# How do Stellar Surveys Like GALAH Improve Our Understanding of Planetary Systems?

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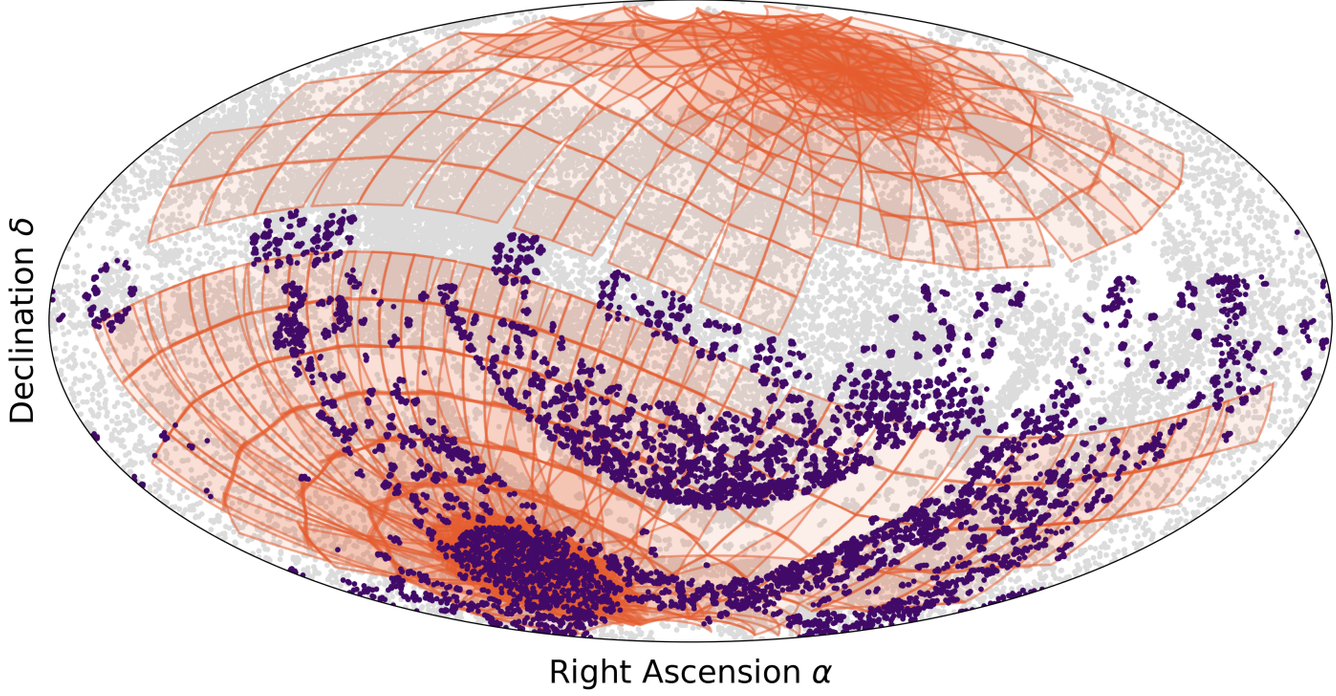
So here's the low down. You've just sat down at your desk on a Monday morning. The smell of coffee permeates through the room as you slowly scroll through the hundreds of emails you've received during the weekend. But one single notification stands out… TESS has just dropped some hot off-the-press candidates. Some are located in the Southern sky, your favourite hemisphere! But, you want to know more about the physical and chemical characteristics of these candidate host's... where do you begin to look? Well, we've got you fam!

I'm going to try and summarise the last four years of my life in one interactive poster… so strap yourself in. If you're viewing the PDF of this interactive poster, I highly recommend checking out the website version of it instead (https://jake-clark.github.io/#TESS21).

## WHY GALAH? WELL, WHY NOT!

Involving fewer shovels and more optical fibres, galactic archeology is a growing sub-field in astronomy, aiming to better understand the formation and evolution of our home galaxy, the Milky Way. Galactic archeology surveys are huge stellar surveys, with rich data sets containing both the physical and chemical properties of stars contained within our galaxy (and sometimes even beyond).

As you can see with the plot below, the overlap between the TESS sectors, in orange, and stars observed with Australia's Galactic Archeology with HERMES survey (GALAH), in purple, is incredible. So why not utilise these big surveys to further characterise current and future TESS planetary systems with GALAH? Sounds like a no brainer to me!




*How beautiful is this overlap Huh?!*

## WHAT TYPES OF ROCKY WORLDS IS TESS LIKELY TO FIND?: The teaser

Now that is a cool question to try to answer. The answer to this question can be found below. But the TL;DR is: Around half of the rocky worlds found by TESS will likely have geological compositions unlike any object found within our Solar System!!

You're probably thinking, Jake and team, how did you work that one out?! Well, here goes the recipe list, without the doom scrolling of me verbosely describing how I made the cosmic cake before the actual cake recipe.

Ingredients:

- Spectral properties from GALAH's Second Data Release (Teff, logg and [M/H]*) (* see graph below for some real talk about our little friend [M/H])
- Photometric magnitudes for these stars, including GAIA (G, GR, GB), 2MASS (J, H, Ks) and V
- Parallax values from GAIA DR2
- Python package iscochrones
- Cross-matching package TOPCAT

Recipe:

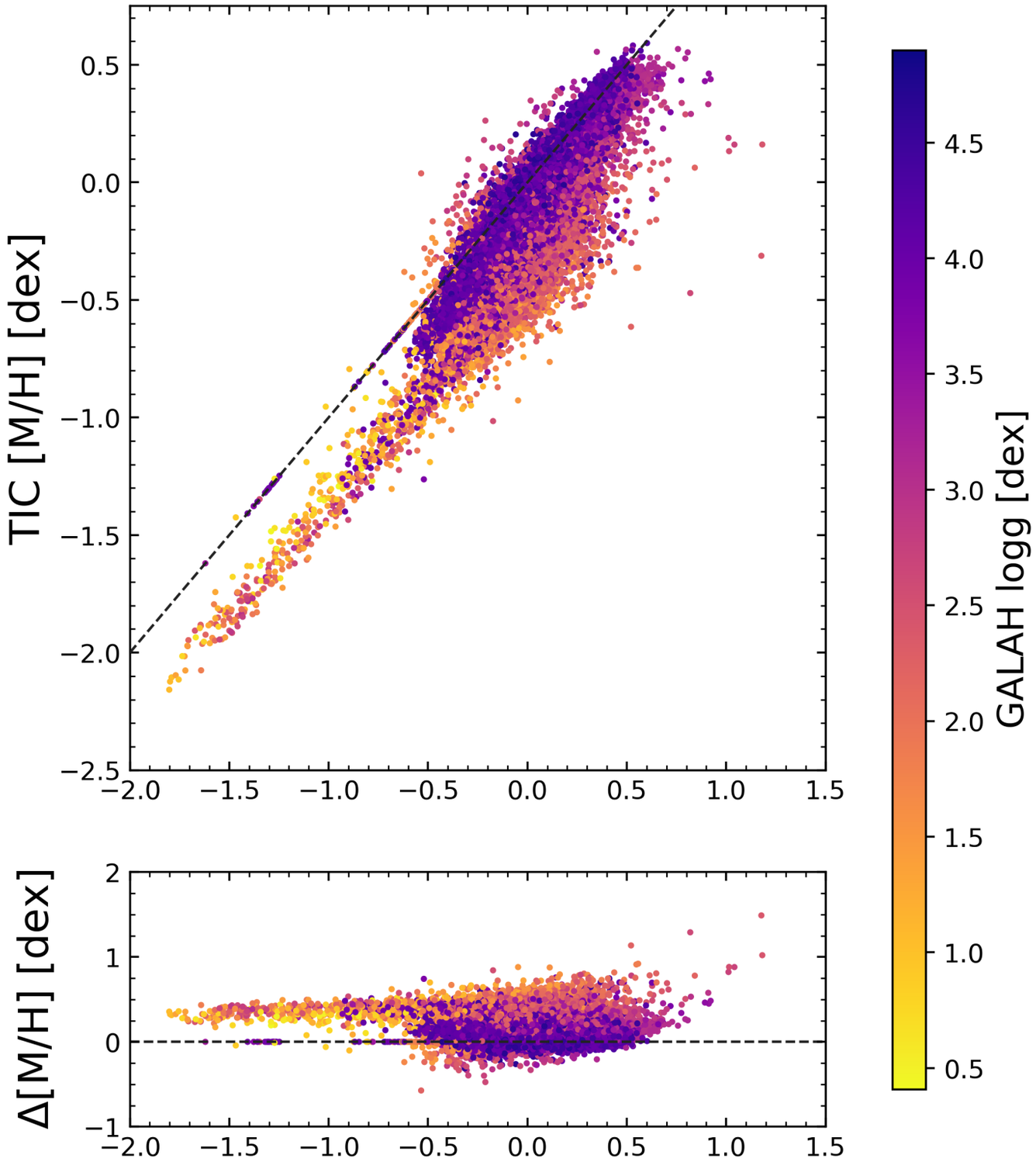
1. Obtain GALAH's second data release
2. Cross match the GALAH catalog with GAIA DR2 and the TESS Input Catalog within the software TOPCAT, keeping the stars with the highest SNR (more detail in our paper)
3. Use the spectral, photometric and astrometric properties from GALAH, GAIA and the TIC above as input for isochrones
4. Obtain mass, radius, luminosity, habitable zones etc. for over 47,000+ stars

And voila, you've just created the GALAH-TESS catalouge! If you'd like to get your hands on some freshly squeezed science, both the data and paper are now publicly available!

## PSA about "Metals"

Real talk for a second though. As a member of the astronomical community, I know that we love making our lives simple. Some simplifications include; always searching for log-log relationships, assuming PETA doesn't know about our obsession with spherical cows in a vacuum and more importantly, assuming the periodic table only contains hydrogen, helium and "metals".

This assumption really breaks down for our iron-poor and alpha-rich thicc disk friends (which you can't tell if the star is a thin or thick boi just based upon their iron-abundance alone) and can have disastrous effects on your isochrone results. We've all been there, lessons learnt! Just remember [Fe/H] != [M/H].



Our [M/H] [dex]

