Deuterated water in low-mass protostars : NGC 1333 IRAS 4A/4B and IRAS 16293-2422

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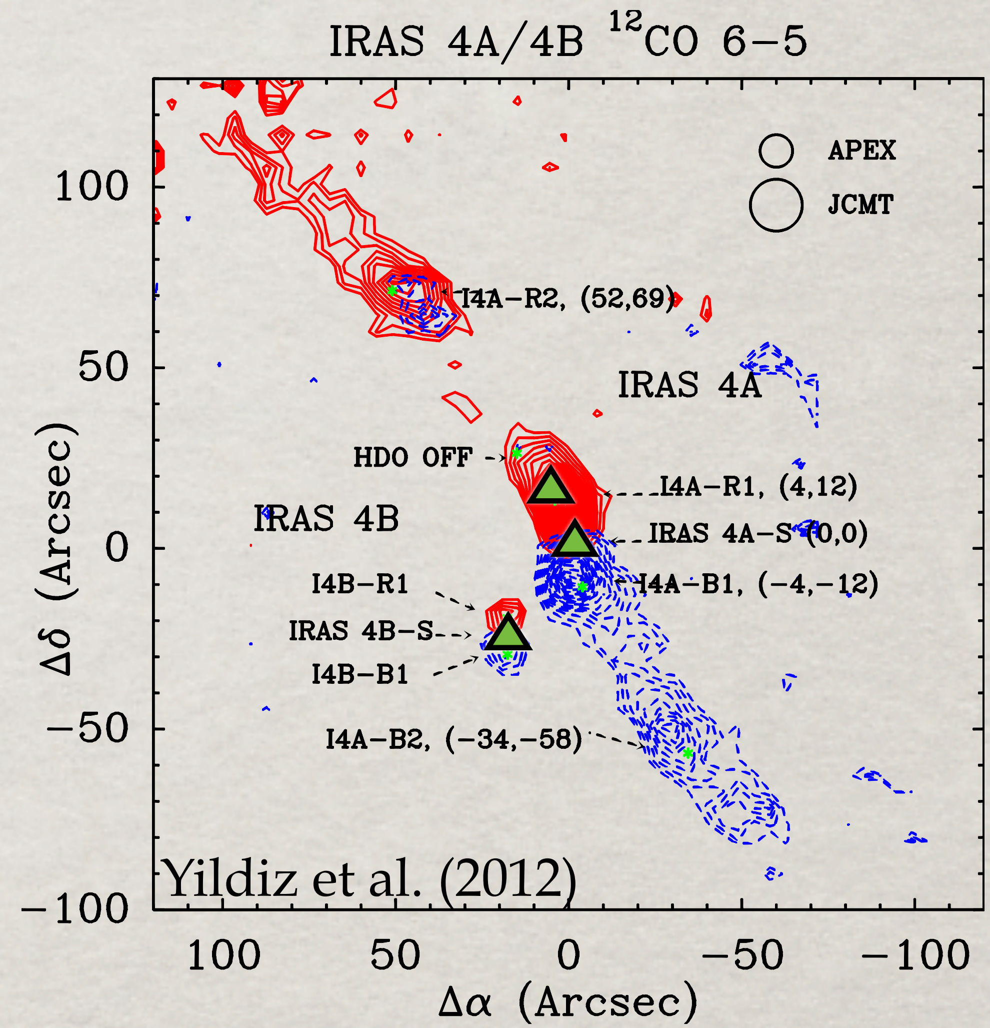
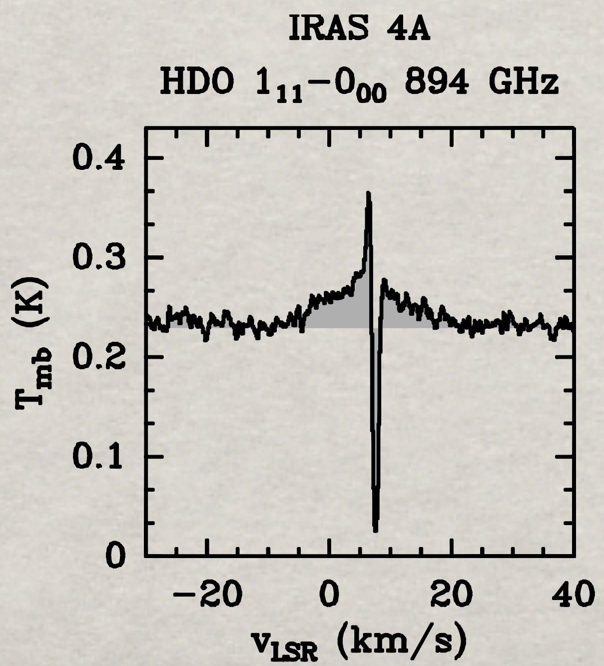
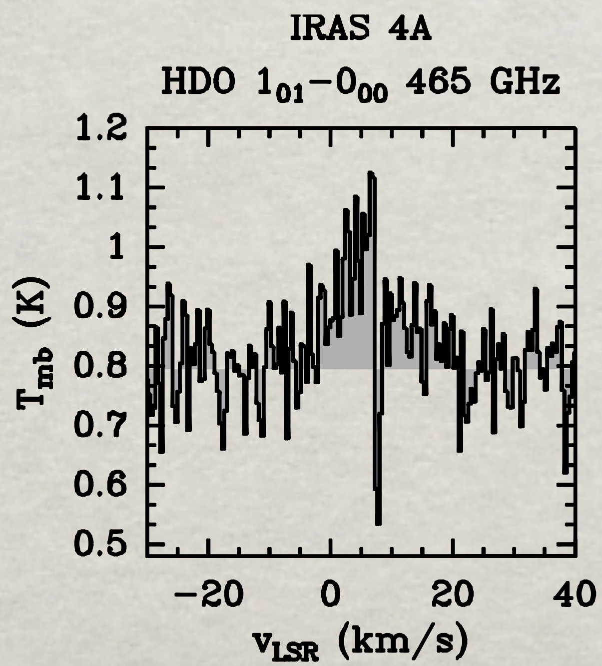
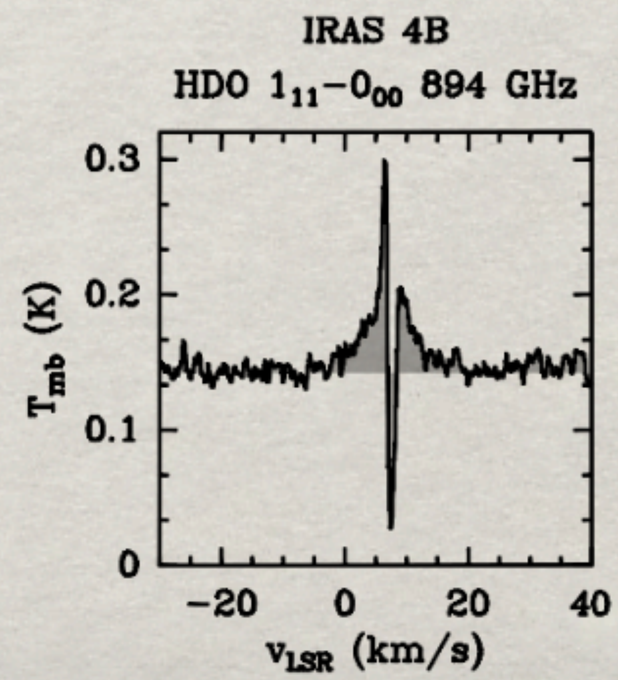
Deuterated water in NGC 1333 IRAS 4

