Interferometric measurements

PLATO GOP Workshop – Geneva

Denis Mourard – OCA/Nice

19 Oct 2022

Basic principles

Interferometry means "*Fringes or Visibility/Closure Phase or Fourier Transform or Aperture Synthesis…*"

But Interferometry means also "brightness distribution" with a unique angular resolution allowing to 'see' details on stars.

"Brightness distribution" means:

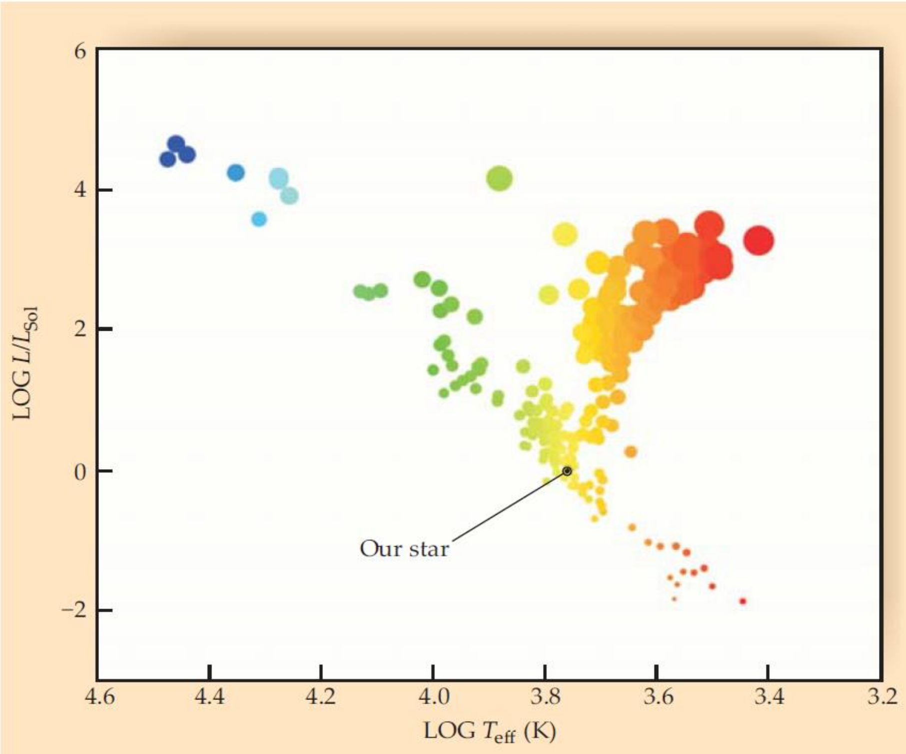
- Limb darkened diameter and limb darkening
  - ➔direct measurements of stellar parameters
  - ➔ calibration of Surface Brightness Colour relations

$$\boldsymbol{R} = \frac{\boldsymbol{\theta_{LD}}}{\mathbf{9.301}\pi}$$

$$\sigma T_e^4 = \frac{4 f_{bol}}{\theta_{LD}{}^2}$$

- Direct fit of intensity profiles from 1D/3D stellar atmosphere models. Constraints on surface of stars and environment.

Examples from these last decades (VLTI & CHARA)