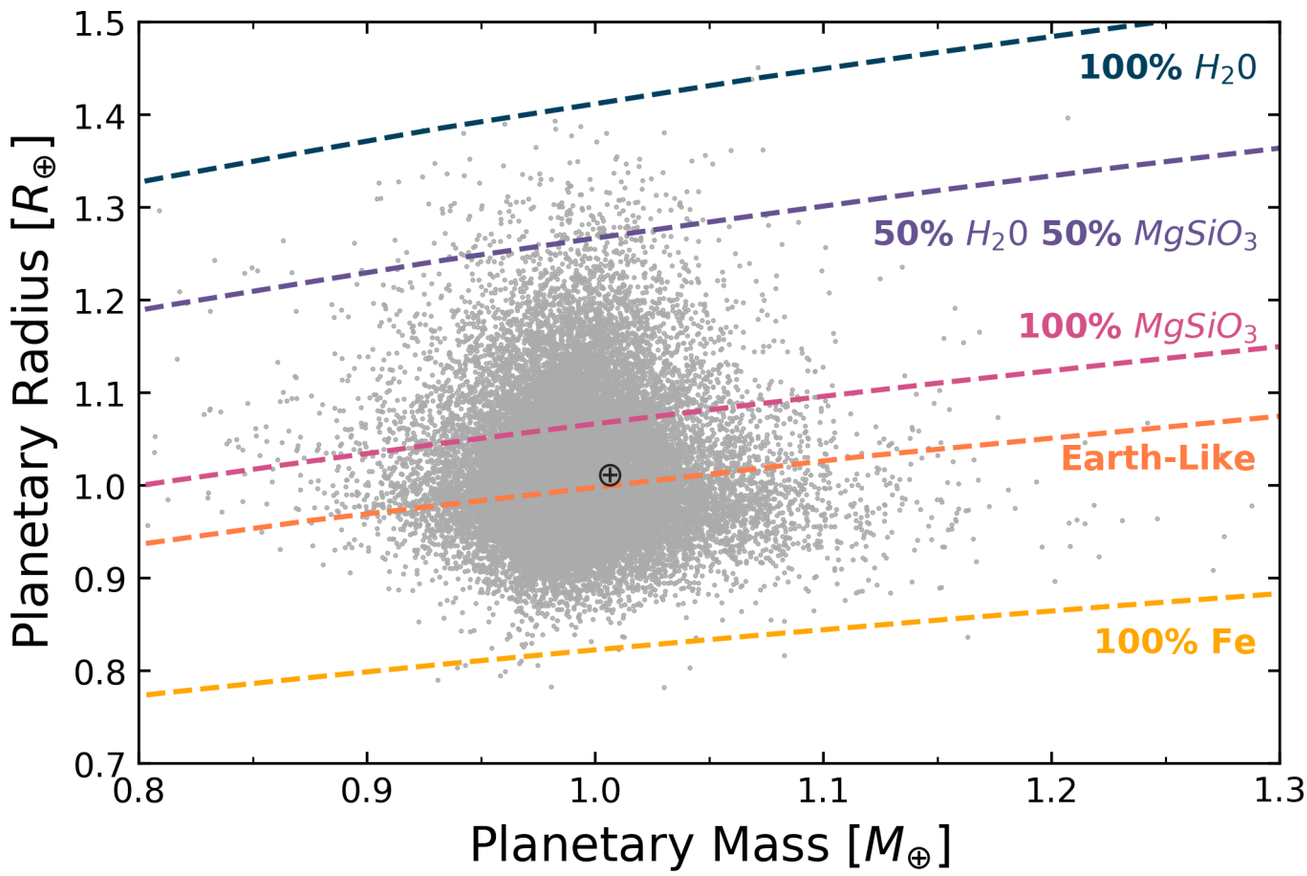
*The TIC has directly incorporated GALAH's [Fe/H] values as [M/H]. For our [M/H] values, we have also incorporated [alpha/Fe] values. As you can see for alpha-rich, thick disc stars, the difference can be as large as 0.5 dex!*

## WHEN IS AN EARTH-LIKE WORLD NOT EARTH-LIKE?

One of the coolest realisations during my PhD is knowing the sheer diversity of stellar interior, photospheric and isochrone models that are out there and available to planetary astrophysicists and astronomers like ourselves. These various models can change the calculated physical properties of the stars being derived, depending upon what models you choose.

As you're probably well aware, we don't directly measure the mass or radius of the planets we discover. We calculate a planet's mass and radius through the relative relationships between a star and planets' mass and radius. Thus if the stellar properties change, then so do the planet's.

So I wanted to test something, a kinda cool experiment as it were. What if you discovered THE first Earth-massed and Earth-sized exoplanet. You've used the GALAH-TESS catalogue because you know how awesome and comprehensive it is to determine the mass and radius of this planet. BUT, what if you used the stellar parameters from the TIC instead. How different would your "Earth-like" world be?




*The spread of our "Earth-like" world stretches to worlds made from solid iron to water dominated worlds.*

As you can see from the graph above, your “Earth-like” world would now be a various mix of different compositions. Some of these would have extremely questionable compositions required for life as we know it. I’m not saying that one method of deriving stellar parameters is better or worse than the other in this comparison. I’m just trying to show that consistent stellar parameters from various sources matter when you’re trying to determine the characteristics of exoplanetary systems.

## WHAT TYPES OF ROCKY WORLDS IS TESS LIKELY TO FIND?

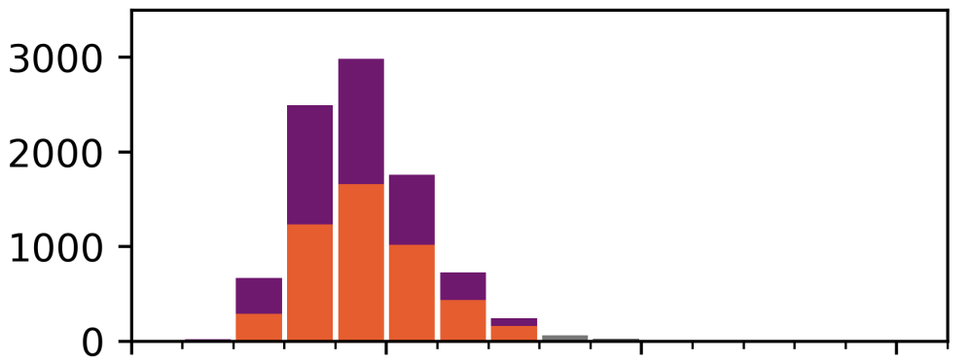
Australia’s GALAH survey is an absolute treasure trove of stellar data, boasting not only the physical properties of the stars being observed, but the chemical abundances for over 20 elements as well. Stellar abundances are incredibly important to help us exoplaneteers determine the likely chemical and geological compositions of rocky planets these stars might host.

