Decoding the Lives of Red Giant Stars: New Spectroscopic Clues

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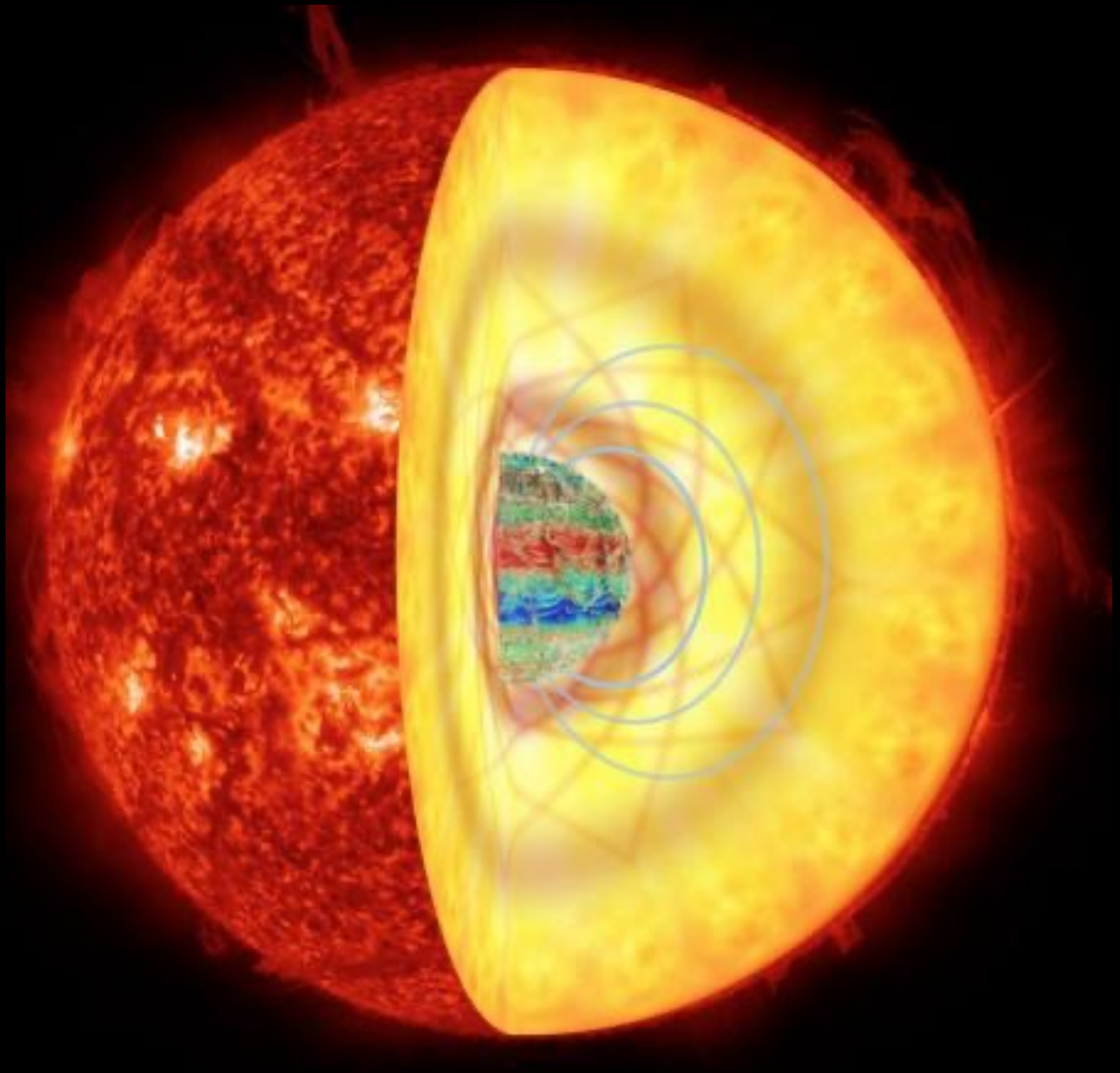


https://skyandtelescope.org/astronomy-news/the-inner-workings-of-red-giant-stars-10272015/

speaking on behalf of many friends & colleagues

Melike Afşar, Zeynep Bozkurt – Ege U. (Izmir, Turkey)

Monika Adamów – U. Illinois

Katia Biazzo – INAF Rome

Claudia Aguilera-Gómez – Pontificia U. Católica de Chile

Anohita Mallick & Eswar Reddy – Indian Inst. Ap. (Bangalore)

Suvrath Mahadevan – Penn State U.

Andrea Dupree – Center for Ap., Harvard/Smithsonian

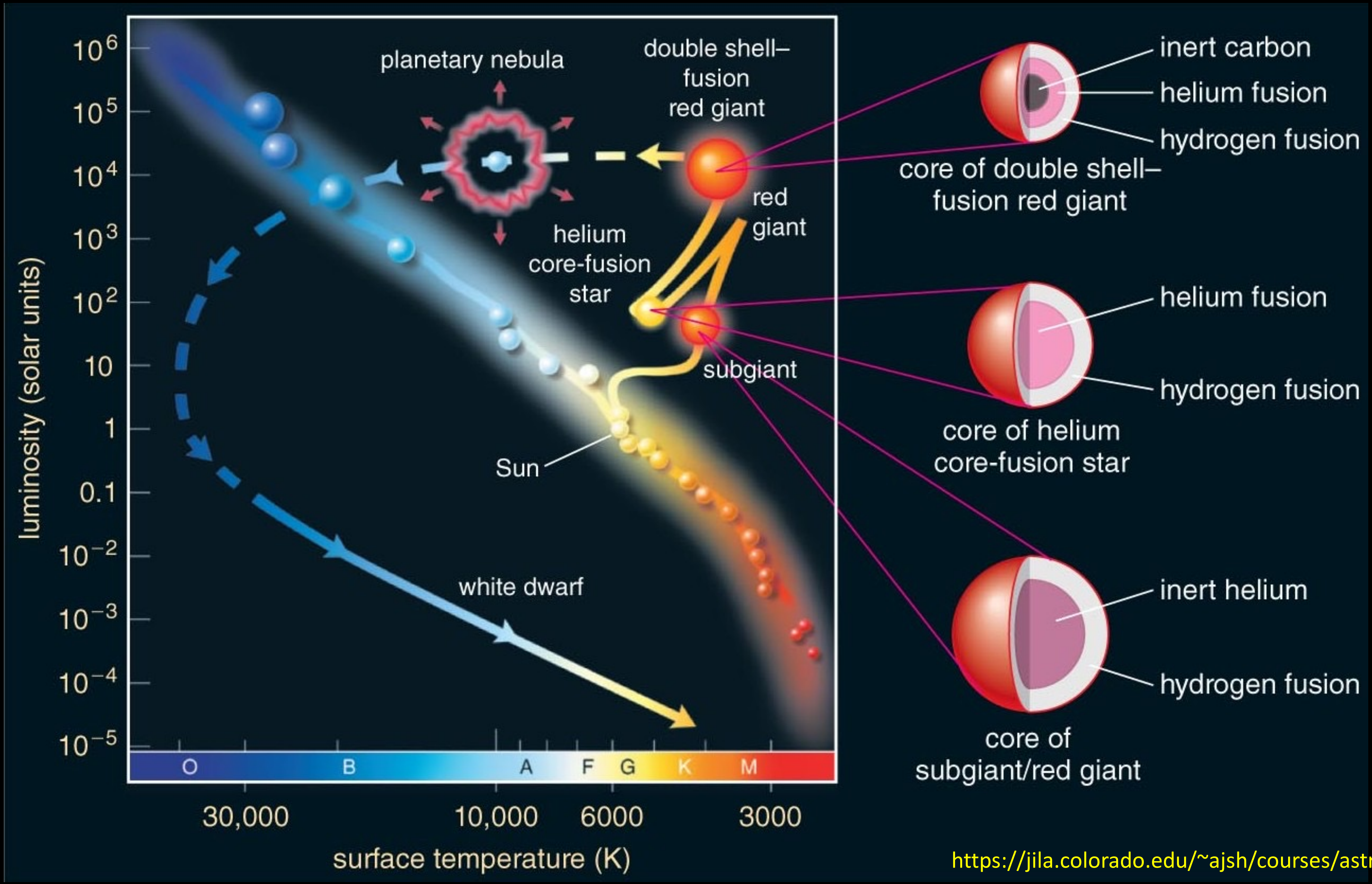
Steven Janowiecki, Greg Mace, Greg Zeimann – McDonald Observatory, U. Texas

Brendan Bowler, Keith Hawkins, Catherine Manea – Dept. Astronomy, U. Texas

Outline

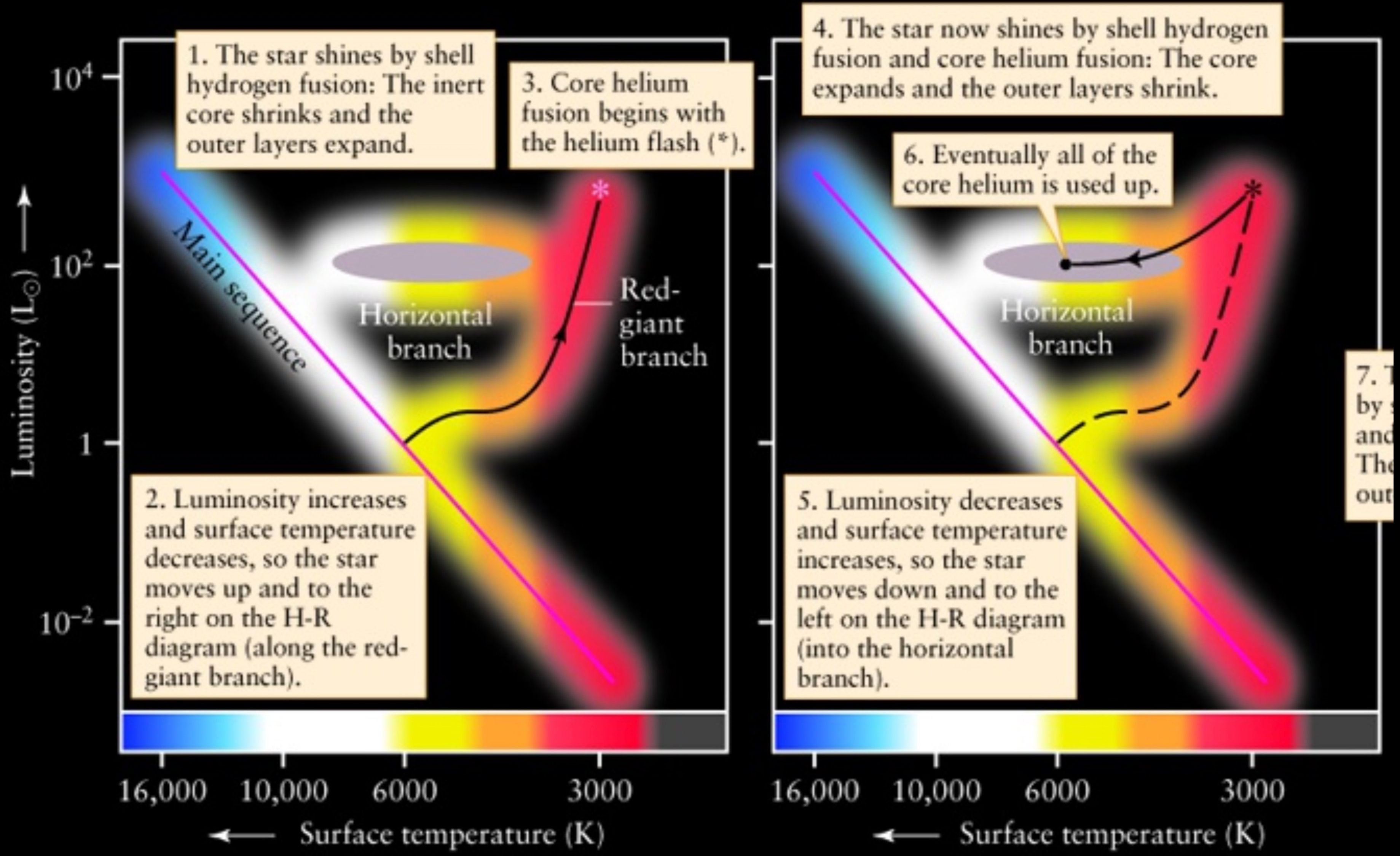
- **Brief reminder of the evolution of low-mass stars**
- **Lithium-rich red giants: an unsolved problem after 40 years**
- **A happy accident: discovery of strong He I 10830 Å in Li-rich stars**
- **“preliminary” survey: good correlation between Li and He features**
- **strong connection with helium core-burning stars**
- **tentative connection with red giant rotation**
- **today: report of an extended survey**
    - **what we now know spectroscopically**
    - **what we must now do in interpretation**

low mass stellar evolution in one slide

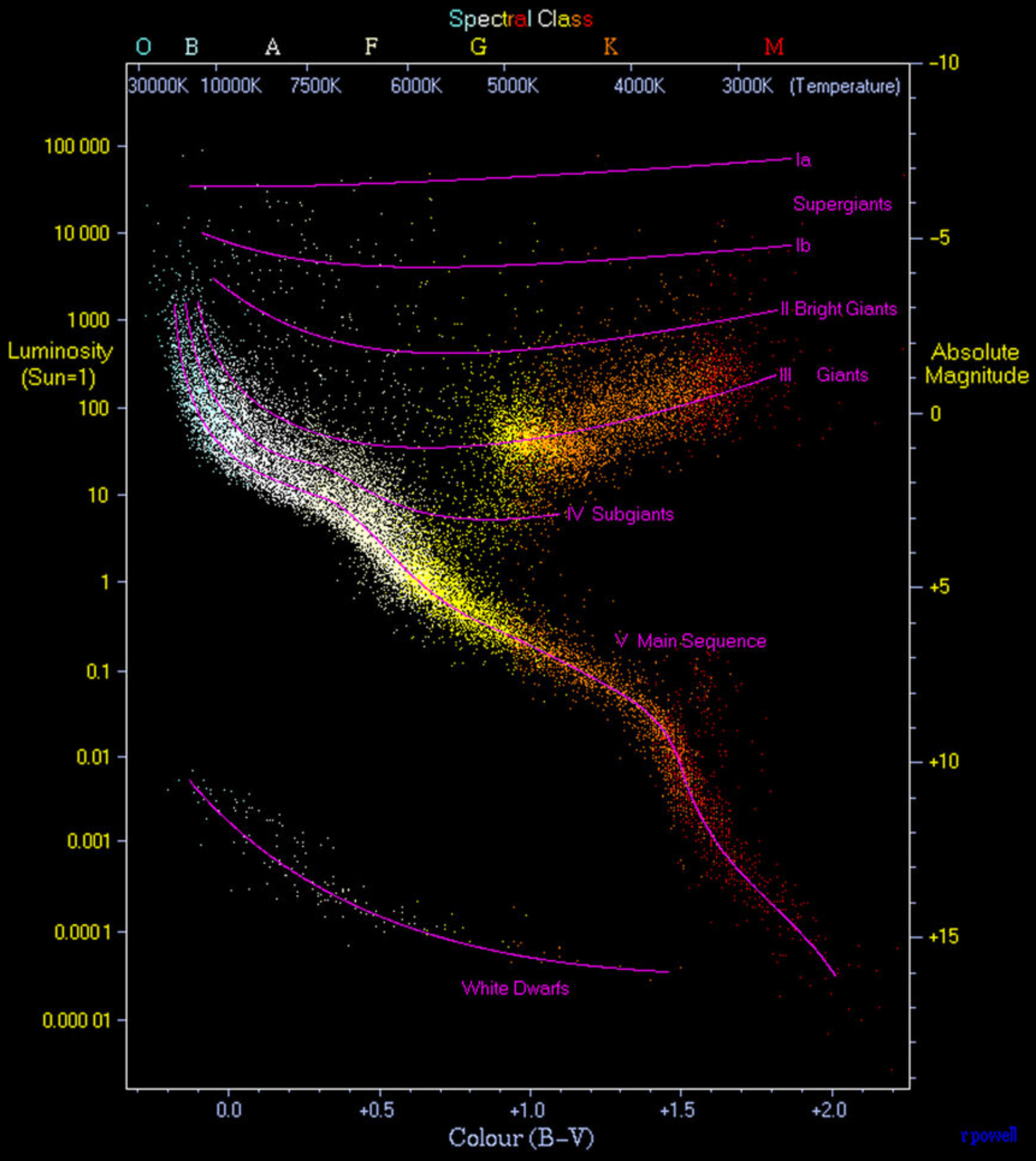


https://jila.colorado.edu/~ajsh/courses/astr1200_18/starevol.html

we are most interested in parts of the last 10% of a star's life



https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect17/lecture17.html

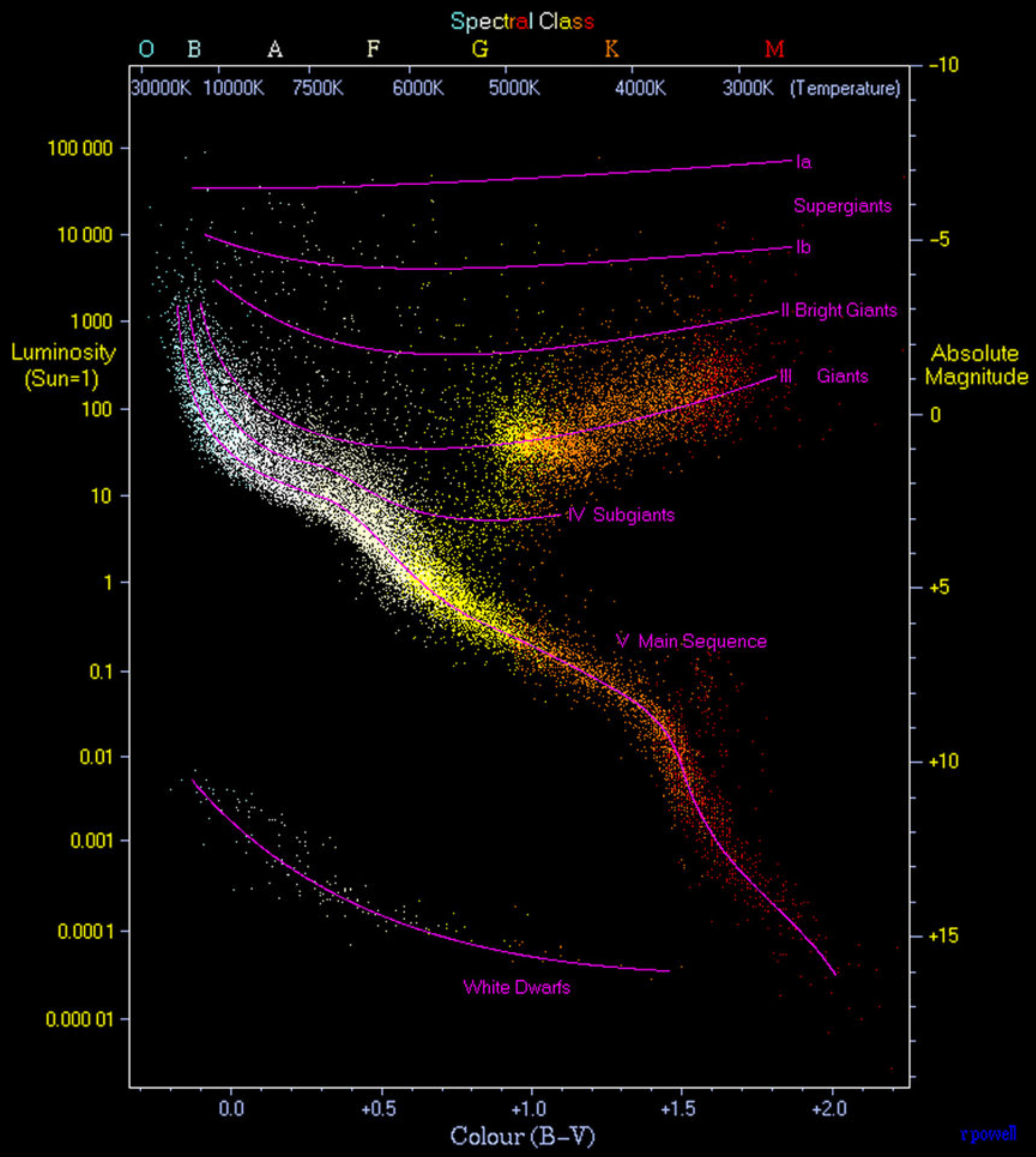


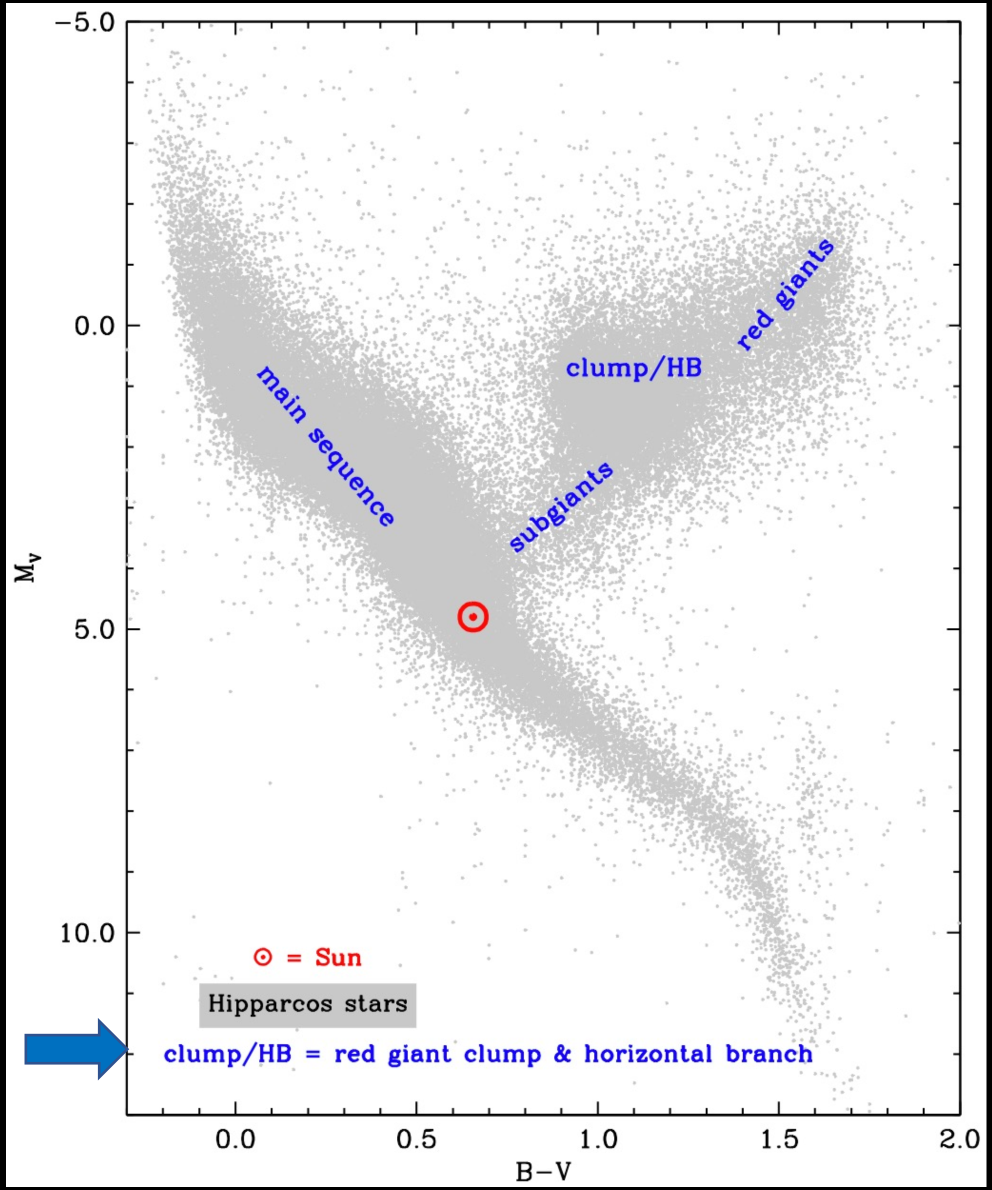
where in the HR diagram do real stars live?

