Water Emission in Supernova Remnants observed with Herschel

Jeonghee Rho
SETI Institute and
SOFIA Science Center, NASA Ames Research Center

Collaborators
J. Hewitt (U. North Florida), J. Bieging (U. Arizona), A. Boogert (SSC/USRA) , M. Kaufman (SJU), A. Gusdorf (O. de Paris), M. Andersen (Gemini Observatory, Chile), W. Reach (SSC/USRA) and R. Güesten (MPIfR, Germany), J.-S., Moon, S-J, Kim, H.-W., Ro (Younsei U., Korea)

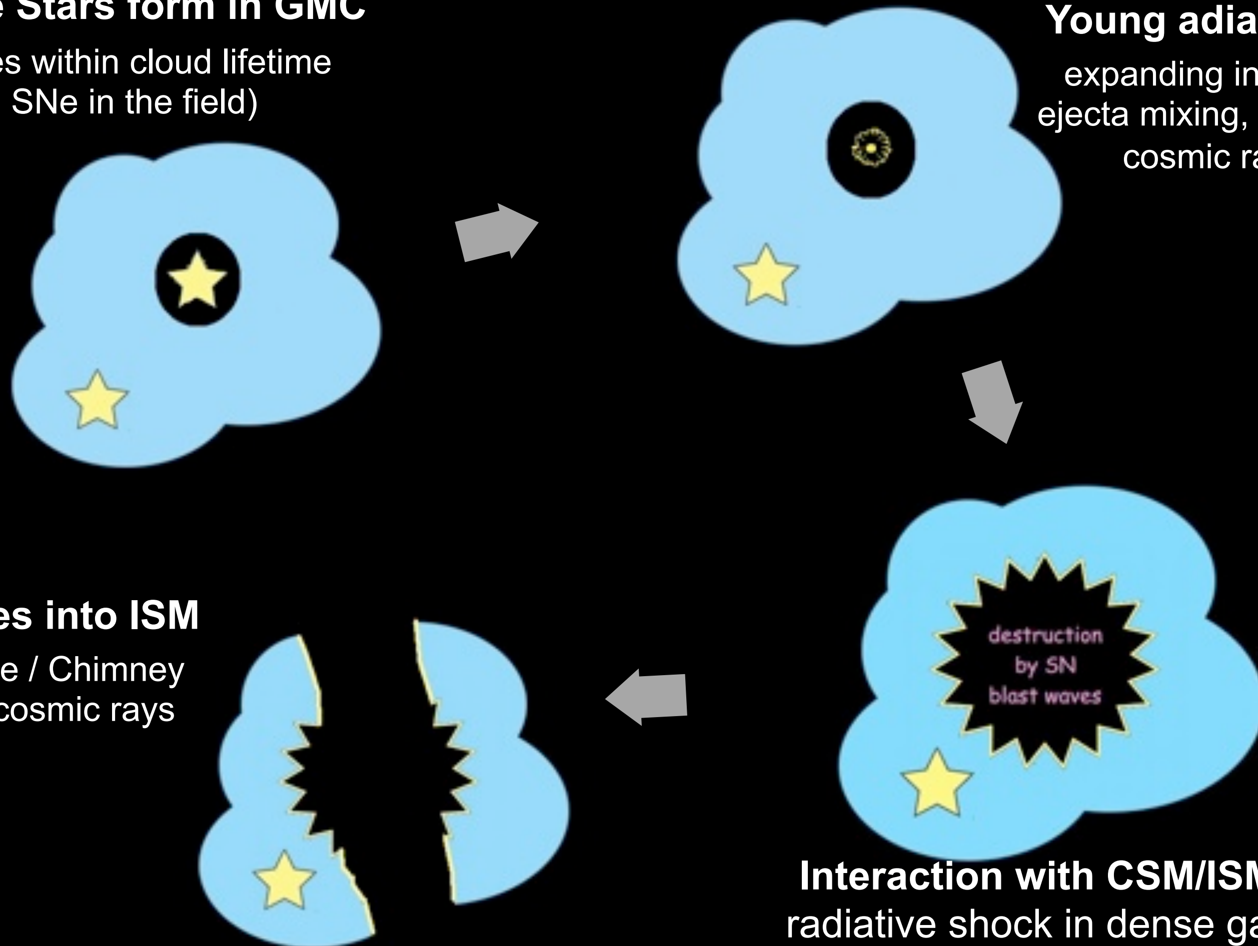
The Violent Evolution of Supernovae in Molecular Clouds

Massive Stars form in GMC

>8 Msol dies within cloud lifetime
(~40% SNe in the field)

Young adiabatic SNR

expanding in wind cavity
ejecta mixing, dust creation,
cosmic ray accel



Interaction with CSM/ISM

radiative shock in dense gas
heating, chemistry, dust processing

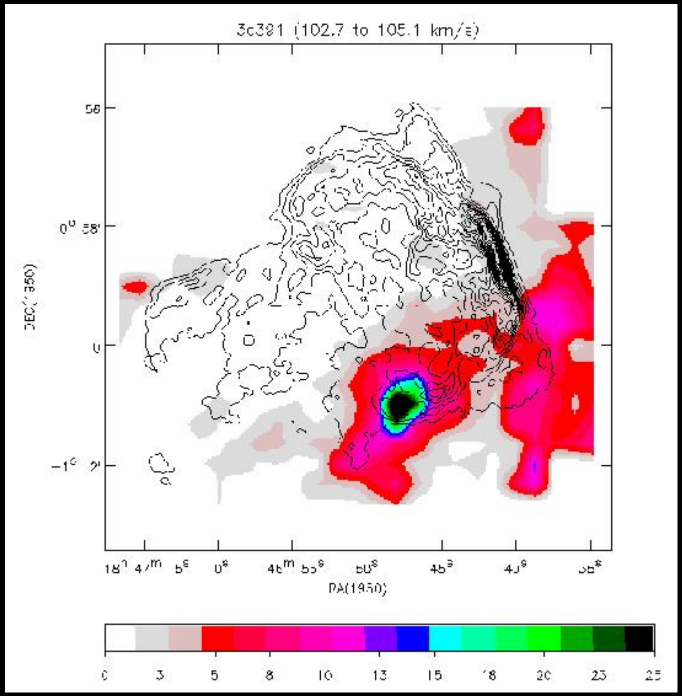
SNR merges into ISM

Superbubble / Chimney
release of cosmic rays

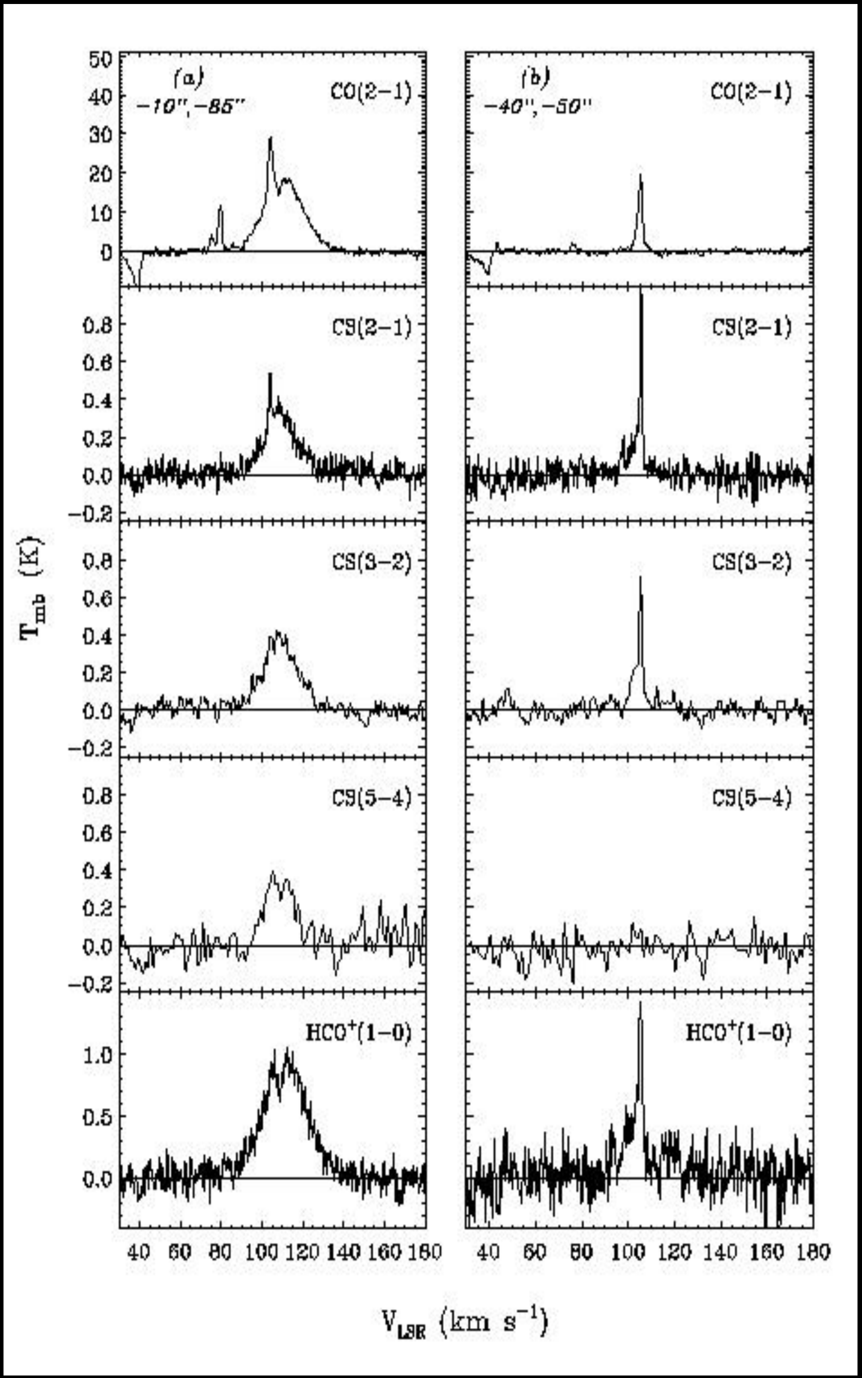
Harbor astro-chemical reactions due to the strong shock

SNR-Cloud Interaction

- Signatures of SNR-MC interactions
  - OH maser lines(1720.5 MHz) from 20 SNR (Frail et al. 96)
  - New Class Mixed-morphology SNR : X-ray center filled, thermal emission from 18 SNR (Rho & Petre 98)
  - H_2 emission from 15 SNRs (Burton et al. 1998, Hewitt 2009)
- Direct Evidence of SNR-MC interactions
  - Broad low J-CO molecular lines: IC 443, W44, W28 and 3C391 show broad (Δv>20 km/s). Currently, a dozen of SNRs.
- Two cases of Water detection
  - IC 443 and 3C391. It is not clear why these two, not W44 and W28.



3C391:

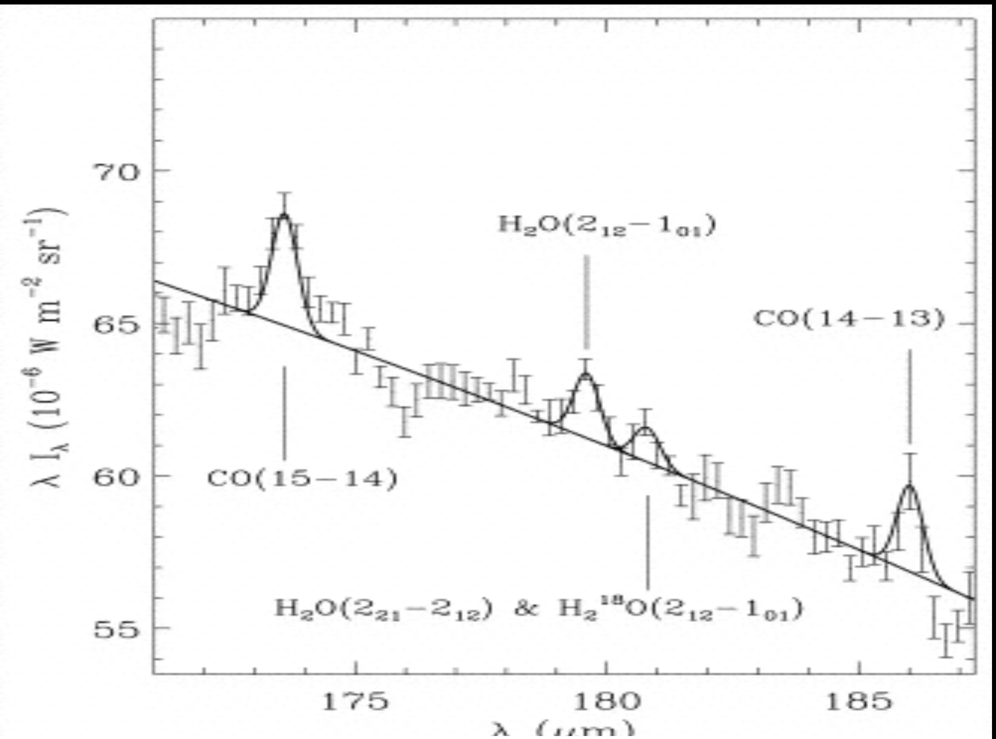


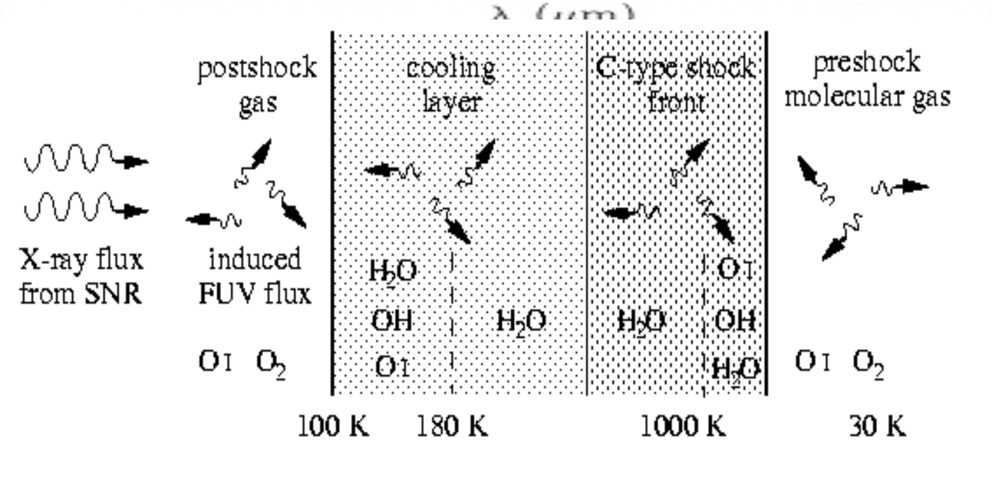
Molecular interacting SNR

Broad CO lines (ΔV~20 kms/s) detected

(Reach & Rho 1998)

Water, OH, CO with ISO





- H_2O, OH, CO lines are detected. Gas is warm (400 K), dense gas, collisonally exicited.
- O+ H_2 ➔ OH

  OH + H_2 ➔ H_2O

High column of OH, H_2O

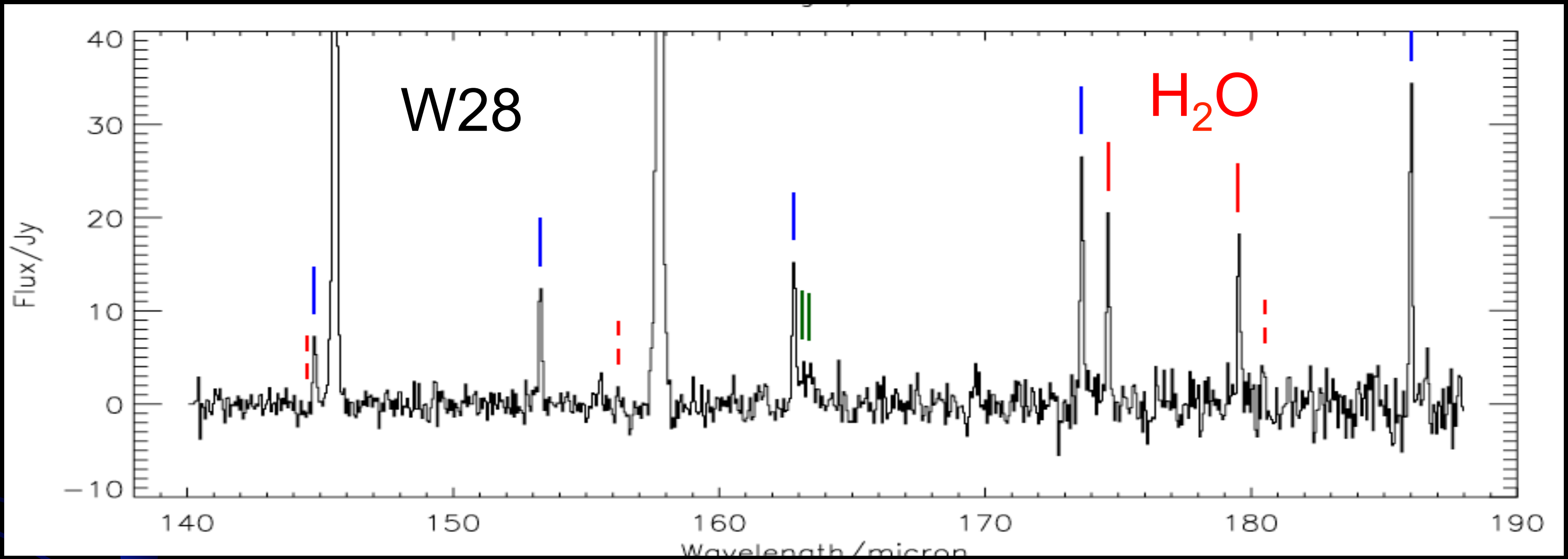
- CO:OH:H_2O=100:1:15

Water amount is smaller and OH is larger than expected.

$n(H_2)=2\text{x}10^5\text{cm}^{-3}$

3C391: Reach & Rho 1998

Water observed with Herschel PACS from W28 and 3C391

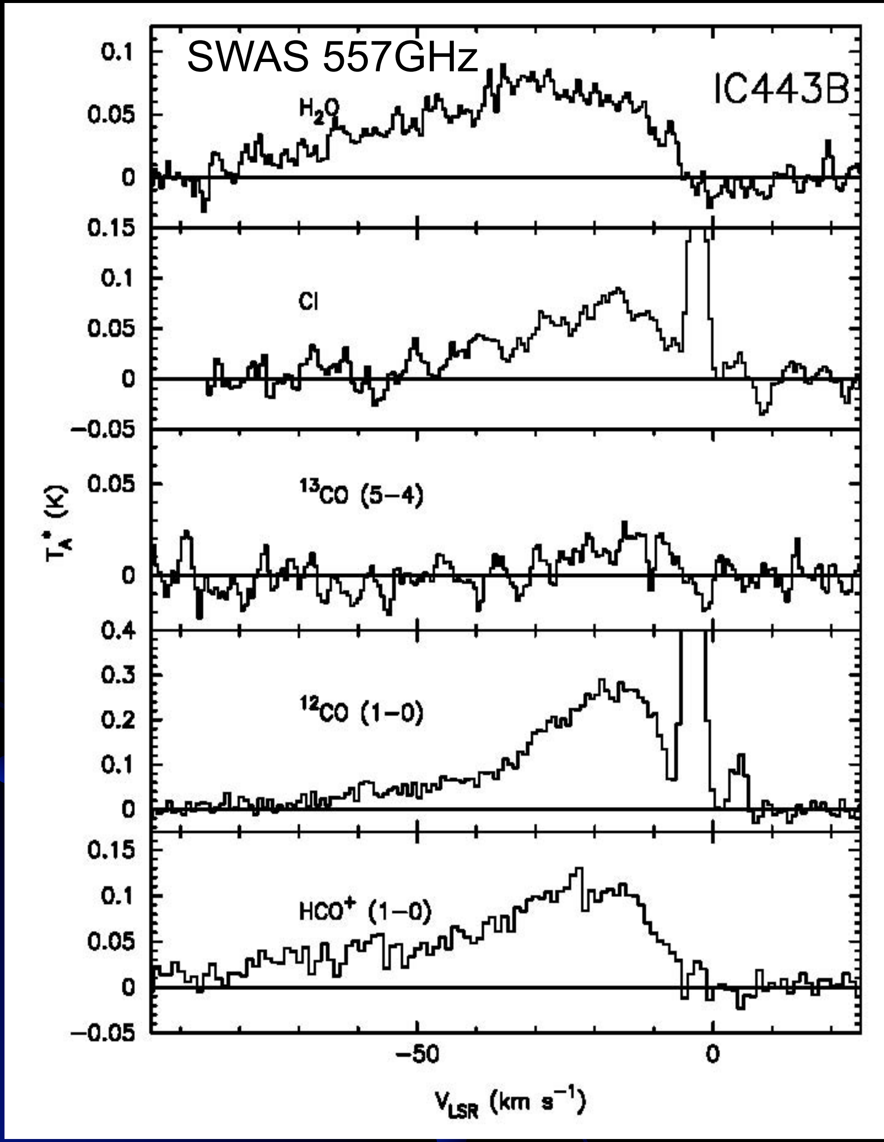


Water:

- Abundance: comparable to the predicted model of non-dissociative shock.
- Shock Model: C-shock with Vs=25 km/s
- T~1300 K

Neufeld et al. 2014

Water from IC443



- H_2O, O_2, CO detection using SWAS
- Shock model: J-shock (100 km/s) + C-shock (12km/s)

or slow J-shock (25 km/s)

- Weak H_2O is due to freezeout of H_2O and photodissociation of H_2O
- H_2O profile is similar to that of CO or HCO^+

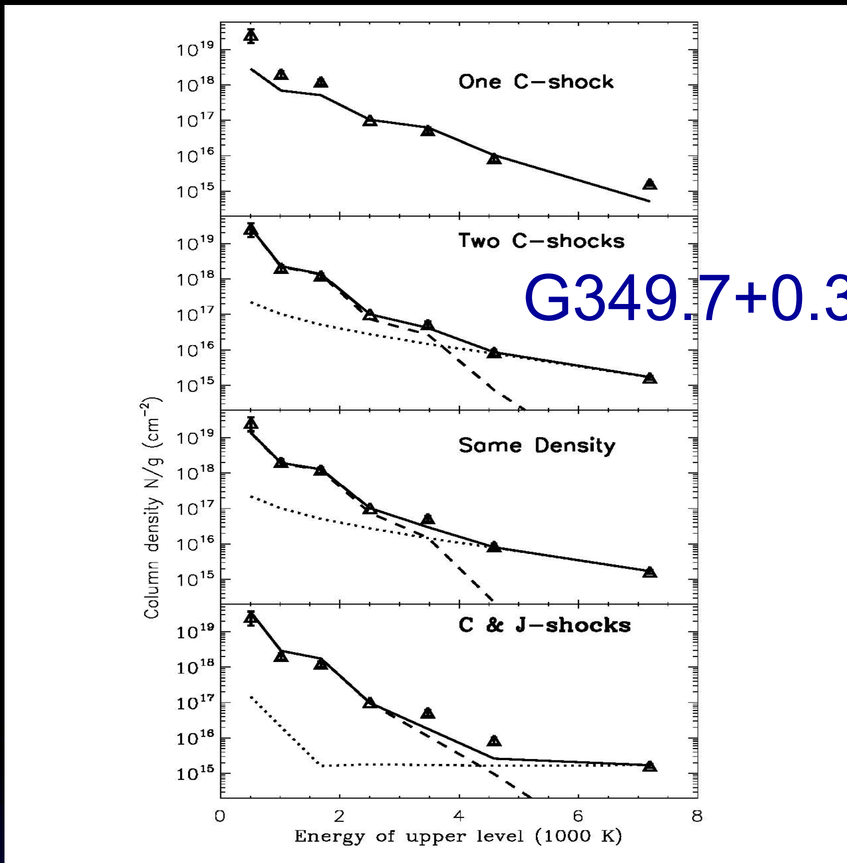
Snell et al. 2005

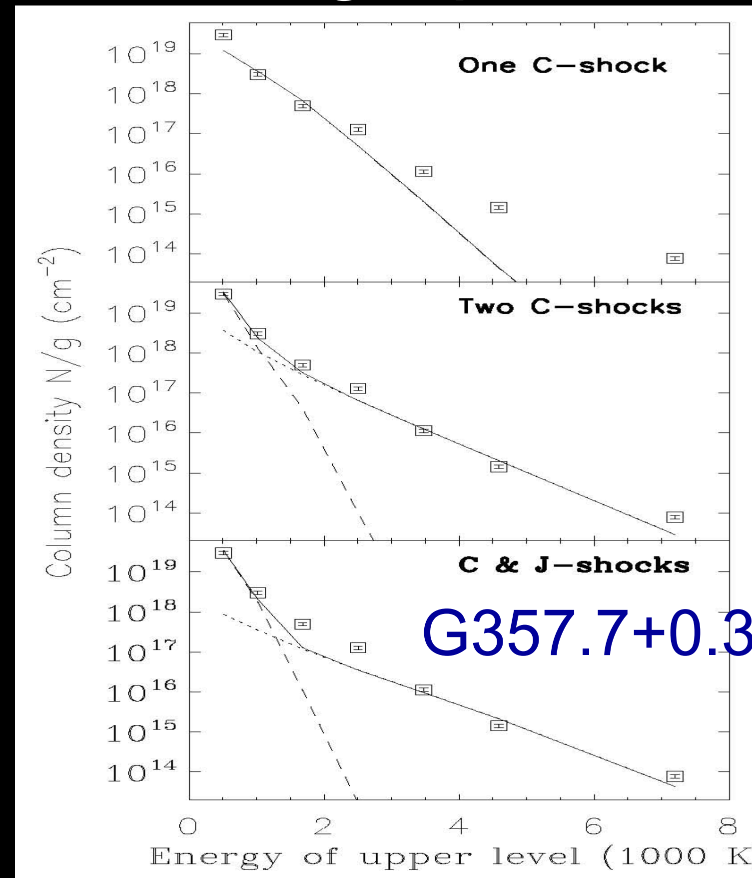
Herschel Observations

- Sample: Three best sample of SNRs from Spitzer catalog of Reach et al. (2006): G349.7+0.2, CTB37A, G357.7+0.3
- Chains of chemistry of CO, H_2O, OH, O

