First results of the CHARA/SPICA ISSP binary program

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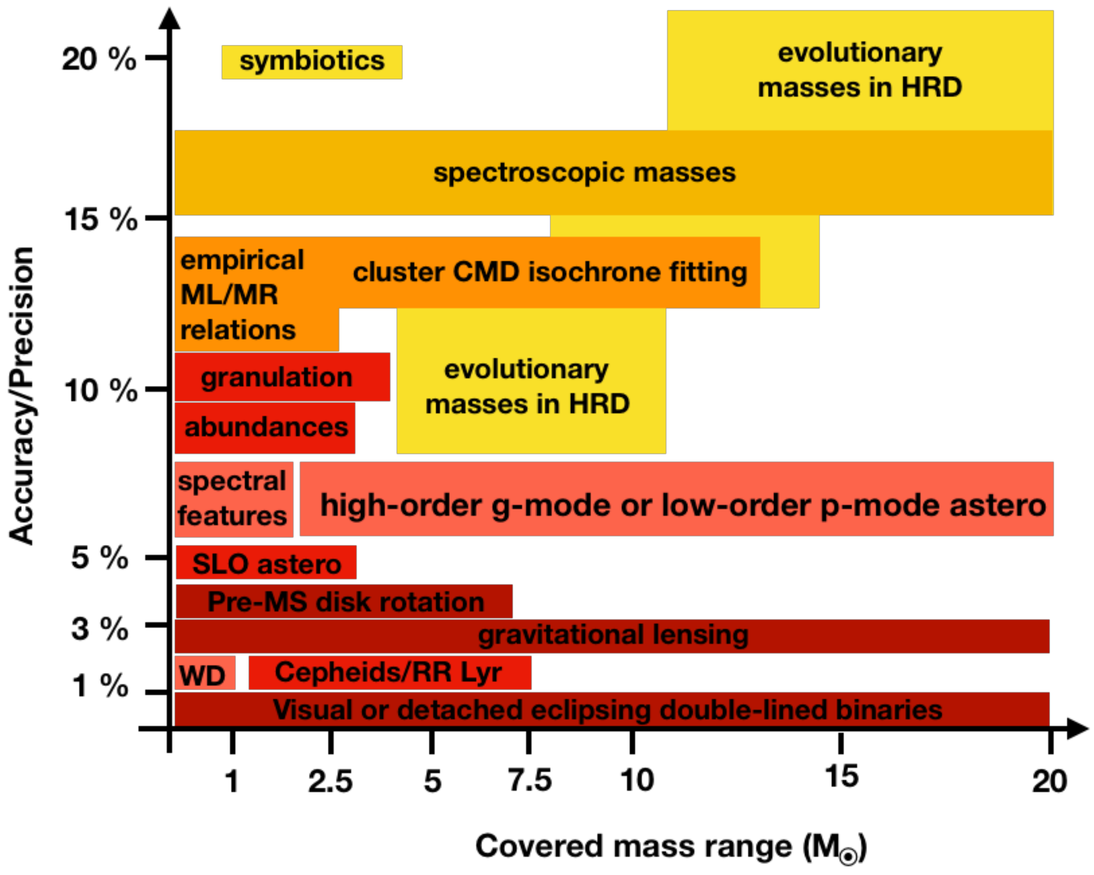
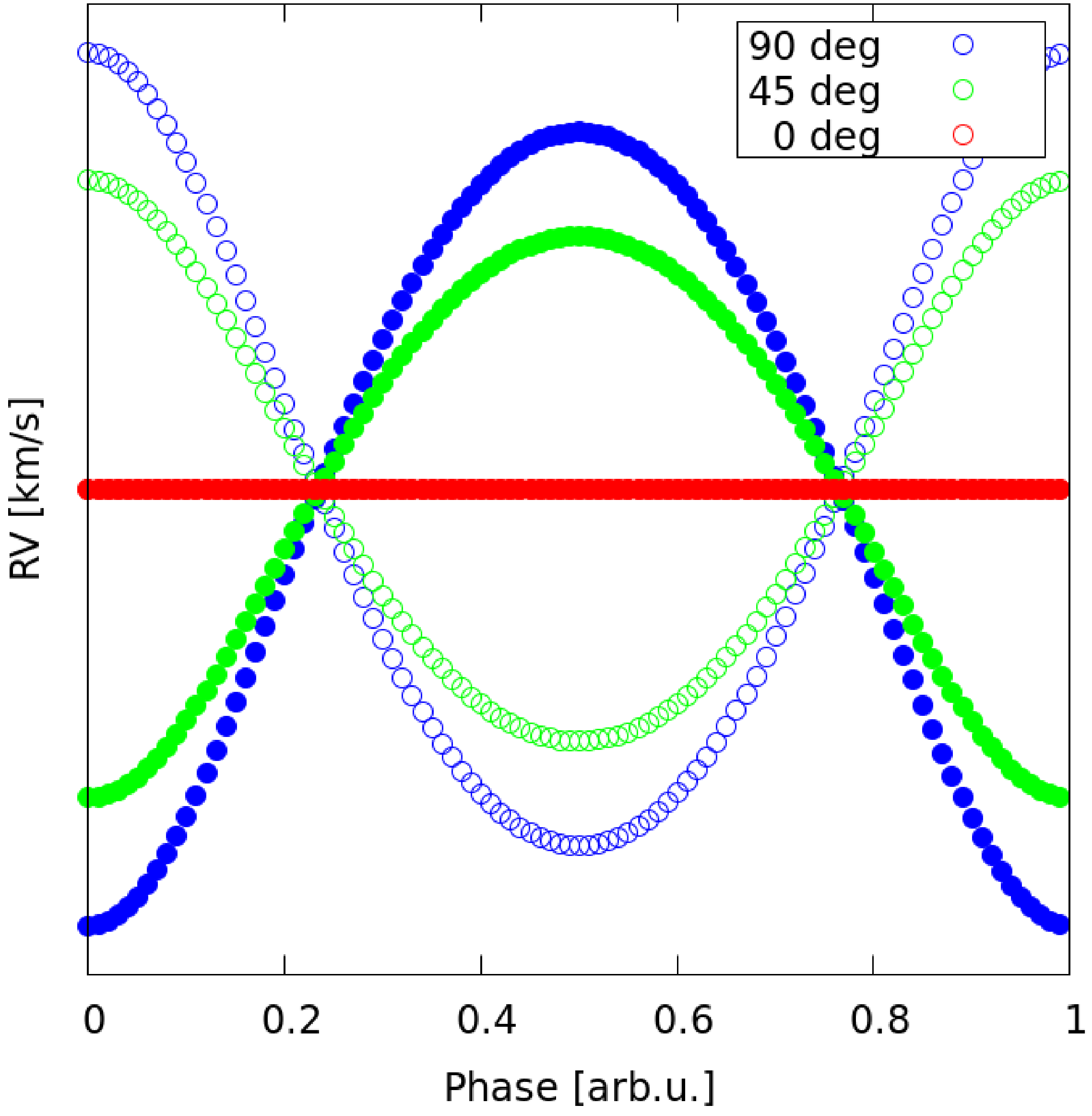
Introduction

- Form the base in determination of stellar masses
- Combination of spectroscopy + photometry - precision ~1%
  (specific cases – eclipsing binaries)
- Interferometry – orbit reconstruction – precision <1%
  (Gallenne+ 2016, Lester+ 2022)
  lifts heavy degeneracy in mass and inclination
- Independent distance



(Serenelli+ 2021)



