Mass-loss from massive evolved stars: the puzzling outflows of the red supergiant NML Cyg

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Overview

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- ★ Stars/Stellar Evolution
- ★ Studying the winds and outflows of massive stars
- ★ NML Cyg
  - ★ Continuum Emission - revealing the dust properties
  - ★ Molecular emission - extended emission and episodic mass loss
  - ★ Comparison to large-scale emission

Why Stars?

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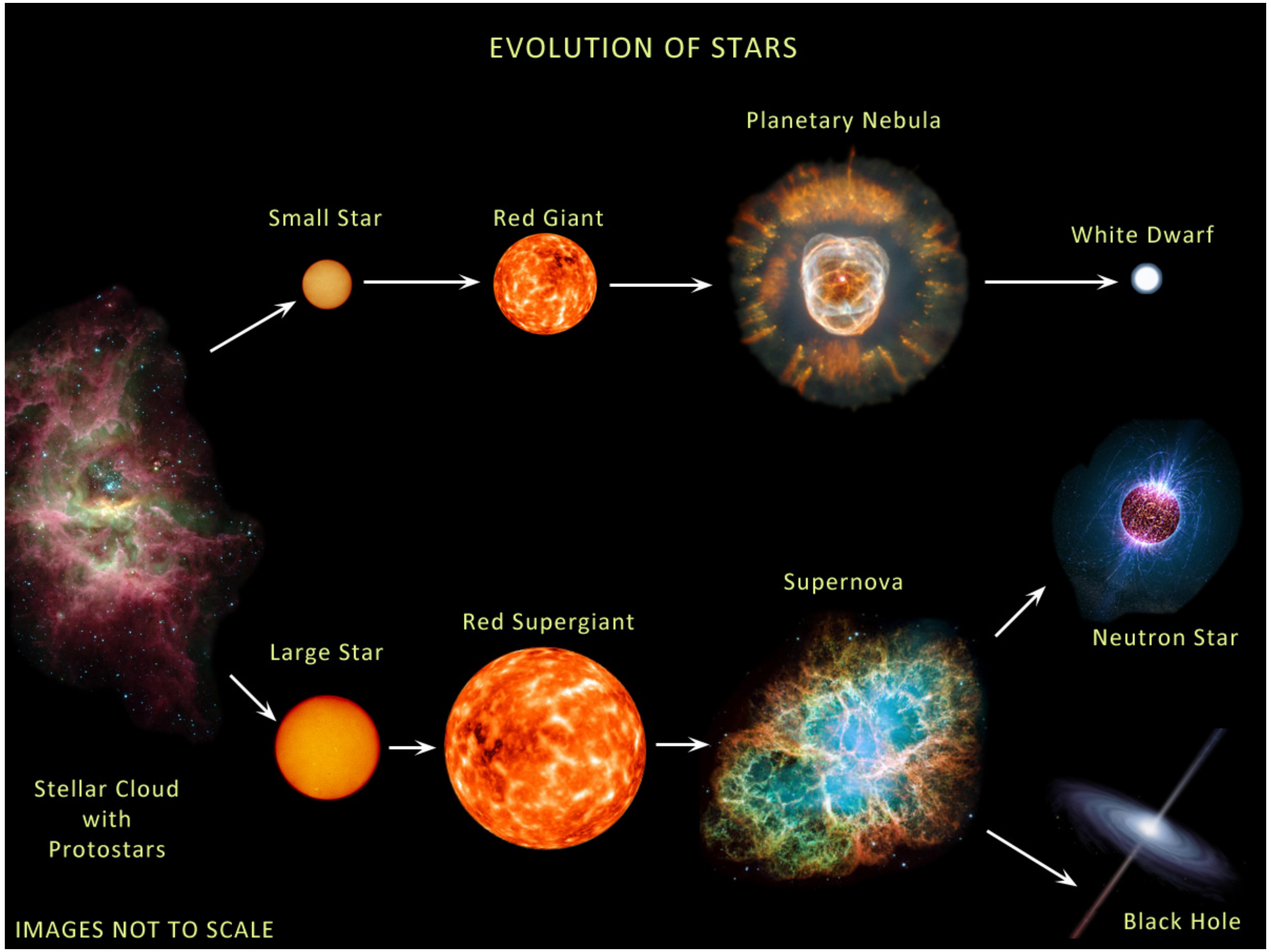
- Stars - responsible for the *radiative and chemical enrichment* of the universe: all elements heavier than lithium come from stars!
  - either through *outflows* of mixed material formed through nuclear fusions
  - or through their supernovae (which then run into the *outflows*)
- Have to understand the evolution of the stars…
  - to understand the evolution of entire galaxies (including the Milky Way)
  - to understand the origin of life

Stellar Evolution: An Overview

- Bifurcation of stellar evolution:
  - Low-mass stars ($< 8M_\odot$)
  - **High-mass stars ($> 8M_\odot$)**
- Mass of a star influences:
  - Stellar luminosity
  - Total stellar lifetime
  - Characteristics of different stellar phases



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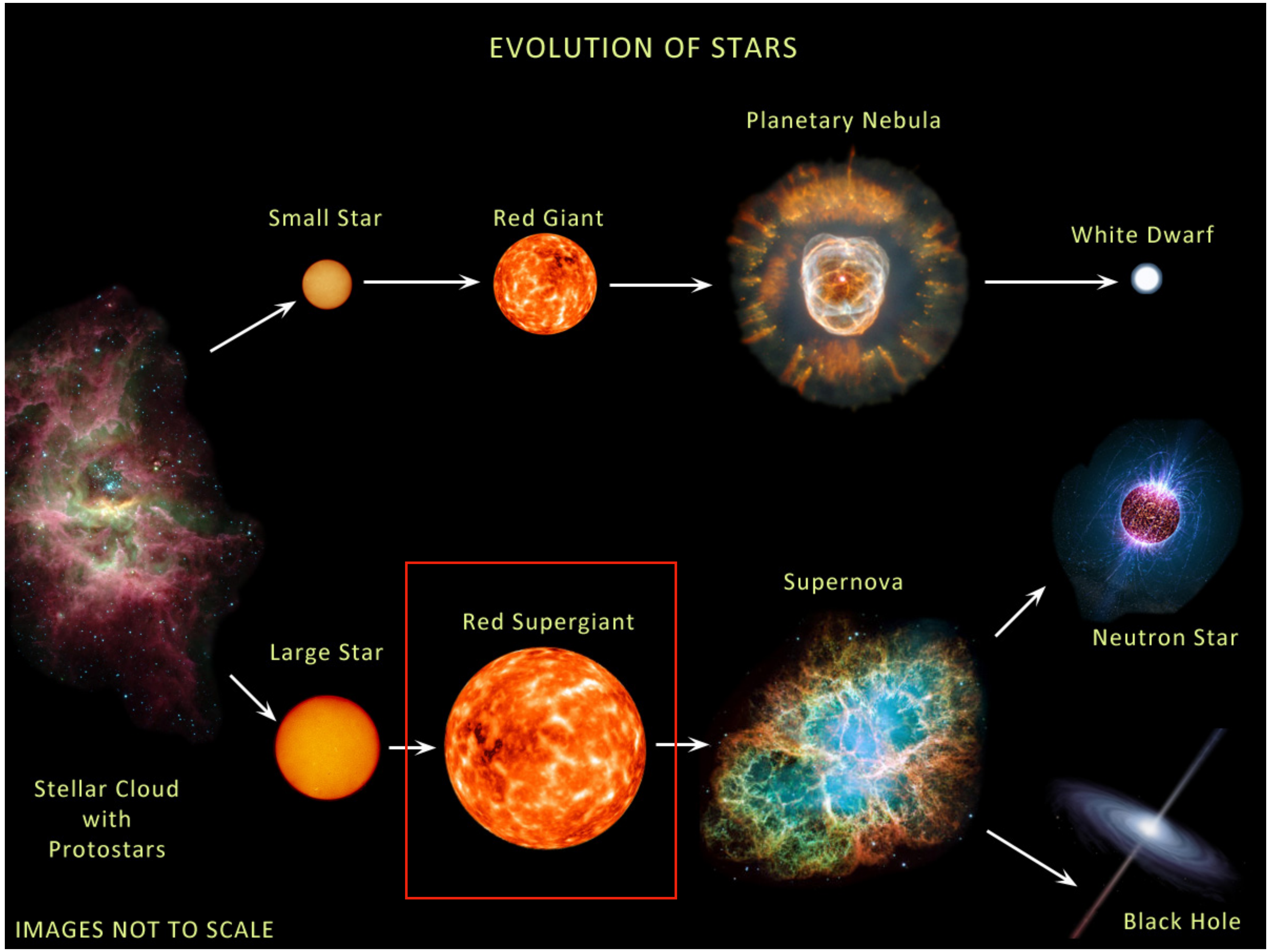
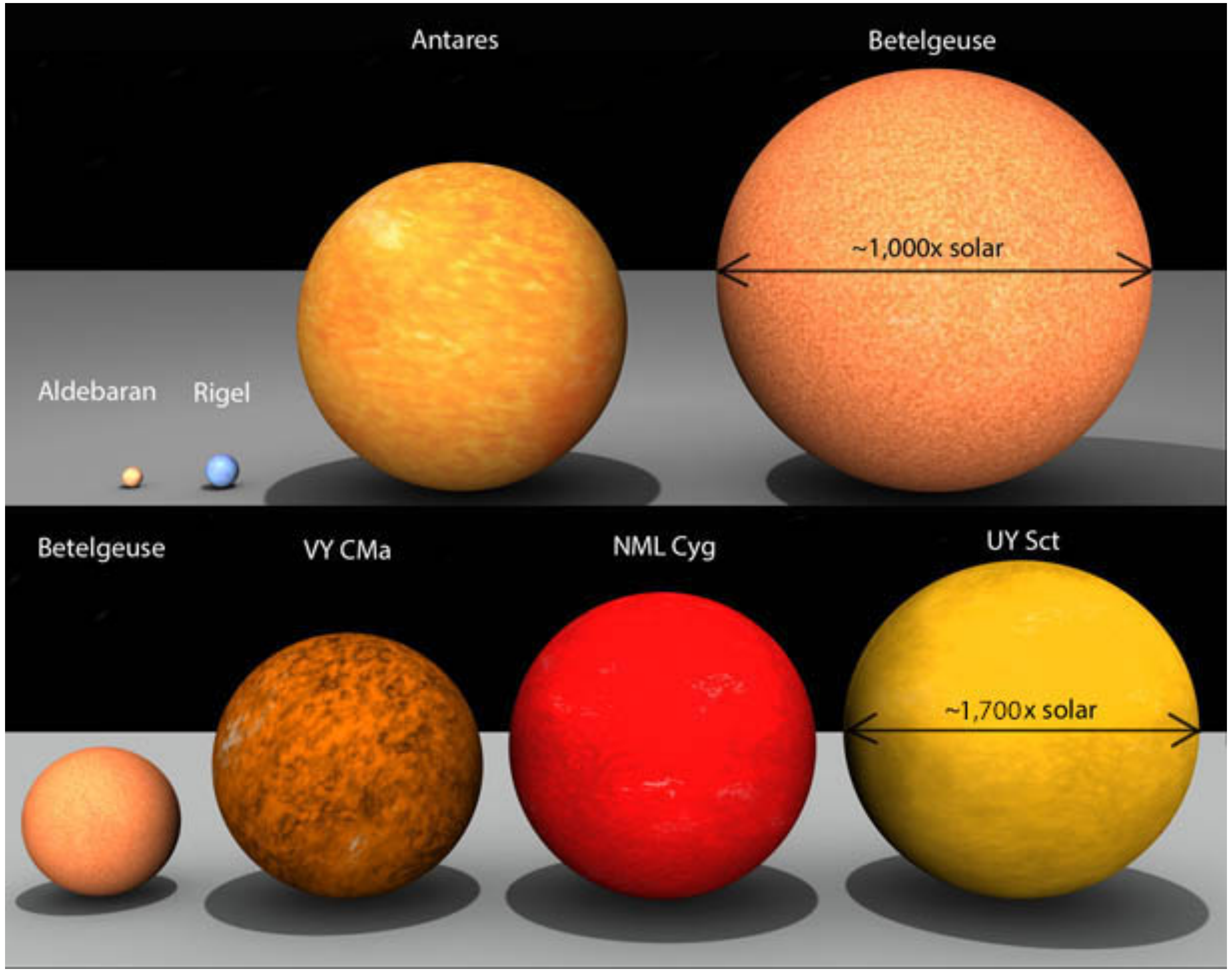


Evolved Stars - Supergiants/Hypergiants

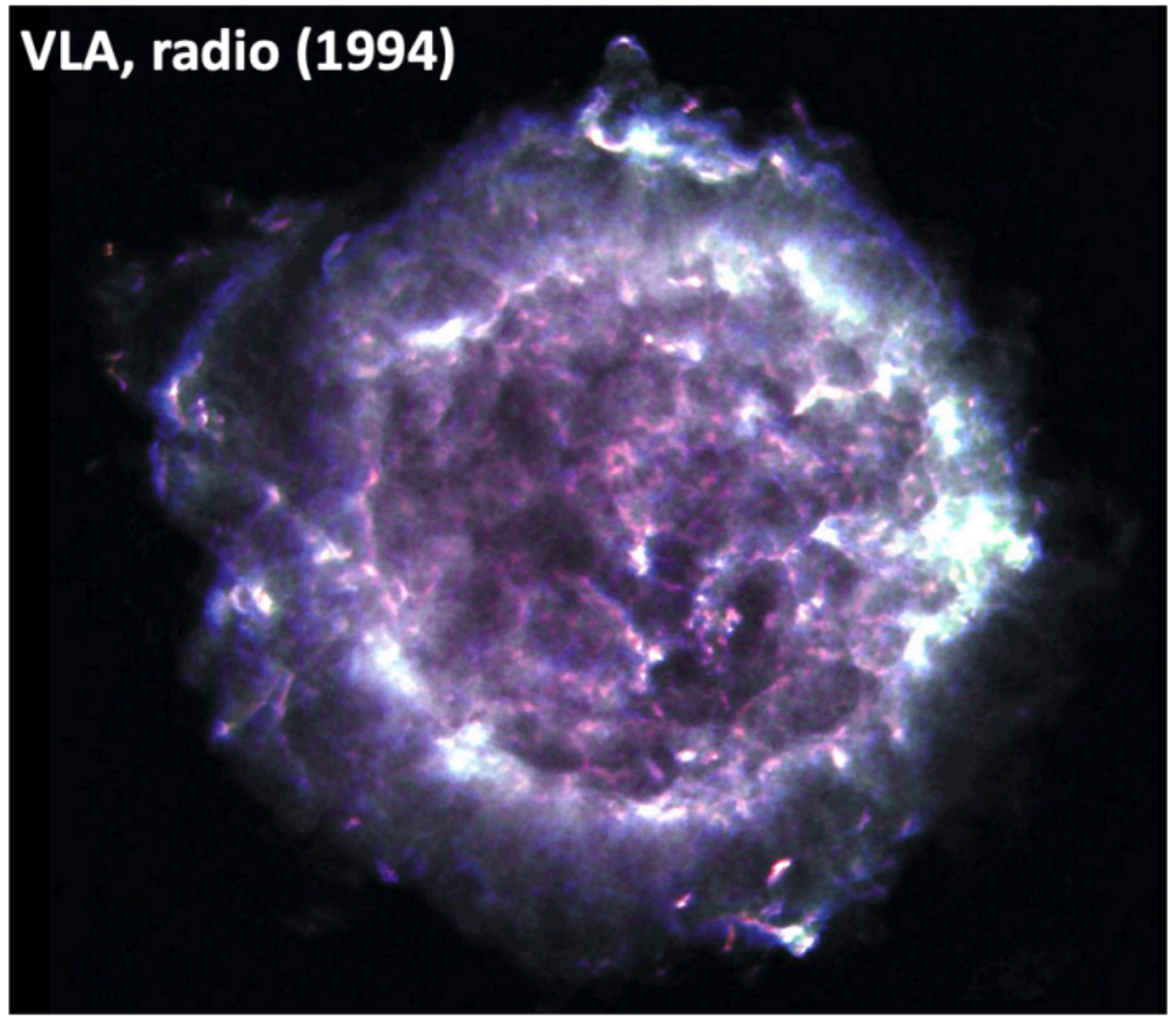
- Characterised by cold temperatures, but high luminosities and large envelopes
- All hydrogen in the core has fused to helium:
    - core contracts
    - envelope expands
- Dense environment - heavier elements form through fusion: C, N, O…
- Short timescales of 10,000 years

