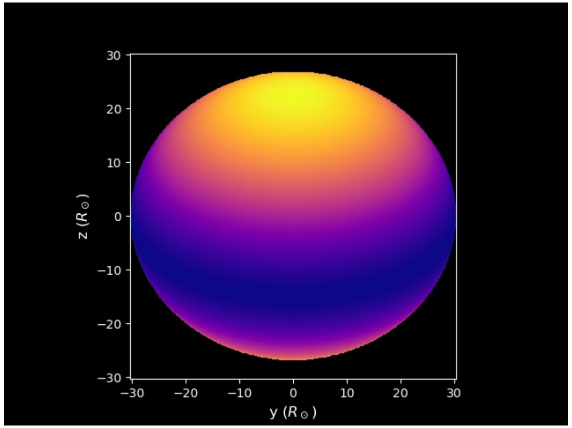
# ISSP meeting - CHARA/SPICA
# Nice 30/5 to 1/6/2023

European Research Council
Established by the European Commission

Interferometric Survey of Stellar Parameters



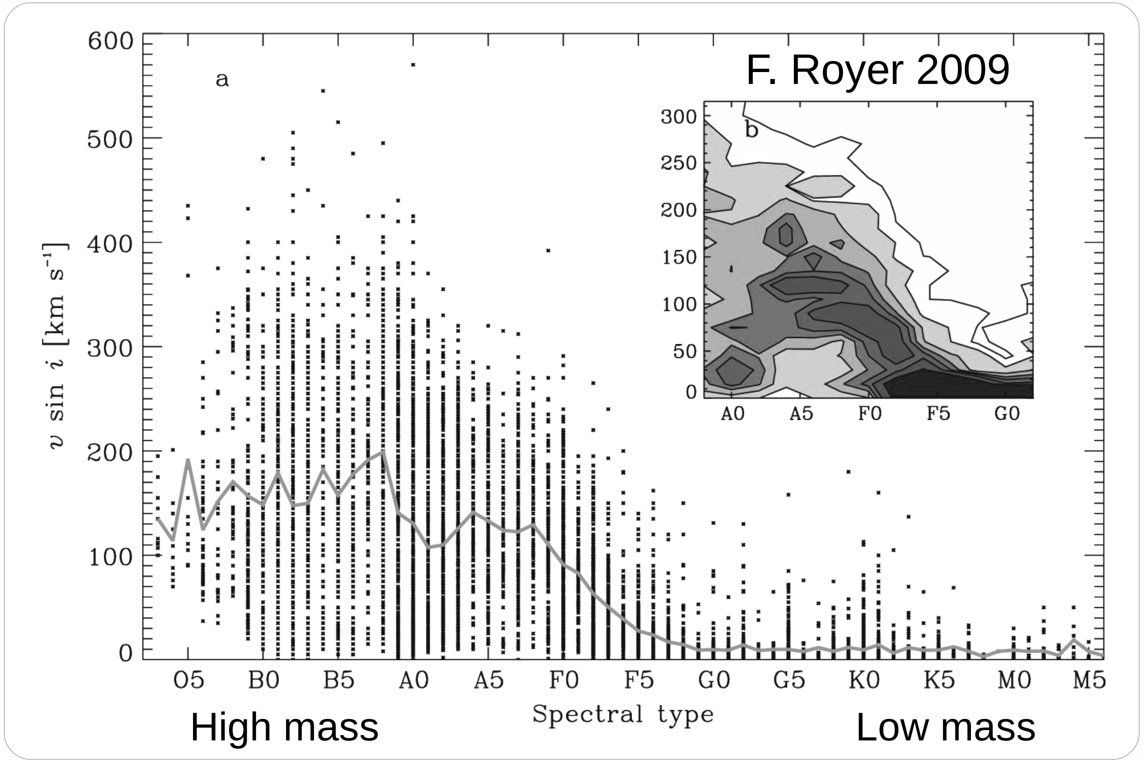

## S07 : Stellar rotation across the HR diagram with SPICA

**A. Domiciano de Souza**

*Initial list of col :* S. Albrecht, A. Claret, A. Gallenne, P. Kervella, A. Meilland, N. Nardetto, M. Rieutord, R. M. Roettenbacher, P. Stee

# S07 Rotation: aim

Study stellar rotation in all HR diagram



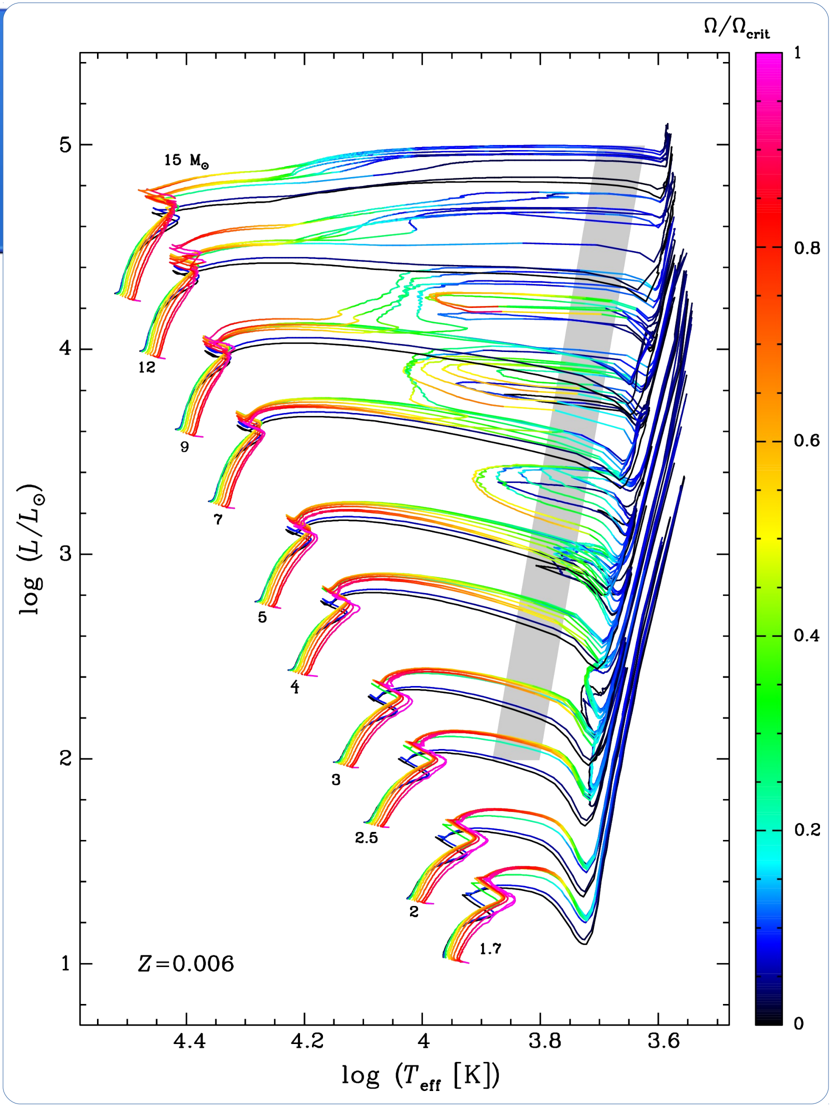
# S07 Rotation: aim

Study stellar rotation in all HR diagram

Rotation impacts evolution:

Evolutionary tracks modified

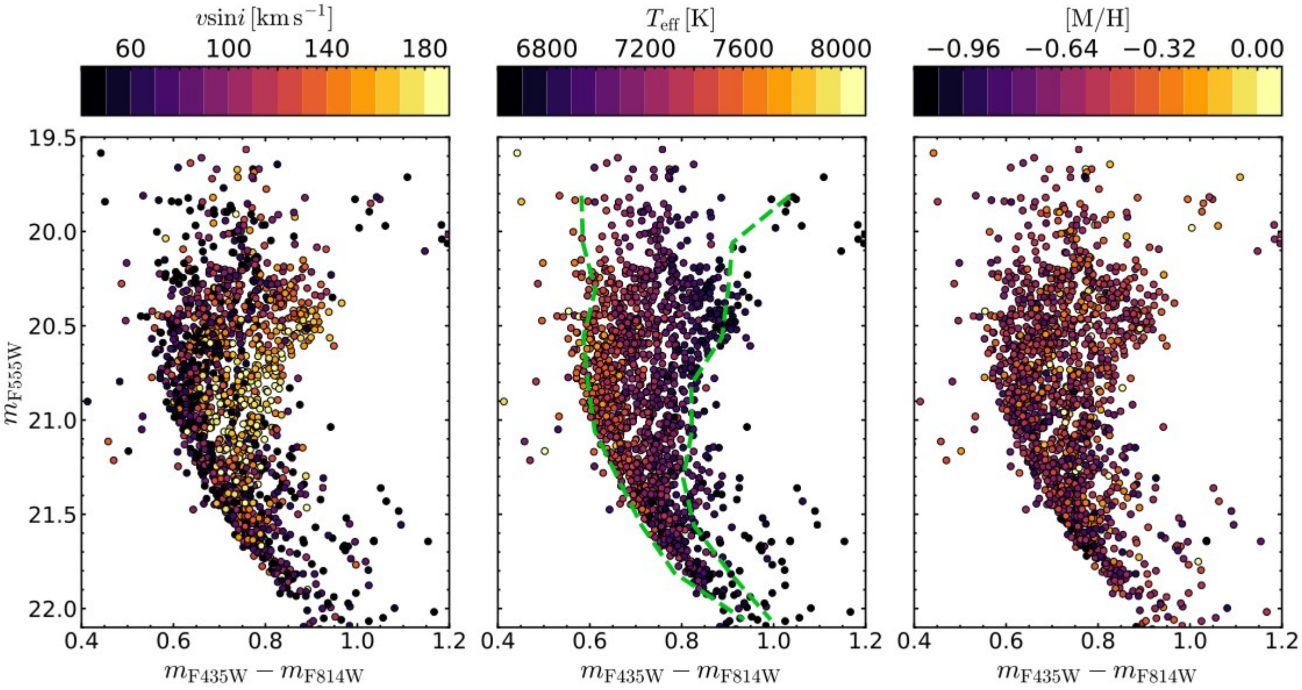
Rotational mixing brings new H in the core
→ longer time spent on MS + different abundances