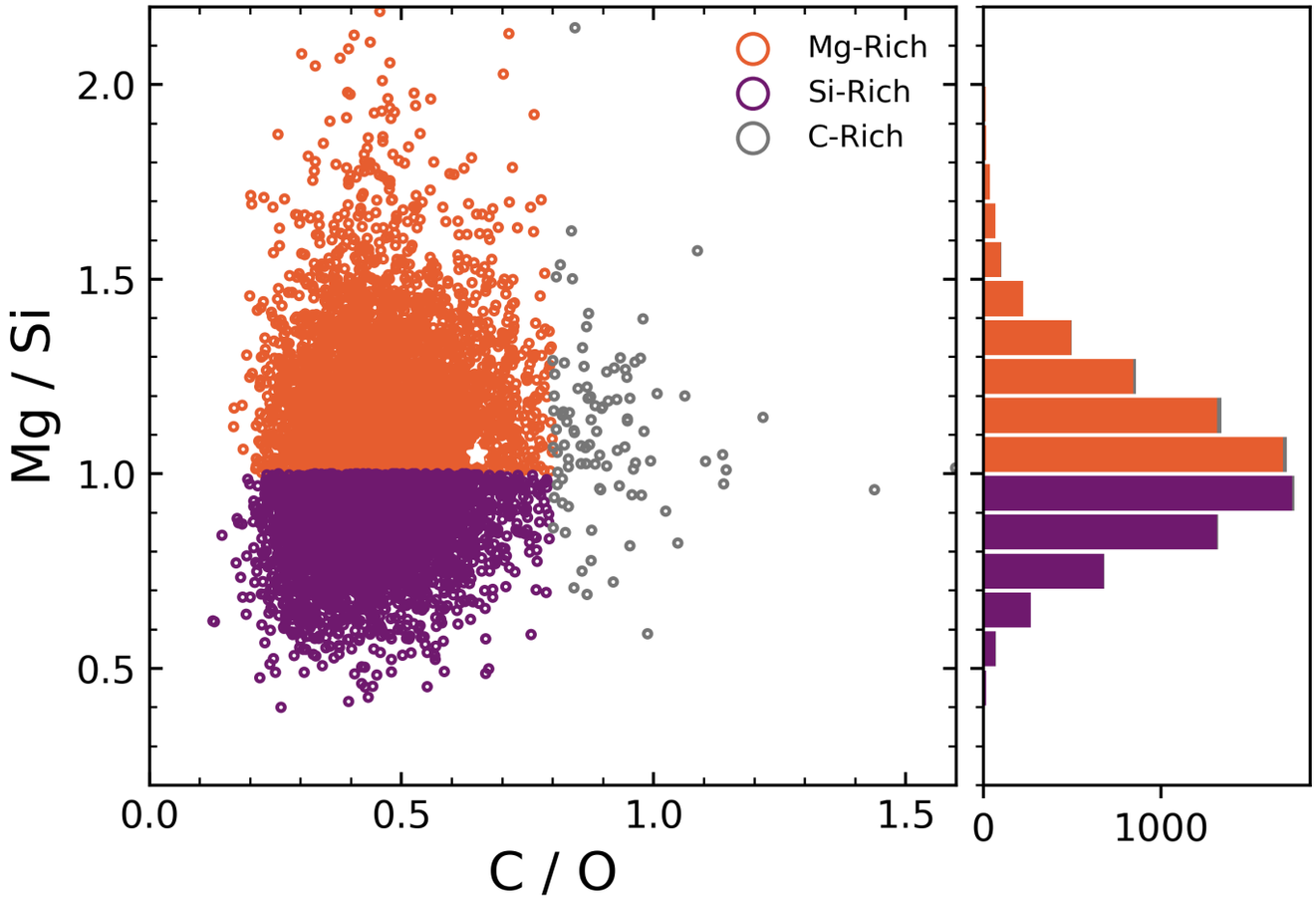
If you want to build a planet, some of the key raw ingredients include Iron (Fe), Magnesium (Mg), Silicon (Si), Carbon (C), Oxygen (O). People a lot smarter than me have been able to determine the likely composition of exoplanets by looking at their host’s Mg/Si and C/O molar ratios (also known as abundance ratios, linear ratios … another story for another day).

So what do you need to know? Well there are three key regimes that’ll help determine the likely composition of rocky worlds from their host stars, them being:

- A stellar C/O molar ratio greater than 0.8 will likely lead to these stars hosting exoctic “carbon-based” worlds, where rocks would be comprised of carbonates rather than silicates (e.g 55 Cne e could be one potential carbon-based world)
- For stellar C/O molar ratios less than 0.8, the star’s Mg/Si ratio will help define what the likely composition will be. For a Mg/Si > 1, a star will host rocky worlds akin to those found within the Solar system, consisting of olivine, pyroxenes etc. known as “magnesium-rich” worlds.
- In a “silicon-rich” environment, with the Mg/Si < 1, an exoplanet’s mantle will be dominated by the likes of majoritic garnet, quartz etc.

So if you were to find a potential rocky world orbiting around a TESS star, what would its likely composition be? Well, eager beaver, before you scroll further, take the poll so I can see what your answer might be before you see what we found out in the plot below! Wanna know the answer? Of course you do! Drum scroll please 🥁🥁🥁






*Want to know more about this graph? You'll just have to read more about it in [my paper](#)* 🤓

As you can see in the plot above, just over half of the stars within the GALAH-TESS catalogue will likely host planets akin to those found within the Solar system. Less than half of these stars will likely host either Silicon or Carbon-rich worlds, completely alien to bodies that we are used to orbiting Sol. So why should you care? Well, if we want to find a planet just like our own, we need to also consider its geological and chemical composition to constrain its habitability. One can do that right now thanks to the abundances found within the GALH-TESS catalogue!

With nearly half of planets discovered by TESS either being Silicon or Carbon rich worlds, this may motivate and grow the great field of exogeology to further study the potential habitability of such exoplanets! The discoveries and research of which is entirely exciting, just on its own.

