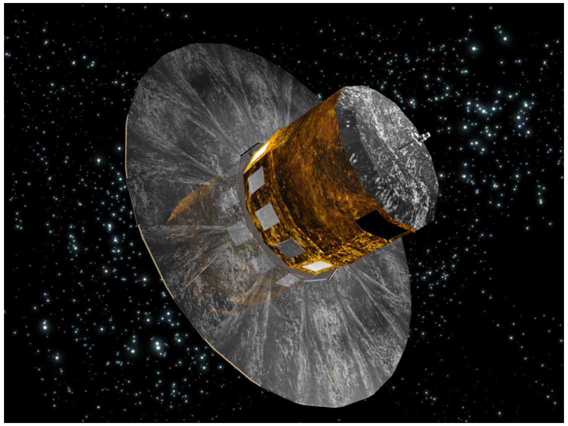

Spectroscopic orbits for astrometric binaries from Gaia

Flavien Kiefer, J.-L. Halbwachs, F. Arenou, H. Boffin, B. Famaey, J.-B. Le Bouquin, D. Pourbaix ,
P. Guillout, R. Ibata, Y. Lebreton, T. Mazeh, A. Nebot

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Measuring stellar mass

- **Why:** one of the fundamental properties of a star (with composition & age)
- **What for:** understanding stellar physics (evolution models, ...) and important for measuring the mass of exoplanets ("*know thy star know thy planet*").
- **how to:** → WP125500 - Benchmark stars

Measuring mass with asteroseismic data. With e.g. scaling relations

$$\frac{M}{M_\odot} \simeq \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu}{\Delta\nu_\odot}\right)^{-4} \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{\frac{3}{2}}$$

(Kjeldsen & Bedding 1995)

But only approximate and depends on T_{eff} ... => indirect measurement

Using stellar models or empirical relations with B-V, M_V, age, T_{eff}, log(g), etc.
E.g. (but still indirect)

$$\log M = a_1 + a_2 X + a_3 X^2 + a_4 X^3 + a_5 (\log g)^2 + a_6 (\log g)^3 + a_7 [\mathrm{Fe/H}]$$

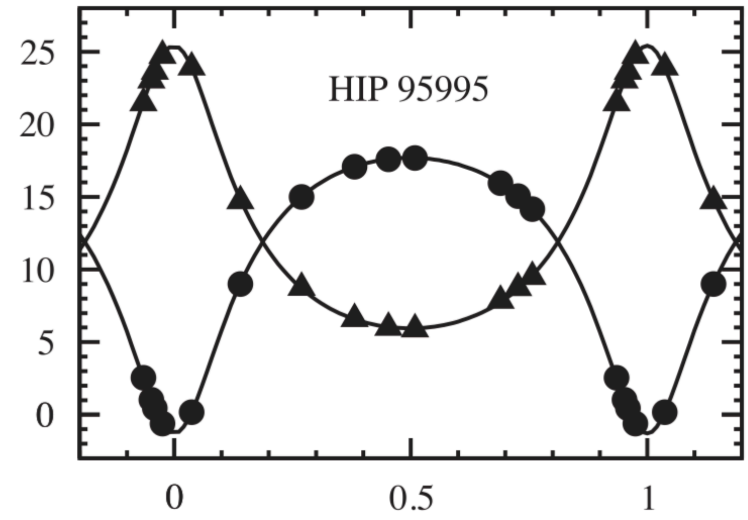
(Torres+ 2010)

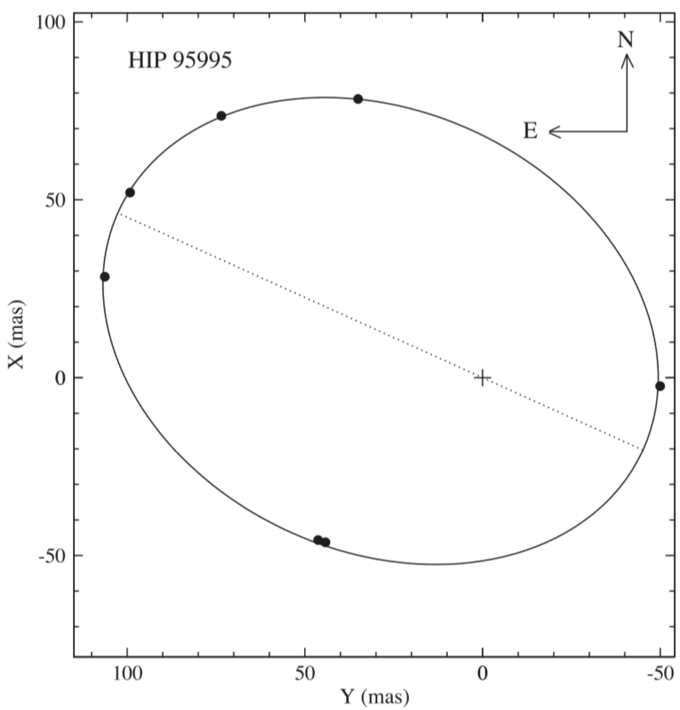
But the only way to directly measure stellar mass is the measurement of gravitational mass in binary systems.

Gravitational stellar mass in SB2 binary systems

RV variations SB2 orbital elements:

- $M_1 \sin^3 i$, $M_2 \sin^3 i$,
- $a_1 \sin i$ (au), $a_2 \sin i$ (au)





Kiefer+ 2018

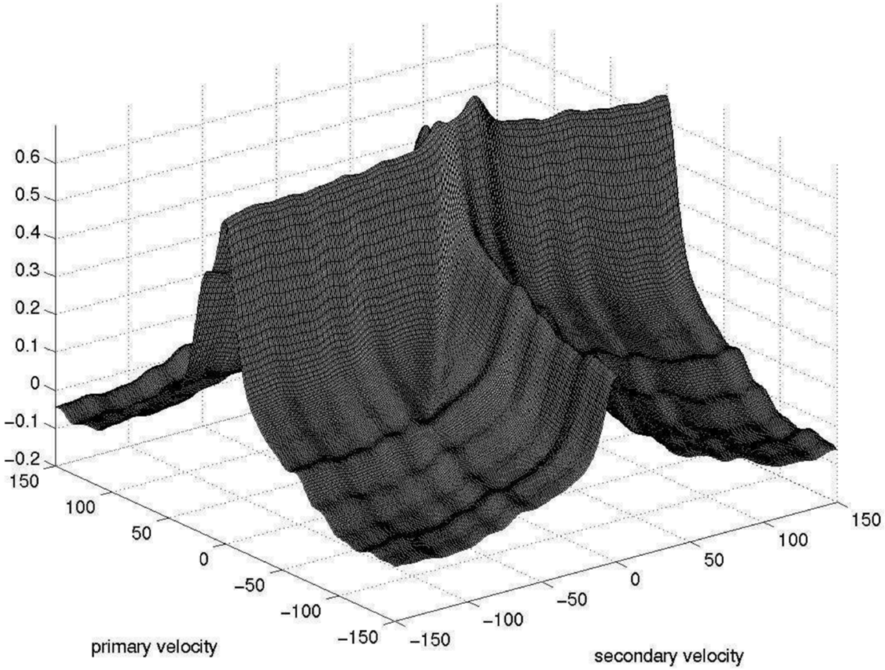
Astrometry:

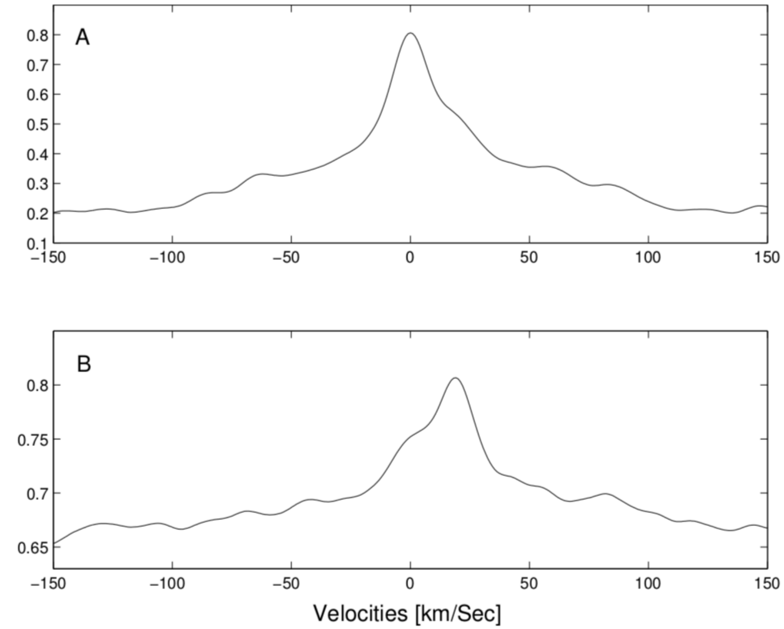
- i, inclination
- $a_{photocenter}$ (mas),
- π, parallax

SB2 + Gaia $\Rightarrow \mathcal{M}_1$ **,** $\mathcal{M}_2$ **,** Δ**G (mag)**

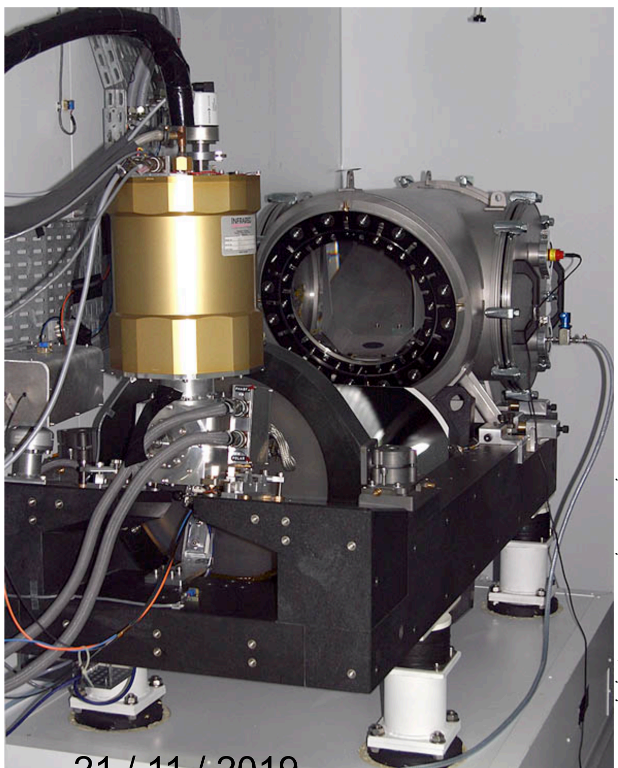
TODCOR: 2-D cross-correlation

- **2D cross-correlation** of high-resolution spectrum with **2 templates** (e.g. PHOENIX library, Husser+ 2013)
- **Least-square spectral matching** to derive the best templates, including line broadening LSF and V sin(i)





Zucker & Mazeh 1994
Zucker+ 2004



Observations of SBs with spectrograph Sophie @T193 of OHP since 2010, in order to

- detect the secondary components of SB1 objects
- improve the orbital elements
- m/s precision of RV => accurate M $\sin^3 i$ (<1%)
- Accurate masses (~ 1%) when the Gaia astrometric observations will be delivered (DR4).

The main sample

- 69 SB2 with $m_V > 6$ mag

Primary components :

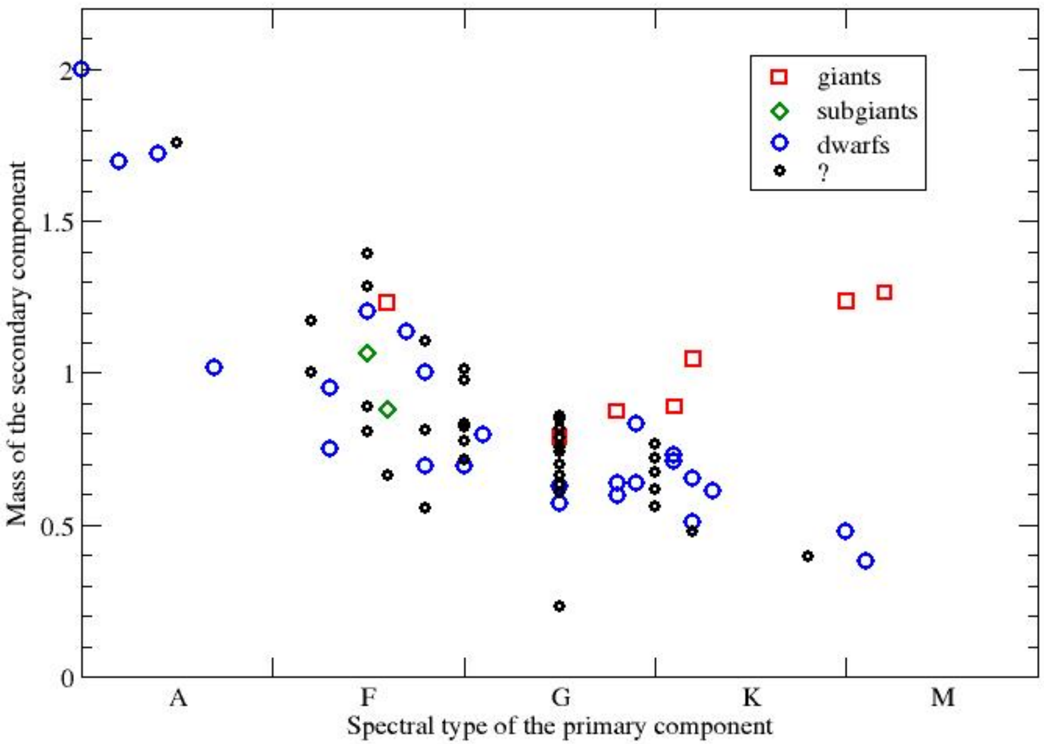
- A0 – M1.5
- 5 late-type giants

Primary masses:

0.3 – 2 $\mathcal{M}_\odot$

+ Backup sample

(mv ≤ 6 mag)



Status of the program

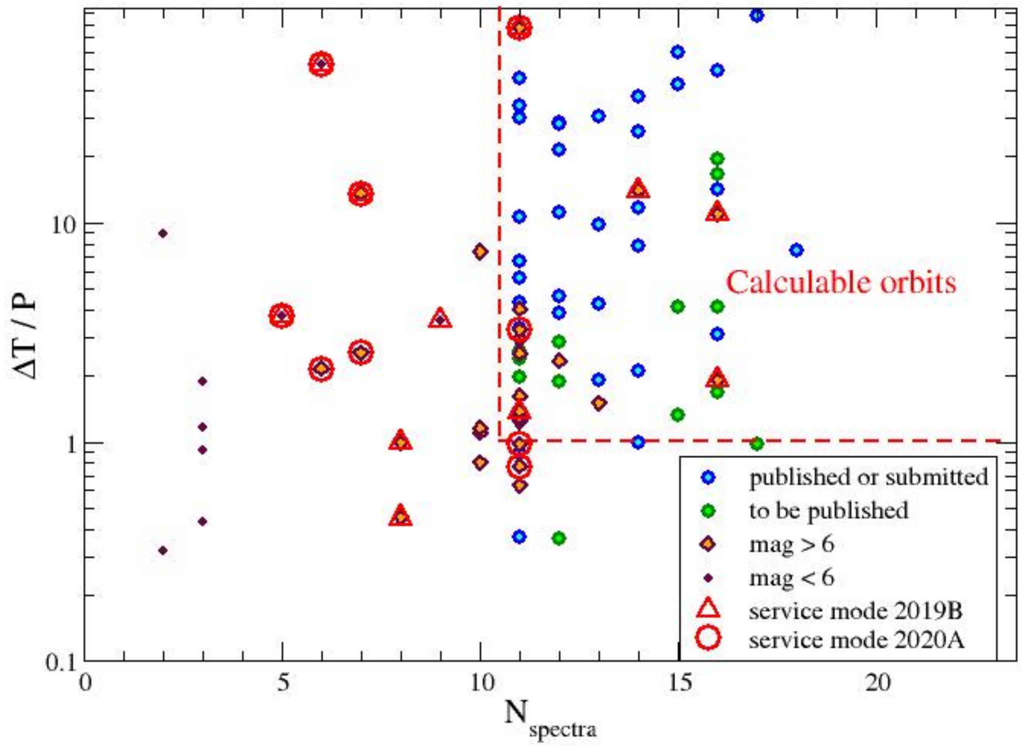
• 1155 spectra + 21 (Sophie archive)