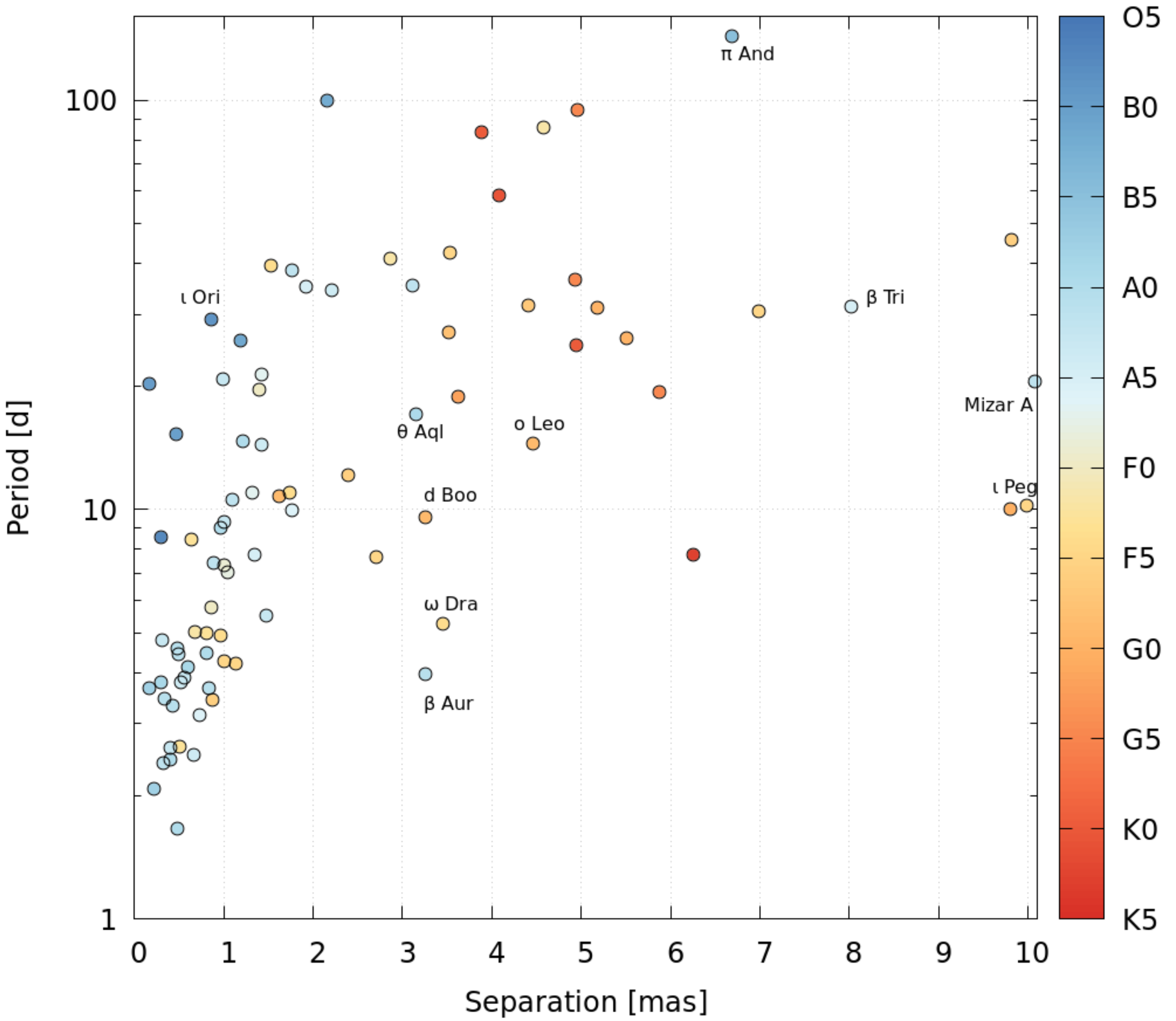
$$RV_j(t) = \gamma - (-1)^j K_j \left[cos\left(\omega + v(t)\right) + ecos(\omega) \right]$$

$$M_j sin^3(i) = \frac{P}{2\pi G} \frac{K_1 K_2}{K_j} (K_1 + K_2)^2 \sqrt{(1 - e^2)^3}$$

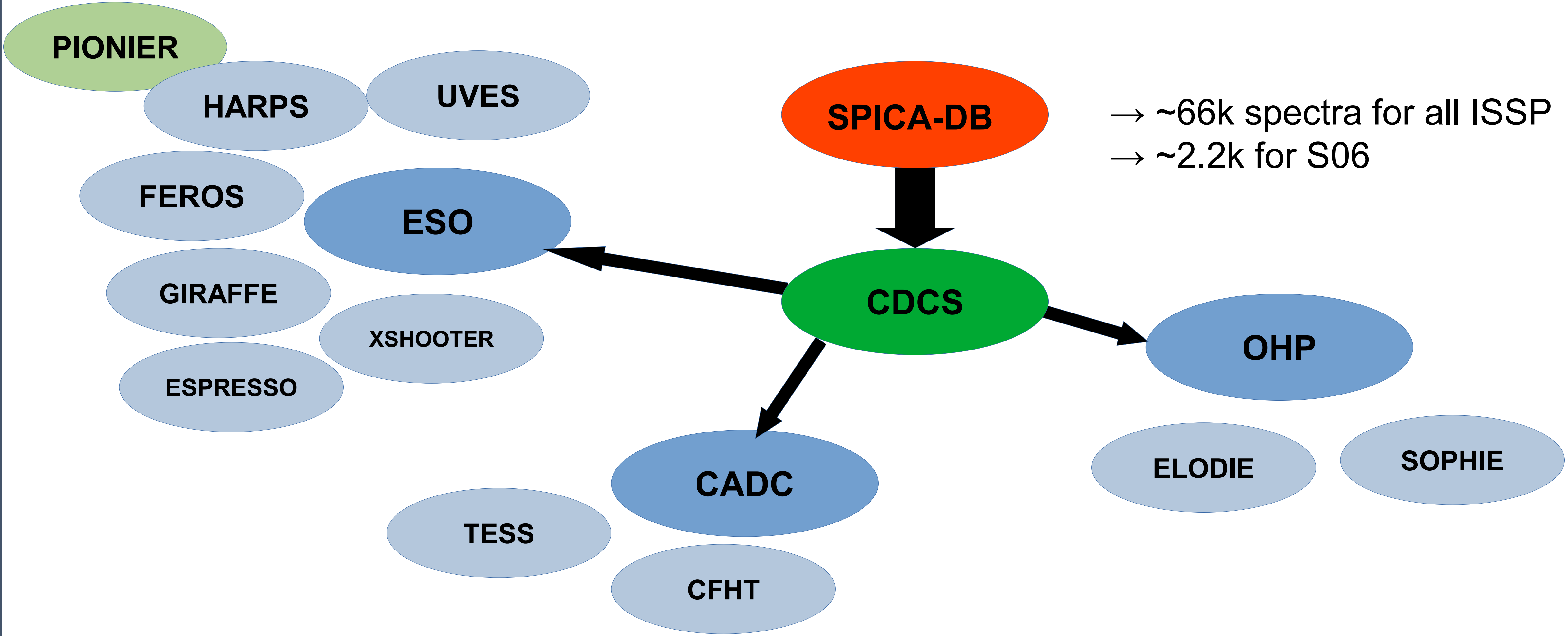
$$asin(i) = \frac{P}{2\pi} (K_1 + K_2) \sqrt{1 - e^2}$$

ISSP S06 Program

- Using IF + spectroscopy, measure masses for binaries across the HR diagram
- only
  - detached non-interacting SB2s
  - non-variable components
- $V < 8^{mag}$
- $DEC > -30^{o}$
- $f > 6\%$
- $\alpha \in [0.15, \sim 10]$ mas
- $\alpha/\theta_1 \in [2.5, 50]$



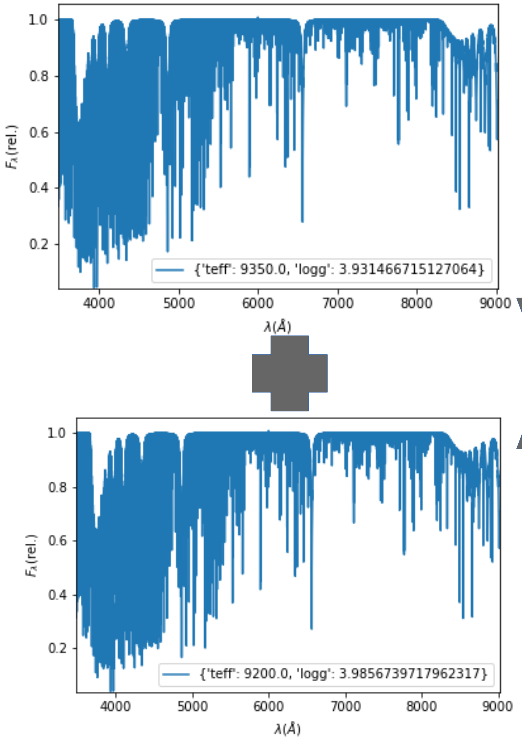
SPICA Complementary Data Collection Software

