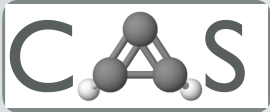
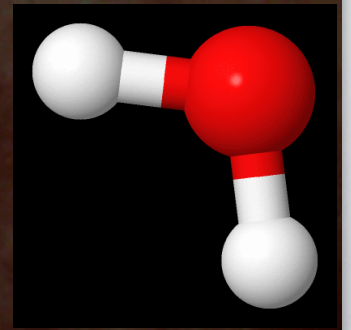


Water at the earliest stages of star formation

Paola Caselli



Center for astrochemical studies, Max-Planck-Institute for extraterrestrial Physics



Credit: ESA/Herschel/SPIRE

OUTLOOK

Pre-stellar Cores

Water in dark clouds

The *Herschel* revolution

Water vapour and ice

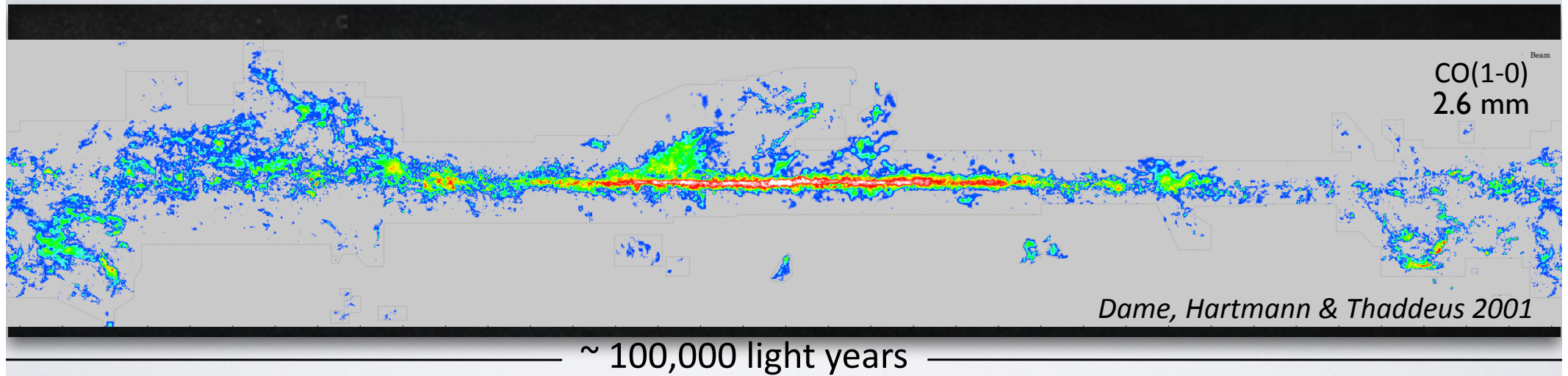
Future perspectives

Our Milky Way and its Dark Clouds

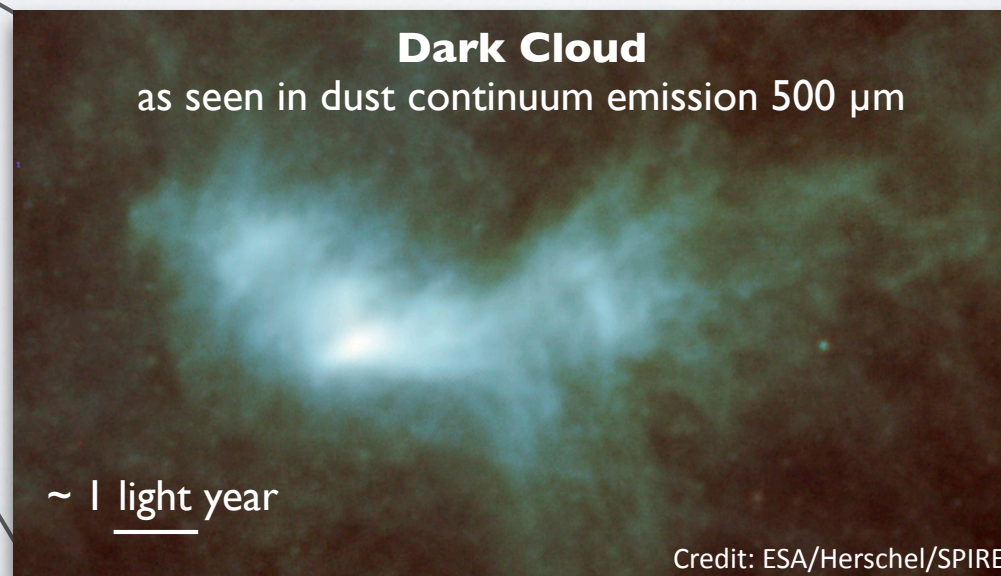
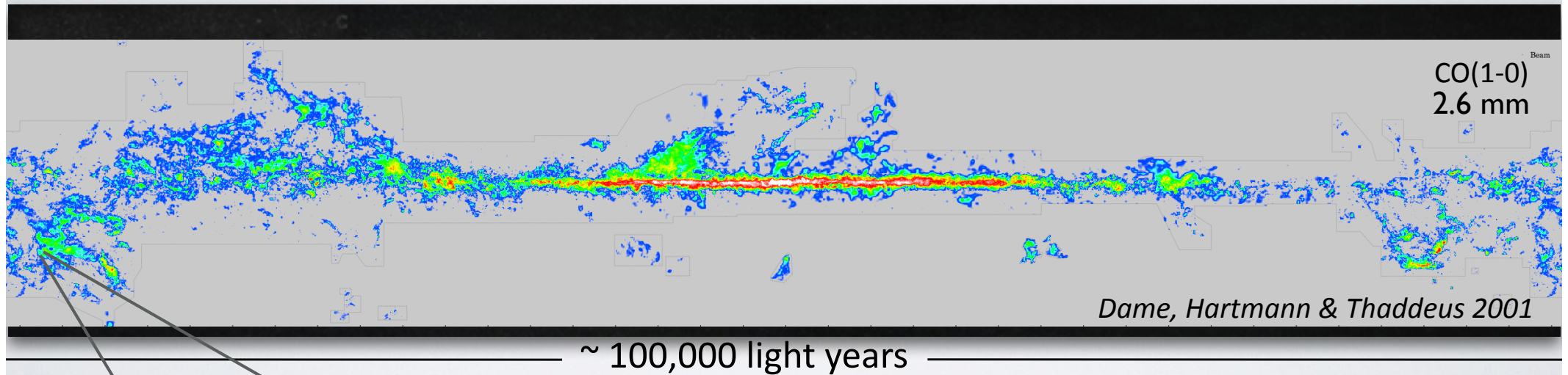


~ 100,000 light years

Our Milky Way and its Dark Clouds

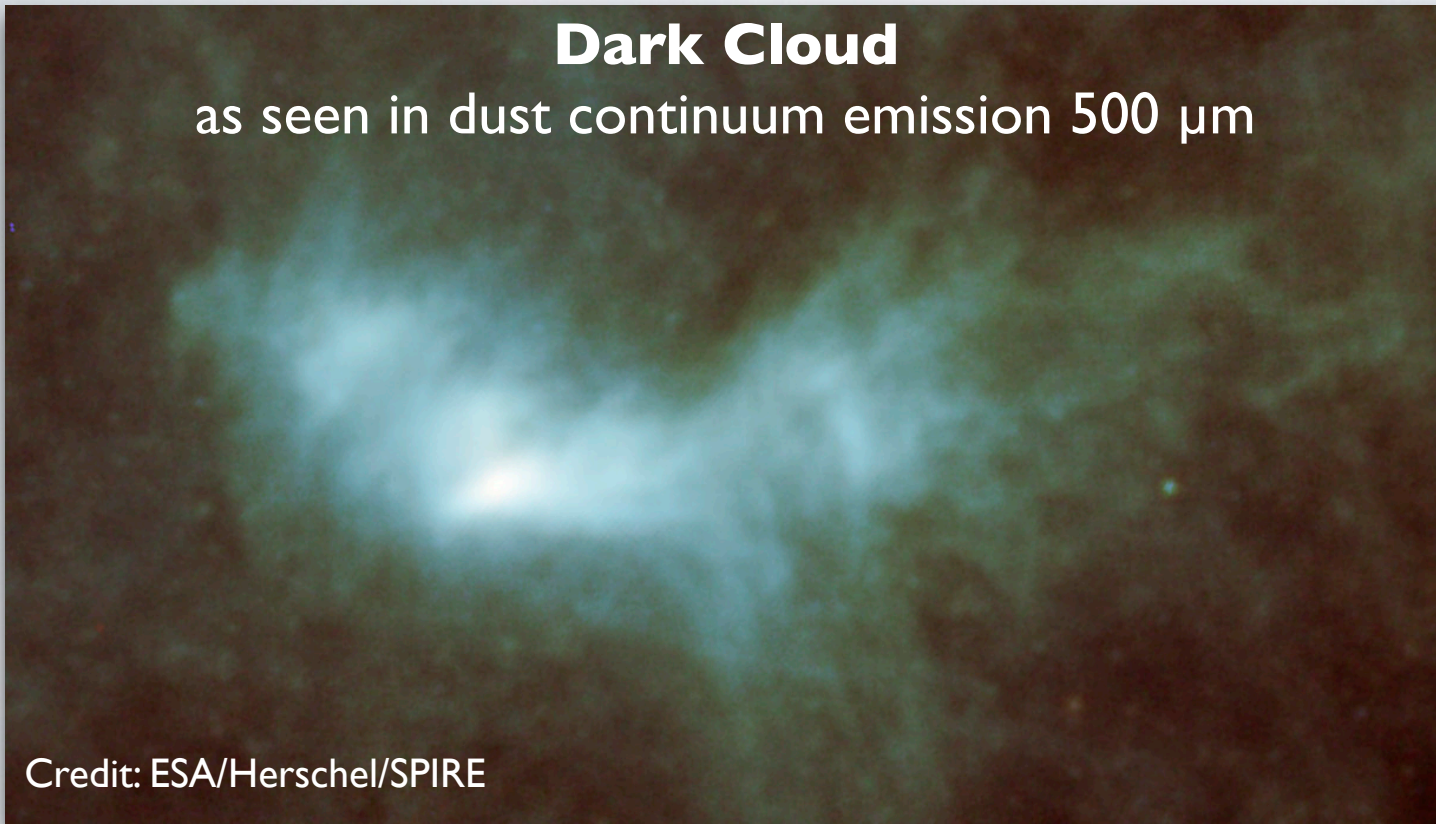


Our Milky Way and its Dark Clouds



Dark Cloud

as seen in dust continuum emission 500 μm



Credit: ESA/Herschel/SPIRE

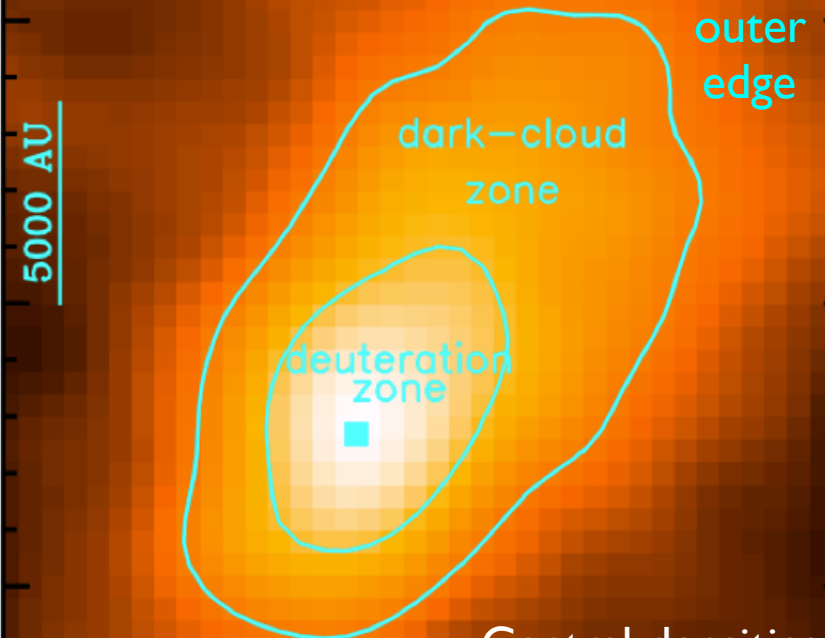
Dark Cloud

as seen in dust continuum emission 500 μm

Credit: ESA/Herschel/SPIRE

Pre-stellar core

1.3mm dust continuum map



Caselli 2011

Central densities:
 $\sim 10^7 \text{ H}_2 \text{ per cc}$

The two classes of dense starless cores

(Keto & Caselli 2008)

Starless (e.g. B68):

$$n_c \sim 10^5 \text{ cm}^{-3}$$

$$T_c \sim 10 \text{ K}$$

Oscillatory motions

(Lada+2003)

