Non-equilibrium chemistry of O-rich AGB stars as revealed by ALMA

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Imaging of Stellar Surfaces

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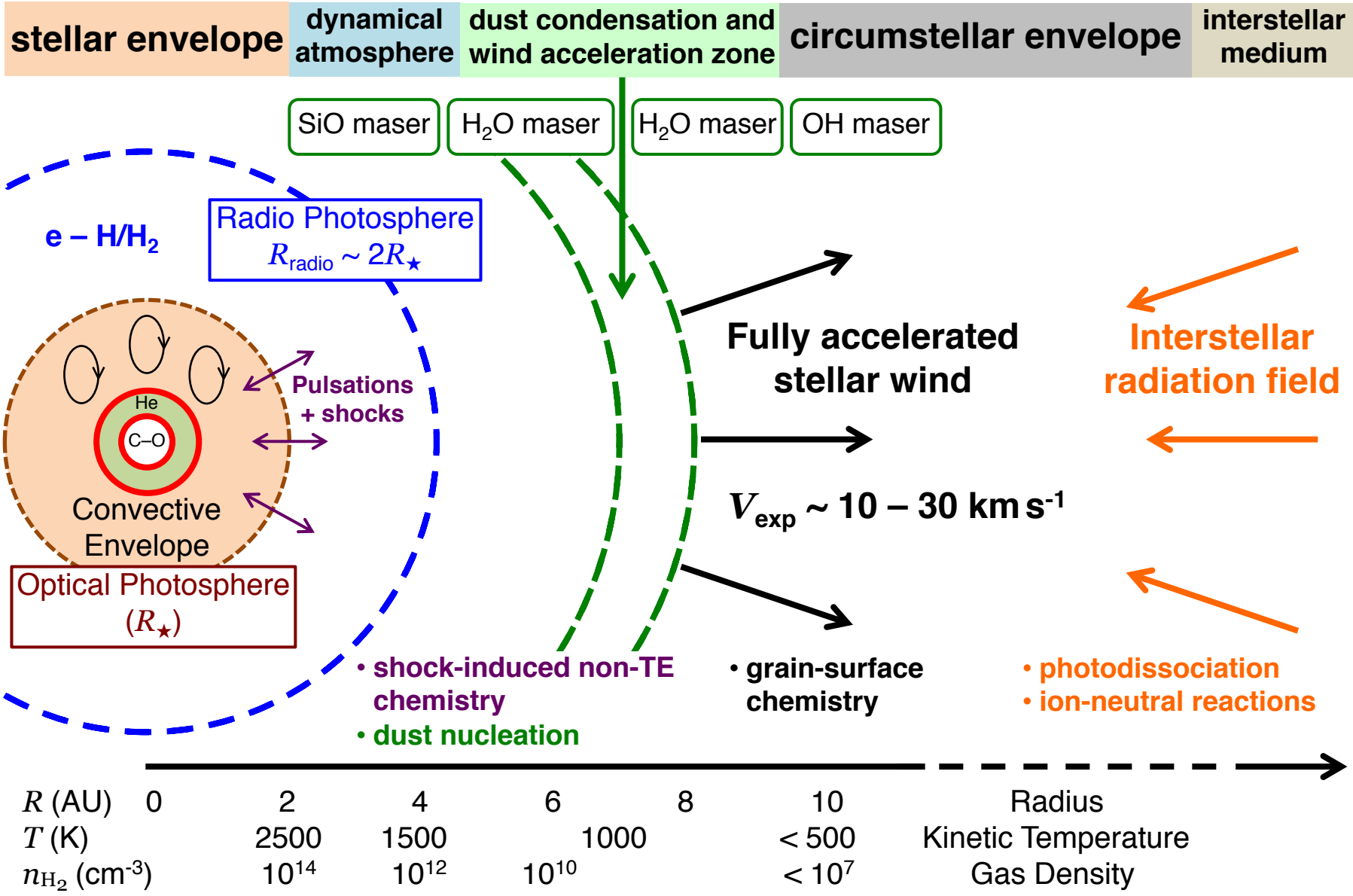
Outline

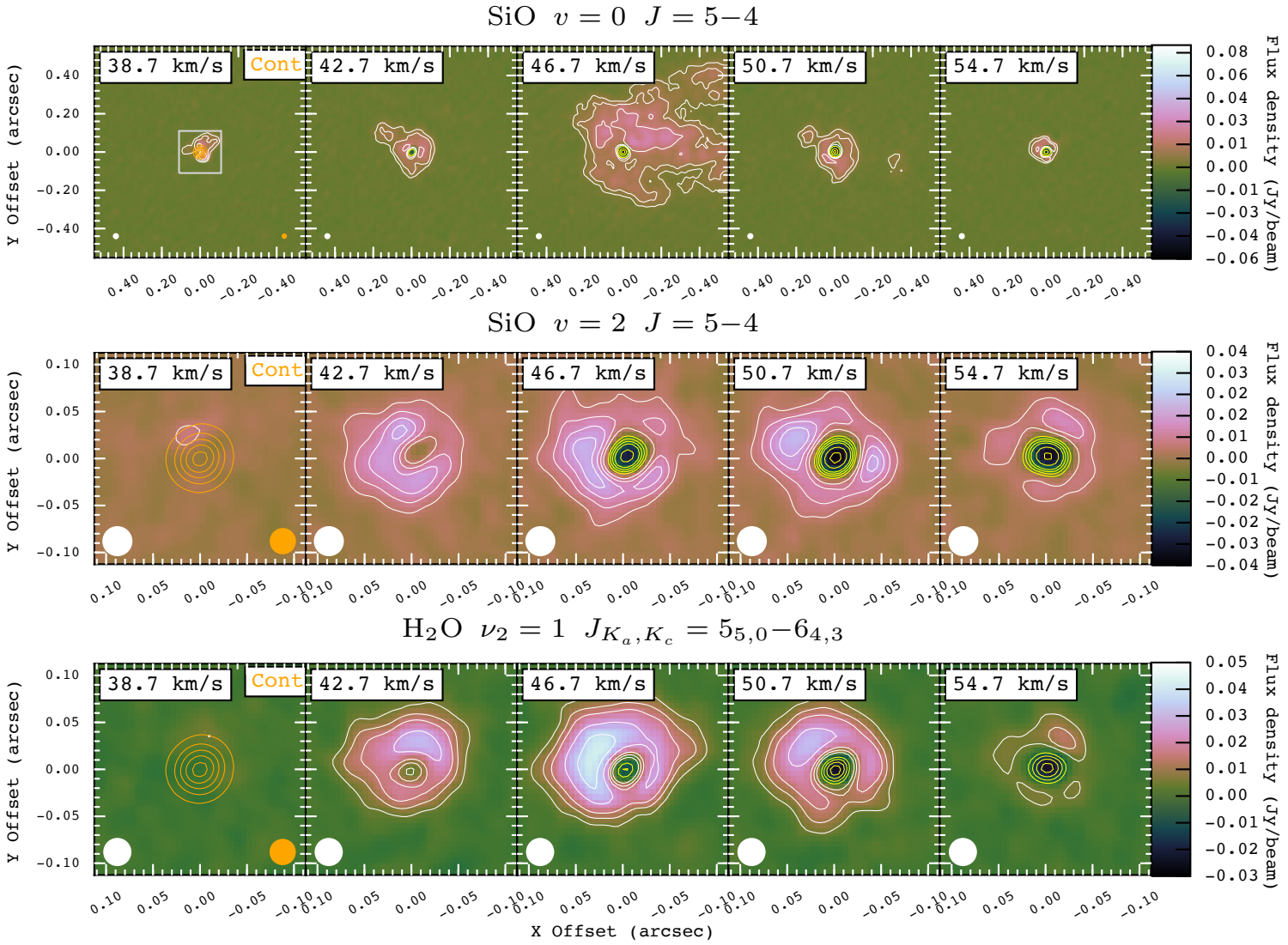
- Circumstellar envelopes
- Previous ALMA observations of Mira's inner wind
- Chemical models and non-equilibrium chemistry
- ALMA long-baseline observations
- Preliminary results on HCN

Circumstellar envelope (CSE)

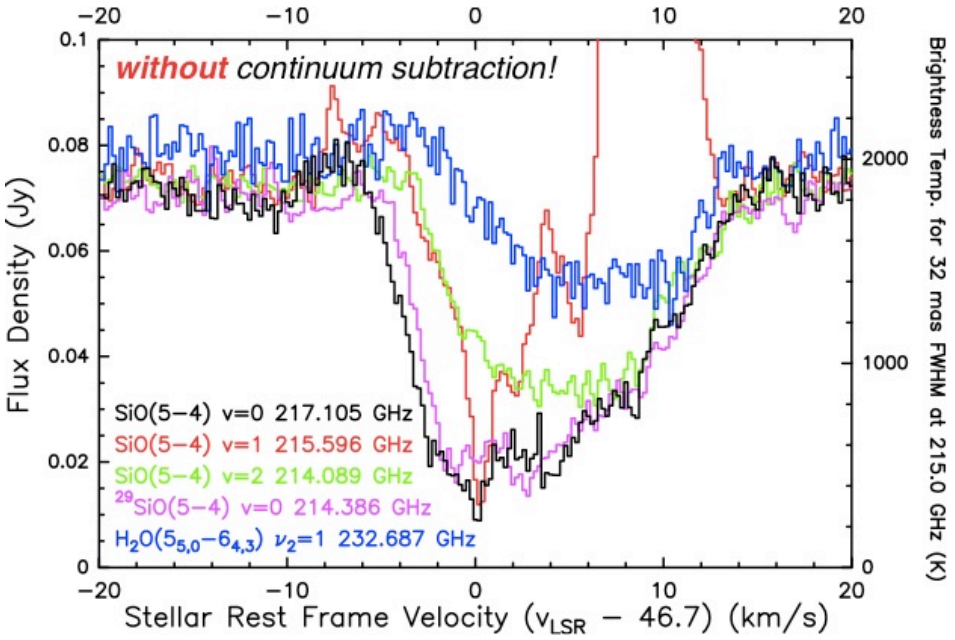


ALMA observations of the inner wind

- SiO and H_2O in *o* Cet (Mira) (Wong et al. 2016, A&A 590, A127)