Georgy et al. 2013

# S07 Rotation: aim

Study stellar rotation in all HR diag




NGC1846 ; Kamann et al. 2020

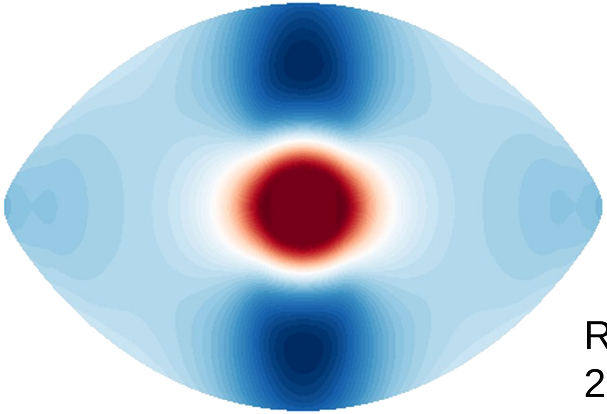
# S07 Rotation: effects of rotation

- Flattening → $R_{eq} > R_p$ (centrifugal force)

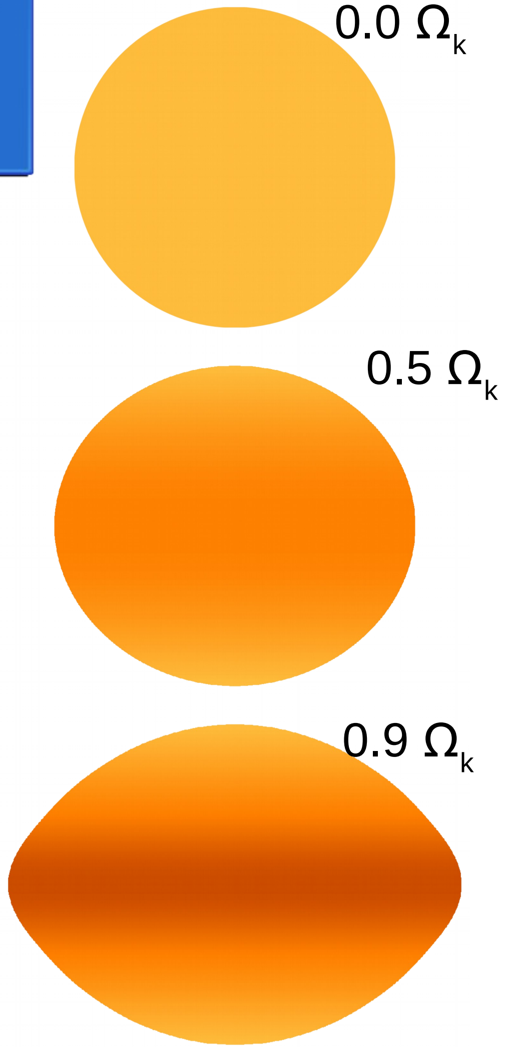
$$\epsilon \equiv 1 - \frac{R_p}{R_{eq}} = \frac{V_{eq}^2 R_p}{2GM} = \left(1 + \frac{2GM}{V_{eq}^2 R_{eq}}\right)^{-1}$$

- Gravity darkening (GD)

- Baroclinicity → differential rotation & meridional circulation



Rieutord et al. 2016



# S07 Rotation: effects of rotation

**Gravity darnening** (flux of the rotating star becomes dependent on the latitute)

$$F = \sigma T_{\rm eff}^4 = C g_{\rm eff} \quad \Rightarrow \quad T_{\rm eff} = \left(\frac{C}{\sigma}\right)^{0.25} g_{\rm eff}^{0.25}$$

(von Zeipel 1924)

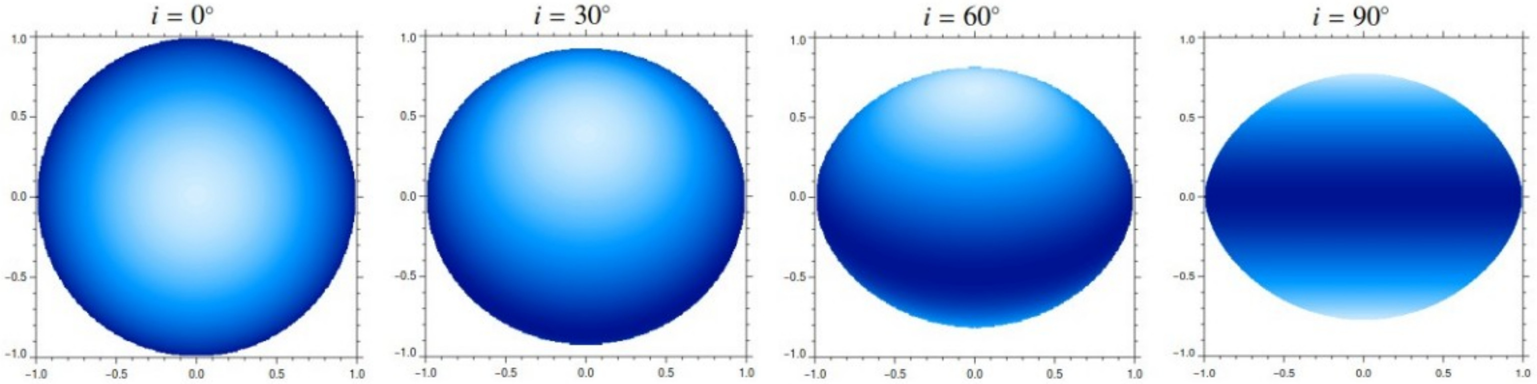



**Fig. 2.** Effective temperature maps for $D = 0.78$ (model A in Table 1), $\beta = 0.25$ and different inclinations. The polar (maximum) and equatorial (minimum) effective temperatures are $T_{\rm p} = 35\,000$ K and $T_{\rm eq} = 25\,100$ K, respectively. Abscissas ($y$) and ordinates ($z$) are normalized by the equatorial radius $R_{\rm eq}$. Note that the projected geometrical deformation increases with higher inclinations but the stellar size in the $y$ direction is constant. Since the local radiative surface flux is defined by $F(\theta) = \sigma T_{\rm eff}^4(\theta)$ this figure gives and idea of the projected brightness changes from pole to equator.

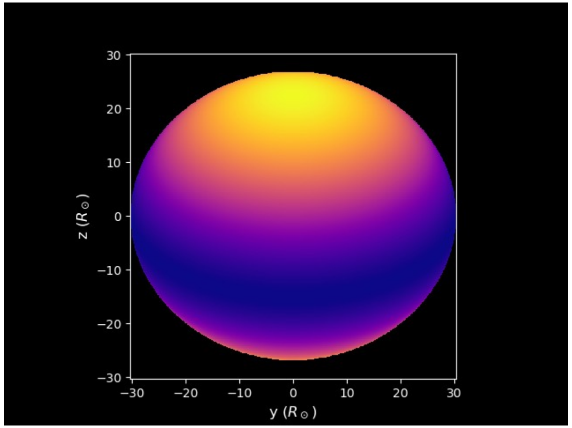
Domiciano de Souza et al. 2002

# S07 Rotation: effects of rotation

- Generalized gravity darkening law:

$$T_{\text{eff}} \propto g_{\text{eff}}^{\beta}$$

  - Von Zeipel: $\beta = 0.25$ (radiative)
  - Lucy: $\beta = 0.08$ (convective)
- Value of $\beta$:
  - Estimated from the local conditions in the external layers (radiation+convection).
    - The structure of the external layers depends on the flux that is coming from the interior and not the opposite.
  - Treated as a free parameter.
    - Introduces an unnecessary additional unknown with no physical meaning.



