Resolving the extended atmosphere and the inner wind of Mira (*o* Cet) with long ALMA baselines

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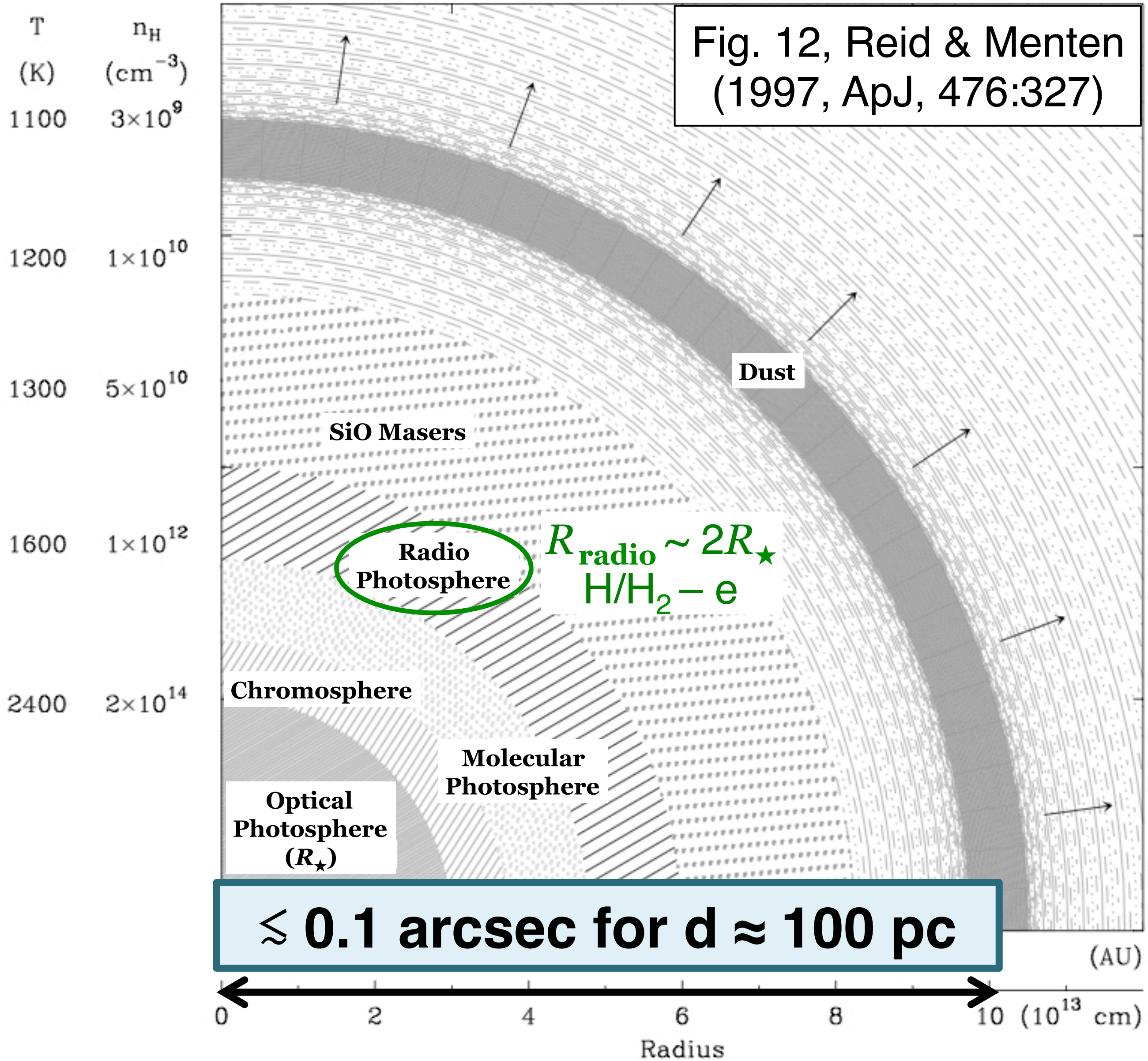
Blowing in the Wind 2016, ICISE, Việt Nam

Outline

- Extended atmosphere, previous obs.
- ALMA long baseline observation
  - continuum
  - images + spectra
- Radiative transfer modelling
  - molecular abundances
  - inner dust shells
  - kinematics
- Comparison with hydrodynamical models
- ~~SiO masers, detailed continuum analysis~~
- ~~… and many more …~~

A&A 590 A127

Extended atmosphere



Hydrodynamical models

- Ireland/Scholz/Wood (2008; 2011; 2014)
  - ✧ **CODEX** model series
- Jeong et al. (2003)
- Höfner et al. (in press)

DARWIN models
➔ **Sofie Liljegren's talk**

Probing the extended atmosphere

- Molecular absorption spectroscopy (ISO)

  ➔ "MOLsphere" (e.g. Tsuji+ 97, Tsuji 00; Woitke+ 99)

- SiO/H_2O maser emission (VLA/VLBA)

  (e.g. Reid & Menten 97, 07; Cotton+ & Perrin+ 04, 09, 10, 15)

- Mid-IR interferometry (VLTI)

  (e.g. Ohnaka et al. 2005; Karovicova et al. 2011)

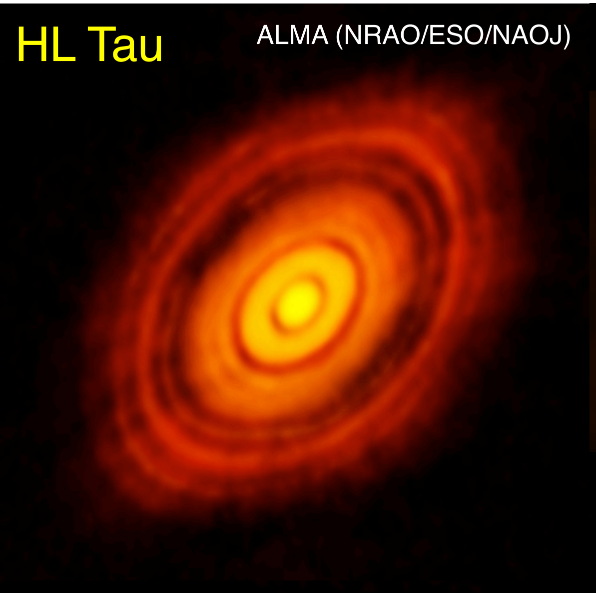
2nd generation VLTI instru.
➔ Xavier Haubois' talk

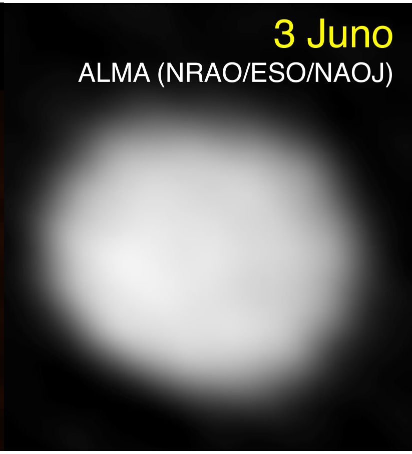
ALMA

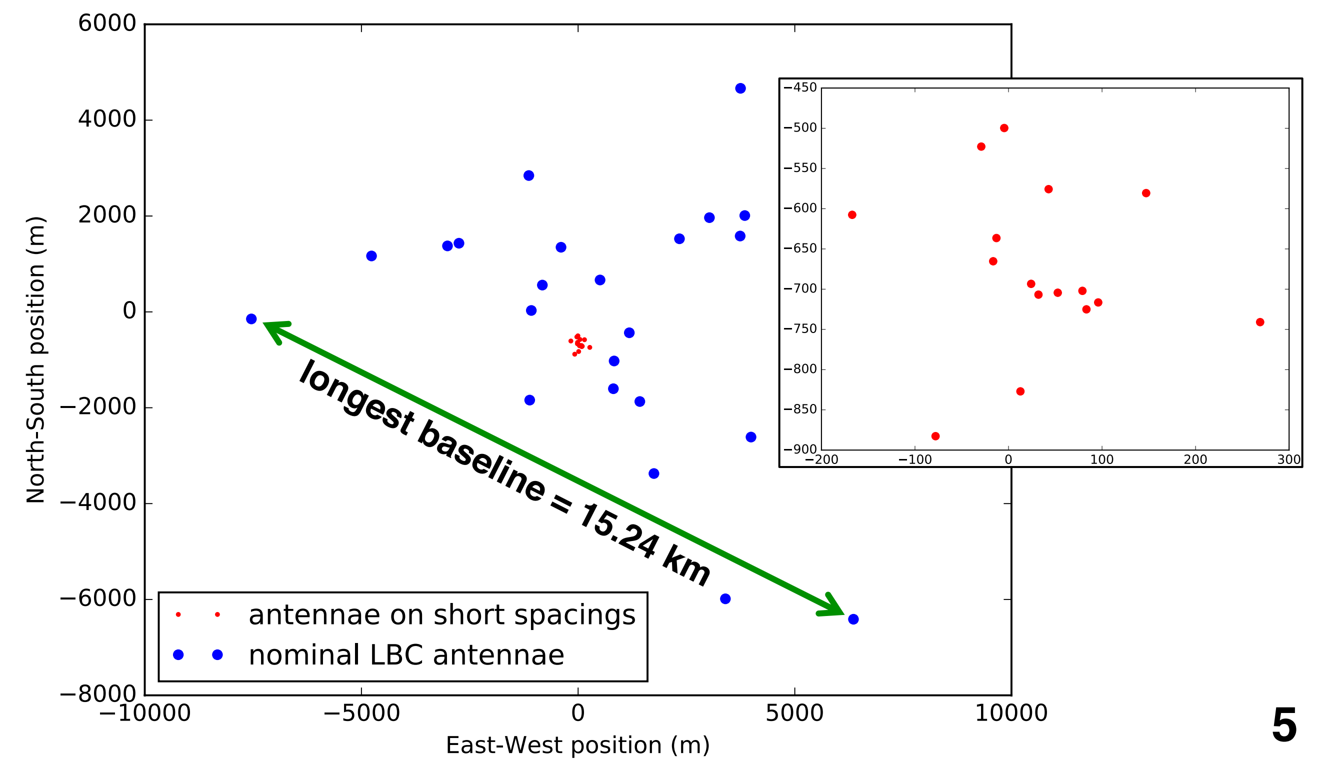
High **spatial resolution** images

(Sub)millimetre **thermal** line emission **& absorption**

2014 Long Baseline Campaign





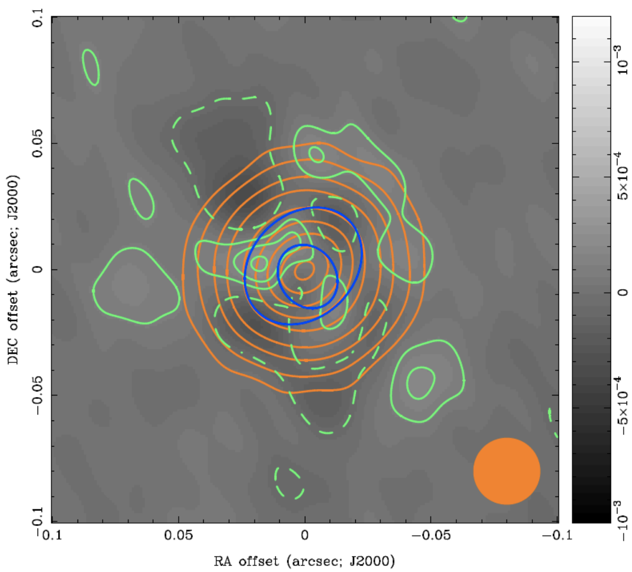


Band 6 data

- 229.6 GHz (1.3 mm) continuum
  (*Matthews et al. 2015; Vlemmings et al. 2015; Planesas et al. 2016; this work*)
- SiO $\upsilon = 0, 1, 2$ $J = 5 - 4$
- ^{29}SiO $\upsilon = 0$ $J = 5 - 4$
- H_2O $\nu_2 = 1$ $J(K_a,K_c) = 5(5,0) - 6(4,3)$
- H30α (Radio Recomb. Line) (*no detection*)
- Angular resolution: 30 – 32 mas
- Velocity resolution: 0.08 – 0.17 km/s

