VEGA Science Review

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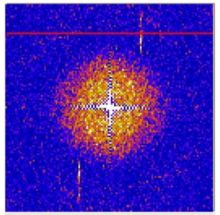
on behalf the VEGA team

VEGA in a few important dates

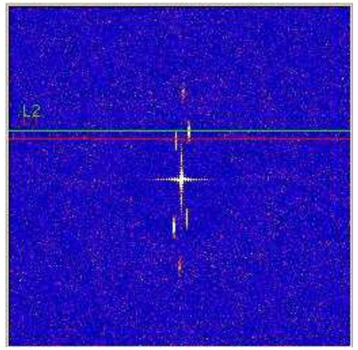
2005 - May: 1st email exchanges
- November: 1st visit on the Mountain

2006 Green light after the Tucson 2-year CHARA Science Meeting



2007 - August: 8 boxes weighting about 1200 kg sent to Mt Wilson
- September, 30th: **1st 2T fringes** (after 3 weeks of integration)

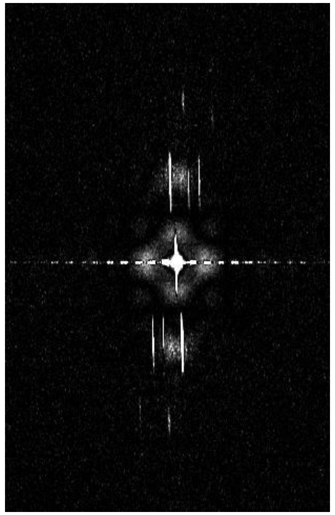
2008 - October: **3T fringes**



2009 - Summer: First remote operation

2010 - May: simultaneous CLIMB and VEGA operation
- Oct, 12th: **4T fringes together with MIRC**

2012 Upgraded detectors and group delay tracking



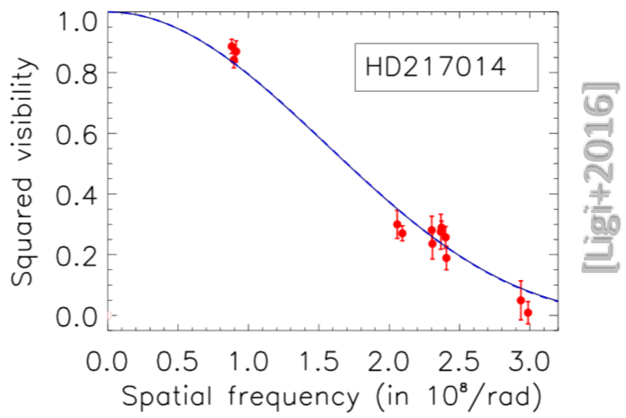
VEGA niches

Limiting magnitude
Rmag = 8 @ $\mathcal{R}$ ~ 5000

Very high angular resolution
($\lambda/2B$ ~ 0.4 mas @ 330 m)

Spectral resolution
($\mathcal{R}$ ~ 5000, 30000)

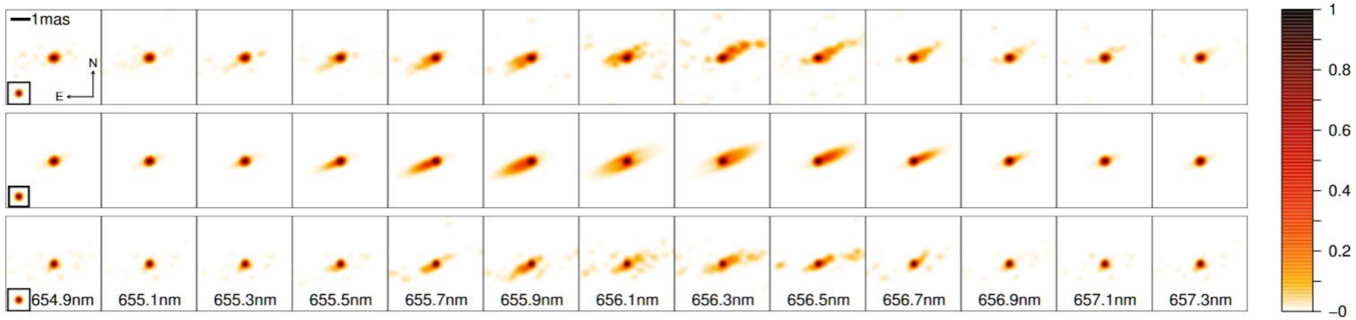
Accurate angular diameters



Fundamental parameters, Surface-Brightness Relations, parameters of multiple and hierarchic systems

Kinematics and environments

[Mourard+2015]

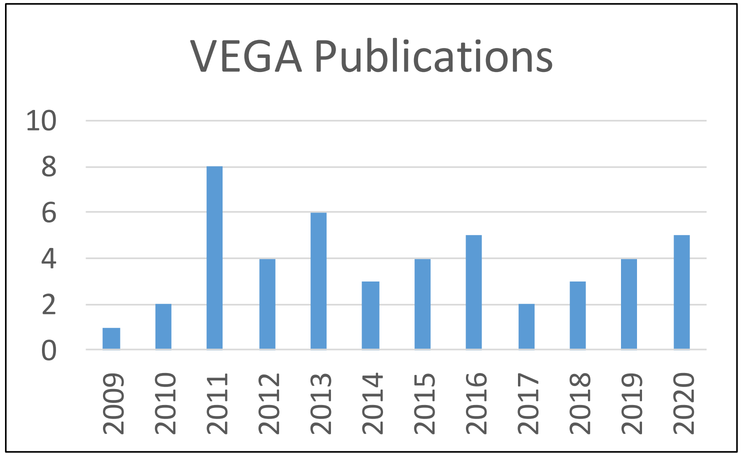


Circumstellar disks, mass-loss, winds, chromospheric activity, spectro-imaging

VEGA operation in a few figures

- 509 nights with recorded data
- 770 stars
- 8500 observations

47 refereed papers



During these 12 years, as other interferometric instrumentations, VEGA has reached a routine observing mode, allowing to:
- **increase the samples**
- be open to **a larger community**, to **non-interferometrists**

→ Statistical studies

Advanced modelling through collaborations

Accurate fundamental parameters

EXOPLANET HOST STARS

Ligi+2012, 2016, 2019; Crida+2018, 2019; Bonnefoy+2018, Borgniet+2019

MULTIPLE/HIERARCHIC SYSTEMS

Nemravova+2013, 2016; Farrington+2014

ro(Ap) STARS

Perraut+2011, 2013, 2015, 2016, 2020; Cunha+2013, Romanovskaya+2019, Deal+2021 (in revision)