Fréquence (GHz)	$J_{\mathrm{Ka,Kc}}$	E_{up}/k (K)	A_{ij} (s^{-1})	Télescope	Lobe ($''$)
NGC 1333 IRAS 4A					
80.5783	$1_{1,0}$-$1_{1,1}$	47	1.32×10^{-6}	IRAM-30m	31.2
225.8967	$3_{1,2}$-$2_{2,1}$	168	1.32×10^{-5}	IRAM-30m	11.1
241.5616	$2_{1,1}$-$2_{1,2}$	95	1.19×10^{-5}	IRAM-30m	10.4
464.9245	$1_{0,1}$-$0_{0,0}$	22	1.69×10^{-4}	JCMT	10.8
599.9267	$2_{1,1}$-$2_{0,2}$	95	3.45×10^{-3}	HIFI 1b	35.9
893.6387	$1_{1,1}$-$0_{0,0}$	43	8.35×10^{-3}	HIFI 3b	24.1
Flot de NGC 1333 IRAS 4A					
599.9267	$2_{1,1}$-$2_{0,2}$	95	3.45×10^{-3}	HIFI 1b	35.9
893.6387	$1_{1,1}$-$0_{0,0}$	43	8.35×10^{-3}	HIFI 3b	24.1
NGC 1333 IRAS 4B					
225.8967	$3_{1,2}$-$2_{2,1}$	168	1.32×10^{-5}	IRAM-30m	11.1
241.5616	$2_{1,1}$-$2_{1,2}$	95	1.19×10^{-5}	IRAM-30m	10.4
464.9245	$1_{0,1}$-$0_{0,0}$	22	1.69×10^{-4}	CSO	16.5
599.9267	$2_{1,1}$-$2_{0,2}$	95	3.45×10^{-3}	HIFI 1b	35.9
893.6387	$1_{1,1}$-$0_{0,0}$	43	8.35×10^{-3}	HIFI 3b	24.1









Deuterated water in NGC 1333 IRAS 4

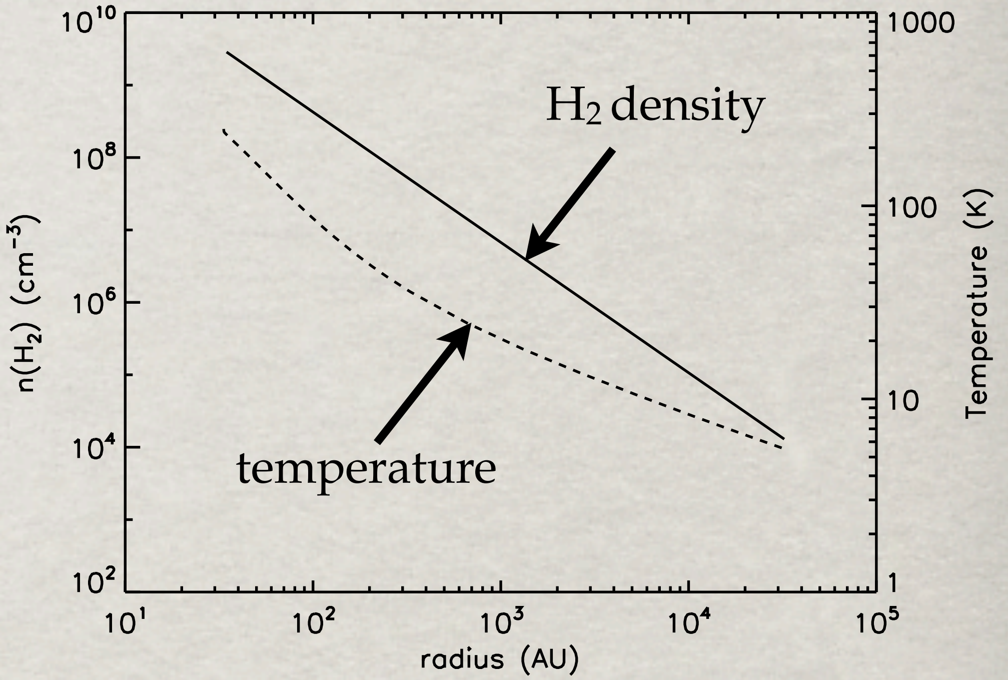
- **RATRAN modeling**

- **Subtraction of the broad outflow component present on the observations of the fundamental transitions :**
  FWHM ~ 16 km/s for IRAS 4A
  FWHM ~ 10 km/s for IRAS 4B

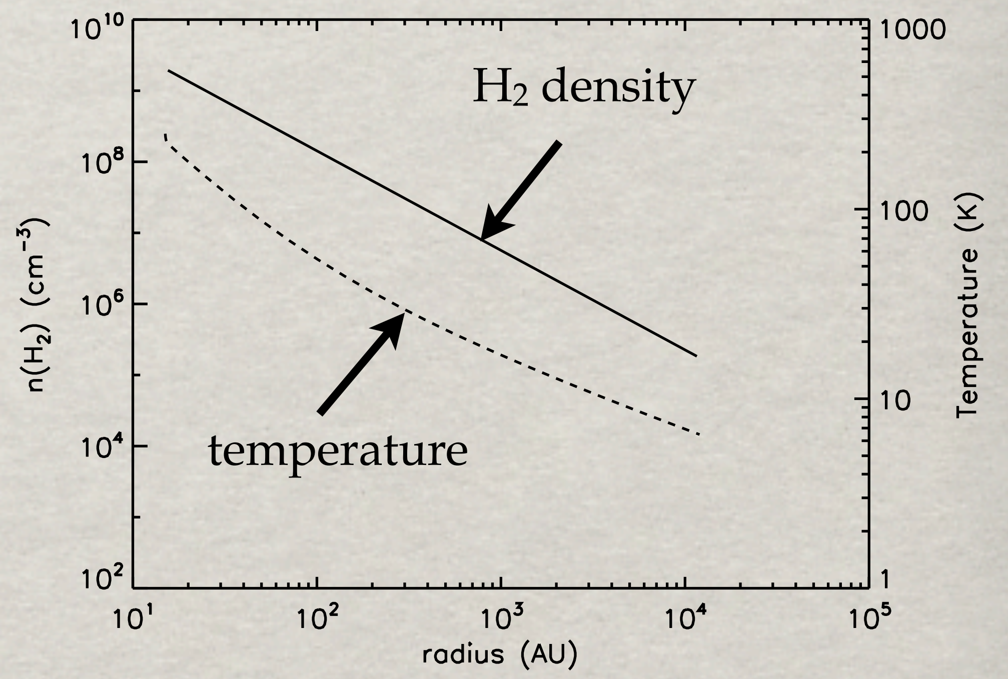
- **Density and temperature profiles determined by Kristensen et al. (2012)**

