# Exploring the M-Dwarf Luminosity-Temperature-Radius Relationships with Gaia DR2

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## Abstract

There is growing evidence that M-dwarf stars suffer radius inflation when compared to theoretical models. We employ an all-sky sample, comprising of >15 000 stars, to determine empirical relationships between luminosity, temperature, and radius. We use only geometric distances and multiband photometry, by utilising a modified spectral energy distribution fitting method. The radii we measure show an inflation of **3 - 7%** compared to models, but no more than a **1 - 2%** intrinsic spread in the inflated sequence. We also present evidence that stellar magnetism is currently **unable to explain** radius inflation in M-dwarfs.

## Introduction

It has been clear for a long time that something may be seriously wrong with our models of M-dwarfs. **Stauffer et al. (2007)** and **Bell et al. (2012)** have shown that both main-sequence (MS) and Pre-MS M-dwarfs are overluminous at a given colour compared to the models. However, colour-magnitude diagram studies are far removed from the fundamental radius (*R*), luminosity (*L*) and effective temperature ($T_{eff}$) outputs of models. Hence, measuring these directly is a promising way of testing models.

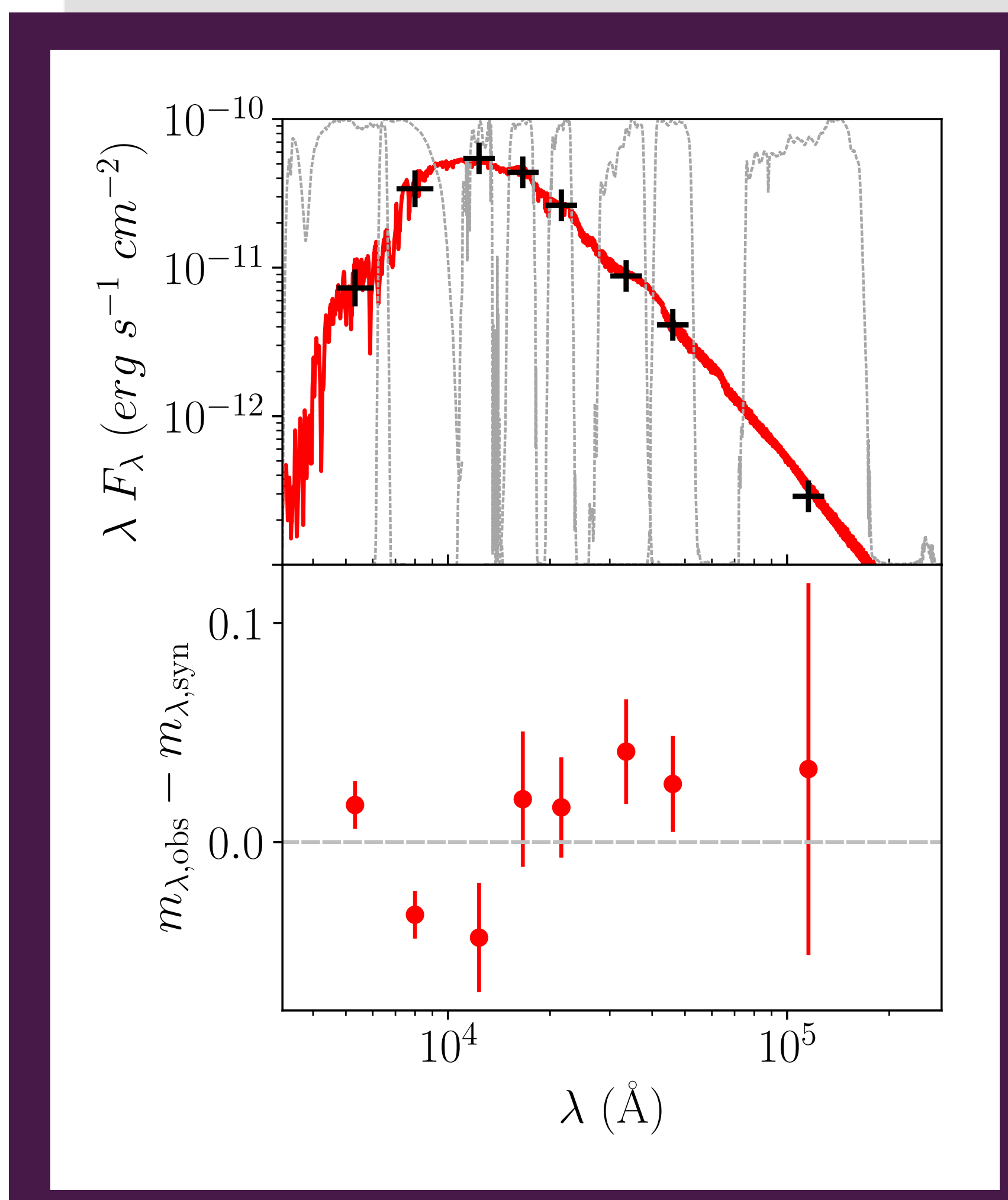
There have been three methods for measuring the radii of main-sequence (MS) M-dwarfs:

- ***Detached Eclipsing Binaries***: provide a direct, fundamental measurement of *R* at a given mass. They have shown M-dwarfs to be inflated, however there has been a concern that their high rotation-rate artificially inflates them; rendering them invalid for validating single star models.
- ***Interferometry***: given astrometric distances, provides a direct measurement of radius, but not mass, so either $T_{eff}$ or *L* must be used. **Boyajian et al. (2012)** use this method to conclude MS M-dwarfs are inflated by about 5%, however their sample is small; consisting of only 21 M-stars.
- ***SED Luminosity and Spectroscopic Temperature***: The work of **Mann et al. (2015)** overcomes the small-number statistics problem by taking 183 M-stars with known distances and measuring their luminosities $L_{SED}$, via their spectral energy distribution (SED). They used optical spectra to measure spectroscopic temperature $T_{sp}$, using the definition of $T_{eff}$ to then find *R*. However, there is a question whether this $T_{sp}$ scale matches the $T_{eff}$ scale.

**In summary**, there are three methods for measuring M-dwarf radii, each suffering from either small number statistics, rapid rotation, or a question of how closely $T_{sp}$ matches $T_{eff}$.

**We introduce a fourth method** for measuring *R*, which uses only geometric distances, from **Bailer-Jones et al. (2018)**, and multiband photometry. The shape of the SED determines the SED temperature $T_{SED}$, and the flux beneath it, the luminosity (as we know the distance).