•More than 10 years of data

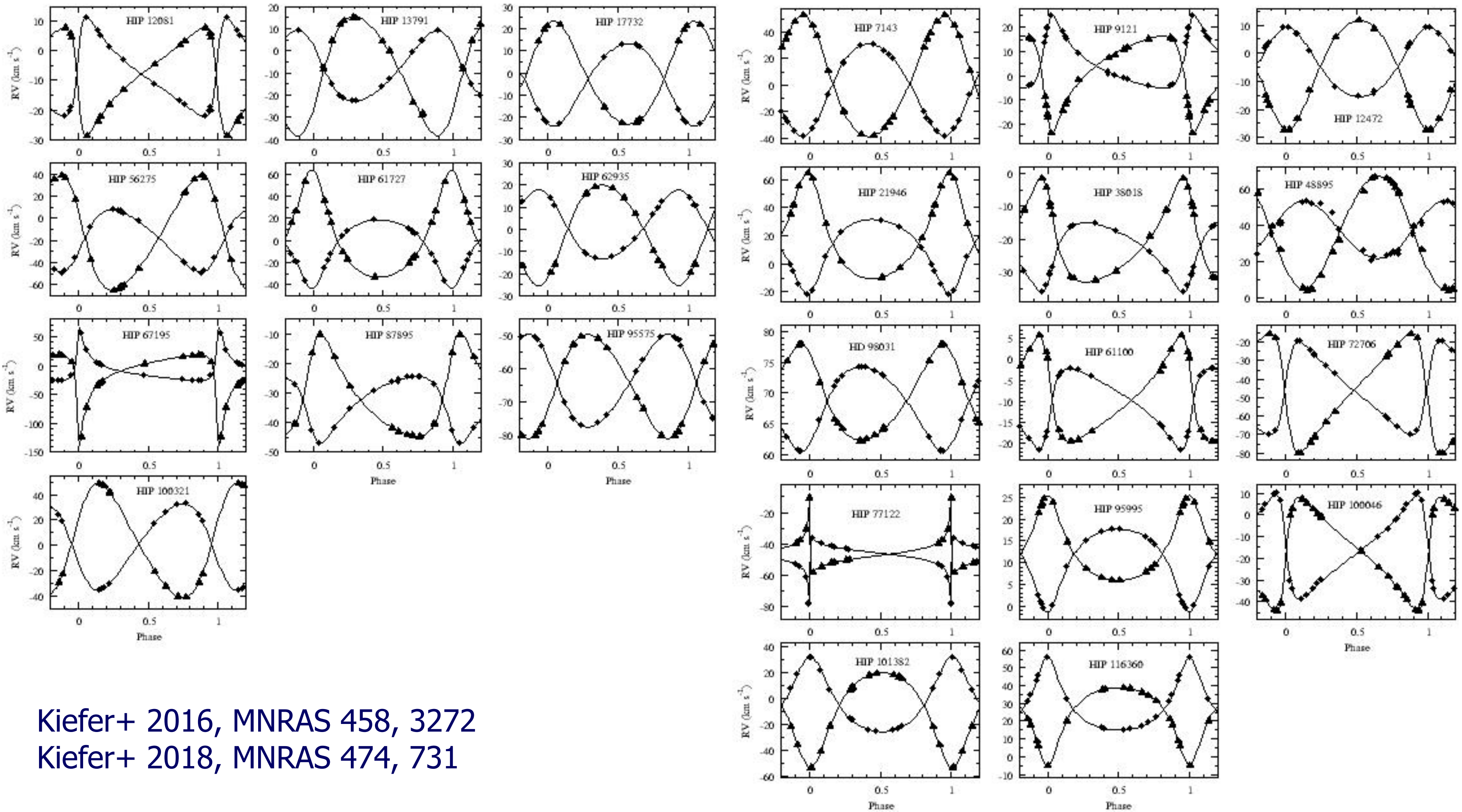
• 20 new secondary components detected + 6 to be confirmed
Halbwachs+ (2014)

• 24 revised SB2 orbits published
Kiefer+ (2016, 2018)

• 10 more SB2 orbits to be published in 2019
Halbwachs+ 2019 (submitted)

