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

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submitted to A&A

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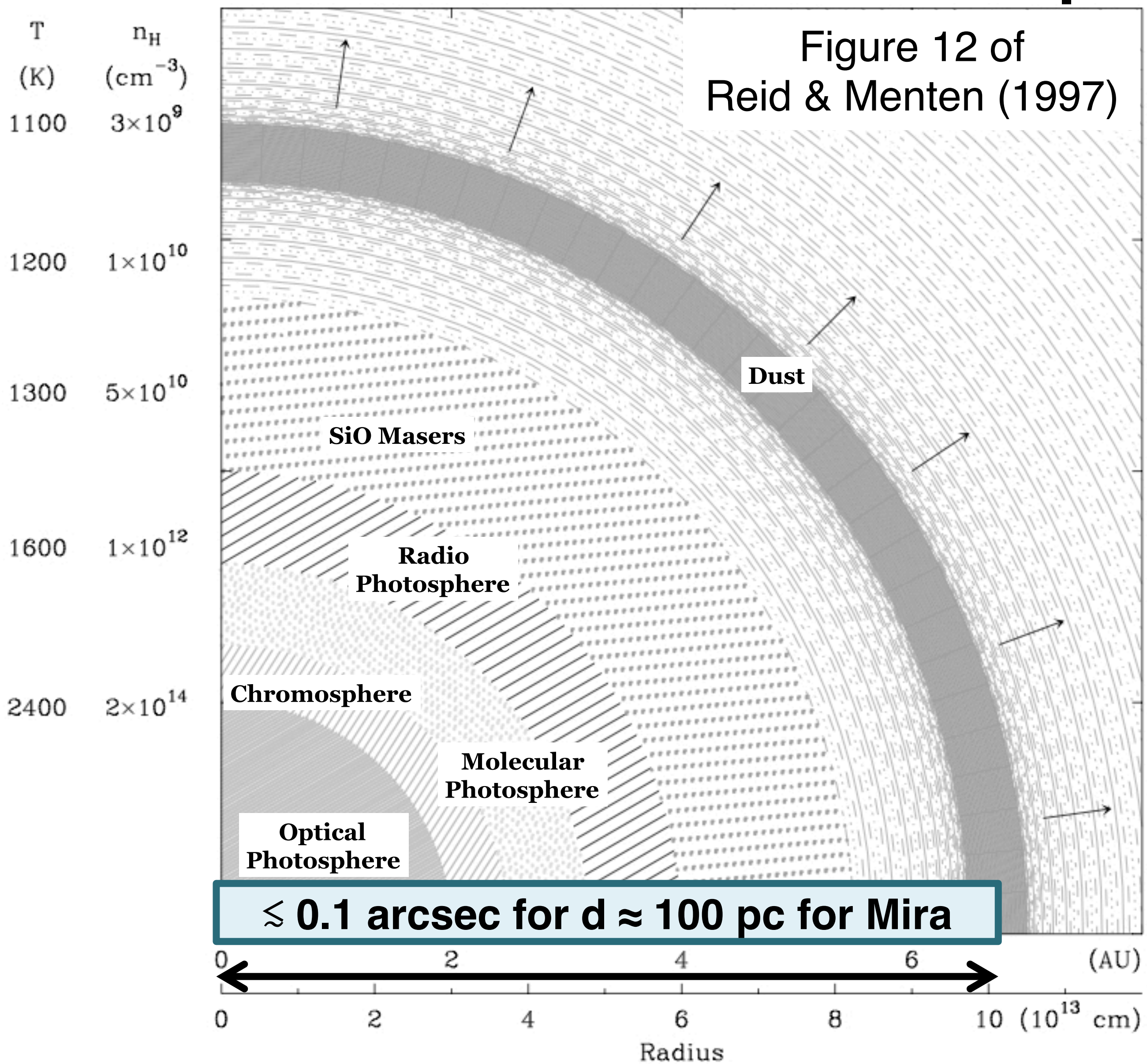
IMPRS astronomy & astrophysics Bonn and Cologne

bcgs Bonn-Cologne Graduate School of Physics and Astronomy

Max-Planck-Institut für Radioastronomie

Extended Atmospheres



Hydrodynamical models

- Ireland/Scholz/Wood (2008; 2011; 2014)
  - ✧ **CODEX** model series
- Höfner et al. (2003)
  - ✧ carbon-rich stars
- Jeong et al. (2003)
  - ✧ O-rich IRC –20197
  - ✧ predict IR SEDs

Probing the extended atmosphere

- SiO/H_2O maser emission (VLA/VLBA)
  (e.g. Reid & Menten 97; Cotton+ & Perrin+ 04, 09, 10, 15)
- Molecular absorption spectroscopy (ISO)
  ➔ MOLsphere (e.g. Tsuji+ 97, Tsuji 00; Woitke+ 99)
- Mid-IR interferometry (VLTI)
  (e.g. Ohnaka et al. 2005; Karovicova et al. 2011)

ALMA → High **spatial resolution** images

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

ALMA SV observation

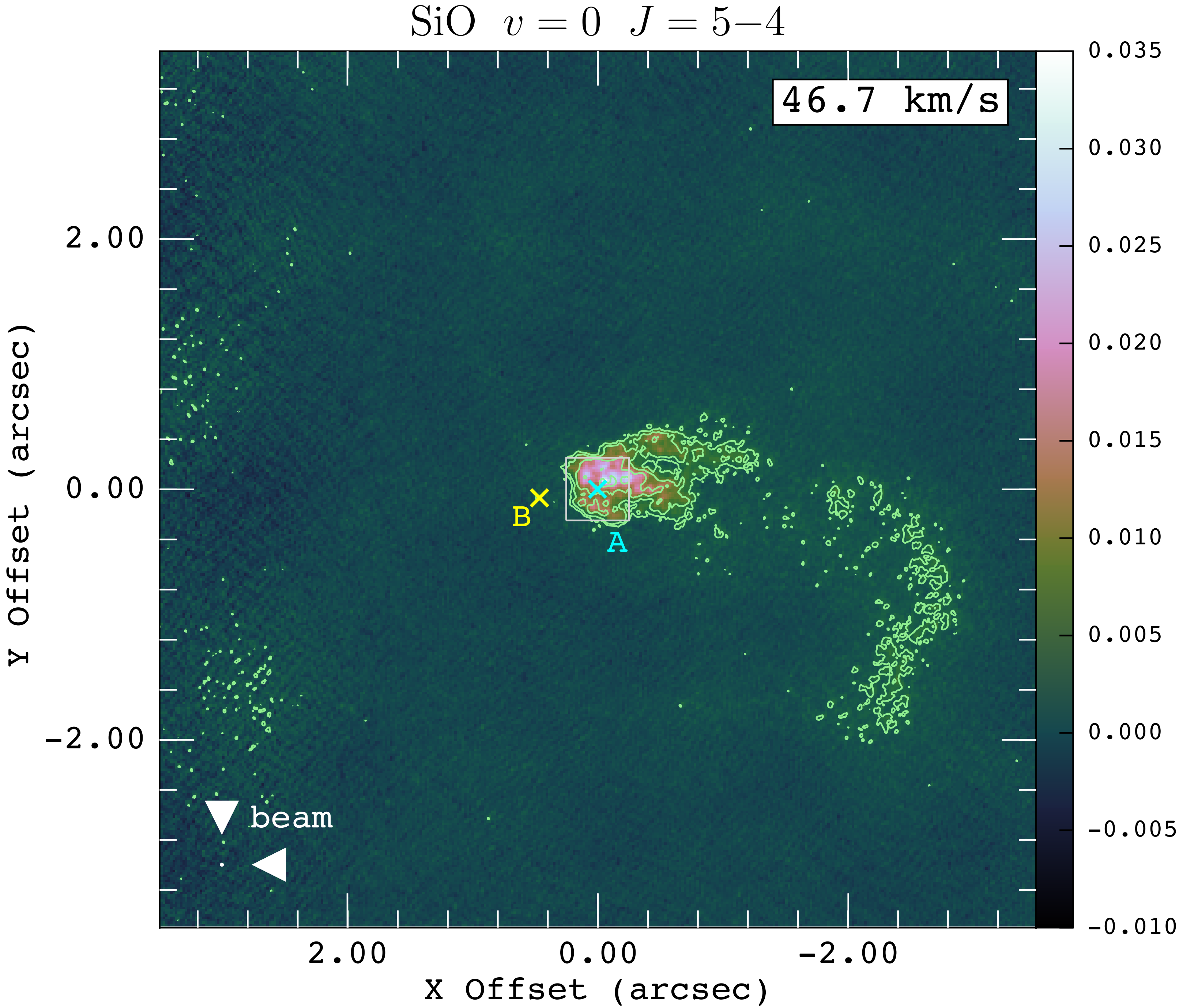
- Mira (= Mira A = *o* Cet) – the prototypical Mira variable
- 2014 ALMA Long Baseline Campaign Science Verification (ALMA Partnership et al. 2015)
- Longest baseline = 15.24 km
- Bands 3 (90 GHz) & **6 (220 GHz)** **(this work)**
- Angular resolution at 220 GHz $\lesssim$ **30 mas**

  ➔ resolving the radio continuum of Mira!