- **Before Gaia, there was Hipparcos!**
- **Here is one of the famous Hipparcos Hertzprung-Russell, color-magnitude diagrams**
- **Our focus today is on red giants**
- **Many astrophysically interesting things happen in the last 10% of a star's life**
- **we concentrate on lithium-rich red giants**

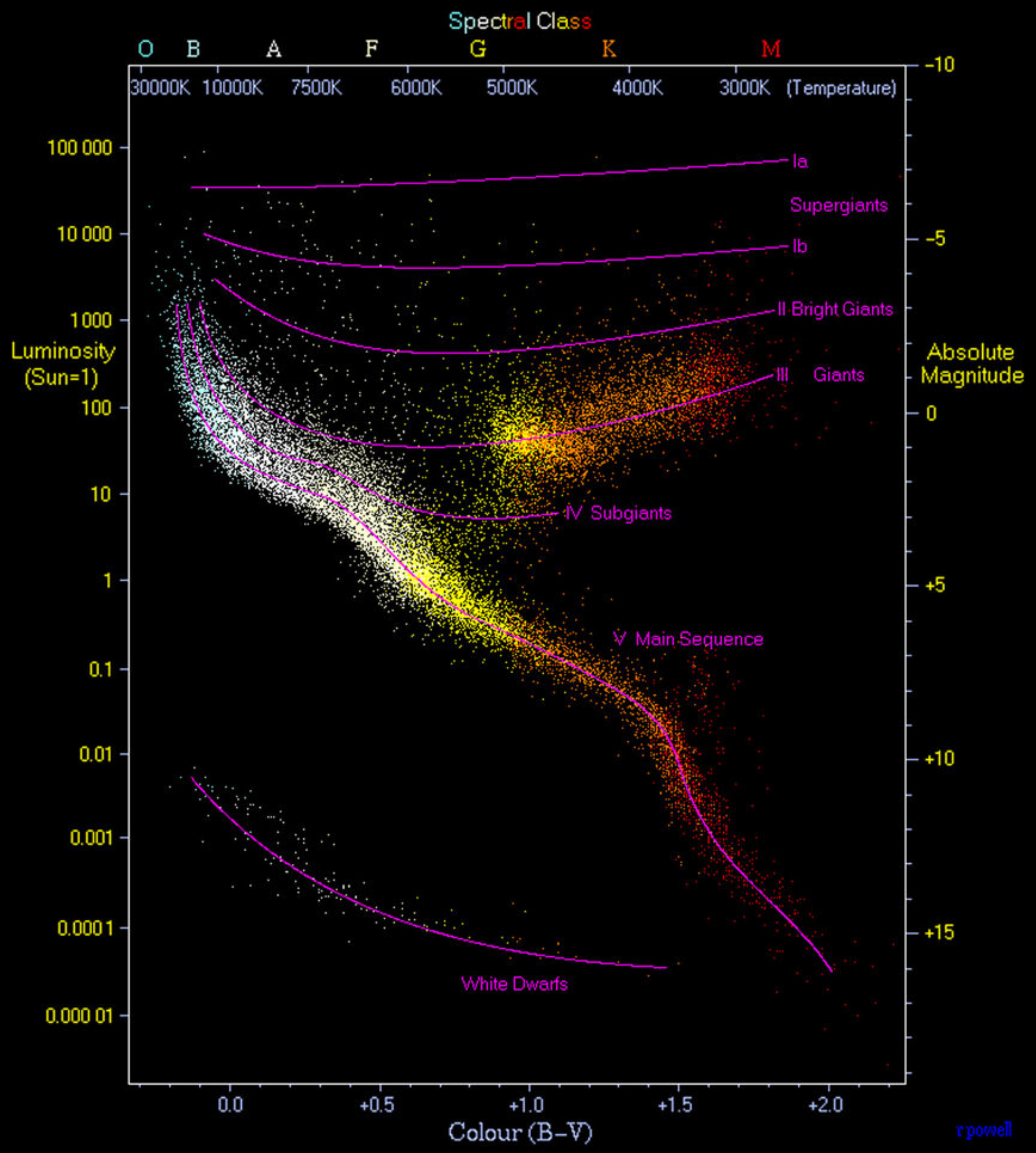
Mignard, F 2019, Comptes rendus - Physique, 20, 140

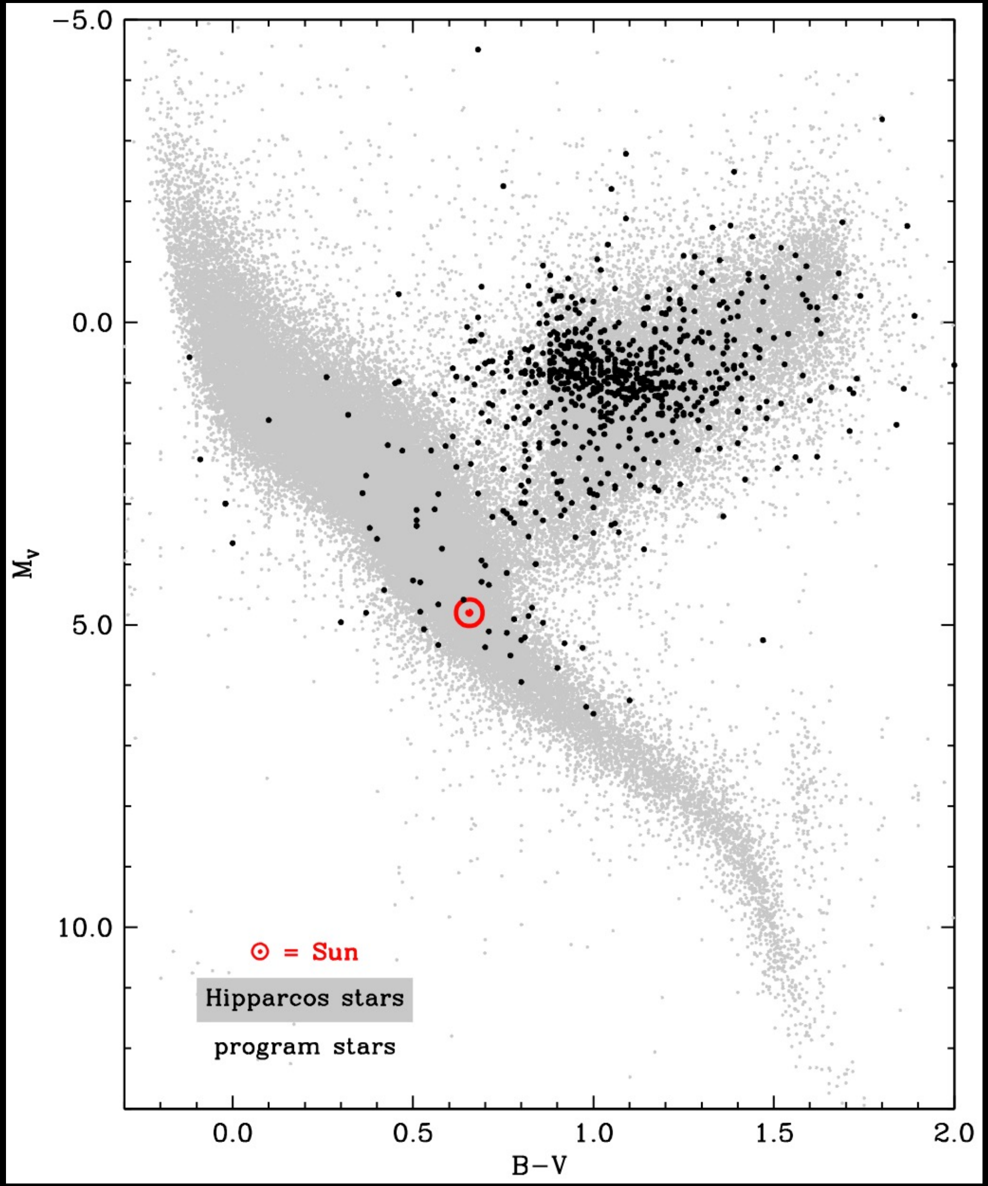
what kinds of stars do we have?



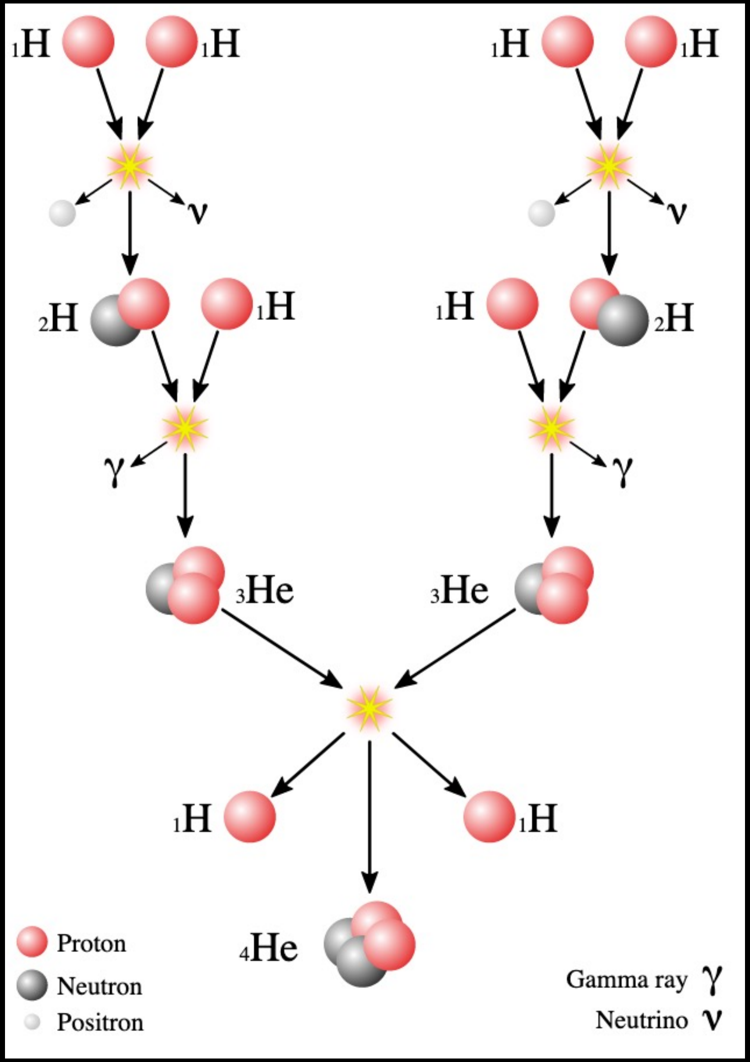


our stellar sample

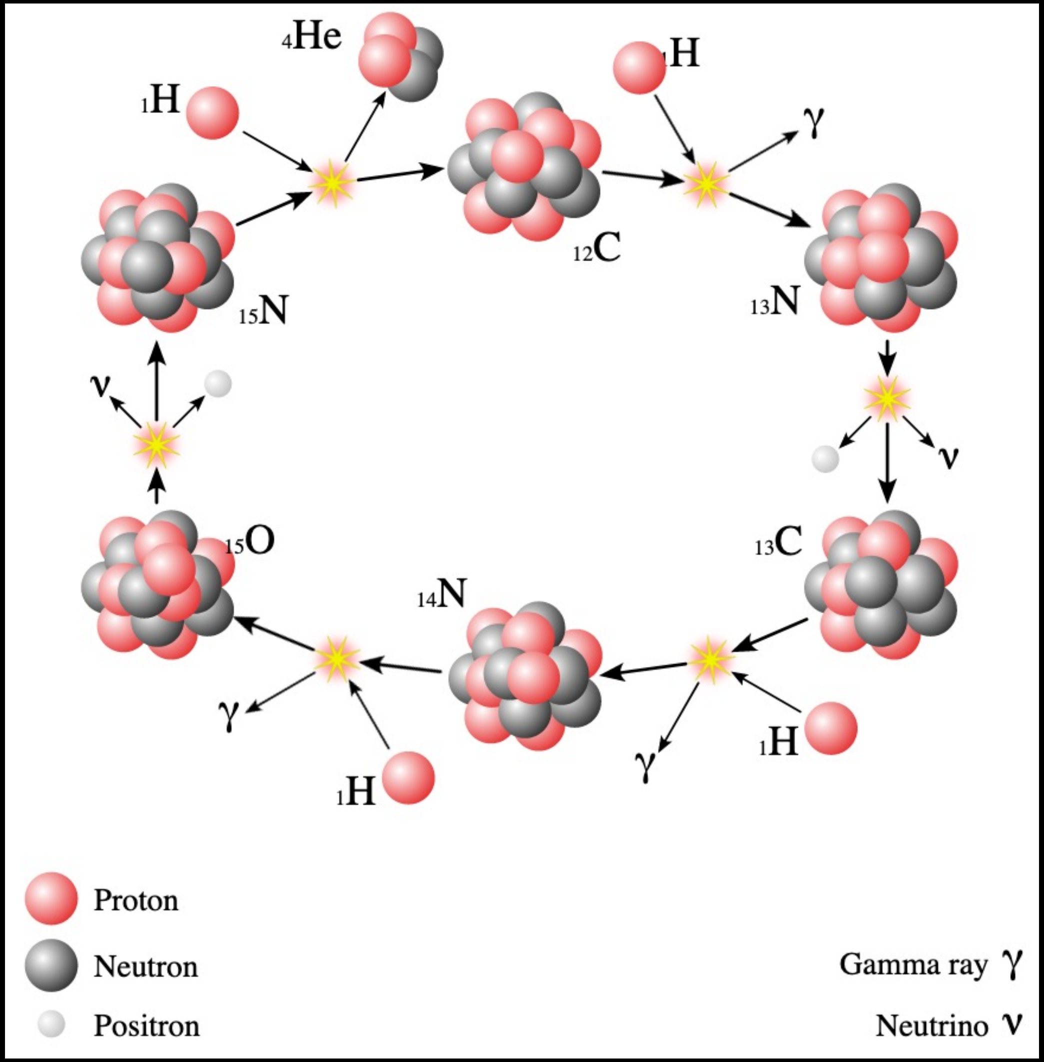




brief comments on interior hydrogen fusion cycles of stars

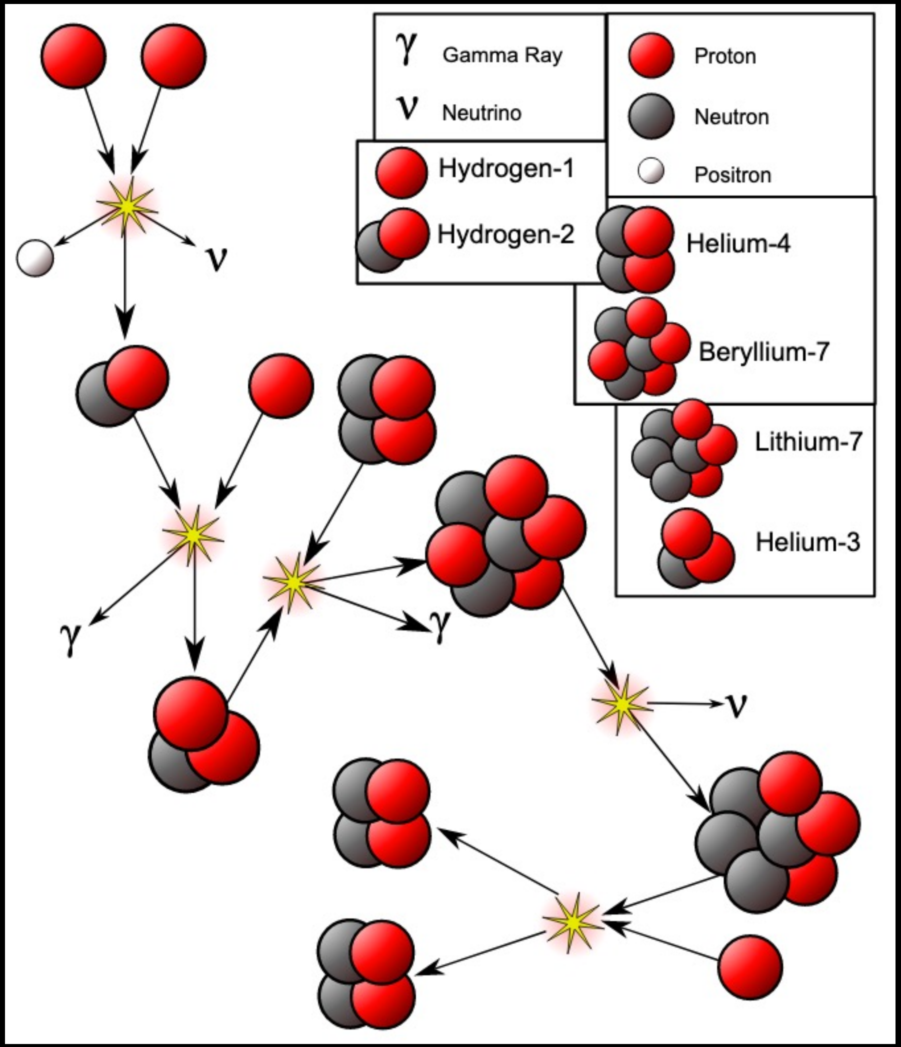


https://en.wikipedia.org/wiki/Proton%E2%80%93proton_chain



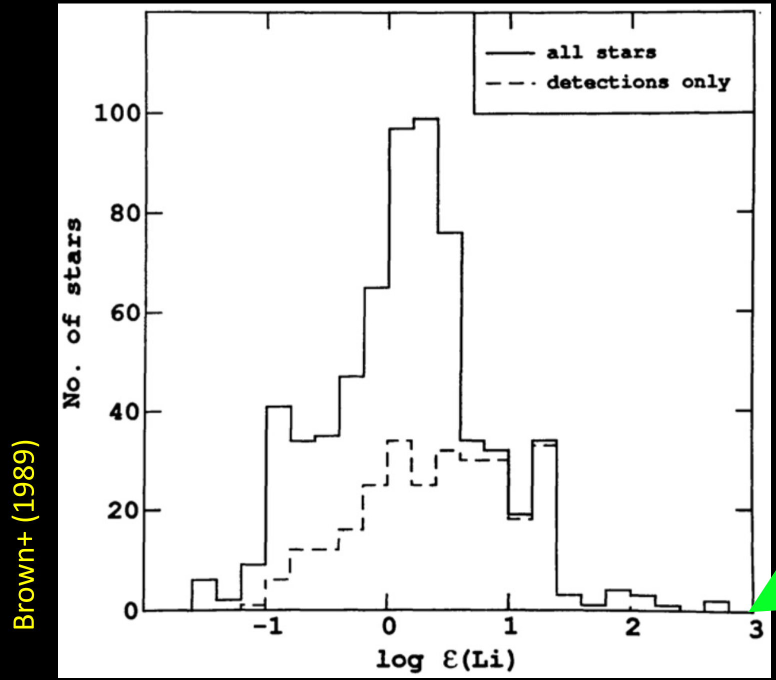
https://en.wikipedia.org/wiki/CNO_cycle

lithium is easily destroyed in hydrogen burning



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

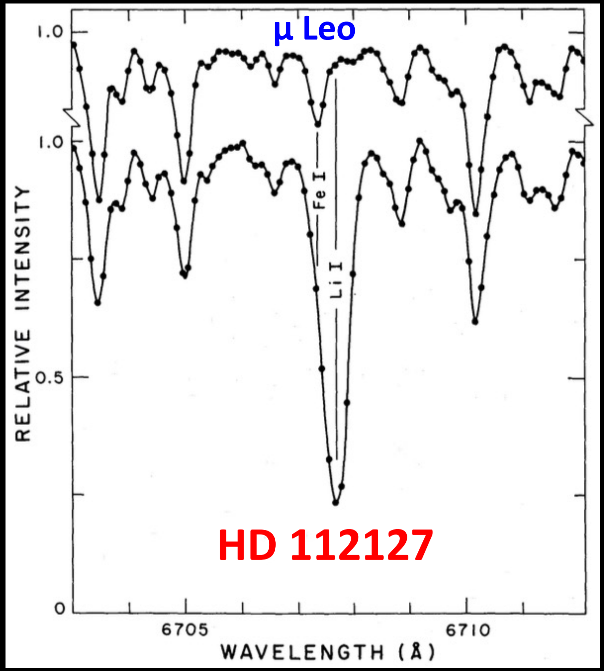
- $^7Li + p \rightarrow 2\,^4He$
- happens at relatively low fusion temperatures
- cleans out interior Li
- as stars leave the main sequence and become red giants, mixing interior and envelope dilutes surface Li
- usually by factors of > 50



$$\log \varepsilon(\mathrm{Li}) = A(\mathrm{Li}) = \log_{10}(N_{Li}/N_H) + 12$$

But about 1% of red giants show VERY strong Li I lines, implying VERY high Li abundances

