ATOMIUM: Inner circumstellar envelopes of oxygen-rich AGB stars as revealed by highly excited SiO lines

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in collaboration with the ATOMIUM consortium

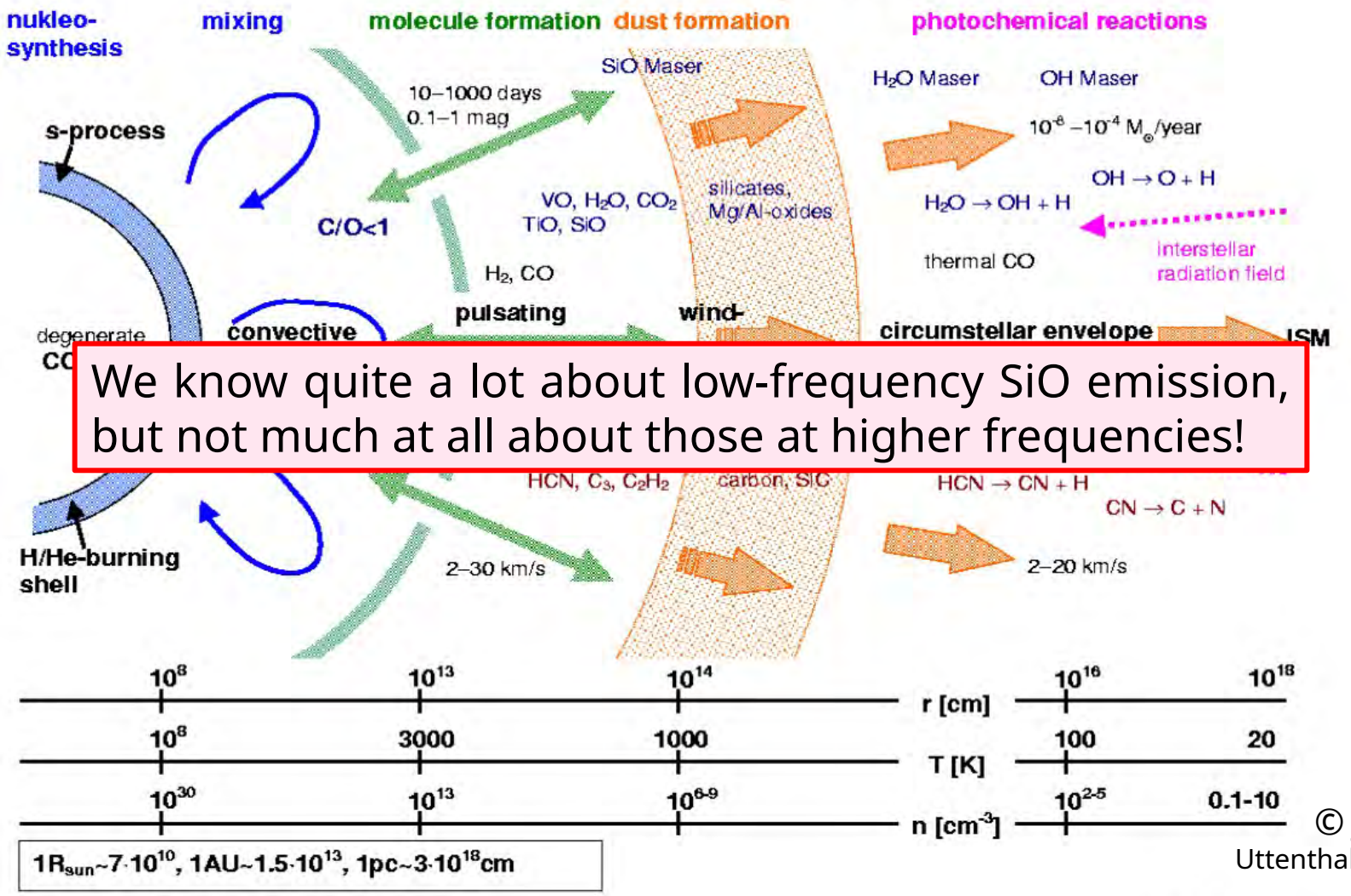
EAMA11 - Niigata, Japan
10 Dec 2025

OUTLINE

Why study SiO in AGB stars?
ATOMIUM Large Programme
High-frequency SiO detections
Inner CSEs through compact emission

Part of Pimpanuwat et al.
(MNRAS, under revision)

Why study SiO in AGB stars?



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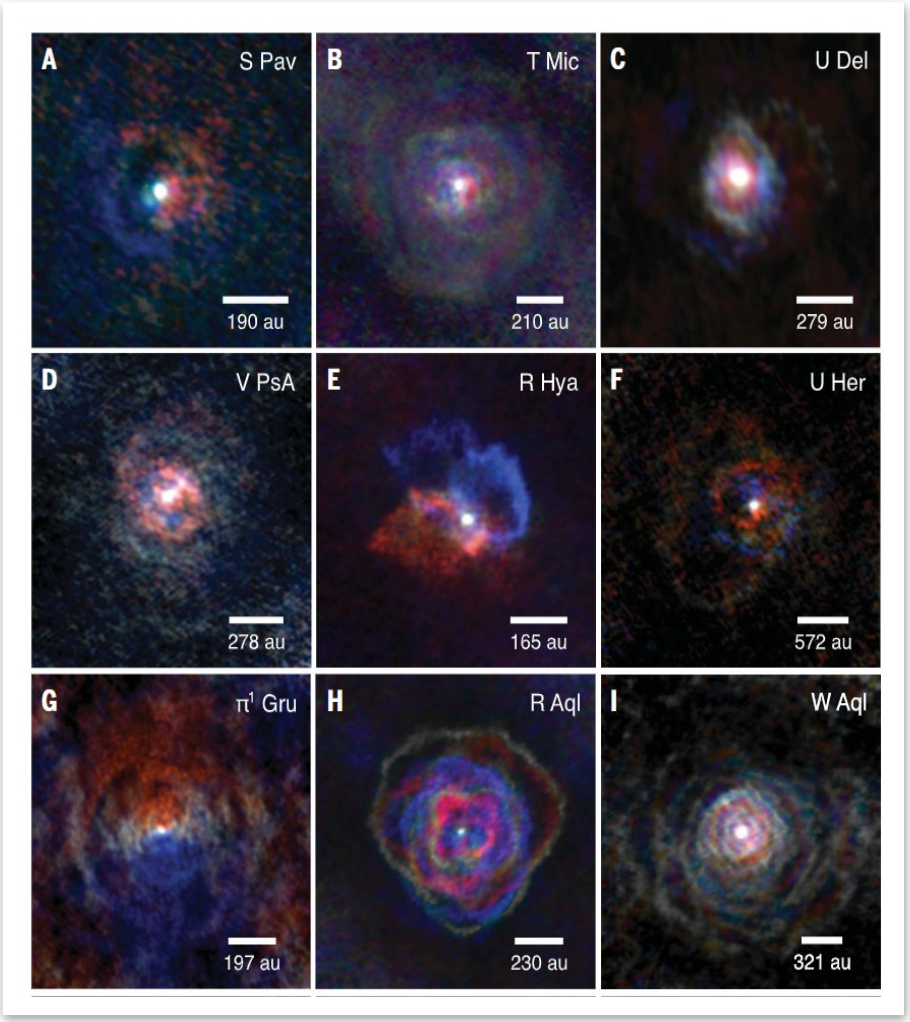
Uttenthaler (2007)