CEPHEIDS

Nardetto+2011, 2016

SURFACE-BRIGHTNESS COLOR RELATIONS

Challouf+2014, 2017; Salsi+2020, 2021 (in prep); Nardetto+2020

ASTEROSEISMIC STARS

Bigot+2011; Karovicova+2018

GAIA BENCHMARK

Creevey+2015

Exoplanet host stars

[Ligi+2012, Ligi+2016, Bonnefoy+2018]
[Ligi+2019, Borgniet+2019, Crida+2018,2019]

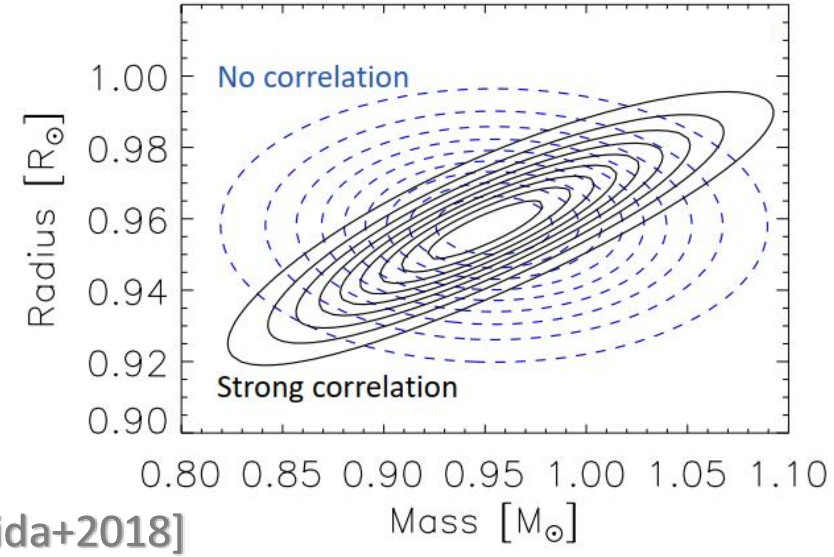
- Characterization of exoplanets relies on that of their host star
- But many stellar internal parameters poorly constrained

→ Combine ρ_* and R_* to derive M_* and refine age
Generalized Bayesian inference analysis; correlations

Scientific objective:

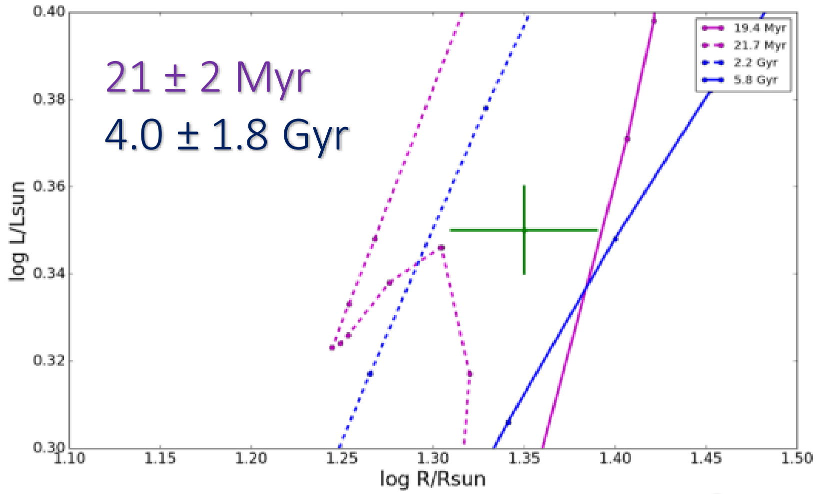
- Obtain exoplanetary parameters accurate enough to constrain their internal structures

55 Cnc



[Crida+2018]

GJ 504



[Bonnefoy+2018]

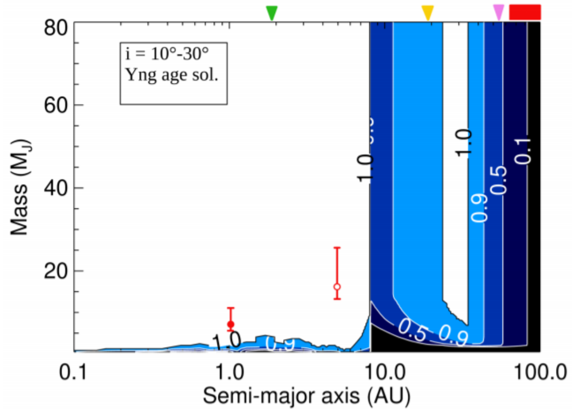
VEGA sample:

- 15 host stars
- 3 systems with transit exoplanets

Constraining the exoplanet properties

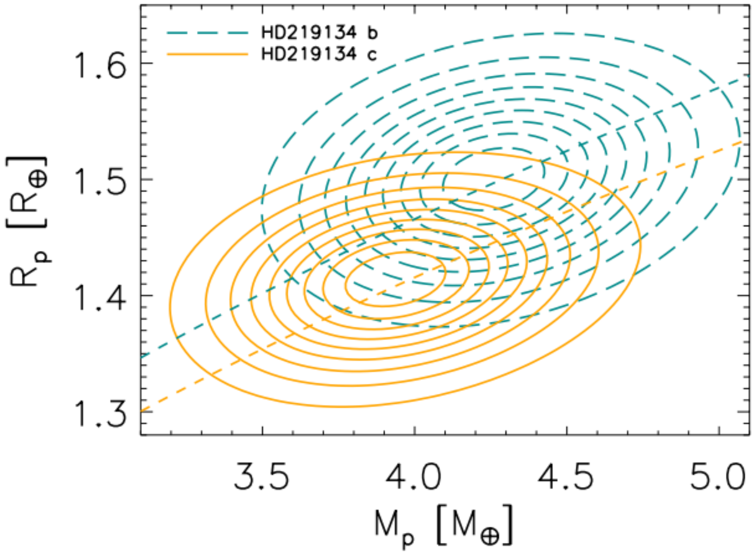
- Planetary mass, radius, and density
  - Atmosphere and interior composition
  - Formation scenario
- Improved detection limits

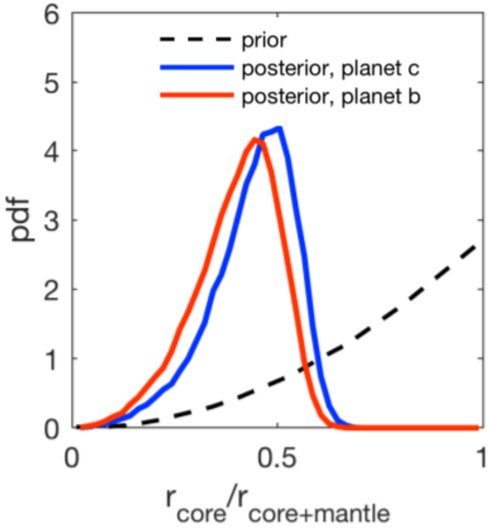
HD 113337



[Borgniet+2019]