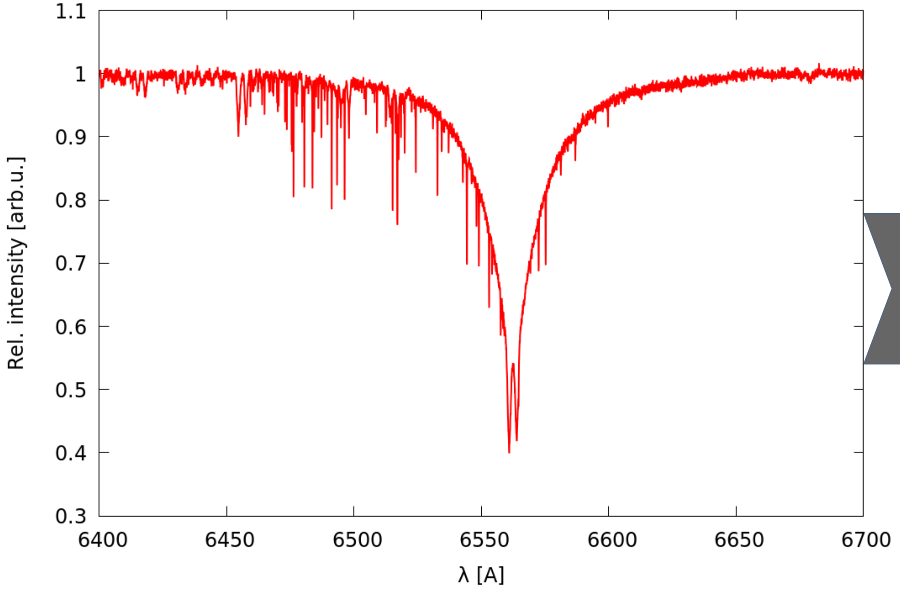


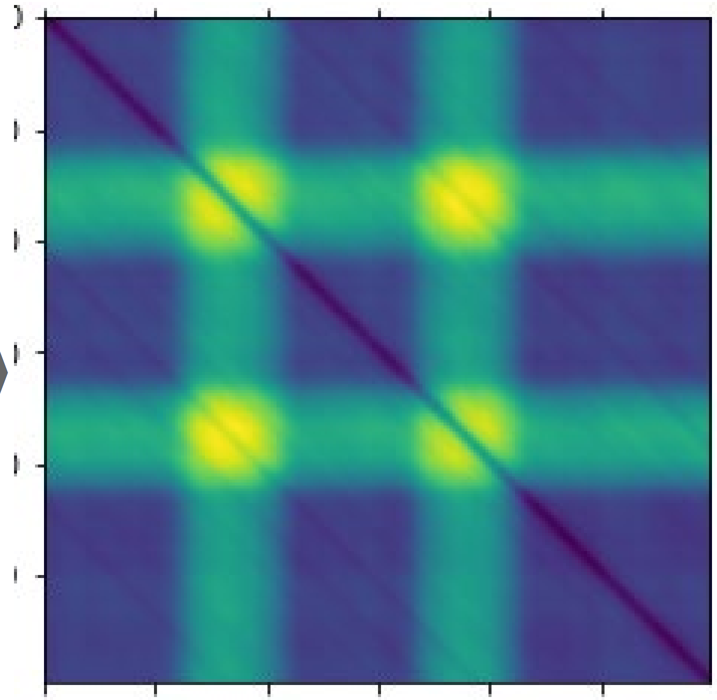
→ ~66k spectra for all ISSP
→ ~2.2k for S06

Measuring radial velocities

- TODCOR algorithm (Zucker & Mazeh 1994; Zucker+ 2003)
- Interpolation within synthetic grid (Nemravová+ 2016)



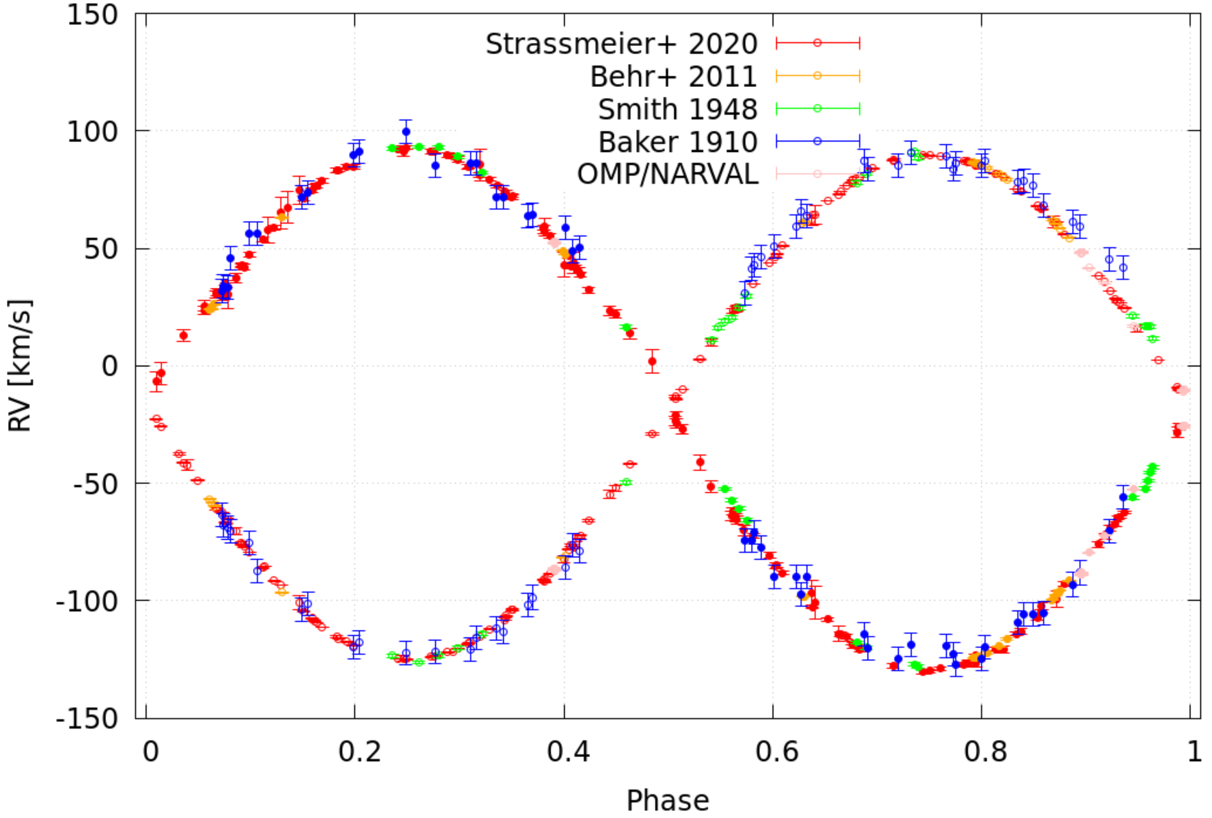


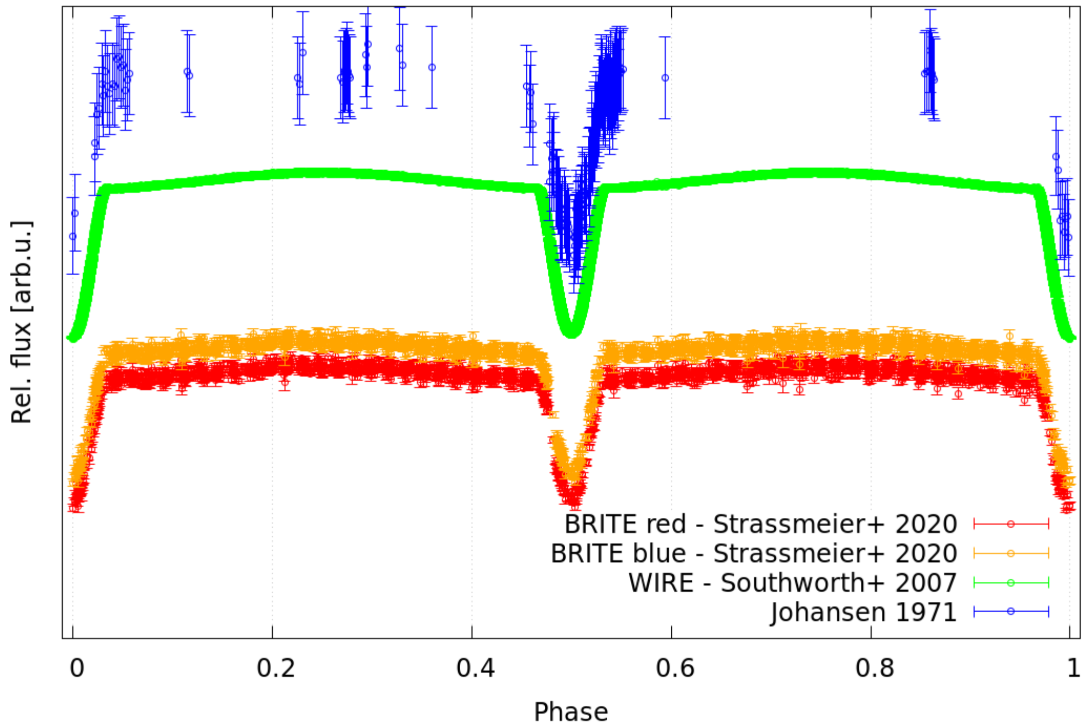


β Aurigae / Menkalinan

- One of the brightest and nearest evolved A-type binaries
- Second discovered spectroscopic binary (Maury 1890)
- Among first eclipsing binaries (Stebbins 1911)
- Two early A-type evolved metallic stars
- V 1.9^{mag}, P 3.96 d

