Determination of fundamental parameters of stars using Interferometry

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ISSP - SPICA /CHARA

Interferometric Survey of Stellar Parameter (ERC grant of D. Mourard)

We employ 6T interferometry with CHARA/SPICA to observe a large number of stars.

With SPICA, by using the SBCR relation on dwarfs and giants with a priori on LD, we can measure the angular diameter of hundreds of stars (top table).

For hundreds of stars (in the green bottom table), SPICA can measure the angular diameter with a **high precision of 1%**, without any prior assumptions about LD, alongside the **LD coefficients** of the stars.

My Work!!!

This work has strong links with ESA/PLATO (Gent et at. 2022) in determination of atmospheric parameters of star.

Dwarfs	Challouf			Salsi-1			Salsi-2			Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4	SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6	V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,10	1,00	3,35	6,28	11,82	22,25	39,94	70,70	125,14	0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96	1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82	2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43	3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83	4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51	5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90	6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98	7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14	8	0,01	0,03	0,08	0,17	0,30	0,52	0,91	1,56	2,67
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98	9	0,00	0,02	0,05	0,11	0,19	0,33	0,58	0,99	1,69
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25	10	0,00	0,01	0,03	0,07	0,12	0,21	0,36	0,62	1,06

Dwarfs	Challouf			Salsi-1			Salsi-2			Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4	SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6	V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,10	1,00	3,35	6,28	11,82	22,25	39,94	70,70	125,14	0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96	1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82	2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43	3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83	4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51	5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90	6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98	7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14	8	0,01	0,03	0,08	0,17	0,30	0,52	0,91	1,56	2,67
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98	9	0,00	0,02	0,05	0,11	0,19	0,33	0,58	0,99	1,69
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25	10	0,002	0,011	0,032	0,067	0,118	0,207	0,364	0,623	1,065

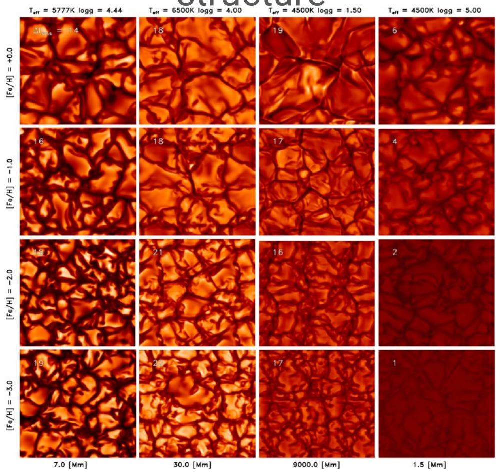
Mourard et al.2022

Limb Darkening

Limb Darkening is the variation of brightness distribution of a star from the centre to the limb of the star.

Provides constraints on the stellar atmosphere models

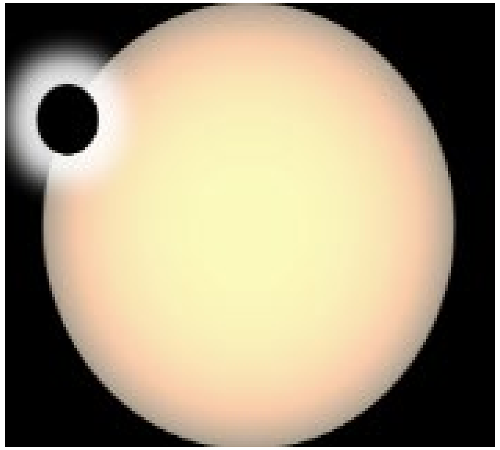
Help understand atmosphere structure



Credit: Magic et al. 2013

Analysing the transiting object, such as Exoplanets.

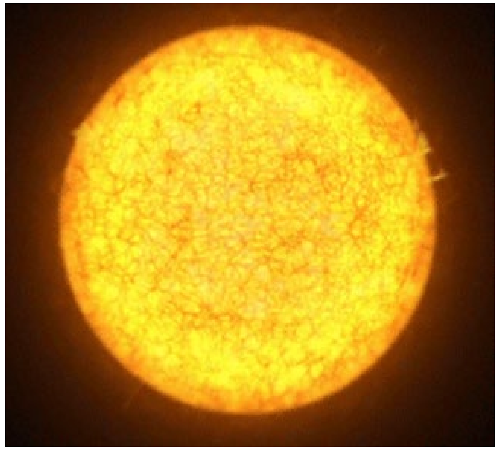
Crucial in missions like PLATO



Credit: NASA

For accurate estimation on the fundamental parameters,

Such as T_{eff}, log g, radius etc.



Credit: NASA

With not much studies on the topic.
It is important to have a better understanding of limb darkening across the HR diagram.

Limb Darkening Observations

With CHARA/SPICA, we aim to observe a large sample of stars using the CHARA/SPICA over the span of 3 years.

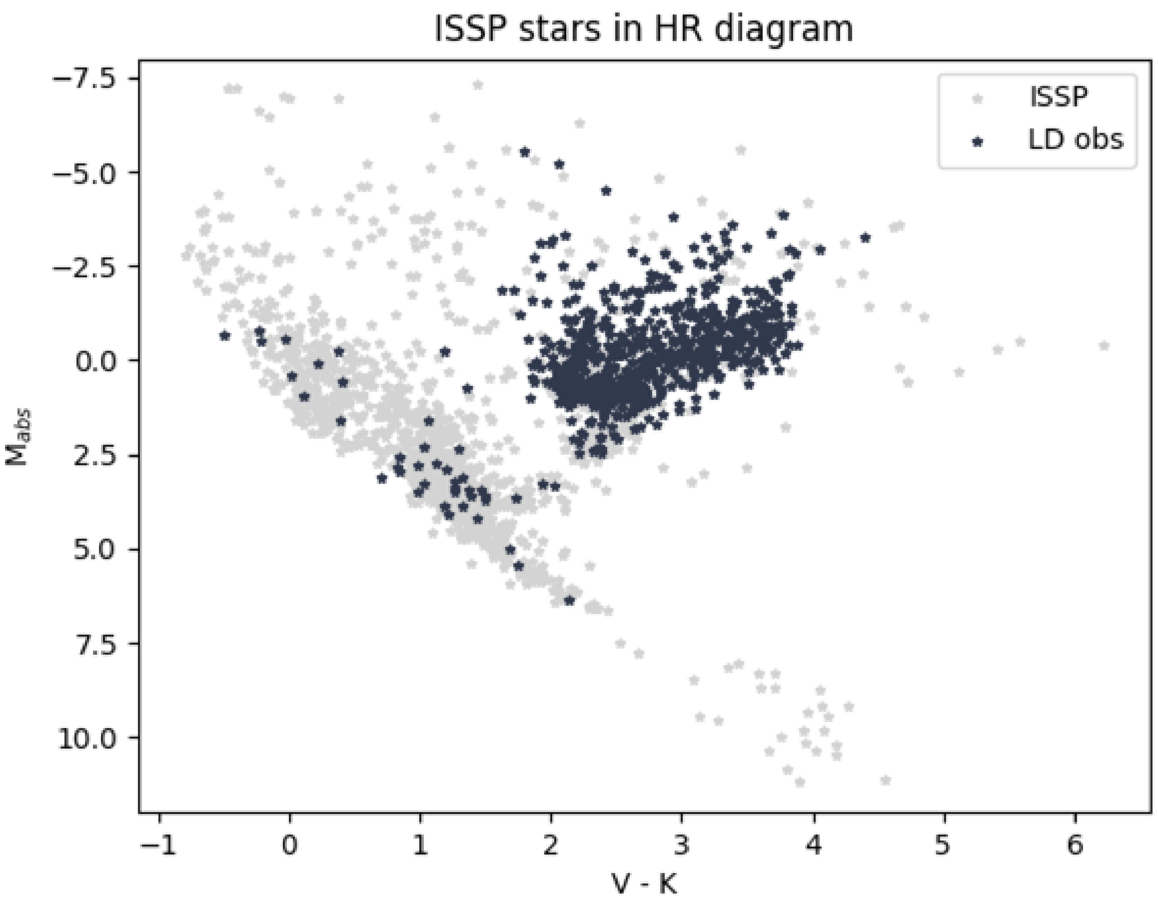
For the limb darkening we have stars different each stellar type from **giant** (780) to **sub giant** (25) to **main sequence** (31).

