The programme: Accurate masses for double-lined spectroscopic binary components

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on behalf of the team:
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Context: benchmark stars for Gaia & asteroseismology

Mass

- leading factor in stellar structure & evolution,
- but no direct measurement except when stars are in binary systems.

Asteroseismology

- can provide masses and radii
  $\rightarrow$ via scaling relations ($\Delta\nu, \nu_{\max}$), but $T_{\rm eff}$ needed,
  $\rightarrow$ via full modeling: frequencies/separations/ratios + $T_{\rm eff}, [\mathrm{M/H}], L$,
- but need to be assessed/compared to direct measurements
  $\rightarrow$ masses (binaries),
  $\rightarrow$ radii (eclipsing binaries, interferometry, lunar occultations).

Goal of this long-term observing programme

$\rightarrow$ to provide **precise masses** for a selection of stars,

- members of double-lined spectroscopic binaries (SB2),
- observed by **Gaia** (astrometric orbit), or ground-based interferometry.

Synopsis of the programme and goals

Observations of SB since 2010 (OHP/Sophie/T193)

- to obtain precise radial velocity curves,
- to try to detect the secondary component of known SB1,
- aim to improve the orbital elements of SB2,
  $\rightarrow \mathcal{M}_1 \sin^3 i$ and $\mathcal{M}_2 \sin^3 i$ $\quad \rightarrow a_1 \sin i, a_2 \sin i$ (km)

How to get the orbit inclination angle?

- if the SB is also an EB: light curve $\rightarrow i$
- interferometric binary? $\rightarrow$ literature & new obs. with Pionier@VLTI,

When Gaia astrometry is available

- astrometric orbit: motion of the photocentre $\rightarrow i, a_0\ (\mathrm{mas}) + \varpi$.
  OK, if P close to observation duration (Gaia: 5 years).

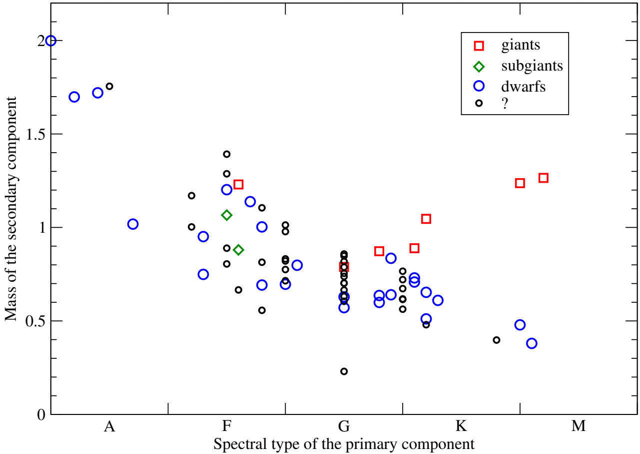
Final outputs (SB2 + Gaia)

- $\mathcal{M}_1, \mathcal{M}_2$ $\rightarrow$ precision at 1% level ; $G, \Delta G\ (\mathrm{mag})$.

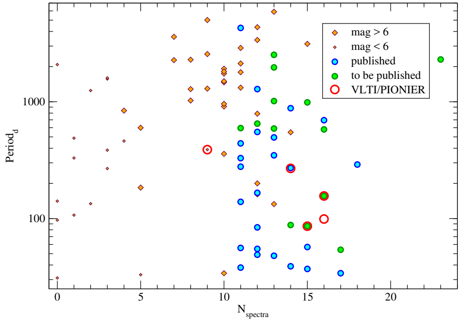
Observational samples

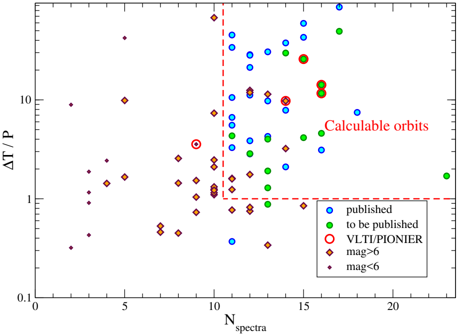
→ **Main sample**, $m_v > 6$: 71 SB2 in a sample of 207 SB,
Primaries: A0 – M1.5 ; 6 red giants | *Secondaries*: $\mathcal{M} \in [0.3\text{–}2]\ \mathcal{M}_\odot$.