Instrument	Feasibility	Conducted Observations	Beam size	Spectral resolution	Goals
SPIRE FTS	194-671μm (450-1550 GHz)	450-1550 GHz	17-42”	500-2000	CO H_2O, OH OI, NII
PACS	51-220μm	79-119μm 144-180μm	47x47” (5x5pixel)	1000-5000	CO, H_2O, OH OI, CII
HIFI	490-1270 GHz (236-615 μm) 1430-1900 GHz (157-210μm)	544-548, 556-560 1100-1104, 1112-1116 GHz	12-47”	10^7	H_2O, OH

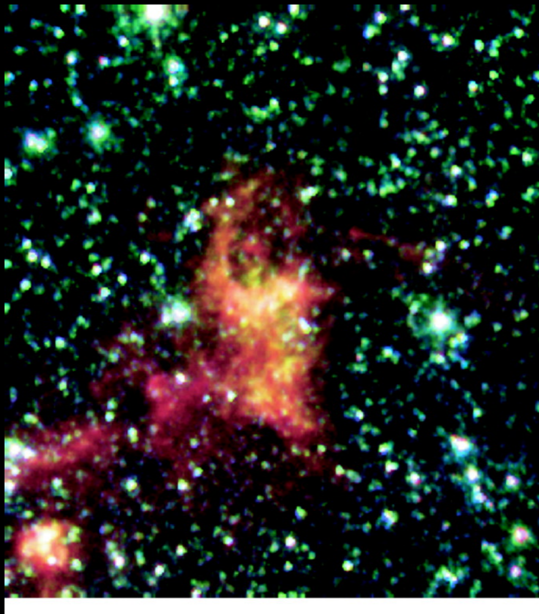
Comparison of H_2 detections using Spitzer

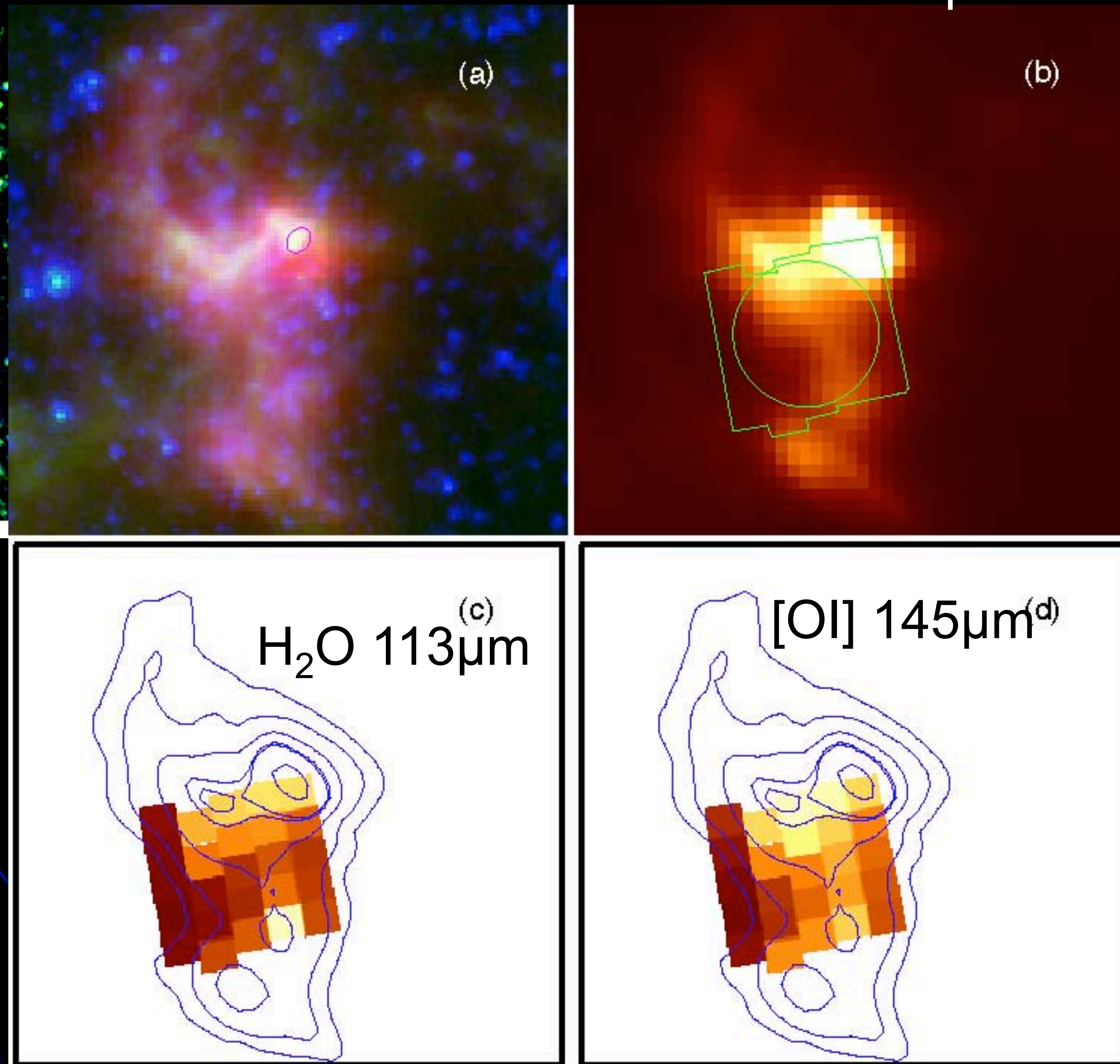




SNR	Best model From H_2	Parameters: n(cm^{-3}) [velocity (km/s)]
G349.7+0.2	1) Two C-shock	10^6 [10] + 10^4 [50]
	2) C- and J-shock	10^6 [10] 10^4 [110]
G357.7+0.3	Two C-shock	10^5 [10] +10^4 [30 or 10]

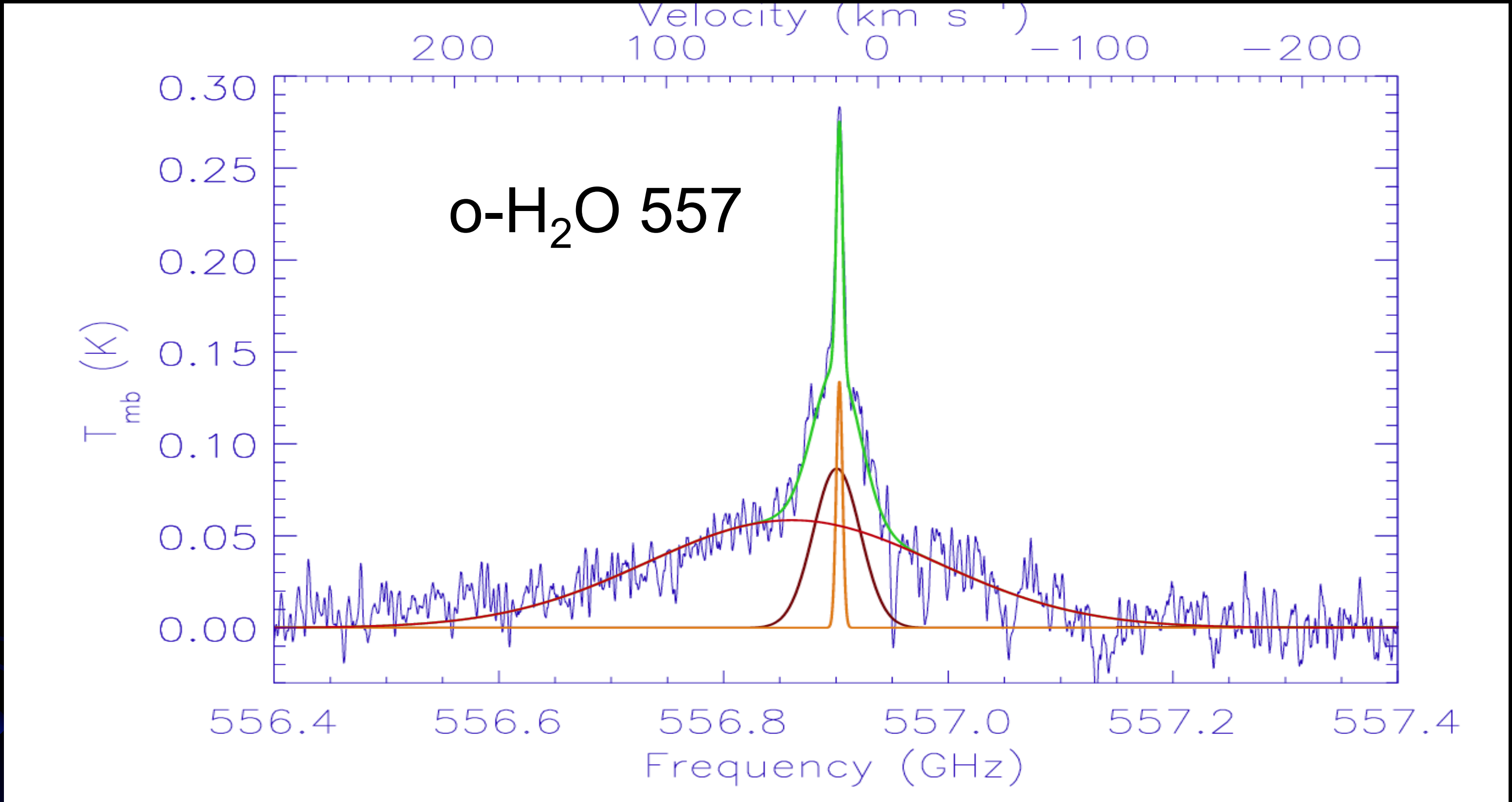
Hewitt et al. 2009
Rho et al., submitted
Anderson et al. 2011
(CTB37A)





