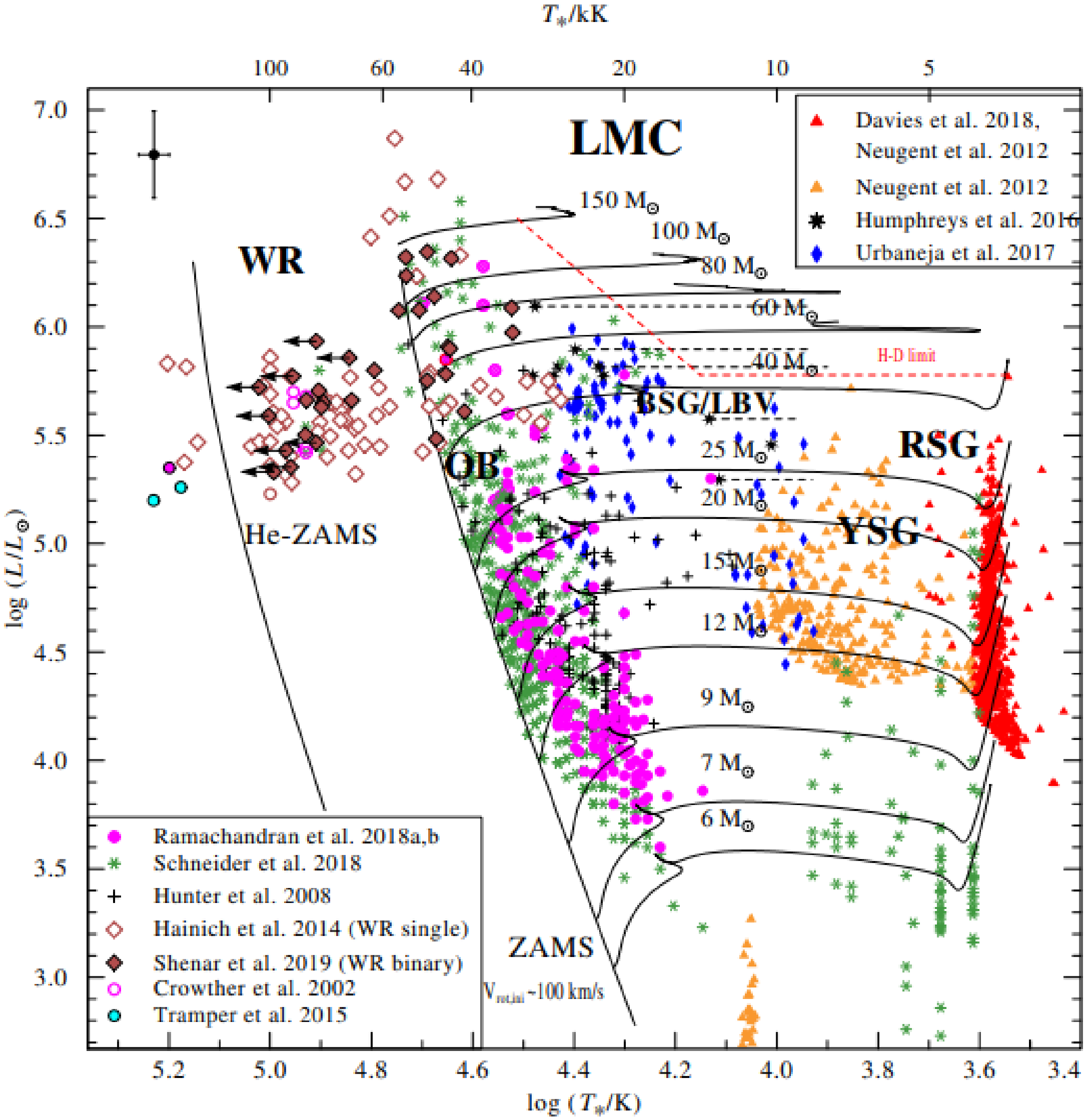
Episodic mass loss in two evolved Red Supergiants in the LMC

Gonzalo Muñoz Sánchez

ASSESS project, PI: A. Bonanos – National Observatory of Athens

1.- Introduction

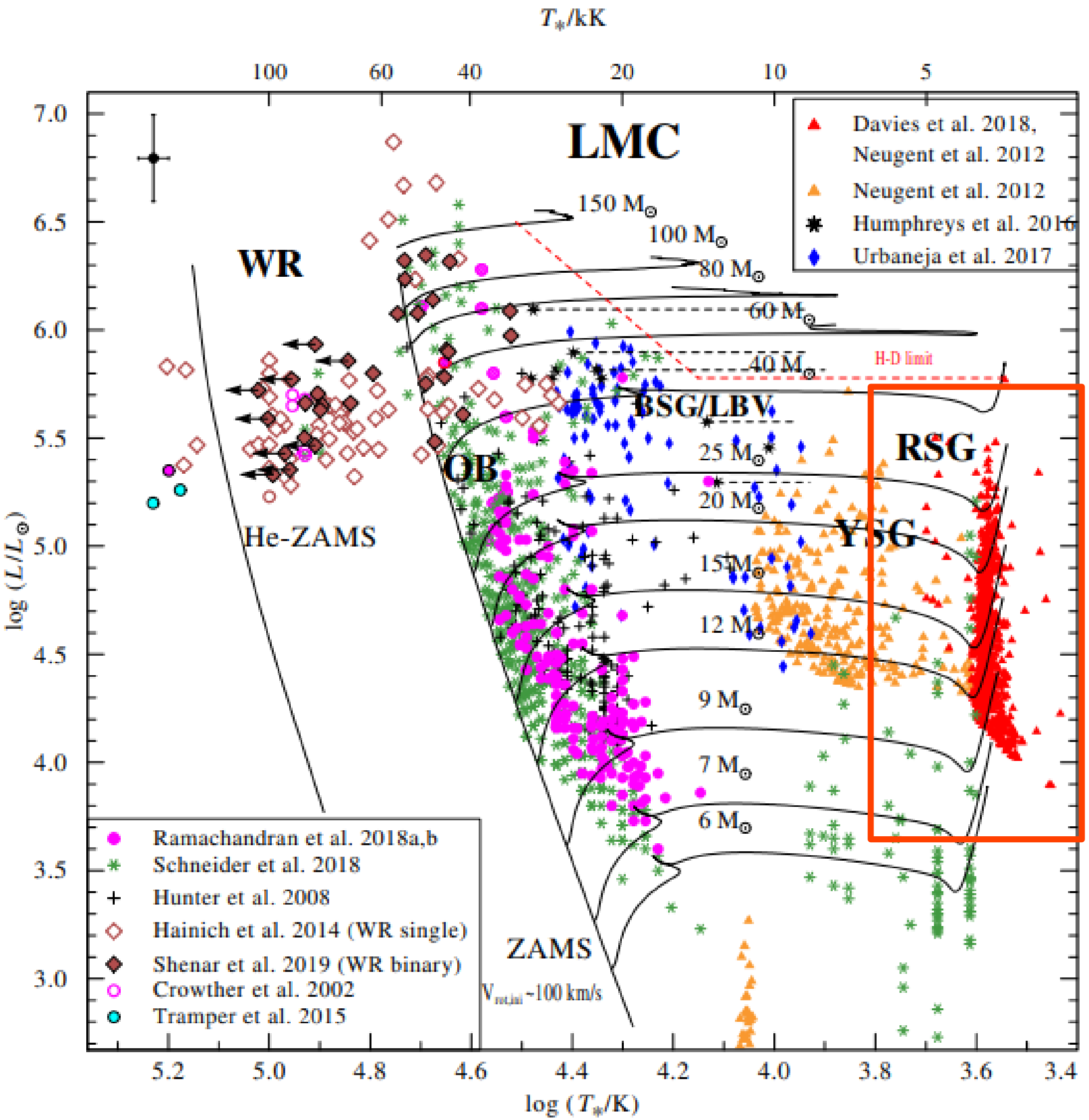
Zoo of massive stars



Gilkis et al 2021

- Wolf-Rayet (WR)
- Luminous Blue Variable (LBV)
- Blue Supergiant (BSG)
- Yellow Supergiant (YSG)
- Red Supergiant (RSG)

Zoo of massive stars



Gilkis et al 2021

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- Blue Supergiant (BSG)
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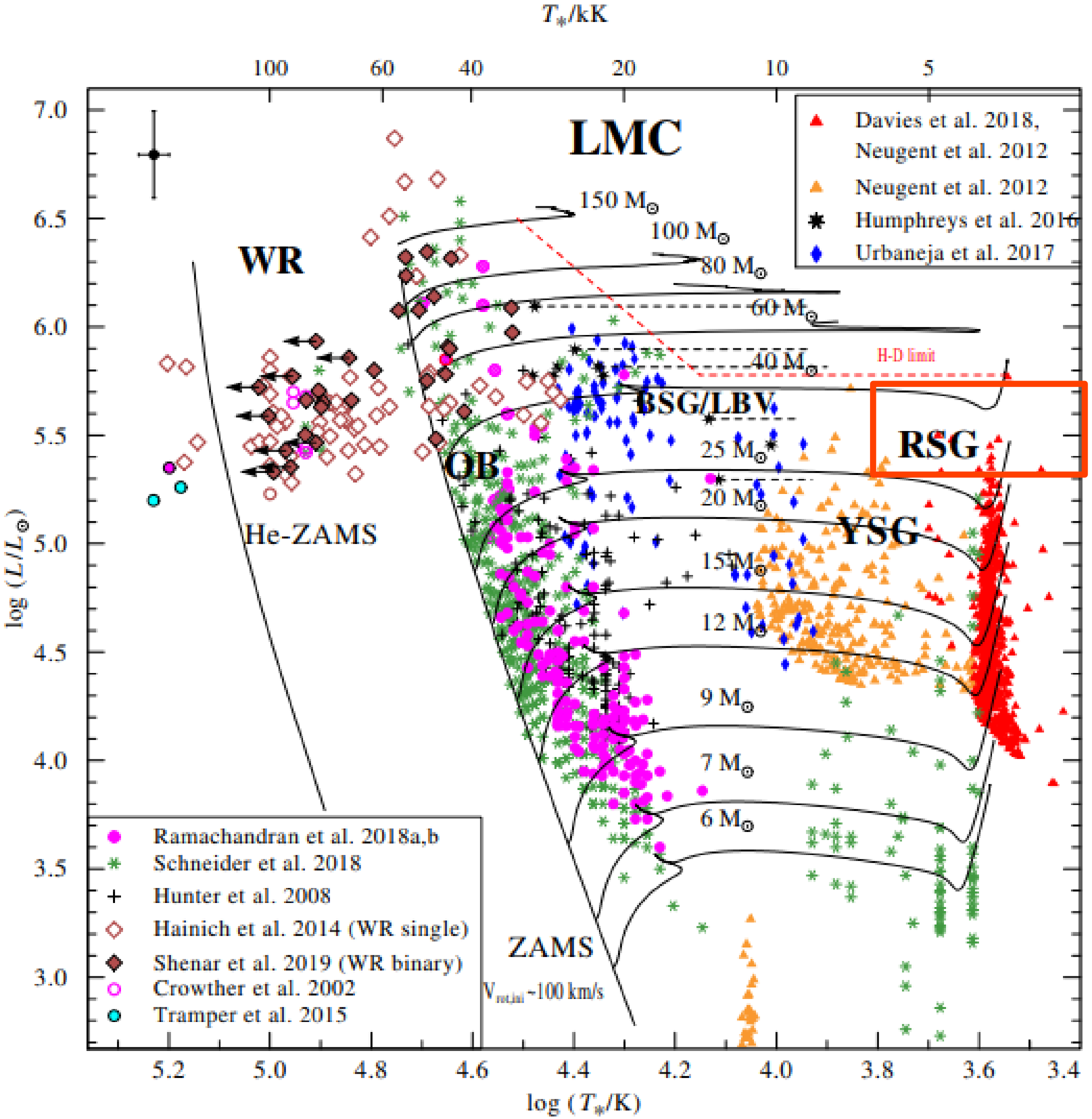
- **Red Supergiant (RSG)**

$8\,M_{sun} < M < 25\,M_{sun}$

$3300\text{ K} < T_{eff} < 4500\text{ K}$

$4.0 < \log(L/L_{sun}) < 5.5$

Zoo of massive stars



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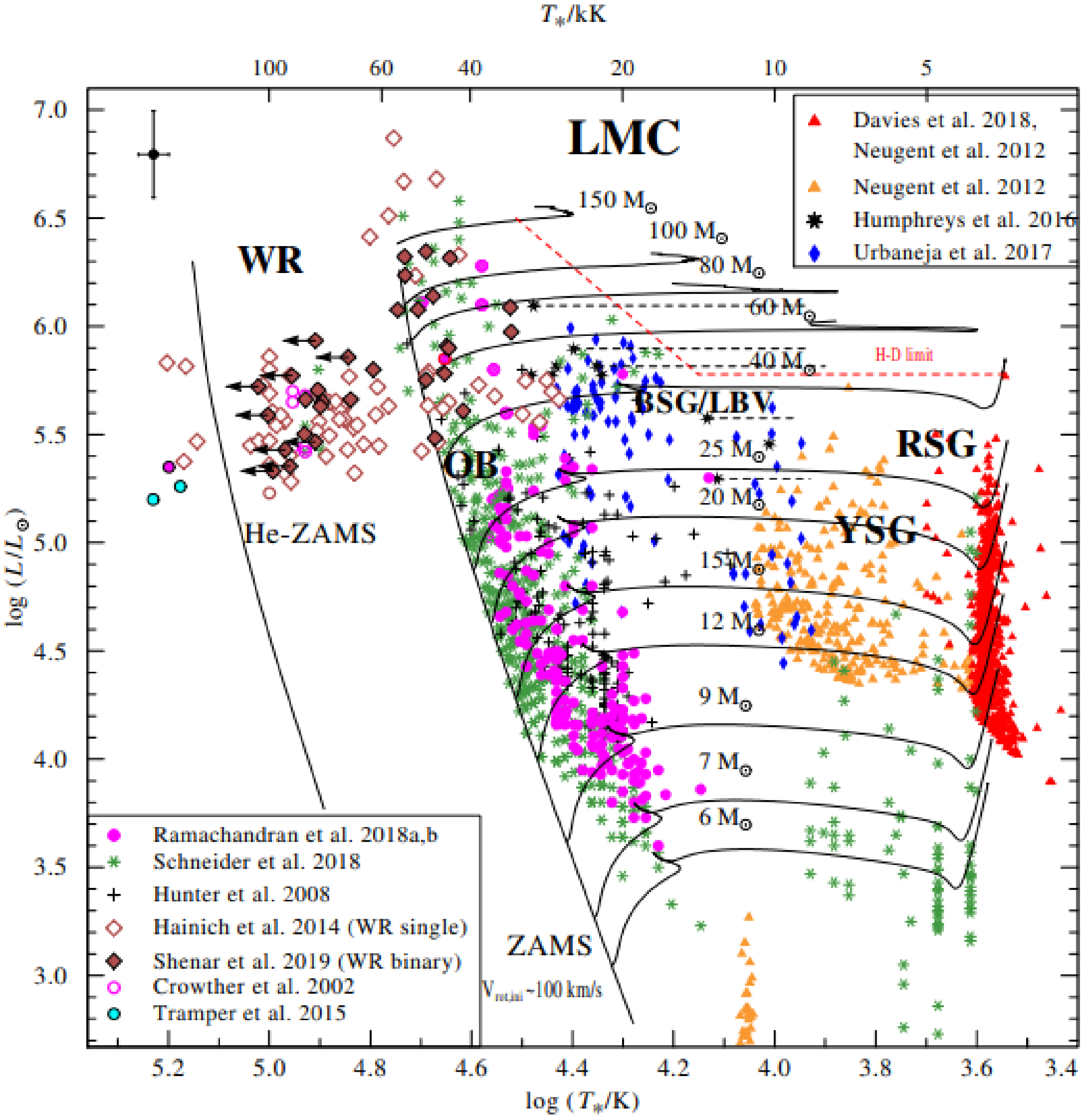
Extreme RSGs



Gilkis et al 2021

- Upper log(L/L_{sun}) limit?

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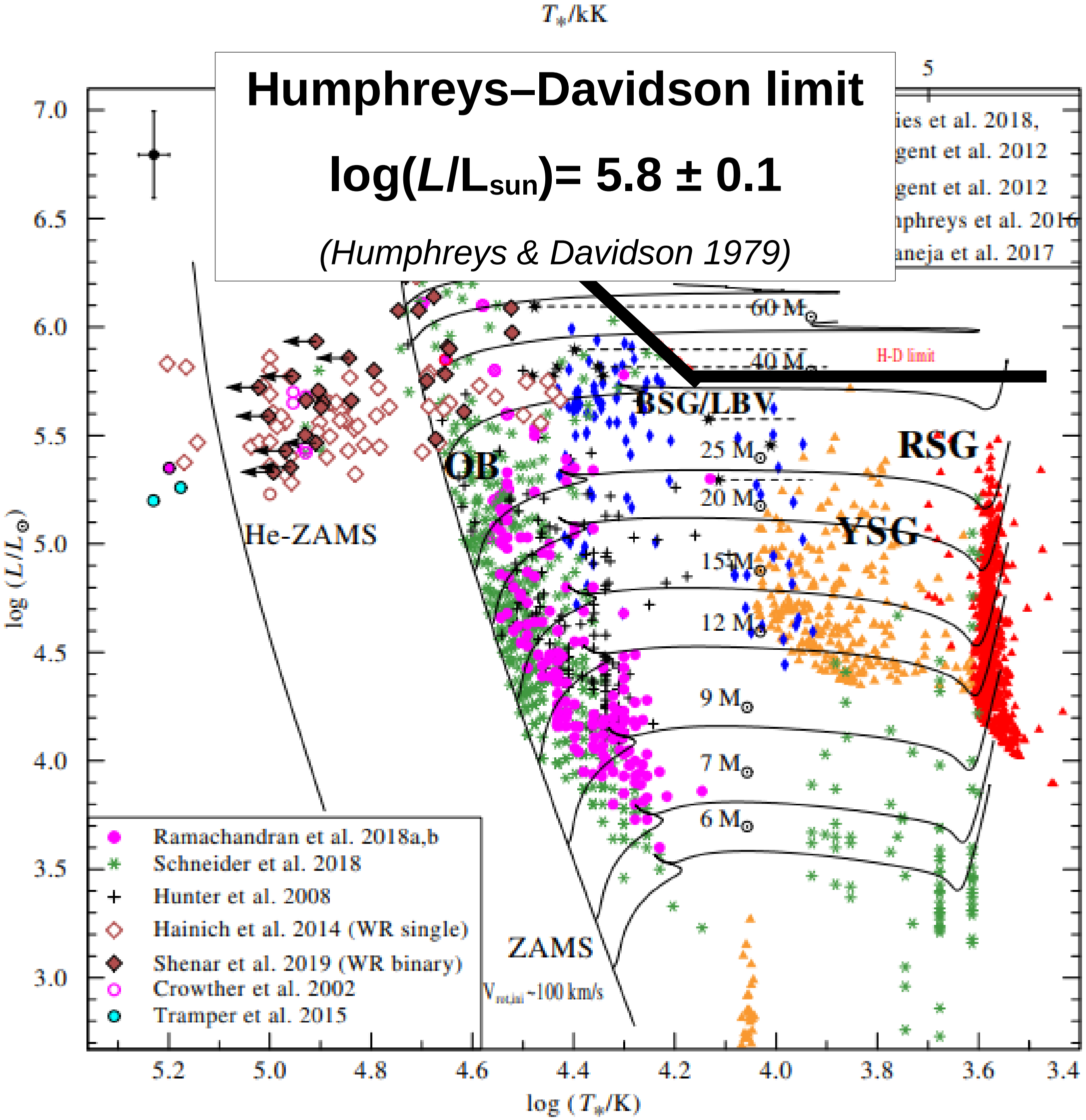

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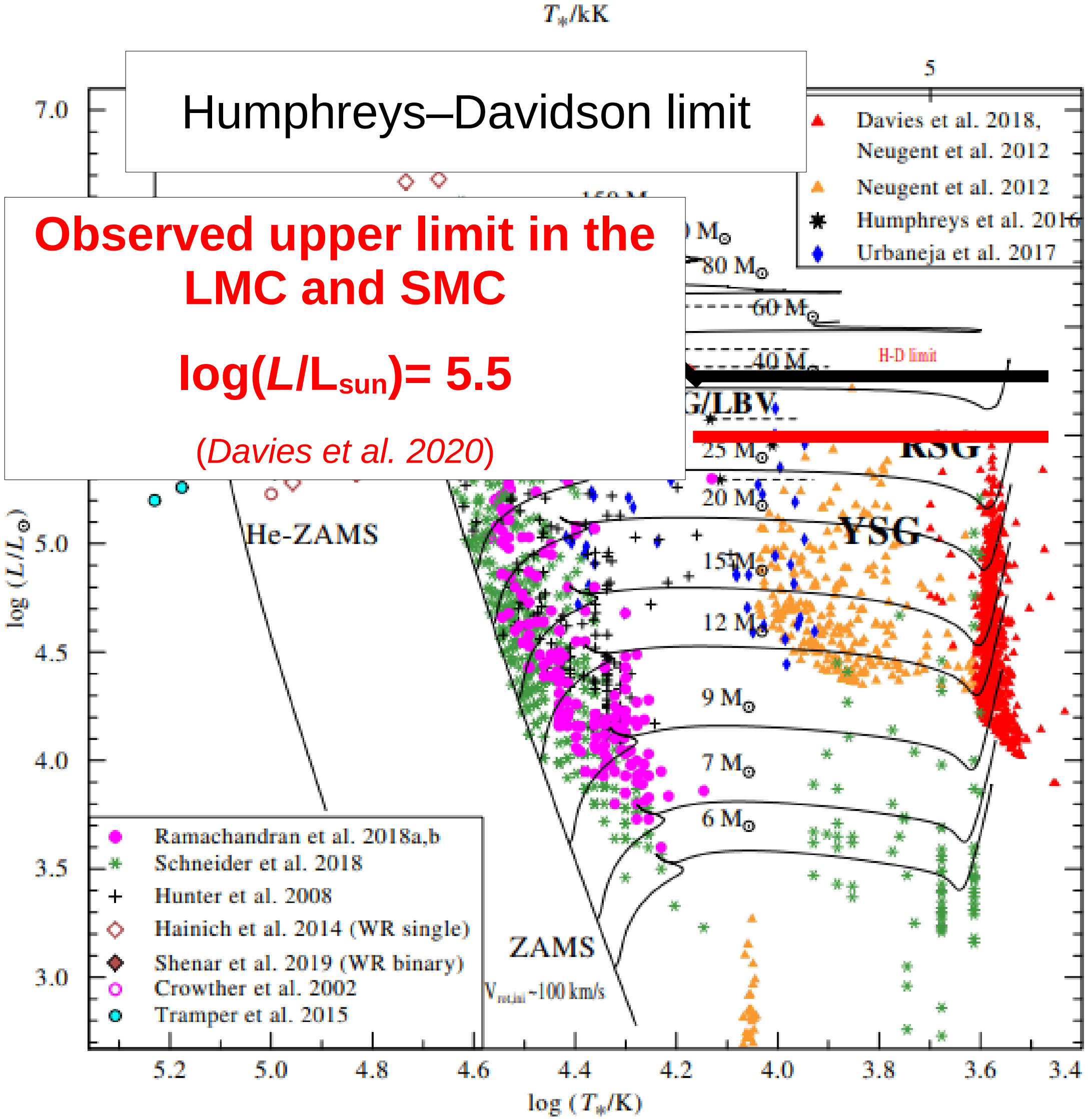


Humphreys–Davidson limit

Observed upper limit in the LMC and SMC

log(L/L_{sun})= 5.5

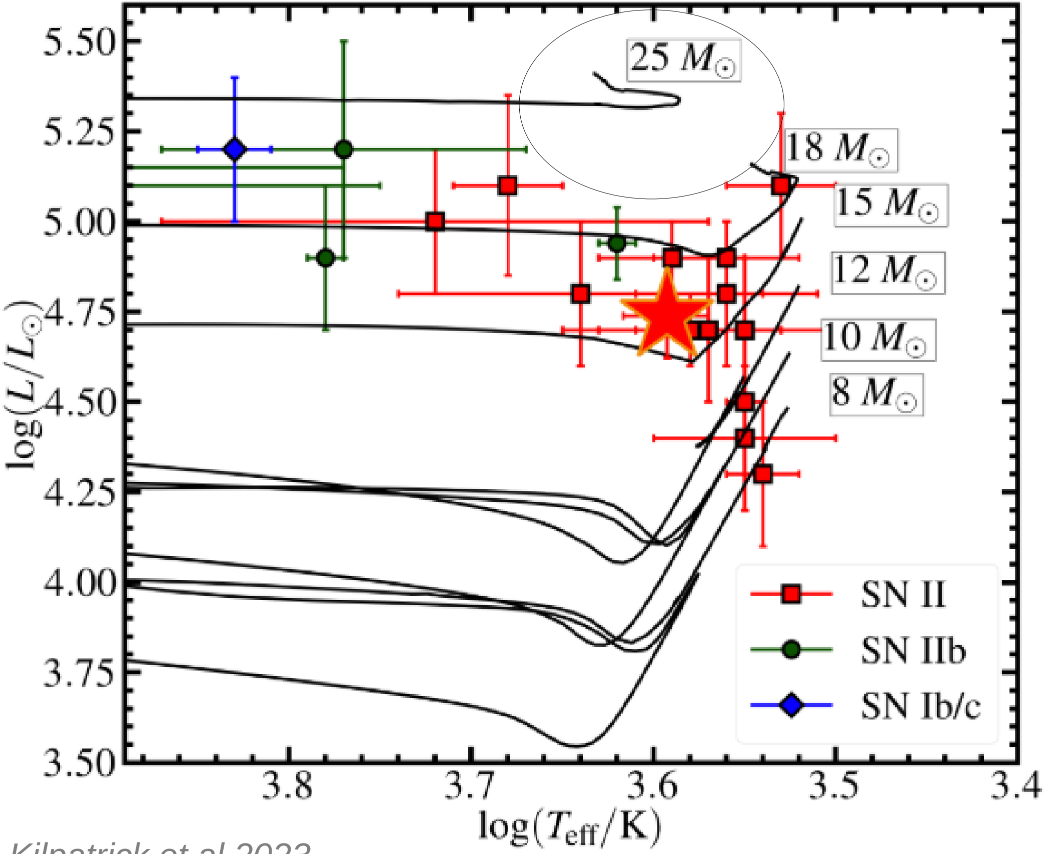
(*Davies et al. 2020*)

Gilkis et al 2021

- Upper log(L/L_{sun}) limit?

Extreme RSGs

Supernova progenitors

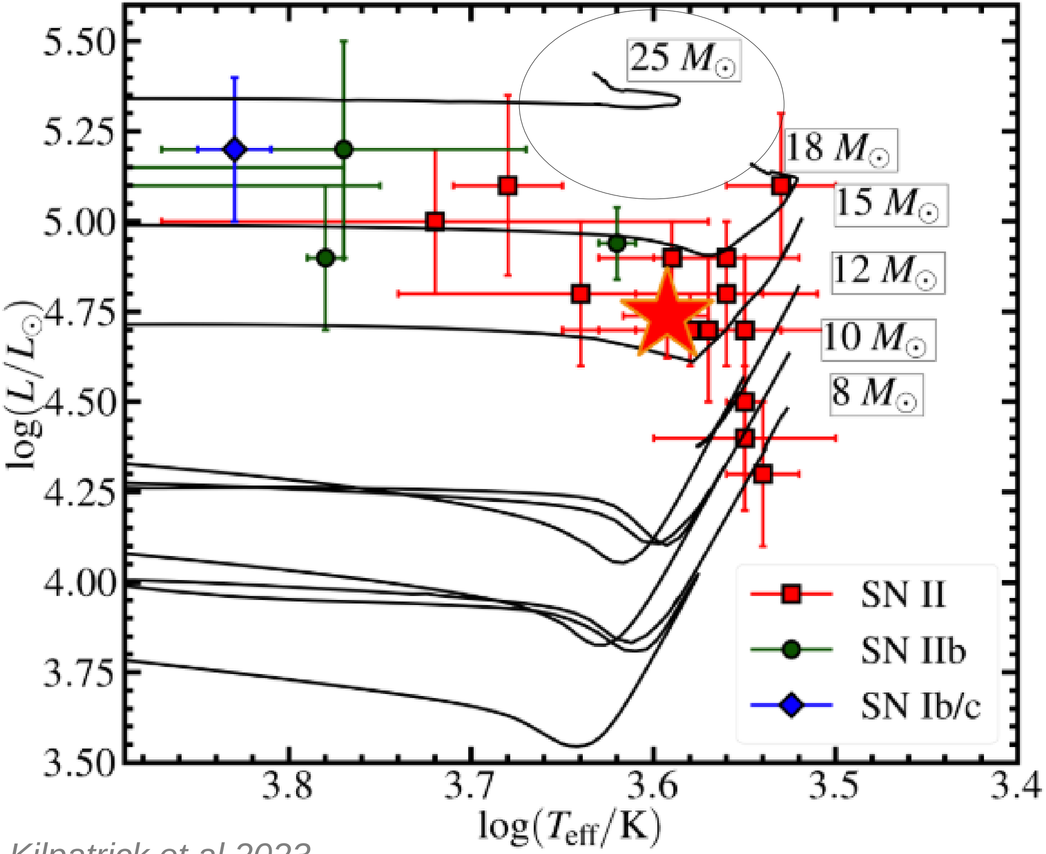


Kilpatrick et al 2023

- Upper $\log(L/L_{sun})$ limit?
- "RSG problem" for M_{in} > 18 M_{sun}

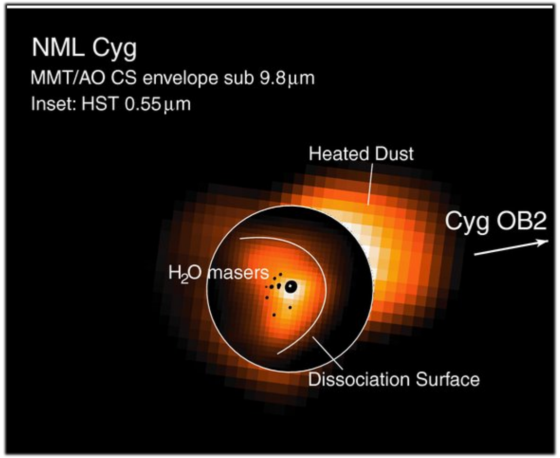
Extreme RSGs

Supernova progenitors



Kilpatrick et al 2023

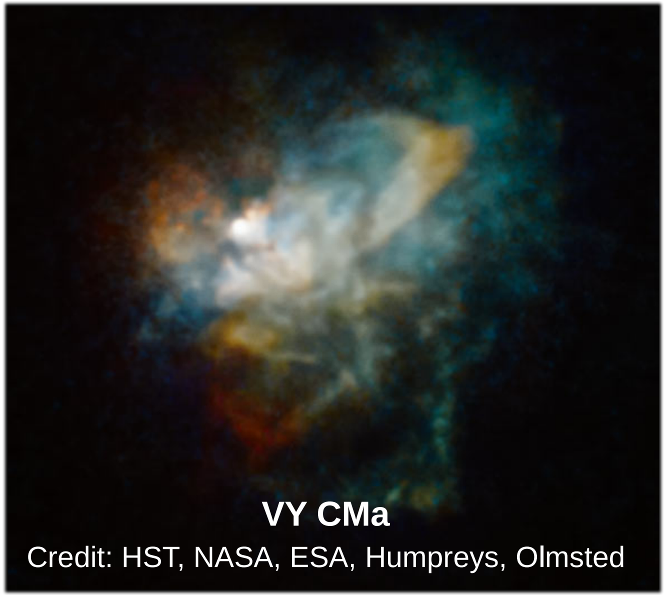
- Upper $\log(L/L_{sun})$ limit?
- "RSG problem" for M_{in} > 18 M_{sun}
  - Hotter post-RSG phase
  - Implosion to black hole
  - Problem not real

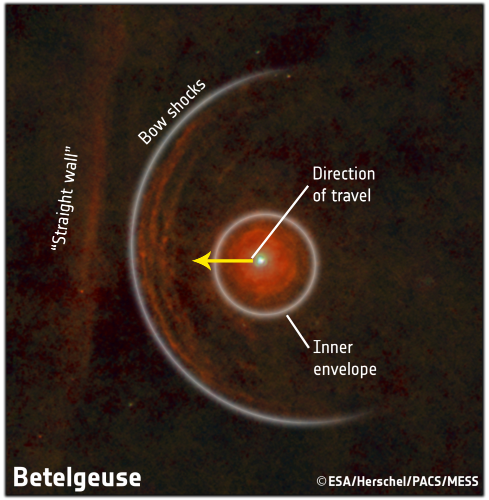


Extreme RSGs

- Upper log(L/L_{sun}) limit?
- "RSG problem" for M_{in} > 18 M_{sun}
- Evidence of episodic mass-loss: role?