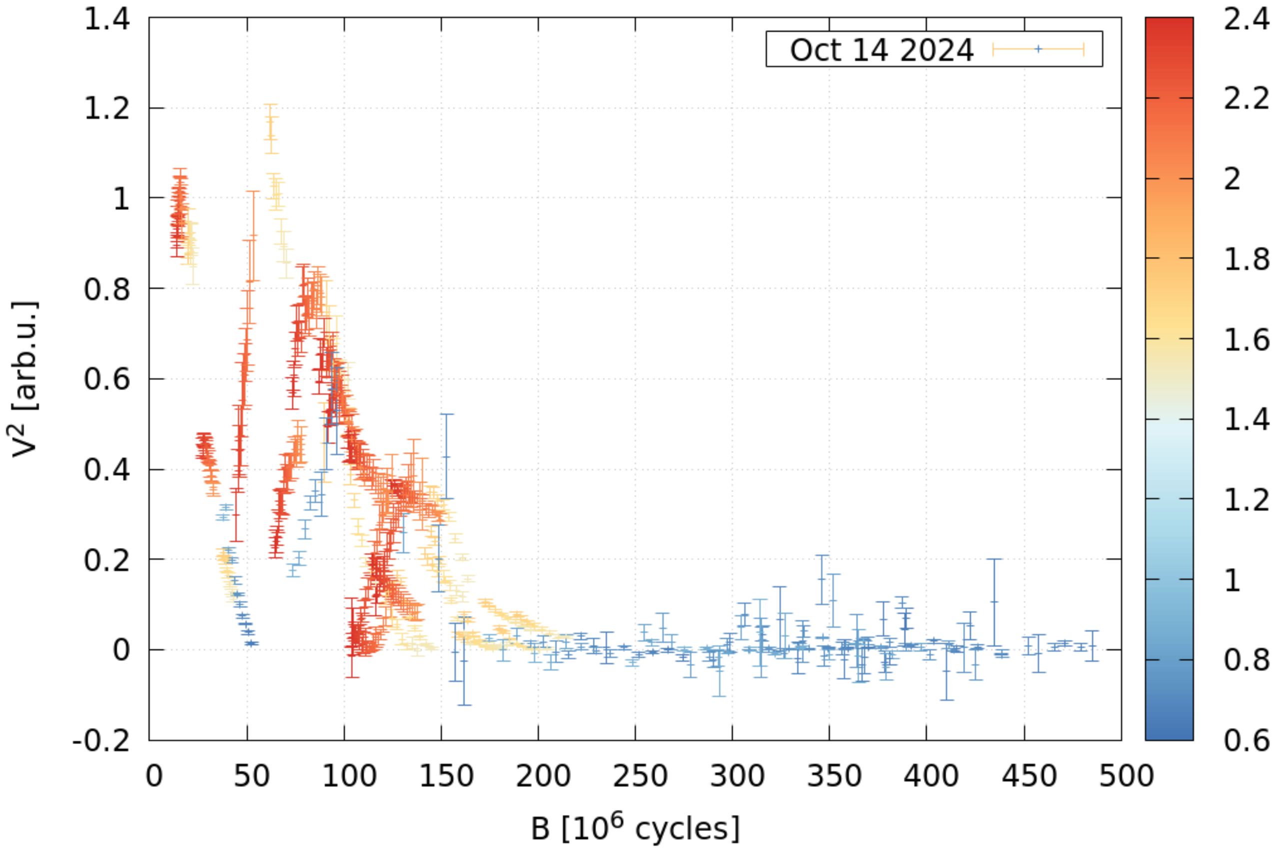
(Stellarium)


Strassmeier+ 2020
Behr+ 2011
Smith 1948
Baker 1910
OMP/NARVAL
RV [km/s]
150
100
50
0
-50
-100
-150
0
0.2
0.4
0.6
0.8
1
Phase


Rel. flux [arb.u.]
BRITE red - Strassmeier+ 2020
BRITE blue - Strassmeier+ 2020
WIRE - Southworth+ 2007
Johansen 1971
0
0.2
0.4
0.6
0.8
1
Phase

Observation journal

SPICA+MIRC-X+MYSTIC			MIRC
15 Oct 2023	2		07 Dec 2012
11 Nov 2023			26 Oct 2014
13 Nov 2023			27 Oct 2014
14 Oct 2024			28 Oct 2014
31 Oct 2024	2		29 Oct 2014
16 Dec 2024	2		30 Oct 2014
			31 Oct 2014
			21 Oct 2016
			22 Oct 2016



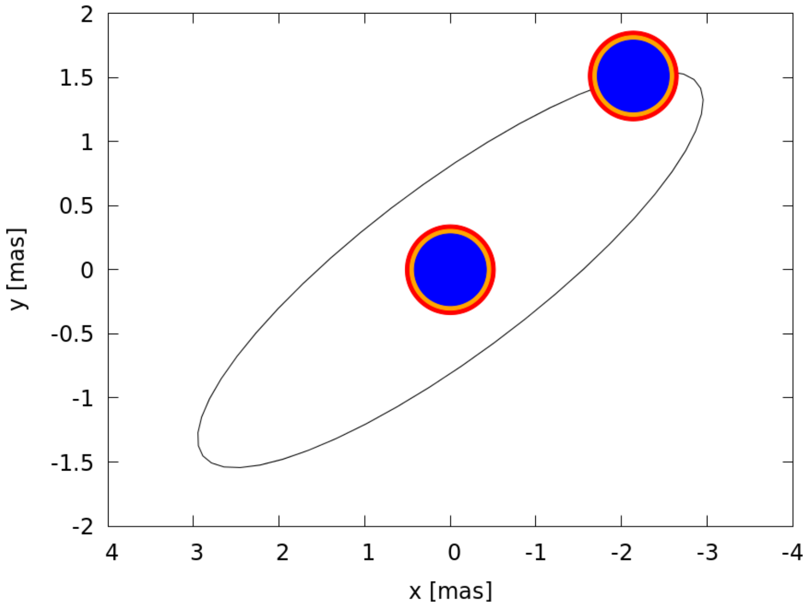
OIModeler

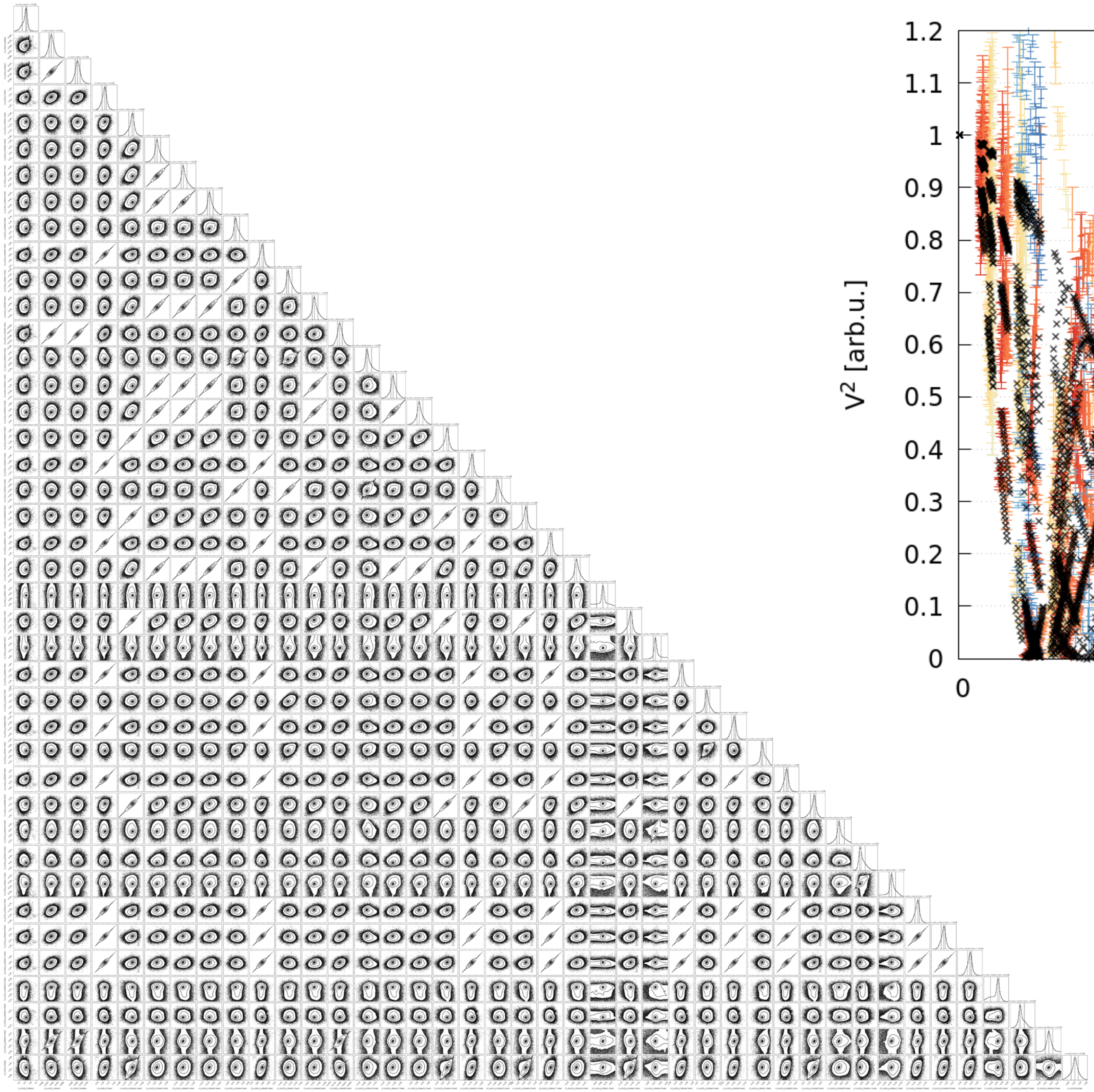
- Python code (Meilland+ 2024) for modeling of interferometric data
- Model:
  - Two disks (θ_1, θ_2)
  - Position (x,y) (n)
  - Flux weight $f(\lambda)$ (3) – 'nearest' interpolation
  - Chromatic scaling $c(\lambda;T,logg)$ - fixed
    - Linear LD coefficients u