Case 1)
G349.7+0.2

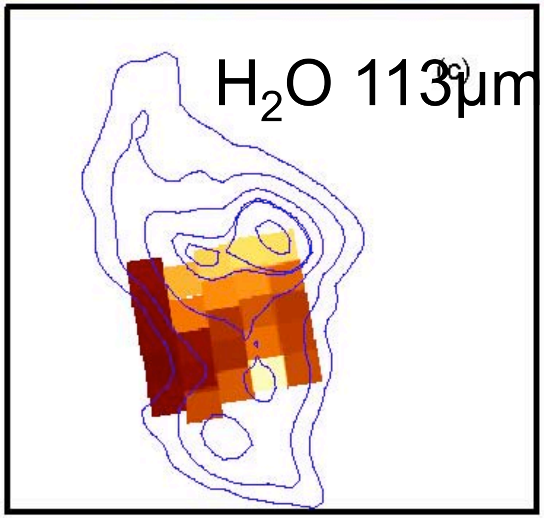
HIFI Observations

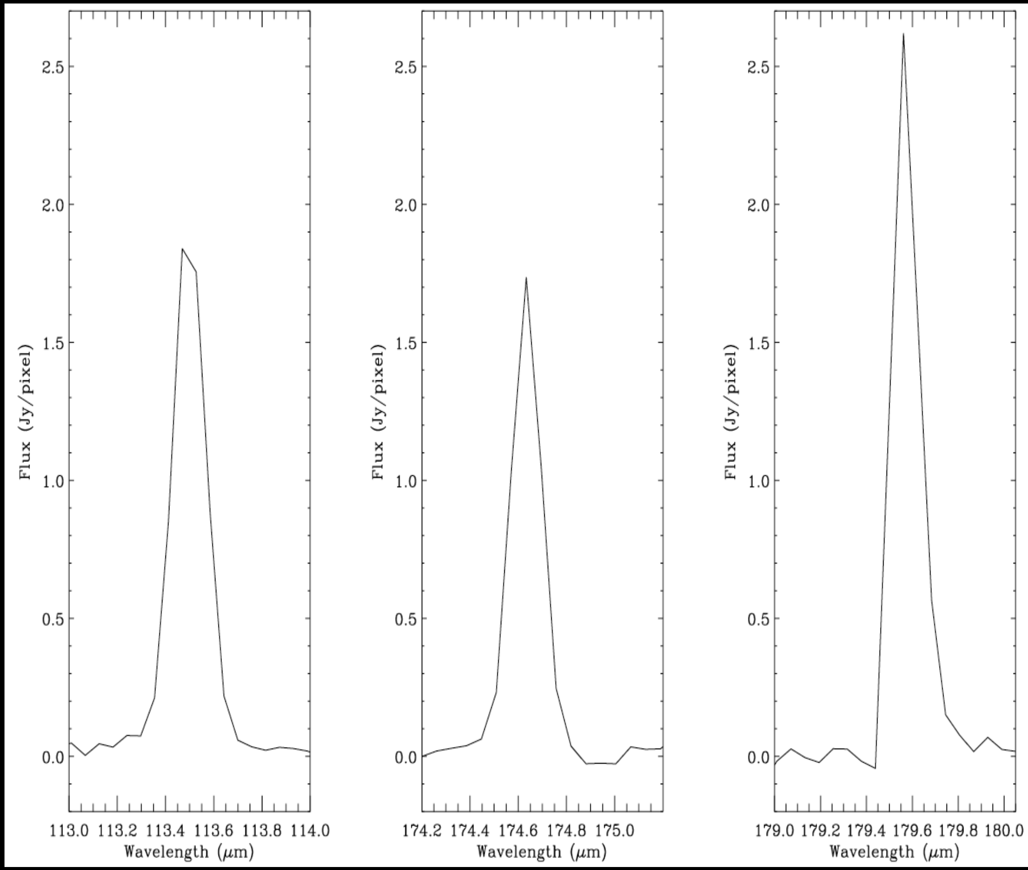


- Broad and narrow components
- H_2O lines probe gas motion due to shock
- 3 velocity components: 144, 27 and 4 km/s
- One of the broadest water lines

3 more water lines using PACS in G349.7+0.2

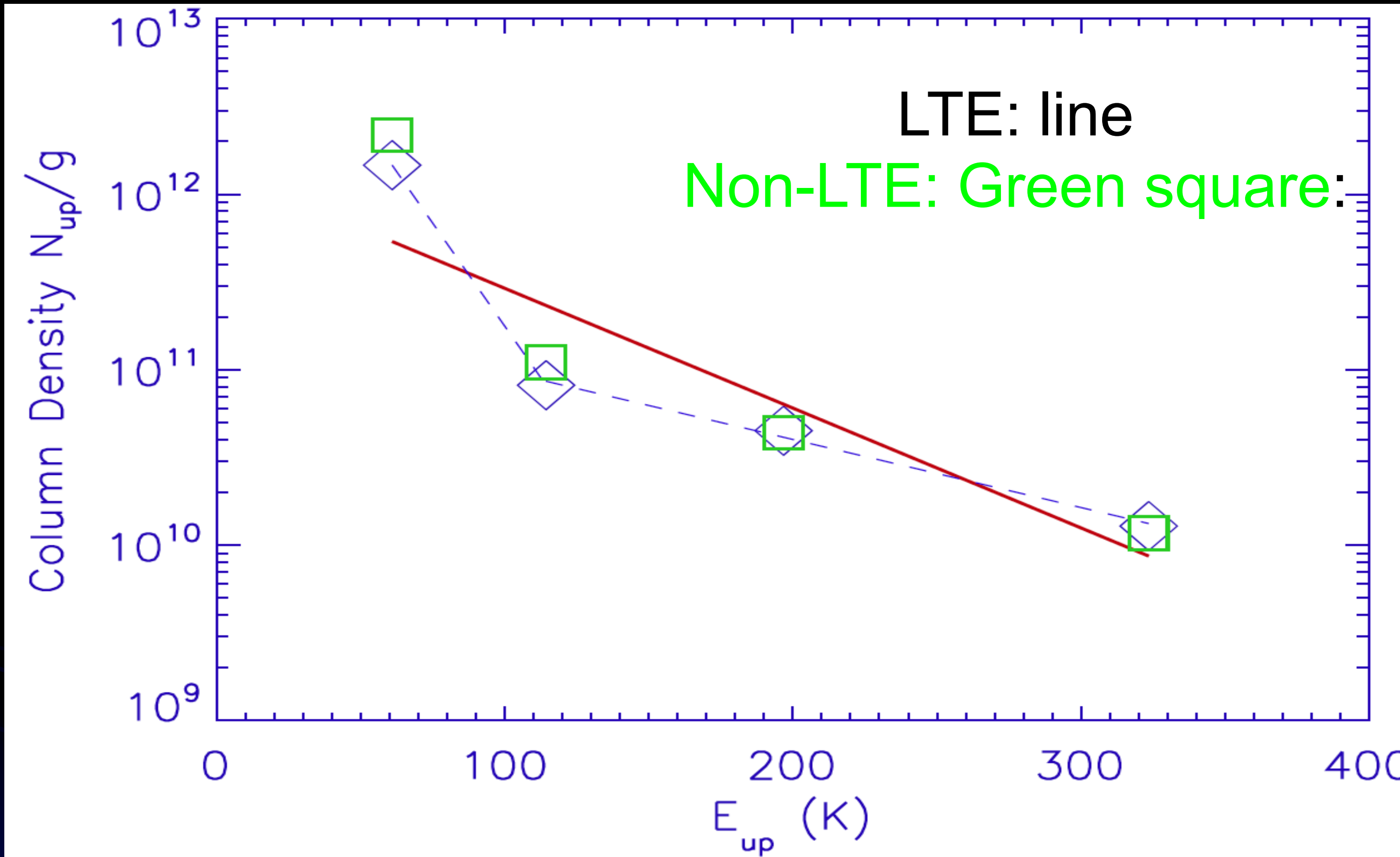
Line	Wavelength(μm)	S.B. (nW/m2/sr)
H_2O (4_{14}-3_{03})	113.54	39.5
H_2O(3_{03}-2_{12})	174.54	14.3
H_2O(2_{12}-1_{01})	179.59	18.0





CO (16-15), CO(18-17), CO(22-21), CO(29-28), CO(30,29), CO(32-31), CO(33-32, CO(36-25), also a few OH lines

Water excitation diagram



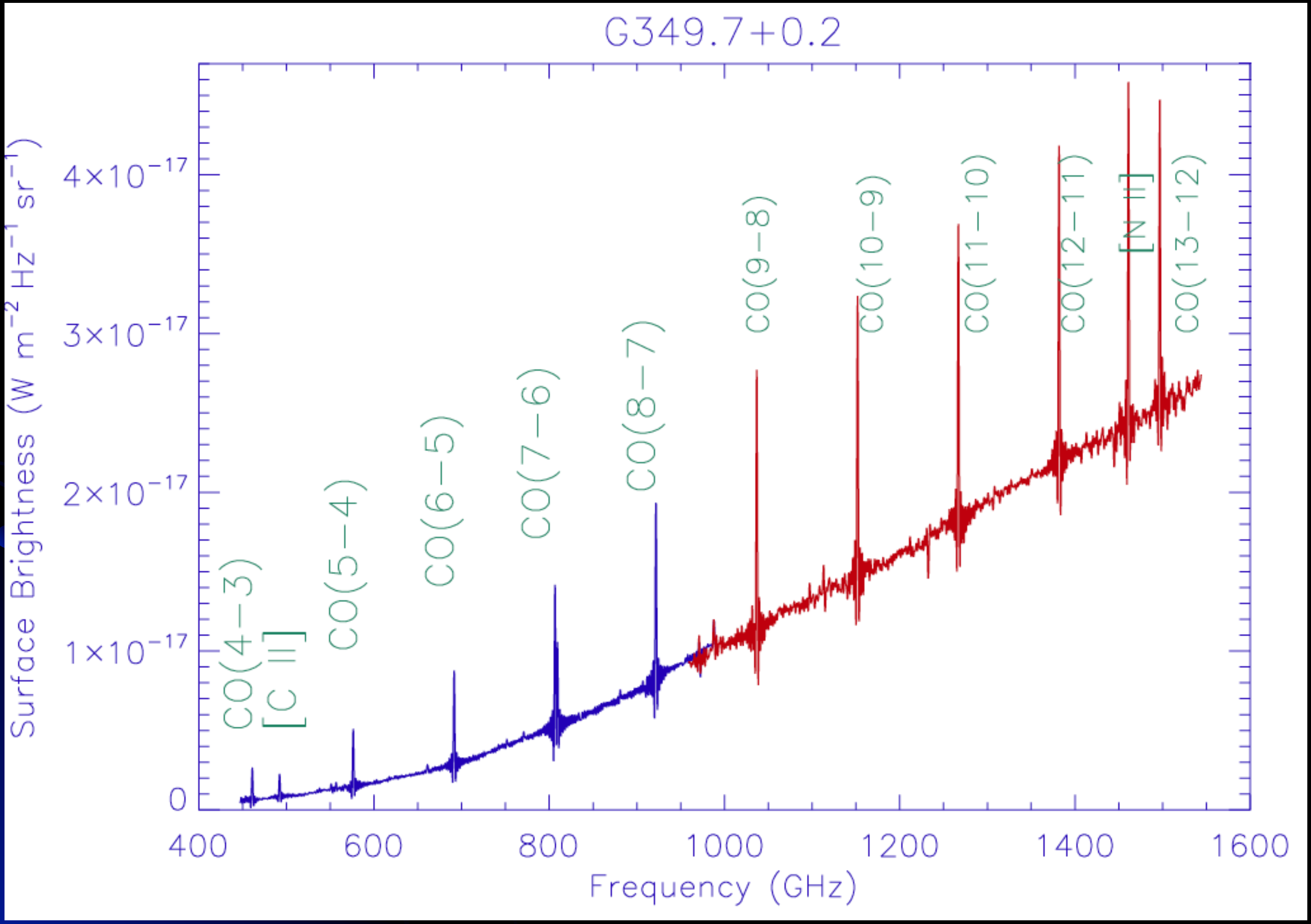
- 2T LTE: $N=4x10^{13}cm^{-2}$, T=18K and $N=2.3x10^{11}cm^{-2}$, T=112K

(1T: $1.4x10^{12}cm^{-2}$, T=68K)

