HCN laser lines in carbon-rich evolved stars

Ka Tat Wong

IRAM ARC node, Grenoble, France

Collaborator

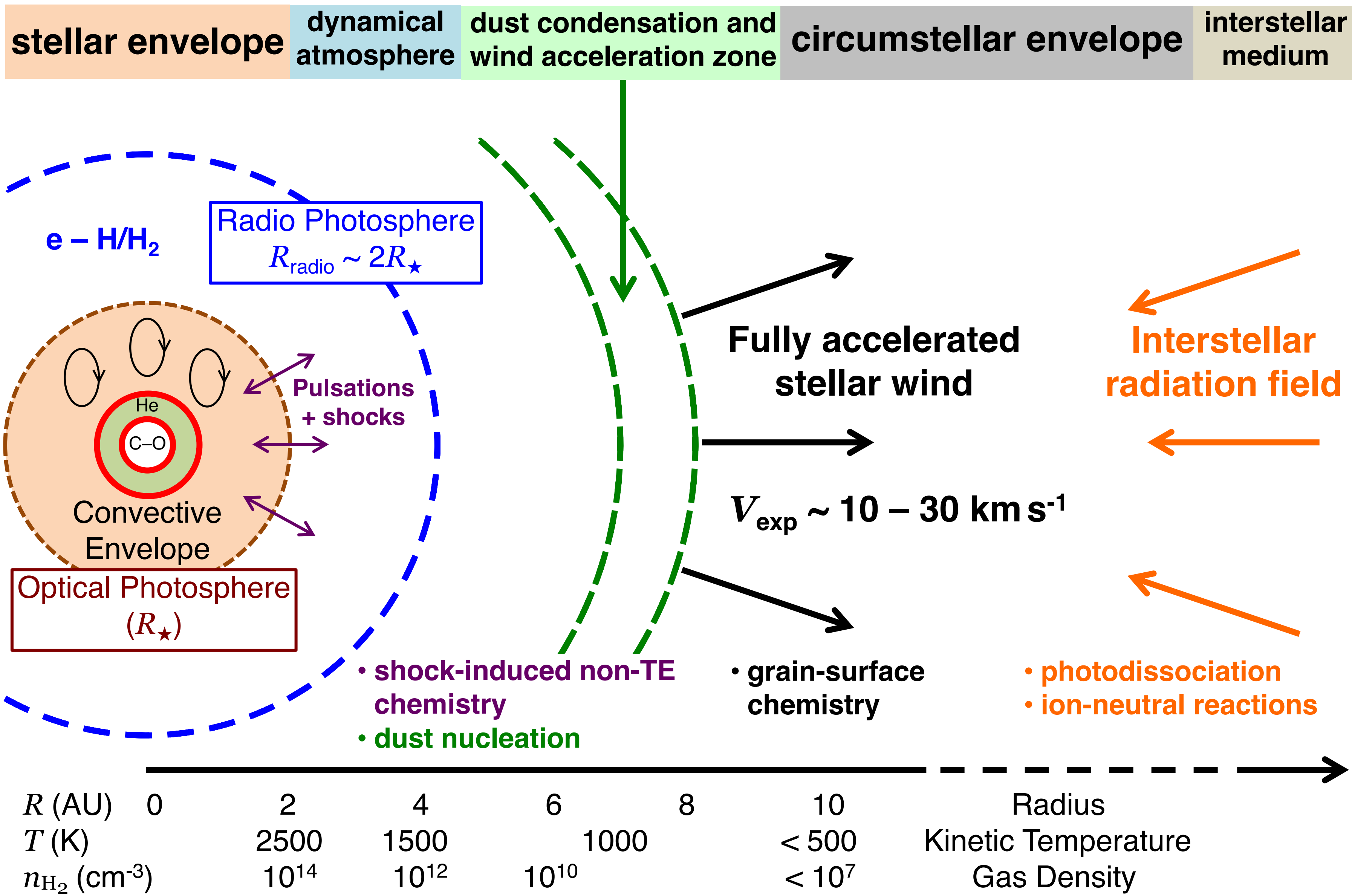
Karl M. Menten (MPIfR)

***ALMA2019*, Cagliari, Italy**

17 October 2019

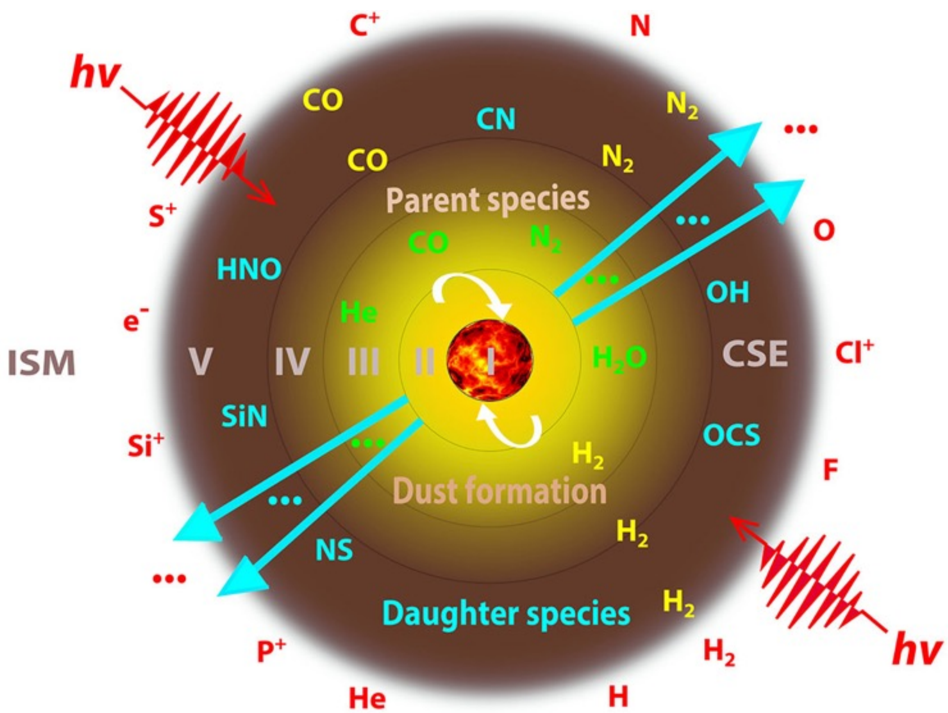
Institut de
Radioastronomie
Millimétrique

Circumstellar envelope (CSE)



Circumstellar chemistry

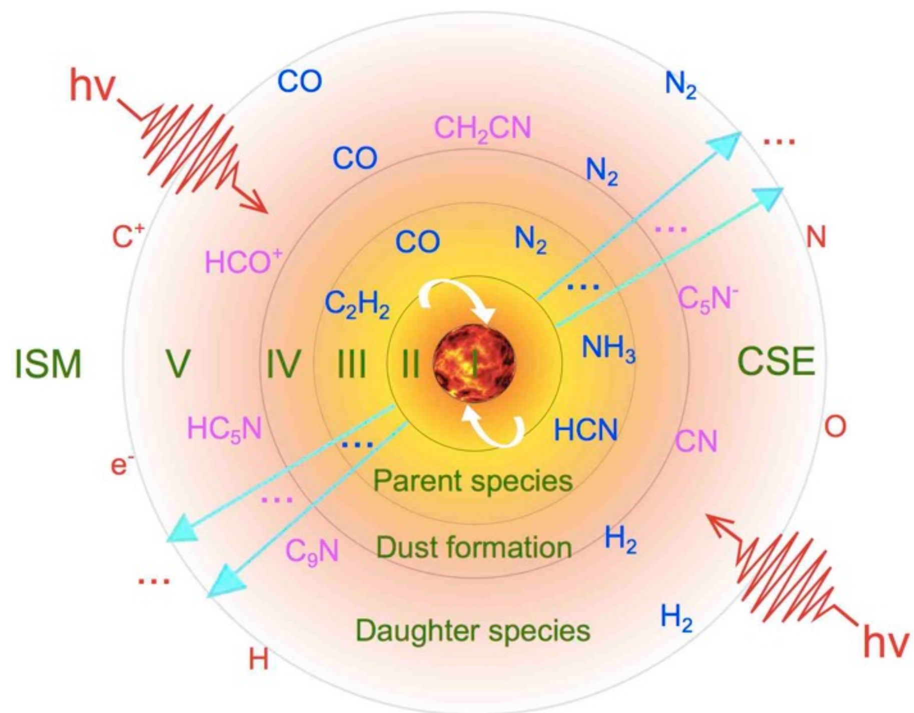
Oxygen-rich



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

CO, SiO, H_2O, OH, etc.