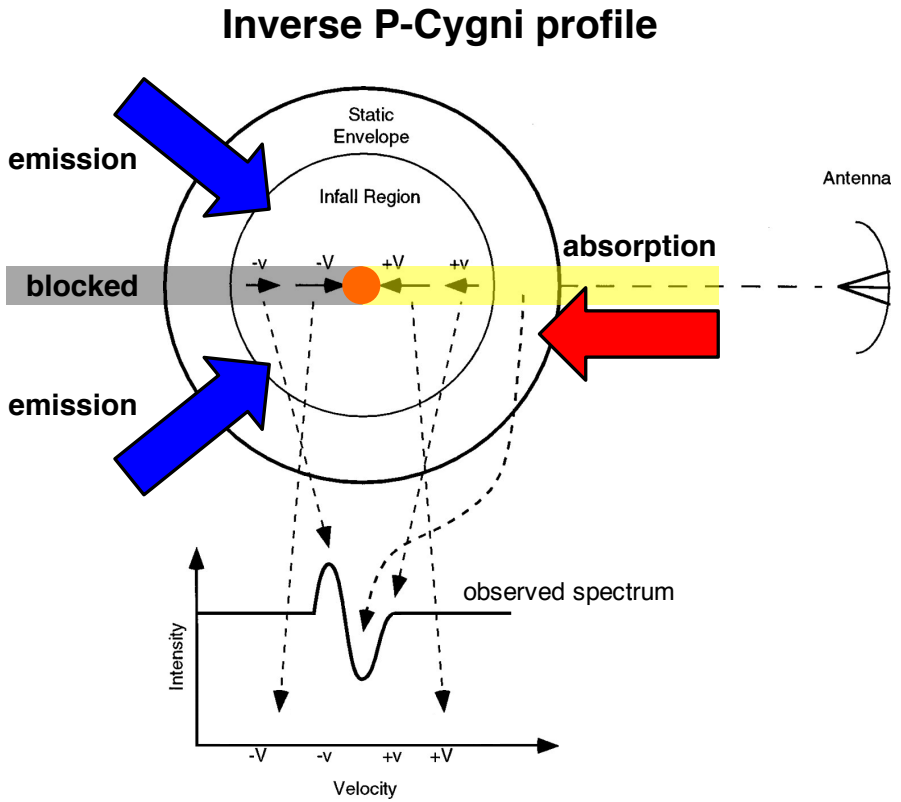


ALMA observations of the inner wind



Wong et al. (2016) A&A 590, A127

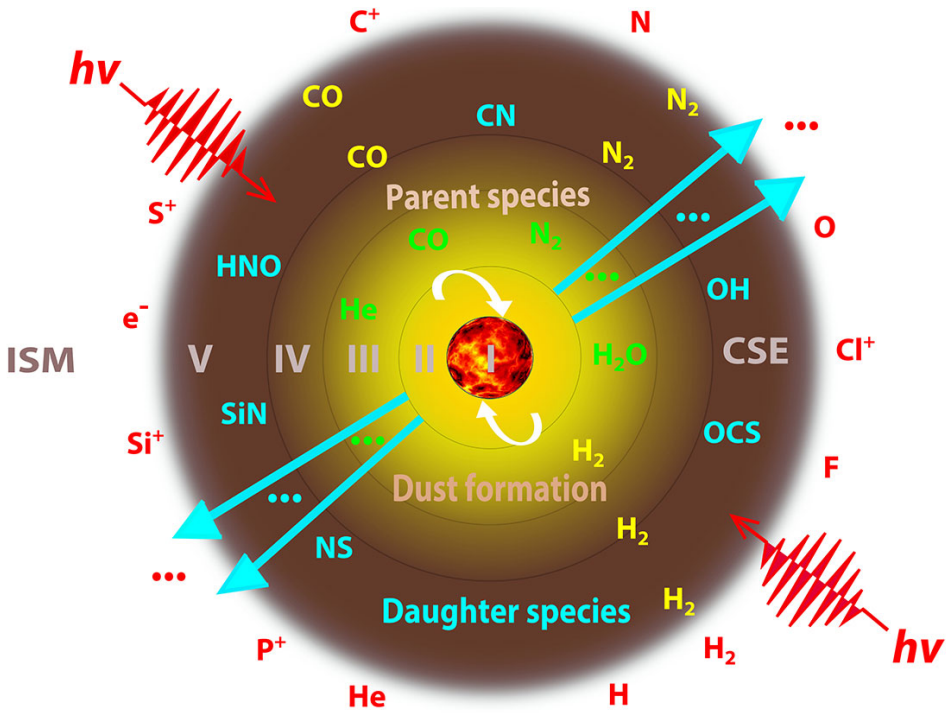
→ **trace inner-wind chemistry and dynamics by (sub)mm molecular transitions**