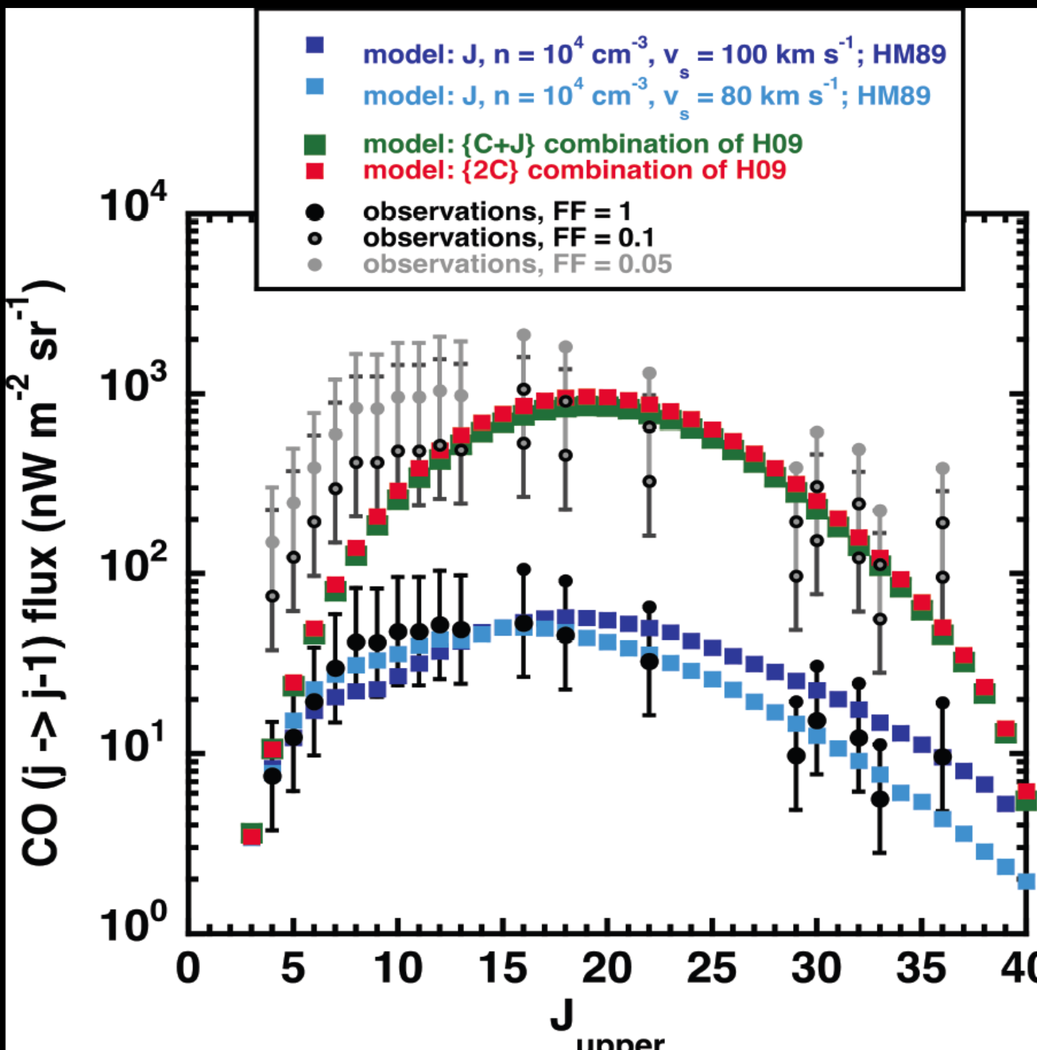
Temperature is low

Non-LTE: $N=3x10^{13}cm^{-2}$, T_{kin}=200-1000 K, $n=10^5$ cm^{-3}

SPIRE Spectrum



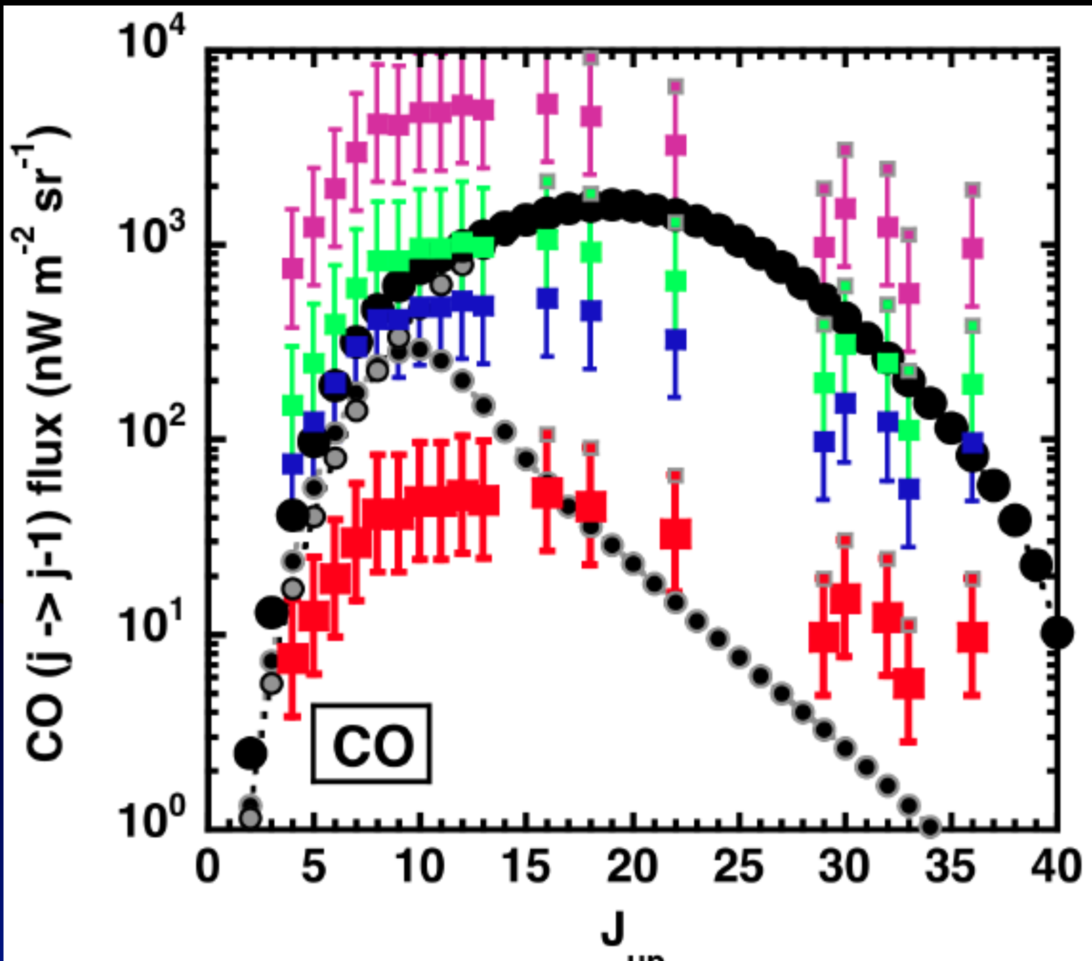
CO Surface brightness



- Two C-shock model (best fit of H_2) doesn't fit the CO data
- J-shock model with $n=10^4 cm^{-3}$ and Vs=100 km/s can reproduce the data
- J-shock vs. water molecules.
- But may still possible with two C-shock using different FF for each or contribution from C-shock

Rho et al. 2015

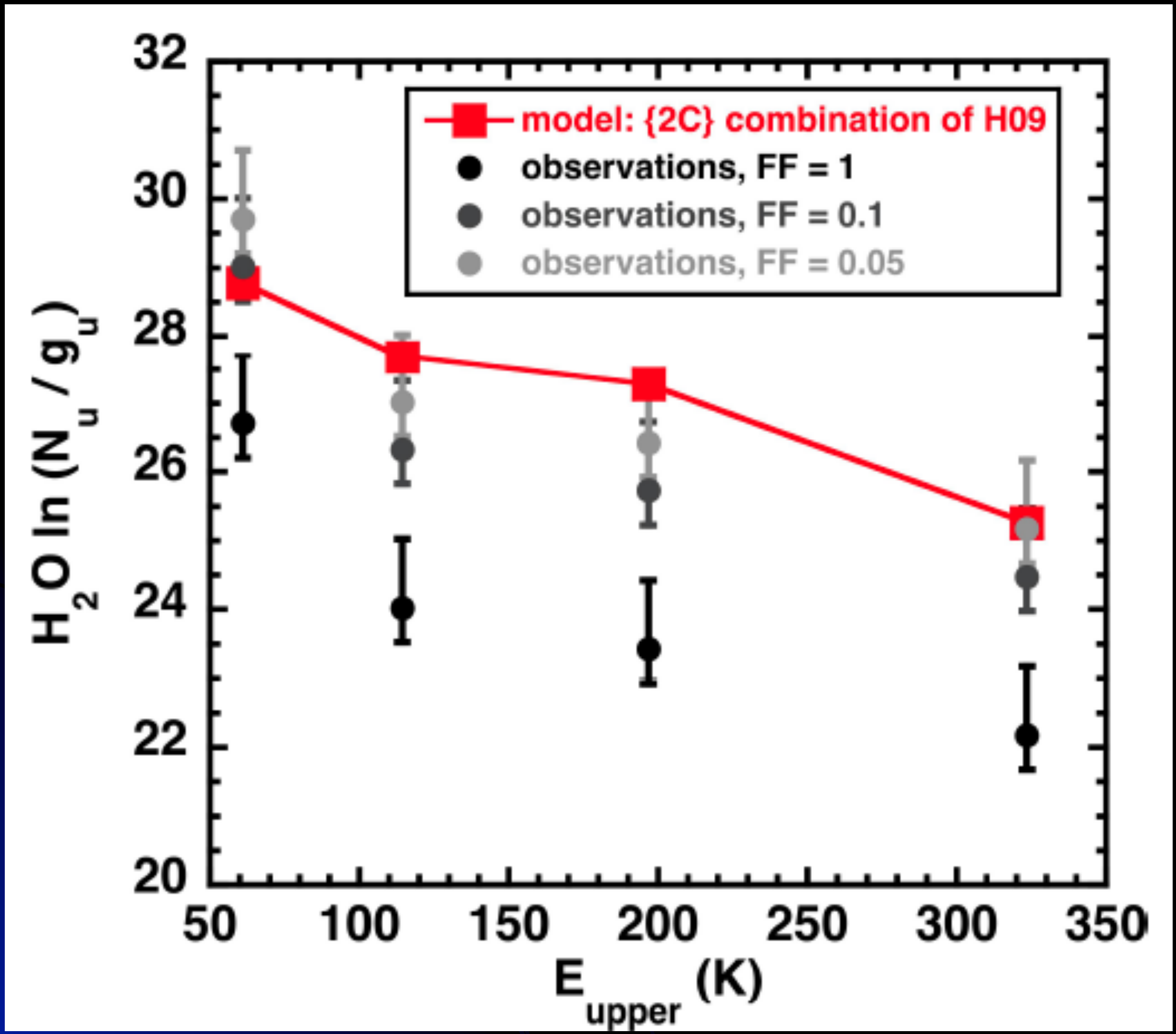
CO Surface brightness of G349.7+0.2



- But still possible with C-shock if we use different filling factor: high density and low velocity contributes low-J lines

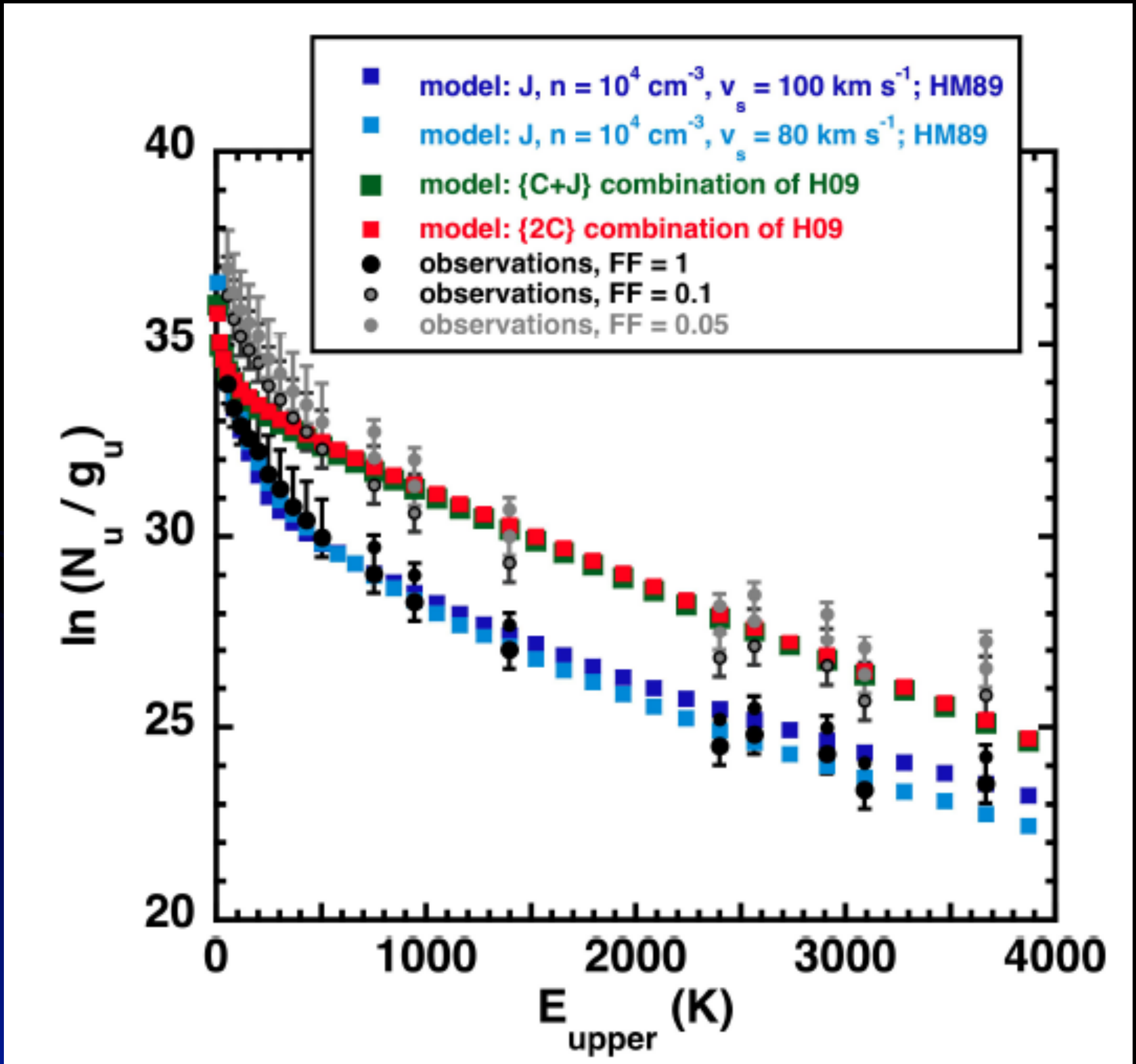
black dots:
$N=10^4 cm^{-3}$, $V=50 km/s$
Gray dots
$N=10^6 cm^{-3}$ $vs=10 km/s$