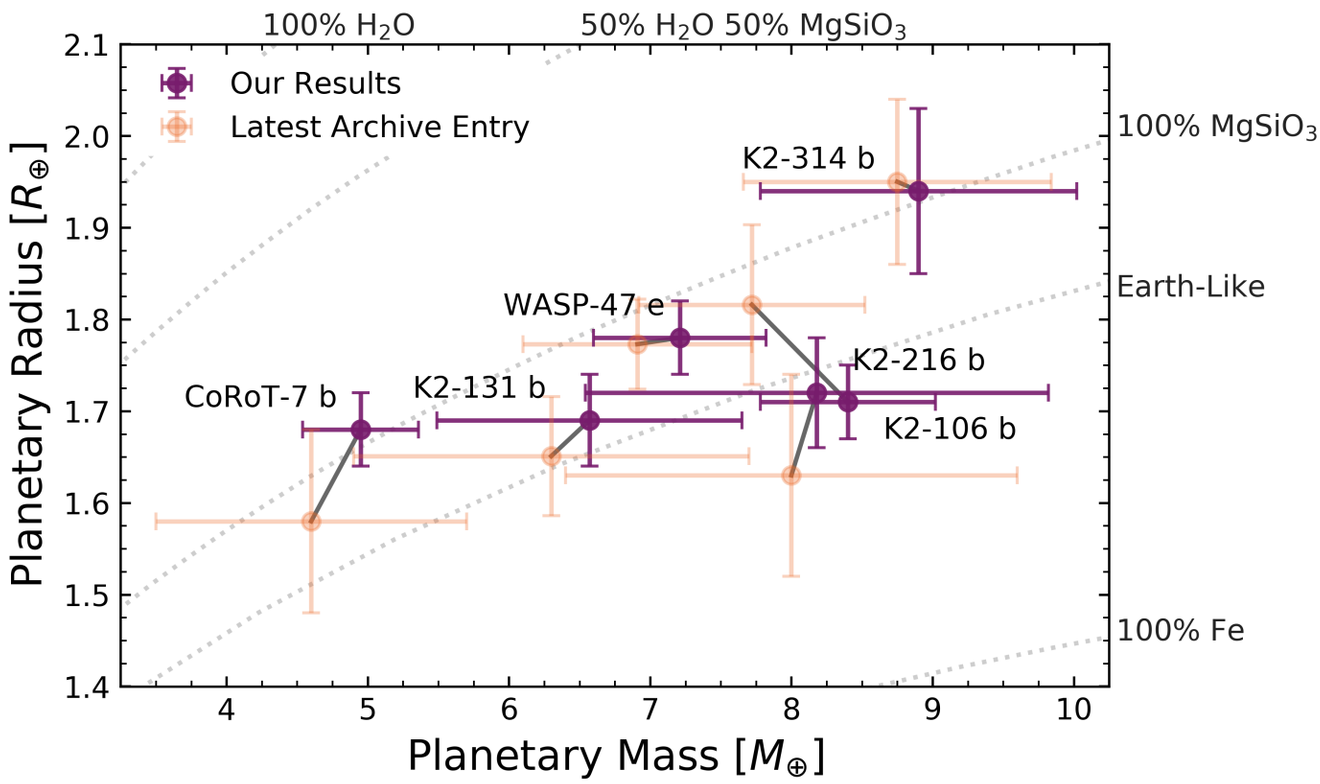
There are slight caveats to equating the abundances of planet-building elements within a star to that of its planetary companions, and is still an exciting field of research (see the work done by Adibekyan+ 21, Plotnykov & Valencia 20 and Wang+ 18).

## GALAH's Third Data Drop: GALAH DR3

As we're all aware, 2020 was an absolute dumpster fire. BUT, there were some redeeming moments through it all, including GALAH's announcement of their third data release, GALAH DR3. What is so freaking cool about GALAH DR3 compared to DR2, is the inclusion of the TESS-HERMES and K2-HERMES surveys within DR3. Aptly titled, these surveys include stars located within the K2 fields and TESS's Southern Continuous Viewing Zone, allowing for more planet-host and candidate-host stars within GALAH DR3… ooo the juicy science that can come out of a data set like that!

With a similar recipe to that of the GALAH-TESS catalogue above, we combined data from GALAH DR3, Gaia EDR3 and 2MASS to recharacterise 280 confirmed and candidate exoplanet hosting stars.

What's even better, is now NASA's Exoplanet Archive boasts numerous records for the same system, instead of just one record per system. We've used the new Archive and a weighted mean approach for observed properties (i.e transit fluxes, radial velocity amplitudes etc.) to recharacterise over 400 confirmed and candidate exoplanets. This weighted mean approach means that we're able to better estimate the planetary system uncertainties, which can then lead to us getting a better idea of what the planet's composition might be!




*Combining GALAH's stellar properties with observables within the NASA Exoplanet Archive has helped us better determine the mass and radius for nearly 400 confirmed and candidate exoplanets.*

So what have we learnt? Well, we've found out that 33 candidates are more likely stellar companions based on new radius values. We are also able to improve the parameters for five ultra-short period exoplanets, in particular, refining the mass and radius of WASP-47 e, K2-106 b and CoRoT-7 b to their most precise values yet, to less than 2.3% and 8.5% respectively!!

With combining GALAH DR3 and the NASA Exoplanet archive we have a new gold medal holder for the "hottest super-Earth" with K2-106 b now having an equilibrium temperature of 2570 K, far exceeding the condensation temperature of most refractory elements. But wait, there's more!

Our radius estimate for CoRoT-7 b suggests that the exoplanet is large enough for an atmosphere to contribute to its overall radius. What type of atmosphere could a rocky planet hold at 2027 K?

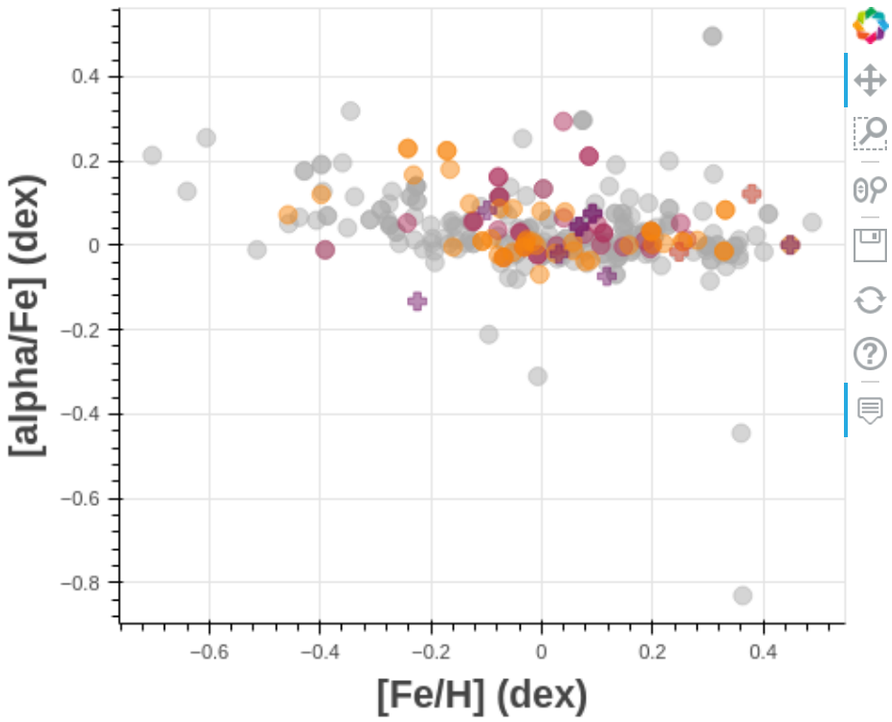
Well, that question is well above my pay grade, and I'll leave it up to the community to work that one out!

