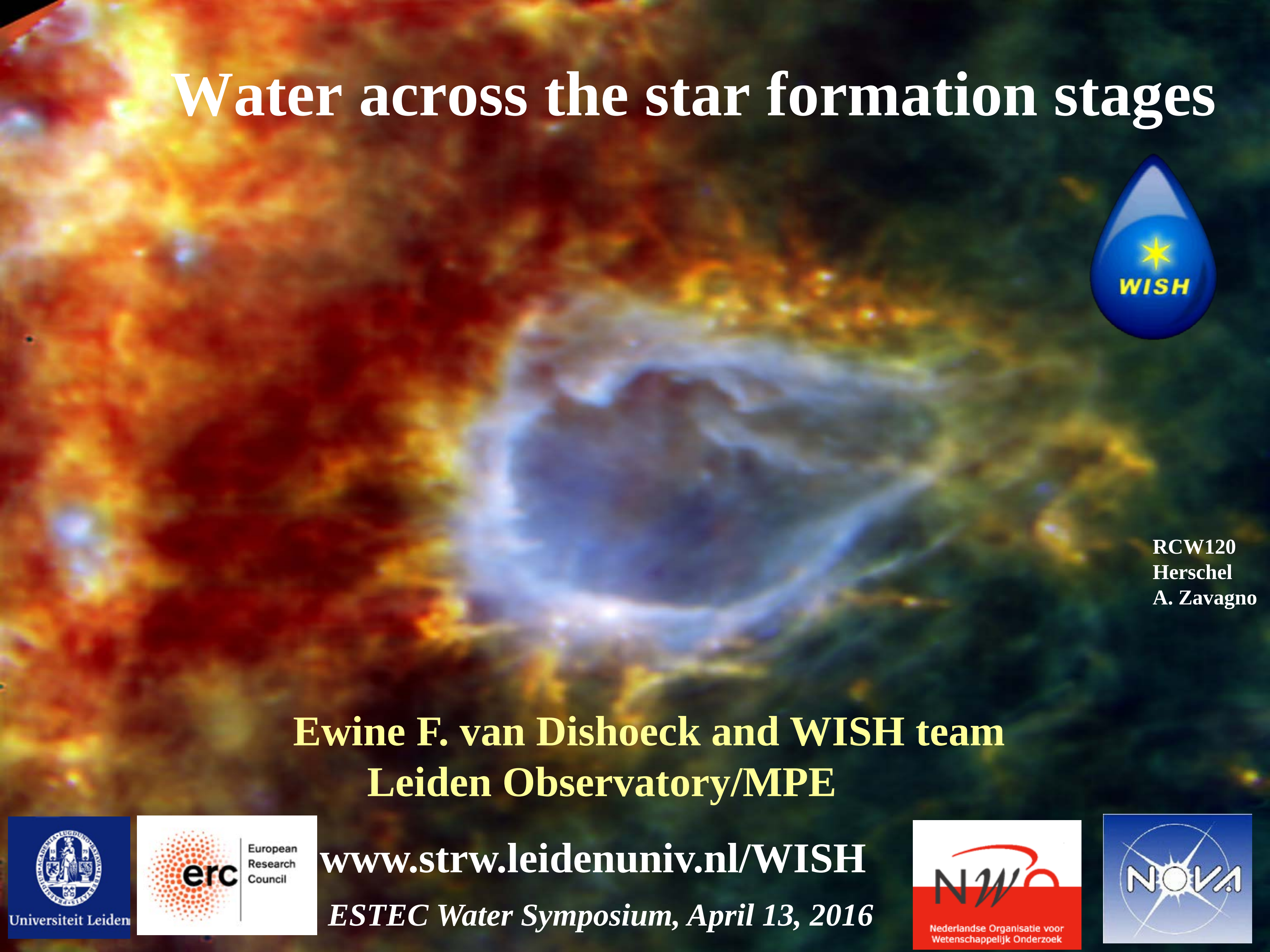
# Water across the star formation stages



RCW120
Herschel
A. Zavagno

**Ewine F. van Dishoeck and WISH team**
**Leiden Observatory/MPE**

Universiteit Leiden

European Research Council

www.strw.leidenuniv.nl/WISH

*ESTEC Water Symposium, April 13, 2016*

Nederlandse Organisatie voor Wetenschappelijk Onderzoek

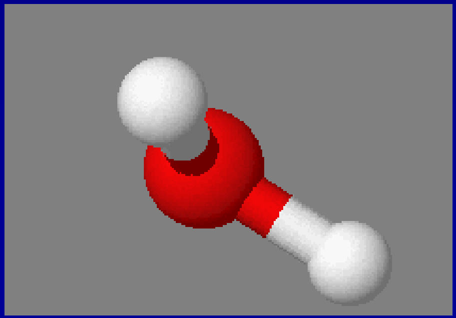
# Water questions

- **Where and how is water formed in space?** Paola Caselli
- **Which physical components does water trace?**
  - **Collapsing envelope, outflows, shocks, …**
  - **Cooling budget, abundances**

  Lars Kristensen, Agata Karska, Joe Mottram
- **What is the water 'trail' from clouds to disks to planets?**