  - NML Cyg
  - VY CMa
  - Betelgeuse

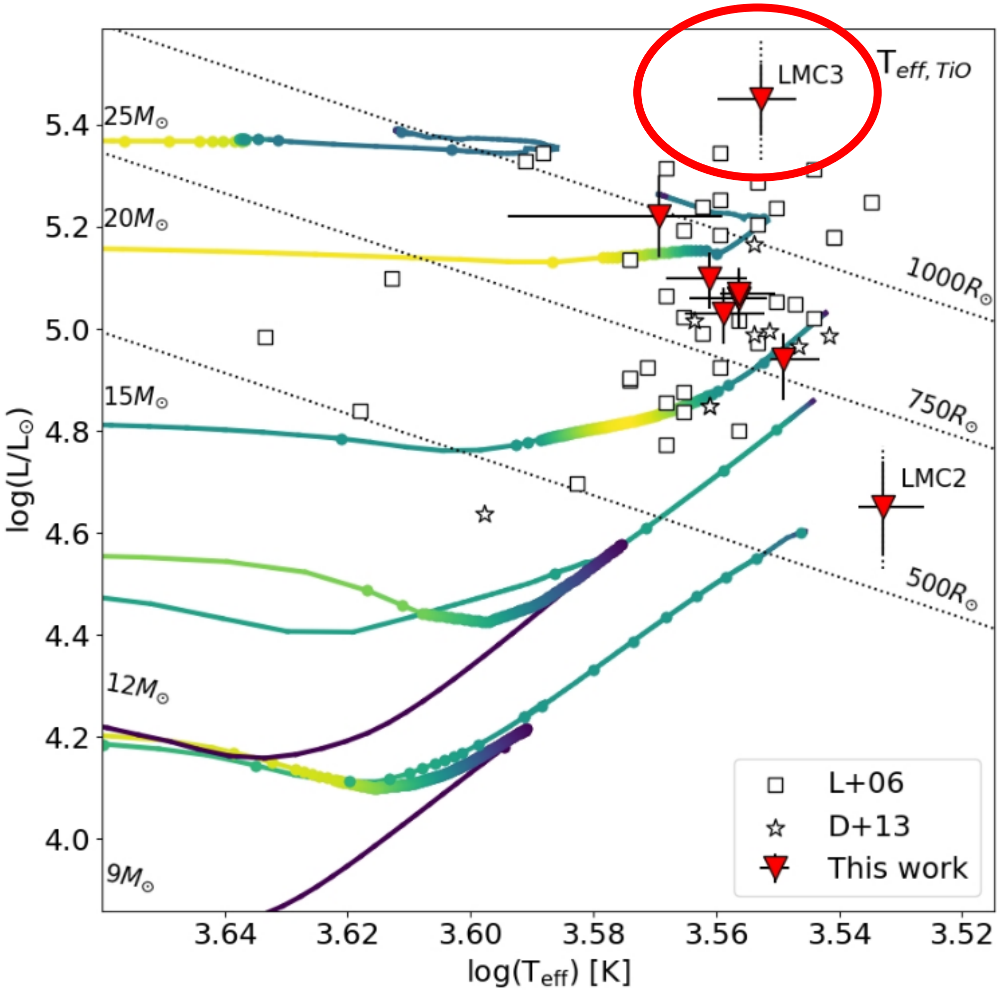




1.- Introduction

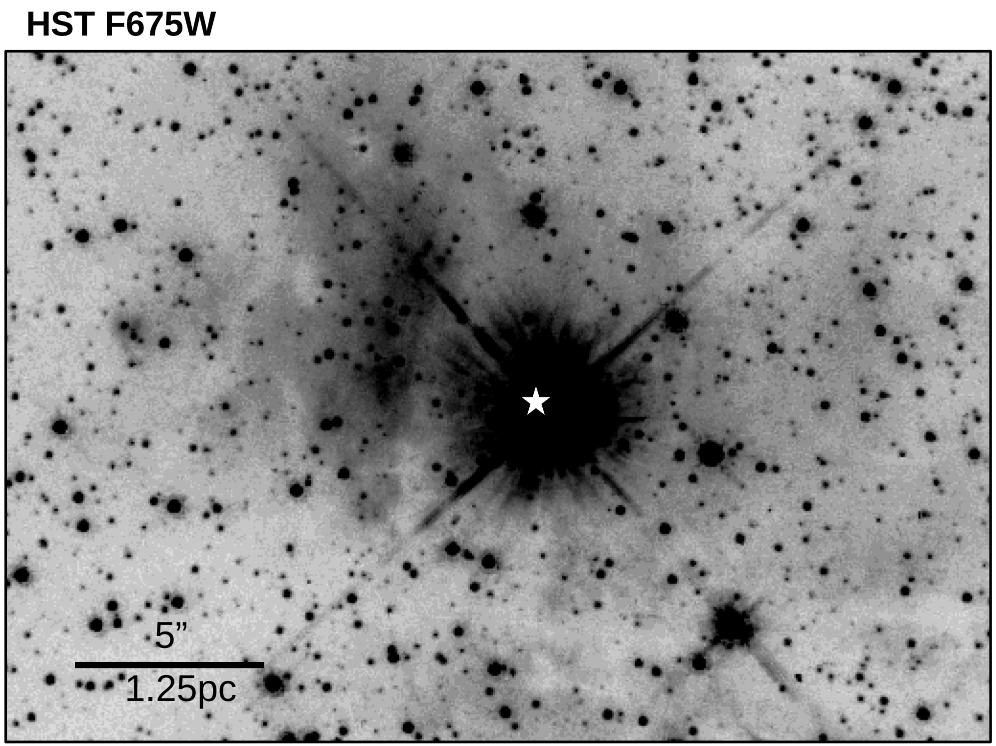
2.- [W60] B90

a) Motivation

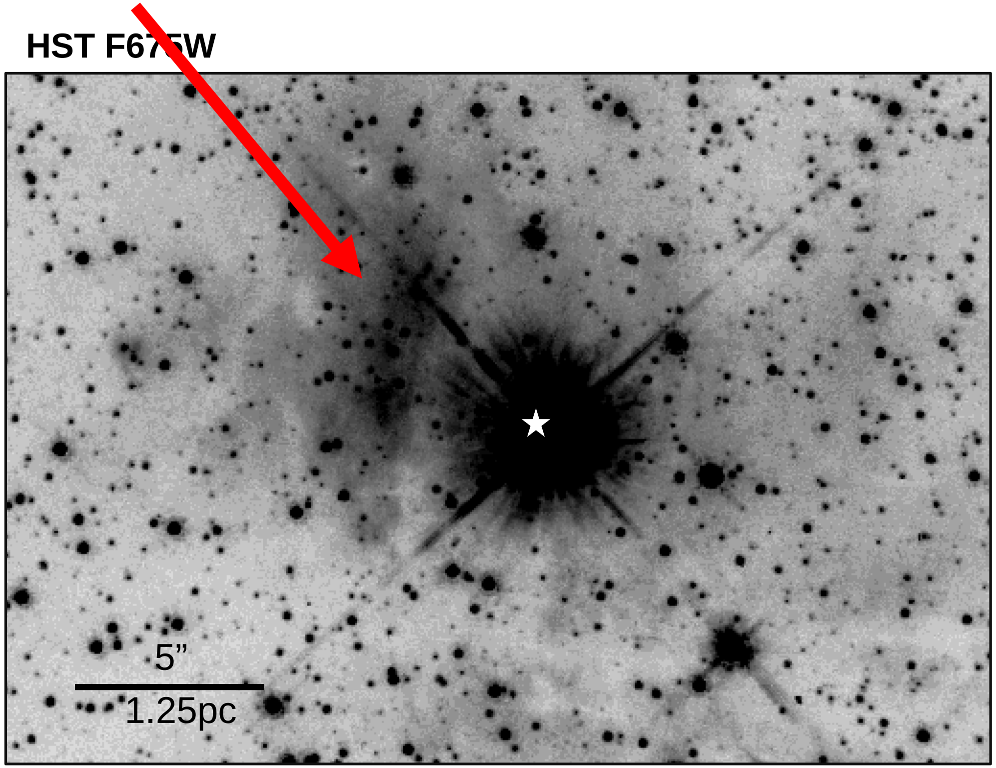


de Wit et al. 2023

- **LMC** (d ≈ 50 kpc)
- **Dusty:** IR-excess
- **Not** predicted by **MIST**
- Properties:
  - **- log(*L*/*L*$_{sun}$)= 5.32 ± 0.01** (*Antoniadis et al. 2024*)
  - **- *R* ≈ 1200 R$_{sun}$**
  - **- *A*$_V$ > 3 mag**
  - - $\dot{M}$ = 4.4 · 10^{-6} M$_{sun}$/yr (*Antoniadis et al. 2024*)



[W60] B90



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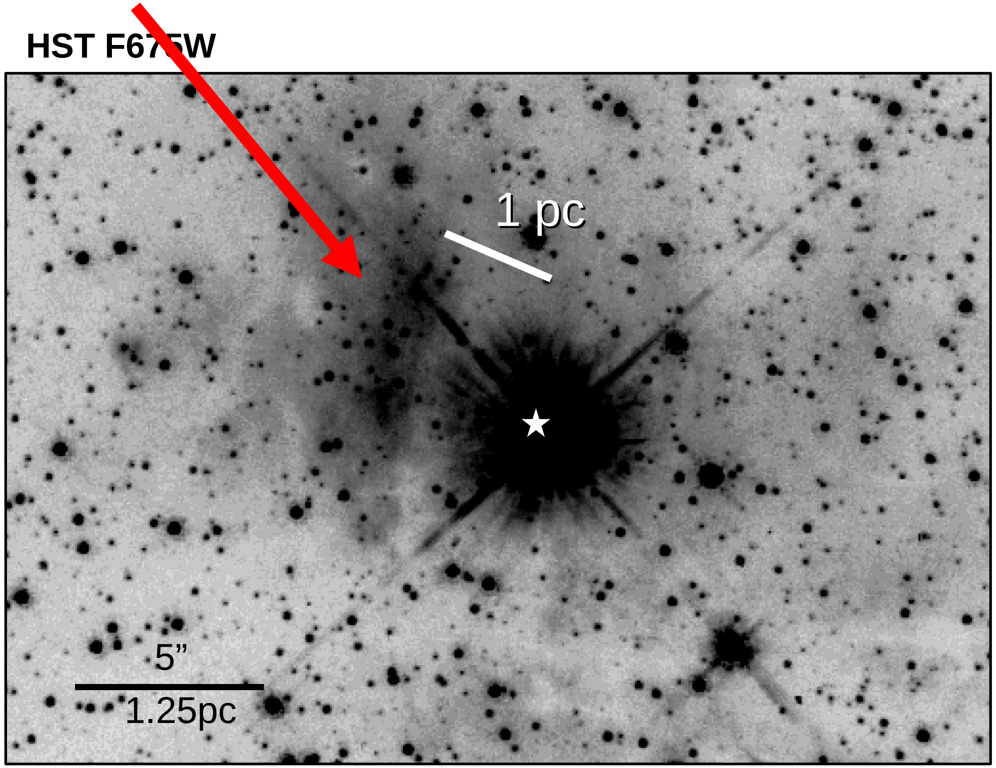

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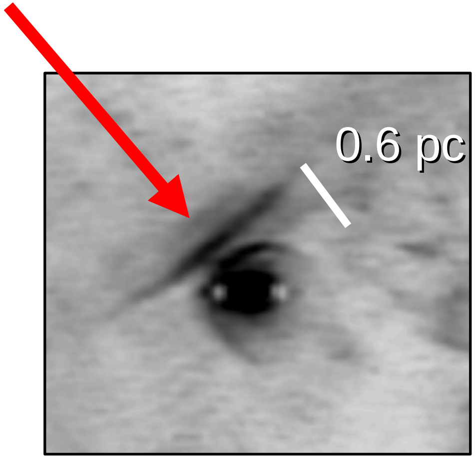
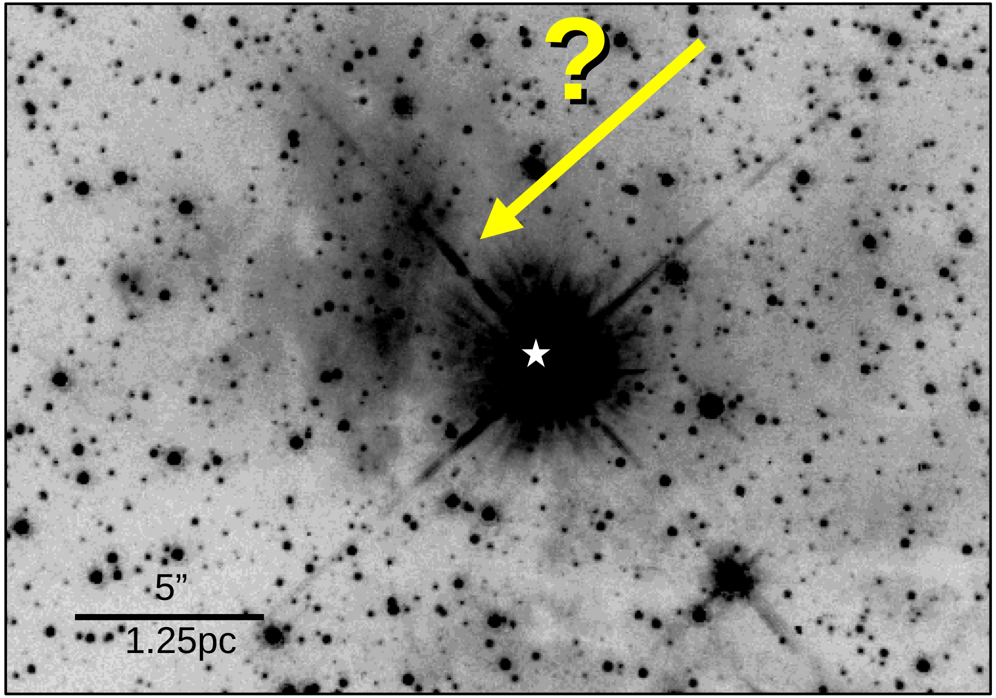


Betelgeuse *Mackey et al. 2012*

HST F675W



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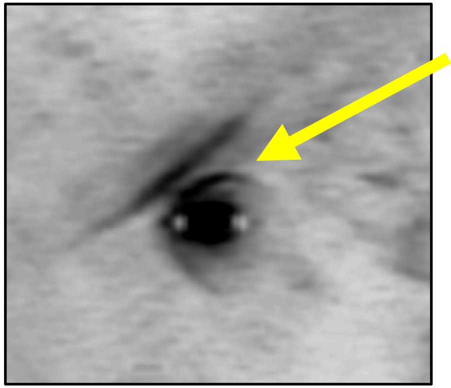

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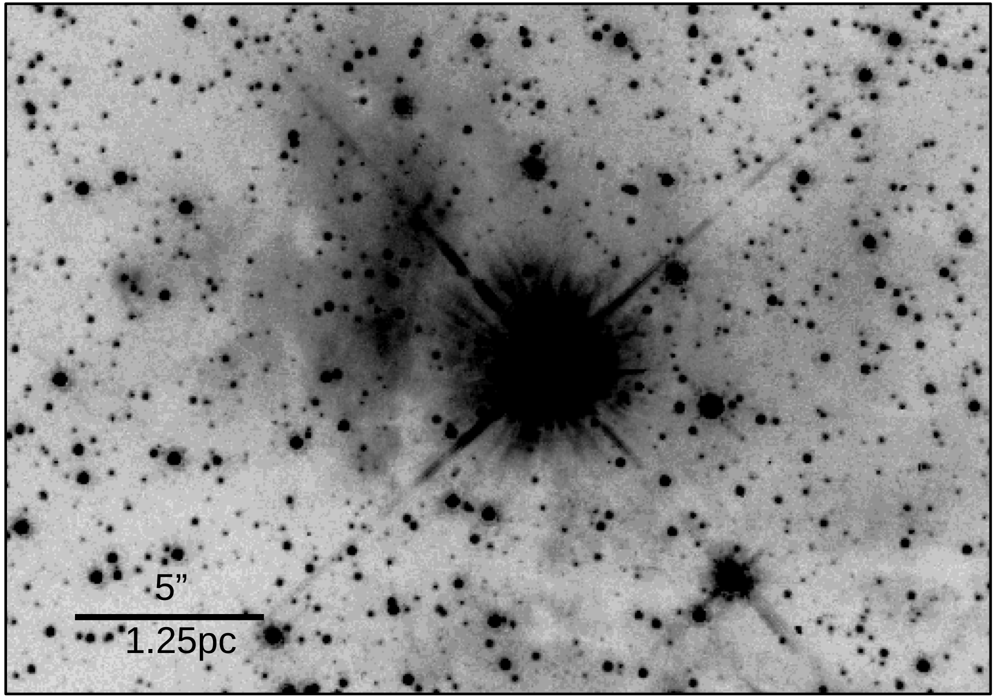
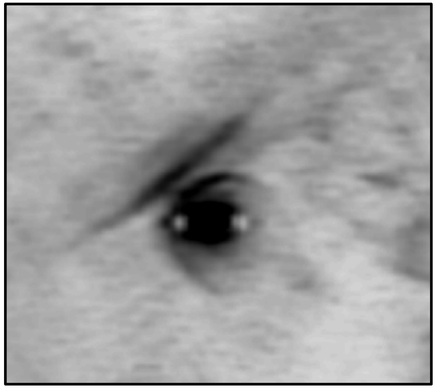


[W60] B90

far-IR



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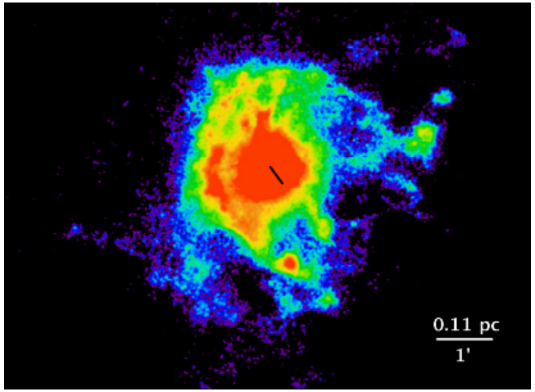
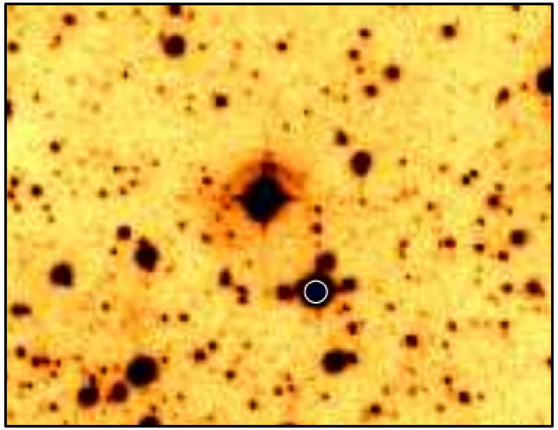


μ Cep *Cox et al. 2012*

Optical



IRC - 10414
Gvaramadze et al. 2012

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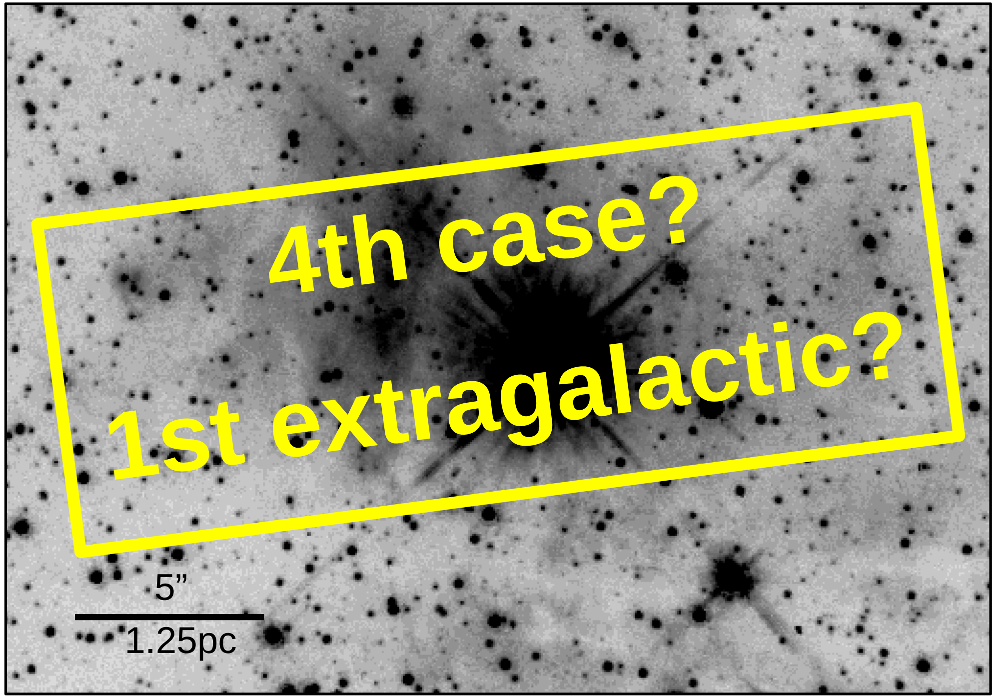

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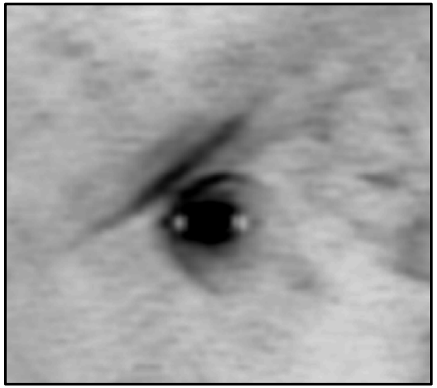

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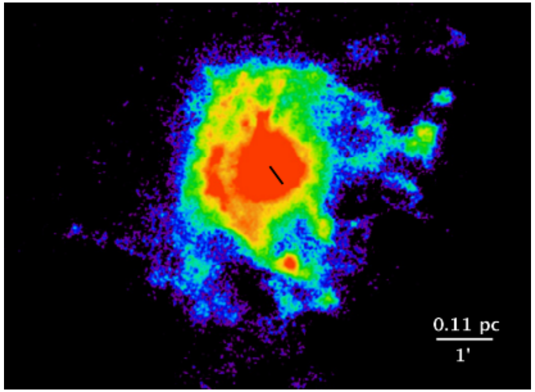

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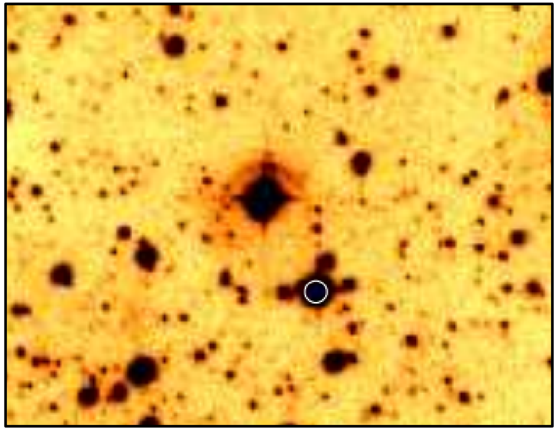


IRC - 10414
Gvaramadze et al. 2012

1.- Introduction

2.- [W60] B90

a) Motivation

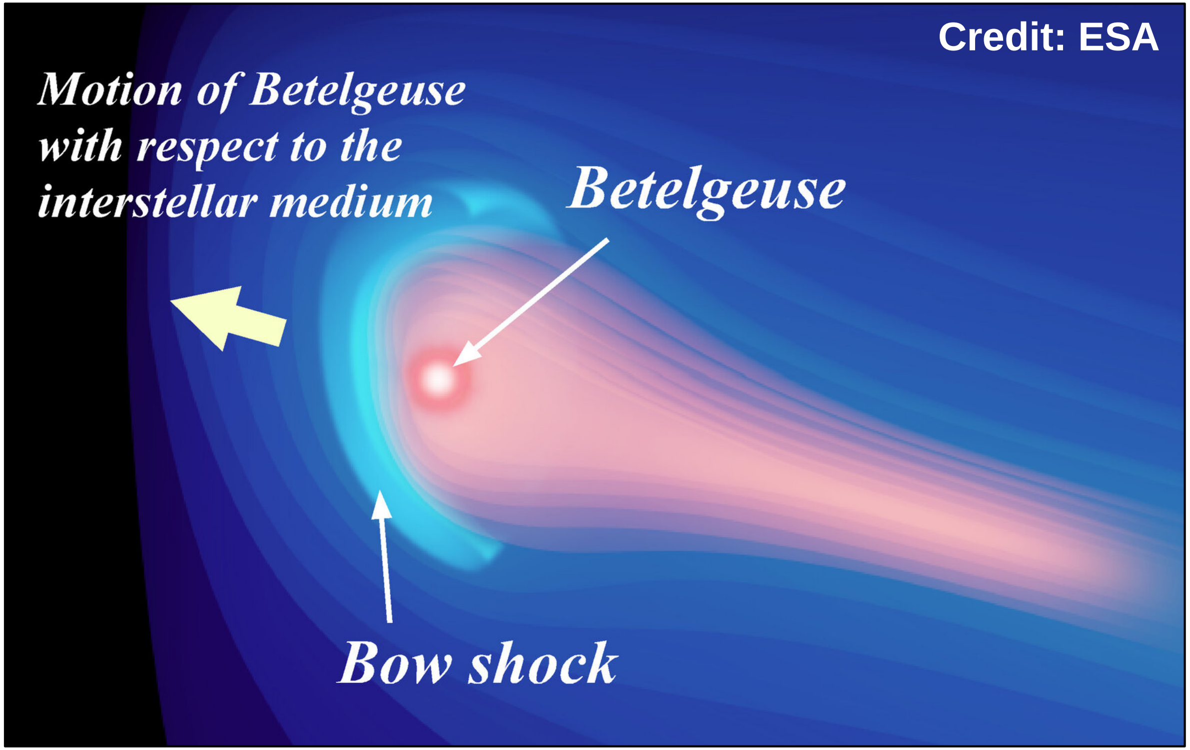
b) Bow shock

Wilkin 1996

- Supersonic movement respect to the ISM
- Wind interacting with ISM

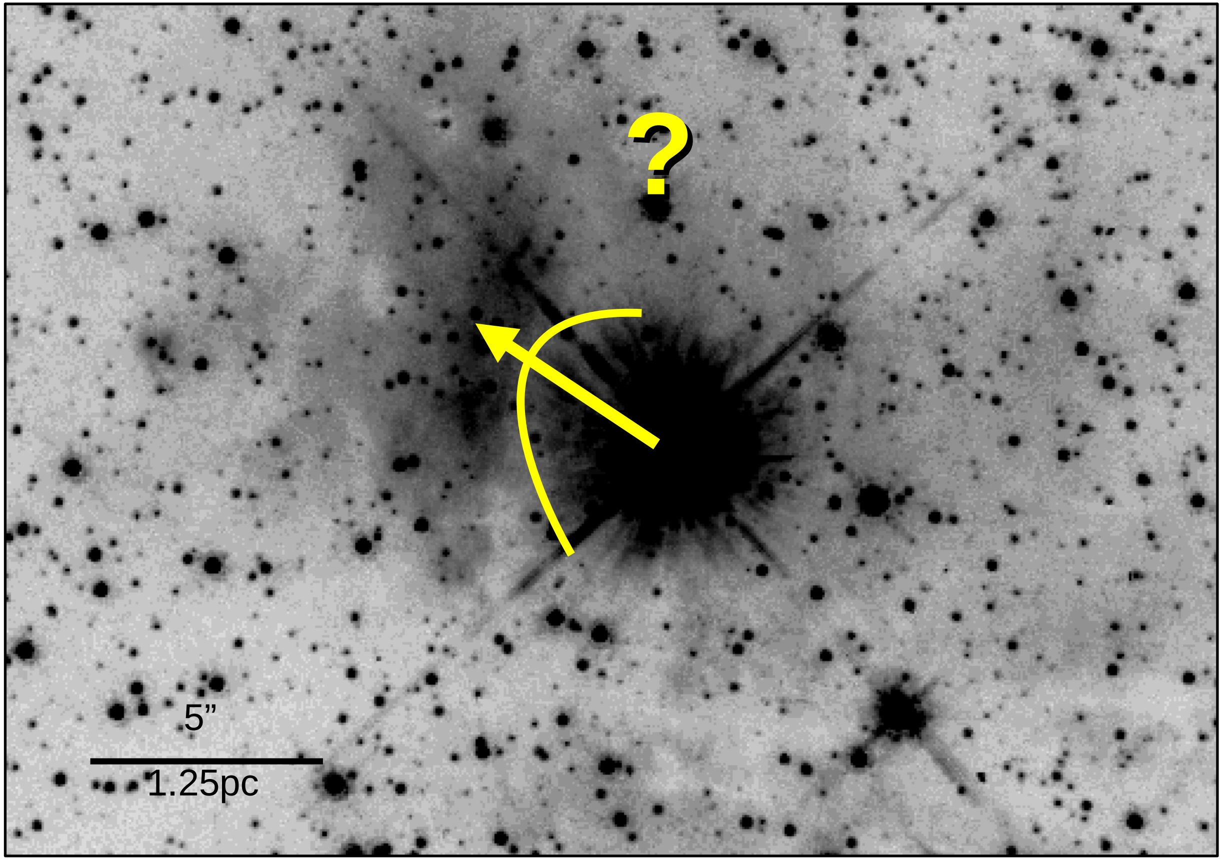
$$R_0 = \sqrt{\frac{\dot{m}_w V_w}{4\pi\rho_a V_*^2}}$$

$\dot{m}_w$: **mass-loss rate** !!
V_w: wind speed
ρ_a: density of the medium
V_*: star's velocity



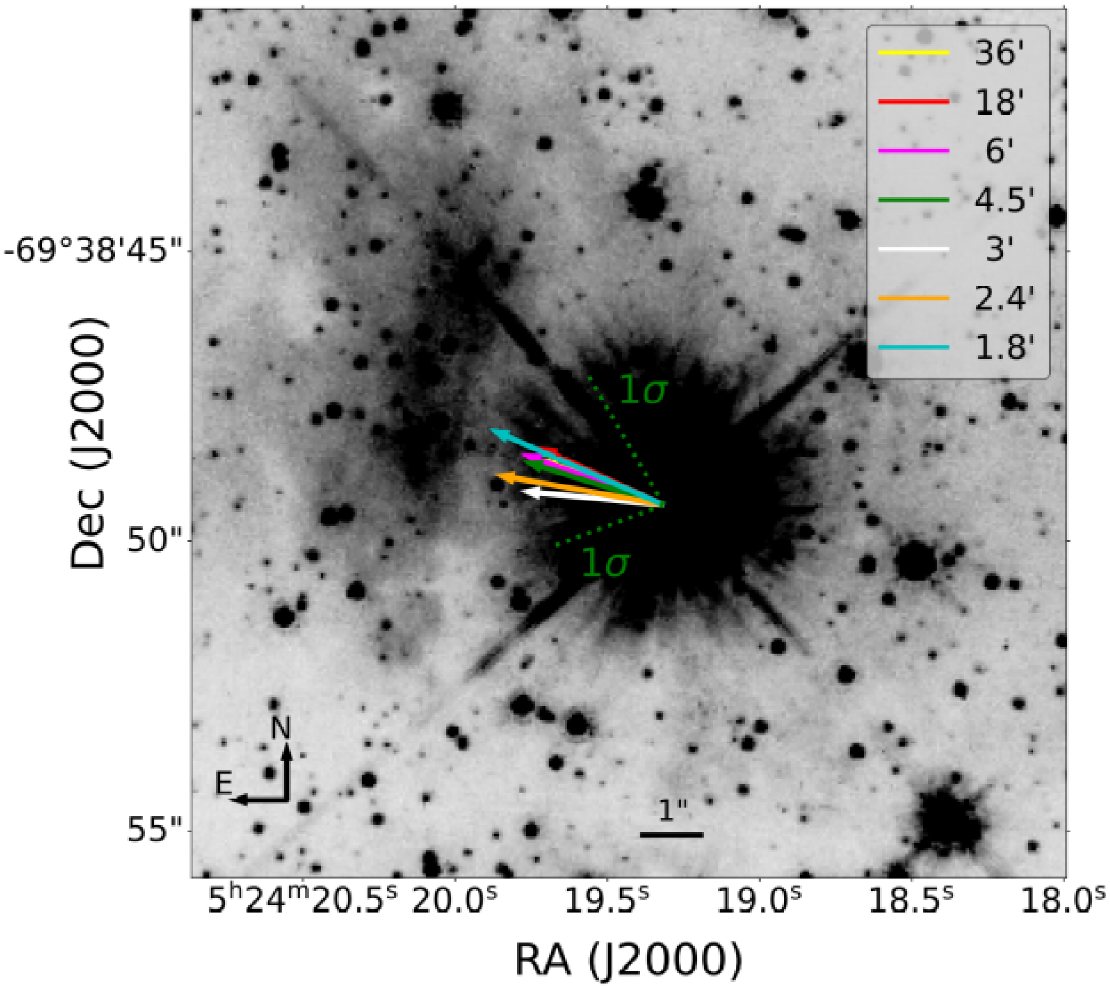
Looking for the bow shock

HST F675W



Looking for the bow shock

- Check [W60] B90 local proper motion



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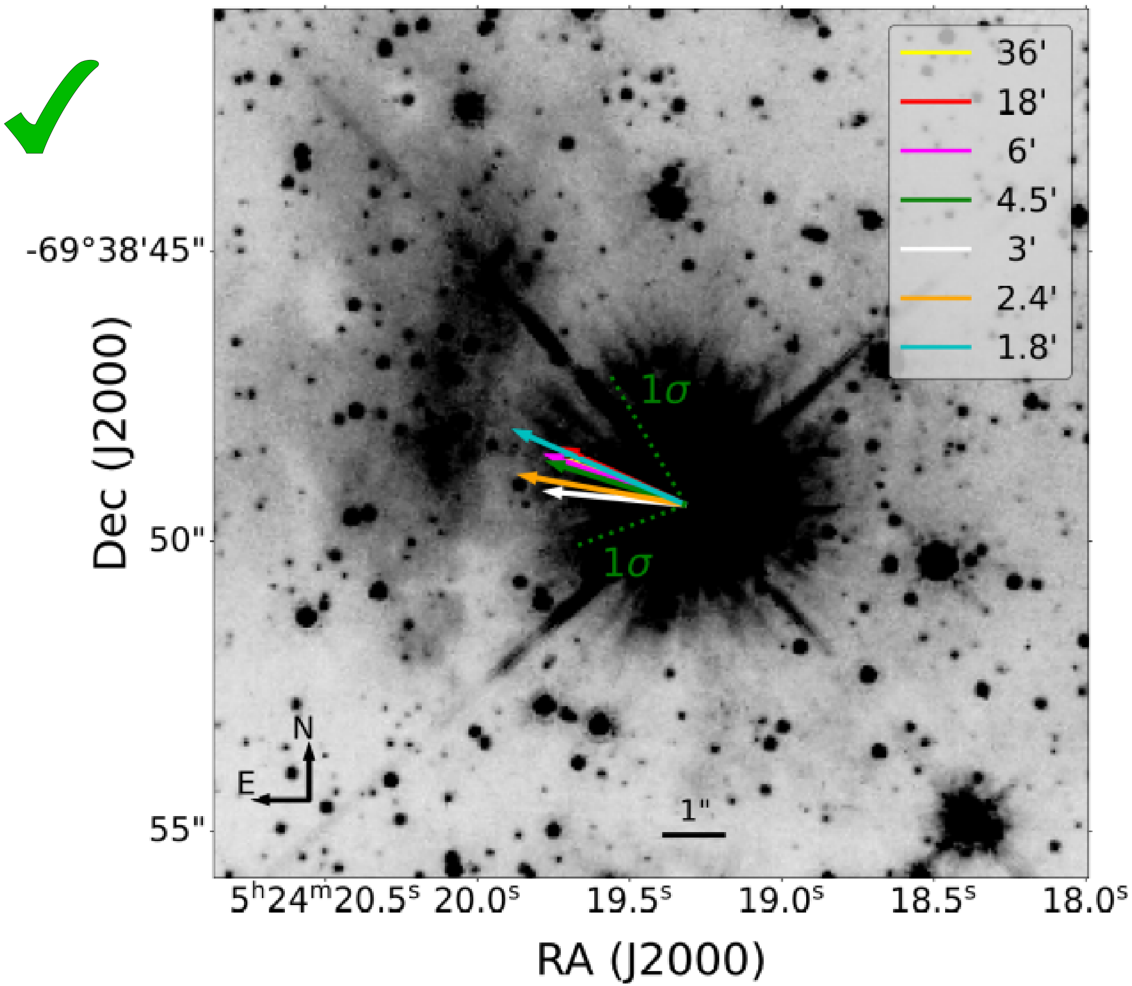


Looking for the bow shock

- Check [W60] B90 local proper motion

- Spectroscopy MagE, 6.5-m Baade
  (Las Campanas, Chile)

- **[S II]/Hα** < 0.4 : photoionization
  ≥ **0.4 : shocked**

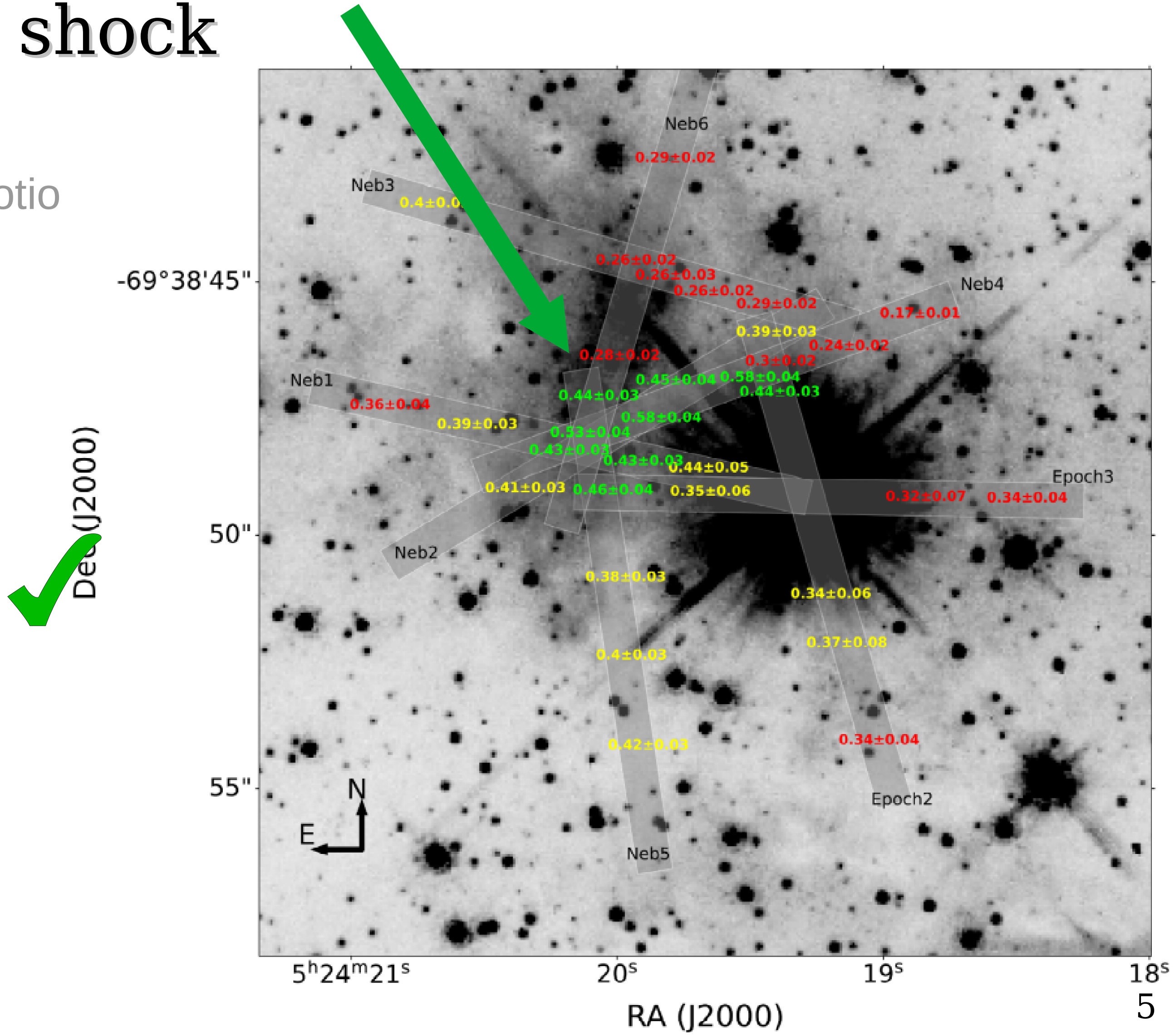
- [S II]: 6716Å & 6731Å

Looking for the bow shock

- Check [W60] B90 local proper motio
- Spectroscopy MagE, 6.5-m Baade
  (Las Campanas, Chile)
- **[S II]/Hα ≥ 0.4**

