The Herschel/HIFI unbiased spectral survey of the solar-mass protostar IRAS16293

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Antares

Scorpius

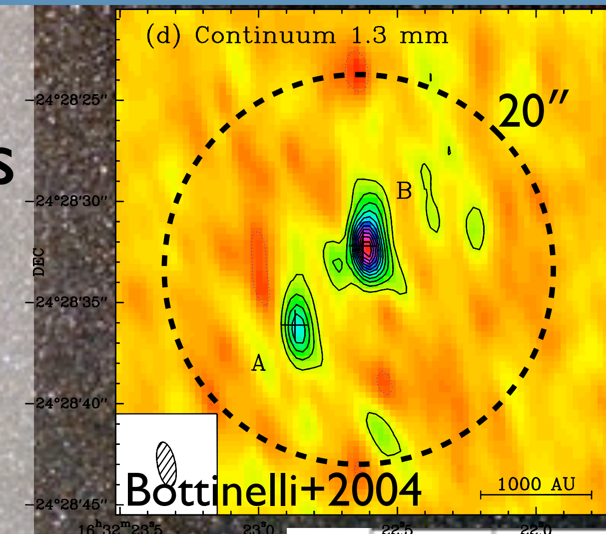
Outline

- Overview
- Highlights:

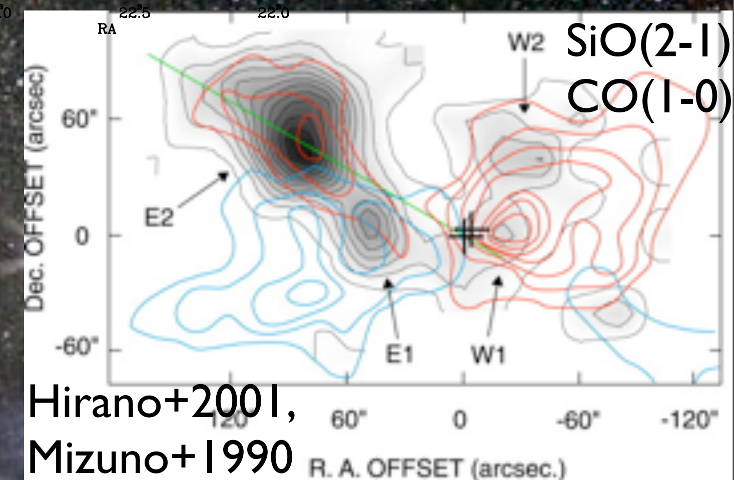
1. CH
2. HDO, D_2O
3. HCl
4. NH_2D, ND_2H

IRAS 16293

- Low-mass (~1M_{sun}), Class 0 source with a complex structure : binary on arcsec scale, multiple outflows
- Target of two spectral surveys :
  - Blake et al. 1994, van Dishoeck et al. 1995
  - Recent unbiased spectral survey with the IRAM-30m and JCMT : TIMASSS (The IRAS16293 Millimeter And Submillimeter Spectral Survey - Caux et al. 2011)

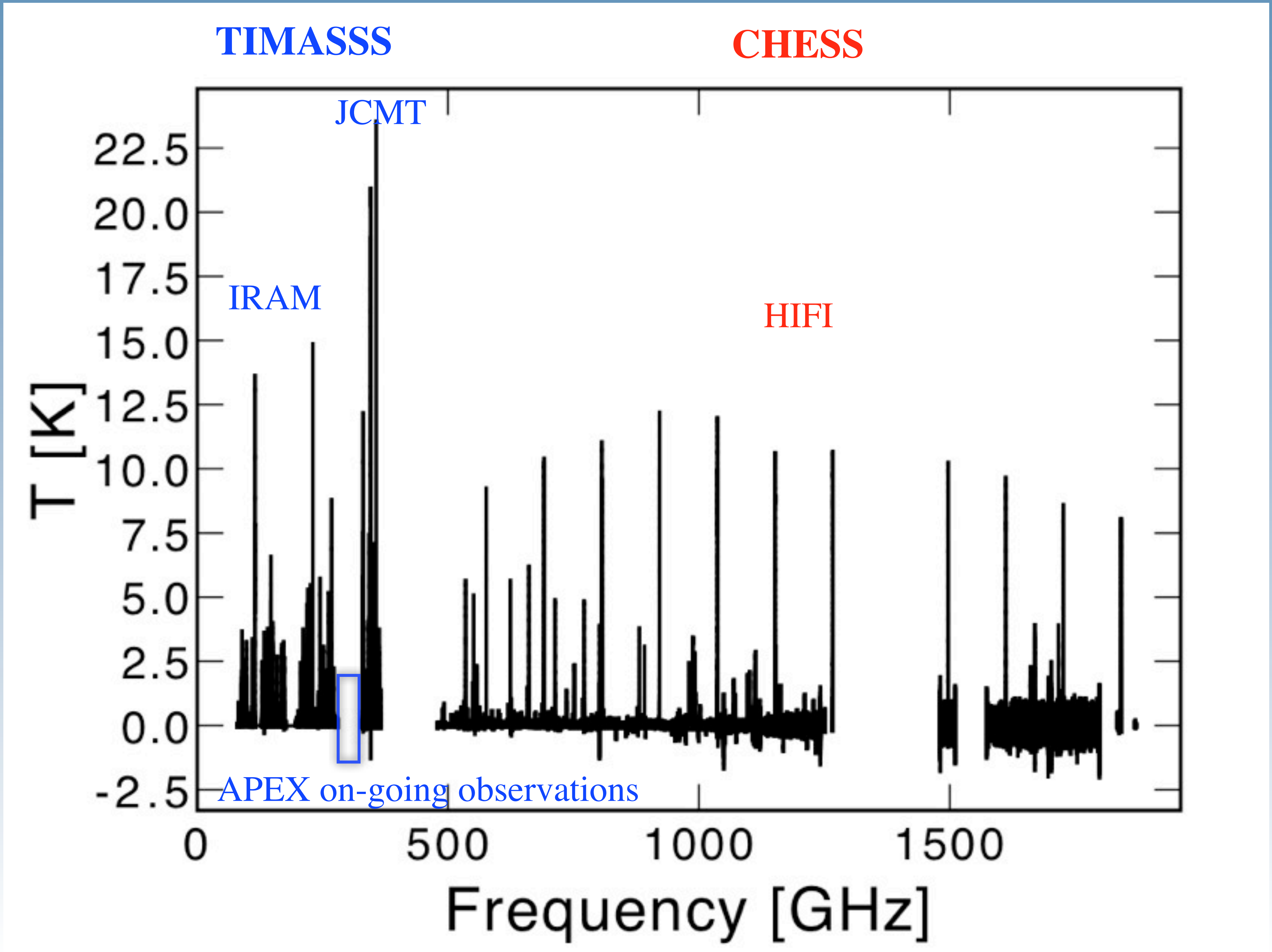


Bottinelli+2004



Hirano+2001,
Mizuno+1990

IRAS16293 full spectrum



Species detected with HIFI

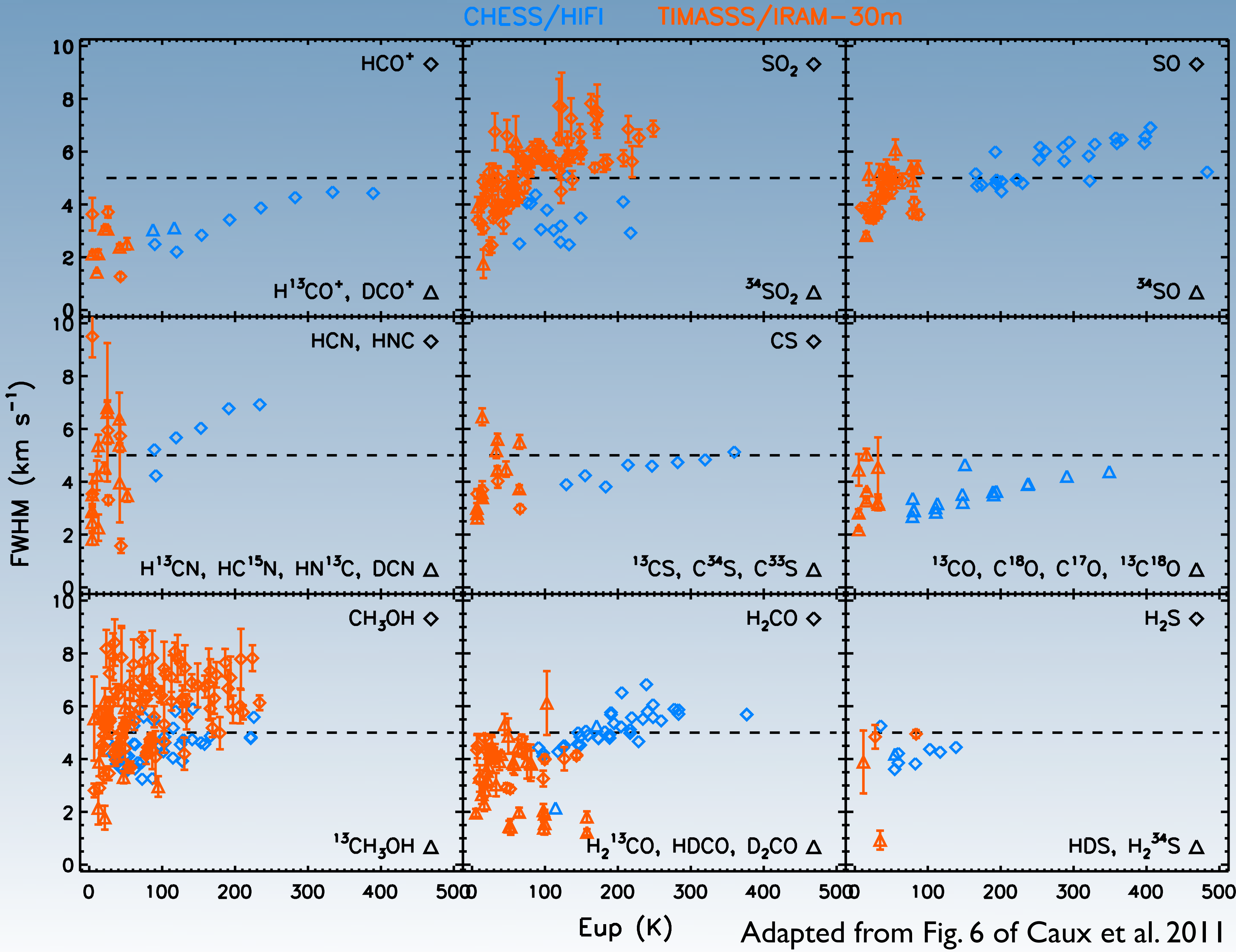
Species	isotopes	Species	isotopes	D	Species	isotopes	D
CI	y	CH	maybe	n	H_2O	y	y
CO	y	CH^+			H_2S	y	
CS	y	CCH	y		HCl	y	
CN	y	OH			HCN	y	y
SO	y	HF		maybe	HNC	y	y
SO_2	y	NH	n	y	HC_3N		
SiO	y	NH_2	n	y	HCO^+	y	y
PN		NH_3	y	y	H_2CO	y	y
		N_2H^+	y		CH_3OH	y	