Water: shock model



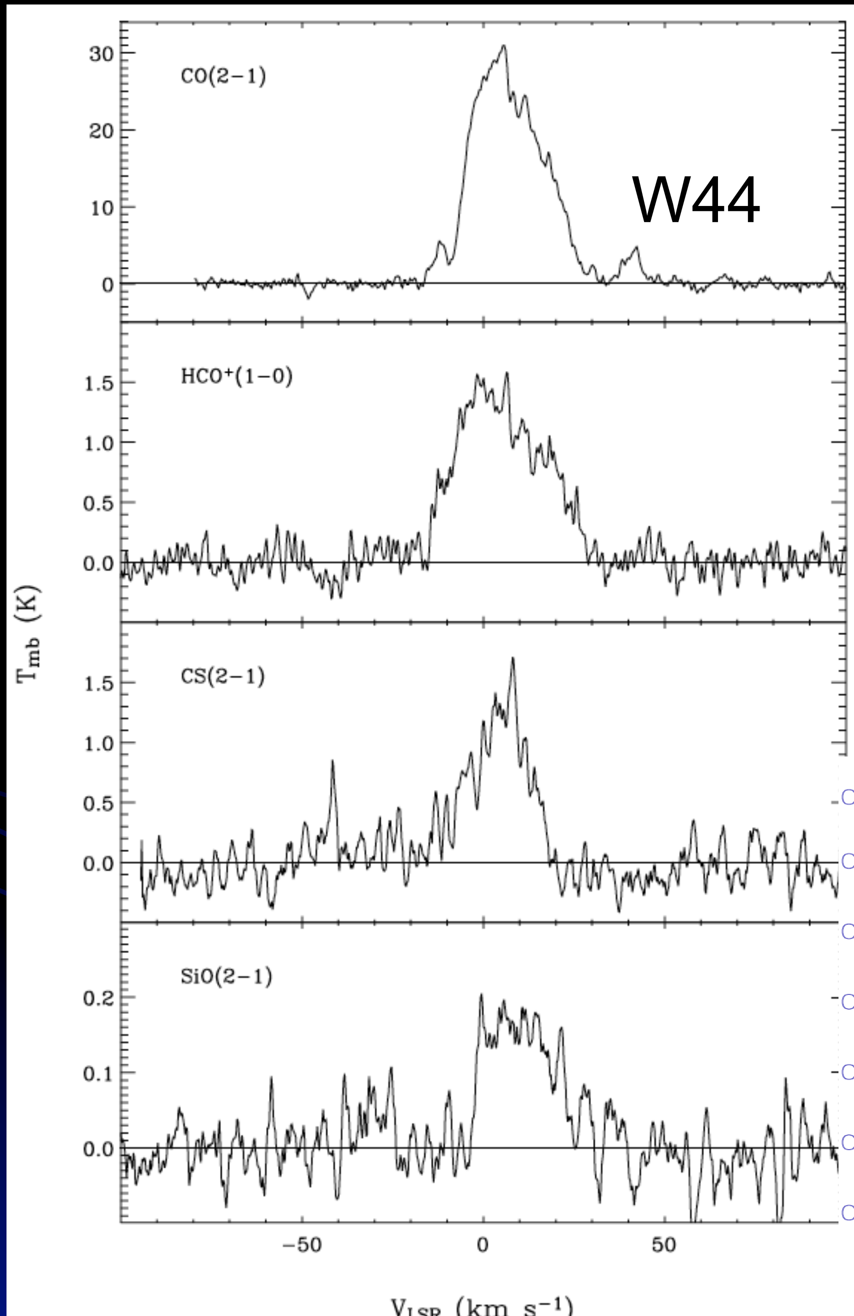
- Two C-shock Produce Water reasonably well, although not CO.
- No water prediction available from J-shock
- We don't know the profiles of other water lines.

CO excitation diagram

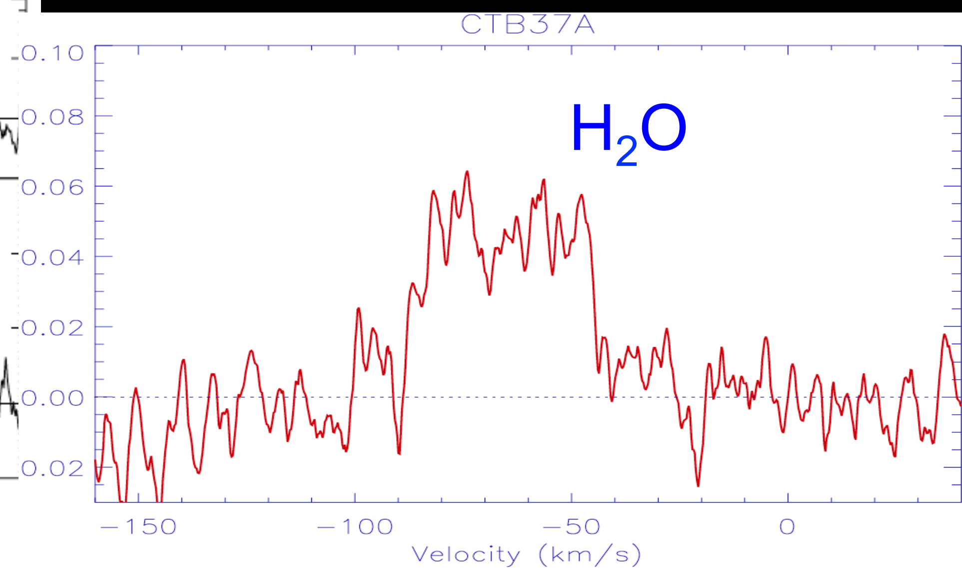


Tex=120 and 520 K

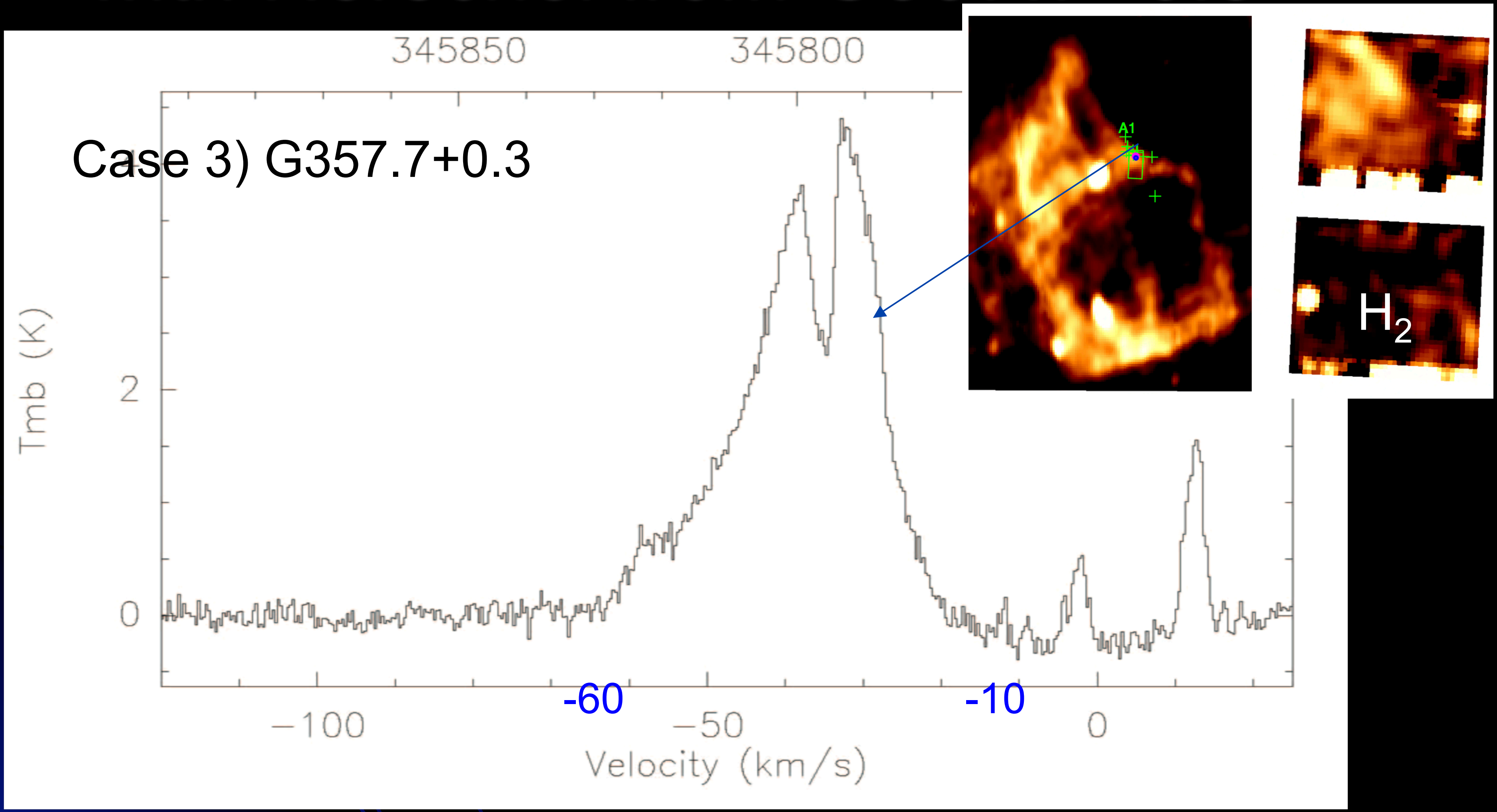
Reach & Rho 2005



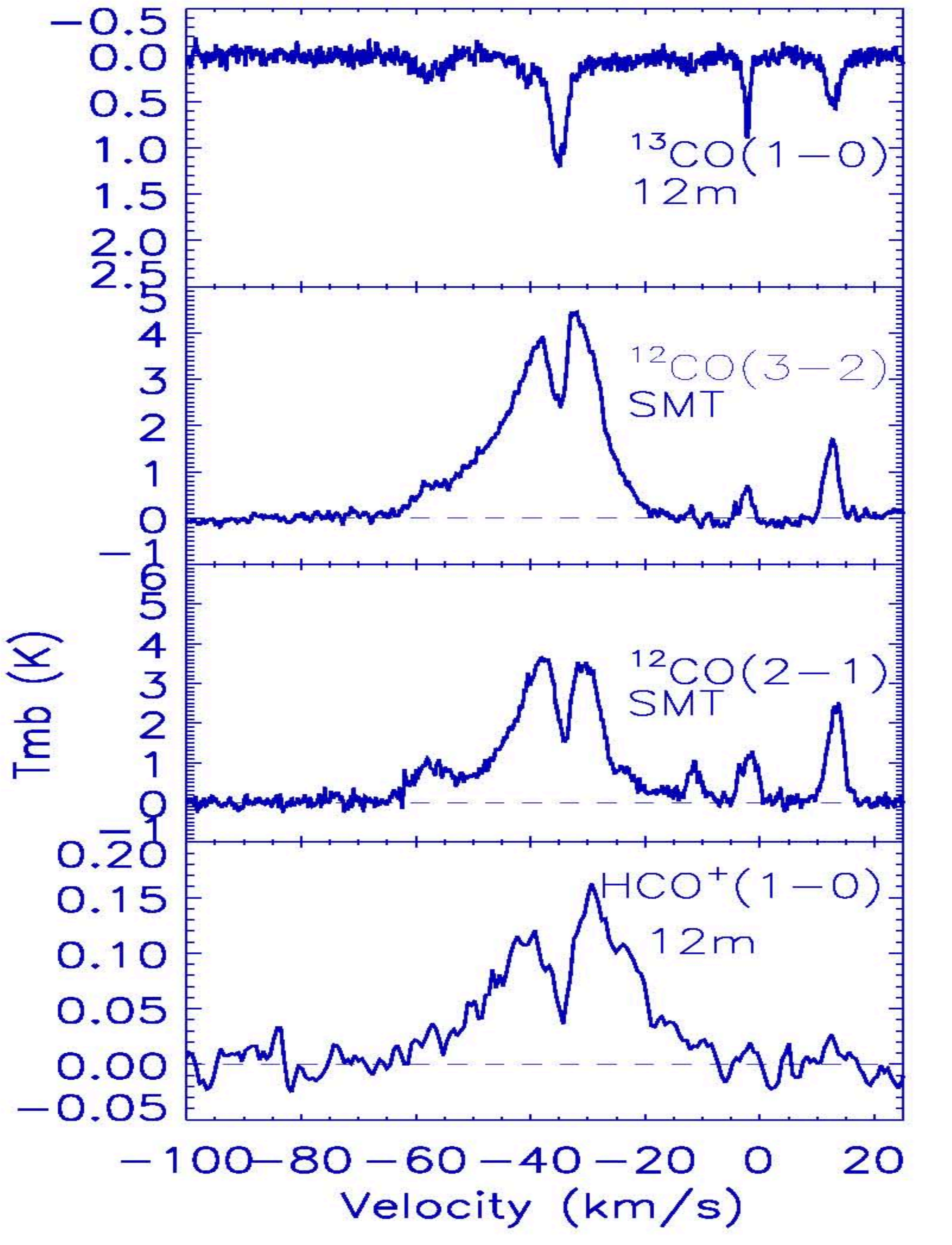
- Water line is at the same velocity as that of CO.
- There has been a similar line profile in W44. A few water PACS lines are detected.