  - Consistent with the proper motion

  - Where the bow shock is expected



Looking for the bow shock

- Check [W60] B90 local proper motio
- Spectroscopy MagE, 6.5-m Baade
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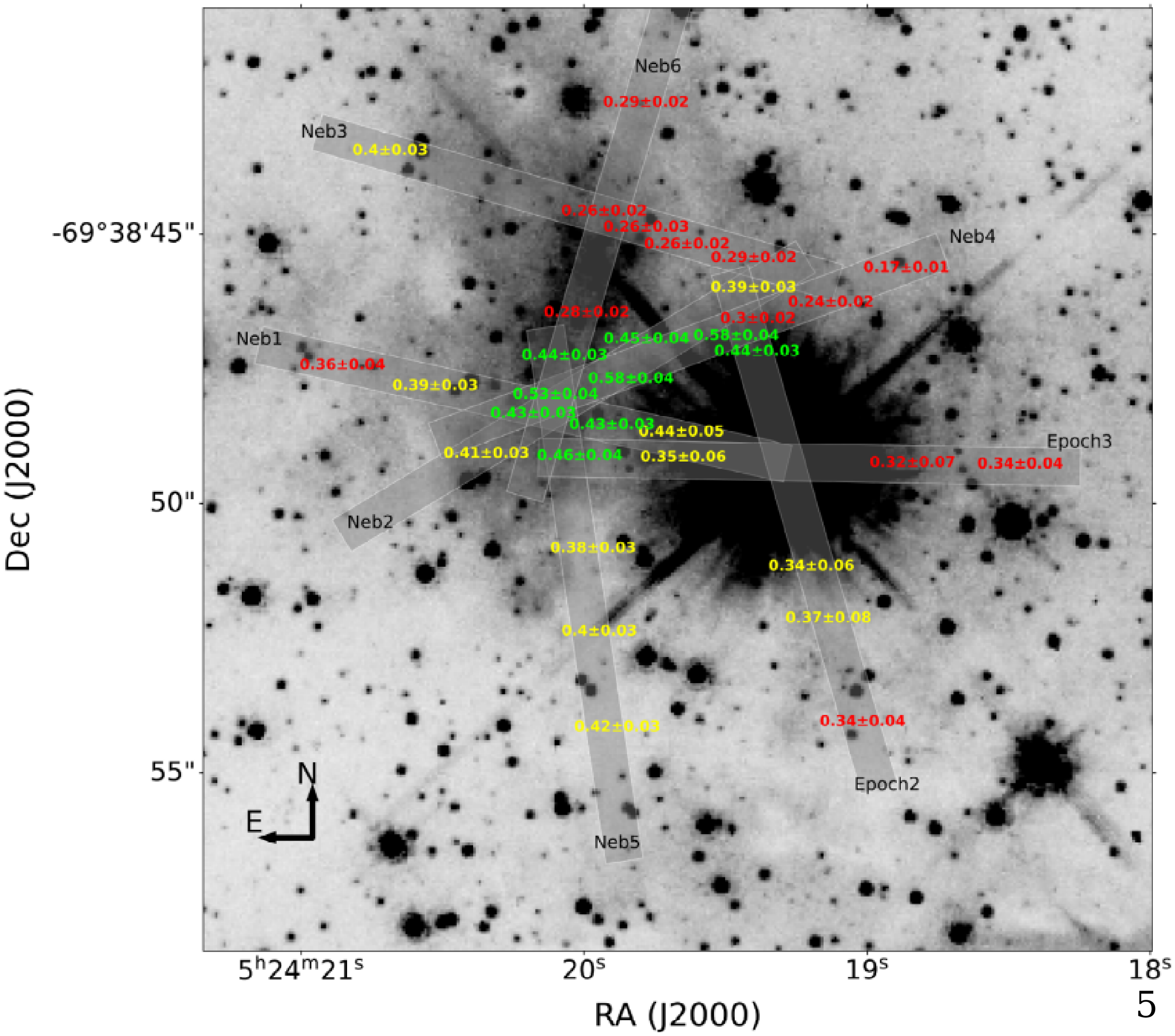
- [S II]/Hα ≥ 0.4
- **No bow-shape structure**
  - **-** Block stellar flux: coronagraph
  - Limited by spatial resolution
  - near-IR & mid-IR



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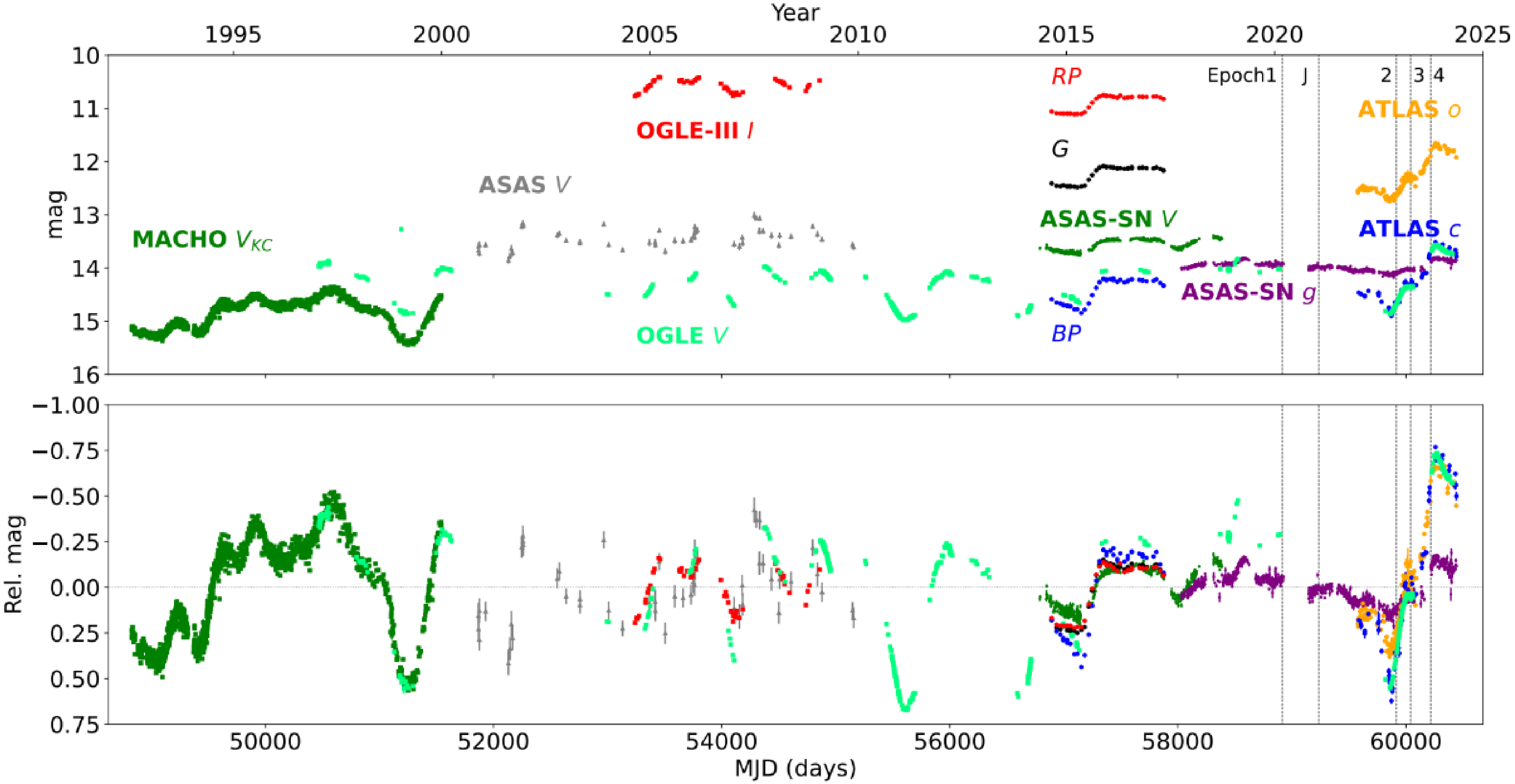
c) Variability

Photometric variability



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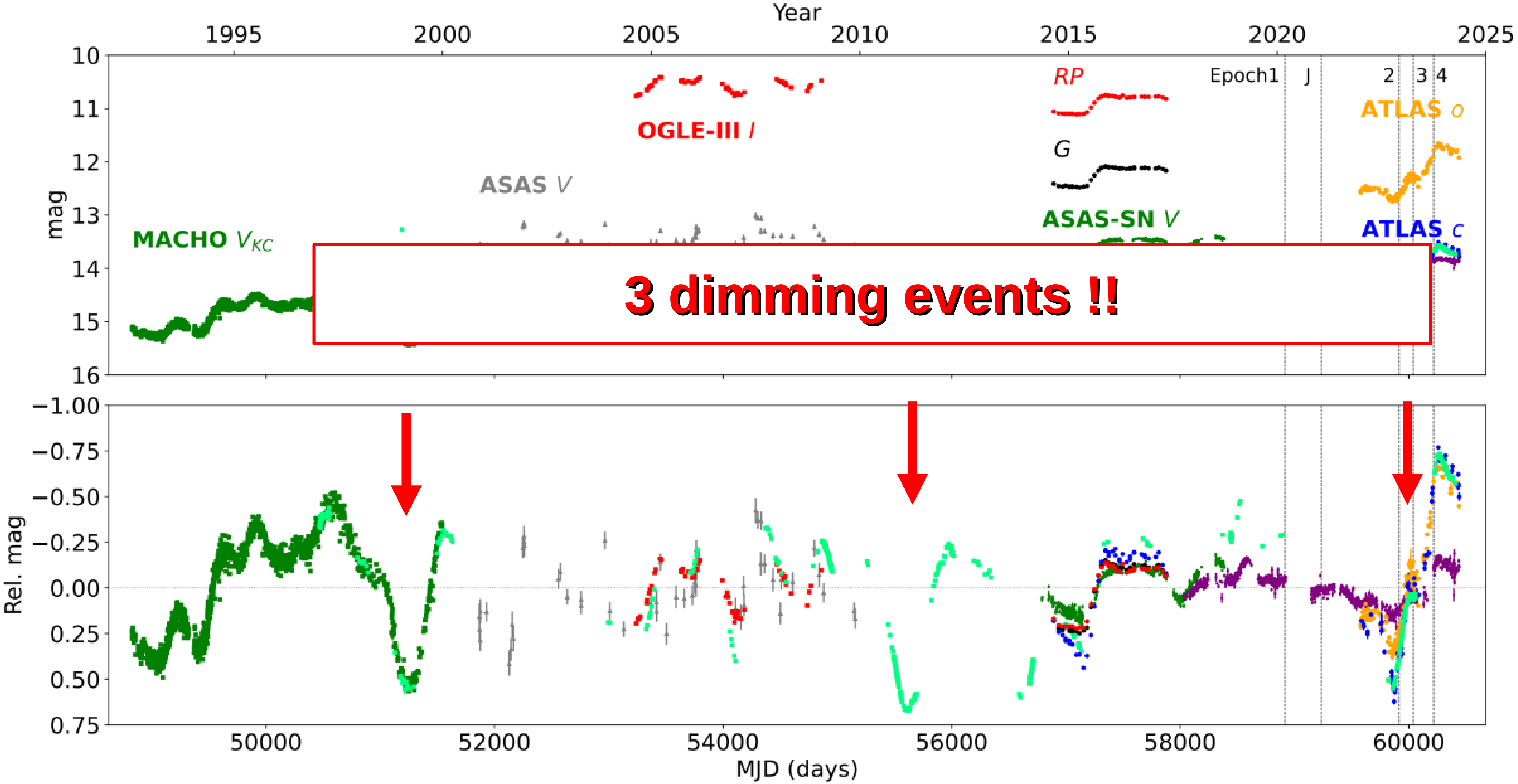


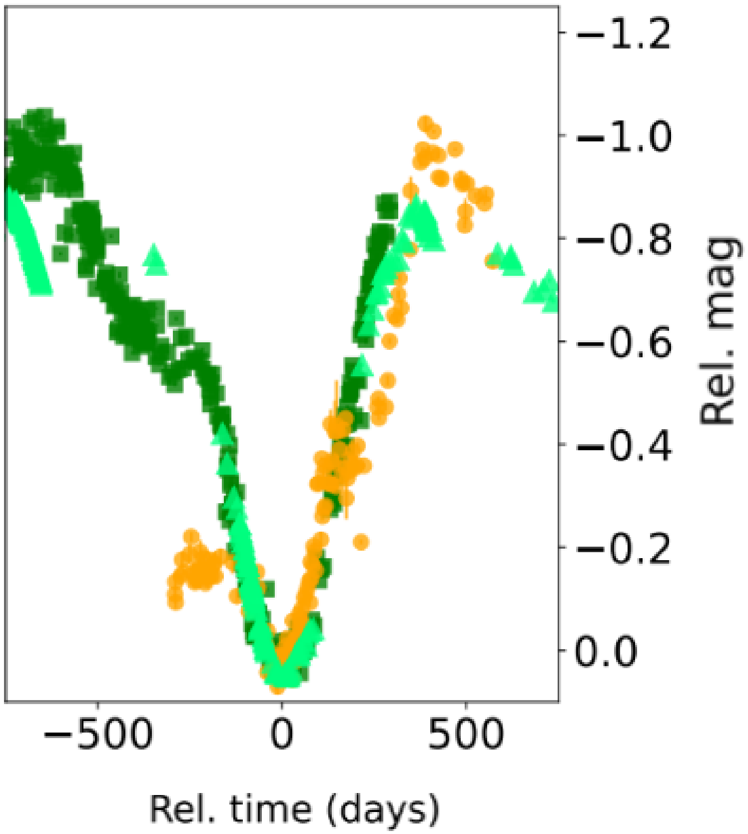
Dimming events

- Common properties

  - Recurrence ~11.8 years

  - Rising time ~400 days

  - ΔV ~ 1 mag



Dimming events

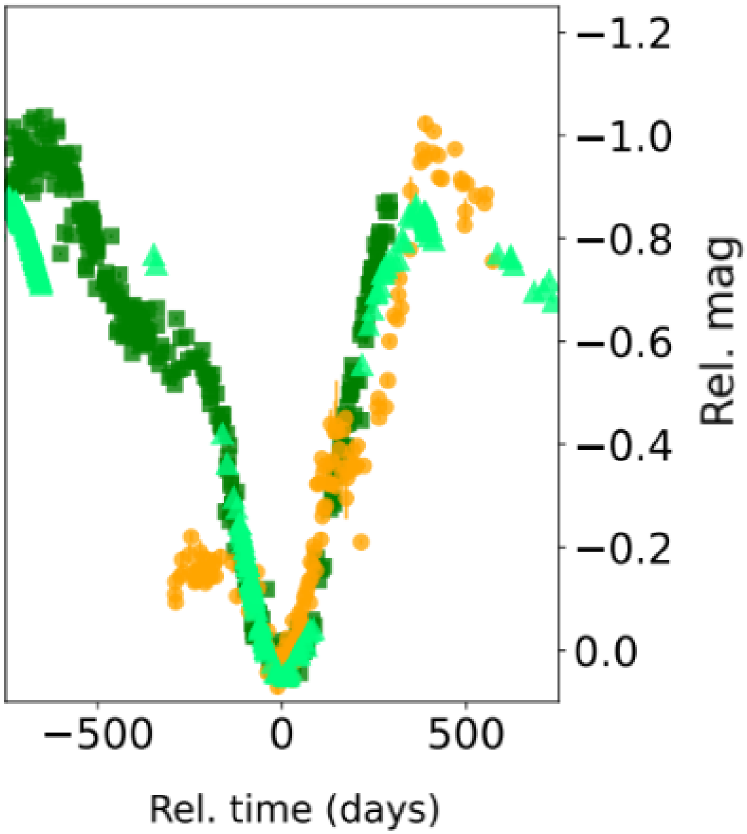
- Common properties

- Spectroscopy in the **last event:** similar properties as **The Great Dimming of Betelgeuse**

  - Correlation Teff – V

  - Complex spectral features close to the minimum

  - Extra extinction after the minimum!!!



Dimming events

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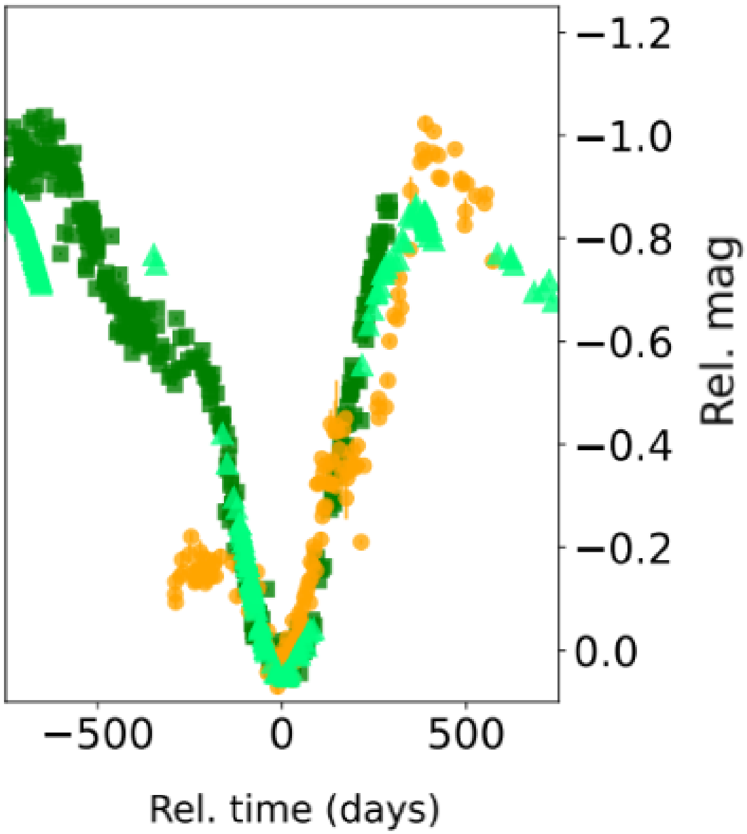
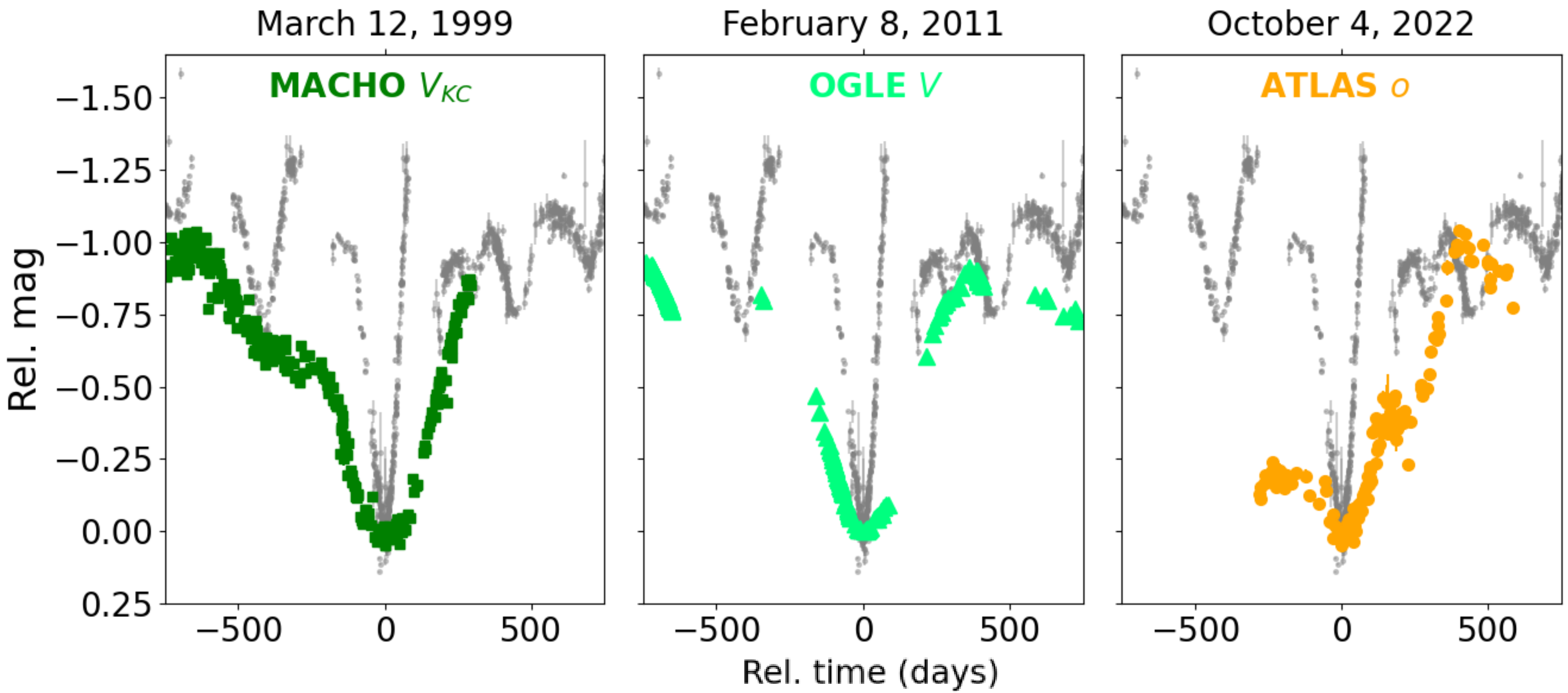
- Spectroscopy in the last event: similar properties as The Great Dimming of Betelgeuse

- **Let’s compare them!!**



Dimming events

AAVSO photometry



[W60] B90: ~11.8 years, ~400 days, ΔV ~ 1 mag

Betelgeuse: no recurrence, ~200 days, ΔV ~ 1.25 mag

(Dupree et al. 2022)

Dimming events

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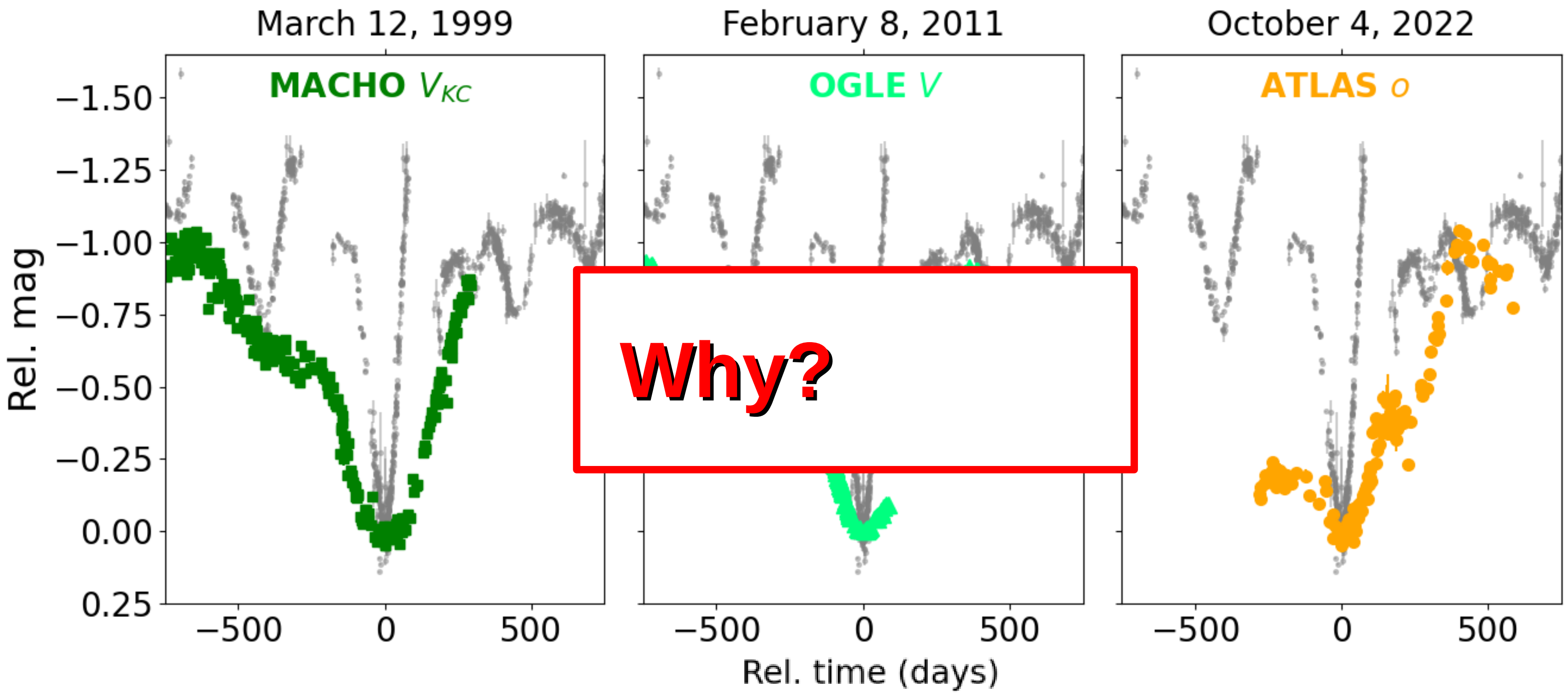

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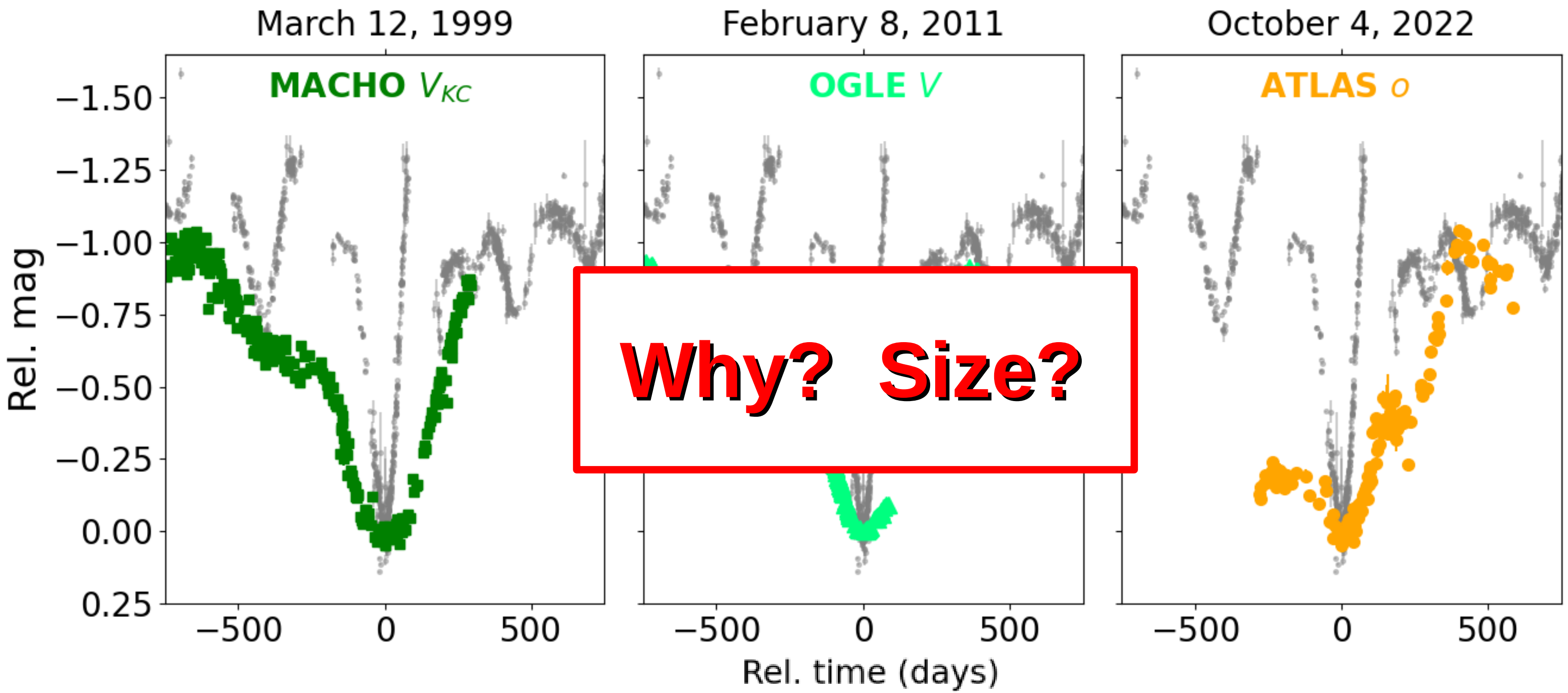

Why? Size?

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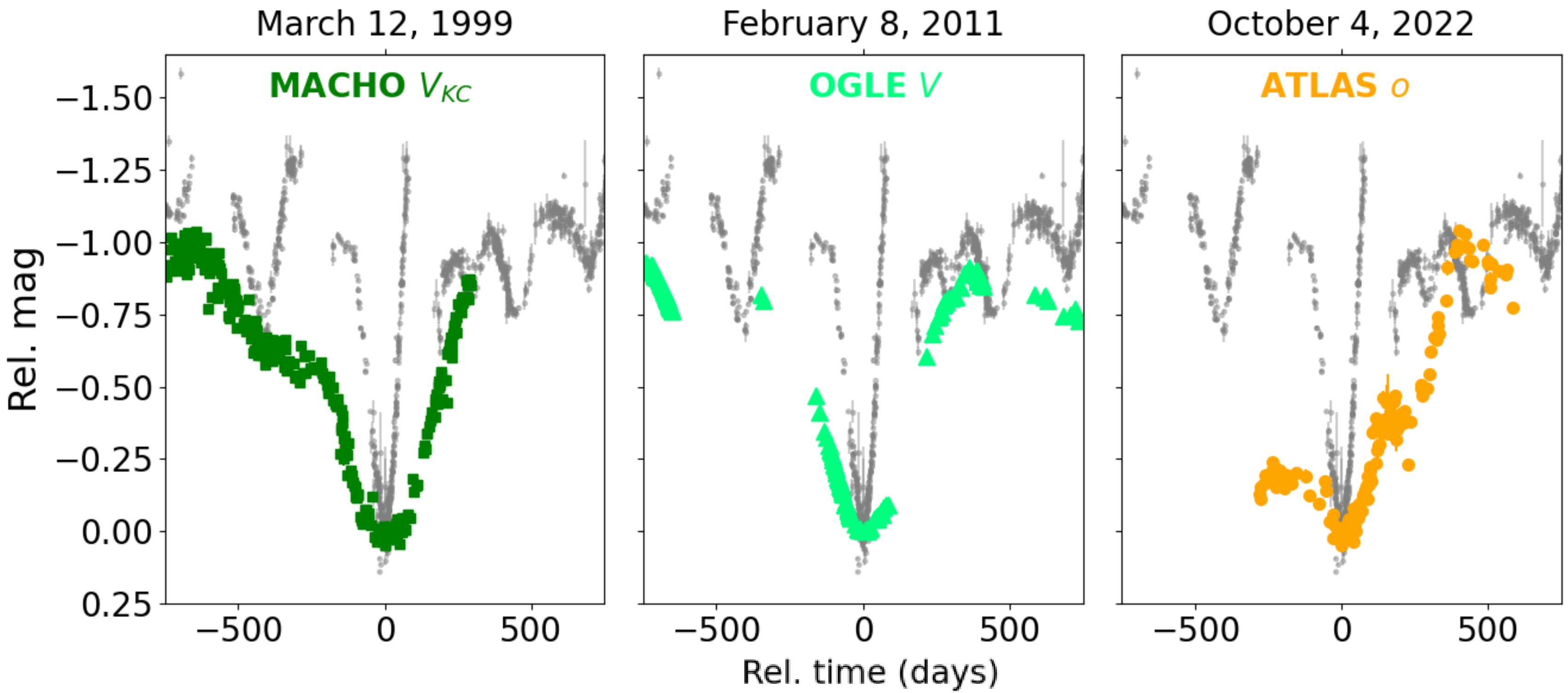


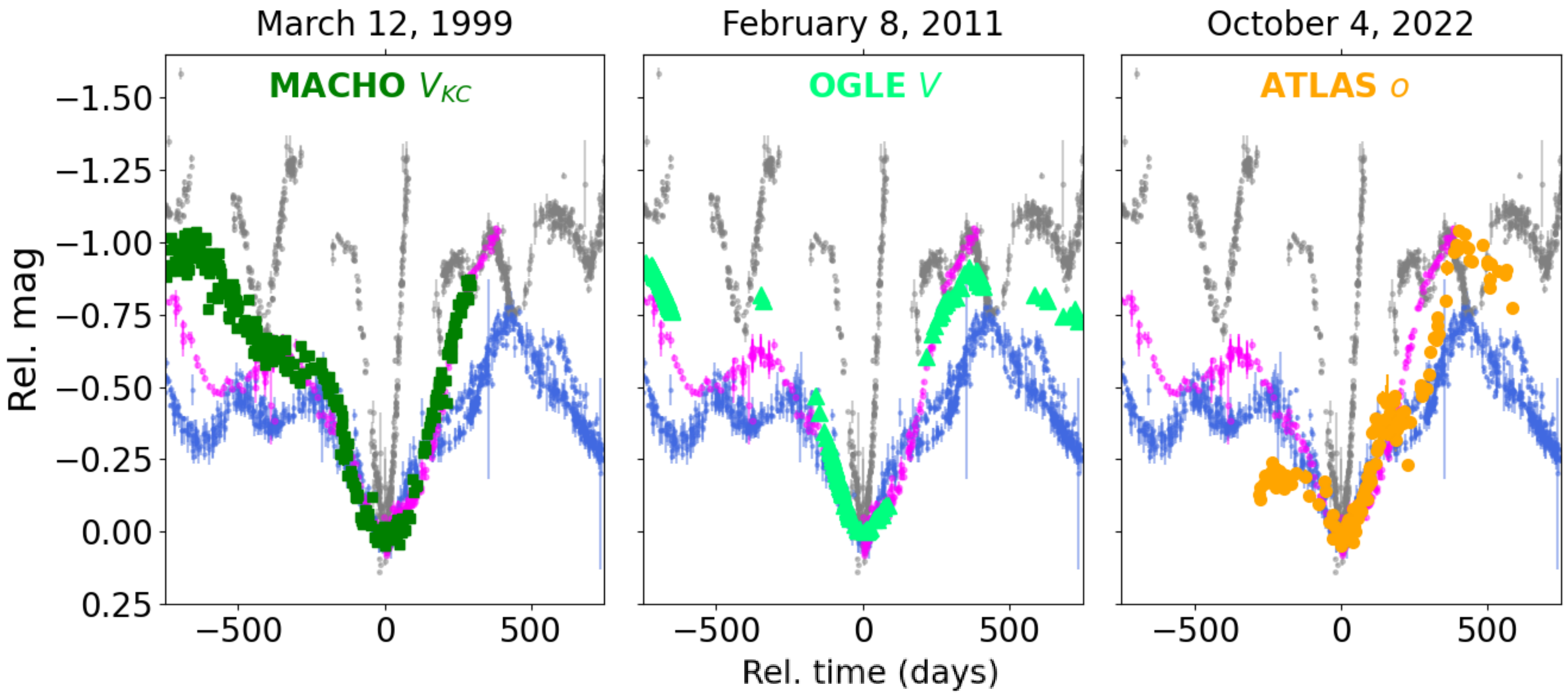
[W60] B90: ~1200 R_{sun}

Betelgeuse: 700-1000 R_{sun}

(Joyce et al. 2020, Kravchenko et al. 2021)

Dimming events

AAVSO photometry



[W60] B90: ~1200 R_{sun}

μ Cep: 1259 R_{sun}

(Josselin & Plez 2007)

Betelgeuse: 700-1000 R_{sun}

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RW Cep: 900–1760 R_{sun}

(Anugu et al. 2023)