red = not detected in TIMASSS

Comparison with TIMASSS

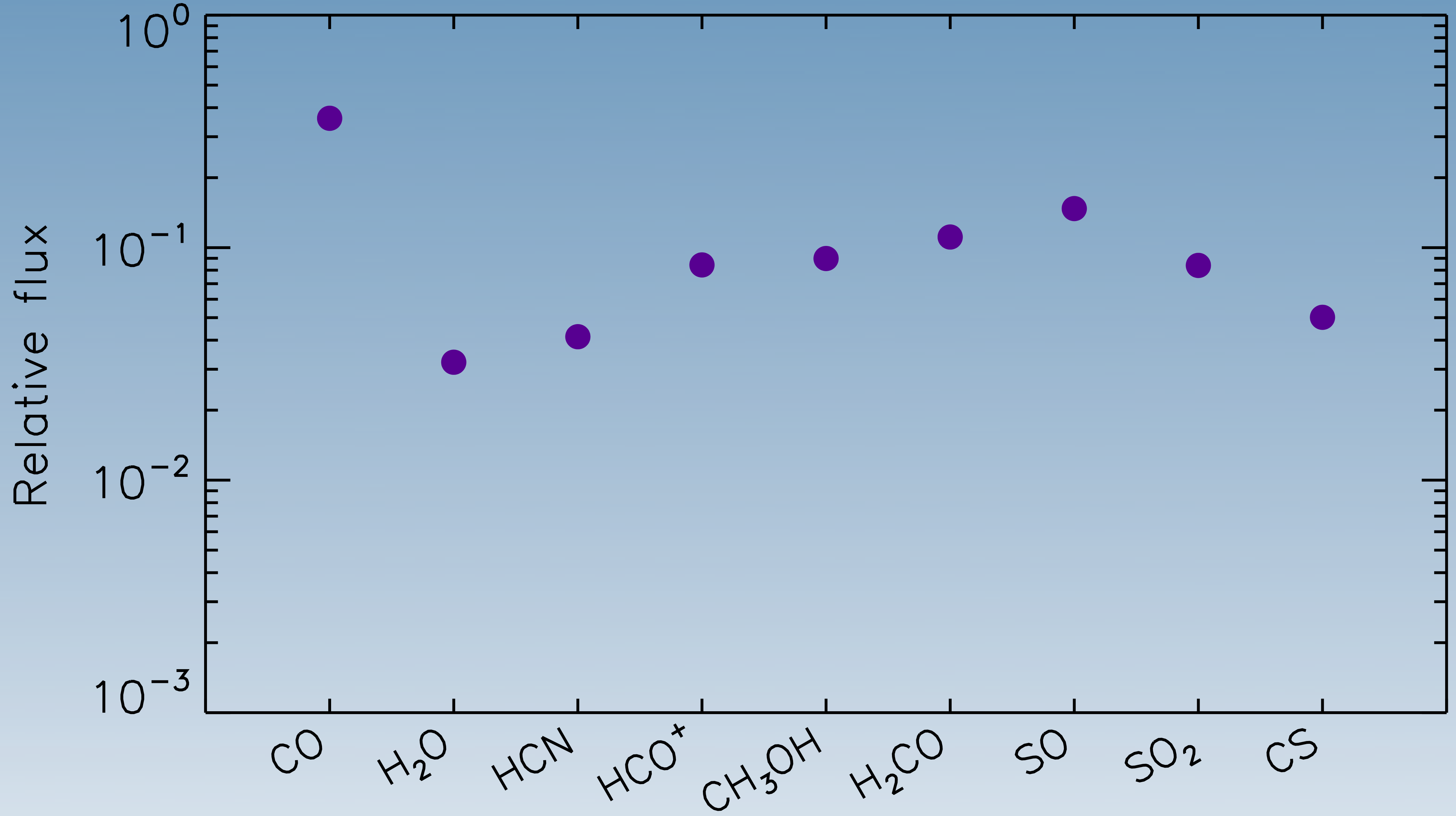
TIMASSS (Caux et al. 2011) = The IRAS16293 Millimeter And Submillimeter Spectral Survey : ground-based observations with the IRAM-30m (80-280 GHz) and the JCMT (328-366 GHz)

- TIMASSS: spread in FWHM due to low spectral resolution and strong line blending
- CHESS/HIFI: brings crucial info at high E_{up}



Adapted from Fig. 6 of Caux et al. 2011

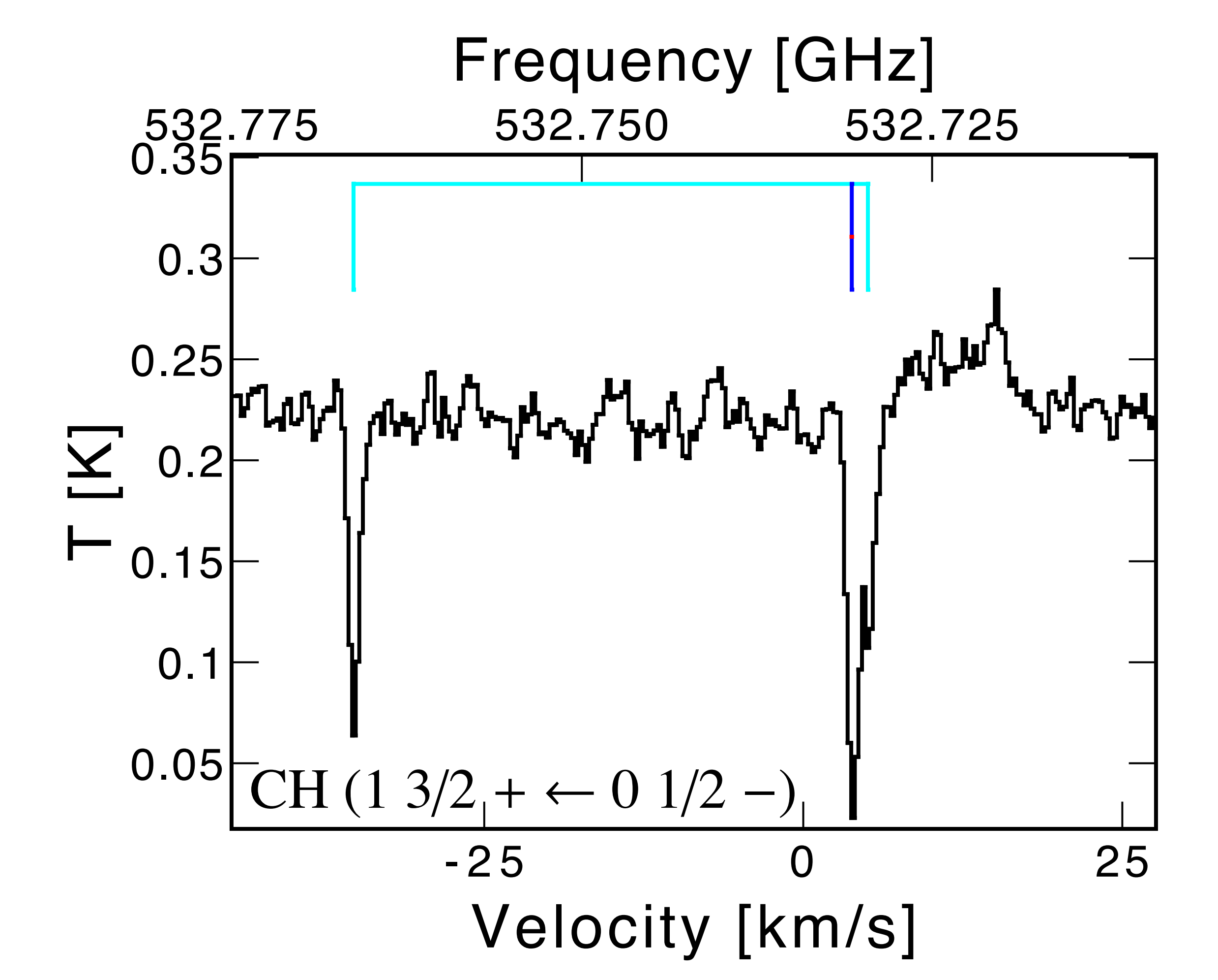
Line contribution from mm to FIR

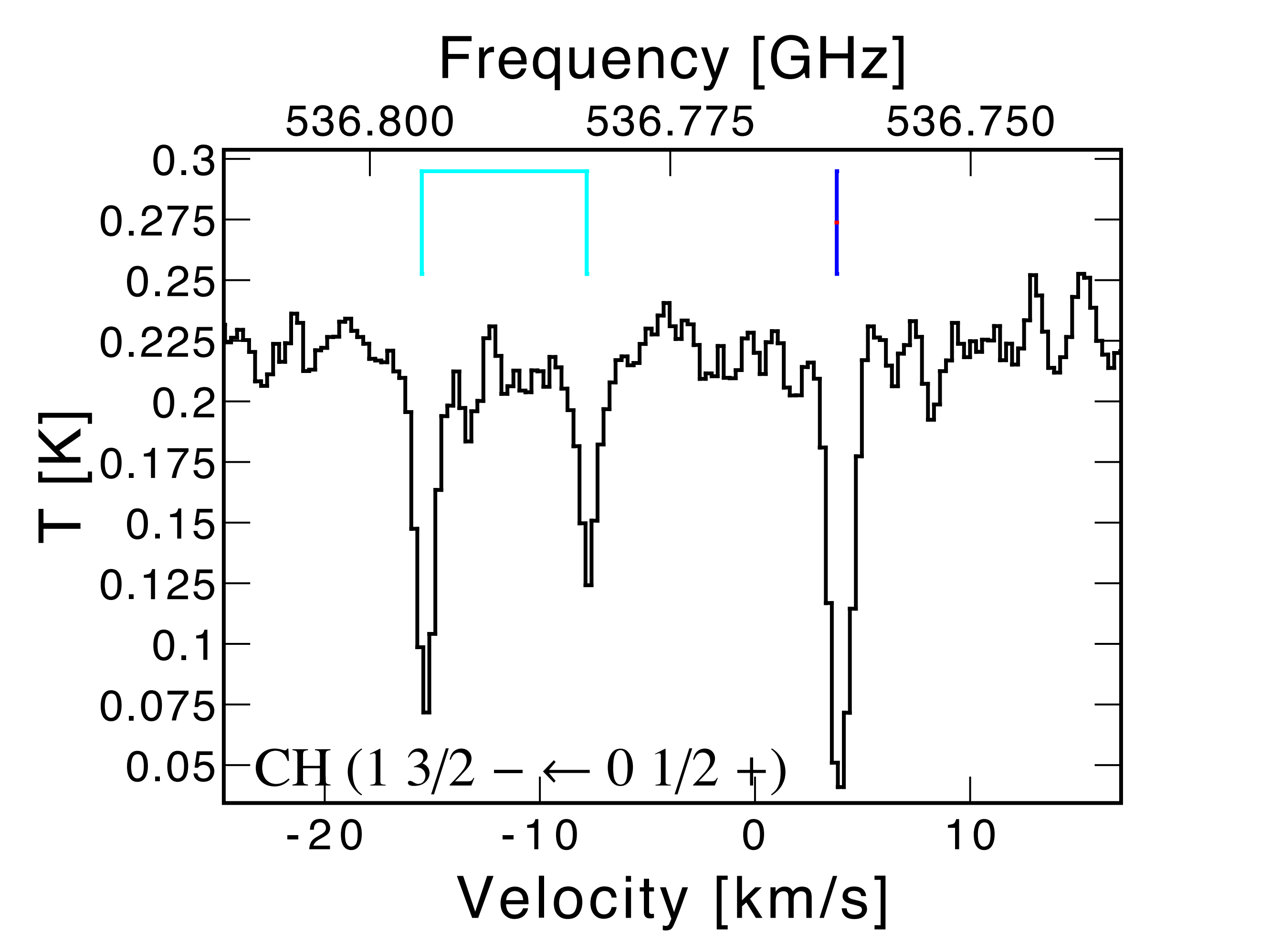


- See also poster (S1#49) by Kama et al., "The HIFI spectral survey of the protostar OMC-2 FIR 4", for comparison of relative fluxes in OMC-2 FIR 4 and Orion-KL.

CH, survey

- CH (1-0) :



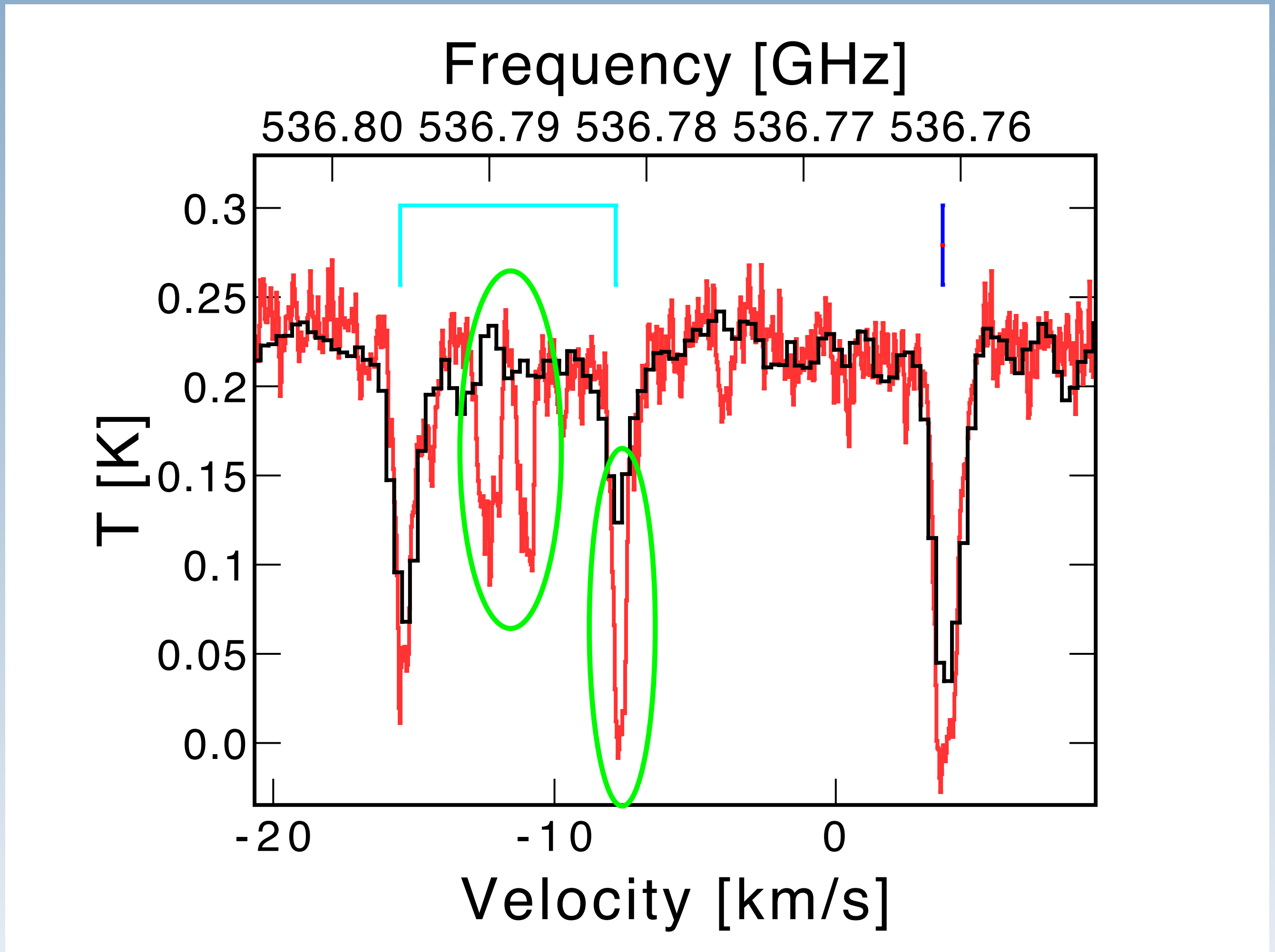


Unresolved narrow lines → follow-up pointed observations with the HRS @ 536.75 GHz