→ **Complementary sample**, $m_v \leq 6$: 17 SB2 (4 new) among 63 SB.



Ongoing status (main sample)





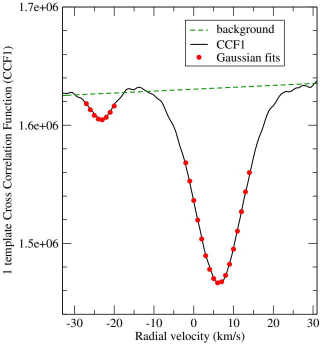
- → 1270 new spectra + 22 taken in the Sophie archive,
- → 20 new secondary components published + 5 to be confirmed,
- → 24 SB2 orbits have been published,
- → 12 SB2 orbits potentially publishable + $\leq$ 9 next year?

Derivation of radial velocities of SB2 components

→ Two techniques:

1. **CCF1** (Cross Correlation Funct.)
   - → CCF from Sophie pipeline,
   - → CCF of spectrum / one mask,
   - → fit with 2 normal distributions.

   ⇒ $V_{R,1}, V_{R,2}$



2. **TODCOR** (*Mazeh, Zucker, 1994*)
   TwO-Dimensional CORrelation

   CC: spectrum with 2 masks
   - → spectra of components, synthetic (PHOENIX)

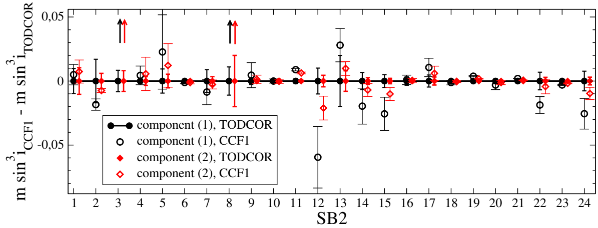
   Correlates the SB2 spectrum
   - → against a combination of the 2 spectra & different shifts

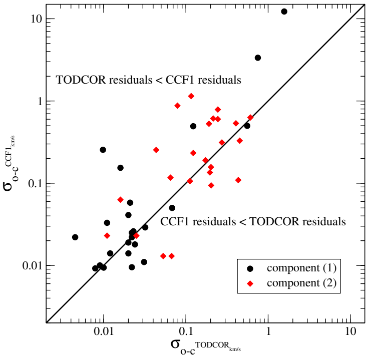
   Maximum correlation
   ⇒ $V_{R,1}, V_{R,2}$

→ Results to be compared.

Comparisons: CCF1 vs TODCOR

The minimum masses, $\mathcal{M} \sin^3 i$, may be significantly different.

