ASTR 421

Stellar Observations and Theory

Lecture 17

Summary & The Future

Prof. James Davenport (UW)

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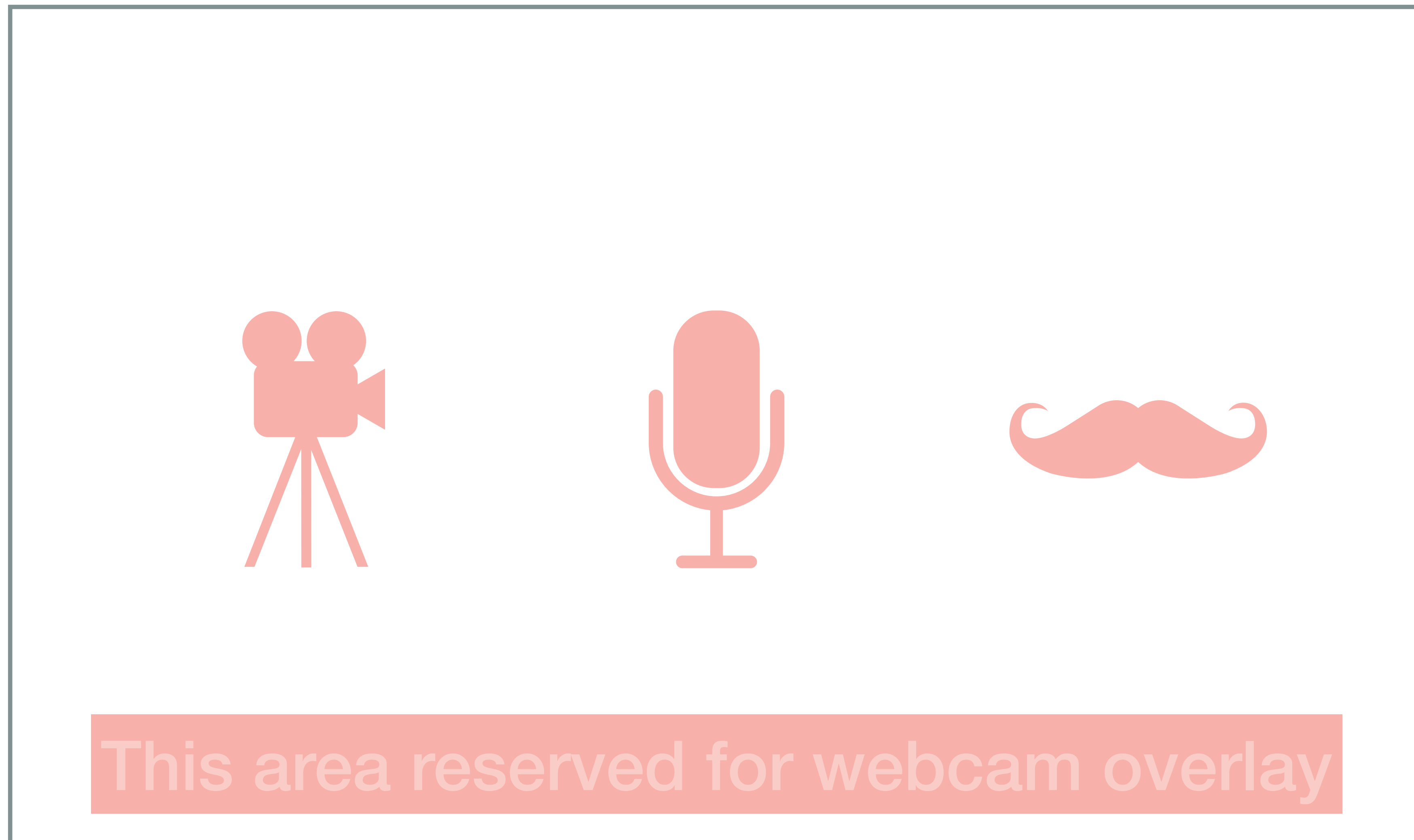
Course Goals

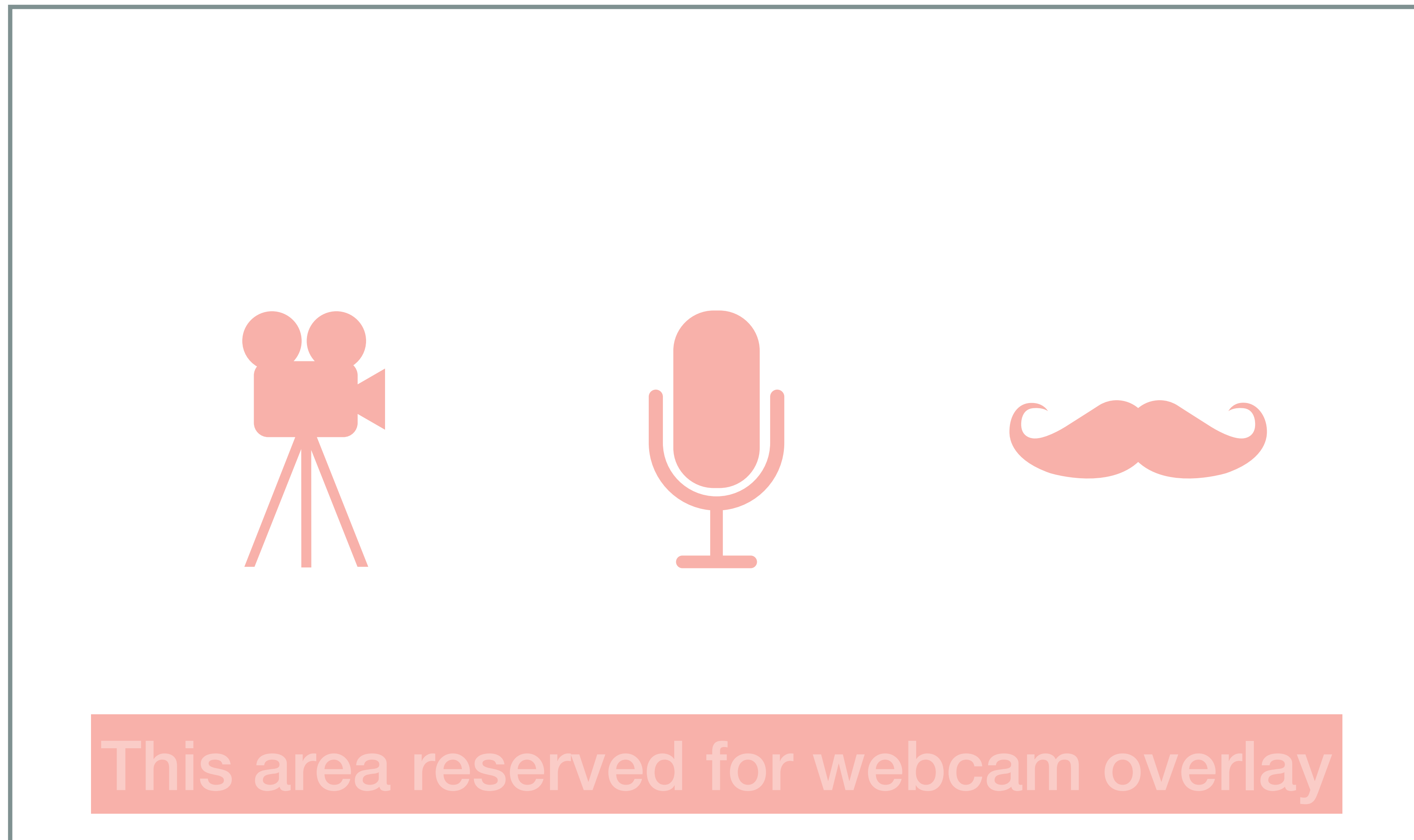
- Let's start by acknowledging the comically broad course description: Stellar Observations and Theory

ASTR 421 Stellar Observations and Theory (3) NW
Observations and theory of the atmospheres, chemical composition, internal structure, energy sources, and evolutionary history of stars.
[View course details in MyPlan: ASTR 421]

- My #1 hope is for you to **gain intuition** about how we observe stars, general theory of their atmospheres and structures, and how to engage with relevant astronomical data/tools.

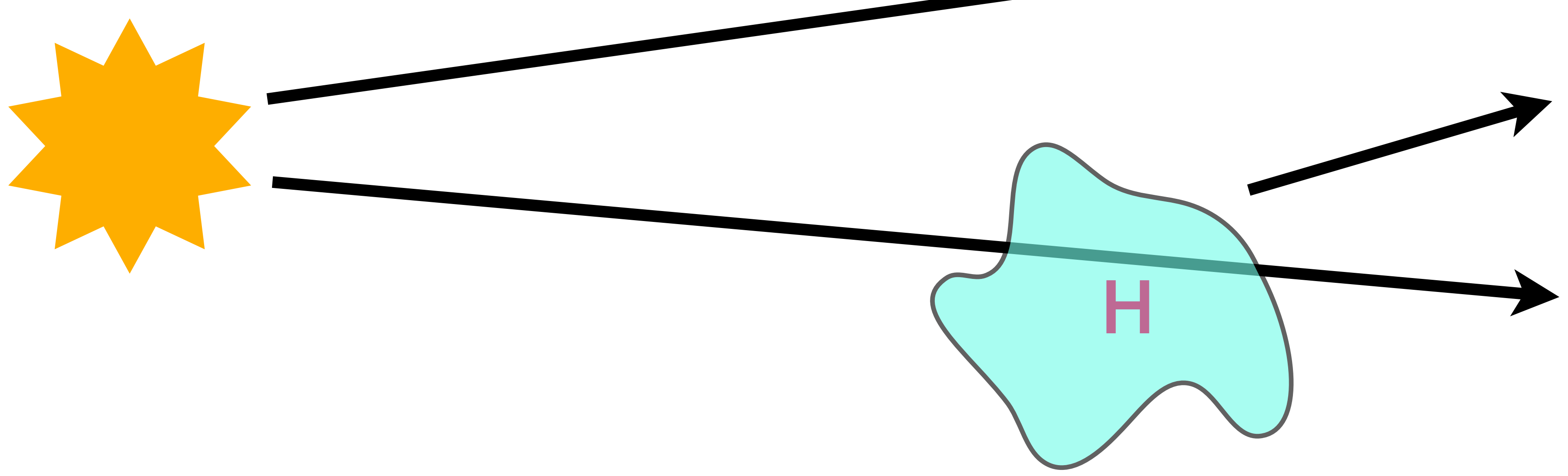


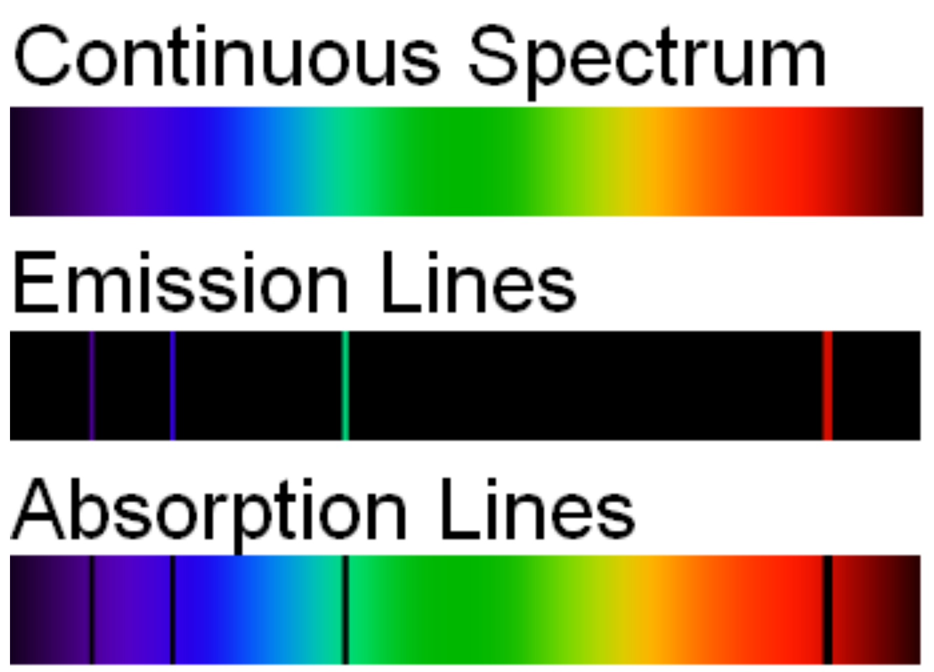
Highlight Reel!



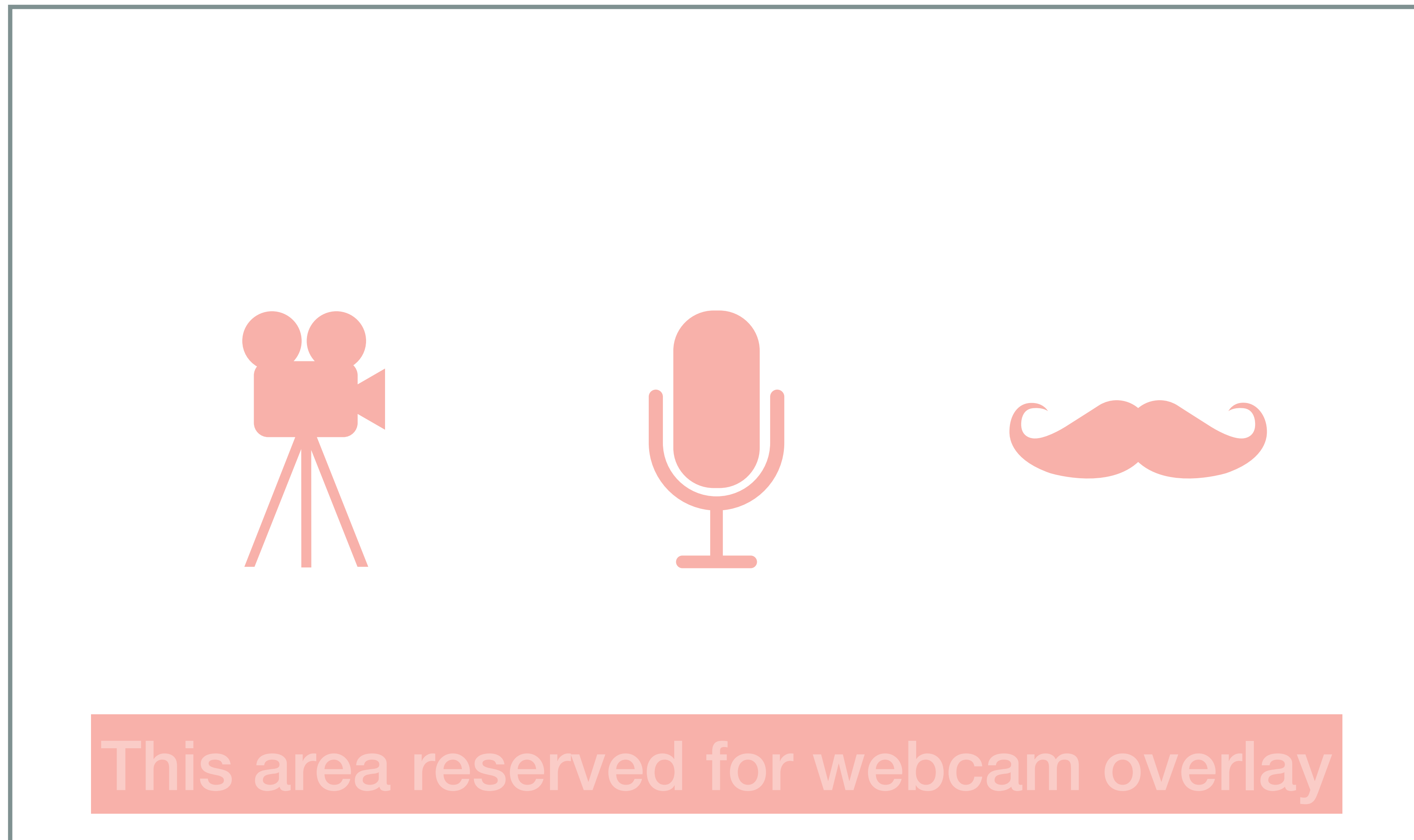
Kirchoff's Laws (of spectra)

1. Dense gas emits a continuous (i.e. blackbody) spectrum
2. Hot, low density gas emits
3. Cool, low density gas absorbs





https://commons.wikimedia.org/wiki/File:Spectral_lines_en.PNG



Boltzmann Equation

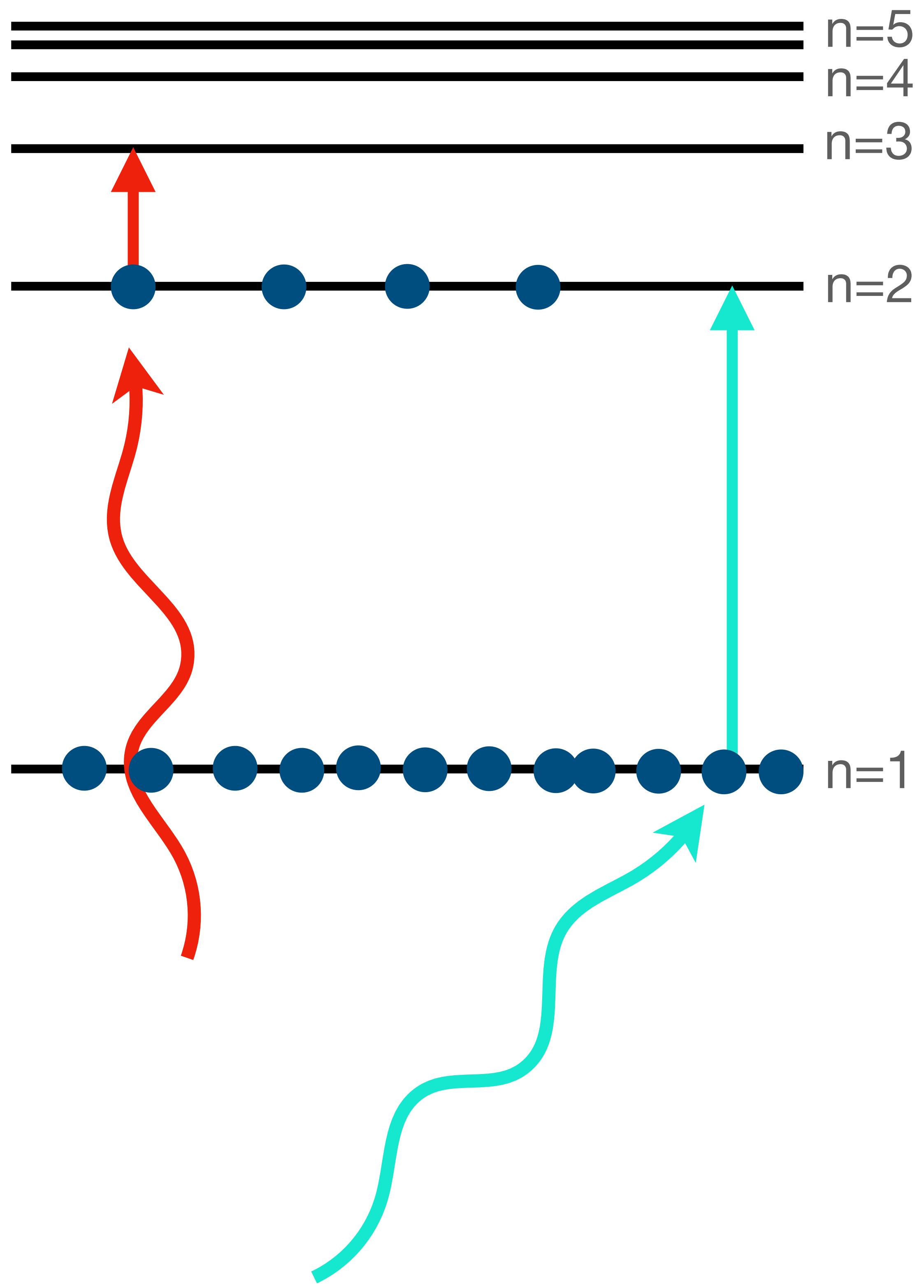
- For a gas in TE, at a given temperature (*T*), what is the probability of finding an electron will be at a given energy state (n)?

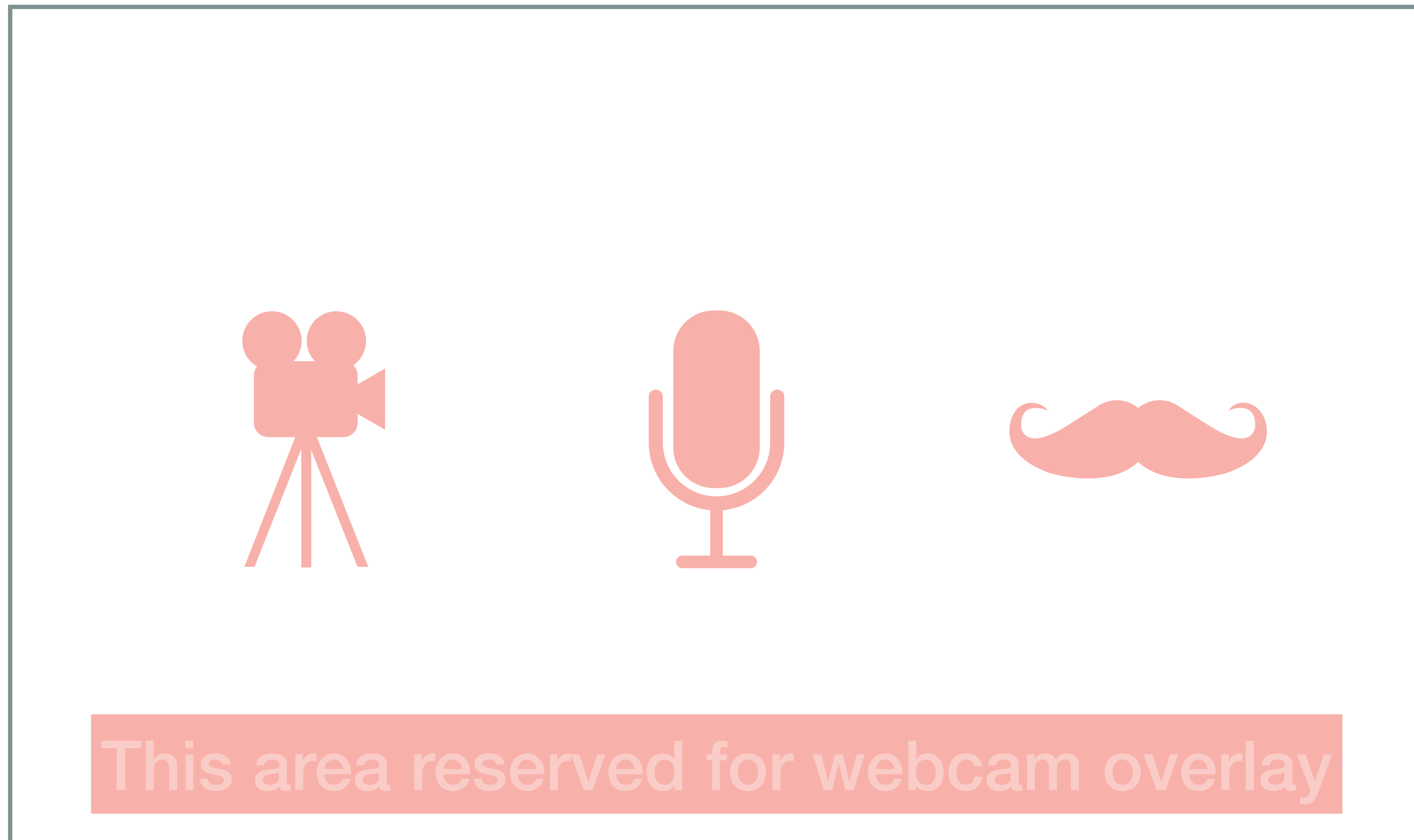
$$n_v dv = n\left(\frac{m}{2\pi kT}\right)^{3/2} e^{-mv^2/2kT}\, 4\pi v^2 dv$$

$$g_n = 2n^2$$

$$\boxed{\frac{N_b}{N_a} = \frac{g_b}{g_a} e^{-(E_b - E_a)/kT}}$$

a,b are energy level numbers (n=1,2,3…)





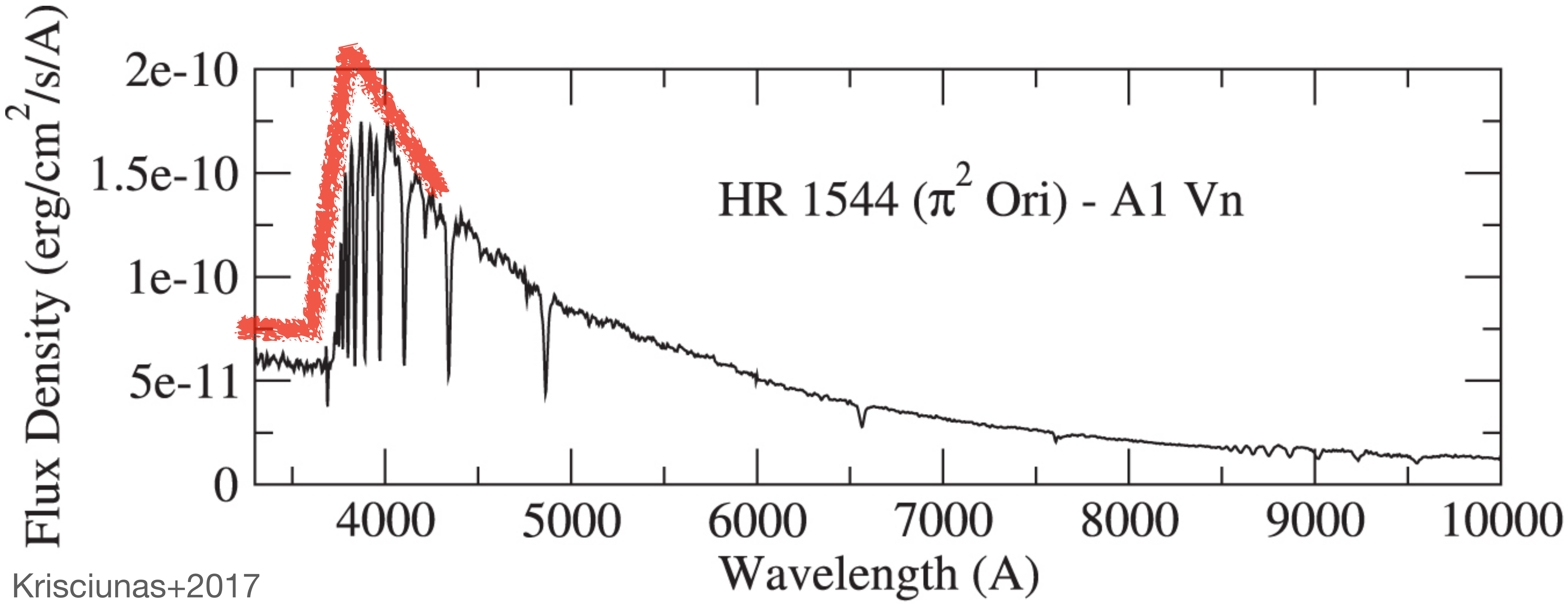
Saha Equation

$$\boxed{\frac{N_{i+1}}{N_i} = \frac{2kT}{P_e}\frac{g_{i+1}}{g_i}\frac{(2\pi m_e kT)^{3/2}}{h^3}\, e^{-\chi_i/kT}}$$

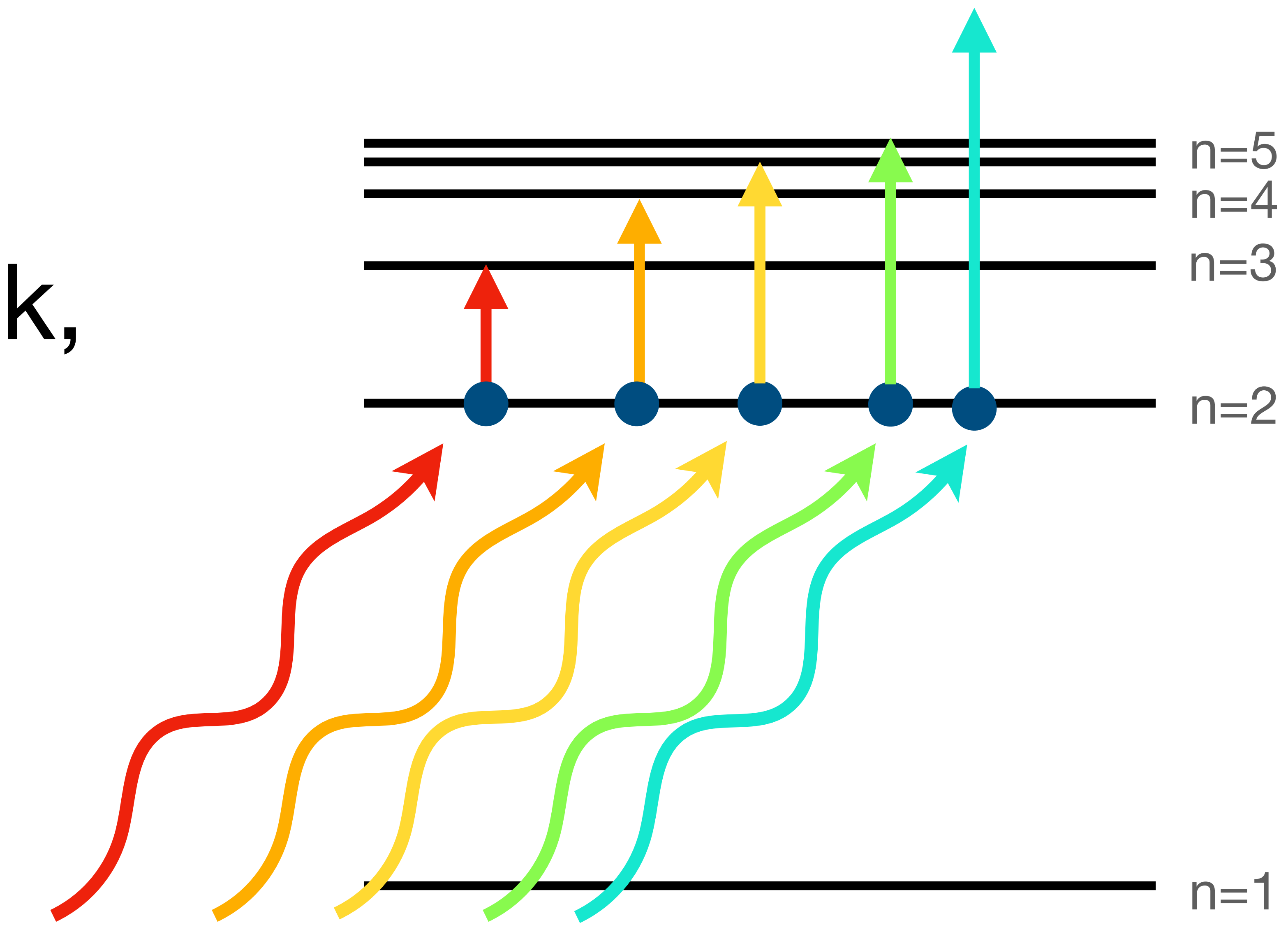
- Several forms of this (2 in BOB ch8, another in your homework!) substituting different variables, etc
    - i.e. $P_e = n_e kT$
- Use Saha to calculate e.g. $\frac{N_{II}}{N_I}$, the number of ionized to neutral atoms as a function of temperature
- The ratio of the statistical weights here is really the *Partition Function ratio*, which sums up the energies of degenerate states

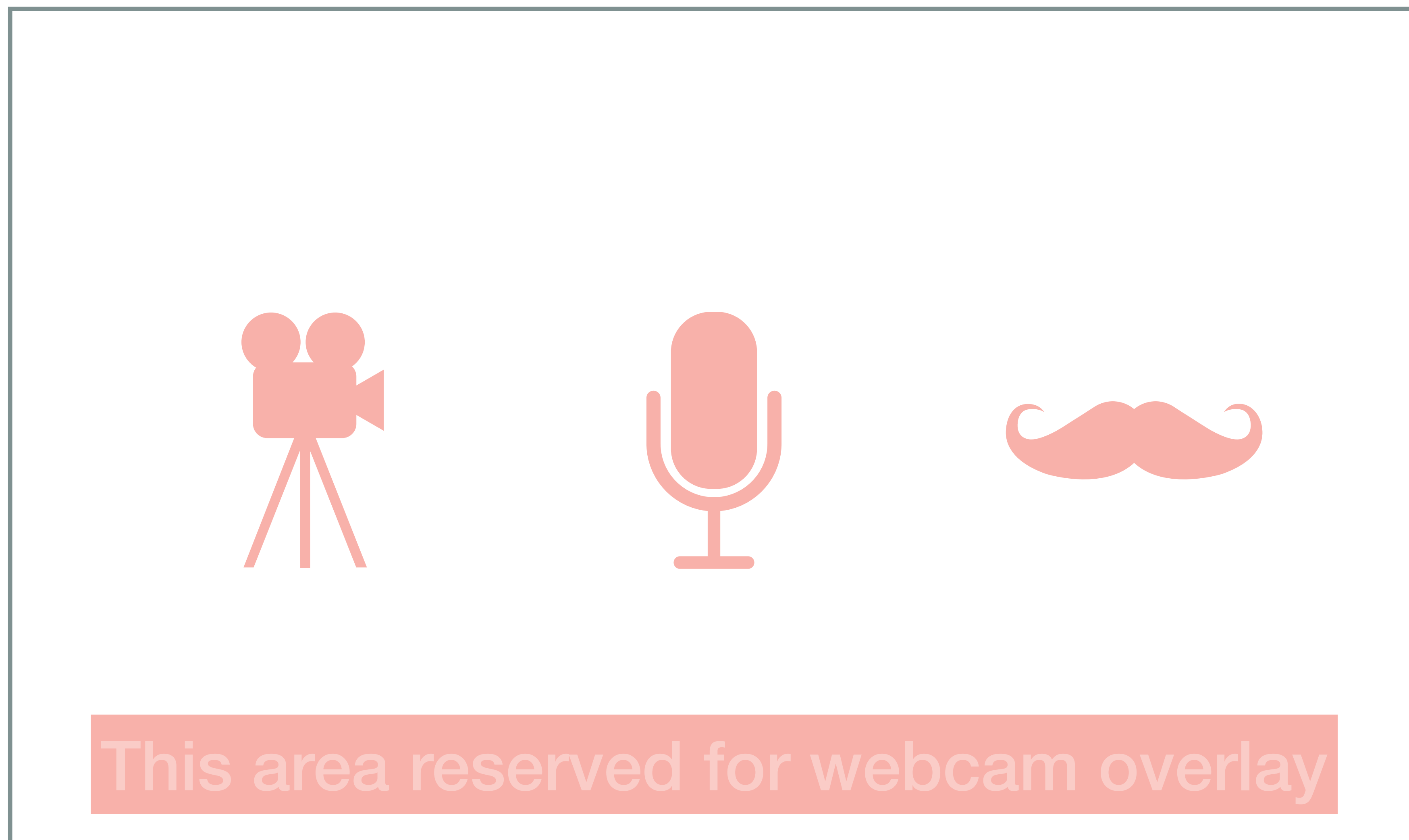
Balmer break/jump

- The "end" of the line series, no more transitions
- Star still producing plenty of photons above the break, but they totally absorbed, ionizing all the available H
- Balmer Jump is strong when Balmer lines are strong



