Cool evolved stars at high angular resolution: results and prospects

Miguel Montargès
and collaborators

CHARA science meeting 2024 - Tucson, AZ
13th March 2024

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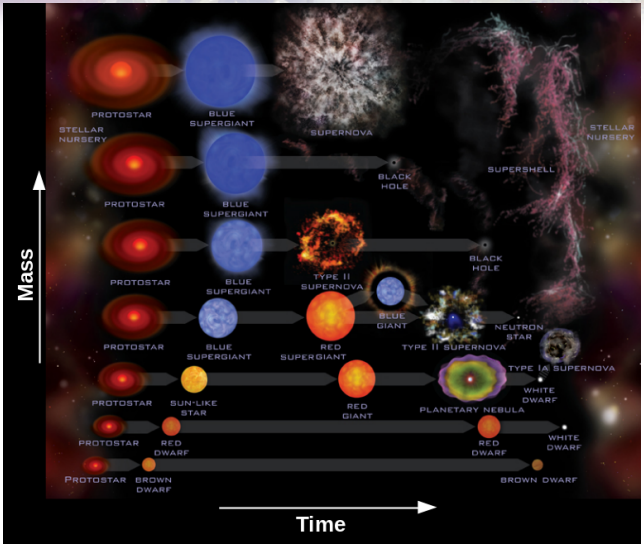
Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

Région îledeFrance

This project received funding under the Framework Program for Research and Innovation "Horizon 2020" under the Marie Skłodowska-Curie Grant Agreement No. 945298.

The stellar life cycle



Credit: NASA/Chandra

The questions

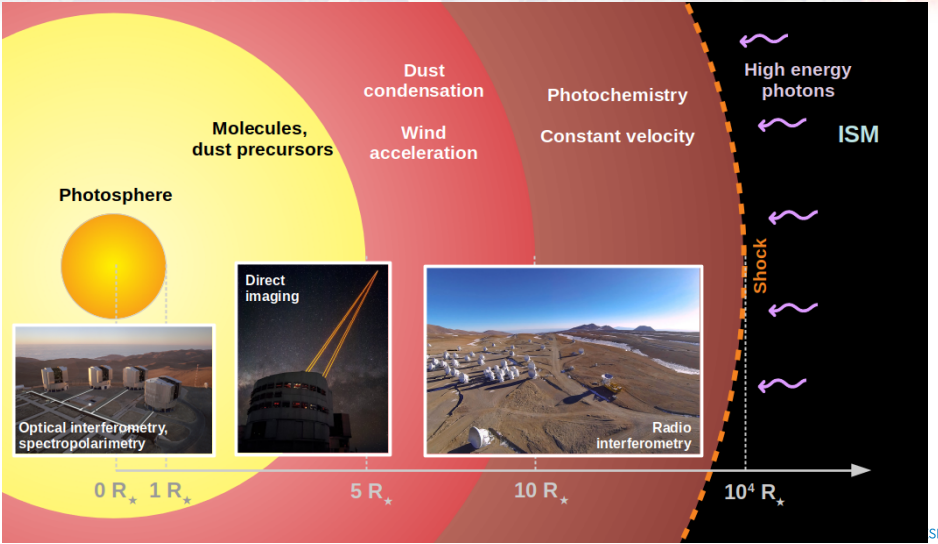
AGB stars, $M_{init} < 8\ M_{\odot}$ (future of the Sun)

- What happens to surviving planets?
- How are planetary nebulæ shaped?
- What is the chemical pathway to dust formation?

RSG stars, $M_{init} > 8\ M_{\odot}$ (SN II progenitors)

- How is the mass loss of RSG triggered? (no large pulsations, no flares)
- How is the light curve of supernovæ modified by the circumstellar material?
- What is the final mass of a star? (case limit between black holes and neutron stars?)
- What is the chemical pathway to dust formation?

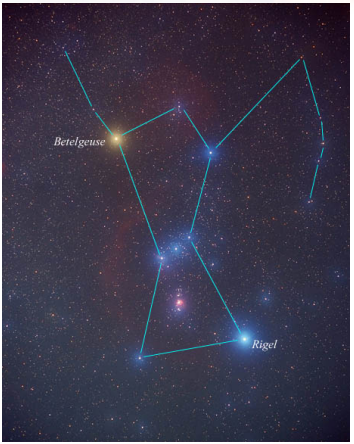
What to observe, with what ?



Betelgeuse (α Ori) : the prototypical red supergiant

Parameter	Value
Spectral type	M1-M2Ia-Iab
Distance	222^{+48}_{-34} pc
Radius	897 ± 211 $R_\odot$
Mass	21 ± 2 $M_\odot$
$T_{\rm eff}$	3690 ± 54 K
Luminosity	$12.7 \pm 6.0 \times 10^4$ $L_\odot$
$\log g$	-0.39 ± 0.22

No known companion !