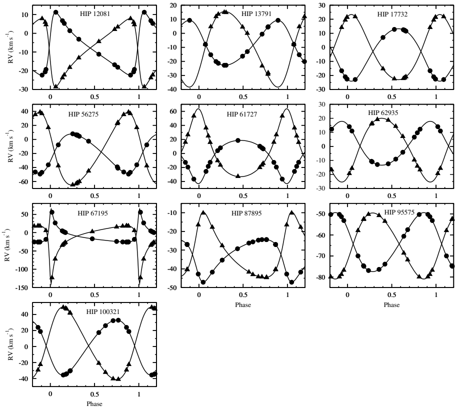


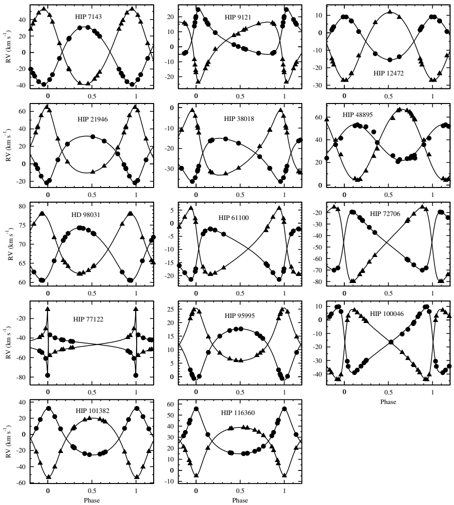


TODCOR orbit residuals generally < CCF1

→ TODCOR more accurate and reliable *Halbwachs+2017, SF2A proc.*

Results: 24 SB2 orbits derived since 2010





Kiefer+16, MNRAS, 458, 3272

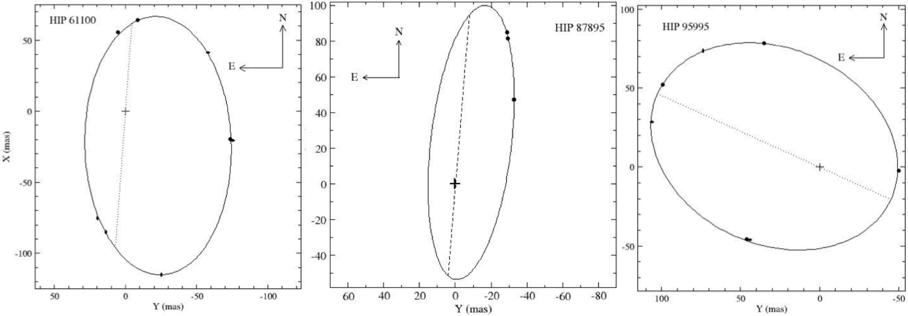
Kiefer+18, MNRAS, 474, 731

→ 32 minimum masses, $\mathcal{M}\sin^3 i$, at better than 1%.

Individual masses: interferometry

SB2 + interferometric binary (VB) $\Rightarrow \mathcal{M}_1, \mathcal{M}_2, \varpi$, flux ratio.

From existing interferometric measurements $\rightarrow$ *i* angle.

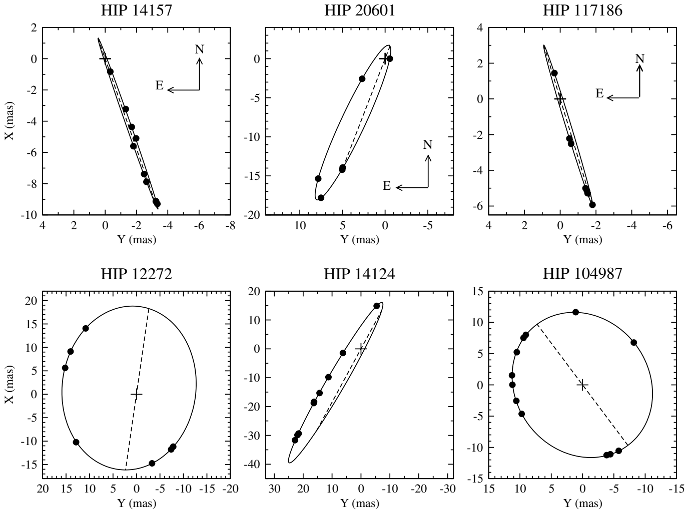


HIP	$\mathcal{M}_1(\mathcal{M}_\odot)$	$\mathcal{M}_2(\mathcal{M}_\odot)$	
61100	0.834 ± 0.017	0.640 ± 0.011	
87895	1.132 ± 0.014	0.7421 ± 0.0073	*Kiefer+16, 18*
95995	0.833 ± 0.031	0.812 ± 0.030	
101382	0.8420 ± 0.0014	0.66201 ± 0.00076	

$\rightarrow$ possibility to secure future Gaia masses,

Interferometry with PIONER@VLTI

Seven resolved SB2, collaborations H. Boffin & J.-B. Le Bouquin
3 in main sample, 2 in complementary sample + 2 from HERMES programme.