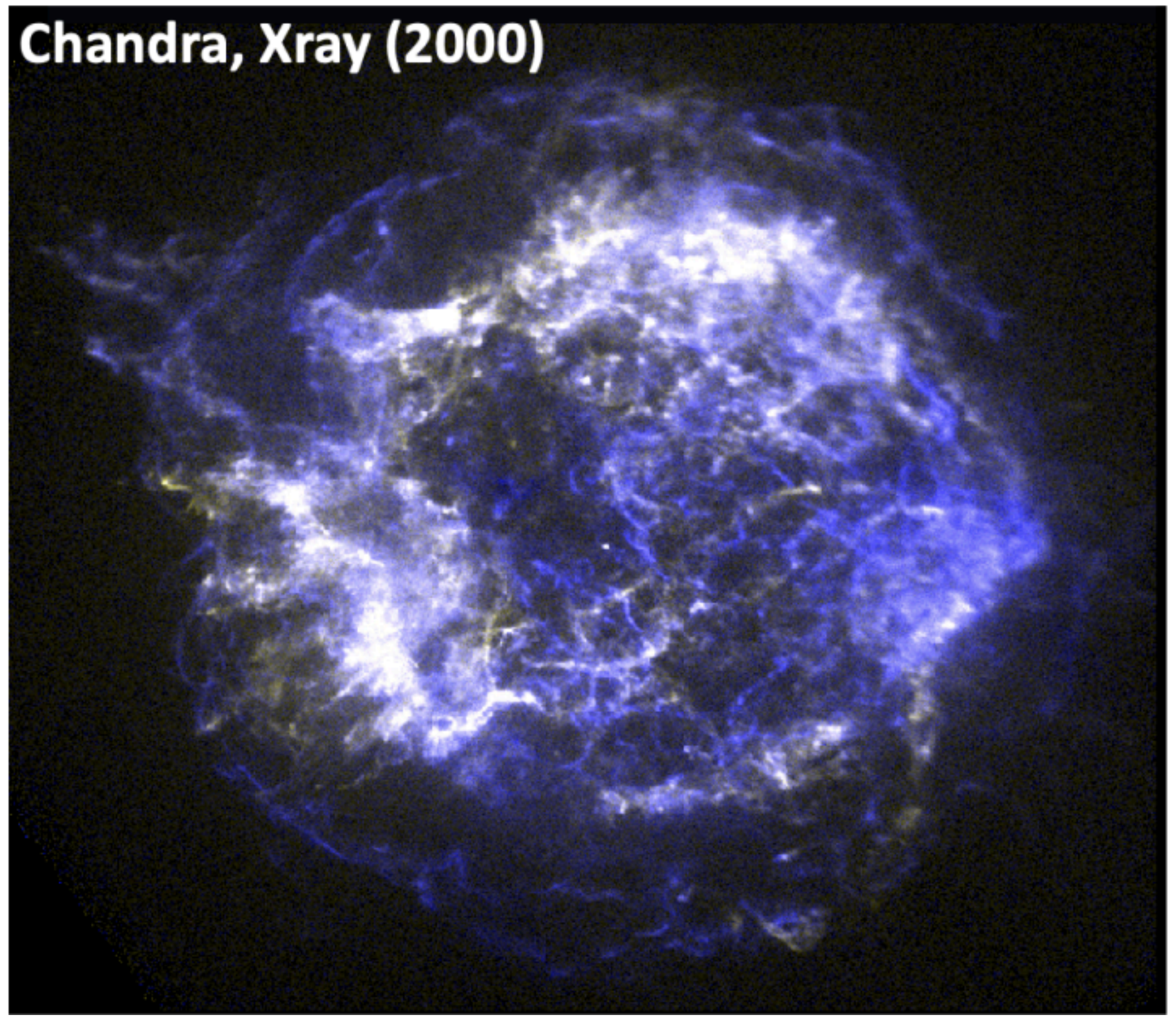


Studying the winds and outflows of massive evolved stars

Why study the winds/outflows?

- Mass is an important parameter to help understand stars and their stellar evolution:
- Impact on other astrophysical phenomena:
  - Supernovae
  - Galactic environment
- Mass-loss is a complex phenomena:
  - Impacted by: rotation, magnetic fields, binarity





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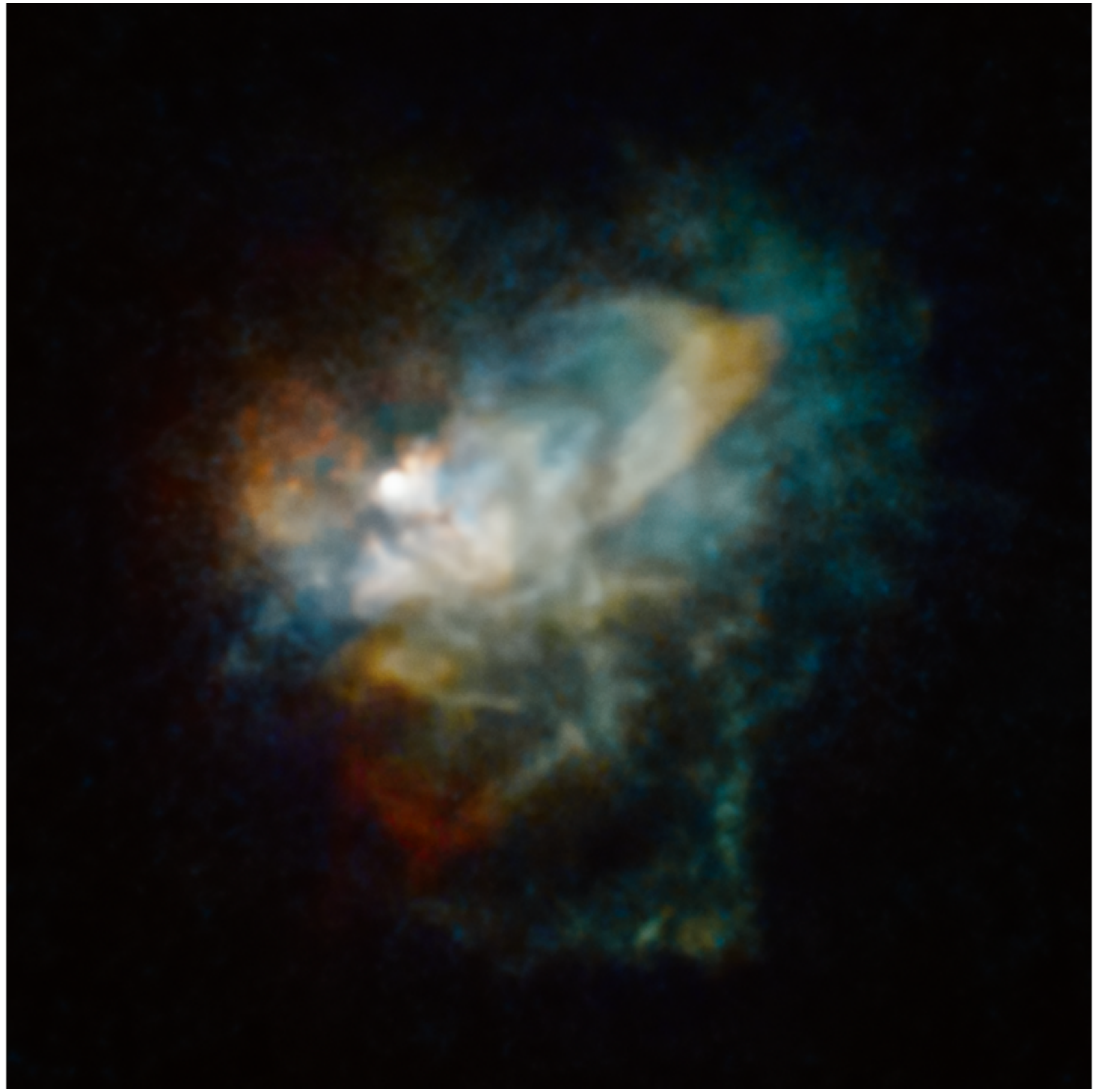
Why study RSG/YHGs?

- Responsible for significant levels of mechanical and chemical enrichment
- Able to probe the chemistry due to the combination of being *bright but cool*
  - It reaches the ISM through their feedback processes of stellar winds
- Stellar winds responsible for high levels of mass-loss (10^{-6} - 10^{-3} $M_{\odot}$ yr^{-1})
  - …and not fully understood!



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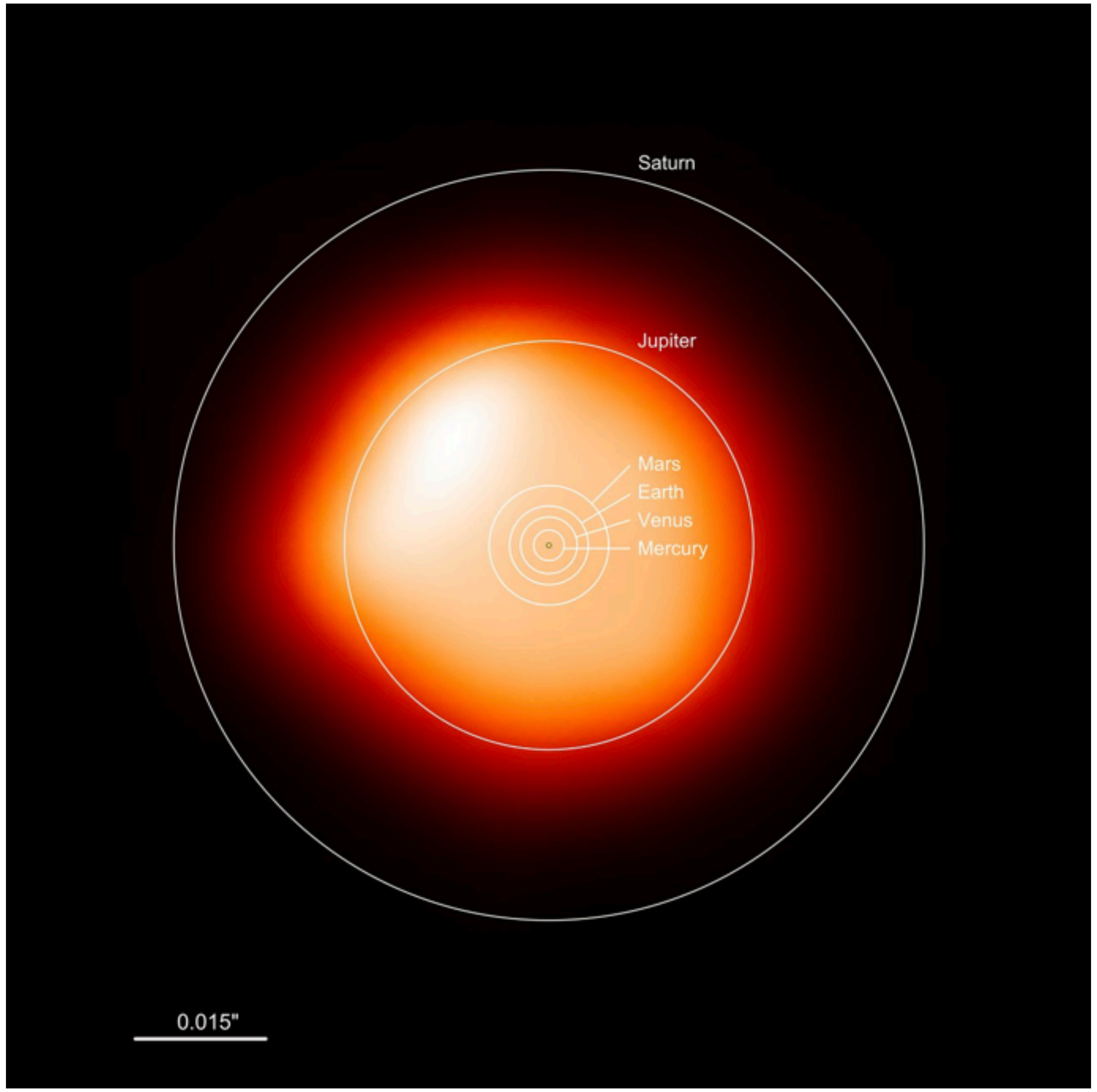
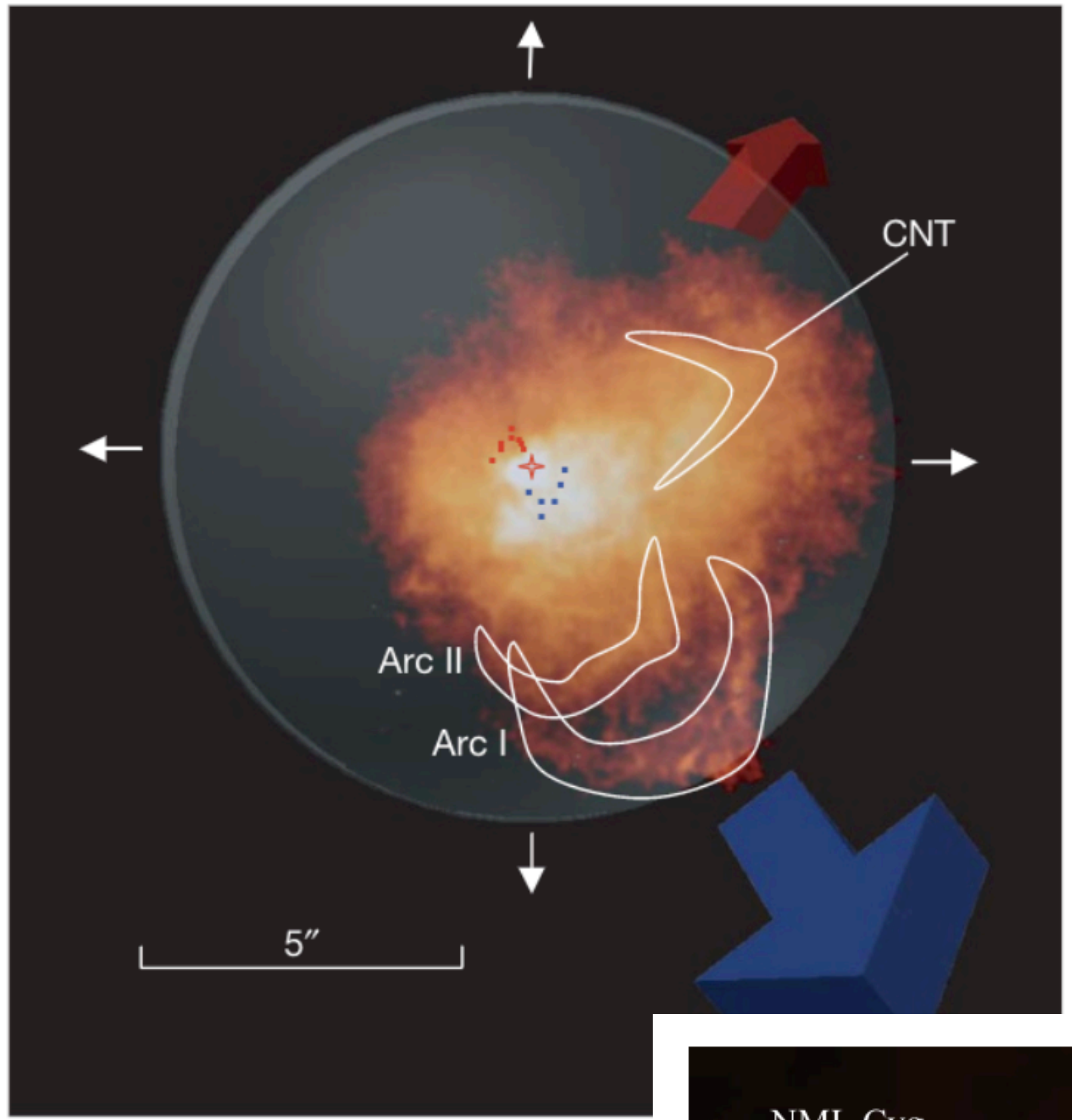
Why study RSG/YHGs?

