Signatures of Planet Formation in the Chemical Composition of Stars? A New Statistical Approach

Jacob Nibauer*, Eric J. Baxter, Bhuvnesh Jain, Rachael L. Beaton, Johanna K. Teske

University of Pennsylvania*

jnibauer@sas.upenn.edu

arxiv: *2010.07241*
ApJ 907 116

Image: PIA06939 The Rocky World of Young Planetary Systems

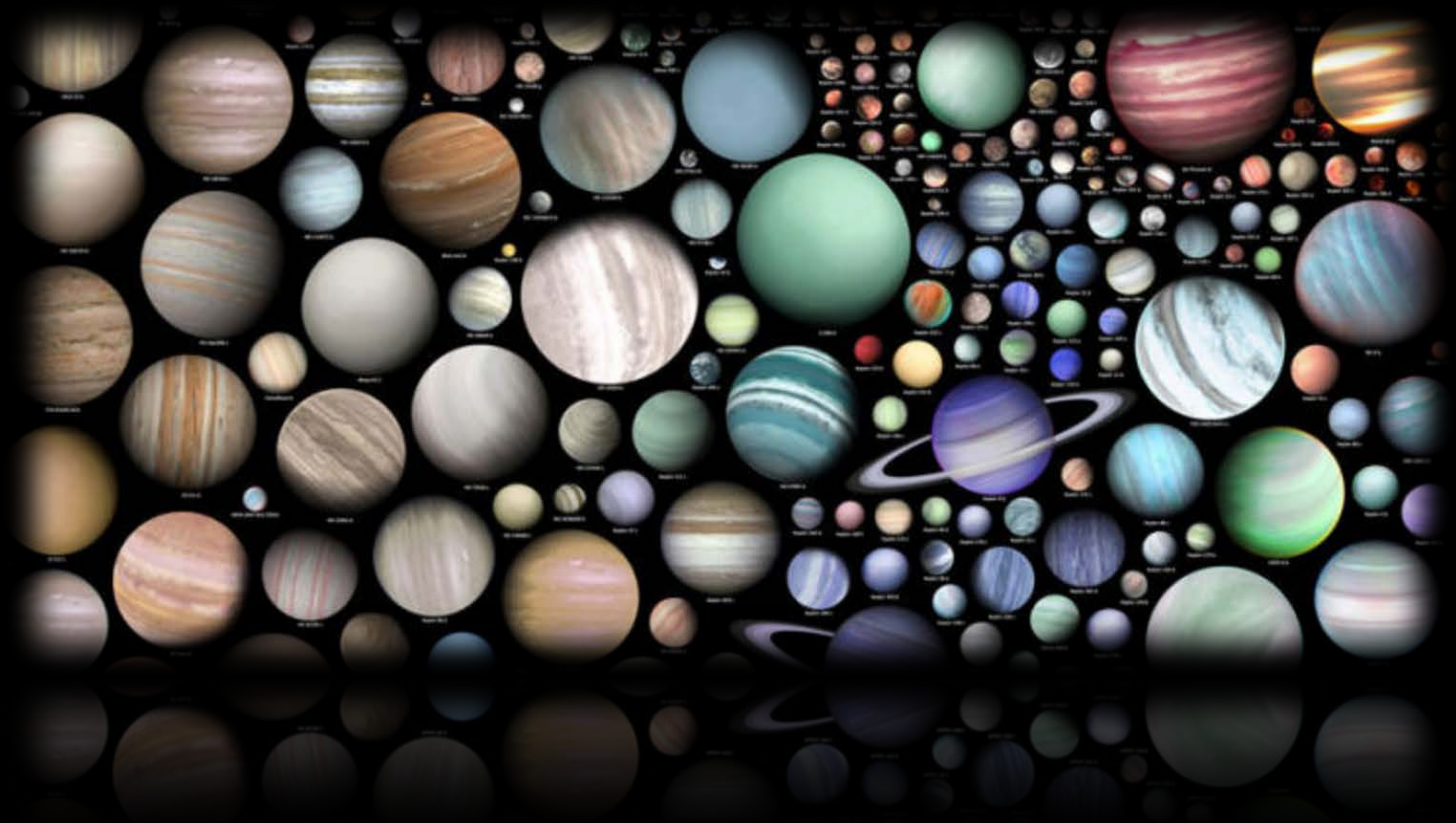
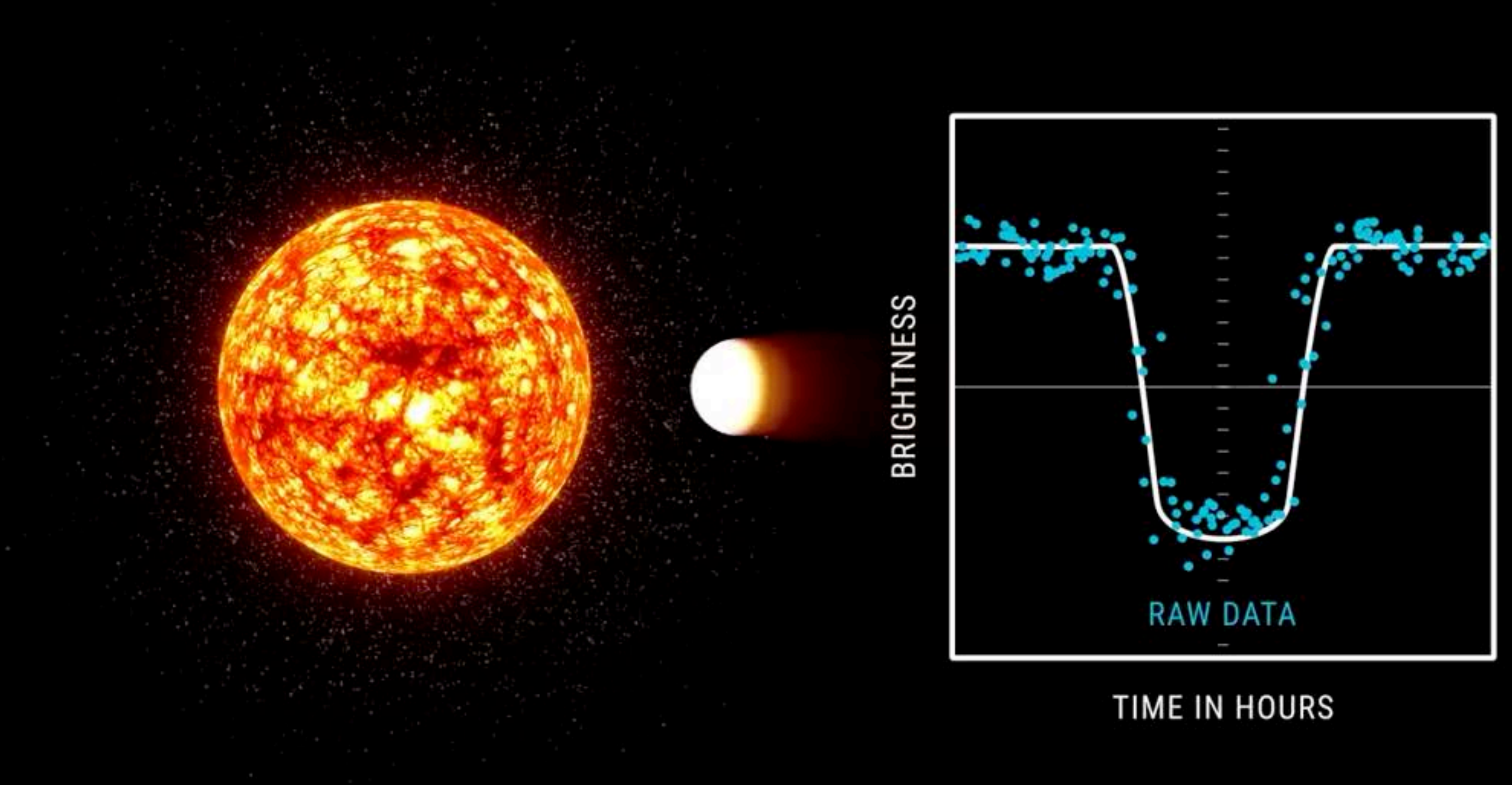
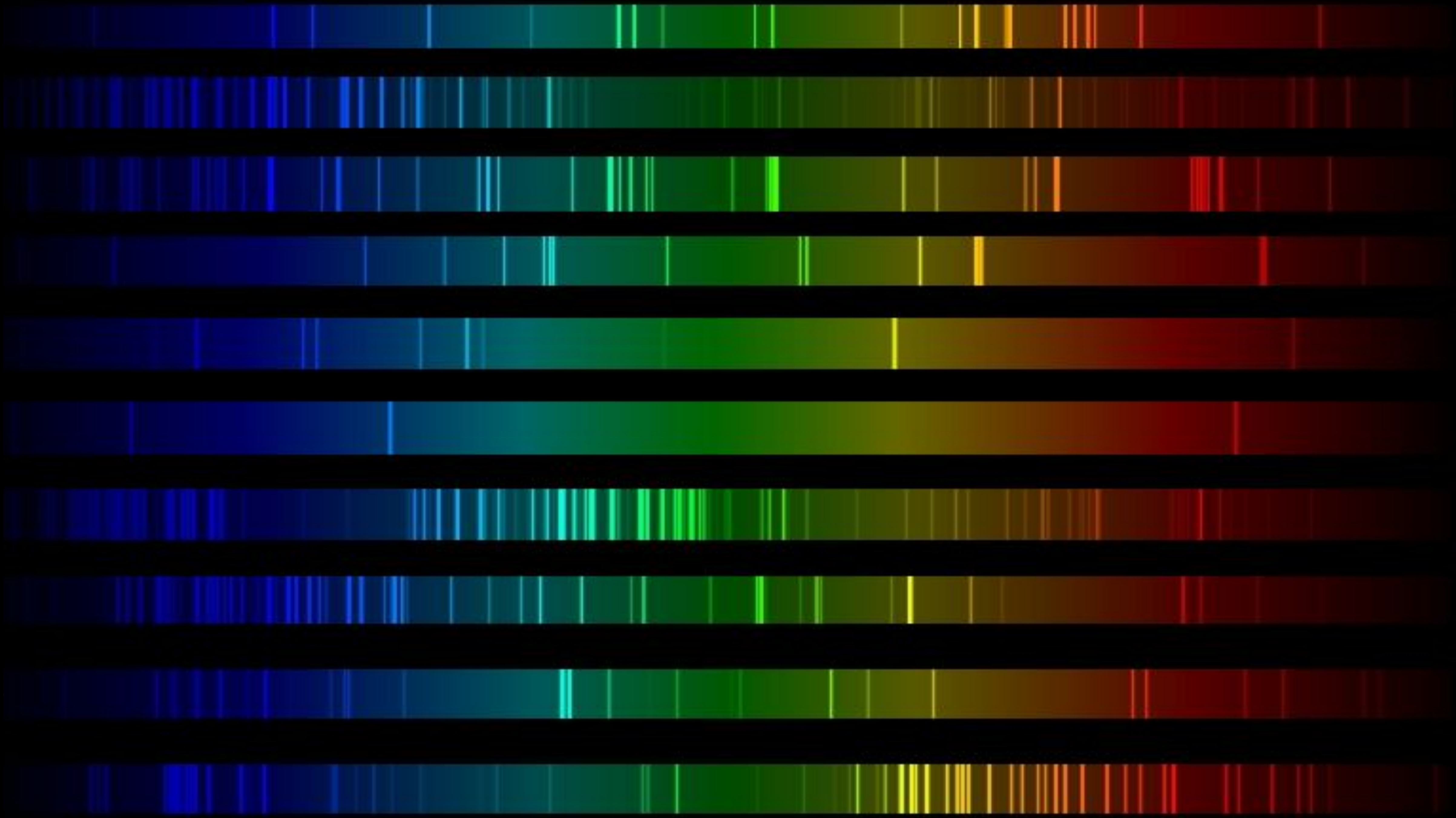


