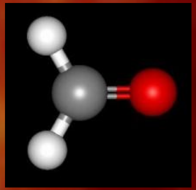
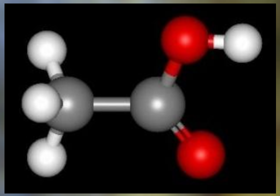
Gas and dust in protoplanetary disks: from Spitzer to Herschel and JWST





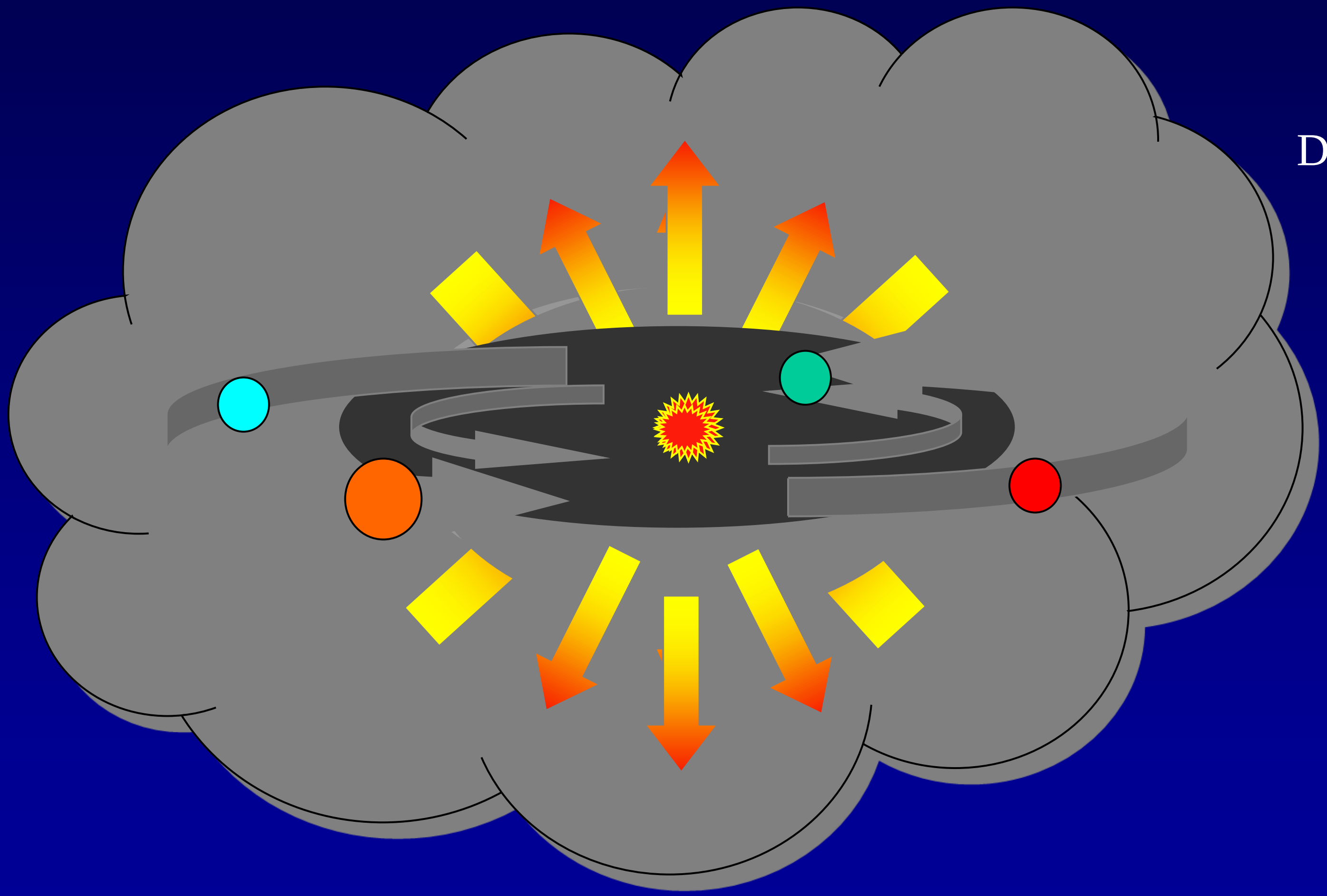
Ewine F. van Dishoeck
Leiden Observatory/MPE

Thanks to many collaborators and colleagues

Herschel image
ESA/A. Zavagno

Strange new worlds, Flagstaff, May 2 2011

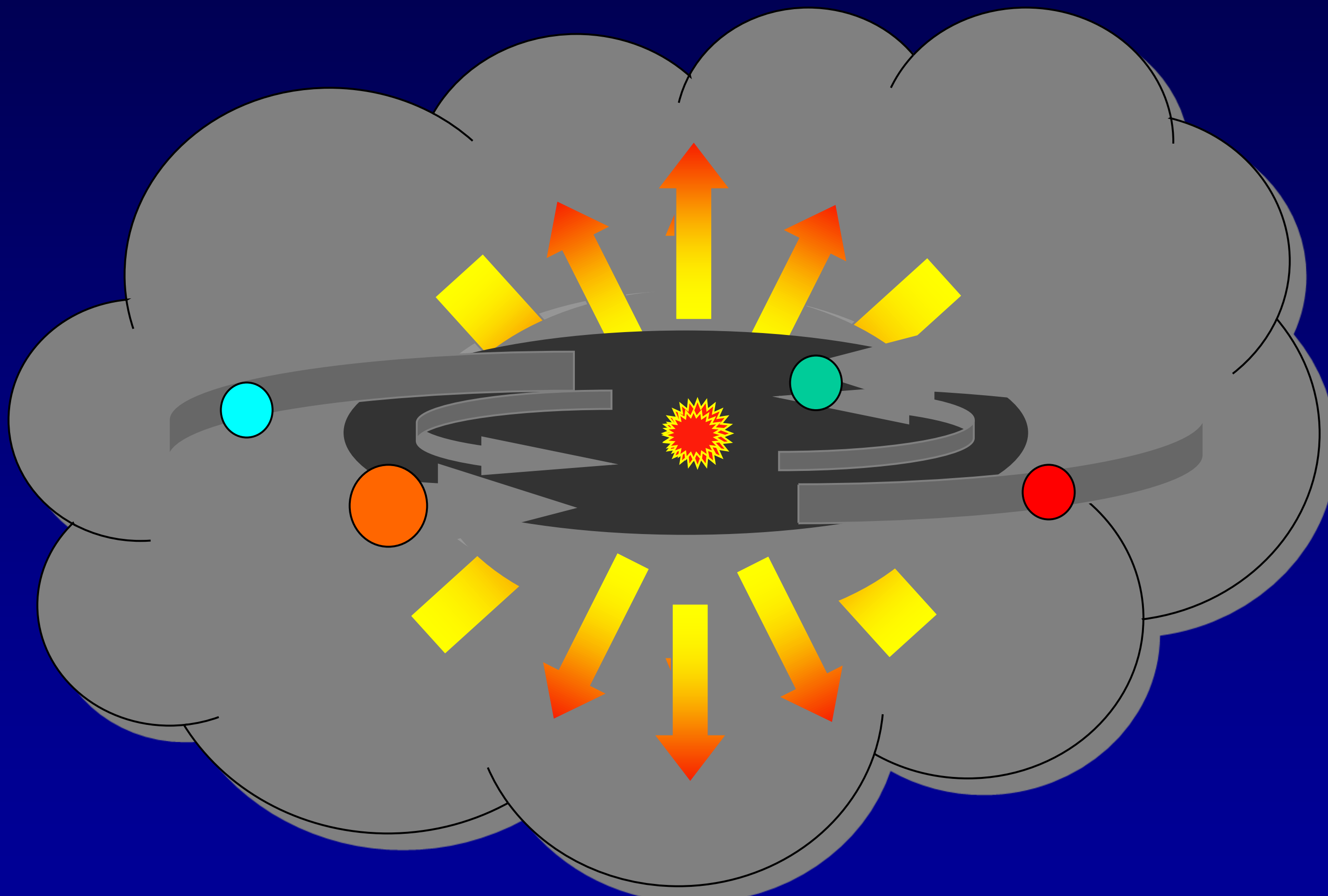
Follow molecules during star and planet formation



D. Lommen

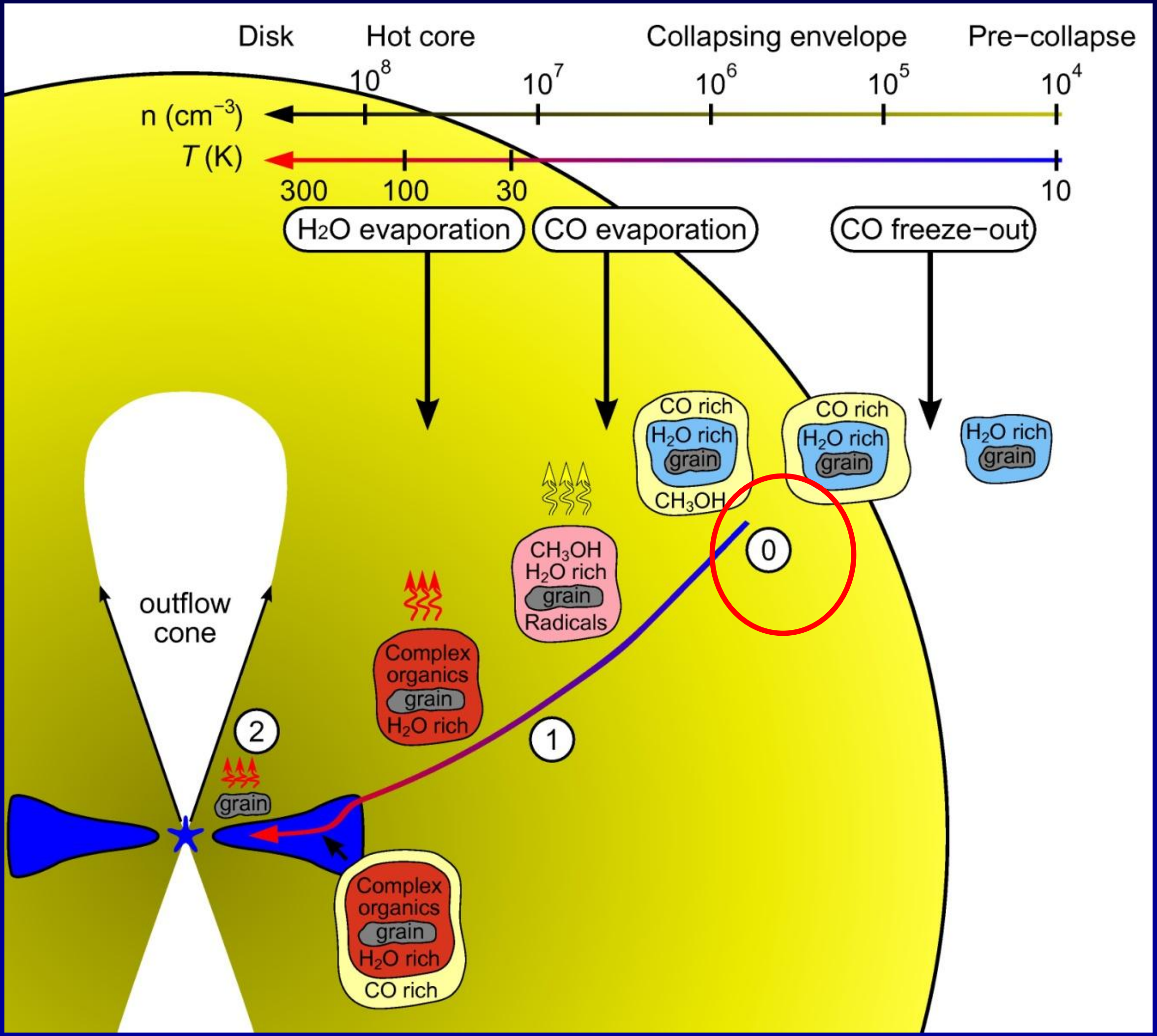
Dark pre-stellar cores → Low-mass protostars → Disks → Comets, Planets

Follow molecules during star and planet formation



Inventory at each stage? How pristine is material in comets and planets? Use molecules as diagnostics?

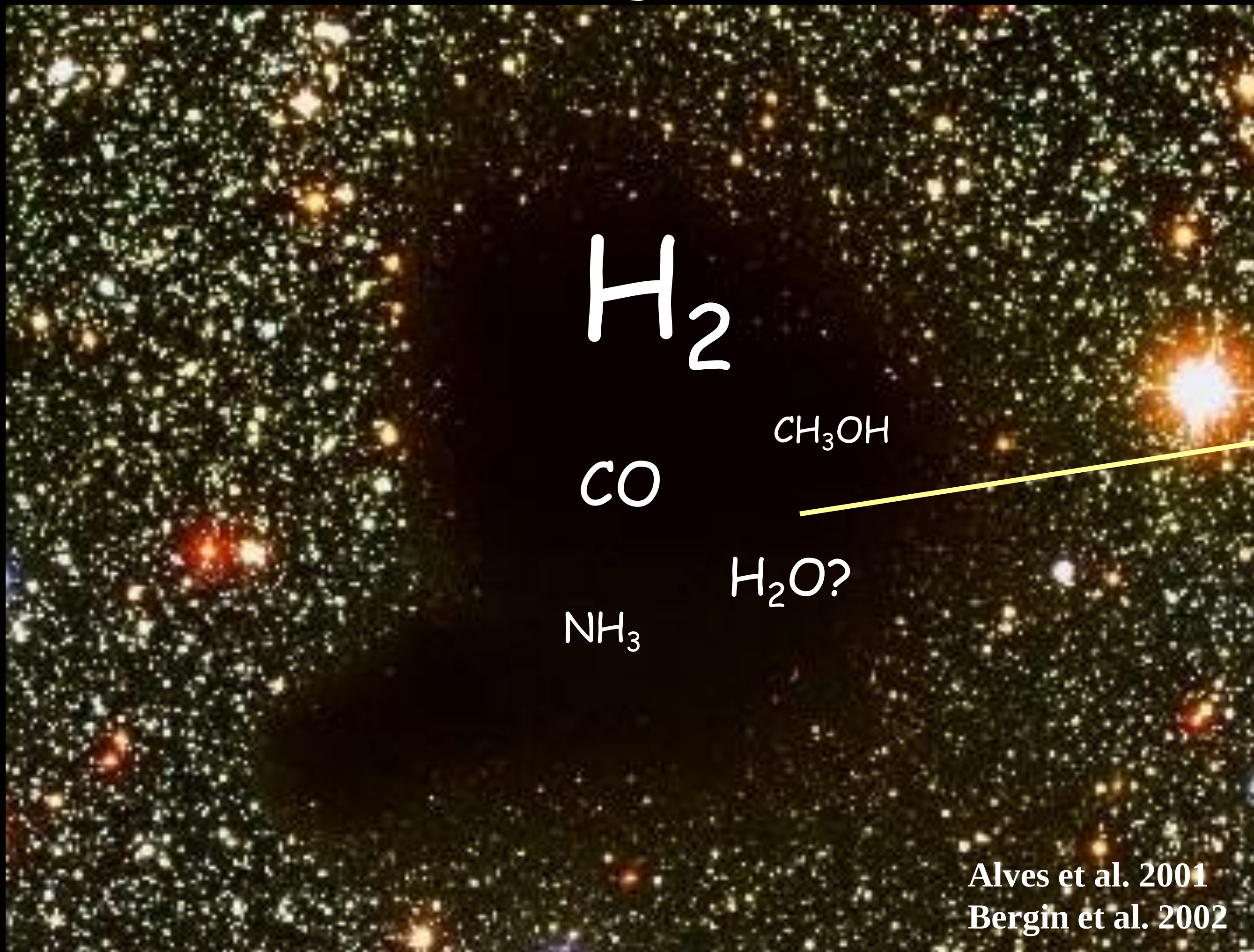
Follow journey of parcel from cores to disk



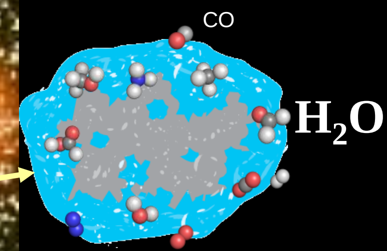
Herbst & vD
ARA&A 2009

Visser et al. 2009

Cold dense cores: sites of solar systems formation



Grains with icy mantles



0.3 μm

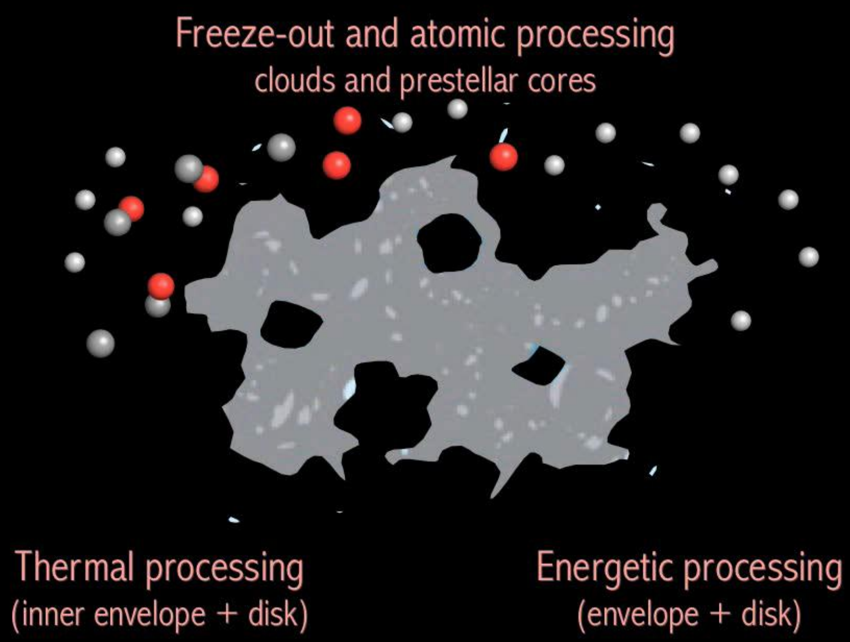
t_{depl}~2.10^9/n yr

n=2.10^4 – 5.10^5 cm^{-3}, T=10 K

Many molecules frozen out onto grains

Formation molecules on grains

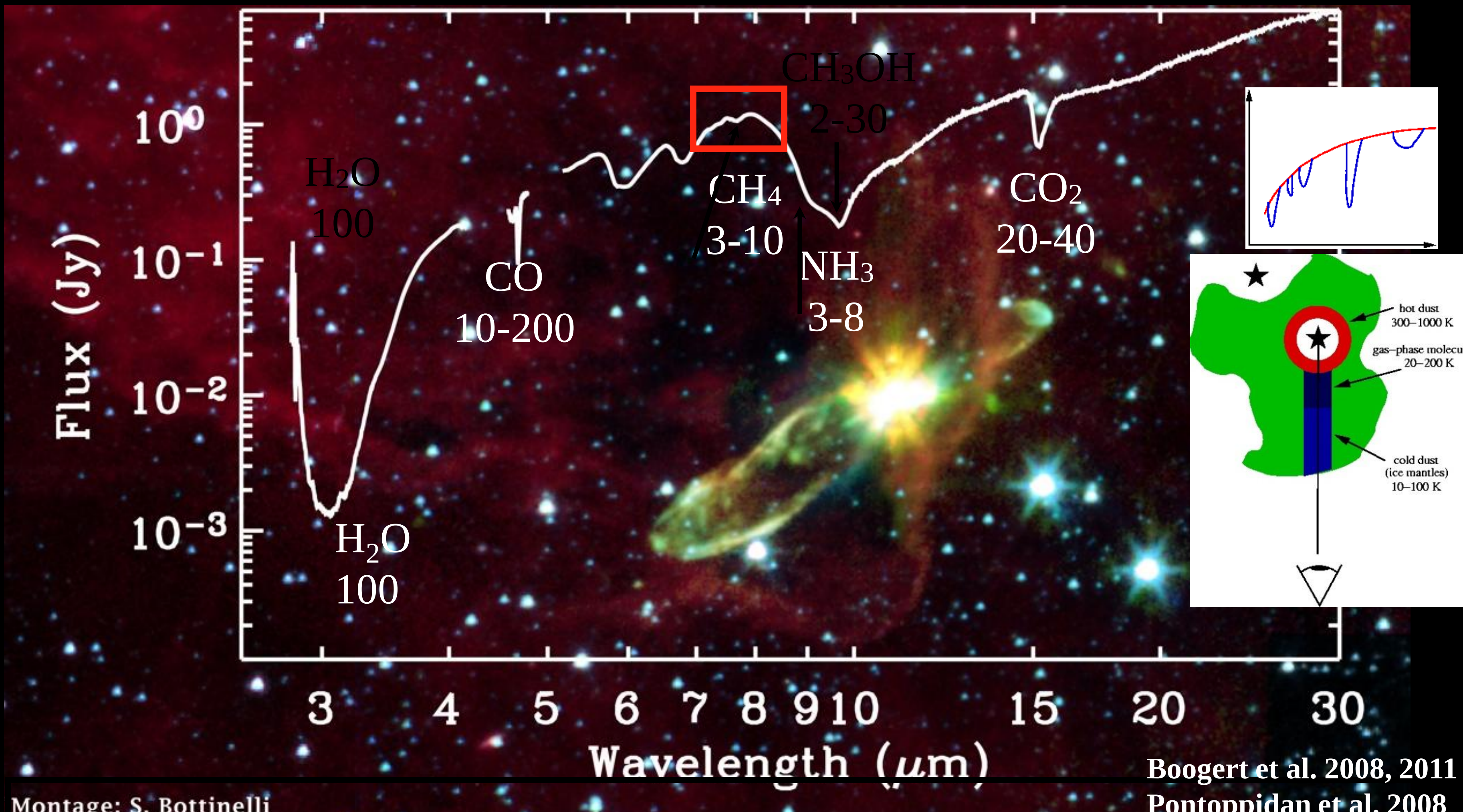
K. Öberg



Hydrogenation of O, C, N and CO

Dominates formation of H_2O, CH_3OH, CO_2, CH_4, NH_3, ….
Occurs at temperatures as low as 10 K