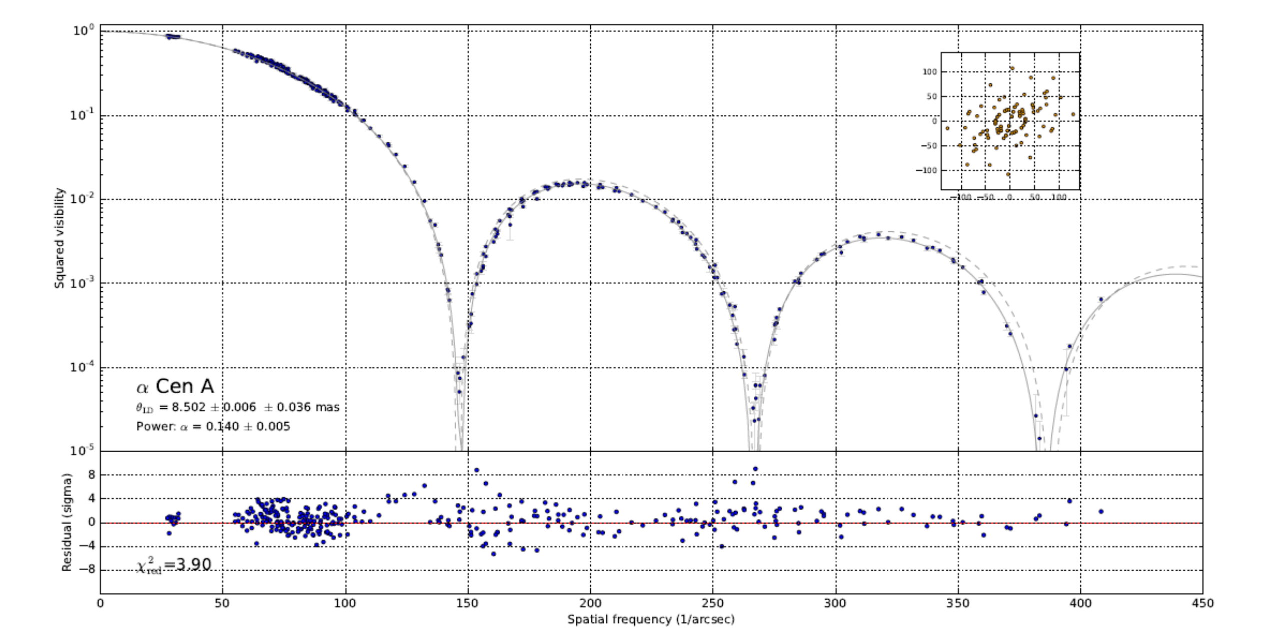
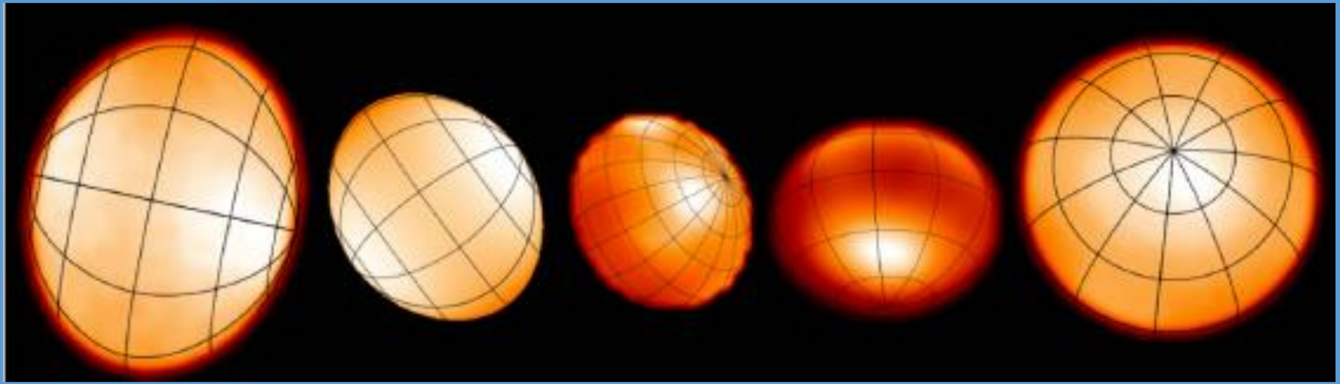