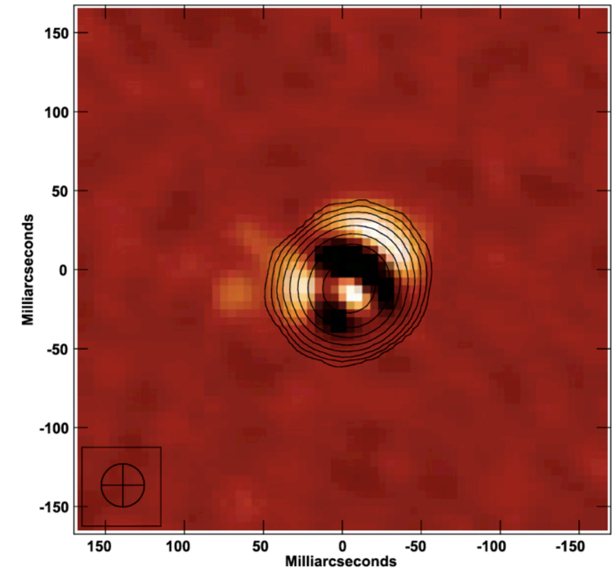
Band 6 data

- 229.6 GHz (1.3 mm) continuum

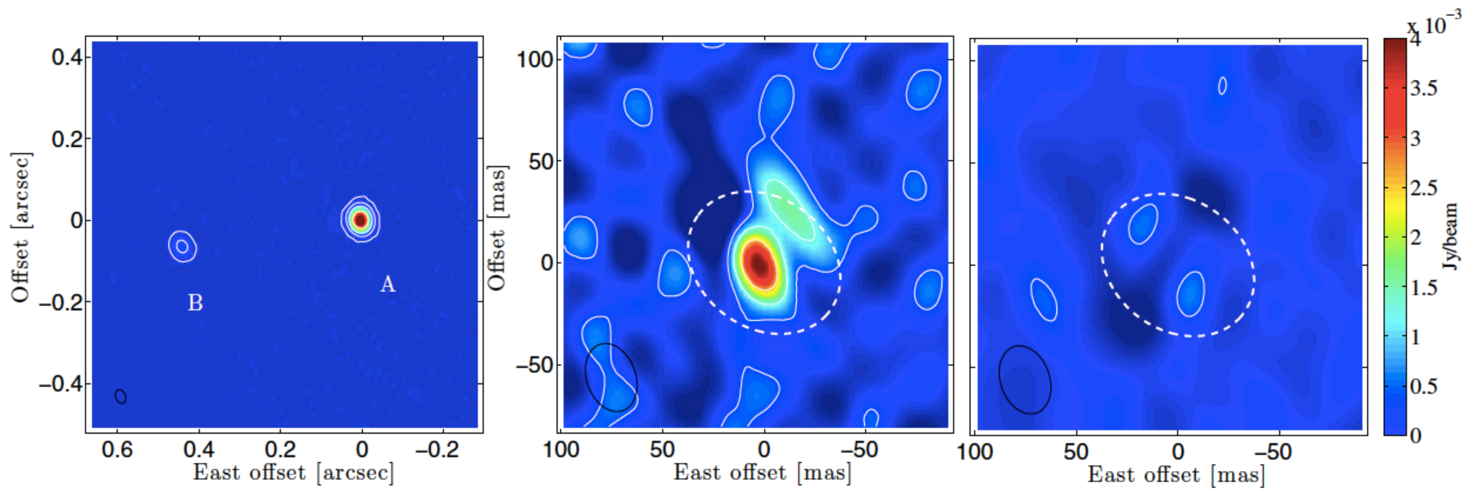


Wong et al. (2016)
Appendix A

Matthews et al. (2015)



Vlemmings et al.
(2015)



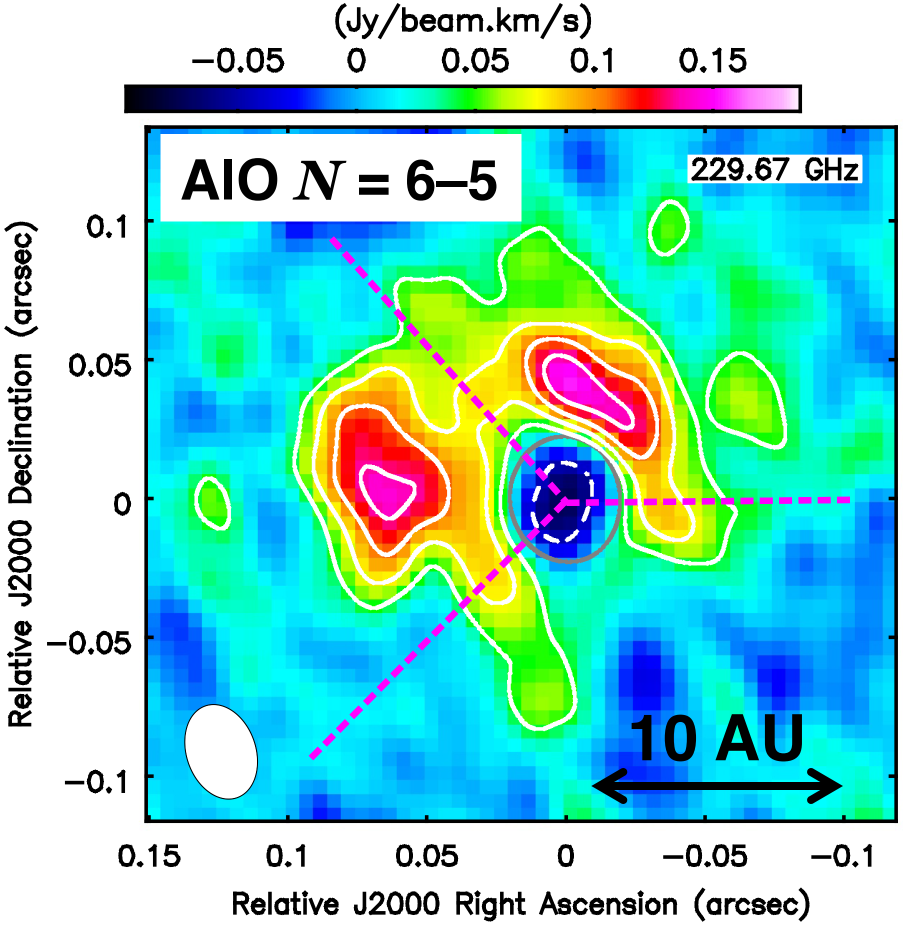
Band 6 data

- 229.6 GHz (1.3 mm) continuum
- ΔV = 20.5 km/s
- Bandwidth = 2 GHz

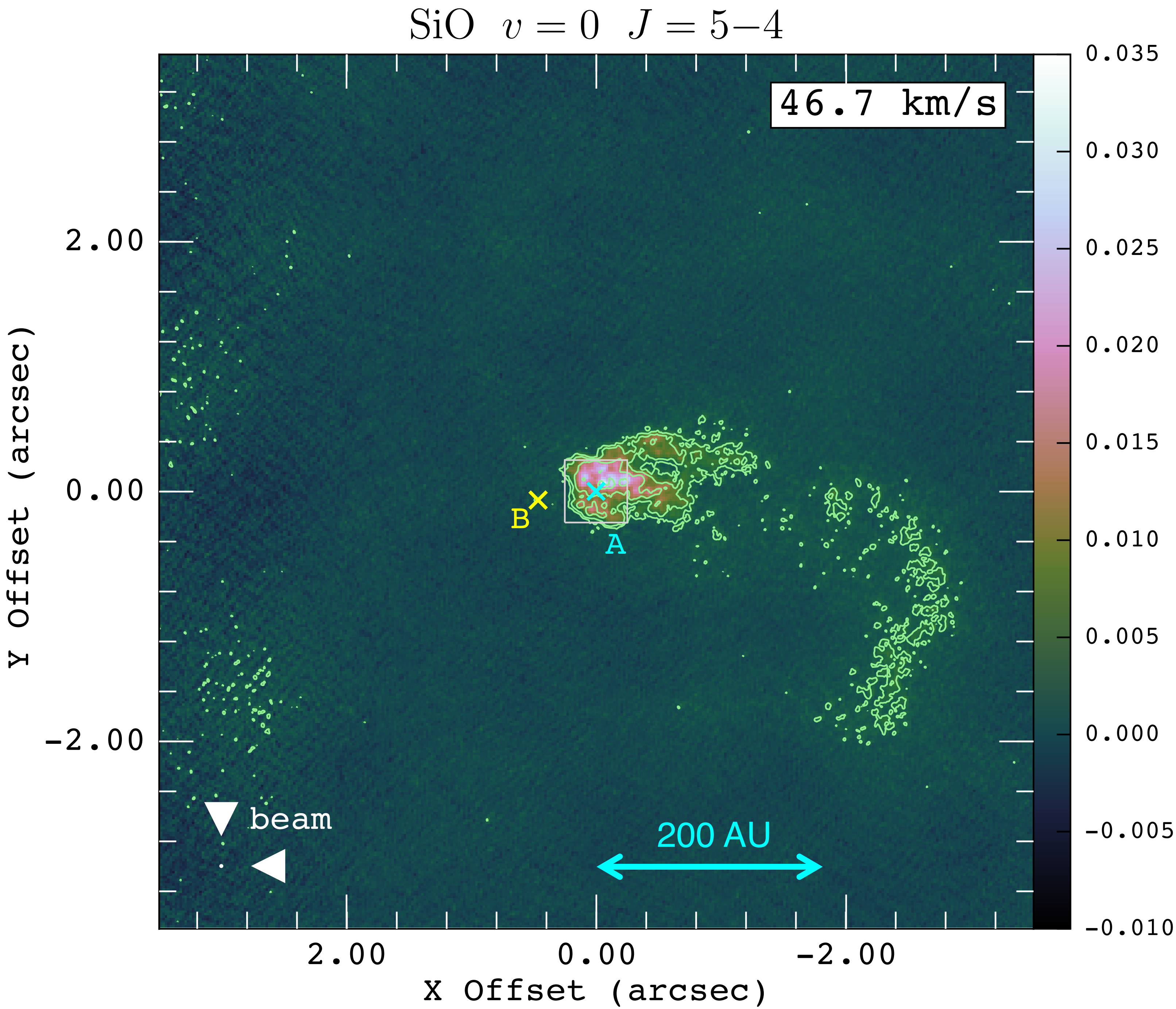
T. Kamiński, K. T. Wong et al.