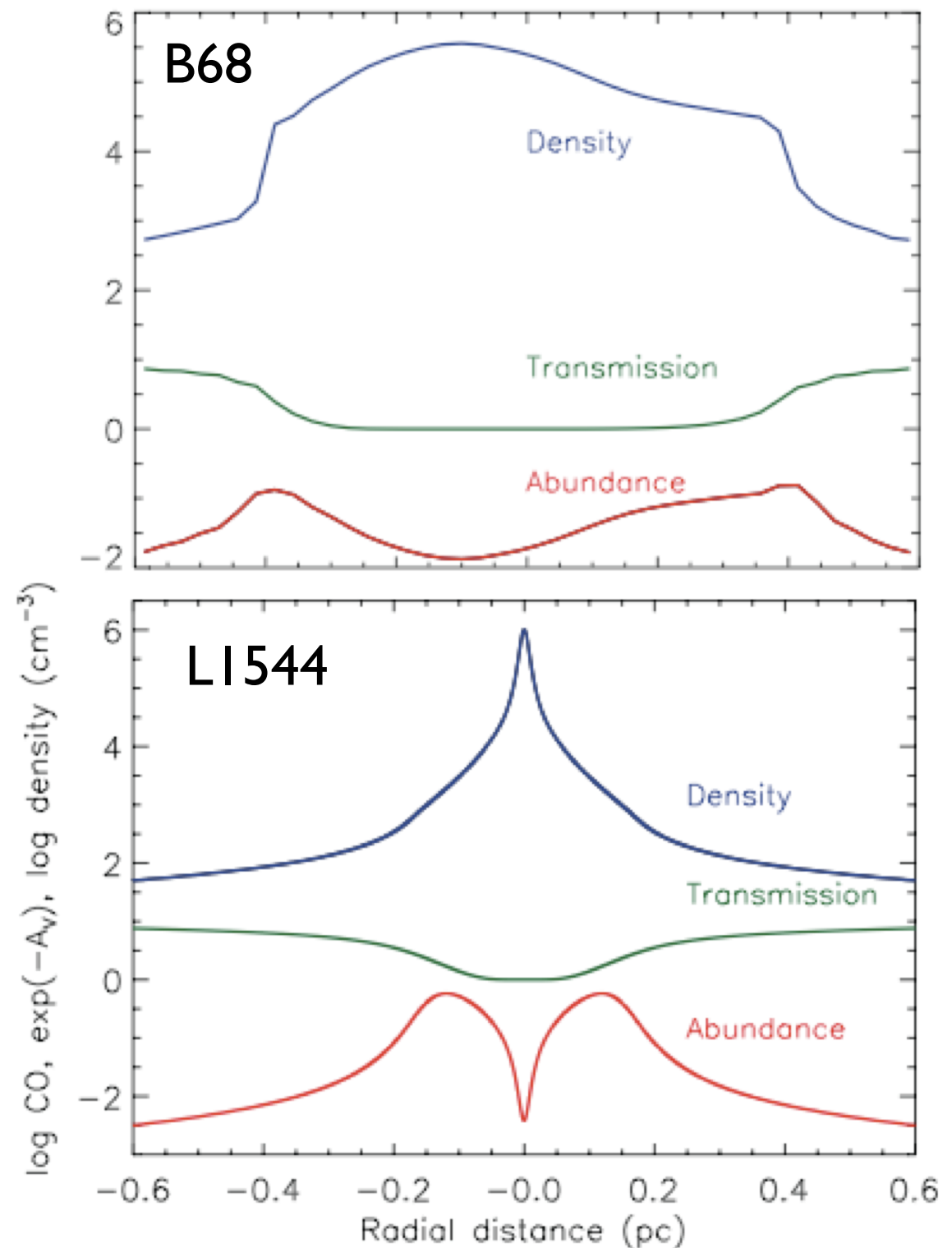
Pre-stellar (e.g. L1544):

$$n_c \sim 10^6 \text{ cm}^{-3}$$

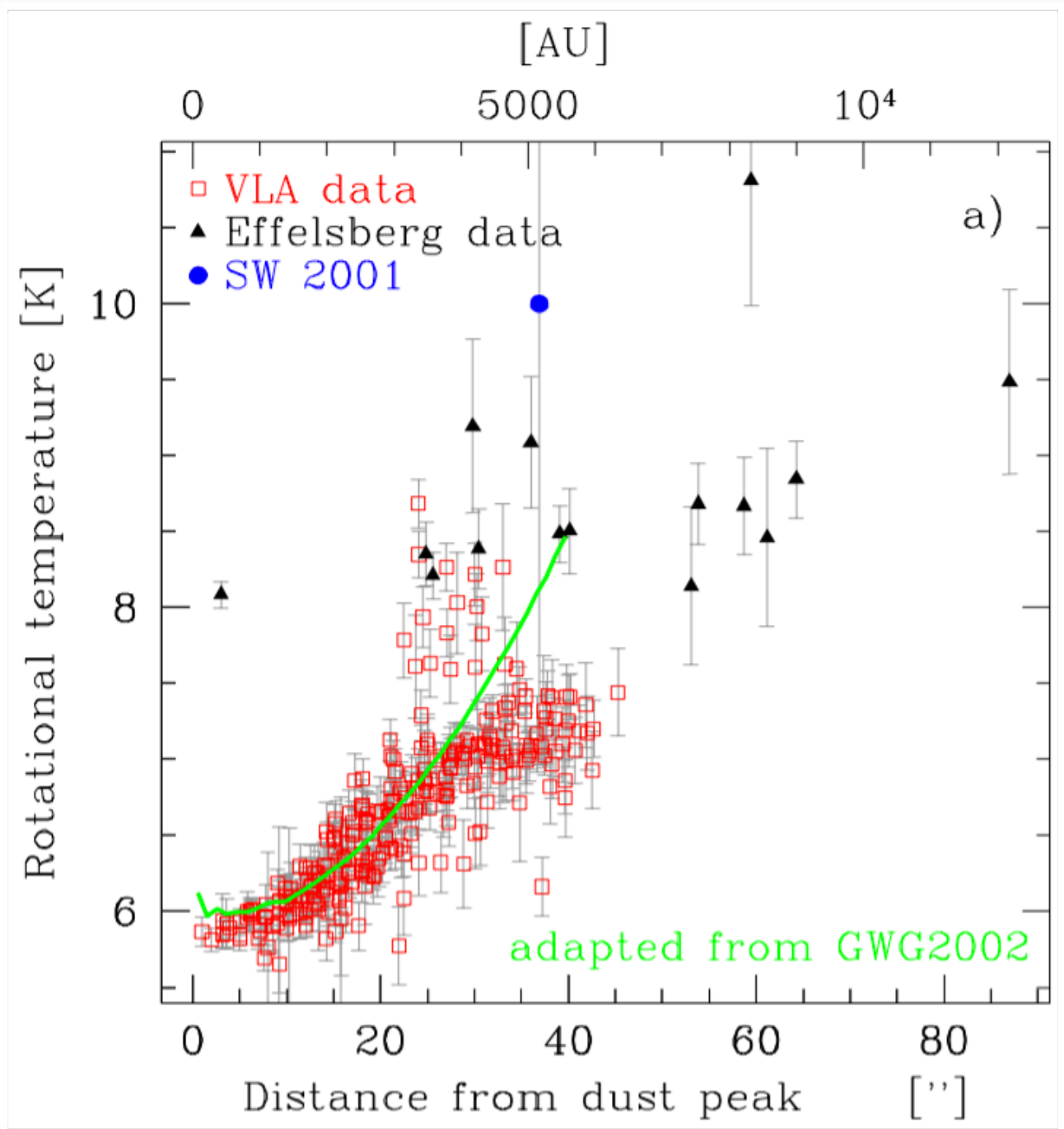
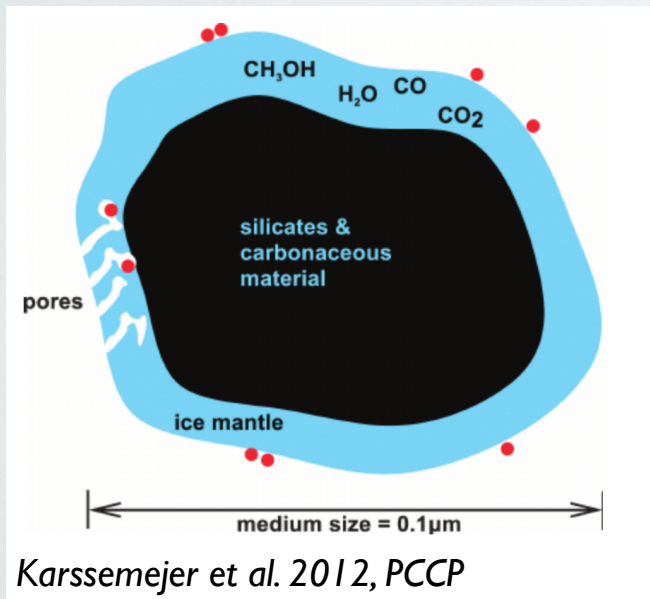
$$T_c \sim 6 \text{ K}$$

Contraction motions

(Tafalla+1998; Caselli+2002)



In pre-stellar cores, the gas temperature drops to ~ 6 K in the central few thousand AU

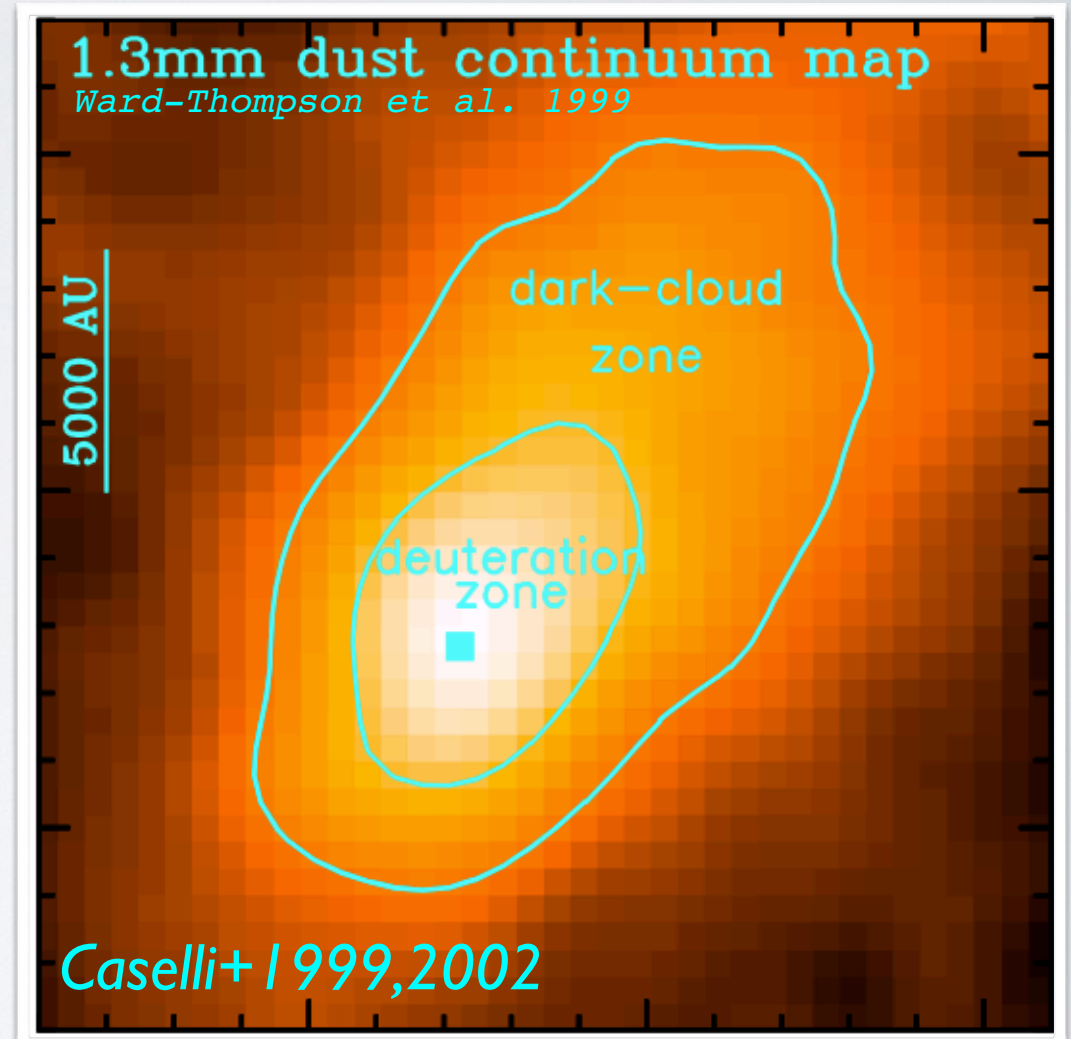
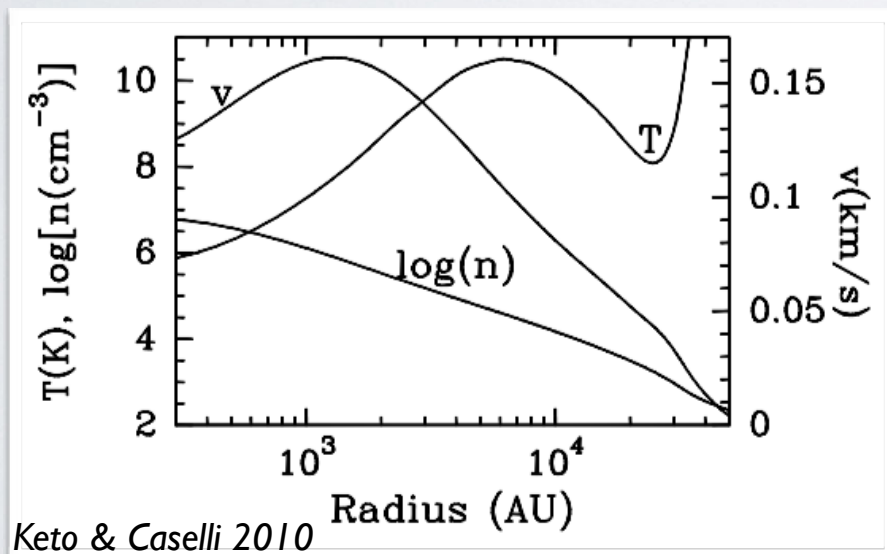