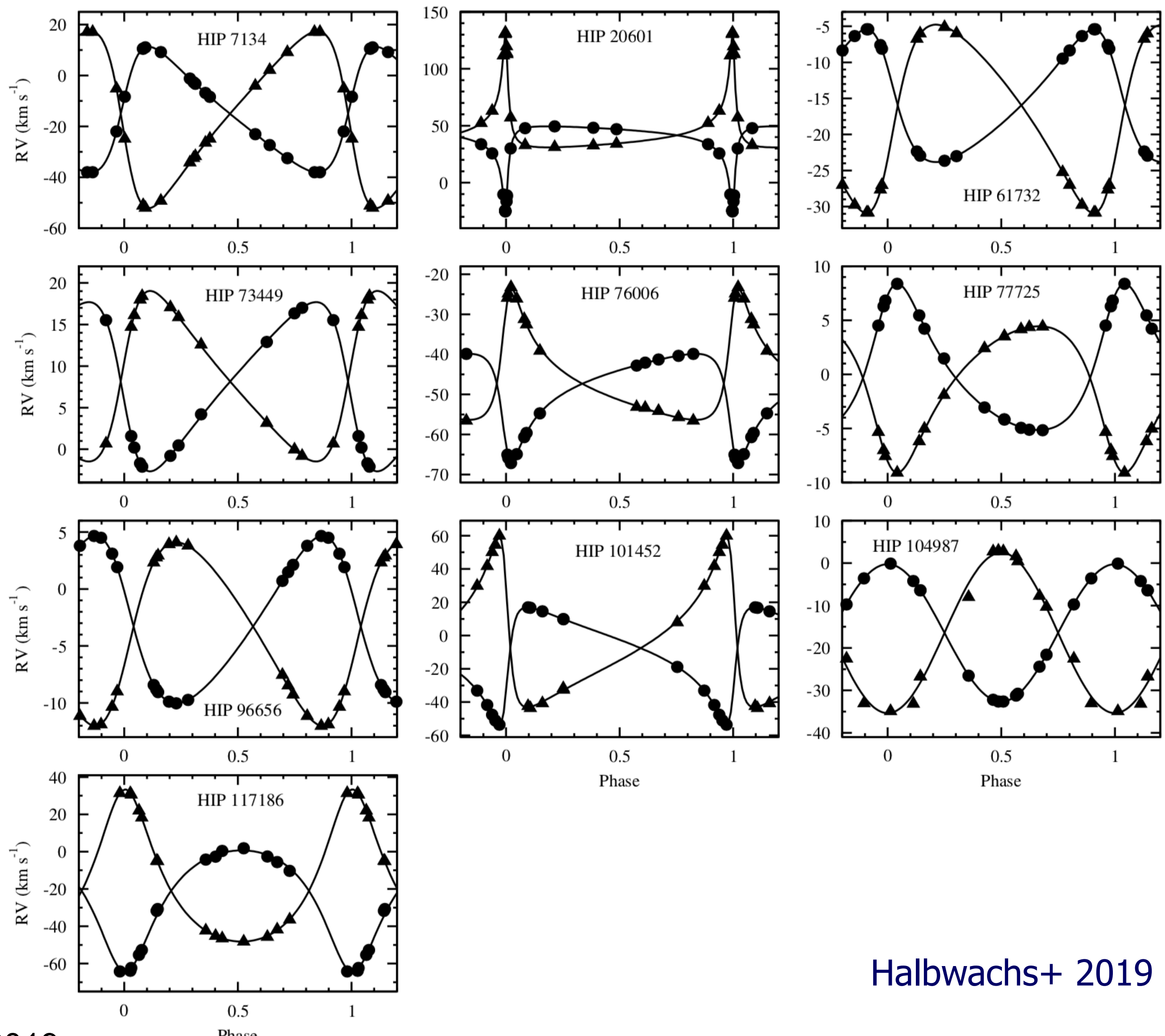


24 SB2 orbits published



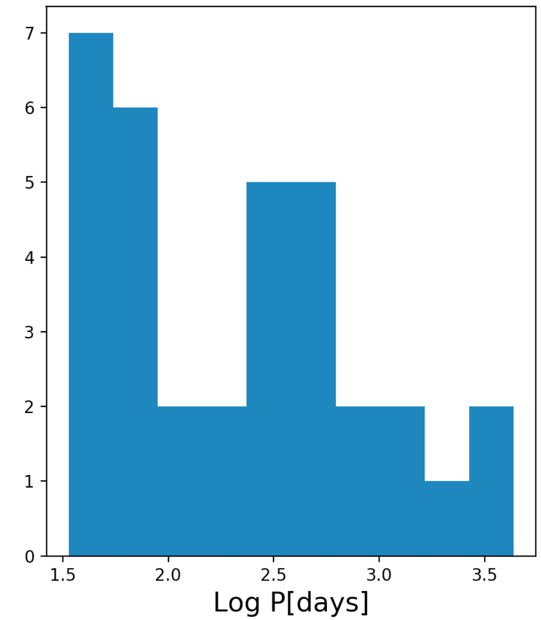
Kiefer+ 2016, MNRAS 458, 3272
Kiefer+ 2018, MNRAS 474, 731

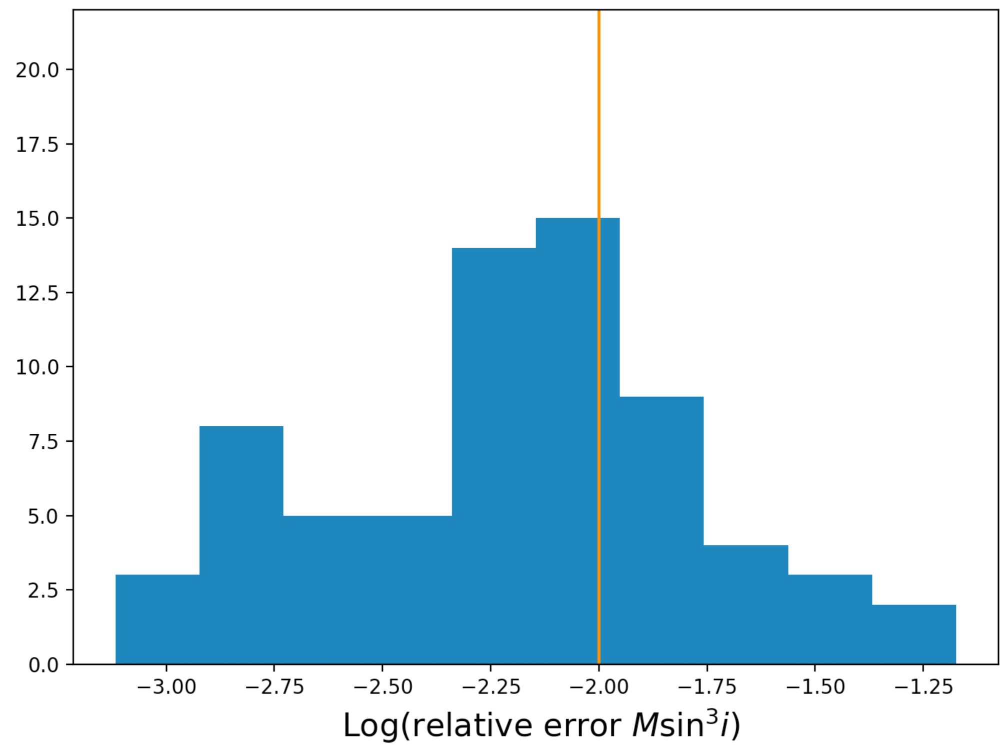
10 more SB2 orbits TBP

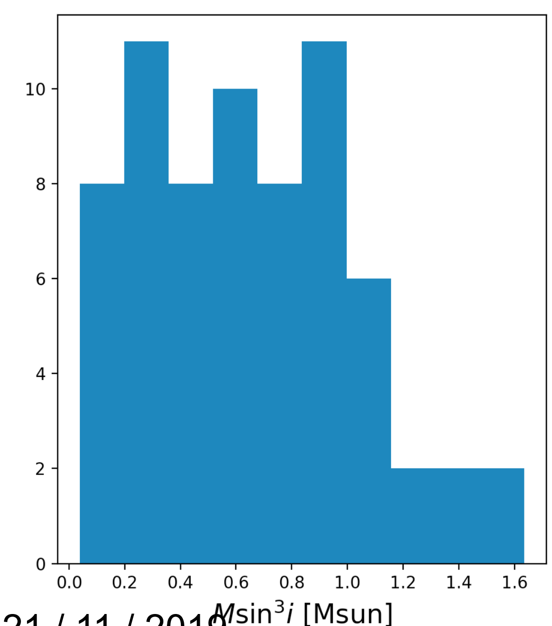


Halbwachs+ 2019 (submitted)

RV results summary







- M sin^3 i of 64 components
- Mass range: 0.1-1.6 $\mathcal{M}_\odot$
- Period range: 30-3,000 days
- 43 components with precision on M sin^3 i better than 1%

Other programmes

- Mercator/HERMES (A. Jorissen & D. Pourbaix) : 7 SB2 in the southern hemisphere.

- 3.5/CARMENES (Tal-Or et al.) : ~ 40 SB1 to observe as SB2 in IR

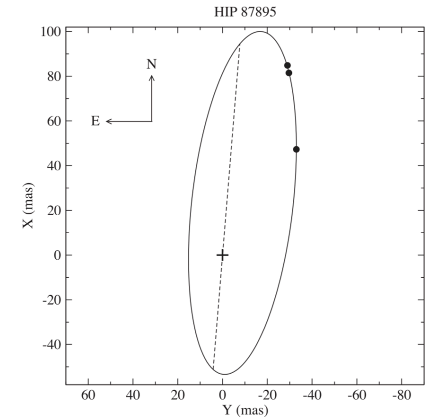
- VLTI/PIONIER (Halbwachs et al.) :
  5 SB2-OHP + 2 SB2-HERMES resolved

$\Rightarrow \mathcal{M}_1$, $\mathcal{M}_2$, π, ΔH

Validation (and corrections) of the Hipparcos parallaxes

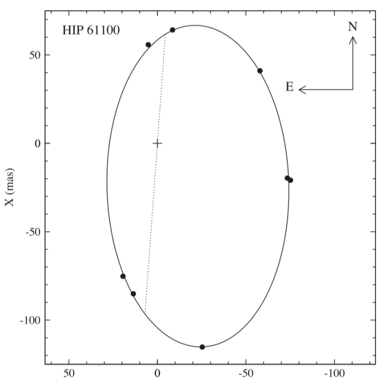
Future validation of the Gaia astrometric orbits in DR4.