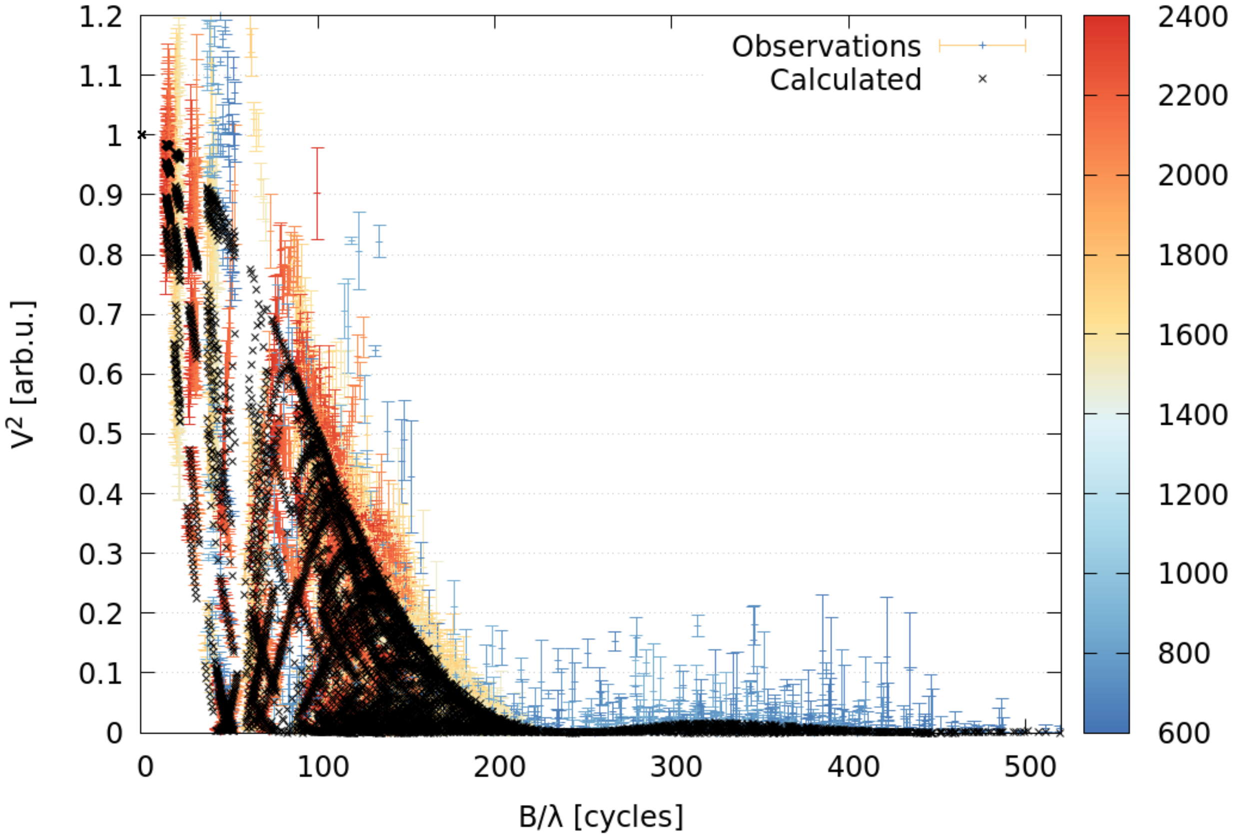
$$V^2 = \frac{1}{(1+f)^2}\left|\frac{2J_1\left(\pi\sqrt{u^2+v^2}c\theta_1\right)}{\pi\sqrt{u^2+v^2}c\theta_1} + f\frac{2J_1\left(\pi\sqrt{u^2+v^2}c\theta_2\right)}{\pi\sqrt{u^2+v^2}c\theta_2}exp[-2\pi i(ux+vy)]\right|^2$$

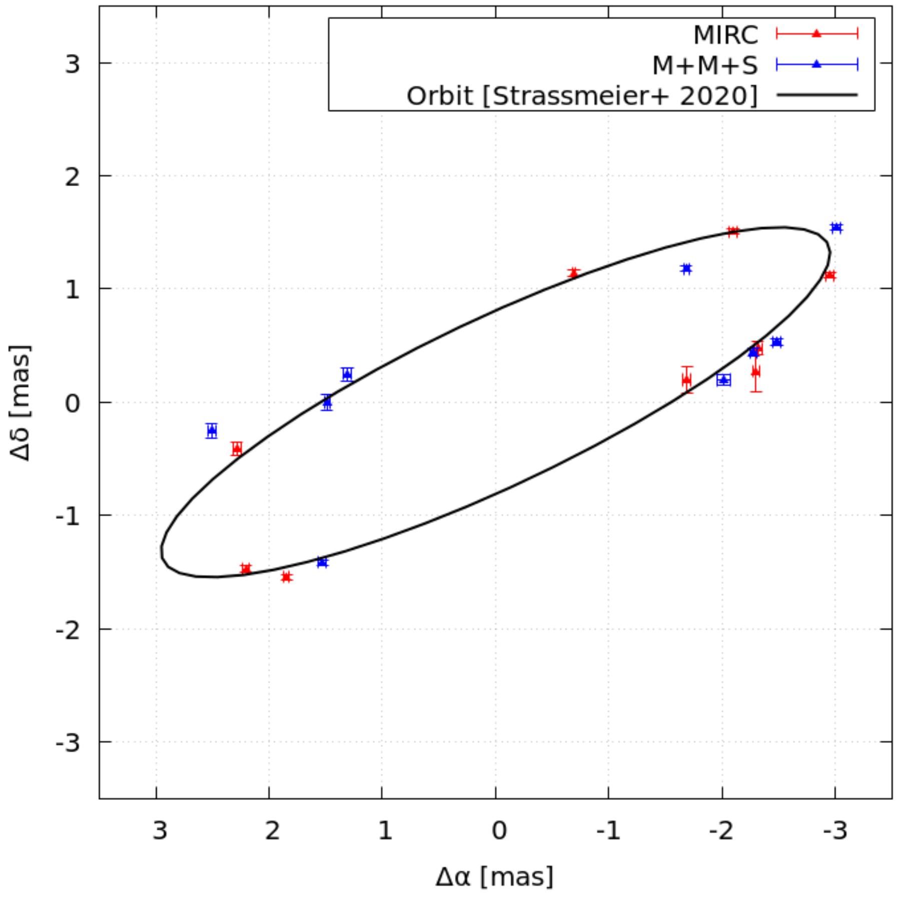
$$\theta = \frac{UD(\lambda)}{c(\lambda)} \qquad c(\lambda) = \sqrt{\frac{15-7u_\lambda}{15-5u_\lambda}}$$