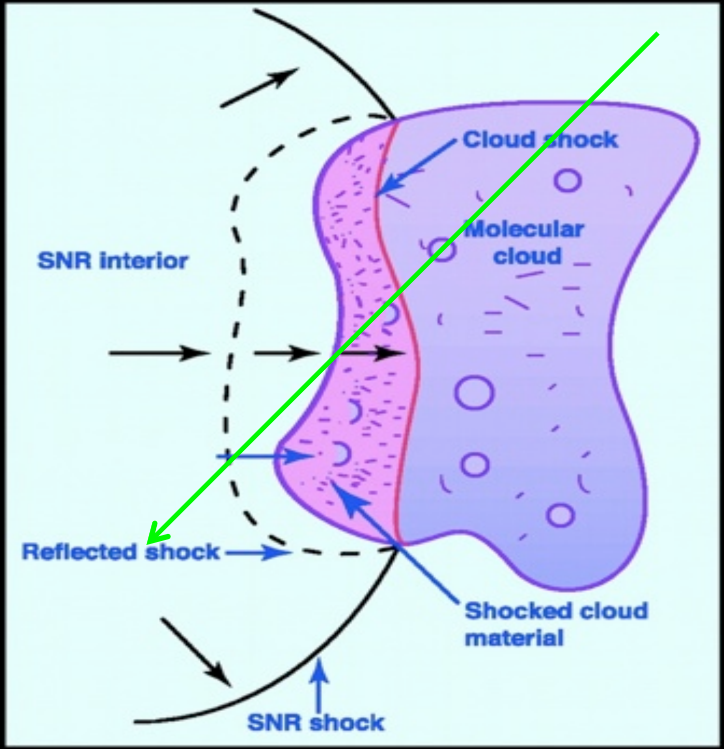


No 557 GHz Water detection with Herschel from G357.7+0.3

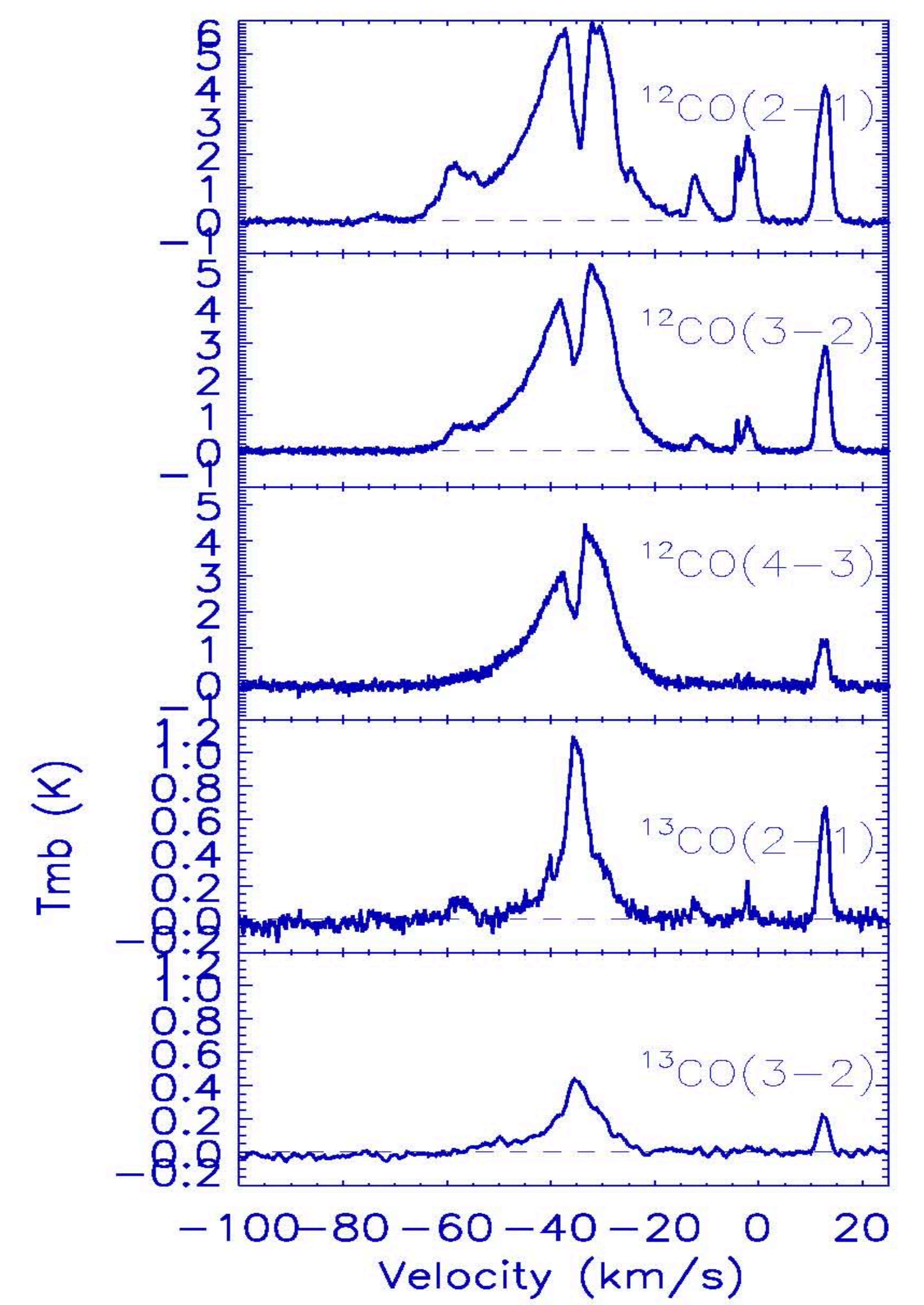


Broad CO(3-2) Millimeter line at 345 GHz with an absorption dip (HHSMT): V_{lsr}=-35km/s, ΔV=18 km/s (Rho et al. submitted)





- Broad lines: ^{12}CO(3-2), ^{12}CO(2-1), HCO$^+$
- Absorption dip is anti-correlated with ^{13}CO(1-0) (from parent cloud, cold gas)
- Unrelated gas at -58, -13, -2, and 13 km/s



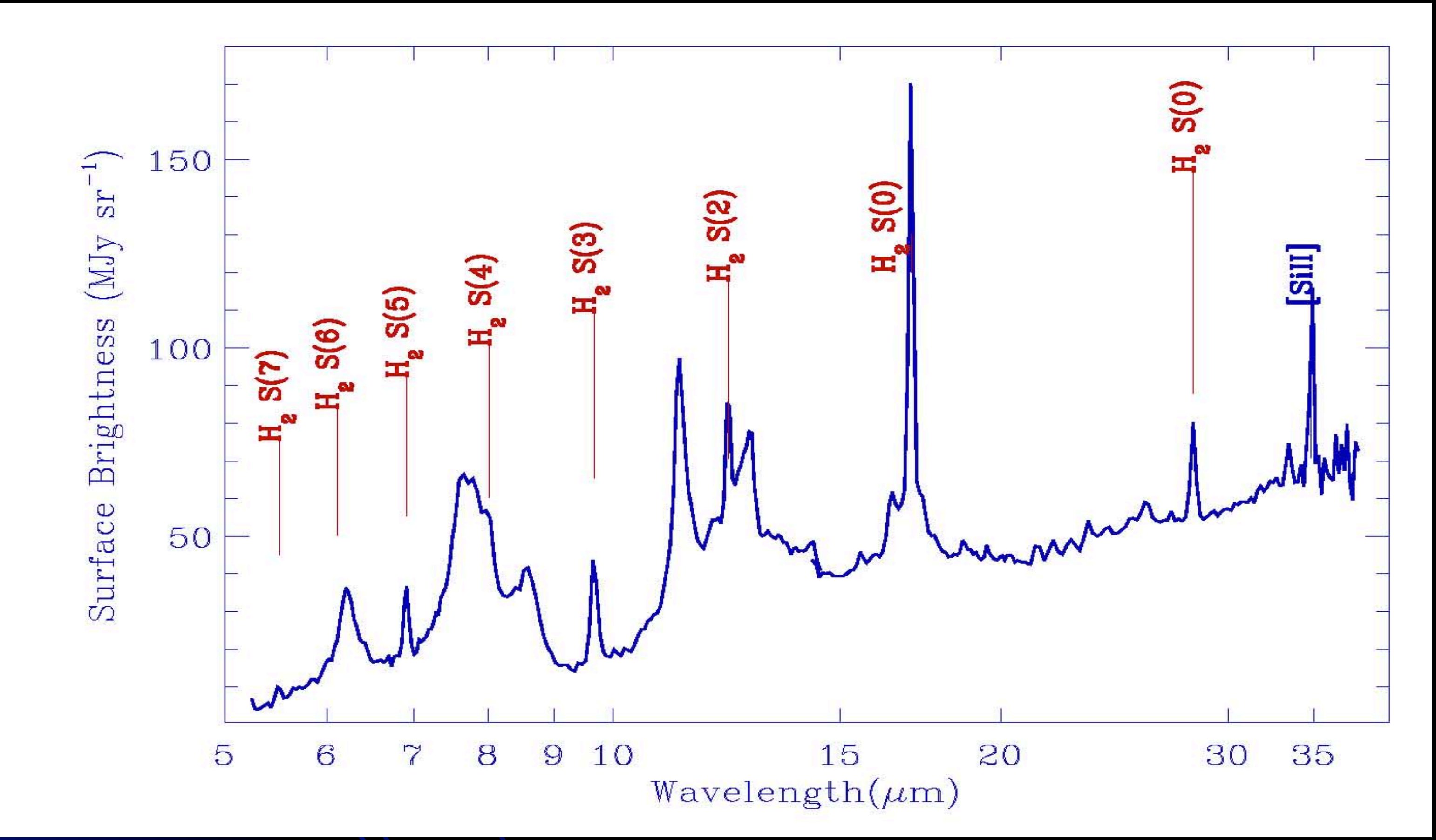
APEX observations

Additional Broad lines:
^{12}CO(4-3), ^{13}CO(3-2), ^{13}CO(2-1)

^{13}CO(2-1): a combination of broad line ^{13}CO(3-2) and narrow emission line ^{13}CO(1-0)