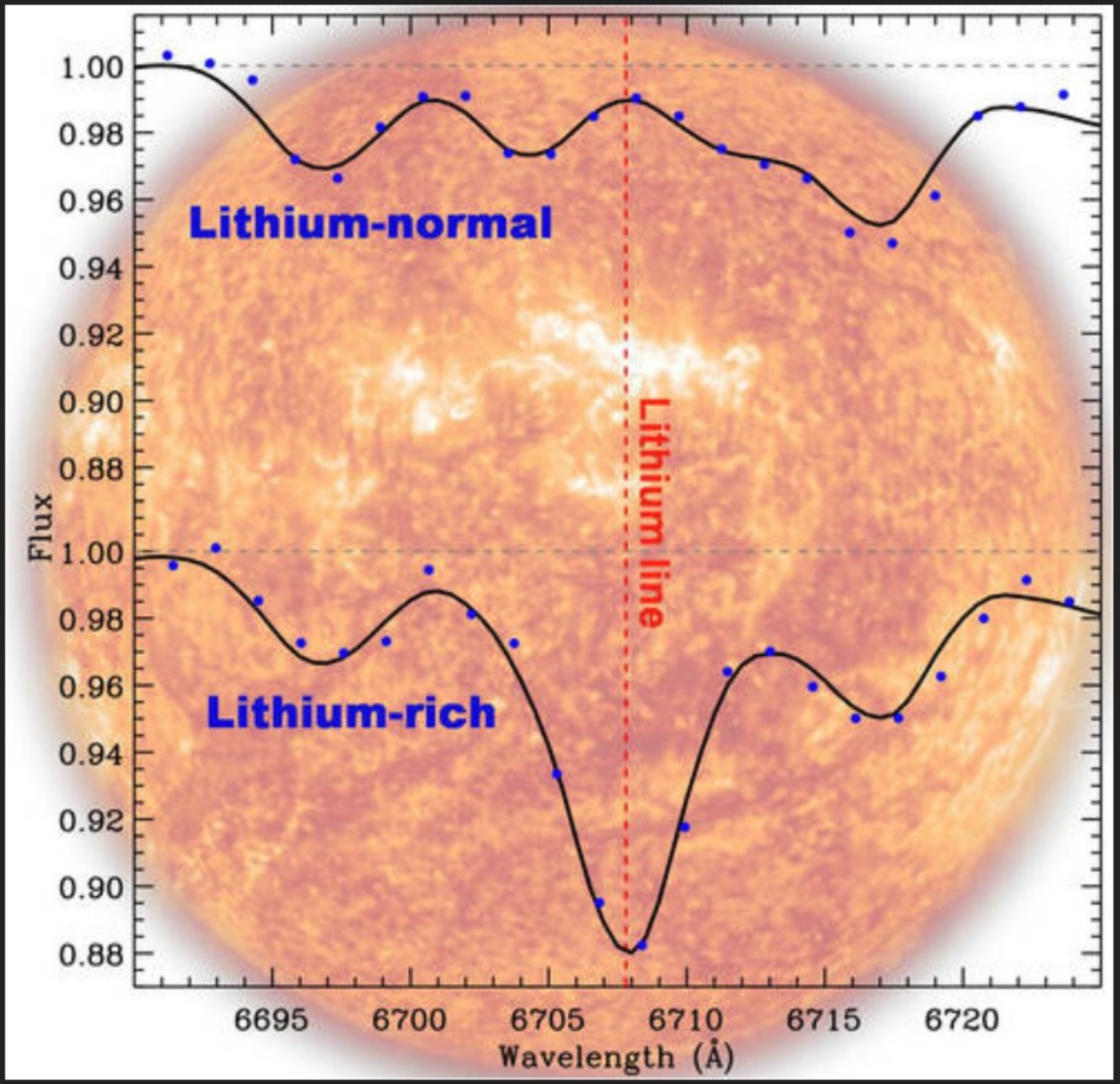
George Wallerstein discovered the fist Li-rich giant: 1982, ApJ, 255, 577



for HD 112127:
A(Li) ≃ 3.2

for many other Li-rich stars, A(Li) > 4, much more Li than they could have had at birth

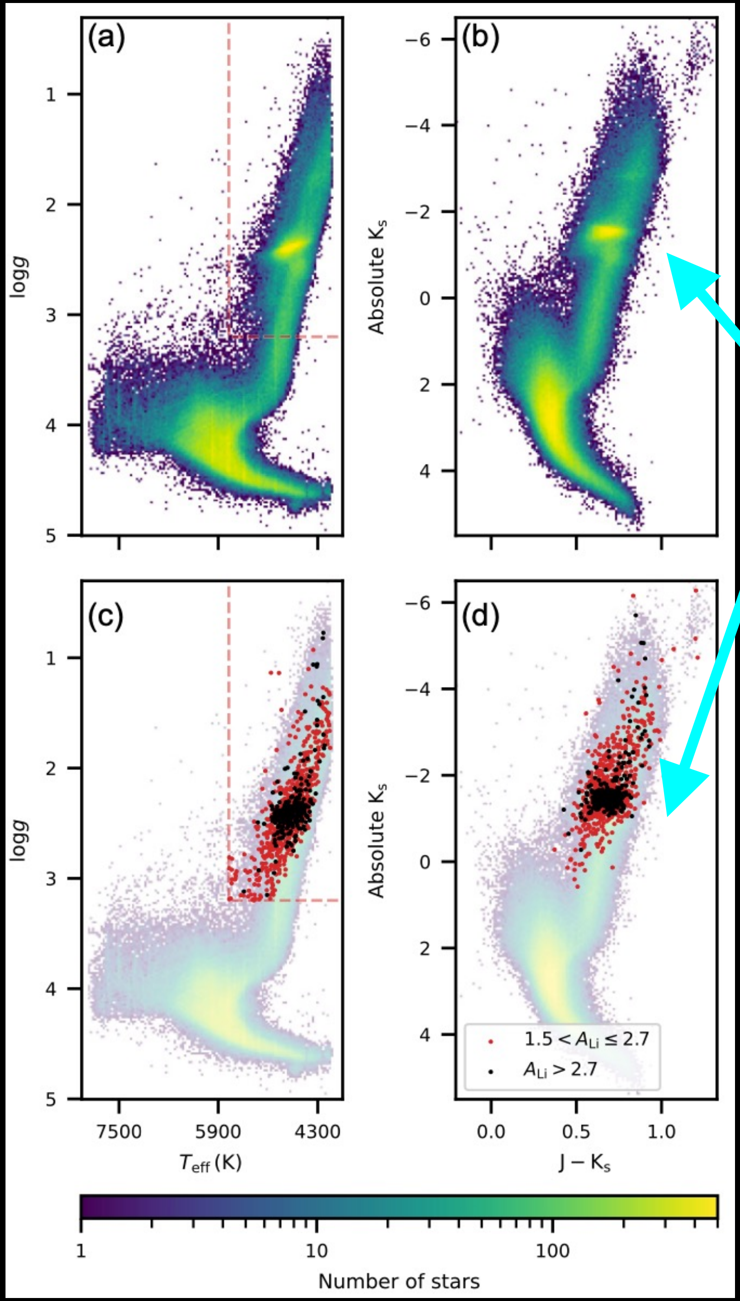
Li has *somehow* been created in/around Li-rich red giant stars



https://www.universetoday.com/147002/stars-like-our-sun-become-lithium-factories-as-they-die/

Since Wallerstein's discovery, many searches for Li-rich stars have been conducted

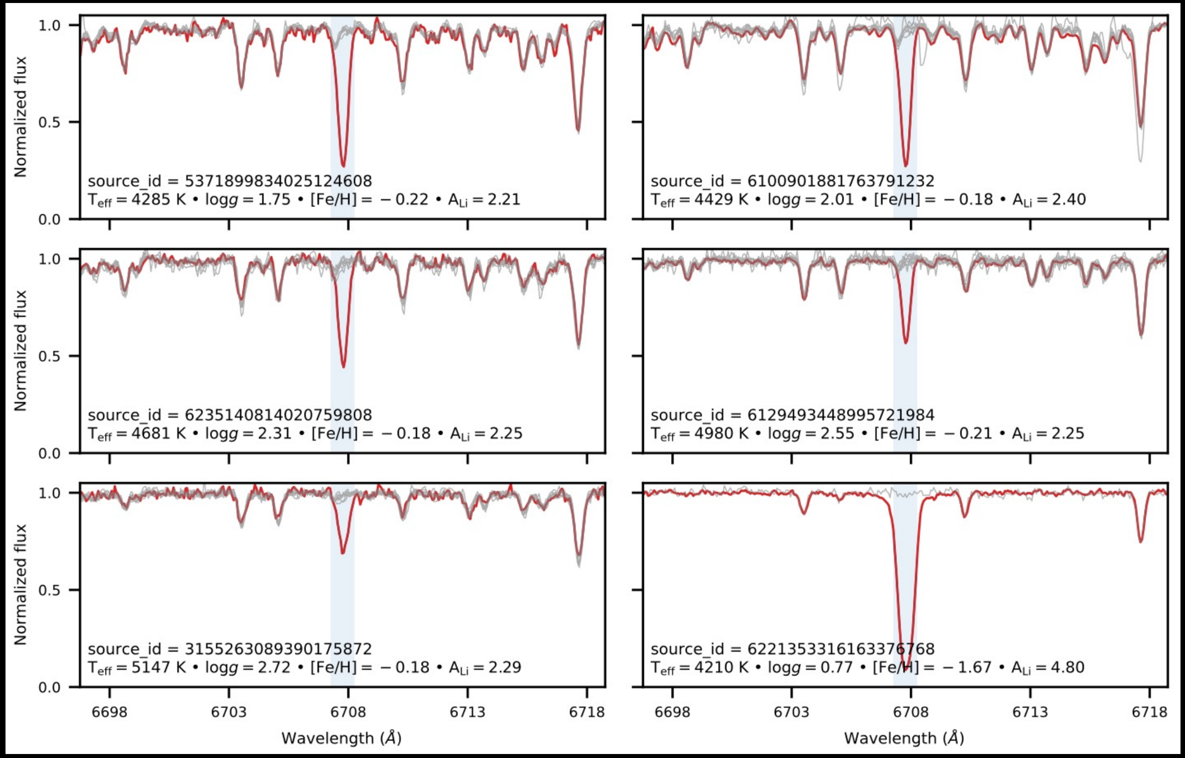
here is one of the best, most complete surveys



Martell+ (2021)

Vast majority of Li-rich giants are red clump / horizontal branch

the huge Li abundances of some stars means recent creation of Li

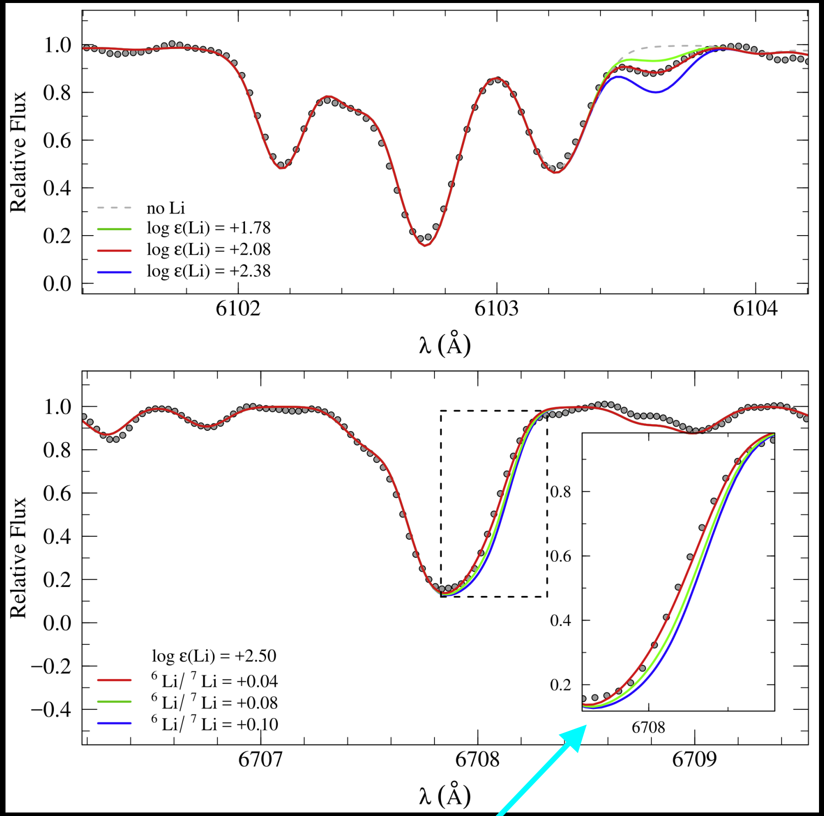


Martell+ (2021)

in large-sample surveys often spectroscopic details must be sacrificed; not all Li abundances are created equal

R = 48,000: all absorption components resolved

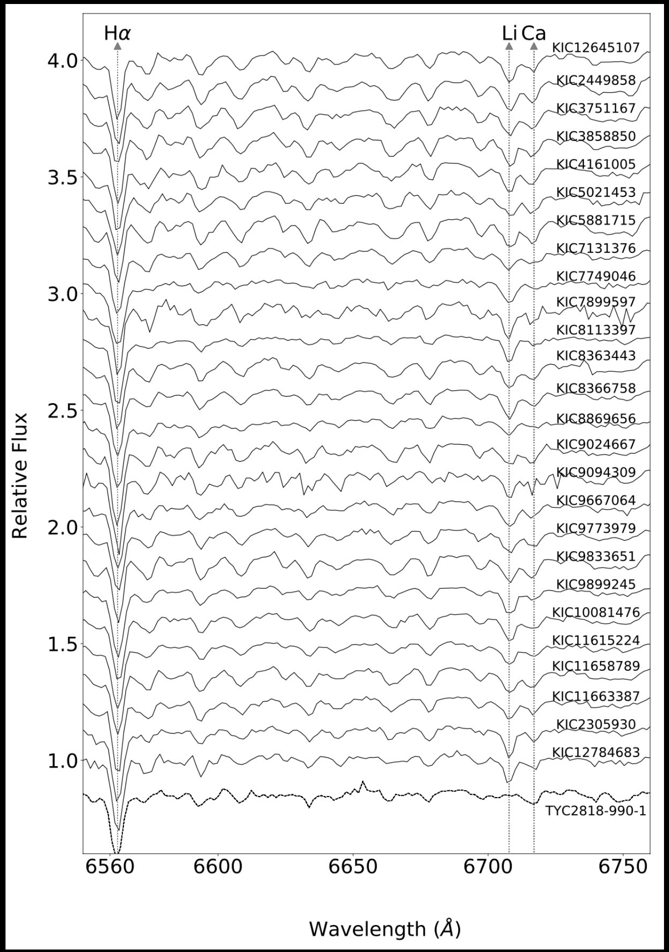
Holanda+2020



even enough detail to attempt a ^{6}Li/^{7}Li estimate

caution: we treat all Li abundances equally

LAMOST spectra: R ≃ 1500



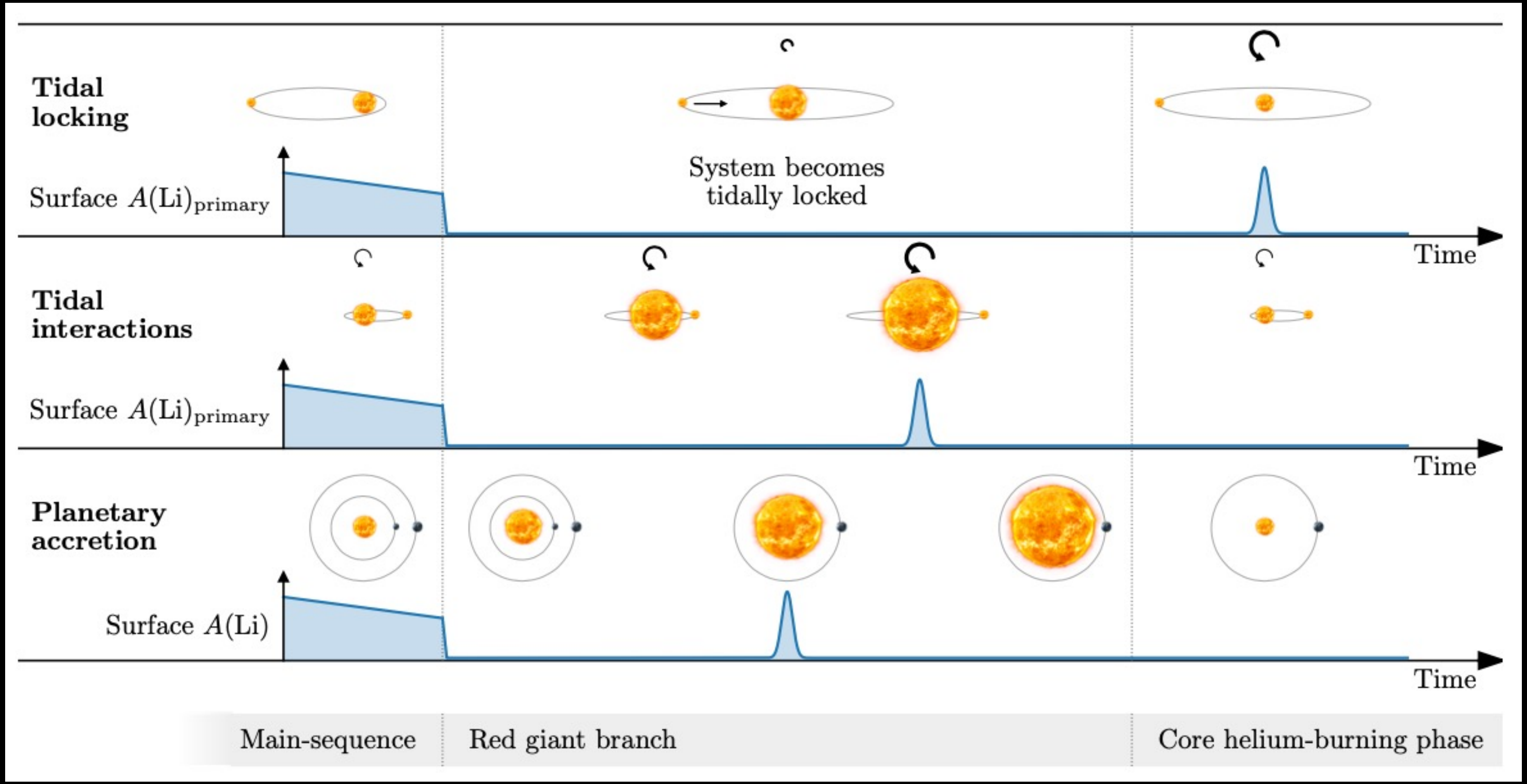
Singh+2019

detection here is the desired outcome

Do binary interactions trigger fresh Li dredge-up?

Cameron & Fowler (1971) beryllium transport mechanism:
$^3He(\alpha,\gamma)^7Be$ … quick transfer outward … $^7Be(\beta^-,\nu)^7Li$ … convect to surface

How a companion can help/kill this production



Casey+2019

more on the Beryllium transport mechanism

- Cameron & Fowler 1971, ApJ, 164, 111
- focused on the high Li seen in carbon stars ⇒ deep He-fusion layers
- special (rare?) conditions must apply
  - in helium-burning regions, ^{3}He(α,γ)^{7}Be
  - helium flashes drive convection into H-rich layers
  - with mixing timescales of hours sends ^{7}Be outward
  - then ^{7}Be(β^{-},ν)^{7}Li can occur in cooler envelope layers
- But our stars are mainly HB, not very advanced AGB
- if the Be transport mechanism works, it probably has happened at the time of the helium flash

$t_{1/2}(^{7}\mathrm{Be}) = 53.3\mathrm{d} = 4.6\times10^{6}\mathrm{s}$

	^{7}B	^{8}B	^{9}B	^{10}B	^{11}B	^{12}B	^{13}B
	^{6}Be	^{7}Be	^{8}Be	^{9}Be	^{10}Be	^{11}Be	^{12}Be
^{4}Li	^{5}Li	^{6}Li	^{7}Li	^{8}Li	^{9}Li	^{10}Li	^{11}Li
^{3}He	^{4}He	^{5}He	^{6}He	^{7}He	^{8}He	^{9}He	^{10}He

https://atom.kaeri.re.kr/old/ton/nuc1.html

What causes the Li-rich phenomenon?

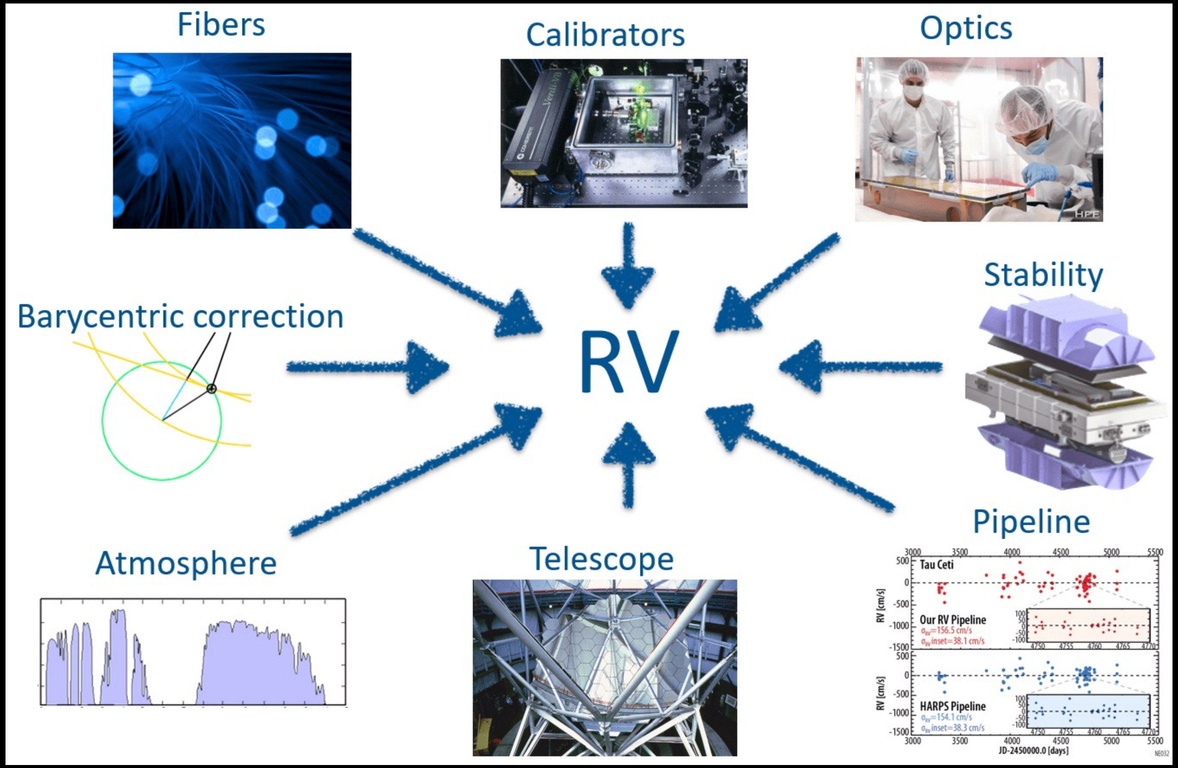
- We mostly know that it is a red clump or red horizontal branch (HB) activity
- Li-rich giants may be rapidly rotating
- It might have something to do with binarity
- But “no one” has monitored Li-rich stars for velocity variations
  - Exception: the Adamów+2014 contribution to the Penn State – Toruń Planet Search survey
- Stellar evolution theory can help, but is there any more direct observational signature?
- introducing HPF into this game: a ”new” high-resolution wavelength domain, a new instrument, and a new phenomenon

HPF is dedicated to radial velocity searches for planets around M dwarfs

The primary science goal of HPF is to find planets around mid-to-late M dwarfs using the radial velocity method

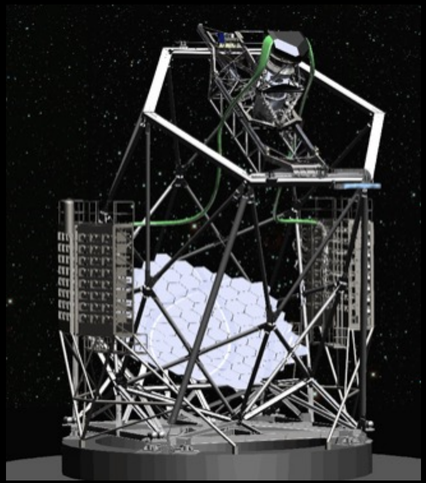
The largest of these are about a third the size of the Sun, and about 2/3rd as hot (~ 3000 K vs 5777 K for the Sun)

To achieve this, HPF conducts intensive super-accurate RV observations of a carefully selected group of such stars