Crapsi, Caselli, Walmsley, Tafalla 2007

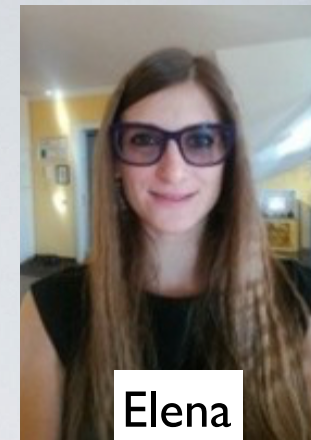
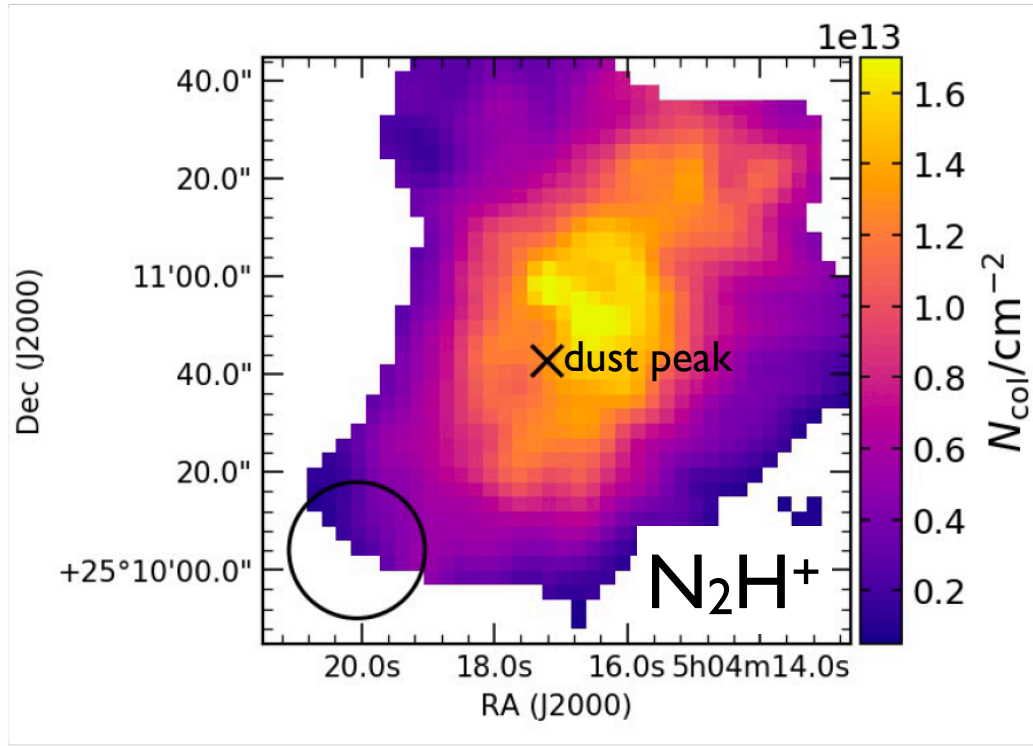
CO freeze-out and the deuteration zone

Within central 5000 AU:

- 99% of CO molecules frozen on dust;
- D-fractions $\sim 20\%$.

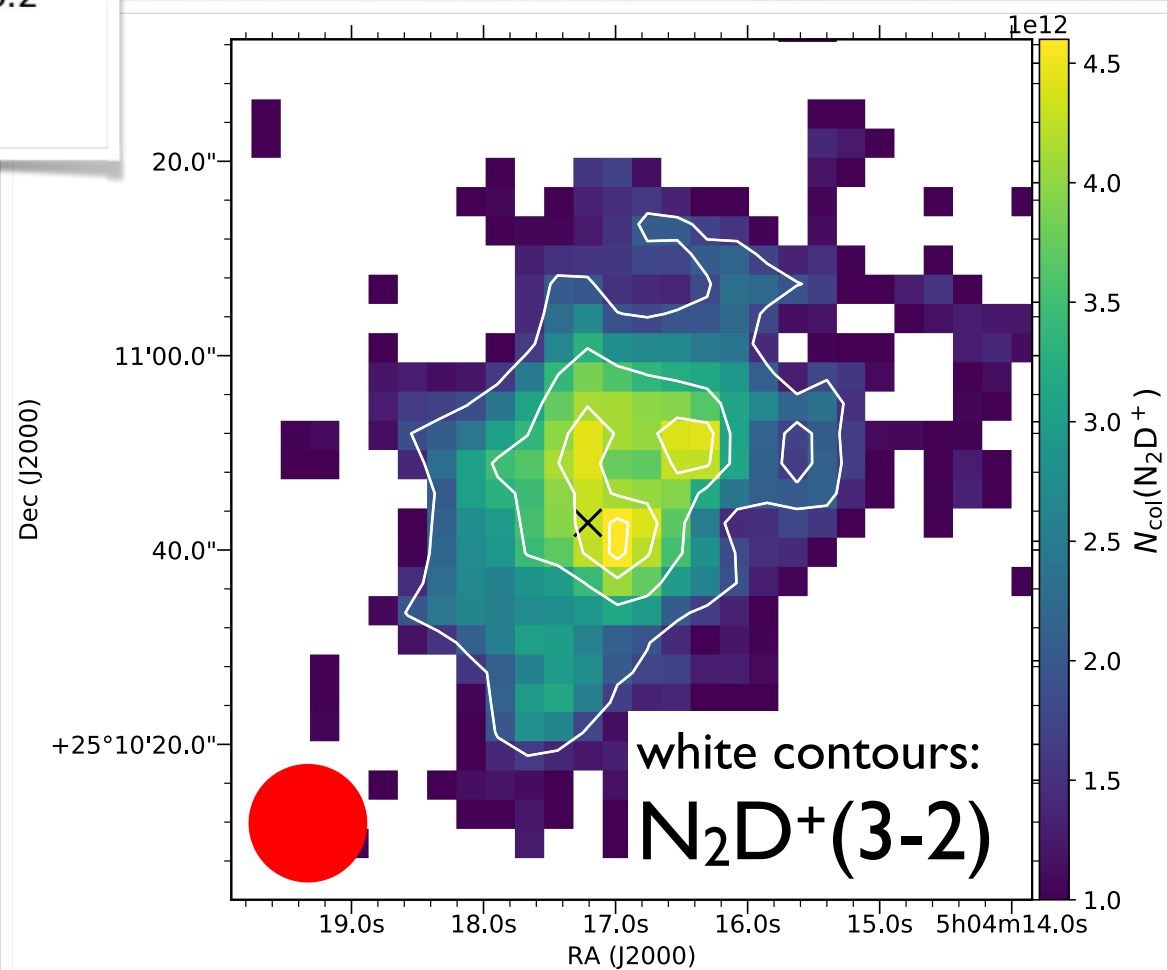


(see also Bacmann+2002, 2003; Hirota+2003; Crapsi+2007; Pagani+2007; Spezzano+2016)



Large D-fraction
(~30%) at high
density and **first
evidence of
 N_2D^+ depletion.**