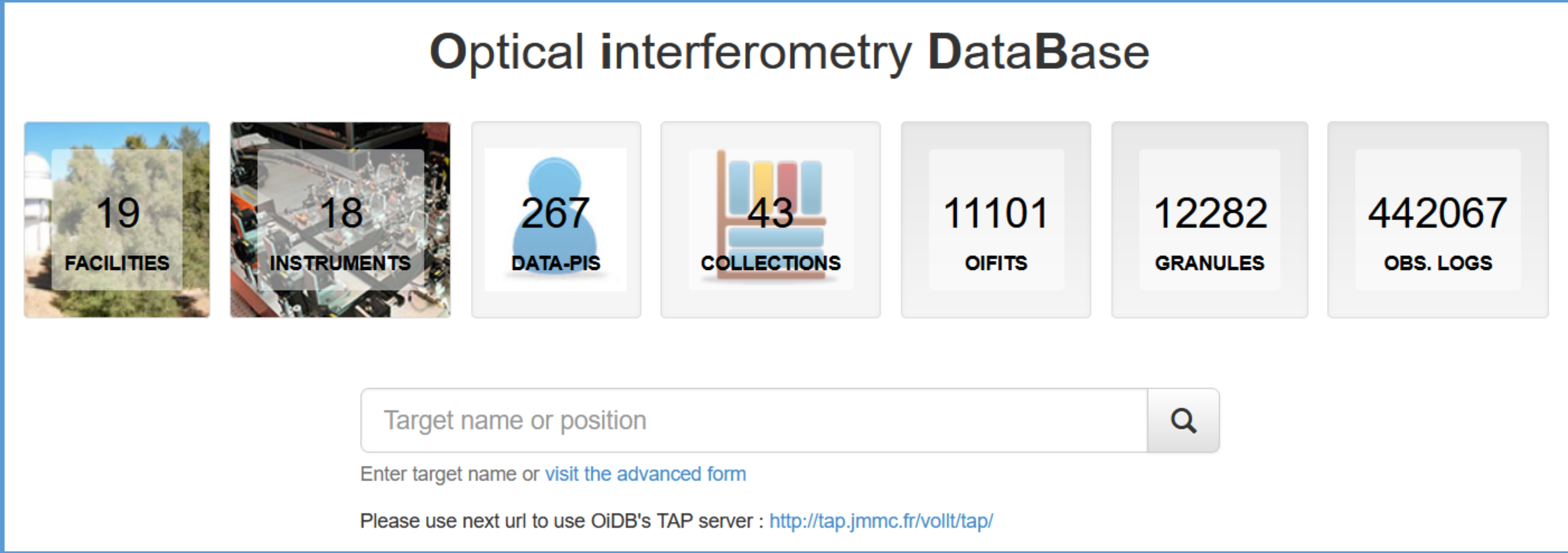