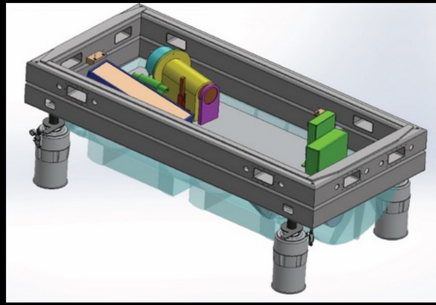


https://hpf.psu.edu/

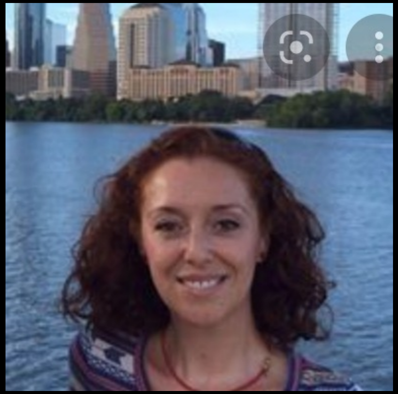
A small 1μ high-res study of red giants turned up a surprise



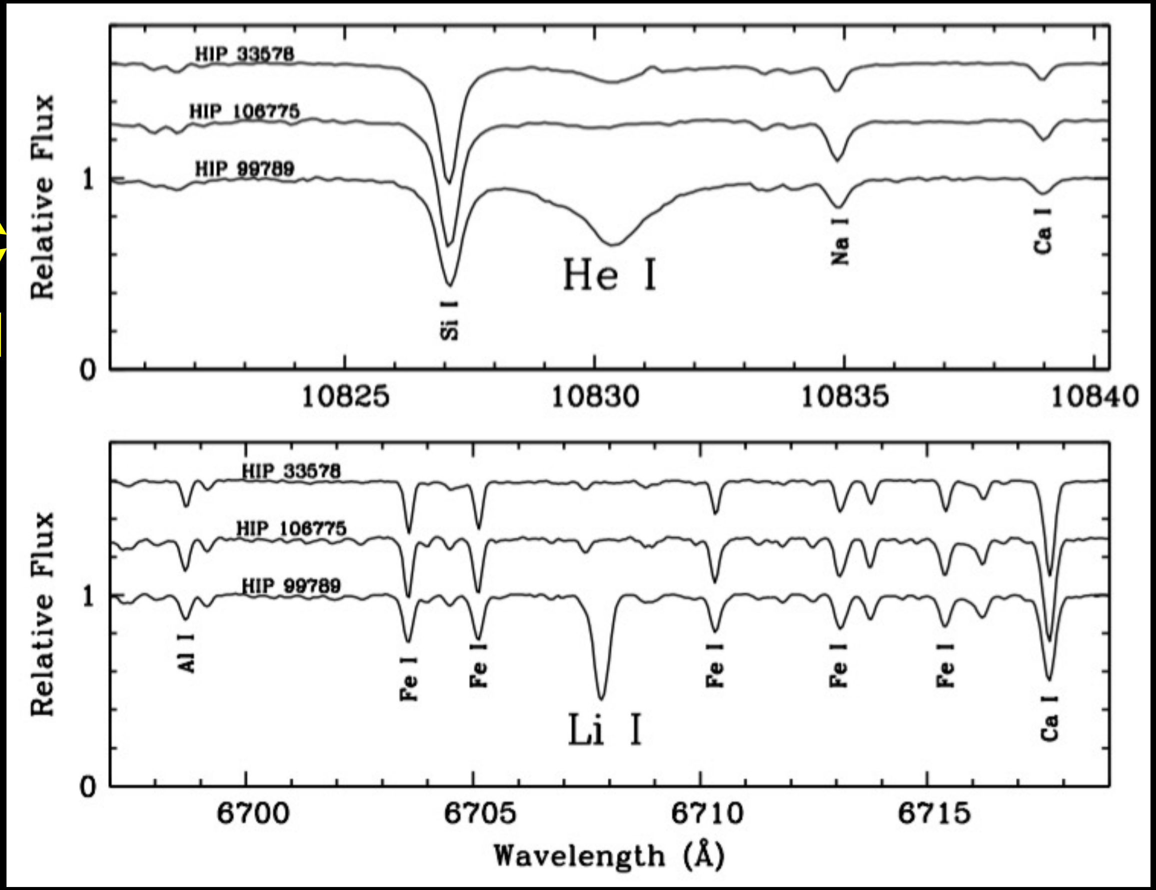
Hobby-Eberly 10m Telescope at McDonald Observatory



Habitable Zone Planet Finder: high-res spectra in 0.85-1.25**μ** range

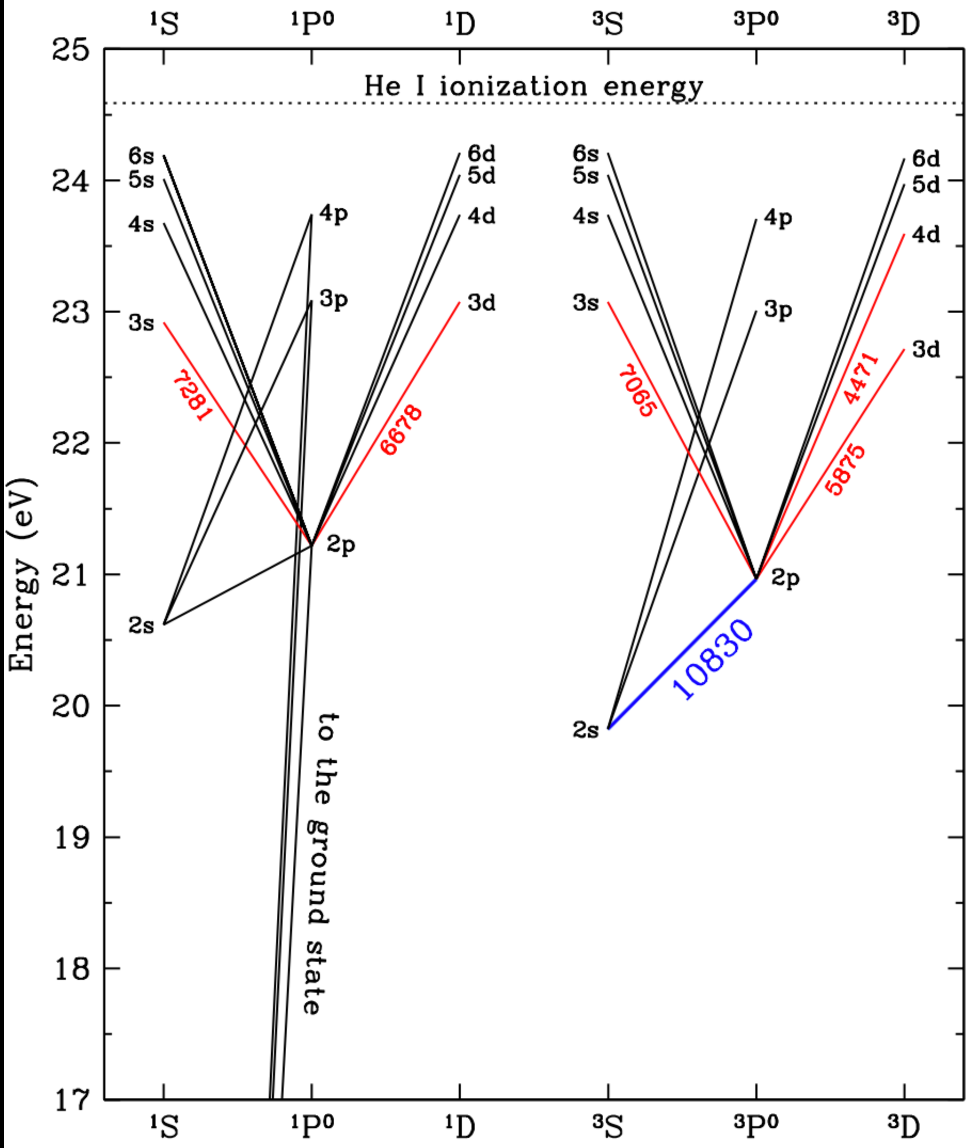


Melike Afşar: exploring spectra of clump/RHB stars at 1μ



one of her targets was a rare Li-rich red giant

He I λ10830 cannot be formed in a cool-star *photosphere*



This figure is adapted from Preston+2022

They studied shock-induced He I & He II lines in the optical spectrum (transitions in red color)

λ10830 (depicted in blue) is part of the triplet system, completely disconnected from the He I singlet system ground state, and its lower excitation level 2s^{3}S is at 19.8 eV

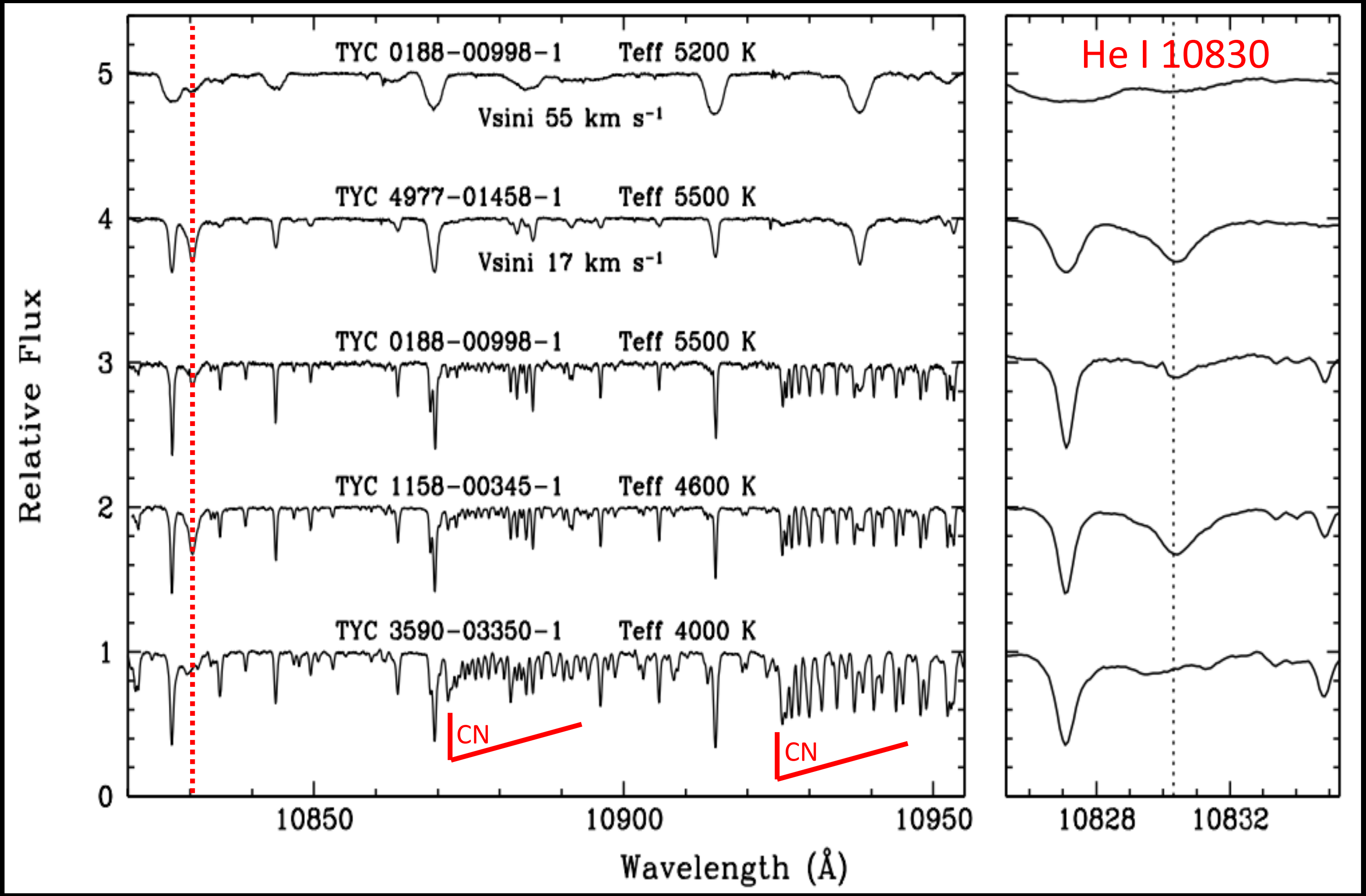
this line is most easily generated first by He chromospheric ionization activity, followed by recombination to its lower state

significant He I λ10830 absorption can only happen in very disturbed cool-star chromospheres or during heavy mass loss

The initial discovery suggested a He I λ10830 survey of Li-rich giants

- Li rich stars: a heterogeneous sample from the literature
- Li-poor stars: surveys of Adamów+2014, Afşar+2018
- HET/HPF (Mahadevan+2012,2014)
  - $R \equiv \lambda/\Delta\lambda \simeq 55{,}000$
  - S/N $\simeq$ 80 to >200
- reductions are important in this spectral region
- analyses are a bit unique
- ***a simple desired outcome:***
  - ***the relation between Li abundances and He I line strengths***
- **Initial survey paper: Sneden, Afşar, et al. 2022, ApJ, 940, 12**

we included a variety of red giants



Sneden+2022

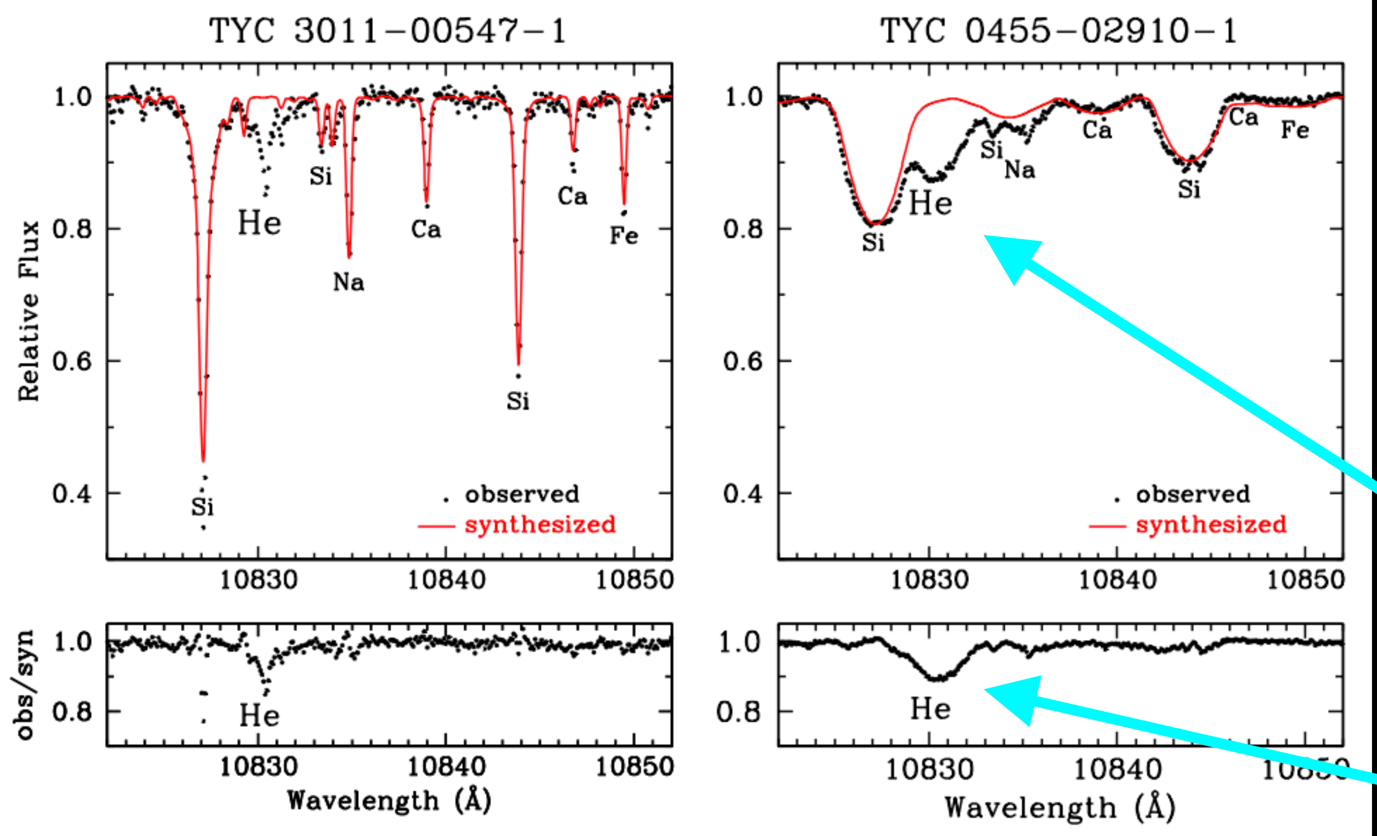
- Li-rich and Li-poor
- warm and cool
- some are rotating
- mostly Galactic disk

lots of other species in HPF spectra:

Na, Si, Ca, Fe

we ignore them here!

Just a little of the analytical details



Sneden+2022

raw spectra are a mess, with need to excise night sky OH emission and H_2O telluric absorption

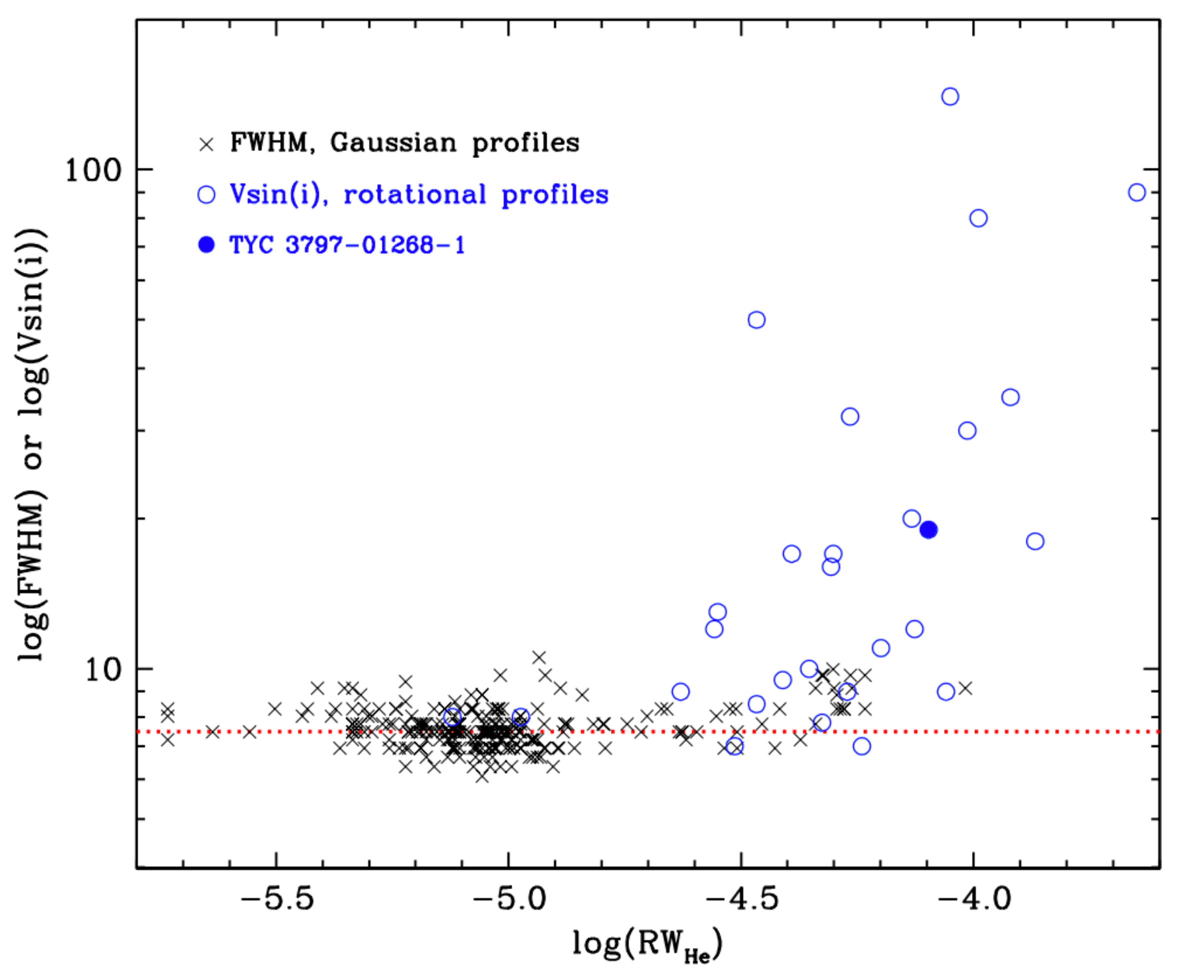
resulting stellar spectrum sometimes has major *photospheric* contaminants crowding the *chromospheric* He I λ10830 very broad line

this is a real problem for rapid rotators

we construct synthetic *photospheric* spectra to match and divide out that part of the total, leaving only λ10830

This process is purely empirical!
We desire "good enough" equivalent widths of λ10830

First basic result:
line broadening correlates with He I 10830 absorption strength; the strongest 10830 lines are for rapidly rotating giants

