How to tackle a giant Star
multi-wavelength study of cool, evolved stars with HST and VLTI

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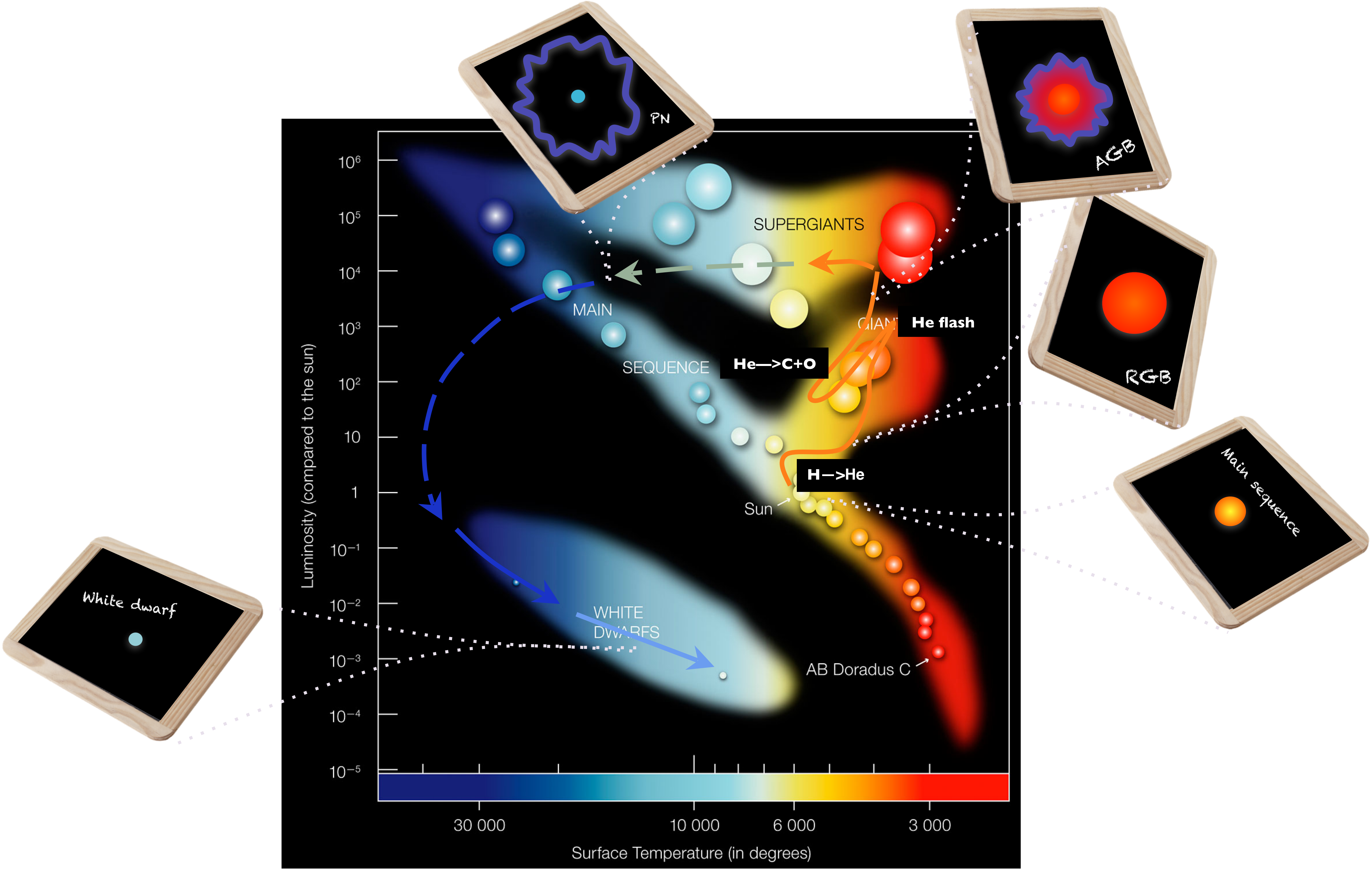
OUTLINE

- Introduction
- Asymptotic Giant Branch (AGB) stars atmospheres
- Chromospheres in K and M Giant stars with HST
- Interferometry with VLTI/MIDI
- Interferometry with VLTI/GRAVITY
- Future plans: VLTI/MATISSE and CHARA/VEGA
- Conclusions

STELLAR EVOLUTION OF GIANT STARS



WHY RGB & AGB STARS?

Formation of planets

Chromospheric emission in K- and M-giants affects **planets habitability**

Dust Formation

Dust affects new **star and planet formation**.

AGB stars may dominate dust production

High Luminosities

Integrated light used to derive galaxy **stellar mass** and **star-formation rate**.

AGB stars contribute a large fraction of a galaxy's NIR flux.

Diagnostic Tools

Distance: (period-luminosity relationship)
Metallicity: (ratio of C to M stars)
Star-formation History: Intermediate-aged stars