All stars are selected with:

- No activity
- DEC > -30^0
- Vmag< 6
- 0.7< angular diameter < 11 mas (to get the second lobe using CHARA.)

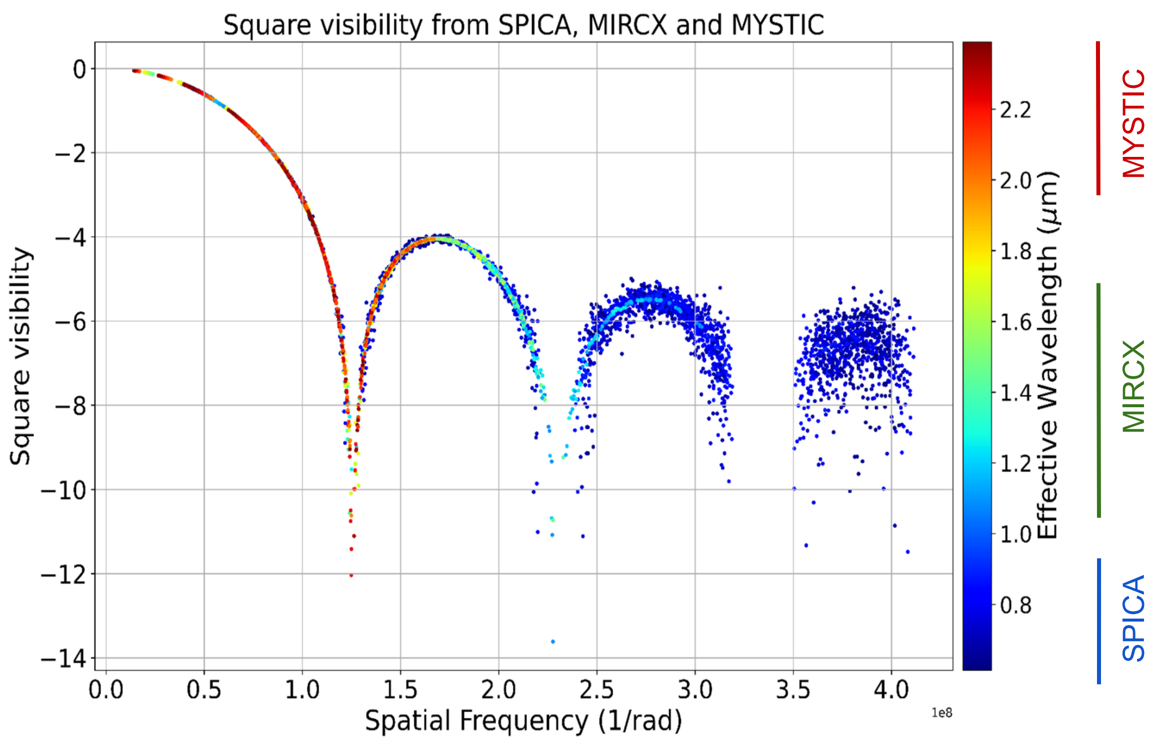
For the first phase of the survey we have prioritised **162** stars from SpTy: **B0** - **M3** and SpC: **III-V**

Overall goal is to produce a **catalog** of directly measured angular diameter (1% precision) and other fundamental parameters.

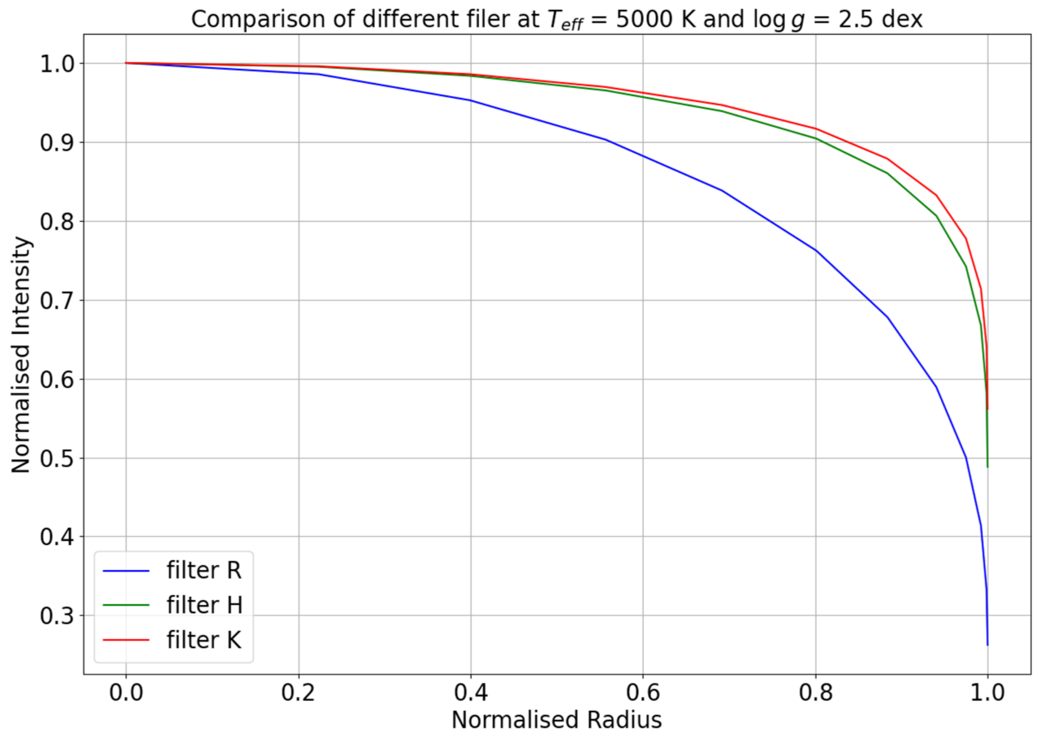


Observation strategy

Combining SPICA, MIRCX and MYSTIC we have more UV coverage and constrain on the visibility.