ATOMIUM Large Programme

(PI: L. Decin, C. Gottlieb)

ATOMIUM (ALMA Tracing the Origins of Molecules In dUst-forming oxygen-rich M-type stars):

- 17 oxygen-rich AGB and RSG stars → range of (circum)stellar properties
- To study the properties and wind morphologies of O-rich CSEs where dust formation commences



CO maps of ATOMIUM stars using ALMA (Decin+2020, Gottlieb+2022)



Name	Stellar type	Variability type	$\dot{M}^{(1)}$ ($M_\odot$ yr^{-1})	$\overline{\dot{M}}^{(2)}$ ($M_\odot$ yr^{-1})	P (d)	$D^{(3)}$ (pc)
S Pav	M-type	SRa	1.3E-7	1.4(0.2)E-7 [ab]	381	190
RW Sco[(6)]	M-type	Mira	1.3E-7	1.6(0.8)E-7 [cd]	389	560
T Mic	M-type	SRb	1.4E-7	1.4(0.7)E-7 [a]	347	175
R Hya[(7)]	M-type	Mira	1.8E-7	1.8(0.5)E-7 [defg]	366	126
SV Aqr	M-type	LPV	2.7E-7	2.7(1.4)E-7 [a]	–	445
U Her	M-type	Mira	3.2E-7	2.6(1.2)E-7 [ehi]	402	266
U Del	M-type	SRb	3.7E-7	3.7(1.9)E-7 [a]	119	330
V PsA	M-type	SRb	4.8E-7	3.2(0.1)E-7 [aj]	148	278
π^1 Gru[(7)]	S-type	SRb	9.2E-7	8.0(2.2)E-7 [hkl]	150	164
R Aql	M-type	Mira	1.6E-6	1.3(0.7)E-6 [ei]	268	230
GY Aql	M-type	Mira	2.3E-6	2.3(1.2)E-6 [m]	468	410
W Aql[(7)]	S-type	Mira	2.7E-6	3.5(2.2)E-6 [n]	479	375
IRC-10529[(6)]	M-type	SRc	1.0E-5	1.9(0.9)E-5 [dgop]	680	930
IRC+10011[(6)]	M-type	Mira	1.9E-5	1.8(0.9)E-5 [d]	660	740