Credit: ESO

Core-He burning RSG (Dolan et al. 2018)

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Betelgeuse: the origin of stellar interfeometry (at Mount Wilson !)

MEASUREMENT OF THE DIAMETER OF α ORIONIS WITH THE INTERFEROMETER[1]

By A. A. MICHELSON and F. G. PEASE

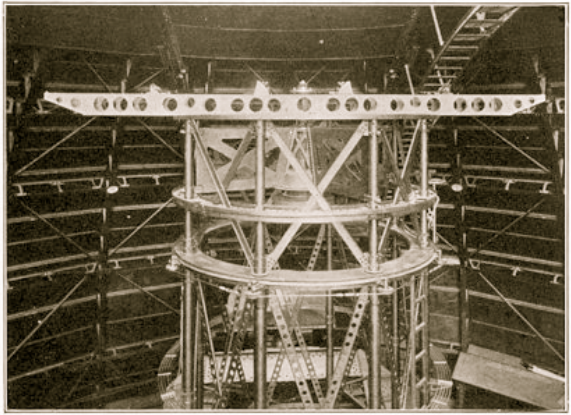
ABSTRACT

Twenty-foot interferometer for measuring minute angles.—Since pencils of rays at least 10 feet apart must be used to measure the diameters of even the largest stars, and because the interferometer results obtained with the 100-inch reflector were so encouraging, the construction of a 20-foot interferometer was undertaken. A very rigid beam made of structural steel was mounted on the end of the Cassegrain cage, and four 6-inch mirrors were mounted on it so as to reduce the separation of the pencils to 45 inches and enable them to be brought to accurate coincidence by the telescope. The methods of making the fine adjustments necessary are described, including the use of two thin wedges of glass to vary continuously the equivalent air-path of one pencil. Sharp fringes were obtained with this instrument in August, 1920.

Diameter of α Orionis.—Although the interferometer was not yet provided with means for continuously altering the distance between the pencils used, some observations were made on this star, which was known to be very large. On December 13, 1920, with very good seeing, no fringes could be found when the separation of the pencils was 121 inches, although tests on other stars showed the instrument to be in perfect adjustment. This separation for minimum visibility gives the angular diameter as 0″.047 within 10 per cent, assuming the disk of the star uniformly luminous. Hence, taking the parallax as 0″.018, the linear diameter comes out 240×10^6 miles.

Interferometer method of determining the distribution of luminosity on a stellar disk.—The variation of intensity of the interference fringes with the separation of the two pencils depends not only on the angular diameter of the disk but also on the distribution of luminosity. The theory is developed for the case in which $I = I_0 (R^2 - r^2)^n$, and formulae are given for determining n from observations.

Table of values of $\int_0^1 (1-x^2)^{n+\frac{1}{2}} \cos kx \, dx$, for n equal to 0, $\frac{1}{2}$, 1, and 2, and for k up to 600°, is given.



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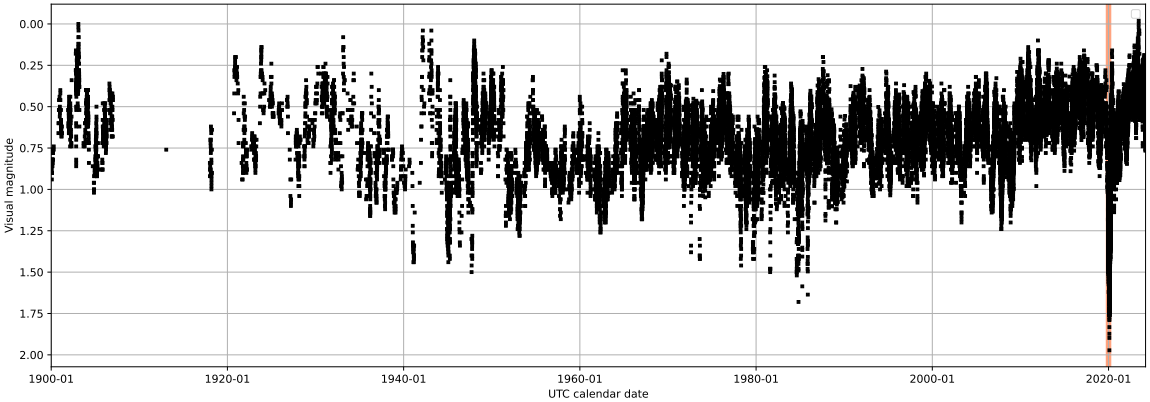
The Great Dimming of Betelgeuse