  Michiel Hogerheijde, Ilse Cleeves

Wikipedia-Mitchidr



vD, Bergin, Lis & Lunine 2014, PPVI

# *Water In Star-forming regions with Herschel*
# The WISH team

**Leiden, April 2010**

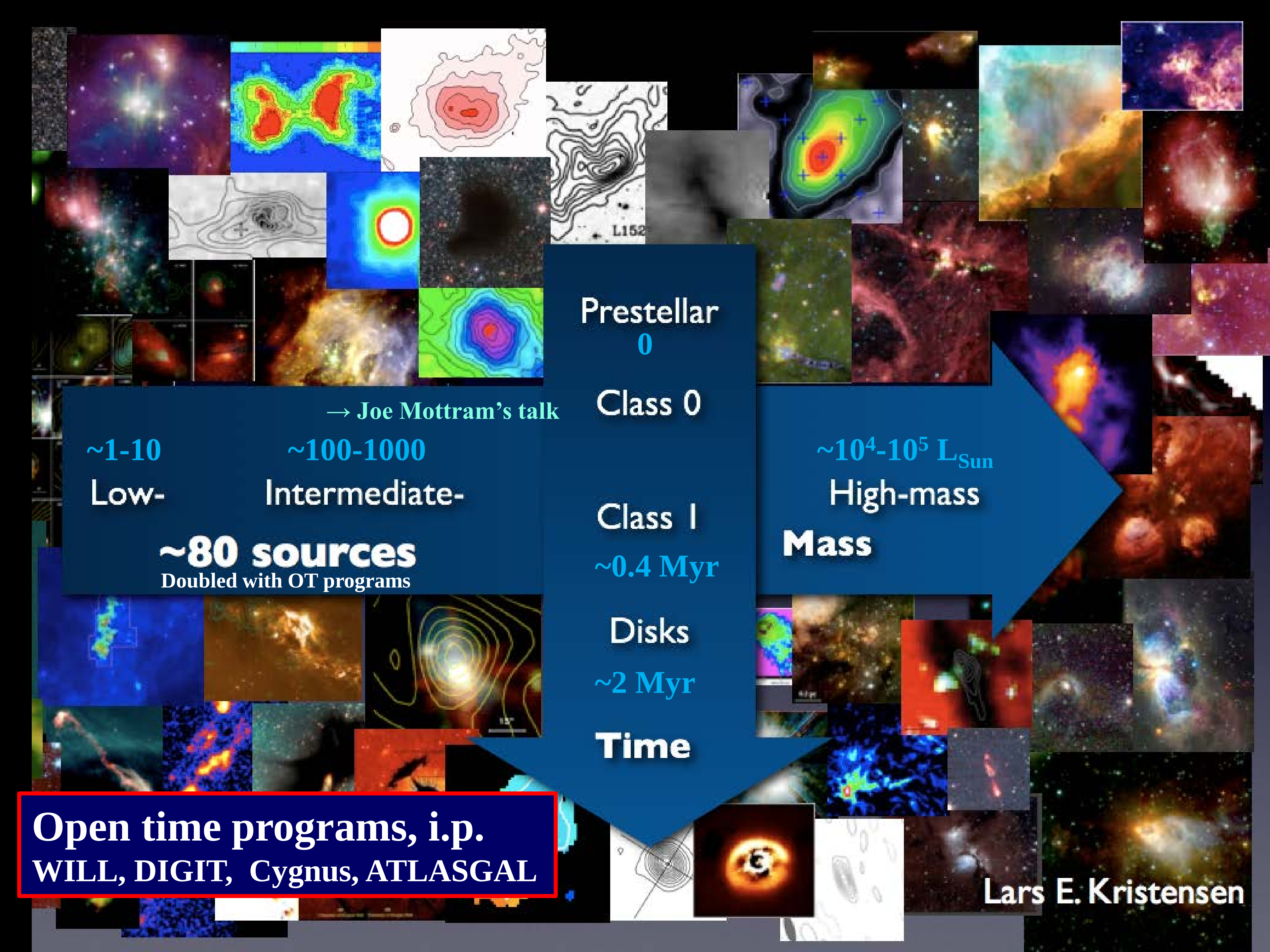
**Rome, October 2014**

**425 hr guaranteed time program + OT**

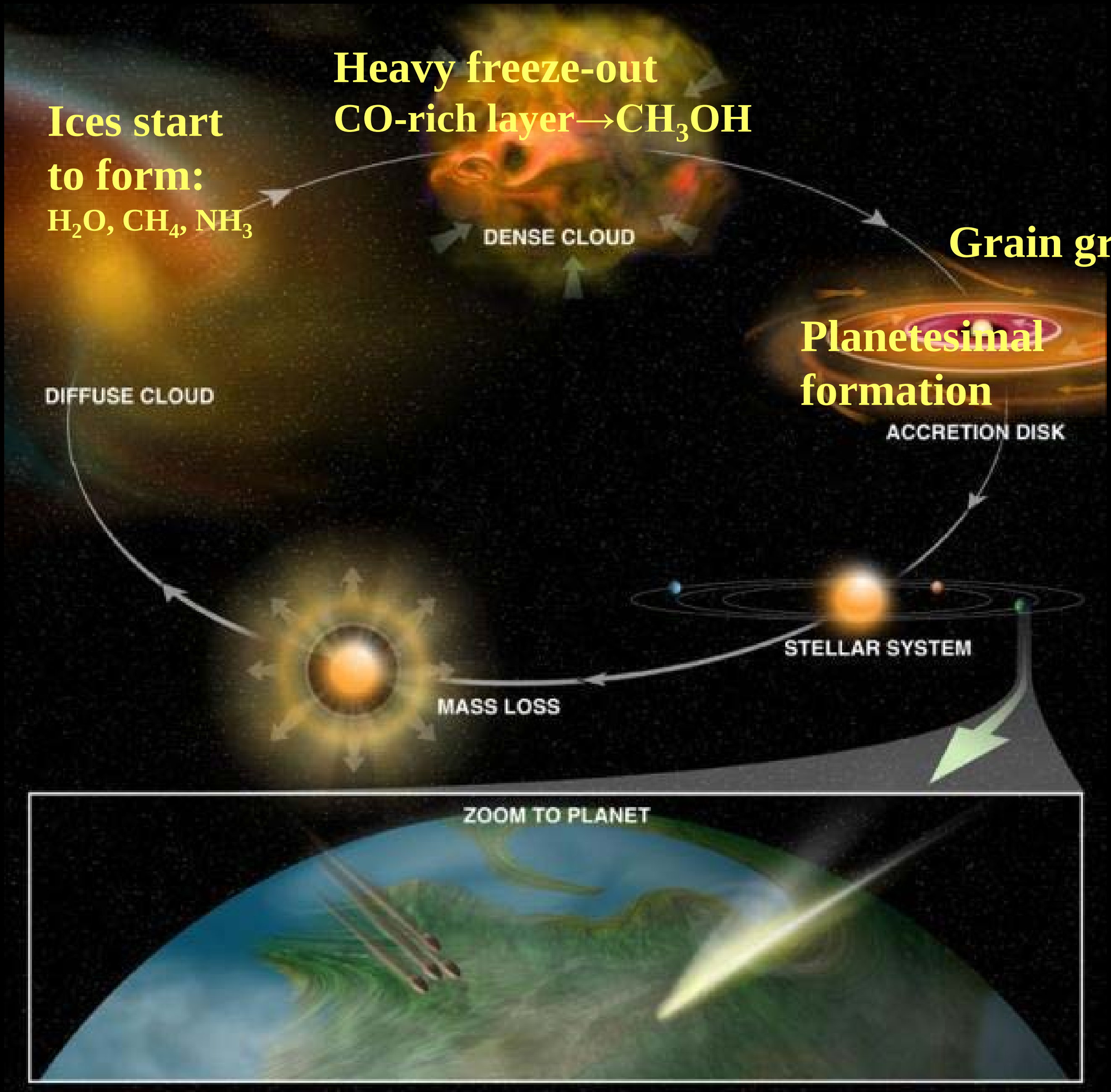
**74 refereed papers**

***Summary in van Dishoeck et al. 2011, PASP***

***Bergin & van Dishoeck 2012, van Dishoeck et al. 2013, Chem. Rev. , 2014, PPVI***


Prestellar
0
Class 0
→ Joe Mottram's talk
~1-10
Low-
~100-1000
Intermediate-
~$10^4$-$10^5$ $L_{Sun}$
High-mass
Mass
Class I
~0.4 Myr
~80 sources
Doubled with OT programs
Disks
~2 Myr
Time
Open time programs, i.p.
WILL, DIGIT, Cygnus, ATLASGAL
Lars E. Kristensen

# From clouds to disks and comets



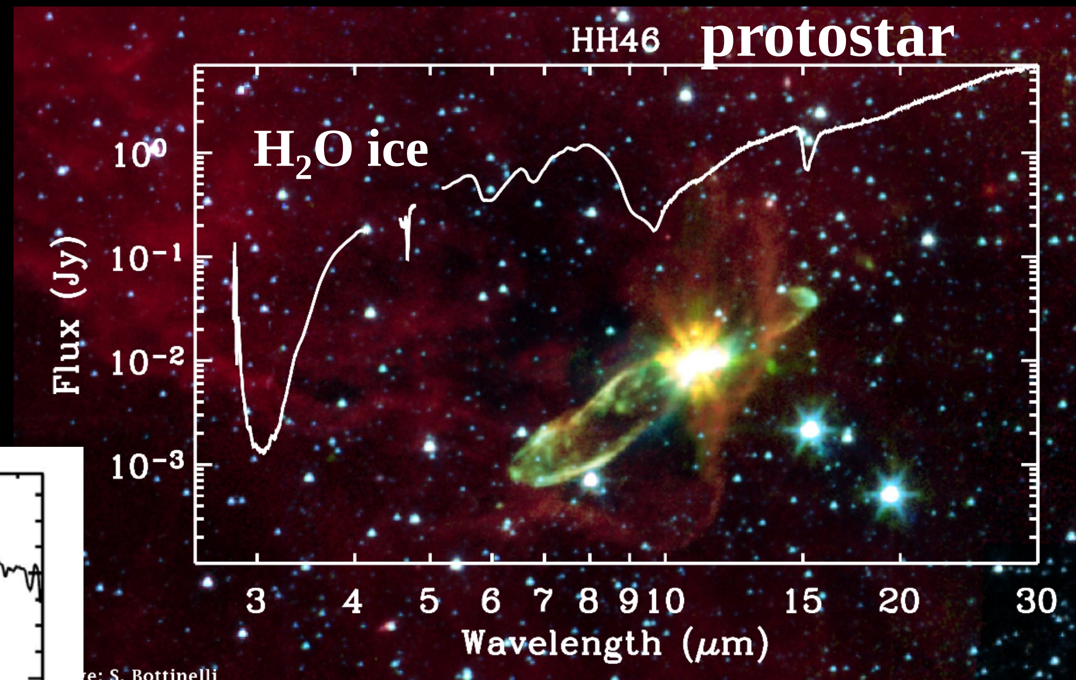

B. Saxton
NRAO

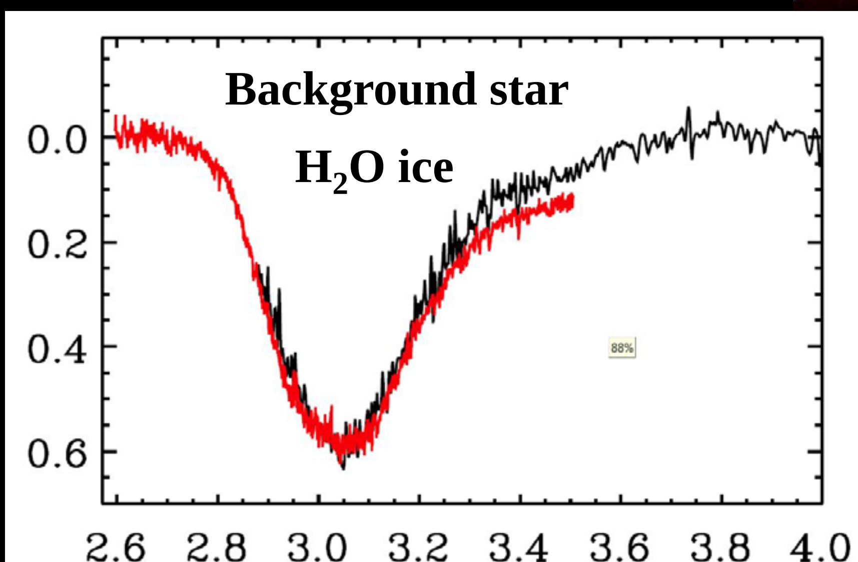
# Formation of water and $O_2$ on dust grains


*Movie posted at www.strw.leidenuniv.nl/WISH*

**Based on laboratory experiments**
**Ioppolo, Cuppen, Linnartz et al. 2010**
**Paris, Japanese groups**

# Ices are abundant and common!

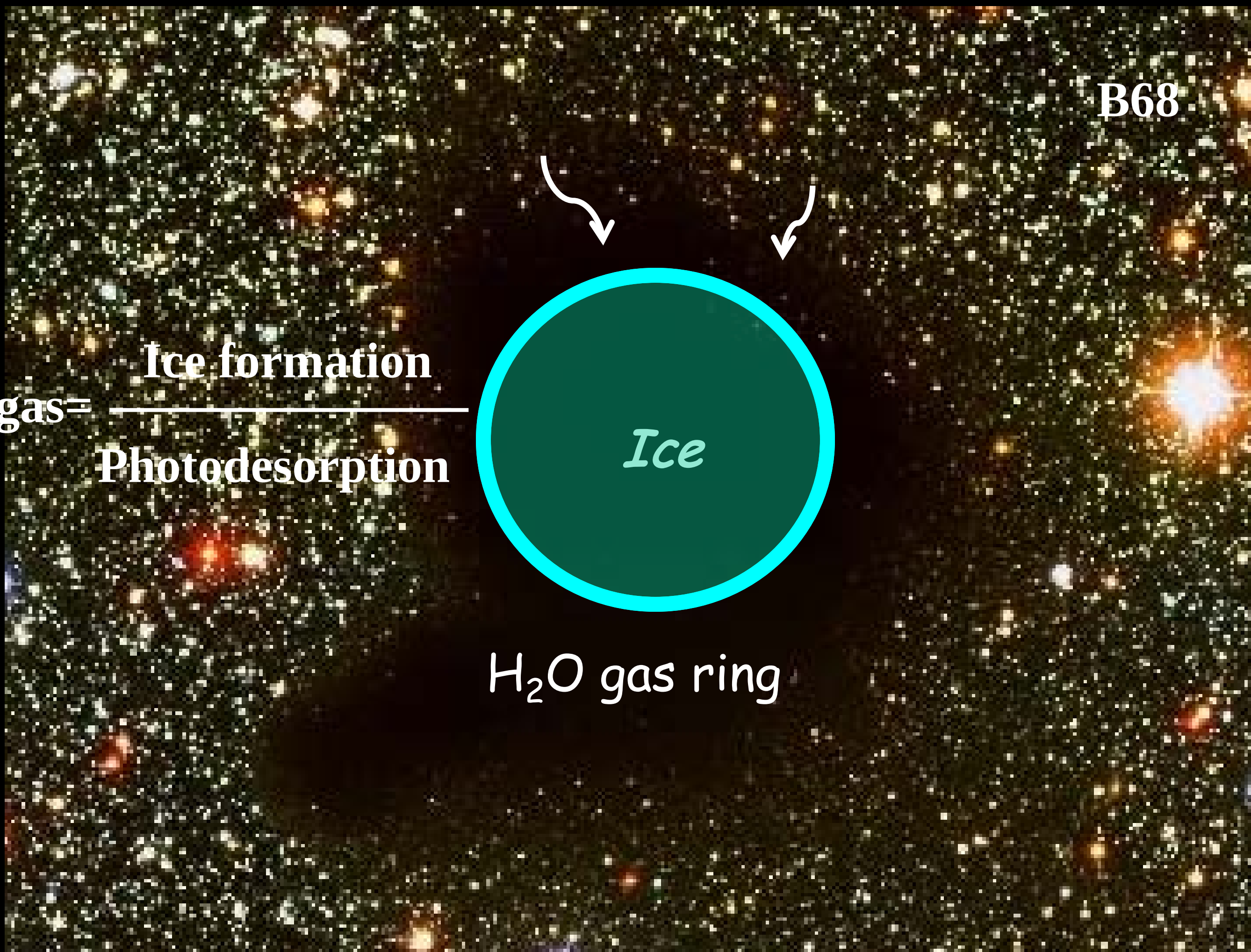



Boogert, Pontoppidan et al. 2008,
Öberg et al. 2011
Boogert et al. 2015, ARAA

**Ices can contain significant fraction of heavy elements (but perhaps not all oxygen)**
**Simultaneous analysis of water gas and ice in a number of sources: Schmalzl et al. 2014**

