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3D-surface modeling of rapidly rotating stars

Spectral synthesis and interferometric synergy with PANORAMA and SPAMMS

D. Galán-Diéguez [1, 2]

M. Abdul-Masih [1,2] S.R. Berlanas [1, 2] A. Herrero [1,2]

[1] *Instituto de Astrofísica de Canarias* [2] *Dpto. Astrofísica, Universidad de La Laguna*

October 7, 2026

EXCELENCIA SEVERO OCHOA

Departamento de Astrofísica
Universidad de La Laguna

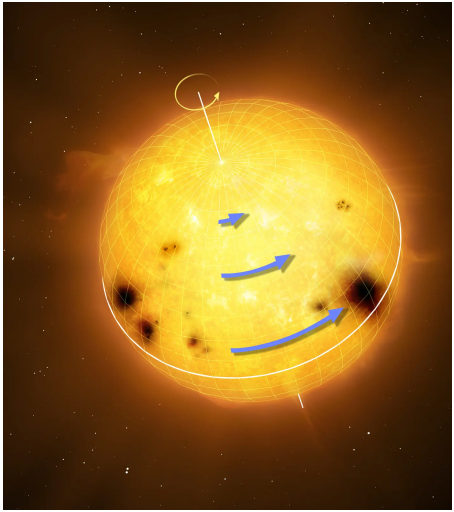
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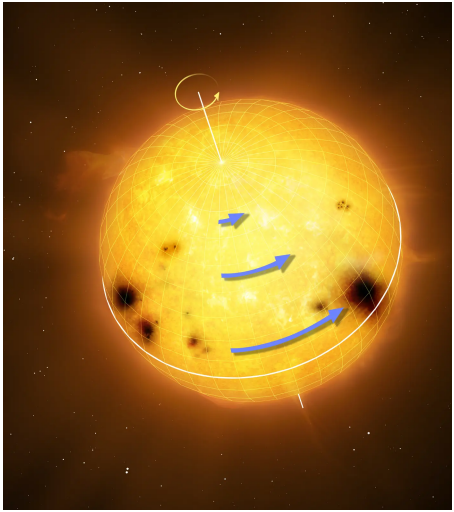
Basics

- Rotation key element
  - Evolution
  - Fate
- Similar
  - Stellar mass
  - Metallicity

Maeder & Meynet (2000)

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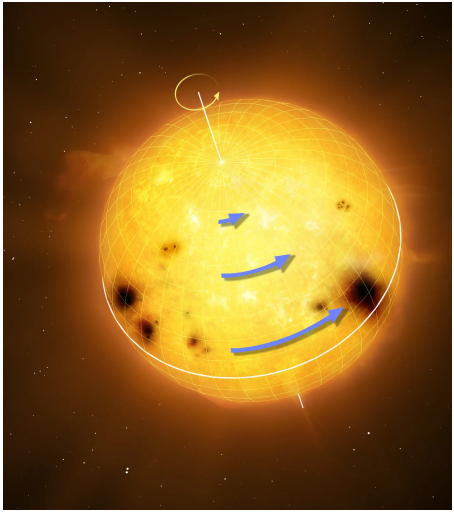
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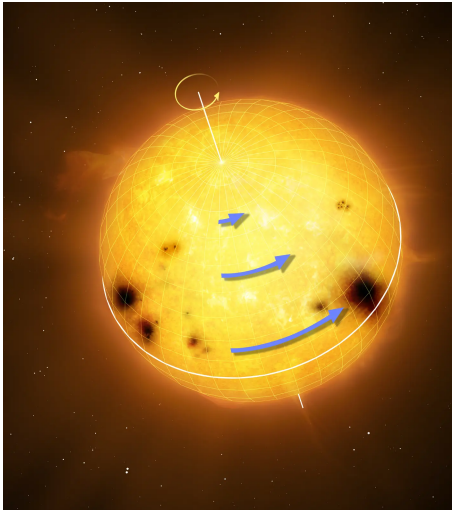
Low rotation

- Natal angular momentum

High rotation

- $> 200\,\mathrm{km\,s^{-1}}$
- Binary products

Rubin (1962) ; de Mink et al. (2013)



MPS/MarkGarlick.com

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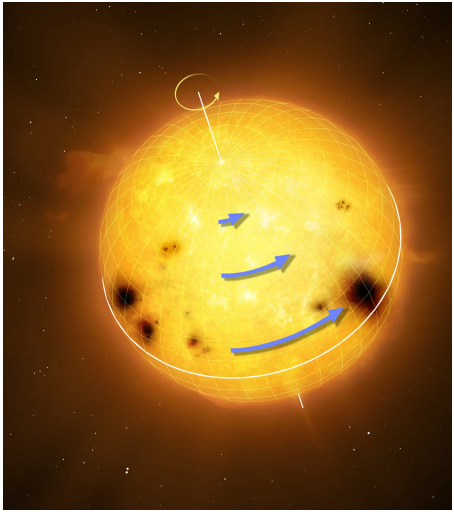
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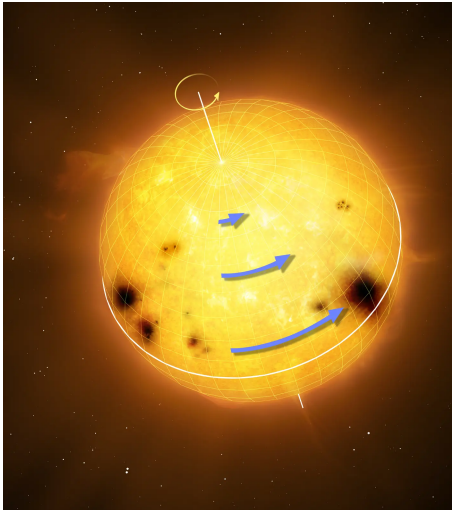
Low rotation