HD 219134bc





b & c = Super-Earth

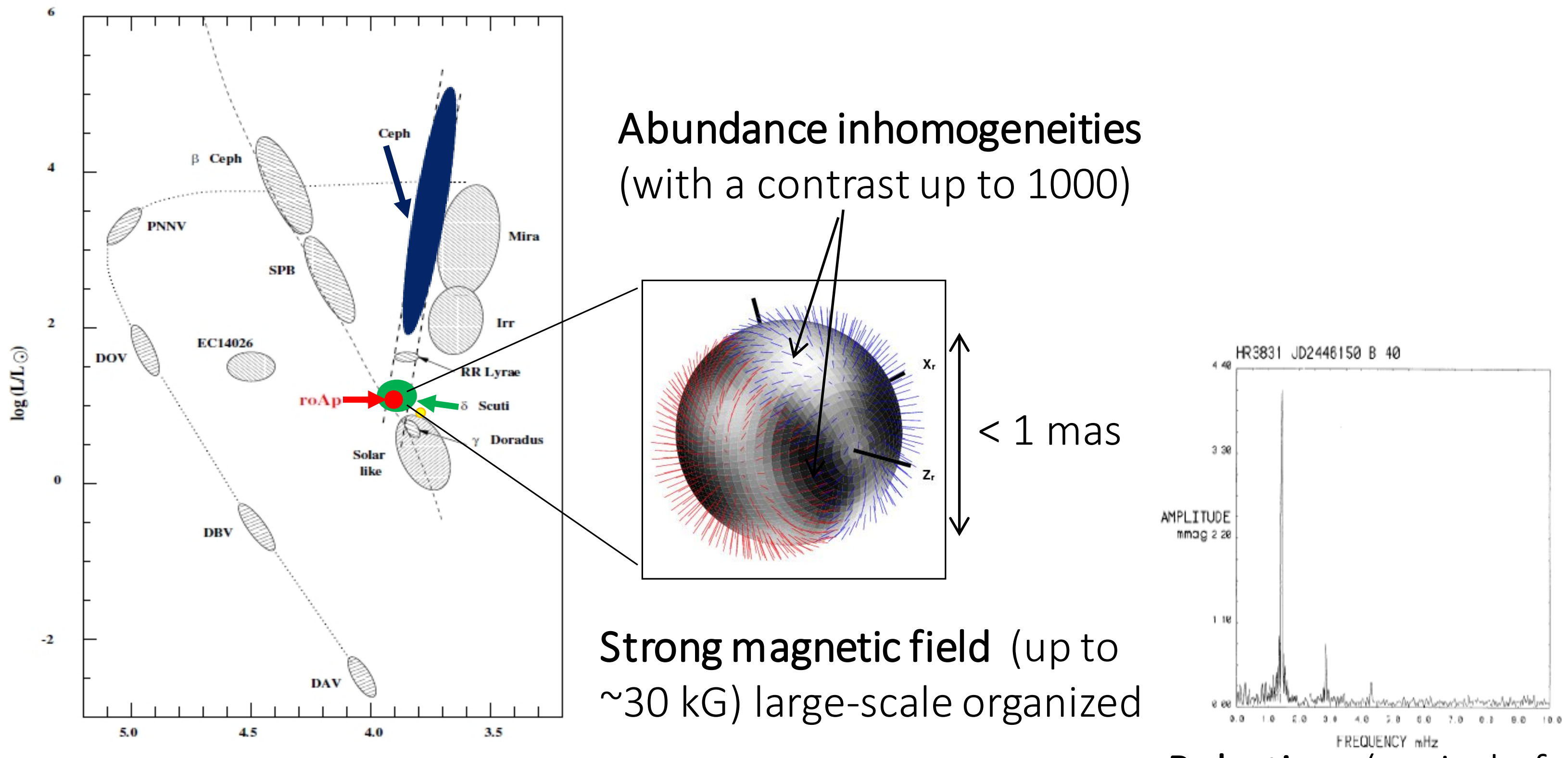
[Ligi+2019]

The (ro)Ap program

[Perraut+2011, 2013, 2015, 2016, 2020]

Scientific objectives:

- Accurate fundamental parameters
- Compare to theoretical models (atmosphere, mechanism of oscillations, …)
- Derive trends with star properties



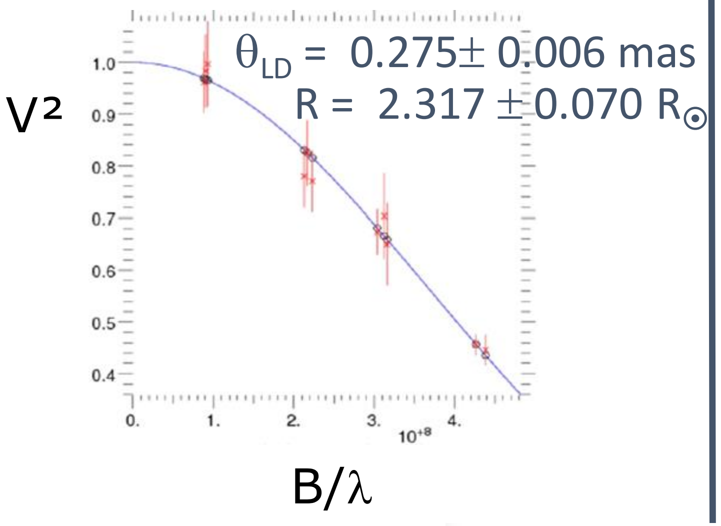
Abundance inhomogeneities (with a contrast up to 1000)

Strong magnetic field (up to ~30 kG) large-scale organized

roAp: intersection of Main-Sequence and instability strip

Pulsations (period of a few minutes)

VEGA sample (14 stars)

