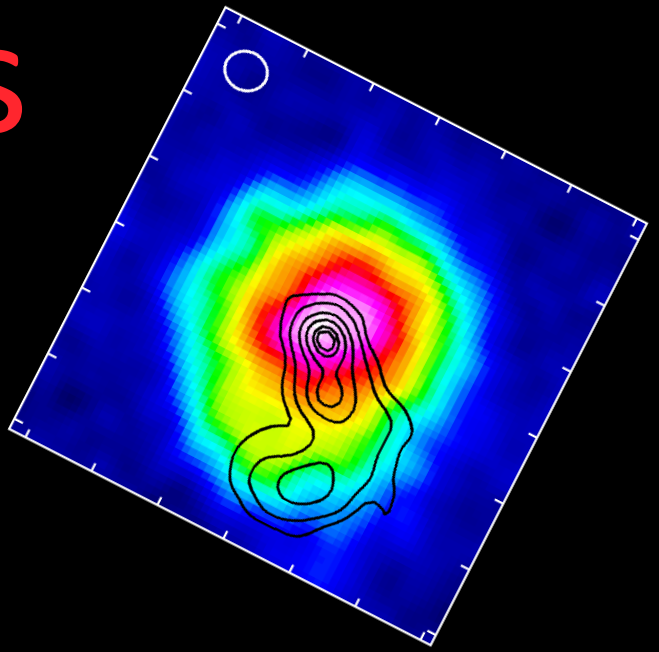
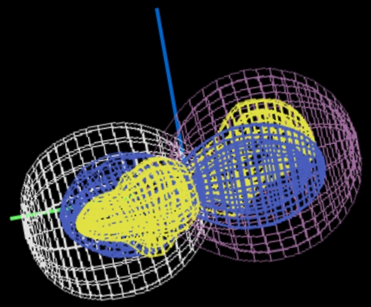
Cool and dusty remnants of stellar mergers



Tomek Kamiński

on behalf of the Mergestars group in Toruń

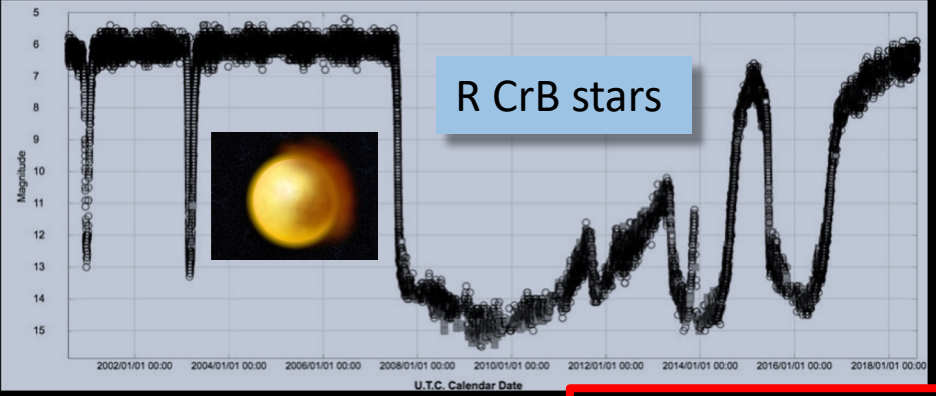
Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences



3 June 2022

NATIONAL SCIENCE CENTRE POLAND

PAN Polska Akademia Nauk



the great eruption of η Car

some pre-planetary nebulae

(Boomerang)

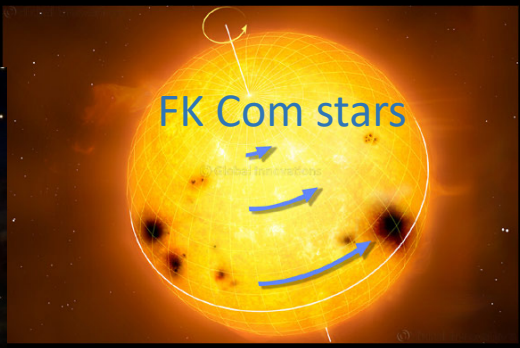
products of mergers (of noncompact stars) are common

★ chemically peculiar stars

★ R –type stars

anomalous Cepheids

protostars OMC1

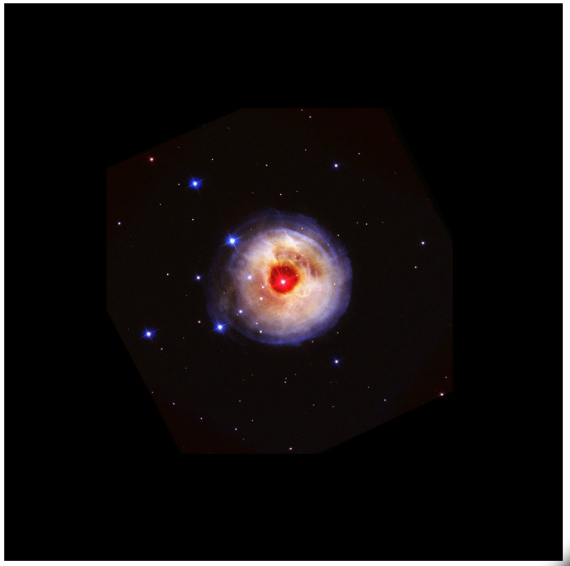


the progenitor of SN 1987A

★ some blue strugglers

★ hot sub-dwarfs

★ Be & B[e] stars

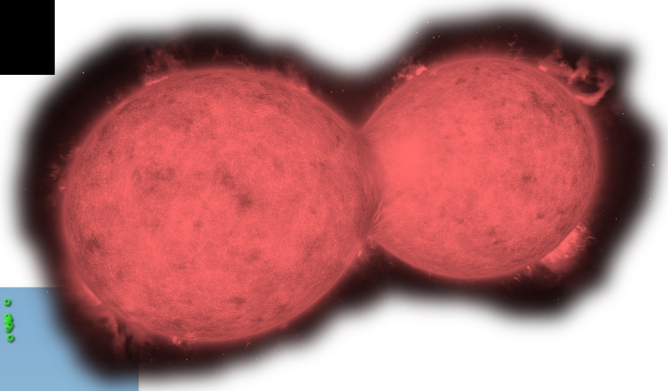


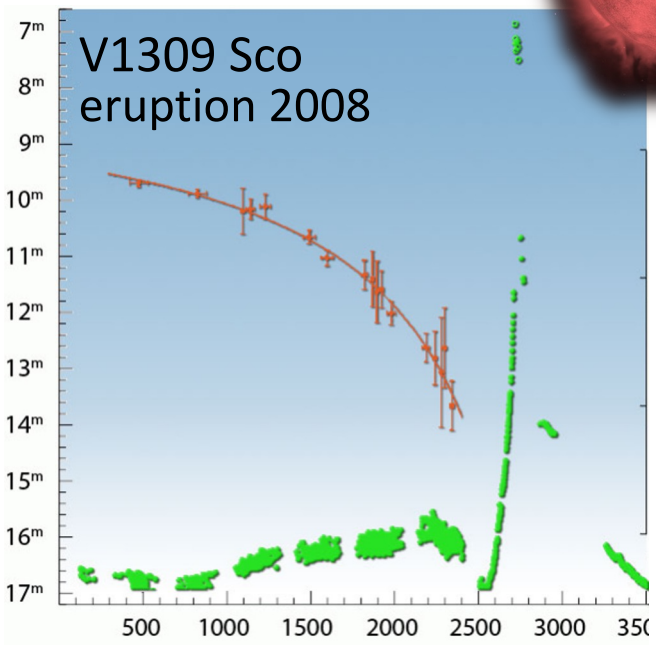
V838 Mon
eruption: 2002

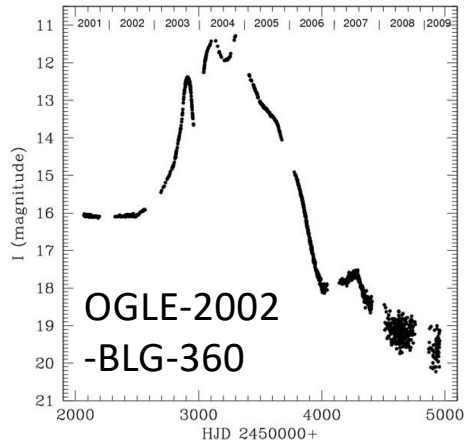
V4332 Sgr
eruption 1994

Red novae are stellar mergers

Soker & Tylenda 2003
Tylenda & Soker 2006
Tylenda+ 2011

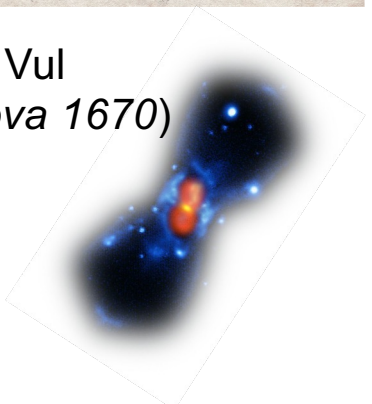


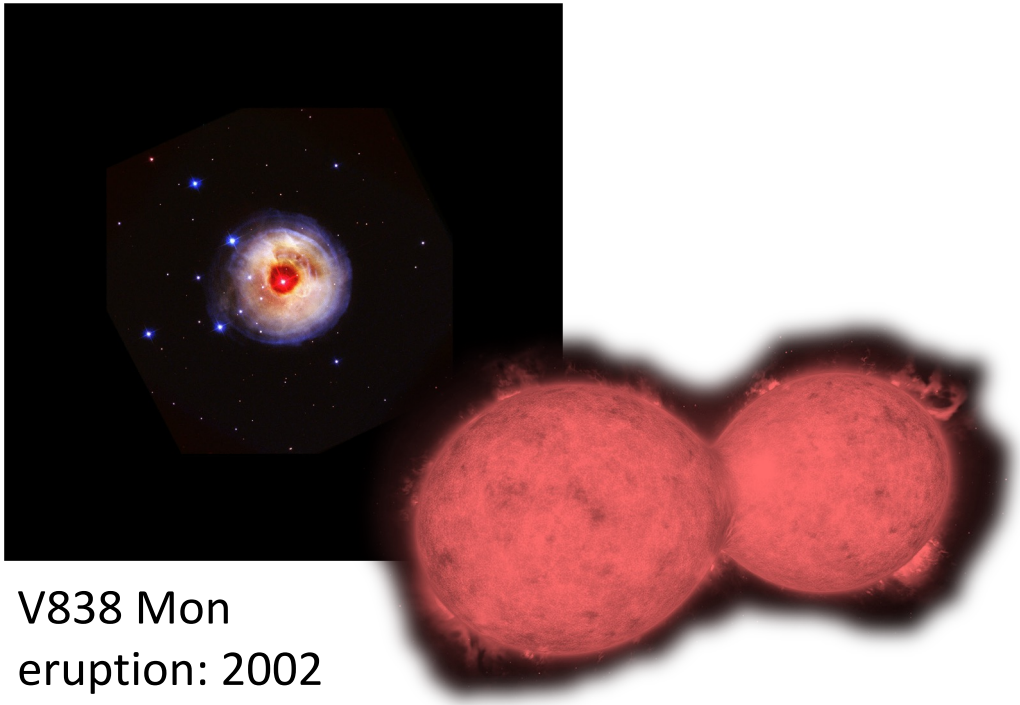




eruption 2003-2005

CK Vul
(*Nova 1670*)

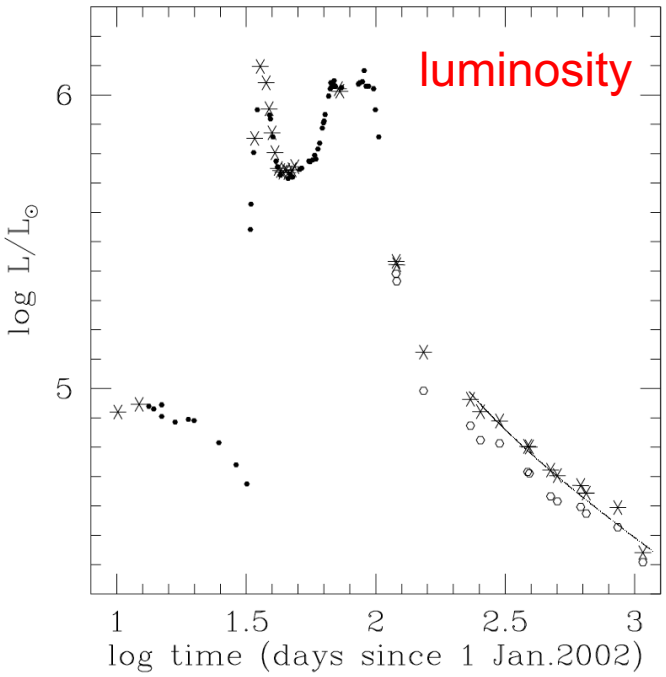


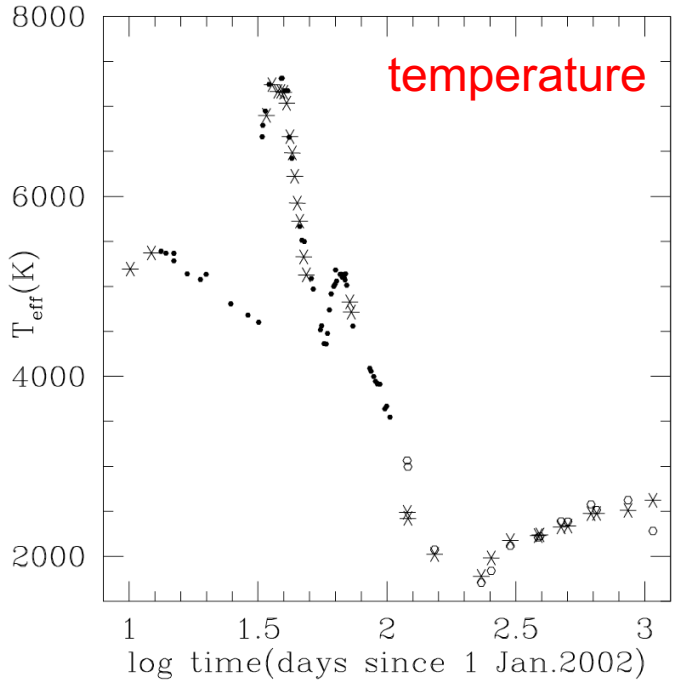


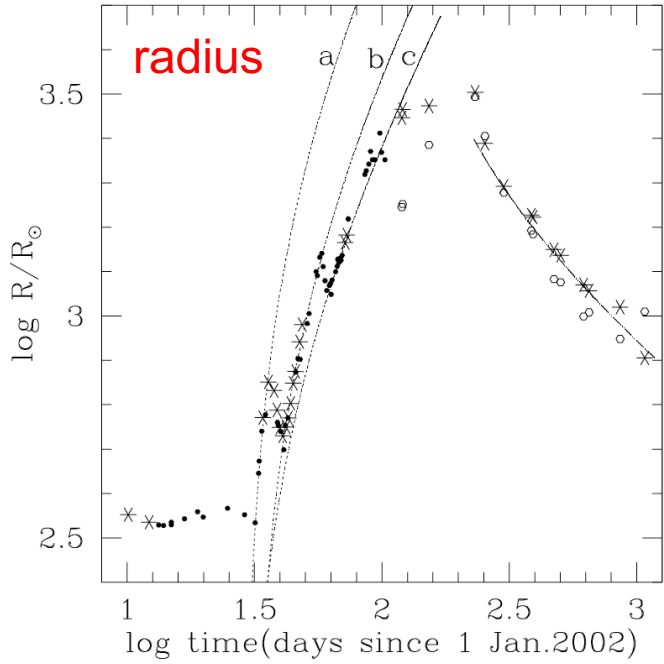
V838 Mon
eruption: 2002

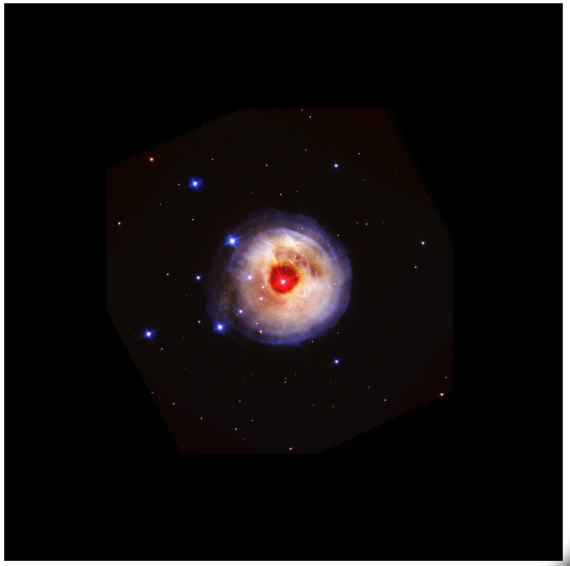
Red novae as a class of transients

Tylenda et al.







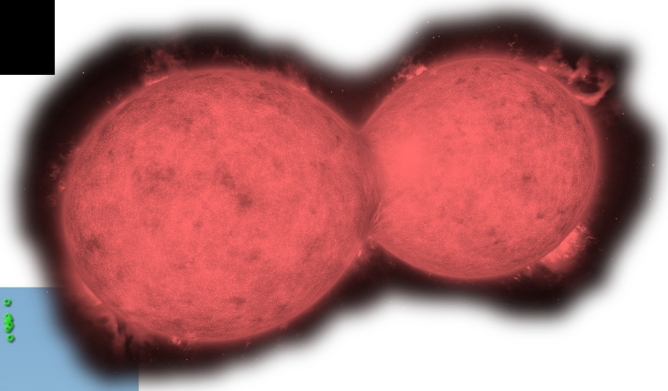


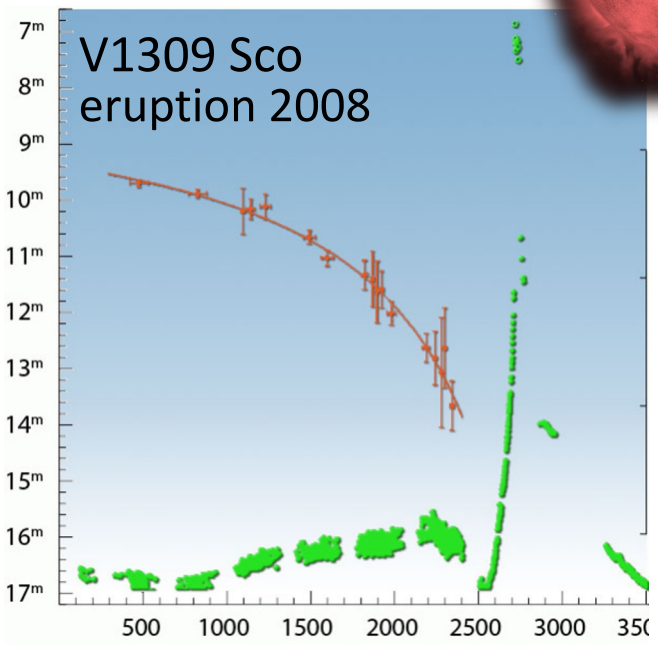
V838 Mon
eruption: 2002

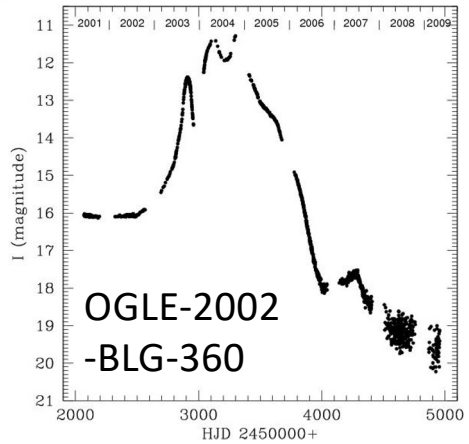
V4332 Sgr
eruption 1994

Are red novae stellar mergers?

Soker & Tylenda 2003
Tylenda & Soker 2006
Tylenda+ 2011







eruption 2003-2005

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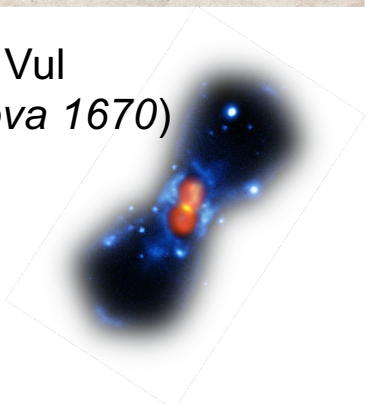
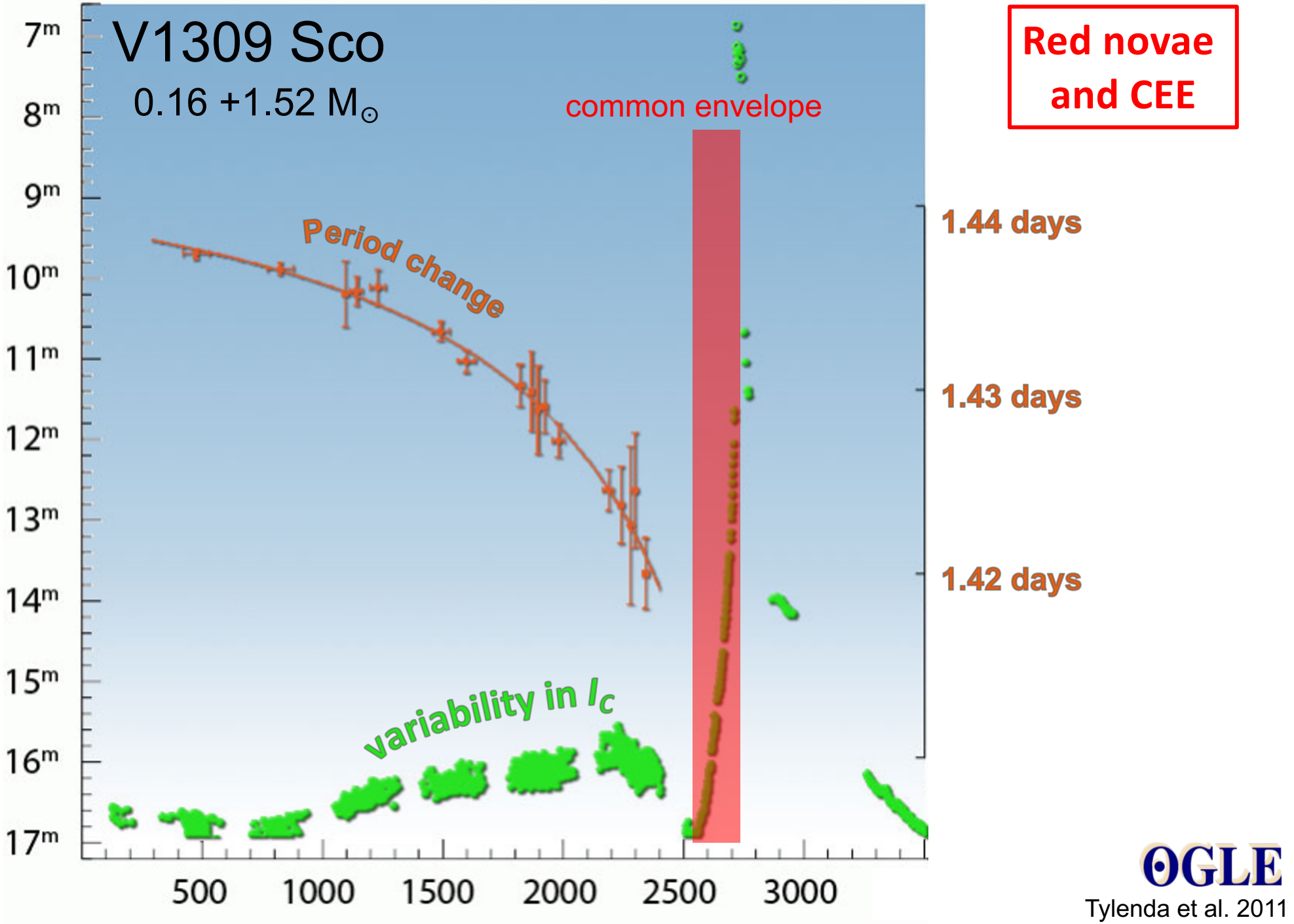
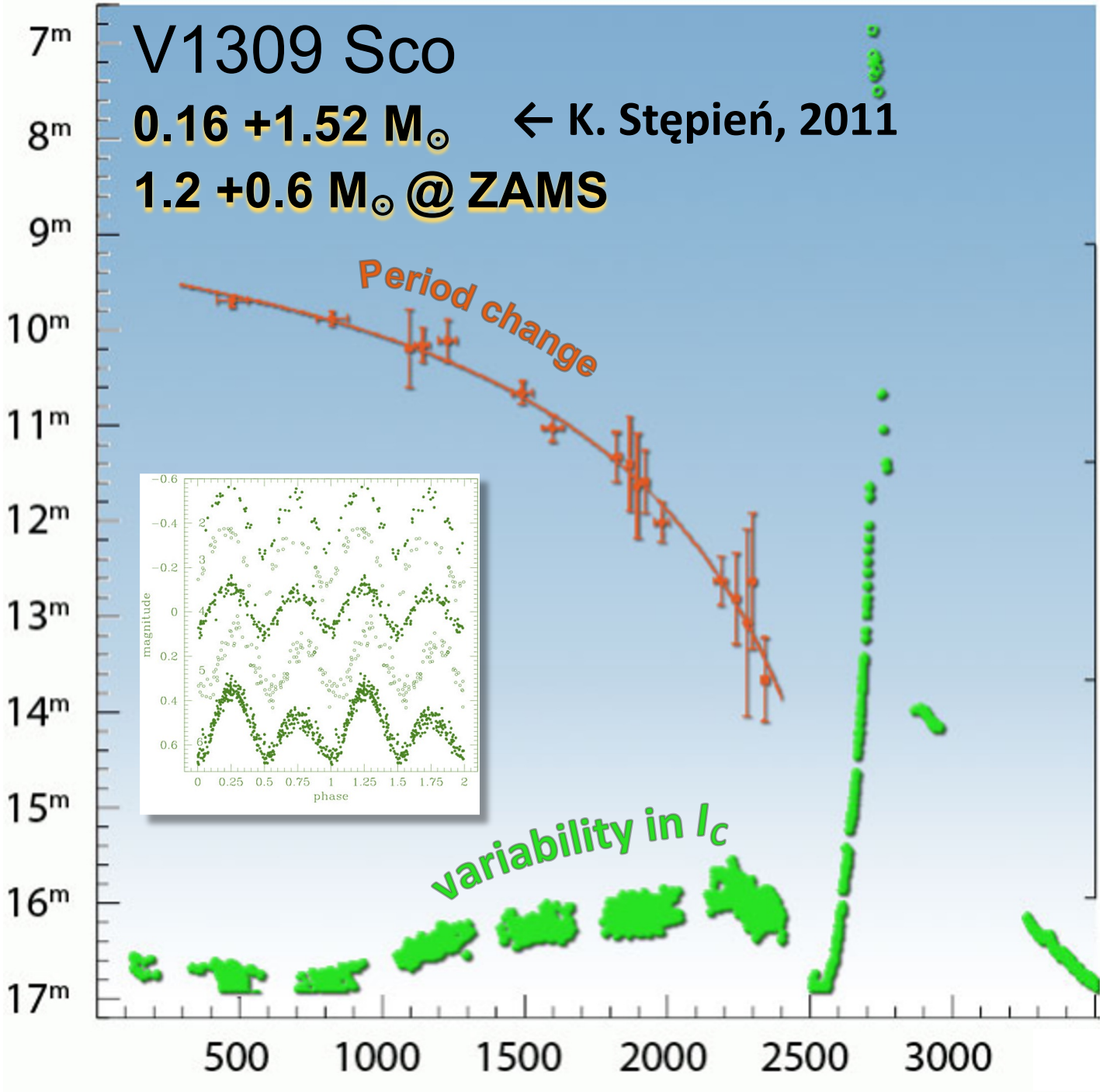