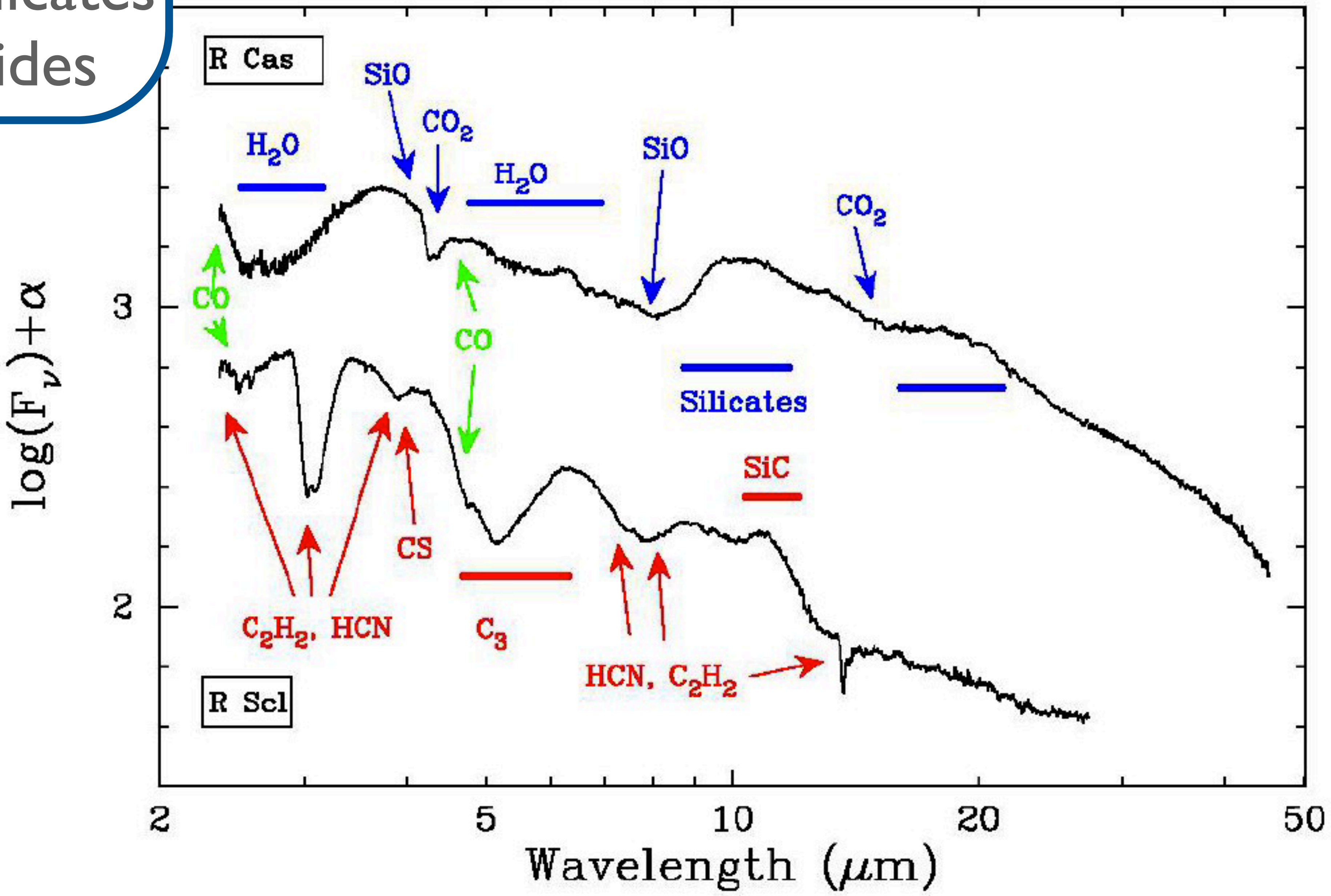
AGB STARS

C-rich

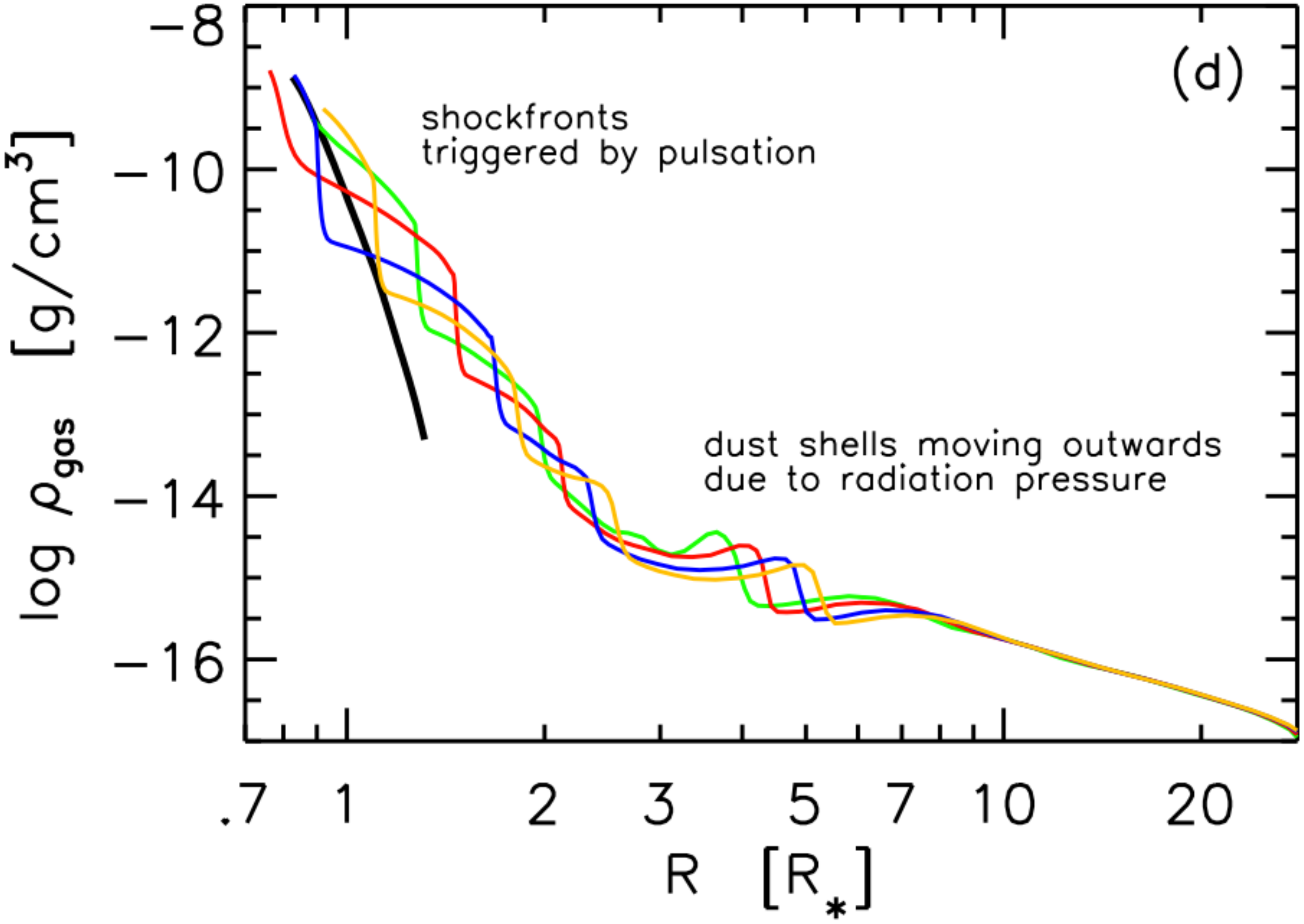
- SiC
- amC

O-rich

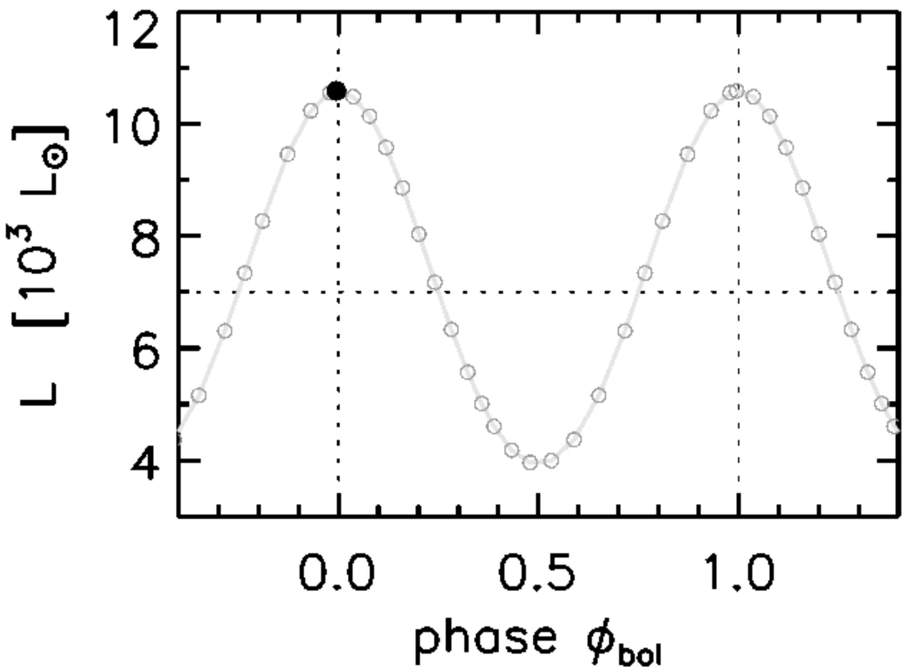
- Mg- & Fe-rich Silicates
- Al-Oxides



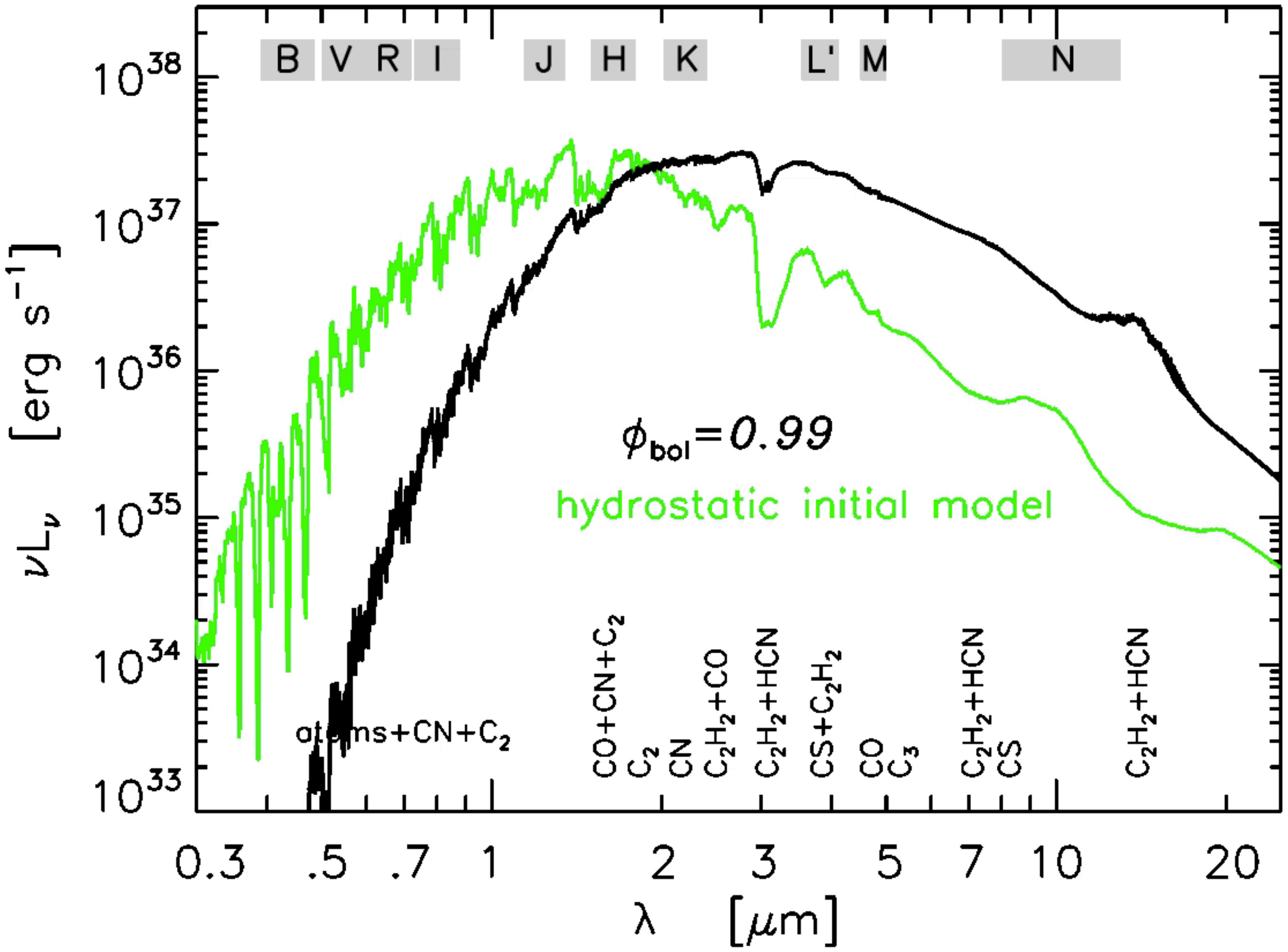
COMPLEX ATMOSPHERES OF AGB STARS



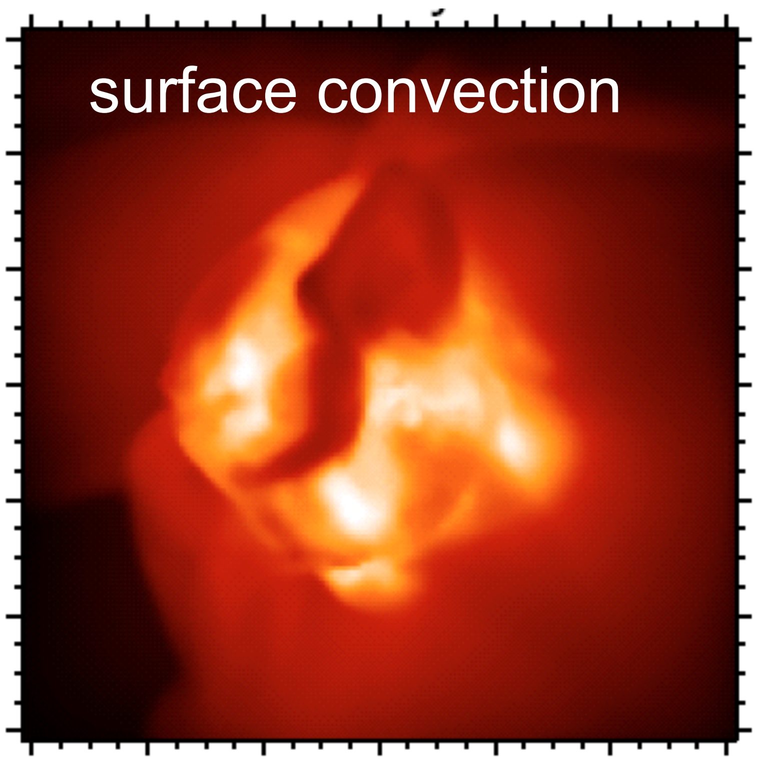
Nowotny et al. (2011)



12
10
8
6
4
$L \ [10^3 \ L_\odot]$
0.0
0.5
1.0
phase ϕ_{bol}



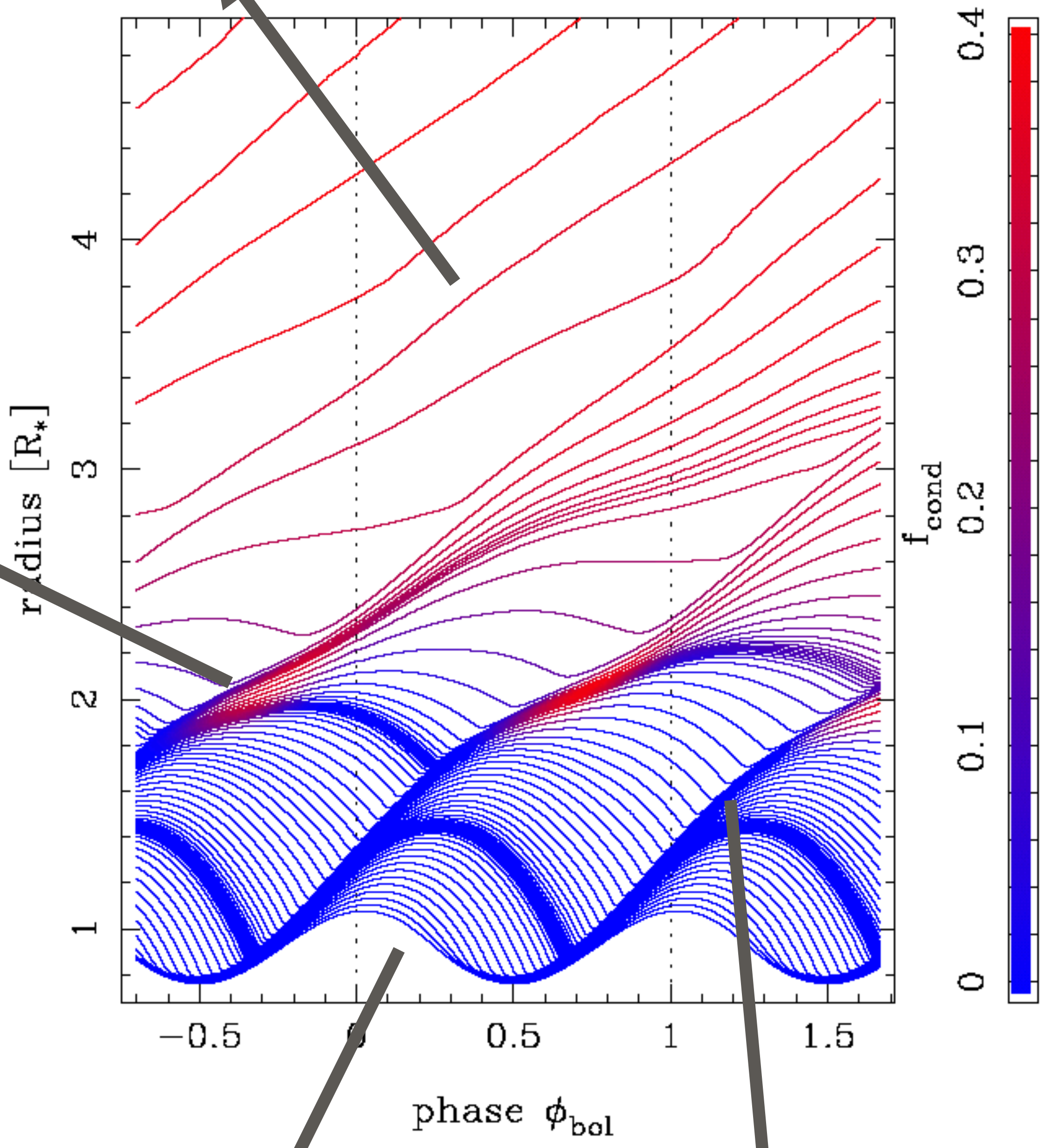
B
V
R
I
J
H
K
L'
M
N
10^{38}
10^{37}
10^{36}
10^{35}
10^{34}
10^{33}
$\nu L_\nu \quad [\mathrm{erg \ s^{-1}}]$
$\phi_{bol}=0.99$
hydrostatic initial model
atoms+CN+C_2
CO+CN+C_2
C_2
CN
C_2H_2+CO
C_2H_2+HCN
CS+C_2H_2
CO
C_3
C_2H_2+HCN
CS
C_2H_2+HCN
0.3
.5
.7
1
2
3
5
7
10
20
$\lambda \quad [\mu m]$



Freytag & Höfner (2008)

Stellar wind

Höfner et al. (2003)



Dust formation

Pulsation

Shock fronts

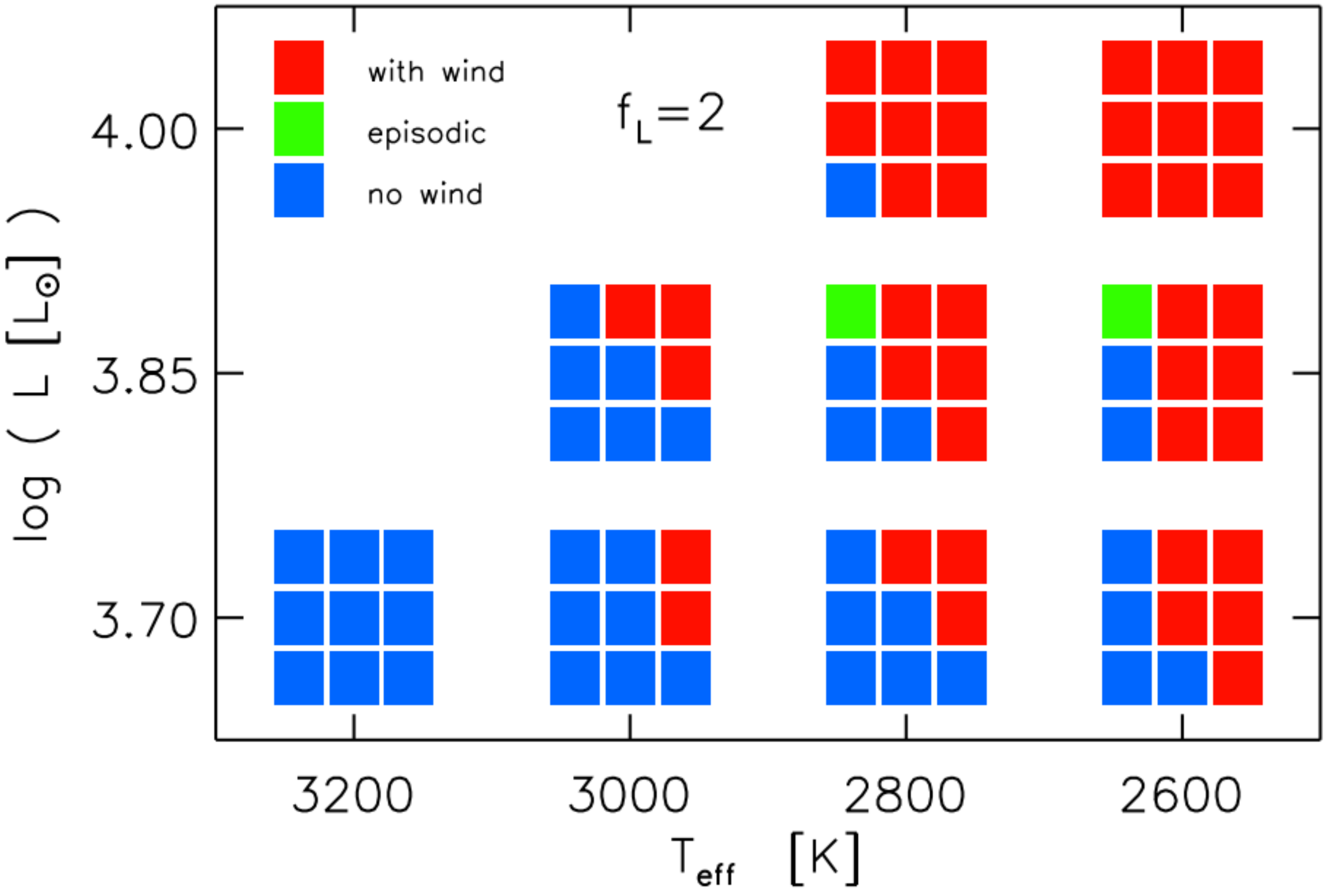
Spatial & temporal fluctuations: temperature, density, abundance, intensity distribution, morphology of the spectrum

DYNAMIC MODEL ATMOSPHERES (DMA) (Mattsson et al., 2010, Eriksson et al., 2014)

