The lithium-rich giant star puzzle


Andy Casey


Anna Ho


Melissa Ness


David W. Hogg


Hans-Walter Rix


George Angelou


Saskia Hekker


Christopher Tout


John Lattanzio


Amanda Karakas


Tyrone Woods


Kevin Schlaufman

MONASH University

@astrowizicist // www.astrowizici.st

Lithium:

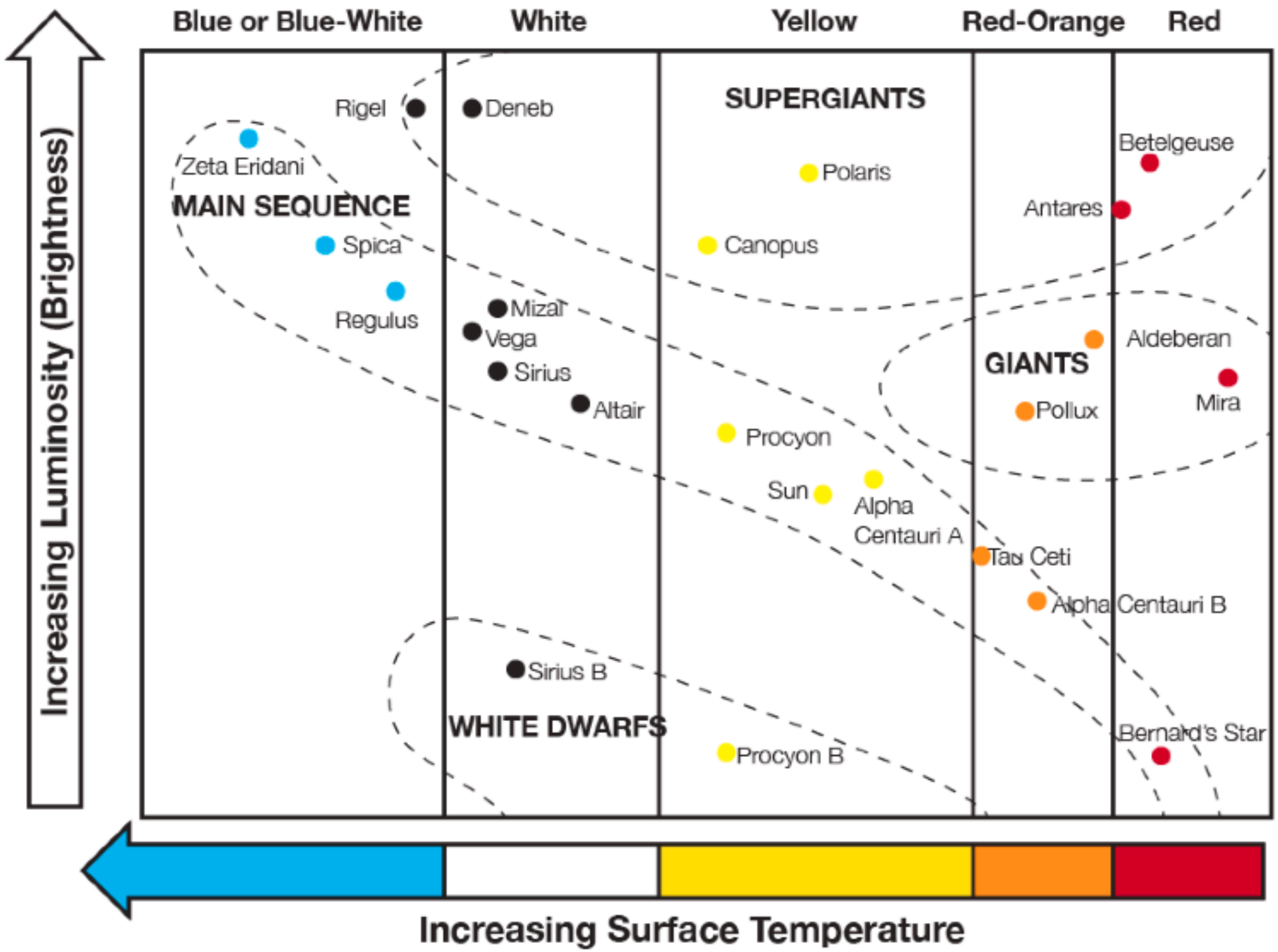
Produced through Big Bang nucleosynthesis.

Can also be produced through different channels in many environments.

Extremely fragile: conditions required to produce it are often extreme enough to destroy it.

Stellar abundances of lithium are extremely informative.

Stellar evolution theory predicts first dredge up



Source: http://rockthe8thgradesciencestaar.weebly.com/

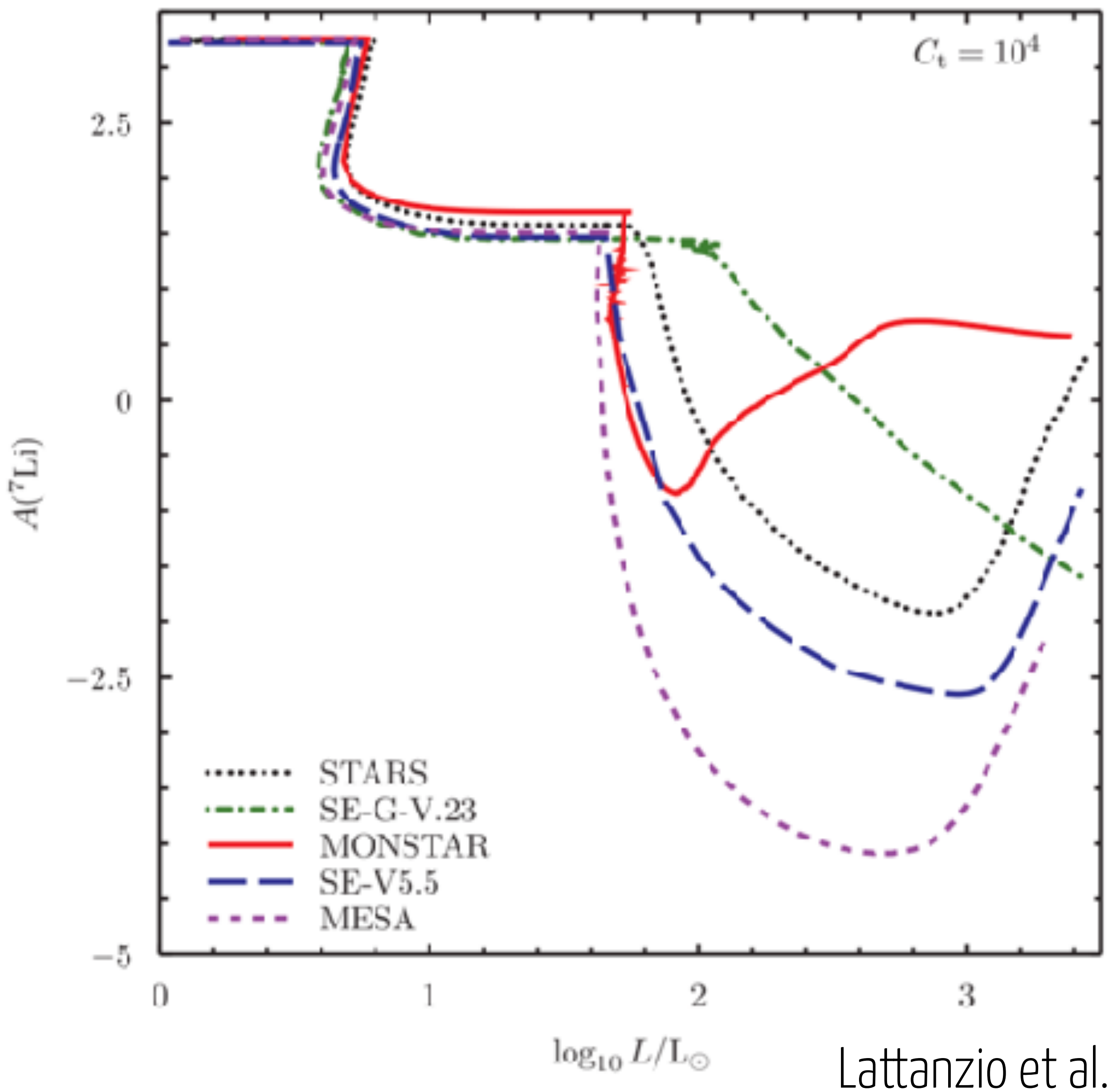
Theory predicts first dredge up will change the observable abundances

1. Decrease in carbon abundance

2. Increase in nitrogen abundance

3. Decrease in 12C/13C isotope ratio

4. **~95% drop** in observed lithium abundance



Lattanzio et al. (2015)

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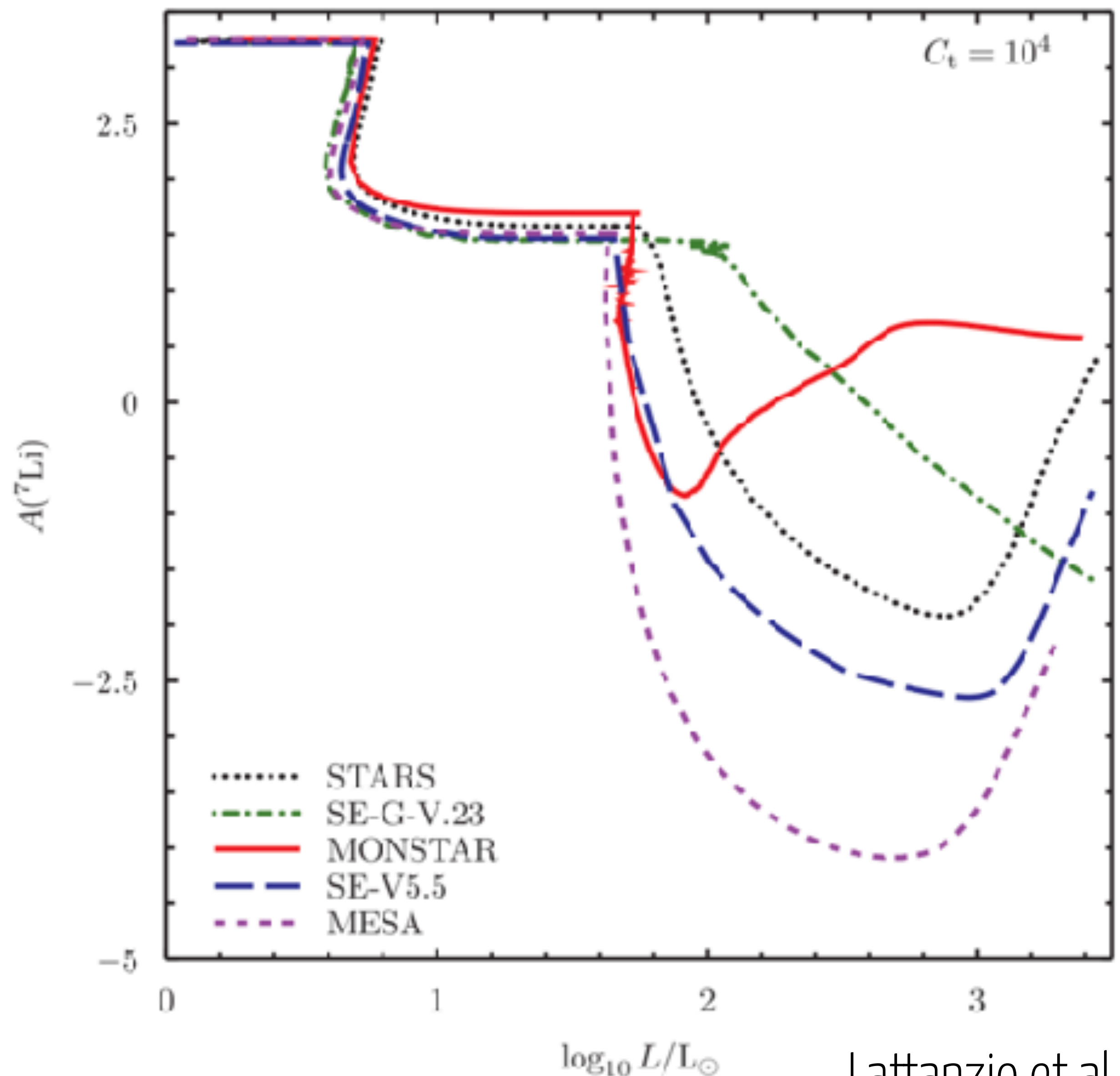
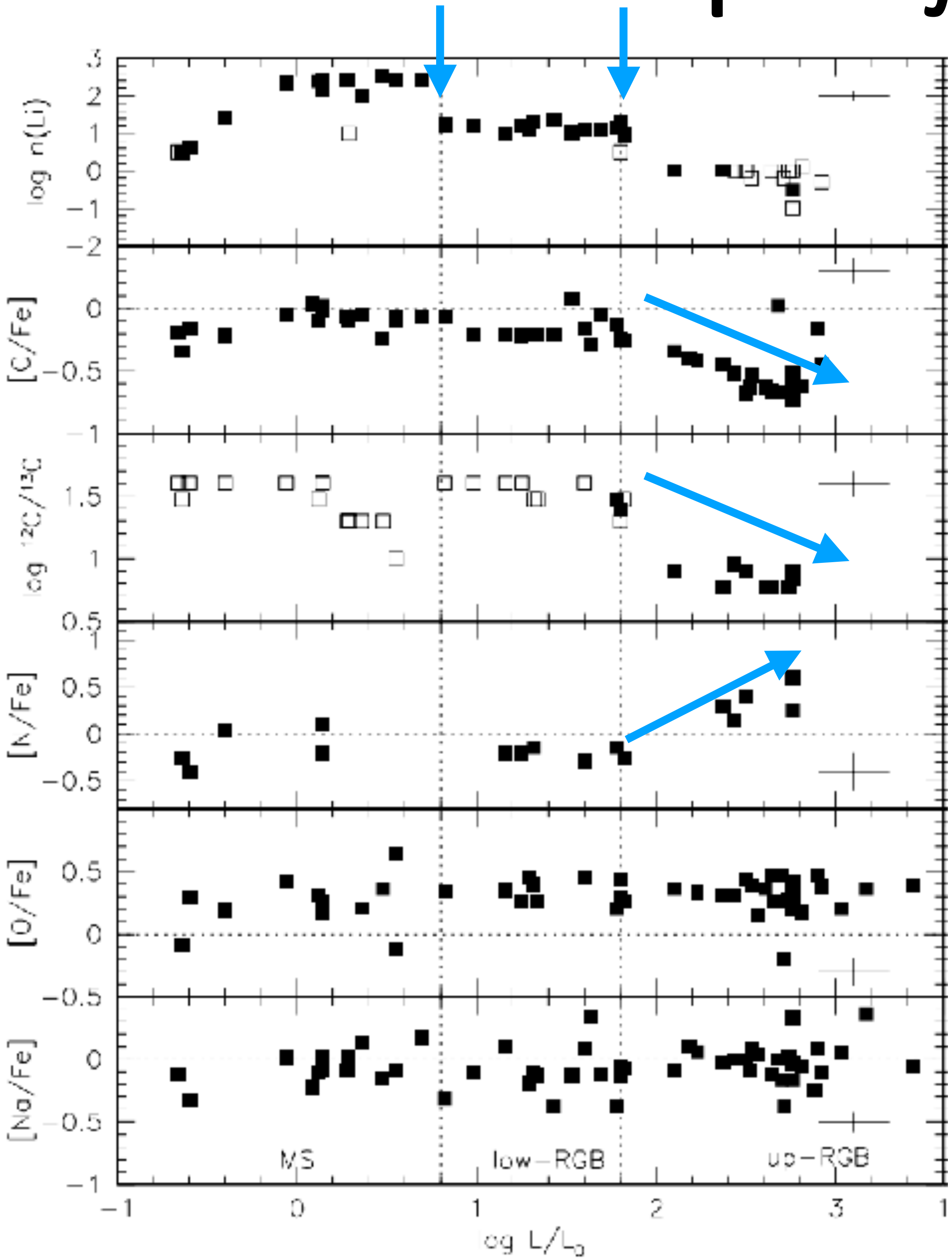
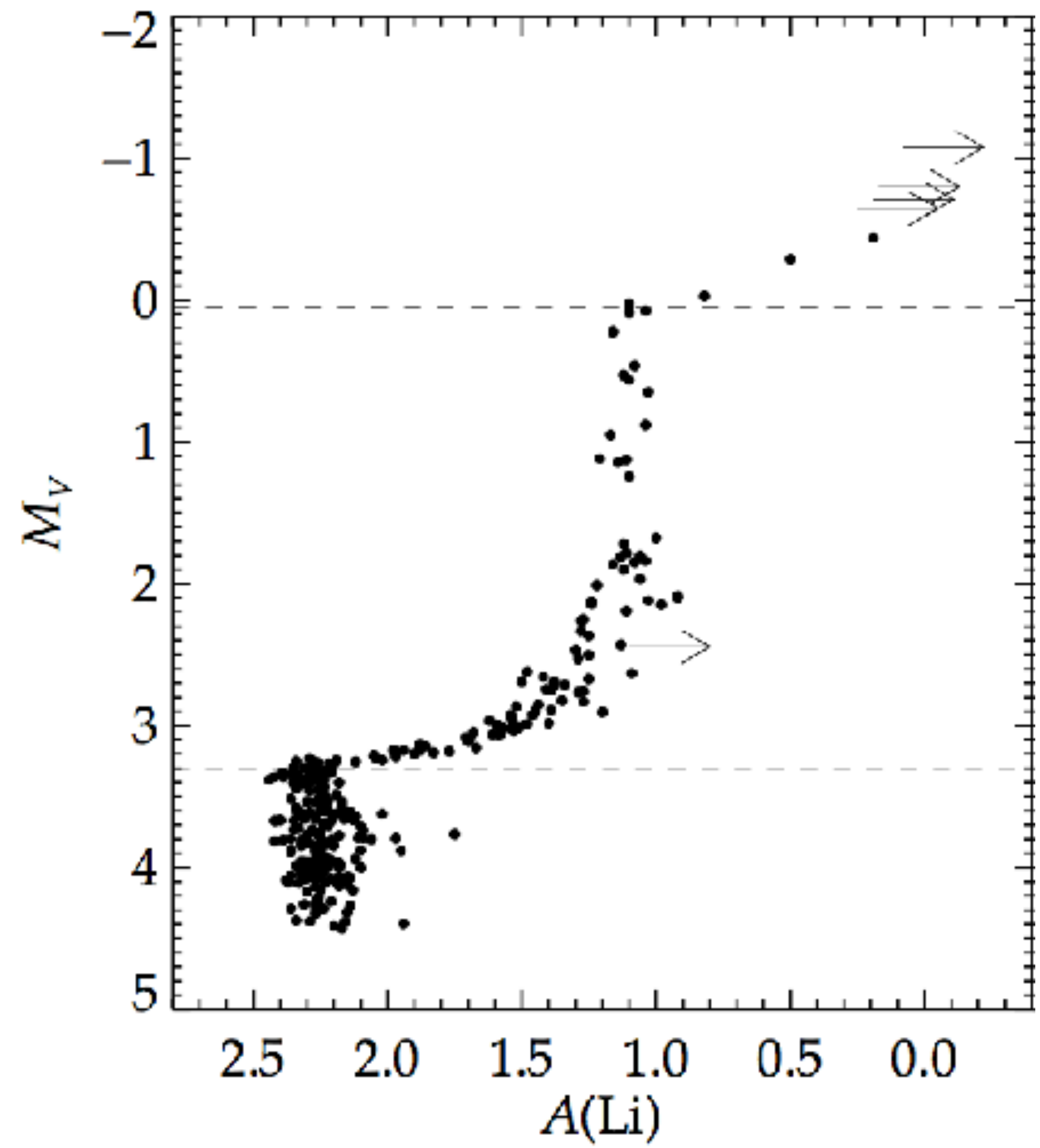


Lattanzio et al. (2015)

Occurs independent of theoretical prescription or implementation.
Theory predicts that giant stars should have very little lithium.

Observations have repeatedly vindicated these predictions

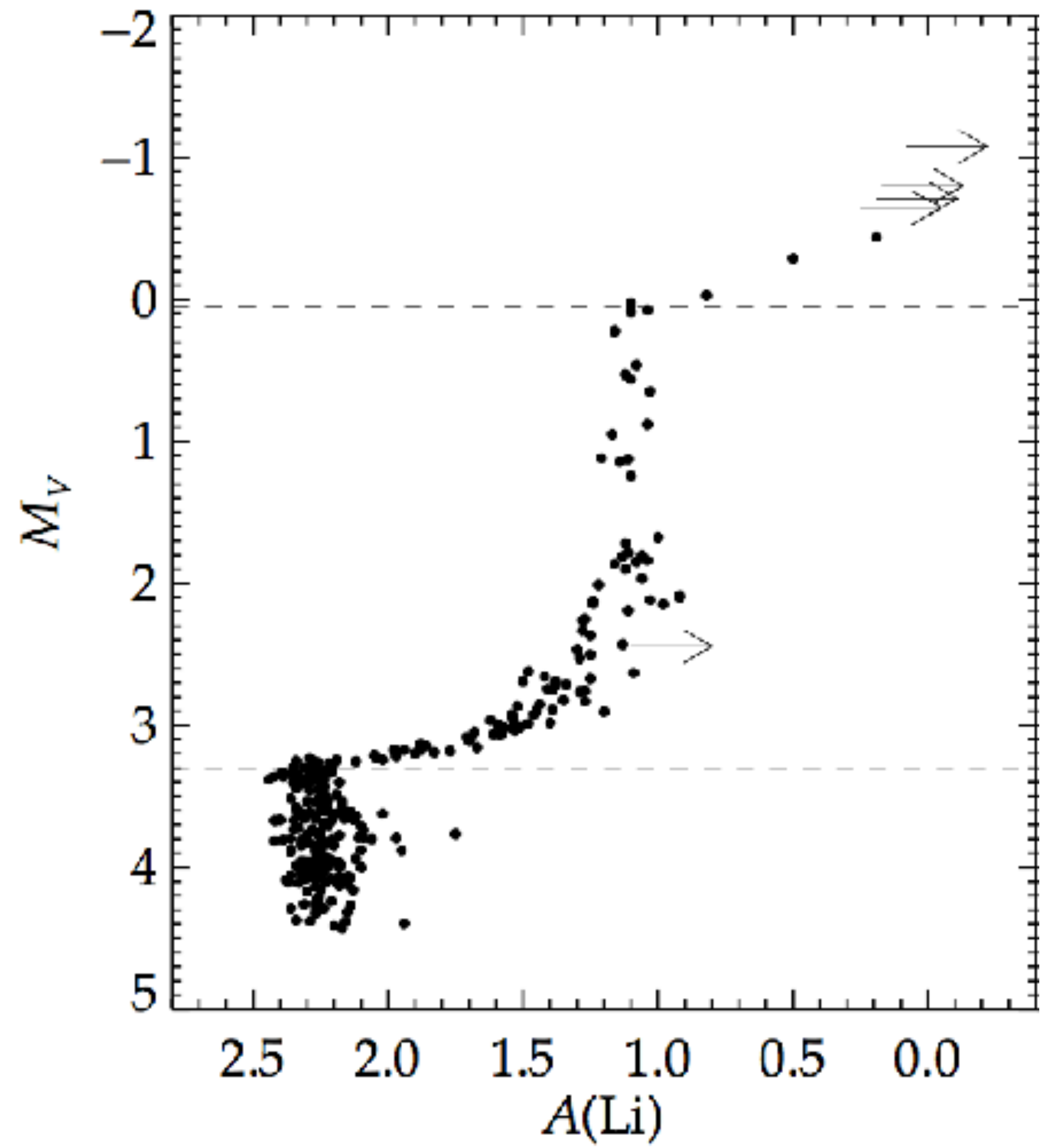




(e.g., Lambert et al. 1989; Gratton et al. 2000, Lind et al. 2009)

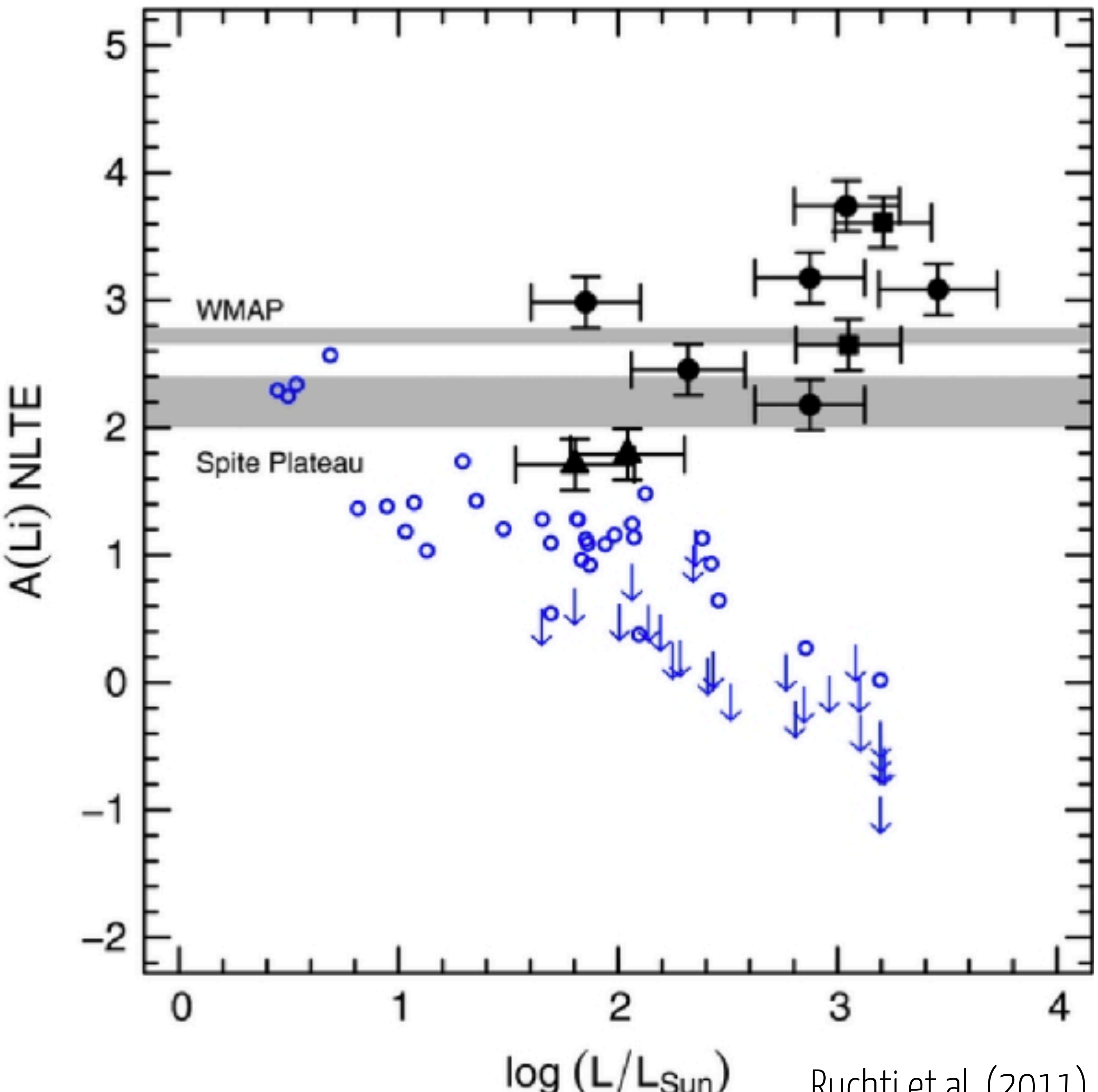
Conflicting observations were found immediately

- Observations have repeatedly vindicated predictions from stellar evolution theory
- Giant stars should not have much lithium
- Around the same time, observations also revealed some giant stars with peculiarly high amounts of lithium, so-called 'lithium-rich giants'



(e.g., Lambert et al. 1989; Gratton et al. 2000, Lind et al. 2009)

Observations have also identified unusually lithium-rich giant stars



Ruchti et al. (2011)

- Higher than the surrounding ISM.
- Higher than estimates of initial lithium abundances in the Milky Way
- Higher than BBN predictions!