Red novae and CEE

OGLE

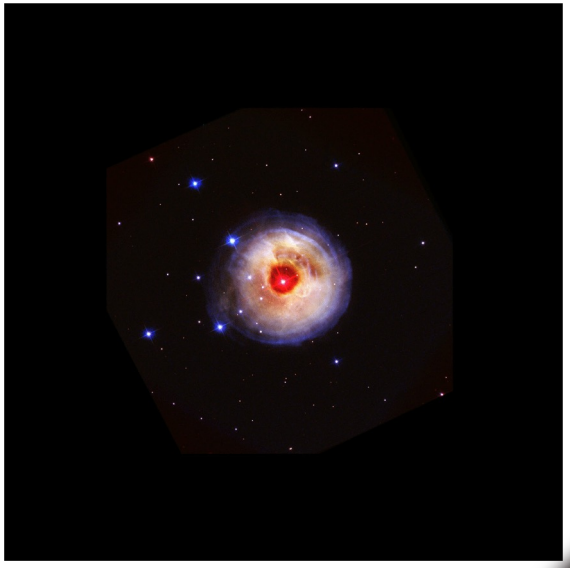
Tylenda et al. 2011



Red novae and mass loss history

OGLE

Tylenda et al. 2011

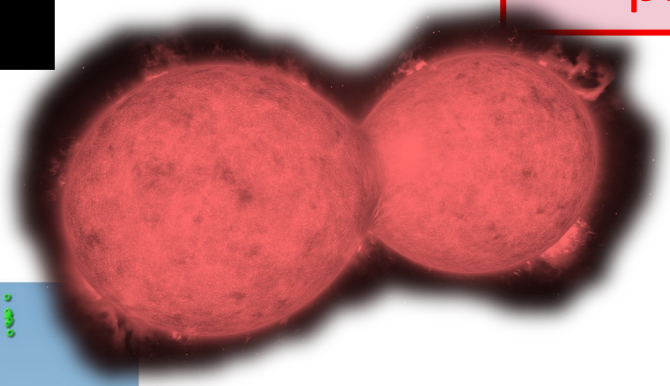


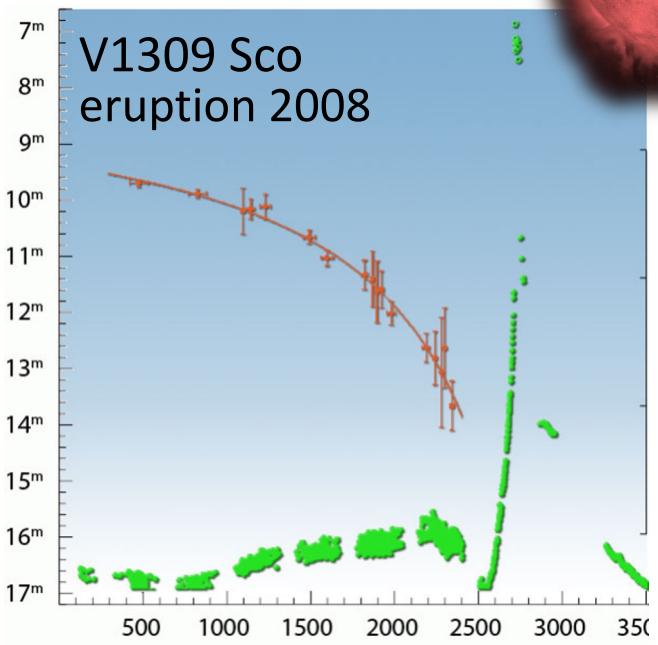
V838 Mon
eruption: 2002

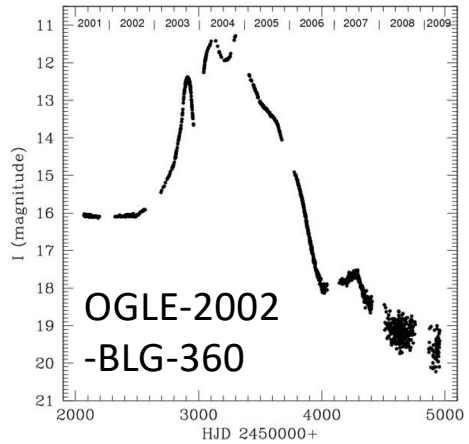
V4332 Sgr
eruption 1994

MERGESTARS and merger physics:

- masses dispersed
- angular momentum budget
- stellar rotation/winds
- disks/torii
- progenitors and merger event







eruption 2003-2005

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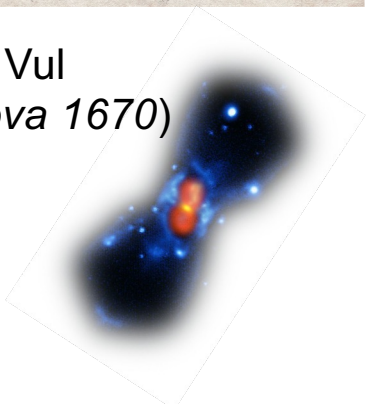
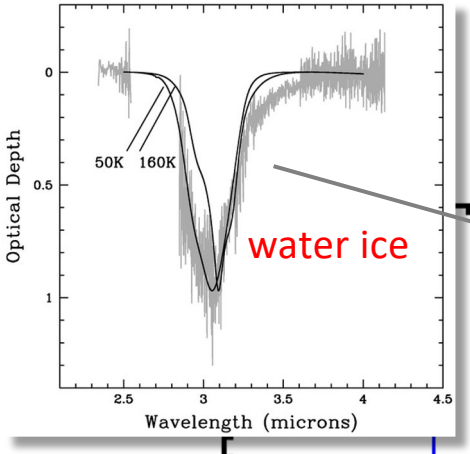


V4332 Sgr

eruption in 1994

clone of V1309 Sco

SED of V4332 Sgr: cool dusty disk



BB 200 K+950 K

silicates &
alumina dust

MARCS 3200
photospheric contribution

Kamiński+ 2010
Banerjee+ 2004

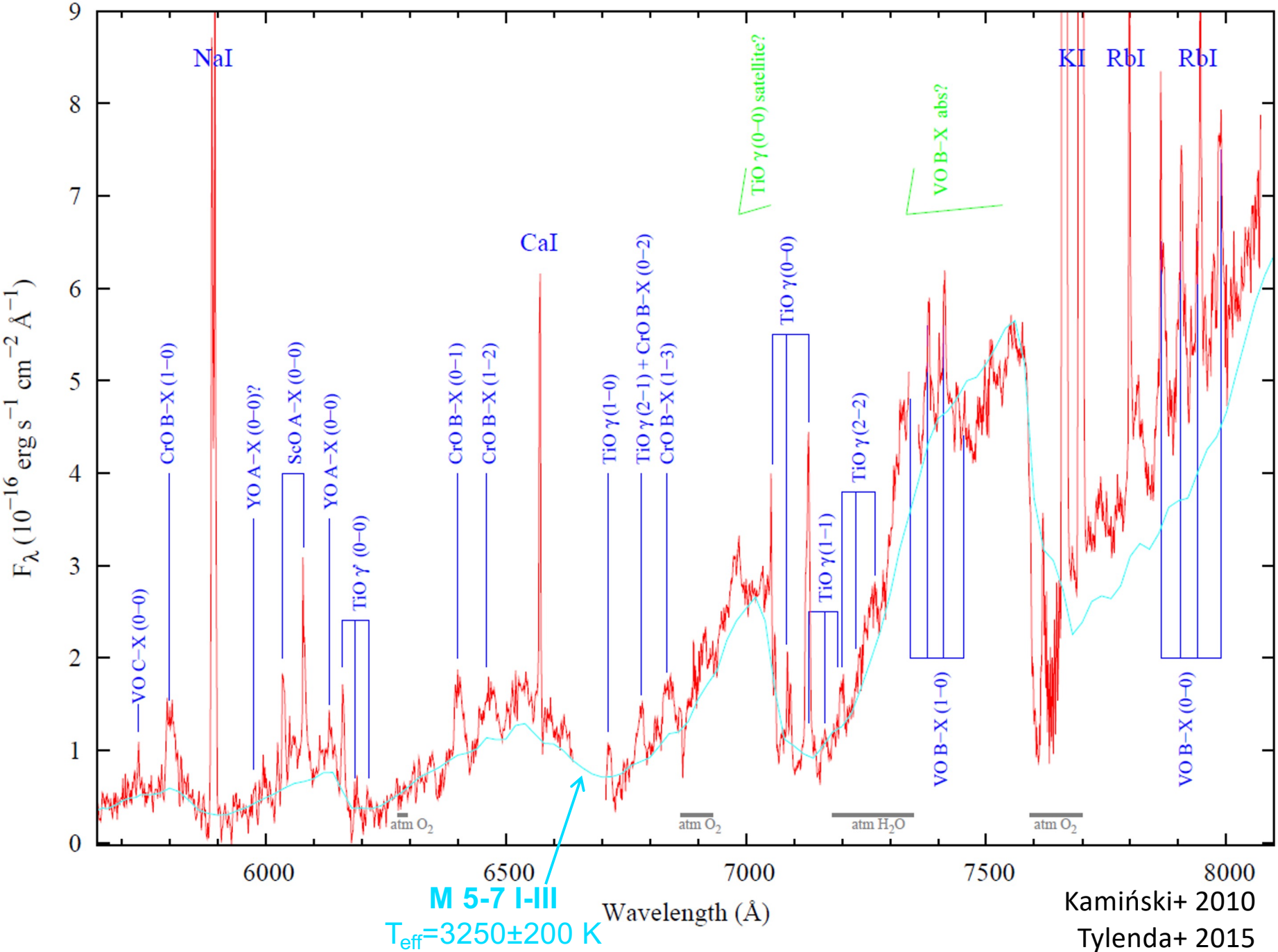
$\log(\nu F_\nu\ (\mathrm{erg\ cm^{-2}\ s^{-1}}))$

-11
-12
-13
-14

1
10
100

λ/μm

V4332 Sgr, 2009



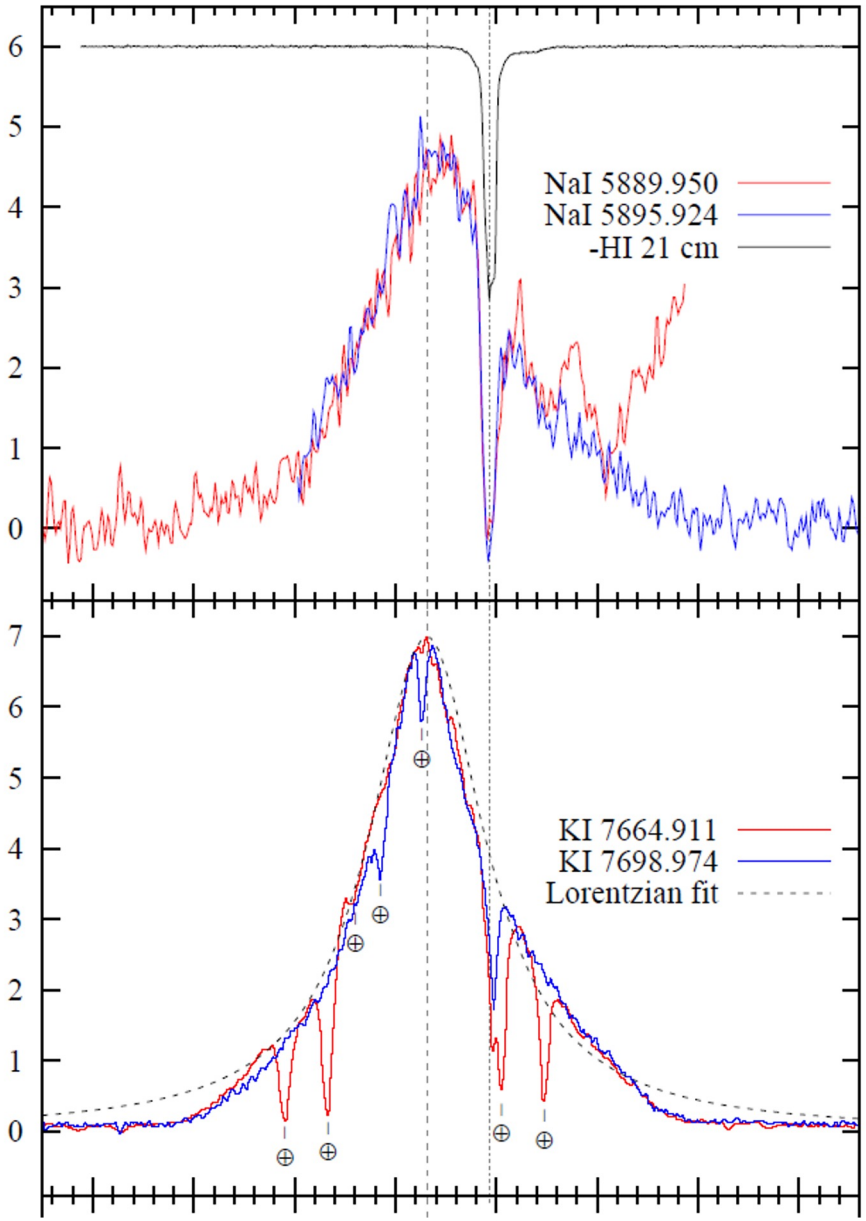
M 5-7 I-III

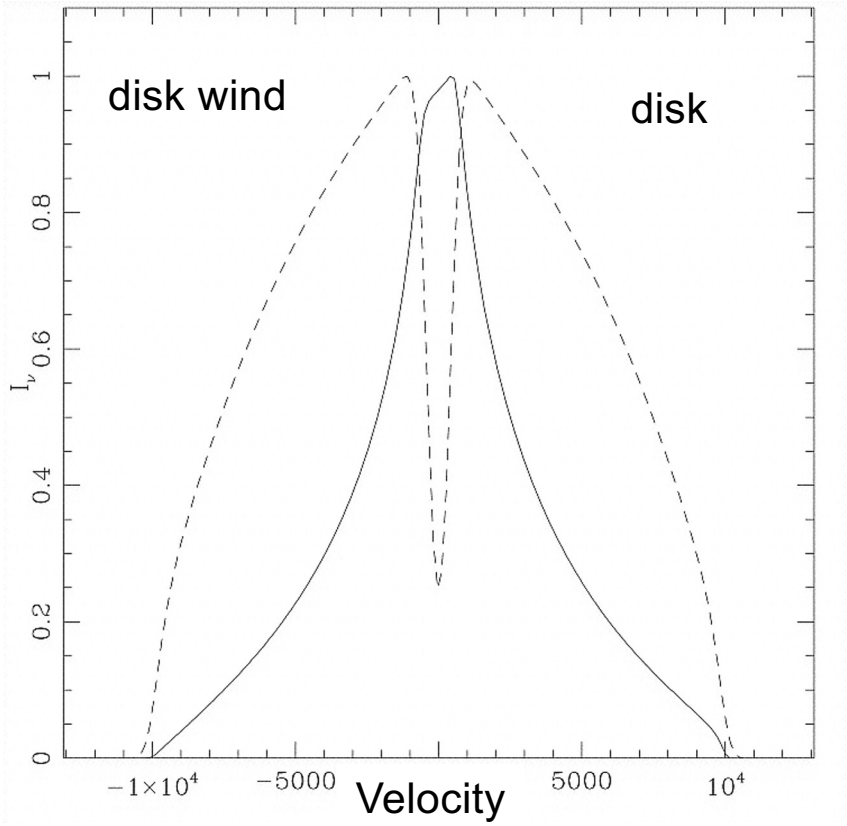
T_{eff}=3250±200 K

Kamiński+ 2010

Tylenda+ 2015

Disk wind in V4332 Sgr

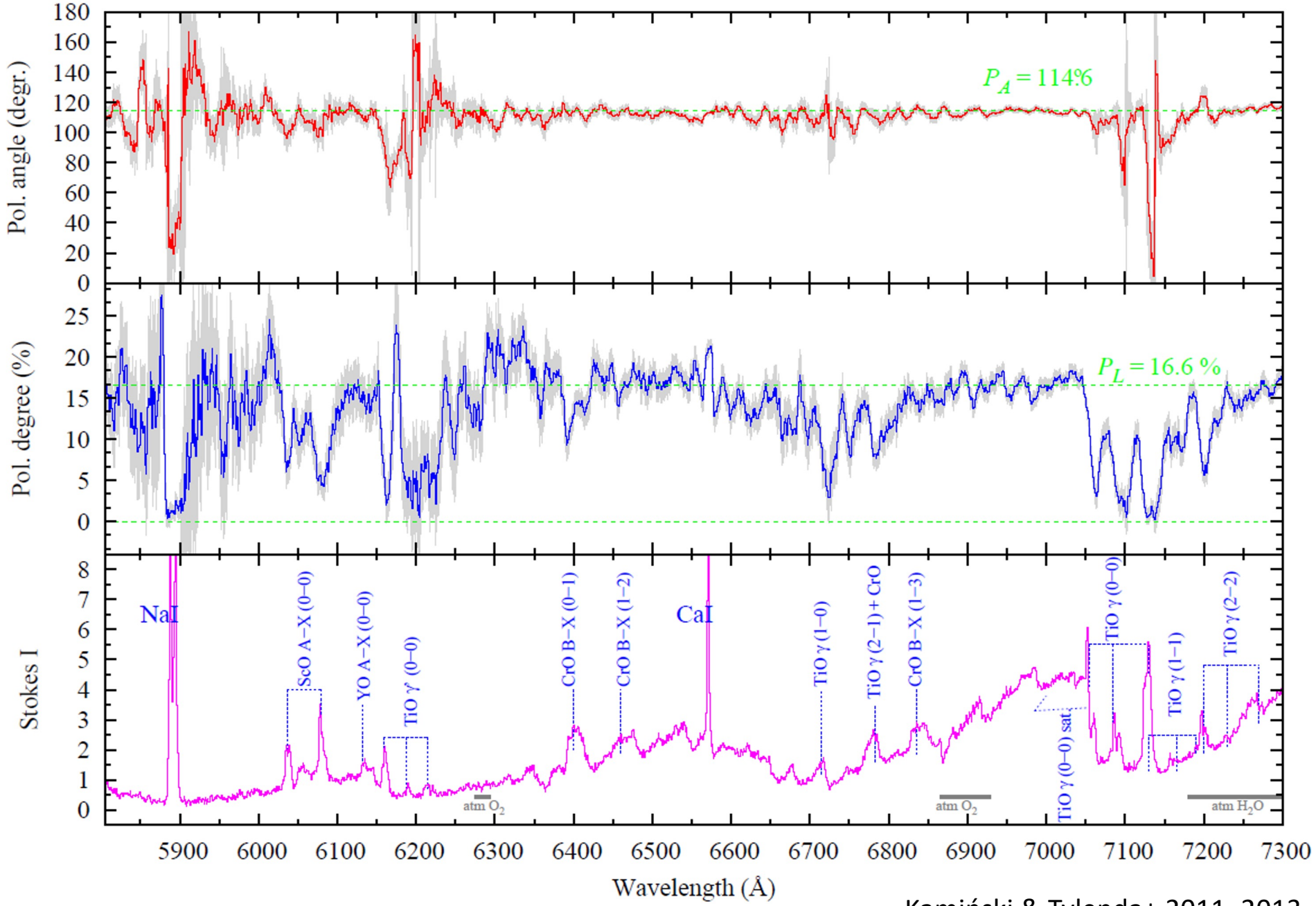




disk vs disk-wind line profiles
(Murray & Chiang 1996)

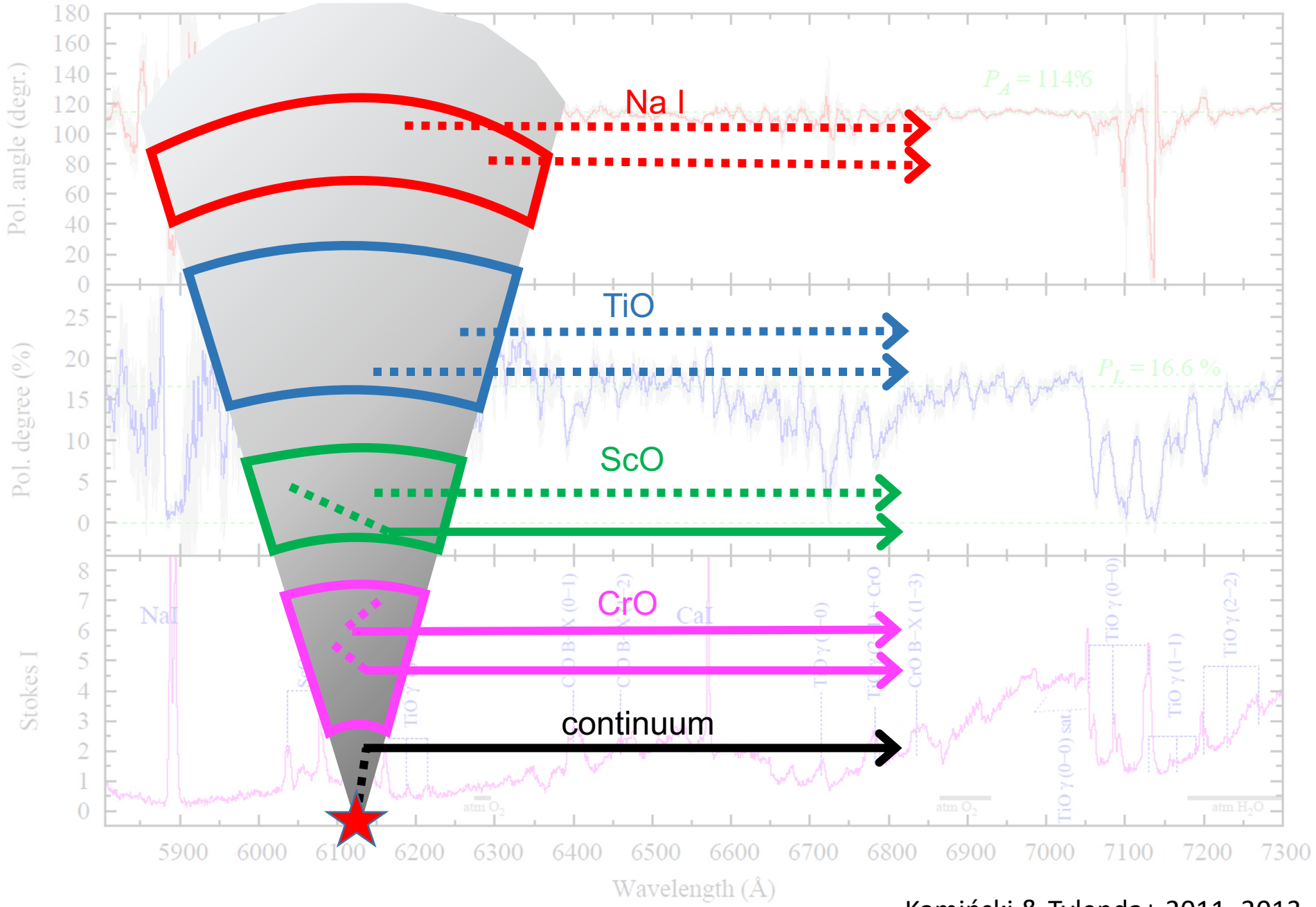
Kamiński+ 2010
Tylenda+ 2015

Spectropolarimetry of V4332 Sgr

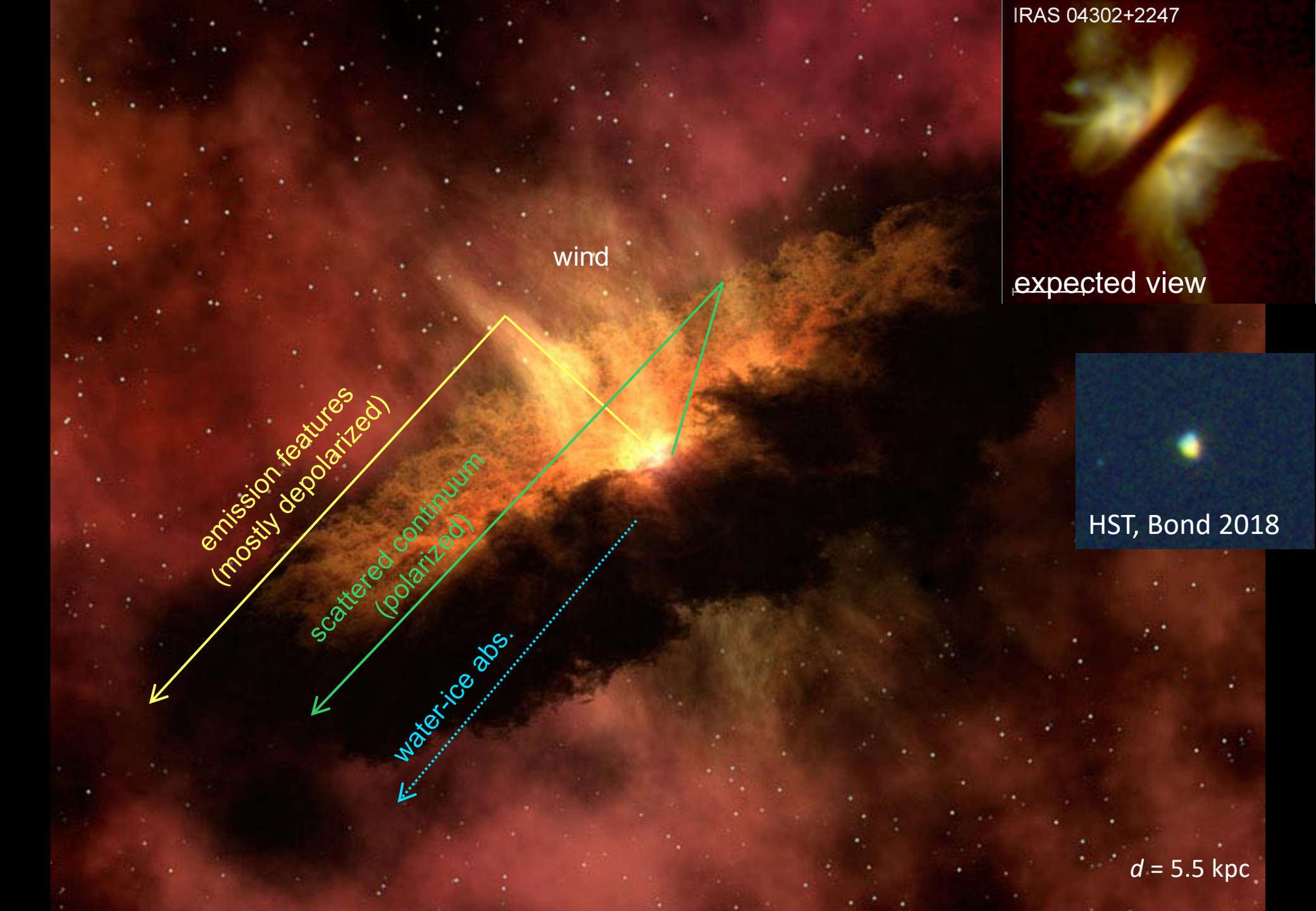


Kamiński & Tylenda+ 2011, 2013

Spectropolarimetry of V4332 Sgr

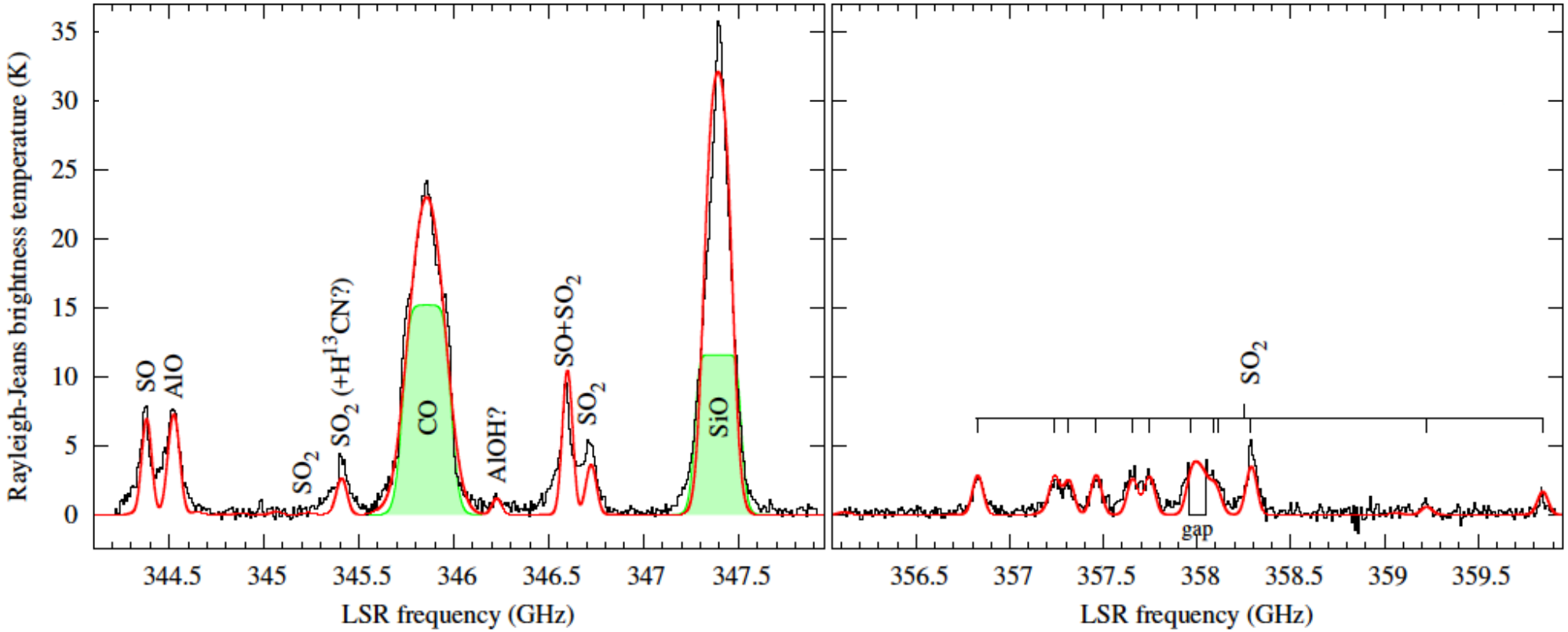


Kamiński & Tylenda+ 2011, 2013


IRAS 04302+2247
expected view
wind
emission features
(mostly depolarized)
scattered continuum
(polarized)
water-ice abs.
HST, Bond 2018
d = 5.5 kpc