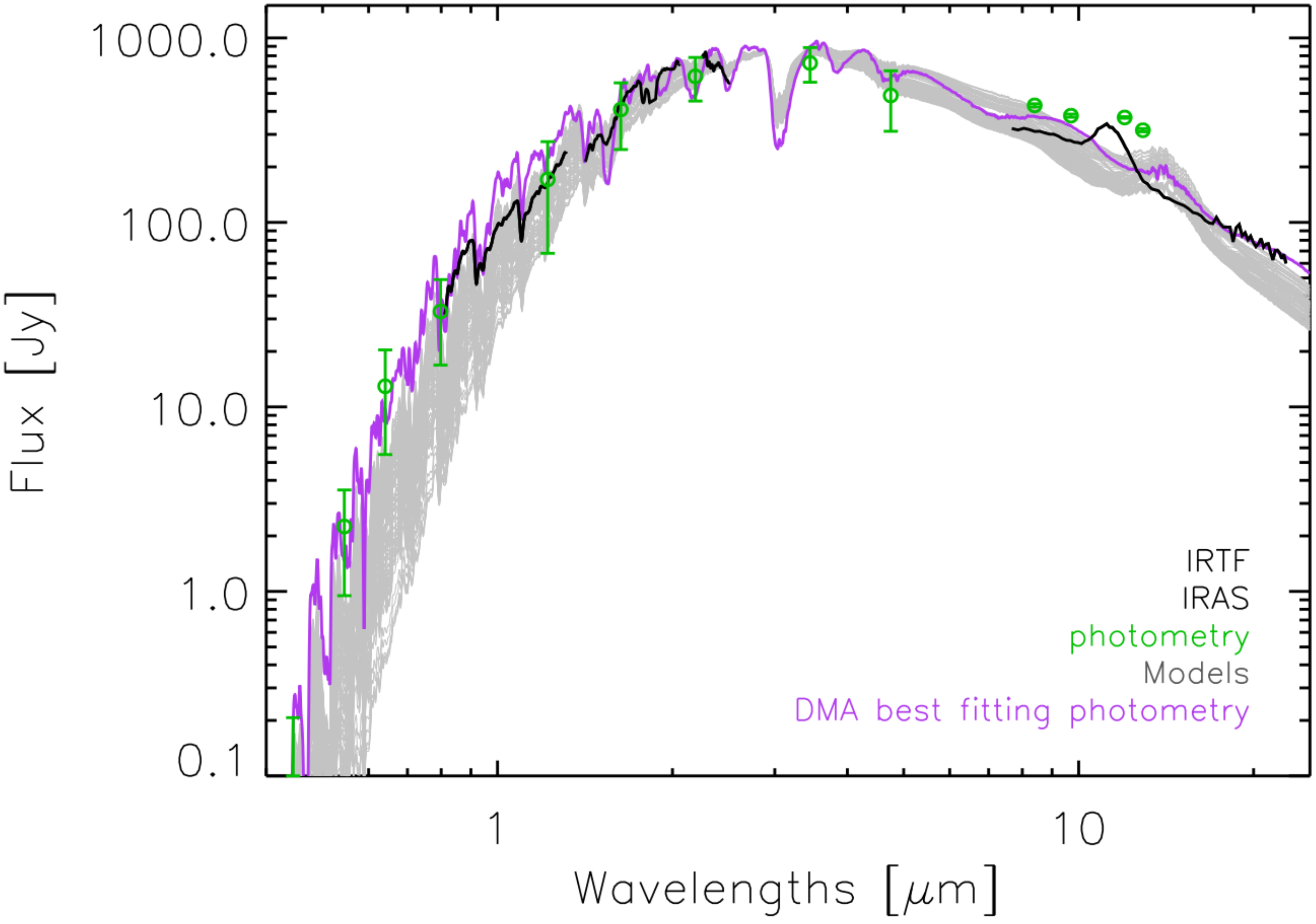
- Grid of 540 Models with 140 000 time-steps (different phases of the stellar pulsation)

- Main parameters that characterize the DMA: L, T_{eff}, M, log(g), C/O, Δu

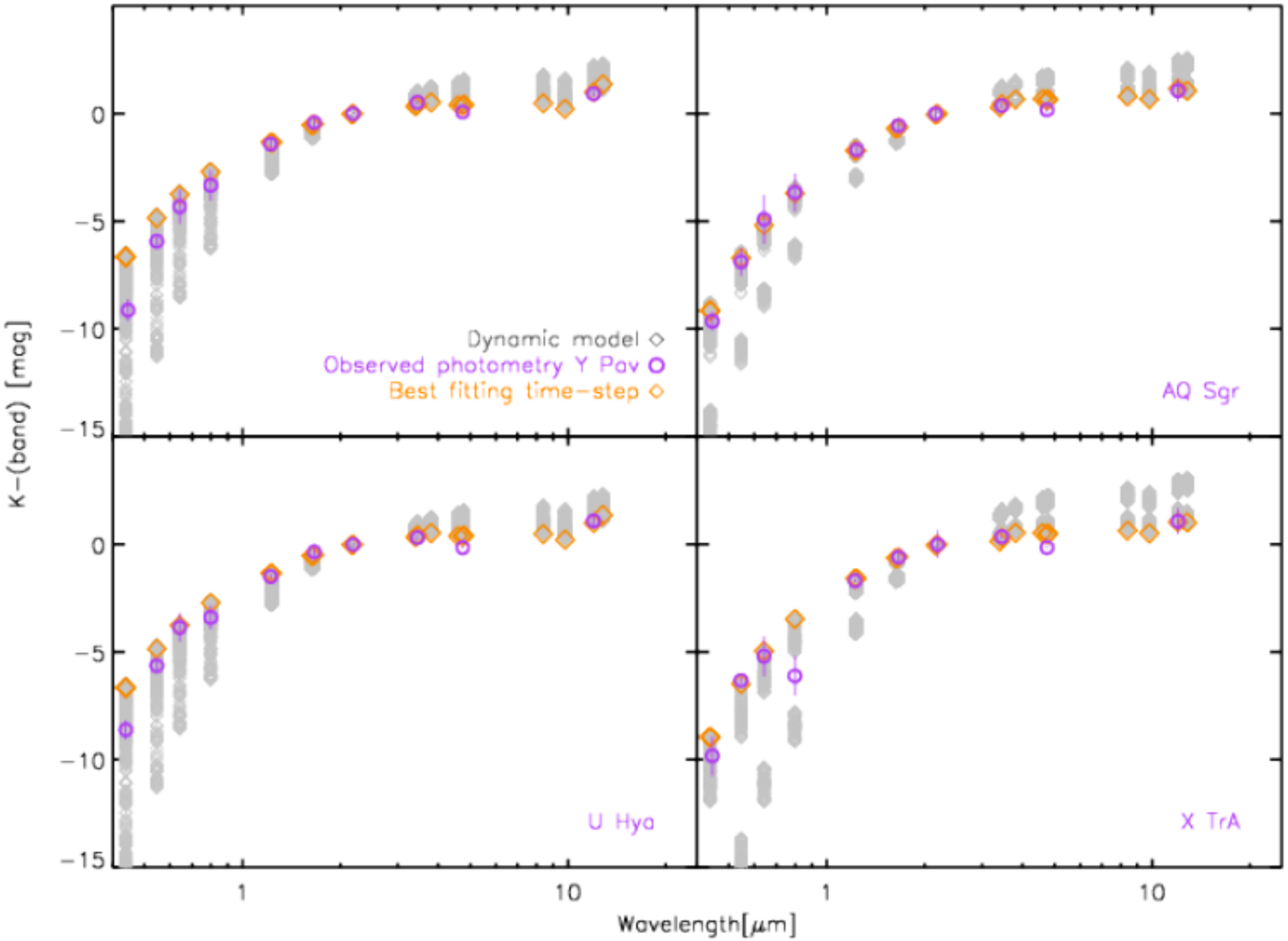
- Independent fit of SED and interferometry (computational reasons)



Eriksson et al. (2014)



Rau et al. (2015)



Rau et al. (2017)

WHY CHROMOSPHERES IN GIANT STARS?

Open questions:

- What drives the wind acceleration in K-M giant and supergiant stars?
- is there a clear border where the chromosphere ends and the wind begins, or do those regions overlap?
- What are the terminal velocities of the winds in those stars?
- Is there a direct relationship between chromospheric activity and the amount of dust in giant and supergiant stars?

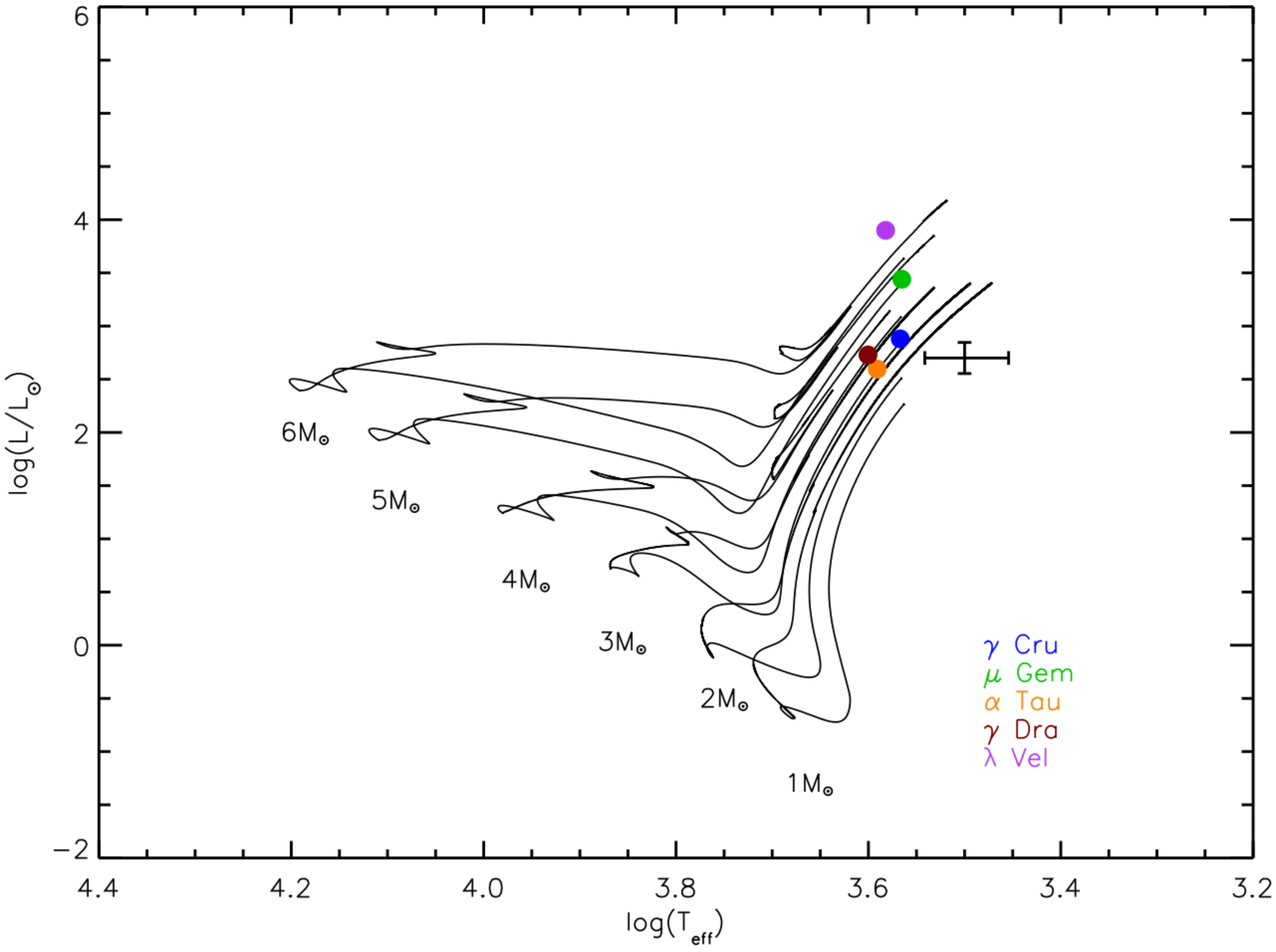
Aims:

- Investigating the shape of a wind's velocity profile with height (turbulence, acceleration, and opacity), and gaining information about the wind acceleration (to understand where the energy is imparted into the outflow) and mass loss
- Reveal the structure and geometry of the circumstellar material: information on the chromosphere/wind and its interface with the photosphere and any circumstellar shell is needed —> interferometry to complement the UV diagnostics!