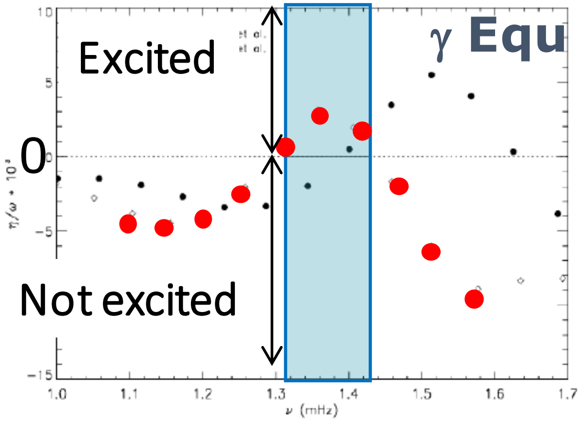


(ro)Ap stars: testing the physics

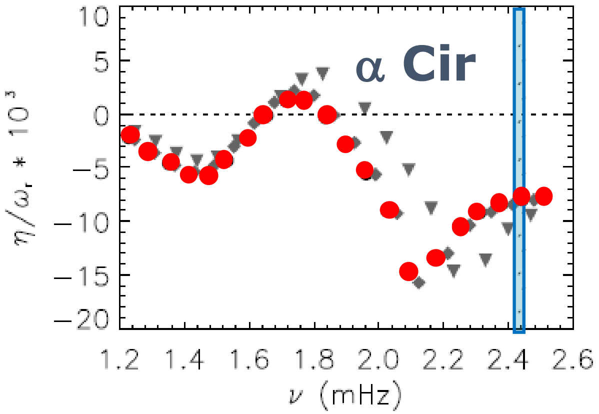
[Cunha+2013; Romanovskaya+2019; Deal+2021, in revision]

Excitation mechanism of pulsation modes in roAp

[Cunha+2013]

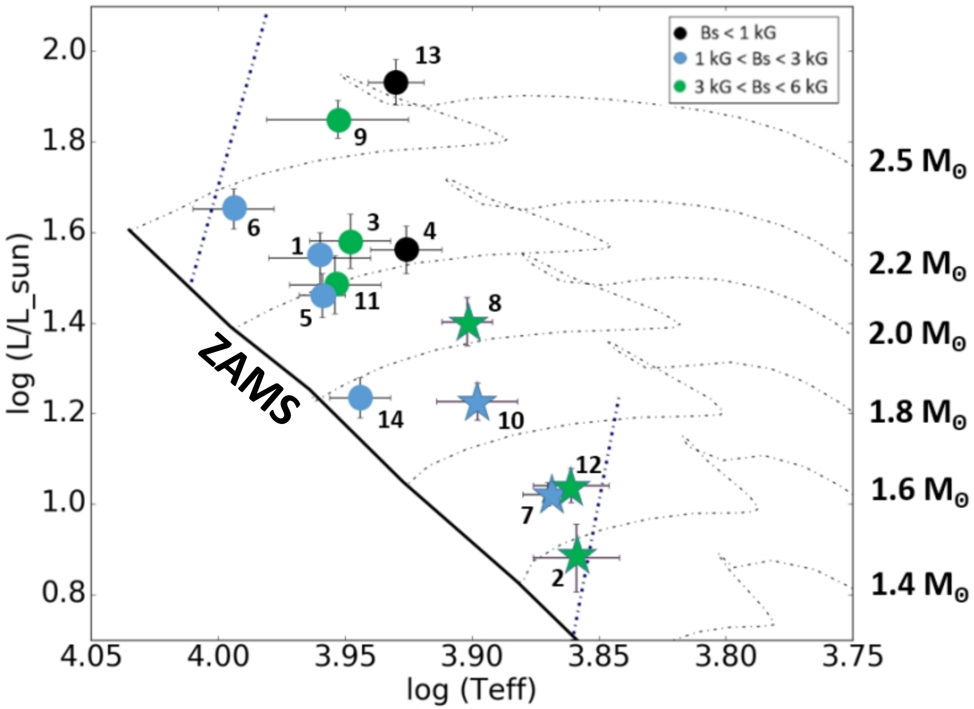


Observed modes



● Interferometric measurements

- Deriving a Bolometric Correction for Ap stars
- Benchmarking the self-consistent atmosphere models
- Looking for trends with magnetic field strength, age, …



B < 1 kG
1 kG < B < 3 kG
3 kG < B < 6 kG

Surface-Brightness Color-Relations

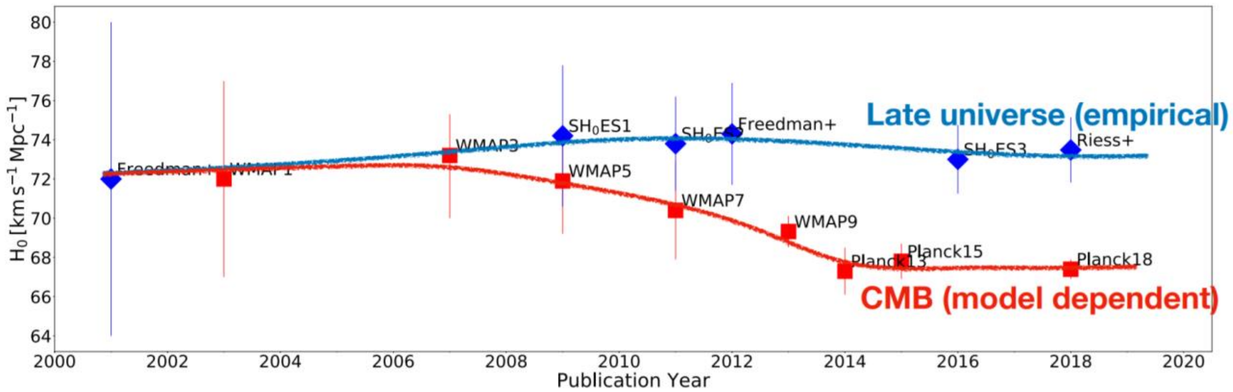
Objective: deriving accurate angular diameters for stars unreachable by interferometry

- The calibration of the cosmic distance scale through Eclipsing Binaries
- The fundamental parameters of PLATO targets

PLATO mission

VEGA sample:
- 14 late-type
- 18 early-type

Tension on H_0

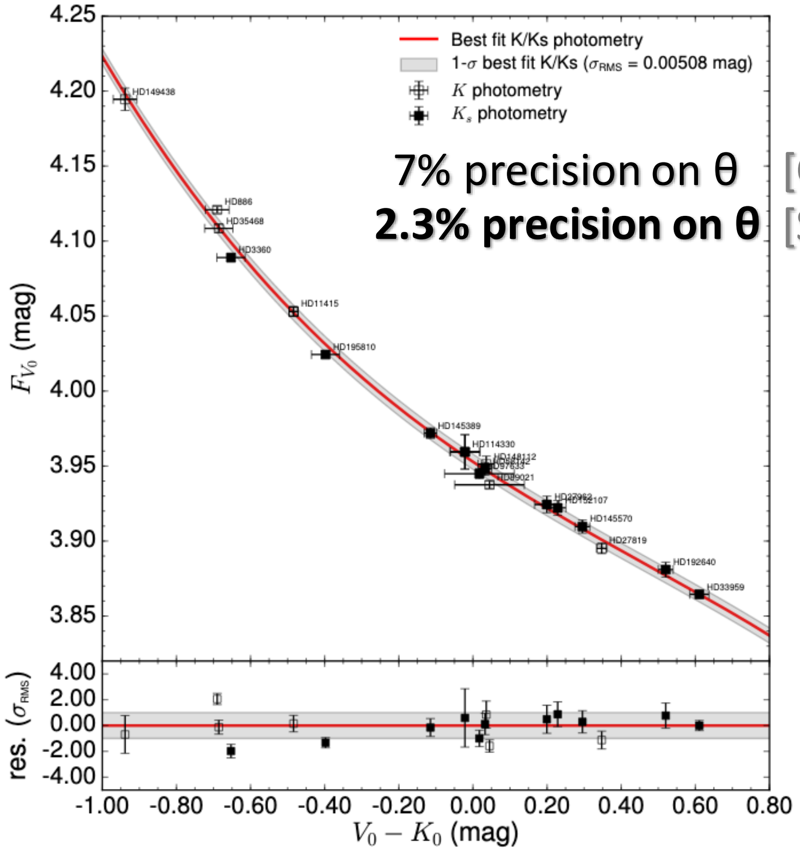


Method based on selection criteria:

- stellar characteristics (rejection of multiplicity, variability, etc)
- interferometric (high visibilities)
- photometric (rejection of high infrared-*K* uncertainty)

Surface-Brightness Color-Relations

Early-type

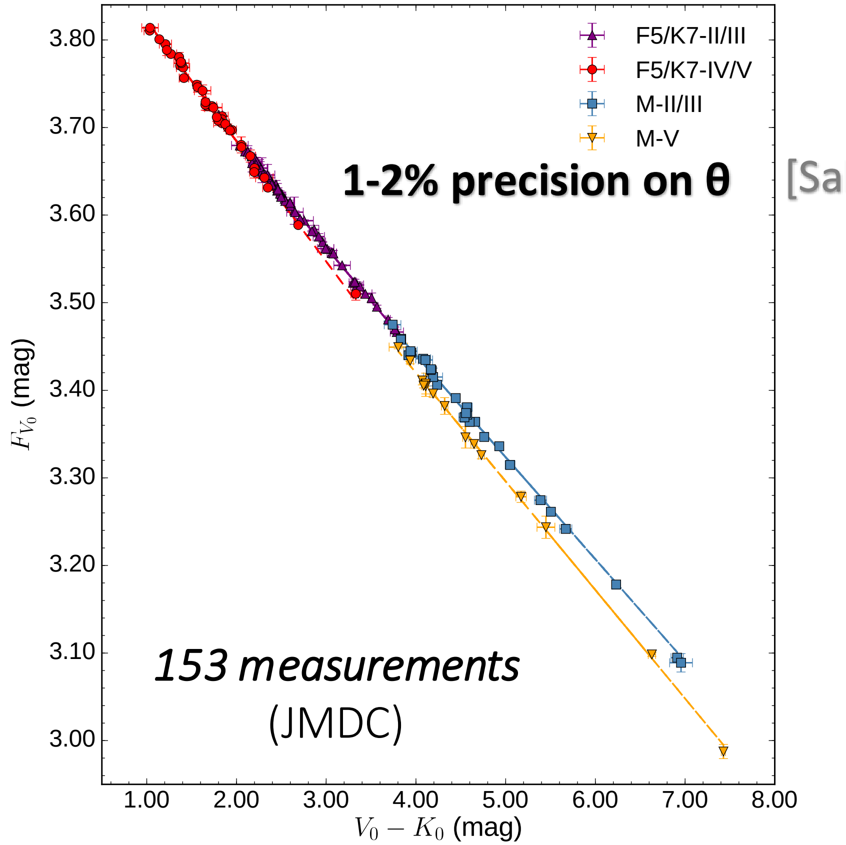


7% precision on θ [Challouf+2014]

2.3% precision on θ [Salsi+2021, subm]

K/Ks conversion issues

Late-type



1-2% precision on θ [Salsi+2020]

153 measurements

(JMDC)

Depend on *spectral type* and *luminosity class*

Kinematics and environments

YOUNG STARS

Perraut+2010, 2016; Benisty+2013; Ellerbroek+2015; Jamialahmadi+2015; Mendigutia+2017

CHROMOSPHERIC ACTIVITY

Berio+2011

ε AUR

Mourard+2012

SPECTRO-IMAGING

Mourard+2015

β LYR

Bonneau+2011; Mourard+2018; Broz+2020

SUPERGIANT WINDS

Chesneau+2010

Be STARS

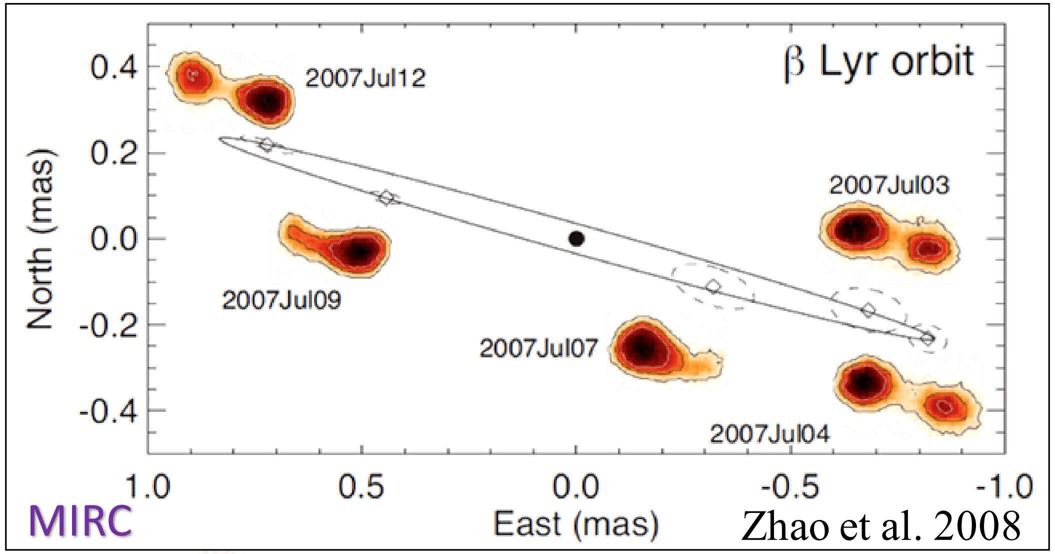
Delaa+2011, 2013; Meilland+2011; Smith+2012; Stee+2012; de Almeida+2019