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

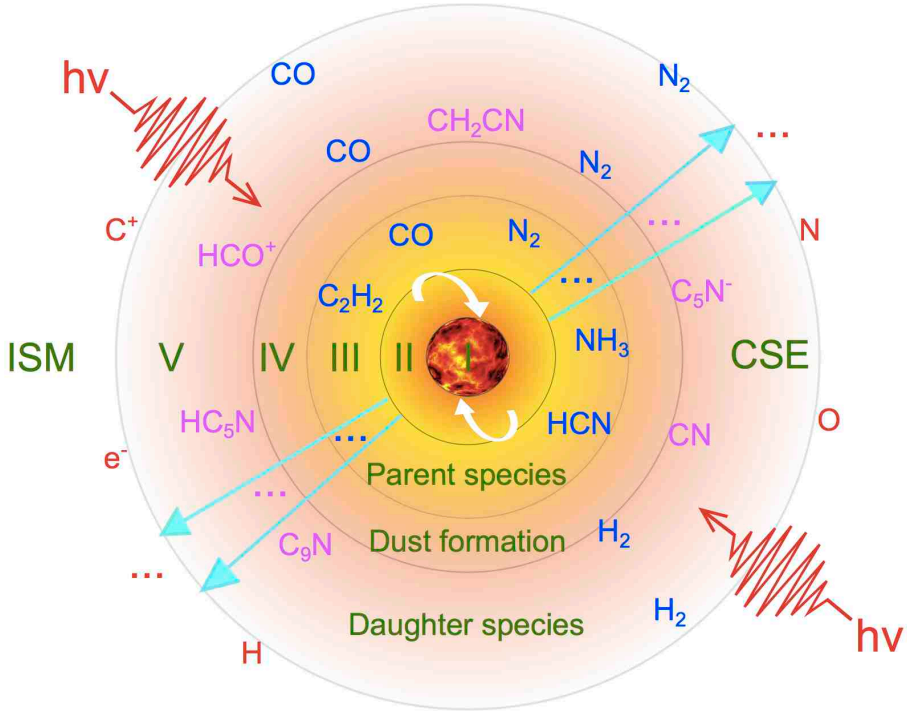
Circumstellar chemistry

Oxygen-rich



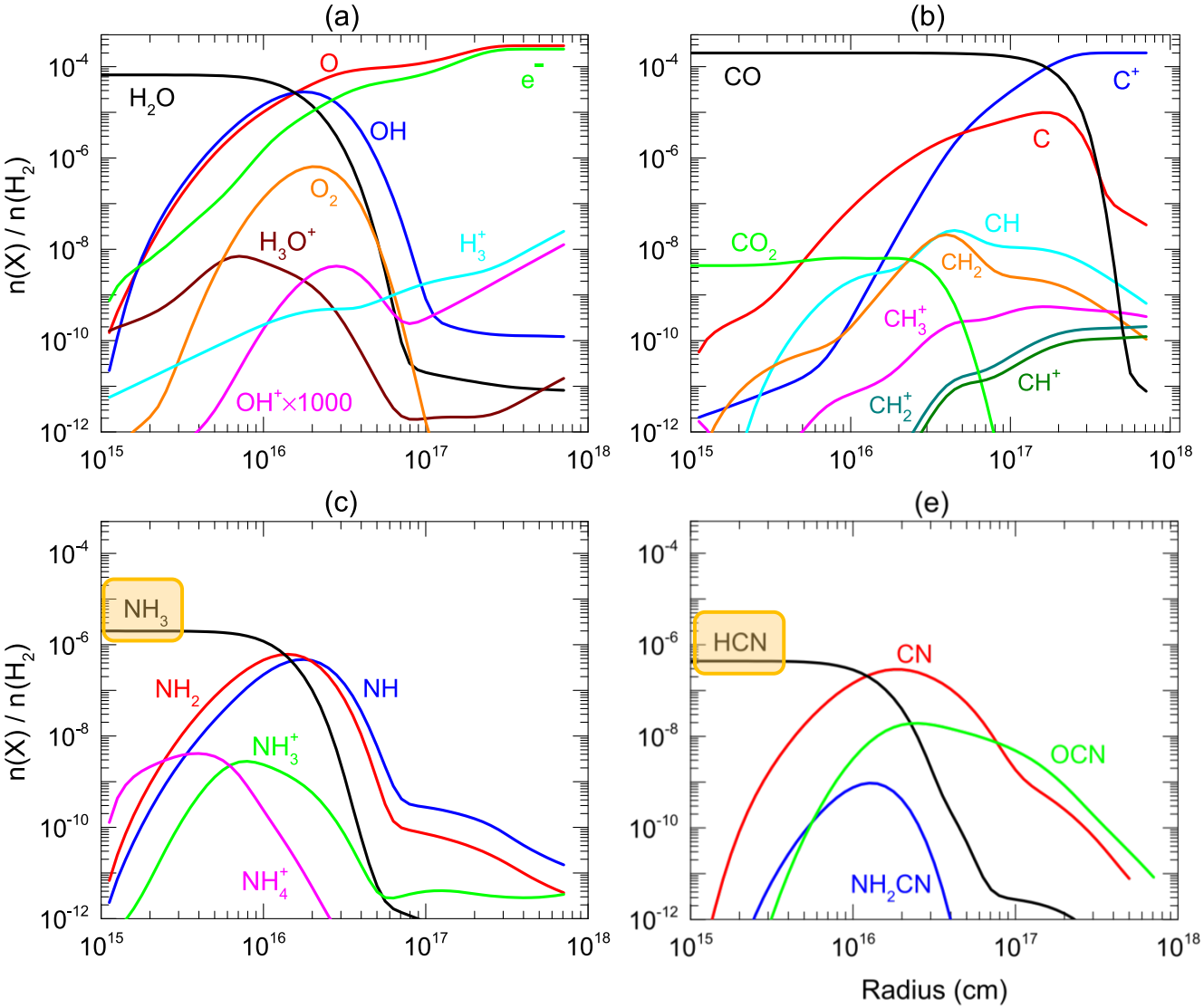
Li et al. (2016) A&A 588, A4

Carbon-rich



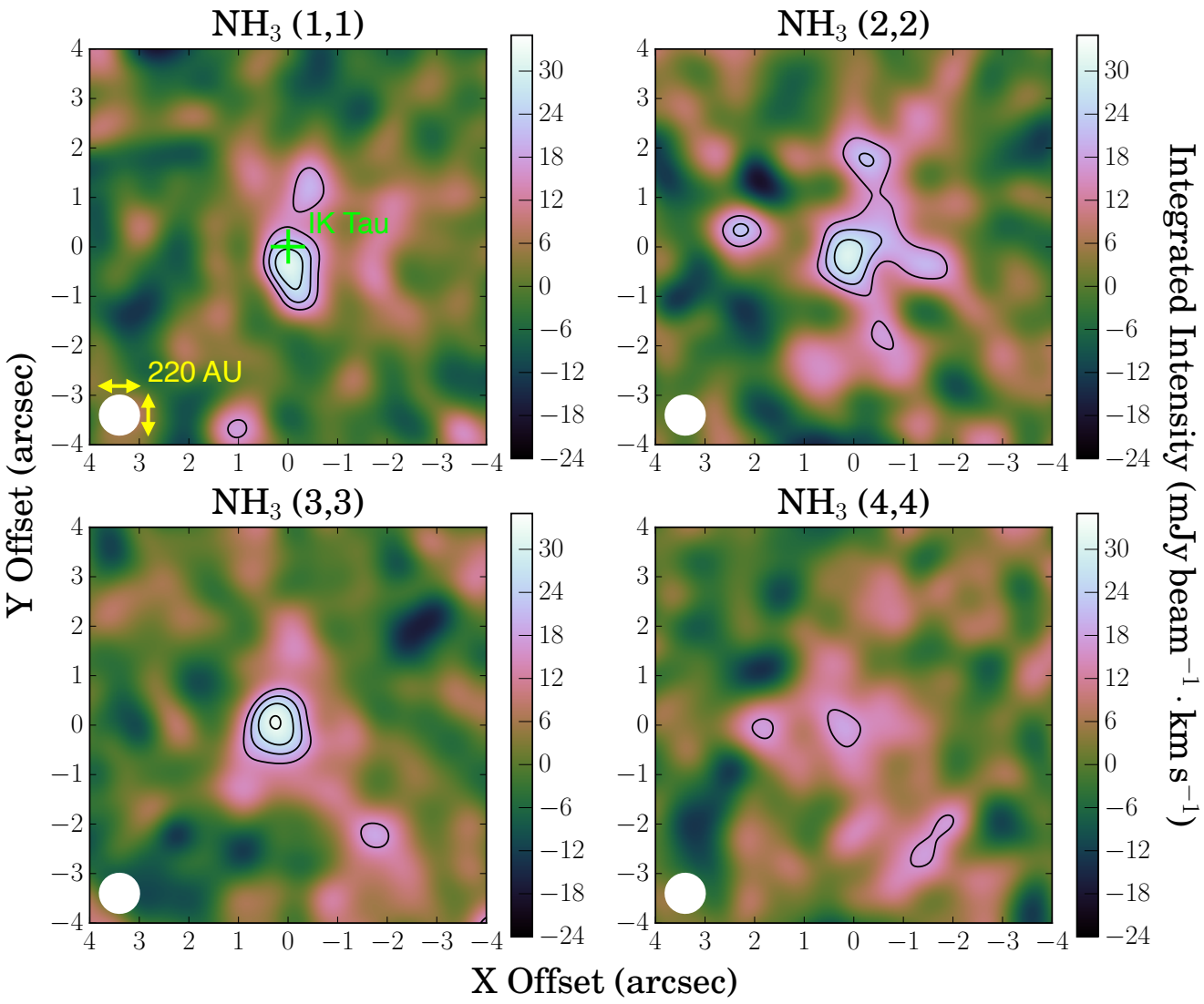
Li et al. (2014) A&A 568, A111

Chemical models



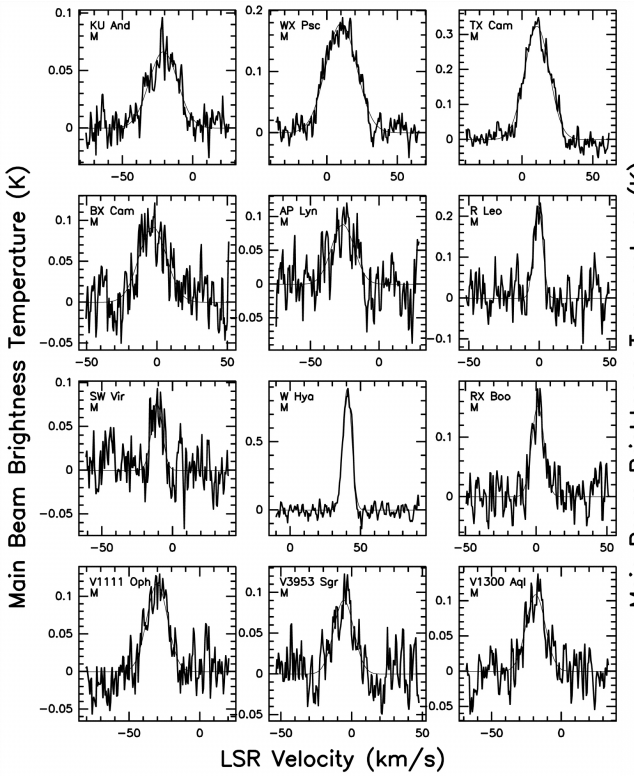
Li et al. (2016) A&A 588, A4, Fig. B.1

Parent species: NH_3



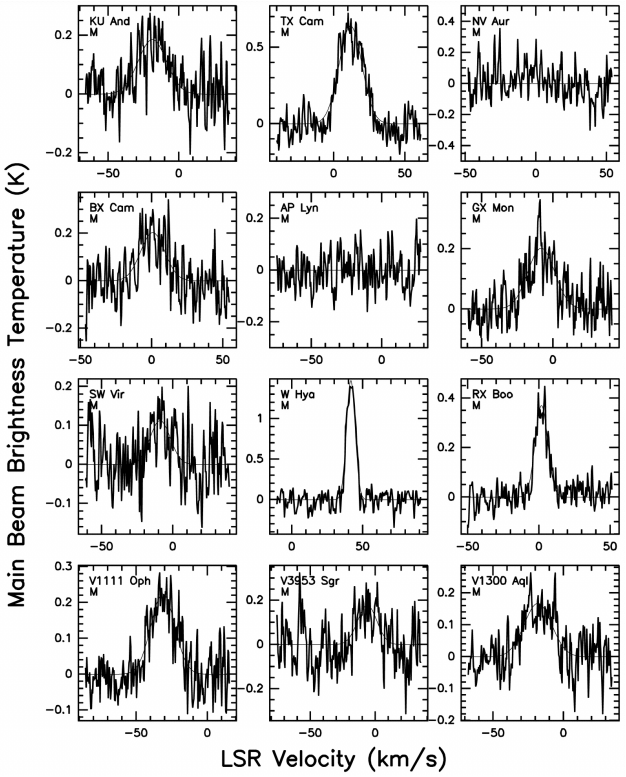
Wong et al., A&A *in press* (arXiv:1710.01027), Fig. 3

Parent species: HCN



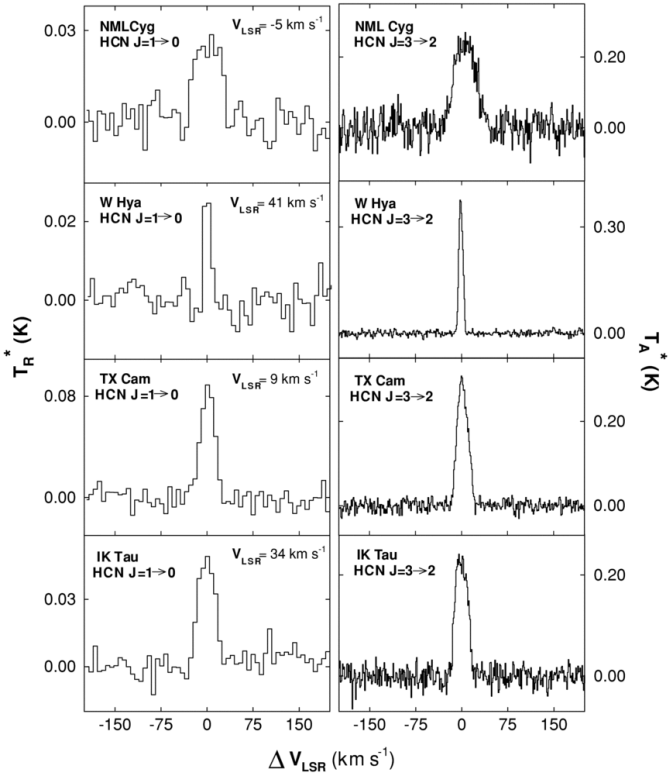
Bieging et al. (2000)