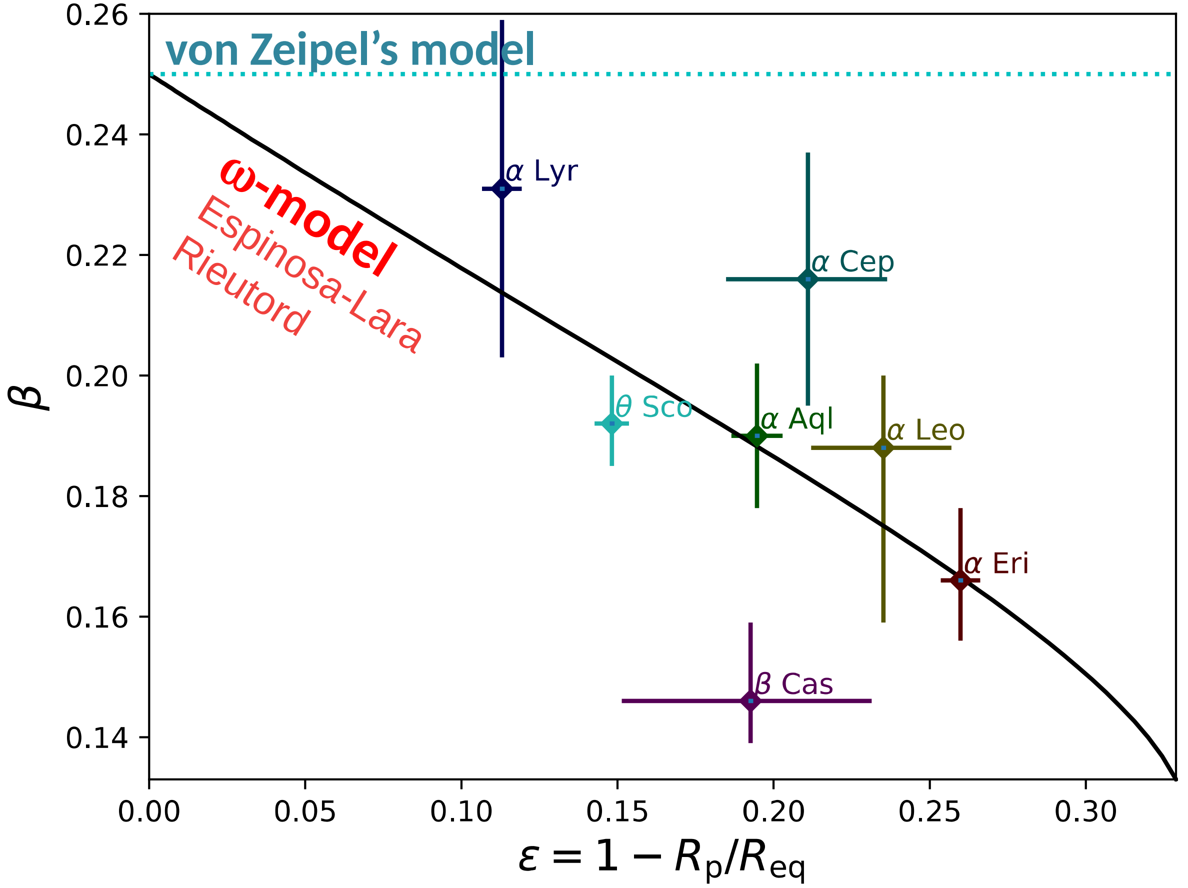

(credits : F. Espinosa-Lara)

# S07 Rotation: interferometry

Interferometry is an ideal tool to directly measure rotational flattening and gravity darkening.

Up to now, only a few $(<10)$ fast rotators in total were studied in detail unsing interferometric data.

**ISSP S07 survey:** About 3 to 5 times more targets expected to be observed with similar quality with CHARA/SPICA.

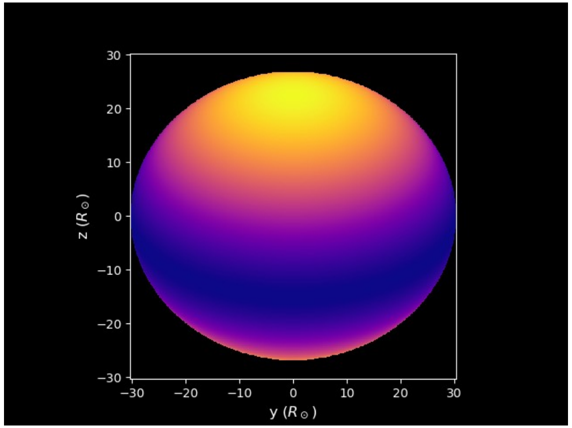


# S07 Rotation: selection of targets

Base catalogue from van Belle (2012), who uses the vsini catalogue from Glebocki.

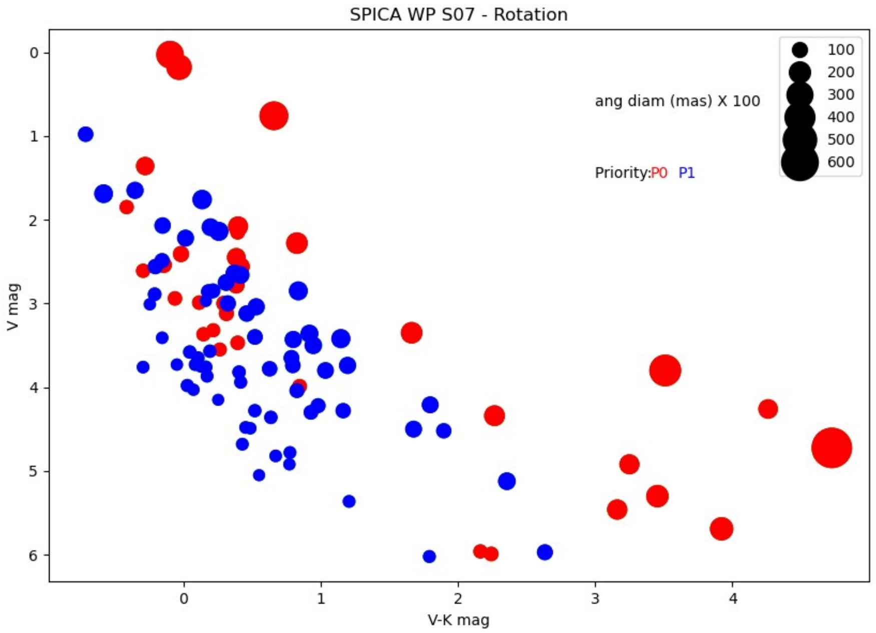
**Selected S07 ISSP stars with:**

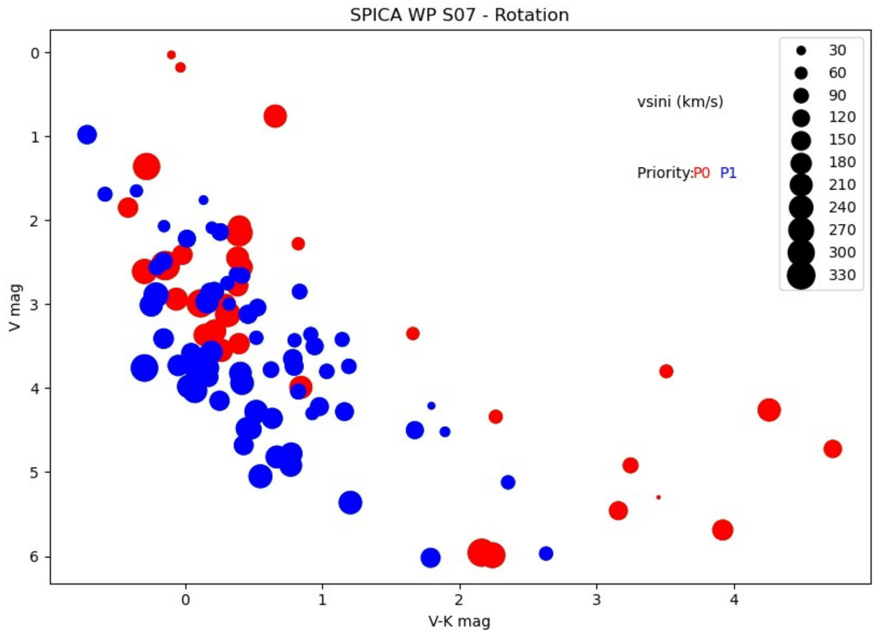
- Angular diameter > ~ 0.5mas (also bright enough for SPICA)
- Dec > -30 deg
- High vsini (>~100 km/s), but low vsini allowed for hot stars (e.g. case of Vega : pole-on)
- Spectral types from O to F to cover the HR diagram of fast-rotators
- Some manual selection to comply with final ISSP requirements (e.g. number of targets)



# S07 Rotation: selected targets

101 targets selected (54 to be observed with 25 in P0)



# S07 Rotation: selected targets

101 targets selected (54 to be observed with 25 in P0)

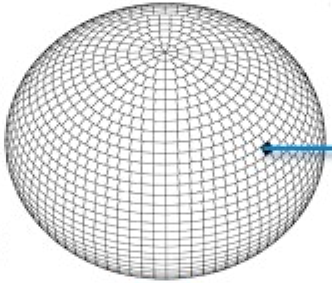
| get_main | vmag | rce_of_v | piname | progname | comments | chara | pica_moo | spi | date | priority_p |
|---|---|---|---|---|---|---|---|---|---|---|
| * alf Lyr | 0.03 | simbad | domician | S07 | HD 172167 / SpType=A0Va / angdiam=3.09 mas / vsini=22.8 km/s | ["S1S2E1 | IMA | | | 0 |
| * bet Ori | 0.18 | simbad | domician | S07 | HD 34085 / SpType=B8Iae / angdiam=2.62 mas / vsini=35.3 km/s / possible emission line | ["S1S2E1 | IMA | | | 1 |
| * alf Aql | 0.76 | simbad | domician | S07 | HD 187642 / SpType=A7Vn / angdiam=3.39 mas / vsini=211.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * alf Leo | 1.36 | simbad | domician | S07 | HD 87901 / SpType=B8IVn / angdiam=1.30 mas / vsini=294.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * eta UM | 1.85 | simbad | domician | S07 | HD 120315 / SpType=B3V / angdiam=0.75 mas / vsini=158.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * alf Oph | 2.08 | simbad | domician | S07 | HD 159561 / SpType=A5IVnn / angdiam=1.56 mas / vsini=208.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * gam Ca | 2.15 | simbad | domician | S07 | HD 5394 / SpType=B0.5IVpe / angdiam=0.81 mas / vsini=295.0 km/s / possible emission line | ["S1S2E1 | IMA | | | 1 |
| * bet Cas | 2.28 | simbad | domician | S07 | HD 432 / SpType=F2III / angdiam=1.84 mas / vsini=61.7 km/s | ["S1S2E1 | IMA | | | 0 |
| * gam UM | 2.41 | simbad | domician | S07 | HD 103287 / SpType=A0Ve+K2V / angdiam=0.99 mas / vsini=160.0 km/s / possible emission line / probable bin | ["S1S2E1 | IMA | | | 0 |
| * alf Cep | 2.45 | simbad | domician | S07 | HD 203280 / SpType=A8Vn / angdiam=1.36 mas / vsini=204.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * zet Oph | 2.54 | simbad | domician | S07 | HD 149757 / SpType=O9.2IVnn / angdiam=0.98 mas / vsini=348.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * del Leo | 2.56 | simbad | domician | S07 | HD 97603 / SpType=A5IV(n) / angdiam=1.27 mas / vsini=177.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * bet Lib | 2.61 | simbad | domician | S07 | HD 135742 / SpType=B8Vn / angdiam=0.75 mas / vsini=251.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * bet Eri | 2.78 | simbad | domician | S07 | HD 33111 / SpType=A3IV / angdiam=1.10 mas / vsini=180.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * del Crv | 2.94 | simbad | domician | S07 | HD 108767 / SpType=A0IV(n)kB9 / angdiam=0.77 mas / vsini=205.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * zet Aql | 2.99 | simbad | domician | S07 | HD 177724 / SpType=A0IV-Vnn / angdiam=0.77 mas / vsini=316.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * gam UM | 3 | simbad | domician | S07 | HD 137422 / SpType=A2III / angdiam=0.91 mas / vsini=167.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * del Her | 3.12 | simbad | domician | S07 | HD 156164 / SpType=A1IVn / angdiam=0.86 mas / vsini=260.0 km/s | ["S1S2E1 | IMA | | | 0 |
| * del UM | 3.32 | simbad | domician | S07 | HD 106591 / SpType=A2Vn / angdiam=0.73 mas / vsini=210.0 km/s | ["S1S2E1 | IMA | | | 0 |