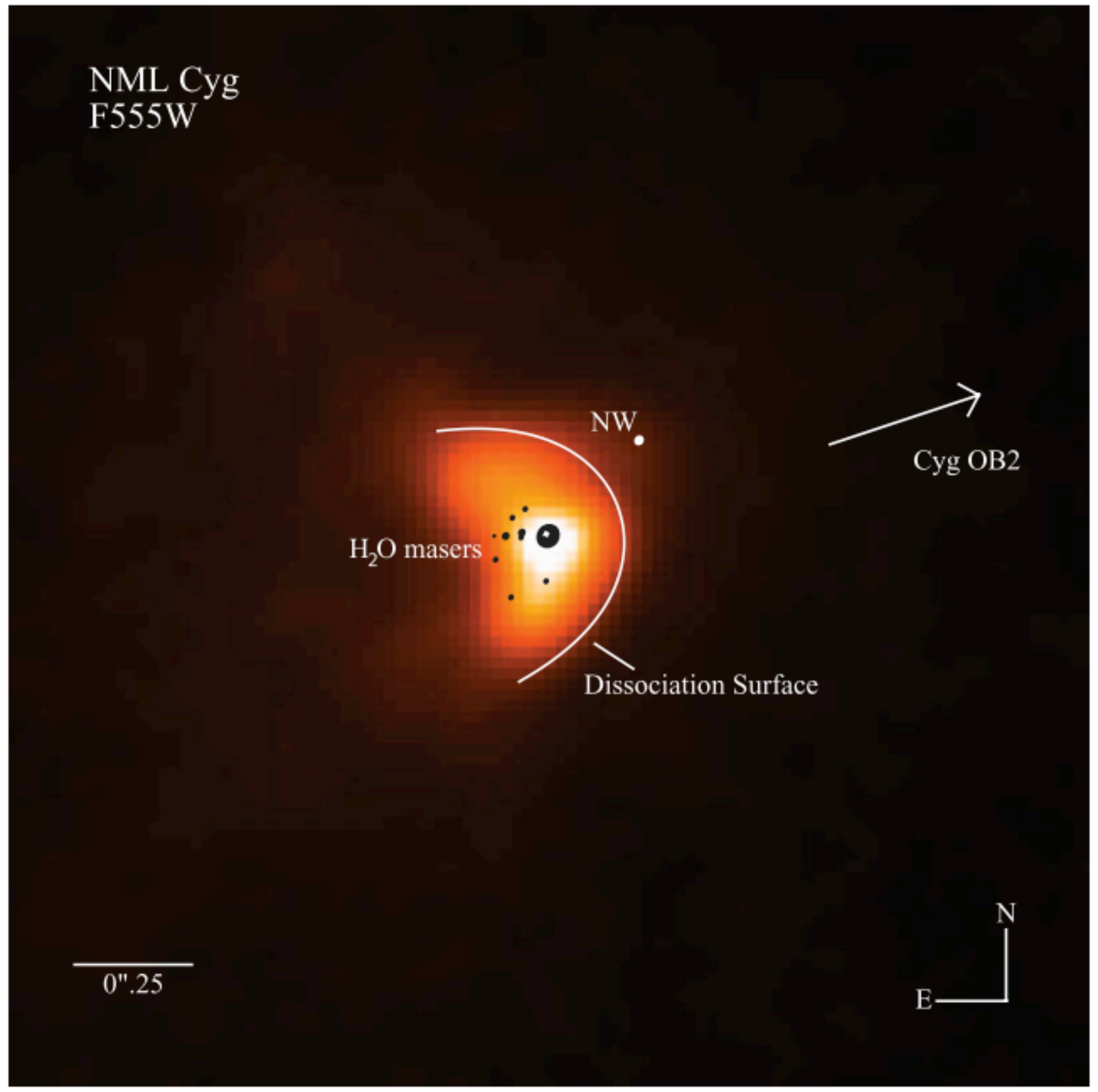
- Current assumptions on mass-loss in stellar models:
  - spherical winds; typically uses an average mass-loss rate ~ $10^{-6}\ M_\odot\ yr^{-1}$
  - dust-driven winds
- Connection between different post-MS evolution stages not fully understood
  - Link between RSGs and YHGs
  - *Missing RSG problem*
- A rare class of star but high levels of mass loss - very small number of well studied objects



Stellar Winds of Massive Stars

- Asymmetry seen in dust observations around RSGs:
    - e.g VX Sgr, VY CMa, NML Cyg and others…
- We can use spectroscopic observations at all wavelengths inc. radio to probe the chemistry of the circumstellar environments.
    - Which species are present?
    - Which regions are traced?
    - How abundant?





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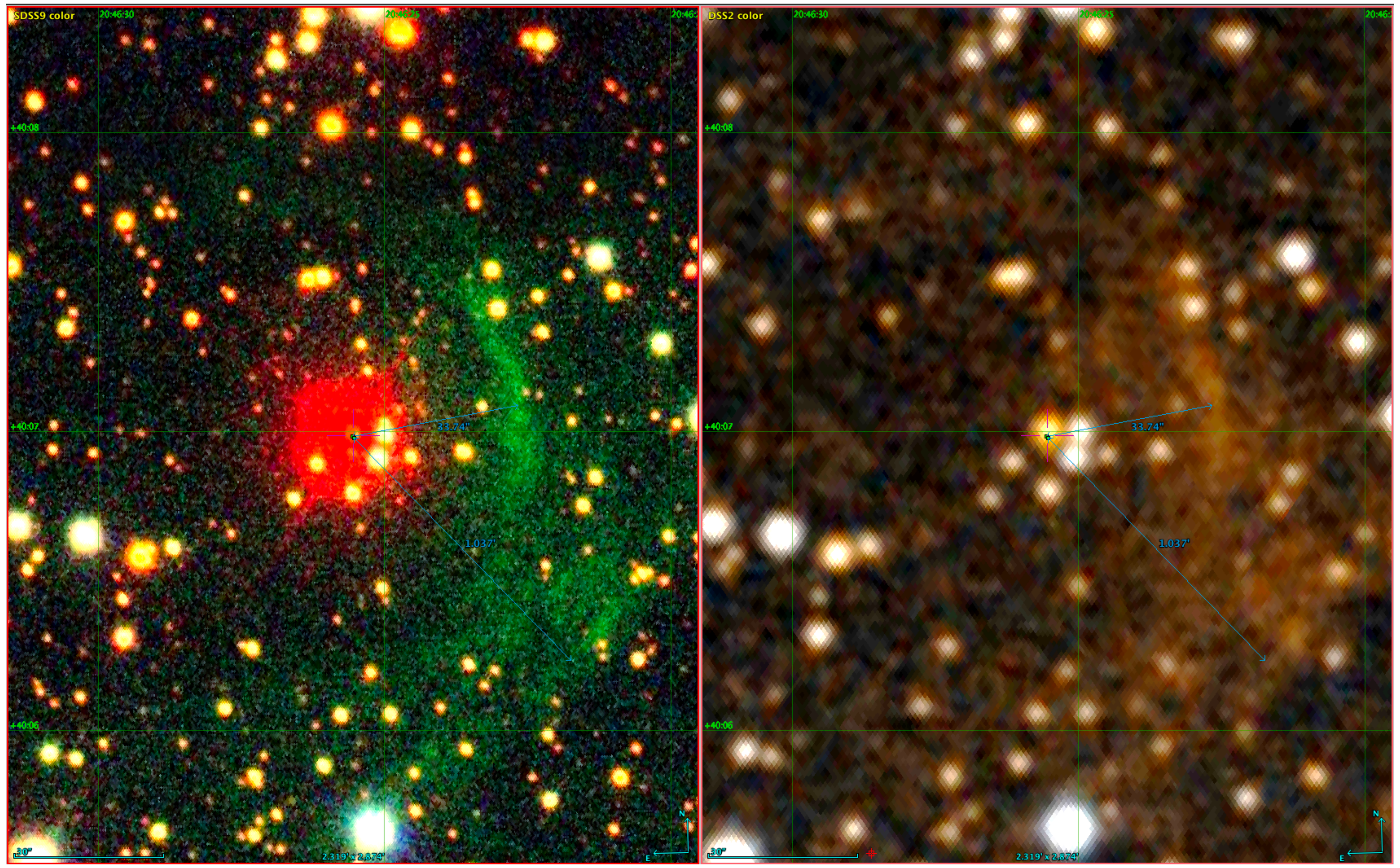
NML Cyg

Properties:

- Distance: 1.6 kpc away (within the Cygnus X region)
- Spectral type: M6 RSG
- Mass: $M_{init} \sim 40\ M_\odot$
- Temperature: 3250 K
- Luminosity: $6 \times 10^5\ L_\odot$
- Mass loss rate: $\dot{M} \sim 10^{-4}\ M_\odot\ yr^{-1}$

Asymmetry possibly connected to nearby massive stellar association, Cyg OB2.