Combining R, H and K band will also bring additional constraints to the parameter estimation.



For each star we will make **at least 2 observation** each.

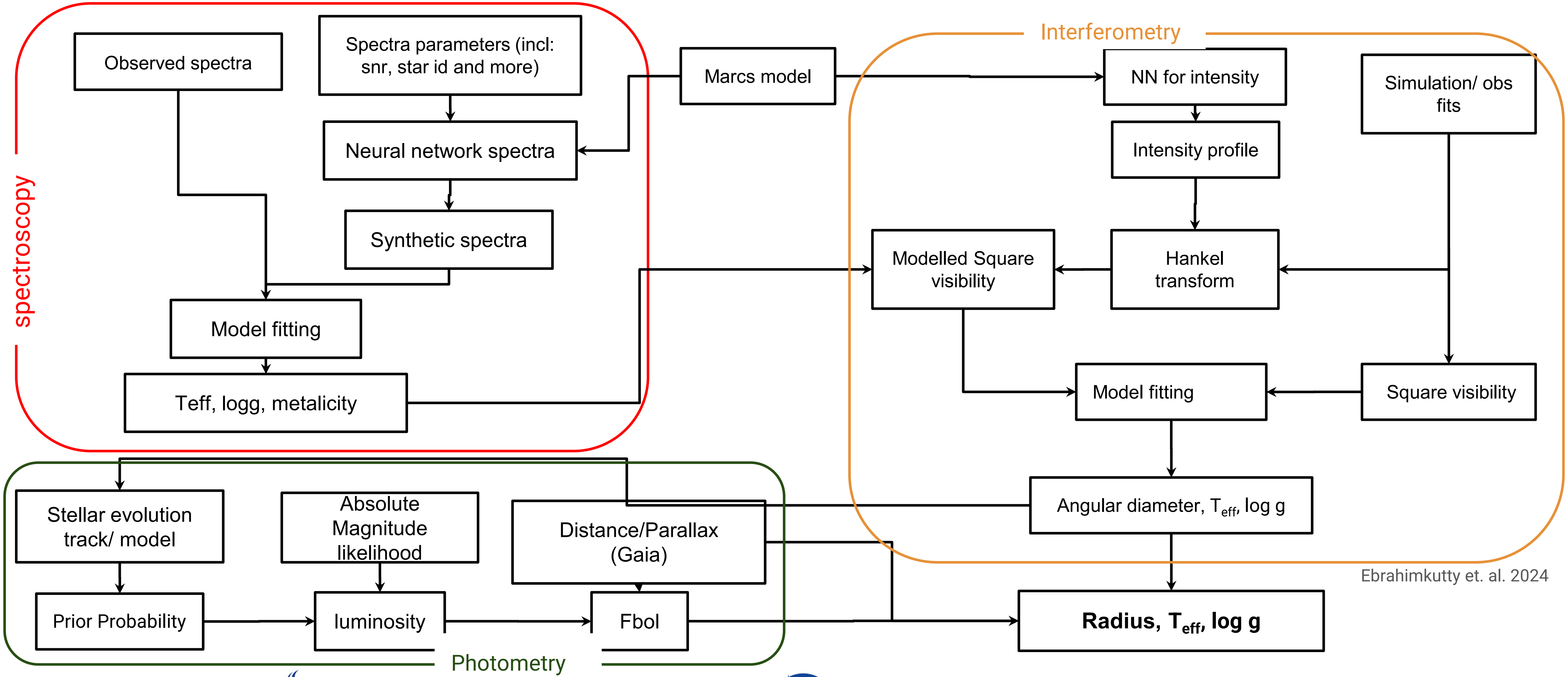
Parameter Determination

- We have developed a pipeline to employ an artificial neural network (ANN) to make a model fitting with stellar atmosphere models (here **MARCS**) and estimate the parameter from this fitting.

- In the pipeline we combine observations from **Spectroscopy**, **Interferometry** and **Photometry** to give an accurate estimation of the fundamental parameters. **Spectroscopic** and **Photometric** modules adapted from the **PLATO MSteSci1** pipeline.

- The idea is to use the parameters from the **Spectroscopy** module obtained using an ANN and guide the model fitting in the **Interferometry** and them combine this result with the **Photometry** to get an accurate estimation of stellar parameters.

Pipeline



Ebrahimkutty et. al. 2024

Grid to train Neural Network

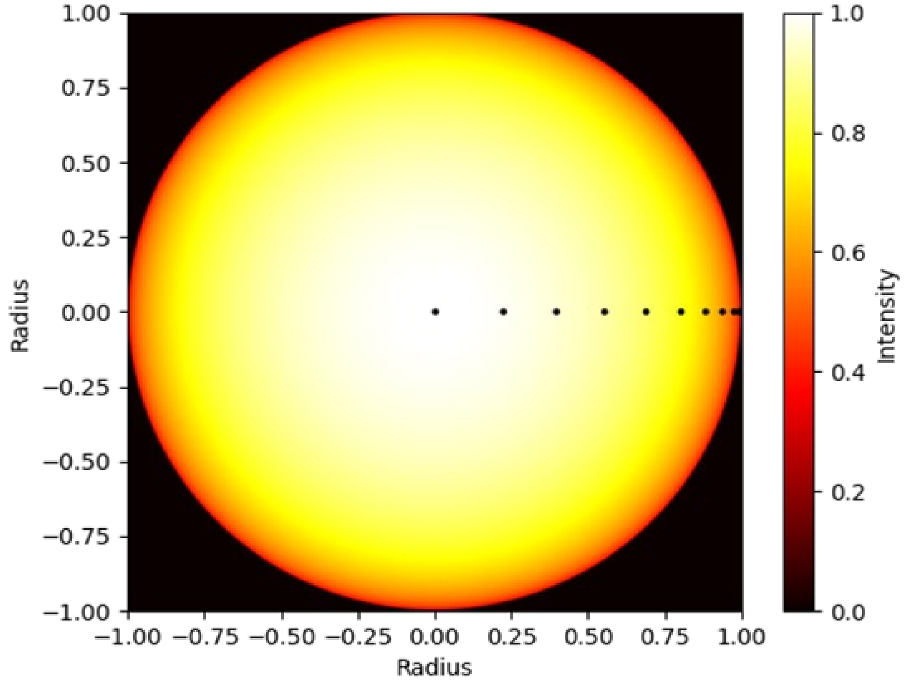
We finished modelling the intensity profiles in the R, H and K bands using Turbospectrum.