Krisciunas+2017





Temperature and T_{eff}

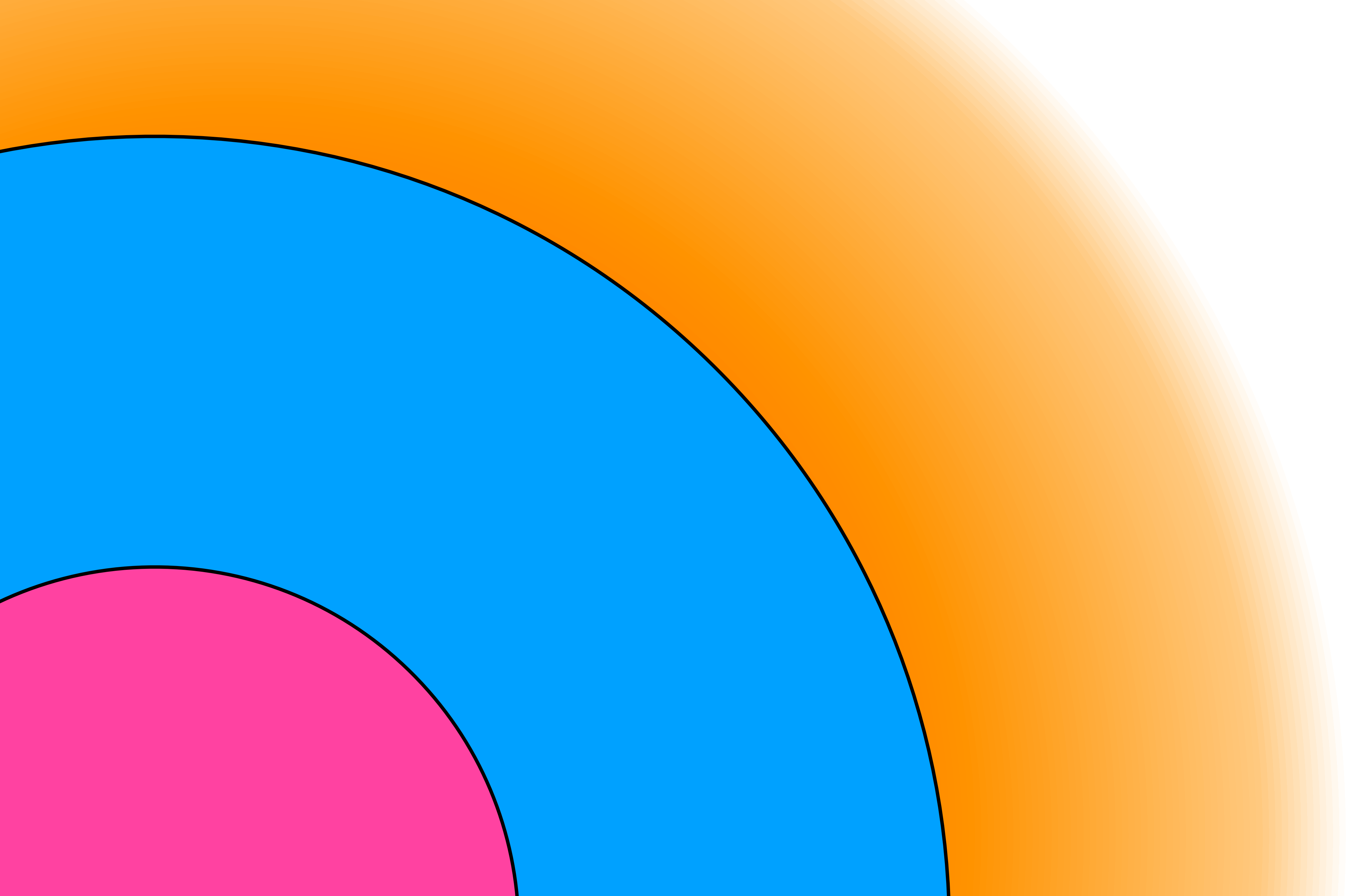
$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

- The "effective temperature" is the Temp that a star would have if it were a perfect blackbody with the same luminosity

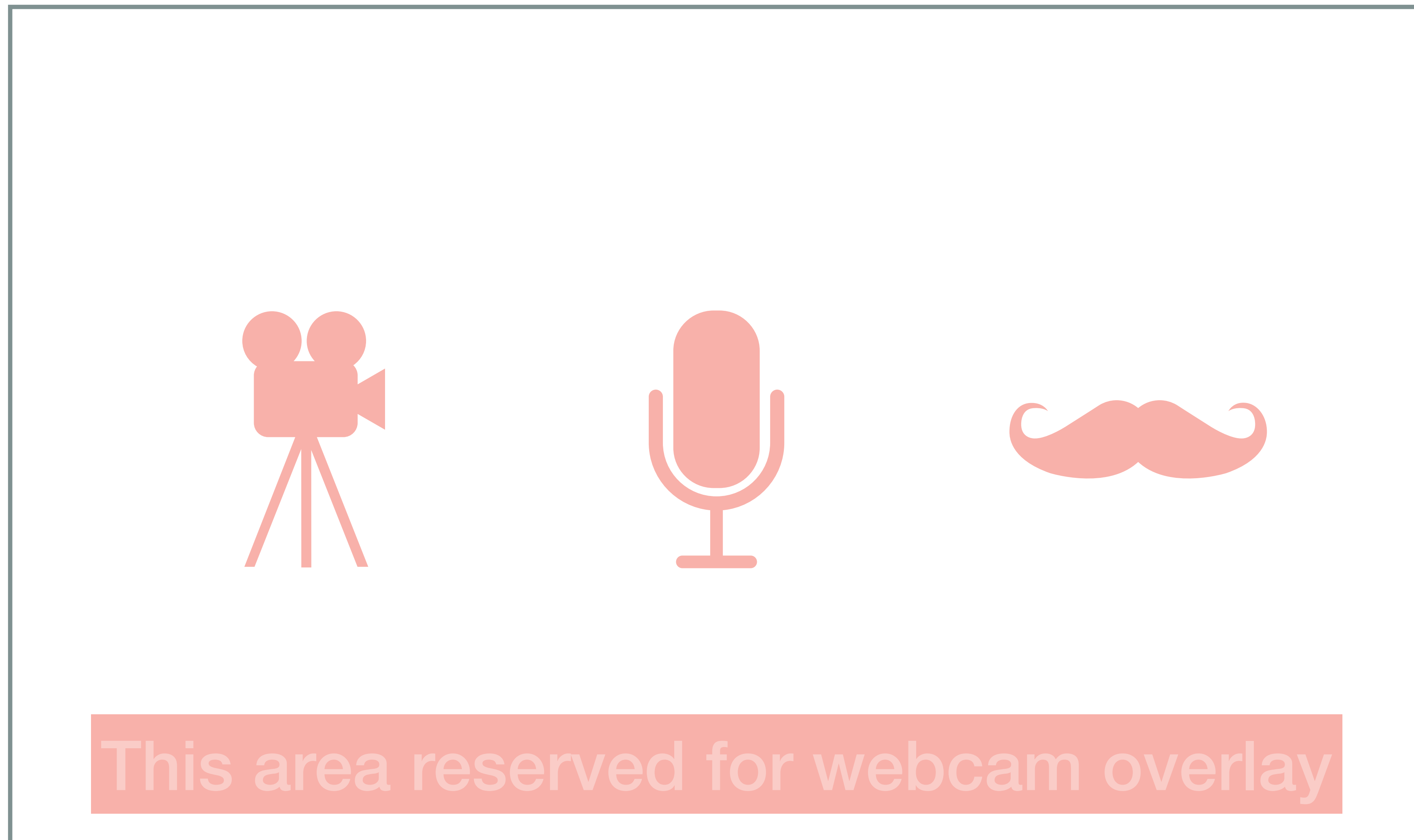
$$\frac{1}{2} m \bar{v}^2 = \frac{3}{2} k_B T$$

- Only works at the "surface" of the star (more on what the "surface" is next week!)

$$n_v dv = n \left(\frac{m}{2\pi kT} \right)^{3/2} e^{-mv^2/2kT} \, 4\pi v^2 dv$$



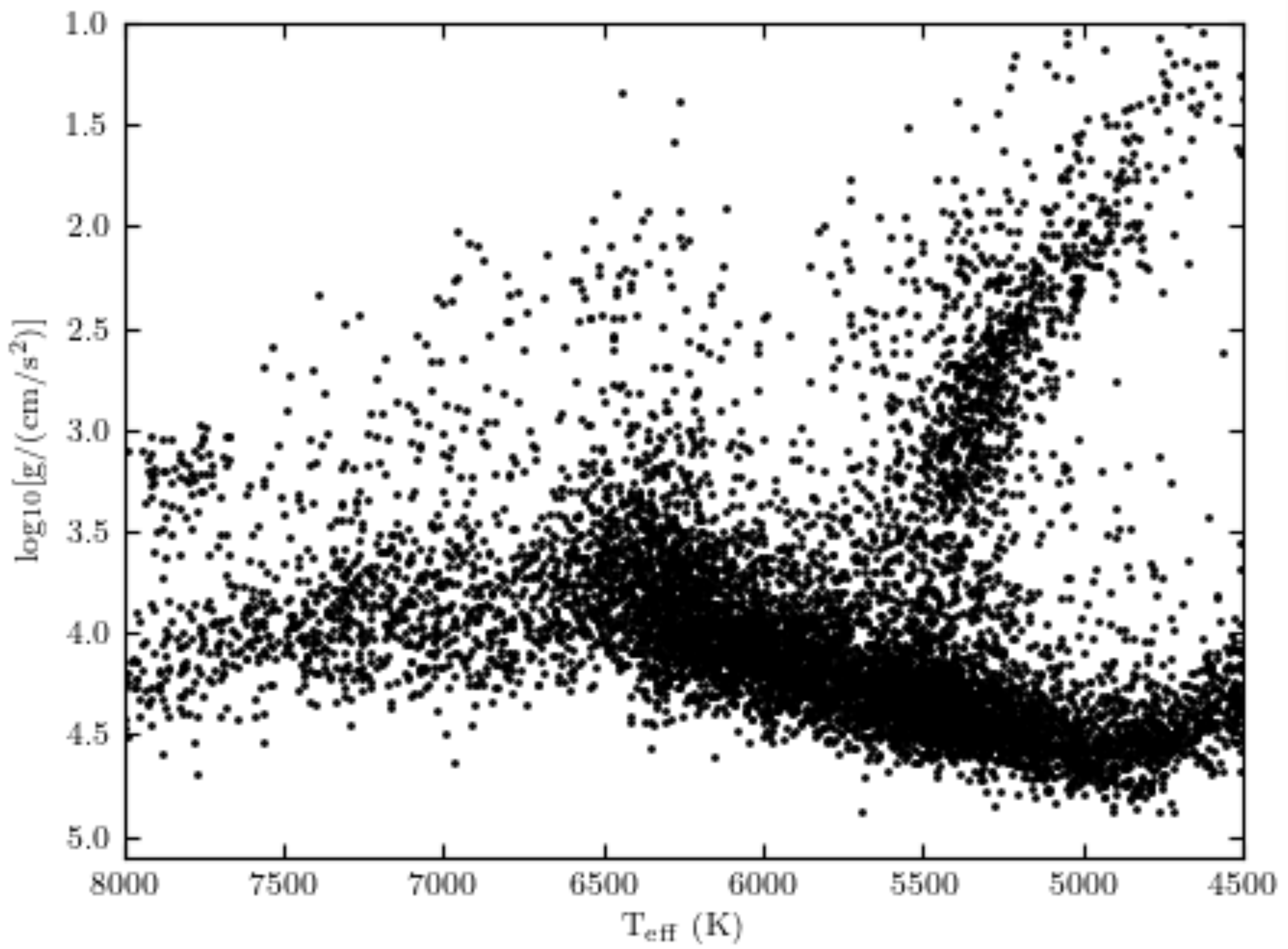
$$L = 4\pi R^2 \sigma_{SB} T^4$$

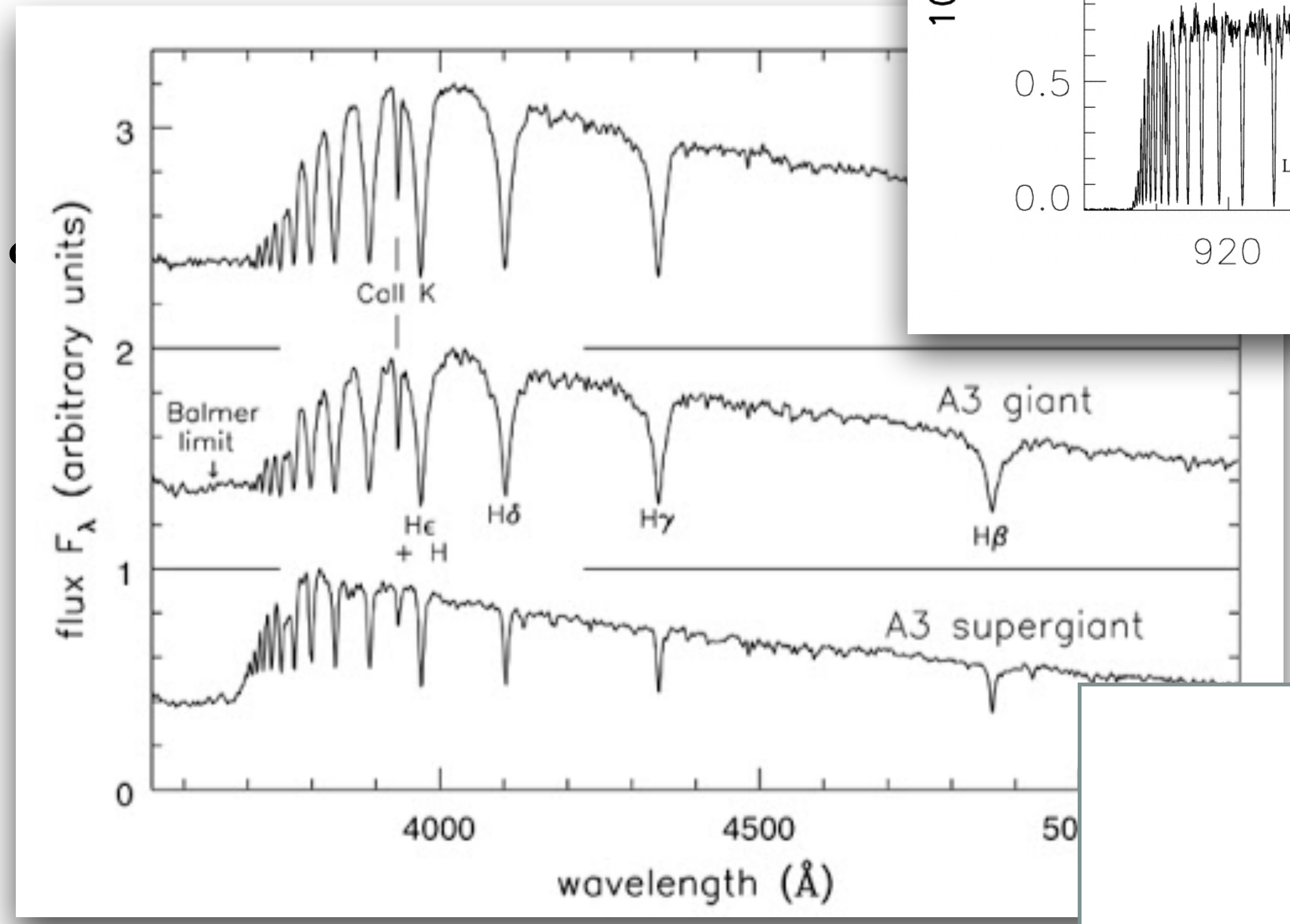


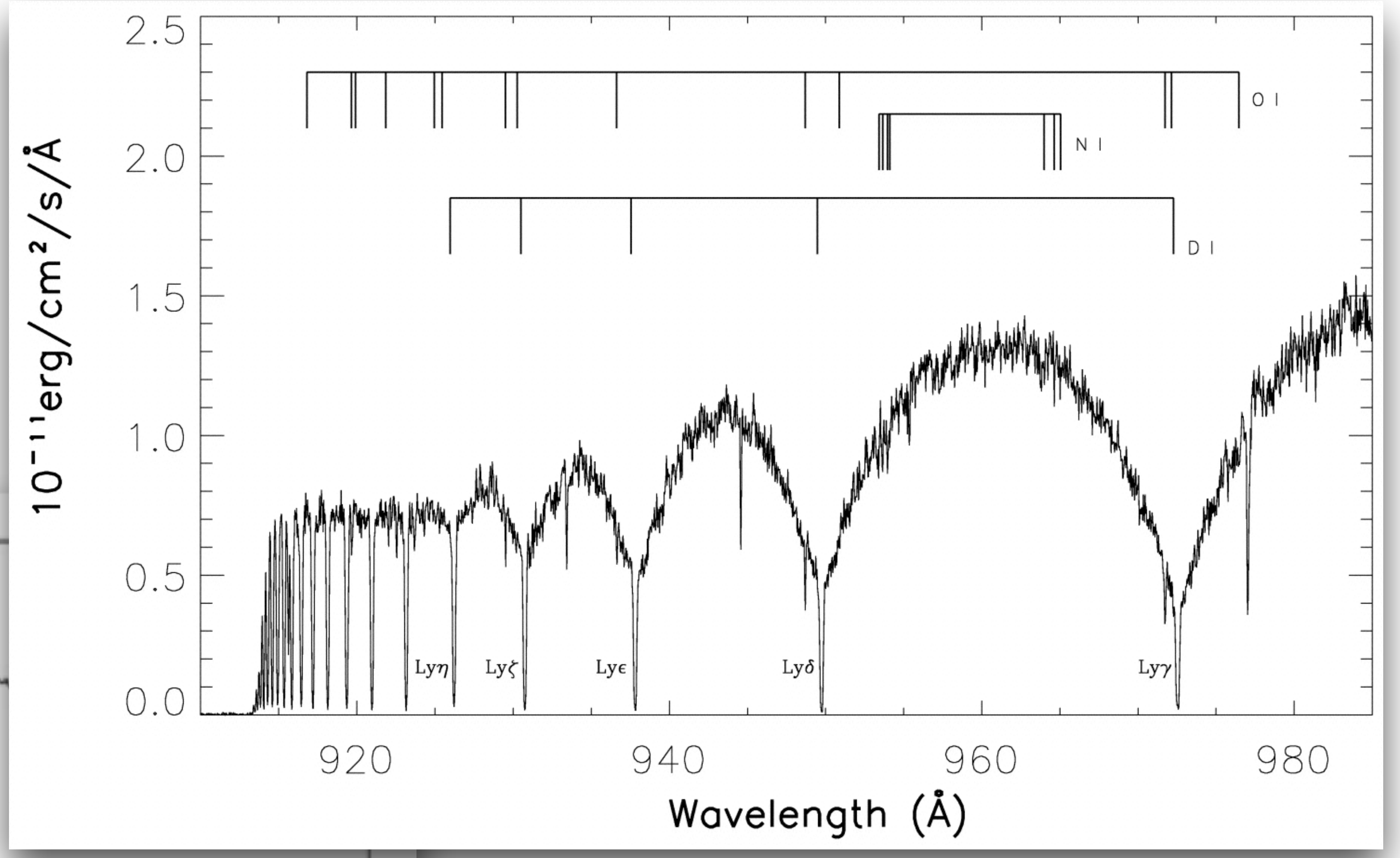
Surface Gravity

- $g = GM/R^2$,
  usually measured w/ spectroscopy
  (line broadening)

- Typically expressed as $\log$
  stars: ~4
  giants: 3-1
  white dwarfs: 6-9







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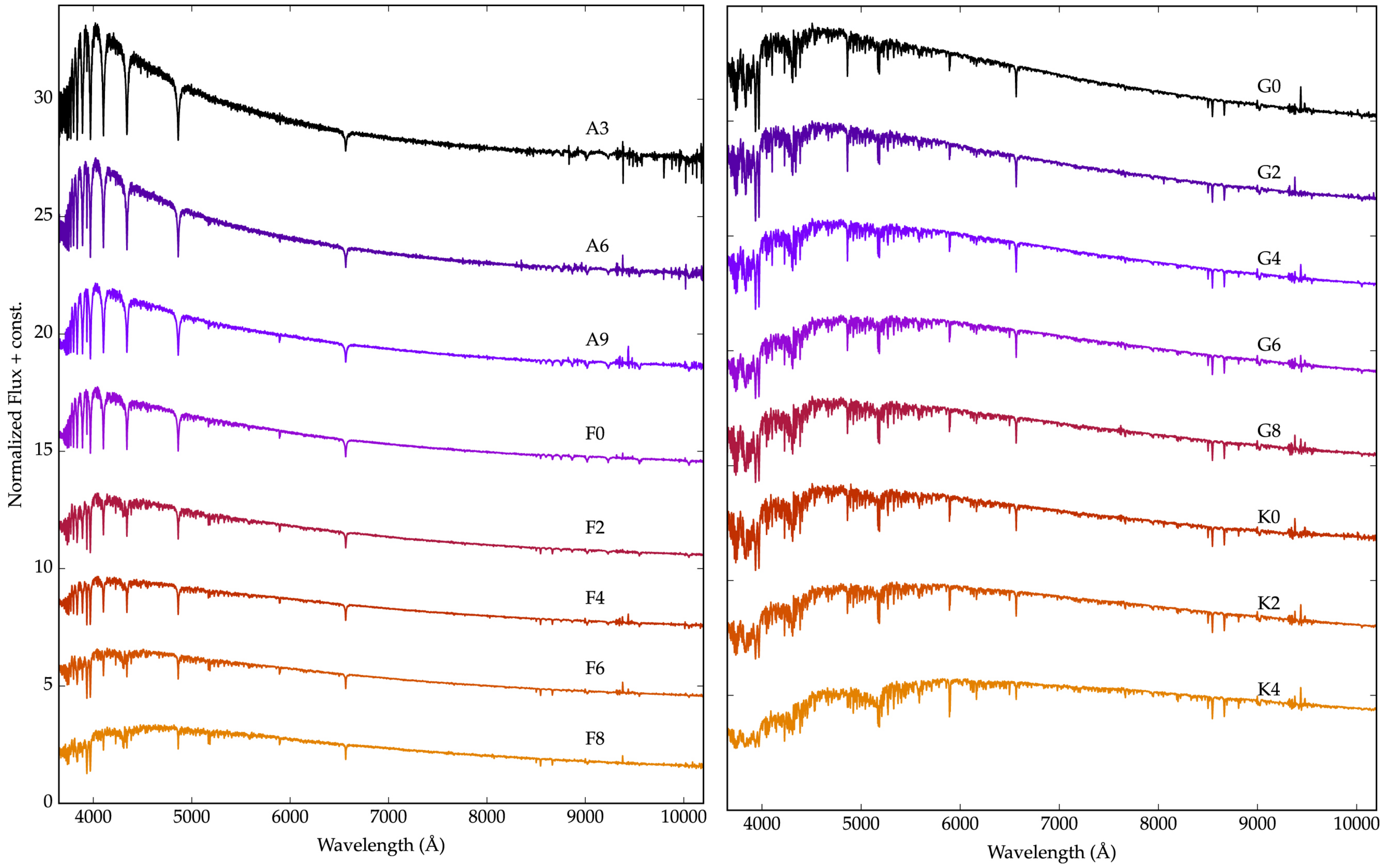
The Story of Spectral Types

- **Annie Jump Cannon** famously realized the sequence didn't quite follow temperature from overall blackbody shape (1912)

- System still in place today

OBAFGKM



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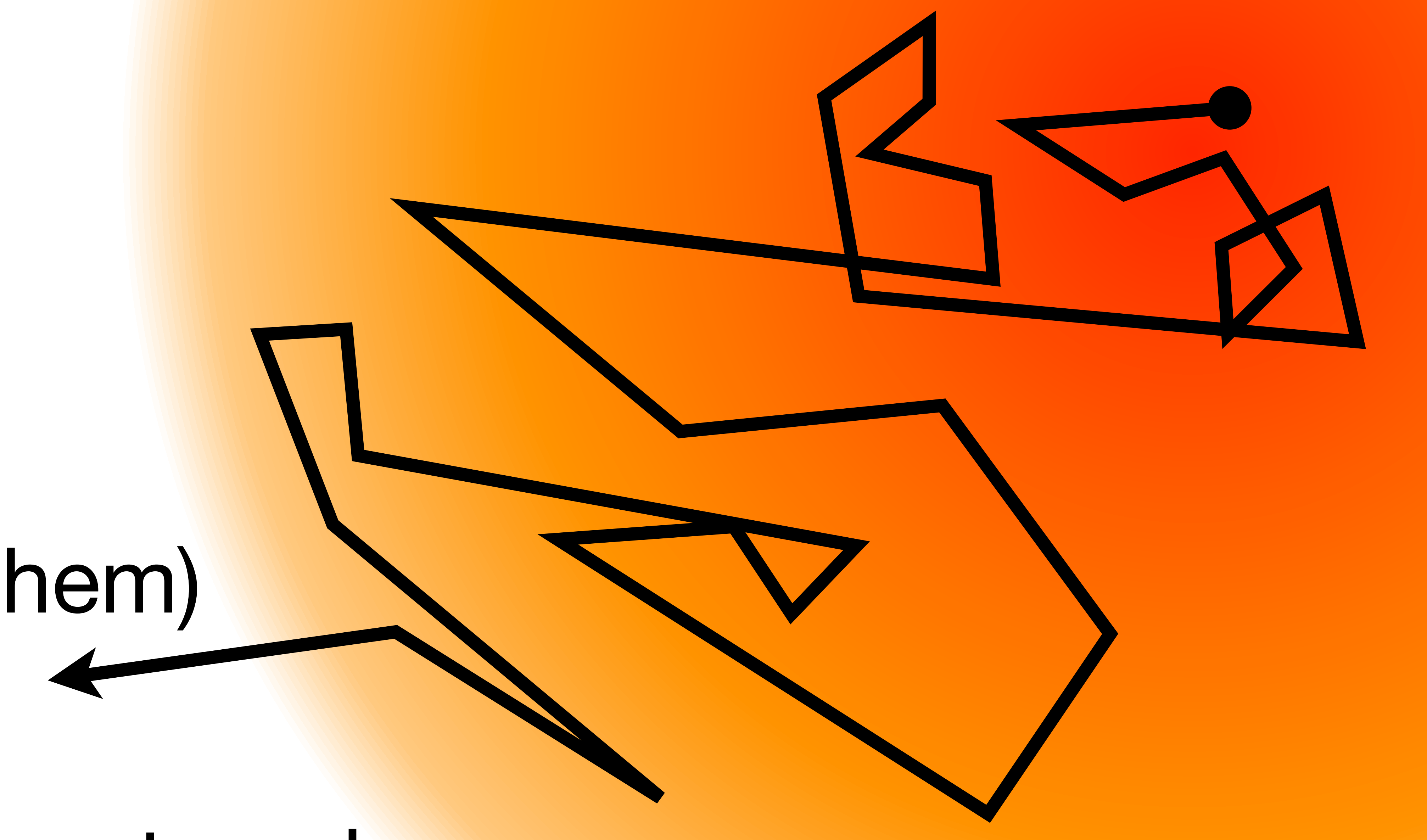
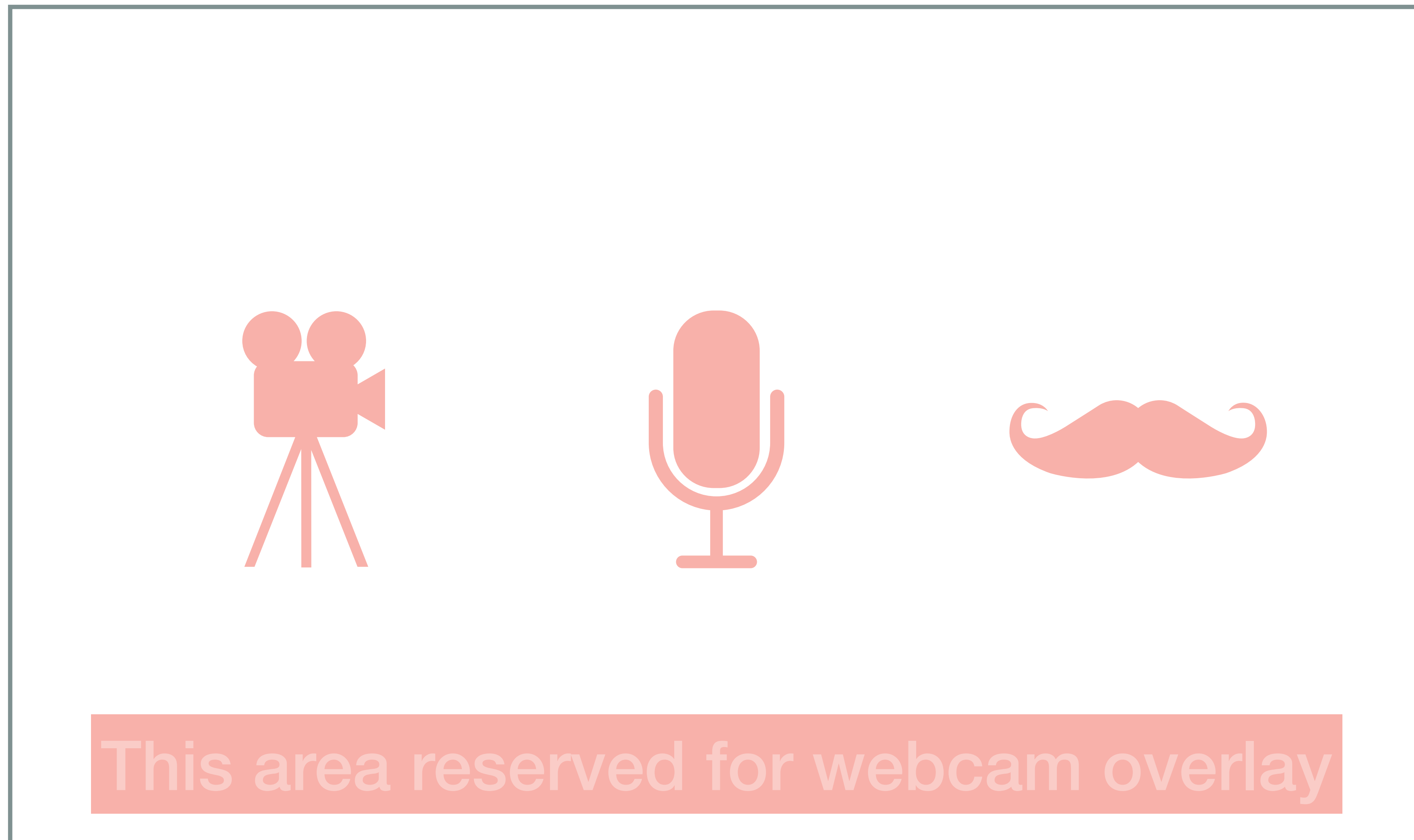
How do photons reach us?



- Remember it takes a LONG time for photons to wander from the core (where fusion is *creating* them) to the “surface” (i.e. where they finally escape)
- This **is** the processes of absorption and emission at work (a “random walk”, as the book defines it)
- The book defines the number of steps in this walk to reach the surface as: $N = \tau_\lambda^2$
    - Total optical depth of the sun is $\tau \sim 10^{11}$ so… that’s a *lot* of steps.

Estimate from: https://www.maplesoft.com/applications/view.aspx?SID=154320&view=html



Optical Depth

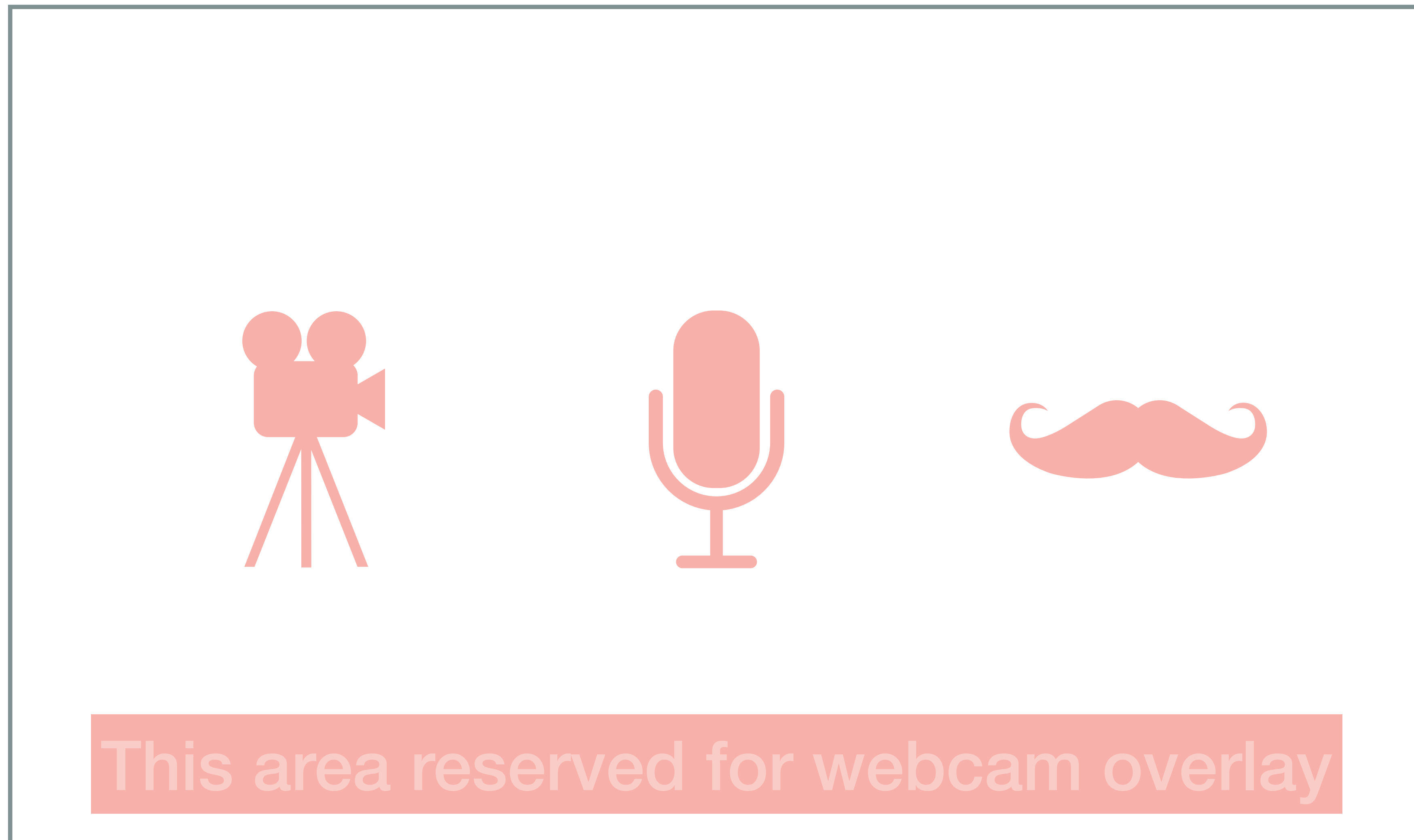
- *Not* the same as the characteristic length!
- Important concept for stars, defining where emission comes from

$$dI_\lambda = -\kappa_\lambda \rho\, I_\lambda ds$$

$$d\tau_\lambda = -\kappa_\lambda \rho\, ds$$

$$I_\lambda = I_{(\lambda,0)}\, e^{-\tau_\lambda}$$

- Where τ (the optical depth) is the number of mean free paths along a line of sight, or the “thickness” of a gas
- τ >>1: optically thick, τ<<1: optically thin



Emission & Absorption

- **Both emission and absorption are happening within a volume of gas!**

$$dI_\lambda = j_\lambda \, \rho \, ds \qquad\qquad dI_\lambda = -\,\kappa_\lambda \, \rho \, I_\lambda ds$$

- Thus it stands to reason you can combine these two processes:

$$dI_\lambda = (-\kappa_\lambda \, \rho \, I_\lambda \, ds) + (j_\lambda \, \rho \, ds)$$

- This is one (simple) way to express the so-called "transfer equation"

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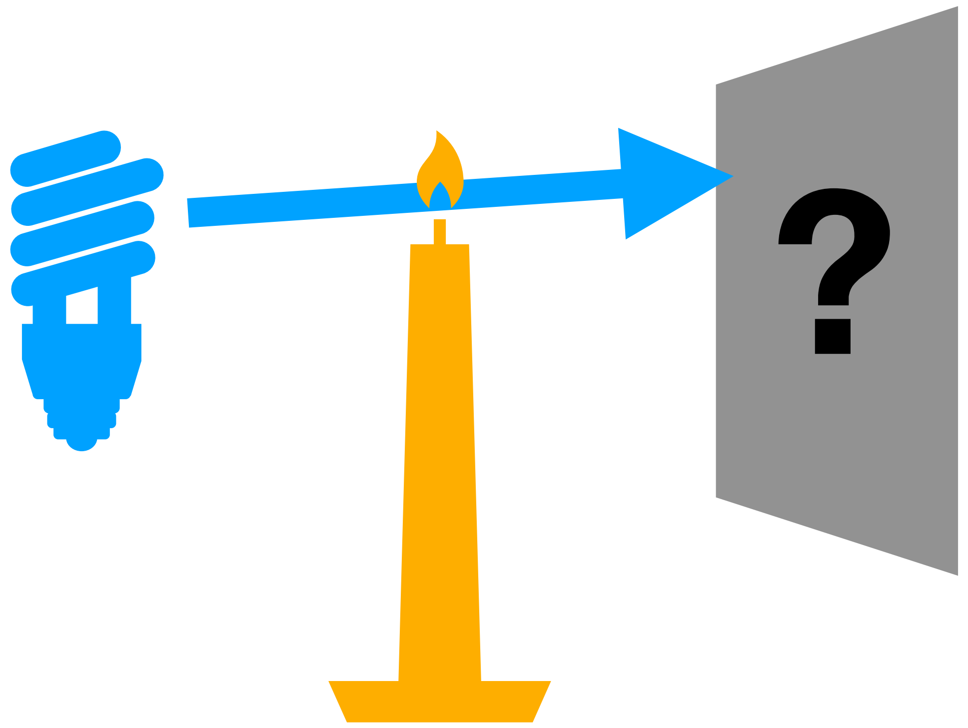
Does a candle flame cast a shadow?