TARGETS

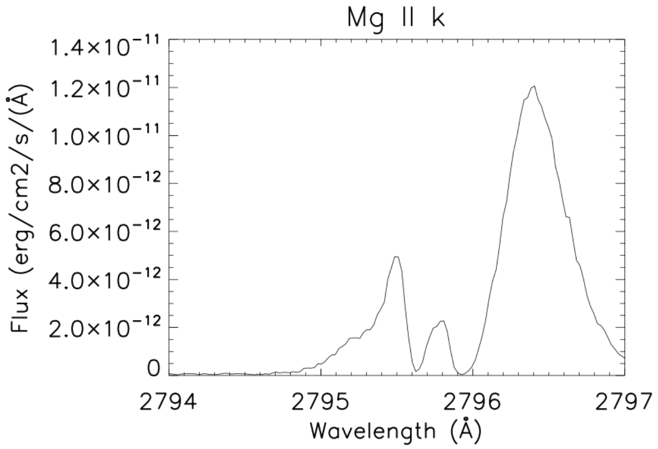
μ Gem (M3III) & γ Cru (M3.4III)

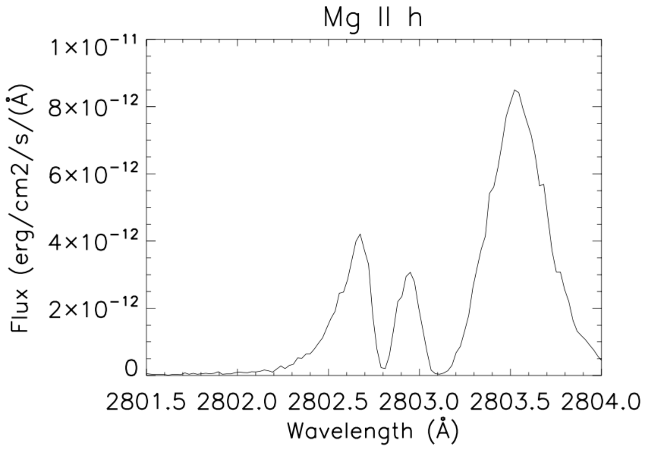
- Slightly different L class —> study the dependence of the wind and mass loss parameters on both sp. type/T_{eff}, surface g/L, by comparison with previous studied stars & each other
- Can be modeled with SEI (requires that wind can be treated as a pure-scattering medium)—> all the emerging photons be created in the chromosphere below the initiation of the wind flow

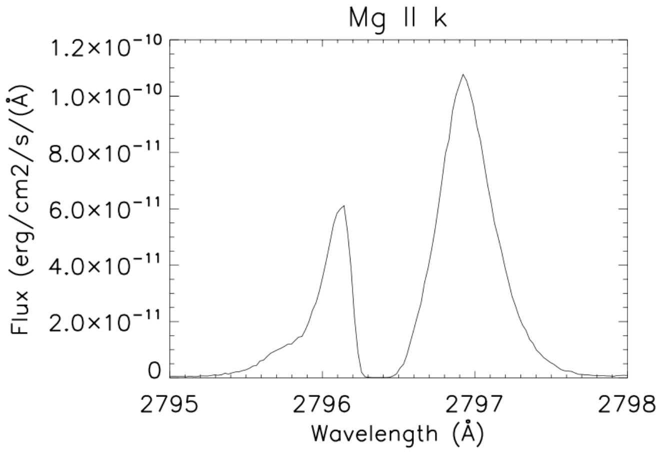


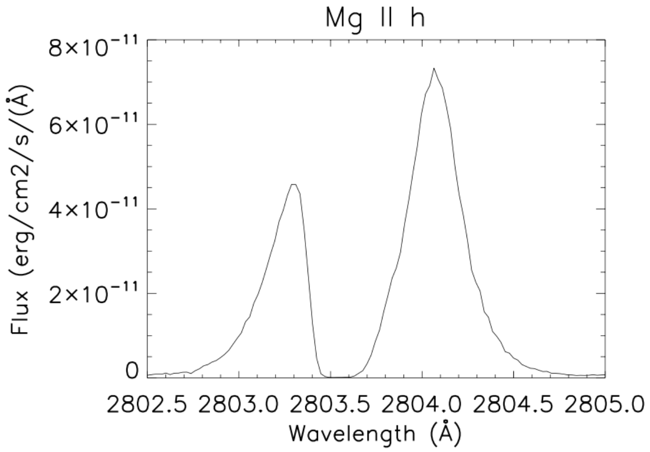
HST DATA

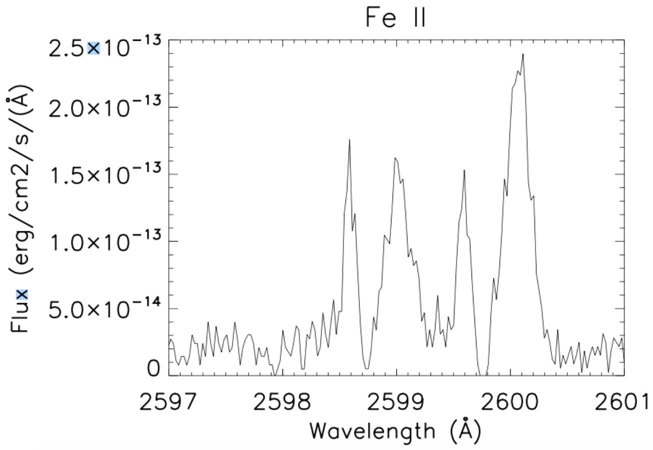
GHRS (Goddard High-Resolution Spectrograph)
λ = 2300—2850 Å
R ~ 20,000



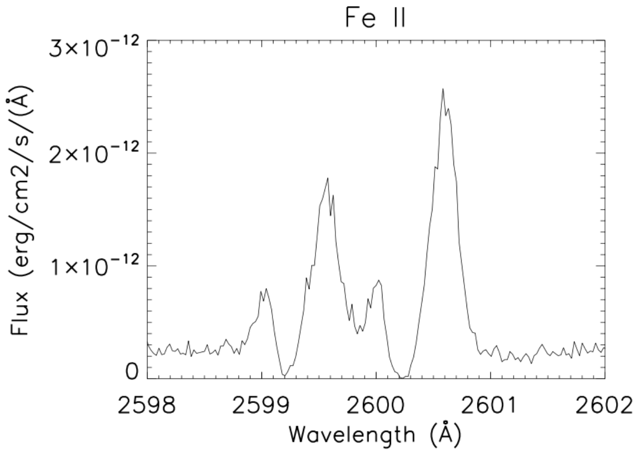








μ Gem (M3III)



γ Cru (M3.5III)

UV spectra HST/GHRS, show emission lines of, e.g. Mg II, Fe II, C II, formed at chromospheric temperatures, many of which are self-reversed by wind absorption

SEMI-EMPIRICAL MODELING

In the Chromosphere:

wings of emission lines, but the photon-scattering winds produce also wind absorption features

Not affected by wind absorption and can be used to measure the velocity of the line photon creating region wrt photosphere

Strength and shape are sensitive to the wind opacity, turbulence, and outflow velocity

Unreversed lines —> fitted with single gaussian —> parameters provide estimates of the flux, width, V of the chromosphere wrt photosph

Self-reversed lines —> empirical model (line wings=gaussian + central reversal formed in an overlying “reversing layer” with a Gaussian profile tau) with a resultant line profile:

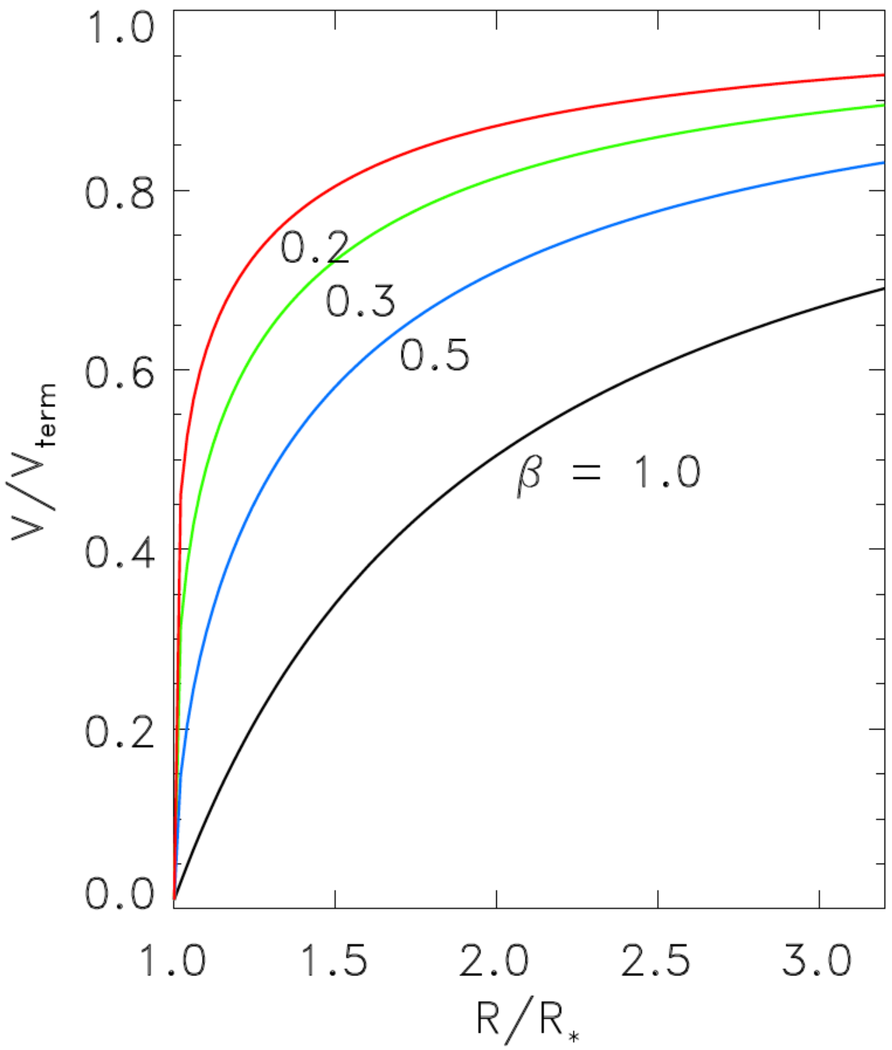
$$I(\lambda) = I_o \exp\left[-\frac{(\lambda-\lambda_w)^2}{\Delta\lambda_w^2}\right] \exp[-\tau(\lambda)]$$

$$\tau(\lambda) = \tau_0 \exp\left[-\frac{(\lambda-\lambda_c)^2}{\Delta\lambda_c^2}\right]$$

SEI MODELING

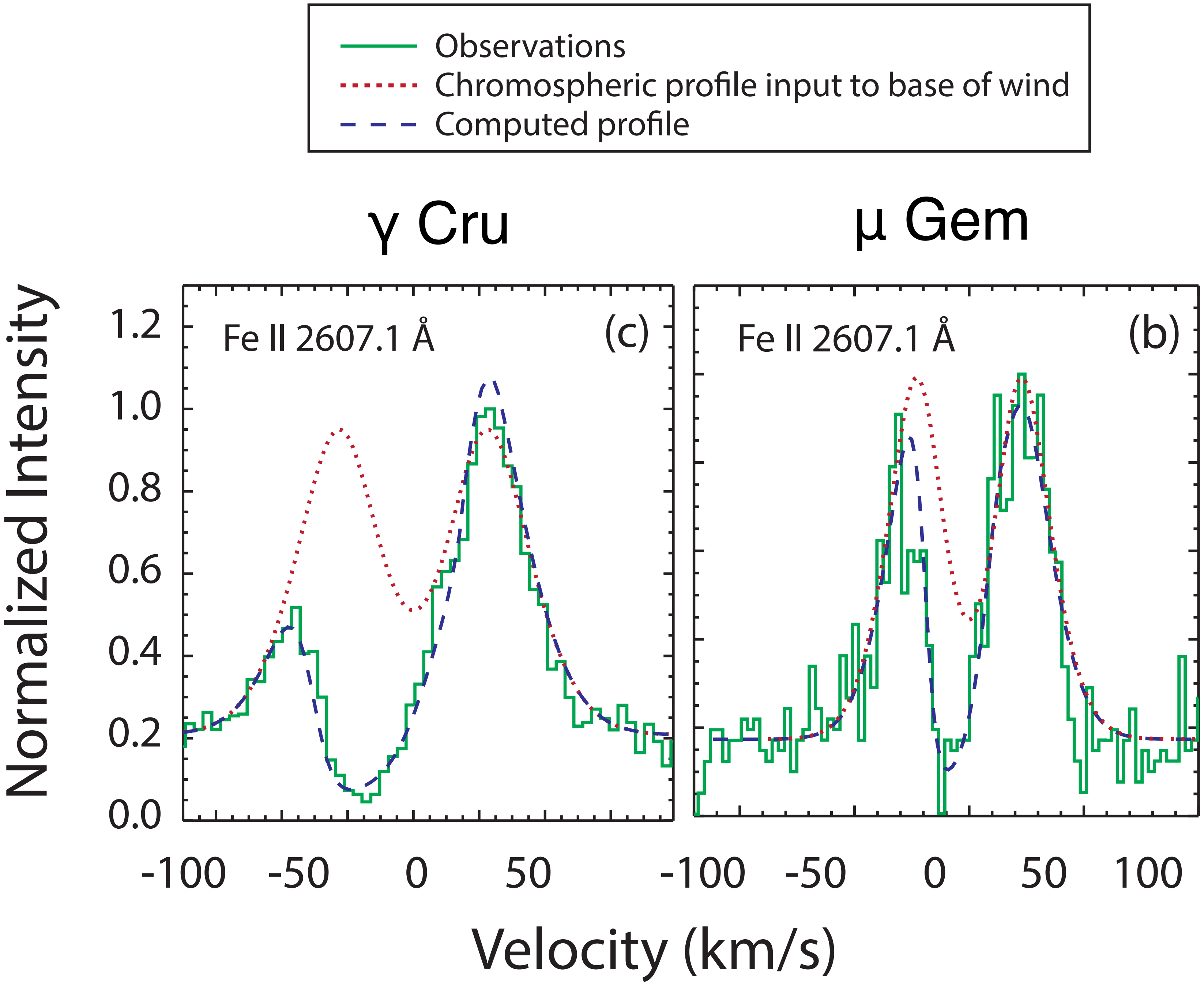
- Sobolev with Exact Integration (SEI) code (Lamers et al. 1987) to solve radiative transfer in a homogeneous, spherically expanding atmosphere using the Sobolev approximation and explicitly including turbulence
- Compute synthetic emission line profiles for chromospheric lines self-reversed by wind absorption and fit lines (e.g., Mg II, Fe II, C II) representing a wide range of optical depths, each of which thus samples a different height in the wind

- To get best fit to the observed lines, we adjust parameters:
  - chromospheric profile input to base of wind
  - wind acceleration parameter β, such that $V(R)/V_{term}=(1-R_*/R)^{\beta}$
  - wind turbulence, wind opacity, wind terminal velocity
  - Estimate mass-loss rate from inferred wind opacity, acceleration parameter, and terminal velocity



Rau, Carpenter et al. (subm.)

COMPARISON WITH LINE PROFILES



Rau, Carpenter, et al. (subm.)