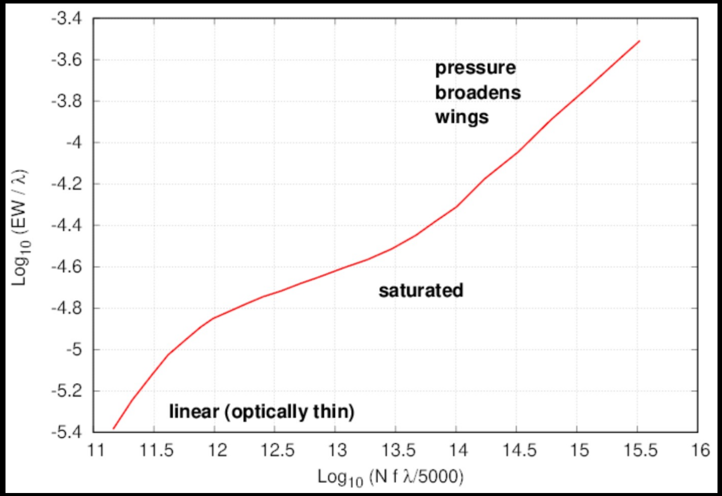


Sneden+2022

$\log(RW_{He}) \equiv$ **RW(He)** $= \log_{10}(EW_{He}/10830)$

RW is a good measure of line strength

RW ~ –6 is an extremely weak line
RW ~ –4 is very strong

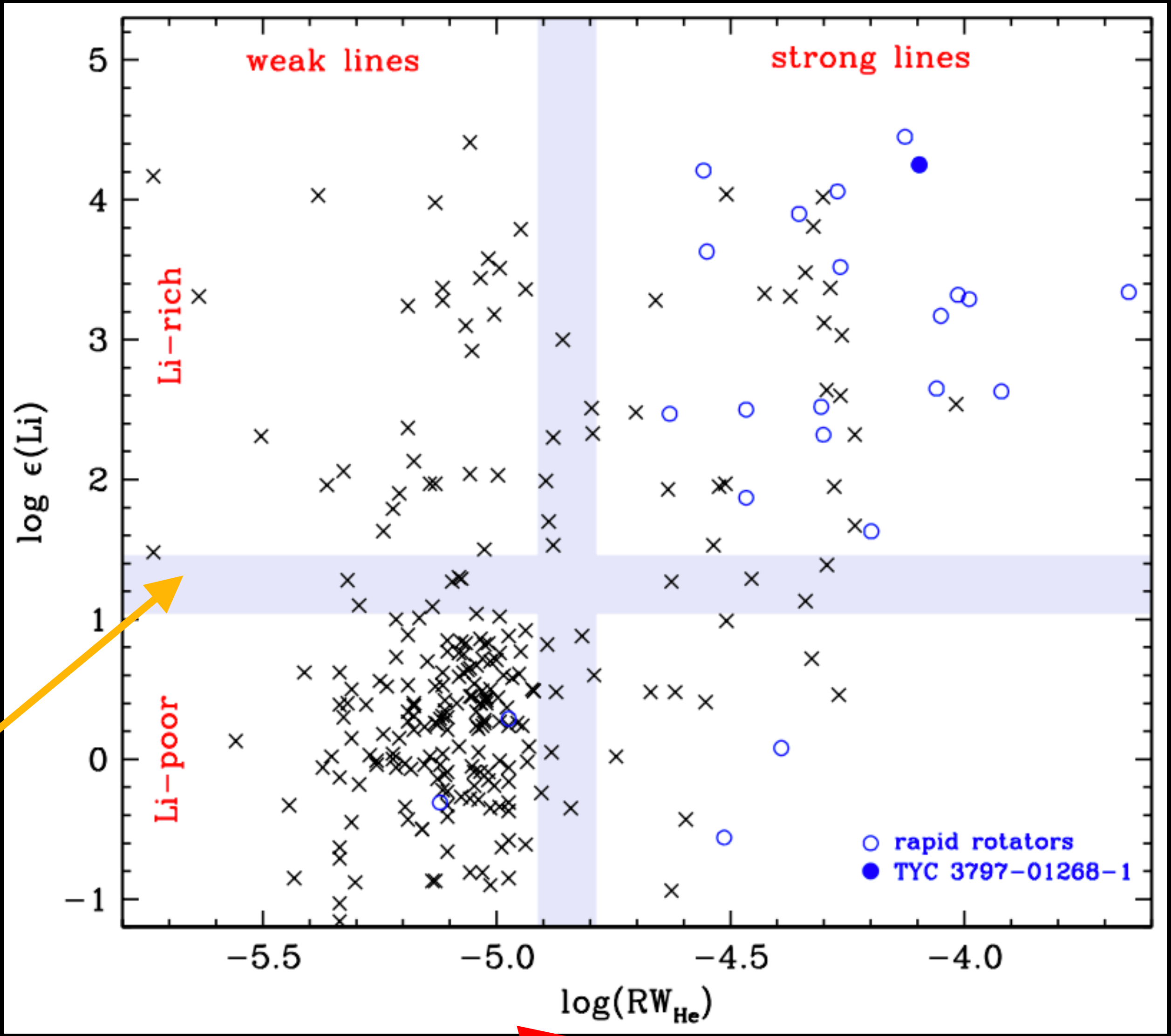


The main result: strong He I λ10830 *often* accompanies large Li abundances in red giants

horizontal lavender bar splits Li-rich from Li-poor (normal) stars … near to the "traditional" dividing line

vertical bar separates weak from strong λ10830 absorption lines … this purely empirical split is at log ε(Li) = 1.25

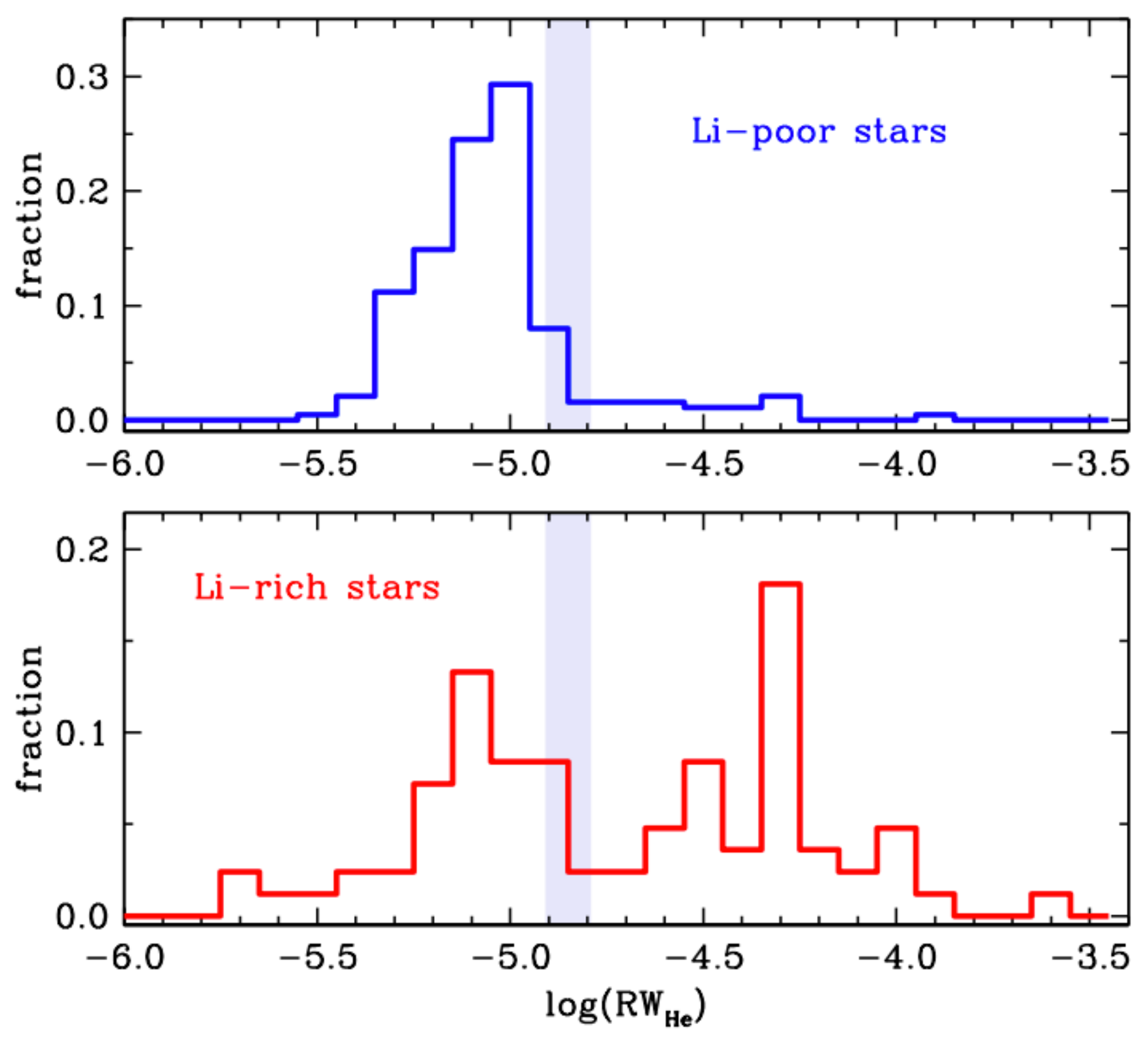
note the many rapid rotators in the Li-rich, big λ10830 quadrant



$\log(RW_{He}) \equiv \log_{10}(EW_{He}/10830)$

expressing in histograms

empirical Li-rich/Li-poor division at $\log(RW_{He}) = -4.85$



90% of Li-poor red giants have $\log(RW_{He}) < -4.85$

generally in line with pioneering investigation of O'Brien & Lambert 1986

possibly special explanation(s) can account for the other 10%

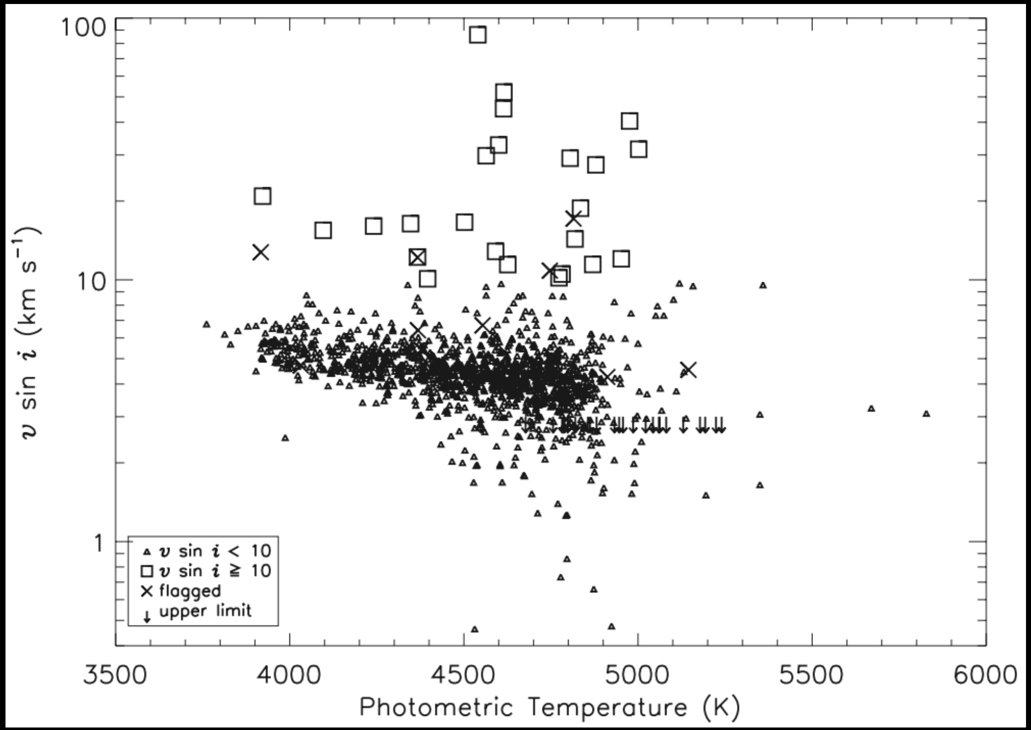
53% of Li-rich red giants have $\log(RW_{He}) > -4.85$

this plot does not distinguish rapid rotators, which populate the high end

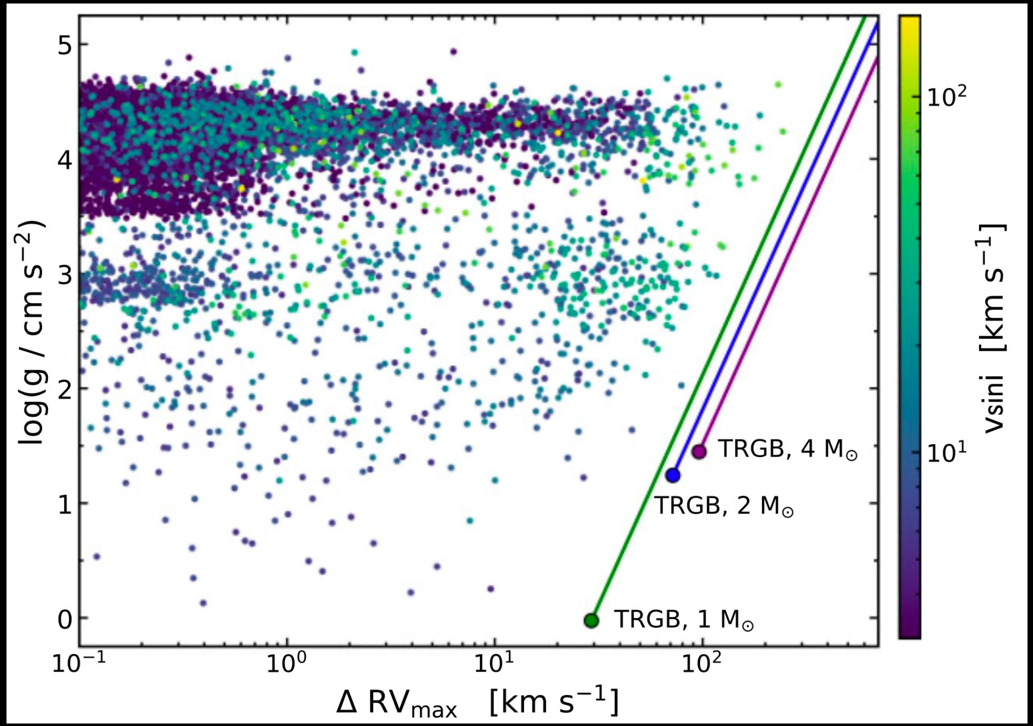
the approximate λ10830 strength break is easy to see with these histograms

A survey of λ10830 was needed for rapidly rotating red giants

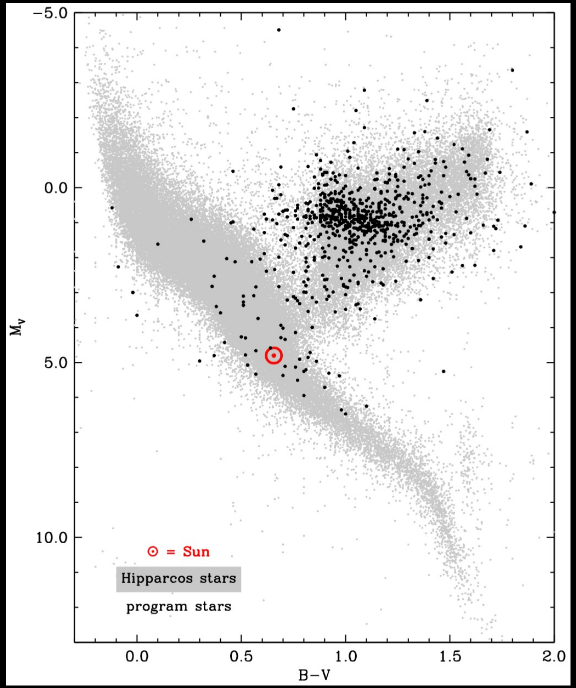
- finding curated samples of stars was most important
- lots of small-sample scattered literature sources were consulted
- two larger surveys help a lot, especially Daher+22
- we have observed about 250 rapid rotators



Carlberg+2011

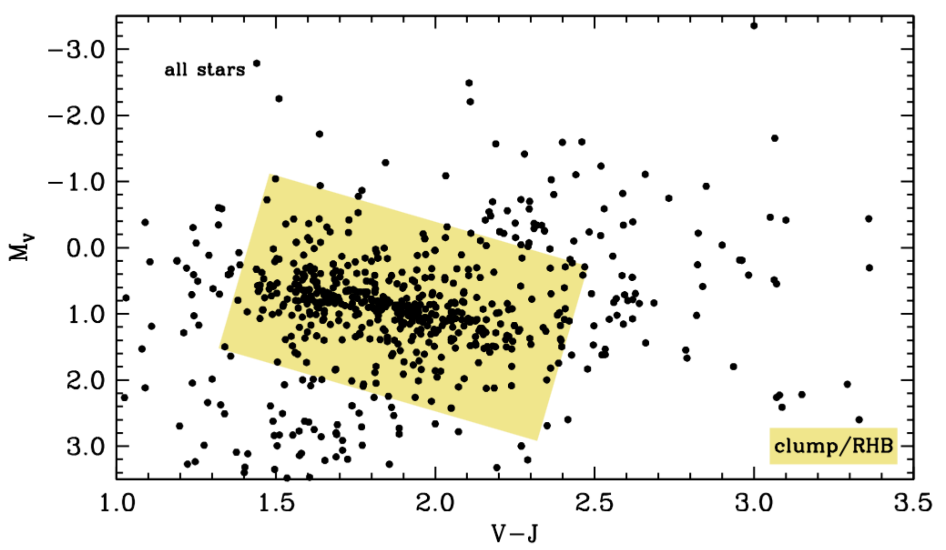


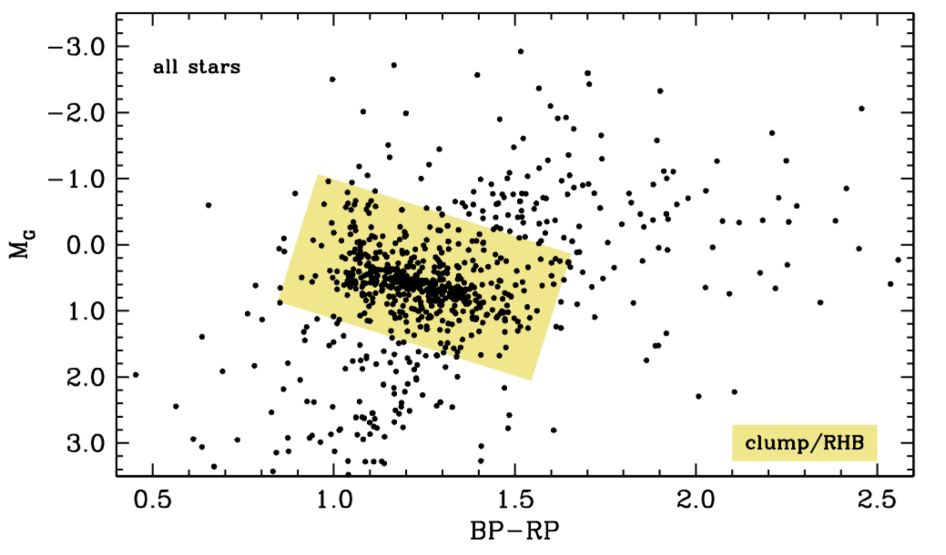
Daher+ 2022



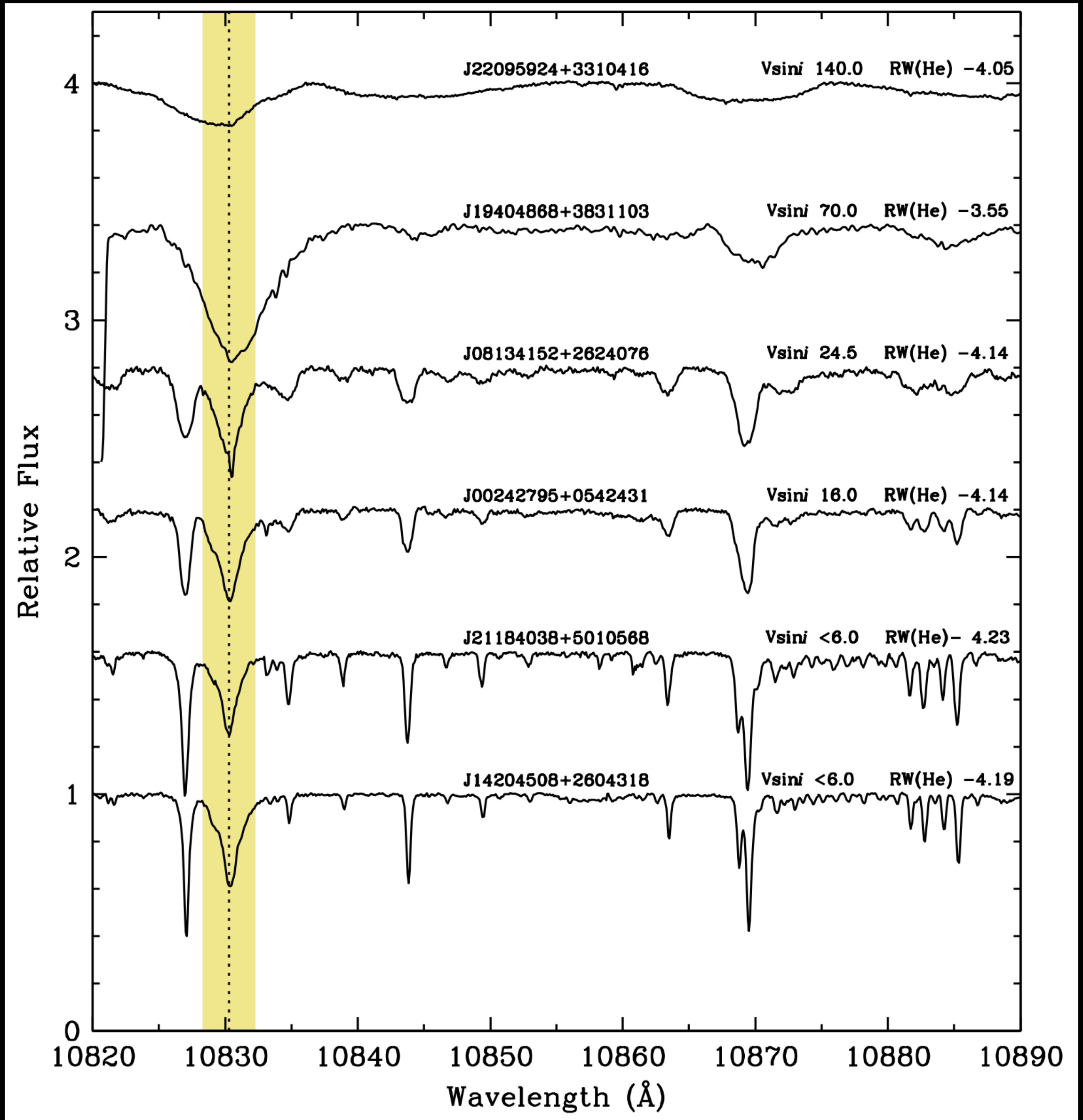
Our sample zoom-in as seen in different photometric systems

- more than 800 red giants with HET/HPF spectra
- sample main sources:
    - Adamów+ 2014 – RG clump & upper RG branch
    - Afşar+ 2018 – red horizontal branch & clump
    - Daher+2022 – APOGEE RG rotating stars
- analyses similar to Sneden+ 2022
    - more attention to photospheric model atmospheres
- survey nearing completion – Afşar+ 2024





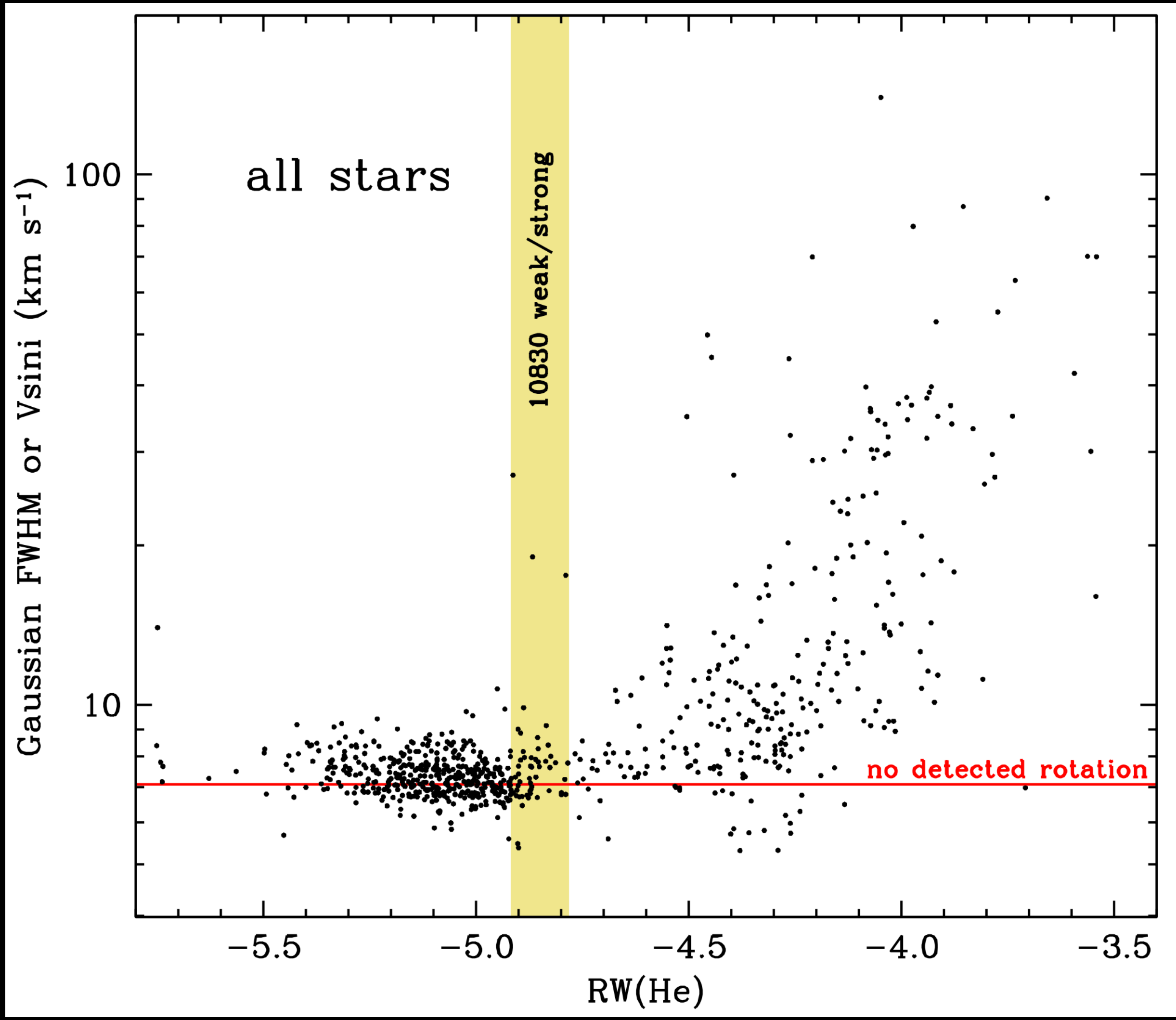
beginning the new survey by adding more rapid rotators leads to *many* more He I 10830 strong stars