Dimming events

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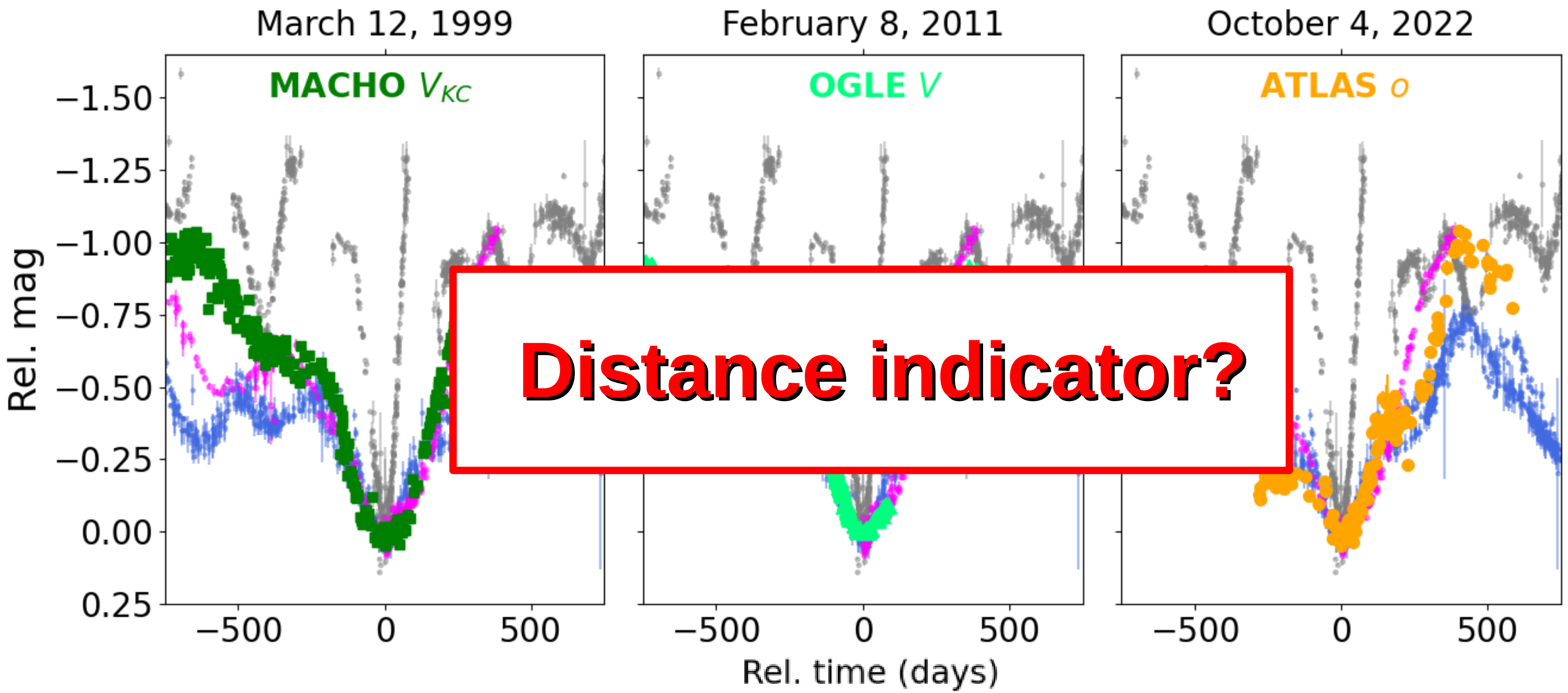

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[W60] B90 & Betelgeuse

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- Luminous
- Dimming events
- Episodic mass-loss
- Bar
- Interacting with ISM

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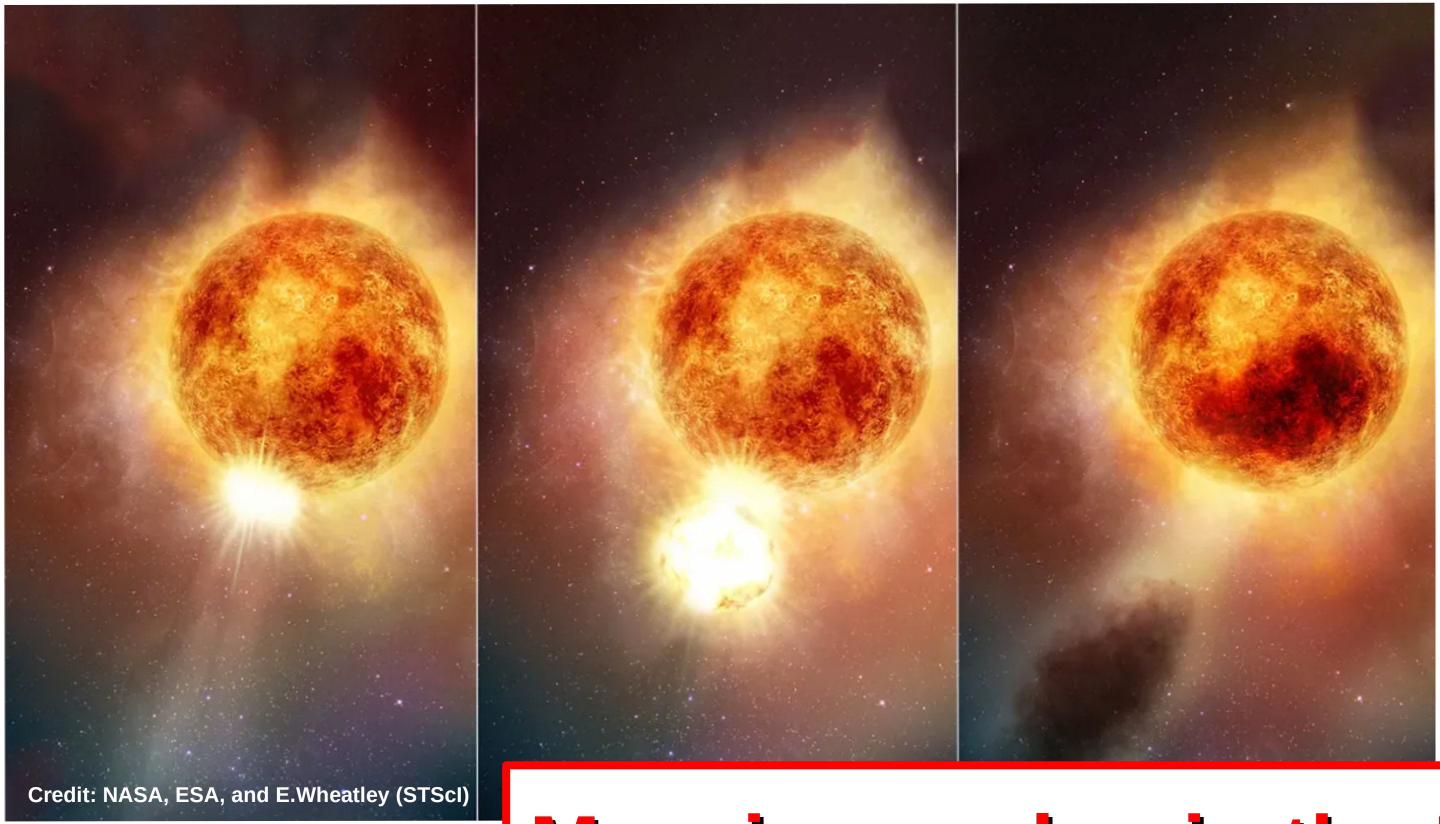
[W60] B90 M_{in}= 25 M_{sun}

Betelgeuse M_{in} < 20 M_{sun}

(*Joyce et al. 2020*)

[W60] B90 & Betelgeuse



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(*Joyce et al. 2020*)

Massive analog in the LMC

Submitted to A&A

Munoz-Sanchez et al. submitted

Episodic mass loss in the very luminous red supergiant [W60] B90 in the Large Magellanic Cloud

G. Munoz-Sanchez[1,2], S. de Wit[1,2], A.Z. Bonanos[1], K. Antoniadis[1,2], K. Boutsia[4,5], P. Boumis[1], E. Christodoulou[1,2], M. Kalitsounaki[1,2], and A. Udalski[6]

1.- Introduction

2.- [W60] B90

a) Motivation

b) Bow shock

c) Variability

d) Future work

Future work

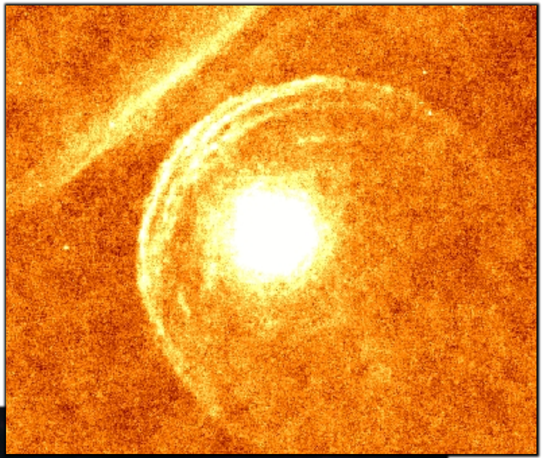
- Resolve the CSM around [W60] B90 (e.g. JWST, ALMA, VLTI)

  - Bow shock: mass-loss rate

  - Past ejections

  - Relation with dimming’s recurrence

Marle et al. 2013

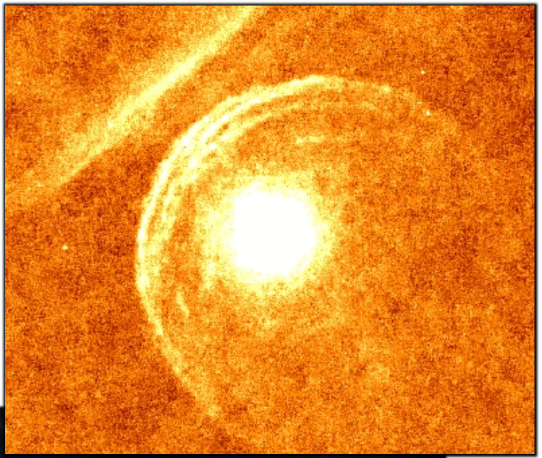


Future work

- Resolve the CSM around [W60] B90 (e.g. JWST, ALMA, VLTI)
  - Bow shock: mass-loss rate
  - Past ejections
  - Relation with dimming's recurrence

- Extend analysis to other luminous RSGs
  - Variability
  - Interaction with the ISM
  - Dimming events

Marle et al. 2013



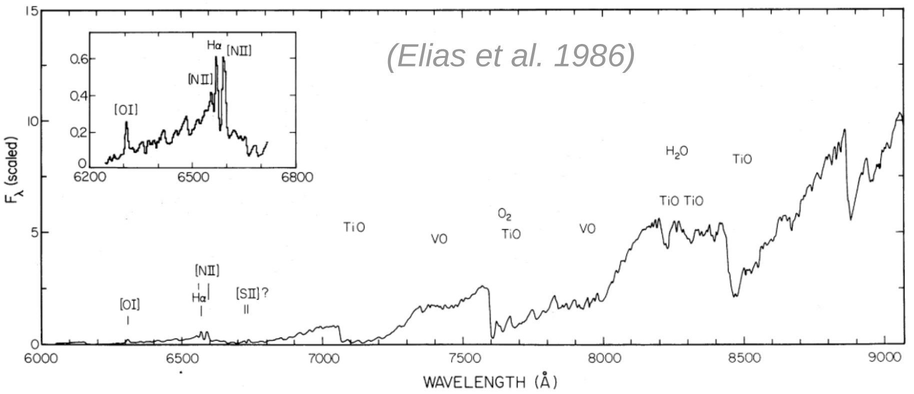
1.- Introduction

2.- [W60] B90

3.- WOH G64

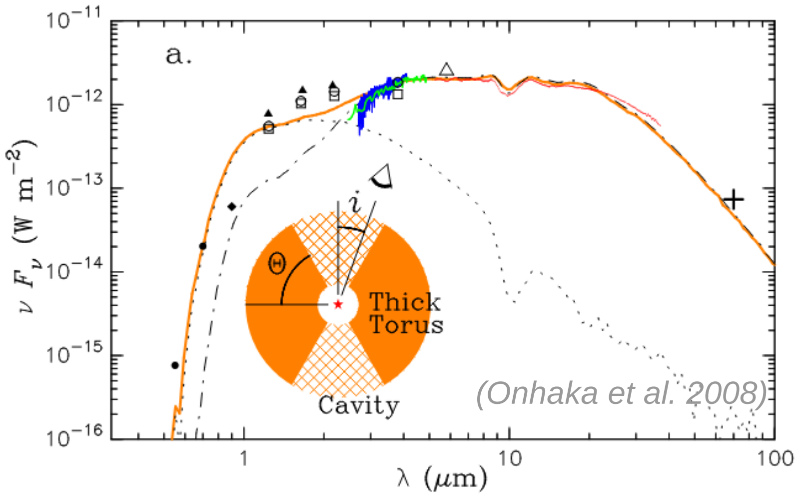
a) Motivation

Historic background



- **M7.5e log(L/L$_{sun}$)= 5.75** (*Elias et al. 1986)*
- **M5-7.5e, log(L/L$_{sun}$)= 5.70** (*van Loon et al. 1995)*
- **M5, log(L/L$_{sun}$)= 5.65**, one of the largest RSGs ever known. (*Levesque et al 2009)*

Historic background



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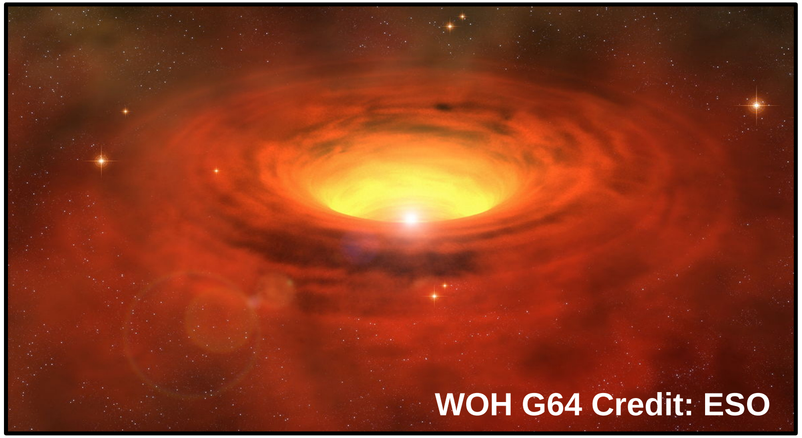
- M5 log(L/L_{sun})= 5.65, one of the largest RSGs ever known. (*Levesque et al 2009)*
- **log(L/L_{sun})= 5.45**, **dusty thick torus** close to pole on i = 20º (*Onhaka et al. 2008*)

Historic background



- M7.5e log(L/L_{sun})= 5.75 (*Elias et al. 1986)*
- M5-7.5e, log(L/L_{sun})= 5.70 (*van Loon et al. 1995)*
- M5 log(L/L_{sun})= 5.65, one of the largest RSGs ever known. (*Levesque et al 2009)*
- log(L/L_{sun})= 5.45, dusty thick torus close to pole on i = 20º (*Onhaka et al. 2008*)
- **Only dust enshrouded** (Av > 8 mag) RSG in the **LMC** *(Beasor et al. 2022)*
- **RSG with highest mass-loss rate in the LMC**, $\dot{M}$= 1.25 · 10^{-4} M_{sun}/yr *(Antoniadis et al. 2024)*

1.- Introduction

2.- [W60] B90

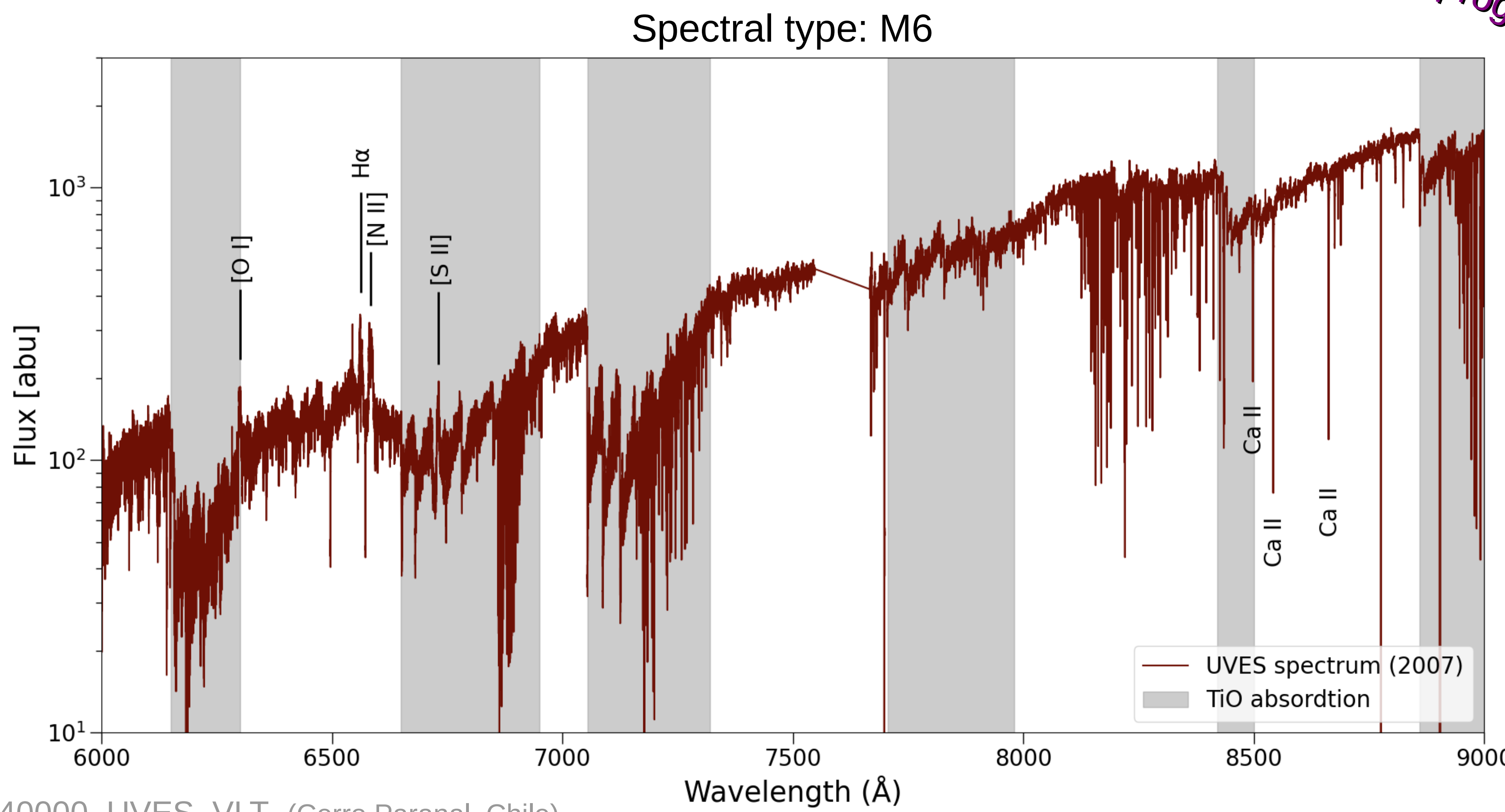
3.- WOH G64

a) Motivation

b) Variability

RSG…

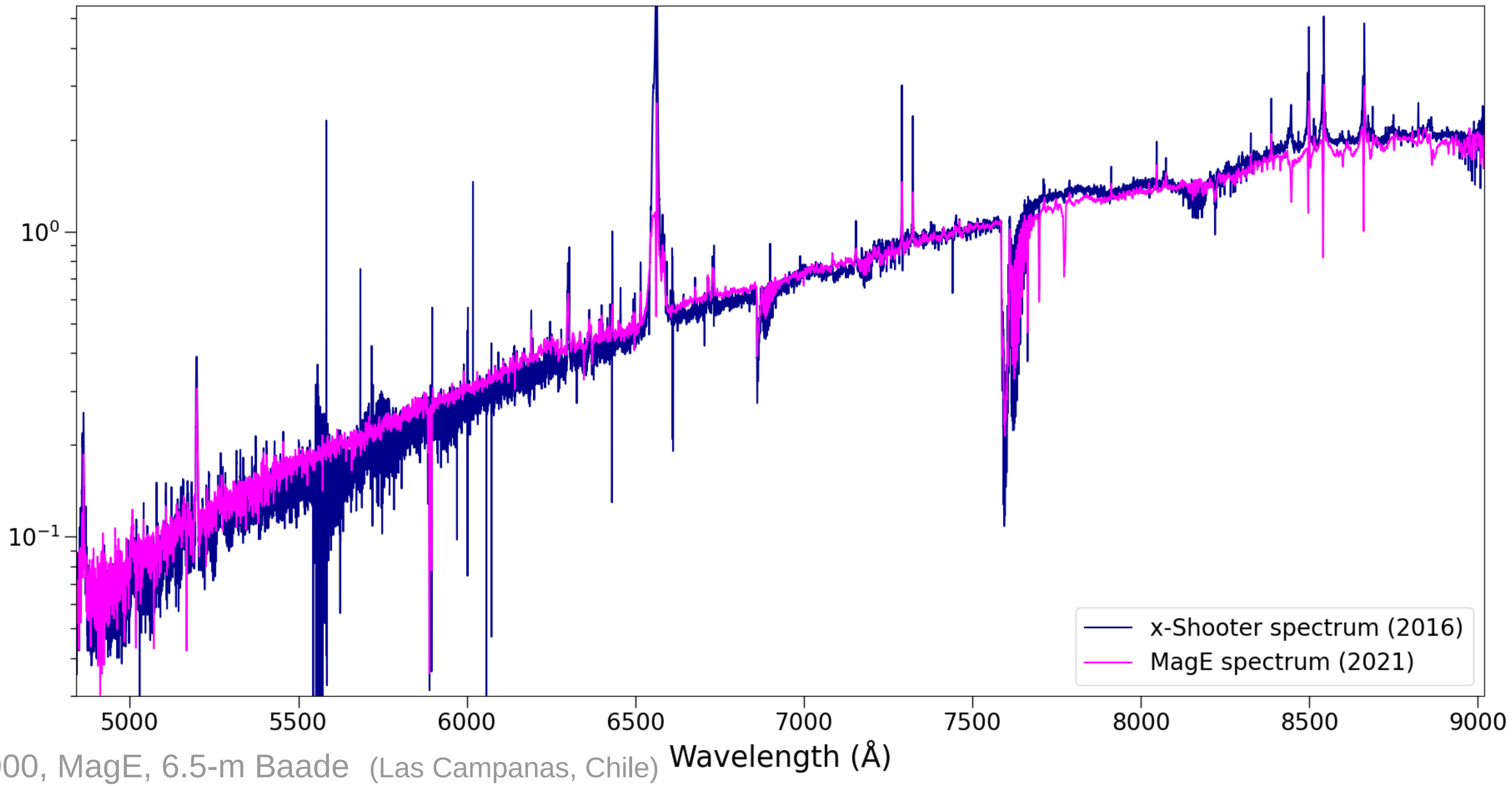
Work in progress



R=40000, UVES, VLT (Cerro Paranal, Chile)

RSG... not anymore!!!

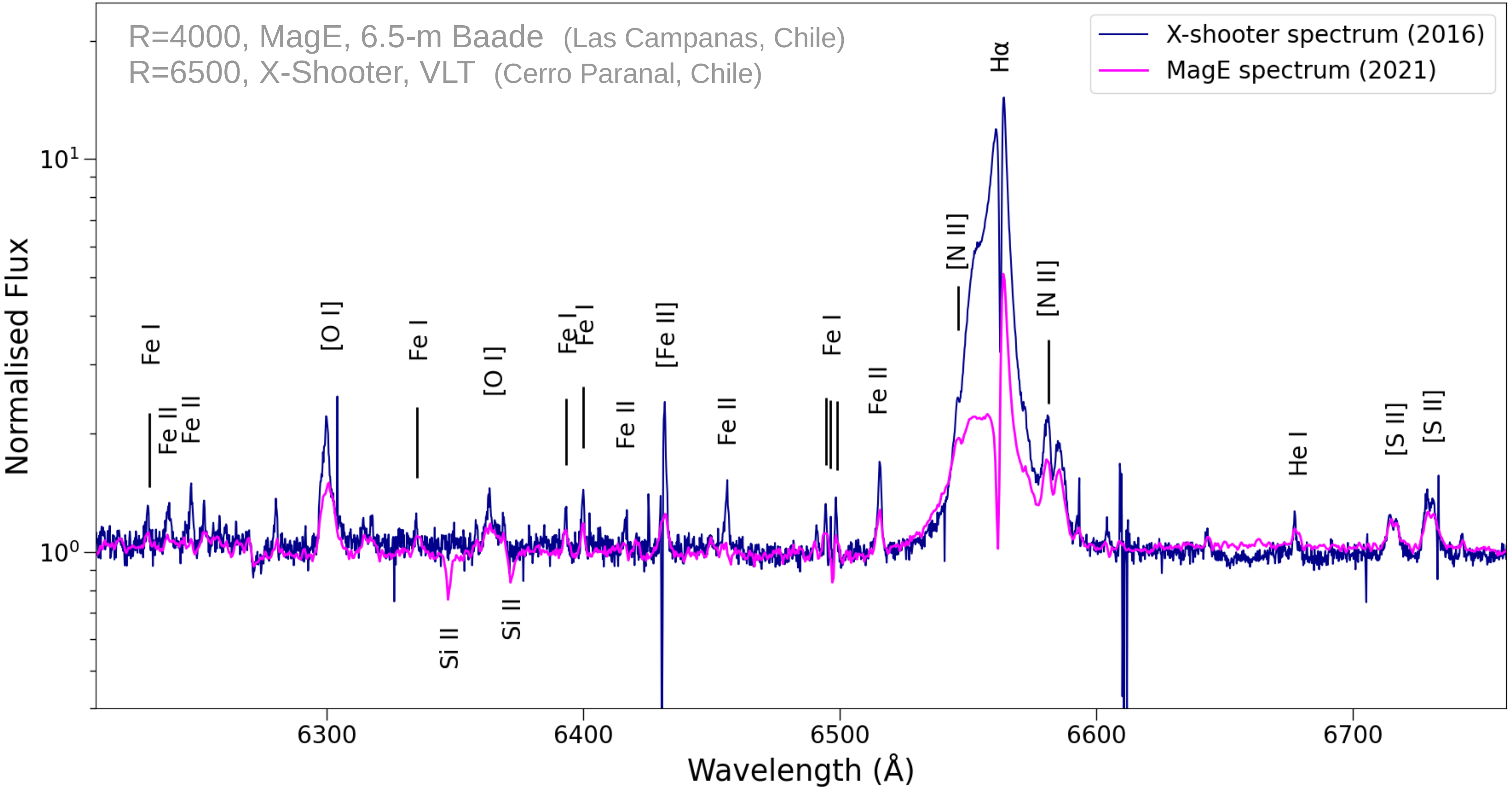
Work in progress



R=4000, MagE, 6.5-m Baade (Las Campanas, Chile)
R=6500, X-Shooter, VLT (Cerro Paranal, Chile)

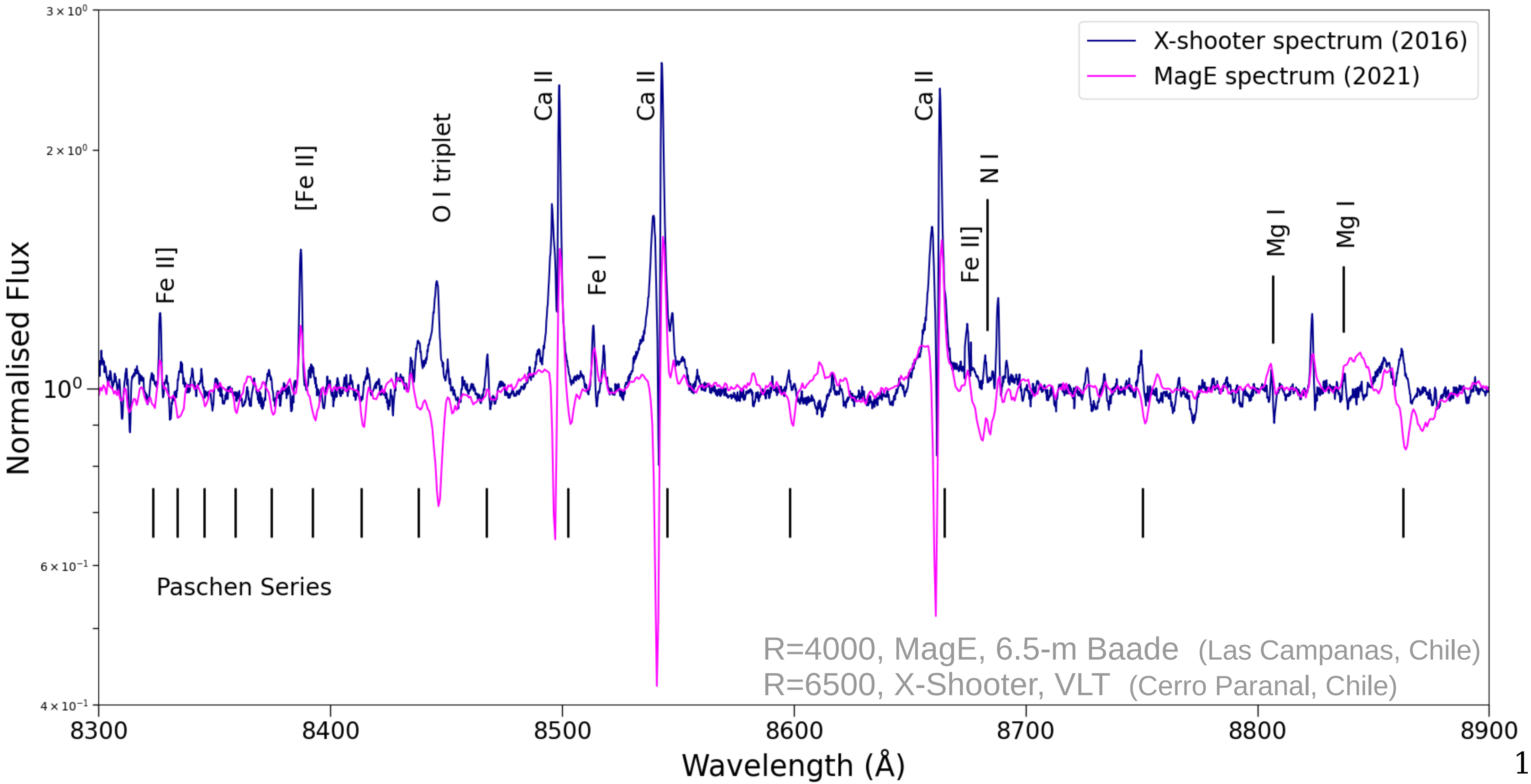
sgB[e] !!!

Work in progress



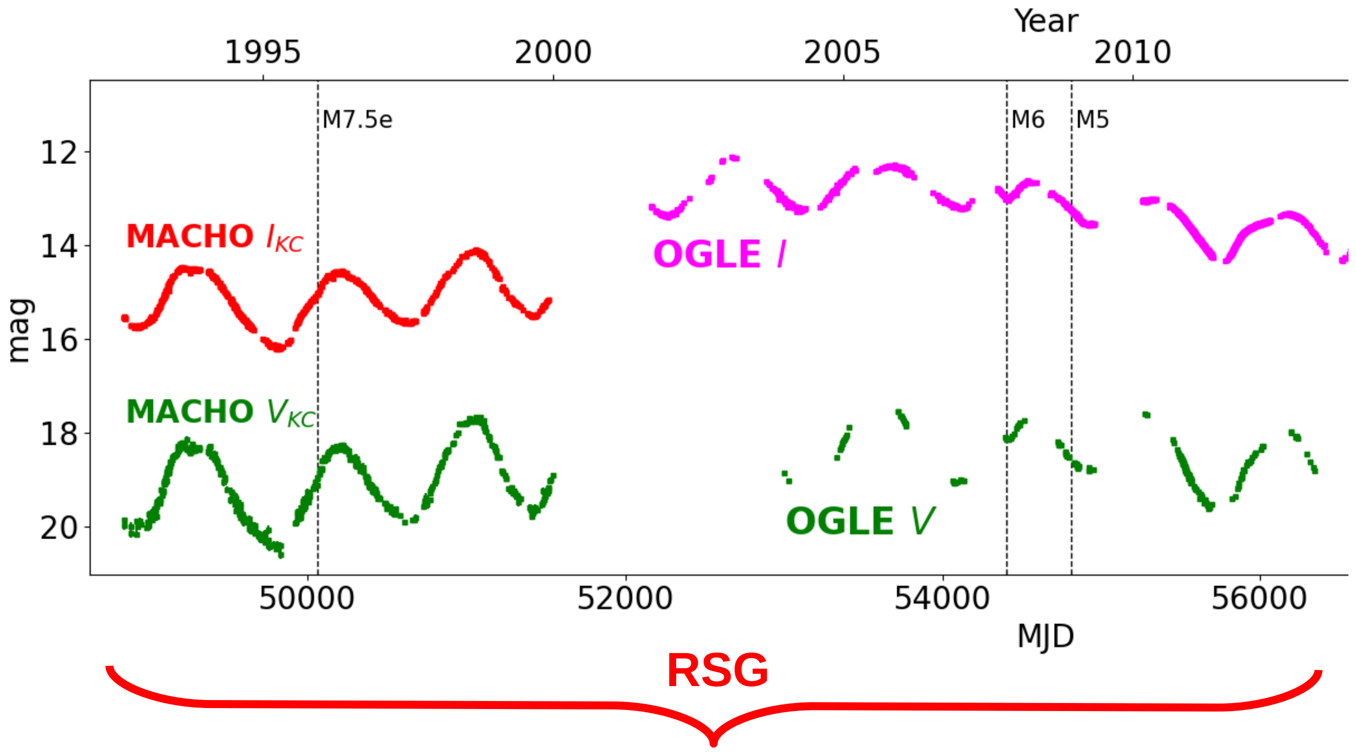
sgB[e] !!!