- **Velocity profiles: vr = $\sqrt{(2GM_*/r)}$**
  IRAS 4A : M_* = 0.5 M_{sol} (Maret et al. 2005, di Francesco et al. 2001)
  IRAS 4B : M_*? → **free parameter**

NGC 1333 IRAS 4A

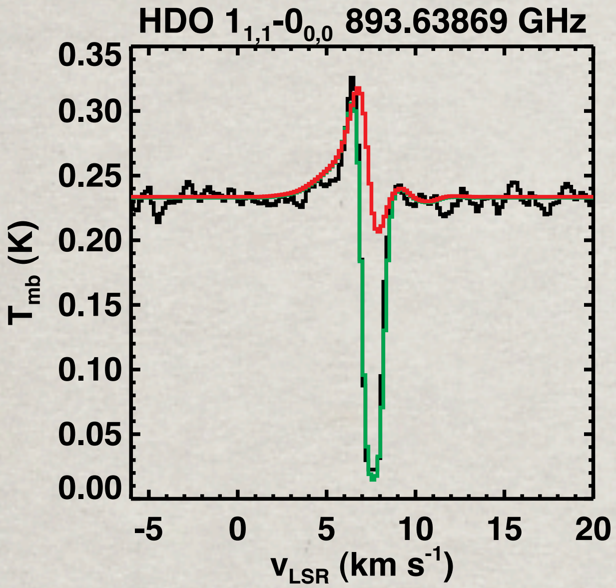


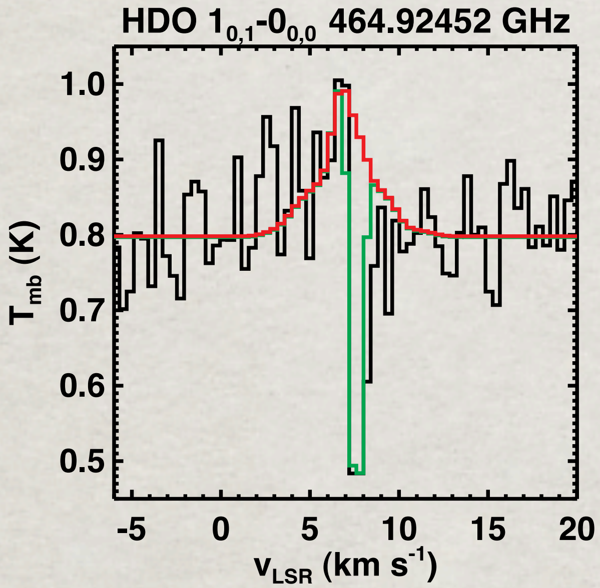
NGC 1333 IRAS 4B



HDO modeling in NGC 1333 IRAS 4A

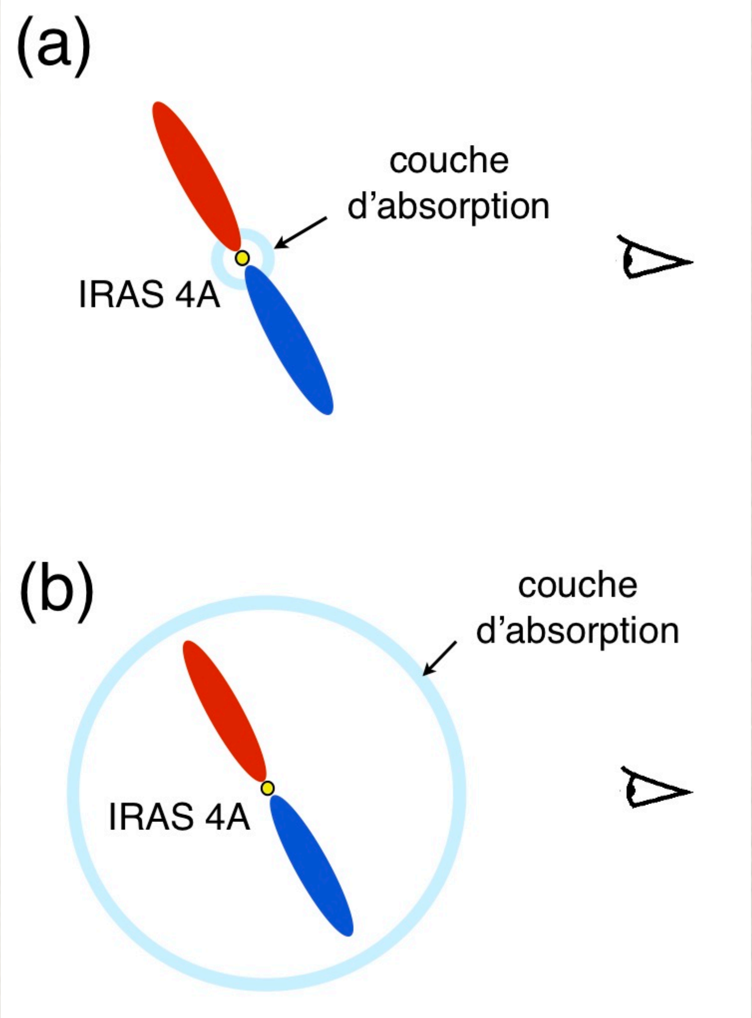
Adding an absorbing layer is needed to reproduce the absorption lines at 894 and 465 GHz : N(HDO)$_{abs}$ ~ 1.4 x 10^{13} cm^{-2}





