Interstellar molecules: from cores to disks

Ewine F. van Dishoeck

Leiden Observatory

Thanks to the c2d and DIGIT teams and many others

and i.p. our PhD students!

April 25, 2013

Nealfest, Austin, TX

My first entry into astrochemistry

IAU Symposium 87 Interstellar Molecules

1980

PHYSICAL AND DYNAMICAL CONDITIONS IN INTERSTELLAR CLOUDS

Neal J. Evans II
The University of Texas at Austin

1. INTRODUCTION

The most far-reaching result to come from the study of inters
molecules has been the recognition of a new class of galactic stru
molecular clouds. These clouds appear to contain most of the mass

Infrared vs submillimeter

- **Submillimeter:**
  - Very high spectral resolution ($R > 10^6$, <0.1 km/s)
  - Many gas-phase molecules with abundances down to 10^{-11} w.r.t. H_2
  - Emission => map of region
- **Infrared:**
  - Moderate spectral resolution ($R \sim 10^3 - 10^4$)
  - Gases *and* solids with abundances down to 10^{-7}-10^{-8} w.r.t. H_2
    - Probe major reservoirs of C, N and O
  - Molecules without permanent dipole moments (H_2, C_2H_2, CH_4, CO_2, …)
  - Absorption => pencil beam line-of-sight; also emission

Evans, Lacy et al. 1991
van Dishoeck 2004

Low density PDRs

THE ASTROPHYSICAL JOURNAL, 568:242–258, 2002 March 20

ISO

PHOTON-DOMINATED REGIONS IN LOW-ULTRAVIOLET FIELDS: A STUDY OF THE PERIPHERAL REGION OF L1204/S140

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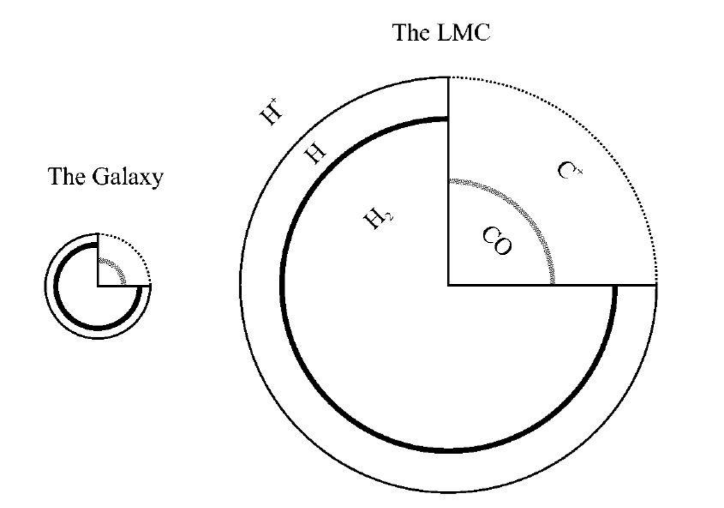
Received 2001 September 1; accepted 2001 November 28

ABSTRACT

We have carried out an in-depth study of the peripheral region of the molecular cloud L1204/S140, where the far-ultraviolet radiation and the density are relatively low. Our observations test theories of photon-dominated regions (PDRs) in a regime that has been little explored. Knowledge of such regions will also help to test theories of photoionization-regulated star formation. [C II] 158 μm and [O I] 63 μm lines are detected