Work in progress



Light curve

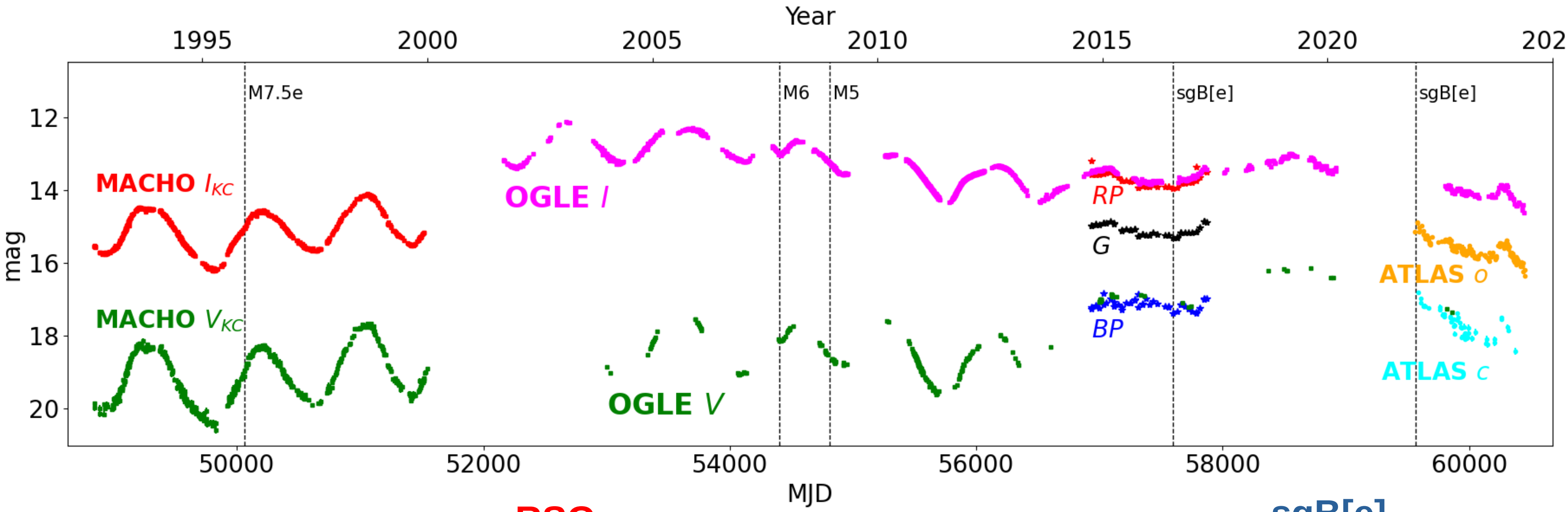
Work in progress



- Amplitude ΔV ~ 2 mag
- Periodicity 800-900 d (*Groenewegen et al. 2009, 2018*)

Light curve

Work in progress



RSG

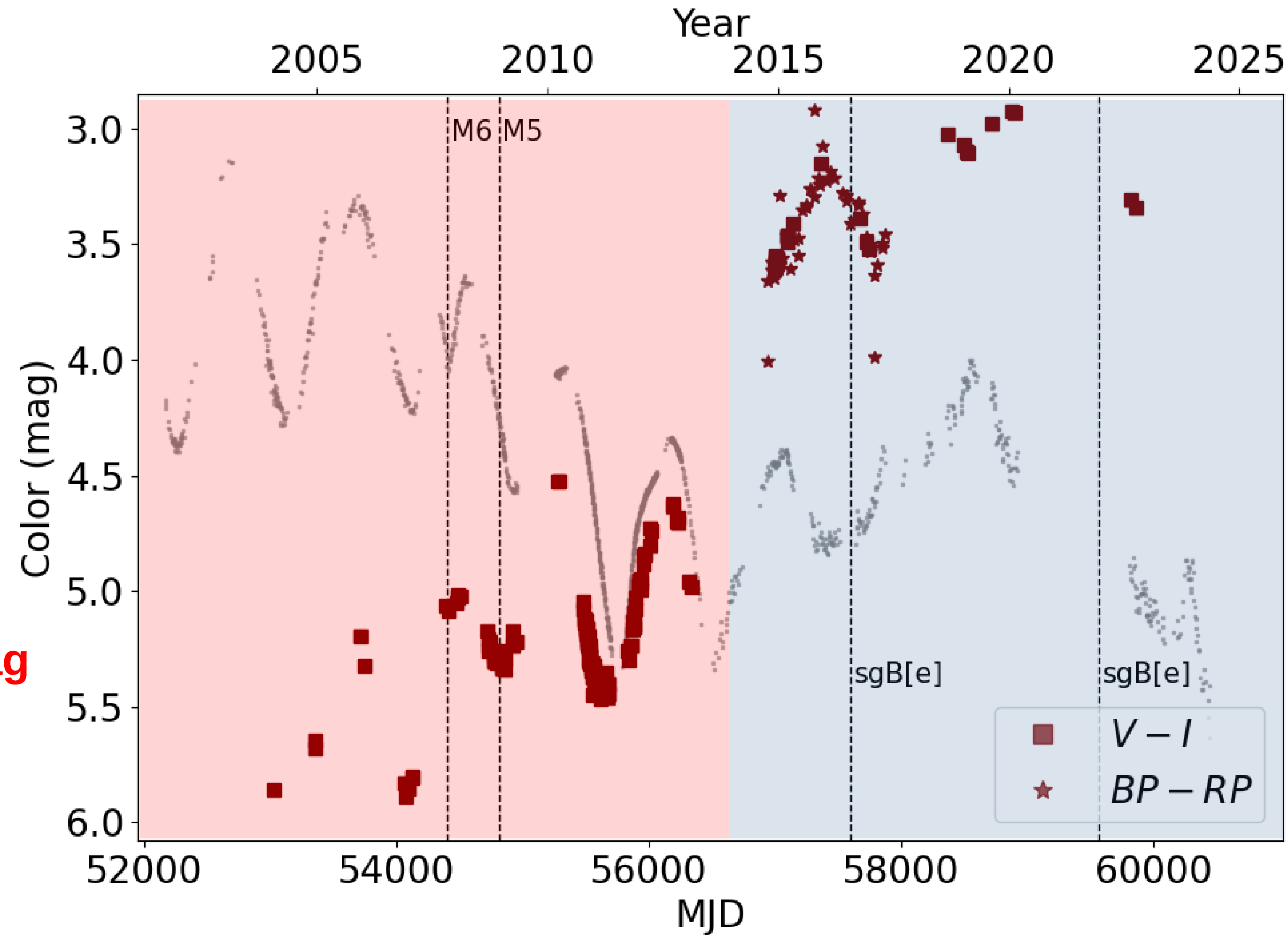
- Amplitude ΔV ~ 2 mag
- Periodicity 800-900 d (*Groenewegen et al. 2009, 2018*)

sgB[e]

- Amplitude ΔV < 2 mag
- No periodicity

Color change

Work in progress



V-I= 3.46 mag

V-I= 5.27 mag

1.- Introduction

2.- [W60] B90

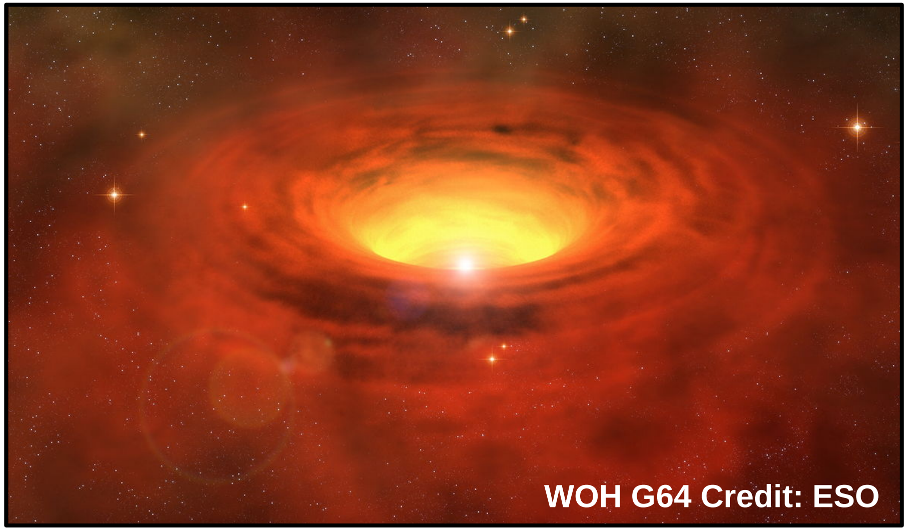
3.- WOH G64

- a) Motivation
- b) Extreme change
- c) Future work

Future work

- Analyze ALMA data (Evgenia Koumpia)

- Analyze deeply the radial velocity structures



Future work

- Analyze ALMA data (Evgenia Koumpia)

- Analyze deeply the radial velocity structures

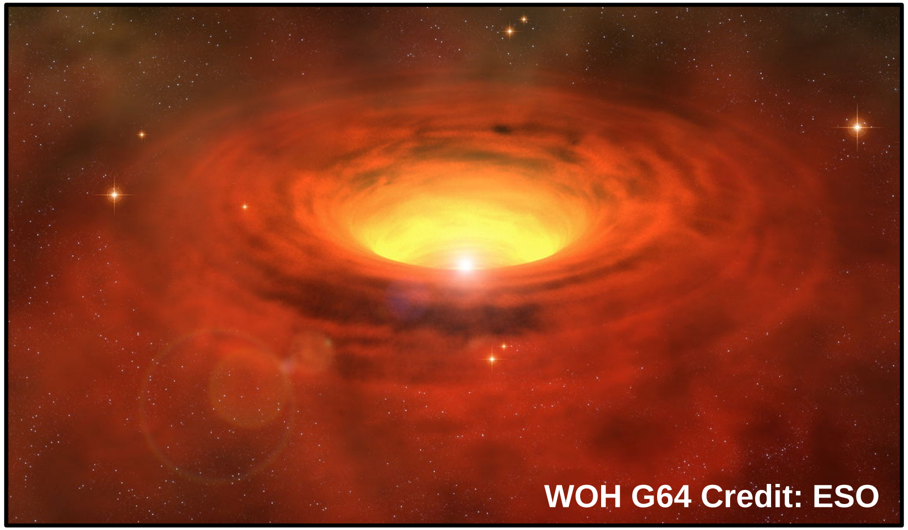
- Propose physical scenarios

  - Loss of stellar atmosphere due to episodic mass loss

  - Loss of atmosphere due to LBV-like mass loss near the Humphreys-Davidson limit

  - Common envelope evolution due to unstable mass transfer onto a companion, which is obscured due to dust

  - Thorne–Żytkow object (TŻO)



- More ideas are welcome

1.- Introduction

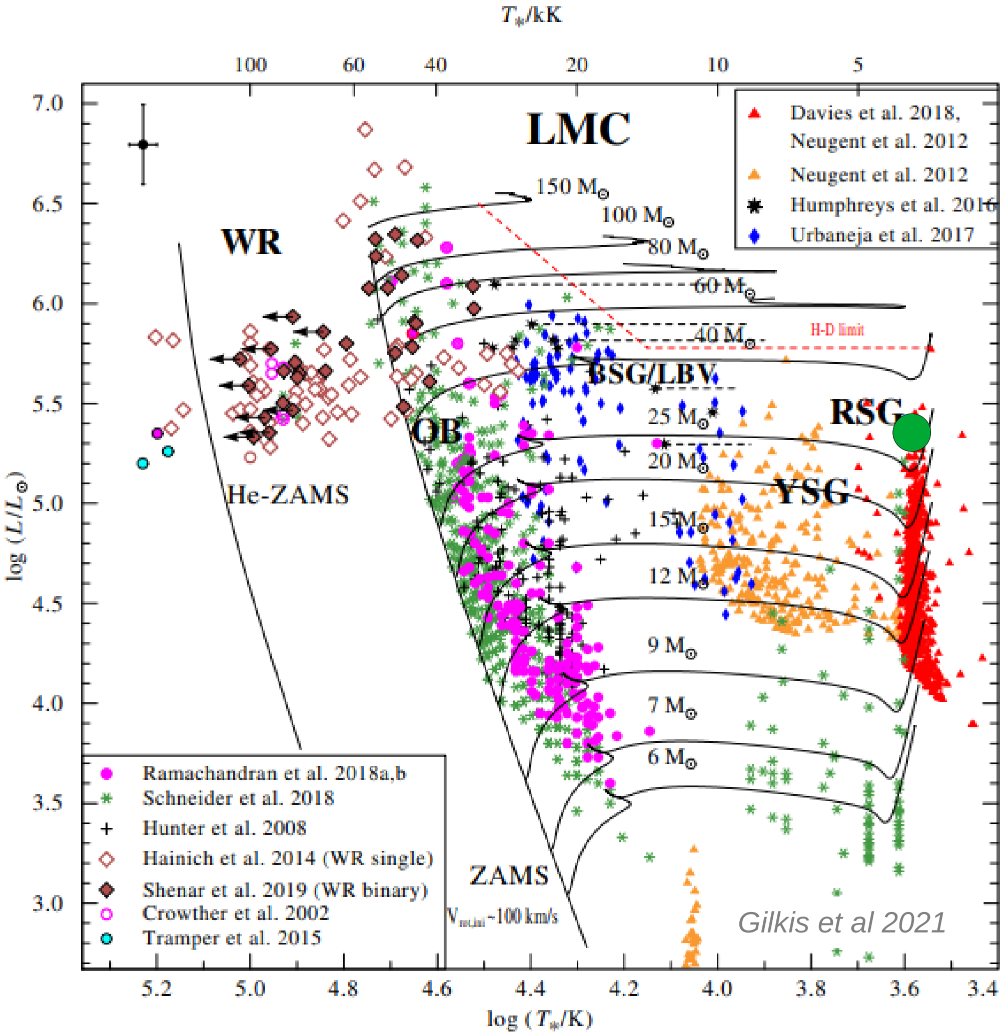
2.- [W60] B90

3.- WOH G64

4.- Summary

Episodic mass loss:

- [W60] B90 *(G. Munoz-Sanchez et al. submitted A&A)*
  - 1st extragalactic RSGc w/ bow shock
  - Surrounded by shocked material
  - Dimming events ejecting material
  - Recurrence of ~12 yr
  - Their duration related with R_{star}?
  - Undergoing episodic mass-loss
  - Massive analog of Betelgeuse



Episodic mass loss:

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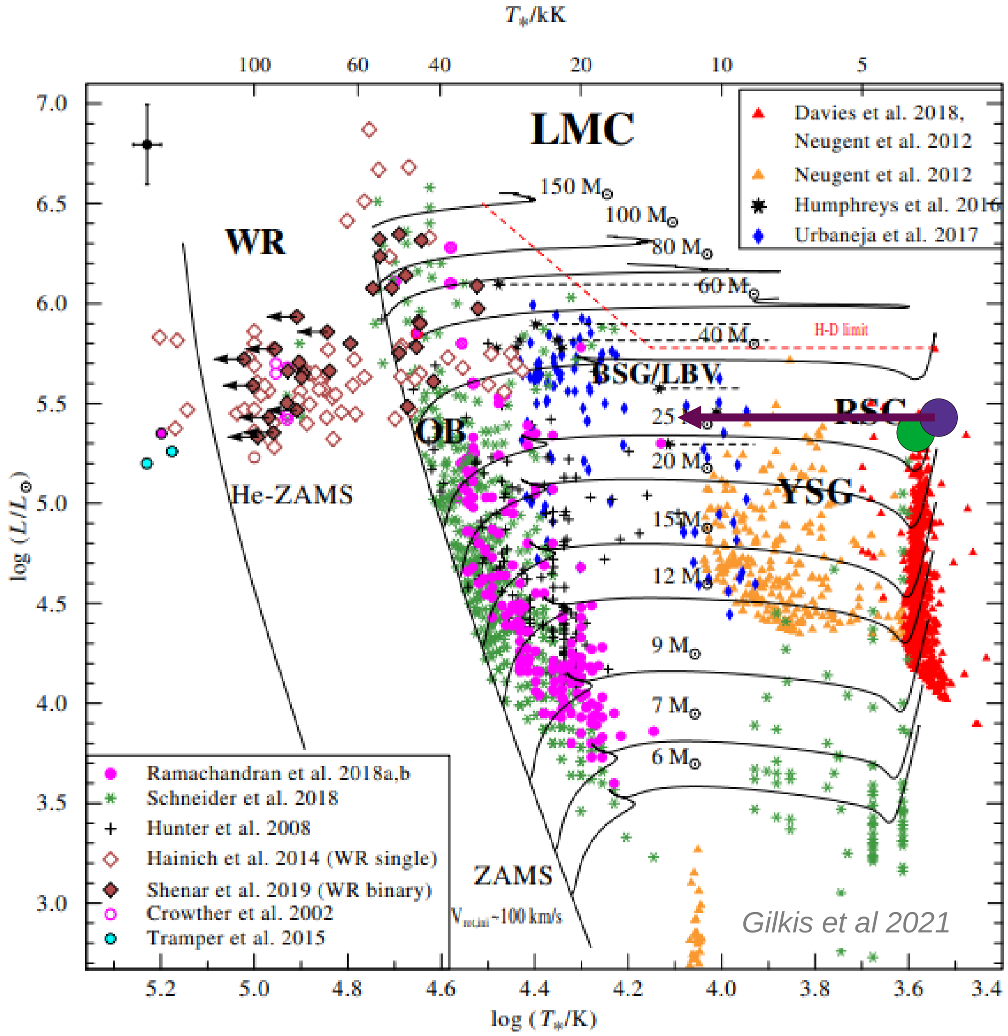
- WOH G64 *(G. Munoz-Sanchez et al. in prep)*
  - Not RSG anymore
  - Probably part of the envelope is lost
  - Evolution towards the blue
  - sgB[e]
  - Pre-SN phase?



Obrigado!!

VII. Red Supergiants

11:00-11:20 Evaggelia Christodoulou
J-band spectroscopy of dusty, mass losing red supergiants in low metallicity galaxies

11:20-11:40 Gonzalo Munoz-Sanchez
Episodic mass loss discovered in two extreme RSG in the LMC

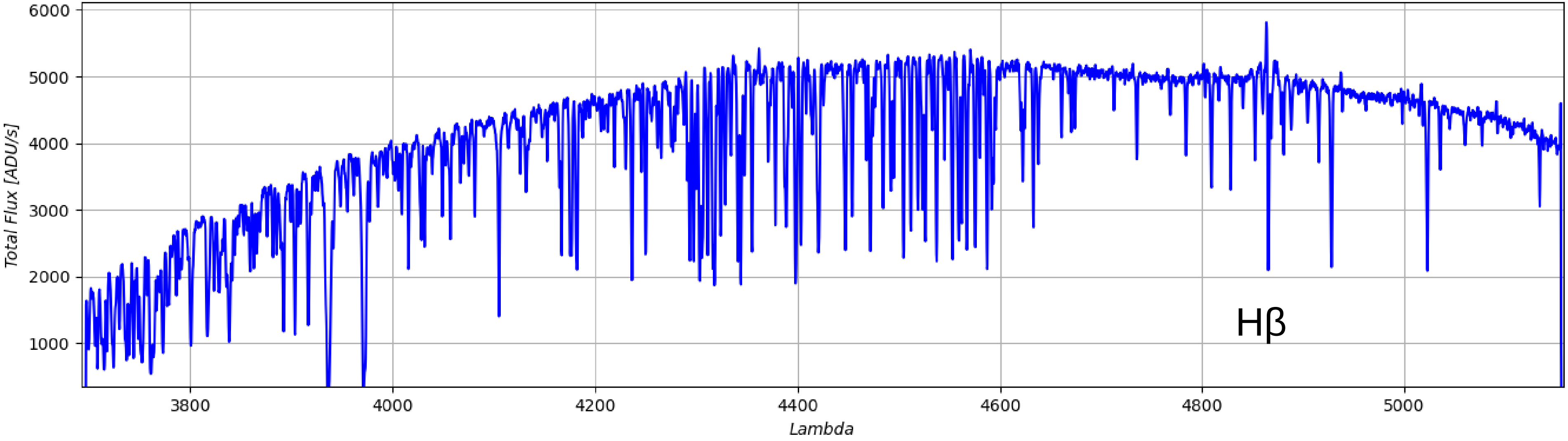
VIII. Yellow Hypergiants and Luminous Blue Variables

11:40-12:25 Alex Lobel (**invited**)
Yellow Hypergiants and Luminous Blue Variables

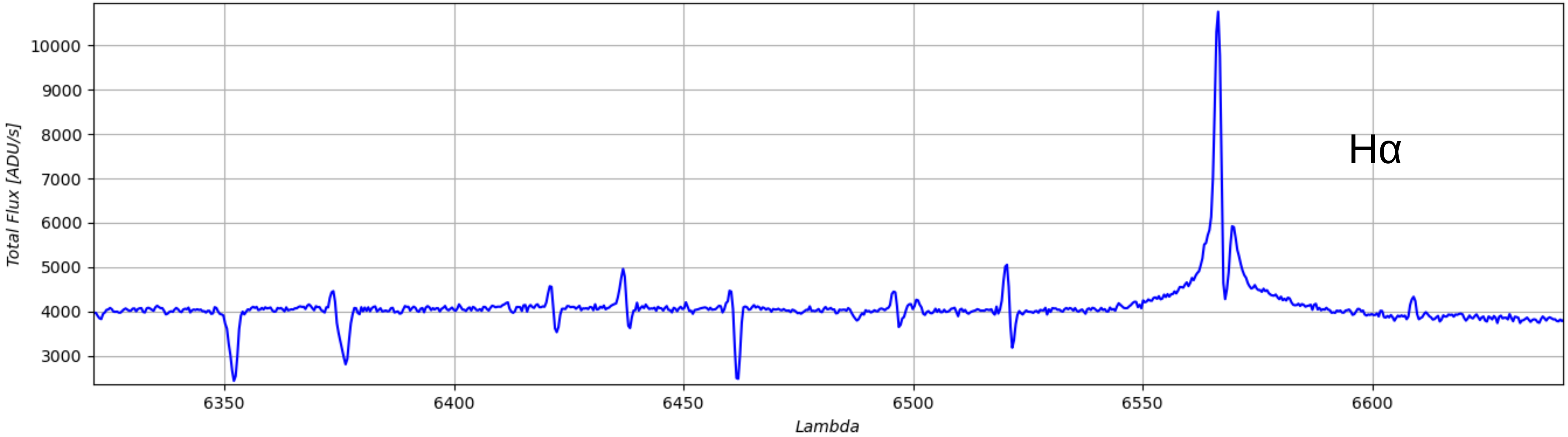
12:25-14:00 Lunch

Optical spectroscopy of BSG, YSG & LBVs in the LMC and SMC

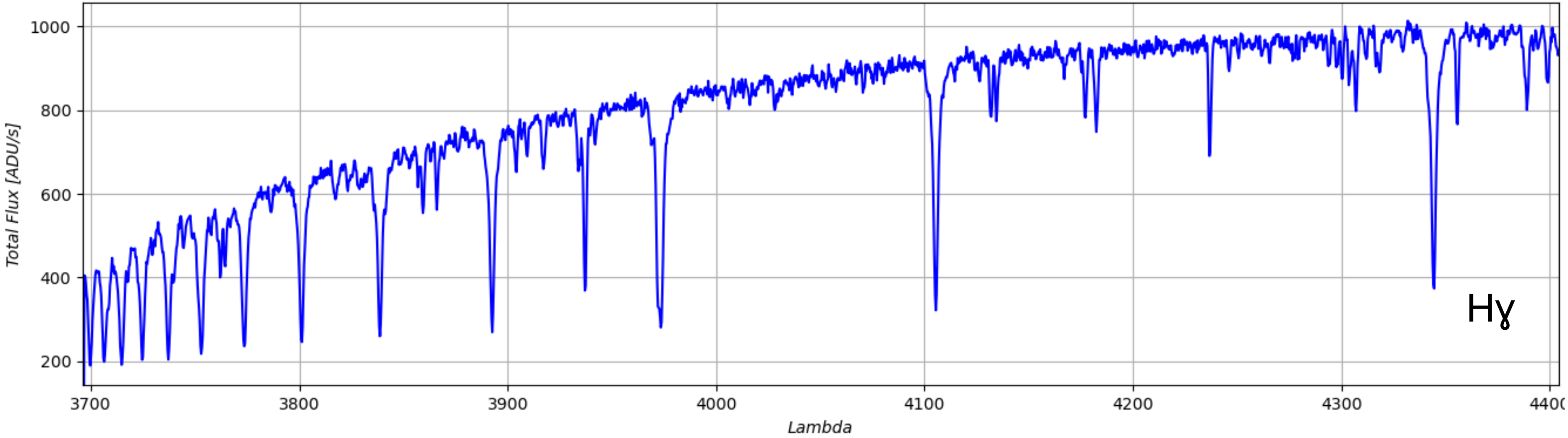
LMC	HD 269687	82.85637648	-69.09404172	1	?	?	?	LBVc
NGC55	222	3.79305	-39.20741	1	3777493	NGC55-222_mod	OB0001	YSG
NGC55	797	3.63505	-39.18644	1	3776755	NGC55-797	OB0003	YSG
NGC300	2285	13.77428	-37.68503	1	3776702	NGC300-2285	OB0004	YSG
LMC	HD 269006	75.53083472	-71.33697743	1	3776838	HD 269006	OB0005	LBV
LMC	RMC 81	77.59497922	-68.77328156	1	3776994	HD 269101	OB0006	LBVc
LMC	HD 269101	77.43829	-68.76942	1	3776994	HD 269101	OB0006	B3Iab
LMC	HD 269171	78.31667	-67.29647	1	3777006	HD 269171	OB0007	A2I
LMC	HD 269154	78.18447544	-67.26603893	1	3777006	HD 269171	OB0007	F6Ia
LMC	HD 269582	81.96944673	-68.98568844	1	3777431	HD 269582	OB0008	LBV
LMC	CD-69 310	81.96335	-69.01538	1	3777431	HD 269582	OB0008	F2I
LMC	HD 269723	83.10403669	-67.69822382	1	3776928	HD 269723	OB0009	G4 0
LMC	HD 269953	85.0507184	-69.66801158	1	3776935	HD 269953	OB0010	G0 0
LMC	HD 269216	78.37827849	-69.53990136	1	3776853	HD 269216	OB0011	LBV
LMC	HD 269604	82.13071761	-68.89881688	1	3776833	HD 269604	OB0012	LBVc/YSG
LMC	HD 269781	83.59363317	-67.02321188	1	3776881	HD 269781	OB0013	B9 Ia
LMC	HD 269787	83.64317	-66.97317	1	3776881	HD 269781	OB0013	A0Ia0
NGC3109	188	150.75881	-26.14946	1	3776262	NGC3109-1	OB0014	LBVc
SMC	HD 7583	18.37710169	-73.33620557	2	3777034	HD 7583	OB0015	A0 Ia+
SMC	Dachs SMC 3-4	18.28501409	-73.33994333	2	3777034	HD 7583	OB0015	F8 I
SMC	LHA 115-S 18	13.53976546	-72.69536402	2	3777058	LHA 115-S 18	OB0016	LBVc
SMC	LHA 115-S 40	15.9933871	-71.90552373	2	3777039	LHA 115-S 40	OB0017	F0:I
SMC	Sk 113	16.0511771	-71.86756579	2	3777039	LHA 115-S 40	OB0017	B3 Ib
SMC	[MA93] 1810	18.83843721	-73.50420114	2	3777031	MA93 1810	OB0018	F8 I
SMC	Flo 675	18.85221233	-73.51233789	2	3777031	MA93 1810	OB0018	F2 I
NGC55	2924	3.90690	-39.23019	2	3778643	NGC55-2-and-3_2night	OB0019	LBVc
NGC55	736*	3.82725	-39.22009	2	3778643	NGC55-2-and-3_2night	OB0019	LBVc
SMC	LHA 115-S 2	10.7985	-73.38633	2	3777026	LHA 115-S 2	OB0020	B8Ia+
SMC	LHA 115-S 23	13.97422743	-72.14986983	2	3777063	LHA 115-S 23	OB0021	B[e]
SMC	HD 7099	17.26649371	-72.53823614	2	3777070	HD 7099	OB0022	B2.5/3 Ia

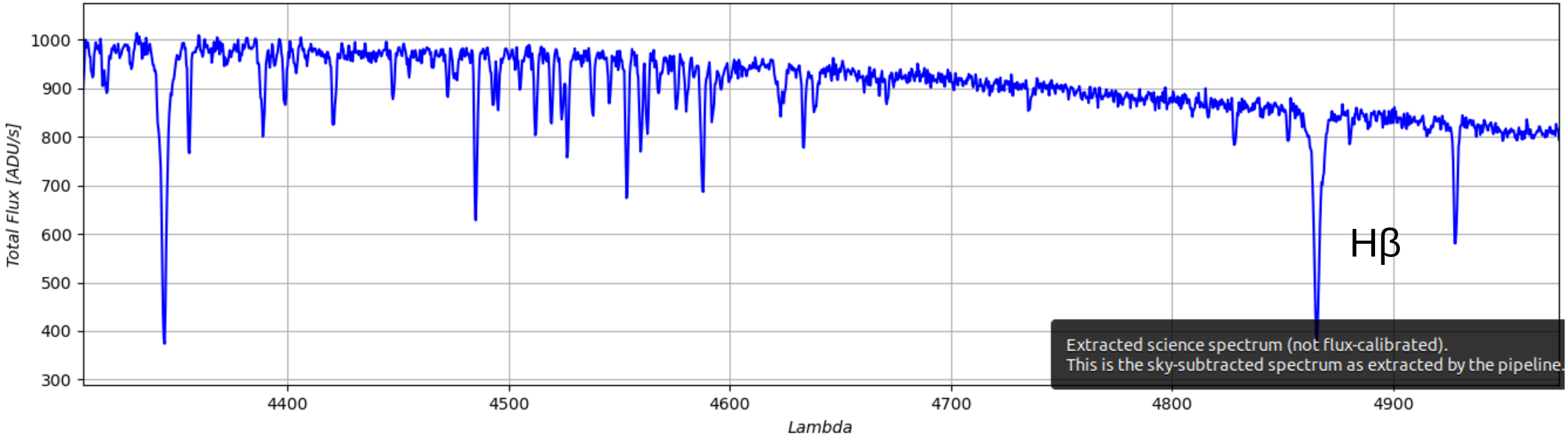


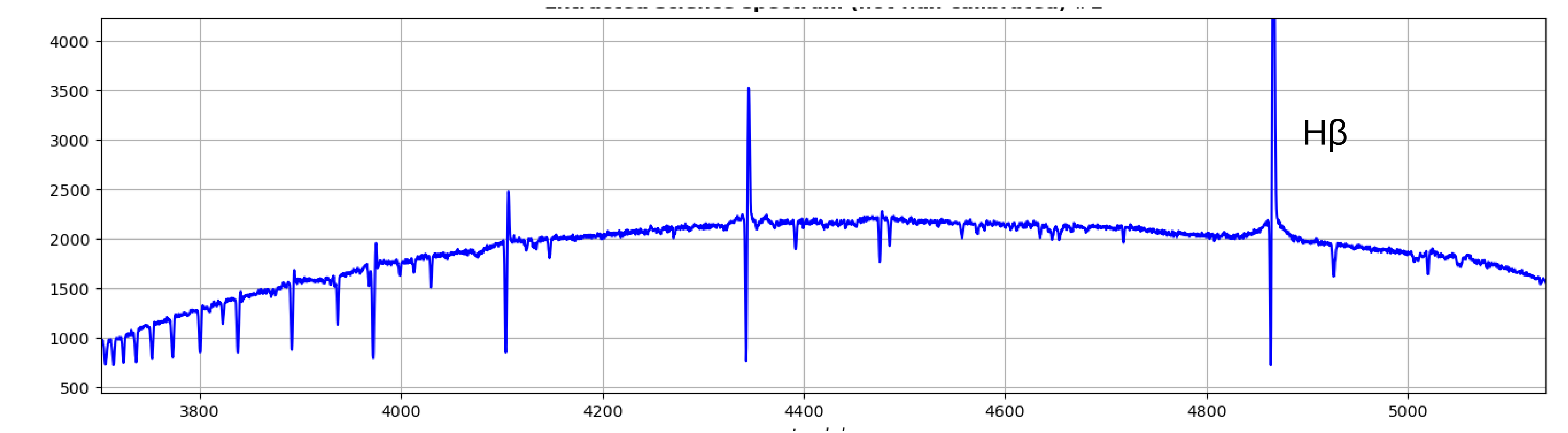
Total Flux [ADU/s]
6000
5000
4000
3000
2000
1000
3800
4000
4200
4400
4600
4800
5000
Lambda
Hβ

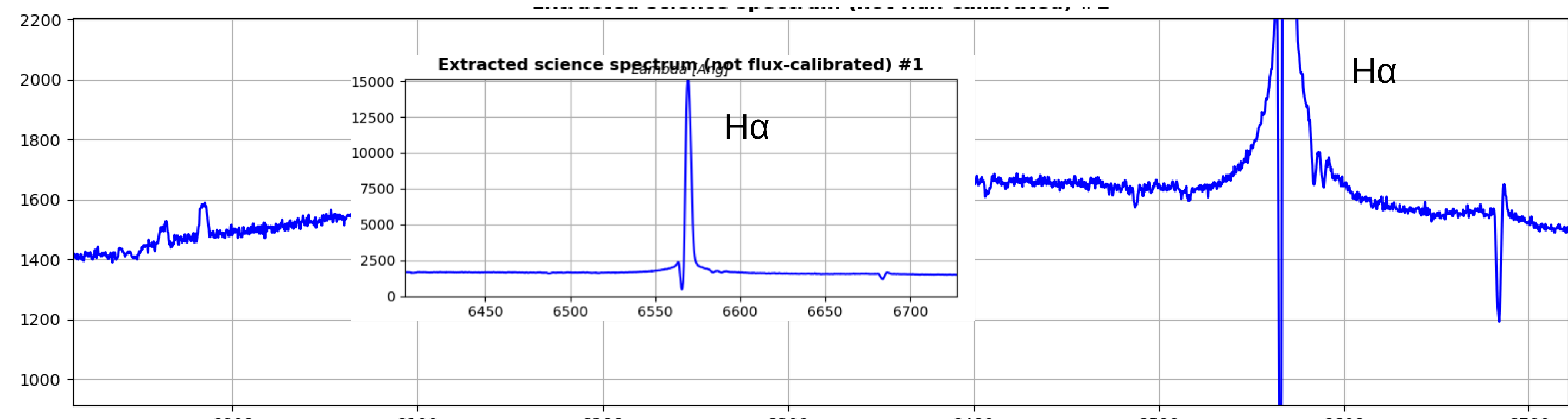


Total Flux [ADU/s]
10000
9000
8000
7000
6000
5000
4000
3000
6350
6400
6450
6500
6550
6600
Lambda
Hα


Total Flux [ADU/s]
Lambda
Hγ


Total Flux [ADU/s]
Lambda
Hβ
Extracted science spectrum (not flux-calibrated).
This is the sky-subtracted spectrum as extracted by the pipeline.


Hβ
4000
3500
3000
2500
2000
1500
1000
500
3800
4000
4200
4400
4600
4800
5000


Hα
2200
2000
1800
1600
1400
1200
1000
Extracted science spectrum (not flux-calibrated) #1
Hα
15000
12500
10000
7500
5000
2500
0
6450
6500
6550
6600
6650
6700

Obrigado!!

gonzalom@noa.gr

evachris@noa.gr

Episodic mass loss:

- [W60] B90 *(G. Munoz-Sanchez et al. submitted A&A)*
  - 1st extragalactic RSGc w/ bow shock
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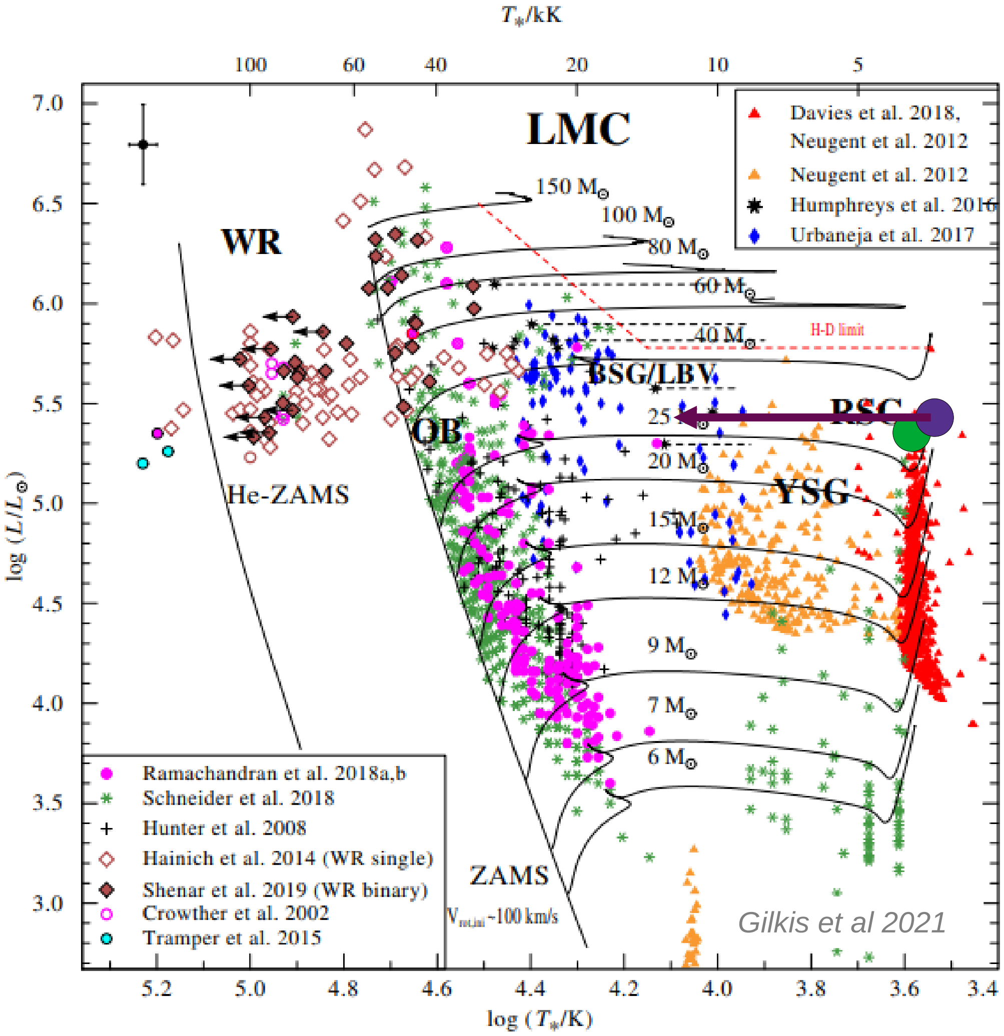


ASSESS group

(http://assess.astro.noa.gr/)

- Episodic M**A**ss Lo**SS** in **E**volved Ma**S**sive **S**tars
- National Observatory of Athens
- ERC-funded project (ID: 772086, 2018-2024)
- PI: Alceste Bonanos

- Catalog of **185 dusty evolved massive stars** in 10 southern galaxies **(*Bonanos et al. 2024*)**
- Discovery of **7 sgB[e] + 4 cLBVs** at **low Z** **(*Maravelias et al. 2023*)**
- **Analysis** of **127 RSGs** found in the survey **(*de Wit et al. 2024*)**
- **Mass-loss rate** relation based on ~2000 **RSGs** in the **LMC** **(*Antoniadis et al. 2024*)**
- Catalog of X dusty evolved massive stars in 5 northern galaxies **(*de Wit et al. in prep*)**
- Dependance of metallicity on RSGs mass loss **(*Antoniadis et al. in prep*)**
- Consequences of RSG winds at SMC metallicity **(*Zapartas et al. in prep*)**

Supplementary material

Bonanos et al. 2024

Investigating episodic mass loss in evolved massive stars:

I. Spectroscopy of dusty massive stars in ten southern galaxies*

A.Z. Bonanos[1], F. Tramper[2,1], S. de Wit[1,3], E. Christodoulou[1,3], G. Muñoz Sanchez[1,3], K. Antoniadis[1,3], S. Athanasiou[1,3], G. Maravelias[1,4], M. Yang[5,1], and E. Zapartas[4,1]

185 evolved massive stars: RSGs, BSGs, YSGs, LBVc, sgB[e]