Observations

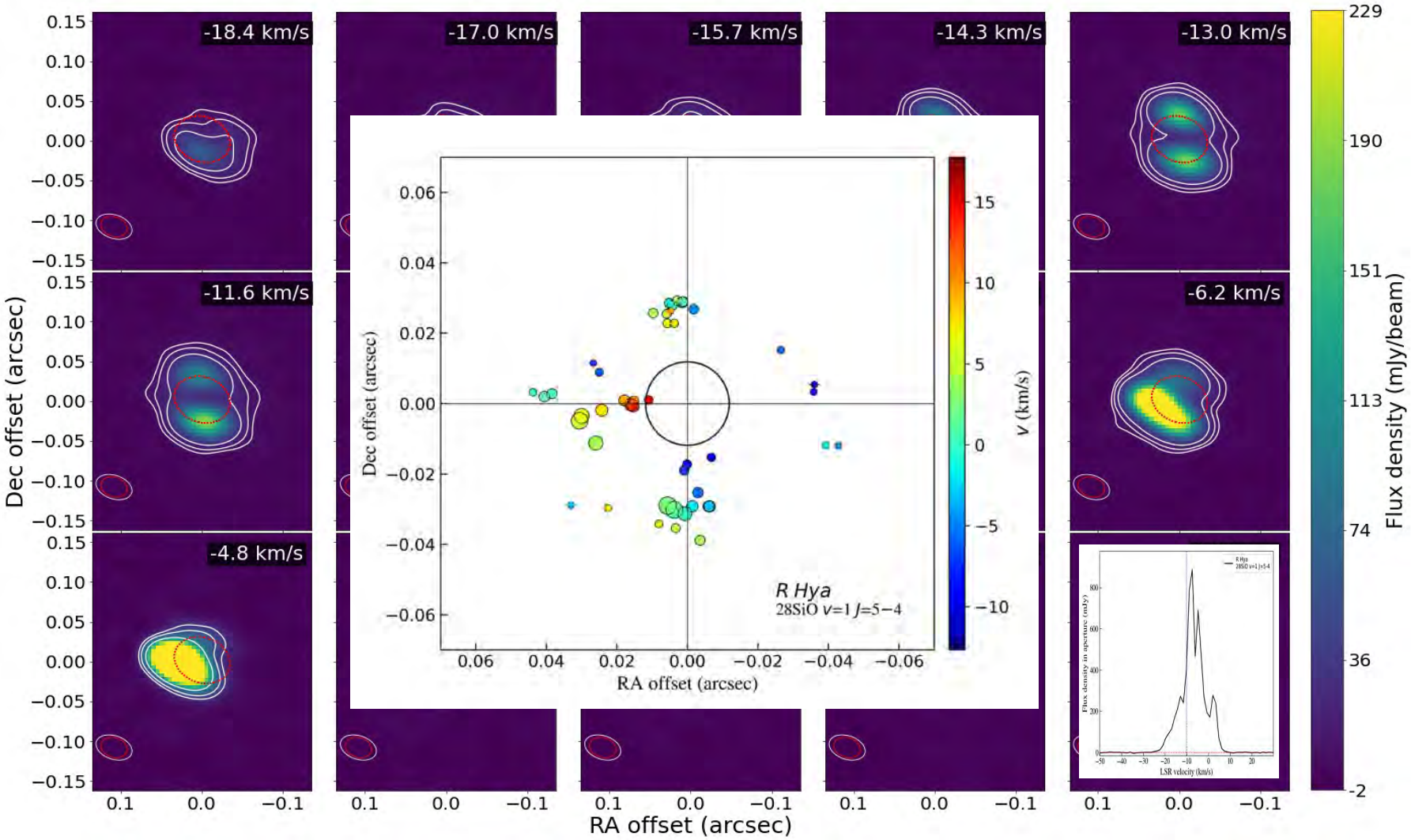
Decin+2020, Gottlieb+2022

(Subset of) the
ATOMIUM source sample

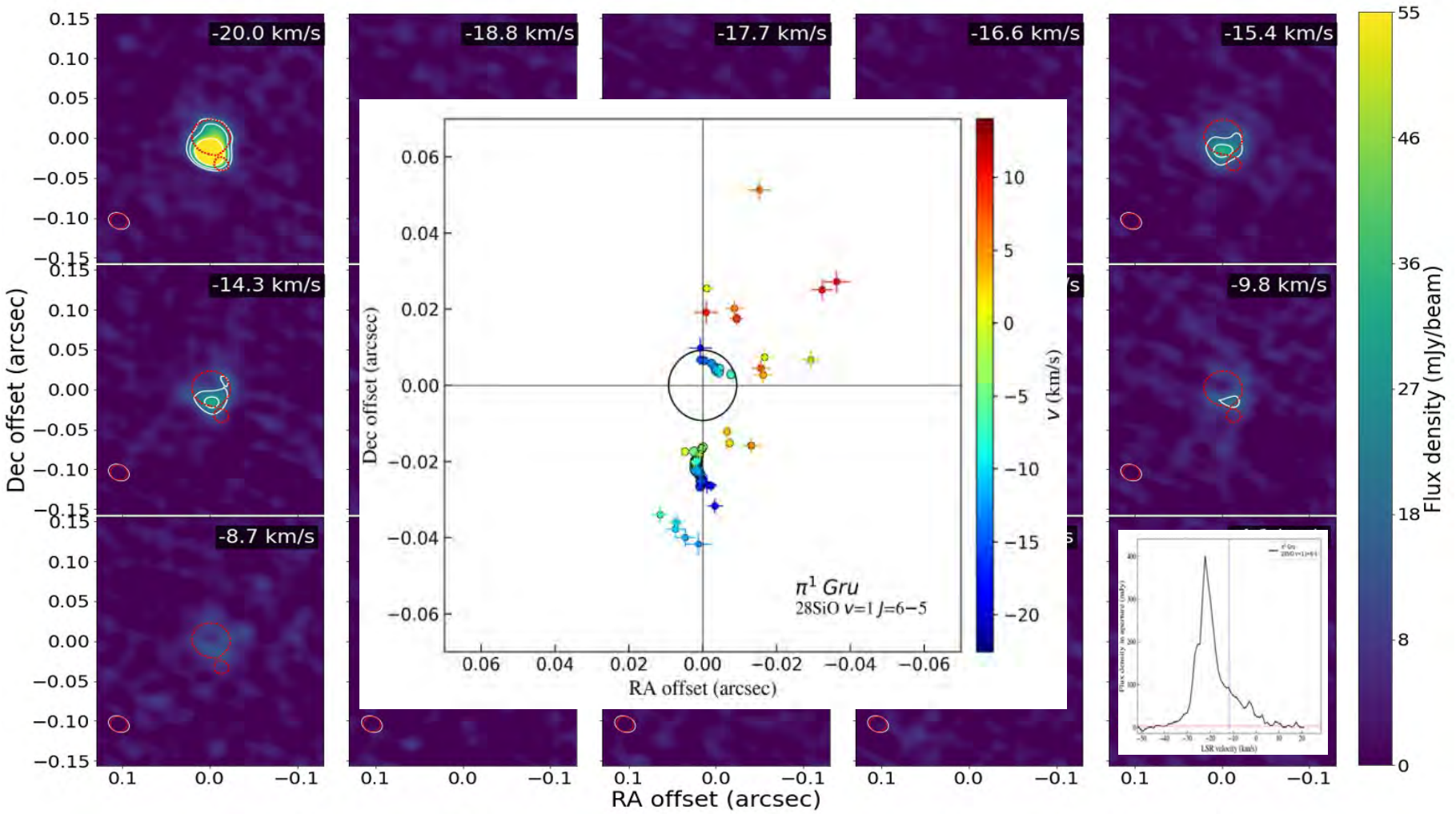
- 14 AGB stars covering a wide range of mass-loss rates and (circum)stellar parameters
- Observed with ALMA in Band 6 (211-275 GHz or 1.4-1.1 mm) between 2018 – 2020
- Extended array configuration (20 – 50 mas angular resolution)
- Mass-loss rate between 10^{-8} – 10^{-5} solar masses/yr
- One of the first studies with high sensitivity and resolution setups!

R Hya
^{28}SiO v = 1 J = 5 – 4

Most compact emission?
Perform 2D Gaussian fitting using *Search and Destroy (SAD)* on AIPS