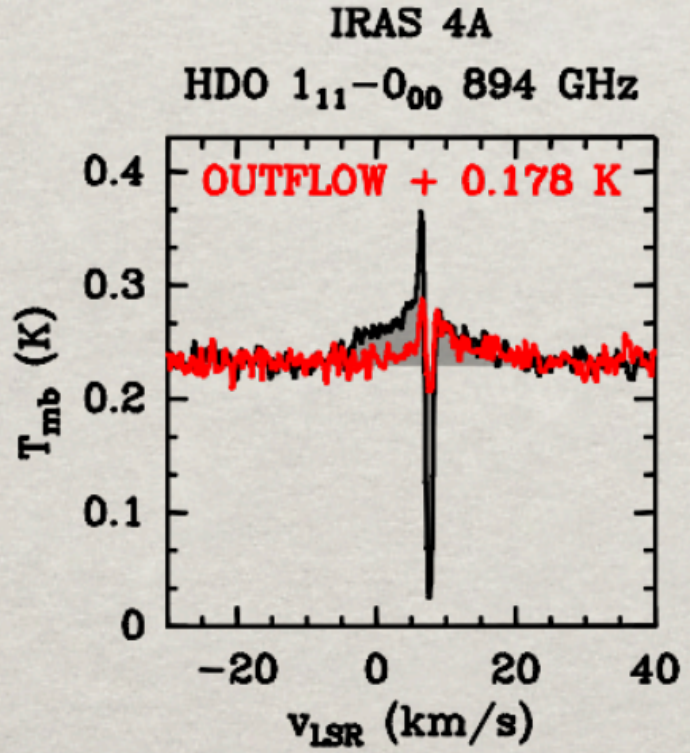
without adding an absorbing layer

adding a foreground absorbing layer



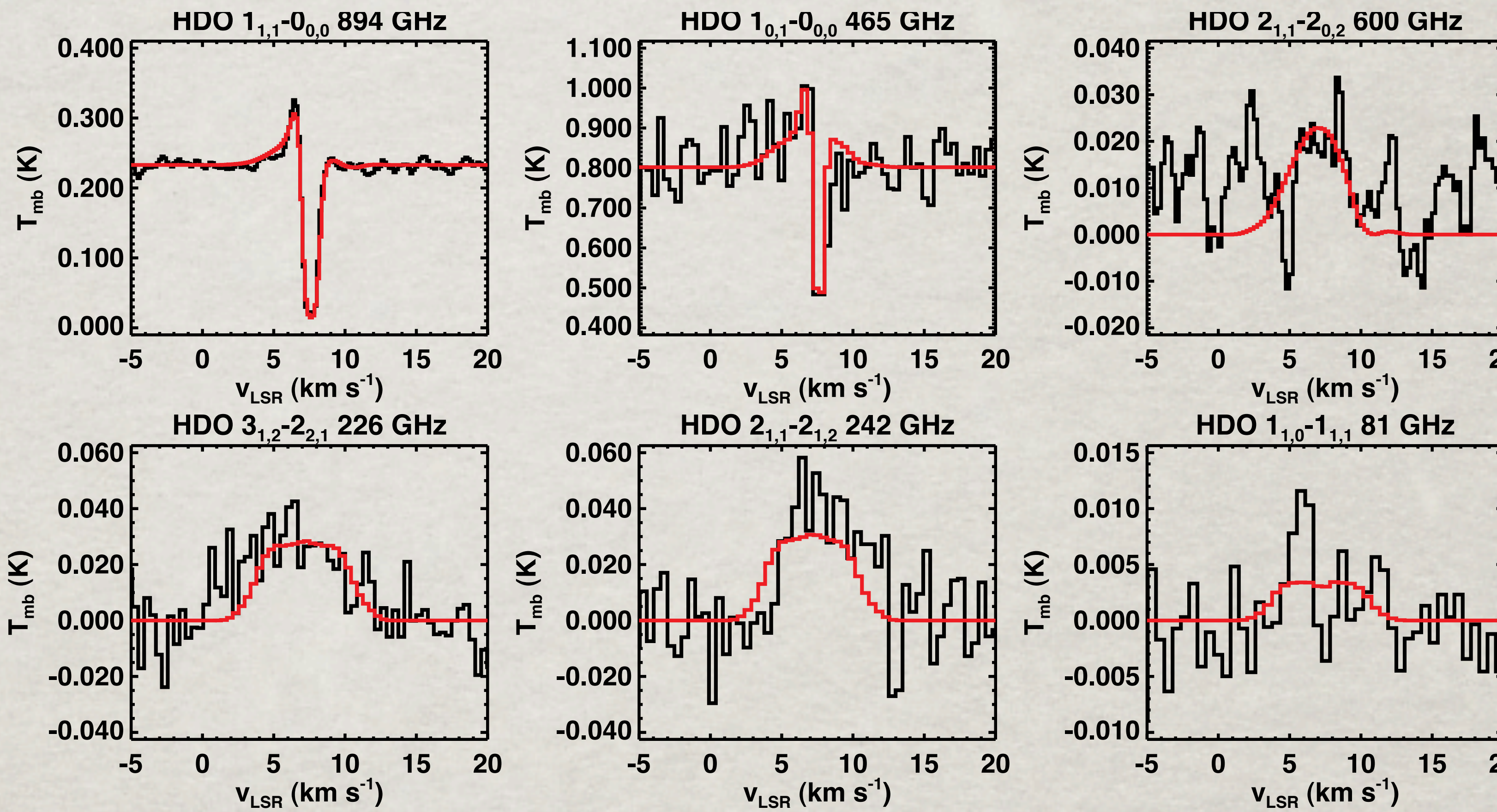
- absorption observed towards an outflow position