Fig. 3. Adjustment of a power law limb darkened disk model to the PIONIER squared visibilities of α Cen A (solid gray curve). The dashed gray curve represents the best-fit uniform disk model. The *bottom panels* show the residuals of the fit in number of times the statistical error bar. The coverage of the (u, v) plane is shown in the *upper right corner.*

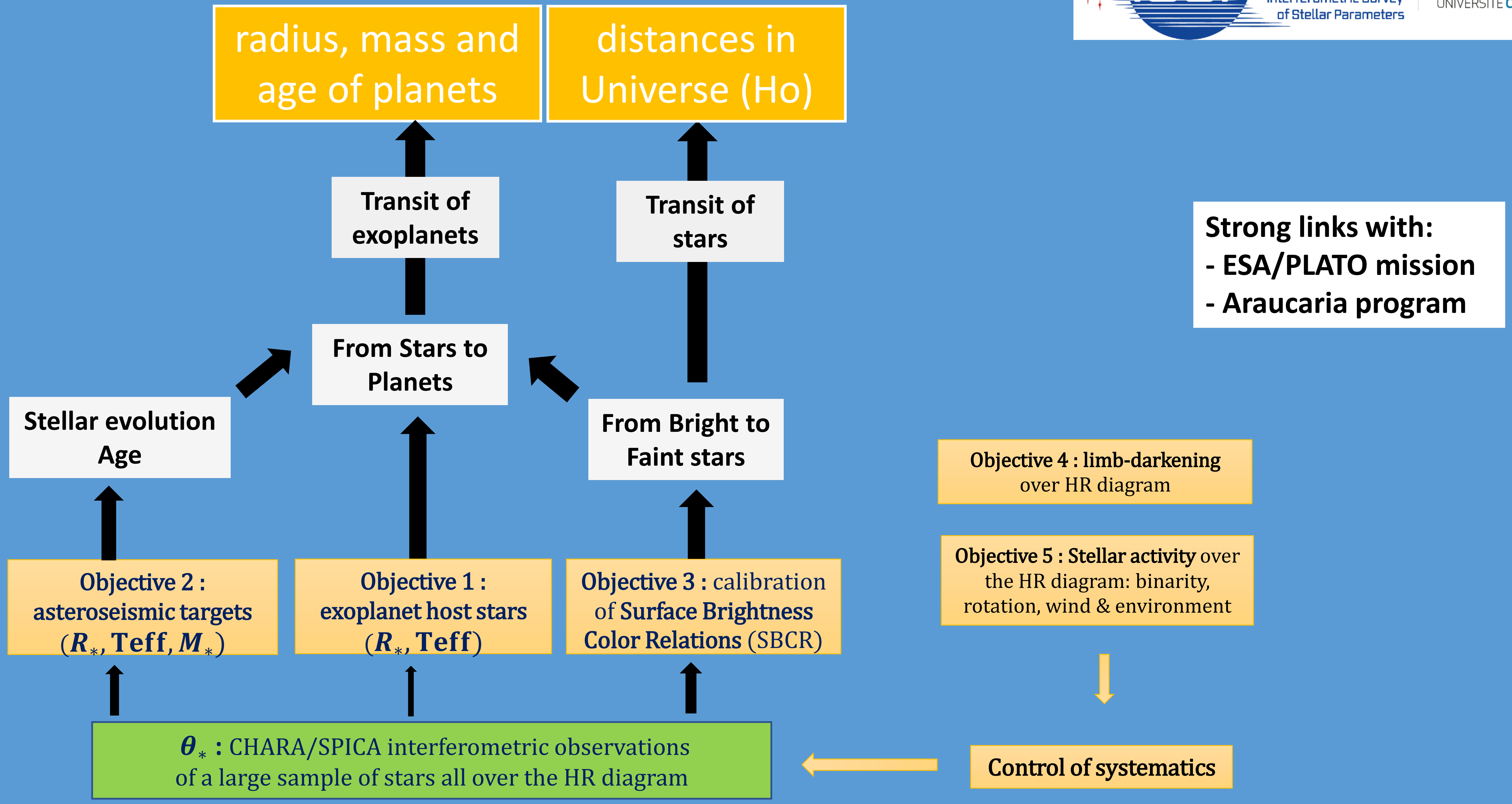




But in 20 years only ~400 stars with an angular diameter and uncertainty less than 2% (~150 with 1%)

And ~70% are giants! And mostly bright stars!

