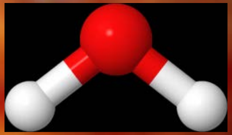
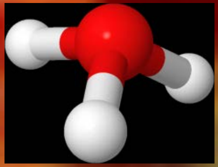
Hydrides in star-forming regions





Ewine F. van Dishoeck

Leiden Observatory/MPE

RCW120
Herschel
A. Zavagno

The Hydride Toolbox, December 12 2016, Paris

Outline

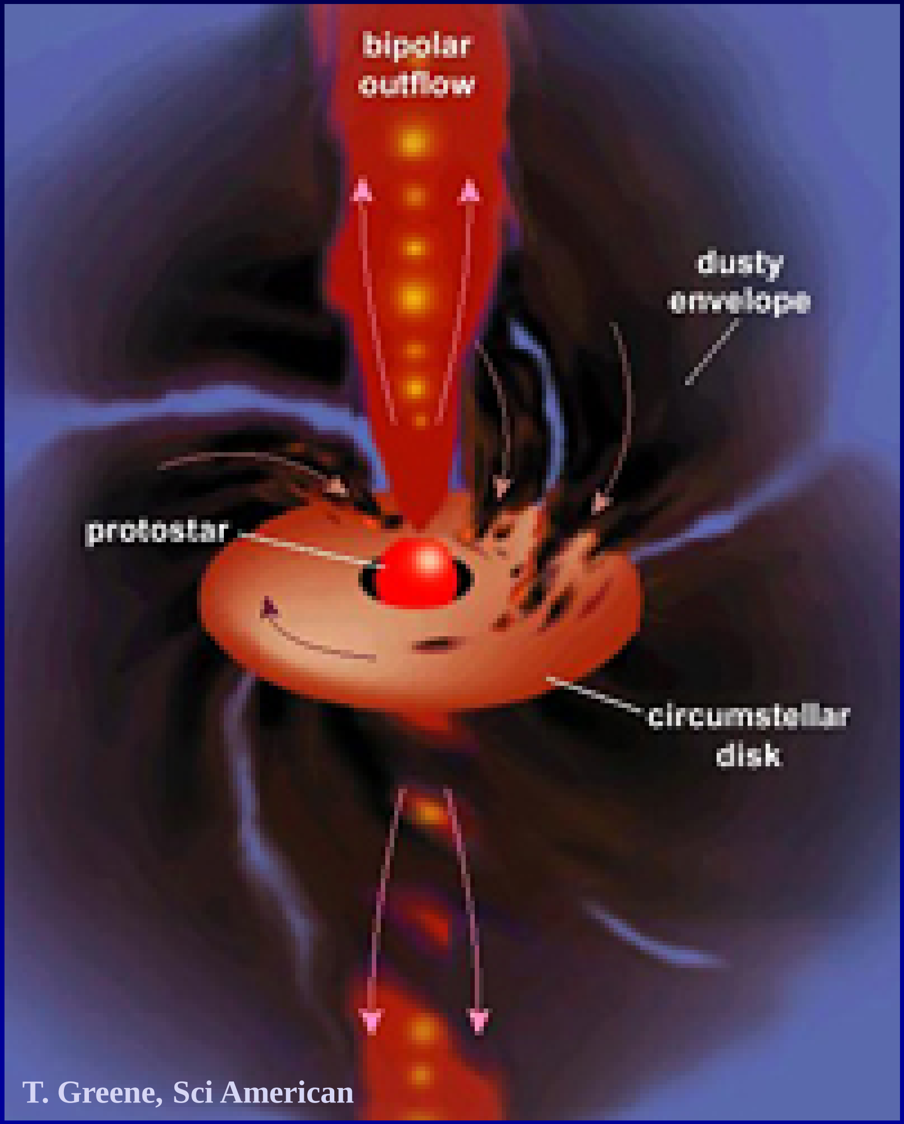
- Introduction
- Cold outer envelope
- Shocks
- Warm inner envelope
- Disks

Focus on: H_2O, NH_3, other hydrides
but not H_2

Diagnostics of - physical processes
- type of chemistry

See reviews by vD et al. 2011, 2013, Bergin & van Dishoeck 2012, Melnick 2009, ...

Embedded protostellar phase



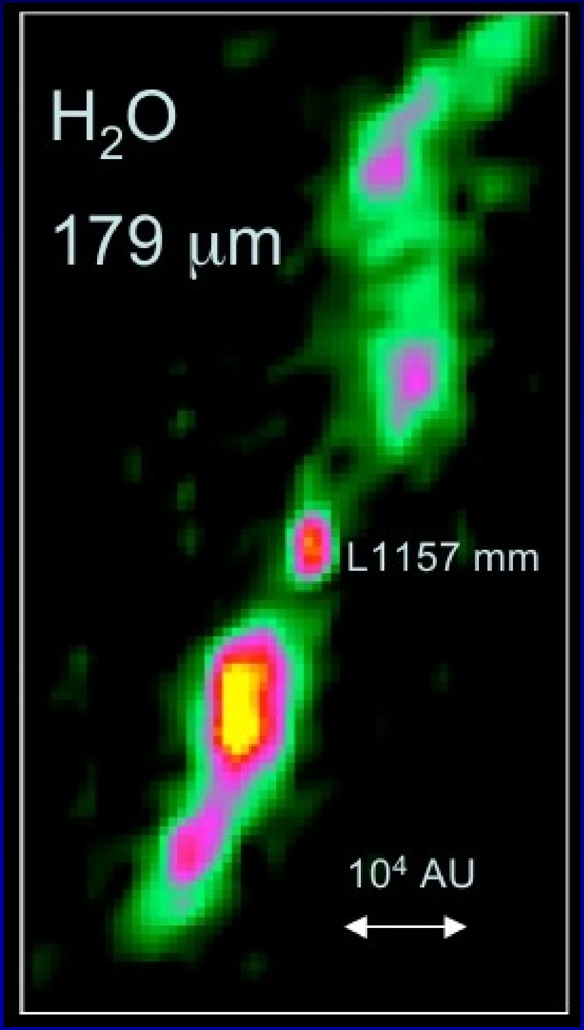
- **Physical components**
  - Cold outer envelope
  - Warm inner envelope→hot core
  - Bipolar outflow→ shocks
  - Disk

- **Multi-wavelength observations**
  - Near-IR (VLT/CRIRES, Keck)
  - Mid-IR (Spitzer-IRS→ JWST)
  - Far-IR (Herschel)
  - Sub-mm (Single dish, ALMA)

T

All these components are contained in a single dish beam; need interferometer to disentangle

Hydrides as tracers of star formation: a beautiful example



Nisini et al. 2010, 2014

Water traces 'hot spots' where shocks dump energy into cloud

Pioneering space missions

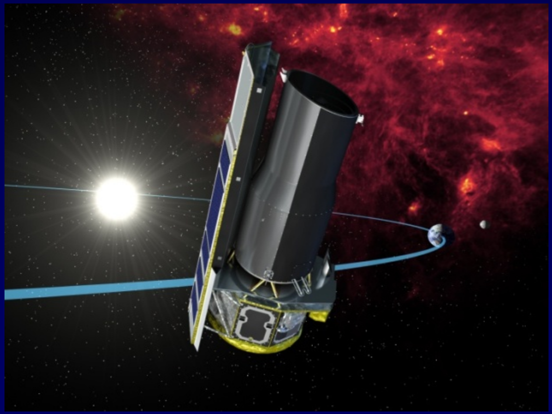
ISO

1995-1998

van Dishoeck 2004

SWAS

Melnick 2009

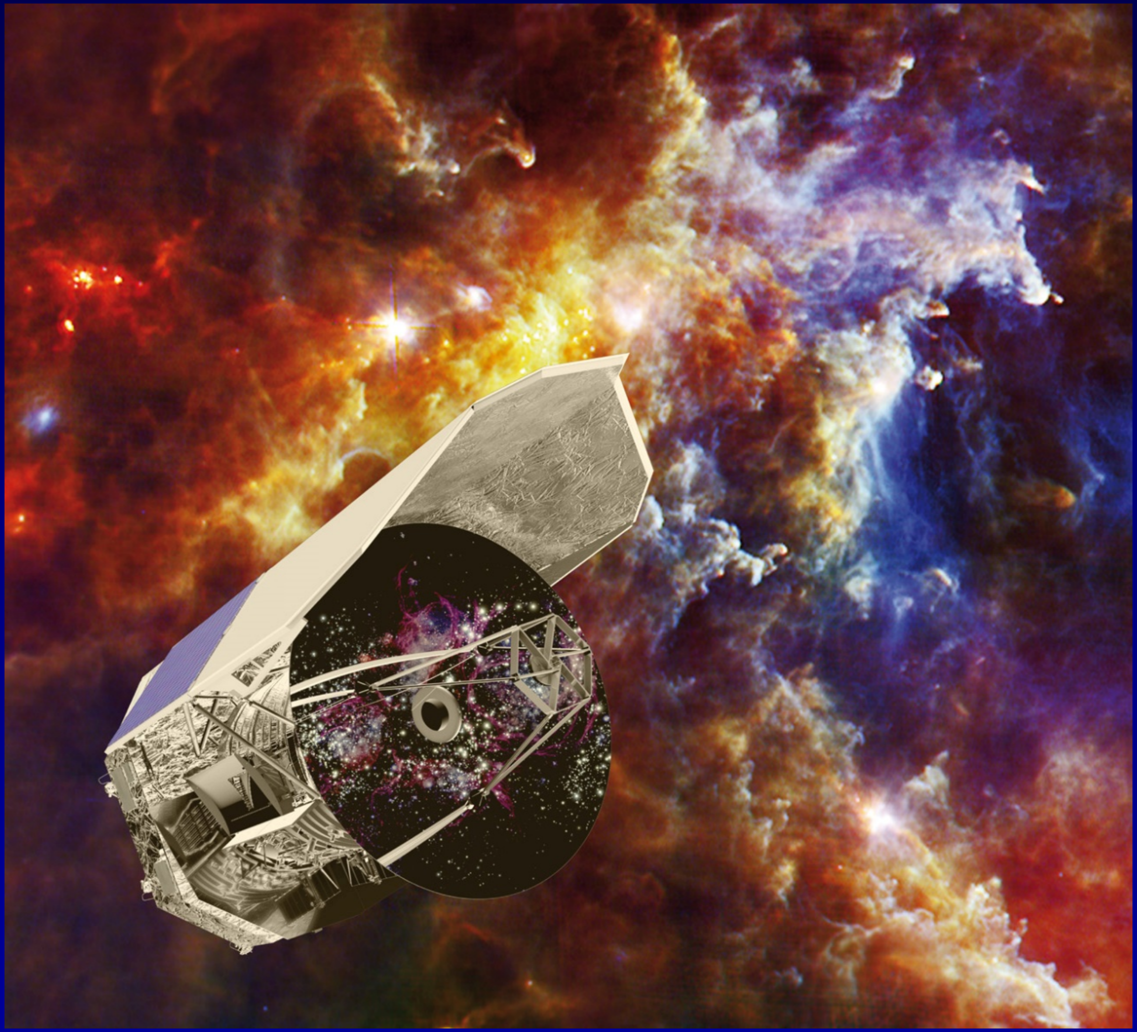


Spitzer

2003-2009

Cannot properly summarize these missions in this talk

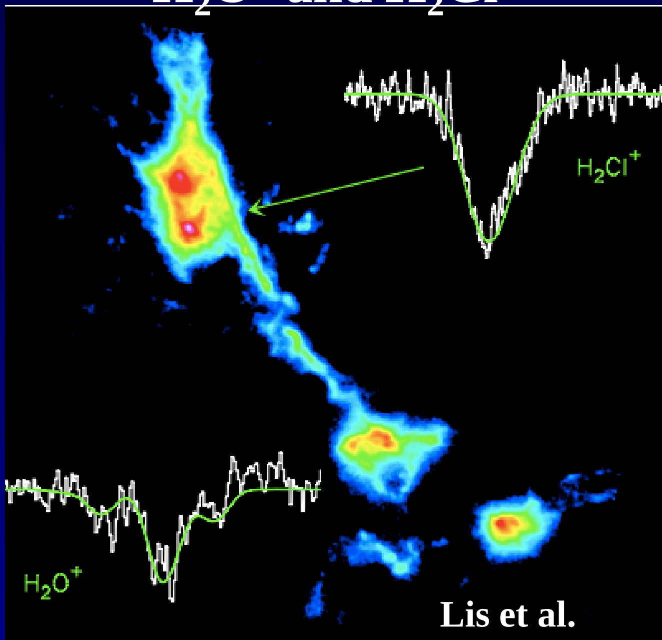
Herschel legacy



HIFI, PACS, SPIRE: 55-600 μm spectroscopy, R=10^3-10^7
Beam 20-47"

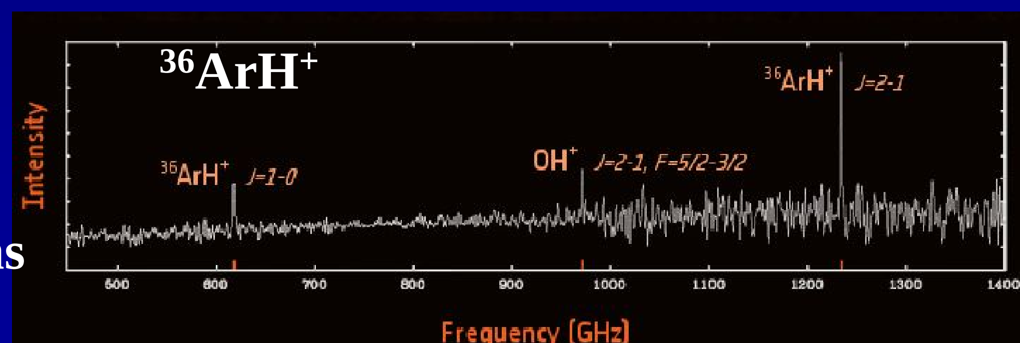
Spectroscopy: new hydrides Herschel

H_2O^+ and H_2Cl^+



H_2O^+

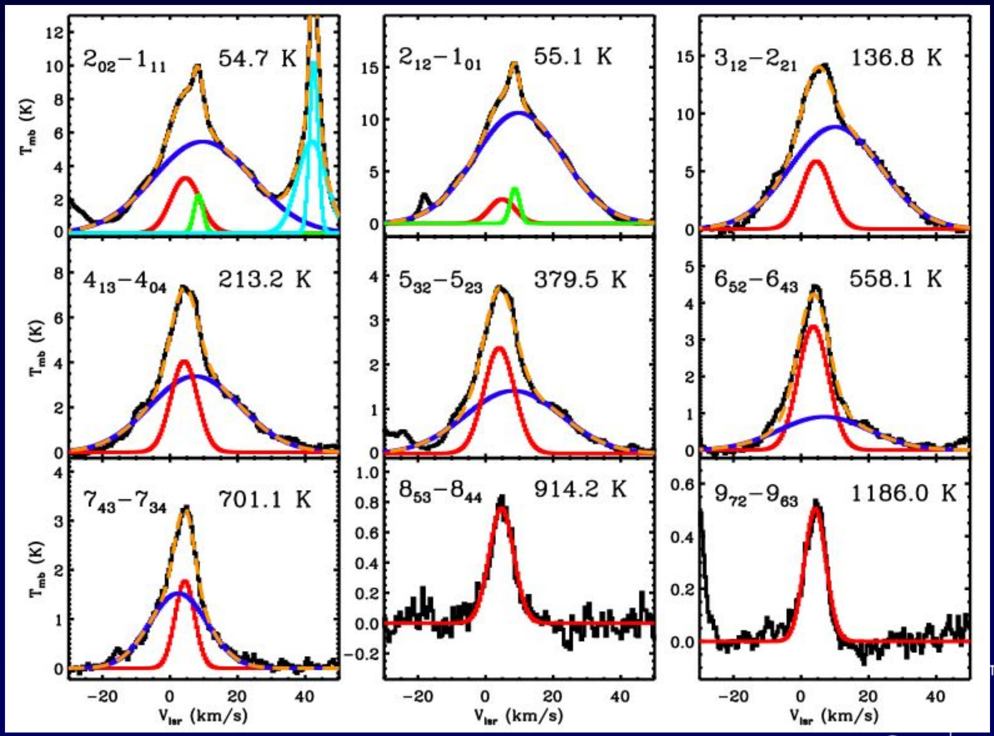
Probes new atomic H-rich phase of diffuse ISM, but also seen in star-forming regions



Ossenkopf et al., Benz et al., Bruderer et al., Gerin et al., Wyrowski et al., Gupta et al., Schilke et al., Lis et al. 2010; Neufeld et al. 2012, de Luca et al. 2012, Indriolo et al. 2015, Barlow et al. 2013

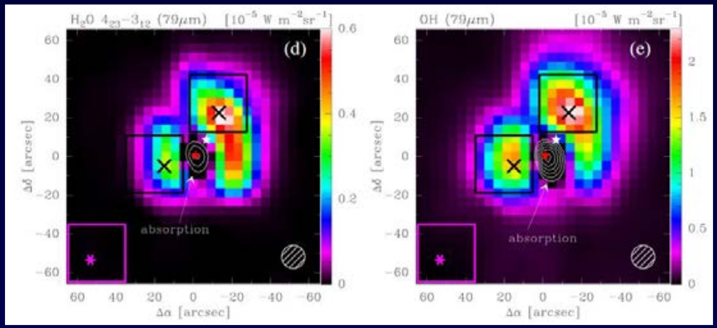
Many lines of the same hydride: Ladders in Orion-KL

H_2S ladder



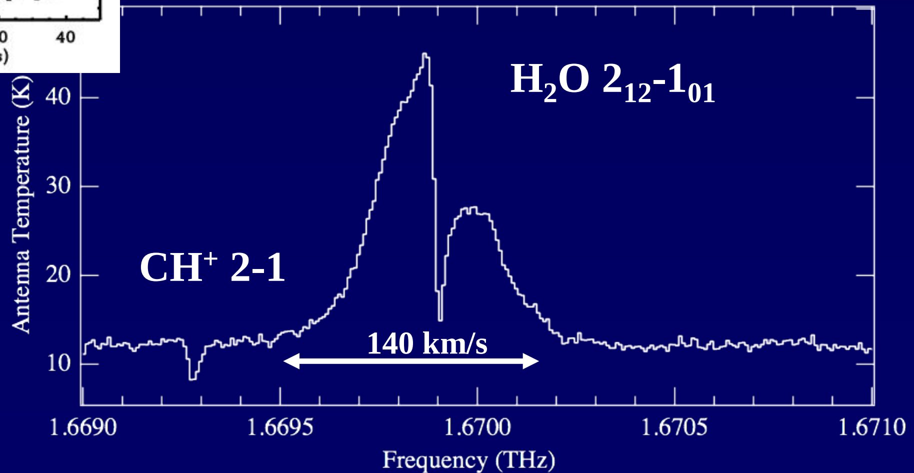
Bergin et al. 2010, Crockett et al. 2014, 2015

H_2O OH



Goicoechea et al. 2015

High-quality line profiles, even at 1.67 THz!



Other hydride telescopes

Herschel protostar surveys

- **WISH:** vD et al.
  - 26 low ($<10^2$), 6 intermediate (10^2-10^4), 19 high-mass ($>10^4$ M_{Sun}) YSOs
  - HIFI, selected PACS lines
- **WILL:** Mottram, vD et al.
  - 45 low-mass YSOs
  - HIFI, selected PACS lines
- **DIGIT:** Evans, Greene et al.
  - 30 low-mass YSOs
  - Full PACS scans
- **COPS:** Kristensen, Greene et al.
  - SPIRE for WISH + DIGIT low-mass YSOs
  - HIFI CO 16-15

Also: HOPS Orion protostars PACS (Manoj et al. 2013), Cygnus protostars HIFI (Bontemps et al.)

Water In Star-forming regions with Herschel
The WISH team

Leiden, April 2010

Rome, October 2014

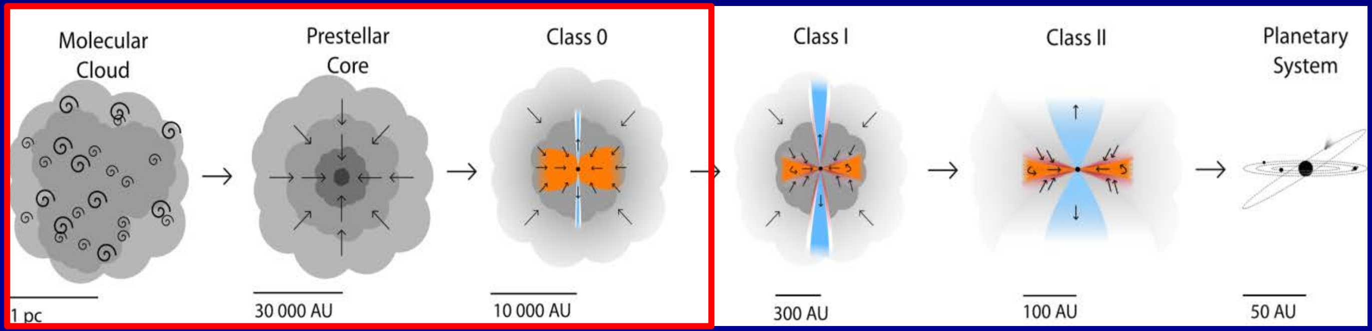
425 hr guaranteed time program + OT
74 refereed papers

Summary in van Dishoeck et al. 2011, PASP
Bergin & van Dishoeck 2012, van Dishoeck et al. 2013, Chem. Rev. , 2014, PPVI

Cold outer envelope

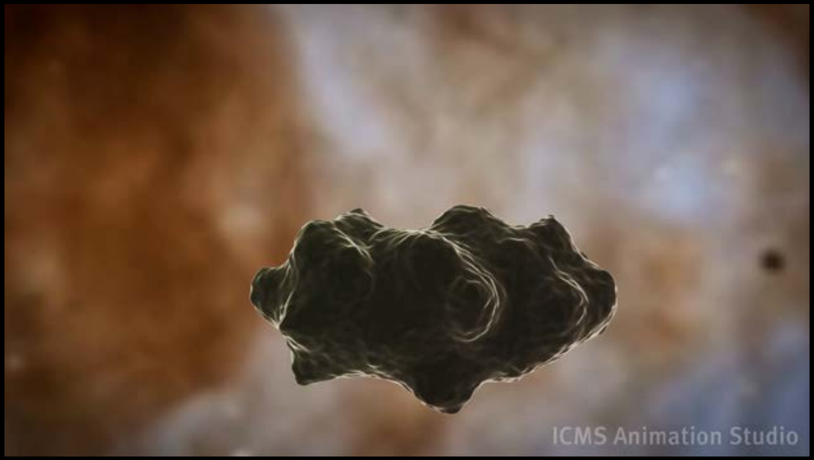
Formation of hydrides on grains

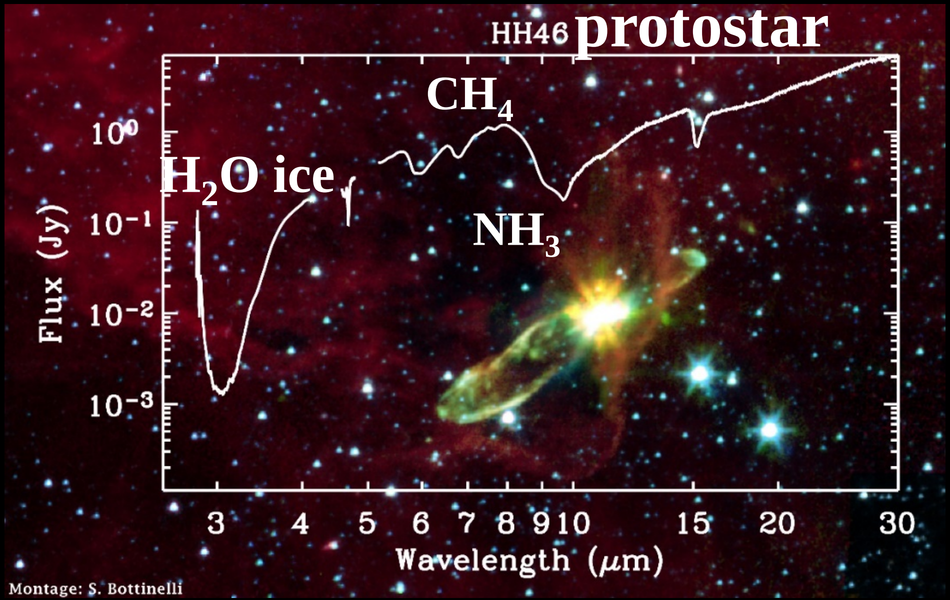
Bulk of water is formed early, before cloud collapse

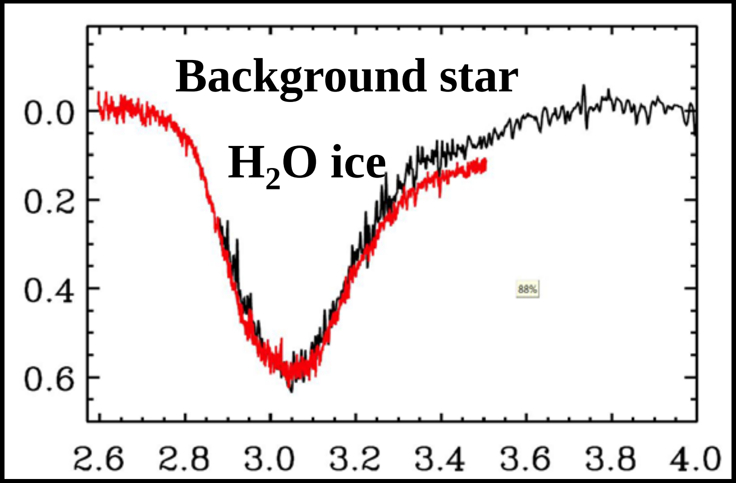


'Water is older than the Sun' **(Cleeves et al. 2015)**

Water ice is abundant and common!