# S07 Rotation: CHARRON & ESTER models

Domiciano de Souza et al. 2002, 2012

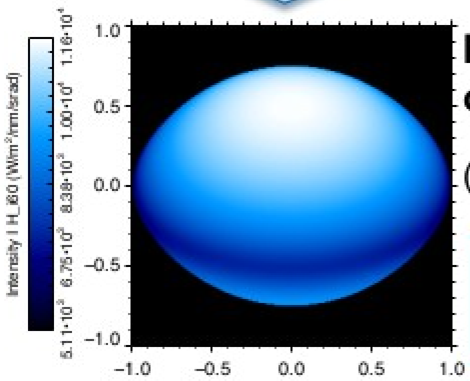
M, $v_{eq}$, $R_{eq}$,
<T> (ou L),
i, d, β

Surface potential Ψ
(e.g. Roche potential)
➔ $g_{eff}$ = |-grad Ψ|
➔ $T_{eff} = C\, g_{eff}^{\beta}$ ;
$C = C(M, \langle T \rangle, v_{eq})$



*At each surface grid element:*
θ, ϕ, μ, $T_{eff}$, $g_{eff}$
$v_{proj}$, $dS_{proj}$

Specific intensities
$I_\lambda = I_\lambda(\mu, T_{eff}, g_{eff})$
from stellar atmosphere models
(e.g. Kurucz or TLUSTY + Synspec)

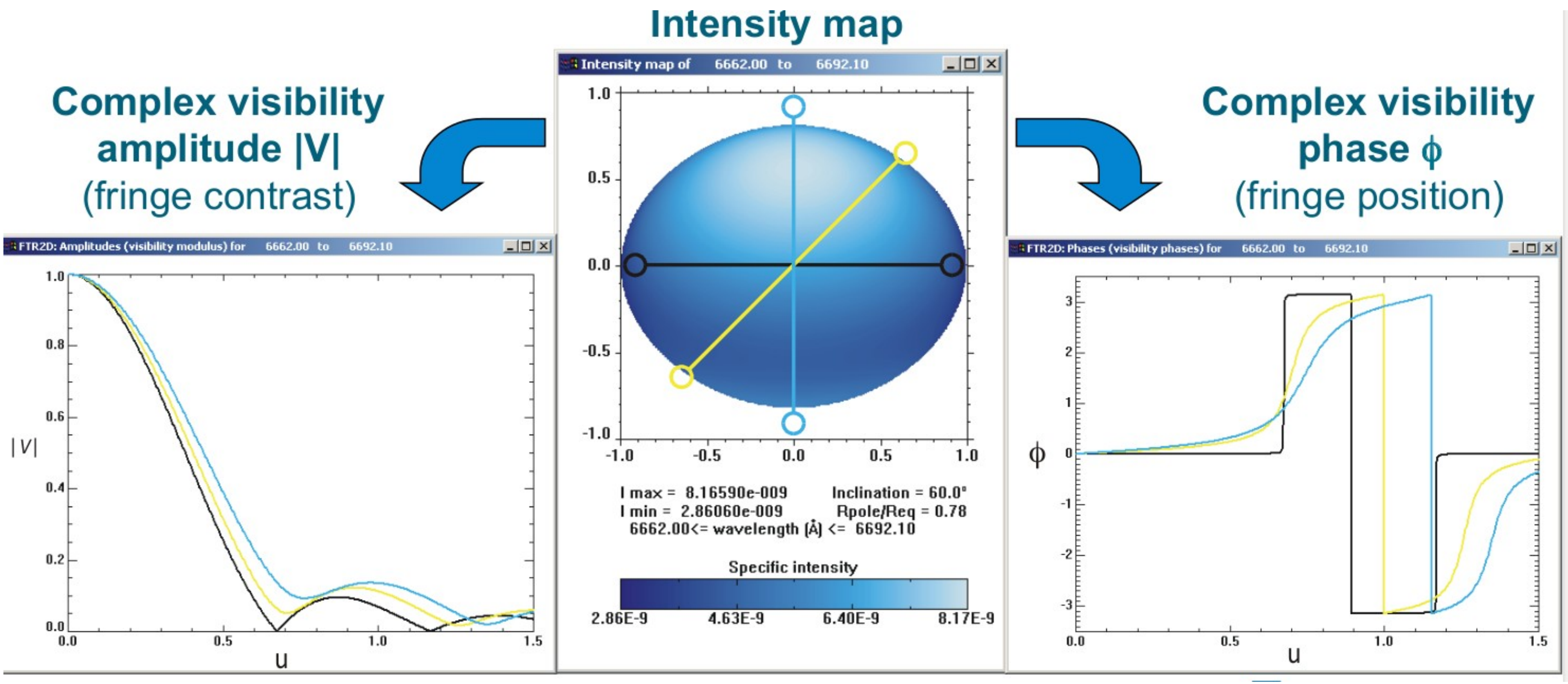



**Intensity maps $I_\lambda(\theta, \phi)$ of stellar photosphere**

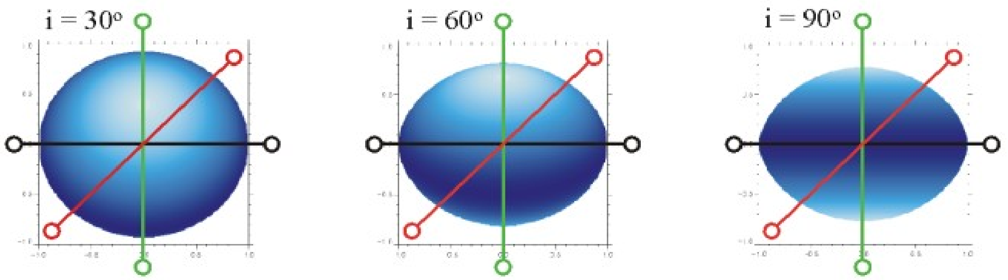
(computation time ~10-30s)

*CHARRON*: ancien métier; spécialiste du bois, maître de tout ce qui tourne et roule.

# S07 Rotation: interferometric signal



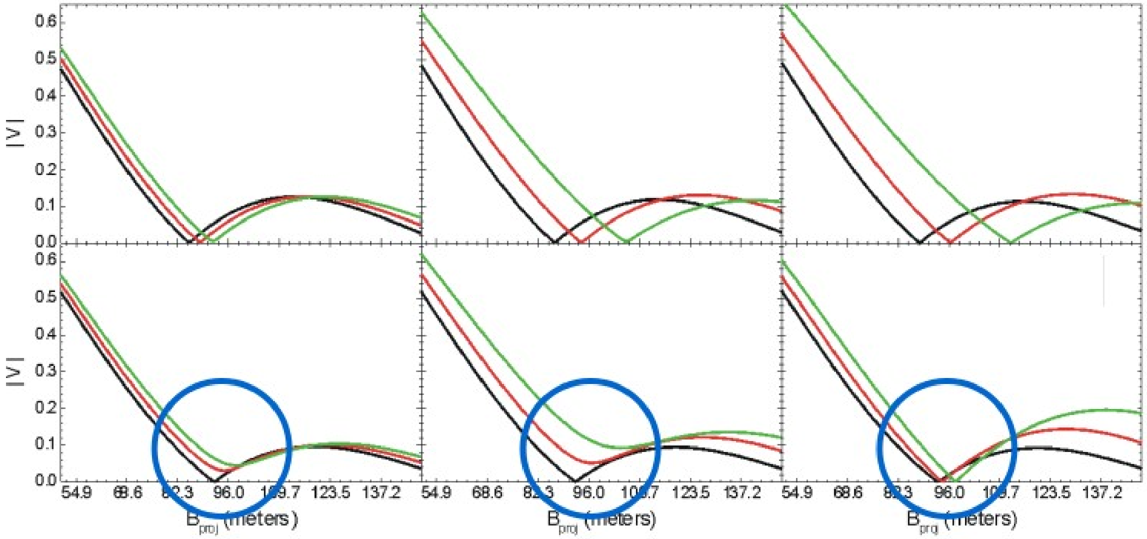
# S07 Rotation: interferometric signal




$$T_{\rm eff} \propto g_{\rm eff}^{\beta}$$

No GD
(β=0)