Interferometric Survey of Stellar Parameters

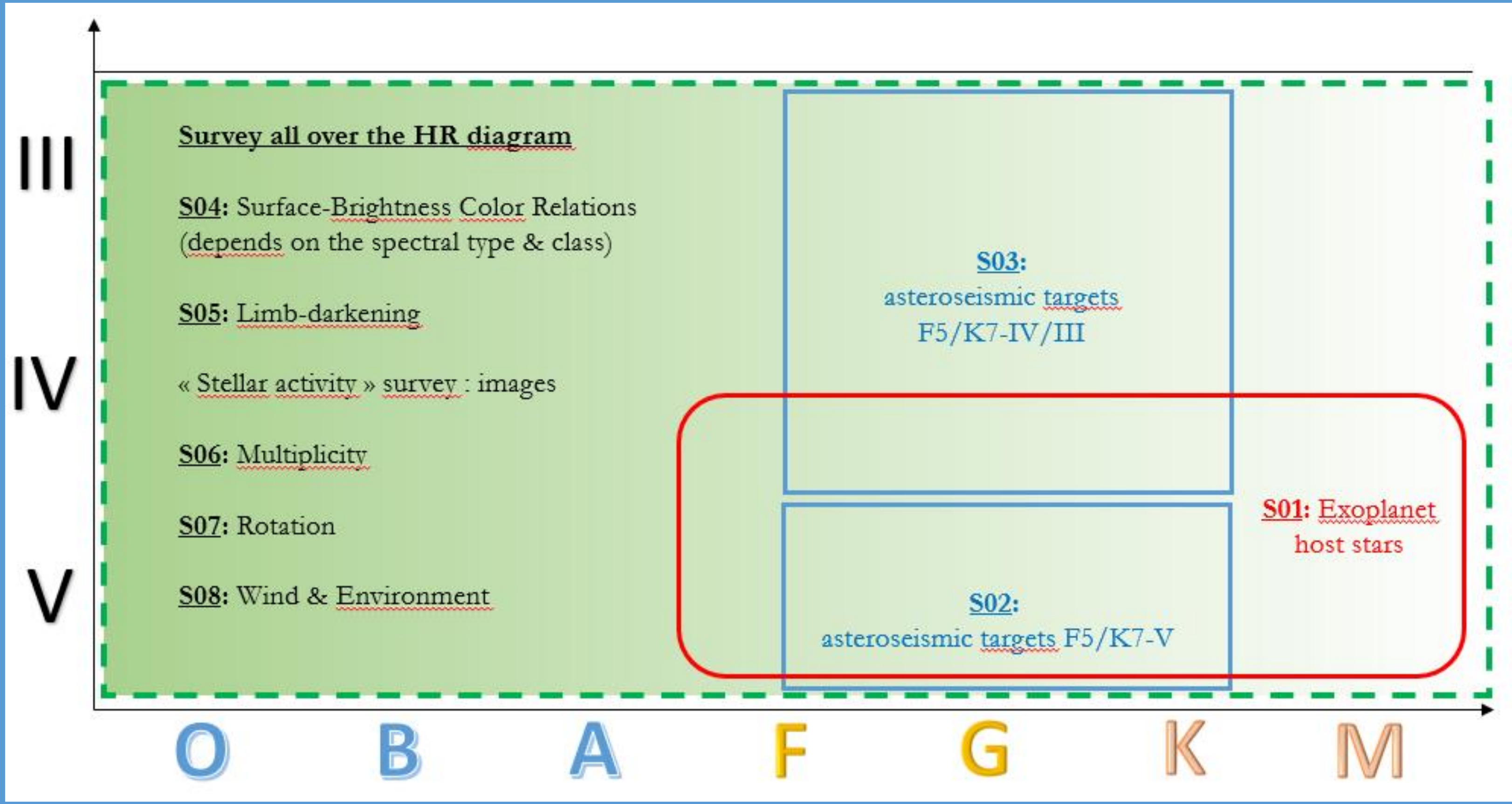


Definition of the main objectives of CHARA/SPICA

Measuring a large number of angular diameters

- To support the exoplanet researches through direct characterization of the host star.
- To support the direct determination of extragalactic distances through accurate and homogeneous SBC relationships, but also to permit precise and accurate angular diameter estimations for many different purposes (including characterization of faint exoplanet host stars).
- Many other science projects

~1000 stars in 3-4 years
(2023-2026)
~800 diameters
~200 images



The Input "HR" diagram for SPICA

Using SBCR relations for dwarfs and giants (Challouf+2014 f[illegible] DWARFS [illegible]5-K7 & M) , we can present the domains (green=OK, o[illegible] GIANTS [illegible]) in which SPICA will be able to measure angular diameter with a precision of 1% as a function of the [illegible] color index:

With a priori on LD

Dwarfs	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
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
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25

Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
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	0,11	0,19	0,33	0,58	0,99	1,69
10	0,00	0,01	0,03	0,07	0,12	0,21	0,36	0,62	1,06

And finally the domains in which SPICA will be able to measure limb darkened angular diameter at a precision of 1% and the limb darkening coefficient at the same time:

Without a priori on LD

Dwarfs	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
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
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25

Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
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	0,11	0,19	0,33	0,58	0,99	1,69
10	0,002	0,011	0,032	0,067	0,118	0,207	0,364	0,623	1,065

Status of CHARA/SPICA

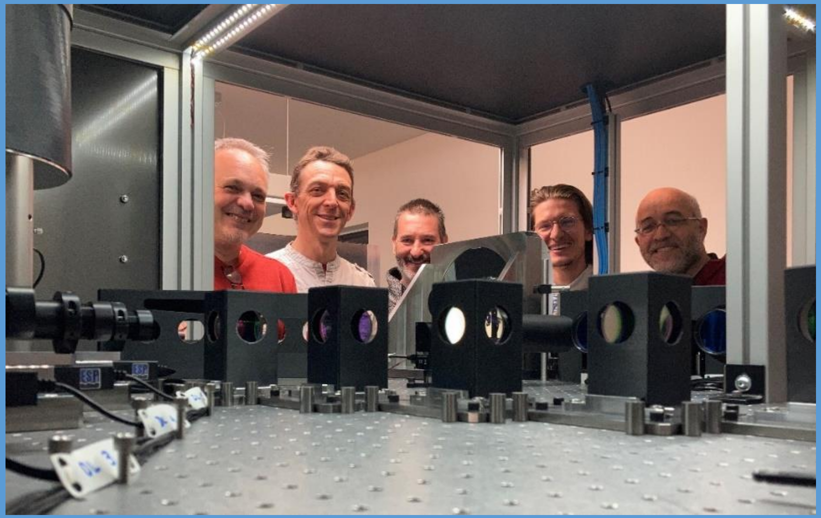
- Integration done in Feb-Mar in Mt Wilson
- Commissioning still going on, first fringes ok.
- Science Verification this winter
- Survey will start in 2023A (Mar-Jul 2023)
- Wider opening to the community in 2023B (call in Jun. 2023)