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- $> 200\,\mathrm{km\,s^{-1}}$
  - $v_{\mathrm{Vega}} \sim 2\,\mathrm{km\,s^{-1}}$
- Binary products
  - Tides
  - Mass accretion
  - Mergers

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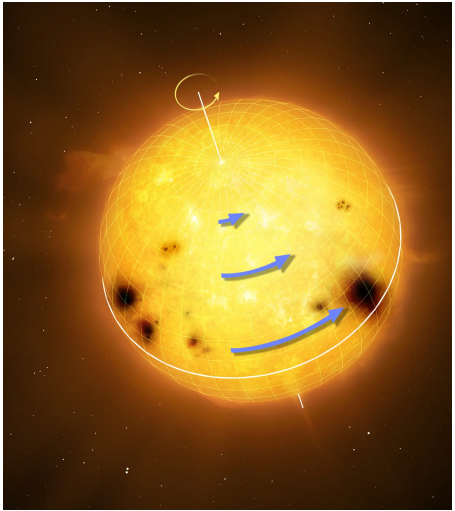
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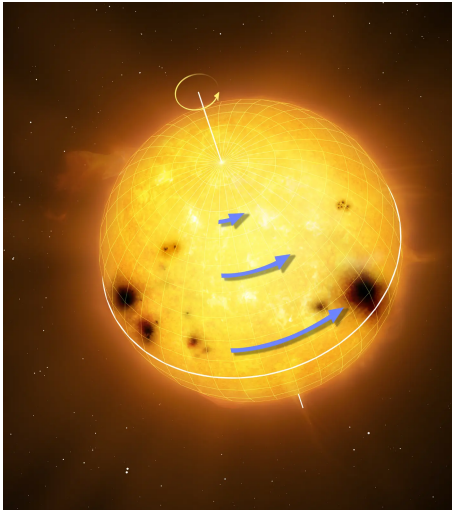
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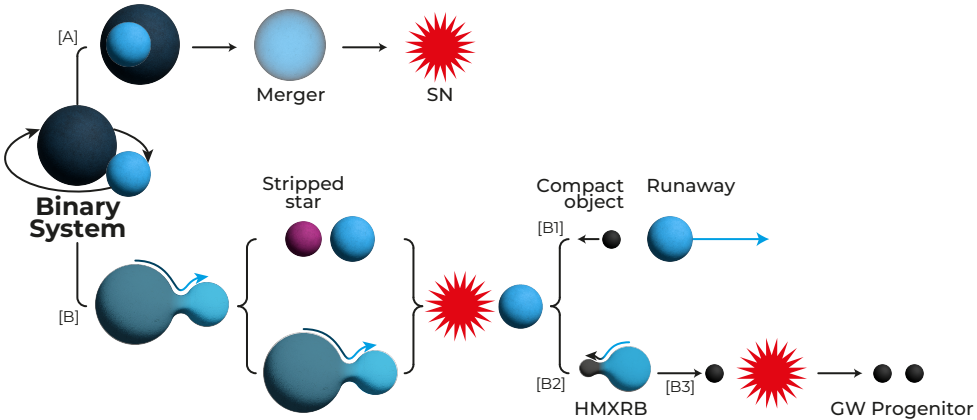
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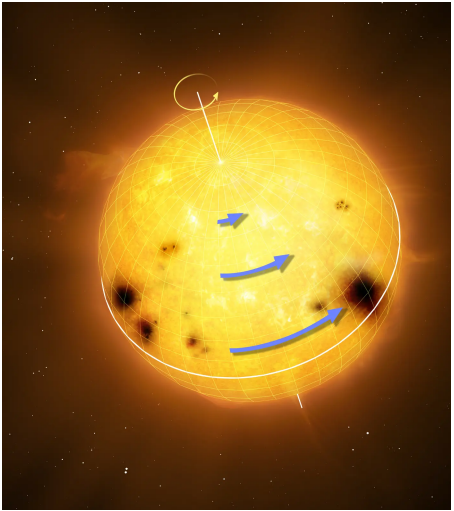
Galán-Diéguez et al. (2026b)