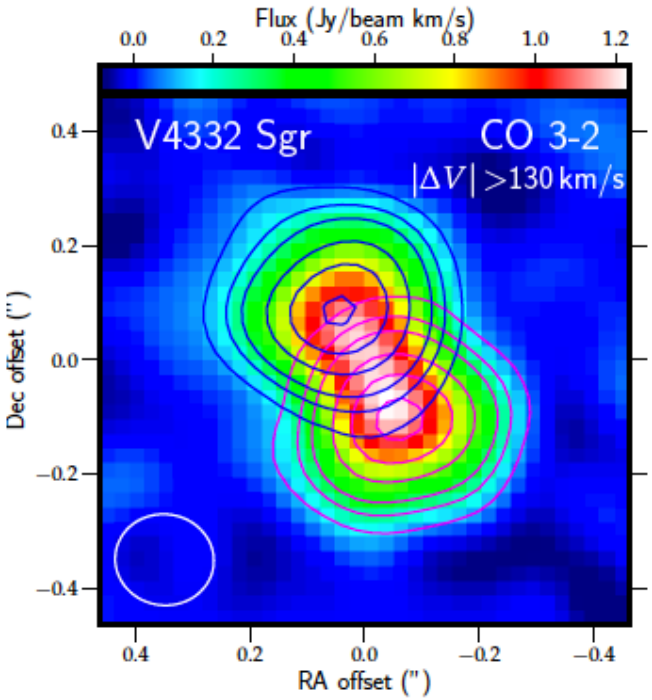
Atacama Large subMillimeter Array

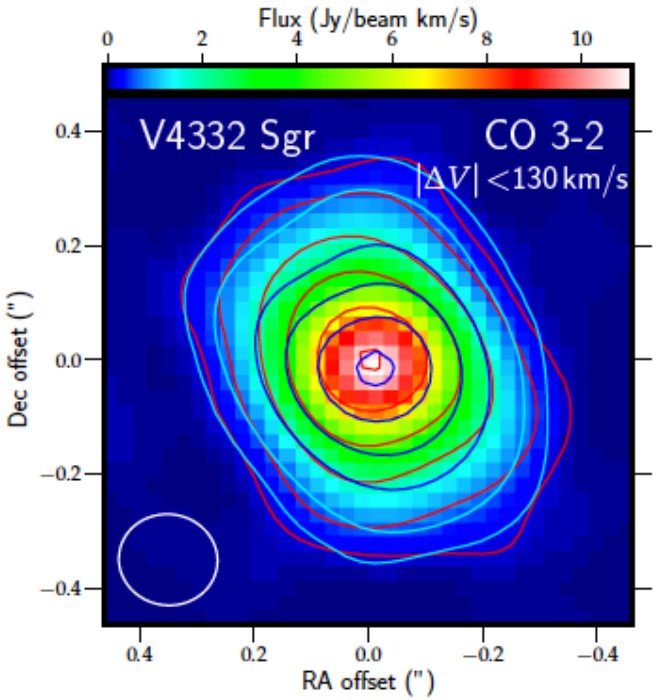
V4332 Sgr, eruption 1994



2016/17

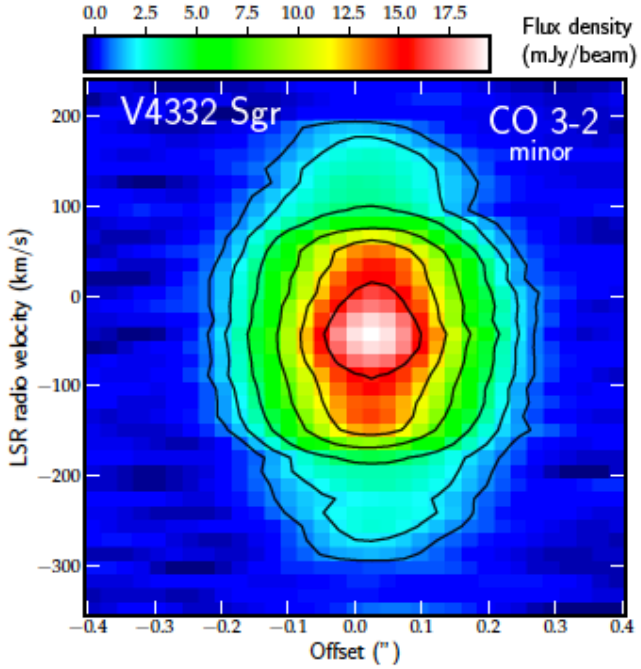
intensity maps

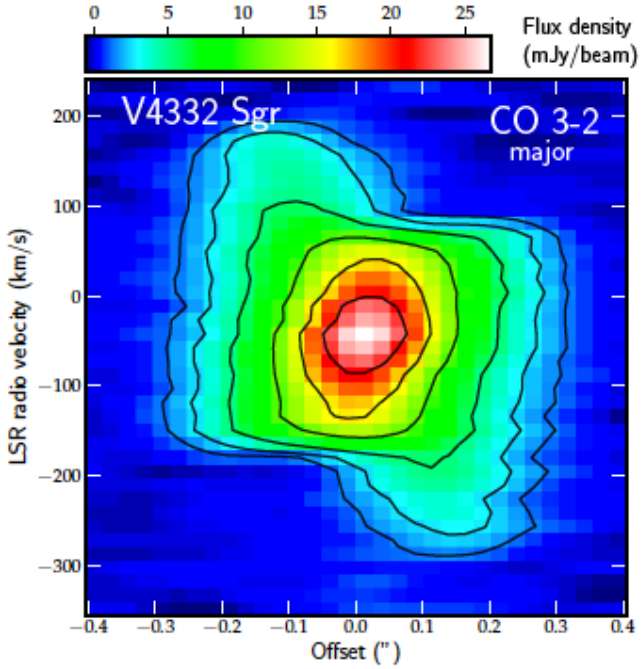




1000 AU at 5 kpc

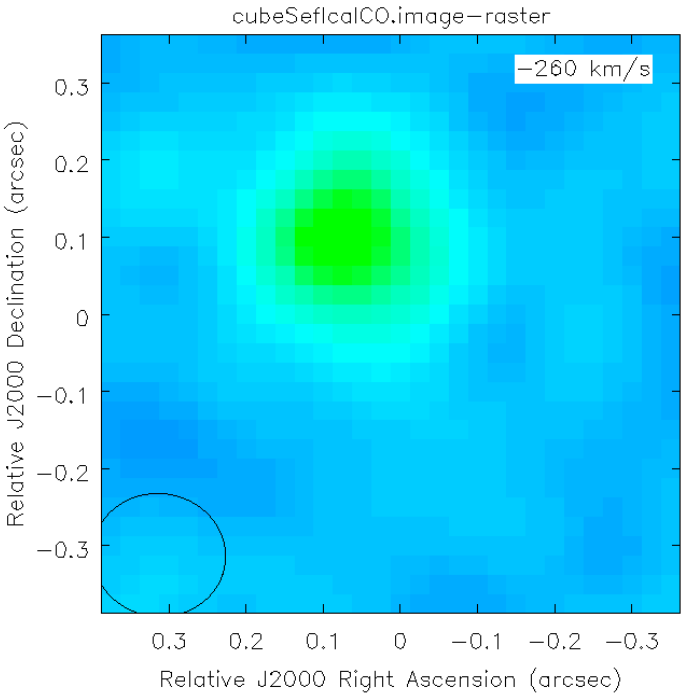
position-velocity diagrams

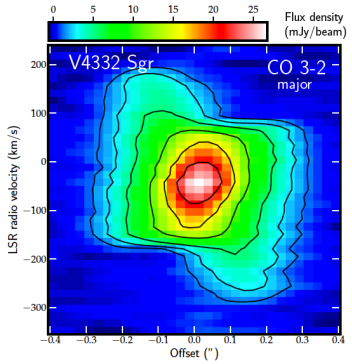




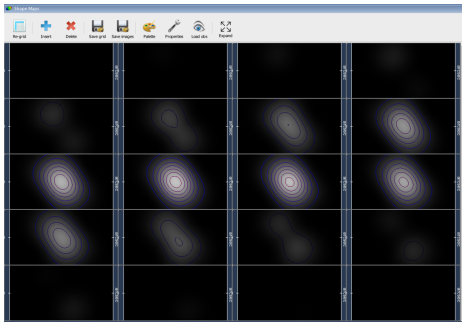
Kamiński+ 2018

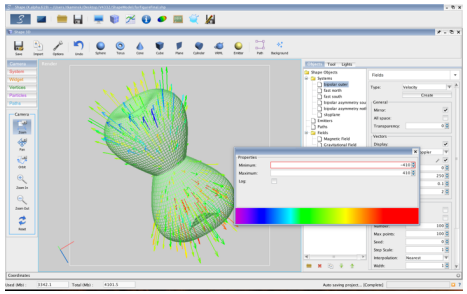
ALMA channel maps
one map per each velocity bin





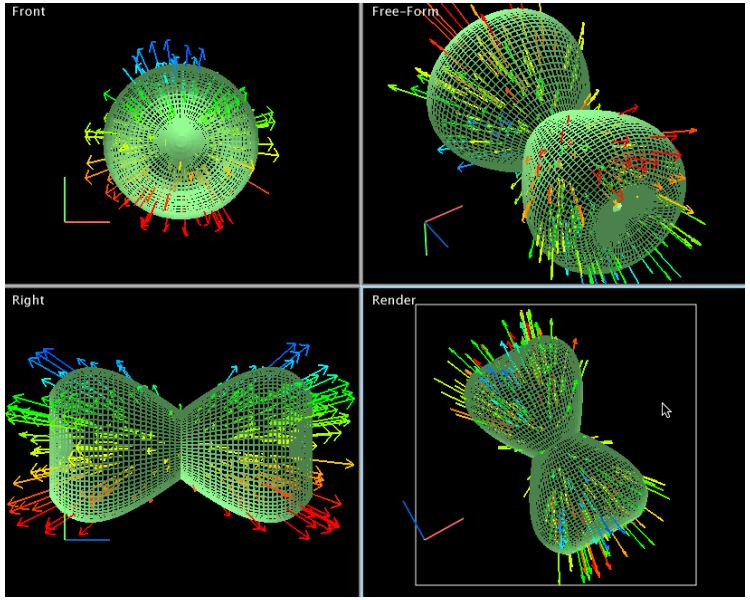
building a 3D model in *Shape* and radiative transfer

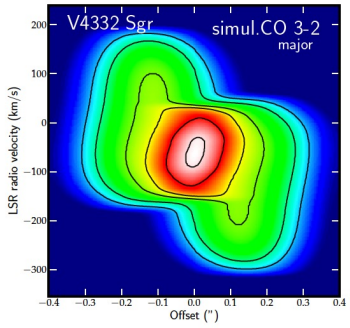




3D structure of the source:

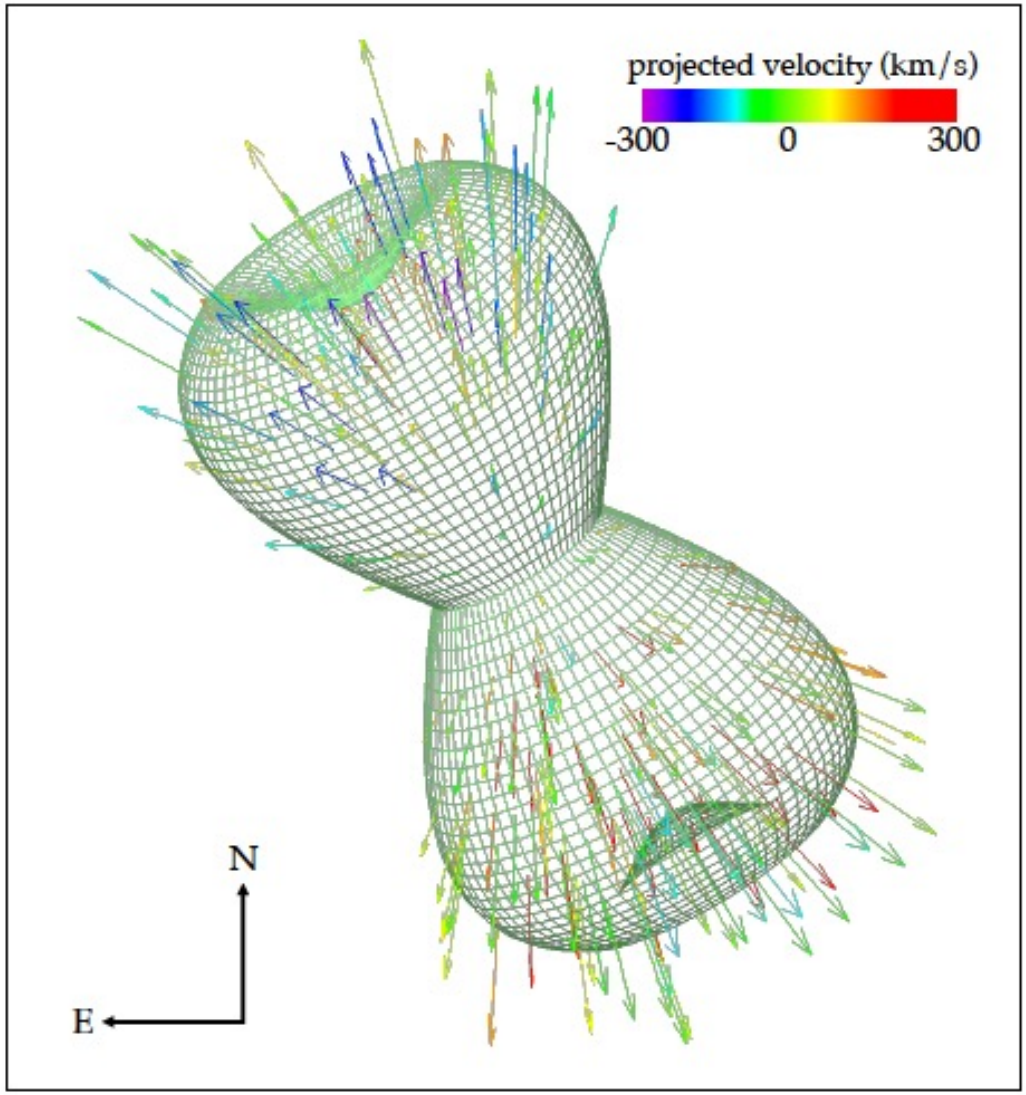
- density
- temperature
- velocity / angular momentum

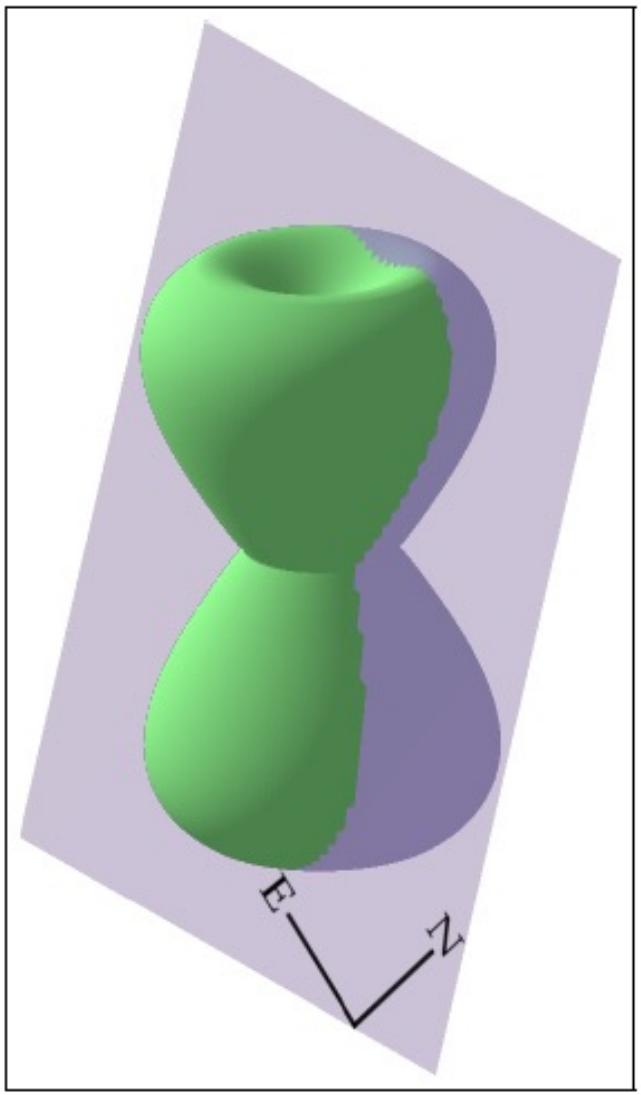




ALMA results for V4332 Sgr:

model reconstructed from observations

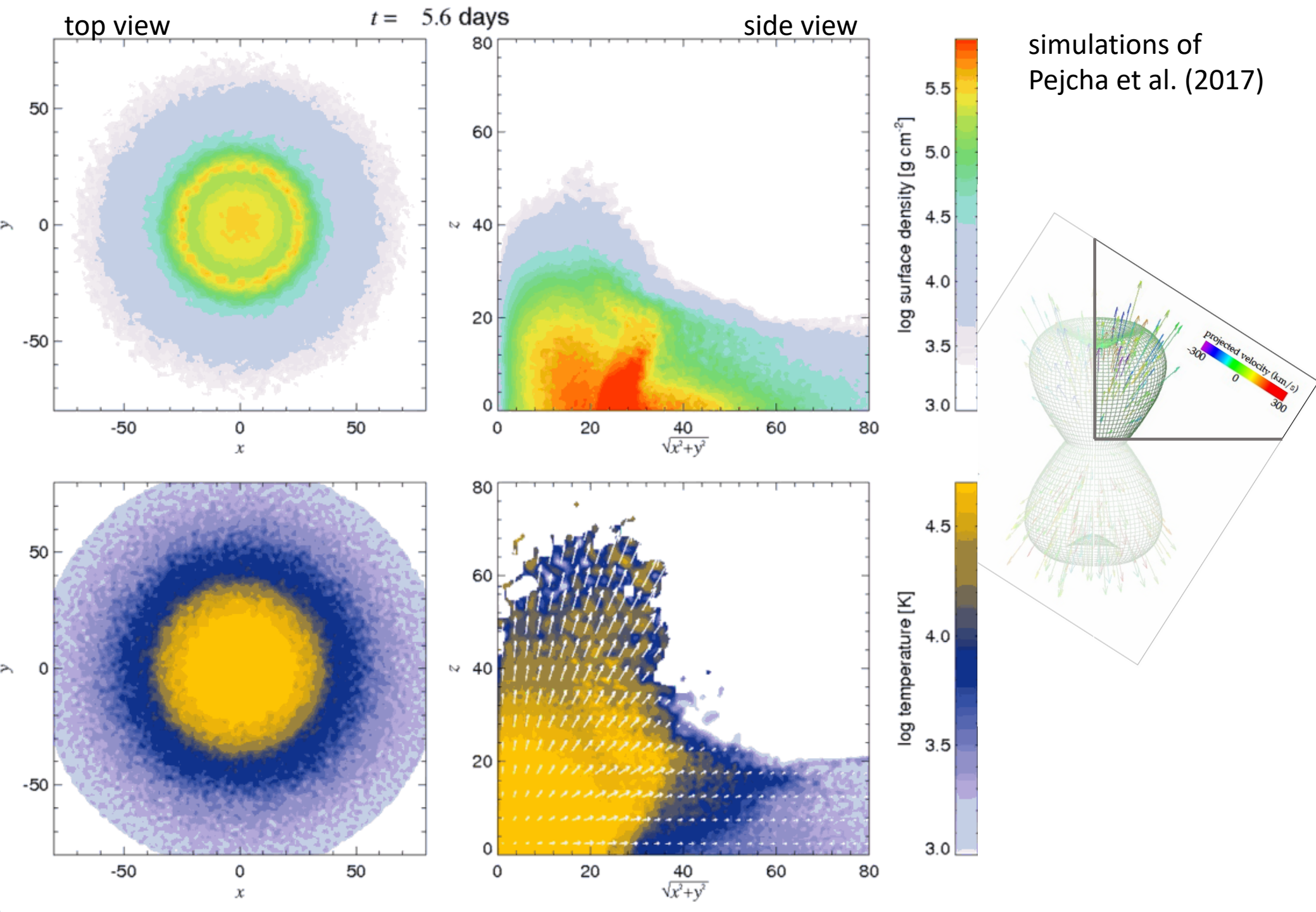




top view

$t =$ 5.6 days

side view

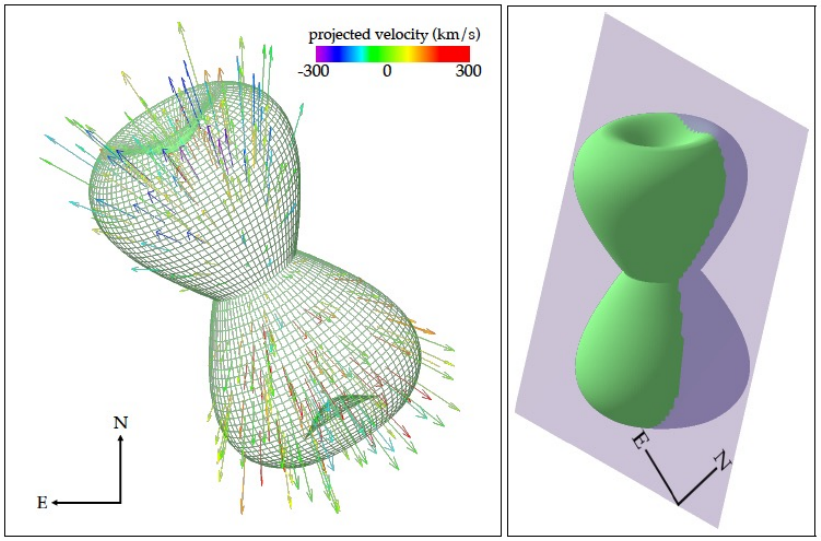


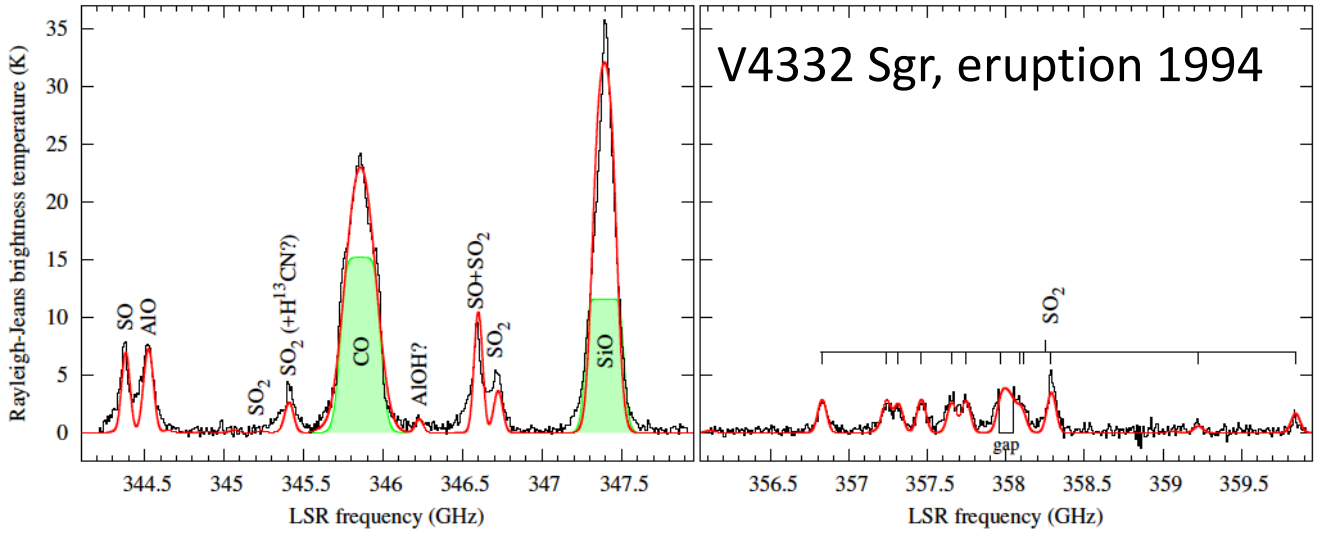
simulations of
Pejcha et al. (2017)

ALMA results for V4332 Sgr:

- 3D spatio-kinematic structure
- kinematic distance 4 kpc
- excitation temperatures ~10-100 K
- elemental and isotopic composition
- ejected mass 0.01 $M_{\odot}$

model reconstructed from observations





UT3 (Melipal)
SPHERE
VISIR
CRIRES (2019)

UT4 (Ye
AOF
HAWK-I
SINFON
MUSE

UT2 (Kueyen)
FLAMES
X-SHOOTER
UVES

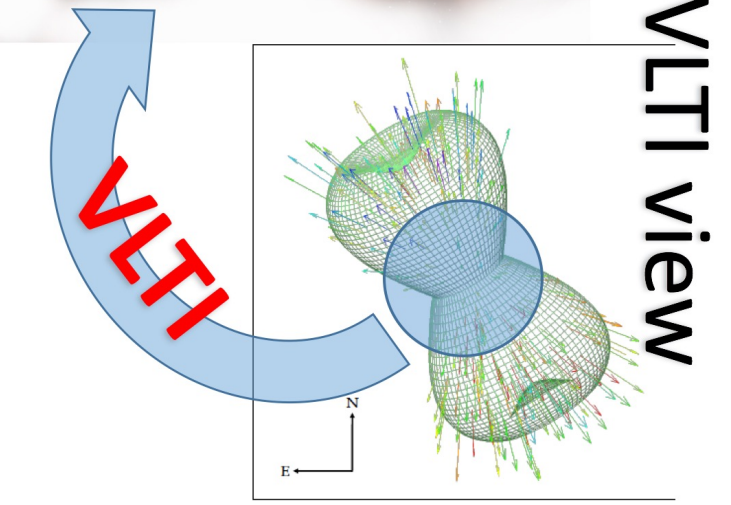
VST
OmegaCAM

UT1 (Antu)
NACO
FORS2
KMOS

140 m

VLTI
PIONIER
GRAVITY
MATISSE (2019)