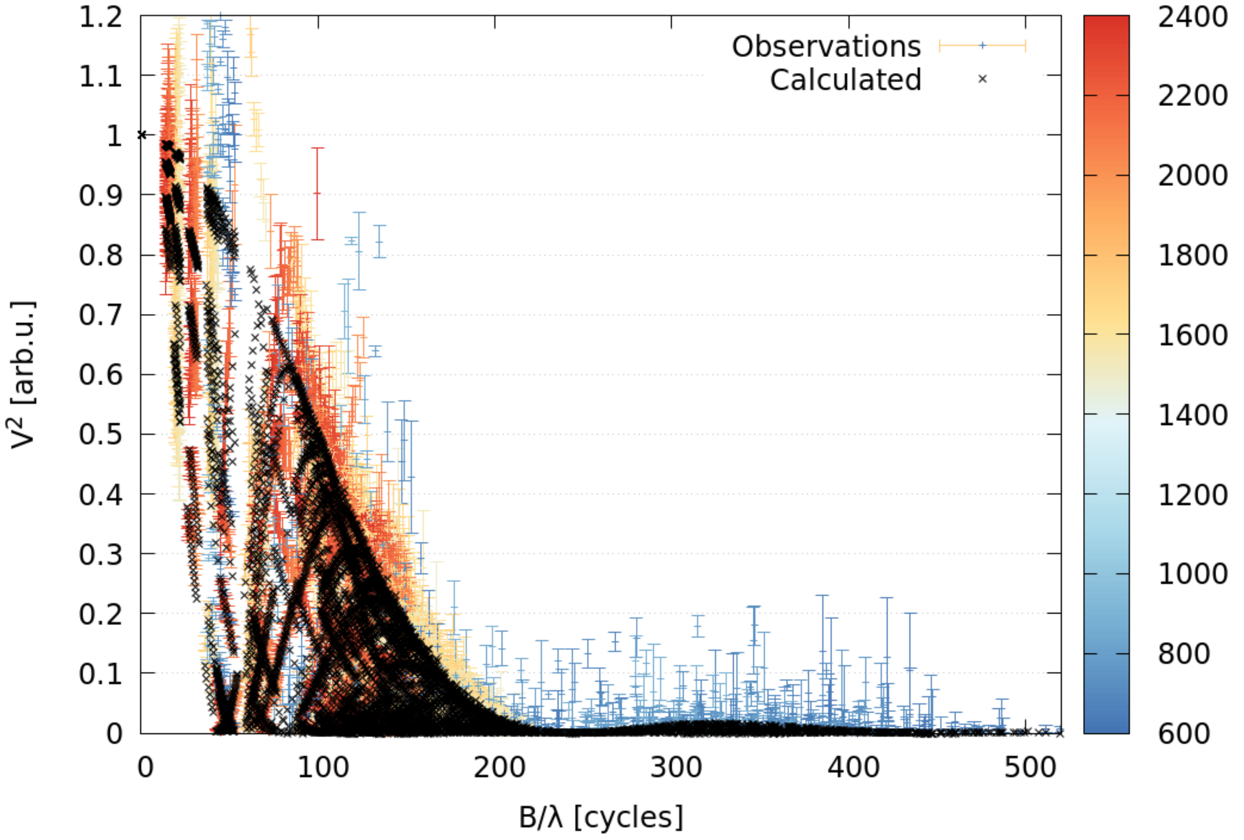
(Hanbury Brown 1974)






Observations
Calculated
V2 [arb.u.]
B/λ [cycles]
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
0
100
200
300
400
500
600
800
1000
1200
1400
1600
1800
2000
2200
2400





θ_1 1.12(6) mas

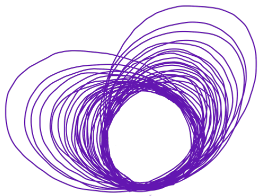
θ_2 1.02(2) mas

Fw_R 0.51(4)

Fw_H 0.550(15)

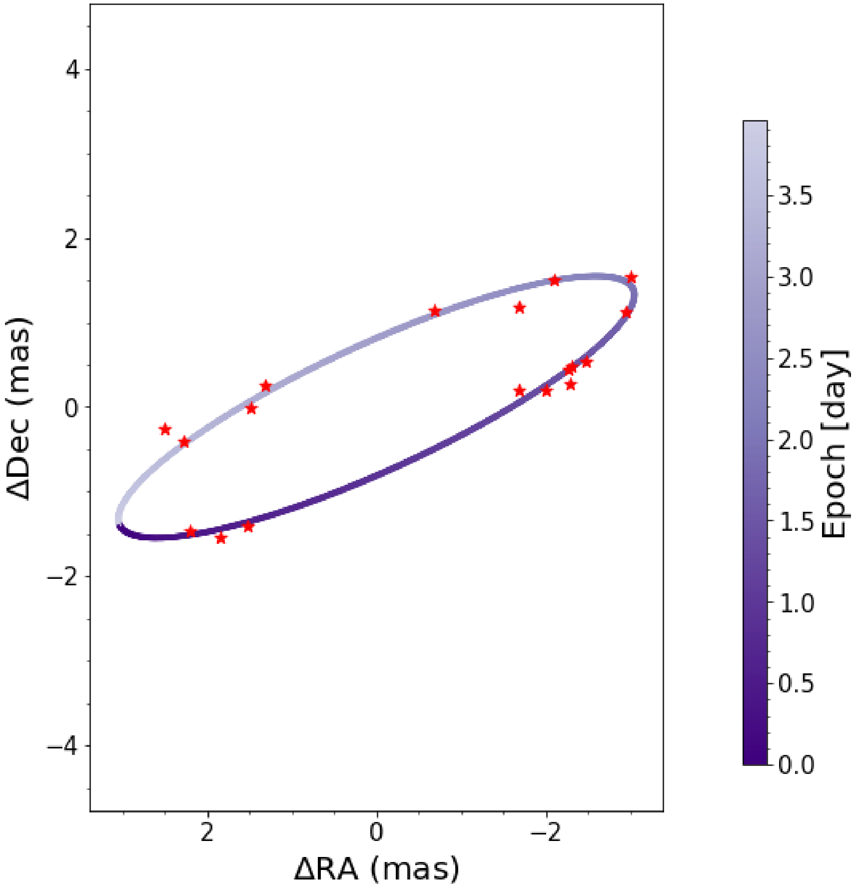
Fw_K 0.534(15)

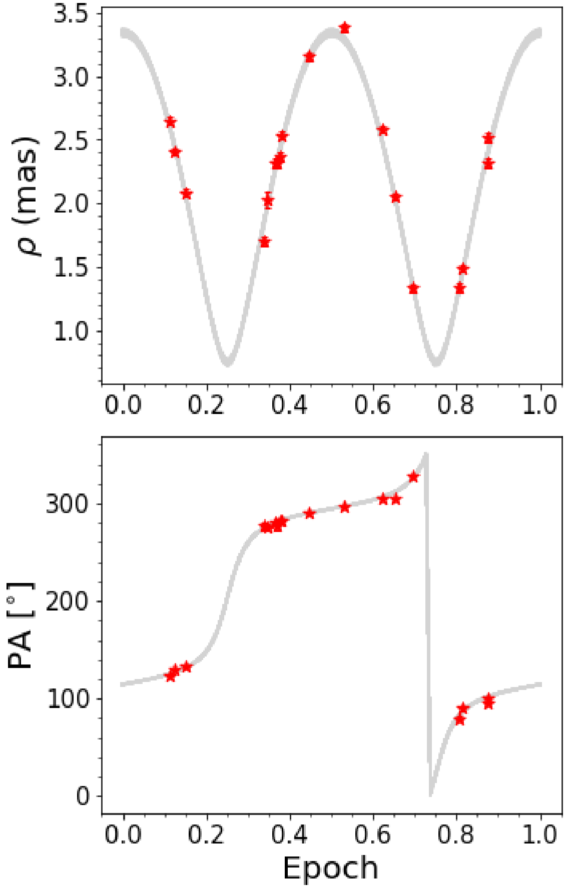
orbitize!



- Orbit-fitting software (Blunt+ 2020)
- Designed for fitting exoplanets
- Result positions from OIModeler → orbital elements

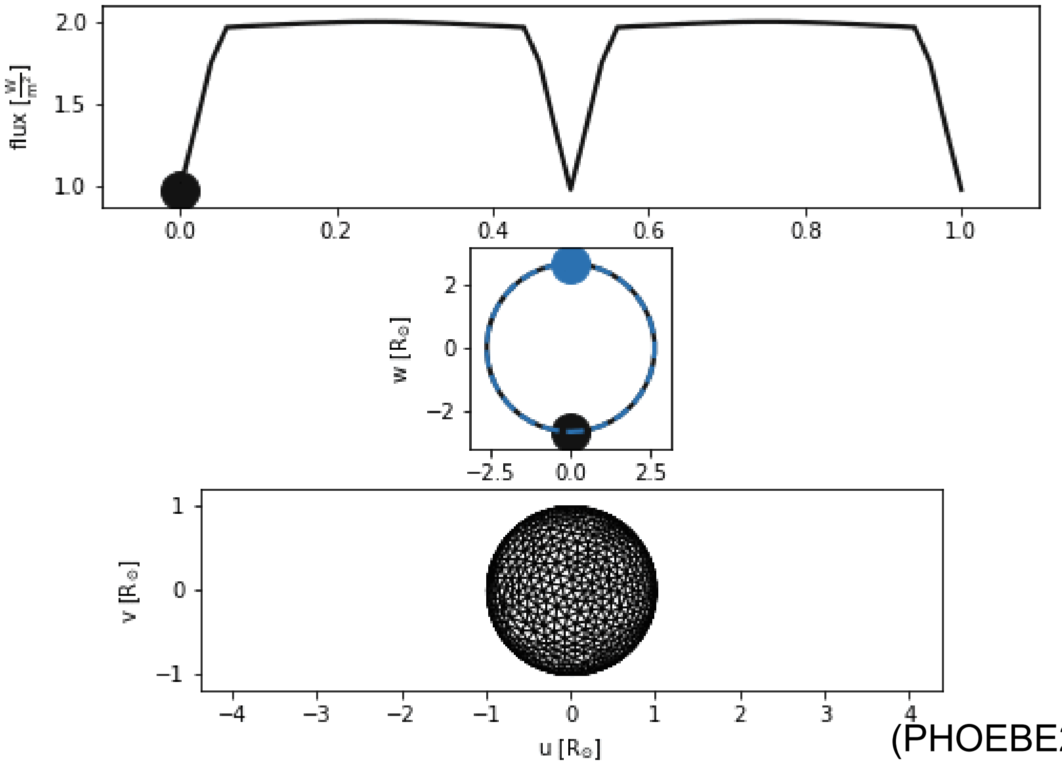
a 0.0820(16) au
i 70(2)°
Ω_N 294.6(2)°
τ 0.5018(5)
π 40.82(16) mas
M_{tot} 4.69(3) M_S