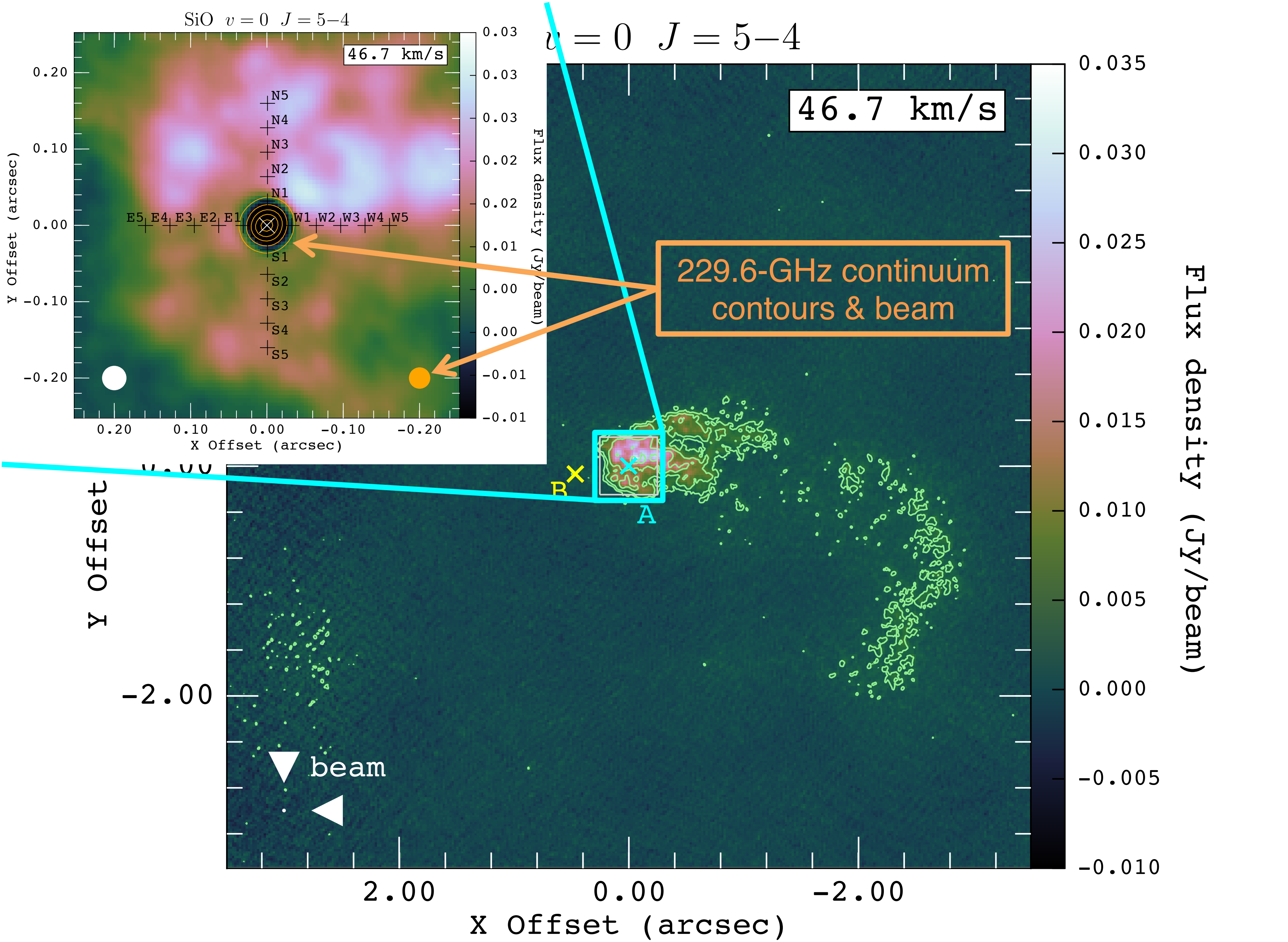
  (Matthews et al. 2015; Vlemmings et al. 2015; this work)

ALMA SV observation: Band 6

- 229.6 GHz (1.3 mm) continuum
  (Matthews et al. 2015; Vlemmings et al. 2015; this work)
- SiO $v = 0, 1, 2$ $J = 5 - 4$
- ^{29}SiO $v = 0$ $J = 5 - 4$
- H_2O $\nu_2 = 1$ $J(K_a,K_c) = 5(5,0) - 6(4,3)$
- Angular resolution: 30 – 32 mas
- Velocity resolution: 0.08 – 0.17 km/s
- Data calibrated & self-calibrated by staff members of JAO/ARC

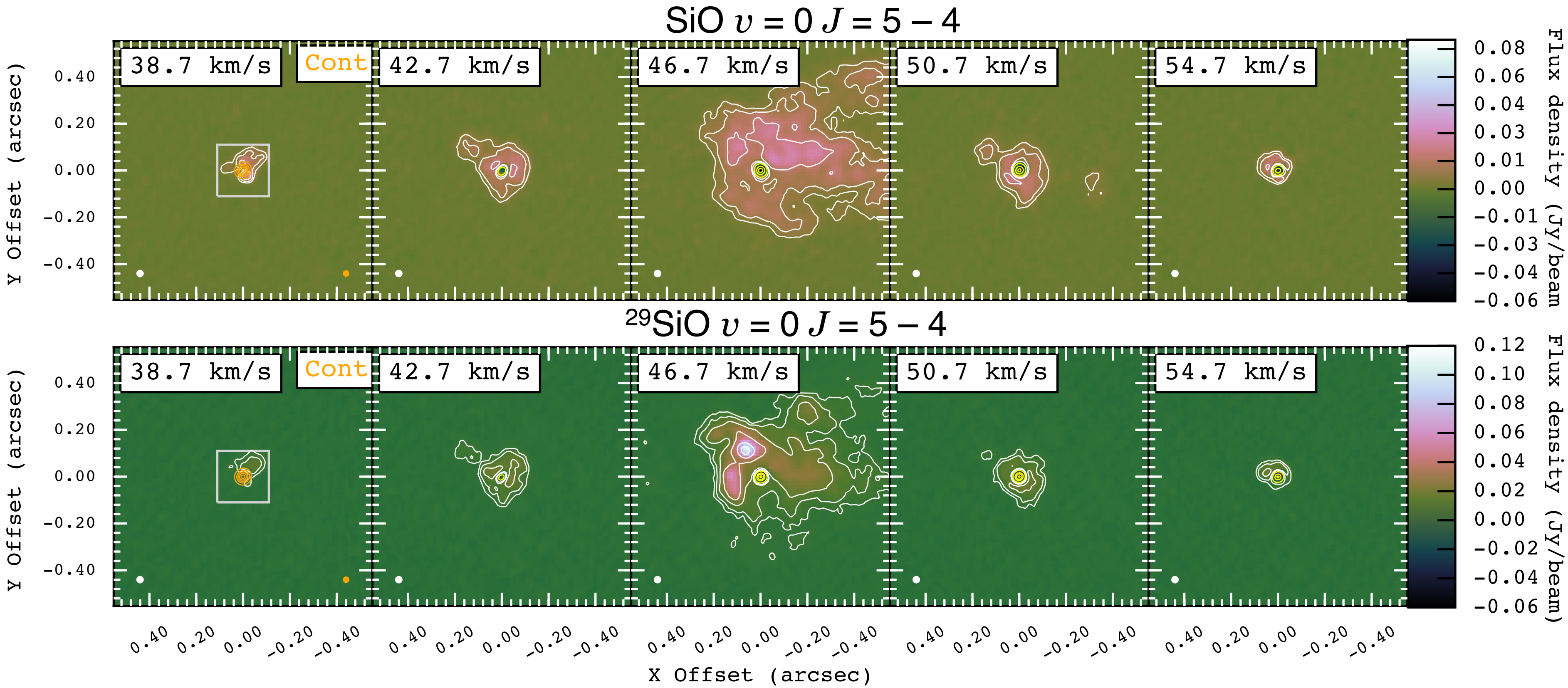


SiO $v = 0$ $J = 5-4$
46.7 km/s
B
A
beam
2.00
0.00
−2.00
2.00
0.00
−2.00
X Offset (arcsec)
Y Offset (arcsec)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
Flux density (Jy/beam)

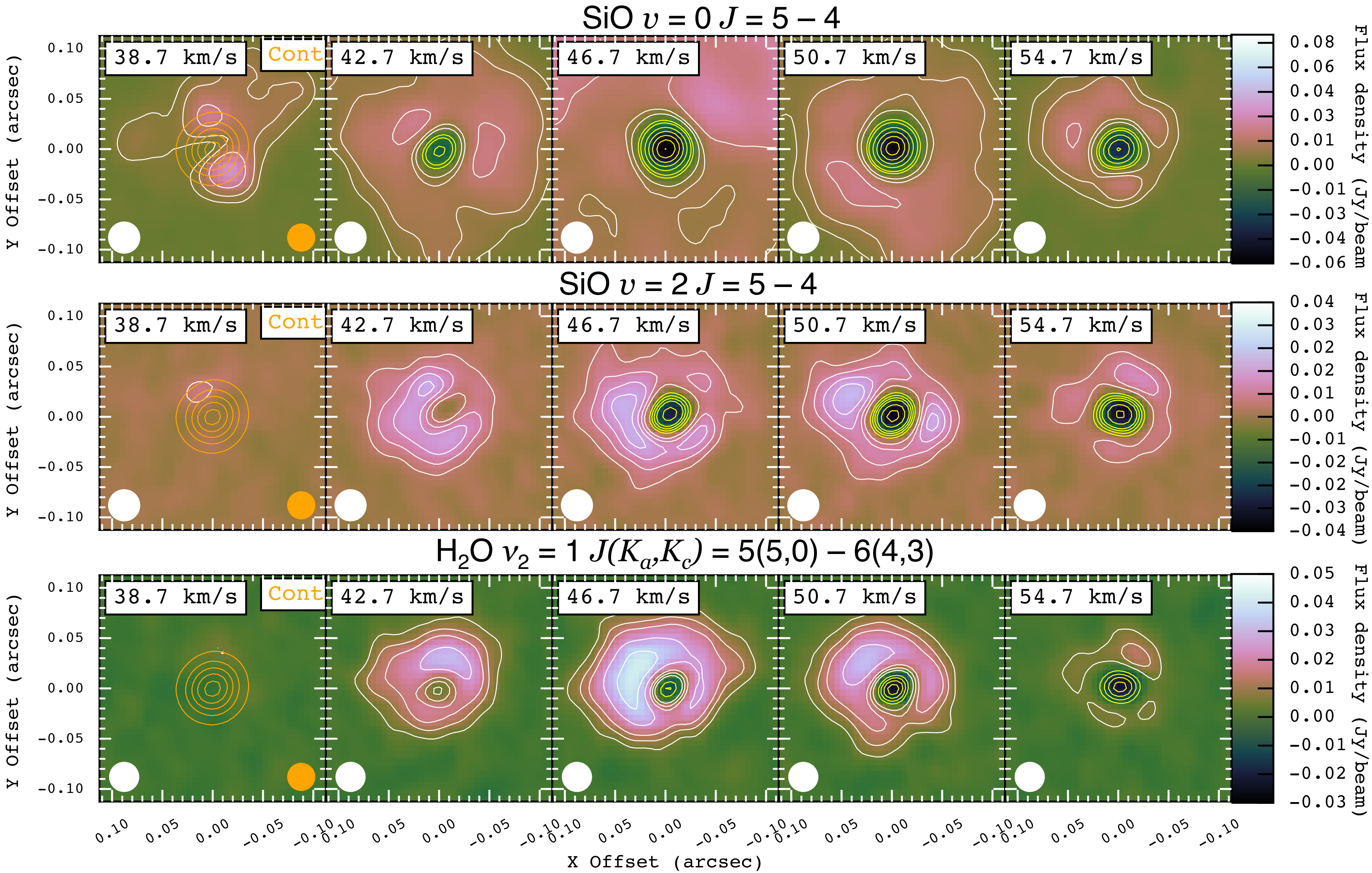


SiO v = 0 J = 5–4
46.7 km/s
N5
N4
N3
N2
N1
E5 E4 E3 E2 E1
W1 W2 W3 W4 W5
S1
S2
S3
S4
S5
Y Offset (arcsec)
X Offset (arcsec)
Flux density (Jy/beam)
229.6-GHz continuum contours & beam
B
A
beam
Y Offset
X Offset (arcsec)
0.035
0.030
0.025
0.020
0.015
0.010
0.005
0.000
−0.005
−0.010
2.00
0.00
−2.00