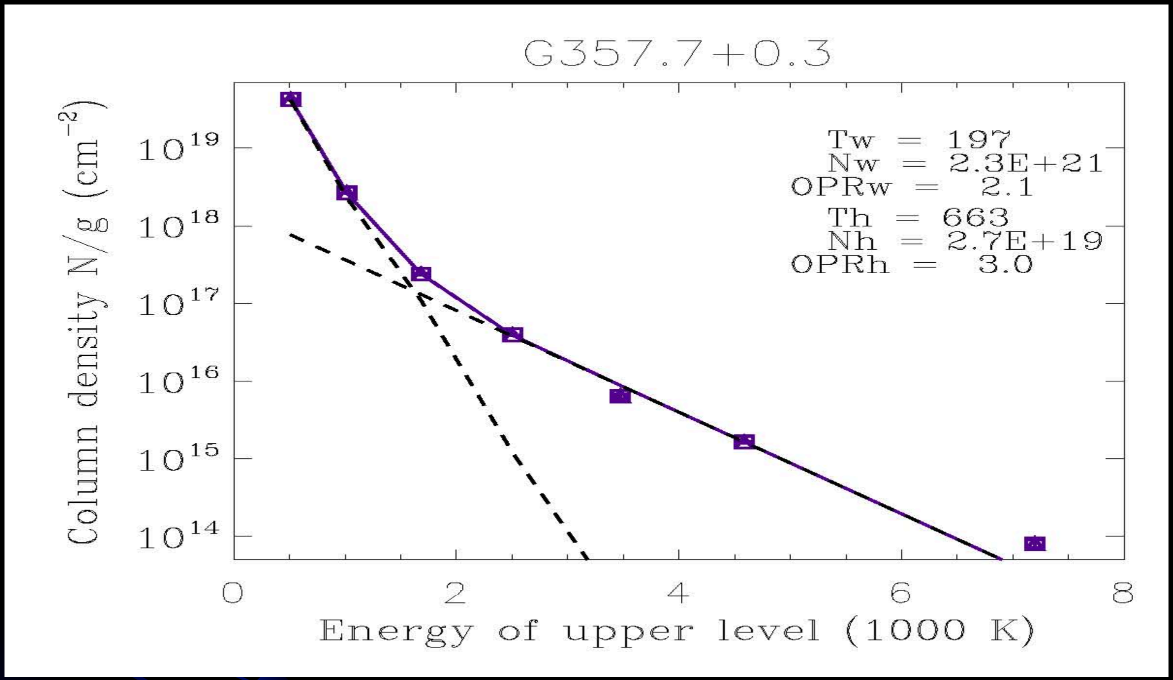
Rho et al., 2016, submitted

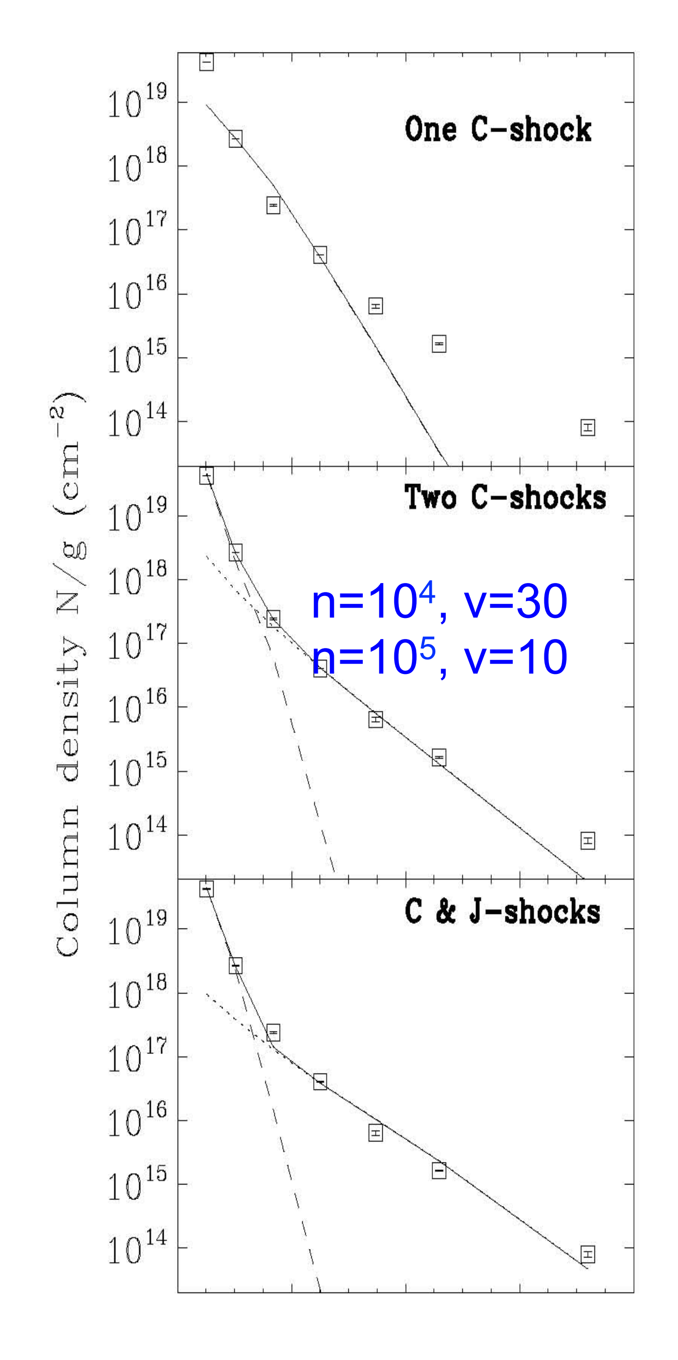
Spitzer IRS observation of G357.7+0.3



- H_2 S(0)-S(5) and S(7) lines
- Lack of ionic lines: only faint [Si II] line

H_2 Excitation Diagram





- 2T LTE fit: 200 (ortho-to-para ratio of 1) and 660 K.
- We fit C-shock (Bourlot et al. 2012; Wilgenbus 2000), and J- shock (Hollenbach & McKee 1989) ➔ Two C-shock model is favored over one C-shock or two C-shock model

Conclusion of G349.7+0.1

1. The velocity resolved spectroscopy of HIFI water line from G349.7+0.3 indicates that there are 3 components of ΔV=144, 27 and 3 km/s. However, low-J CO shows only narrow component.
2. J-shock model with n=10^4 cm^{-2} and Vs=80 km/s reproduced CO excitation diagram . This with the broad water line suggest that J-shock is favored.
3. N(CO)=3x10^{13} cm^{-2}, n(H_2) = 10^5 cm^{-3}, and Tkin =100-1000 K using LVG RADEX model.

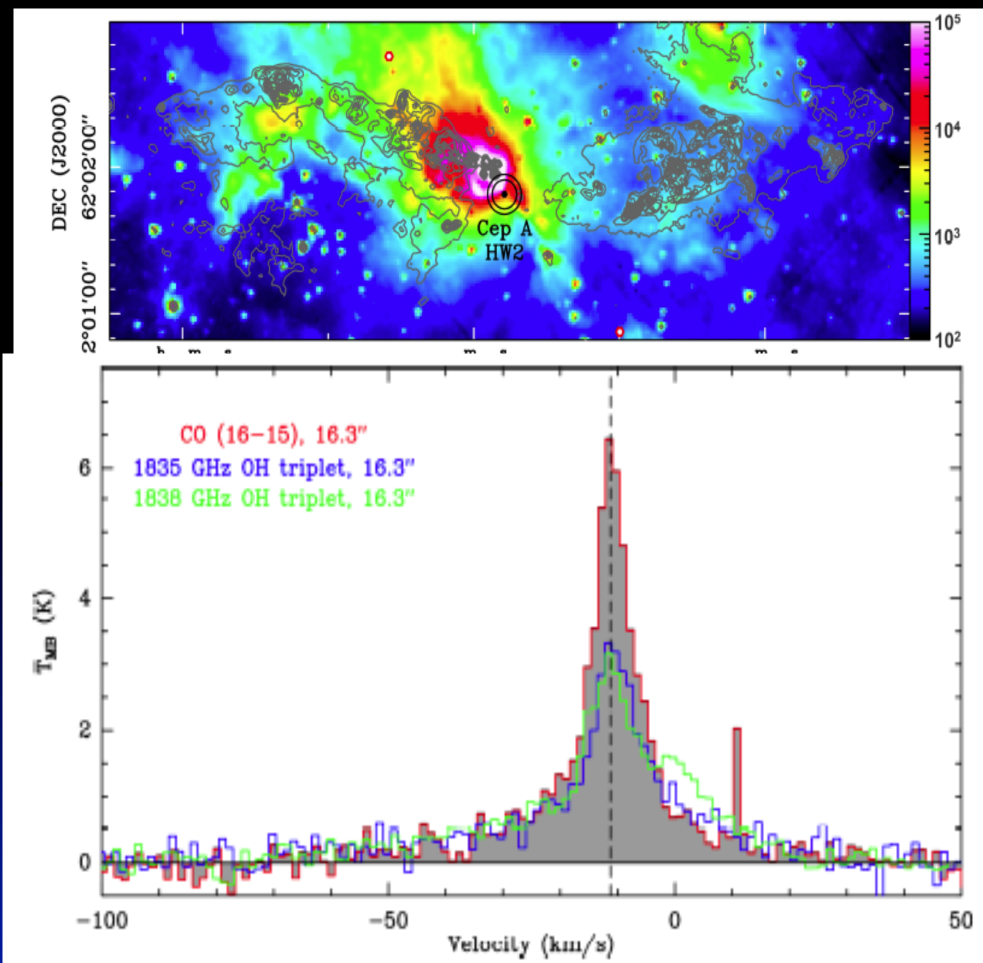
Conclusion of G357.7+0.3

1. From the relatively unknown SNR G357.7+0.3, we discover broad molecular lines of ^{12}CO(4-3), ^{12}CO(3-2), ^{12}CO(2-1), HCO^{+}, ^{13}CO(3-2), ^{13}CO(2-1), and HCN using millimeter telescope and the widths of the broad lines are 15-30 km/s.
2. Neither water or high-J CO lines are detected.
3. The CO line ratio including the upper limit of CO(11-10) indicates N(CO) = 5.5x10^{16} cm^{-2}, n(H_2) = 6 x10^4 cm^{-3}, T=75K, and size ~ 0.01 pc using LVG RADEX model.

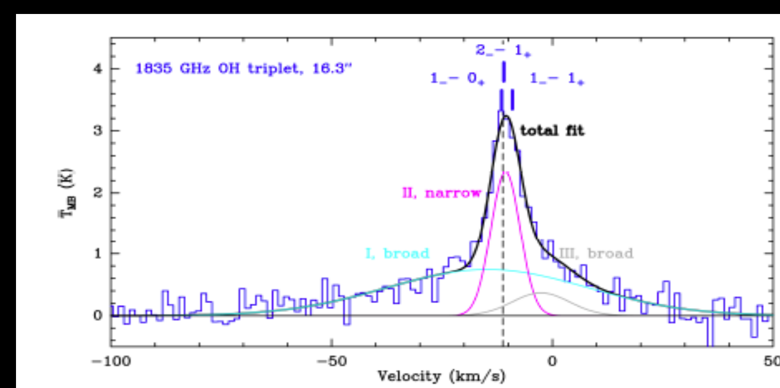
Unsolved Issues

- No para-water line detection. OPR=1-3 doesn't seem to explain this effect.
- Line profile difference between CO and water: The line profiles between water and low-J CO line don't match. Maybe water line is associated with high-J CO, and their origin between low-J and high-J is different. Velocity-resolved line is required to estimate accurate abundance.
- Water detection is related to high-J CO.

Challenging shock models with SOFIA OH observations in the high-mass star-forming region Cepheus A



- Cepheus A (hereafter Cep A) is a well-known star-forming region
- Borad CO and OH lines -> J-shock

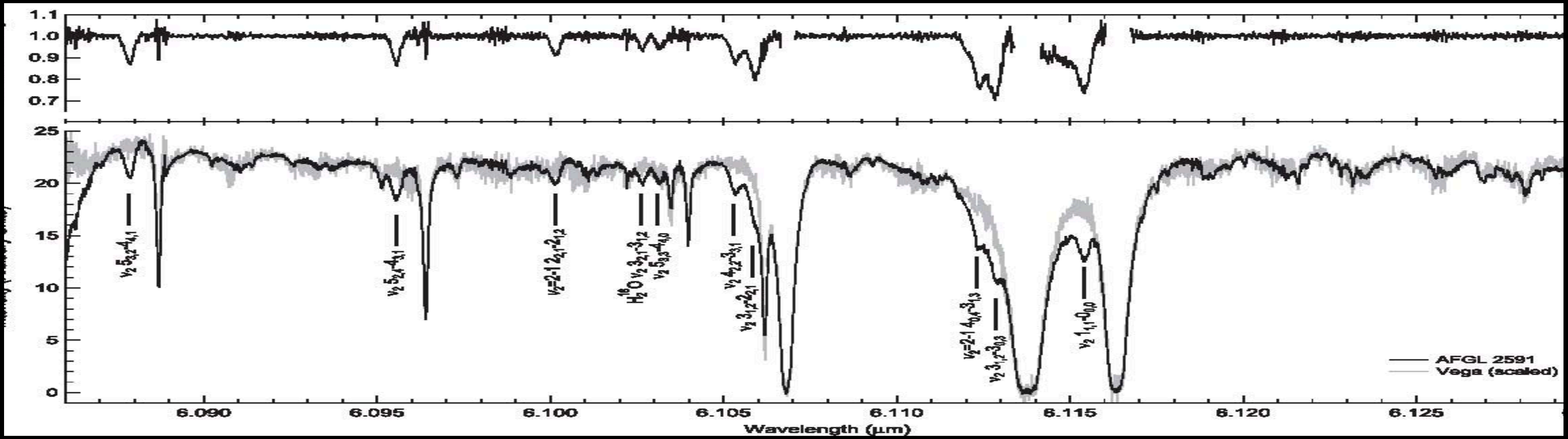


Gusdorf, et al., 2016

H_2O detection from a protostar AFGL 2591

Poster P36: SOFIA

Indriolo et al., 2015, ApJL, 802, L14



H_2O and HDO abundance maps on Mars at 7.2 μm

Encrenaz et al. 2016, A&A, 586, 62