- extended absorbing layer

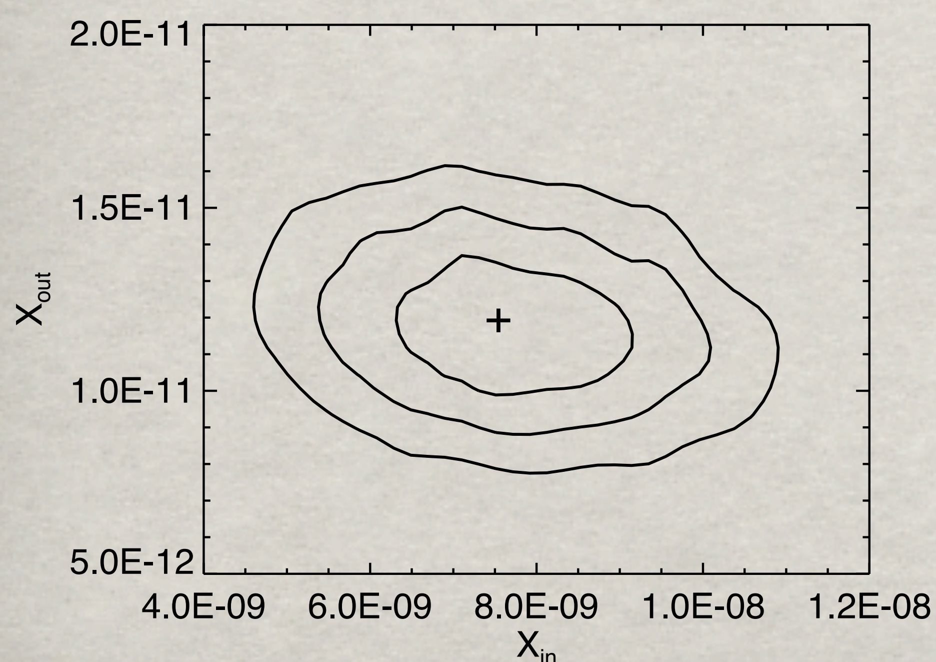


HDO modeling in NGC 1333 IRAS 4A

Best-fit :
$X_{in} = 7.5 \times 10^{-9}$
and
$X_{out} = 1.2 \times 10^{-11}$

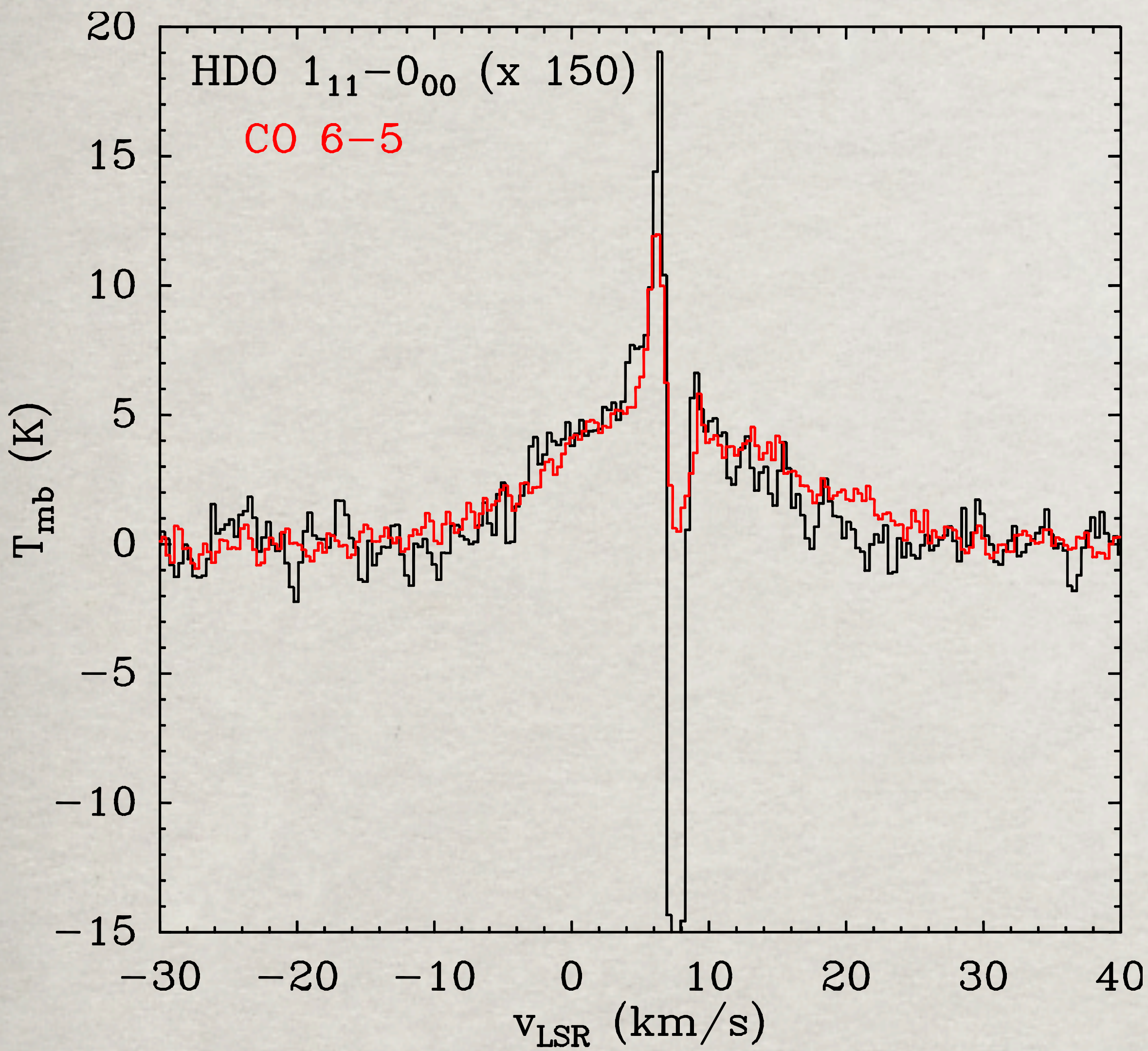


3σ : $4.5 \times 10^{-9} \leq X_{in} \leq 1.1 \times 10^{-8}$
$8 \times 10^{-12} \leq X_{out} \leq 1.6 \times 10^{-11}$



- **What about H_2O ?**
- **Comparison of the HDO/H_2O ratios with the interferometric results**

HDO modeling in NGC 1333 IRAS 4A



OUTFLOWS

- **profiles of the broad component compared with other molecules tracing the outflows**

- **similarity between the HDO and CO line profiles**

- **RADEX modeling used with the excitation conditions derived by Yildiz et al. (2012) for CO : $n(H_2) \sim 3 \times 10^5$ cm^{-3}, $T \sim 100 - 150$ K**

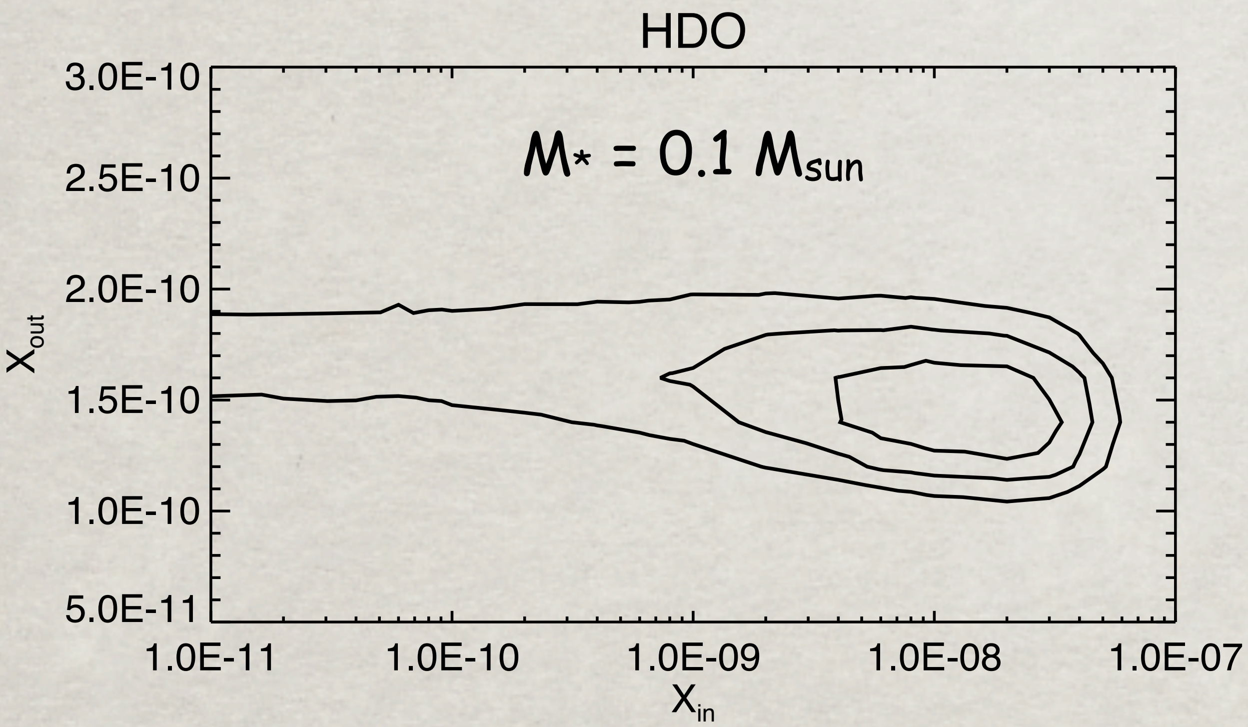
- **$N(HDO) \sim 2 - 4 \times 10^{13}$ cm^{-2}**