Credit: AAVSO

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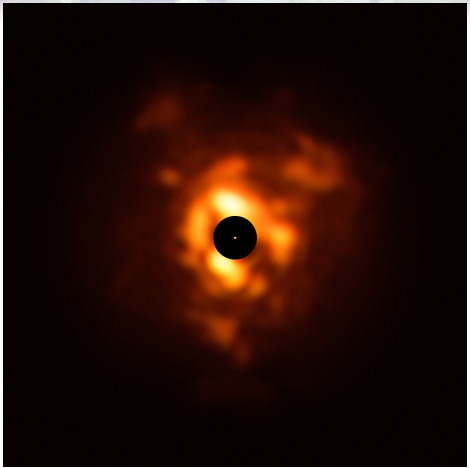

VLT/VISIR @ 10 μm, FoV $\sim$ 5"
ESO/P. Kervella/**M. Montargès** et al.,

Acknowledgement: E. Pantin

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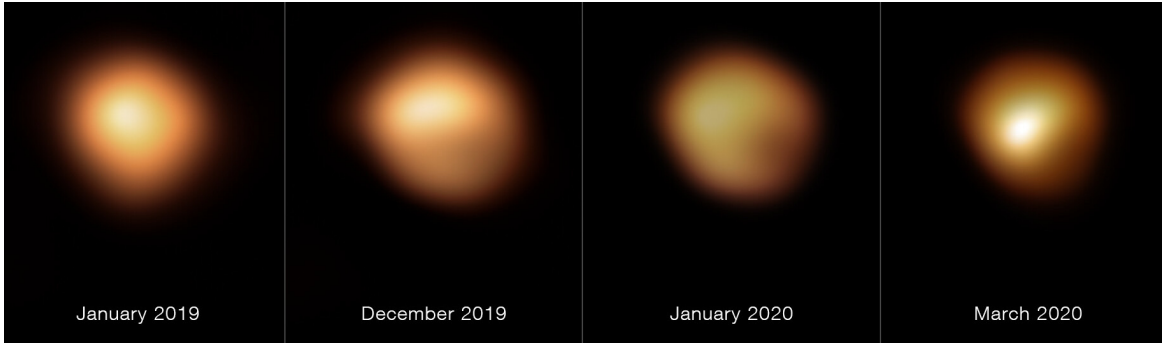

The Great Dimming of Betelgeuse
VLT/SPHERE @ 0.65 μm, FoV $\sim$ 0.1"

Montargès et al. 2021, *Nature*

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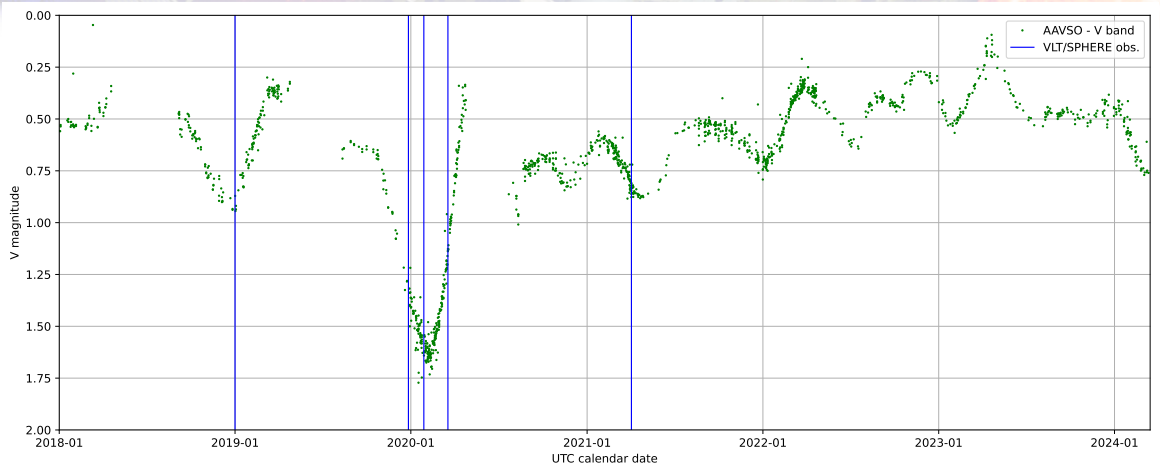
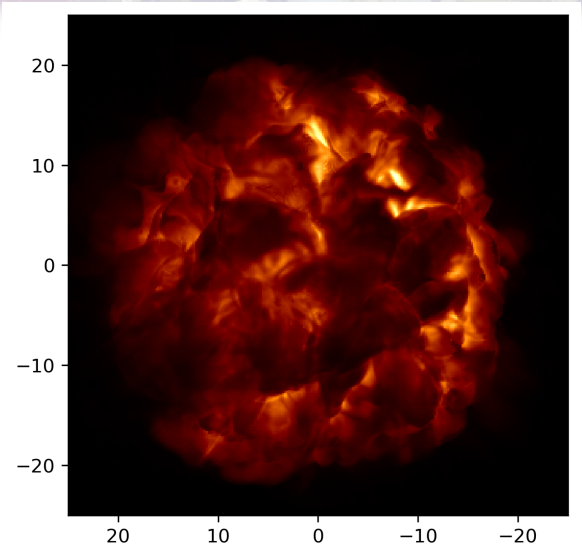