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Consequences

- Surface deformation
- Surface gradients



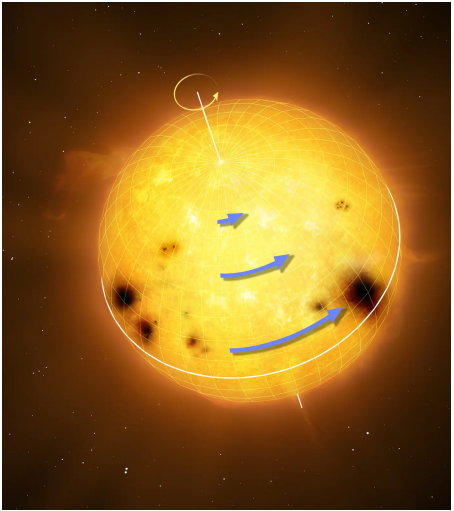
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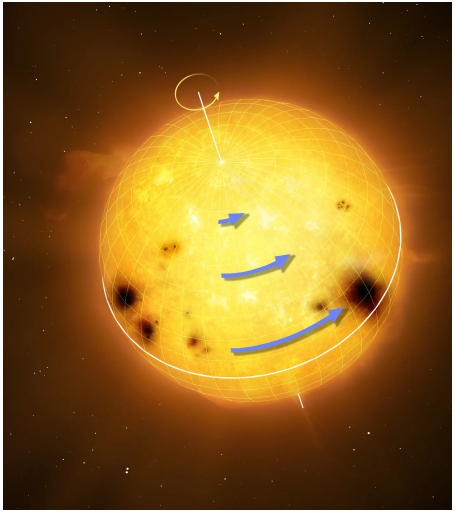
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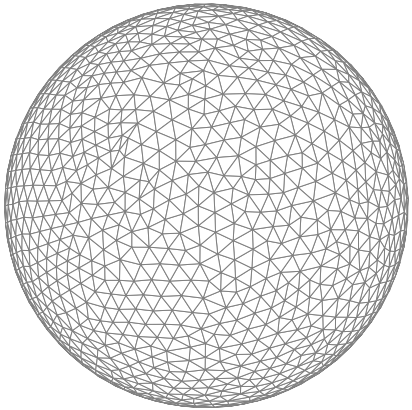
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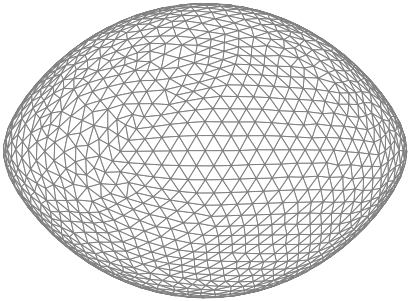
Surface Deformation

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- Dependence on rotation
- Modification of the gravity

Kippenhahn & Weigert (1990)

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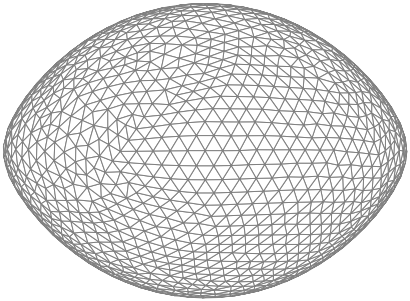
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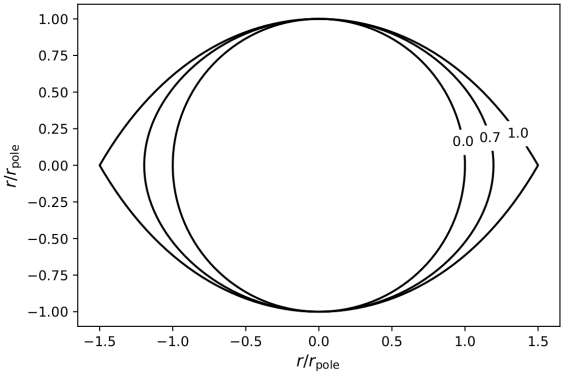
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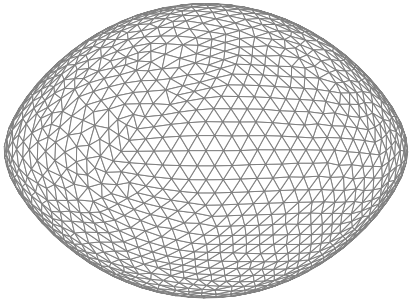
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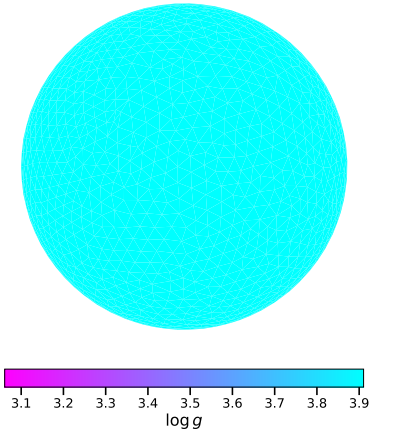
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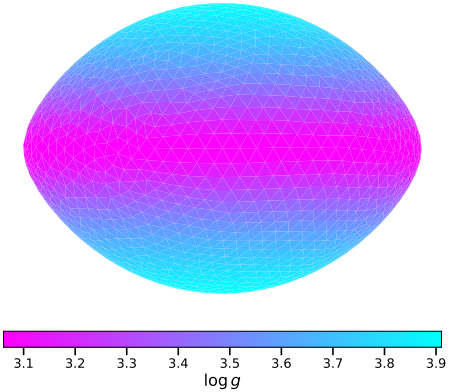
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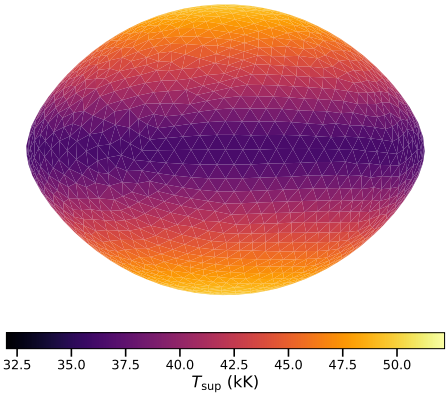
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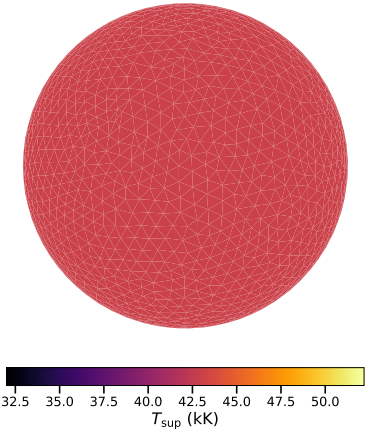
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PANORAMA: 3D-Surface Modeling