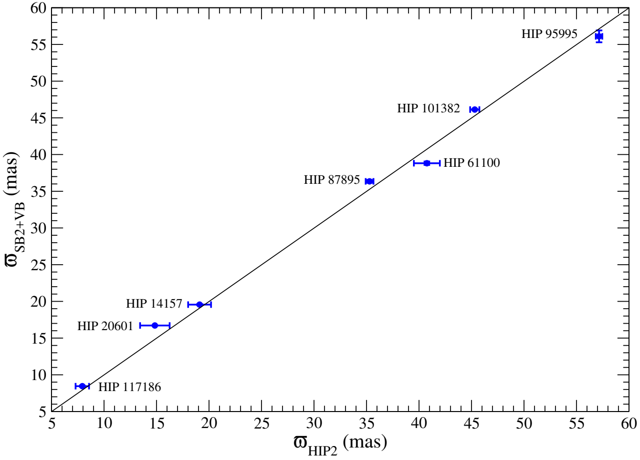
Halbwachs+16

Validation of Hipparcos parallaxes

SB2 + interferometric binary (VB) $\Rightarrow \varpi_{\rm SB2+VB}$
$\rightarrow$ can be compared to Hipparcos 2 parallax $\varpi_{\rm HIP2}$

Results:
$\varpi_{\rm SB2+BV} \approx \varpi_{\rm HIP2}$

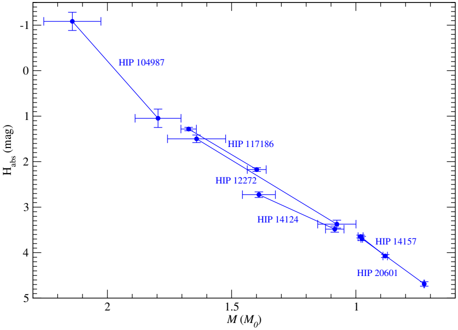
Gaia validation
bright star parallaxes.



Mass-luminosity relation

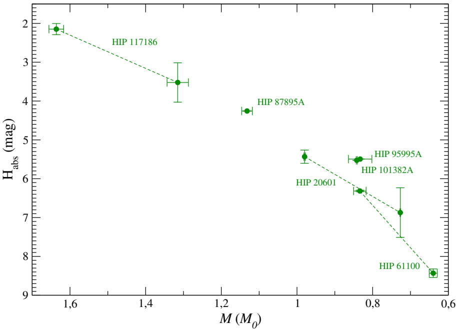
Interferometric binary
Pionier → IR filter (H-band)

- → ΔH
- → H_1, H_2



Hipparcos: photocentre orbit

- → semi-major axis
- → ΔH_{Hip}
- → $H_{\mathrm{Hip},1}, H_{\mathrm{Hip},2}$



Stellar modeling : difficulties

Lack of, or non reliable, uncertain data

- T_{eff}, [M/H] $\rightarrow$ disentangle observed spectra,
- model parameters: helium, mixing-length parameter, etc.

HIP 61100

Star $\in$ UMa Group nucleus

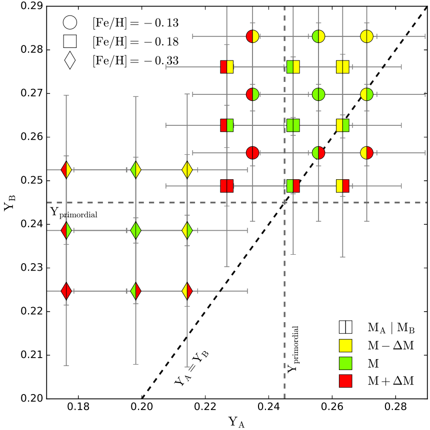
$\mathcal{M}_{\mathrm{A,B}} + K_{\mathrm{A,B}}$ magnitudes
+ [Fe/H]$_A$, $T_{\mathrm{eff,A,B}}$
+ *BC (Casagrande & Vandenberg14)*
+ Hyp: $Y_{0,\mathrm{A}} = Y_{0,\mathrm{B}}$
+ Hyp: $A = A_{\mathrm{Uma\ Group}}$

Models CES2KSMO

$\rightarrow$ low [Fe/H] rejected

$\rightarrow$ $Y_0 = 0.245 - 0.27$

$\rightarrow$ low mass favoured



Kiefer, Halbwachs, Lebreton+2018

Modeling in progress (all systems with masses)

