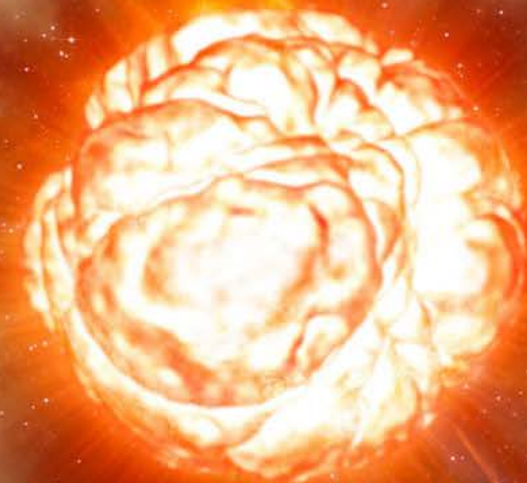


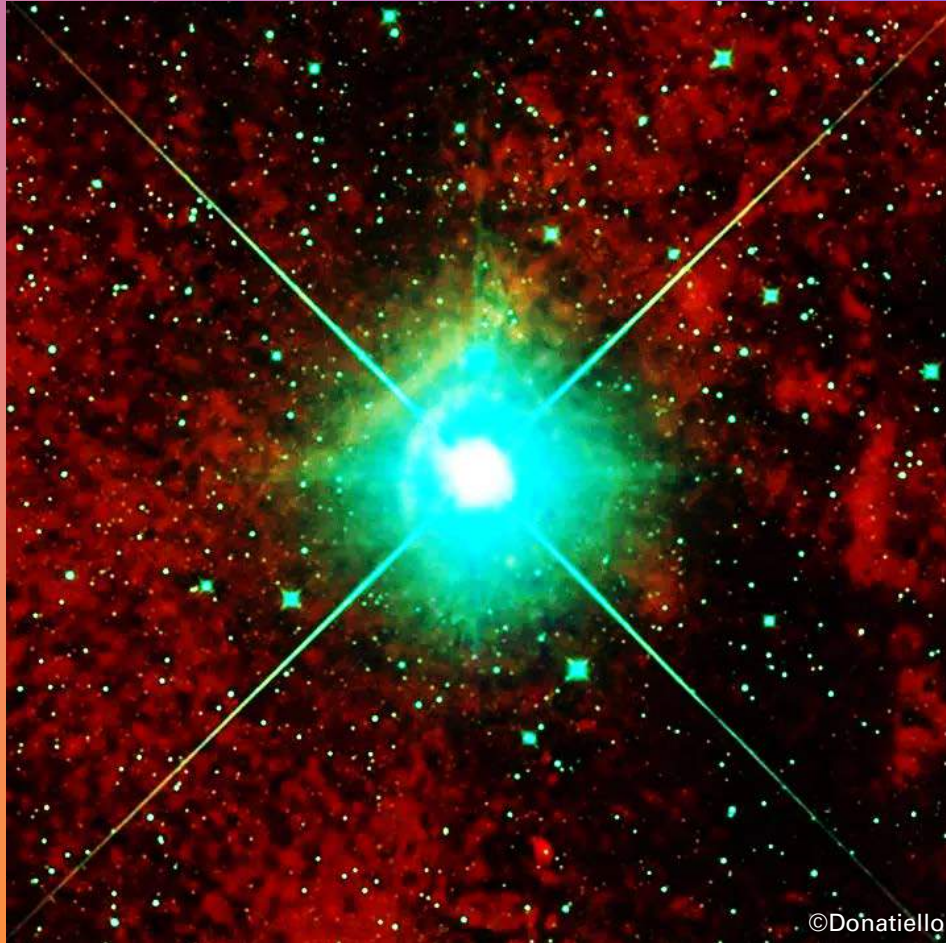
# BÉTELGEUSE

*une cible de choix  
pour le VLT/MATISSE*



Pierre CRUZALÈBES





©Donatiello

Vue infrarouge de Bételgeuse combinant les mesures des satellites WISE et AKARI.

# PLAN

L'ÉTOILE BÉTELGEUSE

L'INTERFÉROMÉTRIE

UNE CIBLE DE CHOIX POUR MATISSE

L'ÉPISODE DU « GRAND OBSCURCISSEMENT »

QUEL AVENIR POUR BÉTELGEUSE ?

# Introduction

Publication de l'Observatoire de Paris du 2 novembre 2023

## **La perte d'éclat de Bételgeuse vue par l'instrument Matisse, au VLT**

« Le grand obscurcissement de Bételgeuse, épisode au cours duquel, entre fin 2019 et début 2020, l'étoile avait manifestement perdu en éclat, avait plongé la communauté scientifique dans la surprise et l'interrogation.

Certains avaient supposé que l'étoile, en fin de vie, était sur le point d'exploser, avant de se transformer en supernova. Il n'en était rien, d'après une étude établie en 2021. (...) Plus récemment, à l'aide de l'instrument infrarouge MATISSE équipant le Very Large Telescope Interferometer (VLT) de l'ESO, une équipe scientifique, dirigée par des astronomes de l'Observatoire de la Côte d'Azur jette sur l'étoile un nouveau regard, en haute résolution. »



Variation de la brillance de Bételgeuse en février 2012 (à gauche) et en février 2020 (à droite).

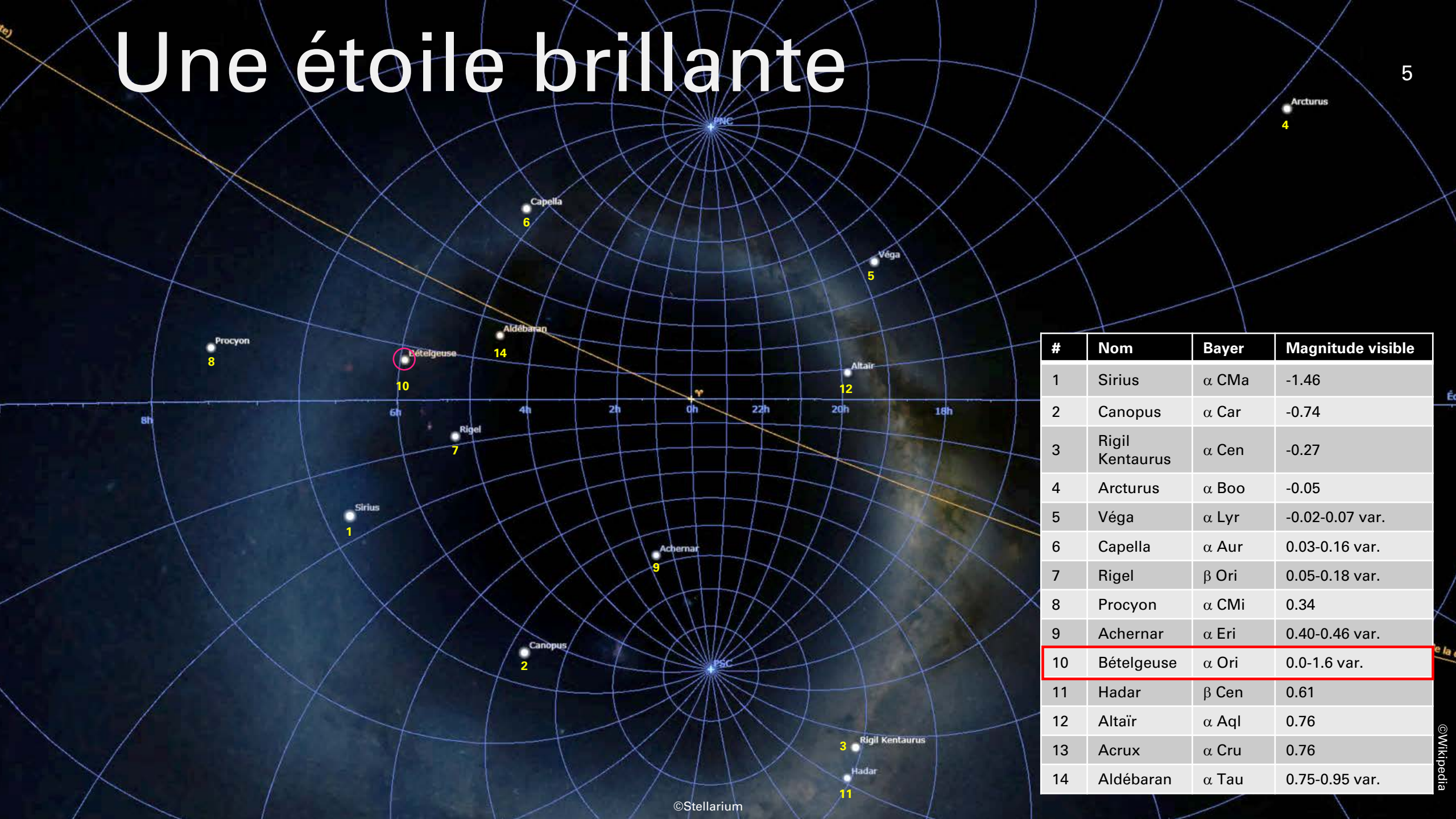


# BÉTELGEUSE

يد الجوزاء, *yad al-jawzā*

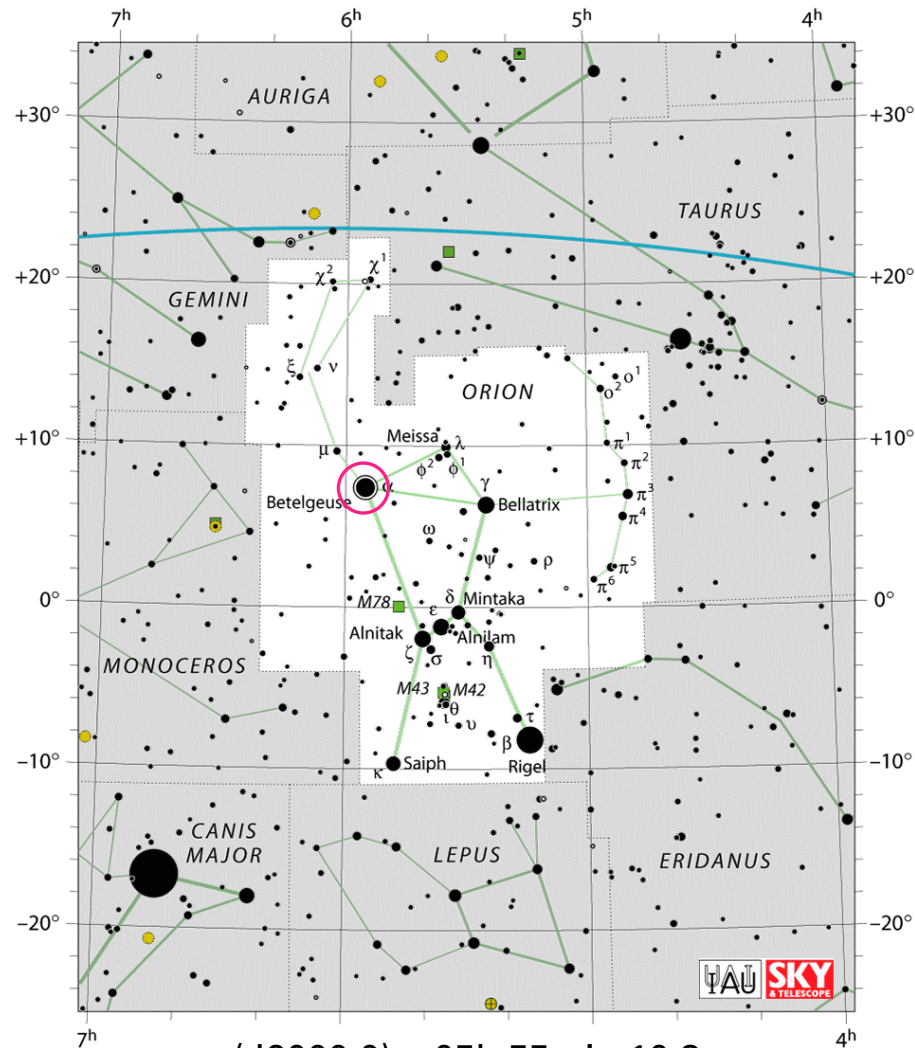
« la main d'Orion »

# Une étoile brillante



#	Nom	Bayer	Magnitude visible
1	Sirius	$\alpha$ CMa	-1.46
2	Canopus	$\alpha$ Car	-0.74
3	Rigil Kentauros	$\alpha$ Cen	-0.27
4	Arcturus	$\alpha$ Boo	-0.05
5	Véga	$\alpha$ Lyr	-0.02-0.07 var.
6	Capella	$\alpha$ Aur	0.03-0.16 var.
7	Rigel	$\beta$ Ori	0.05-0.18 var.
8	Procyon	$\alpha$ CMi	0.34
9	Achernar	$\alpha$ Eri	0.40-0.46 var.
10	Bételgeuse	$\alpha$ Ori	0.0-1.6 var.
11	Hadar	$\beta$ Cen	0.61
12	Altaïr	$\alpha$ Aql	0.76
13	Acrux	$\alpha$ Cru	0.76
14	Aldébaran	$\alpha$ Tau	0.75-0.95 var.

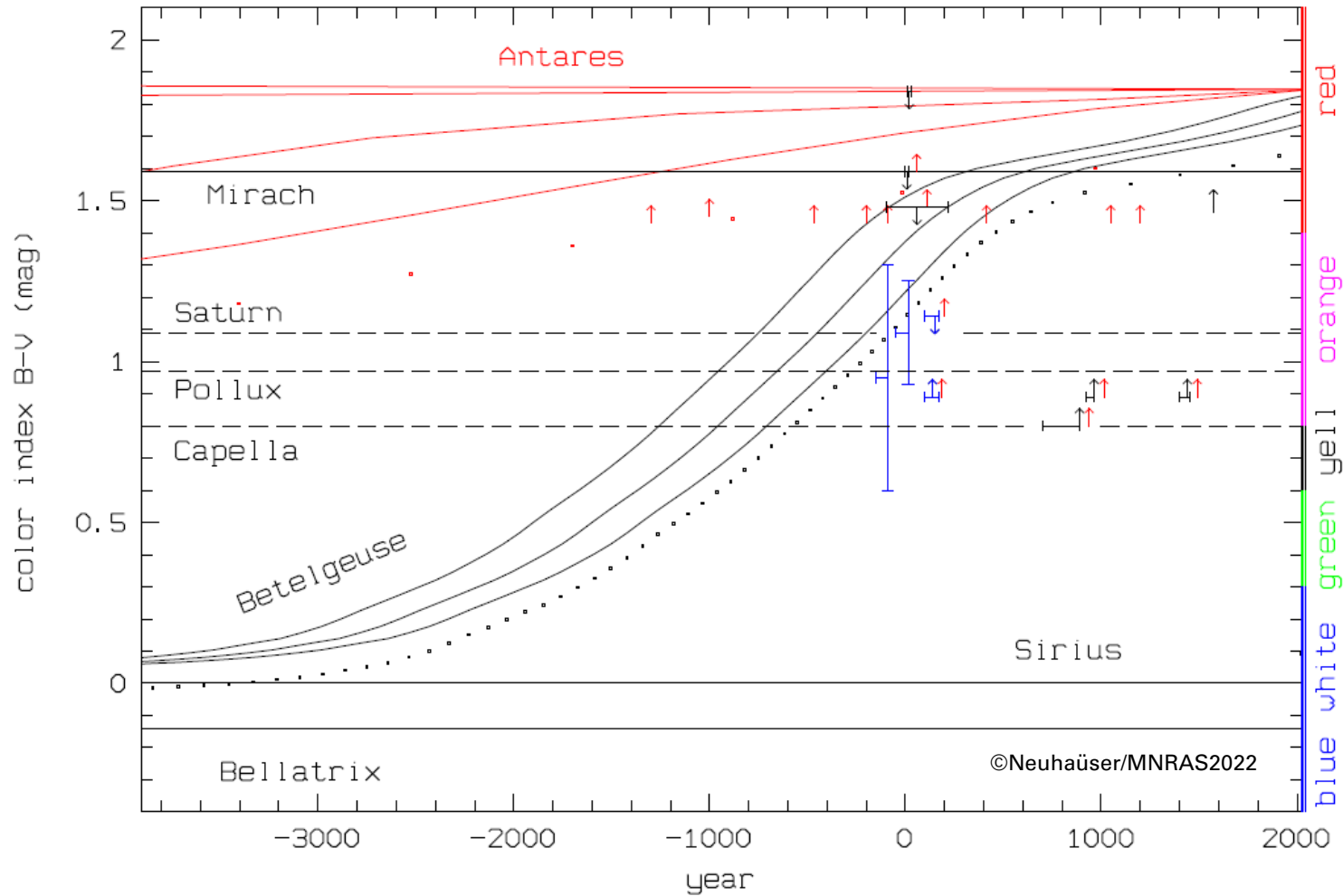
# Dans Orion



$\alpha(\text{J2000.0}) = 05\text{h } 55\text{min } 10.3\text{s}$   
 $\delta(\text{J2000.0}) = +07^\circ 24' 25''$



# Une étoile rouge



Evolution historique des couleurs de Bételgeuse et Antarès estimées au cours des 5 derniers millénaires.