- multi-epoch spectral line obs. (1965 – 2015; mm – optical)
- clumpy, inhomogeneous distribution of AlO
- irregular temporal variation

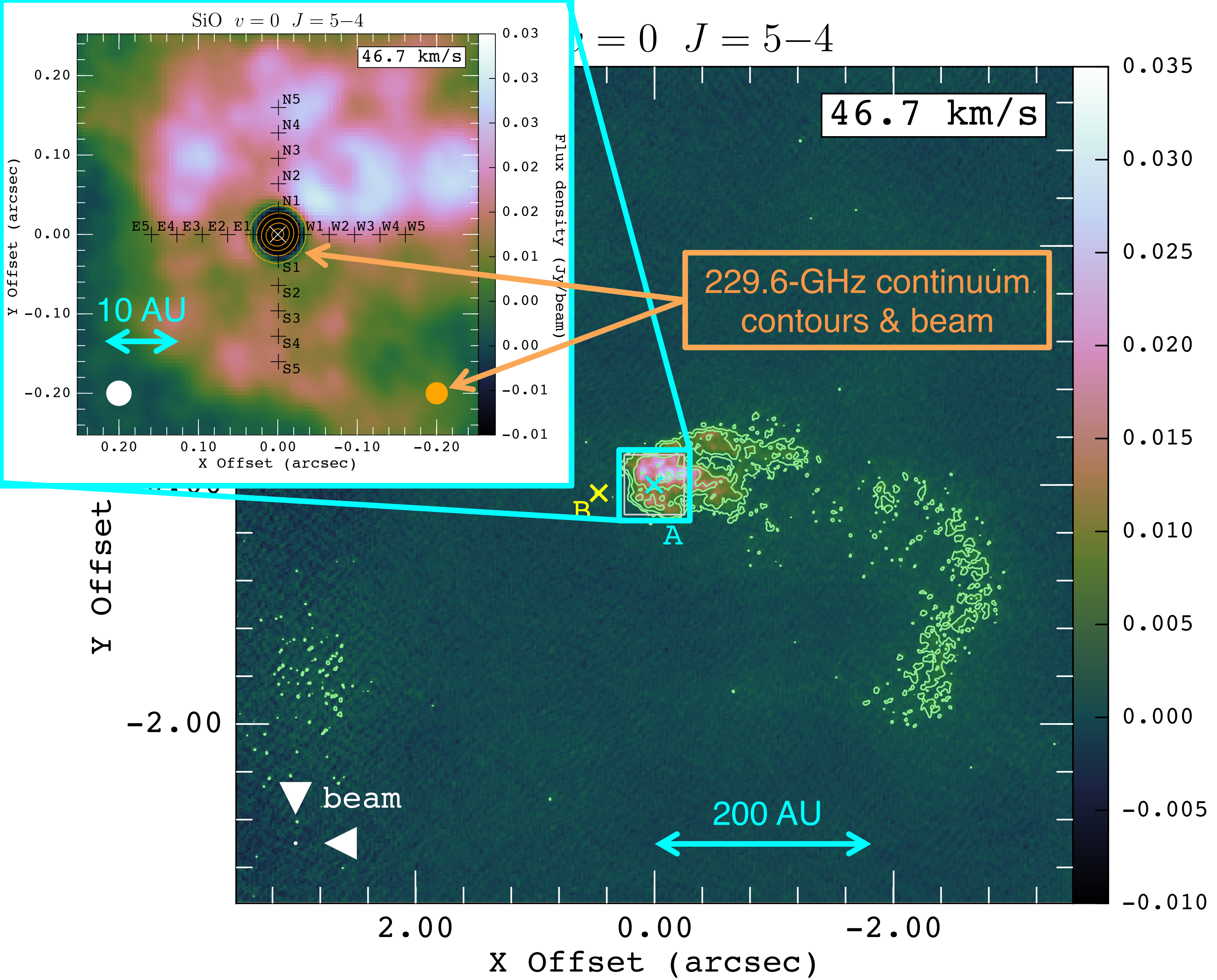
➔ A&A 592, A42



(Fig. 3, Kamiński et al.)

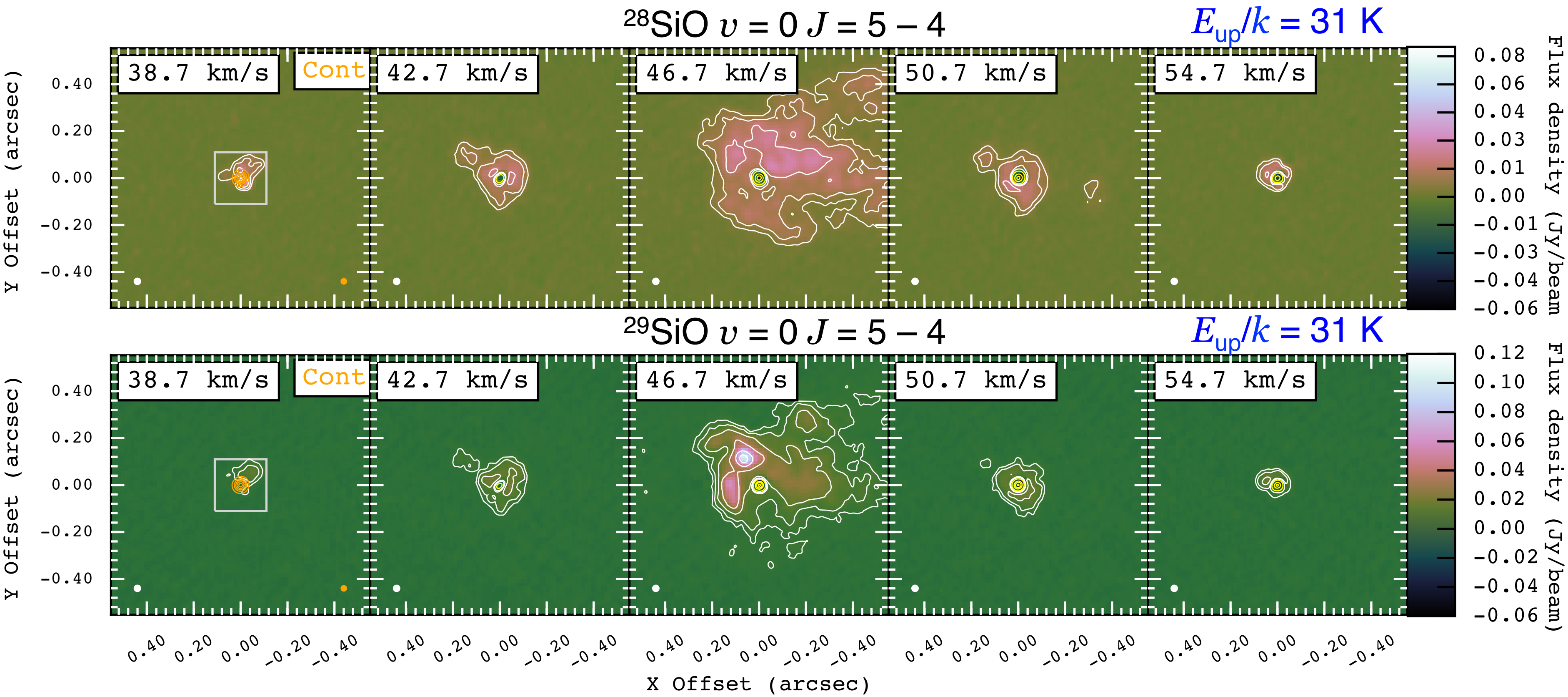


SiO $v = 0$ $J = 5–4$
46.7 km/s
B
A
beam
200 AU
2.00
0.00
−2.00
X Offset (arcsec)
Y Offset (arcsec)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
Flux density (Jy/beam)