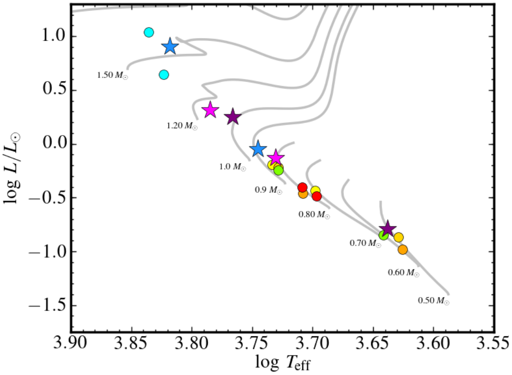
Model optimisation

- CES2KSMO
- standard input phys.
- AGSS09 mixture
- conv CGM $\alpha_\odot$
- cc overshooting
- mic. diff. (no RA)

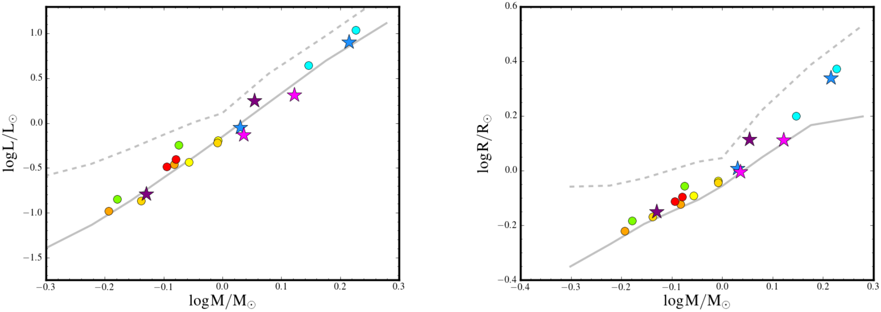
Obs. constraints

- A-component
  $\mathcal{M}$, $M_{H,K,V}$(+BC),
  $T_{\rm eff}$, [M/H]
  $\rightarrow$ $\mathrm{age_A}$, $Y_{0,\mathrm{A}}$, $[\mathrm{M/H}]_{0,\mathrm{A}}$
- B-component
  $\mathcal{M}$, $M_{H,K,V}$
  $+$ $\mathrm{age_A}$, $Y_{0,\mathrm{A}}$, $[\mathrm{M/H}]_{0,\mathrm{A}}$

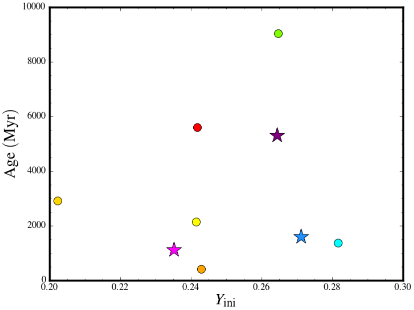
9 systems (SB2 + interferometry)
3 TESS targets:

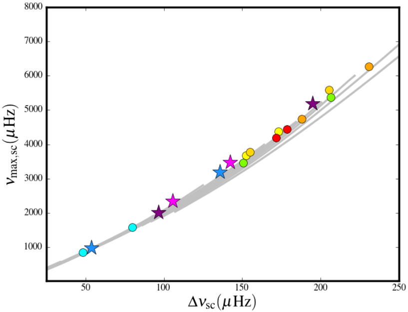


Model mass-luminosity & mass-radius relations



Model predictions: age, initial helium, $\Delta\nu$, $\nu_{\rm max}$





TESS targets:

$\rightarrow$ Primaries : $1.15, 1.30, 1.65\ M_\odot$

$\rightarrow$ Companions: $0.75, 1.10, 1.05\ M_\odot$

Lebreton, Halbwachs, Kiefer et al, in prep.

Summary & perspectives for the programme

Spectroscopy

→ up to now: 24 precise orbits,

→ next year: 40 precise orbits,

→ in 4 yr, time of Gaia DR4 (nominal mission): 70 precise orbits
$\Rightarrow$ validation of P, e, T_0, ω of Gaia astrometric orbits

Interferometry

→ 7 precise interferometric orbits
$\Rightarrow$ validation of i, Ω of Gaia astrometric orbits $+ \varpi$ for bright stars
$\Rightarrow$ validation of the masses of orbits SB2 + AB

Future: extension of the programme from Gaia astrometric binaries?