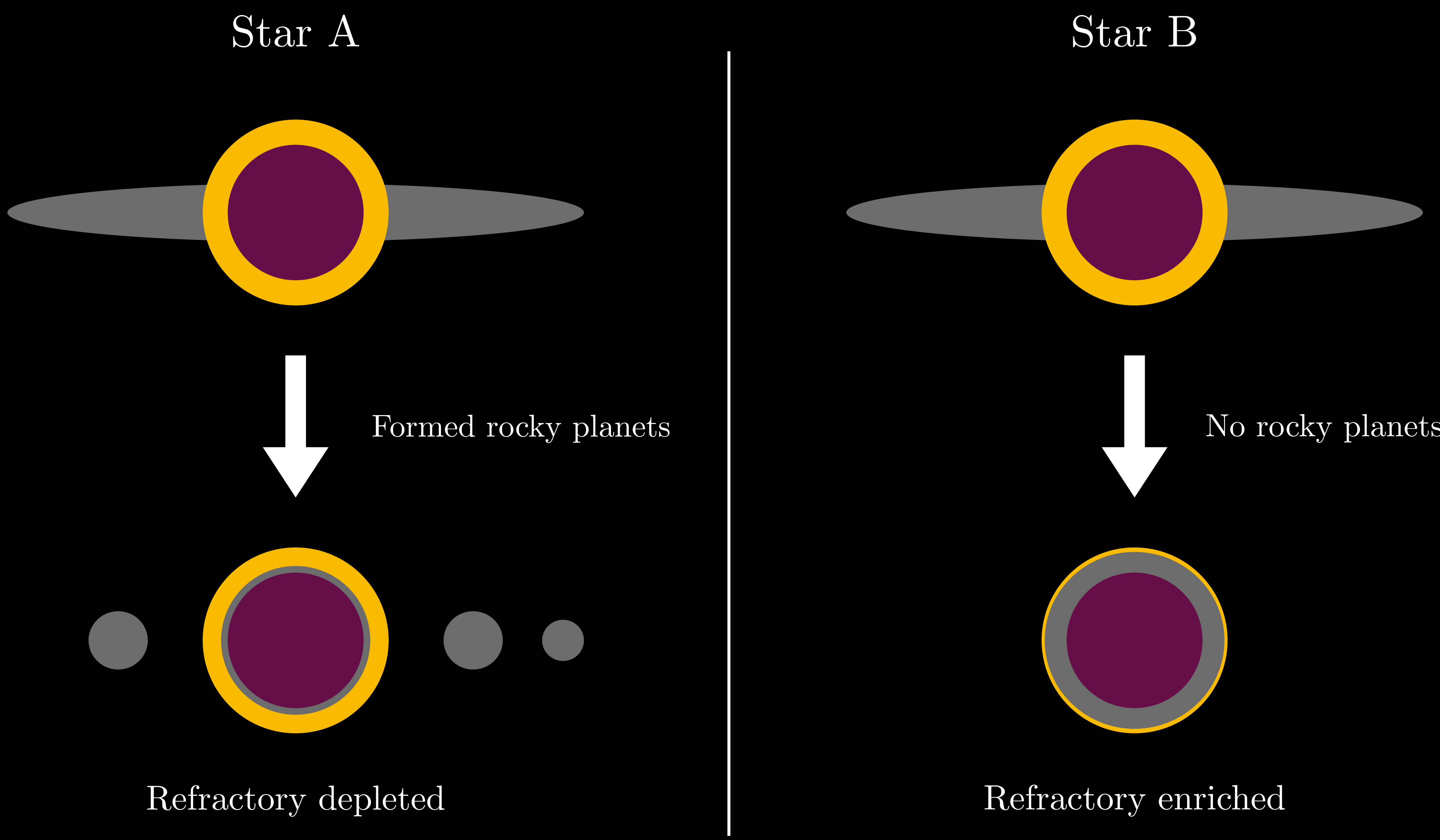
Image Credit: Halcyon Maps



Video Credit: NASA Video



Fingerprints of Planet Formation
in the Chemical Composition of Stars?



Meléndez et al. 2009: Sun appears refractory depleted relative to $\sim$ 12 Sun-like stars

