Water in pre-stellar cores

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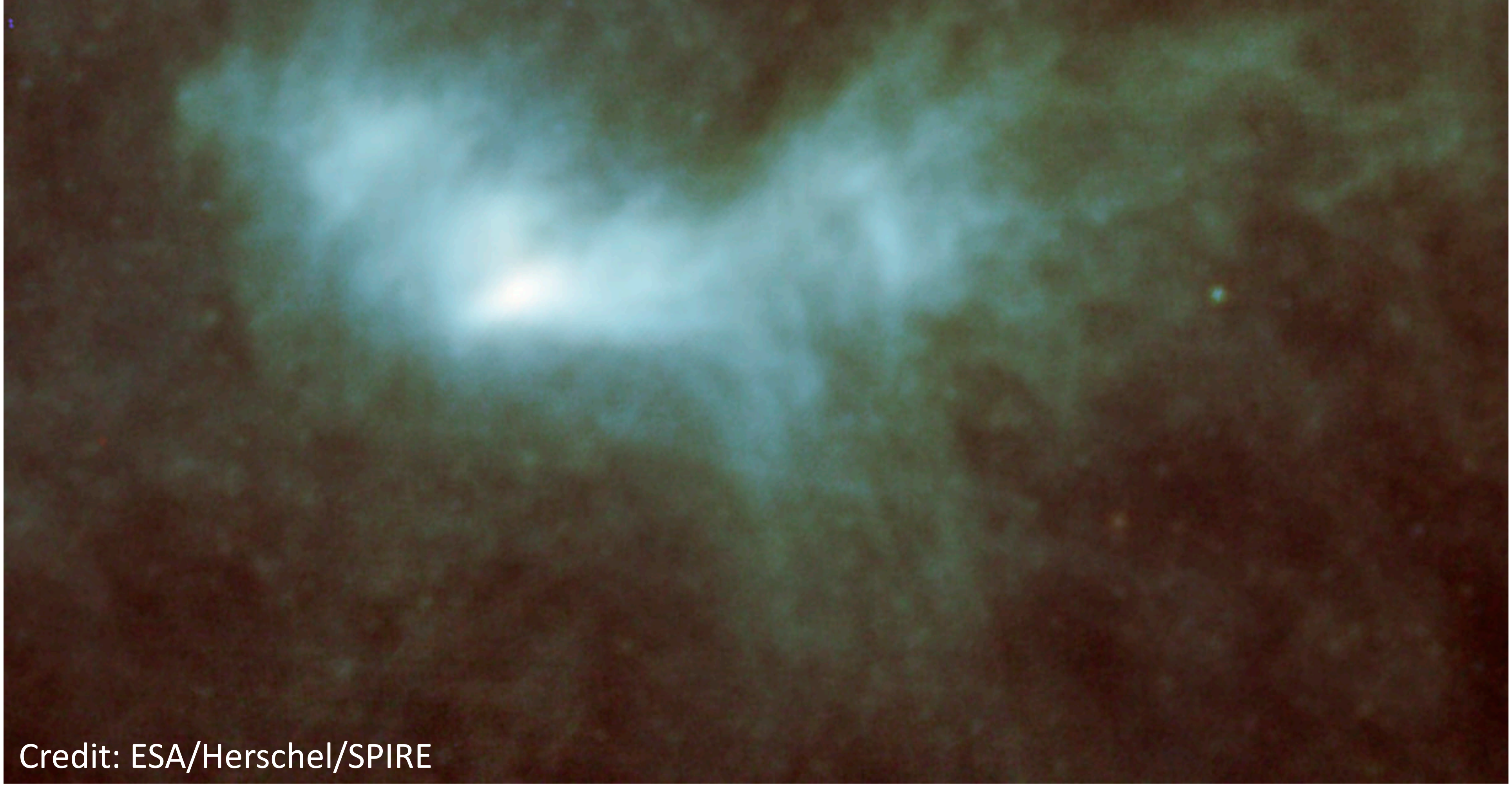


Credit: ESA/Herschel/SPIRE

Together with…

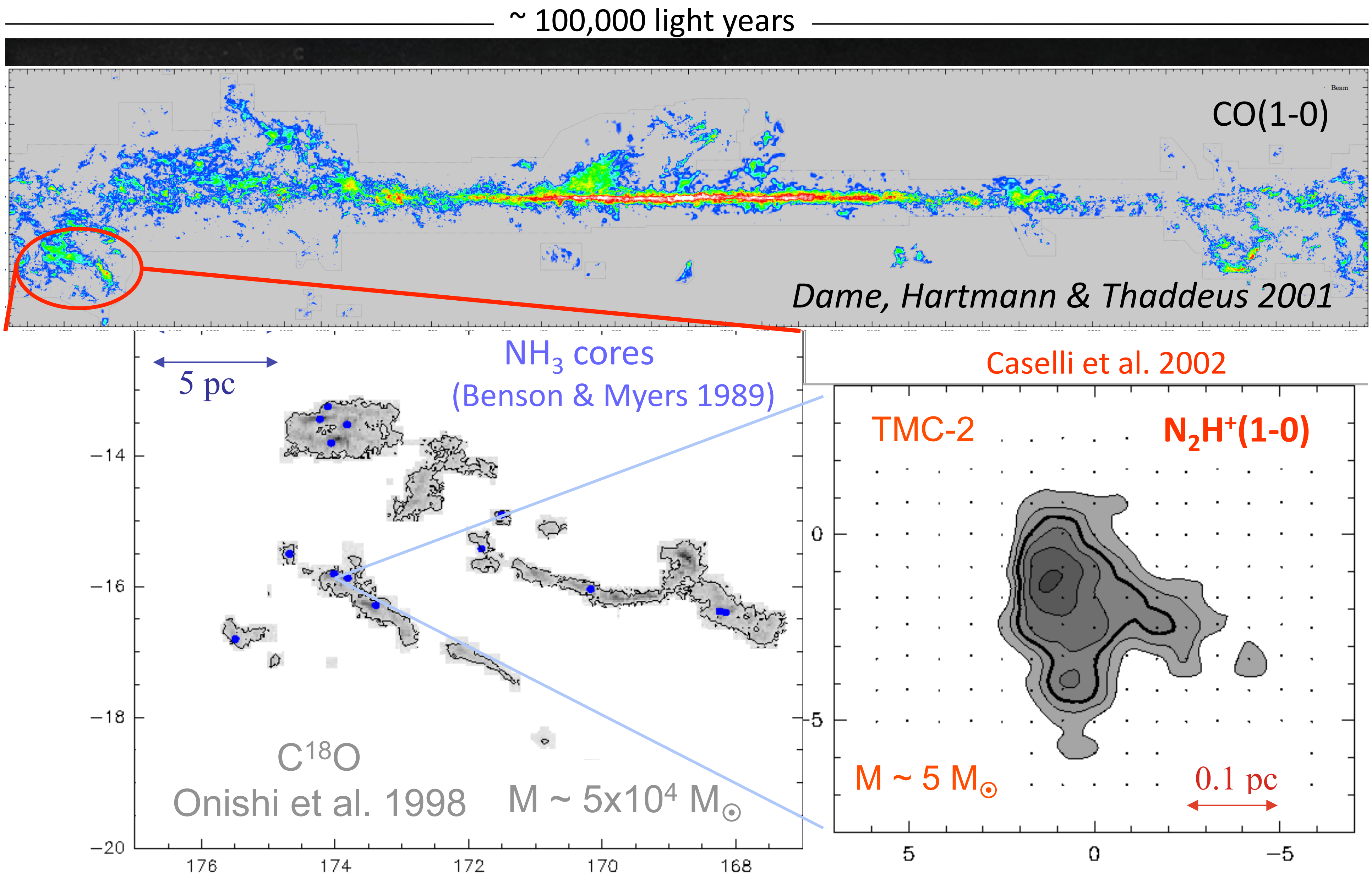
Aikawa (Kobe)
Bergin (Michigan)
Codella (INAF/Arcetri)
Keto (CfA)
Kristensen (CfA)
Nisini (INAF/Roma)
Pagani (LERMA)
Tafalla (Madrid)
van der Tak (Groningen)
van Dishoeck (Leiden)
Walmsley (INAF/Arcetri)
Yildiz (JPL)
…

Credit: ESA/Herschel/SPIRE

Outline

- Introduction: pre-stellar cores
- Detection of water vapor:
  - Previous attempts
  - WISH 2010
  - WISH 2011
- What have we learned?

Molecular clouds, dense cores and star formation



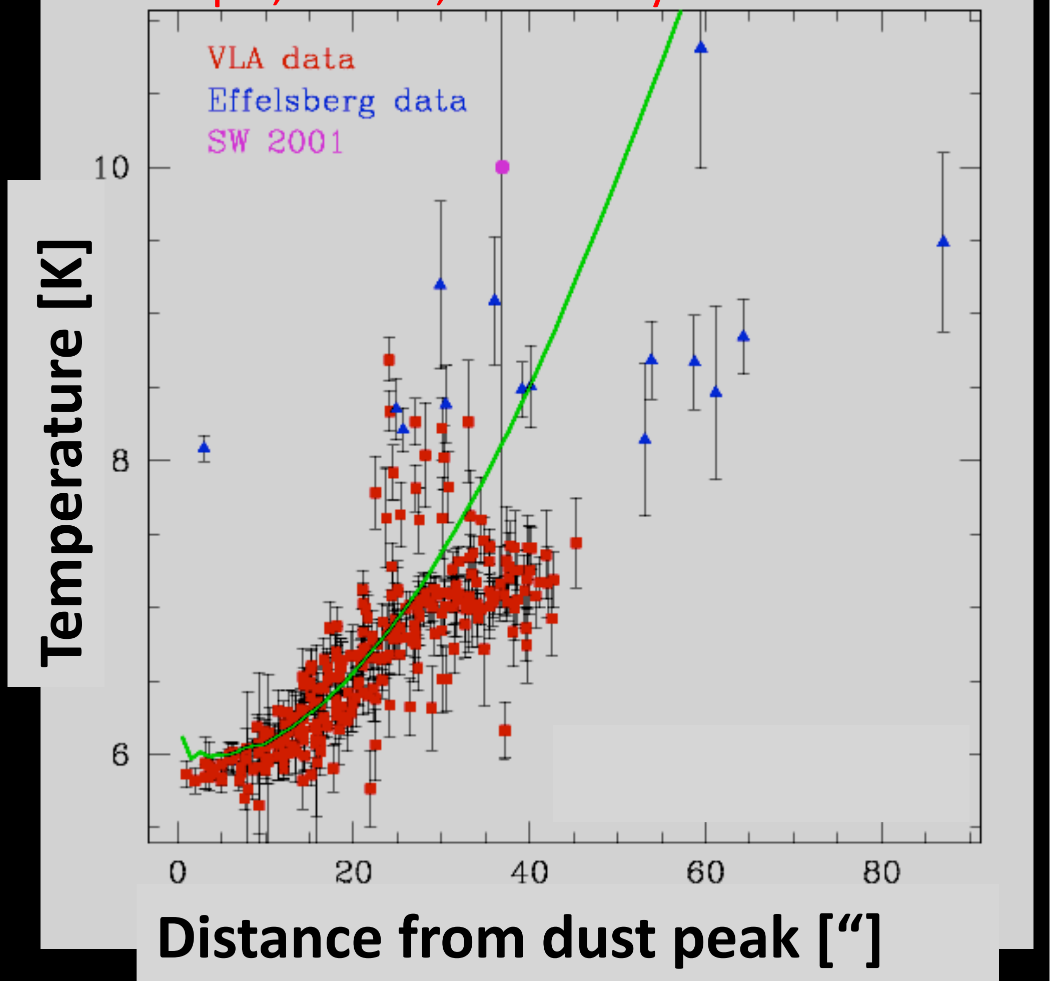
Pre-stellar cores: temperature structure

Pre-stellar cores are gravitationally unstable starless cores

(e.g. Ward-Thompson et al. 1999; Crapsi et al. 2005; Keto & Caselli 2008)

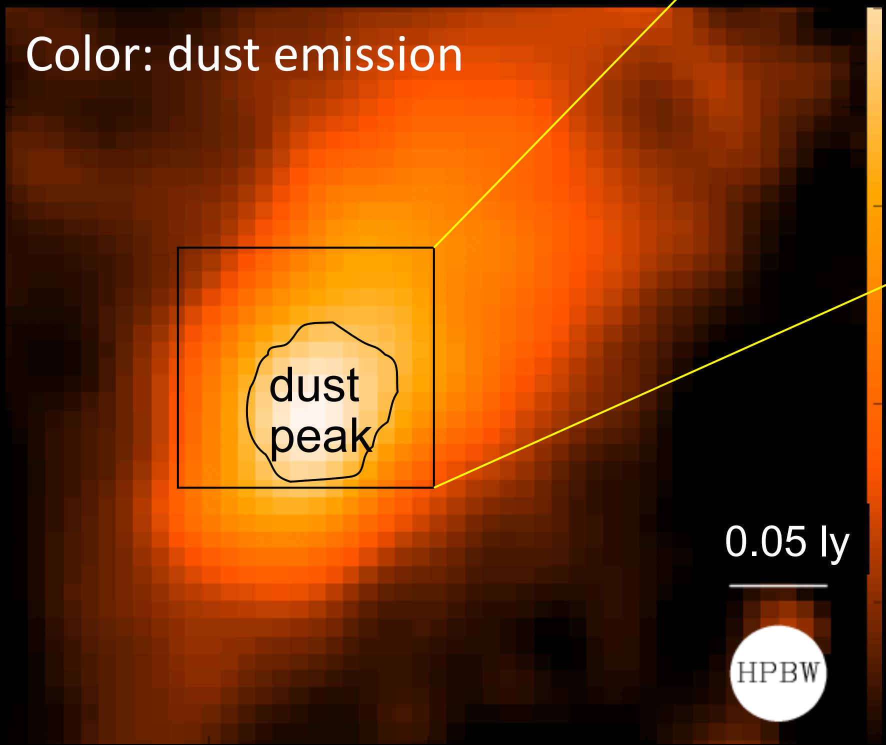
They have temperature gradients (~6-12 K)