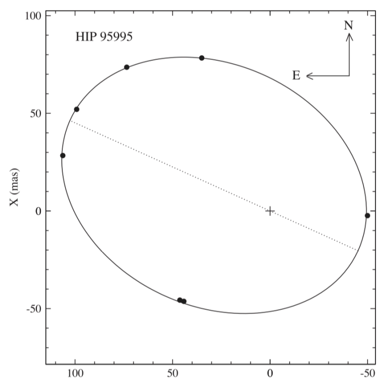
Astrometric detections

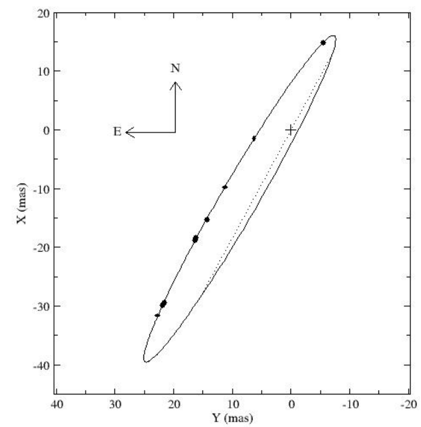


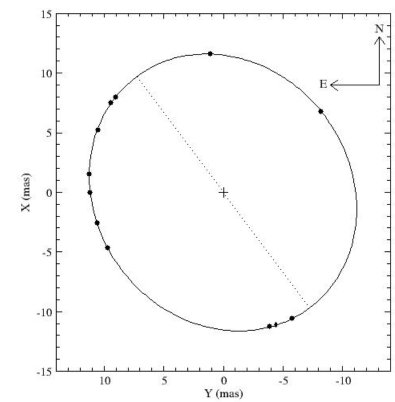
11 SB2 systems resolved with VLTI/PIONIER, PTI and publicly available astrometric data, with masses of both components derived

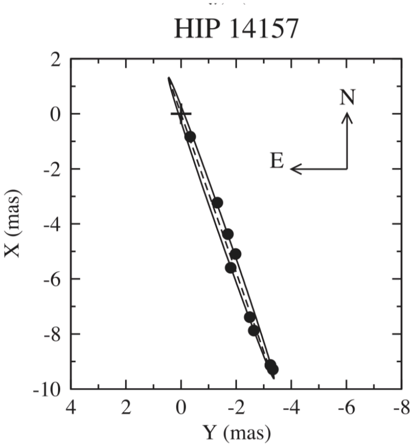
Halbwachs+ (2016)
Kiefer+ (2016)
Kiefer+ (2018)
Boffin+ (in prep)

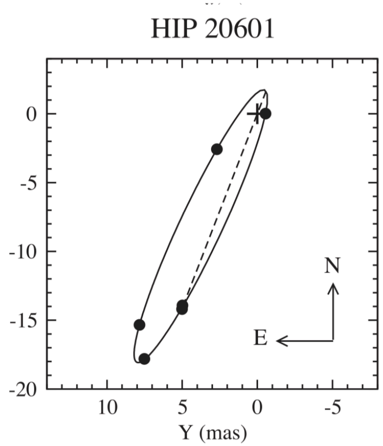


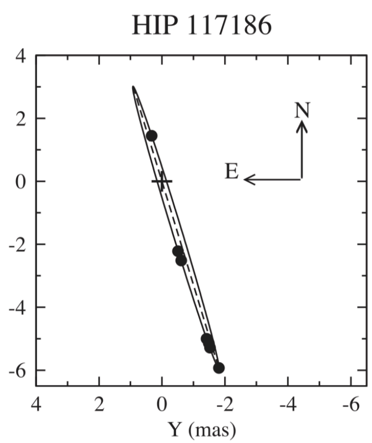


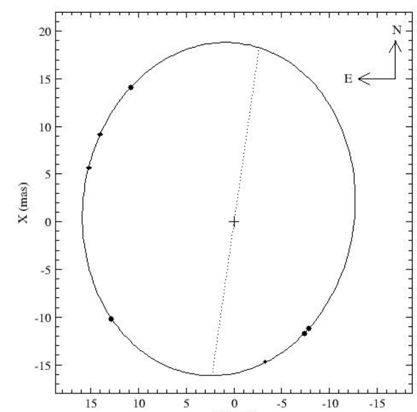


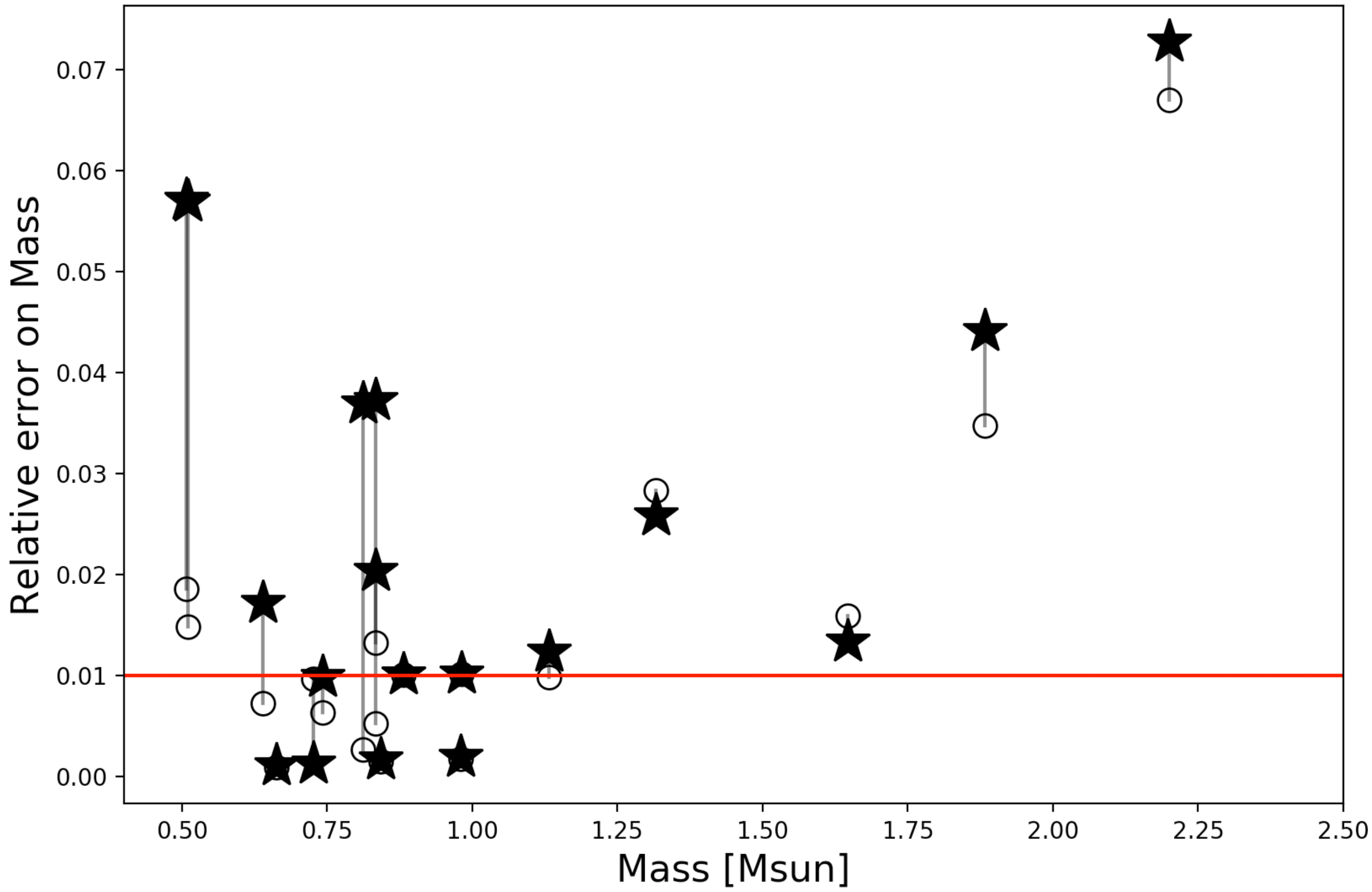












- **7 components** with masses at a precision better than 1%
- At least **4 more** components to reach the 1%-level with more precise astrometry => GAIA