# Water distribution in dense clouds




$$H_2O\ \text{gas} = \frac{\text{Ice formation}}{\text{Photodesorption}}$$

Caselli et al. 2012
Schmalzl et al. 2014

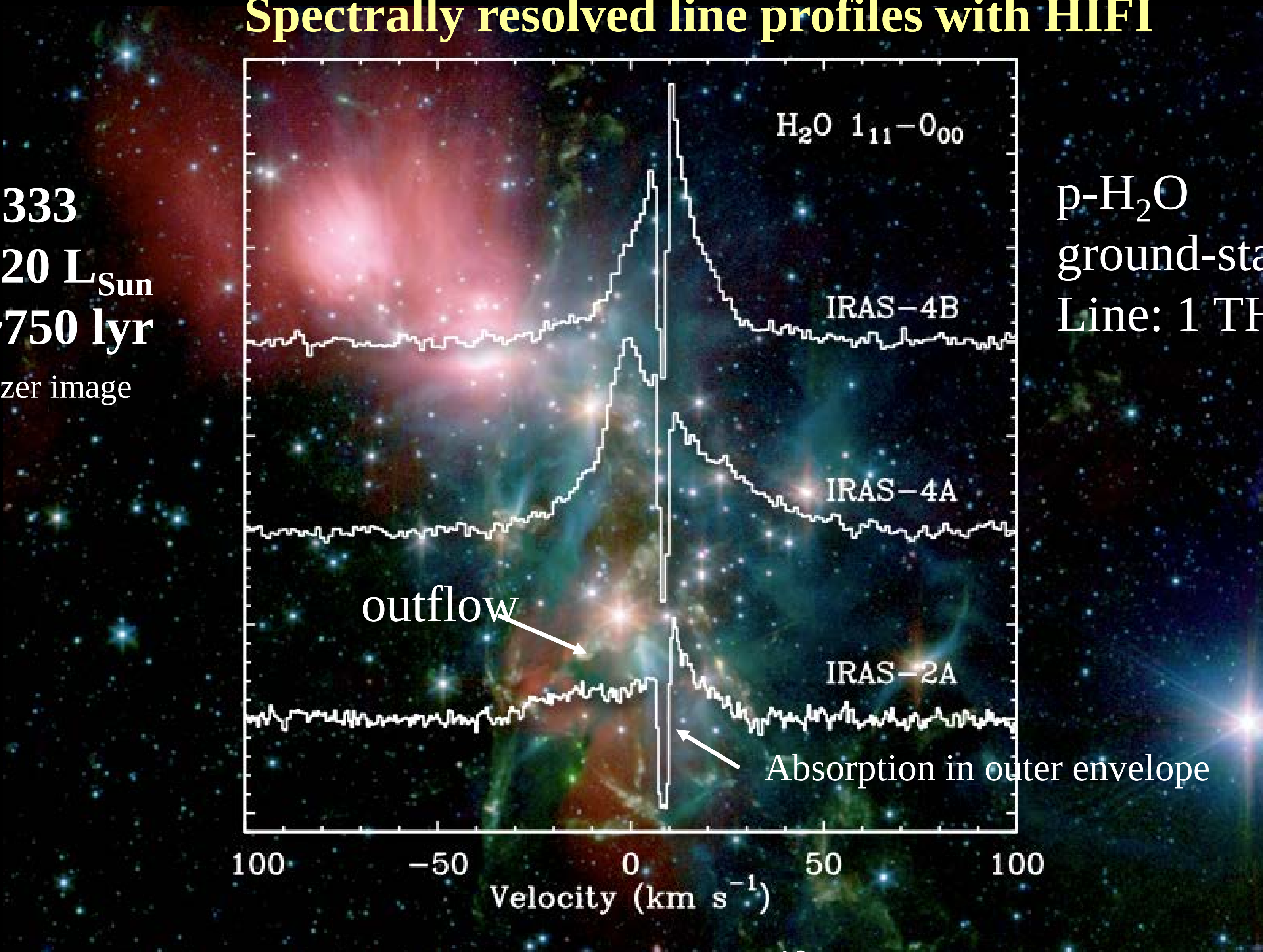
**$n$=2.10$^4$ – 5.10$^6$ cm$^{-3}$, $T$=10 K**

**Layer of water gas where ice is photodesorbed**

# Water in low-mass protostars

## Spectrally resolved line profiles with HIFI

**N1333**
**L~20 $L_{Sun}$**
**D~750 lyr**
Spitzer image

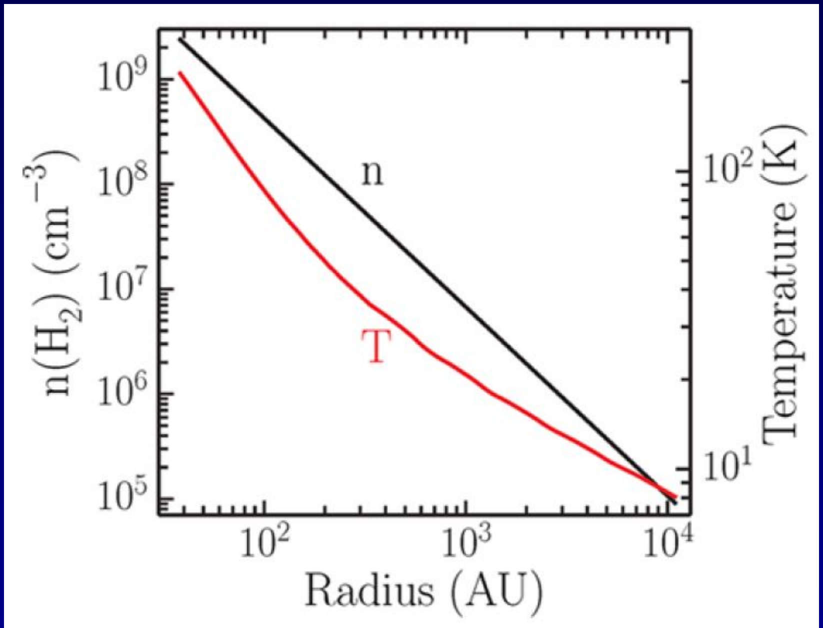



p-$H_2O$
ground-state
Line: 1 THz

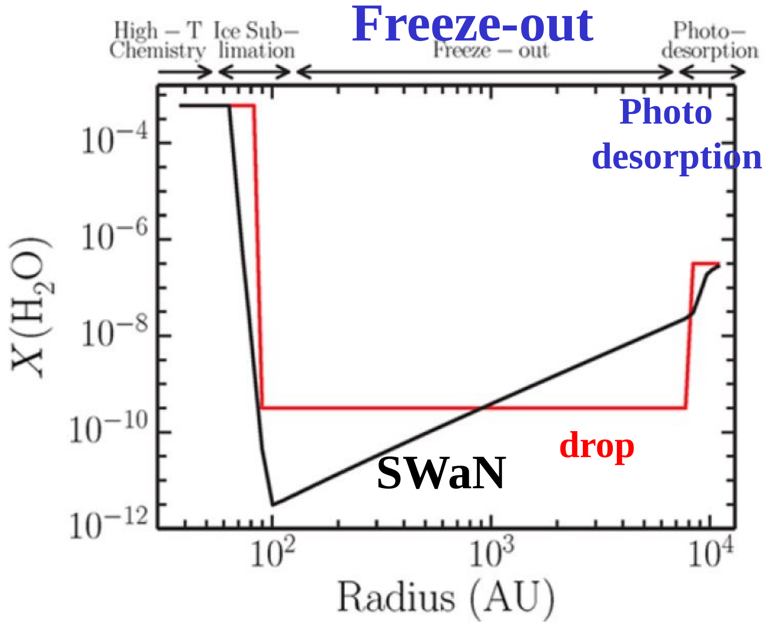
**Broad: outflow dominates, even for $H_2{}^{18}O$**