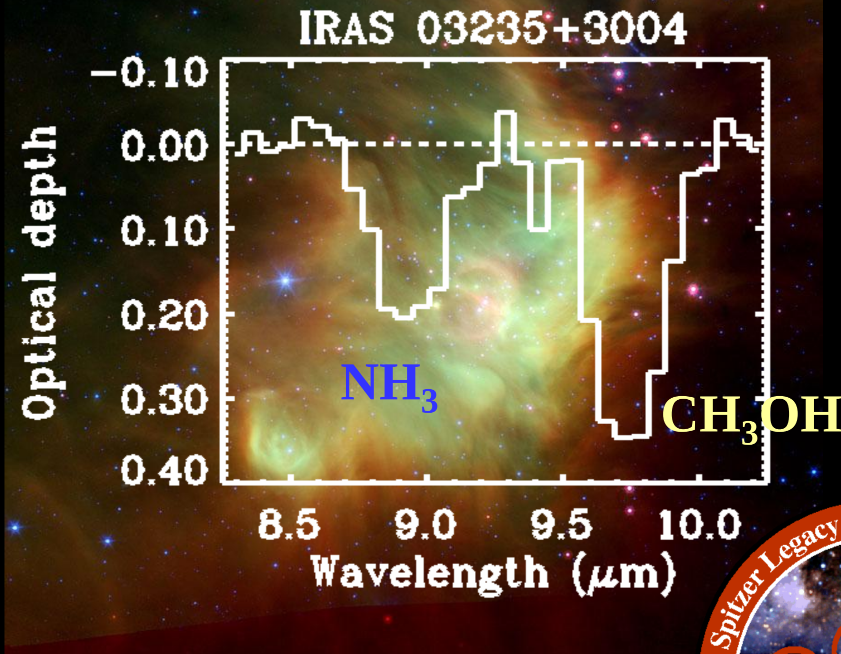
Ice inventory: Spitzer legacy

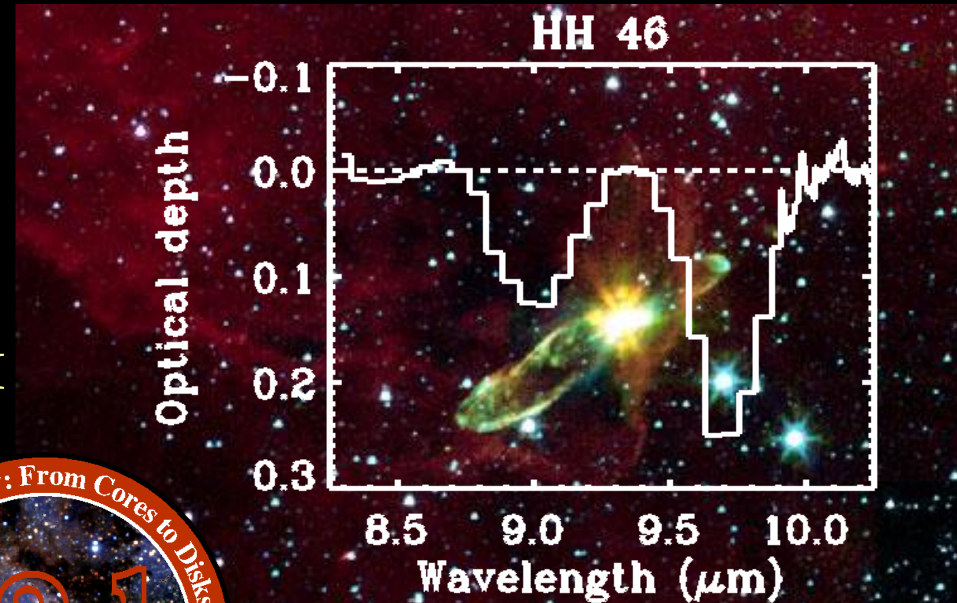


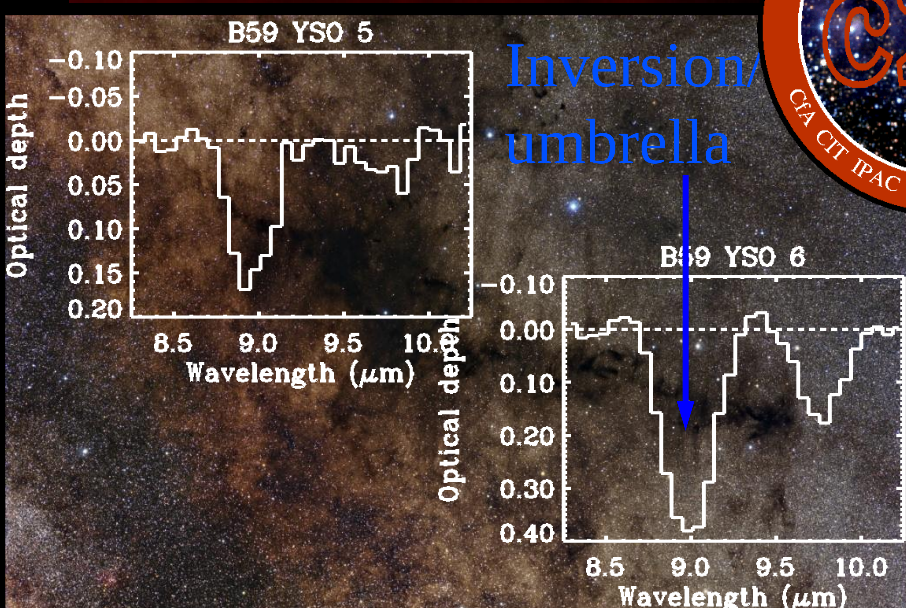
- **Ices contain significant fraction of heavy elements (50% or more)**
- **Overall composition very similar; NH_3, CH_3OH largest variations**

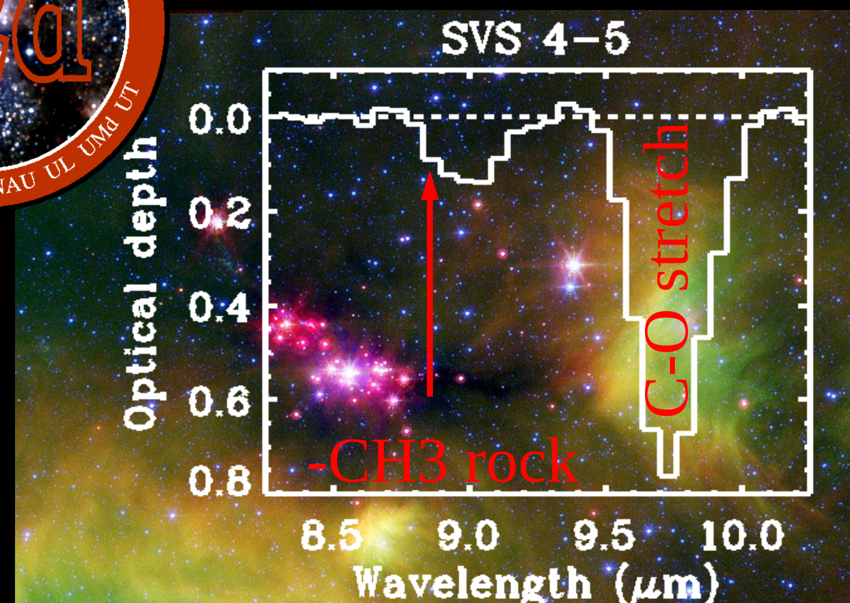
Boogert et al. 2008, 2011
Pontoppidan et al. 2008
Öberg et al. 2008, 2011
Bottinelli et al. 2010
Whittet , Cook, Chiar+

Silicate subtracted spectra: NH_3 and CH_3OH!





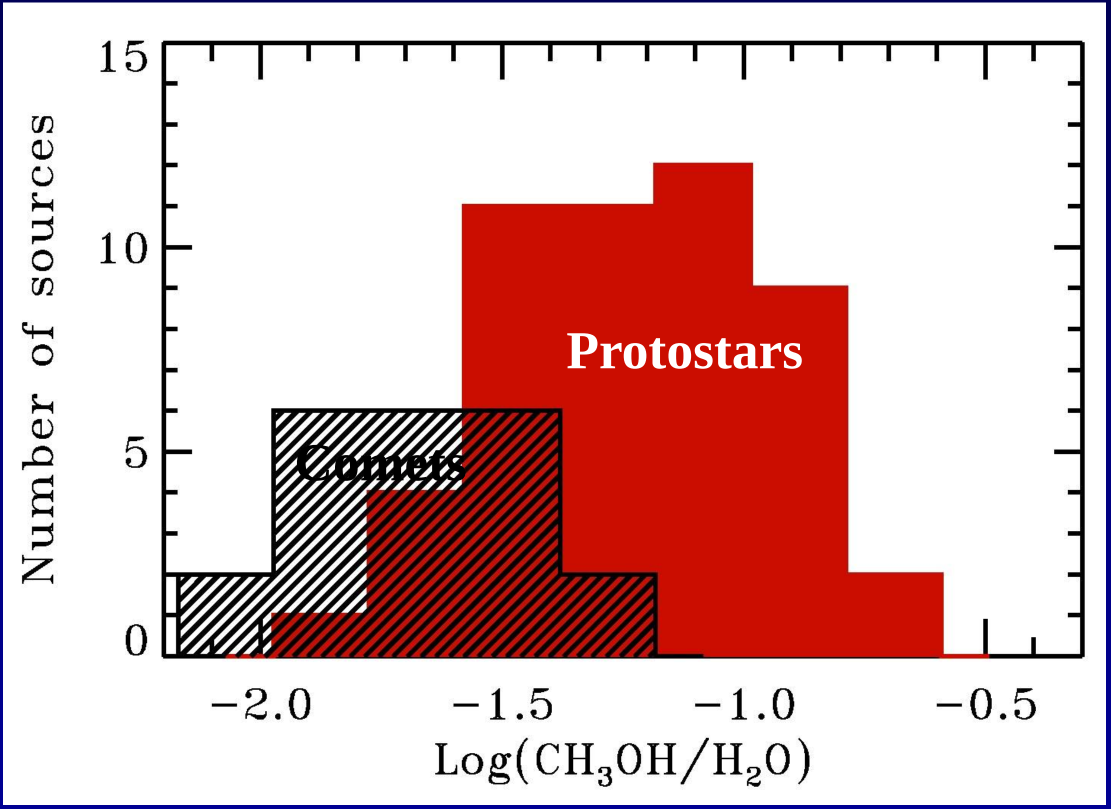




Ingredients for complex organics!

Bottinelli et al. 2010

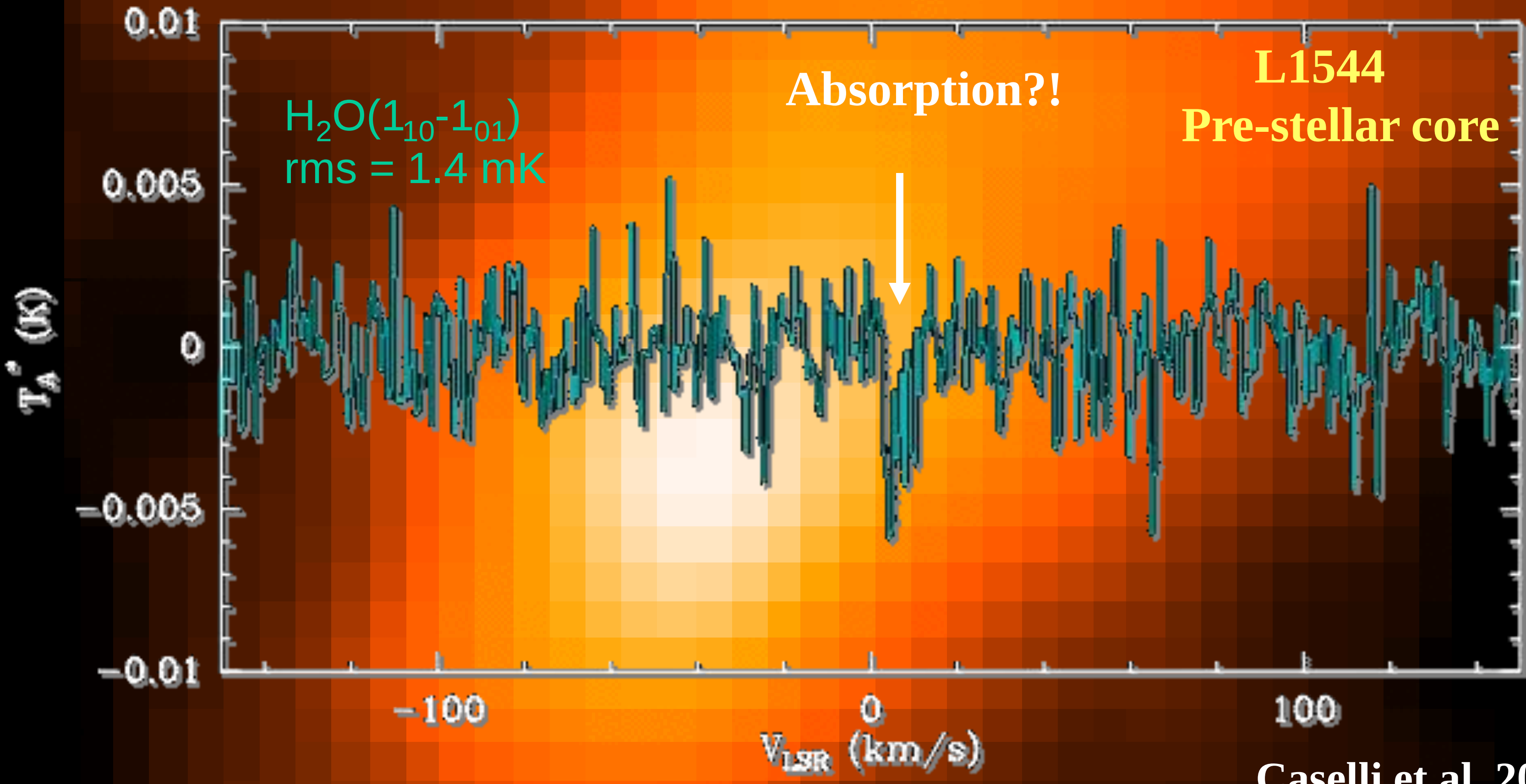
Methanol protostars vs comets



Öberg et al. 2011
Mumma & Charnley 2011

Most water on grains, little in gas

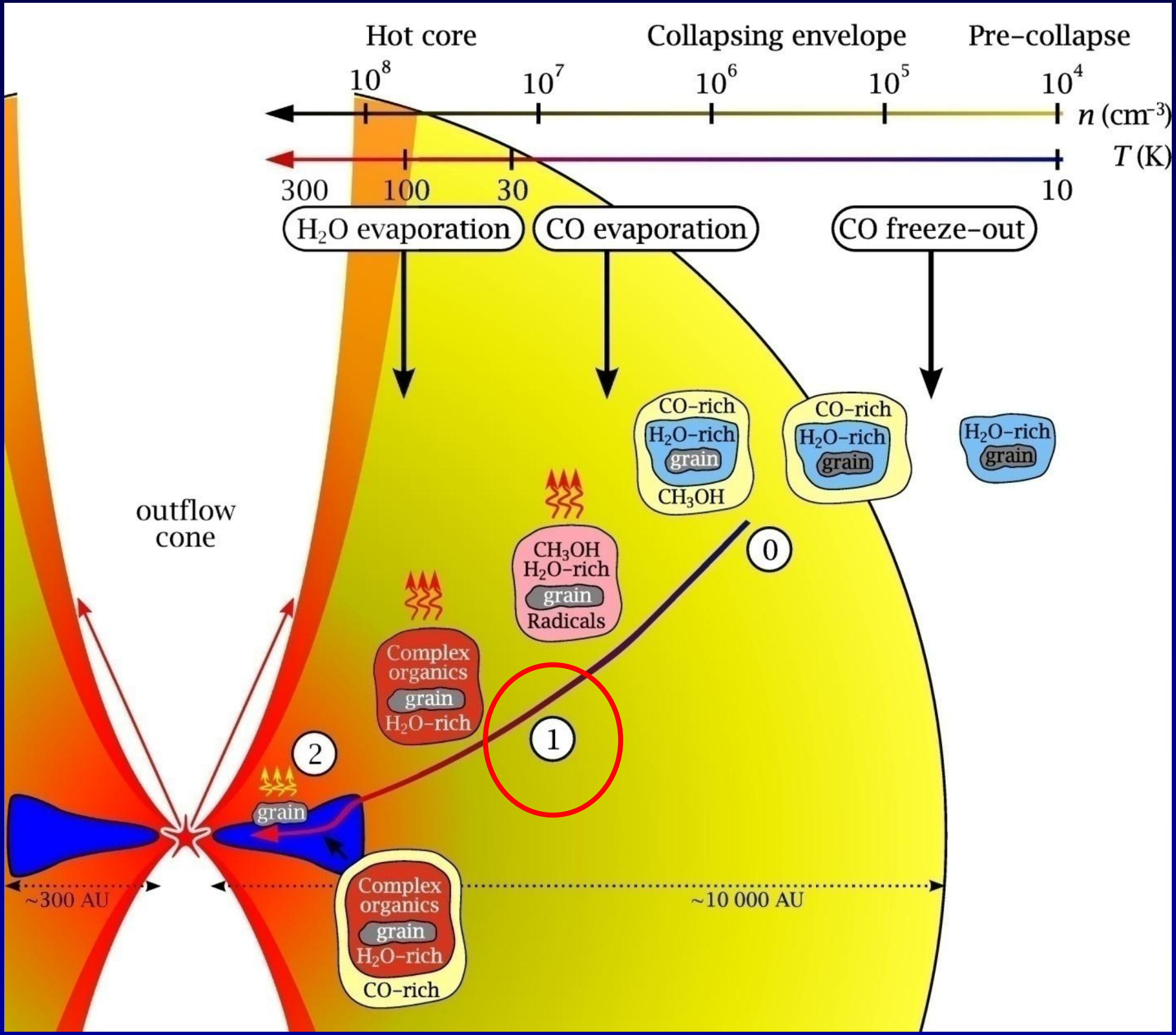
Pushing the limits of Herschel-HIFI



Caselli et al. 2010
and in prep.

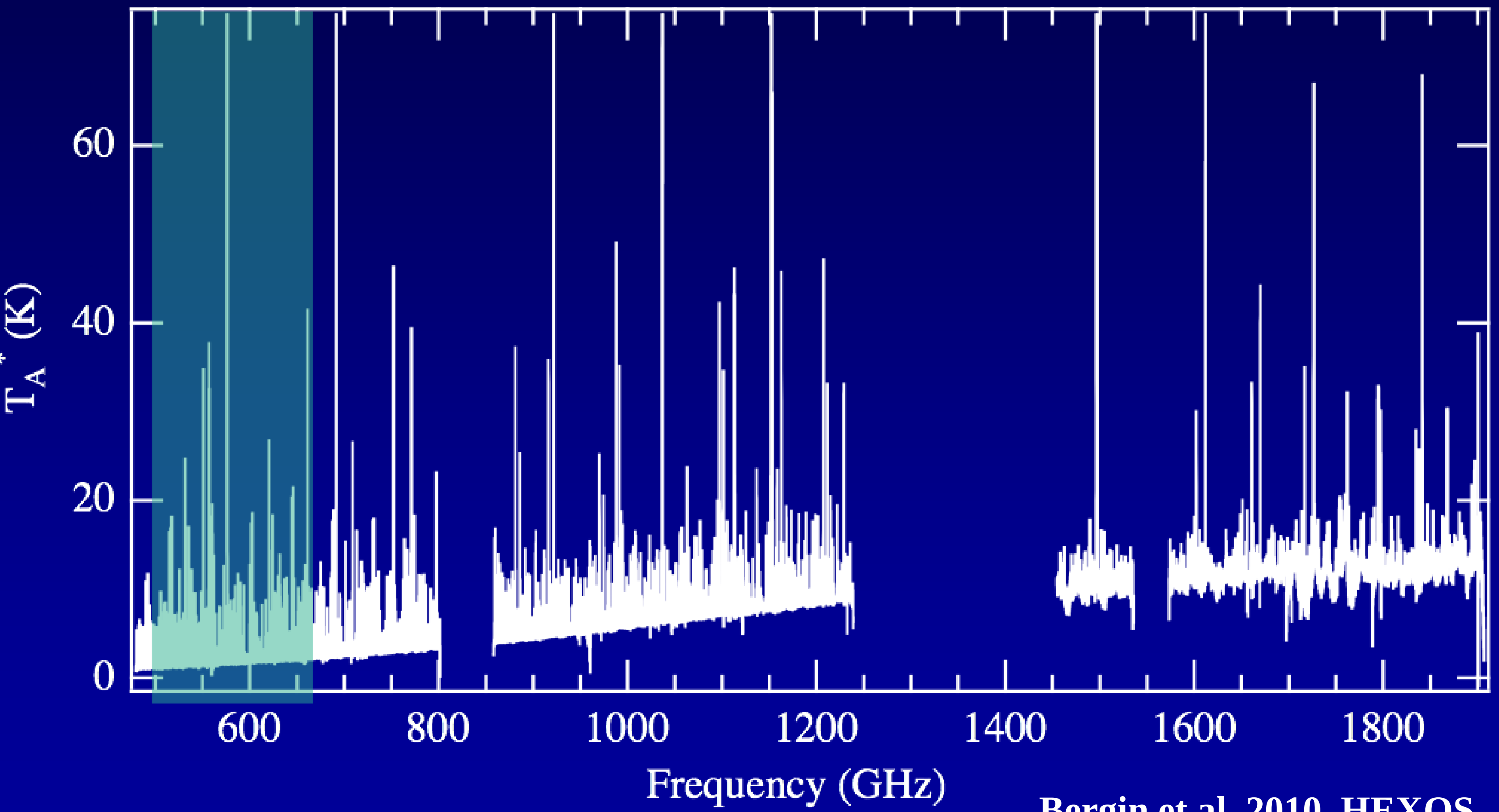
Lines up to factor 100 weaker than predicted