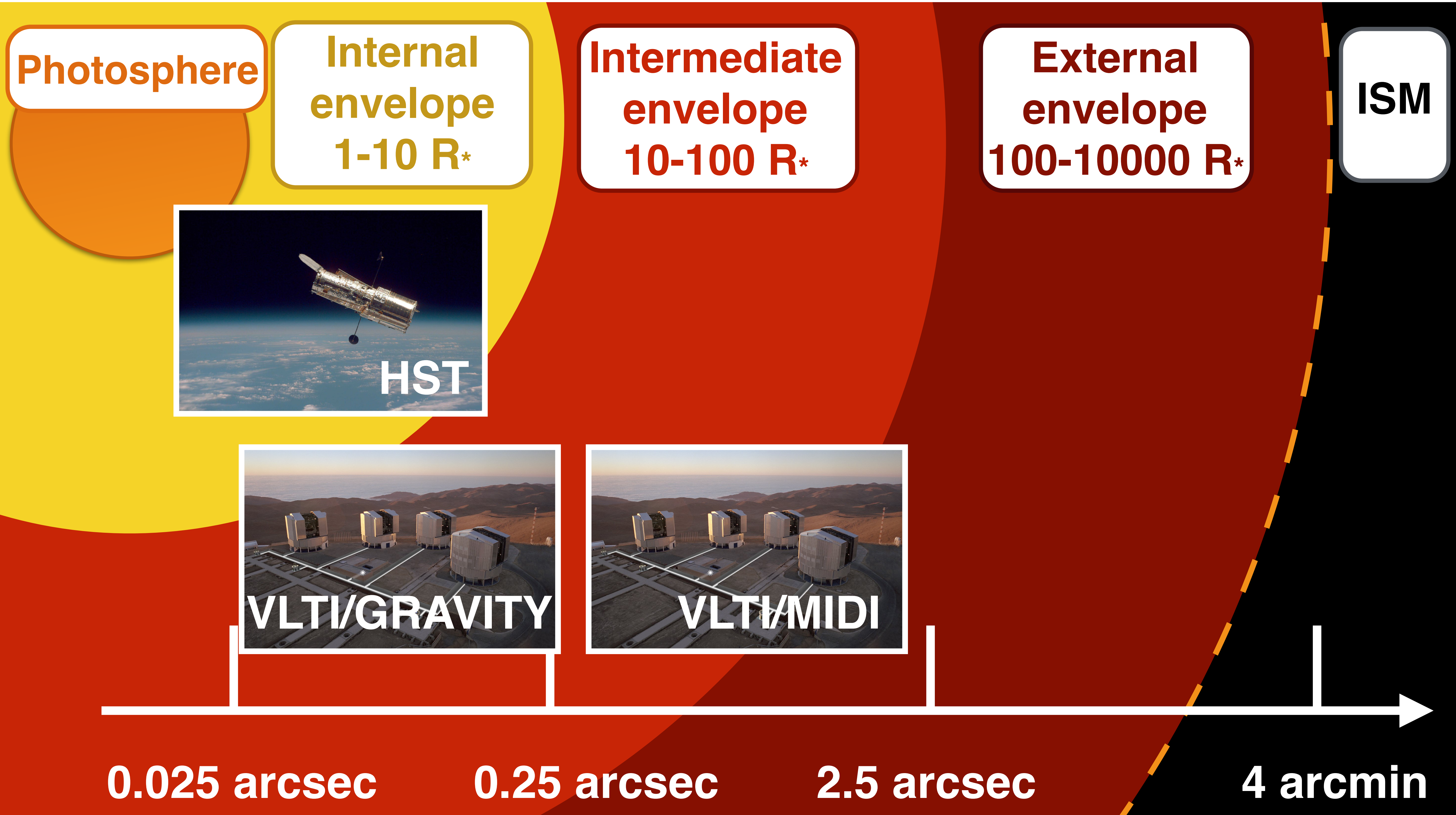
- Sobolev with Exact Integration (SEI, Lamers et al. 1987) modeling of the outflowing winds
- Although the 2 stars have ~same T_{eff} and L class, μ Gem has weaker wind and chromosphere —> μ Gem could be more evolved than γ Cru.

Star	Sp. Type	β	V_{term}[km/s]	V_{turb}[km/s]	$M_{dot}[10^{-11} M_{sun}/yr]$
α Tau	K5 III	0.6	30	24	1.4
γ Dra	Hyb. K5 III	0.35	67	12	1.2[b]
λ Vel	K5 I	0.9	31	9-21	300.
μ Gem	M3 III	0.6	11	9	7.4
γ Cru	M3.4 III	0.7	19	14	45.

- Mean velocities of the wind self-reversals in chromospheric emission lines reflect accelerating outflows:
  - in non-coronal, K-M giants: wind seen accelerating from lower values of 2-9 km/s up to upper values of 13-25 km/s
  - in the hybrid star γ Dra (K5 III): wind seen from 0 km/s up to about 70 km/s
- SEI models of the outflowing winds indicate:
  - rather rapid acceleration (β < 1); turbulent velocities ~ 9-20 km/s
  - terminal velocities of 11-30 km/s fornon-coronal stars; ~ 67 km/s for hybrid star
  - mass-loss rates of ~ 1 x 10^{-11} M_{sun}/yr for K-giants
    ~ 7-45 x 10^{-11} M_{sun}/yr for the M-giants
    ~ 300 x 10^{-11} M_{sun}/yr for the K-supergiant

WHY MULTI-TECHNIQUES?

- **Spectroscopy**
  ISO SWS/IRAS spectra
- **Photometry**
  SAAO, ESO, ASAS
- **Interferometry**
  VLTI/MIDI/GRAVITY



Photosphere

Internal envelope
1-10 R*

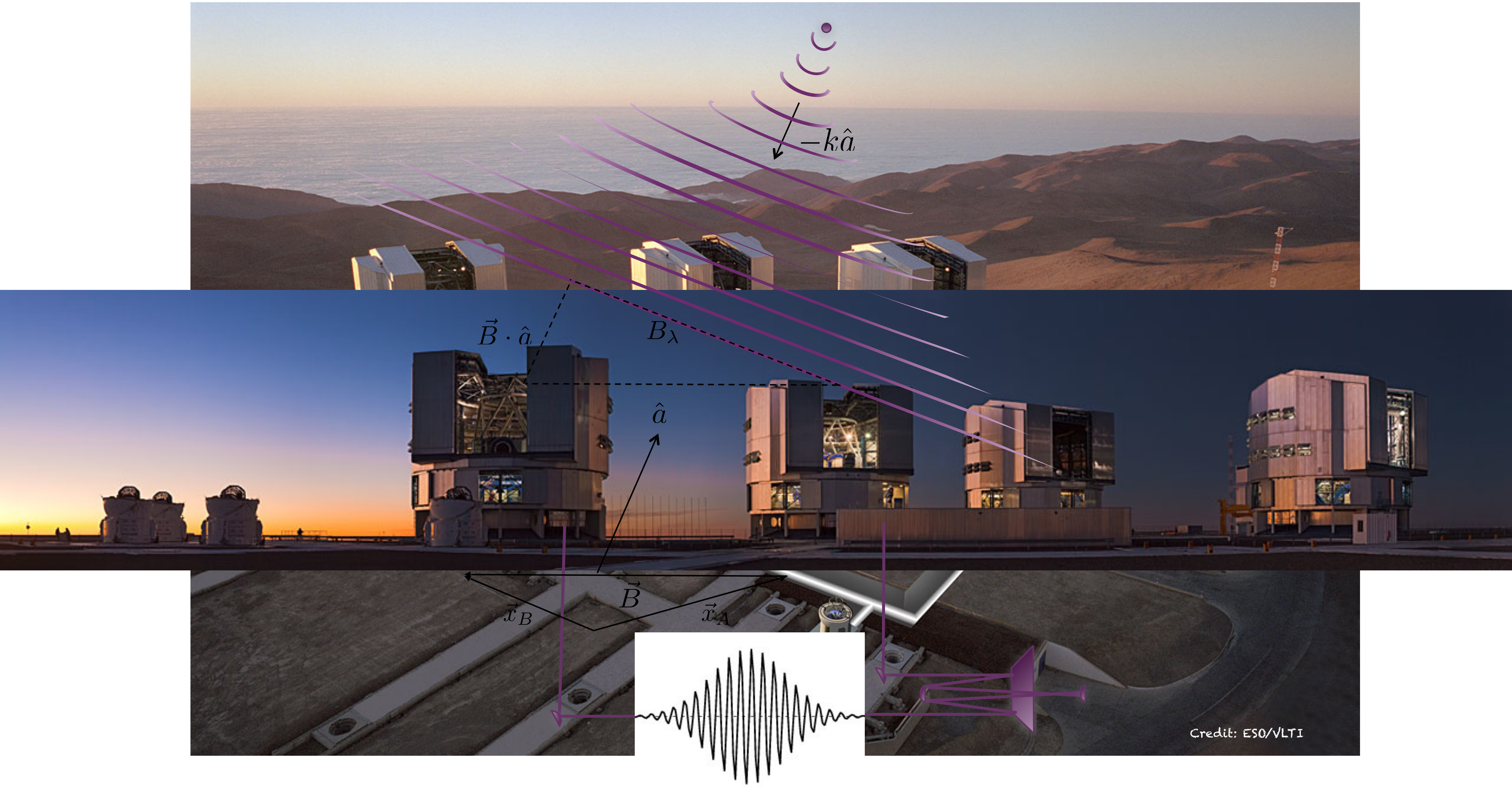
Intermediate envelope
10-100 R*

External envelope
100-10000 R*

ISM

INTERFEROMETRY WITH VLTI

Powerful tool to study the stratification of the stellar atmospheres

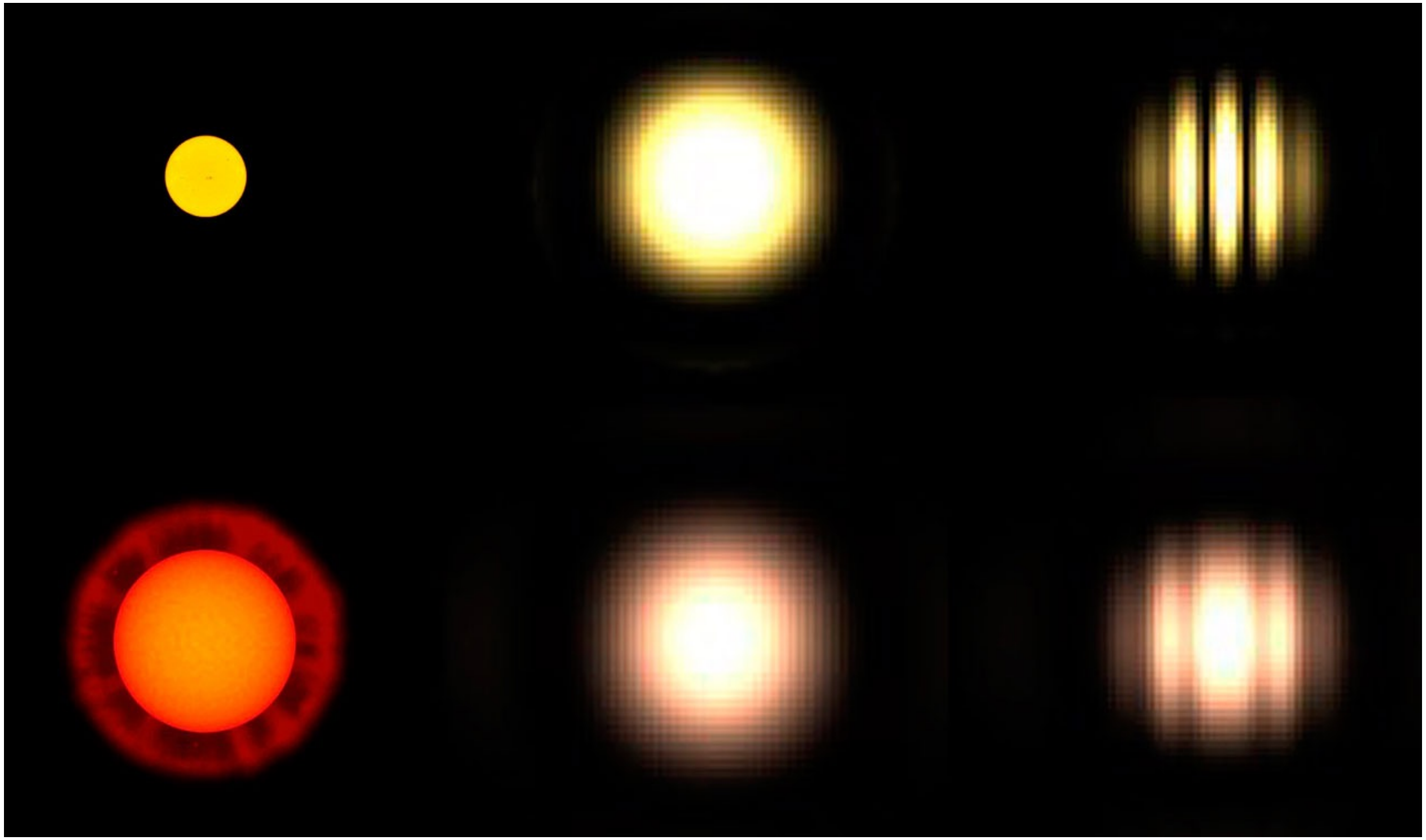


Credit: ESO/VLTI

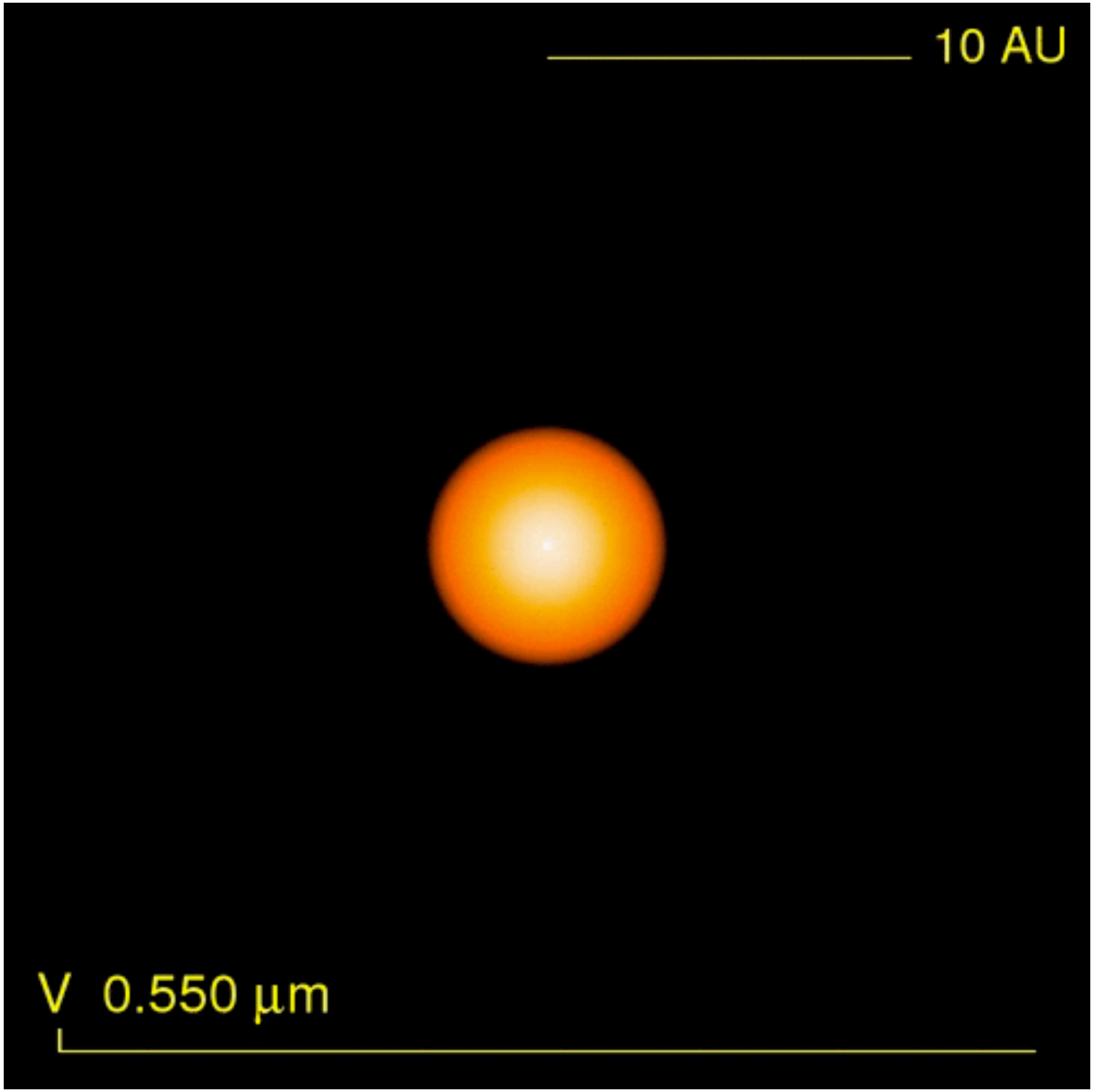
WHAT DO WE OBSERVE WITH INTERFEROMETRY?