- **Other main activities**
  - Finalization of the list of targets for the Survey + software tools
  - Science analysis up to the high-level products (R, Teff, Age, Mass)

- **ERC-Adv 2020 Grant "ISSP"** will support the CHARA/SPICA survey (200n guaranteed, operation, science postdocs > Nov 2022)
  - Postdoc1: exoplanet host stars + stellar evolution models (Age and Mass)
  - Postdoc2: astero+interfero (scaling relations) + stellar atmosphere models (R, T)
  - Postdoc3: SBCR + IR photometry/spectroscopy (bright targets)
  - + 1PhD on multiplicity ➔ masses (starting on 1 Dec 2022)

CHARA/SPICA in a nutshell

6 x 1m telescopes (DEC>-30°)
H-band fringe tracking
330m baseline
600-900nm operation (+H/K data)
Spatial resolution 0.1mas
Spectral Resolution **140**, 4300, 14000
Limiting Magnitude 7-8 (TBC)
Survey mode (~50 to 100n/year)



Current activities within WP122 & WP145

- **Extraction of stellar parameters (classical way)**
  - Classical way with LD fit on interferometric data ➔ pipeline already in place but hypothesis on LD description. Need for Fbol and π to compute R and Teff.

PLATO - TECHNICAL NOTE

PLATO-OCA-PSPM-TN-0061

Issue 1 Revision 0

- **Extraction by direct adjustments of intensity profiles from stellar atmosphere models**
  - Work done with Armando Domiciano (JMMC/AMHRA) + Maria and Matt (Heidelberg)
  - Decision taken to use 12 points, following the Radau distribution, for sampling the intensity profiles.
  - Computation (only once) of :
    - Intensity profiles in the spectral channels of SPICA for all models of the grid (1D/3D)
    - Machine Learning training on this grid of intensity profiles (in progress)
  - Minimization process on actual data, based on the training function + the Hankel transform of the intensity profiles (➔ Interferometric Visibility) of all intensity profiles (Teff, Logg, λ)

  ➔ **interferometric stellar parameters (+ probability density functions)**

PLATO - TECHNICAL NOTE

PLATO-OCA-PSPM-TN-0077

Issue 2 Revision 2

- <u>To be done</u>: Validation on benchmark stars within the SAPP pipeline

Surface Brightness Color Relations (SBCR)

PLATO - TECHNICAL NOTE

PLATO-OCA-PSPM-TN-0061
Issue 1 Revision 0

- G (Gaia) + Ks (2MASS) + SBCR calibrated from interferometry = angular diameter of <u>*any star even faint*</u> (+Teff if fbol available)

