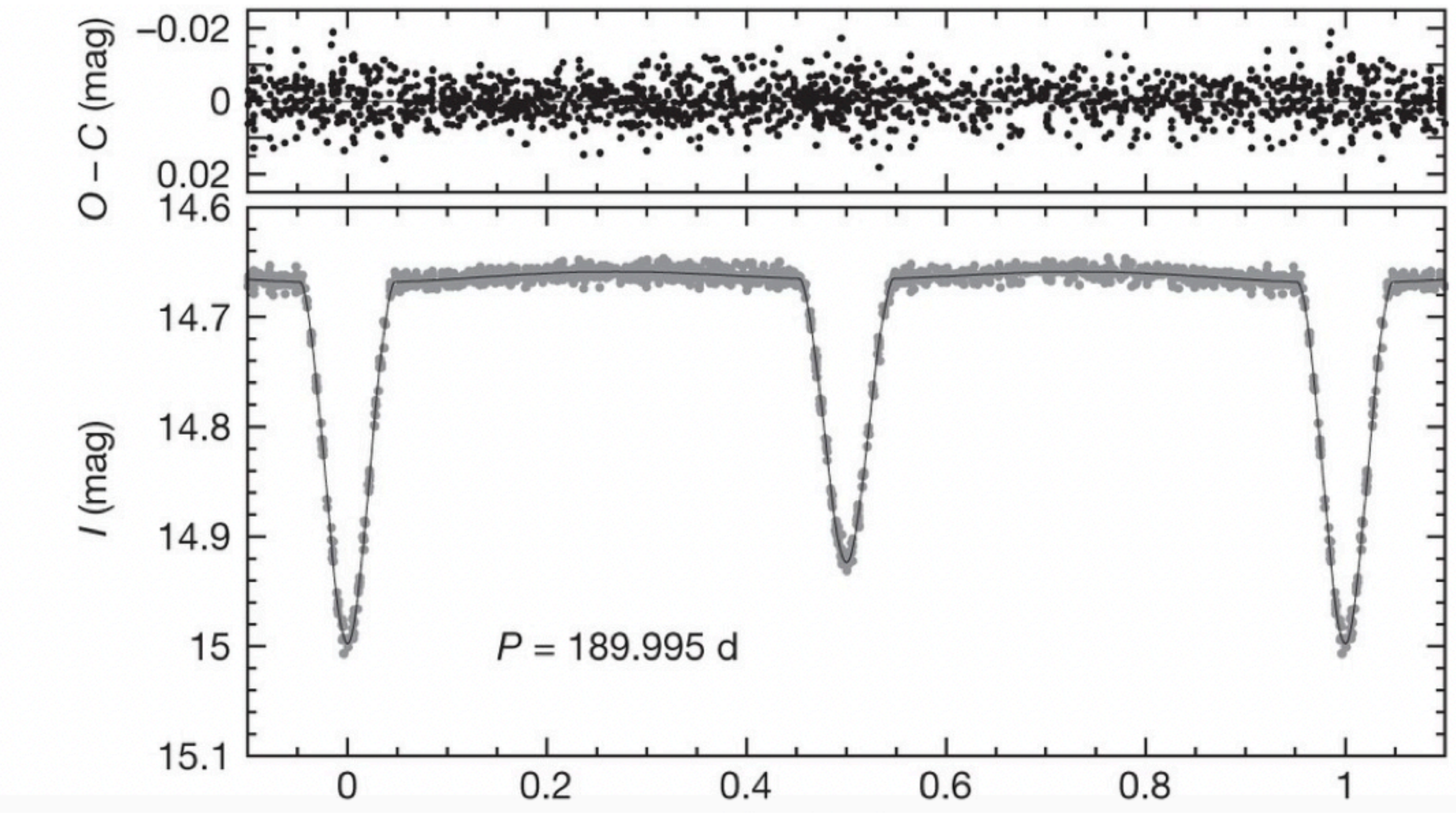
Eclipses

- Usually periodic (driven by orbital dynamics)
- Usually causes light curve to get *darker* (blocking light)
    - Exception: gravitational lensing!
    - depth (and duration) due to ratio of radii
- Binaries: Detached, semi-detached, contact
- For exoplanets, assume small and opaque circle covering star. **Mandal & Agol (2002)**



Orbital Phase

Pietrzyński et al. (2013)

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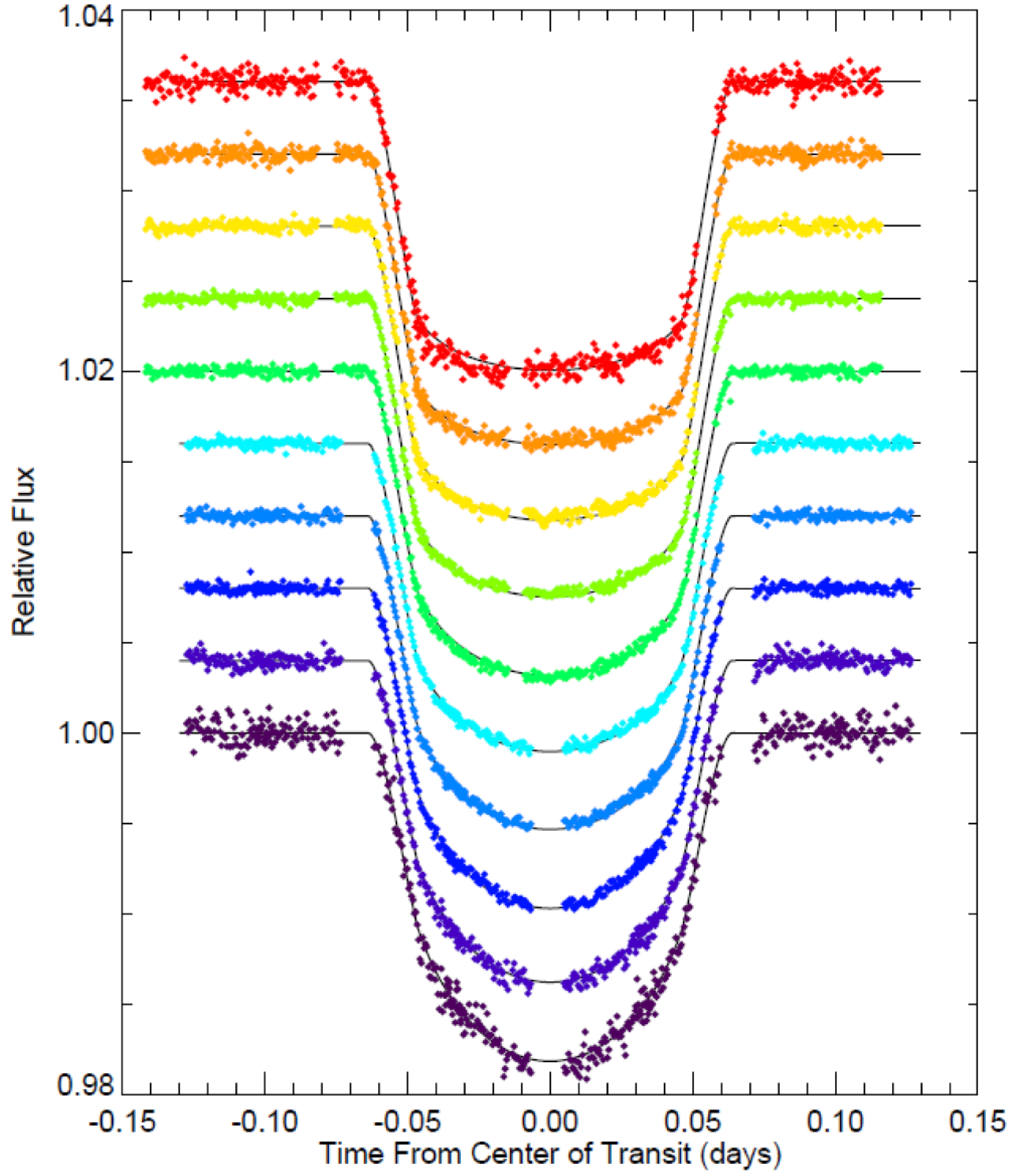
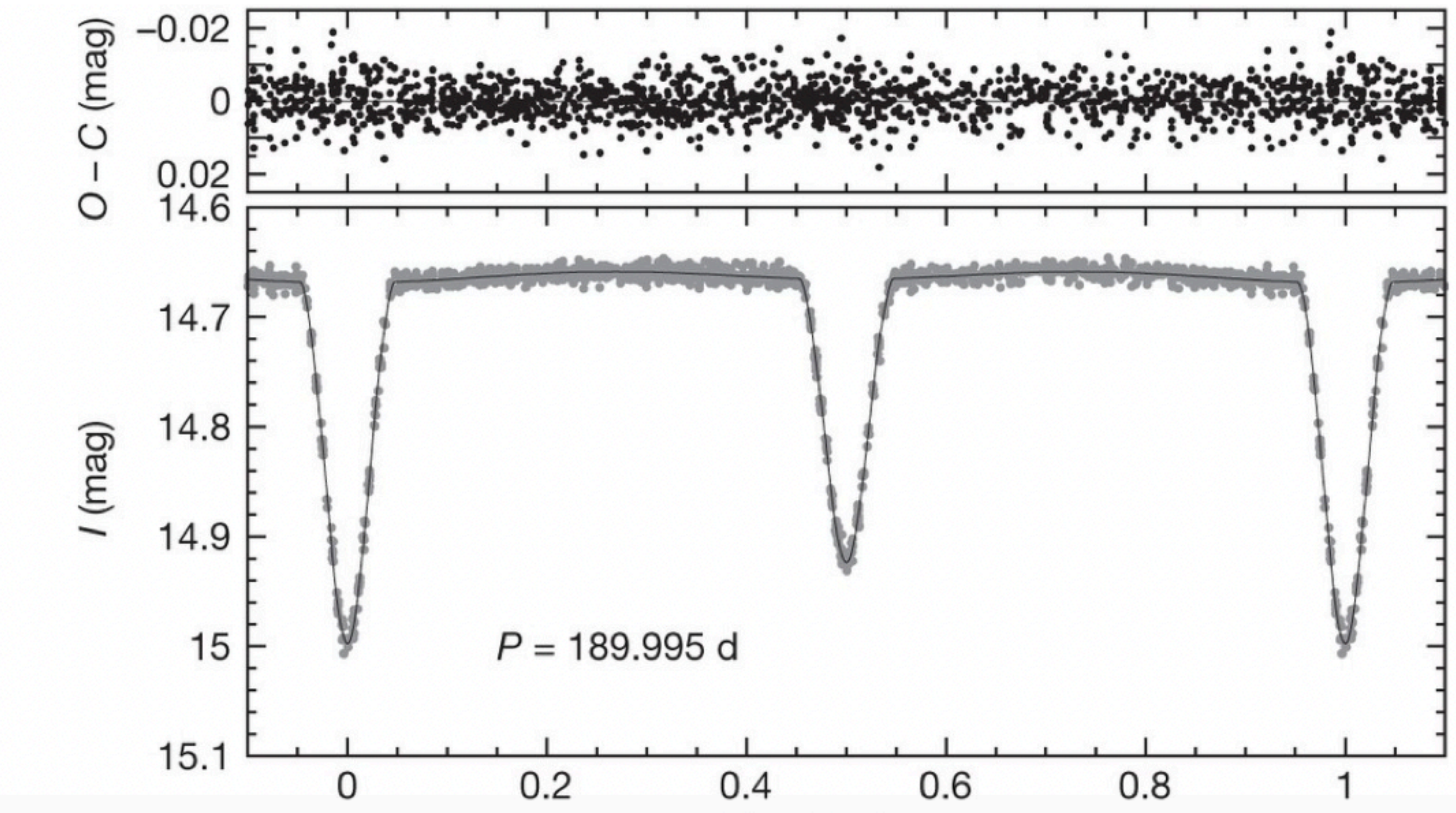
Eclipses

Constraining limb darkening!