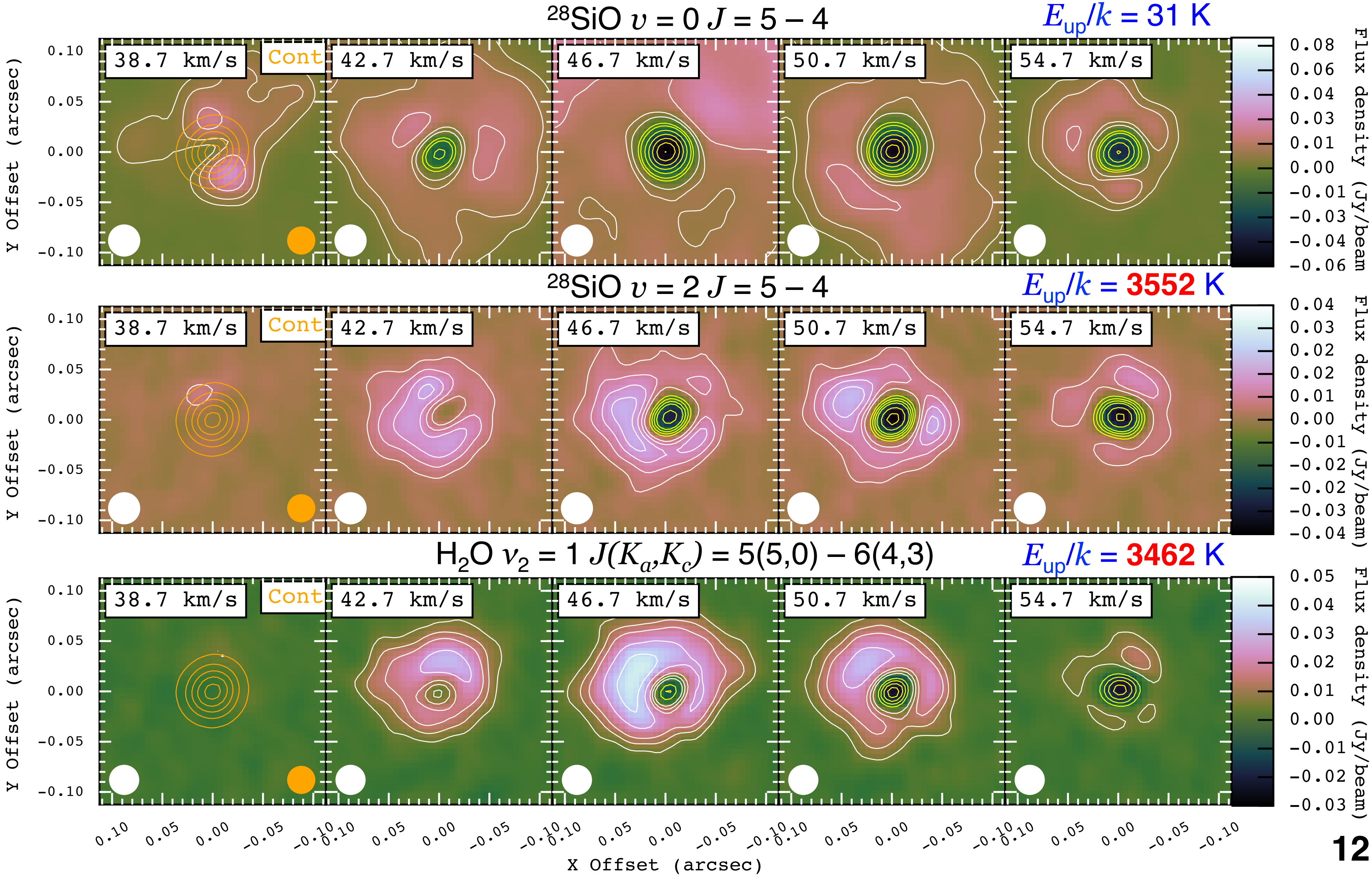


SiO $v=0$ $J=5-4$
46.7 km/s
N5
N4
N3
N2
N1
E5 E4 E3 E2 E1
W1 W2 W3 W4 W5
S1
S2
S3
S4
S5
10 AU
Y Offset (arcsec)
X Offset (arcsec)
Flux density (Jy/beam)
$v=0$ $J=5-4$
46.7 km/s
229.6-GHz continuum contours & beam
B
A
beam
200 AU
Y Offset
X Offset (arcsec)
Flux density (Jy/beam)

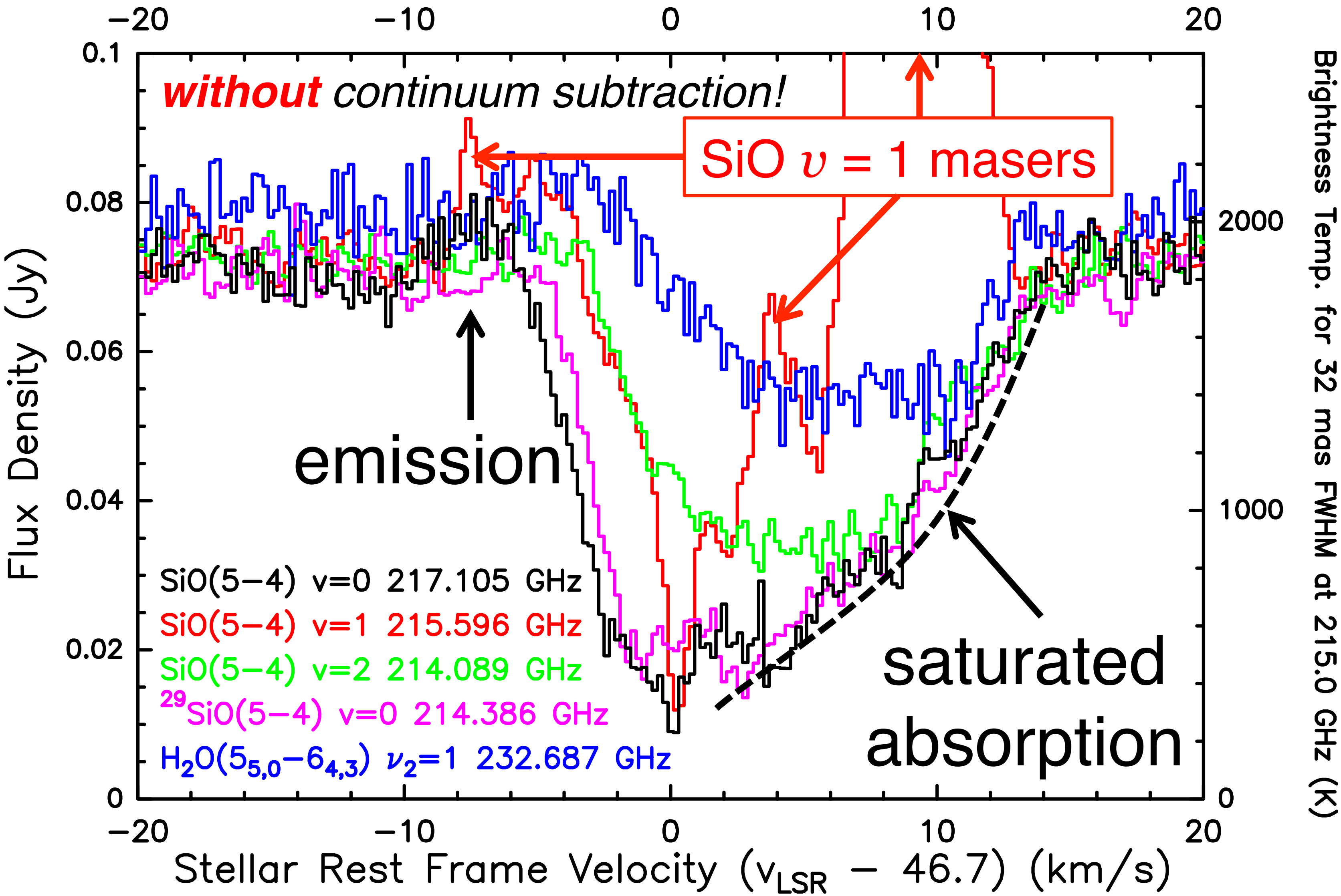
Channel maps: SiO & ^{29}SiO $\upsilon = 0$



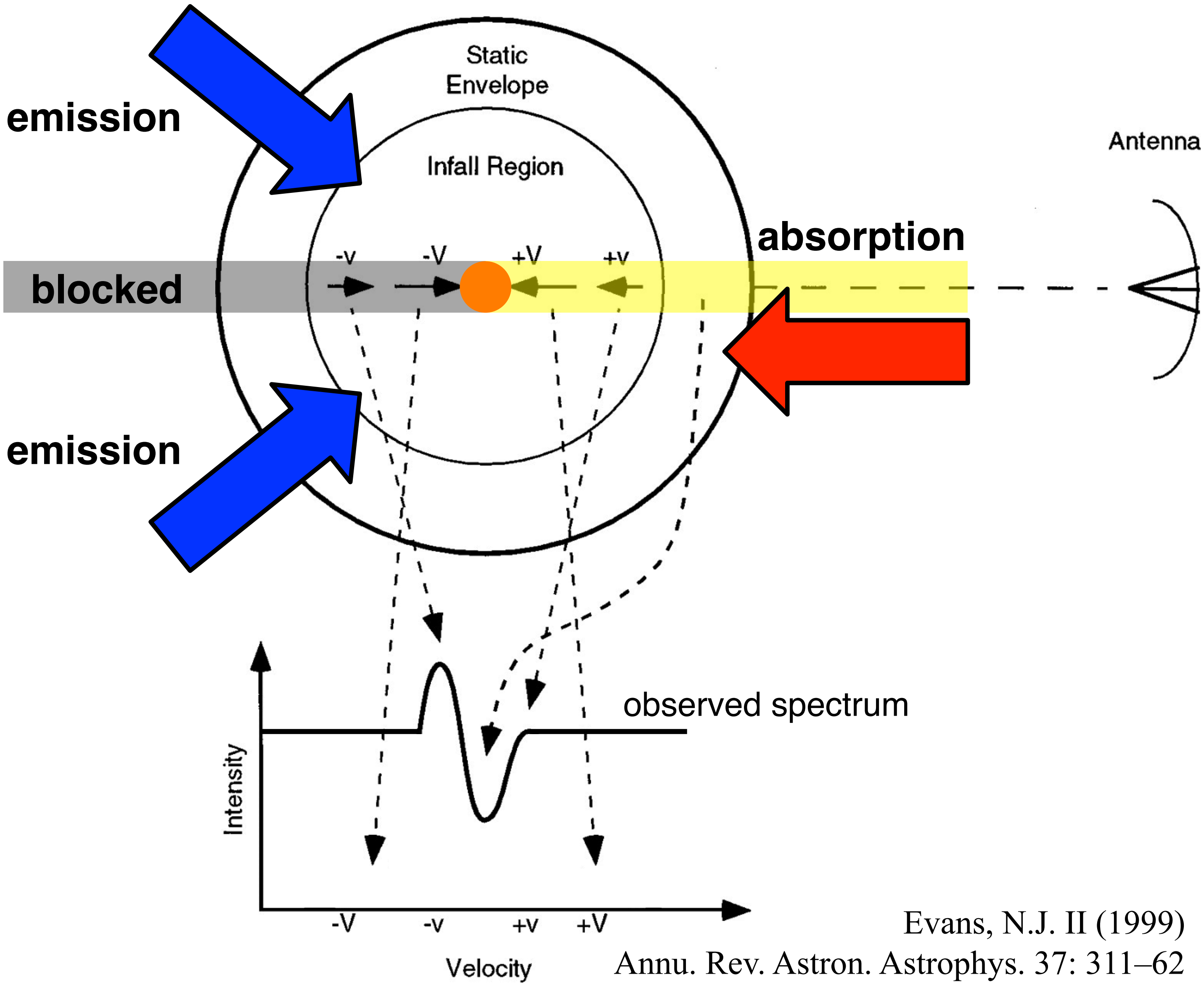
Channel maps: SiO $\upsilon = 2$ & H_2O $\nu_2 = 1$