$Z = 0.06\text{-}1.6\ Z_{sun}$

Galaxy	RA (J2000)	Dec (J2000)	d (Mpc)	Z^a ($Z_\odot$)	R ($'$)
WLM	00:01:58.16	−15:27:39.3	0.96±0.05	0.14[1]	9
NGC 55	00:14:53.60	−39:11:47.9	1.99±0.06	0.27[2]	21
NGC 247	00:47:08.55	−20:45:37.4	3.52±0.06	0.40[3]	14
NGC 253	00:47:33.12	−25:17:17.6	3.56±0.08	0.72[4]	21
NGC 300	00:54:53.48	−37:41:03.8	1.98±0.06	0.41[5]	15
NGC 1313	03:18:16.05	−66:29:53.7	4.25±0.08	0.35[6]	8
NGC 3109	10:03:06.88	−26:09:34.5	1.37±0.06	0.21[7]	13
Sextans A	10:11:00.80	−04:41:34.0	1.37±0.06	0.06[8]	4
M83	13:37:00.95	−29:51:55.5	4.66±0.07	1.58[9]	10
NGC 7793	23:57:49.83	−32:35:27.7	3.58±0.07	0.42[10]	8

Maravelias et al. 2023

Discovering new B[e] supergiants and candidate Luminous Blue Variables in nearby galaxies

Grigoris Maravelias[1,2†], Stephan de Wit[1,3], Alceste Z. Bonanos[1], Frank Tramper[4], Gonzalo Munoz-Sanchez[1,3], Evangelia Christodoulou[1,3]

7 sgB[e] + 4 cLBVs

Investigating episodic mass loss in evolved massive stars:

II. Physical properties of red supergiants at subsolar metallicity★

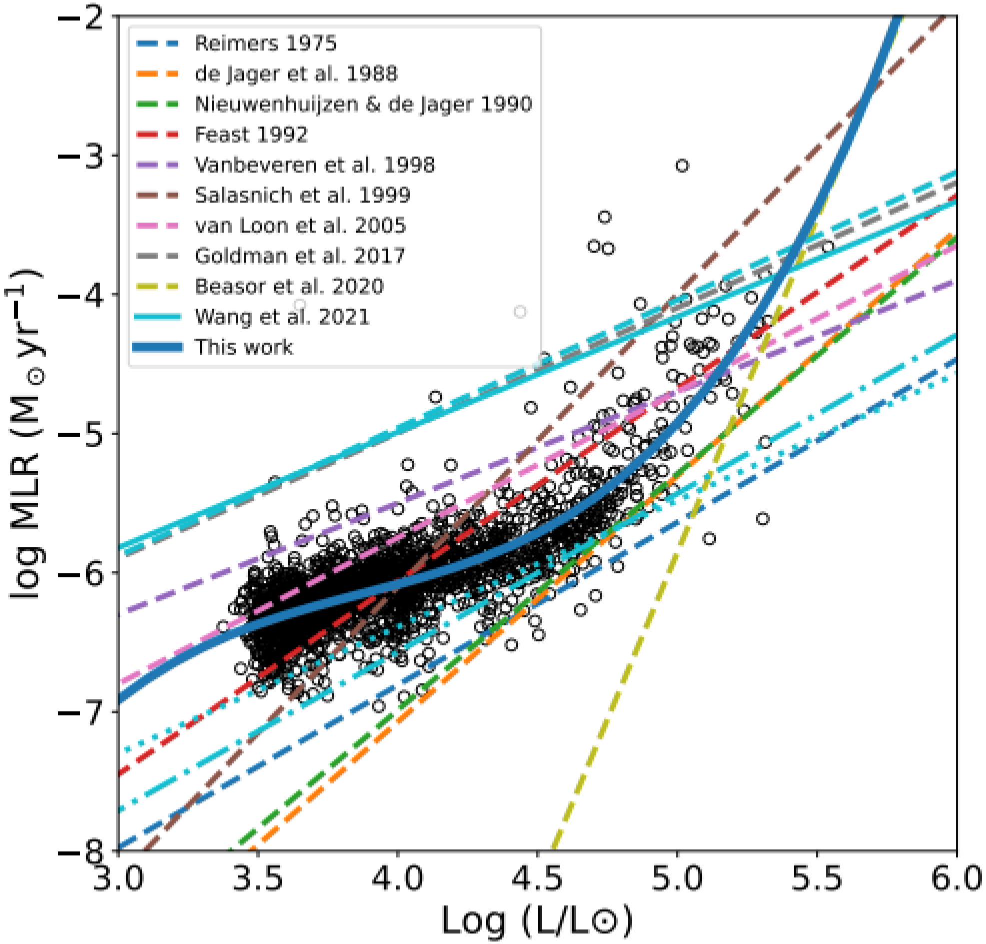
S. de Wit[1,2], A.Z. Bonanos[1], K. Antoniadis[1,2], E. Zapartas[3,1], A. Ruiz[1], N. Britavskiy[4,5], E. Christodoulou[1,2], K. De[6], G. Maravelias[1,3], G. Munoz-Sanchez[1,2], and A. Tsopela[7]

Spectral fitting of **127 RSGs**

de Wit et al. 2024, in press

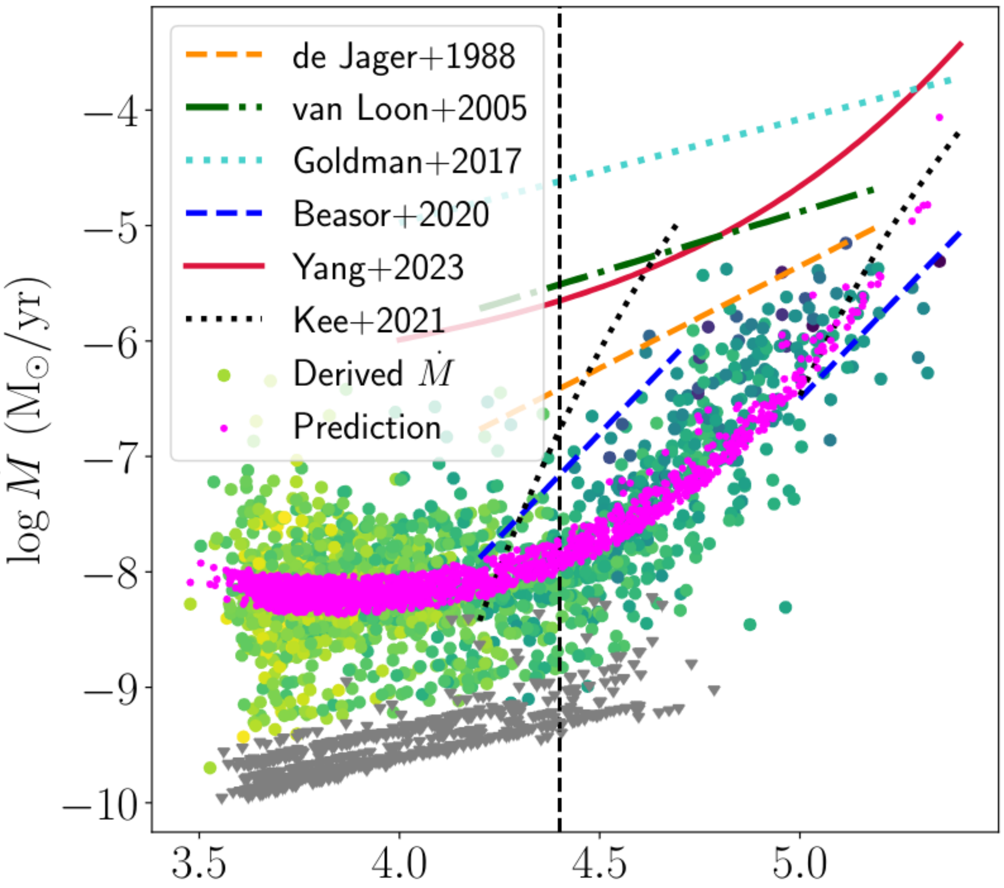
Yang et al. 2023

~2100 RSGs in SMC



Antoniadis et al. 2024, in press

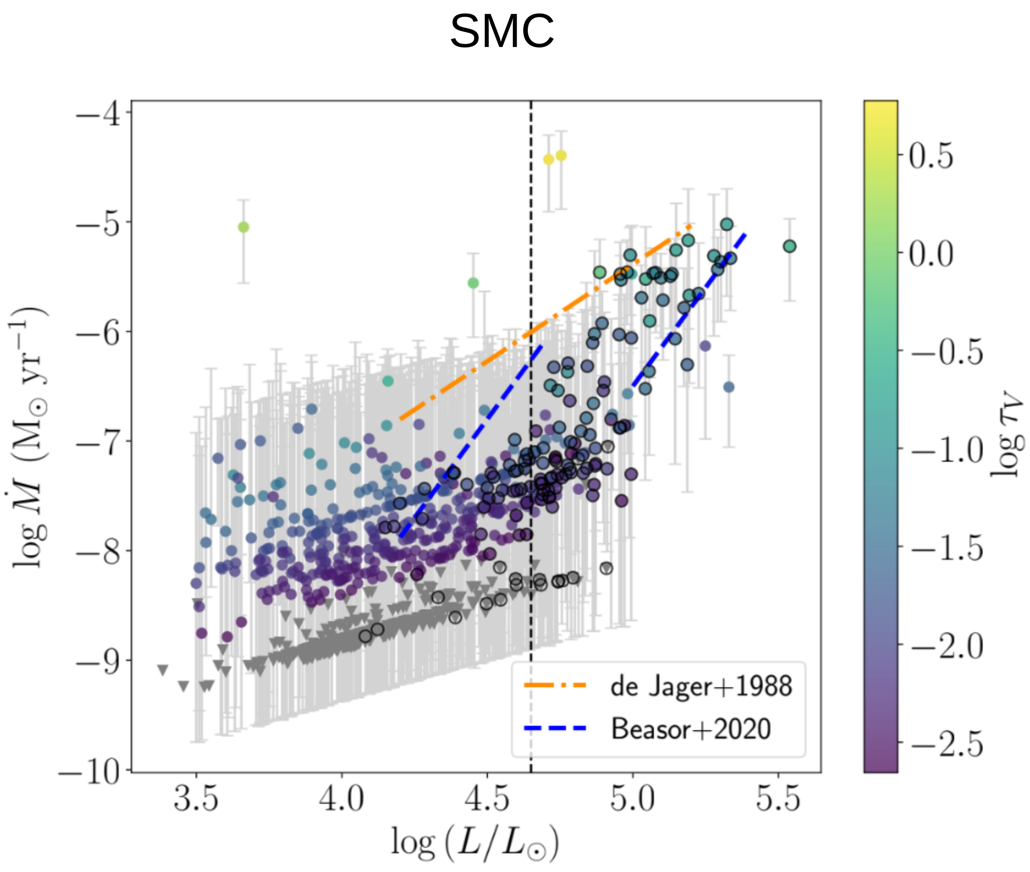
~2000 RSGs in LMC

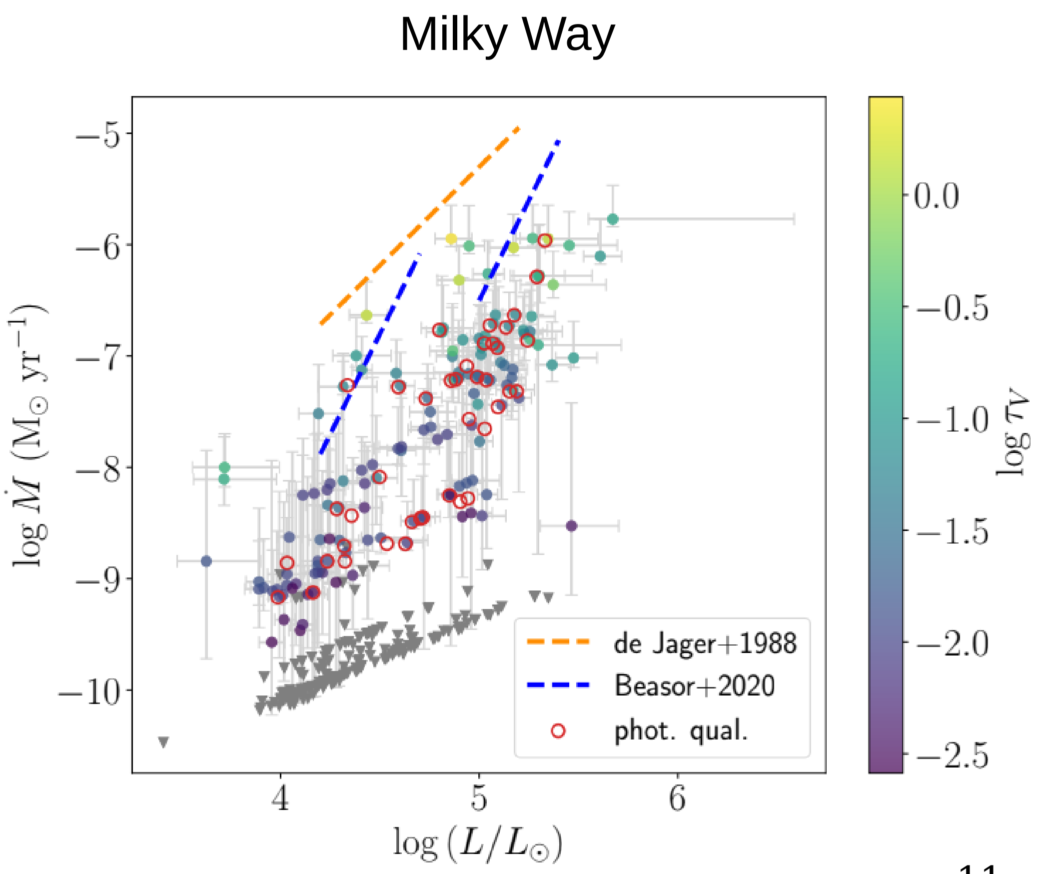


In prep.

Antoniadis et al. in prep

Studying the effects of Z



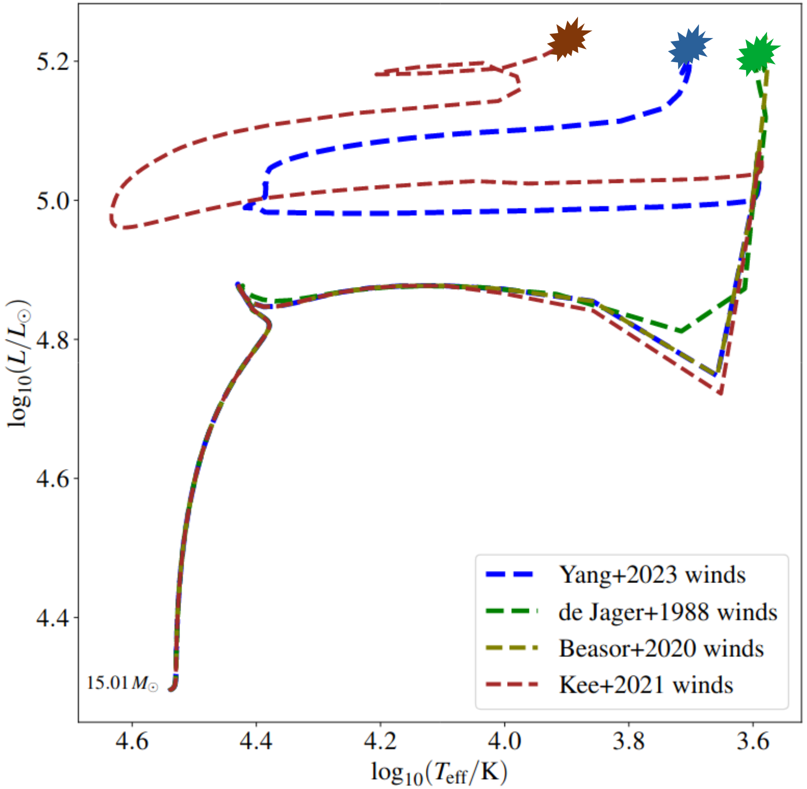


In prep.

Zapartas et al. in prep.

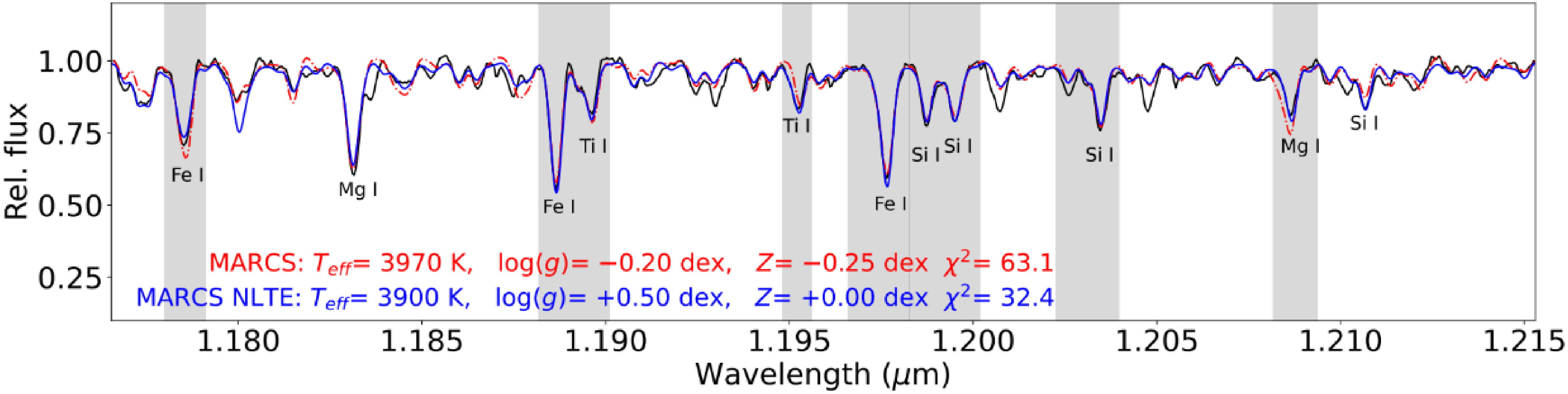
Consequence of mass-loss

Different evolution and SNe progenitor



Atomic lines in J-band

Spectroscopy R=5000, FIRE, 6.5-m Baade (Las Campanas, Chile)

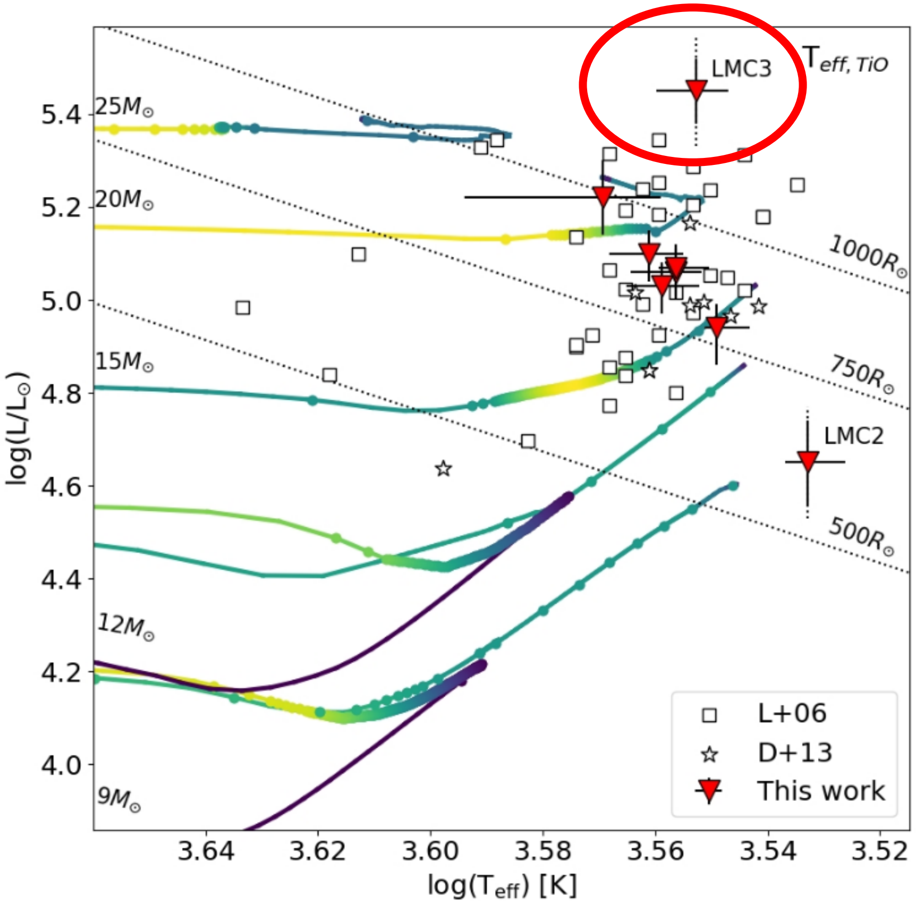


1D LTE MARCS models (Gustafsson et al. 2008)
1D NLTE MARCS models (Bergemann et al. 2012, 2013, 2015)

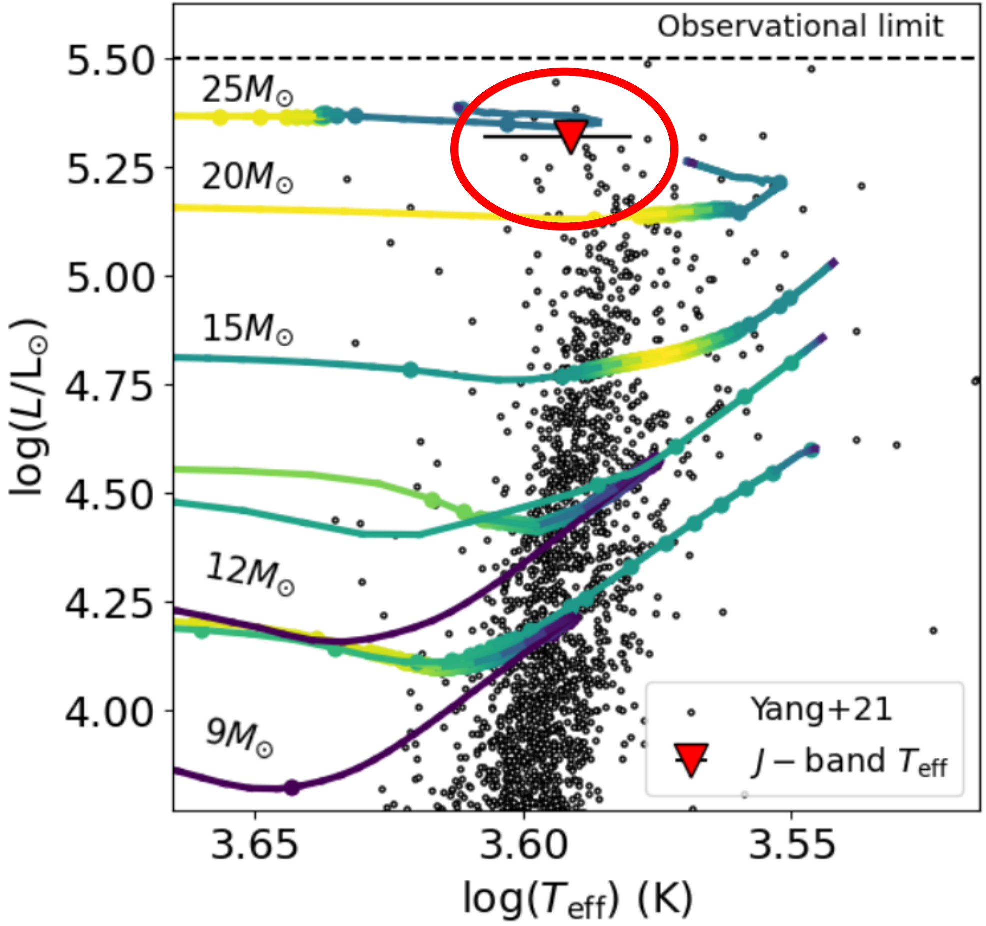
$T_{eff,J\text{-}band}$= 3900^{+150}_{-100} K (MARCS NLTE)

$T_{eff,TiO}$ ~ 3550 ± 150 K (MARCS LTE)

$T_{eff,TiO}$ vs $T_{eff,J\text{-}band}$

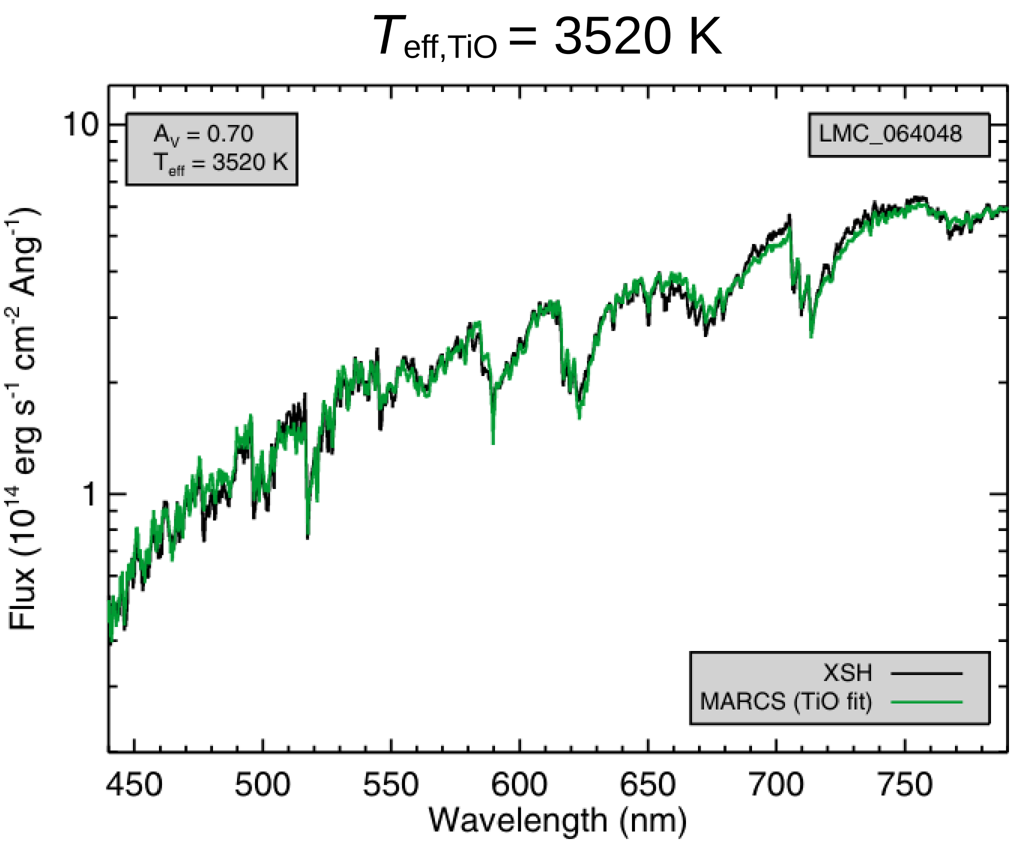


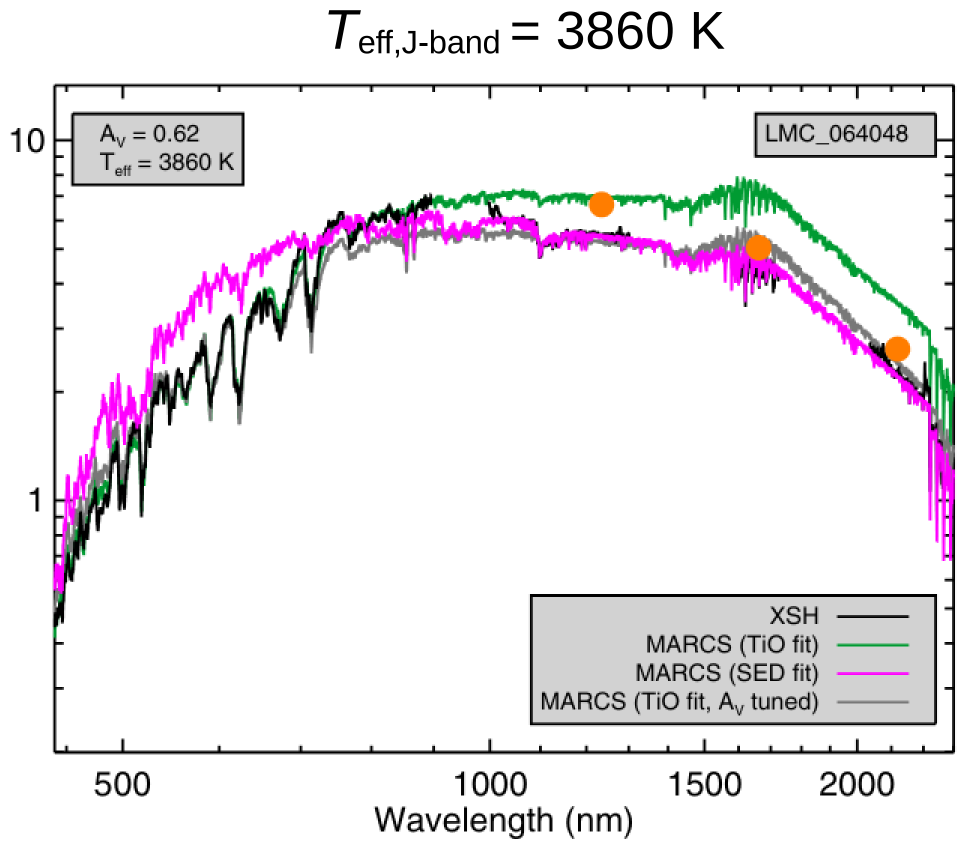
de Wit et al. 2023



Munoz-Sanchez et al. 2024

$T_{eff,TiO}$ vs $T_{eff,J\text{-}band}$

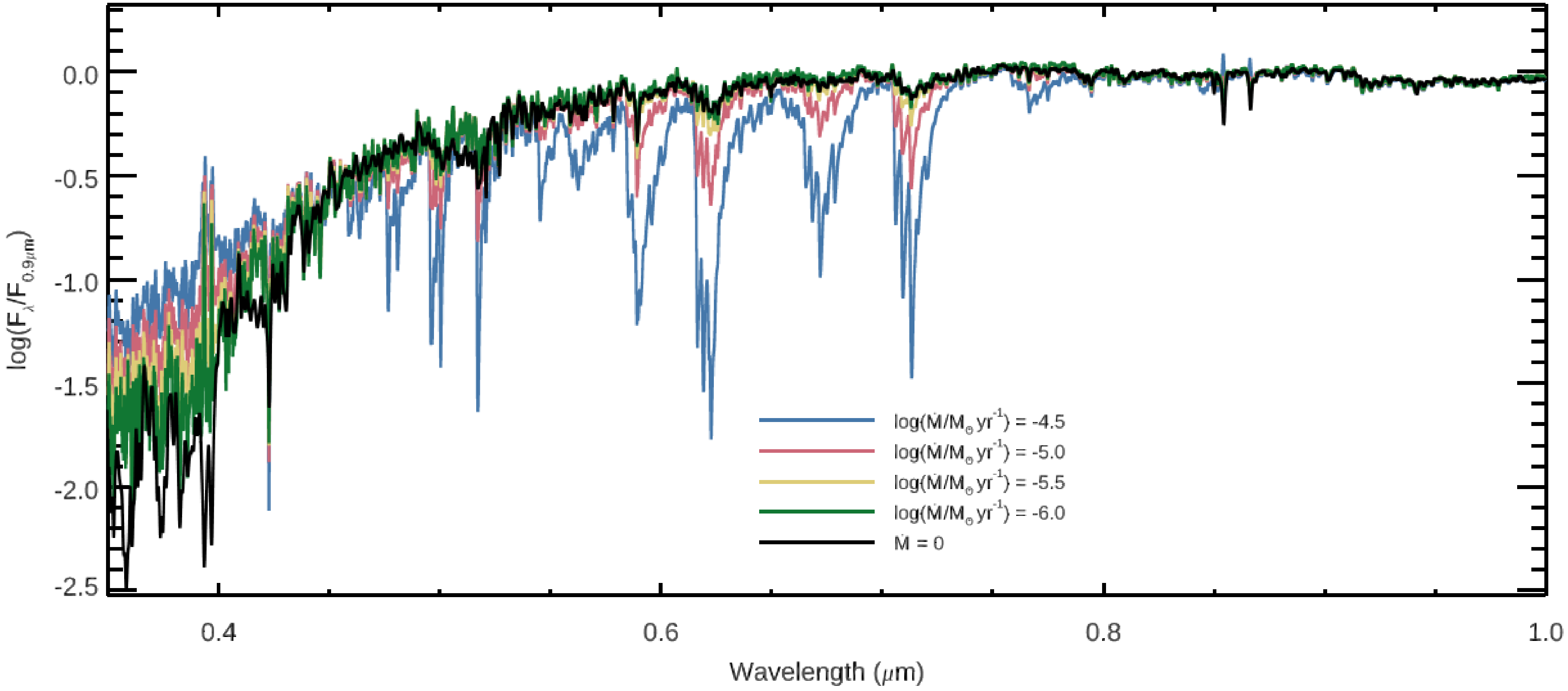




Davies et al. 2013

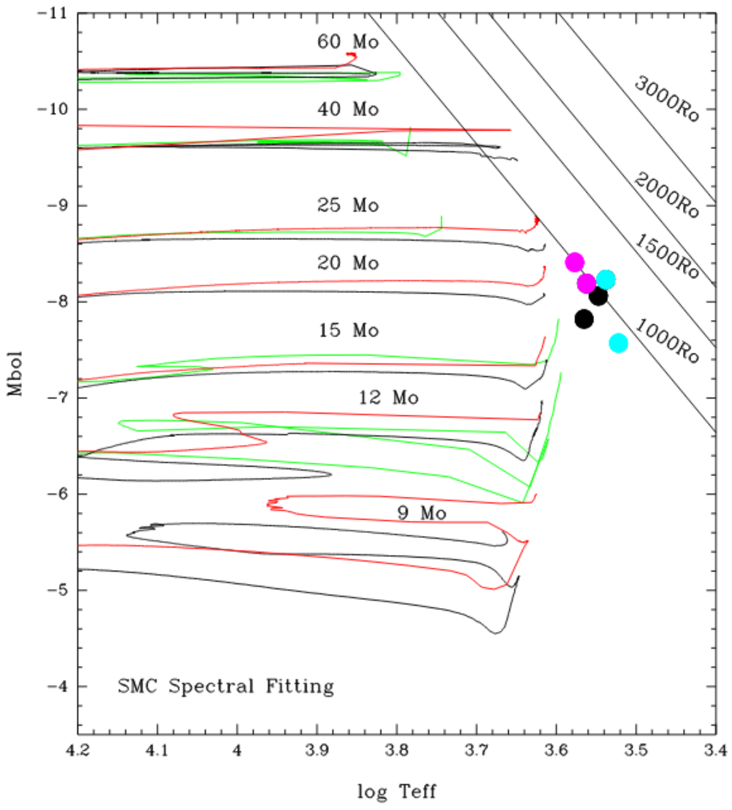
Effect of $\dot{M}$

Deeper TiO bands: ↓T_{eff} ↑$\dot{M}$

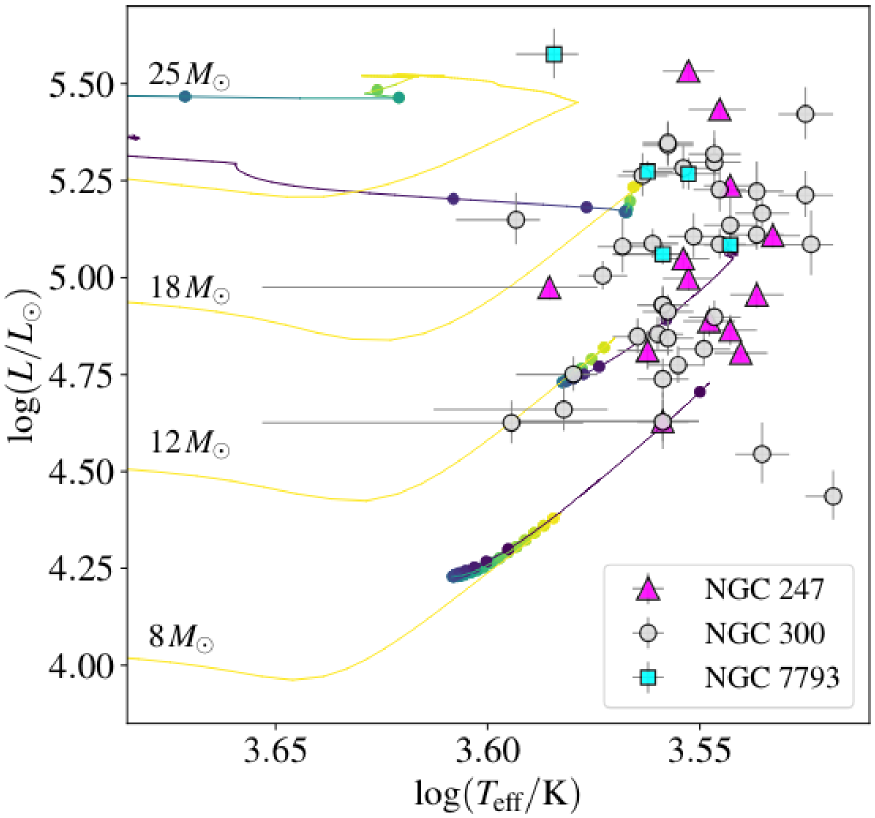


Davies & Plez 2021

$T_{\mathrm{eff,TiO}}$ too cool



Levesque et al. 2007



de Wit et al. 2024

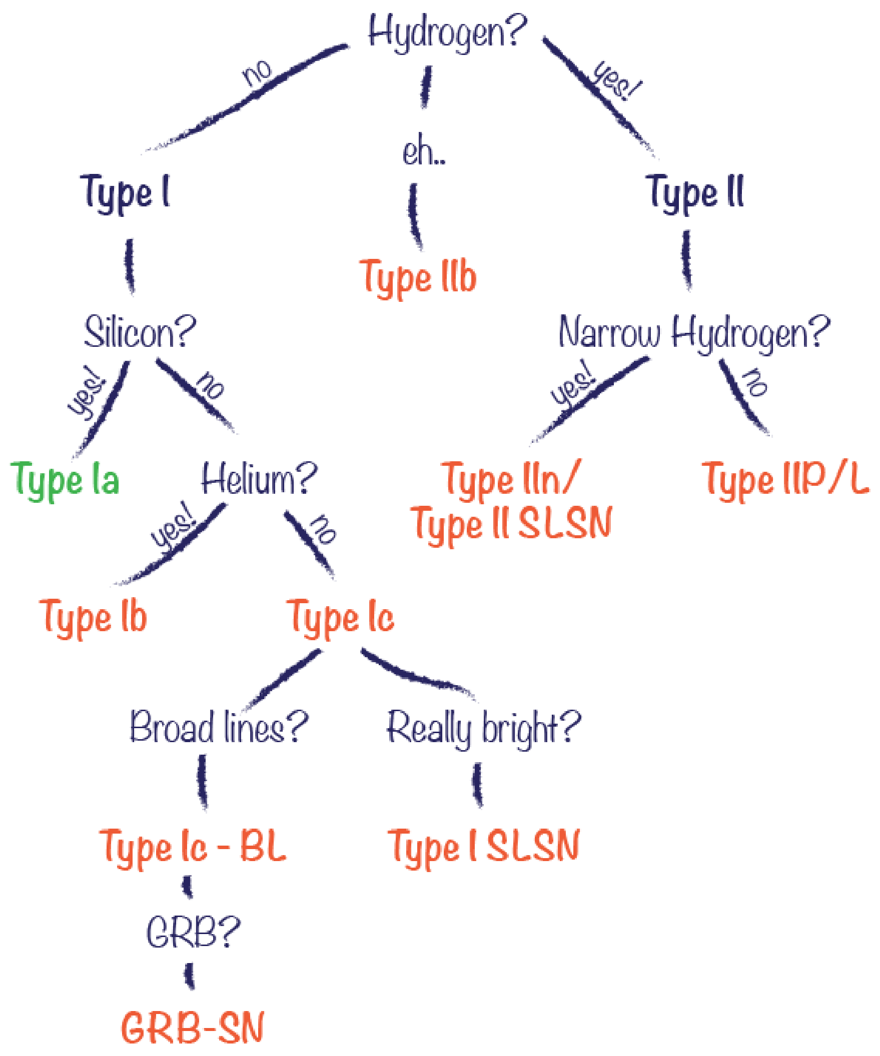
$T_{\mathrm{eff,TiO}}$ too cool

- [W60] B90 example of extreme RSG with inconsistent T_{eff}
- *de Wit et al. 2024* → scaling relation to translate $T_{\mathrm{eff,TiO}}$ into more secure T_{eff}
- 1D assumption: convection
- LTE assumptions: low density atmosphere
- Implementing $\dot{M}$