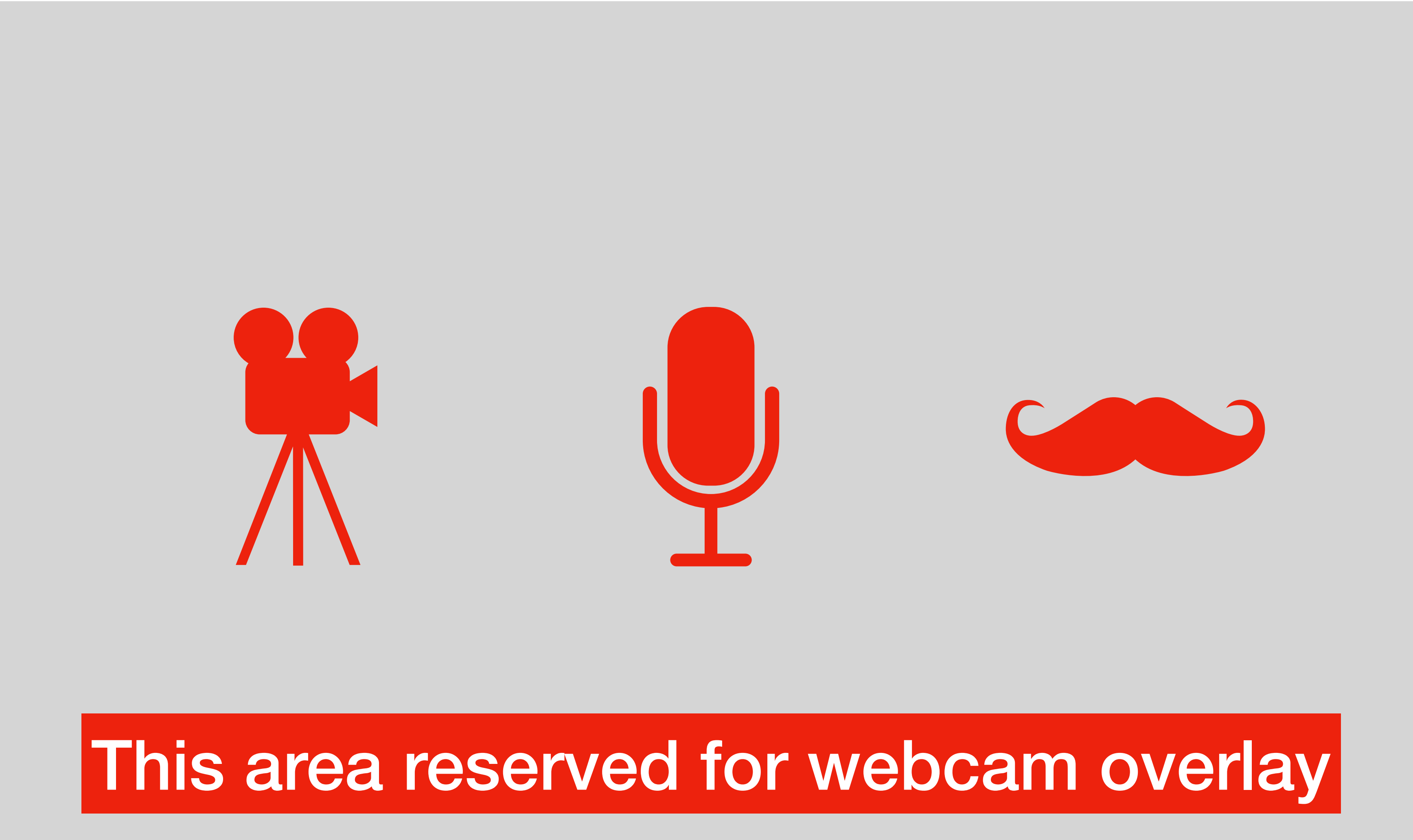


Knutsen+2007



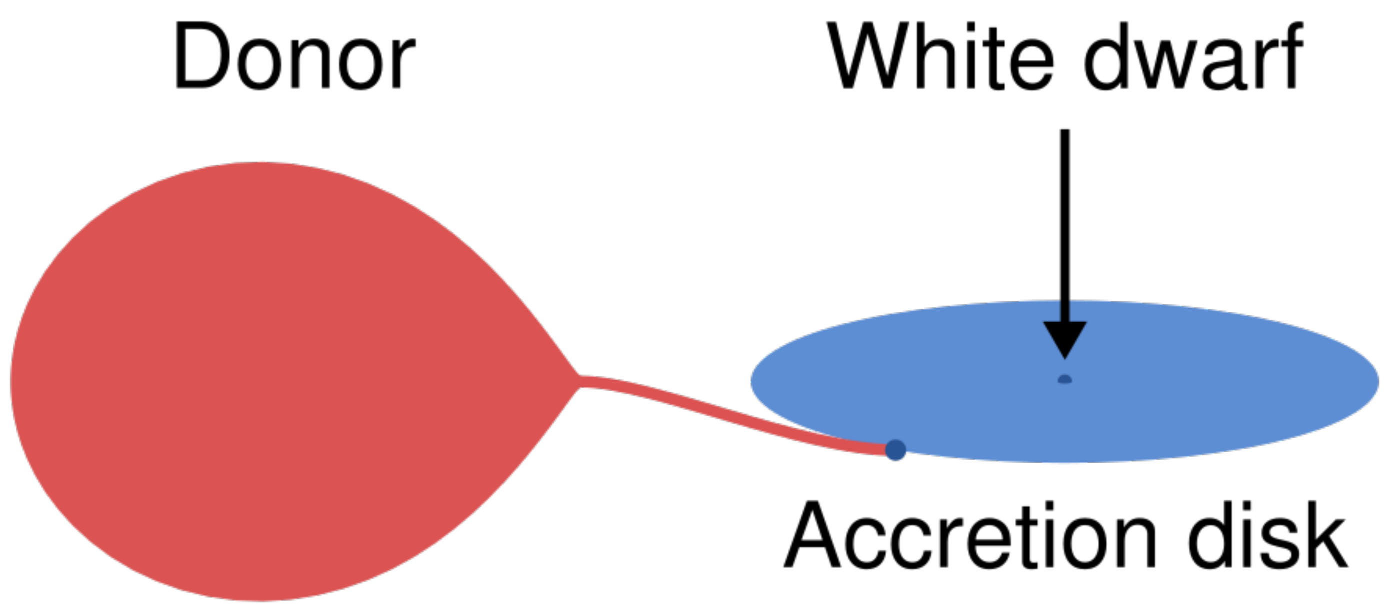
Orbital Phase

Pietrzyński et al. (2013)



Other Binaries

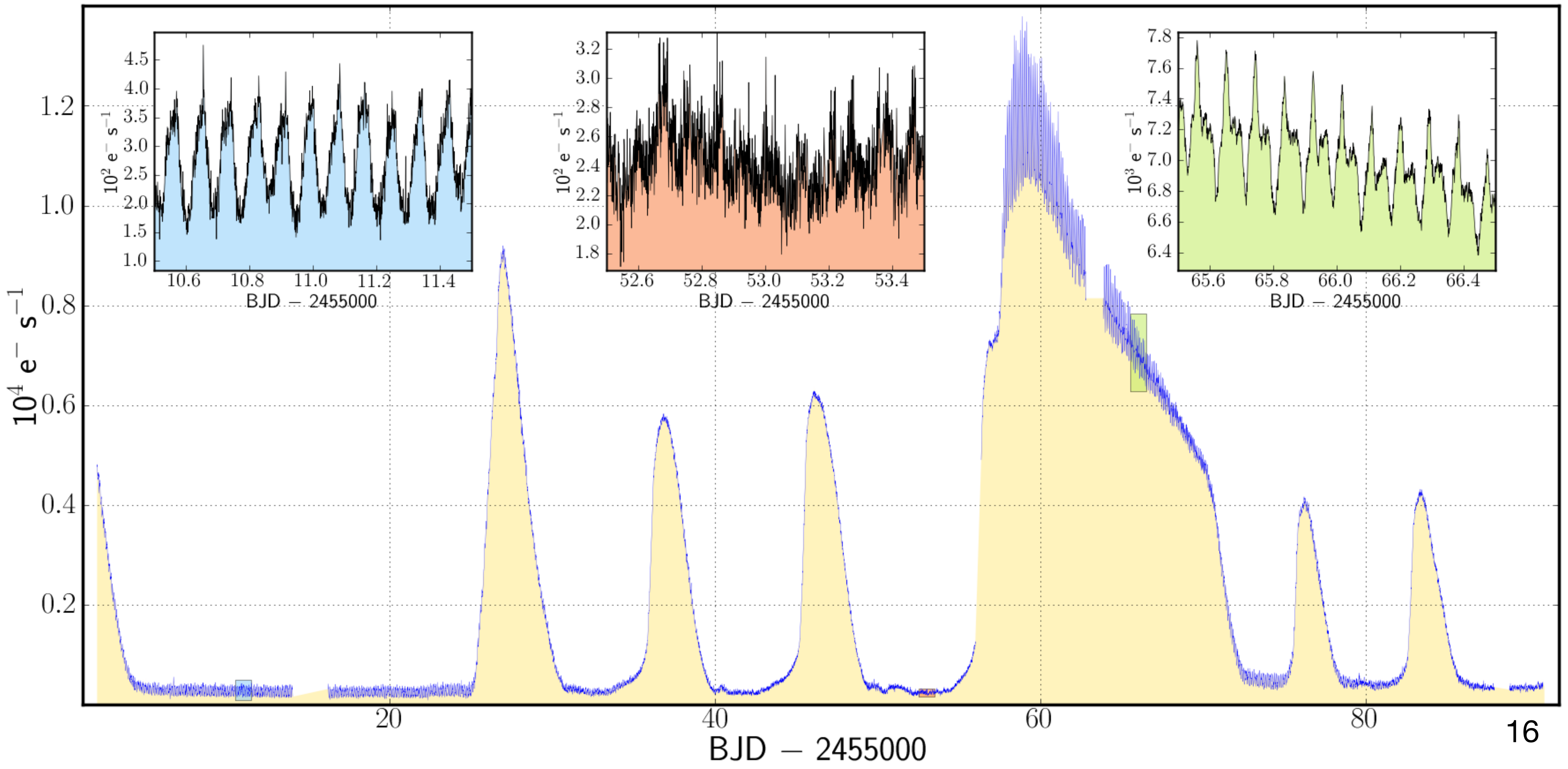
https://commons.wikimedia.org/wiki/File:Cataclysmic_variable.svg



- Many kinds of binary star systems…
  (we could teach a whole course on binary stars!)

- One noteworthy example: **Cataclysmic Variables** (CVs)

- Highly variable due to accretion, including enormous & sometimes repeating outbursts (dwarf novae)



V344 Lyr

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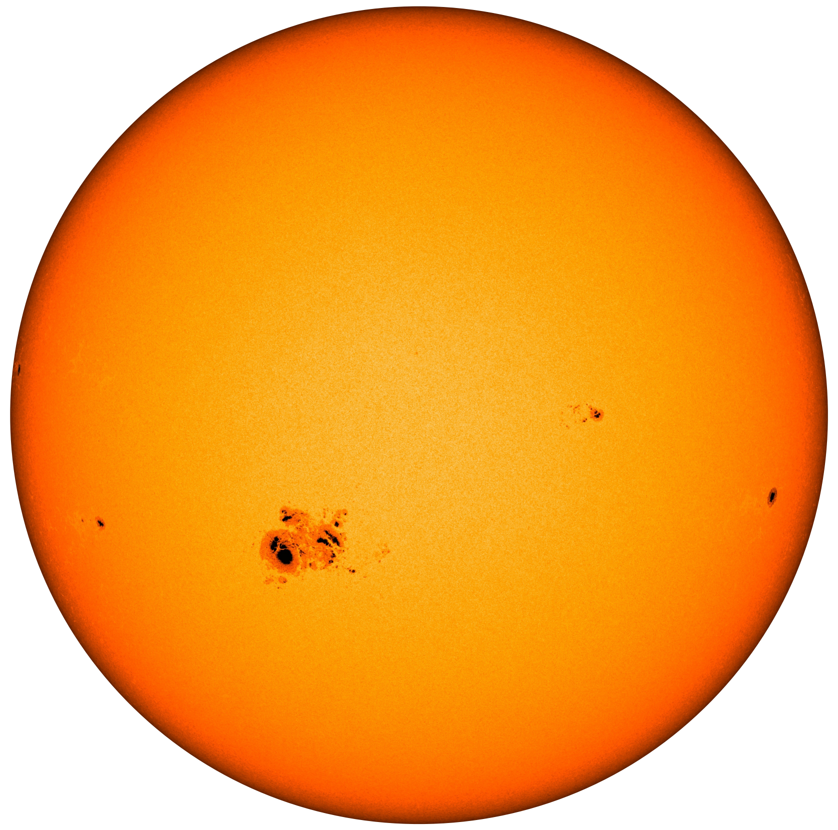
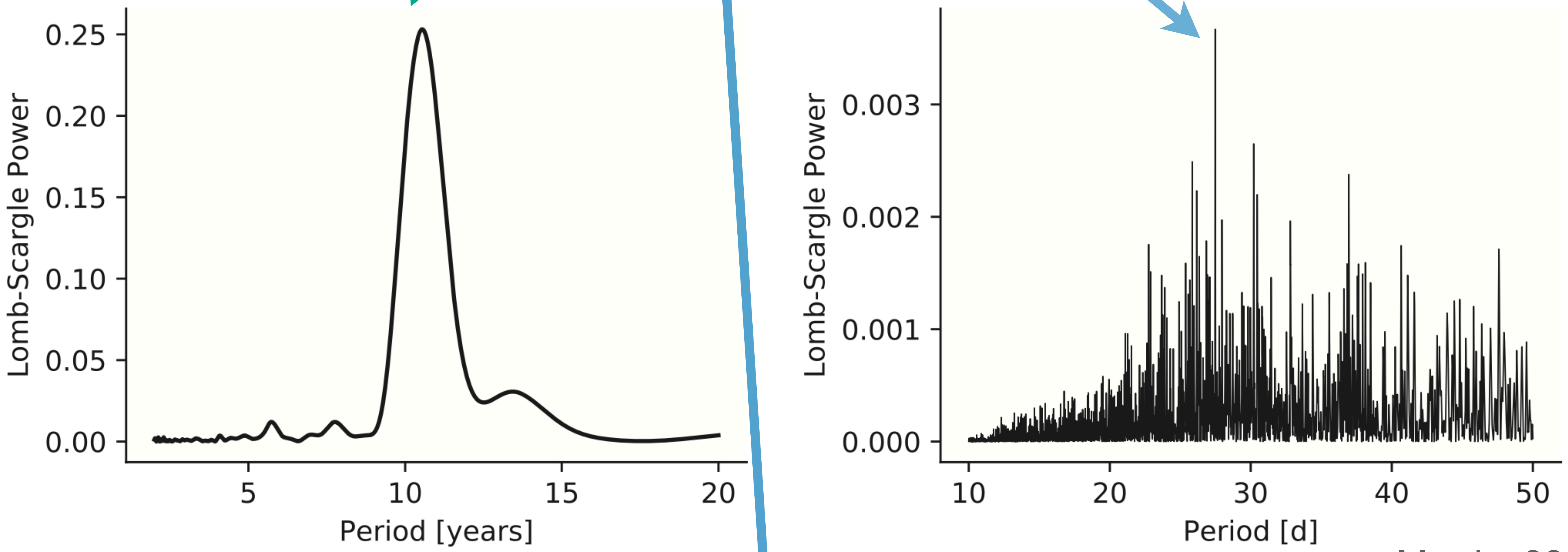
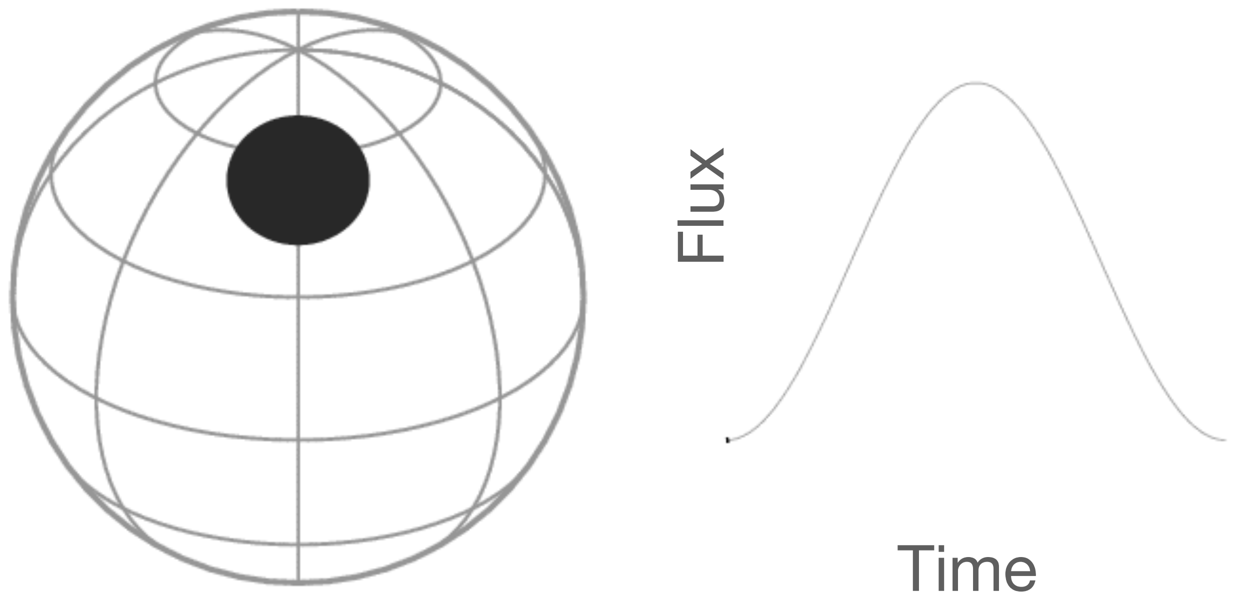
Magnetic Activity

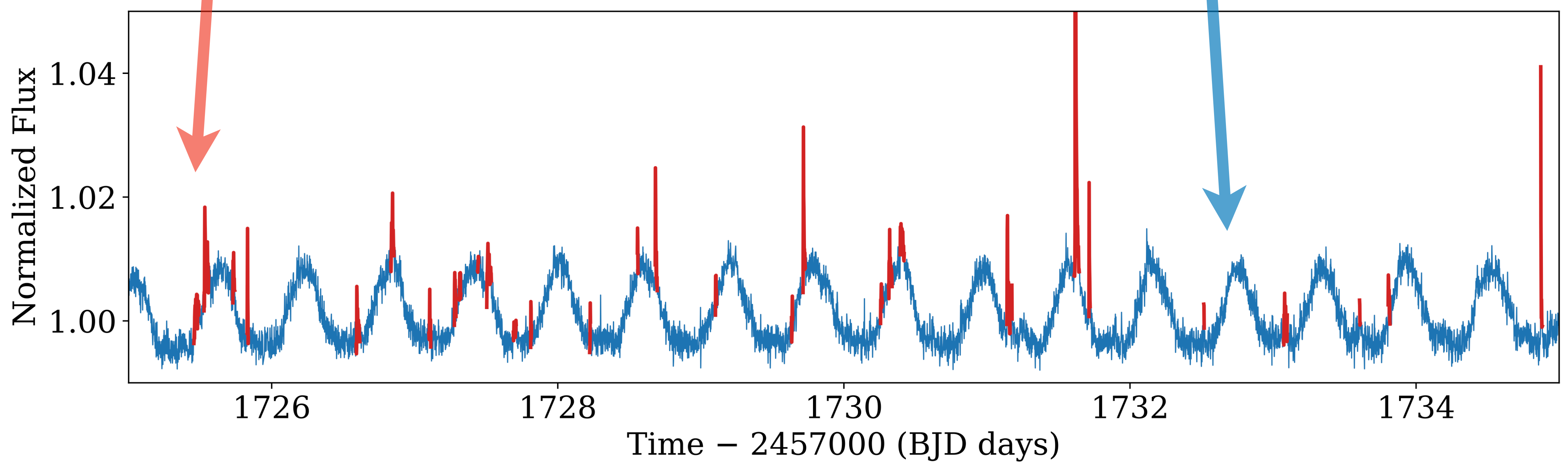


- Flares (minutes-hours), spots (days-weeks), faculae (weeks), activity cycles (years)