# Une étoile (assez) lointaine

Distance = 125-170 pc  $\Rightarrow$  410-550 al

1300 al : Meissa

2000 al : Alnilam

1200 al : Mintaka

1260 al : Alnitak

1345 al : M42

860 al : Rigel

650 al : Saïph

250 al : Bellatrix

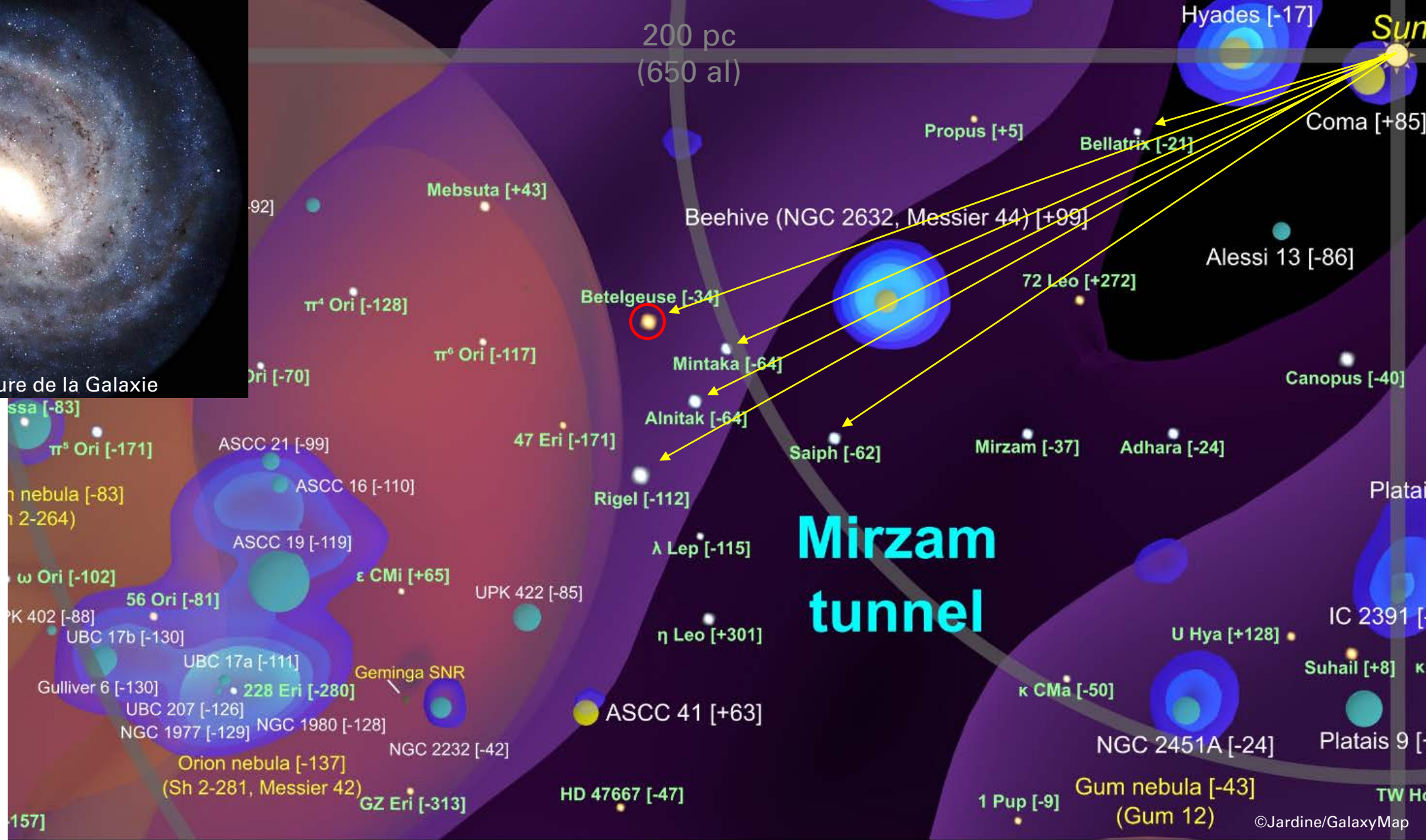
**Bételgeuse**







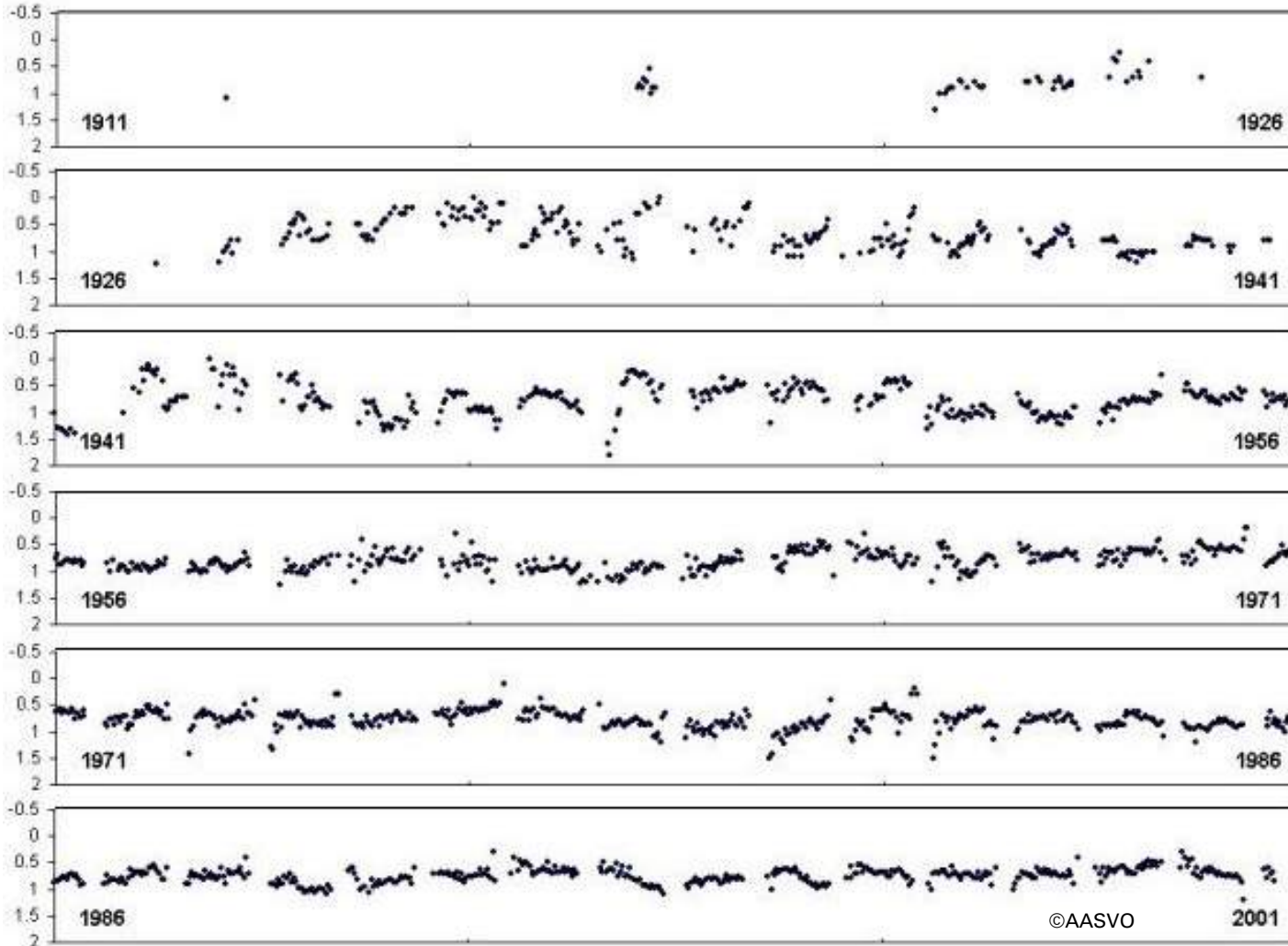
Vue supérieure de la Galaxie



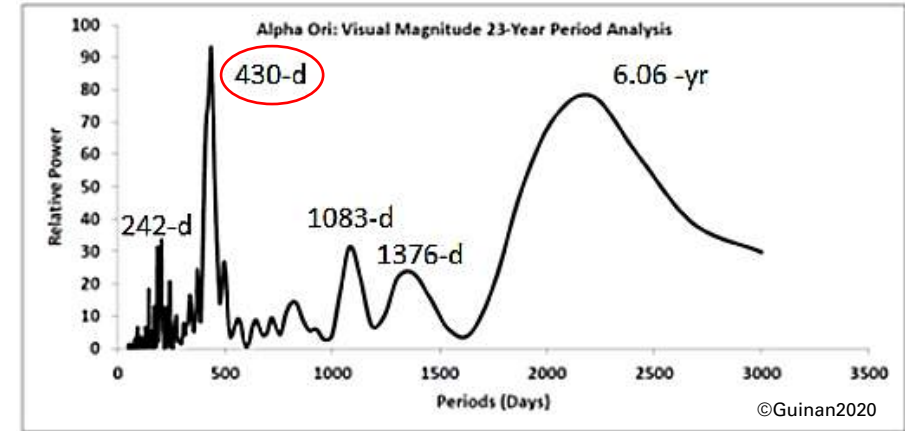
Vue de l'environnement solaire dans la direction de la nébuleuse d'Orion au-dessus du plan galactique

# Une étoile variable

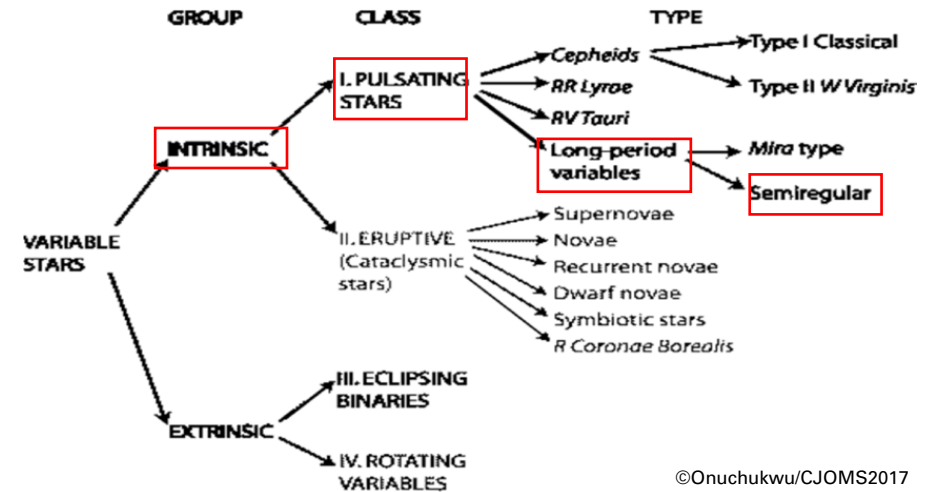
## Type SRc



Courbe de lumière de Bételgeuse au cours du XX<sup>e</sup> Siècle



Périodogramme photométrique 1995-2018



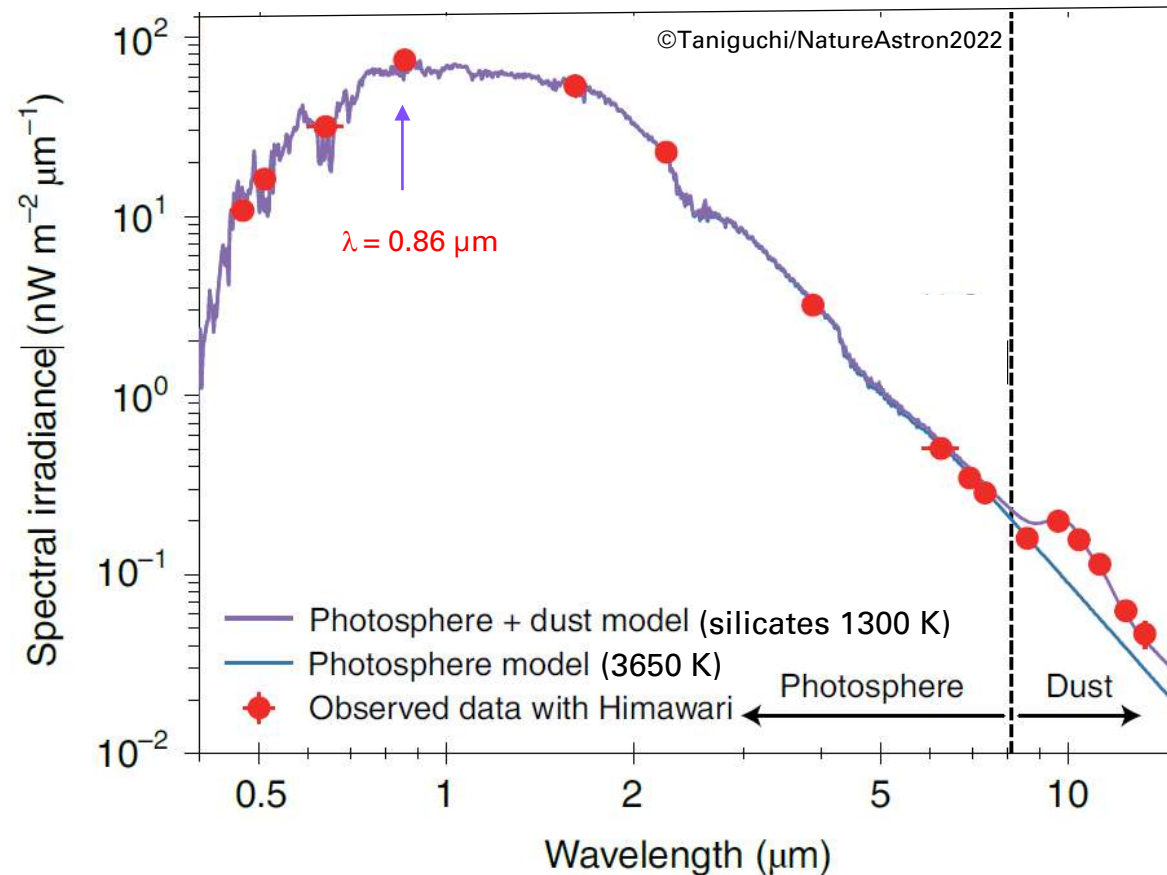
©Onuchukwu/CJOMS2017

Classification des étoiles variables

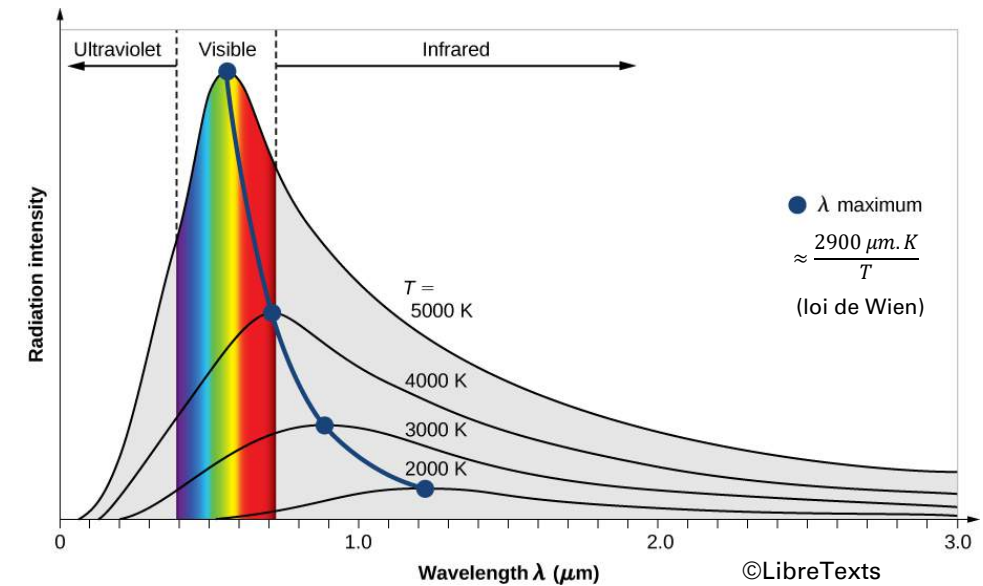
# Une étoile froide

$T_{\text{eff}} = 3600\text{-}3800\text{ K}$

Type spectral M1-M2



Distribution spectrale de l'énergie de Bételgeuse mesurée par le satellite Himawari-8

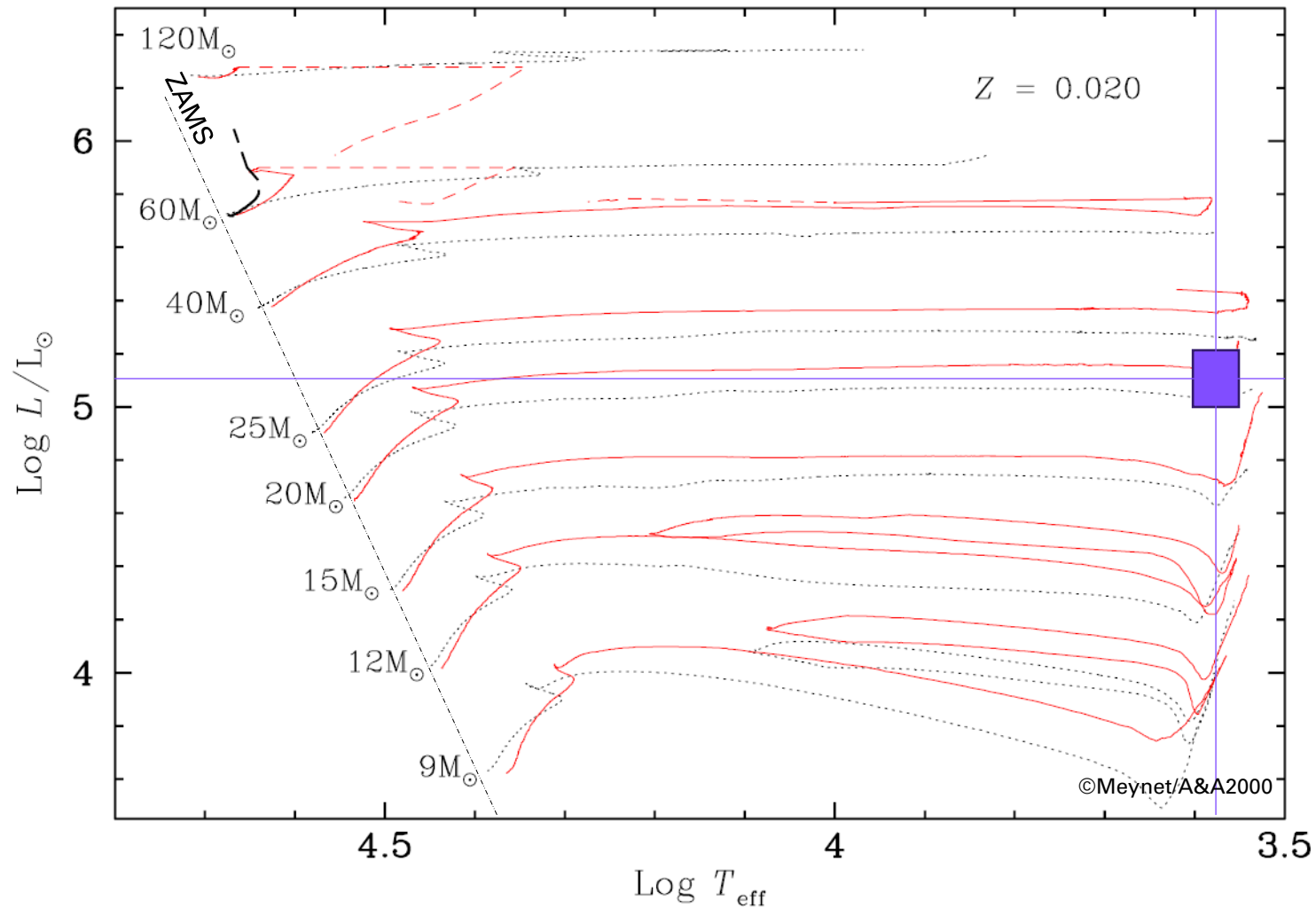


Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>30,000	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*
A	Sirius	10,000 K–7,500 K	Very strong hydrogen lines	290–390 nm (violet)*
F	Polaris	7,500 K–6,000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*
G	Sun, Alpha Centauri A	6,000 K–5,000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)
K	Arcturus	5,000 K–3,500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)
M	Betelgeuse, Proxima Centauri	<3,500 K	Molecular lines strong	>830 nm (infrared)