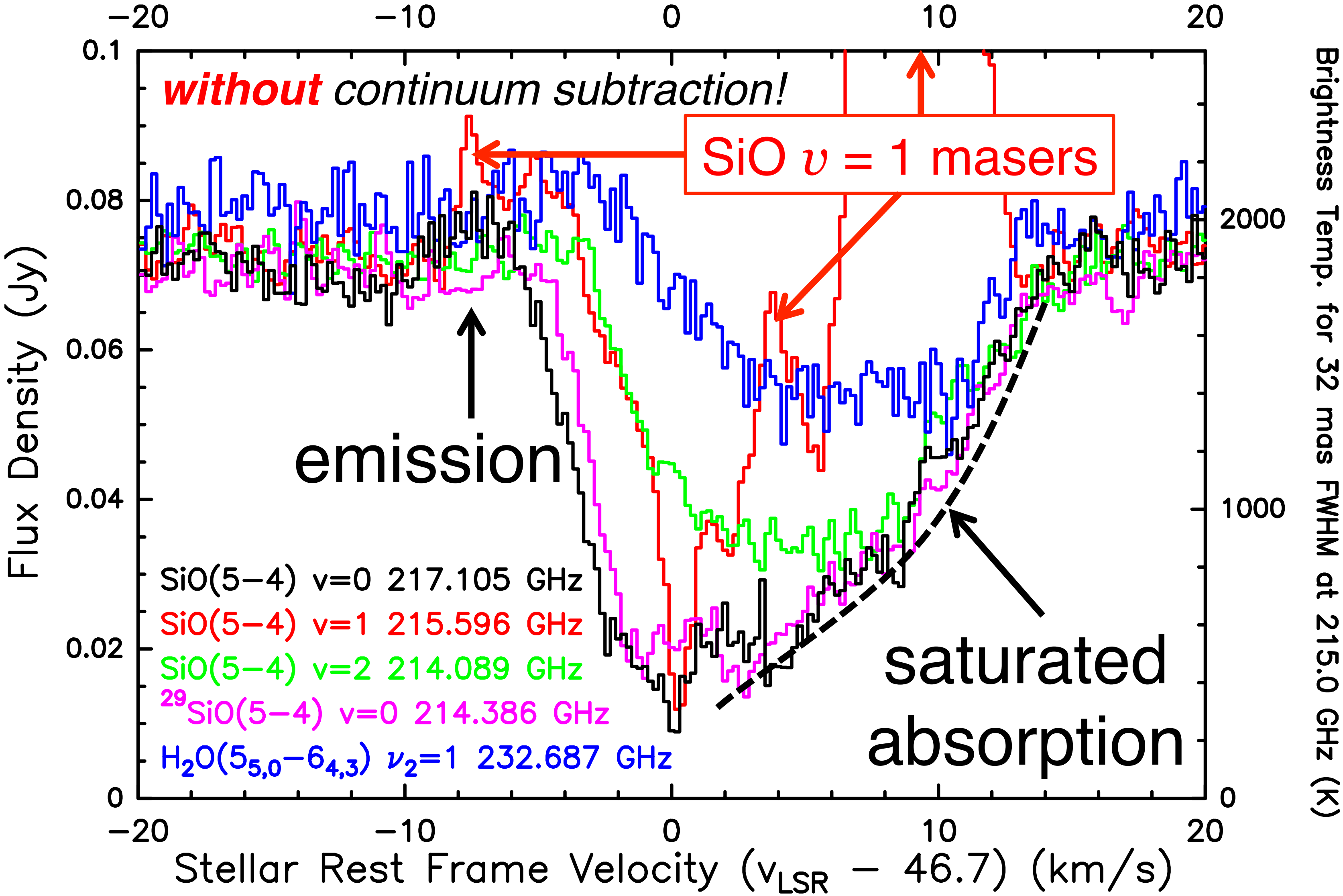
Channel maps: SiO & ^{29}SiO $\upsilon = 0$