- Non-detections: CH (2-1) @~1660 GHz, CD (2-1) @~900 GHz (N.B.: CD (1-0) @ 439 GHz, not observable by HIFI)

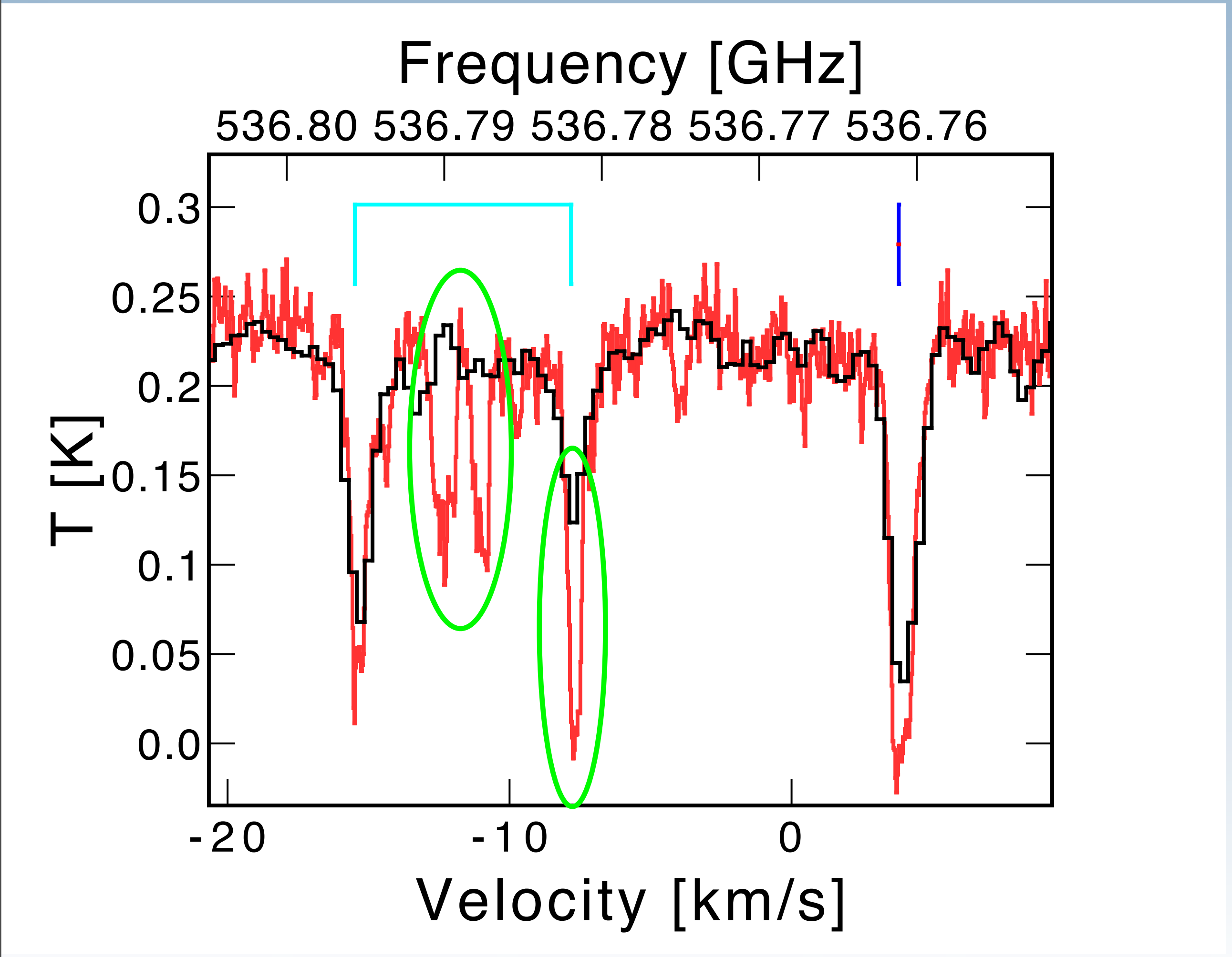
CH, pointed

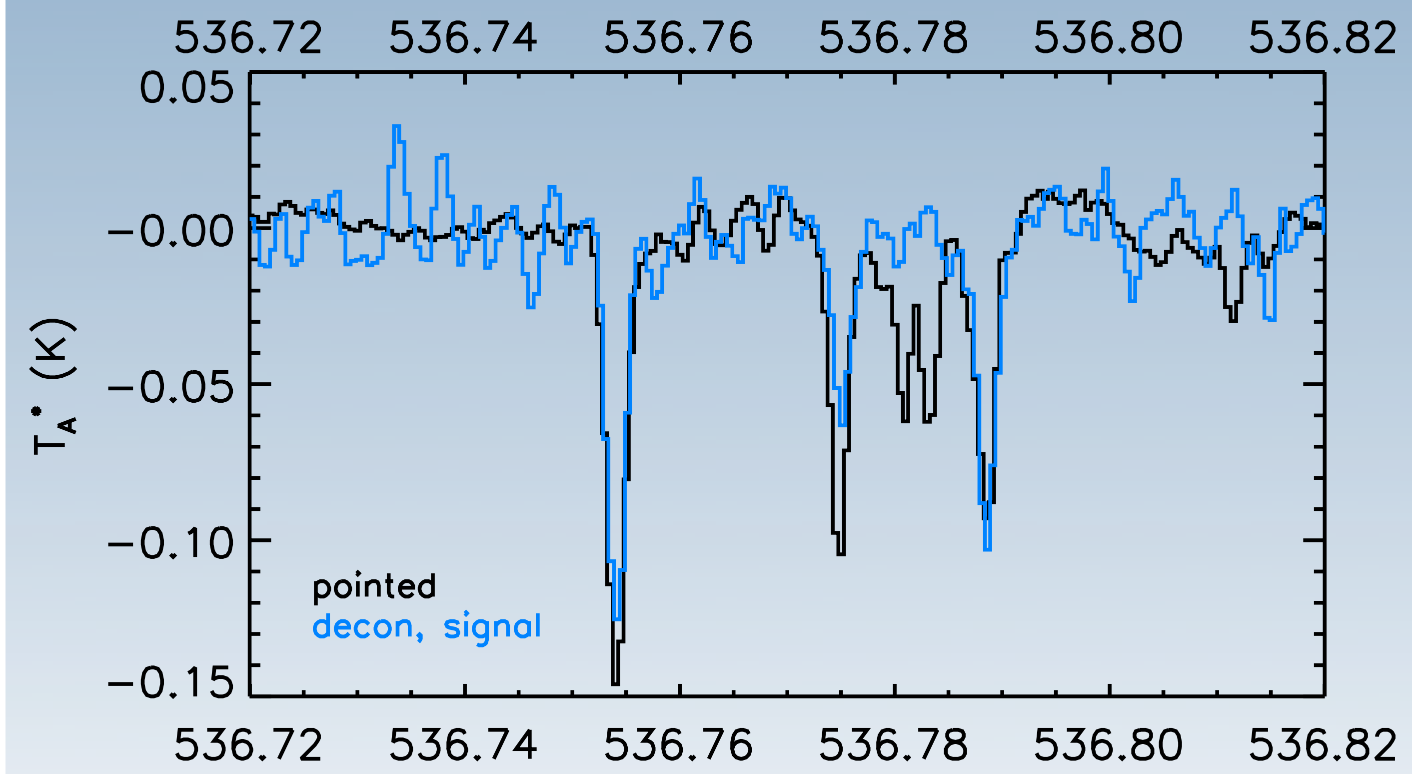
- Contamination by unidentified lines from image band verified with survey data



CH, pointed

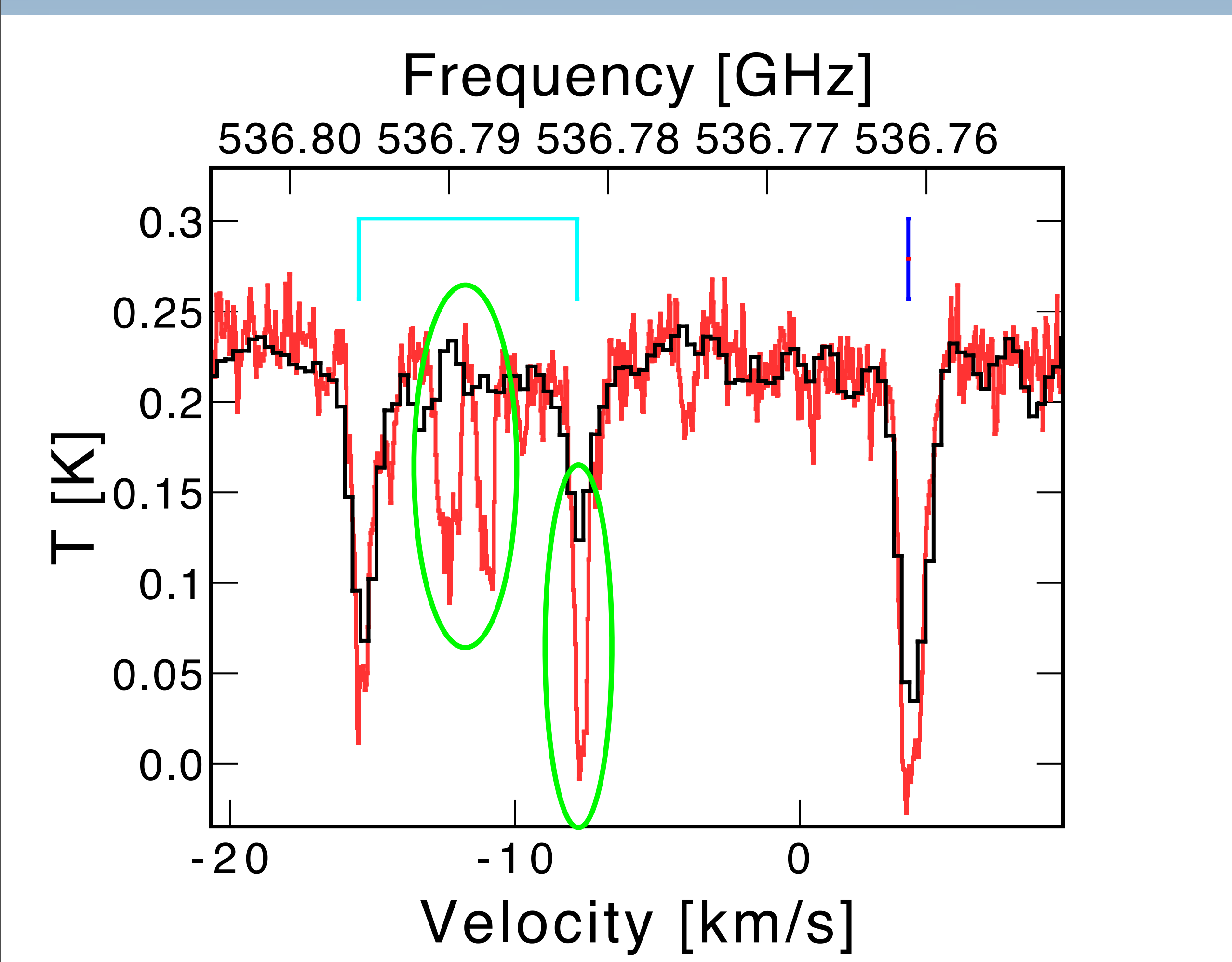
- Contamination by unidentified lines from image band verified with survey data