Package for ANalysis Of RApidly rotating MAssive stars

- Whole analysis chain in one Python package
  - Modular: one tool per stage
  - Consistent conventions, input validation, ready-to-run demos
- Workflow
  - obs → spec → `fitline` → `rot` → `specblur` → `tex`

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Stars ≠ 1D spheres

- Roche shape
- Gravity darkening
- Rotationally broadened lines

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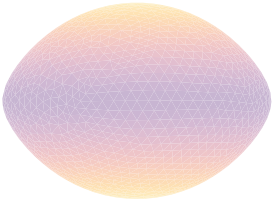
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2. Physical Synthesis



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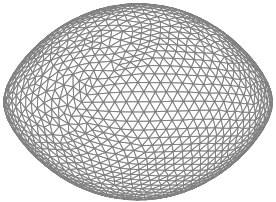
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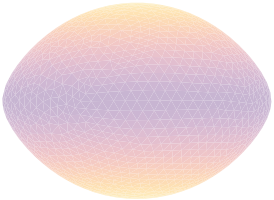
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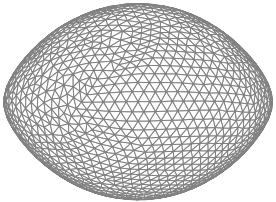


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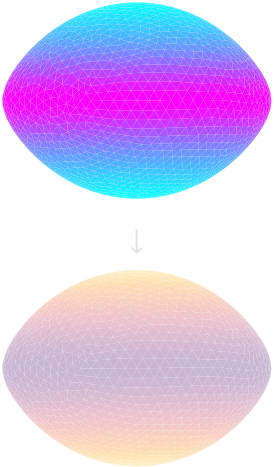


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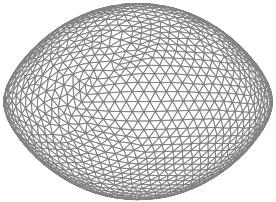


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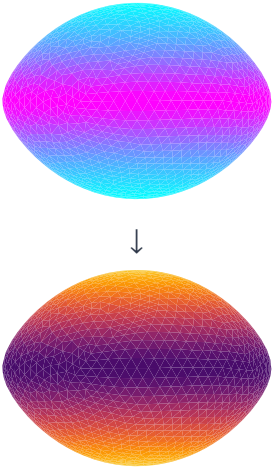


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Shape: Roche model

Point-mass gravity + solid-body rotation:

$$\Phi(r,\theta) = -\frac{GM}{r} - \frac{1}{2}\,\Omega^2 r^2 \sin^2\theta$$

Surface ($\omega = \Omega/\Omega_{\rm K}$, $\tilde{r} = R/R_{\rm eq}$):

$$\tilde{r}(\theta) = \frac{3}{\omega \sin\theta}\,\cos\left[\frac{\pi + \arccos(\omega\sin\theta)}{3}\right]$$

$$\frac{R_{\rm eq}}{R_{\rm p}} = 1 + \frac{\omega^2}{2}, \qquad \vec{g}_{\rm eff} = -\nabla\Phi$$

Espinosa Lara & Rieutord (2011)

Flux $\vec{F} \parallel \vec{g}_{\rm eff}$, no free exponent β:

$$T_{\rm eff}(\theta) = \left(\frac{L}{4\pi\sigma GM}\right)^{1/4} \sqrt{\frac{\tan\vartheta}{\tan\theta}}\; g_{\rm eff}^{1/4}$$

$\Rightarrow$ Hot poles, cool equator, weaker than von Zeipel

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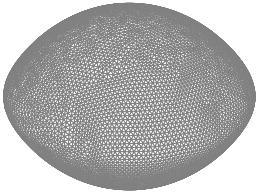
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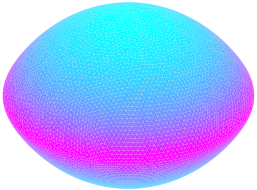
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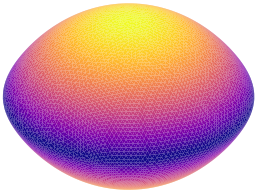
(i) Roche Framework



(ii) Surface Geometry



(iii) Temperature Distribution



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Surface rotation law

$$\Omega(\theta) = \Omega_0 \left[1 + \alpha\, \Upsilon(\theta)\right], \qquad \Upsilon(\theta) = \begin{cases} \cos^k \theta \\ \sin^k \theta \end{cases}$$

Zorec et al. (2017)

Radiation pressure

Local Eddington factor:

$$\Gamma_\Omega(\vartheta) = \frac{\kappa(\vartheta)\, L \left[1 + \zeta(\vartheta)\right]}{4\pi c G M \left(1 - \frac{\Omega^2}{2\pi G \bar{\varrho}_M}\right)}$$

$$\vec{g}_{\rm tot} = \vec{g}_{\rm eff} \left[1 - \Gamma_\Omega(\vartheta)\right]$$