Summary & perspectives for modelling

- → Growing sample of SB2s with precise masses to be modelled
- → Crucial: classical parameters to be determined/improved/secured
- → Complementary: α-elements, lithium, etc.
- → Benchmarks for asteroseismology: **TESS**, PLATO
- → 2022: **Gaia DR4**.

Thank you for your attention

Comparison: CCF1 vs TODCOR

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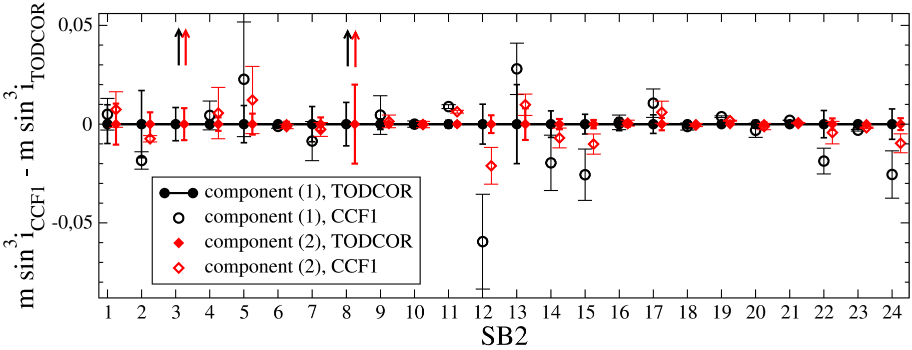
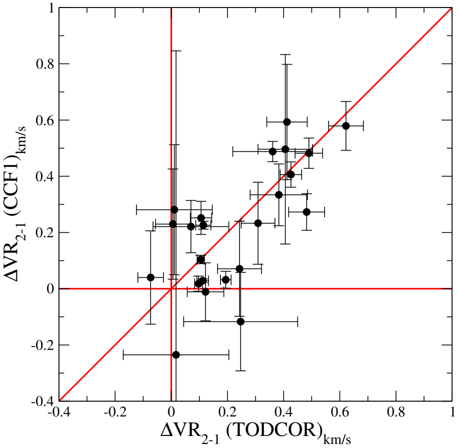
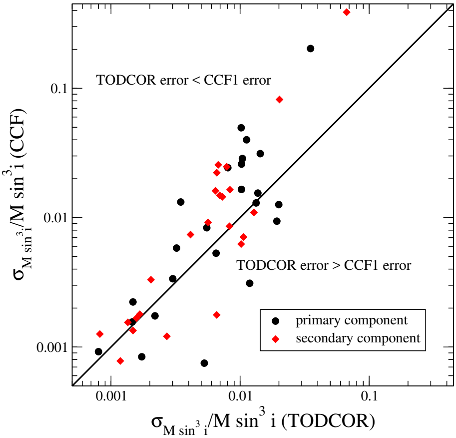


Radial velocity offset CCF1 vs. TODCOR

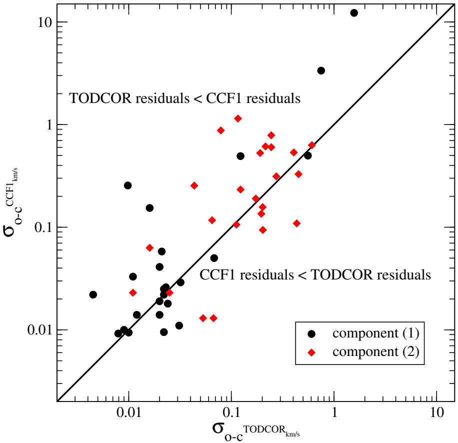
Difference between the spectral type of the template, and that of the component
→ shift between the component RVs.
→ shift expected to be zero with TODCOR.



Comparison: CCF1 vs TODCOR



TODCOR: minimum masses usually more accurate.



TODCOR orbit residuals generally < CCF1 orbit residuals

→ TODCOR more accurate and reliable than CCF1 (Halbwachs+2017)