## Method and Results



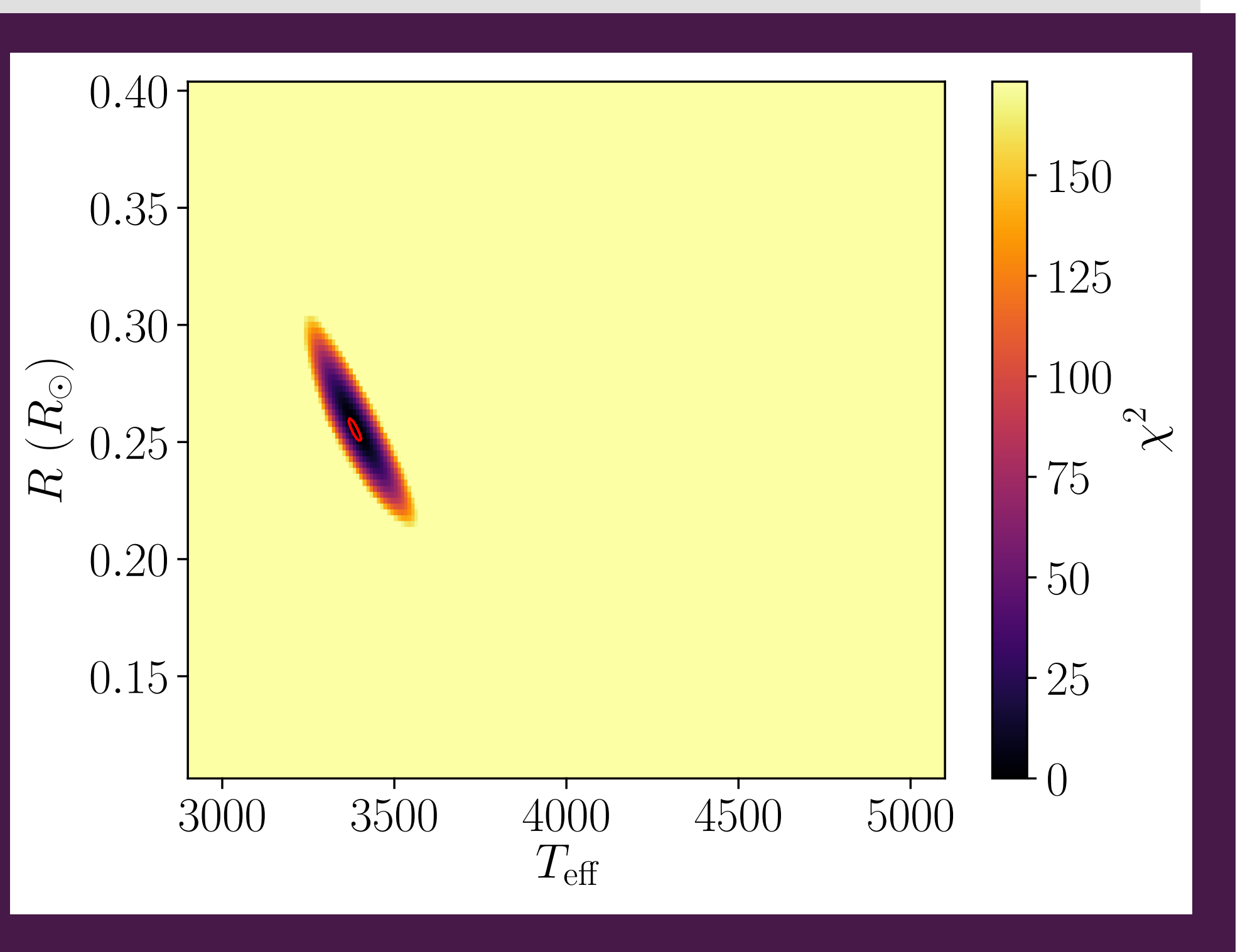


**Figure 1**: A fit for a target whose $\chi^2$ lies at the median of our randomly selected uncertainty sample. The **left** figure shows the best fitting model spectrum (red) with the photometry from which it was derived (black) in the **top** pane, with appropriate bandpasses plotted in grey. The residuals and uncertainties are shown in the **bottom** pane. The search space from which uncertainties are drawn is shown **above**, with the red ellipsoid indicating the 68% confidence contour.

In **Morrell and Naylor (2019, 2020)**, we present radius measurements for **15 274** low-mass stars using our novel SED fitting methodology. The technique performs a search through a $T_{eff}$–*log(g)* grid, analytically solving R at each grid point, to find the best fitting model SED. ***Figure 1*** shows the result of this fitting for one of the stars in our published catalogue.

To gauge the distribution of uncertainty, we performed a full grid search upon a randomly selected 1% of our catalogue. This showed that our median formal uncertainty in radius is **1.9%**.

From this catalogue we derived **$T_{SED}$–R and $L_{SED}$–R relations.** These are provided, along with our full catalogue, at CDS (http://cdsarc.unistra.fr/viz-bin/cat/VI/156), Open Research Exeter (https://doi.org/10.24378/exe.1683) and our GitHub repo of supplementary material (https://github.com/sammorrell/mn19-supplementary-material).

## Discussion and Implications

We would like to highlight and summarise some of the key findings presented, in detail, in **Morrell and Naylor (2019):**