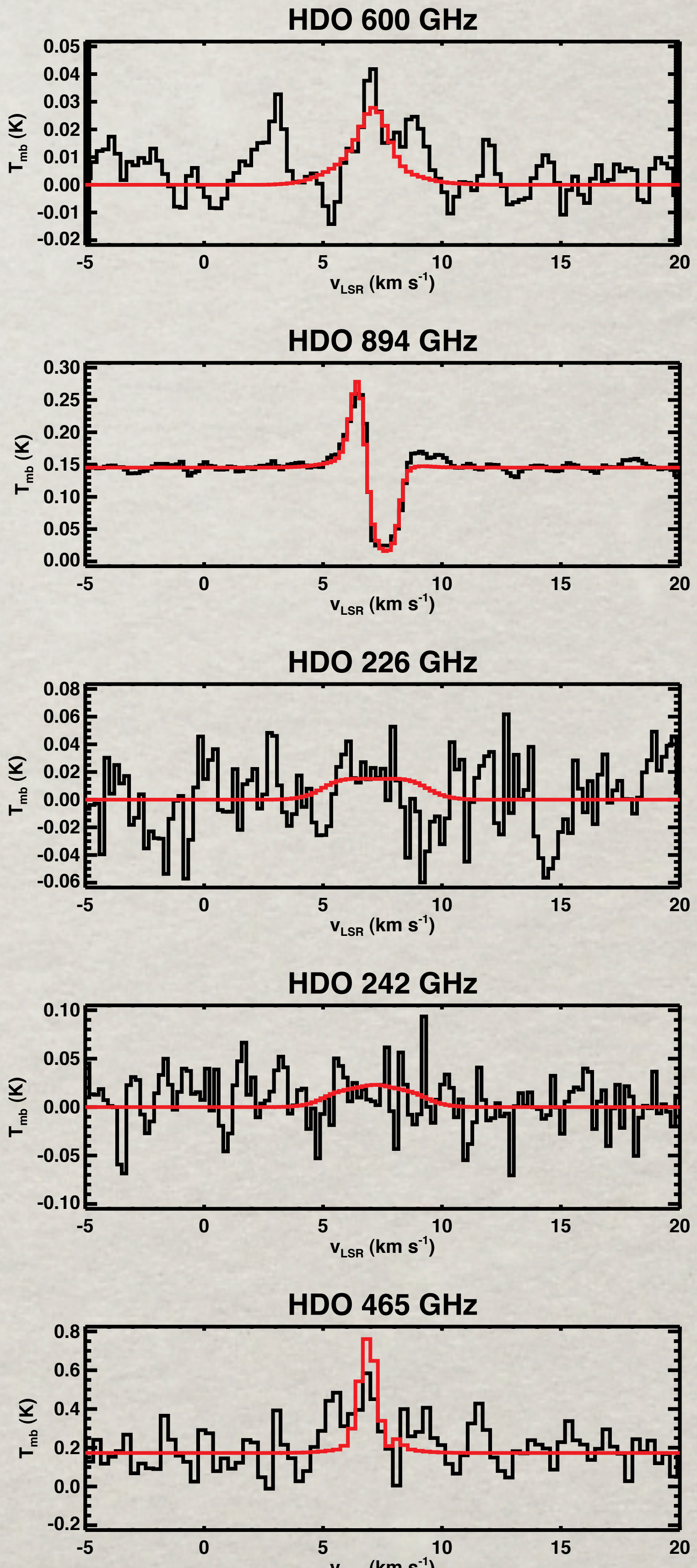
- **$X(HDO) \sim 7 \times 10^{-10} - 1.9 \times 10^{-9}$ using $N(H_2) \sim 2.1 - 2.8 \times 10^{22}$ cm^{-2} (Yildiz et al. 2012)**

- **Estimation of the HDO/H_2O ratio in the outflows?**

HDO modeling in NGC 1333 IRAS 4B

- $v_r = \sqrt{(2GM_*/r)}$ with M_* ?
- grid with 3 parameters: X_{in}, X_{out}, M_*
- absorbing layer N(HDO) ~ 1.4×10^{13} cm^{-2}





Best-fit :
$X_{in} = 2 \times 10^{-8}$
$X_{out} = 1.4 \times 10^{-10}$
$M_* = 0.1\ M_{sun}$

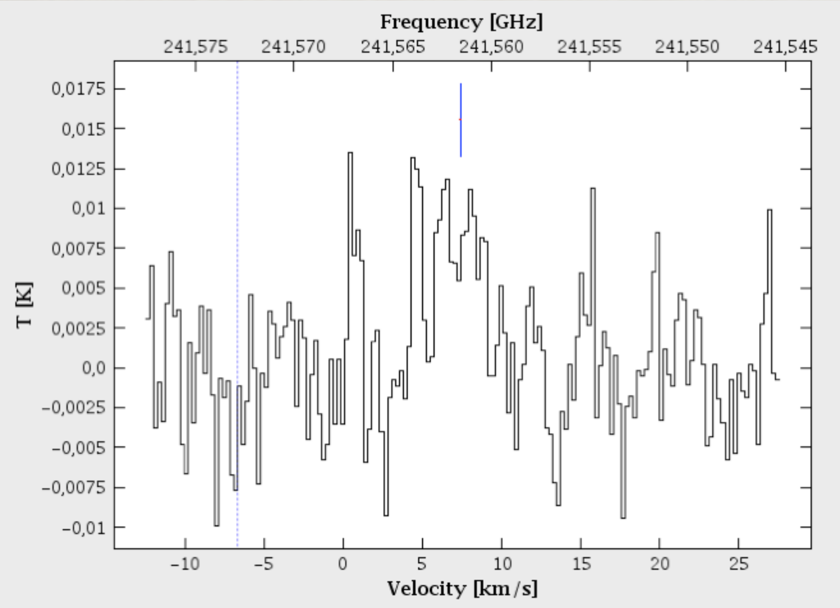
3σ :
$X_{in} \leq 6 \times 10^{-8}$
$1 \times 10^{-10} \leq X_{out} \leq 2 \times 10^{-10}$
$M_* = 0.1\ M_{sun}$

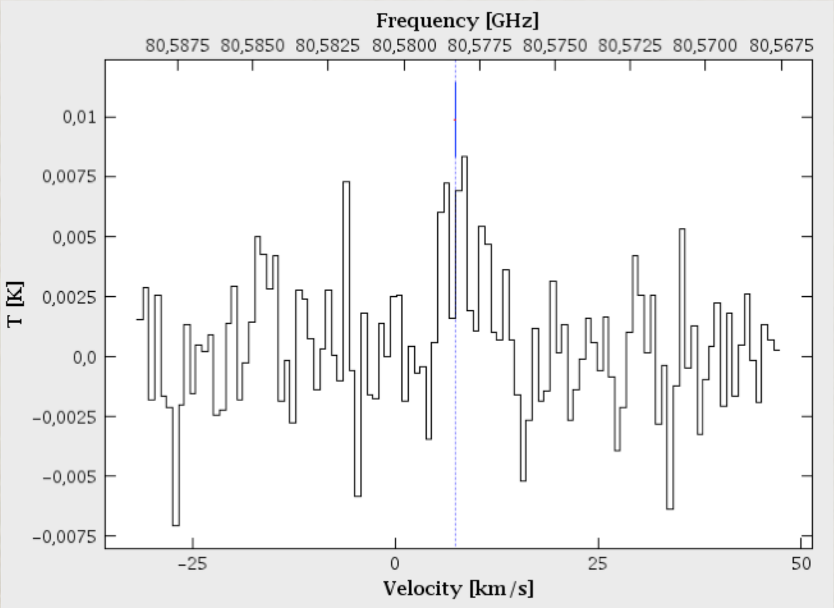
Upper limit on the inner abundance consistent with the undetection of the 226 GHz line with SMA (Jørgensen & van Dishoeck 2010)