Credit: AAVSO

The occultation of Leona on December 12th 2023



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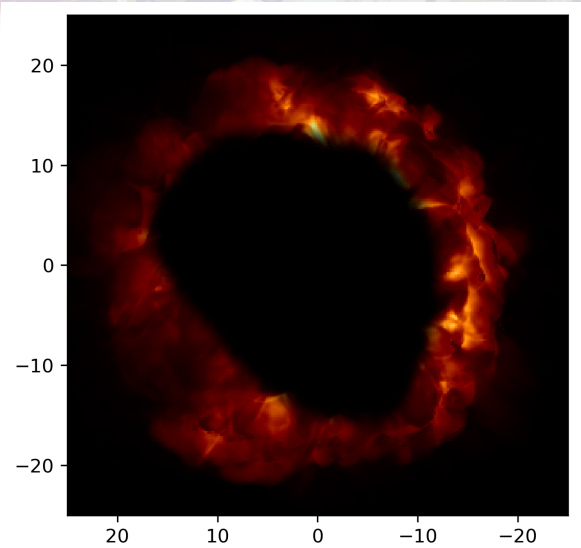

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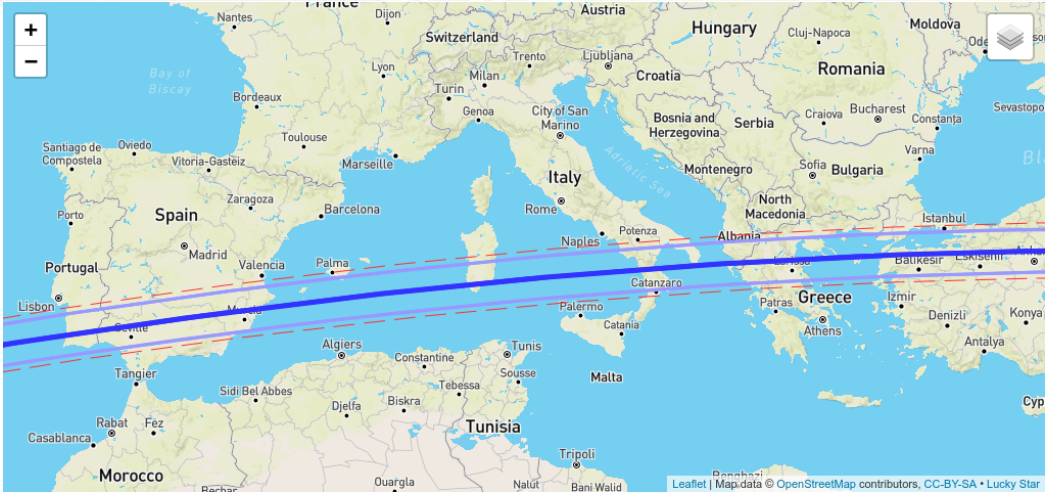
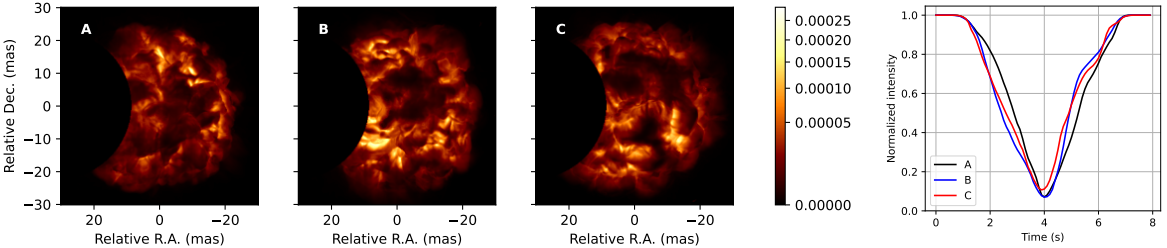


Credits: Lucky Stars

The concept



- Collaboration with B. Sicardy (LESIA), J. Desmars (IMCCE), F. Baron (GSU, Atlanta), and A. Berdeu (LESIA)
- Coordination of a 100+ observers (various chords)
- Unusual protocol for occultations (use of filters, 10-100 fps, ...)

The observations

J. Desmars reharsing the setup 24h before

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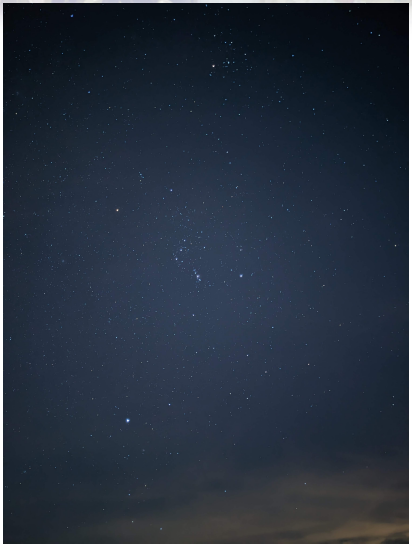
The observations



20min before the event

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The observations

The event: G. Le Gentil syndrom

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I went to Naboo to (not) observe an occultation of Betelgeuse !