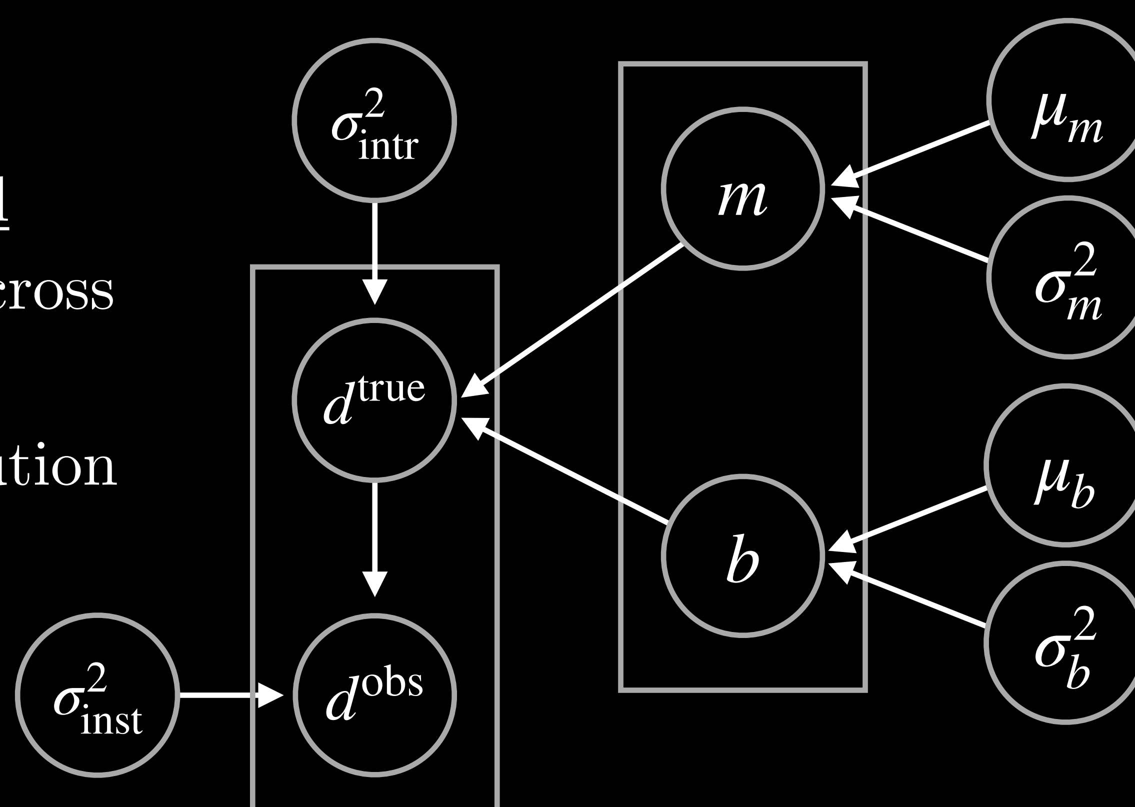
Larger Samples Needed!

Graphic adapted from Ivan Ramírez

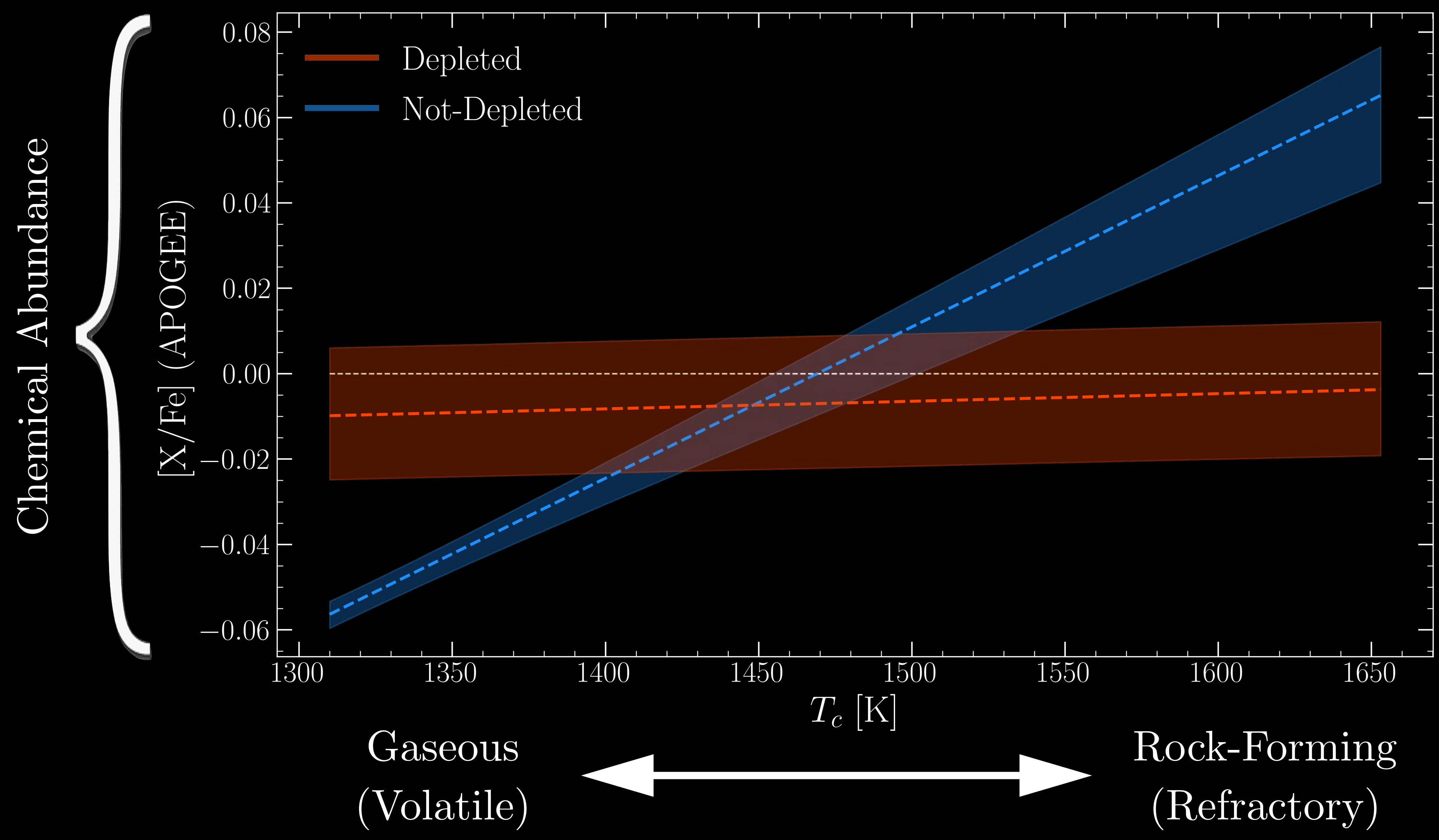
- Spectral measurements for over 450,000 stars
- APOGEE Stellar Parameter and Abundance Pipeline (ASPCAP)
  - Chemical abundances for ~ 20 elements