## Old bois are less likely to have hot bois

What's great about GALAH's data releases is again the combination of physical and chemical properties for over 600,000 stars. We were inspired by Dai 21+ who showed that Ultra-Hot Neptunes might favour iron-rich stars compared to their smaller rockier counterparts, suggesting Ultra-Hot Neptunes and Ultra-Hot Jupiters might form through similar mechanisms.

We have shown independently that there might be some truth to this, as the spread of Ultra-Hot Neptunes tends to iron-rich stars, compared to Ultra-Hot Terrestrial worlds. However, we have also added another dimension to this, a star's alpha abundance, which can be used as a proxy for thick disc stars ( ~ [alpha/Fe] > 1.0 for thick disk stars) and also a proxy for age (Older stars tend to be iron-poor and alpha-rich. For more details check out Sharma +20).

The ⭐⭐INTERACTIVE⭐⭐ plot below shows from our work, that there are very few thick disc stars that host hot terrestrial and hot Neptune worlds. There are also no ultra-hot terrestrial or Neptune exoplanets orbiting thick disc stars within our sample. We are still working out as to why that might be the case. But, if you have an inkling, please get in touch and I would be more than happy to collaborate!

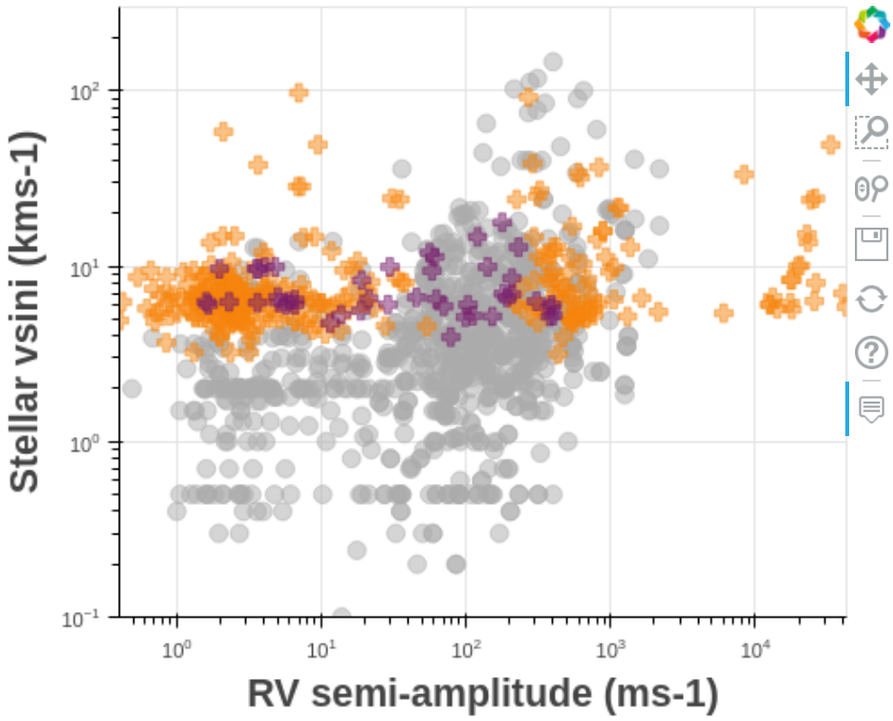



*This interactive plot from our research suggest that ultra-hot Neptunes tend to favour iron-rich stars compared to their terrestrial counterparts. We also see a lack of ultra-short and short period planets around thick disc stars, suggesting different planet formation mechanisms for different stellar populations.*

## Some exoplanets are going to be harder to confirm than others

That title might seem a bit obvious, but in the context of this poster, let's talk about stellar rotation. Ground-based follow-up of TESS targets generally rely on radial velocity measurements to not only confirm the exoplanetary nature of candidates, but also be able to calculate fun stuff like mass, density, composition etc. However, stellar rotation plays incredible havok on obtaining nice, crisp lines for high precision radial velocity follow up. Basically, the faster the star rotates, the harder it will be to confirm planets with smaller radial velocity signals.

We can then plot the stellar rotation of planet-hosts along with confirmed planets with already calculated mass measurements… but what's the point of that, huh? That's a nice baseline to have, but I have used the Chen-Kipping mass-radius relationship to forecast the potential masses of both candidates and confirmed planets within GALAH that have no mass measurements, to obtain a predicted mass. From that mass, one can calculate a predicted semi-amplitude for the mass signal (orange) and plot that against known planets that have confirmed mass measurements, both in GALAH (purple) and those within the NASA Exoplanet Archive (grey).




*Click and drag the plot around. See where your favourite exoplanet sits on this plot and see if there are any candidate or confirmed planets without mass measurements around your favourite one.*

For the likes of TOI-1219.01, a mass confirmation will be extremely tough, with a host's stellar rotational velocity of 58 kms-1 and an expected RV semi-amplitude of just 2 ms-1. This plot thus can help the SG2 and SG4 community better prioritise what targets they should and shouldn't be allocating resources too.