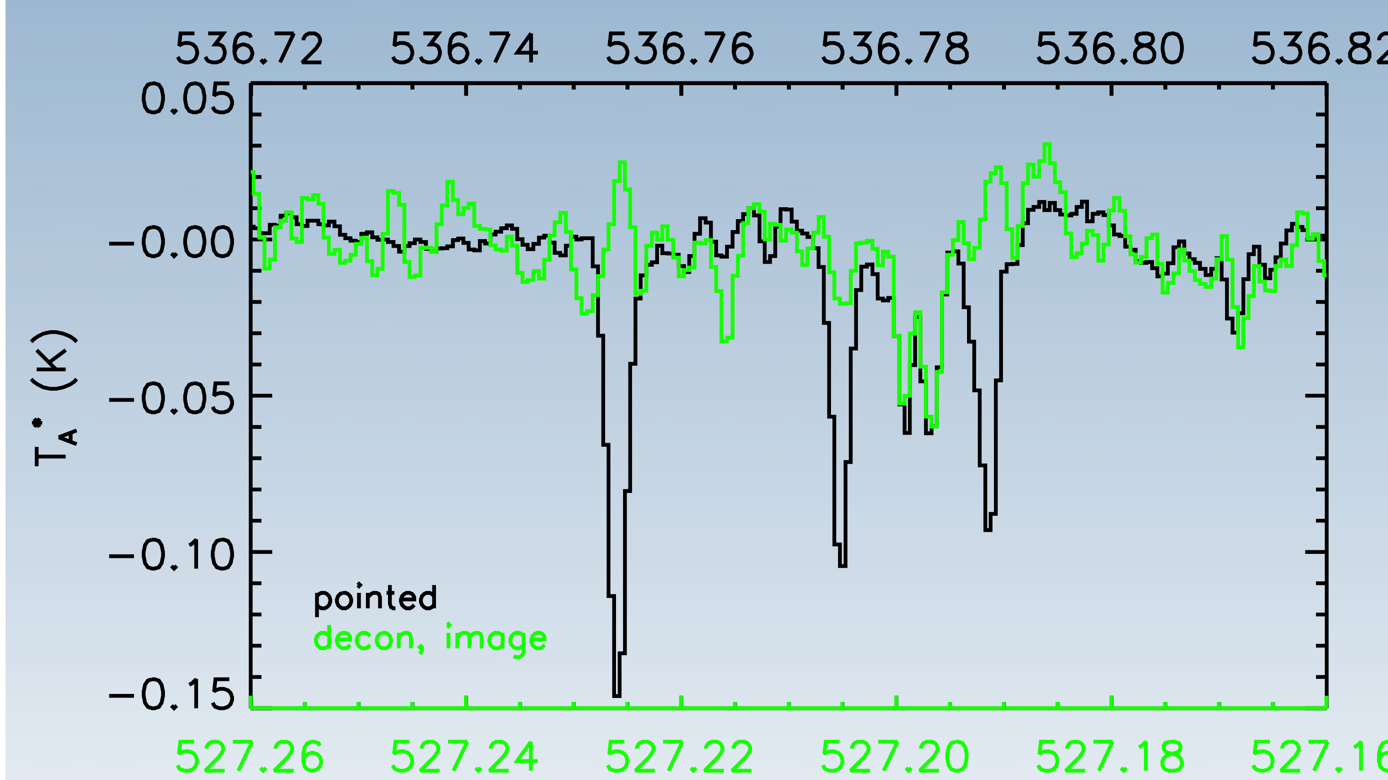




CH, pointed

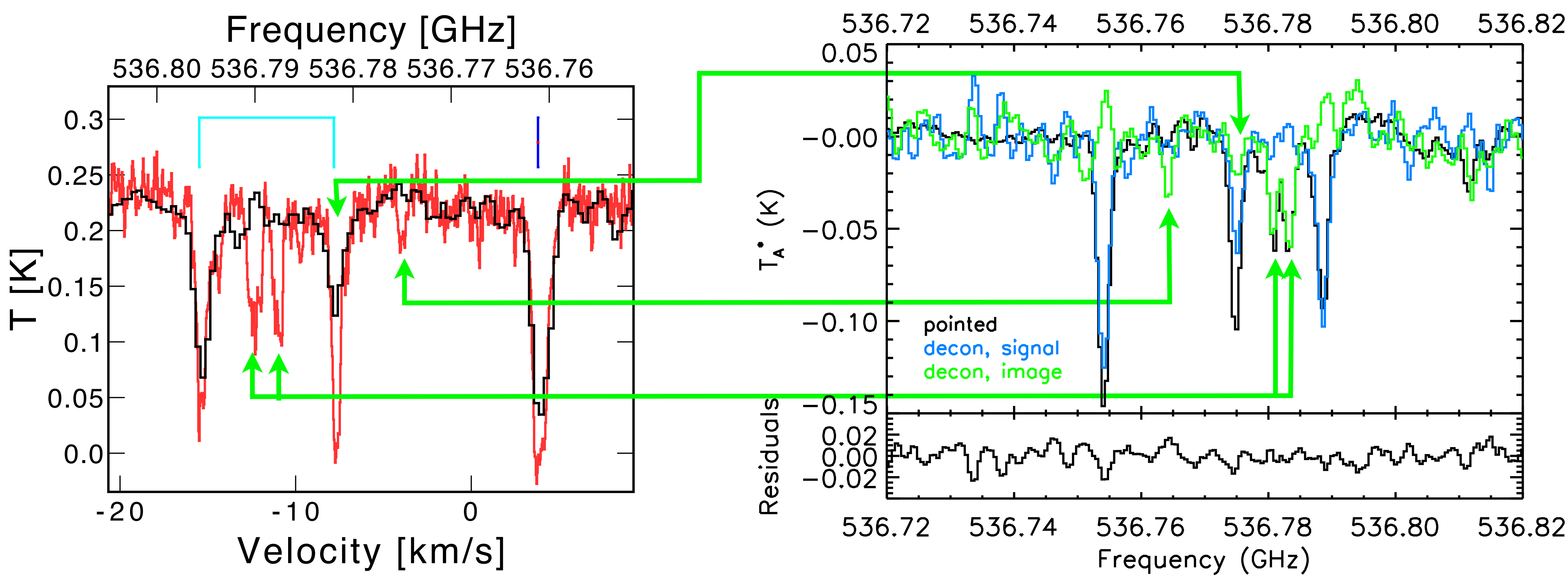
- Contamination by unidentified lines from image band verified with survey data





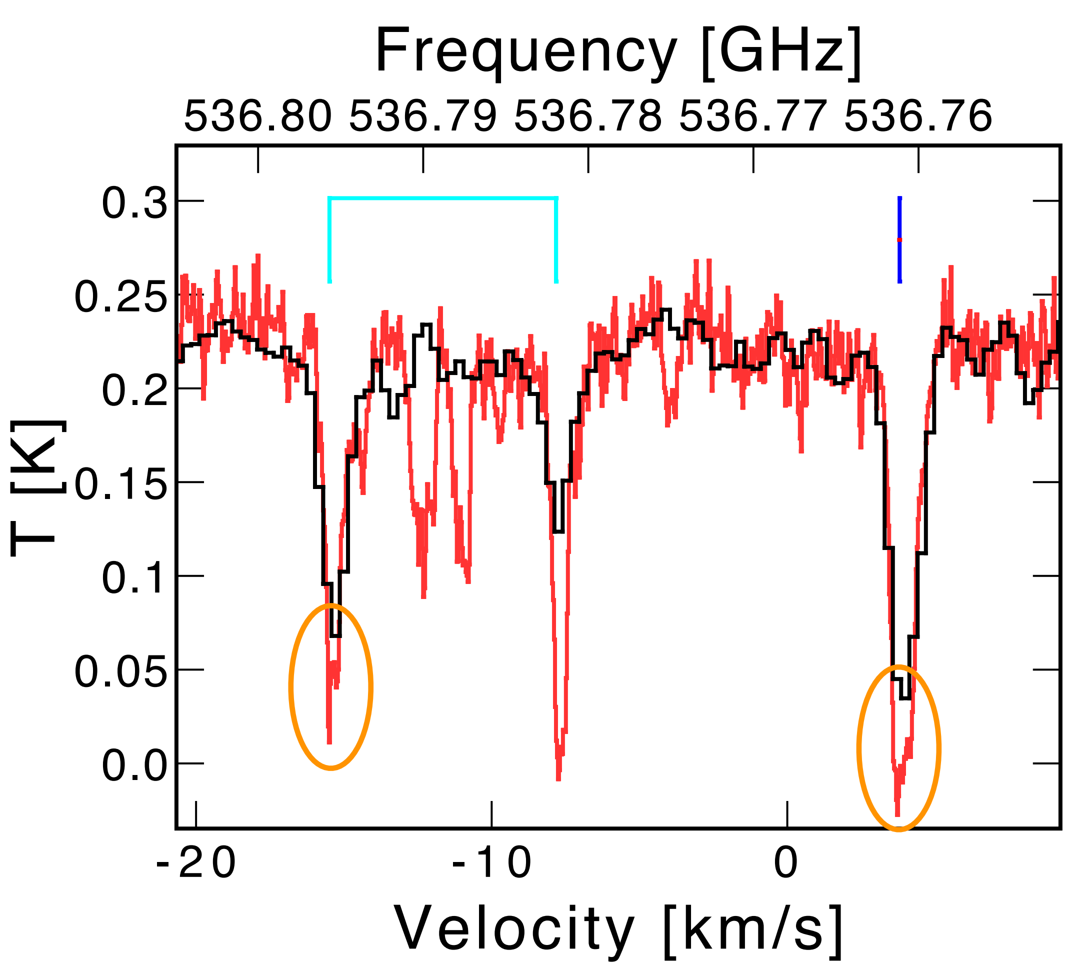
CH, pointed

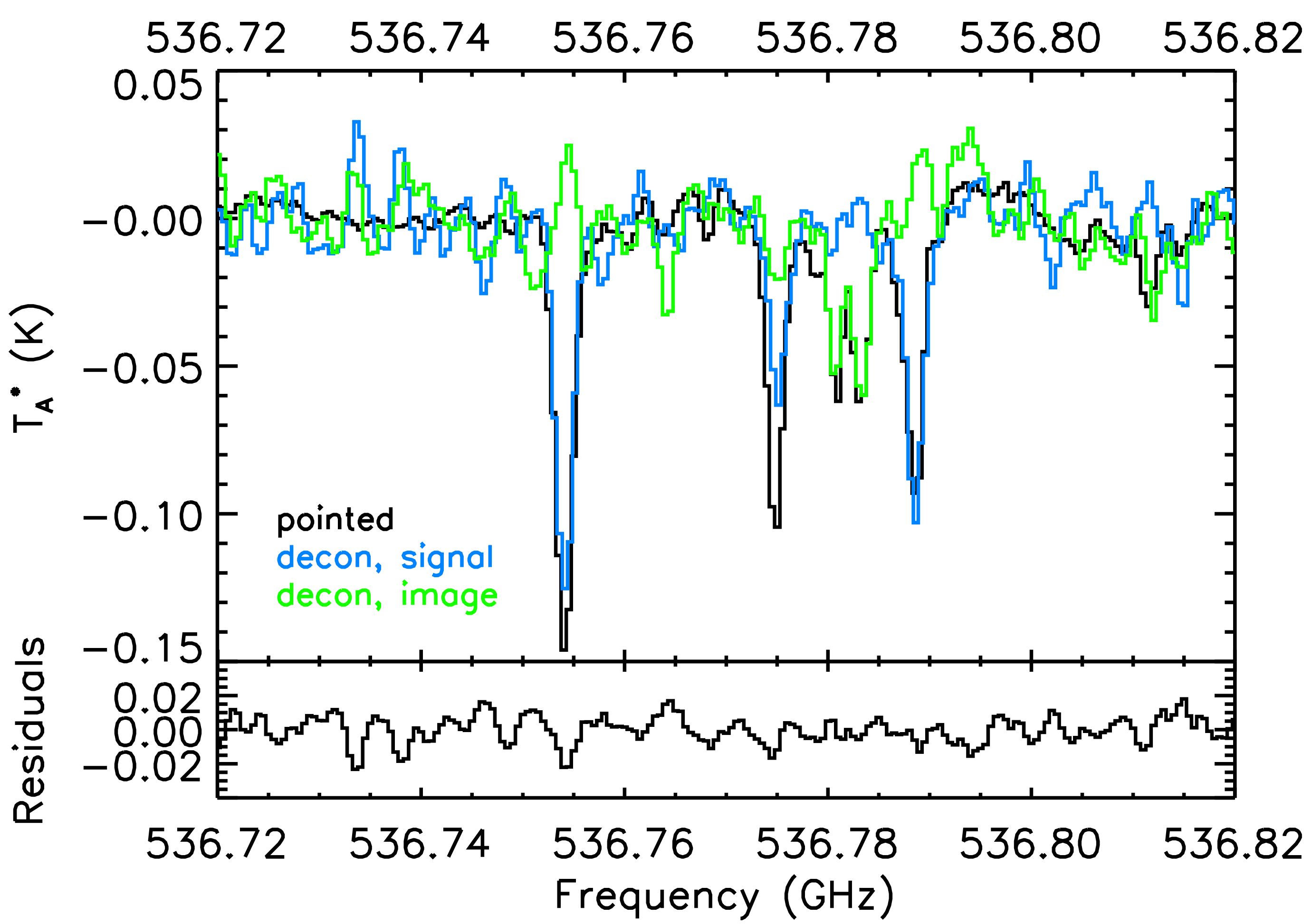
- Contamination by unidentified lines from image band verified with survey data