# Une étoile massive

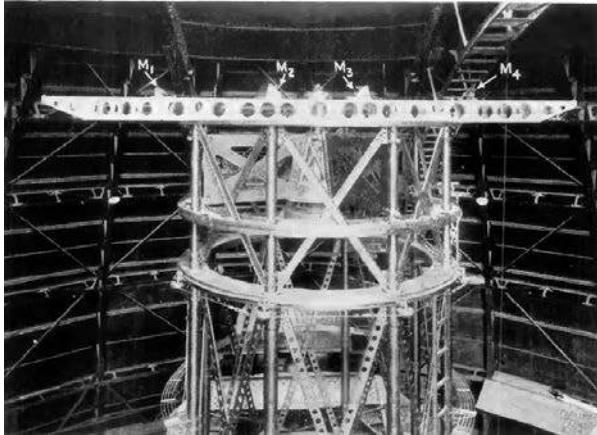
$M = 14-19 M_{\odot}$  / Age = 8-14 millions d'années



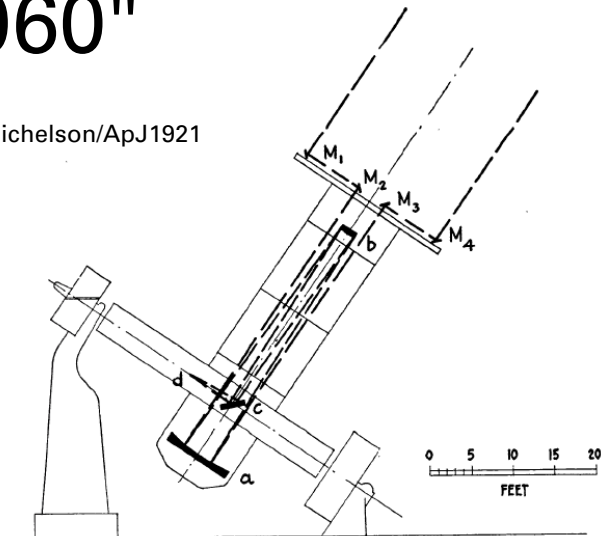
Position de Bételgeuse dans le diagramme HR et trajets évolutifs des étoiles massives

# Une étoile (très) résolue

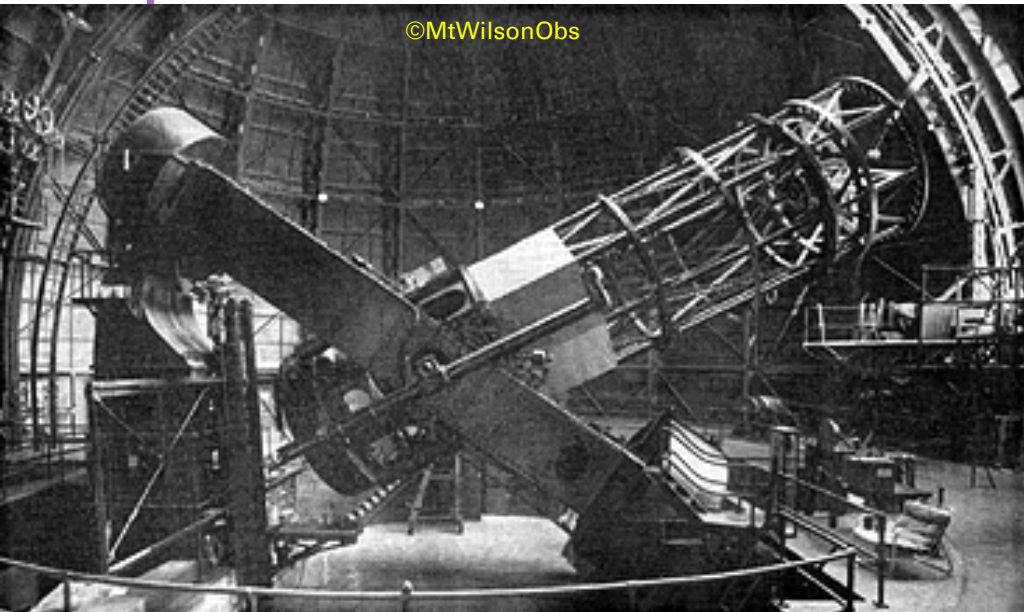
$$\theta = 0.045-0.060''$$



©Michelson/ApJ1921

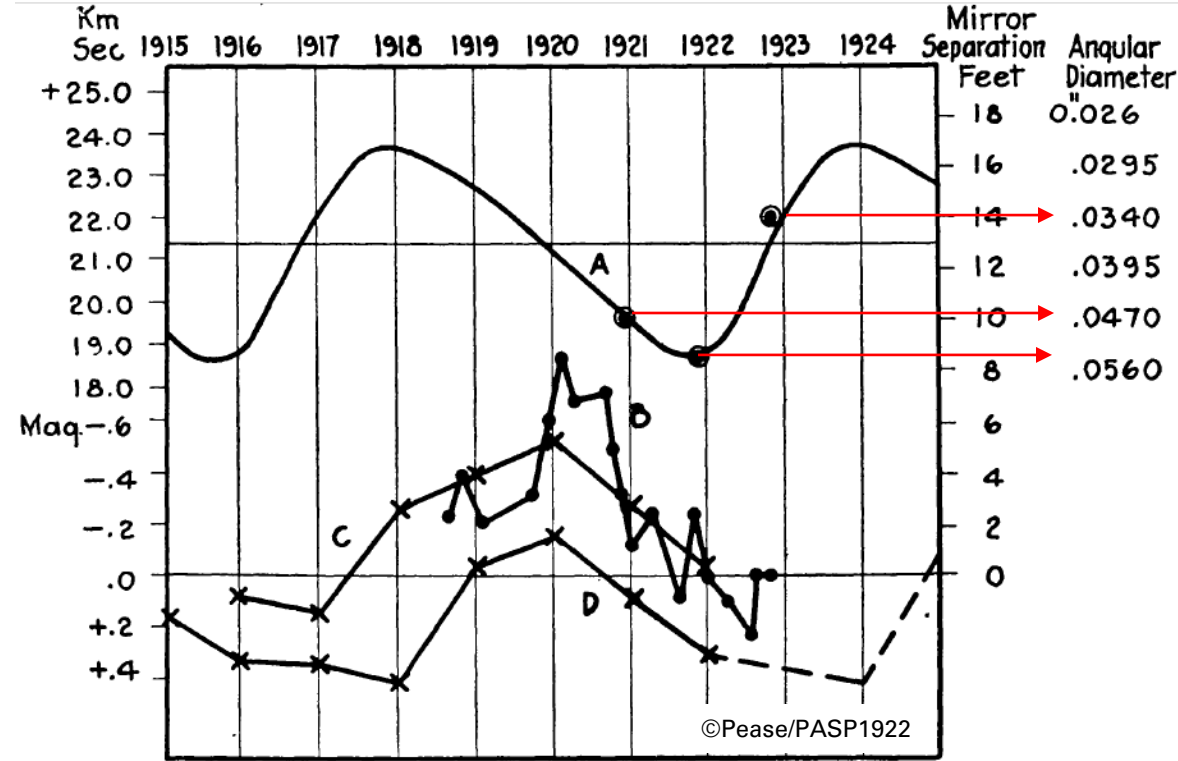


L'interféromètre de 20 pieds (6m) de Pease-Michelson



©MtWilsonObs

Le télescope 100  
pouces (2m50)  
du Mt Wilson



©Pease/PASP1922

- A=Dottinger Radial Velocity
- B=Barnard Visual Brightness  $\alpha$  Orionis -  $\alpha$  Tauri
- C=Osthoff " " " "
- D=" " " " -  $\beta$  Tauri
- =Pease Angular Diameter

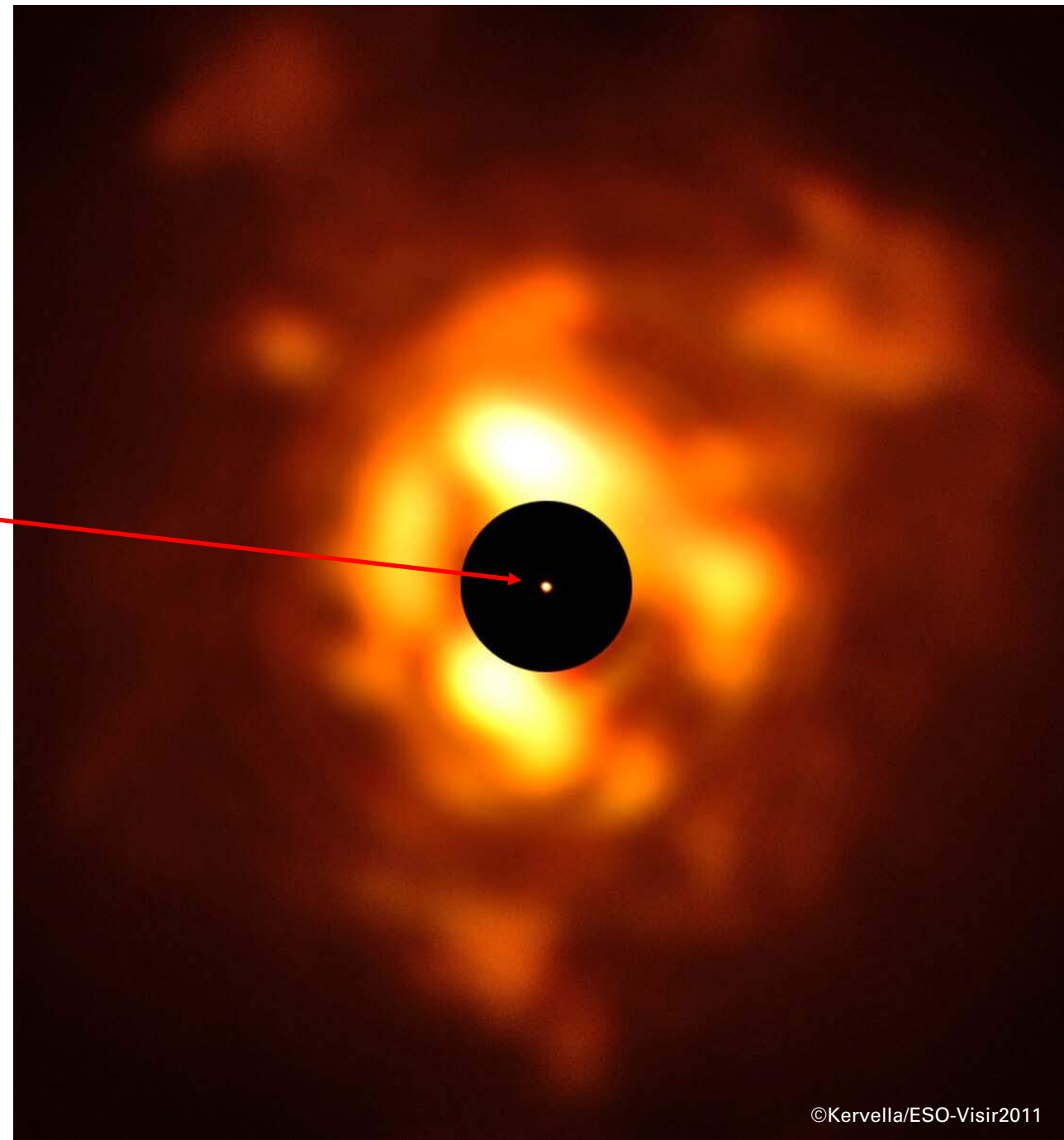
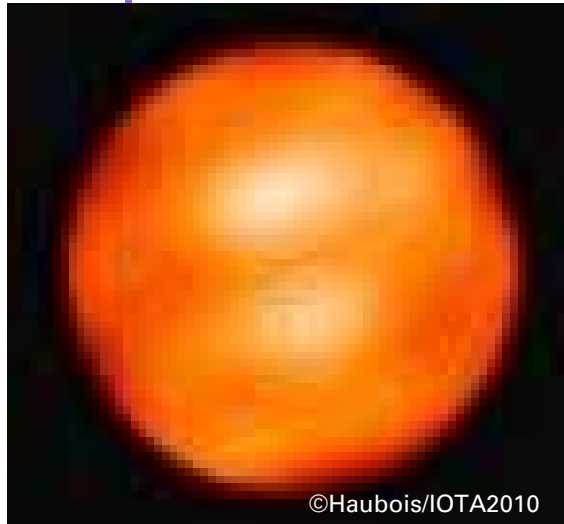
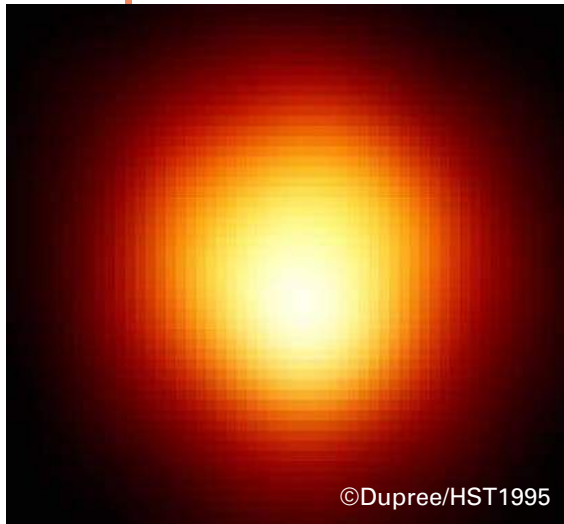
Variations temporelles du diamètre angulaire de Bételgeuse

# Les 10 étoiles les plus résolues

#	Nom	Bayer / GCVS	Type spectral	Distance (parsec)	Mag. vis. (moy.)	Diam. ang. (mas)	Remarque
1	Bételgeuse	$\alpha$ Ori	M1-M2Ia-Iab	150	0.5	45-60	Supergéante rouge
2	Antarès	$\alpha$ Sco	M1.5Iab+B2Vn	170	1.1	42	Supergéante rouge
3	Aldhanab	$\gamma$ Cru	M3.5III	27	1.6	28	Mouvement propre élevé
4	Aldébaran	$\alpha$ Tau	K5+III	20	0.9	23	Variable à longue période (candidate)
5	Scheat	$\beta$ Peg	M2.5II-III	60	2.4	20	Variable à longue période
6	Gorgonea Tertia	$\rho$ Per	M4+IIIa	95	3.3	16	Variable à longue période
7		W Cyg	M4e-M6eIII	195	6.0	16	Variable à longue période
8	Tejat	$\mu$ Gem	M3IIIab	70	2.9	15	Variable à longue période
9	Erakis	$\mu$ Cep	M2-Ia	1820	4.2	14	Supergéante rouge
10	Mirach	$\beta$ And	M0+IIIa	60	2.1	14	Mouvement propre élevé

Source : JMMC Stellar Diameters Catalogue (Version 2) ©Bourges2017 + SIMBAD/CDS

# Une source bien étudiée





# Carte d'identité de Bételgeuse

Paramètre	Valeur	Complément
Nom	Bételgeuse	alpha Orionis
Type spectral	M1-M2Ia-Iab	Etoile supergéante rouge
Distance au Soleil	125-170 parsecs	410-550 années-lumière
Ascension droite	05h 55min 10.3s	Epoque J2000.0
Déclinaison	+07° 24' 25"	
Magnitude visible	0.0 à 1.6	Variable
Variabilité	semi-régulière à longue période de type SRc	Période principale = 420 jours
Température effective	3600 à 3800 Kelvins	Etoile froide
Luminosité	90 000-150 000 $L_{\text{Sol}}$	Supergéante lumineuse
Rayon linéaire	640-1020 $R_{\text{Sol}}$	Variable pulsante
Masse	14-19 $M_{\text{Sol}}$	Etoile massive
Age	8-14 millions d'années (depuis la sortie de la Séquence Principale)	Etoile jeune
Diamètre angulaire	0.045-0.060 secondes de degré	Variable selon époque et longueur d'onde d'observation