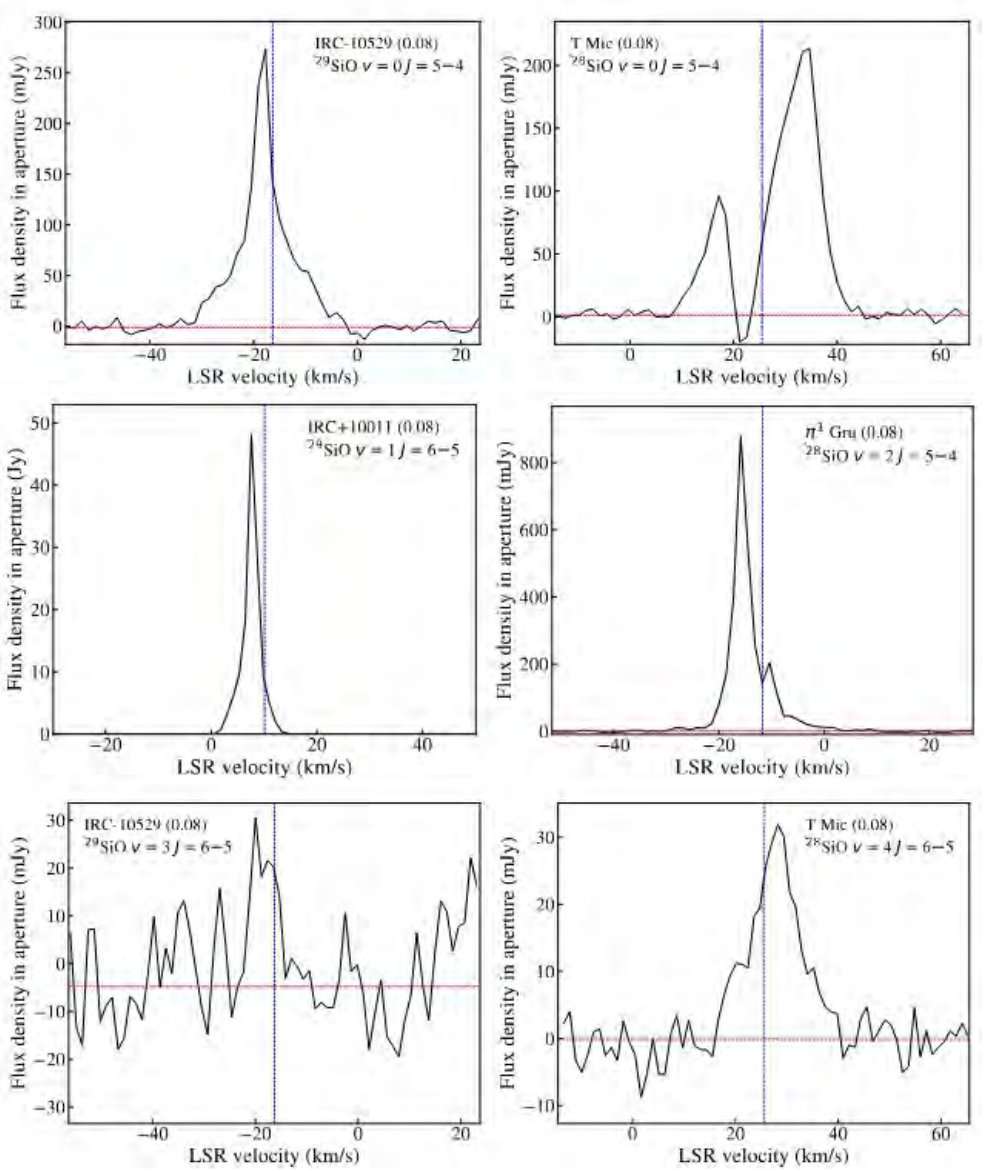
π^1 Gru
^{28}SiO v = 1 J = 6 – 5



SiO line detections

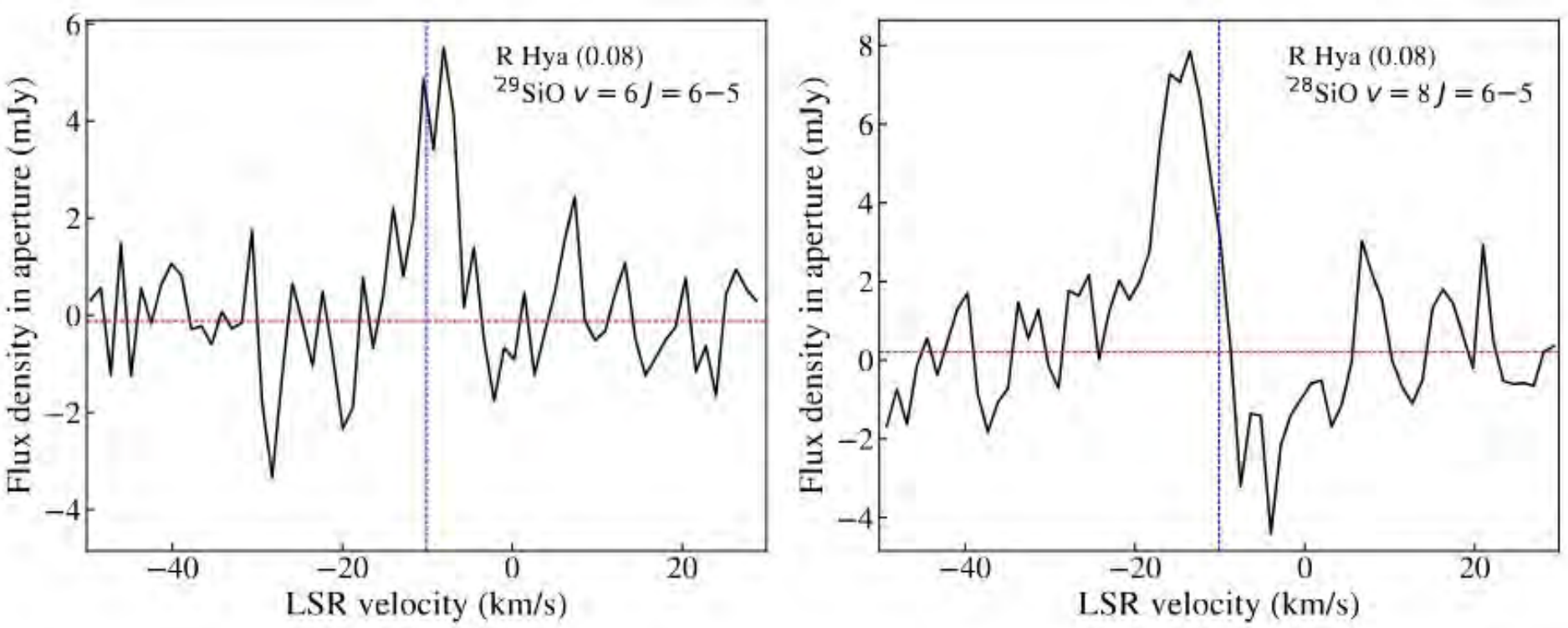
- 16 SiO transitions (from ^{28}SiO, ^{29}SiO, ^{30}SiO) detected
- All 14 stars exhibit at least one SiO line in v = 0, 1 states
- (Quasi-)thermal and maser contributions in low-lying v states ($v < 2$)