Follow journey of parcel from cores to disk
from ice to steam



Visser et al. 2009, 2011

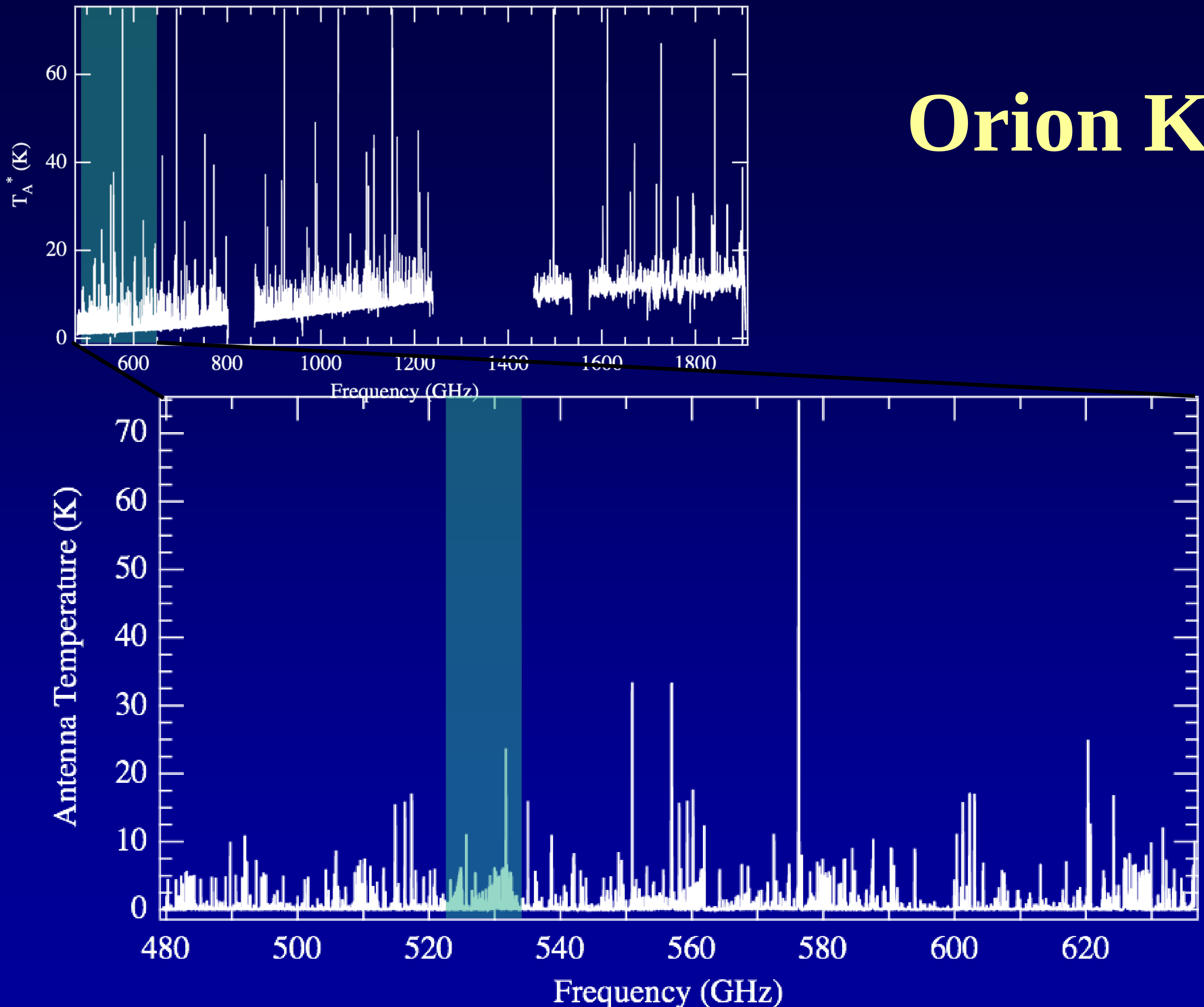
Herschel-HIFI forest of lines in Orion



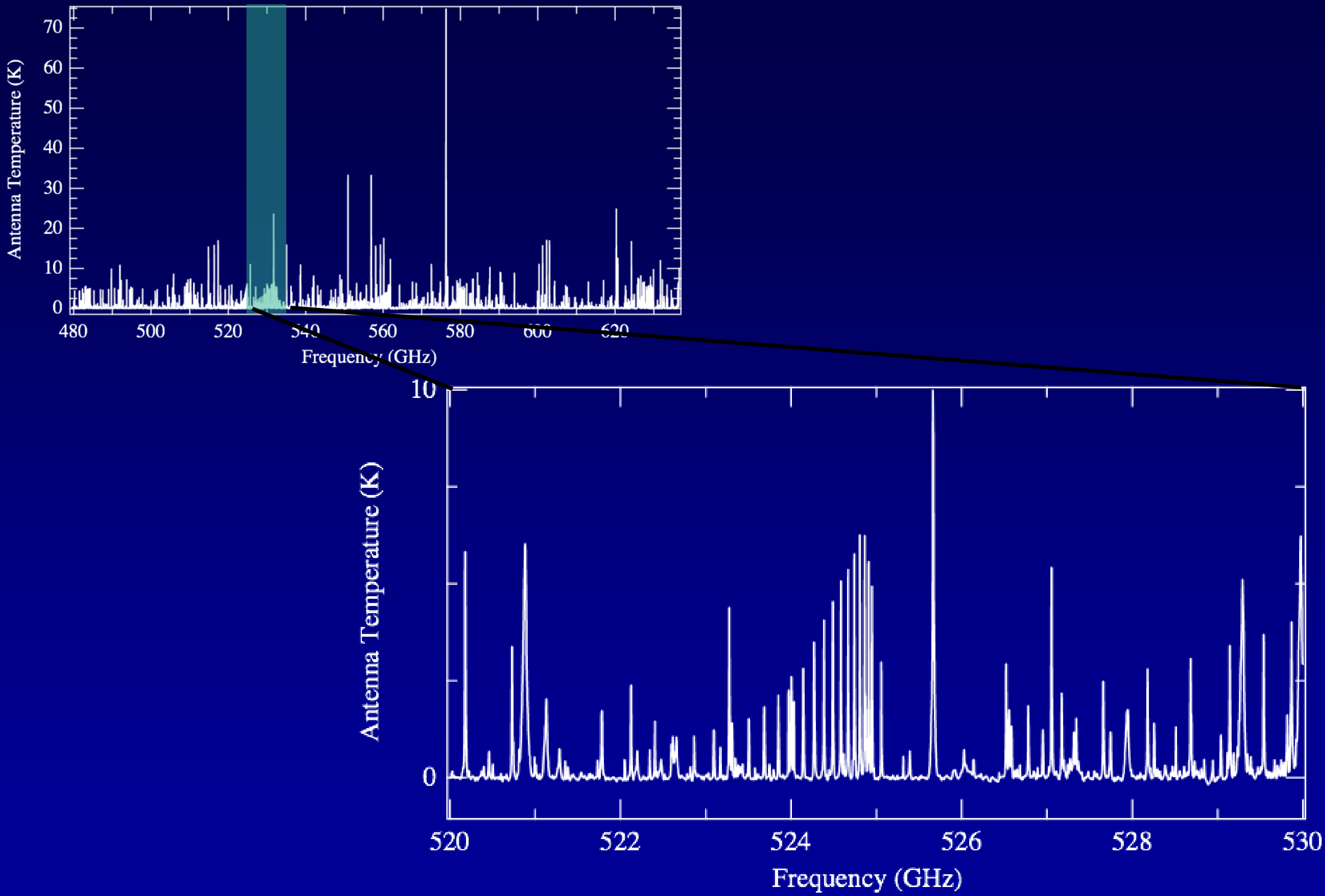
Bergin et al. 2010, HEXOS

Entire spectrum in just tens of hours!

Orion KL

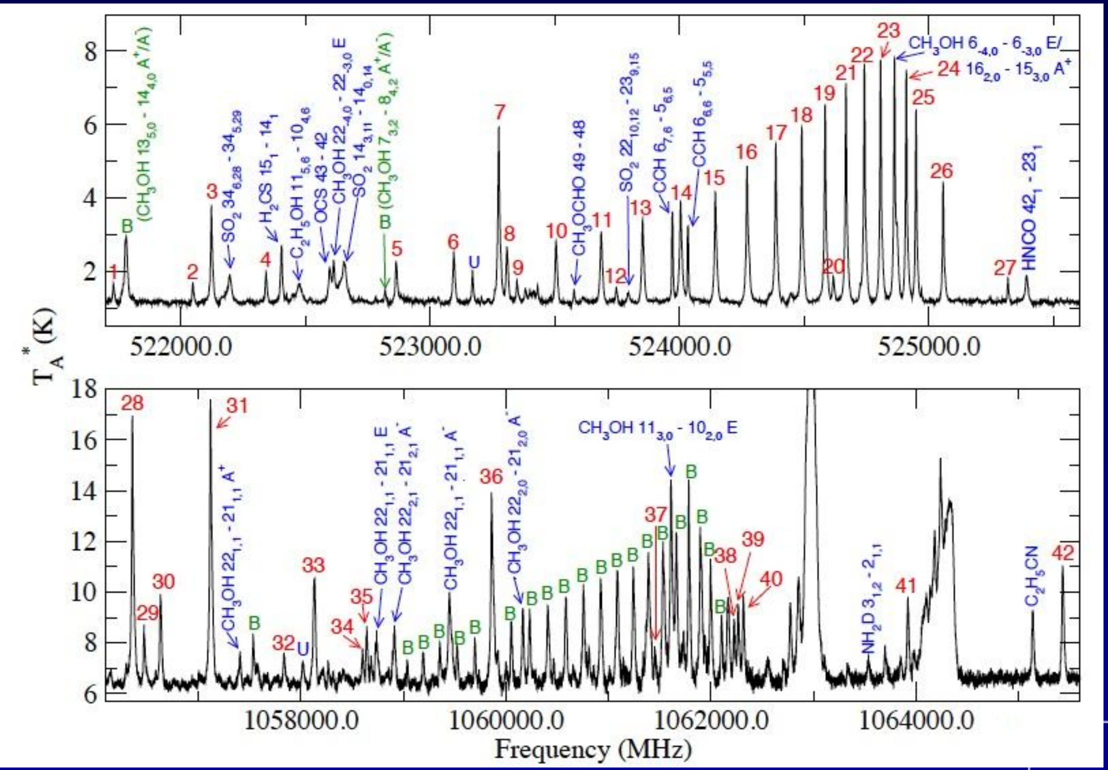


60
40
20
0
T_A^* (K)
600
800
1000
1200
1400
1600
1800
Frequency (GHz)
70
60
50
40
30
20
10
0
Antenna Temperature (K)
480
500
520
540
560
580
600
620
Frequency (GHz)



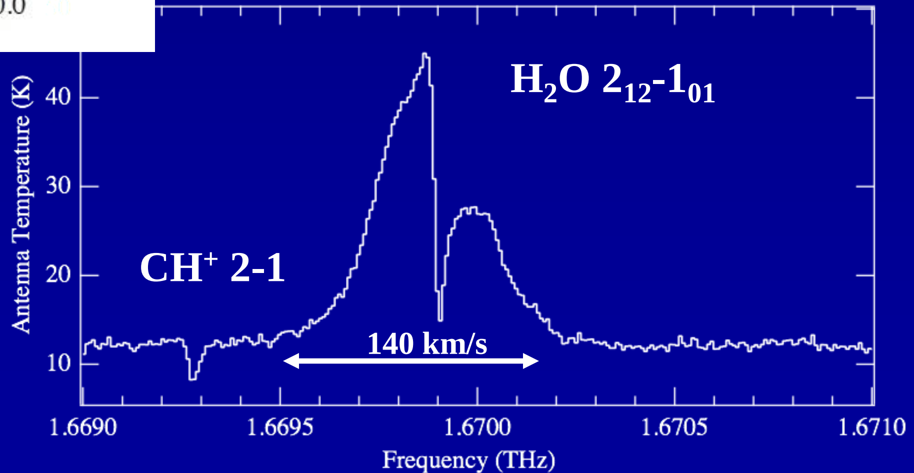
Orion KL - Band 1

Herschel spectroscopy: we have come a long way



Orion-KL
HEXOS

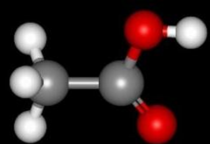
High-quality line profiles, even at 1.67 THz!



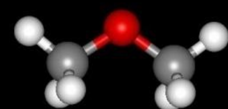
Complex organics also seen in spectra of some (but not all) solar-mass protostars

Some complex organic (pre-biotic) molecules

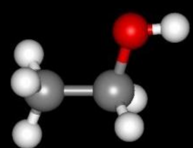
Detected



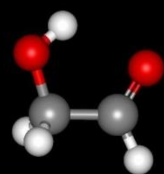
Acetic acid



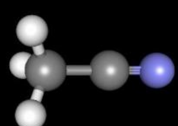
Di-methyl ether



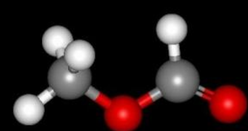
Ethanol



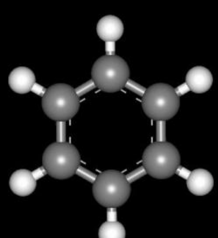
Sugar



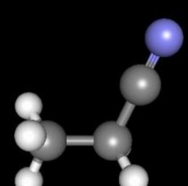
Methyl cyanide



Methyl formate

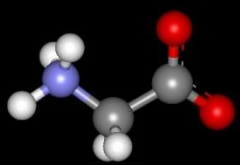


Benzene

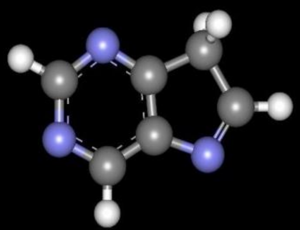


Ethyl cyanide

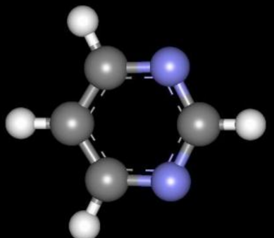
Not (yet) detected



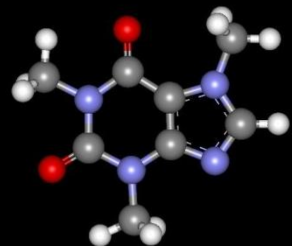
Glycine



Purine



Pyrimidine



Caffeine

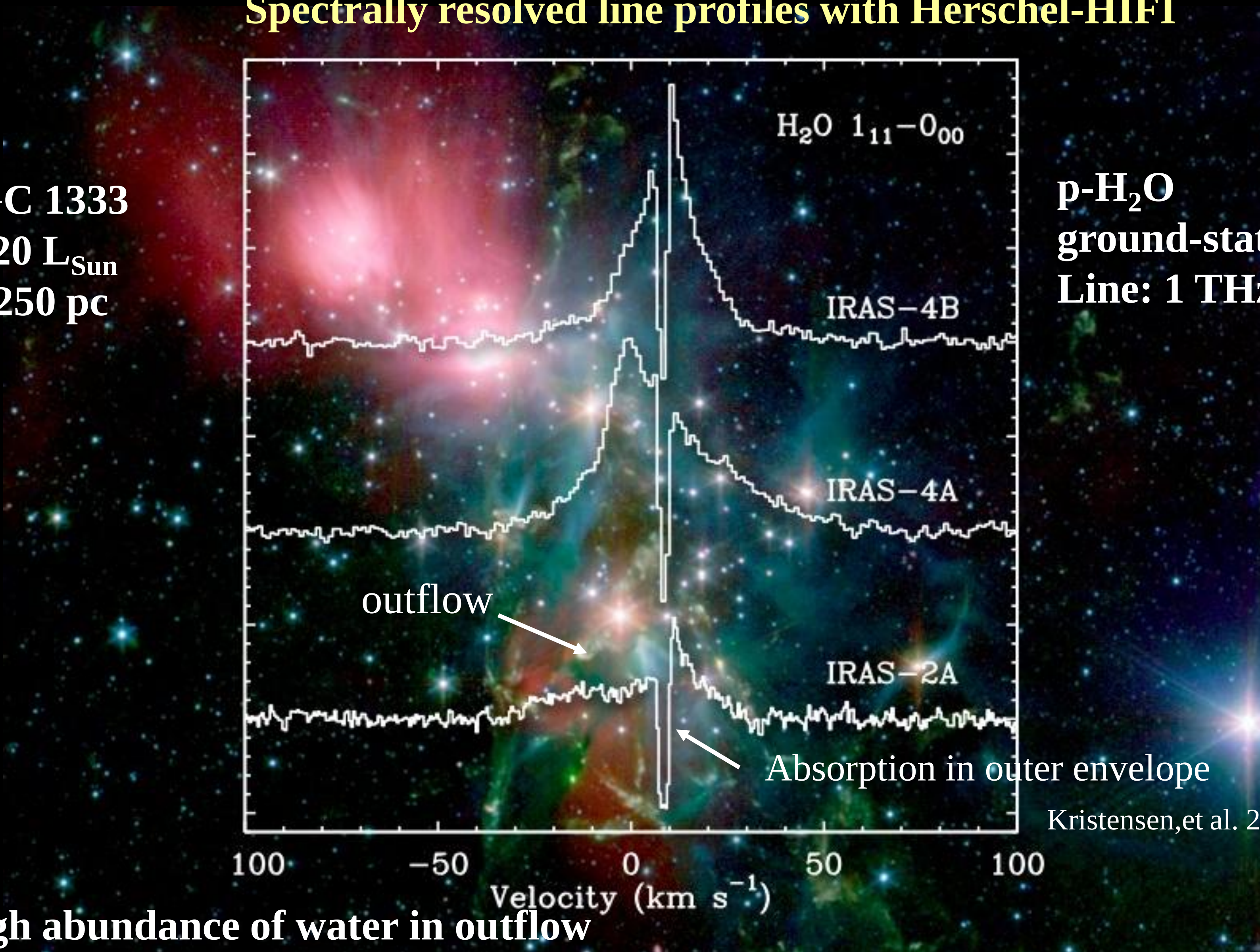
Most detections toward high-mass protostars,
Only few solar-mass protostars, none in disks
NEED ALMA!

Hot and cold gaseous water

Spectrally resolved line profiles with Herschel-HIFI

NGC 1333
L~20 L_{Sun}
D~250 pc

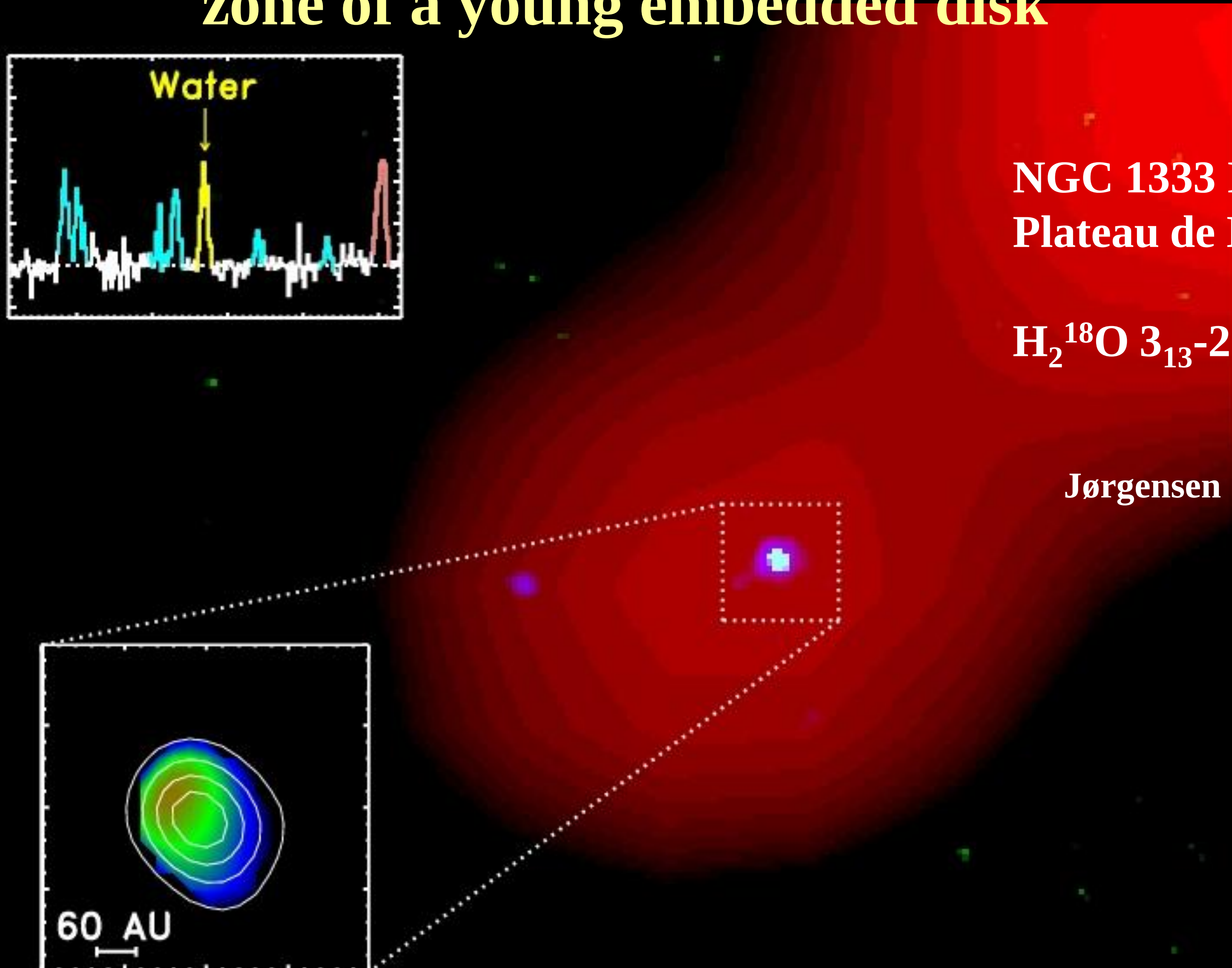
p-H_2O
ground-state
Line: 1 THz



Kristensen,et al. 2010

High abundance of water in outflow
Low abundance in quiescent gas => water mostly on grains