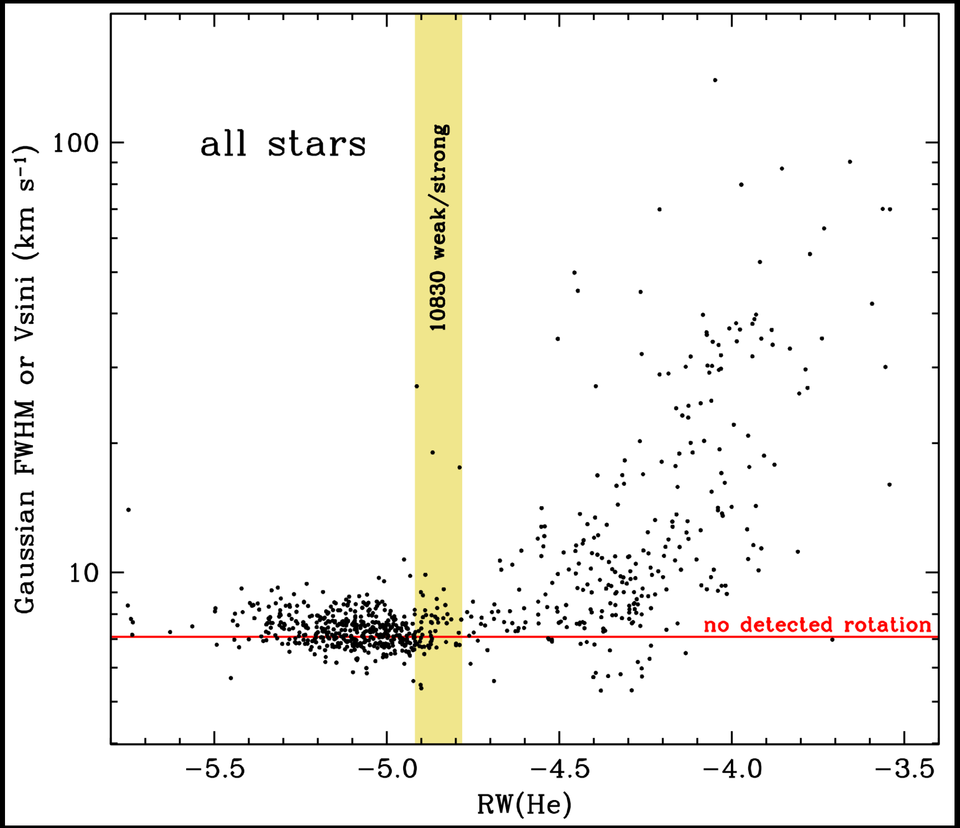
note the difficulties in separating 10830 from nearby photospheric absorbers

But also see that we do not need very accurate RW values for large 10830 lines

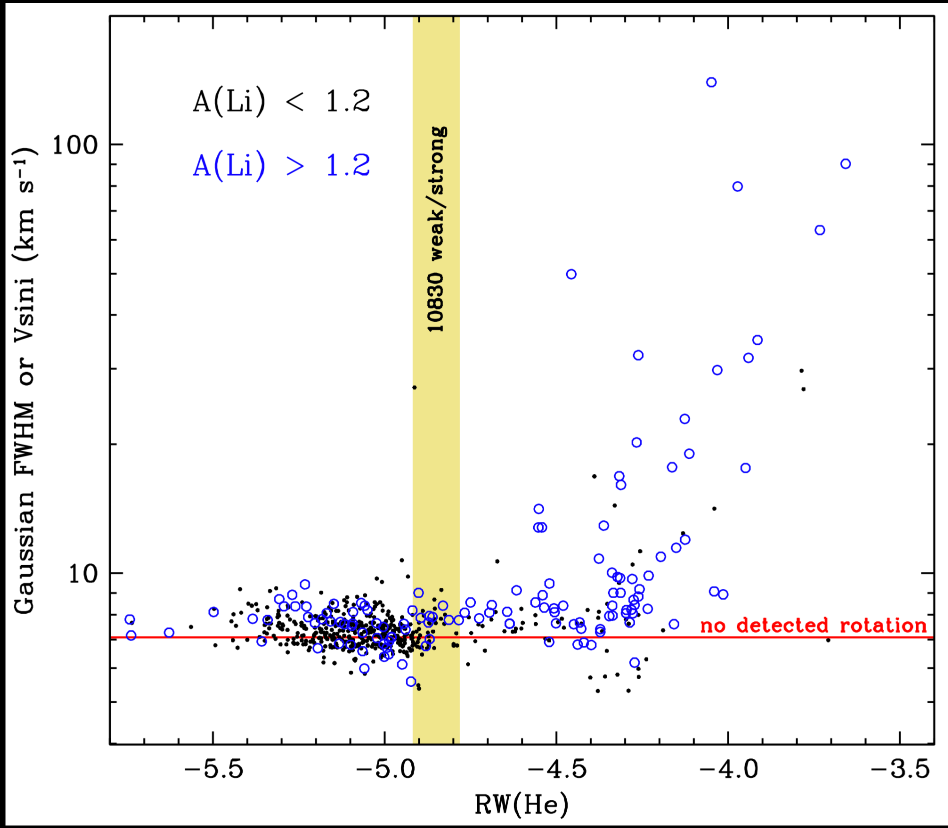
rapid rotation and strong 10830 Å absorption are strongly linked



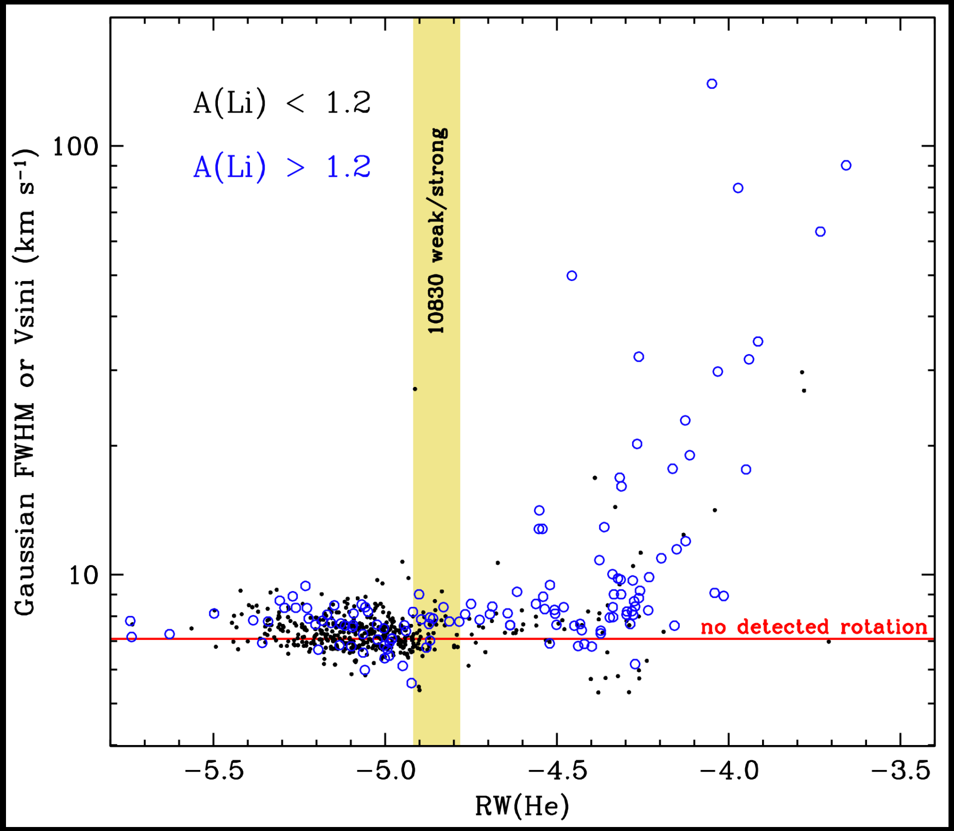
- no detected rotation?
  - modeled broadening: spectrograph slit, thermal, microturbulent
    - these contribute ~ 3 km s^{-1}
  - empirically determined: macroturbulence, rotation
    - macroturbulence contributes ~ 2 km s^{-1}
  - so we can't easily detect rotation $\lesssim$ 6 km s^{-1}
  - rotation is observed as Vsin*i*
    - observed rotations may be lower limits



segregating the points by Li abundance does make sense from our earlier work



But where have most of the He-strong stars gone?



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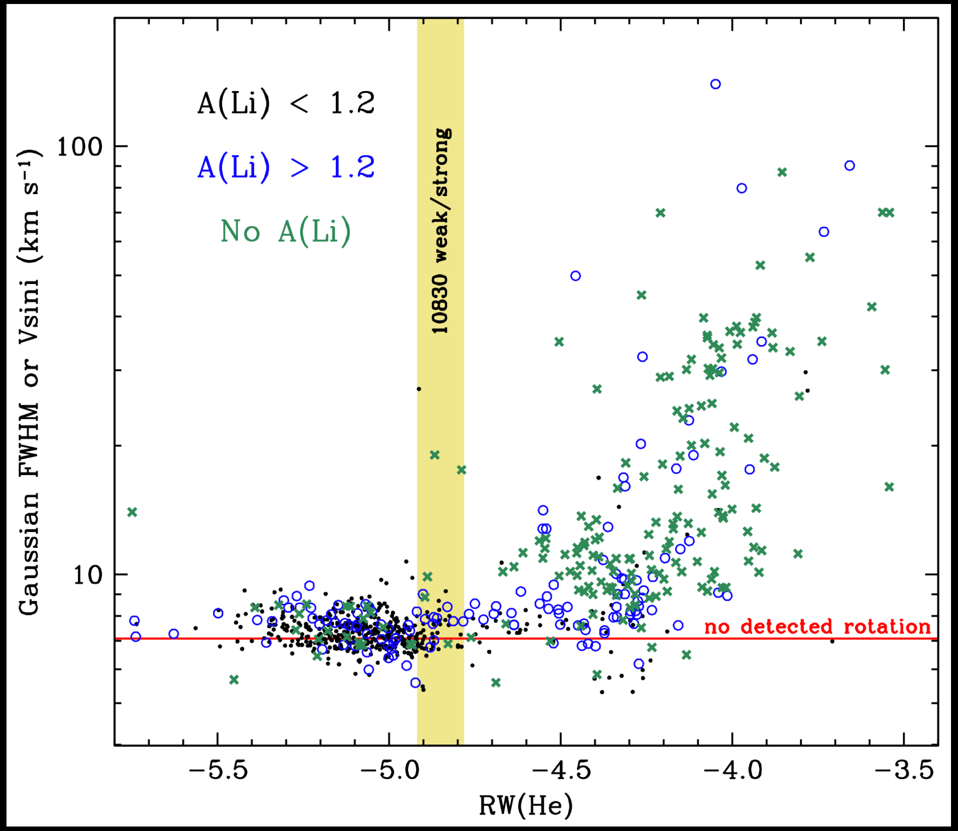
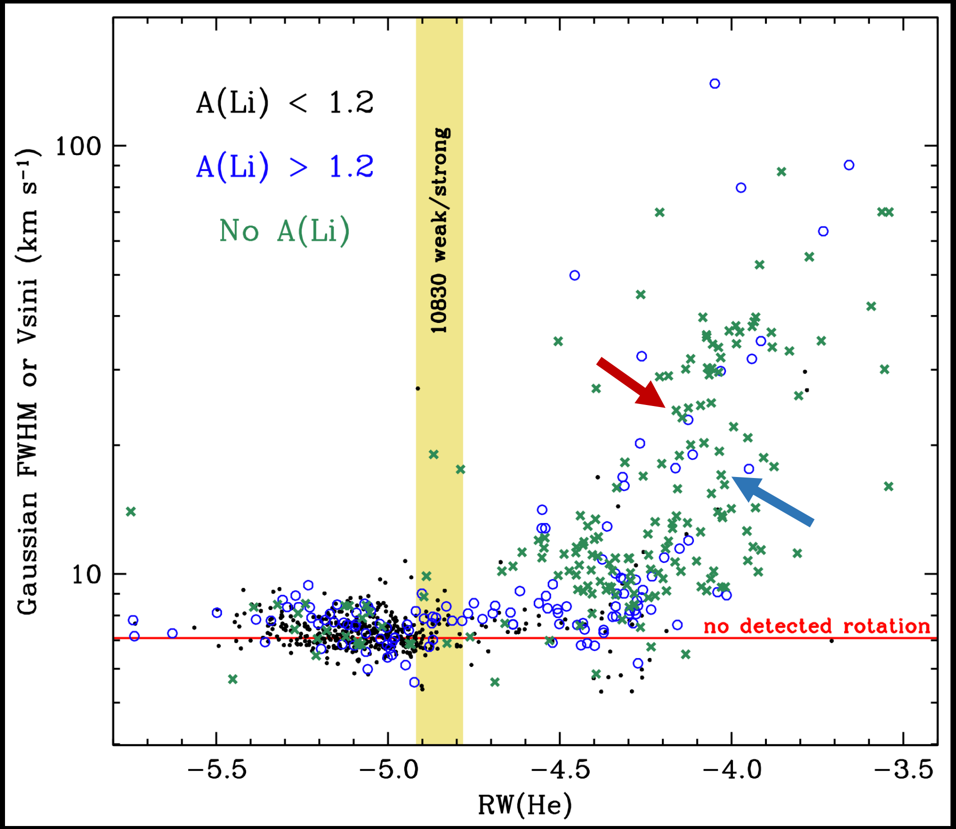
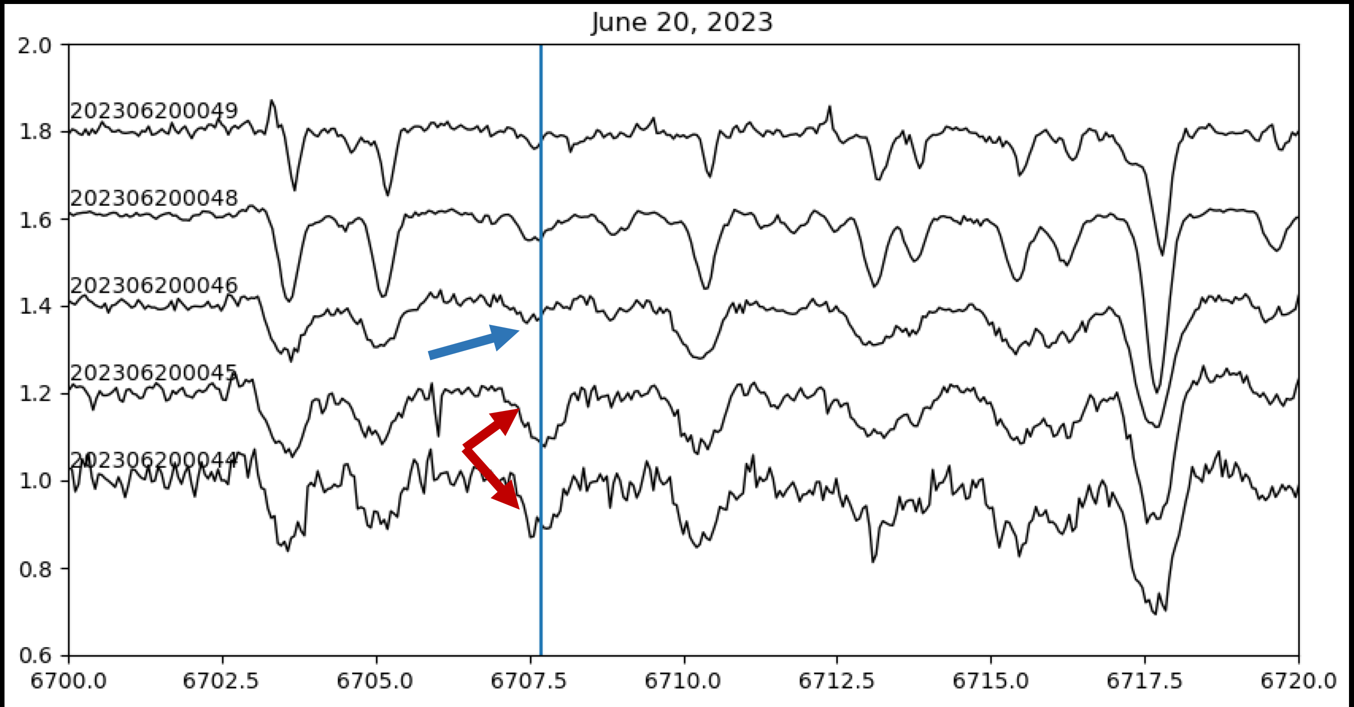


That's the problem with using APOGEE as your source for new rapidly rotating giants! Most of them have not been observed in the optical, where the Li I 6708 Å resonance line is

Observations underway for Li I 6707 Å

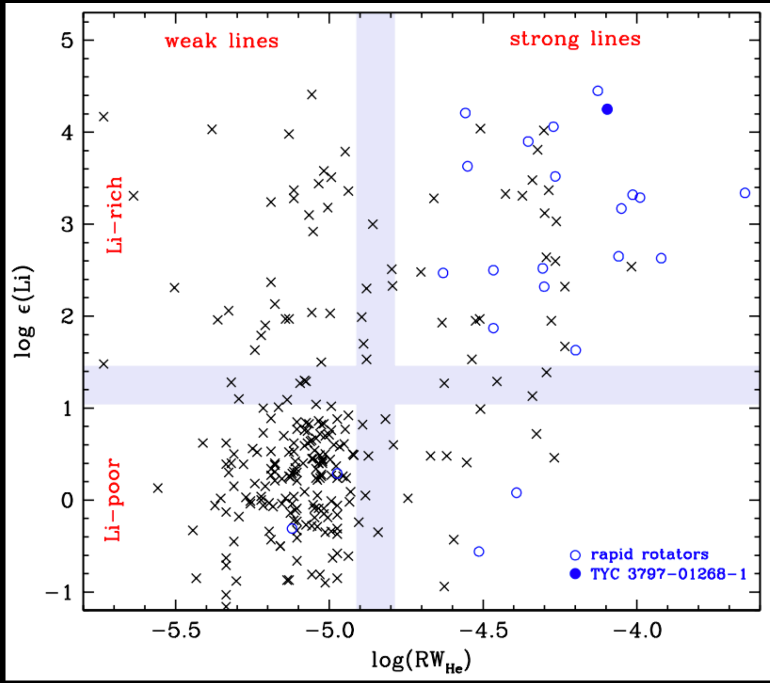


McDonald Observatory 2.7m echelle optical spectrograph
R ≡ $\lambda/\Delta\lambda$ = 60,000, desired S/N ~ 100
we want only to know whether Li abundance is big or small



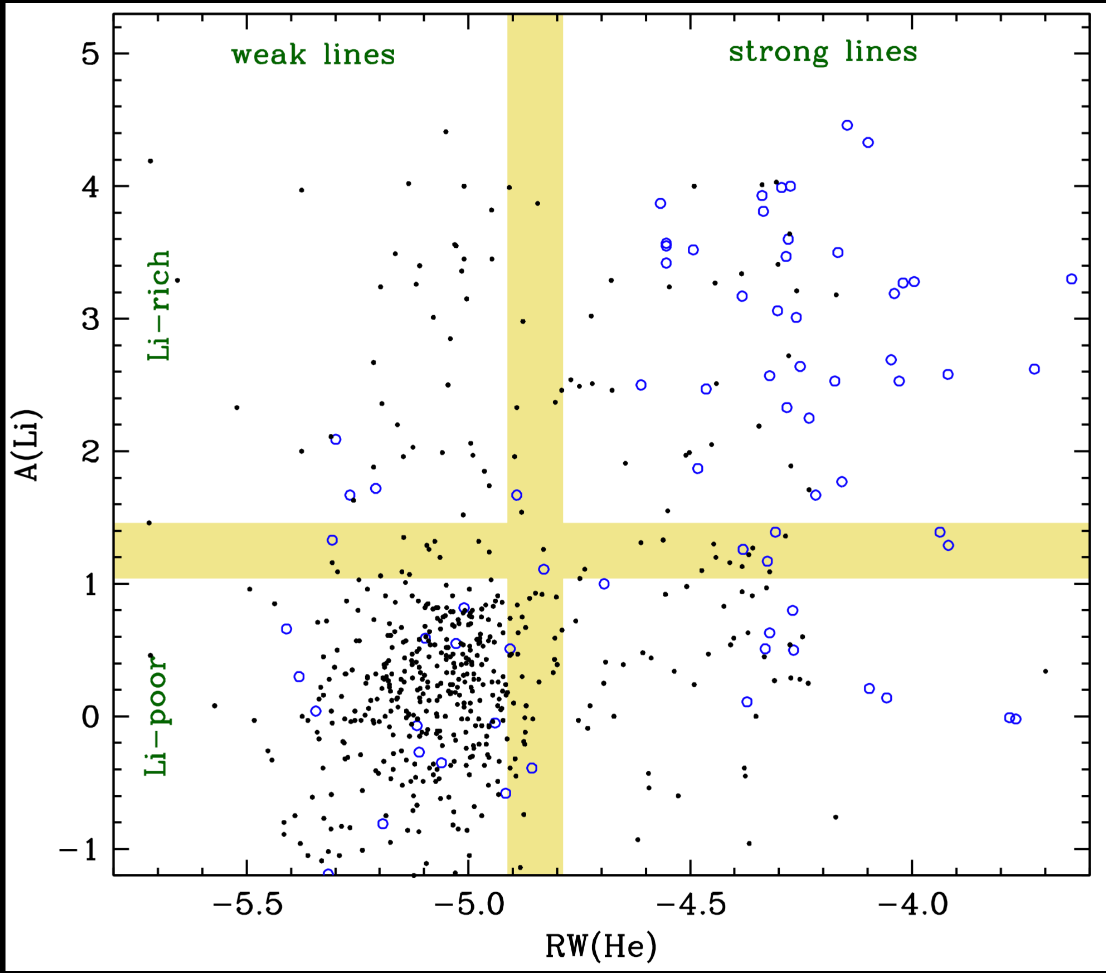
So far it appeats that there is a loose correlation between Li abundnace and Vsin*i* and He 10830 strength