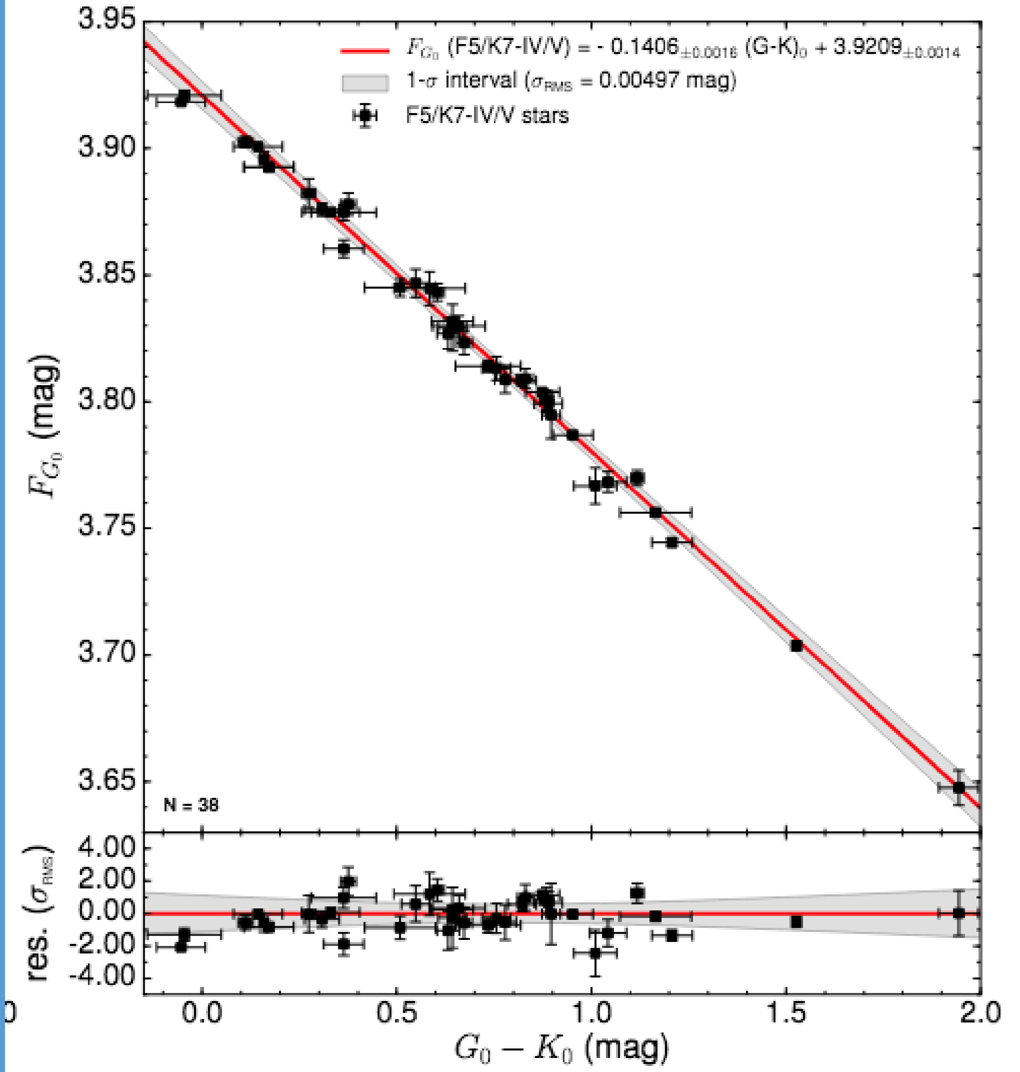
- To reach **1%** of precision on the angular diameter, one needs **0.012 mag** of precision on the photometry's (G and Ks), **0.0022 mag** of RMS on the SBCR, **0.085 mag** of precision on the extinction.

- *Special note*: the SBCR is slightly sensitive to class and metallicity (Cf. **Salsi+22** work based on MARCS models, in press). ~**0.5 dex of precision** is required for logg and Fe/H, respectively.

- <u>The method is *extremely simple, precise (if good photometry) and robust*</u>:
  - ✓ 1% of precision on the distance of LMC with eclipsing binaries (**Pietrzynski+19**); 2% on the SMC distance (**Graczyk+20**)
  - ✓ Consistent with SAPP pipeline results photo/spectro (**Gent+22**)

- Expected relative precision on radii with PLATO:

2% (P1), 2.5% (P2), 1.7% (P4), 2.7% (P5)
  - ✓ the main limitation is the precision on 2MASS photometry
  - ✓ Need to improve the RMS of the SBCR with CHARA/SPICA (currently 2.3% (see figure)