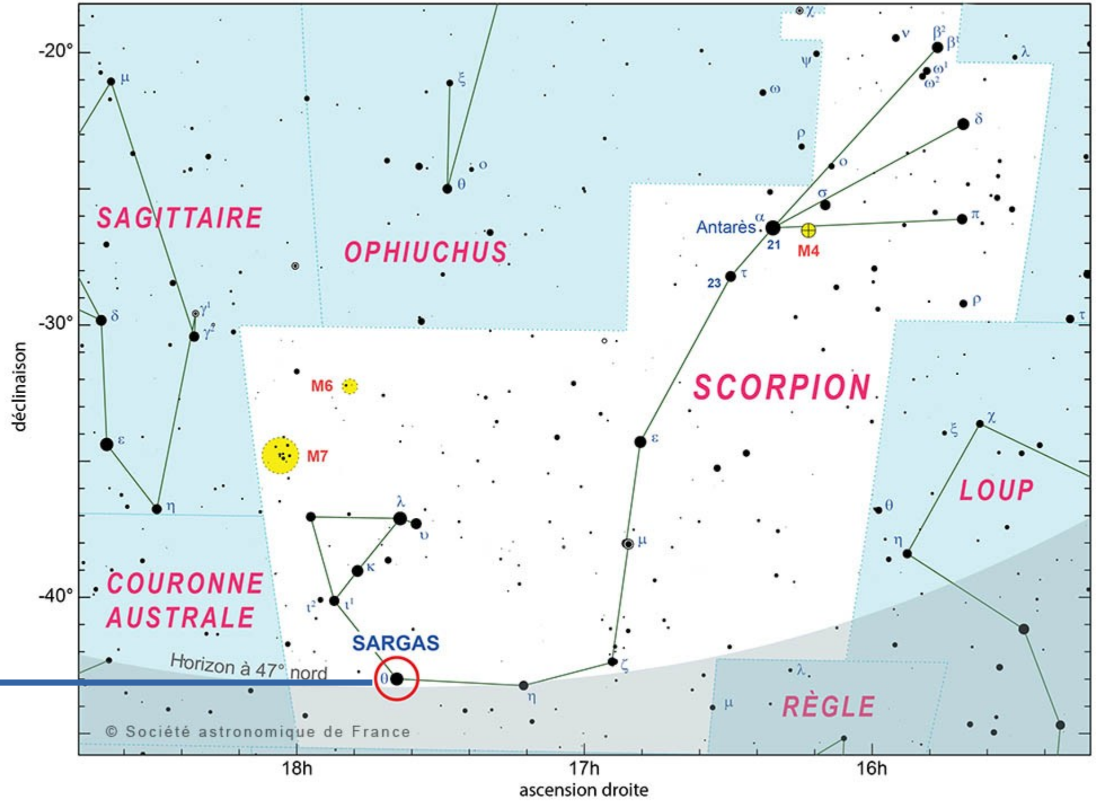
GD
(β=0.25)