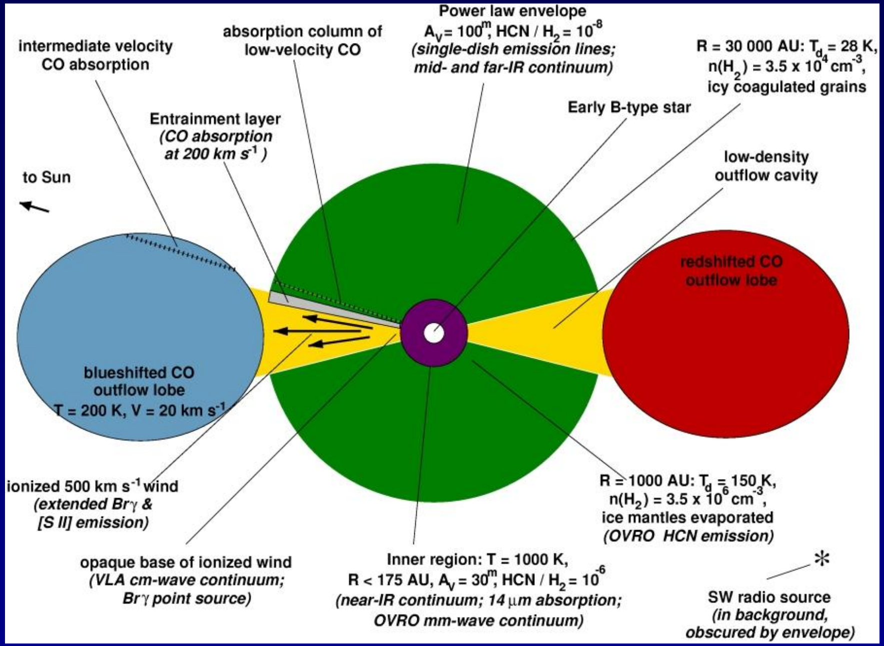
Li et al. 2002



Started when EvD was Tinsley professor 1997

Pak et al. 1998

Structure of massive YSOs



Van der Tak et al. 1999, 2000
Boonman et al. 2002

Birth of c2d
A memorable sabattical in Leiden

- Lorentz Center workshop where proposal was written

c2d and DIGIT
Spectroscopic surveys

- 5-40 μm
- R=600
- 75 hr
- 50 embedded YSOs
- 75 disks

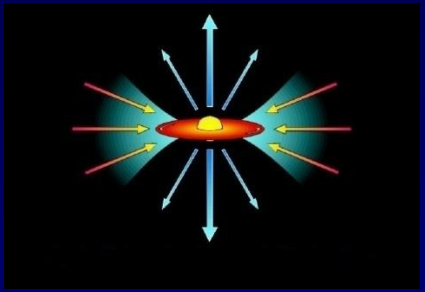
- 25 papers, ~1500 cit

- 56-200 μm
- R=1000-3000
- 250 hr
- 30 embedded YSOs
- 21+12 disks

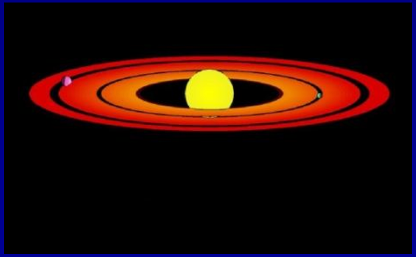
- Papers in prog

Infrared spectral features

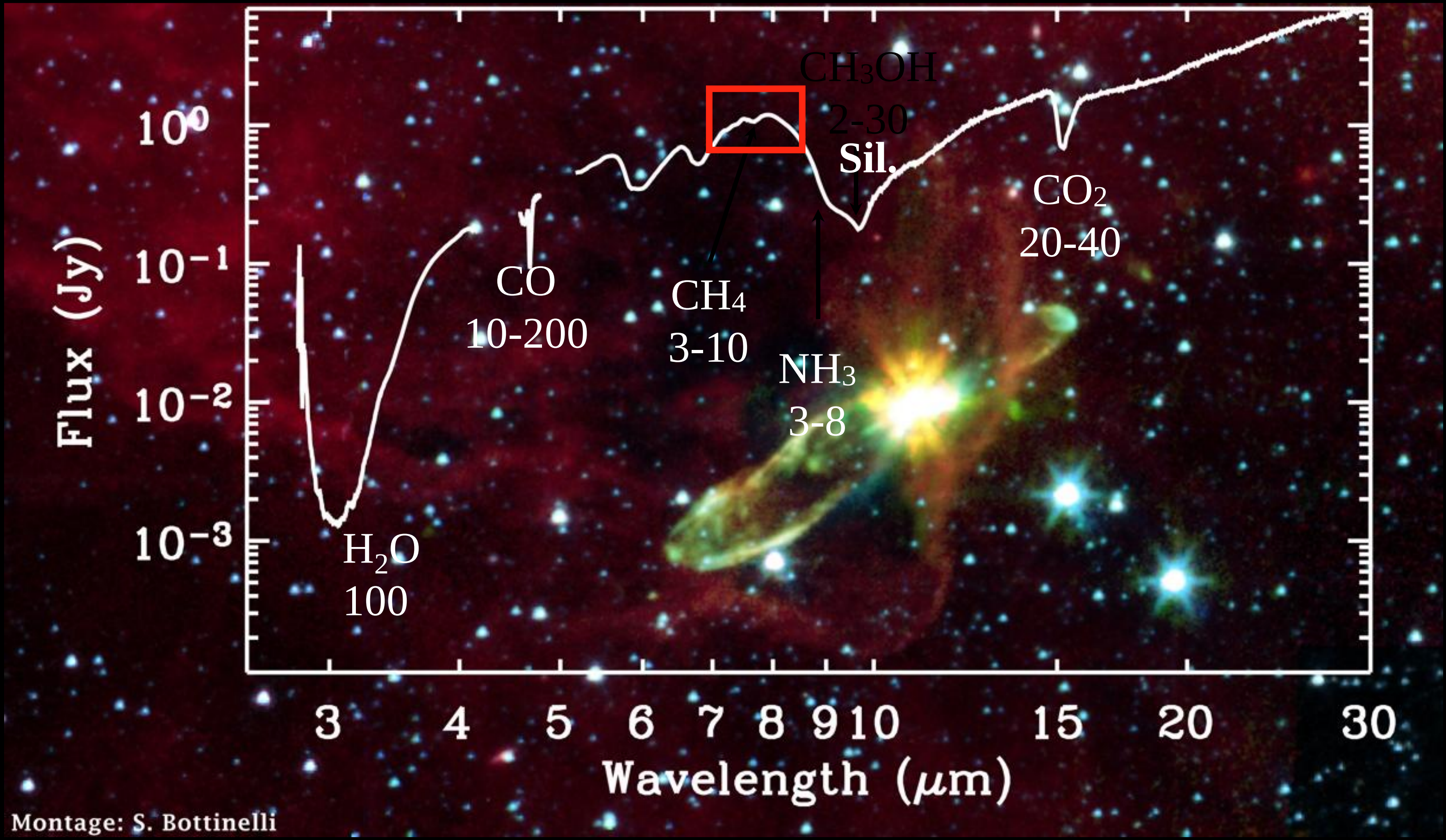
- **Embedded protostars**
  - **Ices and silicates in absorption**
  - **Atomic [Ne II] 12.8, [S I] 25.2 μm, H_2 lines (extended emission from outflow)**
  - **CO, OH, H_2O, [O I] far-IR**