Giants cannot just somehow **preserve** their lithium.

Lithium must be **created** or **accreted** from somewhere else.

Lithium is hard to produce, and easy to destroy

(in net quantities)

$$^{3}\mathrm{He}\,(\alpha,\gamma)^{7}\,\mathrm{Be}\,(\beta^{-},\nu)^{7}\,\mathrm{Li} \rightarrow {}^{7}\mathrm{Li}\,(p,\alpha)^{4}\mathrm{He} \;=\; \mathrm{ppII}$$

$$^{3}\mathrm{He}\,(\alpha,\gamma)^{7}\,\mathrm{Be} \rightarrow {}^{7}\mathrm{Be}\,(p,\gamma)^{8}\mathrm{B}\,(\beta^{+}\nu)^{8}\mathrm{Be}\,(\alpha)^{4}\mathrm{He} \;=\; \mathrm{ppIII}$$

- Even if a star accretes lithium, it will soon be destroyed: lithium is fragile.
- Need to produce beryllium in inner layers (where it is hot).
- Quickly transport beryllium to cooler regions so that lithium can be produced and not be immediately destroyed ('Goldilocks condition').
- **The conditions required to create lithium in stars are also extreme enough to destroy it.**

Lithium-rich giants otherwise appear very normal

- First lithium-rich giant, HD 112127, was discovered by Wallerstein & Sneden (1982)
- No distinguishable feature other than lithium enrichment
- Some frequent traits (rotation, infrared excess), but nothing distinguishable
- Found all across the Hertzprung-Russell diagram, all stages of post-main-sequence evolution.
- Found everywhere in the galaxy (open clusters, globular clusters, field, disk, halo, bulge)
- Very rare (~1% of FGK giant stars)

Cannot use other characteristics (e.g. anomalous broad-band photometry) to identify them.
Reliant on large surveys and other serendipitous discoveries.

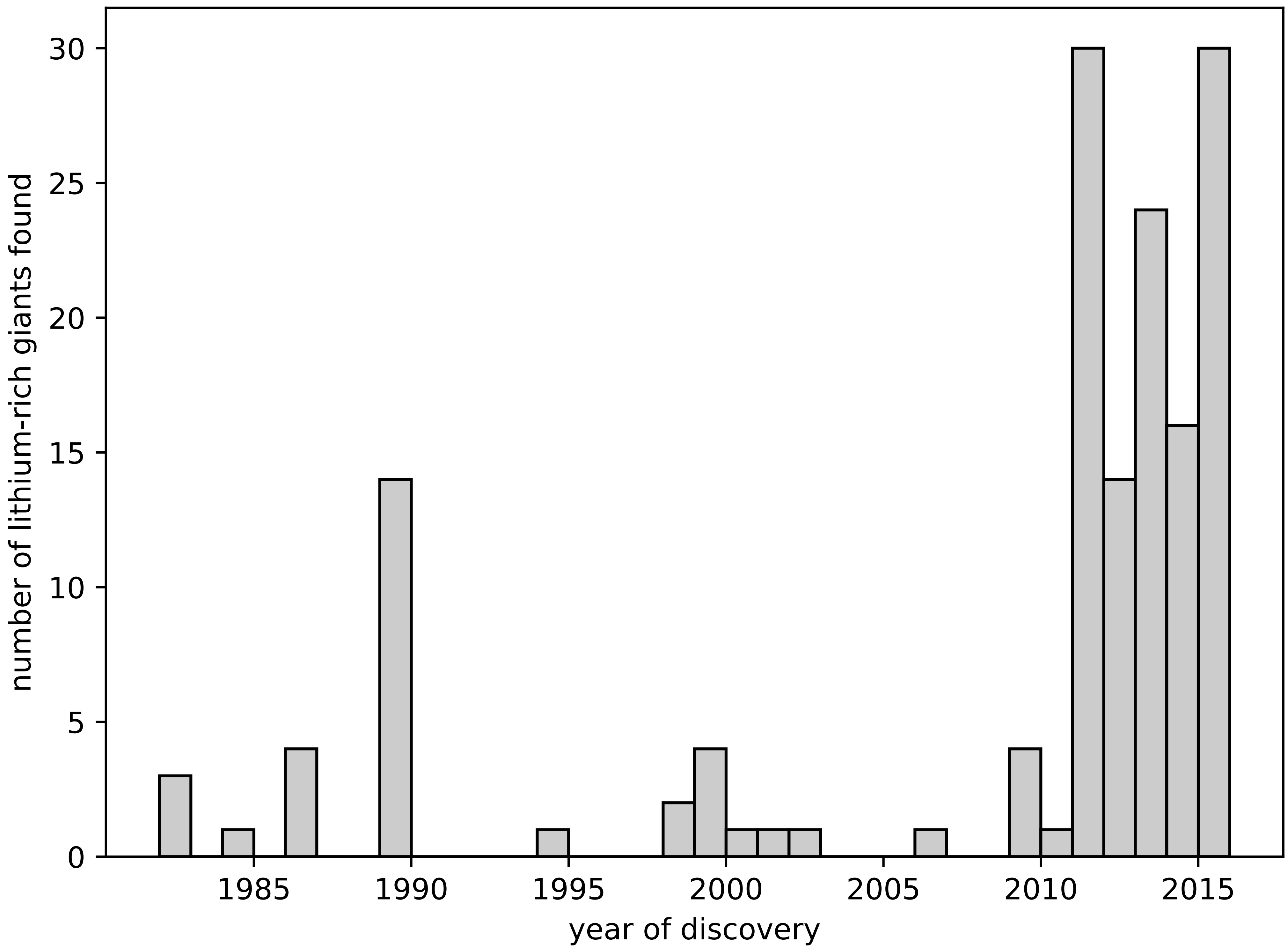
The puzzle:

Lithium-rich* giants exist.
Stellar evolution theory says they shouldn't.

The oldest and most significant contradiction to modern stellar evolution theory.

* Nomenclature and definitions vary. Defined here as A(Li) > 1.5 dex. Sun has A(Li) = 1.05.

Only 151 lithium-rich giant stars discovered in the last 40 years



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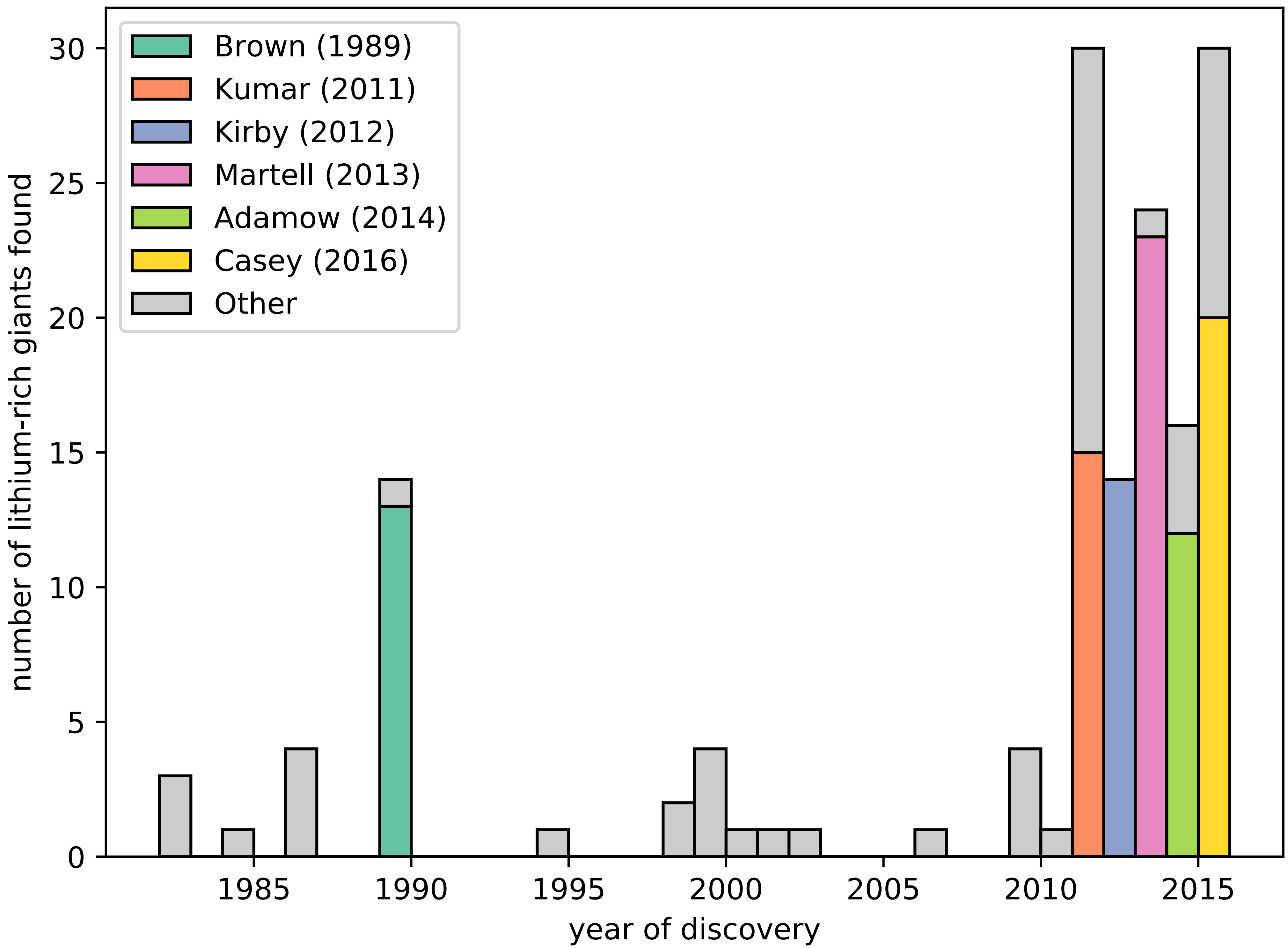

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Many theoretical explanations proposed during those 40 years

Internal mechanisms

- Thermohaline mixing: mixing driven by difference in mean molecular weight
- Meridional mixing: mixing driven by circulation
- "Deep"/"extra" mixing — invented mixing, without a specific origin

External mechanisms

Internal mechanisms through Cameron-Fowler mechanism

$$^{3}\mathrm{He}\,(\alpha,\gamma)^{7}\,\mathrm{Be}\,(\beta^{-},\nu)^{7}\,\mathrm{Li}$$

$$^{7}\mathrm{Li}\,(p,\alpha)^{4}\mathrm{He} \;=\; \mathrm{ppII}$$

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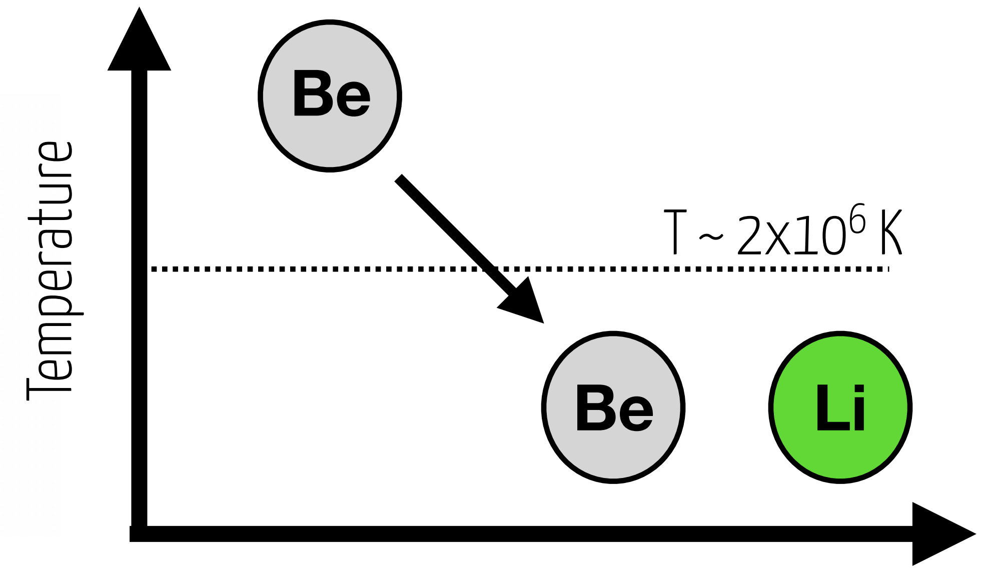
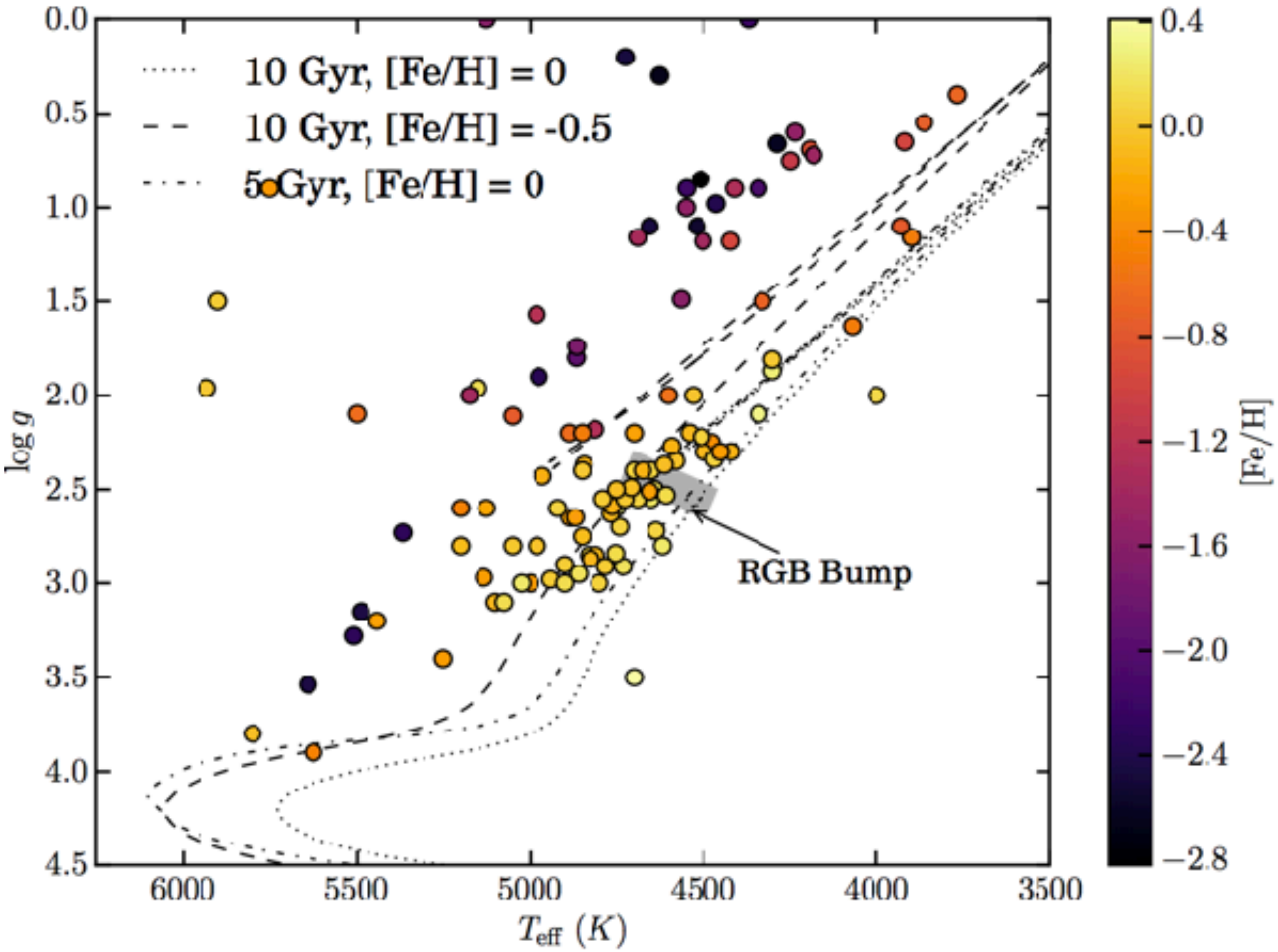


- Need to produce beryllium in inner layers.
- Quickly transport beryllium to cooler regions so that lithium can be produced and not be immediately destroyed.
- Very sensitive to the structure and mixing in a star. **Needs "extra" mixing driven by something.**
- Mixing is (often) sensitive to the evolutionary state. Mixing can only occur at specific stages of stellar evolution.

Mixing is sensitive to the evolutionary state

Cannot (always) differentiate between evolutionary states from spectroscopy alone.



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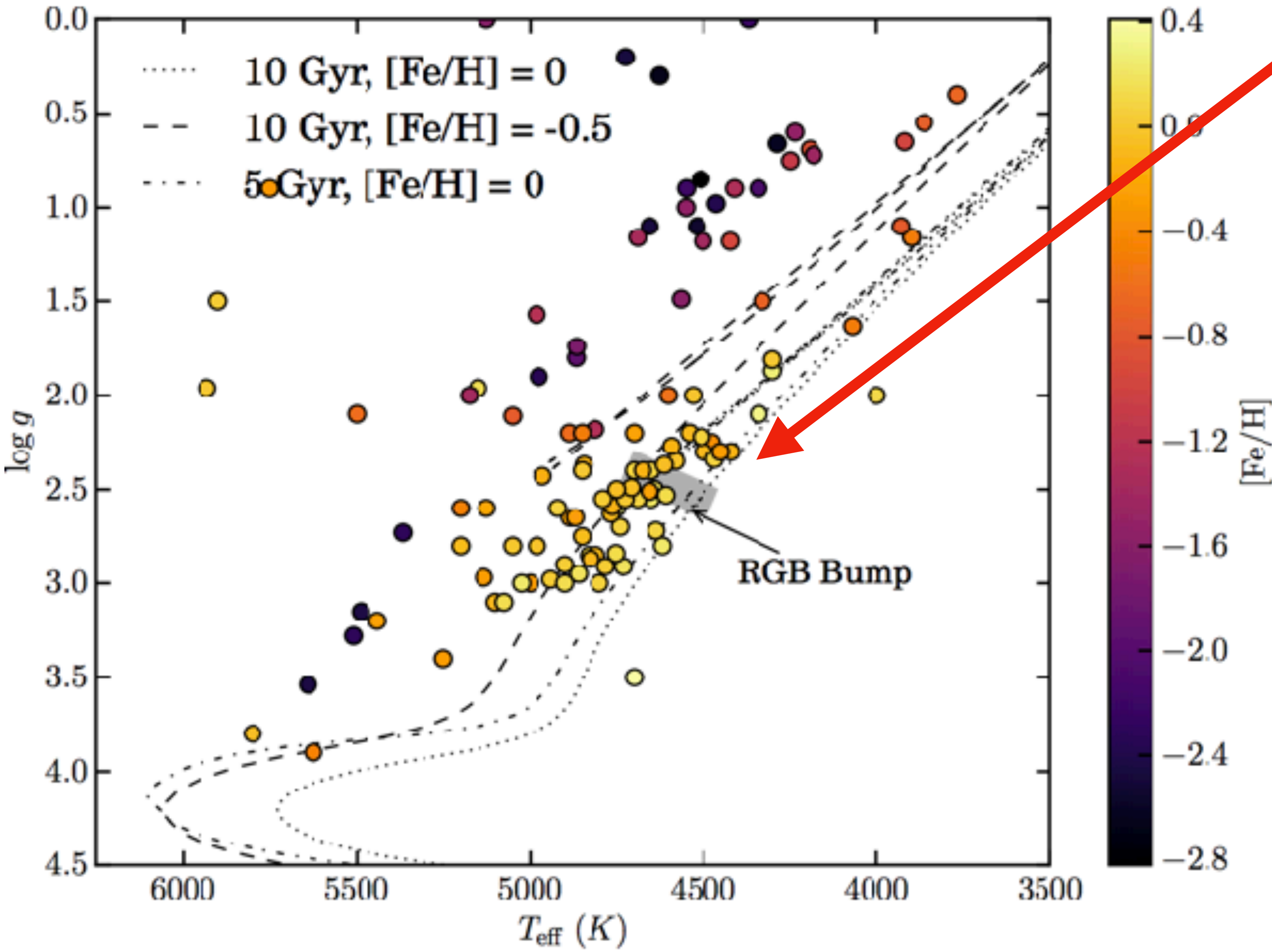

If they are bump stars:

Thermohaline mixing starts at the luminosity bump (regardless of mass).