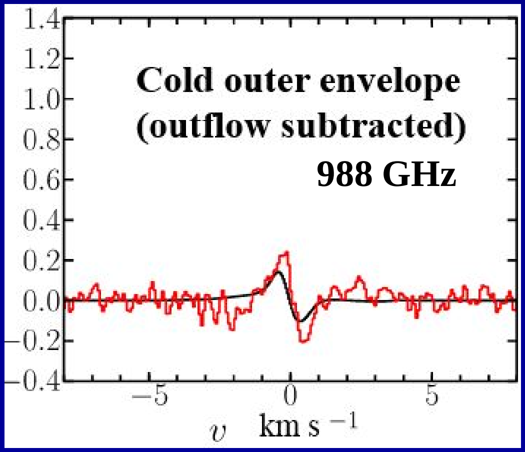
Kristensen, Visser et al. 2010, 2012

# Protostars: water abundance profiles




NGC 1333 IRAS4A

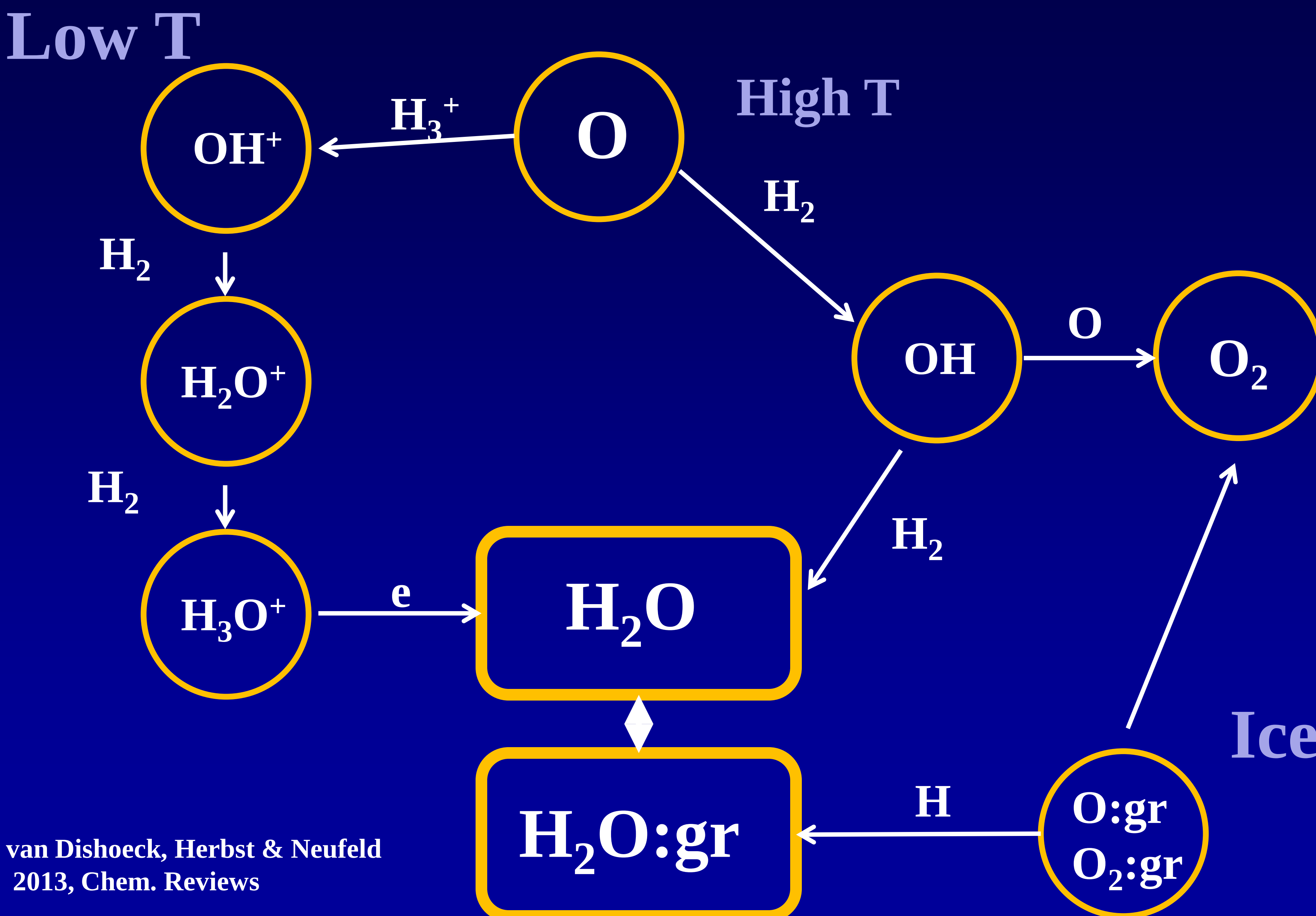



Mottram et al. 2013
Schmalzl et al. 2014

**Simple chemistry works**

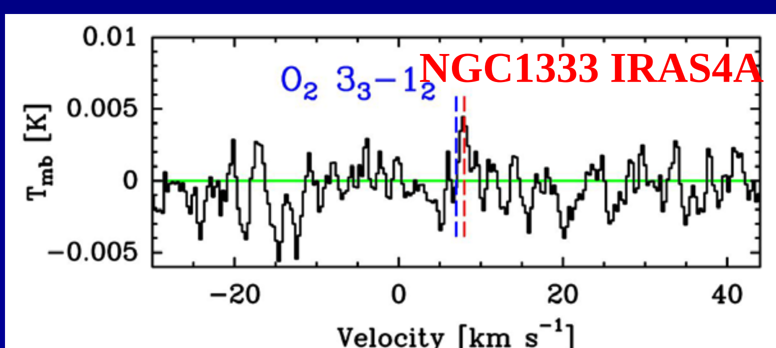
# $H_2O$ chemistry routes and link with $O_2$




van Dishoeck, Herbst & Neufeld 2013, Chem. Reviews

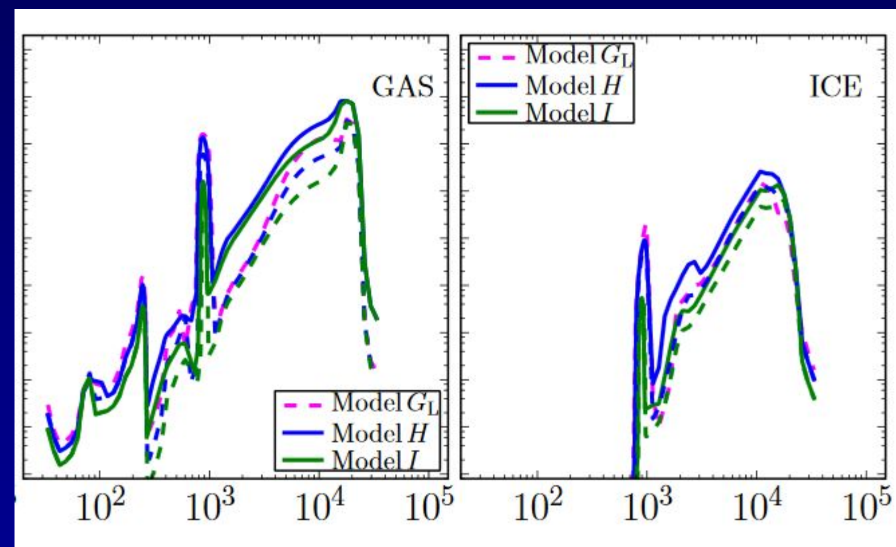
# Lack of $O_2$ in protostellar envelopes