# S07 Rotation: expected results

**Sargas**
F3-4I-II

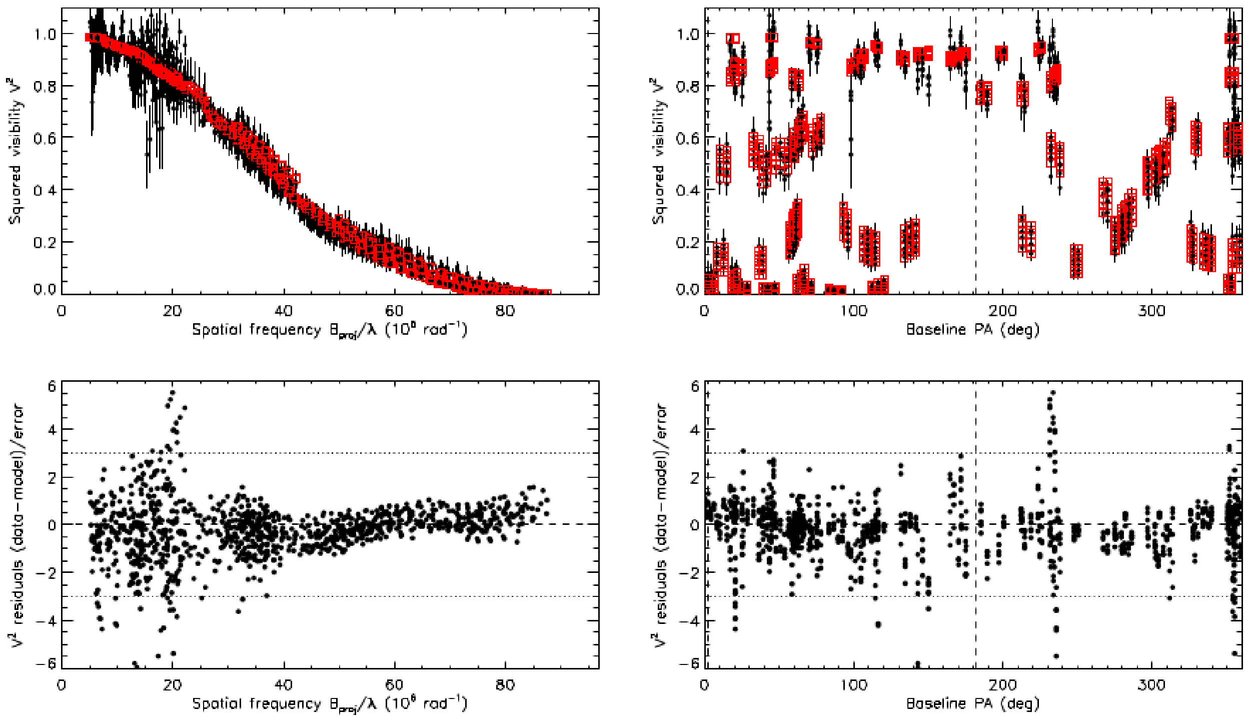
VLTI/PIONIER observations
CHARRON model




Domiciano de Souza et al. 2018, A&A

# S07 Rotation: expected results

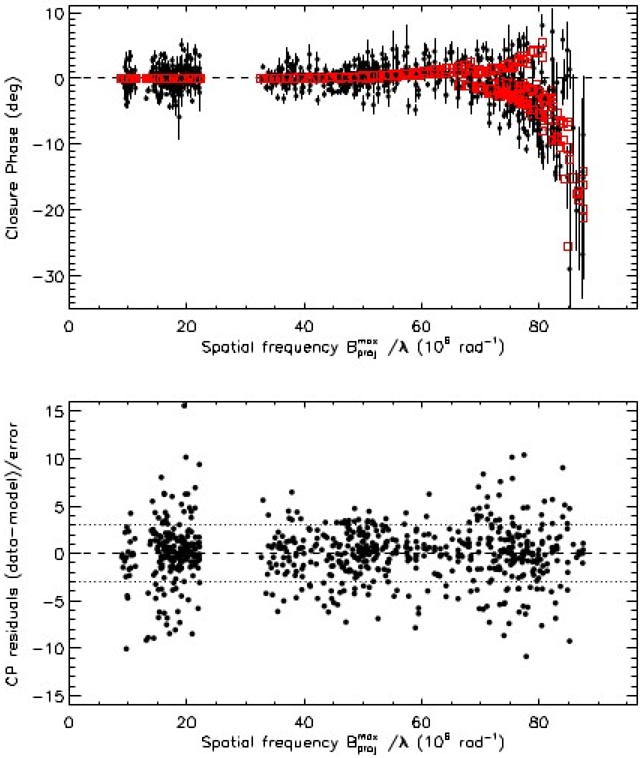
**Sargas**
F3-4I-II

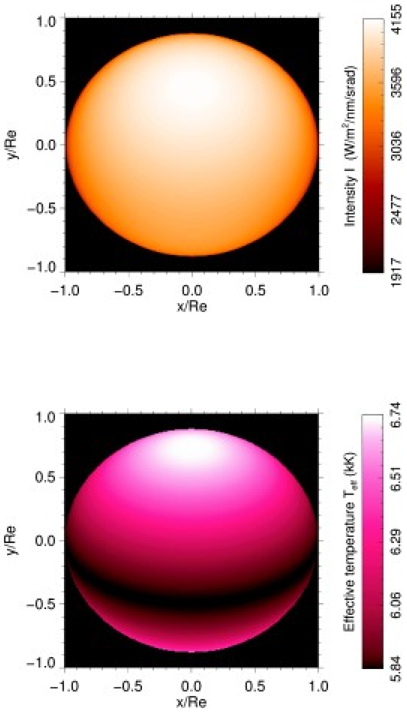



Domiciano de Souza et al. 2018, A&A

# S07 Rotation: expected results

## Sargas
F3-4I-II

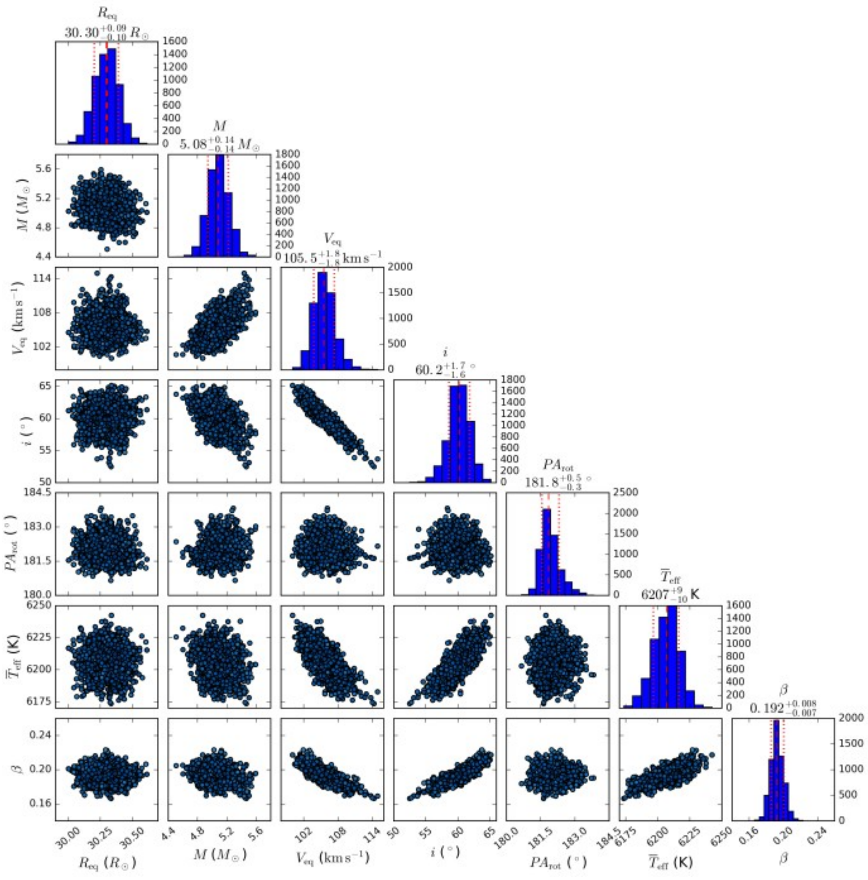


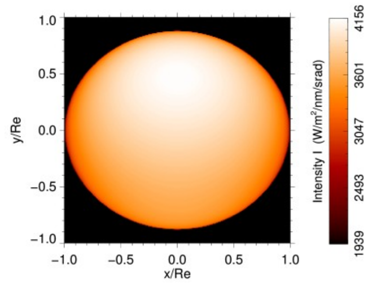

Domiciano de Souza et al. 2018, A&A

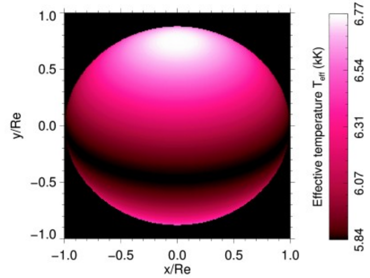
# S07 Rotation: expected results

## Sargas
F3-4I-II




Use of bayesian analysis when possible.




Domiciano de Souza et al. 2018, A&A

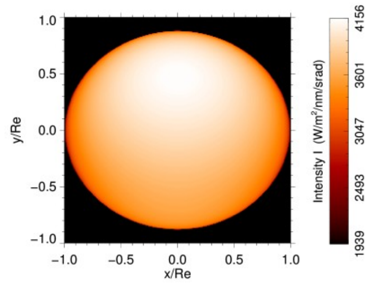
# S07 Rotation: expected results

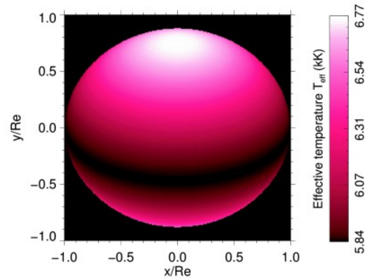
**Sargas**

**F3-4I-II**

| Fitted parameters | $\beta$-model | $\omega$-model |
|---|---|---|
| Equatorial radius: $R_{eq}$ $(R_\odot)$ | $30.30^{+0.09}_{-0.10}$ | $30.30^{+0.08}_{-0.09}$ |
| Stellar mass: $M$ $(M_\odot)$ | $5.08^{+0.14}_{-0.14}$ | $5.09^{+0.13}_{-0.14}$ |
| Equatorial rotation velocity: $V_{eq}$ (km s$^{-1}$) | $105.5^{+1.8}_{-1.8}$ | $104.0^{+0.9}_{-1.1}$ |
| Inclination angle of rotation-axis: $i$ (°) | $60.2^{+1.7}_{-1.6}$ | $61.8^{+0.8}_{-0.9}$ |
| Position angle of rotation-axis[a]: $PA_{rot}$ (°) | $181.8^{+0.5}_{-0.3}$ | $182.1^{+0.5}_{-0.4}$ |
| Average effective temperature: $\overline{T}_{eff}$ (K) | $6207^{+9}_{-10}$ | $6215^{+7}_{-8}$ |
| Gravity-darkening coefficient: $\beta$ | $0.192^{+0.008}_{-0.007}$ | – |
| **Derived parameters** | **$\beta$-model** | **$\omega$-model** |
| Equatorial angular diameter: $\oslash_{eq} = 2R_{eq}/d$ (mas) | 3.09 | 3.09 |
| Polar radius: $R_p$ $(R_\odot)$ | 25.81 | 25.92 |
| Polar angular diameter: $\oslash_p = 2R_p/d$ (mas) | 2.63 | 2.64 |
| Equatorial-to-polar radii ratio: $R_{eq}/R_p$ | 1.1741 | 1.1689 |
| Flattening: $\epsilon = 1 - R_p/R_{eq}$ | 0.14825 | 0.14446 |
| Radius of equivalent spherical star with same surface: $\overline{R}$ $(R_\odot)$ | 28.62 | 28.66 |
| Angular diameter of equivalent spherical: $\overline{\oslash} = 2\overline{R}/d$ (mas) | 2.92 | 2.93 |
| Projected rotation velocity: $V_{eq} \sin i$ (km s$^{-1}$) | 91.5 | 91.7 |
| Equatorial and polar $T_{eff}$: $T_{eq}$; $T_p$ (K) | 5836; 6740 | 5841; 6770 |
| Equatorial and polar gravities: $\log g_{eq}$; $\log g_p$ (dex) | 1.995; 2.320 | 2.003; 2.317 |
| Luminosity: $L$ $(L_\odot)$; $\log L/L_\odot$ | 1091; 3.038 | 1100; 3.041 |
| Rotation period and frequency: $P_{rot}$ (day); $\Omega$ (rad/day) | 14.54; 0.432 | 14.74; 0.426 |
| Critical rotation rate (angular and linear): $\Omega/\Omega_c$; $V_{eq}/V_c$ | 0.852; 0.667 | 0.845; 0.658 |
| Keplerian orbital rotation rate: $V_{eq}/V_k = \Omega/\Omega_k$ | 0.590 | 0.581 |
| Equivalent gravity darkening coefficient: $\beta_\omega$ | – | 0.204 |

Use of bayesian analysis when possible.




Domiciano de Souza et al. 2018, A&A

# S07 Rotation: expected results

**Sargas**
F3-4I-II

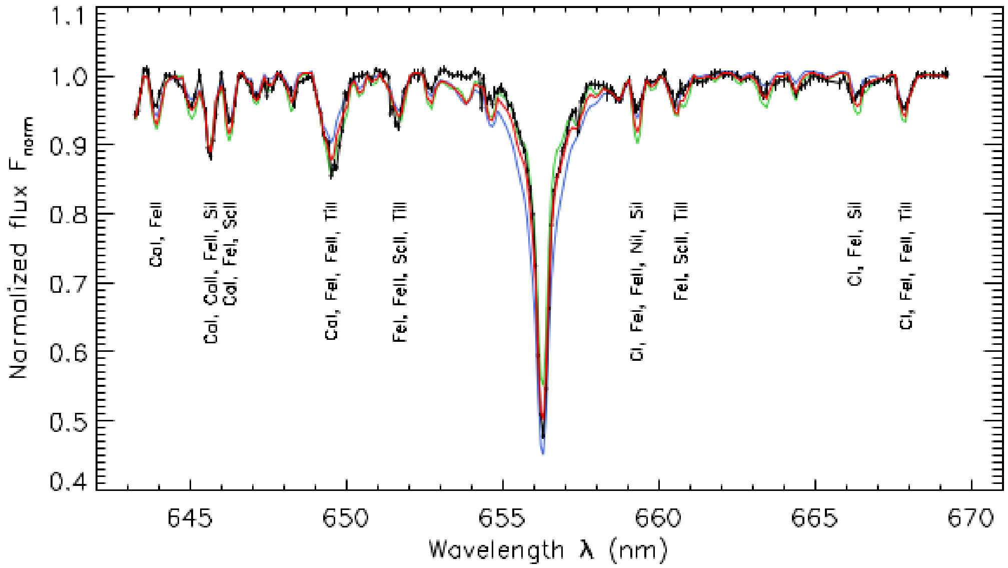


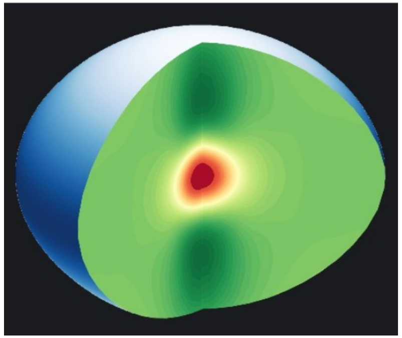

**Fig. 3.** Comparison between the normalized flux from UVES (black dots with error bars) and from the $\beta$-best-fit model (red curve) presented in Table 2. The spectra shown span ~26 nm centered on the H$\alpha$ line, where the main atoms and ions contributing to the strongest absorption lines have been identified. These observations correspond to 257 selected wavelengths, which homogeneously sample the whole relevant spectral range, as shown by the data points. The thin curves correspond to normalized model fluxes for the same $\beta$-best-fit model, but where we have fixed $T_{eff}$ to $T_p$ (blue) and $T_{eq}$ (green) over the whole photosphere (model without GD, i.e., $\beta = 0$). Clearly the complete best-fit model, with GD, better reproduces the observed spectral lines compared to the simpler model spectra computed with $\beta = 0$.