- Teff 4500-7000 K
- log g 3-5 dex
- Solar metallicity
- 12 Radau sampling points
- Resolution 300000

We trained the Artificial Neural Network (ANN) with this data, reducing the number of wavelength to 500 for each band and setting the resolution to ~1000.

Using the training, we extend the interferometric module to fit the data from these ranges.

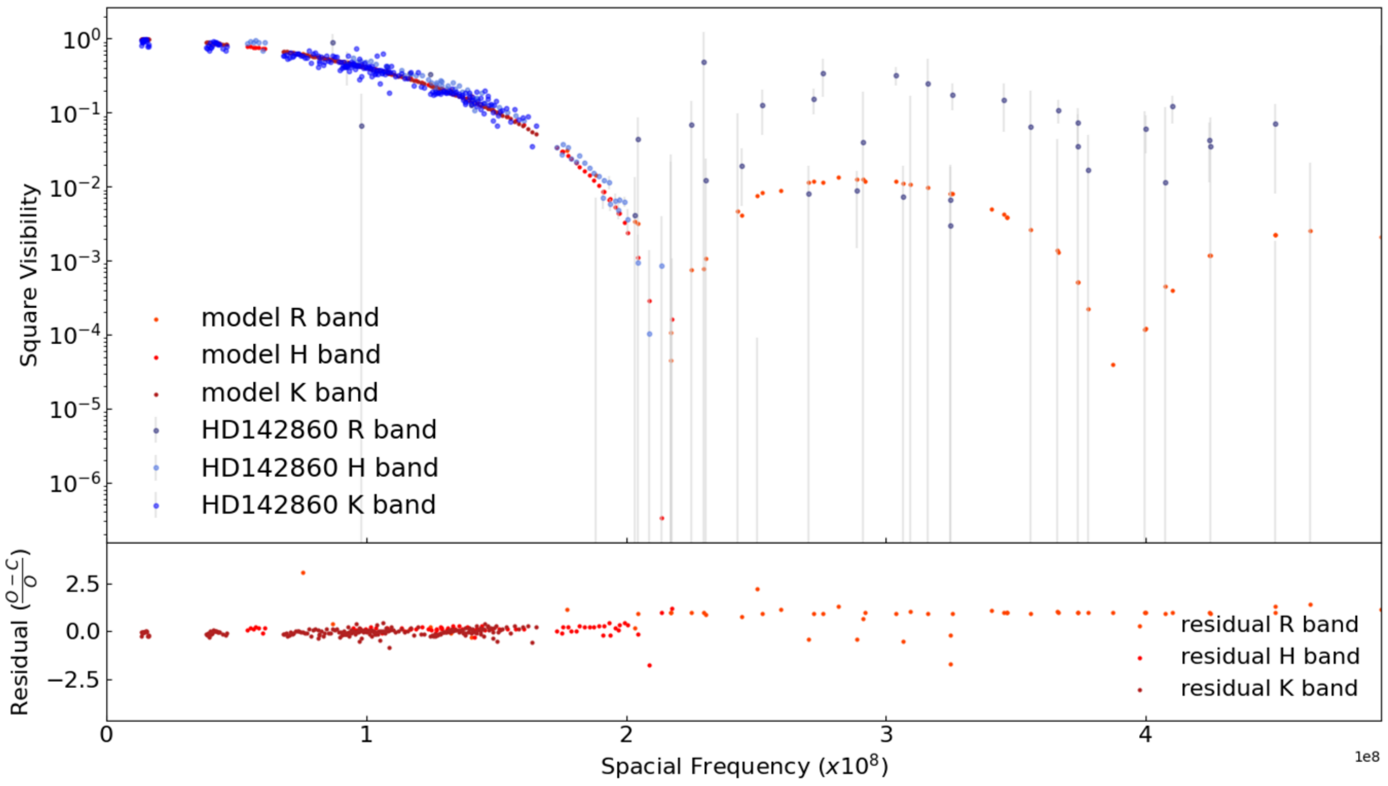
The new method is able to adapt to the actual spectral channels; It works on all three observing bands.



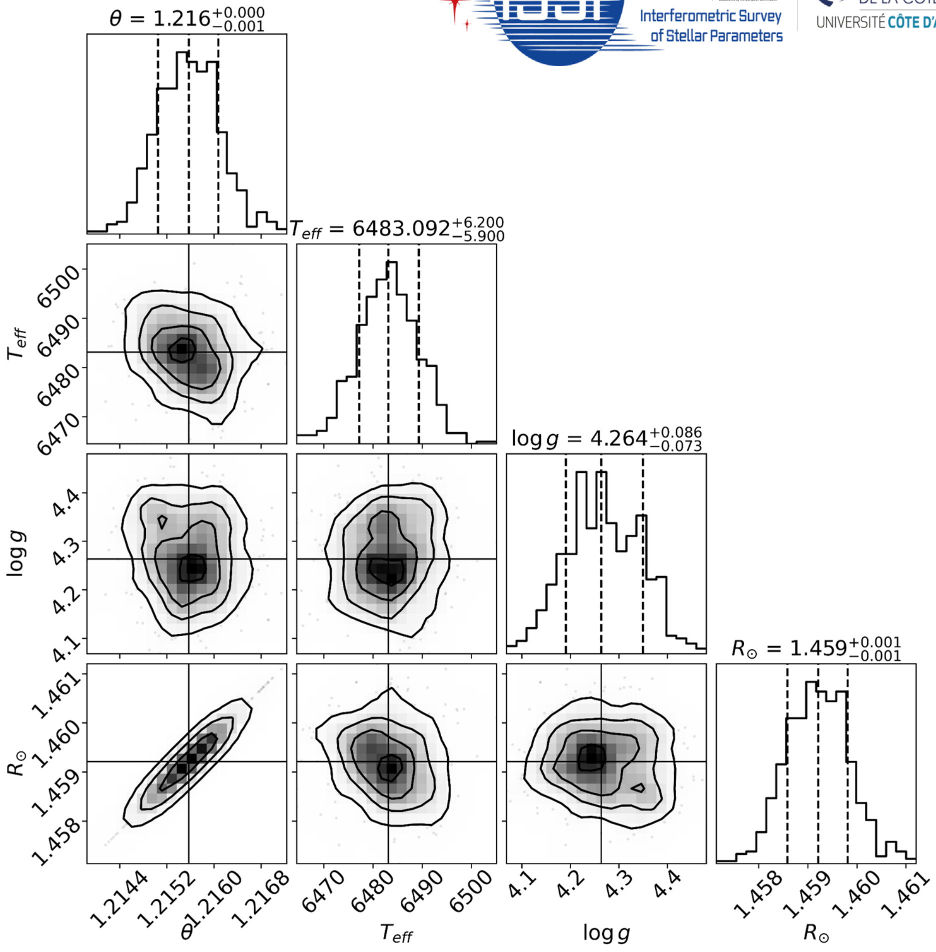
the intensity profiles is considered with 12 Radau points to ensure correct calculations of visibilities up to the third visibility lobe.