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

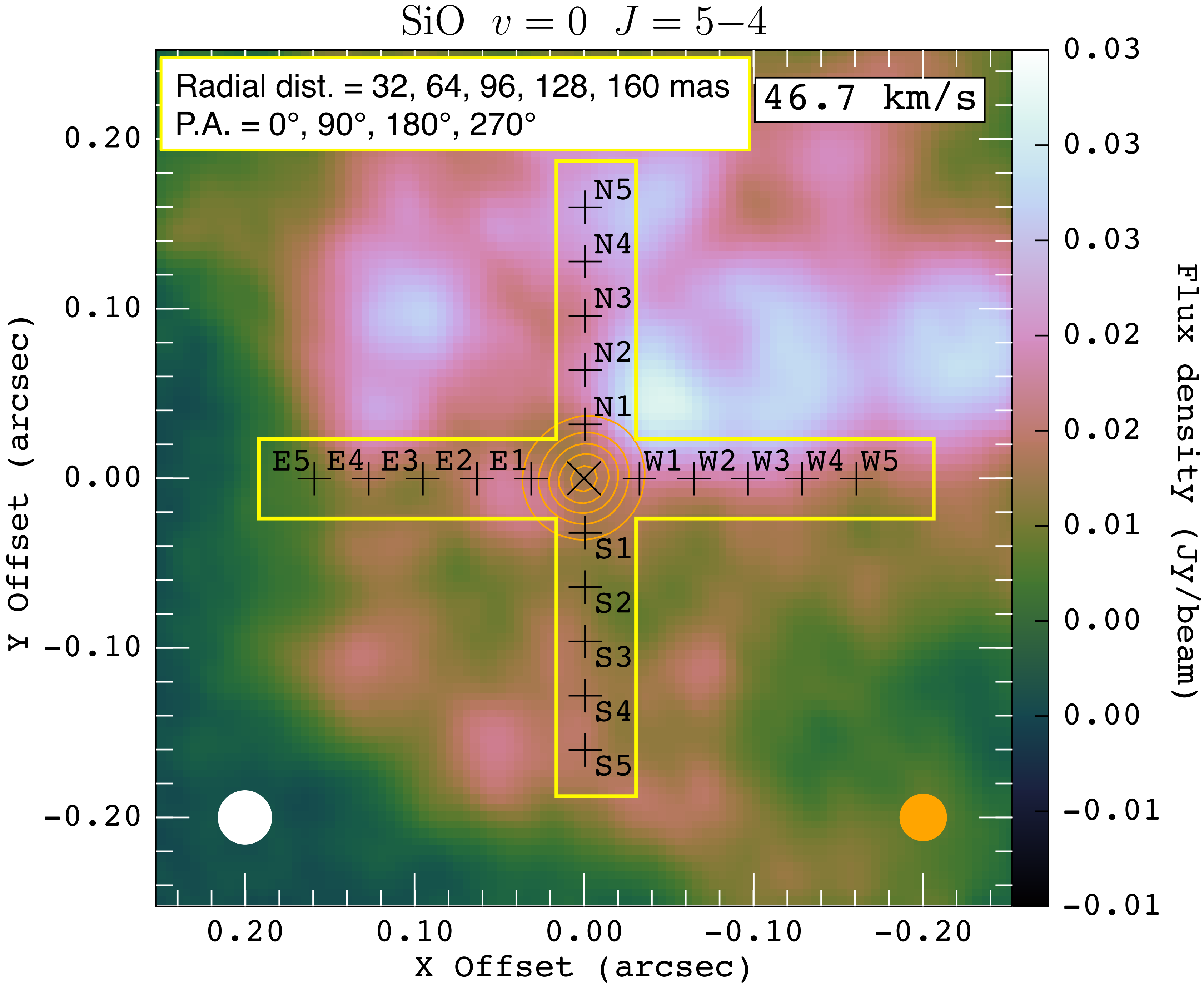


Band 6 SiO & H_2O spectra

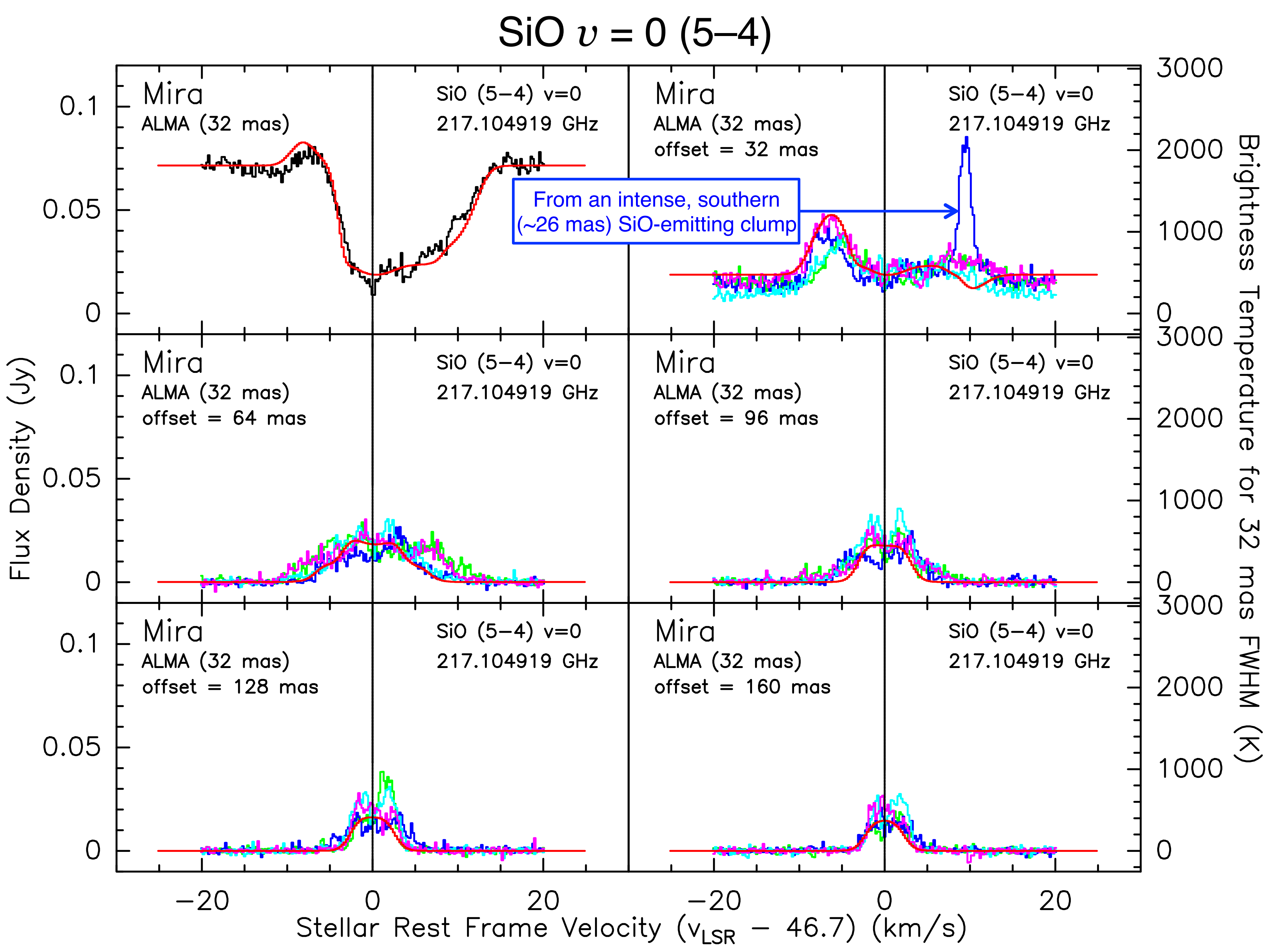


Radiative transfer modelling

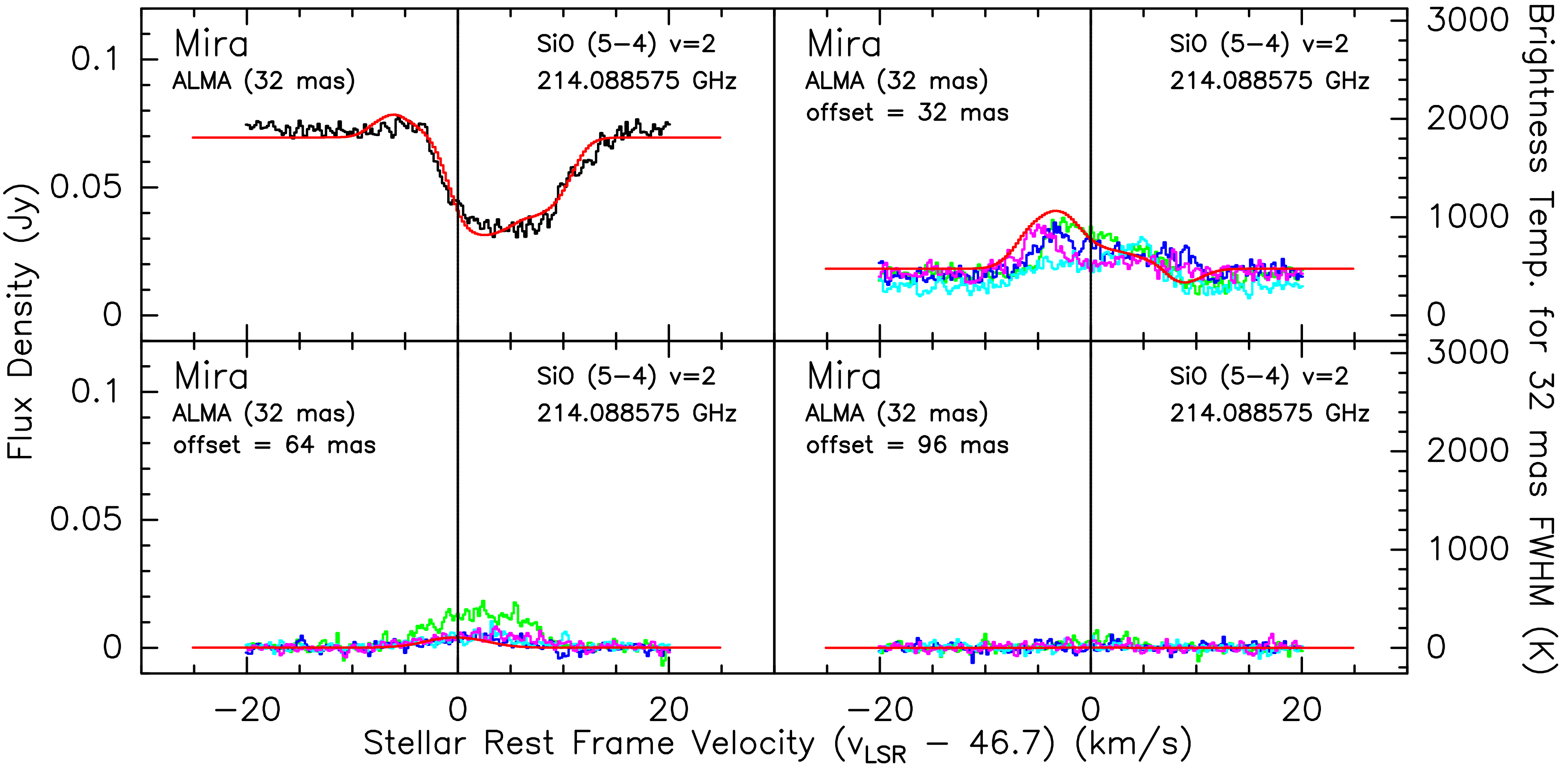
- 1-D code: **`RATRAN`** (Hogerheijde & van der Tak 2000)
- ^{28}SiO $\upsilon = 0, 1, 2$
  - ➢ extrapolated from Bieniek & Green (1983) and Dayou & Balança (2006)
  - ➢ different from Doel+ (1995), Humphreys+ (1996), and Gray+ (2009)
- H_2O $\nu_2 = 0, 1$
  - ➢ truncated LAMDA datafile – $E_{up}/k_B \leq 5130$ K
- *pseudo*-continuum
  - ➢ innermost few grid cells of the 1-D input model
  - ➢ 21.8 mas = 3.6×10^{13} cm; $T_B = 2600$ K ➔ realistic input stellar flux
  - ➢ extremely optically thick (excessive abundance) ➔ “continuum”
  - ➢ very high turbulence velocity (100 km/s) ➔ flat spectrum



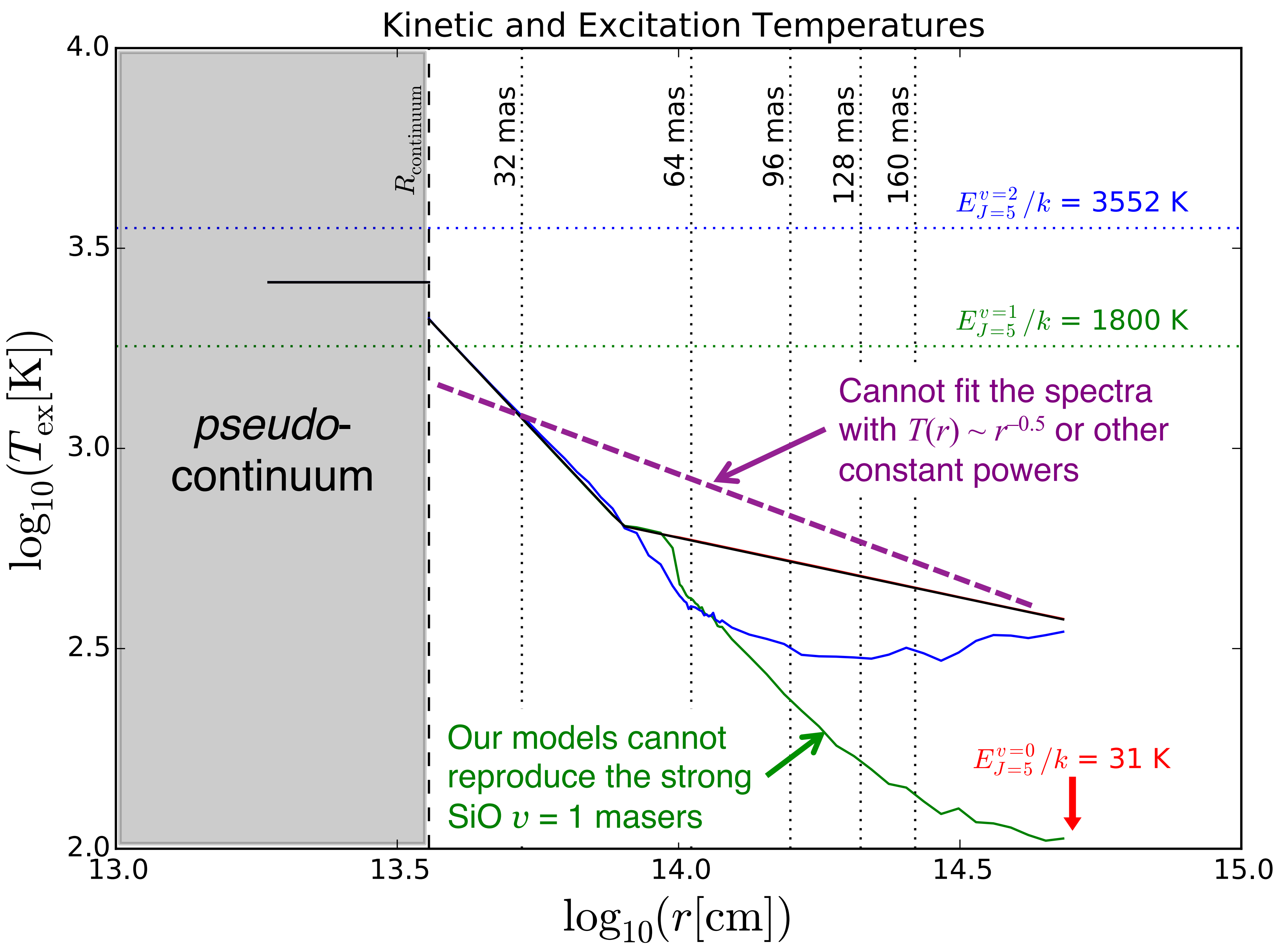
SiO $v = 0$ $J = 5-4$
Radial dist. = 32, 64, 96, 128, 160 mas
P.A. = 0°, 90°, 180°, 270°
46.7 km/s
N5
N4
N3
N2
N1
E5 E4 E3 E2 E1
W1 W2 W3 W4 W5
S1
S2
S3
S4
S5
0.20
0.10
0.00
−0.10
−0.20
Y Offset (arcsec)
X Offset (arcsec)
0.03
0.03
0.03
0.02
0.02
0.01
0.00
0.00
−0.01
−0.01
Flux density (Jy/beam)