Star Wars Episode II

Sevilla, December 11th 2023

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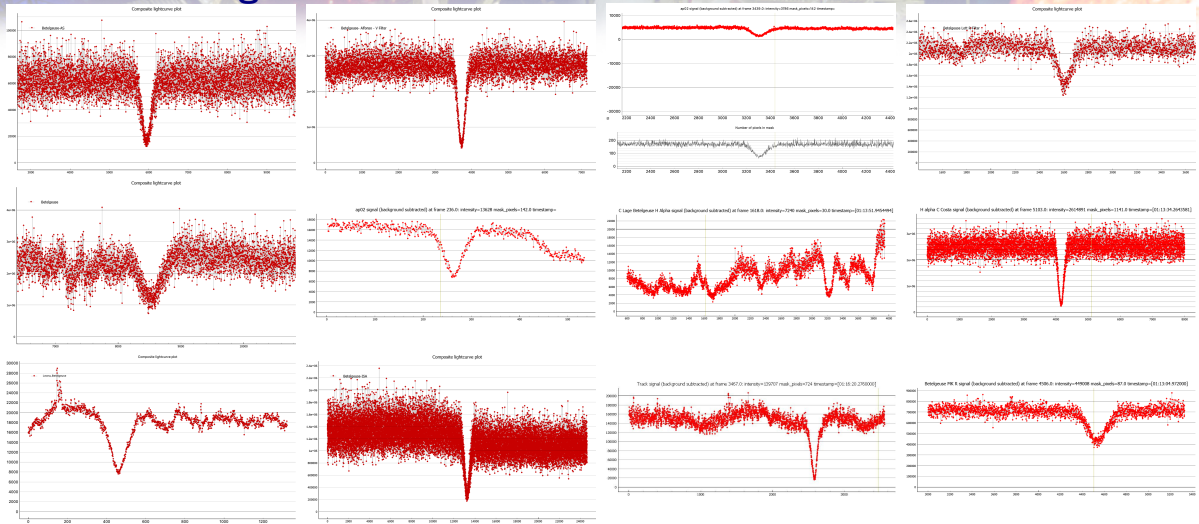
About 100 light curves



Montargès et al. in prep.

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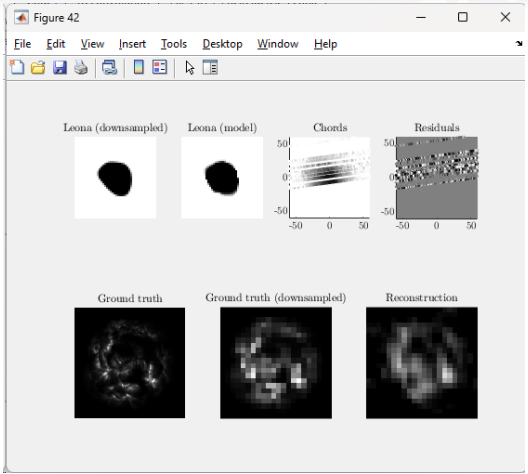
Reconstruction: preliminary test with simulations



- Deconvolution of the light curves

→ Retrieving the stellar surface

→ Retrieving the shape of the asteroid

Courtesy: Anthony Berdeu

Montargès et al. in prep.

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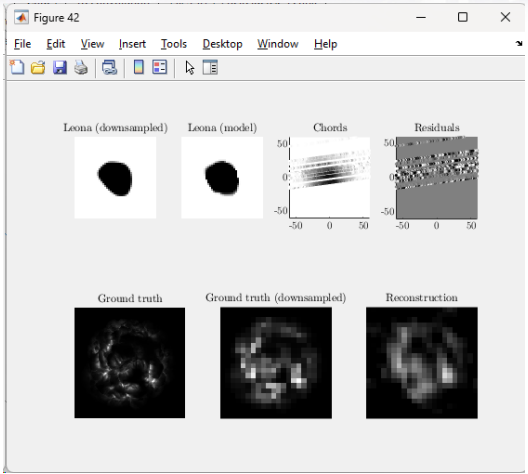

Courtesy: Anthony Berdeu

Montargès et al. in prep.