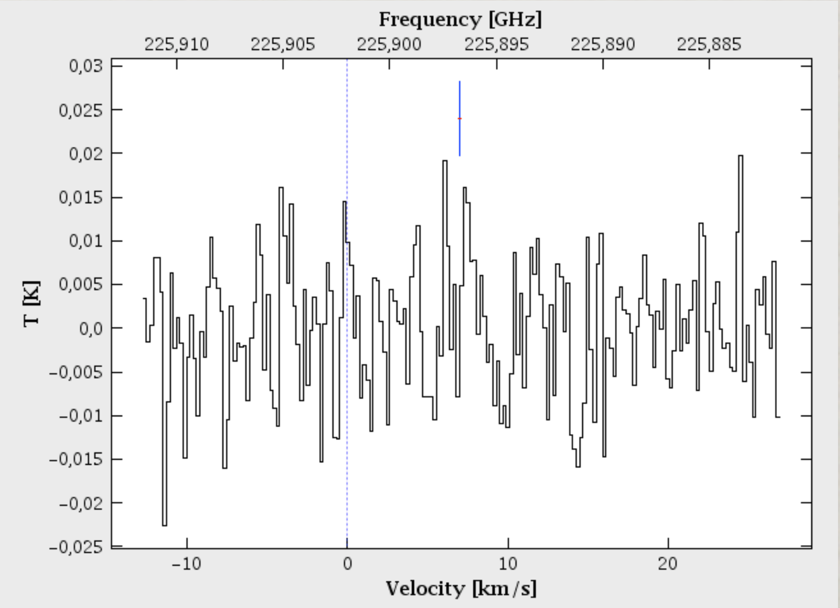
Deuterated water in NGC1333 IRAS4B

New observations

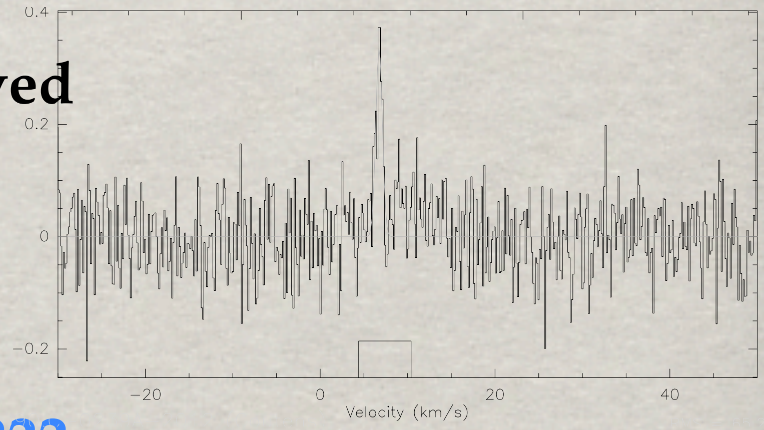
- **IRAM-30m observations :**
  241 GHz line (Eup = 95 K), 81 GHz line (Eup = 47 K) & 226 GHz line (Eup = 170 K)







- **APEX observations at 465 GHz : proposal accepted, 5 hours observed instead of the 15h required (5σ detection)**



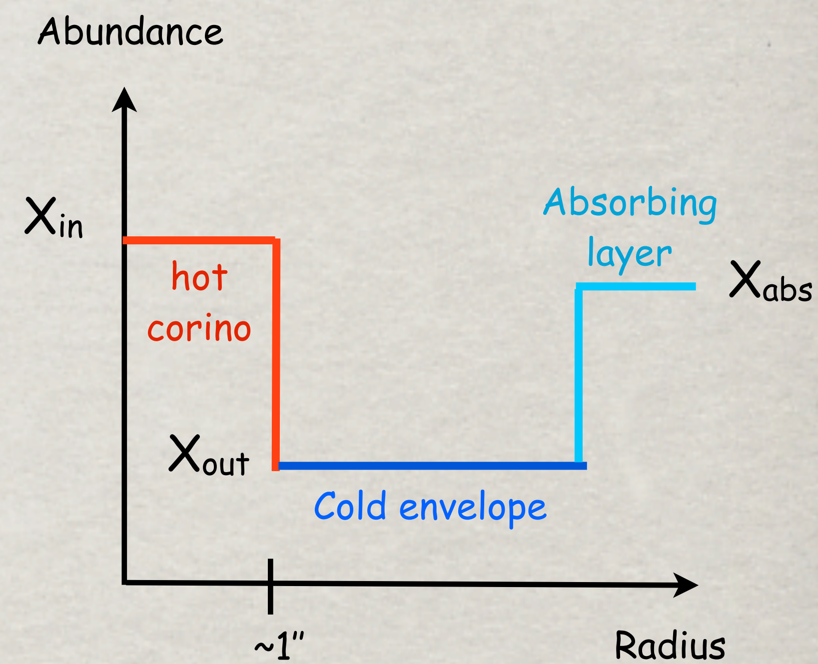
- **Improvement of the modeling with the new observations ?**

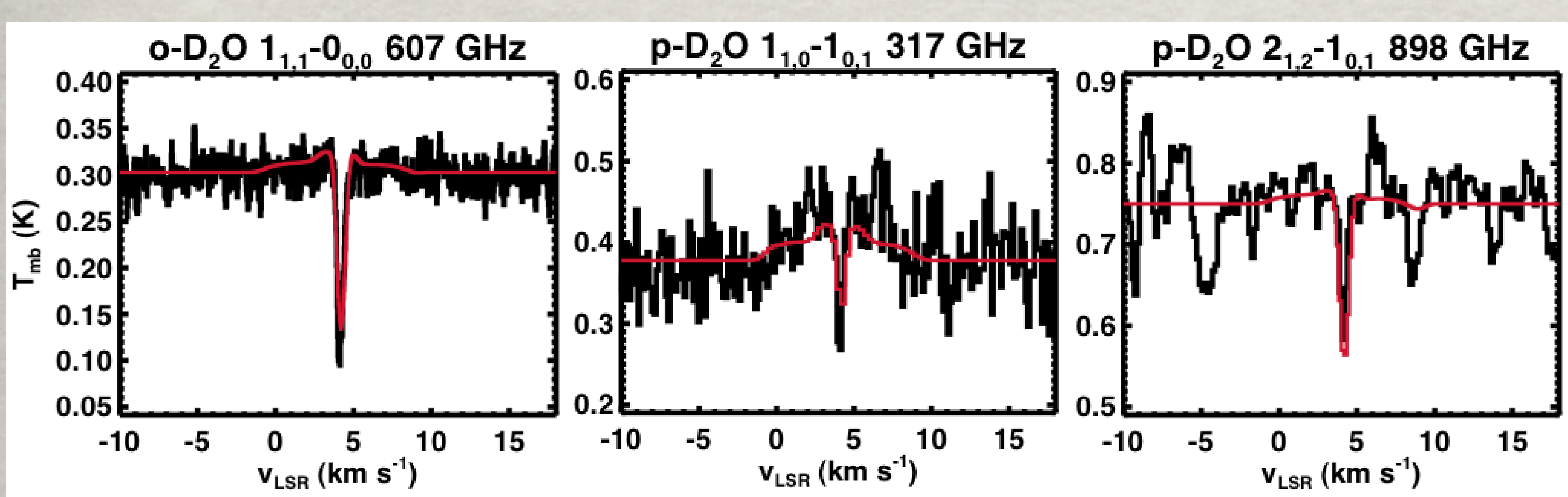
Add IRAS 4B to the paper about IRAS4A???