# L'interférométrie



# Principe

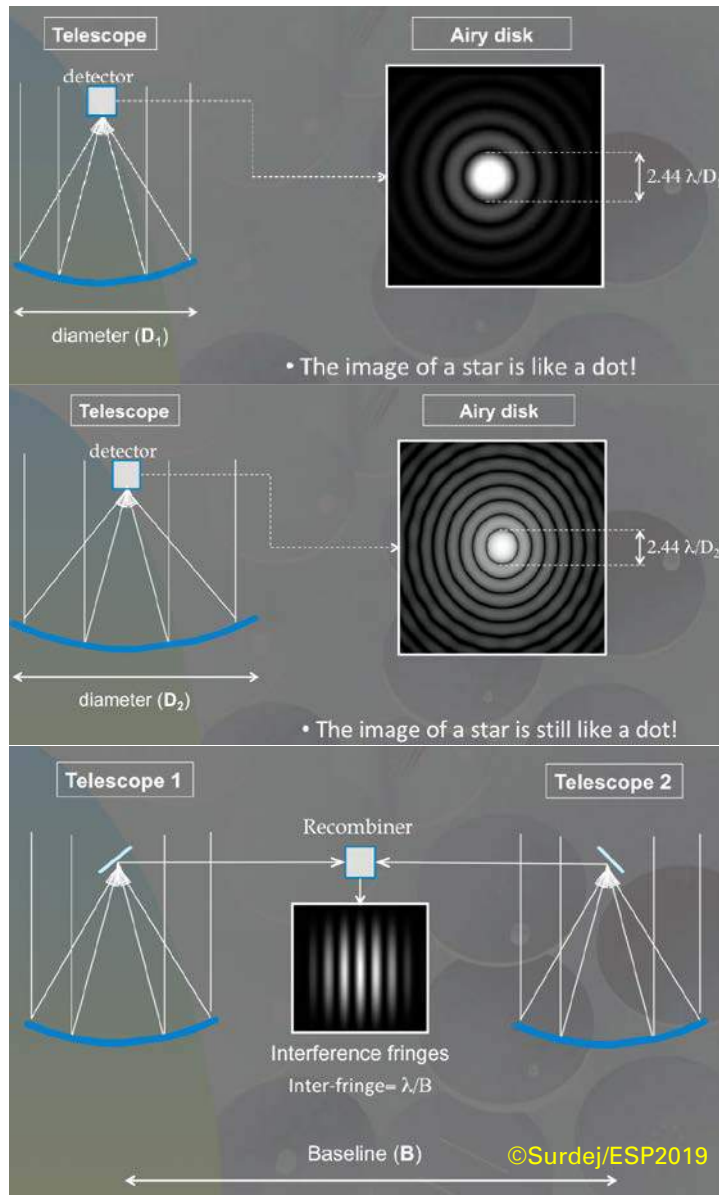


image  
observée

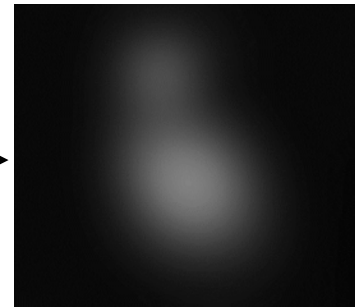


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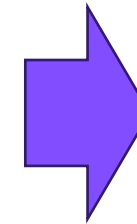
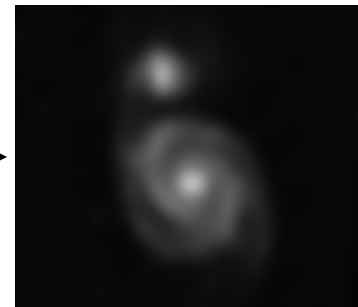


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reconstruite

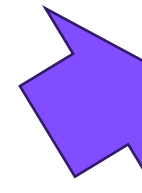
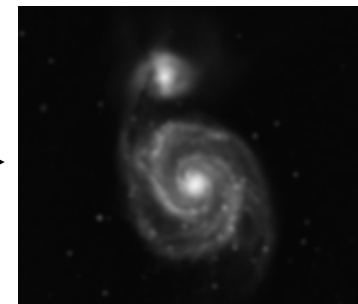
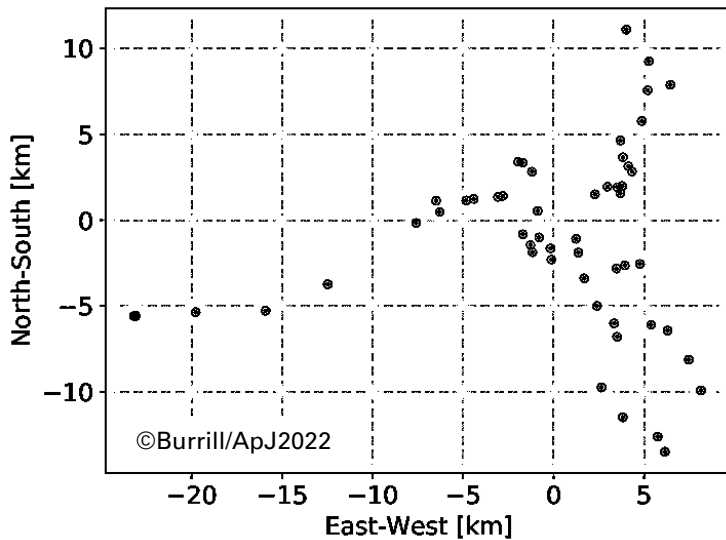


image source (M51)

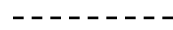
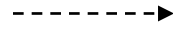
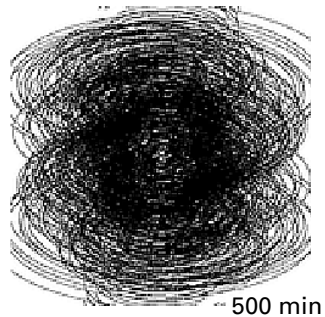
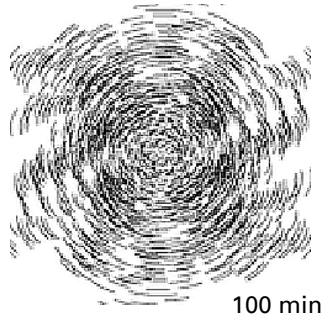
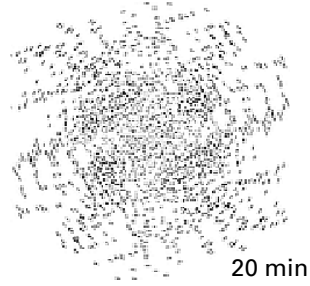
# La synthèse d'ouverture



Le réseau interférométrique ALMA (66 antennes)



La configuration étendue (44m à 33 km)



images reconstruites

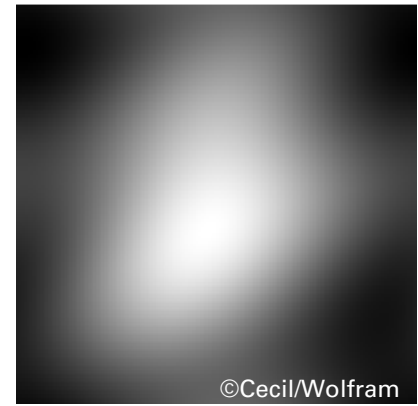
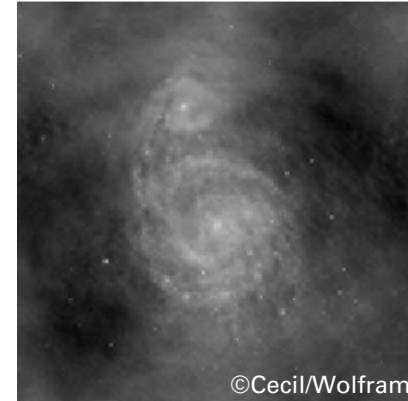
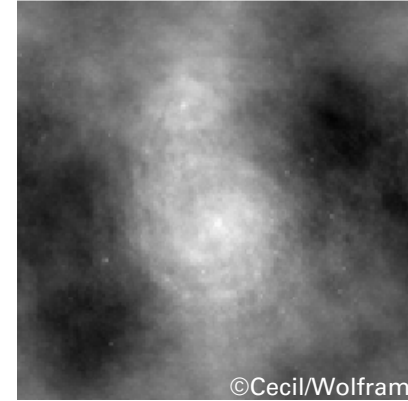
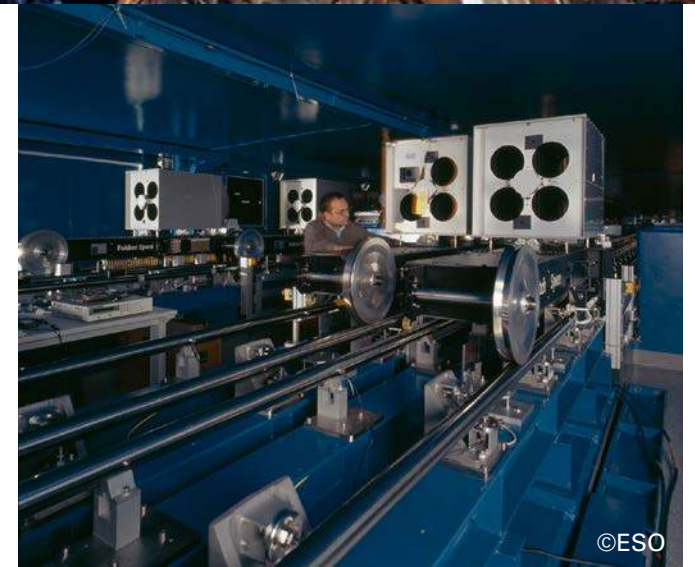
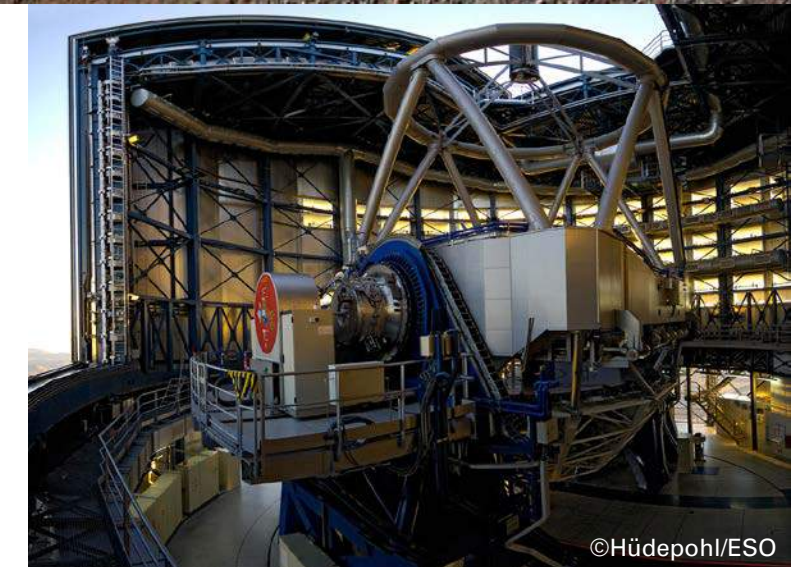


image obtenue avec 1 seule antenne (12m)