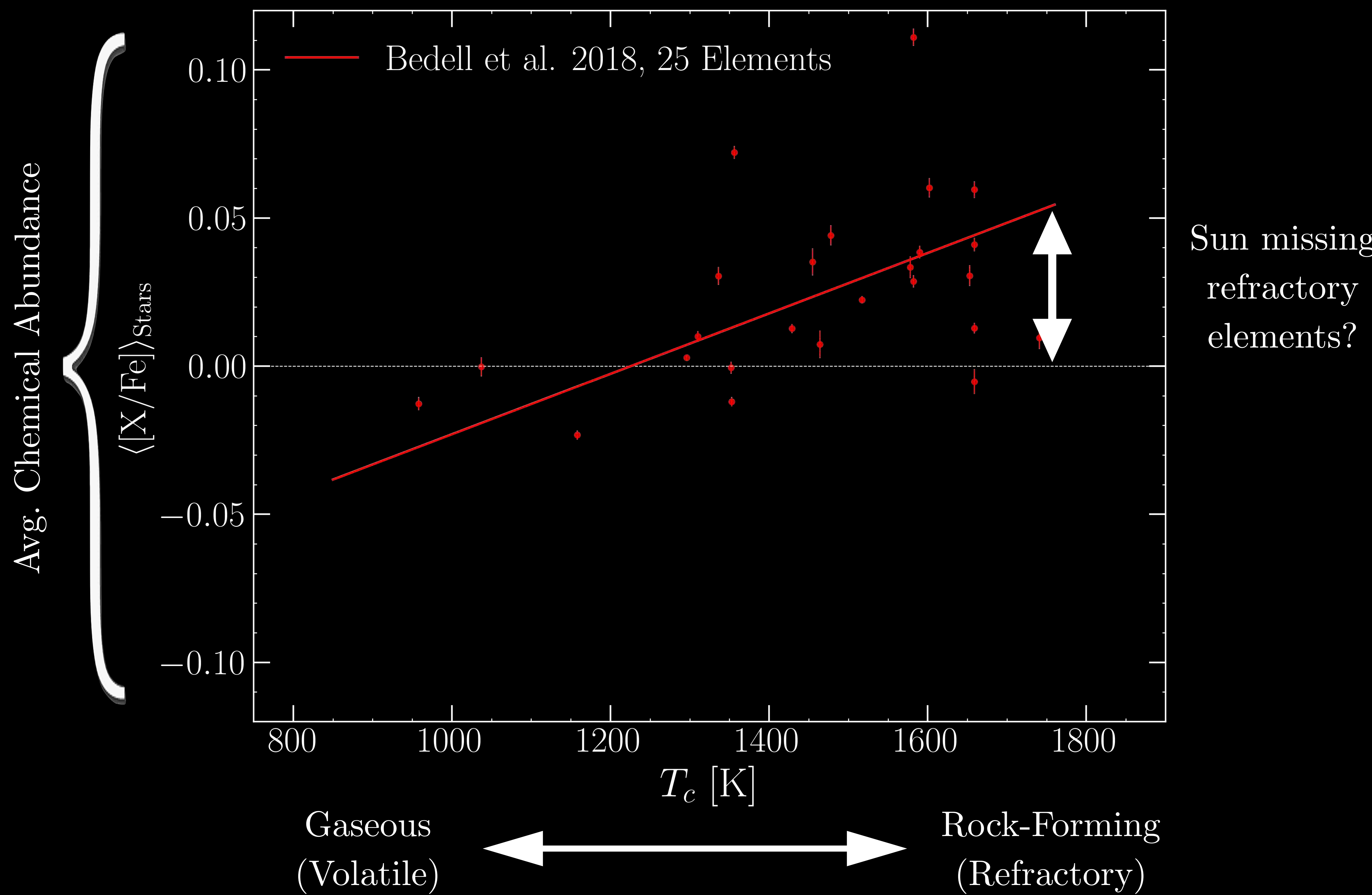
<u>Hierarchical Bayesian Model</u>

- Combines informations across many stars/elements
- Constrains global distribution