SiO v = 0 (5–4)
Mira
ALMA (32 mas)
SiO (5–4) v=0
217.104919 GHz
offset = 32 mas
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

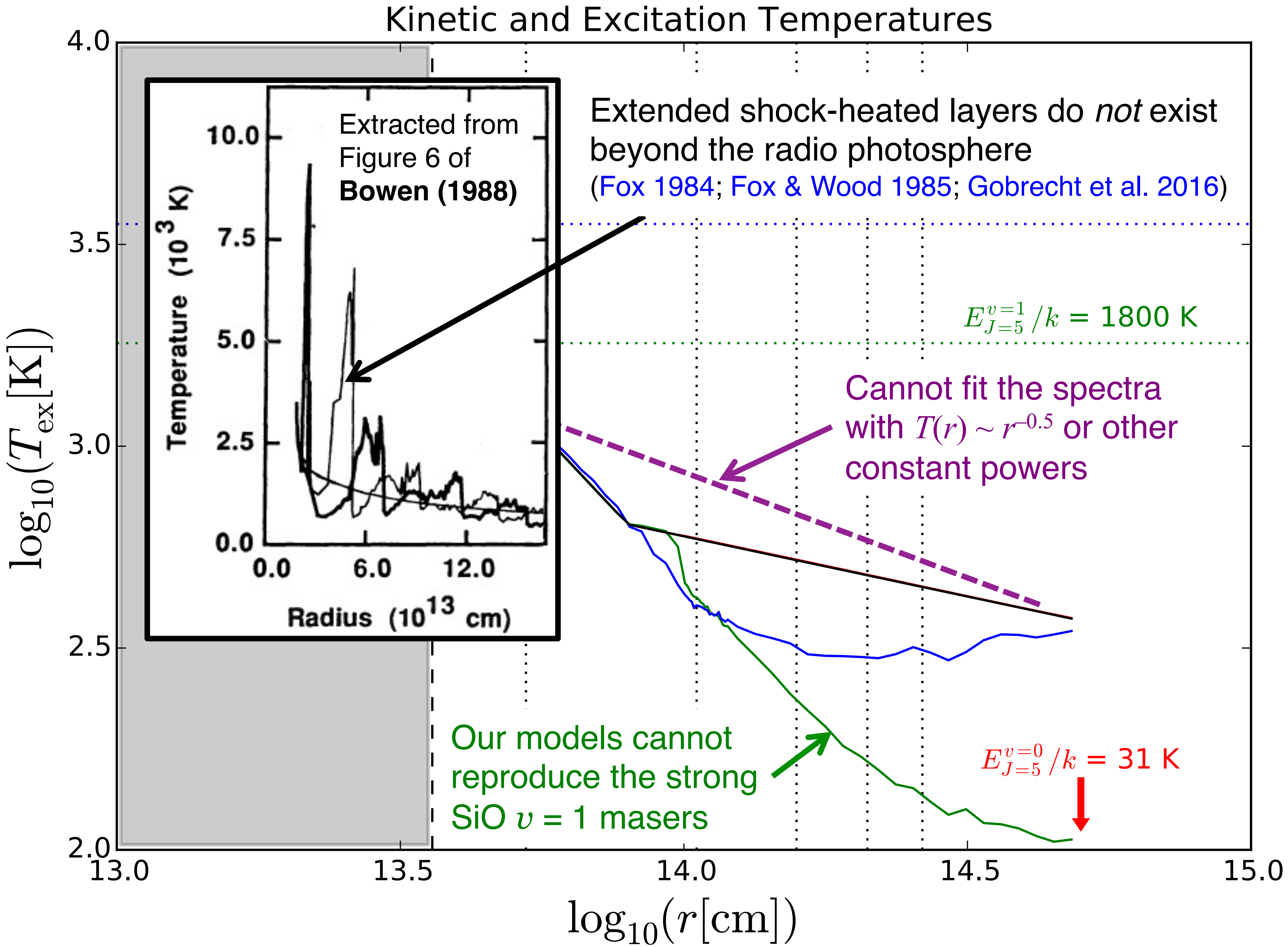
SiO $v = 2$ (5–4)



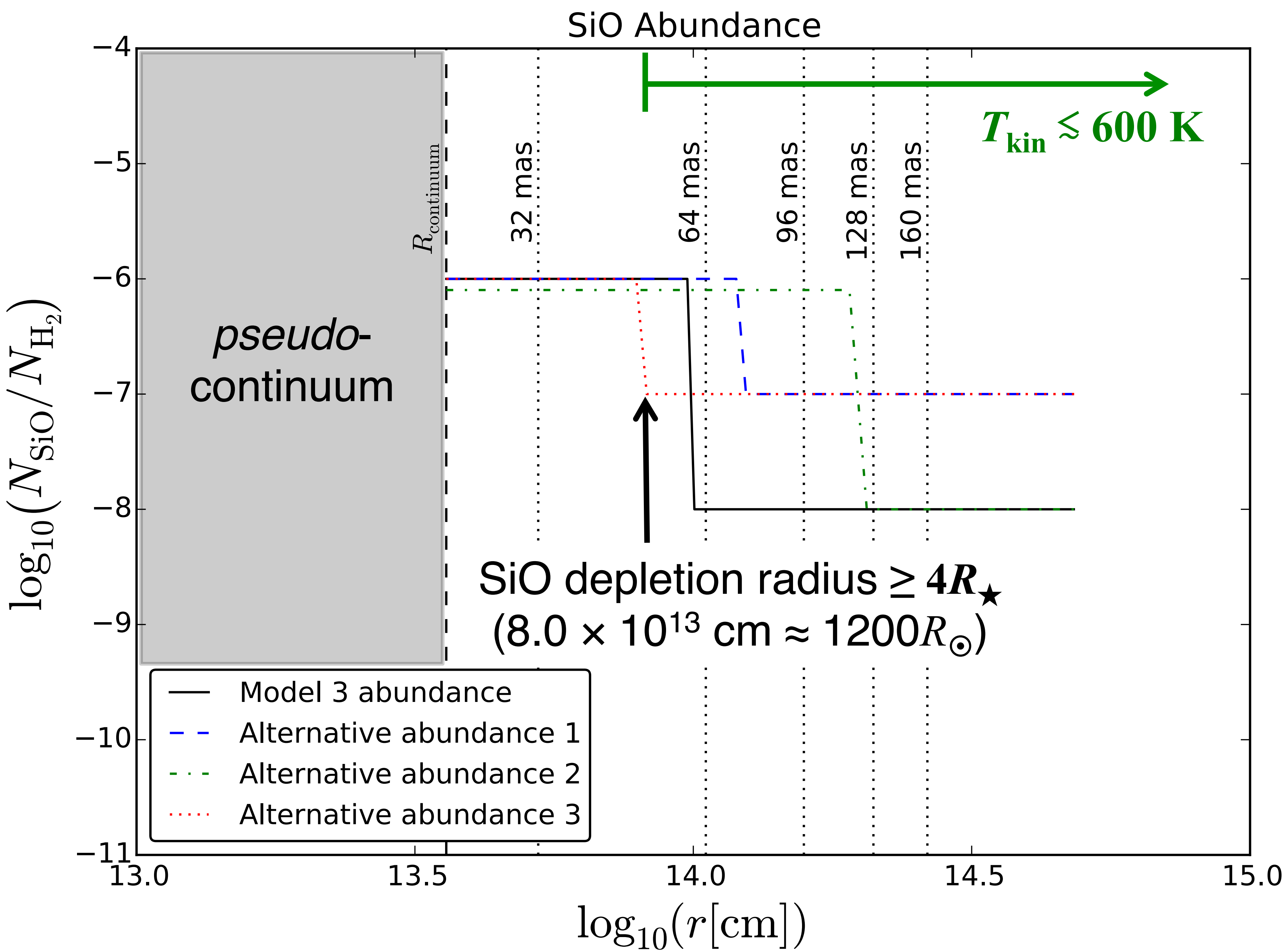
Mira
ALMA (32 mas)
SiO (5−4) v=2
214.088575 GHz
Mira
ALMA (32 mas)
offset = 32 mas
SiO (5−4) v=2
214.088575 GHz
Mira
ALMA (32 mas)
offset = 64 mas
SiO (5−4) v=2
214.088575 GHz
Mira
ALMA (32 mas)
offset = 96 mas
SiO (5−4) v=2
214.088575 GHz
0.1
0.05
0
Flux Density (Jy)
3000
2000
1000
0
Brightness Temp.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