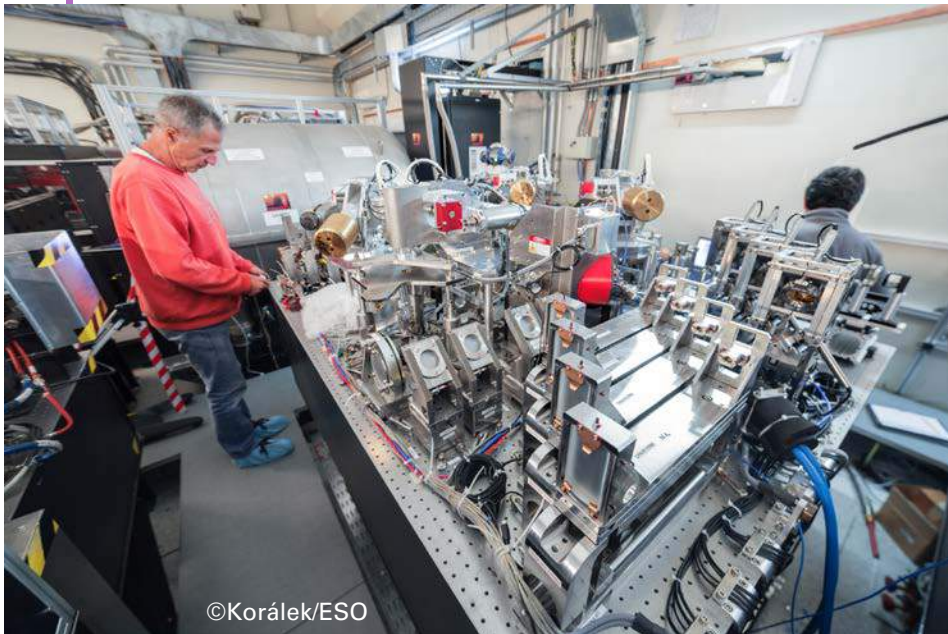
image source



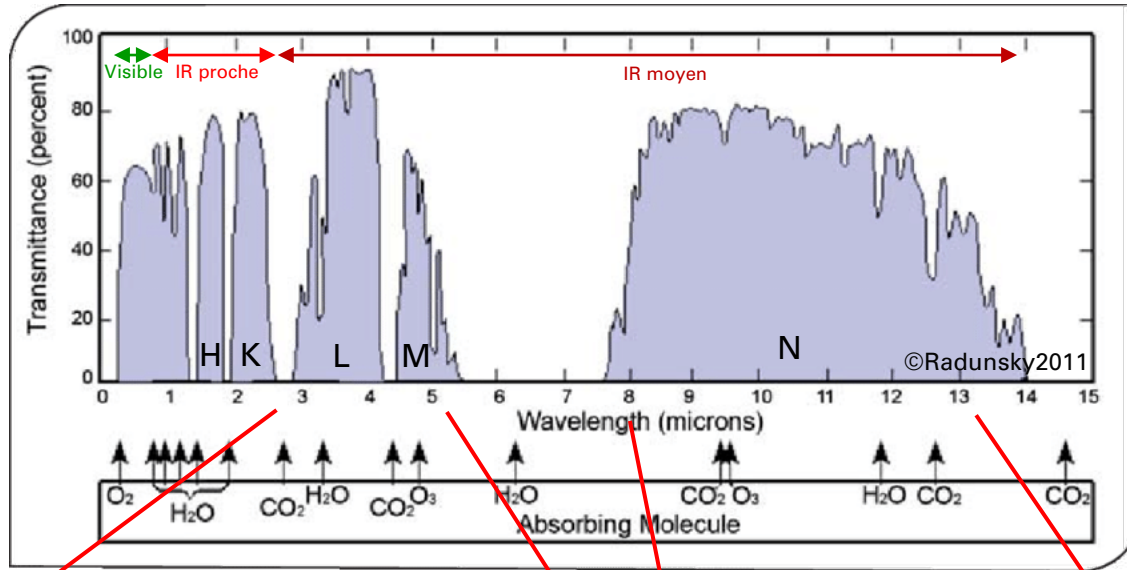
# L'interféromètre VLT



# MATISSE

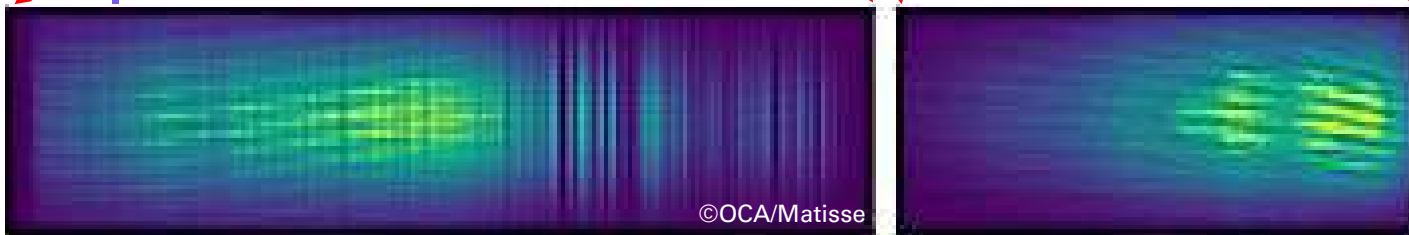


# Les premières franges (fév. 2018)



Bandes L + M

Bande N



Spectres de franges obtenus avec MATISSE sur Bételgeuse



Les premières franges de MATISSE fêtées (dignement) au Paranal

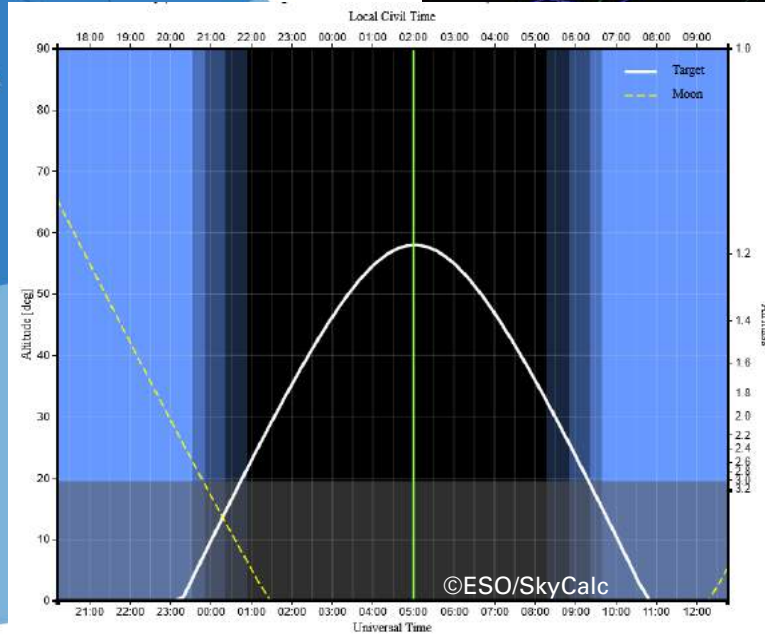
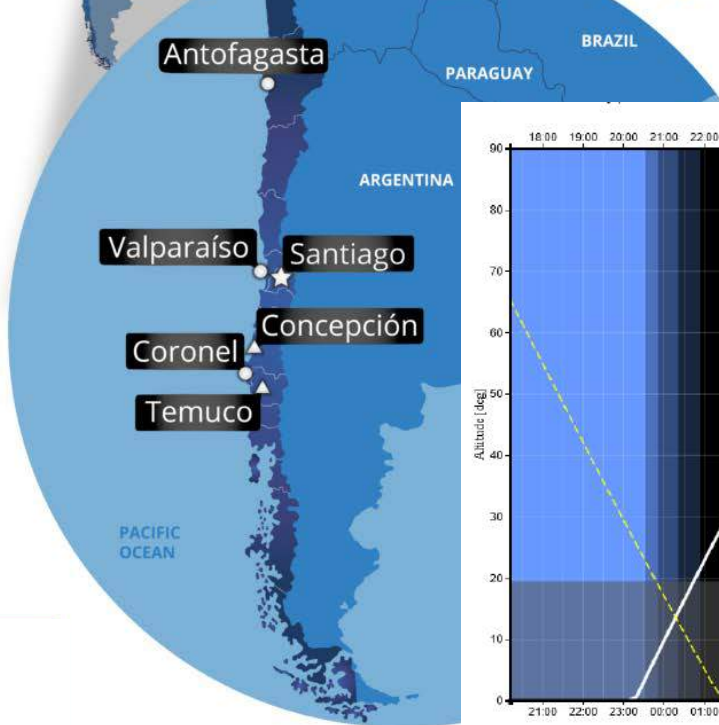
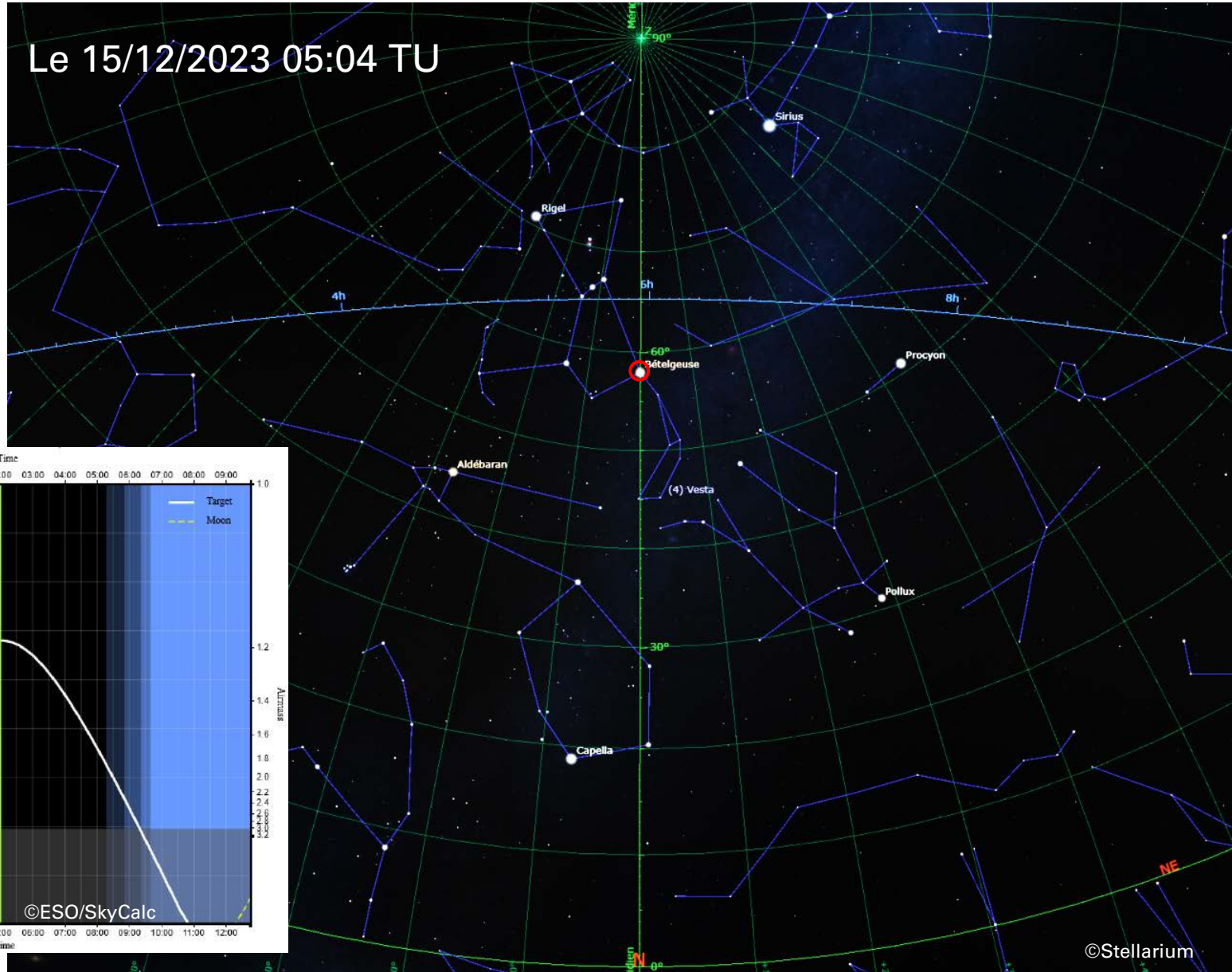
+  
• ○

**UNE CIBLE DE CHOIX**

+  
• ○



# Bien observable

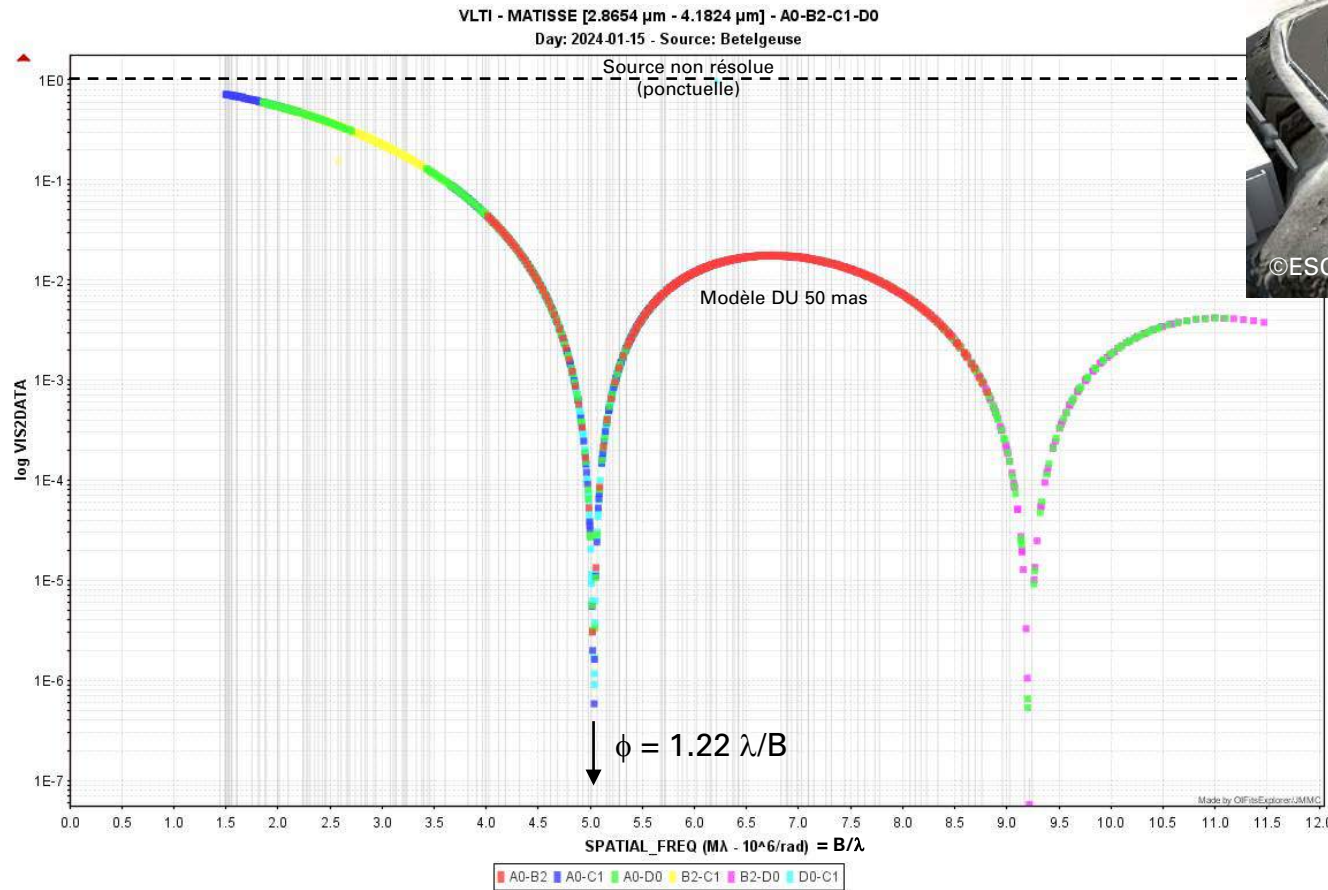


# Une source infrarouge (très) brillante

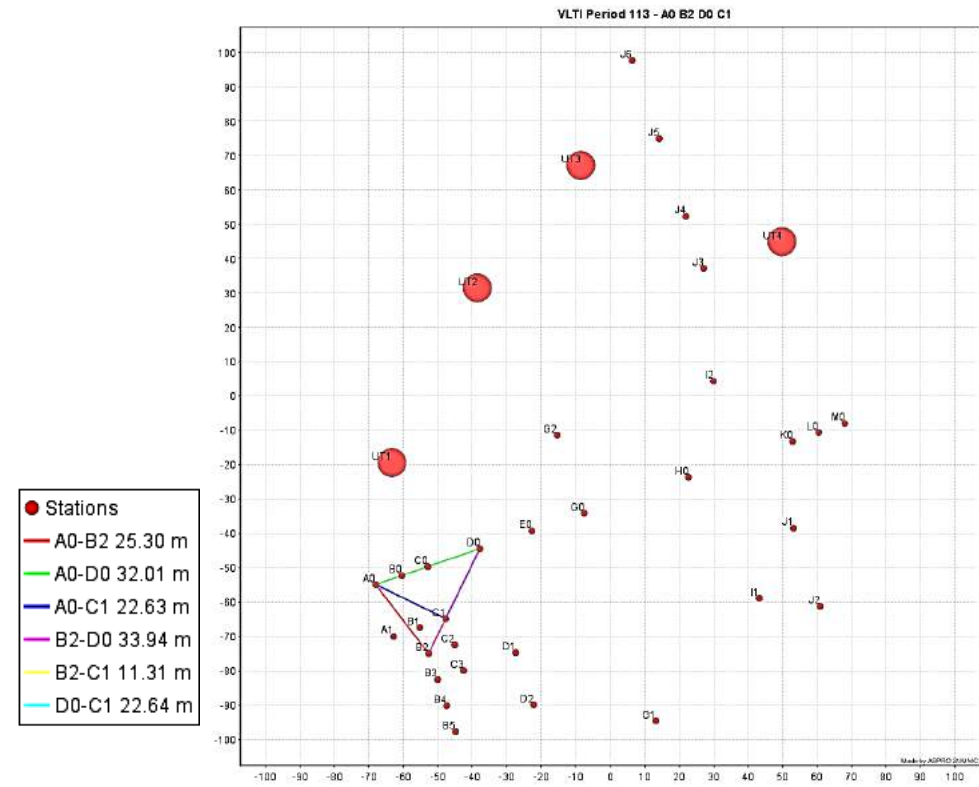
#	Nom	Bayer / GCVS	Type spectral	Distance (parsec)	Flux en L (Jy)	Flux en N (Jy)	Remarque
1	Bételgeuse	$\alpha$ Ori	M1-M2Ia-Iab	150	15700	3850	Supergéante rouge
2	Antarès	$\alpha$ Sco	M1.5Iab+B2Vn	170	12200	2100	Supergéante rouge
3		W Hya	M7.5-9e	160	7900	3300	Variable Mira
4		P Dor	M8III:e	55	7900	4100	Géante de la Branche Asymptotique
5	Rasalgethi	$\alpha$ Her	M5Ib-II+G5III+F2V:	110	7600	1100	Etoile multiple
6	Mira A	$\omicron$ Cet	M5-9IIIe+DA	90	6000	2400	Variable Mira
7	Aldhanab	$\gamma$ Cru	M3.5III	30	5500	750	Mouvement propre élevé
8		R Leo	M7-9e	70	5100	1950	Variable Mira
9	Arcturus	$\alpha$ Boo	K1.5IIIFe-0.5	11	4900	700	Etoile de la Branche des Géantes
10	Aldébaran	$\alpha$ Tau	K5+III	20	4300	570	Variable à longue période (candidate)

Source : Mid-infrared stellar Diameters and Fluxes compilation Catalogue ©Cruzalèbes2019 + SIMBAD/CDS

# Résolue par le VLTI

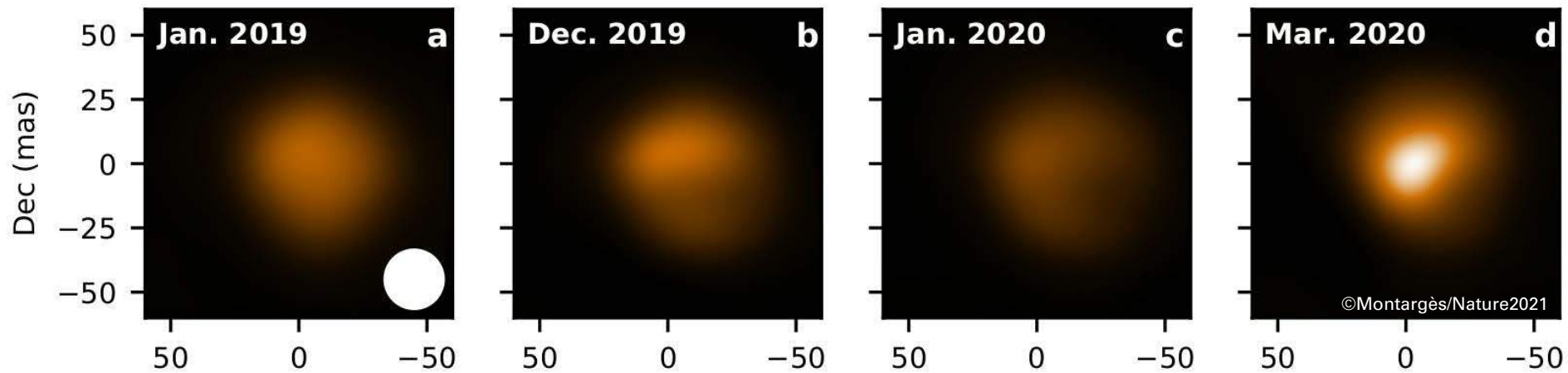
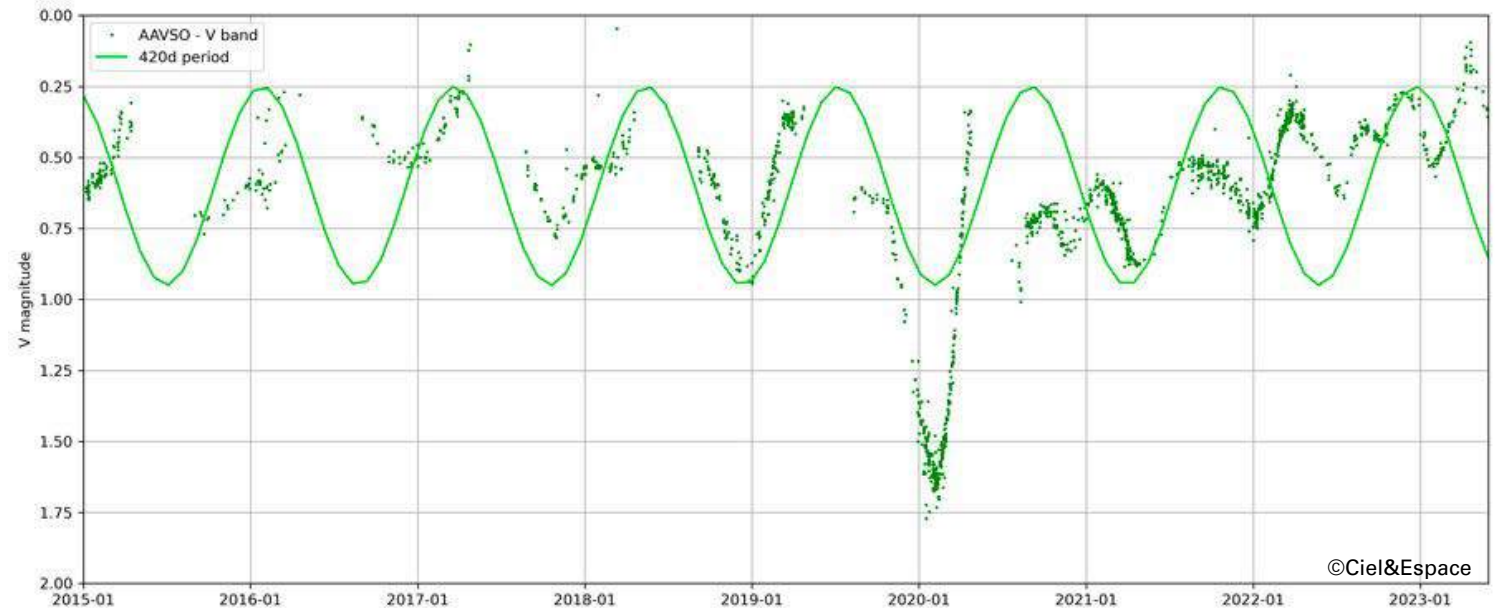


Fonction de visibilité théorique pour un disque uniforme de diamètre angulaire  $\phi=50$  mas observé avec MATISSE en bande L ( $\lambda=3.5 \mu\text{m}$ ) avec la configuration compacte A0-B2-C1-D0 du VLTI