of chemical abundances
- Data-driven



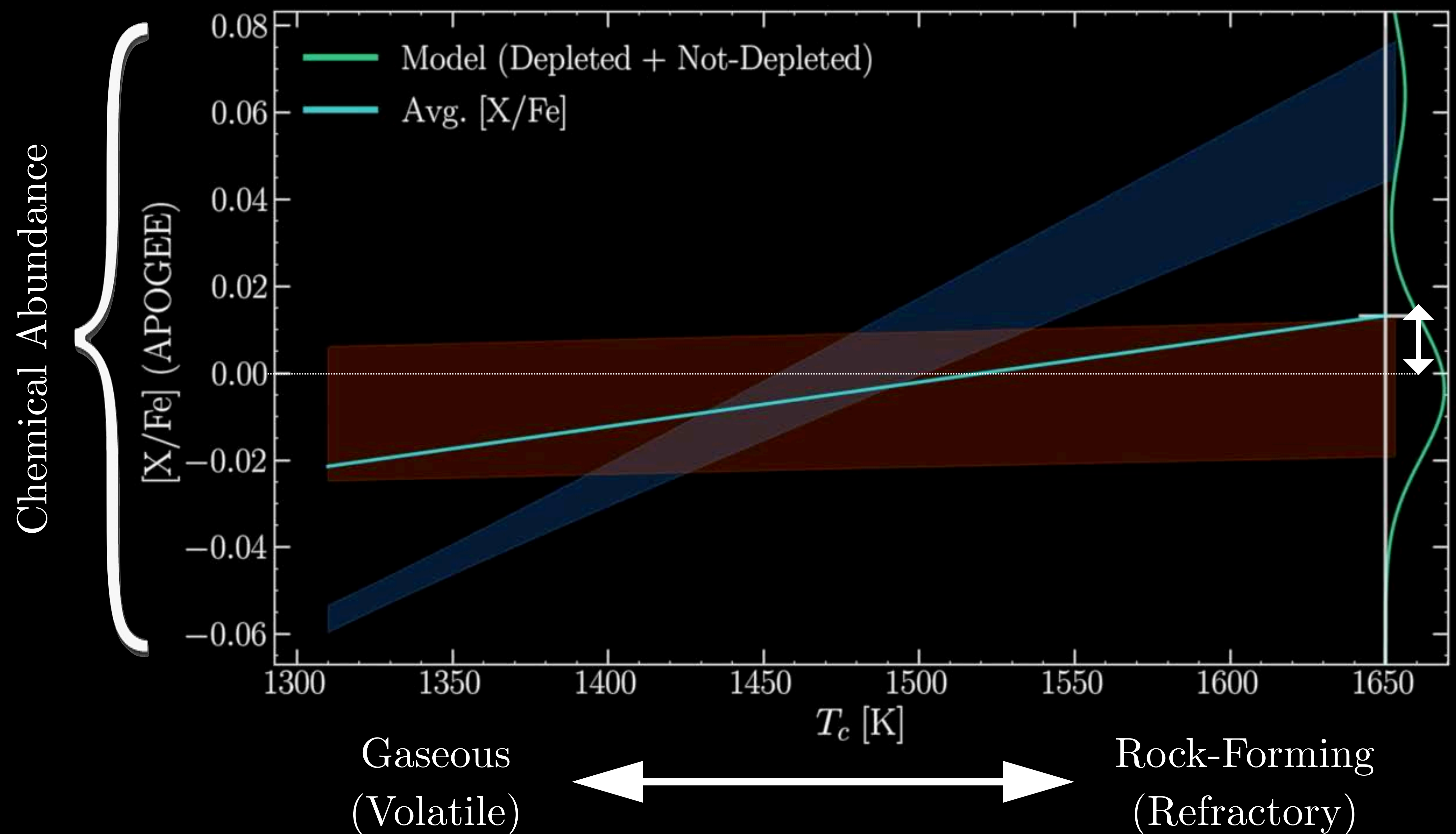
Fraction of stars in Depleted group: $> 60\,\%$, including the Sun