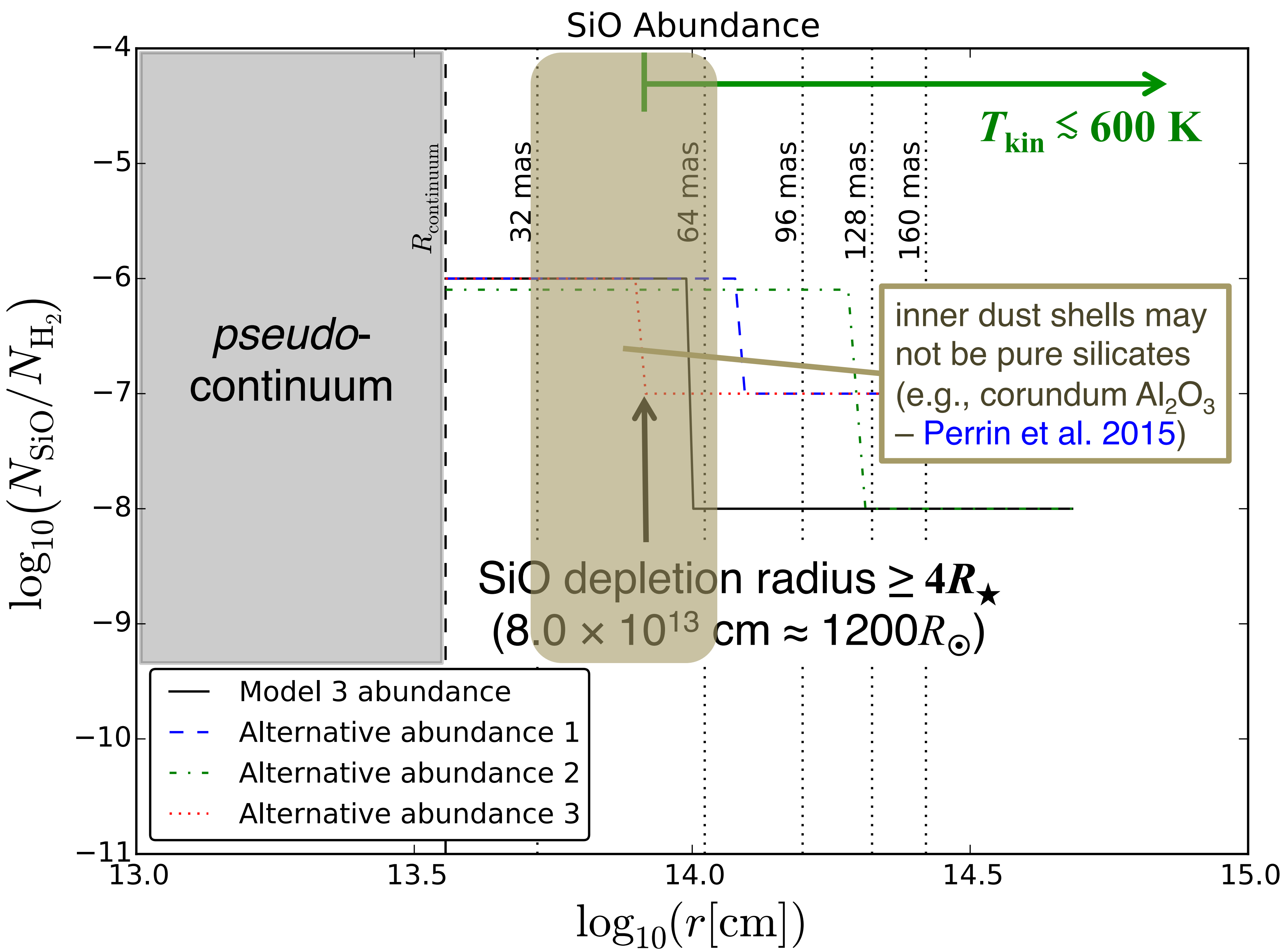


Kinetic and Excitation Temperatures
$\log_{10}(T_{\rm ex}[\rm K])$
$\log_{10}(r[\rm cm])$
4.0
3.5
3.0
2.5
2.0
13.0
13.5
14.0
14.5
15.0
$R_{\rm continuum}$
32 mas
64 mas
96 mas
128 mas
160 mas
$E^{v=2}_{J=5}/k$ = 3552 K
$E^{v=1}_{J=5}/k$ = 1800 K
$E^{v=0}_{J=5}/k$ = 31 K
pseudo-
continuum
Cannot fit the spectra
with $T(r) \sim r^{-0.5}$ or other
constant powers
Our models cannot
reproduce the strong
SiO v = 1 masers

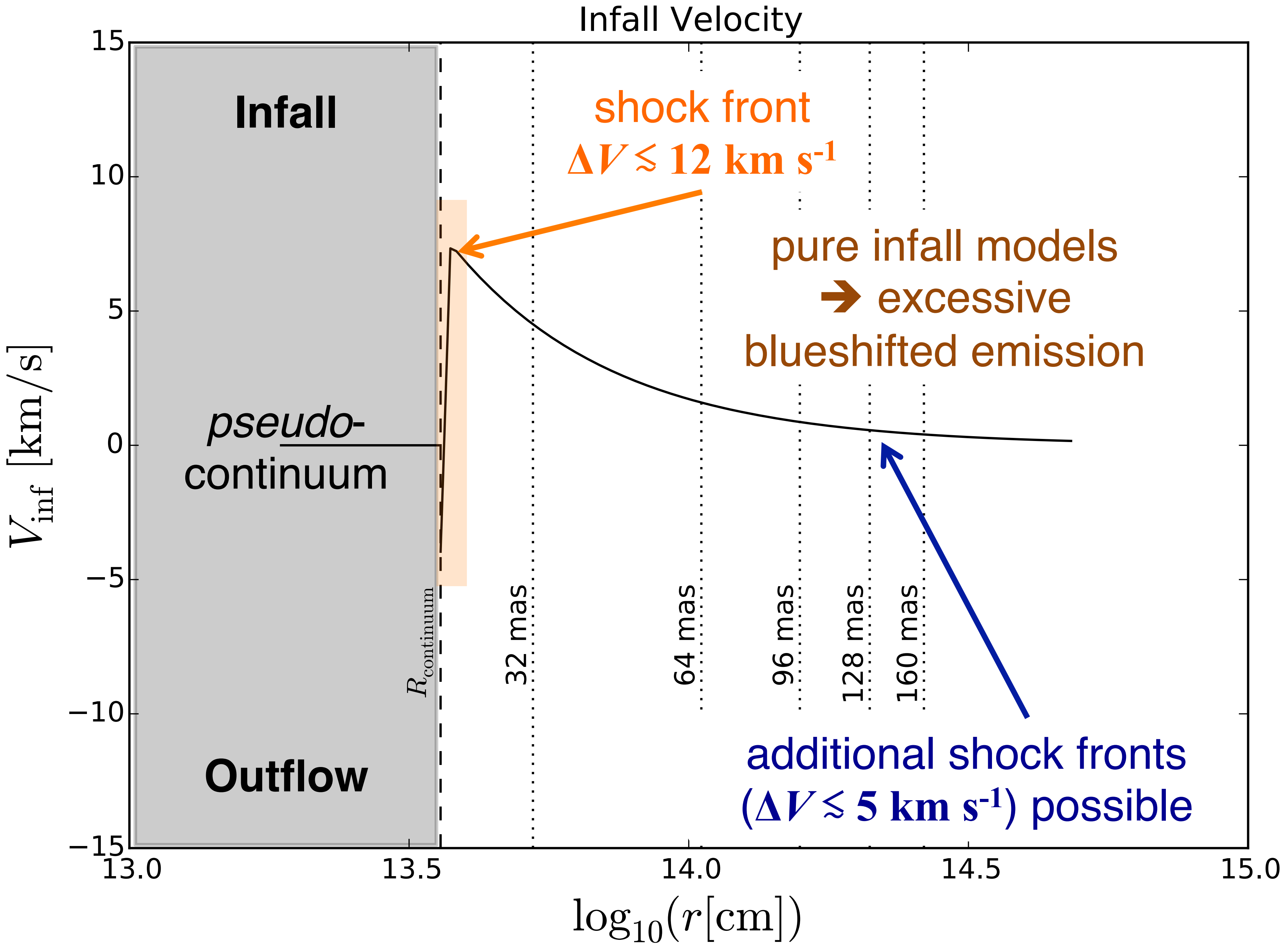


Kinetic and Excitation Temperatures
Extended shock-heated layers do *not* exist beyond the radio photosphere
(Fox 1984; Fox & Wood 1985; Gobrecht et al. 2016)
Extracted from Figure 6 of **Bowen (1988)**
Temperature (10^3 K)
Radius (10^{13} cm)
$E^{v=1}_{J=5}/k$ = 1800 K
Cannot fit the spectra with $T(r) \sim r^{-0.5}$ or other constant powers
Our models cannot reproduce the strong SiO v = 1 masers
$E^{v=0}_{J=5}/k$ = 31 K
$\log_{10}(T_{ex}[\mathrm{K}])$
$\log_{10}(r[\mathrm{cm}])$


SiO Abundance
$\log_{10}(N_{SiO}/N_{H_2})$
$\log_{10}(r[\mathrm{cm}])$
$T_{kin} \lesssim 600$ K
$R_{continuum}$
32 mas
64 mas
96 mas
128 mas
160 mas
pseudo-
continuum
SiO depletion radius $\geq 4R_\star$
(8.0×10^{13} cm $\approx 1200 R_\odot$)
Model 3 abundance
Alternative abundance 1
Alternative abundance 2
Alternative abundance 3