ApJ, 543: 896, Fig. 4



Bieging et al. (2000)

ApJ, 543: 896, Fig. 5



Ziurys et al. (2009)

ApJ, 695: 1604, Fig. 5

Non-equilibrium chemistry

- Shock-induced chemistry: Duari et al. (1999), Cherchneff (2006), and Gobrecht et al. (2016)
- Formation of CN after shock front

$$N + CO \rightarrow CN + O$$

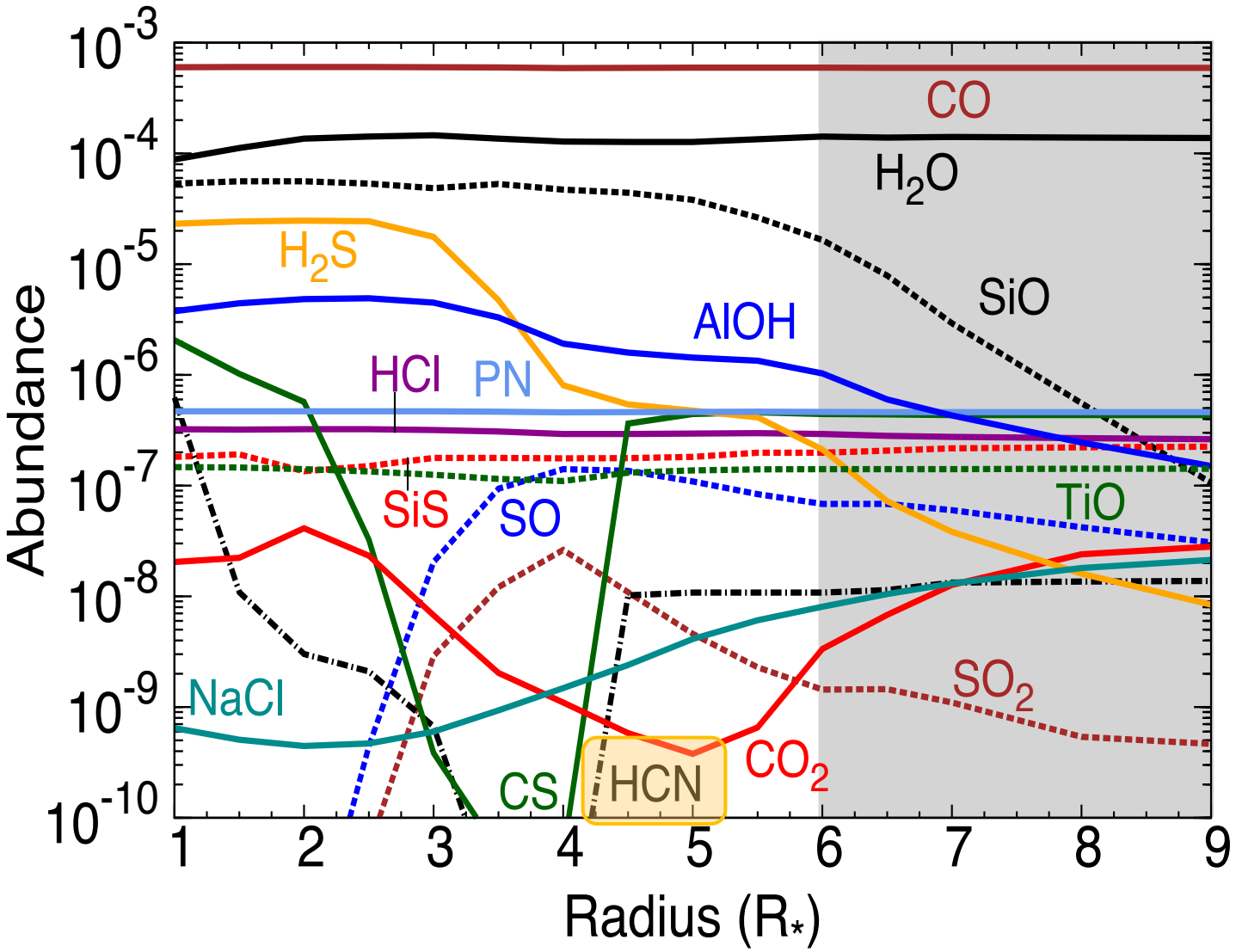
$$N + CS \rightarrow CN + S$$

- Formation of HCN

$$CN + H_2 \rightarrow HCN + H$$

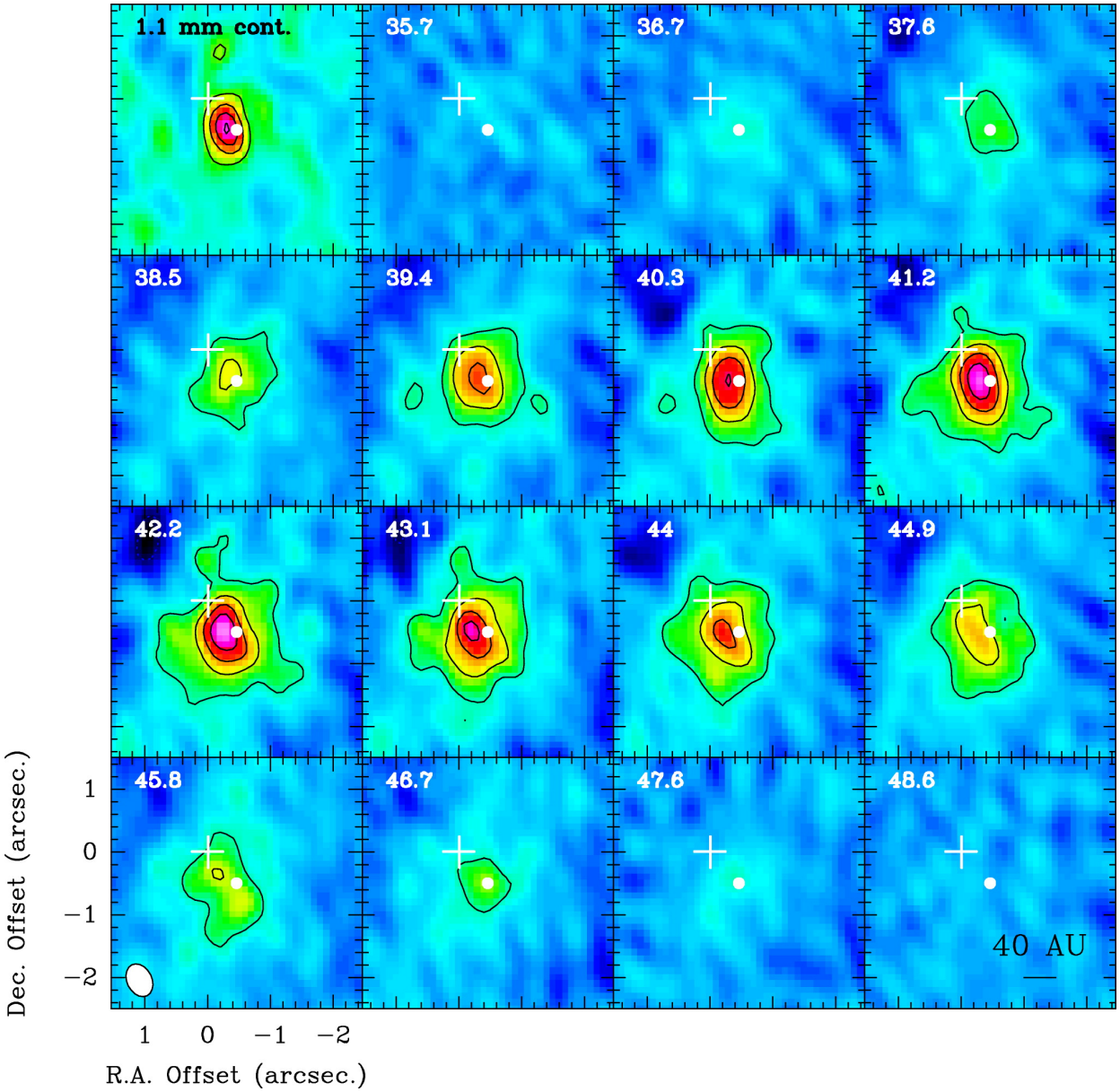
- Contribution from UV photodissociation allowed by clumping and porosity in the CSEs: Van de Sande et al., A&A *in press* (arXiv:1803.01796).