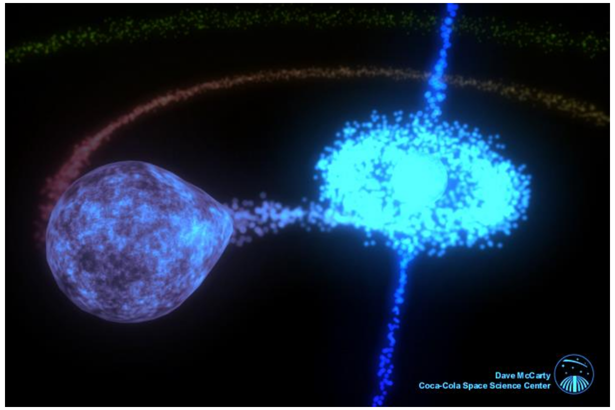
AGB

Chiavassa+2020

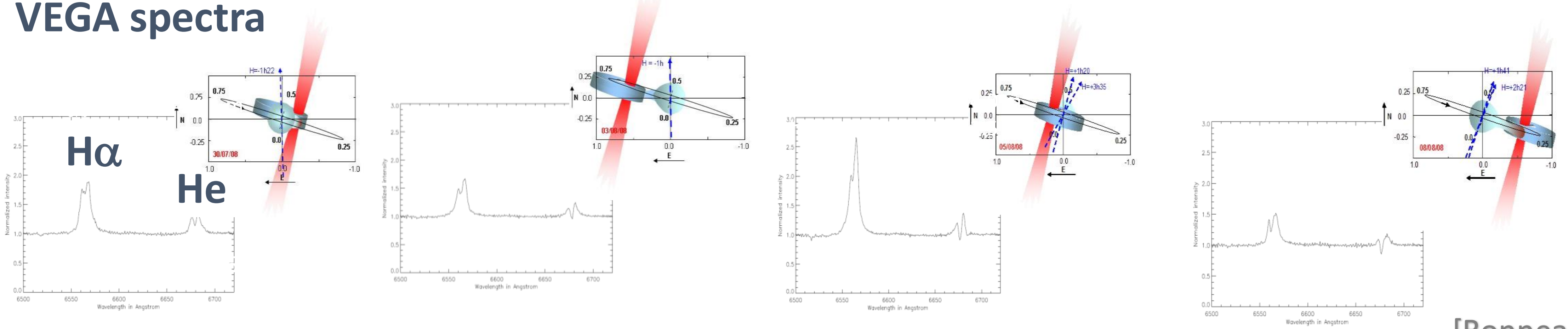
The β Lyr eclipsing and interacting binary

- Period: 12.9 d
- Nearly edge-on
- Donor: B6-8 II
- Gainer: a hidden B star in the opaque disk





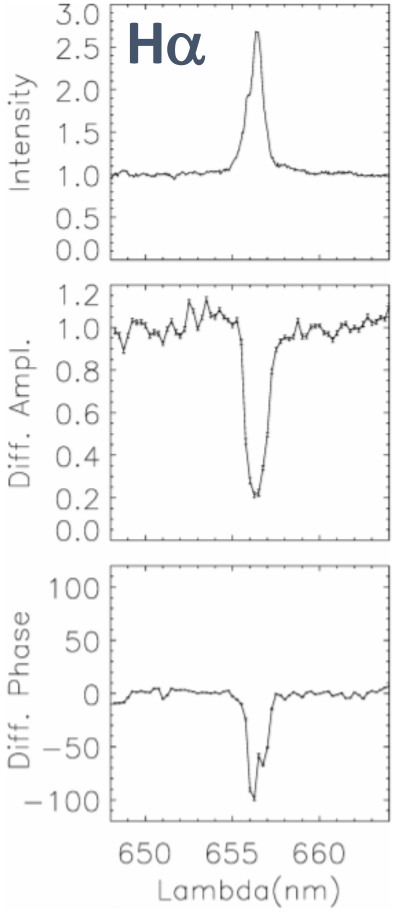
VEGA spectra



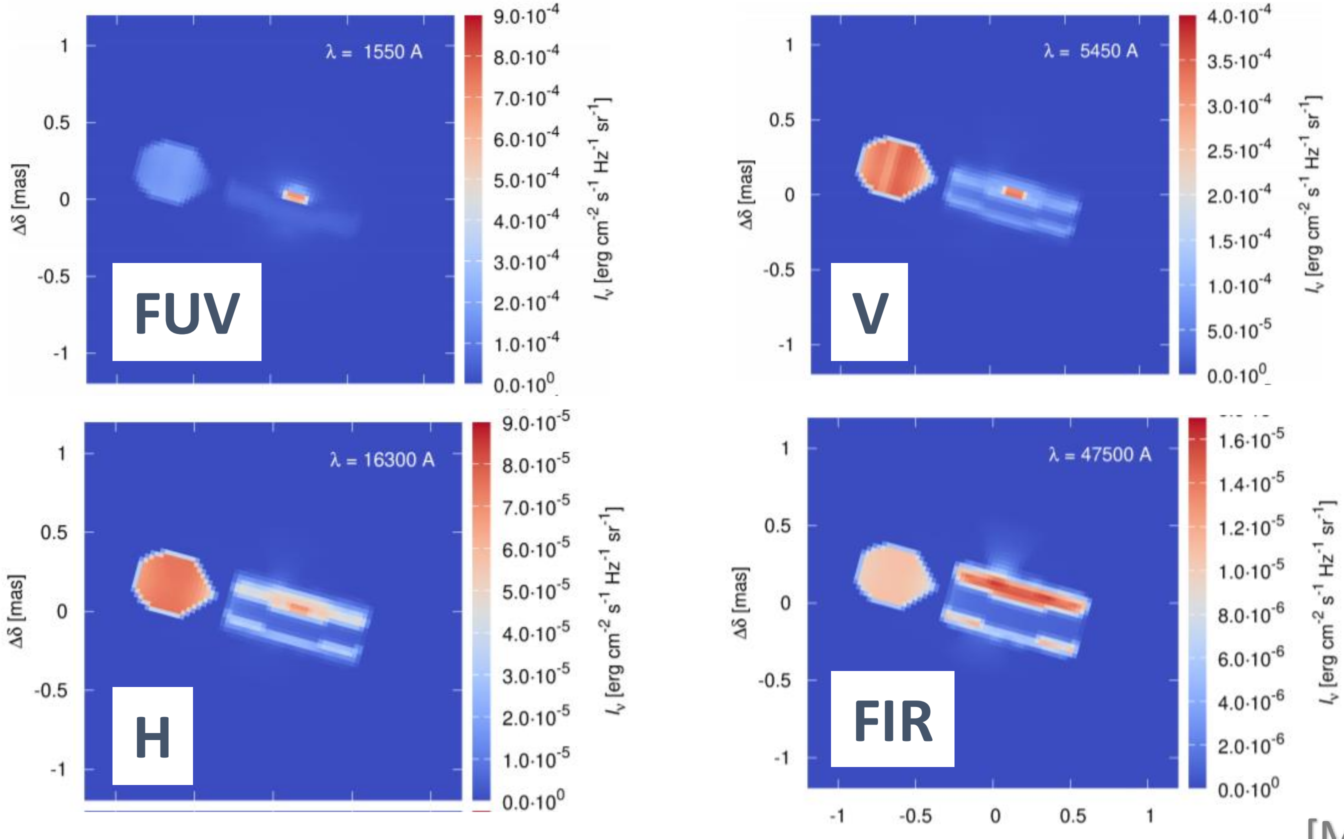
[Bonneau+2011]