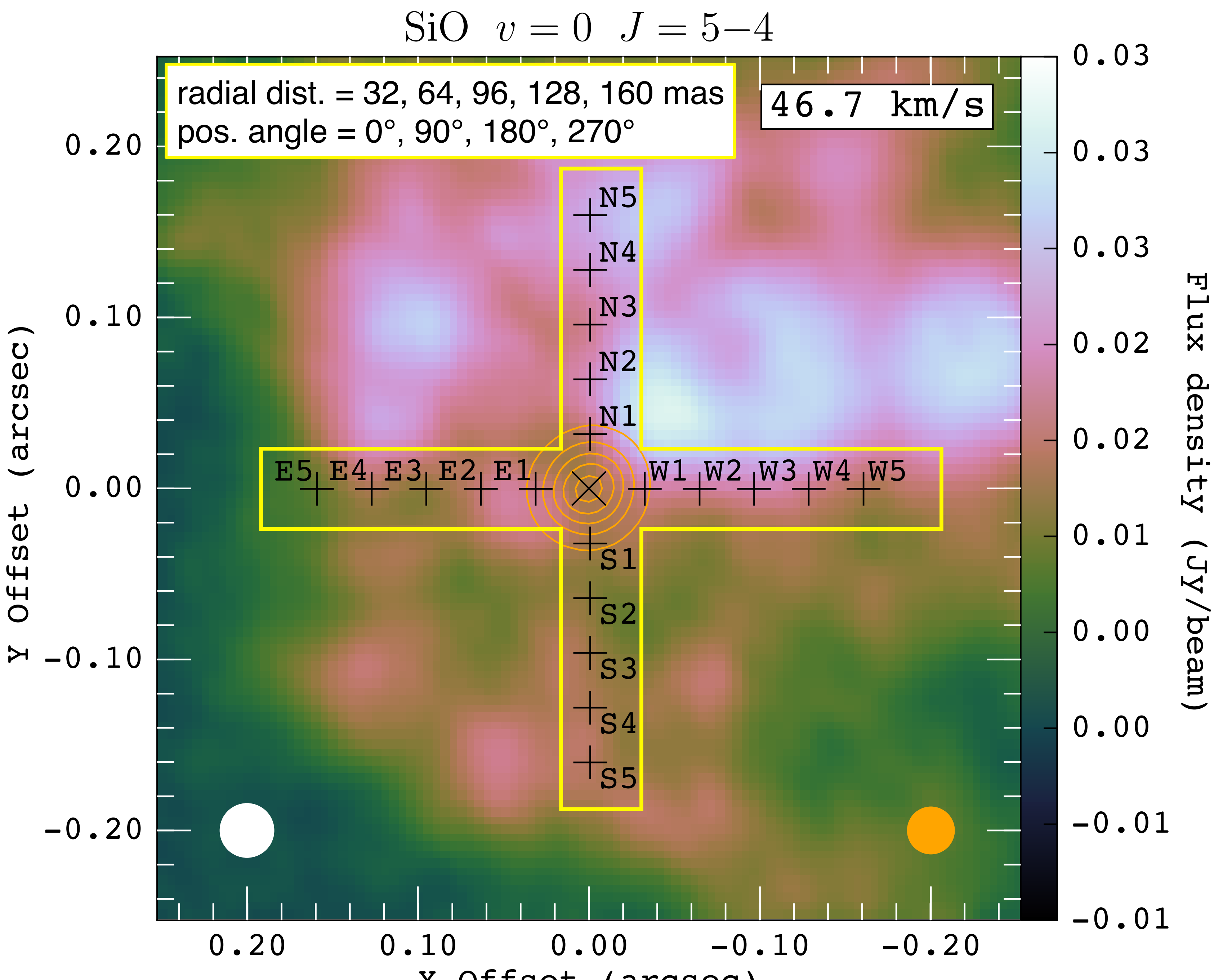
SiO & H_2O spectra

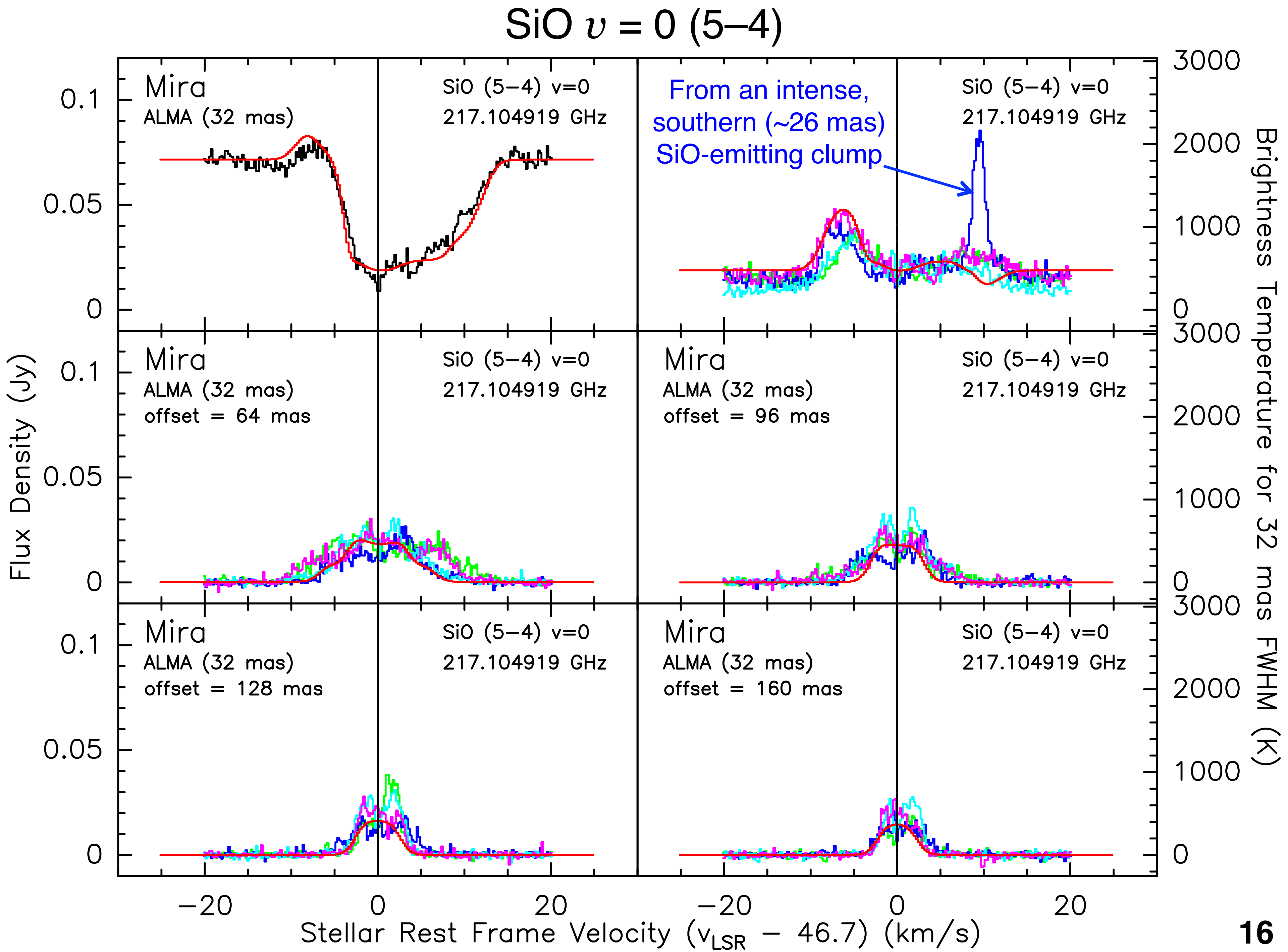


Inverse P-Cygni profile

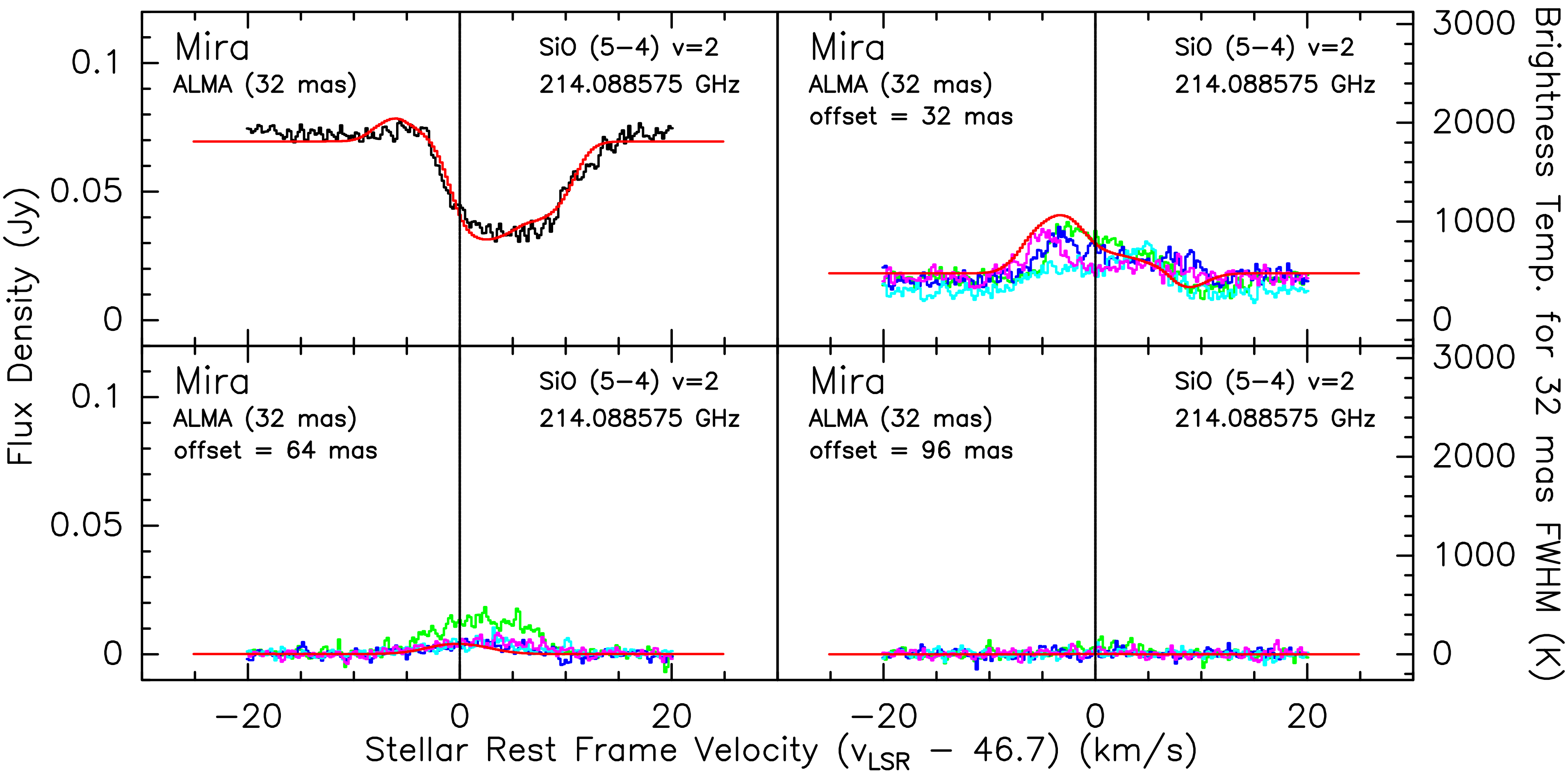


Evans, N.J. II (1999)
Annu. Rev. Astron. Astrophys. 37: 311–62

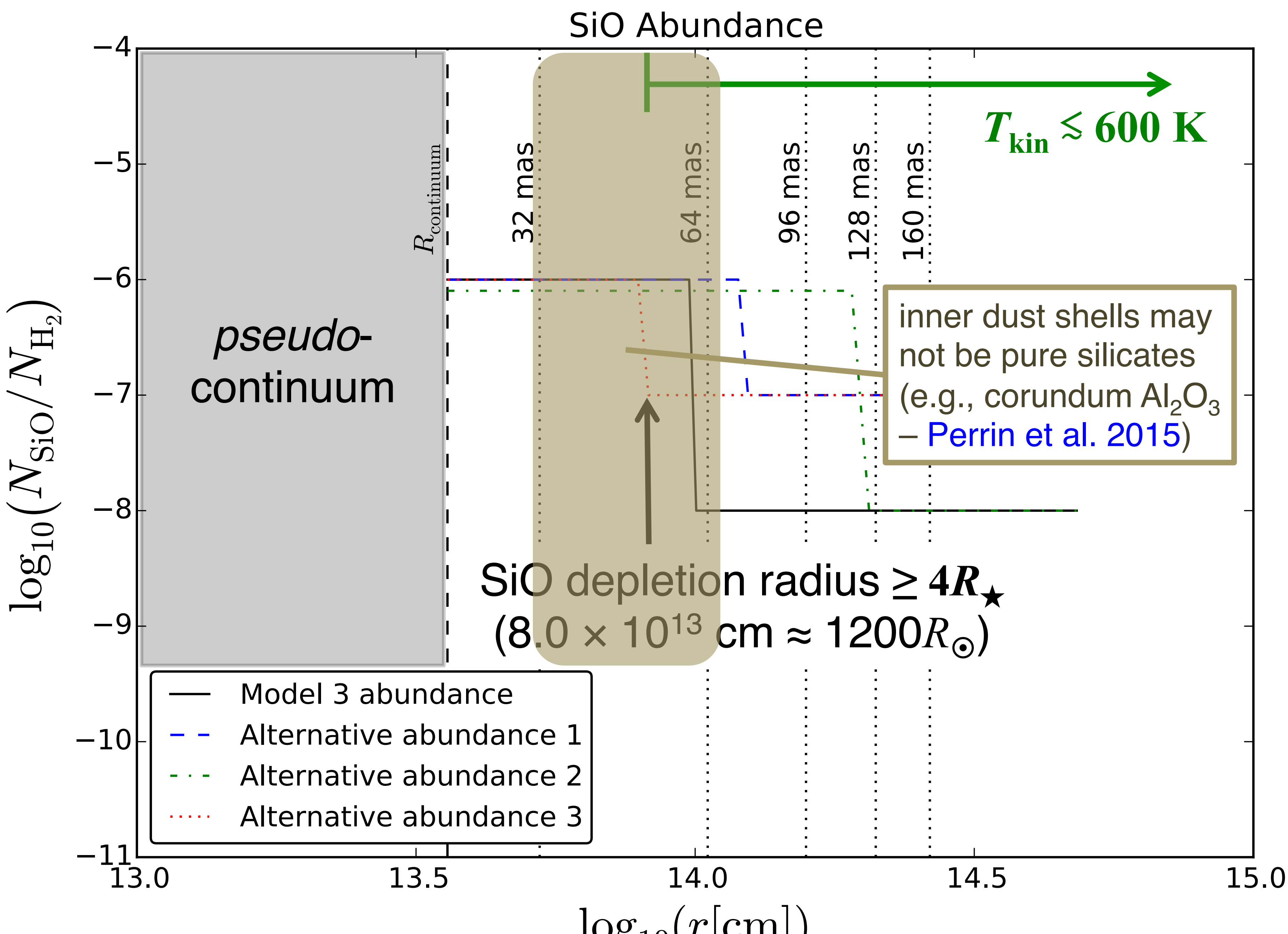

SiO $v=0$ $J=5-4$
radial dist. = 32, 64, 96, 128, 160 mas
pos. angle = 0°, 90°, 180°, 270°
46.7 km/s
N5
N4
N3
N2
N1
E5 E4 E3 E2 E1
W1 W2 W3 W4 W5
S1
S2
S3
S4
S5
0.20
0.10
0.00
−0.10
−0.20
Y Offset (arcsec)
X Offset (arcsec)
0.03
0.03
0.03
0.02
0.02
0.01
0.00
0.00
−0.01
−0.01
Flux density (Jy/beam)


SiO v = 0 (5–4)
Mira
ALMA (32 mas)
SiO (5–4) v=0
217.104919 GHz
From an intense, southern (~26 mas) SiO-emitting clump