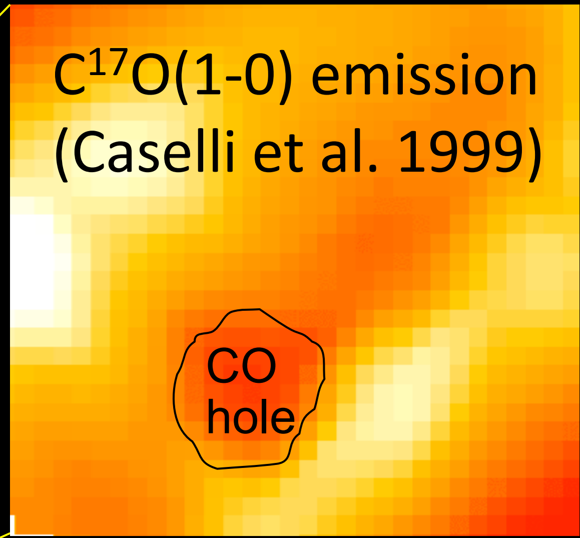
Crapsi, Caselli, Walmsley & Tafalla 2007



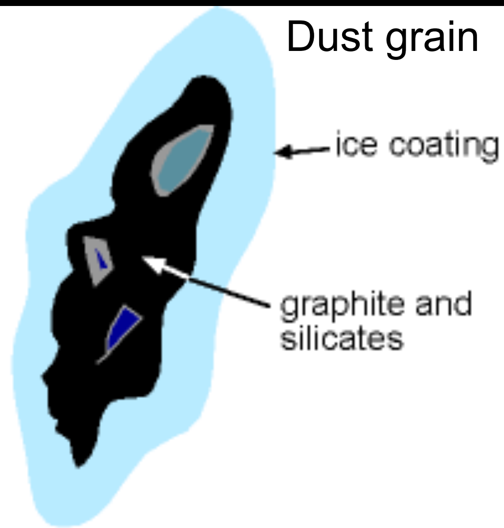
Pre-stellar cores: CO freeze-out

Using CO observations:
2.3 $M_\odot$ lost to view
(out of 8 $M_\odot$)



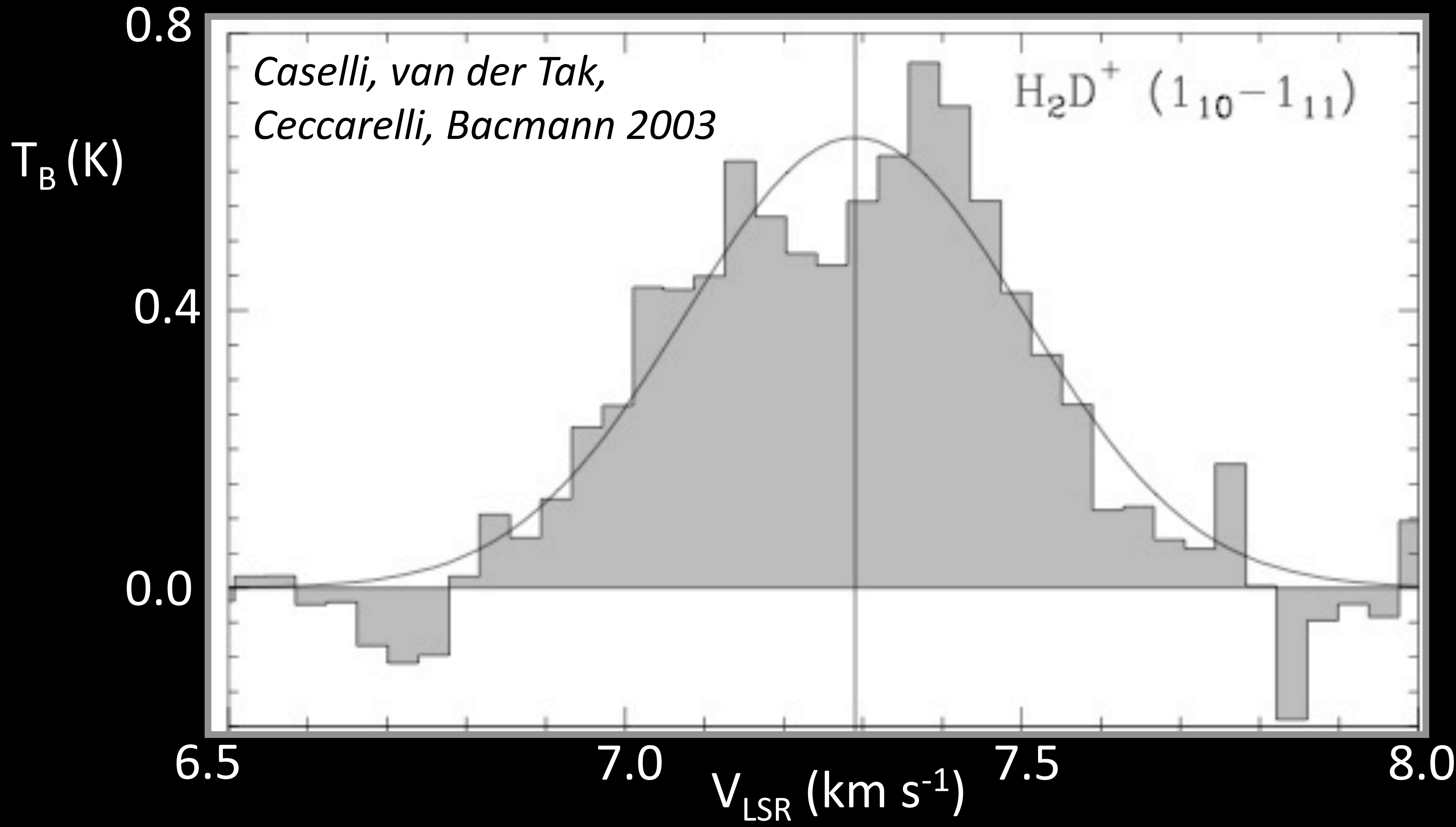


Molecules freeze out onto dust grains in the center of pre-stellar cores

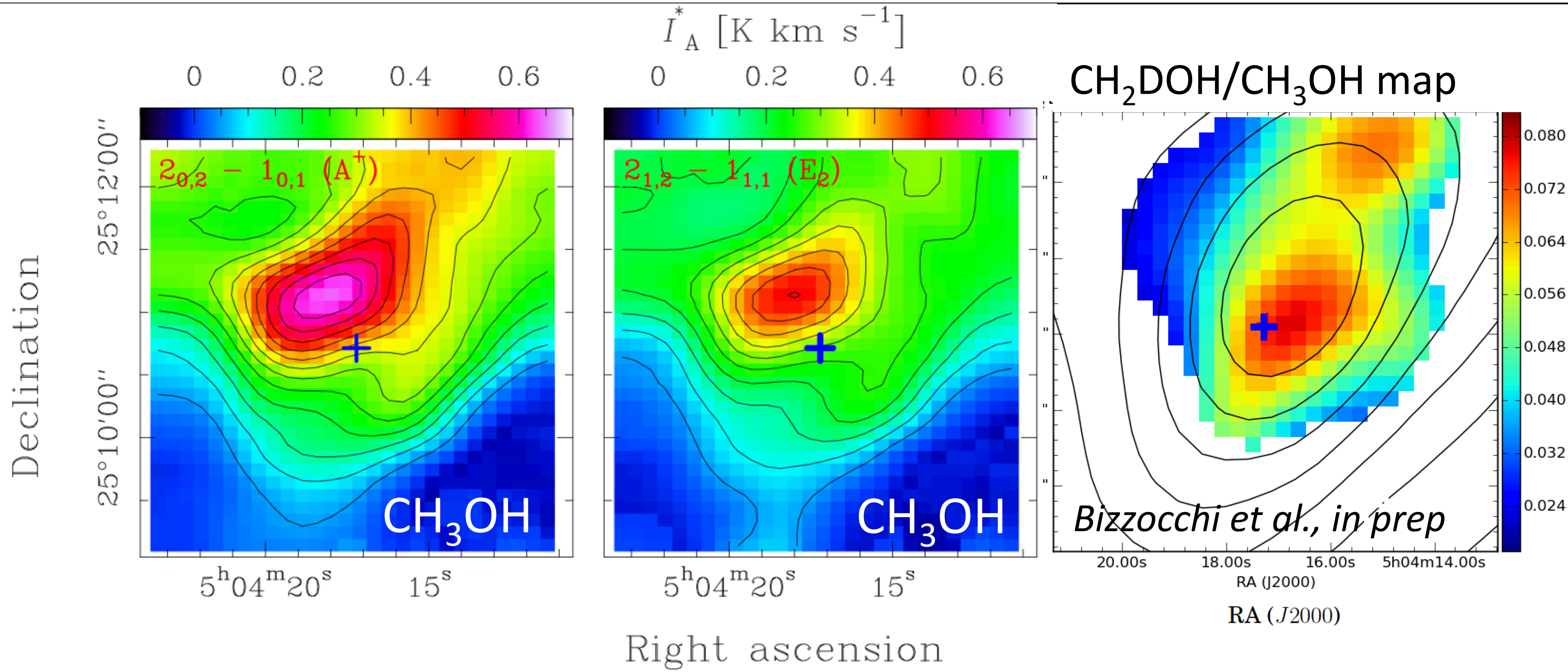


Pre-stellar cores: strong ortho-H_2D^+

- Led to strong revision of astrochemical models (e.g. Roberts et al. 2003)
- Triggered new laboratory work (e.g. Hugo et al. 2009)



Pre-stellar cores: deuterium fractionation



CH_3OH traces the region where CO is freezing out
(R ~ 4000 AU; *Bizzocchi et al. 2014*)

CH_2DOH/CH_3OH ~ 0.1 (toward center)
[to be compared with D_{frac} ~ 0.4 from NH_2D/NH_3; *Crapsi et al. 2007*]

Pre-stellar cores: complex organic molecules

A&A 541, L12 (2012)
DOI: 10.1051/0004-6361/201219207

Astronomy & Astrophysics

LETTER TO THE EDITOR

Detection of complex organic molecules in a prestellar core: a new challenge for astrochemical models*,**

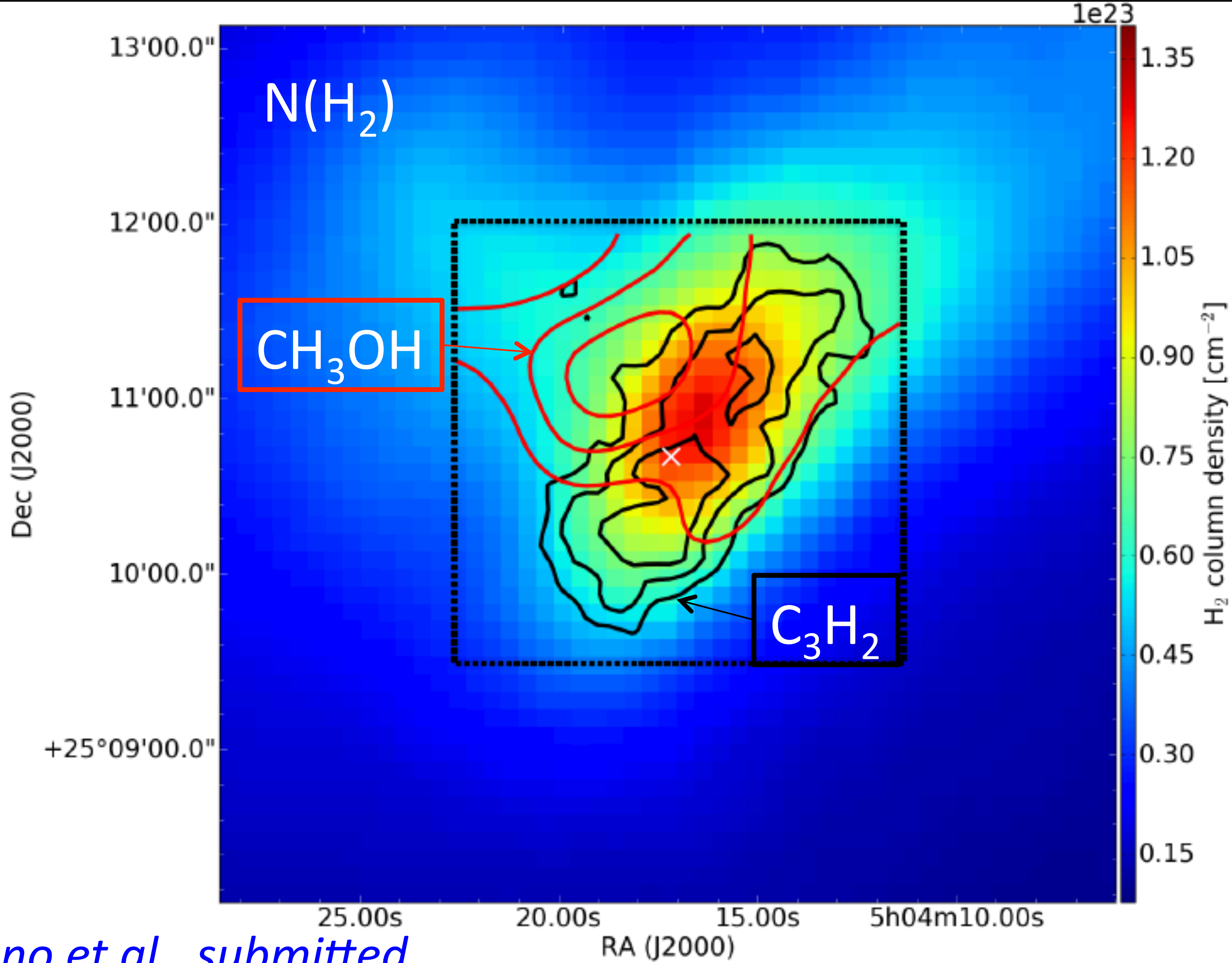
A. Bacmann[1], V. Taquet[1], A. Faure[1], C. Kahane[1], and C. Ceccarelli[1]

Table 1. Line fluxes[a] and column densities.