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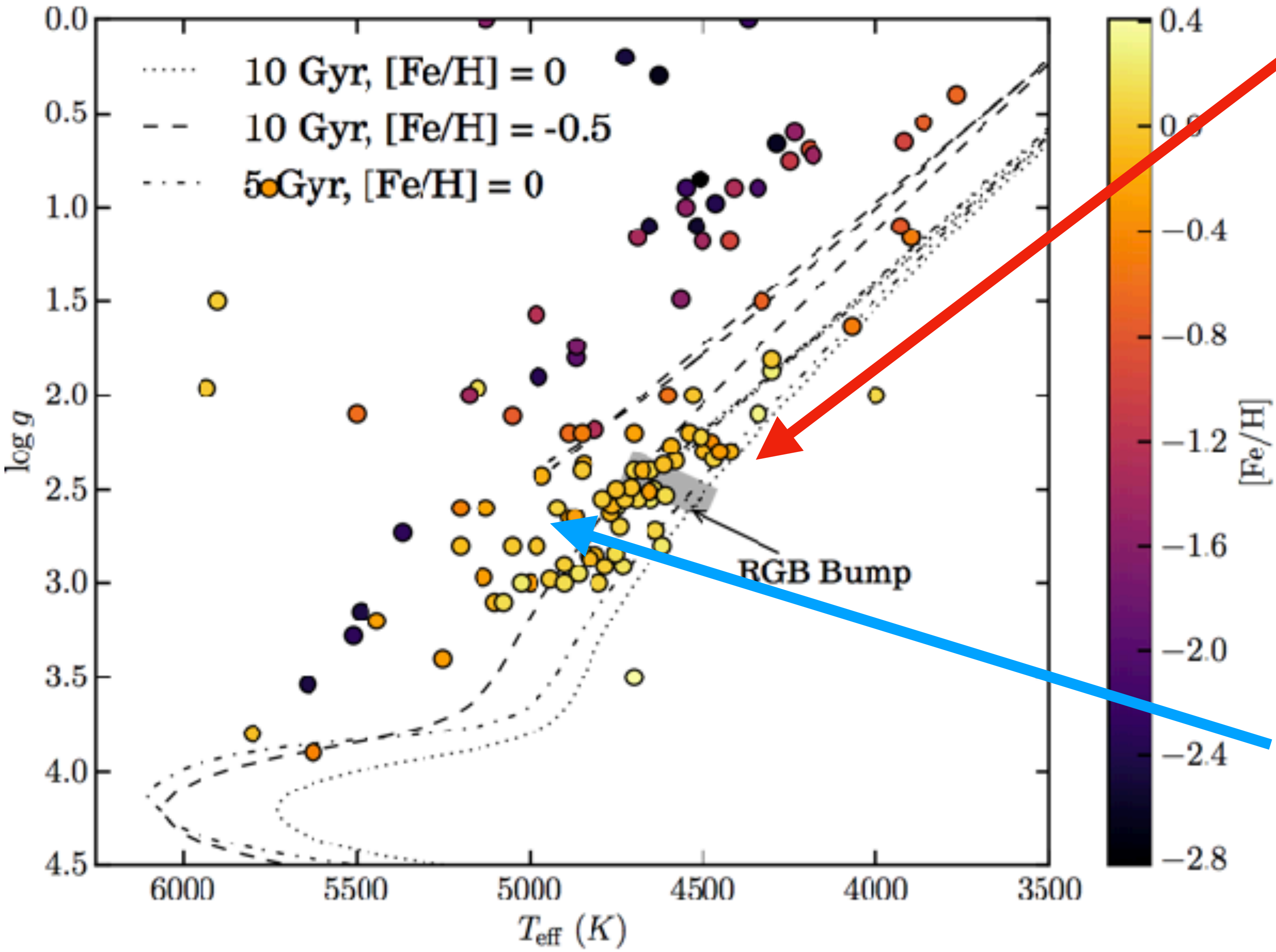


If they are bump stars:

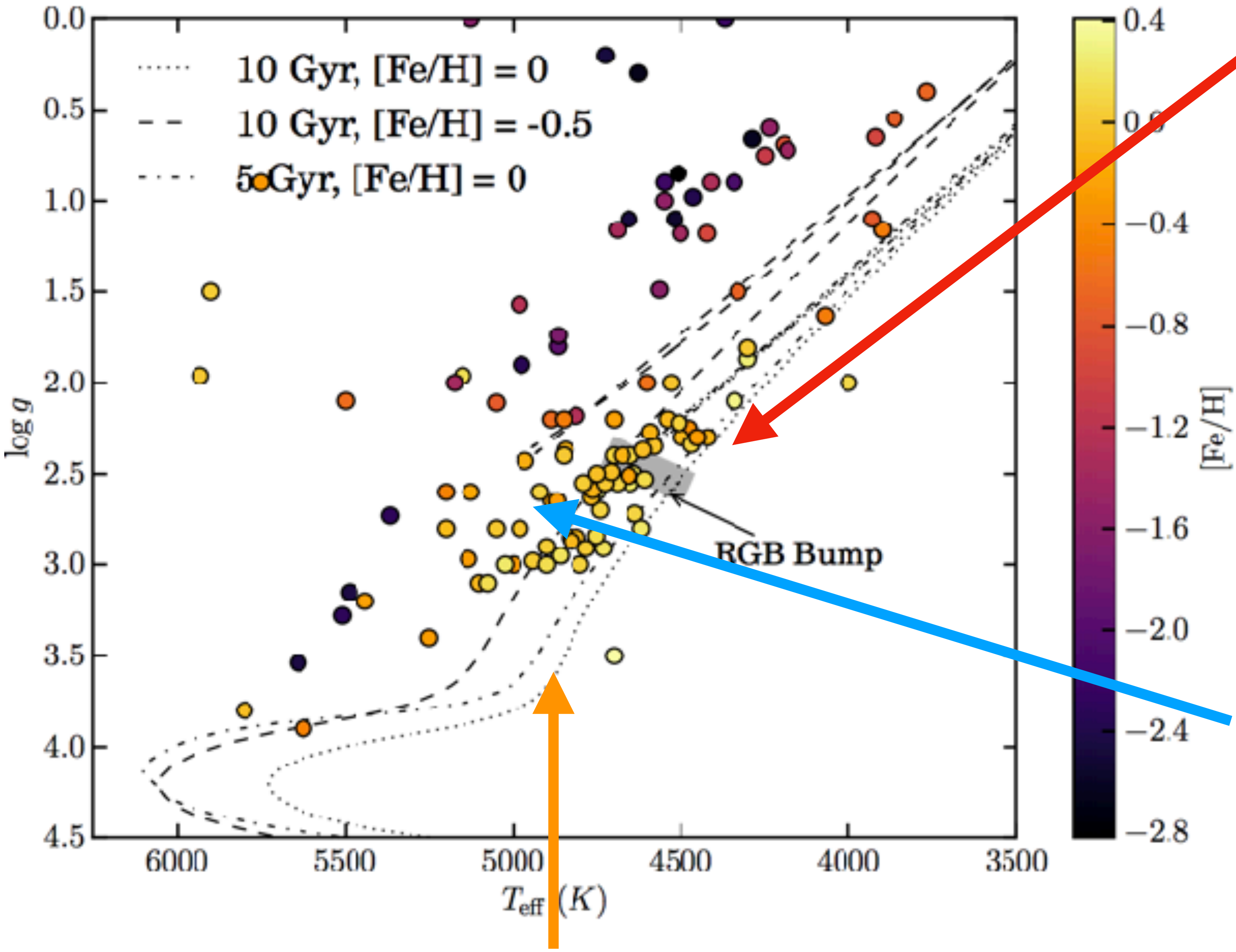
Thermohaline mixing starts at the luminosity bump (regardless of mass).

If they are clump stars:

Mixing at the helium flash?

Mixing is sensitive to the evolutionary state

Cannot (always) differentiate between evolutionary states from spectroscopy alone.



If they are bump stars:
Thermohaline mixing starts at the luminosity bump (regardless of mass).

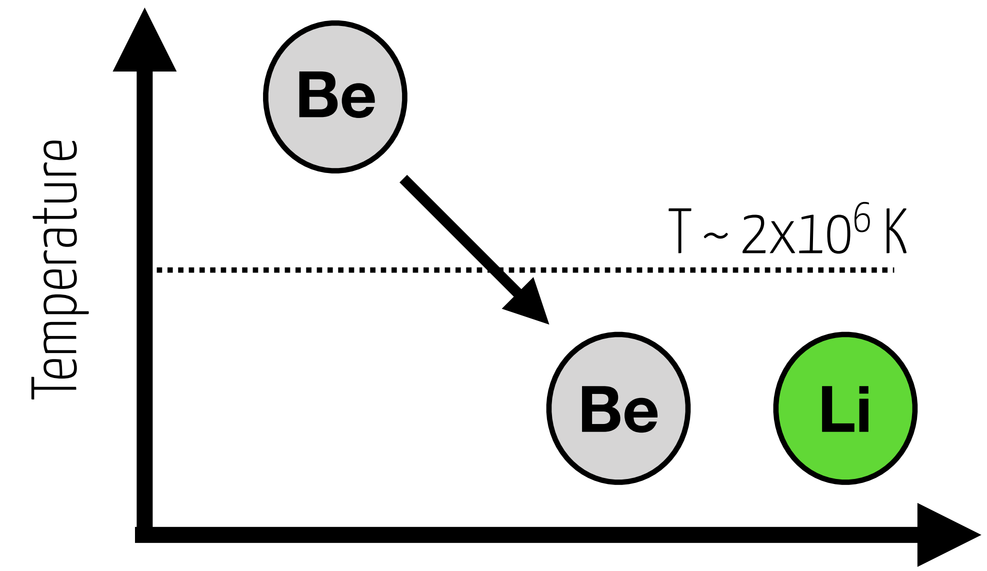
If they are clump stars:
Mixing at the helium flash?

If they are before the bump: ???

Many theoretical explanations proposed during those 40 years

Internal mechanisms

- Thermohaline mixing: mixing driven by difference in mean molecular weight
- Meridional mixing: mixing driven by circulation
- “Deep”/“extra” mixing **-> induced by what?**



External mechanisms

Many theoretical explanations proposed during those 40 years

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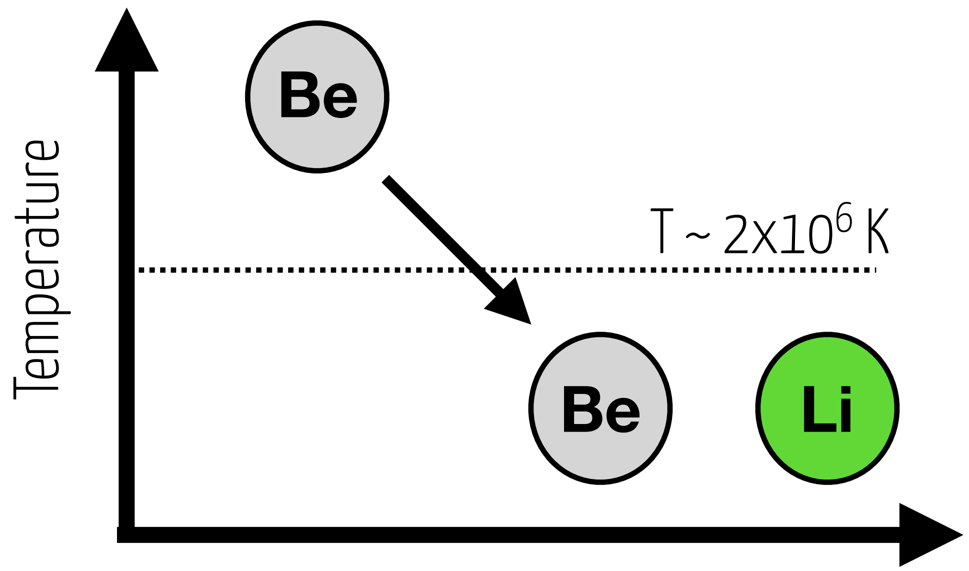


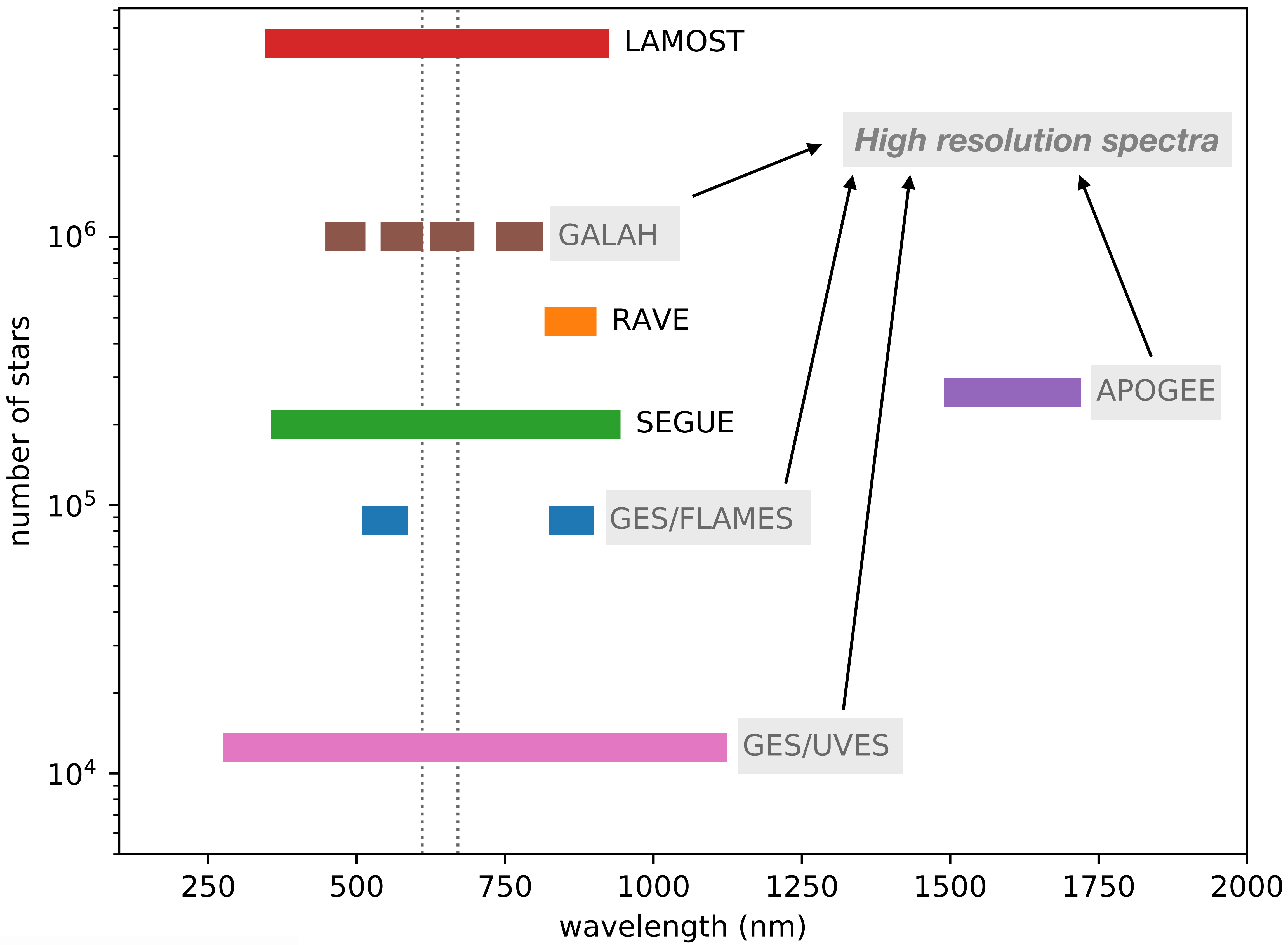
External mechanisms

- Nova
- **Planet engulfment**
- **Merger of two stars/common envelope**
- Transient X-ray binaries
- Cosmic spallation and accretion
- Accretion from nearby AGB stars

“More data are required”

- Need many more lithium-rich giants.
- And lithium-rich giants that have additional information (asteroseismology, etc).
- Most discoveries of lithium-rich giants have been just by luck, because there are no distinguishable traits other than lithium enrichment.
- Can’t select by colours, or anything else.
- And remember: they are rare (~1% occurrence rate)

Observational challenges make it difficult to find lithium-rich giants



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Finding lithium-rich (or weird stars) in large data sets.

- Cannot use physical models, because the physical models make bad predictions for the data.
- Predictions could have a large chi-squared value because the wrong model parameters were found, or because the predictions are bad.
- Need something that can identify significant discrepancies from what typical stars look like.

A data-driven approach.

Why use a data-driven approach?

- A data-driven approach allows us to use every pixel in the spectrum ("maximal" information content).
- Same precision in stellar parameters for about 1/3rd the S/N ratio (or about 1/9th the observing time).
- More precise stellar parameters than physics-based approaches.
- Much faster (six orders of magnitude) and often more reliable than physics-based approaches (analytic derivatives; convex optimisation).

Steps to a data-driven model

1. Construct a **training set** of well-studied stars, where the "labels" are known with high fidelity.

2. **Train** a model for the data that is a function of the training set labels.

3. **Validate** the model (using held-out data; cross-validation).

4. Use the trained model and run the **test step** to estimate labels for new data.

Data-driven model for LAMOST spectra using The Cannon

Stellar flux in the **j-th** pixel for the **n-th** star can be modelled by some (nearly linear) combination of the stellar labels (effective temperature, surface gravity, etc), plus noise.

$$\underbrace{y_{jn}}_{\text{Flux}} = \underbrace{\boldsymbol{v}(\ell_n)}_{\text{“Vectoriser”}} \cdot \underbrace{\boldsymbol{\theta}_j}_{\text{Coefficients}} + \underbrace{e_{jn}}_{\text{Scatter}}$$

At the training step:

We have these. **We want these.**

See Ness et al. (2015, 2016, 2017), Ho et al. (2017a,b), Casey et al. (2016d, 2017a., 2018b.).

Training step, then test step

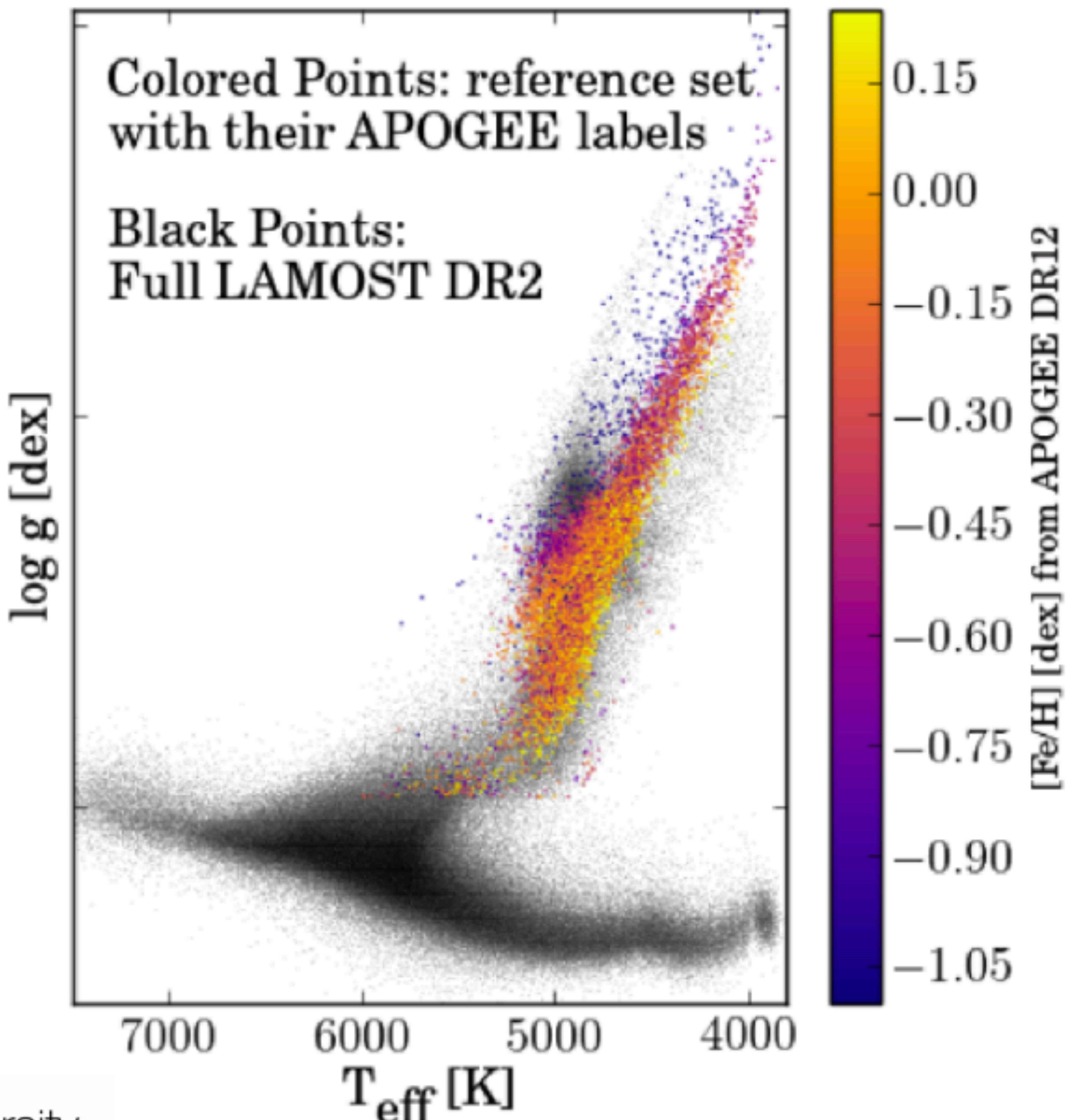
At the **training step** we use a sample of stars with precise stellar parameters to calculate the model coefficients and noise terms.

$$\boldsymbol{\theta}_j, s_j^2 \quad \leftarrow \quad \underset{\boldsymbol{\theta}, s^2}{\operatorname{argmin}} \left[\sum_{n=0}^{N-1} \frac{[y_{jn} - \boldsymbol{v}(\ell_n) \cdot \boldsymbol{\theta}]^2}{\sigma_{jn}^2 + s^2} + \sum_{n=0}^{N-1} \ln(\sigma_{jn}^2 + s^2) + \Lambda_j \, Q(\boldsymbol{\theta}) \right]$$

At the **test step** we use model coefficients and noise terms to infer stellar labels for new stars:

$$\ell_m \quad \leftarrow \quad \underset{\ell}{\operatorname{argmin}} \left[\sum_{j=0}^{J-1} \frac{[y_{jm} - \boldsymbol{v}(\ell) \cdot \boldsymbol{\theta}_j]^2}{\sigma_{jm}^2 + s_j^2} \right]$$

Data-driven model of LAMOST spectra



Ho et al. (2017b)

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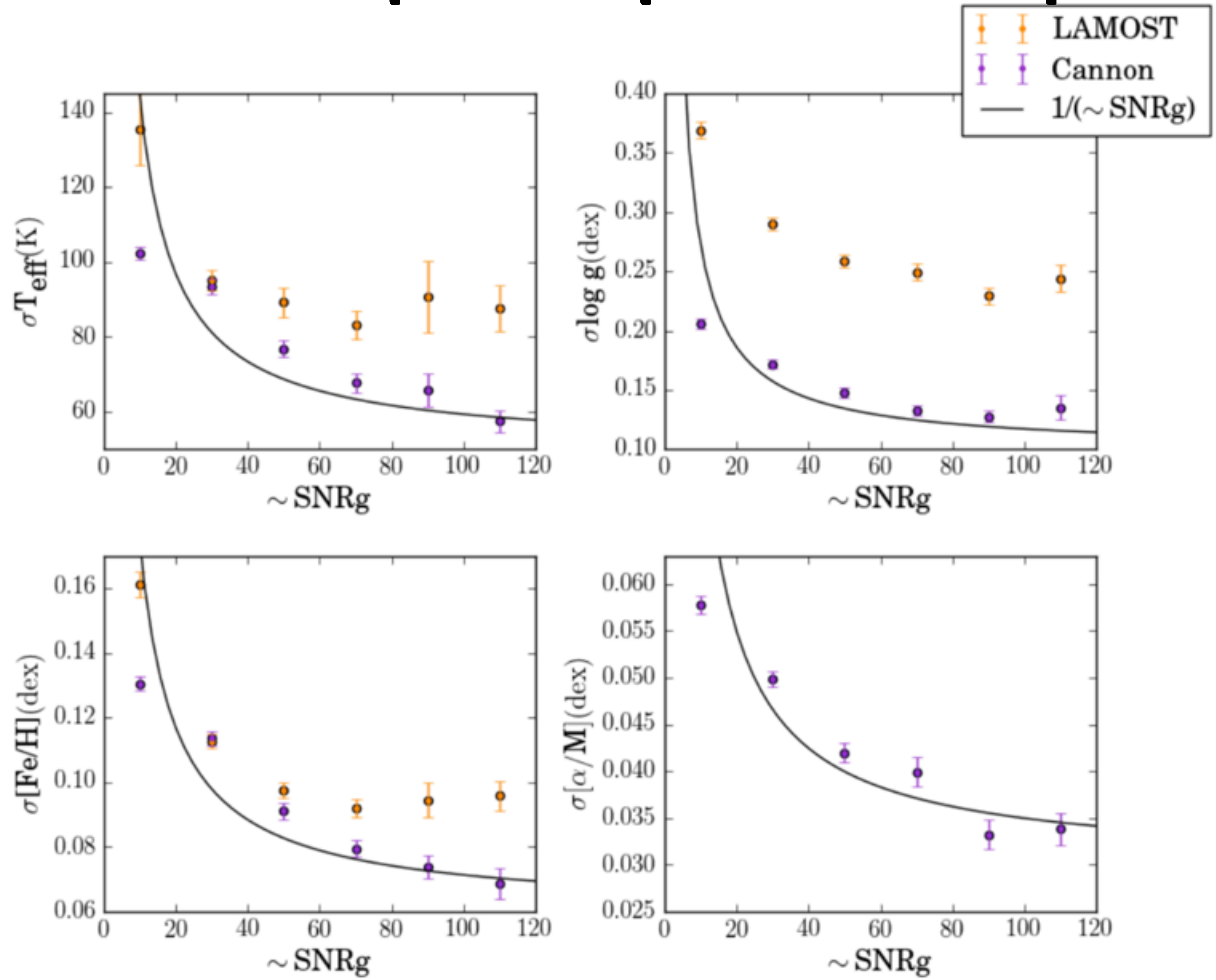
Data-driven model provides precise stellar parameters



Ho et al. (2017b)

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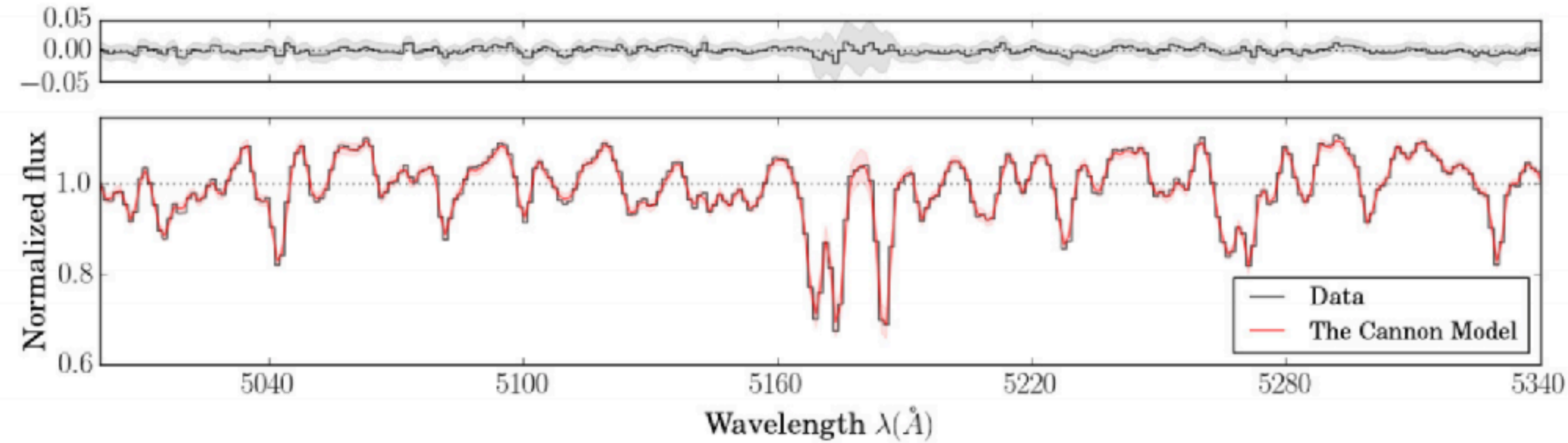
Data-driven model provides extremely accurate predictions of stellar spectra



Depending on your background in data analysis, there are at least two possible reactions:

'oh wow, that's a good fit!'

or **'duh, it's trained on the data!'**

Ho et al. (2017b)

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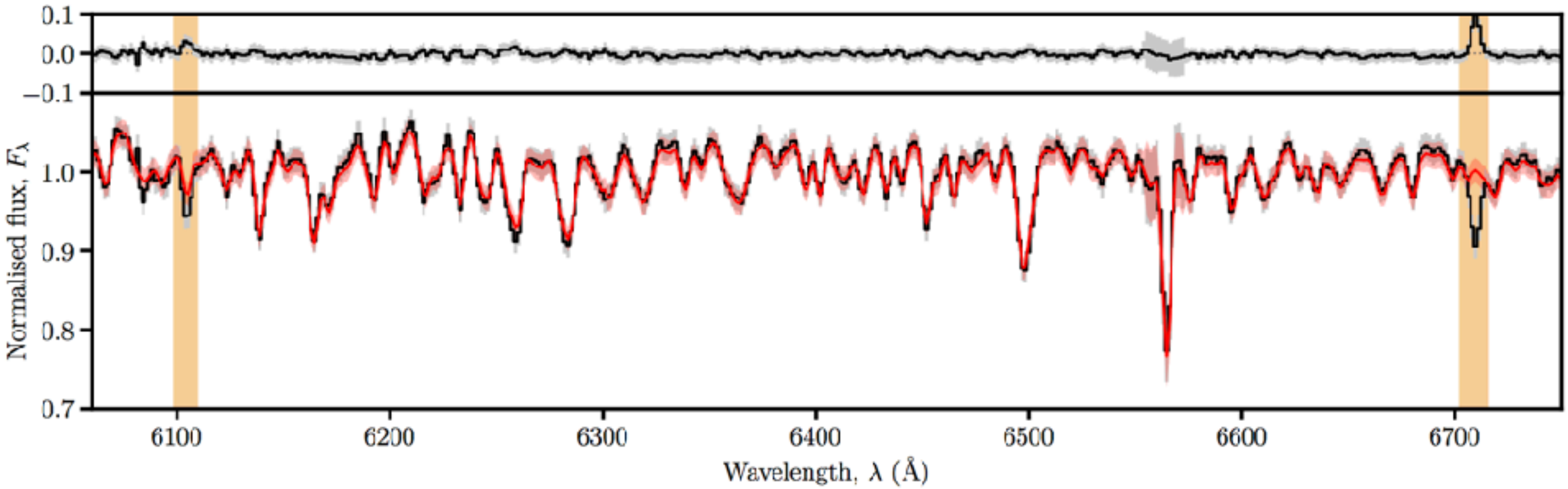
Deviations from the model are extremely significant

Applying a matched-filter algorithm to the residuals revealed **4,558 candidate lithium-rich giants** with **>3-sigma** detections at either the 610.4 nm or the 670.7 nm transition.