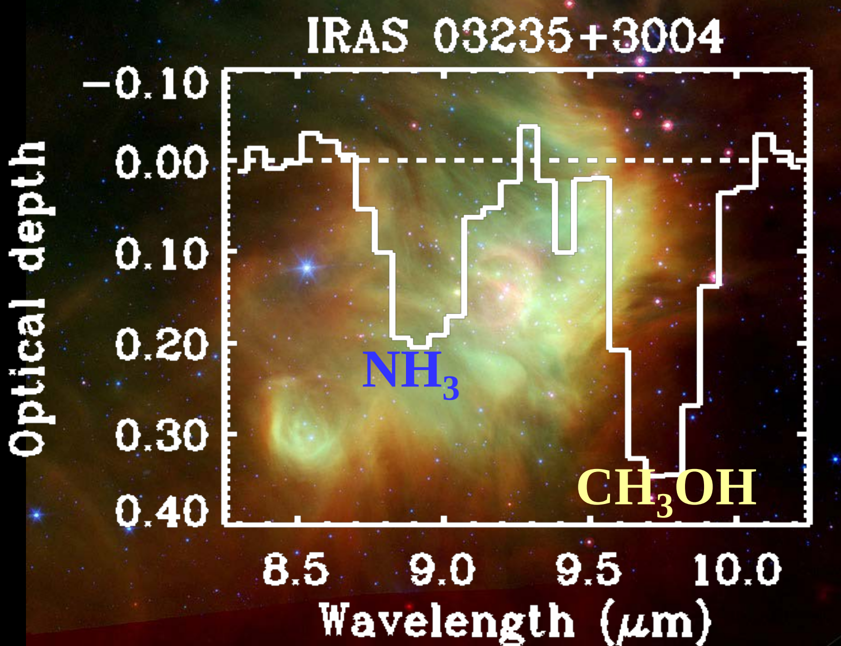




Boogert, Pontoppidan et al. 2008,
Öberg et al. 2011
Boogert et al. 2015, ARAA

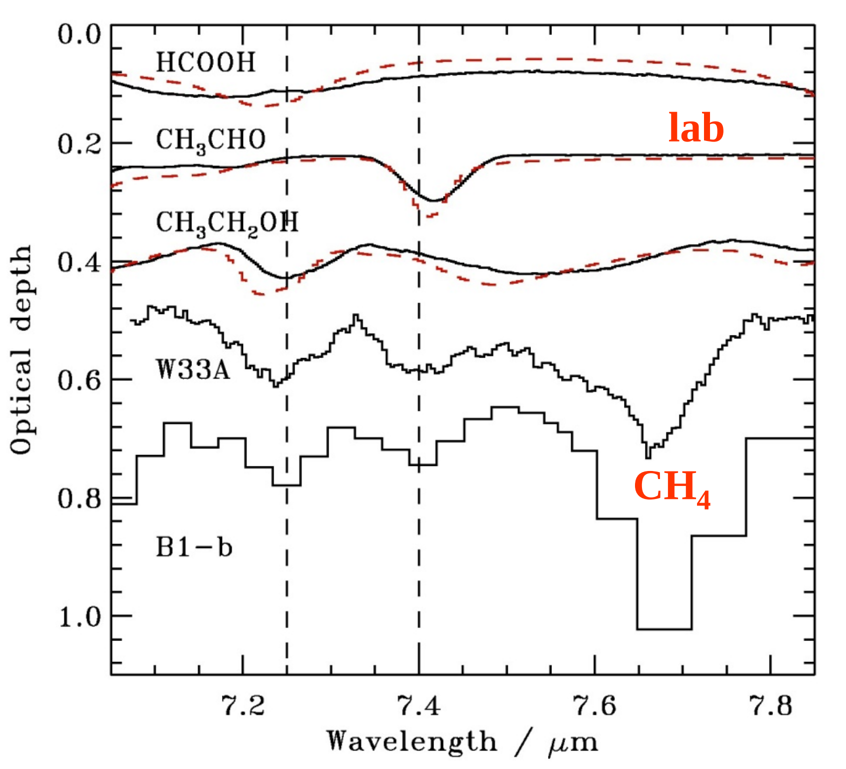
Ices contain significant fraction of heavy elements (but perhaps not all of oxygen)

Ammonia and methane ices



Bottinelli et al. 2010

Silicate subtracted



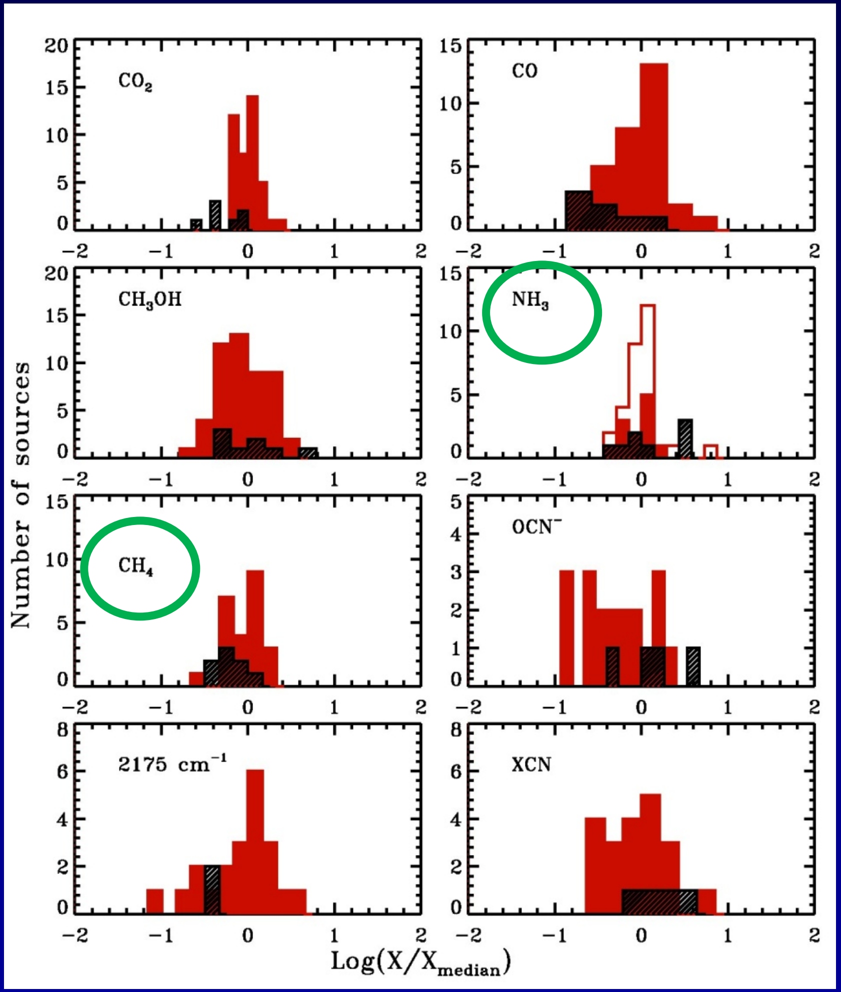
Median ice abundances

Species	Low mass	High mass	Background
H_2O	100	100	100
CH_4	5	2	<3
NH_3	6	7	<7

JWST!

Öberg et al. 2008, 2011
Boogert et al. 2015

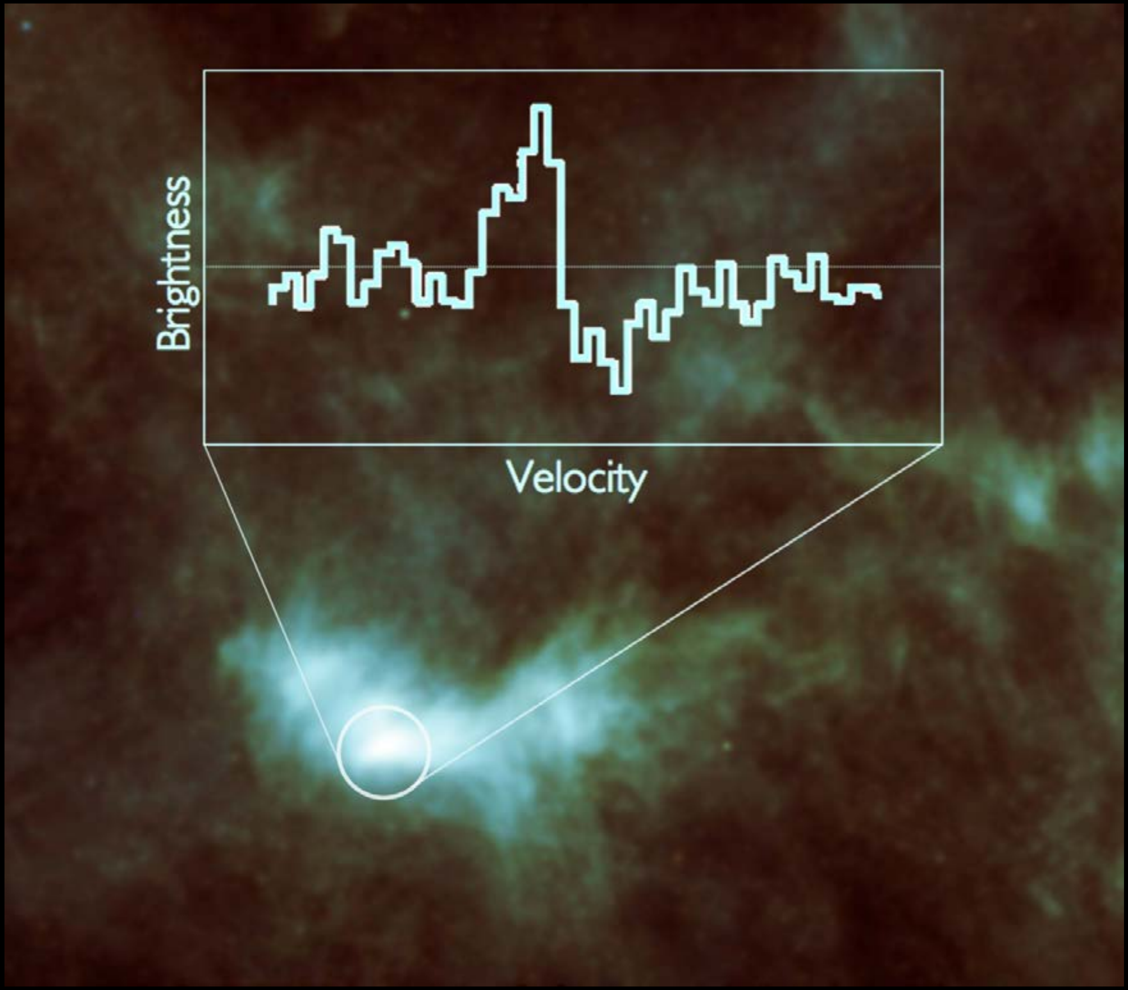
Ice abundance distributions



Red= low mass
Black= high mass

Note narrow distributions for CH_4/H_2O and NH_3/H_2O
→ similar ice formation conditions across the Galaxy (T_{dust}, H/O, ...)

Water formation: gaseous water reservoir with *Herschel*

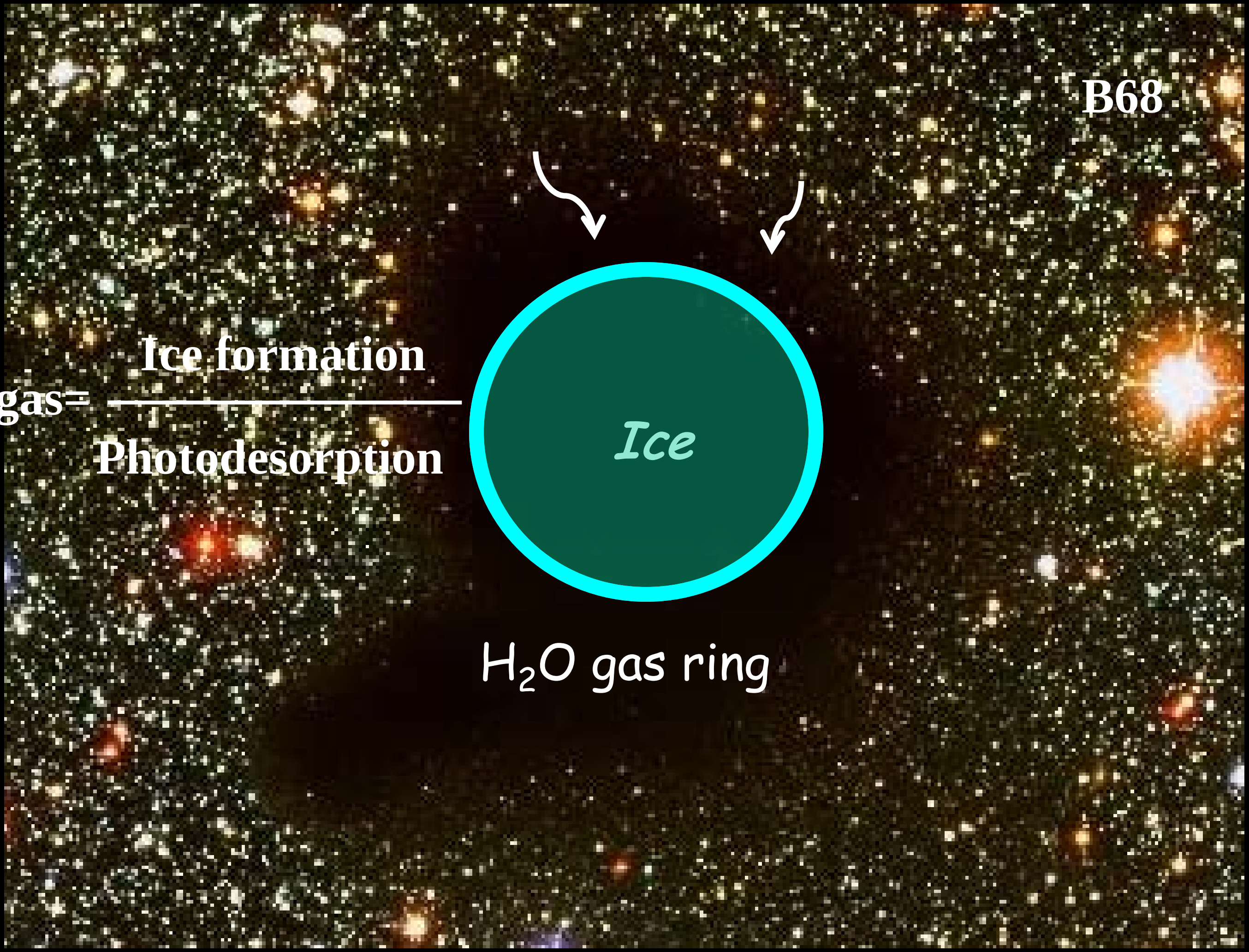


L1544
Pre-stellar core

Caselli et al. 2012
Mottram et al. 2013
Schmalzl et al. 2014

Dark cloud on verge of collapse (red-shifted absorption→inward motions)
Simple chemistry reproduces abundance structure well

Water distribution in dense clouds



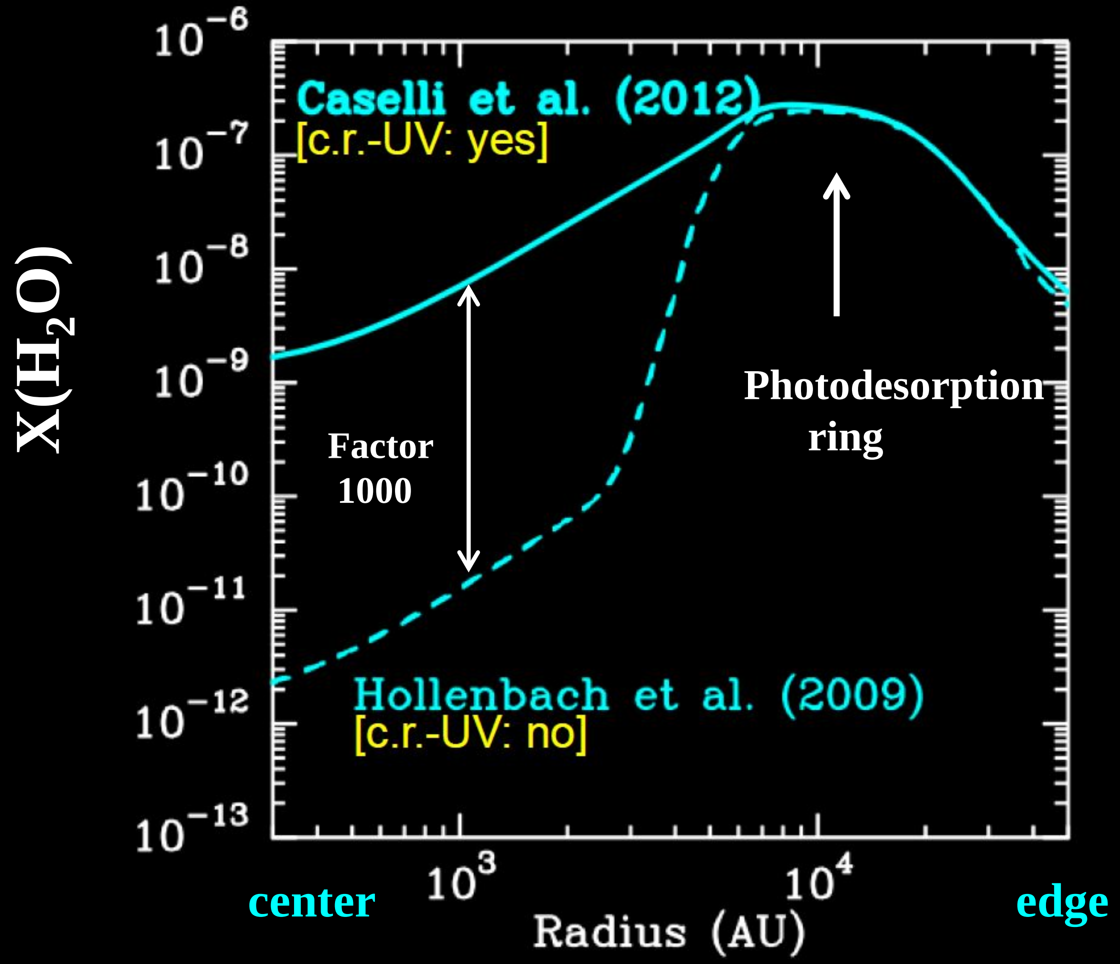
H_2O gas= Ice formation / Photodesorption

Caselli et al. 2012
Schmalzl et al. 2014

n=2.10^4 – 5.10^6 cm^{-3}, T=10 K

Layer of water gas where ice is photodesorbed

Inferred water abundance L1544

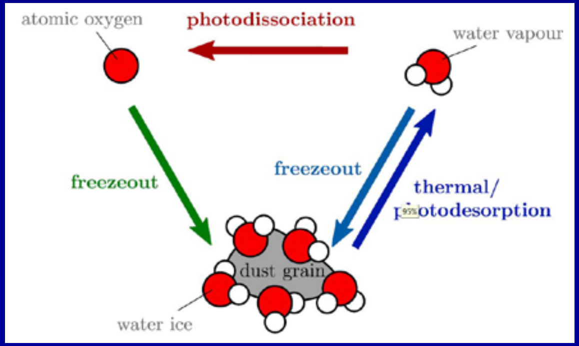


Caselli et al. 2012
Keto et al. 2014

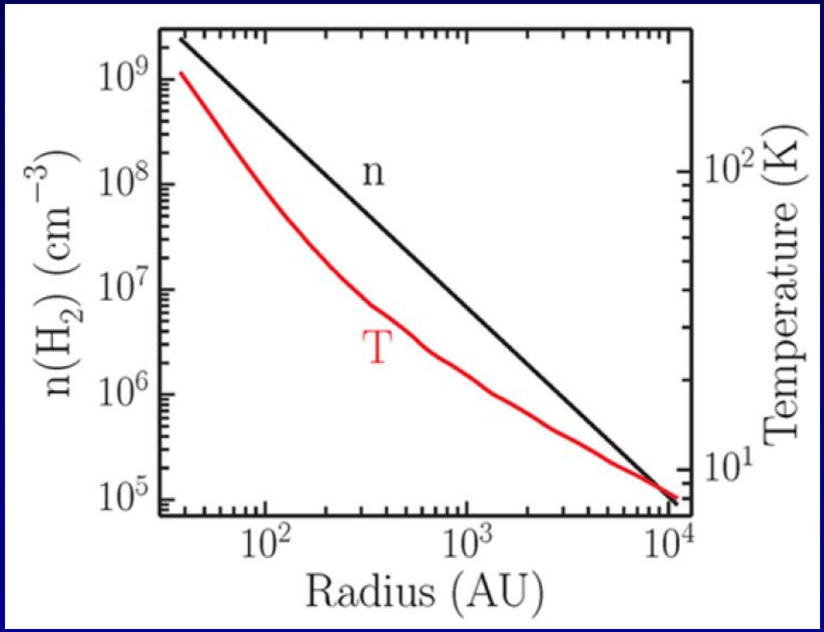
Also need efficient photodesorption in center→ G_{ISRF}, G_{CR}

Cold water abundance

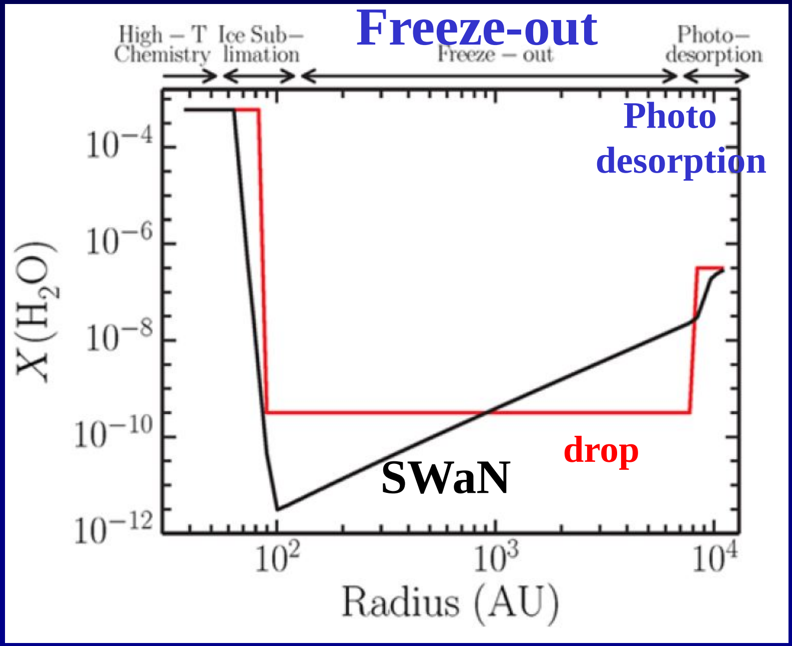
- **Water abundance profiles constrained for low-mass pre- and protostellar cores**
  - **Caselli, Keto et al. 2012, Mottram et al. 2013, Schmalzl et al. 2014**
- **High mass: jump profiles**
  - **Marseille et al. 2010, Herpin et al. 2012, 2016, Choi et al. 2016**
- **Simple network (SWaN)**
  - **Identify main processes and parameters → FUV radiation: internal and external**



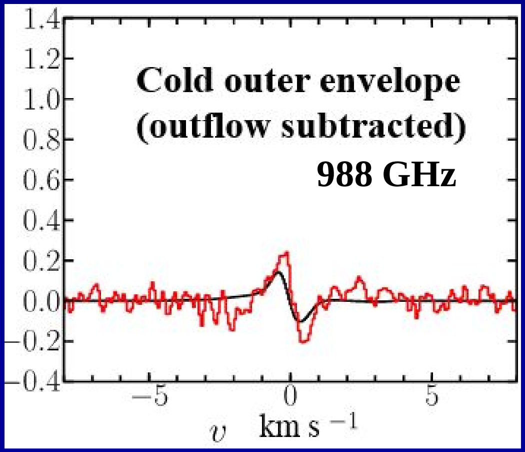
Protostars: water abundance profiles



NGC 1333 IRAS4A



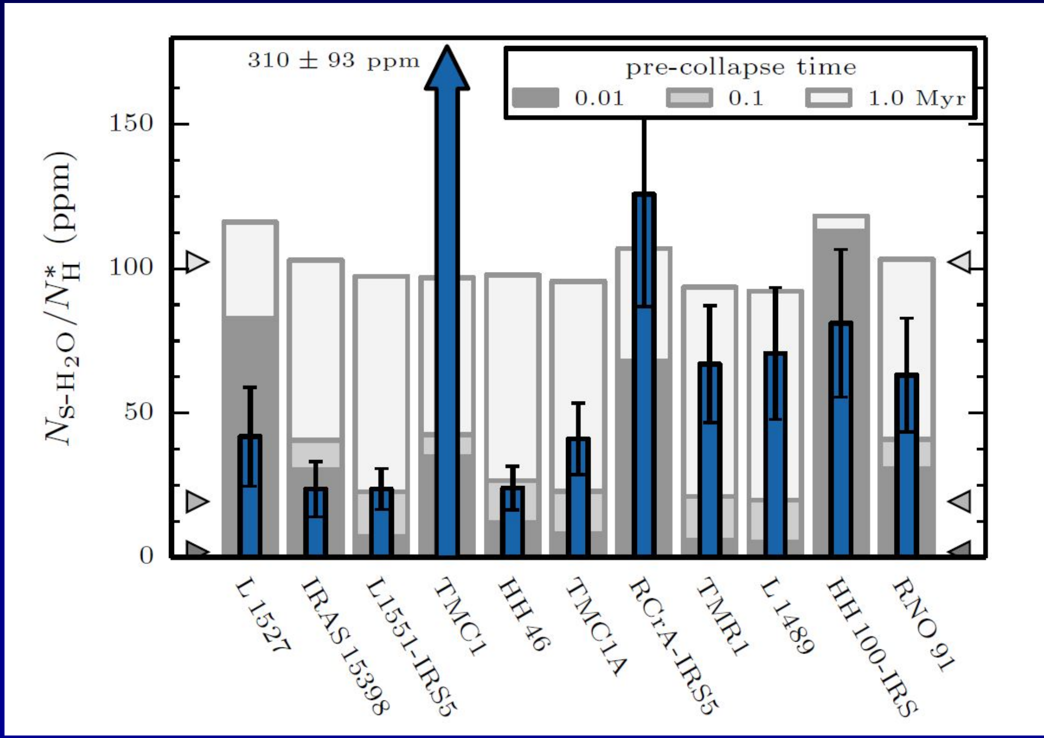
Mottram et al. 2013
Schmalzl et al. 2014