CH, pointed

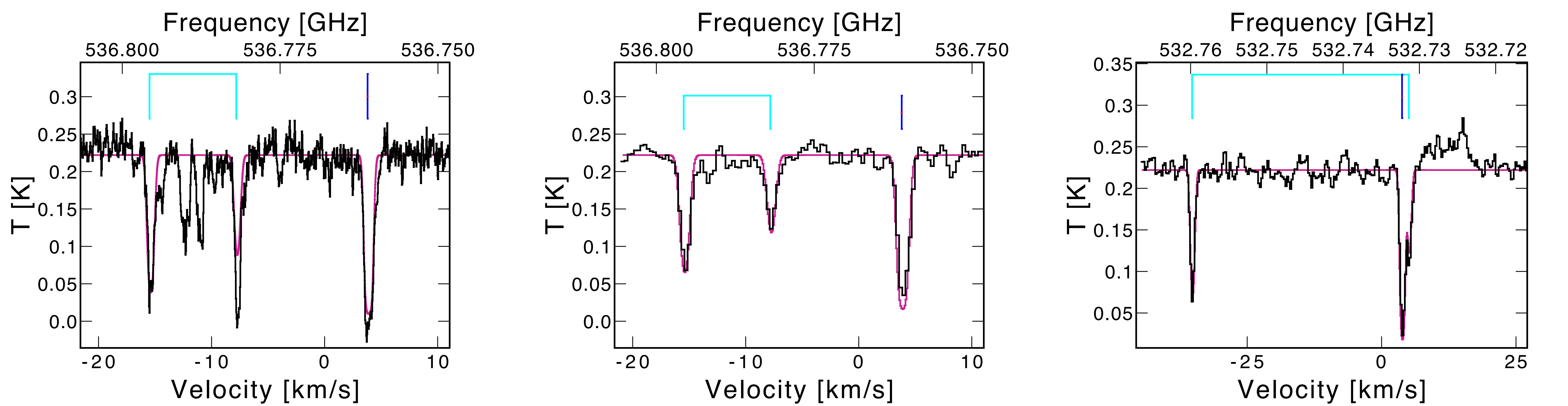
- Contamination by unidentified lines from image band verified with survey data
- Lines are resolved and absorption deeper





CH, LTE modeling

- Data fitted with hyperfine structure routine in CLASS => T_{ex}, N
- HRS: $T_{ex} \sim 3.1 \pm 0.3$ K, N ~ $(1.0 \pm 0.1) \times 10^{14}$ cm^{-2}.
- WBS: $T_{ex} \sim 3.95 \pm 0.85$ K, N ~ $(1.25 \pm 0.35) \times 10^{14}$ cm^{-2}.

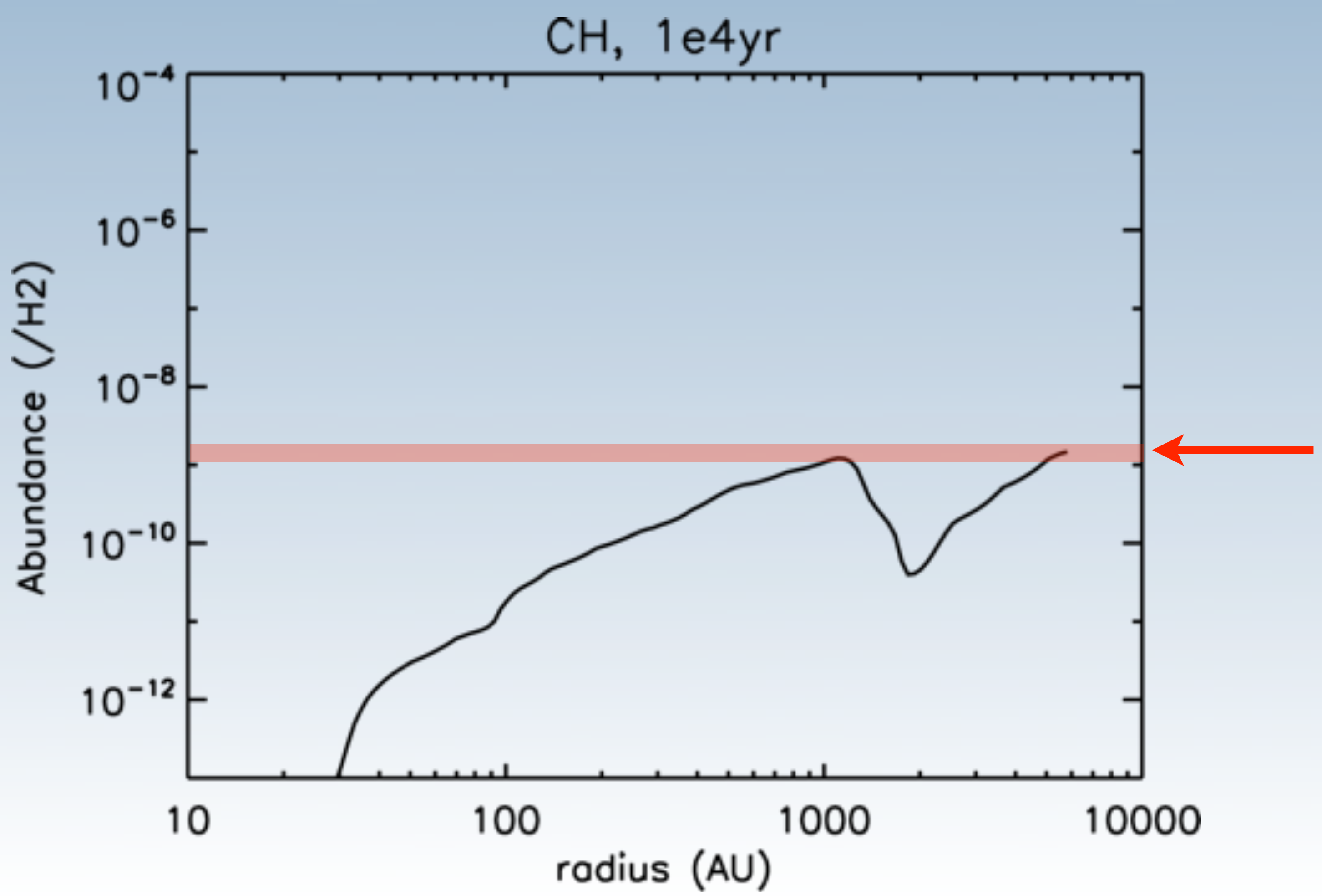


LTE model in CASSIS with N = 1.0×10^{14} cm^{-2}, T_{ex} = 3.3 K, FWHM = 0.54 (HRS) and 0.80 (WBS) km s^{-1}.
(consistent with non-detections of CH(2-1) and of CD(2-1), even assuming high deuteration fraction)

- HRS data crucial to constrain T_{ex} : using the CASSIS software, could not reproduce the depth of the absorption in the HRS data for T_{ex} > 3.7 K.

CH, chemical modeling

- Gas-grain chemical model Nahoon (Wakelam et al. 2012)
- Profile does not evolve much with time.
- Corresponding column density: 1.9×10^{14} cm^{-2}, consistent with observed value of ~ 1.0×10^{14} cm^{-2}.

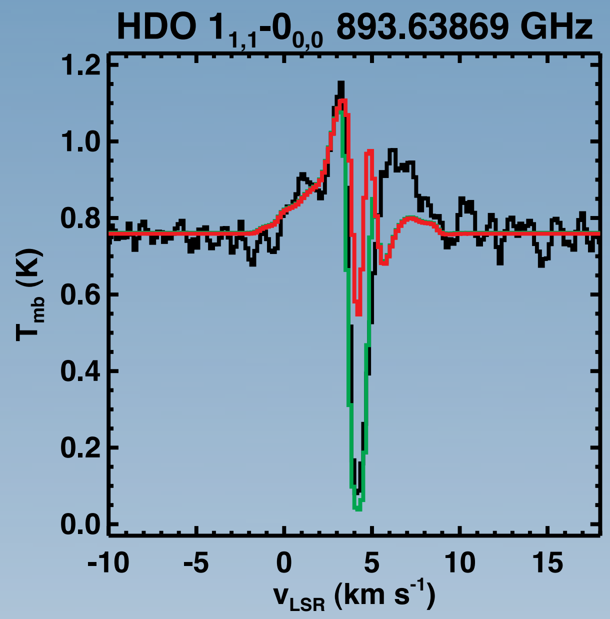


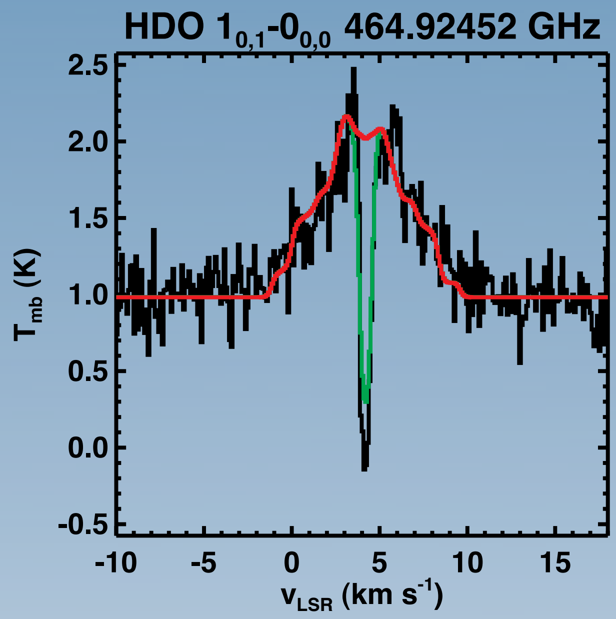
Observed abundance assuming $N(H_2) = 5 \times 10^{22}$ cm^{-2}.

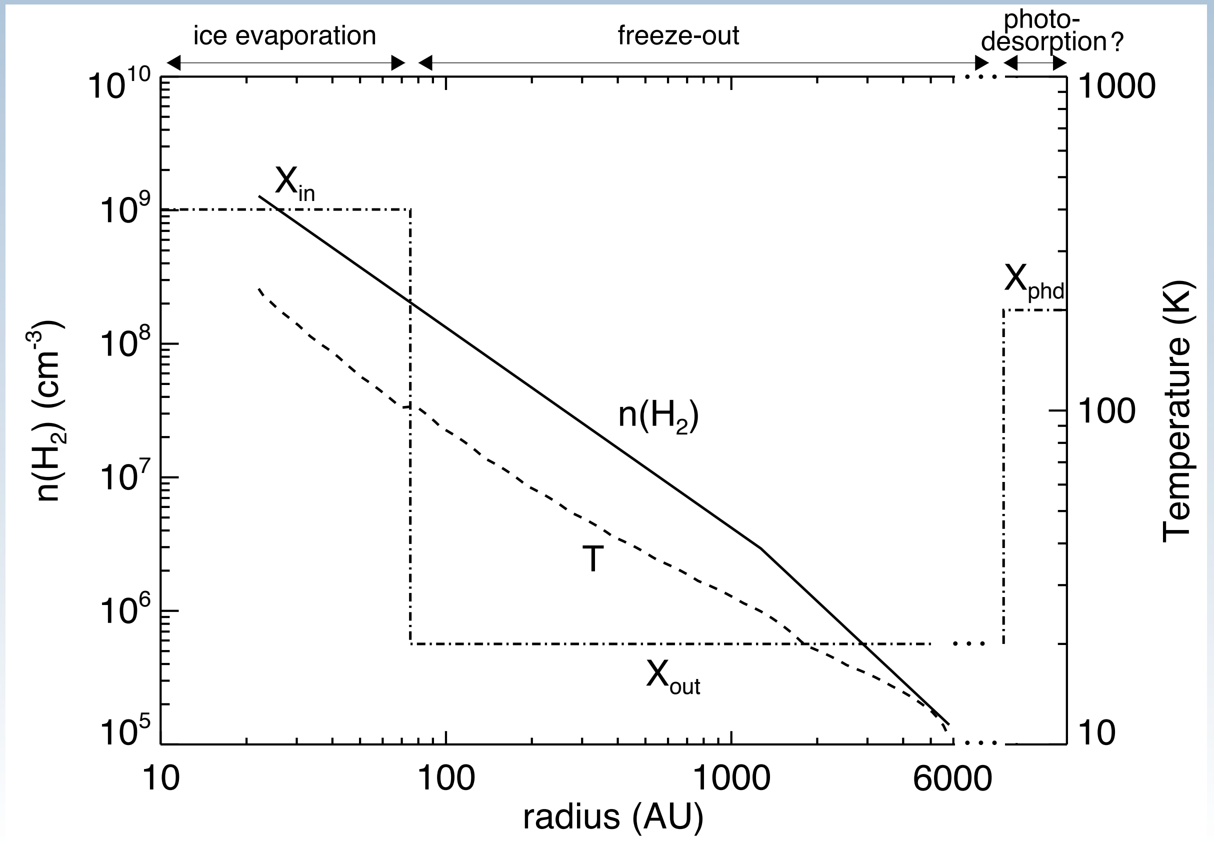
HDO

Coutens et al. 2012, A&A, in press ; poster (S1#42) : "Study of deuterated water in the low-mass protostar IRAS16293-2422"

- TIMASSS+CHESS surveys : 13 detected transitions (HIFI=9, IRAM=3, JCMT=1) + 3 upper limits
- $H_2{}^{18}O$ (CHESS) : 5 detections, 10 upper limits → determine water abundance, using $H_2{}^{16}O$ / $H_2{}^{18}O$ = 500
- Use RATRAN (Hogerheijde & van der Tak 2000) to perform a grid of models and determine best HDO and $H_2{}^{18}O$ abundances via χ^2 minimization.