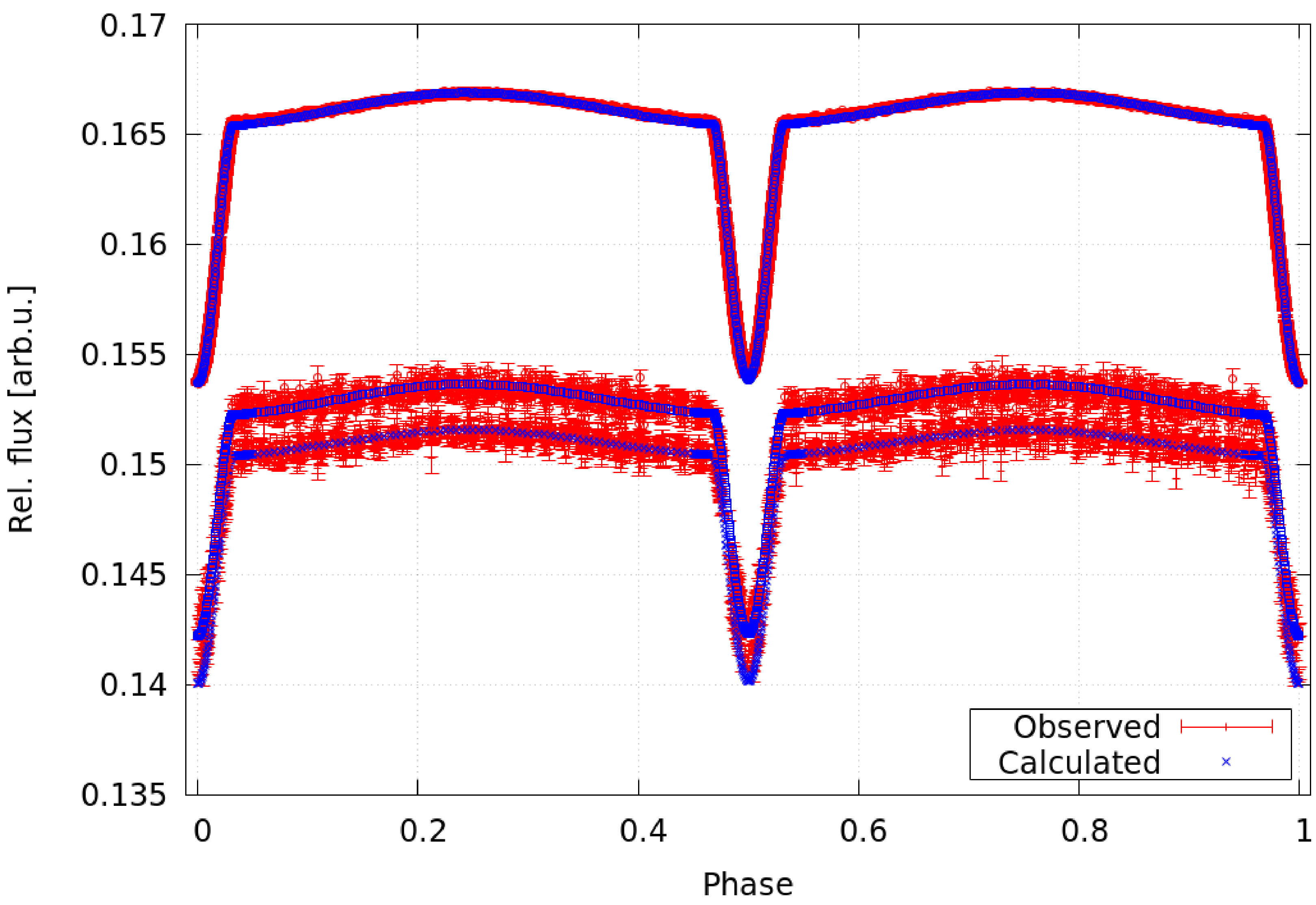


PHOEBE2

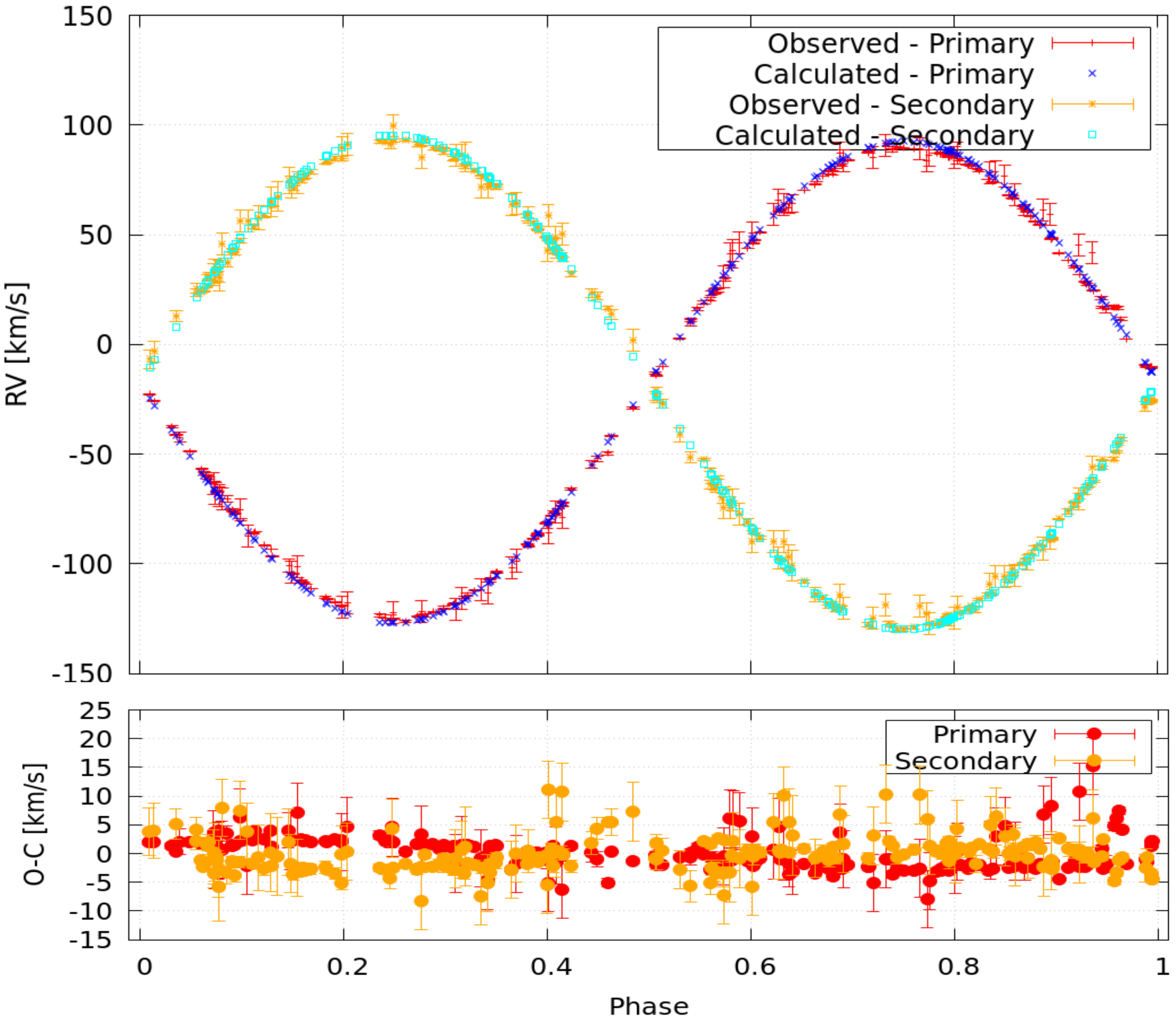
- Python-based modelling tool (Prša+ 2016)
- Surface of the stars modeled as a mesh of triangles
- Simultaneous solution of RV + LC + V^2 + CP
- Scheduled for v1.5 (Brož+ 2025, accepted)