- NO shadow if $T_{soot} > T_{bulb}$ (i.e. $S > I_0$)

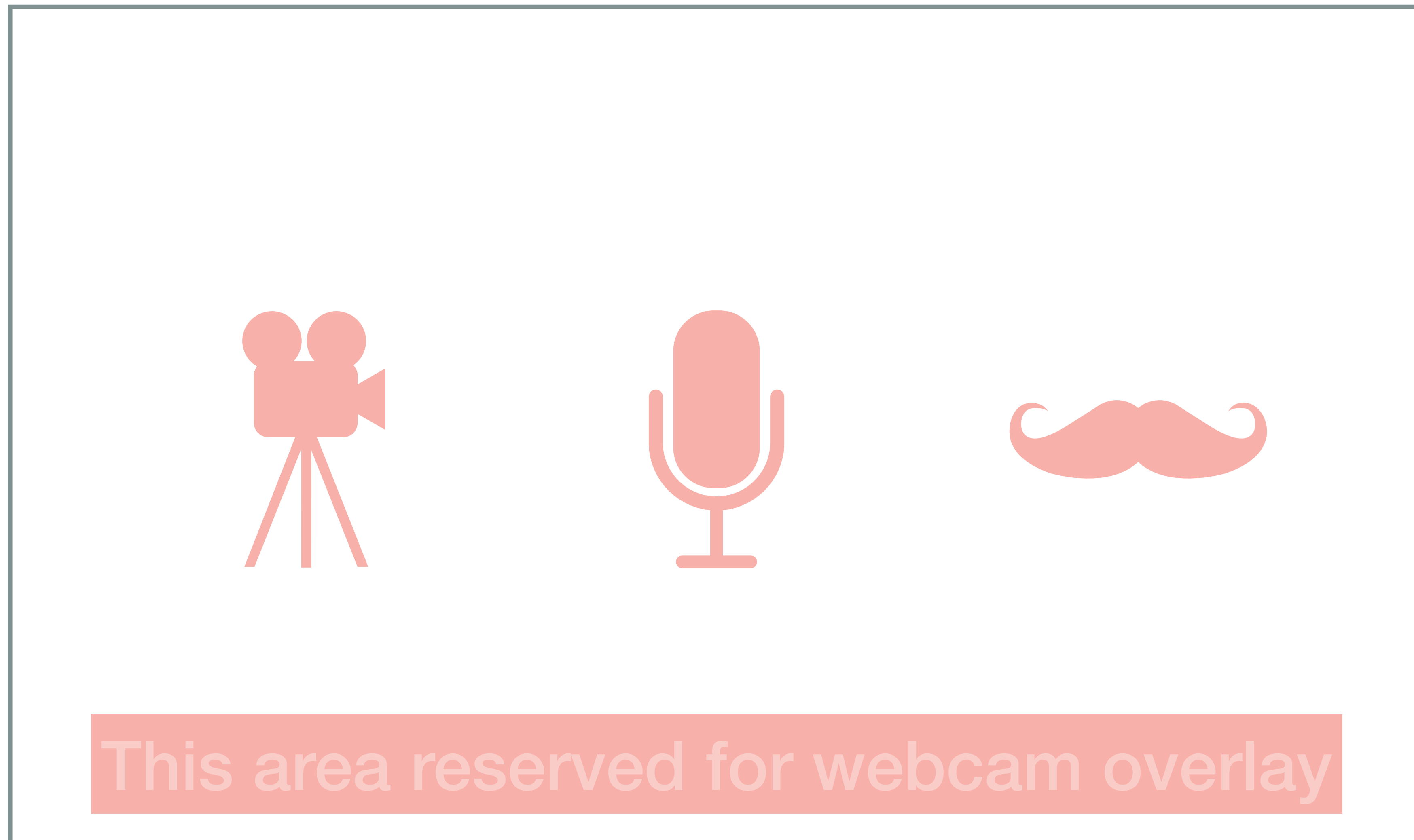
$$I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda} + S_\lambda\,(1 - e^{-\tau_\lambda})$$



- YES shadow if $T_{soot} \leq T_{bulb}$

- You can try this w/ the Sun (carefully)

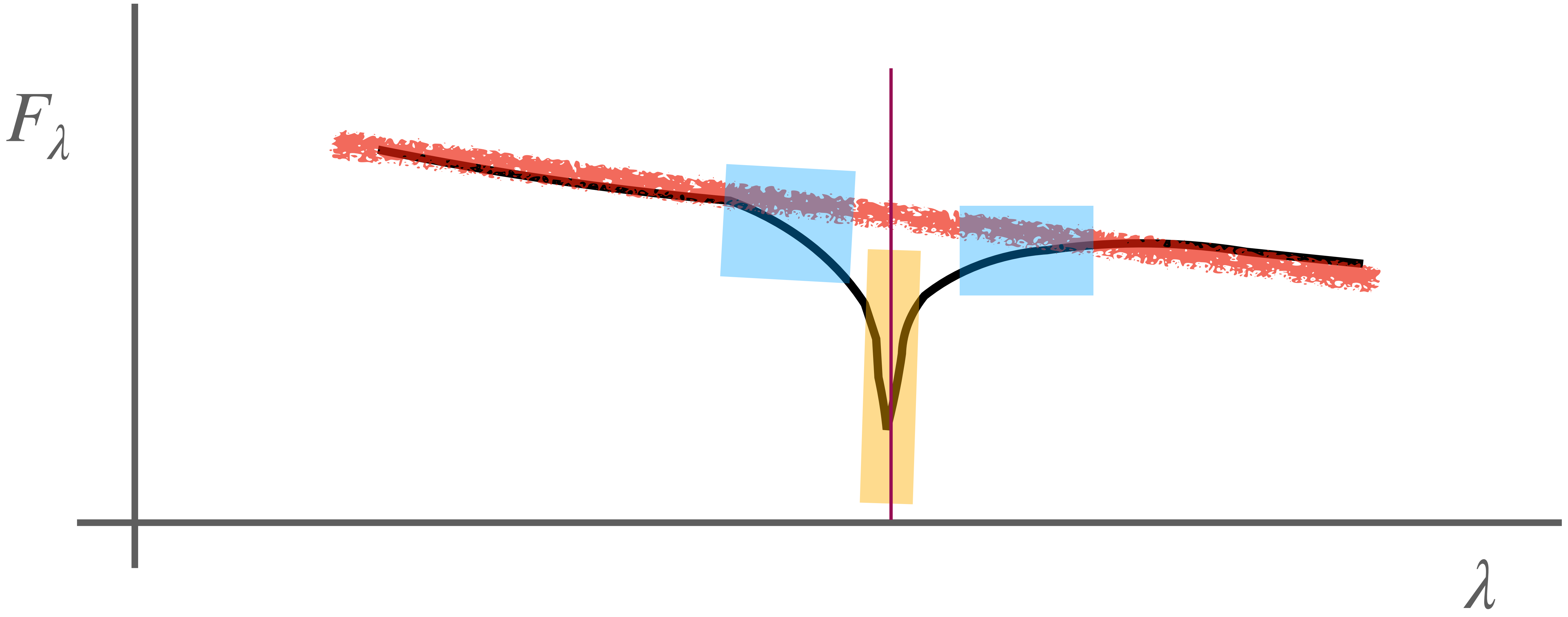
- $T_\odot = 5800K$, while $T_{candle} \sim 1200K$

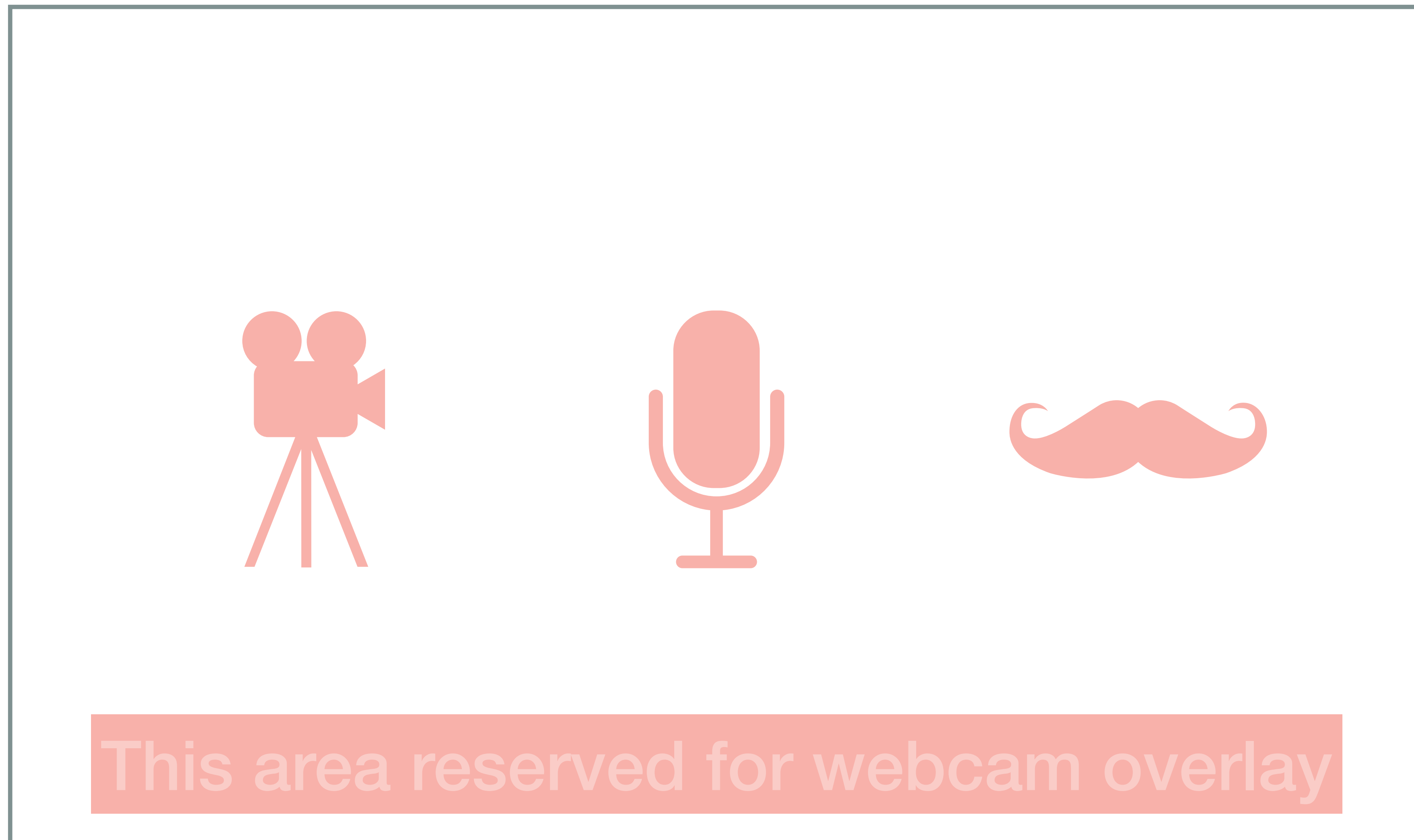


http://www-star.st-and.ac.uk/~kw25/teaching/nebulae/lecture03_radtrans.pdf

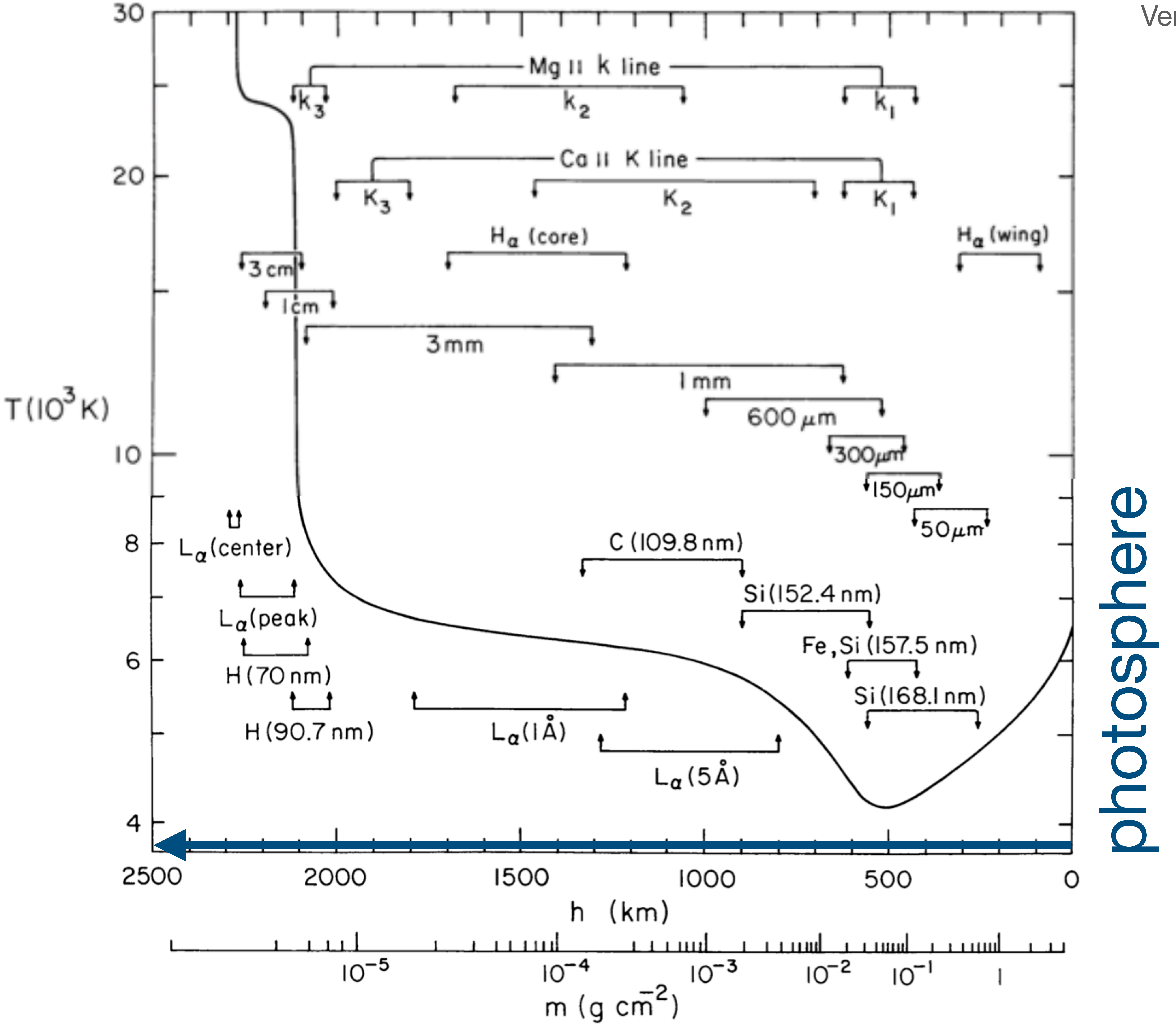
Where do lines form?

- First, some terminology:
  - Spectrum $\equiv (\tau = 2/3)$
  - Continuum (blackbody)
  - Wings (both sides)
  - Core (center)
  - λ_{lab} (note: vac or air wavelengths)





Line depth = $\tau(\lambda)$



Vernazza+1981

Need to model:
non-LTE, optically thick behavior
many transitions of many elements

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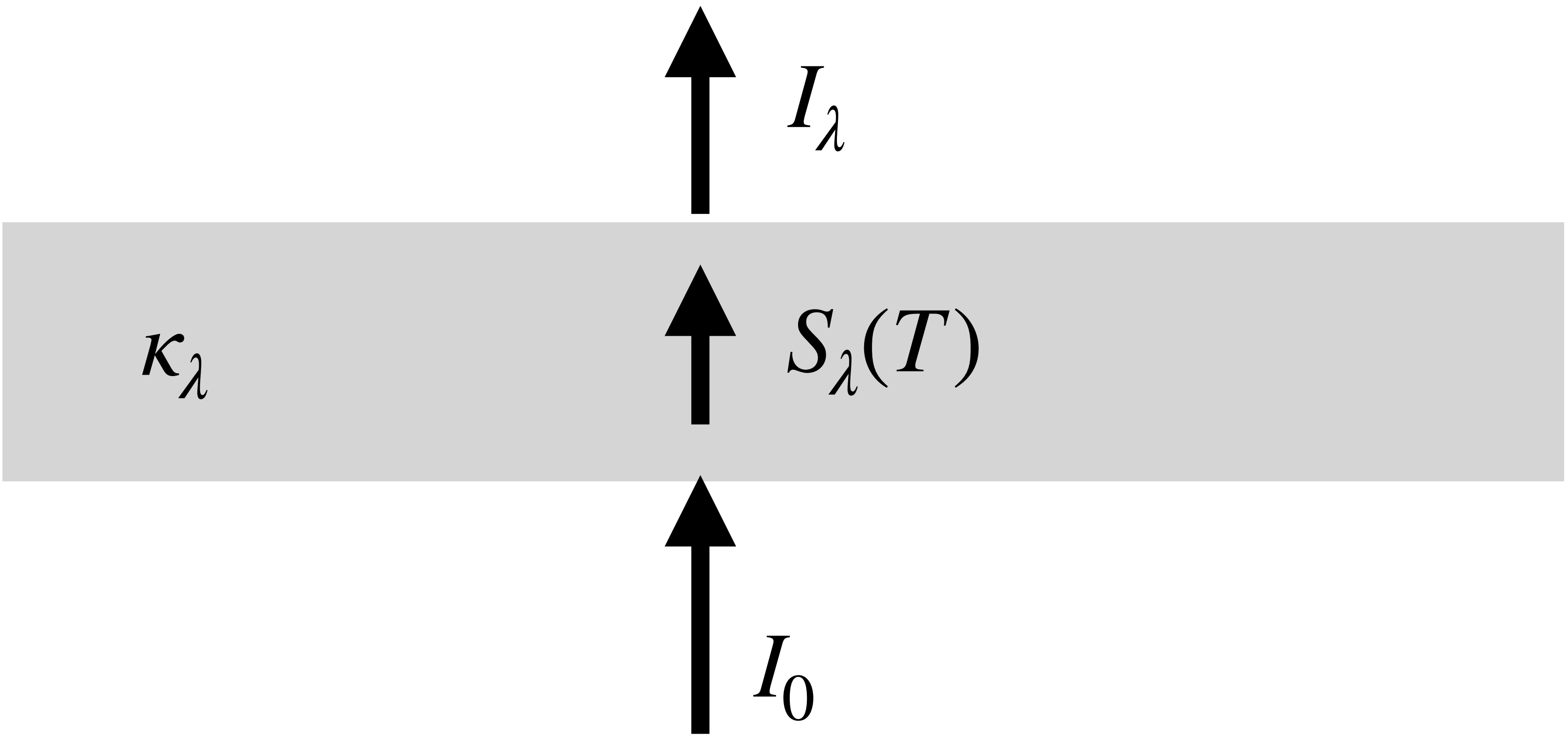
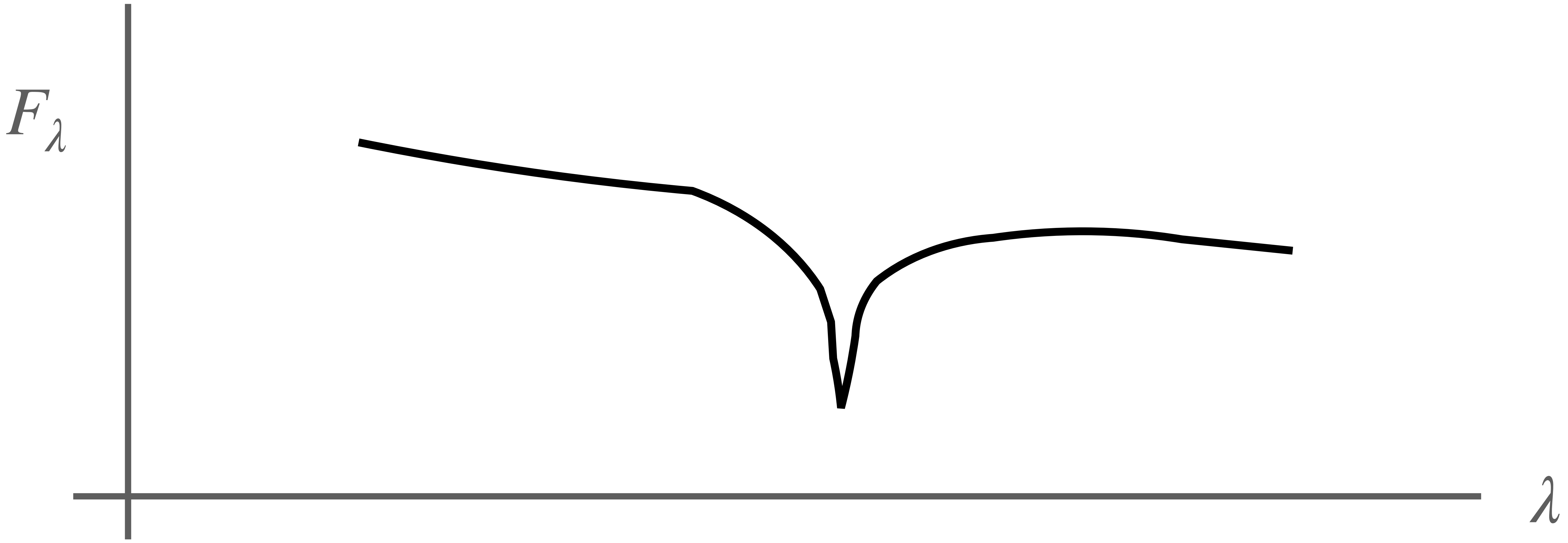
The Voigt Profile: $\sim \tau(\lambda)$

- Consider a “slab” atmosphere, for a single spectral line…

$$I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda} + S_\lambda\,(1 - e^{-\tau_\lambda})$$

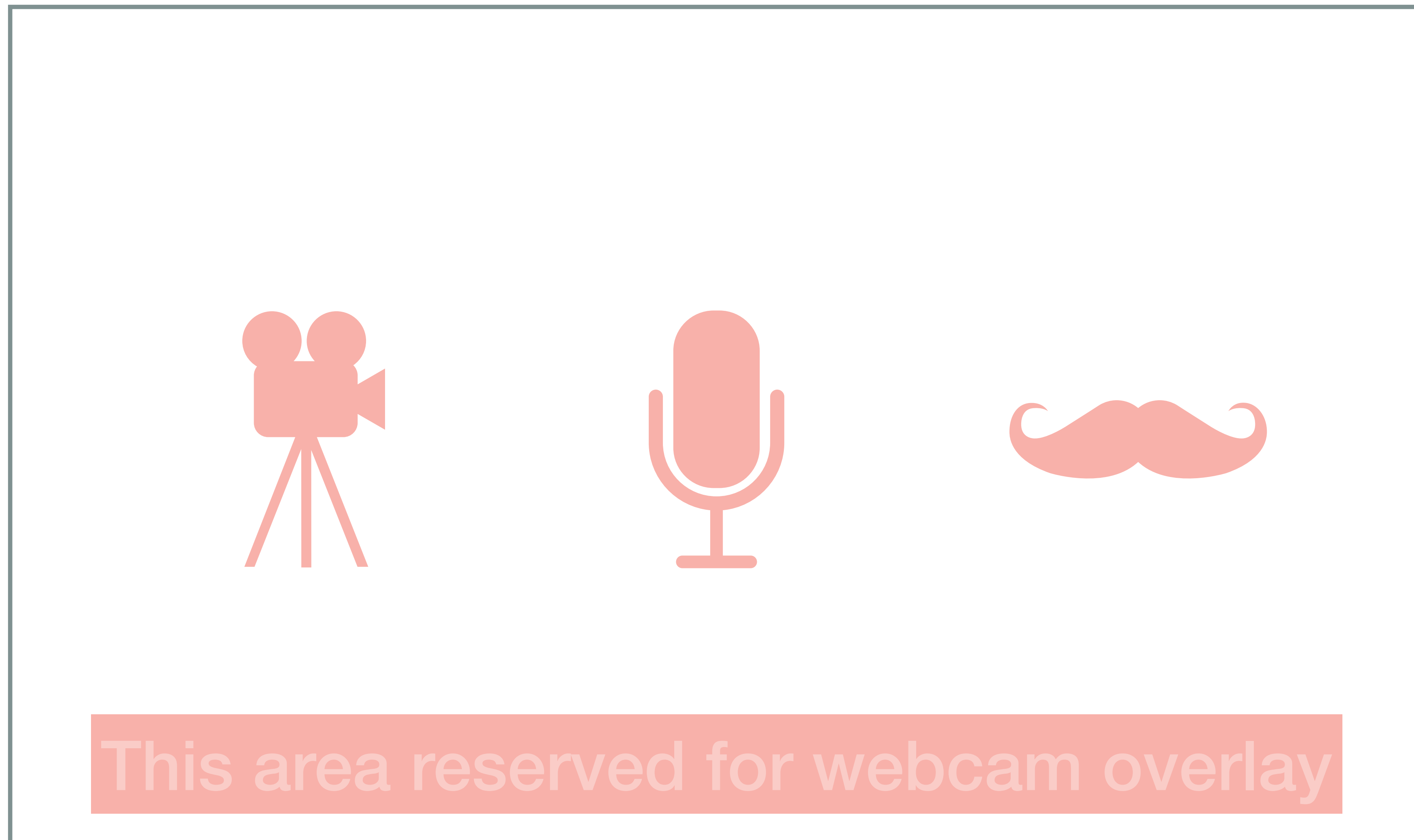




$$\tau(\lambda) = \tau_0\, V(\lambda, \sigma, \gamma)$$

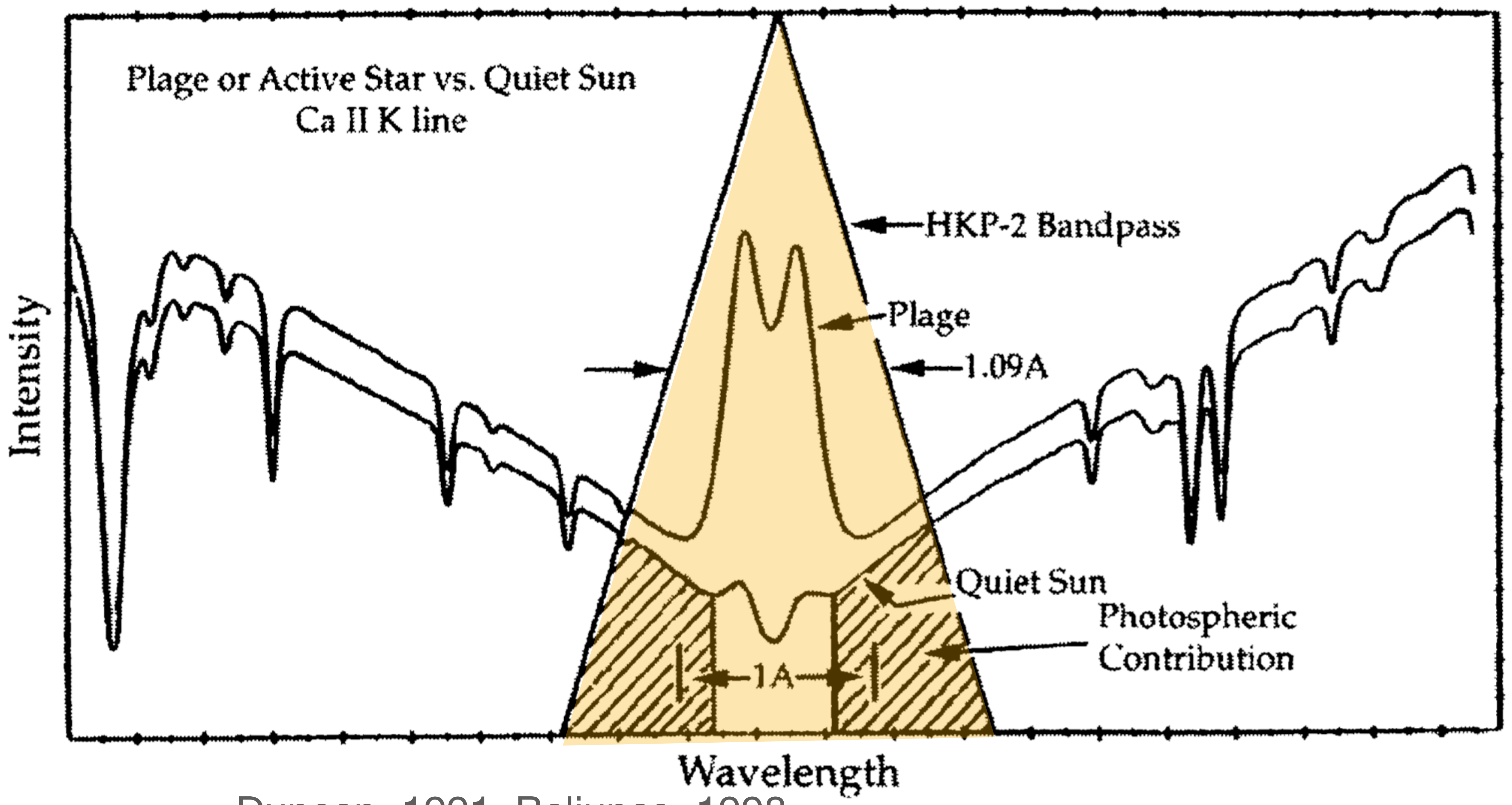
Gaussian

Lorentzian

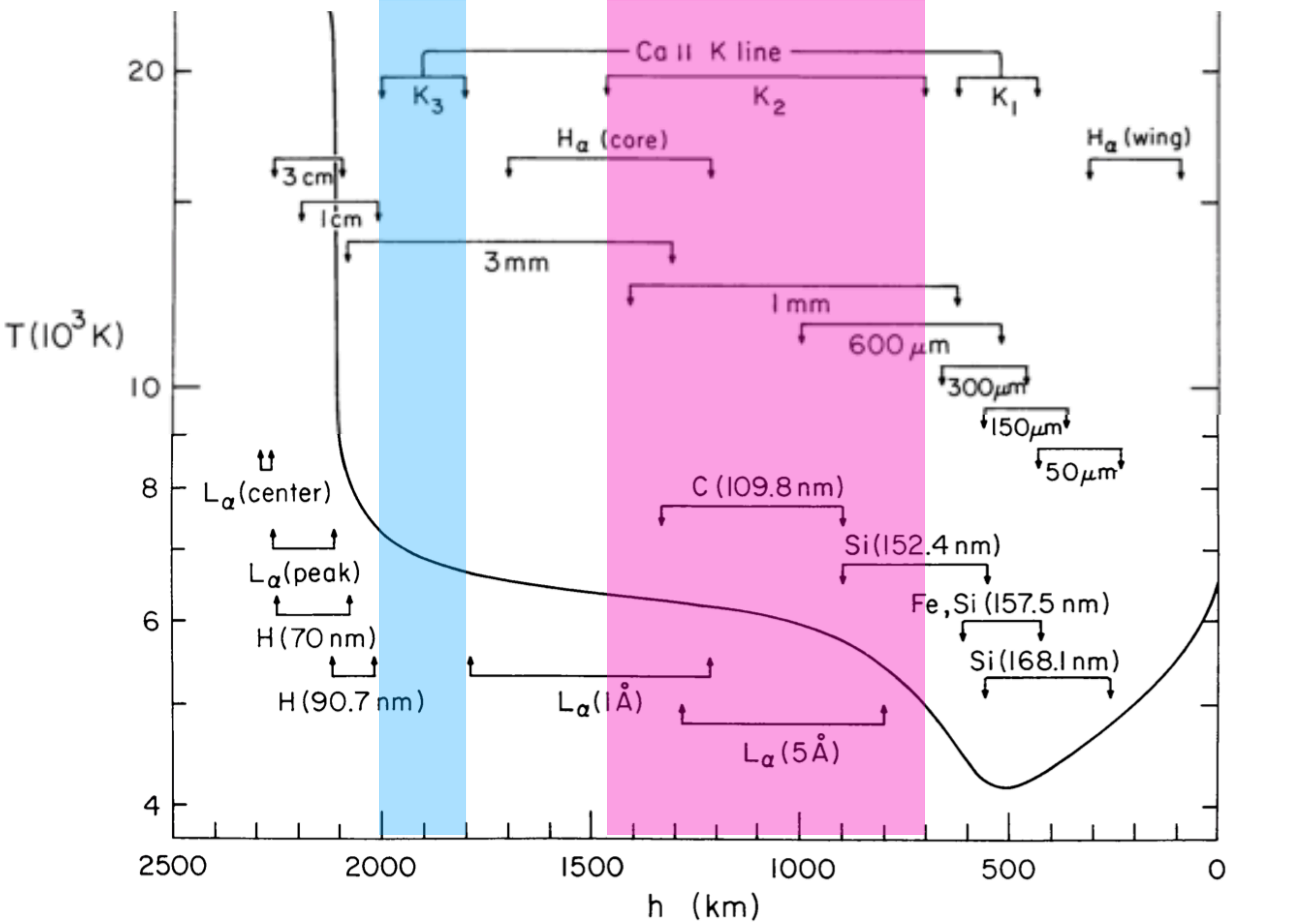


Ca II (or Ca+) “HK”

- The core is the most “interesting” part historically
- Strongly dependent on **B** heating of the chromosphere!