offset = 64 mas
offset = 96 mas
offset = 128 mas
offset = 160 mas
Flux Density (Jy)
Brightness Temperature for 32 mas FWHM (K)
Stellar Rest Frame Velocity (v_{LSR} − 46.7) (km/s)
0.1
0.05
0
3000
2000
1000
−20
20

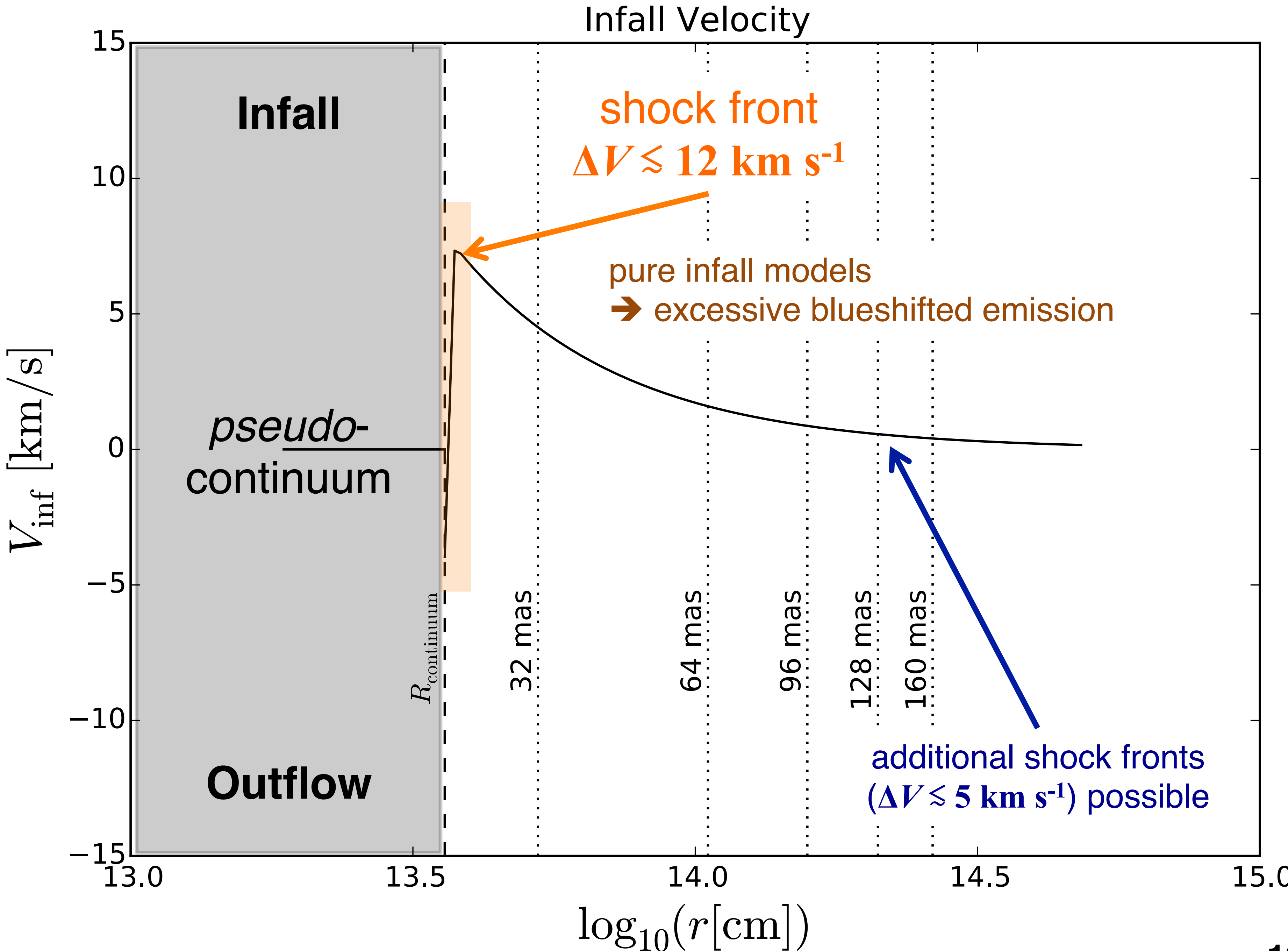
SiO $v = 2$ (5–4)



Mira
ALMA (32 mas)
SiO (5–4) v=2
214.088575 GHz
Mira
ALMA (32 mas)
offset = 32 mas
SiO (5–4) v=2
214.088575 GHz
Mira
ALMA (32 mas)
offset = 64 mas
SiO (5–4) v=2
214.088575 GHz
Mira
ALMA (32 mas)
offset = 96 mas
SiO (5–4) v=2
214.088575 GHz
Flux Density (Jy)
0.1
0.05
0
Brightness Temp. for 32 mas FWHM (K)
3000
2000
1000
0
−20
0
20
Stellar Rest Frame Velocity (vLSR − 46.7) (km/s)