Fitting with pipeline - HD142860

Fitting interferometric data from SPICA, MIRCX and MYSTIC guided with spectroscopic and photometric module.



ISSP S04 star (Romina Ibañez-Bustos)



Angular diameter (θ): 1.216 ± 0.001 mas

Eff. Temp. (T_{eff}): 6483 ± 12 K

log g: 4.264 ± 0.159 dex

Radius ($R_{\odot}$): 1.459 \± 0.001 $R_{\odot}$

ISSP Observations

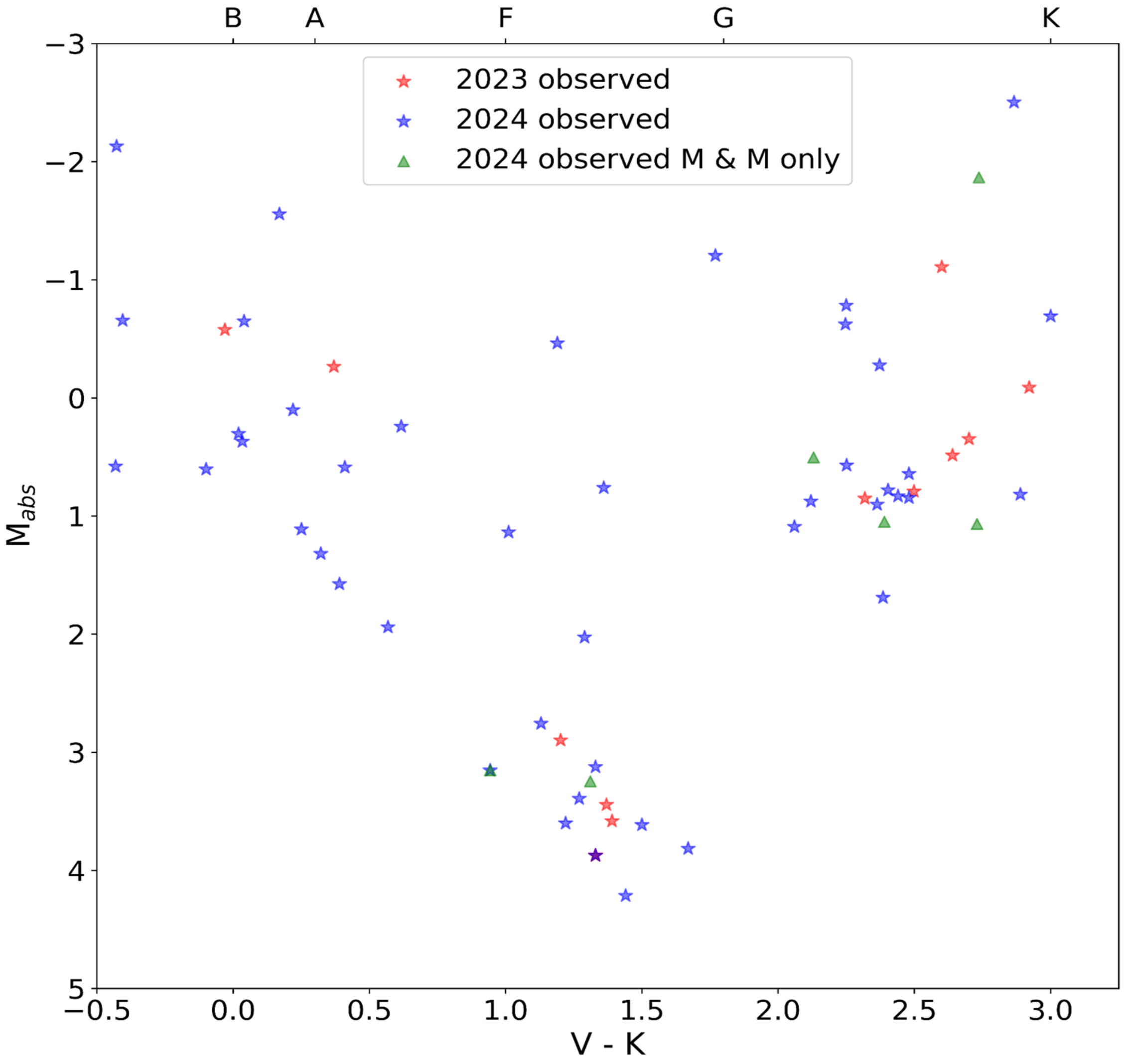
As part of ISSP in 2023B, our program observed over 15 stars. However, most of the observations were of low quality due to weather conditions and other technical reasons.

In 2024, we made a total observations of:

- SPICA + MIRC-X + MYSTIC: 40+ stars
- MIRC-X + MYSTIC: 6 stars

The analysis is ongoing, and so far, we have identified a few promising stars that could potentially be suitable for publications.

We are continuing our observations into 2025A.