Species	Transition	T_{mb} (mK)	rms (mK)	Integrated area (K km s^{-1})	Column density[c] (cm^{-2}) T_{ex} = 5 K	Column density[c] (cm^{-2}) T_{ex} = 4 K	Column density[c] (cm^{-2}) T_{ex} = 8 K
AA-CH_3OCH_3	$4_{14}-3_{03}$	55	7	0.026 ± 0.005	(3.32 ± 0.74) 10^{12}	(5.08 ± 1.12) 10^{12}	(2.49 ± 0.55) 10^{12}
EE-CH_3OCH_3	$4_{14}-3_{03}$	90	7	0.037 ± 0.005	(6.81 ± 0.92) 10^{12}	(10.4 ± 1.40) 10^{12}	(5.11 ± 0.69) 10^{12}
EA-CH_3OCH_3	$4_{14}-3_{03}$	36[b]	7	0.014 ± 0.003	(1.65 ± 0.55) 10^{12}	(2.53 ± 0.84) 10^{12}	(1.24 ± 0.41) 10^{12}
AE-CH_3OCH_3	$4_{14}-3_{03}$	22[b]	7	0.009 ± 0.003	(1.67 ± 0.37) 10^{12}	(2.55 ± 0.56) 10^{12}	(1.25 ± 0.28) 10^{12}
E-CH_3CHO	$5_{14}-4_{13}$	125	3	0.149 ± 0.015	(9.12 ± 0.92) 10^{12}	(2.67 ± 0.27) 10^{13}	(2.12 ± 0.21) 10^{12}
A-CH_3CHO	$5_{14}-4_{13}$	110	4	0.137 ± 0.014	(8.26 ± 0.84) 10^{12}	(1.73 ± 0.18) 10^{13}	(3.86 ± 0.39) 10^{12}
A-CH_3OCHO	$8_{17}-7_{16}$	20	3	0.025 ± 0.005	(2.01 ± 0.40) 10^{13}	(5.73 ± 1.15) 10^{13}	(5.91 ± 1.18) 10^{12}
A-CH_3OCHO	$9_{09}-8_{08}$	12	2	0.016 ± 0.005	(1.73 ± 0.54) 10^{13}	(5.50 ± 1.71) 10^{13}	(4.33 ± 1.35) 10^{12}
E-CH_3OCHO	$8_{17}-7_{16}$	19	3	0.024 ± 0.005	(1.90 ± 0.40) 10^{13}	(5.44 ± 1.15) 10^{13}	(5.59 ± 1.18)10^{12}
E-CH_3OCHO	$9_{09}-8_{08}$	12	2	0.016 ± 0.003	(1.72 ± 0.32) 10^{13}	(5.47 ± 1.03) 10^{13}	(4.32 ± 0.81) 10^{12}
o-CH_2CO	$5_{15}-4_{14}$	140	3	0.171 ± 0.018	(1.50 ± 0.16) 10^{13}	(3.09 ± 0.33) 10^{13}	(6.75 ± 0.71) 10^{12}
p-CH_2CO	$5_{05}-4$ [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

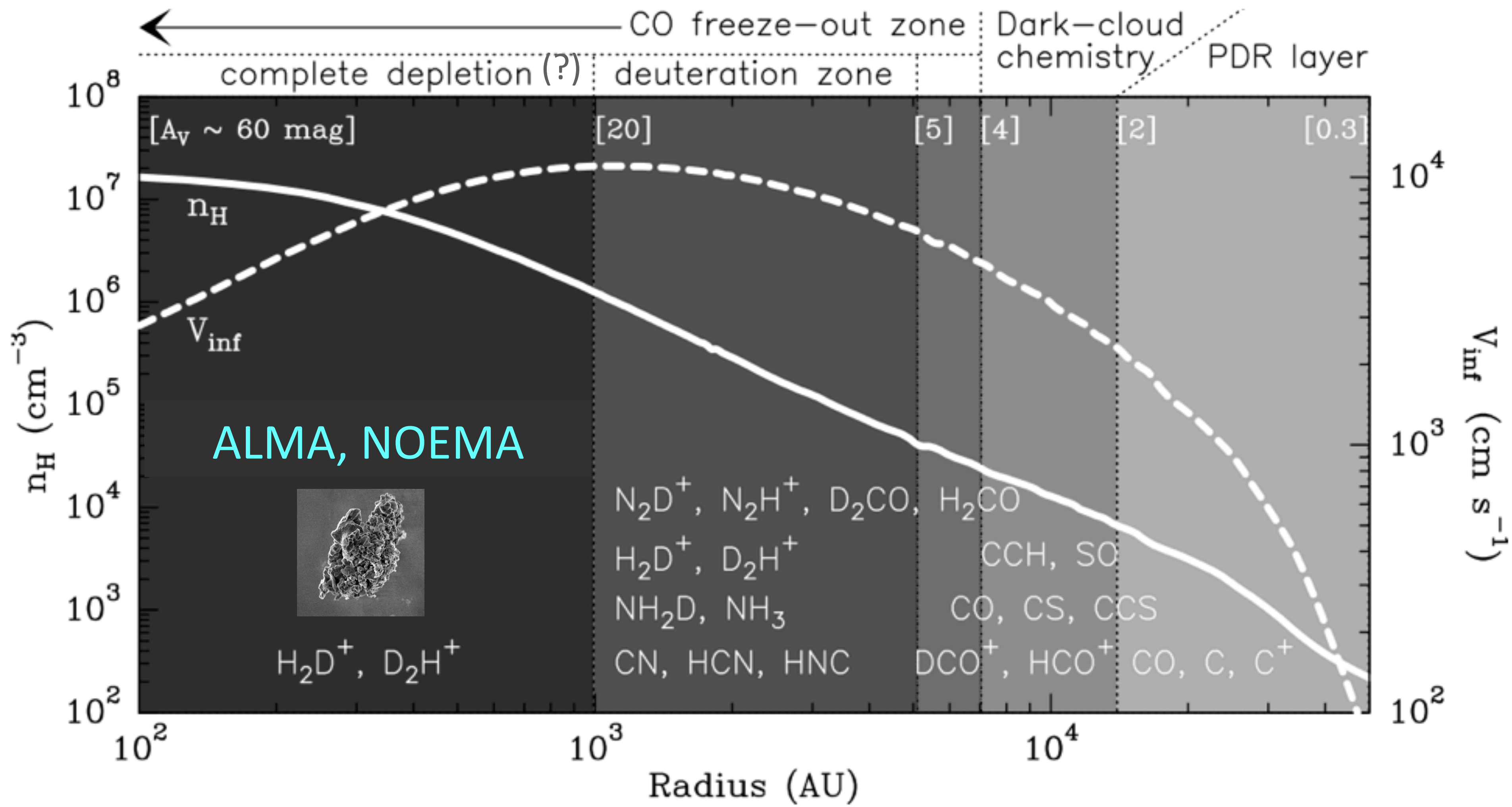
see also Öberg et al. 2010; Vastel et al. 2014; Jiménez-Serra et al. 2014

Pre-stellar cores: chemical differentiation



Spezzano et al., submitted

The pre-stellar core physical/chemical structure



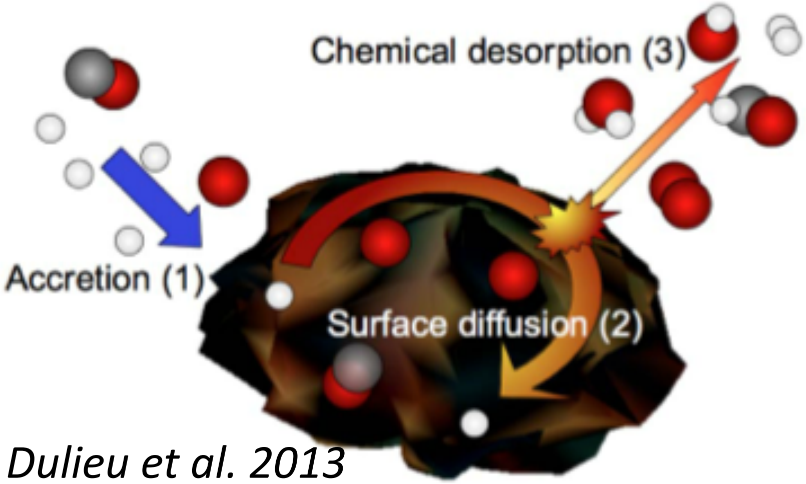
Caselli et al. 1999, 2002, 2003; Vastel et al. 2006; Keto & Caselli 2008, 2010

Pre-stellar cores: the central 1000 AU with ALMA

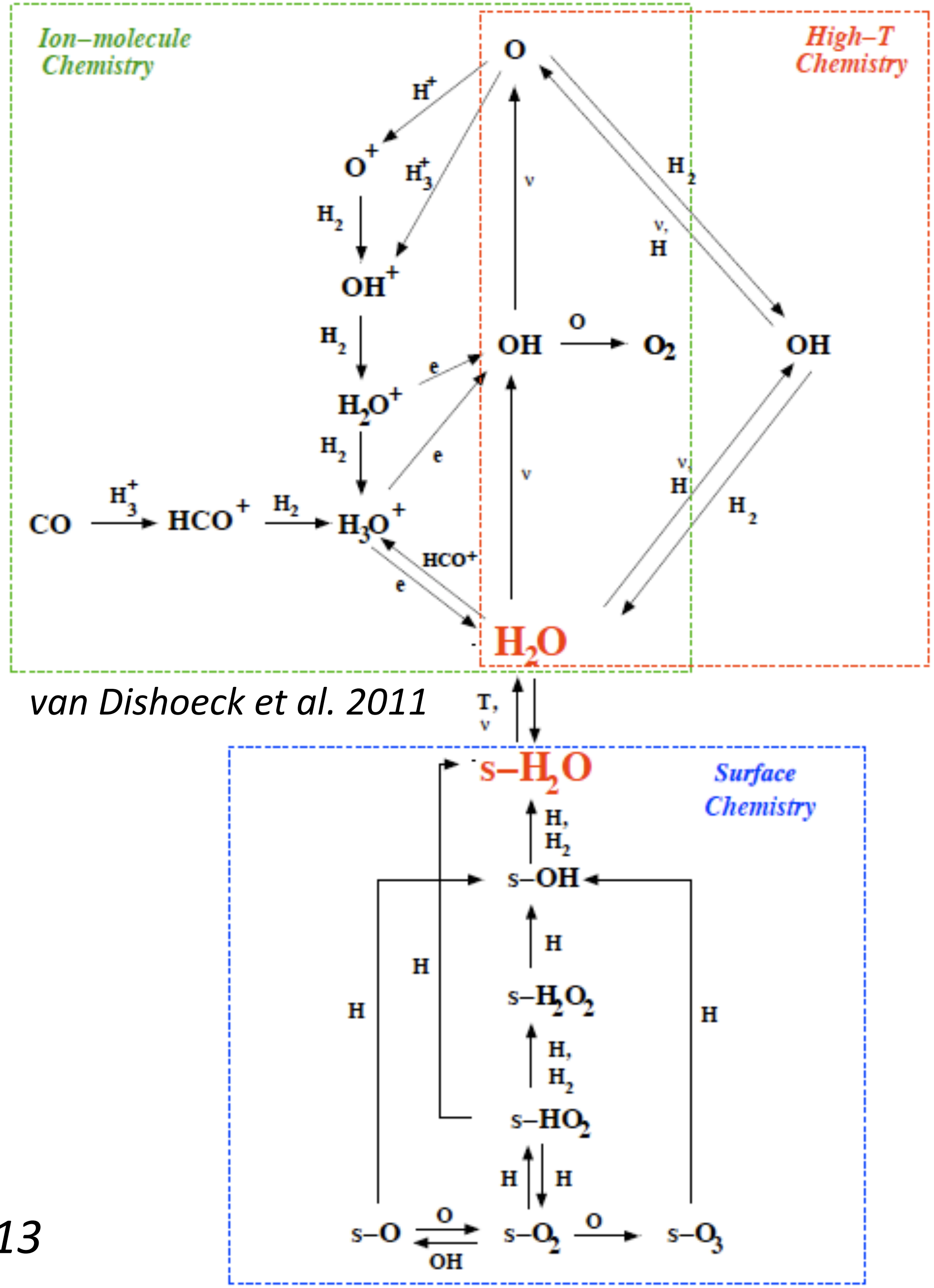
Caselli, Pineda et al., in prep.

Water vapor in dark clouds

In cold regions, H_2O is mainly formed on the surface of dust grains.