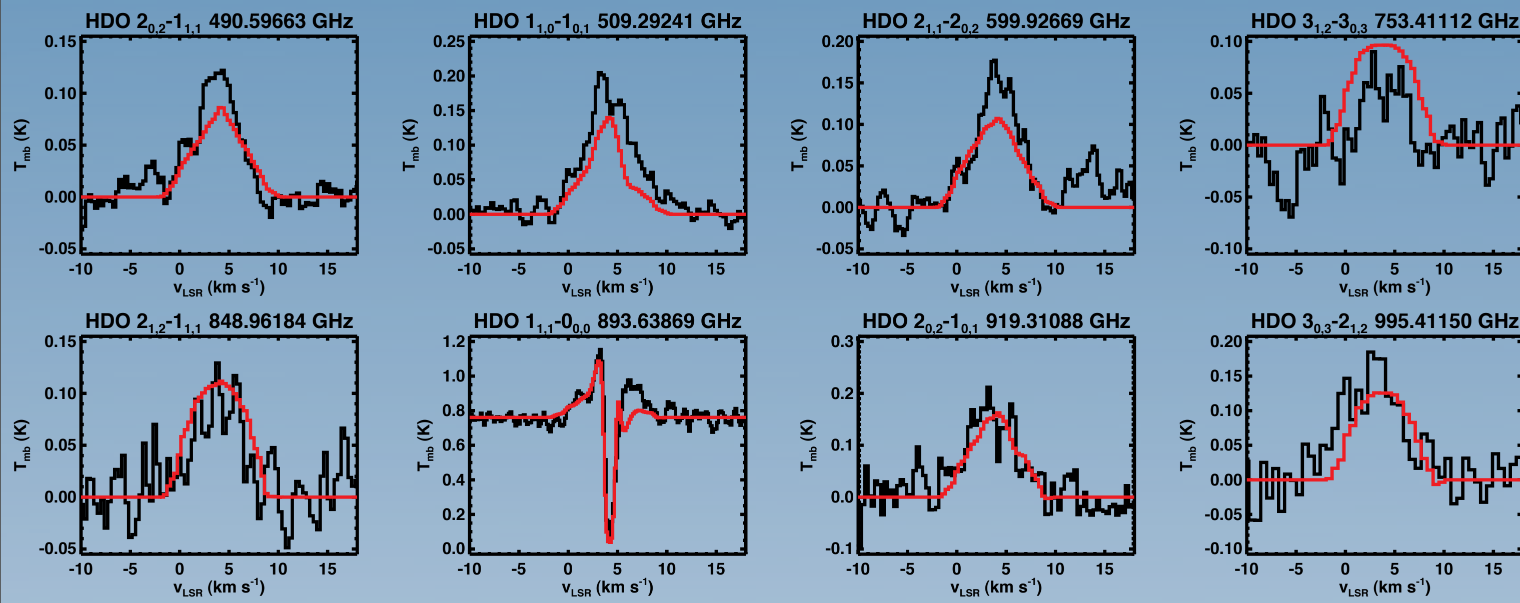




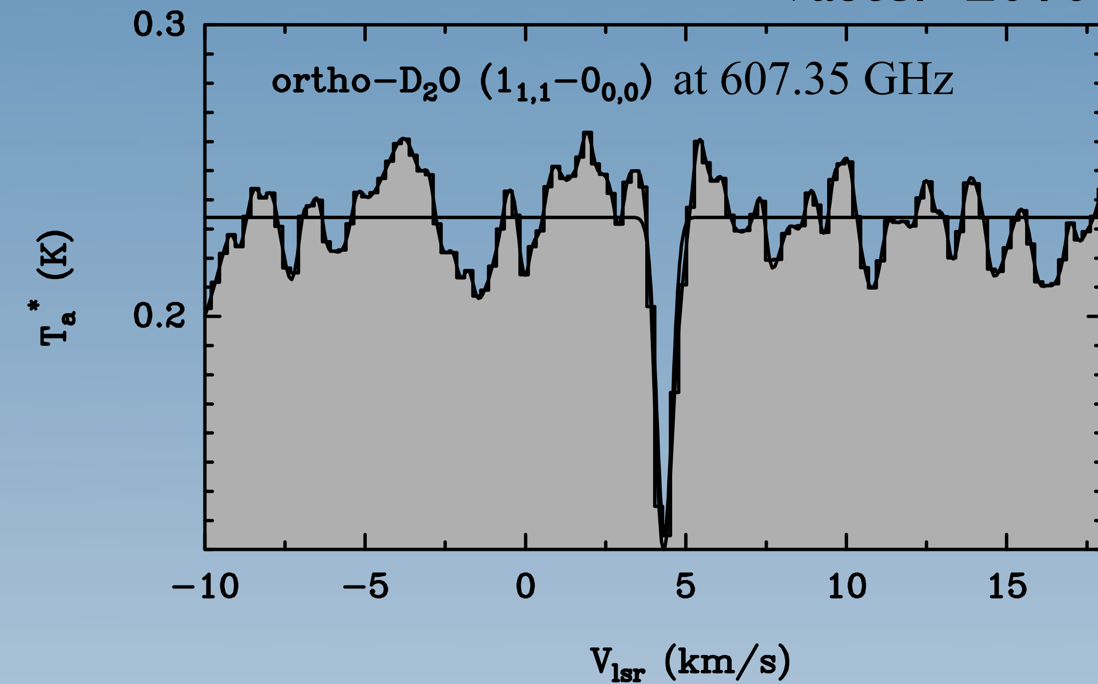


HDO, D_2O

Coutens+2012



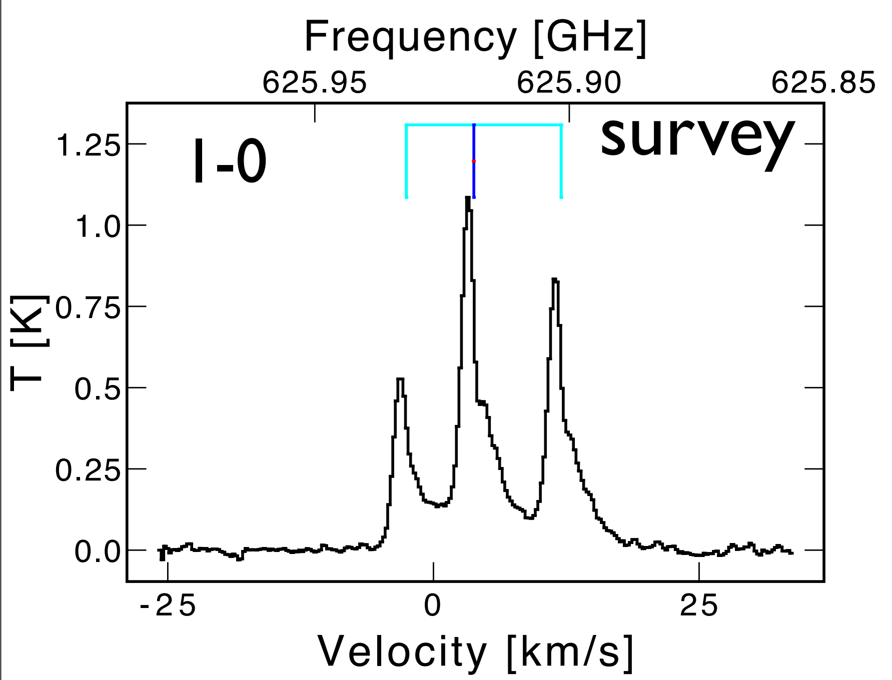
Vastel+2010

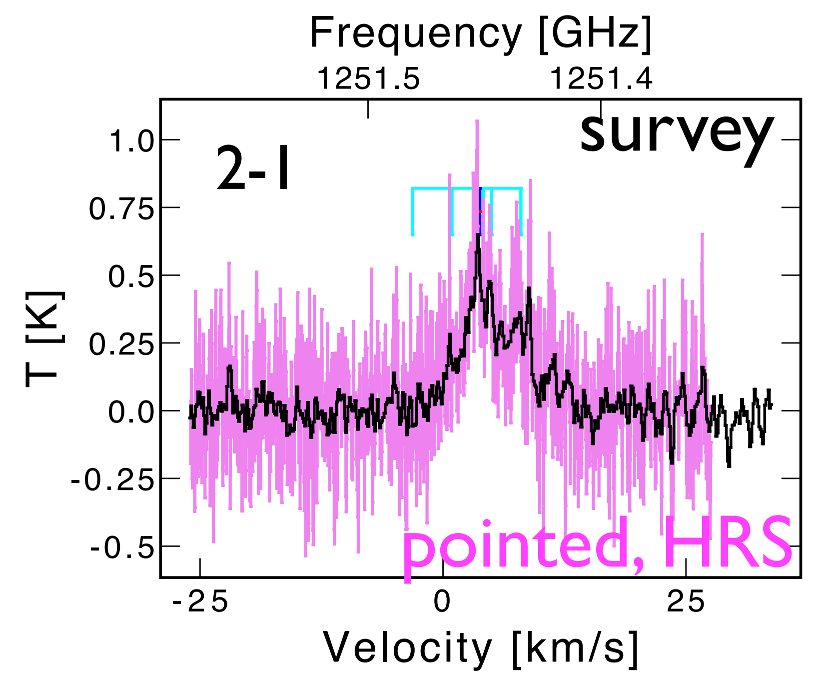


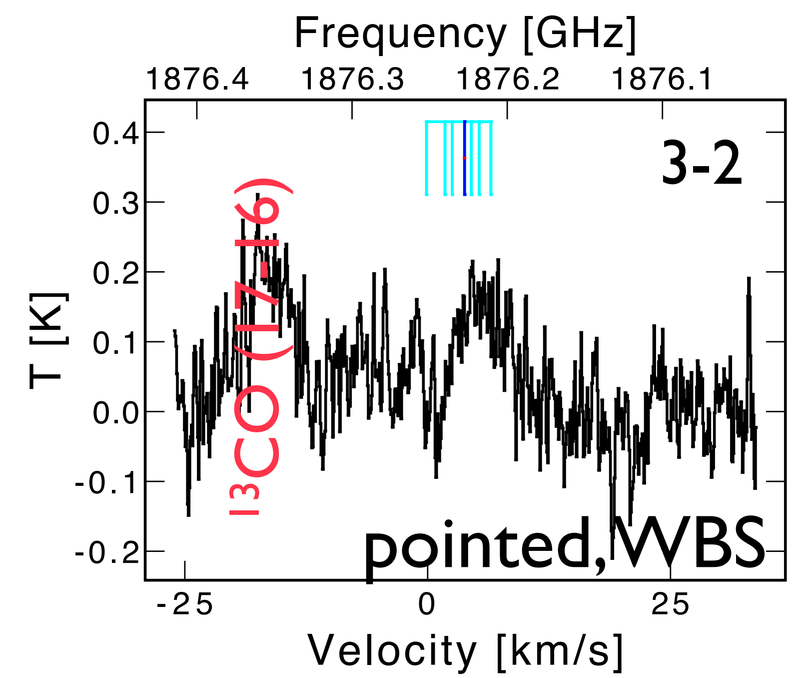
- HDO/H_2O ~ 3.5%, 0.5% and 4.5% in hot corino, outer envelope and photodesorption layer (p.d.l.), resp.
- ≥ 10× ratio in Earth's ocean : if confirmed, need a mechanism to explain the decrease of HDO/H_2O from protostars to comets/planets.
- D_2O absorption due to cold+p.d.l. → D_2O/H_2O ~ 0.1-4×10^{-3} and D_2O/HDO ~ 1-10%, consistent with statistical distribution in Butner et al. 2007.
- → larger sample needed to understand deuteration of water in protostars.