Non-equilibrium chemistry



Gobrecht et al. (2016) A&A 585, A6, Fig. 4

HCN in the inner wind

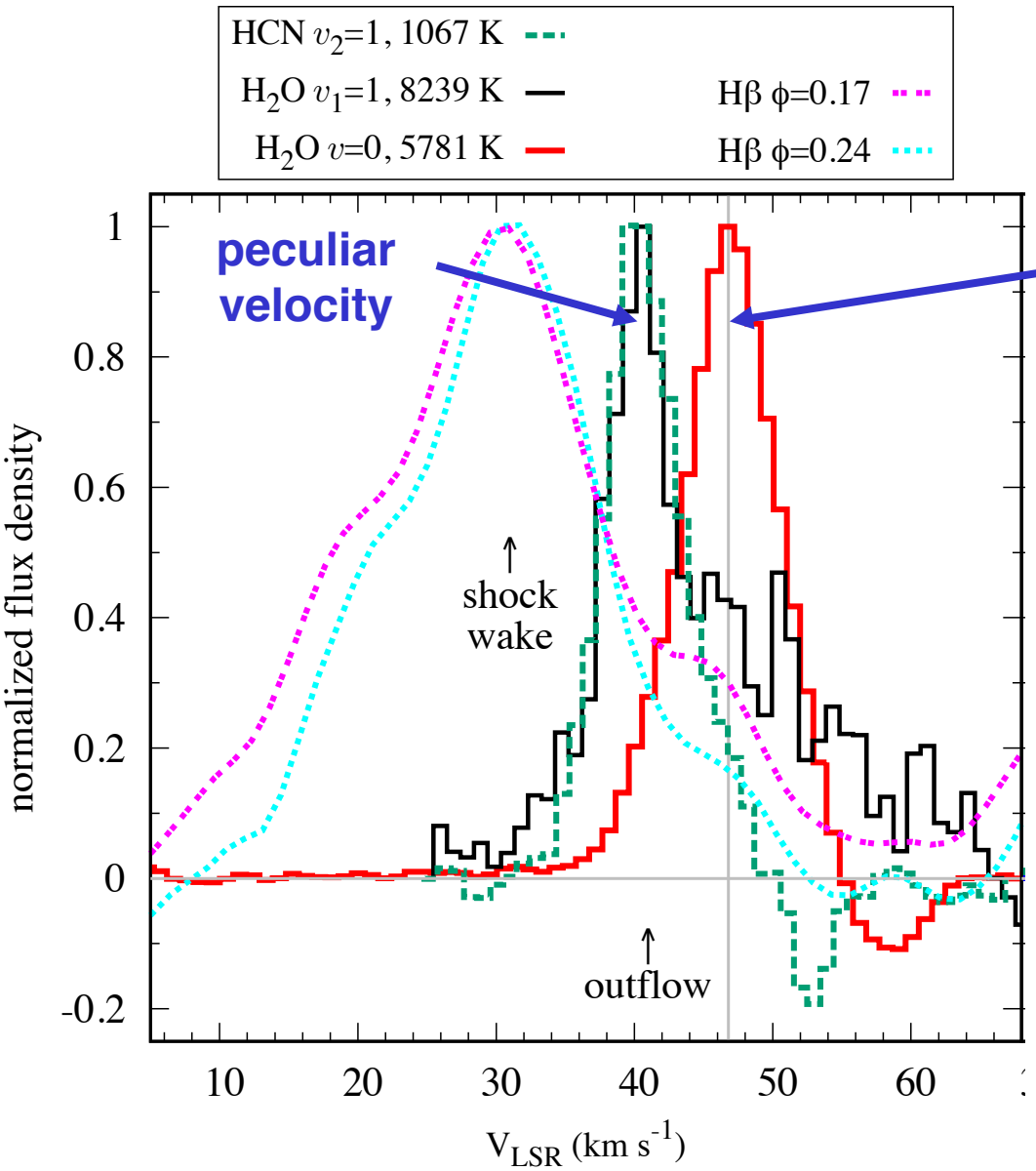


HCN v=0 (3–2) W Hya

Muller et al. (2008)

ApJ, 684: L33, Fig. 1

HCN in the inner wind



HCN v_2=1 (4–3) *o* Cet

Kaminski et al. (2017)

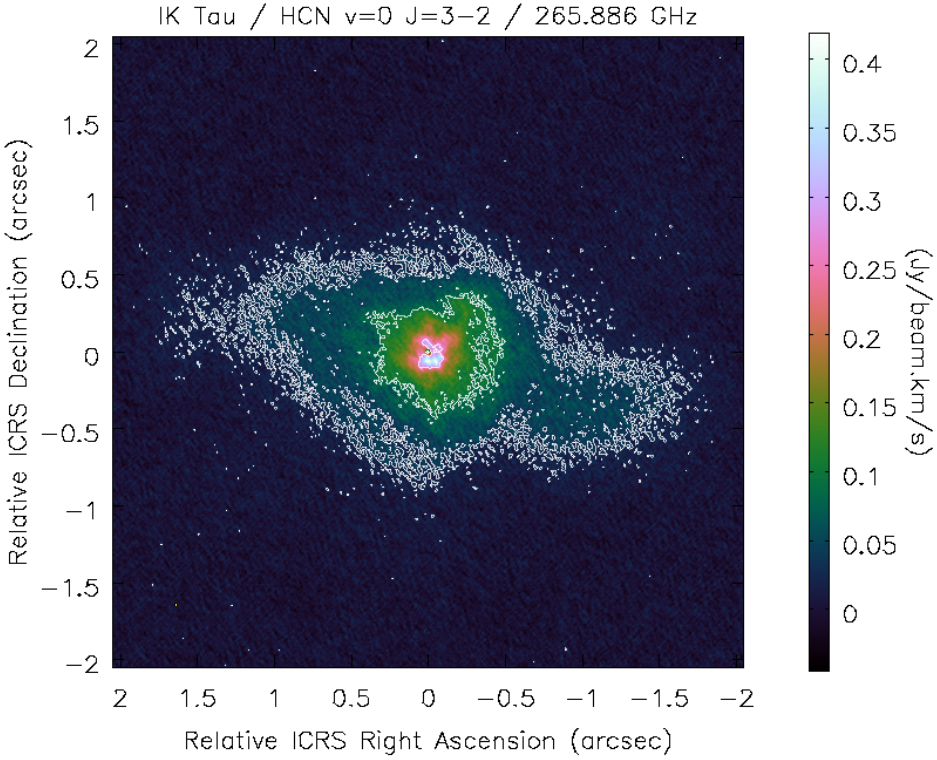
A&A 599, A59, Fig. 1

ALMA observations

- Targets: IK Tau ($\phi \sim 0.0$), *o* Cet ($\phi \sim 0.6$)
- Tuning: 15 GHz in 210–270 GHz (Band 6)
- Configuration: C43-10 (max baseline = 16.2 km)
  → angular resolution: ~20 milliarcsec ~ few $R_\star$
- Some identified species:
  SiO (up to v=5), H_2O, SiS, SO, SO_2, TiO_2, NS, …

HCN v=0 (3–2) images

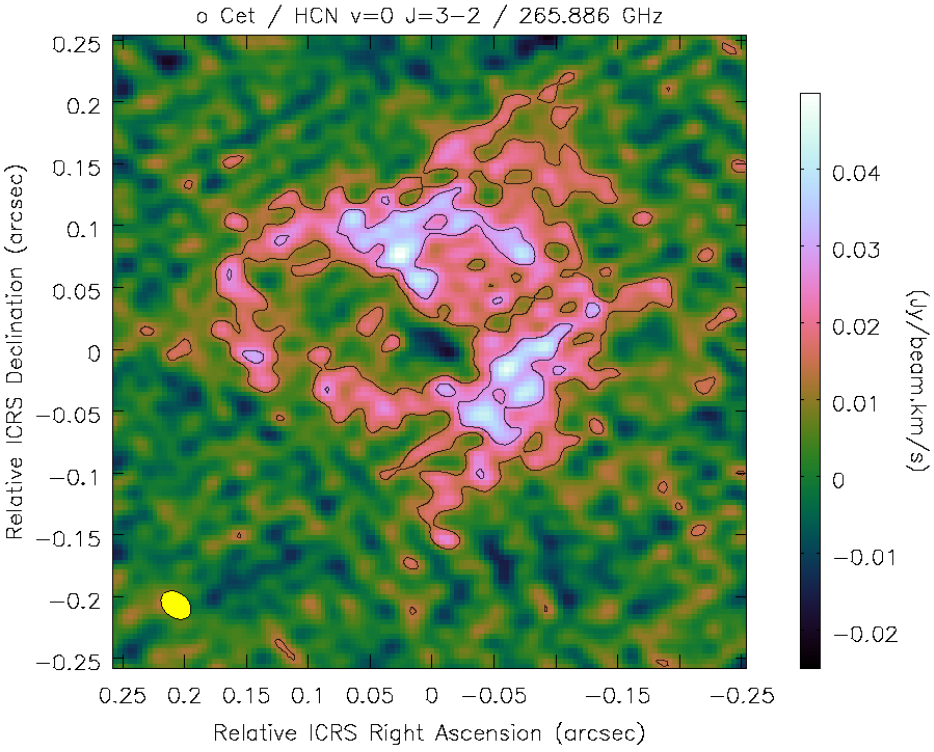
IK Tau



Beam ~ 26 × 19 mas

Contours: [5, 15, 45] σ

o Cet (Mira)