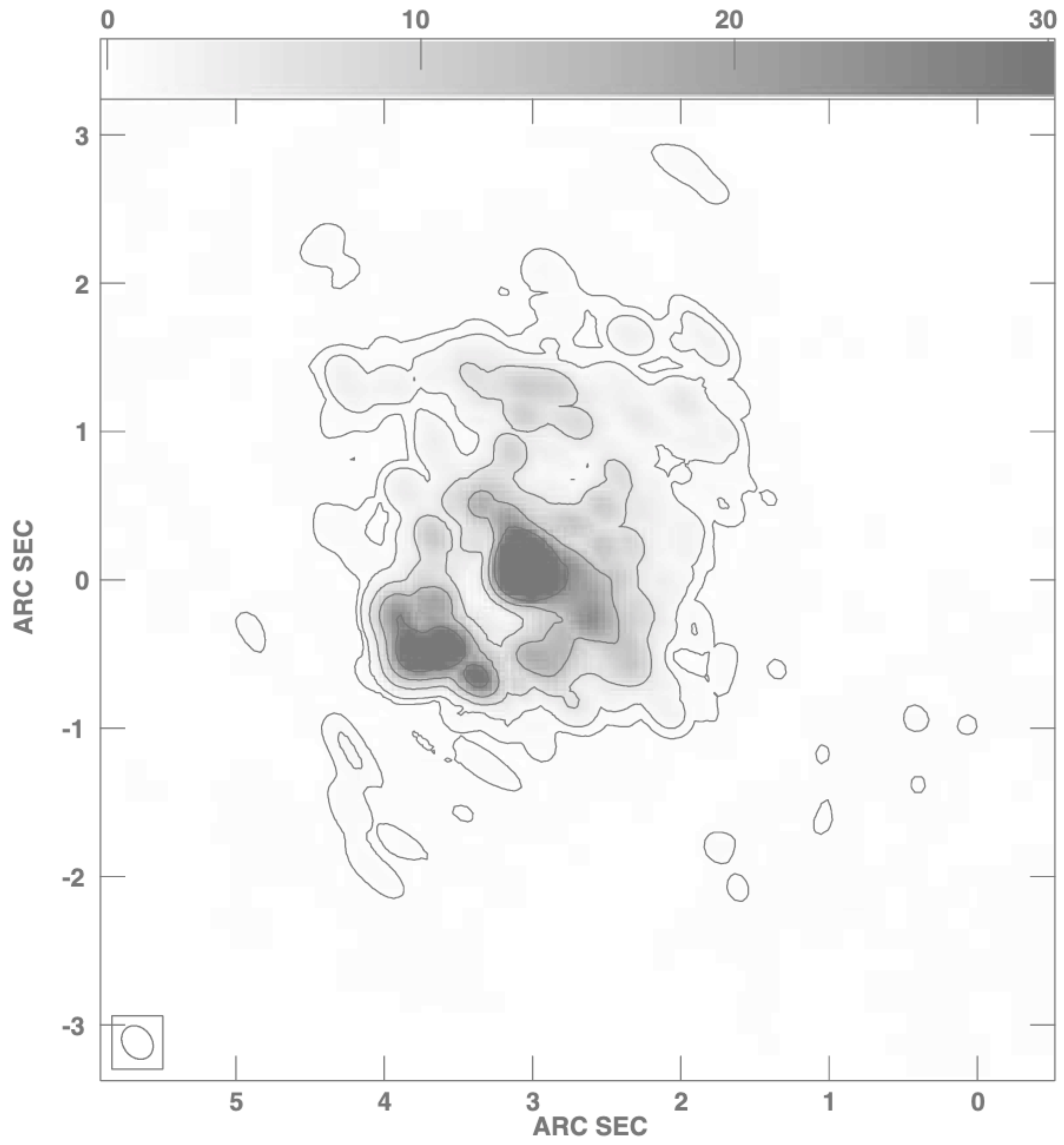
Credit: SDSS

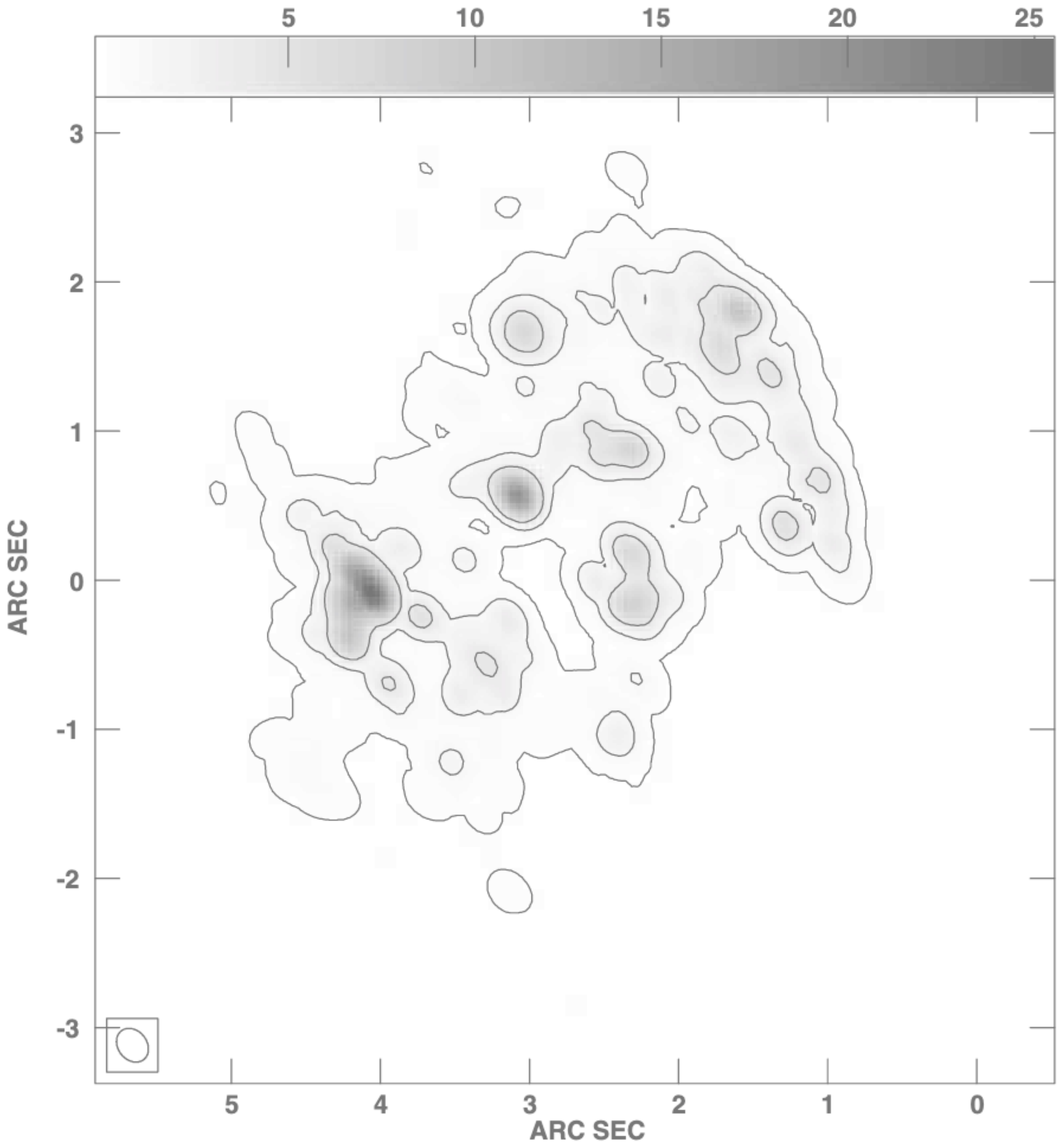
NML Cyg

Previous indications of multiple components present in outflow:

Maser emission (OH)

Complex line spectra





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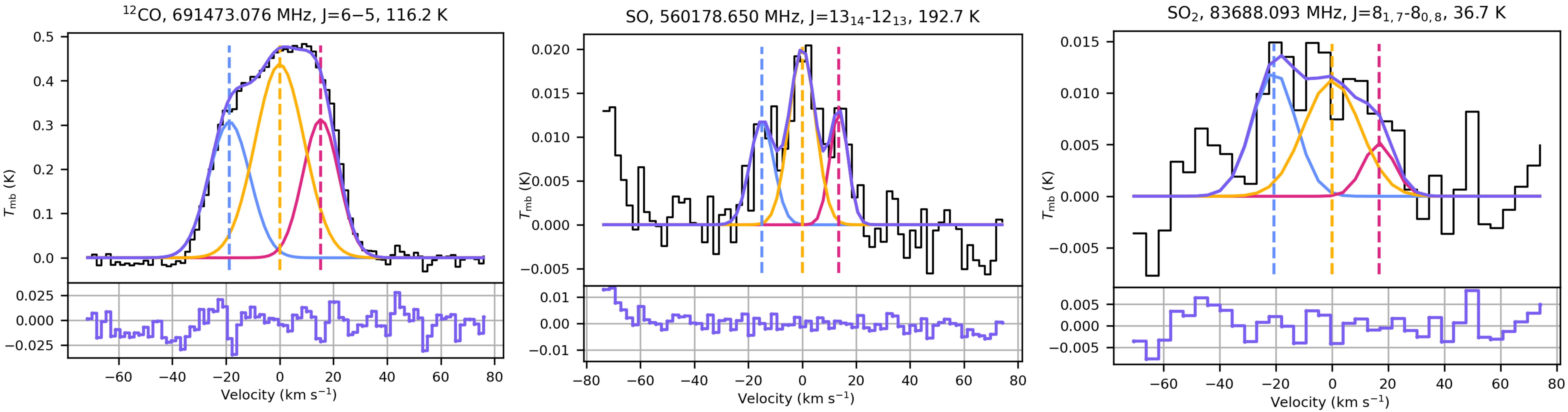

Observations

Observations taken in 2021 with NOEMA interferometer.

Over 8 GHz bandwidth each sideband:

- Led to 60 line detections from 27 molecular species and isotopologues.
- Detections include: $^{(34)}SO$, $^{(33,\,34)}SO_2$, $^{(13)}CO$, $H_2{}^{(33)}S$
  - First detections of KCl, AlOH, OCS for RSGs

Spectral Overview

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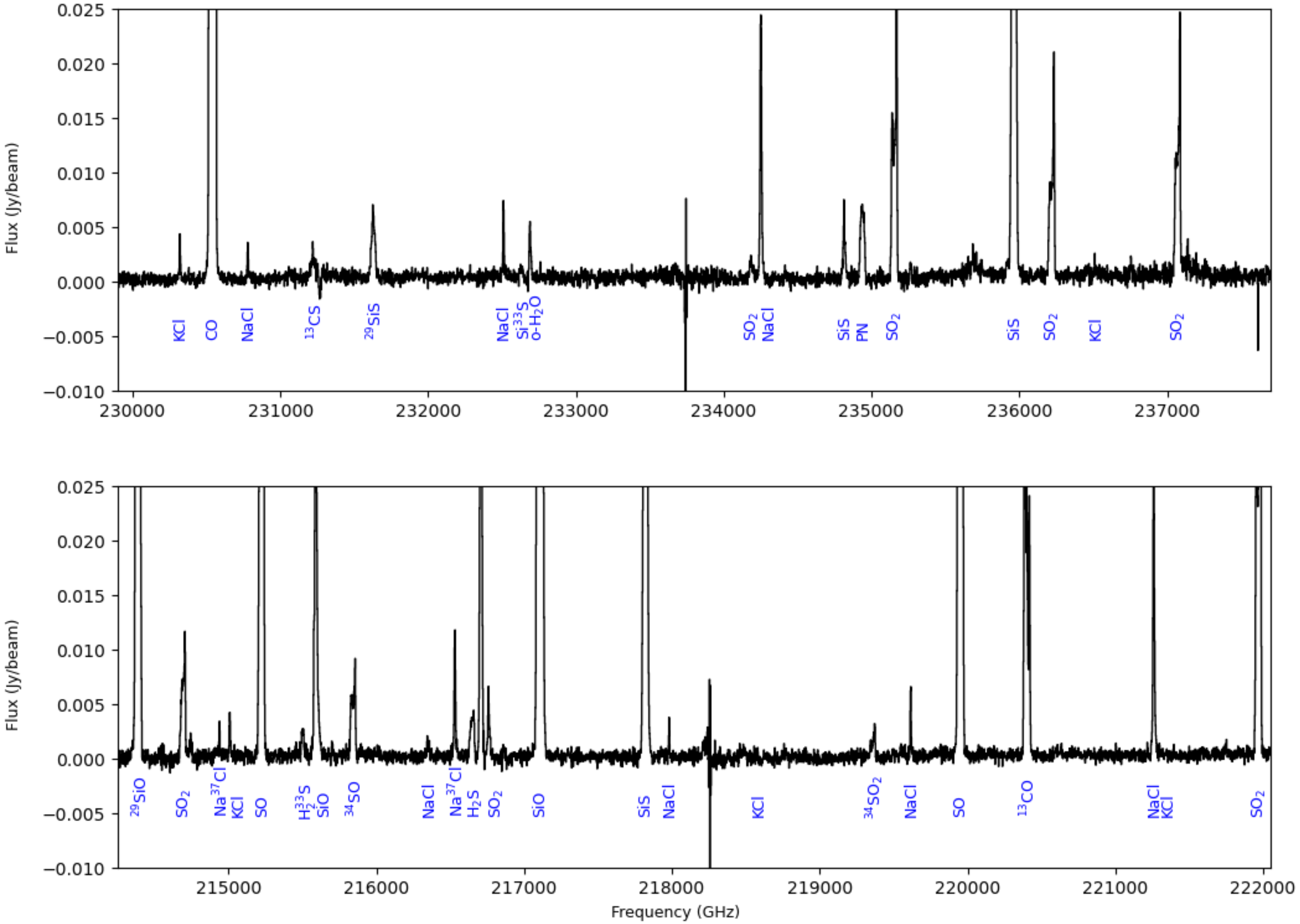
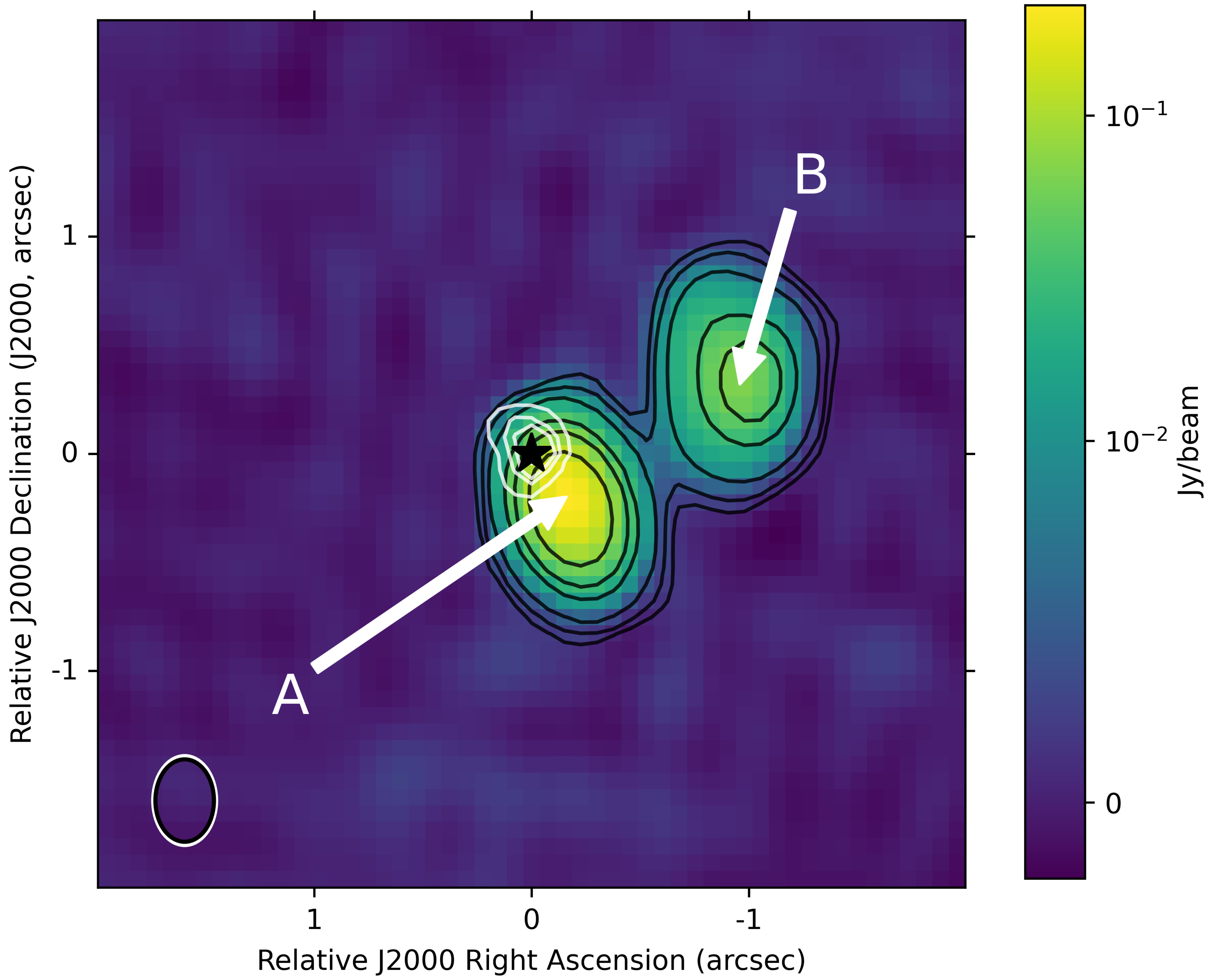