4 telescopes
6 baselines
full closure phase

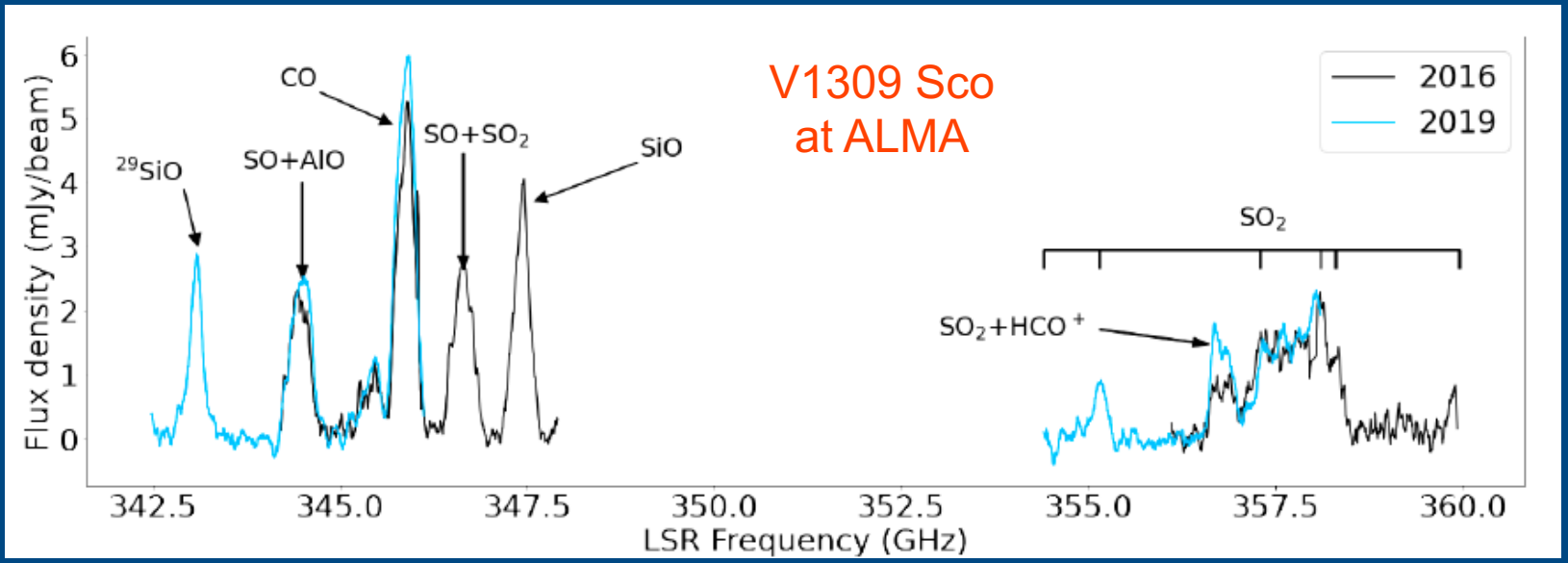


Expected VLTI view

V1309 Sco

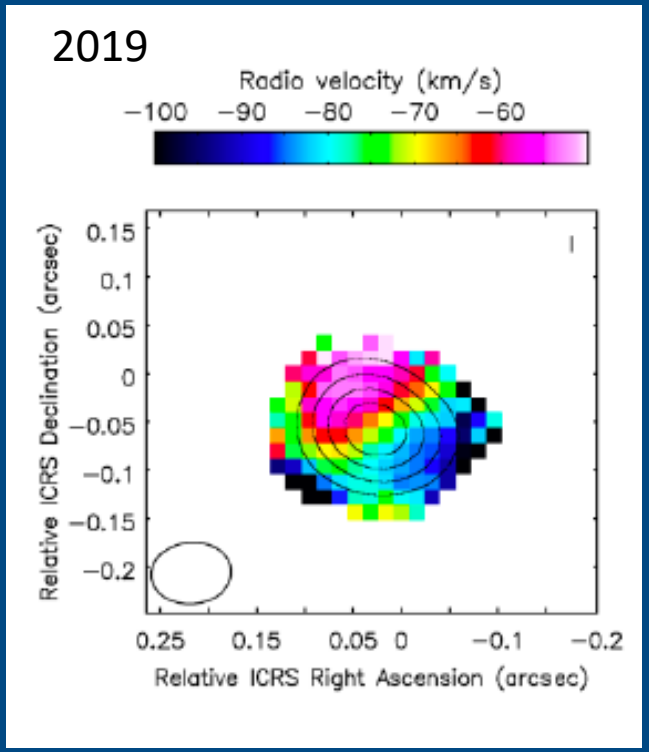
eruption in 2008

clone of V4332 Sgr

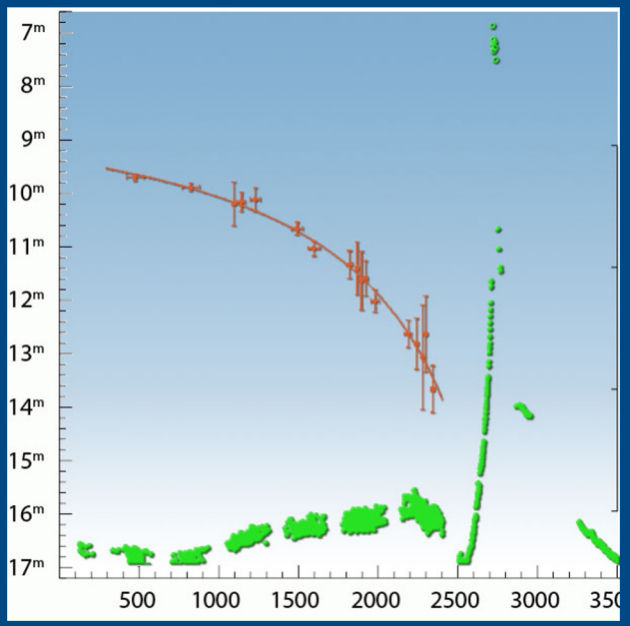


ALMA

2019



V1309 Sco (outburst in 2008) still too small and too weak to be resolved at submm & IR

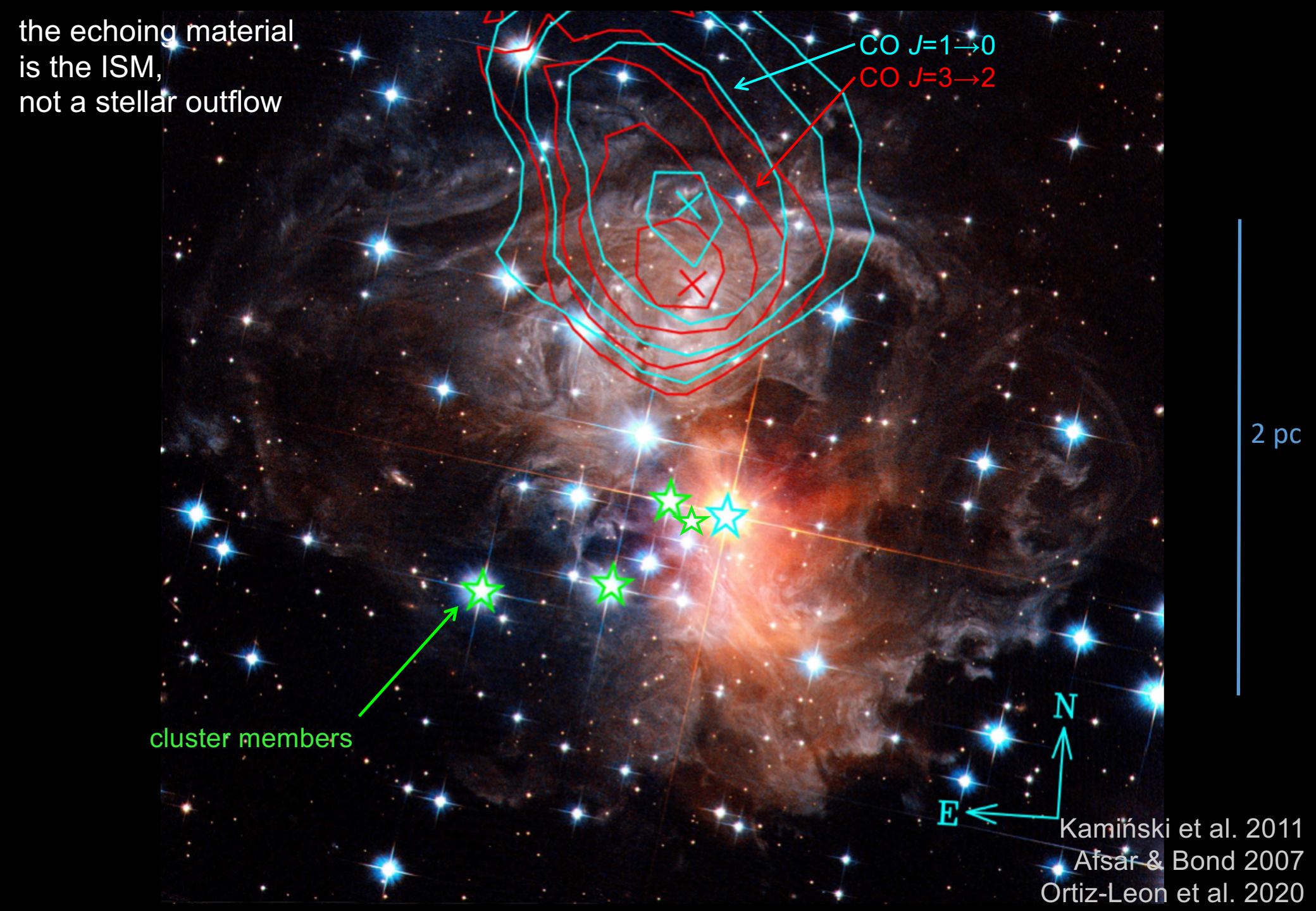


Far-infrared data from Herschel reveal presence of a cold (~30 K) dust at a distance of a few thousand AU from the object.

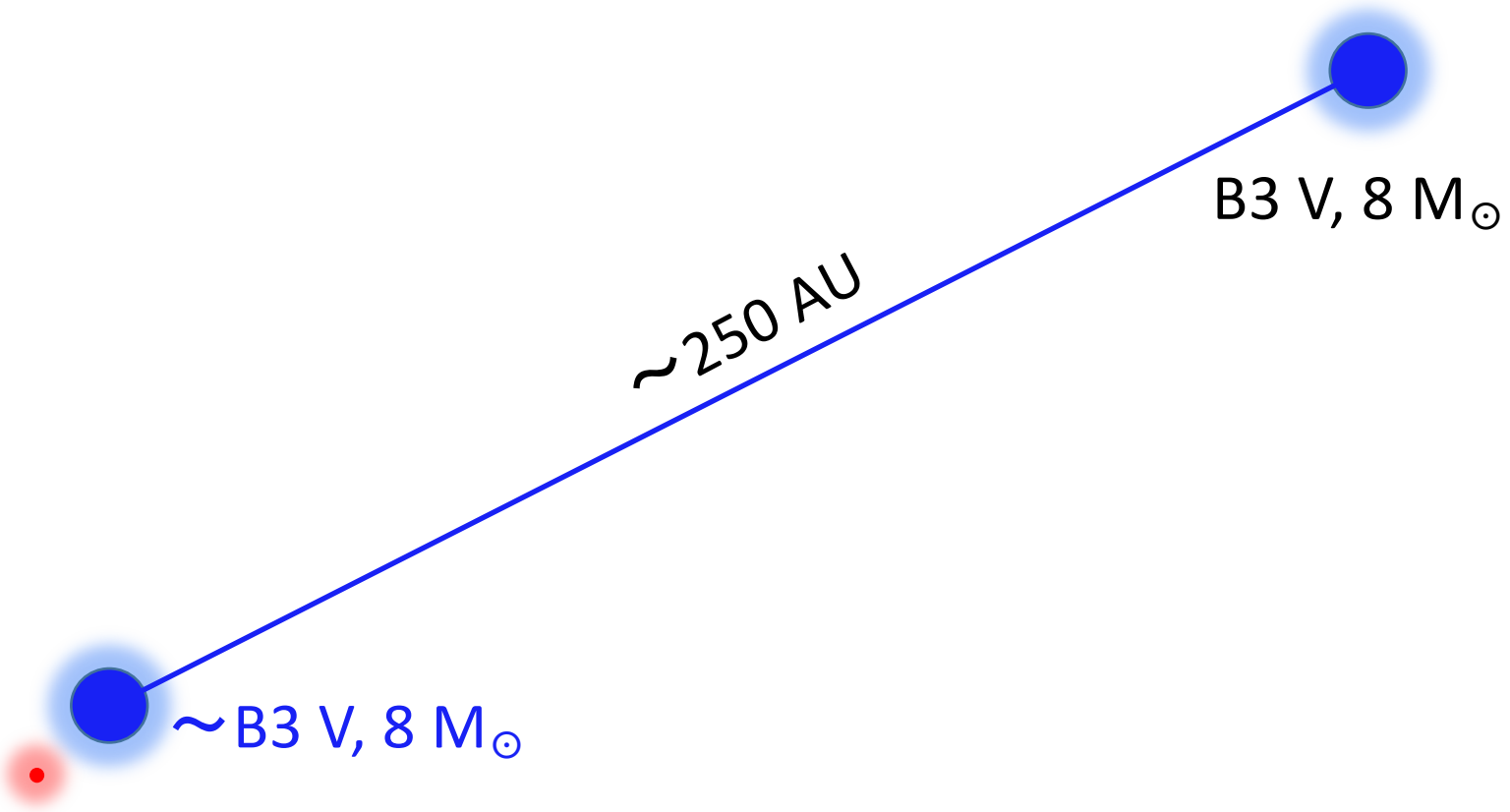
Steinmetz in prep.
Tylenda & Kamiński 2016,
McCollum et al. 2015, Pejcha

V838 Mon

eruption 2002

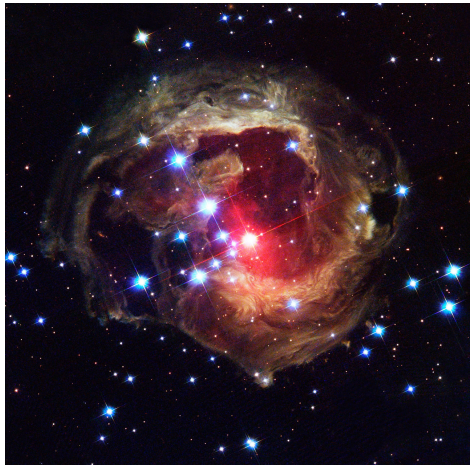

the echoing material
is the ISM,
not a stellar outflow
CO J=1→0
CO J=3→2
2 pc
cluster members
N
E
Kamiński et al. 2011
Afšar & Bond 2007
Ortiz-Leon et al. 2020

V838 Mon prior to the 2002 eruption



was a young triple (multiple) system

Tylenda et al. 2005
Tyelnda & Soker 2006
Tylenda, Kamiński, Schmidt 2009

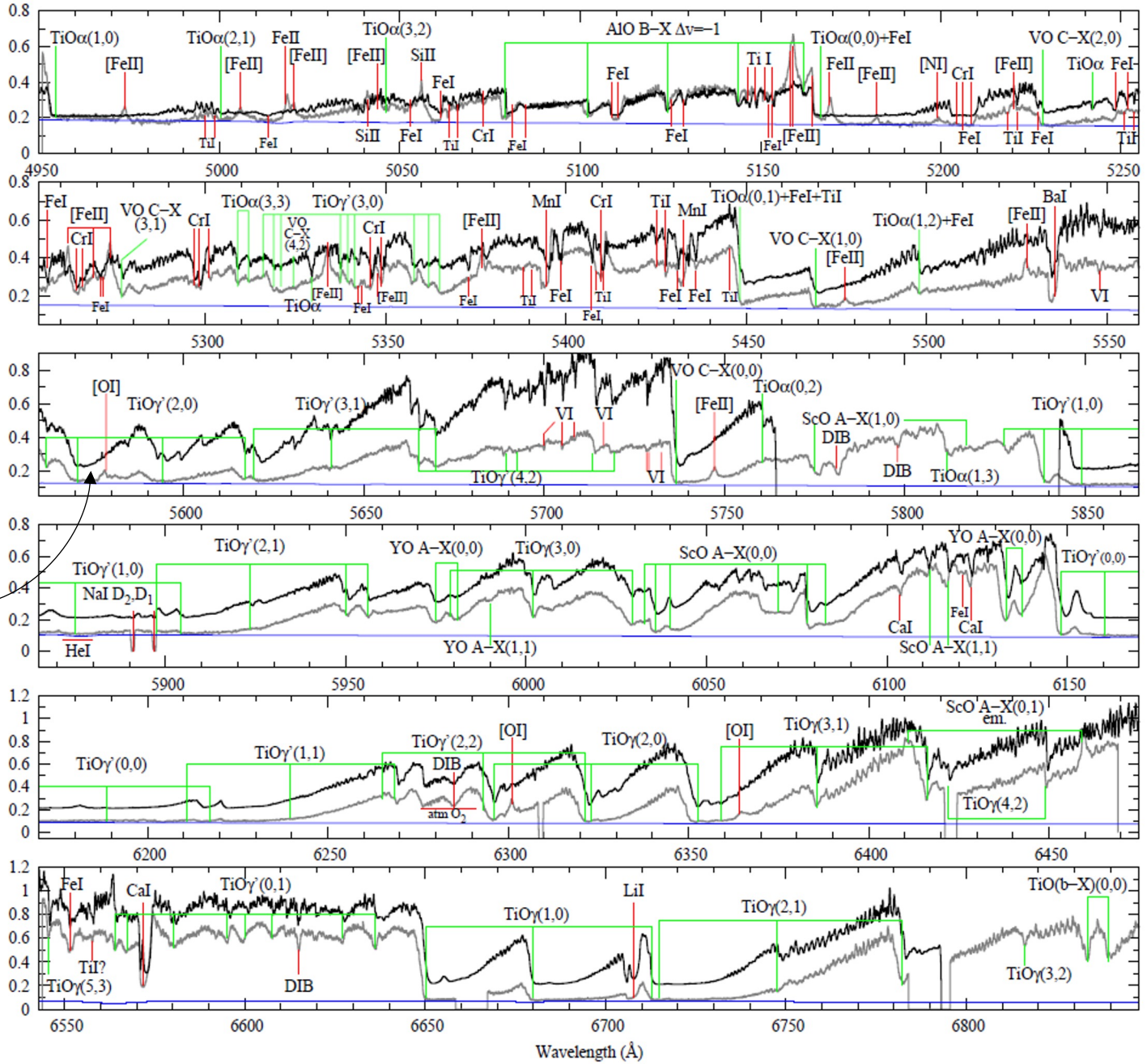


merger remnant in V838 Mon

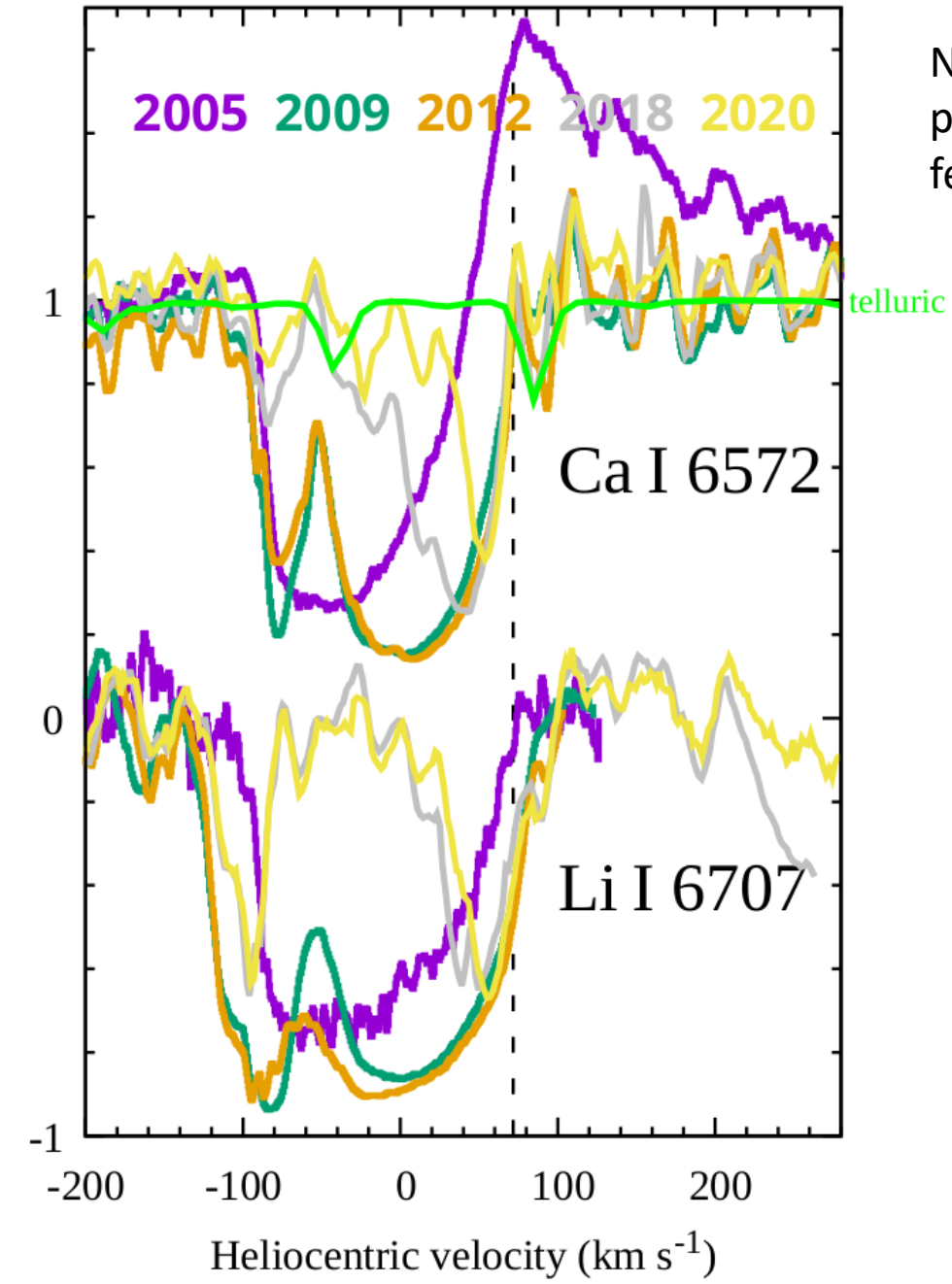
optical studies: 2005 vs 2009

M-type giant + cool circumstellar gas

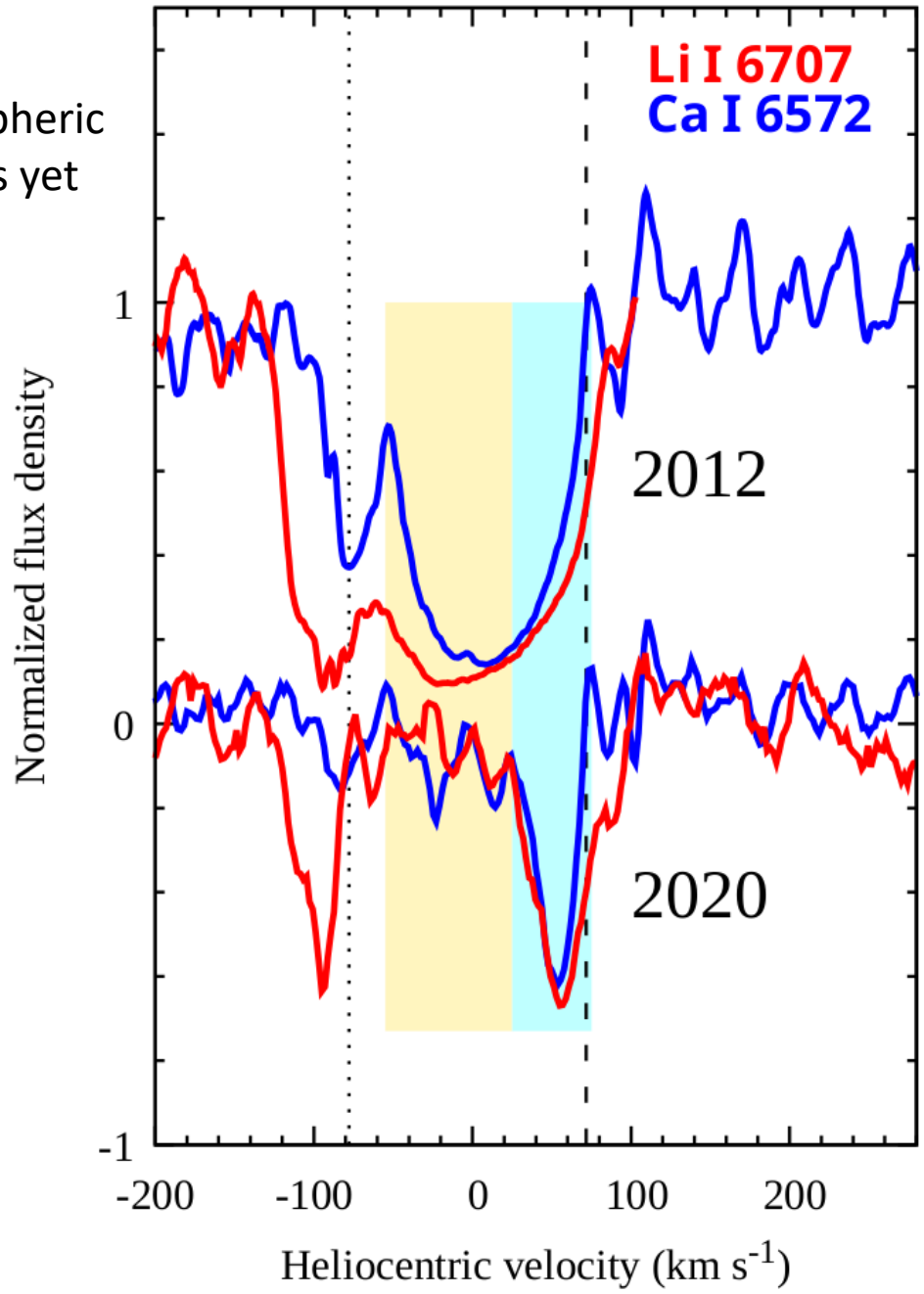
remarkably strong molecular bands in absorption