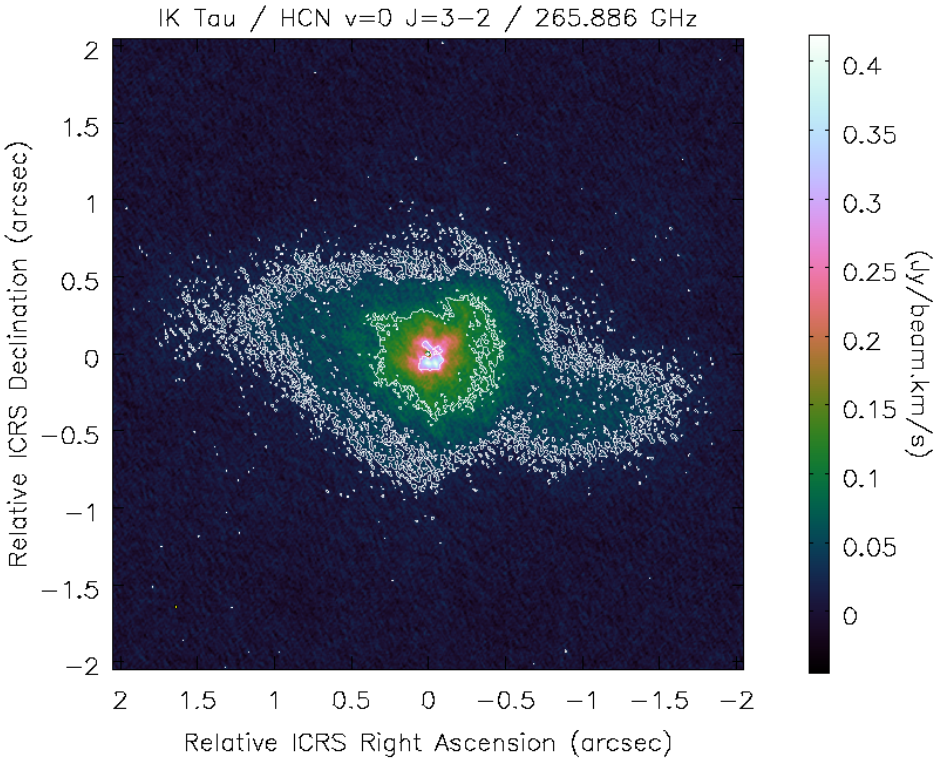


Beam ~ 27 × 20 mas

Contours: [3, 6] σ

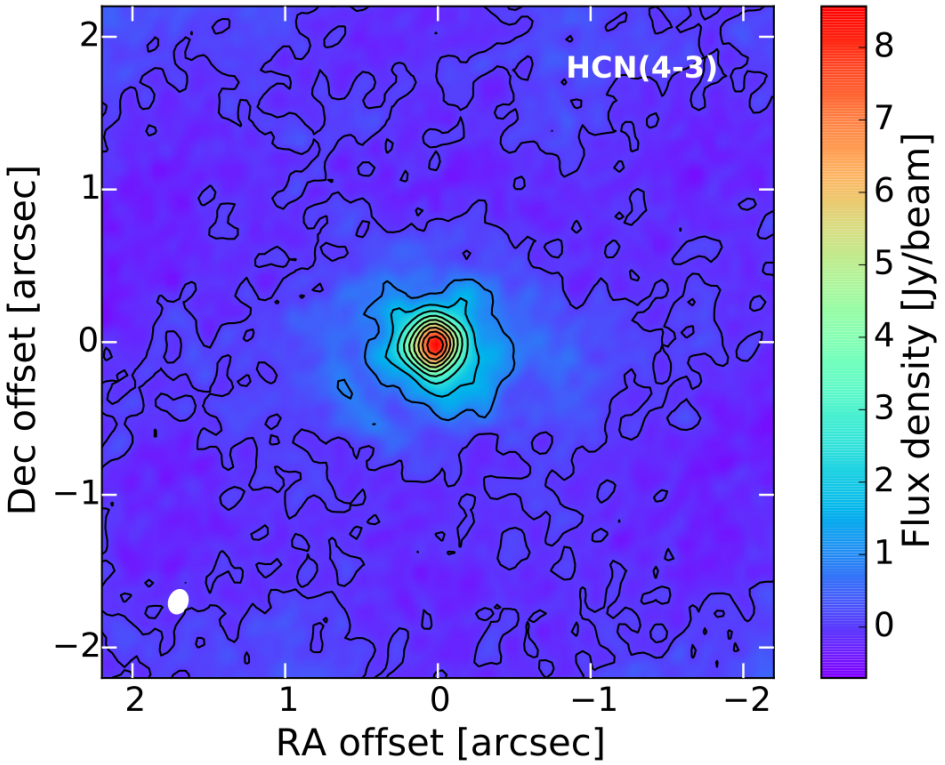
HCN from IK Tau

J = 3–2



Beam ~ 26 × 19 mas

J = 4–3

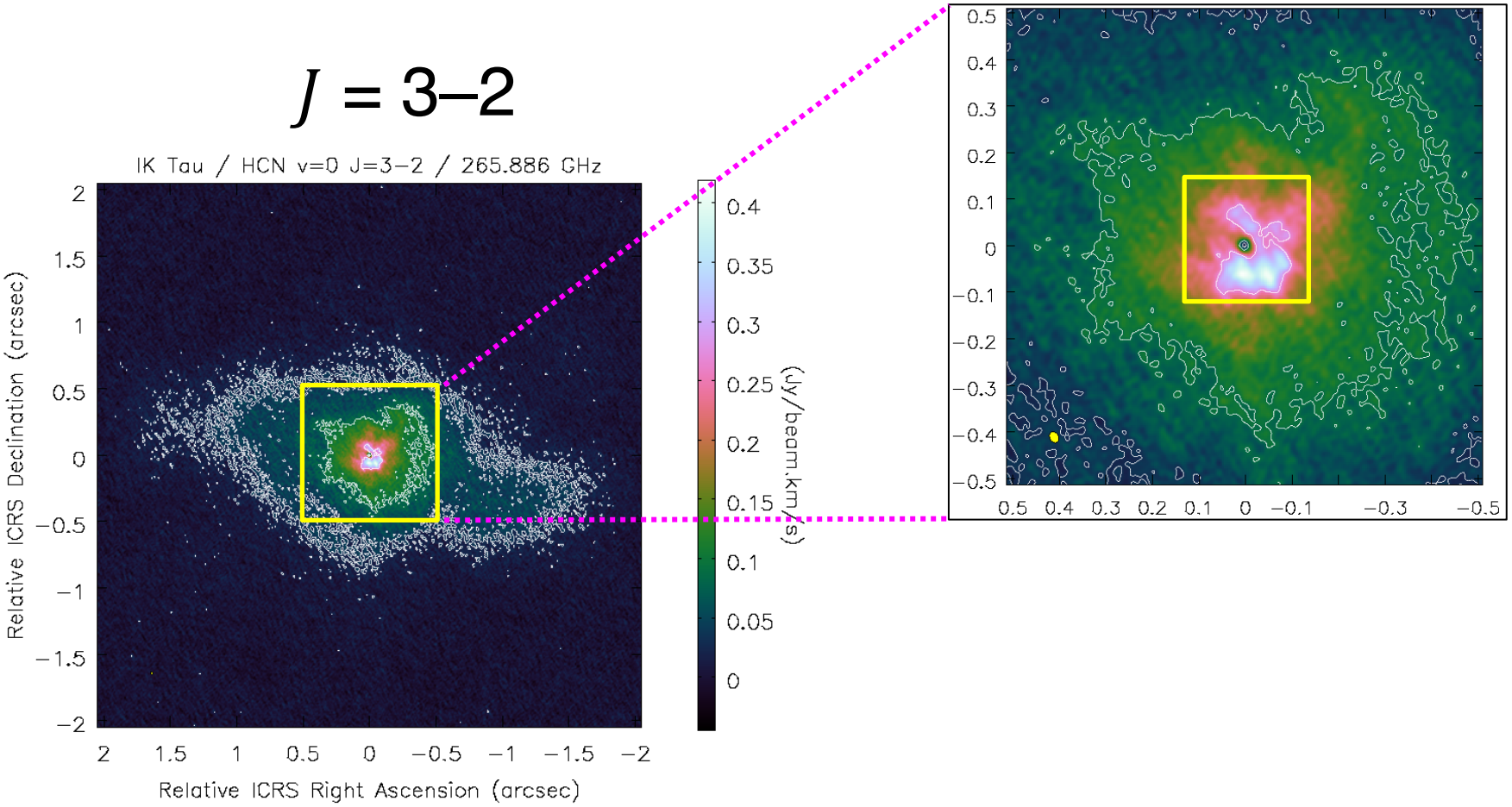


Beam ~ 180 × 160 mas

Decin et al., A&A *in press*, Fig. 7

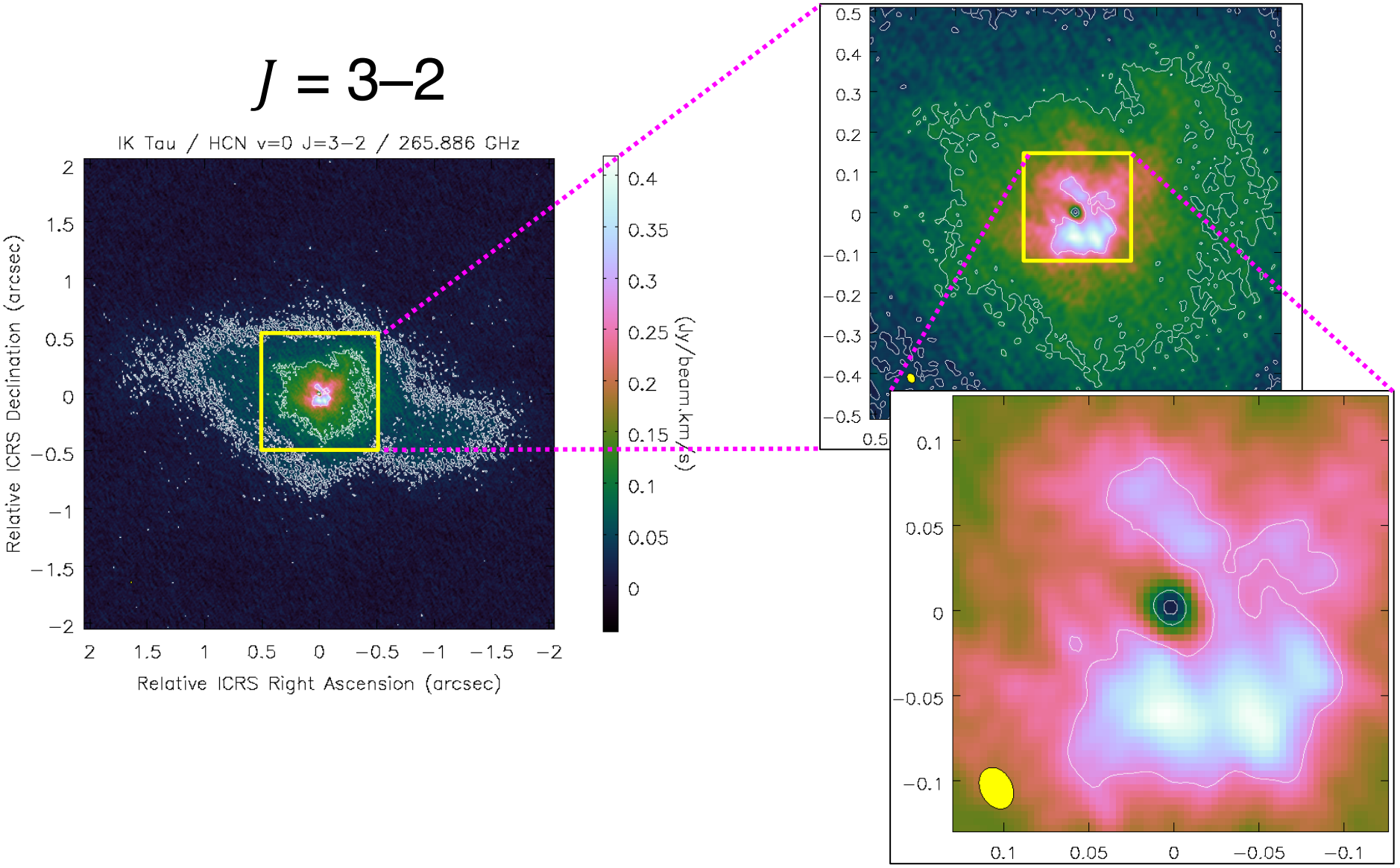
HCN from IK Tau

$J = 3–2$

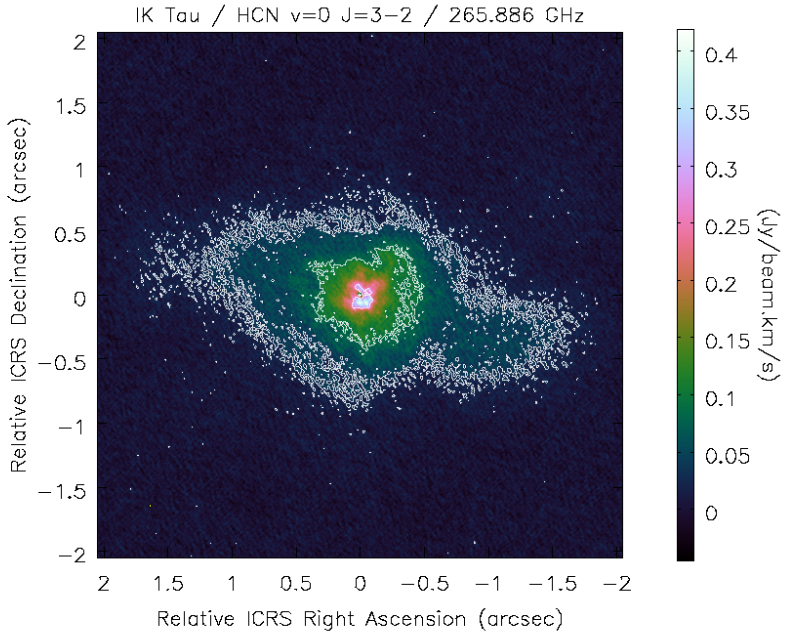


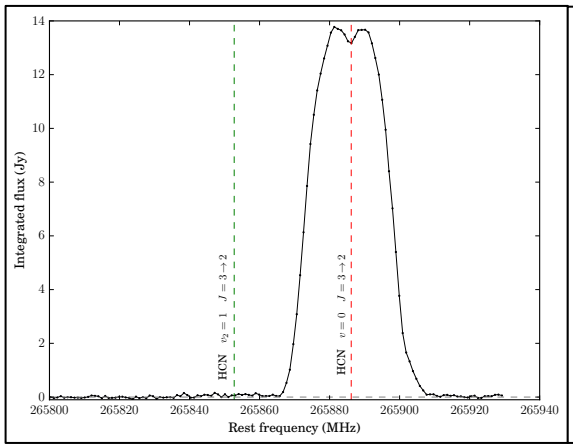