β Lyr: a multi-technique and multi-λ campaign

VEGA observables

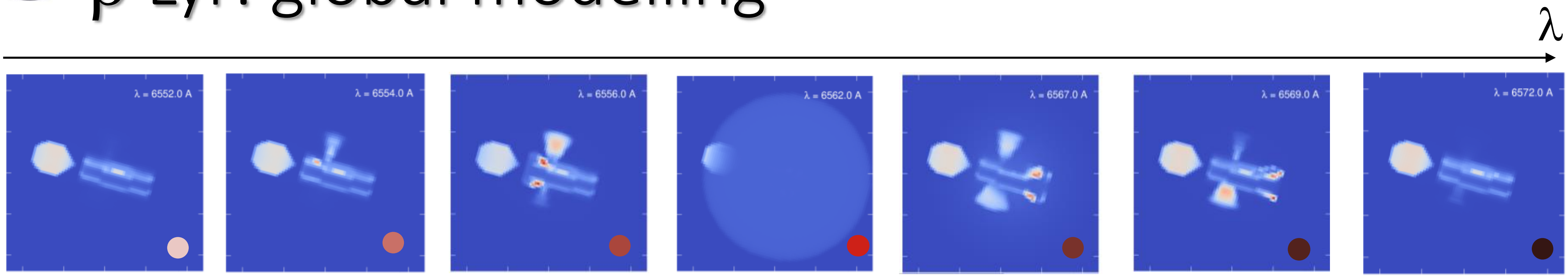


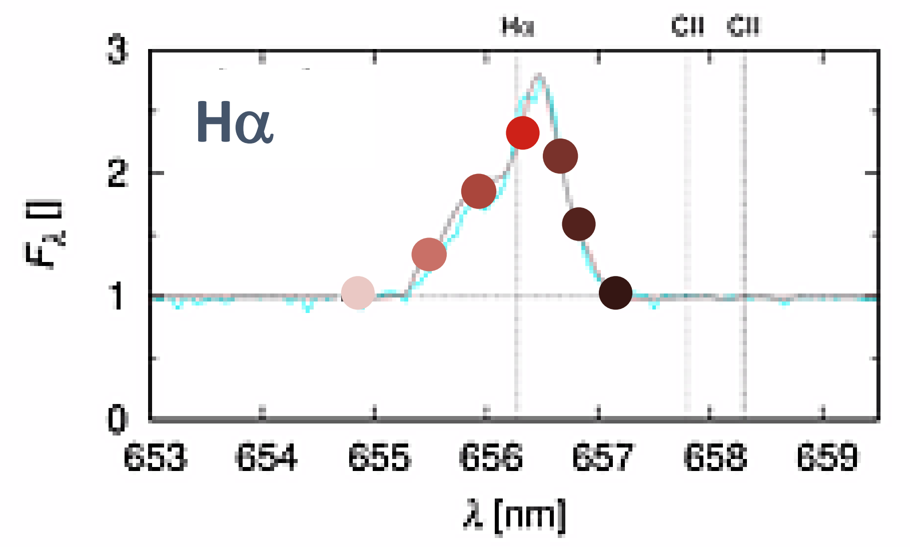
- NPOI + CHARA/MIRCx (6T) + CHARA/VEGA (2T/3T + multi λ) in 2013
- Spectroscopic and photometric contemporaneous + archive data



[Mourard+2018]

β Lyr: global modelling





Upgraded version of ShellSpec

Emission formed in:

- an extended atmosphere of the disk
- 2 perpendicular jets expanding at ~ 700 km/s
- a symmetric shell with the radius ~ 70 $R_{\odot}$

[Broz+2020 (highlight A&A)]

Geometrical extent of K giant chromospheres

- Fundamental parameters: Teff, L, R, mass
- Ratio of radius chromosphere/photosphere in
  - Hα
  - CaII triplet lines (@849nm, @854nm and @866nm)

➡ **Chromosphere extents range between 16% to 47% of R***

VEGA sample (7 giants)

HD	Name	θ_{LD} (mas)	f_{bol} (10^{-6} erg s^{-1} cm^{-2})	T_{eff} (K)	$L/L_\odot$	$R/R_\odot$
4128	β Ceti	5.288 ± 0.075	5.10	4838 ± 70	139.1 ± 7.0	16.78 ± 0.25
6805	η Ceti	3.698 ± 0.160	1.64	4356 ± 55	74.0 ± 3.7	15.10 ± 0.10
98430	δ Crateris	3.667 ± 0.022	1.66	4408 ± 57	171.4 ± 9.0	22.44 ± 0.28
127665	ρ Bootis	4.090 ± 0.031	1.76	4298 ± 56	131.9 ± 6.8	21.57 ± 0.25
161096	β Ophicus	4.606 ± 0.045	3.04	4621 ± 62	63.4 ± 3.2	12.42 ± 0.13
169414	109 Herculis	3.223 ± 0.034	1.17	4334 ± 59	50.7 ± 2.7	12.63 ± 0.22
216228	ι Cephei	2.646 ± 0.048	1.28	4831 ± 74	49.6 ± 2.5	10.05 ± 0.18