First image of warm water in the planet-forming zone of a young embedded disk



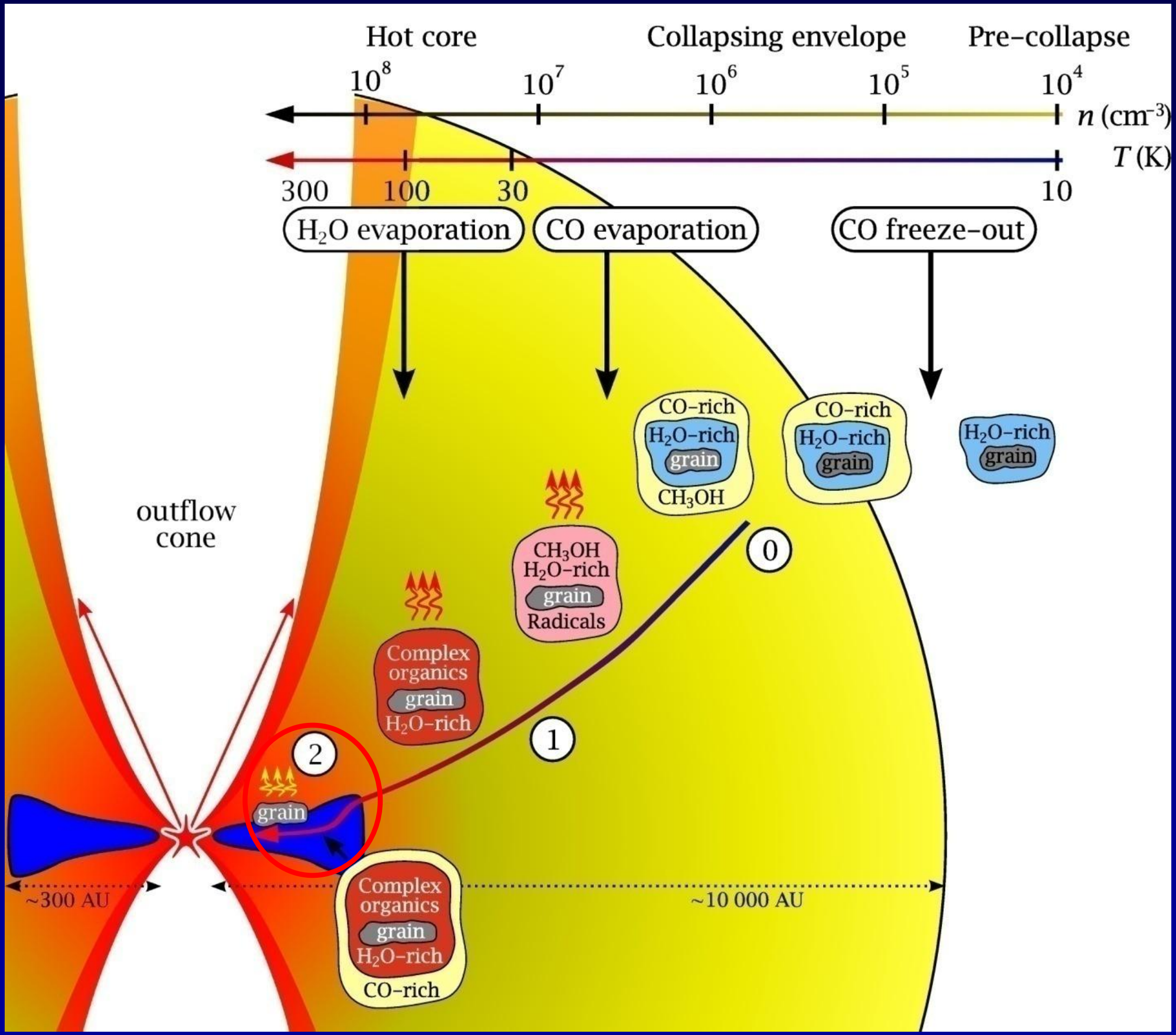
NGC 1333 IRAS4B
Plateau de Bure

$H_2{}^{18}O$ 3_{13}-2_{20} 203 GHz
E_u~200 K

Jørgensen & vD 2010a,b

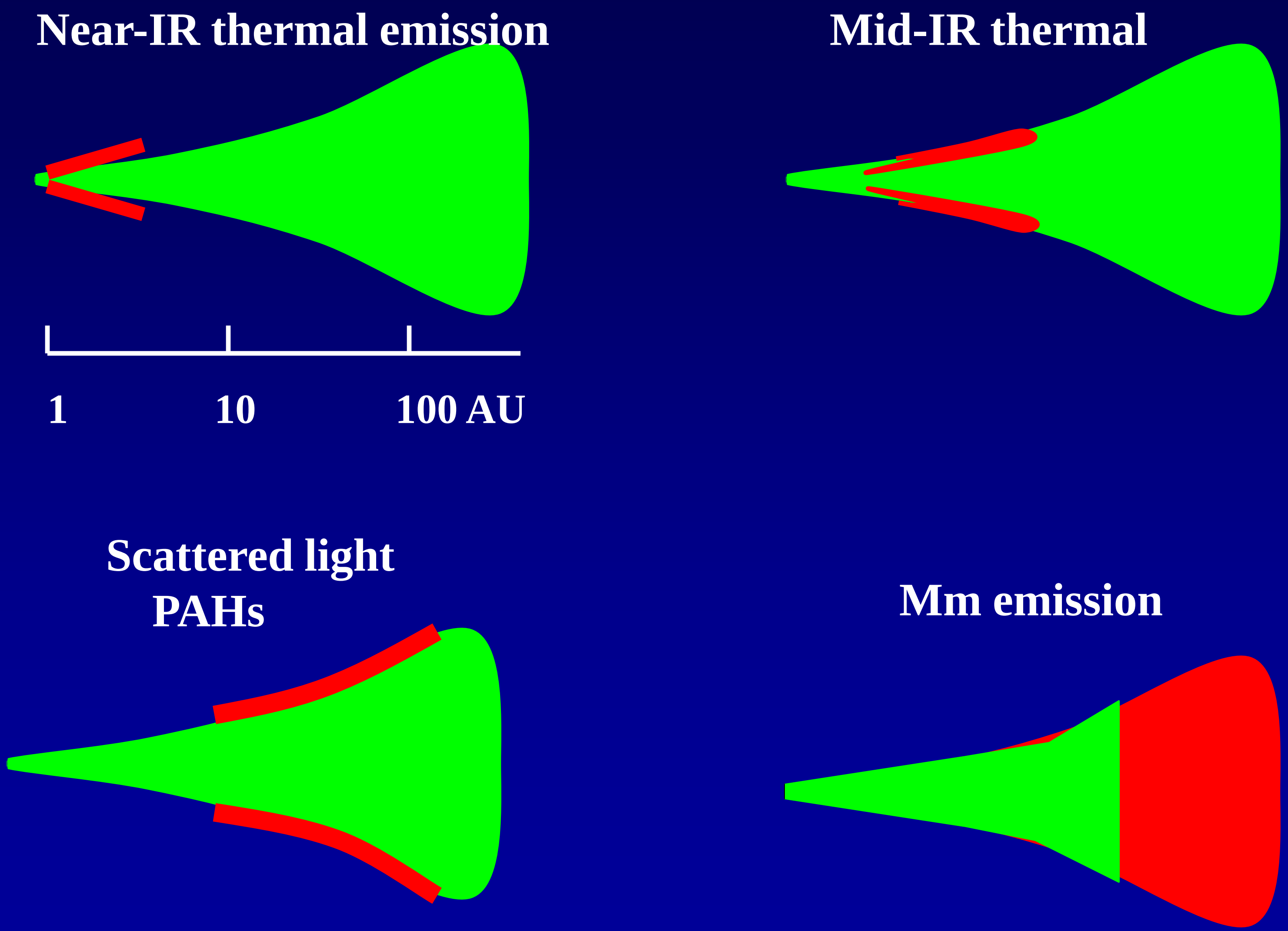
Probing the snow line at 30 AU? Also HDO/H_2O<$6x10^{-4}$
50-100 times higher spatial resolution than Herschel (ALMA Band 5!)

Into the disk



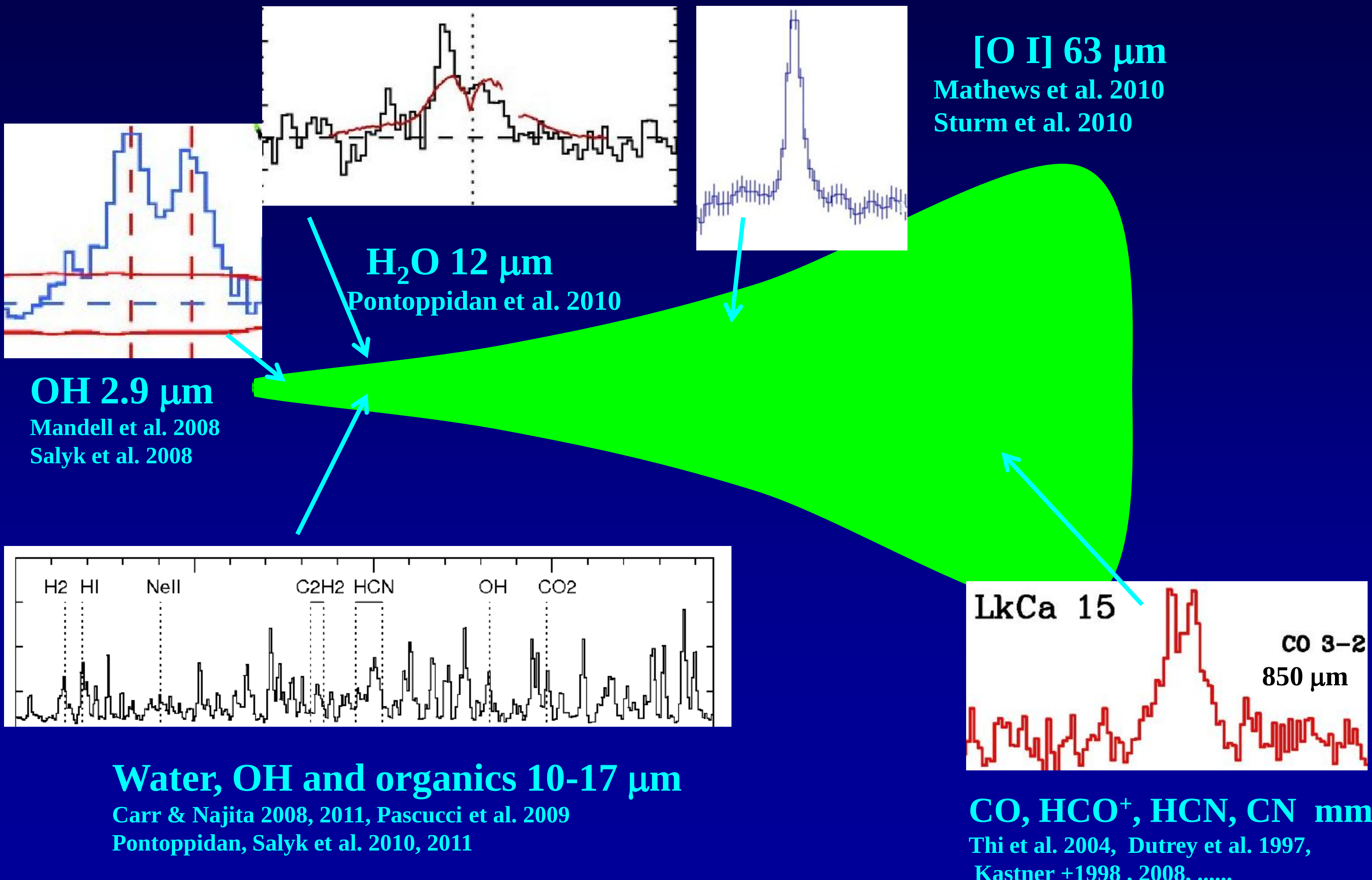
Visser et al. 2009, 2011

Mm vs IR: probing different parts of disks

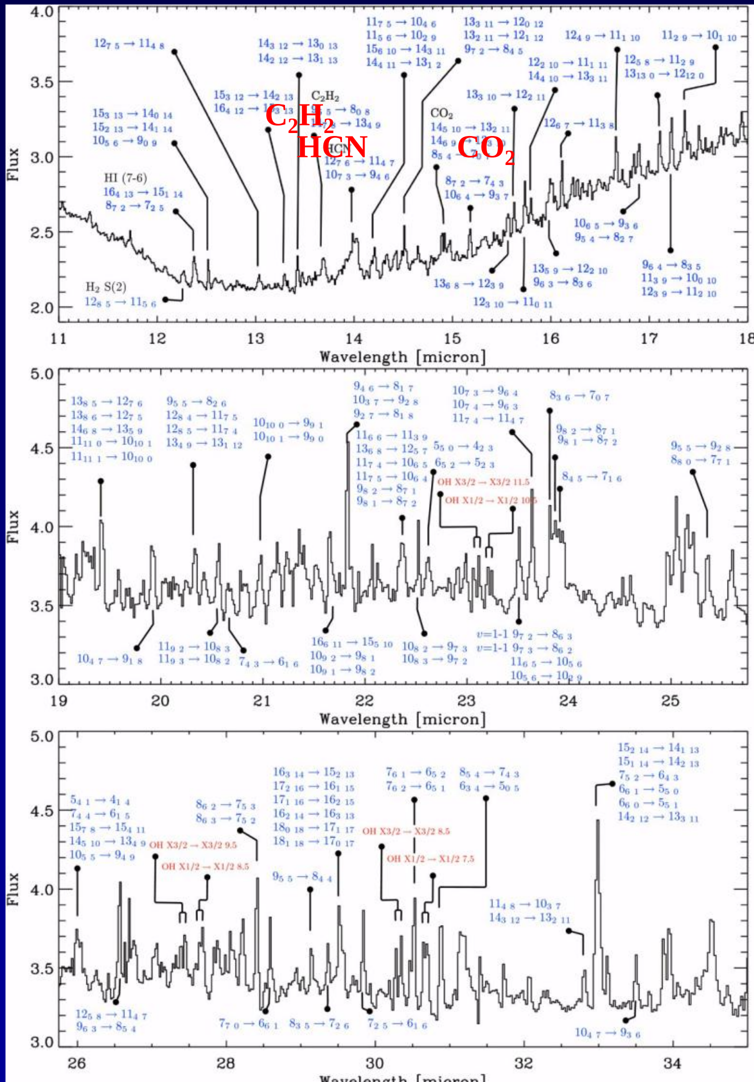


Williams & Cieza 2011, ARAA

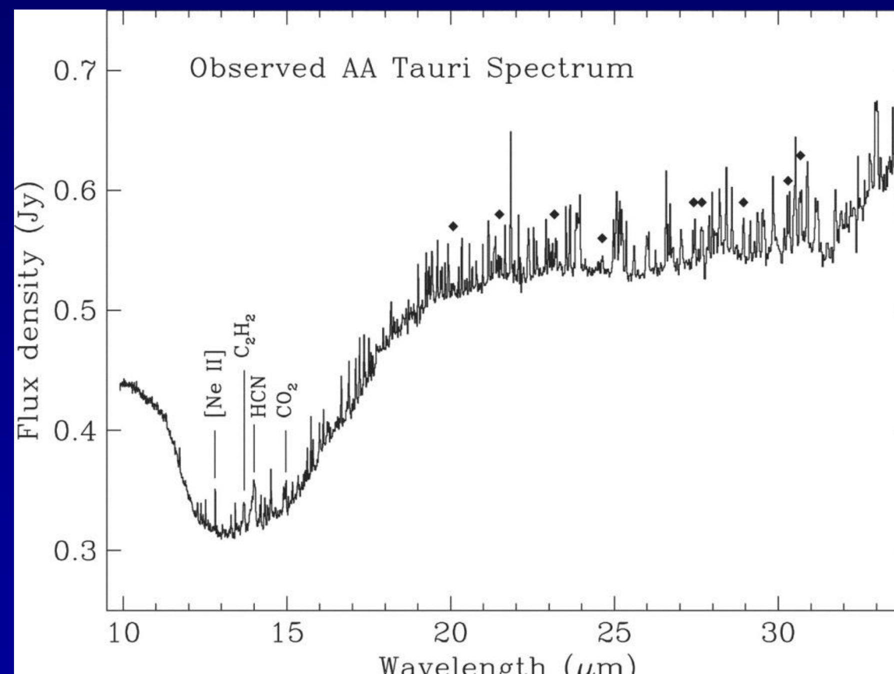
Rich variety of probes



Hot water and organics in inner 1 AU



- T_{ex}~400-1000 K
- Emitting area locates gas within ~1AU



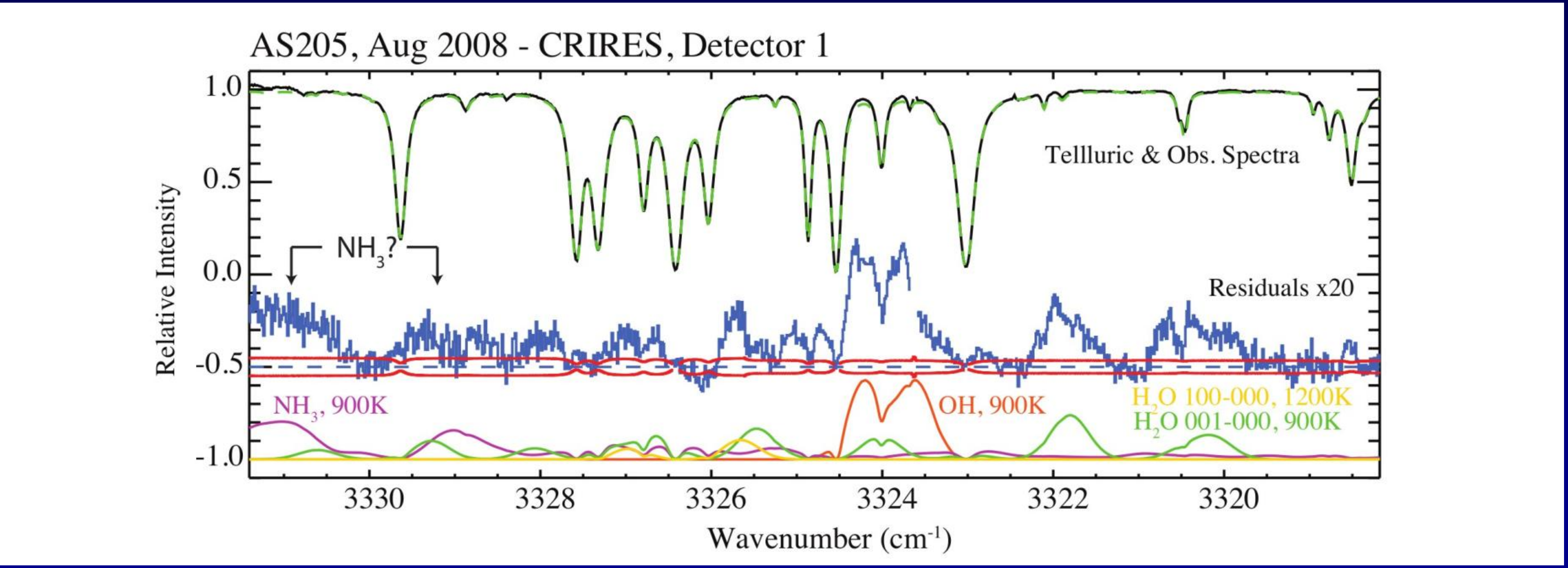
Pontoppidan et al. 2010,
Salyk et al. 2011

Carr & Najita 2008, 2011, Pascucci et al. 2009

Salyk et al. 2008, Lahuis et al. 2006, Gibb et al. 2007

Search for other species at NIR

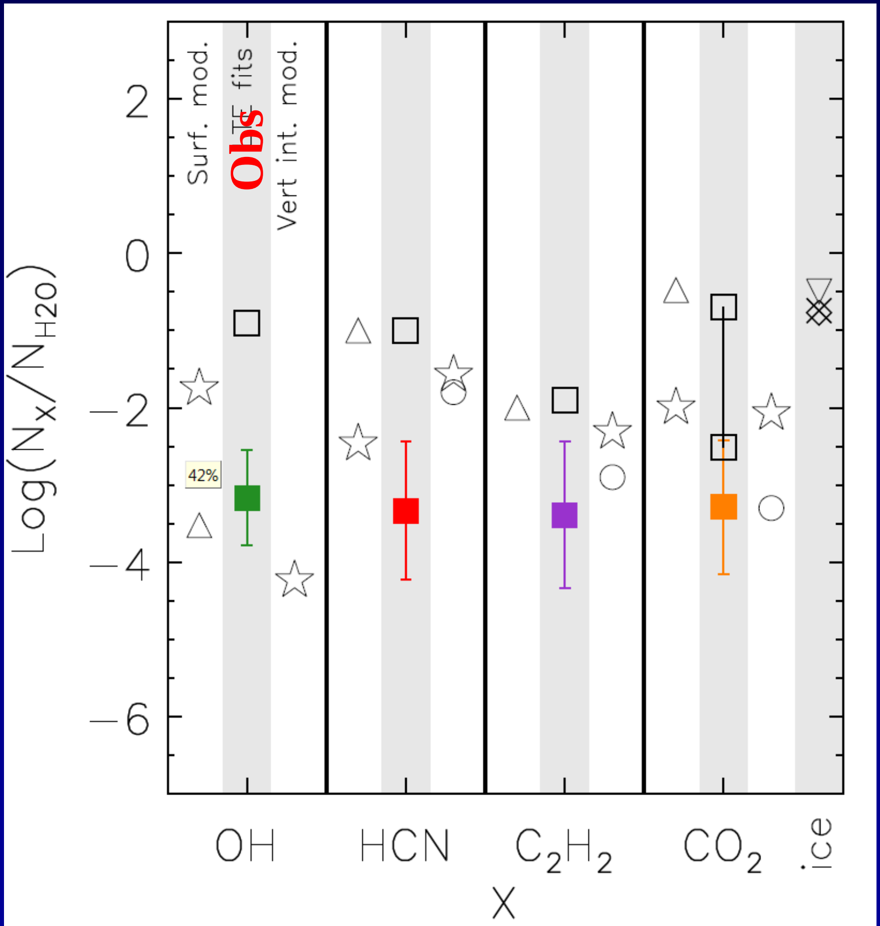
VLT-CRIRES, R=100,000, S/N>500



Mandell, Bast et al. in prep

- HCN, OH, H_2O detected in several sources
- CH_4 and NH_3 not yet convincingly found