We excluded suspicious candidates (data reduction problems; deviations did not match the spectral resolution; low S/N ratios; evidence of being a young star), leaving **2,330 bonafide lithium-rich giants.**

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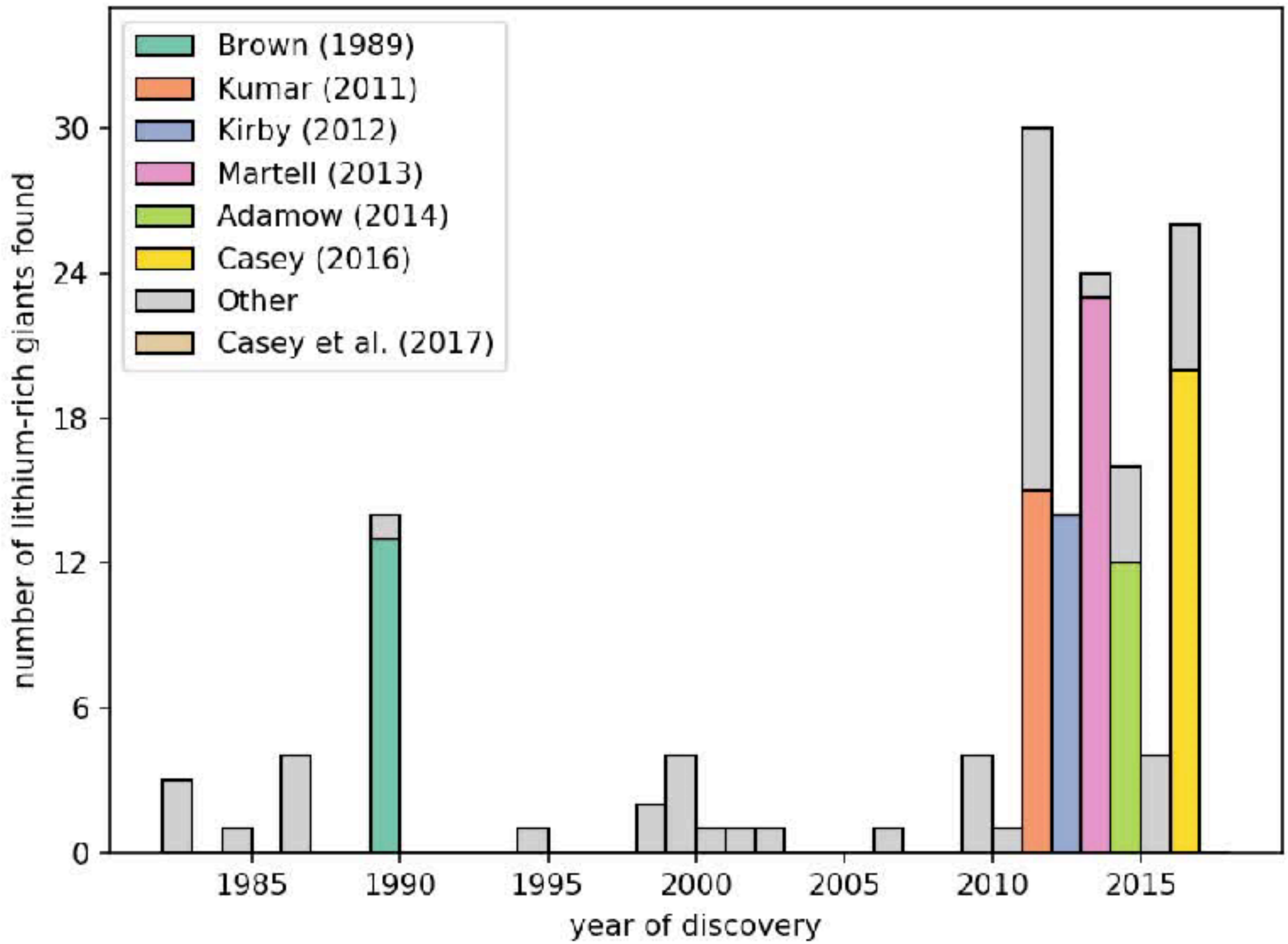
A sample size larger by about a factor of 1,000 over previous studies



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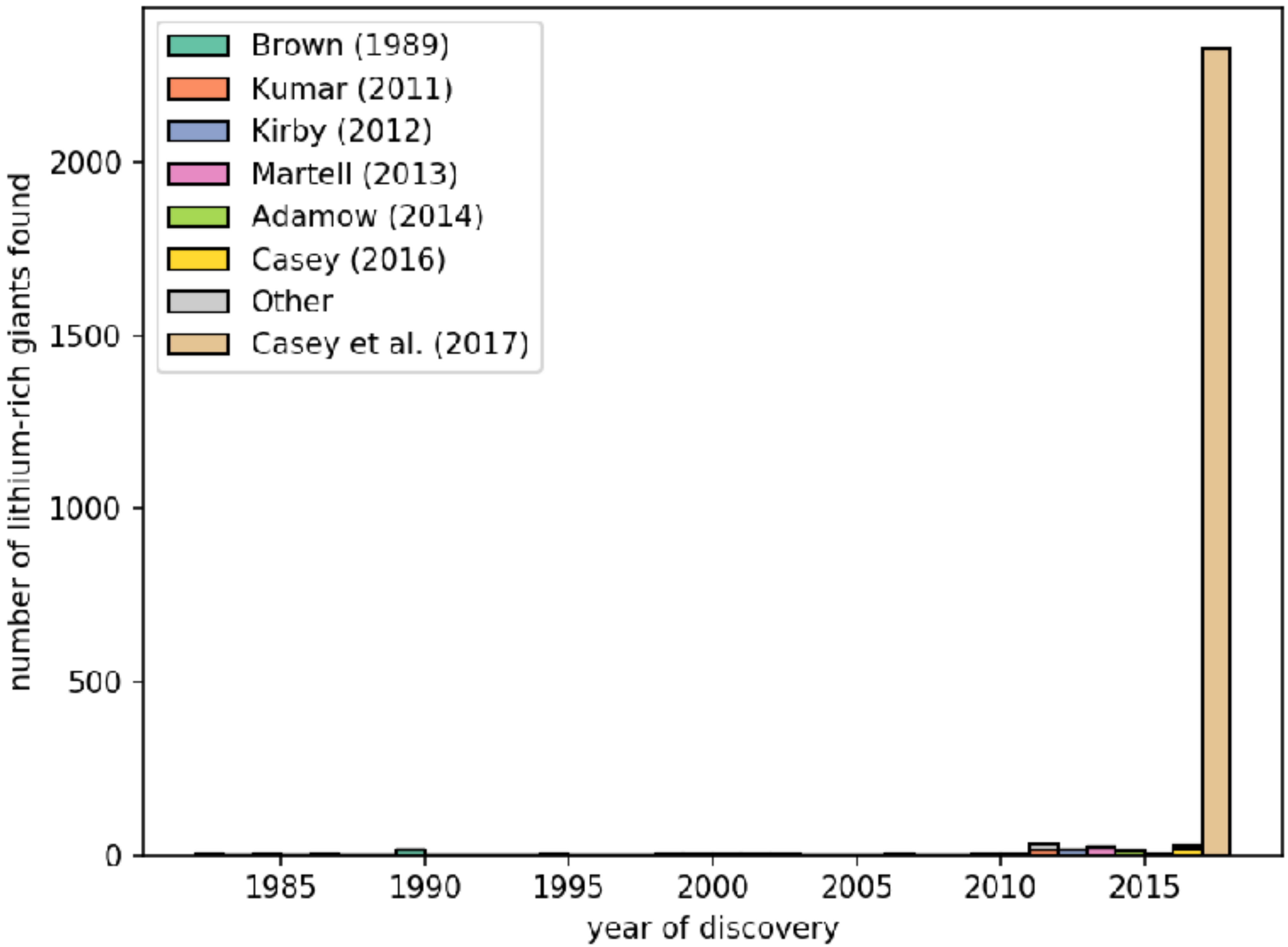
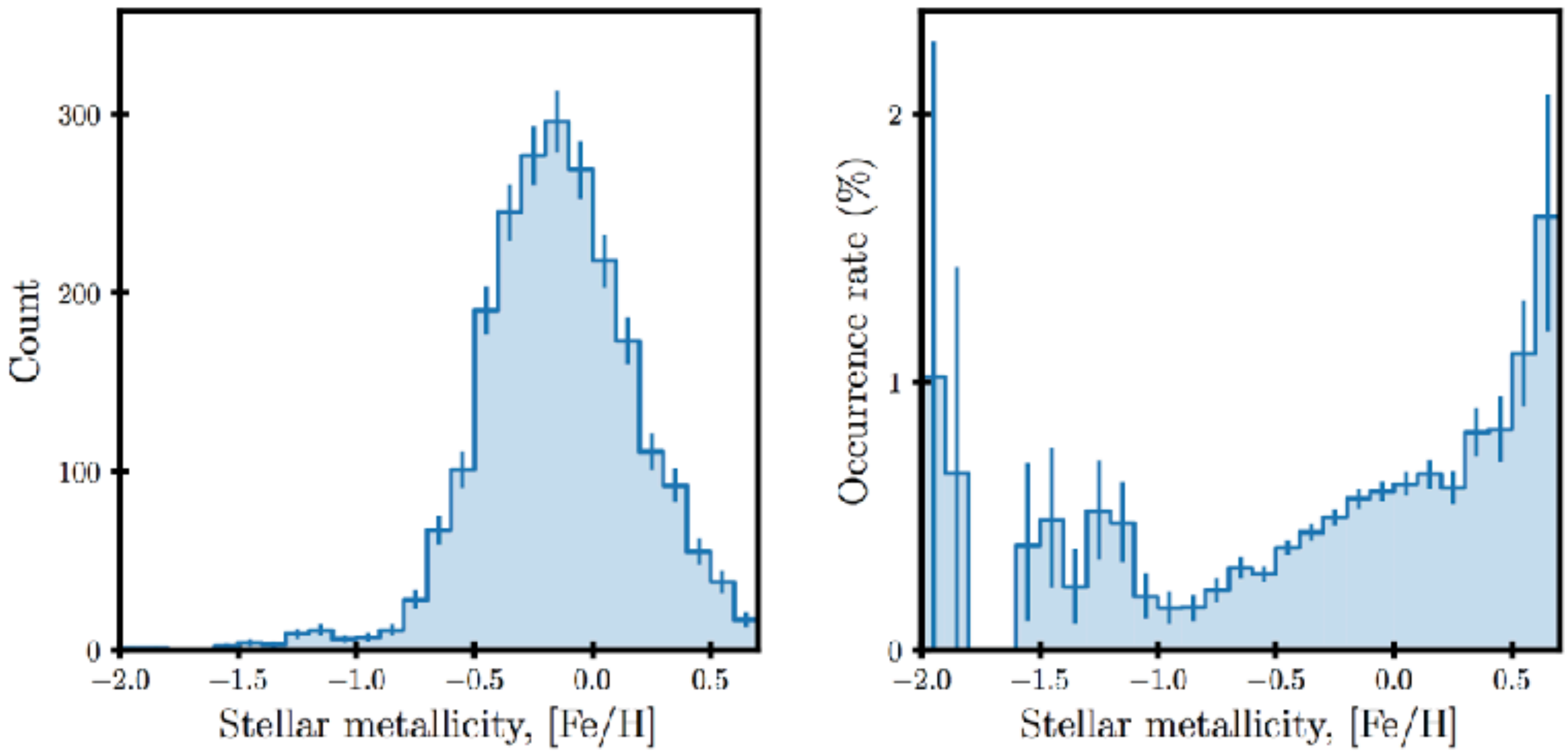


The frequency of lithium-rich giants increases with increasing metallicity

The number of lithium-rich giants in LAMOST is about as expected, given about a 1% frequency.



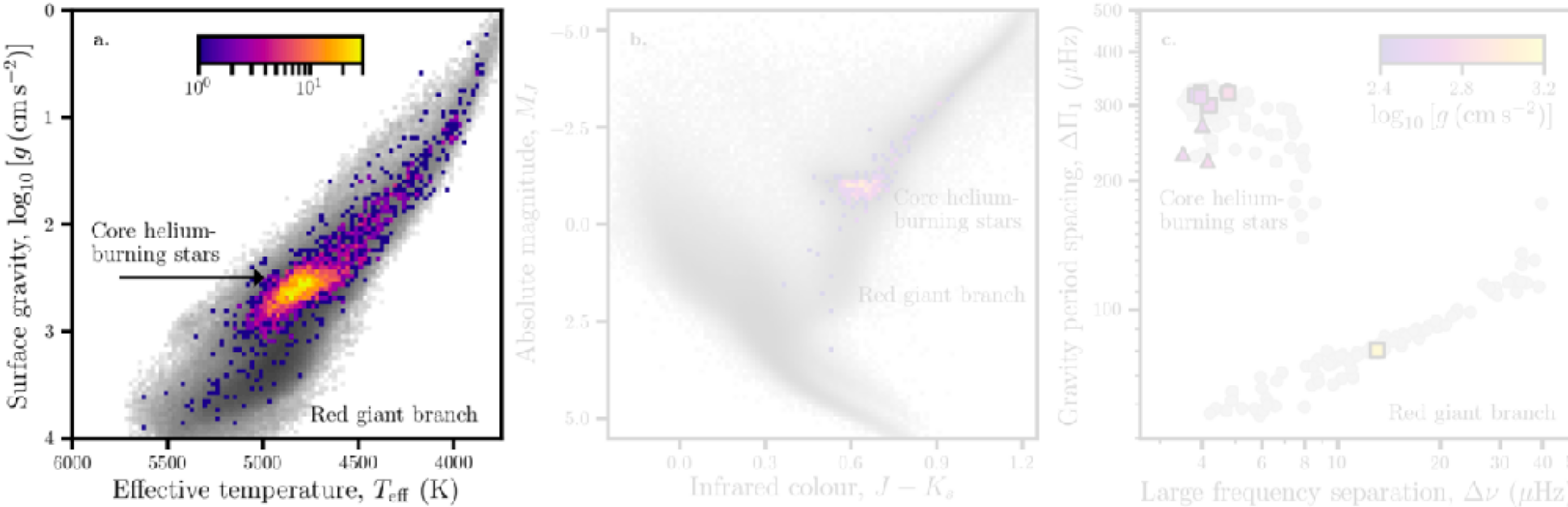
Isolated metal-poor systems with controlled systematics suggest a frequency of 0.3 +/- 0.1%.

(e.g., Kirby et al. 2009, 2016; D'Orazi et al. 2016)

Field studies of more metal-rich stars suggest a frequency of about 1-2%.

(e.g., Brown et al. 1989; Martell et al. 2013; Kumar et al. 2011; Casey et al. 2016a)

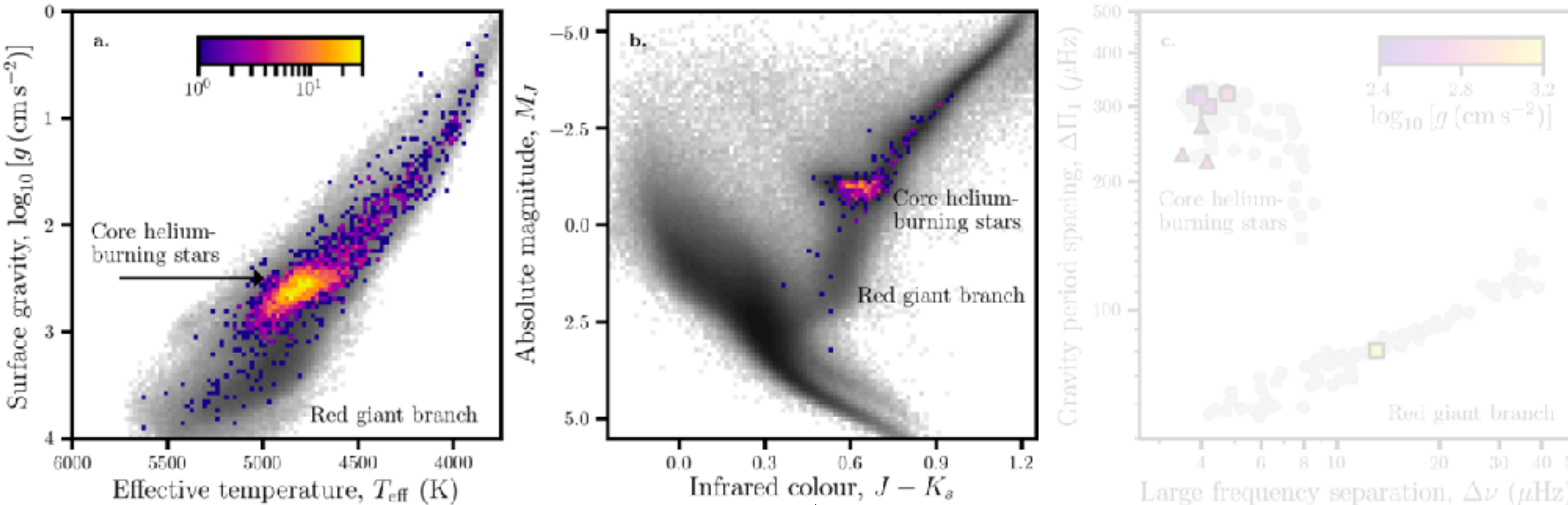
Most lithium-rich giants have helium-burning cores



Concentrated near the **clump/bump**, and on the upper red giant branch.

Showing 2,330 lithium-rich giant stars and 455,000 LAMOST stars in grey.

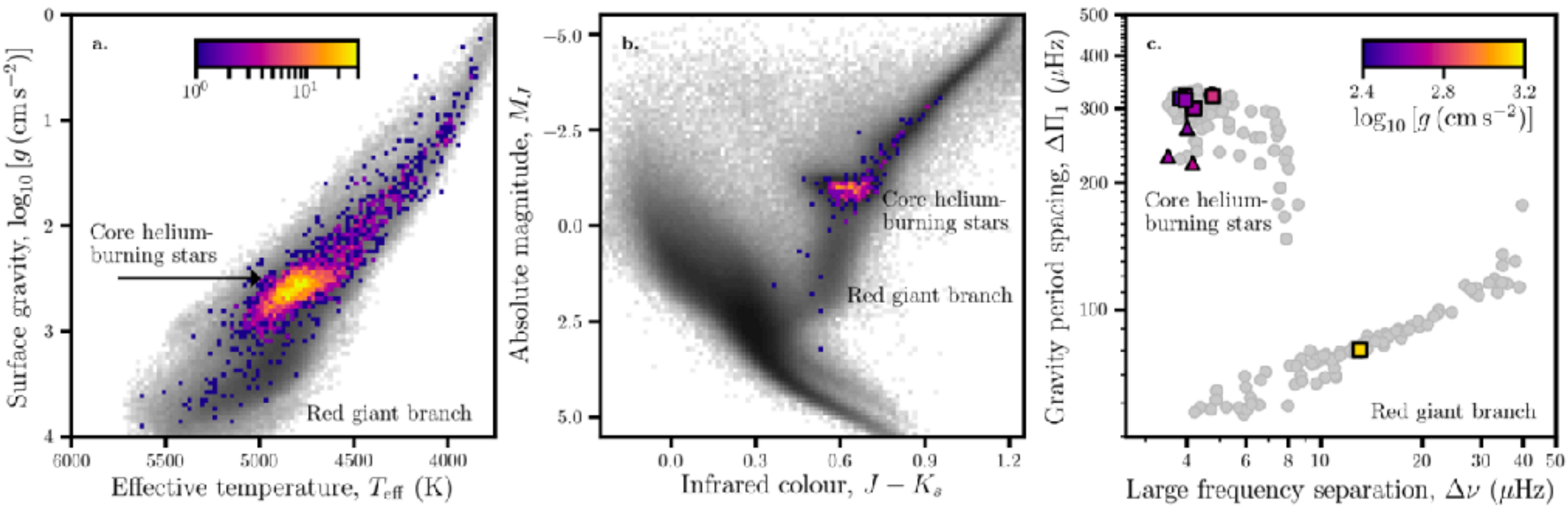
Most lithium-rich giants have helium-burning cores



Concentrated near the clump/bump, and on the upper red giant branch.

240 lithium-rich giants with Gaia (deconvolved) parallaxes from Anderson et al. (2017).

Most lithium-rich giants have helium-burning cores



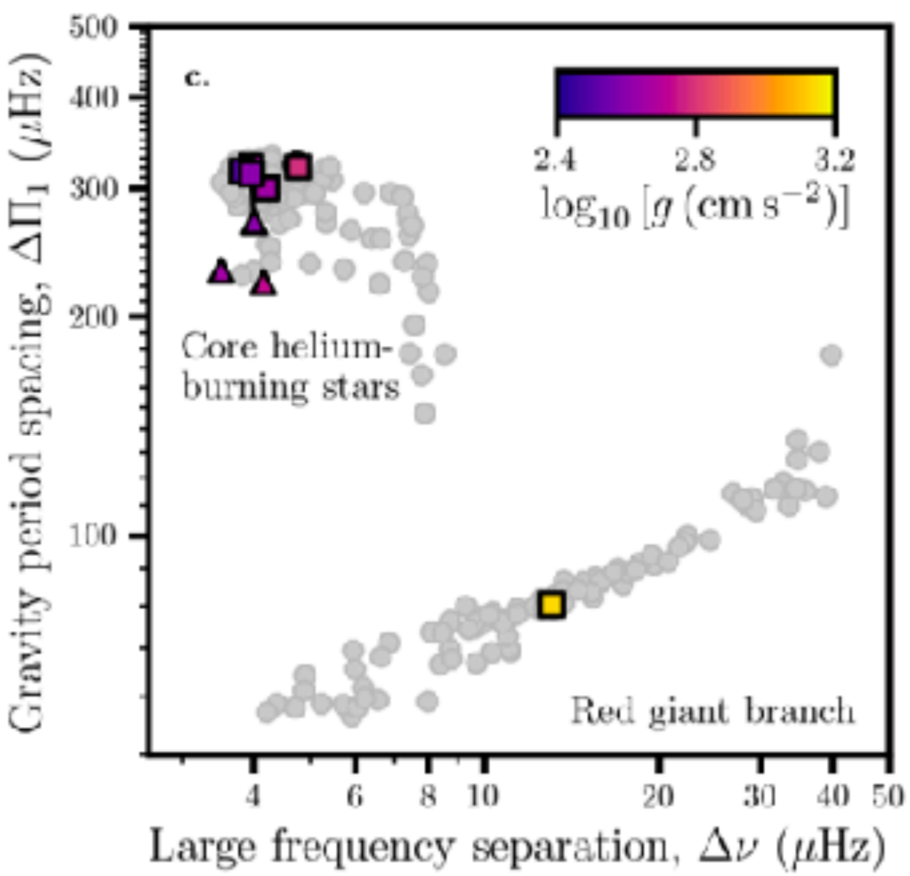
Eight lithium-rich giants have reported asteroseismic parameters in the literature.