Simple chemistry works
Inferred G_{ISRF}=0.01-100
$G_{CR}=10^{-5}-10^{-4}$

Water ice abundances are low

Analysis of sources for which both ice and gas detected



Observations: only 30-80 ppm locked up in water ice (vs 320 ppm expected)

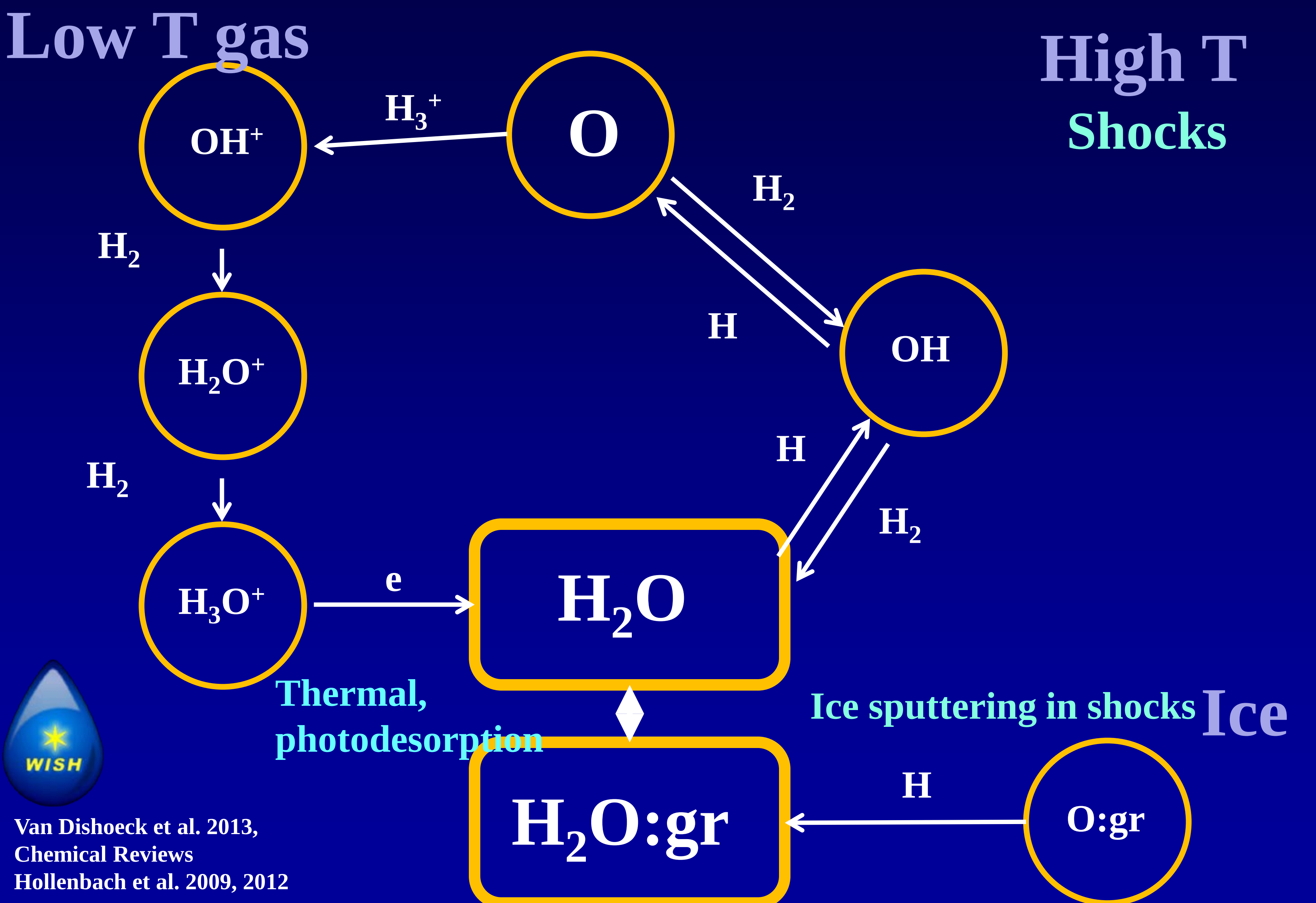
→ Requires low initial water ice abundance

→ *Short pre-stellar stage (10^5 yr at $n(H_2)$~10^4 cm^{-3})* or

Water ice locked in larger grains

Schmalzl et al. 2014

Water formation routes

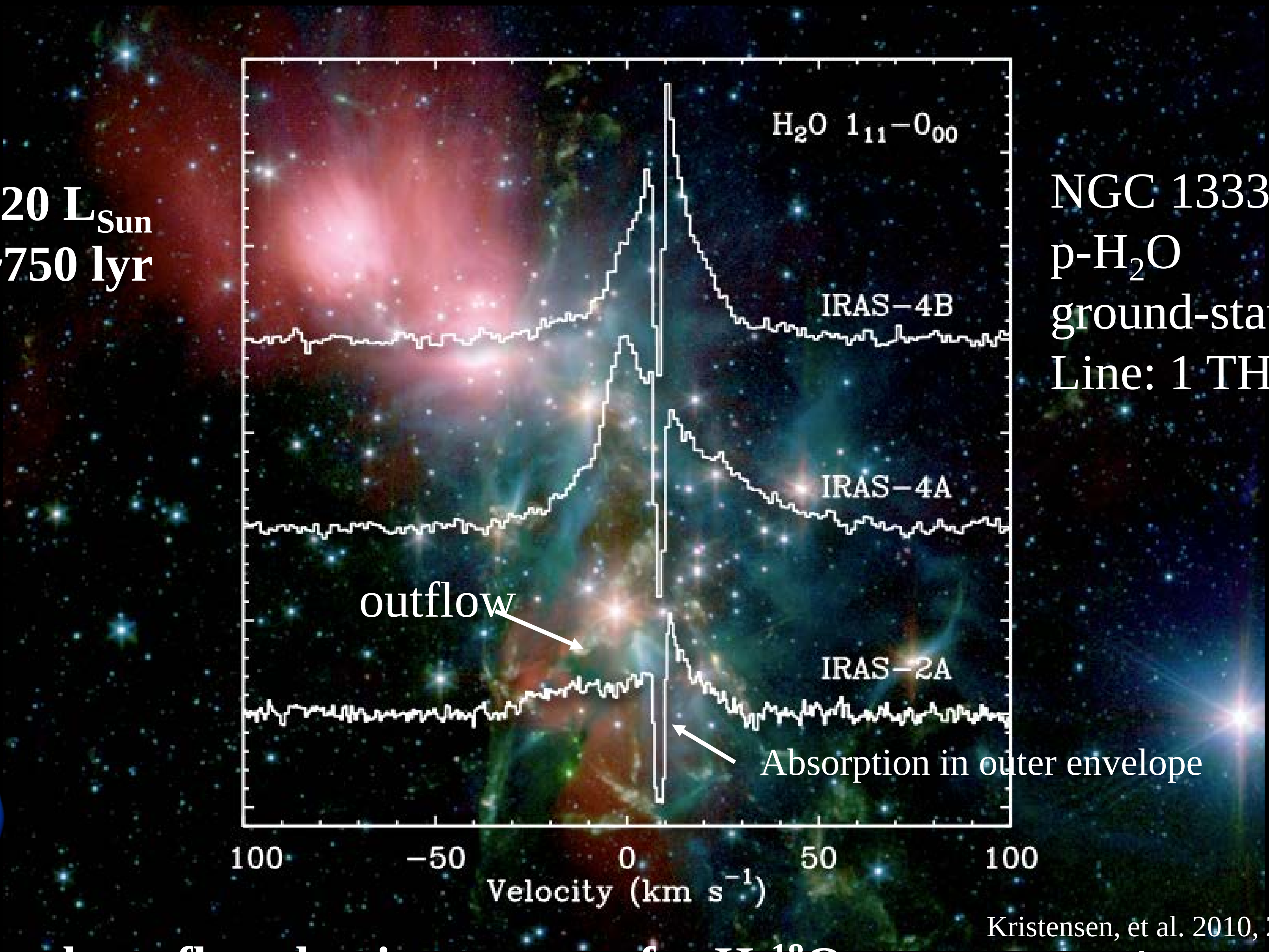


Van Dishoeck et al. 2013, Chemical Reviews
Hollenbach et al. 2009, 2012

Warm water

Water in low-mass protostars

L~20 L_{Sun}
D~750 lyr

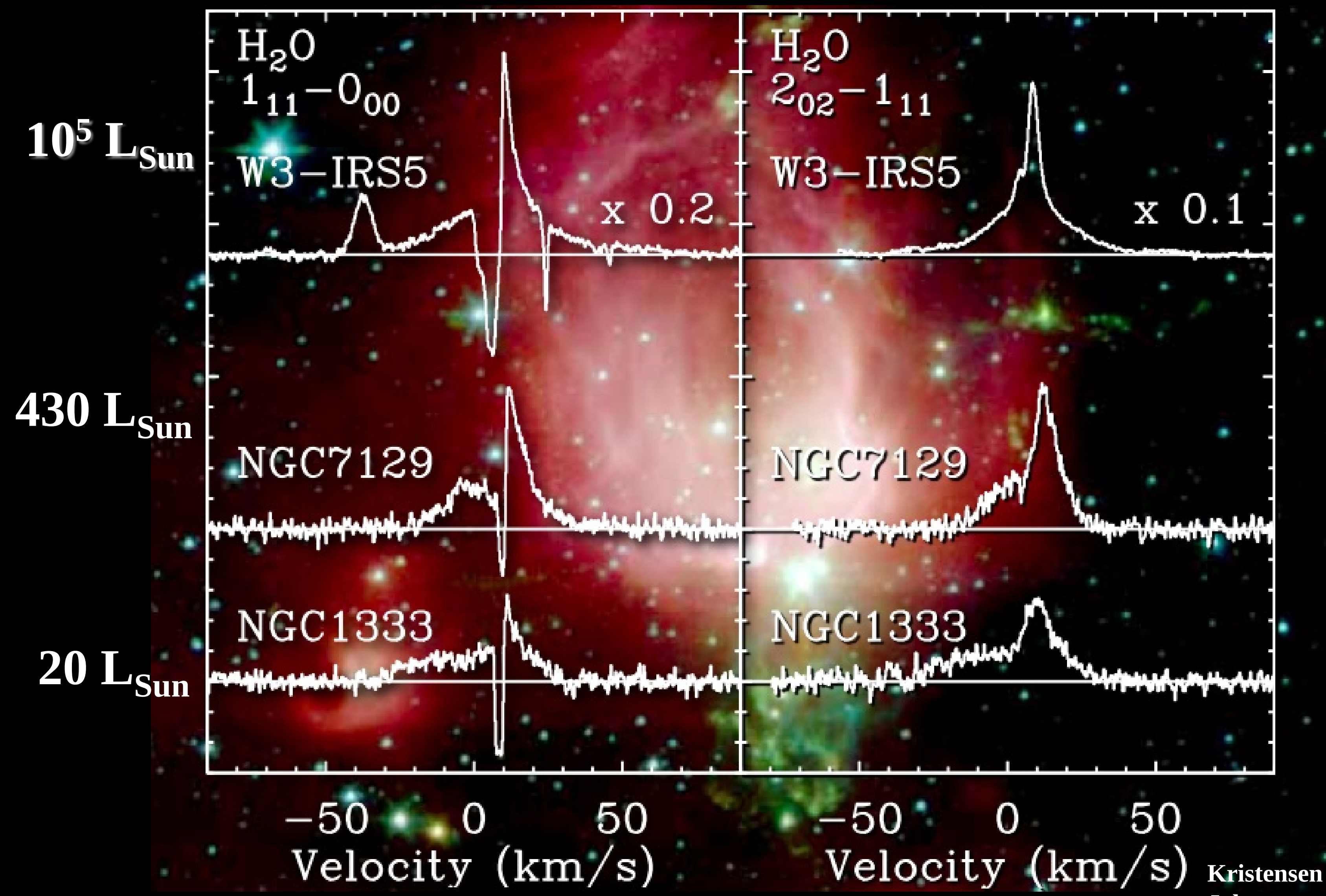


NGC 1333
p-H_2O
ground-state
Line: 1 THz

Kristensen, et al. 2010, 2012
Mottram et al. 2014

Broad: outflow dominates, even for $H_2^{18}O$

From low to high mass protostars

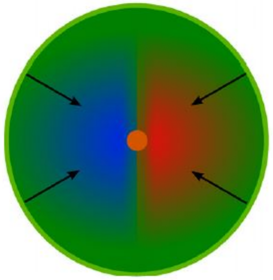


Kristensen et al. 2010
Johnstone et al. 2010
Chavarria et al. 2010
San Jose-Garcia et al. 2015

Note similar profiles

Measuring infall rates with hydrides

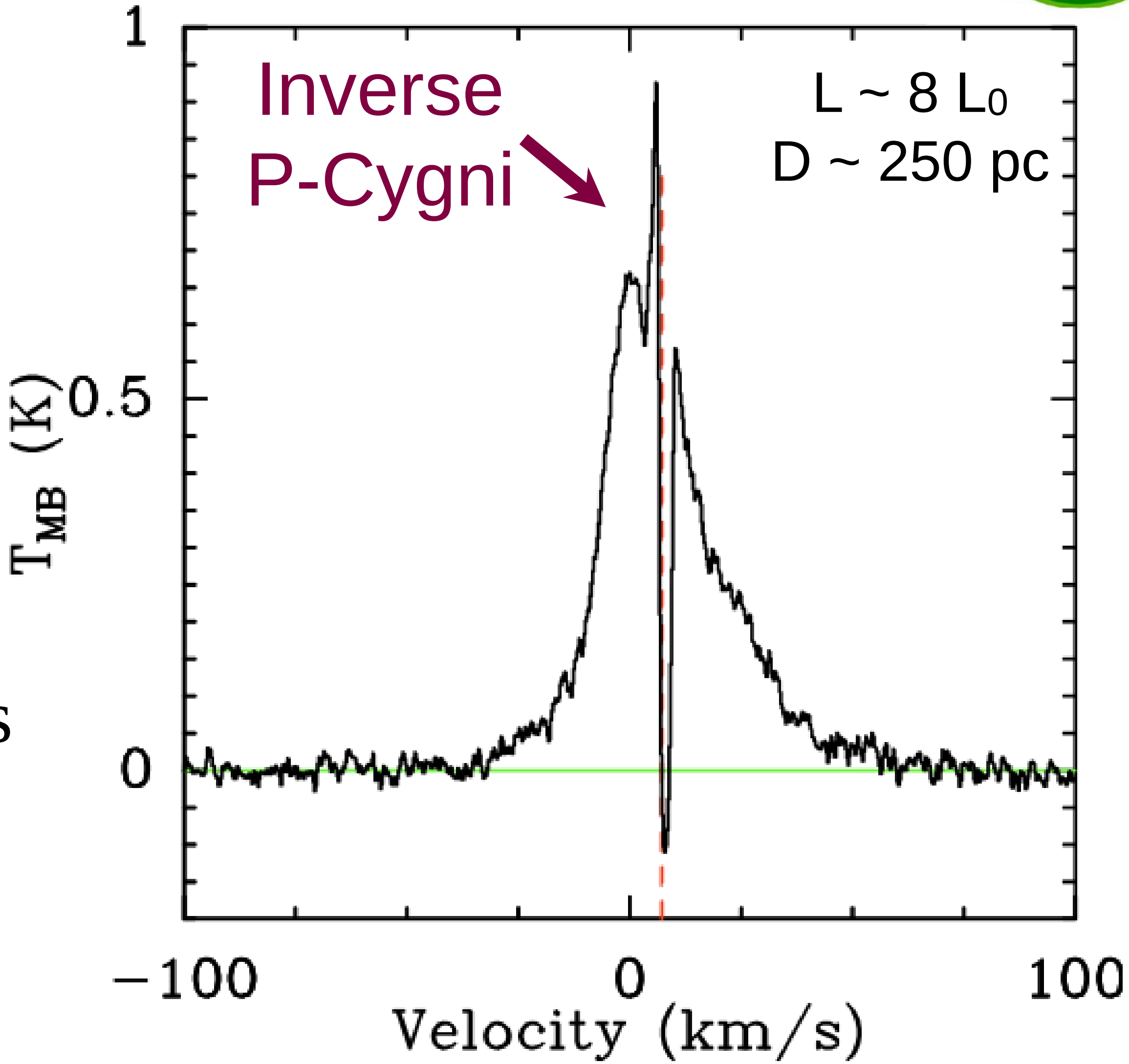
Water moving inwards



NGC1333-I4A
Class 0

Inverse P-Cygni profile in 40” beam

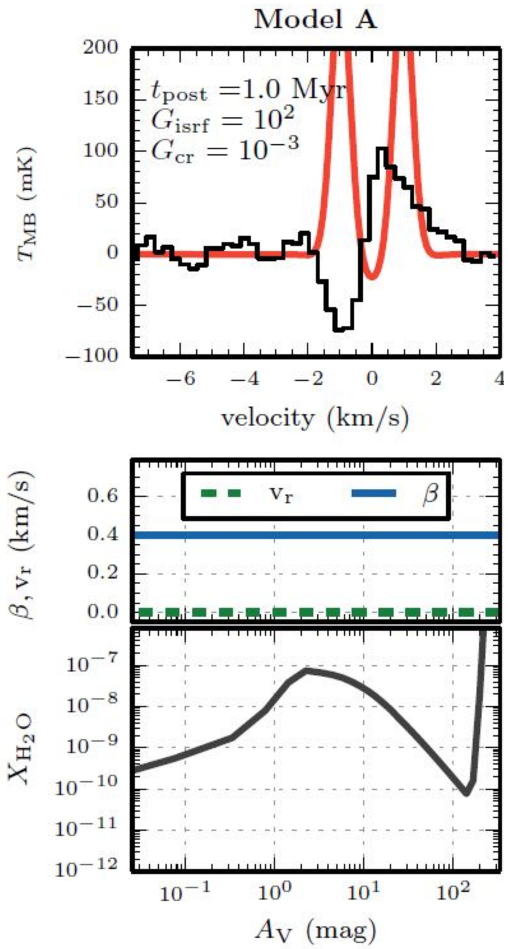
Indicates large-scale infall with mass accretion rates on scales of a few 1000 AU (envelope→disk)



Kristensen et al. 2012, Mottram et al. 2013

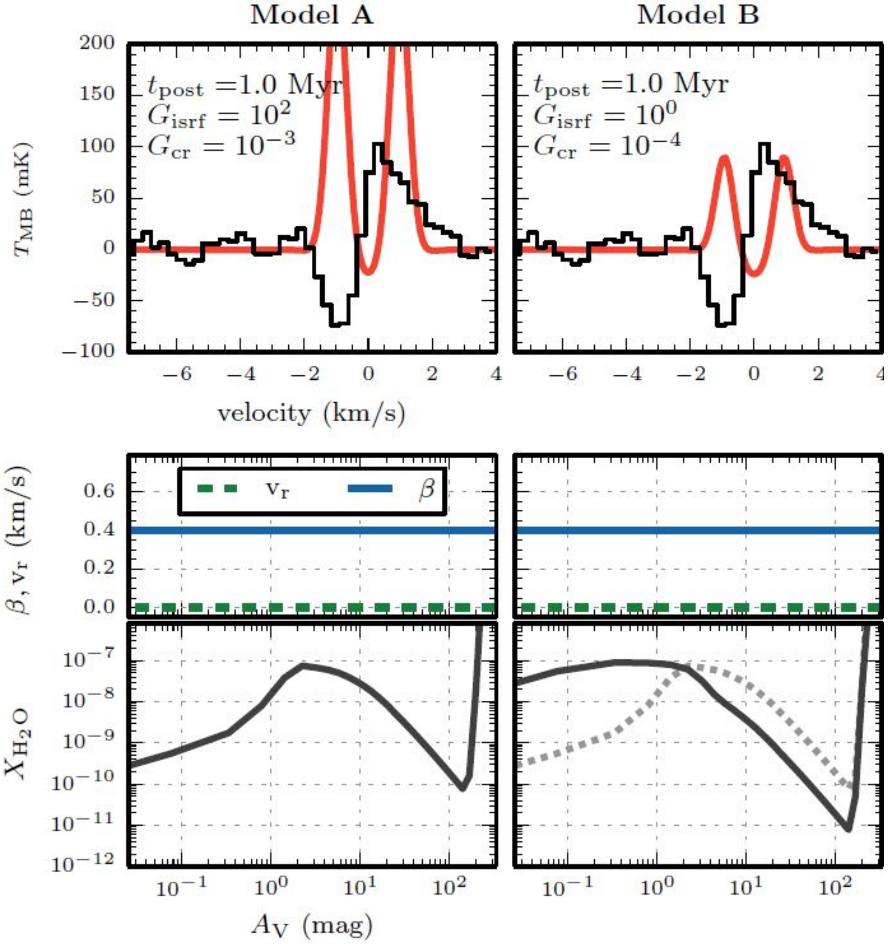
Fit to observed line profiles

L1551 557 GHz outflow subtracted



Fit to observed line profiles

L1551 557 GHz outflow subtracted



Fit to observed line profiles

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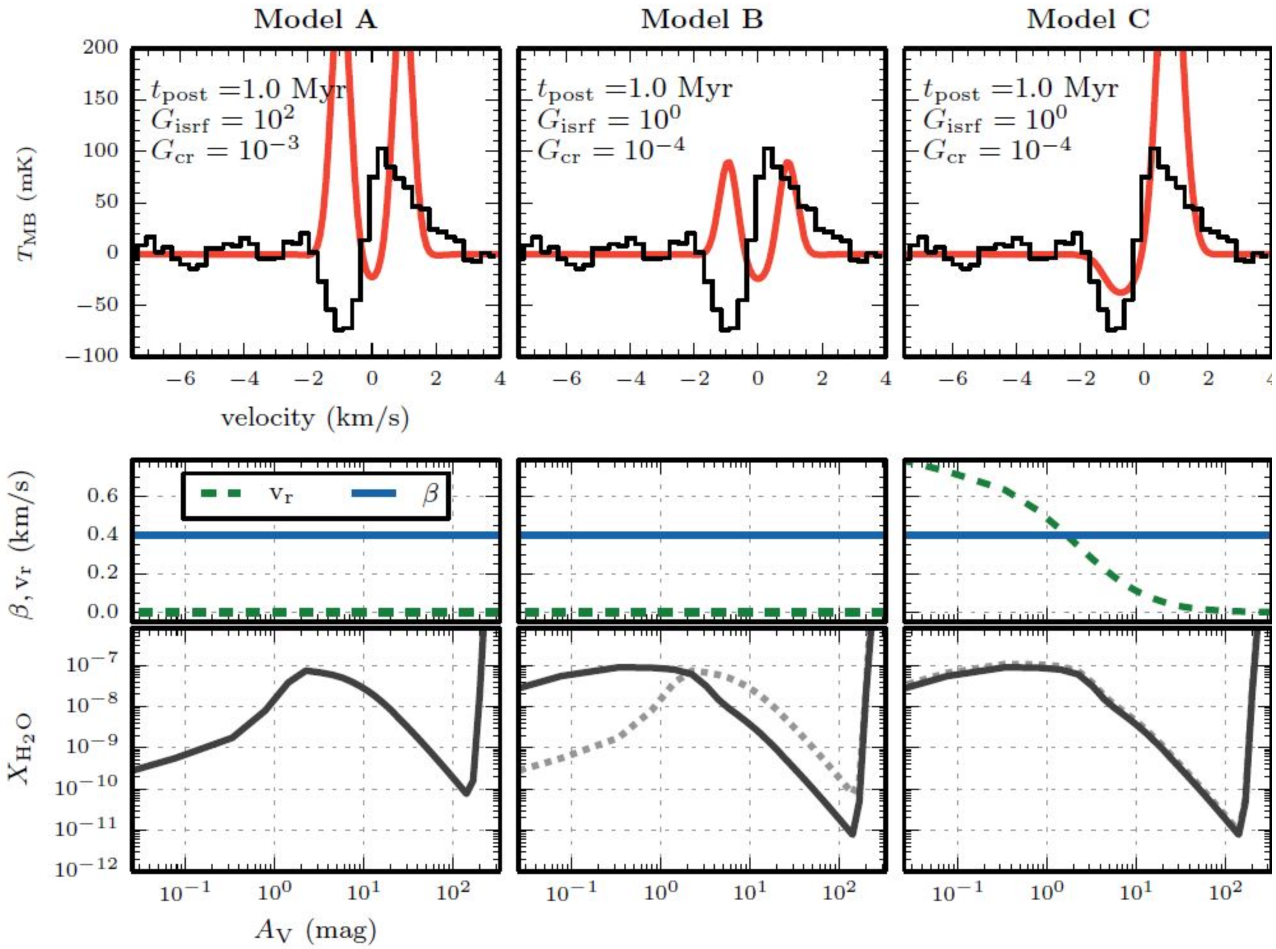
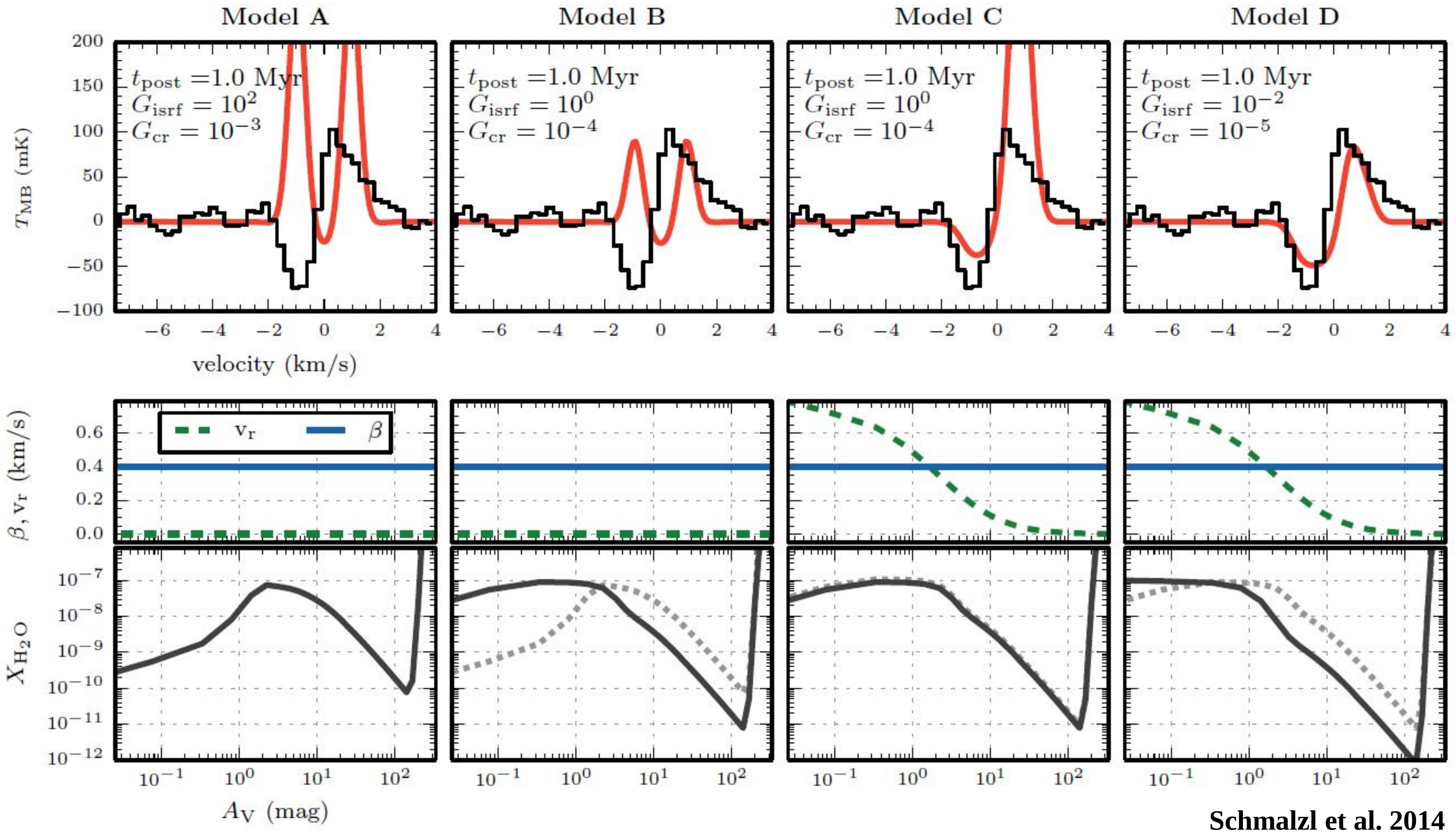