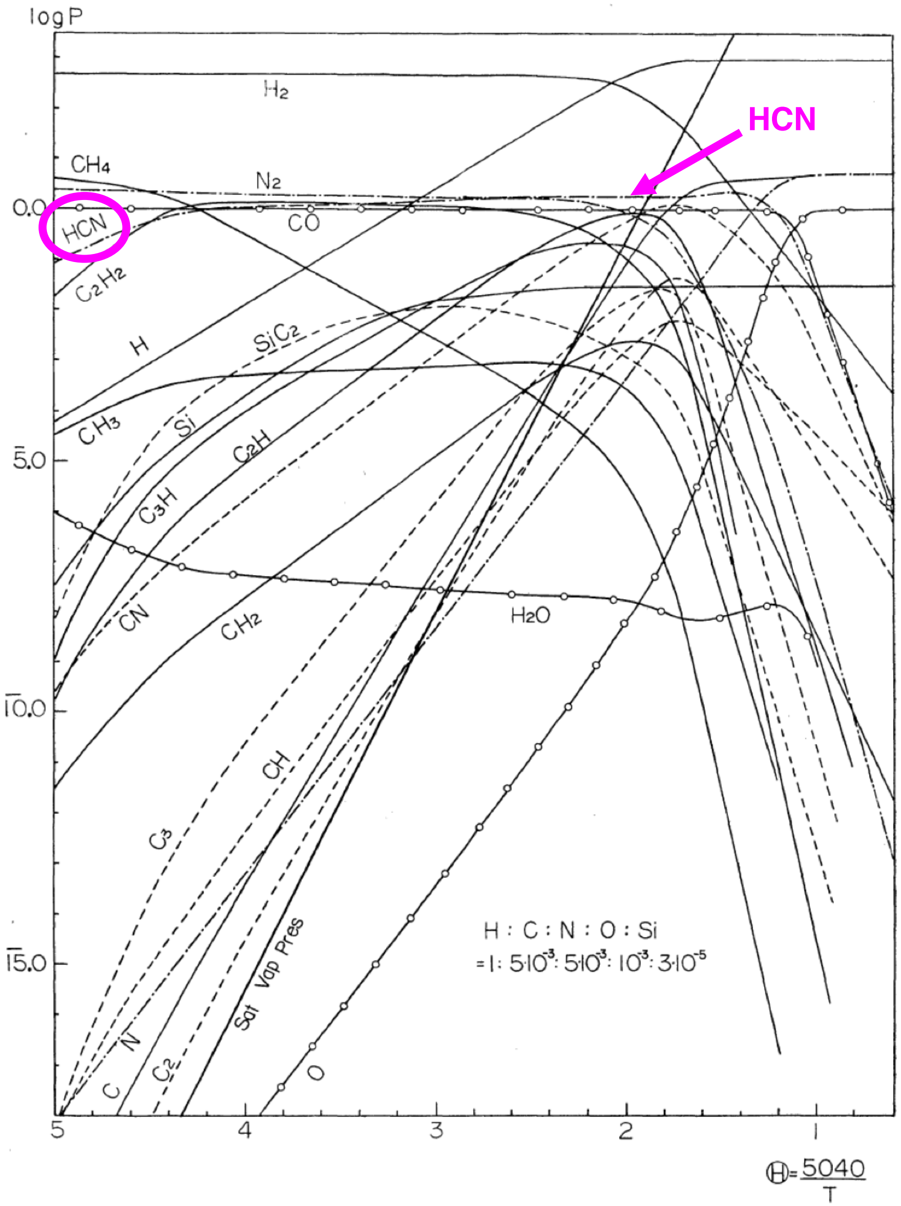
Carbon-rich

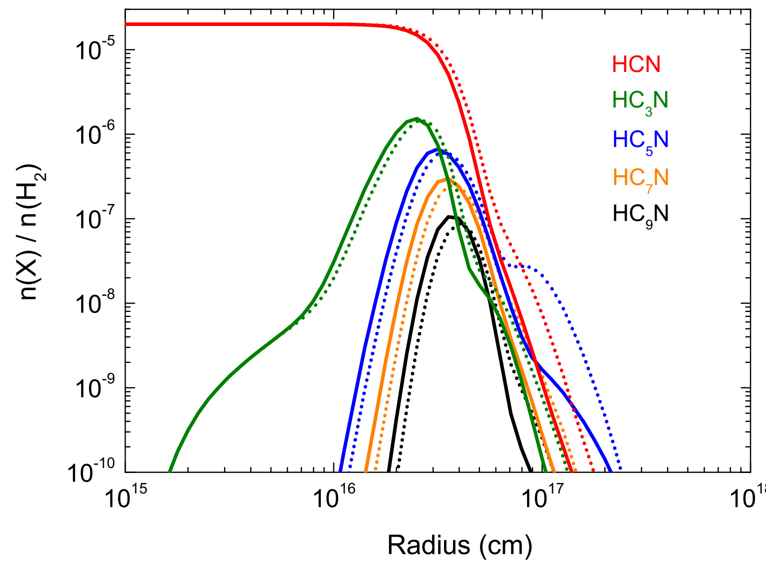


Li et al. (2014) A&A 568, A111

CO, HCN, CN, C_2H_2, etc.

HCN in carbon-rich stars





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

Abundance $HCN/H_2 \sim \mathbf{10^{-5}}$
(Schöier et al. 2013)

Fig. 1. The equilibrium composition in carbon rich giants ($\log P_g \sim 3.0$). The logarithm of the partial pressure of atoms and molecules is plotted against $\Theta = 5040/T$.

Tsuji (1964) PJAB, 40, 2, 99

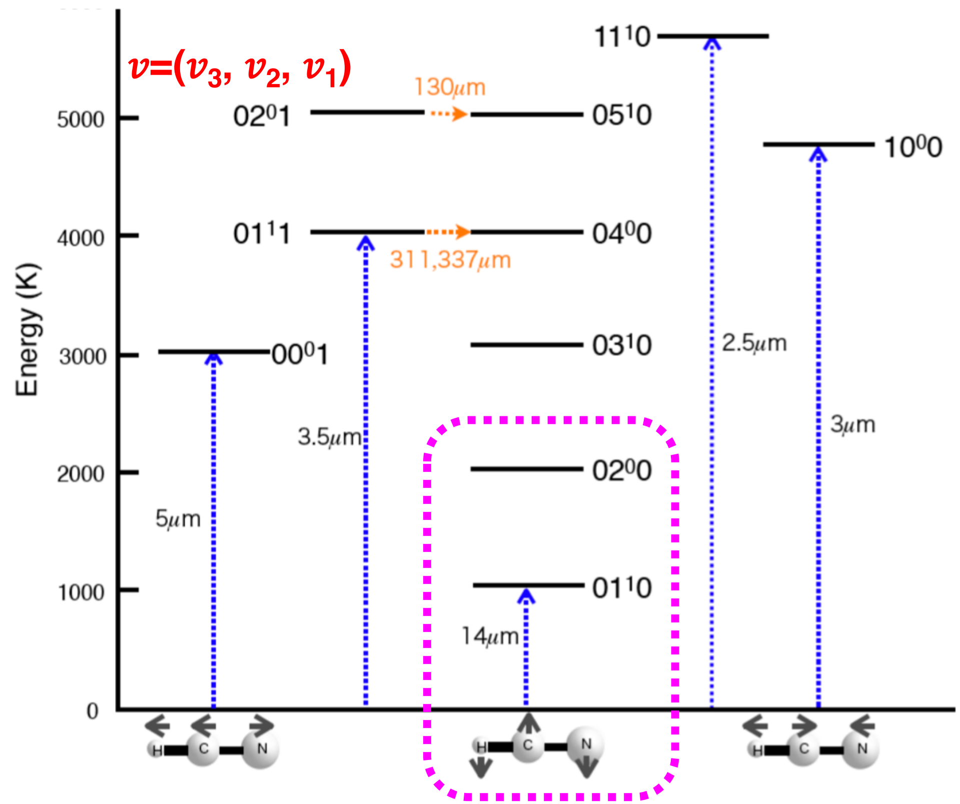
HCN masers in C-rich stars

- Absence of strong (sub)millimetre SiO, H_2O, OH masers (unlike O-rich stars)
- Strong HCN masers in ground and excited vibrational states

➢ $v = (v_1, v_2, v_3)=(0, 2^0, 0)$
$J = 1–0$
(Guilloteau et al. 1987;1988)

➢ $v = (0, 1^{1c}, 0)$ $J = 2–1$
~400 Jy in IRC +10216
(Lucas & Cernicharo 1989)

➢ $v = (0, 0, 0)$ $J = 1–0$
(Izumiura et al. 1995)



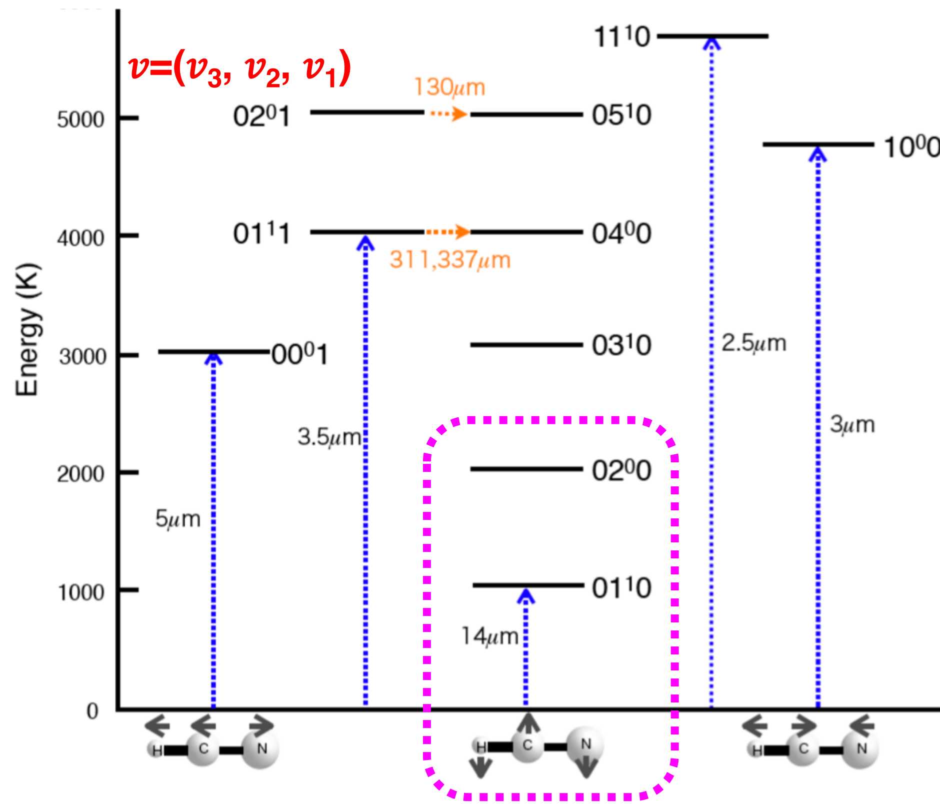
Shinnaga et al. (2009) ApJ 698:1924

HCN masers in C-rich stars

- HCN masers exist in a considerable fraction of carbon stars.

➢ (0, 1^{1c}, 0) + (0, 1^{1d}, 0) 2–1
11, 4 out of 13 targets
(Menten et al. 2018)

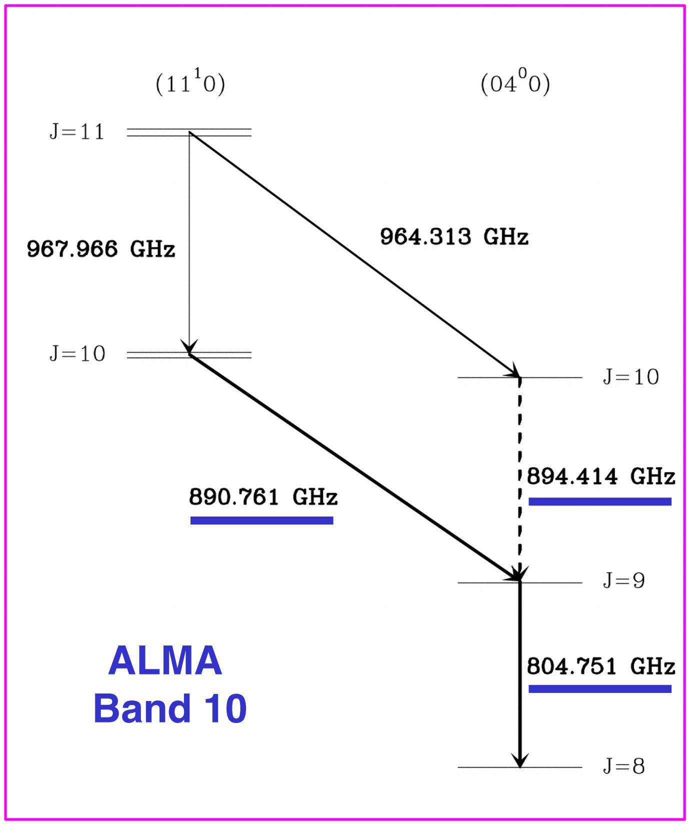
➢ (0, 1^{1c}, 0) 3–2 and 4–3
5/12 and 4/11 targets
(Bieging 2001)