- **Protoplanetary disks**
  - **Silicate and PAH emission**
    - **Absorption if viewed close to edge-on**
  - **H_2 + other molecules emission**
  - **[Ne II], [O I] emission**



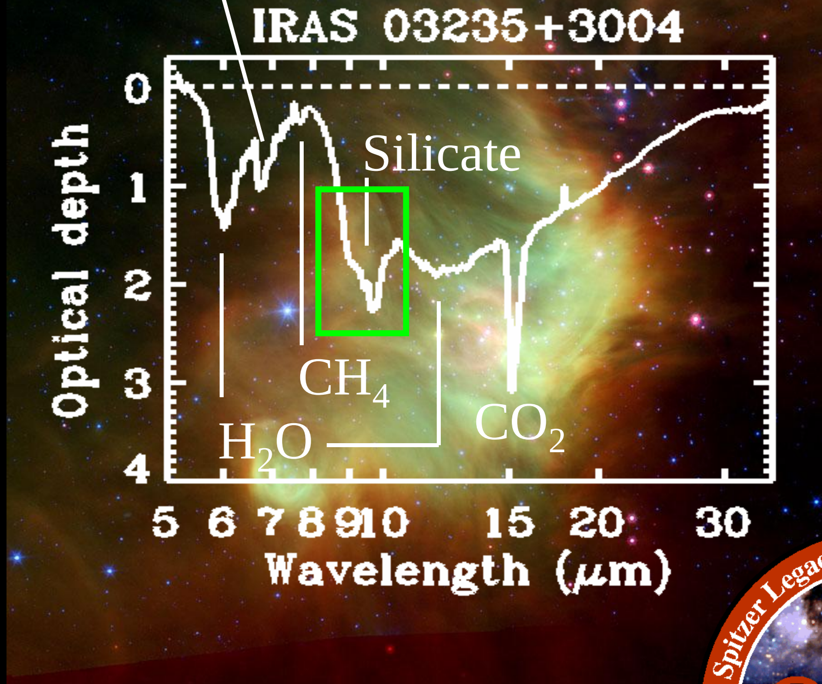
Ice inventory