Fit to observed line profiles

L1551 557 GHz outflow subtracted



Schmalzl et al. 2014
Mottram et al. 2013

Constrain G_{ISRF}, G_{CR} and velocity profile / infall or expansion rate

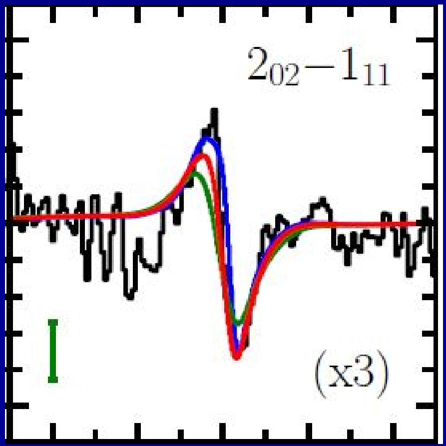
Low-mass sources

Source	r_{mdi} (10^3 AU)	M_g ($M_\odot$)	$\dot{M}_{inf}$ (10^{-5} $M_\odot$ yr^{-1})	t_{inf} (10^4 yr)	t_{ff} (10^4 yr)
IRAS4A	1	0.68	15.4	0.44	10.4
L1527	5	0.08	1.6	0.47	7.6
BHR71	3	0.90	3.7	2.42	19.7
IRAS15398	3	0.50	3.4	1.46	7.4
L1157	3	1.17	5.3	2.22	13.5

Mottram et al. 2013

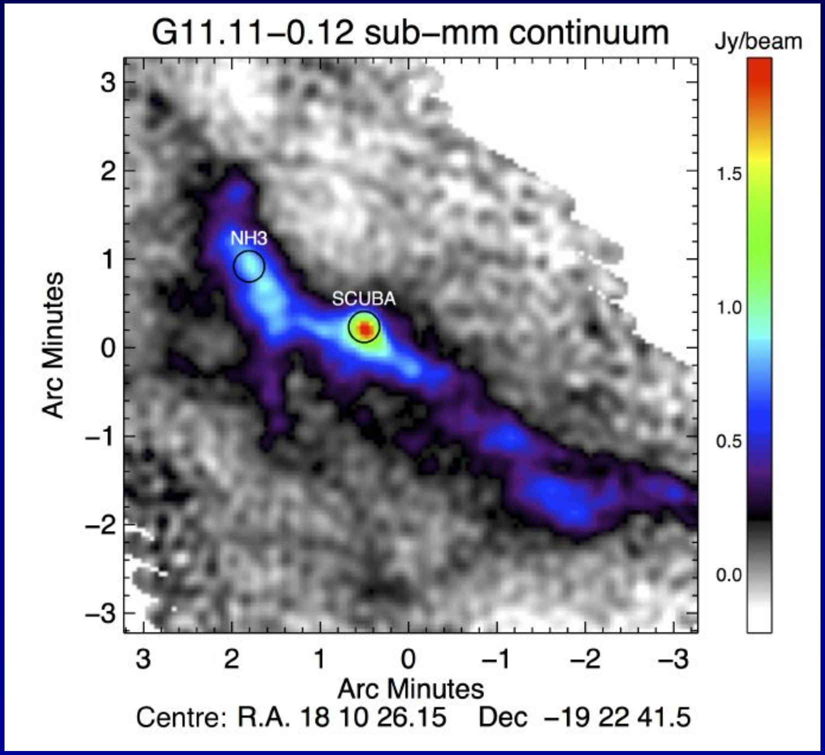
dM/dt infall=10^{-5}-10^{-4} M_{sun}/yr

Only a small fraction of sources shows infall!
A few show expansion
Most sources show no signature



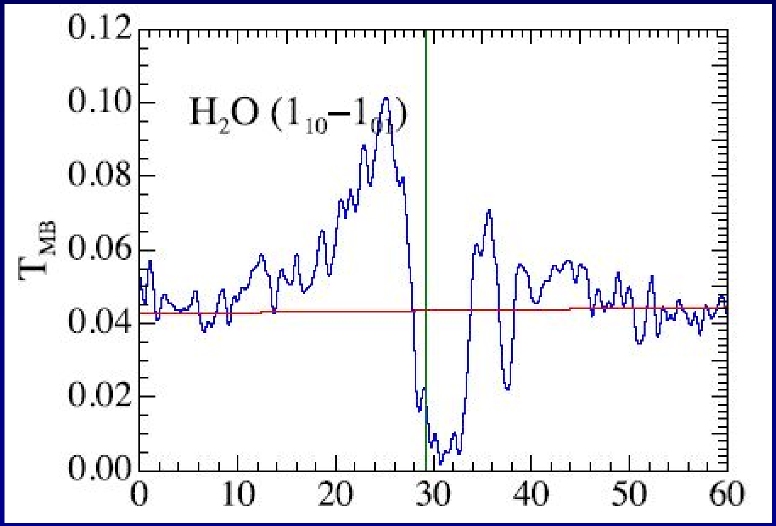
High-mass sources

Infrared Dark Cloud



Shipman et al. 2014

SCUBA peak



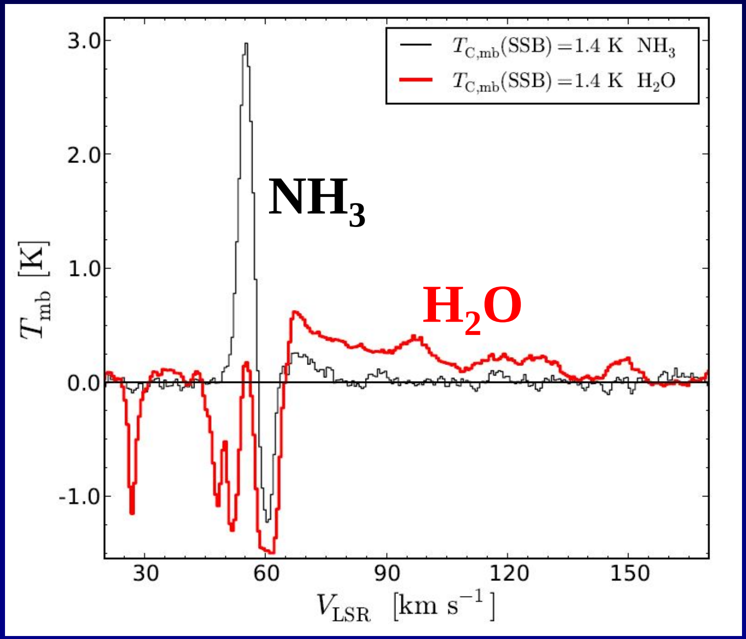
Inverse P-Cygni profile
→ Infall rate 10^{-3} M_{sun}/yr

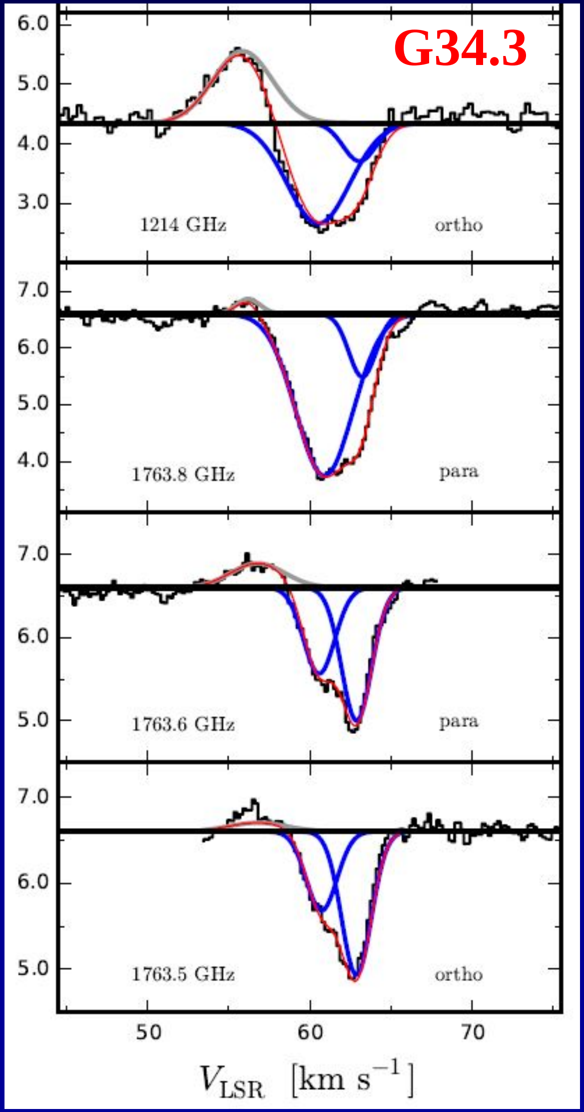
- dM/dt infall=10^{-4} – 10^{-2} M_{sun}/yr for sample of high mass HMPOs

(Herpin et al. 2012, 2016)

NH_3 as infall tracer

G34.3





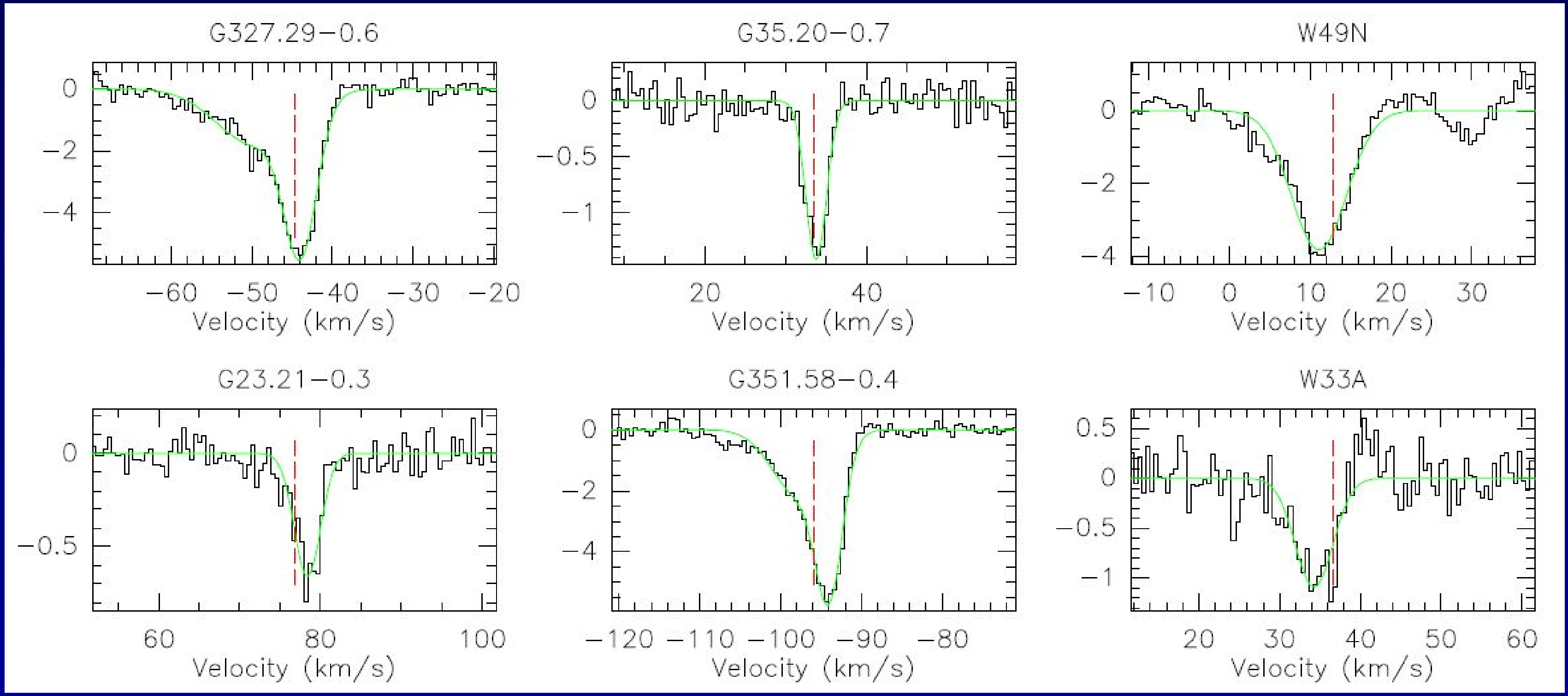
- NH_3 suffers less from contamination by outflow and foreground clouds

dM/dt infall = (0.4-4.5)x10^{-2} M$_{sun}$/yr

Hajigholi, C. Persson et al. 2015

NH_3 as infall tracer

Infall onto protocluster

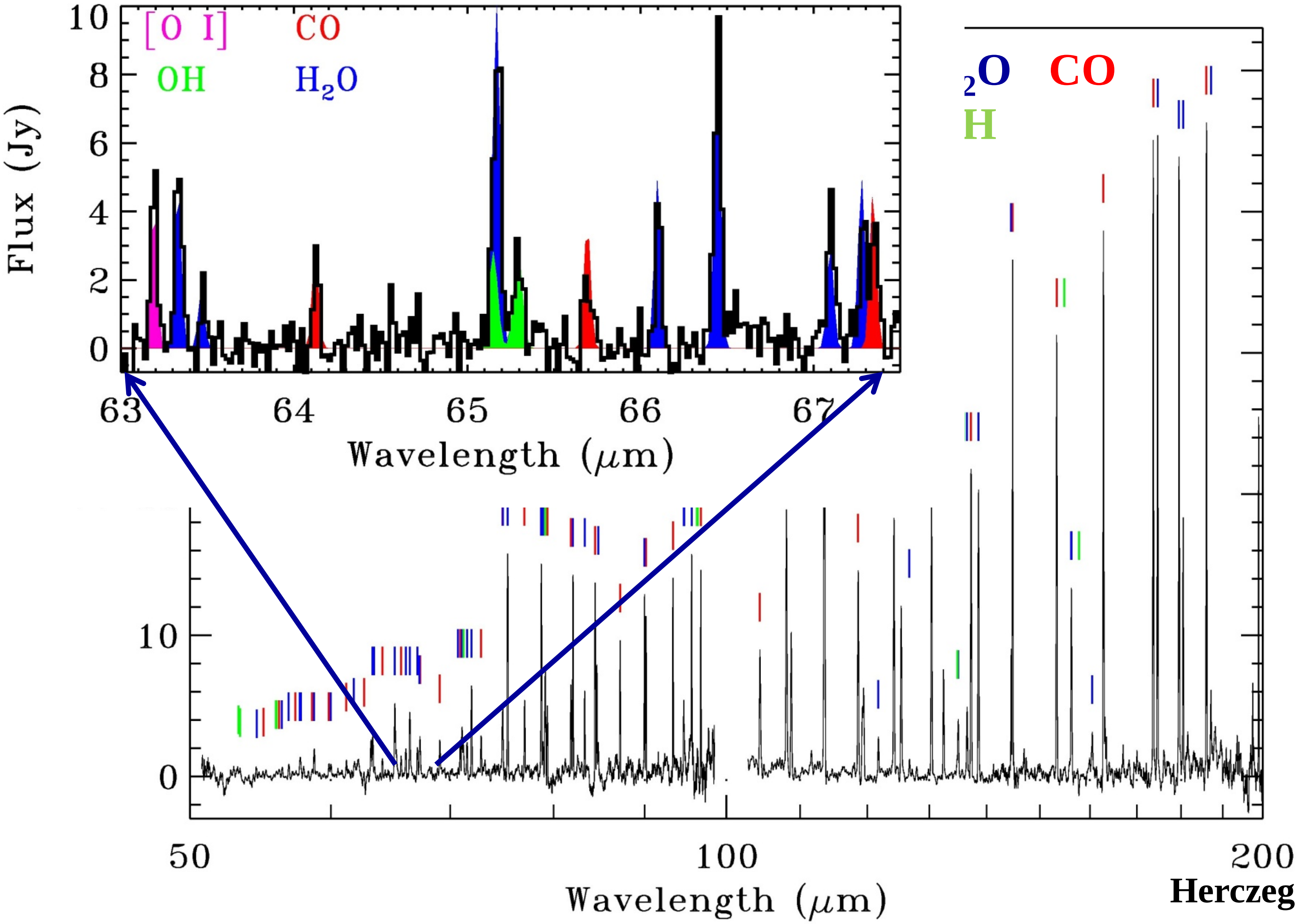


Wyrowski et al. 2012, 2016
SOFIA-Great

- **dM/dt infall = 0.3-16 x 10^{-3} M_{sun}/yr on clump/cluster scale (similar to H_2O results)**
- **Infall rates ~10-30% of free fall →Test of quasi-static vs turbulent scenarios**

Hydrides as a tracer of shock physics

Hot H_2O, OH in low-mass protostars

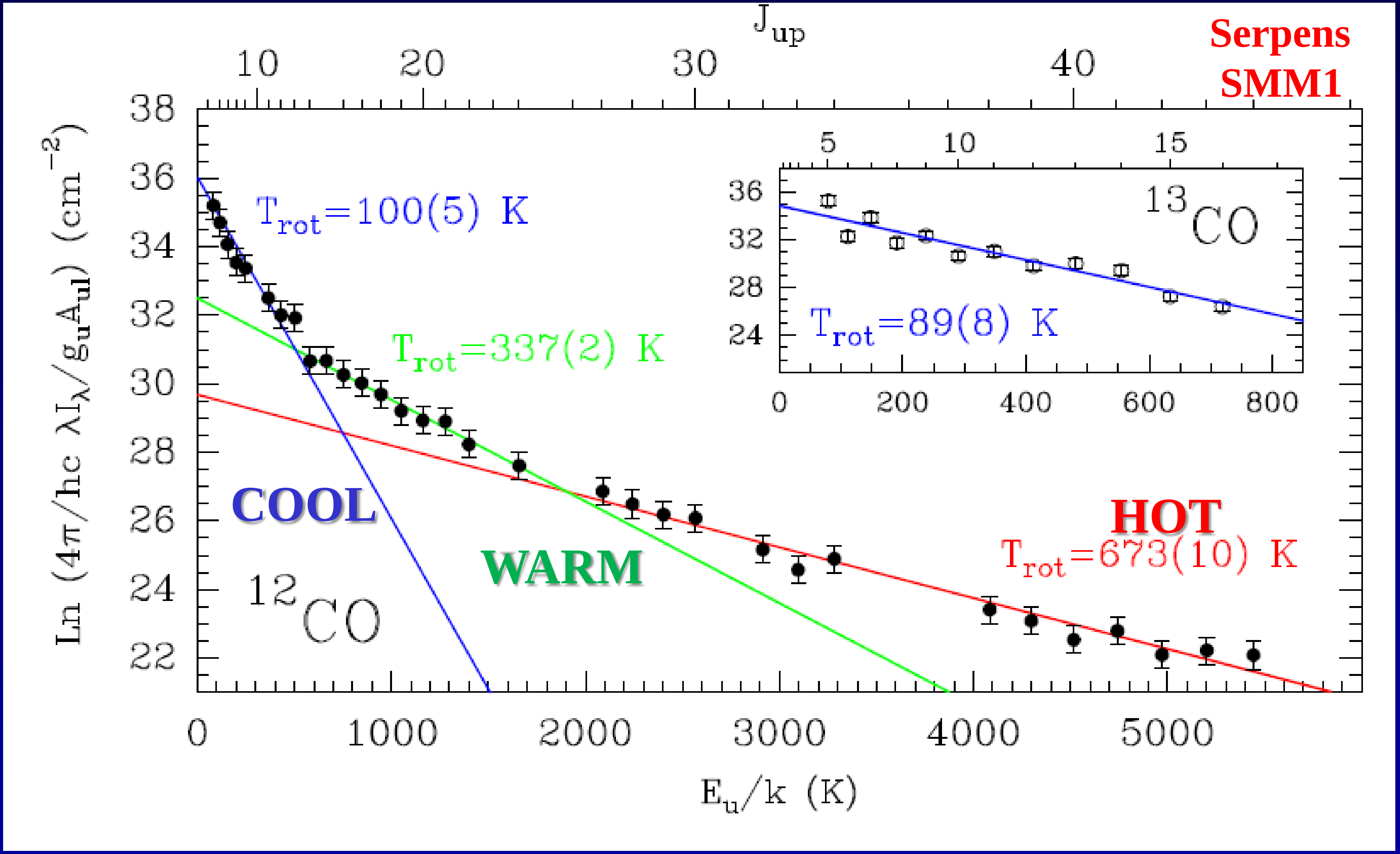


NGC1333
IRAS4B
PACS
Spectral scan (continuum subtracted)