Use of additional data (e.g. spectra) when they are available.

Domiciano de Souza et al. 2018, A&A

# S07 Rotation: expected results

**Altair**
A7V

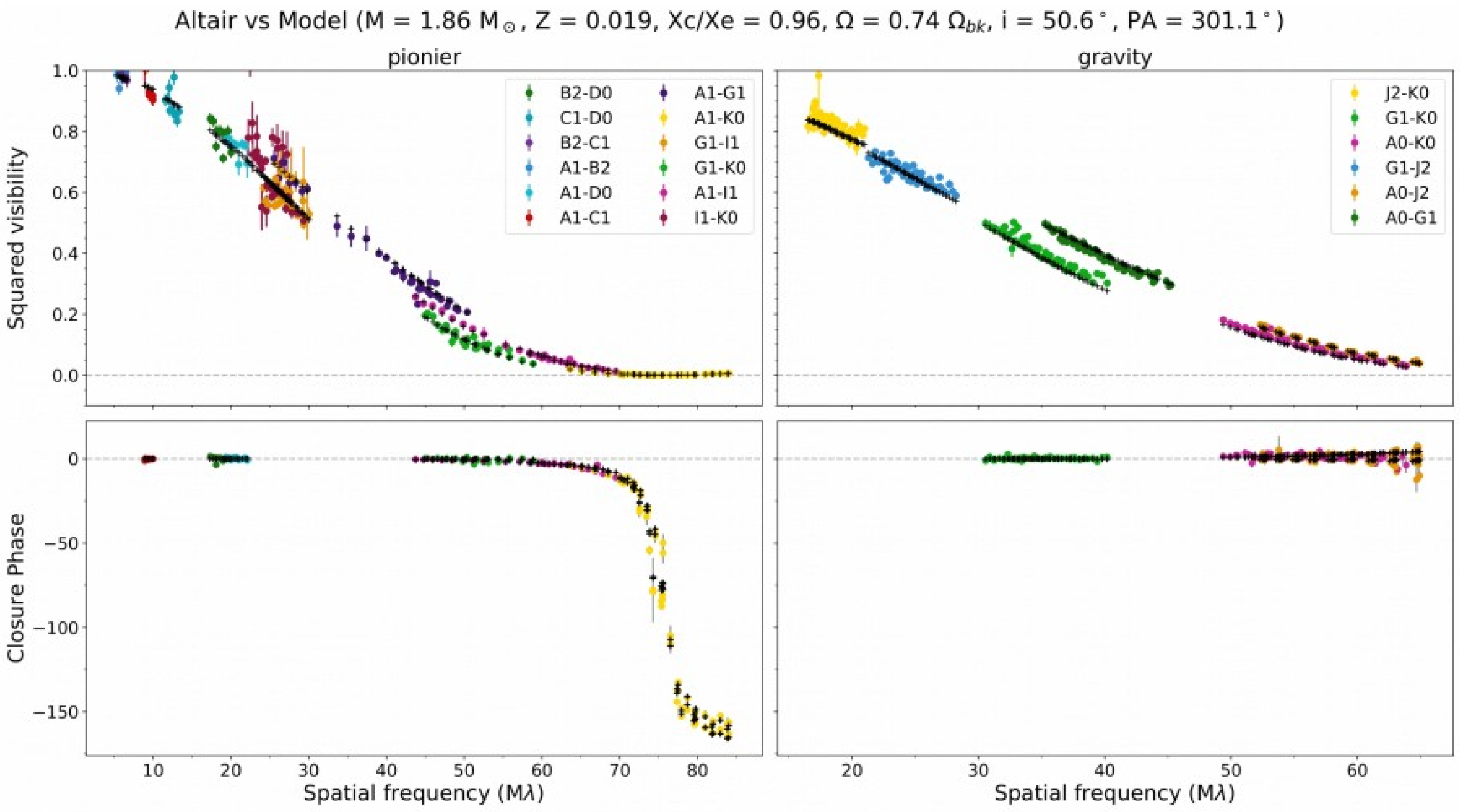



VLTI/PIONIER and GRAVITY observations
ESTER model

Bouchaud, Domiciano de Souza et al. 2020, A&A

# S07 Rotation: expected results

**Altair**
A7V




Bouchaud, Domiciano de Souza et al. 2020, A&A

# S07 Rotation: expected results

Altair

A7V

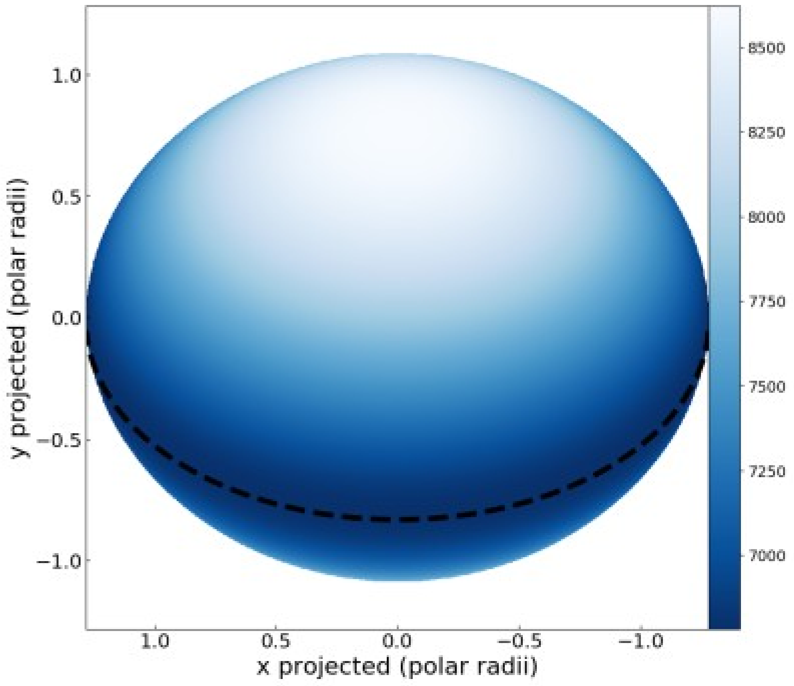



**Fig. 12.** Surface map of the effective temperature of our best ESTER model (parameters in Table 5). The dashed line marks the equator. The values are in Kelvin.

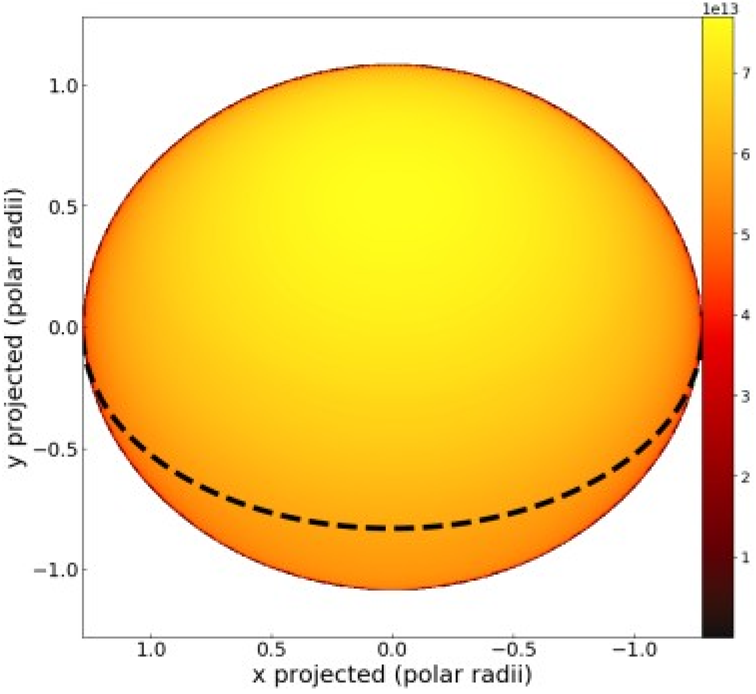



**Fig. 13.** Monochromatic intensity map of our best ESTER model (parameters in Table 5), at 1.5 $\mu$m in the $H$ band. The values are in erg $s^{-1}$ $cm^{-2}$ $cm^{-1}$ $srad^{-1}$.

Bouchaud, Domiciano de Souza et al. 2020, A&A

# S07 Rotation: expected results

**Altair**

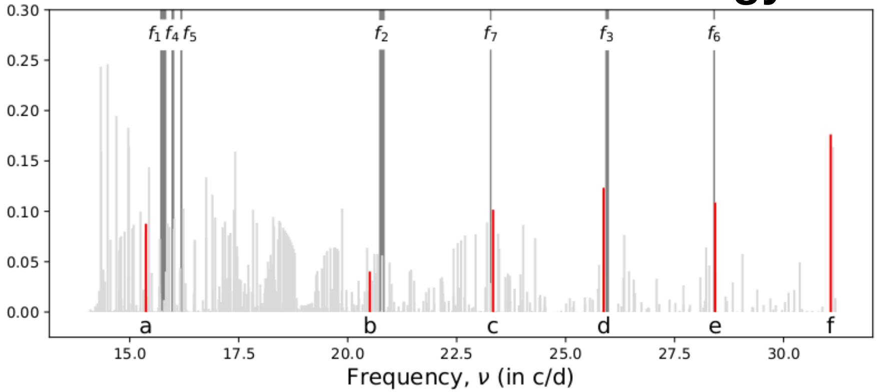
A7V

**Table 5.** Comparison of the fundamental parameters of Altair derived by Monnier et al. (2007) and from our work where we use $X = 0.739$ from Asplund et al. (2005).