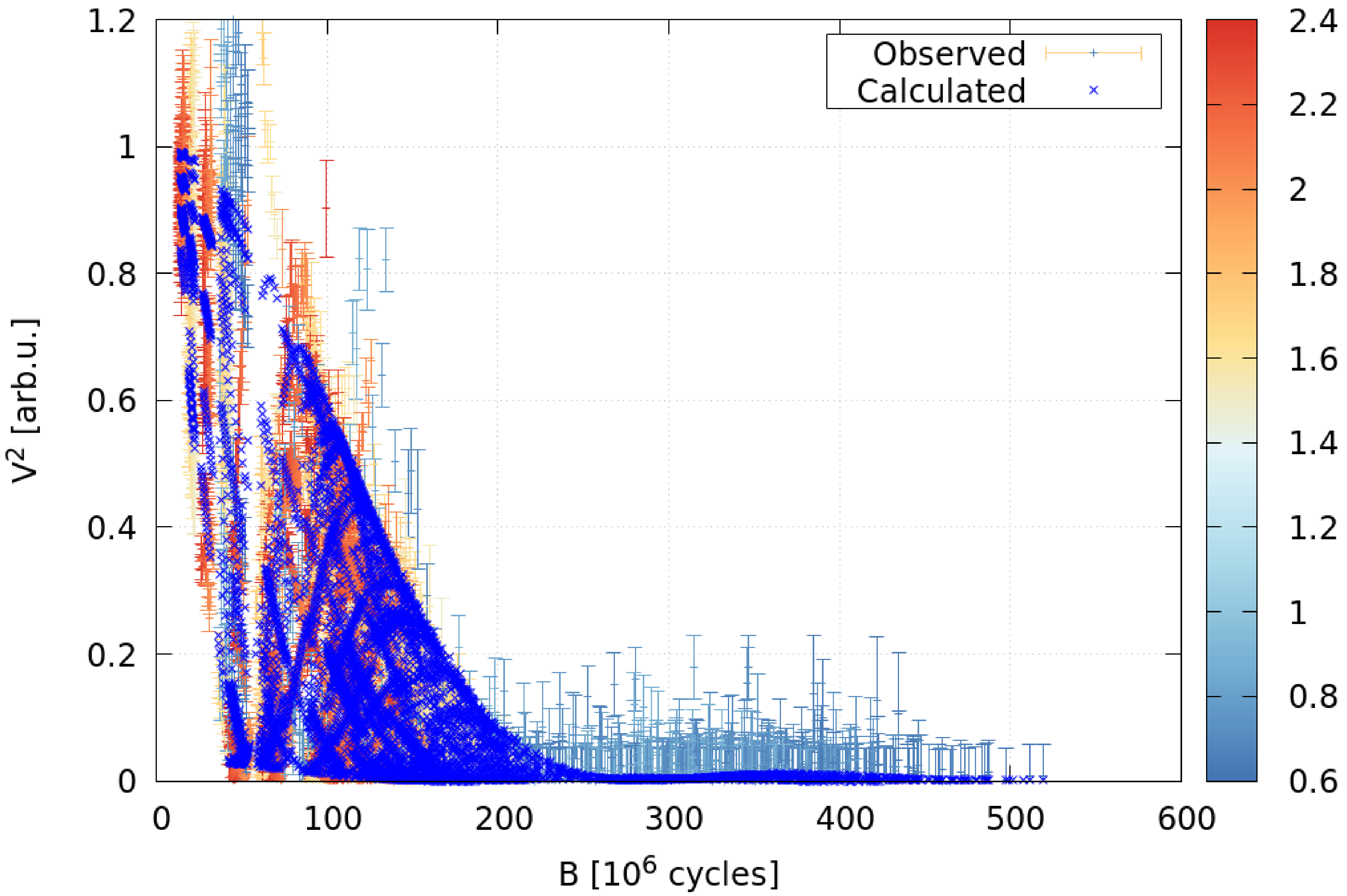
(PHOEBE2 docs)

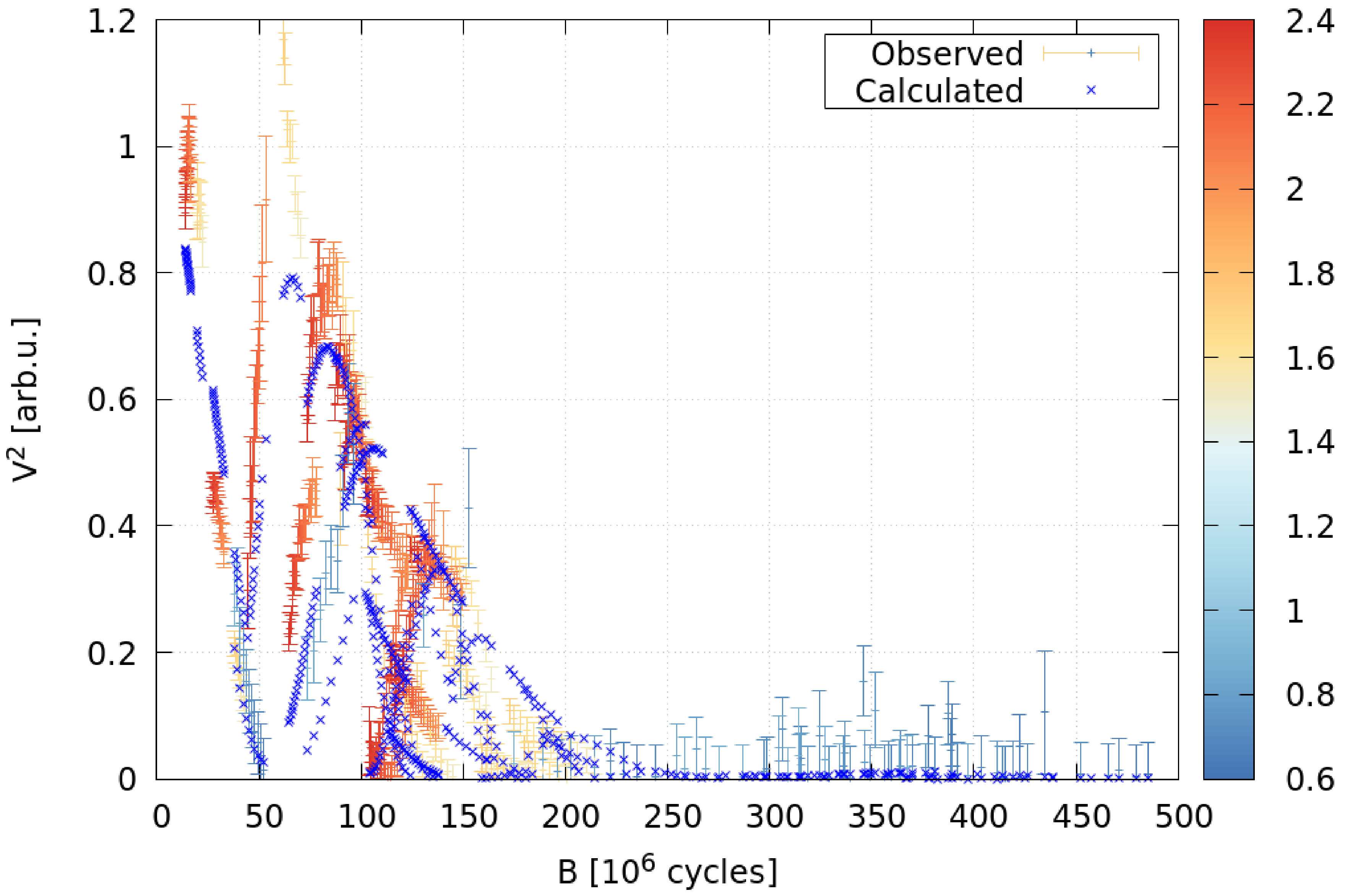


Rel. flux [arb.u.]
0.17
0.165
0.16
0.155
0.15
0.145
0.14
0.135
0
0.2
0.4
0.6
0.8
1
Phase
Observed
Calculated



150
100
50
0
-50
-100
-150
RV [km/s]
Observed - Primary
Calculated - Primary
Observed - Secondary
Calculated - Secondary
25
20
15
10
5
0
-5
-10
-15
O-C [km/s]
Primary
Secondary
0
0.2
0.4
0.6
0.8
1
Phase


1.2
1
0.8
0.6
0.4
0.2
0
V^2 [arb.u.]
0
100
200
300
400
500
600
B [10^6 cycles]
Observed
Calculated
2.4
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6


Observed
Calculated
V² [arb.u.]
B [10⁶ cycles]
0
0.2
0.4
0.6
0.8
1
1.2
0
50
100
150
200
250
300
350
400
450
500
0.6
0.8
1
1.2
1.4
1.6
1.8
2
2.2
2.4

Conclusions

- Simultaneous multi-band & multi-epoch fitting of SPICA MIRC/MIRC-X and MYSTIC data
  - Following Monday discussion, perhaps a revisit to M&M data is required for systematic V^2 shift
- More work is required for simultaneous modeling of RV, LC and IF
  - Though hoping that understanding the current issues will help in a quicker solution for future targets
- Observations separate from the ISSP:
  - VLTI/PIONIER – 115.28F2
  - NOIRLab CHARA/MIRC-X + MYSTIC 2025A/198989