Duncan+1991, Baliunas+1998



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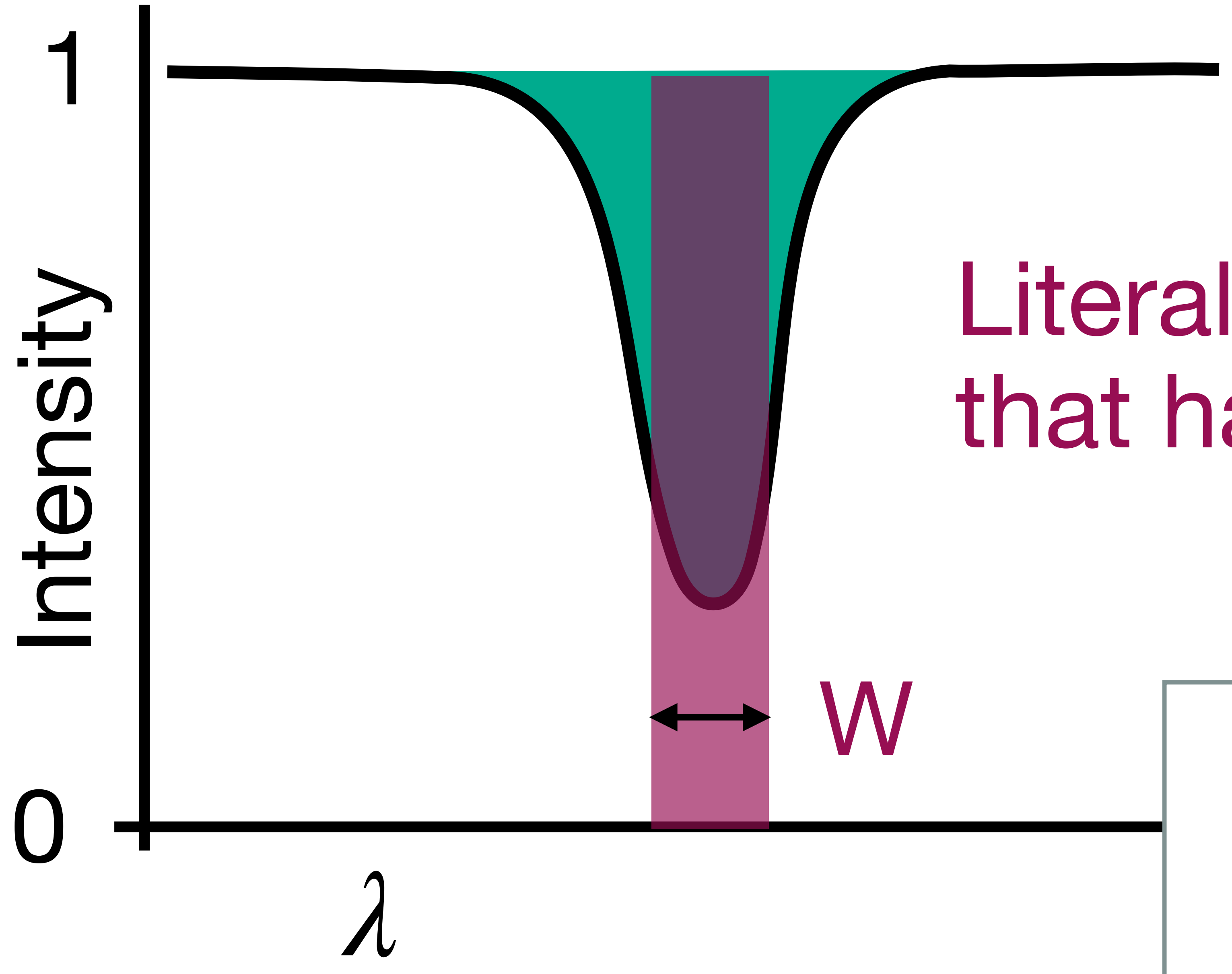
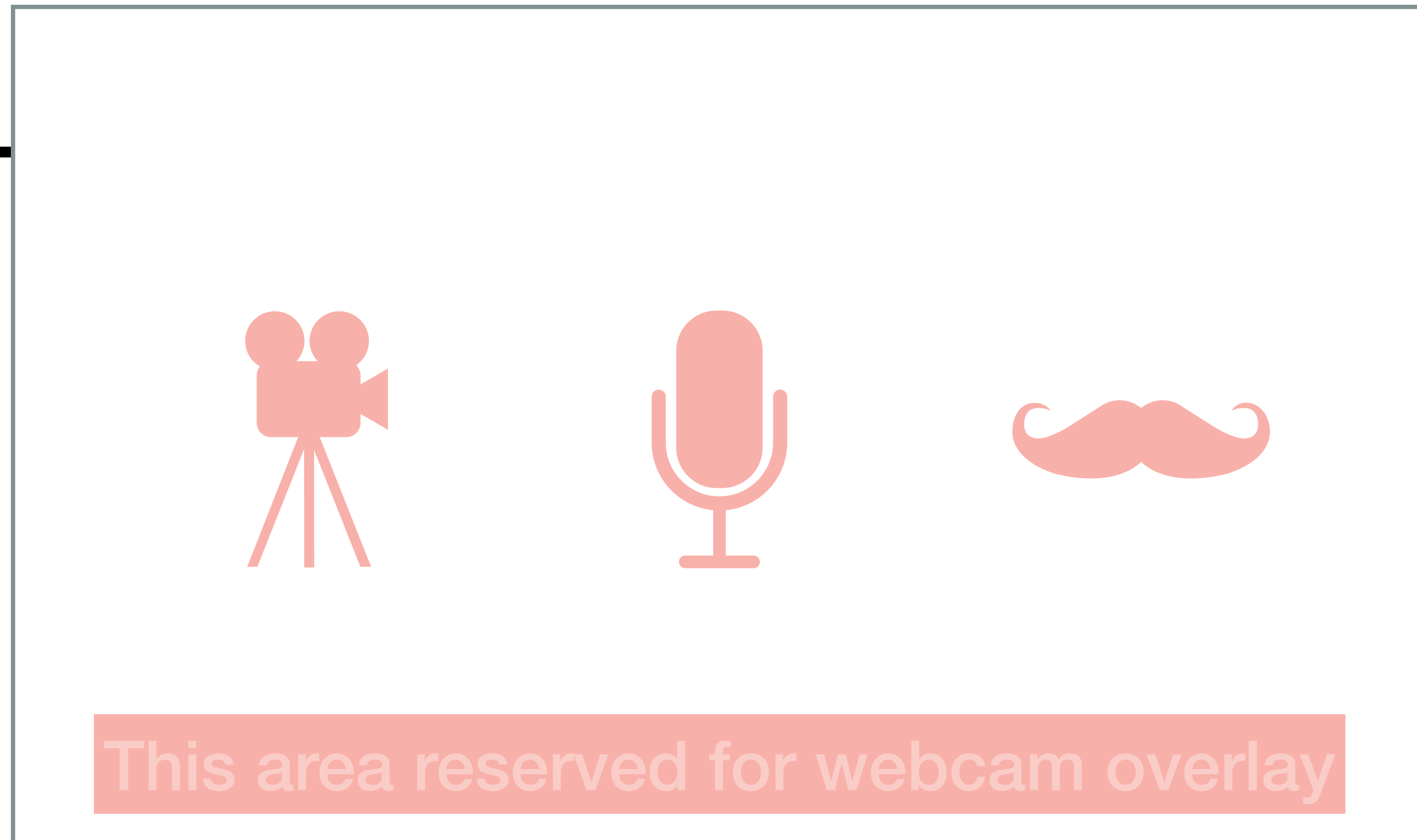
Equivalent Width

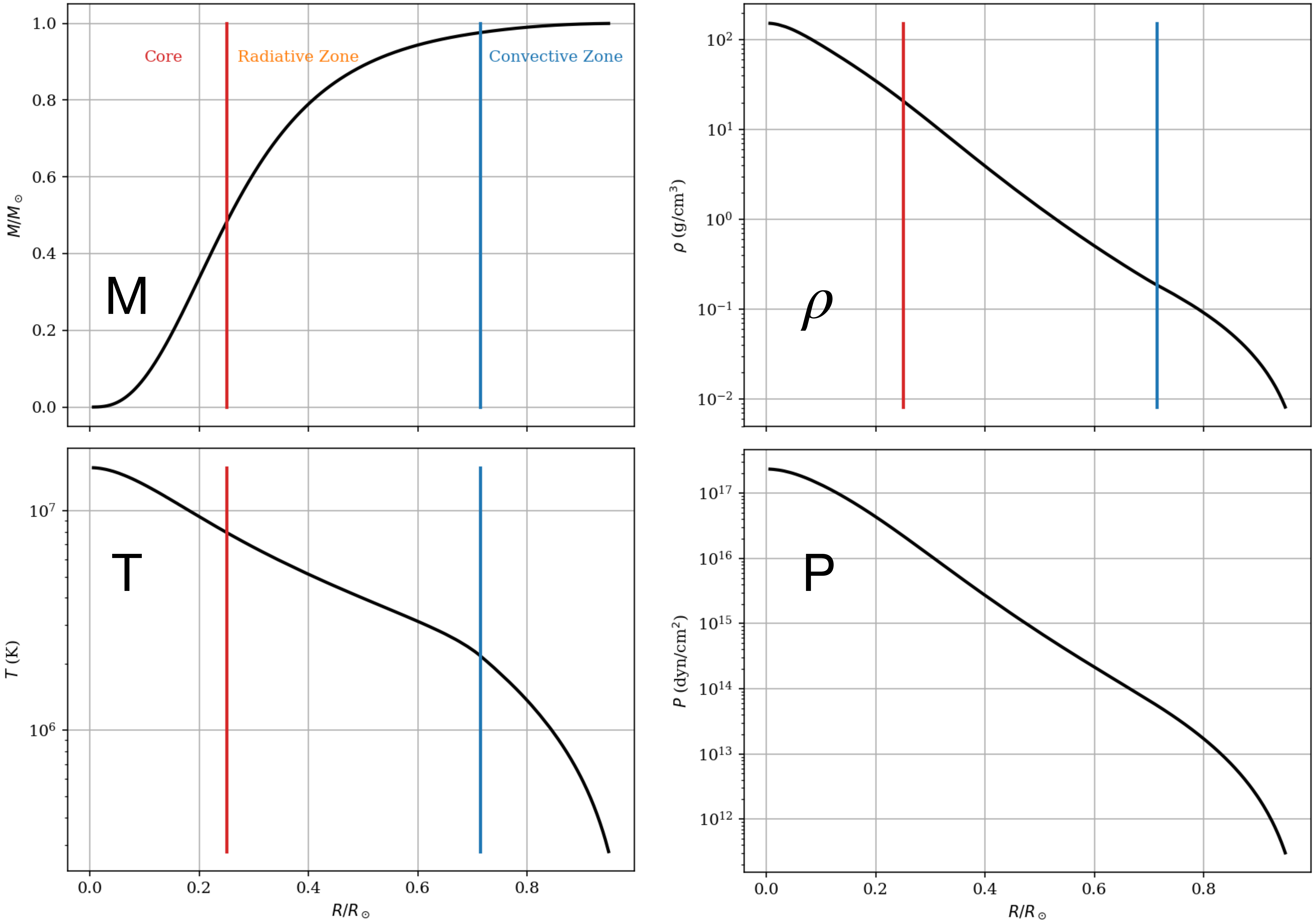
A strangely useful unit of measurement…

- When we talk about "line widths" we sometimes mean broadening (e.g. FWHM) and sometimes Equivalent Widths (i.e. **line intensity**)
- How to compute:
  - Normalize line to the continuum
  - Integrate area
  - Since Intensity here is unit-less, area under the curve has units of λ
  - Hence we talk about "1Å equiv. widths"…

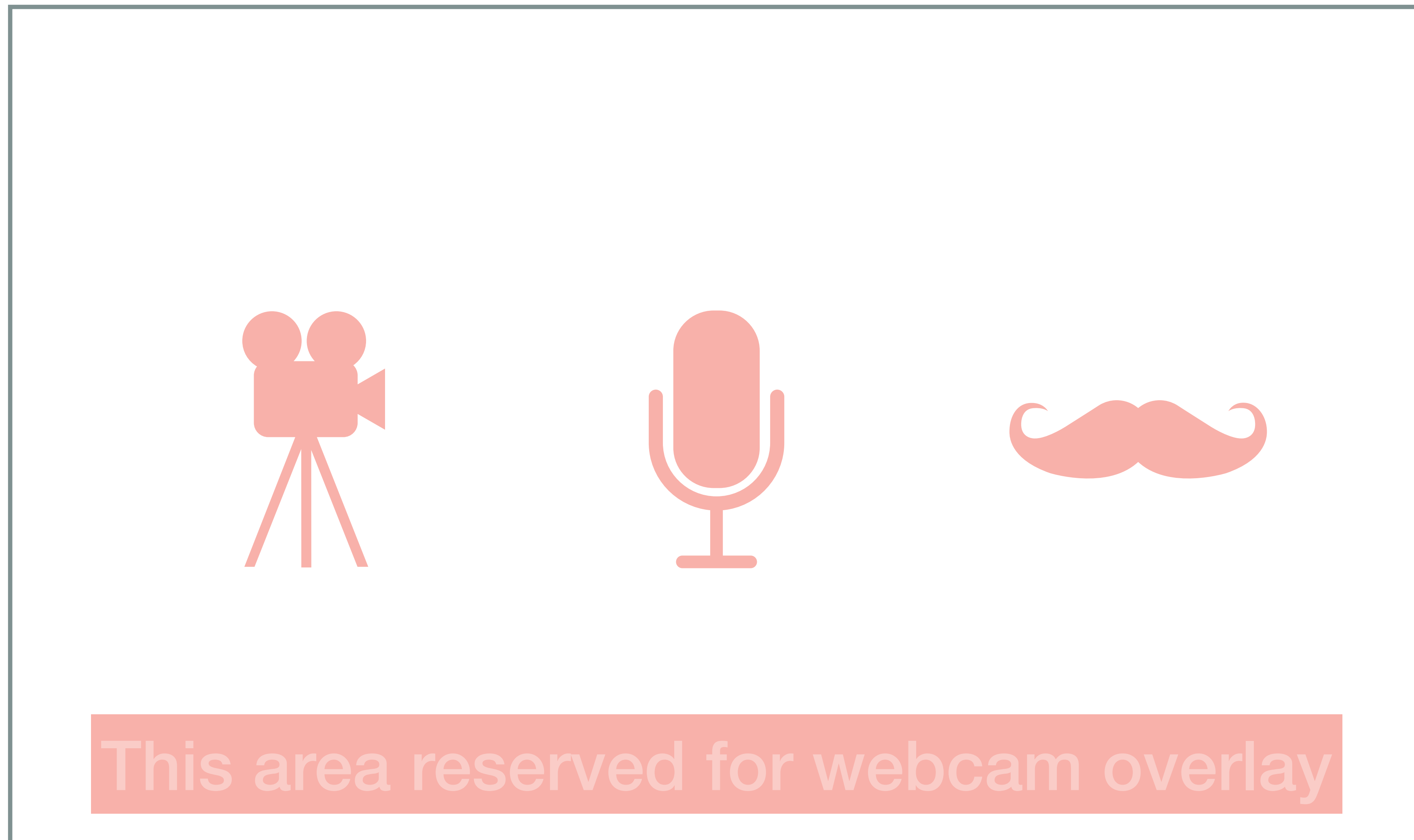




Stellar Structure Equations



- Last time we looked at *solar* structure qualitatively



Stellar Structure Equations

$$\frac{dP}{dr} = -G\frac{M_r \rho}{r^2} = -\rho g$$

$$\frac{dM}{dr} = 4\pi r^2 \rho$$

$$\frac{dL}{dr} = 4\pi r^2 \rho\, \epsilon$$

$$\frac{dT}{dr} = \frac{3\bar{\kappa}\rho L}{64\pi r^2 \sigma T^3} \qquad \frac{dT}{dr} = -\frac{g}{C_P}$$

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Stellar Timescales

- $t_{ff} = \frac{1}{2}\sqrt{\frac{R^3}{GM}}$ ~27 min (for the Sun)
- $t_{KH} \approx \frac{GM^2}{RL}$ ~30 Myr
- $t_{nuc} = \frac{E_{nuc}}{L}$ ~10^{10} yr

Pre-MS (star formation) Timescales!

Main Sequence Timescale

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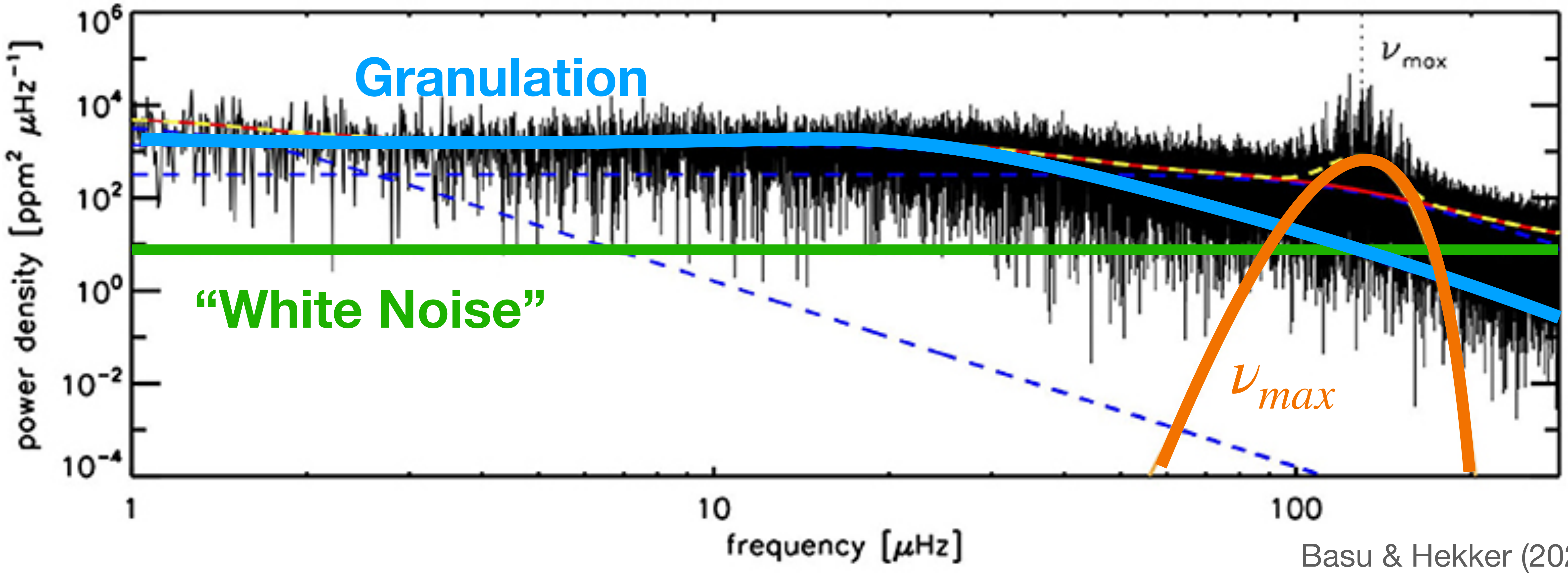
Pulsation

- **Asteroseismology**
- Based on solar-scaling

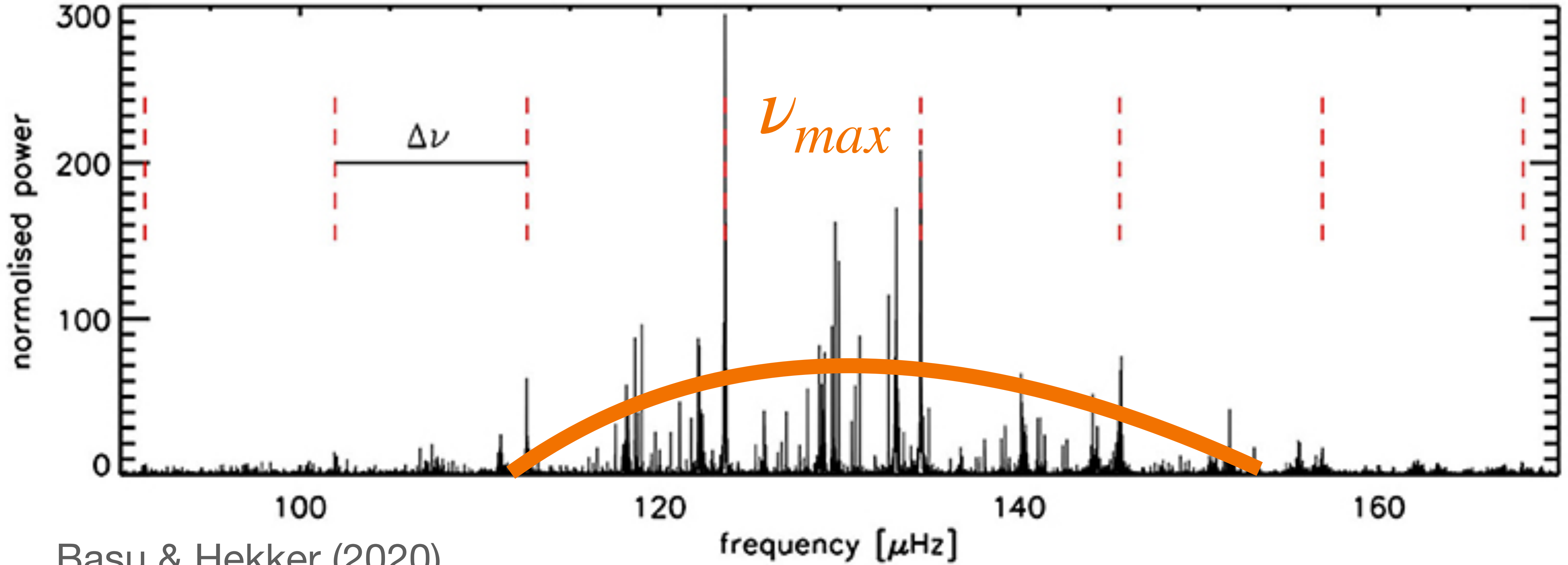
Ulrich 1986, Brown+1991



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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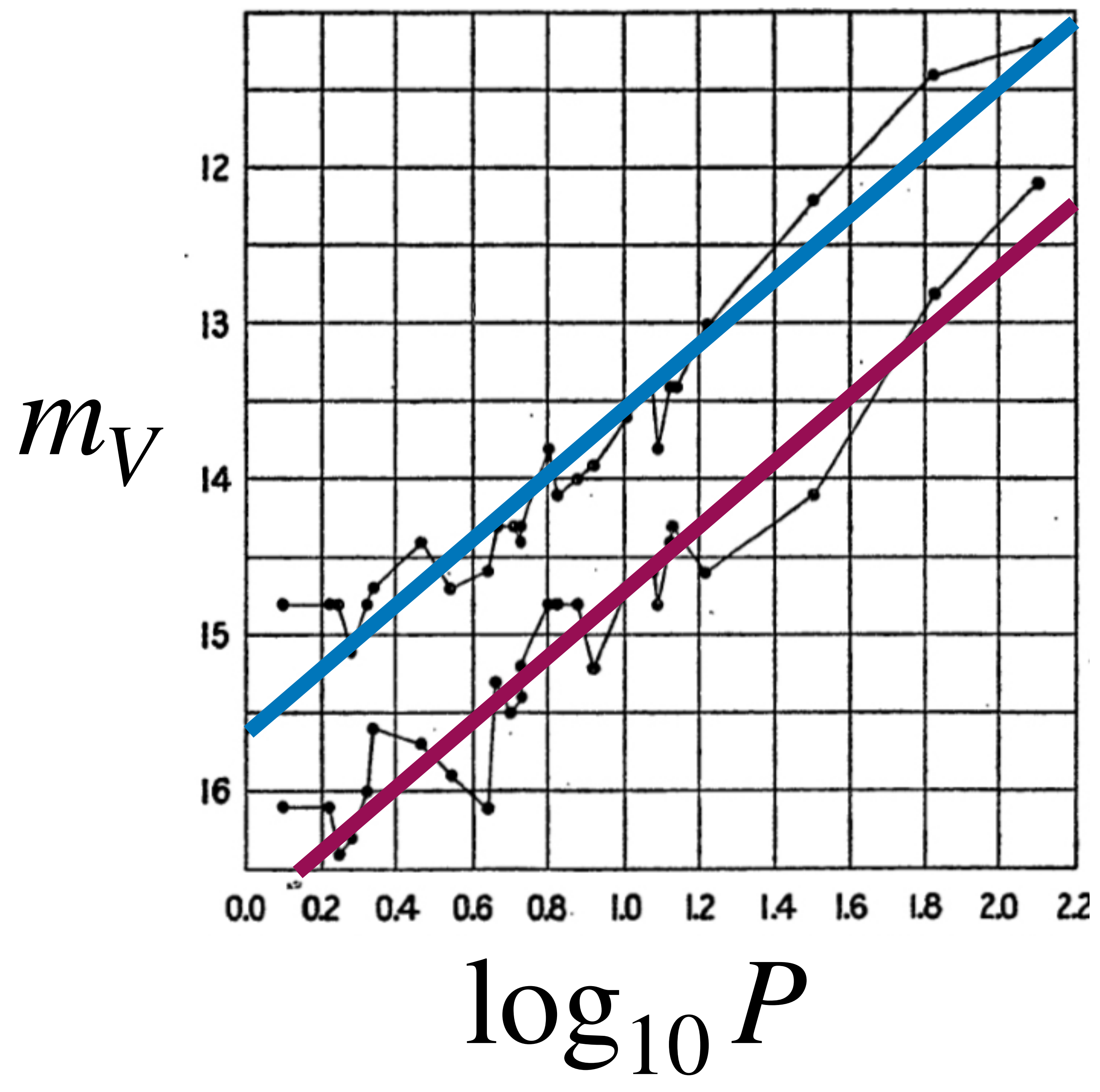
Period - Luminosity Relationship

"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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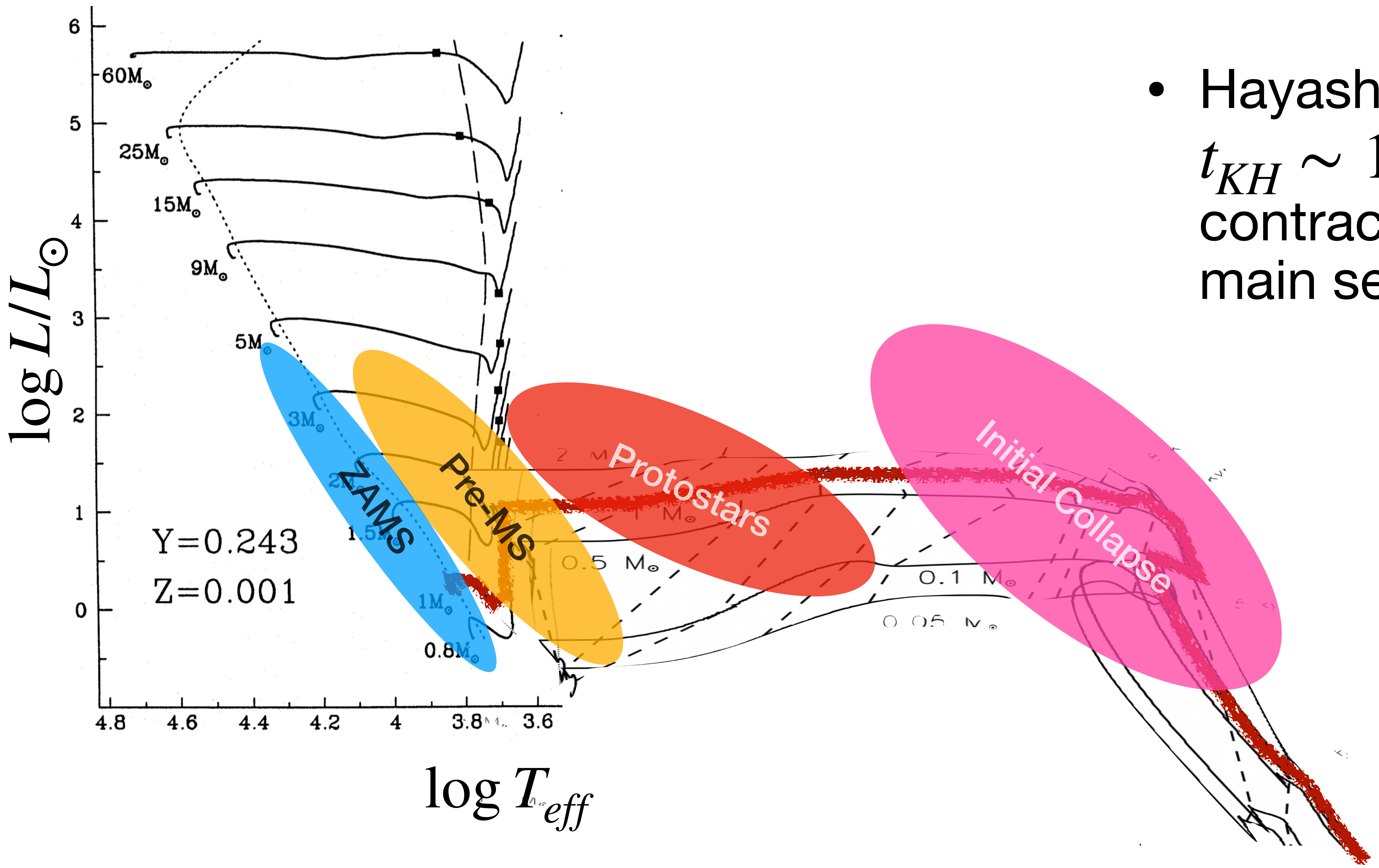
Putting it all together



- Cloud collapse: $t_{ff} \sim 10^5 - 10^6$ yr forms a protostar, creates the IMF
- Hayashi and Henyey tracks: $t_{KH} \sim 10^4 - 10^7$ yr contraction of protostar towards main sequence

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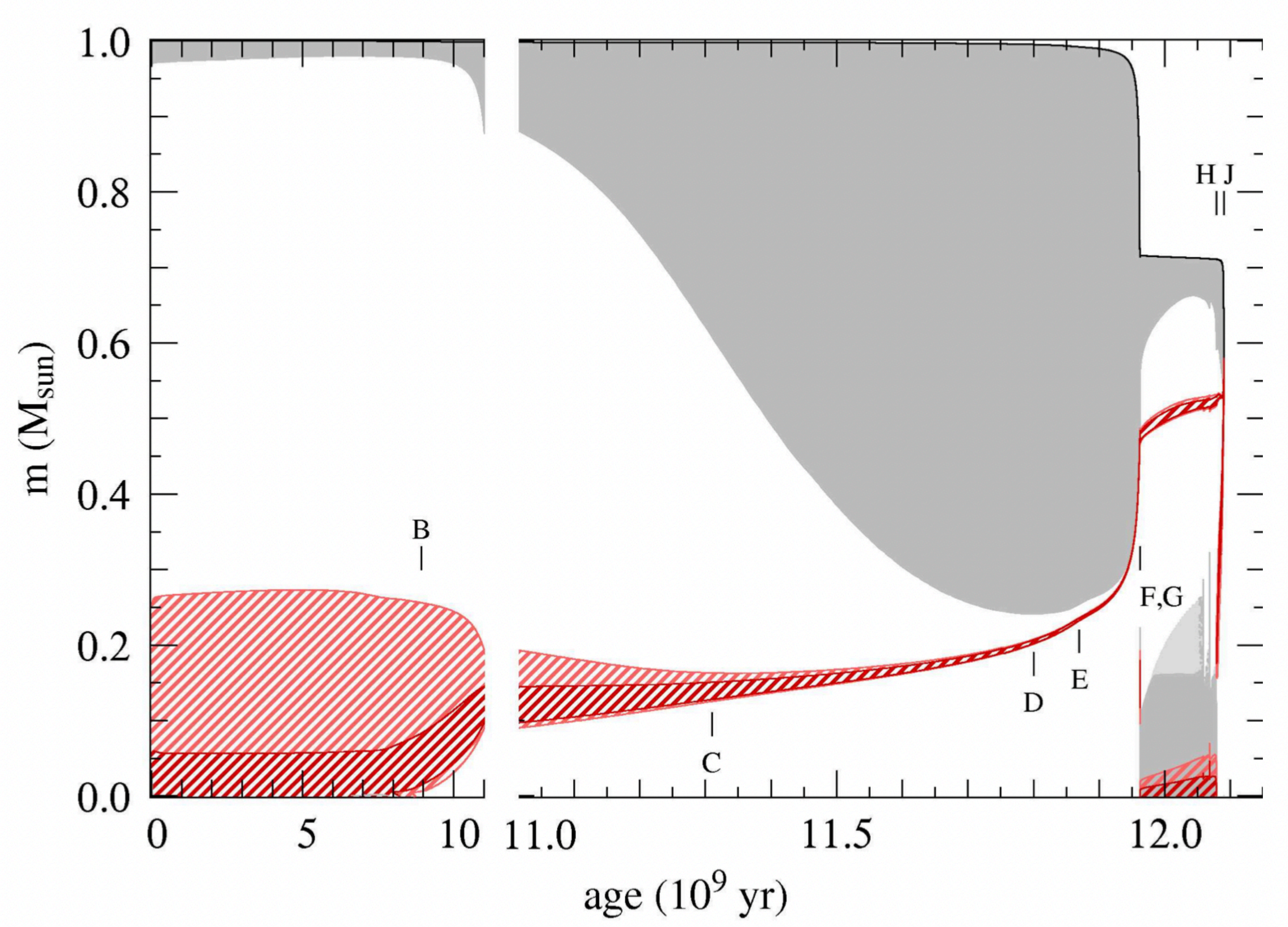
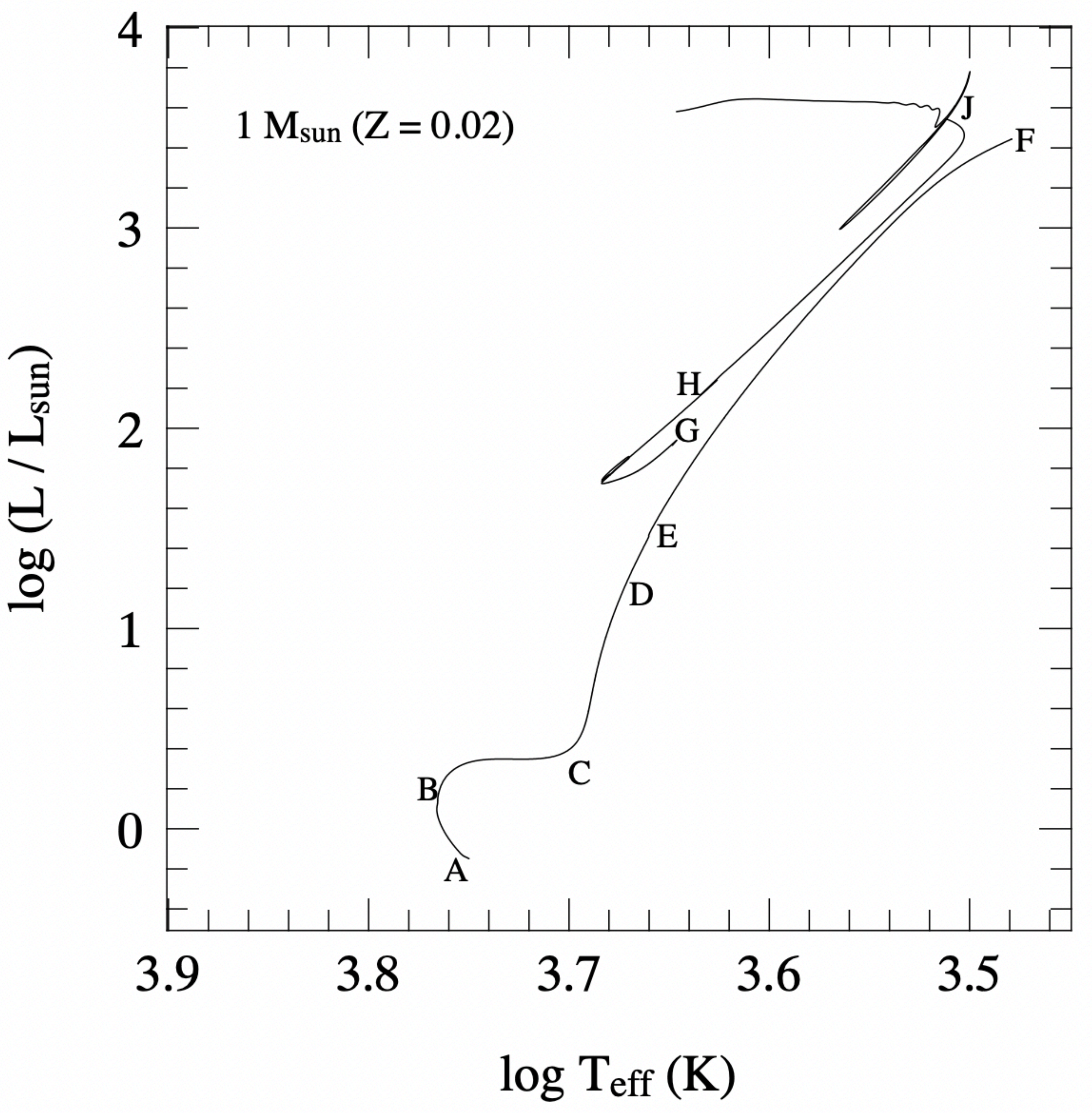
Kippenhan Diagrams





- If you like stars, Pols (2011) grad notes on Stellar Evolution are *awesome*…

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The Future

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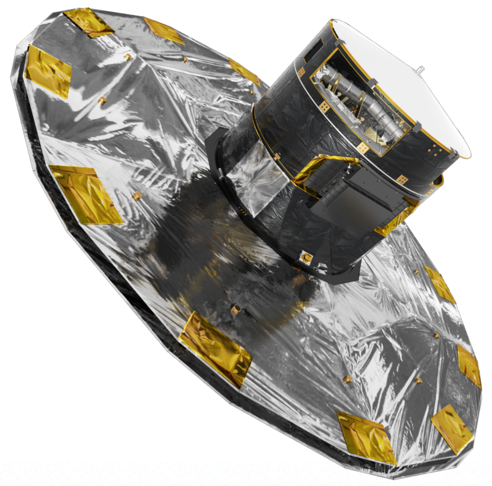
So much stellar data!