Research Projects: NML Cyg



Research Projects: NML Cyg

Determine the expected masses of each continuum component

Continuum Component	LSB Δ (mas)	LSB θ_{maj} (mas)	LSB θ_{min} (mas)	LSB PA	LSB $S_{218.15}$ (mJy)	LSB $S(\star)$ (mJy)	USB Δ (mas)	USB θ_{maj} (mas)	USB θ_{min} (mas)	USB PA	USB $S_{233.75}$ (mJy)	USB $S(\star)$ (mJy)	M_d ($10^{-4}\ M_{\odot}$)
A	262	281	104	35.1°	284.9	21.1	240	296	140	34.8°	322.7	24.2	> 2.9
B	987	384	279	12.2°	118.5	-	1012	372	286	7.7°	142.0	-	> 8.3

Can use observations of molecules to better determine the location of these continuum clumps (H_2S, SO, SO_2)

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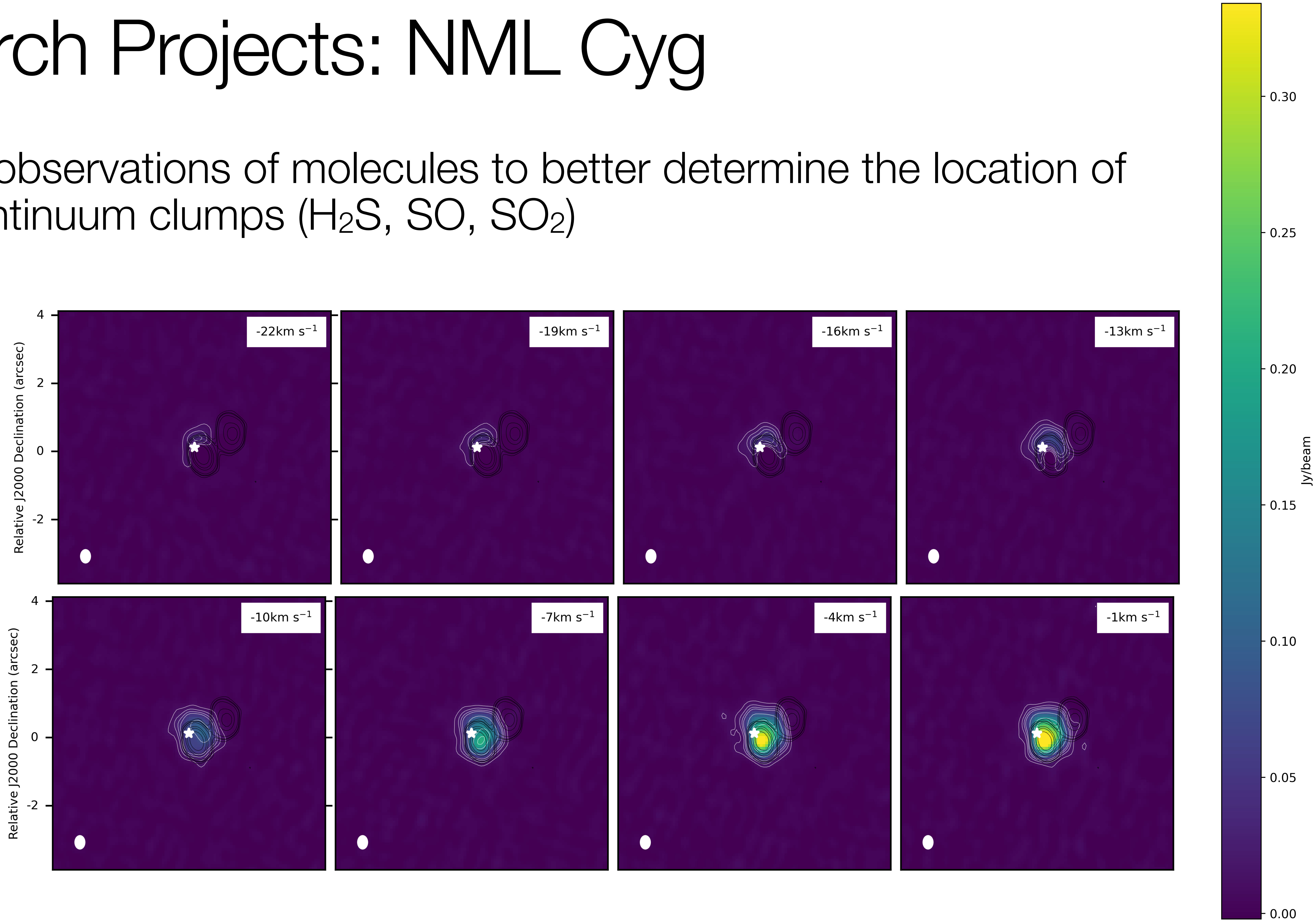

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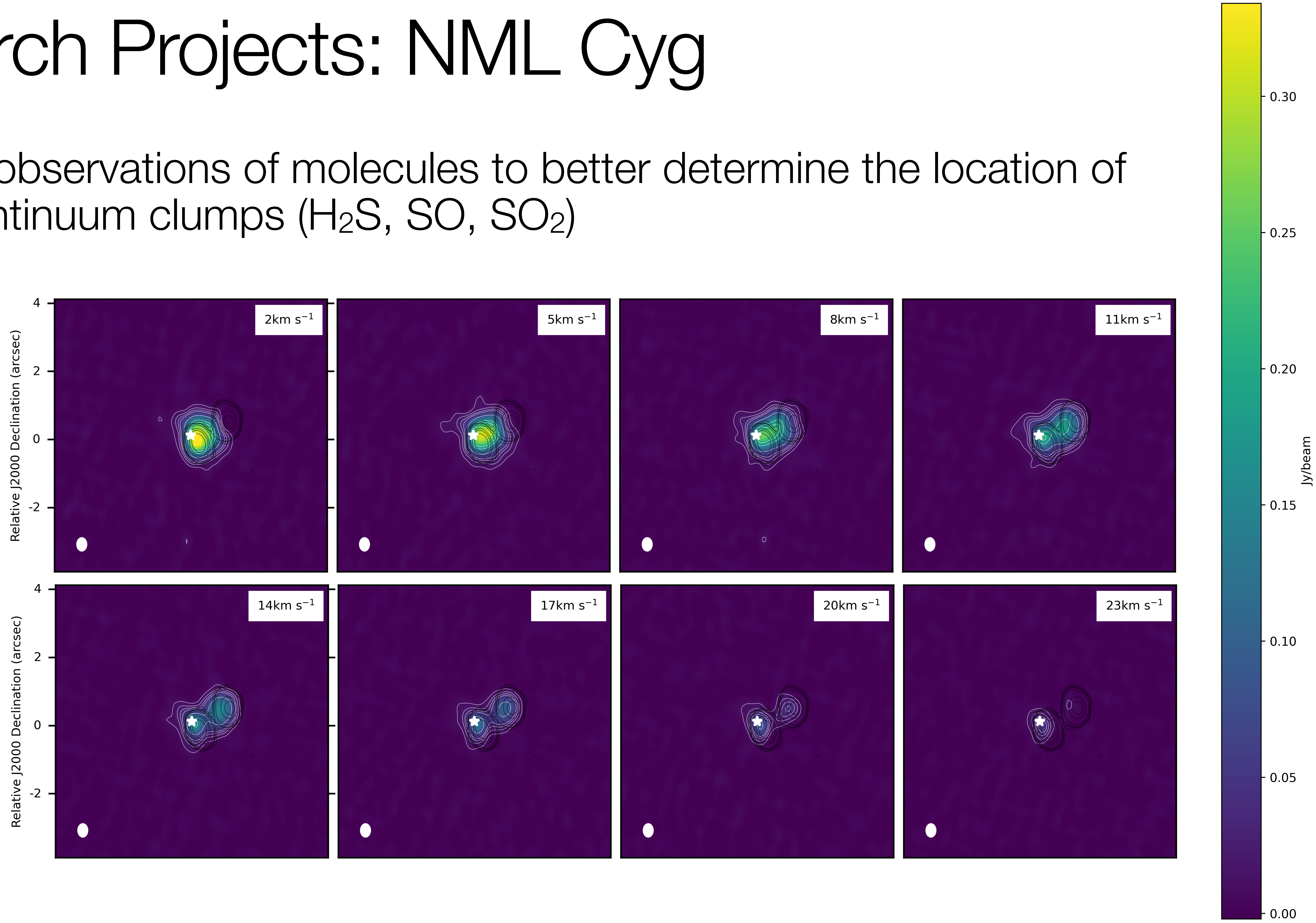

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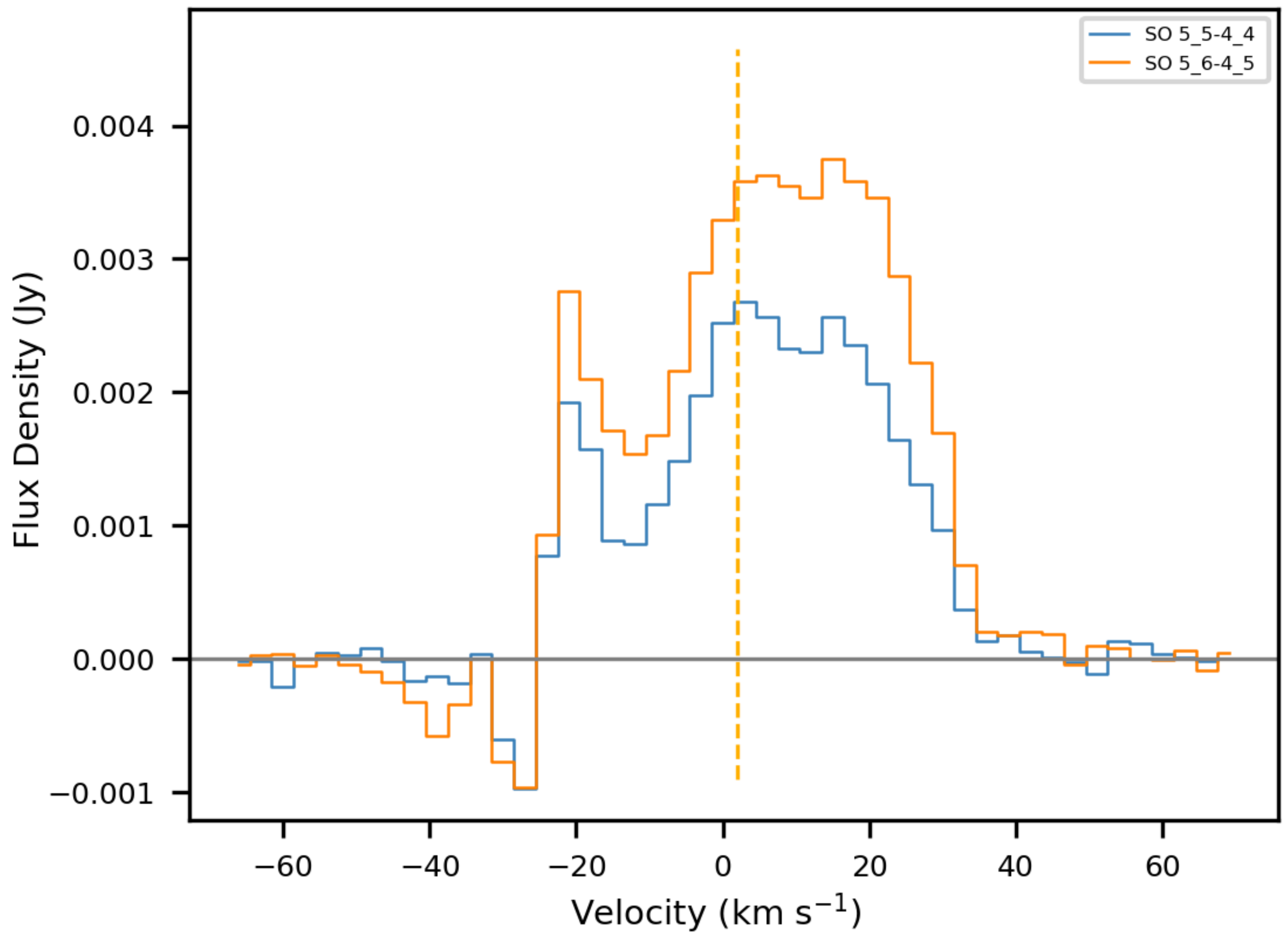