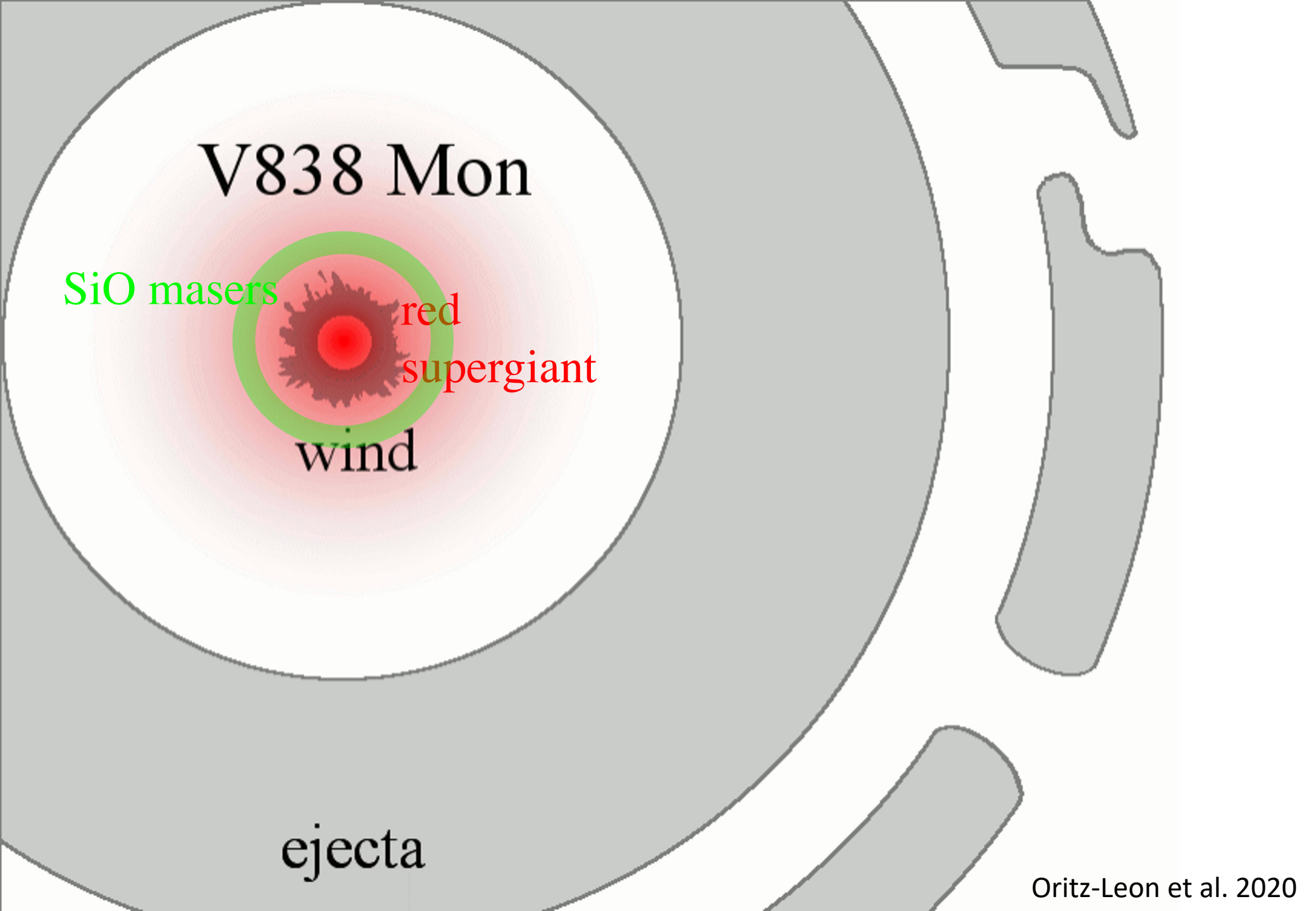


Kamiński+2009
Tylenda+2009
Tylenda+2011



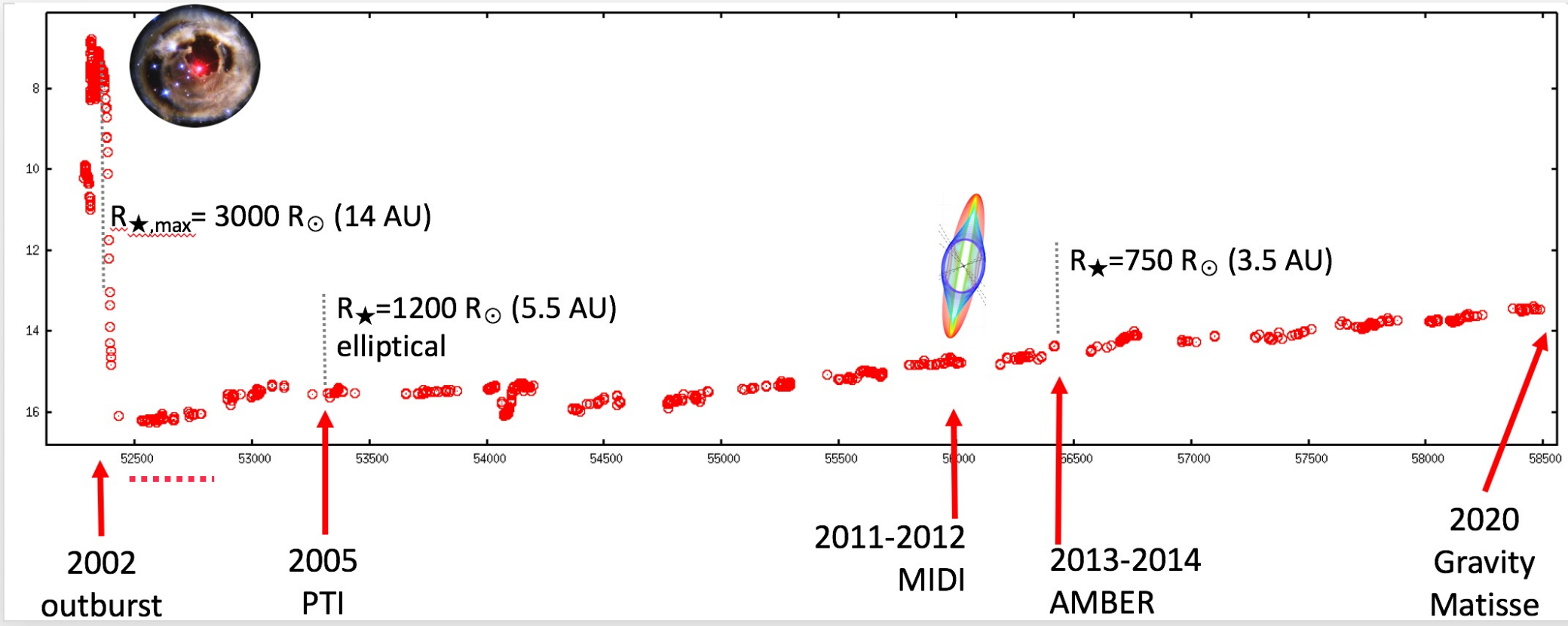
No photospheric features yet





Oritz-Leon et al. 2020

V838 Mon is shrinking



and pulsating?

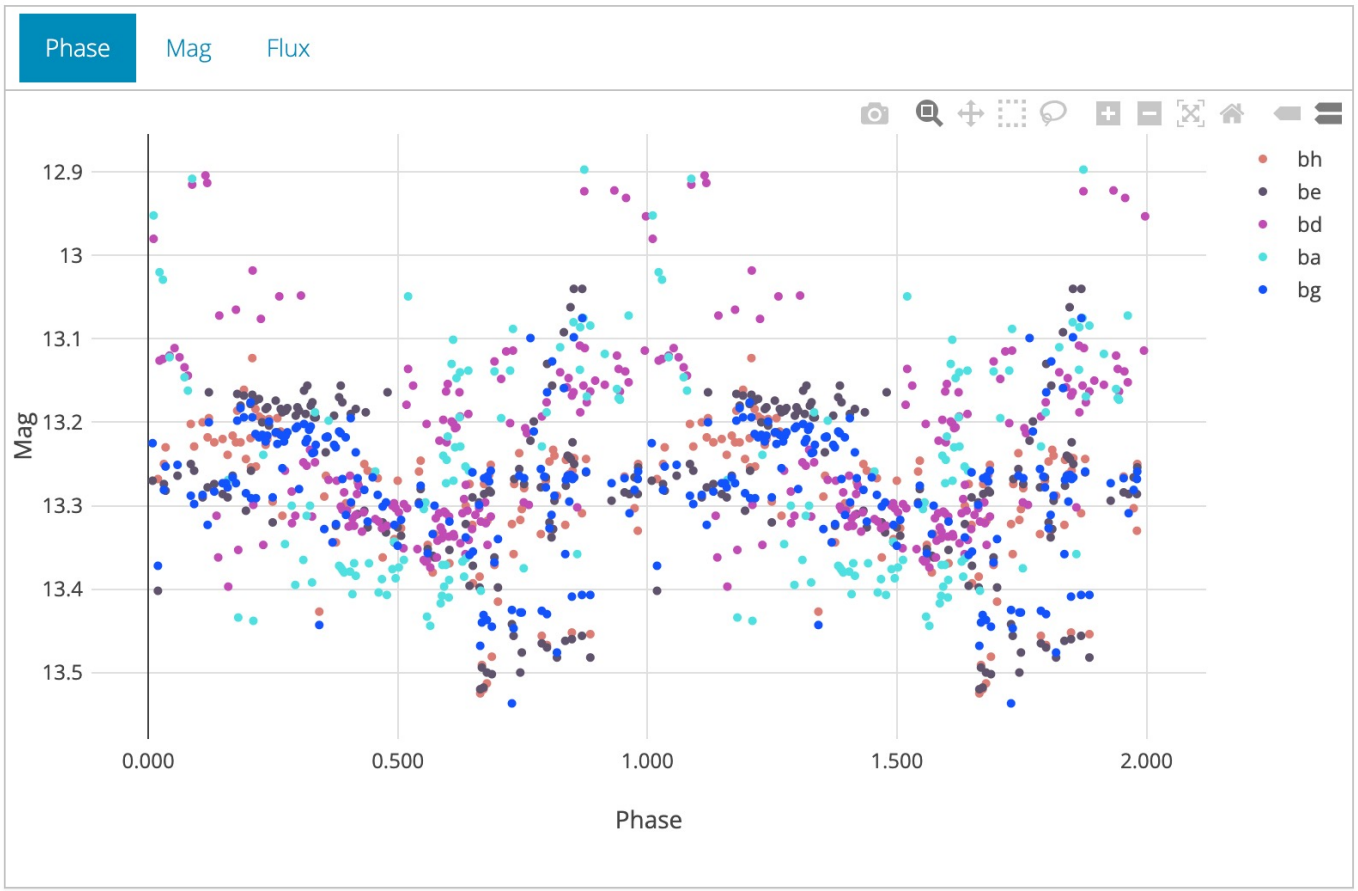
Goranskij et al. 2002-2020, Lane et al. 2005, Chesneau et al. 2011, Tylenda et al. 2003, Mobeen et al. 2021,

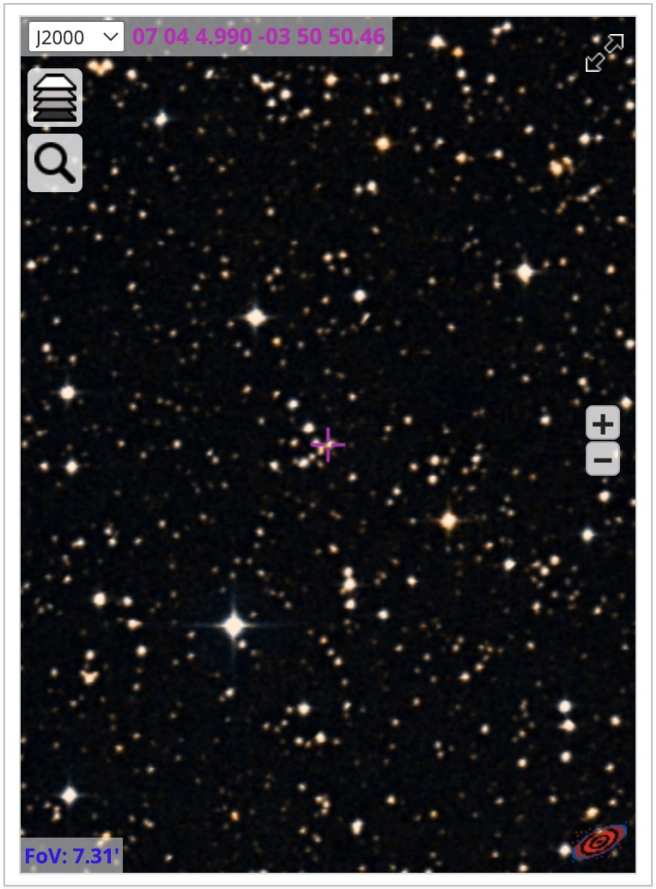
and pulsating?

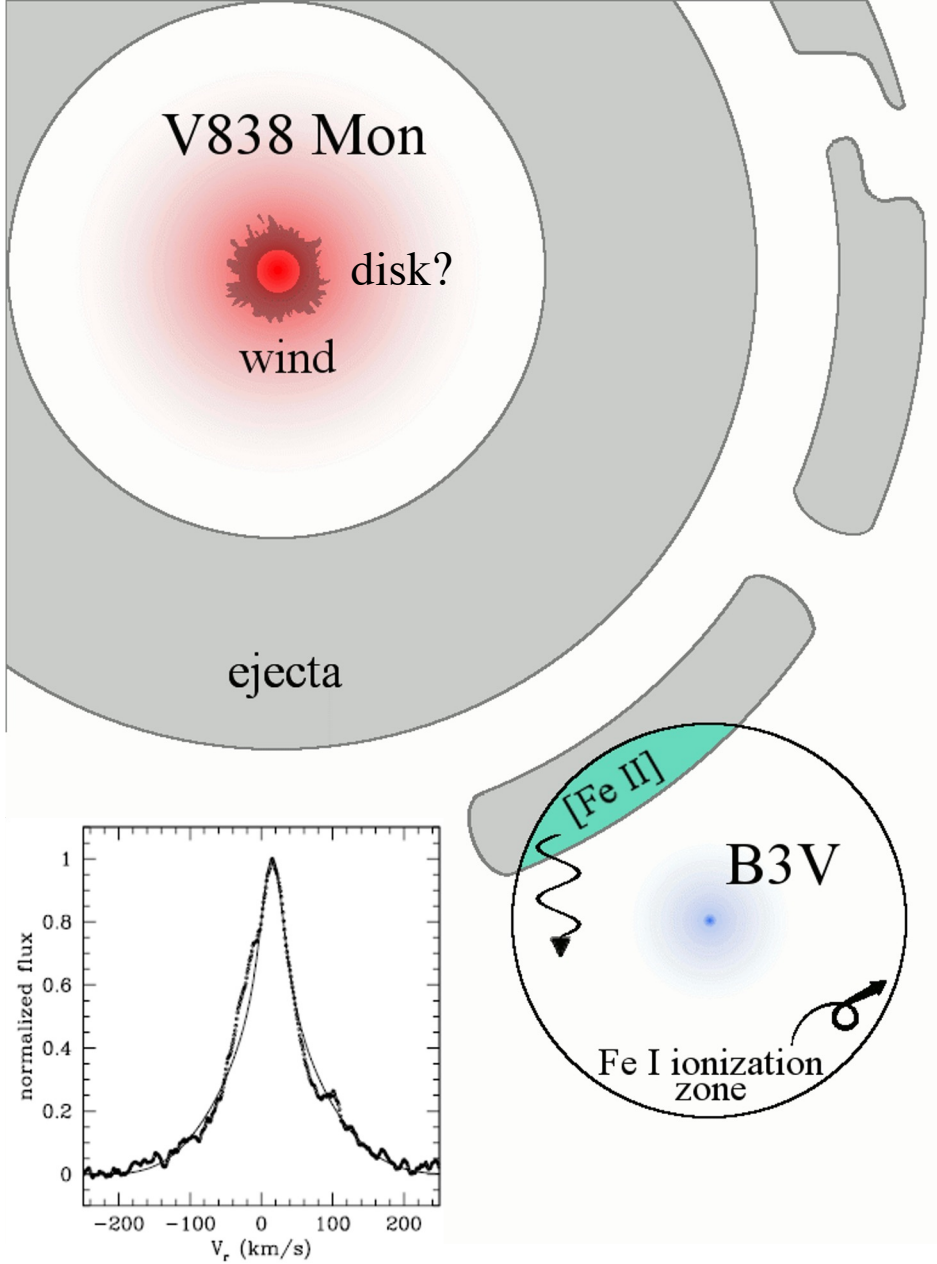
ASASSN-V J070404.99-035050.5 / V0838 Mon (106.02079, -3.84735)

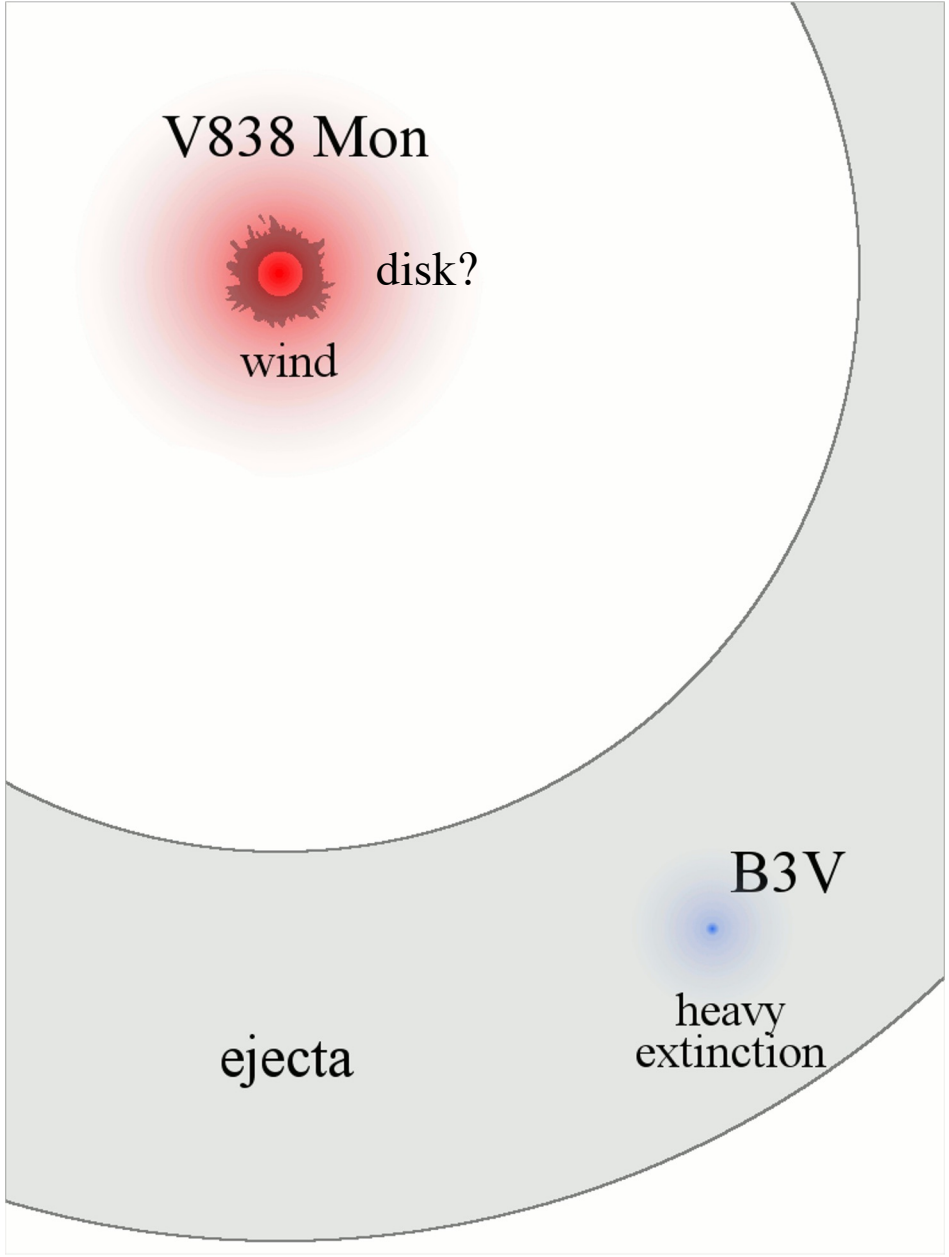
Mean VMag	Amplitude	Period	Type
13.27	0.36	298.3817772	V838MON

Classification Probability	LKSL Statistic	RFR Score	Epoch (HJD)
-	0.52	0.7	2458403.07871







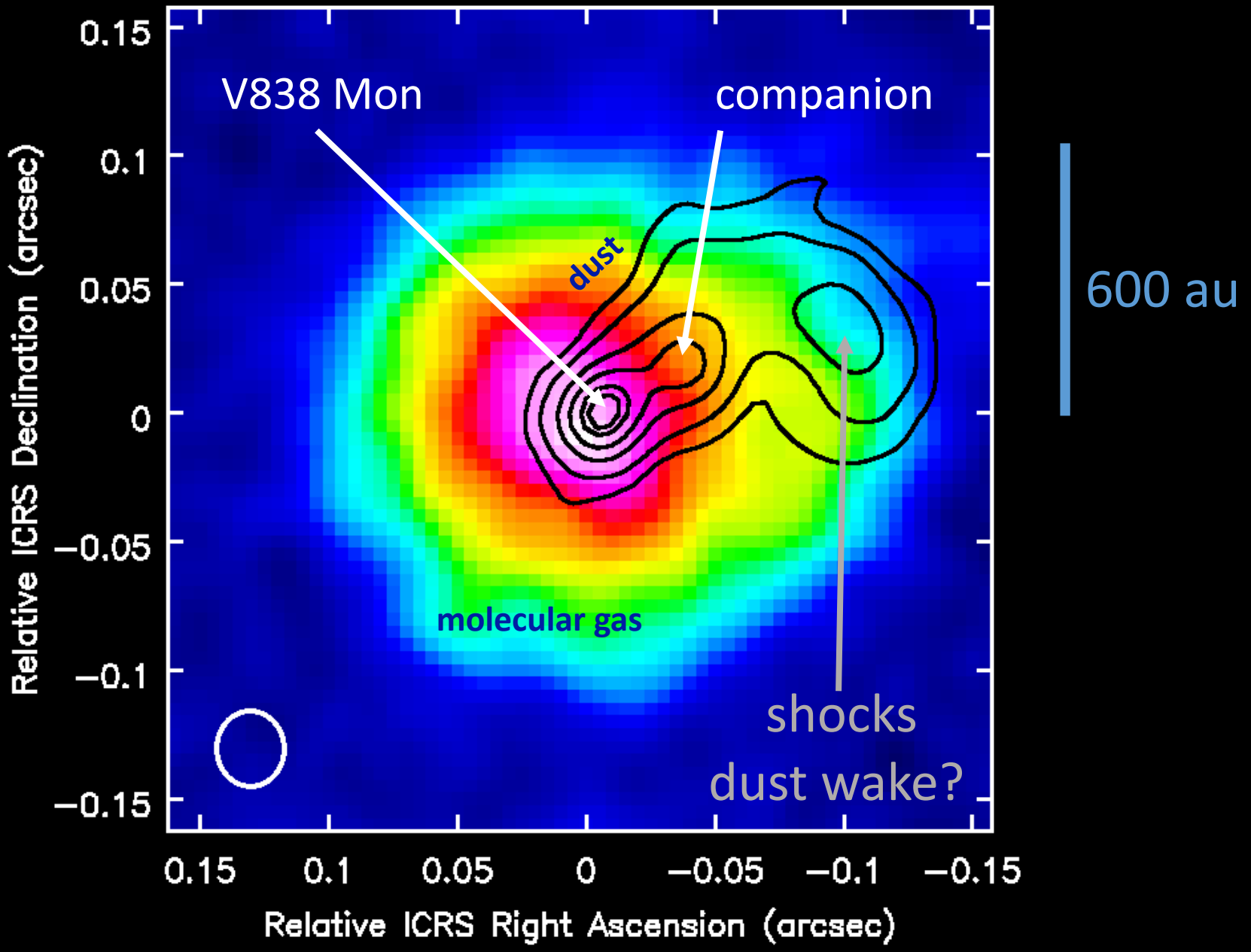


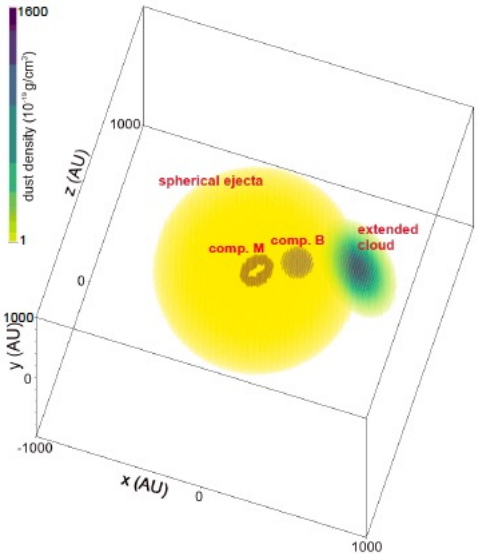
V838 Mon in ~2005 → *and after ~2006*

Atacama Large subMillimeter Array

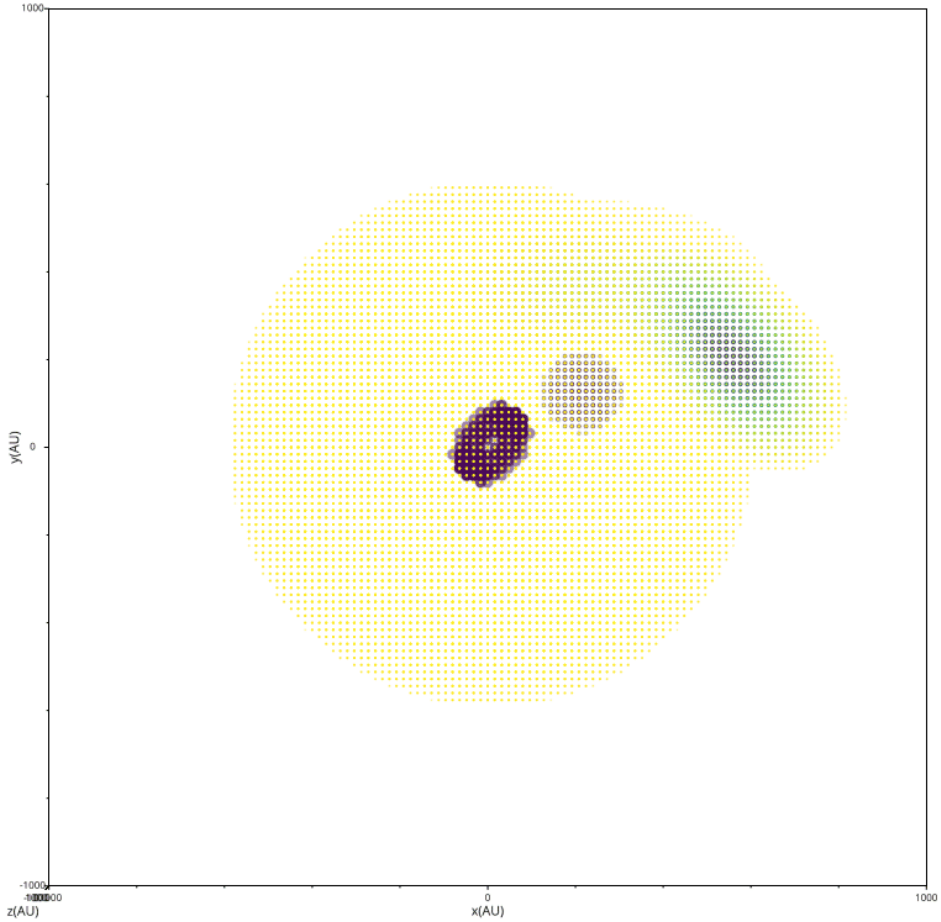
ALMA
2019
16 km !