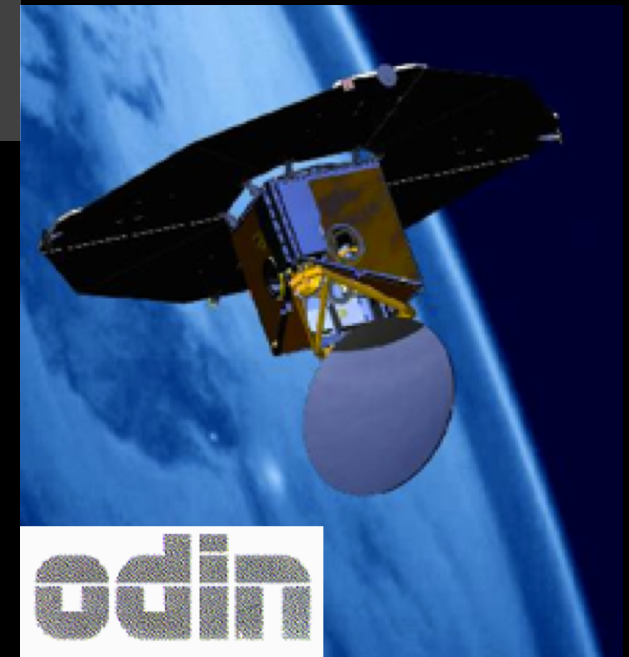
Redaelli+20 / 9



Previous attempts to detect cold water vapor

$$x(\text{H}_2\text{O}) < 10^{-8}$$

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

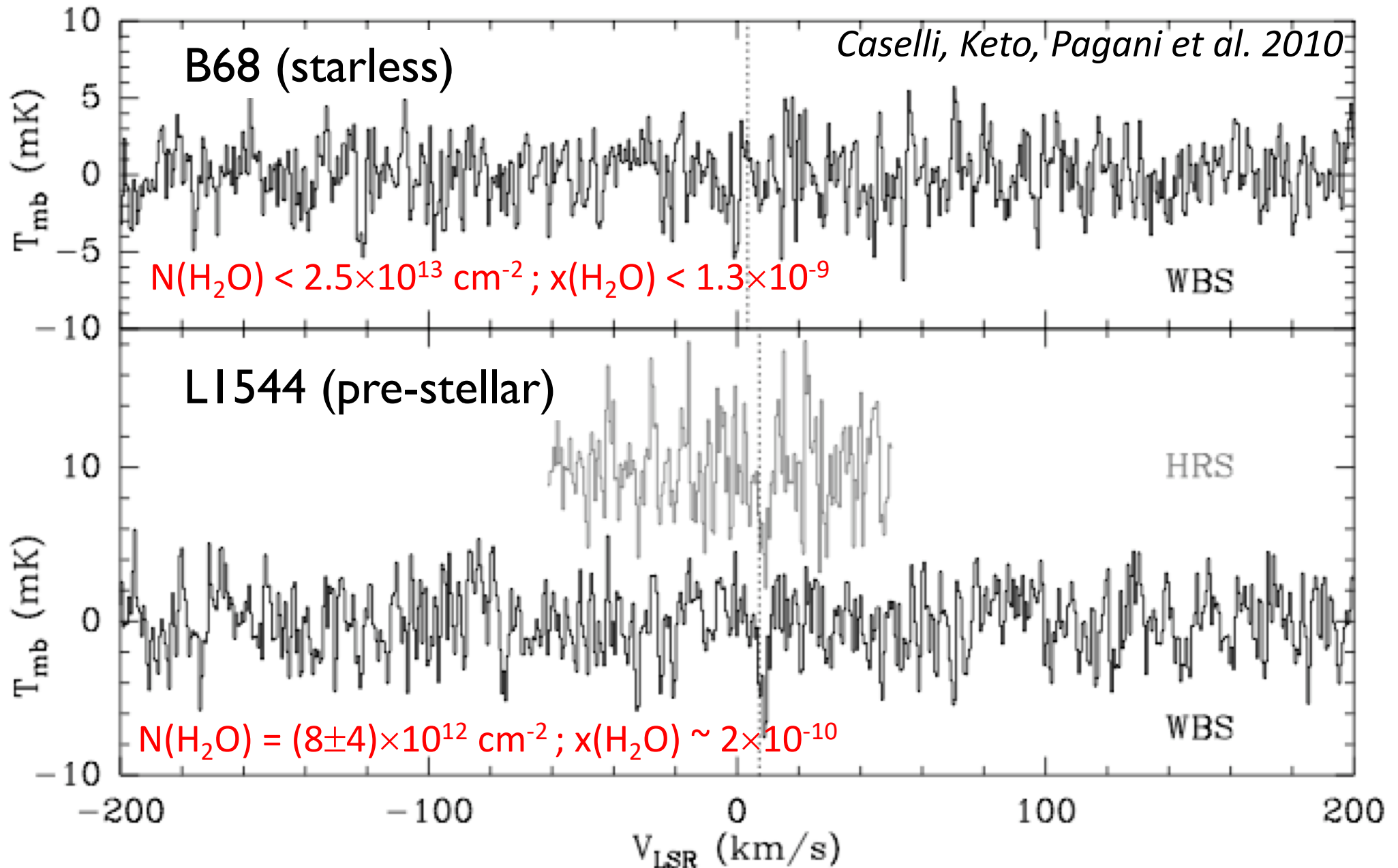


The *Herschel* (HIFI) revolution





2010 WISH Data (HIFI-WBS)

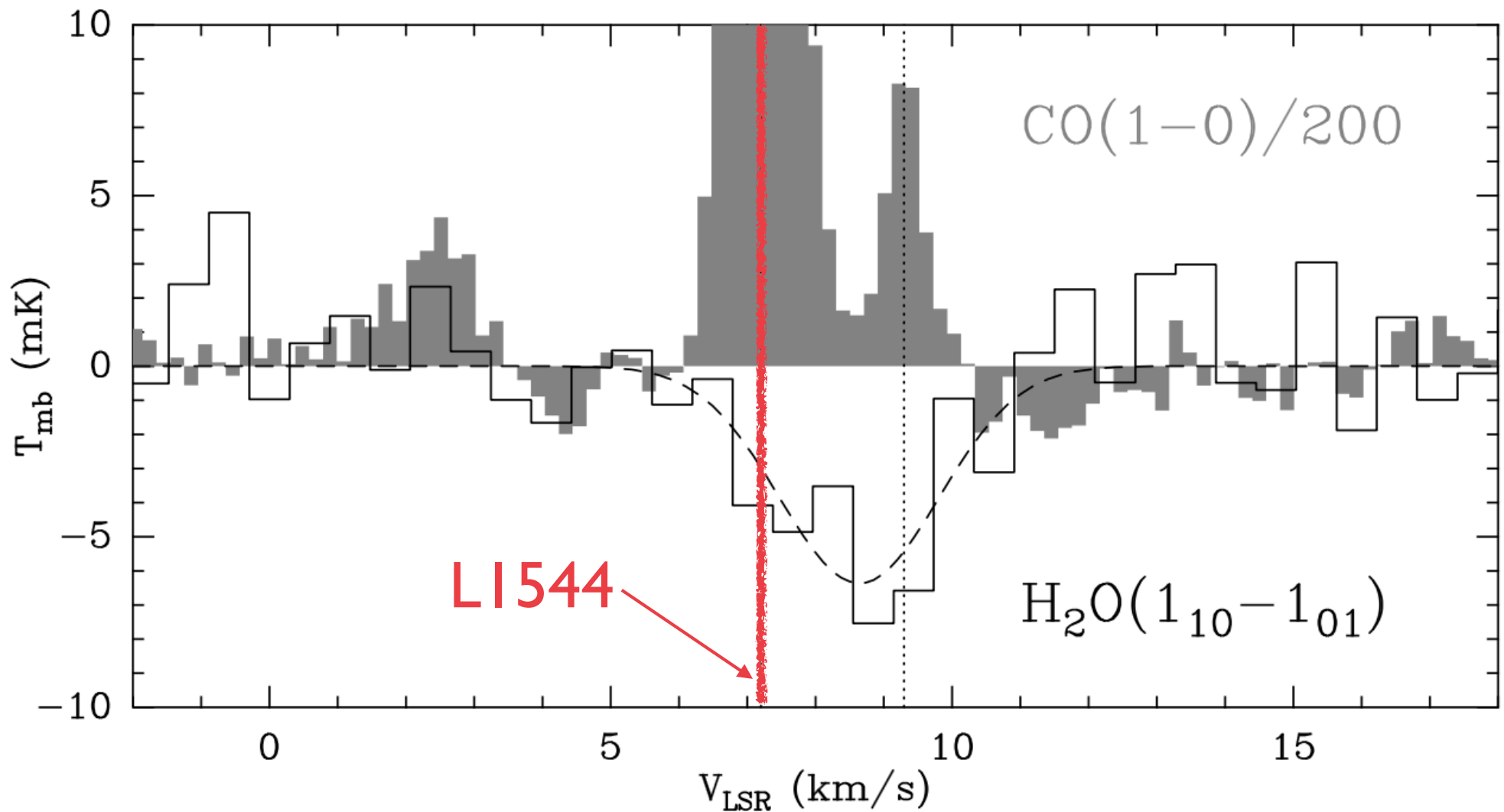




2010 WISH Data (HIFI-WBS)

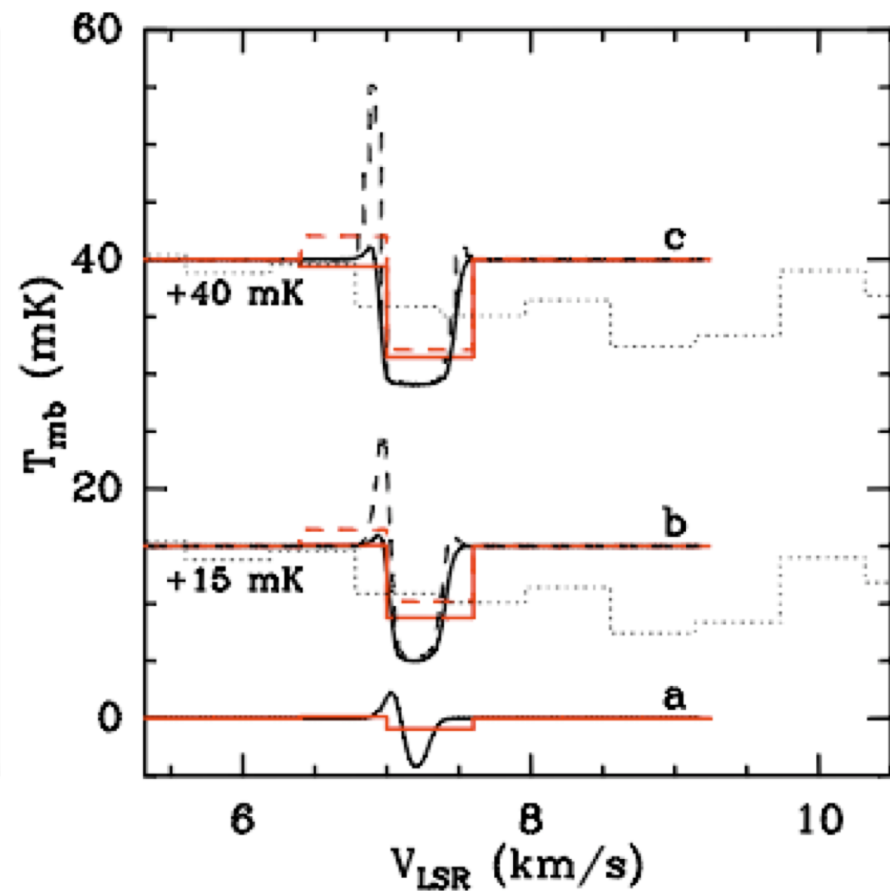
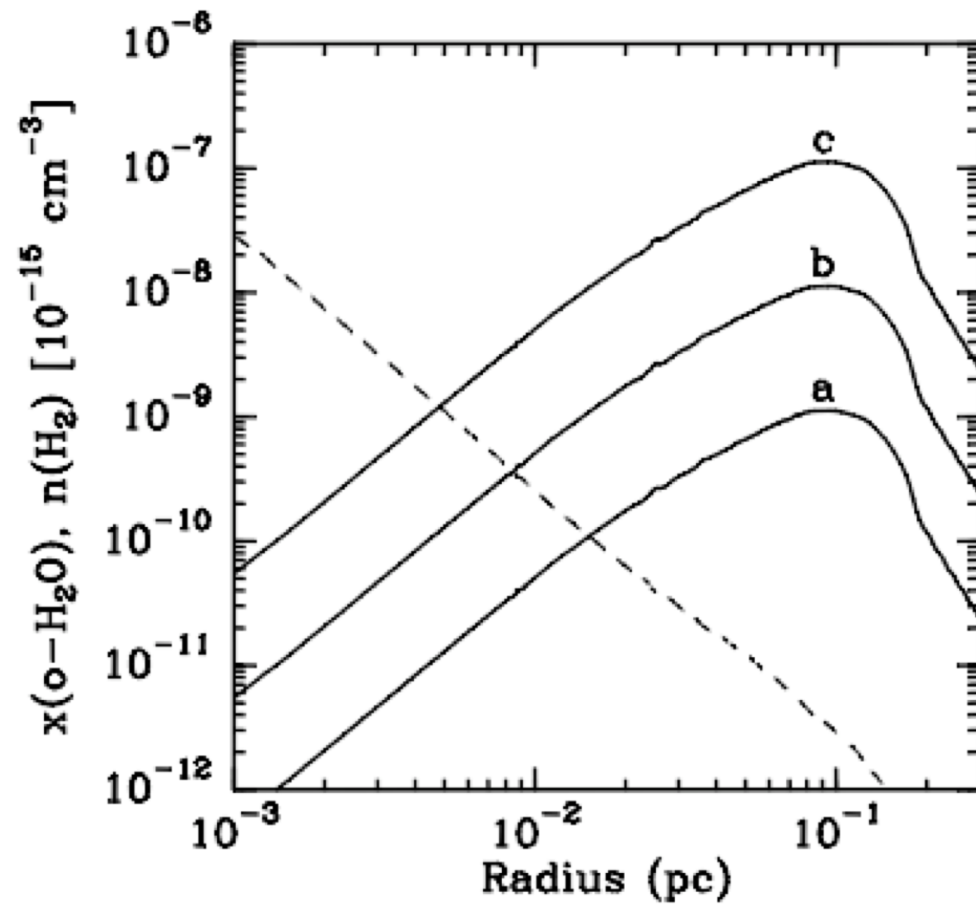


Water absorption is dimmer toward LI544!





2010 Data

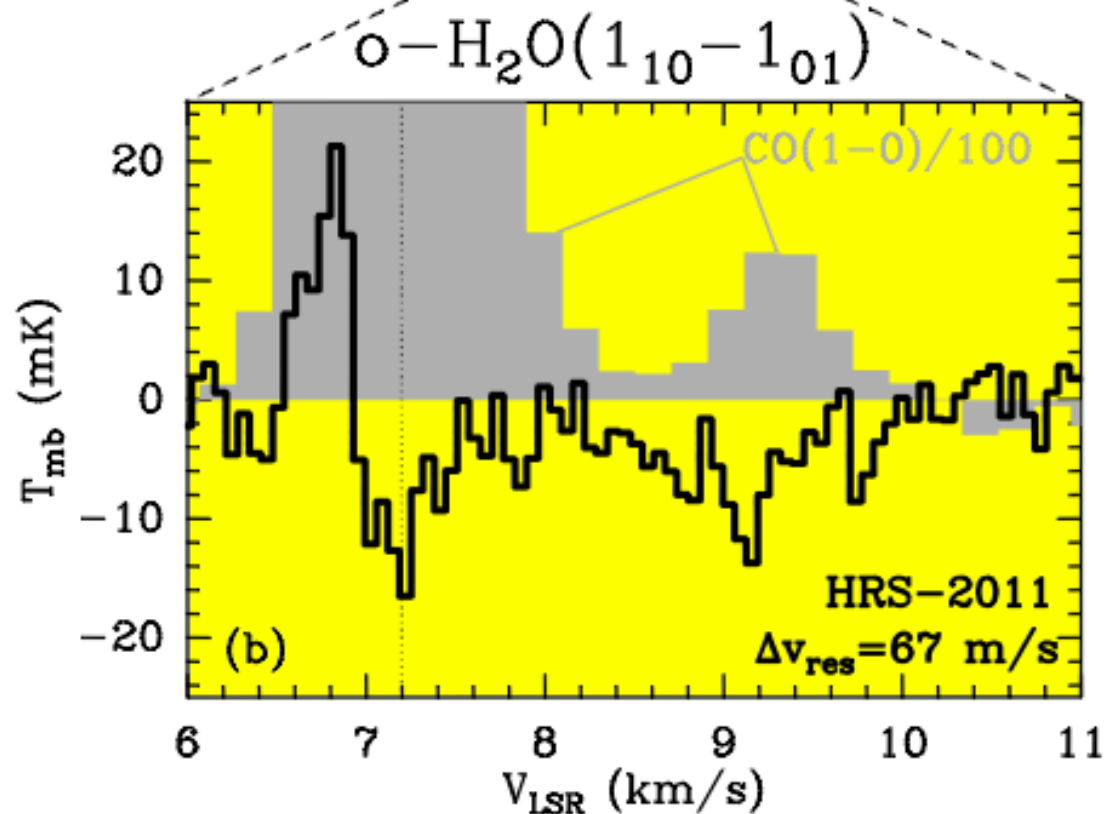
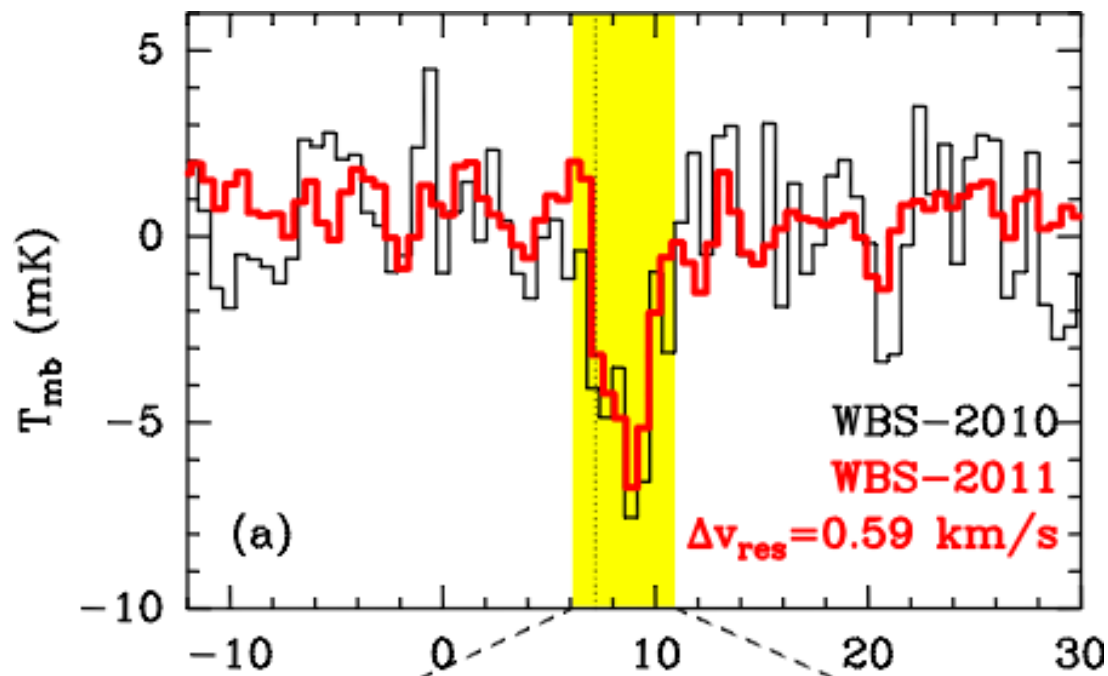


Caselli, Keto, Pagani et al. 2010

2011 WISH Data (HIFI-HRS)

The background of the slide is a deep space image showing a nebula. A bright, yellowish-white central source is surrounded by a diffuse, blue-green cloud of gas and dust. The overall color palette is dark, with the nebula's glow providing the primary light source.