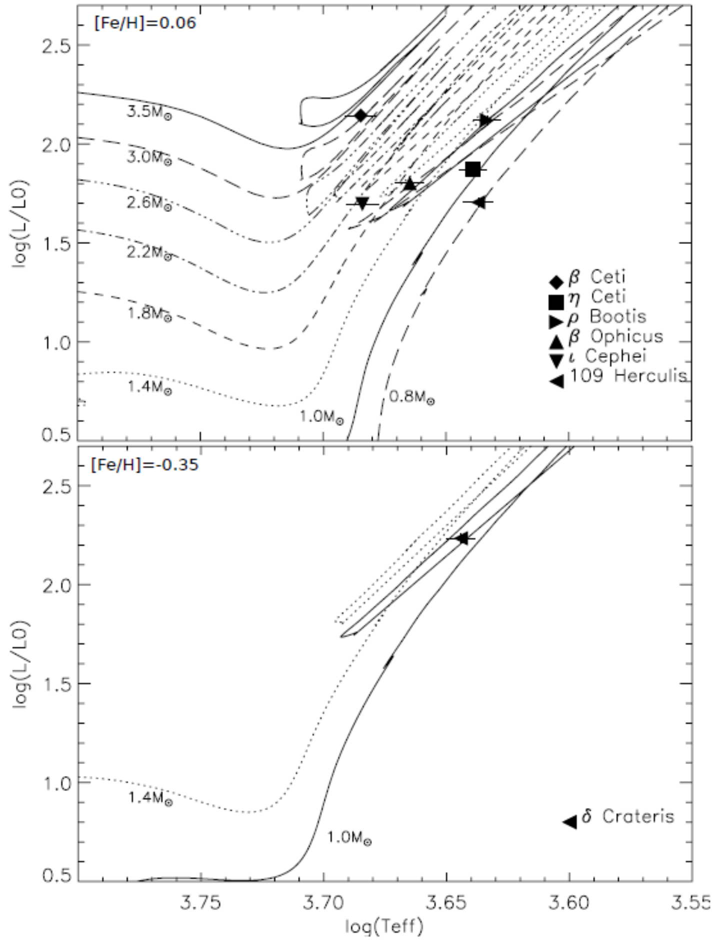


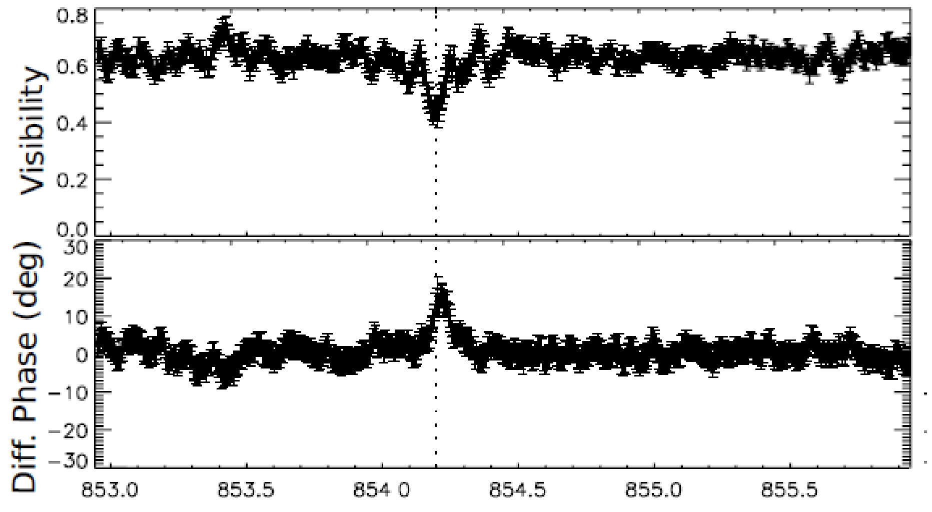
Fig. 4. HR diagram of the program stars and comparison with evolutionnary track models for different masses. *Top*: [Fe/H] = 0.06; *bottom*: [Fe/H] = −0.35.

[Berio+2011]

Spatial structures of the chromosphere

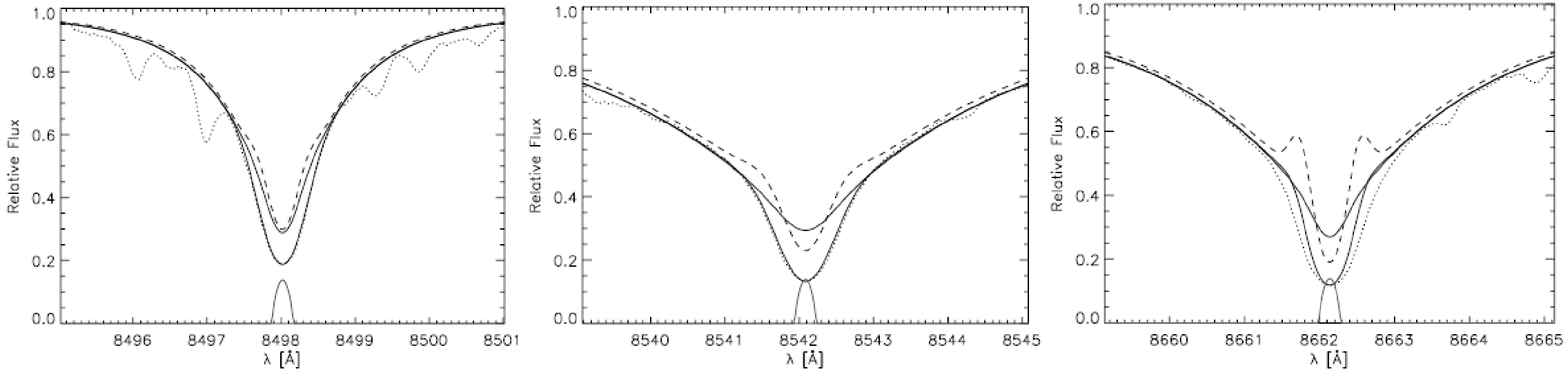
- Signature of **differential phase showing the presence of asymmetries** in the chromosphere
- Semi-empirical NLTE model of β Ceti derived by fitting the Ca II triplet line cores:
    - Lines formed at the mean chromosphere temperature
    - Ca II/849 nm line formed significantly deeper within the atmosphere
    - Limb-darkening law of CaII triplet lines similar to the Sun

β Ceti



Ca II

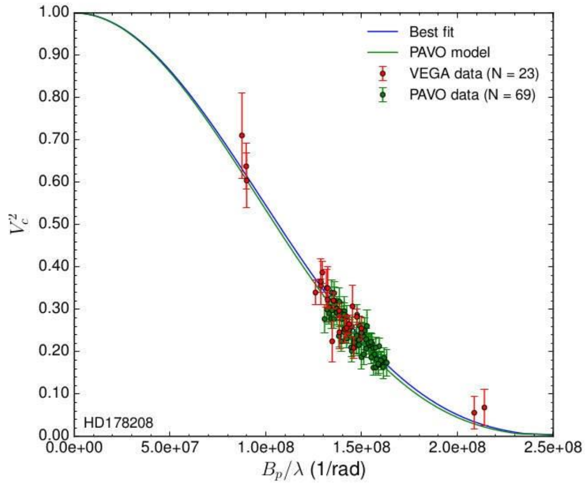
Ca II triplet



[Berio+2011]

Take away messages and perspective

- VEGA: real niches (high angular resolution, visible range, medium and high spectral resolution) well exploited
- 47 papers published + several papers to come on large samples:
  - Comparison PAVO/VEGA
  - Metal-poor and asteroseismic sources (~ 40 stars)
  - Be stars (34 stars)
- Some studies have been limited by its sensitivity (YSOs)
- Lessons learned: operation, statistical approaches, …



2021 VEGA disassembly (hopefully)

SPICA

Many thanks to the whole CHARA group!