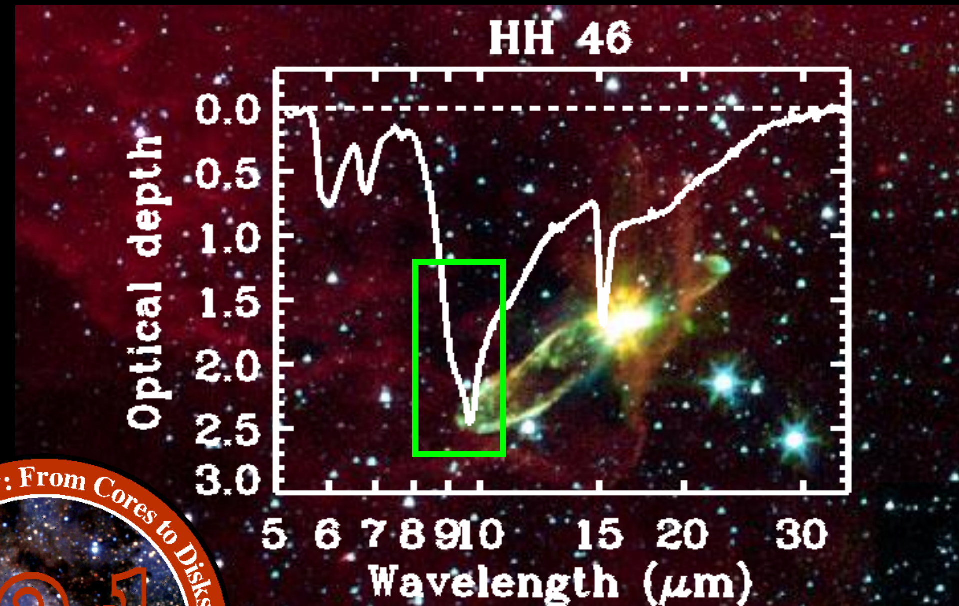


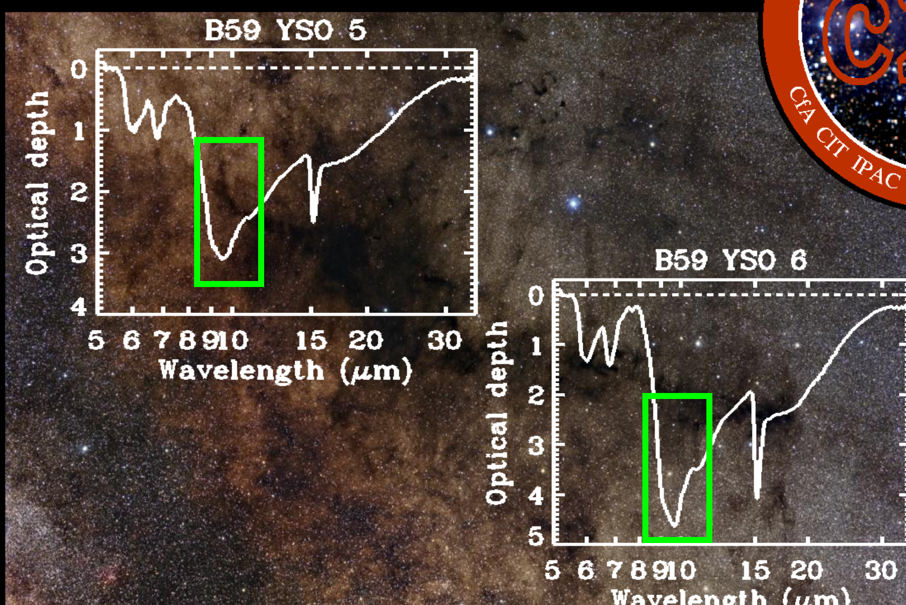
- **Ices can contain significant fraction of heavy elements (50% or more)**

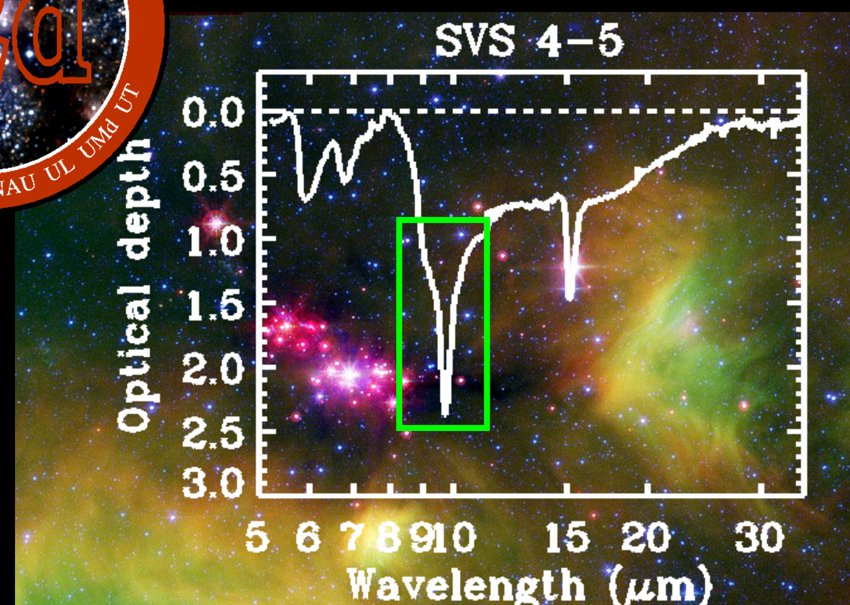
Boogert et al. 2004, 2008
Pontoppidan et al. 2008
Öberg et al. 2008, 2011