Not shown:

Another 7 are in K2: 2 are first ascent red giants and 5 are likely CHeB stars.

15 have classifications from Hon et al. (2017): at least 14/15 are CHeB stars.

Most lithium-rich giants have helium-burning cores



We trained a machine-learning classifier to do asteroseismology directly from the LAMOST spectra

(without the need for Kepler data)

- 1,365 stars with LAMOST spectra and asteroseismic labels
- Accuracy (recall) of 93.4% (precision 96.9%; F-measure 0.95).
- Fraction of CHeB stars among Li-rich giants: **0.80** (+0.07, -0.06; 95% confidence interval)
- Consistent with smaller sample (N = 25): fraction is **0.84 to 0.88.**

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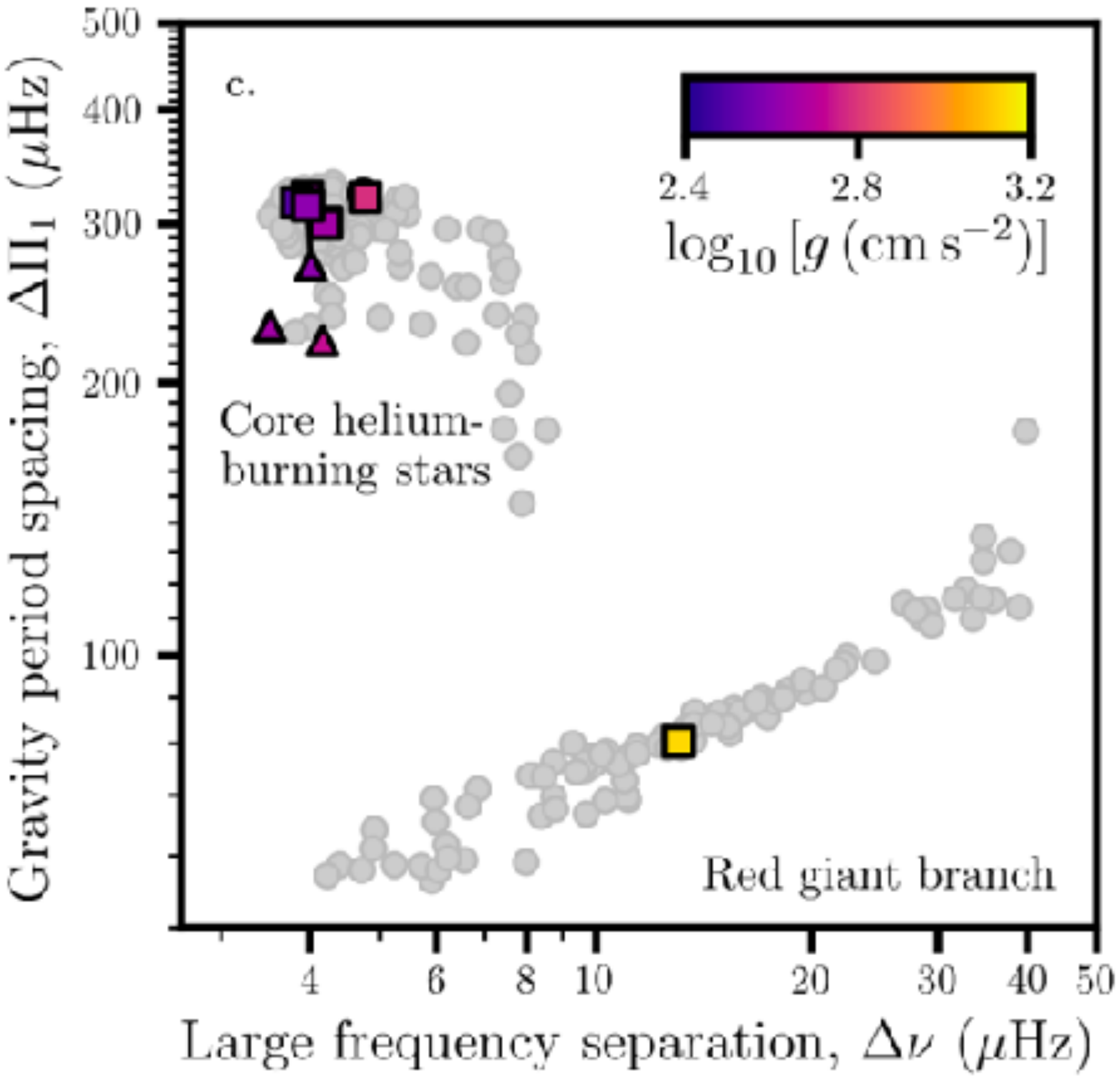
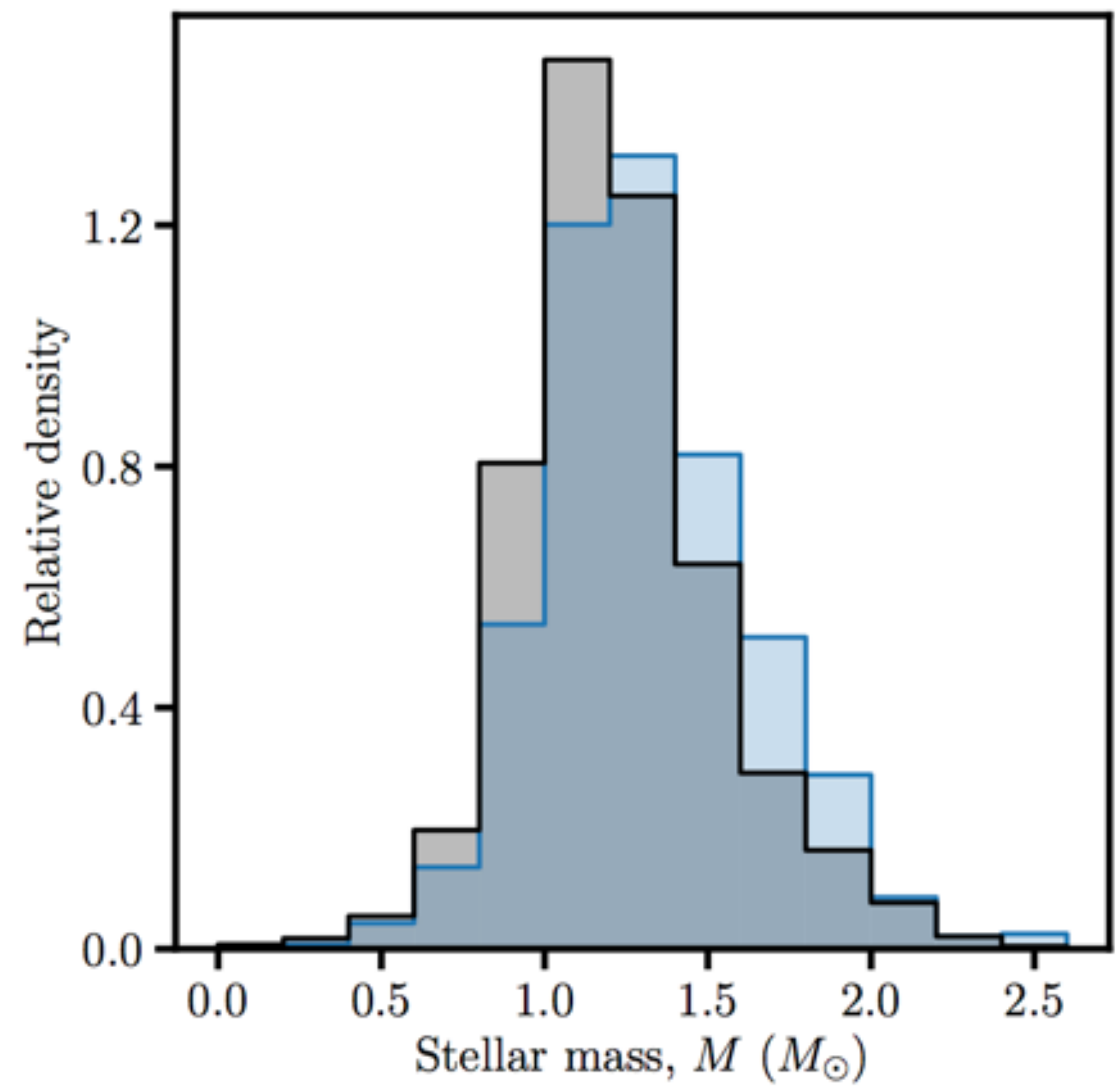
Asteroseismology confirms the results we derive from spectroscopy





Most lithium-rich giants are core-helium burning stars

Most lithium-rich giants are low-mass (between 1-3 solar masses)

The lithium enrichment phase is temporary!

Without prescribing a mechanism for lithium enrichment, we can use this sample to infer **when** stars become lithium-rich, and **how long** they remain lithium-rich.

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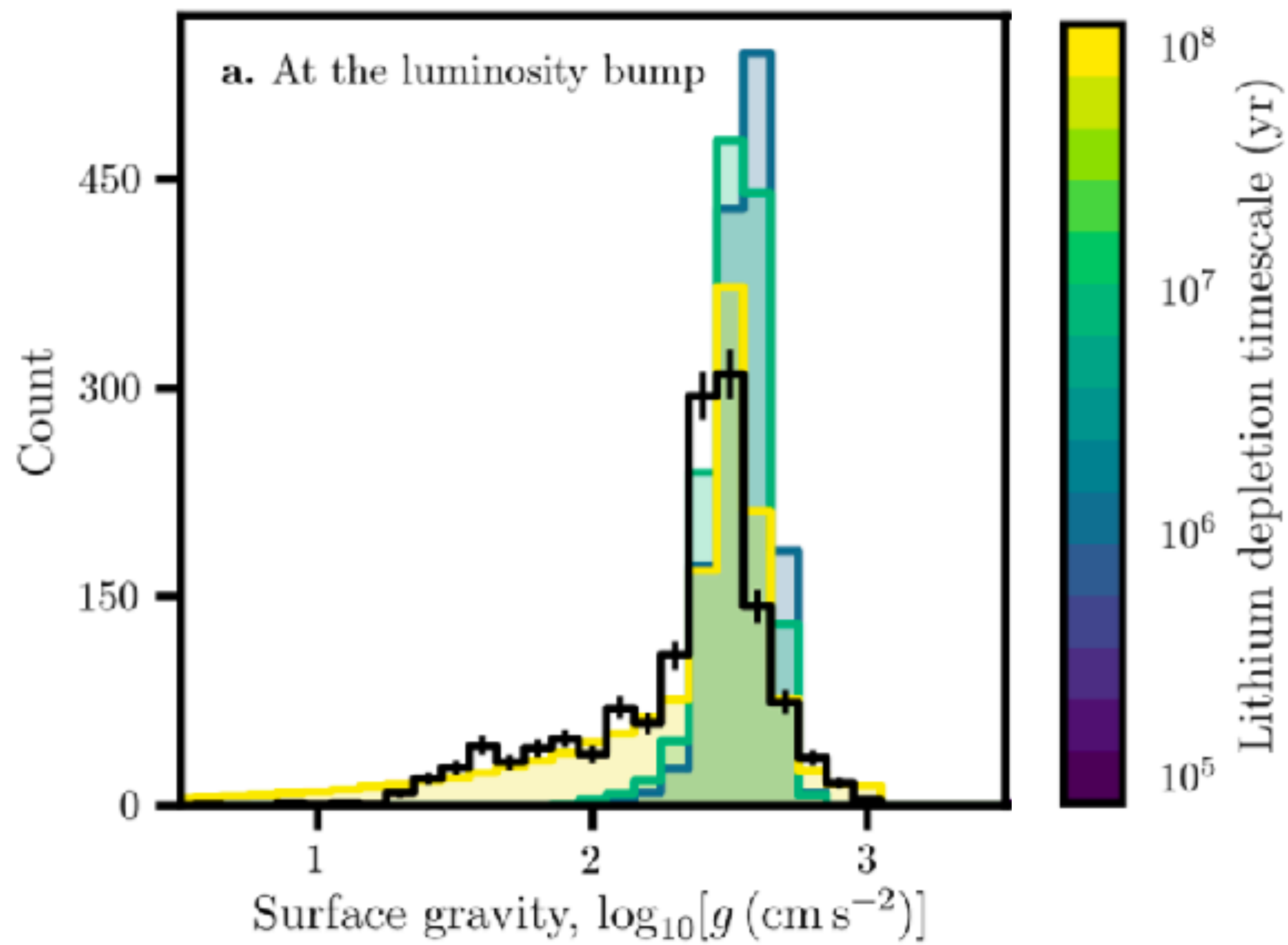
Without prescribing a mechanism for lithium enrichment, we can use this sample to infer **when** stars become lithium-rich, and **how long** they remain lithium-rich.

Procedure:

1. Assume some evolutionary stage where stars become lithium-rich.
2. Assume stars remain lithium-rich for X years.
3. Take an evolutionary track for each star and build up the expected (relative) distribution that we should observe in stellar parameters.

Lithium-rich giants are not primarily produced at the luminosity bump

If lithium-rich giants form at the luminosity bump, then we would need a lithium depletion timescale of **about 10^8 years or more** for any lithium-rich giants to have helium-burning cores.

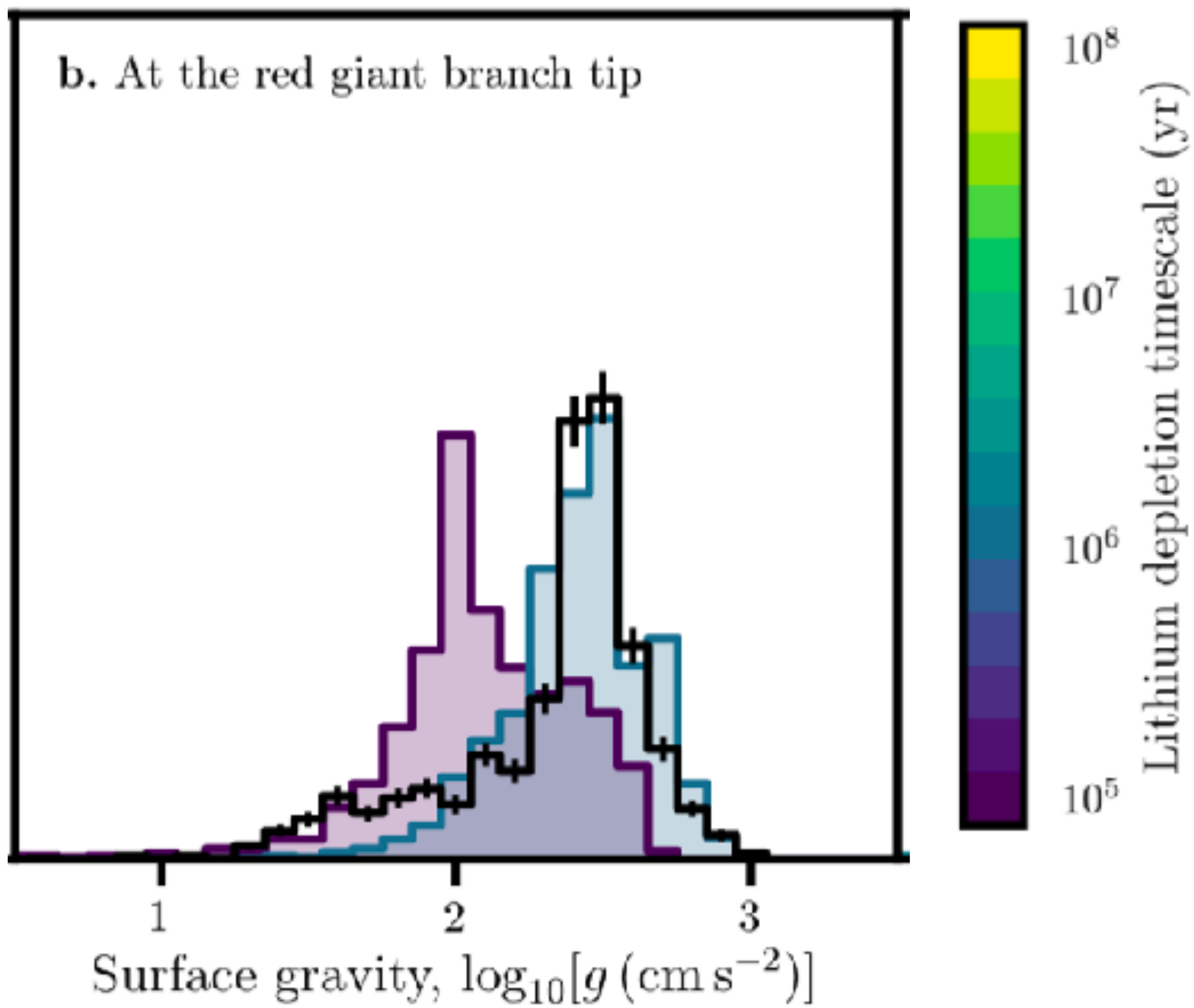


Max CHeB fraction achievable (regardless of timescale): 40%, half what is observed (80%).

Lithium-rich giants are not primarily produced at the red giant branch tip

(e.g., thermohaline mixing — maybe, helium flash)

If lithium-rich giants form at the red giant branch tip, then a lithium depletion timescale of about **10^6 years** is needed for most stars to reach the core helium-burning phase.



Poorly predicts the number of luminous giants, and **cannot explain first ascent lithium-rich giants**.

The luminosity bump and the red giant branch tip are the only two (significant) evolutionary stages that occur on the red giant branch!

The luminosity bump and the red giant branch tip are the only two (significant) evolutionary stages that occur on the red giant branch!

when and why

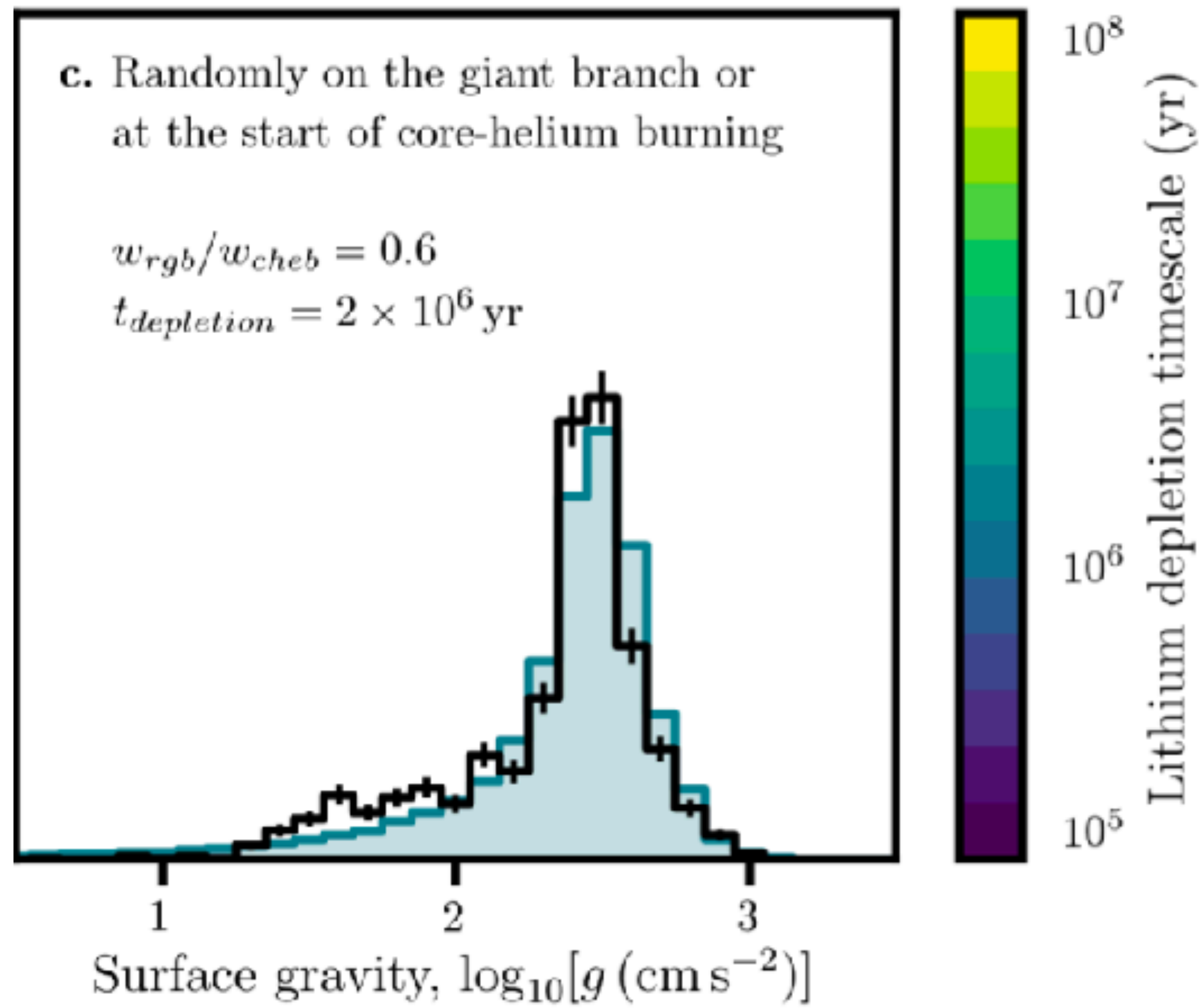
do giants become lithium-rich?

Stars become lithium-rich at a random time, or at the start of ChEB

Introduce a model where lithium-rich giants can form:

1. At a uniformly random time on the red giant branch.

2. At the start of the core helium-burning phase.



Timescale argument rules out most models of lithium enrichment

1. There is **not a particular phase of stellar evolution** where significant internal lithium production occurs.

2. The increasing frequency of lithium-rich giants we find with higher stellar metallicity also suggests that **not every star will experience lithium enrichment.**

3. We find a steady state formation rate of lithium-rich giants of 0.5/yr, which **excludes merged binary stars** and the **engulfment of a brown dwarf** (1 OoM), **nova** (2 OoM), and intermediate-mass **AGB stars.**

4. Moreover, we do not observe the chemical abundance signatures expected if intermediate-mass **AGB stars or nova** were the cause of lithium-rich giants.

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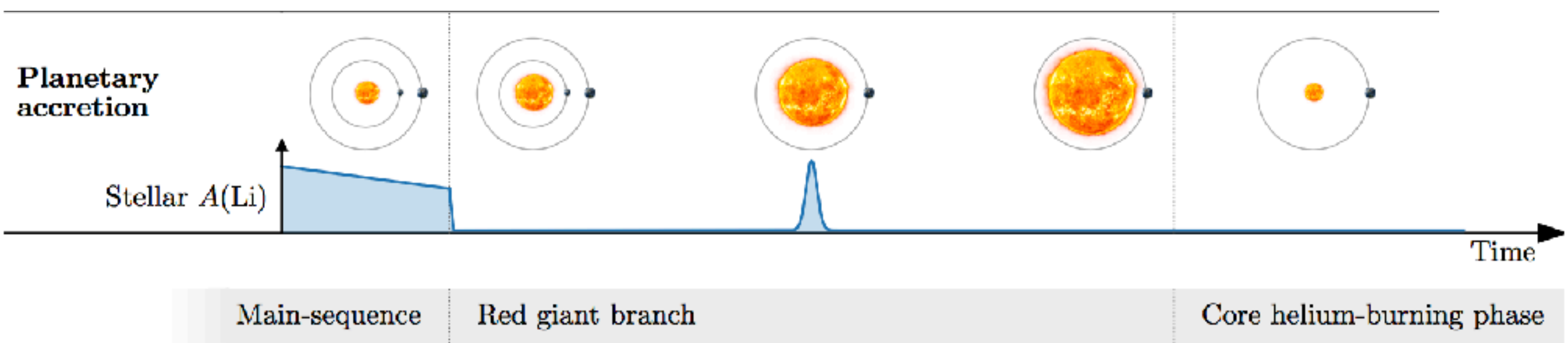
Rules out nearly every hypothesis proposed to explain lithium-rich giants!

Planet engulfment

(e.g., Siess & Livio 1999a,b)

- Provides a reservoir of unburnt lithium.
- Can induce lithium production through deep mixing (depending on accretion rate, episodicity, rotation, etc).