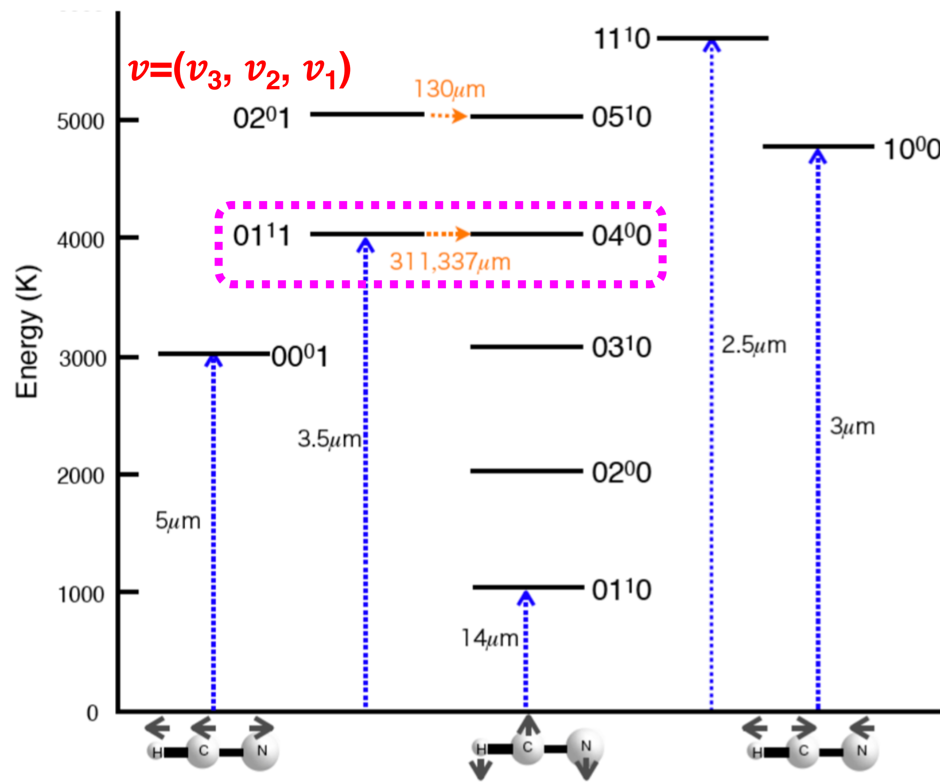
Shinnaga et al. (2009) ApJ 698:1924

Far-infrared HCN laser lines

- Rotation-vibration interactions of $(1, 1^1, 0)$ and $(0, 4^0, 0)$ states
- Strong laboratory lasers (Lide & Maki 1967)



Schilke & Menten (2003) ApJ 583:446

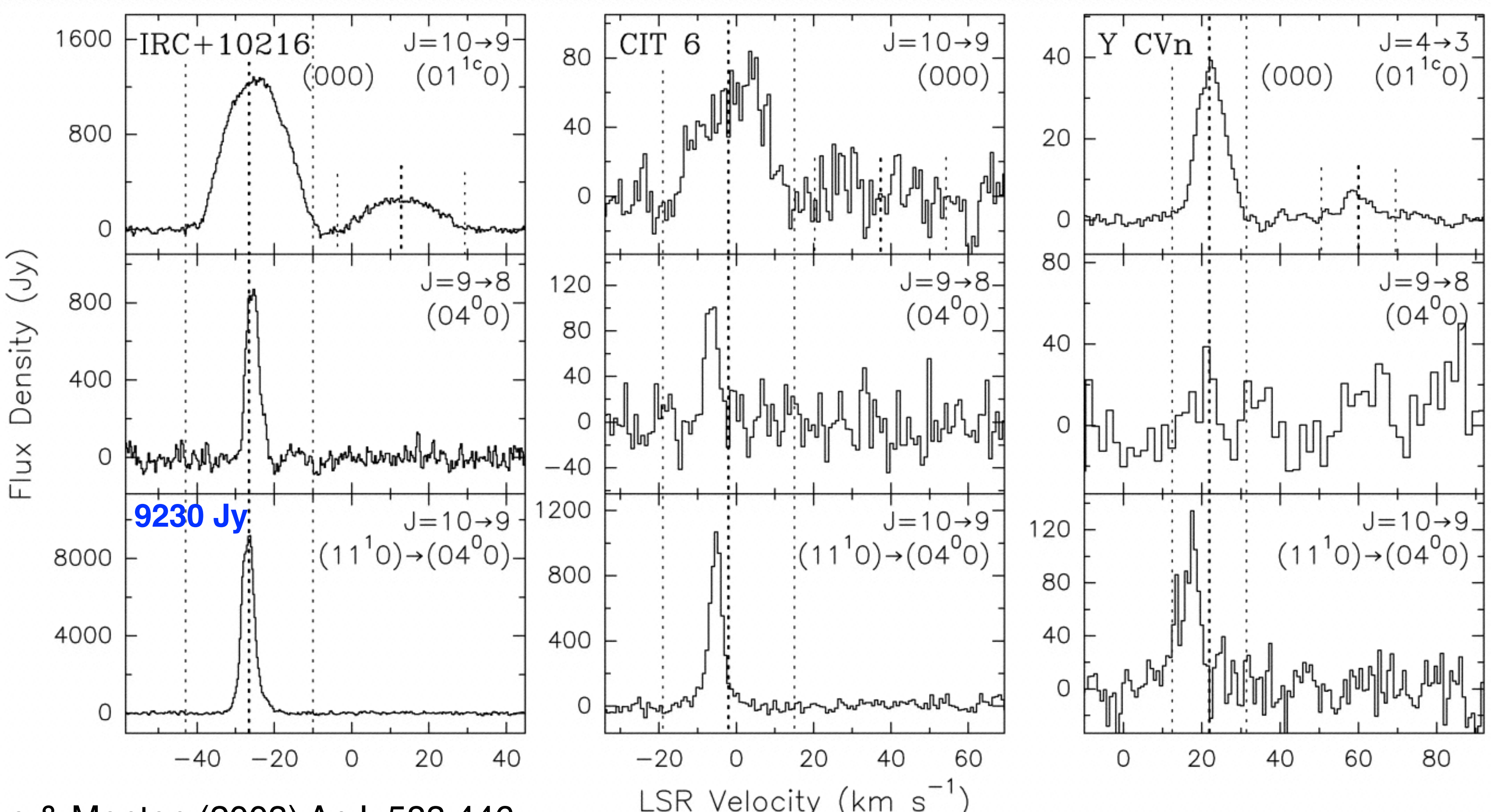


Shinnaga et al. (2009) ApJ 698:1924

Far-infrared HCN laser lines

- (0, 4^0, 0) 9–8 (Schilke et al. 2000): 804.75 GHz
- (1, 1^1, 0)–(0, 4^0, 0) 10–9 (Schilke & Menten 2003): 890.76 GHz

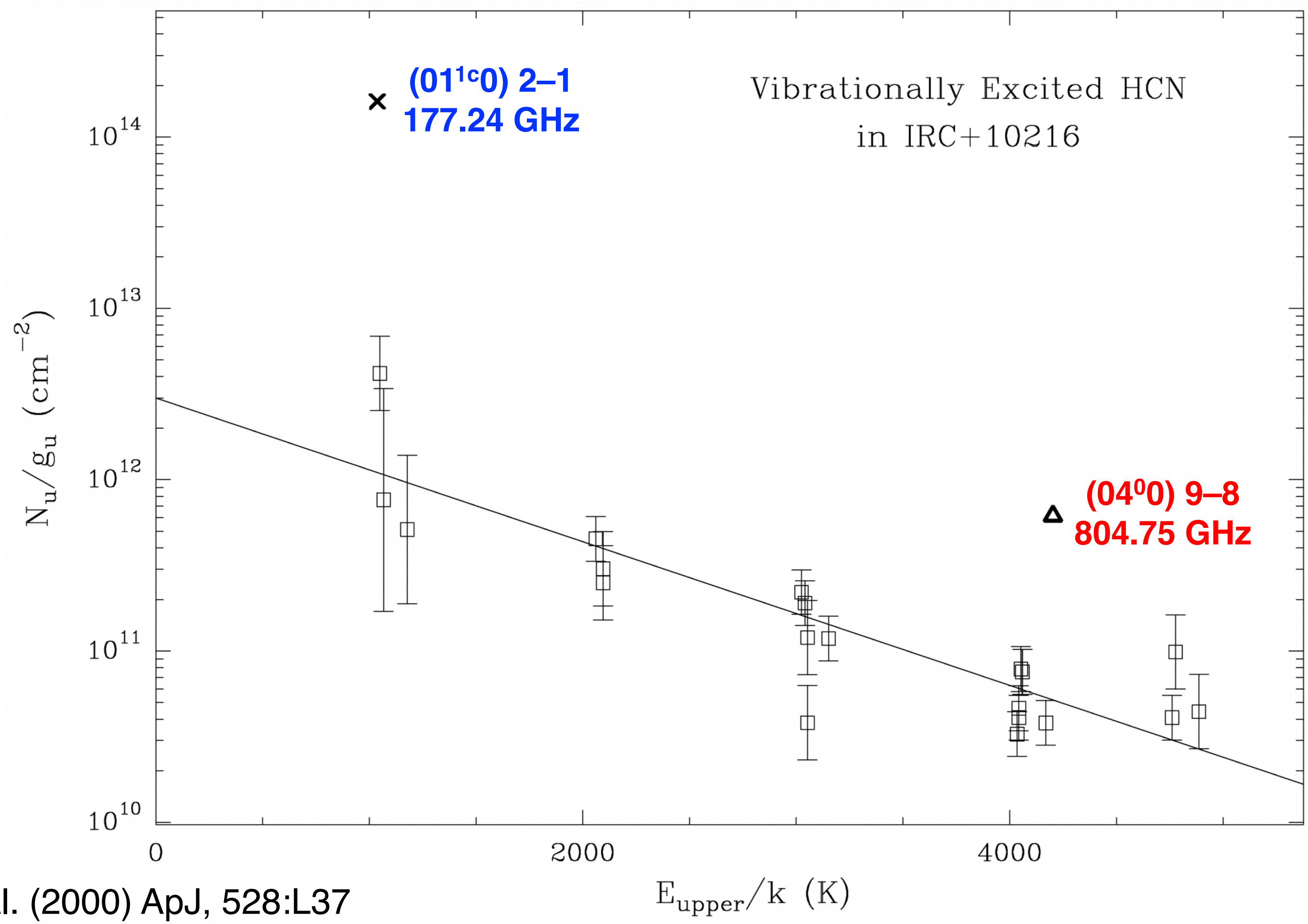
Caltech Submillimeter Observatory (CSO) spectra



Schilke & Menten (2003) ApJ, 583:446

Far-infrared HCN laser lines

- (0, 4^0, 0) 9–8 (Schilke et al. 2000): 804.75 GHz
- (1, 1^1, 0)–(0, 4^0, 0) 10–9 (Schilke & Menten 2003): 890.76 GHz