HCN from IK Tau

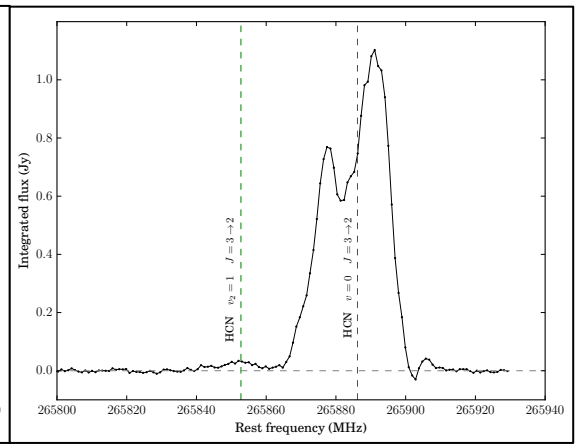
$J = 3–2$

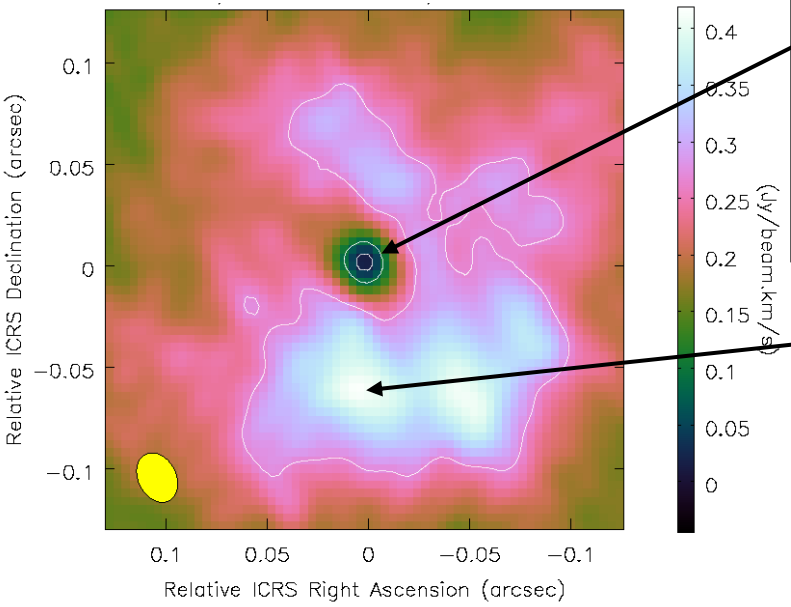


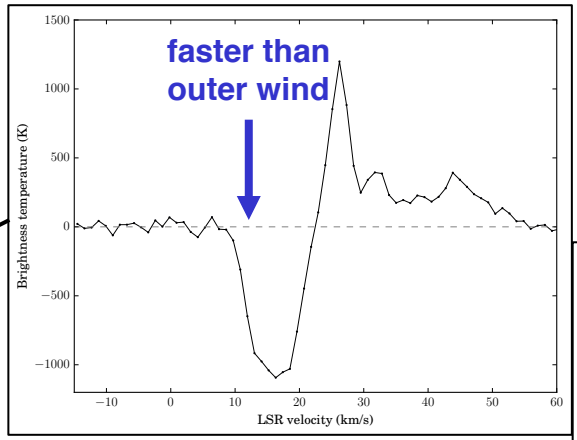
HCN spectra

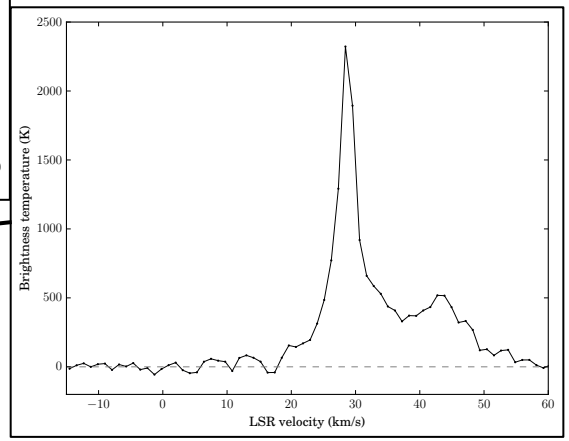

IK Tau / HCN v=0 J=3−2 / 265.886 GHz
Relative ICRS Declination (arcsec)
Relative ICRS Right Ascension (arcsec)
(Jy/beam.km/s)


Integrated flux (Jy)
Rest frequency (MHz)
HCN $v_2=1$ $J=3\rightarrow2$
HCN $v=0$ $J=3\rightarrow2$