HCl

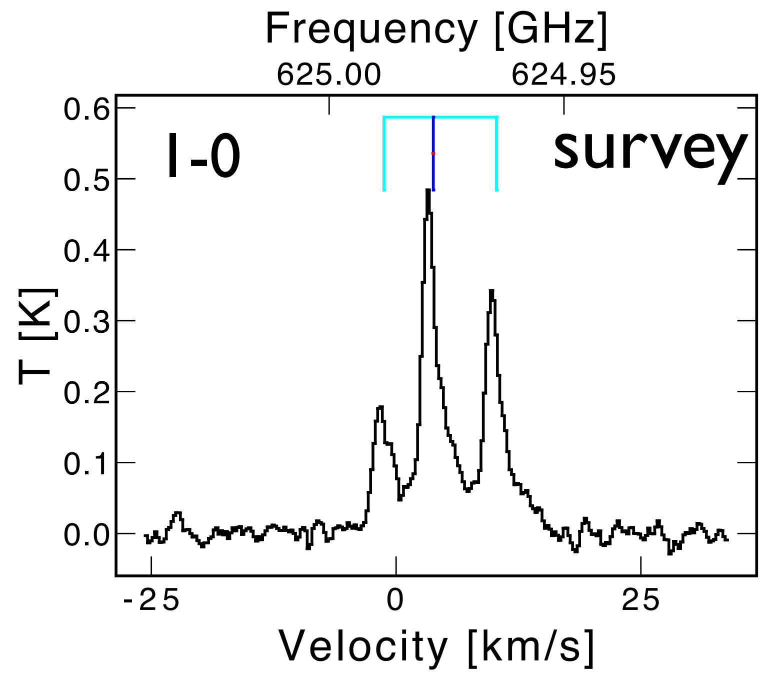
- $H^{35}Cl$

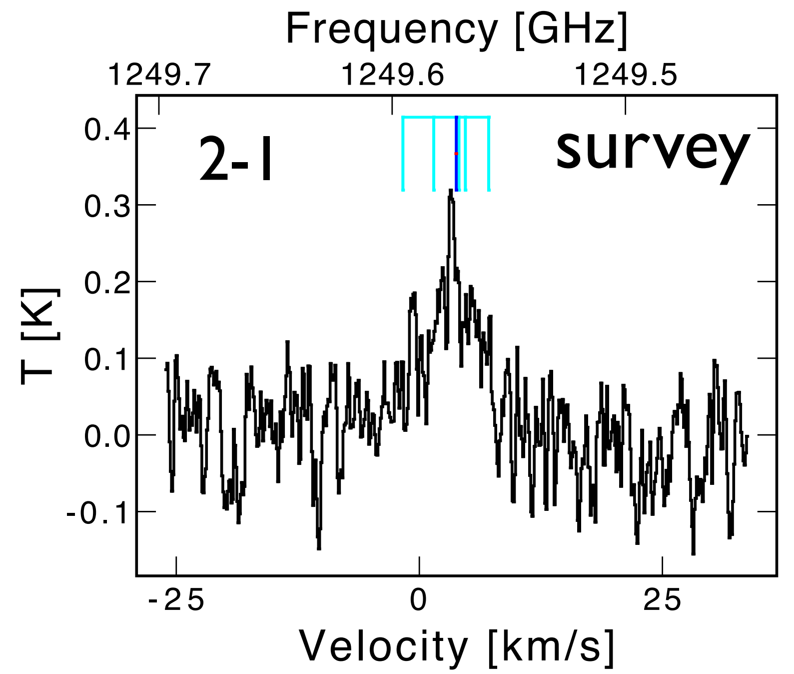




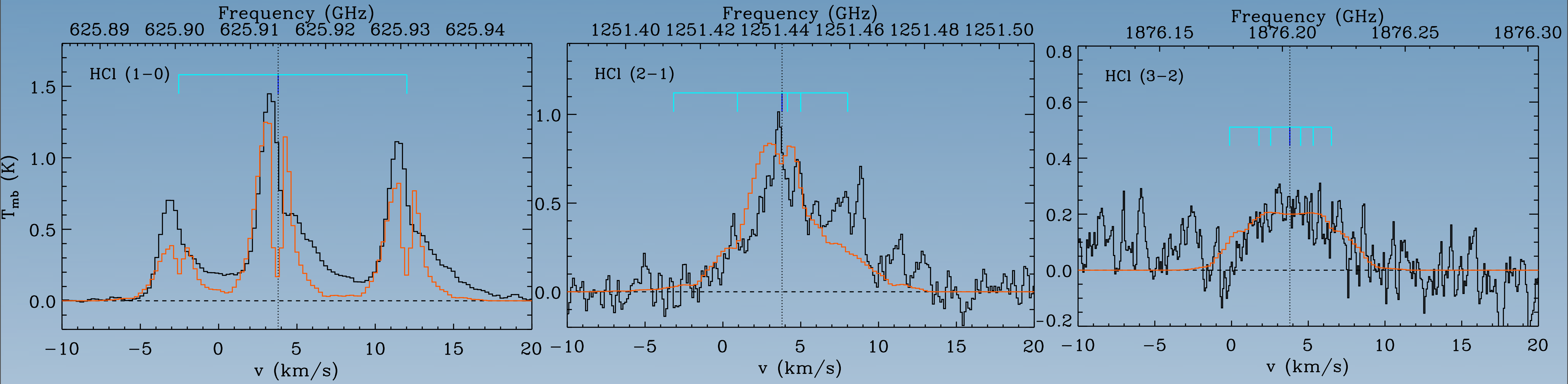


- $H^{37}Cl$

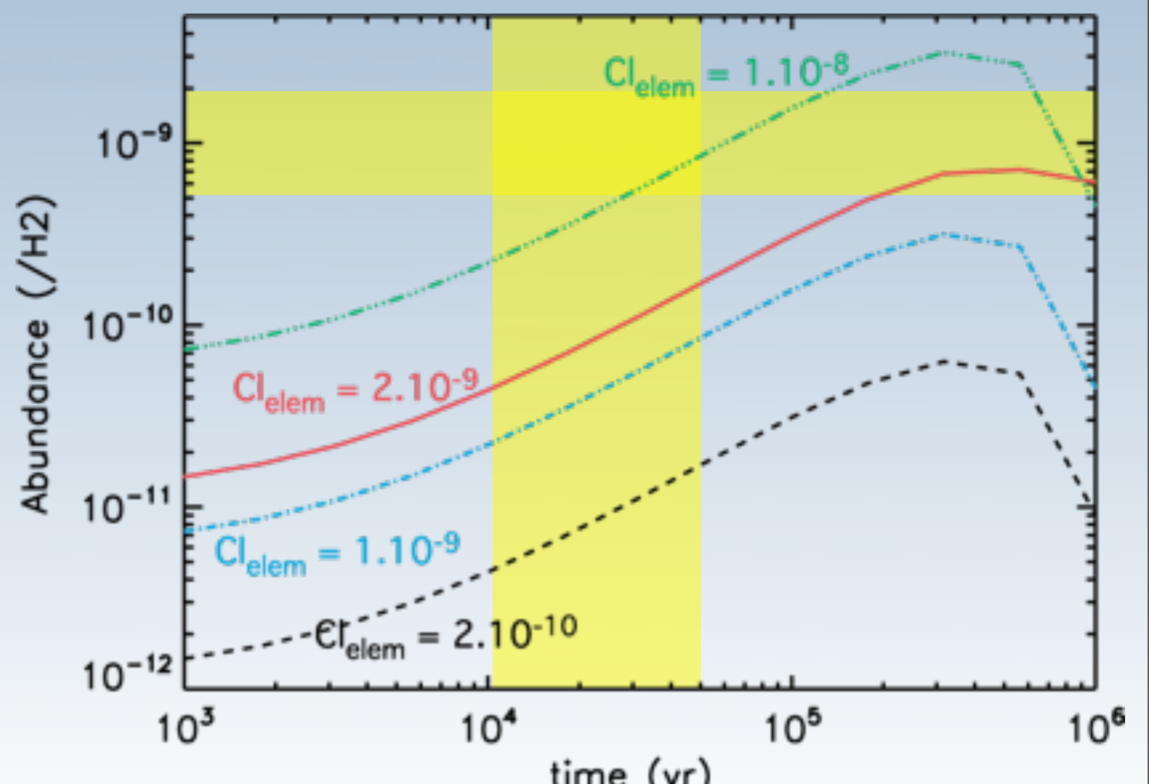




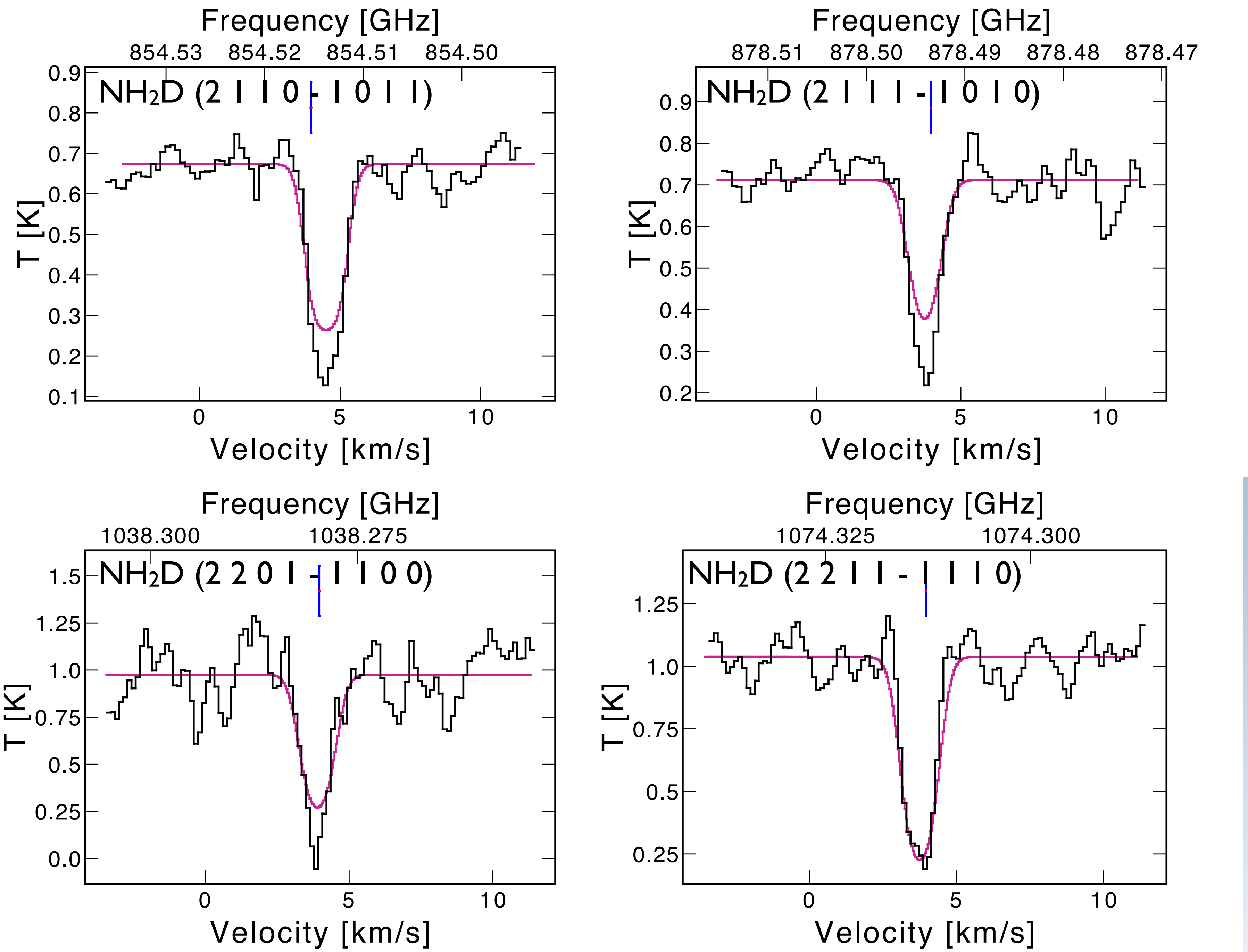
HCl, modeling



- RATRAN (1D) modeling with same physical structure as Coutens et al. 2012, and x(HCl) = 10^{-9}.
- Consistent with predictions by chemical model assuming Cl elemental abundance of 10^{-8} (Nautilus, Wakelam priv. comm.).
- OT2 (P2) proposal to observe 5 low-mass protostars.