Schilke et al. (2000) ApJ, 528:L37

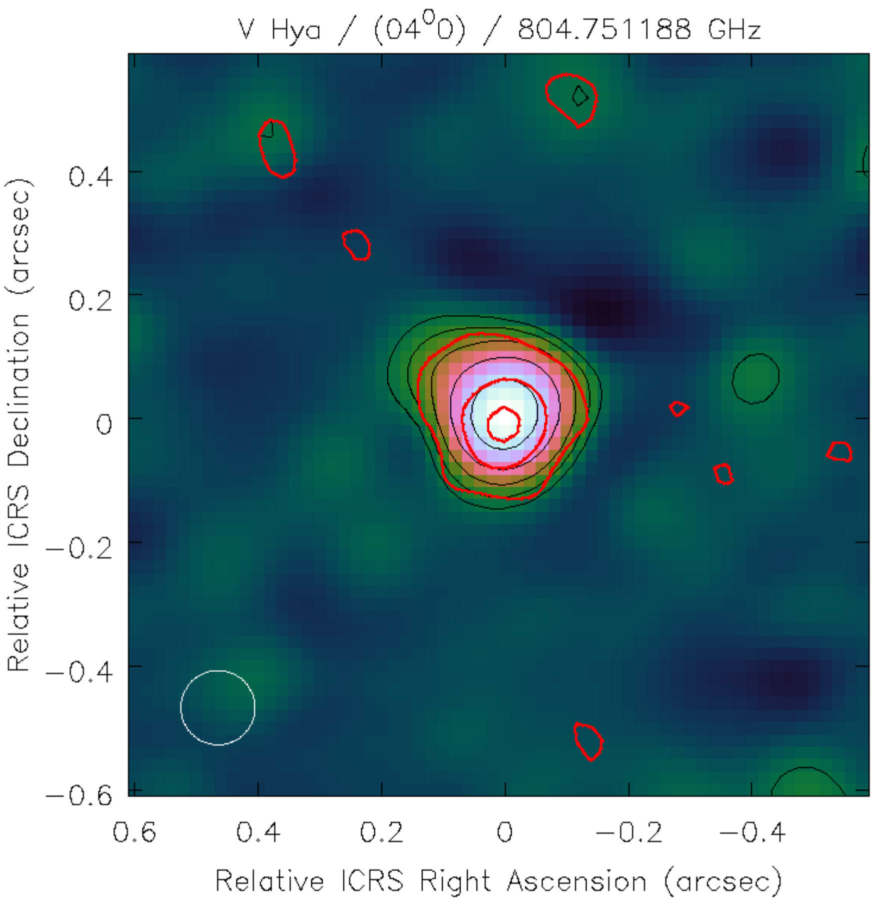
Pilot ALMA survey on HCN lasers

- Identify more HCN laser-emitting sources
- Self-calibrate Band 10 data with intense HCN laser emission

Target	**v = (0, 4^0, 0) J = 9–8** **804.75 GHz**	**v = (1, 1^1, 0)–(0, 4^0, 0) J = 10–9** **890.76 GHz**
R For	Detected (raw data)	Detected (QA2 SemiPass)
R Lep	Detected (QA2 SemiPass)	Detected (raw data)
CQ Pyx	Detected (raw data)	Detected (QA2 Pass)
IRC +10216	*Herschel*/HIFI	**Detected (QA2 SemiPass)**
X Vel	—	Detected (QA2 SemiPass)
CIT 6	*Herschel*/HIFI	*Herschel*/HIFI
V Hya	**Detected (QA2 Pass)**	**Detected (QA2 Pass)**
V358 Hya	—	—
II Lup	*Herschel*/HIFI	*Herschel*/HIFI
X TrA	—	—

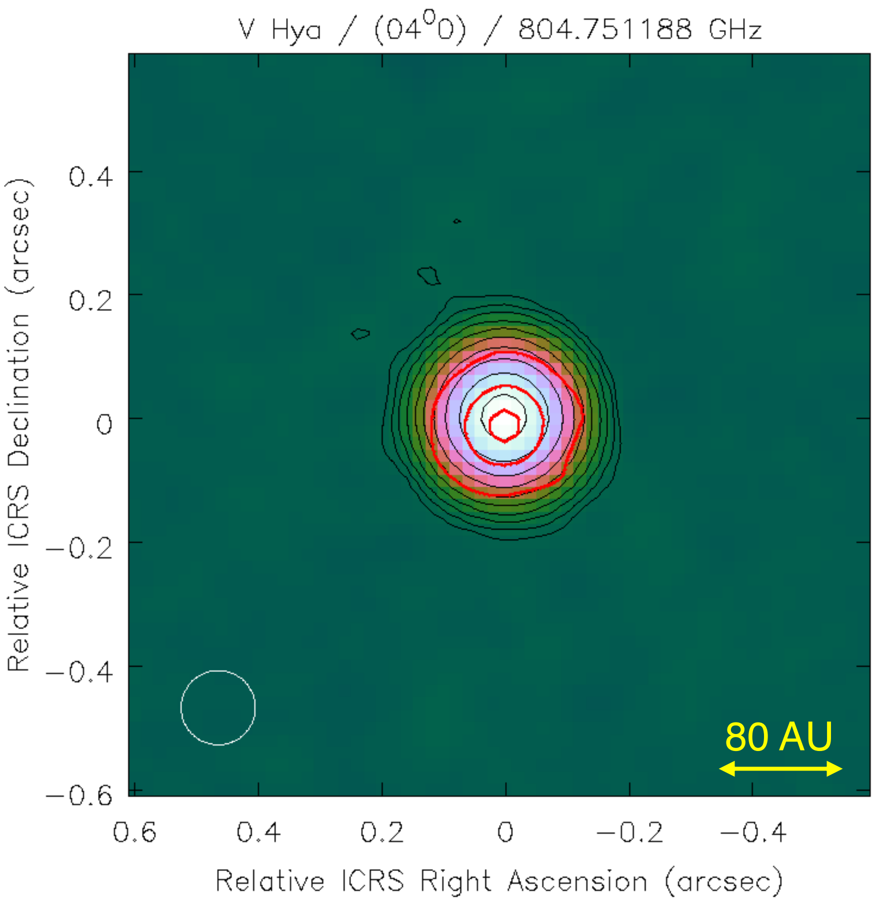
HCN laser at 804.75 GHz in V Hya

Phase-referencing



Contours: 3, 6, 12, 24, 48 × 1.4 Jy/beam
Dynamic range ~ 76

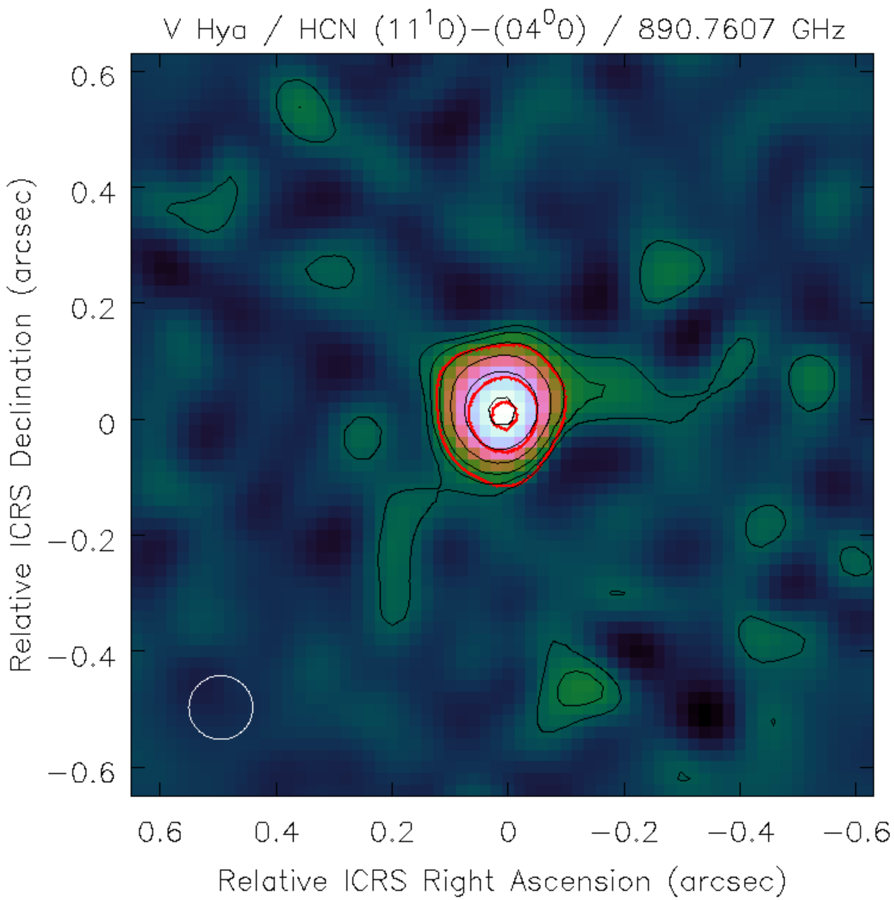
Self-calibration



Contours: 3, 6, 12, ···, 1536 × 0.09 Jy/beam
Dynamic range ~ 2000 (26× improvement)