**Very deep $O_2$ upper limit**




**Yildiz et al. 2013**
**HOP program (PI P. Goldsmith)**

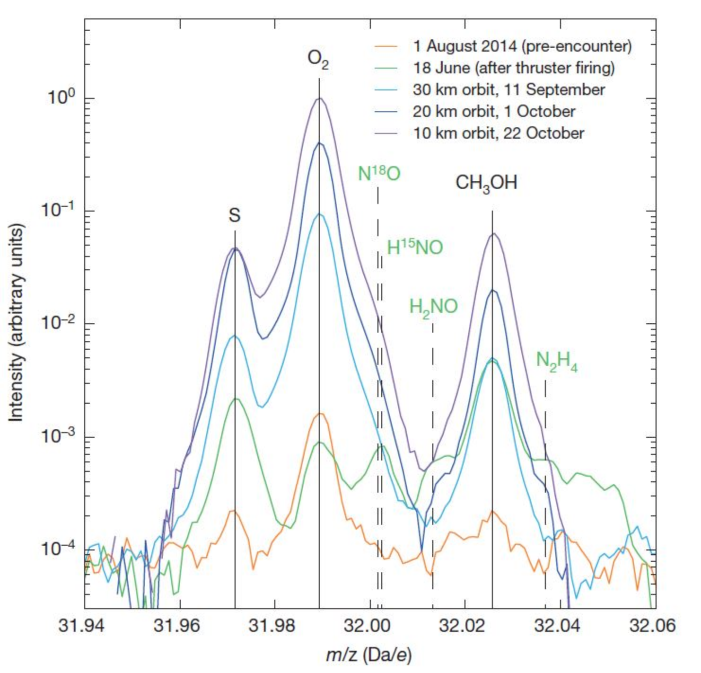
**Cold protostellar envelope**




***Amount of $O_2$ entering the disk is low, gas or ice***

# Abundant cometary $O_2$ mystery

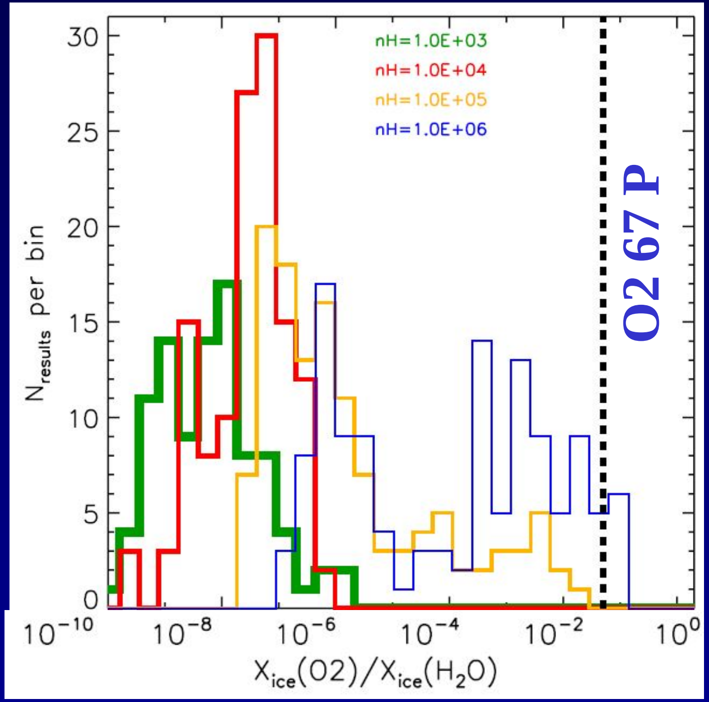
## 67 P/C-G ROSINA




$O_2/H_2O=3.7\pm1.5\%$

Bieler et al. 2015
Rubin et al. 2015

## Interstellar $O_2$ ice models



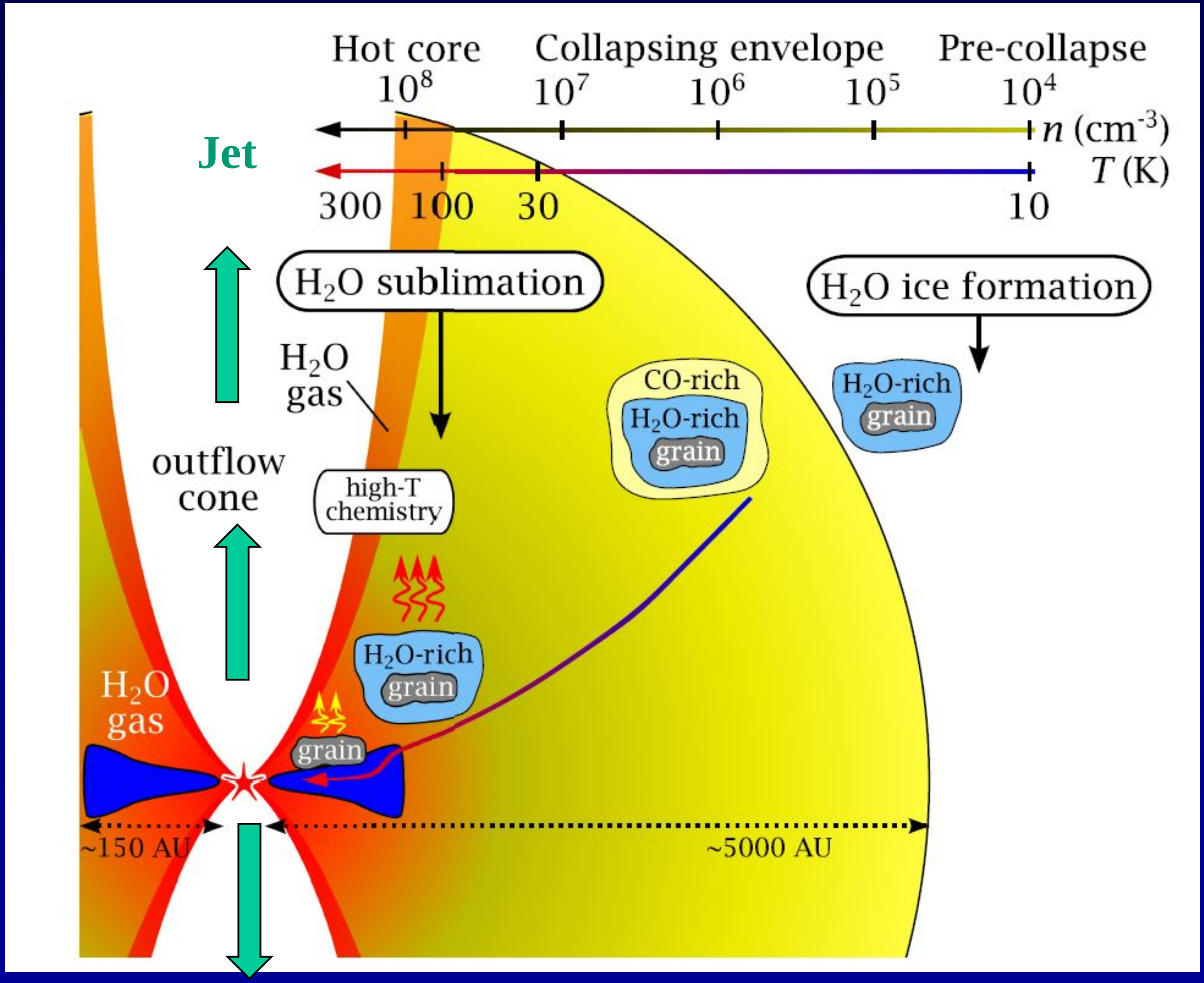

Taquet et al. 2016
Walsh et al. 2015

*Talk Vianney Taquet*

- Problem: $O_2$ readily transformed by H to $H_2O$ in ice

- Only models with low H/O ratio (high density) and relatively warm conditions ($T$~20-30 K) can reproduce high observed $O_2/H_2O$ ice ratio

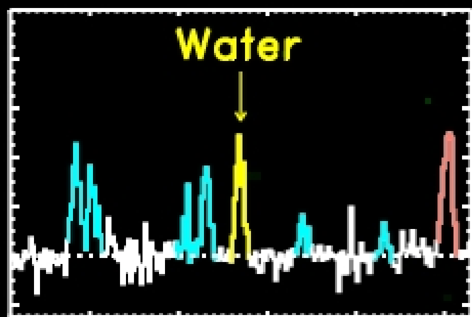
# Follow water trail from cores to disk

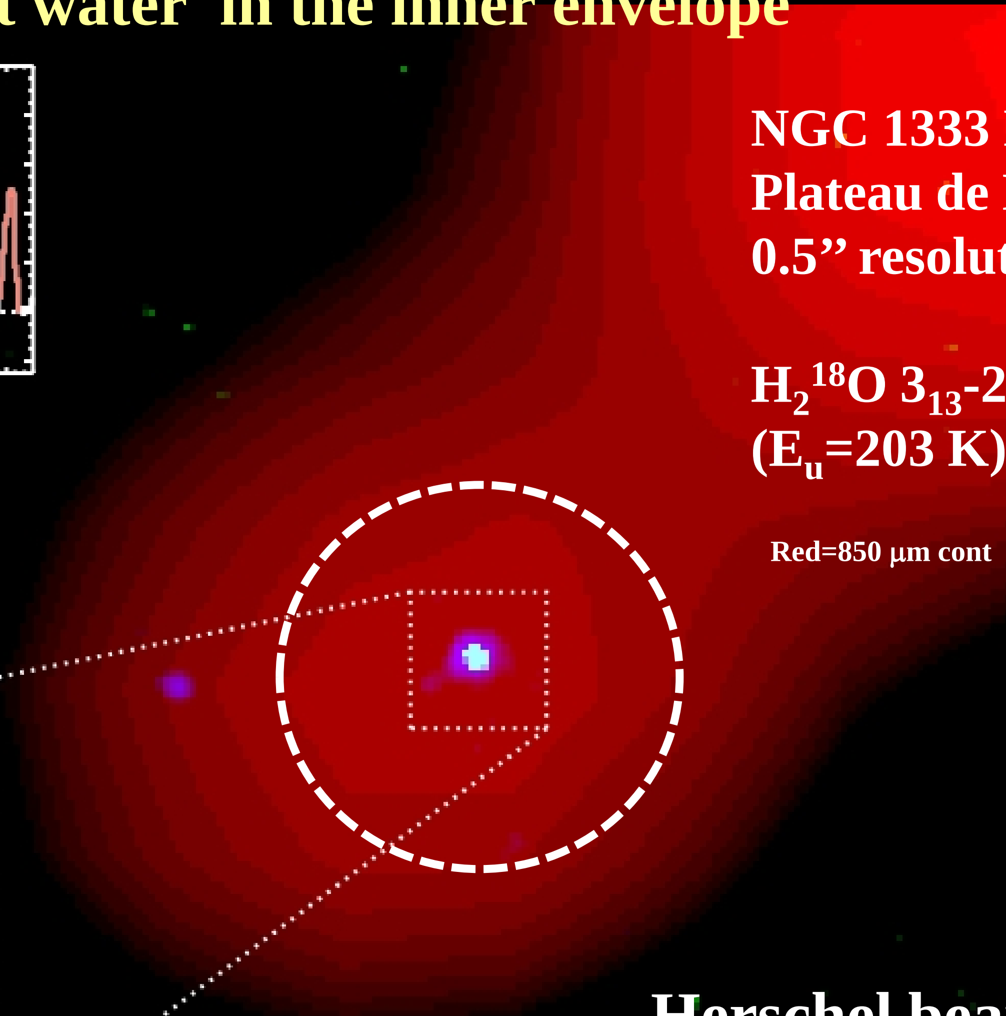



Visser et al. 2009
Herbst & vD 2009

# Zooming in with interferometers:

## Hot water in the inner envelope



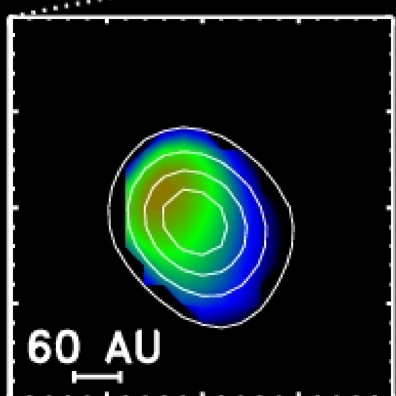



NGC 1333 IRAS4B
Plateau de Bure
0.5” resolution

$H_2{}^{18}O$ $3_{13}$-$2_{20}$ 203 GHz
($E_u$=203 K)