Dulieu et al. 2013



van Dishoeck et al. 2011

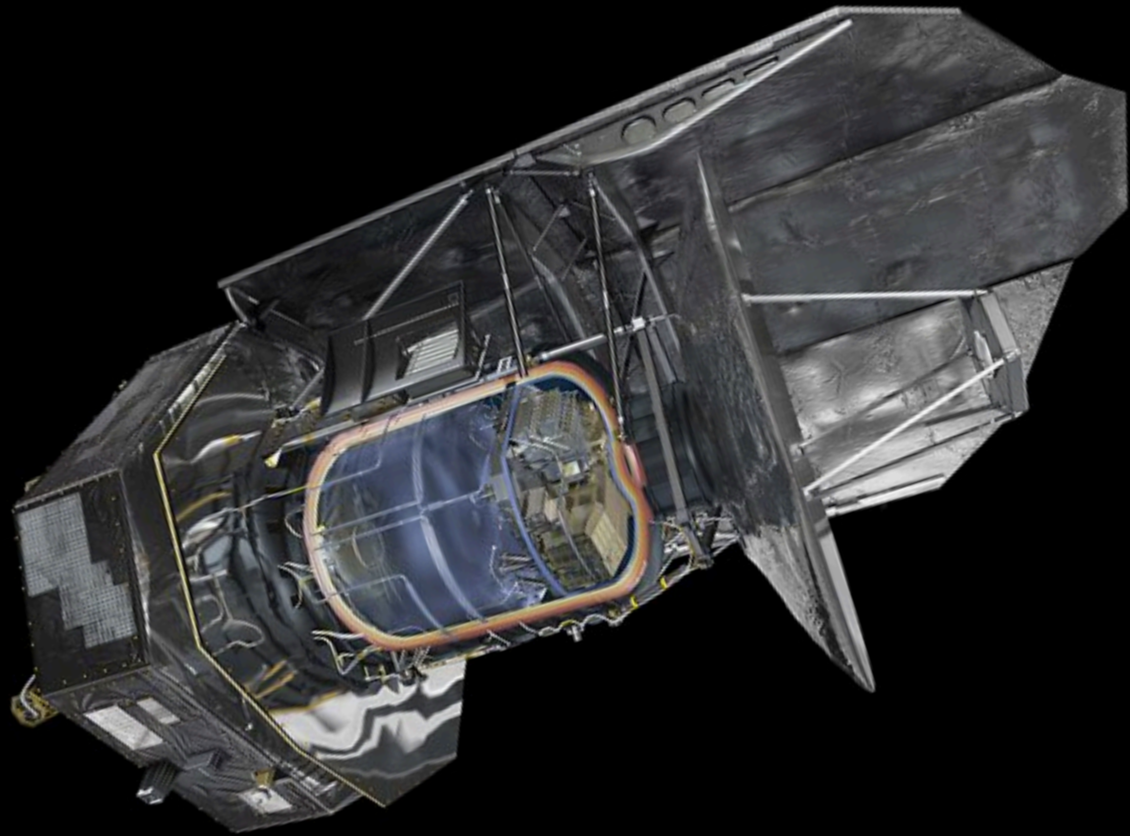
e.g. Tielens & Hagen 1982; Cuppen & Herbst 2007; Ioppolo et al. 2008, 2010; Miyauchi et al. 2008; Cazaux et al. 2010, 2011; Dulieu et al. 2010; Taquet et al. 2013

Previous attempts

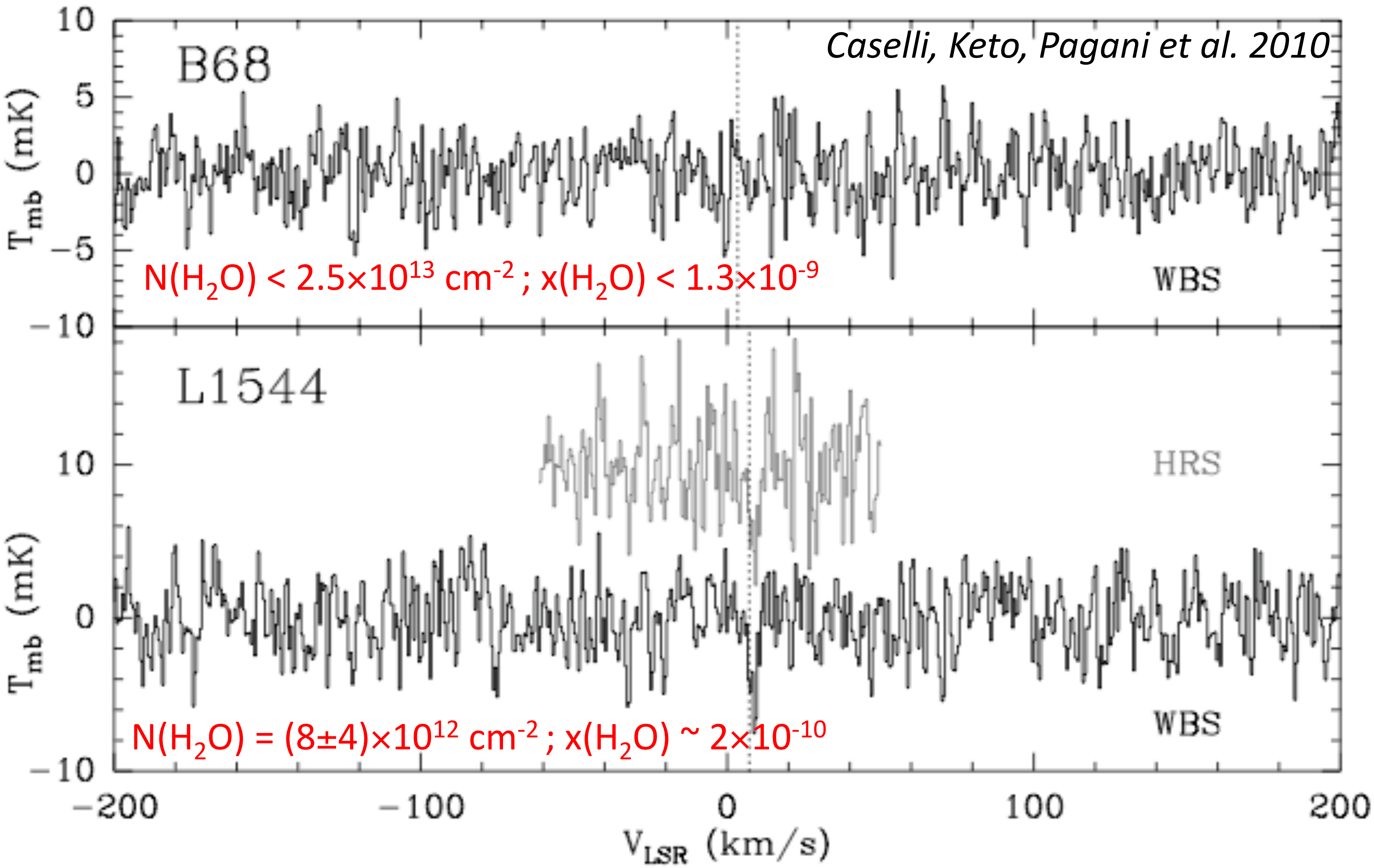
$x(H_2O) < 10^{-8}$

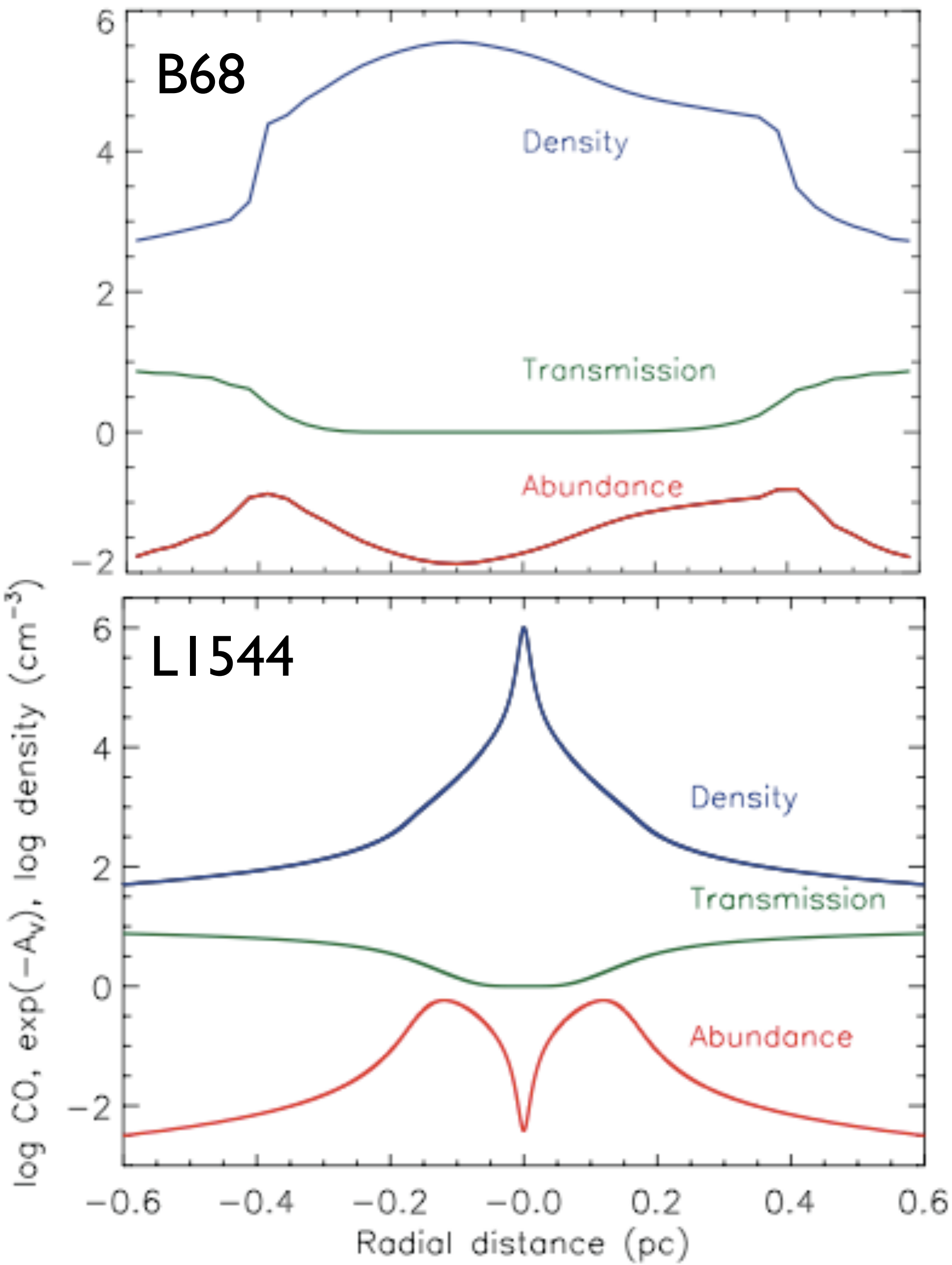
(Bergin & Snell 2002; Klotz et al. 2008)