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- Provides a reservoir of unburnt lithium.
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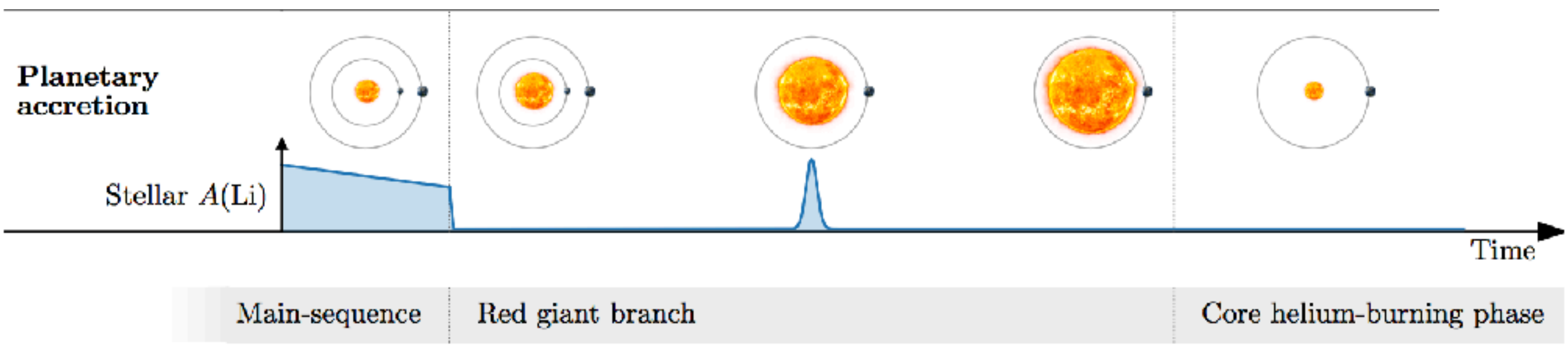
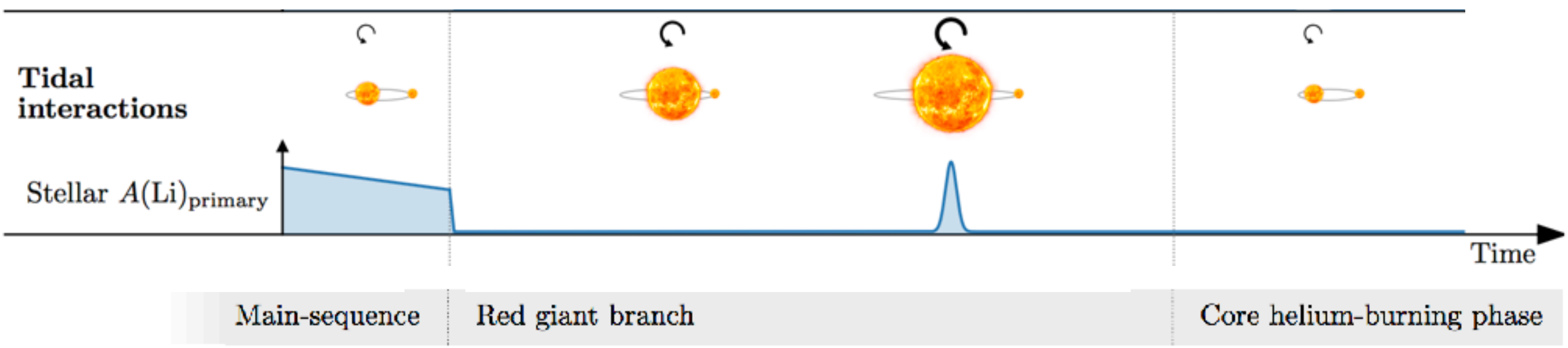
Planet engulfment cannot explain lithium-rich giants that have helium-burning cores.

(e.g., 80% of them)



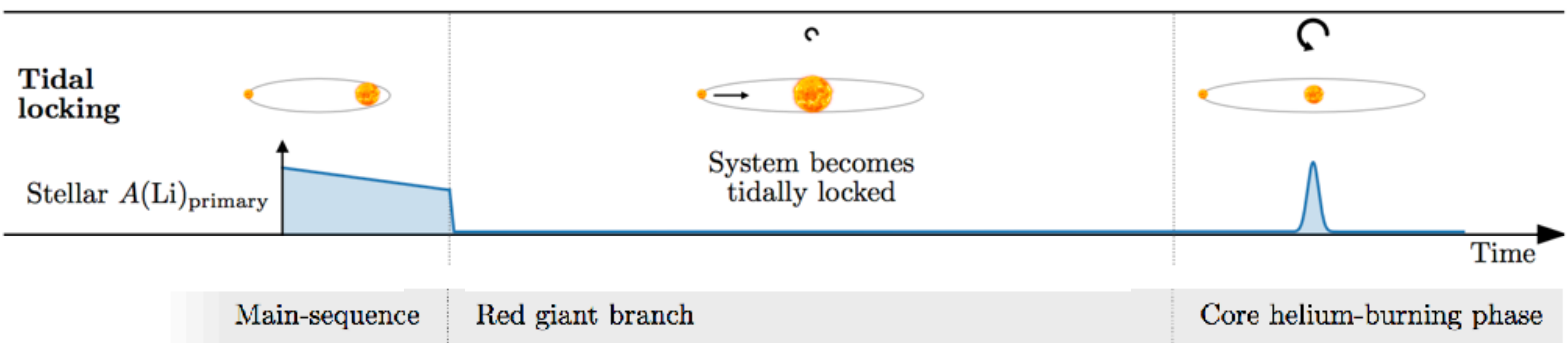
Tidal interactions by a binary companion

- Transfer of angular momentum in detached systems as the system circularises.
- Spin-up the primary giant star such that lithium can be produced through Cameron-Fowler mechanism by rotationally-driven mixing.
- Time of spin up occurs on initial separation, masses of each system, etc. Distributions of these could approximate a uniform-in-time production of lithium-rich giants.



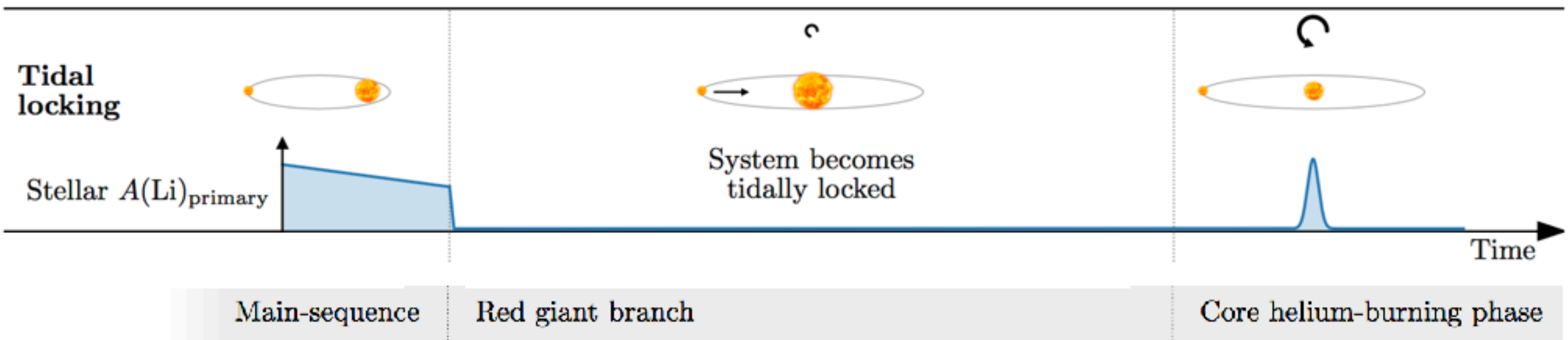
Tidal interactions by a tidally-locked binary companion

- System becomes tidally locked when the primary is on the giant branch.



Tidal interactions by a tidally-locked binary companion

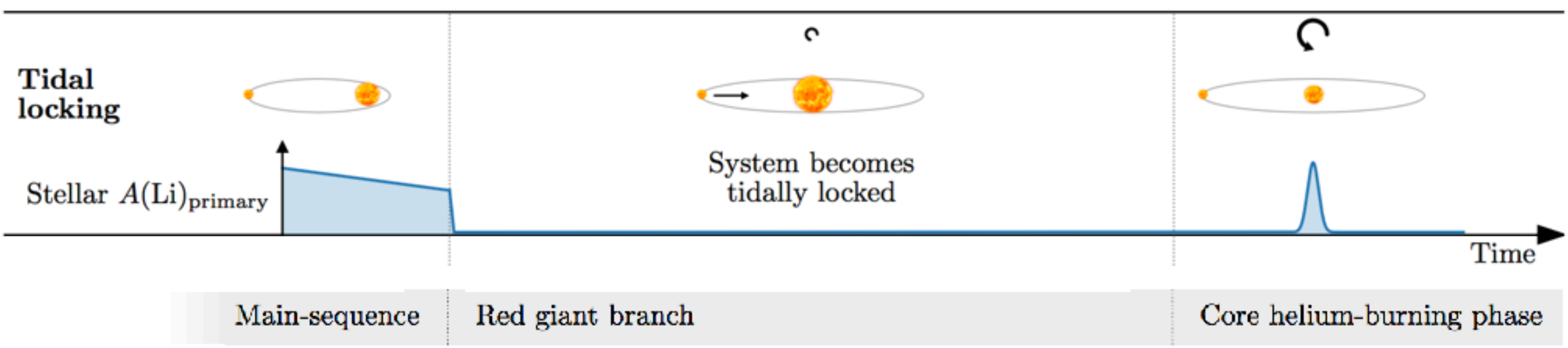
- System becomes tidally locked when the primary is on the giant branch.
- Primary reaches tip of the giant branch and starts to contract in size.



Tidal interactions by a tidally-locked binary companion

- System becomes tidally locked when the primary is on the giant branch.
- Primary reaches tip of the giant branch and starts to contract in size.
- As the primary contracts and the system is tidally locked, conservation of angular momentum demands that the primary will spin faster.

(We learned after the fact that this has been seen in main-sequence binary companions: Costa et al. 2002)

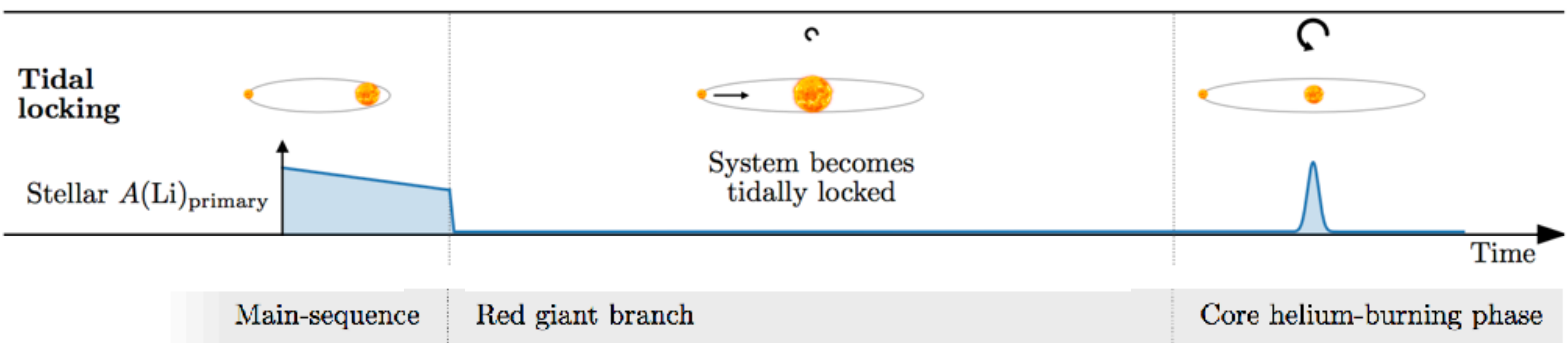


Tidal interactions by a tidally-locked binary companion

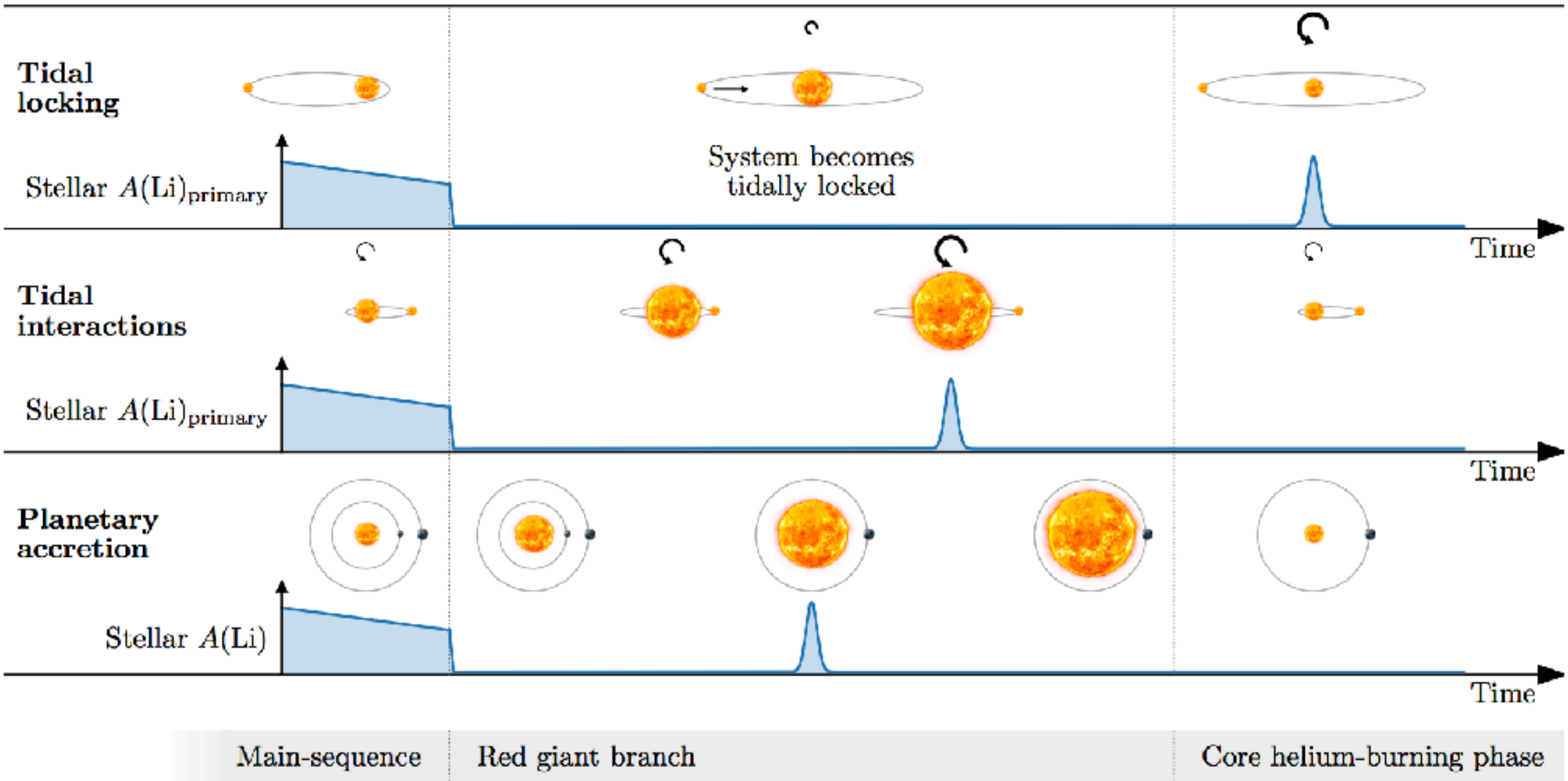
- For a 1.5 M and 1.0 M system, the resulting surface rotation is **between about 18-182 km/s** (depending on initial orbital period). 1.5 M star will expand to about 100 solar radii.

- The shortest orbital period to avoid RLOF in this system is P_{orb} = 279 days. If the system is tidally locked then $P_{spin} = P_{orb}$. This spin period corresponds to an equatorial velocity of **182 km/s**.

- If we just require that the two circularise before the primary reaches the giant branch tip, then an initial period of P_{init} = 7.64 yr is needed, which will give an equatorial velocity about **18 km/s.**



Only tidal locking can explain lithium-rich giants with helium-burning cores



Implications and predictions

- **Explains link between rotation and lithium-rich giants.**
  (e.g., 50% of fast-rotators are lithium-rich; Fekel and Balachandran 1993)

- **Explains infrared excess in some systems (previously interpreted as mass loss).**
  (e.g., de La Reza et al. 1996, 1997; Rebull et al. 2015; Kumar et al. 2015)

- **Consistent with red clump observations with high rotation and no close binary.**
  (e.g., Carney et al. 2003)

- **Consistent with no planets found within 0.6 AU around core helium-burning stars.**
  (e.g., Kunimoto et al. 2011)

Prediction:

Every core-helium burning lithium-rich giant star has a binary companion.

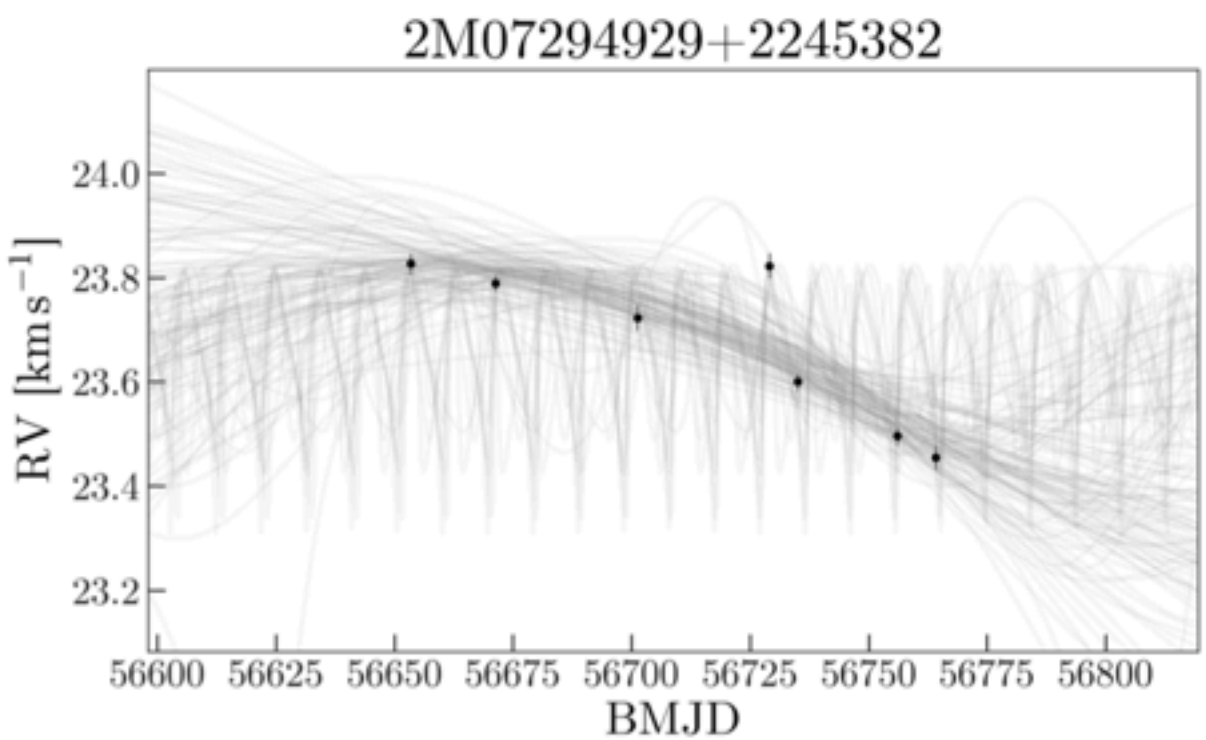
Tidal interactions between binary stars can drive lithium-production in low mass giants

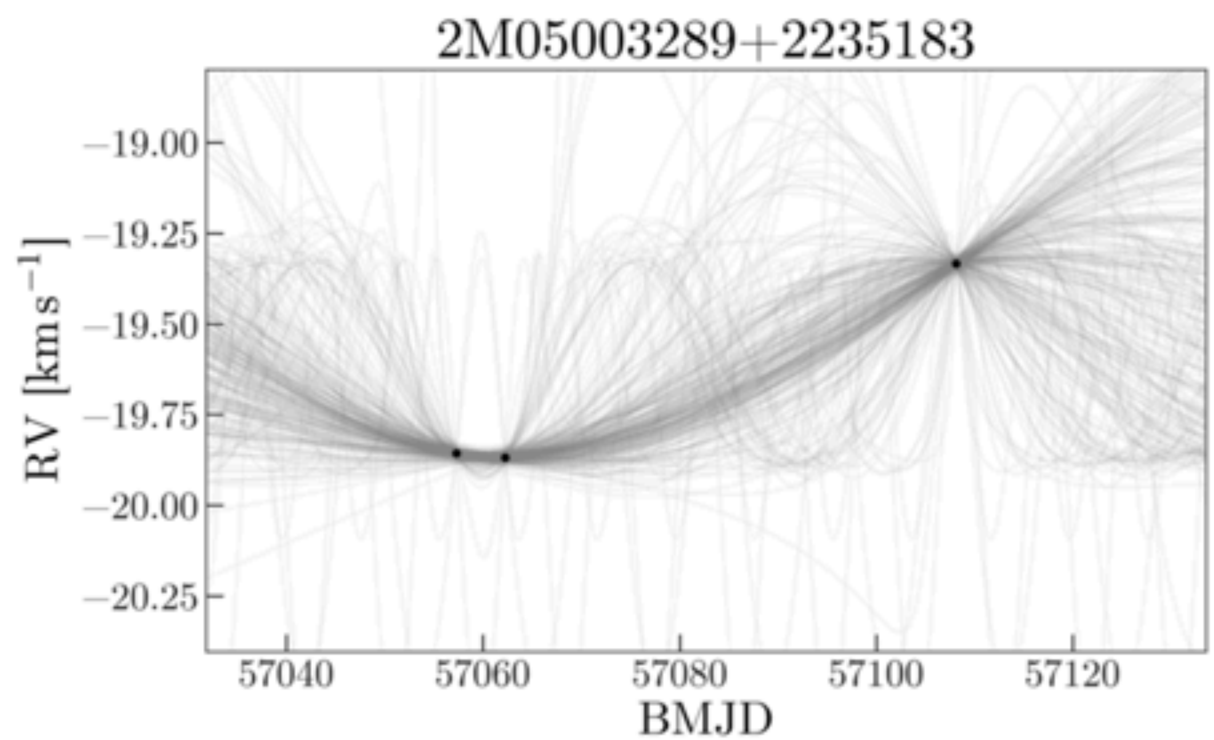
- Most lithium-rich giants have helium-burning cores, which cannot be explained by planet accretion (without significant tidal decay).
- Planet engulfment can only explain up to 20% of lithium-rich giants.
- The frequency of lithium-rich giants increases with stellar metallicity.
- Giants remain lithium-rich for only about two million years.
- Lithium production not associated with a particular stage of stellar evolution. We rule out every other proposed mechanism.

What's next?

Long-term radial velocity curves (for many stars) is expensive

(And these can have **long** orbital periods)

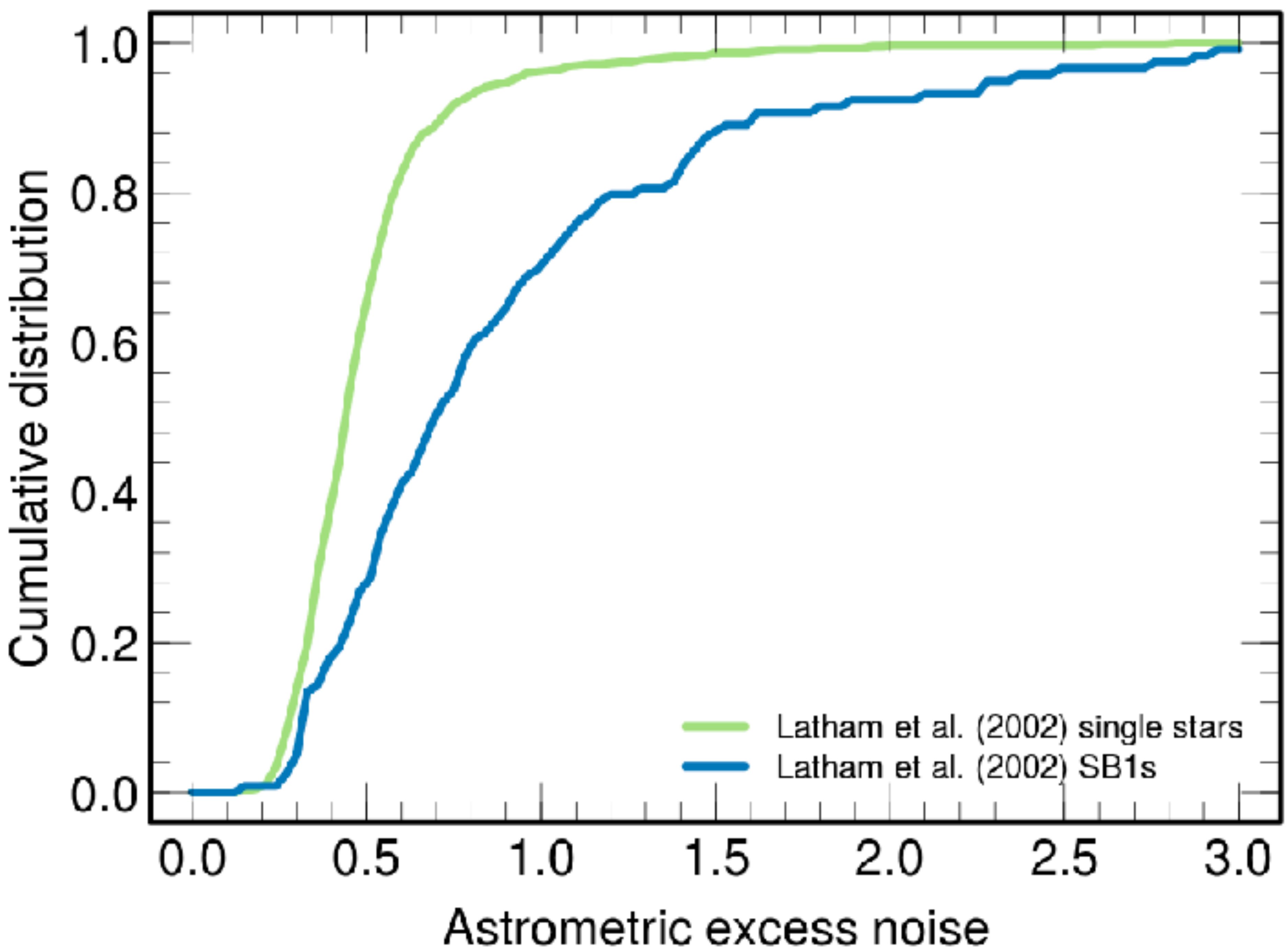




5/8 lithium-rich giants discovered serendipitously in RV survey showed binarity
(epochs — or number of epochs — not reported: Adamow et al. 2014)

A (statistical) method to test binarity

(Without needing precise radial velocity measurements over many years)