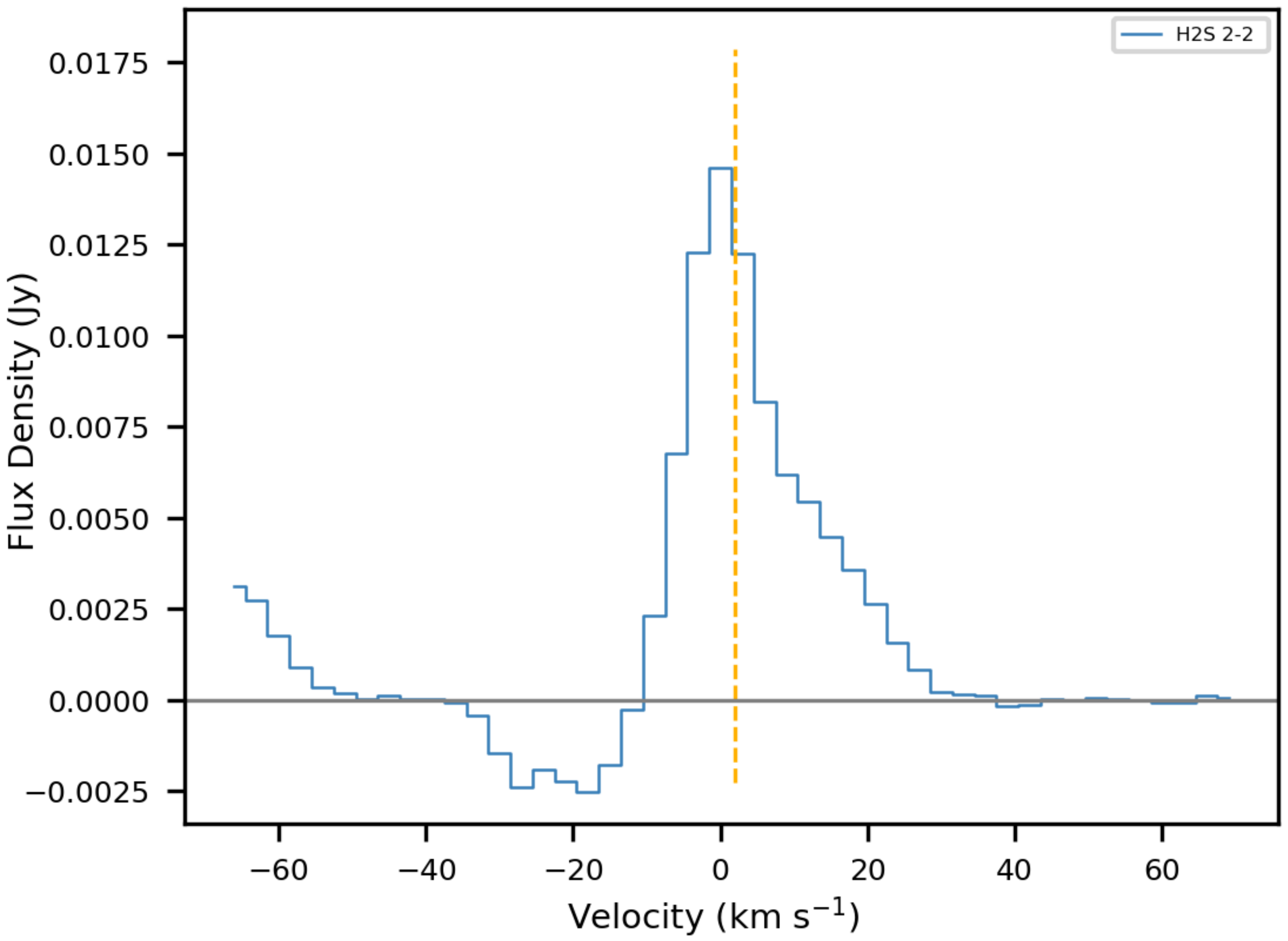

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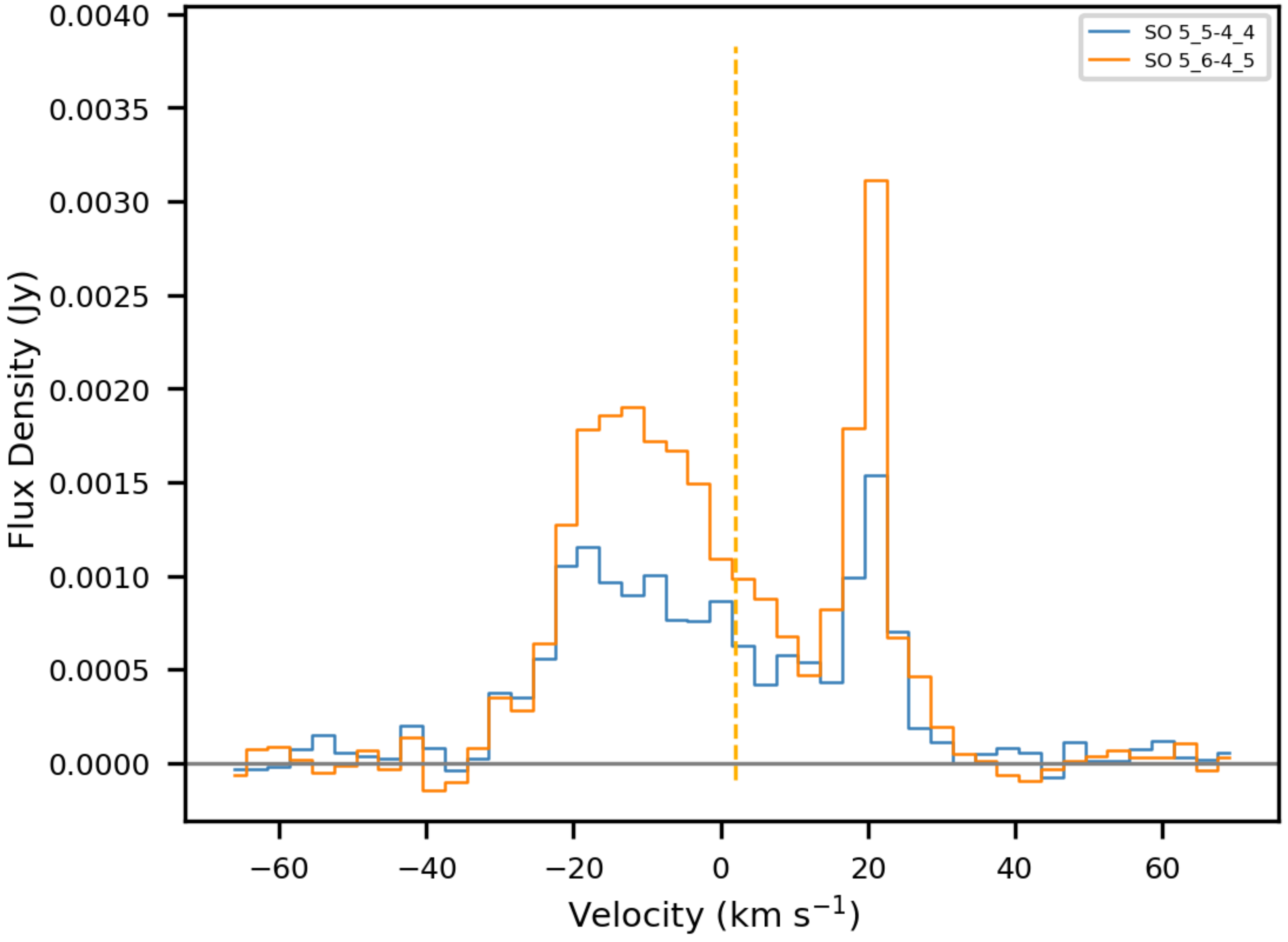
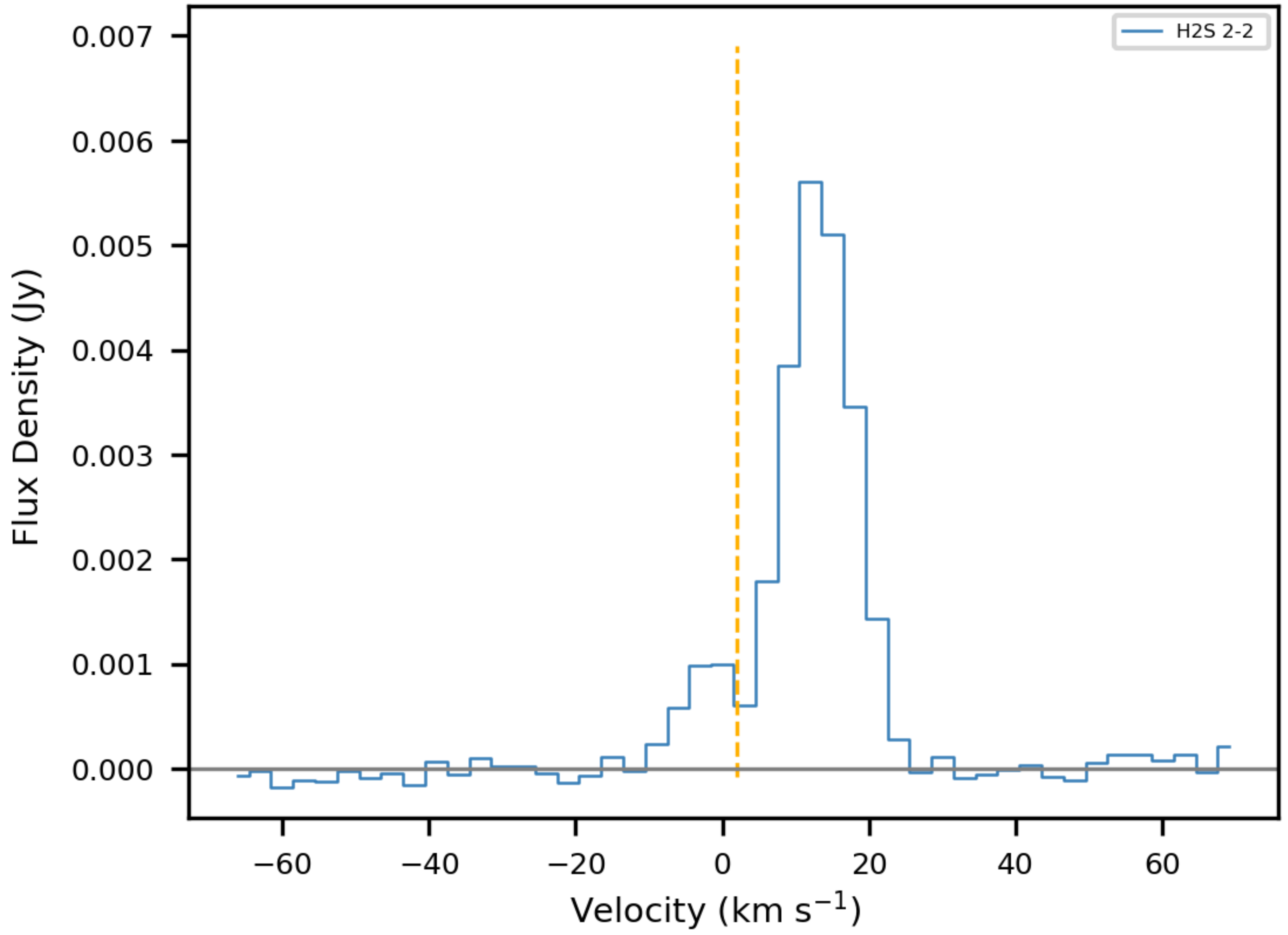
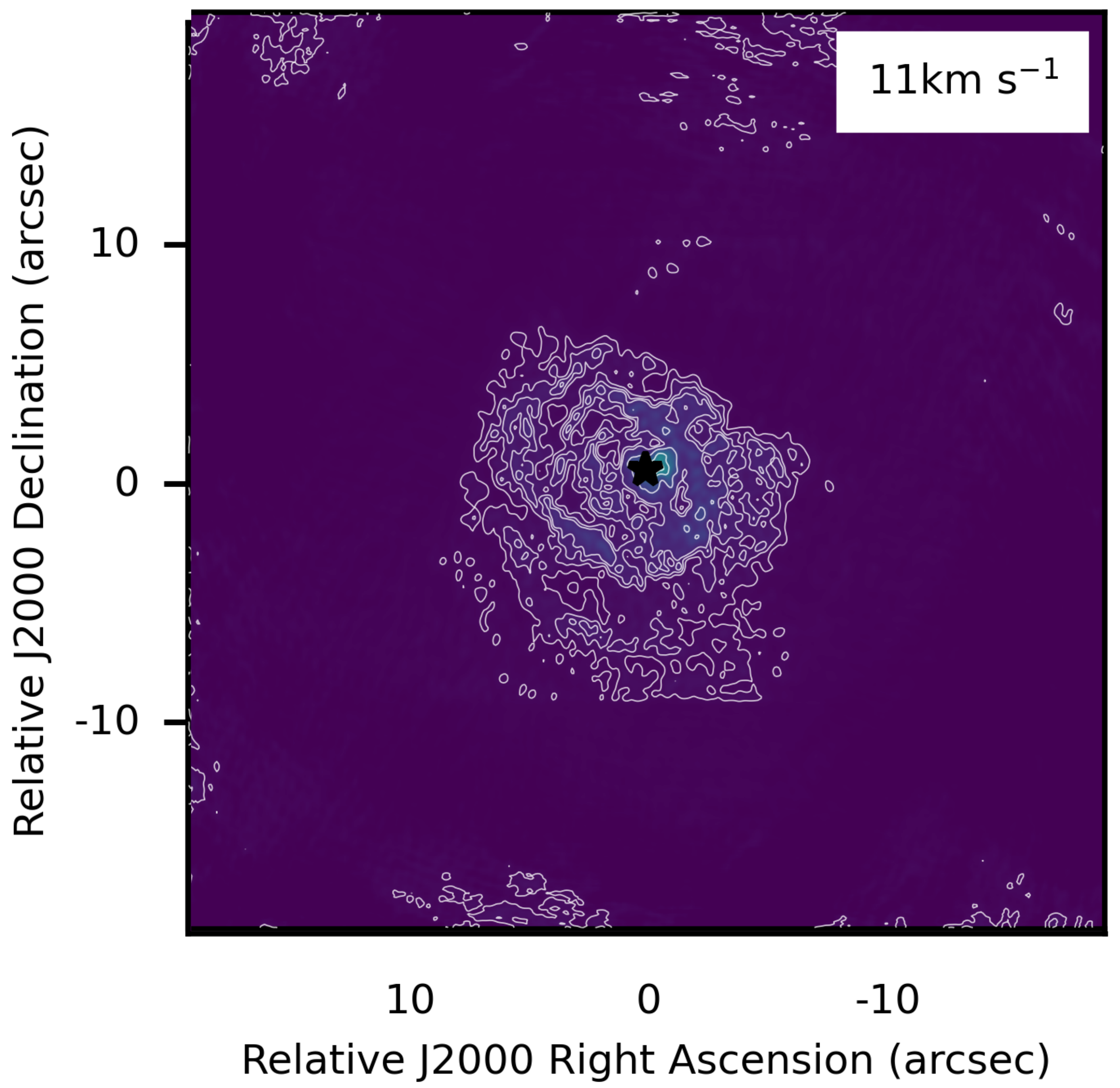
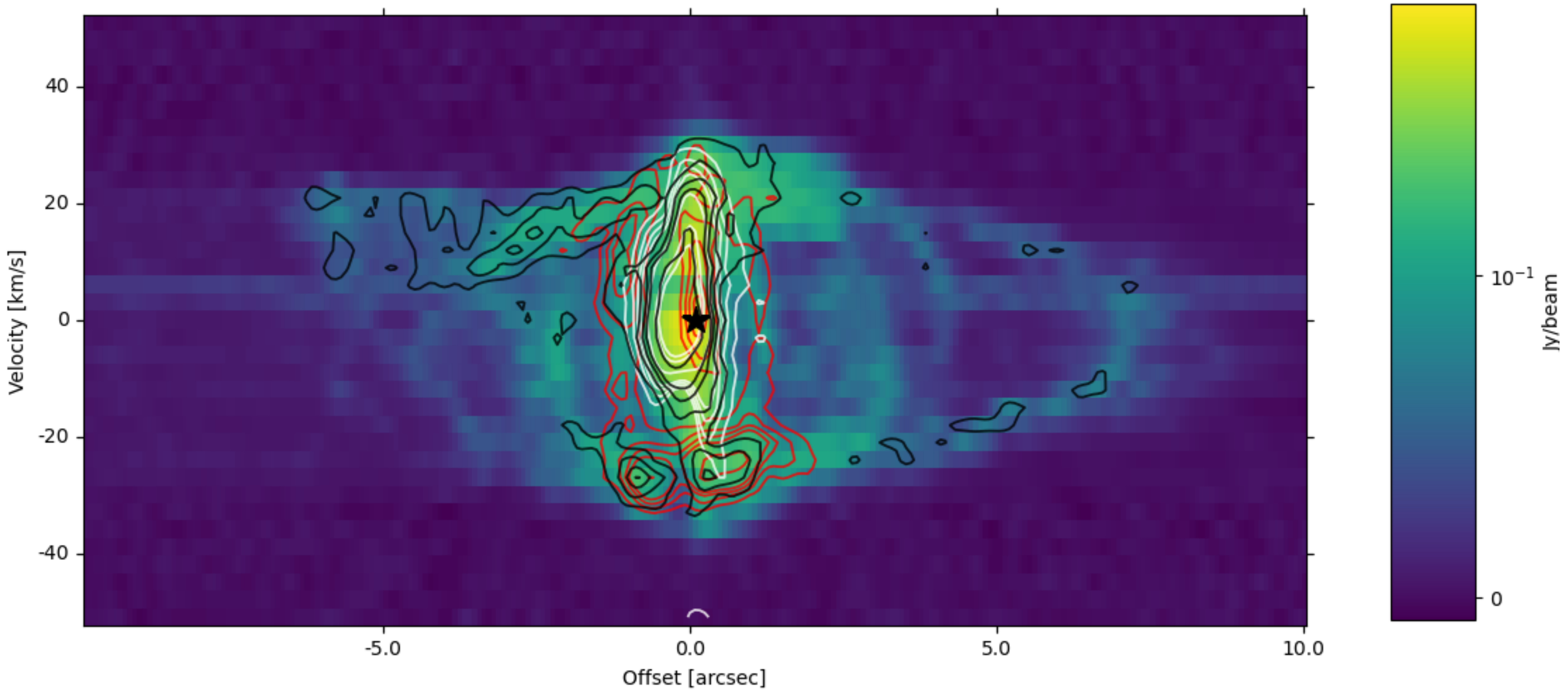