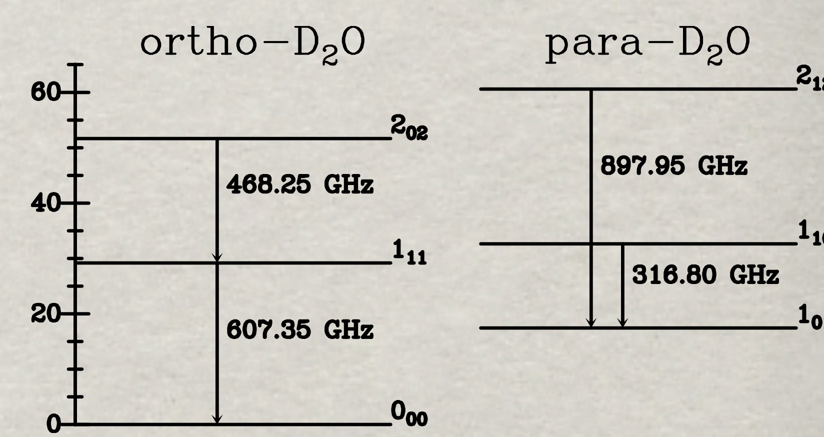
Deuterated water in IRAS16293-2422

New D_2O analysis

- RATRAN modeling similar to HDO and $H_2^{18}O$ (Coutens et al. 2012) :
- No prediction of D_2O absorption lines without adding an absorbing layer to the structure of Crimier et al. (2010)
- adding an absorbing layer produces an absorbing line at 898 GHz consistent with observations
- $N(D_2O)_{abs} = 2.5 \times 10^{12}$ cm^{-2}
- ortho/para $(D_2O)_{abs} \sim 1.3$

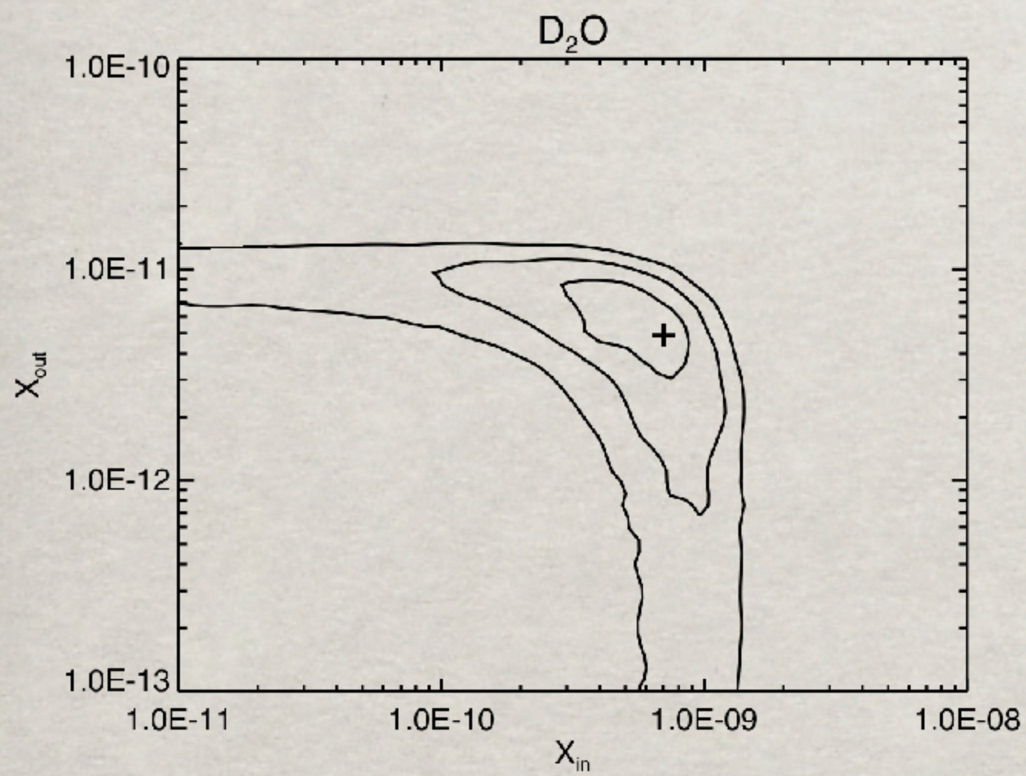






Deuterated water in IRAS16293-2422

	Hot corino		Outer envelope		Photodesorption layer
	Best-fit	3σ	Best-fit	3σ	$A_V \sim 1 - 4$ mag
HDO^a	1.8×10^{-7}	$1.4 - 2.4 \times 10^{-7}$	8×10^{-11}	$5.5 - 10.6 \times 10^{-11}$	$\sim 0.6 - 2.4 \times 10^{-8}$
$H_2O^{a,b}$	1×10^{-5}	$4.7 - 40.0 \times 10^{-6}$	1.5×10^{-8}	$7.0 - 22.5 \times 10^{-9}$	$\sim 1.3 - 5.3 \times 10^{-7}$
D_2O	7×10^{-10}	$\leq 1.3 \times 10^{-9}$	5×10^{-12}	$\leq 1.3 \times 10^{-11}$	$\sim 6.6 - 27 \times 10^{-10}$
HDO/H_2O	1.8%	0.4% – 5.1%	0.5%	0.3% – 1.5%	$\sim 4.8\%^c$
D_2O/HDO	0.4%	$\leq$ 0.9%	6.3%	$\leq$ 23%	$\sim 10.8\%^c$
D_2O/H_2O	0.007%	$\leq$ 0.03%	0.03%	$\leq$ 0.2%	$\sim 0.5\%^c$



▸ **D_2O/H_2O ratio lower in the hot corino than in the absorbing layer :**

- different mechanisms of water formation in the two regions ?

- isotopic exchange between water molecules during heating of the grain surfaces (~ 150 K), leading to a decrease of the D_2O abundance (Smith et al. 1997, Dulieu et al. 2010) ?

- self shielding in the hot corino ? H_2O less photodissociated ?

▸ **Comparison with the grain surface chemical model of Cazaux et al. (2011) : D/H ratios in agreement with dense gas (~10^4 cm^{-3}) and warm dust (~20 K)**