NH_2D (2-1)

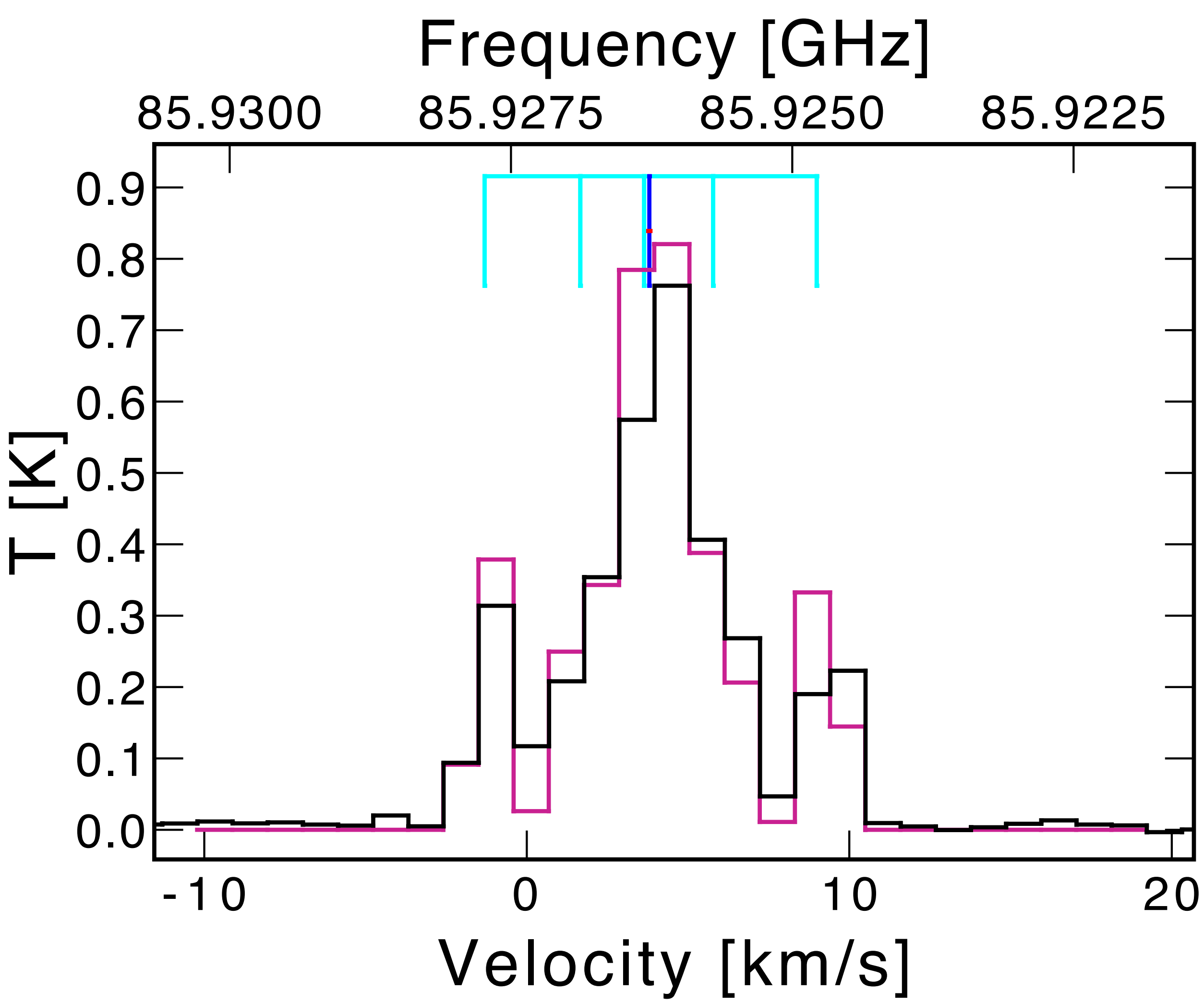


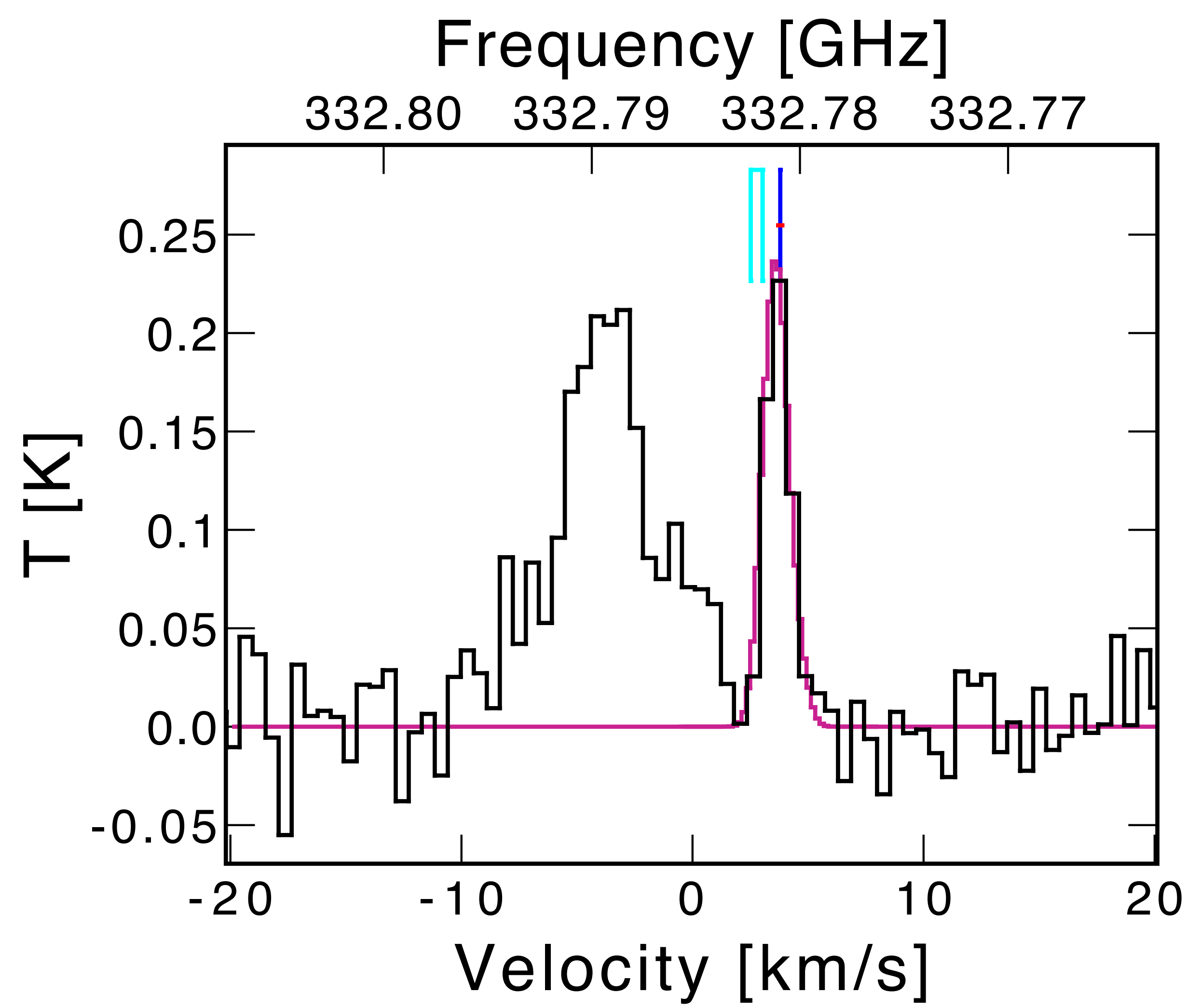
χ^2 minimization:

$N = (1.3 - 3.0)\times10^{14}$ cm^{-2} ;
T_{ex} = 7 - 9 K ;
FWHM = 0.8 - 1.35 km/s

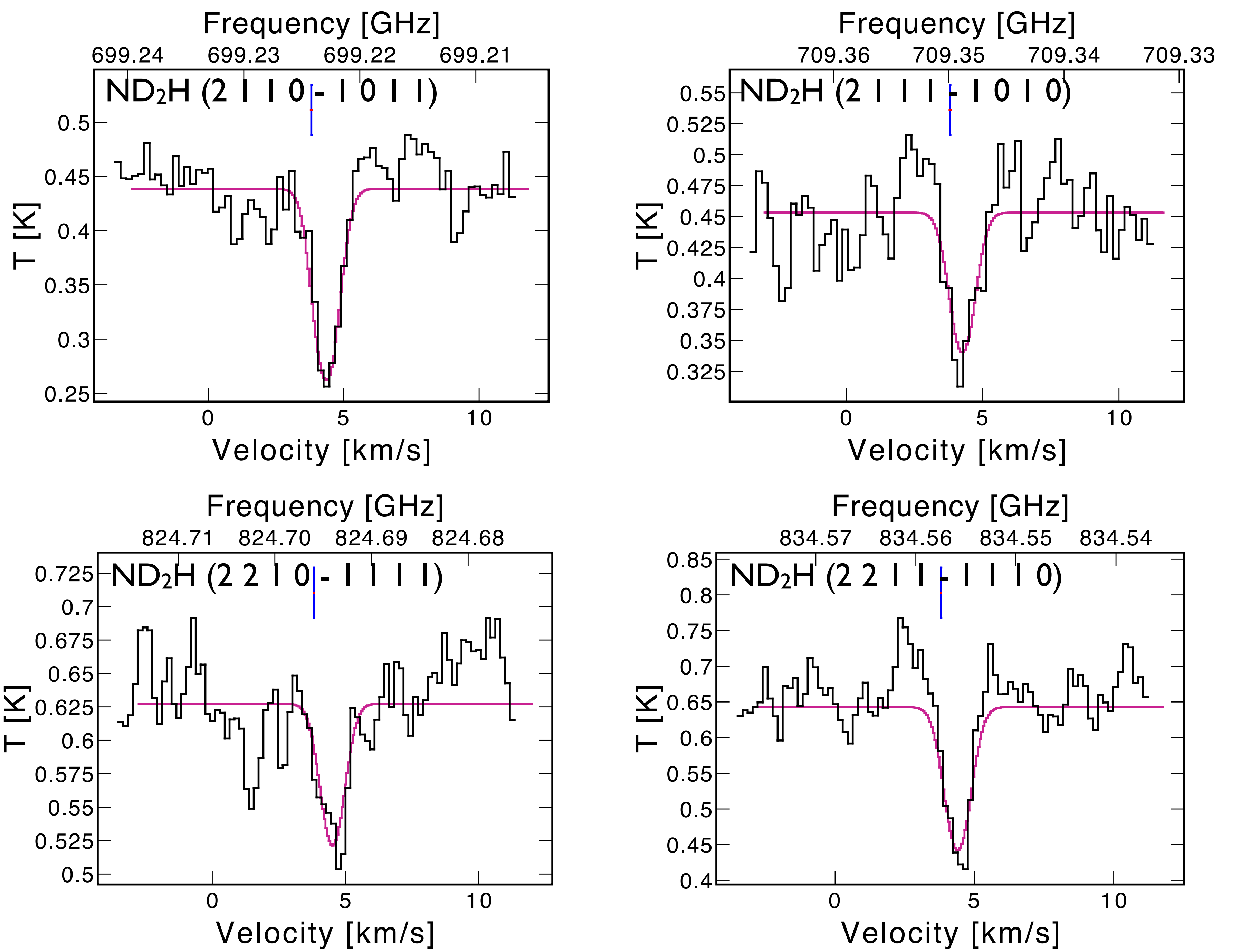
NH_2D from the ground

- Derived column density consistent with value published by van Dishoeck et al. 1995
- LTE model with derived parameters also reproduces well transition detected in TIMASSS.





ND_2H (2-1)



χ^2 minimization:

$N = (0.2 - 3.0)\times10^{14}$ cm^{-2} ;
$T_{ex} = 3 - 7$ K ;
FWHM = 1.0 - 3.0 km/s

Deuterated NH_3

Species	N (10^{14} cm^{-2})	T_{ex} (K)	X/NH_3 (%)
NH_3[a]	200 - 3.5	8 - 10	-
NH_2D	3.0 - 1.3	7 - 9	~ 1 - 40
ND_2H	3.0 - 0.2	3 - 7	~ 1 - 6

[a]From Hily-Blant+ 2010

[b]From Roueff+ 2005 and refs therein ; Models 1-3: n(H_2) ↗, depletion ↗, ionization ↘

Ratio	16293	L134N[b]	L1689N[b]	B1[b]	Models[b]		
					1	2	3
$[NH_2D]/[NH_3]$	~ 0.01-0.4	0.1	0.19	0.23	0.05	0.1	0.15
$[ND_2H]/[NH_2D]$	> 0.06	0.5	0.22	0.15	0.03	0.07	0.08

- Only a few studies of ND_2H, e.g., Roueff+2000, 2005, Lis+2006. Mostly in PSCs ; non-detections in high-mass protostars (e.g., Pillai+2007).
- Ratios in IRAS16293 consistent with model predictions of Roueff+2005. See also Bacmann+ 2010 for NH, ND.
- Next step: detailed radiative transfer using collisional rates (Machin&Roueff 2006 for NH_2D, Wiesenfeld+2011 for ND_2H).

Summary and perspectives

- HIFI survey of the low-mass protostars IRAS16293 contributed to:
  - explore parameter space of spectroscopic parameters, in particular high excitation levels
  - confirm/reveal trends such as FWHM ↗ as E_{up} ↗
  - perform more accurate modeling owing to the constraints provided by the numerous detected transitions of a given species (e.g. HDO)
  - study of "new" species, e.g., HCl, CH
  - study of deuteration, e.g., of NH, NH_2, NH_3, H_2O.
- Full (CHESS+TIMASSS) survey shows ~ equal contribution (w/i factor of 3) from several species: H_2O, HCN, HCO^+, CH_3OH, H_2CO, CS, SO, SO_2.
- Perspectives:
  - more to come from more sophisticated analysis of current data.
  - lots of interesting follow-up observations to be done with ground-based single-dish and interferometers.