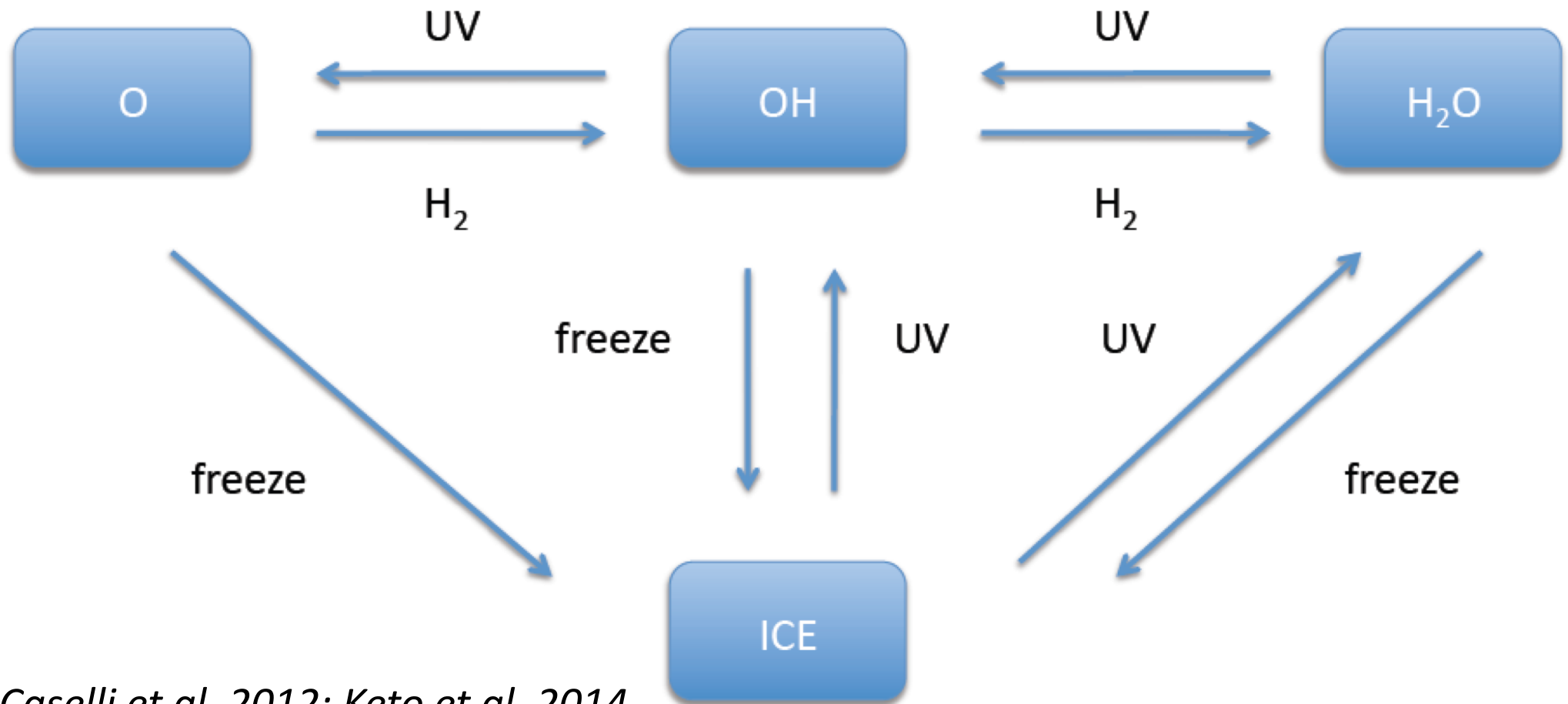
Credit: ESA/Herschel/SPIRE



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

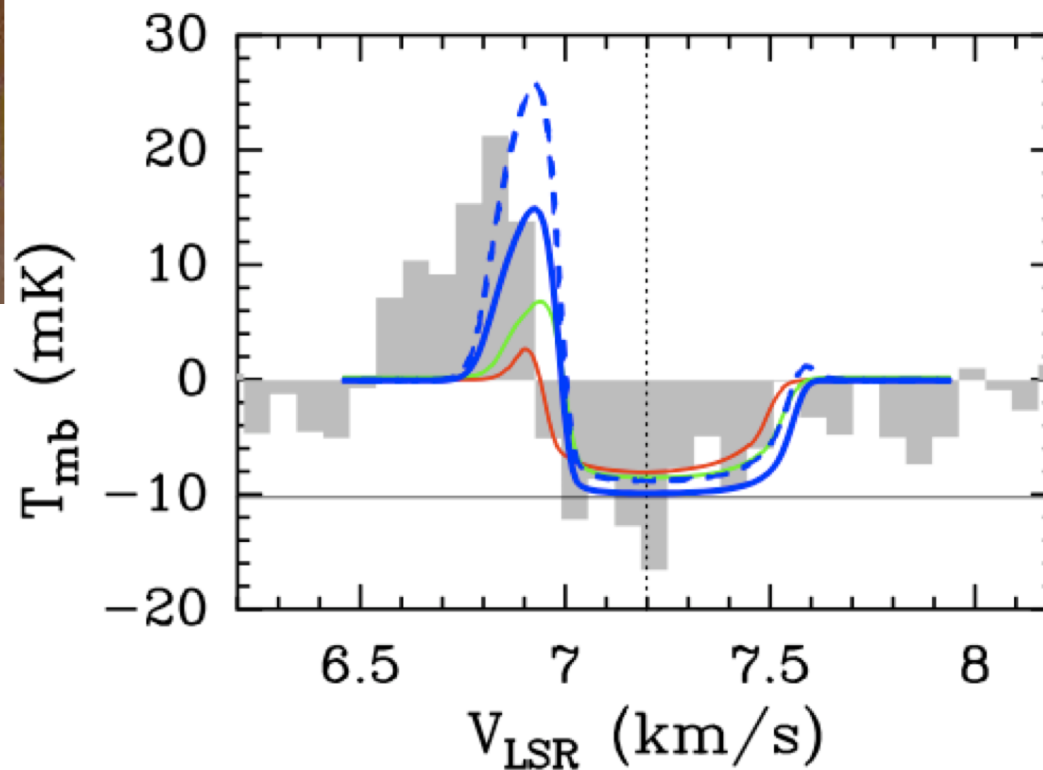


Simplified O-chemistry



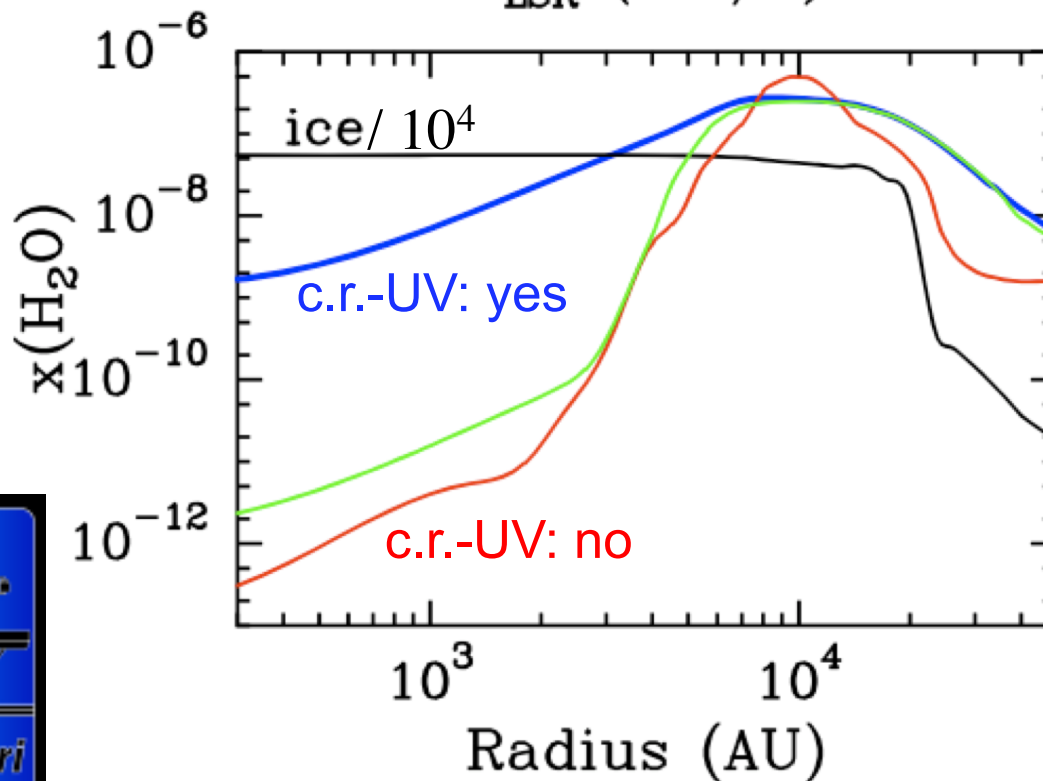
Caselli et al. 2012; Keto et al. 2014

see also Schmalzl et al. 2014



Key factors to explain observed spectrum:

◆ $x(\text{H}_2\text{O}) \sim 10^{-9}$ in center maintained by FUV photons produced by cosmic-ray impacts with H_2 .



◆ $n_{\text{H}} \geq 10^6 \text{ cm}^{-3}$, to explain H_2O emission.

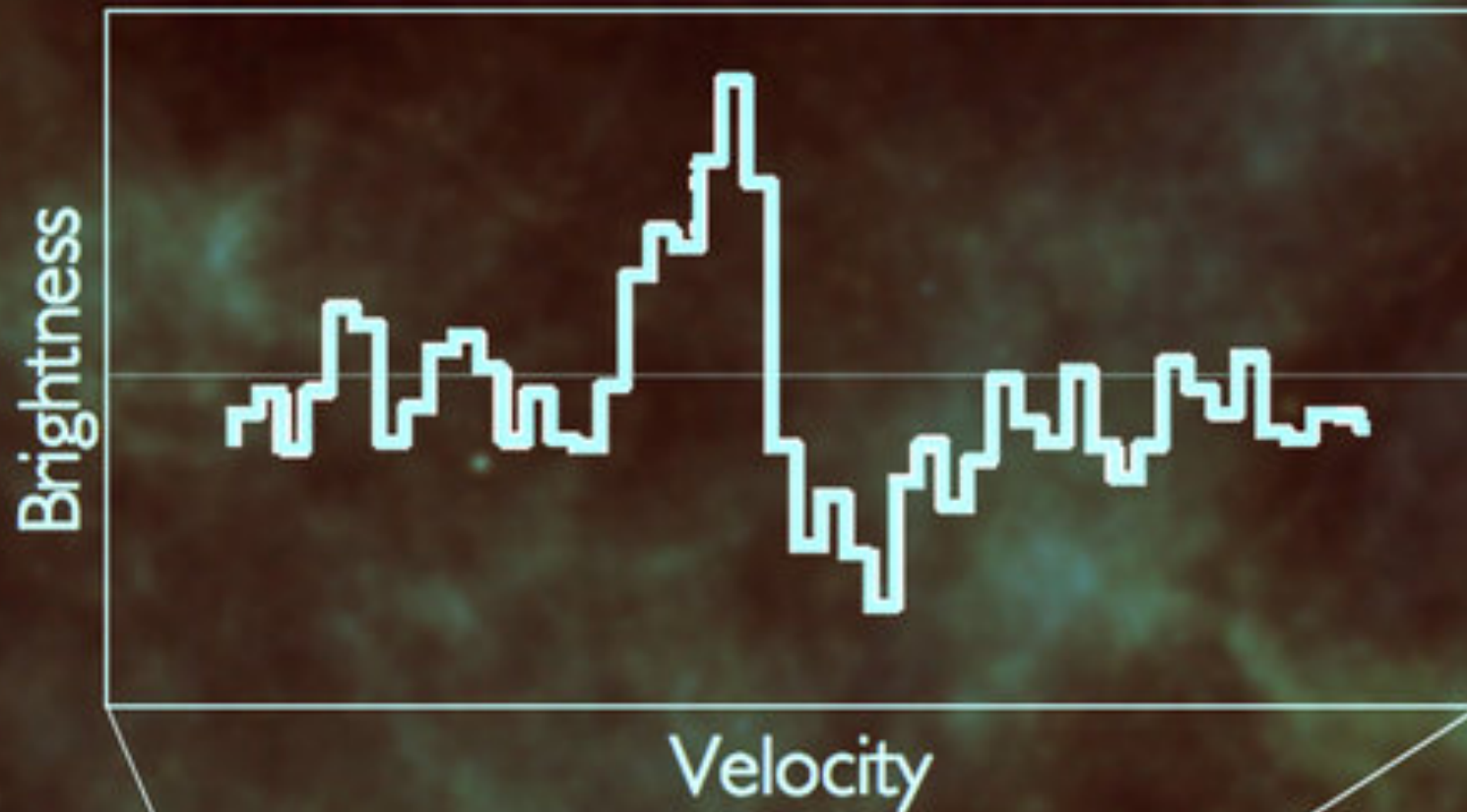
◆ Gravitational contraction to see blue wing in emission.



Brightness

Velocity

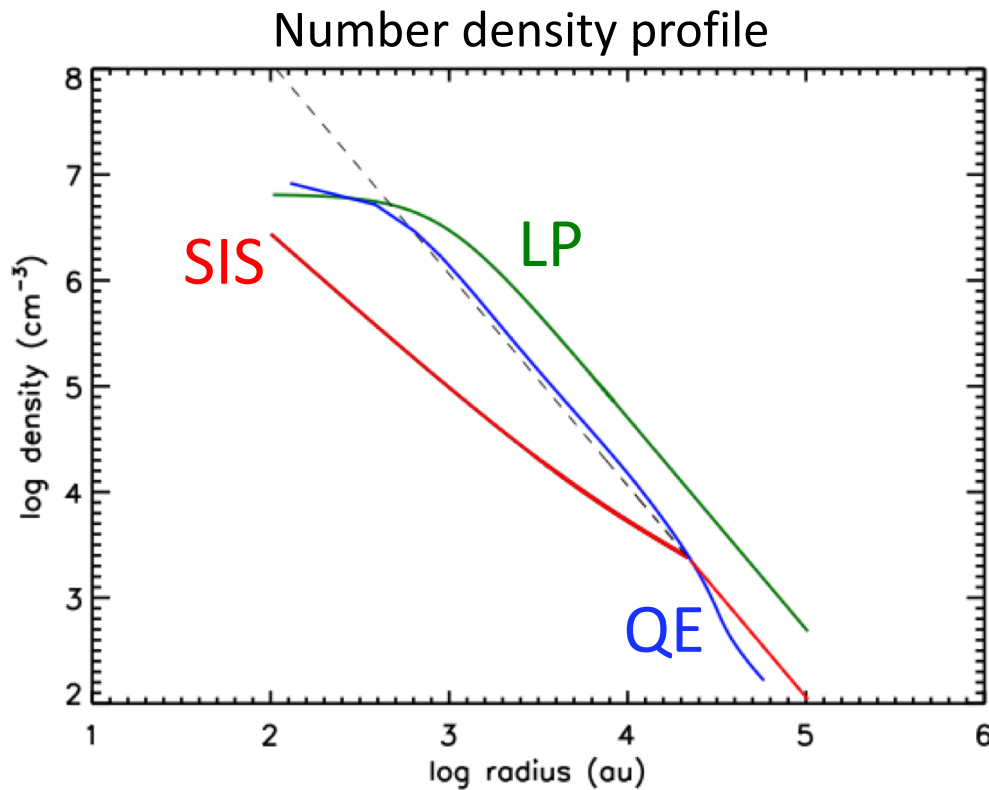
First detection of water vapor in a pre-stellar core



MAIN RESULTS:

1. Unveiled gravitational infall within central 1,000 AU;
2. Measured total mass of water vapor: ~ 0.5 Earth masses;
3. Deduced total mass of water ice: ~ 2.6 Jupiter masses;
4. Cosmic rays important for water desorption.