Red=850 µm cont

Herschel beam

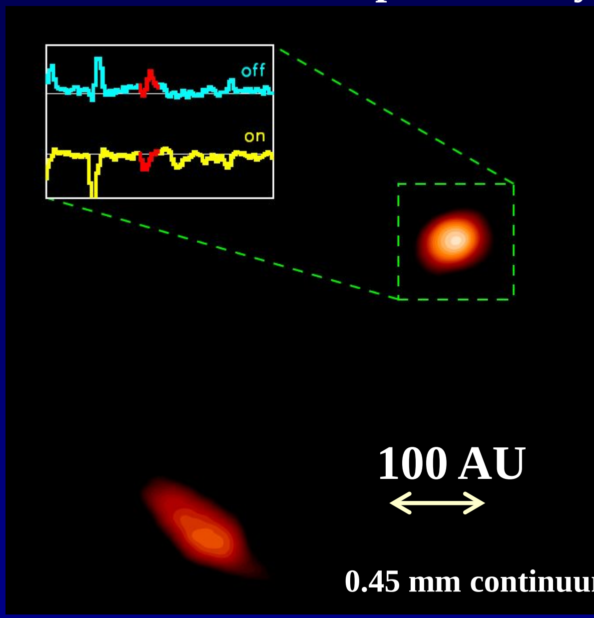



Jørgensen & vD 2010a
Persson et al. 2012, 2013

Hot water detected, but at low abundances

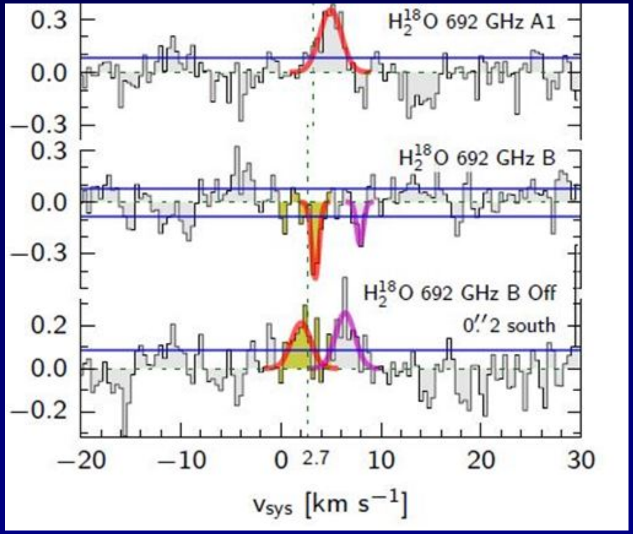
# Hot water with ALMA

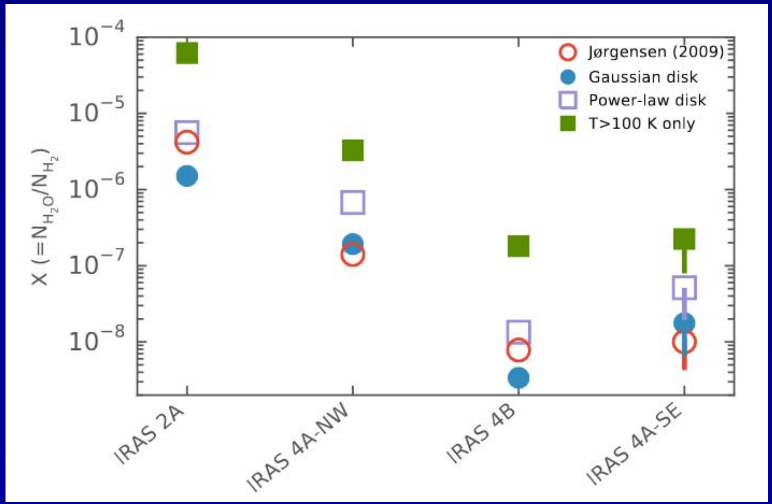
**IRAS16293-2422 protobinary**




**Persson et al. 13**

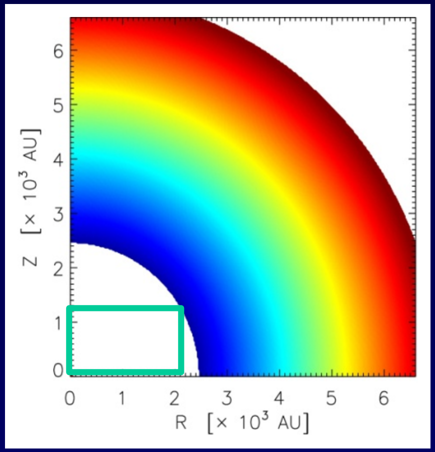
**Band 9 692 GHz data**

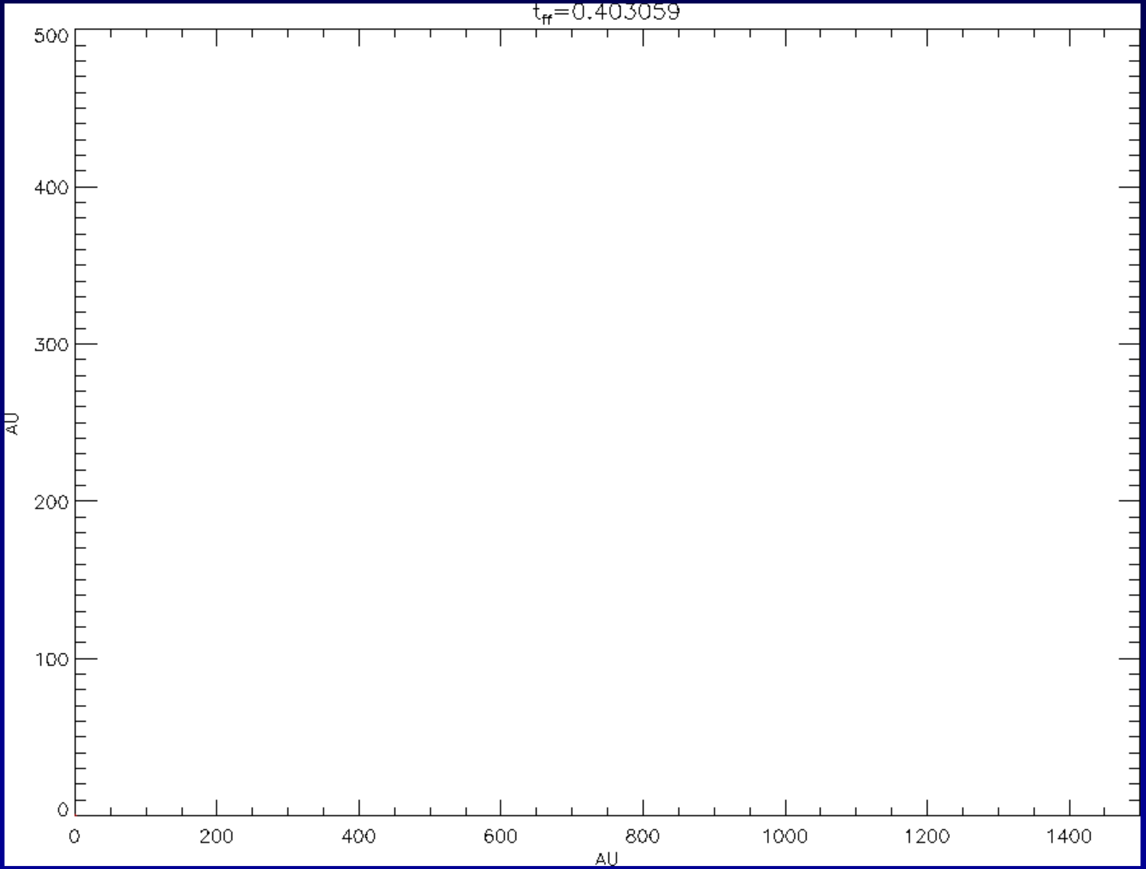



- Hot water detection at both sources
- Source size ~25 AU (orbit Uranus)
- Not all oxygen is in hot water
  (seen both for low and high mass
  protostars)

# 2D Disk formation



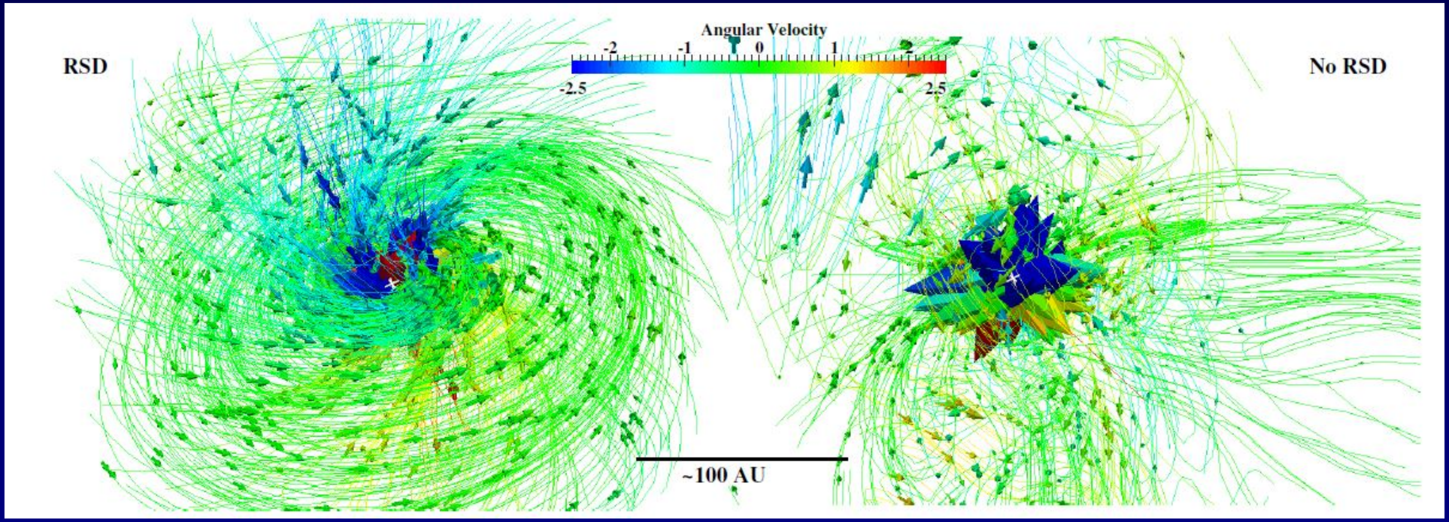




**Numerical:**
**Van Weeren , Brinch & Hogerheijde 2008 using Bodenheimer & Yorke code**

**Semi-analytic:**
**Visser et al. 2009, 2011**
**Visser & Dullemond 2010**

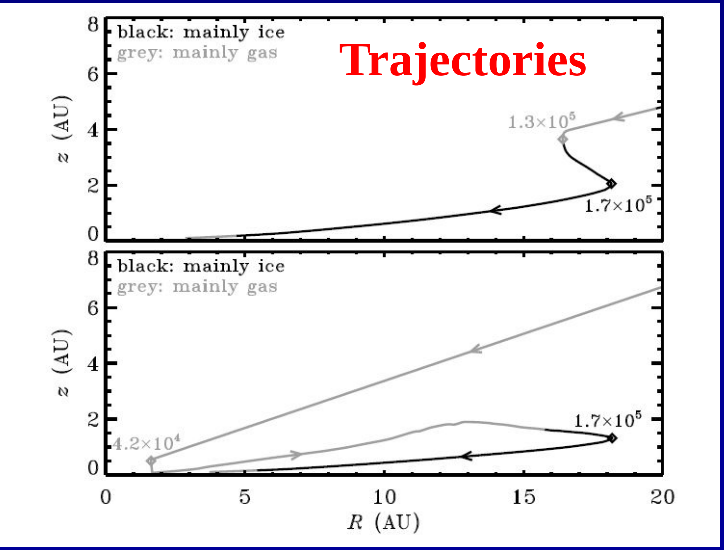
- **Accretion onto 2D disk fundamentally different from 1D**
- **More material enters disk far from star, weak accretion shock**

# Chemistry and disk formation




Harsono et al. 2014, using Z. Li et al. 2011 models

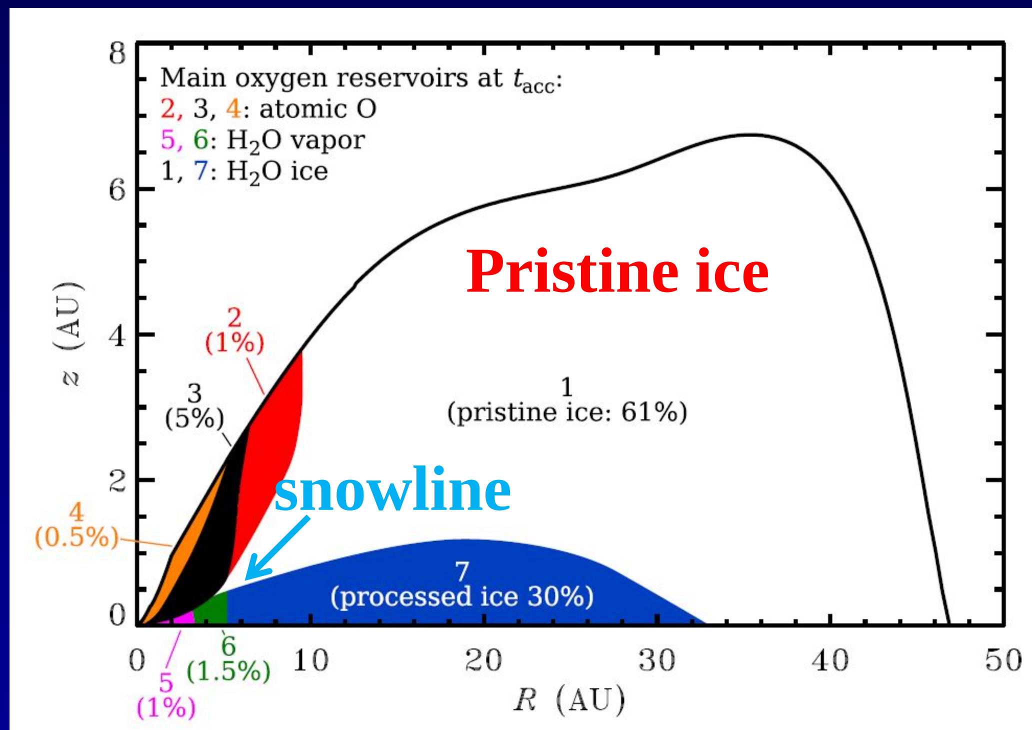
*Infalling parcels experience different T, n, UV en route to disk*