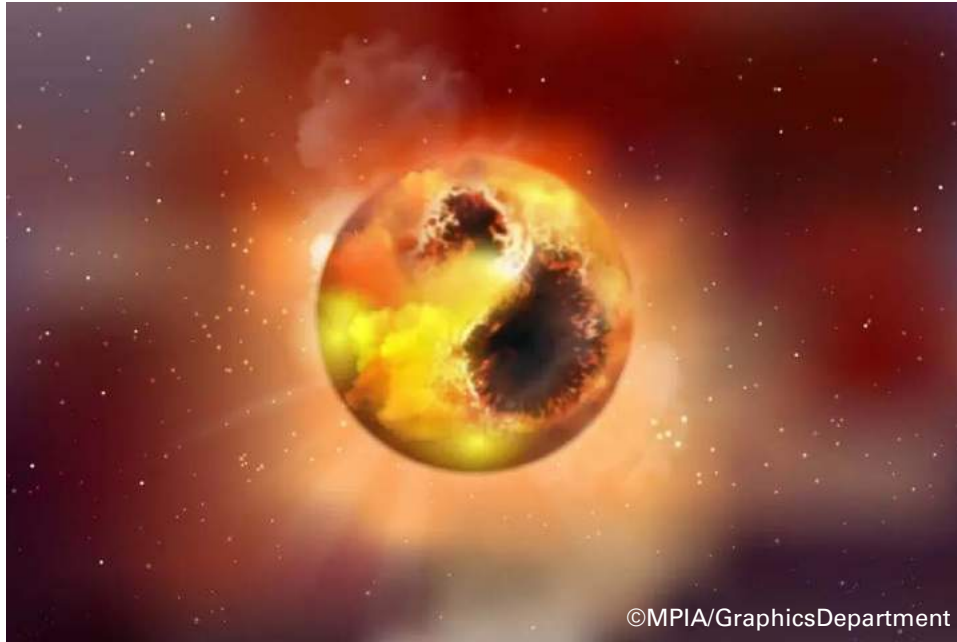
+ L'ÉPISODE DU +  
« GRAND OBSCURCISSEMENT »

# Les observations



Images de Bételgeuse en  $H\alpha$  ( $\lambda=0.645 \mu\text{m}$ ) obtenues avec le spectro-polarimètre VLT/SPHERE-ZIMPOL

# Les hypothèses

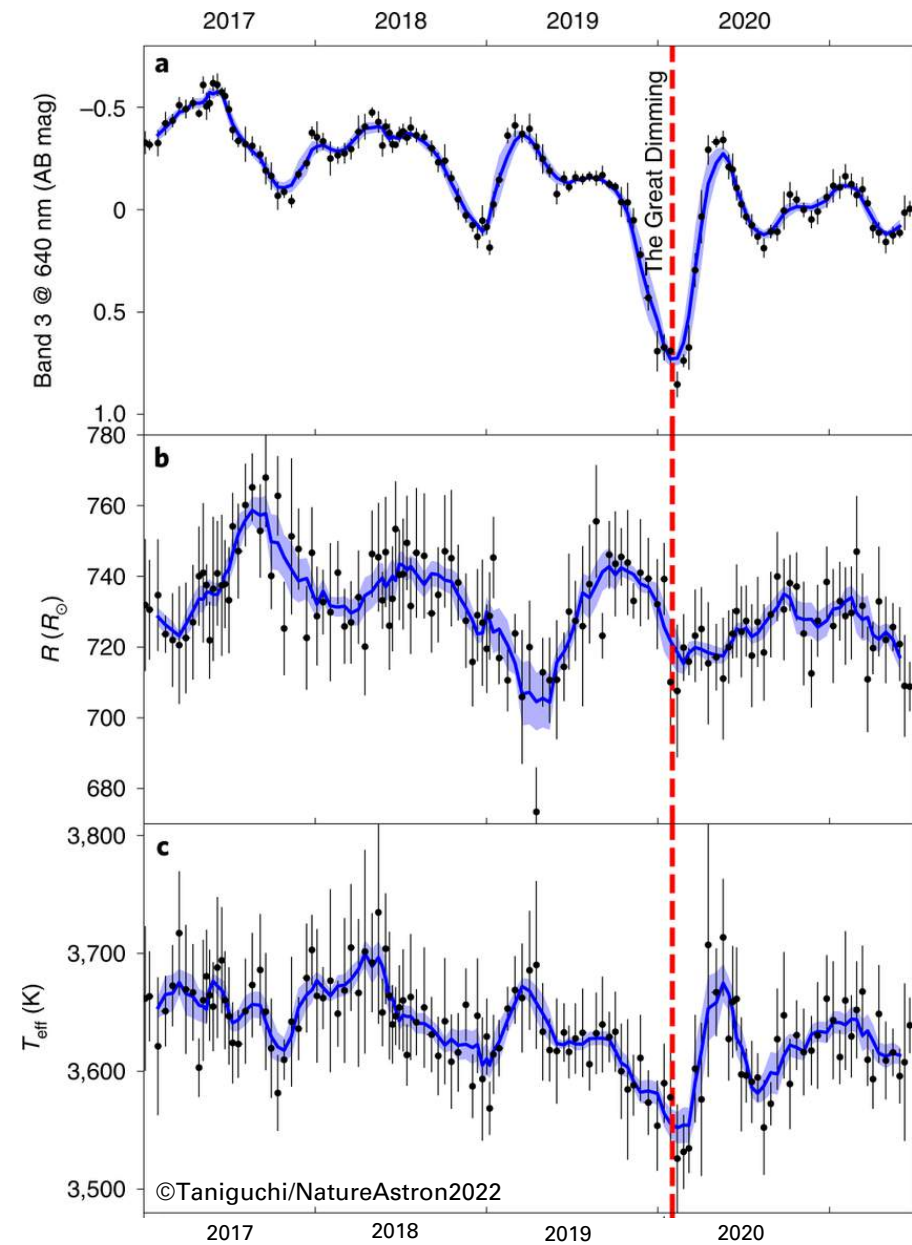


Une grande  
plage sombre  
soudainement  
apparue au  
niveau de la  
photosphère

...

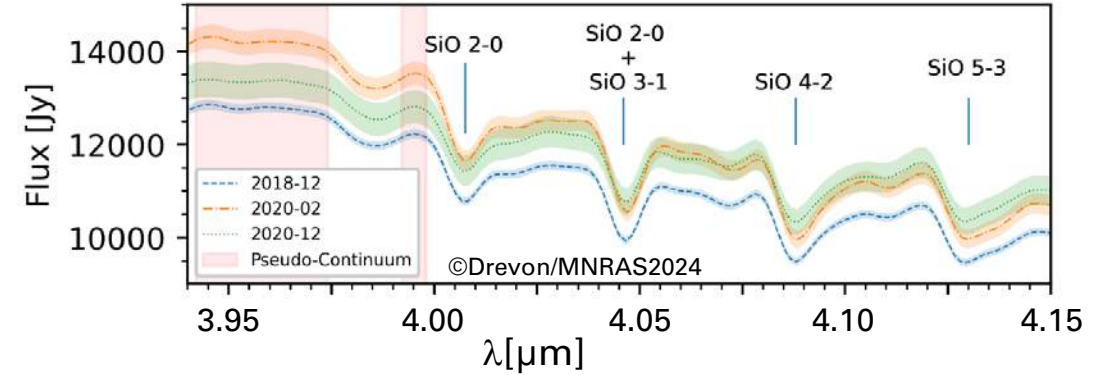
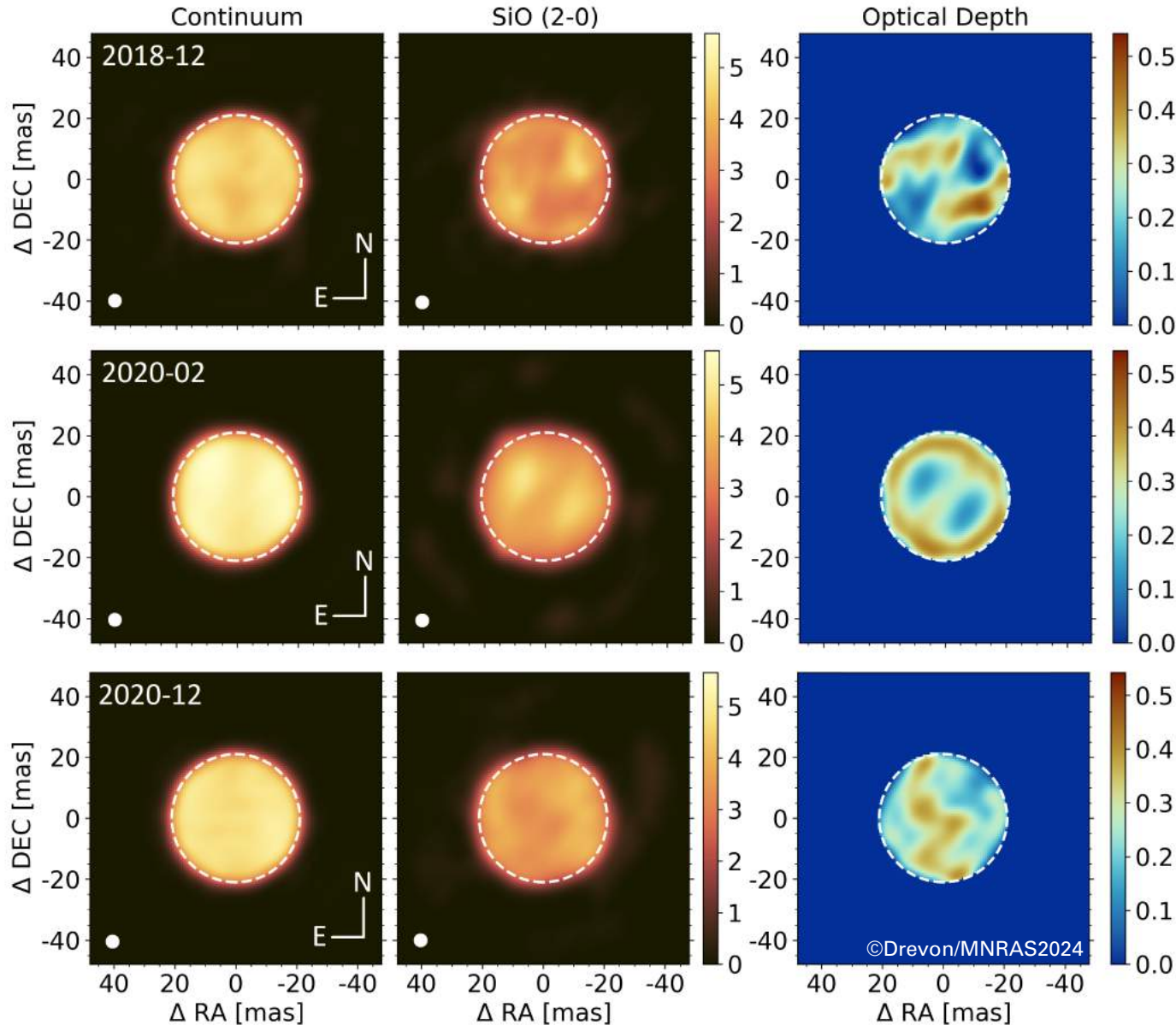


... ou un  
grand nuage  
de poussières  
venu nous  
masquer  
l'étoile ?



Variation temporelle des paramètres stellaires de Bételgeuse déduite de la modélisation des mesures photométriques du satellite Himawari-8

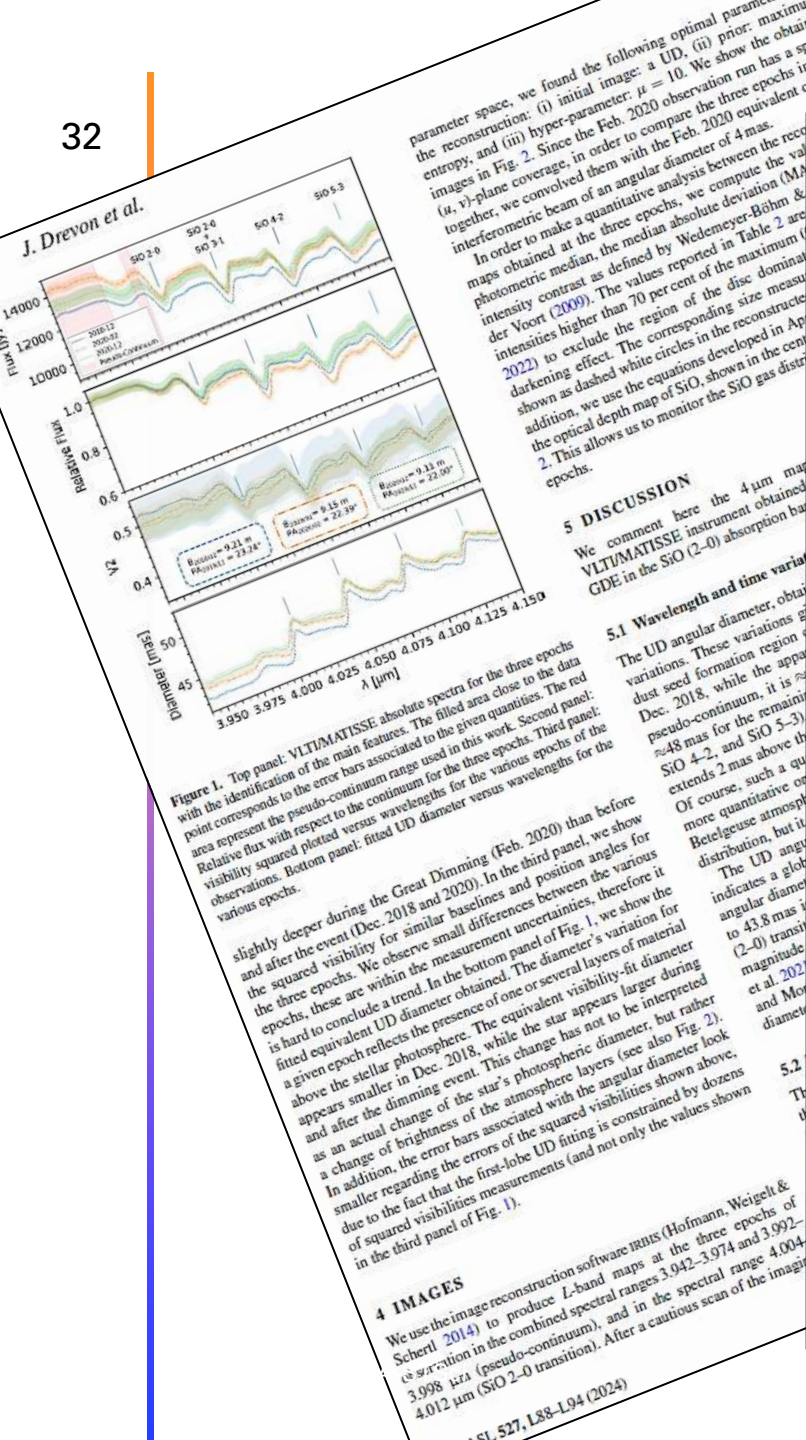
# Les résultats de MATISSE



Spectres en bande L de Bételgeuse obtenus avec MATISSE avant, pendant et après l'épisode du « Grand Obscurcissement » (GO).

Images en bande L de Bételgeuse avant, pendant et après l'épisode du GO :

- à gauche : dans le pseudo-continu
- au centre : dans la raie en absorption correspondant à transition 2-0 de la molécule SiO
- à droite : les cartes de profondeur optique montrant la distribution du gaz de SiO aux 3 époques.



**Figure 1.** Top panel: VLT/MATISSE absolute spectra for the three epochs with the identification of the main features. The filled area close to the data area represent the pseudo-continuum range used in this work. Second panel: Relative flux with respect to the continuum for the three epochs. Third panel: visibility squared plotted versus wavelengths for the various epochs of the observations. Bottom panel: fitted UD diameter versus wavelengths for the various epochs.

slightly deeper during the Great Dimming (Feb. 2020) than before and after the event (Dec. 2018 and 2020). In the third panel, we show the squared visibility for similar baselines and position angles for the three epochs. We observe small differences between the various epochs, these are within the measurement uncertainties, therefore it is hard to conclude a trend. In the bottom panel of Fig. 1, we show the fitted equivalent UD diameter obtained. The diameter's variation for a given epoch reflects the presence of one or several layers of material above the stellar photosphere. The equivalent visibility-fit diameter appears smaller in Dec. 2018, while the star appears larger during and after the dimming event. This change has not to be interpreted as an actual change of the star's photospheric diameter, but rather a change of brightness of the atmosphere layers (see also Fig. 2). In addition, the error bars associated with the angular diameter look smaller regarding the errors of the squared visibilities shown above, due to the fact that the first-lobe UD fitting is constrained by dozens of squared visibilities measurements (and not only the values shown in the third panel of Fig. 1).

**4 IMAGES**

We use the image reconstruction software IRIS (Hofmann, Weigelt & Scherl 2014) to produce  $L$ -band maps at the three epochs of 3.998  $\mu\text{m}$  (pseudo-continuum), and in the spectral range 4.004–4.012  $\mu\text{m}$  (SiO 2–0 transition). After a cautious scan of the image

parameter space, we found the following optimal parameters for the reconstruction: (i) initial image: a UD, (ii) prior: maximum entropy, and (iii) hyper-parameter:  $\mu = 10$ . We show the obtained images in Fig. 2. Since the Feb. 2020 observation run has a sparse ( $u, v$ )-plane coverage, in order to compare the three epochs images together, we convolved them with the Feb. 2020 equivalent circular interferometric beam of an angular diameter of 4 mas.

In order to make a quantitative analysis between the reconstructed maps obtained at the three epochs, we compute the photometric median, the median absolute deviation (MAD) and intensity contrast as defined by Wedemeyer-Böhm & der Voort (2009). The values reported in Table 2 are intensities higher than 70 per cent of the maximum (to exclude the region of the disc dominated by the darkening effect). The corresponding size measured as dashed white circles in the reconstructed maps shown as dashed white circles in the center of the optical depth map of SiO, shown in the center of Fig. 2. This allows us to monitor the SiO gas distribution.

**5 DISCUSSION**

We comment here the 4  $\mu\text{m}$  map obtained with the VLT/MATISSE instrument obtained in the SiO (2–0) absorption band.

**5.1 Wavelength and time variations.**

The UD angular diameter obtained with the VLT/MATISSE instrument shows variations. These variations correspond to the dust seed formation region in the pseudo-continuum, it is  $\approx 48$  mas for the remaining SiO 4–2, and SiO 5–3) extends 2 mas above it. Of course, such a quantitative analysis is more difficult, but it indicates a global angular diameter variation of 43.8 mas (2–0) transition (see also Fig. 2).