The new Li observations will populate the Li-He plot

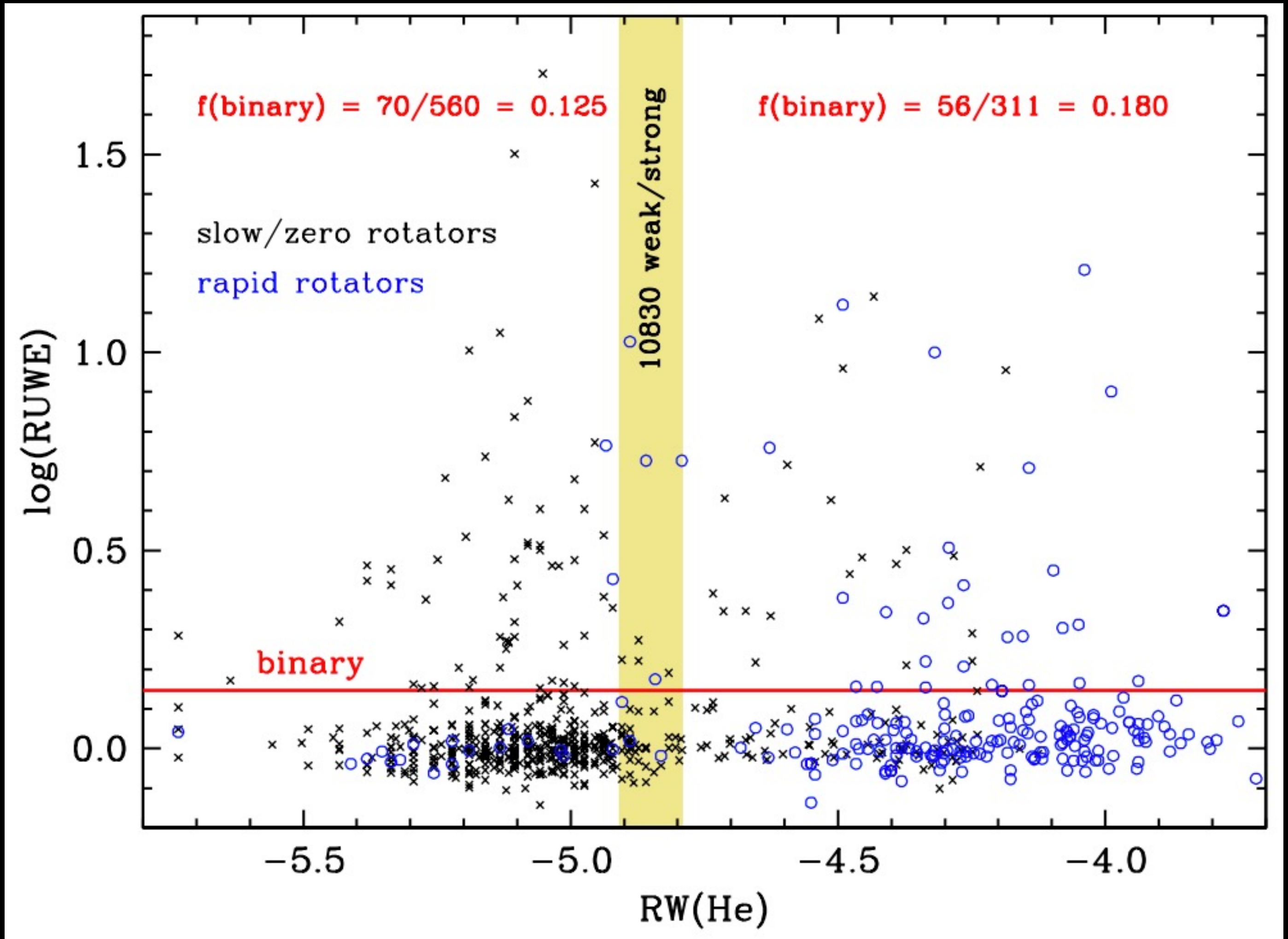


clearly new insights in the rapid rotation stars are needed

especially in the high Li, strong He domain



Interpretation? Here is a clue from Gaia RUWE values



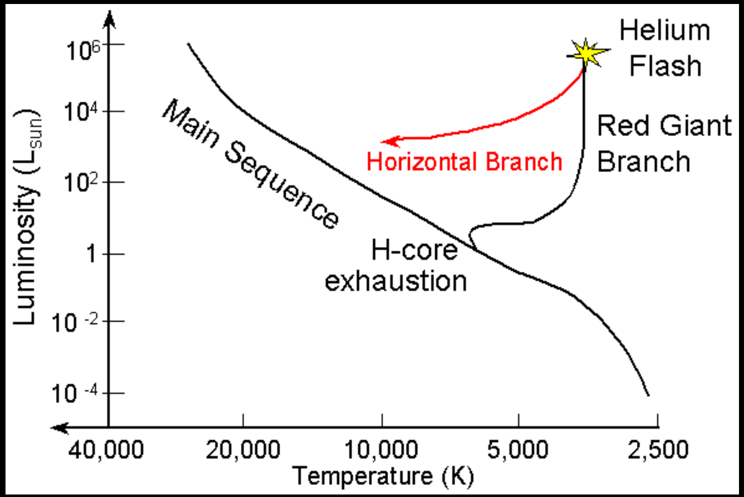
Gaia provides a Renormalized Unit Weight Error (RUWE) for the astrometry of each source

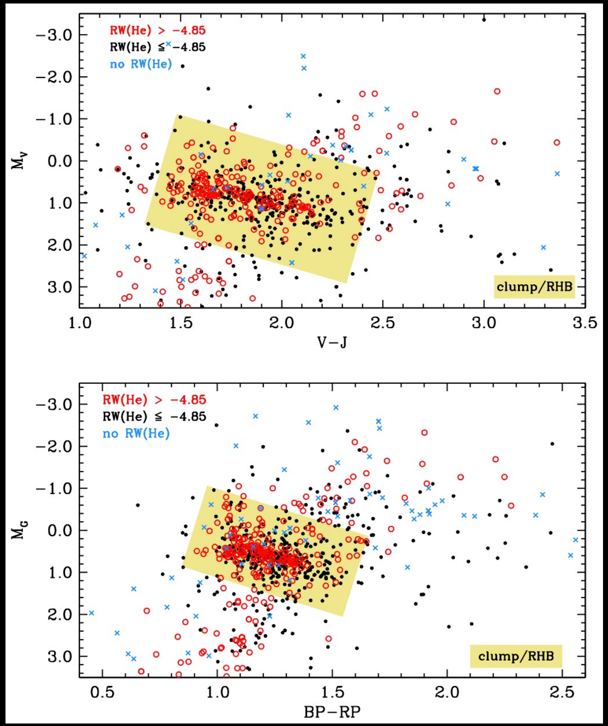
RUWE ≃ 1.0 for single, ordinary stars

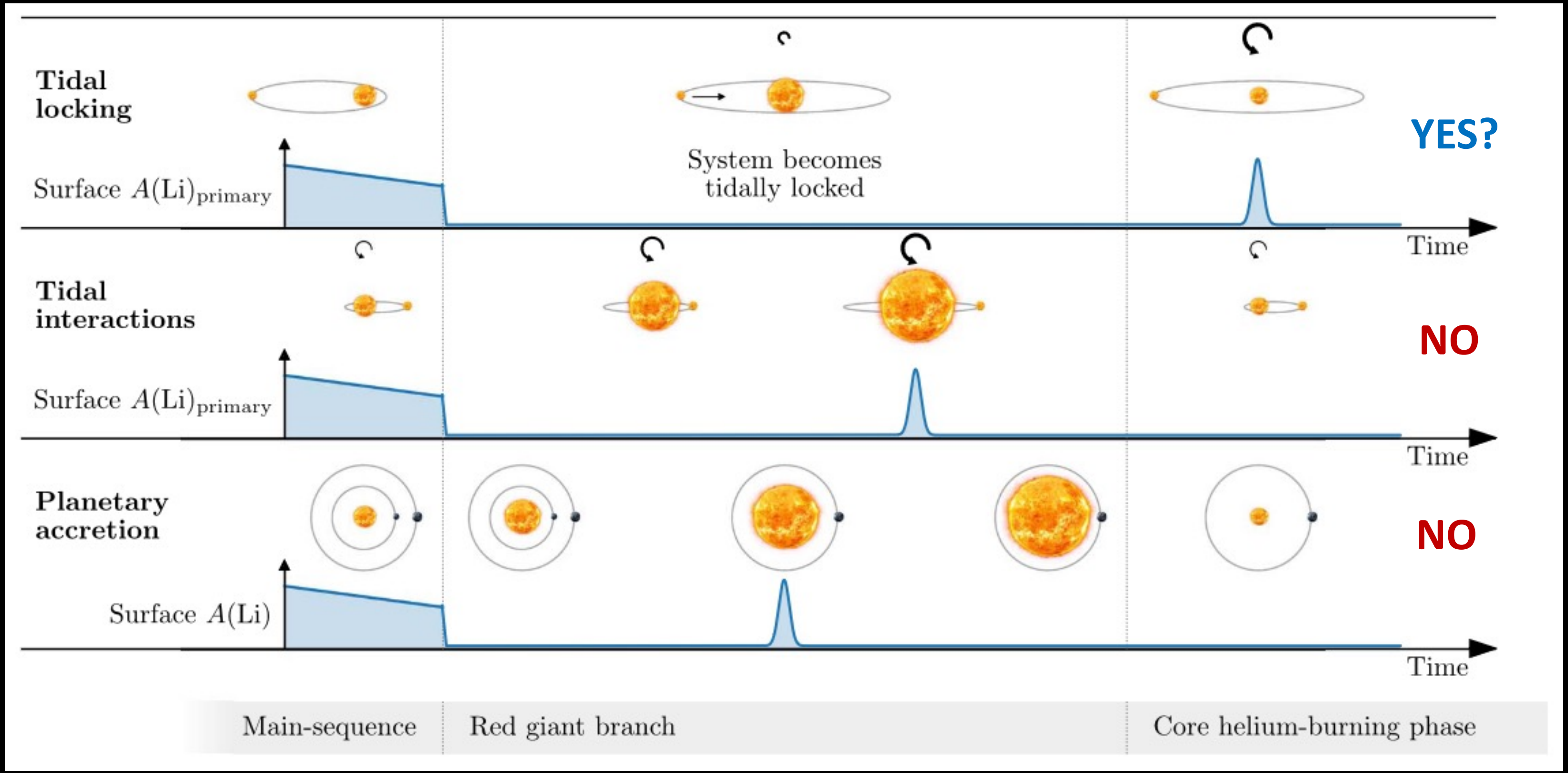
if RUWE ≳ 1.4, then either "the source is non-single or otherwise problematic for the astrometric solution"

The RUWE astrometric signal is clear: the probable binary fraction is 50% larger in He-strong stars

So one strong formation probability lies with binary interactions







YES?

NO

NO

This cartoon suggests that tidal locking is the only plausible way

Here we stop for the moment

- red giant stars, mostly clump and horizontal branch, have striking correlations:
  - “old news”: about 1% have anomalous very large Li abundances
  - recent development: a small fractions of red giants have detectable rotation
  - our addition: a small fraction also have strong chromospheric He I 10830
  - and: Li abundance, rotation, and He I line strength are correlated

- what must be done to finish this phase of our studies:
  - many more Li abundances of He-strong stars must be obtained
  - Kepler giants are being analyzed – much sharper evolutionary state data
  - binarity and rotation must be investigated further

- the next step: a study of more luminous, cooler red giants – mass loss?
  - a subject for some other talk …

many thanks for allowing me to share this work with you!

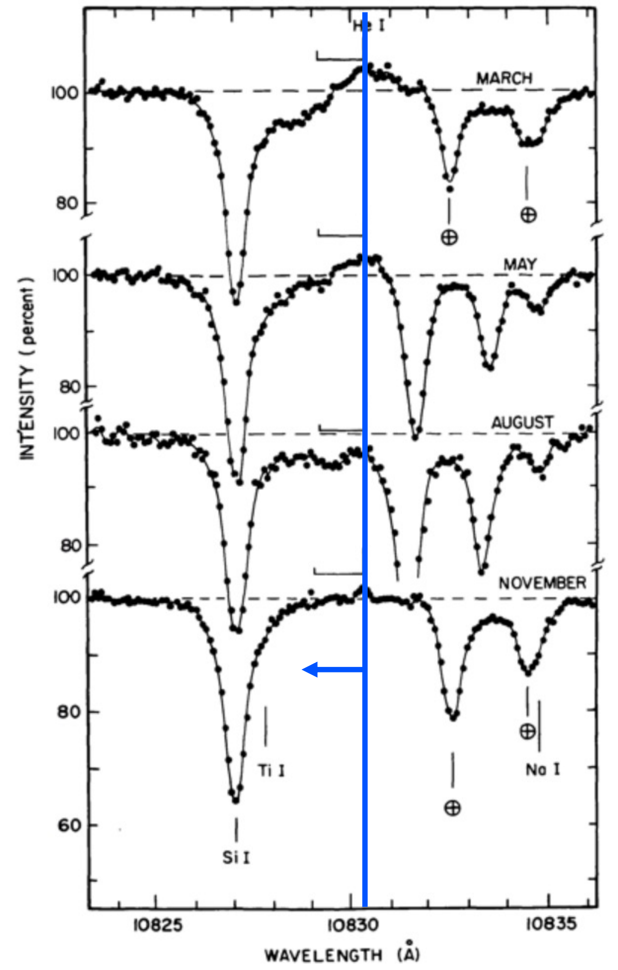
Helium in high luminosity upper red giant stars

The 10830 line can signal a hot chromosphere
OR significant mass loss

Can we say something about this with our sample?

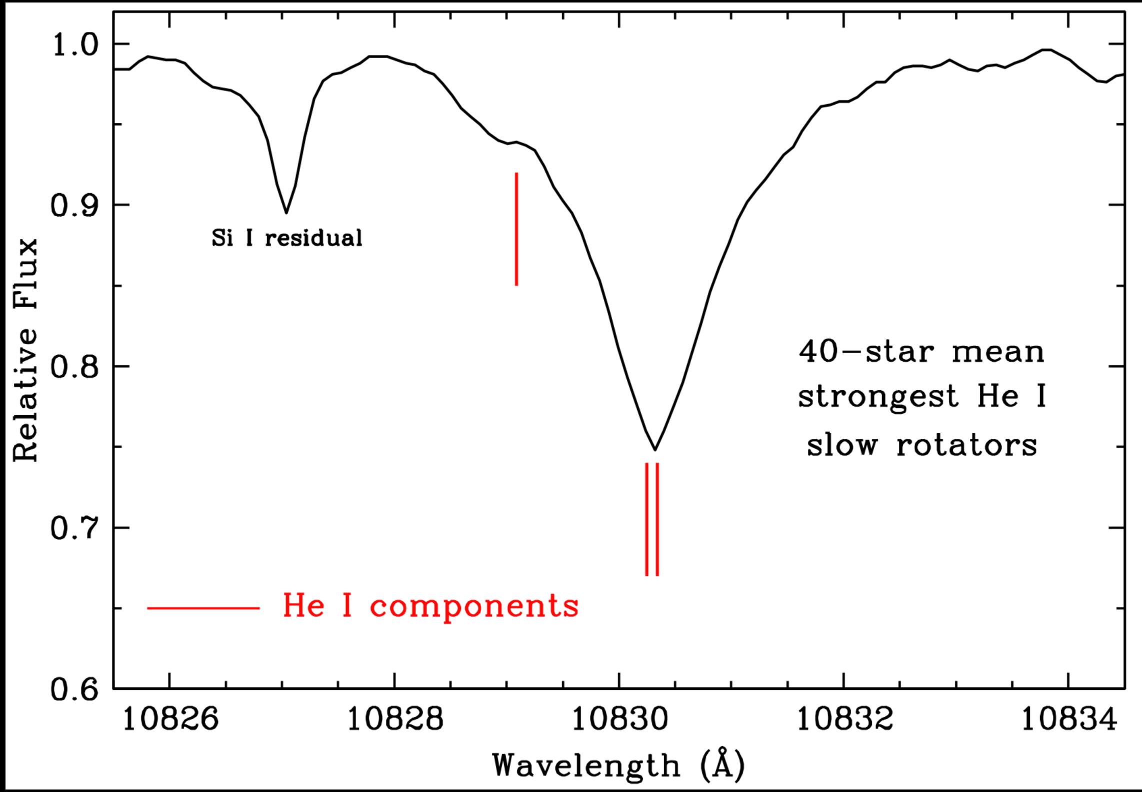
some red giants show blue-shifted 10830 profiles … a definite mass loss signature

Arcturus has significant and variable blue-shifted 10830



O'Brien & Lambert 1986

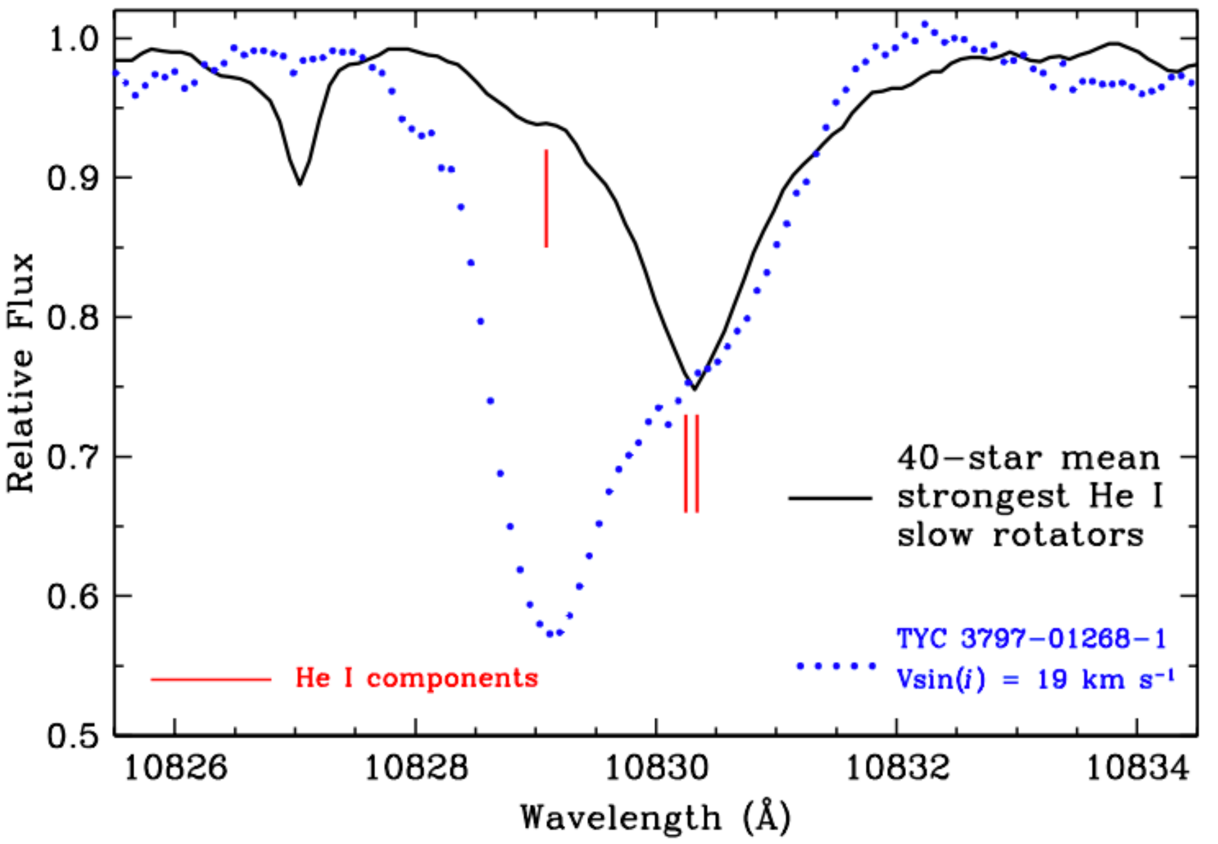
But nearly all Li-rich giants show no λ10830 profile anomalies; no evidence for significant mass loss



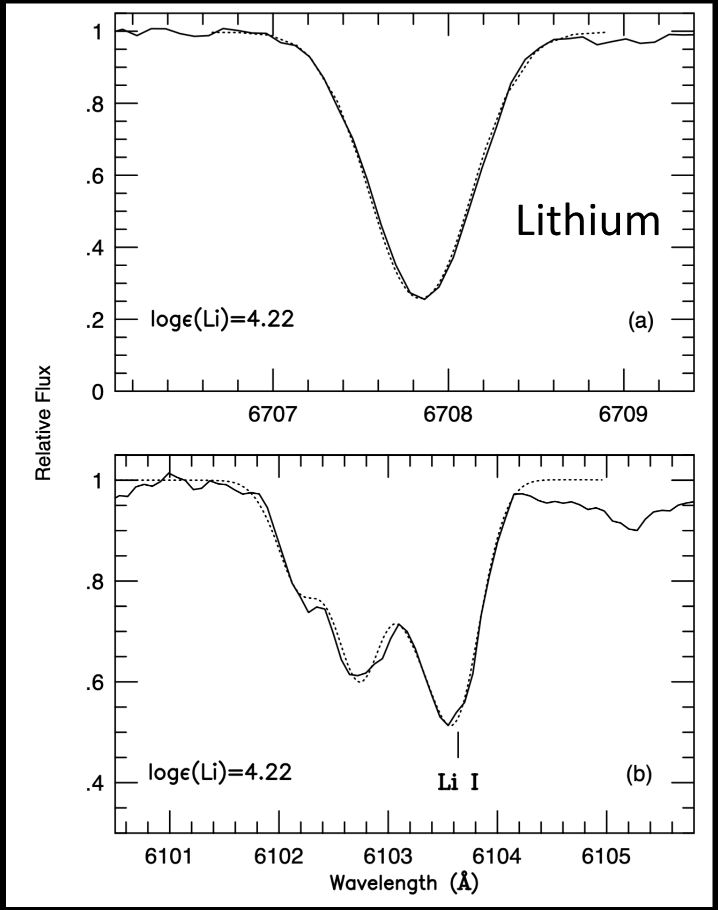
Sneden+2022

there was one exception in the earlier paper: TYC 3797-01268-1 (HD 233517)