Morris+2019





Davenport+2020

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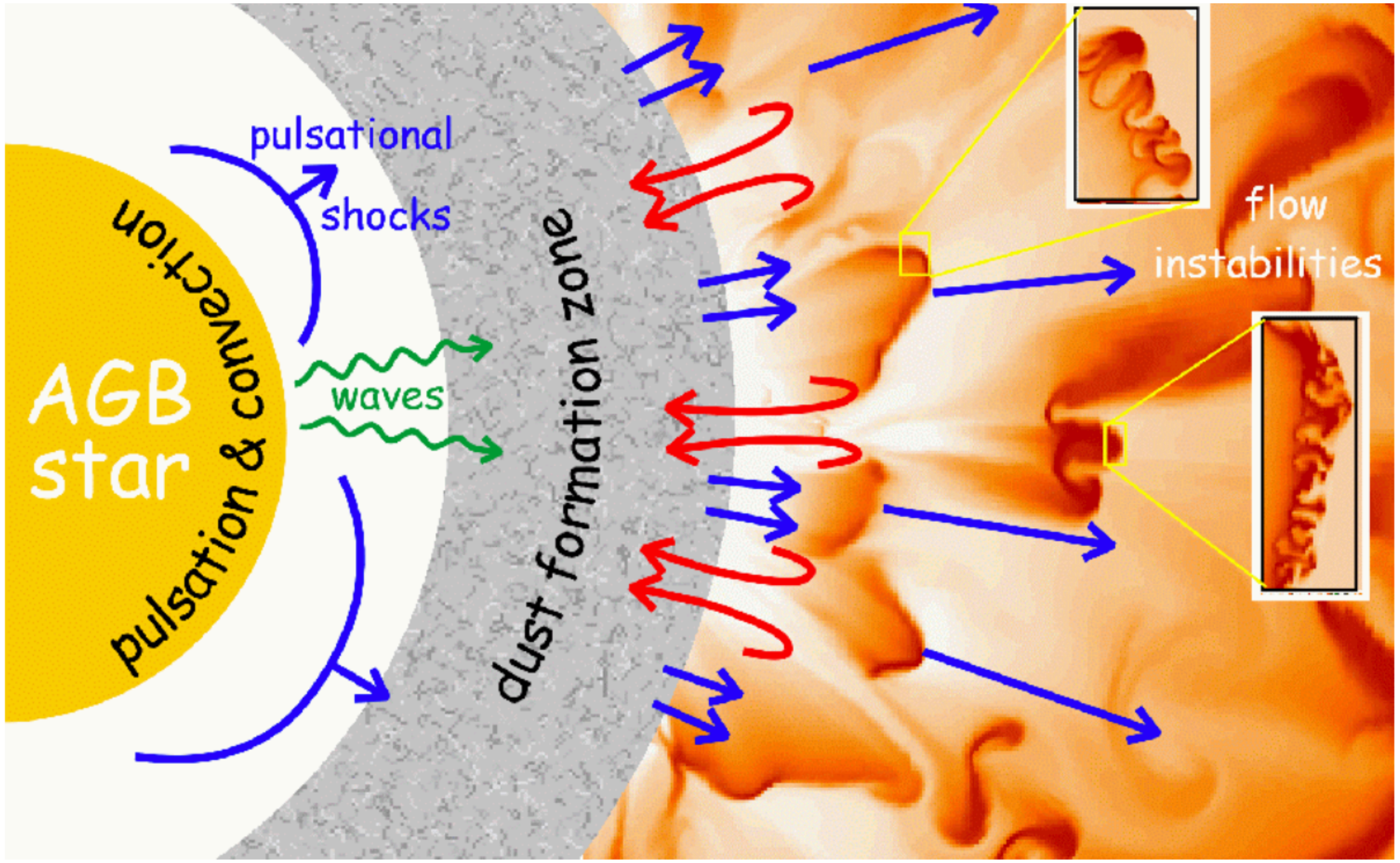
From Lecture 06

Opacity driven dust formation (e.g. AGB stars)

At *very* large radius, material cools, forms dust.

Dust has VERY high opacity, blocks light from star well.

Radiation pressure ejects dust!

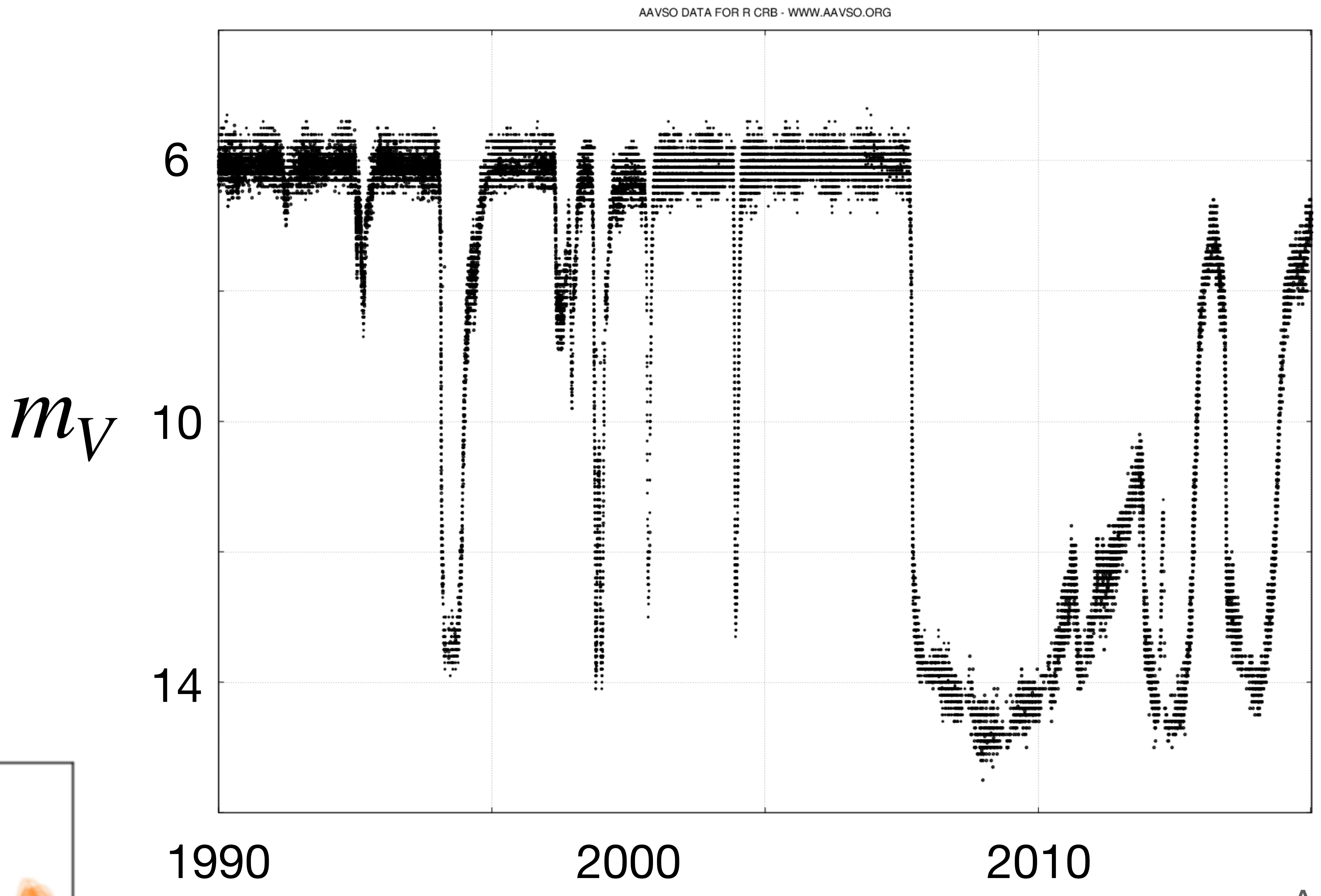


http://www-star.st-and.ac.uk/~pw31/AGB_popular.html

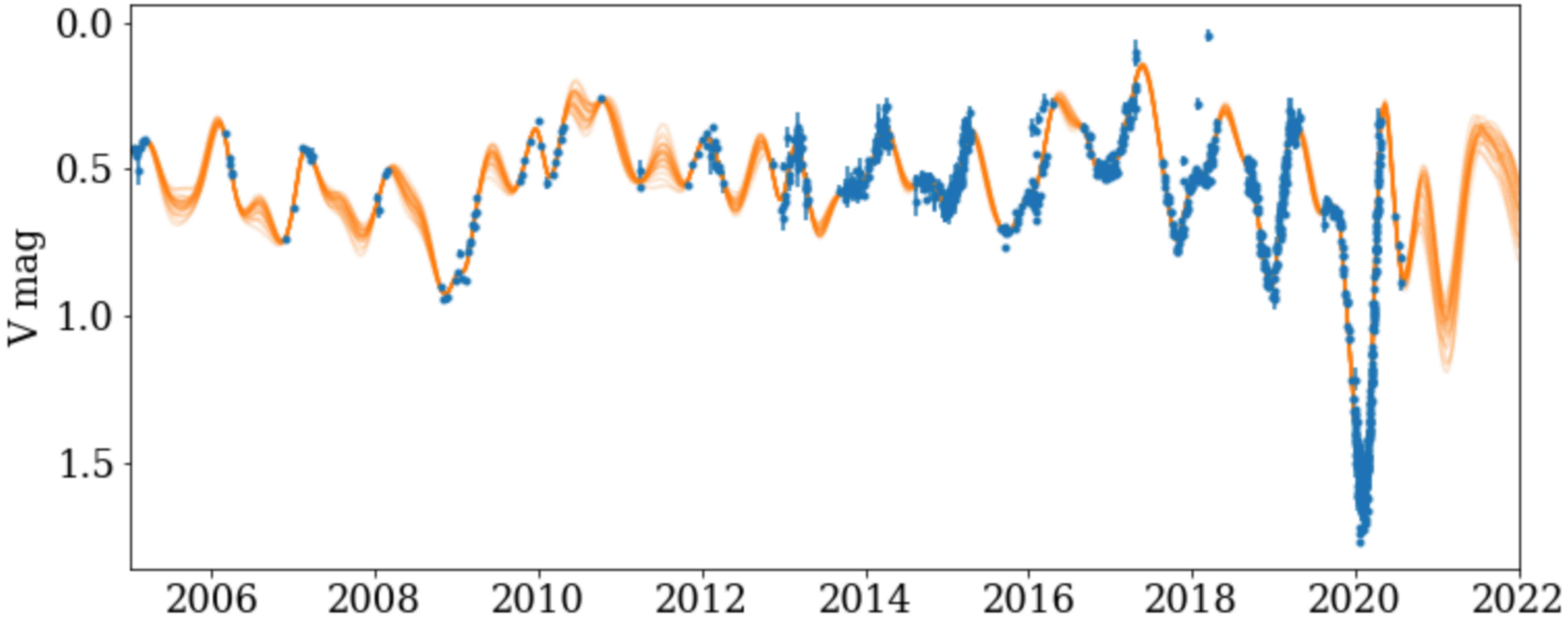
Dust Formation

- The most dramatic of these:
  R Coronae Borealis (R CrB)

- Also very famous: Betelgeuse (α Ori)



AAVSO



https://github.com/jradavenport/betelgeuse

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Part II

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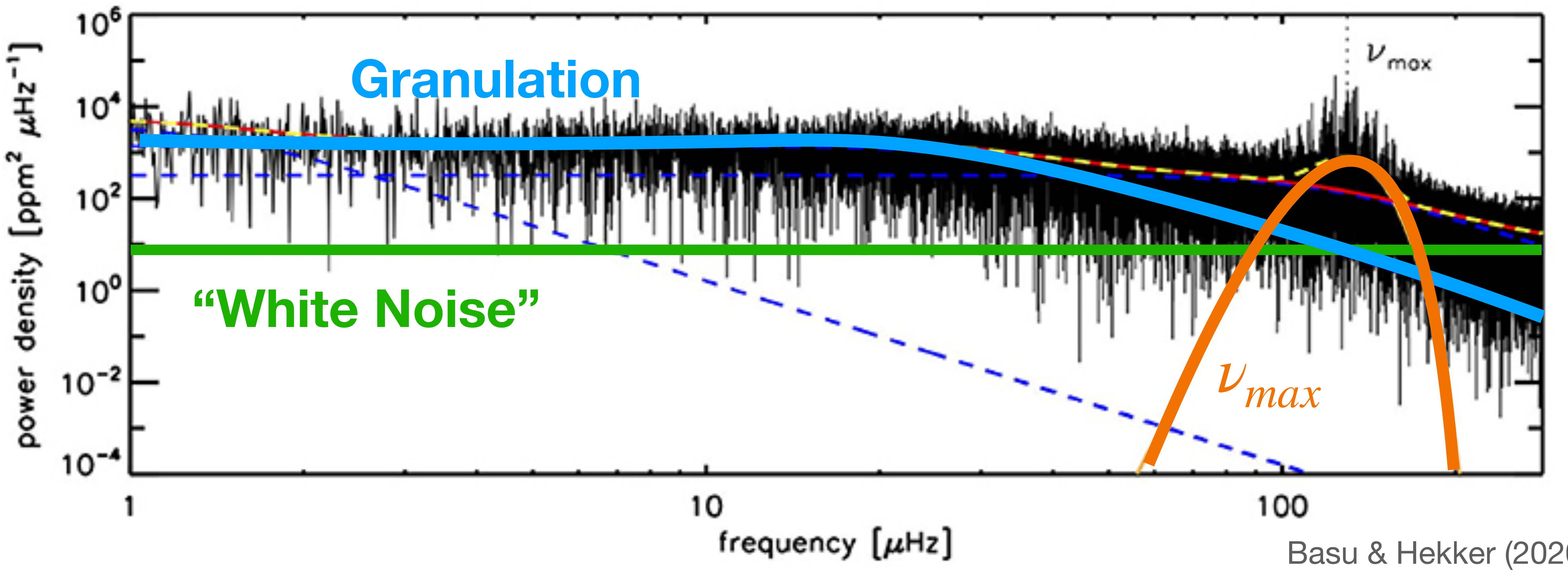
Pulsation