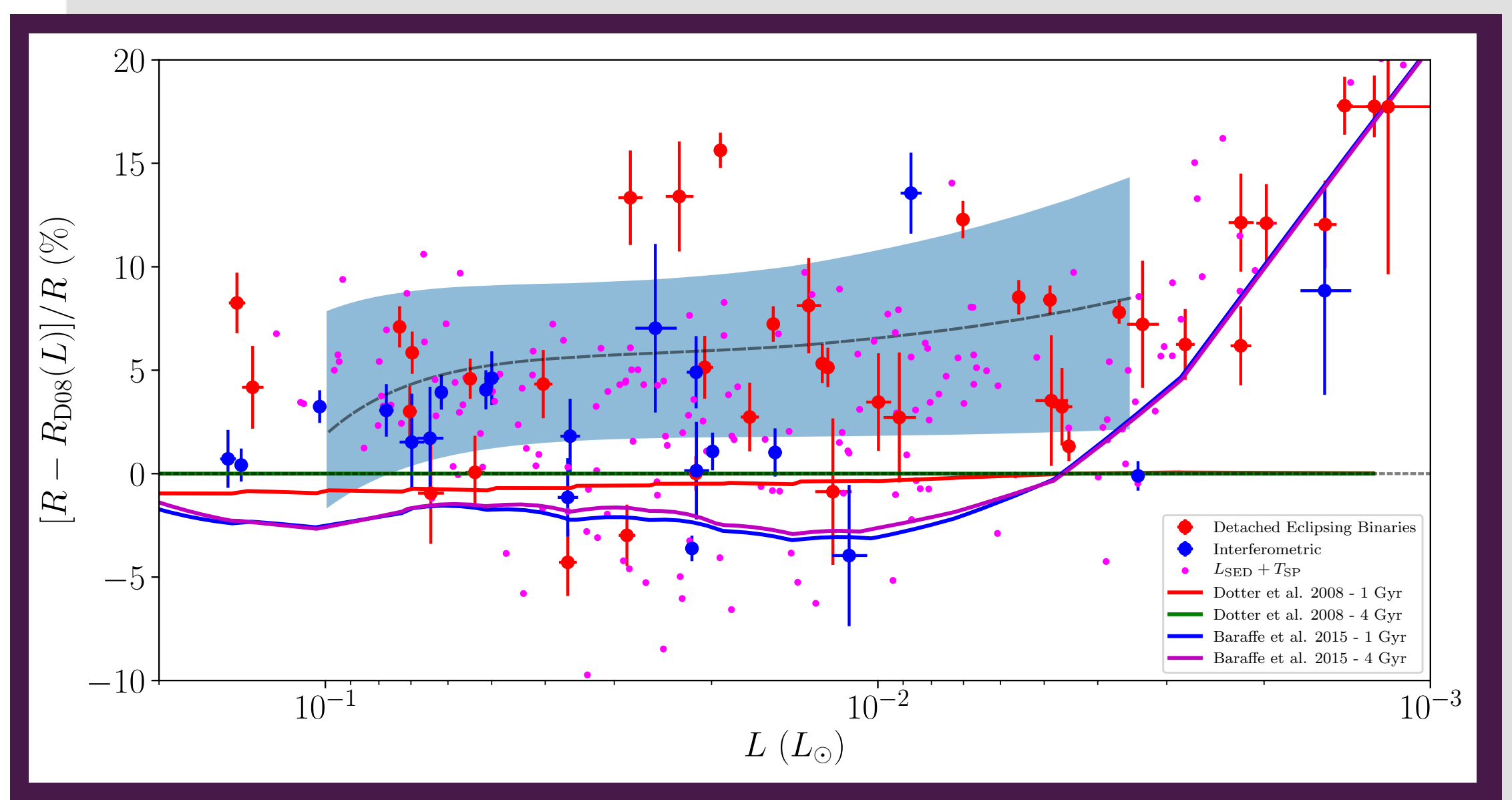


**Figure 2:** The radius inflation with respect to the **Dotter et al. (2008)** 4 Gyr isochrone obtained by the four different methods. The points show measurments from DEBs from **Southworth et al. (2015)** and **Parsons et al. (2018)** (red), interferometry from **Boyajian et al. (2015)** (blue) and **Mann et al. (2015)** (pink). Our $L_{SED}$–R relation, with its 68% density bounds is shown in the shaded region.

1. **The M-dwarf MS**: Currently, **none** of the purely theoretical models can describe the mean radius inflation of the MS at temperatures lower than about 4000 K. Figure 2 shows that we observe a 3–7% spread in *R* for a given $L_{SED}$. As, we cannot attribute this spread to observational uncertainties, we investigated whether other physical effects could explain it.

2. **Starspots**: As we assumed a single temperature component while generating synthetic photometry, varying levels of spot coverage on an observed stellar surface would cause an apparent radius spread. To model this effect, we simulated a catalogue with starspots, and fitted it with the same process as the main catalogue. The resulting scatter corresponded closely with the 68% confidence contours of our $T_{SED}$–*R* relation, assuming unphysically high spot coverage and a correlation with activity indicators.

3. **Stellar activity**: Variations in stellar magnetism would suggest a spread in radius, from the theoretical sequence for non-magnetic models to a maximum inflation. However, our work showed that there are no appreciable correlations between markers of magnetic activity (rotation period, X-ray luminosity and $H_\alpha$ luminosity) and radius inflation, both in the saturated and unsaturated regimes. Hence, we reluctantly conclude that magnetism is **currently unable** to explain radius inflation in MS M-dwarfs. This places an upper limit of 10% upon starspot coverage.

4. **Stellar metallicity**: We found that fitting a distribution of metallicities using only solar metallicity atmosphere models introduces an apparent correlation between [Fe/H] and *R*, explaining the spread in ***Figure 2***. If we fit the sub-sample of stars which have known metallicity using the appropriate metallicity atmospheres, the correlation is removed and we measure the radius to an accuracy of **2.4%** (see ***Figure 3***). Given that the uncertainty for [Fe/H] measurements results in a 1.7% spread, M-dwarfs lie on a tight sequence, with a scatter smaller than 1–2%.