Right: Example spectra extracted from images - 0”.08 circular aperture

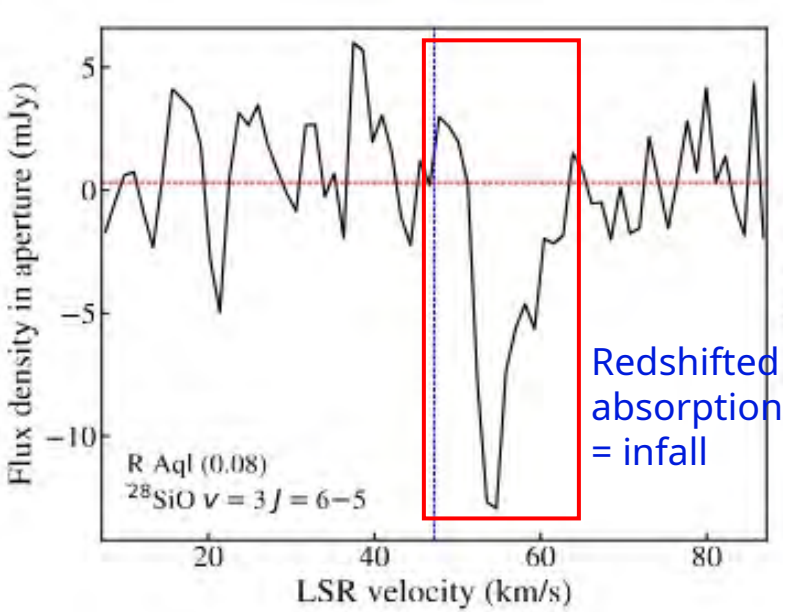


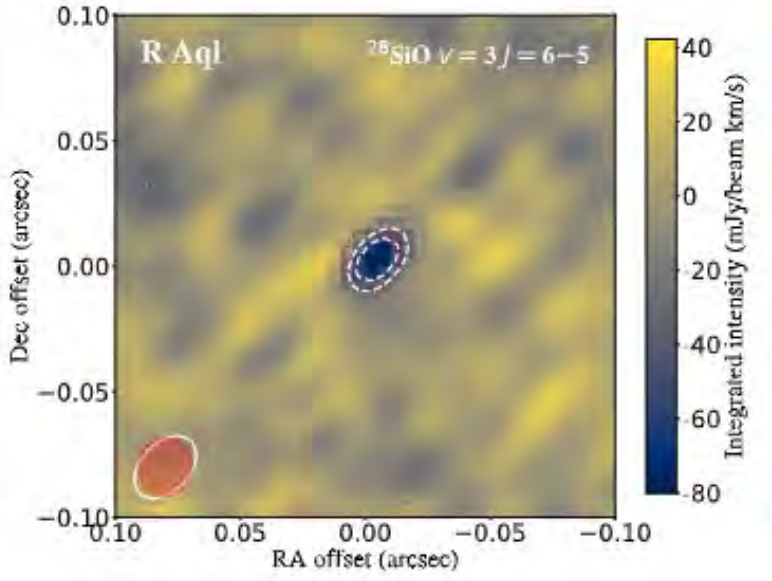
$v = 6$ and $v = 8$ detections!!!

Upper-state energy ~10^4 K(!) so definitely non-thermal
→ likely masing?