Abundance ratios: starting to test models

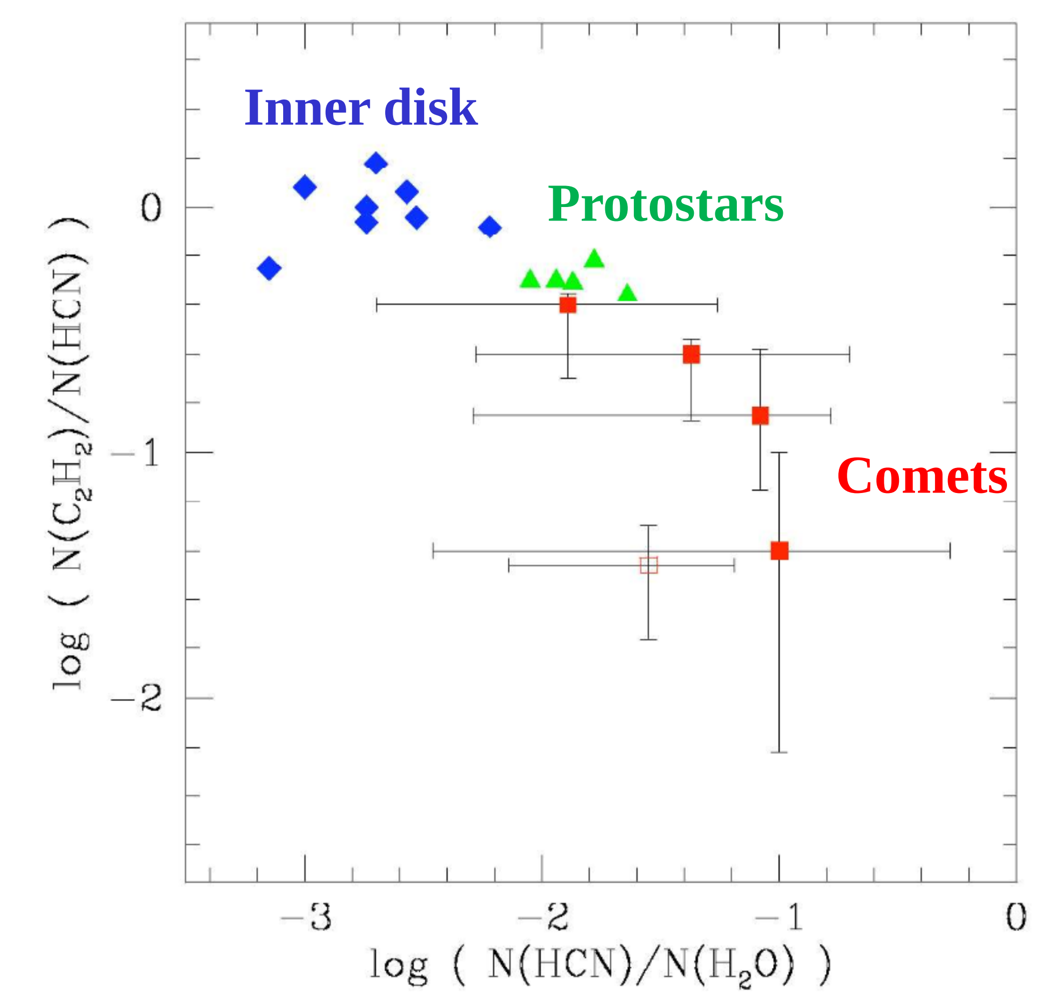


Salyk et al. 2011

Carr & Najita 2011

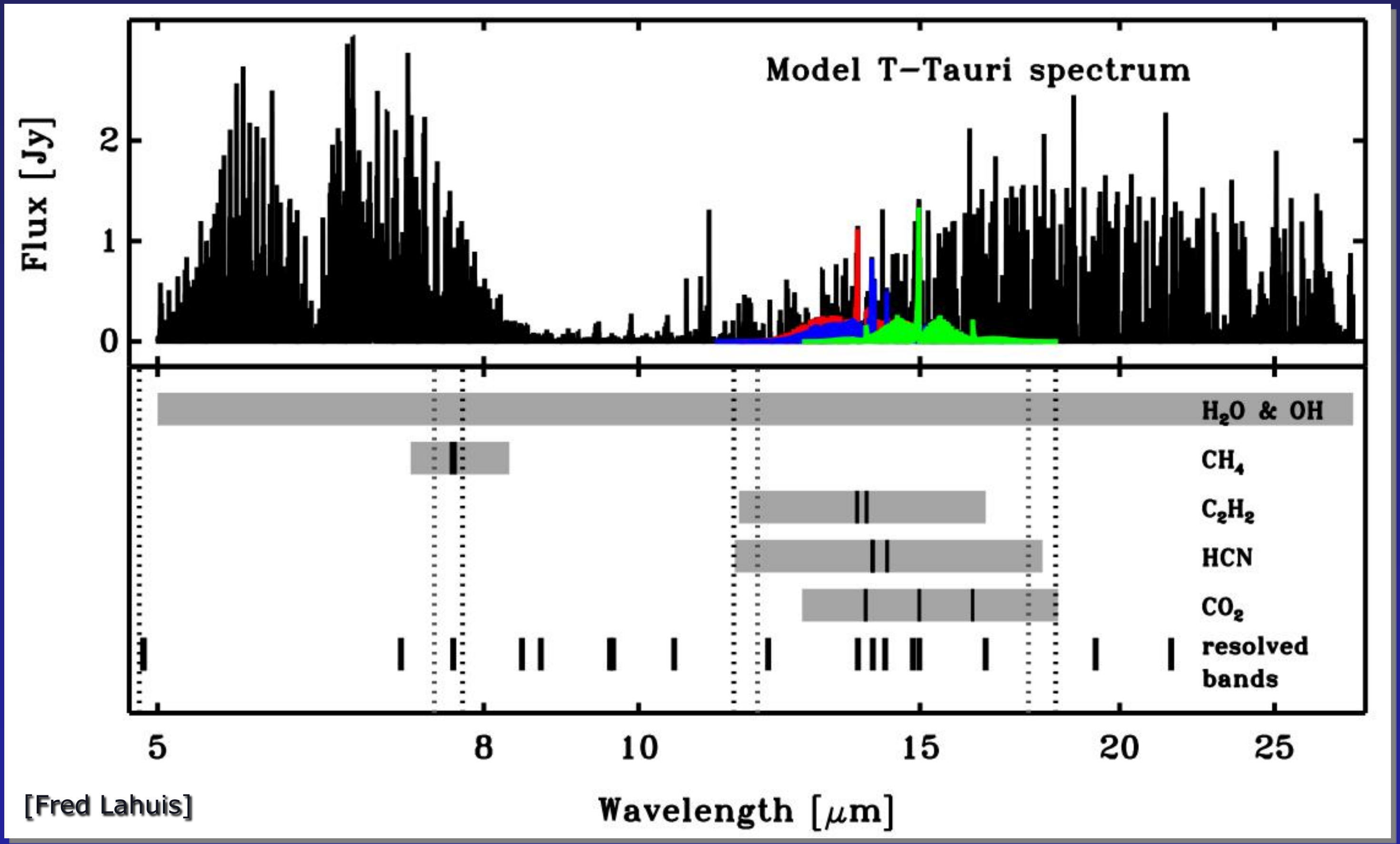
Large uncertainties in abundances due to LTE assumptions and low spectral resolution Spitzer

Abundance ratios:
Inner disk vs protostars vs comets



Carr & Najita 2008, 2011

Power of JWST-MIRI

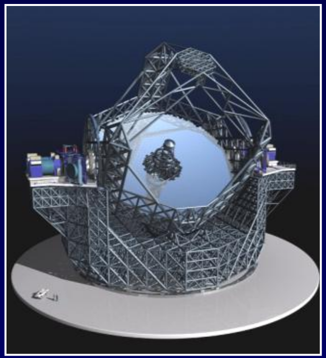


High spectral resolution (R=3000), high sensitivity, continuous λ coverage:

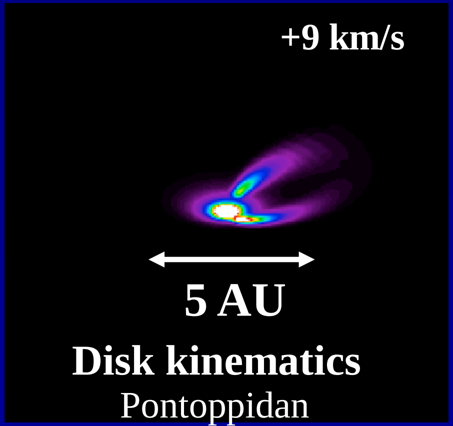
- **line-to-continuum ratio sufficient to detect minor species**
- **extend studies to faint brown dwarf disks (mJy @ 10μm)**

JWST-MIRI ⇔ ELT-midIR

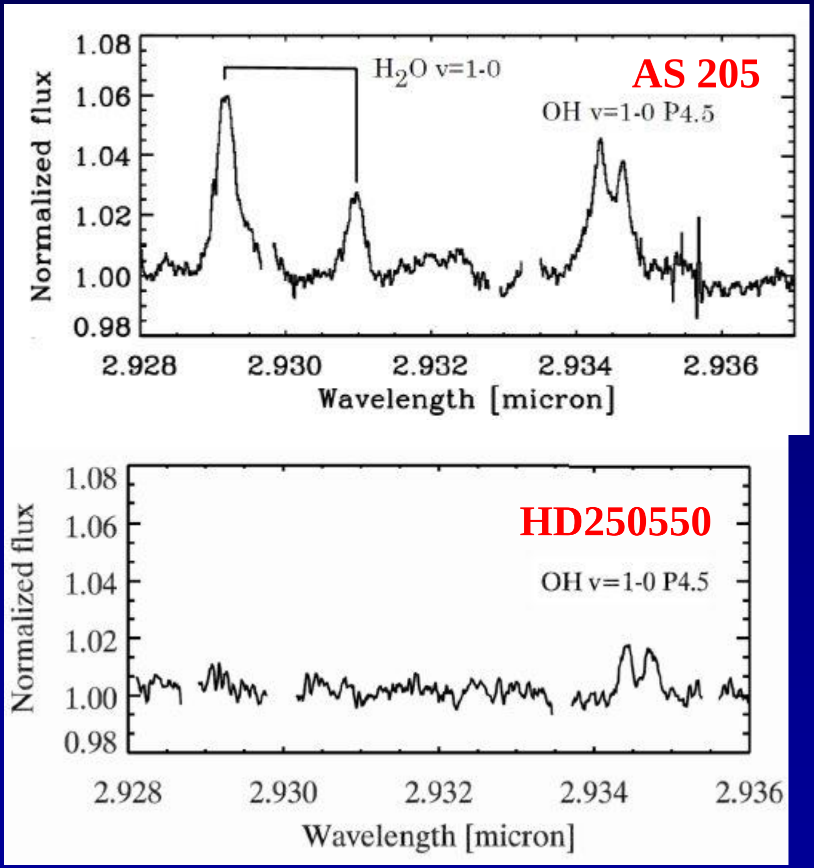
- continuous spectral coverage
- better spectro-photometric stability
- 100% sky coverage, good weather



- 5 – 8 times higher angular resolution
- high spectral resolution (kinematics!)
- comparable PS spectroscopic sensitivity



Herbig vs T Tau stars: H_2O vs OH in inner disk



M star
$OH/H_2O \sim 10^{-3}$

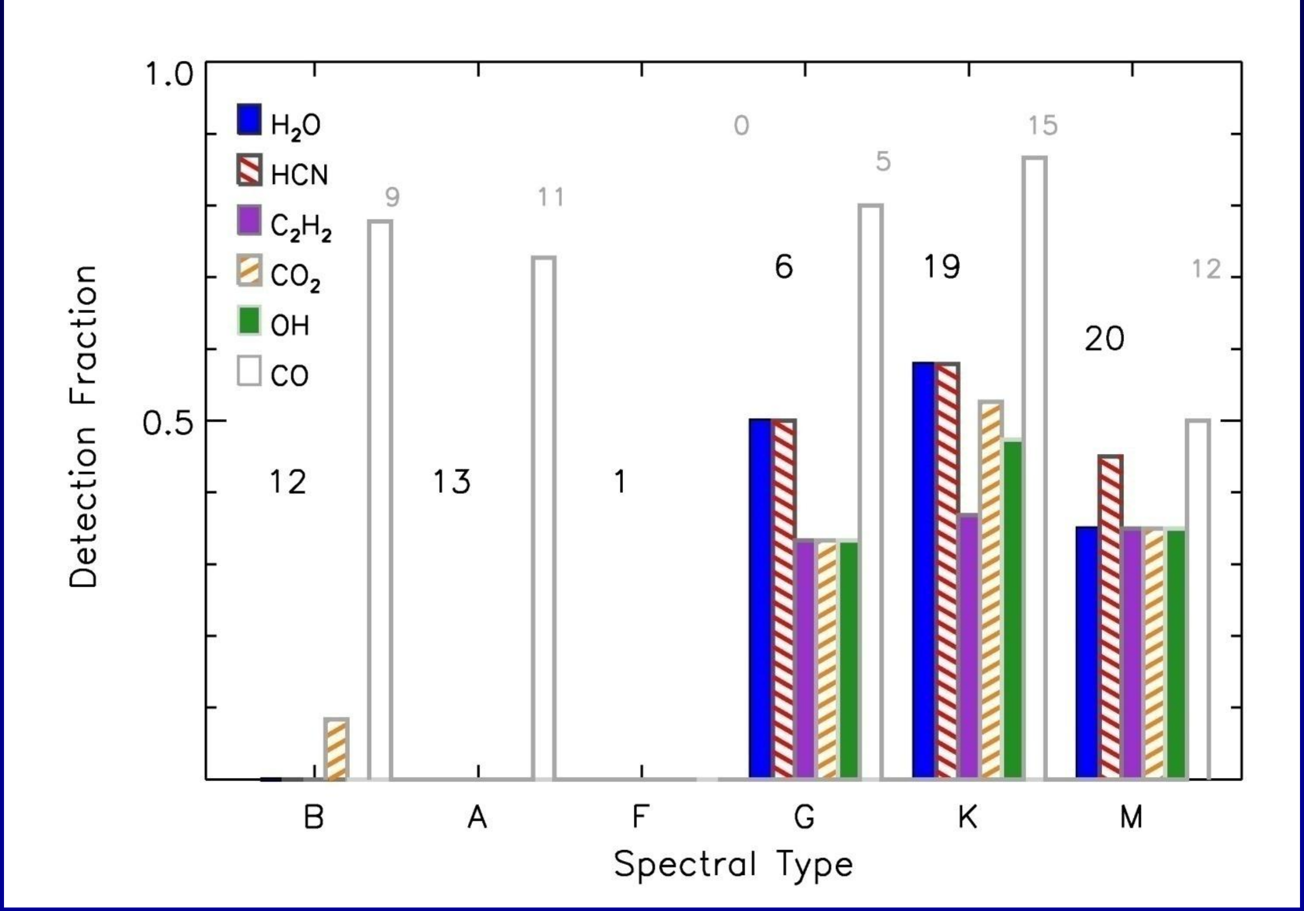
Salyk et al. 2008,2011, Pontoppidan et al. 2010

A star
$OH/H_2O = 1\text{-}30$

Fedele et al. 2011
Mandell et al. 2008

Water absent around A-type stars

Dependence on spectral type star

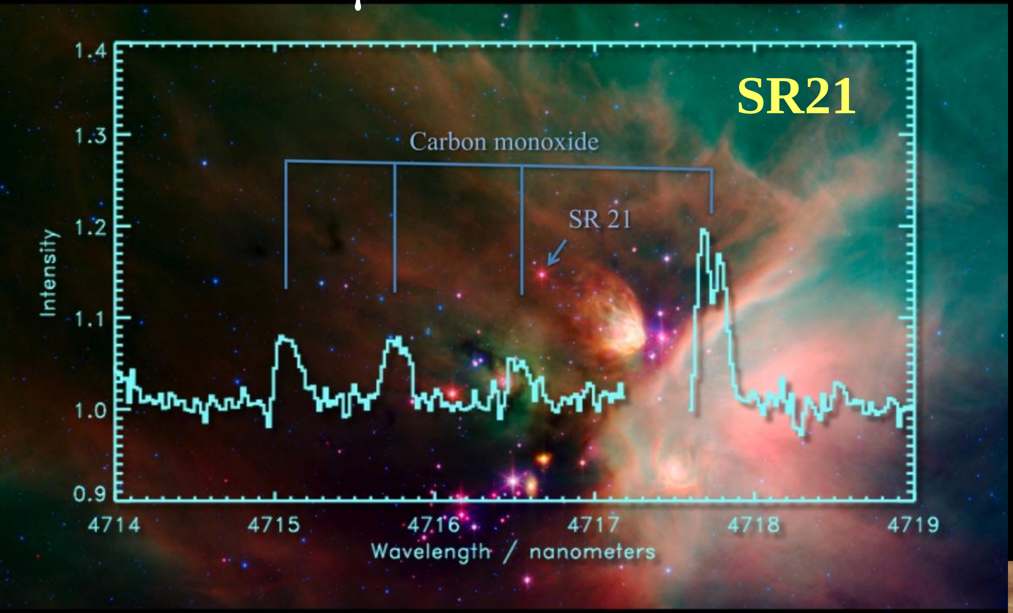


Pontoppidan et al.2010
Salyk et al. 2011
Carr & Najita 2011

- Water and organics detected for ~40-50% of T Tauri stars (M-G)
- Only CO and some OH, CO_2 detected for Herbig stars (F-B)

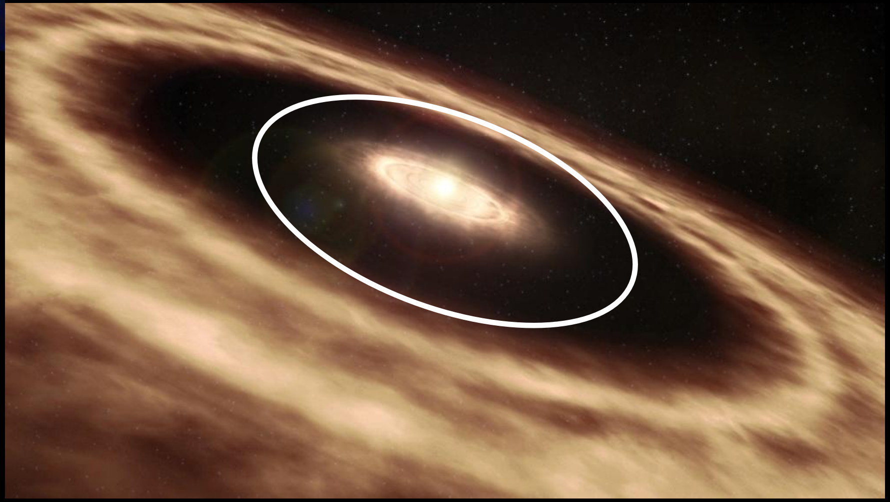
Few molecules in transitional disks

CO 4.7 μm v=1-0 VLT-CRIRES



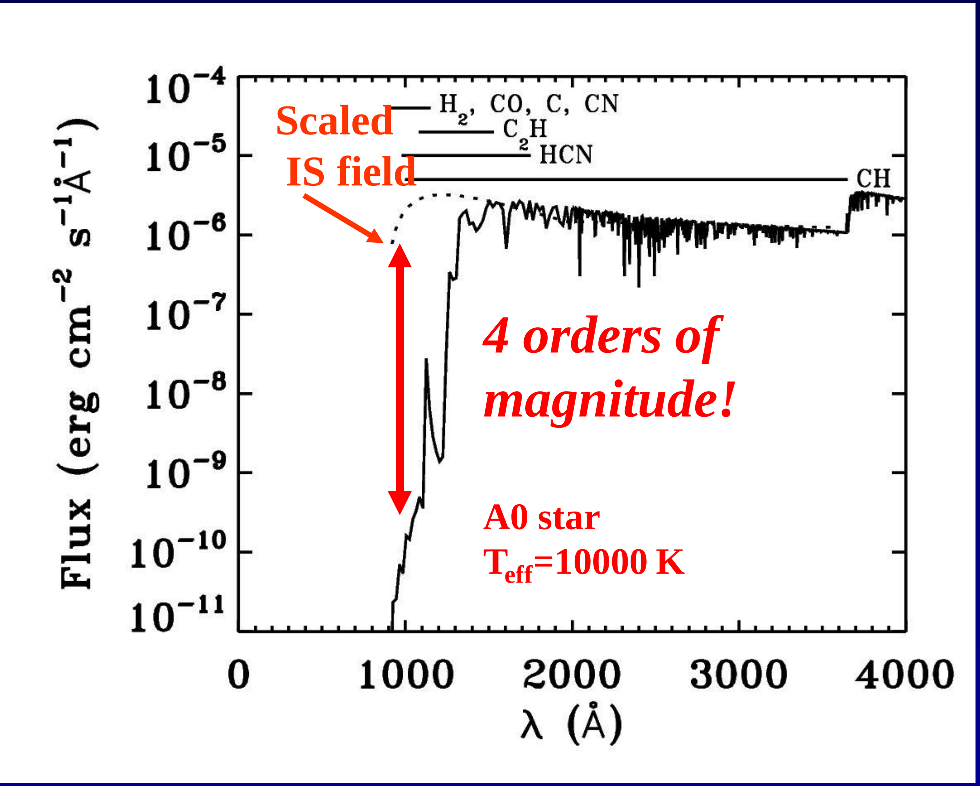
- **SR 21 disk has dust gap of ~20 AU, perhaps due to forming planet**
  Brown et al. 2007

- **Spectroastrometry of near-IR lines allows to pinpoint location to 7±1 AU ⇒ well inside gap!**
  Pontoppidan et al. 2008



CO readily detected but no other molecules seen in midIR spectra transitional disks