- **Asteroseismology**
- Based on <u>solar-scaling</u>

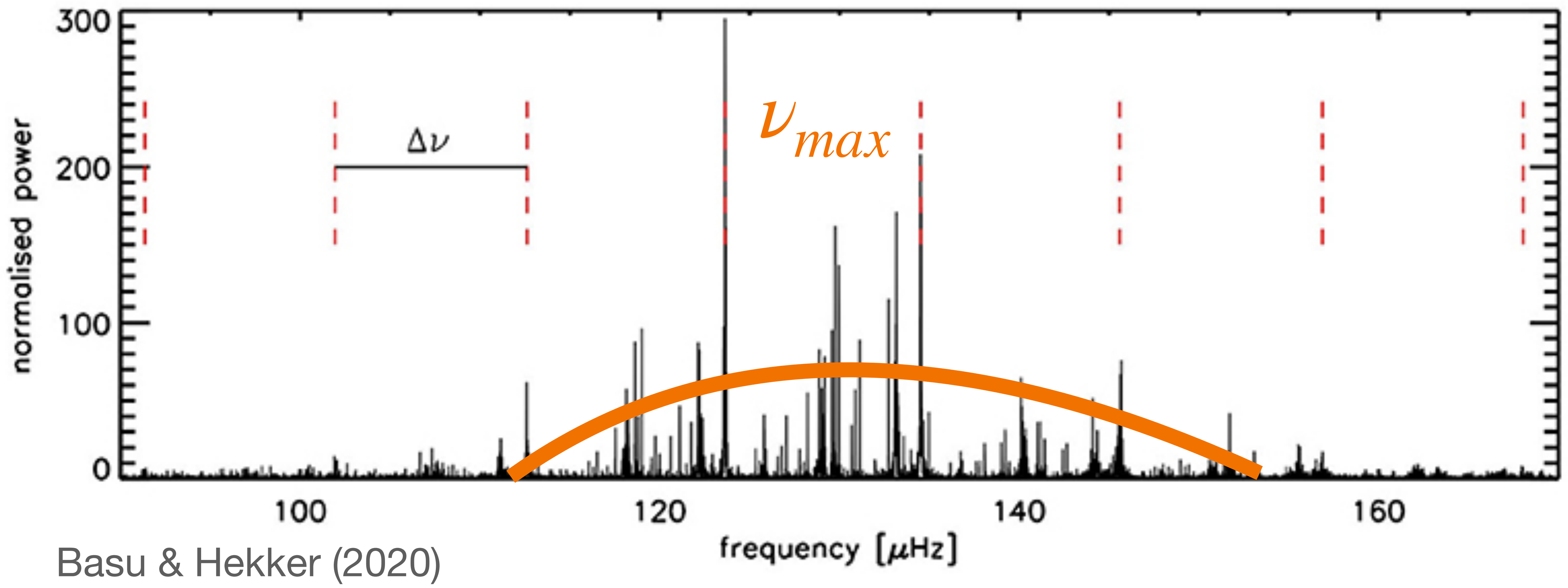
Ulrich 1986, Brown+1991



Basu & Hekker (2020)

$$\left(\frac{\langle\Delta\nu\rangle}{\langle\Delta\nu_\odot\rangle}\right)^2 \propto \frac{\bar{\rho}}{\bar{\rho}_\odot}$$

$$\frac{\nu_{max}}{\nu_{max,\odot}} \propto \frac{M}{M_\odot}\left(\frac{R}{R_\odot}\right)^{-2}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{-1/2}$$



Basu & Hekker (2020)

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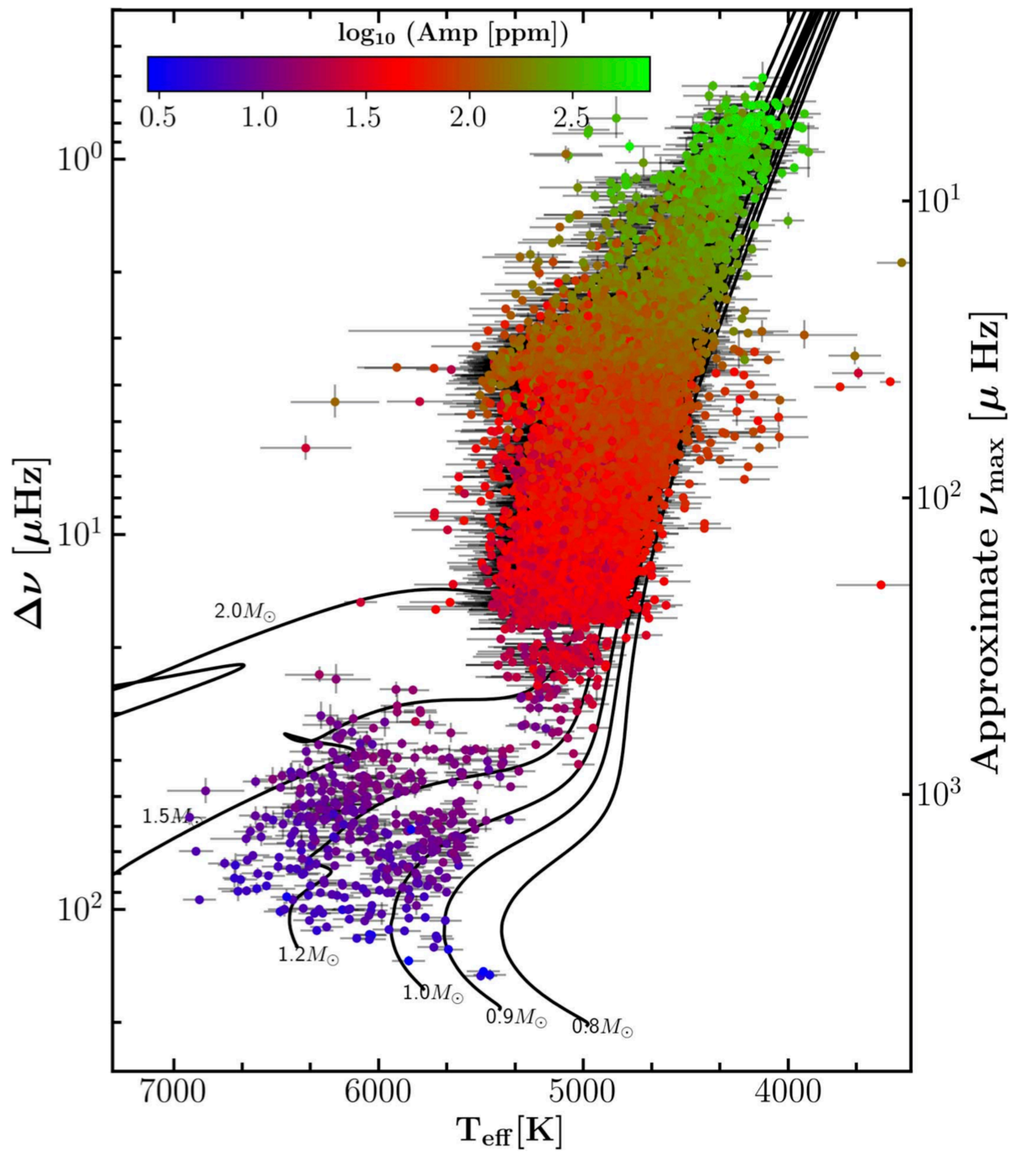
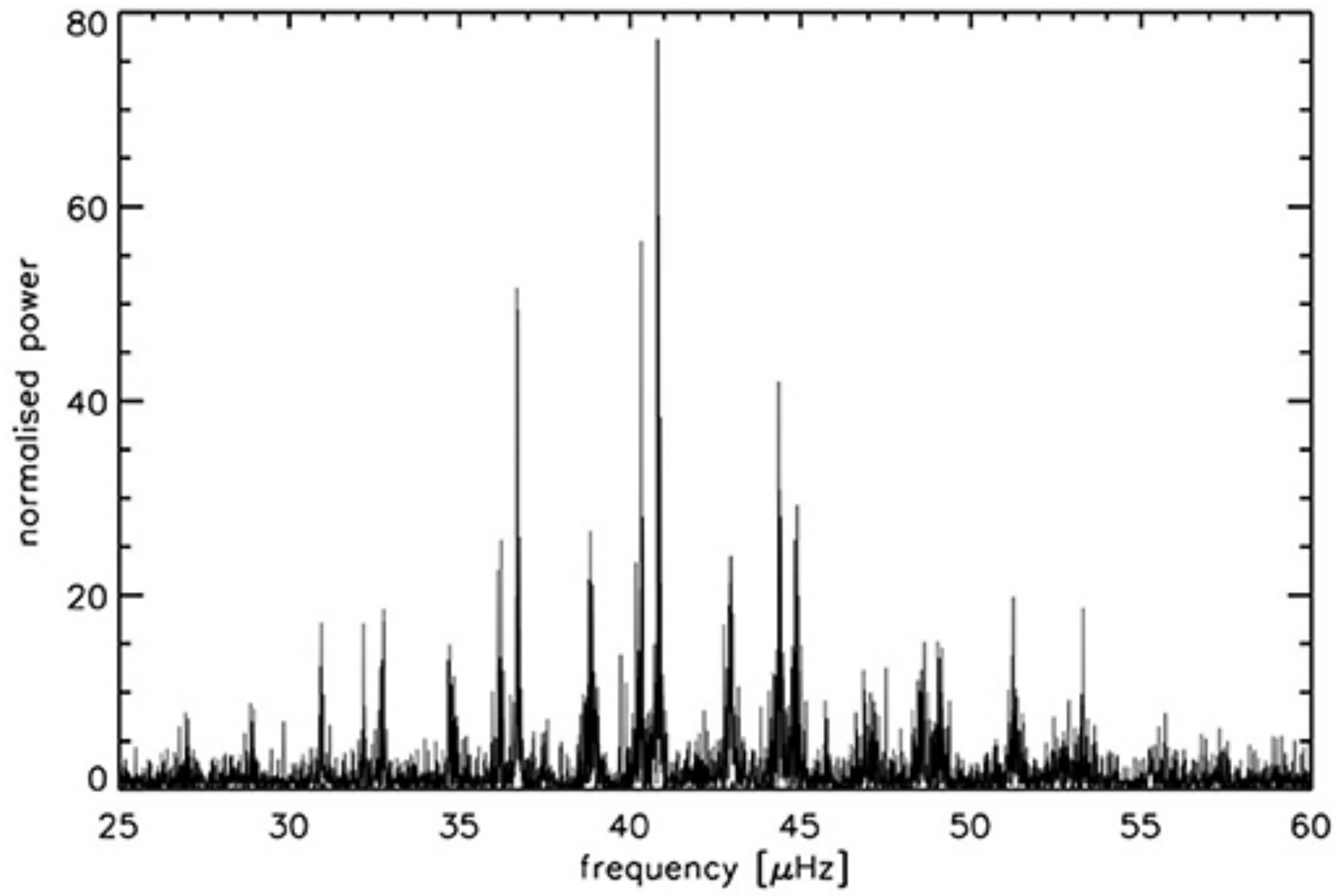
Pulsation

- **Asteroseismology**
- VERY useful for estimating properties of giant stars
- If you combine w/ [Fe/H] & better models (isochrones), can estimate *age*!