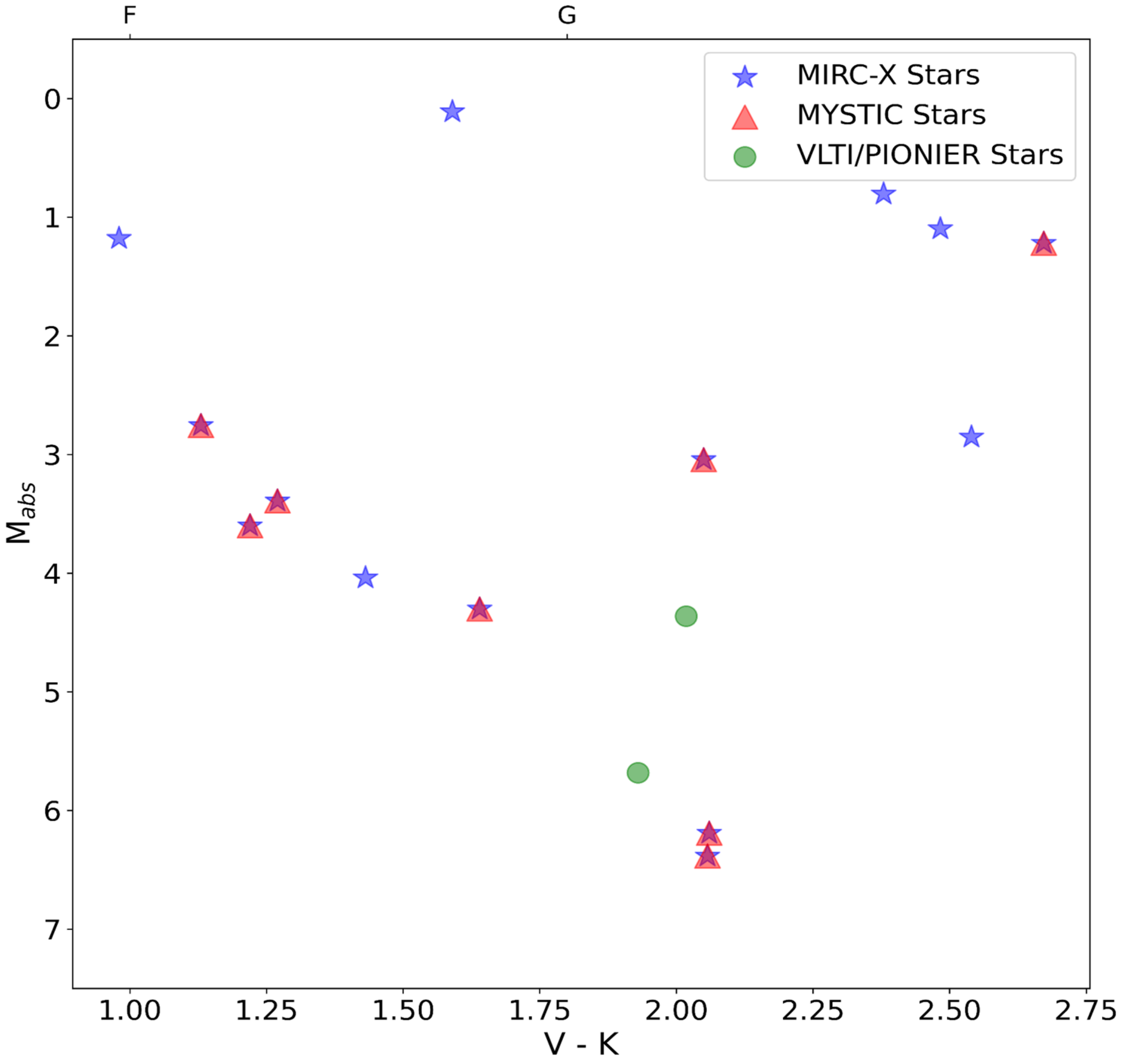
Additional data

In addition to the stars observed within the ISSP program, this method can be applied to stars from any instruments that fall within the range of the trained artificial neural network (ANN).

We have requested access to MIRCX (blue) and MYSTIC (red) data from the archive to run the pipeline using these datasets.

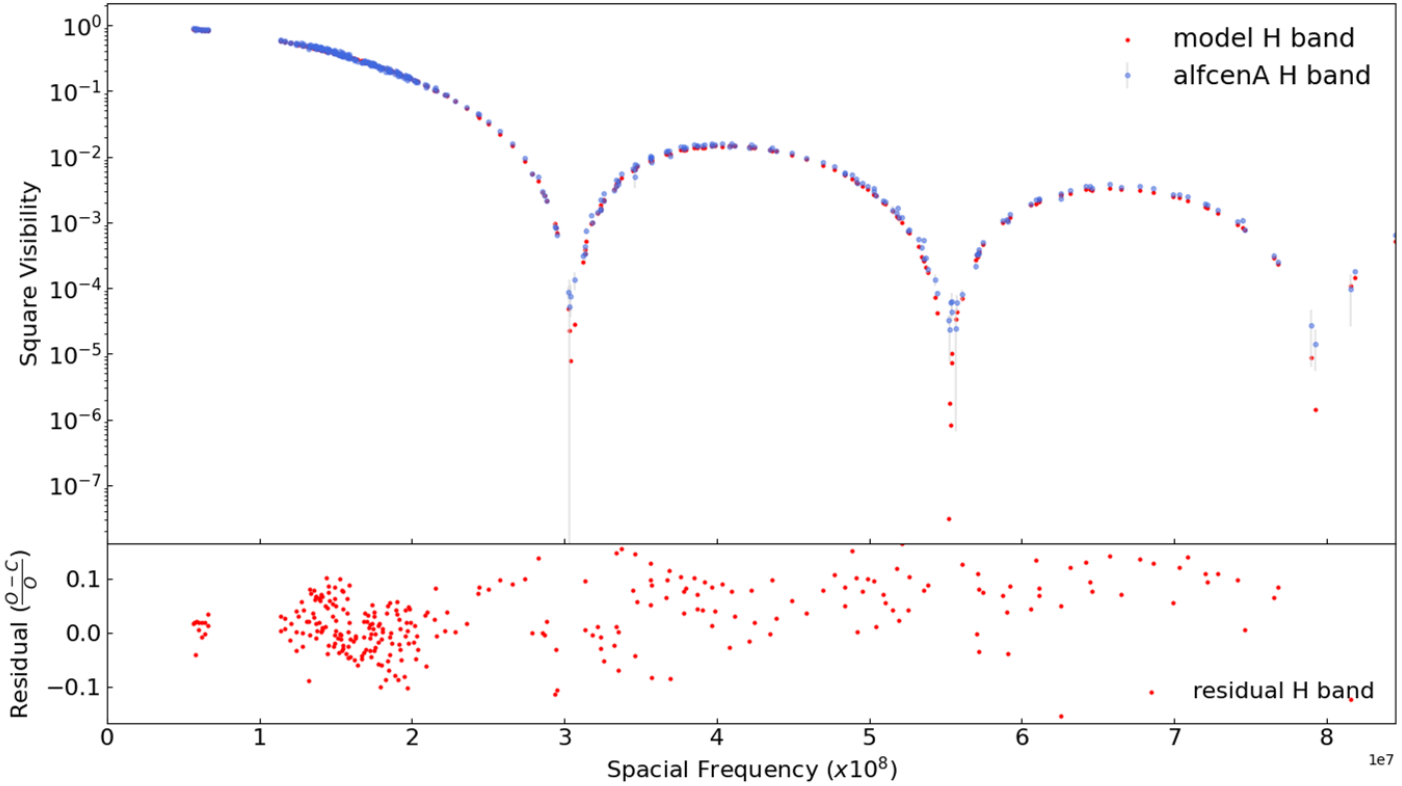
From this, we have shortlisted a few stars that are compatible with this pipeline, and we will attempt to fit these data shortly.