VanCittert-Zernicke: The complex visibility is the Fourier transform of the source intensity distribution

- Contrast of the fringes = visibility —> angular dimension of the object
- Location of the fringes = phase —> symmetry of the object

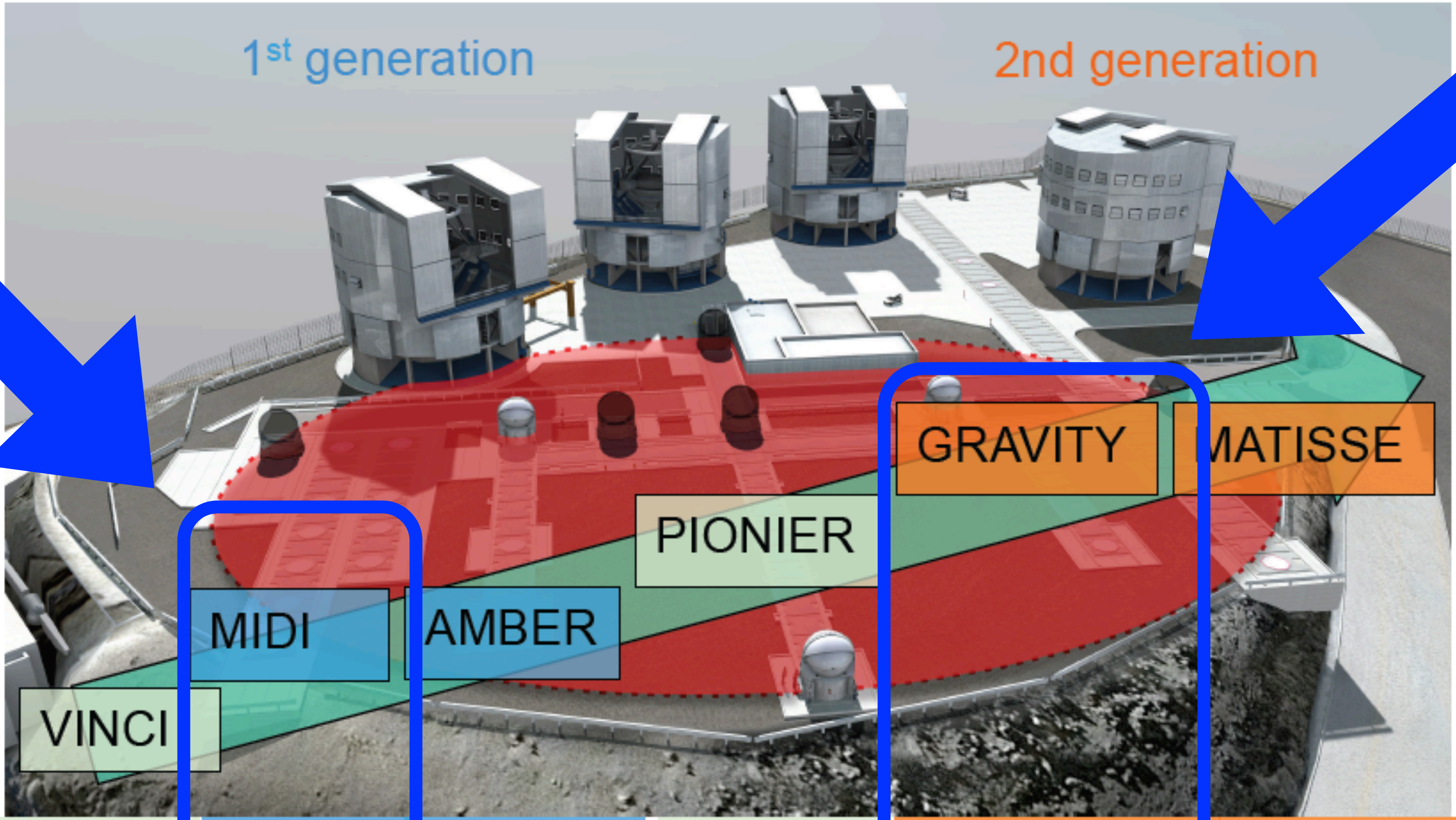


WHY MULTI-WAVELENGTH?



Based on dynamic models for C-stars by Höfner et al. (2003), Eriksson et al. (2014)

VLTI: A virtual 130+ -meter telescope



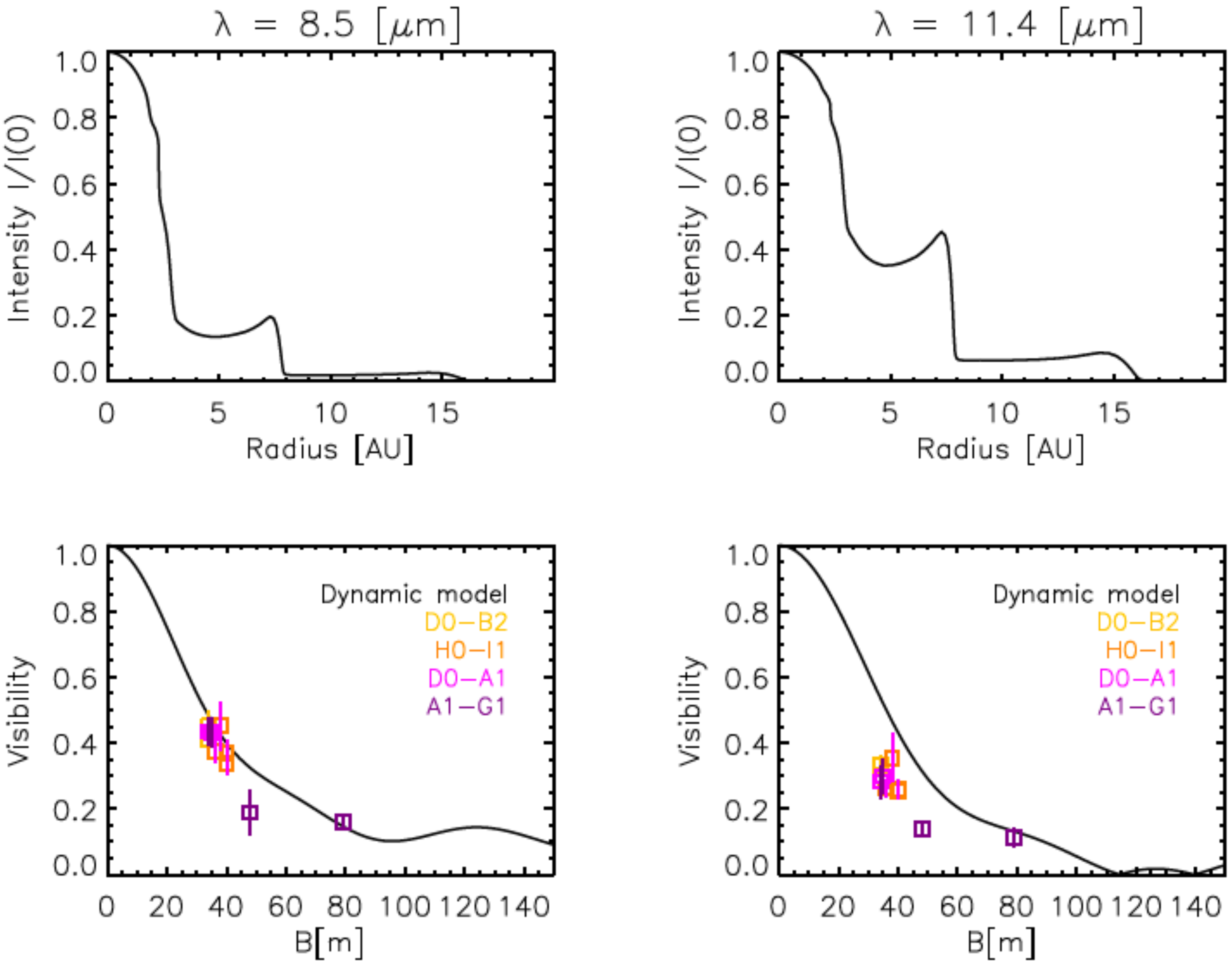
Spectro-Interferometry

Spectro-Imaging

2001 K-band (broad) 2-way beam comb. (Test) Instrument High-precision	2002 N-band 2-way *R*=30,230	2004 (J)HK-band 3-way *R*=30,1500, 12000	2010/2015 H(K)-band 4-way *R* ~20	2016 K-band 4-way *R*~22, 500, 4000 Astrometry	(2018) LMN-band 4-way *R*~30, 450/200

- **Interferometry**

VLTI/MIDI



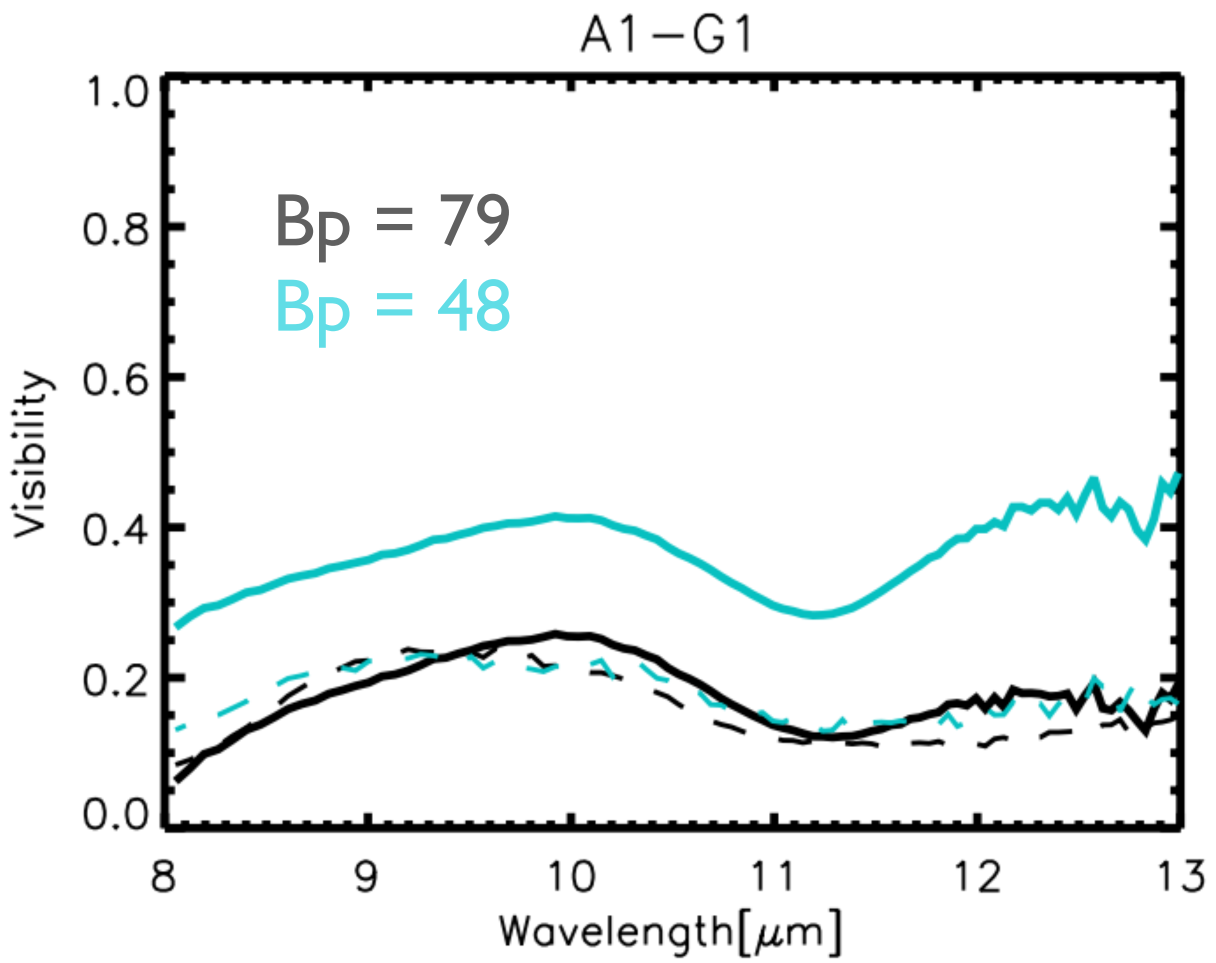
R Lep

Rau et al. (2017)