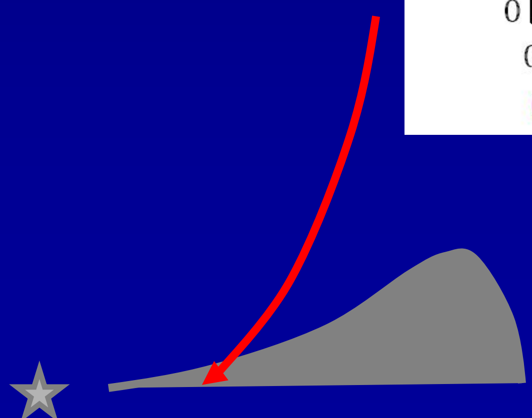

Visser et al. 2011, Drozdovskaya et al. 2014

# History of water in young disk

**End of accretion phase**

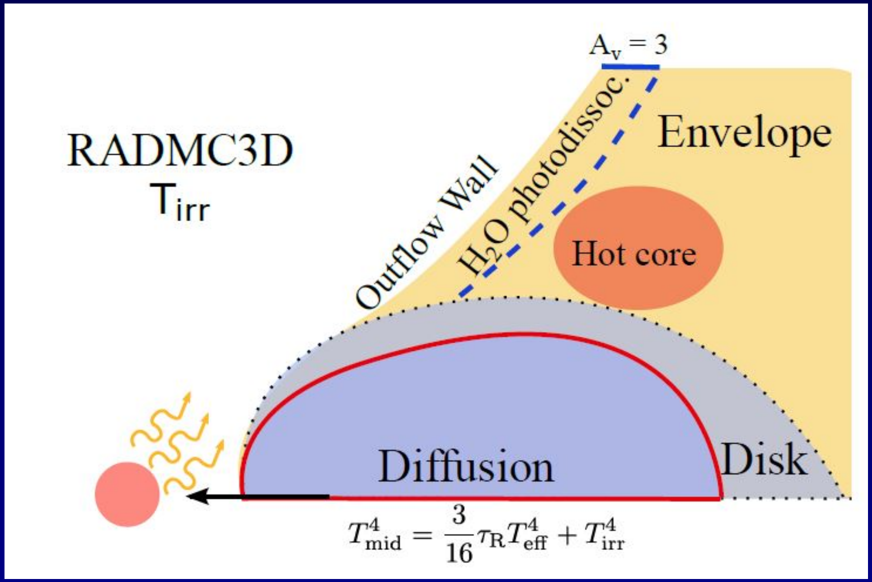



**Visser et al. 2011**
**Furuya et al. 2016**



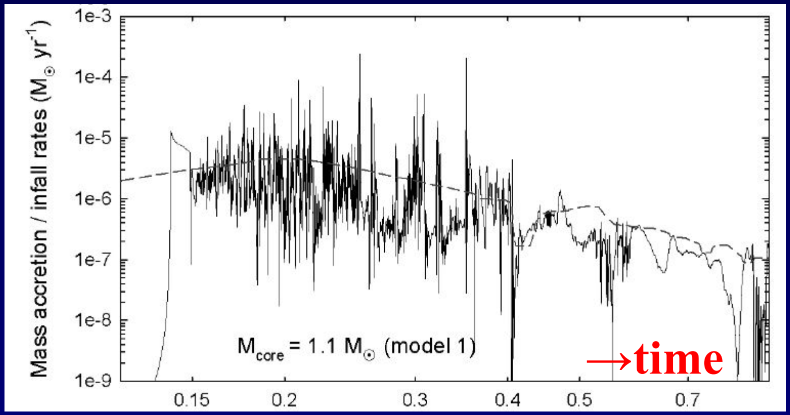
- **Some water is preserved in tact, some water has been processed**
- **Bulk of water enters disk as ice**