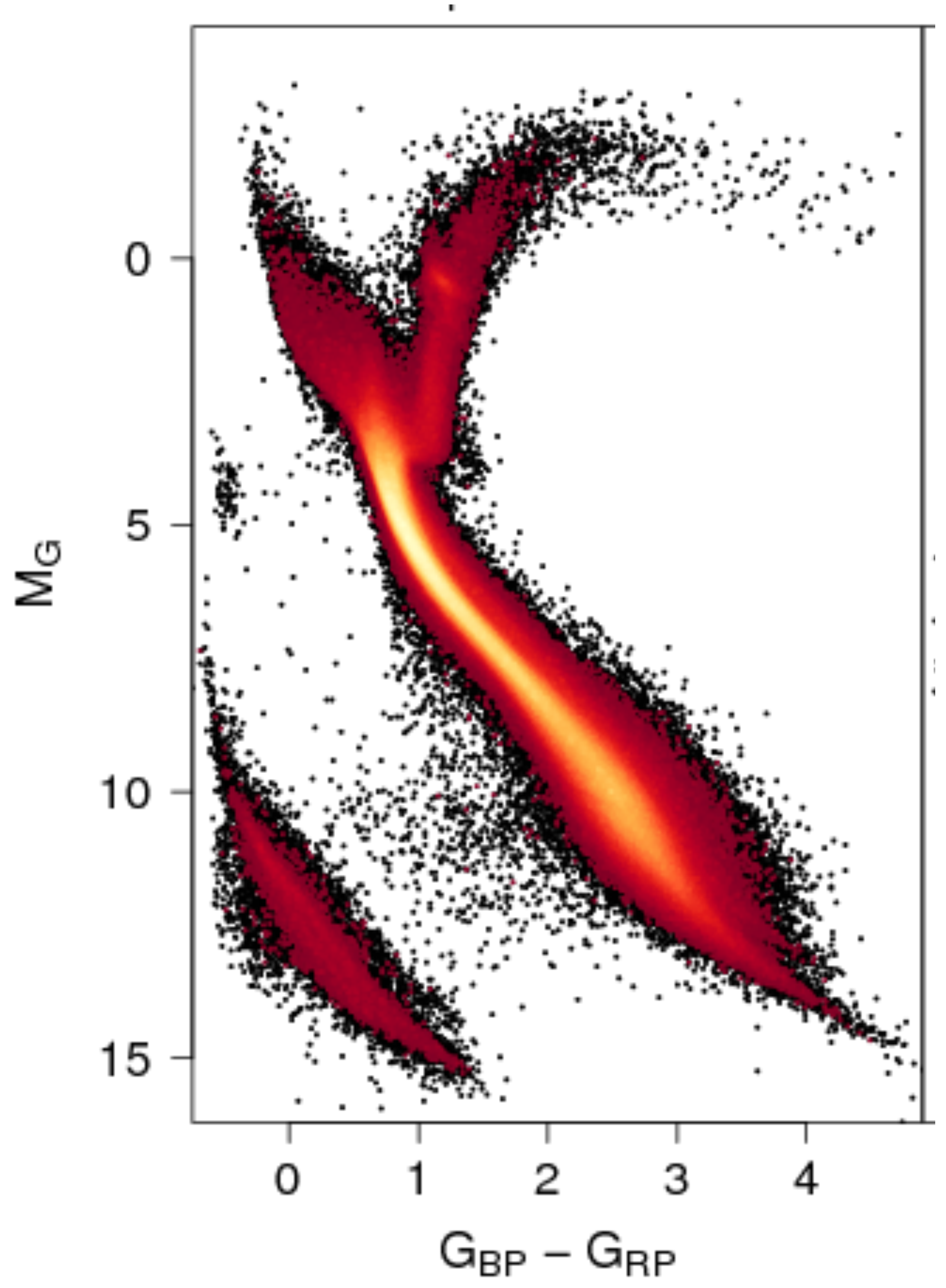
- Distances & properties for billions of stars
- Precise light curves for millions of stars
- High res spectra for hundreds of thousands of stars

- All textbook figures becoming obsolete
- Major challenges for theory/modeling

Gaia



	# sources in Gaia DR3	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	**1,811,709,771**	**1,692,919,135**	**1,142,679,769**
	Gaia Early Data Release 3		
Number of sources with minimally 5 astrometric parameters	1,467,744,818	1,331,909,727	2,057,050
Number of 5-parameter sources	585,416,709		
Number of 6-parameter sources	882,328,109		
Number of 2-parameter sources	343,964,953	361,009,408	1,140,622,719
Gaia-CRF sources	1,614,173	556,869	2,191
Sources with mean G magnitude	1,806,254,432	1,692,919,135	1,142,679,769
Sources with mean G_{BP}-band photometry	1,542,033,472	1,381,964,755	-
Sources with mean G_{RP}-band photometry	1,554,997,939	1,383,551,713	-
	New data in Gaia Data Release 3 (pending validation)		
Sources with radial velocities	≈ 33,000,000	7,224,631	-
BP/RP spectra	> 100,000,000	-	-
RVS spectra	≈ 1,000,000	-	-
Variable source classifications	≈ 13,000,000	550,737	3,194
Object classifications	≈ 1,000,000,000	-	-
Sources with astrophysical parameters	≈ 500,000,000	161,497,595	-
Non-single stars	≈ a few 100,000	-	-
QSO host and galaxy morphological characterisation	≈ a few 1,000,000	-	-
Solar system objects	≈ 150,000	14,099	-
Reflectance spectra for solar system objects	≈ 50,000	-	-
Average BP/RP reflectance spectra of asteroids	≈ 10,000	-	-
Gaia Andromeda Photometric Survey (GAPS)	≈ 1,000,000	-	-



Data Release 3: June 13 2022

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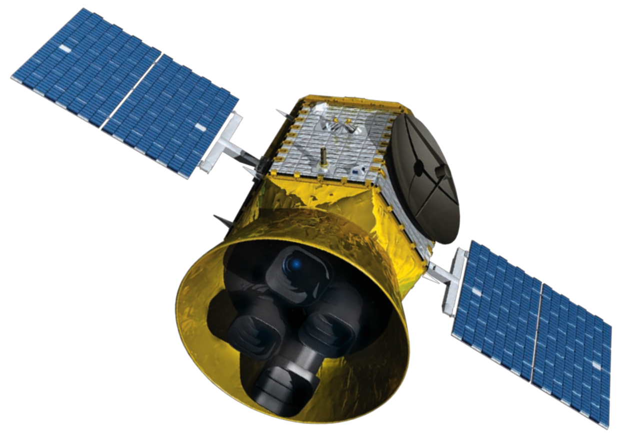

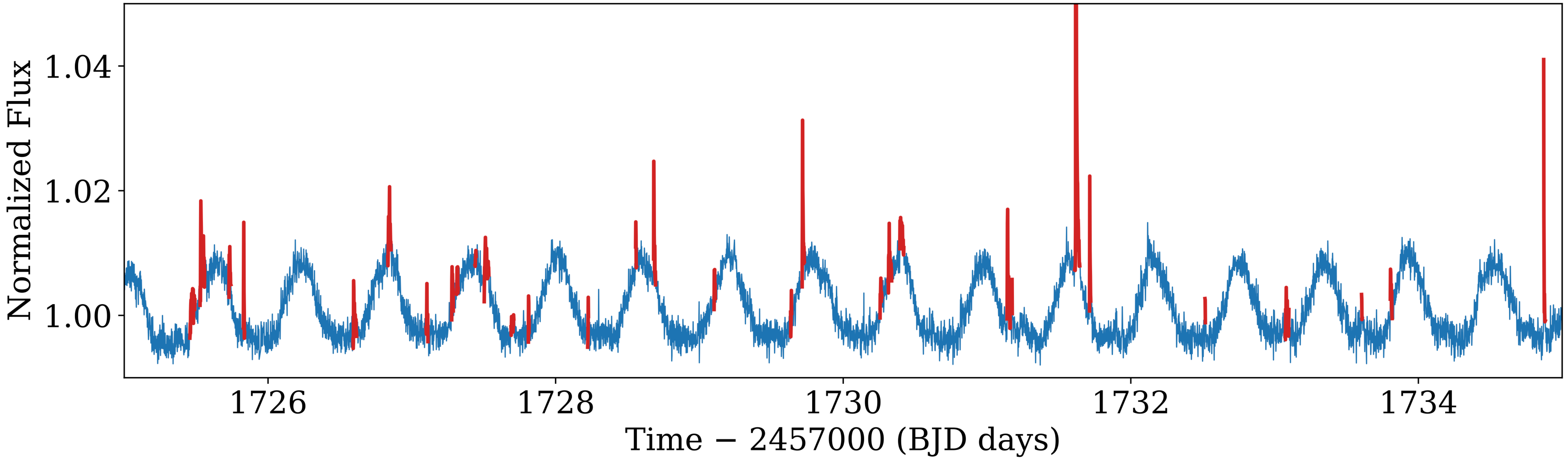

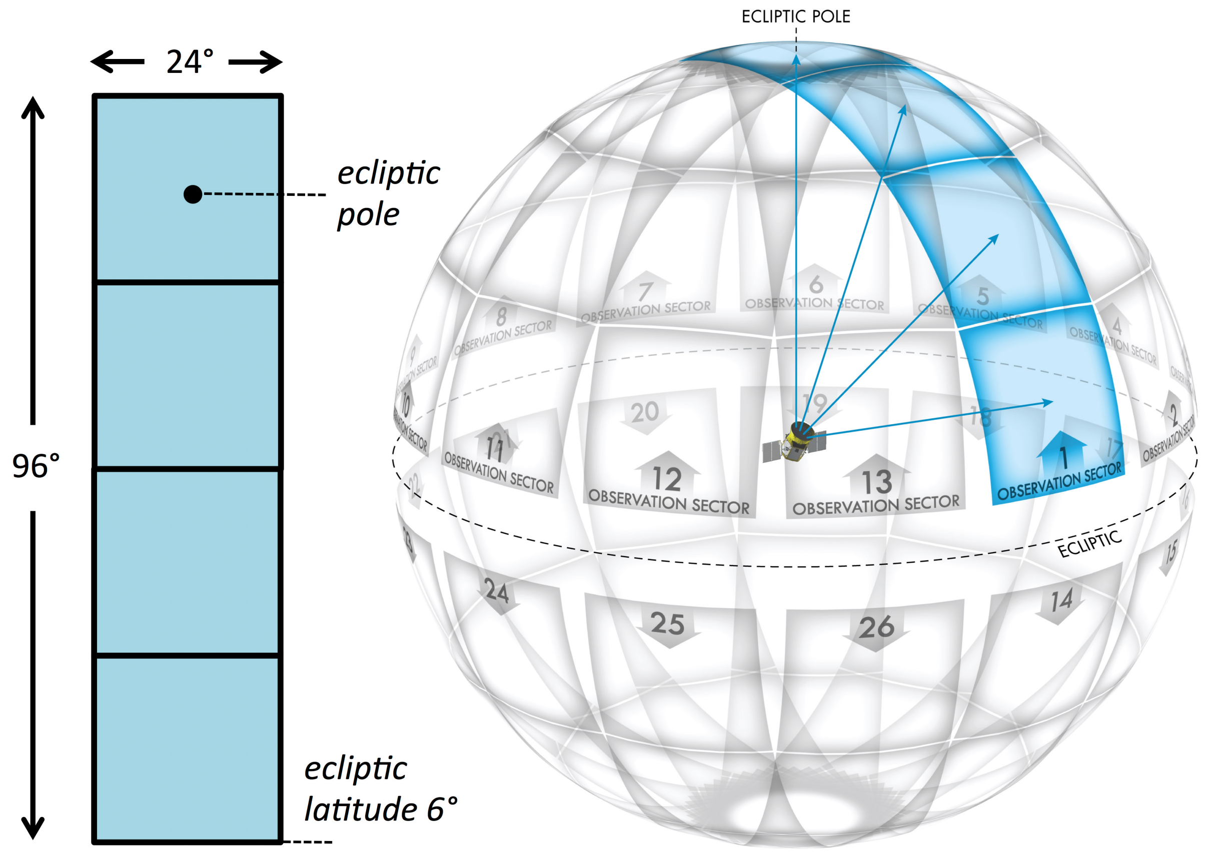

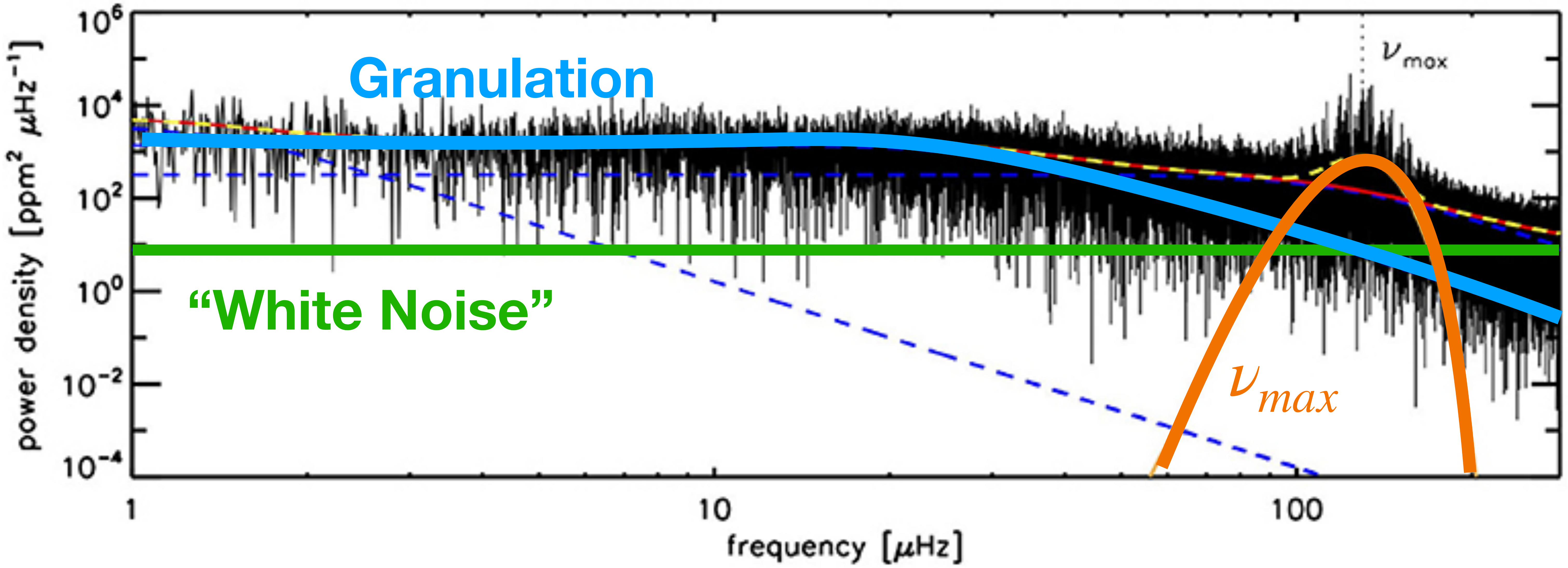

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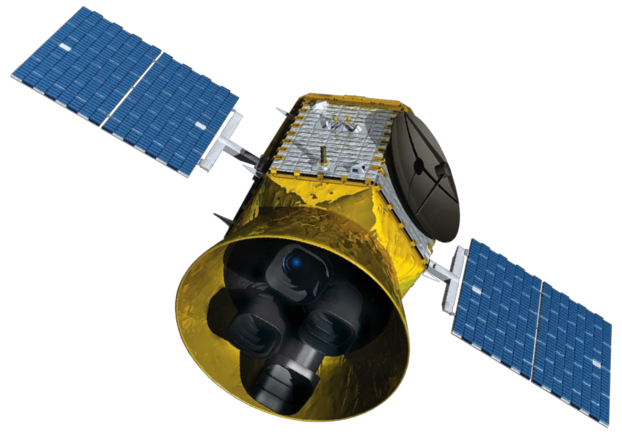
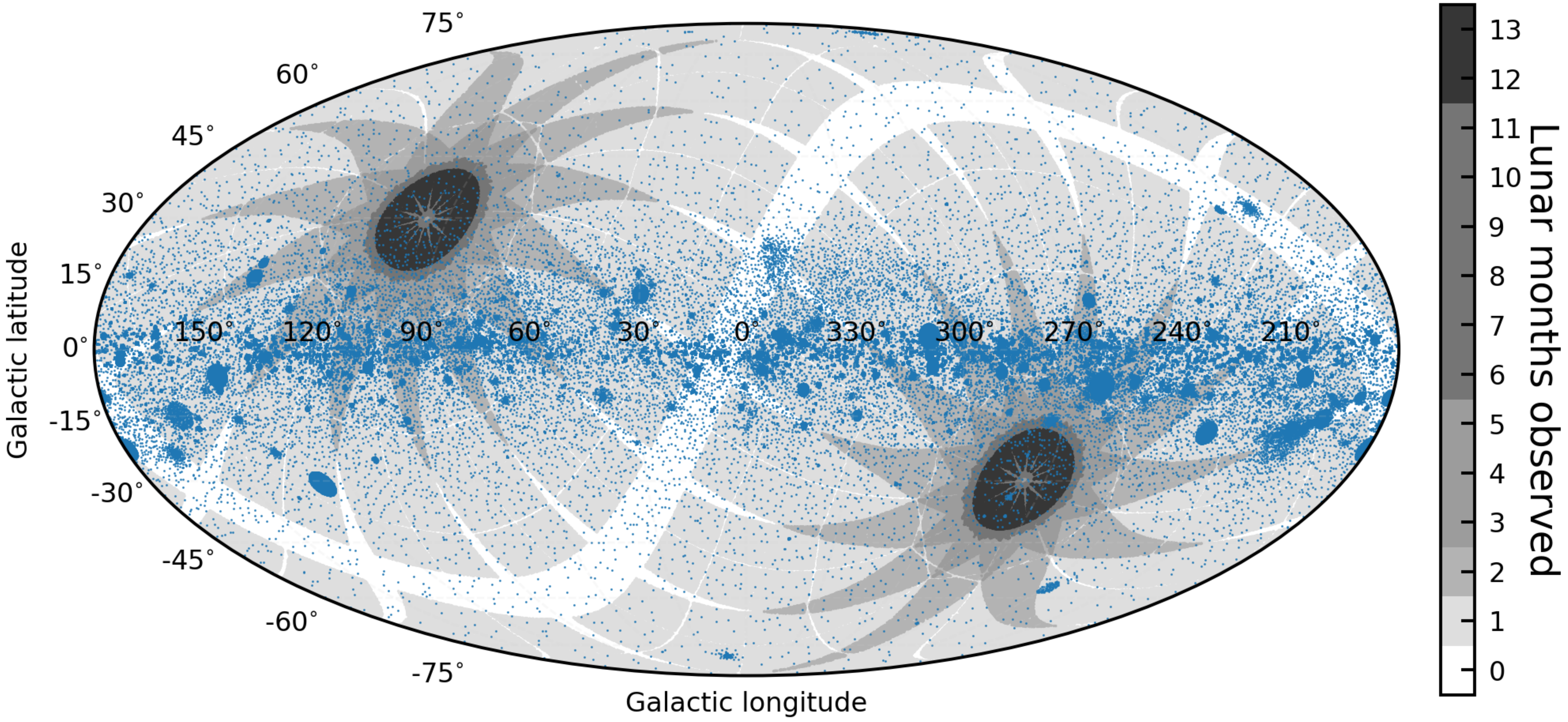
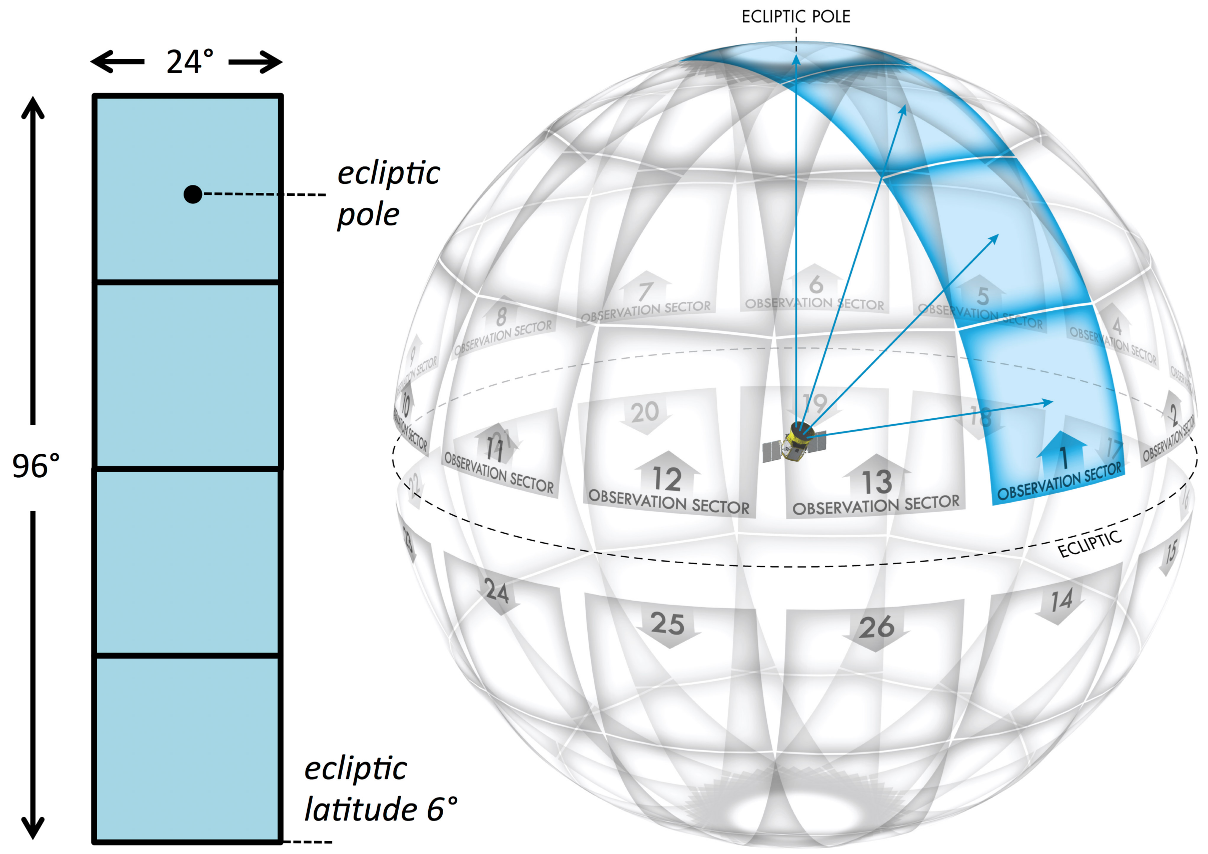


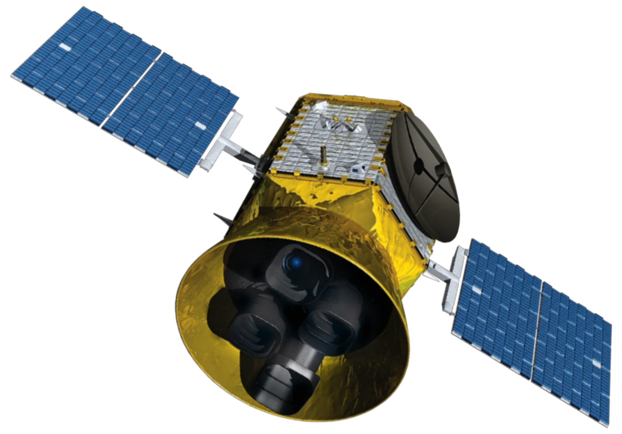


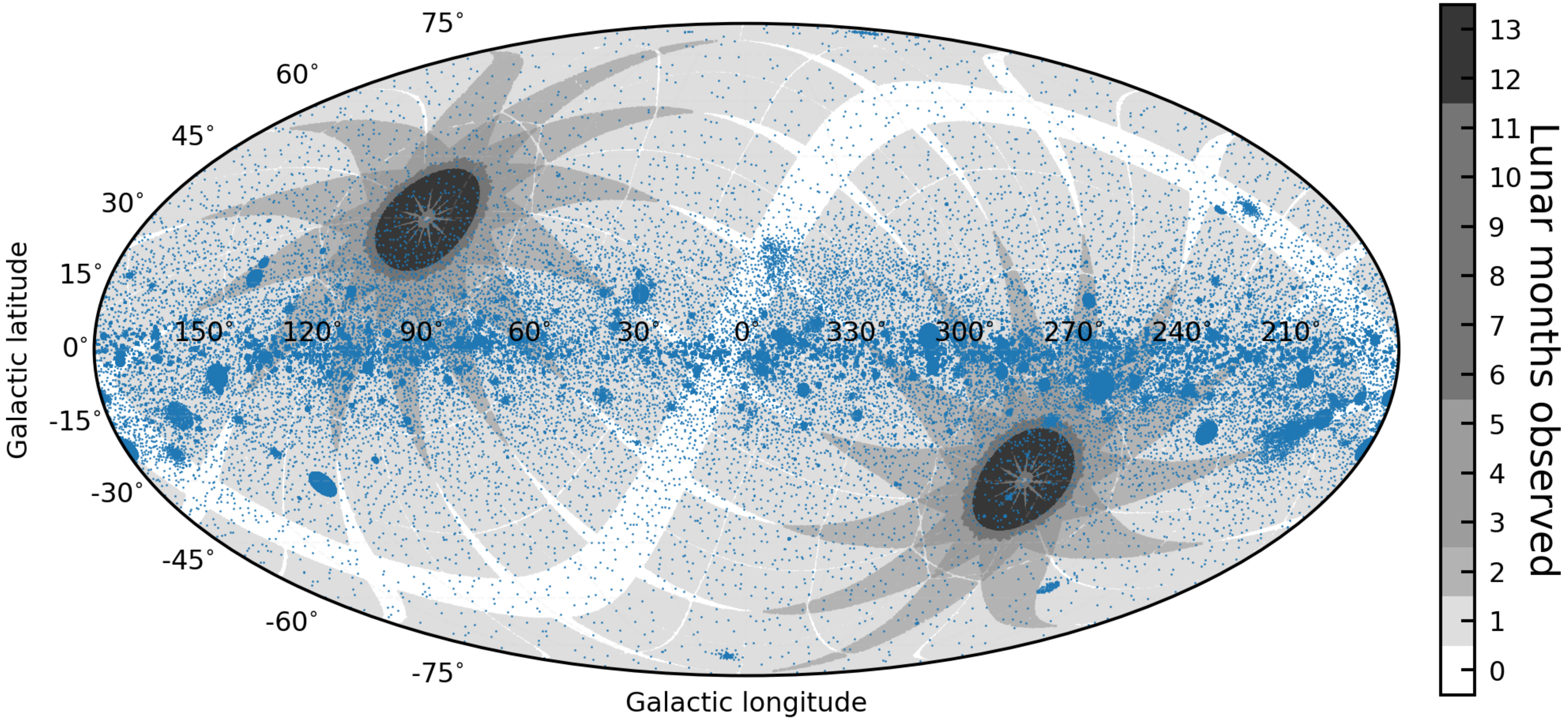


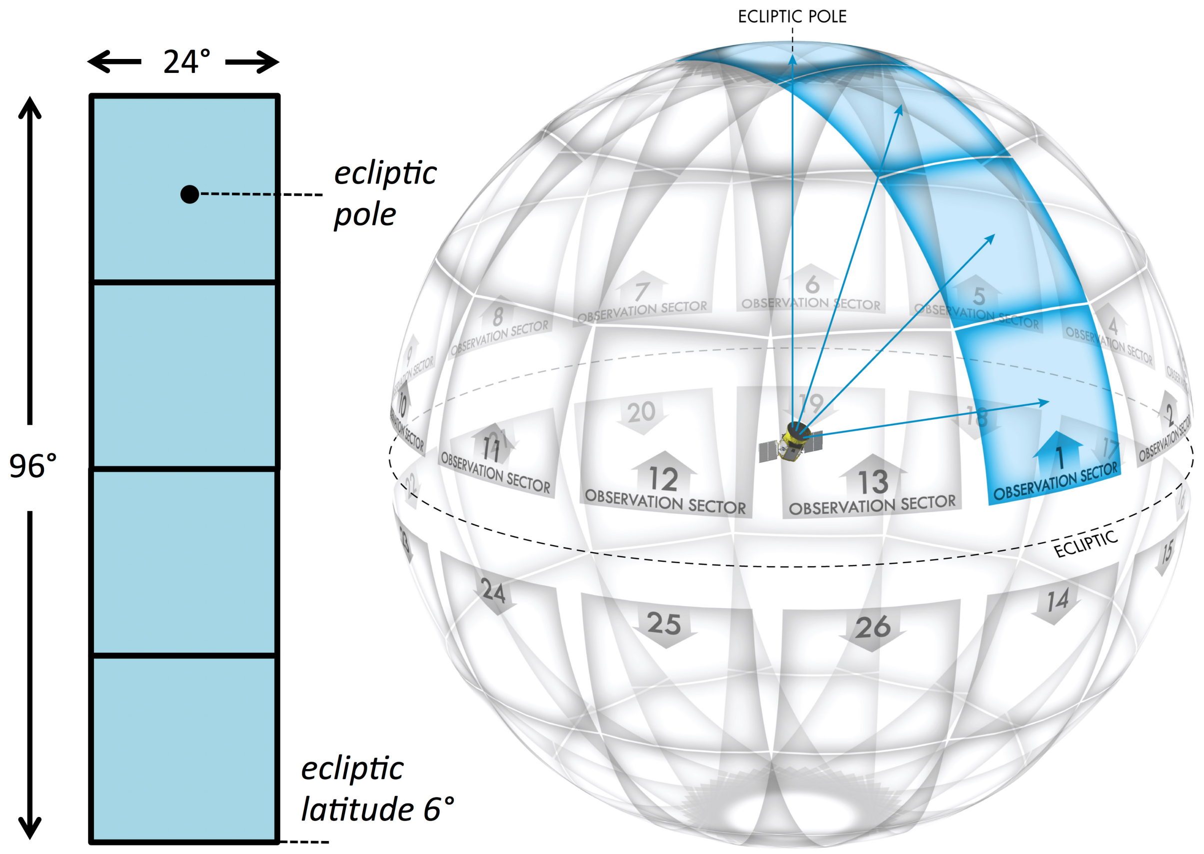
Bouma+2019

This area reserved for webcam overlay

TESS



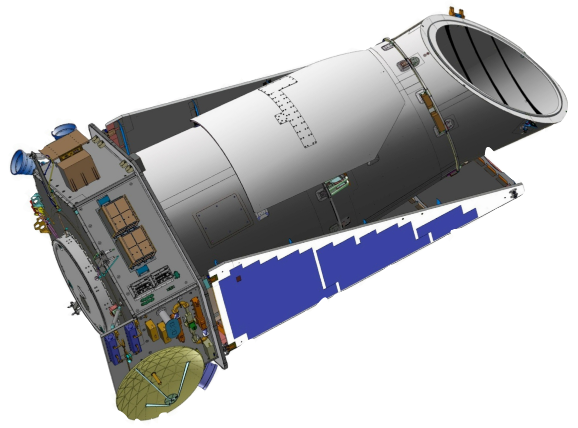


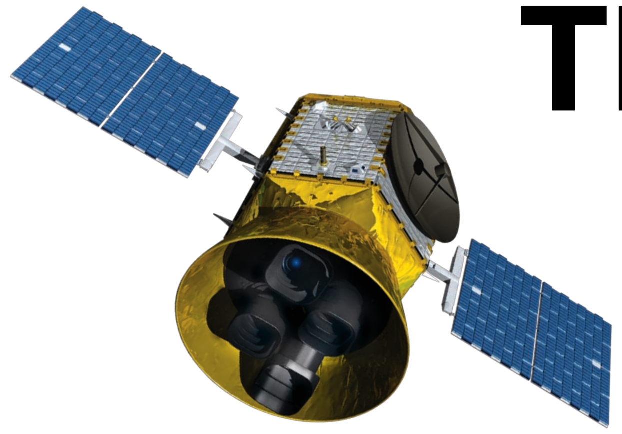


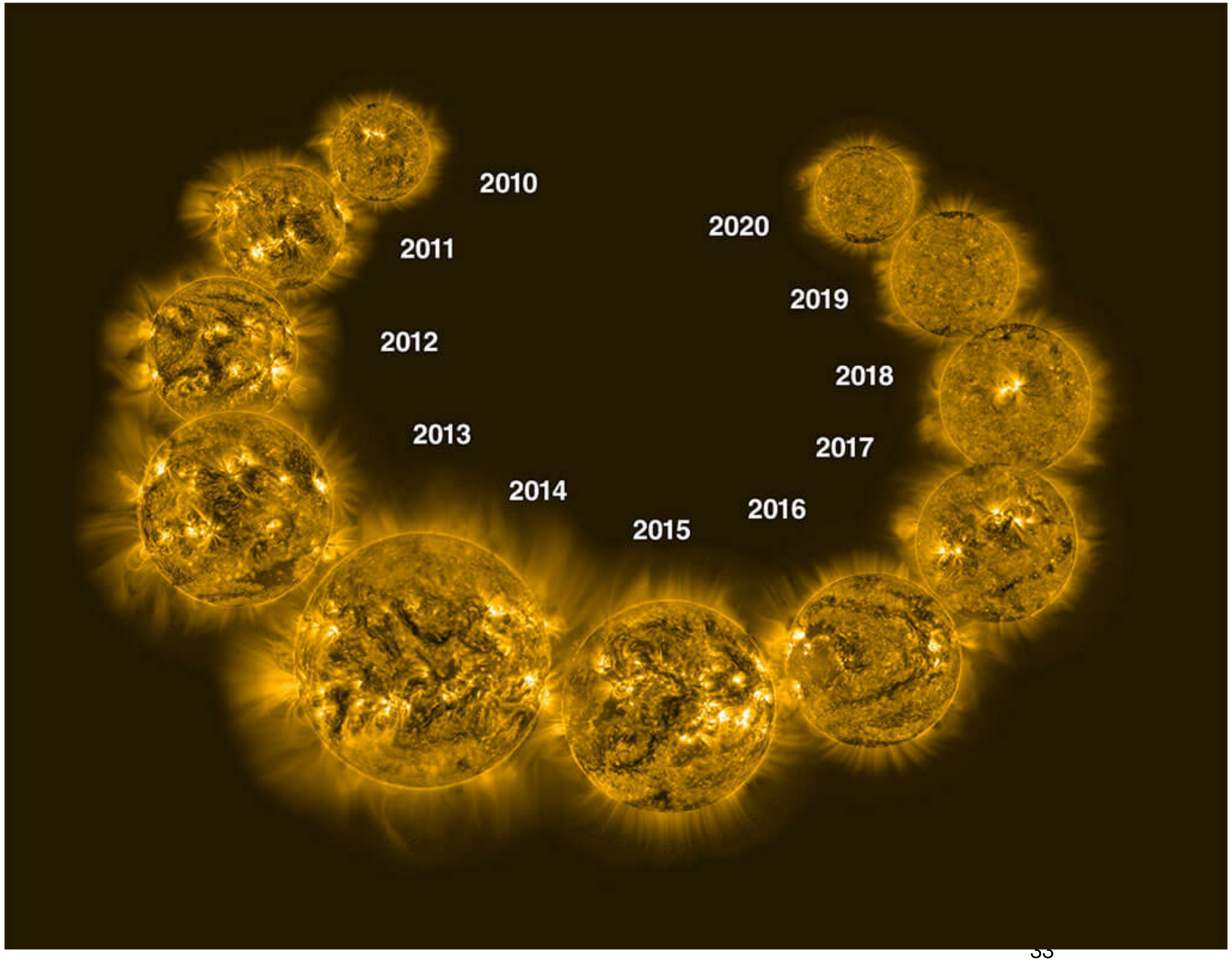
Bouma+2019

This area reserved for webcam overlay

TESS + Kepler = 10year+ Baseline







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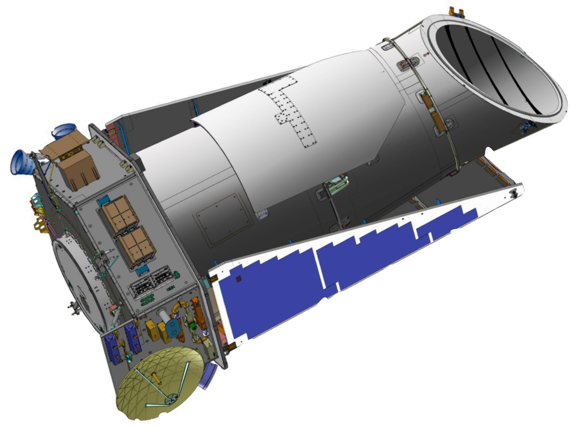