Maeder & Meynet (2000)

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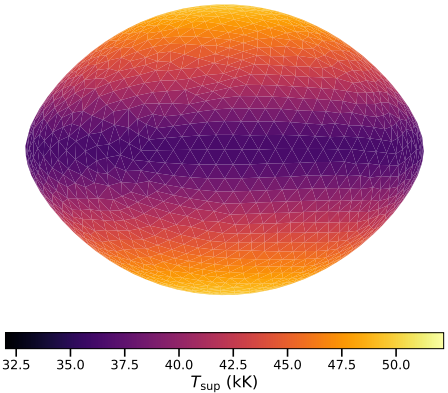
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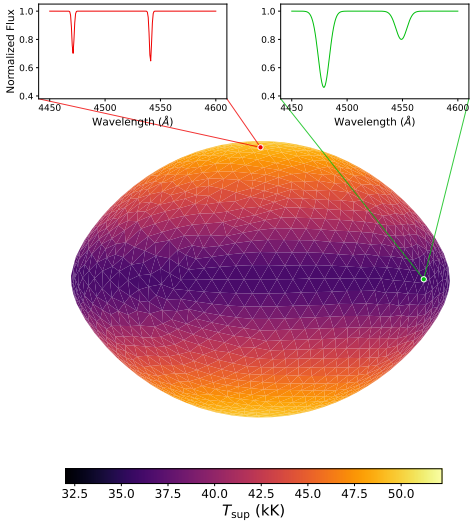


$M_* = 36\,\mathrm{M}_\odot$, $T_{\rm eff} = 43\,\mathrm{kK}$, $R_{\rm p} = 11\,\mathrm{R}_\odot$, $\Omega = 0.9$

Different Radiative Emission

- $T_{\rm eff}$, $\log g \rightarrow$ Spectral emission
- Different emission $\rightarrow$ Different lines
  - Equator vs Pole
  - Local surface velocity
  - Projection effects
  - Inclination

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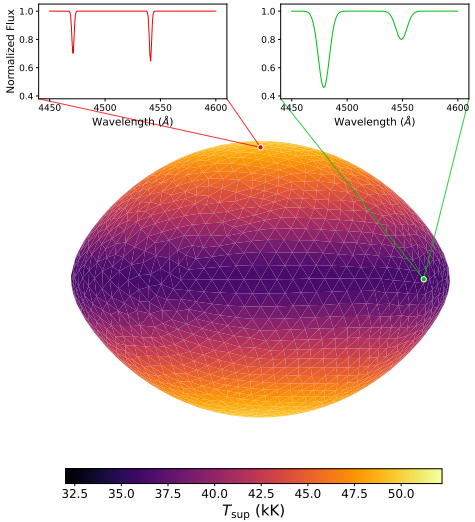
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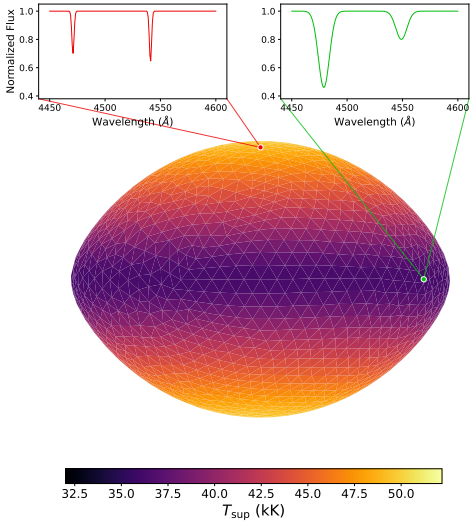
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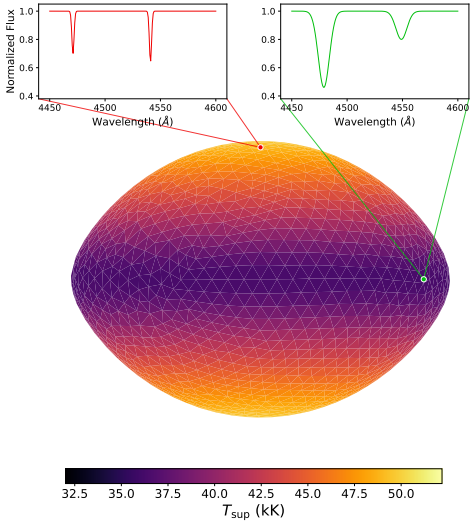


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SPAMMS: Spectral effects of binarity



SPAMMS: 3D spectroscopic modeling of stellar surfaces

Spectroscopic PAtch Model for Massive Stars

- Synthetic spectra
  - Distorted stars
  - Non-spherical geometry
- 3D-surface modeling
  - Classical 1D-spherical model atmosphere → Deformed surfaces

Abdul-Masih et al. (2020)

Stars ≠ spheres

- Rotation
- Binary systems

Stars ≠ alone

- Binary systems

SPAMMS: 3D spectroscopic modeling of stellar surfaces

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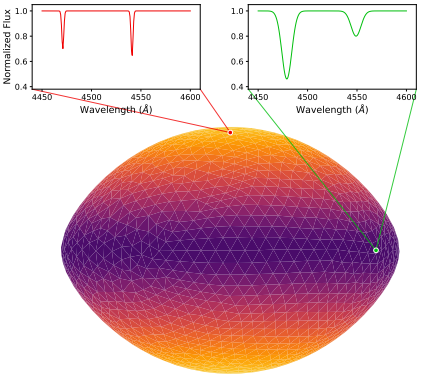
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Filling the patches