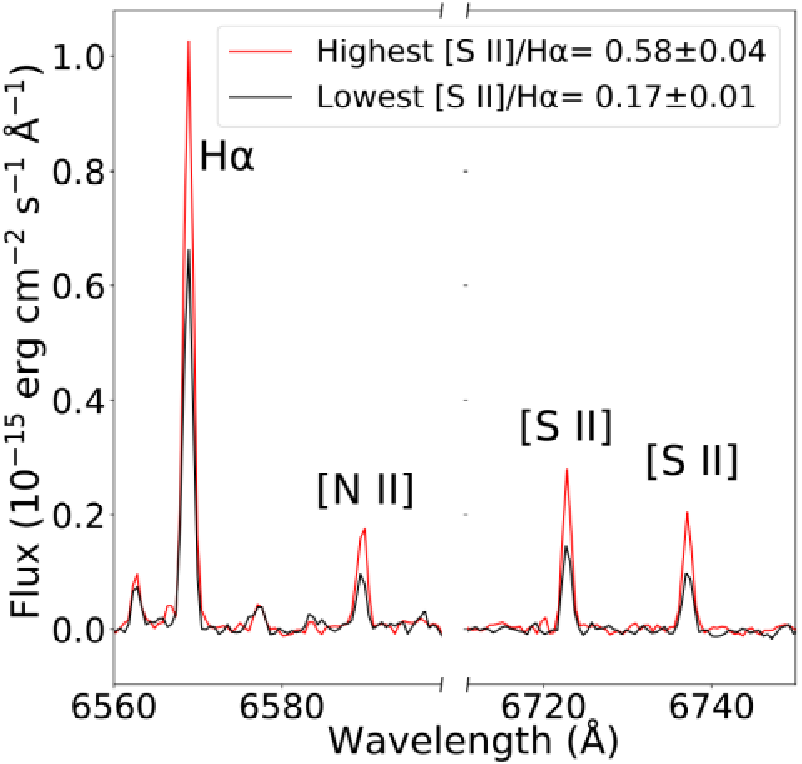
New generation of models

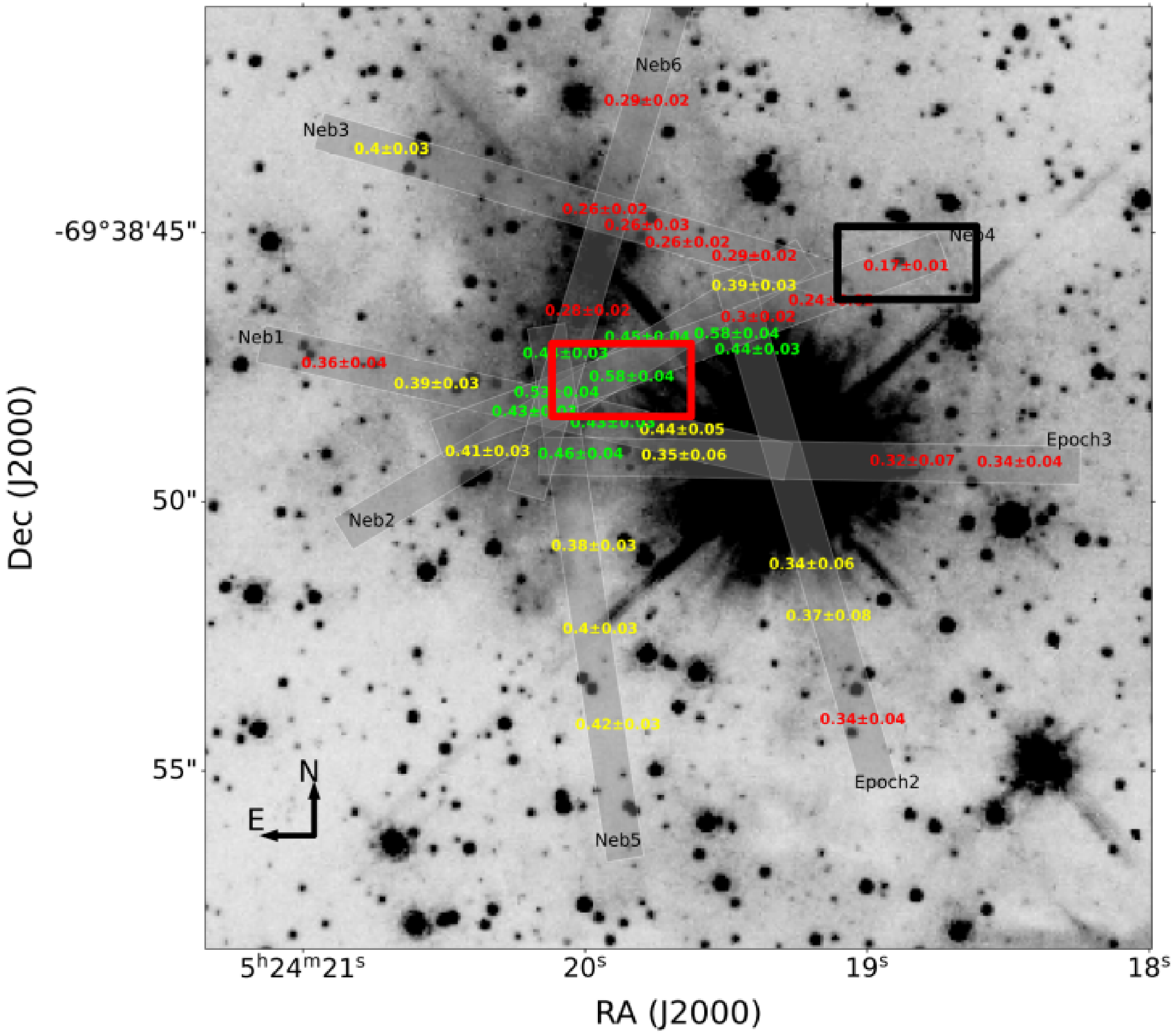
- *Gonzalez-Tora et al. 2024* → 1st state-of-art models with $\dot{M}$ in the near-IR

The Supernova Zoo

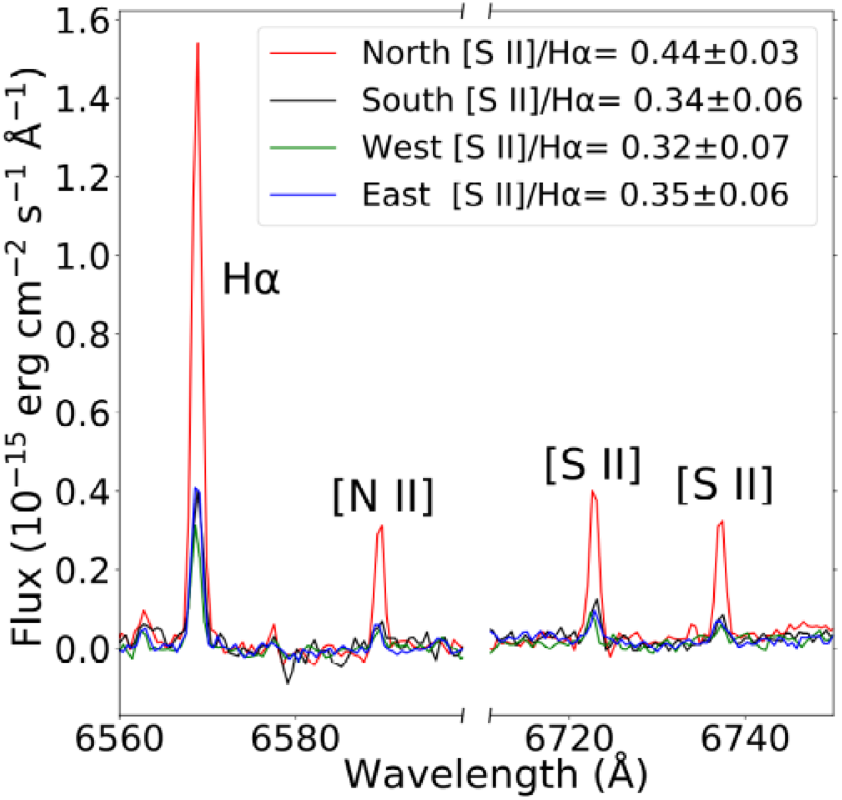


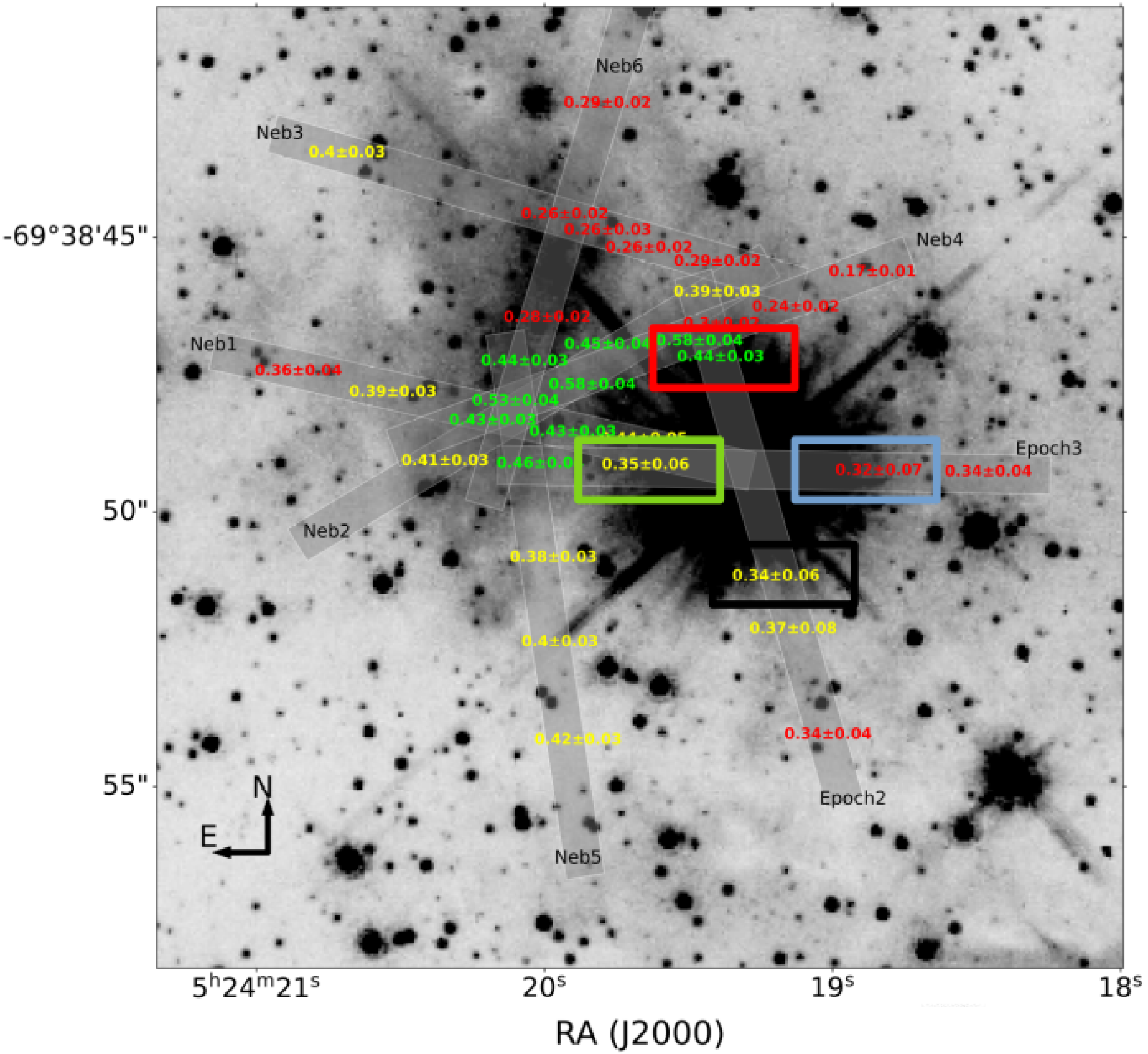
Shocked material





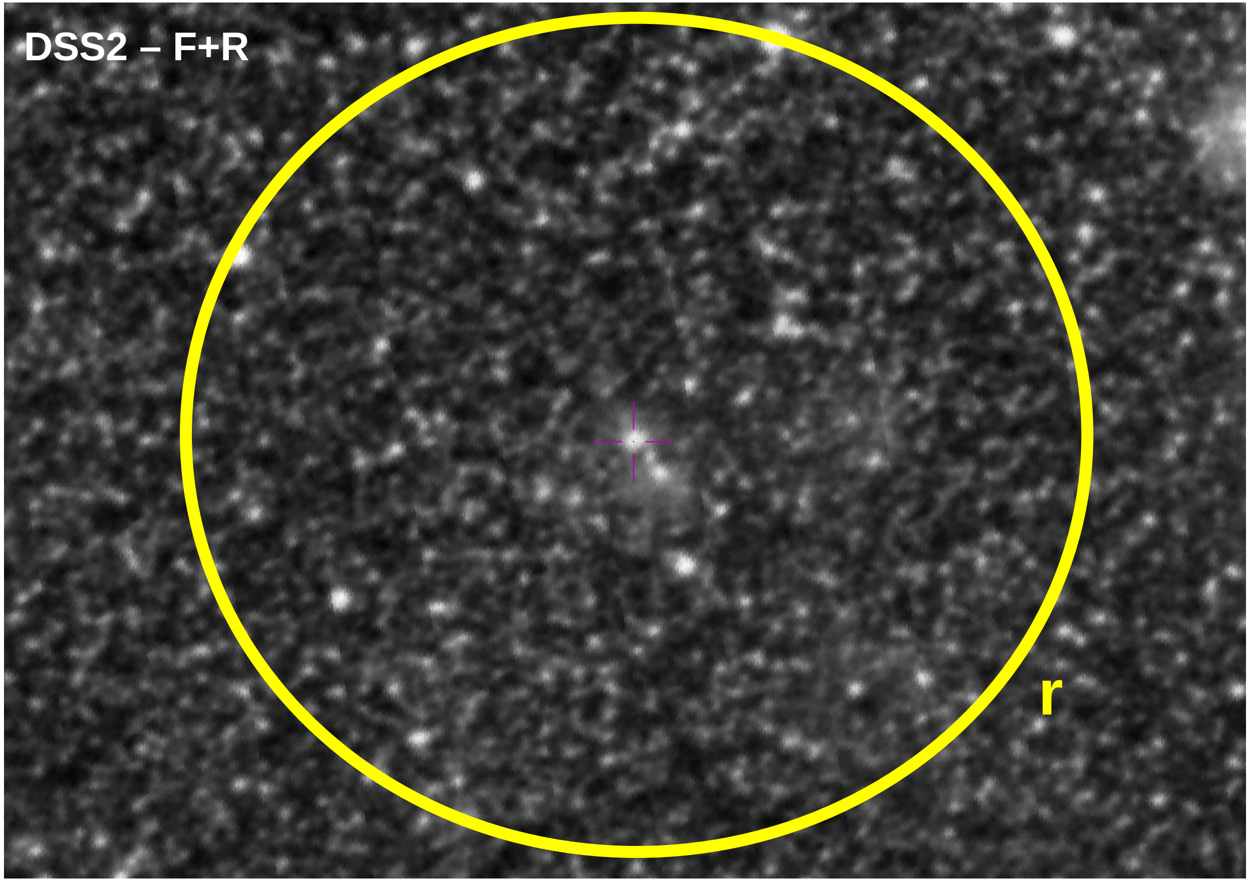
Shocked material





Proper motion

a) Gaia query:



Proper motion

Jimenez-Arranz et al. 2023

a) Gaia query

b) Remove foreground contamination

Kinematic analysis of the Large Magellanic Cloud using Gaia DR3⋆

Ó. Jiménez-Arranz[1, 2, 3], M. Romero-Gómez[1, 2, 3], X. Luri[1, 2, 3], P. J. McMillan[4], T. Antoja[1, 2, 3], L. Chemin[5], S. Roca-Fàbrega[6, 7], E. Masana[1, 2, 3], and A. Muros[1, 2]

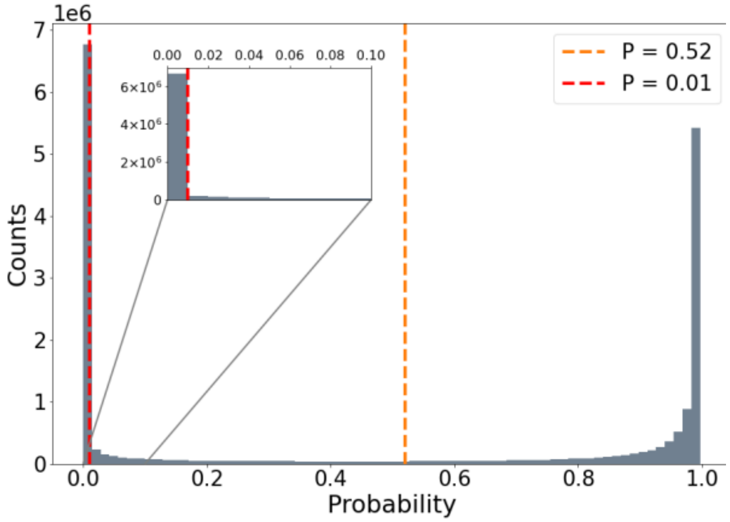


Fig. 4: Probability distribution of the *Gaia* base sample for the Neural Network classifier. A Probability value close to 1 (0) means a high probability of being a LMC (MW) star.

Proper motion

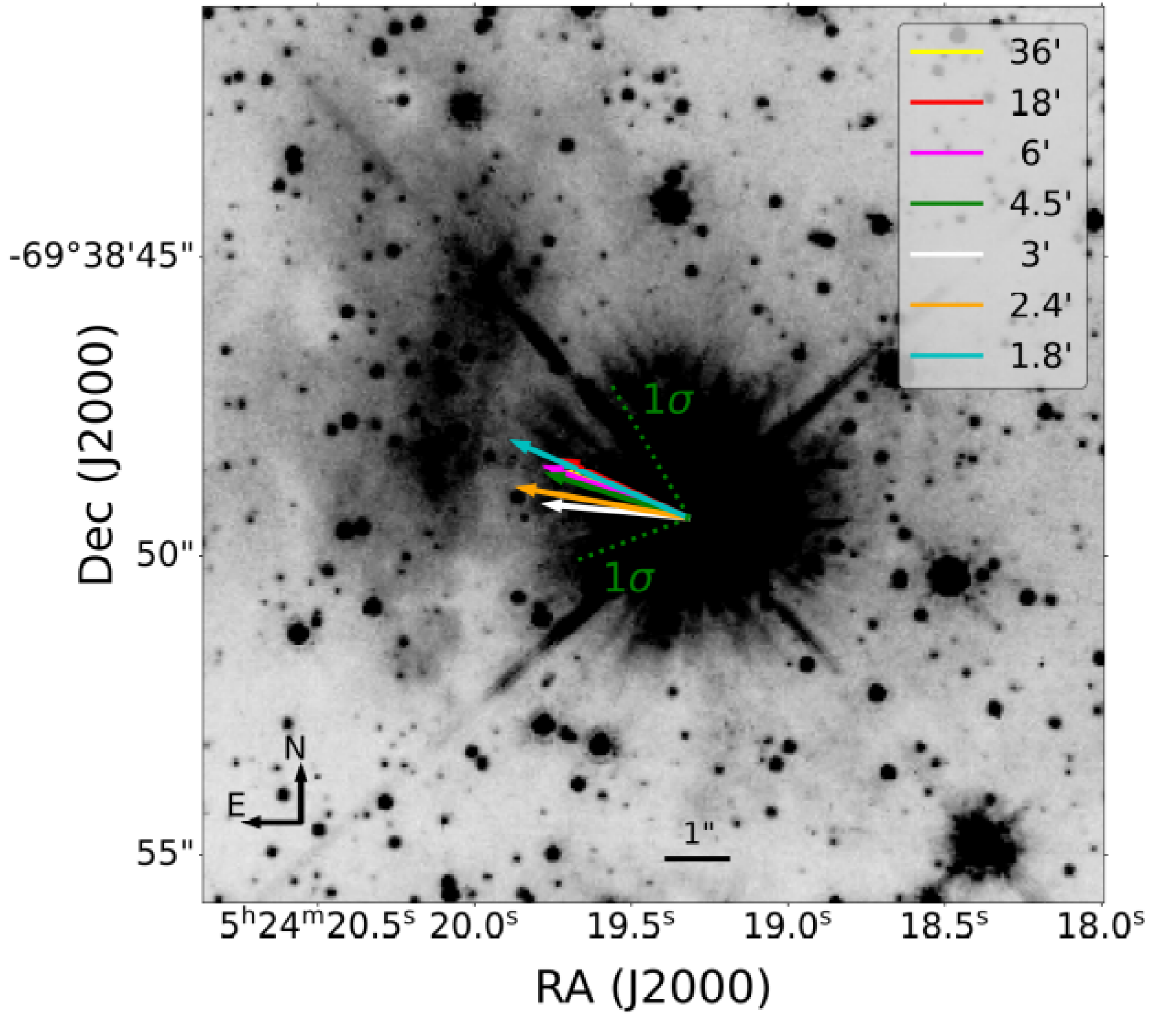
a) Gaia query

b) Remove foreground contamination

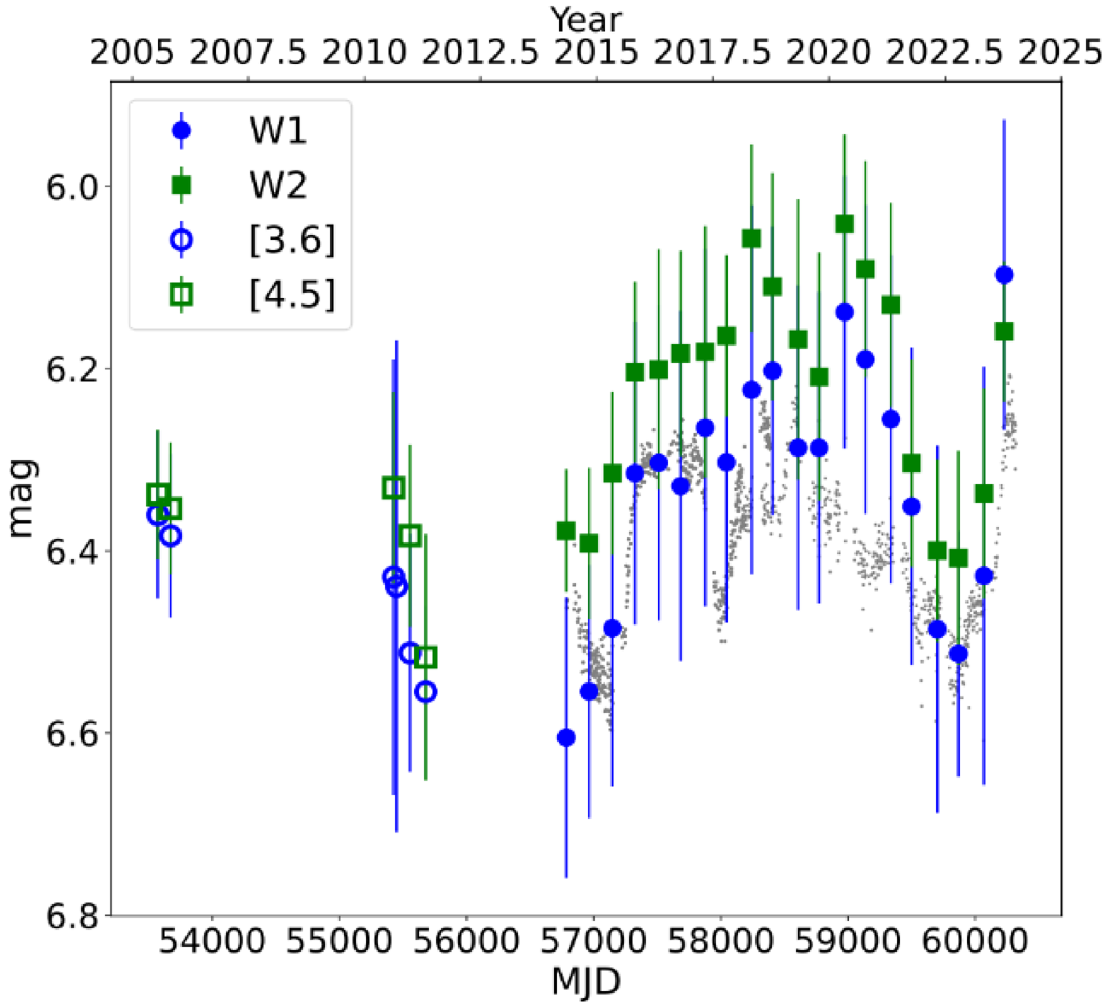
c) Obtain “local LMC” proper motion

d) Subtract from [W60] B90

e) Check [W60] B90 local proper motion

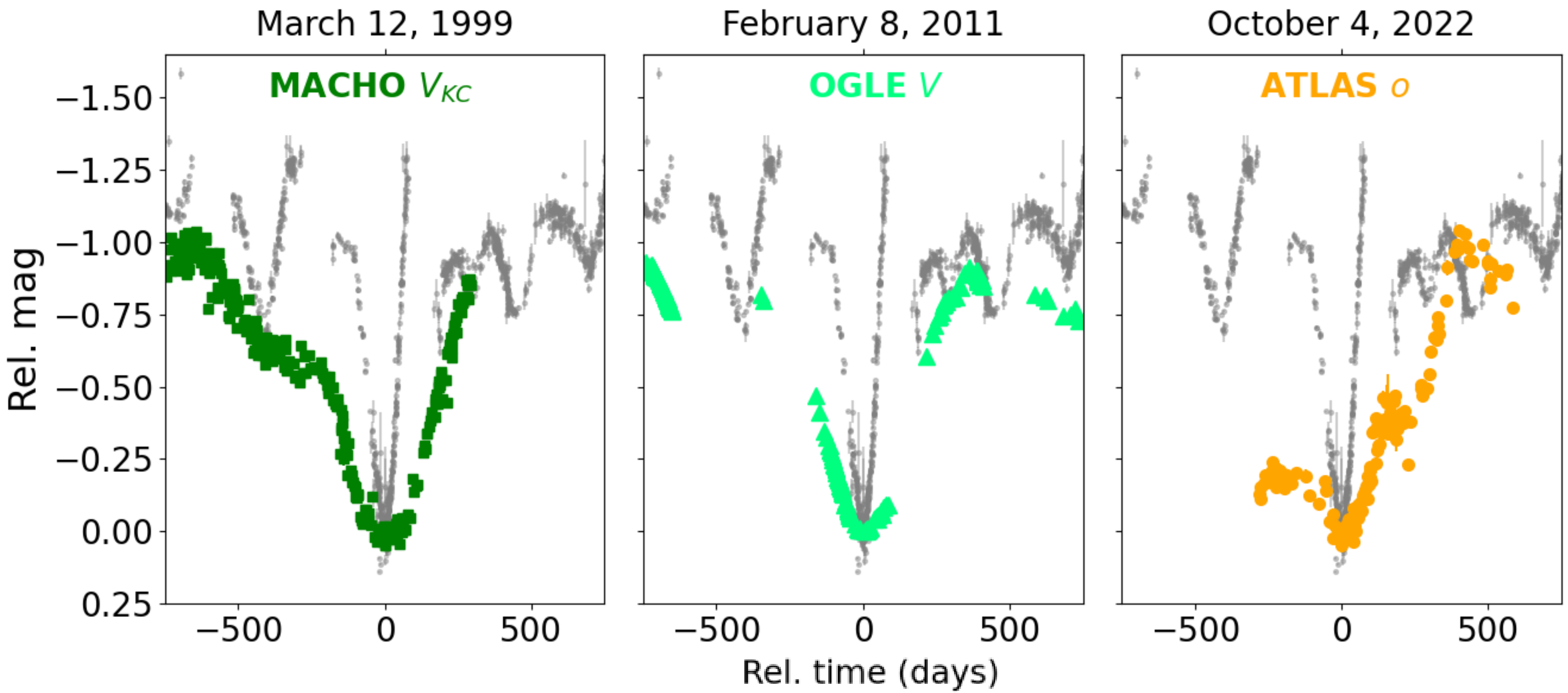


mid-IR variability



Dimming events

AAVSO photometry



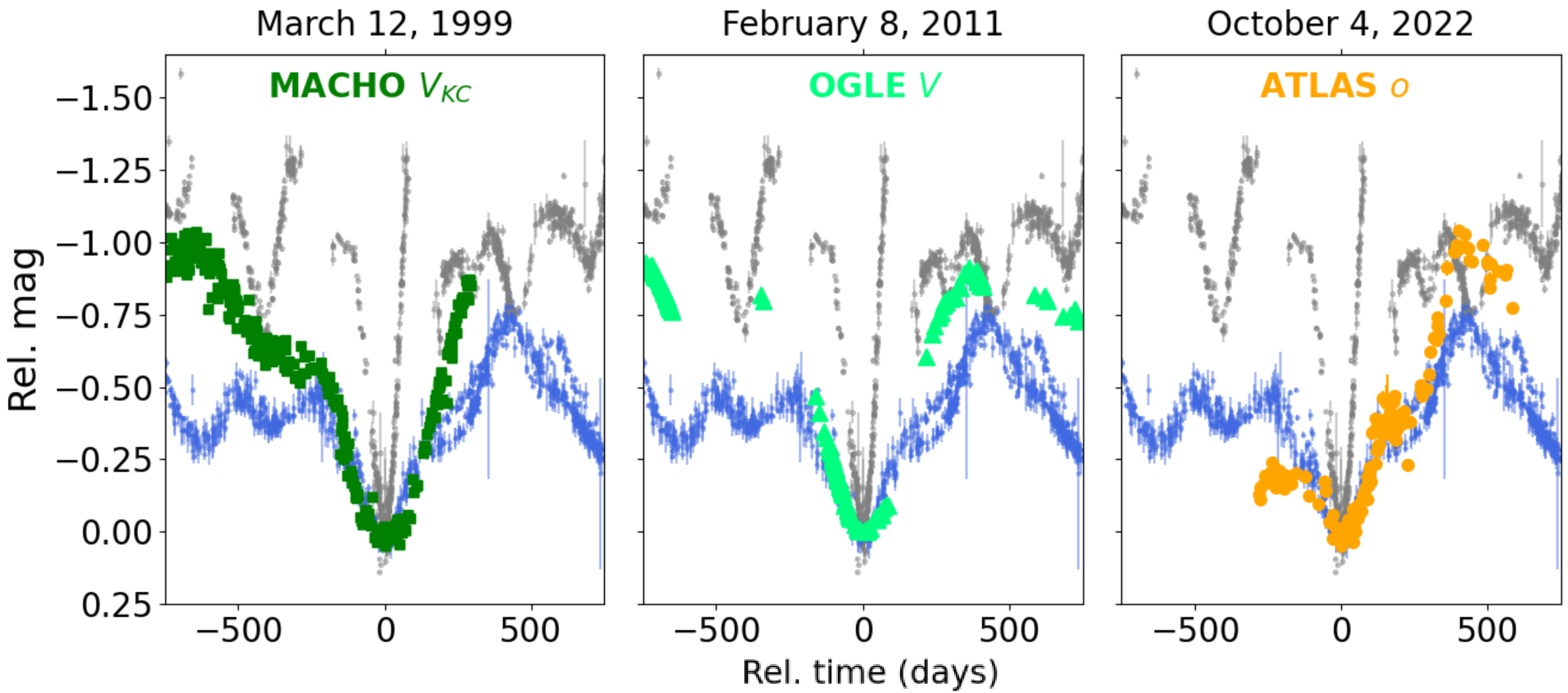
[W60] B90: ~1200 R_{sun}

Betelgeuse: 700-1000 R_{sun}

(Joyce et al. 2020, Kravchenko et al. 2021)

Dimming events

AAVSO photometry



[W60] B90: ~1200 R_{sun}

μ Cep: 1259 R_{sun}

(Josselin & Plez 2007)

Betelgeuse: 700-1000 R_{sun}

(Joyce et al. 2020, Kravchenko et al. 2021)

Teff

Atomic lines in the J-band[a]					
Name	Model	Z (dex)	$T_{\mathrm{eff,J}}$ (K)	log(g) (dex)	χ^2
EpochJ	MARCS LTE	$-0.25^{+0.25}_{-0.12}$	3970^{+130}_{-280}	$-0.20^{+0.20}_{-0.30}$	63.1
	MARCS NLTE	$+0.00^{+0.20}_{-0.10}$	3900^{+150}_{-100}	$+0.50^{+0.00}_{-0.75}$	36.4

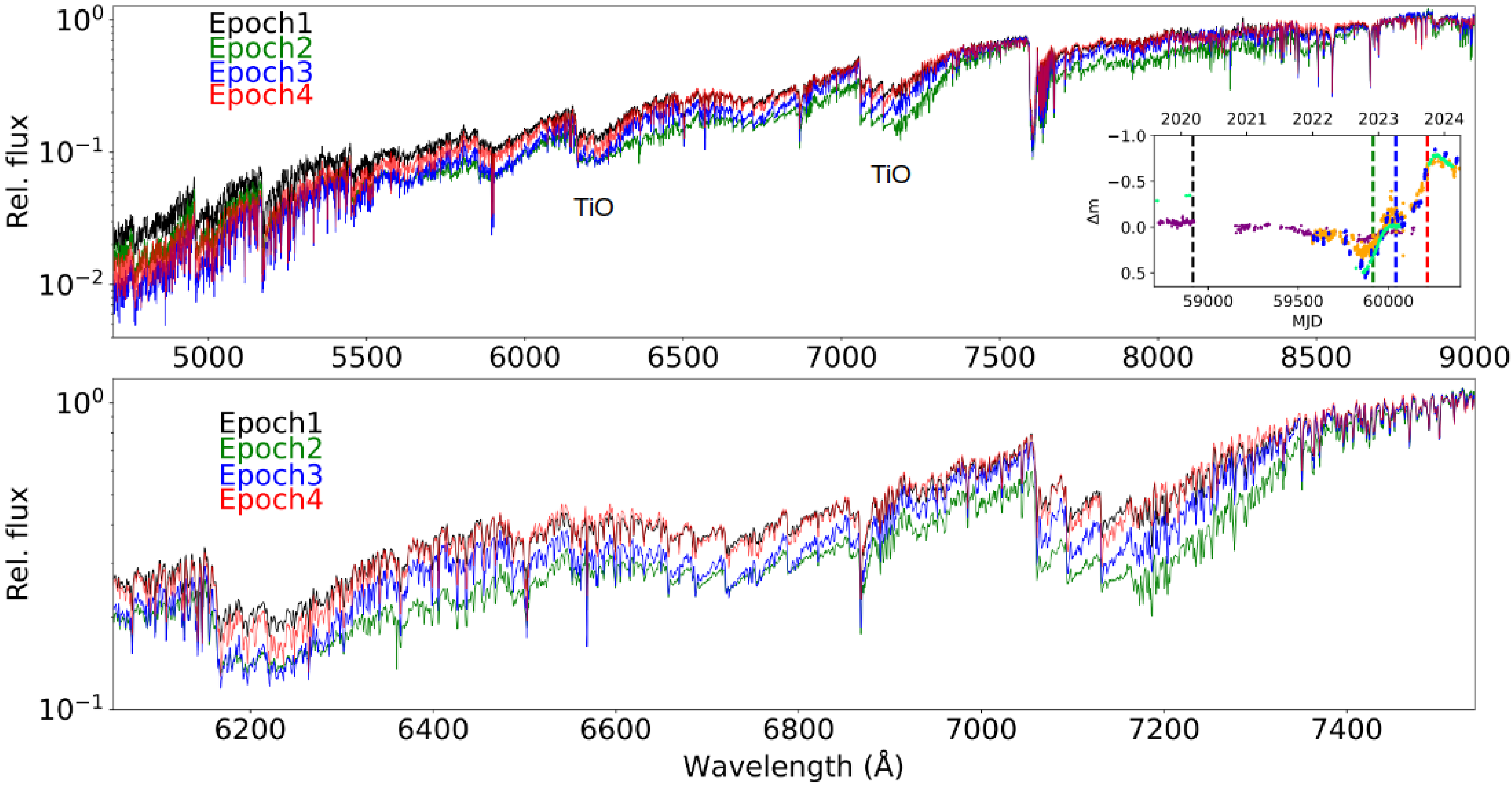
TiO bands from the optical						
	Spectral type	ATLAS o (mag)	$T_{\mathrm{eff,TiO}}$ (K)	$E(B-V)$ (mag)	A_V[b] (mag)	χ^2
Epoch1[c]	M3 I	–	3550±40	1.00±0.15	3.41±0.51	13.0
Epoch2	M4 I	12.6±0.1	3460^{+20}_{-30}	1.10±0.10	3.75±0.34	193.7
Epoch3	M3 I	12.3±0.1	3550^{+40}_{-30}	$1.35^{+0.10}_{-0.05}$	$4.60^{+0.34}_{-0.17}$	47.9
Epoch4	M3 I	11.8±0.1	3610^{+60}_{-50}	$1.25^{+0.10}_{-0.05}$	$4.26^{+0.34}_{-0.17}$	26.9

Notes. [(a)] Assuming $Z = -0.25$ dex and $\log g = -0.2$ dex from the J-band fit.[(b)] Converted from $E(B-V)$ assuming $R_V = 3.41$. [(c)] T_{eff}=3570^{+60}_{-50} K and $E(B-V) = 1.00 \pm 0.14$ mag from de Wit et al. (2023).