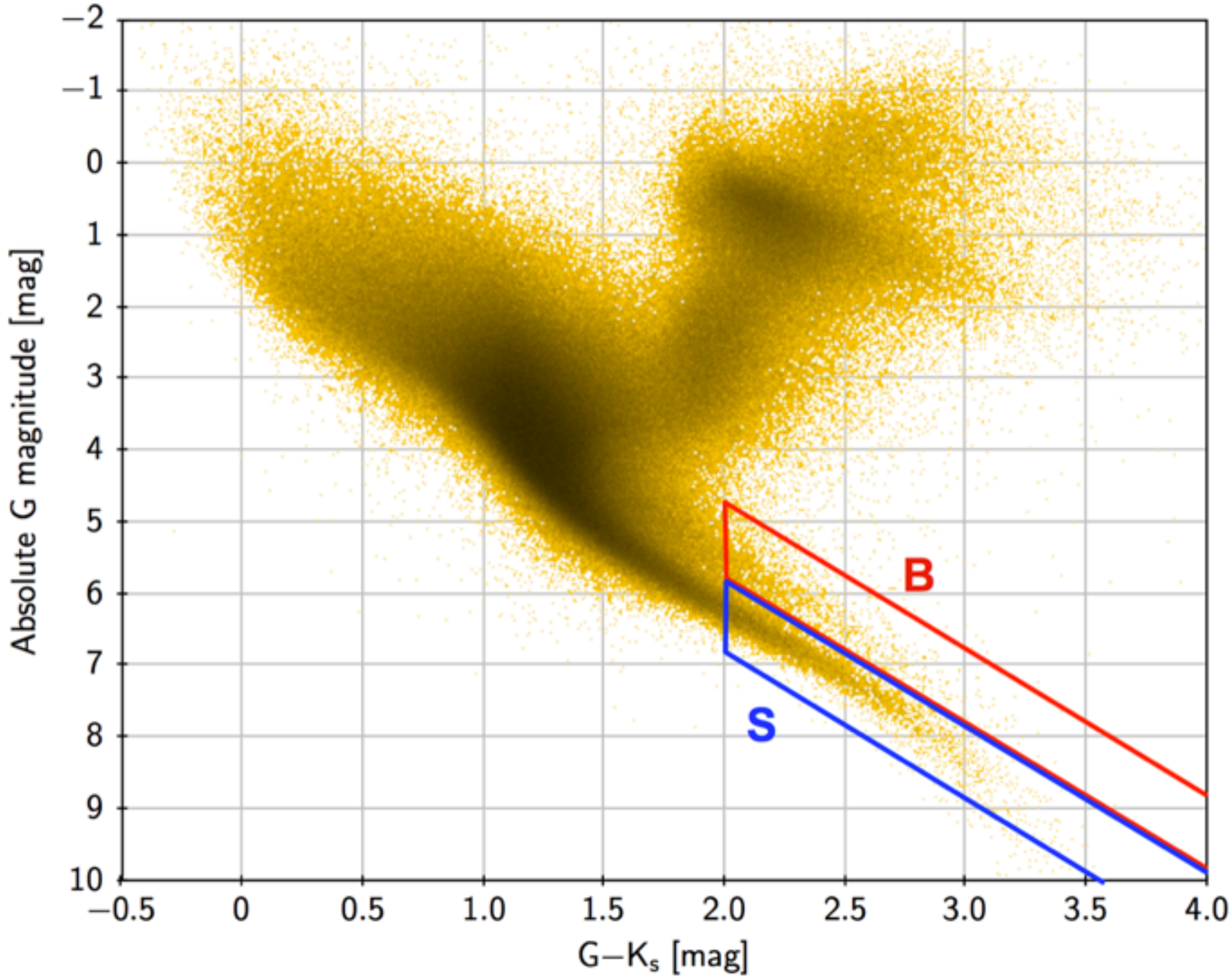


MONASH University

Andy Casey

A (statistical) method to test binarity

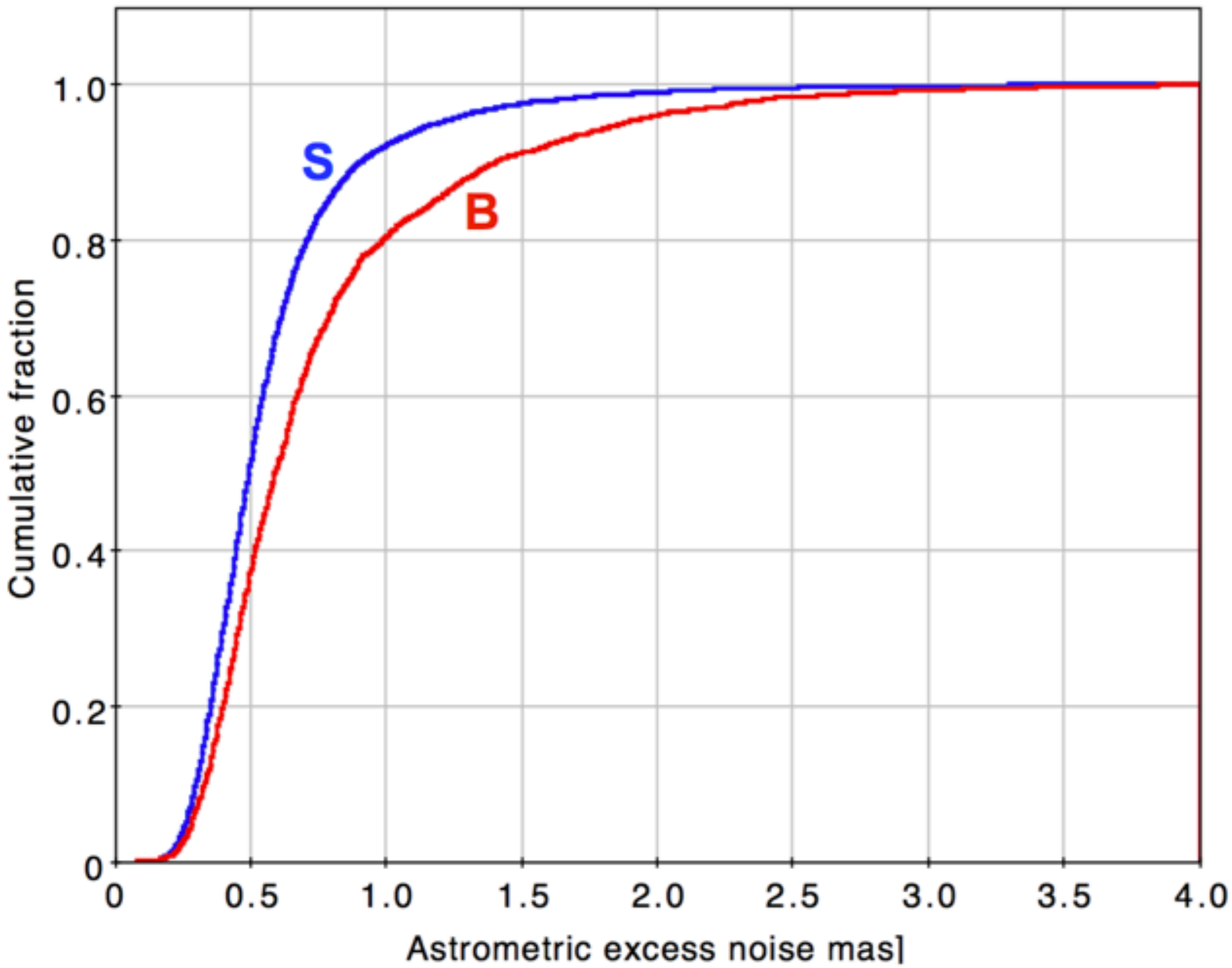
(Without needing precise radial velocity measurements over many years)



L. Lindegren (priv. comm.)

A (statistical) method to test binarity

(Without needing precise radial velocity measurements over many years)



Excess noise > 1 mas is twice as common in sample B as in S

L. Lindegren (priv. comm.)

The revolution will not be supervised

The revolution will not be supervised

- Unsupervised machine learning algorithms to find new weird classes of stars. (And find thousands of them).
- Find transformative number of weird stars (e.g., r-process stars, s-process stars, CH stars, PISN, Mg-K, Na-O).
- Find the kinds of objects that challenge/break our understanding of stellar evolution.
- Students: Kate Henkel, Alex Kemp, Brodie Norfolk, Matt Miles.

Tidal interactions between binary stars can drive lithium-production in low mass giants

- Most lithium-rich giants have helium-burning cores, which cannot be explained by planet accretion (without significant tidal decay).
- Planet engulfment can only explain up to 20% of lithium-rich giants.
- The frequency of lithium-rich giants increases with stellar metallicity.
- Giants remain lithium-rich for only about two million years.
- Lithium production not associated with a particular stage of stellar evolution. We rule out every other proposed mechanism.

BONUS ROUND

(Select your question)

- Projected rotational velocities
- Claims of infrared excess
- On sky distribution of lithium-rich giants
- Rediscoveries of known lithium-rich giants
- One component model with 10^4 year timescale
- Relative weighting of two component models
- Young stars, H-alpha emission, etc
- Galactic enrichment of lithium in the Milky Way

Rotational velocities summary

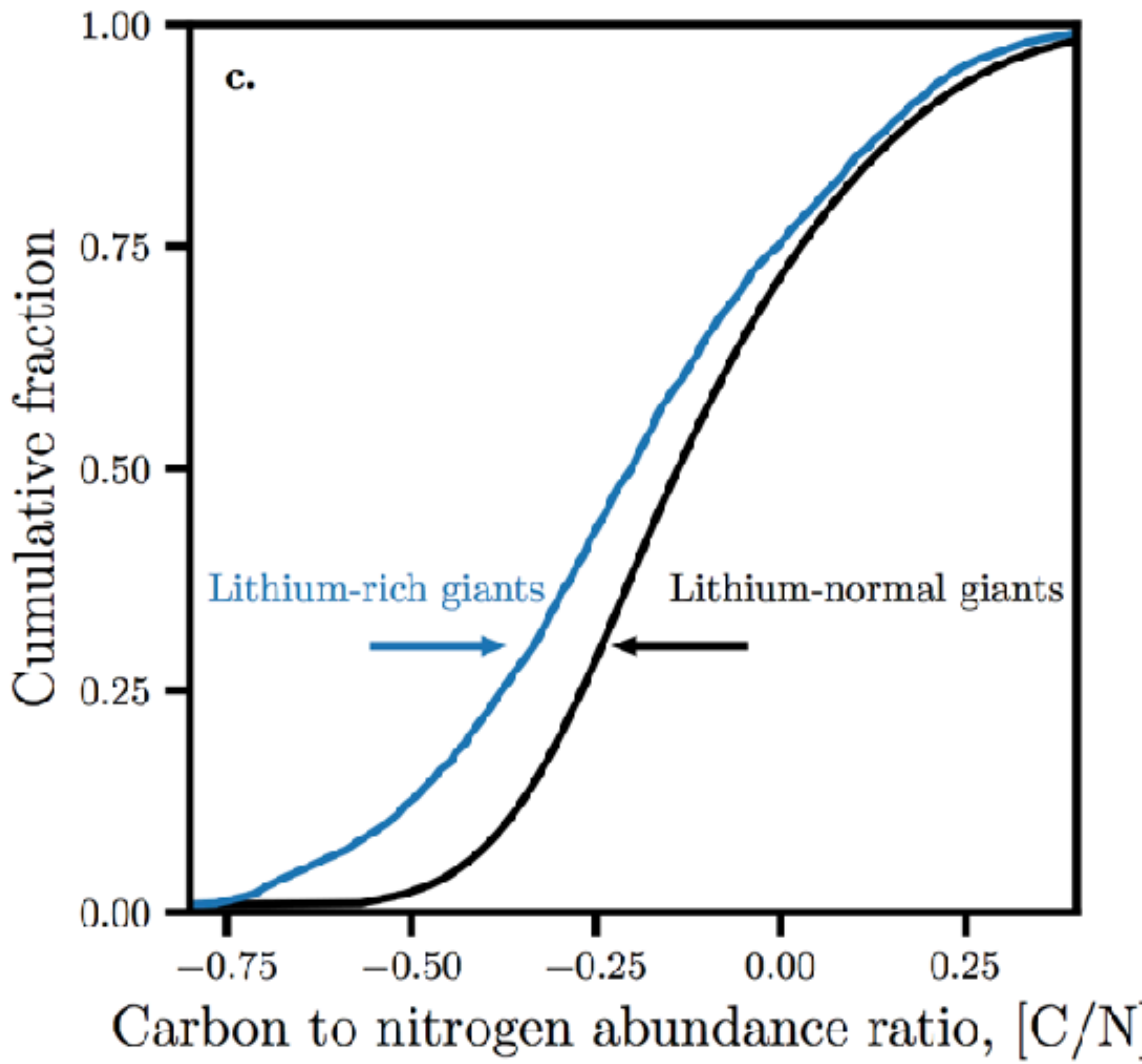
- Only projected rotational velocities **above 120 km/s** can be measured from LAMOST spectra. **(Trust me: we really, really tried).**

- **103 of our lithium-rich giants appear in Frasca et al. (2016).** Of these, 3/103 have projected rotational velocities above 120 km/s: between 150-260 km/s.

- **140 of our lithium-rich giants were observed as part of APOGEE.** Only 5 of 140 have vsini measurements, and those values range from 16 to 76 km/s.

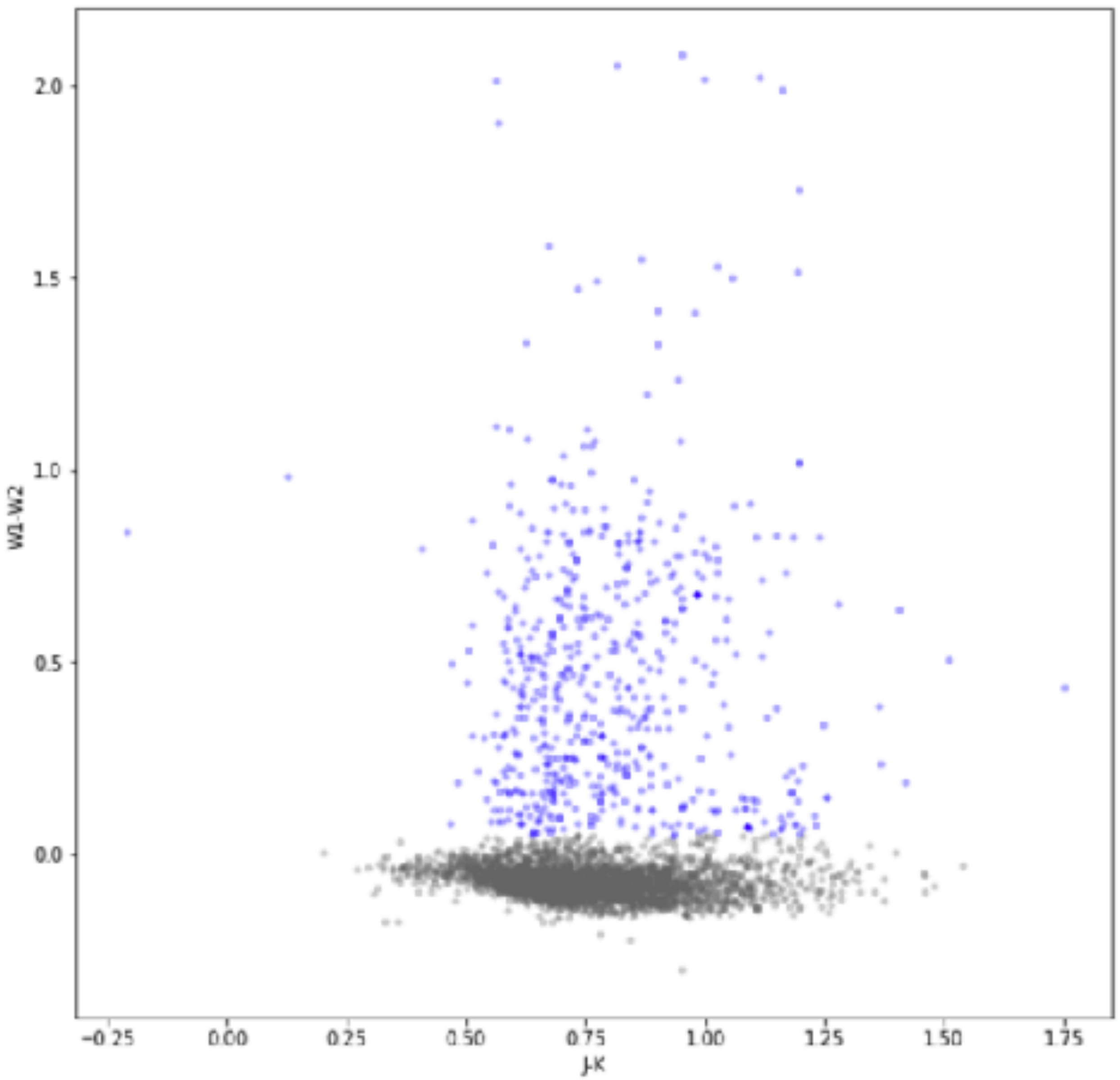
- **13 lithium-rich giants were also observed by RAVE.** 11 of those 13 have vsini measurements, which range from 20 to 41 km/s.

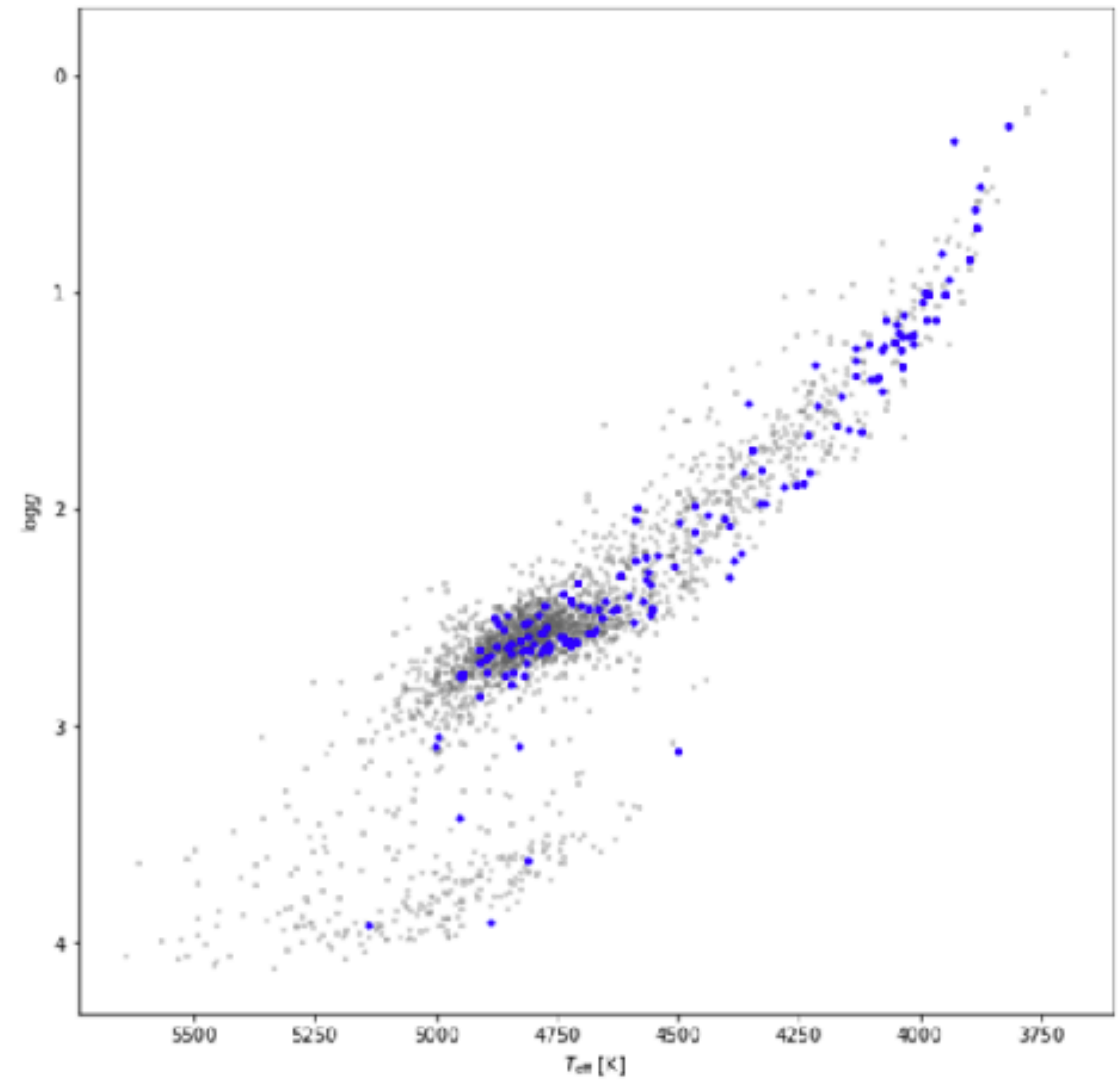
Lithium-rich giants are depleted in [C/N], consistent with internal mixing



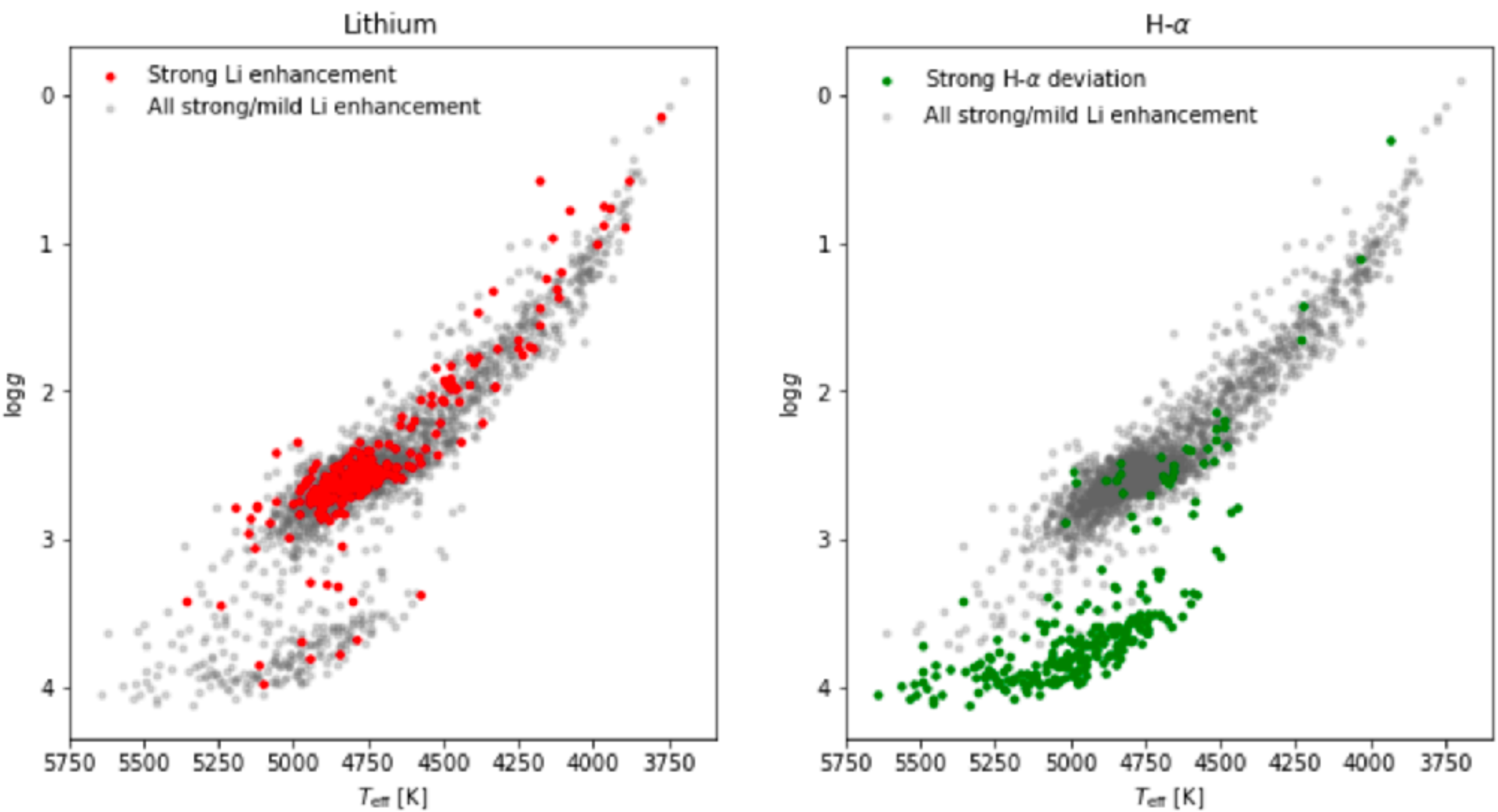
First time **any other abundance signature** observed among lithium-rich giants.