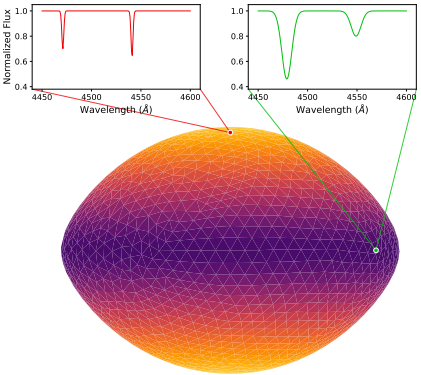
- **Stellar model atmosphere**
  - $T_{\rm eff}, \log g, Z, \xi, \zeta$
  - $I(\lambda, \mu)$ for each patch



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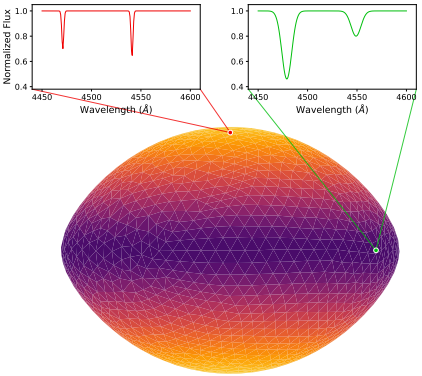
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Computation of $I(\lambda, \mu)$

- PRISMAS
  - High-performance Python pipeline
  - 1D model atmosphere

Galán-Diéguez et al. (2026a)



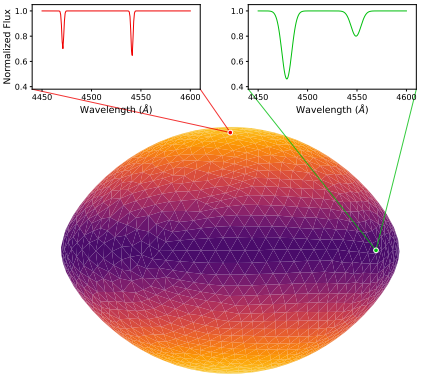
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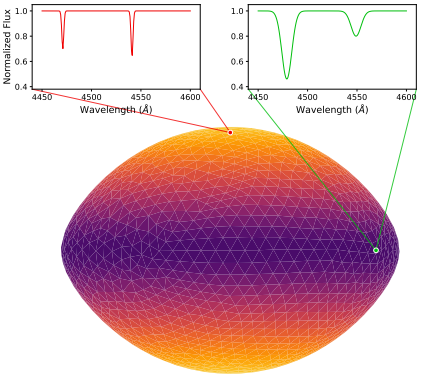
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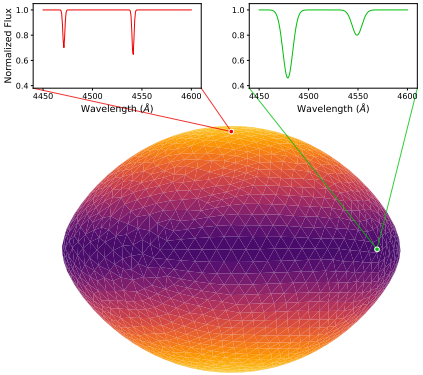


SPAMMS: 3D spectroscopic modeling of stellar surfaces

Computation of $I(\lambda, \mu)$

- FASTWIND
  - 1D spherical + NLTE
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- TLUSTY
  - 1D plane-parallel + NLTE
  - OSTAR2002 + BSTAR2006
- Kurucz ATLAS9
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Santolaya-Rey et al. (1997); Rivero González et al. (2011); Puls et al. (2020)
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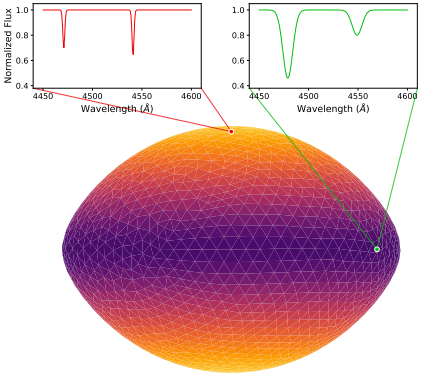
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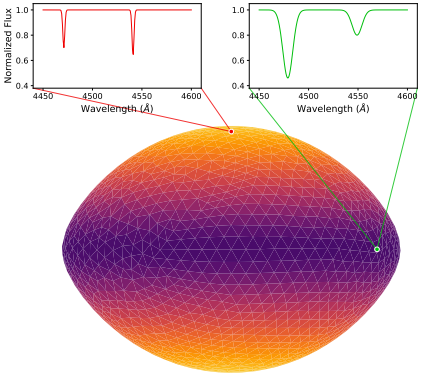


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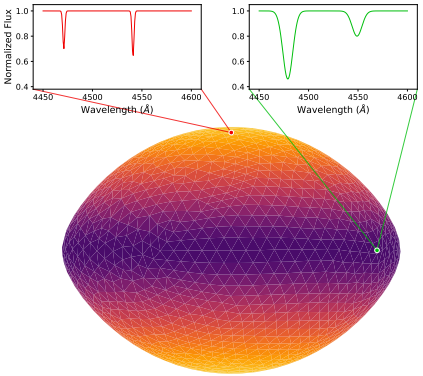