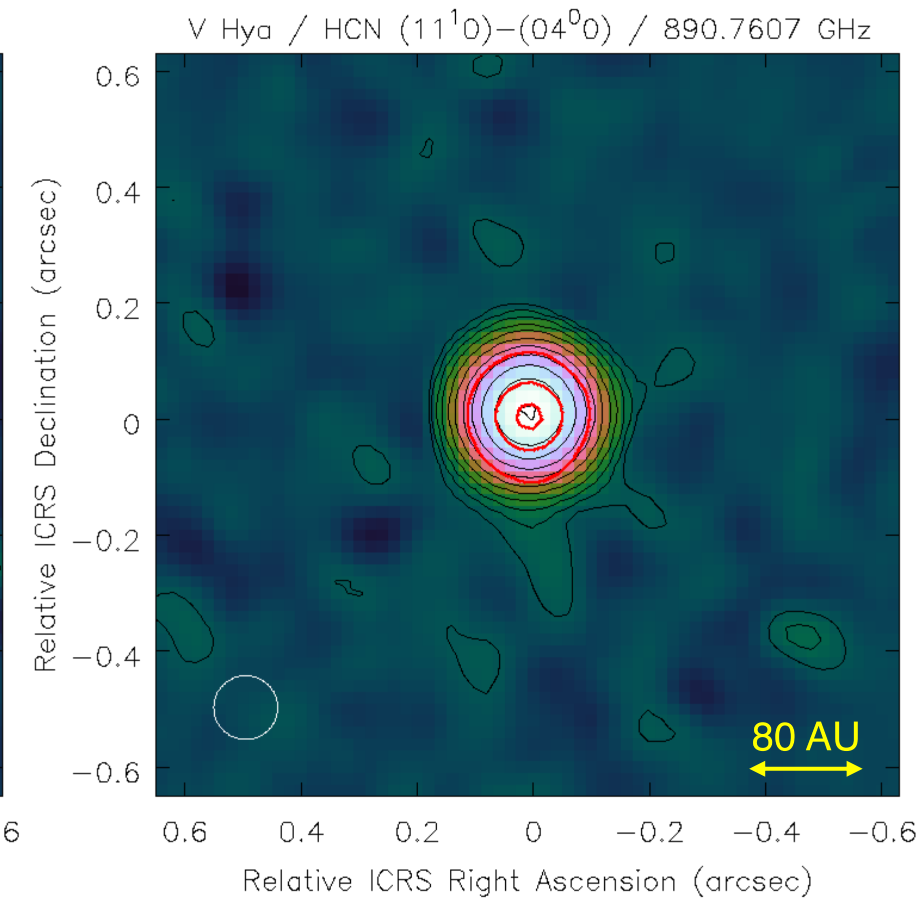
HCN laser at 890.76 GHz in V Hya

Phase-referencing



Contours: 3, 6, 12, 24, 48, 96 × 4.0 Jy/beam
Dynamic range ~ 107

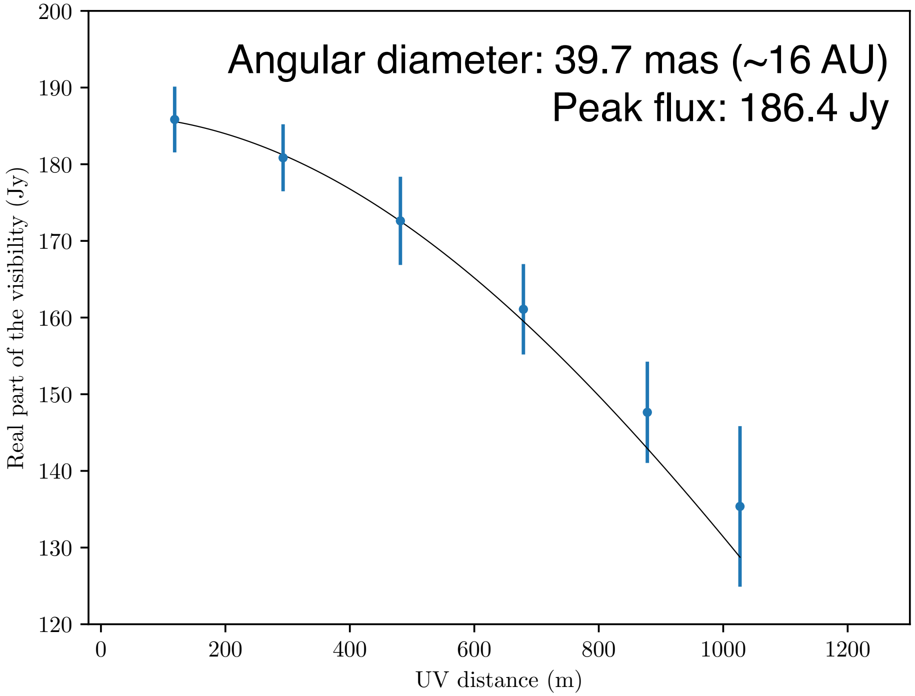
Self-calibration



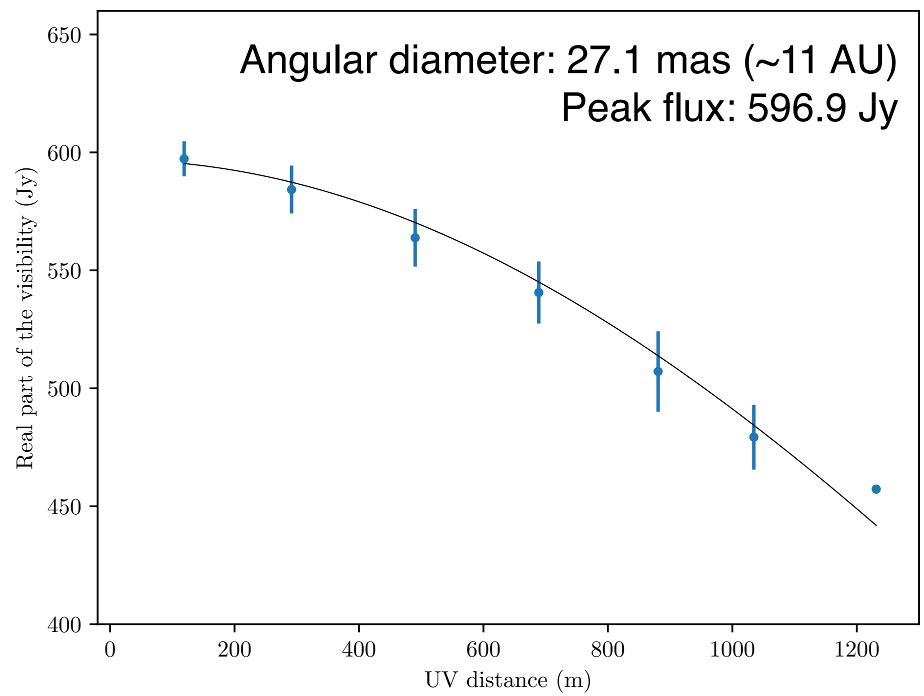
Contours: 3, 6, 12, …, 3072 × 0.18 Jy/beam
Dynamic range ~ 3100 (29× improvement)

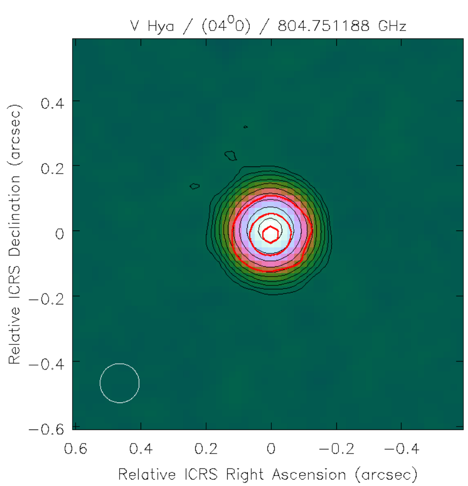
HCN laser visibilities

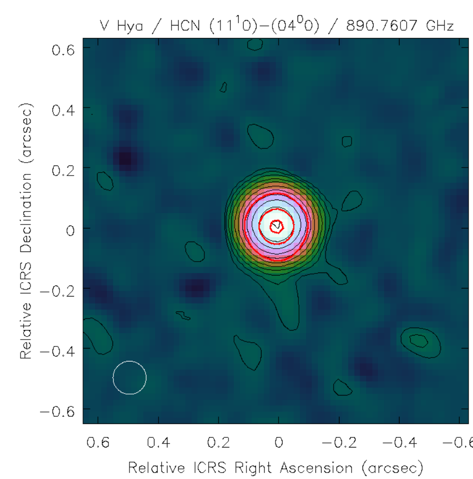
804.75 GHz



890.76 GHz



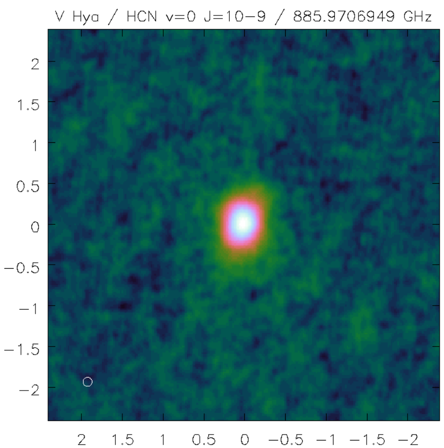


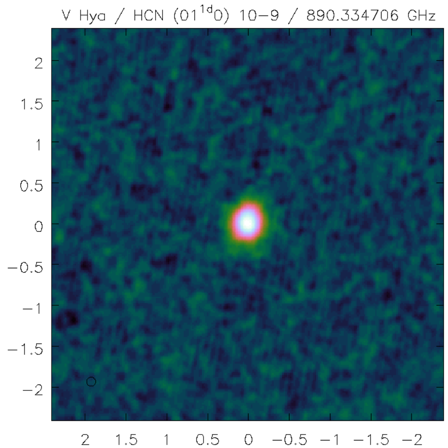


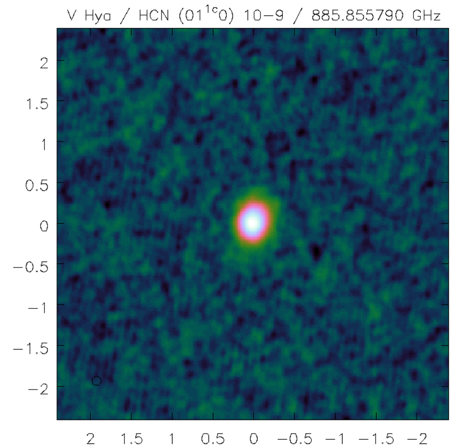
HCN integrated intensity maps

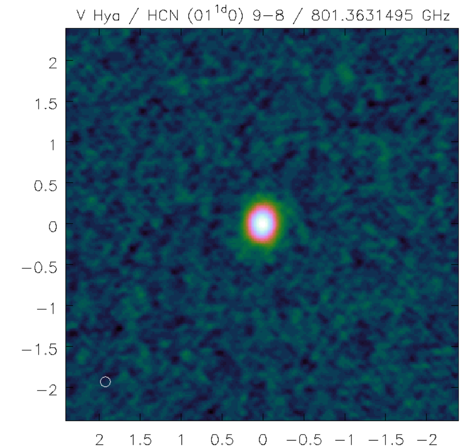
v=0

v_2=1





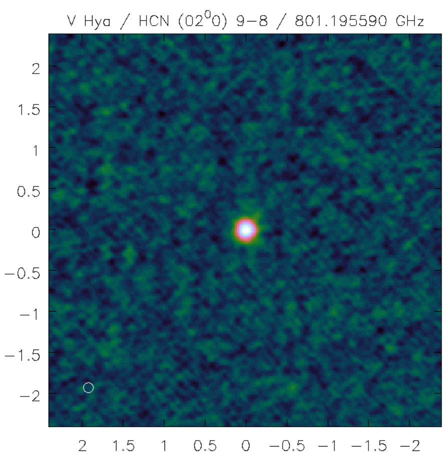


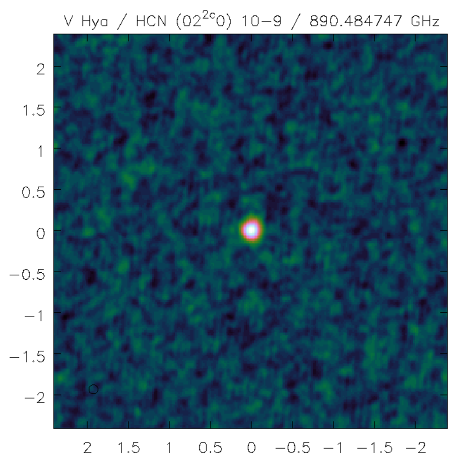


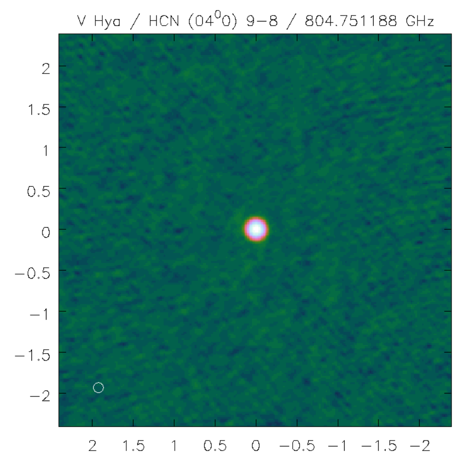
v_2=2

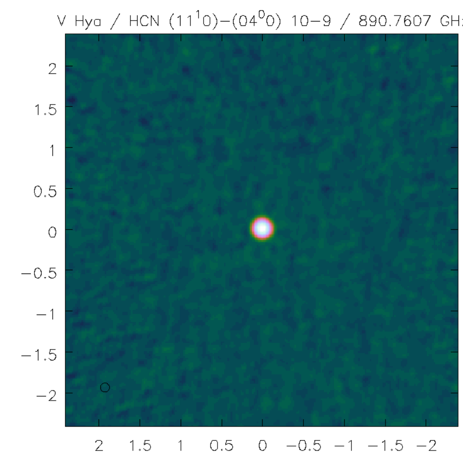
v_2=4

(11^10)–(04^00)