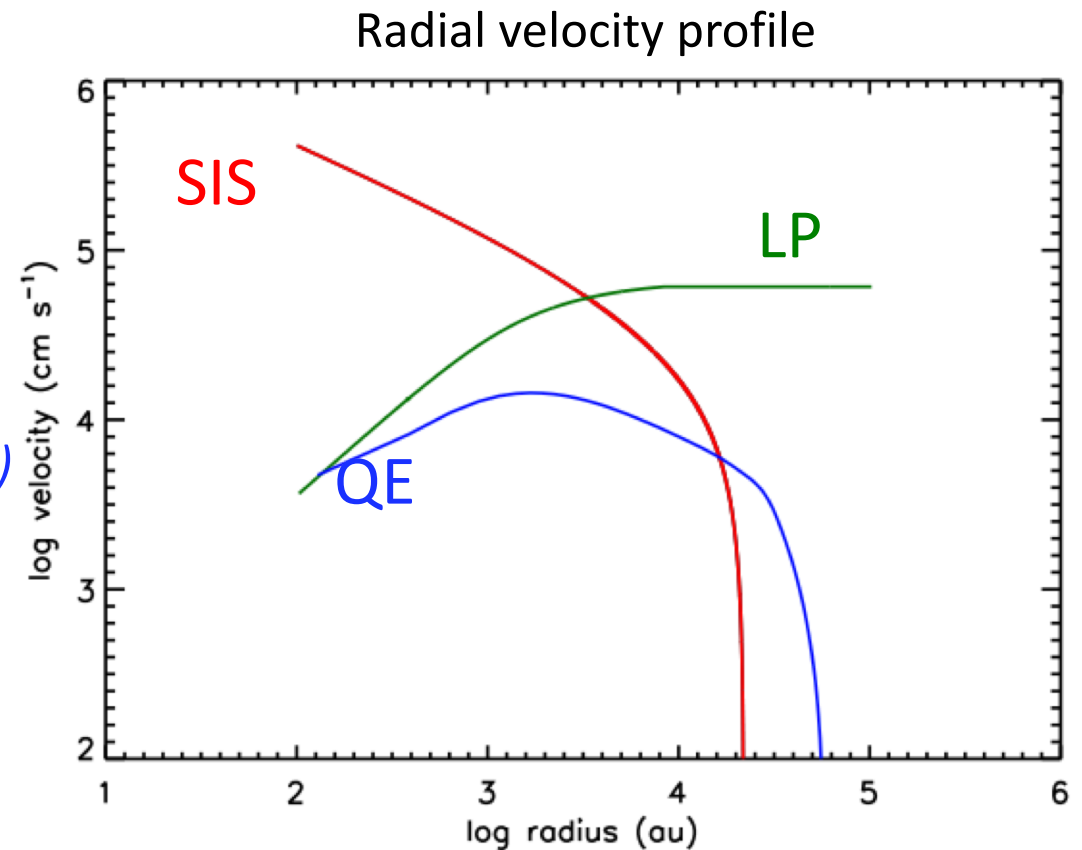
The dynamics of collapsing cores constrained by ortho-H₂O and C¹⁸O



SIS=Singular Isothermal Sphere (*Shu 1977*)

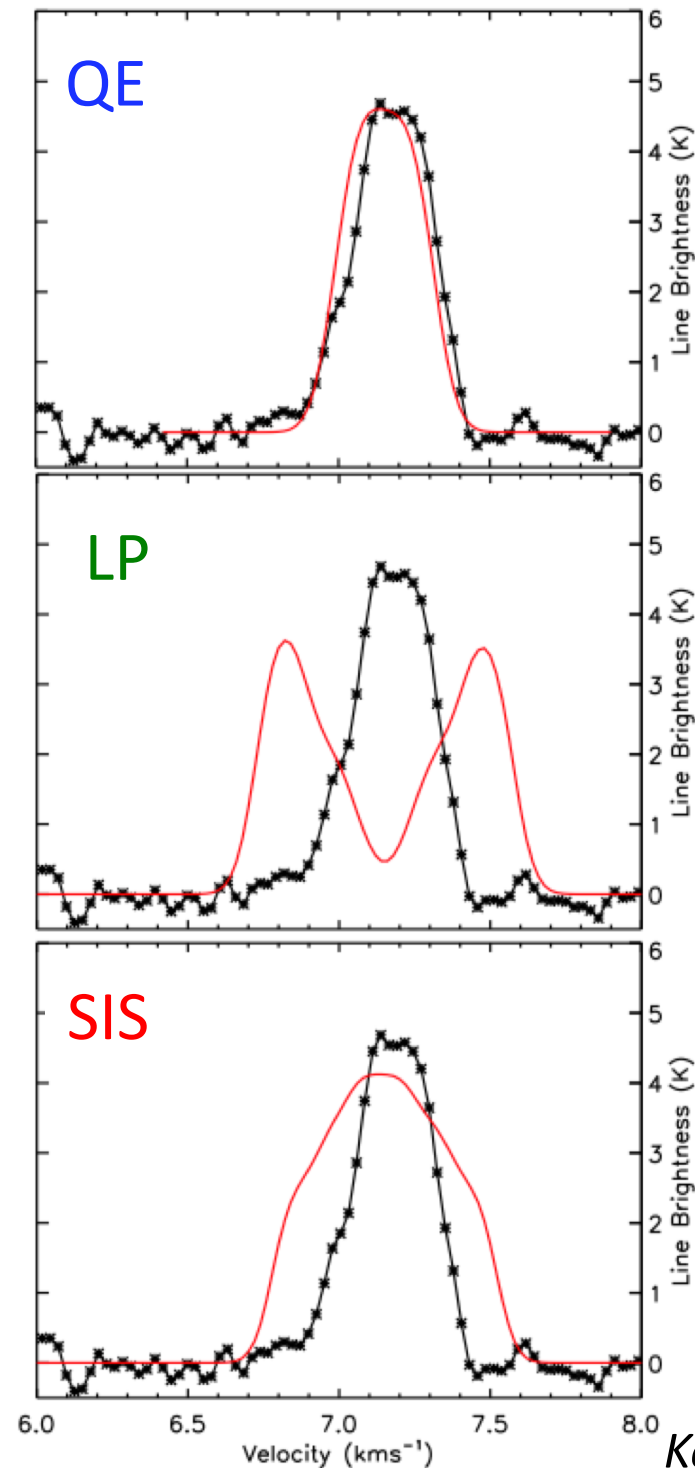
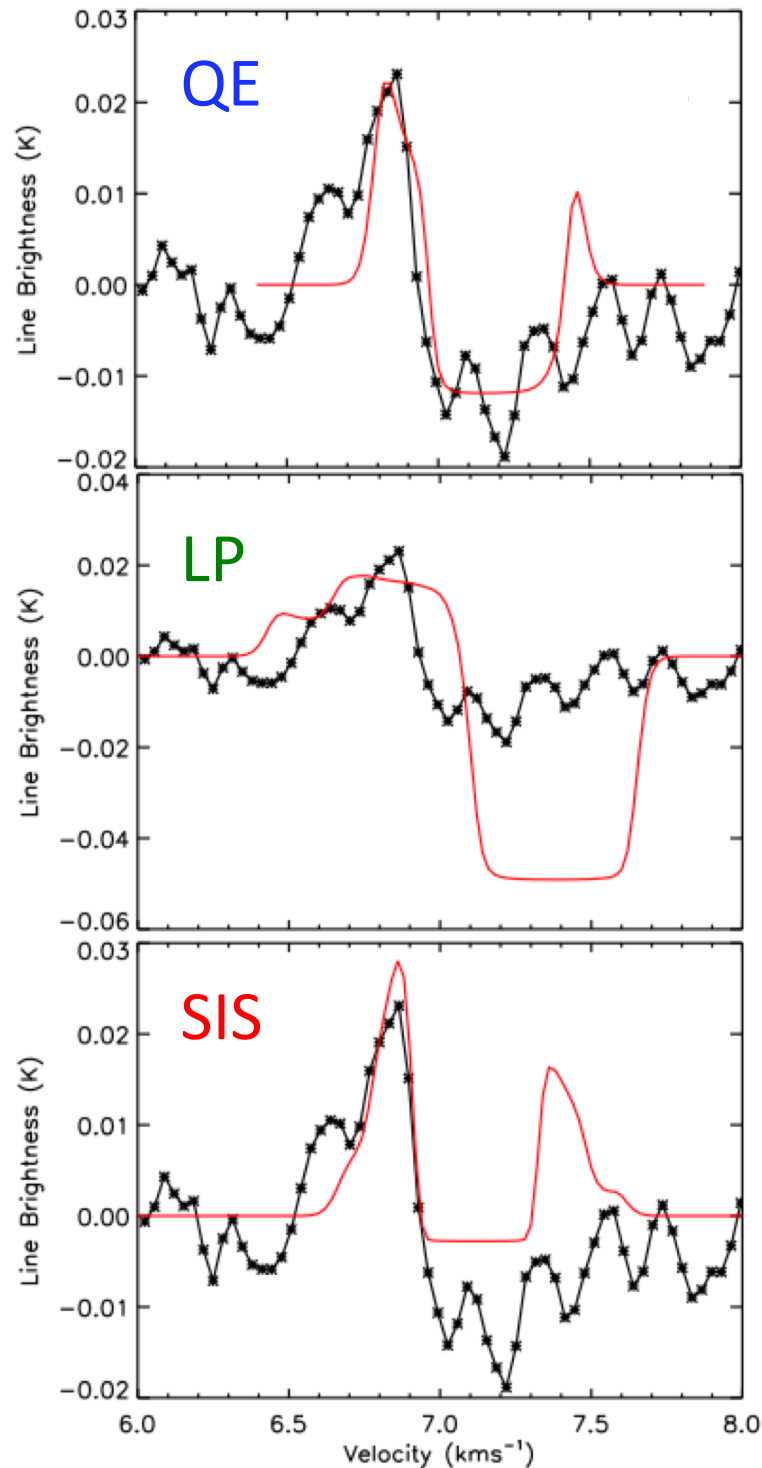
LP=Larson-Penston (1969)

QE=Quasi-Equilibrium BES (*Keto & Caselli 2010*)



ortho-H₂O(1₁₀-1₀₁)

C¹⁸O(1-0)



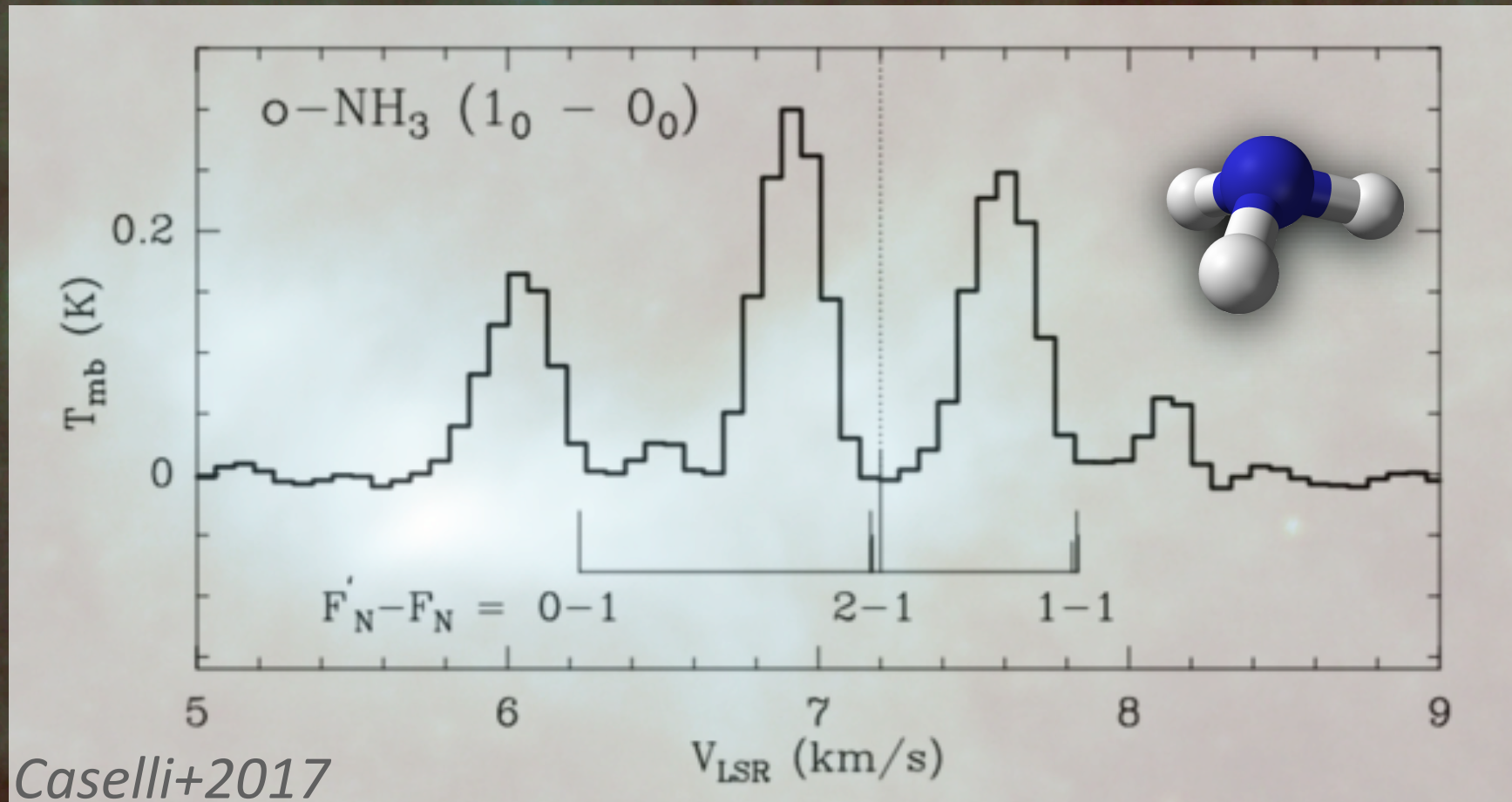
The dynamics of collapsing cores constrained by H₂O and C¹⁸O:

L1544 is contracting in quasi-static equilibrium

Keto, Caselli, Rawlings 2015

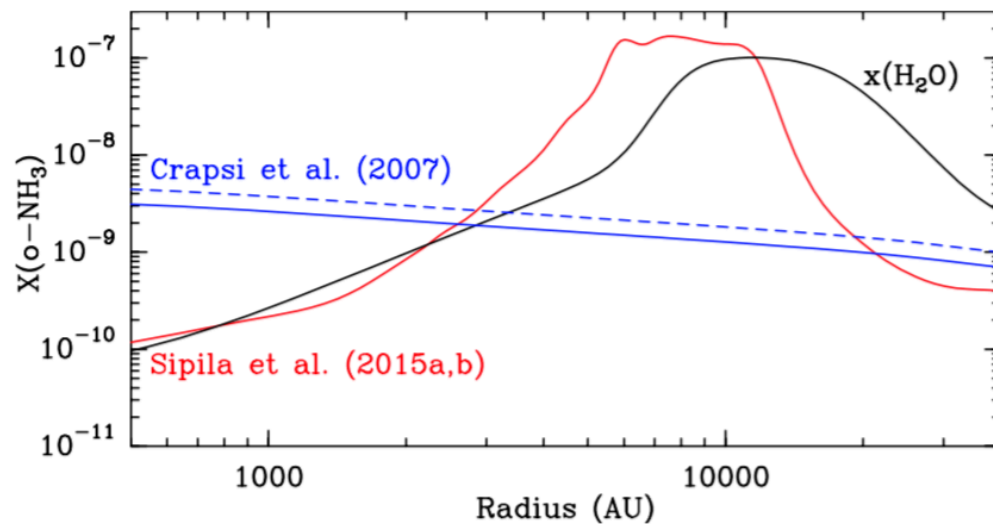


The ortho-NH₃(1₀-0₀) spectrum toward L1544 with Herschel



Taken simultaneously with ortho-H₂O(1₁₀-1₀₁)

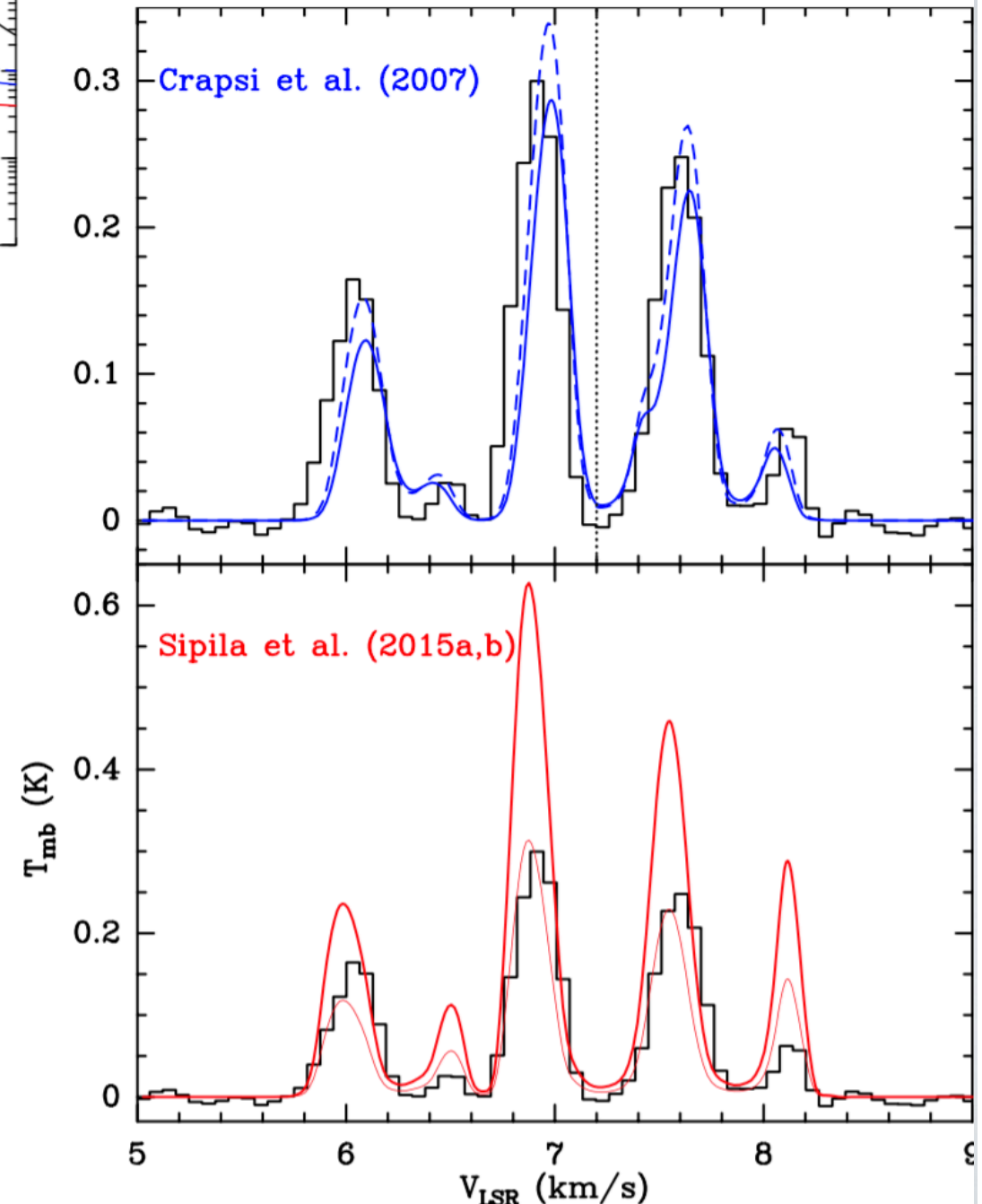
Caselli+2017 (see also Sipilä+2019)



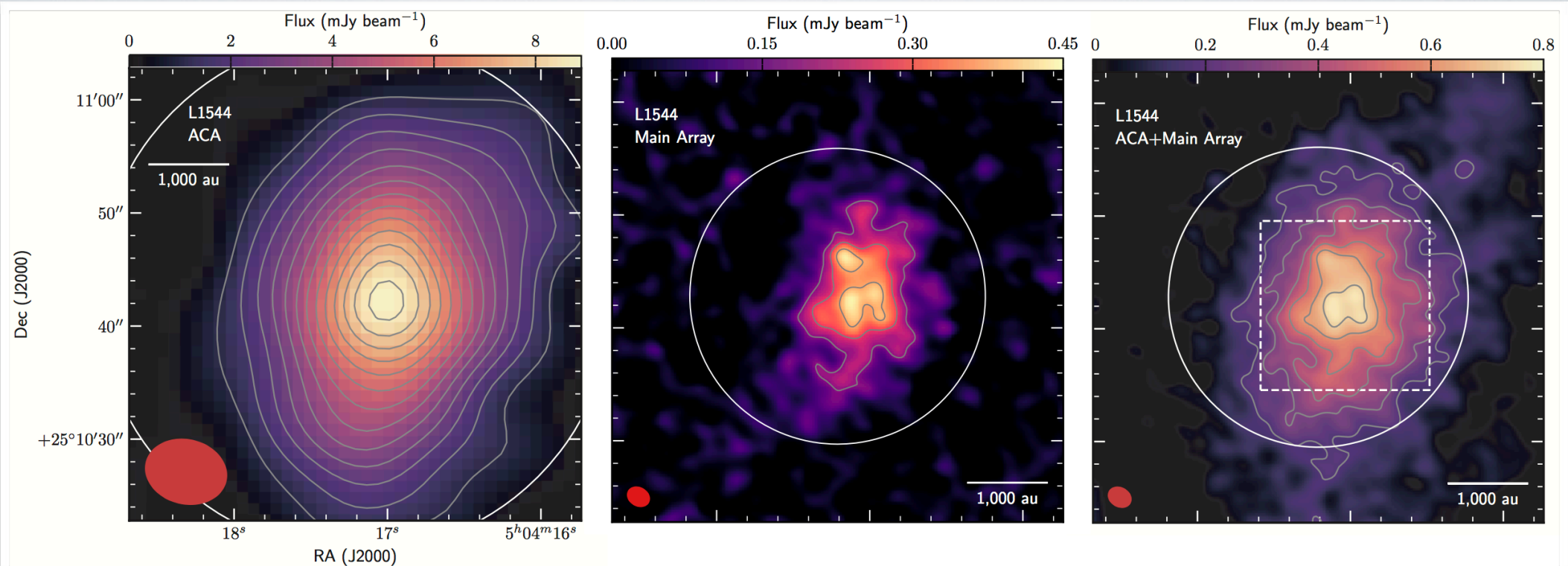
The ortho-NH₃ profile is well-reproduced with the Keto+(2014) physical model of L1544, if NH₃ has almost constant abundance across the core (Crapsi+2007).

Comprehensive gas-grain chemical models do not agree with observations (Sipilä+2015).

NITROGEN CHEMISTRY IS STILL NOT UNDERSTOOD!



ALMA observations of a $8 M_{\odot}$ pre-stellar core reveal a dense (10^6 cm^{-3}) “kernel” of $0.1 M_{\odot}$ and radius 1400 au

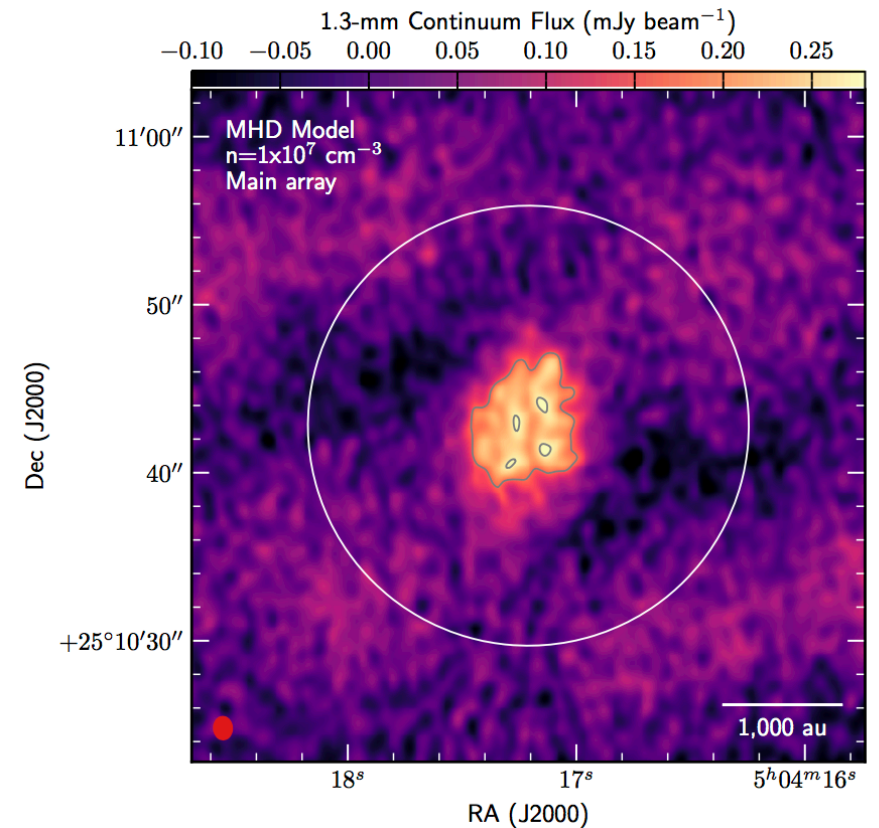
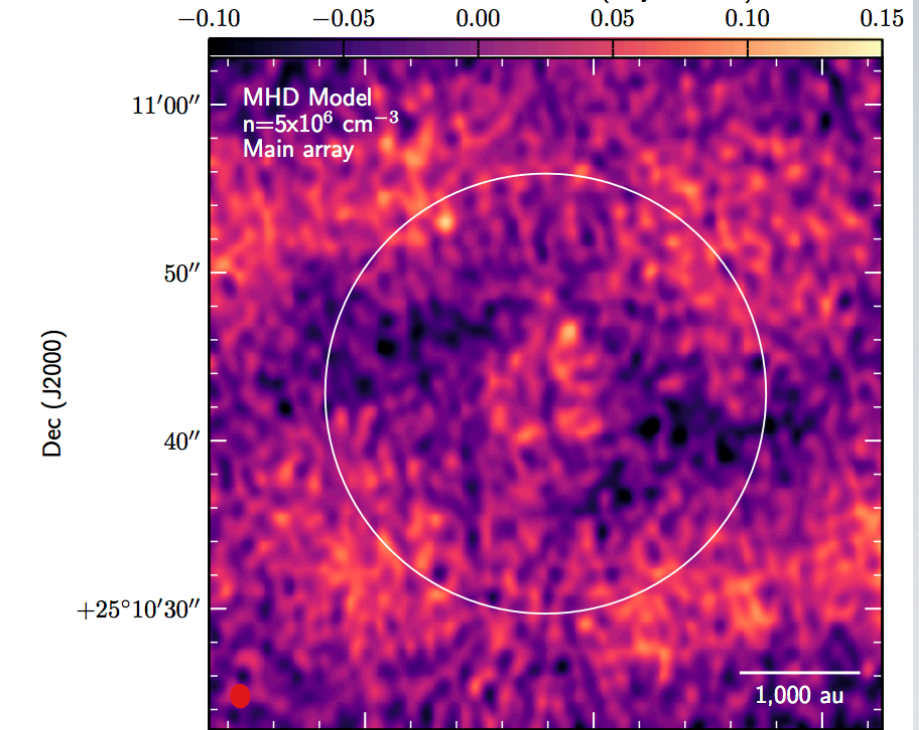
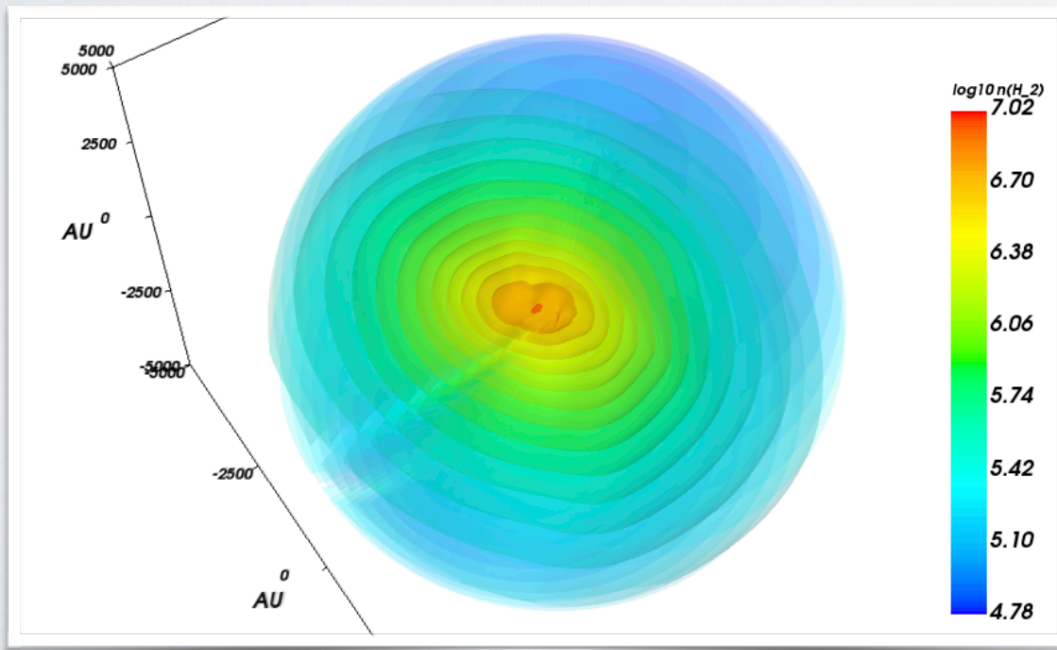