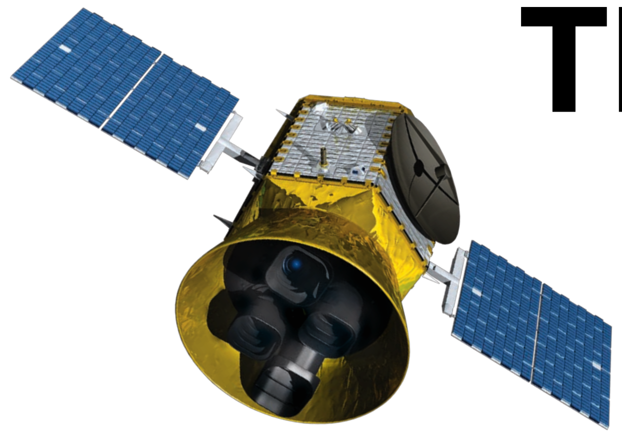

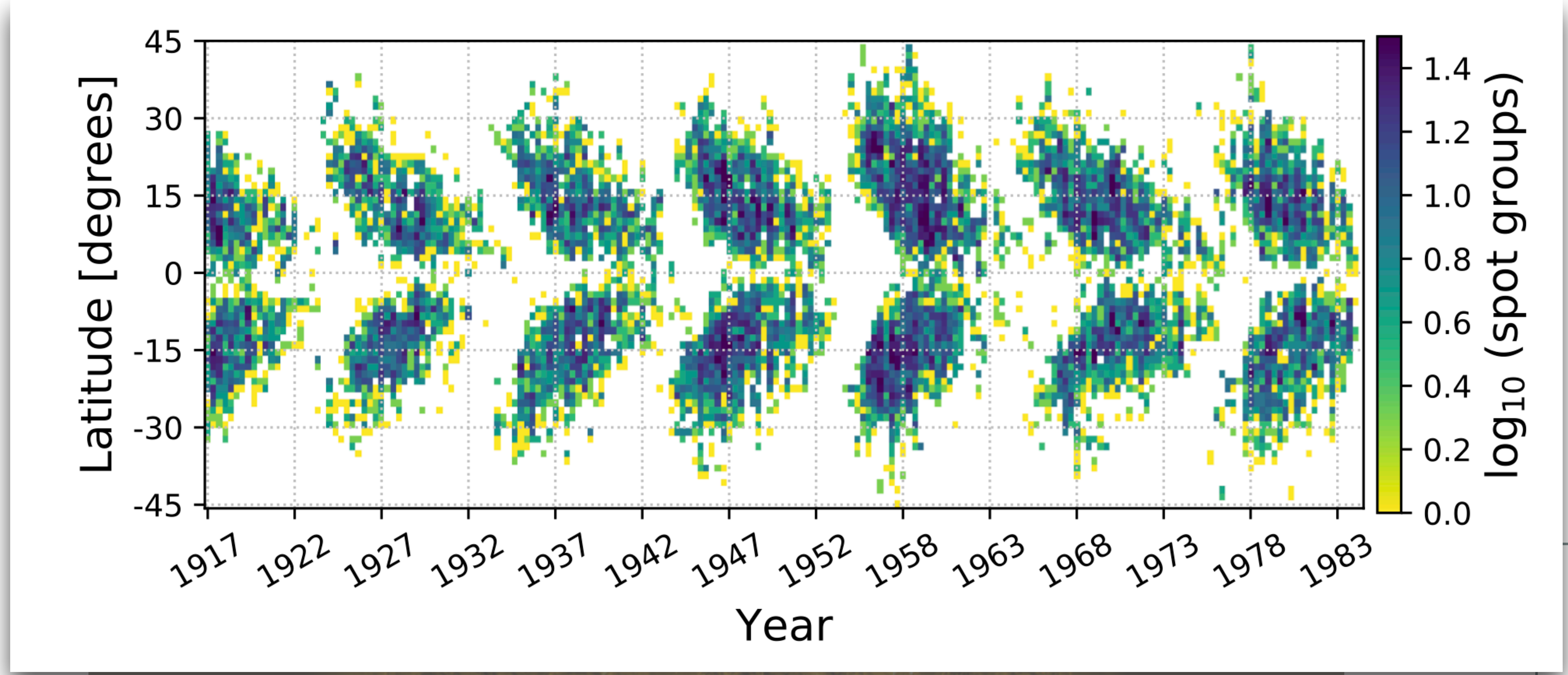

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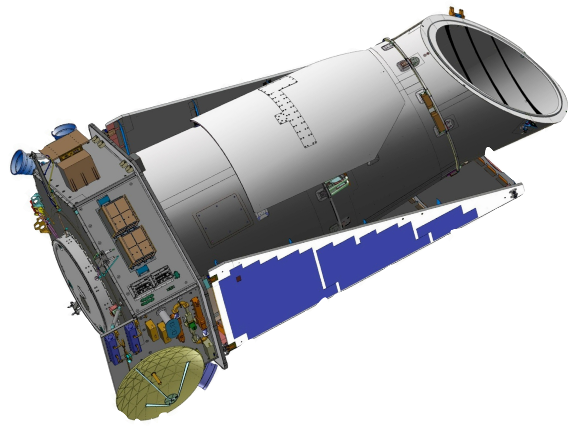
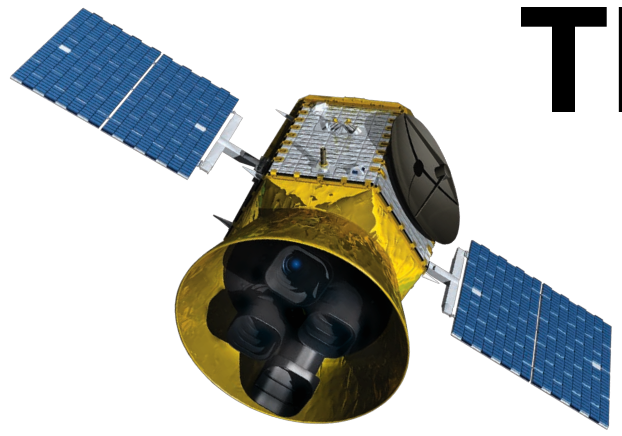
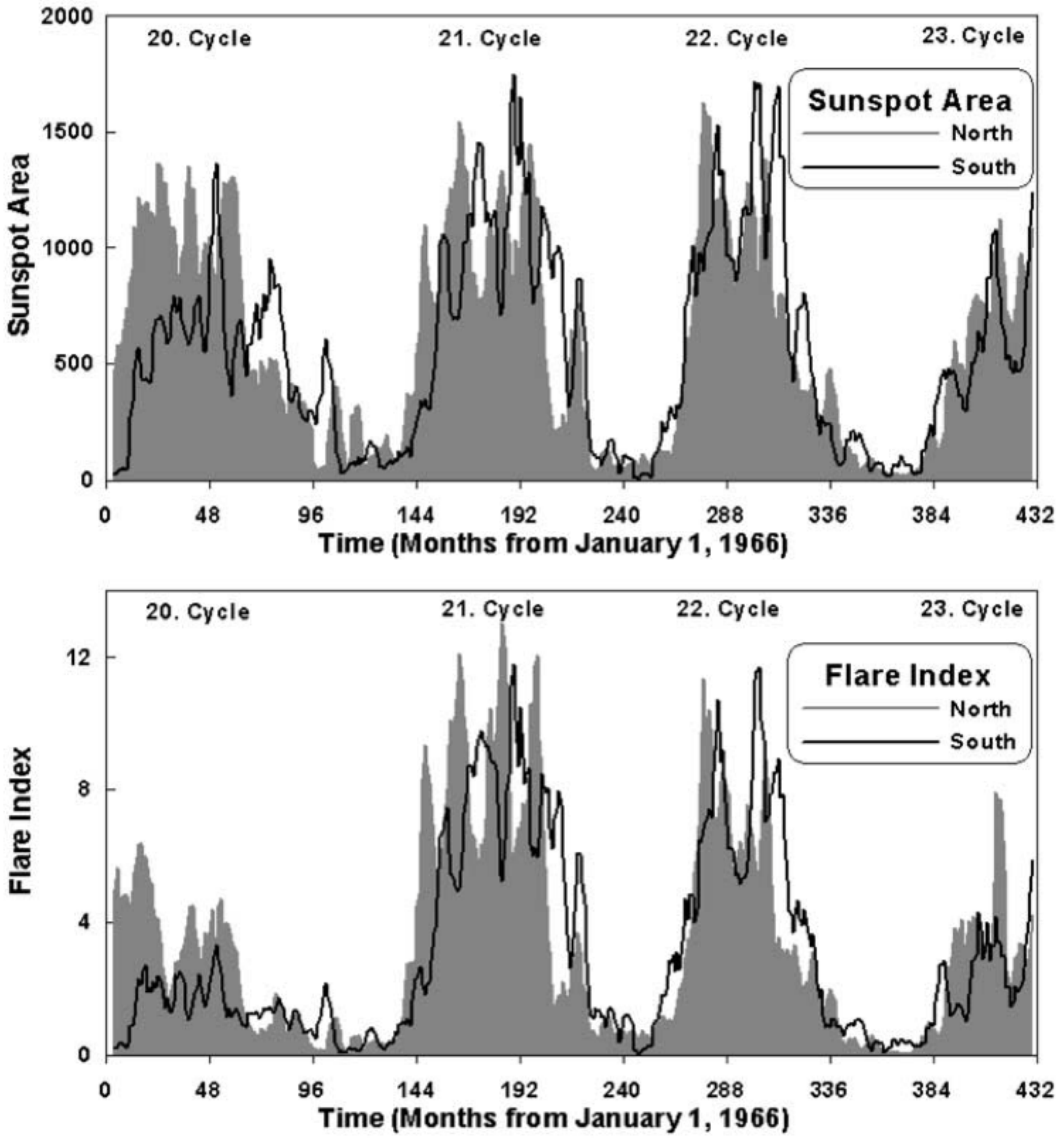
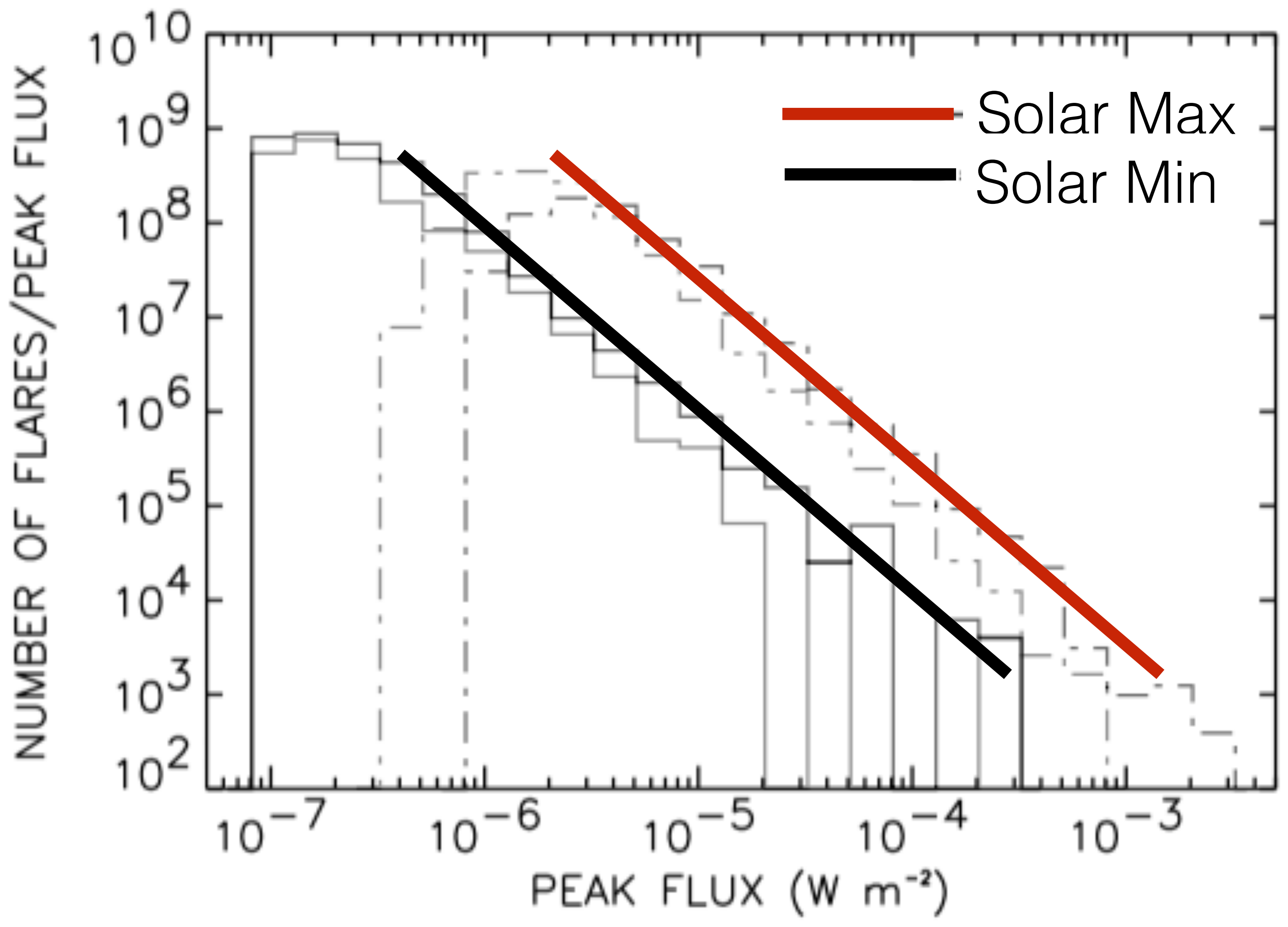


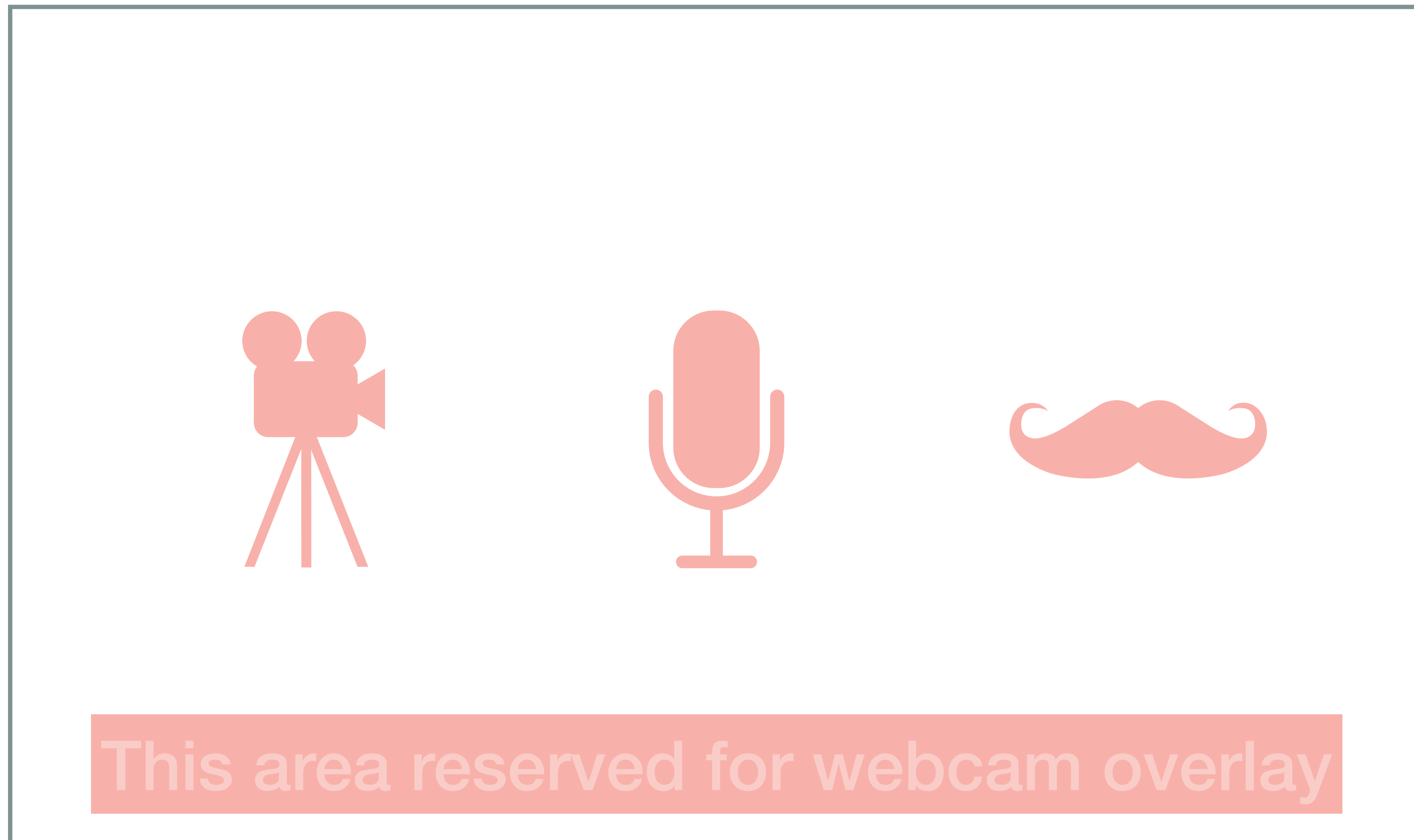




A. Özgüç, et al. (2003), SoPh



Veronig et al. (2002)



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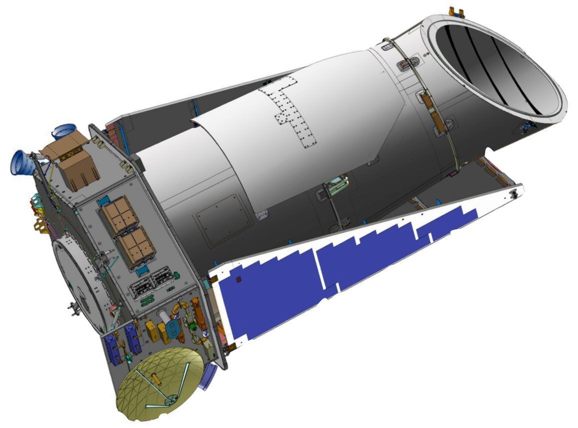
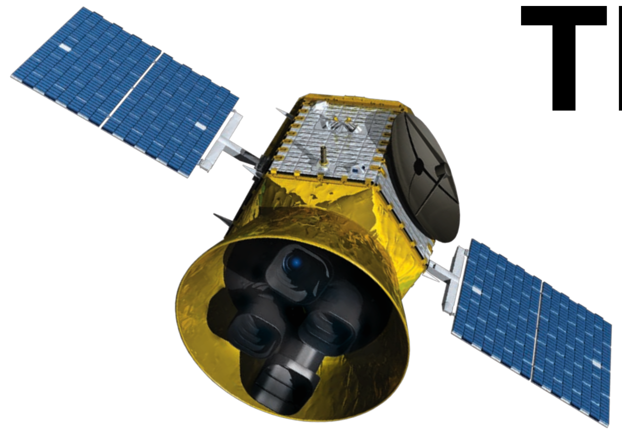
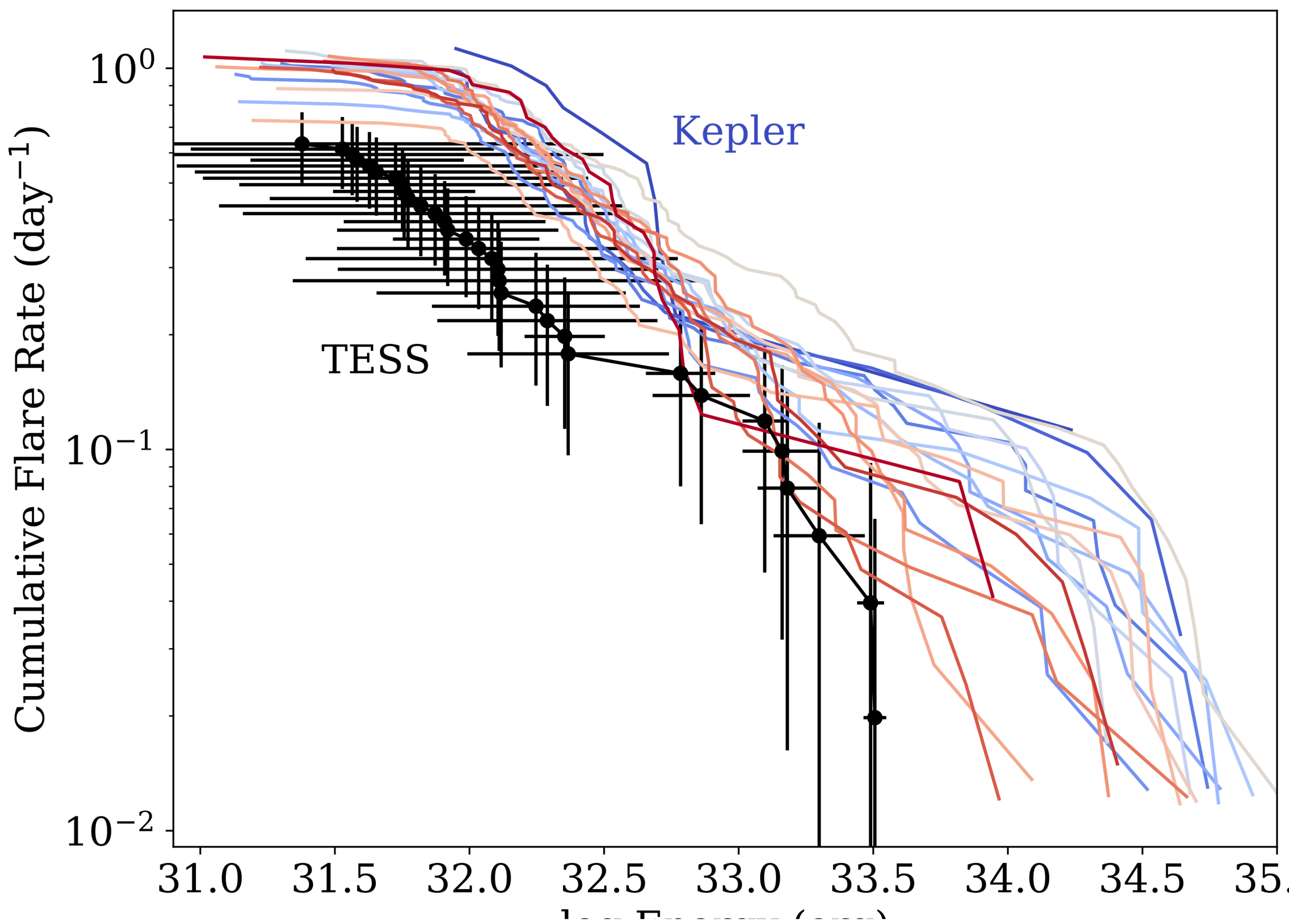
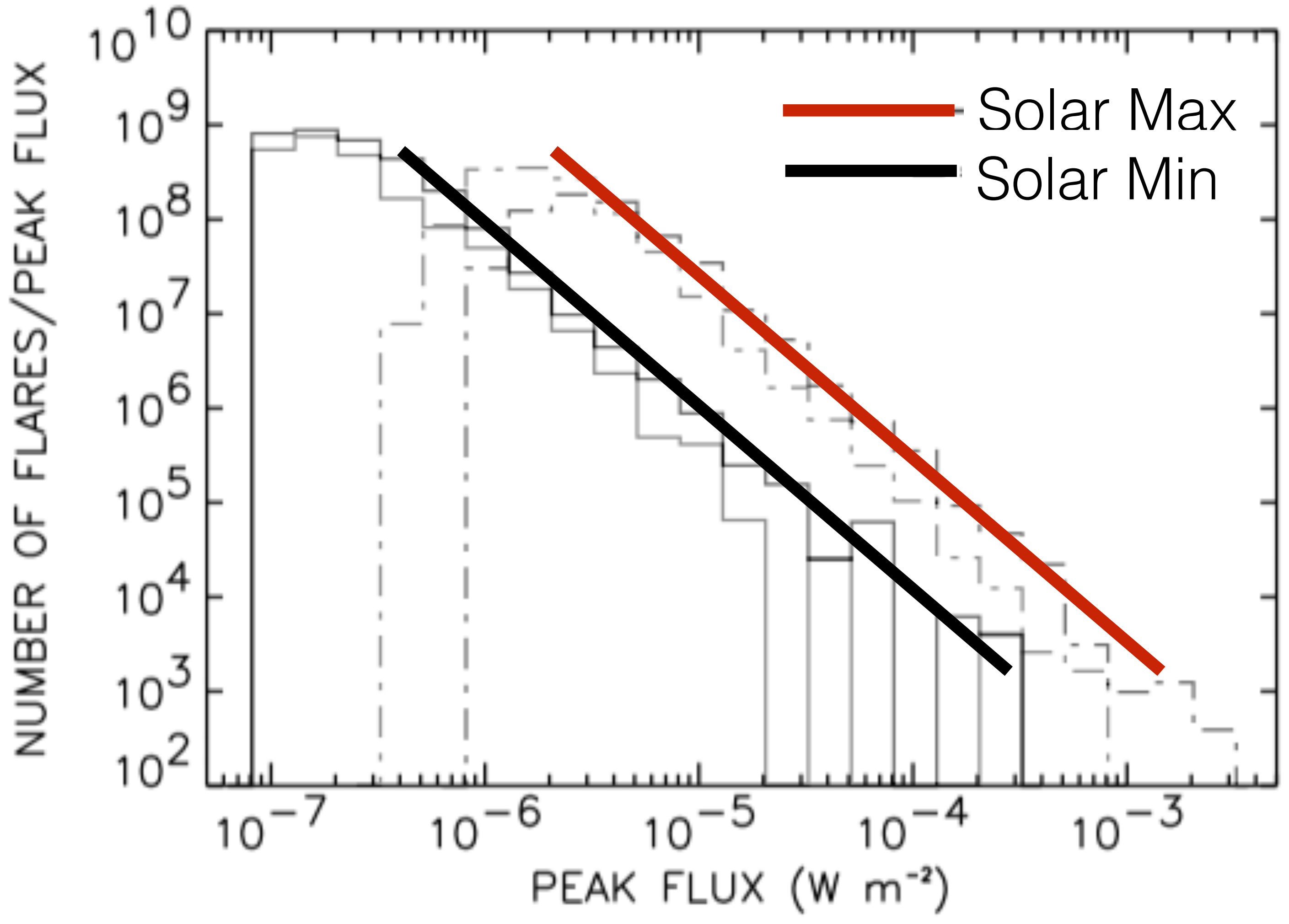
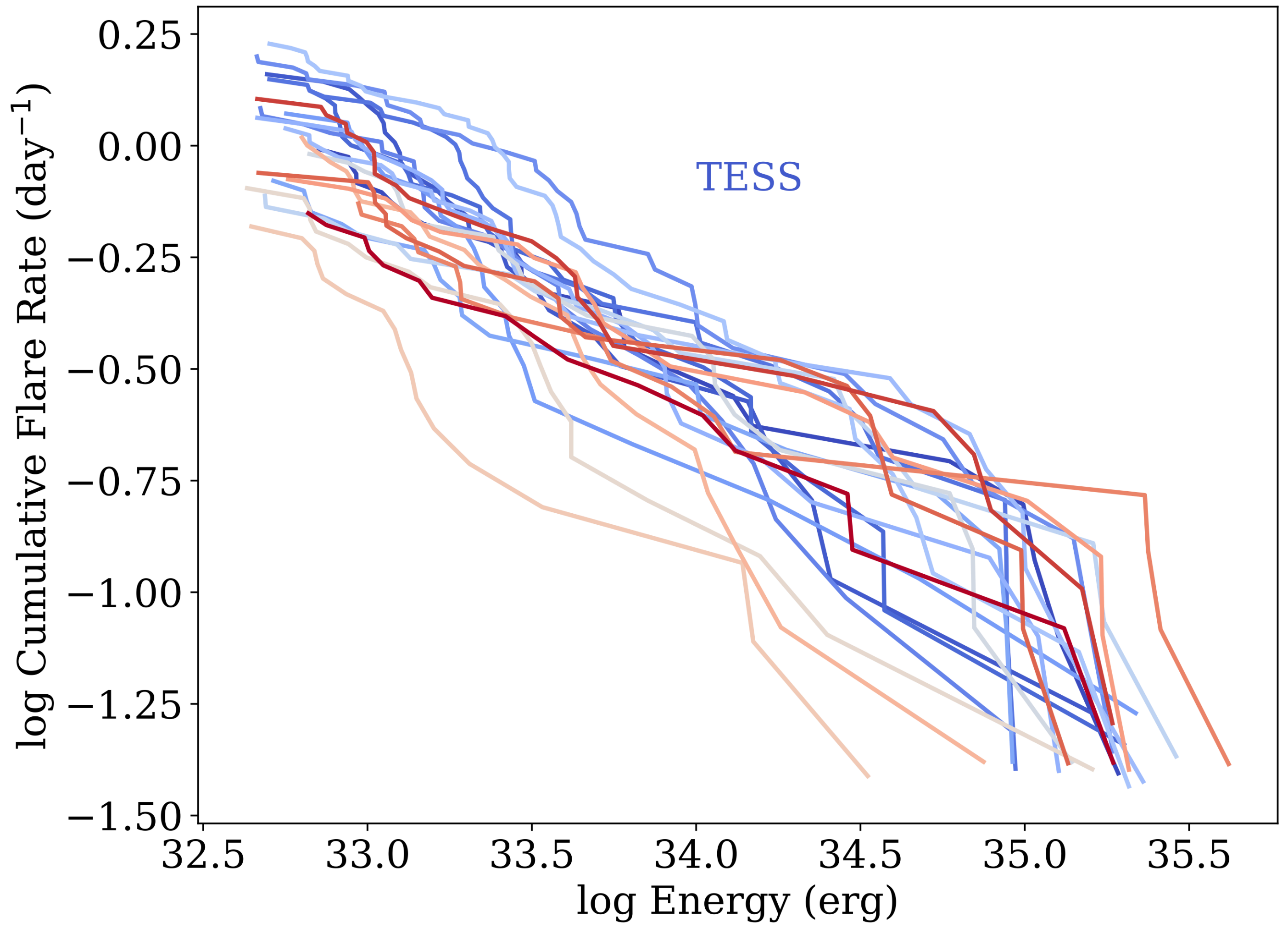