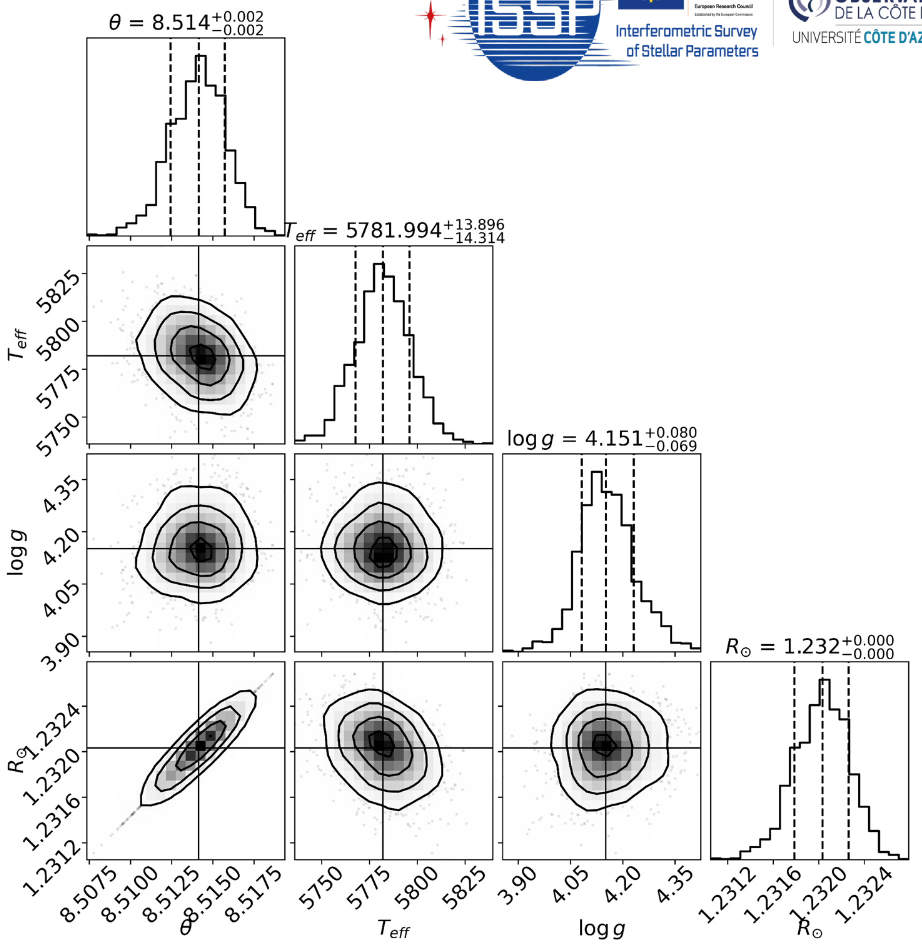
Furthermore, we have successfully fitted data for Alpha Centauri A and B from the VLTI/PIONIER (green) using this method.



VLTI/PIONIER Data - alf Cen A

Fitting interferometric data from VLTI/PIONIER guided with spectroscopic and photometric module.