Samples for future SBCRs with SPICA/ISSP

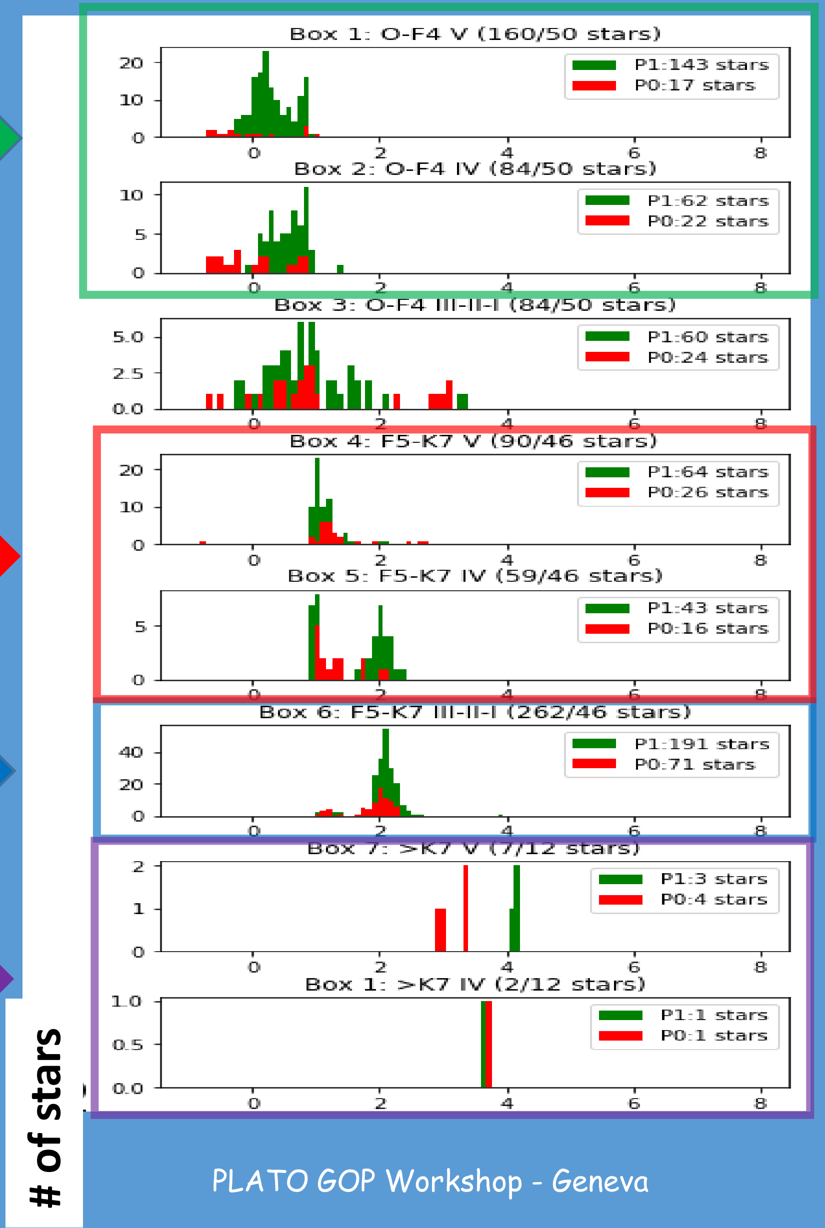
G-Ks

~100 targets to calibrate the SBCR of dwarf early-type stars for the distance of eclipsing binaries in M31 and M33 (**Araucaria**)

~92 targets to calibrate the SBCR for F5-K7 IV/V stars in the context of **PLATO**

~46 targets to calibrate the SBCR of giant F5-K7 stars for the distance of eclipsing binaries in LMC and SMC (**Araucaria**)

~10 V/IV later than K7 (tbc)



- A special care to **weak stellar activity** : faint companion, slow rotation (50km/s correspond to 1% of flattening), weak wind/environment
- The possibility to increase the samples by 50% if **an infrared photometer for bright objects is developed**. Also, for these bright resolved stars, limb-darkening can be measured (check of atmosphere models) !
- **Complementary work on spectroscopy** needed (logg, Fe/H) and also extinction (use of different approaches)

Synergy between CHARA/SPICA and the PLATO space mission

- Direct CHARA/SPICA contribution into **WP120** « Stellar Science » . VLTI is also considered for southern targets but with some limitations in terms of angular diameter.

- Part of WP14 Ground Observing Program (Before and During Operation)

Before operation: use of <u>CHARA/SPICA measurements</u> into the PLATO pipeline. 200n secured through ERC funding

During operation: CHARA/SPICA follow-up

From bright to faint stars

Before operation: implementation of <u>SBCRs</u> into the PLATO pipeline; validation of the methodology using PIC catalogue or benchmark stars (Gent+21)

During operation: use of CHARA/SPICA SBCR in the PLATO pipeline

Thanks to CHARA and SPICA teams, N. Nardetto, T. Morel, M. Bergemann, S. Udry, N. Mowlavi
+ ISSP Team: J. Dejonghe, P. Geneslay, D. Salabert + C. Pannetier, J. Jonak (PhDs) + R. Ligi, R. Ibanez, xxx (postdocs)
+ O. Creevey, S. Deheuvels, A. Domiciano, N. Nardetto, K. Perraut, M. Wittkowski (coI ISSP)