Spectral variability

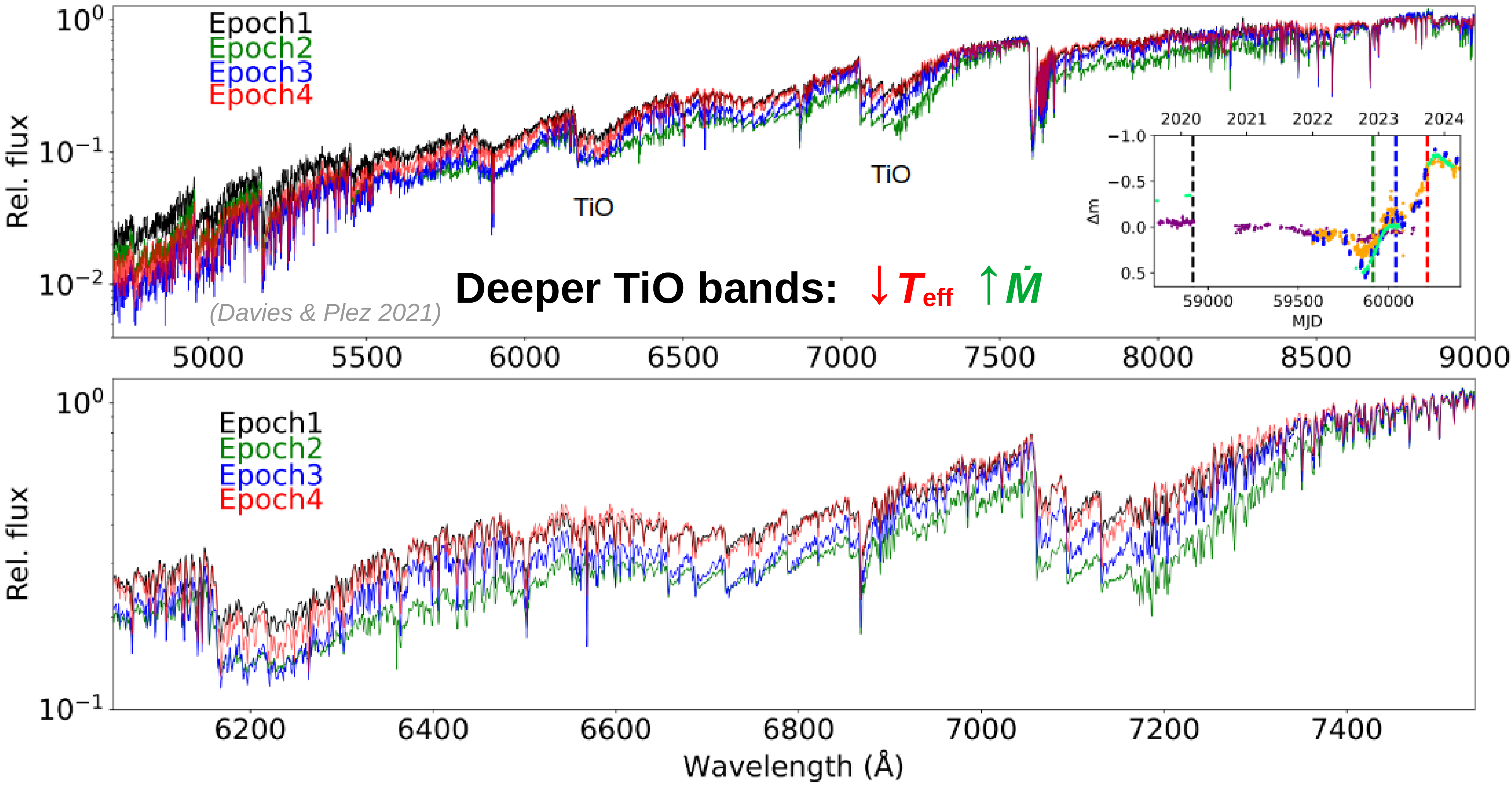
Spectral variability

Spectroscopy R=4000, MagE, 6.5-m Baade (Las Campanas, Chile)



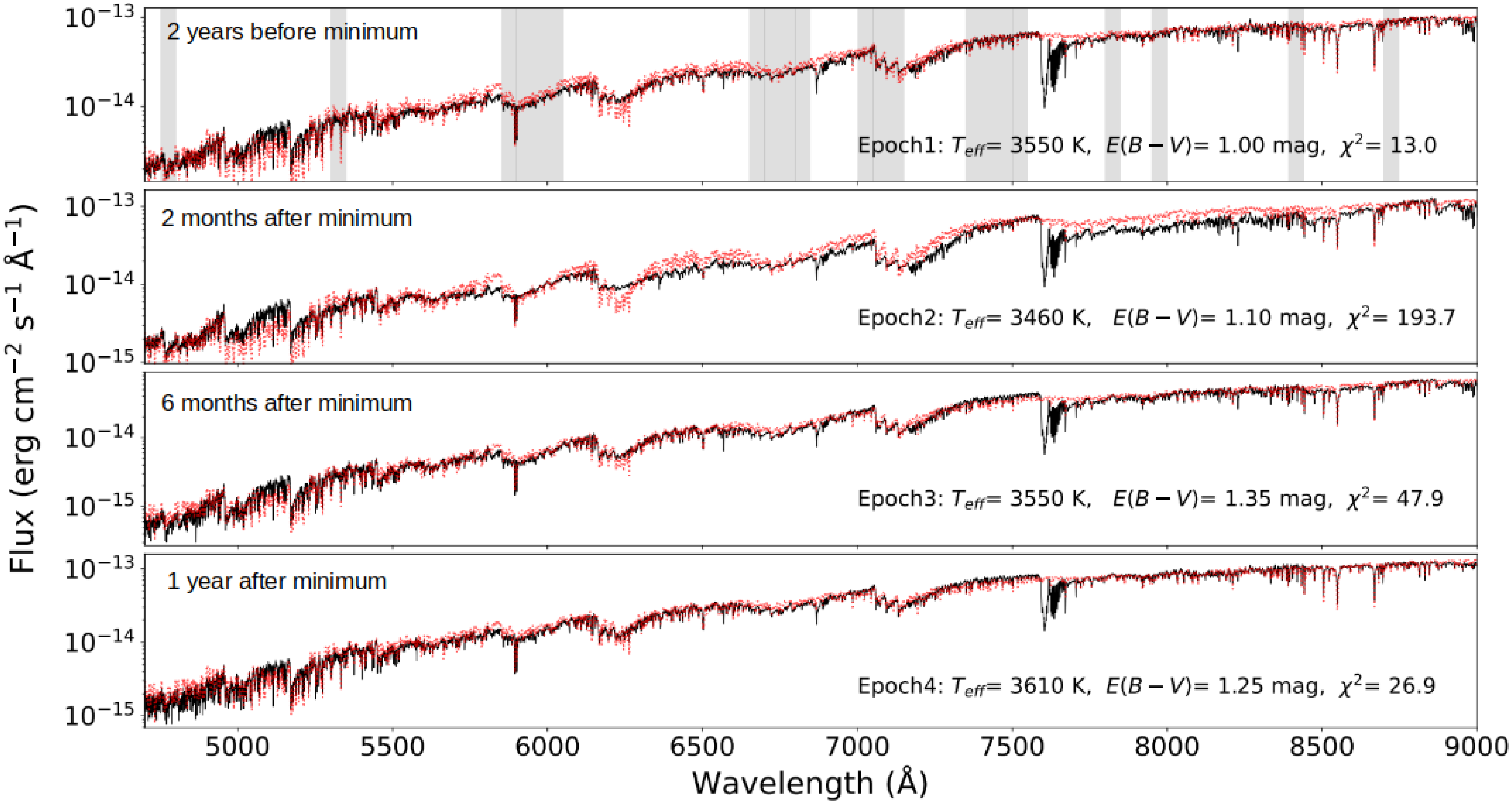
Spectral variability

Spectroscopy R=4000, MagE, 6.5-m Baade (Las Campanas, Chile)



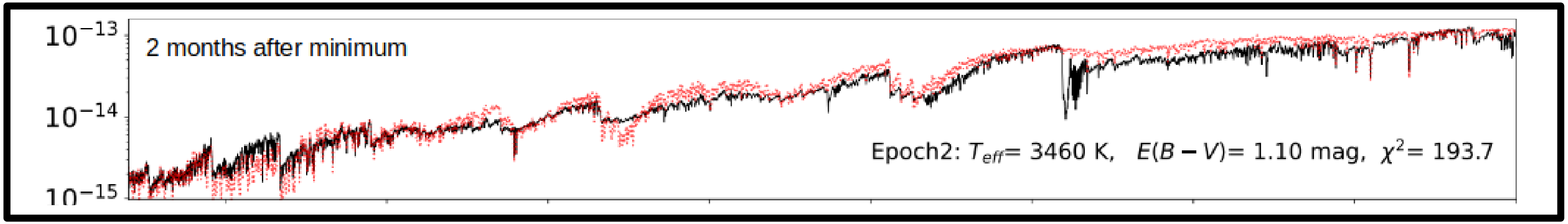
Physical parameters

1D LTE MARCS models (Gustafsson et al. 2008)



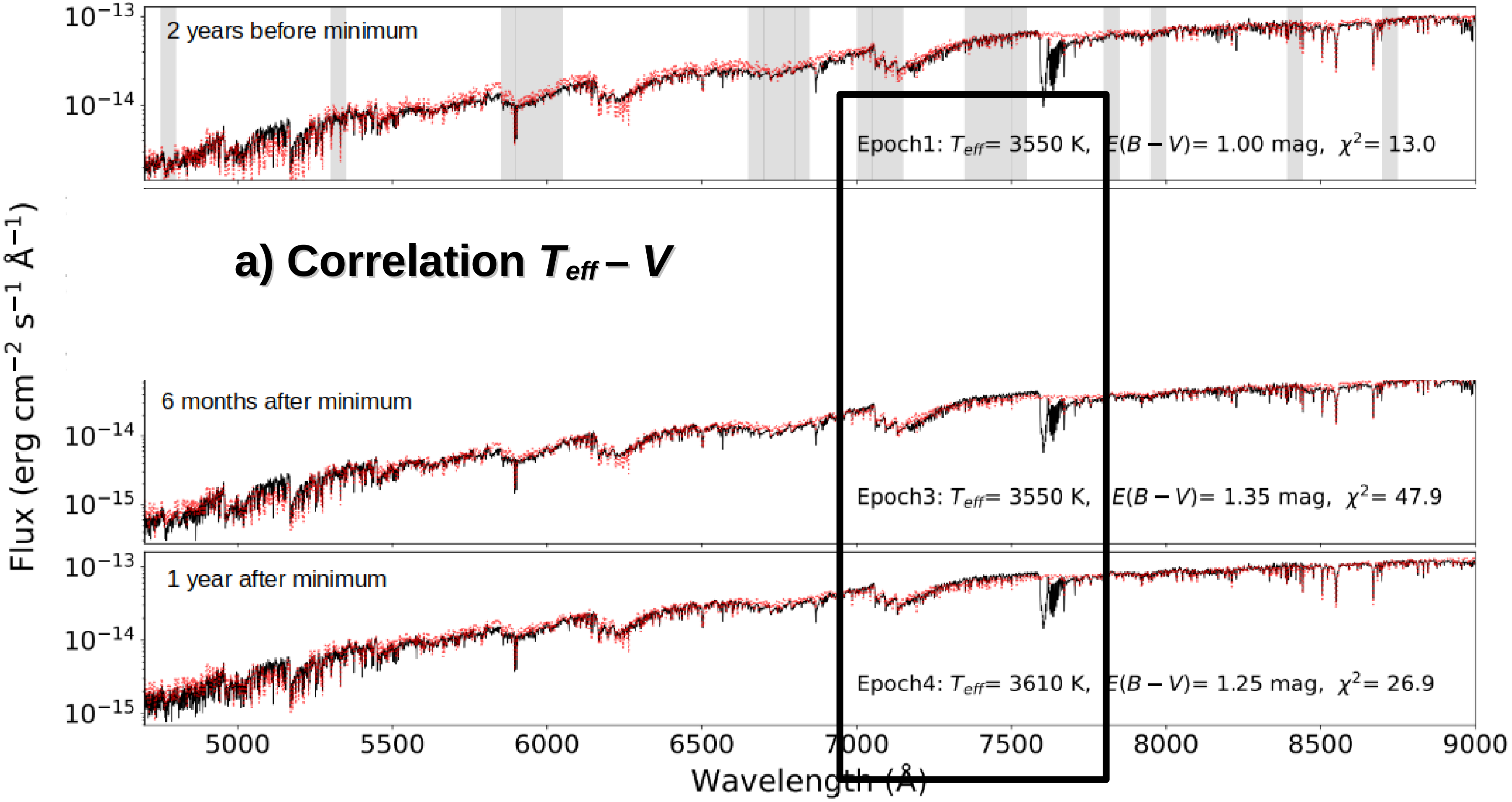
Physical parameters

Not reproduced by MARCS models



Physical parameters

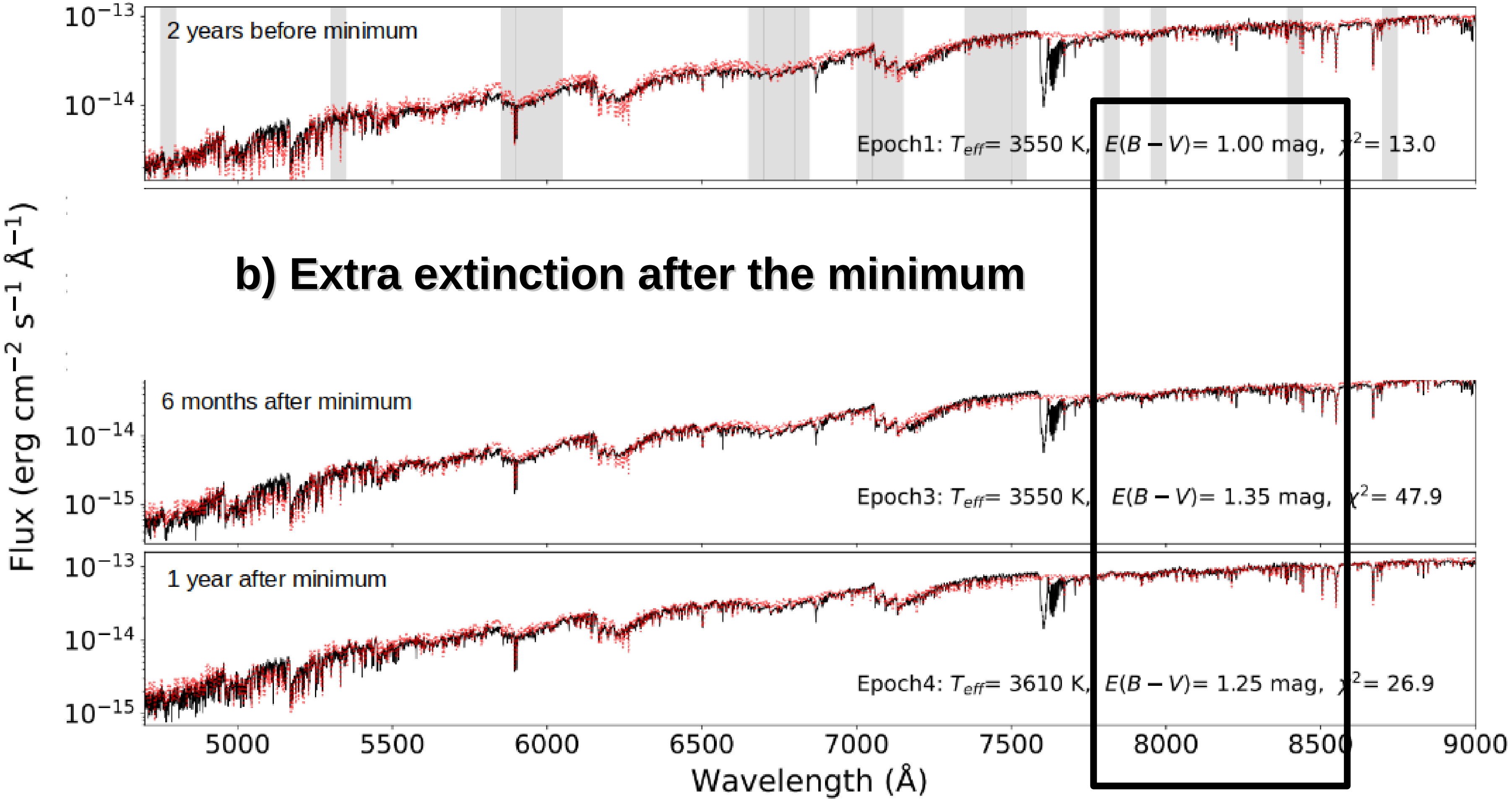
1D LTE MARCS models (Gustafsson et al. 2008)



a) Correlation $T_{eff} - V$

Physical parameters

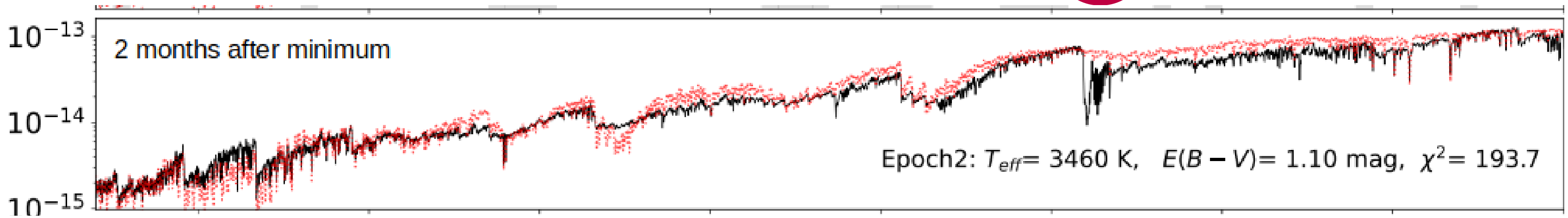
1D LTE MARCS models (Gustafsson et al. 2008)



b) Extra extinction after the minimum

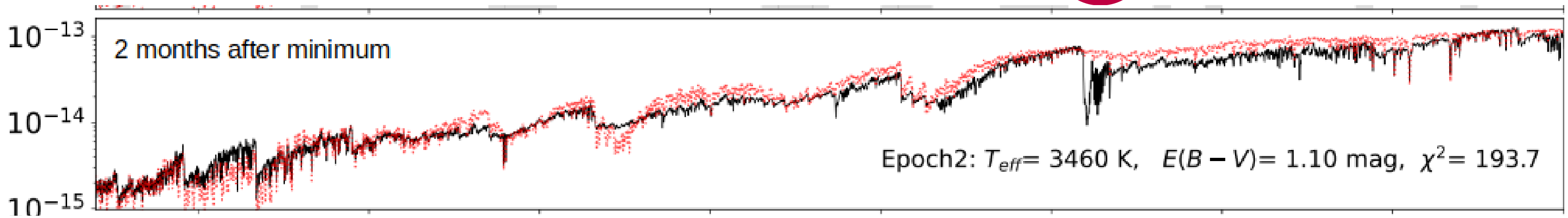
Dimming event

Single MARCS model

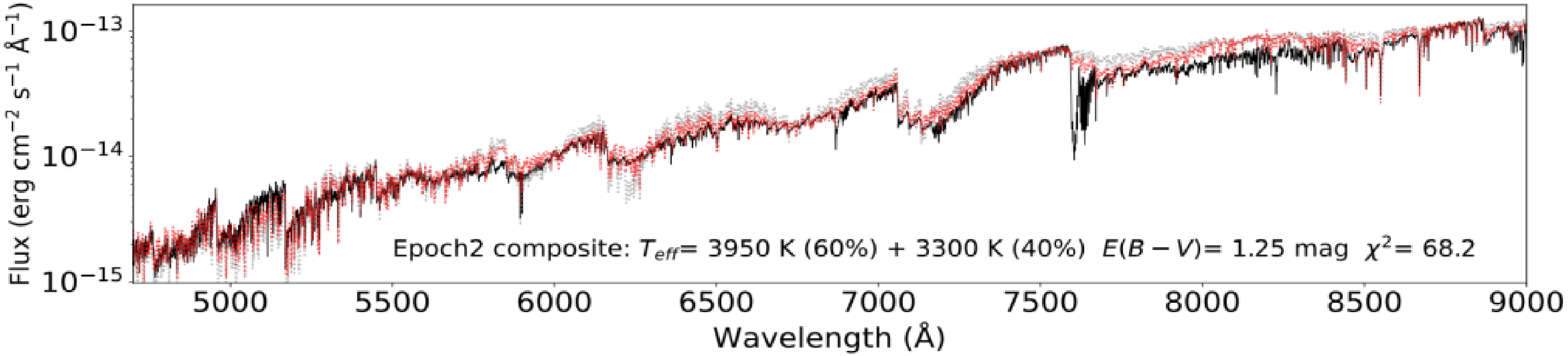


Dimming event

Single MARCS model

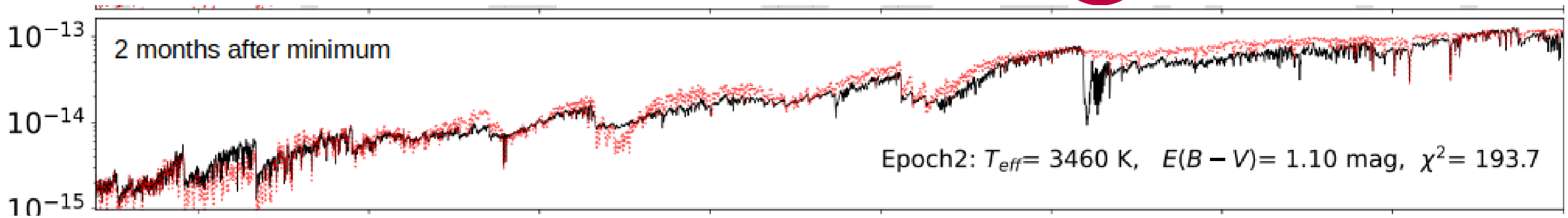


c) Composite MARCS model

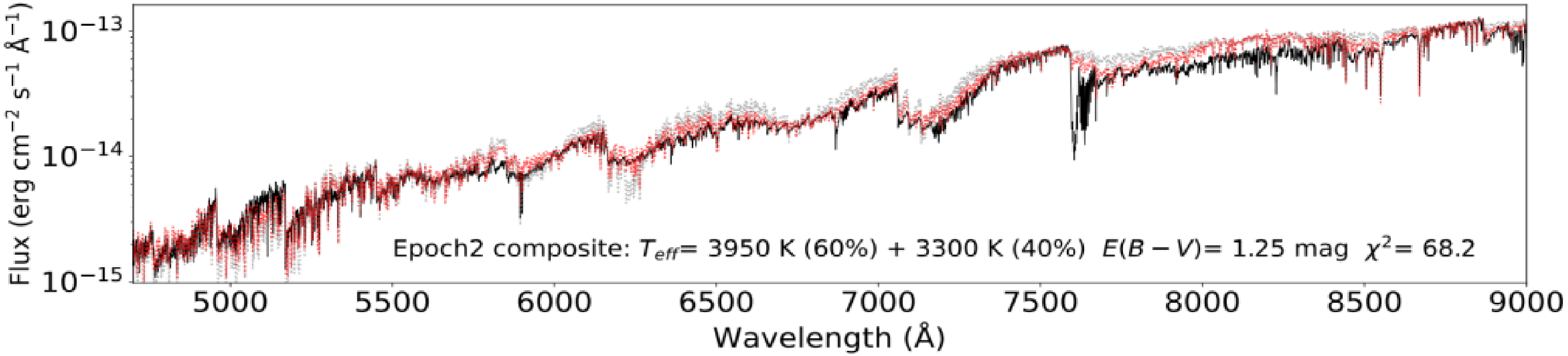


Dimming event

Single MARCS model



c) Composite MARCS model !



Spectral variability

a) Correlation T_{eff} – V

b) Extra extinction after the minimum

c) Complex atmospheric properties close to the minimum: cool+hot components

Spectral variability

a) Correlation $T_{\rm eff}$ – V

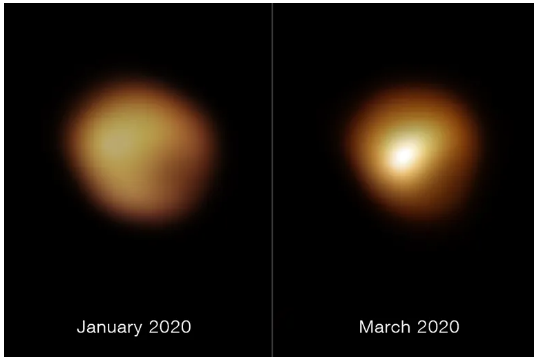
b) Extra extinction after the minimum

c) Complex atmospheric properties close to the minimum: cool+hot components

↓

Betelgeuse

The Great Dimming of Betelgeuse



Montarges et al. 2021

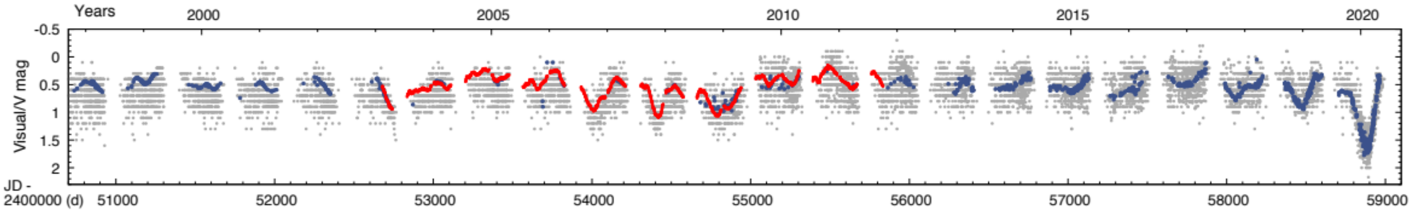


Figure 7: Century long record of the visual and V band brightness of Betelgeuse complied by the American Association of Variable Star Observers supplemented by data from the Solar Magnetic Ejection Imager (SMEI). The final large dip is the Great Dimming of 2020 (§4). From Joyce et al. (2020) by permission of Meridith Joyce, László Molnár, and the Astrophysical Journal.

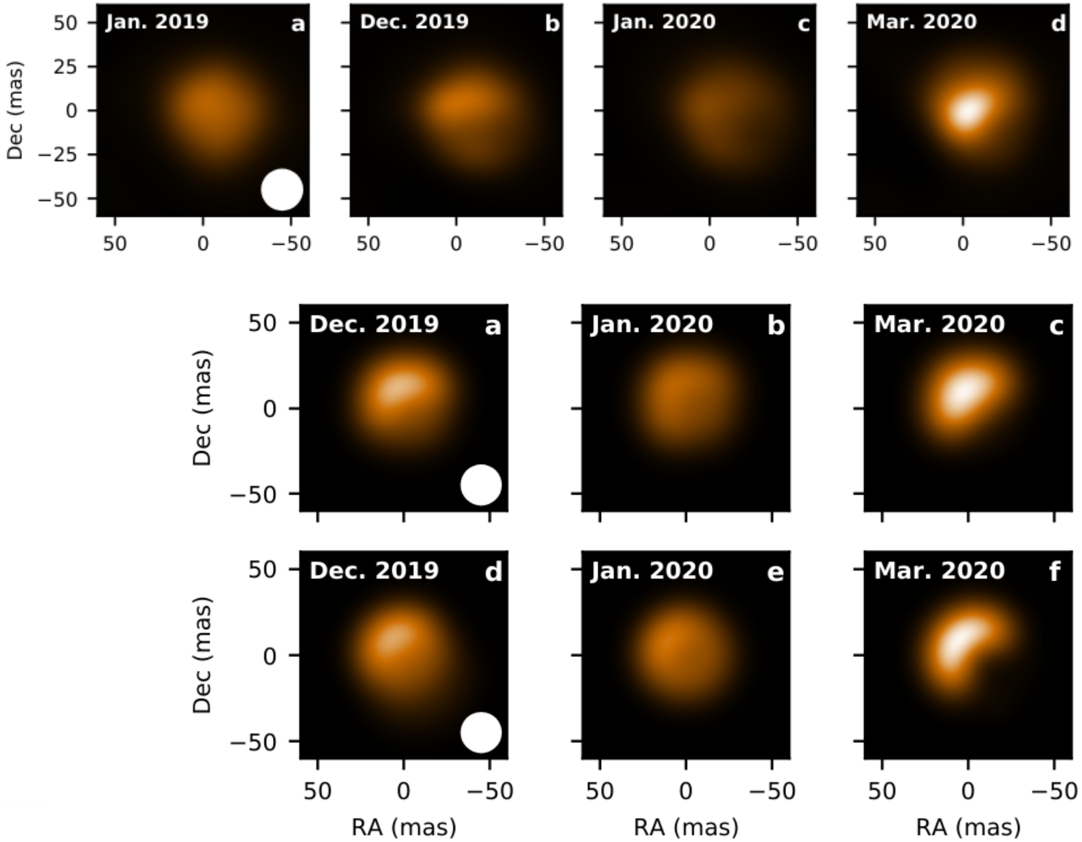
Craig Wheeler J. & Chatzopoulos 2023

“An anomalously hot convective plume can rise and break free from the surface, powering an upwelling that becomes the surface mass ejection”

MacLeod et al. 2023

3-120% of the annual mass loss of Betelgeuse !!!

Betelgeuse dimming (Montargues et al. 2021)

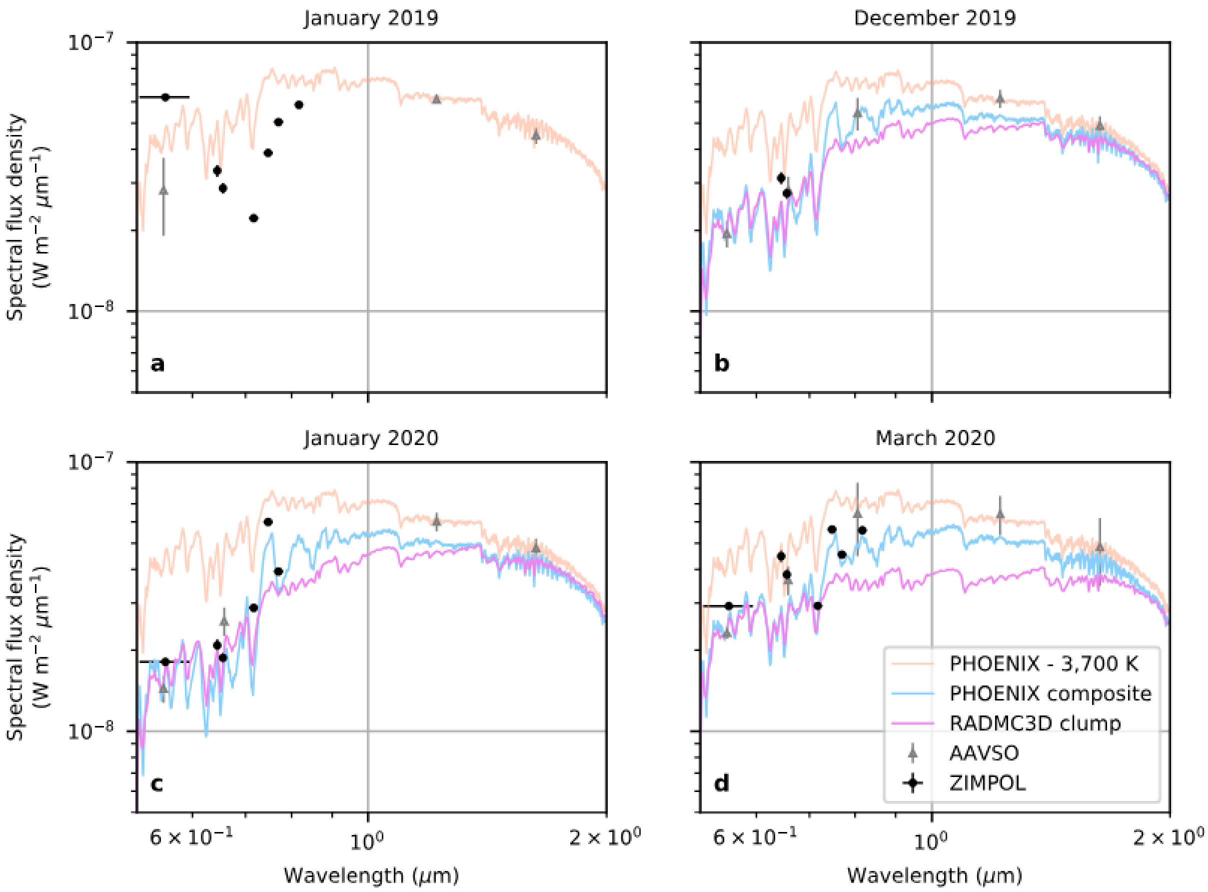


SPHERE observations (Cont. Hα)

Composite PHOENIX model

RADMC3D simulations (dusty clump)

Betelgeuse dimming (Montargues et al. 2021)



Mass-loss rate