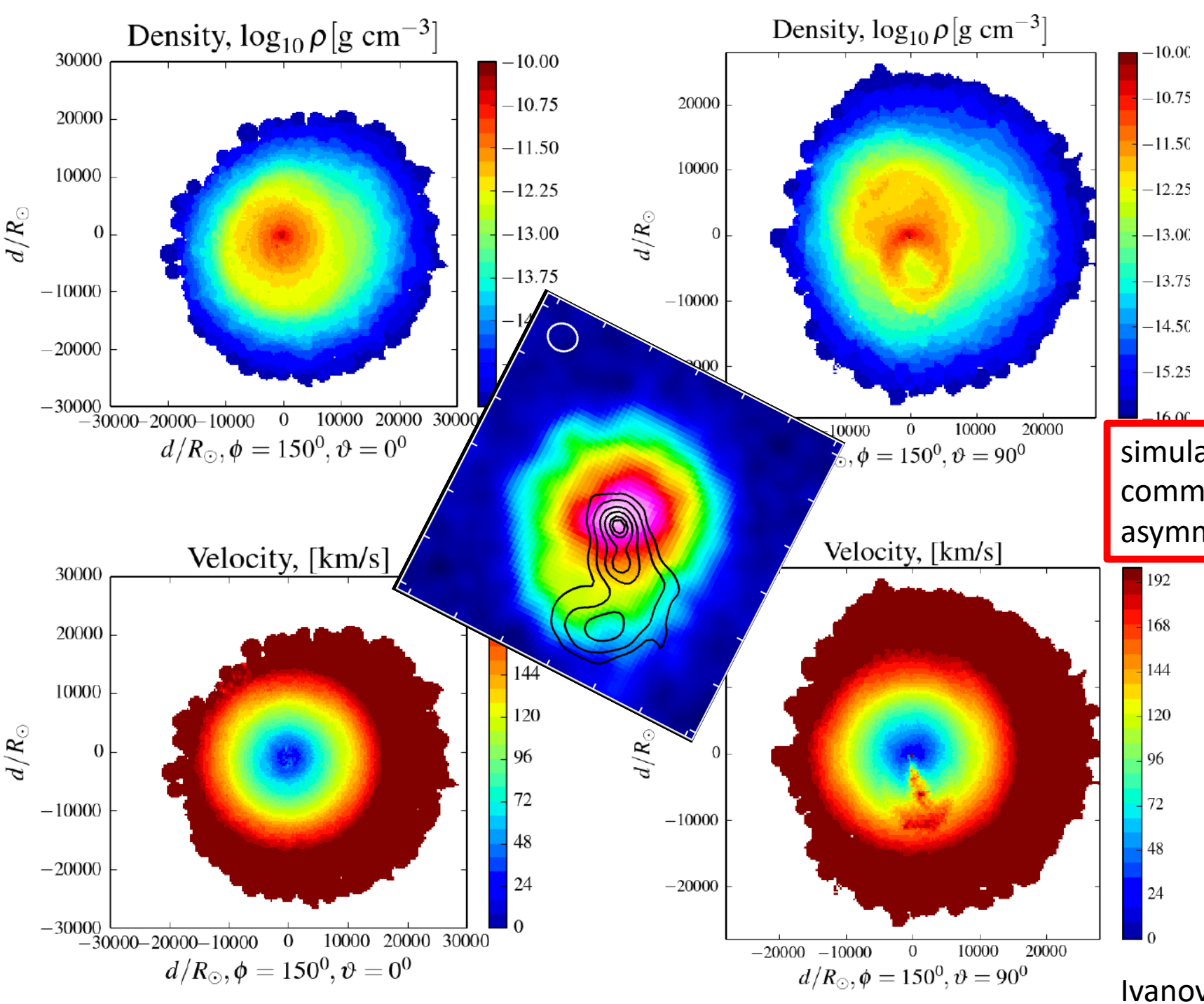
M^*_{tot} = 0.05 $M_\odot$





Dust density
Box 2000^3



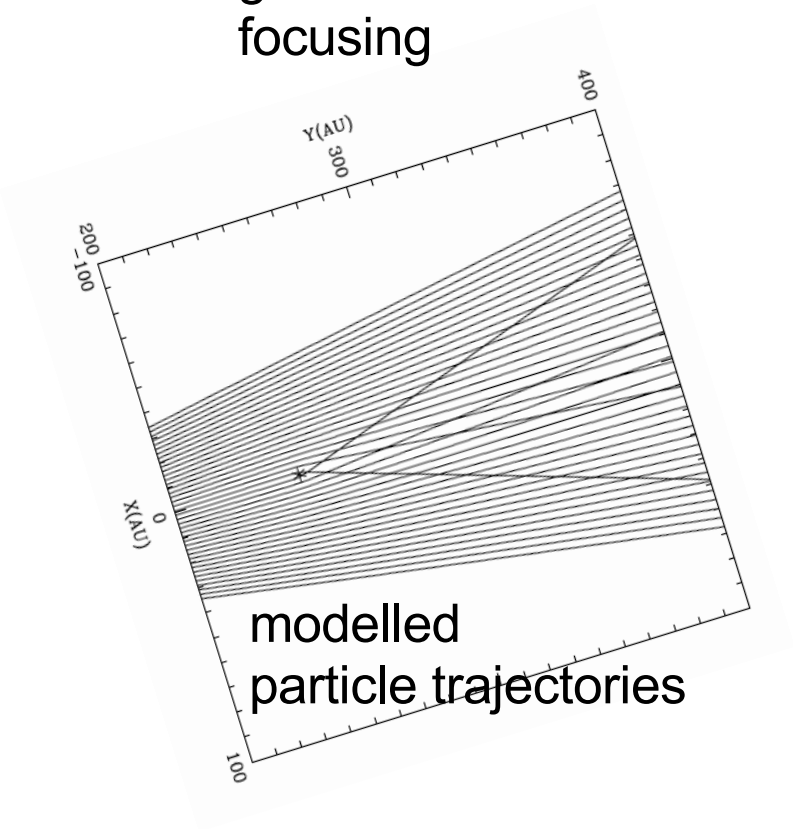


simulated ejecta of the common envelope is asymmetric

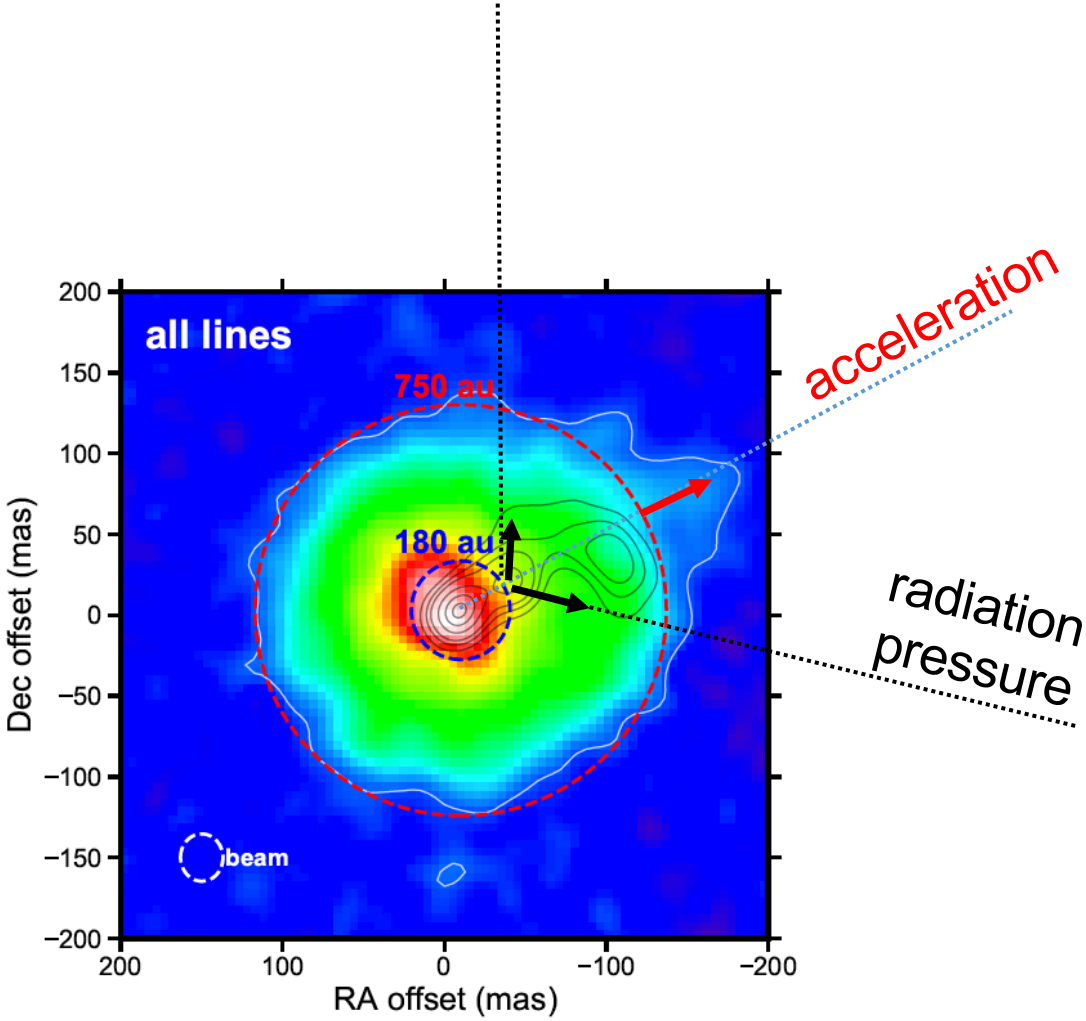
Ivanova & Nandez 2018

Interaction of the merger ejecta with the companion

gravitational focusing

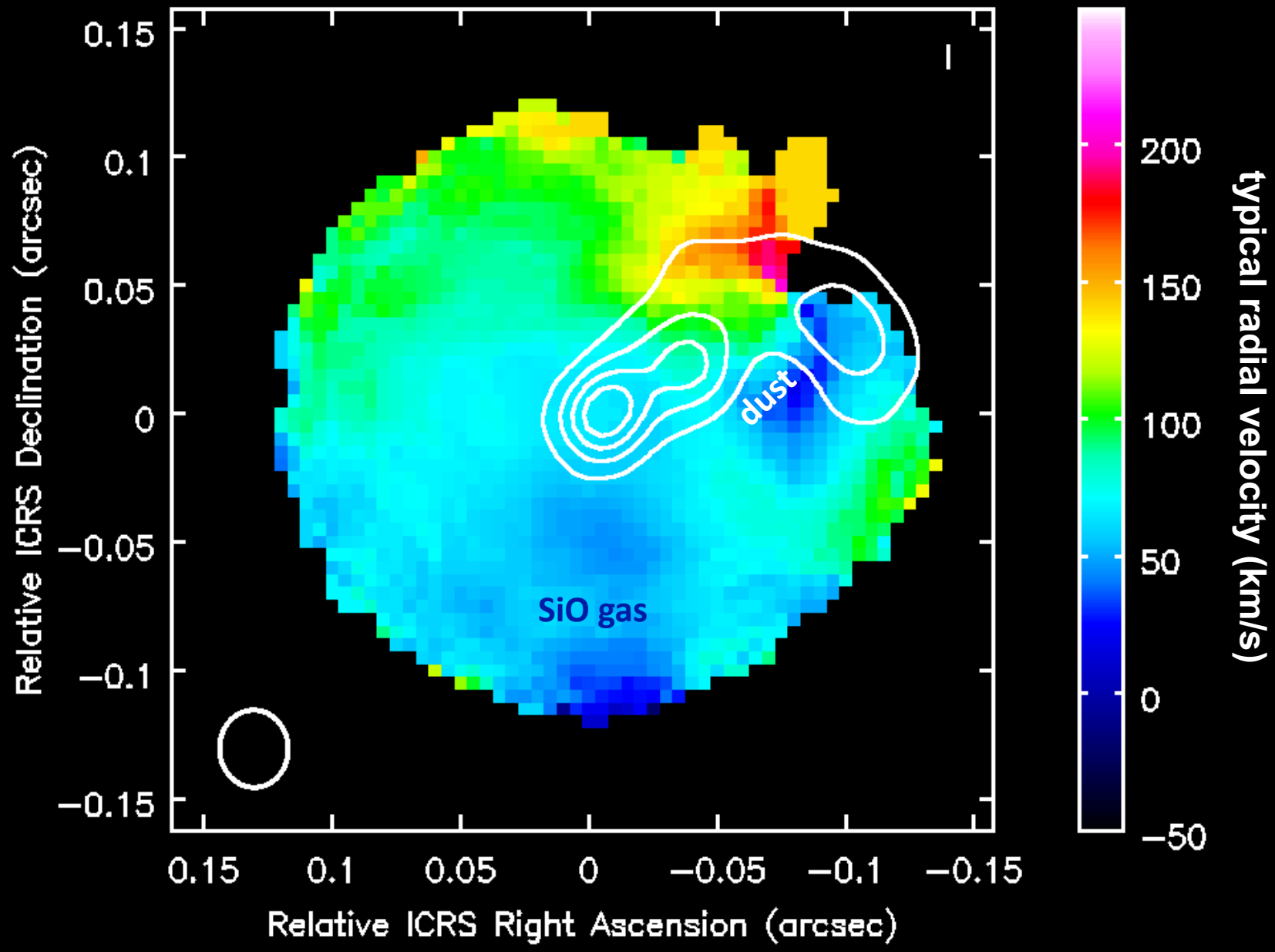


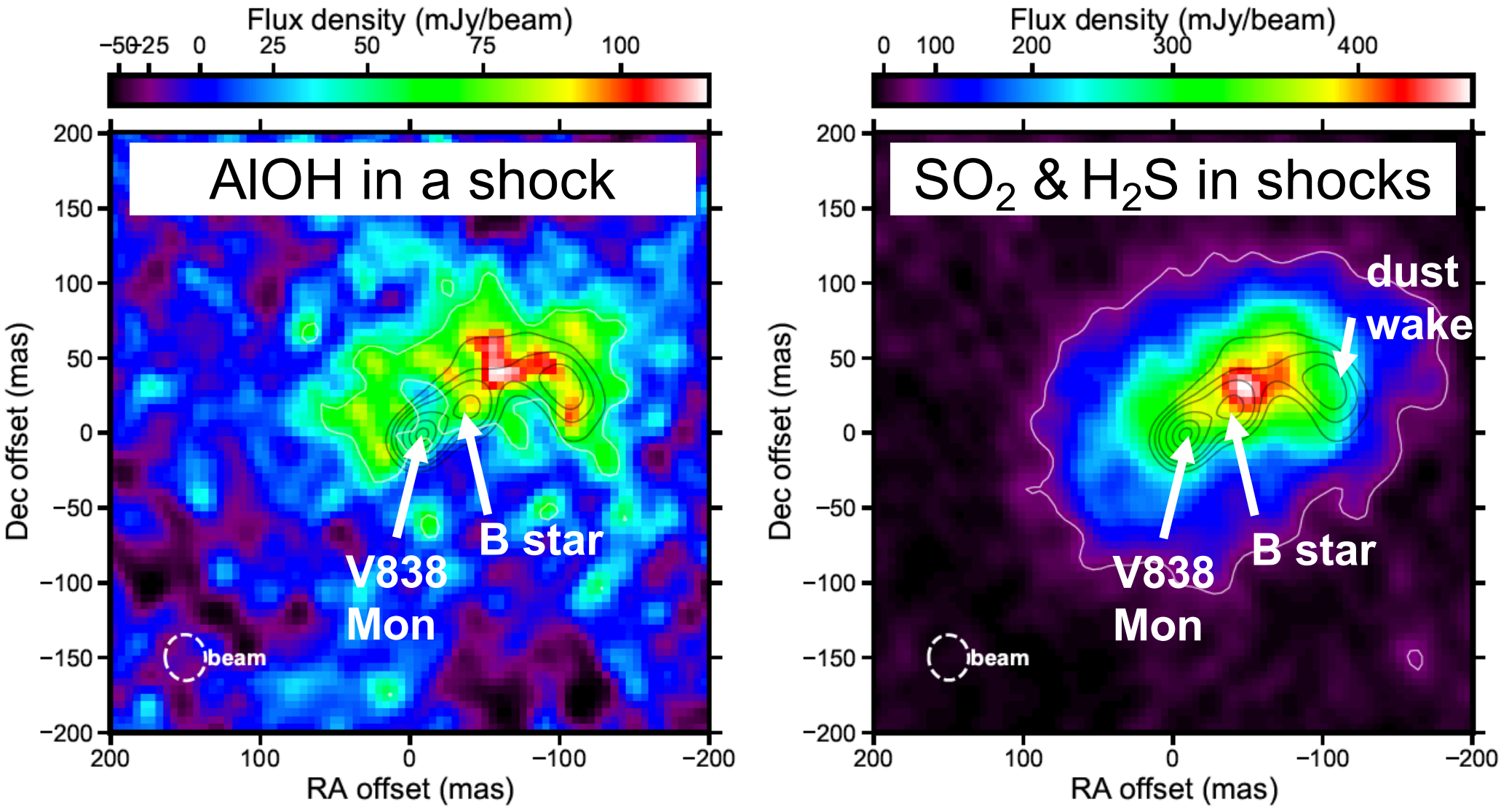
modelled particle trajectories



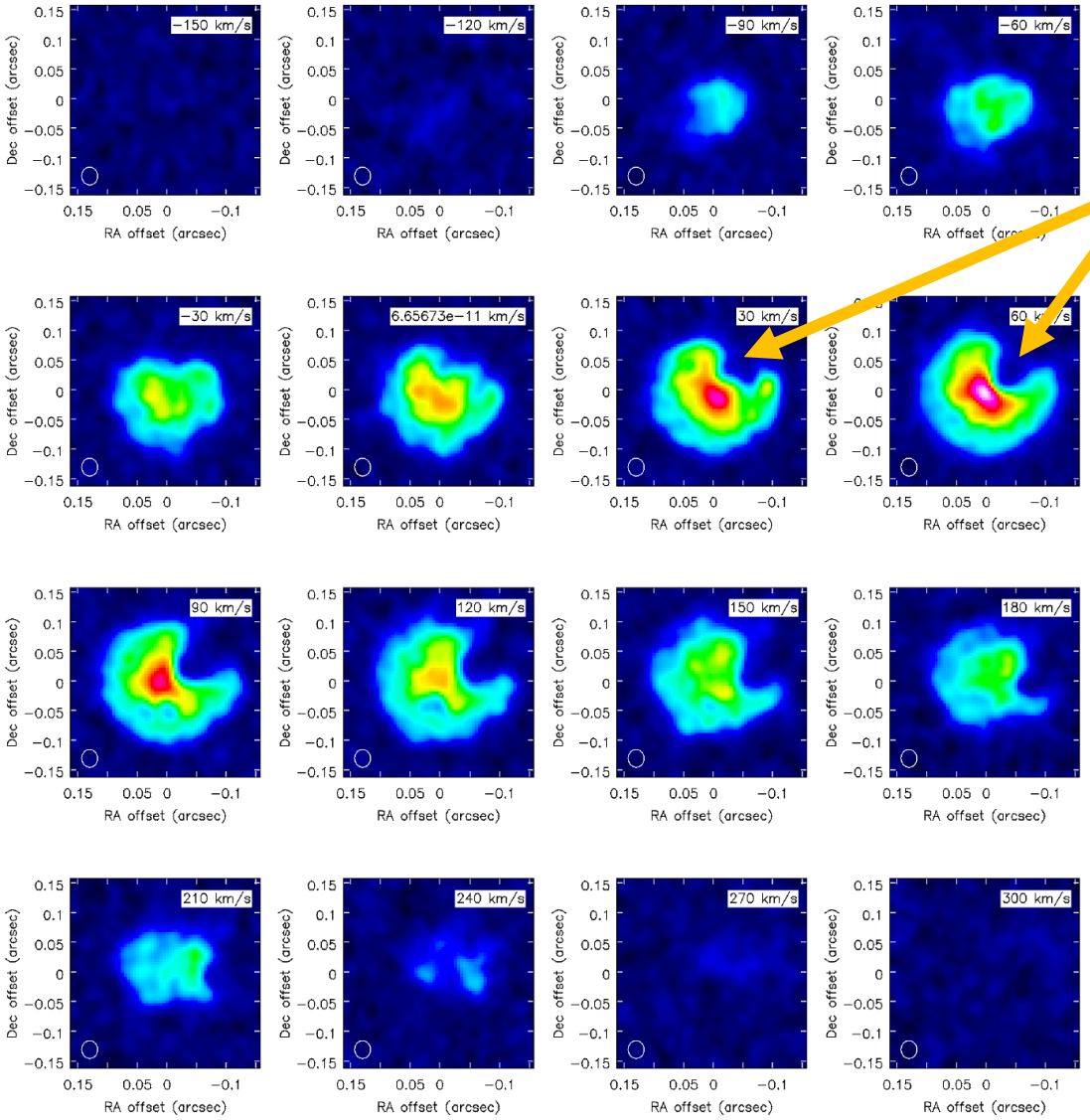
ALMA
2019
16 km !

Tracing gas kinematics (first-moment SiO map)

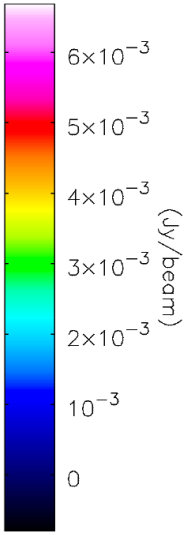


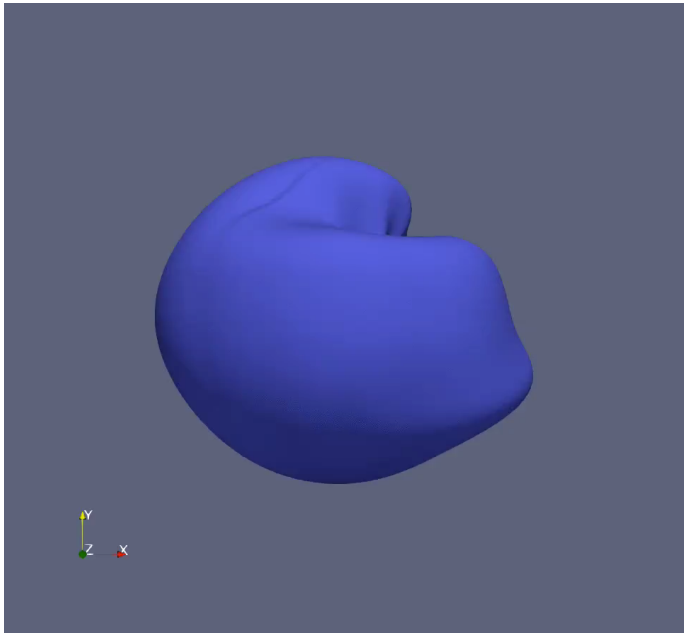

Flux density (mJy/beam)
−50 −25 0 25 50 75 100
AlOH in a shock
V838 Mon
B star
beam
Dec offset (mas)
RA offset (mas)
200 150 100 50 0 −50 −100 −150 −200
Flux density (mJy/beam)
0 100 200 300 400
SO2 & H2S in shocks
dust wake
V838 Mon
B star
beam
Dec offset (mas)
RA offset (mas)

SiO depletion! on channel maps



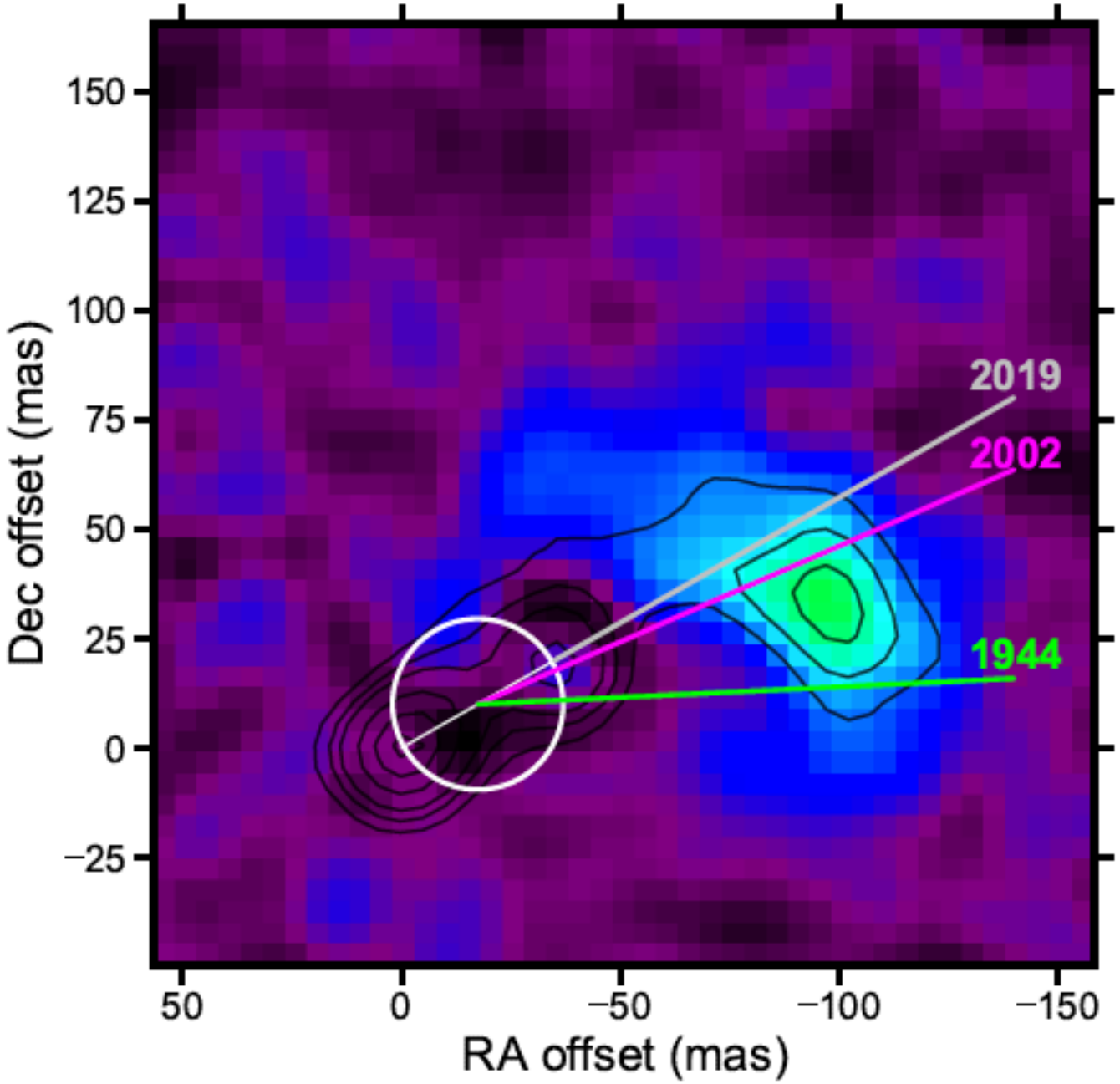
conical void



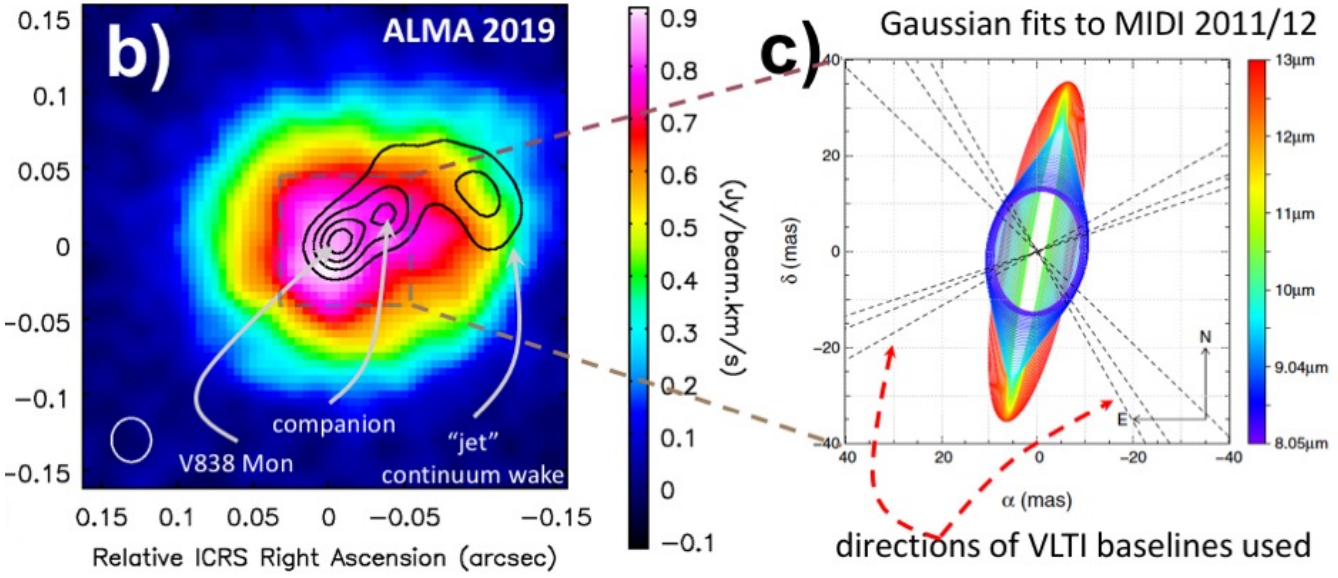


3D reconstruction of the SiO “surface”