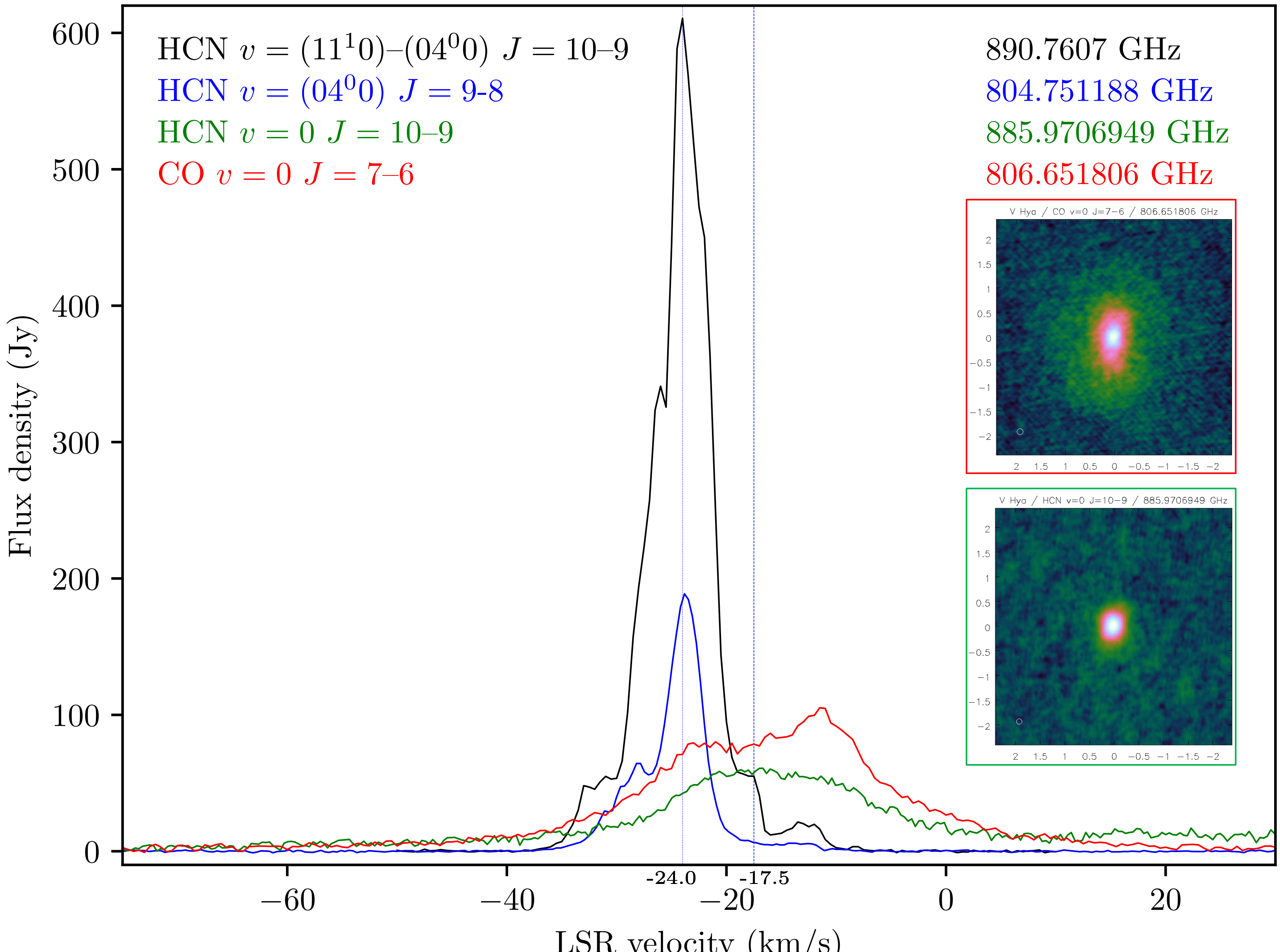




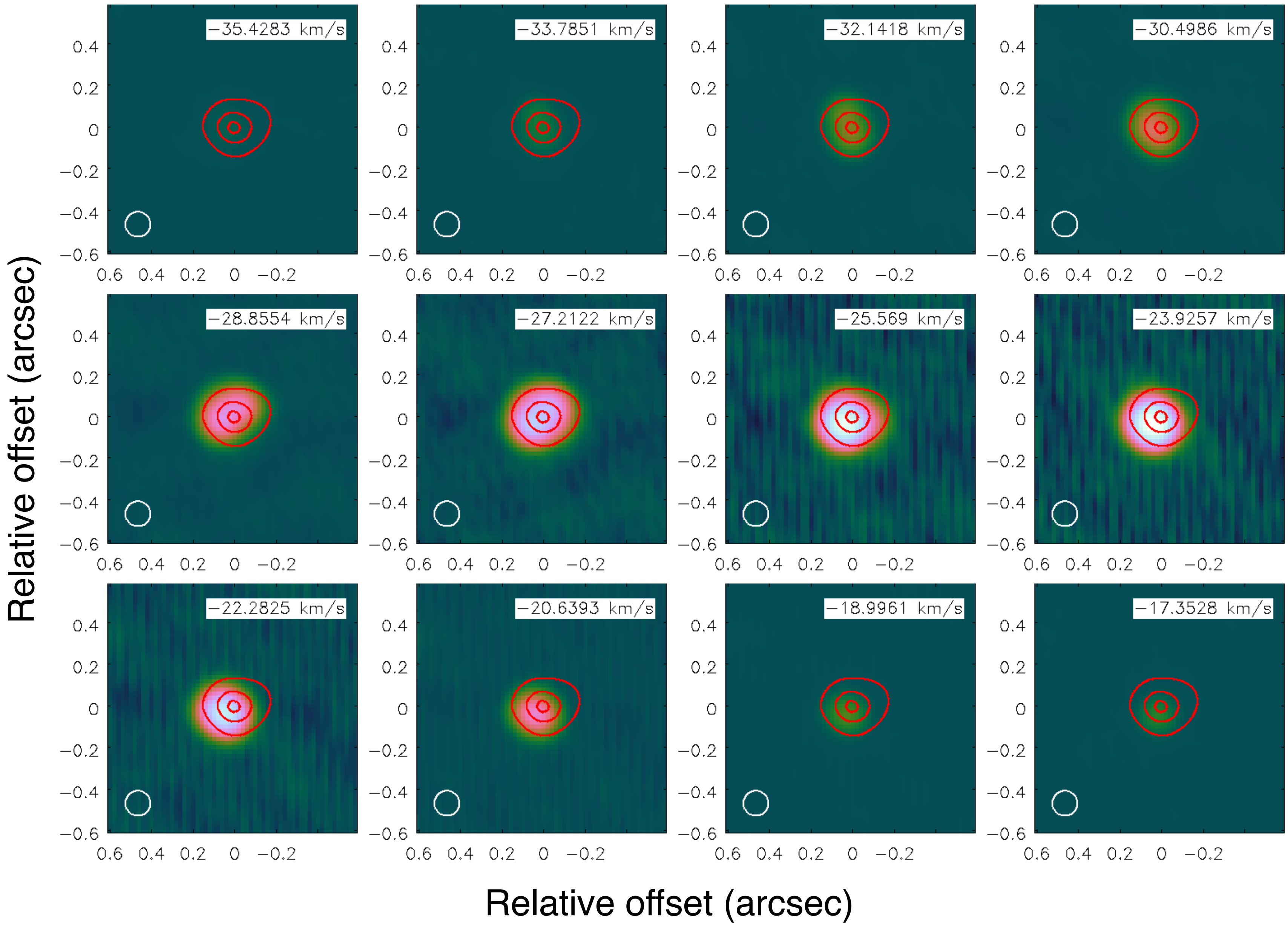




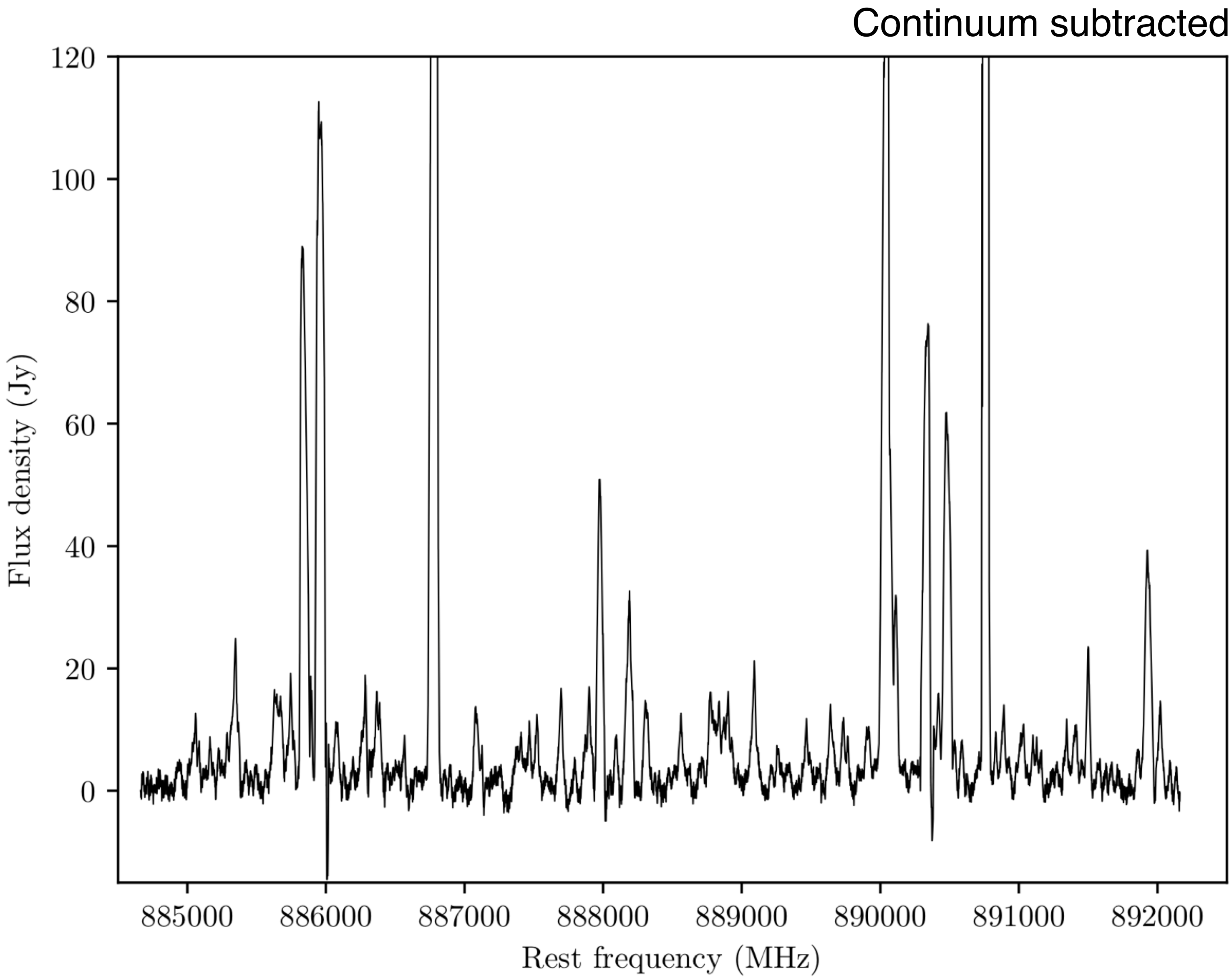
HCN and CO spectra of V Hya



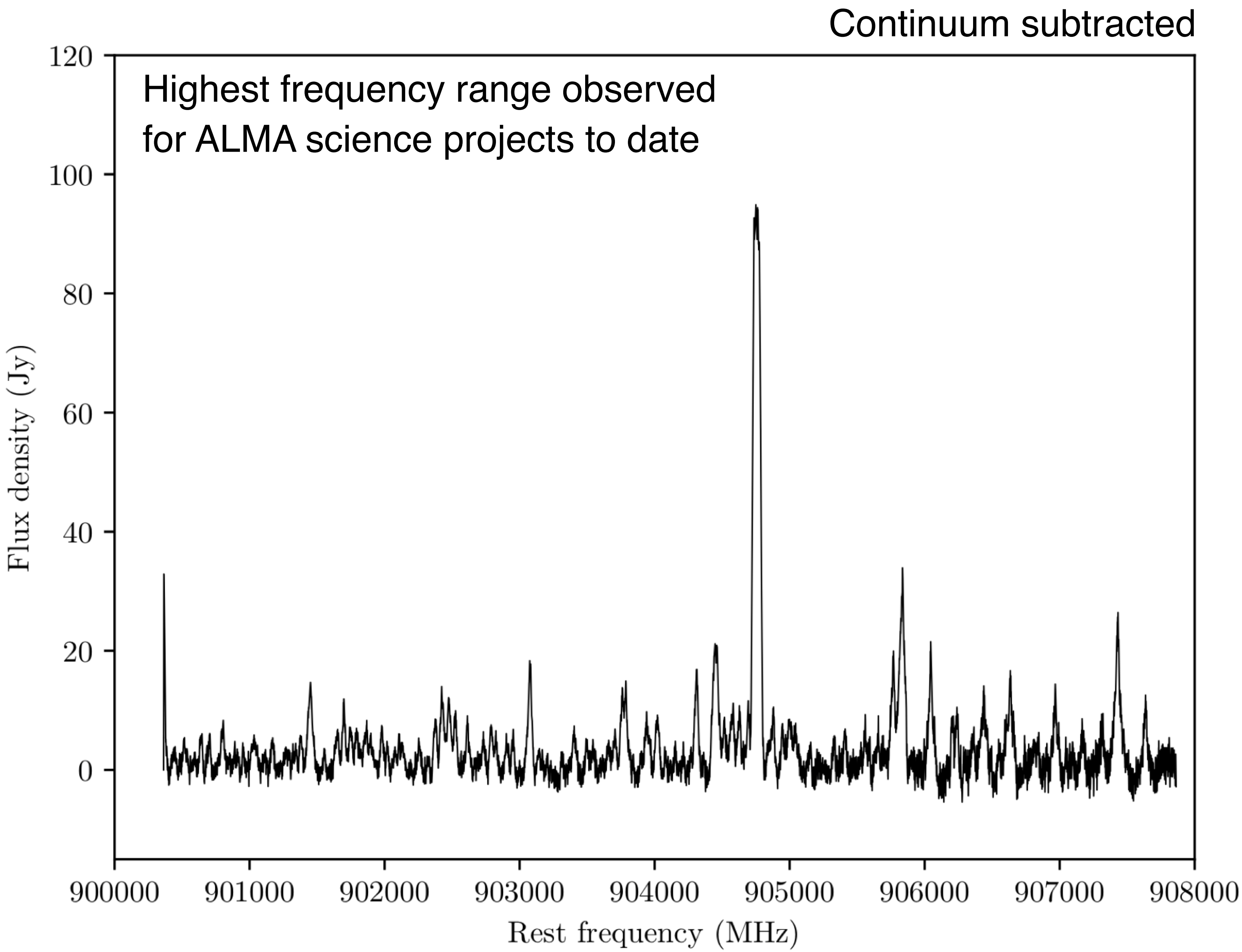
HCN laser at 890.76 GHz in IRC +10216



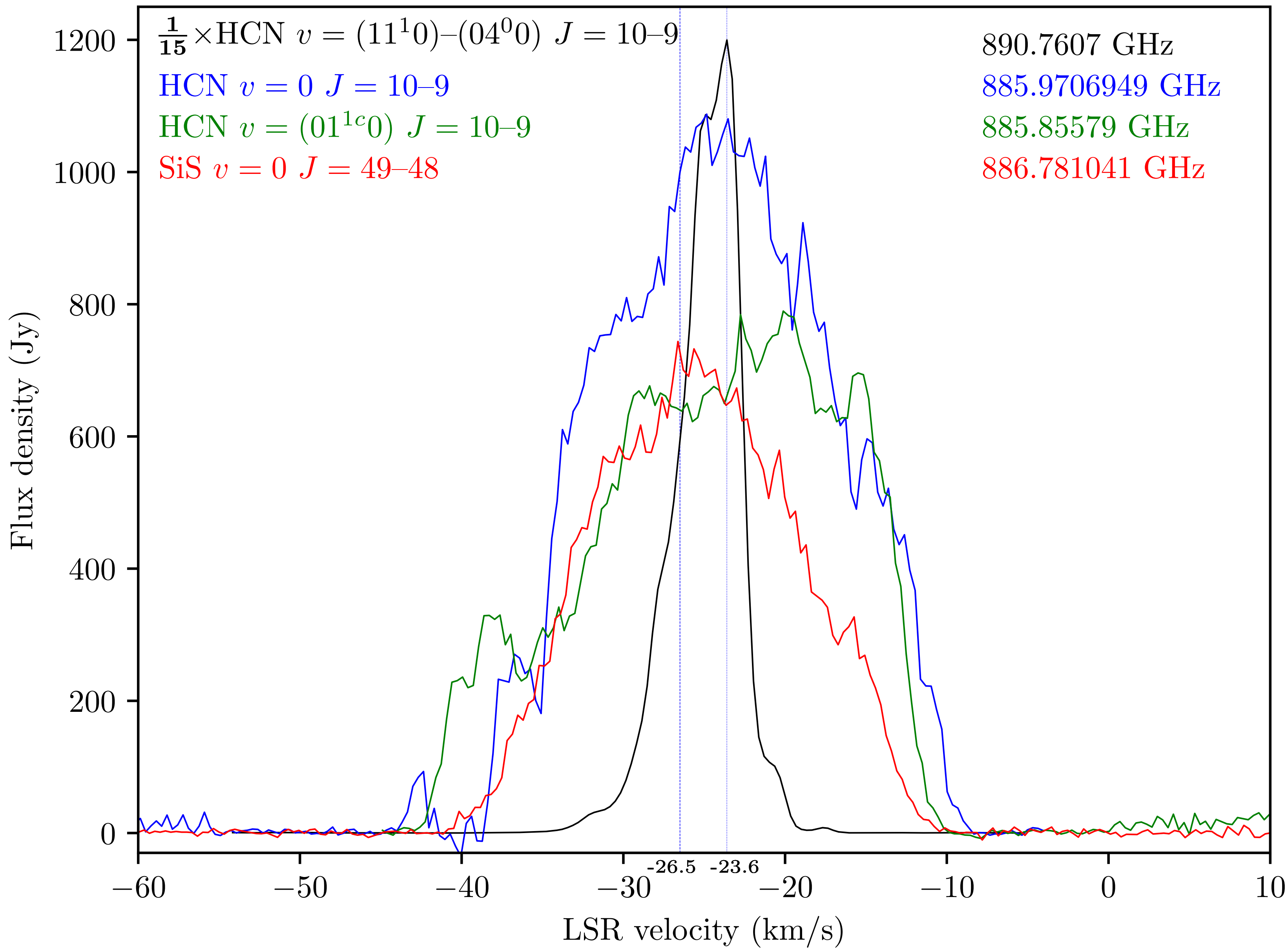
IRC +10216 LSB spectrum



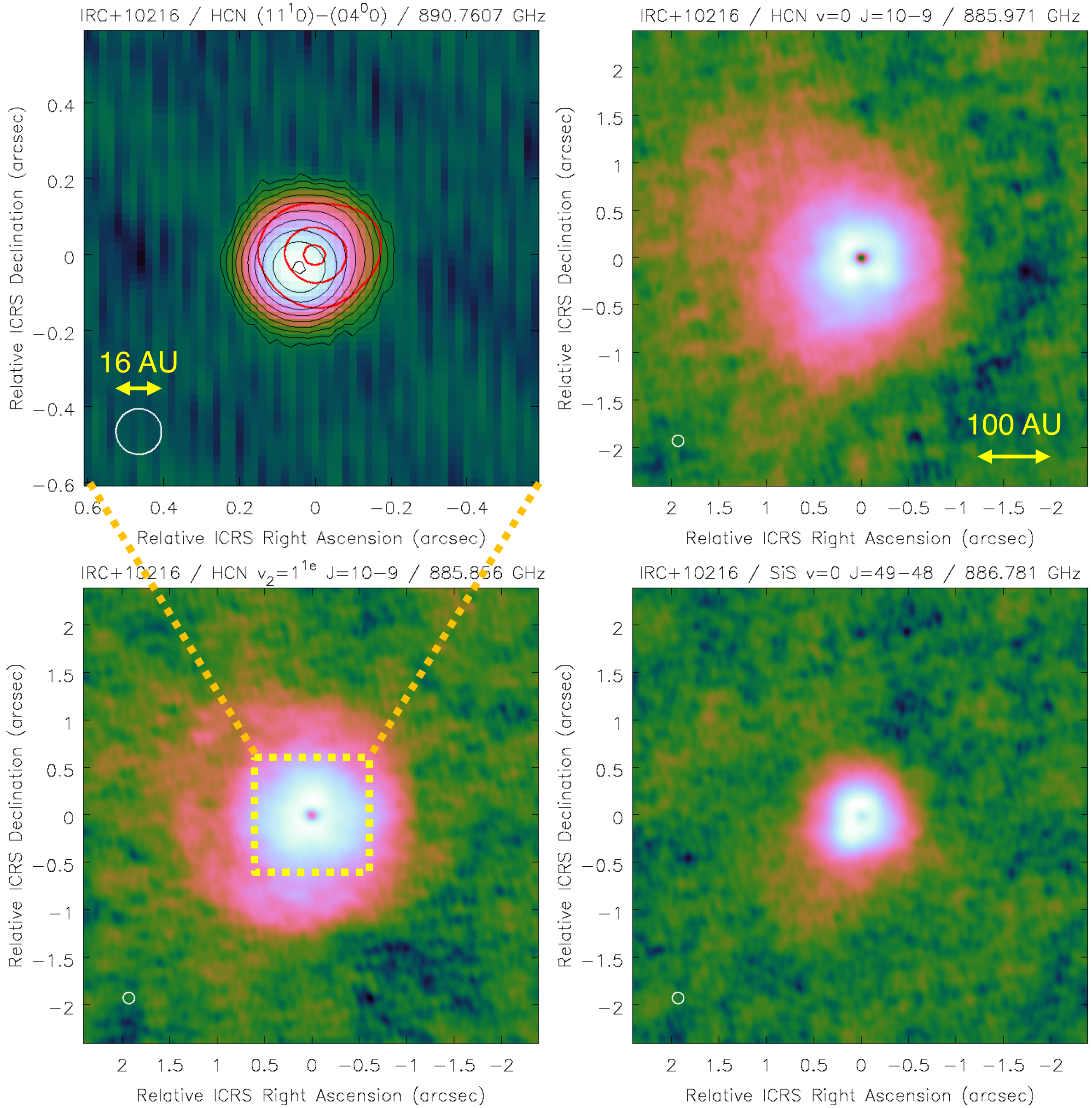
IRC +10216 USB spectrum



HCN and SiS spectra of IRC +10216



HCN and SiS integrated intensity maps



Self-calibration with HCN laser lines

- Strong, compact laser emission in certain velocity channels
- Potentials for high-frequency, long-baseline observations

Table A-1: Angular Resolutions (AR) and Maximum Recoverable Scales (MRS) for the Cycle 7 Array configurations

Config	Lmax		Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
	Lmin		100 GHz	150 GHz	183 GHz	230 GHz	345 GHz	460 GHz	650 GHz	870 GHz
7-m Array	45 m	AR	12.5″	8.4″	6.8″	5.4″	3.6″	2.7″	1.9″	1.4″
	9 m	MRS	66.7″	44.5″	36.1″	29.0″	19.3″	14.5″	10.3″	7.7″
C43-1	161 m	AR	3.4″	2.3″	1.8″	1.5″	1.0″	0.74″	0.52″	0.39″
	15 m	MRS	28.5″	19.0″	15.4″	12.4″	8.3″	6.2″	4.4″	3.3″