Veronig et al. (2002)



Scoggins, Davenport, Covey (2019) RNAAS

Davenport+*in prep*

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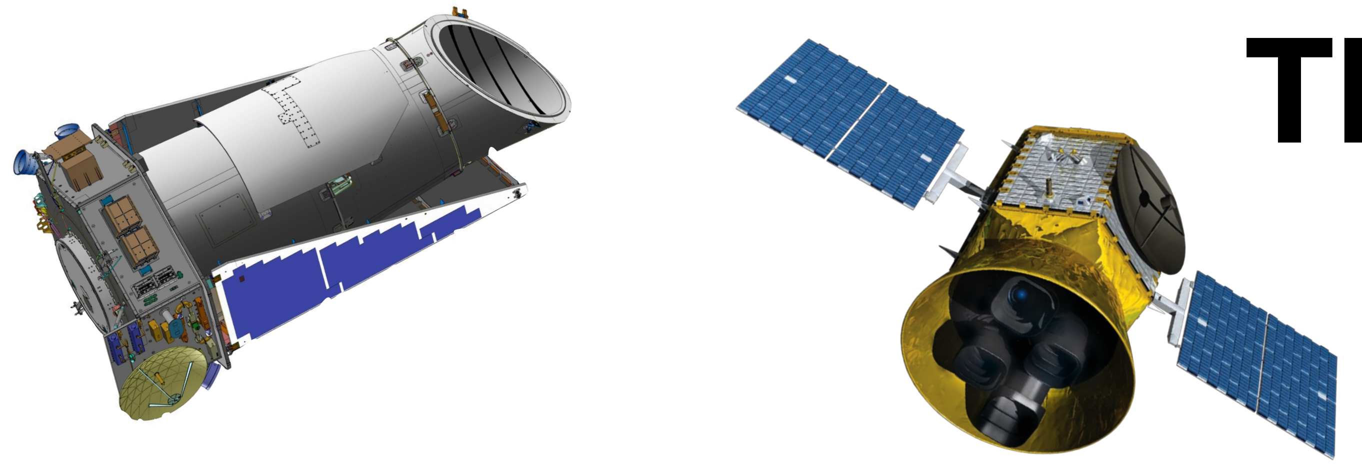

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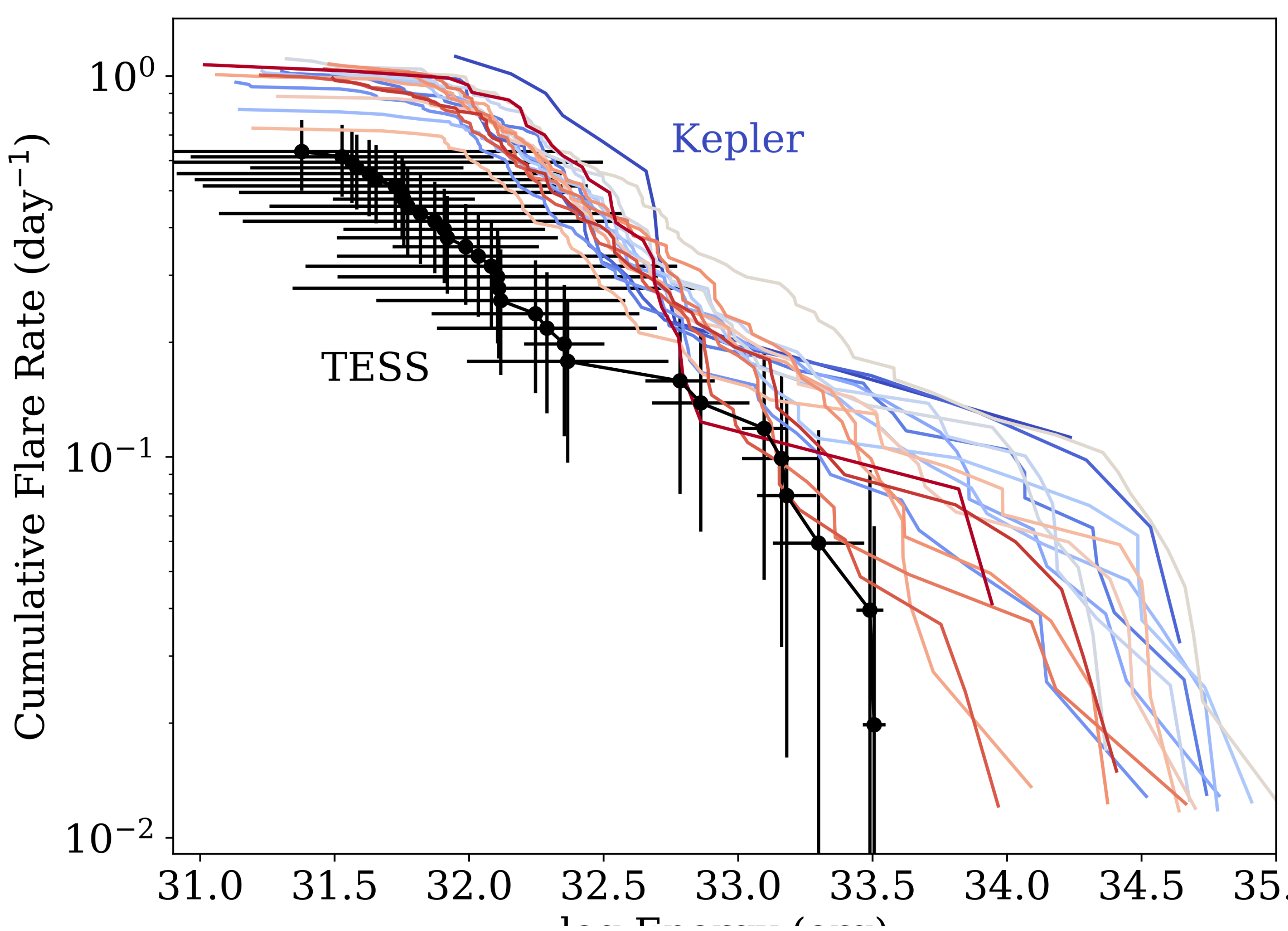

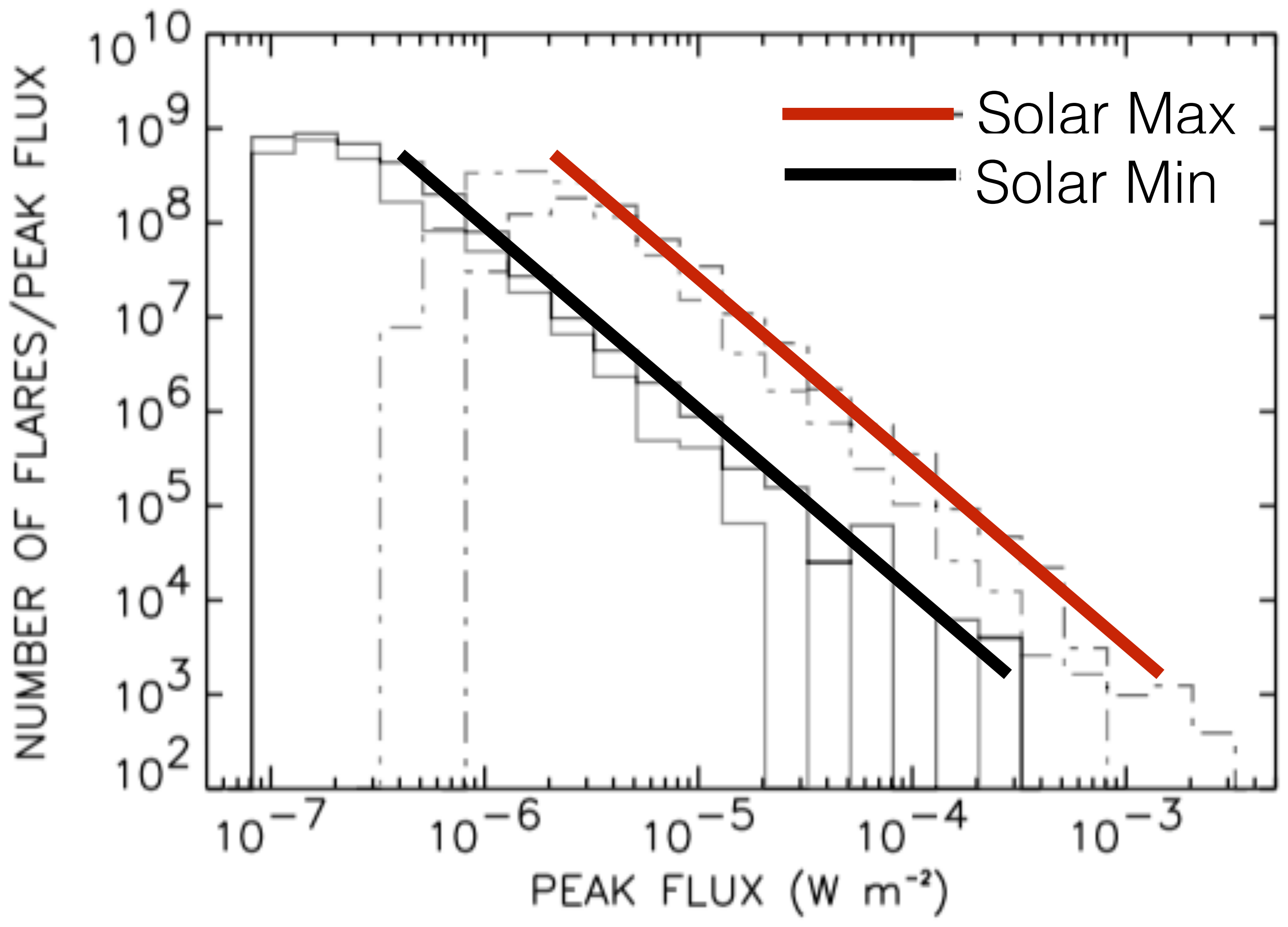

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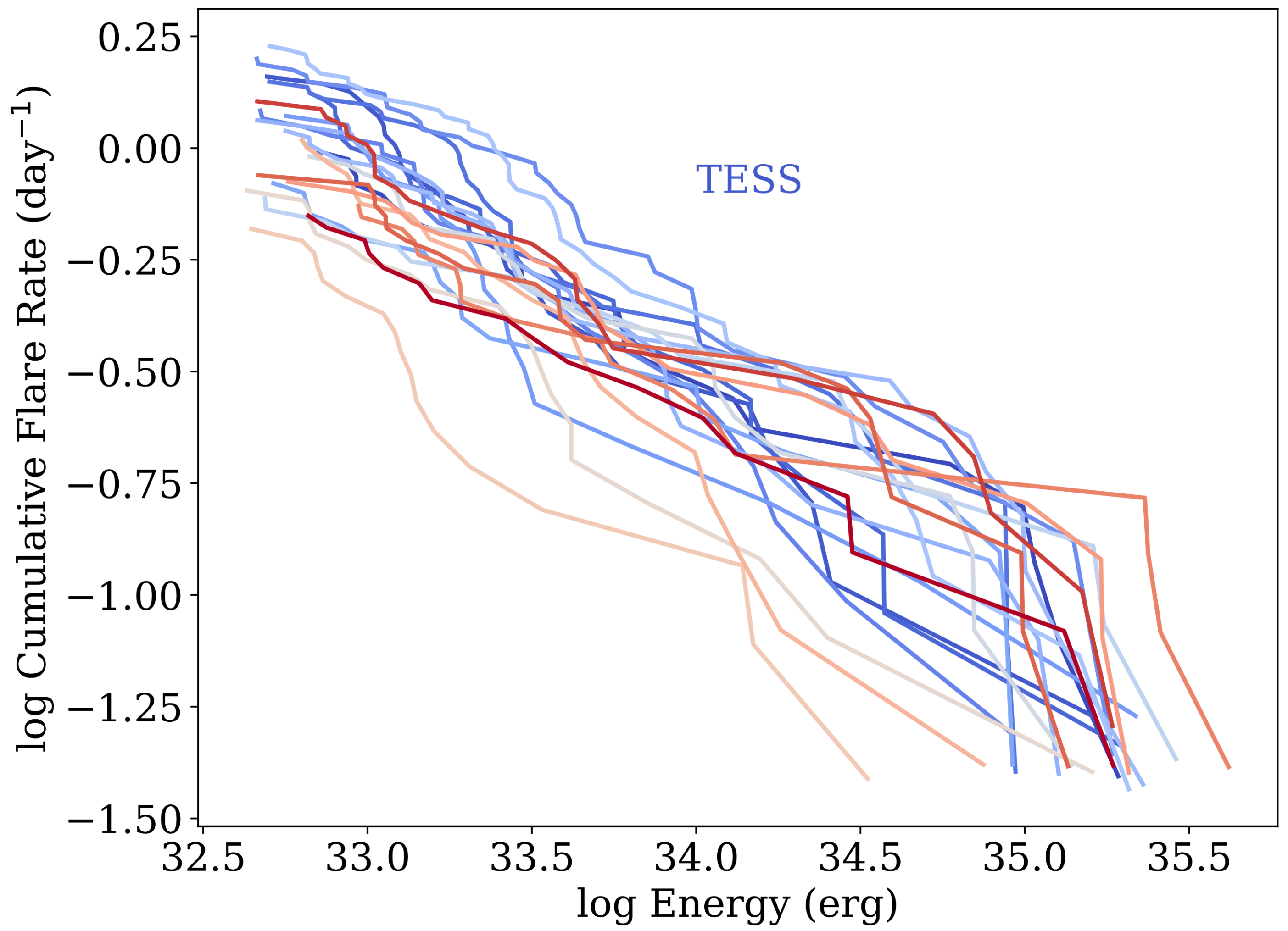

Scoggins, Davenport, Covey (2019) RNAAS

Davenport+*in prep*

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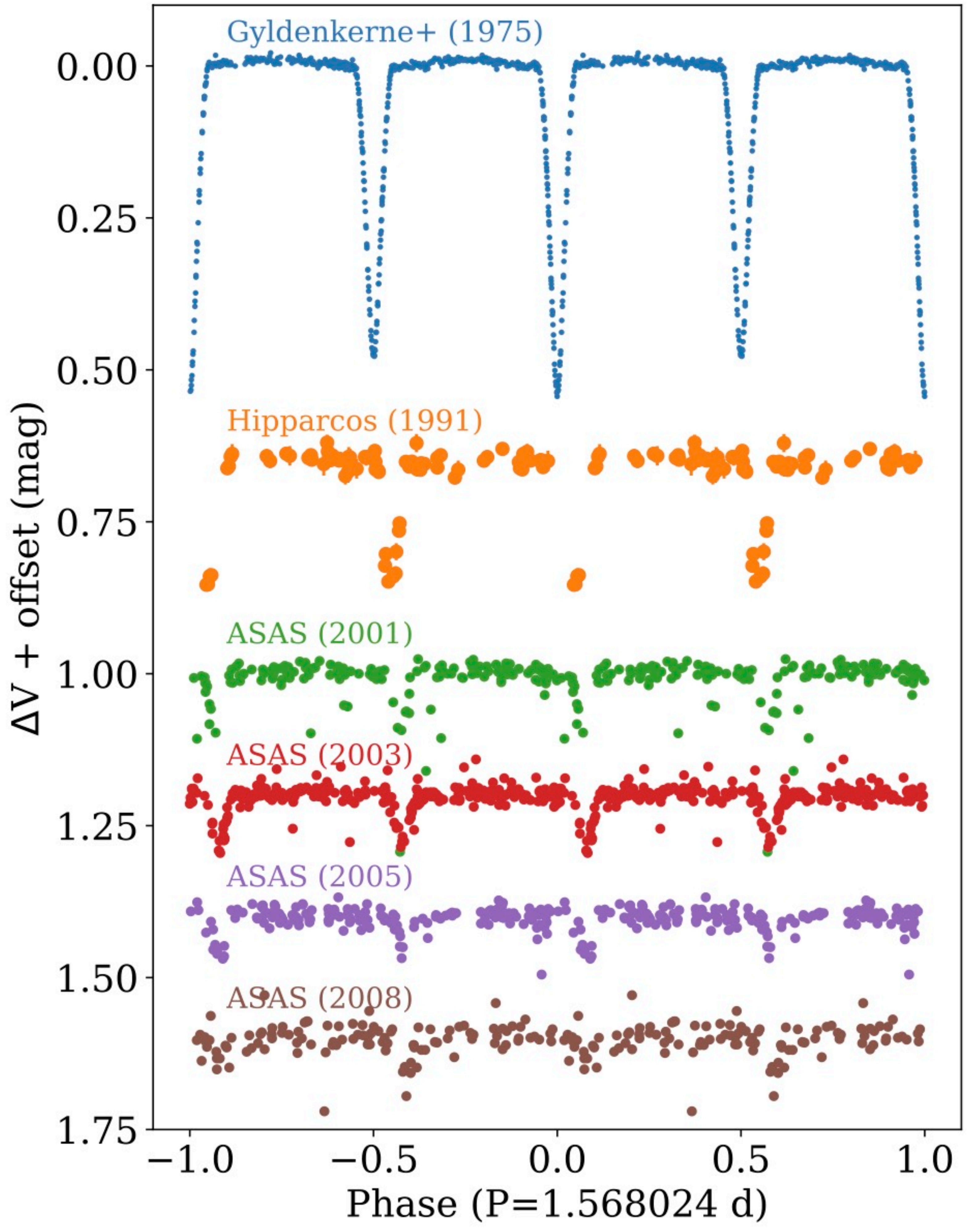
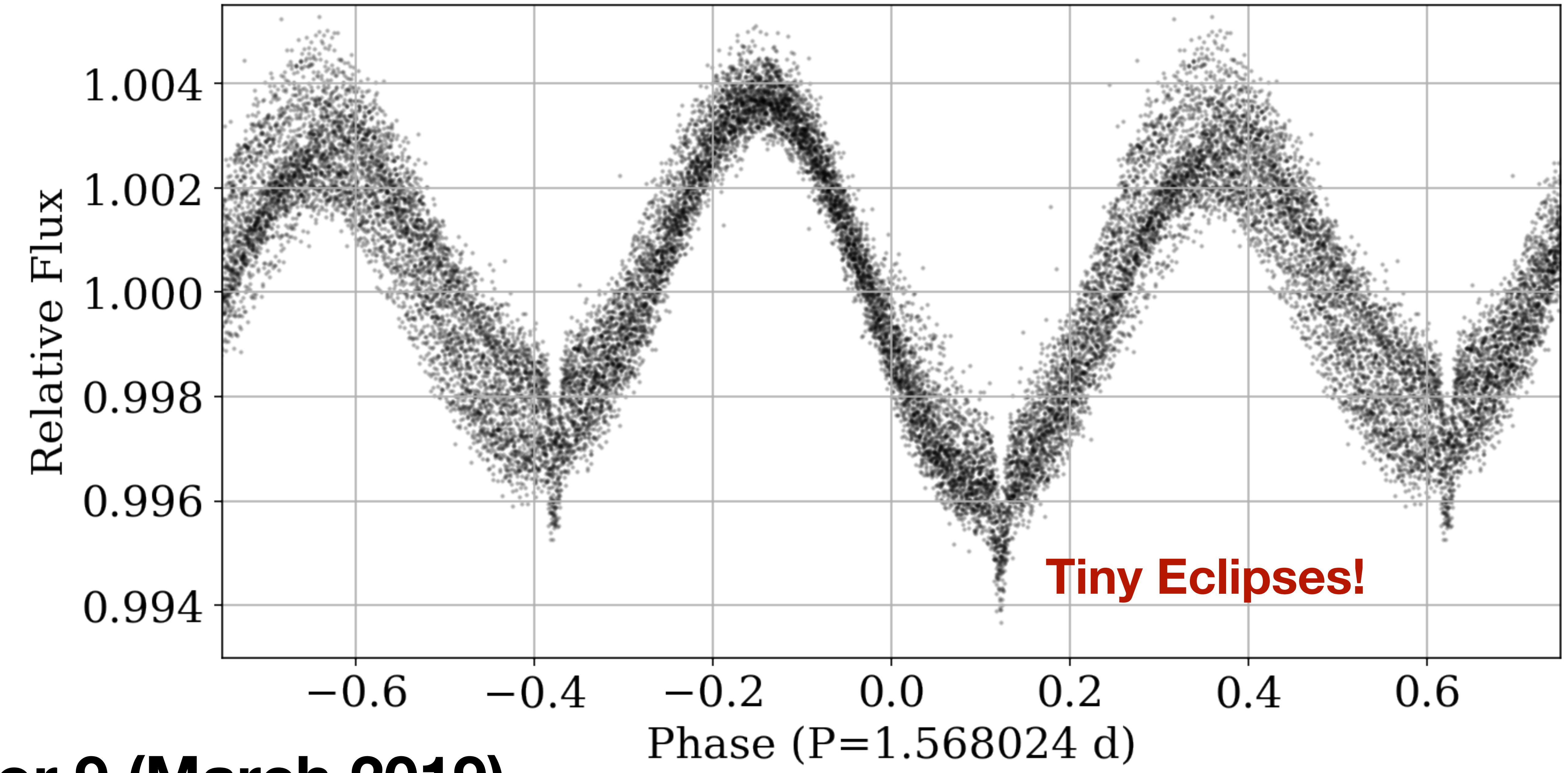
TESS + Kepler = 10year+ Baseline

Find rare or slow things! e.g. HS Hydrae





TESS Sector 9 (March 2019)

Davenport+2021

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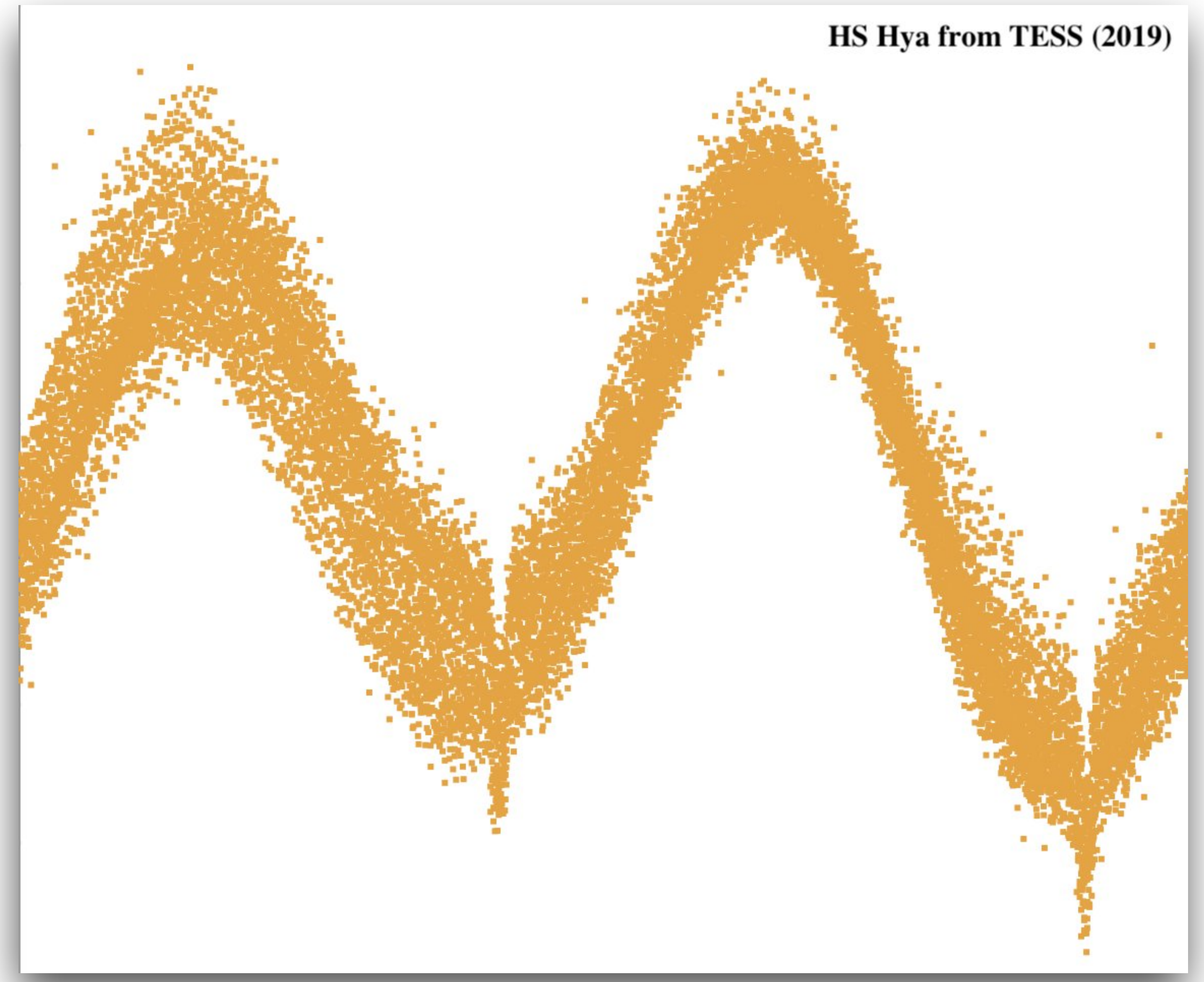
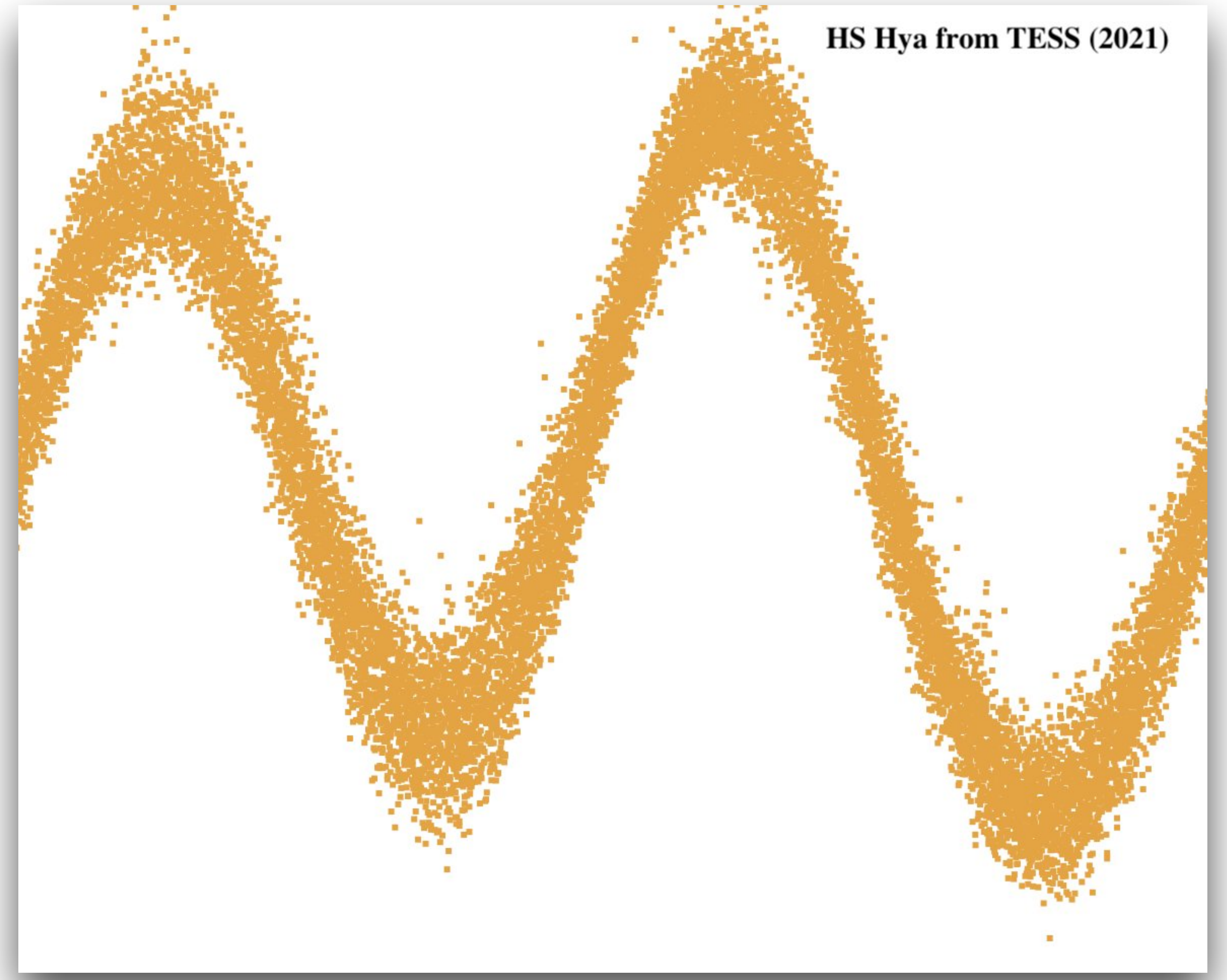
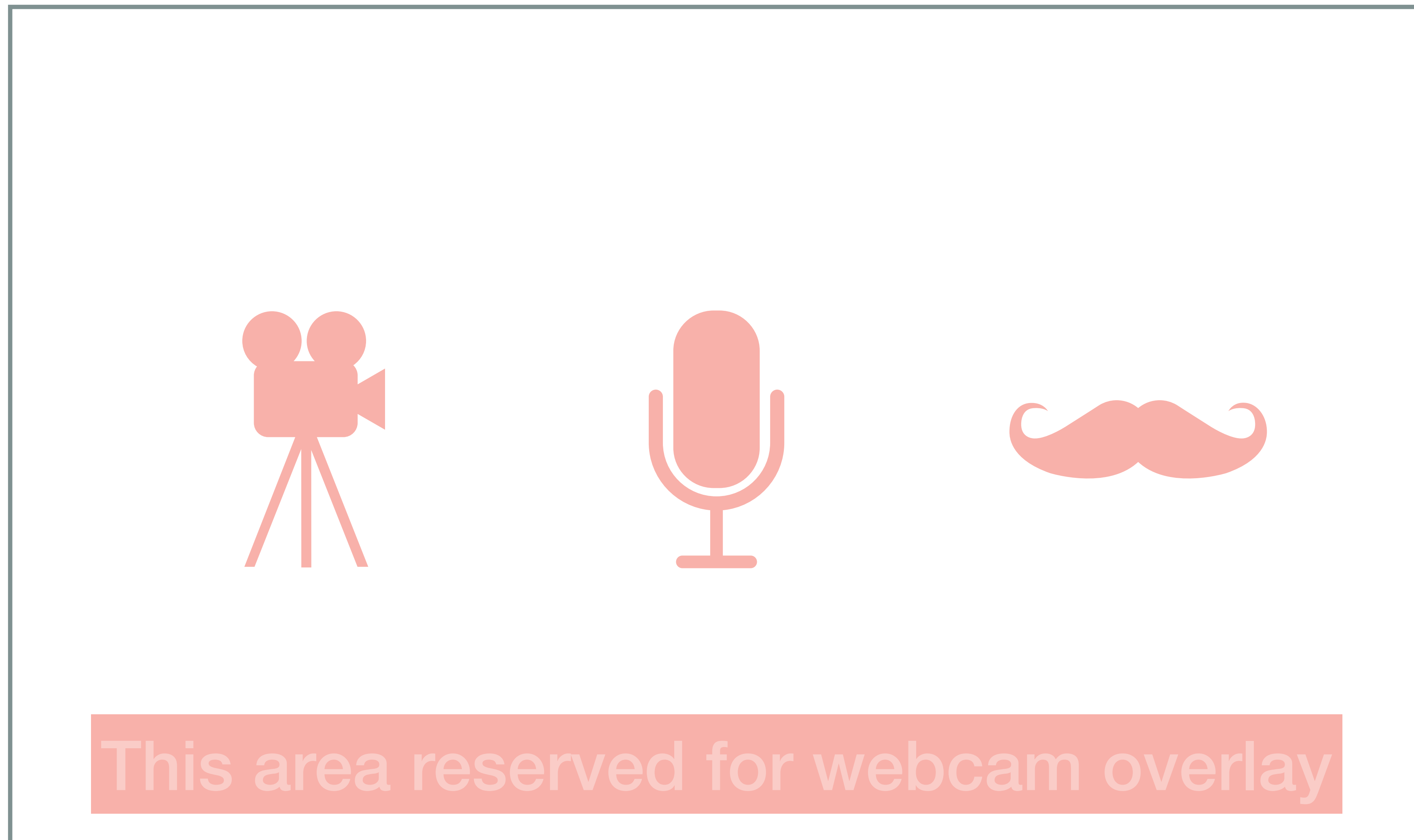
TESS + Kepler = 10year+ Baseline

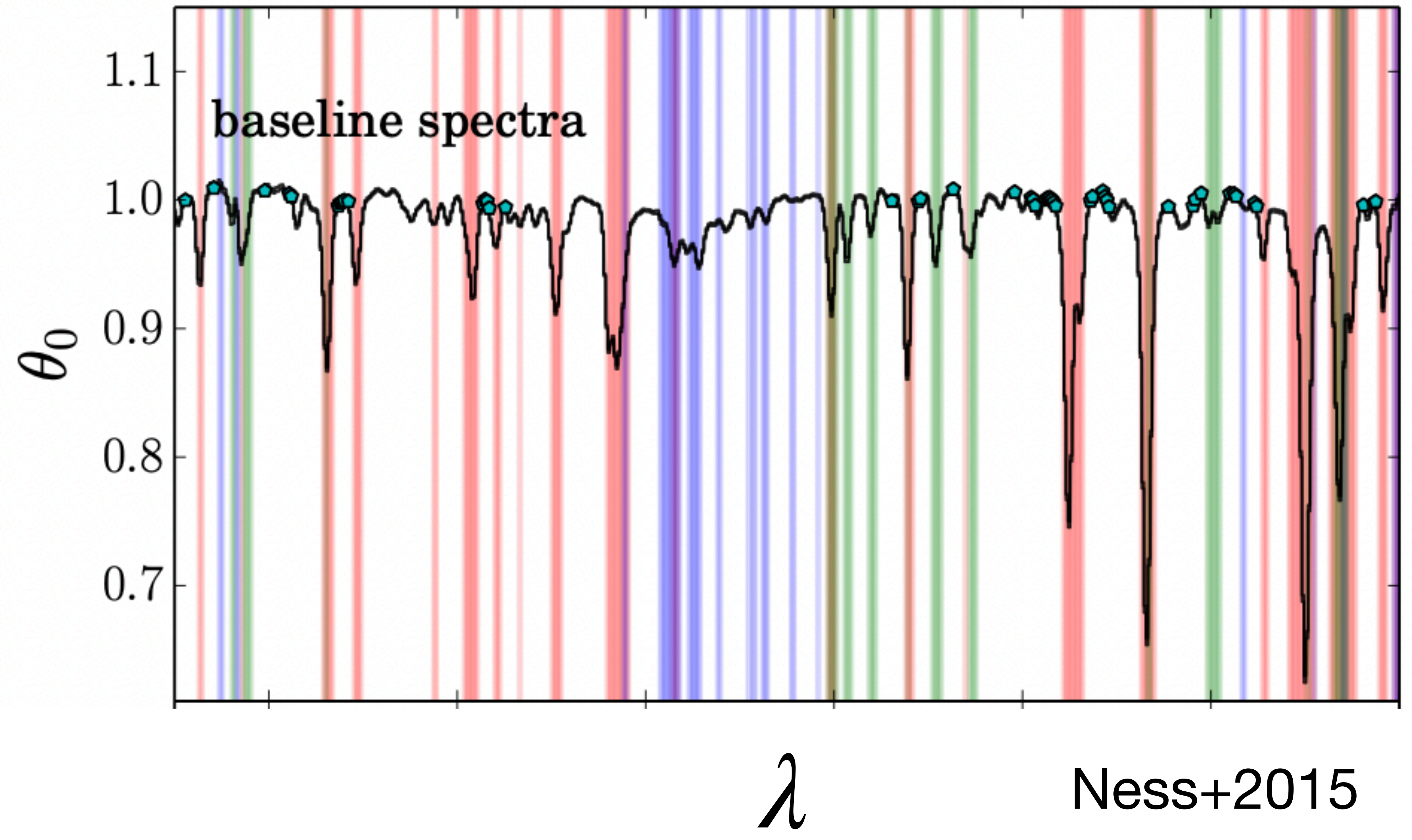
Find rare or slow things! e.g. HS Hydrae