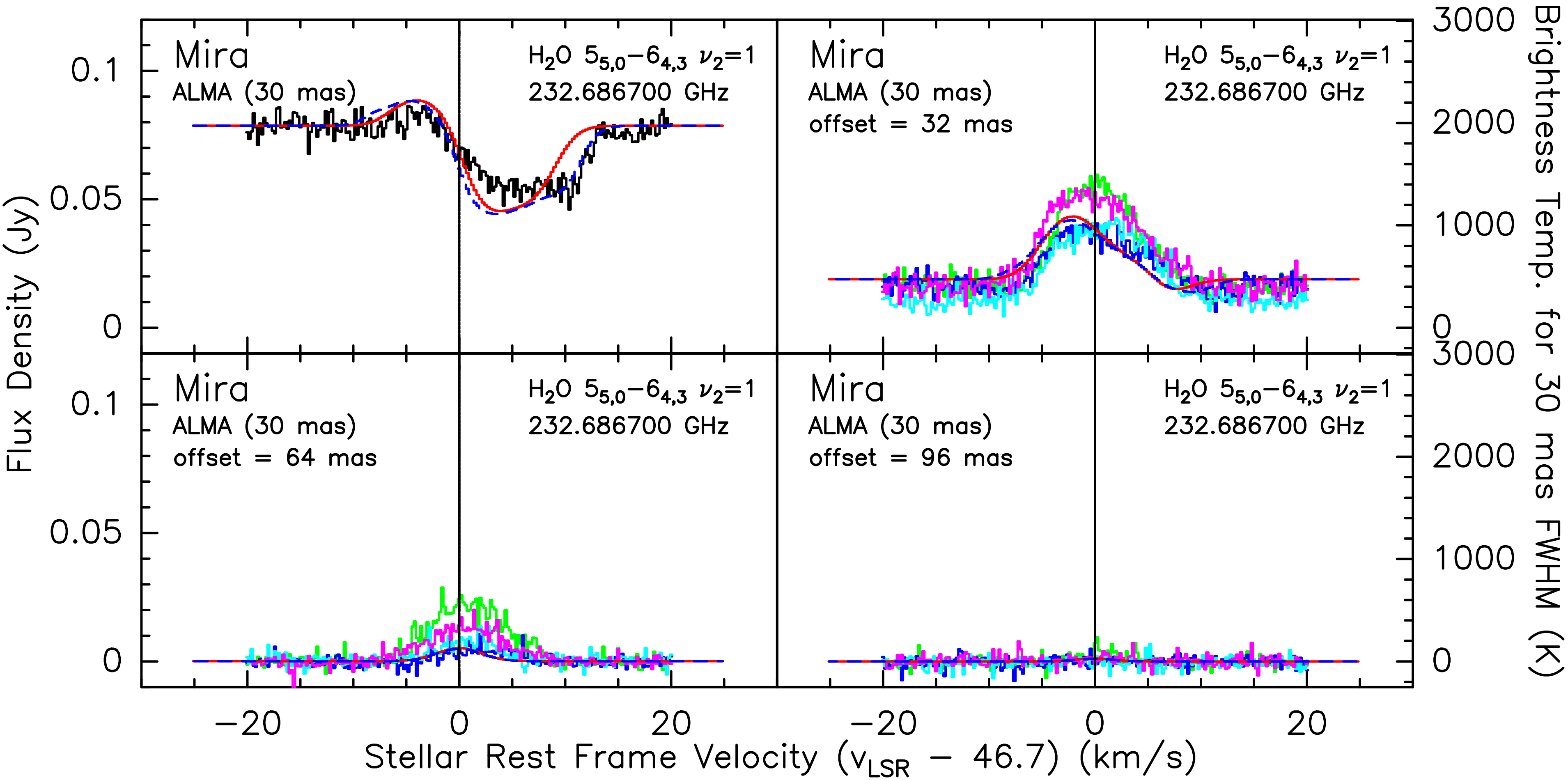


SiO Abundance
$T_{kin} \lesssim 600$ K
$R_{continuum}$
32 mas
64 mas
96 mas
128 mas
160 mas
pseudo-
continuum
inner dust shells may not be pure silicates (e.g., corundum Al_2O_3 – Perrin et al. 2015)
SiO depletion radius ≥ $4R_\star$
(8.0×10^{13} cm ≈ $1200R_\odot$)
Model 3 abundance
Alternative abundance 1
Alternative abundance 2
Alternative abundance 3
$\log_{10}(N_{SiO}/N_{H_2})$
$\log_{10}(r[cm])$
−4
−5
−6
−7
−8
−9
−10
−11
13.0
13.5
14.0
14.5
15.0

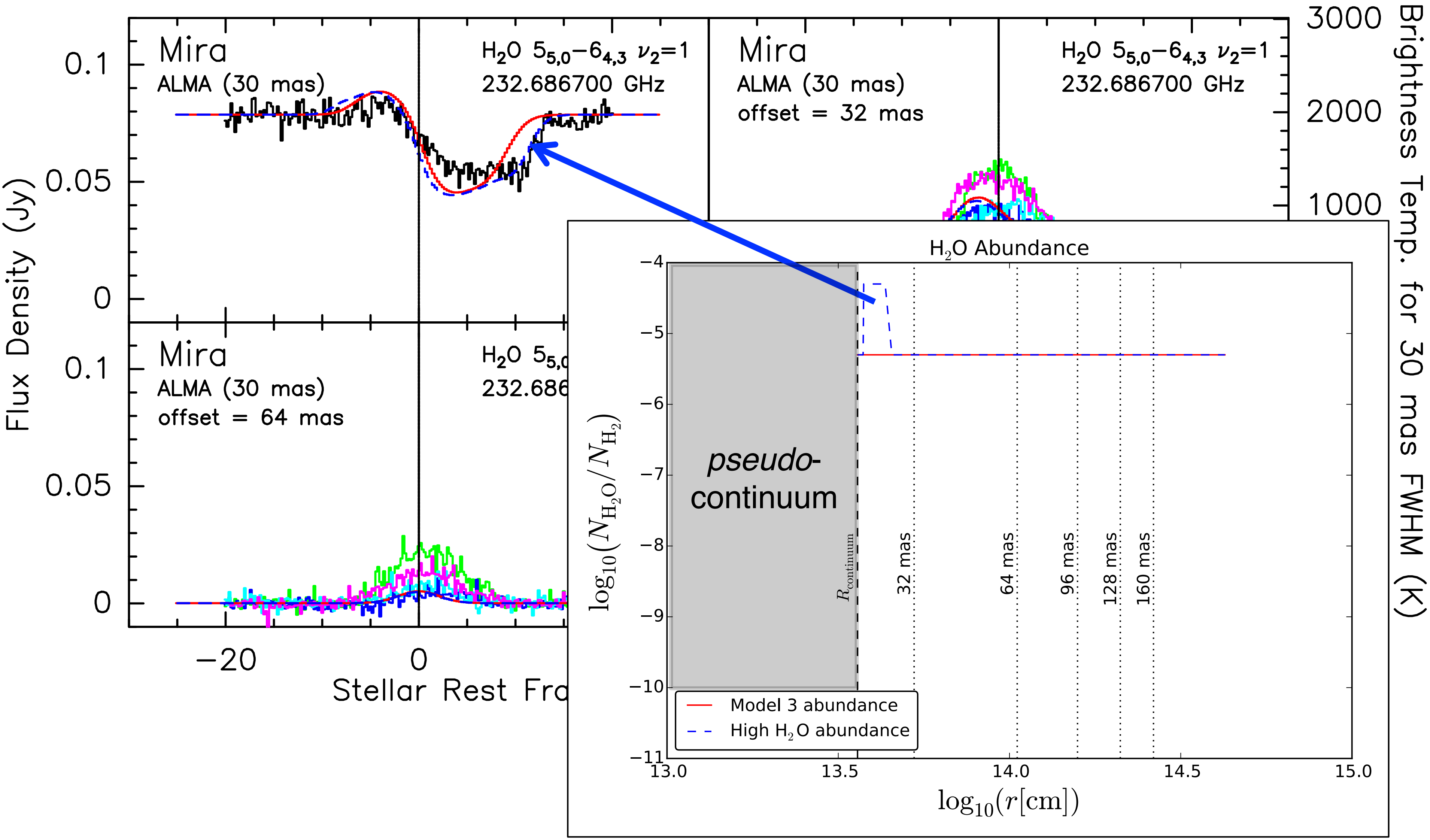


Infall Velocity
Infall
shock front
ΔV ≲ 12 km s-1
pure infall models
➔ excessive blueshifted emission
pseudo-
continuum
Outflow
R_continuum
32 mas
64 mas
96 mas
128 mas
160 mas
additional shock fronts
(ΔV ≲ 5 km s-1) possible
V_inf [km/s]
log10(r[cm])
15
10
5
0
−5
−10
−15
13.0
13.5
14.0
14.5
15.0

H_2O $\nu_2 = 1$ 5(5,0)–6(4,3)



H_2O $\nu_2 = 1$ 5(5,0)–6(4,3)