HERSCHEL HIFI



2010 WISH Data

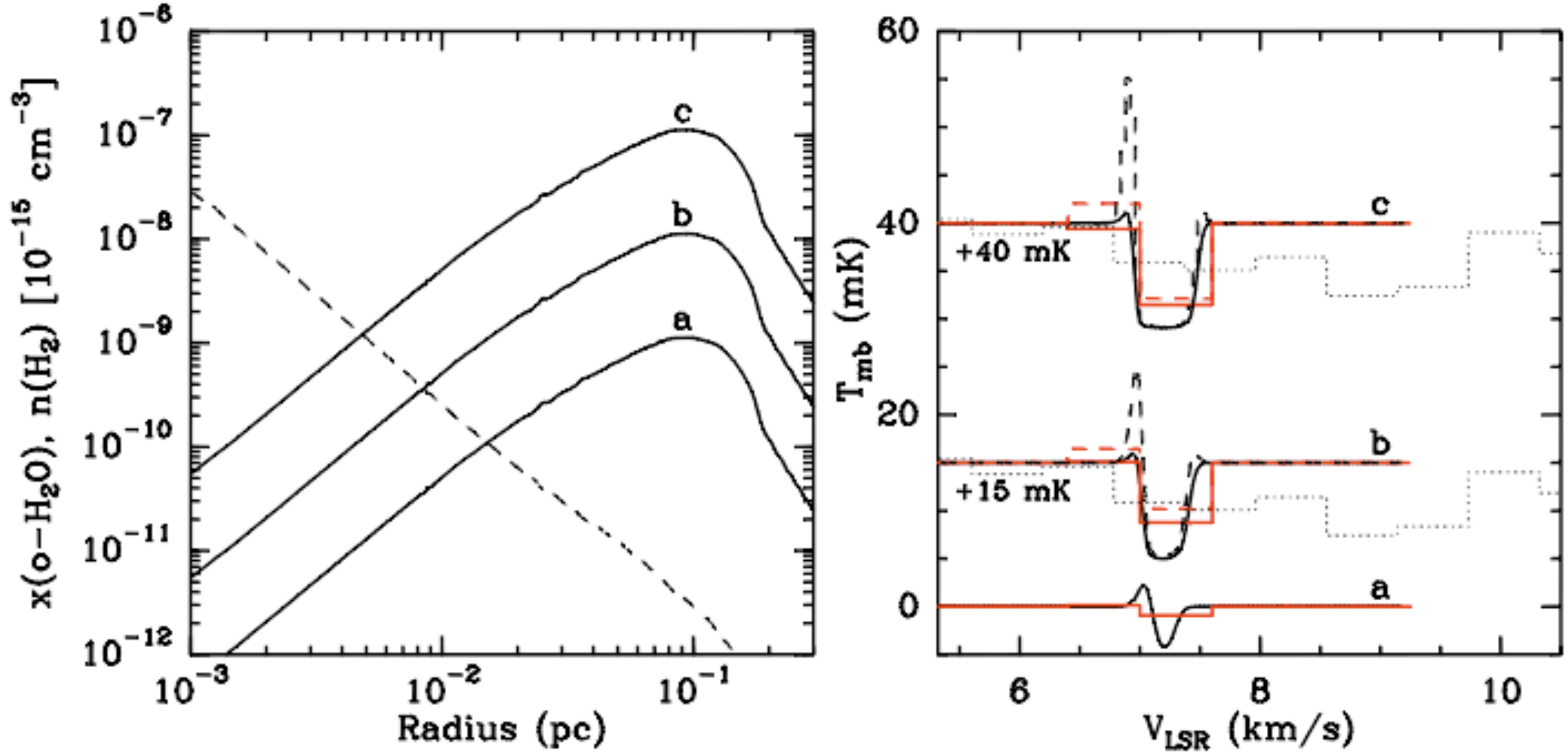




The two classes of starless cores

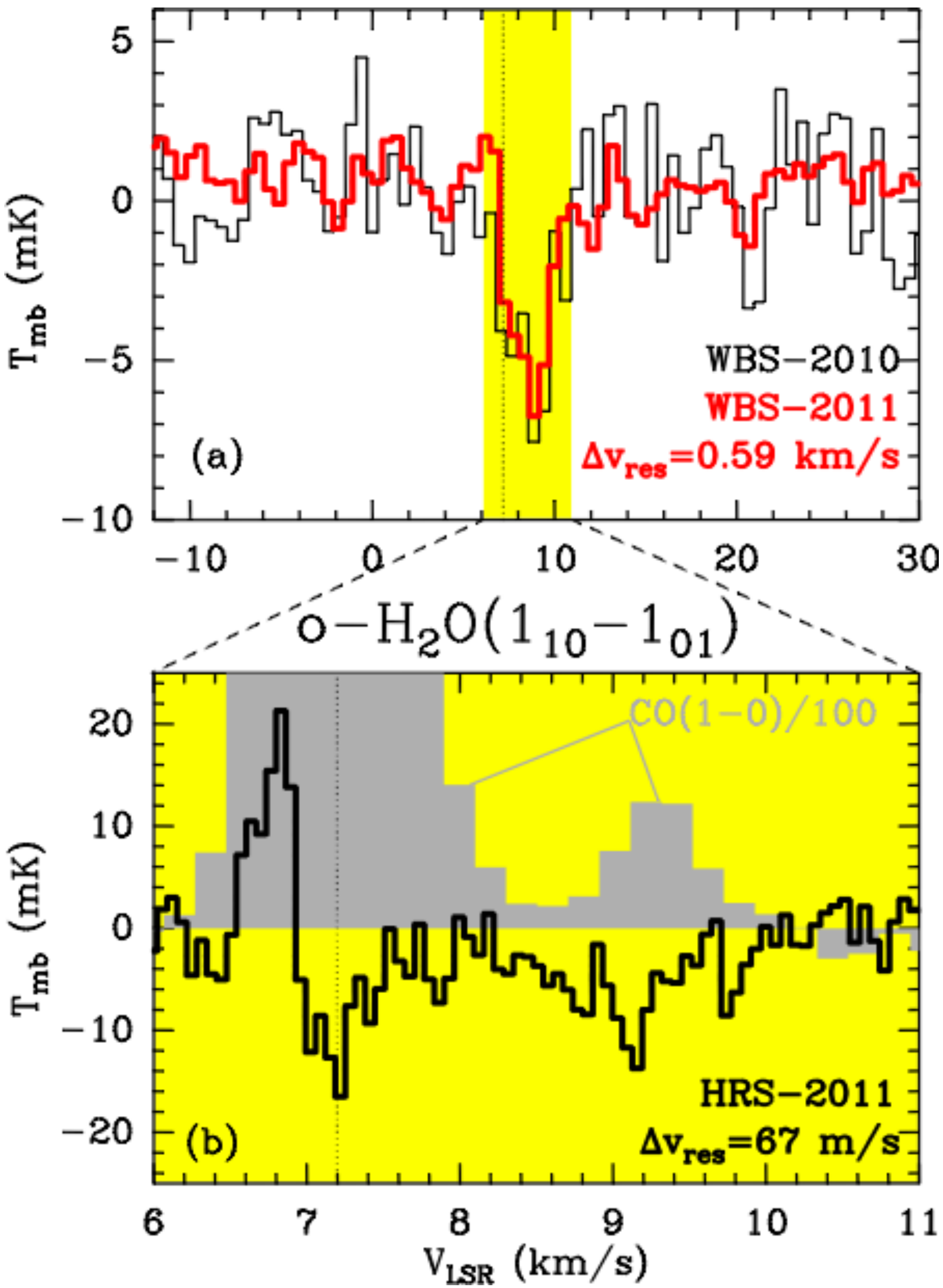
Keto & Caselli 2008

2010 Data



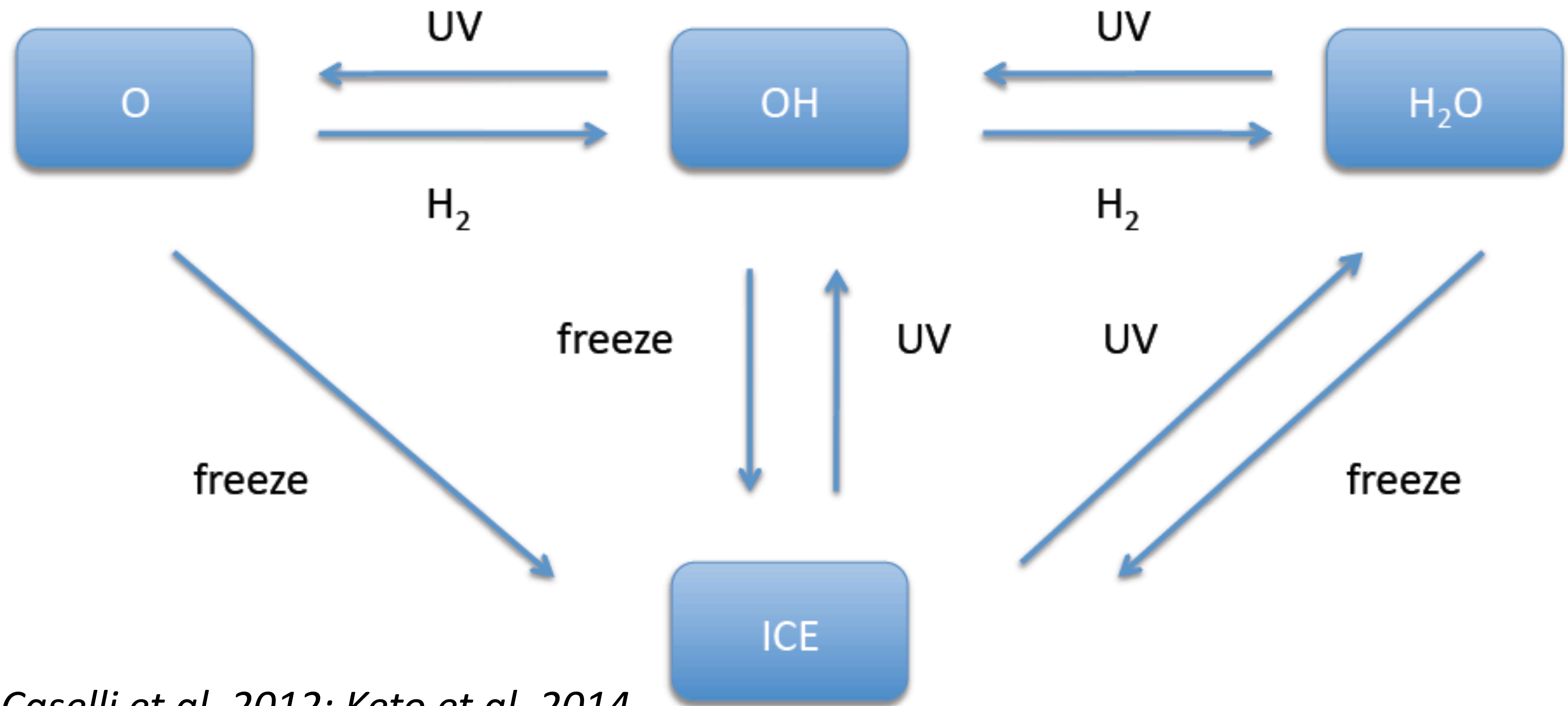
Caselli, Keto, Pagani et al. 2010

Credit: ESA/Herschel/SPIRE



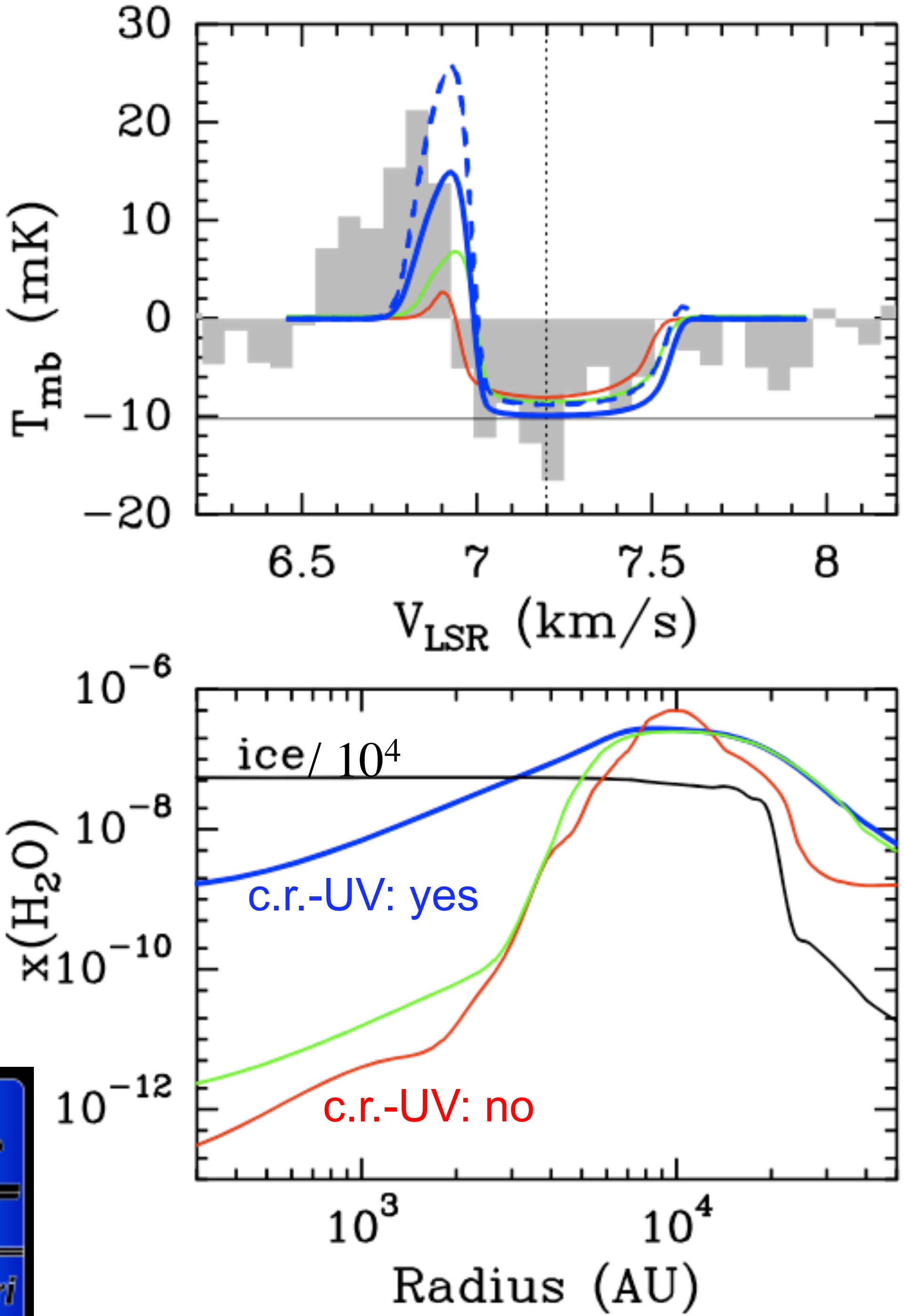
Caselli,
Keto,
Bergin,
Tafalla,
Aikawa,
Douglas,
Pagani
Yildiz,
van der Tak,
Walmsley,
Codella,
Nisini,
Kristensen,
van Dishoeck
2012, ApJL

Simplified O-chemistry



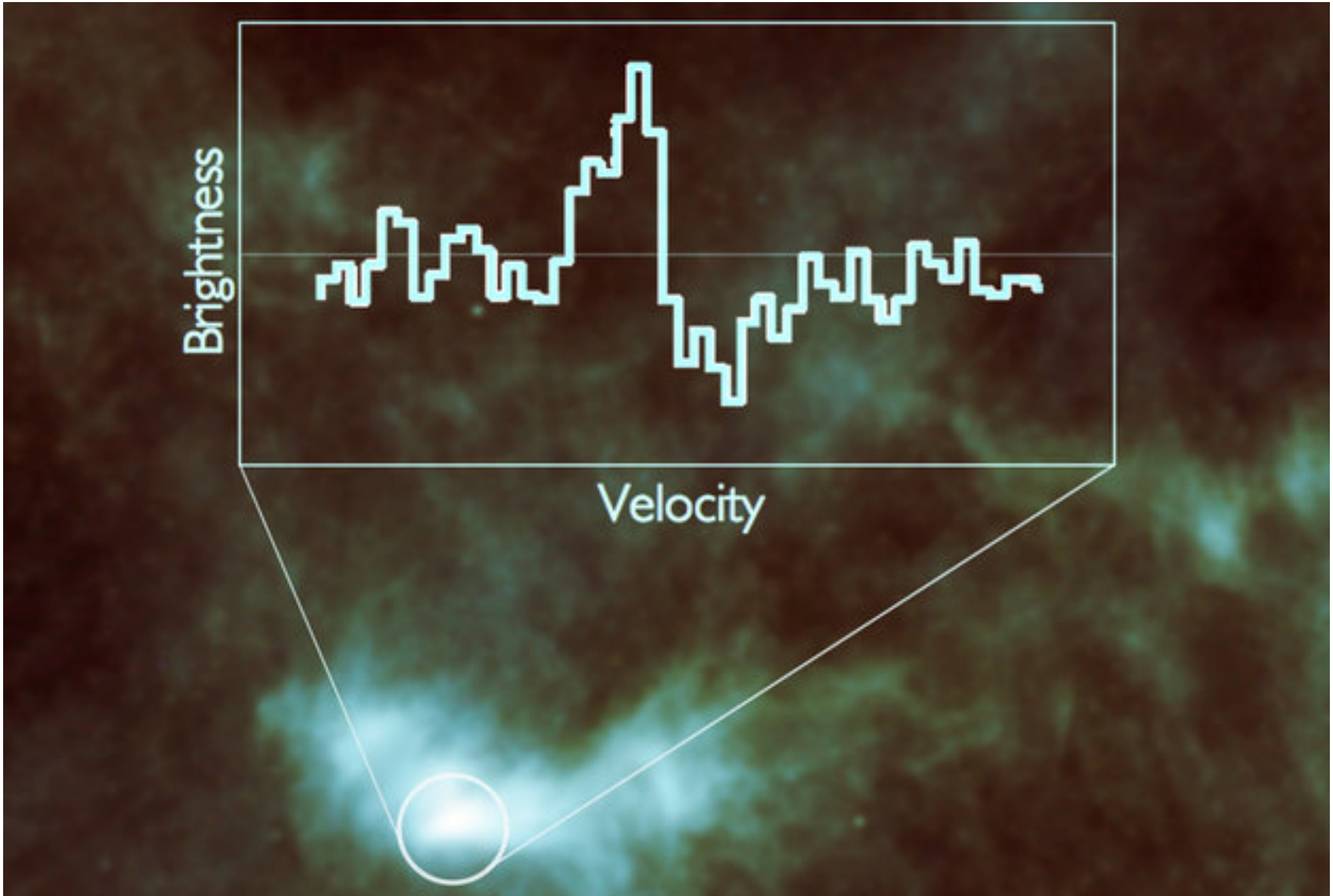
Caselli et al. 2012; Keto et al. 2014

see also Schmalzl et al. 2014



KEY PHENOMENA:

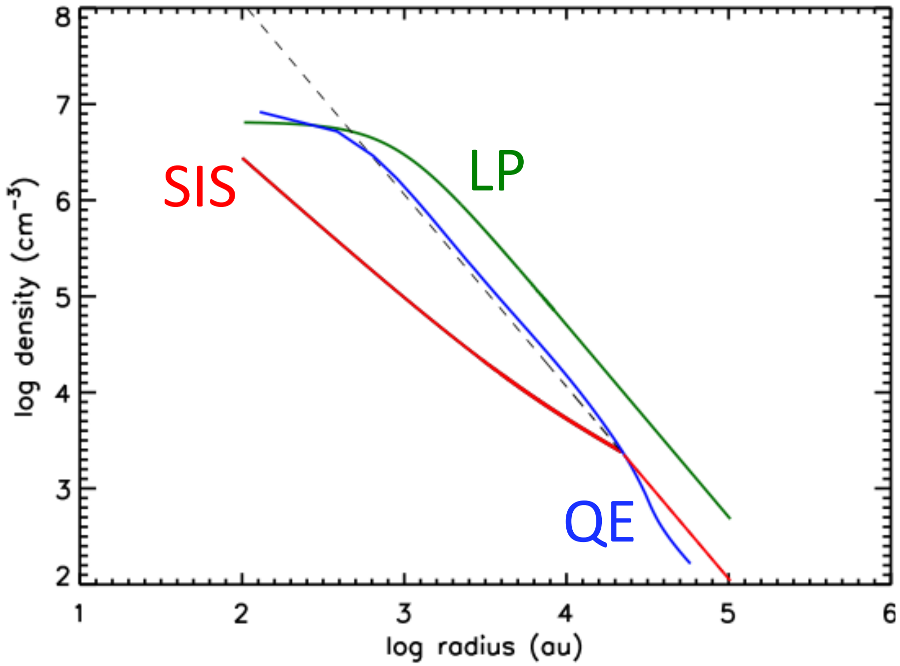
- $x(H_2O) \sim 10^{-9}$ - maintained by FUV photons produced by c.r. (total mass of water vapor: ~0.5 Earth masses; total mass of water ice: ~2.6 Jupiter masses).
- $n_H \geq 10^6$ cm^{-3}, to explain H_2O emission.
- Gravitational contraction to see blue wing in emission.



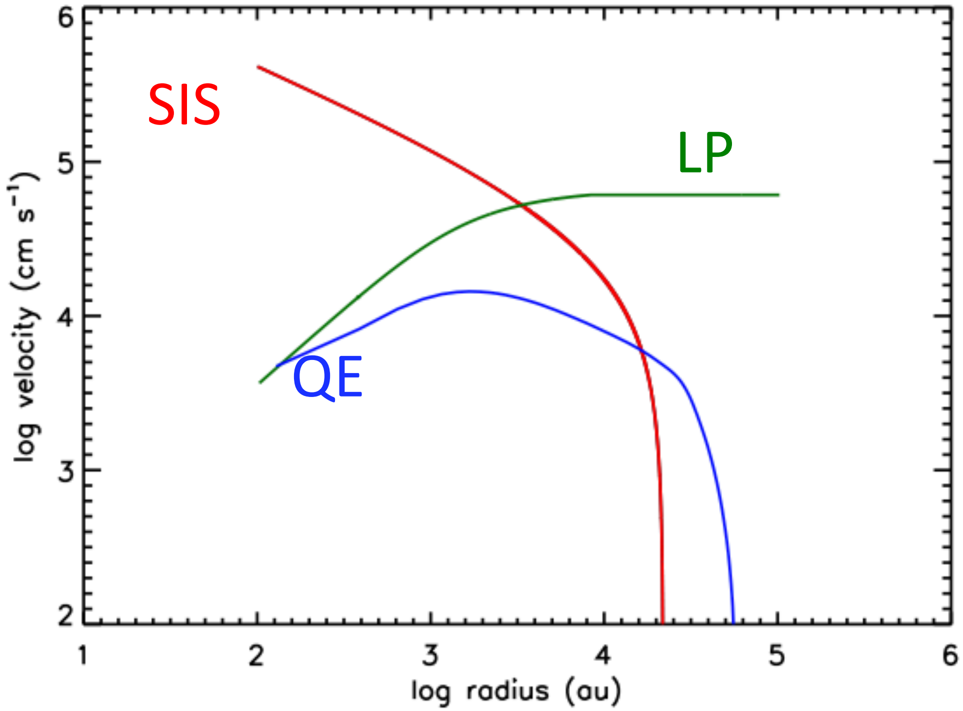
LARGE WATER RESERVOIRS AT THE DAWN OF STELLAR BIRTH

The dynamics of collapsing cores constrained by ortho-H_2O and $C^{18}O$

Number density profile

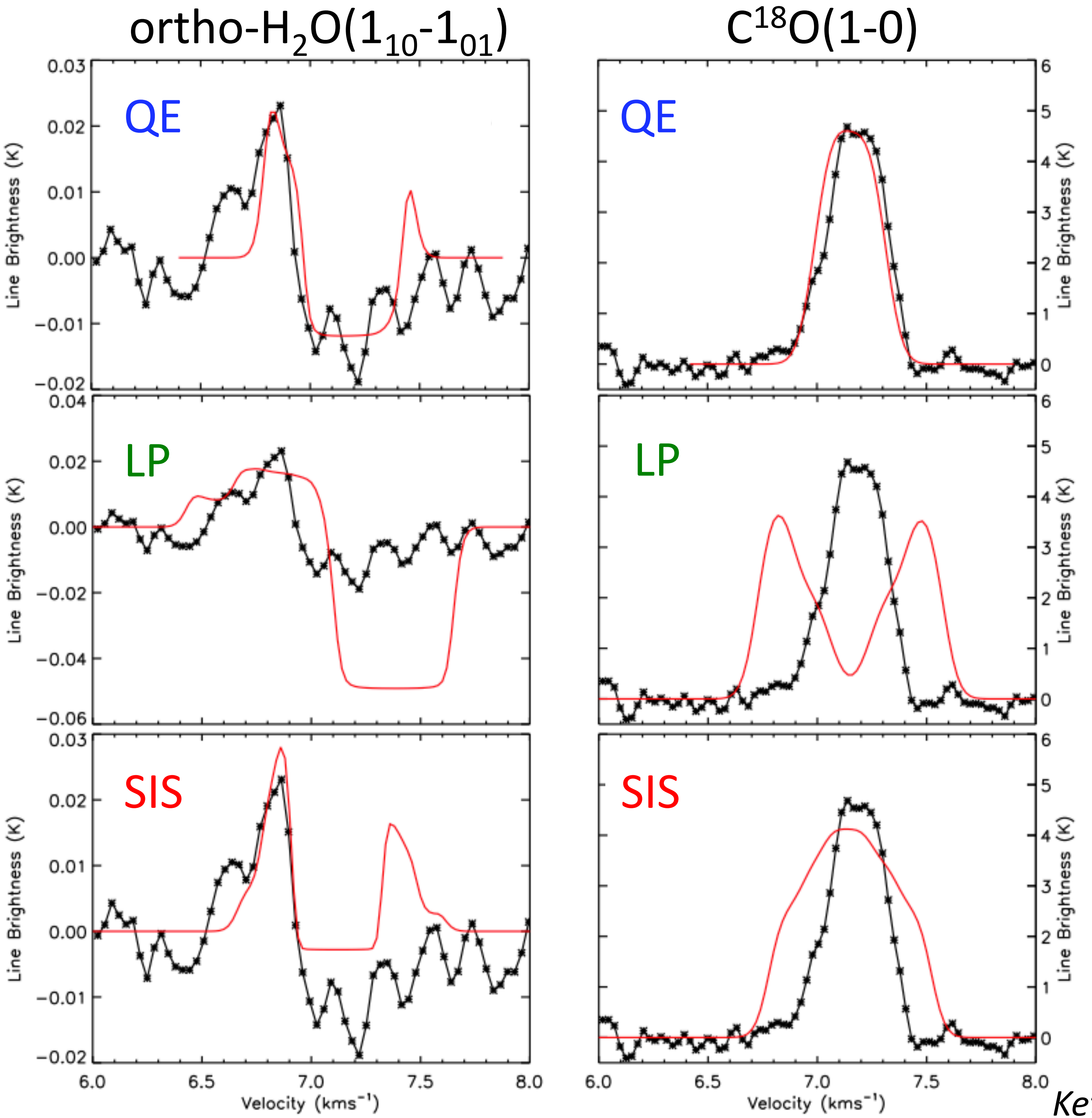


Radial velocity profile



SIS=Singular Isothermal Sphere *(Shu 1977)*
LP=Larson-Penston (1969)
QE=Quasi-Equilibrium BES *(Keto & Caselli 2010)*