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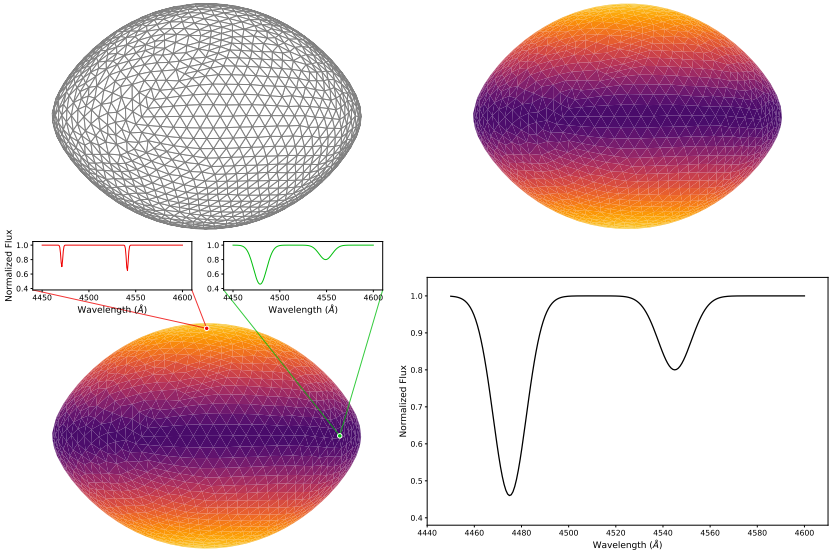
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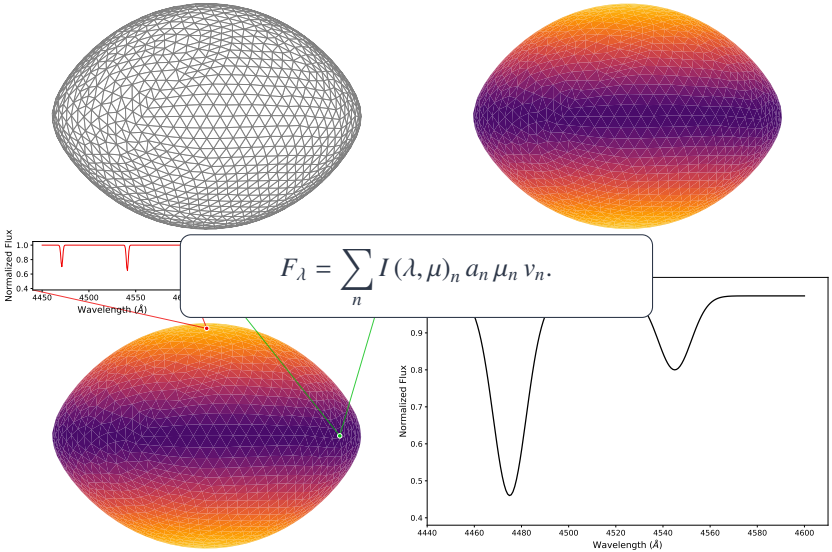
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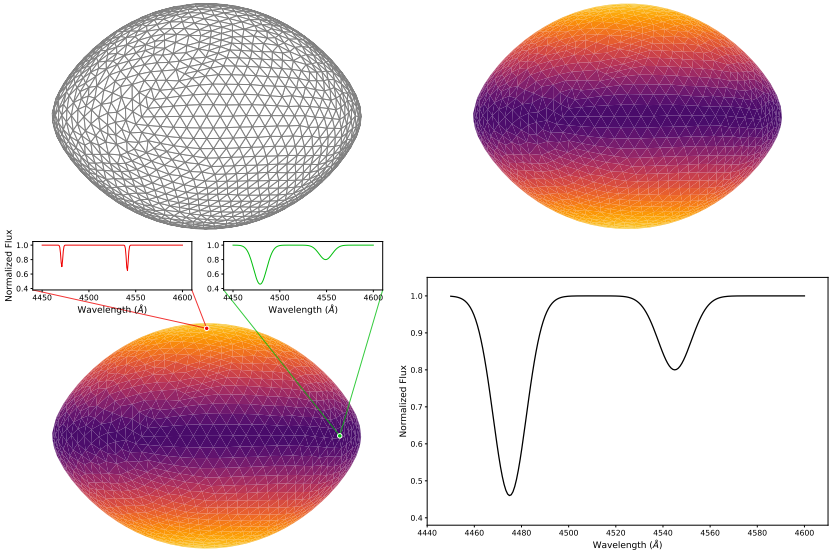
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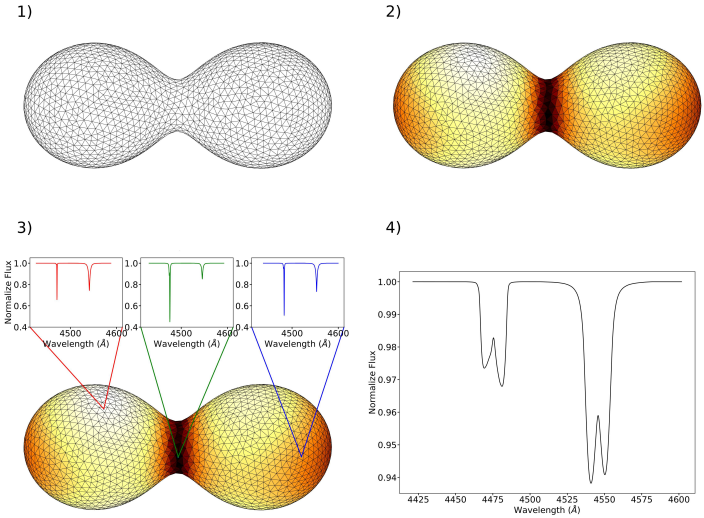
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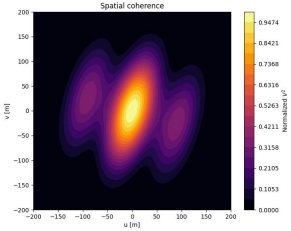
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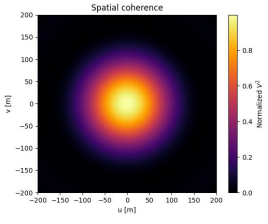
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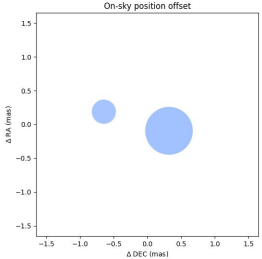
- Interferometry community
- Massive stars community