Herbig vs T Tau stars:
Importance of strength and shape UV field



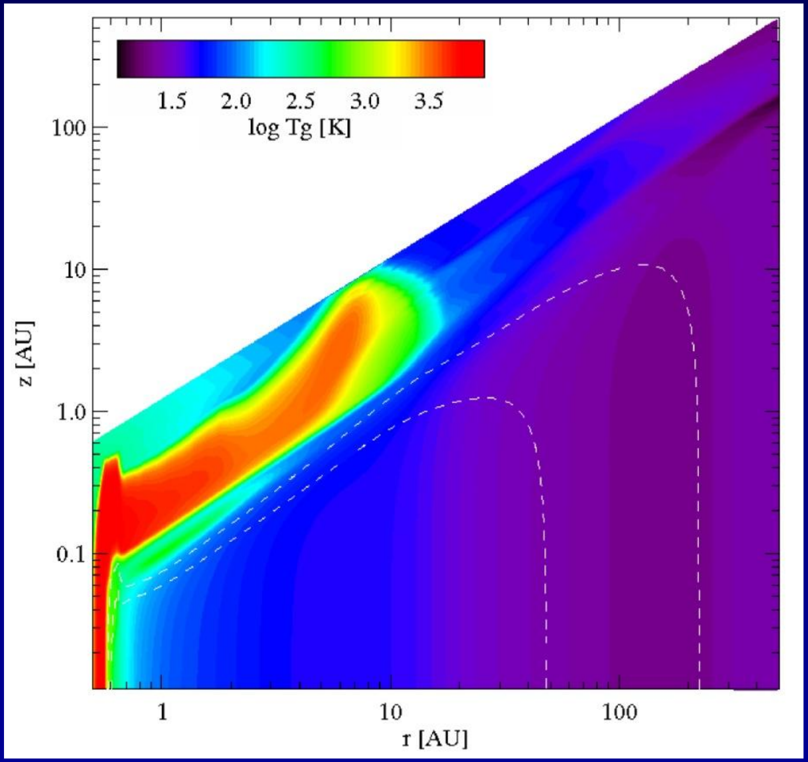
vD et al. 2006
Bergin et al. 2003

- Far UV field orders of magnitude larger for A vs M star
- Accretion can boost UV for T Tau star by orders of magnitude (+Ly α!)
- Photodissociation sensitive to wavelength

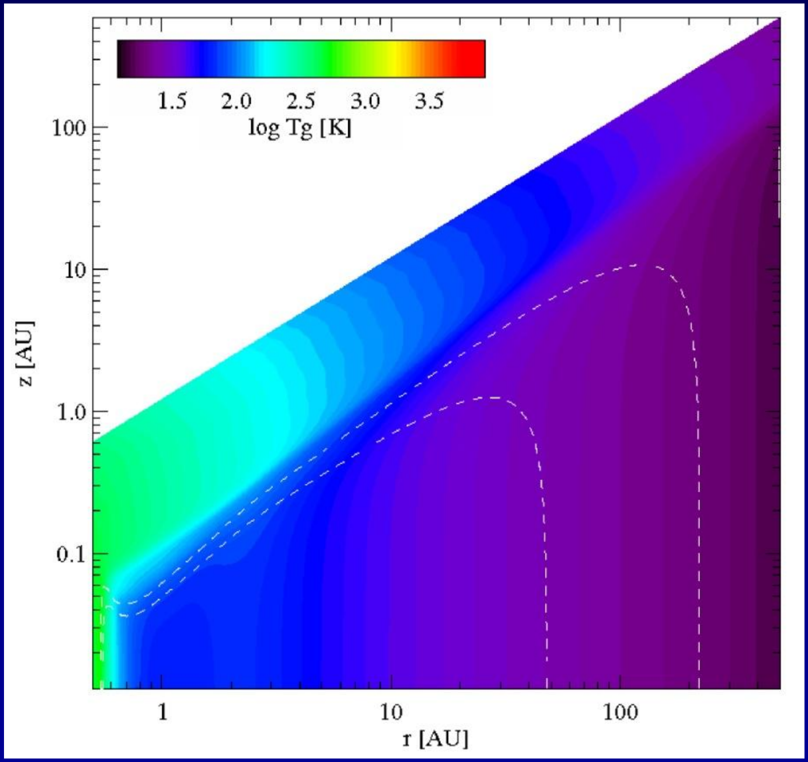
FUV heats gas in surface layers

T-Tauri star+ disk

T gas computed



T gas = T dust



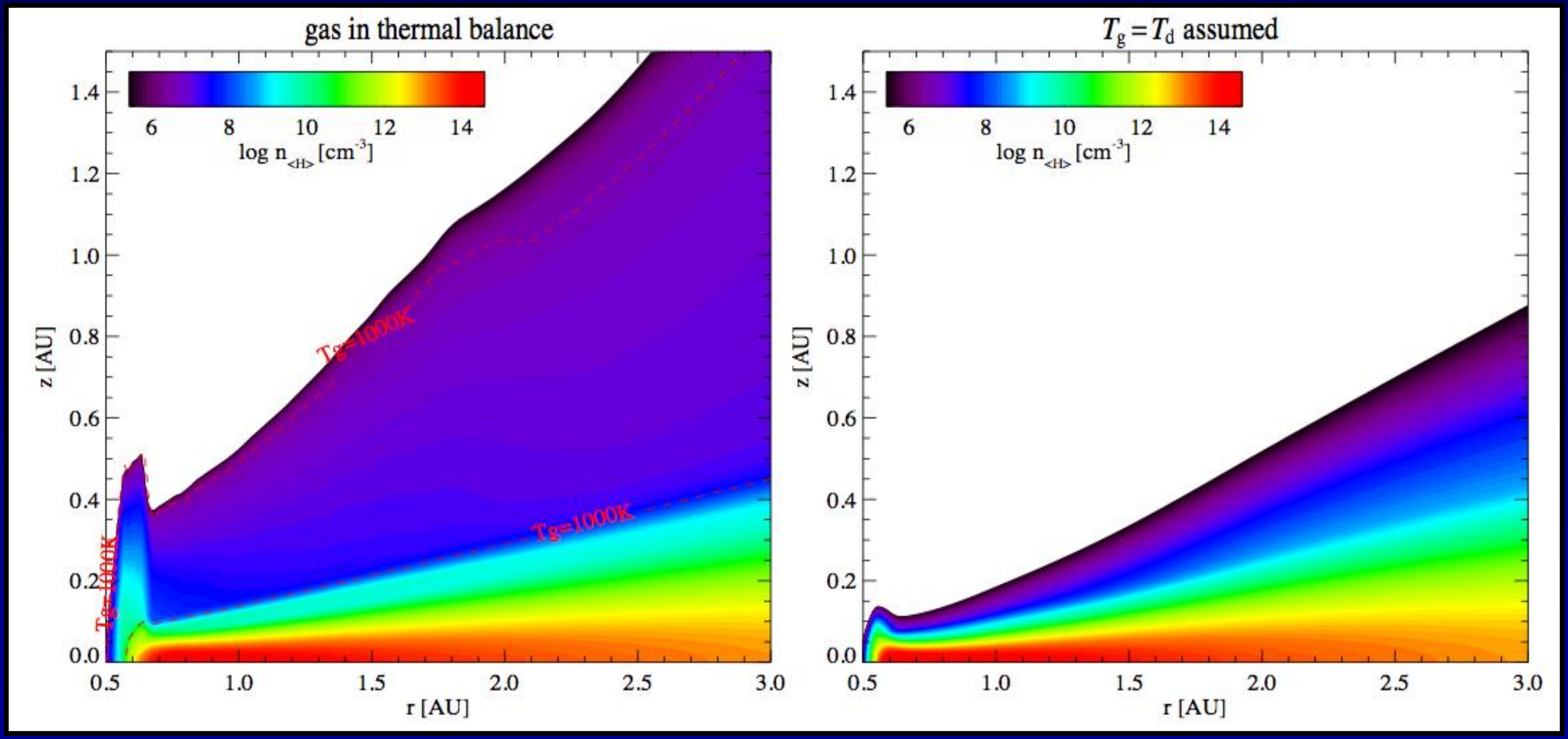
ProDiMo: Woitke, Kamp & Thi 2009

High gas temperatures result in flaring disk; affect chemistry and dynamics

Also: Jonkheid et al. 2004, 2007, Kamp & Dullemond 2004, Gorti & Hollenbach 2004, 2005, 2009 Nomura & Millar 2005, Aikawa&Nomura 2006, Glassgold et al. 2009,Woitke et al. 2009, ...

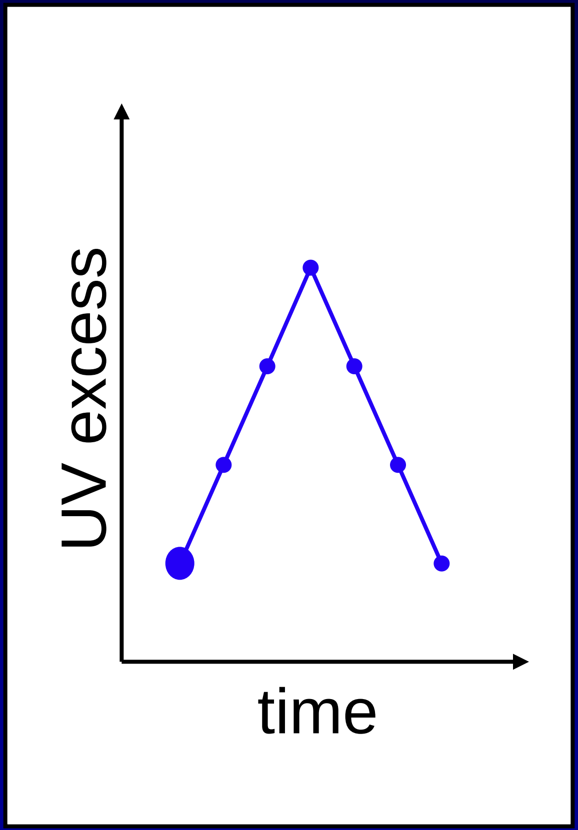
High temperatures cause strong disk flaring and photoevaporation

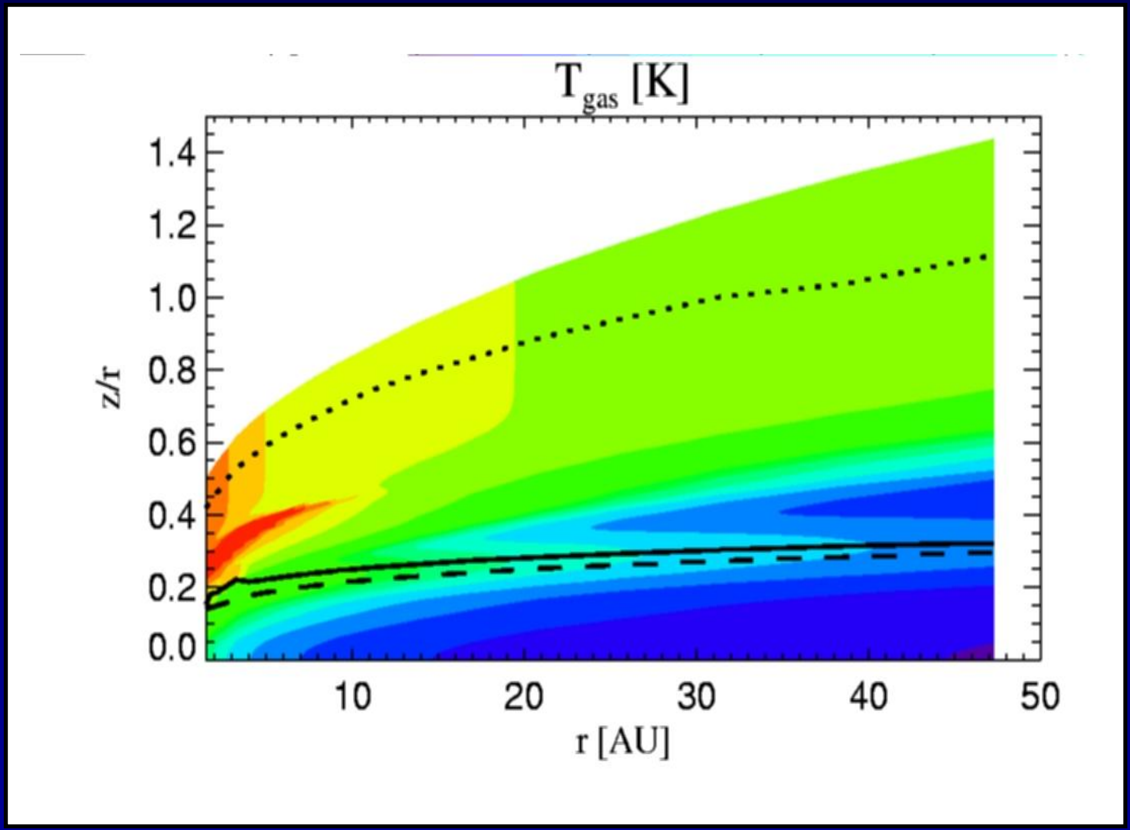
Density structure

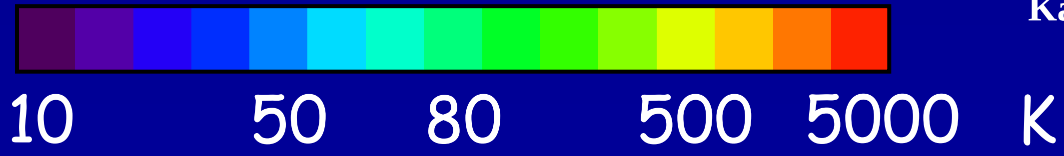


Woitke et al. 2009

Impact of UV irradiation



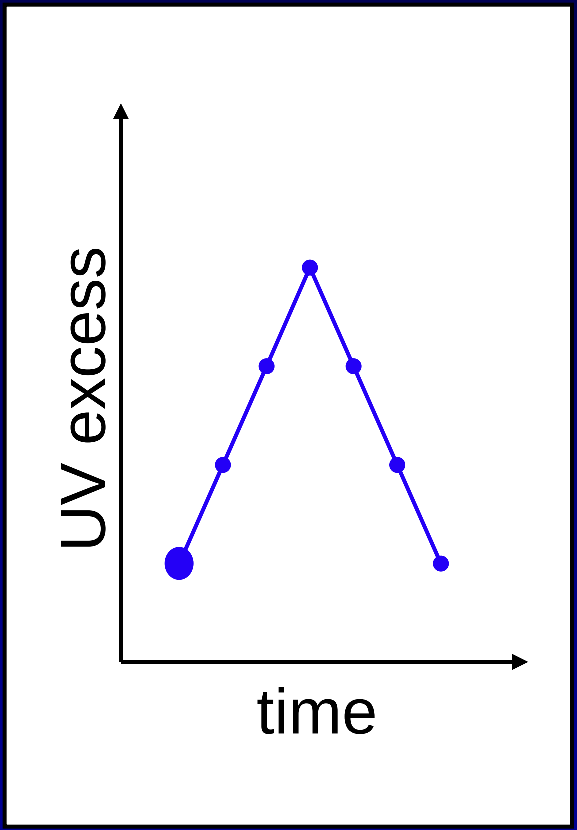


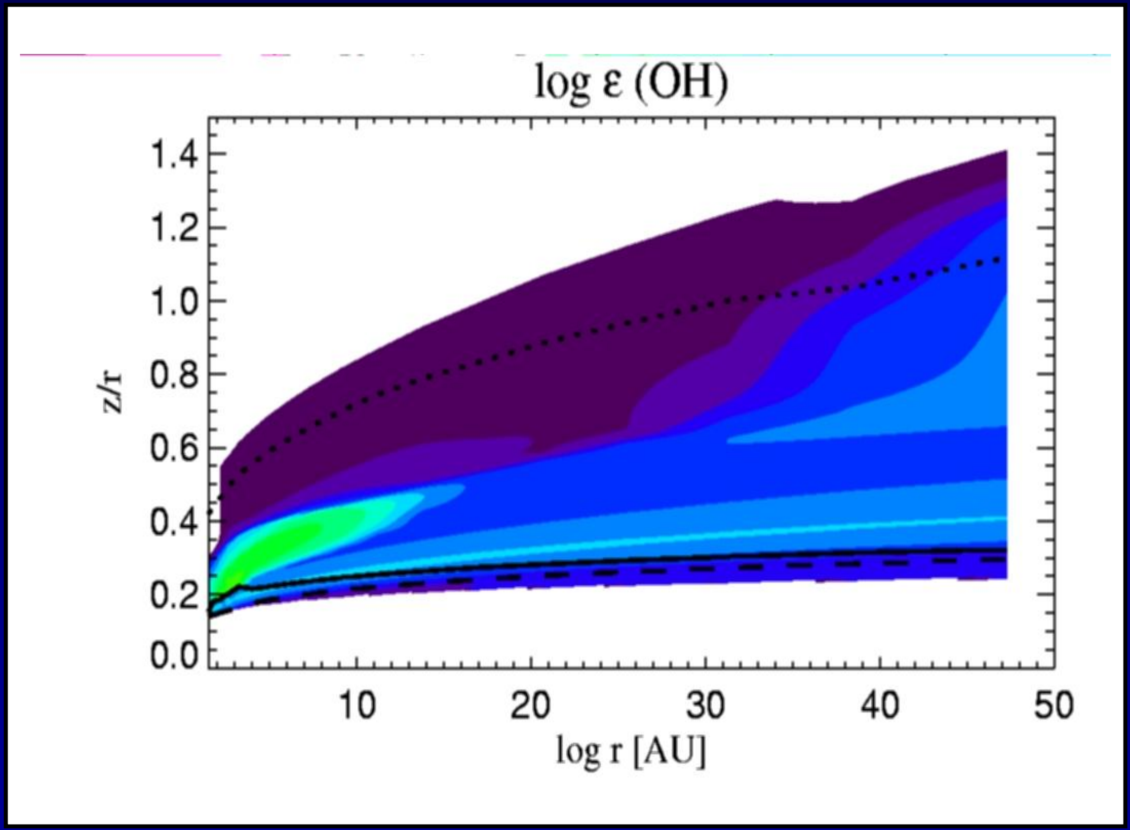


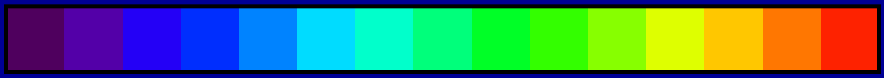
Kamp et al., in prep

Shape **of radiation field also important for chemistry, especially <1100 Å**

Impact of UV irradiation: OH







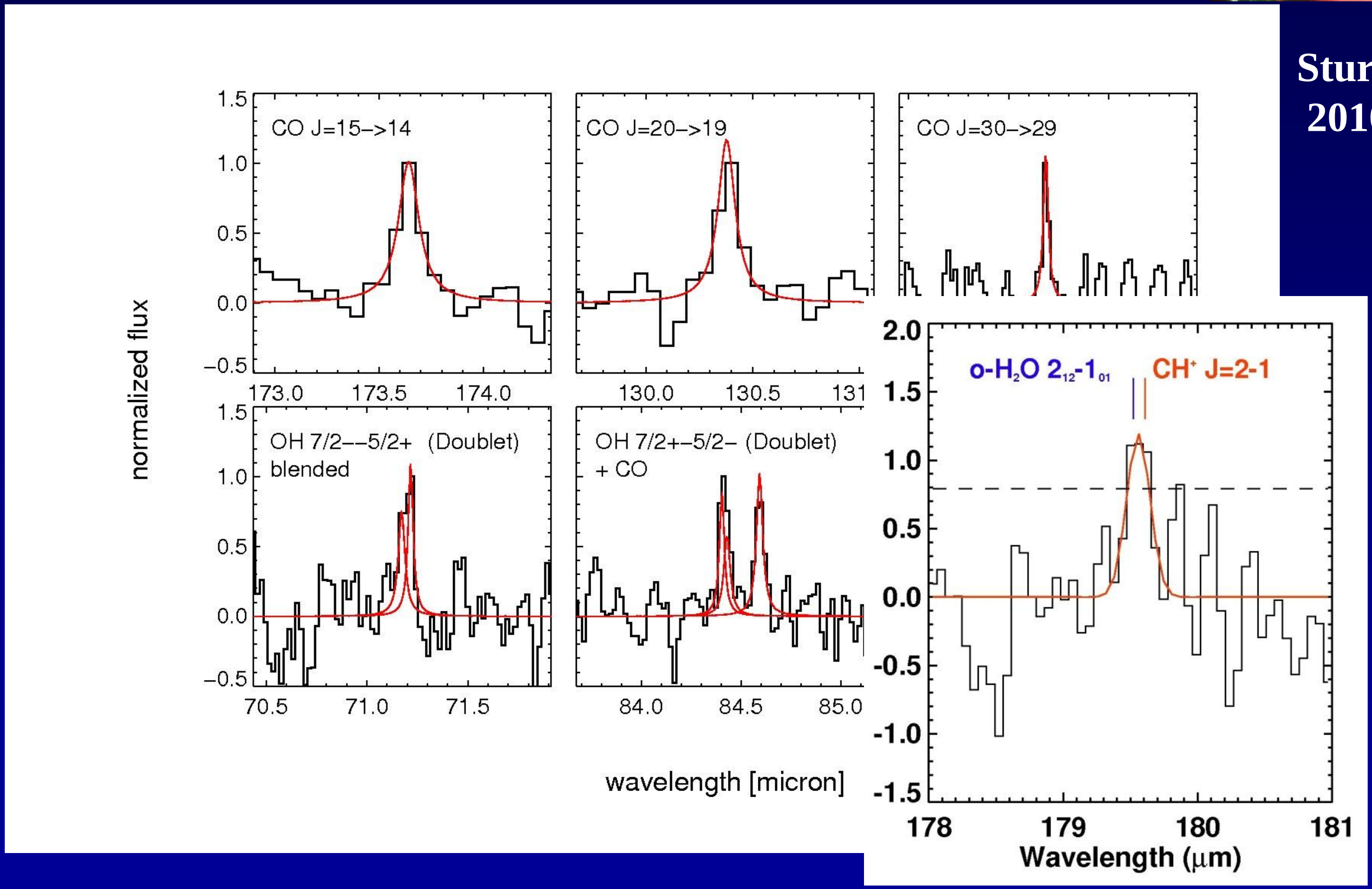
Kamp et al., in prep.