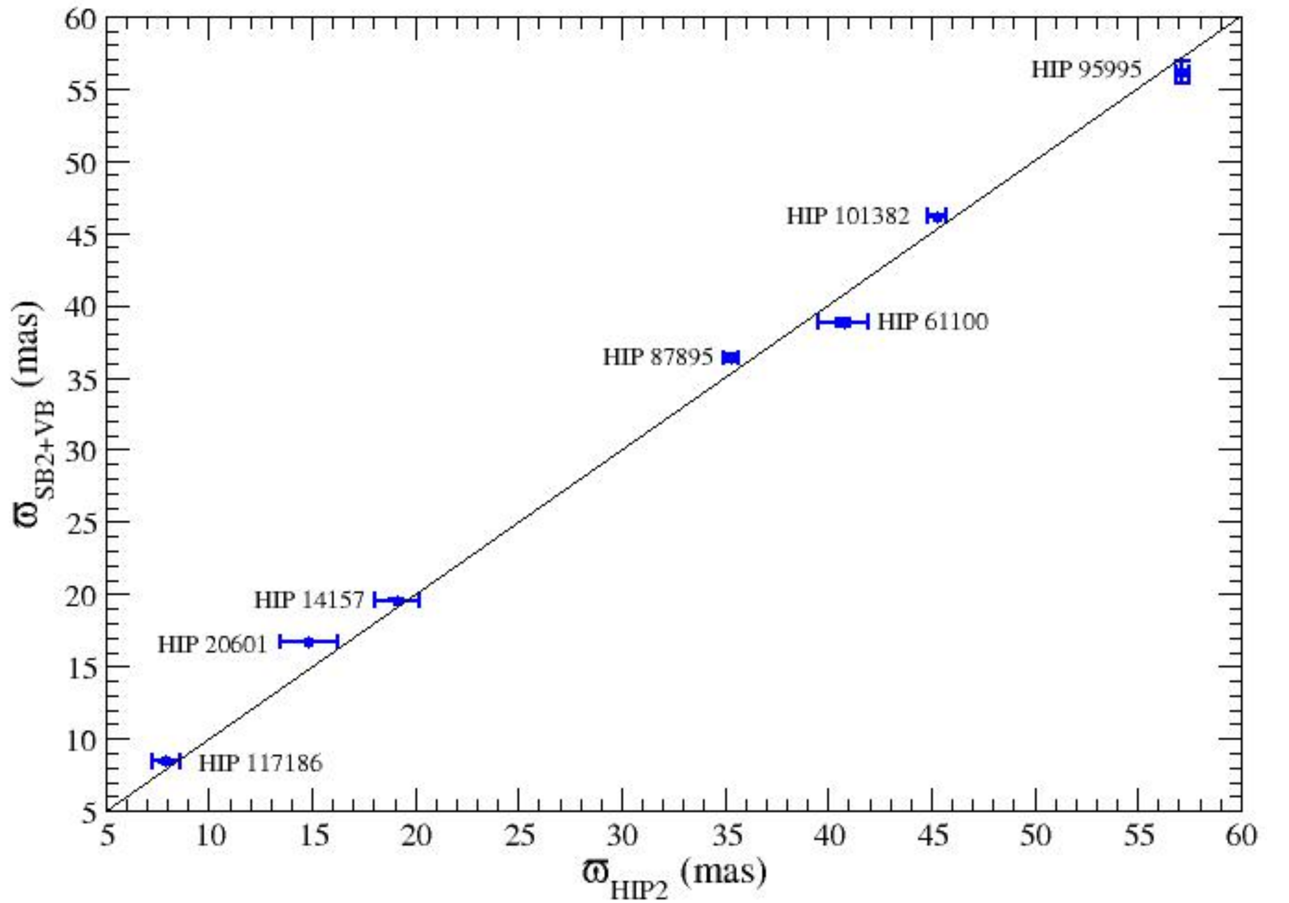
Validation of the Hipparcos-2 parallax

SB2 + BV ⇒ π_{SB2+BV}

The Hipparcos-2 parallaxes are recomputed taking into account the orbital elements

⇓

$\pi_{SB2+BV} \approx \pi_{HIP2}$



Mass-luminosity relation

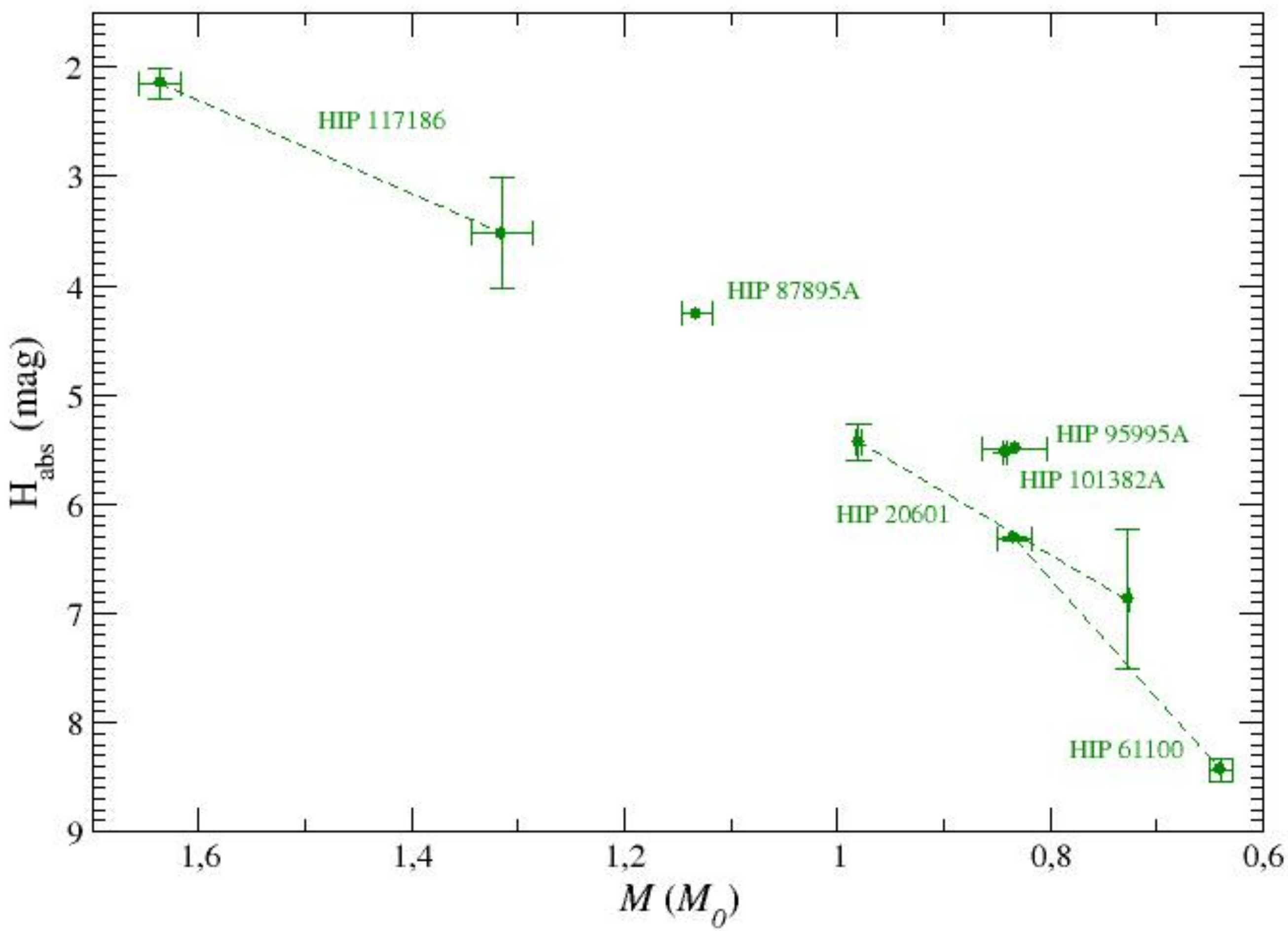
Semi-major axis of the astrometric orbit from Hipparcos