**Images of Betelgeuse with VLT/MATISSE across the Great Dimming**

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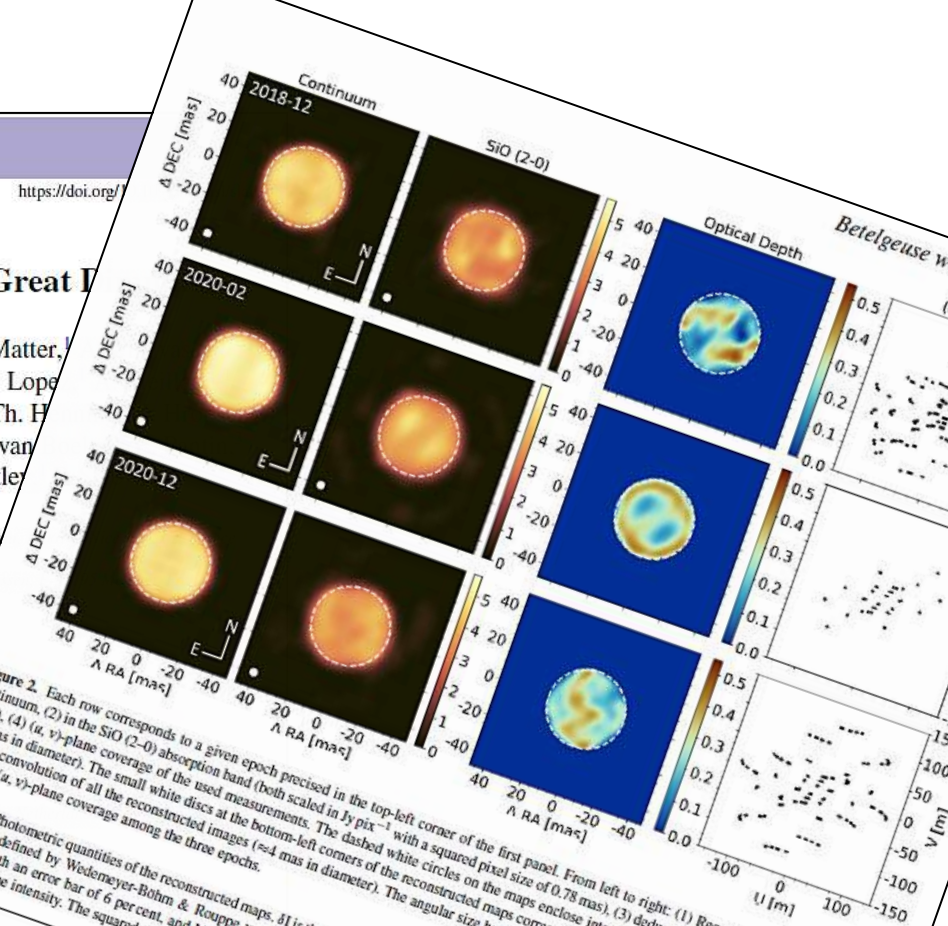
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**ABSTRACT**

From Nov. 2019 to May 2020, the red supergiant star Betelgeuse experienced a domain called the Great Dimming event (GDE). Large atmospheric dust layers are suspected to be responsible for it. To better understand the dimming event, we performed interferometric measurements of Betelgeuse taken with the Very Large Telescope Spectroscopic Experiment (VLT/MATISSE) instrument before (Dec. 2018) and after (Feb. 2020) the GDE. We present data in the 3.98–4.15  $\mu\text{m}$  range to cover SiO spectral features. We employed geometrical models, image reconstruction, as well as radiative transfer modeling of SiO over the stellar surface. We find a strongly inhomogeneous spatial distribution of SiO between our observing epochs, indicative of a vigorous activity in the pseudo-continuum for all epochs, implying that our MATISSE

Key words: techniques: image processing – techniques: interferometry – stars: massive – stars: variables: general.



**Figure 2.** Each row corresponds to a given epoch: (1) Reconstructed map in the pseudo-continuum, (2) in the SiO (2–0) absorption band (both scaled in  $\text{Jy pix}^{-1}$  with a squared pixel size of 0.78 mas), (3) deduced map of the optical depth for the pseudo-continuum, (4) in the SiO (2–0) absorption band (both scaled in  $\text{Jy pix}^{-1}$  with a squared pixel size of 0.78 mas). The dashed white circles on the maps enclose intensities higher than 70 per cent of the maximum (to exclude the region of the disc dominated by the darkening effect). The corresponding size measured as dashed white circles in the reconstructed maps shown as dashed white circles in the center of the optical depth map of SiO, shown in the center of Fig. 2. This allows us to monitor the SiO gas distribution.

**Table 2.** Photometric quantities of the reconstructed maps.  $\delta I$  is the intensity deviation with an error bar of 6 per cent, and MAD is the median absolute deviation of the intensity. The squared pixel size is 0.78 mas.

Date	Band	$\delta I$	Median ( $\text{Jy pix}^{-1}$ )	MAD ( $\text{Jy pix}^{-1}$ )
2018–12	Pseudo-cont.	0.12	4.4	0.3
2020–02	Pseudo-cont.	0.12	5.1	0.3
2020–12	Pseudo-cont.	0.14	4.7	0.3
2018–12	SiO (2–0)	0.16	3.4	0.4
2020–02	SiO (2–0)	0.11	3.8	0.3
2020–12	SiO (2–0)	0.11	3.6	0.3

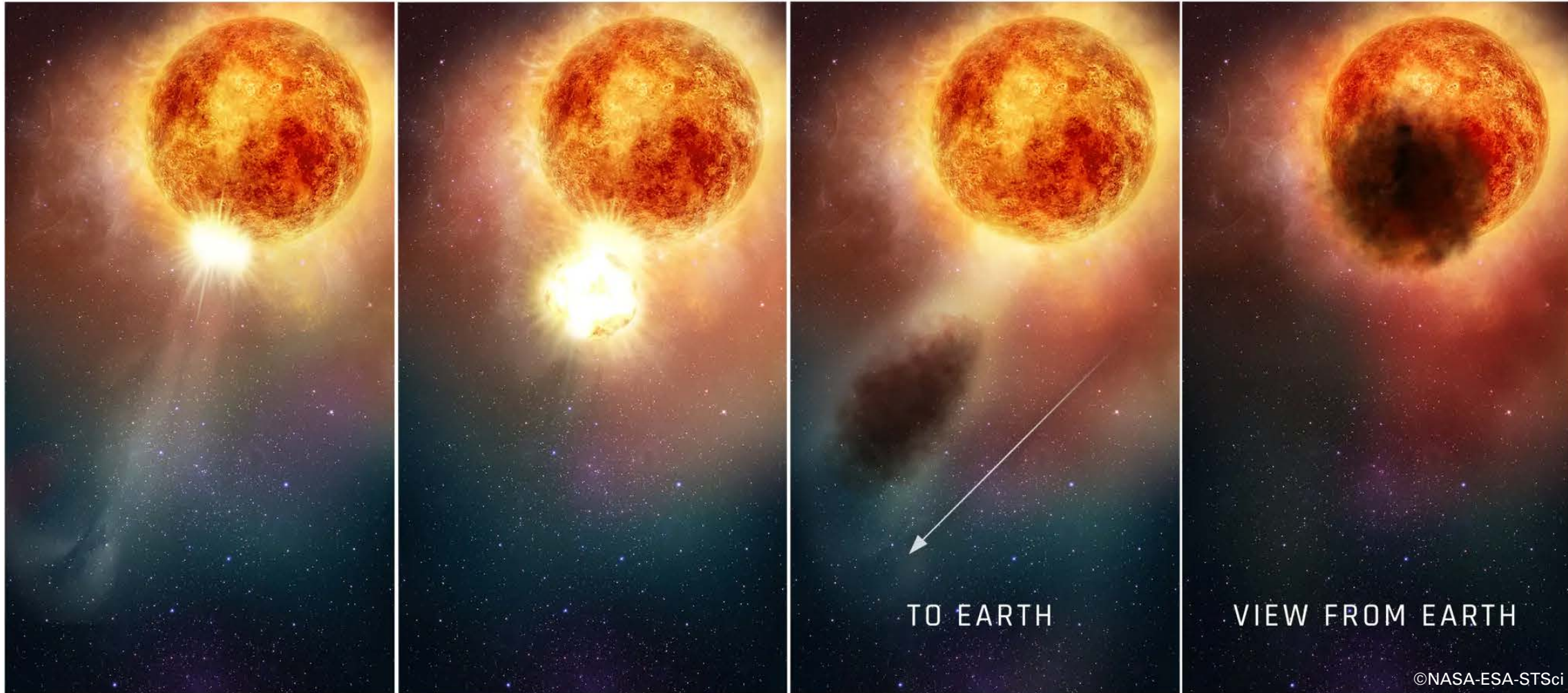
pseudo-continuum images around 4  $\mu\text{m}$  of  $\sim 17$  percent between Dec. 2018 (before the GDE) and Feb. 2020 (during the GDE). Coupling these quantities with a slight increase of the median flux, this transcribe the appearance of a global brighter surface during the GDE which might be associated with recently formed dust in the line of sight. Fig. 1 also shows a global increase of the infrared emission in the continuum of  $\sim 13$  percent which is in agreement with the presence of dusty material recently formed close to the star as proposed by Montargès et al. (2021). The results of Harper

et al. (2020a), who do not find any infrared excess around the star, are not necessarily in disagreement with our results. The complementary to constrain the nature of the newly formed dust in the GDE (but this last point is still under discussion).





# Le scénario du « Grand Obscurcissement »



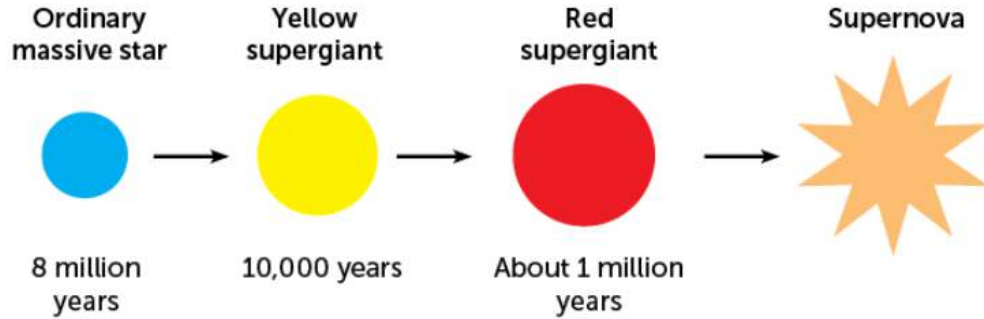
Fév 2018 - Jan. 2019 : une cellule convective de plasma chaud remonte à la surface créant une plage lumineuse au niveau de la photosphère.

Sept – nov . 2019 : une bulle lumineuse dense et chaude se forme et traverse la chromosphère.

Nov . 2019 – févr. 202: la bulle de gaz s'éloigne. Les molécules se condensent en poussières dans sa partie la plus froide.

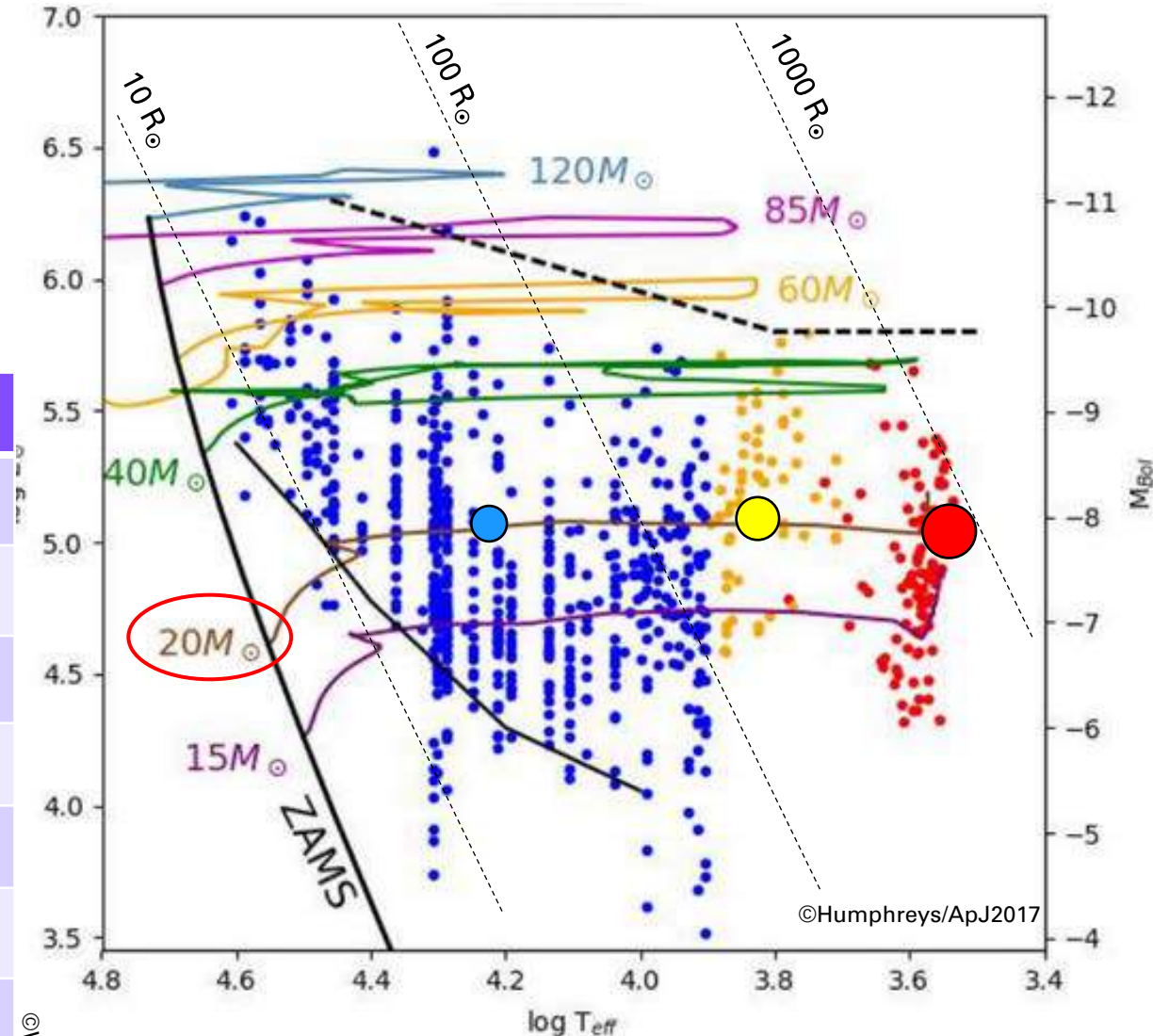
# QUEL AVENIR POUR BÉTELGEUSE ?

# Evolution des étoiles $> 8 M_{\odot}$



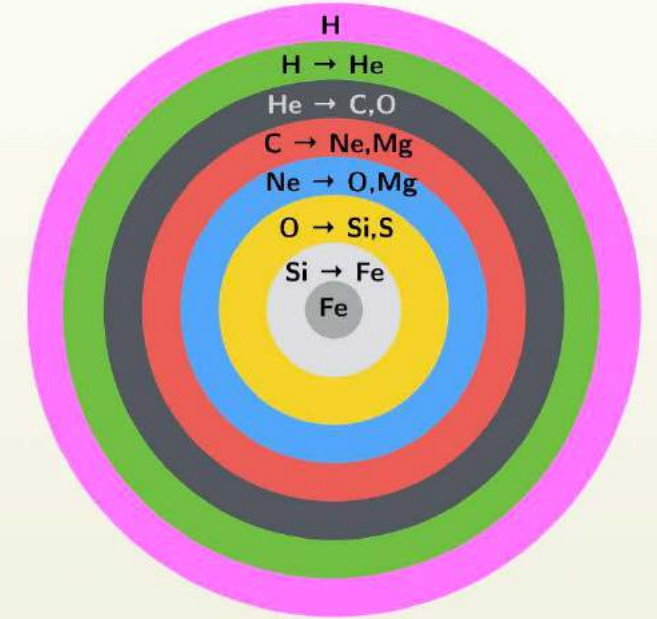
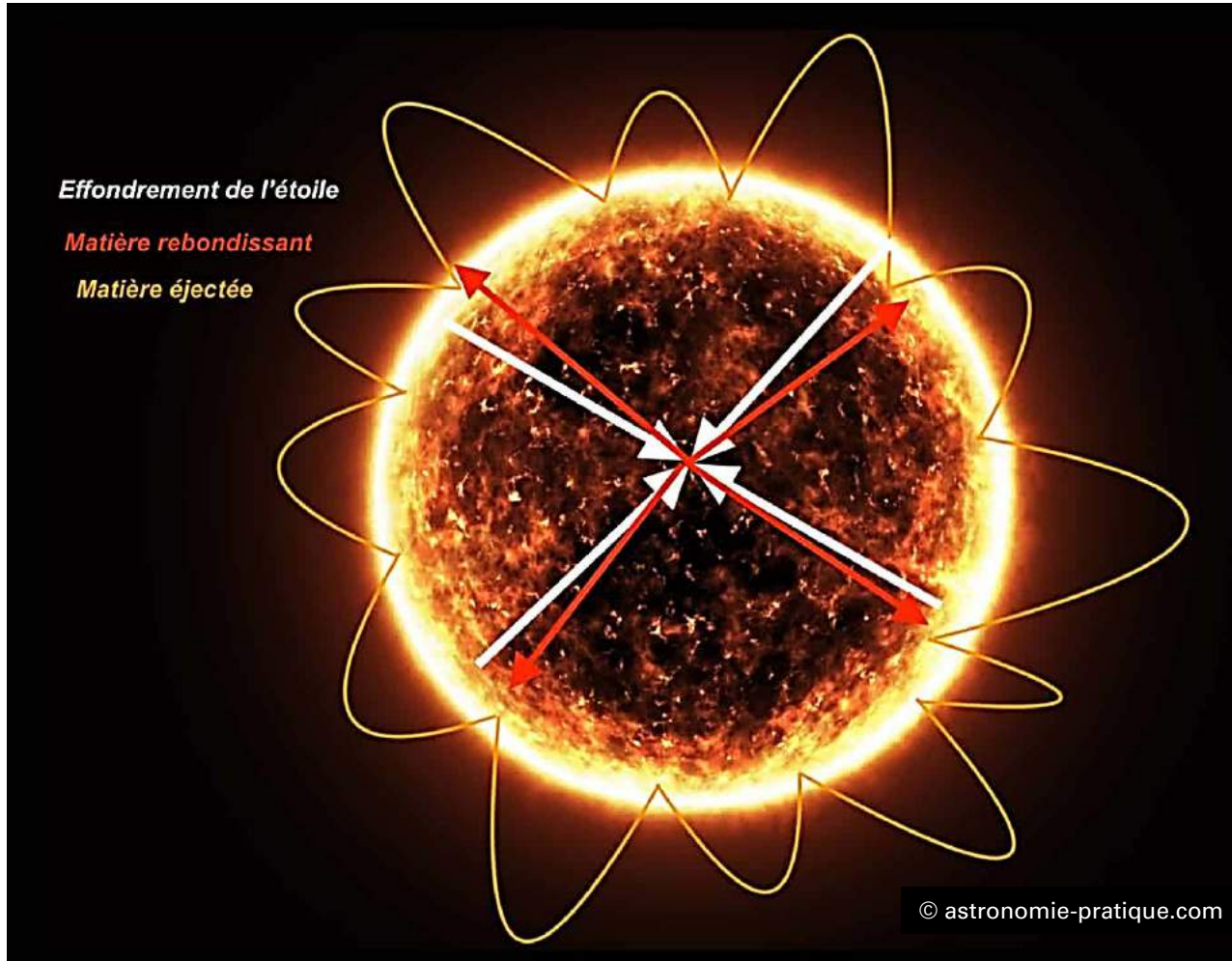
C. CHANG; SOURCES: KATHRYN NEUGENT/UNIV. OF WASHINGTON; S. EKSTRÖM ET AL/ASTRONOMY & ASTROPHYSICS 2012

Masse initiale	$30 M_{\odot}$	$10 M_{\odot}$
Luminosité séquence principale	$10000 L_{\odot}$	$1000 L_{\odot}$
Durée de vie séquence principale	60 millions d'années	100 millions d'années
Fin des réactions nucléaires	Fer	Silicium
Stade terminal	Supernova (type II)	Supernova (type II)
Masse éjectée	$24 M_{\odot}$	$8.5 M_{\odot}$
Rémanent stellaire	Trou noir	Etoile à neutrons / pulsar
Masse du rémanent	$6 M_{\odot}$	$1.5 M_{\odot}$
Rayon du rémanent	6 km	20 km



Evolution post-séquence principale des étoiles massives dans le diagramme HR.