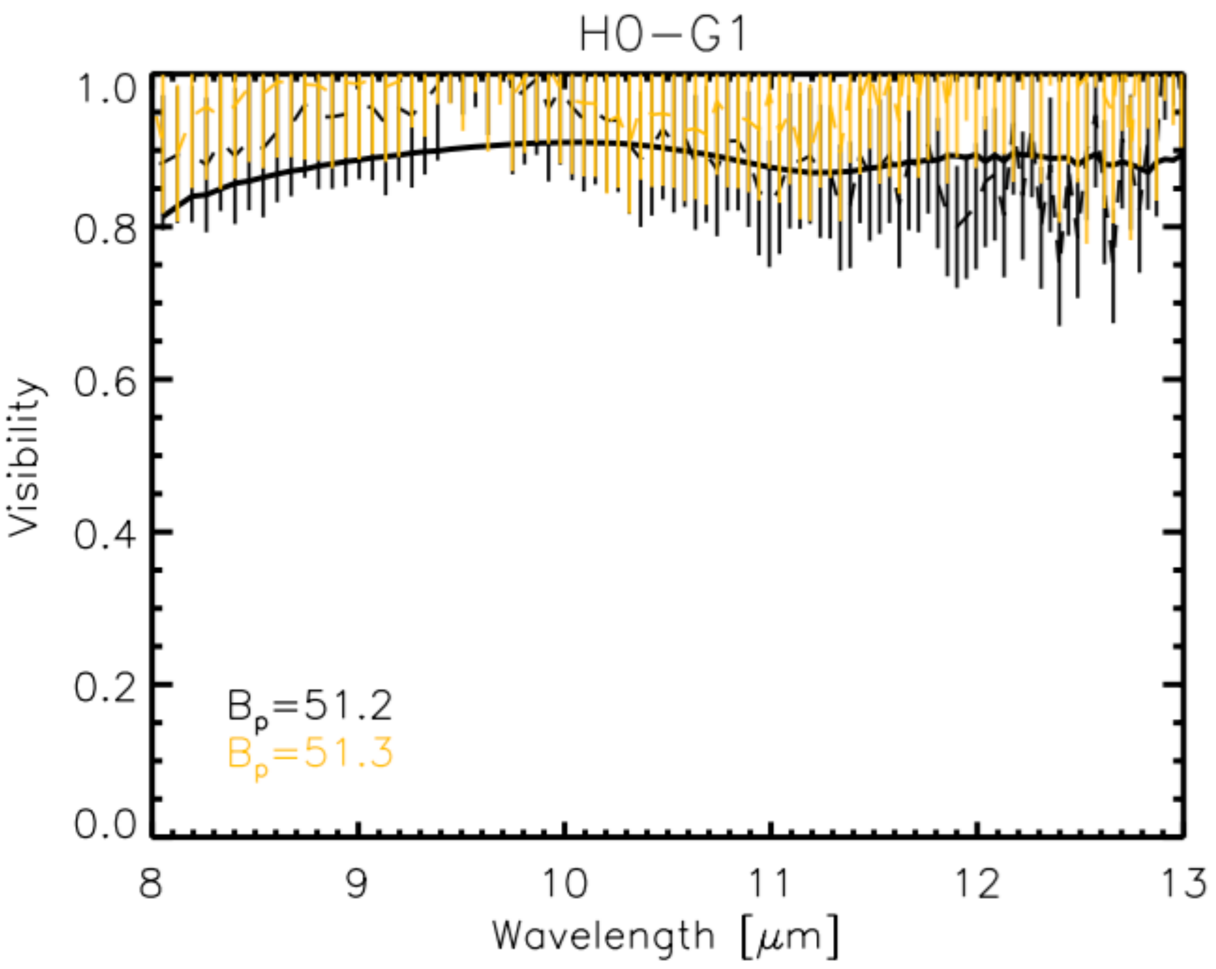
• Interferometry

VLTI/MIDI

R Lep,



Y Pav,



Rau et al. (2017)

DERIVING FUNDAMENTAL STELLAR PARAMETERS

- From DMA fitting —> parameters of the models: L, T_{eff}, M, log(g), C/O, Δu, R_{Ross}, θ_{Ross}

- From the photometric observations —> $\theta_{(V\text{-}K)}$ (Van Belle et al. 2013), L_{bol}

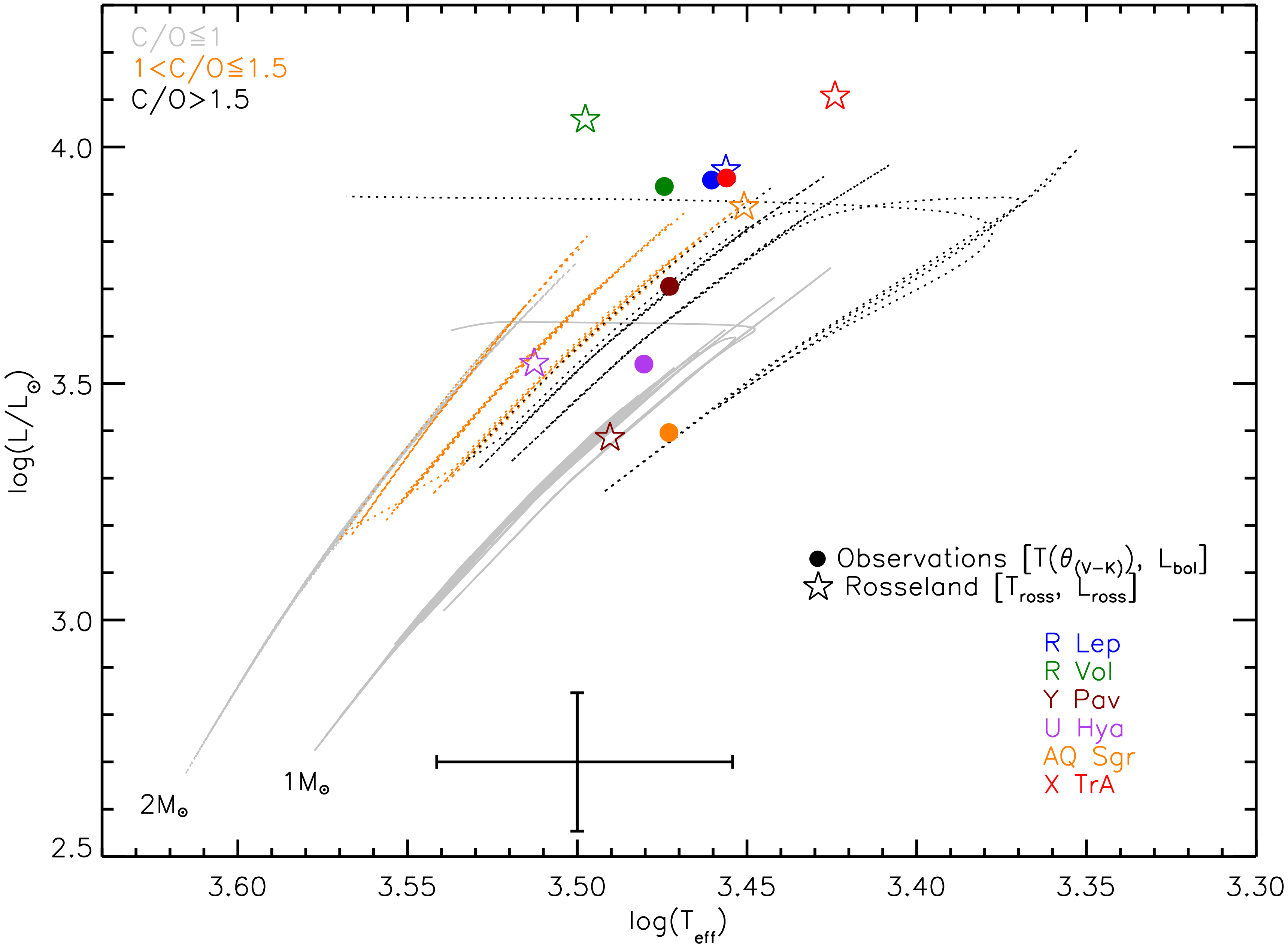
- From interferometric observations —>10µm UD diam

DERIVING FUNDAMENTAL PARAMETERS & STUDYING STELLAR EVOLUTION

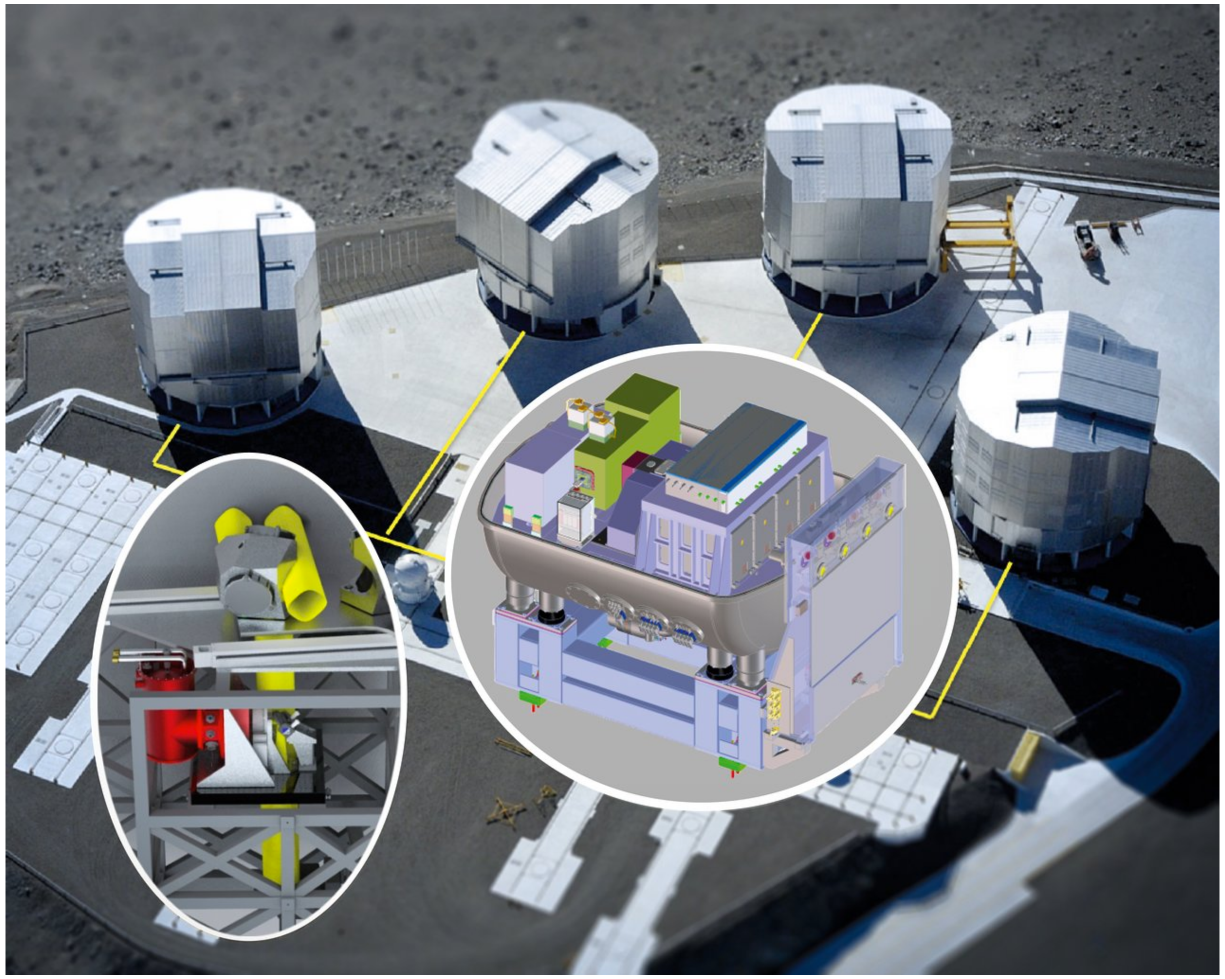
- Good agreement with the C/O ratio & M of the dynamic models for all the stars

- Good agreement of the parameters derived from observations and models (within the errors)

Rau et al. (2017)



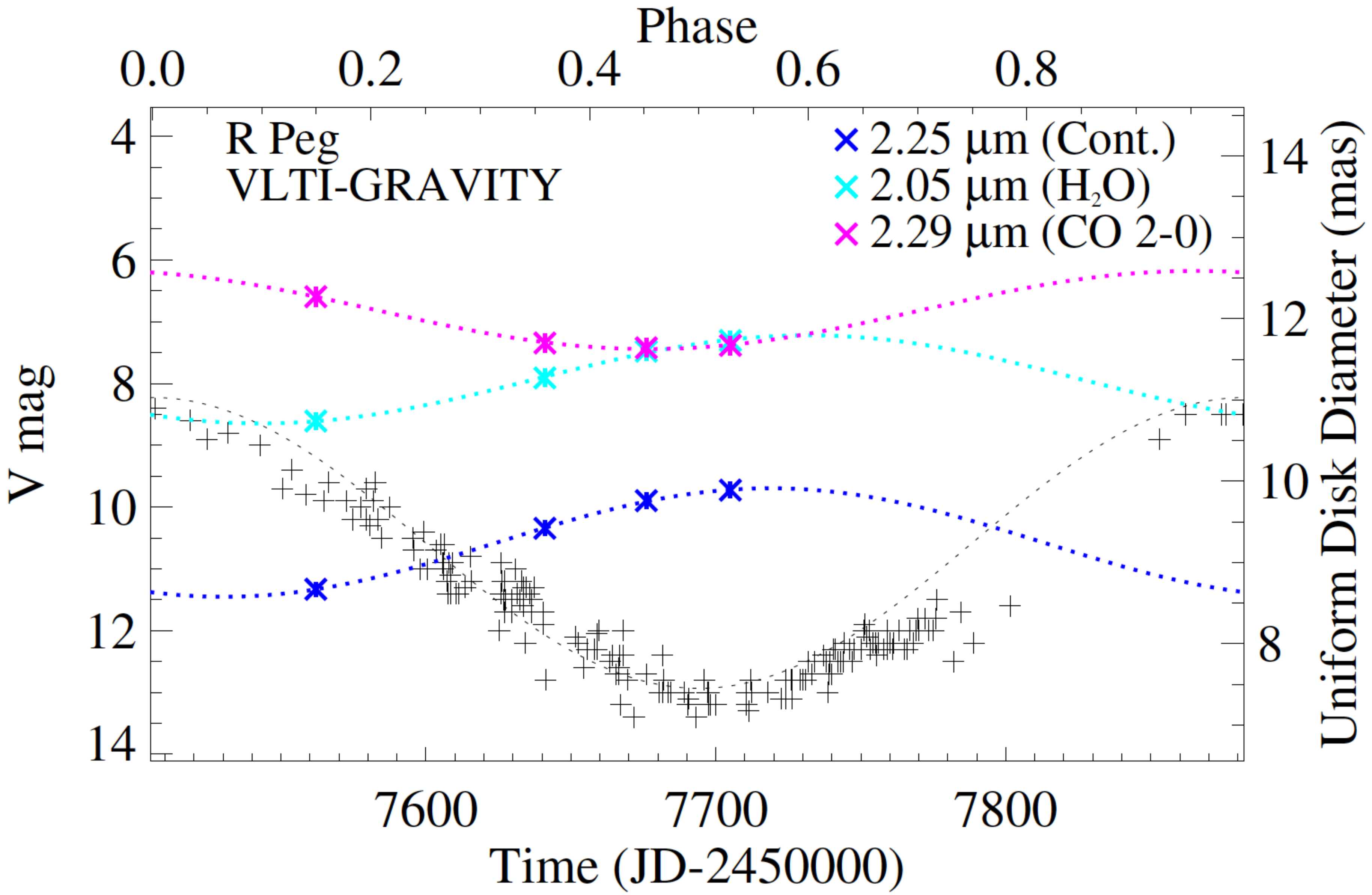
VLTI/GRAVITY MEASUREMENTS OF EVOLVED STARS I: THE CASE OF R PEG