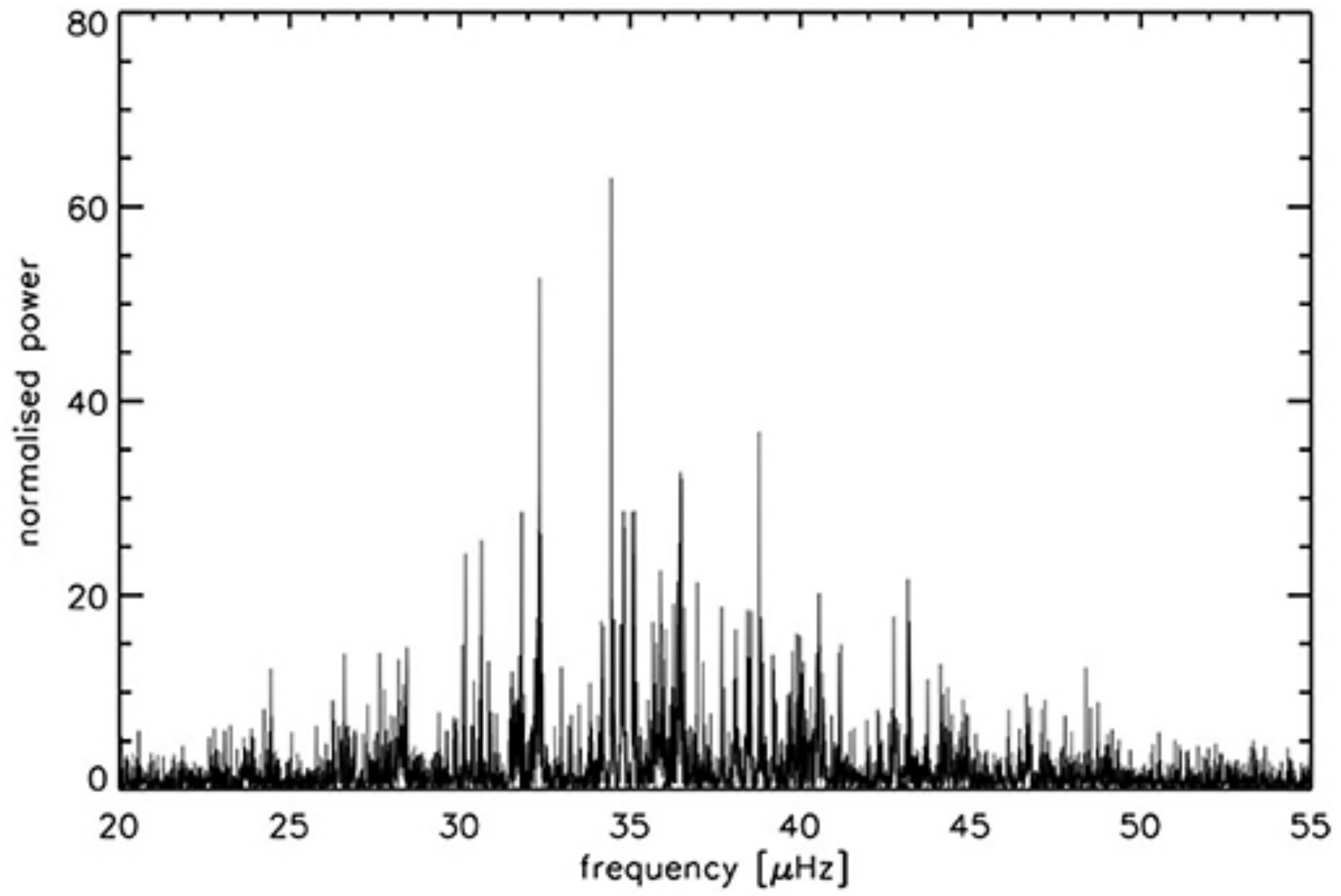
Yu+2018



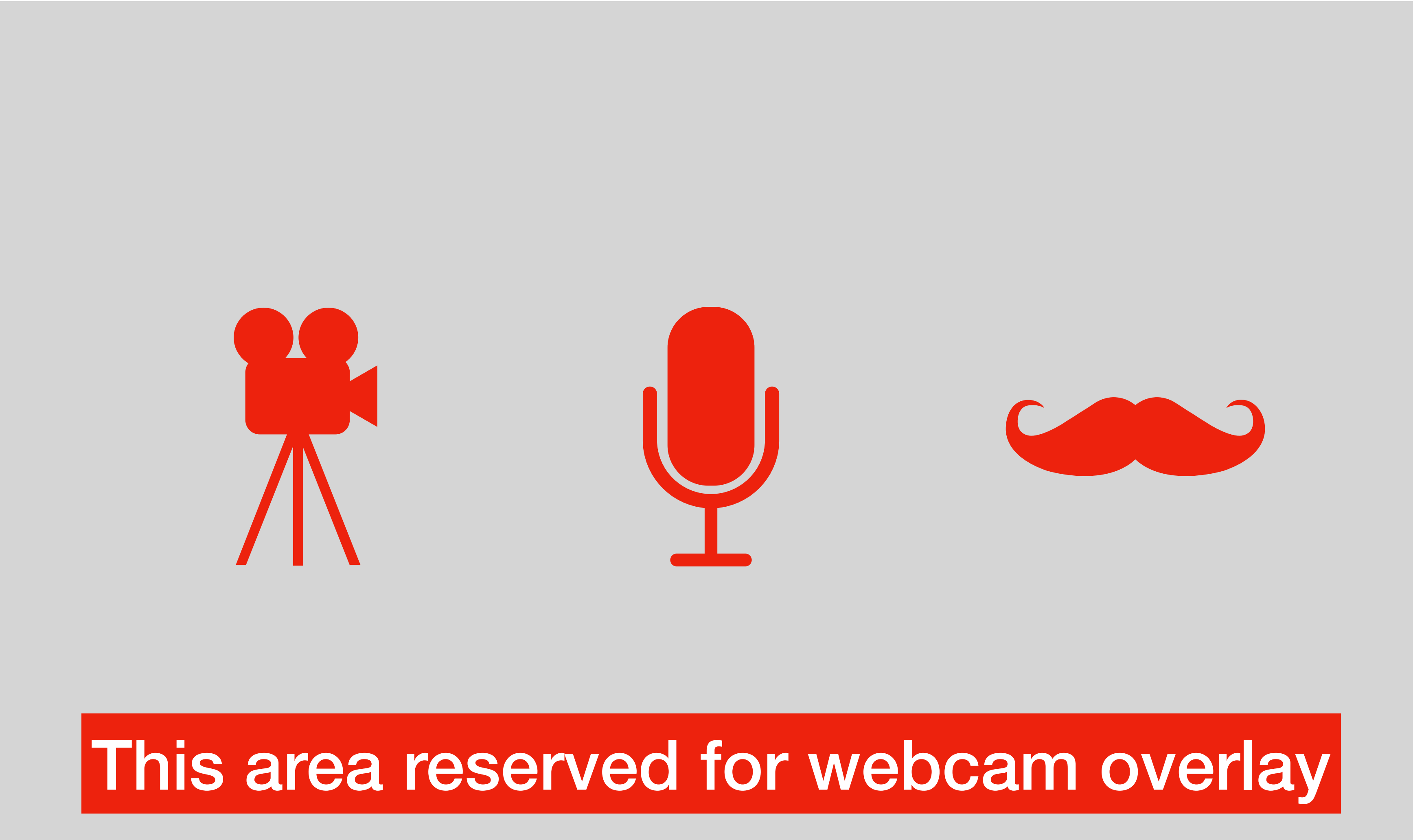
RGB



"Red Clump"
aka horizontal branch stars



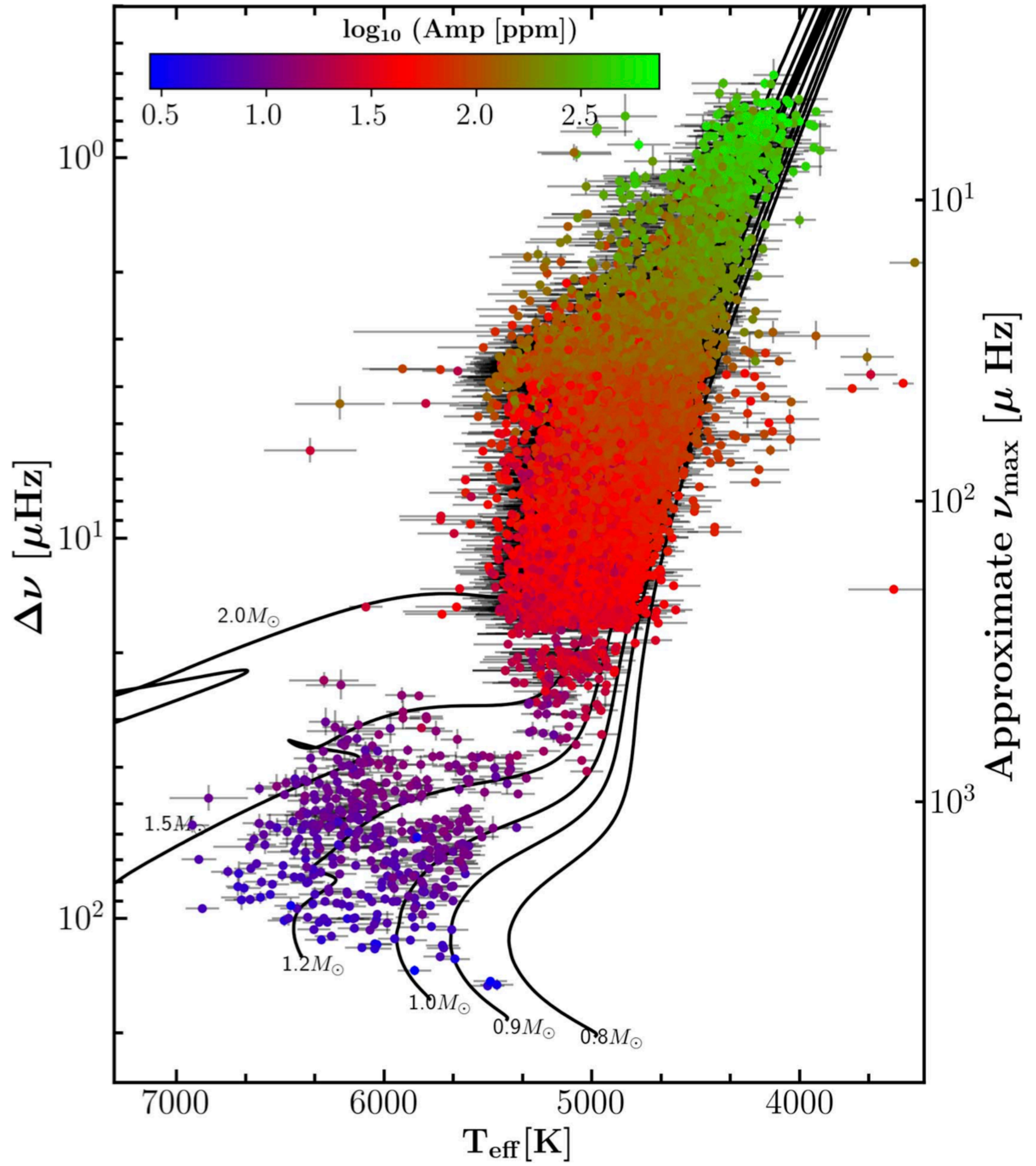
Basu & Hekker (2020)



Pulsation

- **Asteroseismology**
- Generally limited to giant stars… timescales & amplitudes for main sequence stars are *small!*

Yu+2018



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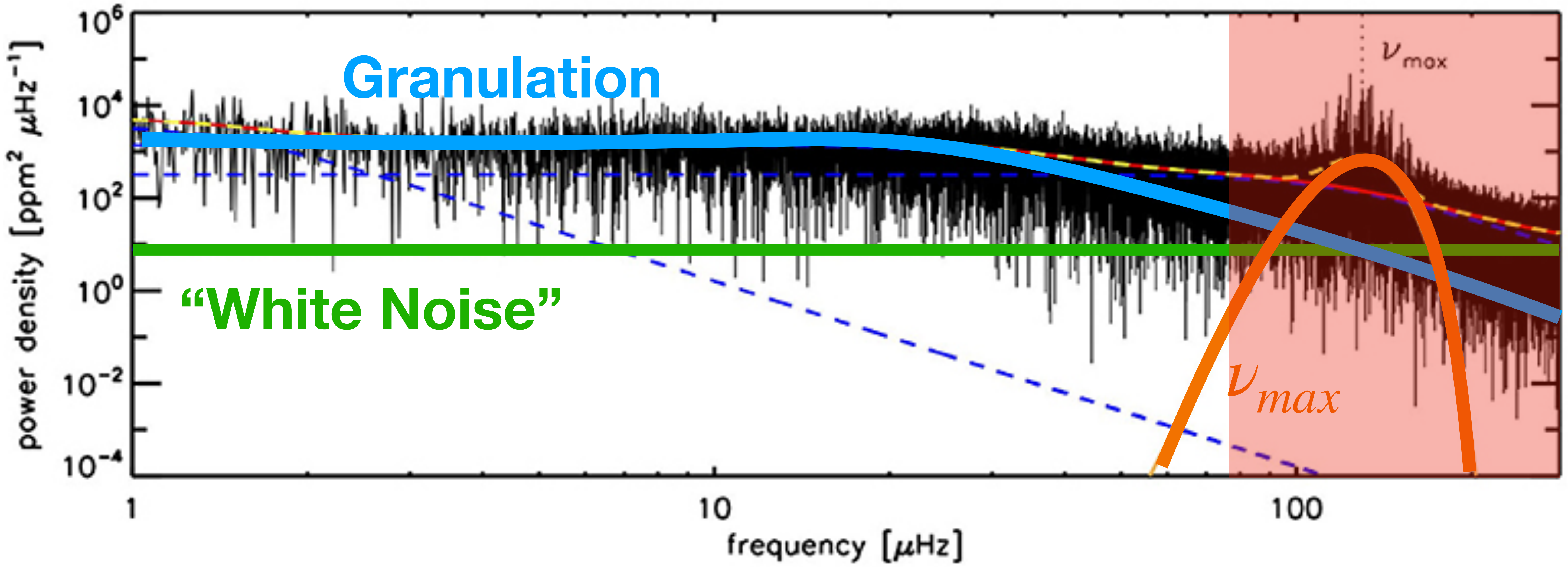
Basu & Hekker (2020)

Pulsation

- **Flicker**, Asteroseismology’s clever cousin!



Too fast or low amplitude for our data for dwarfs

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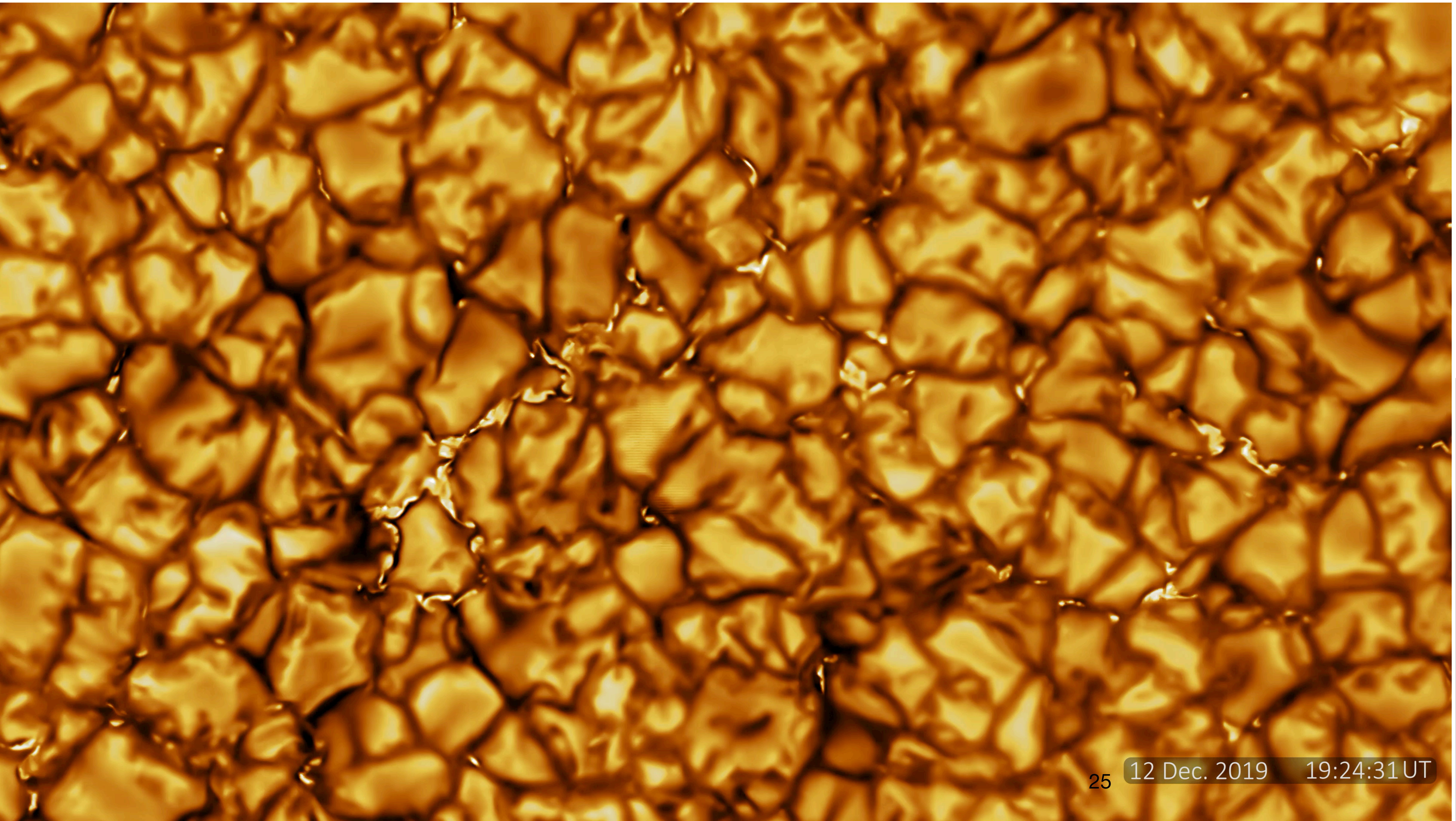
Pulsation

- **Flicker**, Asteroseismology’s clever cousin!

https://nso.edu/telescopes/dkist/first-light-cropped-field-movie/



Granulation

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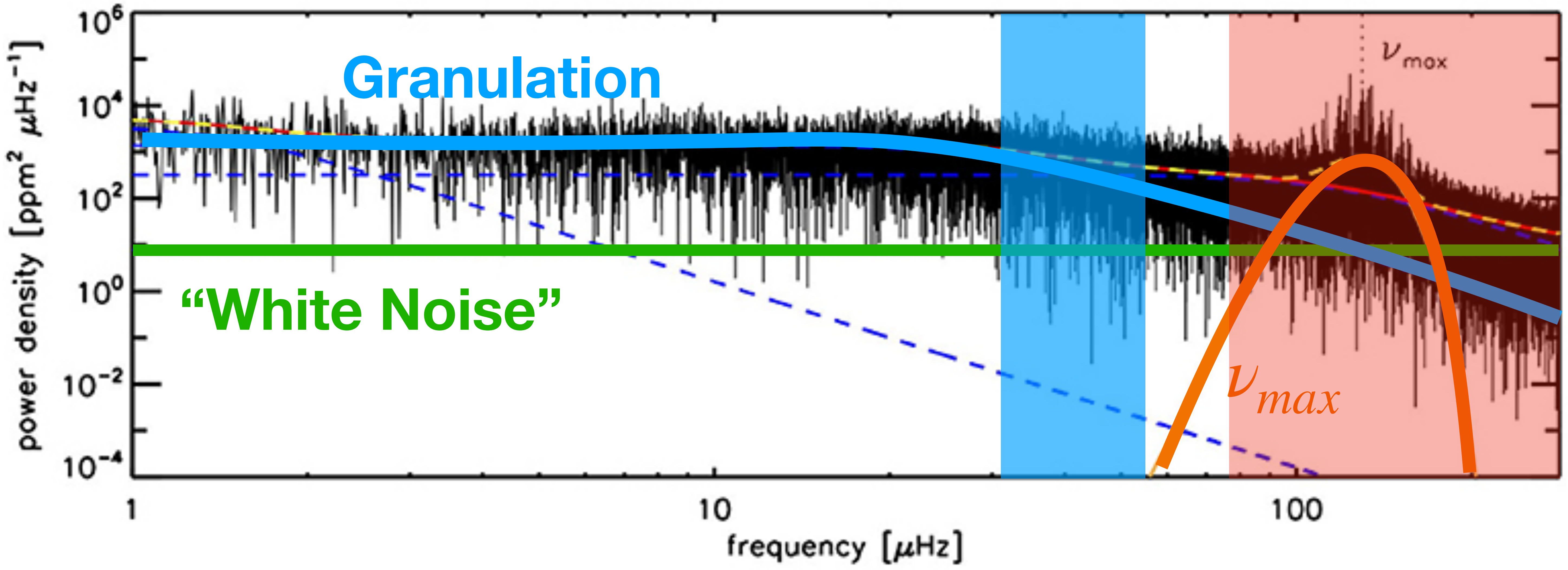
Pulsation