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→ Retrieving the stellar surface

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Current problems

Inconsistent light curves :

- Position errors ?
- Timing errors ?
- Lack of absolute flux calibration

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Betelgeuse with ELT/MICADO

13th Feb. 2024 - M. Montargès

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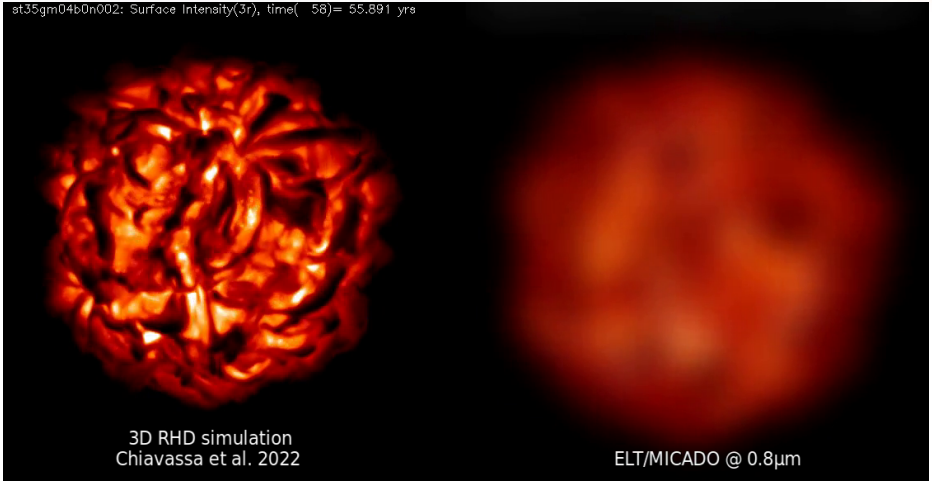
Betelgeuse with ELT/MICADO



Credits: M. Montargès

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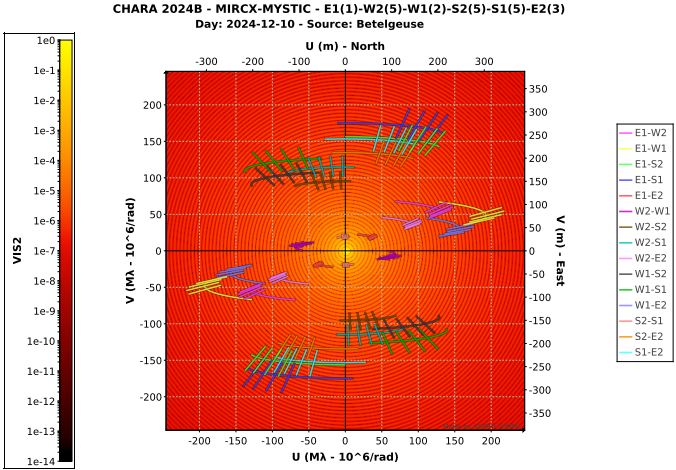
Soon, Betelgeuse at CHARA ?



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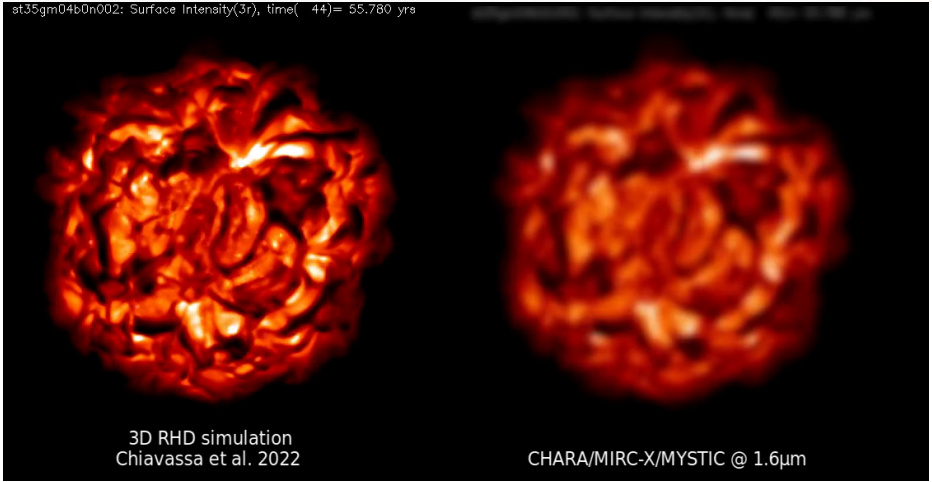