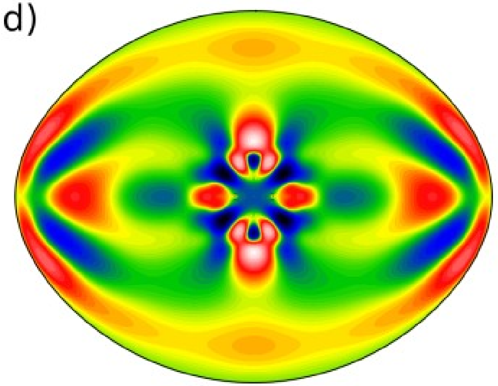
| Parameters | Monnier et al. (2007) | This work |
|---|---|---|
| $i$ (°) | $57.2 \pm 1.9$ | **$50.65 \pm 1.23$** |
| PA (°) | $298.2 \pm 0.8$ | **$301.13 \pm 0.34$** |
| $M$ ($M_\odot$) | 1.791 | **$1.86 \pm 0.03$** |
| $T_{\rm pole}$ (K) | $8450 \pm 140$ | 8621 |
| $T_{\rm eq}$ (K) | $6860 \pm 150$ | 6780 |
| $R_{\rm pole}$ ($R_\odot$) | $1.634 \pm 0.011$ | $1.565 \pm 0.014$ |
| $R_{\rm eq}$ ($R_\odot$) | $2.029 \pm 0.007$ | $2.008 \pm 0.006$ |
| $v_{\rm eq}$ (km s$^{-1}$) | $285.5 \pm 6$ | 313 |
| $v \sin i$ (km s$^{-1}$) | 240 | 242 |
| $\Omega$ ($\Omega_k$) | $0.695 \pm 0.009$ | **$0.744 \pm 0.010$** |
| $Z$ | – | **0.019** |
| [M/H] | −0.2 | **0.19** |
| $X_c$ | – | **0.71** |
| $\varepsilon$ | $0.195 \pm 0.002$ | $0.220 \pm 0.003$ |
| $\beta$ | $0.190 \pm 0.012$ | 0.185 |

Physical parameters, including gravity darkening, mass, age

**Combine with asterosismology**




d)



Bouchaud, Domiciano de Souza et al. 2020, A&A

# S07 Rotation: expected results

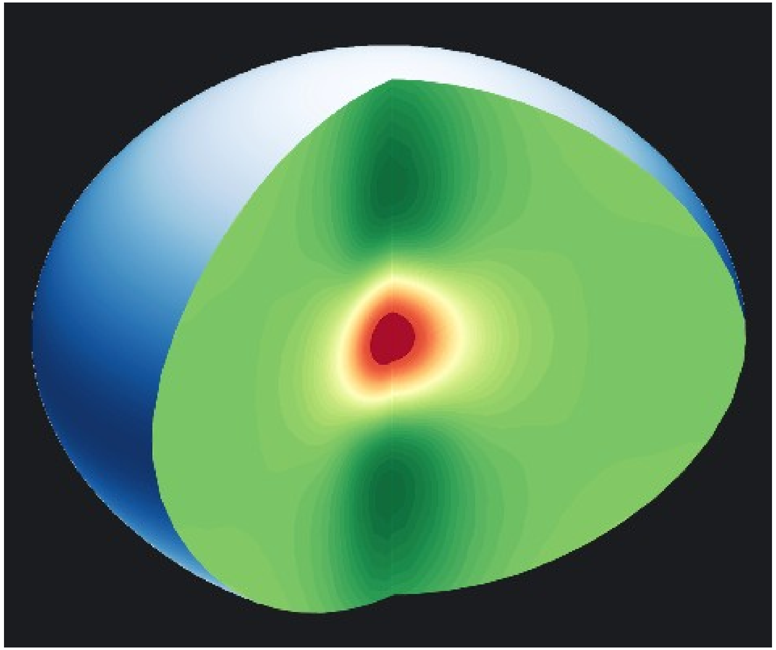
**Altair**
A7V

**Bouchaud, Domciano et al. 2020, A&A**

| Parameters | Mesurements |
|---|---|
| $i$ (°) | **50.65 ± 1.23** |
| PA (°) | **301.13 ± 0.34** |
| $M$ ($M_\odot$) | **1.86 ± 0.03** |
| $T_{pole}$ (K) | 8621 |
| $T_{eq}$ (K) | 6780 |
| $R_{pole}$ ($R_\odot$) | 1.565 ± 0.014 |
| $R_{eq}$ ($R_\odot$) | 2.008 ± 0.006 |
| $v_{eq}$ (km s$^{-1}$) | 313 |
| $v \sin i$ (km s$^{-1}$) | 242 |
| $\Omega$ ($\Omega_k$) | **0.744 ± 0.010** |
| $Z$ | **0.019** |
| [M/H] | **0.19** |
| $X_c$ | **0.71** |
| $\varepsilon$ | 0.220 ± 0.003 |
| $\beta$ | 0.185 |

**Interferometry**
**Asterosismology**
**Spectroscopy**
**2D modeling (ESTER)**
**(interior and surface)**
**Stellar evolution**

Type spectral d'Altaïr: A7V



Bouchaud, Domiciano de Souza et al. 2020, A&A

# S07 Rotation: data analysis strategy

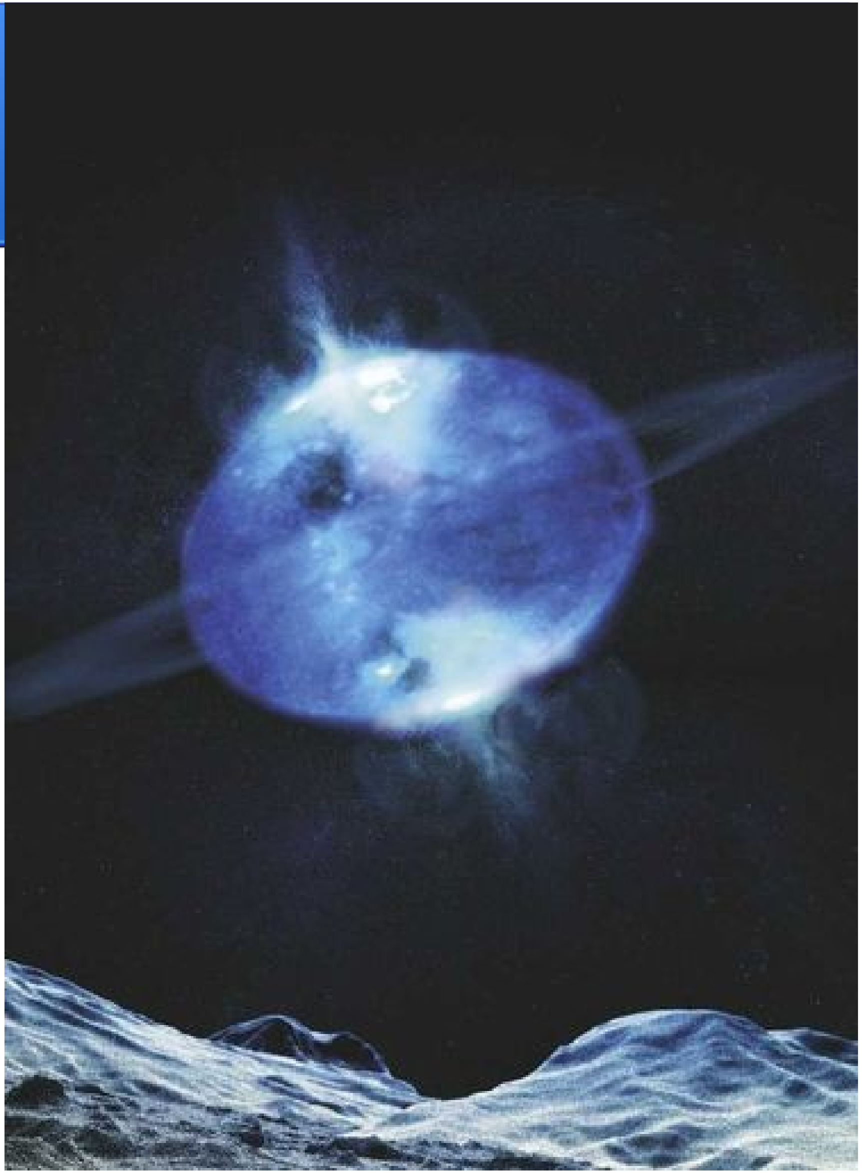
**For all stars of the survey**

- Bayesian analysis of all stars with CHARRON (A.Domiciano de Souza) with a simple surface intensity model (blackbody + analytical limb-darkening)
  - $\omega$-model (no $\beta$ parameter) and $\beta$-model for well resolved stars (beyond 1st V minimum)
  - Otherwise, only $\omega$-model (no $\beta$ parameter)
- Include vsini prior constraints and spectral profiles when available

**For a few highlight stars (similar to 2020 Altair paper)**

- Analysis with ESTER (M.Rieutord) combined with dedicated stellar atmosphere models $\Rightarrow$ internal and surface rotation, age
- Include spectral and asterosismic data when available

# Thank you for your attention



Credits:
P. Kervella