L=4.4 L_{Sun}
d=235 pc

All lines assigned to 4 species, from levels up to several thousand K

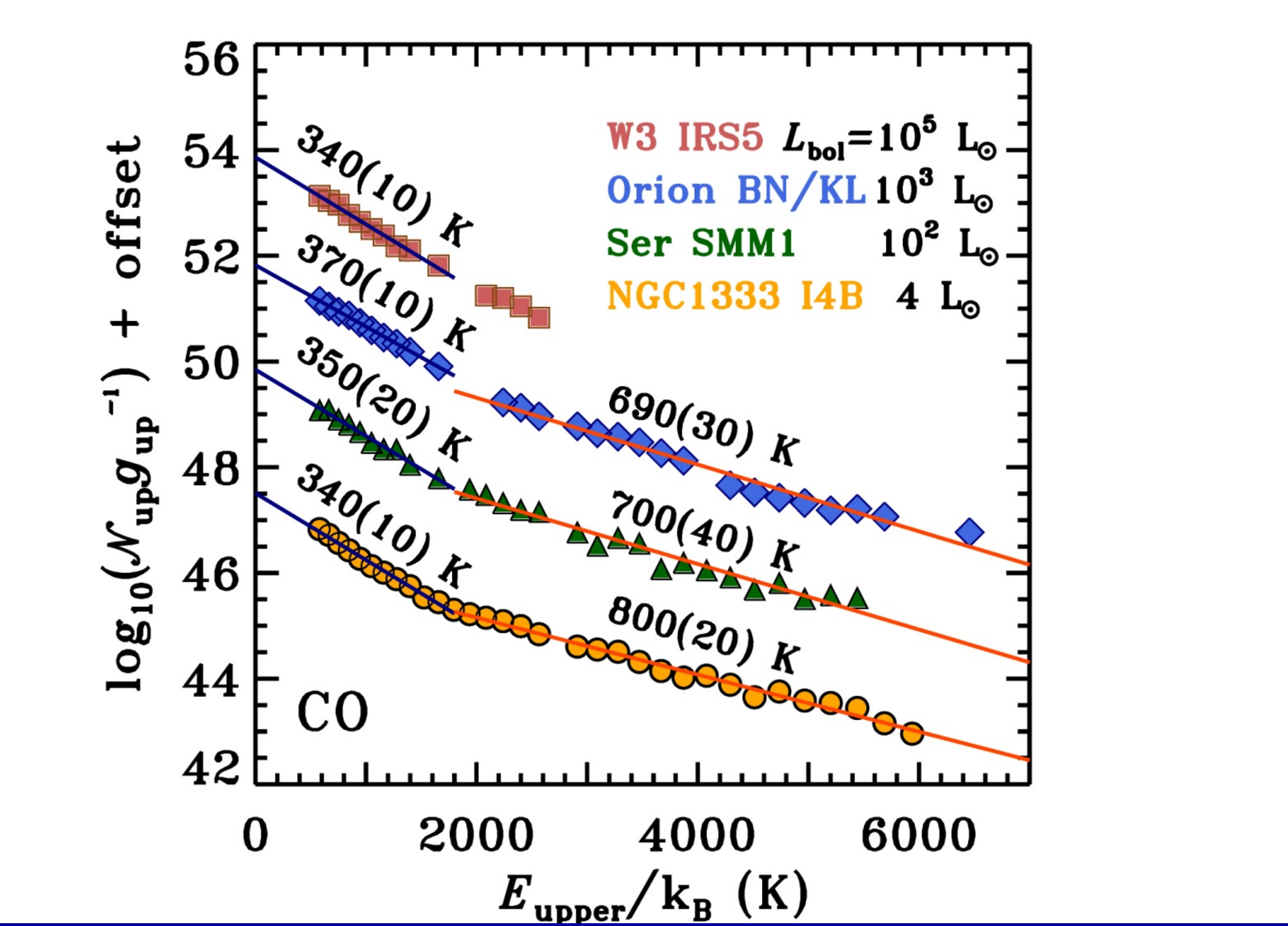
CO rotational diagram: 3 components



~**100** (*J*$_u$=1-12), **300** (*J*$_u$=13-25) and **700** (*J*$_u$>25) K

Goicochea et al. 2012

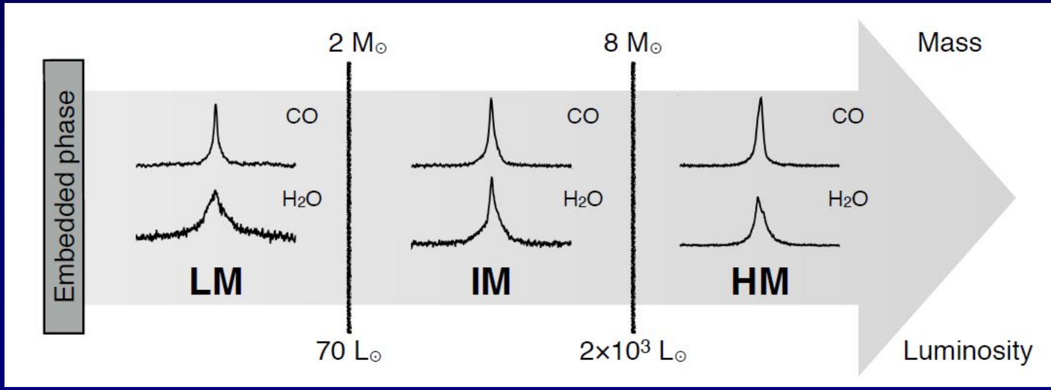
Universal CO ladders
low vs high-mass YSOs



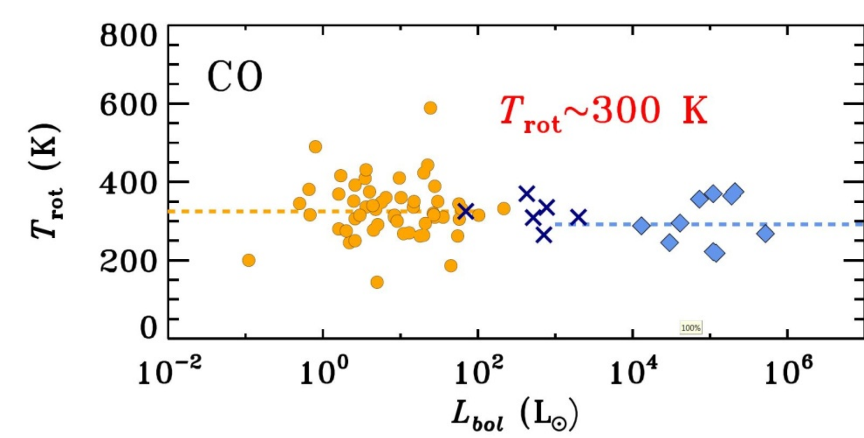
Karska et al. 2013, 2014a, 2017

Similar temperature components

Universal profiles and T_{rot}



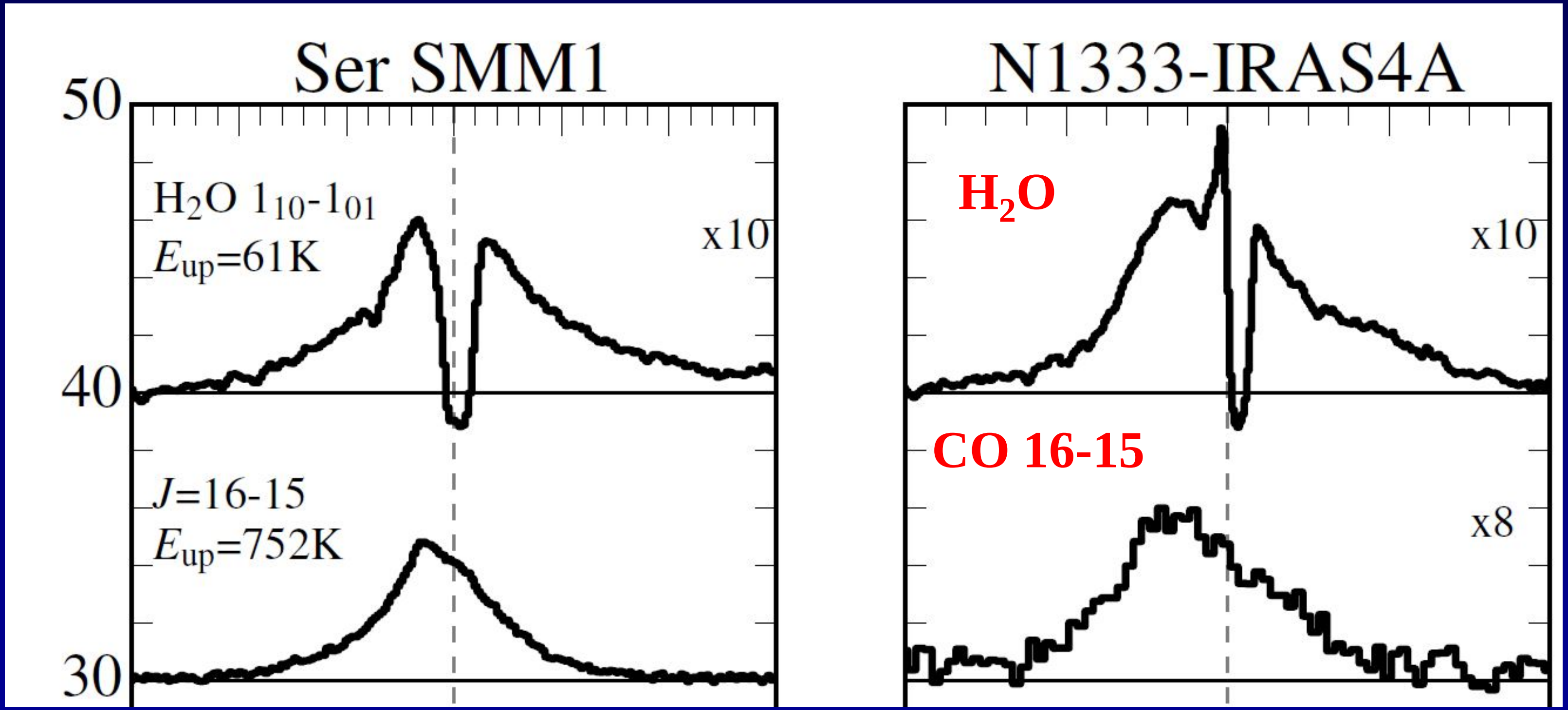
San José-García et al. 2015



LM HM

Karska et al. 2014a
Manoj et al. 2013

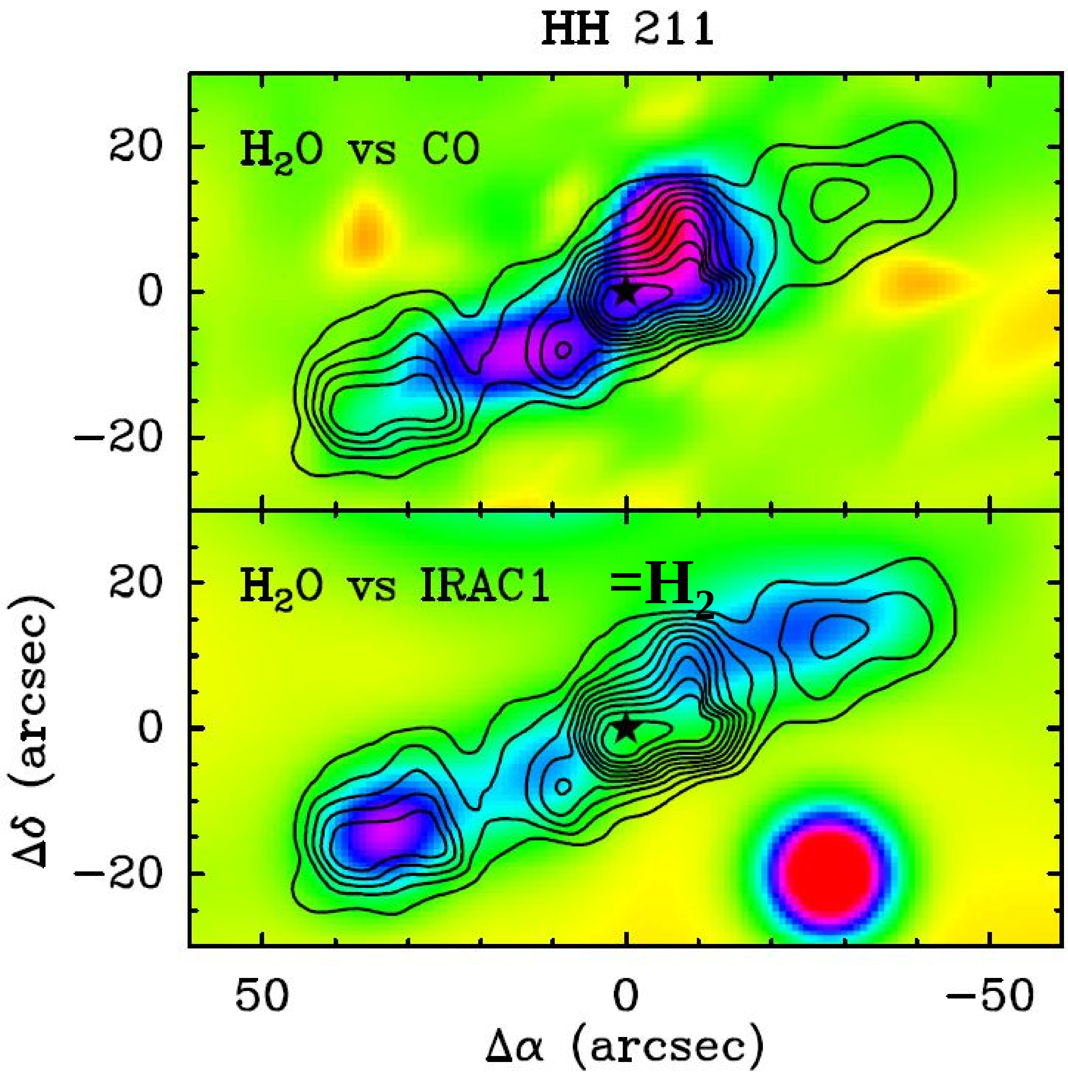
HIFI evidence for multiple components water vs CO 16-15



Kristensen et al. 2017

Water and high-J CO follow each other, *not* CO low J

Water does not follow low-J CO

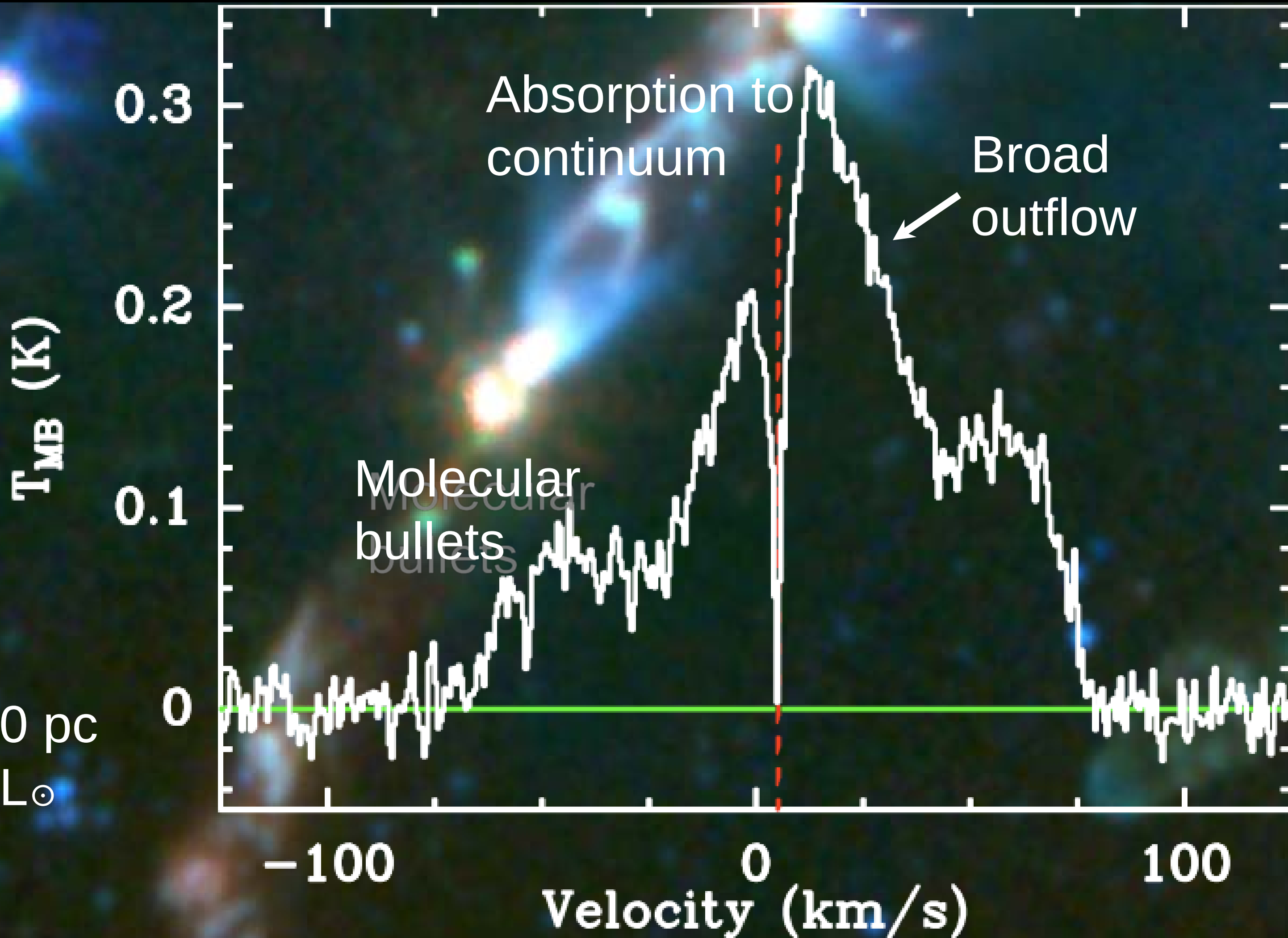


Contours: H_2O
Image: CO

Tafalla et al. 2013
Nisini et al. 2013
Santangelo et al. 2014

- **H_2O and H_2 go together, but not with CO low J**
- **H_2O abundance as low as 10^{-7}**

H_2O: multiple components

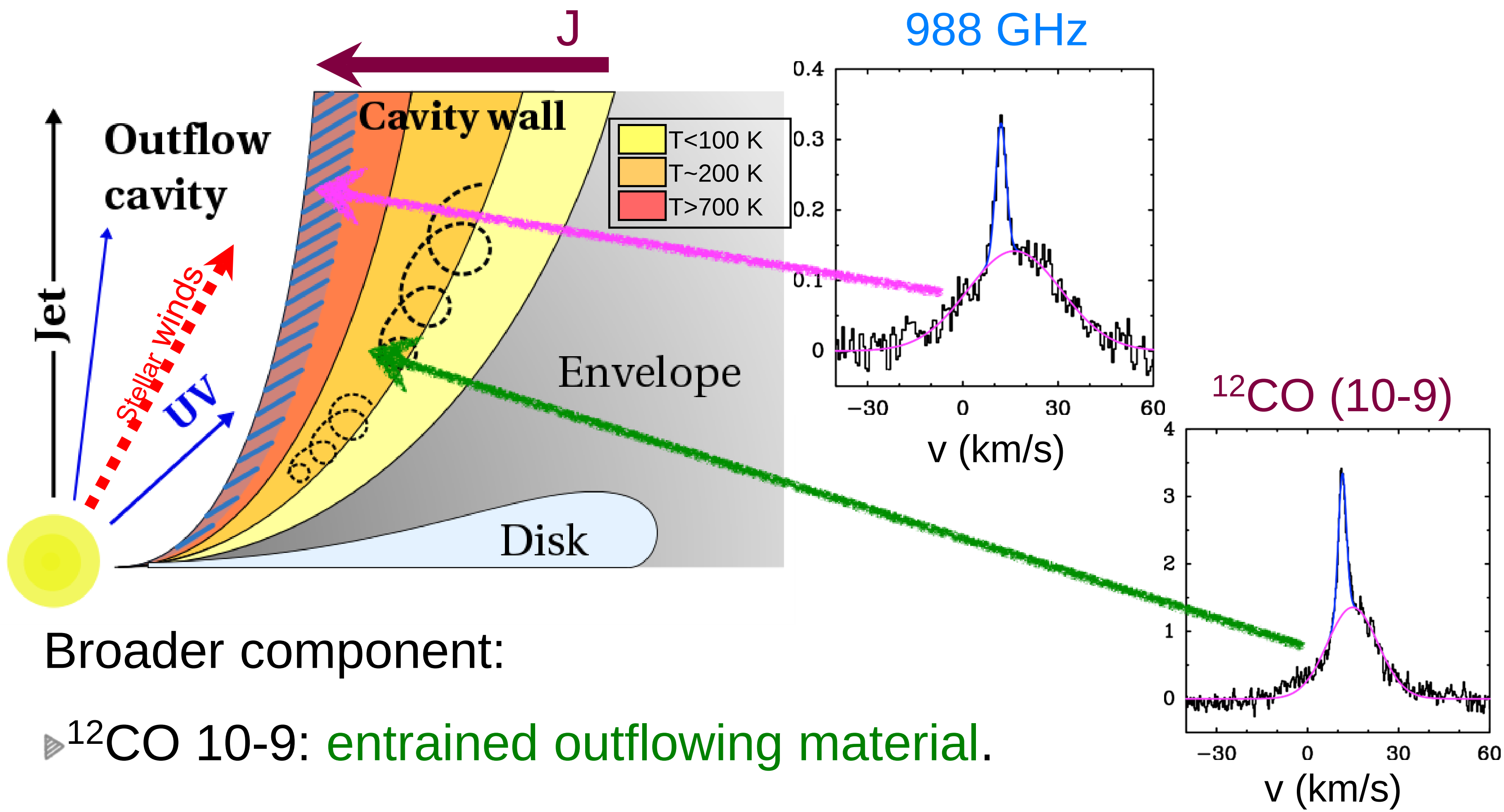


L1448:
D ~ 250 pc
L ~ 11 L⊙

H_2O bullets in protostellar jet

Kristensen et al. 2011

Understanding the line profiles



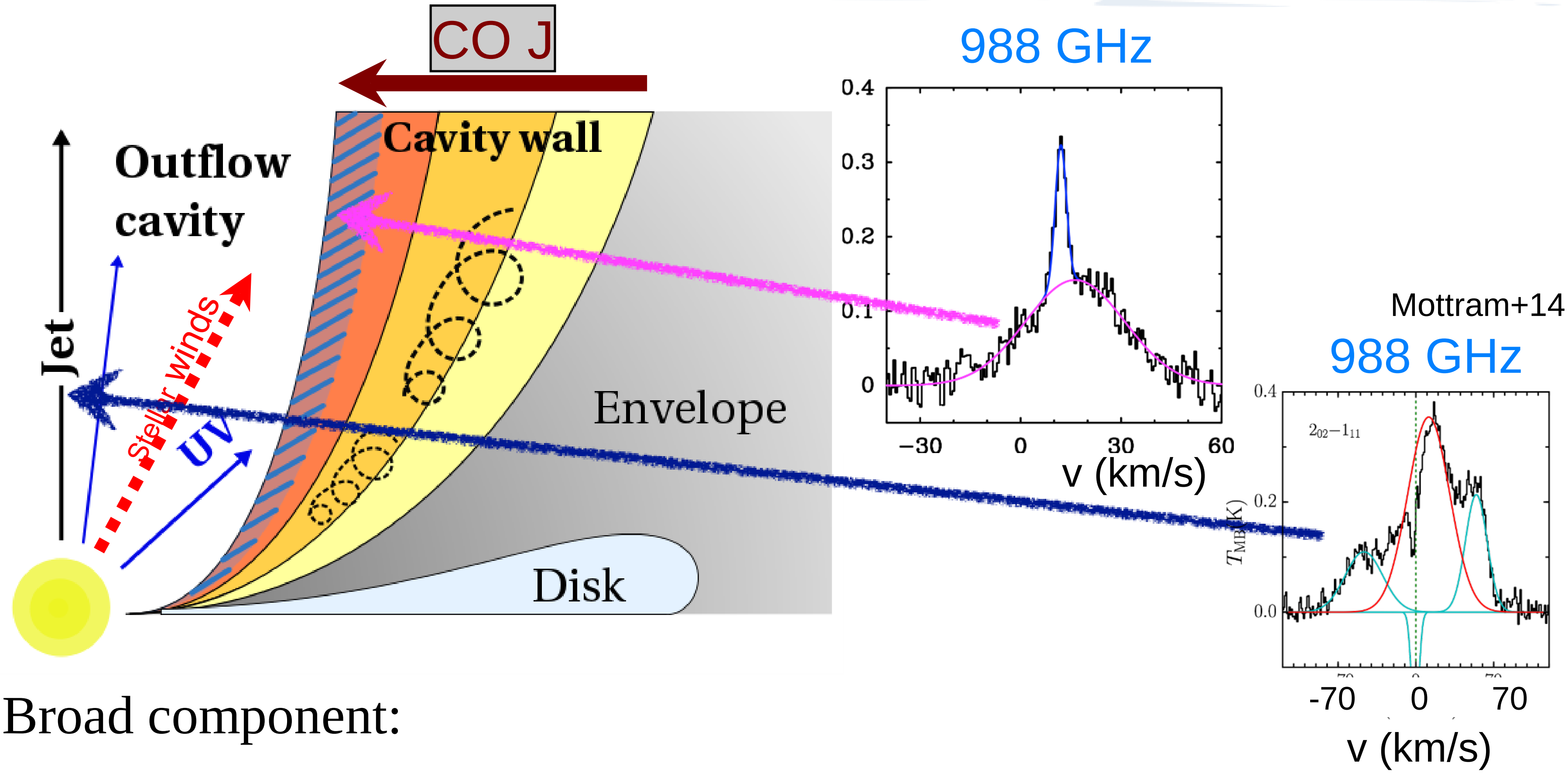
Broader component:

- ^{12}CO 10-9: entrained outflowing material.
- H_2O: shocked gas in outflow cavity wall (cavity shock)

  narrow layer, ~10 AU wide

San José García et al. 2015
Mottram et al. 2014, 2017

Understanding the line profiles



Broad component:

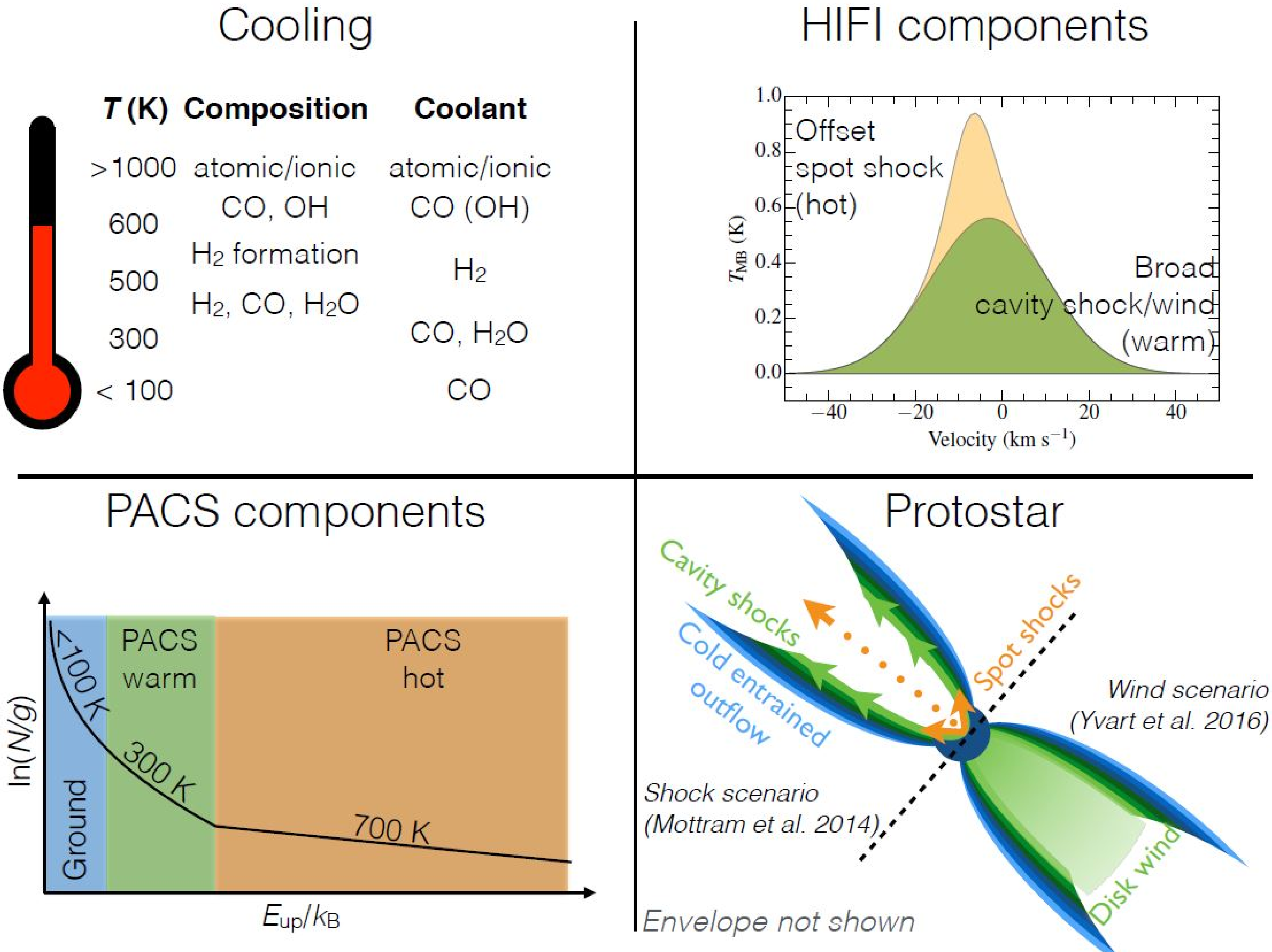
H_2O: cavity shock component = non-dissociative shocks.