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The ATOMIUM project

17 O-rich stars

3 ALMA configurations
4 spectral settings

Chemical networks

VLT/SPHERE
&
VLTI/MATISSE
ToO program

3D radiative transfer
modelling

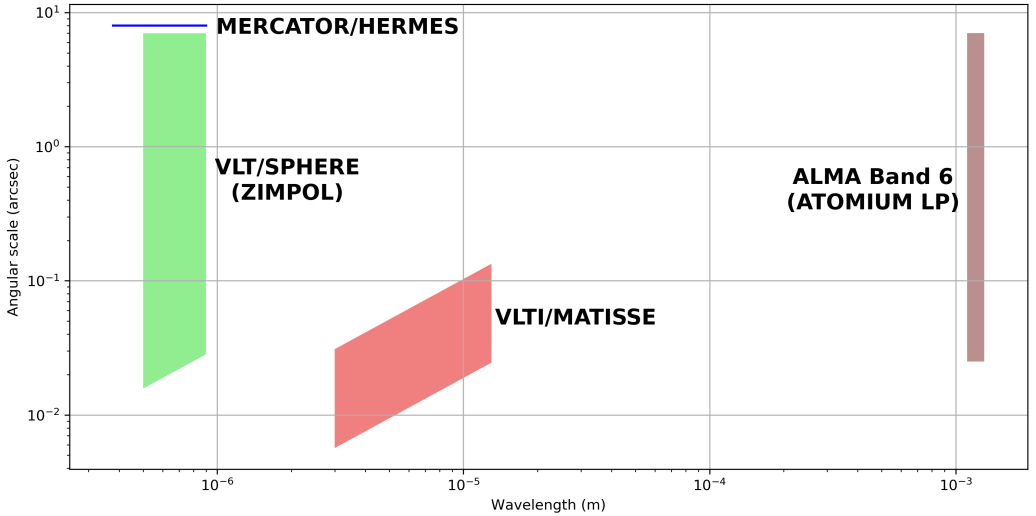
Species identifications

Dust nucleation
experiments

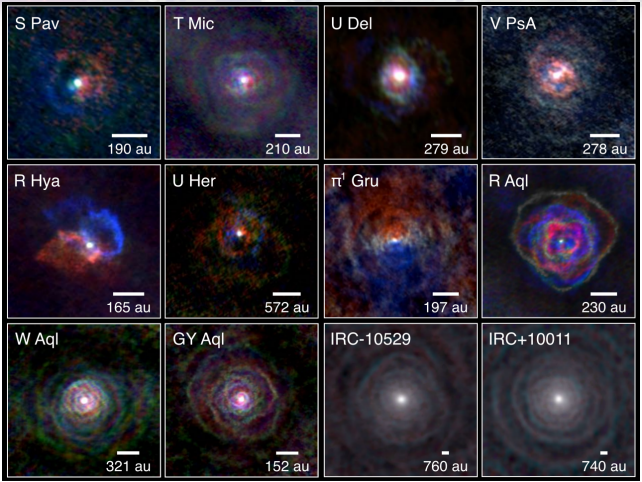
The ATOMIUM project

2 PIs + 40 CoIs

Angular resolution vs wavelength



ALMA: signature of undetected companions everywhere



CO $J = 2 - 1$ transition

Decin, **Montargès** et al. 2020, *Science*

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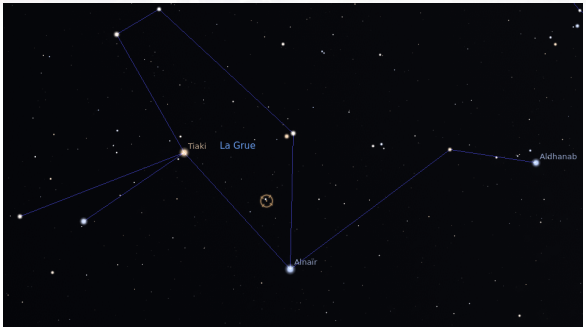
ATOMIUM: multiple results

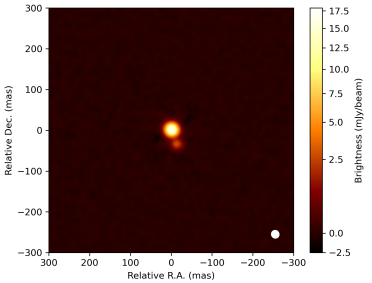
Companions shaping the wind	Decin, Montargès et al. 2020, *Science*
Overview of the program	Gottlieb et al. 2022, *A&A*
The circumstellar environment of π^1 Gru	Homan, Montargès et al. 2020, *A&A*
The circumstellar environment of R Hya	Homan et al. 2021, *A&A*
Halide molecules around W Aql	Danilovich et al. 2021, *A&A*
VLT/SPHERE point of view	Montargès et al. 2023, *A&A*
Chemical inventory	Wallström et al. 2024, *A&A*
Interaction between the wind of W Aql and its companion	Danilovich et al. 2024, *Nat. Ast.*

The S-type star π^1 Gru



- S-type star
- d $= 162 \pm 12$ pc
- $\theta = 18.37 \pm 0.18$ mas
- T $= 2300$ K
- $\dot{M} = 7.7 \times 10^{-7}$ M$_\odot$ yr^{-1}
- π^1 Gru B: G0V at 2.8 arcsec (> 450 au)