$O + H_2 \rightarrow OH + H$ at high T

$H_2O + h\nu \rightarrow OH + H$

Hot CO in disk surface

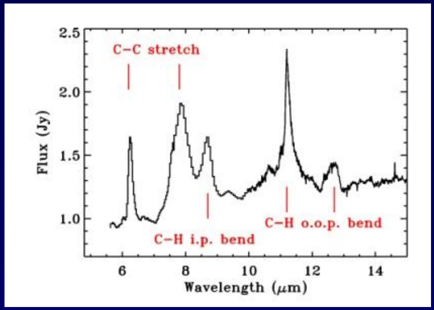
HD 100546 disk (B9.5): Herschel-PACS (~10-50 AU)

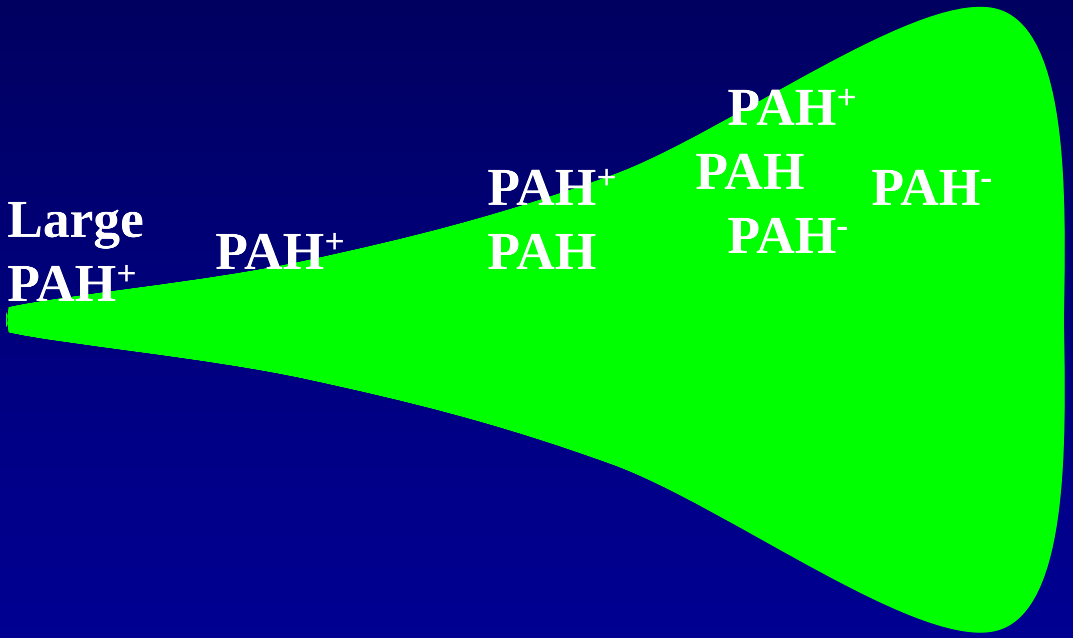


Sturm et al. 2010

- Hot CO well reproduced by thermo-chemical models (Bruderer et al.)
- CH^+, no (?) H_2O detected (Thi et al. 2011)

PAHs in disks





LePage et al. 2001
Habart et al. 2004
Visser et al. 2007

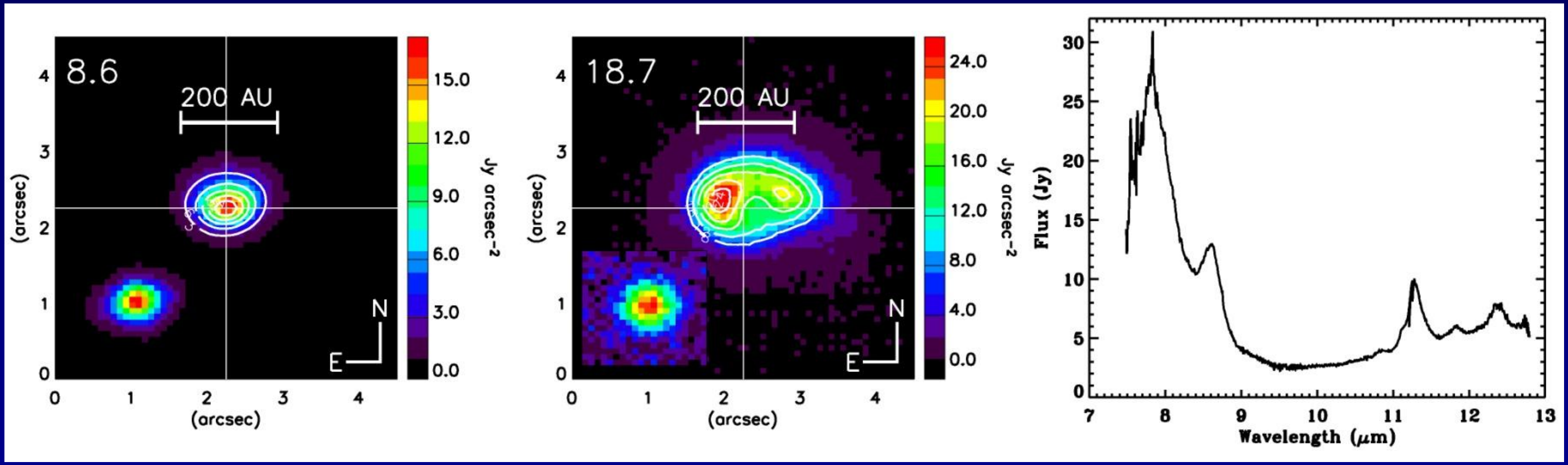
- Only 8-11% of T Tauri stars show PAHs features vs ~70% Herbig stars
- Abundance PAHs is factor 10-100 lower than in ISM
- Only large PAHs (N_C>80) can survive in inner disk Herbig stars
- Freeze-out/coagulation starts in cold core and embedded phase

Geers et al. 2006, 2007, 2008; Oliveira et al. 2010, Acke et al. 2010

PAHs inside disk gaps

8.6 PAH

18.7 μm large grains



IRS48
A star

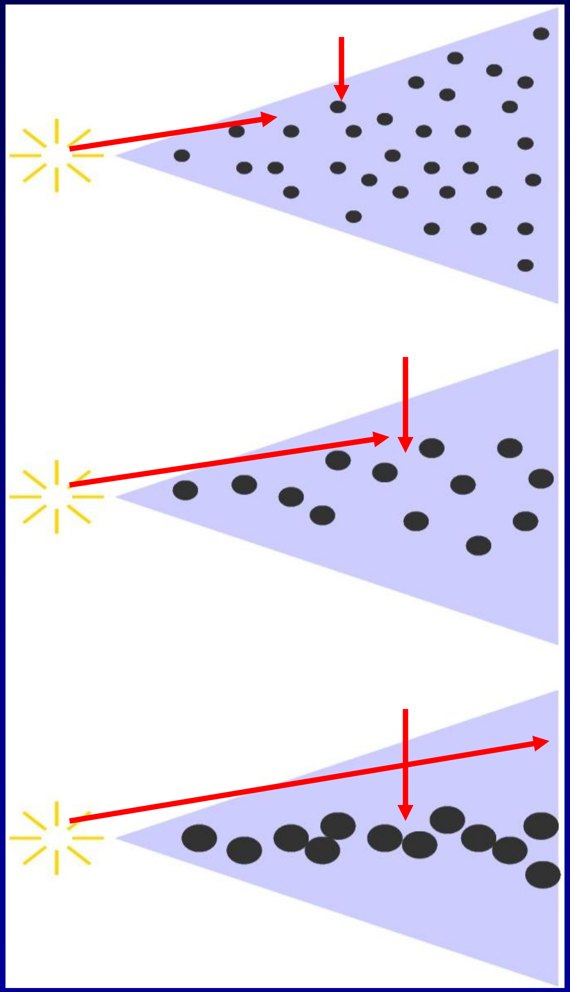
VLT VISIR image and spectrum

- Gap seen in large grains, but NOT in PAHs

Geers et al. 2007

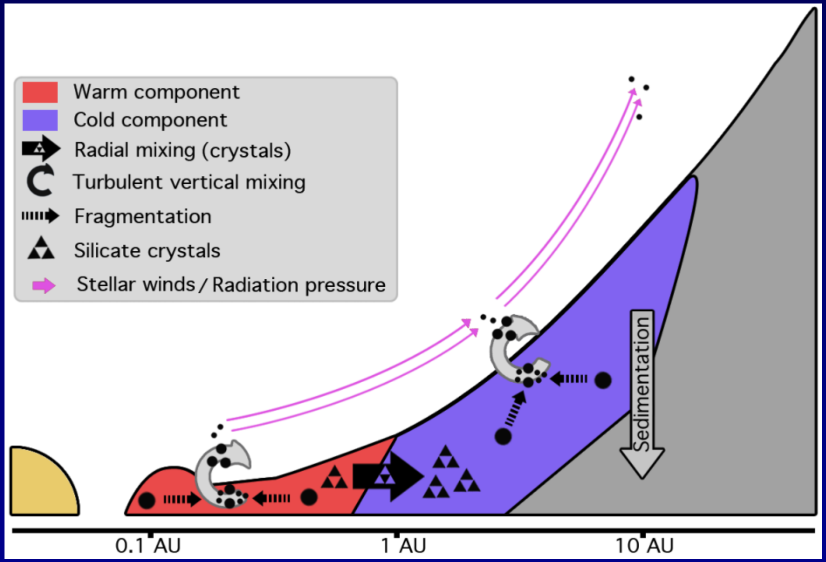
Importance of grain growth + settling

- Disk evolution
  - Grain growth + settling
  - Mass loss
- Much deeper penetration of UV
  - Enhances photodissociation and photodesorption
  - Heats gas deeper into disk

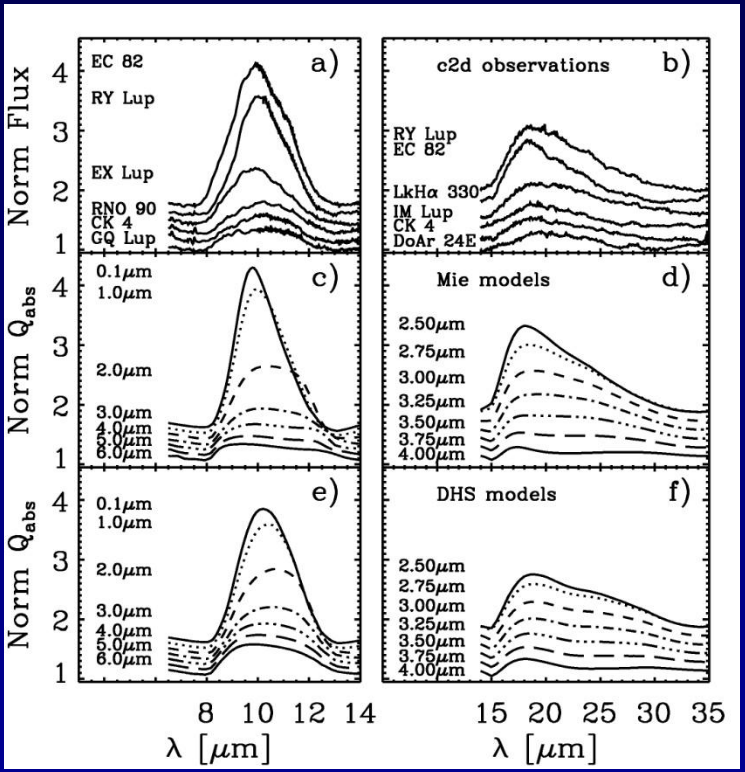


Jonkheid et al. 2004, 2007
Aikawa & Nomura 2006
Vasyunin et al. 2010, …

Dust processing in inner disk



Olofsson et al. 2010
Oliveira et al. 2010, 2011
Sturm et al. 2010 Herschel



Kessler-Silacci et al. 2006

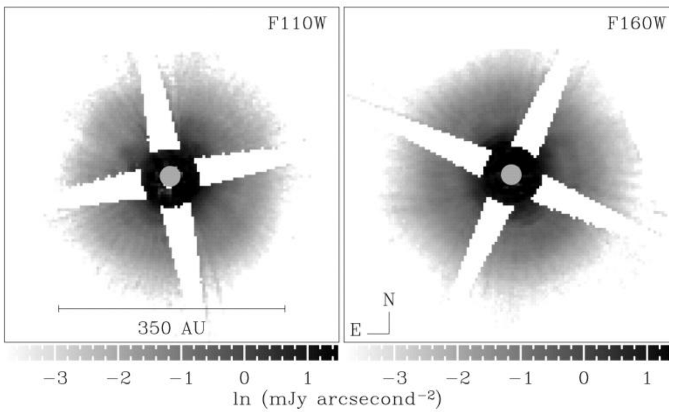
Also:
Van Boekel et al. 2004, 2005
Furlan et al. 2006
Bouwman et al. 2008
Watson et al. 2009
Juhasz et al. 2010

- Grains grow to μm size in surface layers inner disk
- Continuous balance between growth and destruction
- Crystallinity around 10-20% independent of 'age' during protoplanetary disk phase

Simple molecules in outer disk

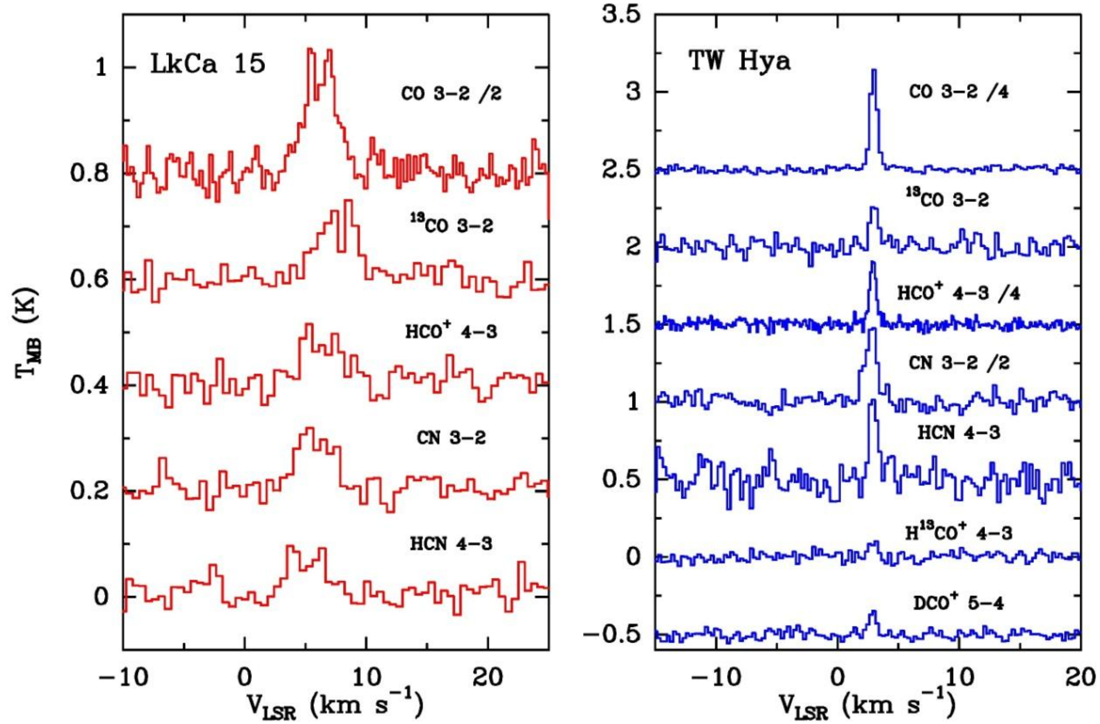
TW Hya face-on disk

1.1 μm **1.6 μm**



Scattered light => radius 200 AU

Weinberger et al. 2002



- **Simple molecules detected, including deuterated species**
- **Evidence for ion-molecule chemistry (HCO^+) and photodissociation (CN)**
- **Instruments do not yet have sensitivity to search for complex molecules**

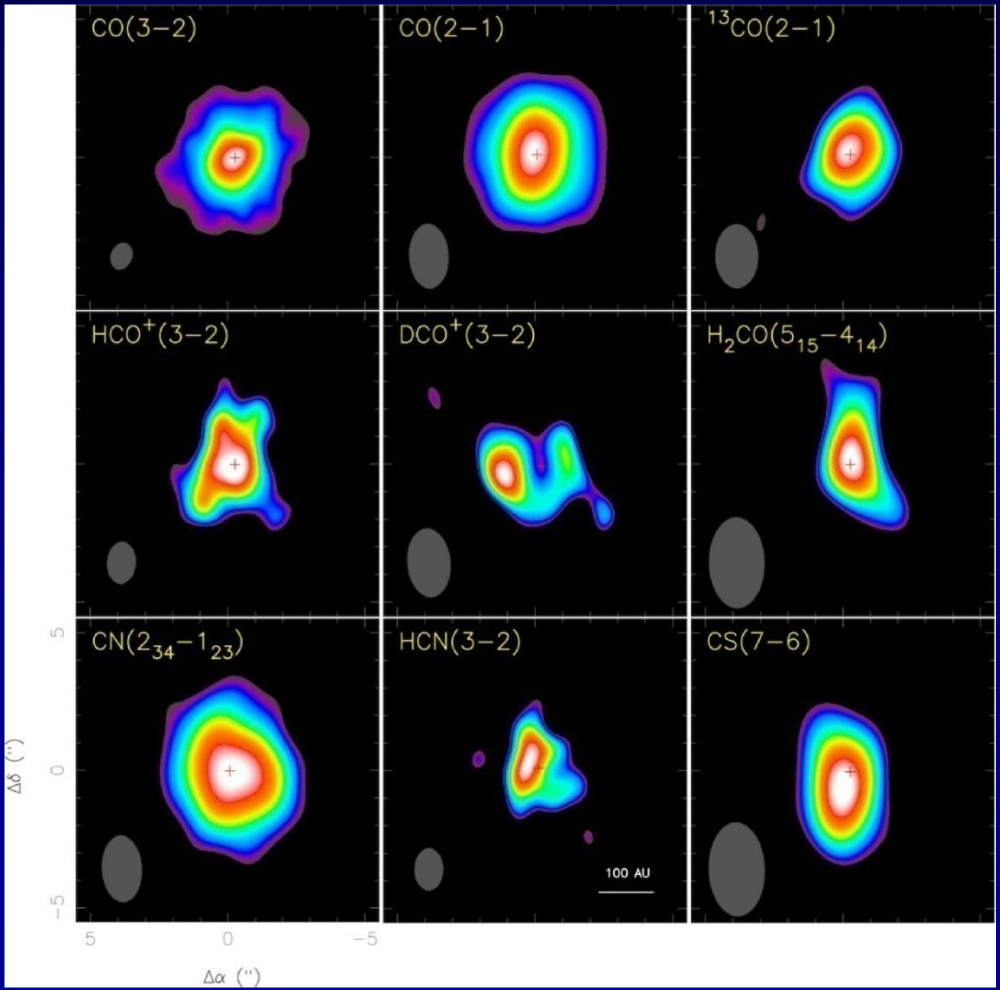
Kastner et al. 1997, Dutrey et al. 1997,
Pietu et al., Henning et al., Öberg et al. 2010, ...

Thi et al. 2004

Starting to image outer disk chemistry

TW Hya disk

ALMA CSV
data by June!

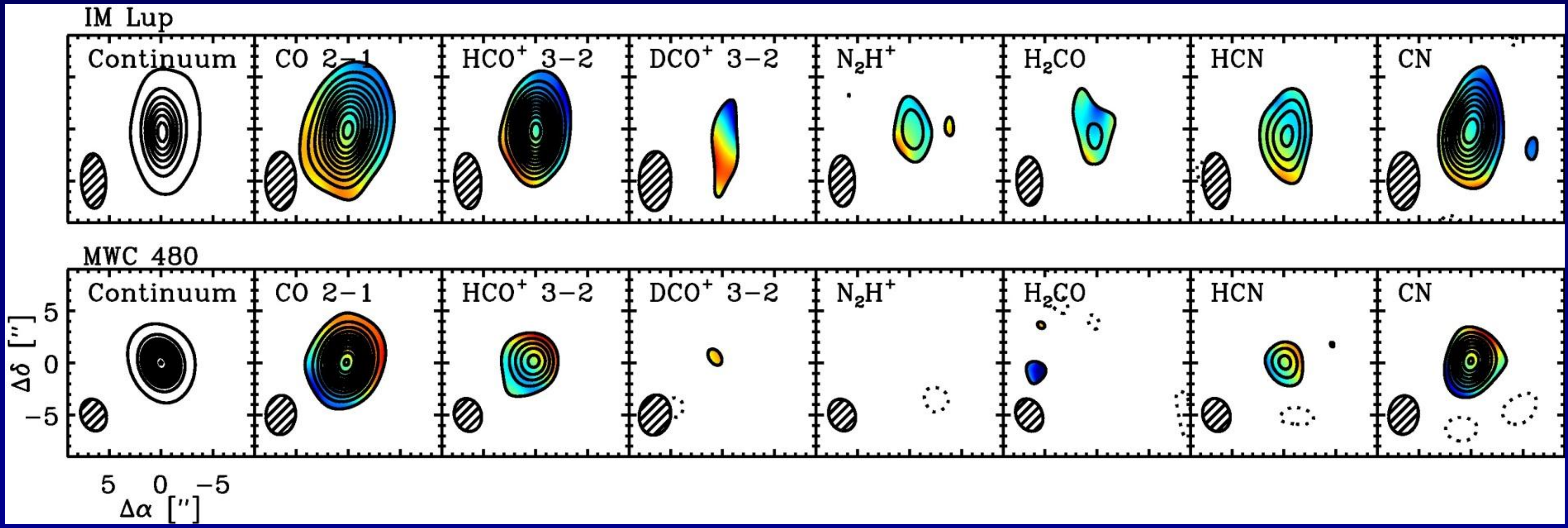


Qi et al.,
SMA data
Williams & Cieza 2011

Molecules have different spatial distributions,
related to chemistry and excitation

Herbig vs T Tau stars

DISCS SMA survey



M star

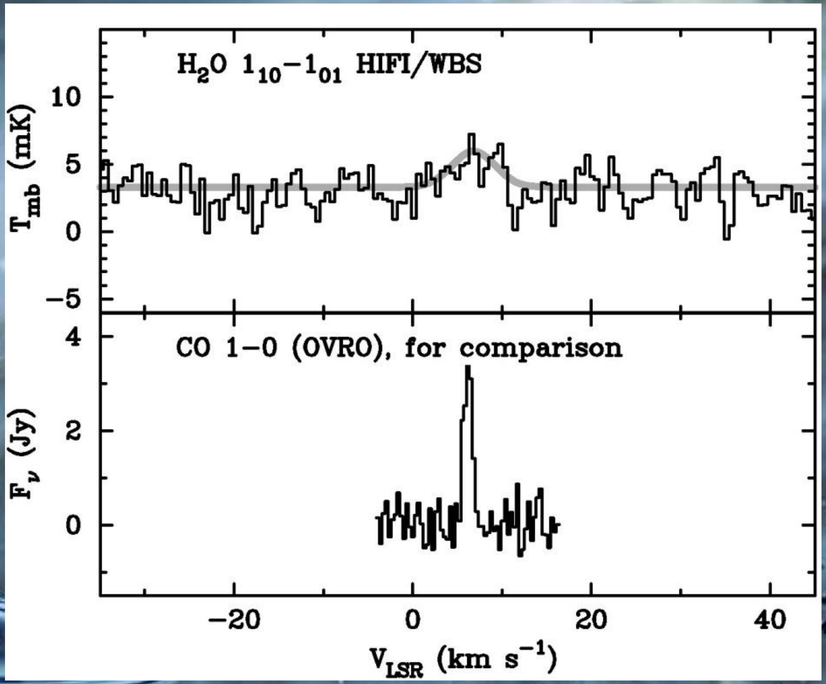
A star

- Absence of most molecules around A stars
- No detection of molecules more complex than H_2CO