C43-2	314 m	AR	2.3″	1.5″	1.2″	1.0″	0.67″	0.50″	0.35″	0.26″
	15 m	MRS	22.6″	15.0″	12.2″	9.8″	6.5″	4.9″	3.5″	2.6″
C43-3	500 m	AR	1.4″	0.94″	0.77″	0.62″	0.41″	0.31″	0.22″	0.16″
	15 m	MRS	16.2″	10.8″	8.7″	7.0″	4.7″	3.5″	2.5″	1.9″
C43-4	784 m	AR	0.92″	0.61″	0.50″	0.40″	0.27″	0.20″	0.14″	0.11″
	15 m	MRS	11.2″	7.5″	6.1″	4.9″	3.3″	2.4″	1.7″	1.3″
C43-5	1.4 km	AR	0.54″	0.36″	0.30″	0.24″	0.16″	0.12″	0.084″	0.063″
	15 m	MRS	6.7″	4.5″	3.6″	2.9″	1.9″	1.5″	1.0″	0.77″
C43-6	2.5 km	AR	0.31″	0.20″	0.16″	0.13″	0.089″	0.067″	0.047″	0.035″
	15 m	MRS	4.1″	2.7″	2.2″	1.8″	1.2″	0.89″	0.63″	0.47″
C43-7	3.6 km	AR	0.21″	0.14″	0.11″	0.092″	0.061″	0.046″	0.033″	0.024″
	64 m	MRS	2.6″	1.7″	1.4″	1.1″	0.75″	0.56″	0.40″	0.30″
C43-8	8.5 km	AR	0.096″	0.064″	0.052″	0.042″	0.028″	N/A	N/A	N/A
	110 m	MRS	1.4″	0.95″	0.77″	0.62″	0.41″			
C43-9	13.9 km	AR	0.057″	0.038″	0.031″	0.025″	0.017″	N/A	N/A	N/A
	368 m	MRS	0.81″	0.54″	0.44″	0.35″	0.24″			
C43-10	16.2 km	AR	0.042″	0.028″	0.023″	0.018″	0.012″	N/A	N/A	N/A
	244 m	MRS	0.50″	0.33″	0.27″	0.22″	0.14″			

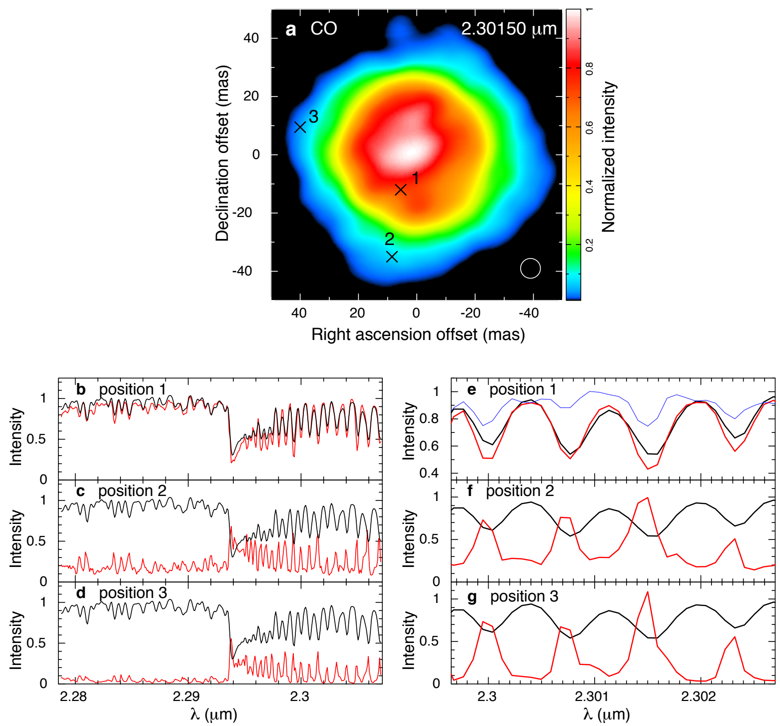
Best possible angular resolution with current infrastructure **~ 5 mas**