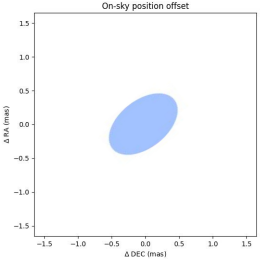
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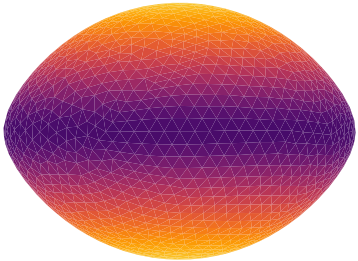
We can do better and more complete!

- And you already know how to do it...

Interferometry & spectroscopy synergy: we can do better

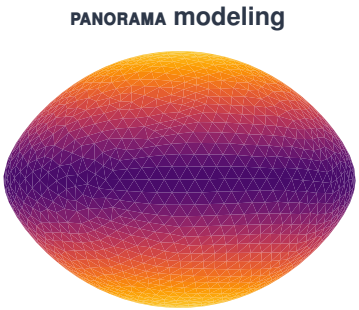
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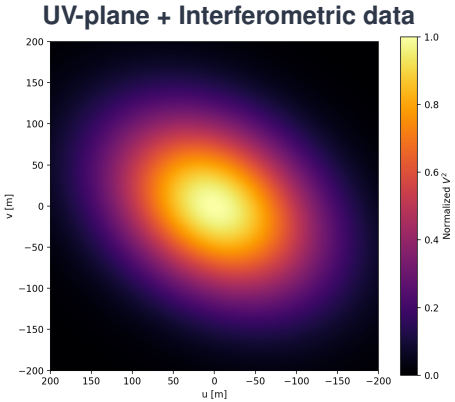
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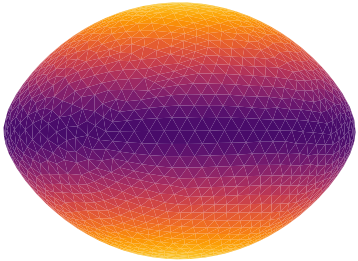




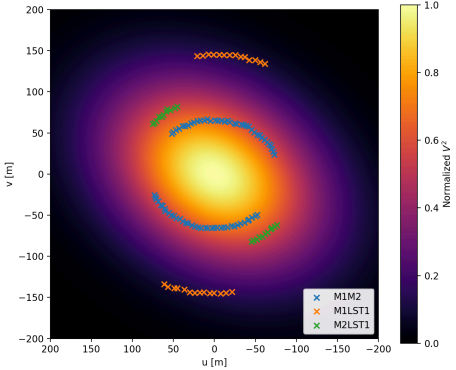
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UV-plane + Interferometric data



Interferometry & spectroscopy synergy: we can do better

Spectroscopy with SPAMMS

- Line profiles from the **same 3D surface** (PANORAMA mesh)
- Constrains $v \sin i$, $T_{\rm eff}$ and $\log g$ gradients

Interferometry

- V^2 + FT of the **same 3D surface**
- Constrains angular size, **projected flattening**, position angle

Joint fit: breaking the degeneracies

$$\text{Spectrum + Interferometry} \Longrightarrow \begin{cases} M_*, R_{\rm p}, R_{\rm eq} \\ T_{\rm eff,rot}, T_{\rm eff,p}, T_{\rm eff,eq} \\ \log g_{\rm eff,p}, \log g_{\rm eff,eq} \\ \text{Abundances} \\ \omega, i, v_{\rm rot} \end{cases}$$

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3D-surface modeling of rapidly rotating stars

Spectral synthesis and interferometric synergy with PANORAMA and SPAMMS

Take-home points:

- Massive stars are **intrinsically 3D-deformed:** rotation and binarity.
- **Classical 1D analysis can therefore be biased:** dependence on the surface geometry, rotation rate and inclination.
- **PANORAMA and SPAMMS** accounts for these effects.
- **Interferometry** adds the missing geometric information.

See my work!

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