- **Flicker**, Asteroseismology's clever cousin!
- Instead of detailed $\Delta\nu$, ν_{max}, just measure **variability on 8-hr timescales** due to granulation



Too fast or low amplitude for our data for dwarfs

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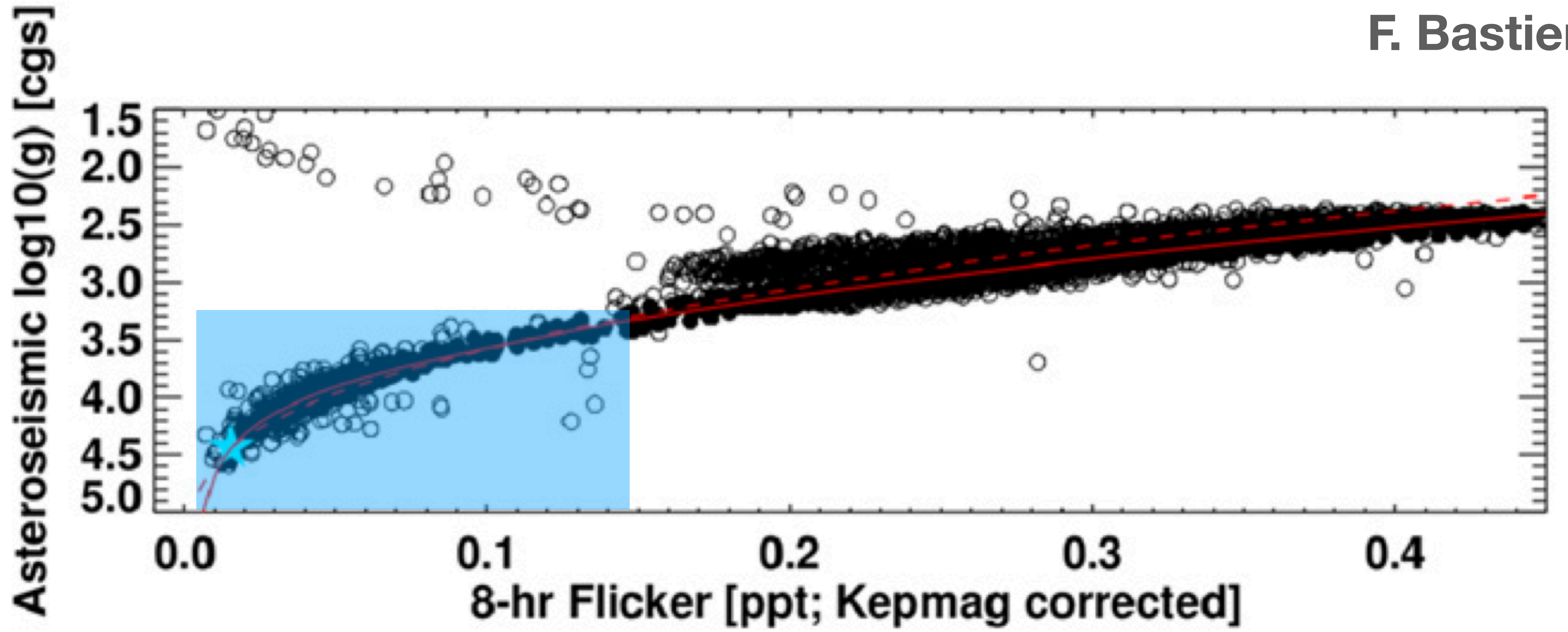
Pulsation

- **Flicker**, Asteroseismology's clever cousin!
- Instead of detailed $\Delta\nu$, ν_{max}, just measure **variability on 8-hr timescales** due to granulation

F. Bastien+2016



Works for main sequence stars!

See also recent review by Van Kooten+2021

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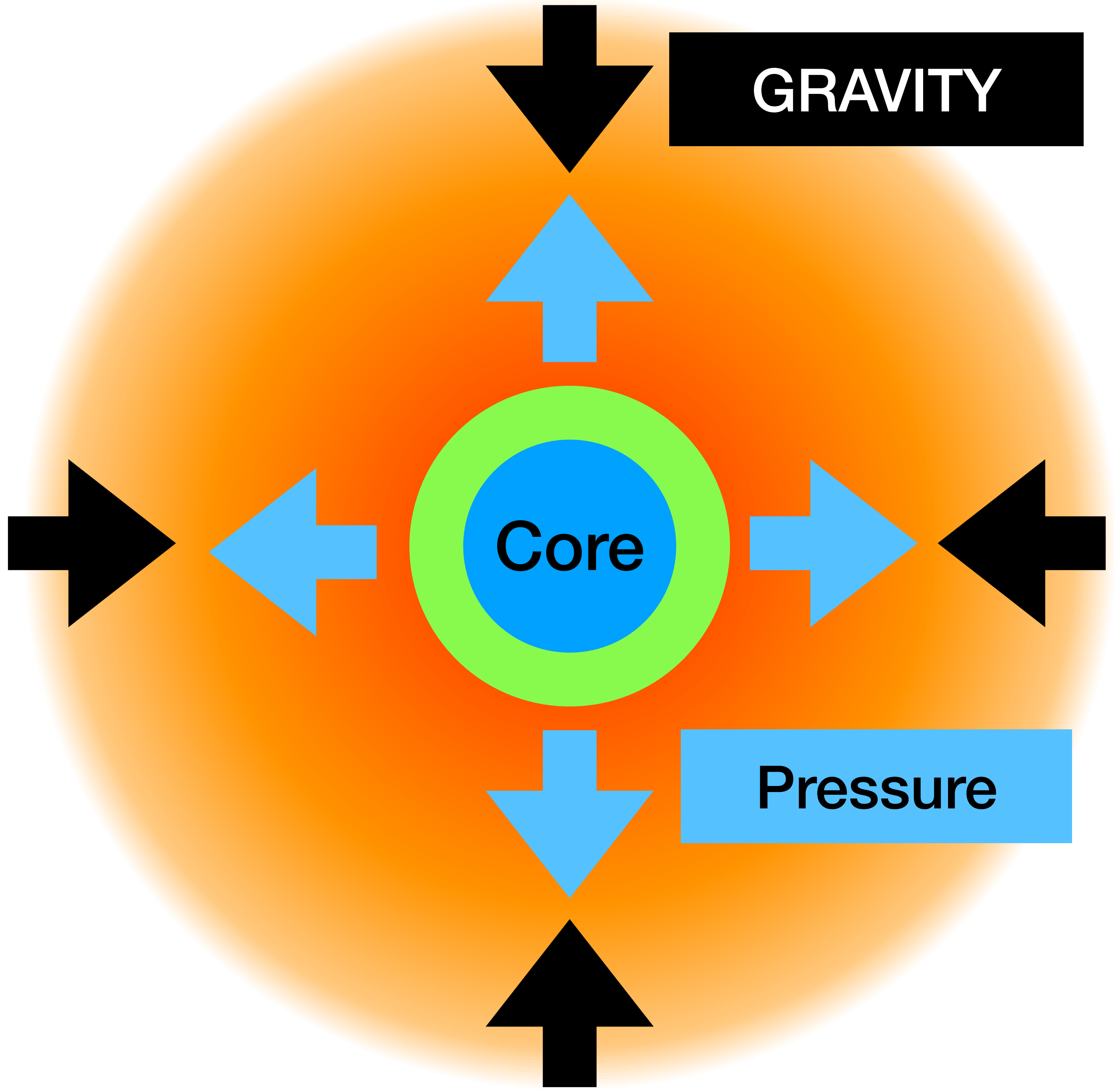
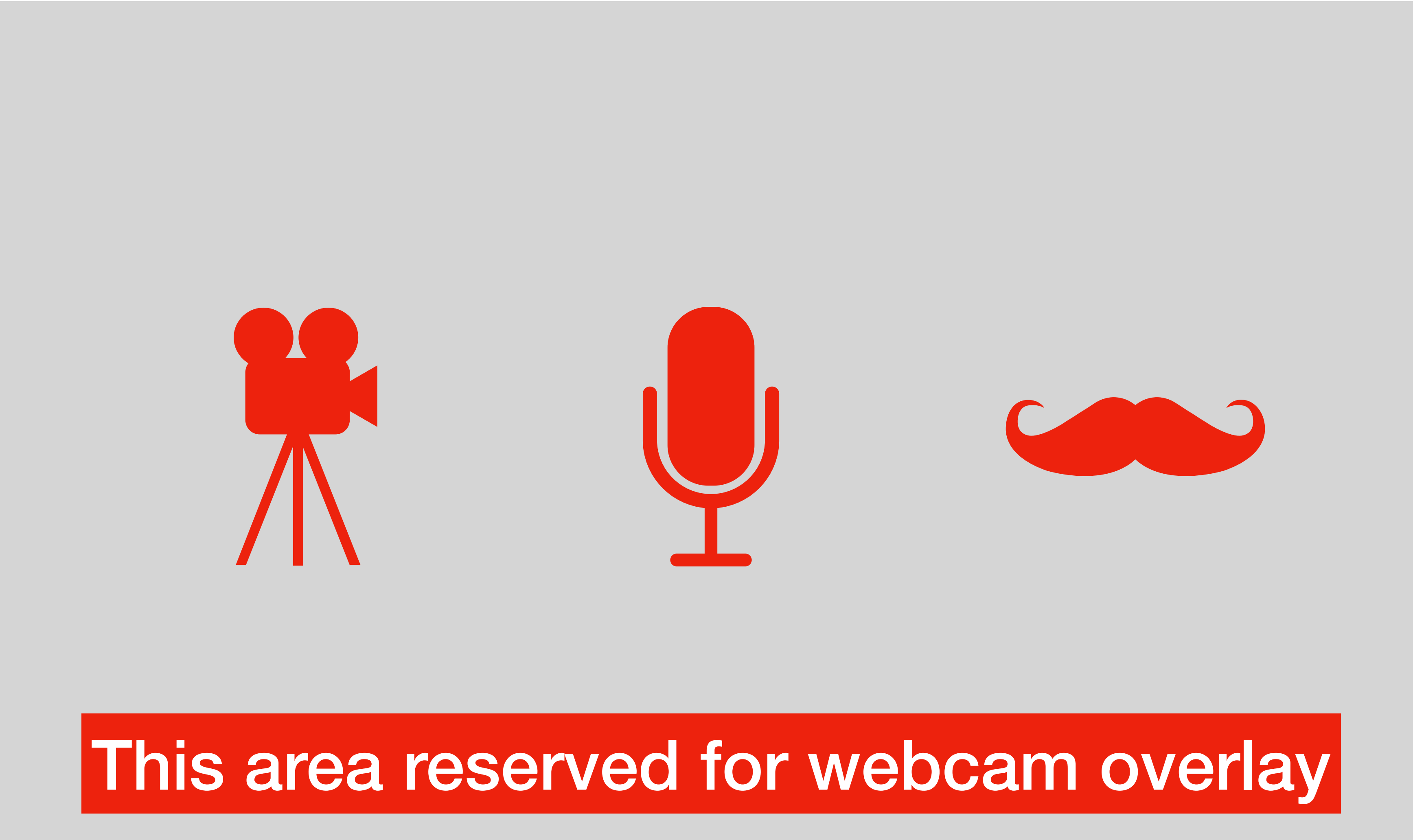
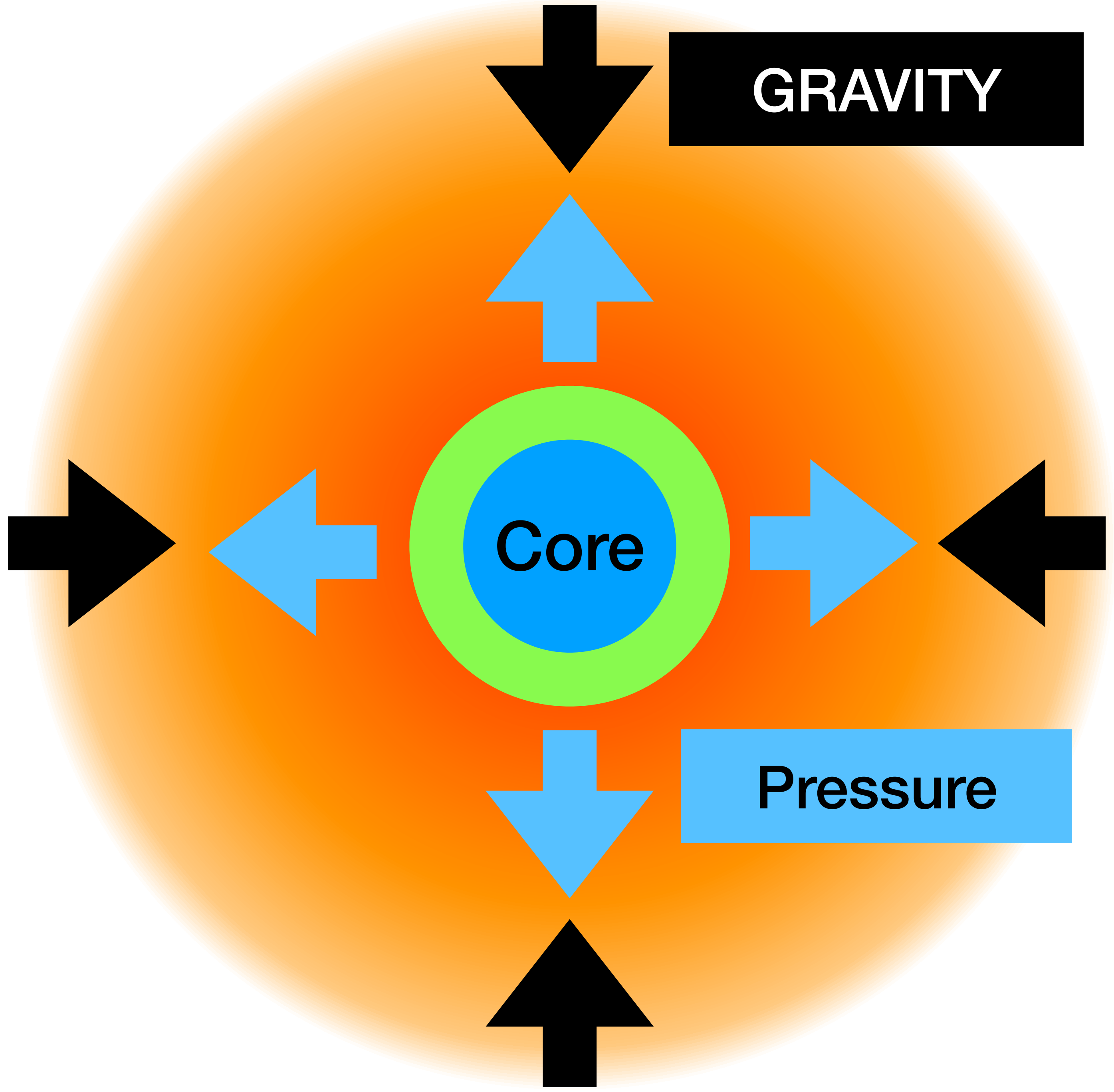
Pulsation