⇓

ΔH_{Hip}

⇓

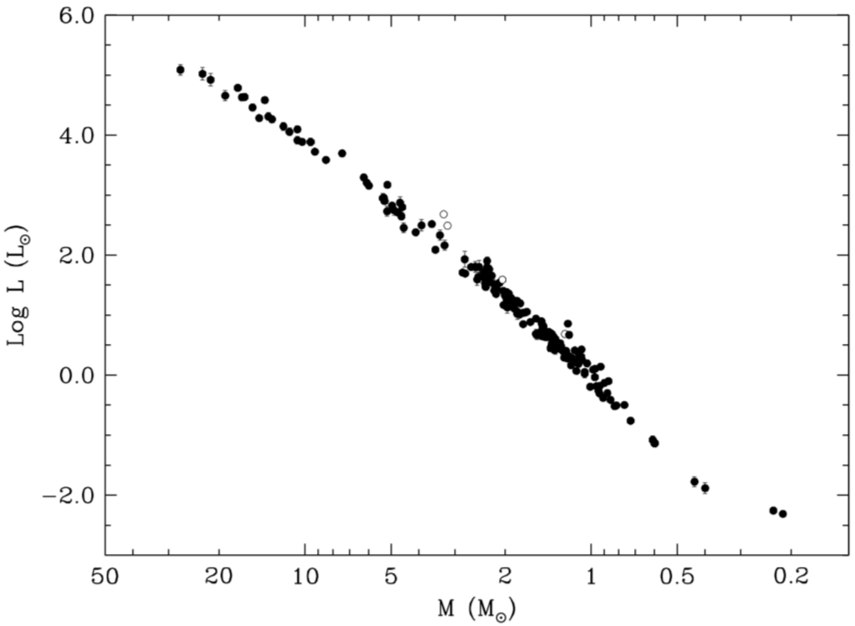
H_1, H_2

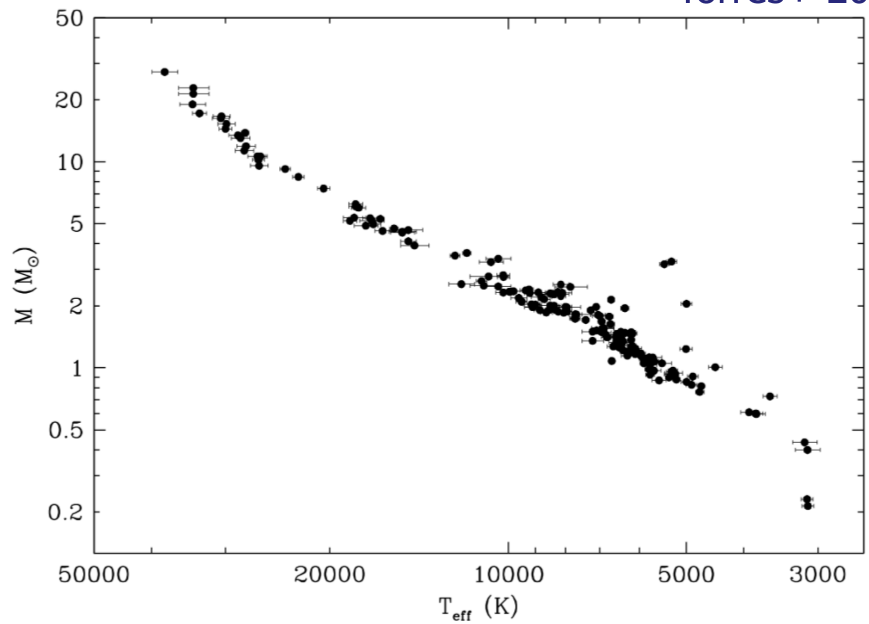


Updating empirical mass relations

- Need well derived parameters for both SB2 components.
- Usually a difficult task... more work TBD here
- Issues with line broadening, [Fe/H], undetermined Log(g) if F_B/F_A <10%, missing lines in the templates...
- Currently performed by **recurrent least-square** spectral matching with PHOENIX templates (Husser+ 2013) around Ca I line @ 6120Å