Values from Kervella et al. 2017

Ang diam - 8.502 ± 0.036 mas Eff Temp. 5795 ± 19 K

log g - 4.3117 ± 0.0015 dex Radius 1.2234 ± 0.0053 $R_\odot$

Angular diameter (θ): 8.513 ± 0.003 mas

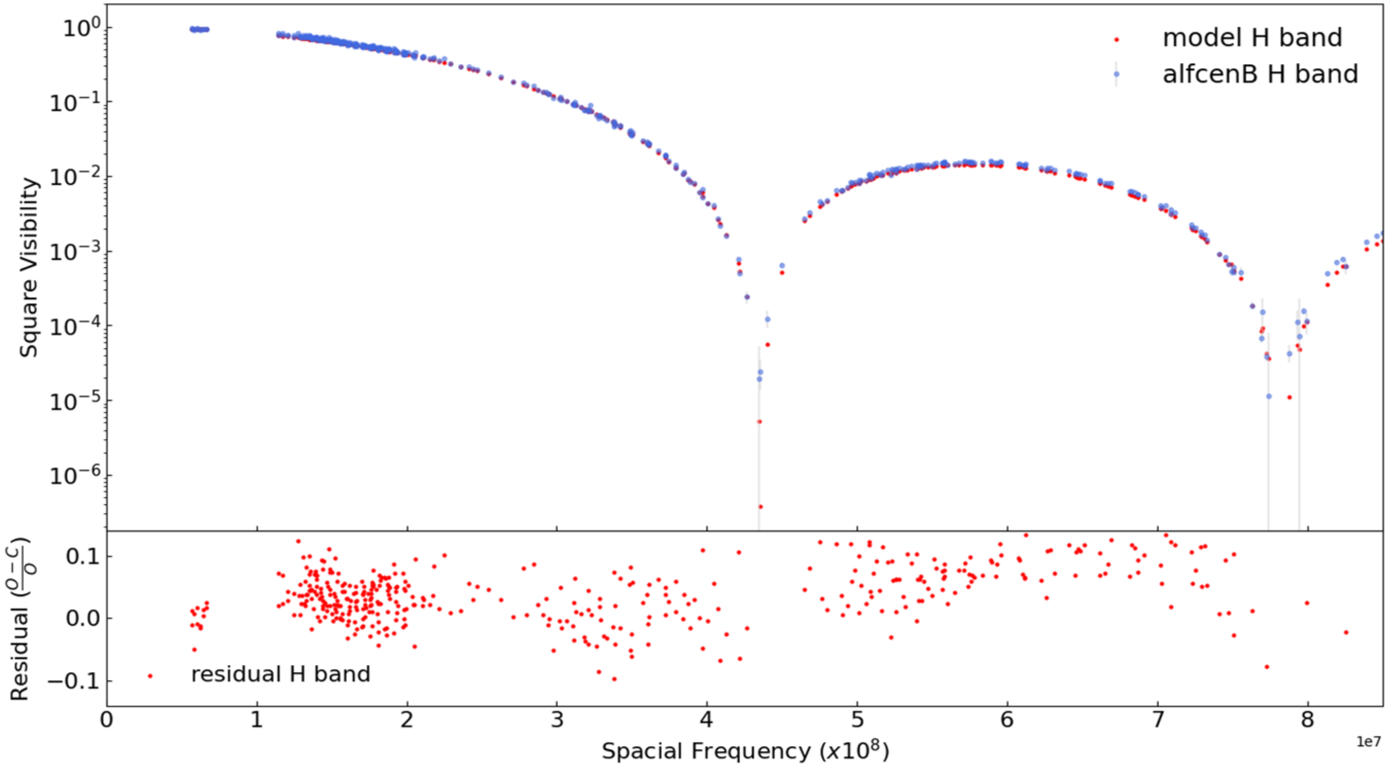
Eff. Temp. (T_{eff}) : 5783 ± 28 K

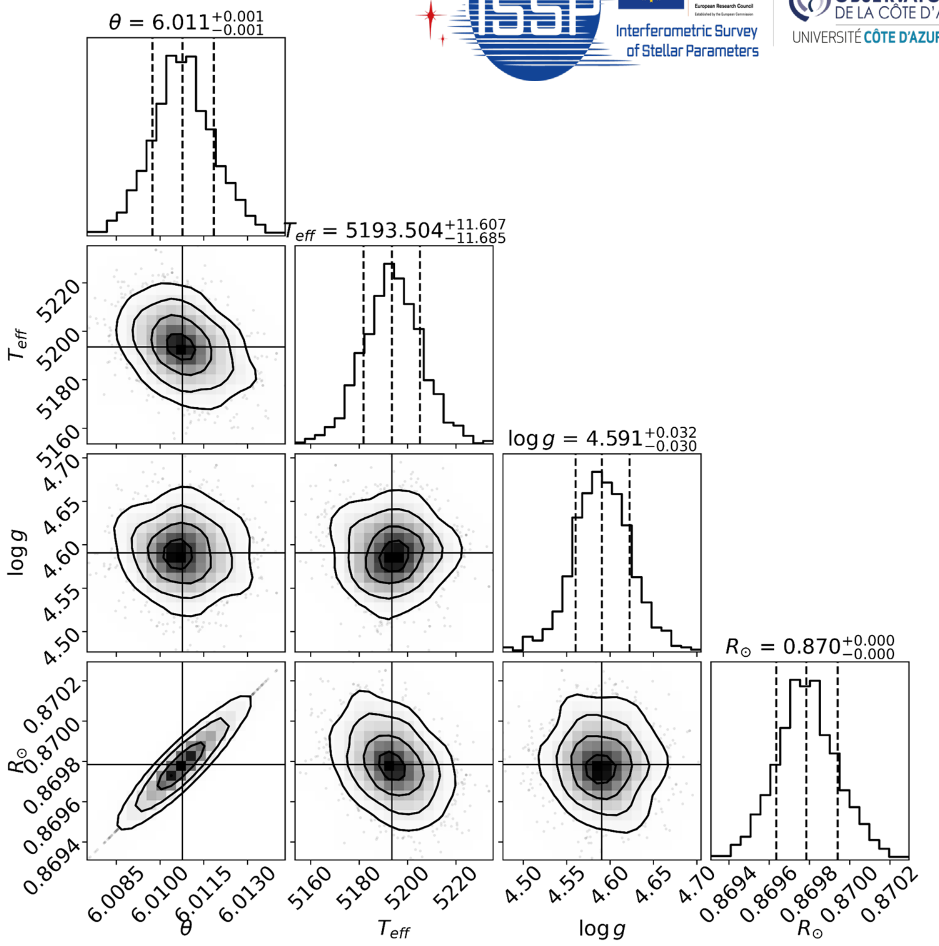
log g: 4.151 ± 0.149 dex

Radius ($R_\odot$): 1.232 ± 0.001 $R_\odot$

VLTI/PIONIER Data - alf Cen B

Fitting interferometric data from VLTI/PIONIER guided with spectroscopic and photometric module.





<u>Values from Kervella et al. 2017</u>

Ang diam - 5.999 ± 0.025 mas Eff Temp. 5231 ± 21 K

log g - 4.5431 ± 0.0015 dex Radius 0.8632 ± 0.0037 $R_\odot$

Angular diameter (θ): 6.011 ± 0.002 mas

Eff. Temp.: 5193 ± 23 K

log g: 4.591 ± 0.062 dex

Radius ($R_\odot$): 0.8703 ± 0.0003 $R_\odot$

Future Work

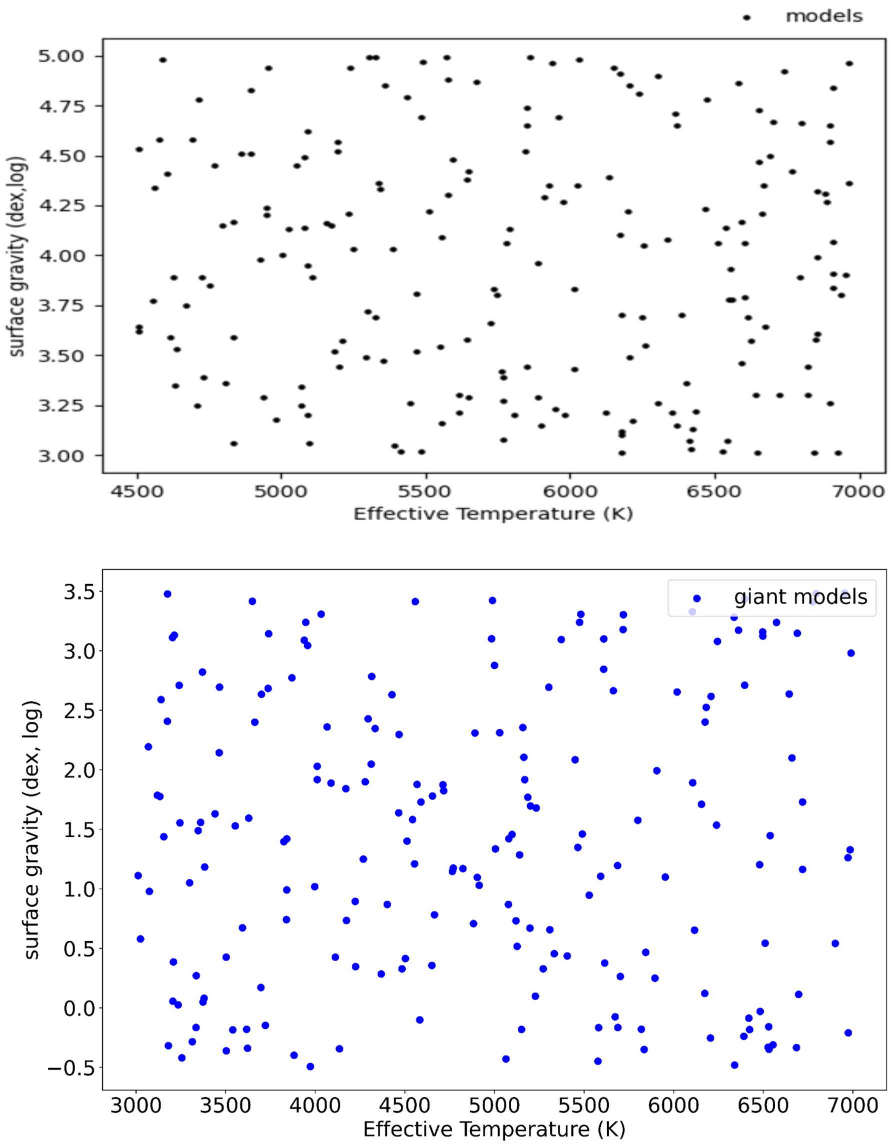
At present, the neural network uses plane parallel MARCS intensity grid

- Effective temperature 4500 to 7000 K
- Log g from 3 to 5 dex

Currently, the pipeline is primarily focused on dwarf stars, which limits us to examining only these types of stars.

In the next step, we will train a new ANN to analyze giant stars using the spherical MARCS models within the same framework.

Additionally, we will transition from 1D models to 3D models to enhance the accuracy of our fittings.



1D MARCS model to train ANN, dwarf (top) Giant (bottom)

Conclusion

Using the pipeline developed, we are able to determine the angular diameter of stars, along with other parameters to **1%** using the direct measurements from the interferometry.

We have a few promising data and we will have a more detailed analysis of the data will be conducted in the coming days adding to the ISSP survey.

An article (**Ebrahimkutty et al. 2025, in prep.**) on this work is under preparation which will be published this year.

We will soon expand the ANN grid to include both giant stars and dwarf stars.