Medium (offset) component:

H_2O: spot shock component = dissociative shocks.

Two components also seen in CO ladder

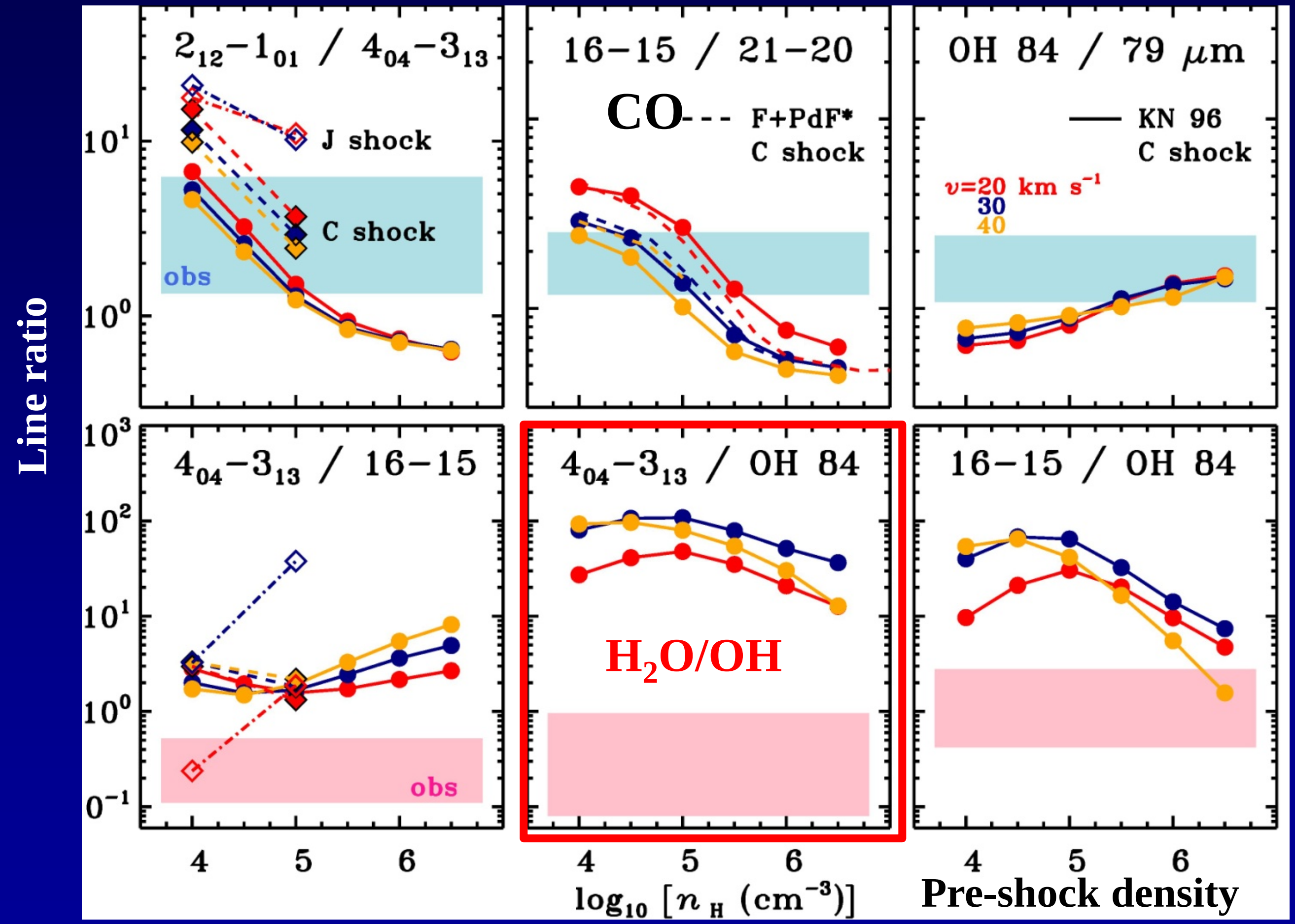
San Jose Garcia et al. 2015
Mottram et al. 2014, 2017
Kristensen et al. 2012, 2017



Kristensen et al. 2017

Shock physics: Line ratios

Compare with shock models



Same species

n_{pre}~10^5 cm^{-3}

v_S>20 km s^{-1}

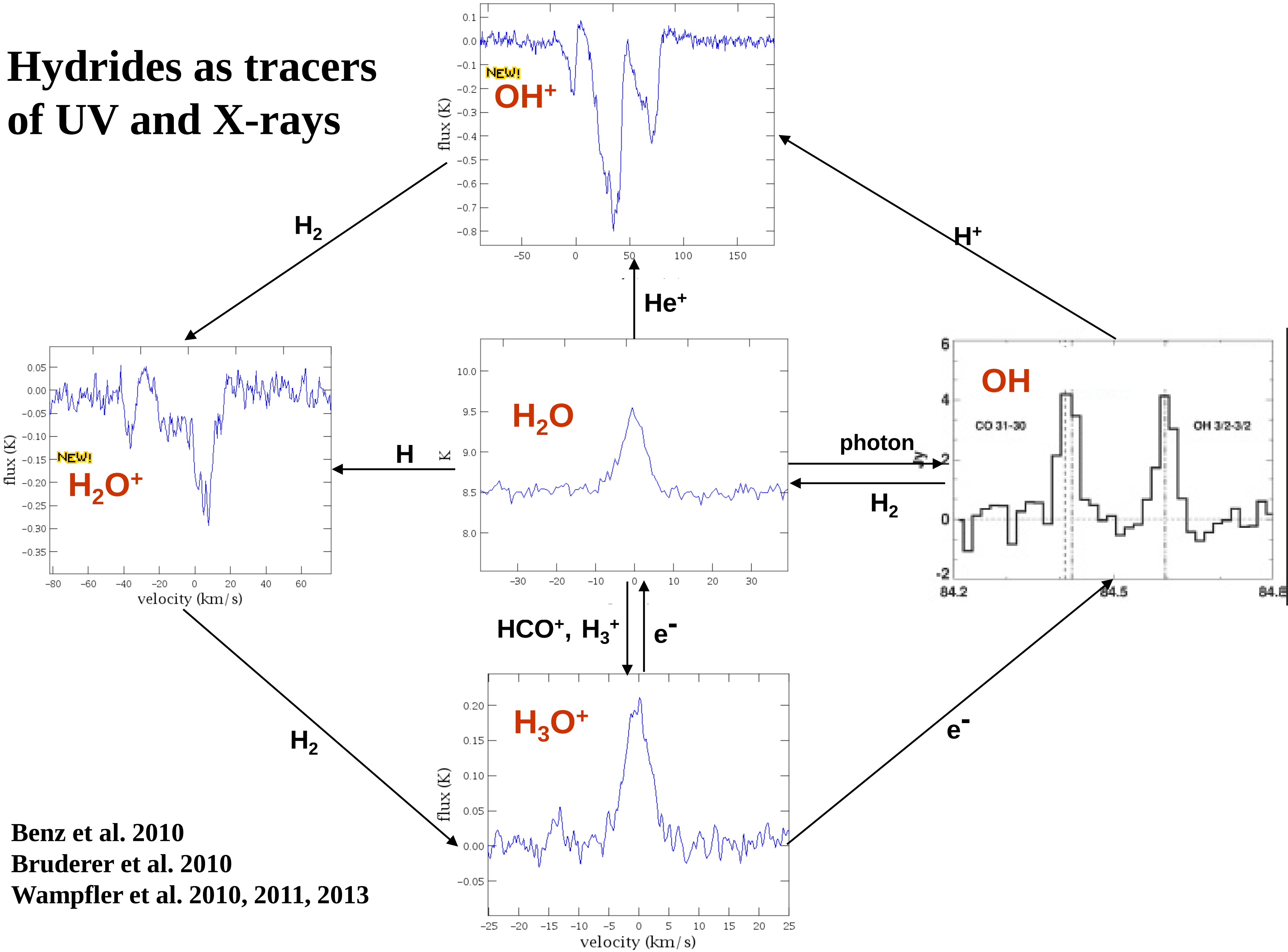
Different species

Karska et al. 2014b
Perseus sample
Karska et al. 2017
Kaufman, Melnick et al.

Shocks reproduce excitation, but not chemistry: H_2O overproduced

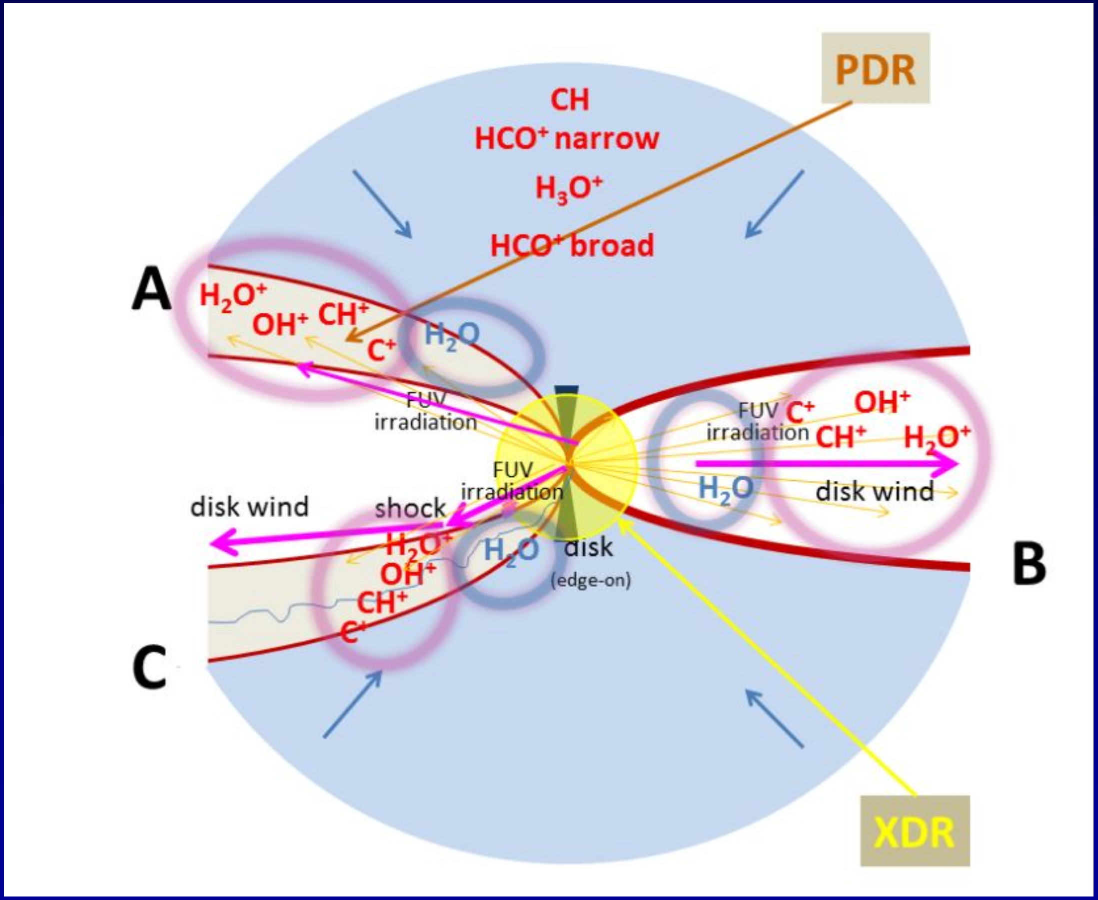
Points to need for UV irradiated shock models

Hydrides as tracers of UV and X-rays



Benz et al. 2010
Bruderer et al. 2010
Wampfler et al. 2010, 2011, 2013

Origin of hydrides: irradiated shocks



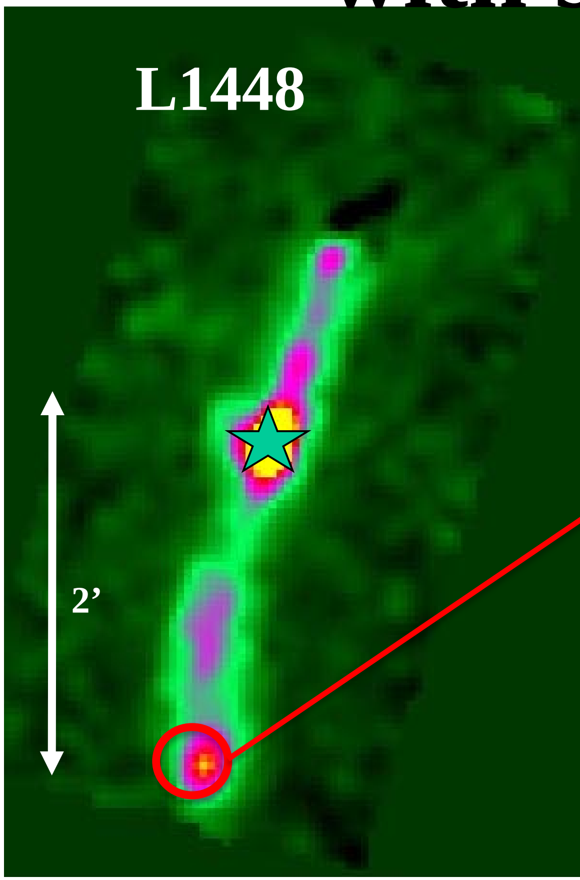
Talk by Benz

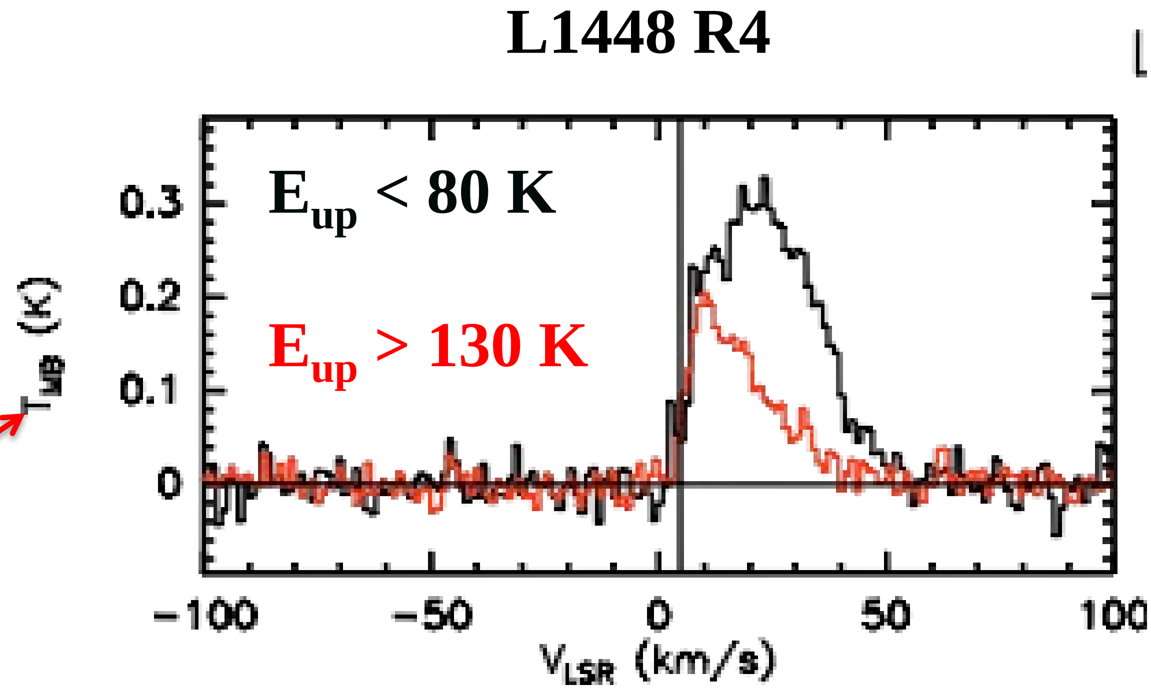
Benz et al. 2016
Bruderer et al. 2009

Kristensen et al. 2013

Favor scenario C of irradiated shock with FUV enhanced by factor G_0=few hundred

Offset from protostar: outflow spots with shocked water lines



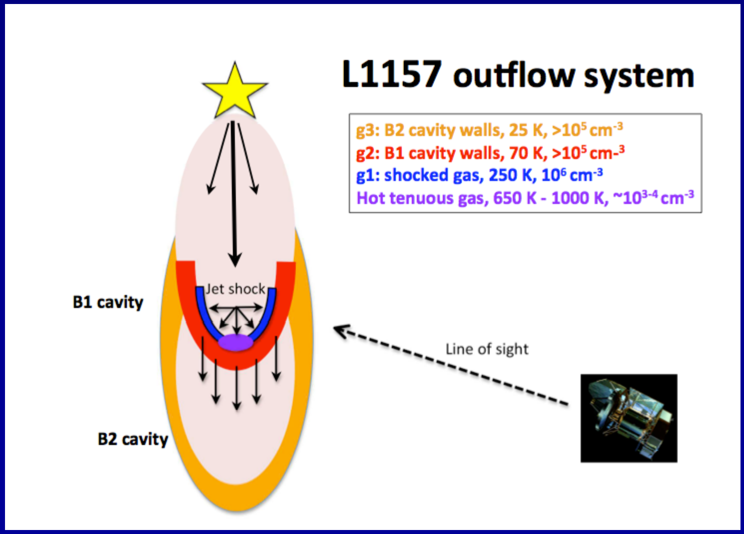


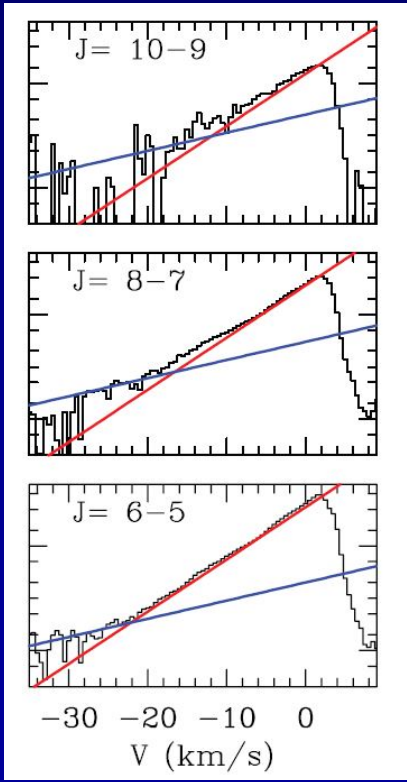
Santangelo et al. 2012
Nisini et al.

Variations of physical conditions vs velocity uniquely probed by profiles of H_2O lines at different energies

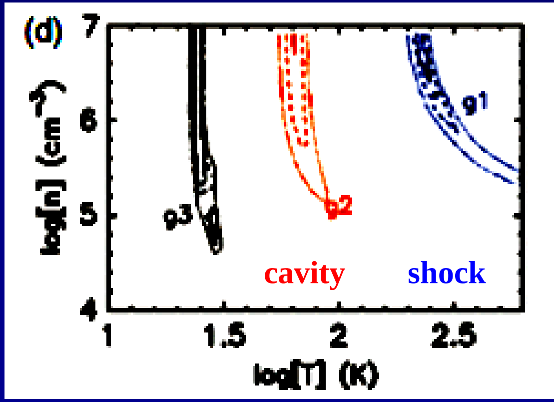
Outflow shocks probed by CO and H_2O

- The jet impact on the cavity (Mach disk) upstream of the bow, associated with a hydrodynamical shock
- The cloud shock (bow), associated with a magnetized shock





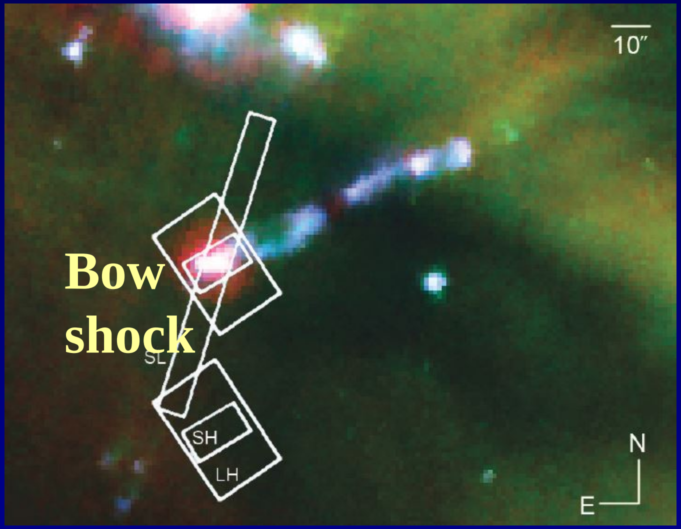
(Lefloch et al. 2012)



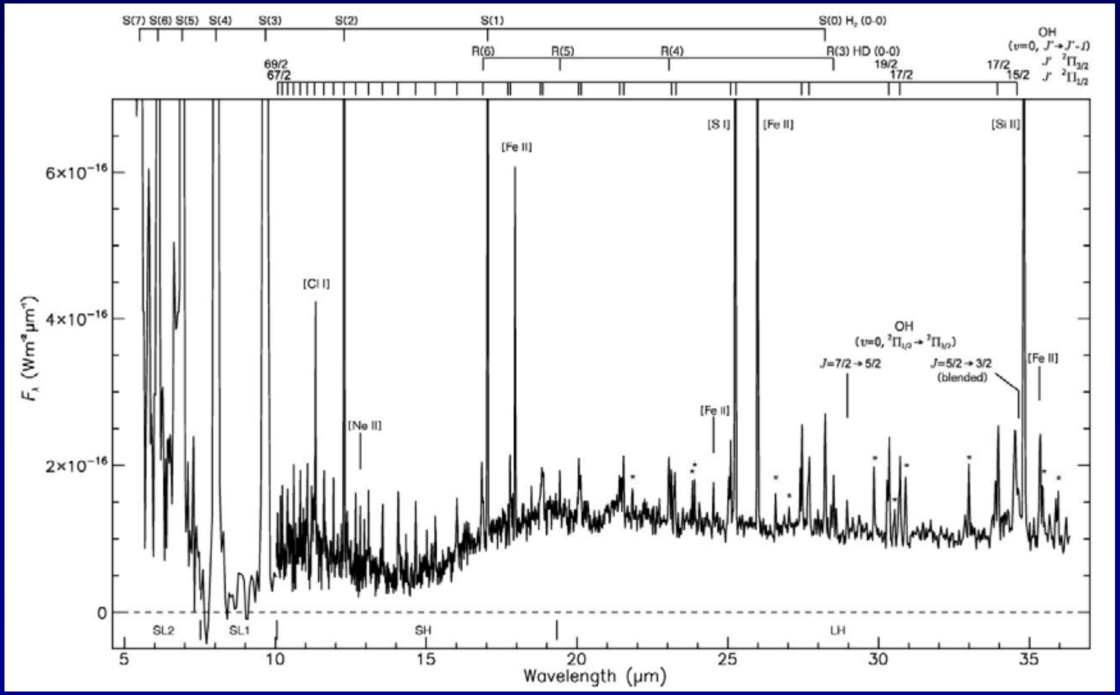
Busquet, Lefloch, Benedettini et al. 2013

Highly excited OH as probe of Ly α

HH211



Tappe et al. 2008, 2012
Carr & Najita 2014 disks



$H_2O + h\nu \rightarrow OH\ (v,J) + H$ through B state

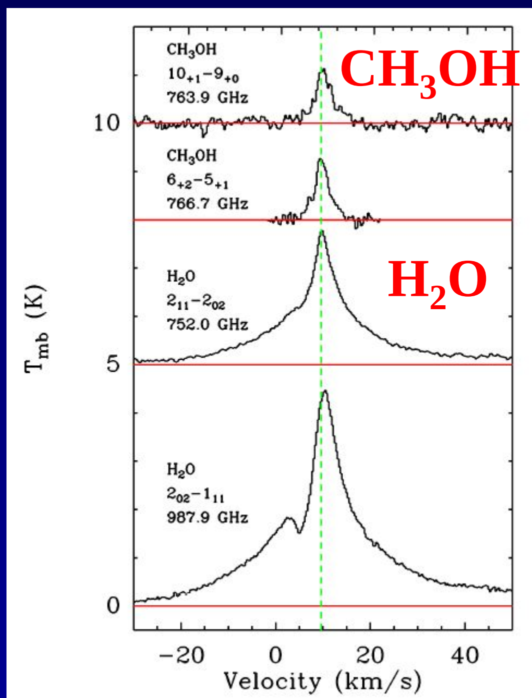
Theory: van Harrevelt & van Hemert 2001; in Yang, Harich et al. 2000

Conclusion physics

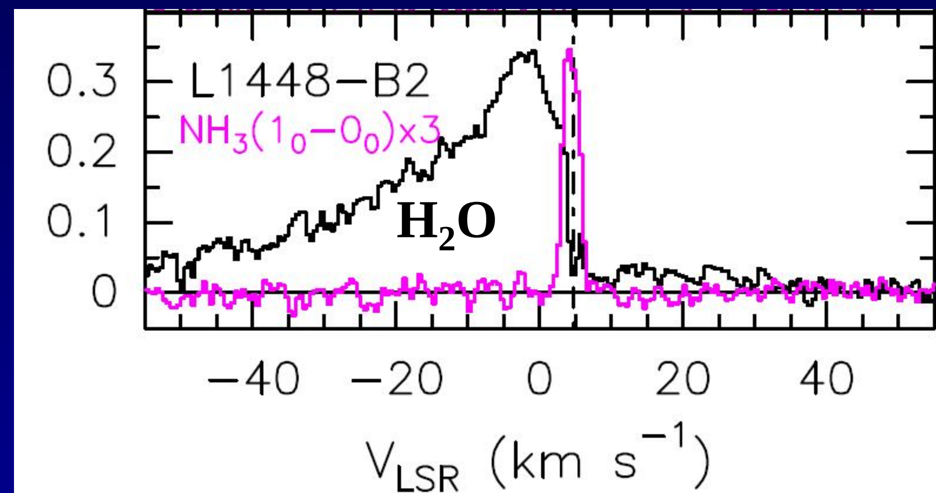
- CO ladder reveals universal cold, warm and hot components through excitation
- H_2O reveals multiple (new) physical components through kinematics
- Emission dominated by shocks
  - Non-dissociative shock CO, H_2O, some OH
    - Current models too much H_2O emission → UV
  - Dissociative shock O I, OH, some H_2O (medium/offset)
- Processes similar from low- to high-mass YSOs

Hot water chemistry in shocks
Ice sputtering vs high-*T* water production

Water vs CH_3OH, NH_3, ...