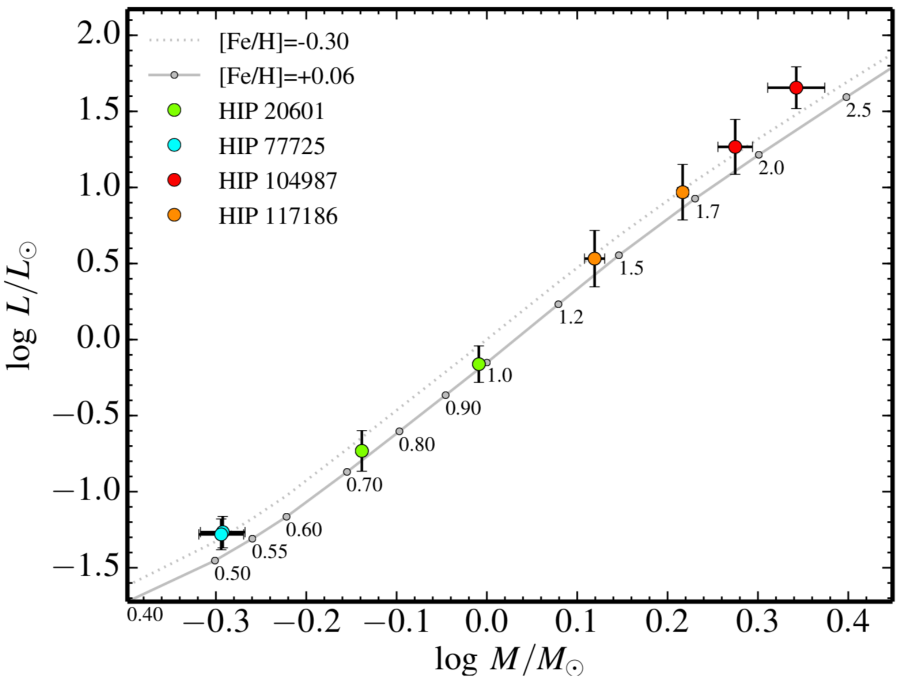
Torres+ 2010

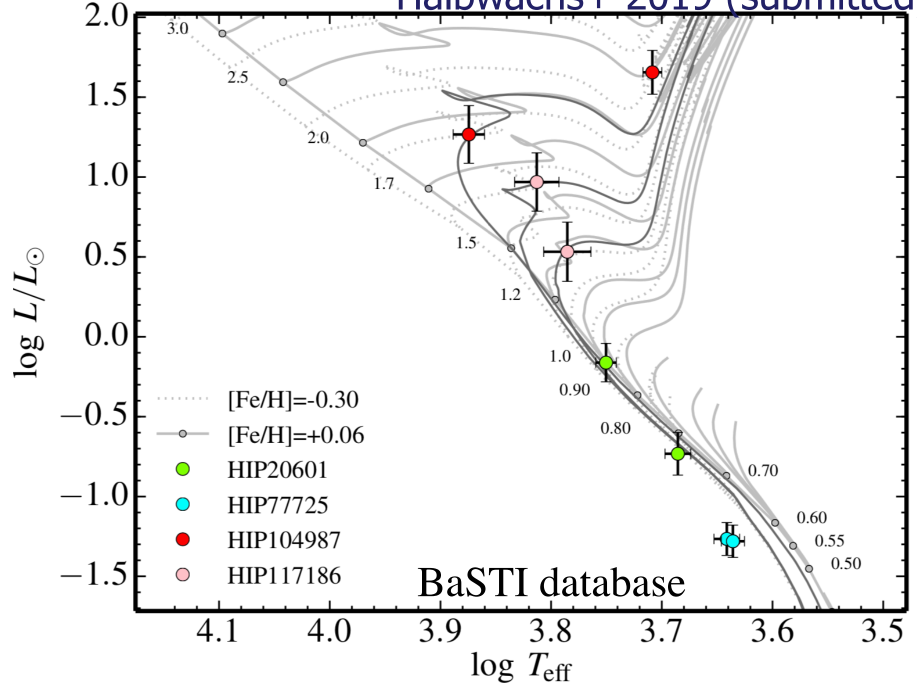




Confronting with stellar models

Halbwachs+ 2019 (submitted)

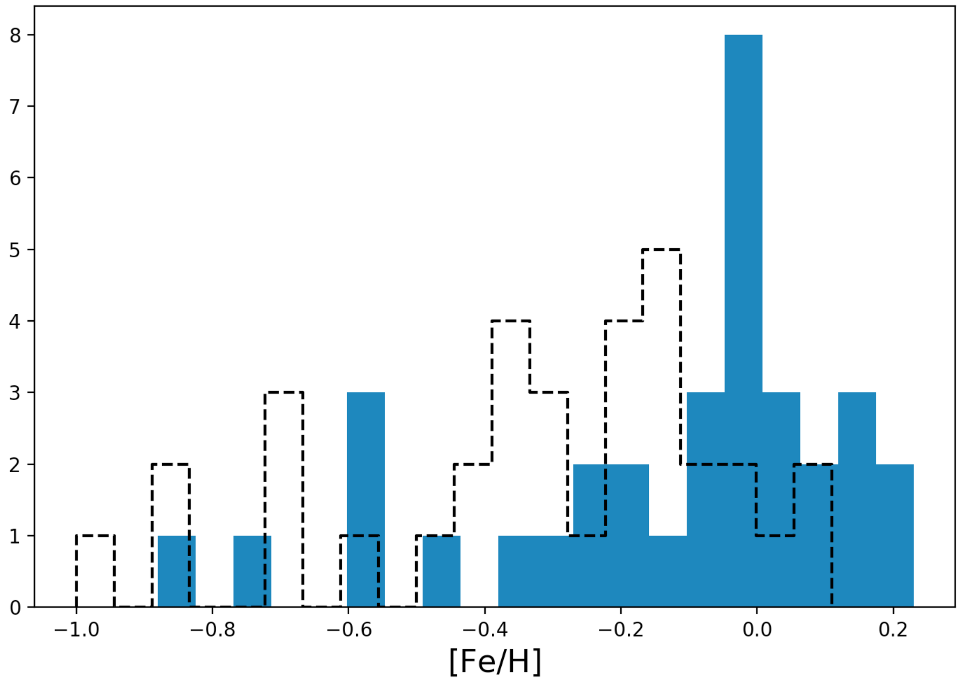


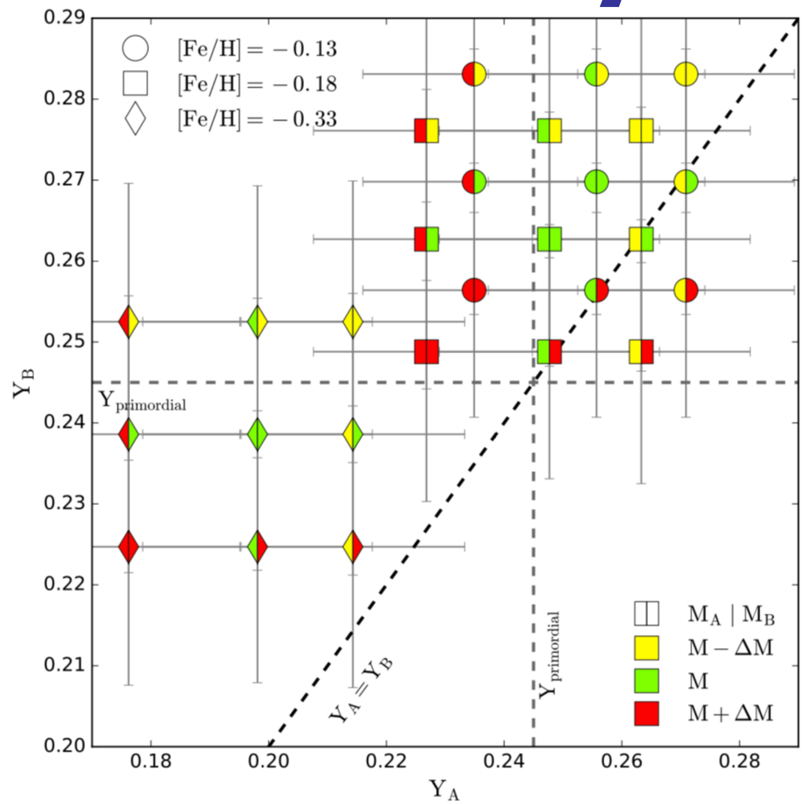


- Some good agreements e.g. here HIP104987 : an evolved system (1.1-1.3 Gyr) of massive stars >2$\mathcal{M}_\odot$
- Some more difficult systems, e.g. HIP117186
  - Comp A on a 3 Gyr and comp B on a 7 Gyr isochrone
  - [Fe/H]=-0.60, Teff=6200 K
  - Not compatible with Casagrande+ (2011): [Fe/H]=-0.1 and Teff=6800 K

=> systematics on the spectroscopic parameters Teff and [Fe/H] of SB2s

The issue with the metallicity





- Calibrating the metallicity on the Sun
- Remaining systematics (caused by e.g. line broadening)
- Few 0.1 dex in [Fe/H] -> Few 100K in T_{eff}
- Building a robust spectrum fitting algorithm for SB2
- Every SB2 spectrum is different -> flux ratio, Vsin(i), T_{eff}, log(g) combinations, missing lines...

Conclusion

- 34 accurate SB2 orbits, 35 more within a few years. May be used to check P, e, T_0, and ω of Gaia astrometric orbit.
- 11 VB accurate orbits, for validation of Gaia astrometric orbits and preliminary parallaxes. **7 components with M better than 1% precision**.
- Our first masses from Gaia with the first Data Release that will include astrometric orbits (2021 ?)
- Extension of the programme with the Gaia astrometric binaries.

- Several candidates benchmark binaries
- Well-derived M $\sin^3 i$ for both components, and spectroscopic parameters not to difficult to derive (small flux ratio).