# Le phénomène supernova

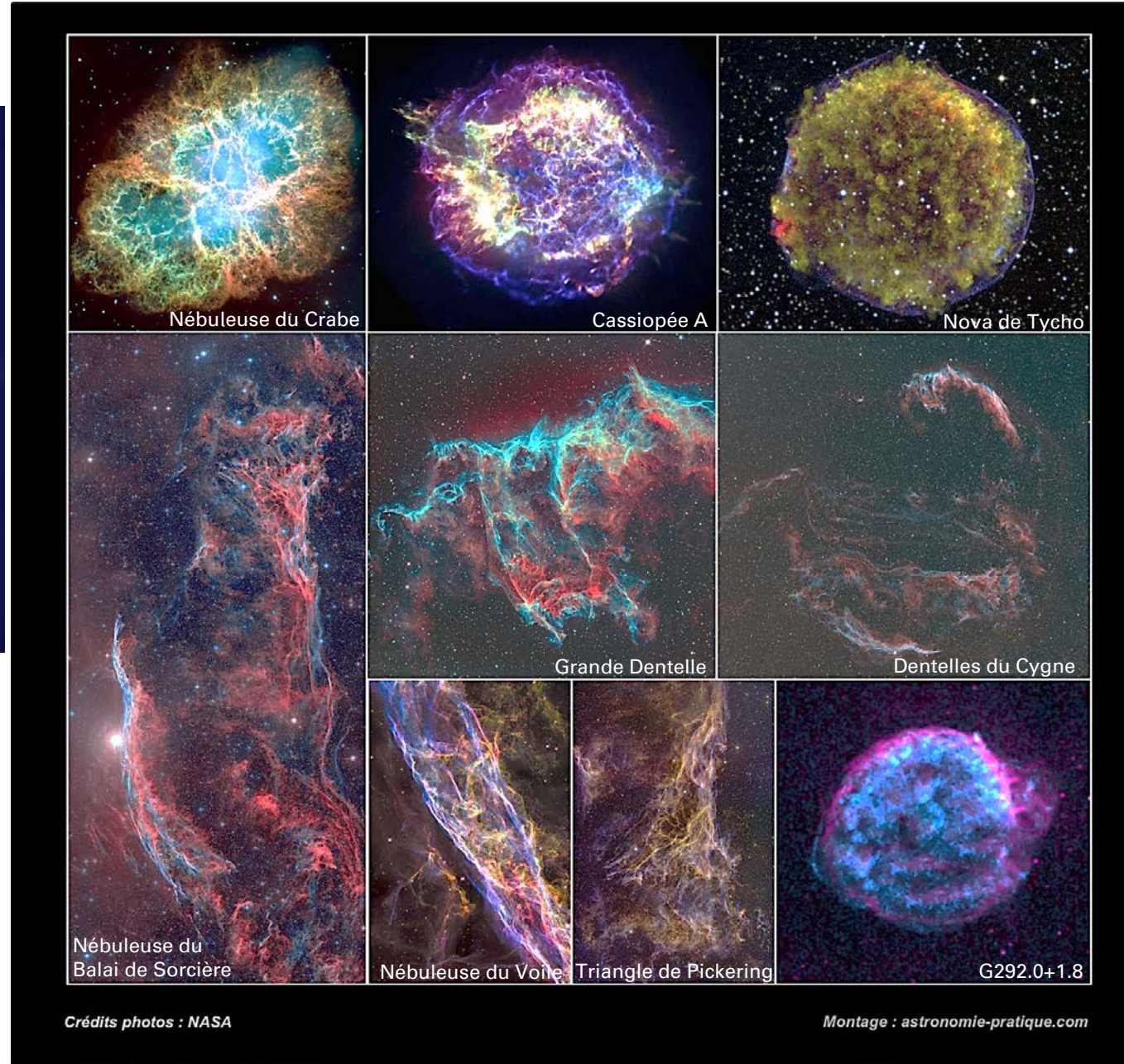
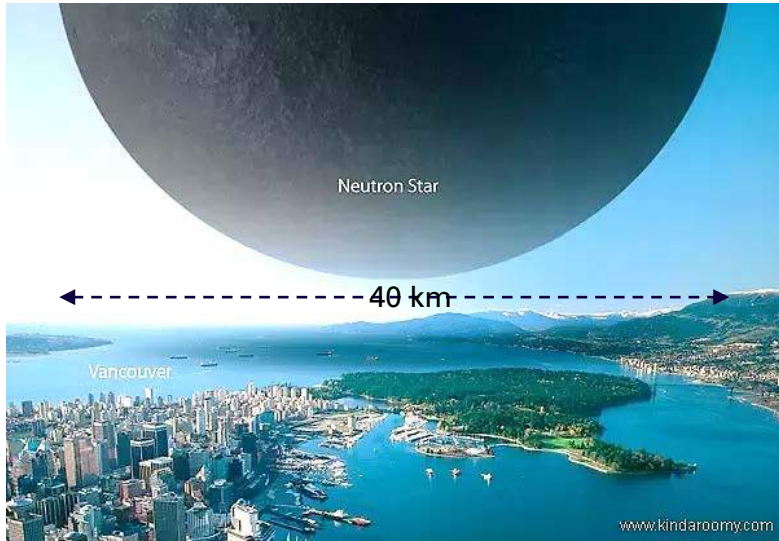
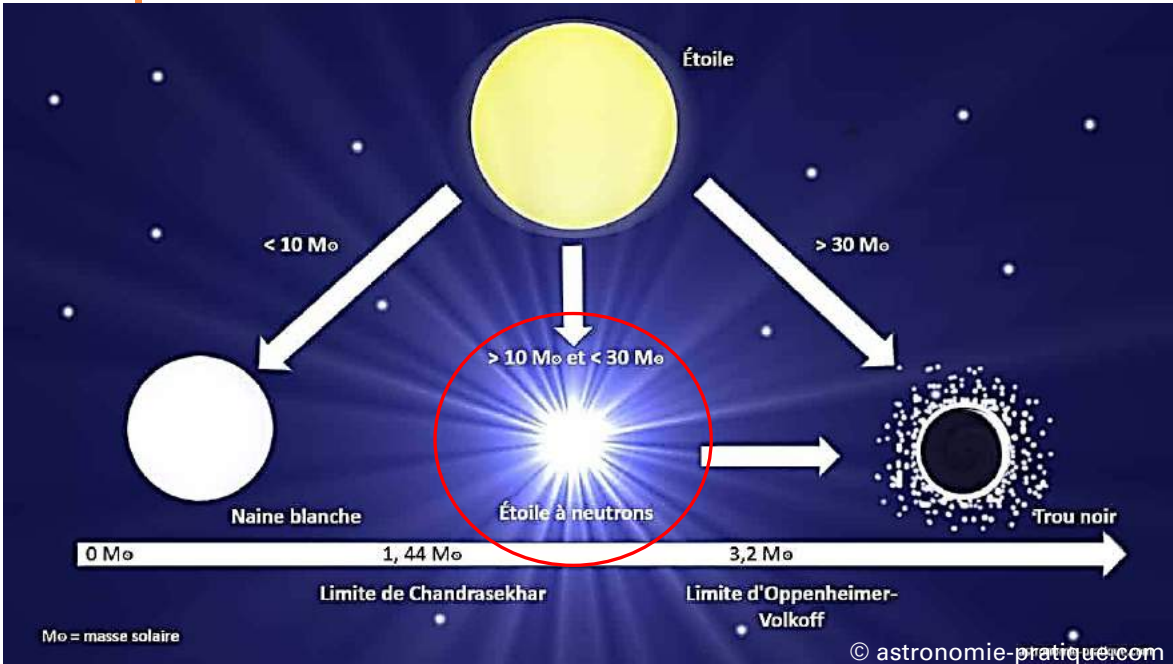


Process	Bi-product	Duration (roughly)
H → He	$^{18}\text{N}$	10 million years
He → C, O	$^{18}\text{O}, ^{22}\text{N}$	1 million years
C → Ne, Mg	Na	1000 years
Ne → O, Mg	Al, P	3 years
O → Si, S	Cl, Ar, K, Ca	9 months
Si → Fe	Ti, V, Cr, Mn, Co, Ni	1 week
Core collapse		¼ second

# Les supernovae historiques

Année	Observation	Vmag@max	Distance	Remarque
185	Centaure	-6	9100 al	SN ou comète ?
386	Sagittaire	+1.5	14000-23000 al	SN ou nova ?
393	Scorpion	-3	3000 al	Probable SN
1006	Loup	-7.5	7000 al	Rémanent identifié
1054	Taureau	-6	6500 al	Rémanent+pulsar identifiés
1181	Cassiopee	-2	7500 al	SN de type Ia associée au rémanent Pa30
1572	Cassiopee	-4	8000-9800 al	Rémanent identifié
1604	Ophiuchus	-2	20000 al	Rémanent identifié
1680 ?	Cassiopee	+6	11000 al	Rémanent identifié, observation SN incertaine
1890-1908 ?	Sagittaire	?	27700 al	Rémanent identifié mais SN non observée
1885	Galaxie d'Andromède	+6	2.6 millions d'al	Certaine
1987	Grand Nuage de Magellan	+3	16800 al	Certaine

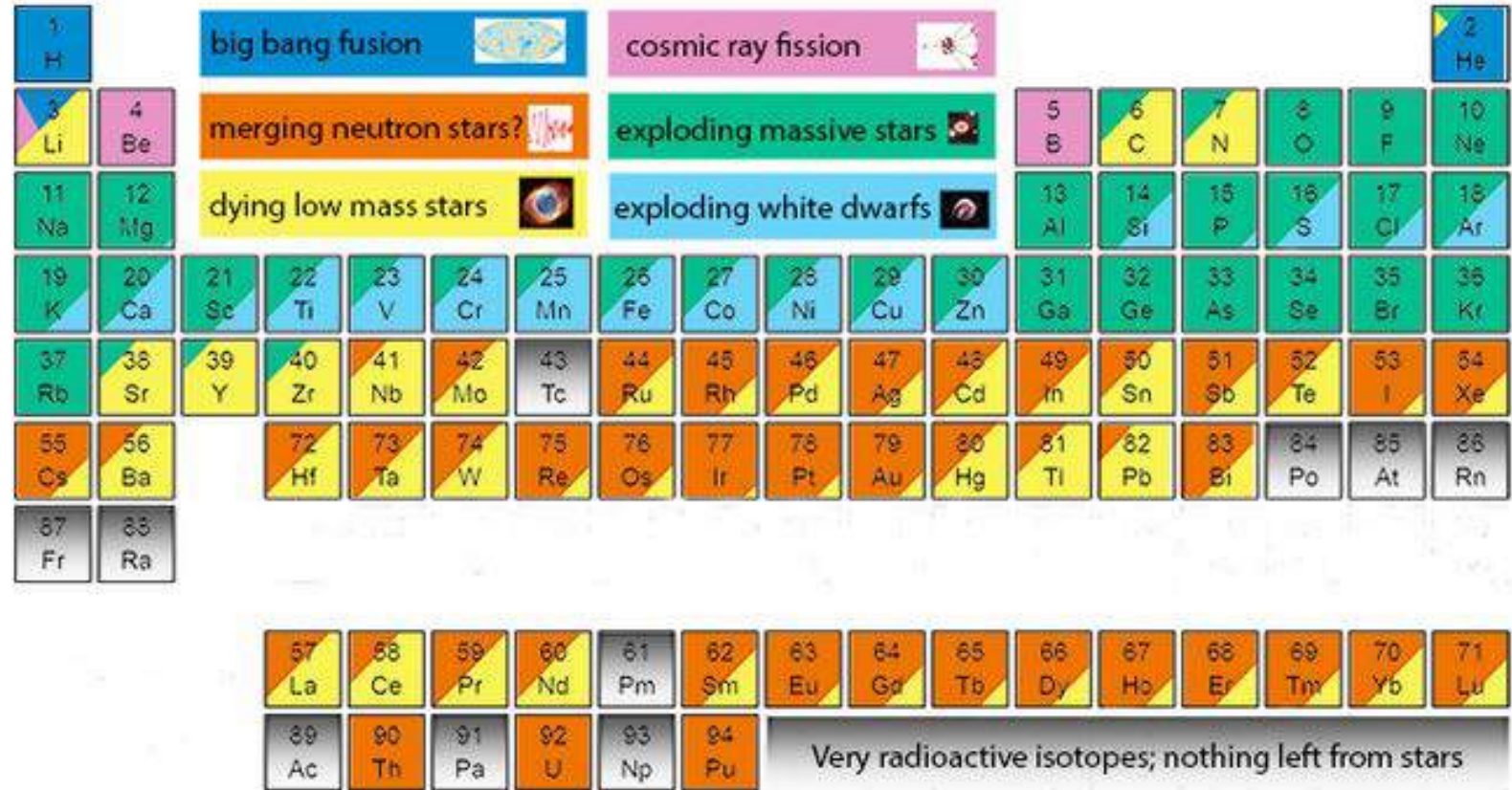
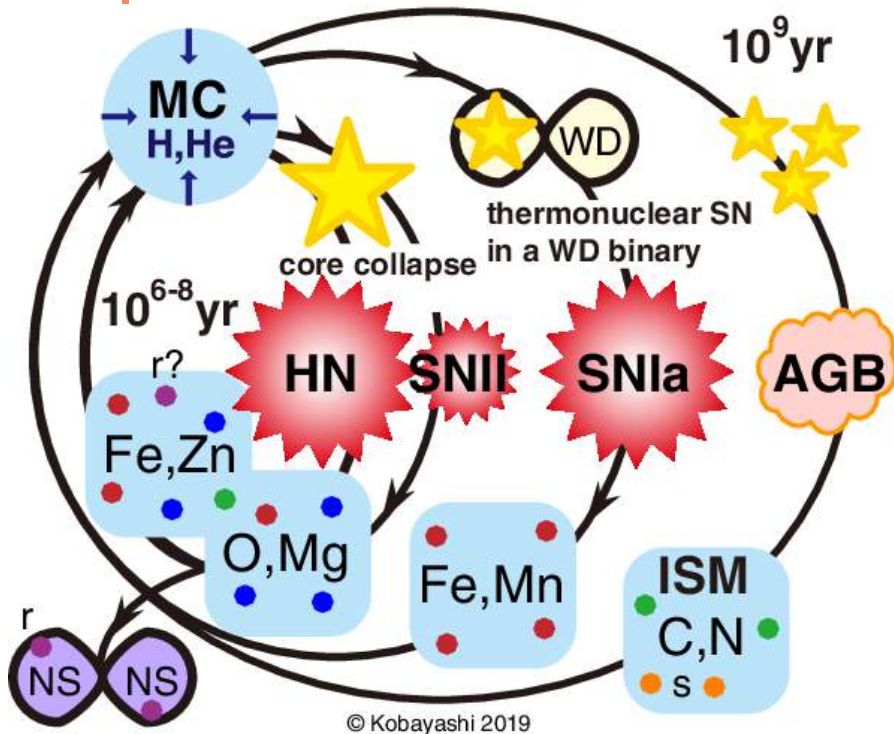
# Les rémanents



# Le cycle des étoiles



# L'enrichissement de la Galaxie



Graphic created by Jennifer Johnson  
<http://www.astronomy.ohio-state.edu/~jaj/nucleo/>

Astronomical Image Credits:  
 ESA/NASA/AASNova

Tableau périodique des éléments montrant leur abondance relative selon les sources naturelles responsables de leur création.



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# MERCI

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