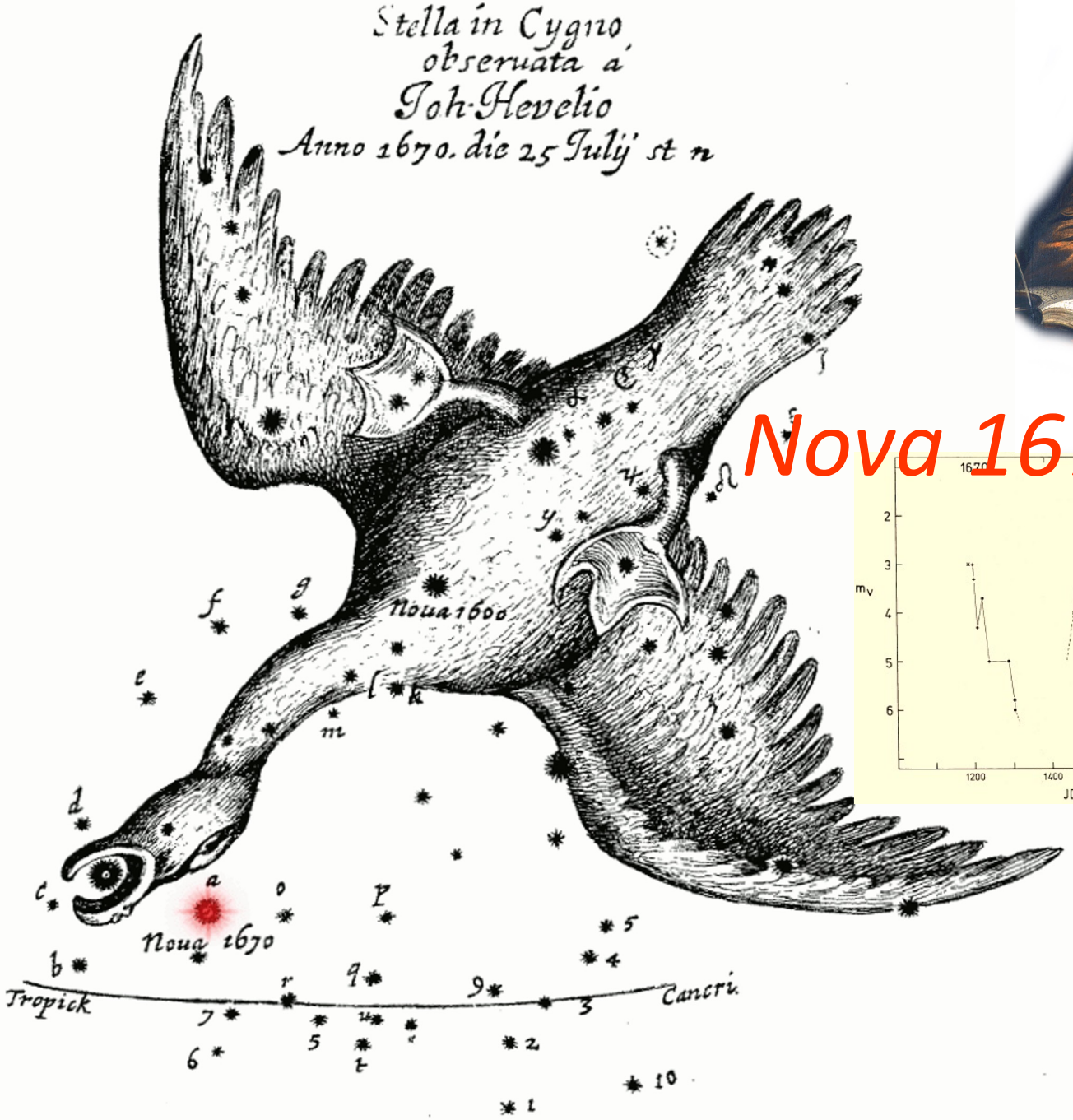
Enhanced mass loss by the companion's orbit?



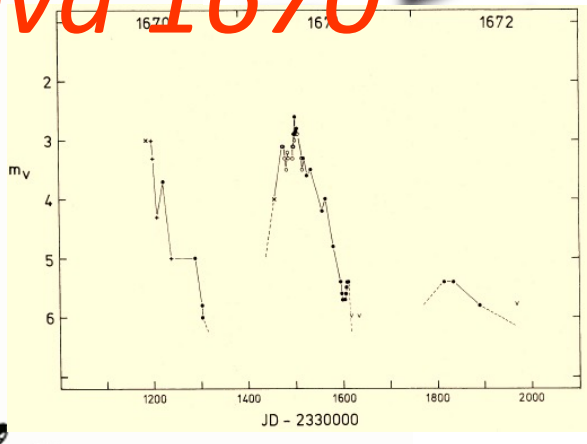
IR interferometric observations of V838 Mon inner system

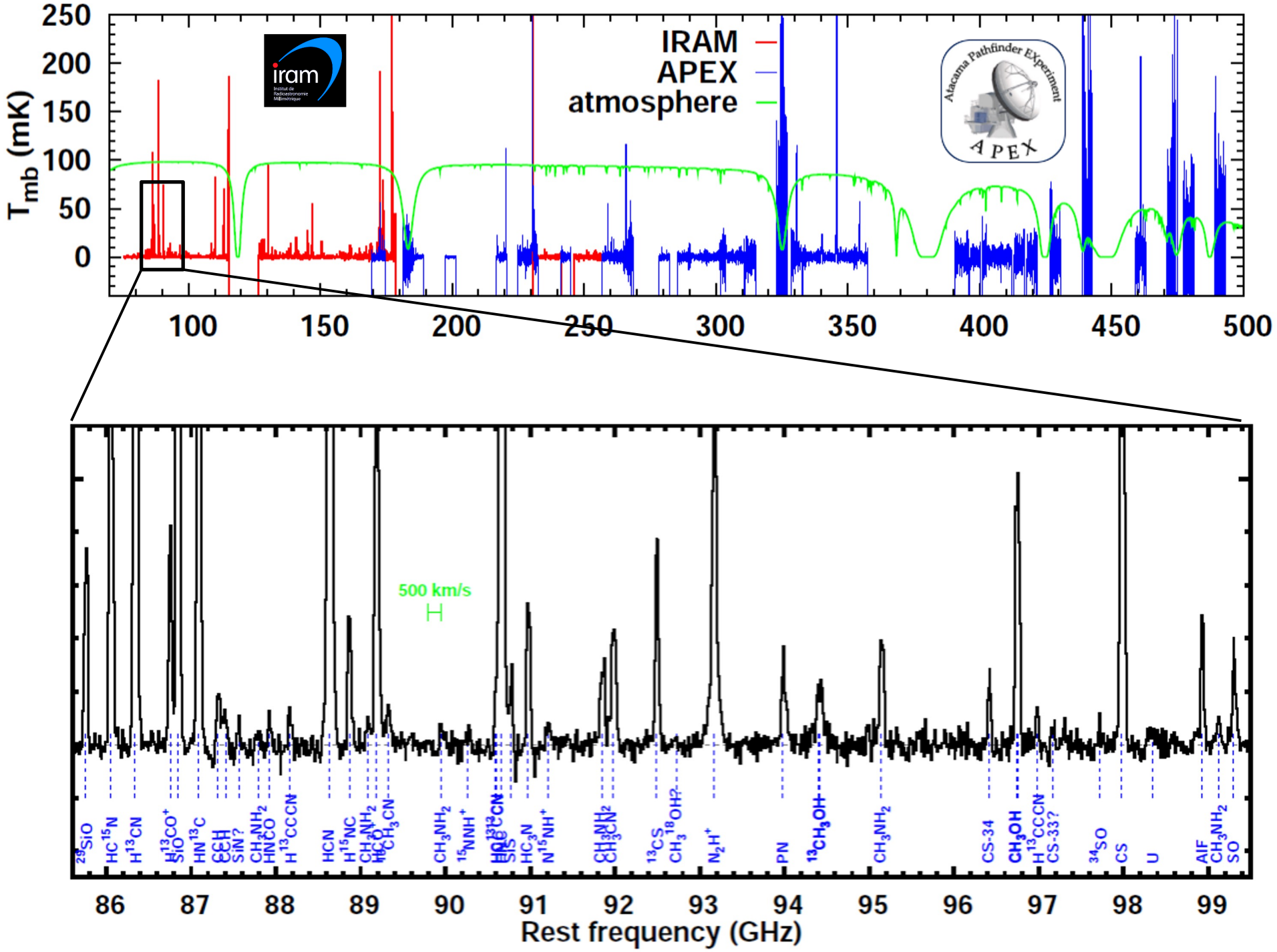


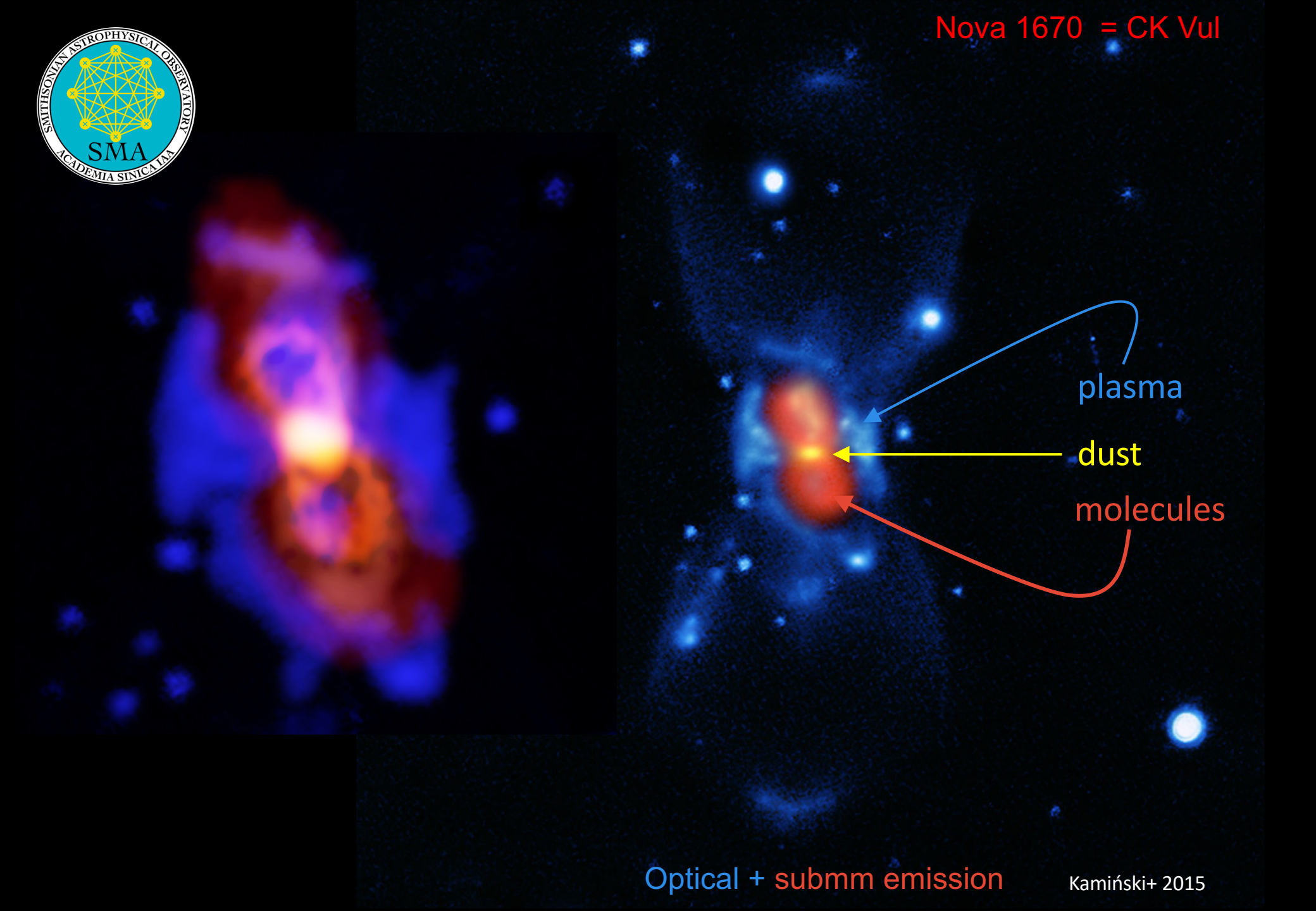
M. Zain Mobeen PhD project

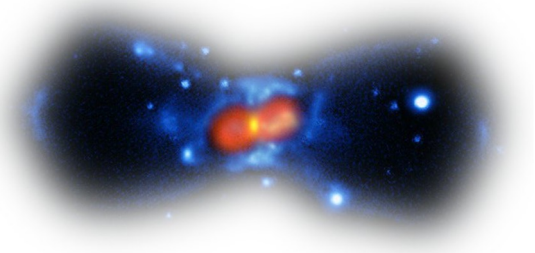

Stella in Cygno
observata á
Joh. Hevelio
Anno 1670. die 25 Julij st n
Noua 1600
Noua 1670
Tropick
Cancri

Nova 1670


1670
1672
m_V
2
3
4
5
6
1200
1400
1600
1800
2000
JD – 2330000


IRAM
APEX
atmosphere
T_{mb} (mK)
250
200
150
100
50
0
100
150
200
250
300
350
400
450
500
500 km/s
^{29}SiO
HC^{15}N
H^{13}CN
H^{13}CO$^+$
SiO
HN^{13}C
CCH
SiN?
CH$_2$NH$_2$
HNCO
H^{13}CCCN
HCN
H^{15}NC
CH$_2$NH$_2$
H$_2$CO
CH$_3$CN
CH$_3$NH$_2$
^{15}NNH$^+$
HC^{13}CN
HNC
SiS
HC$_3$N
N^{15}NH$^+$
CH$_3$NH$_2$
CH$_3$CN
^{13}CS
CH$_3$^{18}OH$_2$
N$_2$H$^+$
PN
^{13}CH$_3$OH
CH$_3$NH$_2$
CS-34
CH$_3$OH
H^{13}CCCN
CS-33?
^{34}SO
CS
U
AlF
CH$_3$NH$_2$
SO
86
87
88
89
90
91
92
93
94
95
96
97
98
99
Rest frequency (GHz)


Nova 1670 = CK Vul
plasma
dust
molecules
Optical + submm emission
Kamiński+ 2015

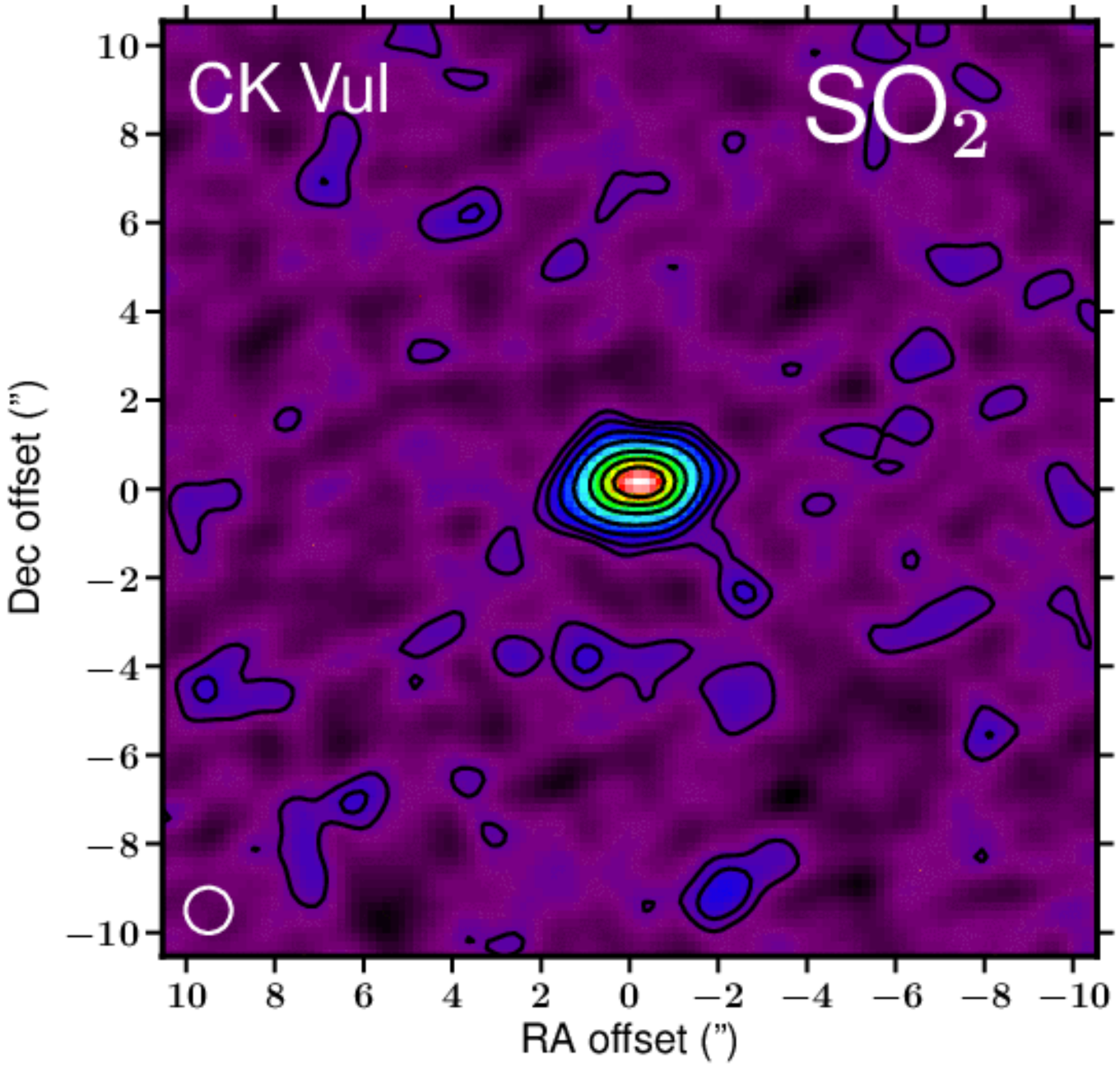


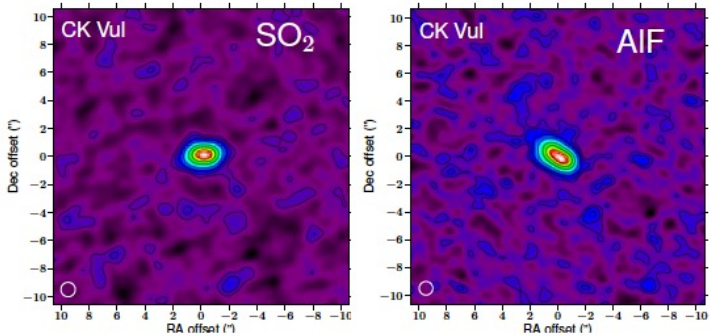
Detected molecules

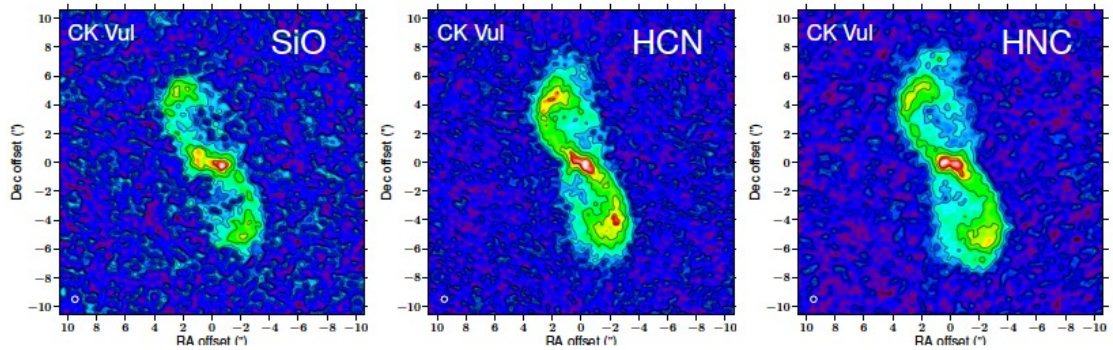
2 atoms	3 atoms	4 atoms
AlF	CCH	NH_3
CN	H_2S	H_2CO
CO	HCN	HNCO
CS	HCO^+	H_2CS
NO	HNC	
NS	N_2H^+	
PN	SO_2	
SO		
SiO		
SiN		
SiS		

5 atoms	6 atoms	7 atoms
CH_2NH	CH_3CN	CH_3NH_2
HC_3N	CH_3OH	

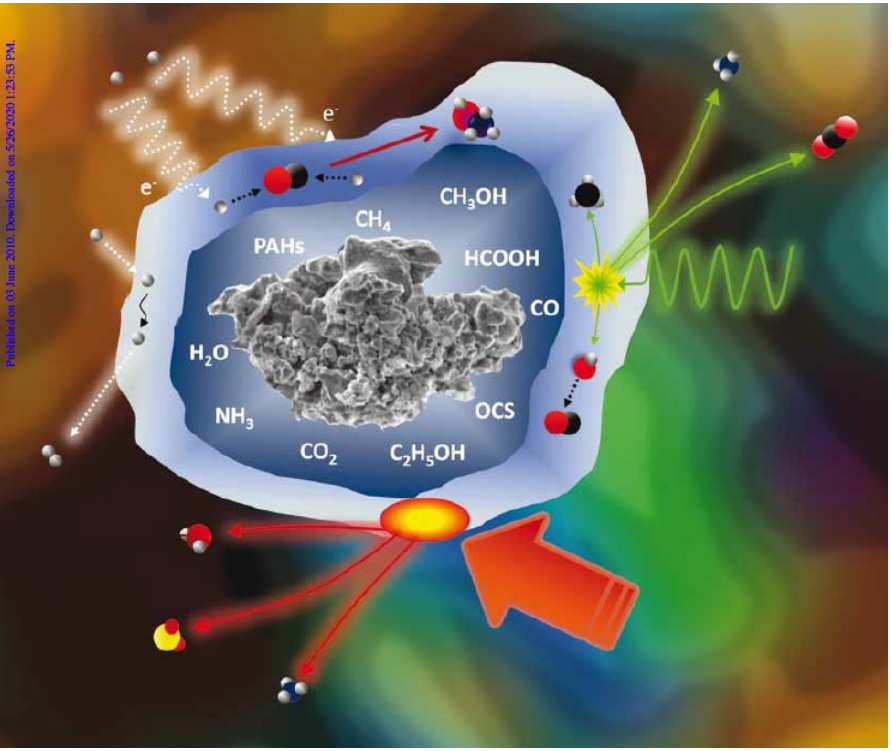
2018: line surve
bands 3,4,5 & 6

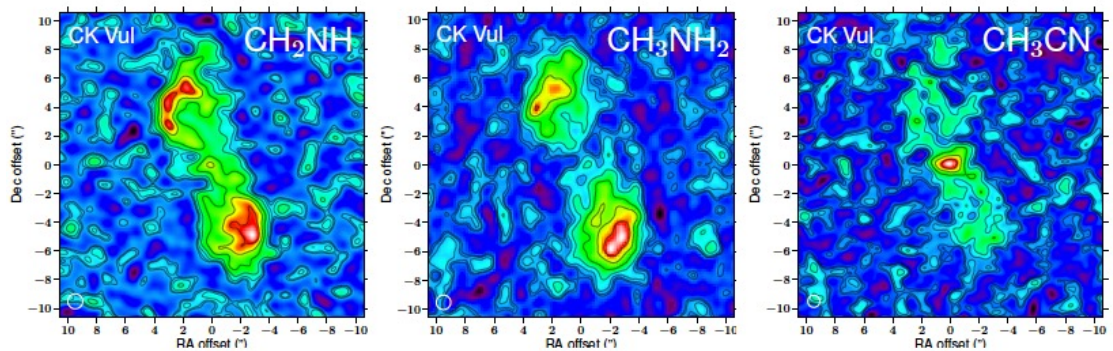


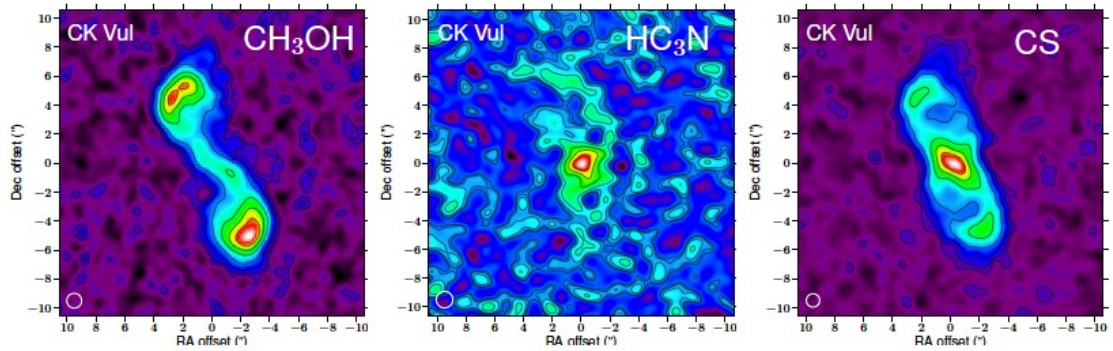


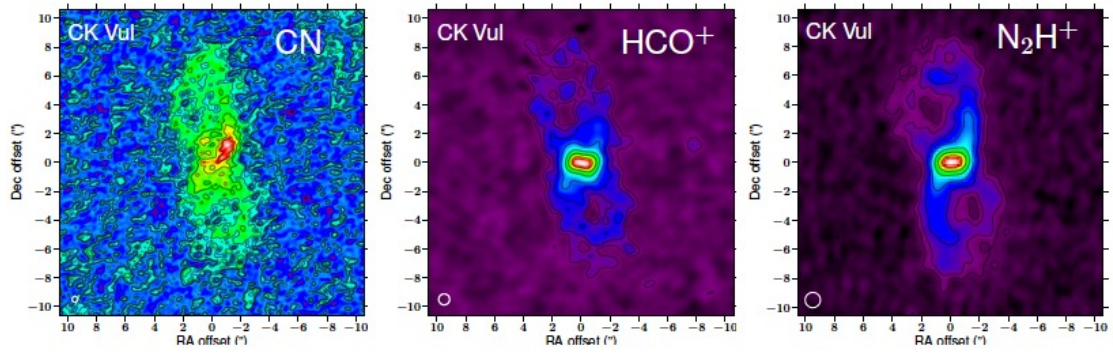


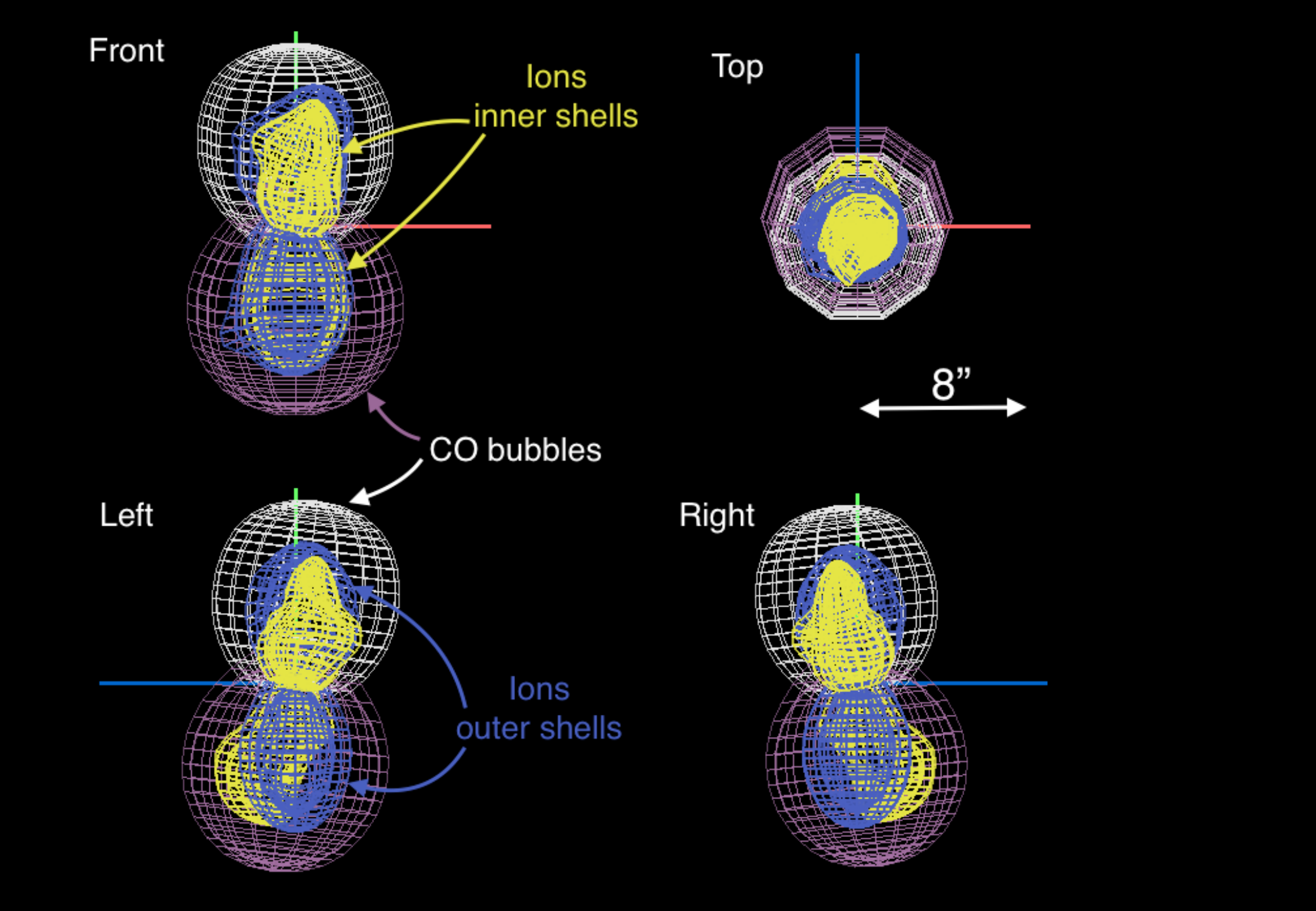
shock chemistry!