λ = 1.99—2.45 μm
R ~ 4000
4-telescopes

Aim:
Measuring the variability of sizes in near-continuum and molecular bands of R Peg (O-rich Mira)

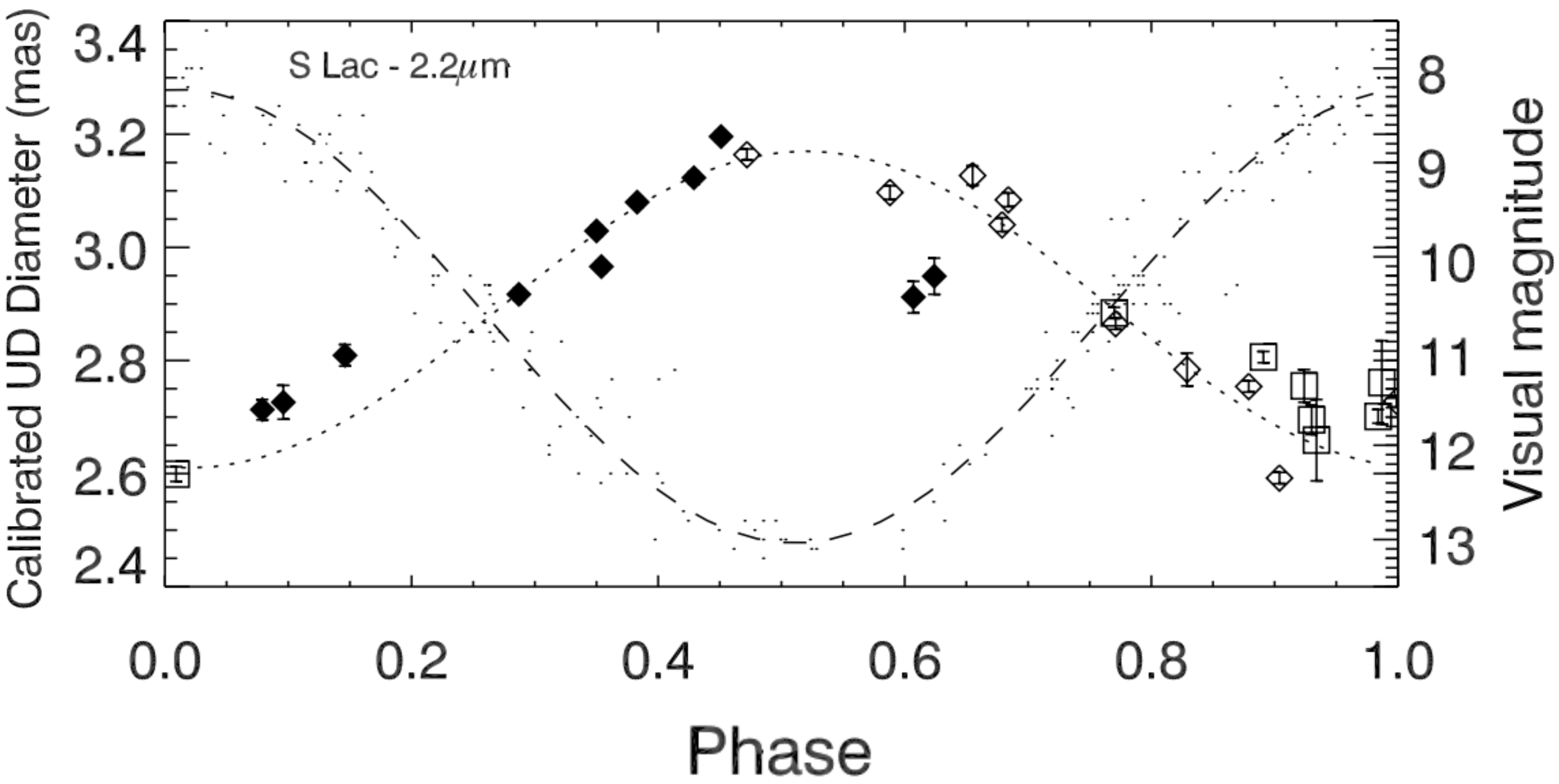
- Near-continuum @2.25 μm —> photospheric continuum R
- Bandpass @2.05 μm —> strength of H_20 vapor
- Narrow bandpasses @lowest points of the visibility drops in the CO (2-0) @2.29 μm and in the CO (3-1) @2.32 μm



Wittkowski, Rau et al. (2018)

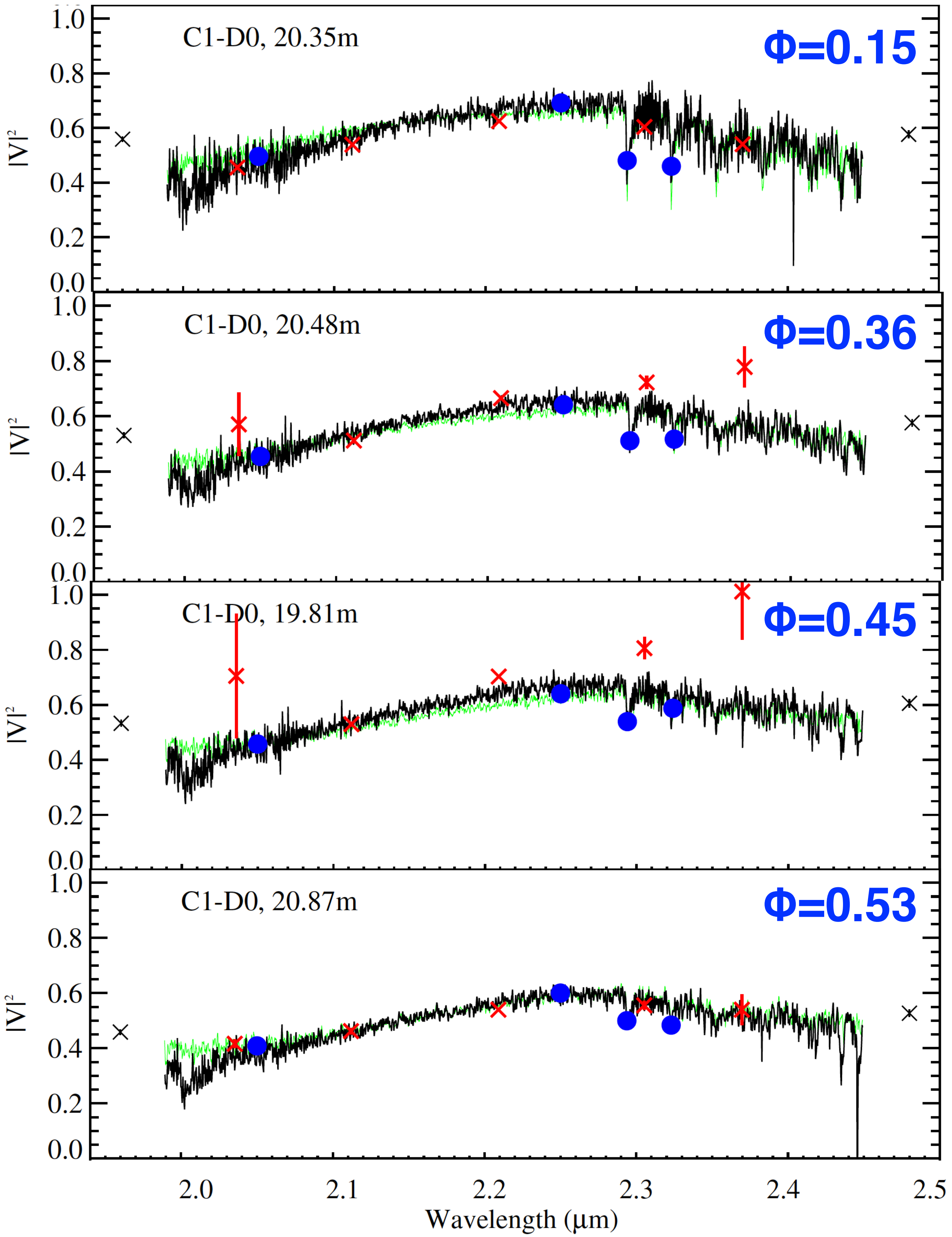
UD angular diameters @:

- Near-continuum: steadily increasing at visual Φ between post-max and min.
- H_2O shell follow the variability of the near-continuum R at larger UD diameters.
- CO 2-0 line: instead, are correlated with the visual lightcurve and anti-correlated with the near-continuum UD diameter.



Continuum radius is anti-correlated with the visual light curve, as for S Lac (Thompson et al. 2002)

CODEX MODELING



From Φ=0.15 to Φ=0.53:

- V_{cont} decreases ==> R_{cont} increases
- At the same time the contrast of the CO visibility drop is decreasing

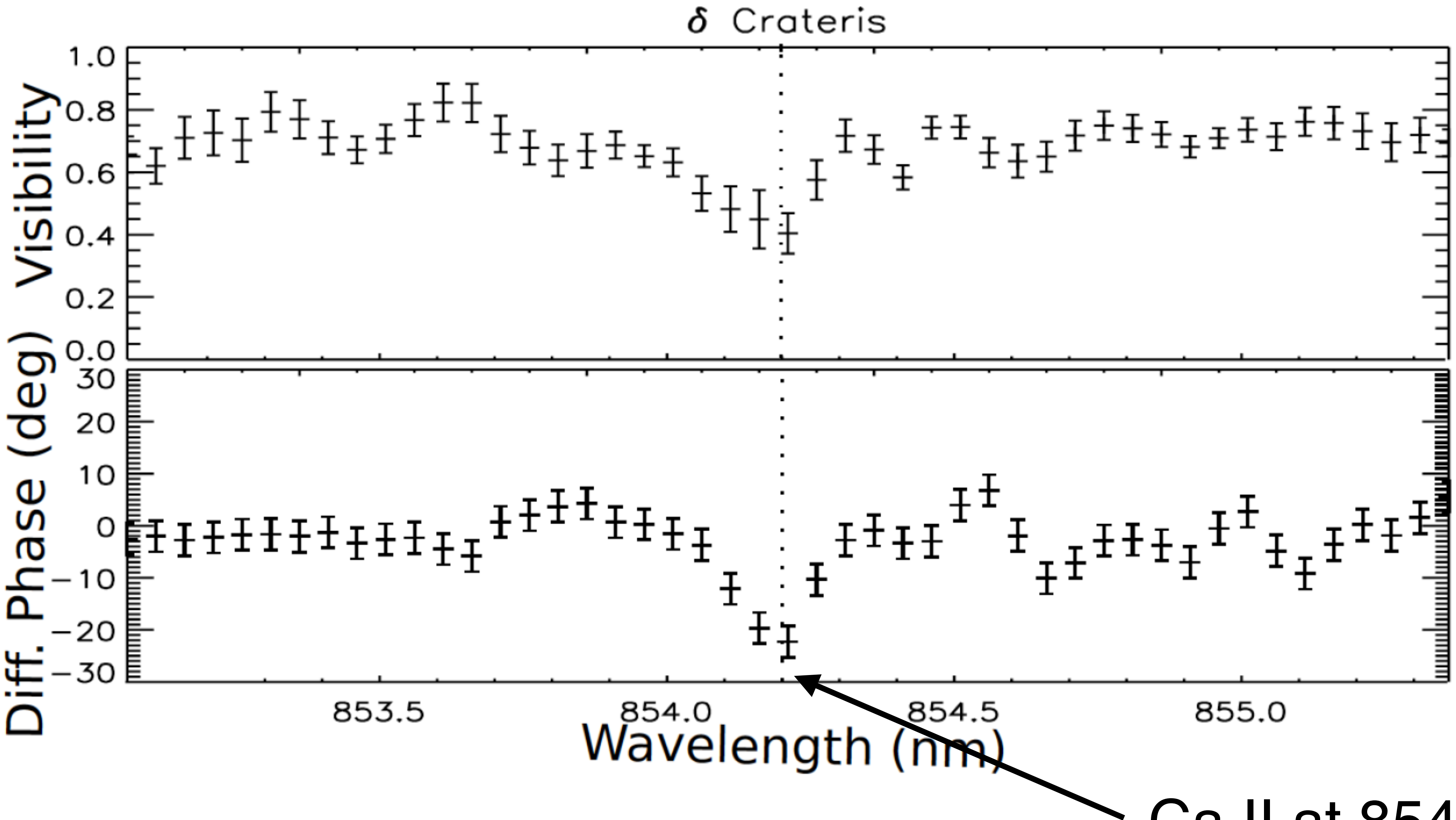
CO further from star at Φ=0.15, closer to the star at Φ=0.65

Wittkowski, Rau et al. (in prep)

FUTURE PLANS: CHARA

Visible spEctroGraph and polArimeter (VEGA) instrument to study with it the geometrical extent of the chromosphere, by comparing the estimated radius in the continuum (photosphere) and in the chromospheric lines (H Alpha and Ca II triplet line).

Berio et al. (2011)



Ca II at 854 nm

TAKE-HOME MESSAGES

- **Interferometry** is necessary to **resolve the atmosphere and chromosphere** of RGBs and AGBs

- Need to tackle giant stars with using a **multi-technique, multi-wavelength approach**, to explore different atmospheric layers

- RGB & AGBs are key ingredients for improving our knowledge of the chemical **enrichment of the ISM** and of **planets habitability**

& FUTURE PERSPECTIVES…

- RU Vir & V Oph (C star) studies w/ model atmospheres & **RADMC3D**, and preparation for **MATISSE** observations

- Study of **chromospheric emission w/ interferometry (CHARA/VEGA), and HST** on a sample of Giant stars with different gas/dust (collaboration encouraged, contact me: gioia.rau@nasa.gov)