Bedell et al. 2018, 25 Elements
0.10
0.05
0.00
−0.05
−0.10
800
1000
1200
1400
1600
1800
T_c [K]
$\langle[X/Fe]\rangle_{Stars}$
Avg. Chemical Abundance
Sun missing refractory elements?
Gaseous (Volatile)
Rock-Forming (Refractory)

Not-Depleted population shifts the mean from low to high chemical abundances



Sun missing refractory elements? Maybe not!

- Hierarchical modeling approach
  - High significance constraint from a large sample of individually low signal-to-noise measurements
- Evidence for multiple stellar populations:
  - One with an abundance pattern roughly in line with the Sun
  - Another which is enhanced in refractory elements
- The Sun's chemical abundance pattern may not actually be anomalous
  - Sun is a member of a majority population (>60%), not far off from estimates for the fraction of stars with rocky planets
  - Two populations may be related to the presence/absence of rocky planets

Future Work

What is the origin of the T_c trends?

Goals:

1. Cross-match with *Kepler* and *TESS* exoplanet hosts
   - Identify population membership (depleted v.s. not-depleted)
2. Connection to binarity?
   - Binary fraction $\sim 10\,\%$ for this sample (Price-Whelan+2020)
3. Refractory enrichment: signature of planetary engulfment?
4. Extend beyond the Sun-like sample + more elements!

jnibauer@sas.upenn.edu

Thank You!

Statistics of the Chemical Composition of Solar Analog Stars and Links to Planet Formation

Jacob Nibauer,[1] Eric J. Baxter,[2] Bhuvnesh Jain,[1] Jennifer L. van Saders,[2] Rachael L. Beaton,[3,4,*] and Johanna K. Teske[5]

[1] *Center for Particle Cosmology, Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA*
[2] *Institute for Astronomy, University of Hawai'i, 2680 Woodlawn Drive, Honolulu, HI 96822, USA*
[3] *Department of Astrophysical Sciences, 4 Ivy Lane, Princeton University, Princeton, NJ 08544, USA*
[4] *The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101*
[5] *Earth and Planets Laboratory Carnegie Institution of Washington, 5241 Broad Branch Road, N.W., Washington, DC 20015*

ABSTRACT

The Sun has been found to be depleted in refractory (rock-forming) elements relative to nearby solar analogs, suggesting a potential indicator of planet formation. Given the small amplitude of the depletion, previous analyses have primarily relied on high signal-to-noise stellar spectra and a strictly differential approach to determine elemental abundances. We present an alternative, likelihood-based approach that can be applied to much larger samples of stars with lower precision abundance determinations. We utilize measurements of about 1700 solar analogs from the Apache Point Observatory Galactic Evolution Experiment (APOGEE-2) and the stellar parameter and chemical abundance pipeline (ASPCAP DR16). By developing a hierarchical mixture model for the data, we place constraints on the statistical properties of the elemental abundances, including correlations with condensation temperature and the fraction of stars with refractory element depletions. We find evidence for two distinct populations: a depleted population of stars that makes up the majority of solar analogs including the Sun, and a not-depleted population that makes up between $\sim 10 - 30\%$ of our sample. We find correlations with condensation temperature generally in agreement with higher precision surveys of a smaller sample of stars. Such trends, if robustly linked to the formation of planetary systems, provide a means to connect stellar chemical abundance patterns to planetary systems over large samples of Milky Way stars.

Nibauer et al. 2021, ApJ | arxiv: 2010.07241

jnibauer@sas.upenn.edu