- **Radial Pulsators**
  - 3 *primary* types:
    RR Lyr, Cepheids (aka "δ Cep"), δ Scuti variables
  - Driven by the "Eddington Valve" (κ) mechanism, requiring deep H and He II ionization zones

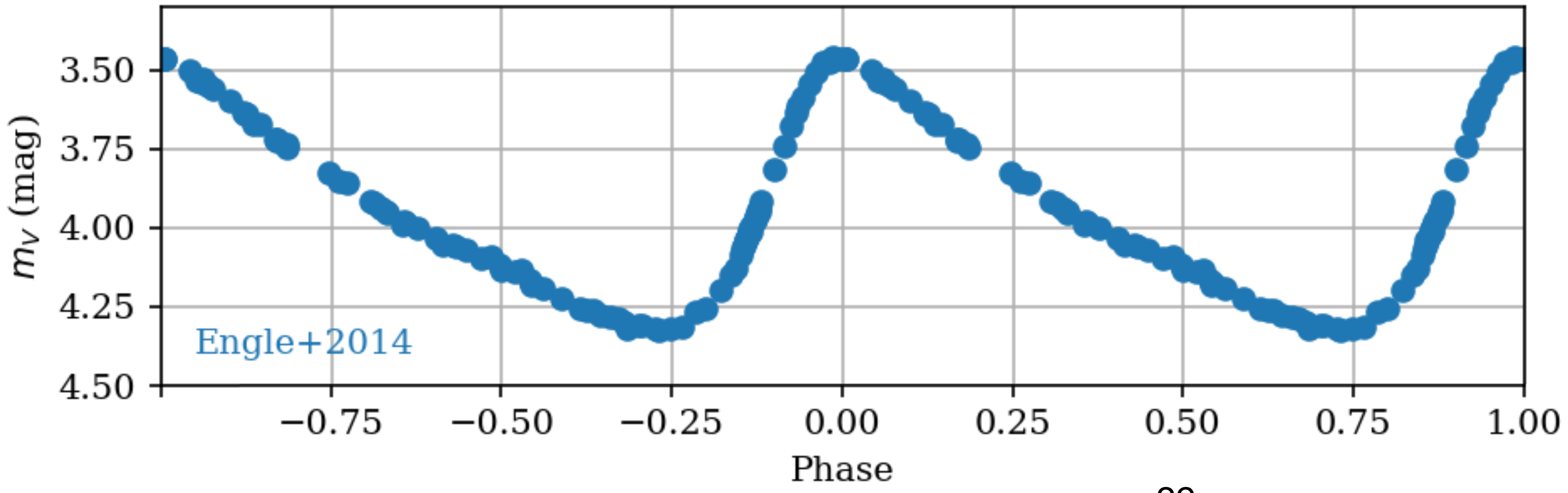


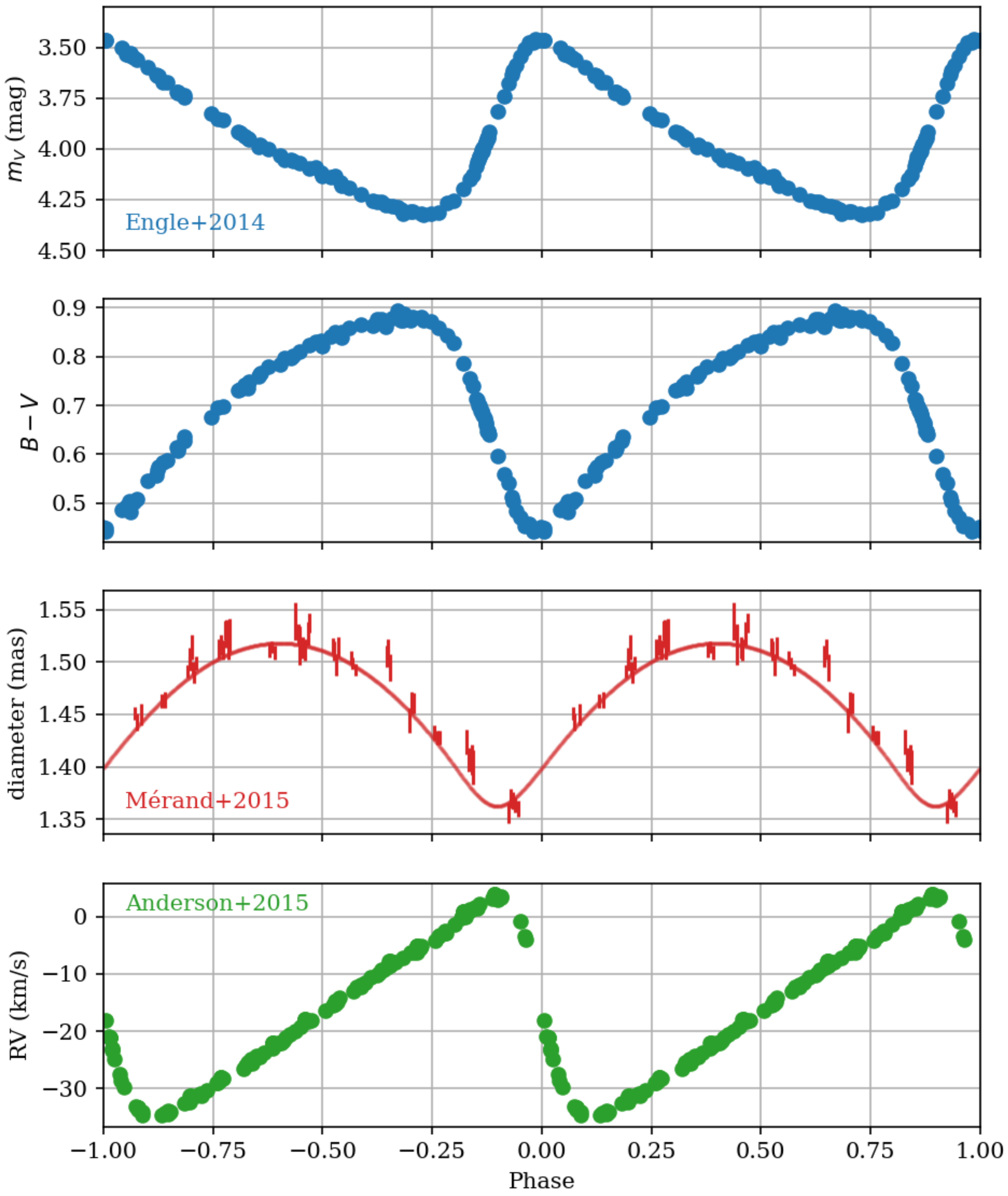


κ mechanism



- Opacity driven pulsation!
- Gas "falls" (gravity), density increases
- **Key oddity:** because of partial ionization, the Temp *doesn't increase as much as you expect,* so increased ρ leads to *increased opacity (κ)*
- This increases radiation pressure, as expected, moves ionization zones, surface expands…





κ mechanism

- The H ionization layer (above) lags the He II layer, resulting in a *phase* offset between peak brightness and minimum radius

See also BOB, Fig 14.7

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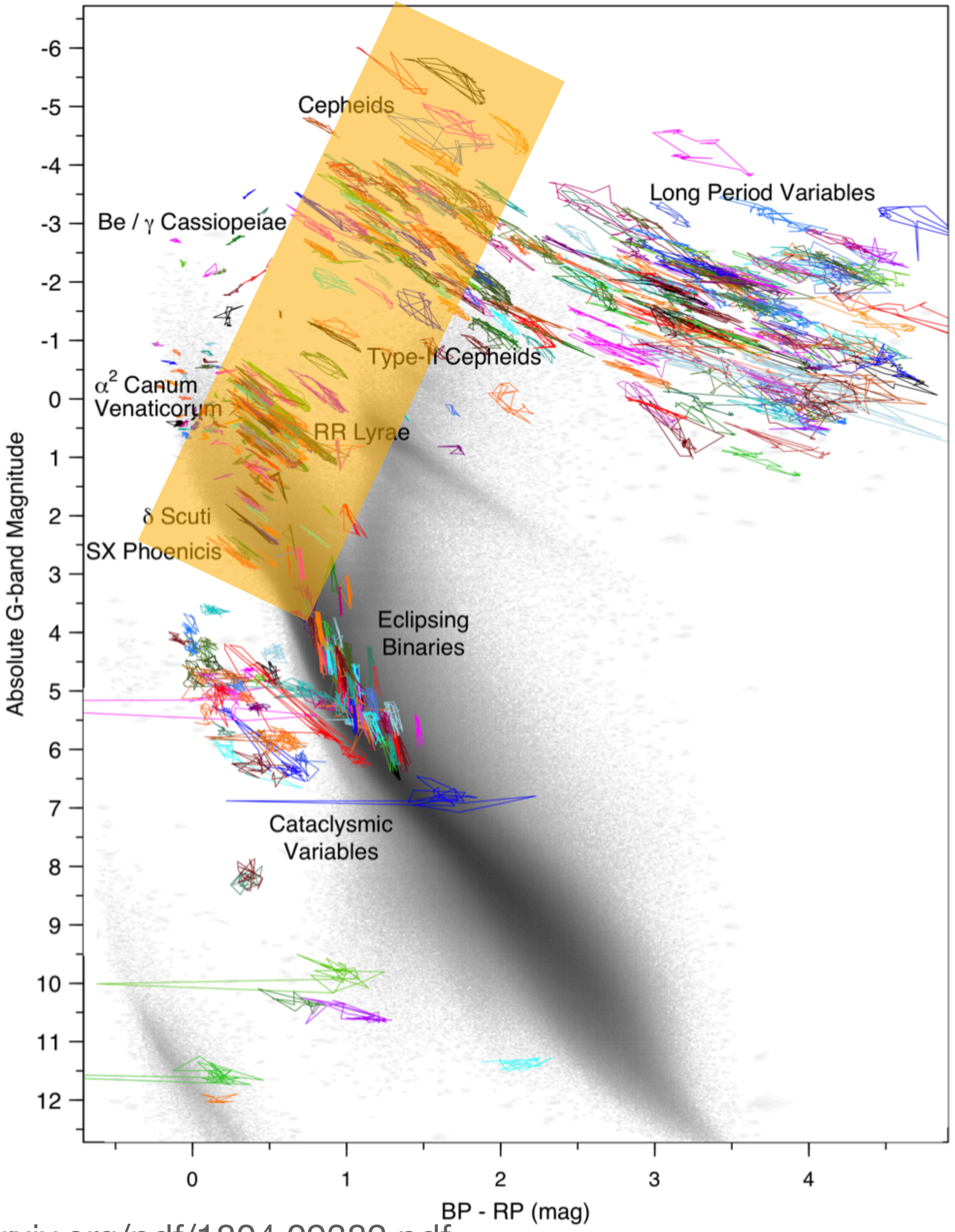
Pulsators on the CMD



https://arxiv.org/pdf/1804.09382.pdf

- The “instability strip”, the sweet spot where the He and H ionization layers are sufficiently strong and deep to drive pulsations

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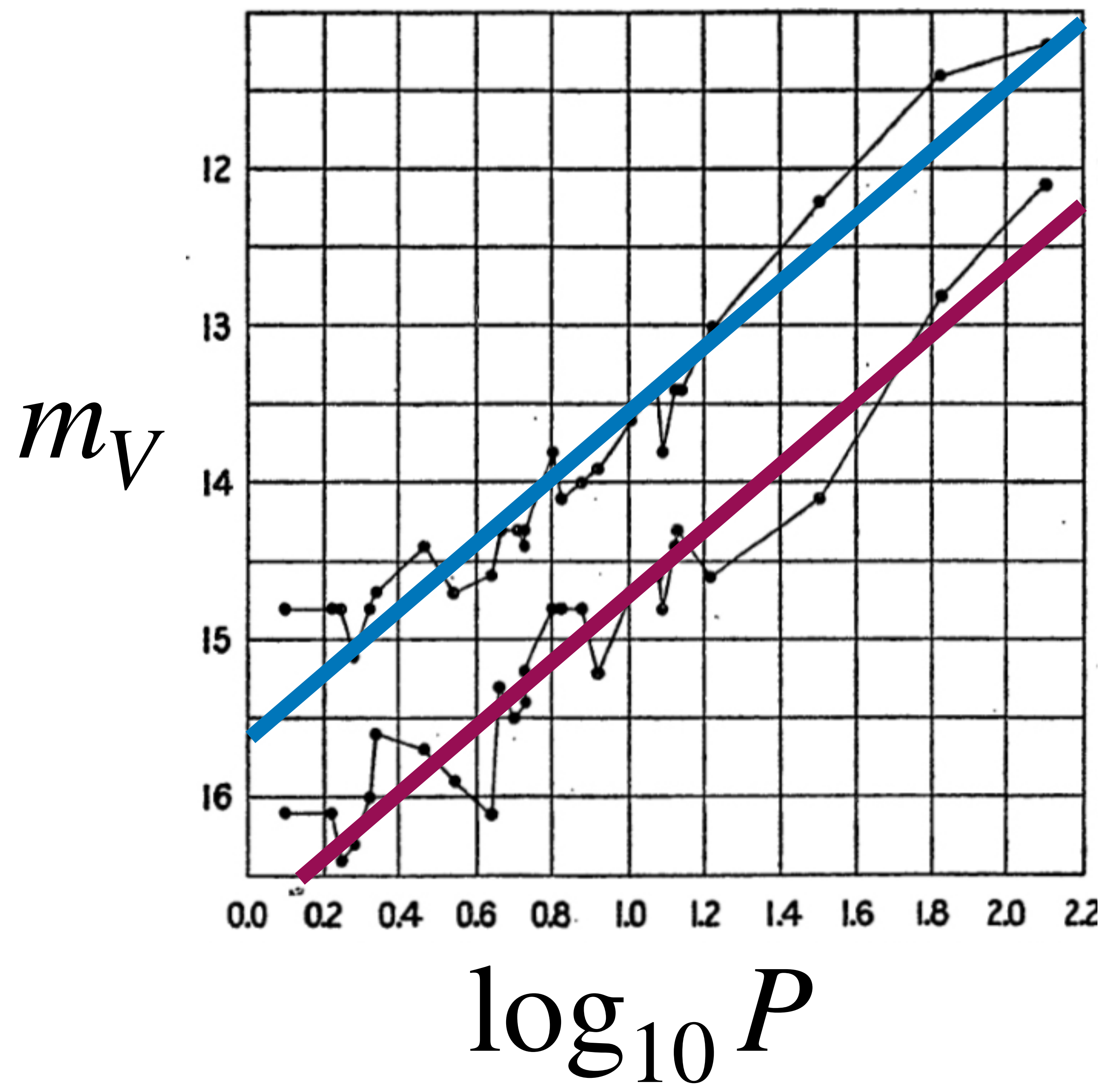
Period - Luminosity Relationship

"Leavitt Law"

- Radial pulsations are driven as sound (pressure) waves to surface, **larger stars will take longer to pulsate!**

- This makes the pulsation period *very* useful for estimating luminosity



LMC, 50kpc

SMC, 62kpc

Leavitt (1912)