AND it is rotating rapidly: vsin*i* 19 km/s
AND it has high lithium



Sneden+2022

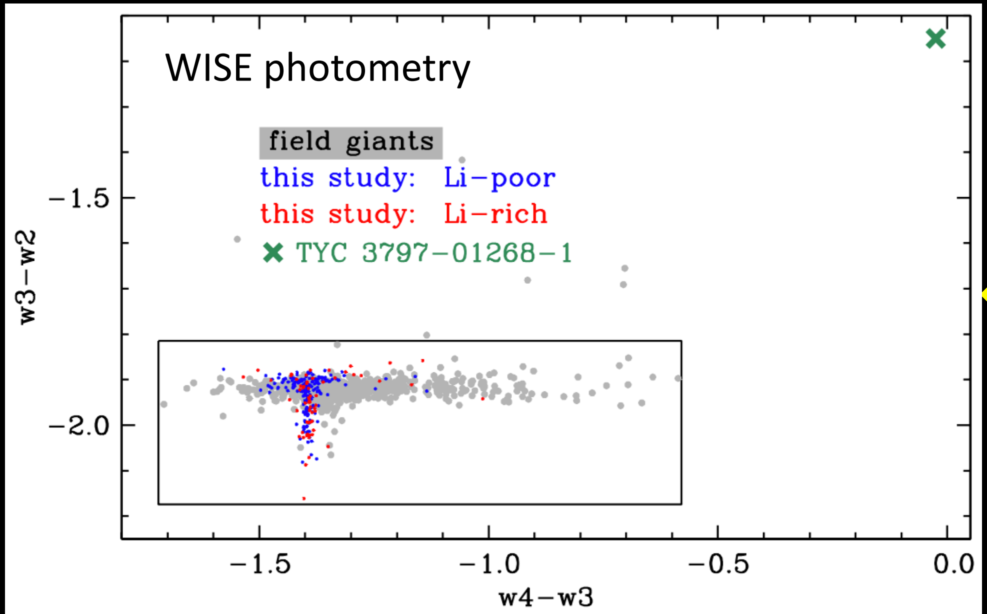


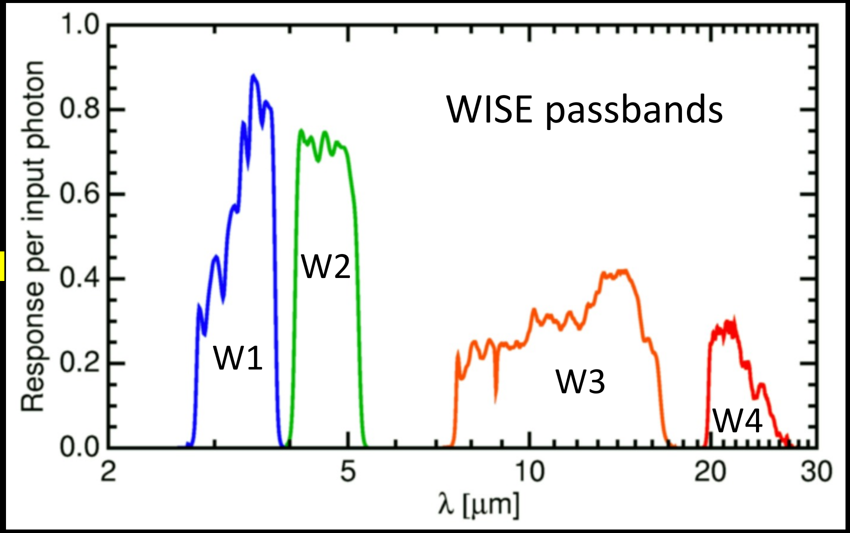
Balachandran+2000

complex profile with a dominant blueshifted (about –55 km/sec) component

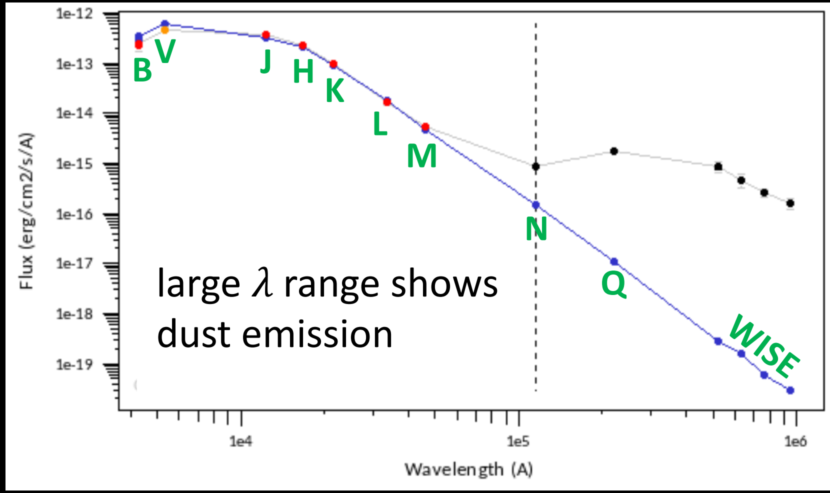
TYC 3797-01268-1 has a large IR excess

Sneden+2022





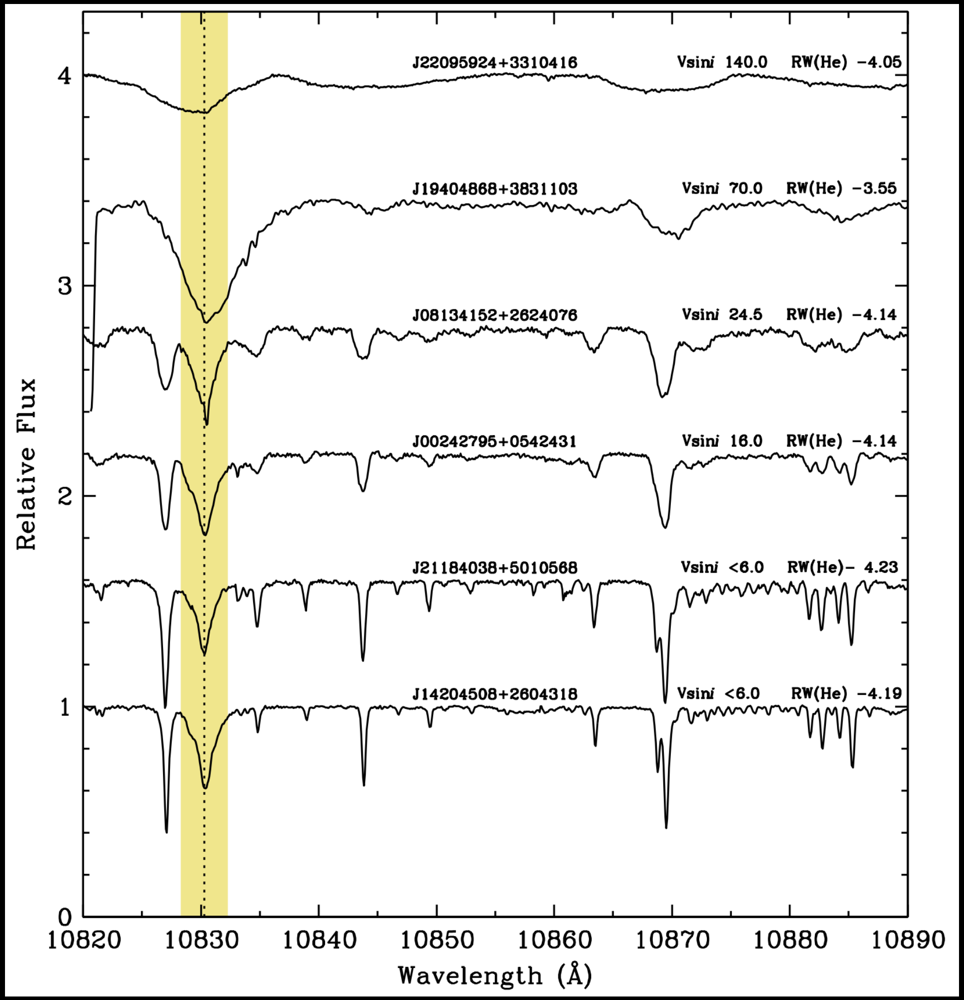
https://www.astro.ucla.edu/~wright/WISE/passbands.html



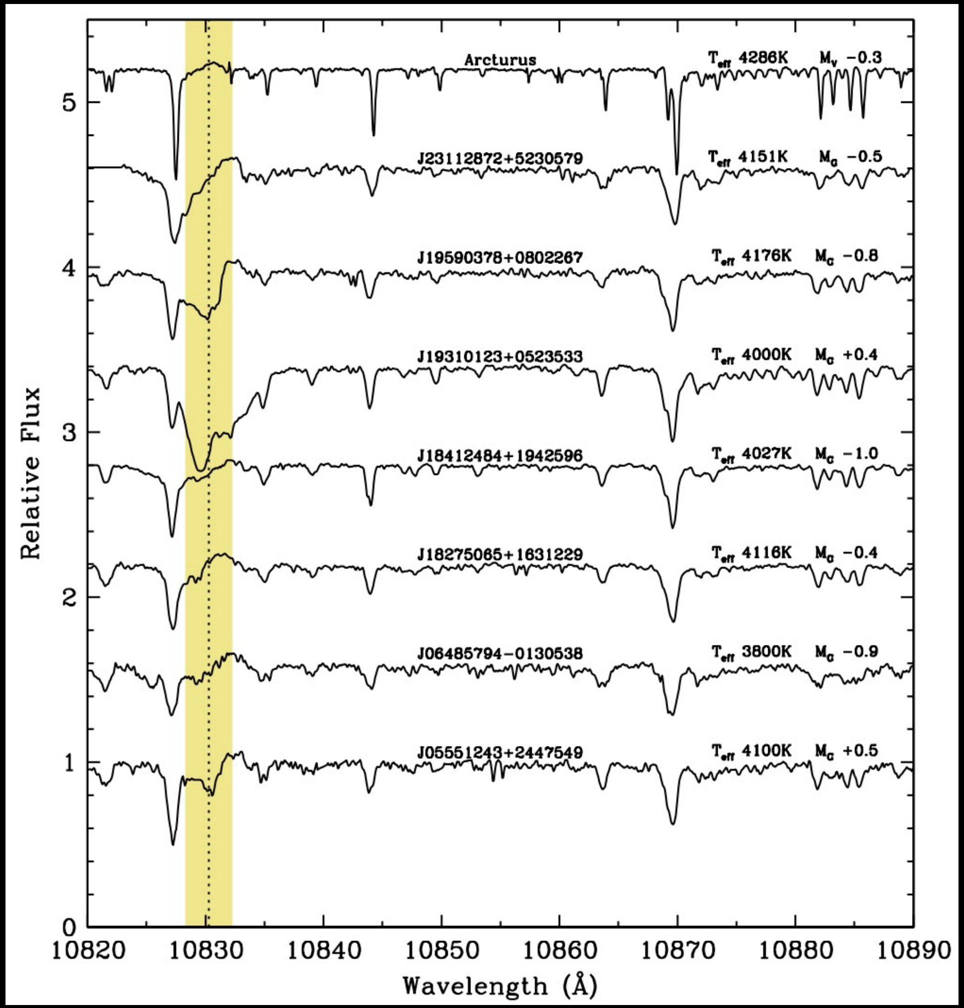
- multiple observational indicators for significant mass loss
- the far-IR colors mean dust shell emission
- this must be an AGB star shedding its outer envelope
- it is a unique object in our collection of targets

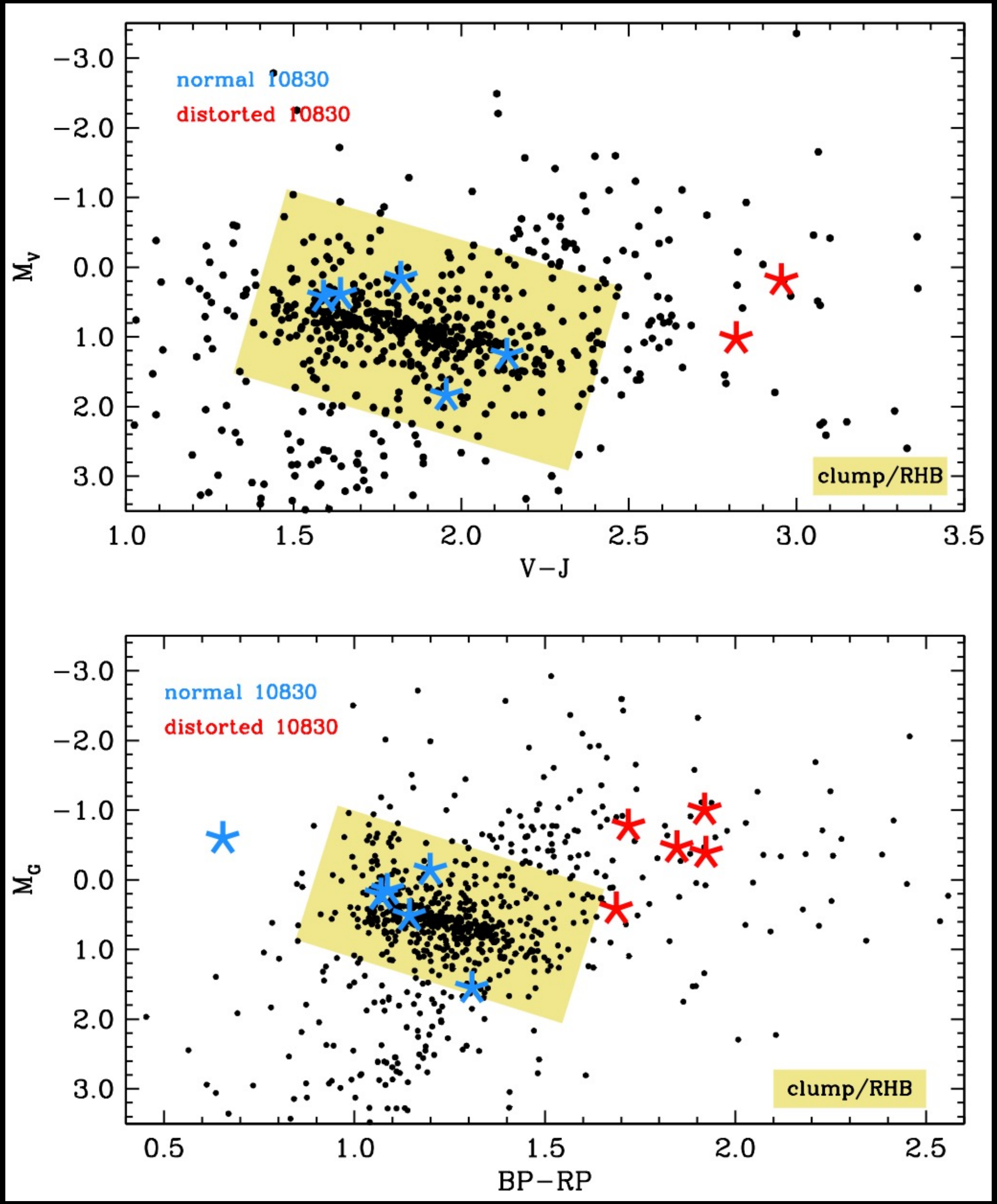
stars like this one in our new sample

“normal” He-strong stars



low temperature, high luminosity, weird λ10830

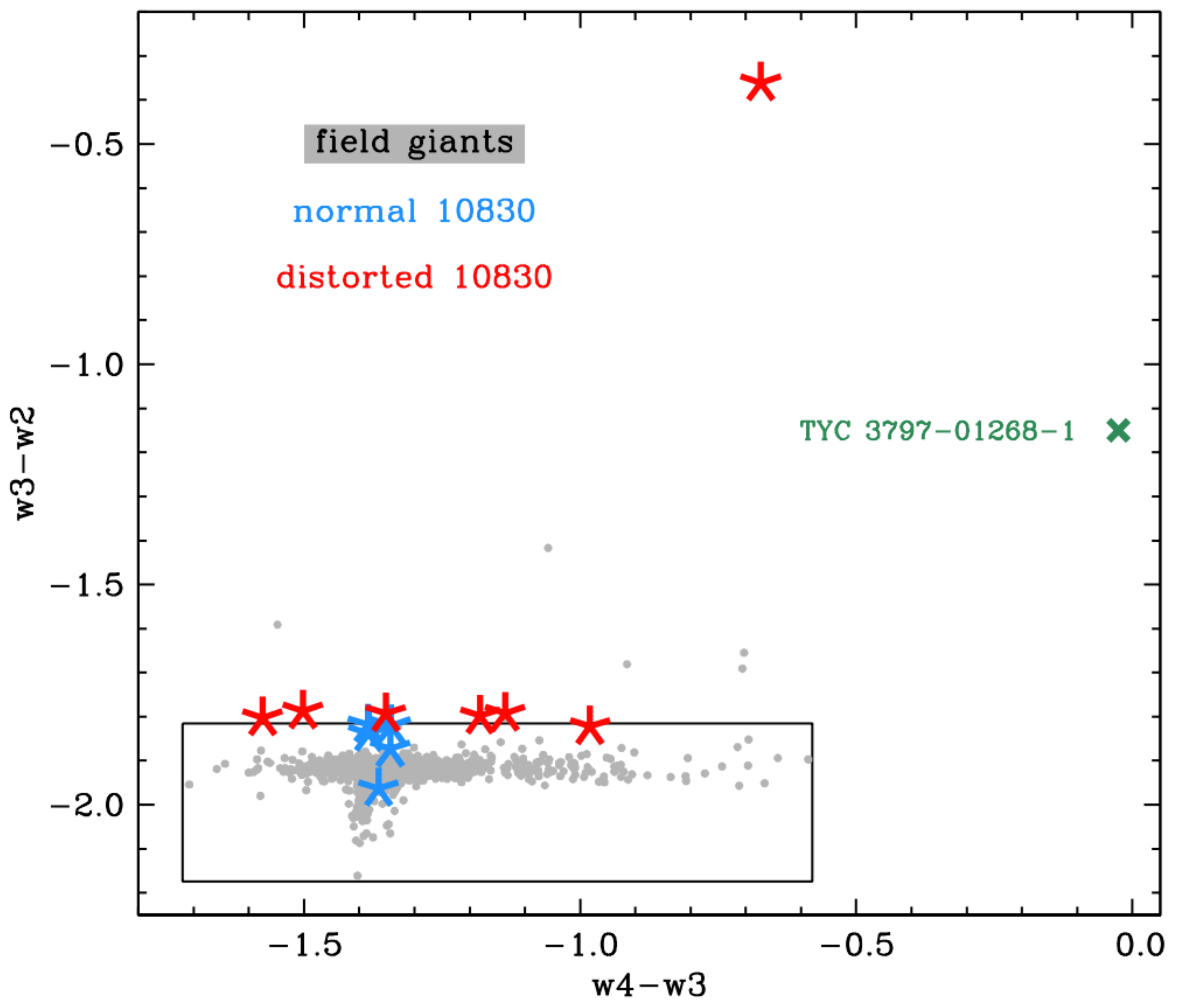




Here are color-magnitude diagrams for the stars with spectra shown in the previous slide

(there are fewer V,J magnitdes published for our stars than Gaia G, BP, RP magnitudes)

Here are far-infrared colors for these stars



small but significant separation of the stars with normal and distorted λ10830 He I lines

One huge freak has very large w3-w2, meaning a large dust shell

Our simple approach to modeling λ10830 is clearly inadequate;we exclude the low-temperature stars from our present work

sophisticated outer atmosphere modeling will be required

to be led by co-I Andrea Dupree

fred

fred

fred

Katia Biazzo & Valentina D’Orazi

fred

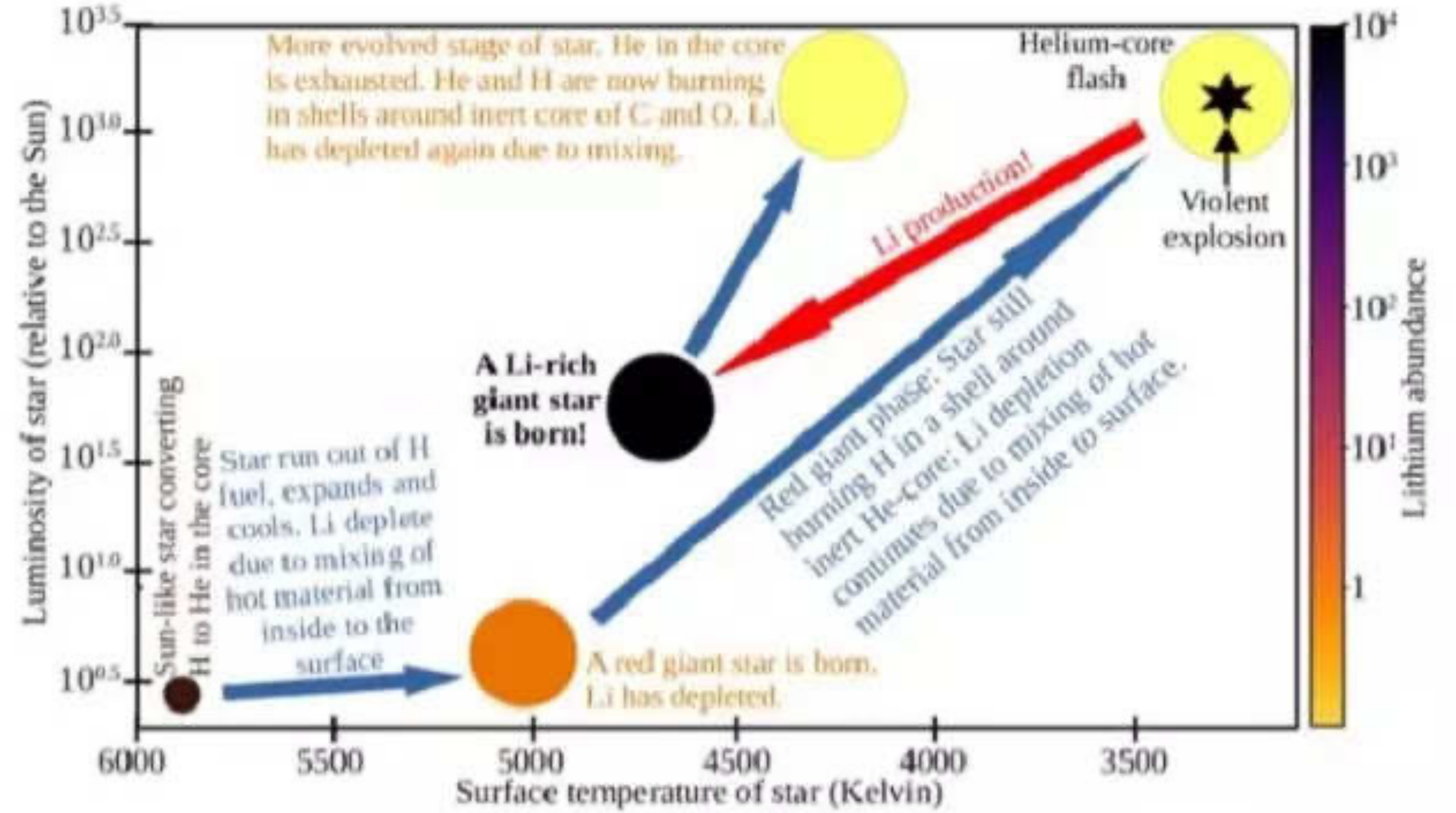


Figure 1: A cartoon illustration of the evolution of lithium (Li) in a Sun-like star. Color of the star symbol (filled circle) is proportional to star's Li abundance as shown in the color bar. Here, H is hydrogen, He is helium, C is carbon and O is oxygen.

https://timesofindia.indiatimes.com/home/science/astronomers-find-clue-to-mystery-behind-some-lithium-rich-stars/articleshow/88004063.cms