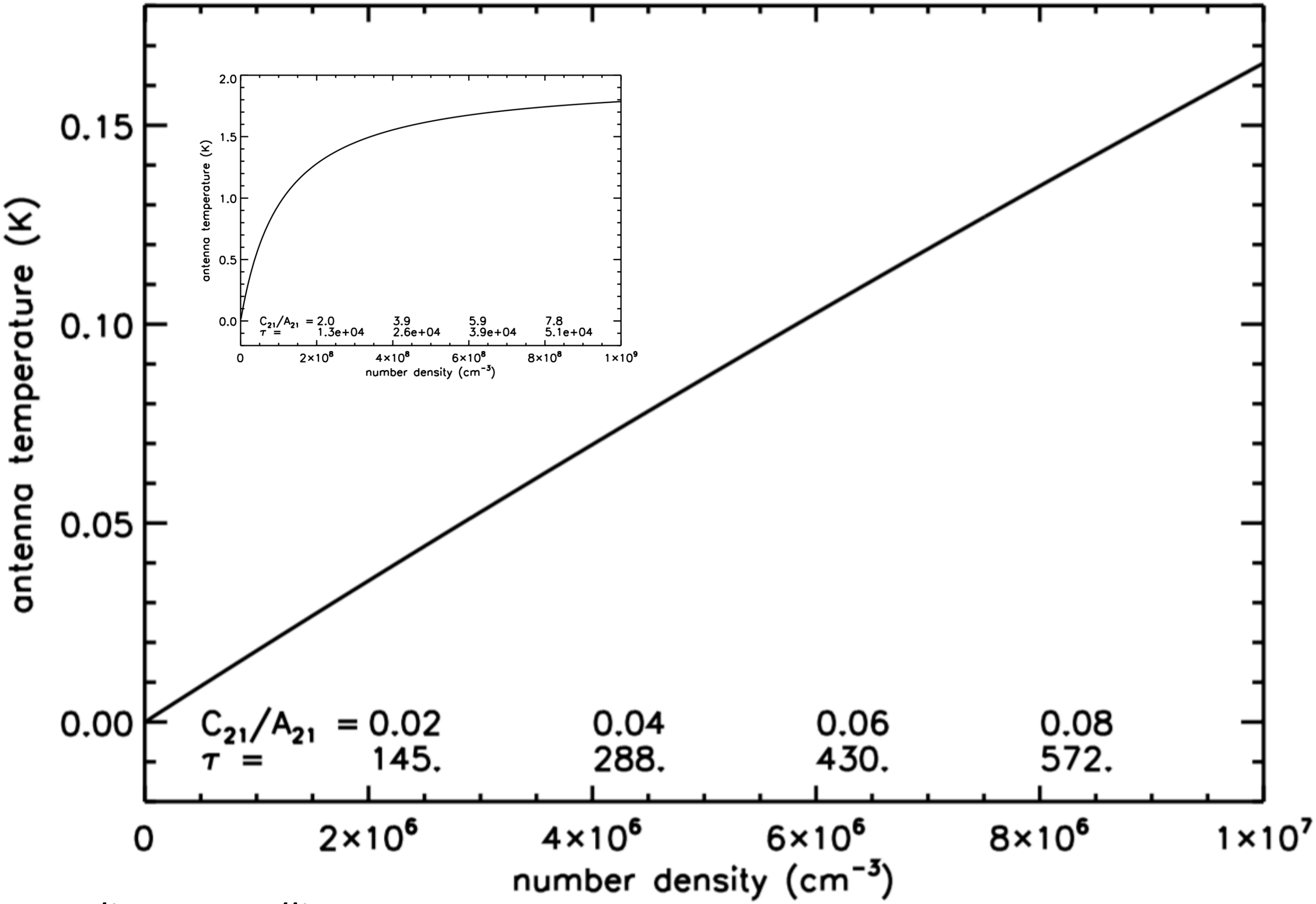
Keto, Caselli, Rawlings 2015



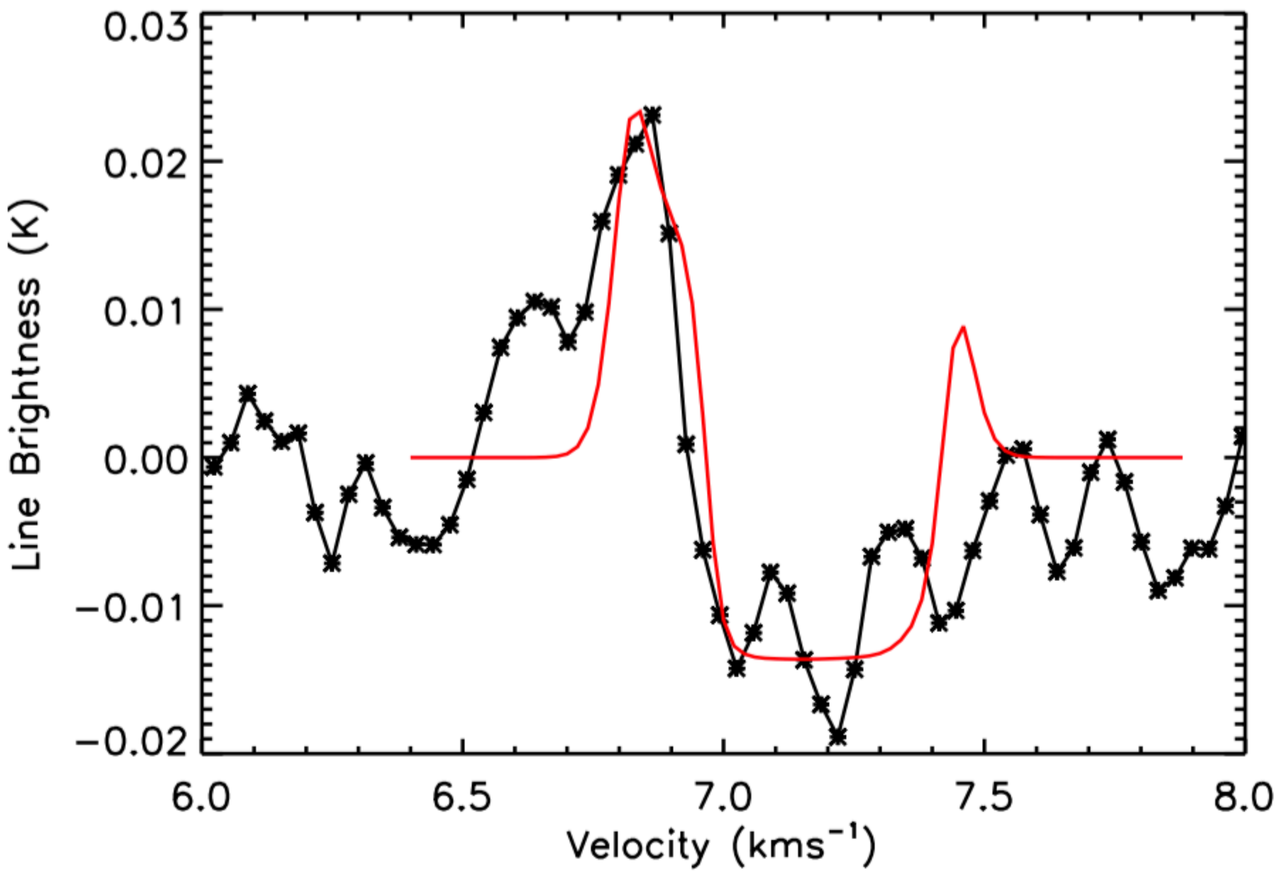
The dynamics of collapsing cores constrained by ortho-H_2O and $C^{18}O$

Keto, Caselli, Rawlings 2015

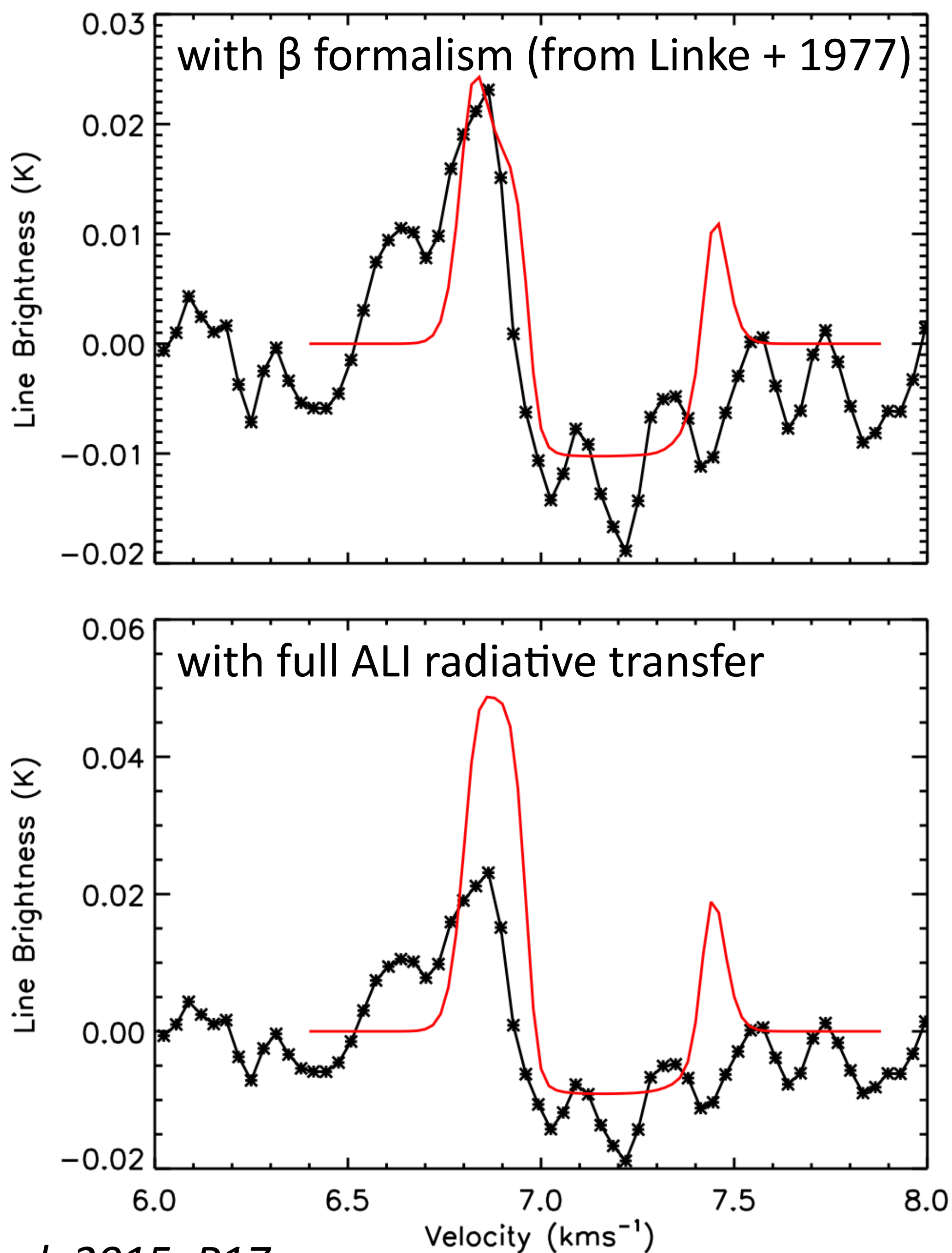
The radiative transfer of water



Keto, Rawlings, Caselli 2014

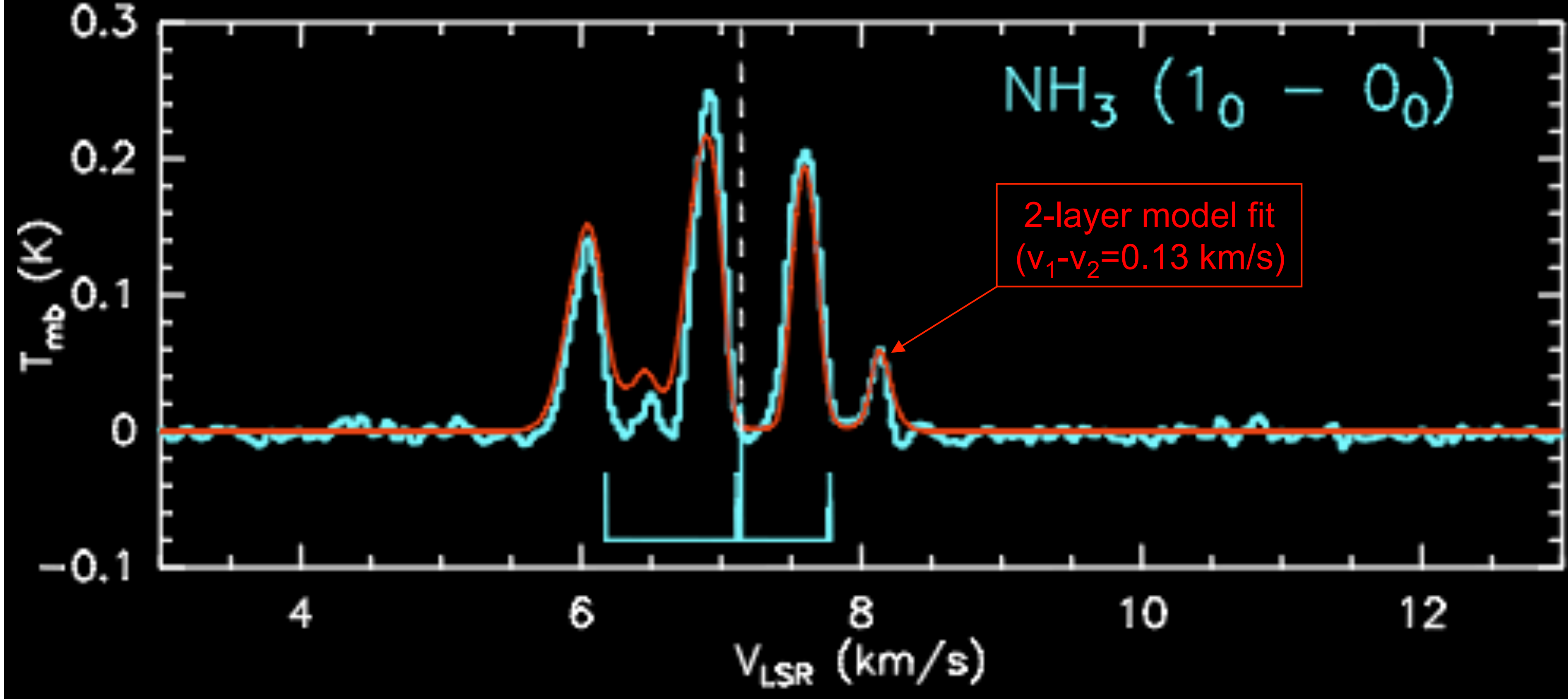


Keto, Rawlings, Caselli 2014



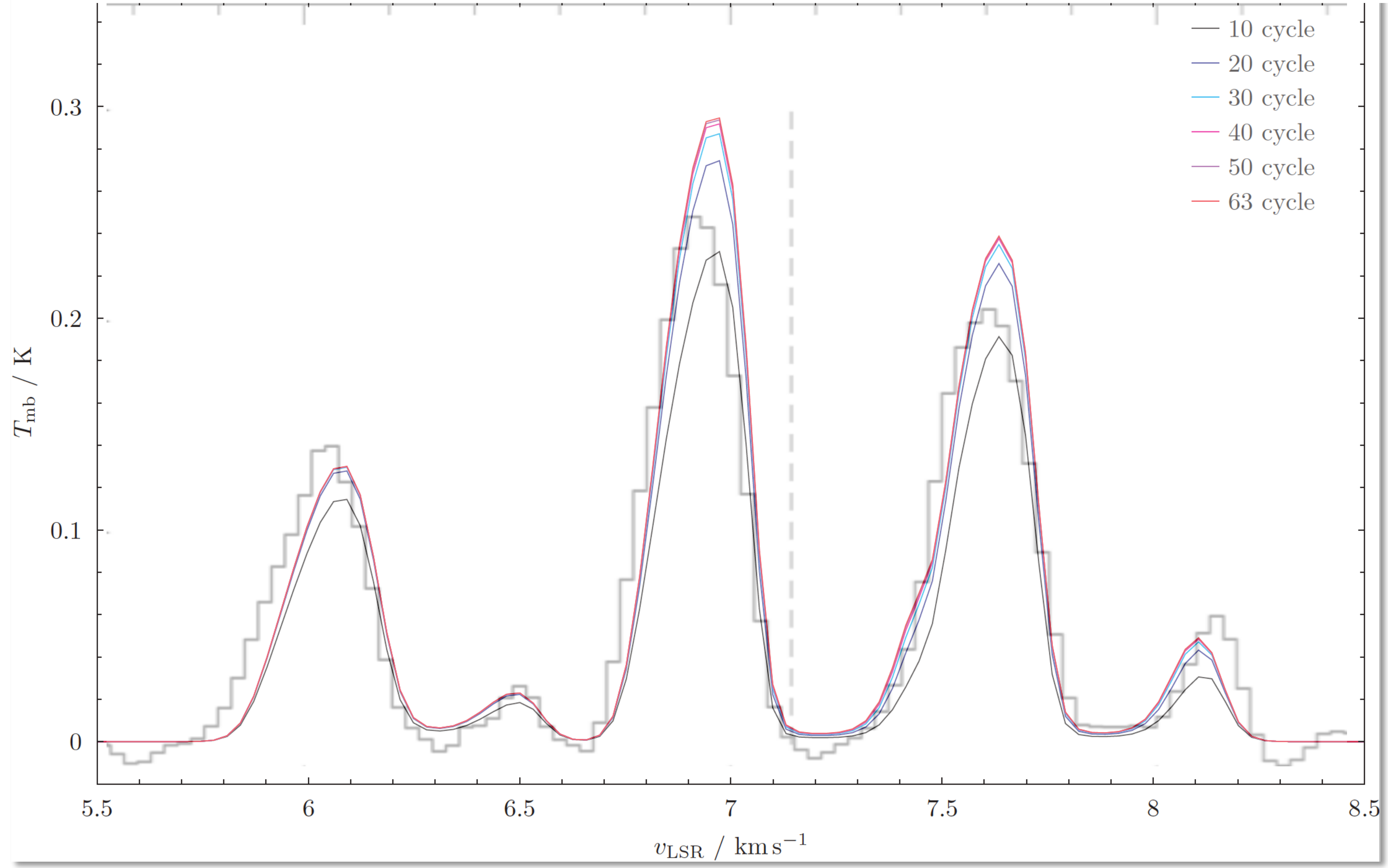
see also Quénard et al. 2015, P17

Not just water !