Mass-loss history of NML Cyg

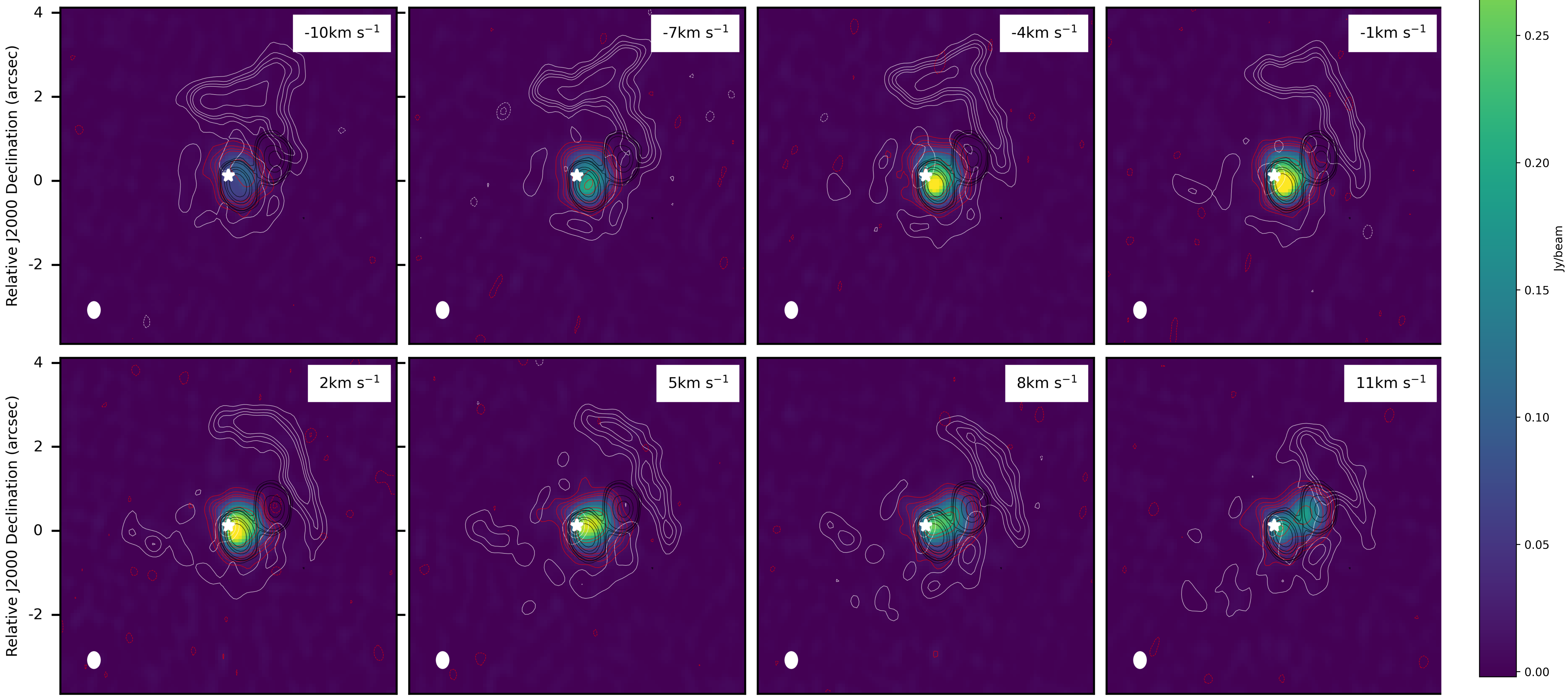
- Dust observations in continuum imply presence of outflows over last 250 years
- Prior literature suggested that molecular emission could not survive beyond spatial scales of 0.25”
- Molecular emission reveals the presence of partial shells/arc and CO clumps implying episodic outflows over larger timescales, up to 1200 years, with more steady mass-loss over timescales of 3000-4000 years



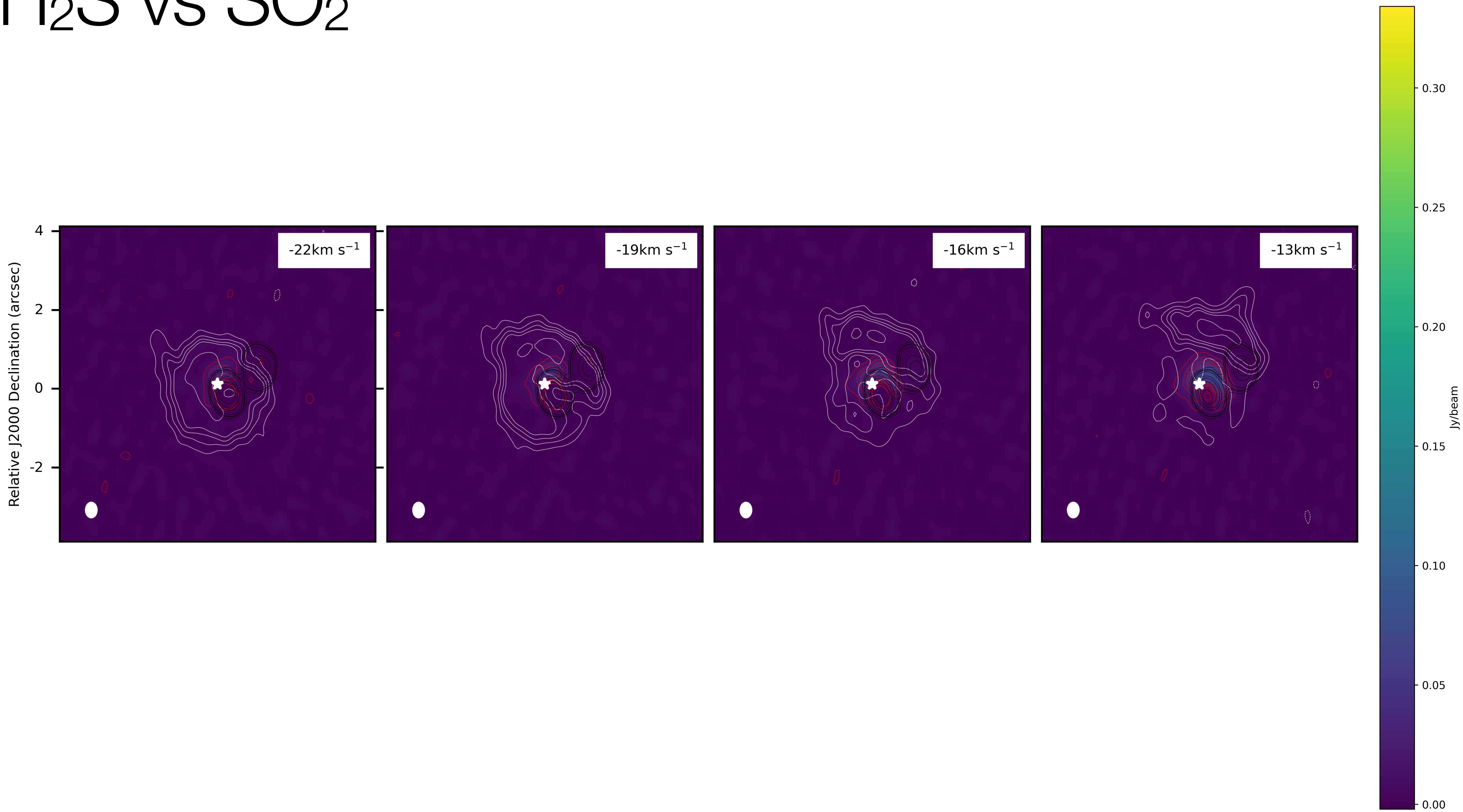


Molecular Comparison

- H_2S emission can be seen to “run-into” local peaks of SO_2 emission

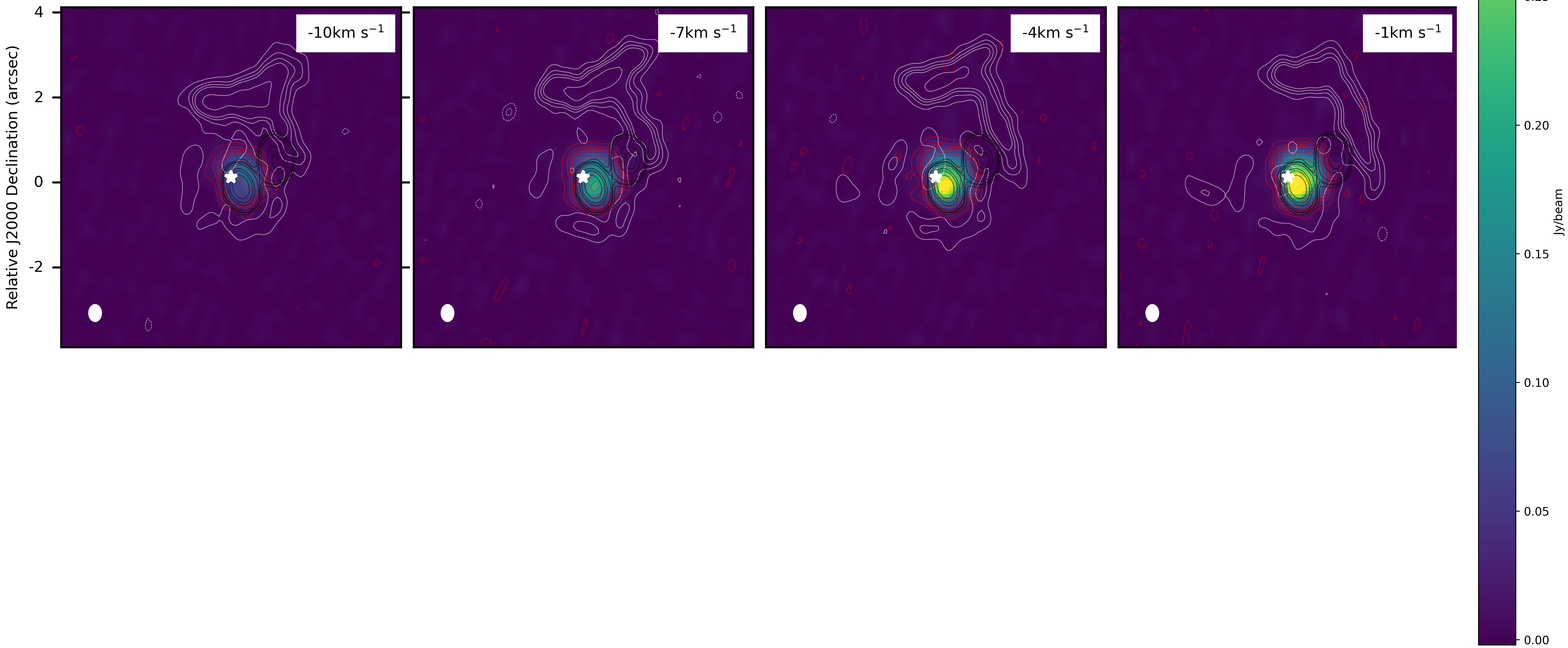


H_2S vs SO_2



-22km s^{-1}
-19km s^{-1}
-16km s^{-1}
-13km s^{-1}
Relative J2000 Declination (arcsec)
4
2
0
-2
Jy/beam
0.30
0.25
0.20
0.15
0.10
0.05
0.00