The ATOMIUM view of π^1 Gru



ALMA 1mm continuum

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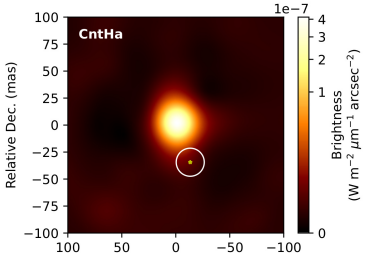
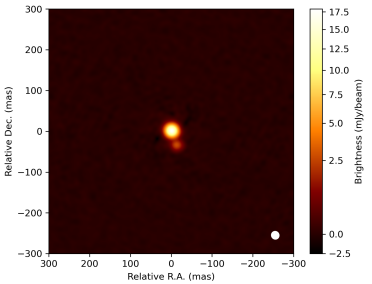


Intensity in the visible



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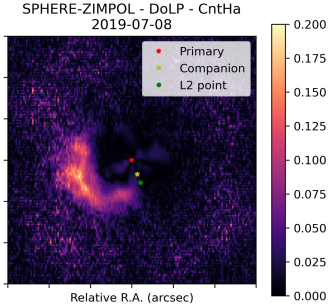
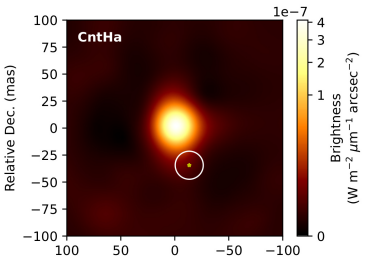


Linear polarisation in the visible



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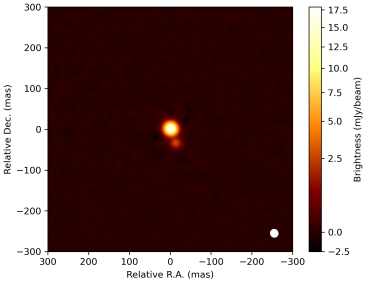

ALMA 1mm continuum

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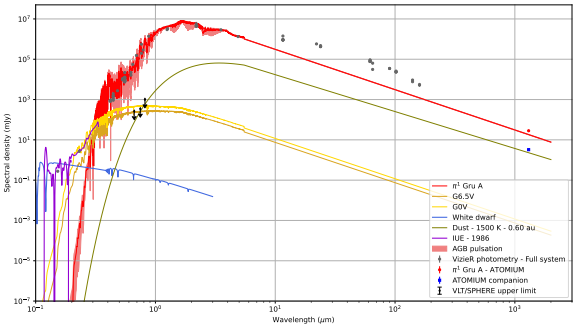
The nature of the new companion π^1 Gru C



From photometry/imaging across the spectrum, Gaia proper motion :

- Main sequence G6.5V star
- White dwarf

$\Rightarrow$ Another Montargès et al. in prep.

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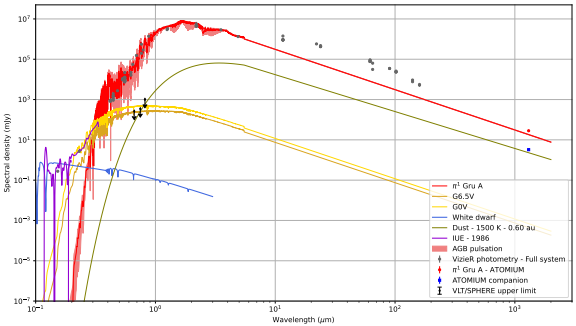

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It is accreting :

$\rightarrow$ Classical nova (P $\sim$ 600 to 2100 yrs)

$\rightarrow$ SN type Ia progenitor at 162 pc ? (unlikely)

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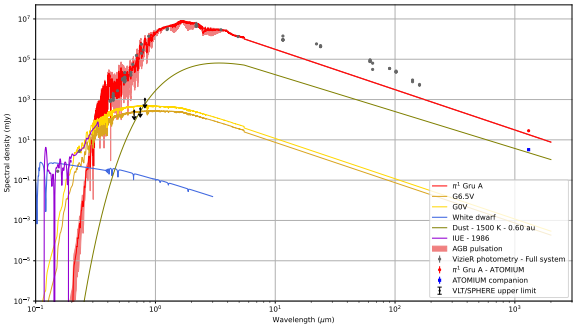

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Potential CHARA program to unveil companions to evolved stars ?

Conclusion / summary

Red supergiants ($M_{init} \geq 8\ M_{\odot}$)

- Betelgeuse, Betelgeuse, Betelgeuse... $\Rightarrow$ The 7th telescope will allow unprecedented imaging of its surface
- Other RSGs: Antares, μ Cep, VY CMa, CE Tau, ...

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- Other RSGs: Antares, μ Cep, VY CMa, CE Tau, ...

AGBs ($M_{init} \leq 8\ M_{\odot}$)

- Unveiling close binaries and their interactions
- Objects (planets, stars, WD) shaping planetary nebulæ

$\rightarrow$ Fate of the solar system and numerous stars of the Galaxy

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