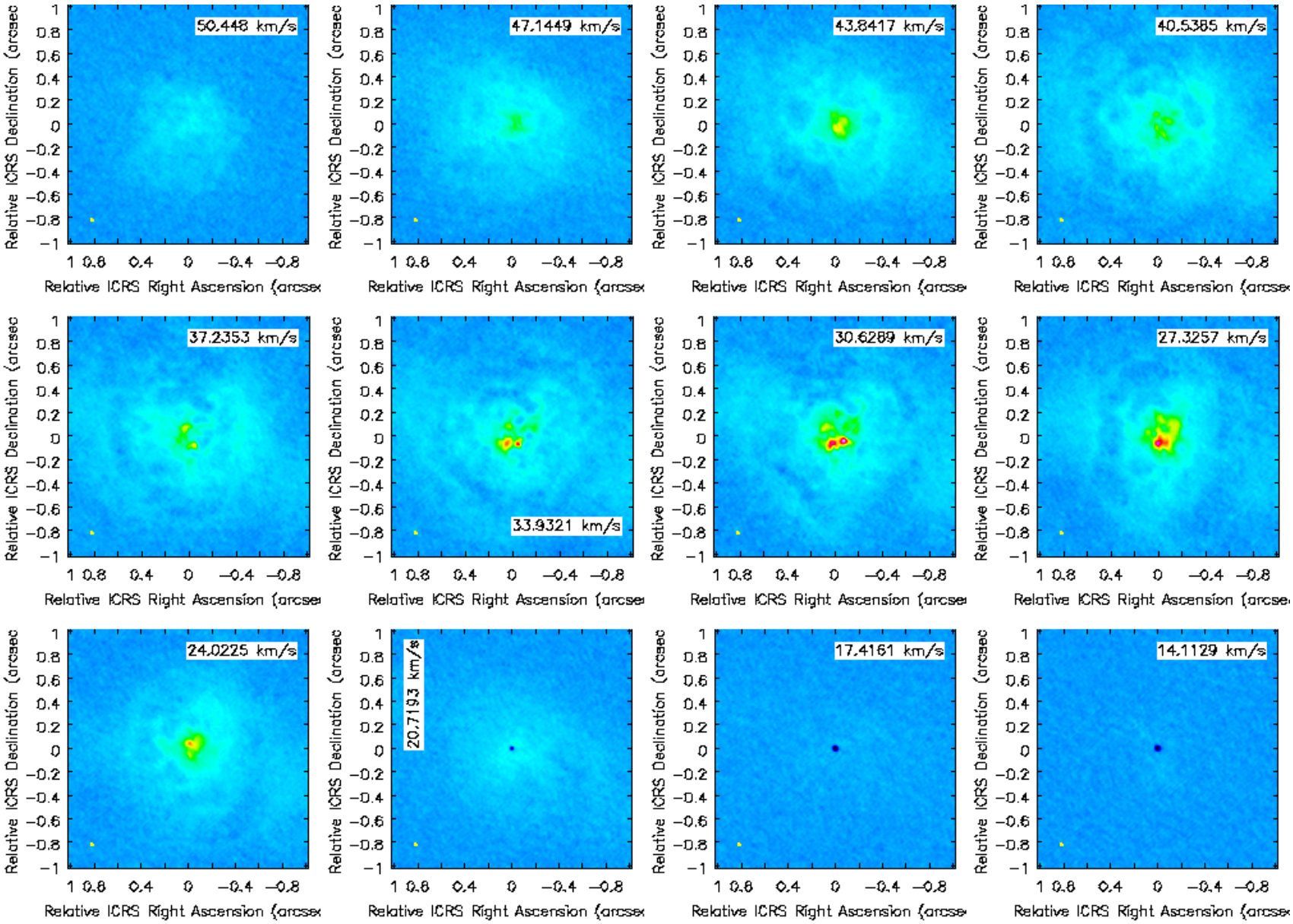

Integrated flux (Jy)
Rest frequency (MHz)
HCN $v_2=1$ $J=3\rightarrow2$
HCN $v=0$ $J=3\rightarrow2$


Relative ICRS Declination (arcsec)
Relative ICRS Right Ascension (arcsec)
(Jy/beam.km/s)


faster than
outer wind
Brightness temperature (K)
LSR velocity (km/s)

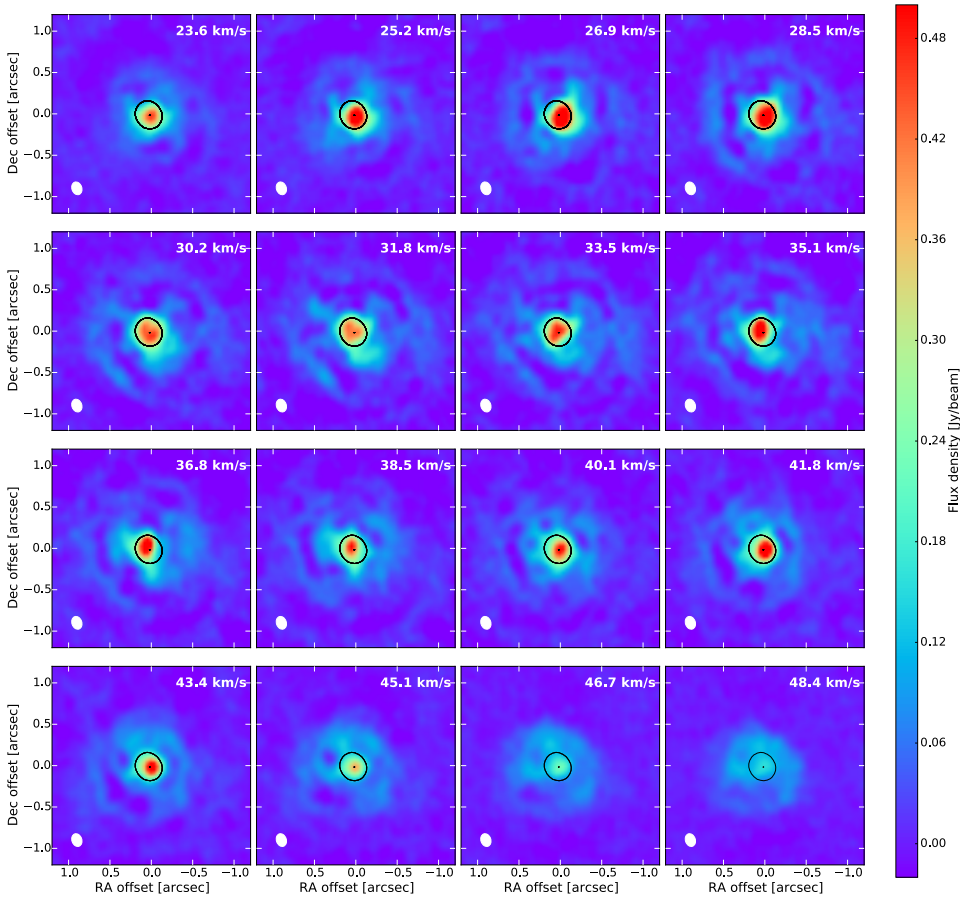

Brightness temperature (K)
LSR velocity (km/s)

Larger-scale structures



Larger-scale structures

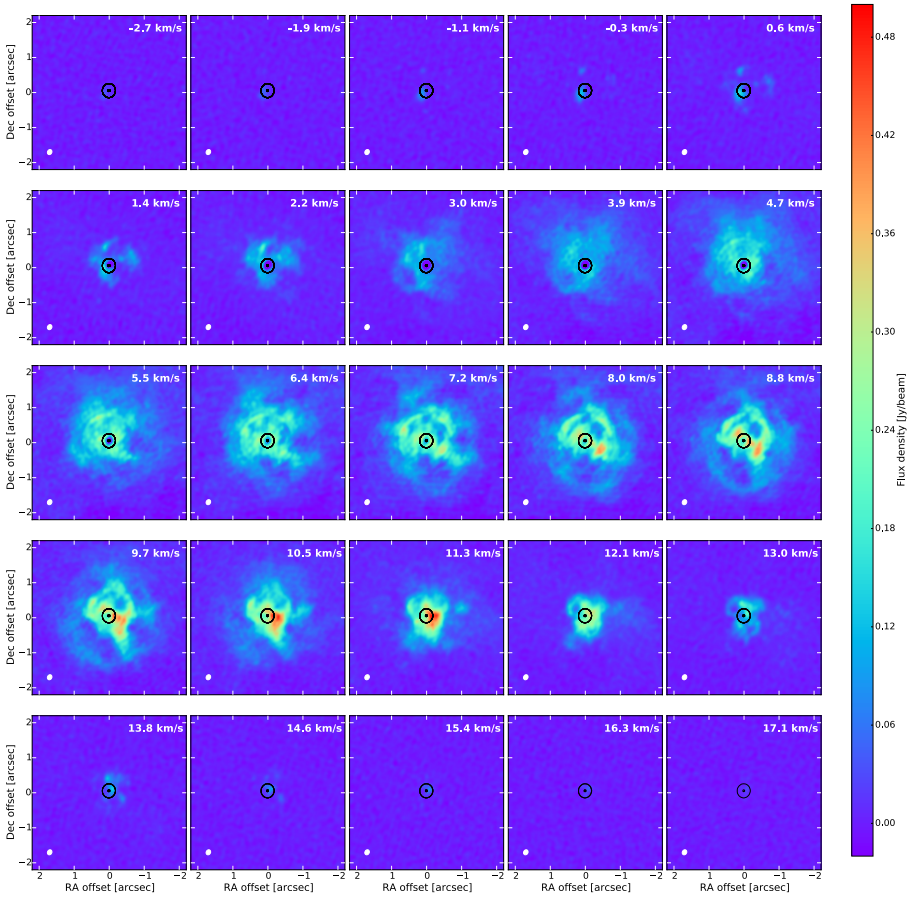
IK Tau



Decin et al.

A&A *in press* (arXiv:1801.09291), Fig. A.2

R Dor



Decin et al.

A&A *in press* (arXiv:1801.09291), Fig. A.1

Summary and outlook

- HCN in IK Tau
  → forms within the dust formation zone
  → qualitatively consistent with shock-induced chemistry
  → appears to trace multiple arcs/spiral arms?

- High-resolution (long-baseline) + high-sensitivity ALMA imaging
  → probe the inner winds of AGB stars
  → trace non-equilibrium processes
  → reveal detailed structures of CSEs