H_2S



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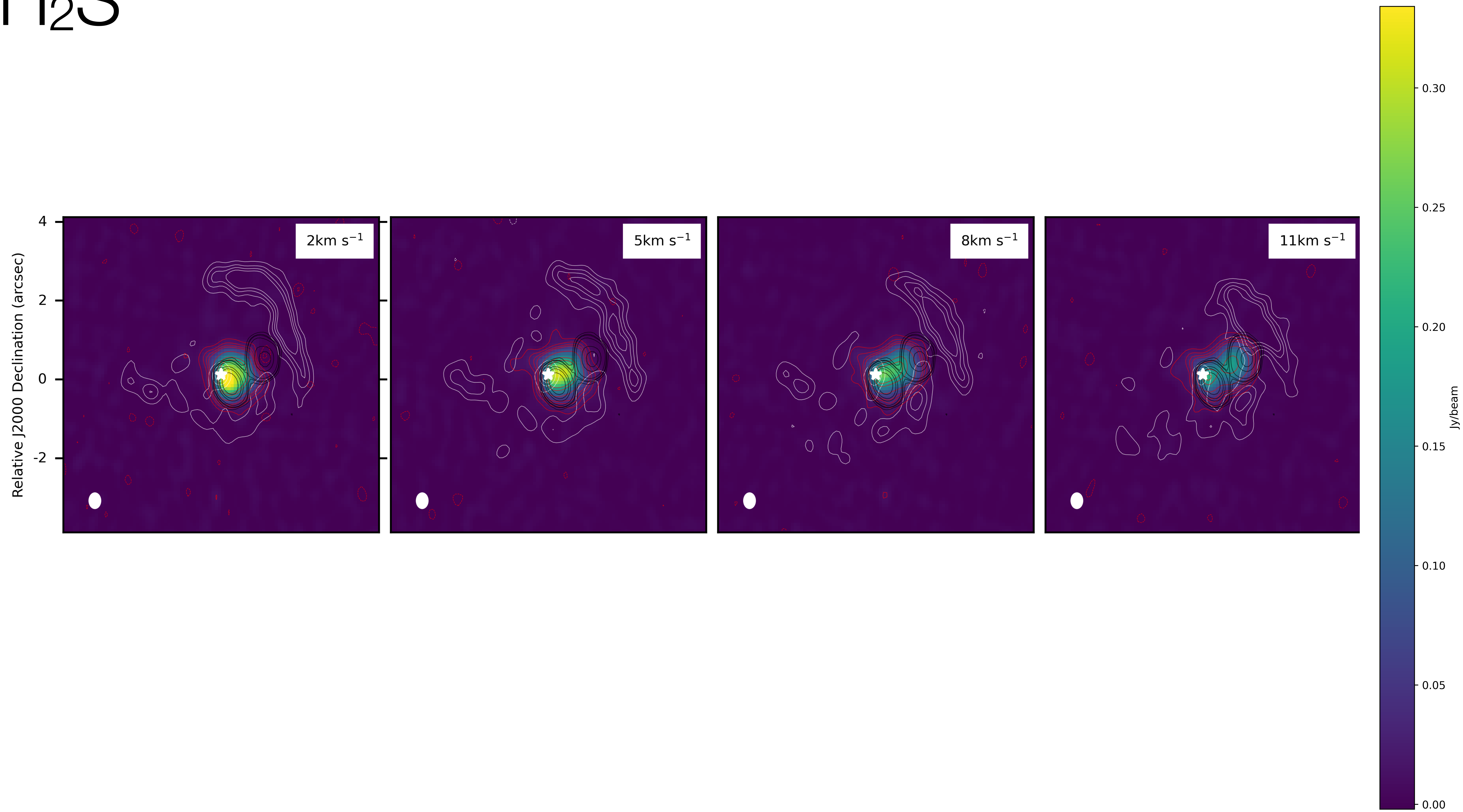
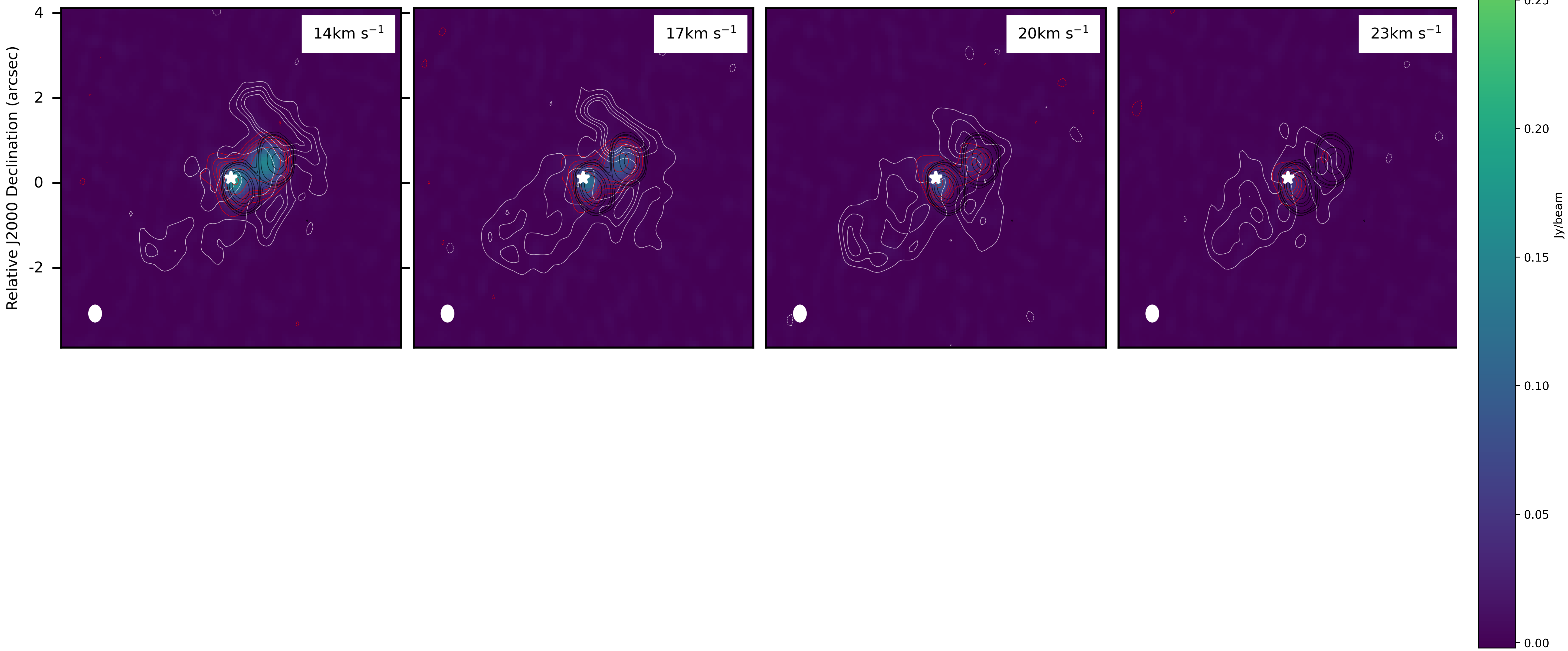
H_2S



2km s^{-1}
5km s^{-1}
8km s^{-1}
11km s^{-1}
Relative J2000 Declination (arcsec)
Jy/beam

H_2S



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Multi-wavelength context of NML Cyg

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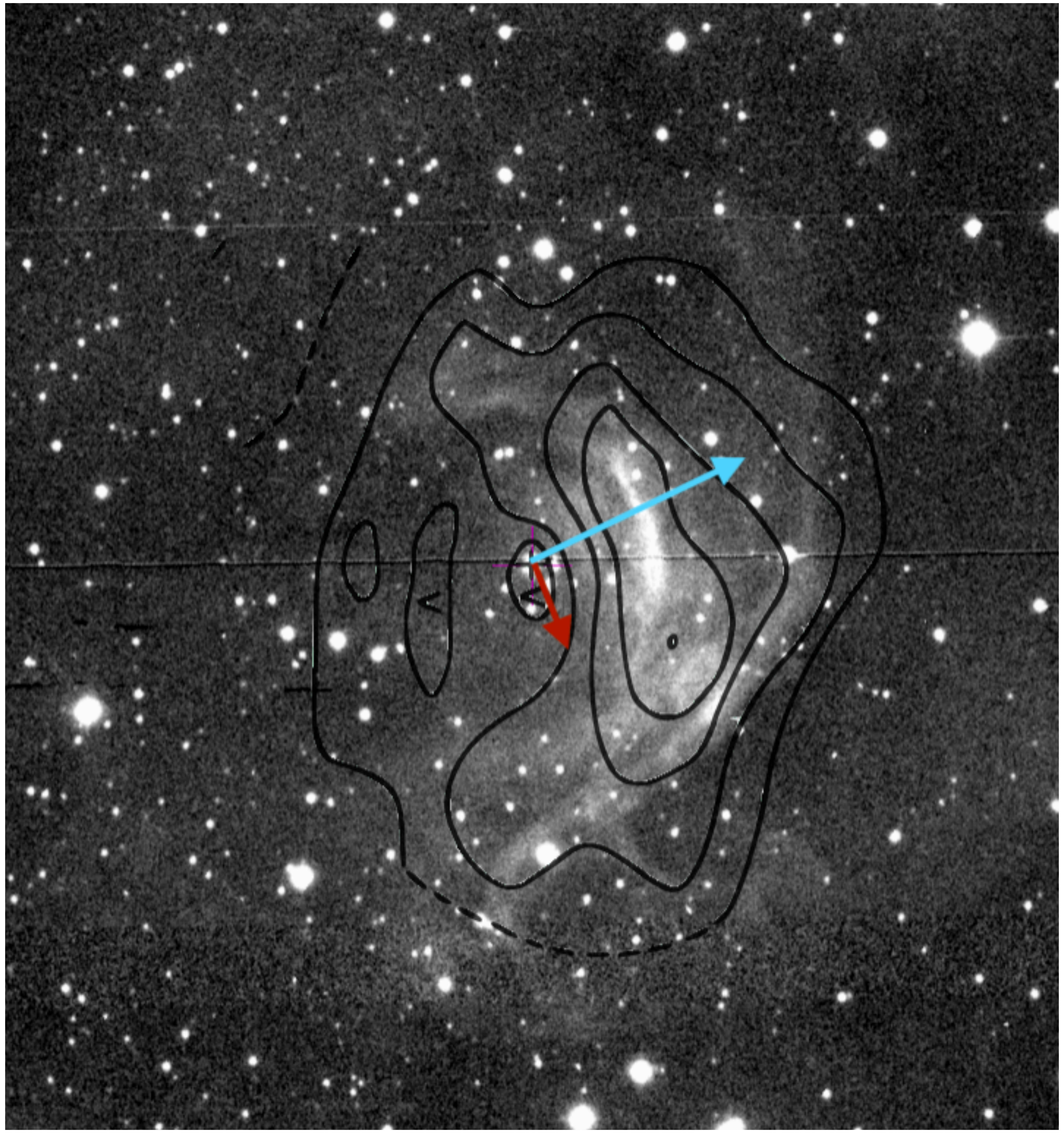
H-alpha emission:

Shows evidence of ionised material emitted from NML Cyg sustained mass-loss ~1’ in size:

Mass produced over timescale of 15,000 years

NML Cyg itself in a “bay” of H-alpha emission

Ionised by presence of nearby stellar association Cyg OB2



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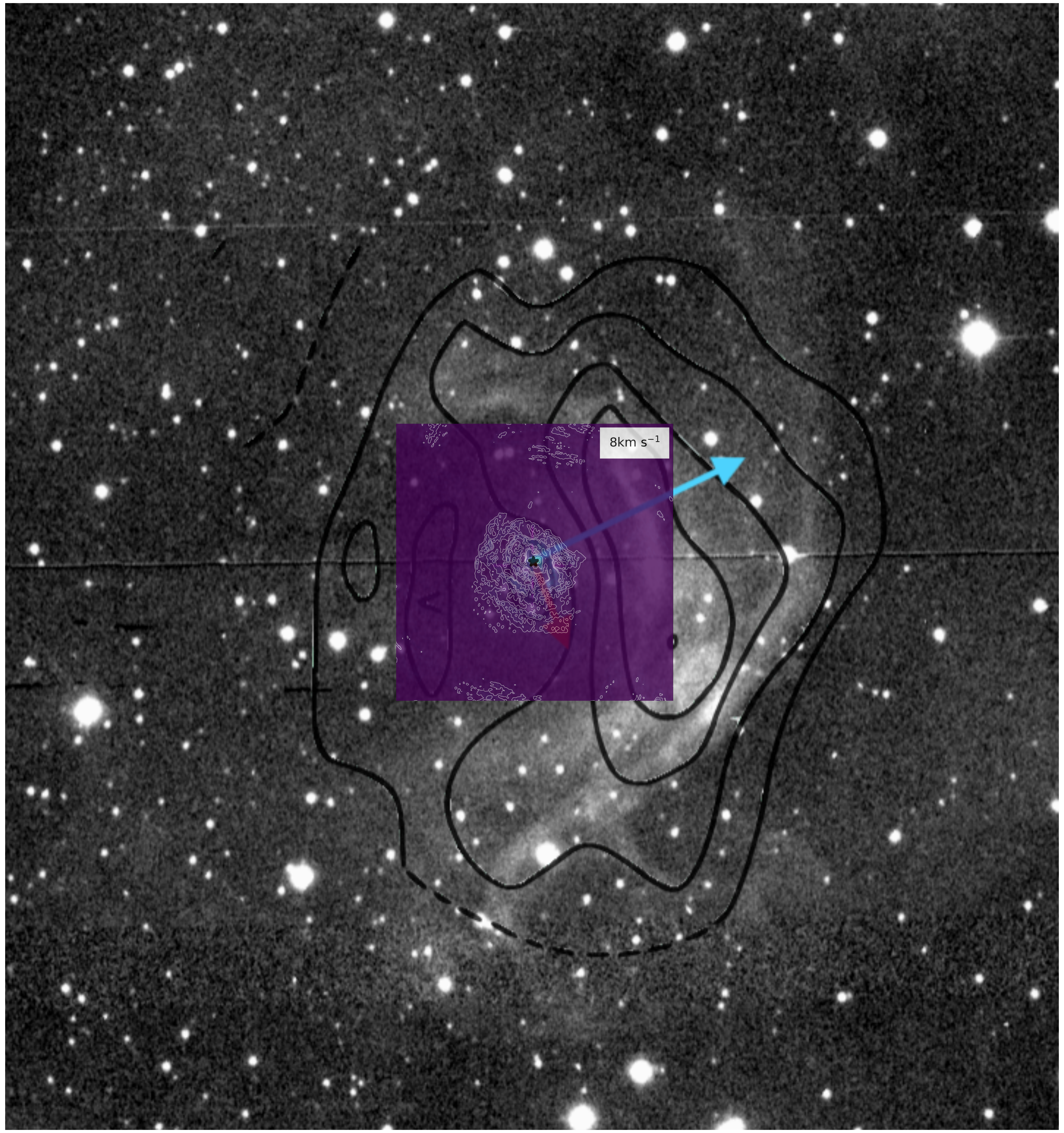

Internal factors on mass-loss structure

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Evidence for both quiescent and episodic mass-loss for star:

- Molecular emission found around central stellar region, tracing current quiescent mass-loss
- In addition, partial shells and arcs traced by S-rich species (SO, SO_2) and CO indicate episodic outflows over last 1200 years

Origin of this:

- Not just dust-driven winds that play a role!
- Magnetic fields also come into play (as seen for a similar analogue VY CMa)?

External factors on mass-loss structure

NML Cyg is known to be co-located with stellar association, Cyg OB2:

- Evidence of possible preferential dissociation towards the NW (direction fo Cyg OB2)

Evidence found for other sources that young massive stellar populations may sculpt extended CSEs around cool supergiants:

- e.g Westerlund 1

Also influencing other supergiants - IRC-10414

NML Cyg

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★ RSGs and YHGs are home to complex outflows and winds, where the driver is not fully understood.

★ NML Cyg can be seen to host at least two continuum components, linked to ~10^{-3} $M_{\odot}$ dust located 0.240” and 1.01” from the star

★ Molecular emission reveals the presence of several outflows, partial shells and shocks

Future Goals

★ Higher resolution observations of NML Cyg, at other continuum bands

★ Aim to resolve the possible clumps of dust present around the star (as has been seen for other objects, e.g. VY CMa, Kaminski 2019)

★ Determine spectral indices - better handle on characteristics of emission

★ Systematic measurements of other RSGs; better determine the number of sources for which multiple factors influence mass-loss and CSE