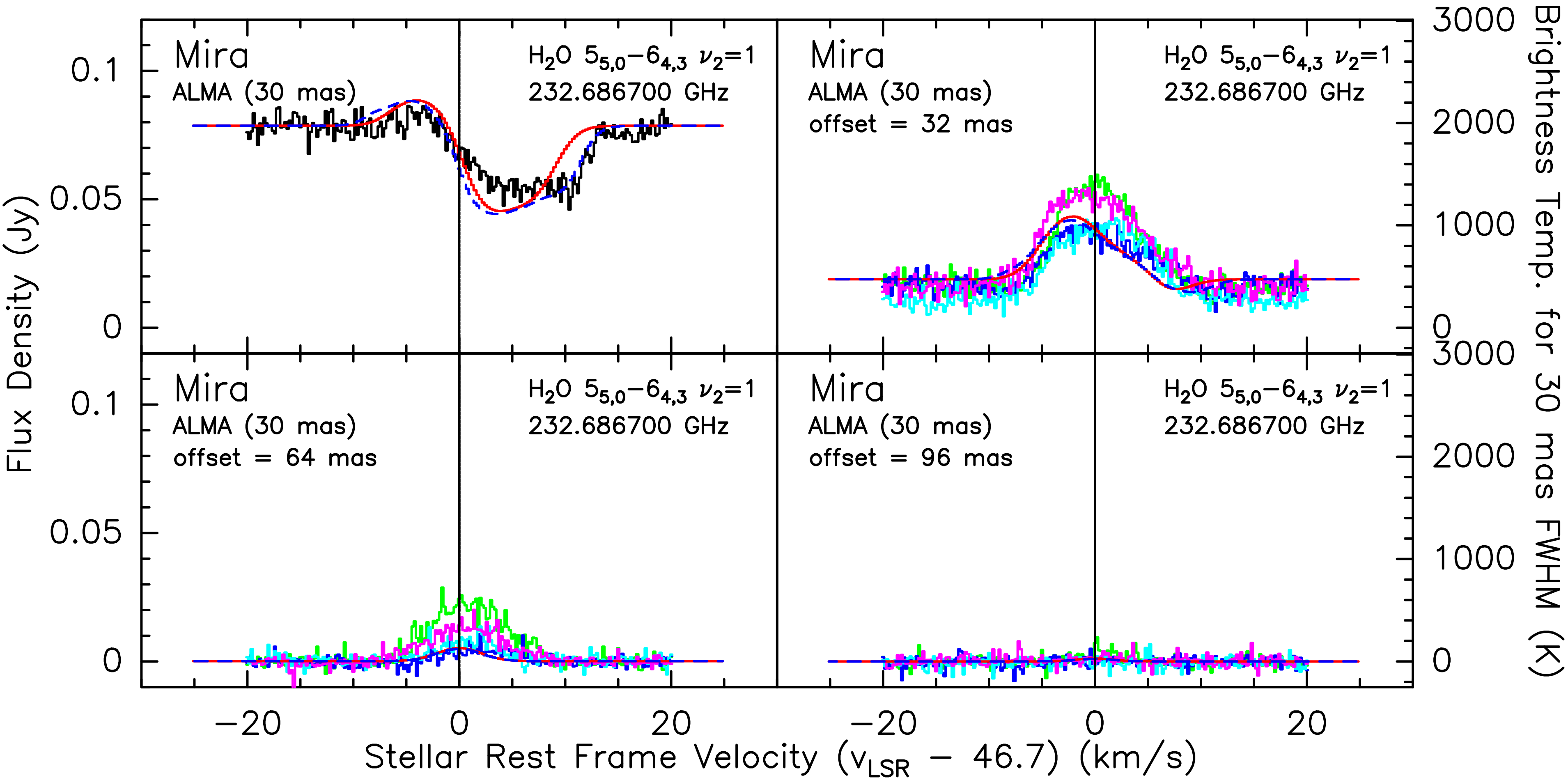


SiO Abundance
$T_{\rm kin} \lesssim 600$ K
$R_{\rm continuum}$
32 mas
64 mas
96 mas
128 mas
160 mas
pseudo-
continuum
inner dust shells may not be pure silicates (e.g., corundum Al_2O_3 – Perrin et al. 2015)
SiO depletion radius $\geq 4R_\star$
(8.0×10^{13} cm $\approx 1200R_\odot$)
Model 3 abundance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

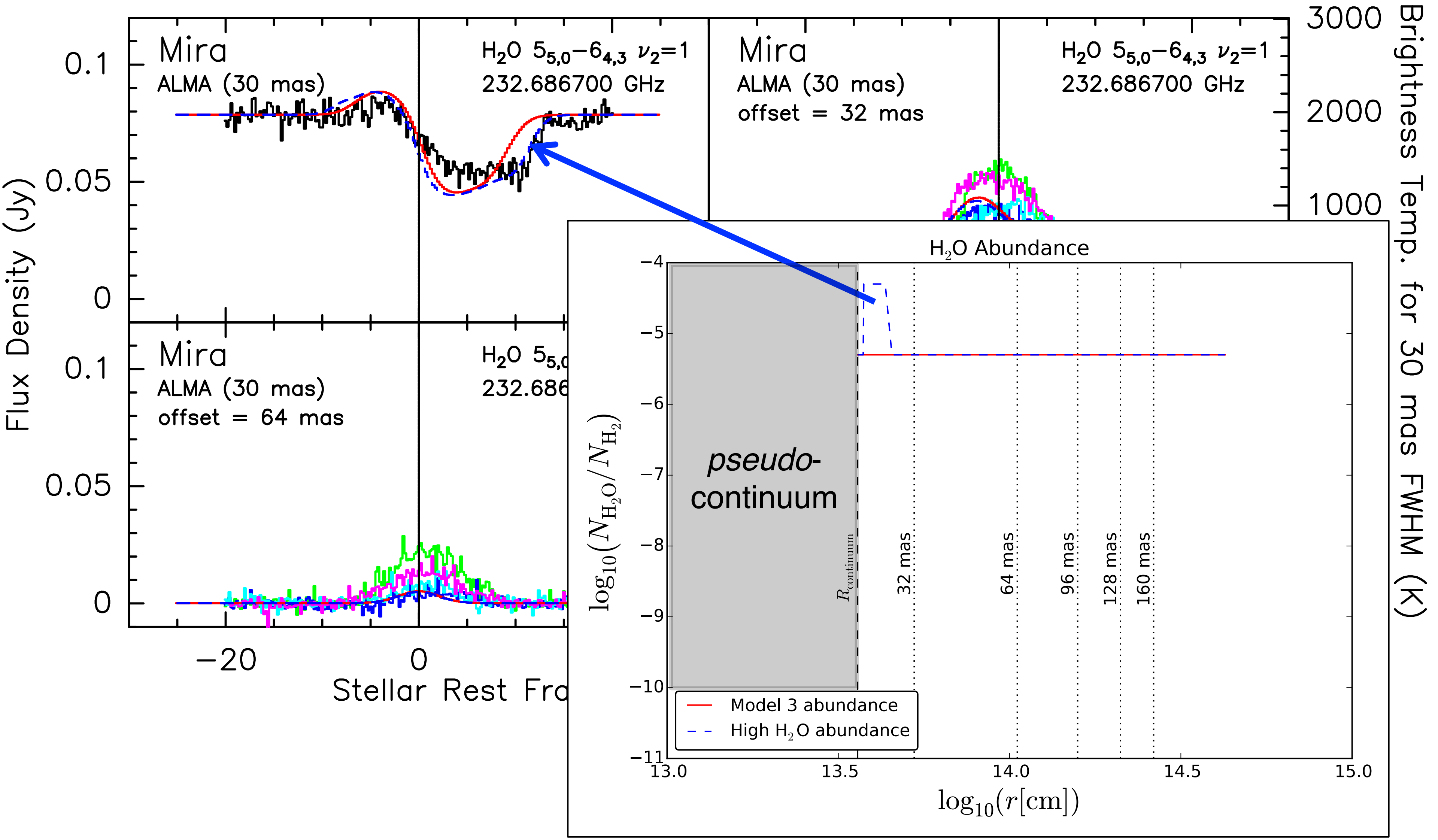


Infall Velocity
Infall
Outflow
shock front
ΔV ≲ 12 km s-1
pure infall models
➔ excessive
blueshifted emission
pseudo-
continuum
R_continuum
32 mas
64 mas
96 mas
128 mas
160 mas
additional shock fronts
(ΔV ≲ 5 km s-1) possible
V_inf [km/s]
log10(r[cm])
15
10
5
0
−5
−10
−15
13.0
13.5
14.0
14.5
15.0

$H_2O\ \nu_2 = 1\ 5(5,0)–6(4,3)$



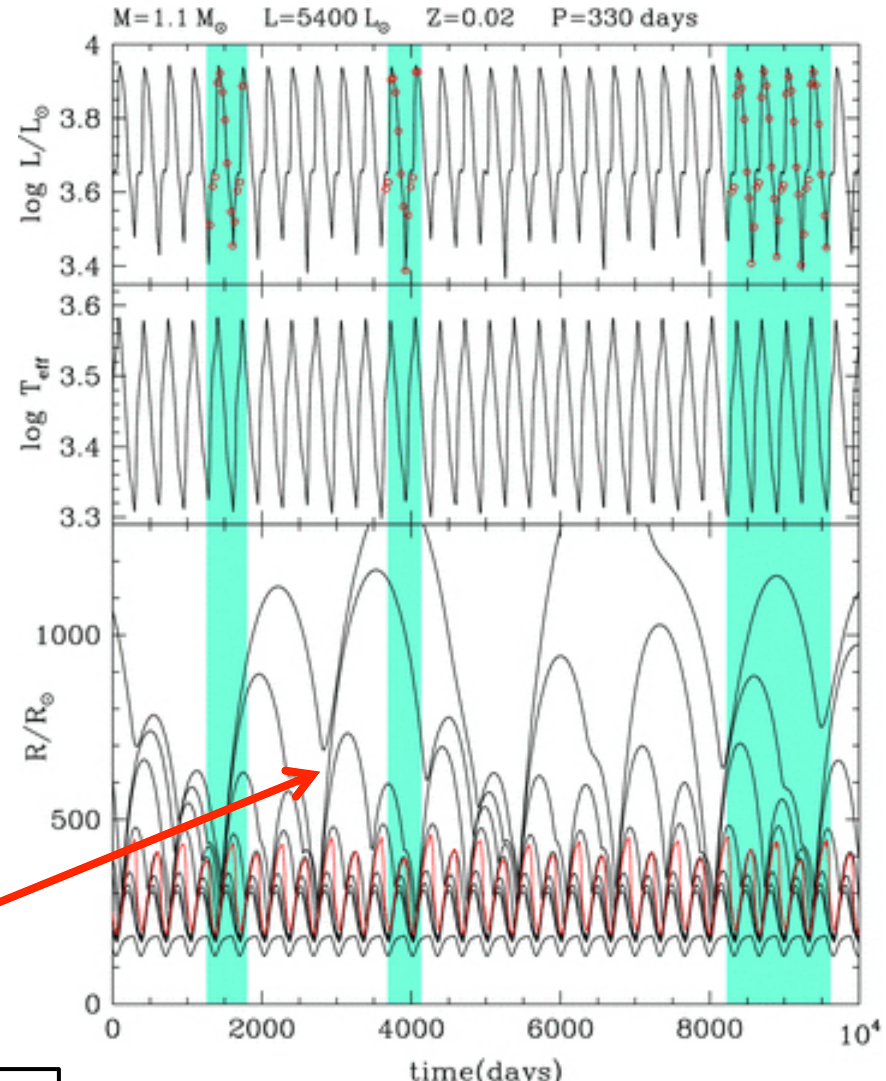
H_2O $\nu_2 = 1$ 5(5,0)–6(4,3)