HIGHEST v-states observed in AGB stars to date

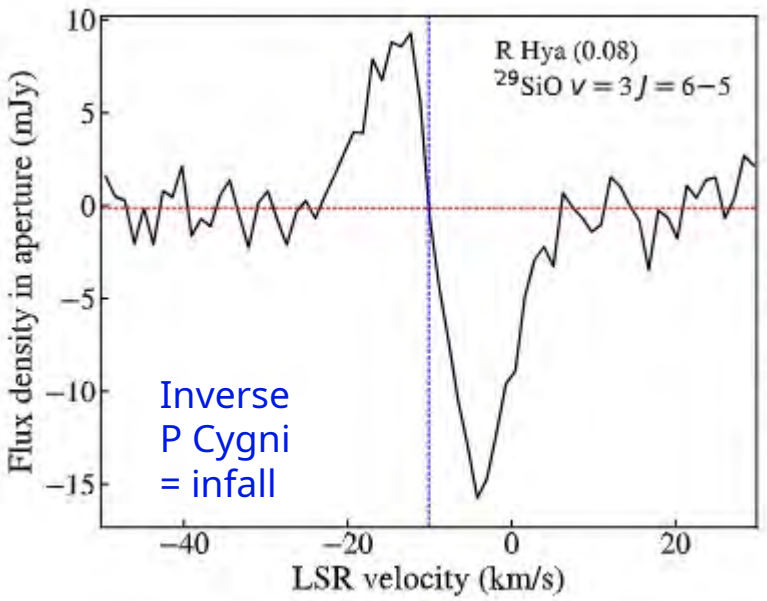


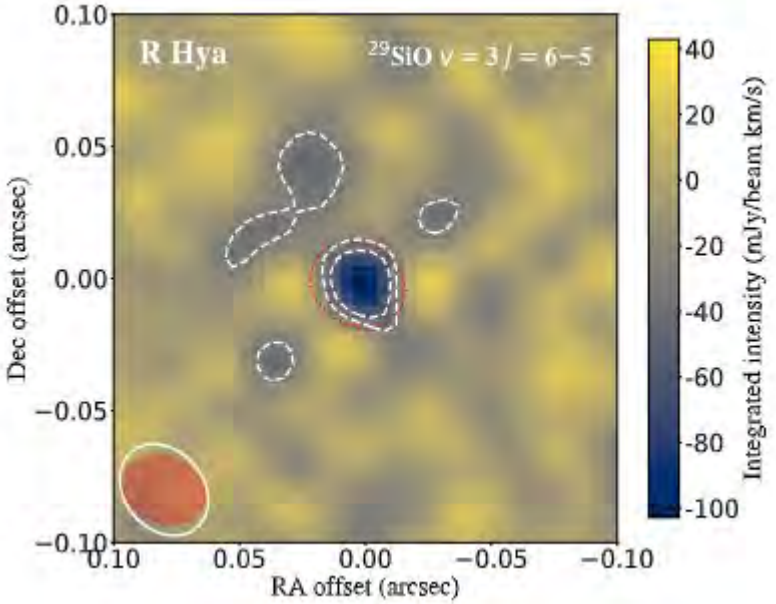


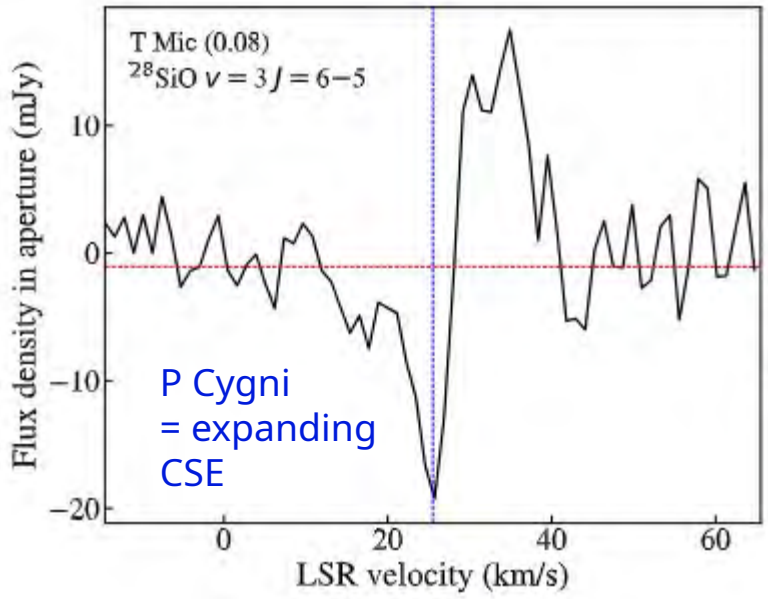
SiO line absorption

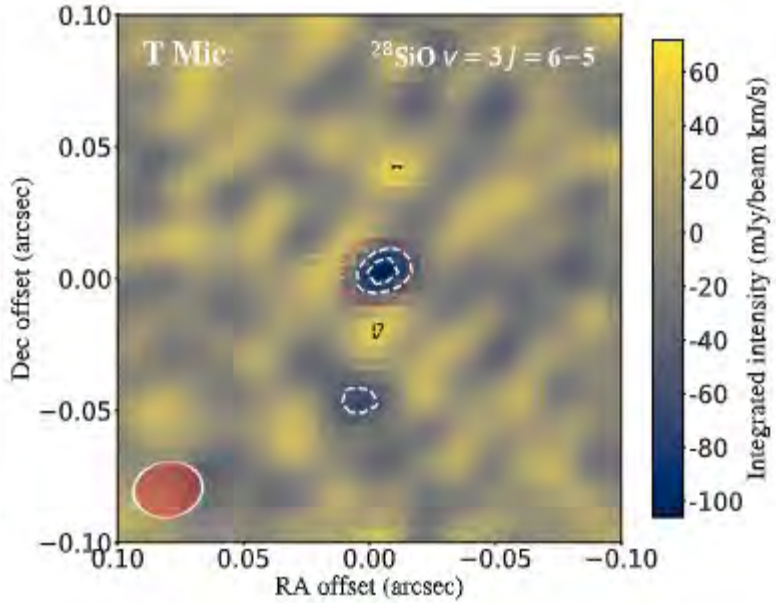
- Absorption in the $v = 3$, $J = 6-5$ lines of ^{28}SiO and ^{29}SiO, with rest frequencies 255.091 GHz and 251.929 GHz
- 12 – 25 mJy absorption features with half min widths < 10 km/s
- Spatially compact (10 – 25 mas) near continuum emission