Öberg et al. 2010, 2011

Probing the cool water reservoir with Herschel

limit few mK:
disk averaged
H_2O abundance
few x 10^{-10}

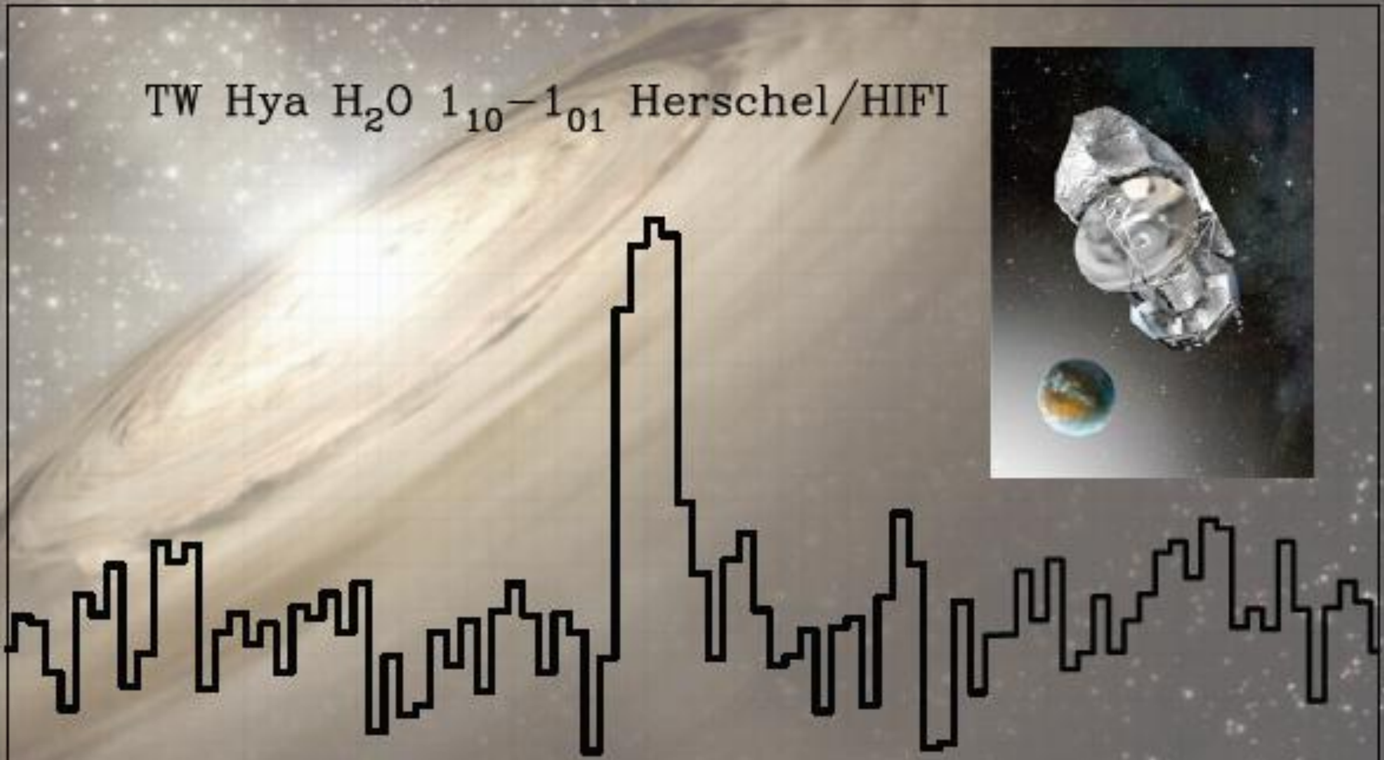


- Low limits indicate that icy grains have grown and settled to the disk midplane (⇒ assist planet formation)
- Grains in upper disk layers are 'dry' (bare silicates)

Bergin, Hogerheijde
+ WISH team 2010

-If icy rocks big enough, can sequester O in outer disk?

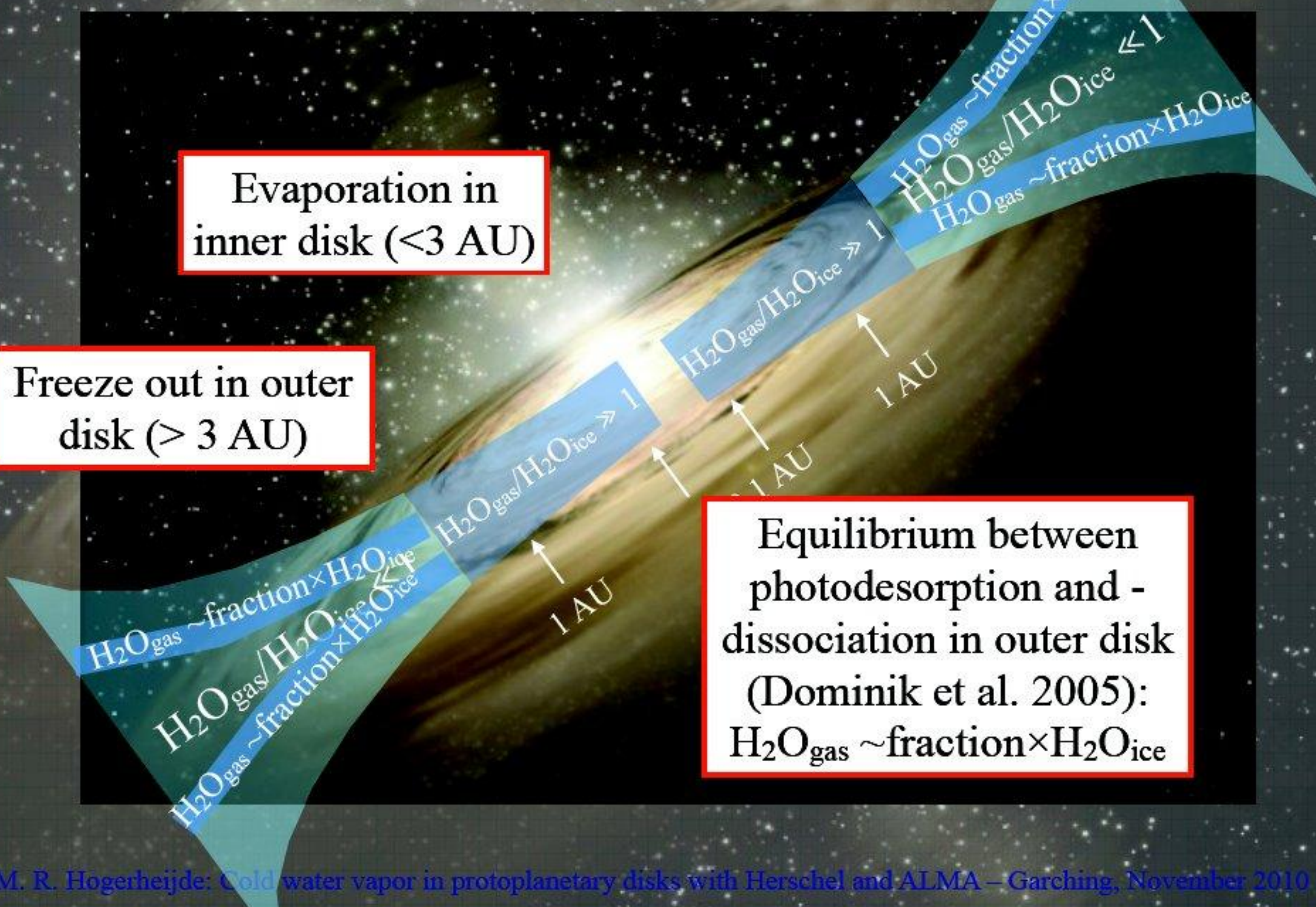
Clear detection in TW Hya!



Measures ice reservoir in outer disk

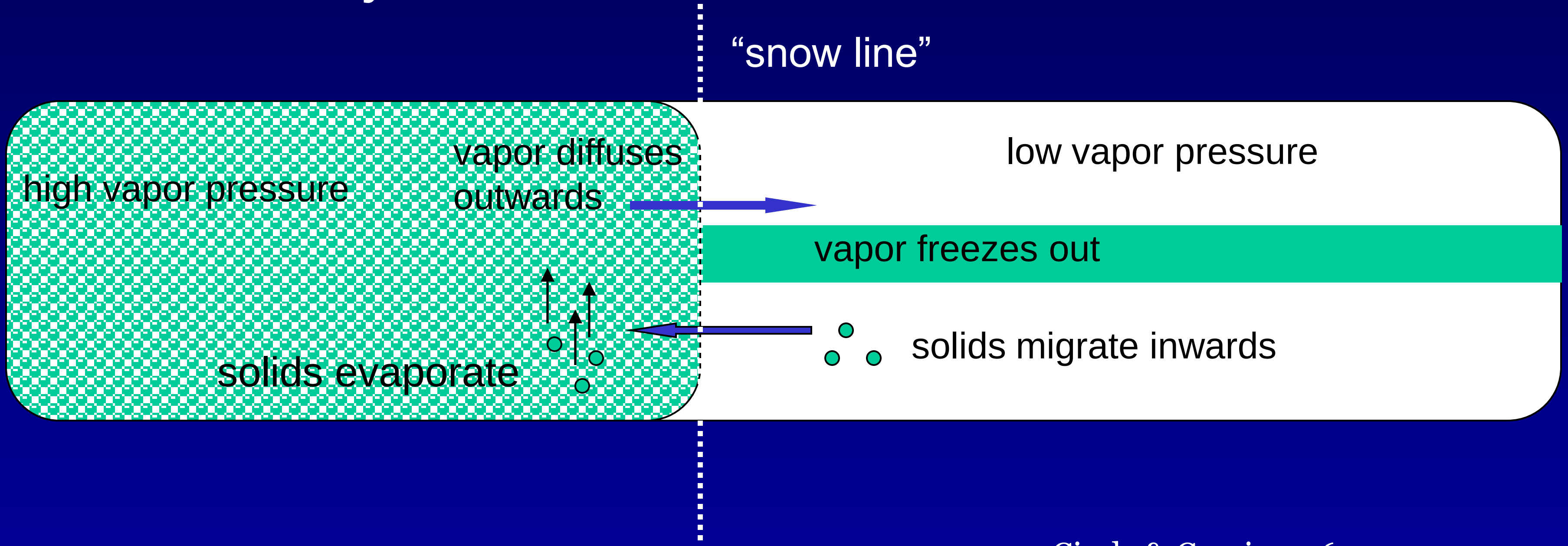
Hogerheijde et al. 2011

The chemistry of water in disks



Does water vapor trace dynamical processes?

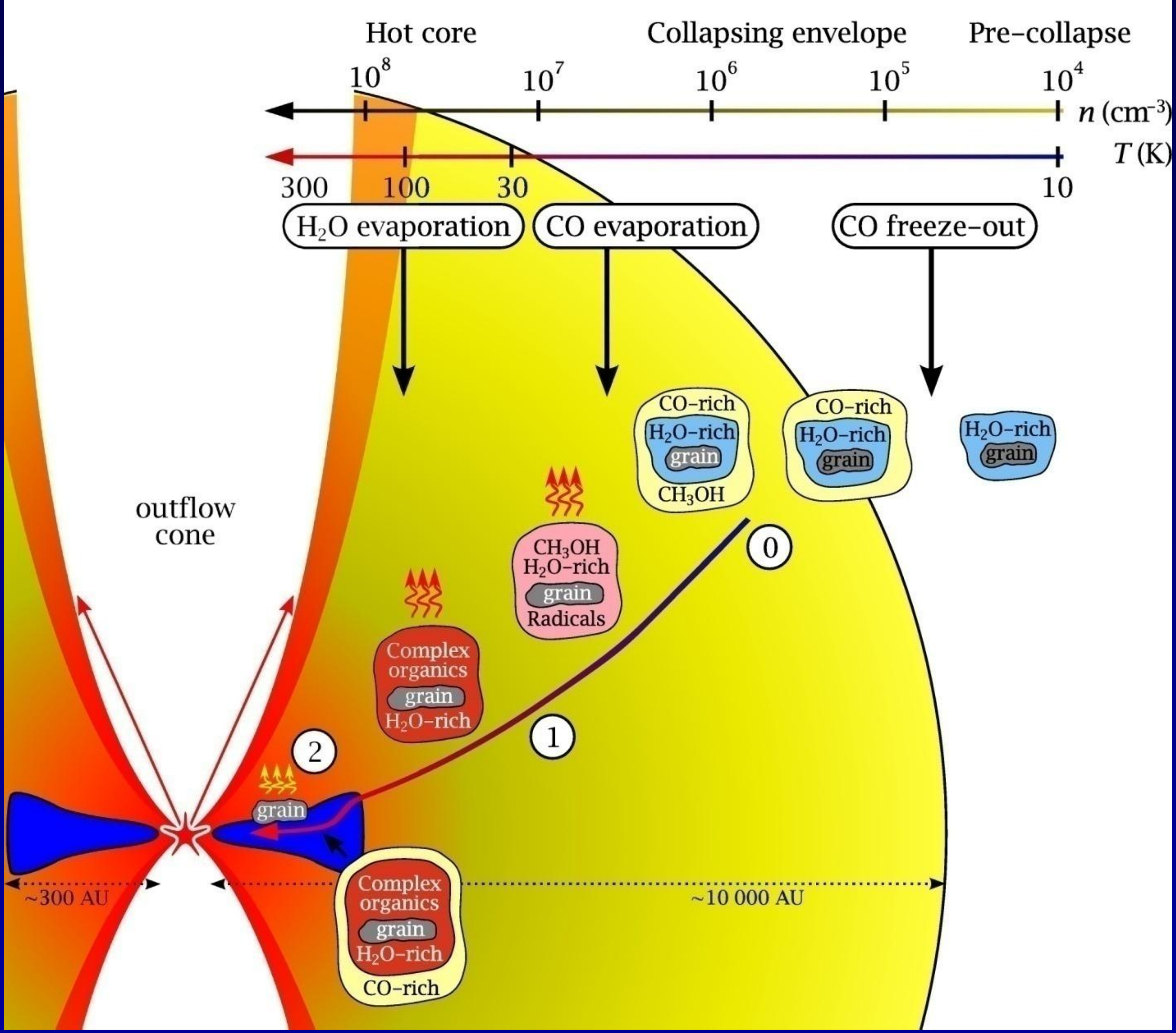
Water vapor contents may be set by a balance between vapor diffusion and icy planetesimal migration, both radially and vertically



Ciesla & Cuzzi 2006

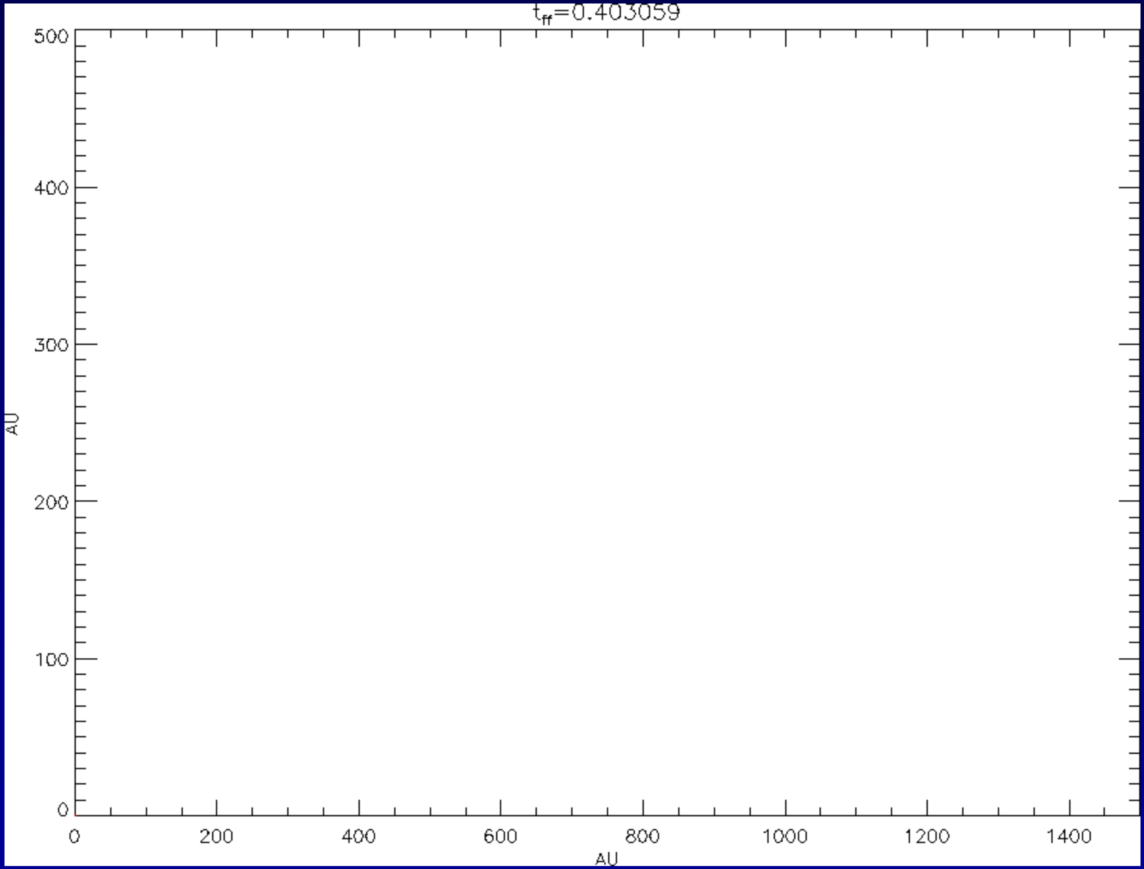
- Other (non-dynamical) processes may control H_2O and organics as well

The big picture



Visser et al. 2009, 2011

2D Disk formation



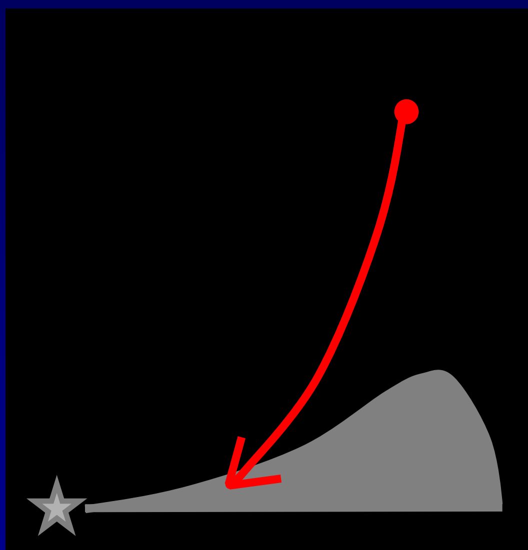
Numerical:
Van Weeren , Brinch & Hogerheijde 2008

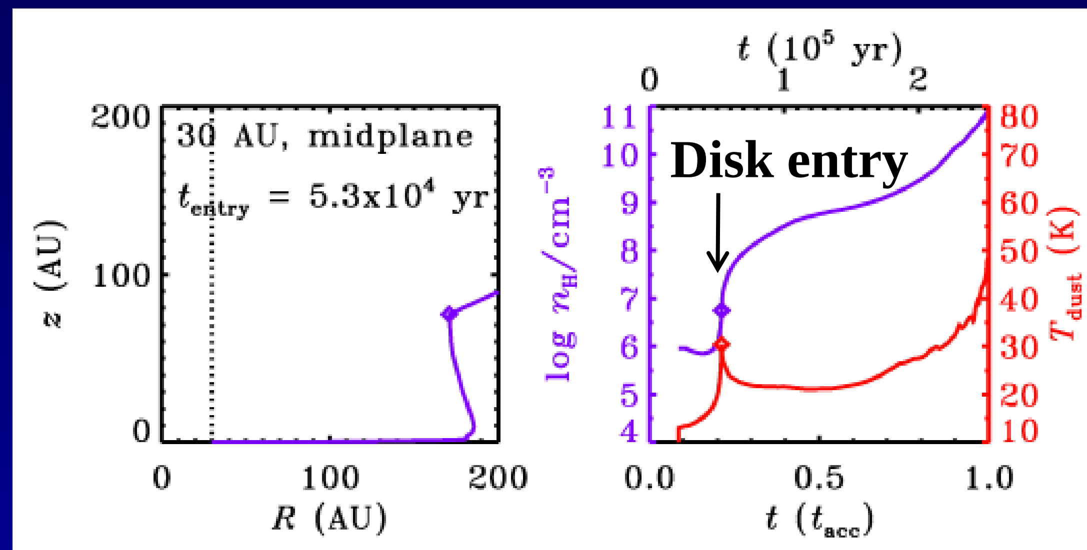
Semi-analytic:
Visser et al. 2009
Visser & Dullemond 2010

- **Accretion onto 2D disk fundamentally different from 1D**
- **More material enters disk on back side, far from star**
- **Layered accretion: outer envelope parcels end up in surface layer disk**

Follow infalling parcels

- **Need to solve chemistry dynamically along many trajectories with changing *n*, *T***





Visser et al. 2009, 2011

- **Jump in *n*, *T* upon entering disk**
- **Strongly-bound ices (H_2O) survive, weakly-bound ices (CO) desorb and re-adsorb**

→ Material that ends up in planet-forming zones is partially preserved, partially processed

Conclusions

- Enormous observational progress thanks to Spitzer, Herschel, ground based IR + mm
  - Structure of protoplanetary disks
  - Gas in surface layers of disks from <1 to >100 AU
  - Chemistry and dynamics in inner disk
    - Need JWST, ELTs for higher sensitivity and resolution
- High expectations for ALMA
  - Will image molecules to the midplane down to ~10 AU
- Freeze-out, desorption, UV and high *T* determine composition
- Early evolution during embedded phase important for outcome planetary system
- Material in planet-forming zones is likely a mix of original cloud ice and highly-processed material

ALMA

Proposal deadline June 30! **Chile 5000 m**