# Embedded disks with (episodic) accretion heating



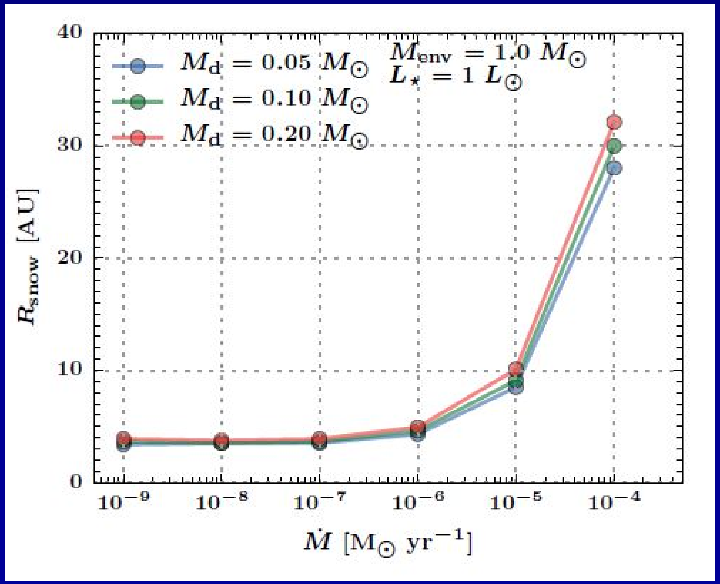

Harsono et al. 2015

## Variable accretion rate



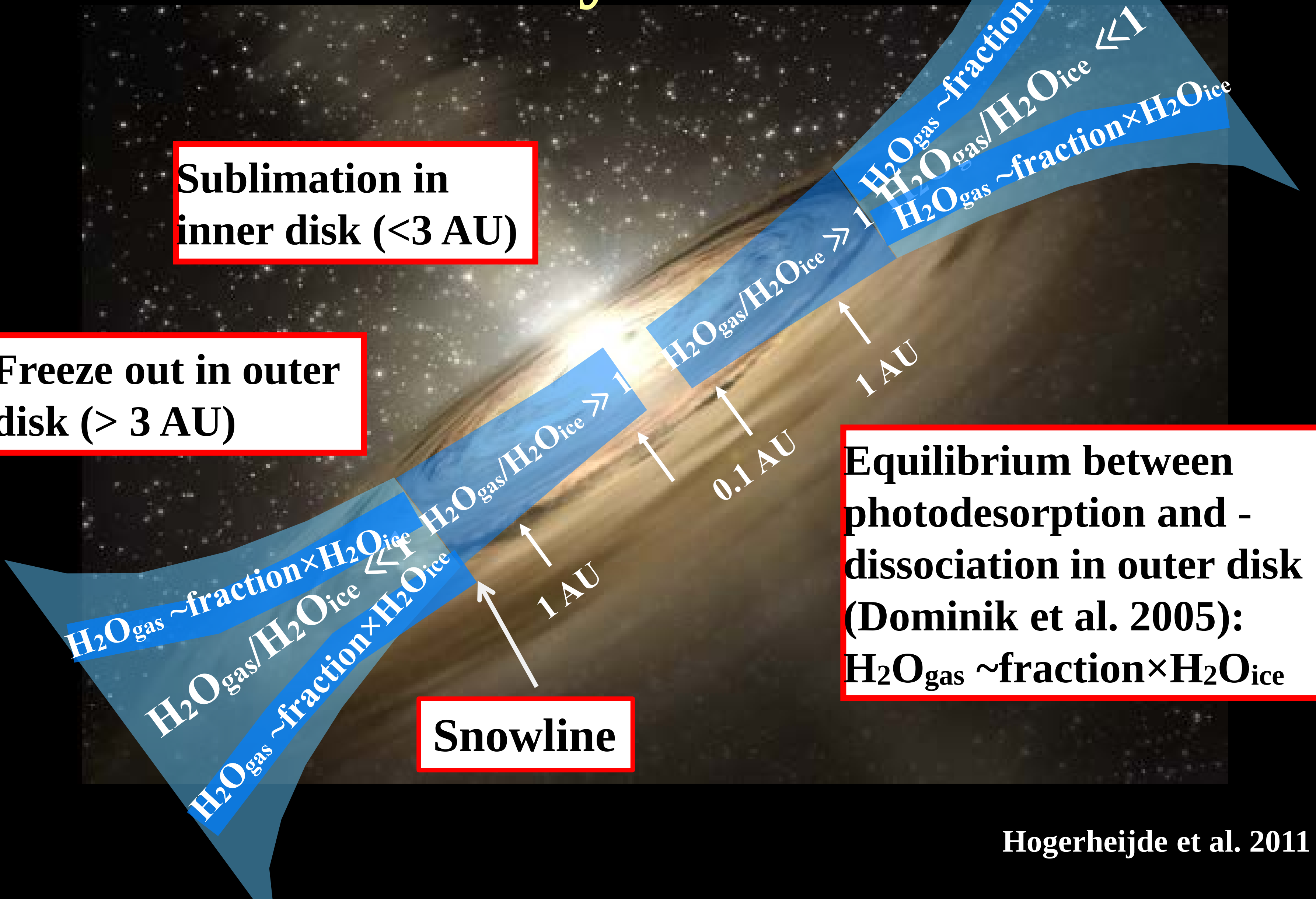

Vorobyov & Basu 2015

## Midplane snowline (100-160 K)



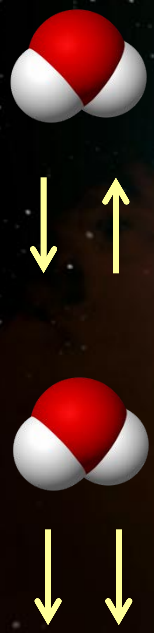

**$H_2O$ snowline moves out from 3 to 30 AU for $dM/dt=10^{-4}\ M_{sun}$ /yr**

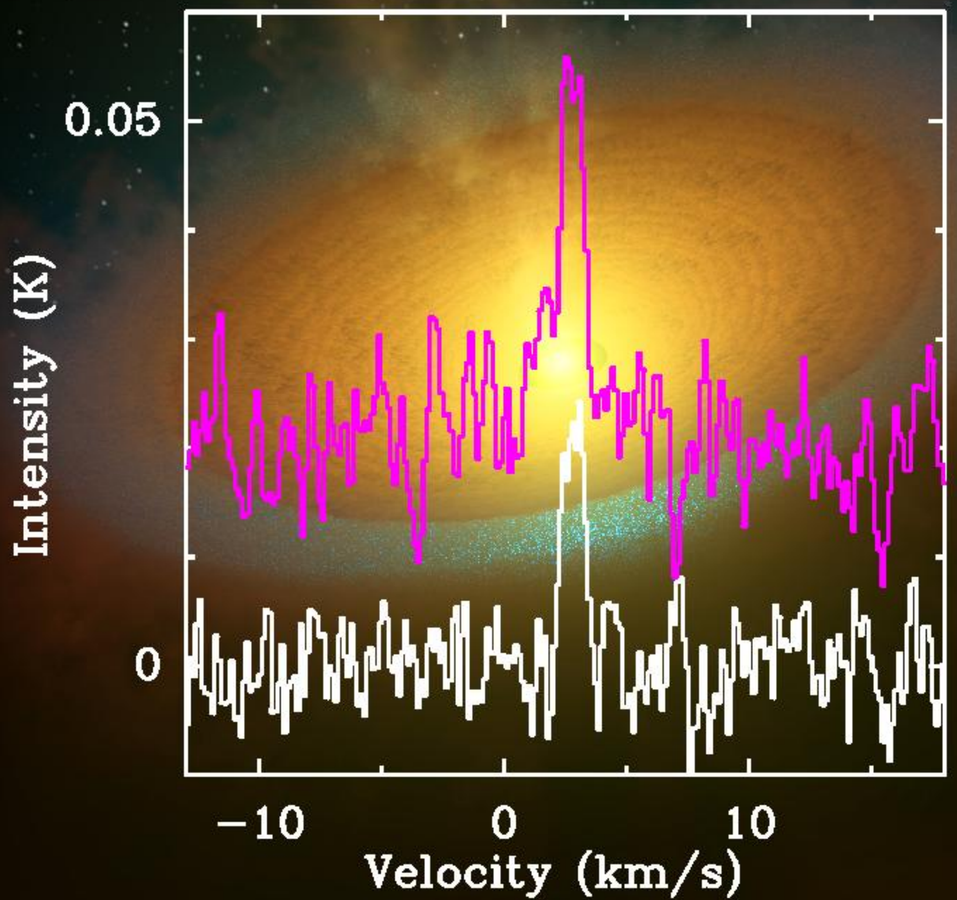
# The chemistry of water in disks




Hogerheijde et al. 2011

# Cold water in disks






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

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

Hogerheijde et al. 2011, Science

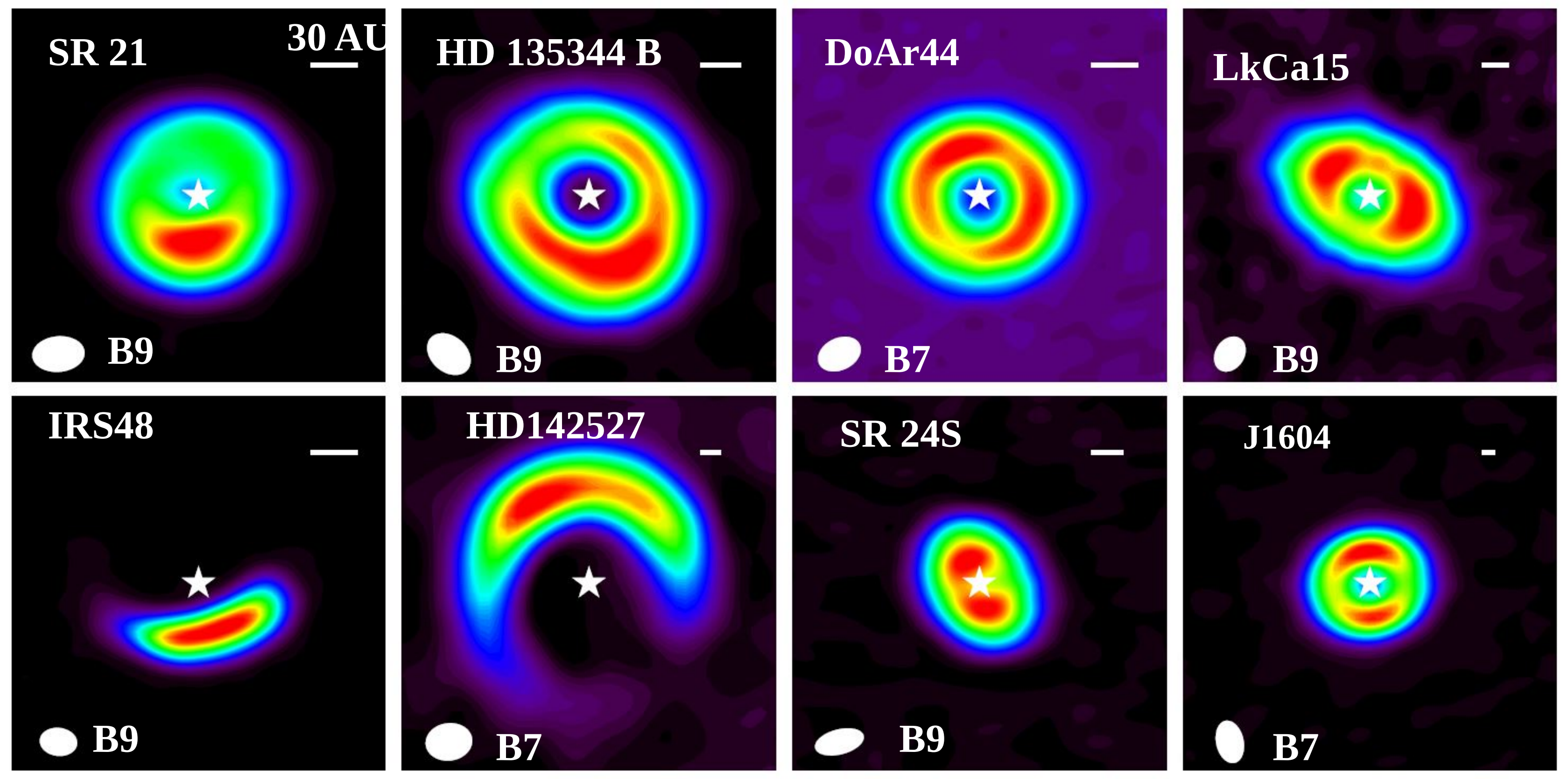
Bergin et al. 2010
Du et al. 2015
Cleeves et al. 2015

**Water lines weaker than expected → water sequestered in large bodies early on**

*Talks Hogerheijde, Cleeves*

# Dust traps in disks: formation of large bodies

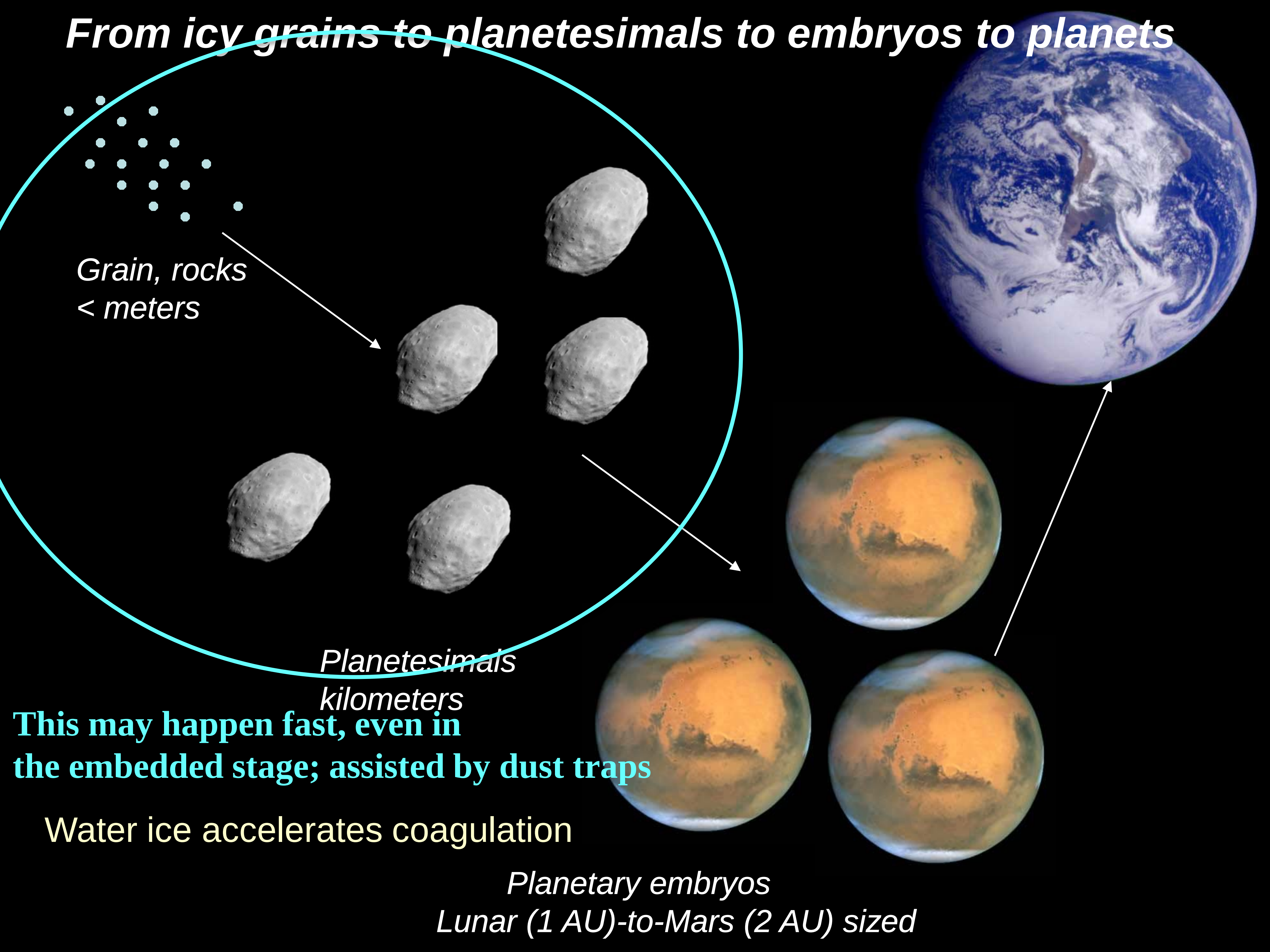
**ALMA mm continuum images disks at few Myr**




vD et al. 2015

Data from van der Marel et al. 2013, 2015
Perez et al. 2014, , Casassus, Fukugawa et al. 2013
Carpenter, Zhang et al. 2014

- Dust traps help to overcome radial drift problem and fragmentation barrier
  → Planetesimal/'Comet' factories


From icy grains to planetesimals to embryos to planets
Grain, rocks
< meters
Planetesimals
kilometers
This may happen fast, even in
the embedded stage; assisted by dust traps
Water ice accelerates coagulation
Planetary embryos
Lunar (1 AU)-to-Mars (2 AU) sized

# Summary

- Where and how is water formed in space?
  - Mostly on grains, some in hot gas in shocks
  - Hot water abundance lower than expected (TBC)
  - Constraints also from (lack of) $O_2$
- What is the water 'trail' from clouds to planets?
  - Water enters disk mostly as ice
    - Some of it processed, some not
    - Disk formation stage uncertain; episodic accretion
  - Water is sequestered in large bodies early on