Left:
Absorption
spectra







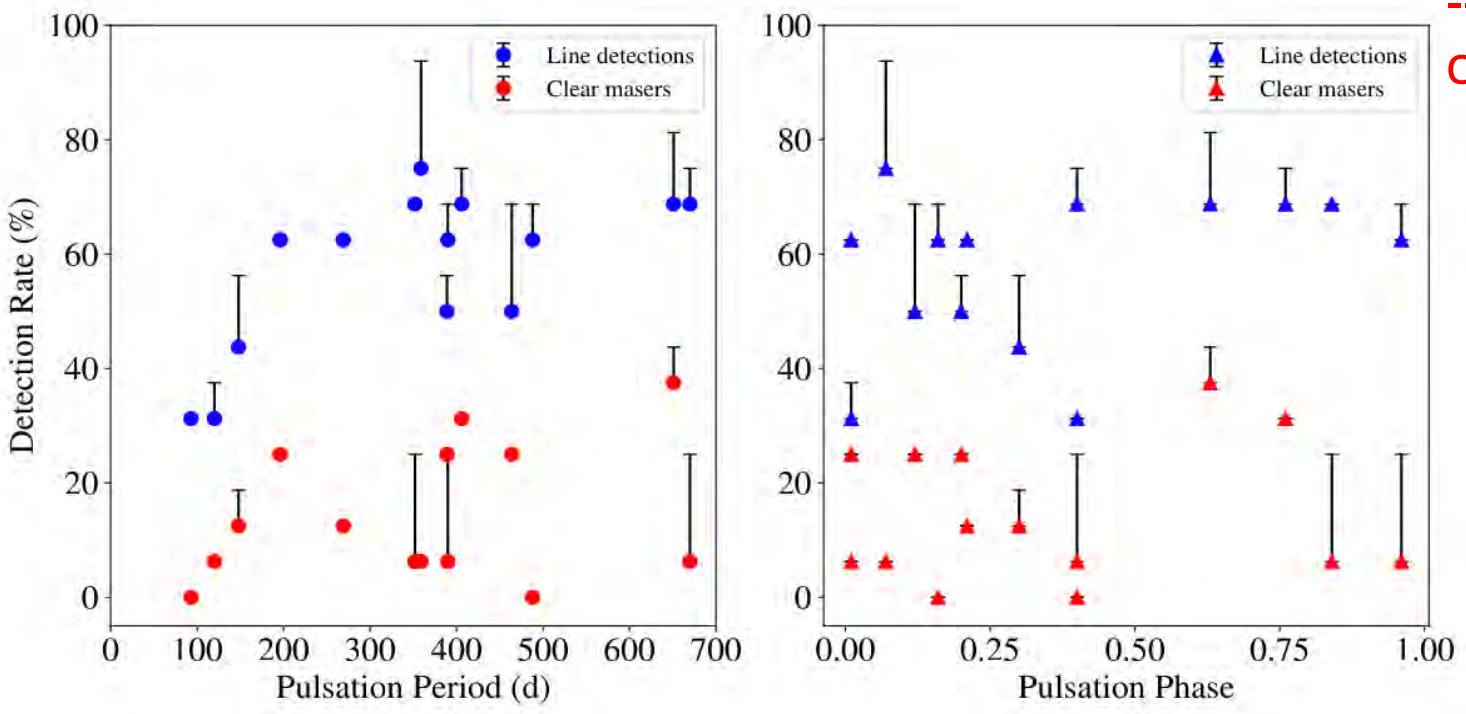


Right:
Integrated
intensity maps

Red dashed
contour:
continuum peak

Effects of pulsation period/phase

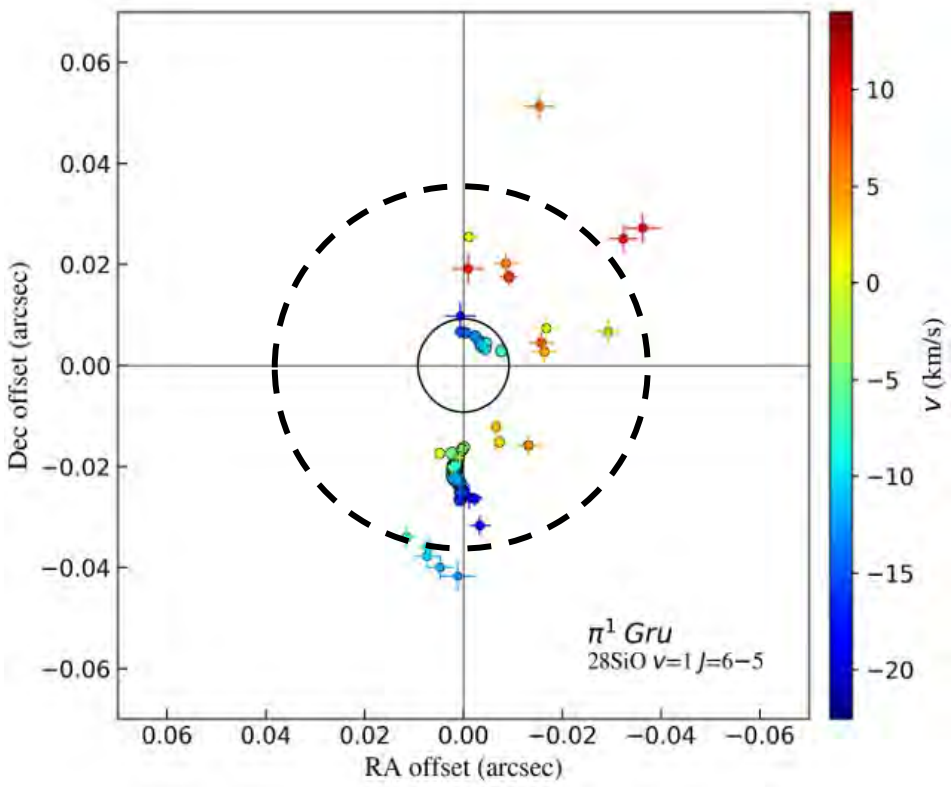
- Tentative correlation between SiO detection and pulsation period?
- SiO maser detections (at 43 GHz, Lewis+2024):
  - increase with longer pulsation periods
  - are more likely near an infrared maximum (0.1 – 0.2 behind optical)