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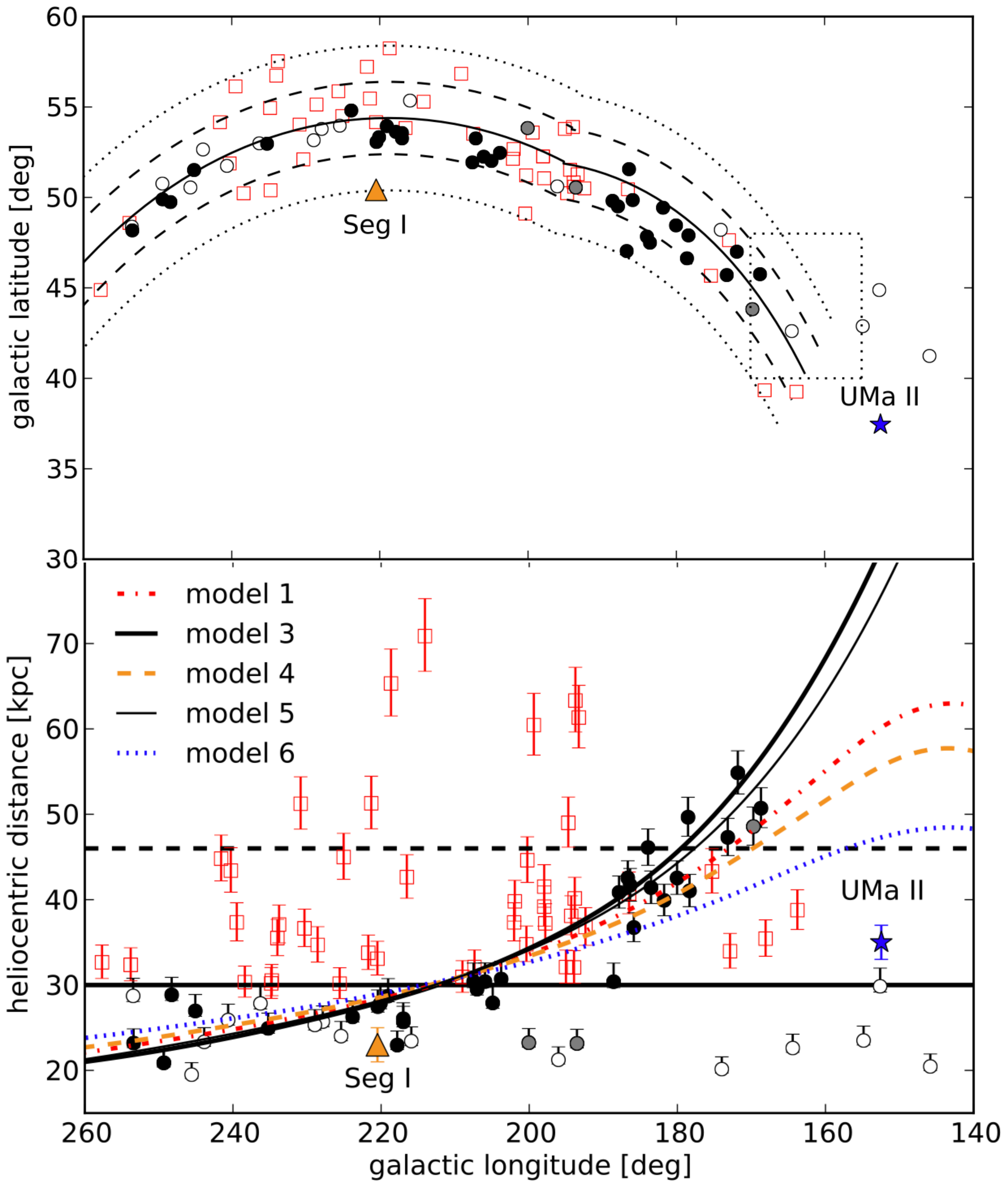
Period - Luminosity Relationship

“Leavitt Law”

- Can trace structure within our Galaxy!



Tracing the “Orphan Stream” with RR Lyr stars
Sesar+2013

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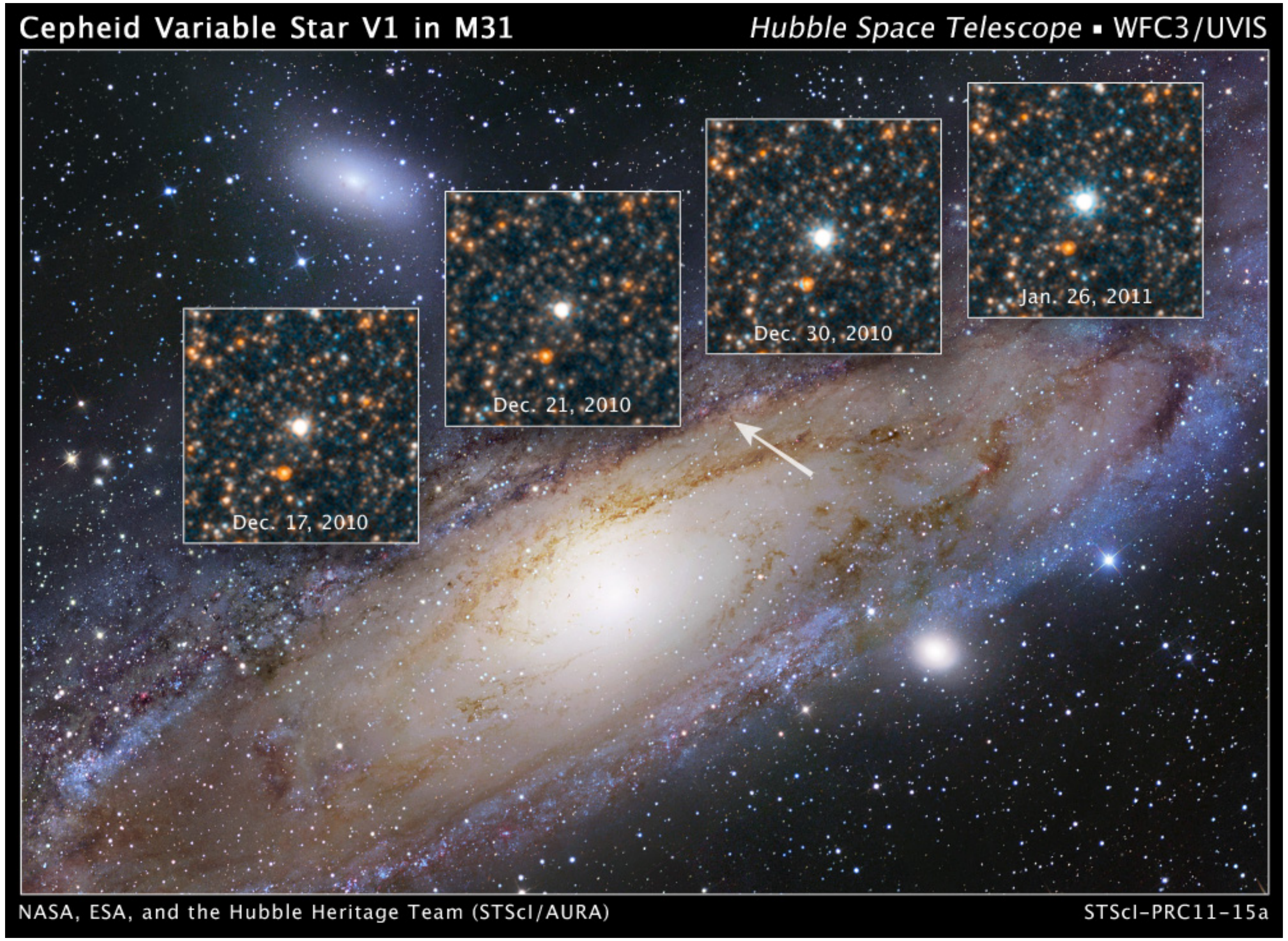
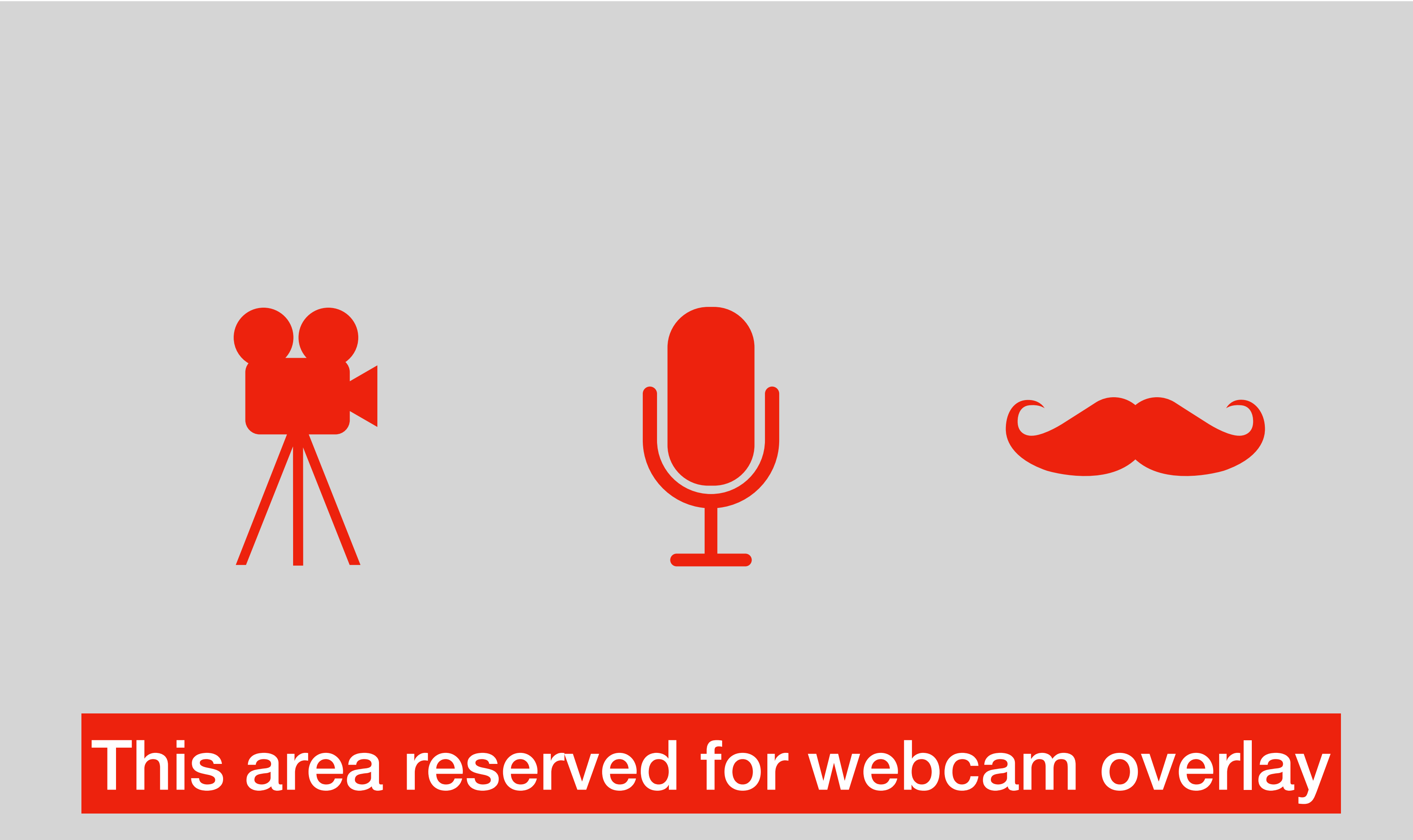
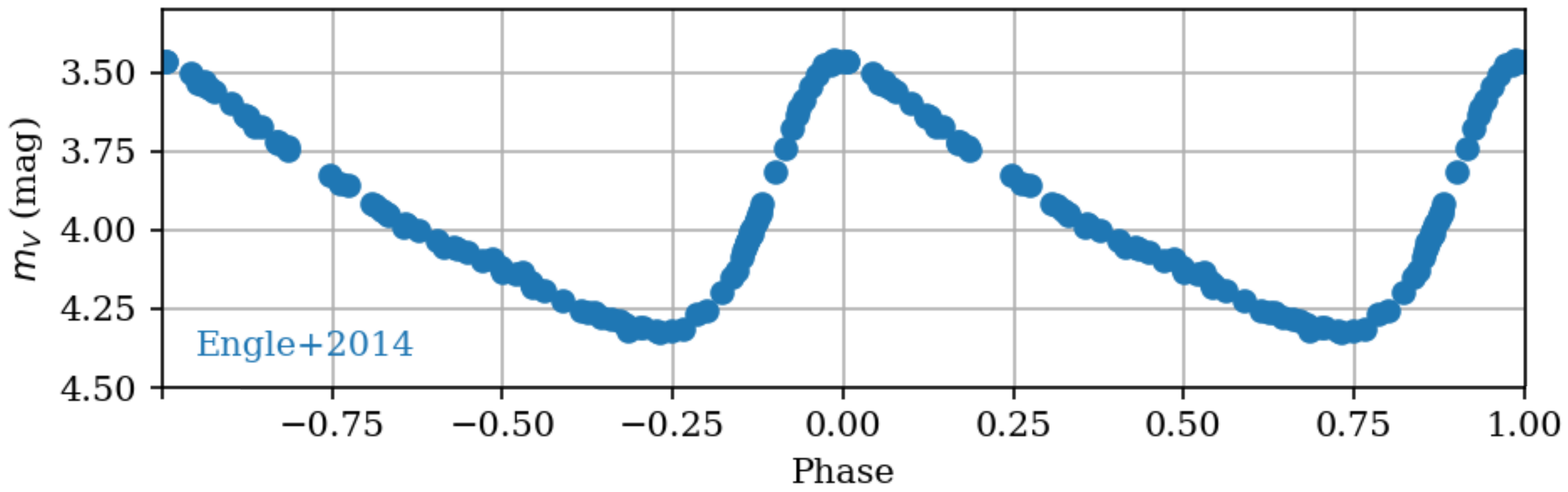
Anchoring the cosmic distance ladder

- "… the most important star in the history of cosmology"
  -Dave Soderblom

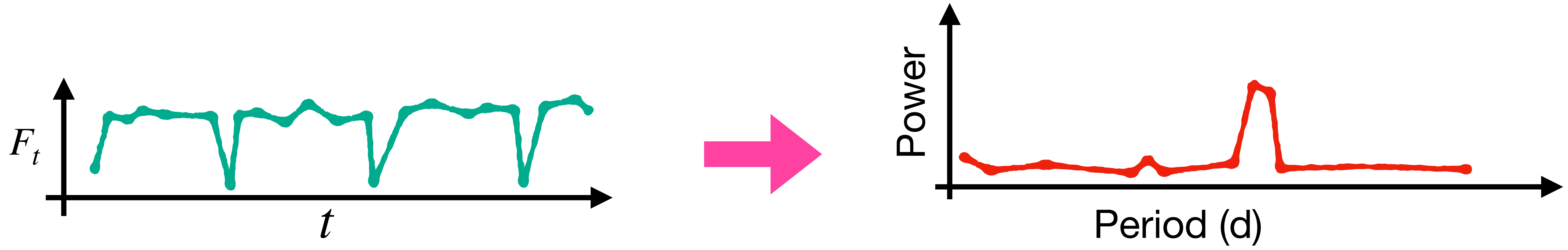




Finding Pulsators



- **Strongly periodic!**
- Periods are very stable (though not *perfectly stable*, see Turner+2006 for $\dot{P}$) so can combine data even if very irregularly sampled in time
- Look fairly sinusoidal, can use "Lomb-Scargle Periodogram" to recover them
- L-S is a *power spectral density estimator*, which assumes sinusoidal shape (like the FFT), but allows sparse/uneven sampling (unlike FFT!)… and is very fast!



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Homework 5

- Exploring RR Lyr from ZTF!

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