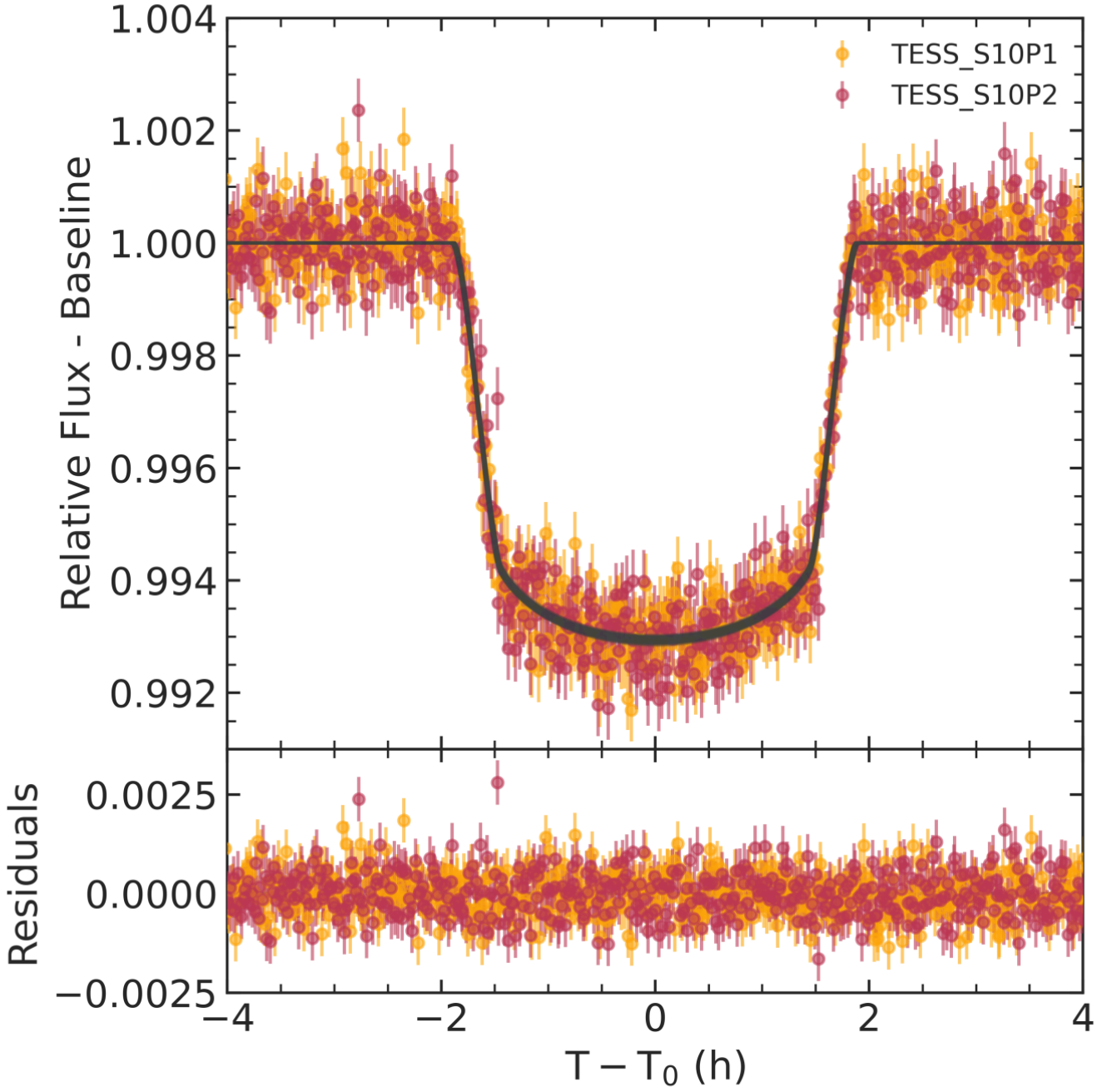
There are quite a number of exoplanets that have an expected RV amplitude between 1-10 ms-1 with their stellar host's rotational velocity between 10-4 kms-1. We expect that for the stars nearer to 4-5 kms-1, this might be more of an upper limit due to the resolution of GALAH, so these targets might actually have slower rotating hosts, which might make them reasonable targets for high-precision radial velocity followup!

## BUT BOOM TOI 778 YO!!

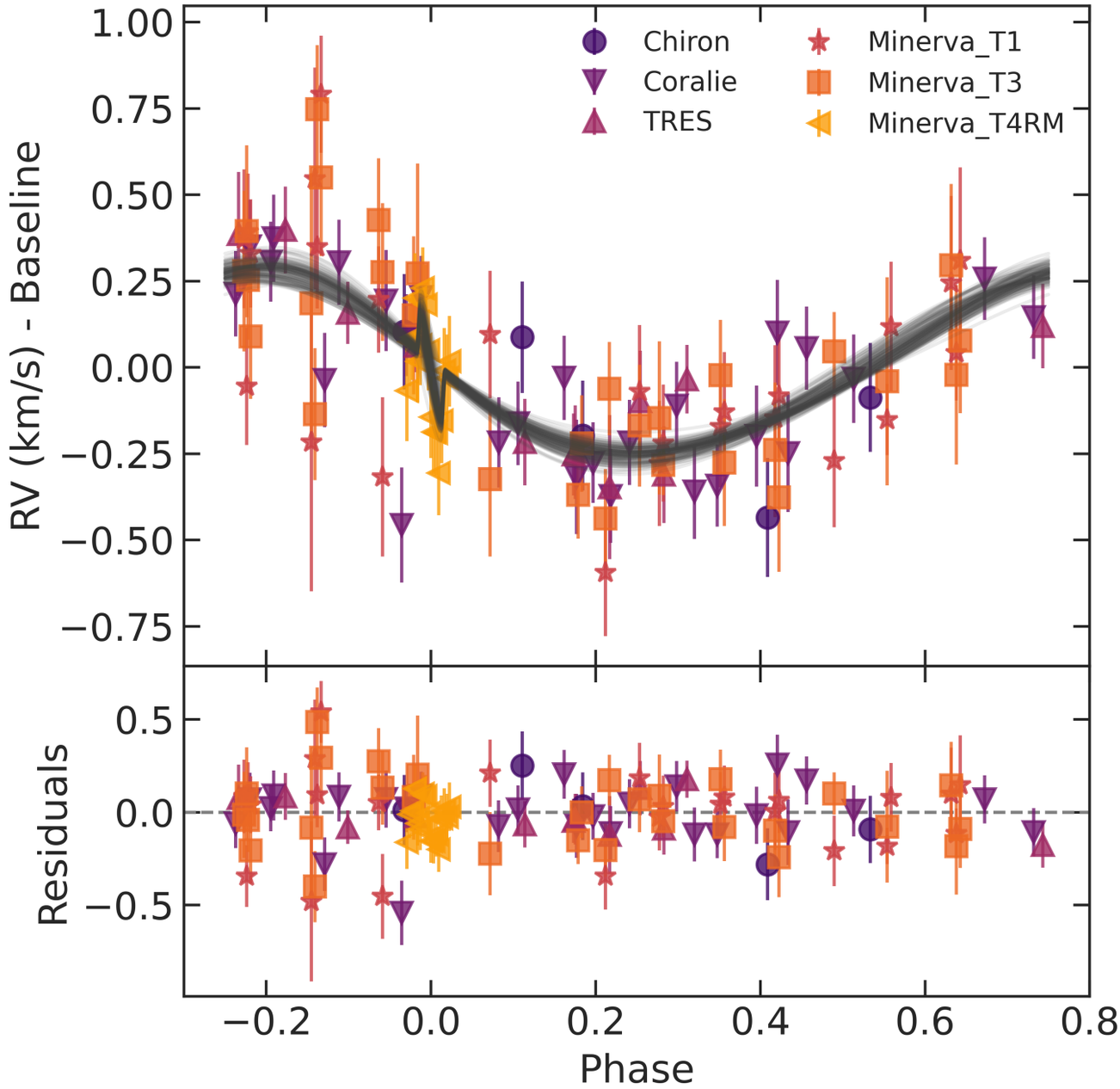
Higher stellar rotation might make following up targets around this cosmic spinning tops tough, but it's not impossible. Over the last couple of years the Minerva-Australis team, along with teams around the world, have been following up a hot-Jupiter, orbiting around the rapid rotator TOI-778.