Caselli et al., in prep.

ortho-NH_3 (1_0-0_0) with full radiative transfer (MOLLIE)

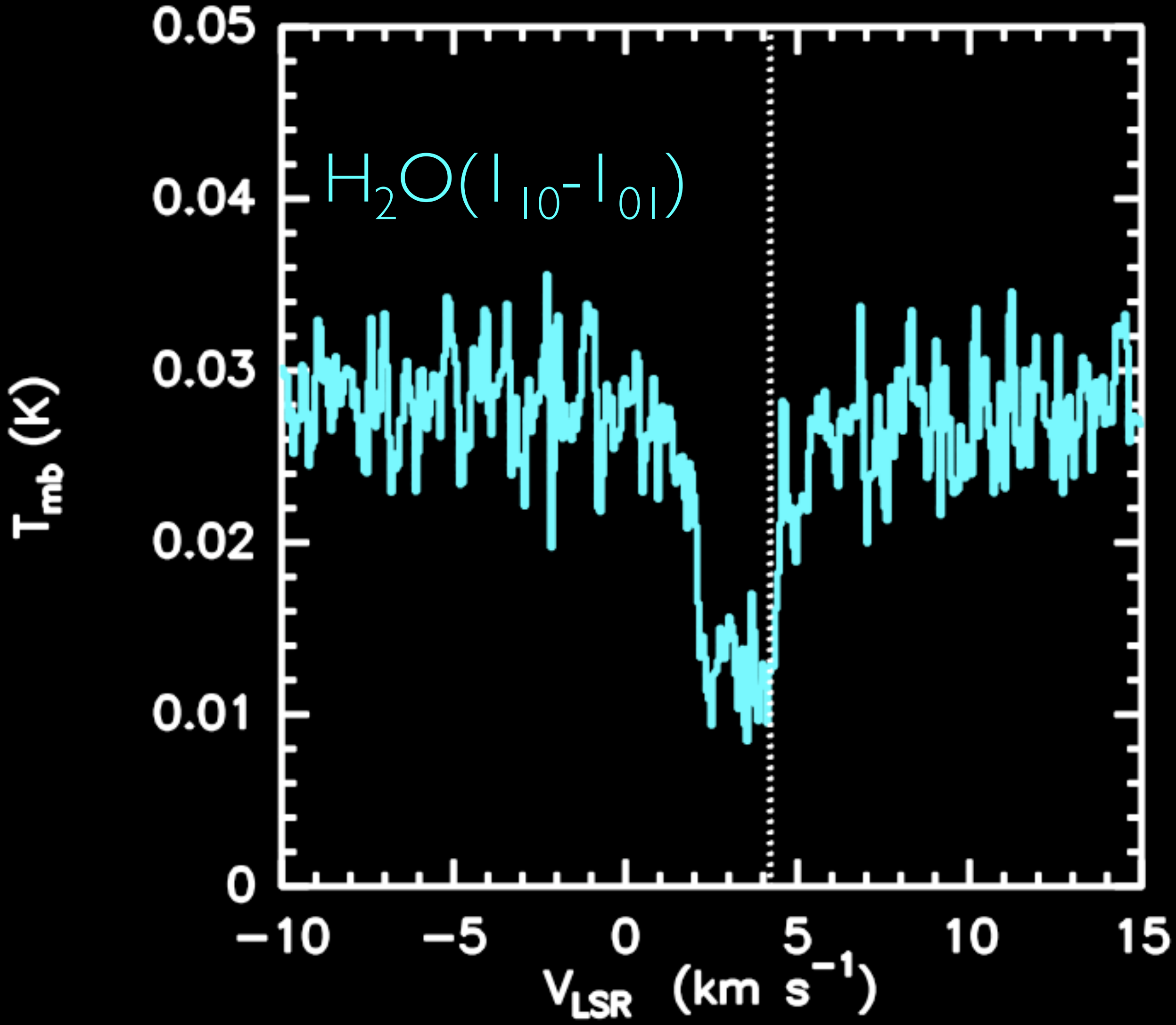


Courtesy of Luca Bizzocchi

The *Herschel Space Observatory* has:

1. detected water vapor in a pre-stellar core for the first time;
2. unveiled gravitational infall within the central 1,000 AU;
3. measured the total mass of water vapor (~0.5 Earth masses ➔ deduced total mass of water ice ~2.6 Jupiter masses);
4. given us insight into the radiative transfer and the chemistry of water in cold gas.

OT2 Herschel data on 2 low-mass PSCs and …

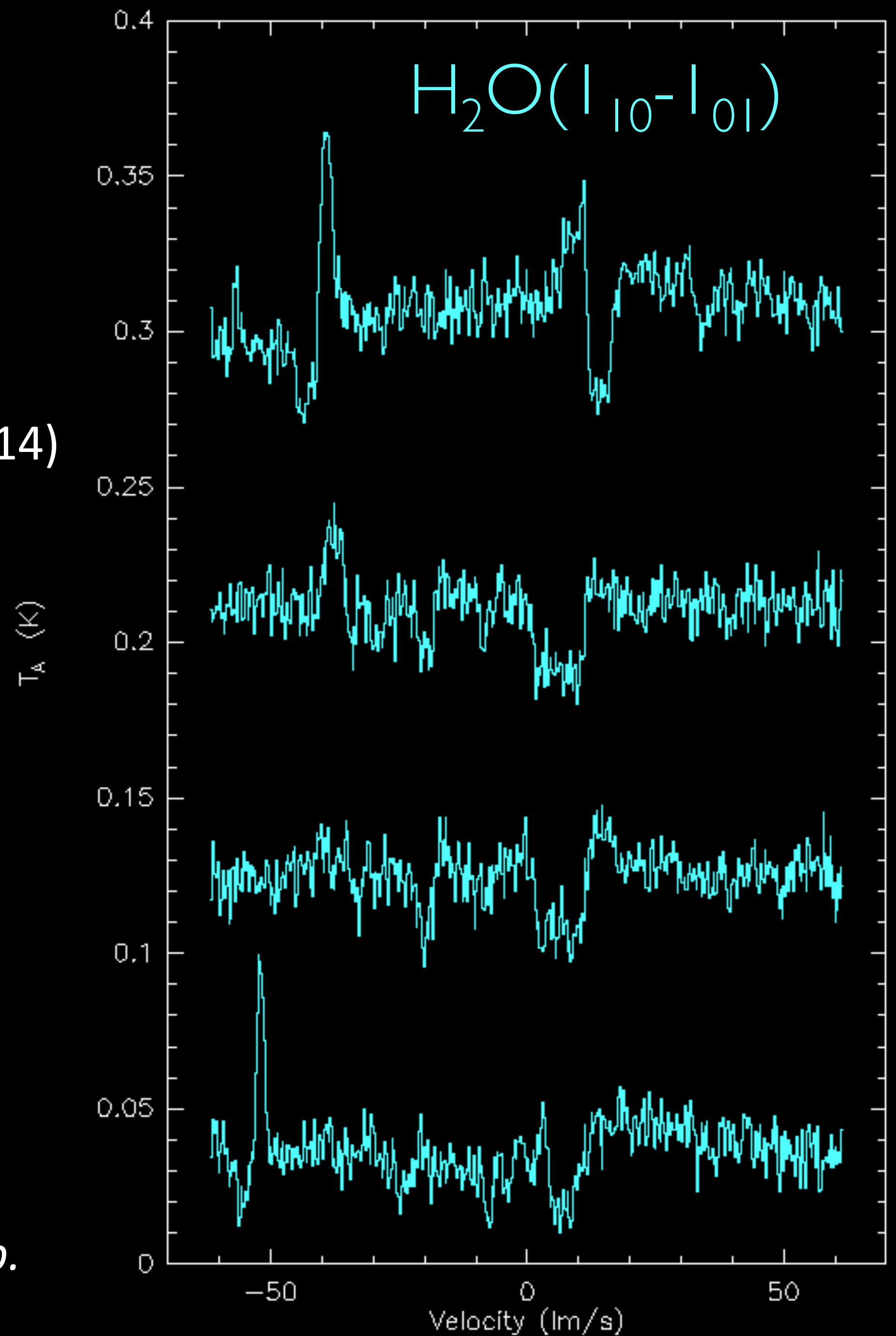


Caselli, Pagani, Yildiz, Aikawa, Tafalla, et al.

… on 4 high-mass PSCs

(also observed with ALMA; Tan et al. 2014)

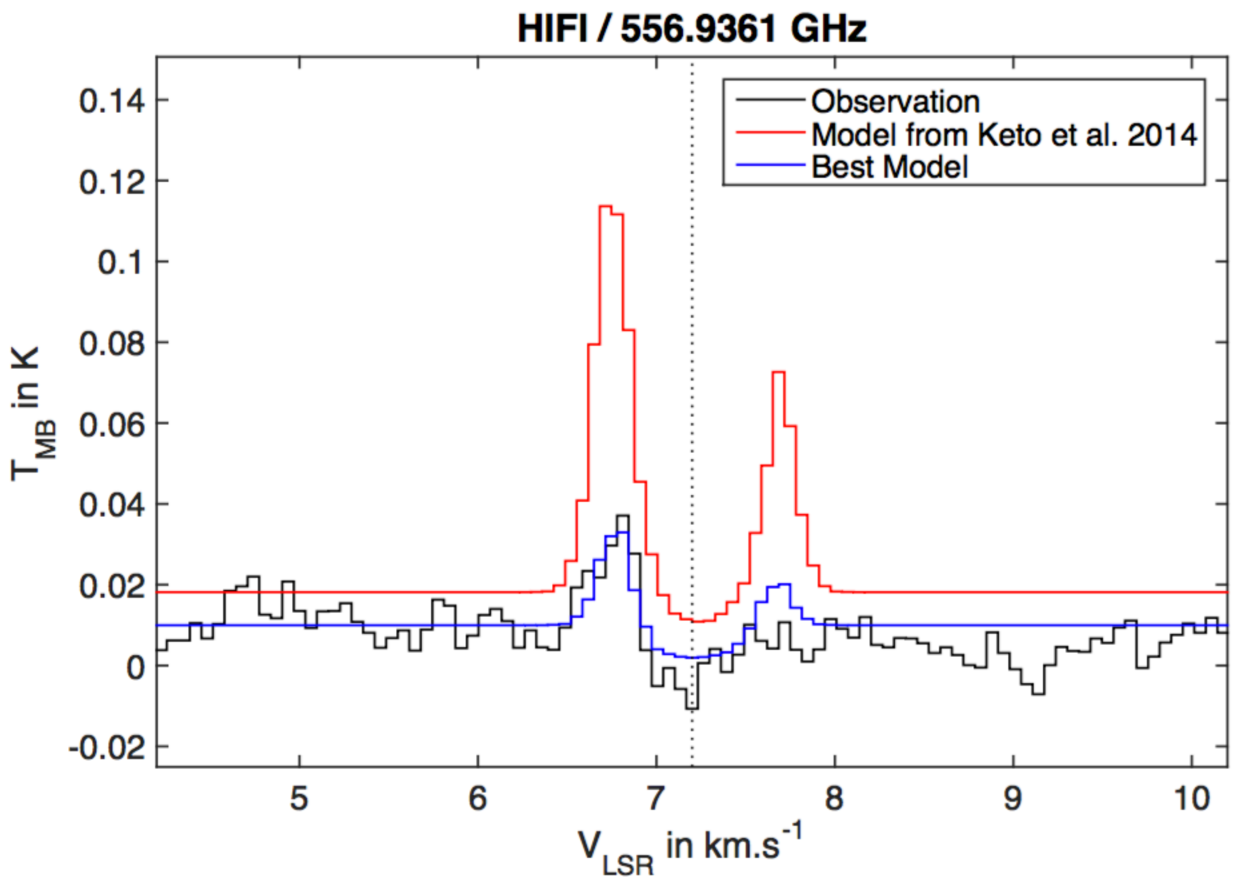
Caselli et al., in prep.



\+
CO(8-7)
CO(9-8)
CO(10-9)
maps to check presence of shocked gas produced by turbulence decay in the process of pre-stellar core formation.

Pon et al., in prep.

The use of full radiative transfer



Quénard, Vastel et al. 2014

A SPECIAL THANK TO:

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