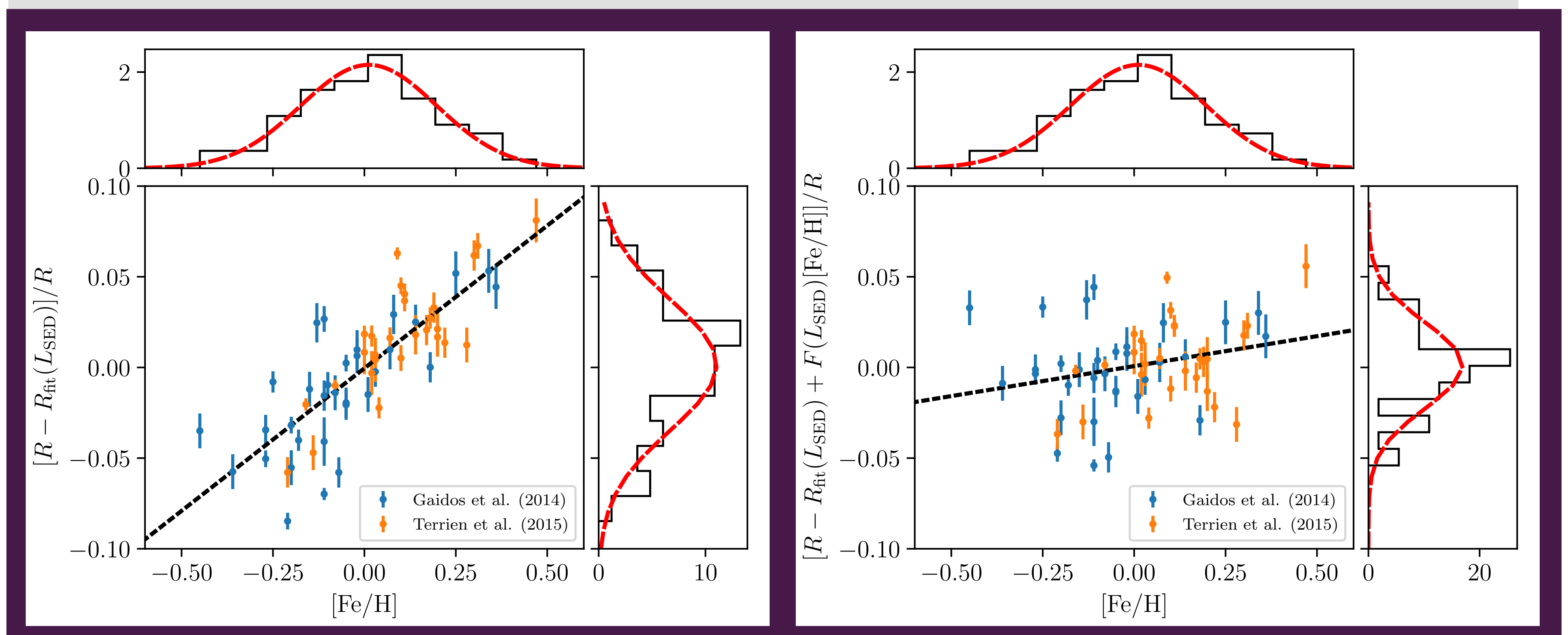


**Figure 3:** The correlation between radius residual and [Fe/H] for stars in our sample which have metallicity measurements in **Terrien et al. (2015)** (orange) and **Gaidos et al. (2014)** (blue). The **left** plot shows our sample fitted using synthetic photometry generated using only solar metallicity atmospheres. The **right** shows the same but with our correction for metallicity applied.

## References and Acknowledgements

1. Stauffer J. R., et al., 2007, ApJS, 172, 663
2. Bell C. P. M., Naylor T., Mayne N. J., Jeffries R. D., Littlefair S. P., 2012, MNRAS, 424, 3178
3. Boyajian T. S. et al., 2012, ApJ, 757, 112
4. Mann A. W., Feiden G. A., Gaidos E., Boyajian T., von Braun K., 2015,ApJ, 804, 64
5. Bailer-Jones C. A. L., Rybizki J., Fouesneau M., Mantelet G., Andrae R., 2018, AJ, 156, 58
6. Morrell S., Naylor T., 2019, MNRAS, 489, 2615
7. Morrell S., Naylor T., 2020, MNRAS, 498, 5048
8. Dotter A., Chaboyer B., Jevremovi ́c D., Kostov V., Baron E., Ferguson J. W., 2008, ApJS, 178, 89
9. Southworth J., 2015, in Rucinski S.M., Torres G., ZejdaM., eds, ASP Conf. Ser., Vol. 496. Living Together: Planets, Host Stars and Binaries. Astron.Soc. Pac., San Francisco, p. 164
10. Parsons S. G. et al., 2018, MNRAS, 481, 1083
11. Terrien R. C.,Mahadevan S., Deshpande R., Bender C. F., 2015, ApJS, 220, 16
12. Gaidos E. et al., 2014, MNRAS, 443, 2561

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