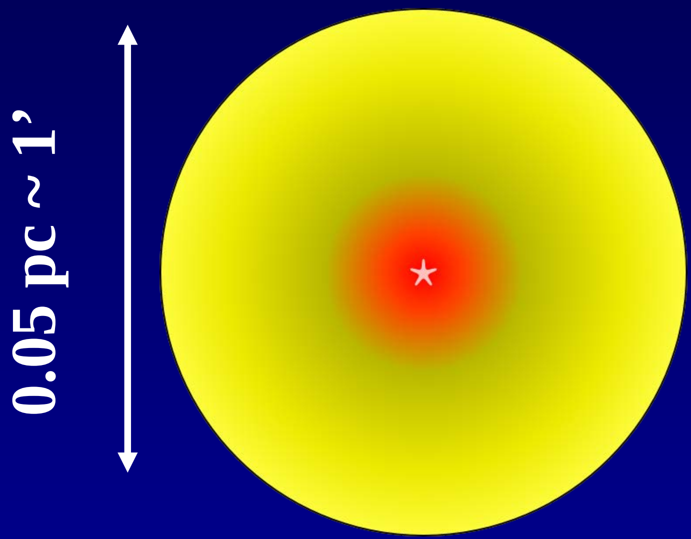
Suutarinen et al. 2014, Leurini et al. 2014
van Kempen et al. 2014, Herpin et al. 2016

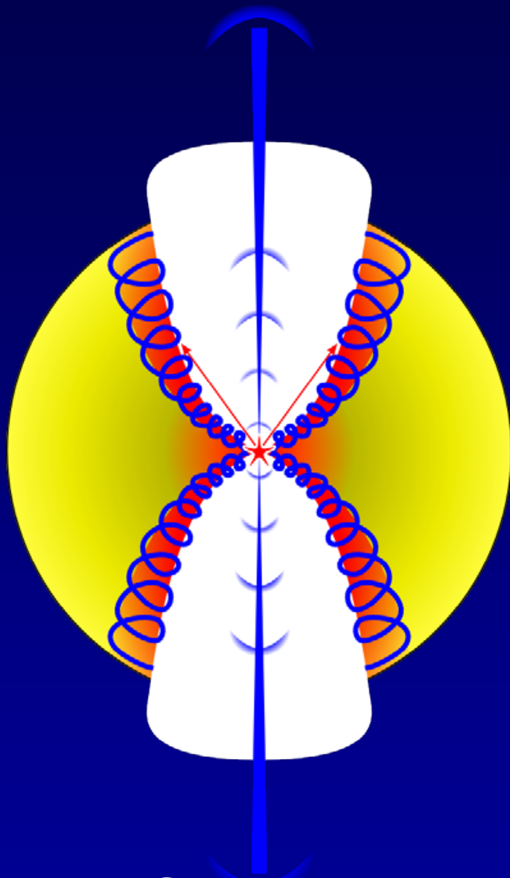


Viti et al. 2011, Gomez-Ruiz et al. 2016

- Water at low velocities mostly sublimated/sputtered
- Water at high velocities formed by high-*T* chemistry
- NH_3 and CH_3OH destroyed by reactions with H at high *T* → diagnostic

Hot cores vs outflows





Hot core

Compact (~200 AU) region where H_2O ice sublimates

Dominates NOEMA, ALMA $H_2^{18}O$ emission

Outflows, shocks

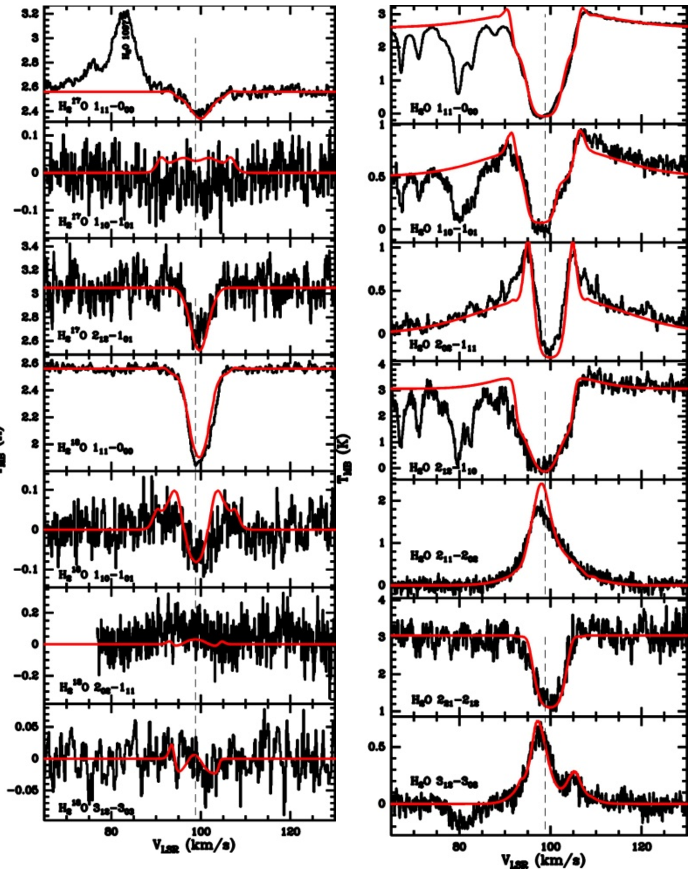
Extended emission along outflow; H_2O enhanced in shock

Dominates Herschel emission

JWST for *imaging* shocks

High mass inner abundance

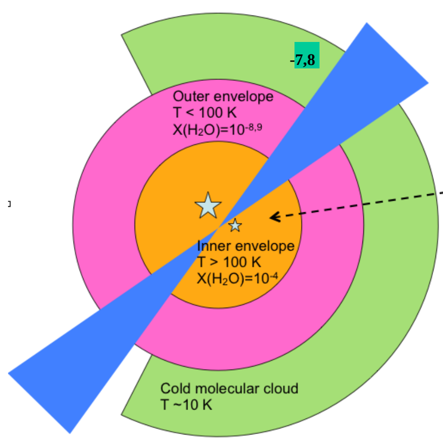
Isotopes **$H_2^{16}O$**



Herpin et al. 2012

W43
$L=2.10^4\ L_{sun}$
D=5.5 kpc

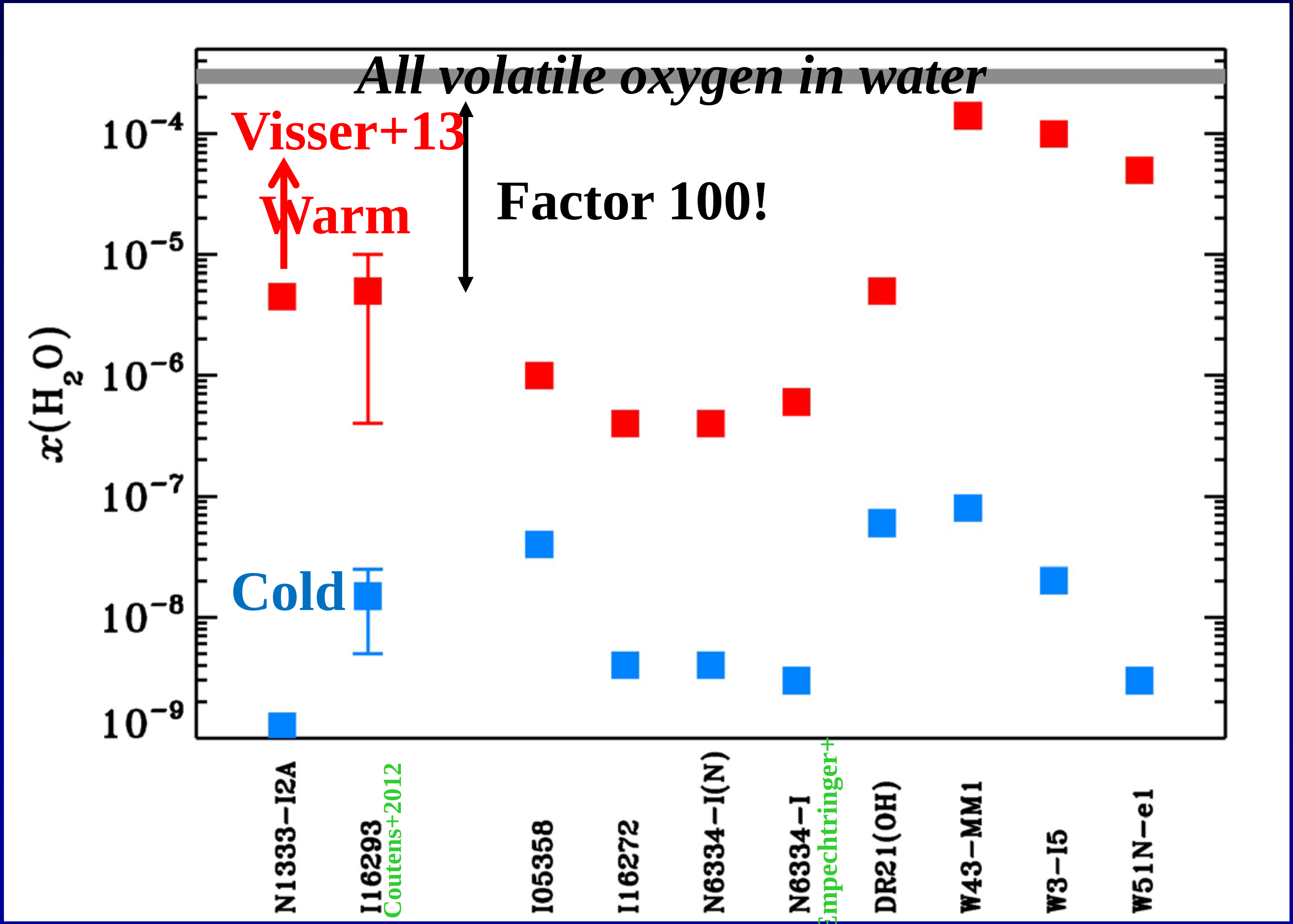
Parameter	
X_{H_2O}	8.0 (±1.0) ×10^{-8}
Post-jump X_{H_2O}	1.4 (±0.4) ×10^{-4}
o/p	3 ±0.2
$X_{^{18}O/^{17}O}$	4.5
$X_{^{16}O/^{18}O}$	450
V_{tur} (km s^{-1})	2.2-3.5
$V_{outflow}$ (km s^{-1})	10.2-35.5
$V_{infall,max}$ (km s^{-1})	-2.9
V_{LSR} (km s^{-1})	99.4



enhanced water abundance

Model requires jump in water abundance in inner envelope

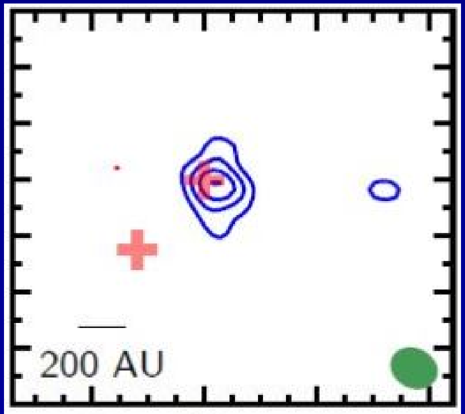
High temperature chemistry: How 'wet' are hot cores?



- H_2O destroyed in inner envelope or physical structure?

Hot core abundances: low mass

- *Herschel* $H_2^{18}O$ lines are broad => dominated by outflow
- Narrow (envelope) $H_2^{18}O$ high-*J* lines in a few sources, but high optical depth line + cont
- Use $H_2^{18}O$ 203 GHz narrow line with NOEMA/ALMA to constrain abundances

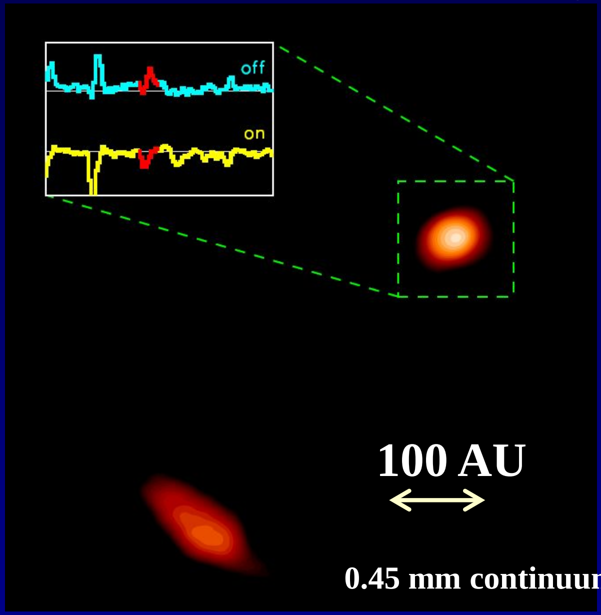


IRAS4A
NOEMA

Jørgensen & vD 2010
Persson et al. 2012, 2014

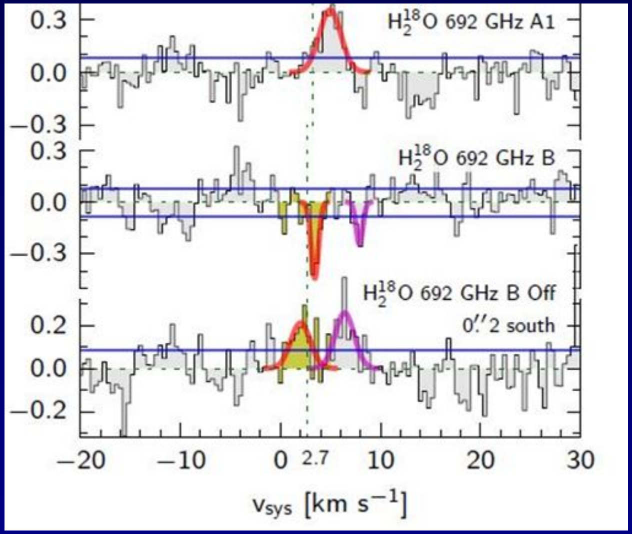
Hot water with ALMA

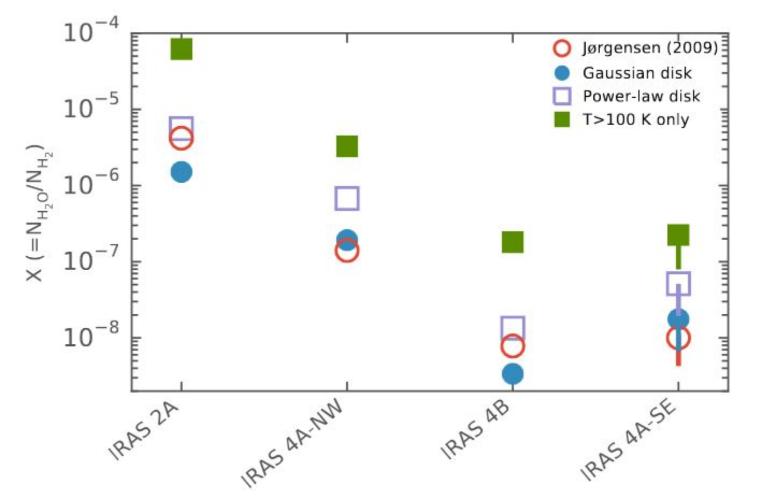
IRAS16293-2422 protobinary



Persson et al. 13

Band 9 692 GHz data





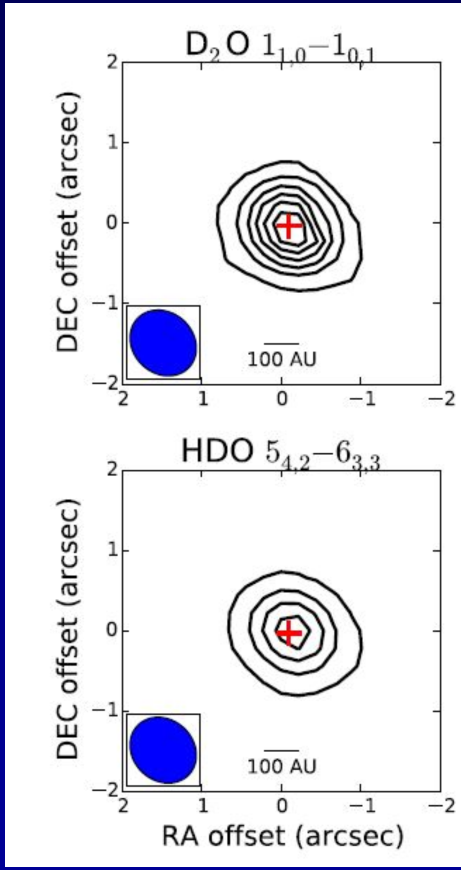
Persson et al. 2016

- Hot water detection at both sources
- Source size ~25 AU (orbit Uranus)

H_2O abundance less than 10^{-4} even if disk is taken into account (except IRAS2A) (not yet understood)

Surprise: high D_2O/HDO in warm gas

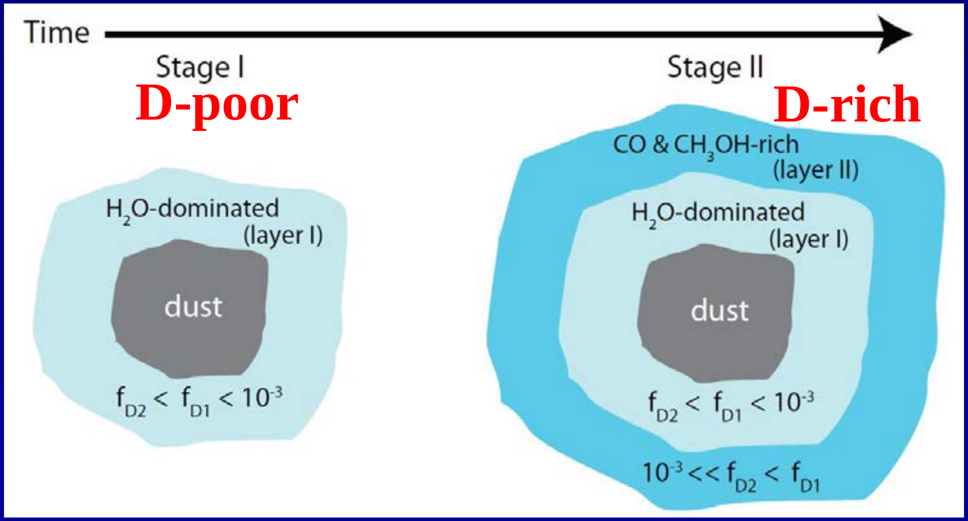
N1333



Coutens et al. 2014a,b

$D_2O/HDO \sim 10^{-2}$ >>
$HDO/H_2O \sim 10^{-3}$

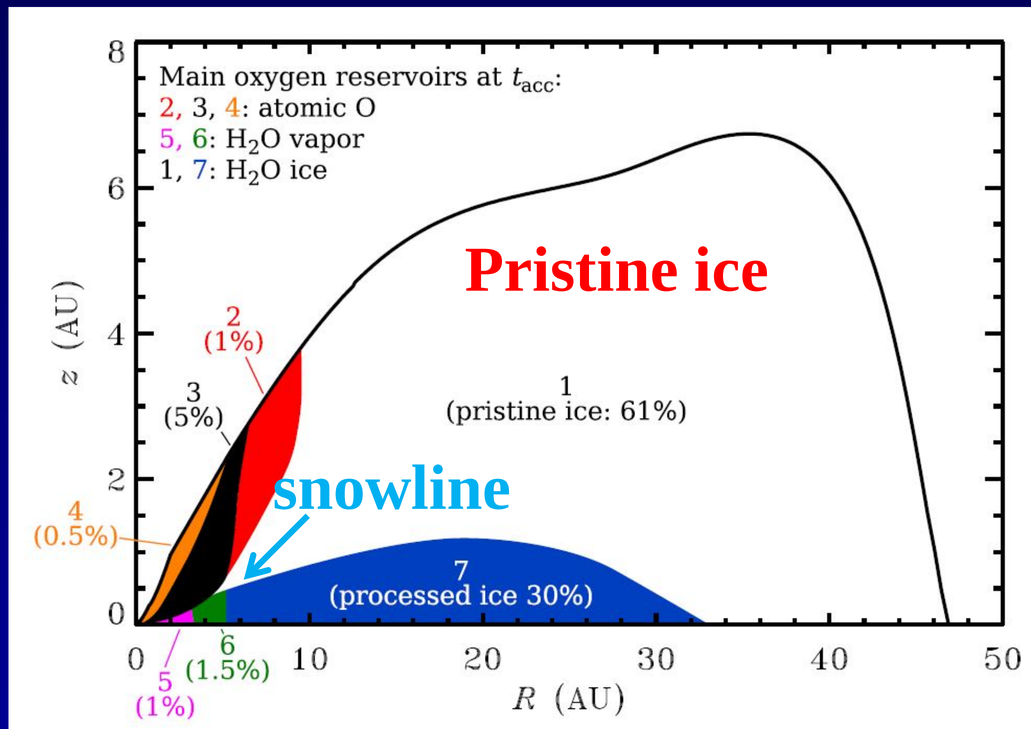
Can be understood as evolution



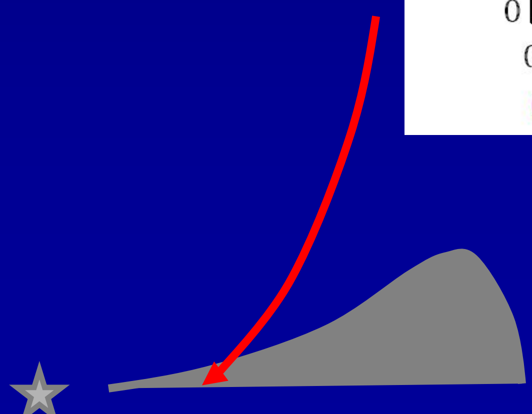
Furuya et al. 2016

History of water in young disk

End of accretion phase

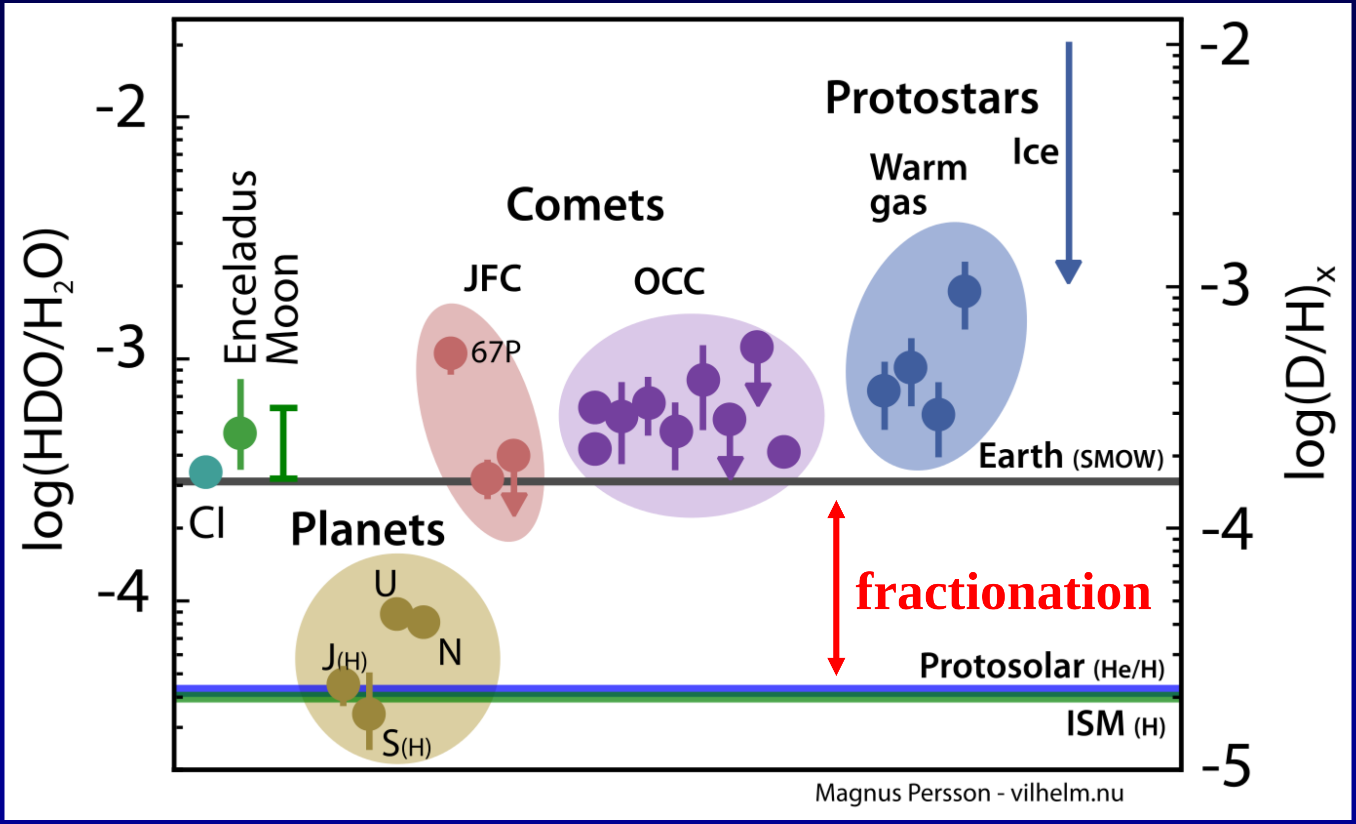


Visser et al. 2011
Furuya et al. 2016



- Most water is preserved in tact, some water has been processed
- Bulk of water enters disk as ice

HDO/H_2O as tracer history solar system?