Front
Ions
inner shells
Top
8”
CO bubbles
Left
Ions
outer shells
Right

Molecular ions in CK Vul

rotx = 000°
roty = 000°
rotz = -17°

point symmetry

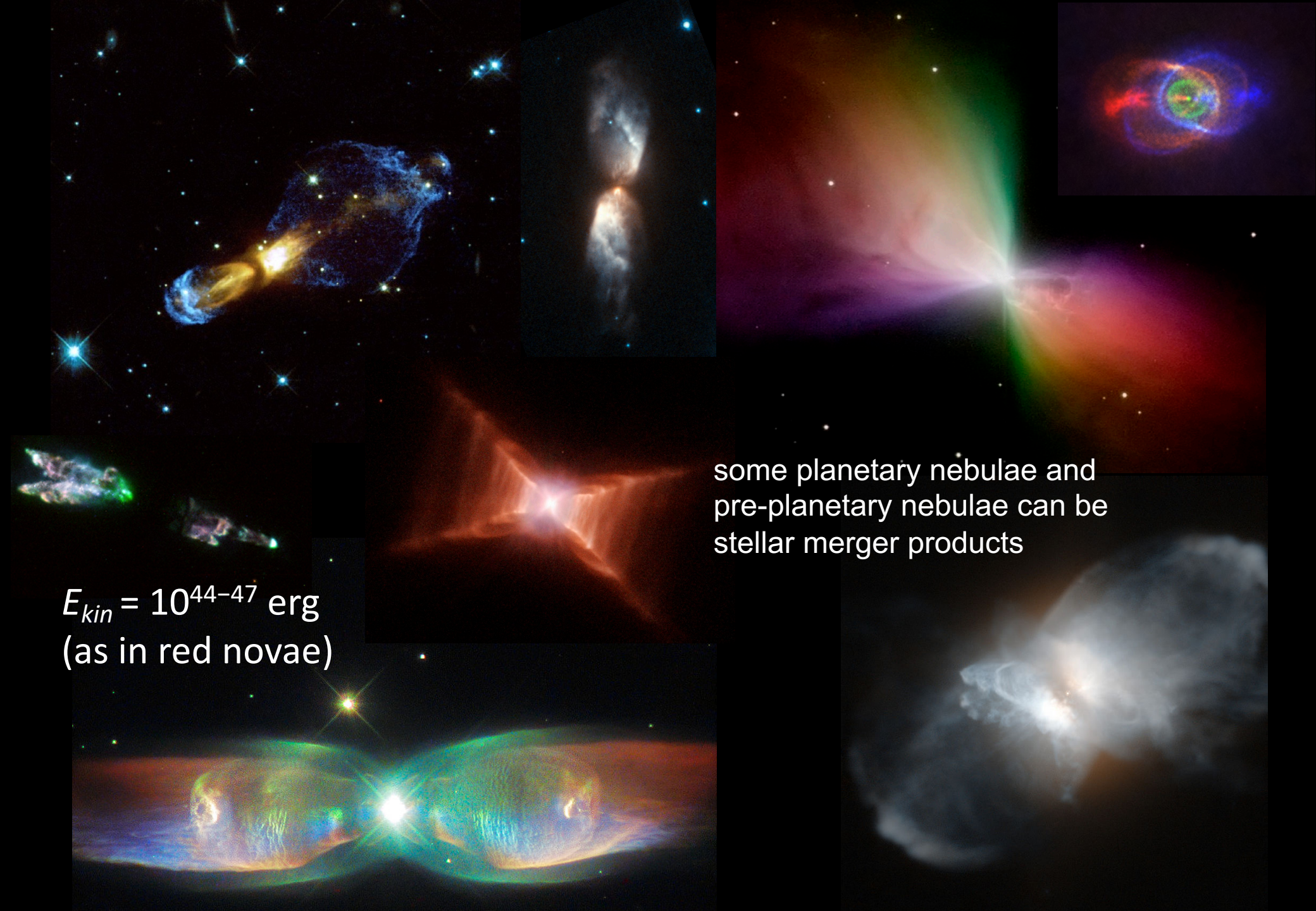
multiple ejections

possible jet-type activity

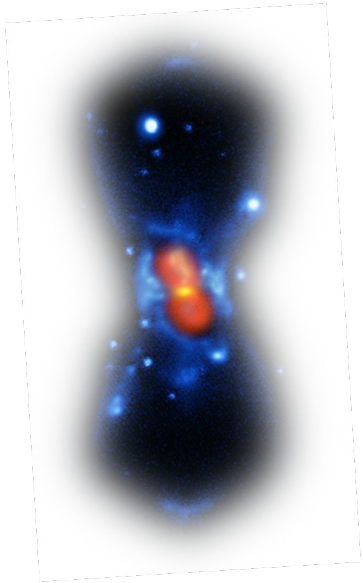
possibly younger than 340 yr

Kamiński et al. 2020

Kamiński et al 2021

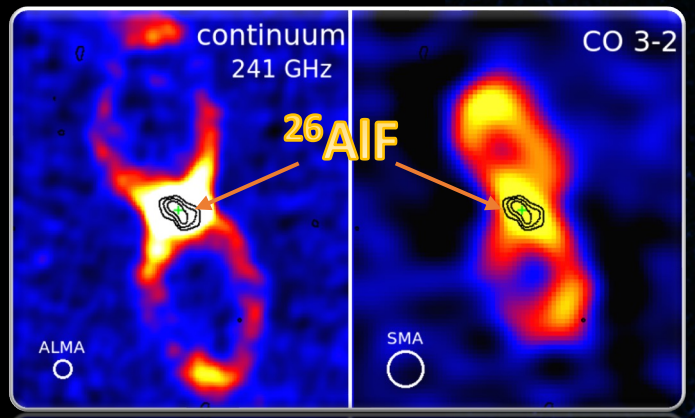

some planetary nebulae and
pre-planetary nebulae can be
stellar merger products
$E_{kin} = 10^{44-47}$ erg
(as in red novae)

Most peculiar isotopic composition: CNO and He burning



CK Vul	Solar
$^{12}C/^{13}C = 3.8 \pm 1.0$	89.3
$^{13}C/^{14}C > 141$	
$^{14}N/^{15}N = 20 \pm 10$	441
$^{16}O/^{18}O = 36 \pm 14$	498.8
$^{18}O/^{17}O \gtrsim 5$	5.4
$^{27}Al/^{26}Al = 6.0 \pm 0.9$	
$^{28}Si/^{29}Si = 6.7 \pm 0.4$	19.7
$^{29}Si/^{30}Si = 1.0 \pm 0.1$	0.7
$^{32}S/^{34}S = 14 \pm 3$	22.5
$^{32}S/^{33}S > 34$	126.6

Nova 1670 = CK Vul



plasma

dust

molecules

CAUTION

RADIOACTIVE

26AlF

Optical + submm emission

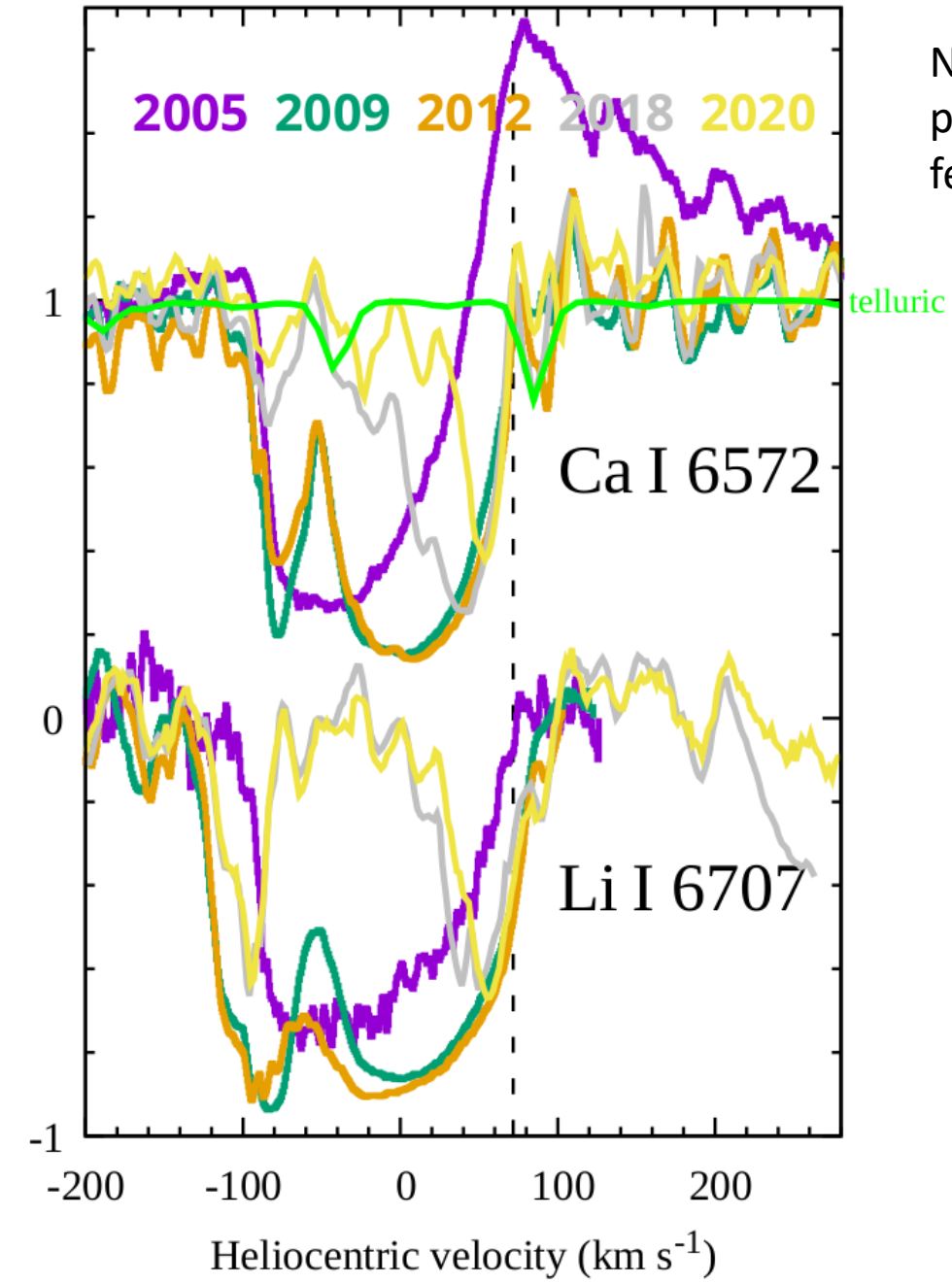
Kamiński+ 2015

the progenitor system contained a Red Giant Branch star

NRAO/T. Kamiński

Lithium in LRN*
Cameron-Fowler effect in CE systems

*Paper in prep., please no screenshots



No photospheric features yet

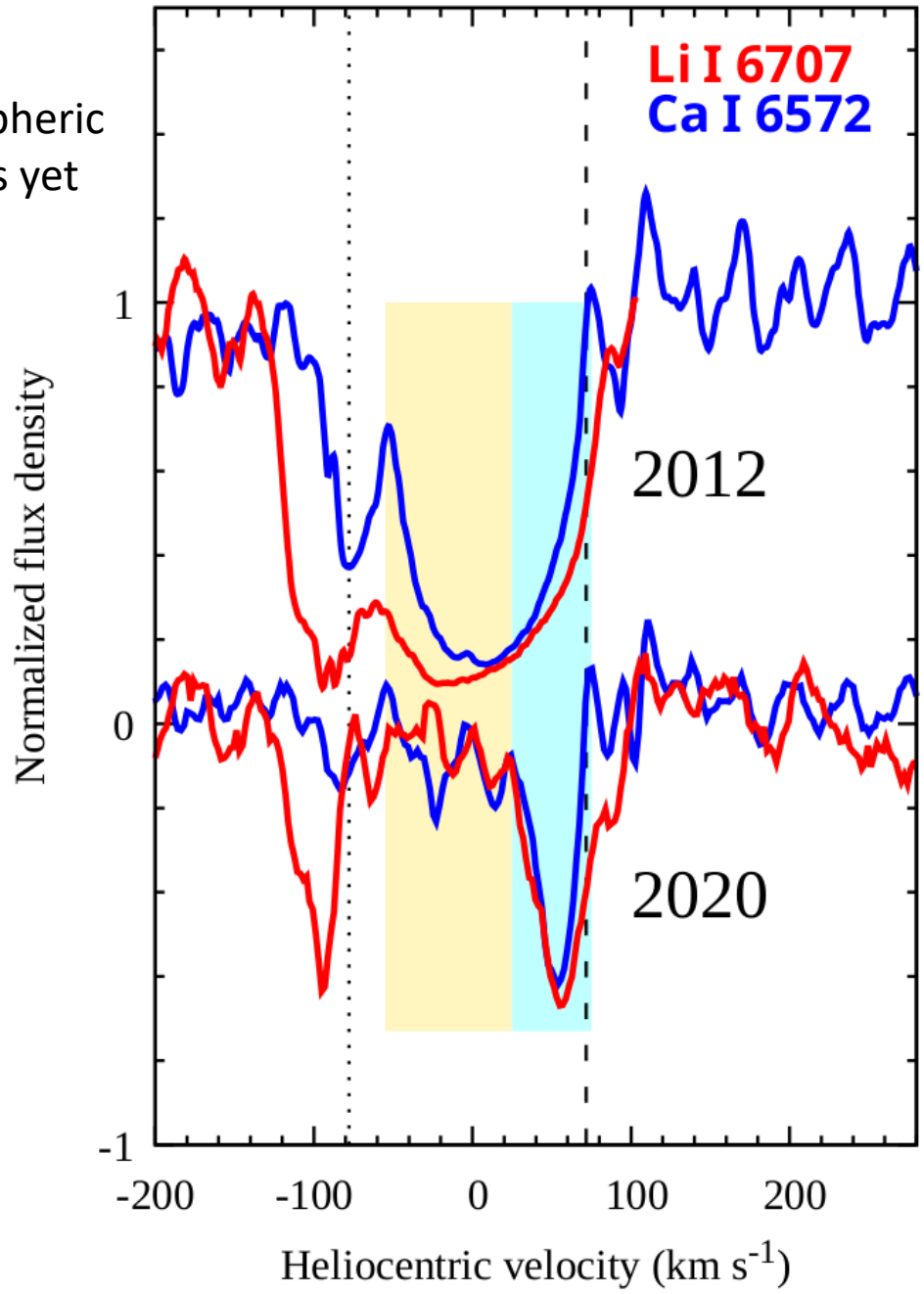
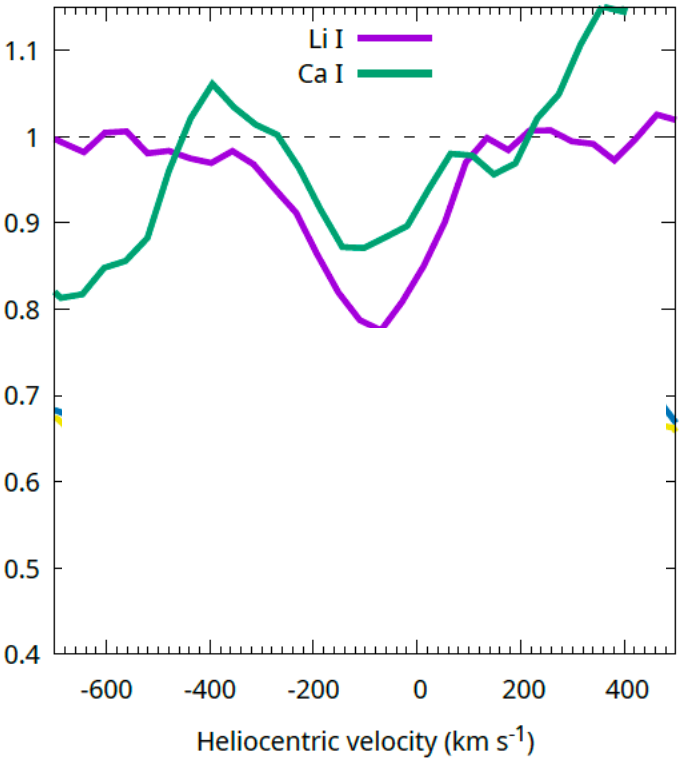


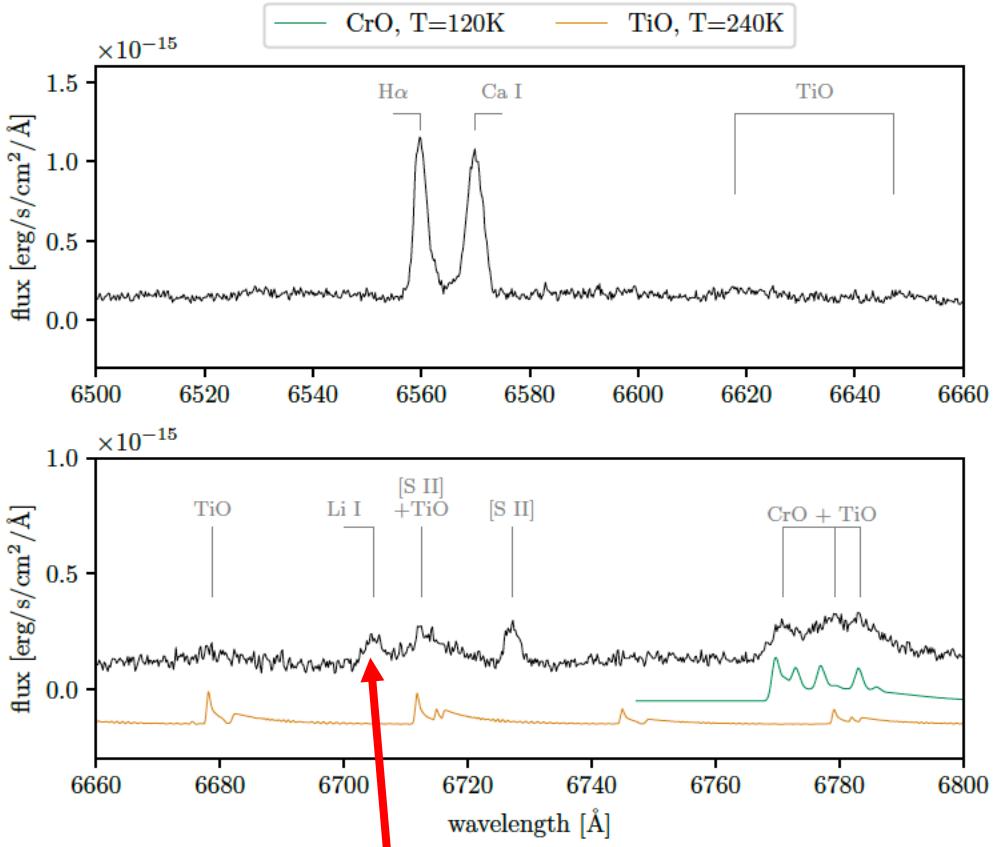
Table 4. Abundances in V838 Mon on March, 18 2002.

El.	$\log \varepsilon(\mathrm{El})_{\mathrm{V838Mon}}$	$[\mathrm{El/Fe}]_{\mathrm{V838Mon}}$
Li	3.8	0.9
Si	6.5 ± 0.2	−0.6
Ca	6.1 ± 0.3	0.2
Sc	2.9 ± 0.2	0.1
Ti	4.3 ± 0.3	−0.3
V	3.6 ± 0.4	−0.1
Cr	5.0 ± 0.2	−0.3
Mn	4.9 ± 0.2	−0.1
Fe	7.1 ± 0.3	
Co	4.3 ± 0.3	−0.2
Ni	5.7 ± 0.3	−0.2
Y	1.8 ± 0.2	0
Ba	2.5 ± 0.3	0.7
La	1.5 ± 0.4	0.7

Lithium in V1309 Sco

Li I in CK Vul outflow:





emission

$^3He(\alpha, \gamma)^7Be(e-, \nu)^7Li$

often in RGB stars

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LITHIUM AND THE *s*-PROCESS IN RED-GIANT STARS

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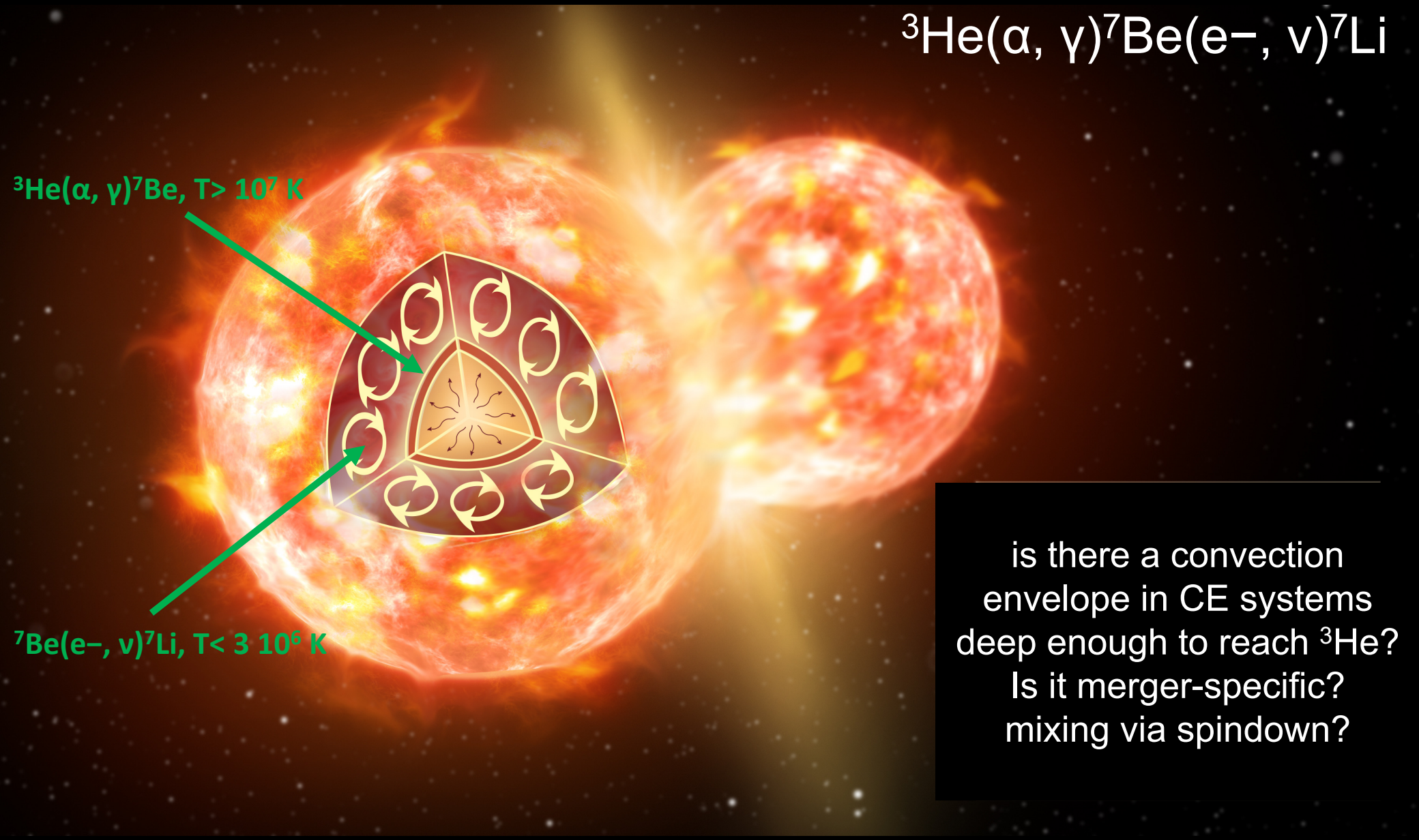
ABSTRACT

Some consequences are discussed of the possibility that helium-burning shell flashes in advanced stages of stellar evolution occasionally induce complete convection of the outer envelope down to the helium-burning shell. If the hydrogen mixing is relatively small for the first 10^7 seconds, the result may be the production of large amounts of heavy elements by the *s*-process. When complete mixing commences, the ^3He in the envelope will be converted to ^7Be, and the subsequent delayed electron capture to form ^7Li may allow enough lithium to remain near the surface to account for the very large lithium abundances in some S and carbon red-giant stars. On this basis the $^7Li/^6Li$ ratio in these stars should be quite large (>100).

Cameron-Fowler in CE?

$^3He(\alpha, \gamma)^7Be(e-, \nu)^7Li$



is there a convection envelope in CE systems deep enough to reach ^3He? Is it merger-specific? mixing via spindown?

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Summary

- we can observe stellar collisions in real time

- detailed studies of their cool remnants with interferometers constrain theoretical models of stellar mergers and of the common envelope phase

- in addition to merger and common-envelope problems, studying red novae sheds light on complex process related to
  - binary interaction via outflows (e.g. V838 Mon & CK Vul)
  - molecule and dust formation
  - shock chemistry
  - elemental and isotopic anomalies in the context of Galactic evolution
  - formation of bipolar nebulae

Problems

- How to find/identify more of old merger remnants (e.g. among PPNe or CNe, Rotten Egg, Boomerang, HD101184, water fountains, Phoenix Giants of C. Melis)
- How to calculate masses? (dust to gas mass ratios, CO to H2 conversion)
- Are the stellar remnants rapid rotators? V838 Mon gives hope
  - the angular momentum budget (star + CSE)
- How to measure magnetic fields?
- What is the role of nuclear reactions in highly disturbed (most violent) mergers. Head-on collisions possible in dense clusters?