Kernels are the future stellar system cradles and large telescopes are needed to study their dynamical and chemical evolution.

Caselli, Pineda, Zhao+ 2019

LI544 ALMA observations are consistent with *non-ideal MHD simulations* of a contracting pre-stellar cores with peak density $\sim 10^7 \text{ cm}^{-3}$.

The “fragments” are interferometric artefacts.



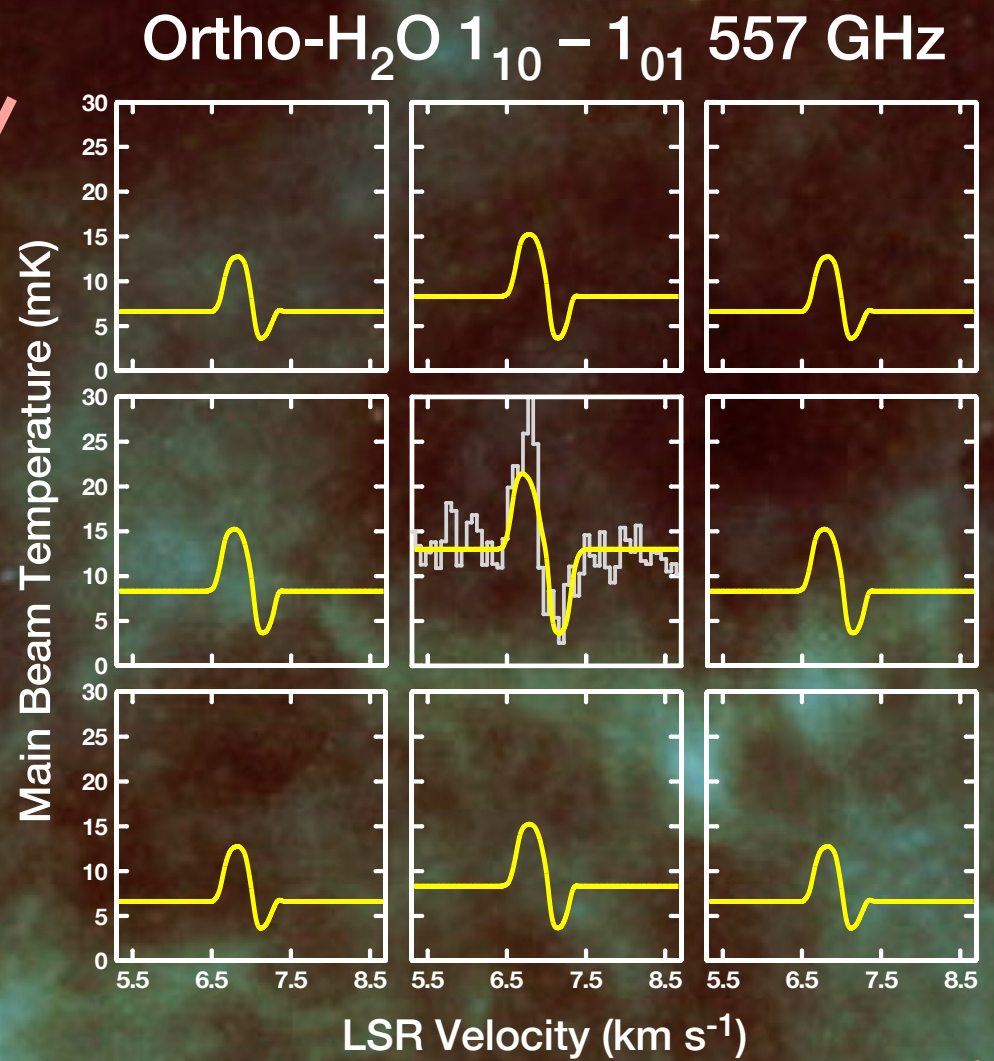
Caselli, Pineda, Zhao+ 2019



(with HERO!)



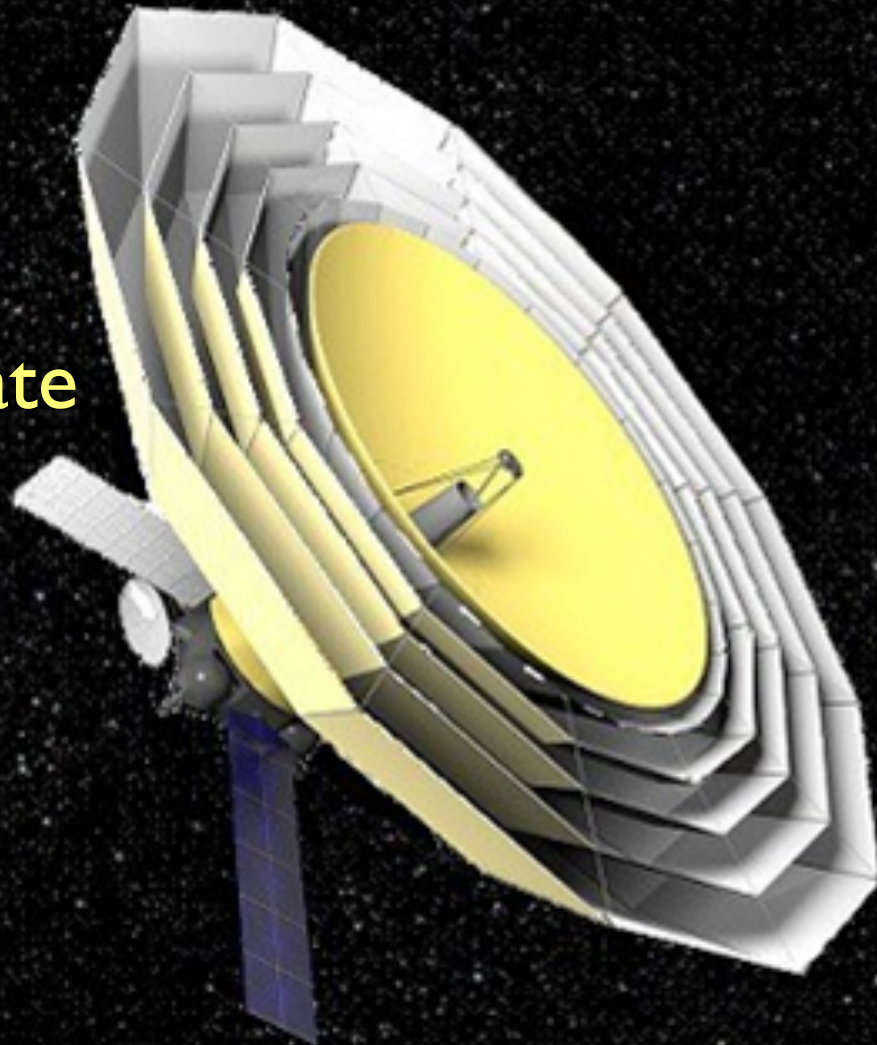
L1544

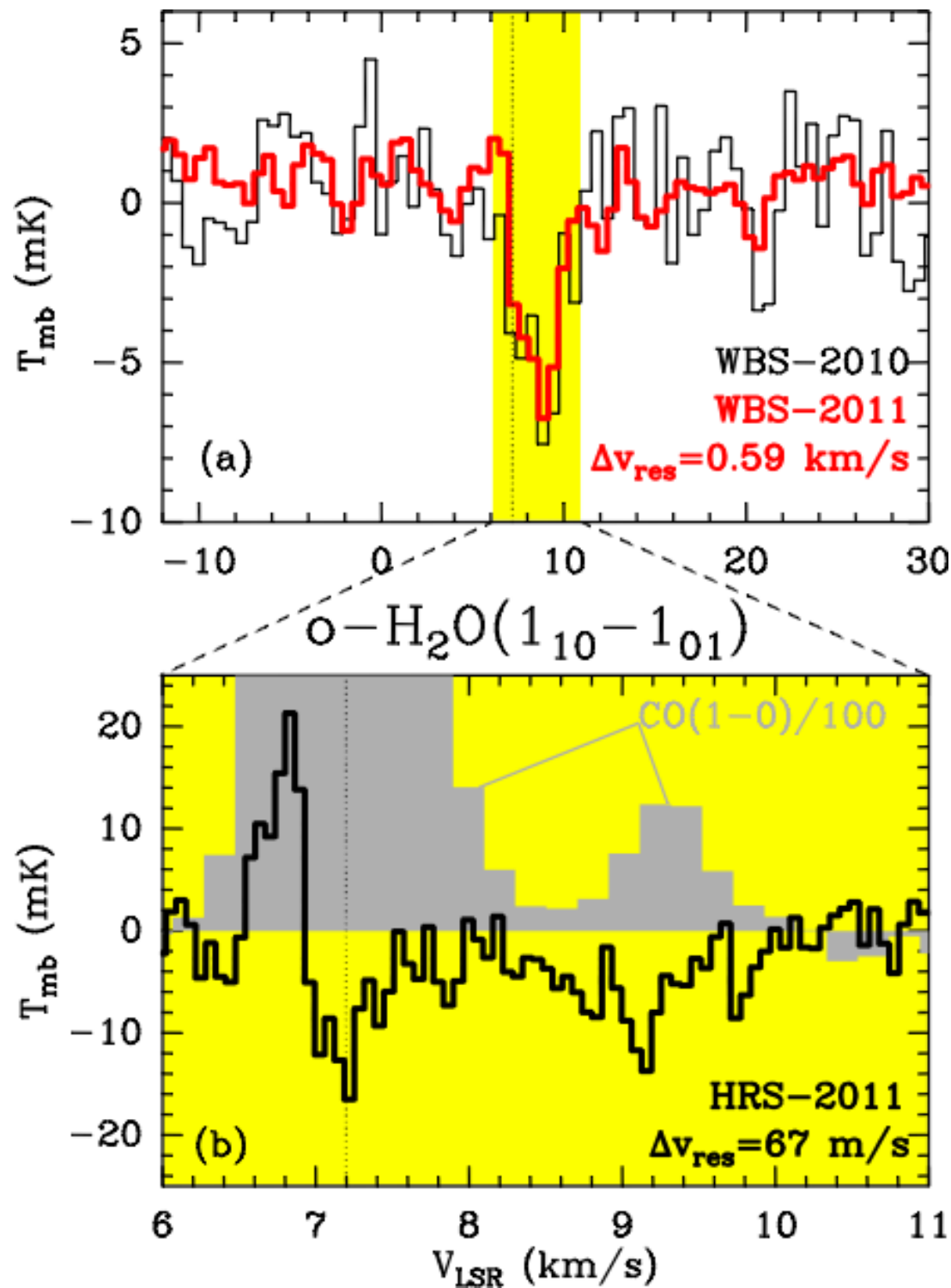


Courtesy of G. Melnick

MILLIMETRON would allow us to obtain the sharpest view of “waterfall” (and ammonia) within pre-stellar cores, *resolving their kernels* (the future stellar system cradles), and providing important constraints on the initial conditions for star&planet formation:

1. Water & NH₃ content
2. Infall velocity profile
3. Cosmic-ray ionisation rate
4. Surface processes
5. Gas-ice interface





CONCLUDING REMARK

The high spectral resolution of *Herschel*-HIFI (10^7) has been crucial to derive the water vapour profile across **one** pre-stellar core and constrain its chemical & dynamical structure. The sample should be enlarged.

The water (+ stellar system) trail starts in pre-stellar cores!