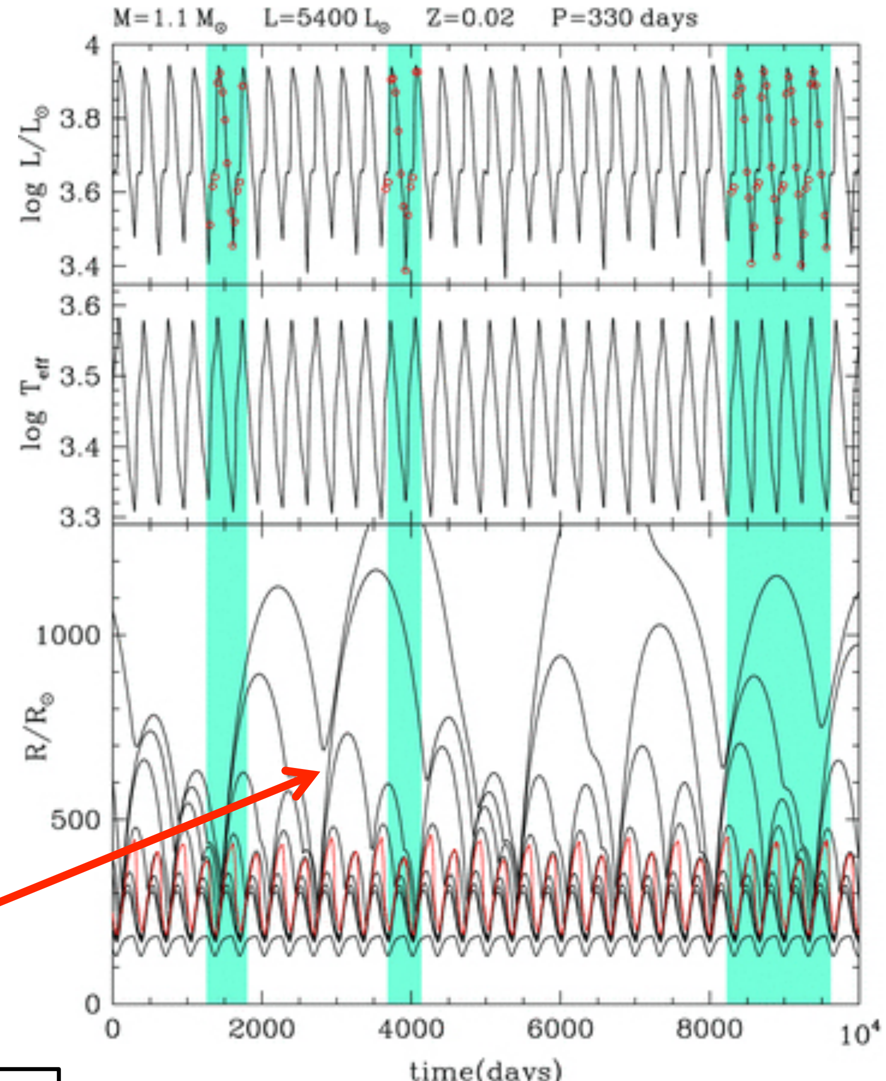


Testing **CODEX** models

- `o54` series: 6 cycles

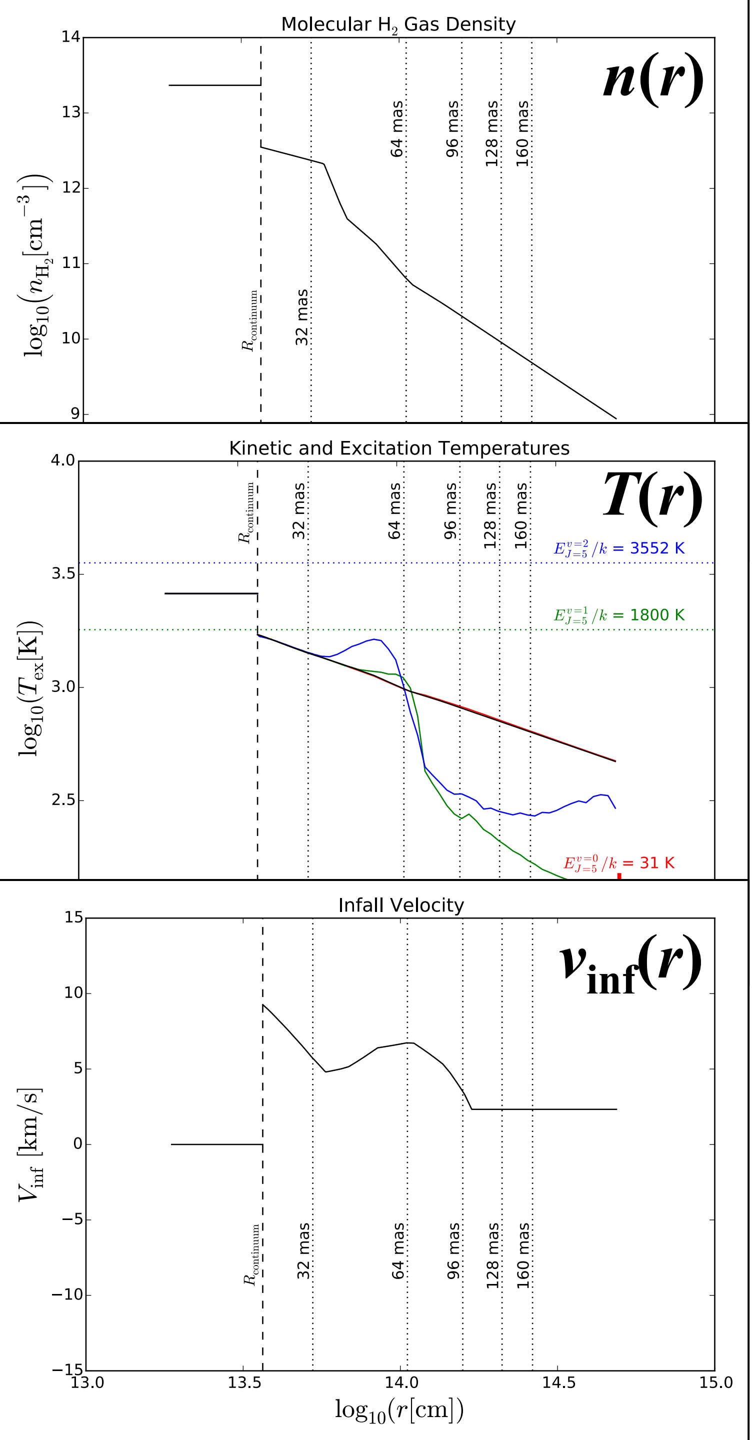
  (Ireland et al. 2008; 2011)
- predict $\rho(r)$, $T(r)$, $v(r)$
- select models near phase ~0.45 (SV obs.)
- reproduce SiO & H_2O spectra

chaotic shocks

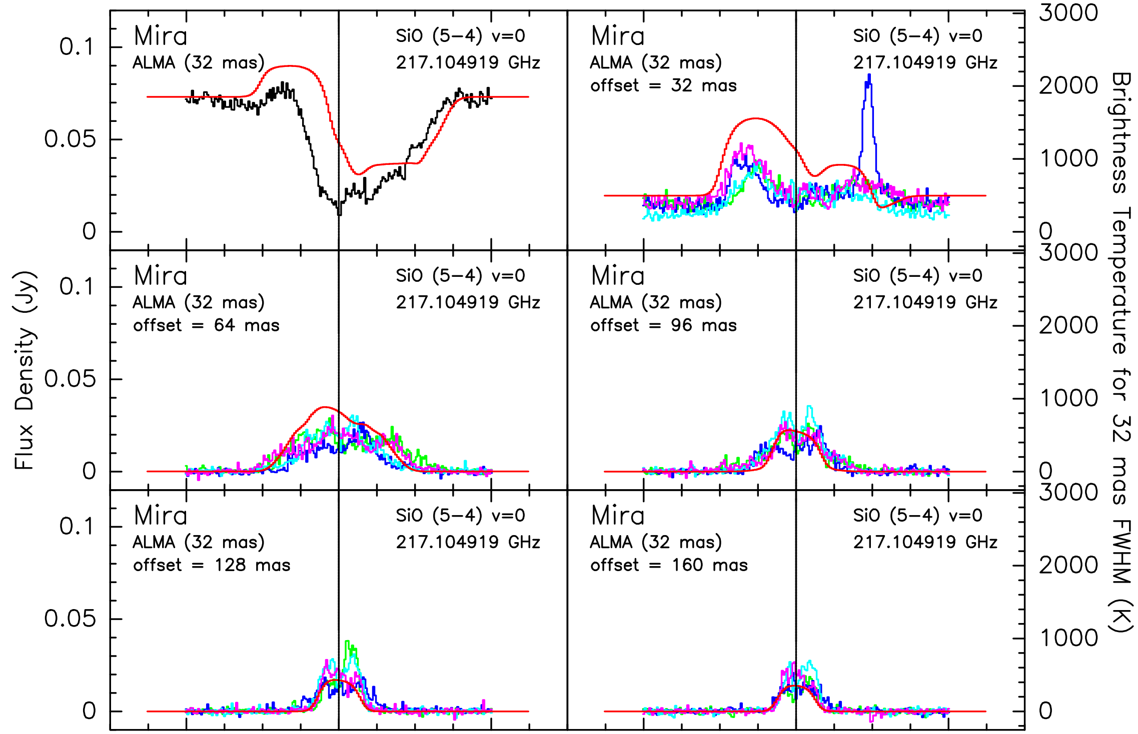


Thanks M. J. Ireland, M. Scholz, and P. R. Wood for providing the results of the ***o54*** *model series.*

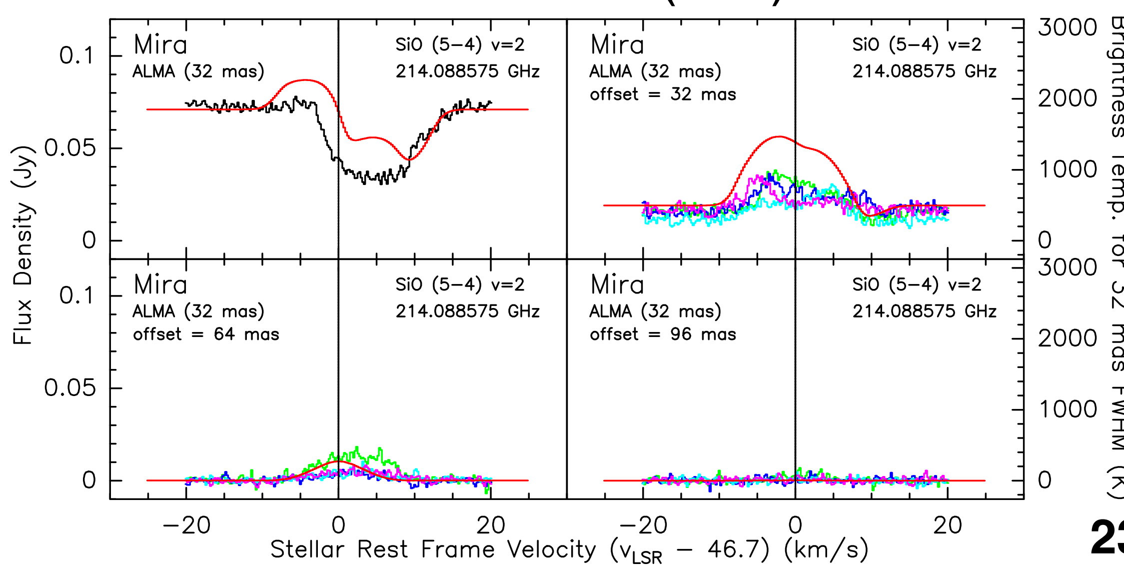
M. J. Ireland et al. MNRAS 2011; 418:114-128



SiO $v = 0$ (5–4)



SiO $v = 2$ (5–4)



CODEX models

- $\boldsymbol{n_{\mathrm{H_2}}(r) \gtrsim 10^{12}}$ **cm^{-3}** near radio photosphere to reproduce enough absorption (consistent with Reid & Menten 1997 & Yamamura et al. 1999)
- $\rho(r)$ ➔ $n_{\mathrm{H_2}}(r)$: gas density underestimated by $10^2 - 10^4$ times

Summary

1. ALMA long baselines clearly resolve SiO & H_2O **line absorption** against Mira's radio continuum.
2. Gas-phase SiO starts to deplete significantly at radius $\geq 4R_\star$ and temperature $T_{\mathrm{kin}} \lesssim 600$ K.
3. The extended atmosphere generally shows **infall** motion, with shock velocity $\Delta V \lesssim 12$ km s^{-1}.
4. Hydrodyn. models from **`CODEX`** can predict the atmospheric structures in remarkable detail.

A&A 590, A127