Testing **CODEX** models

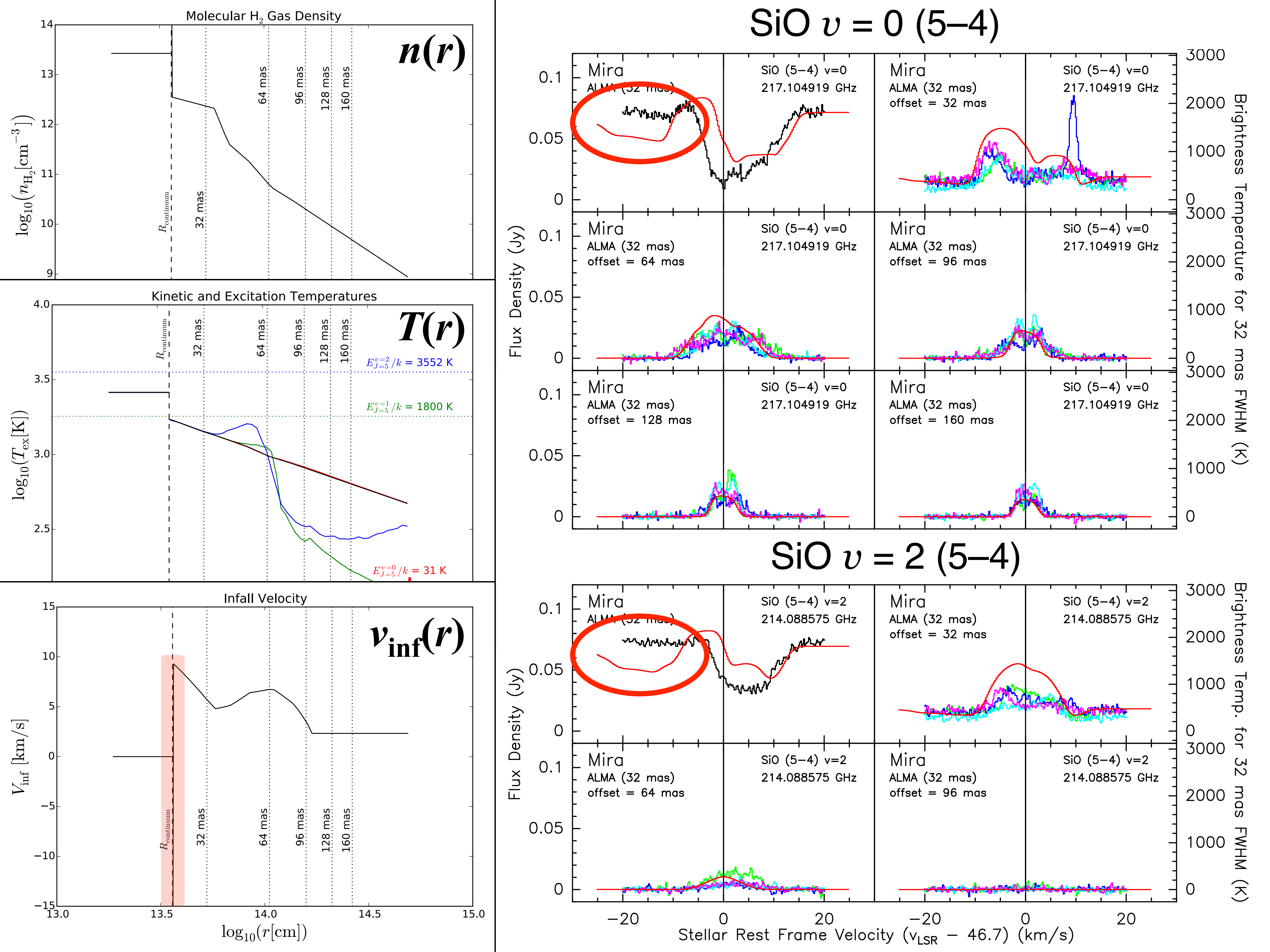
- `o54` series: 6 cycles
  (Ireland et al. 2008; 2011)
- predict $\rho(r)$, $T(r)$, $v(r)$
- select models near phase ~0.45 (SV obs.)
- reproduce SiO & H_2O spectra

chaotic shocks



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

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



Molecular H2 Gas Density
n(r)
log10(nH2[cm−3])
Rcontinuum
32 mas
64 mas
96 mas
128 mas
160 mas
Kinetic and Excitation Temperatures
T(r)
log10(Tex[K])
E v=2 J=5 /k = 3552 K
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E v=0 J=5 /k = 31 K
Infall Velocity
vinf(r)
Vinf [km/s]
log10(r[cm])
SiO v = 0 (5–4)
SiO v = 2 (5–4)
Mira
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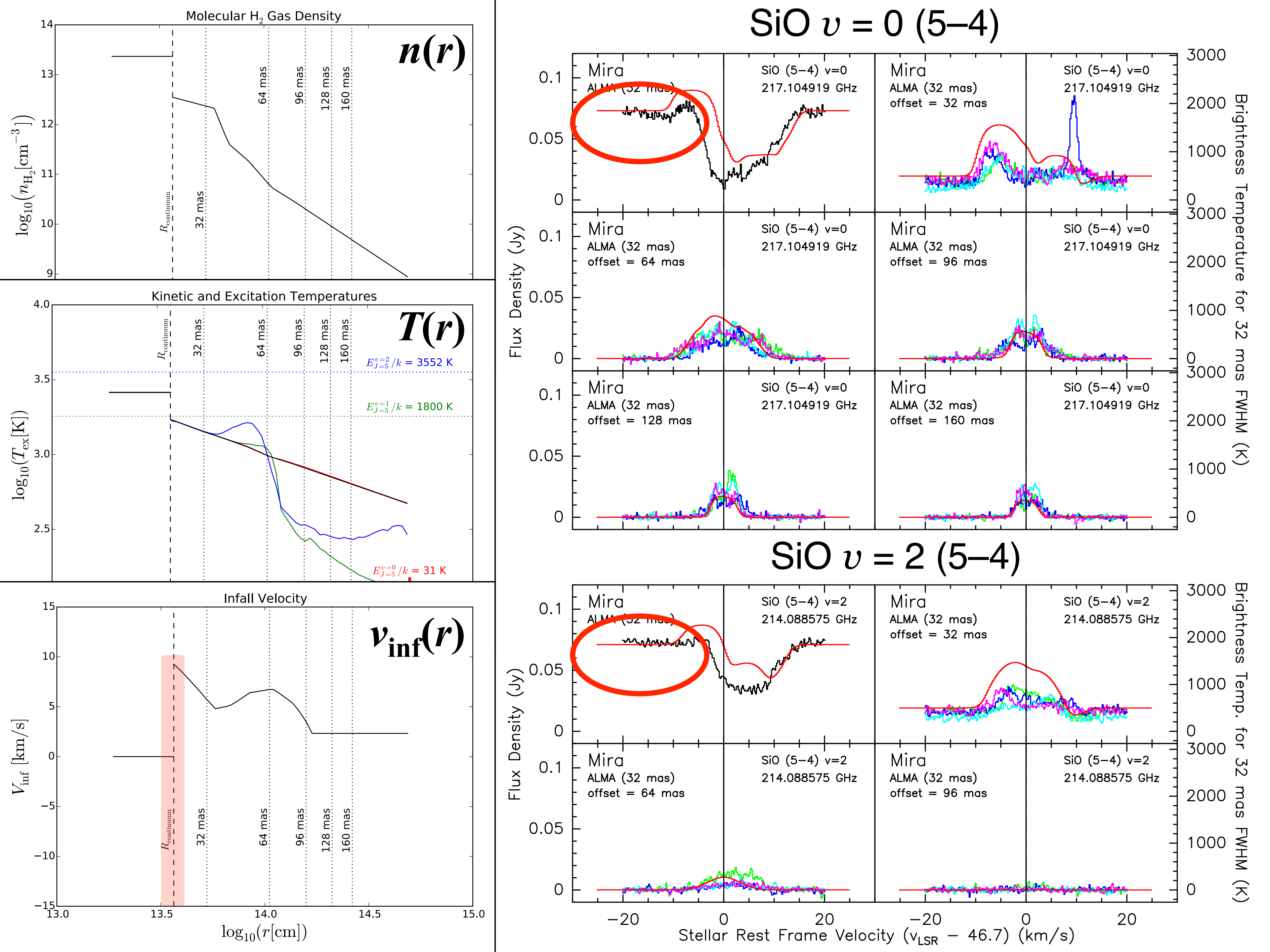

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CODEX models

- $\boldsymbol{n_{H_2}(r) \gtrsim 10^{12}\ \mathrm{cm^{-3}}}$ near radio photosphere to reproduce enough absorption (consistent with Reid & Menten 1997 & Yamamura et al. 1999)
- $\rho(r)$ ➔ $n_{H_2}(r)$ – 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. SiO starts to deplete $\geq 4R_\star$ & $T_{\mathrm{kin}} \lesssim 600$ K.
3. The extended atmosphere generally shows infall motion, with shock velocity $\boldsymbol{\Delta V \lesssim 12}$ **km s^{-1}**.
4. No evidence for a chromosphere (or extended shock-heated layer) beyond radio photosphere.
5. Hydrodynamical models series from **`CODEX`** are able to predict the atmospheric structures in remarkable detail.