Claims of infrared excess



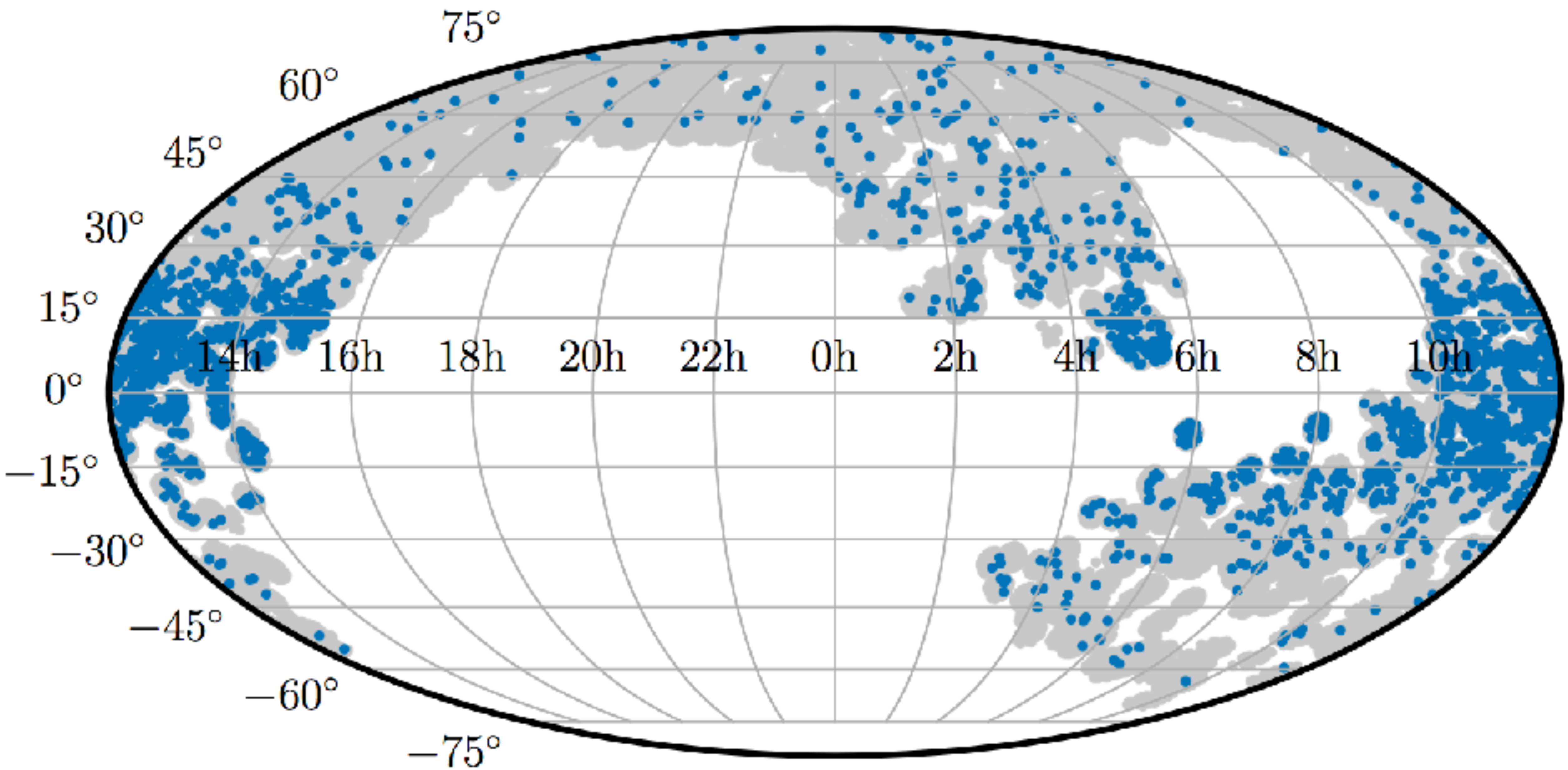


Young stars and H-alpha emission



Sky distribution of lithium-rich giant stars

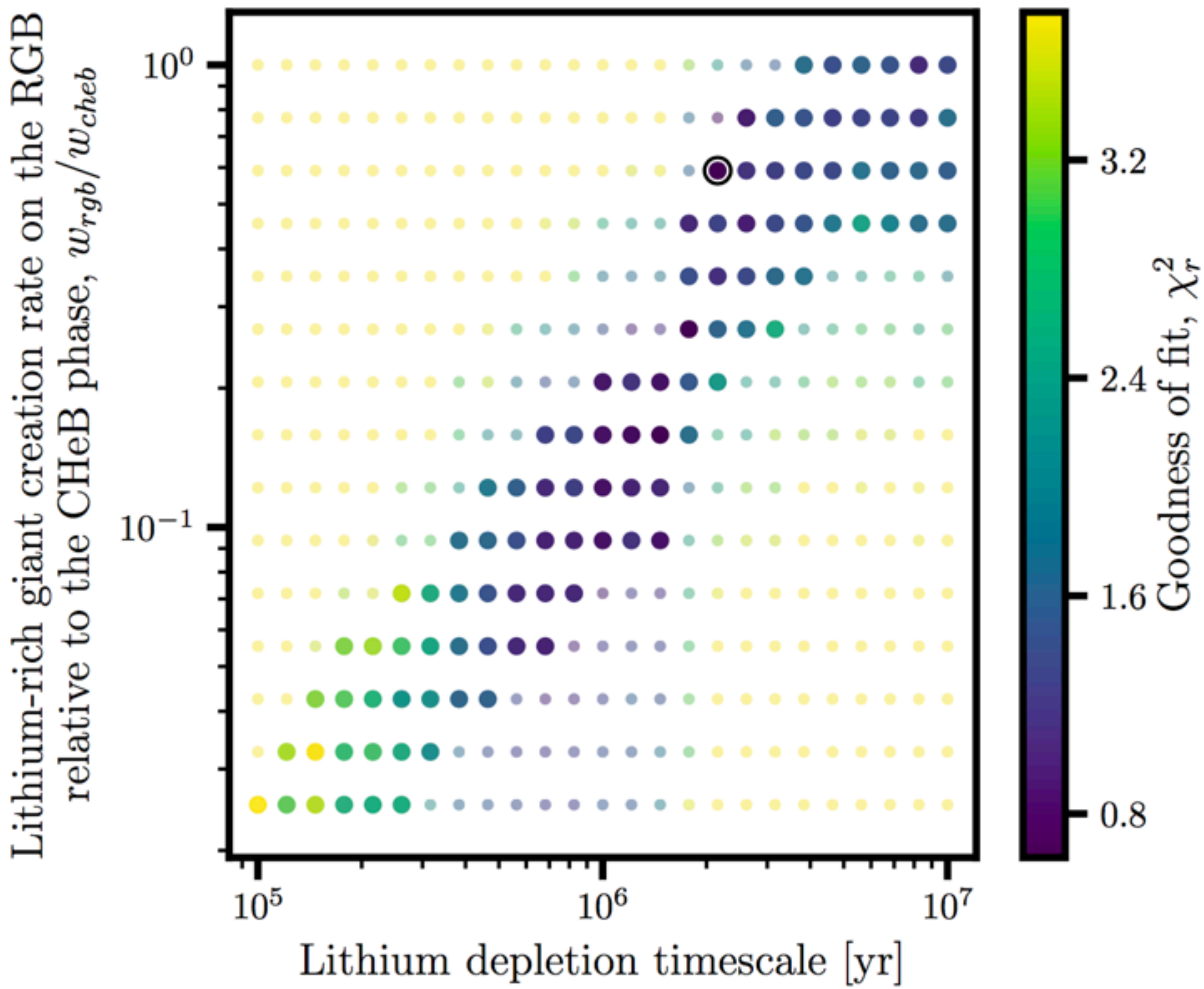
(Galactic coordinates)



Note: Some lithium-rich giant candidates excluded because they had H-alpha emission and were located in known star-forming regions (e.g. young stars!).

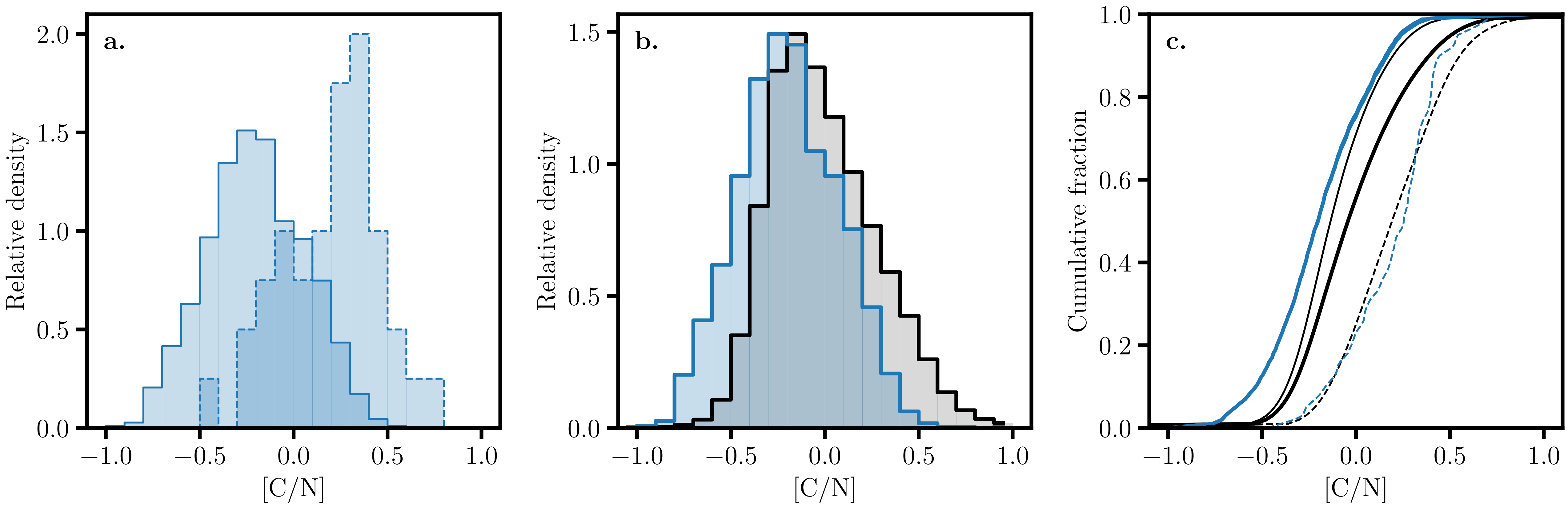
Rediscoveries of known lithium-rich giants

We find that two of our lithium-rich giant stars are rediscoveries[3]: SDSS J0652+4052 and SDSS J0654+4200. The stellar parameters and lithium abundances ($T_{\rm eff}$, $\log_{10} g$, [Fe/H], $A(\rm Li)$) we derive are all consistent within the joint 2σ uncertainty between this work and the literature, with most measurements agreeing within 1σ of the quoted uncertainty in either study. In particular we find $A(\rm Li) = 3.26 \pm 0.08$ for SDSS J0652+4052, 0.04 below the literature value, and we find $A(\rm Li) = 3.47 \pm 0.19$ for SDSS J0654+4200, in good agreement with the previously reported $A(\rm Li) = 3.3 \pm 0.2$. We also note that LAMOST obtained a high signal-to-noise ratio spectrum for another known lithium-rich giant star (SDSS J0304+3823)[3], but this was not included in our sample because the residuals surrounding the lithium doublet at 6707 Å reached 2.7σ and did not meet our 3σ threshold for detection.

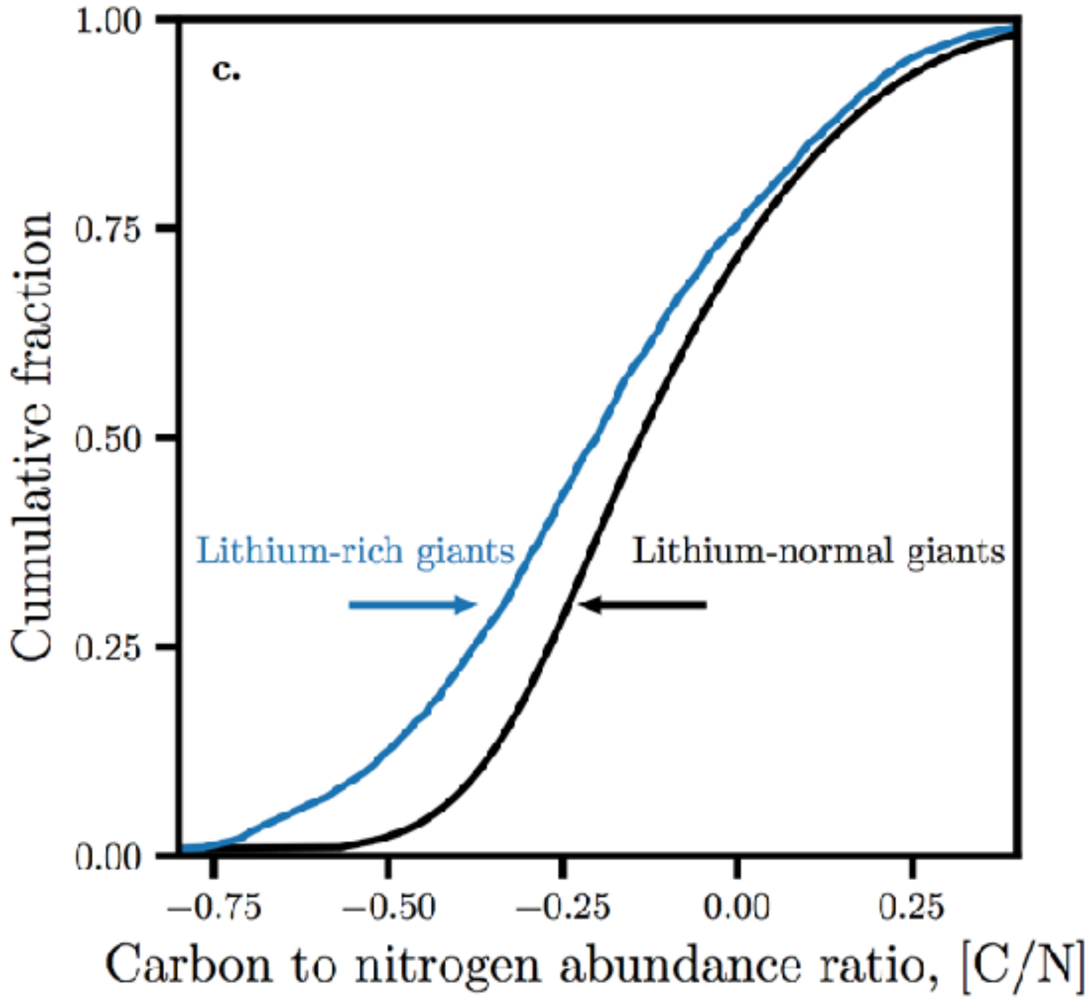


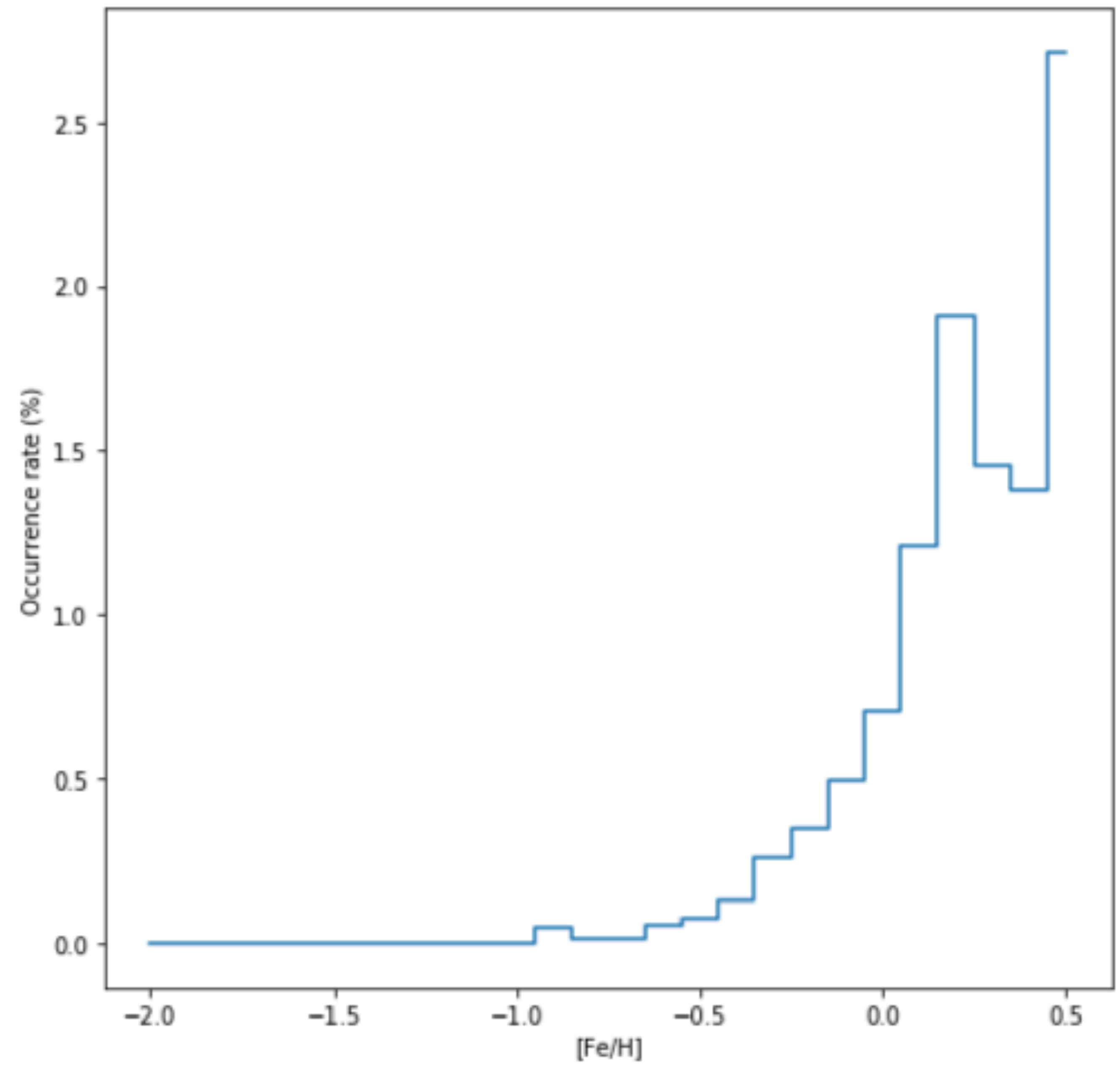
Lithium-rich giant creation rate on the RGB relative to the CHeB phase, w_{rgb}/w_{cheb}
10^0
10^{-1}
10^5
10^6
10^7
Lithium depletion timescale [yr]
Goodness of fit, χ^2_r
3.2
2.4
1.6
0.8

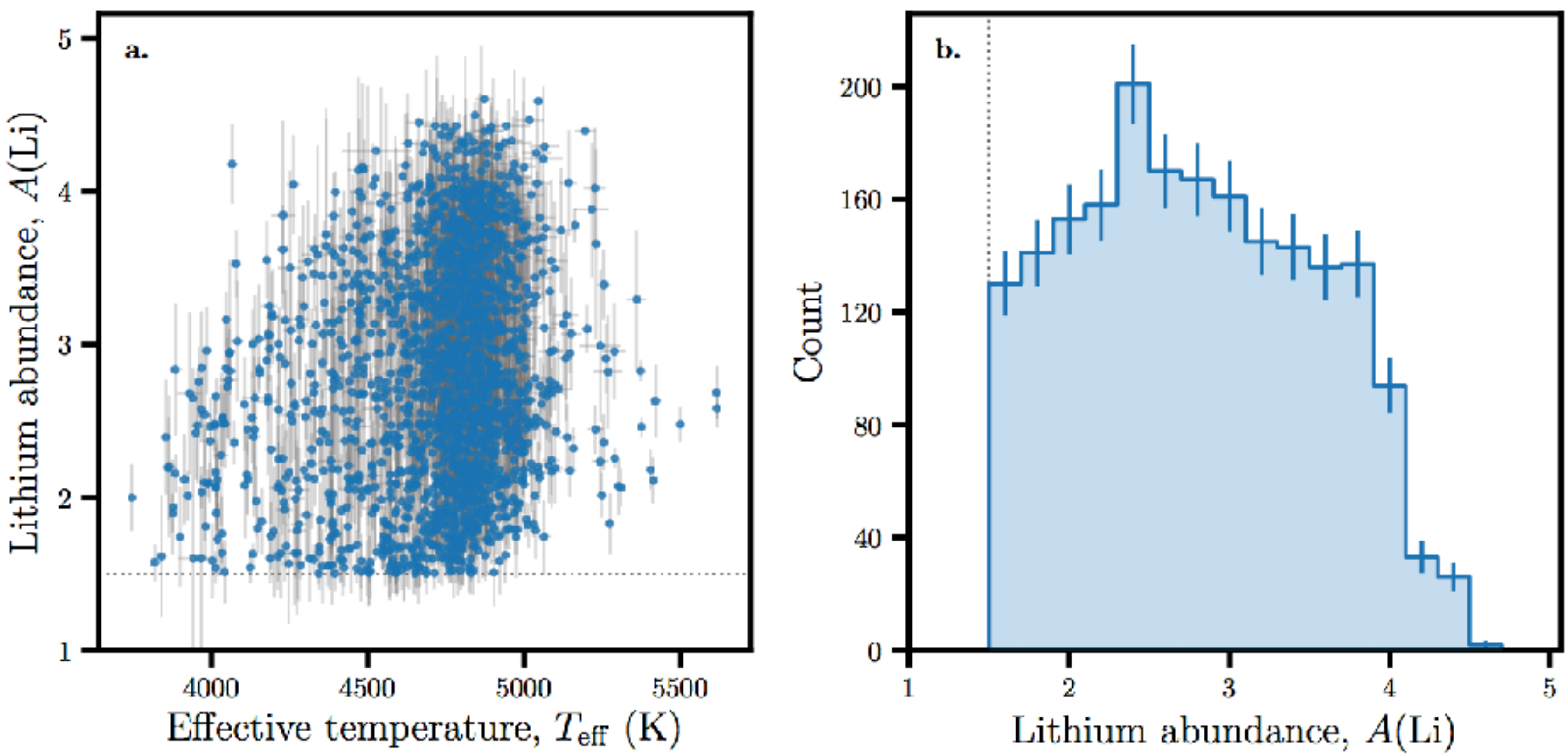
Carbon to nitrogen abundance ratios

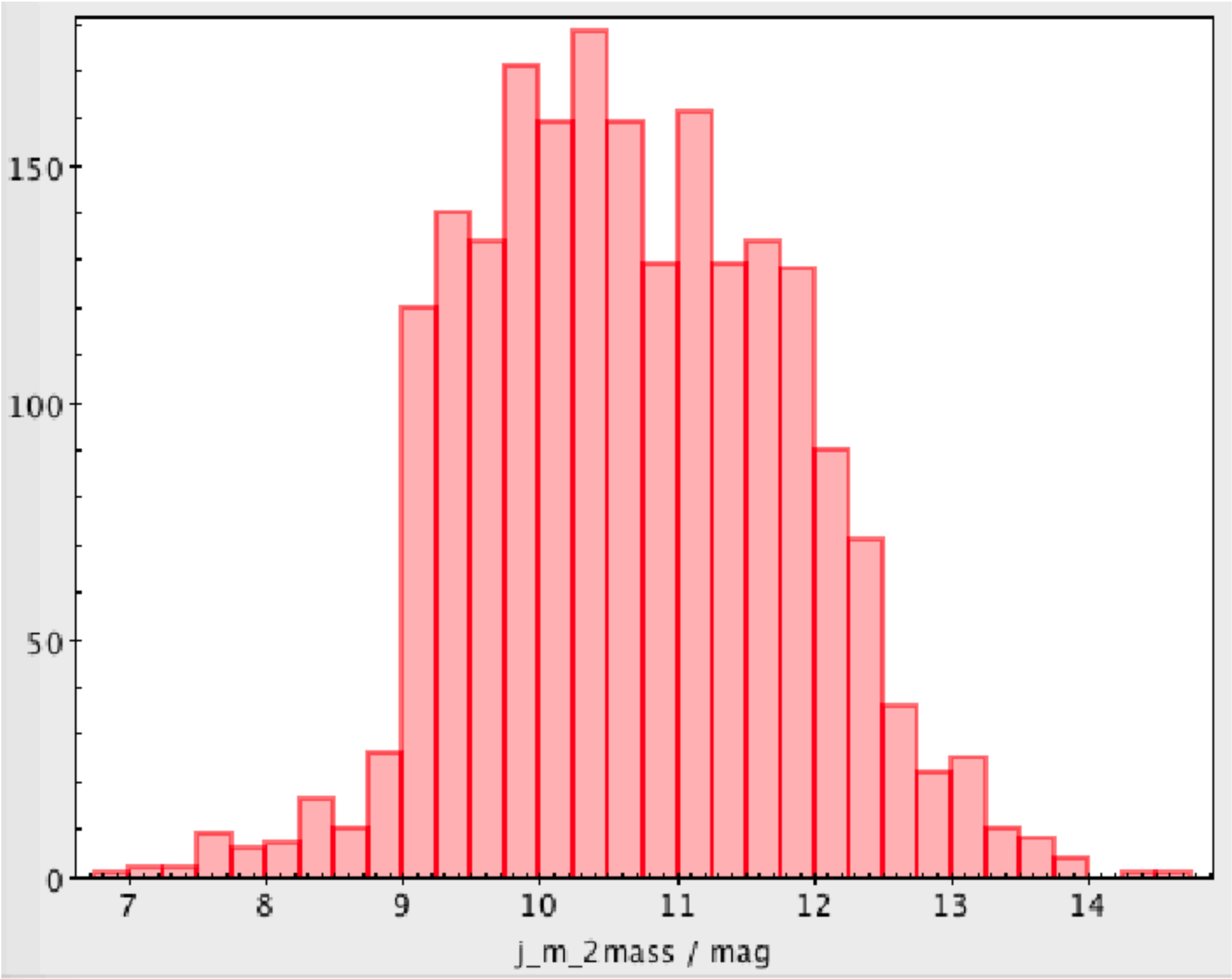


Stars that used to be lithium-rich






a.
Lithium abundance, A(Li)
Effective temperature, $T_{\rm eff}$ (K)
b.
Count
Lithium abundance, A(Li)



150
100
50
0
7
8
9
10
11
12
13
14
j_m_2mass / mag