TOI-778 has a rotational velocity of 28 kms-1, making it a pretty hard star to confirm targets around. However, over the coming months, on an arXiv near you, you will see a paper confirming the planetary nature of TOI-778 b.

The confirmation of this planet has also been part of an exciting Research Experiences for Undergraduates summer program Indigenous Skywatchers with undergraduates at the St. Cloud University. I can not wait to share our results with this awesome community.




*B E A U ti-ful TESS light curve from Sector 10 showchasing the transit of TOI-778 b*




*We've managed to constrain the orbit, mass and Rossiter Mclaughlin effect for TOI-778 b*

## Take Away Message

You've made it to the end 🥳🥳

It's been a delightful four years, and I hope I've shown you how pioneering stellar surveys such as GALAH and Gaia are vital for our community. These surveys help to better constrain the fundamental properties of stars and planets contained within our galaxy and provide a rich data set for planetary demographics, ground-based follow up, recharacterising planetary systems and more. Please feel free to catch up with me during the conference, and if you have any exciting projects that you think I would be perfect to collaborate on, please get in touch. 🖤🤘

## References

Adibekyan, Vardan, et al. "The Chemical link between stars and their rocky planets." arXiv preprint arXiv:2102.12444 (2021).

Brown, Anthony GA, et al. "Gaia Early Data Release 3-Summary of the contents and survey properties." Astronomy & Astrophysics 649 (2021): A1.

Brown, A. G. A., et al. "Gaia Data Release 2-Summary of the contents and survey properties." Astronomy & astrophysics 616 (2018): A1.

Buder, Sven, et al. "The GALAH+ survey: Third data release." Monthly Notices of the Royal Astronomical Society 506.1 (2021): 150-201

Buder, Sven, et al. "The GALAH Survey: second data release." Monthly Notices of the Royal Astronomical Society 478.4 (2018): 4513-4552.

Chen, Jingjing, and David Kipping. "Probabilistic forecasting of the masses and radii of other worlds." The Astrophysical Journal 834.1 (2016): 17.

Clark, Jake T., et al. "The GALAH Survey: using galactic archaeology to refine our knowledge of TESS target stars." Monthly Notices of the Royal Astronomical Society 504.4 (2021): 4968-4989.

Dai, Fei, et al. "TKS X: Confirmation of TOI-1444b and a Comparative Analysis of the Ultra-short-period Planets with Hot Neptunes." arXiv preprint arXiv:2105.08844 (2021).

Morton, Timothy D. "isochrones: Stellar model grid package." Astrophysics Source Code Library (2015): ascl-1503.

Plotnykov, Mykhaylo, and Diana Valencia. "Chemical fingerprints of formation in rocky super-Earths' data." Monthly Notices of the Royal Astronomical Society 499.1 (2020): 932-947.

Sharma, Sanjib, Michael R. Hayden, and Joss Bland-Hawthorn. "Chemical Enrichment and Radial Migration in the Galactic Disk--the origin of the [$\alpha/\rm Fe] $ Double Sequence." arXiv preprint arXiv:2005.03646 (2020).

Sharma, Sanjib, et al. "The TESS–HERMES survey data release 1: high-resolution spectroscopy of the TESS southern continuous viewing zone." Monthly Notices of the Royal Astronomical Society 473.2 (2018): 2004-2019.

Skrutskie, M. F., et al. "The two micron all sky survey (2MASS)." The Astronomical Journal 131.2 (2006): 1163. Stassun, Keivan G., et al. "The revised TESS input catalog and candidate target list." The Astronomical Journal 158.4 (2019): 138.

Taylor, Mark B. "TOPCAT & STIL: Starlink table/VOTable processing software." Astronomical data analysis software and systems XIV. Vol. 347. 2005.

Wang, Haiyang S., et al. "Enhanced constraints on the interior composition and structure of terrestrial exoplanets." Monthly Notices of the Royal Astronomical Society 482.2 (2019): 2222-2233.

Wittenmyer, Robert A., et al. "K2-HERMES II. Planet-candidate properties from K2 Campaigns 1-13." Monthly Notices of the Royal Astronomical Society 496.1 (2020): 851-863.