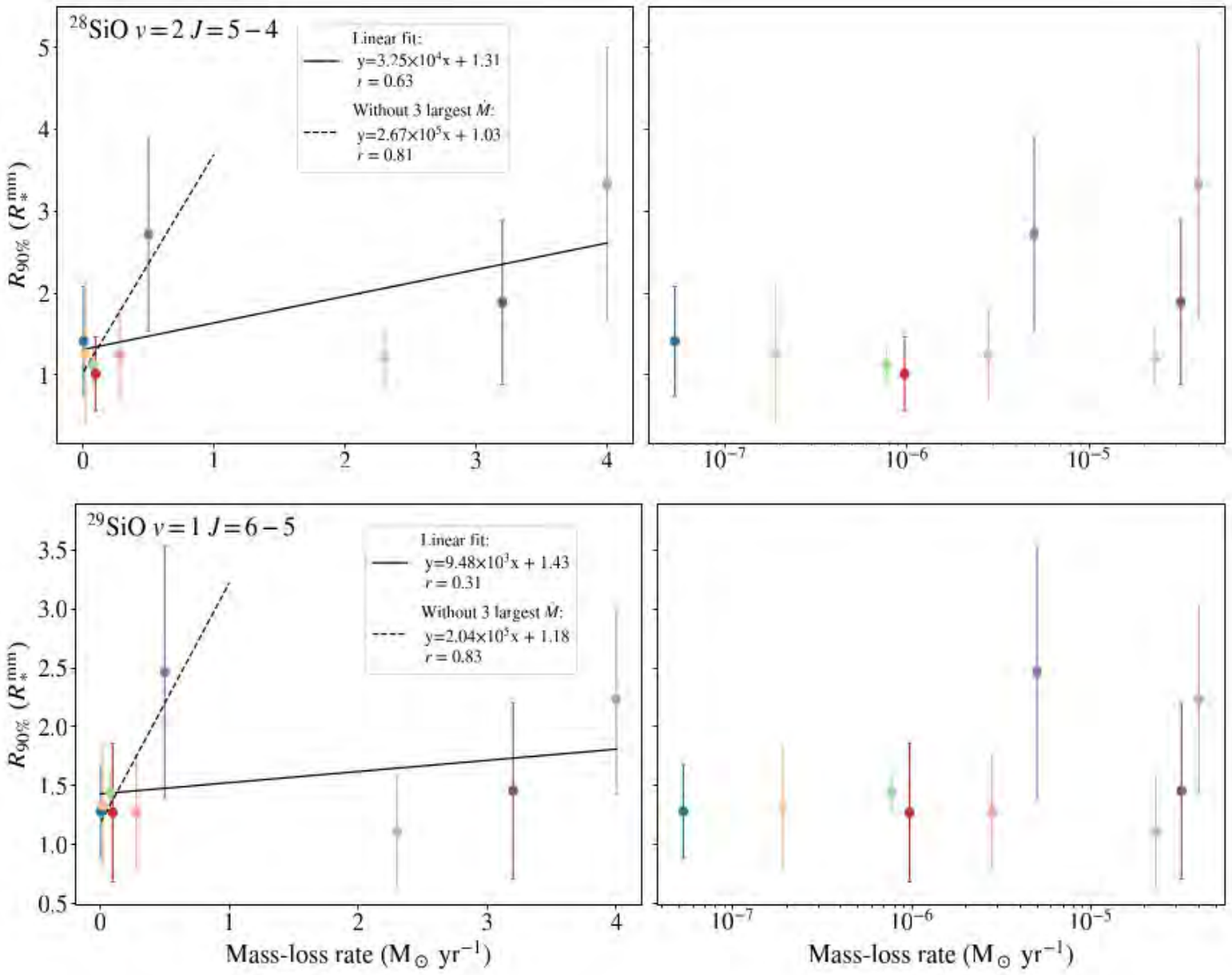


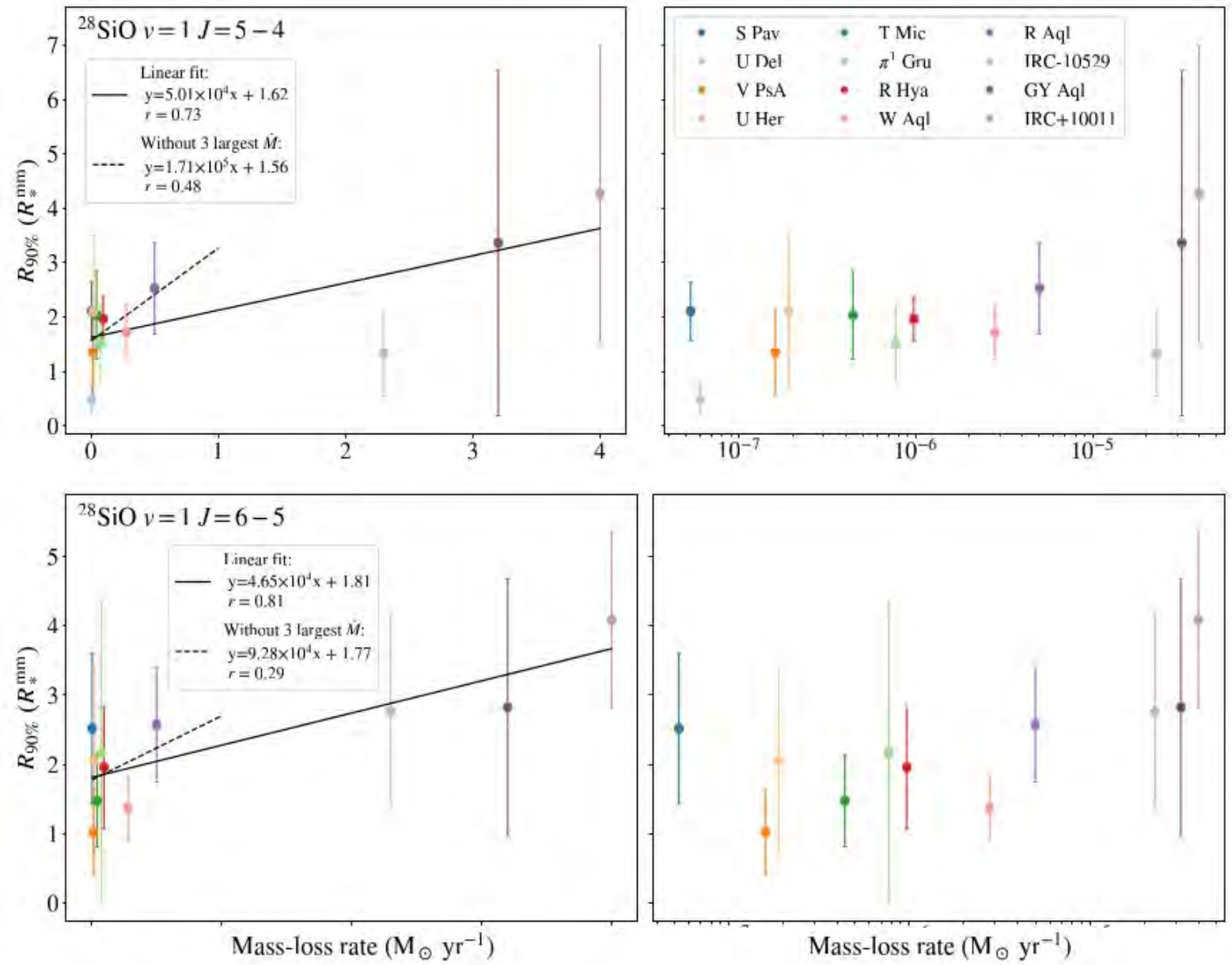
-- not the case here?

Mass-loss rate *vs* SiO angular extent

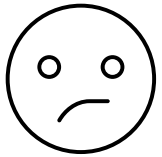
- Wide range of mass-loss rates = unique opportunity to search for a potential correlation
- Compiled mass-loss rates from literature (Danilovich+2025)
- Define “angular extent” - angular size that encloses 90% of total emission
- Choose only sources with at least 10 components
- Plot and calculate the correlation coefficient




^{28}SiO $v=2$ $J=5-4$
Linear fit:
y=3.25×10^{4}x + 1.31
r = 0.63
Without 3 largest $\dot{M}$:
y=2.67×10^{5}x + 1.03
r = 0.81
^{29}SiO $v=1$ $J=6-5$
Linear fit:
y=9.48×10^{3}x + 1.43
r = 0.31
Without 3 largest $\dot{M}$:
y=2.04×10^{5}x + 1.18
r = 0.83
$R_{90\%}$ (R_*^{mm})
Mass-loss rate ($M_\odot$ yr^{-1})


^{28}SiO $v=1$ $J=5-4$
Linear fit:
y=5.01×10^{4}x + 1.62
r = 0.73
Without 3 largest $\dot{M}$:
y=1.71×10^{5}x + 1.56
r = 0.48
$R_{90\%}$ (R_*^{mm})
S Pav
U Del
V PsA
U Her
T Mic
π^1 Gru
R Hya
W Aql
R Aql
IRC-10529
GY Aql
IRC+10011
^{28}SiO $v=1$ $J=6-5$
Linear fit:
y=4.65×10^{4}x + 1.81
r = 0.81
Without 3 largest $\dot{M}$:
y=9.28×10^{4}x + 1.77
r = 0.29
$R_{90\%}$ (R_*^{mm})
Mass-loss rate ($M_\odot$ yr^{-1})
Mass-loss rate ($M_\odot$ yr^{-1})

Exciting results, but…



…we cannot say with confidence (yet) whether:

- the observed characteristics of high-frequency SiO are intrinsic to the transitions
- the compact SiO emission is tracing different morphologies at low vs high frequencies

with only one epoch of (interesting!) ALMA observations.

SUMMARY

- Analysed ATOMIUM extended-configuration SiO data of 14 AGB stars
- Found 16 high-frequency SiO lines, **up to *v* = 8, the highest *v*-state transition to date**
- Channel maps and component maps show complex morphologies
- The relationship between SiO emission, pulsation phases and periods at high frequencies may not exist(?)
- Tentative correlation between mass-loss rate and angular extent of SiO emission