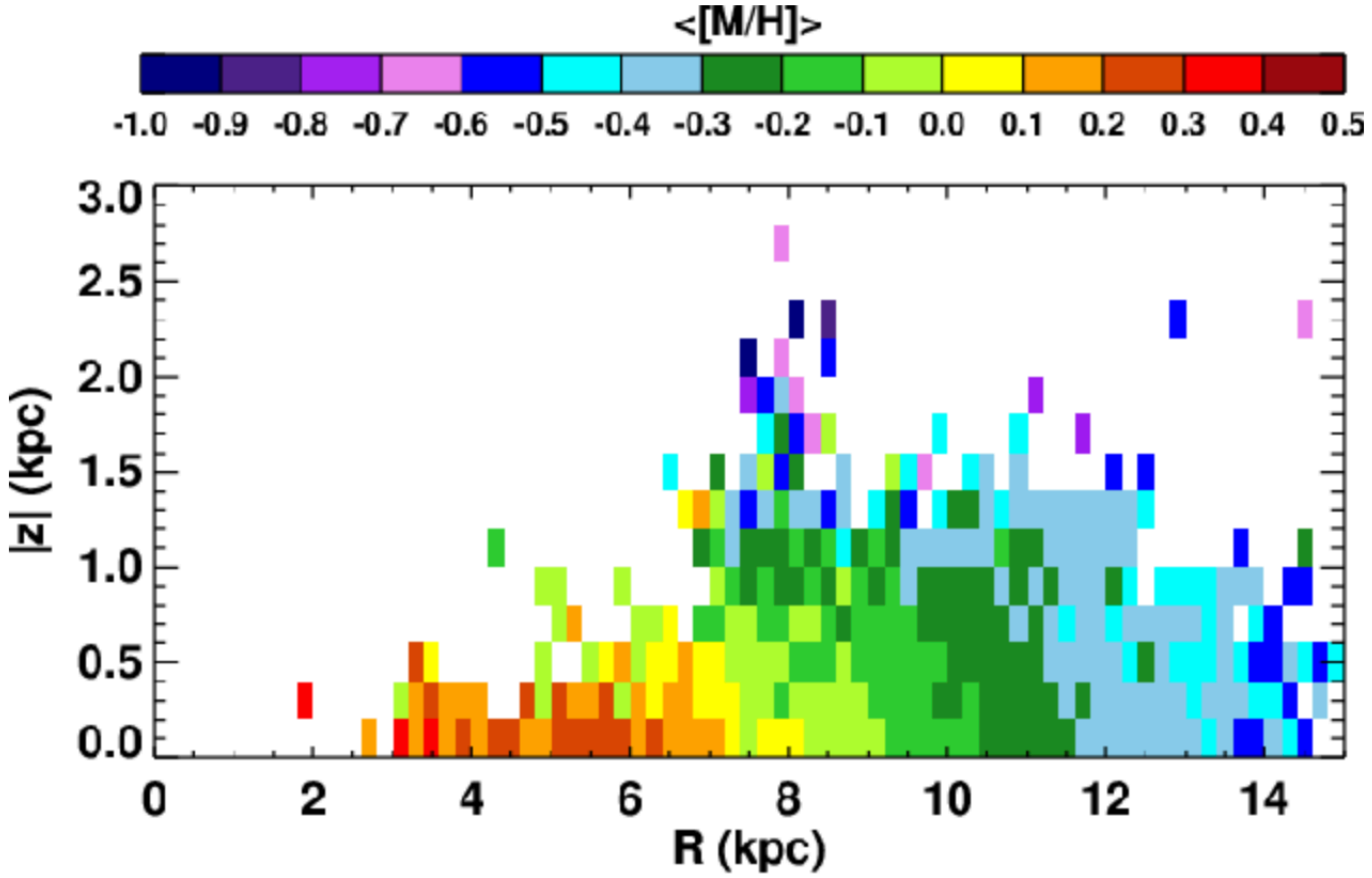


ASPCAP & APOGEE & The Cannon

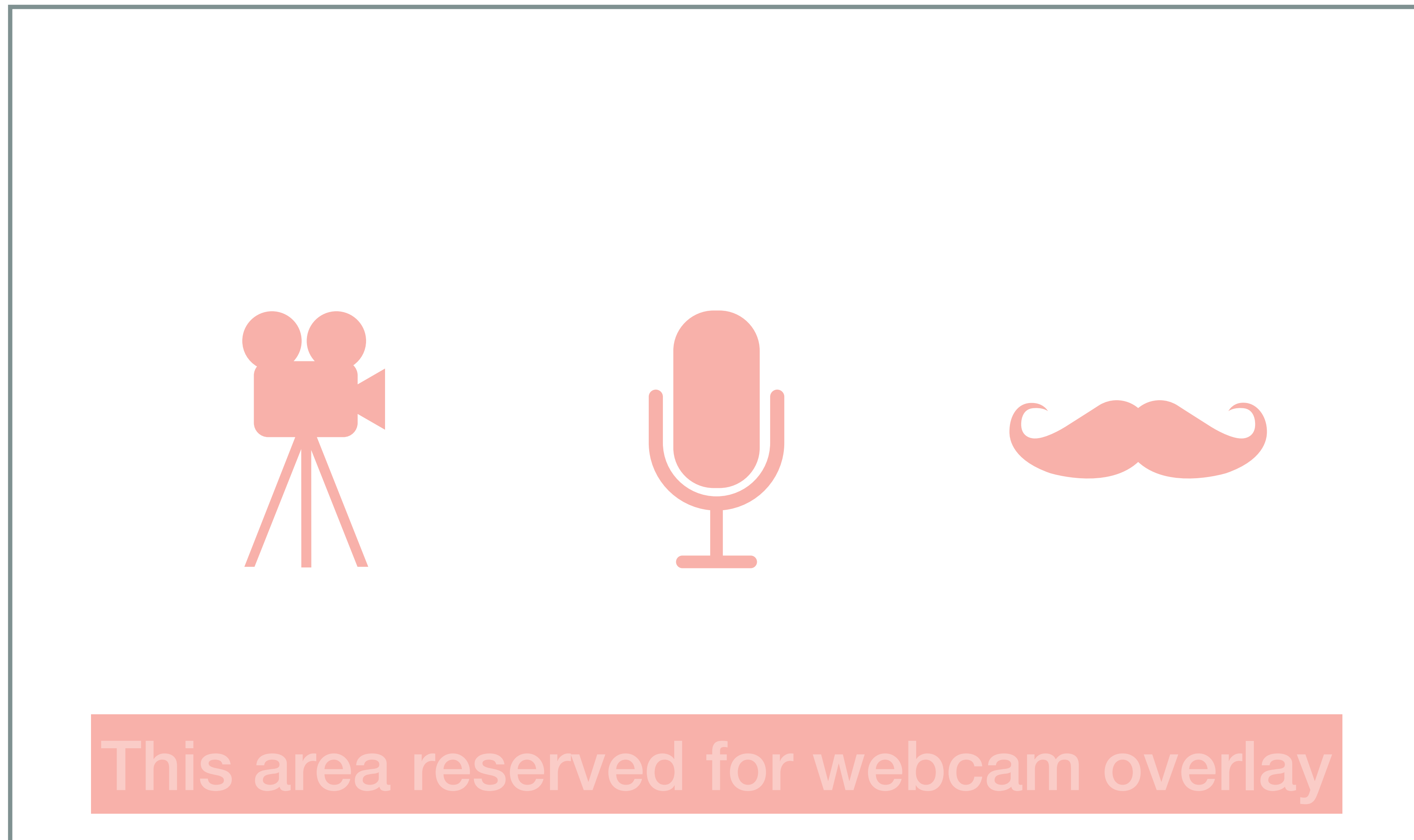


Ness+2015

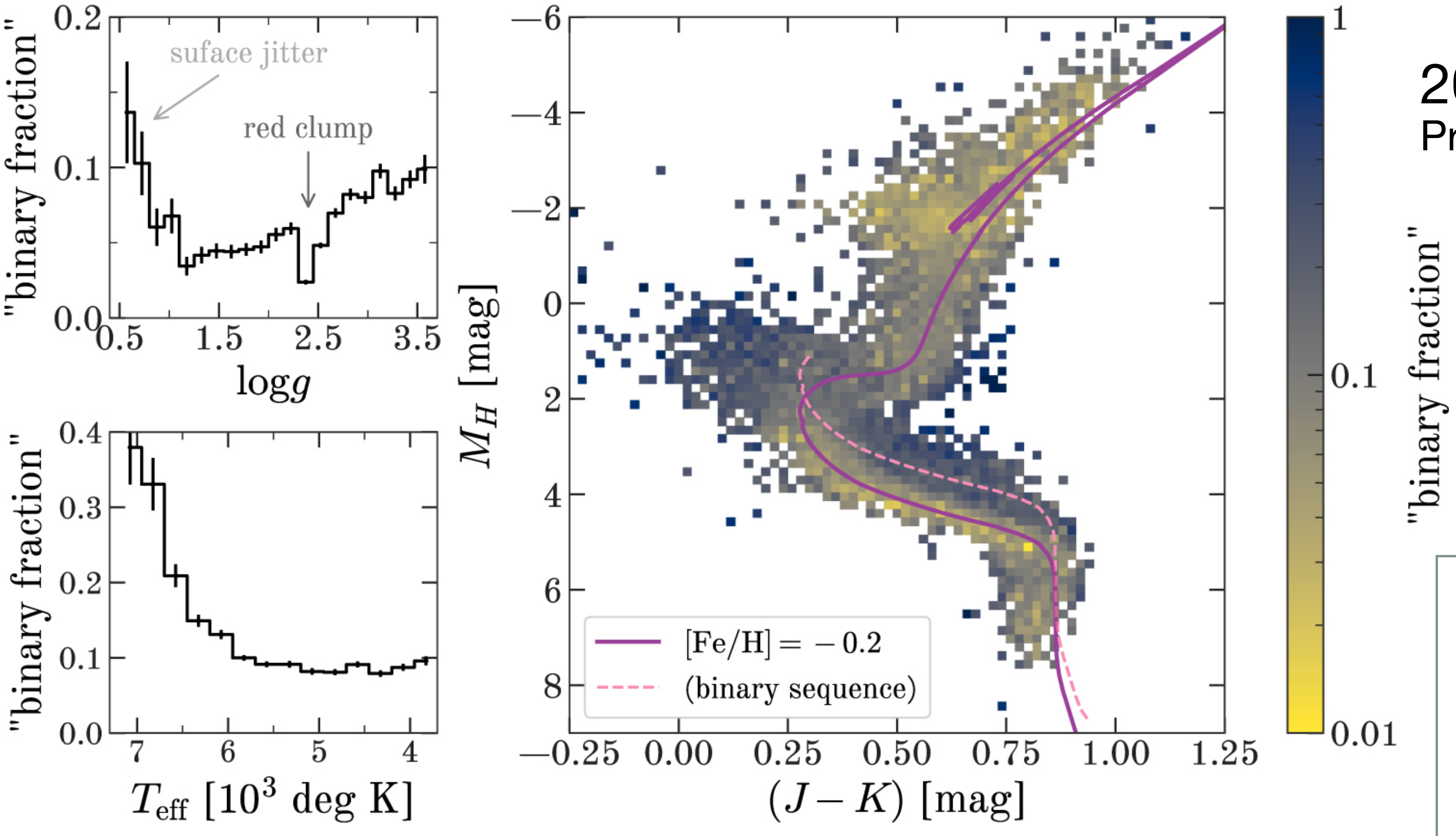
[Fe/H]
log g
Teff



Hayden+2013

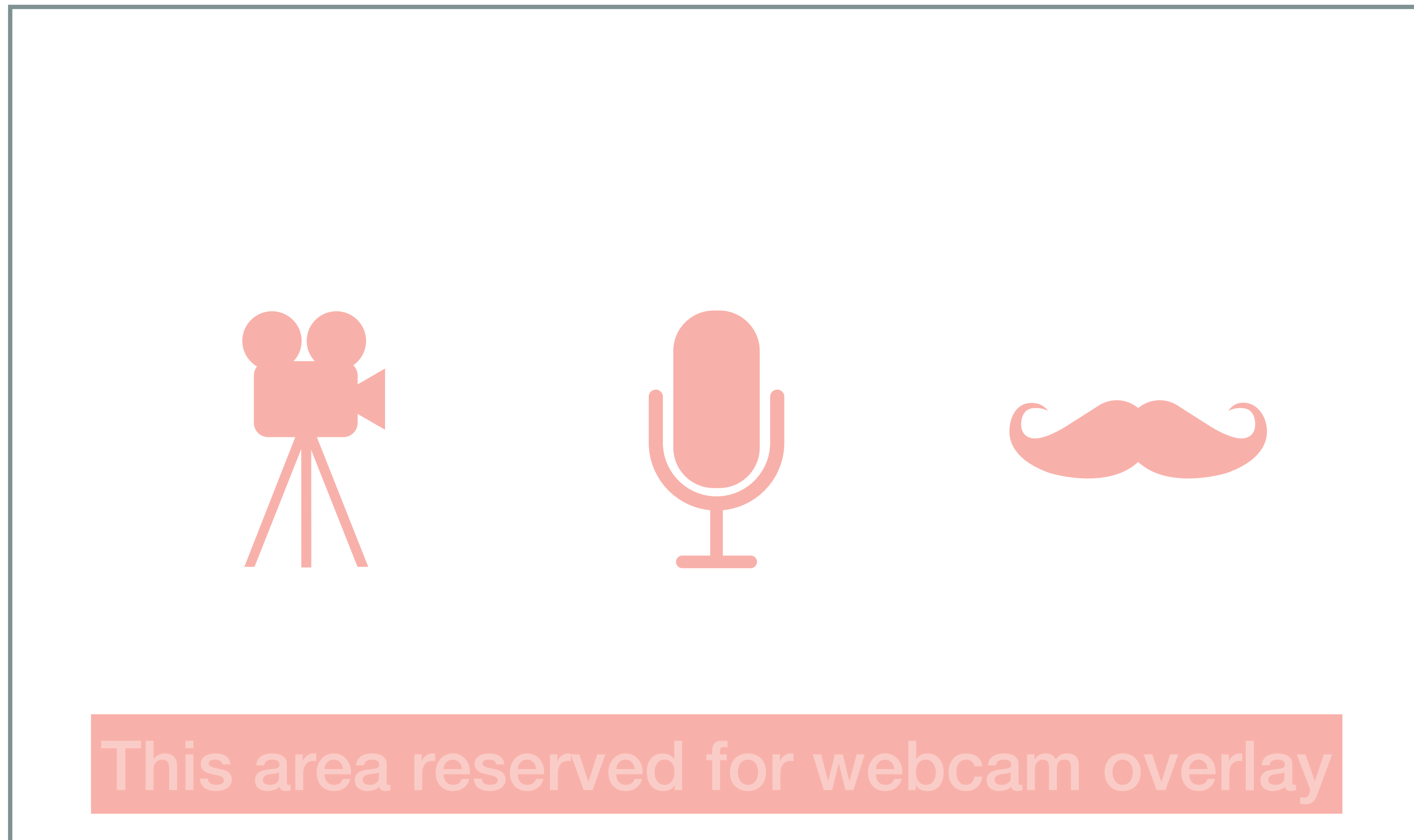


ASPCAP & APOGEE & The Cannon

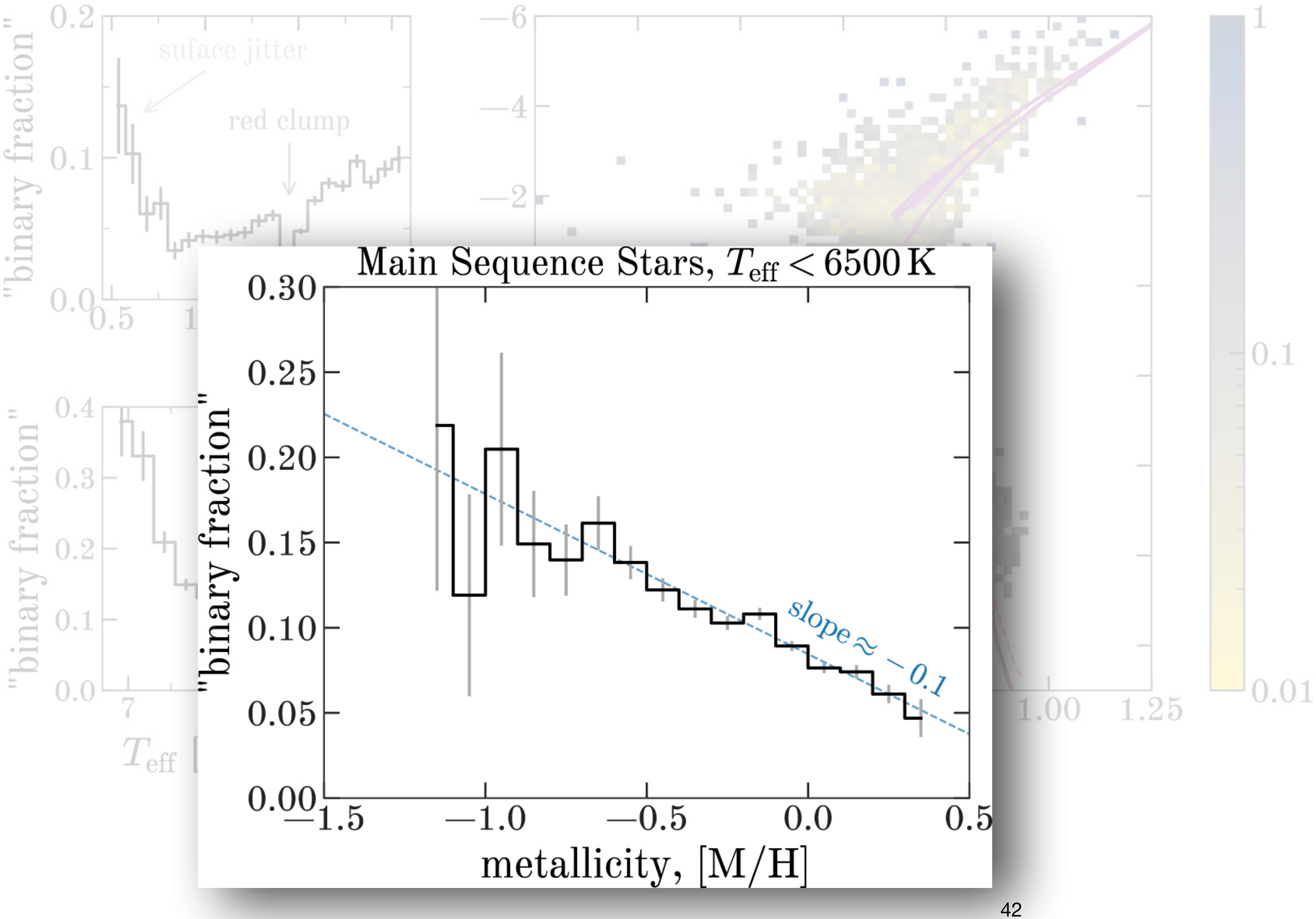


20k *spectroscopic* binaries

Price-Whelan+2020

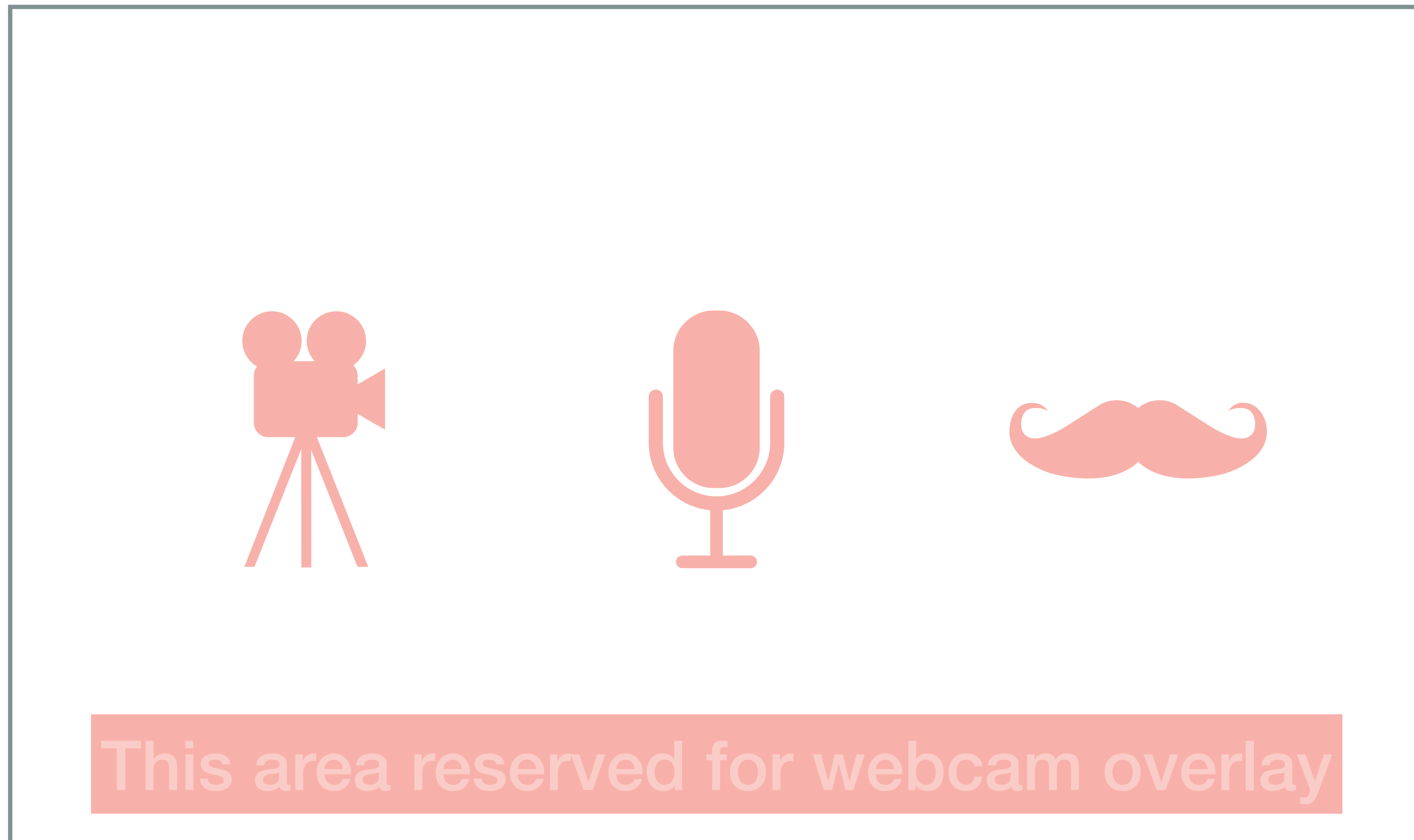


ASPCAP & APOGEE & The Cannon



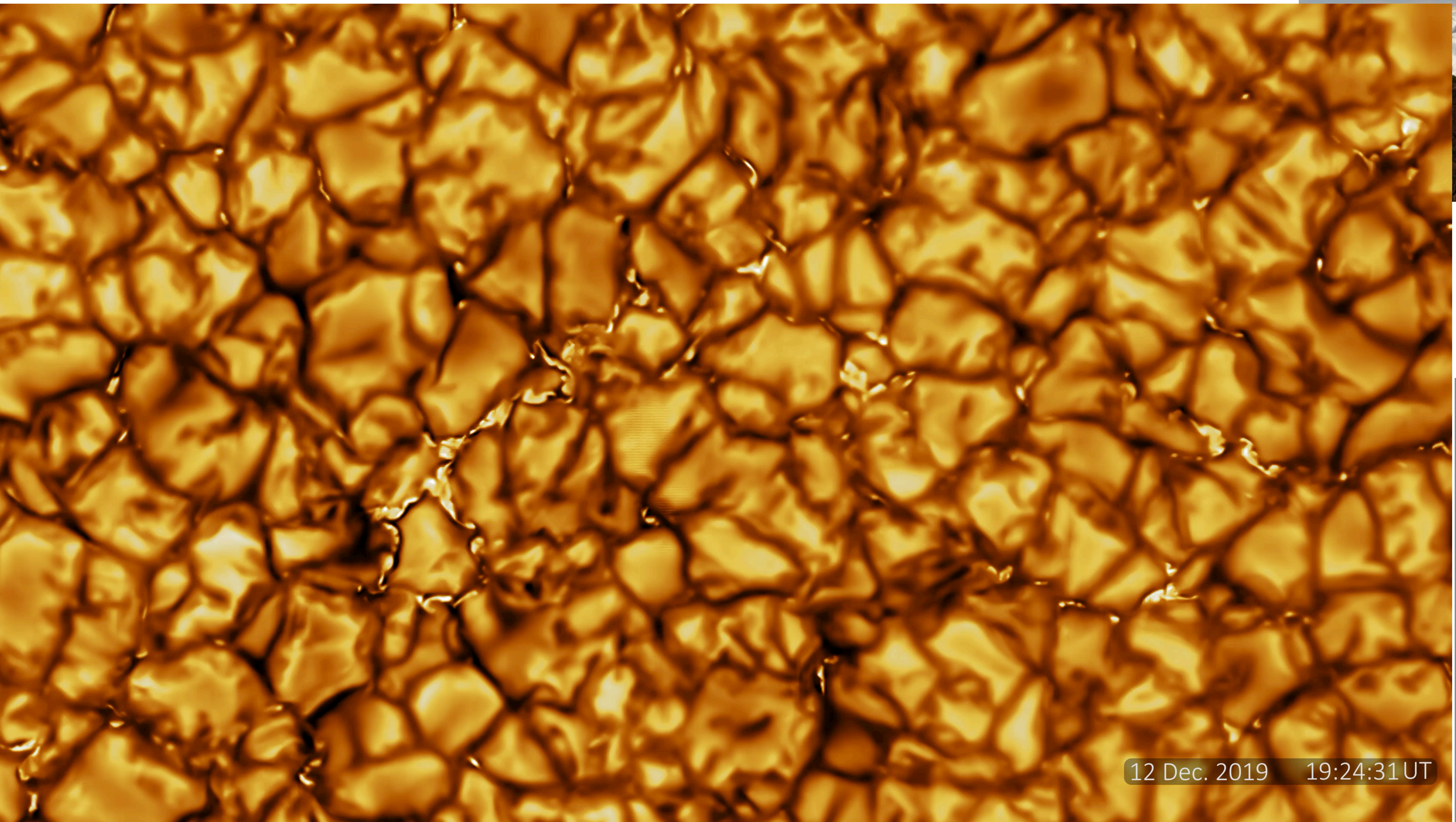
20k *spectroscopic* binaries
Price-Whelan+2020

Disk fragmentation & cooling! **Moe+2019**



DKIST

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



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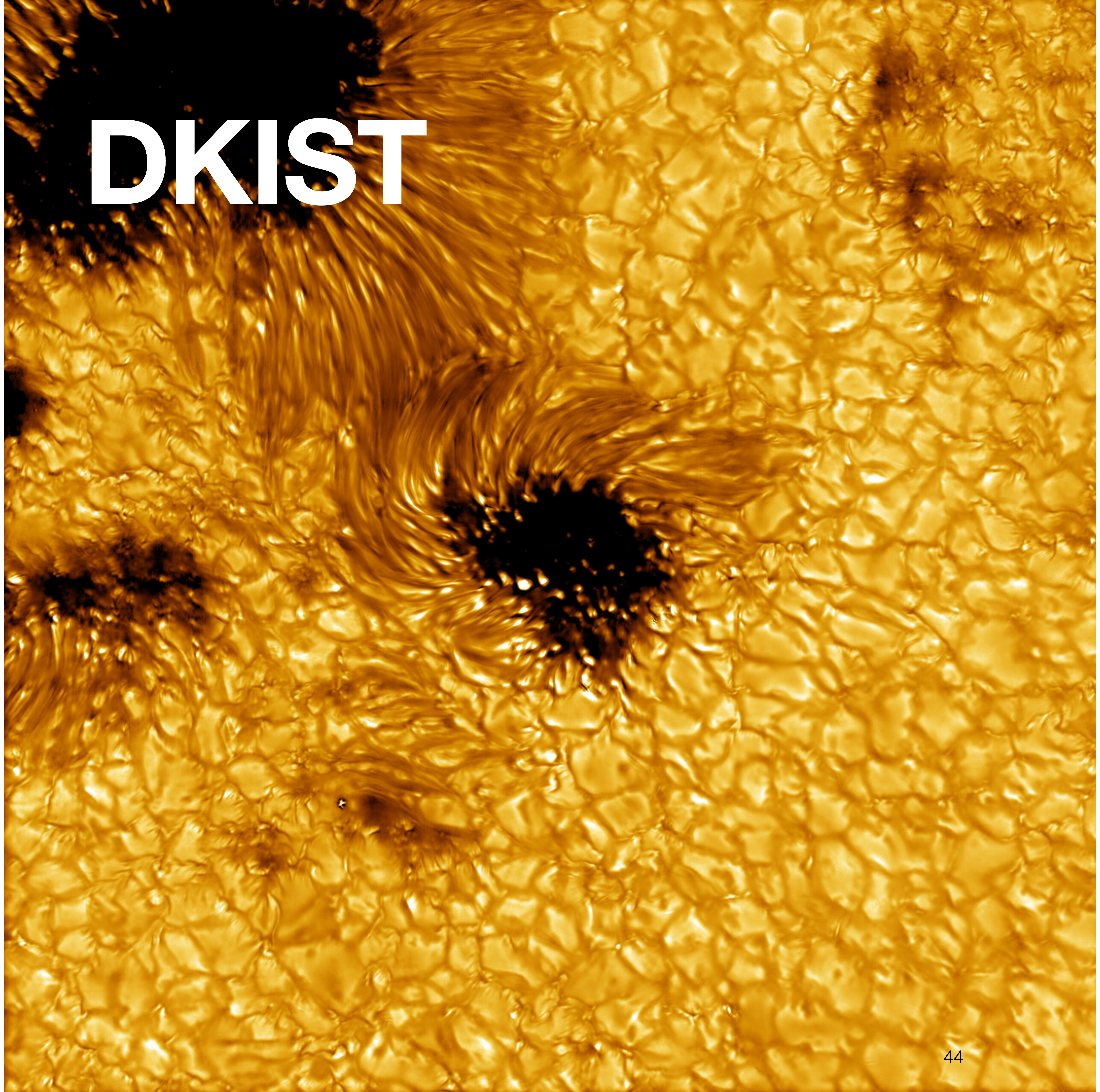
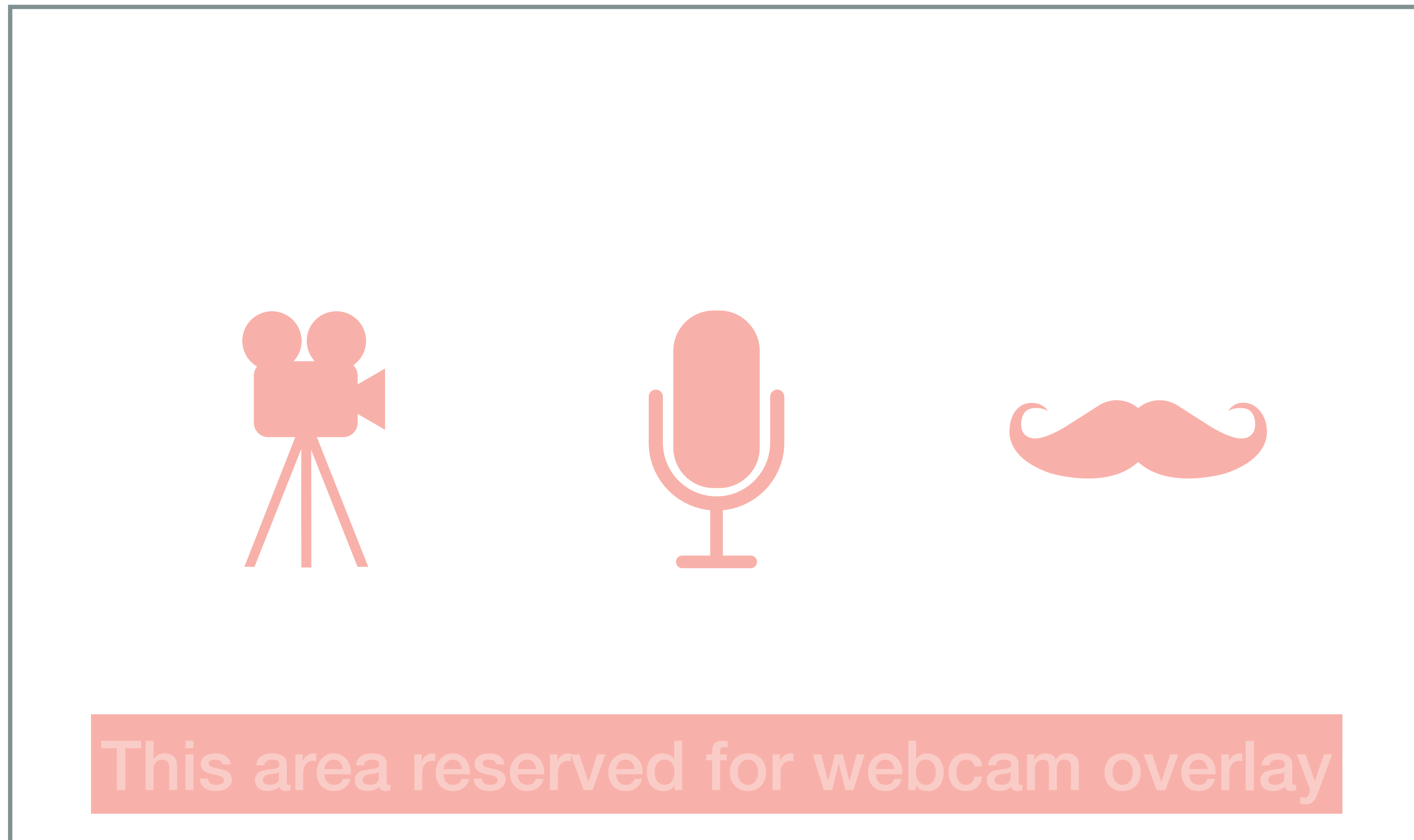
DKIST



<u>Feb 24, 2022:</u> Begin of science operations commissioning!



Thank you!

- It’s been (once again) a wild quarter… you’ve all impressed me with your professionalism and resilience

- Can’t wait to see *your* presentations on interesting stars next!