- Challenging phase calibration
- Lack of nearby, bright-enough quasars

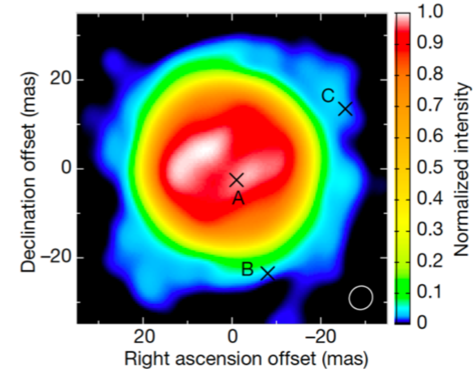
Self-calibration with HCN laser lines

- Achieving angular resolution of <10 mas with ALMA(?)

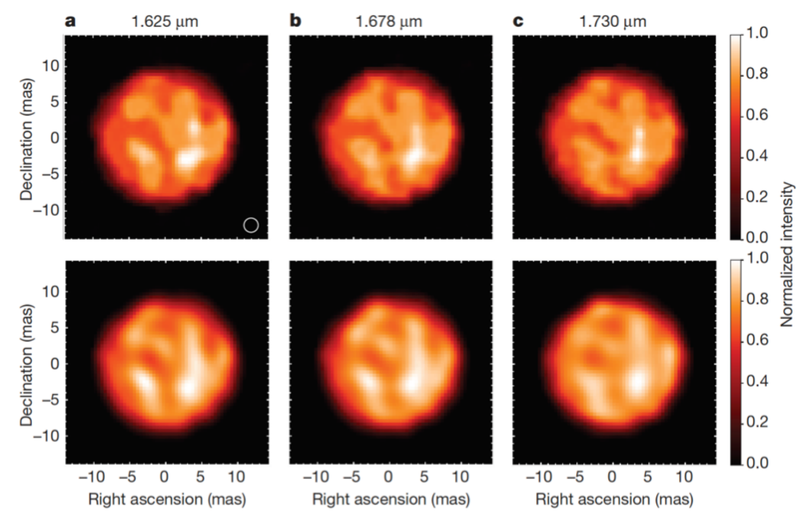
  → stellar surface tomography, hydrodynamics



NIR image of R Dor with VLBI/AMBER
Ohnaka et al. (2019) ApJ, 883, 89



NIR image of Antares with VLBI/AMBER
Ohnaka et al. (2017) Nature, 548, 310



NIR image of π^1 Gru with VLBI/PIONIER
Paladini et al. (2018) Nature, 553, 310

Summary

- HCN laser lines at 804.75 and 890.76 GHz in C-AGBs are **imaged for the first time** using ALMA.
- Both laser lines are **detected in all observed C-AGBs**:
  - The rovibrational transition (891 GHz) is stronger than the rotational transition (805 GHz).
  - Laser-emitting regions **have an extent of ~10–30 AU** in V Hya and IRC +10216.
- Intense FIR HCN laser emissions allow amplitude and phase **self-calibration** with intermediate (~1 km) ALMA baselines.
- High-quality molecular line images are produced in the highest frequency band of ALMA.