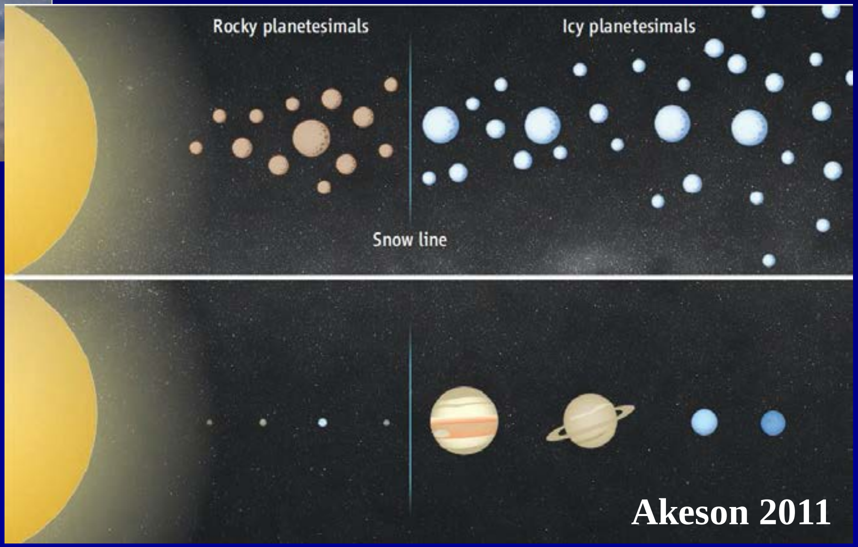


Persson et al. 2014

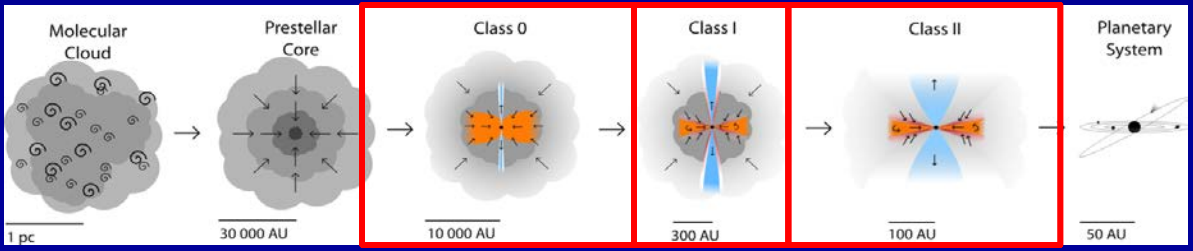
Bockelée-Morvan et al. 2014
Ceccarelli et al. 2014
Altwegg et al. 2014

What does similarity cometary and protostellar envelopes values imply?

Young disks, snowlines

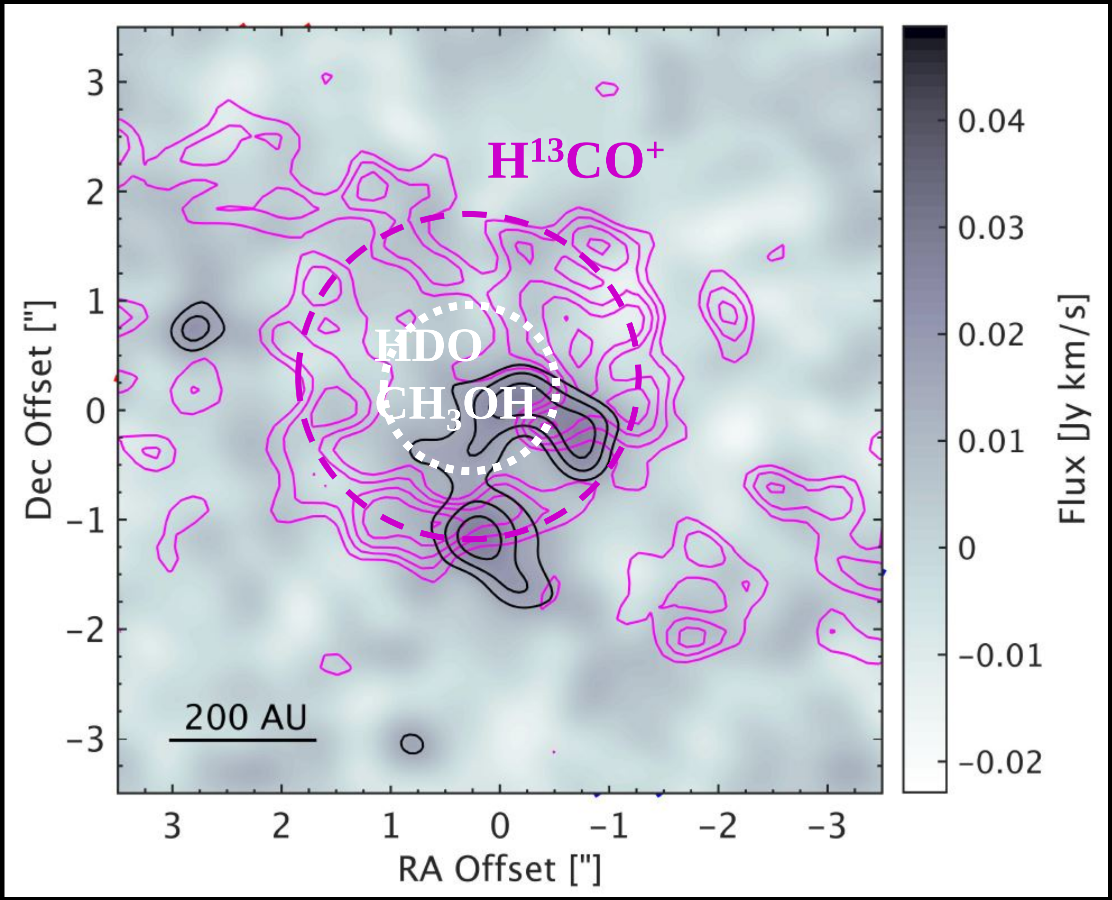


Akeson 2011



Inner disk: Talk Pontoppidan

H_2O snowline traced by HDO, HCO^+



IRAS15398
ALMA

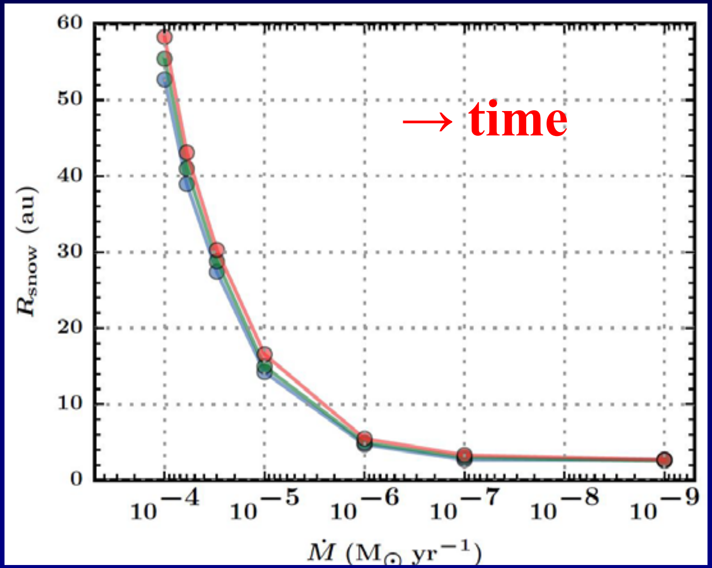
Jørgensen et al. 2013
Bjerkeli et al. 2016

Van 't Hoff et al. 2017
N1333 IRAS2A

$$H_2O + HCO^+ \rightarrow H_3O^+ + CO$$

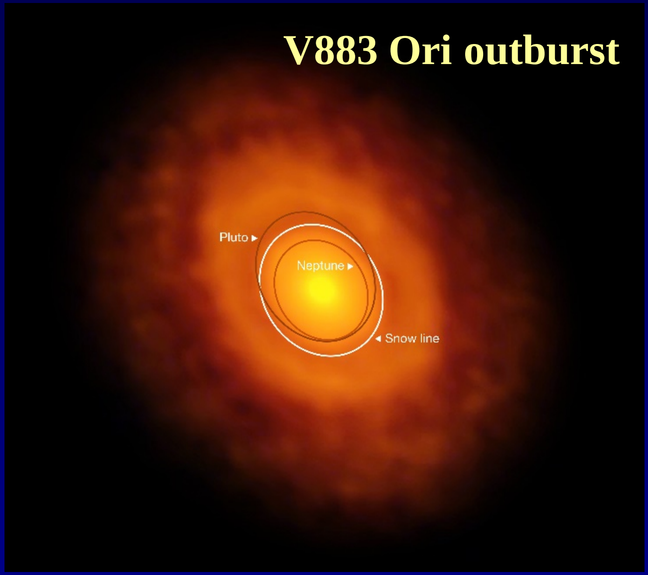
Snowlines move

Water snowline vs dM/dt

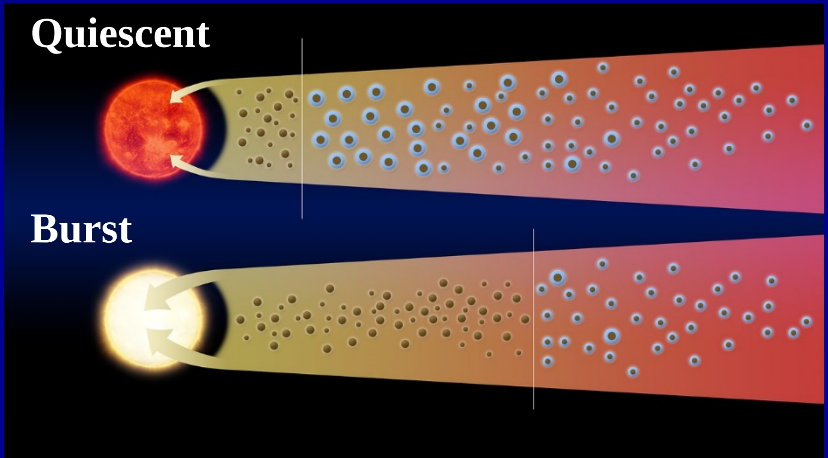


Harsono et al. 2015

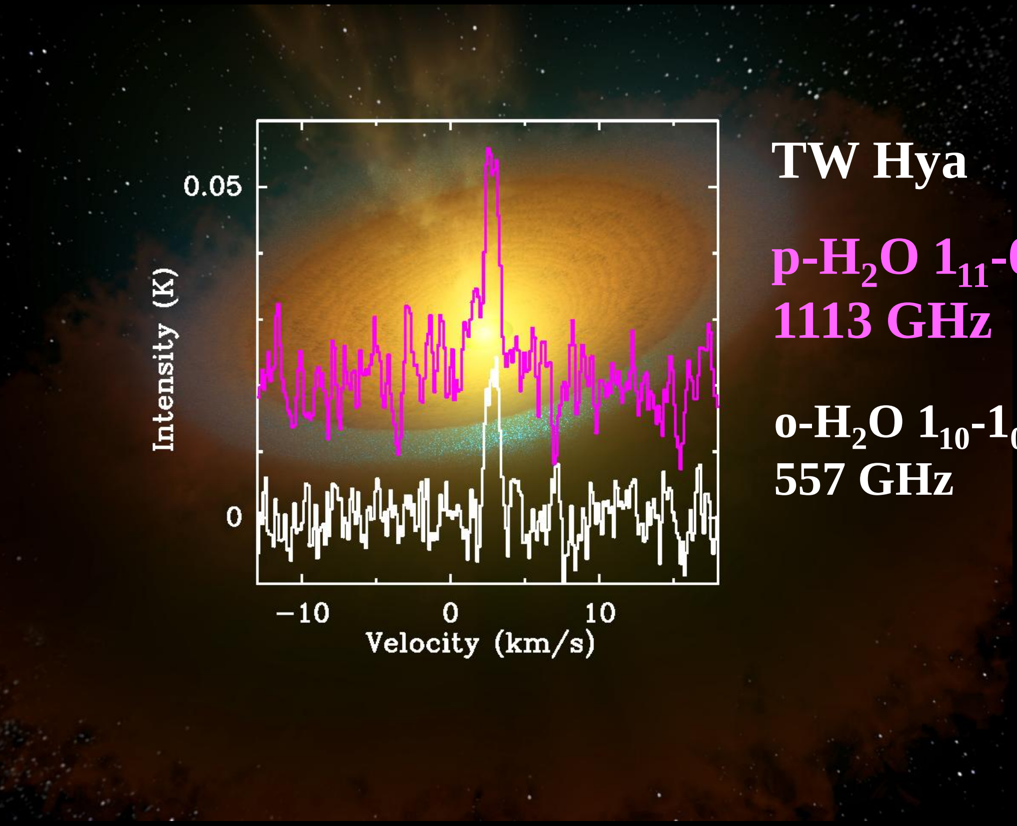
Imaging water snowline (indirect)



Cieza et al. 2016



Cold water in disks



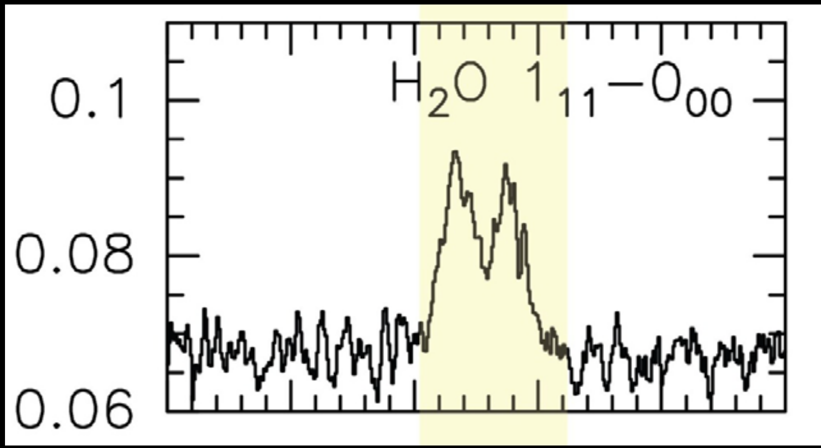
TW Hya

p-H_2O 1_{11}-0_{00}
1113 GHz

o-H_2O 1_{10}-1_{01}
557 GHz

7 disks deep observations
2 detections

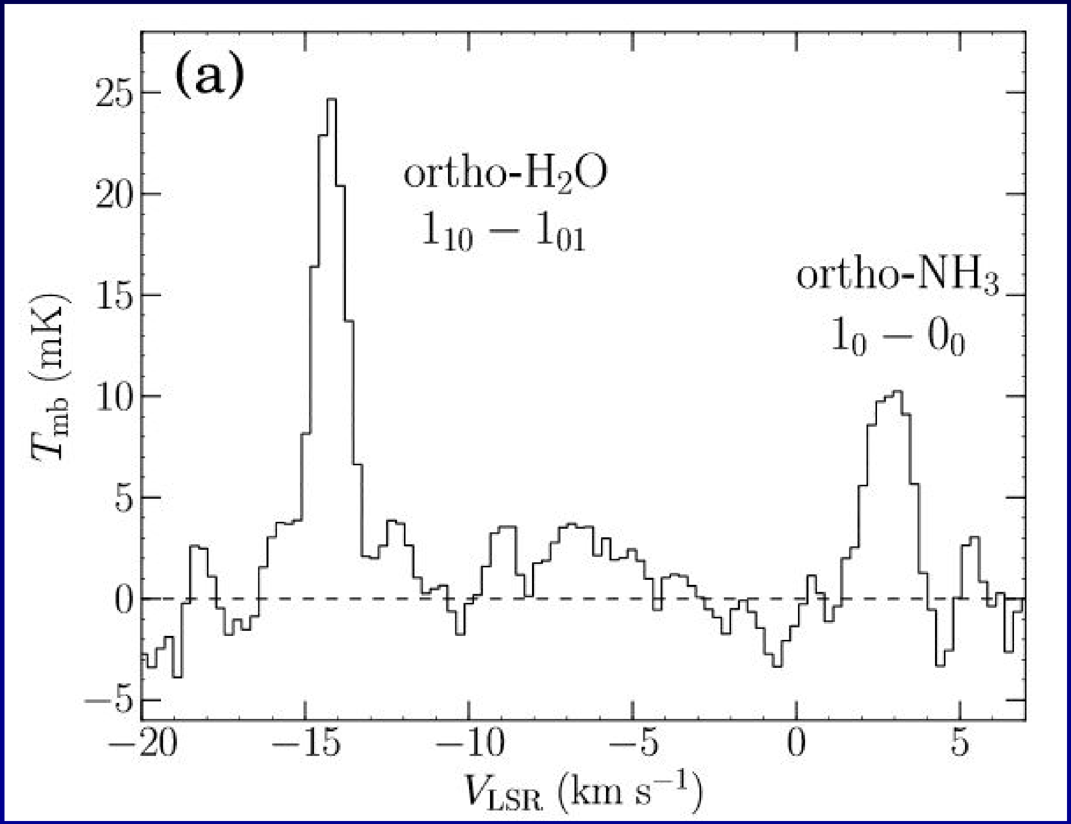
HD100546



Water emission consistently up to factor 10 lower than expected,
even in models with heavy freeze-out

Hogerheijde et al. 2011, in prep.
Du, Bergin et al. 2017
Fedele et al. in prep.

Detection NH_3 in disks

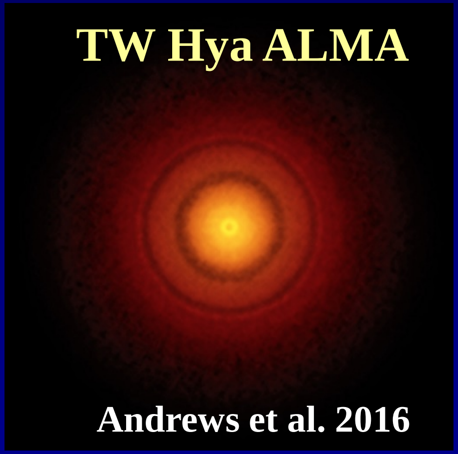


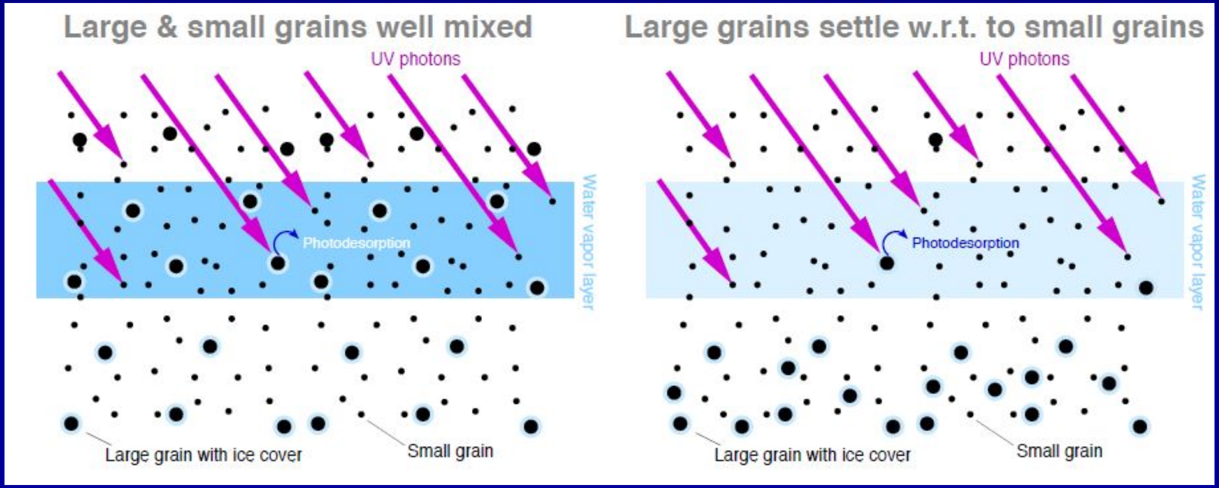
Salinas et al. 2016

NH_3/H_2O~0.05-0.1, consistent with interstellar ices

Absence of cold gaseous water

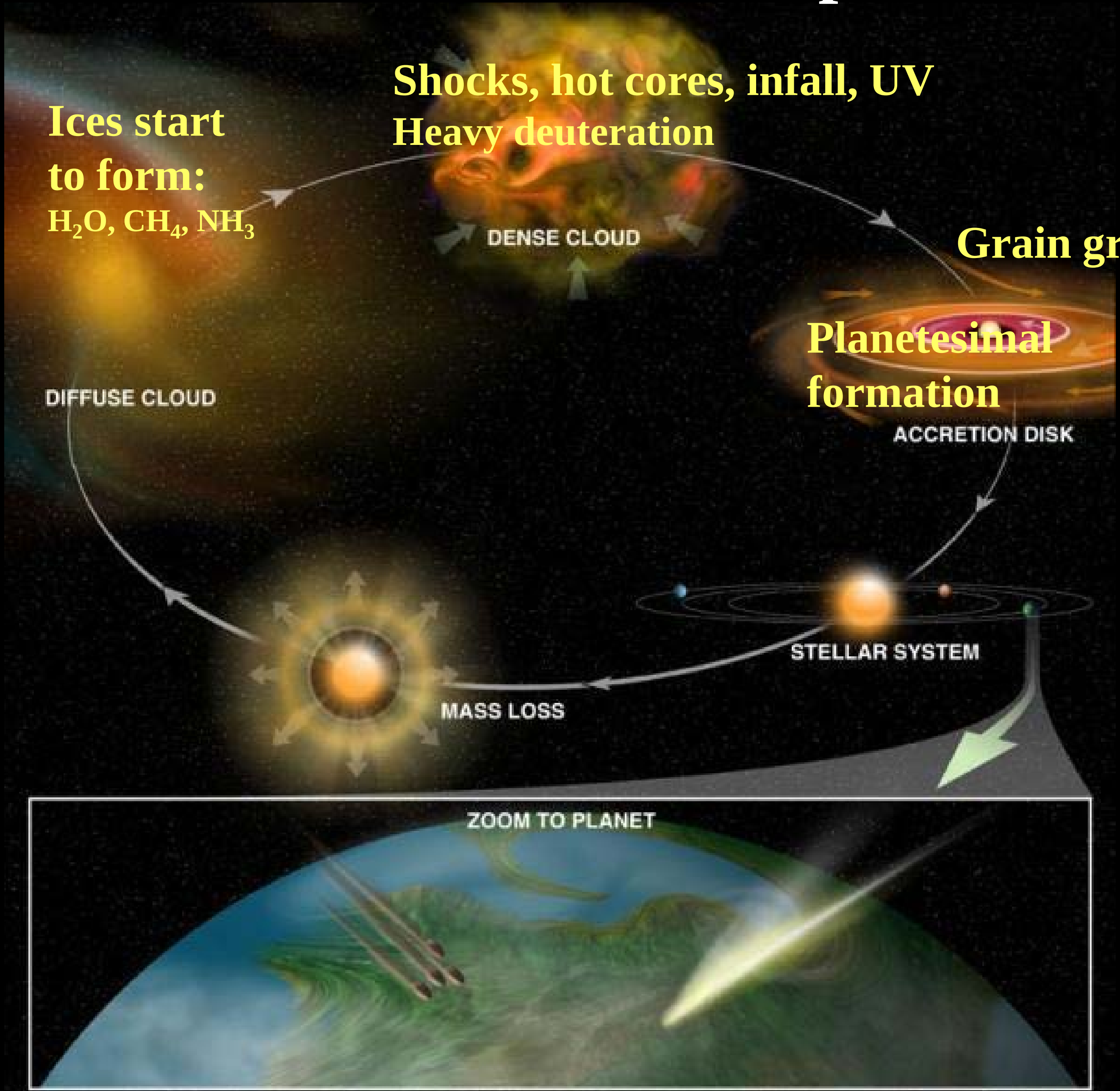
- Water sequestered in large bodies early
  - Settling of mm-sized grains, planetesimal formation
- Water follows mm grains
  - Moved inward due to radial drift





Bergin et al. 2010
Du et al. 2015
Salinas , Hogerheijde et al. 2016

Hydrides as tracers of star- and planet formation



B. Saxton
NRAO