Ices toward low-mass protostars



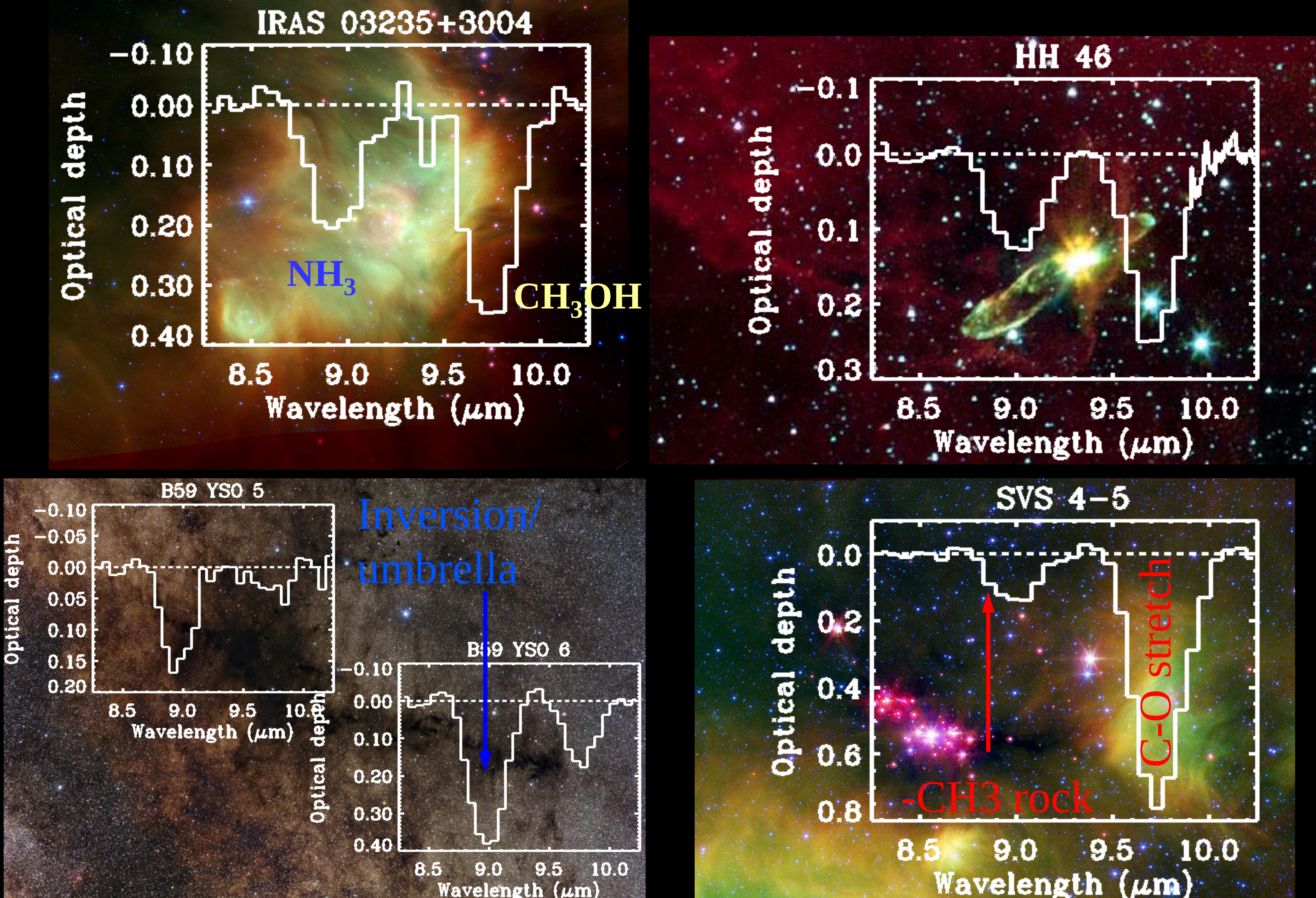






Bottinelli et al. 2010

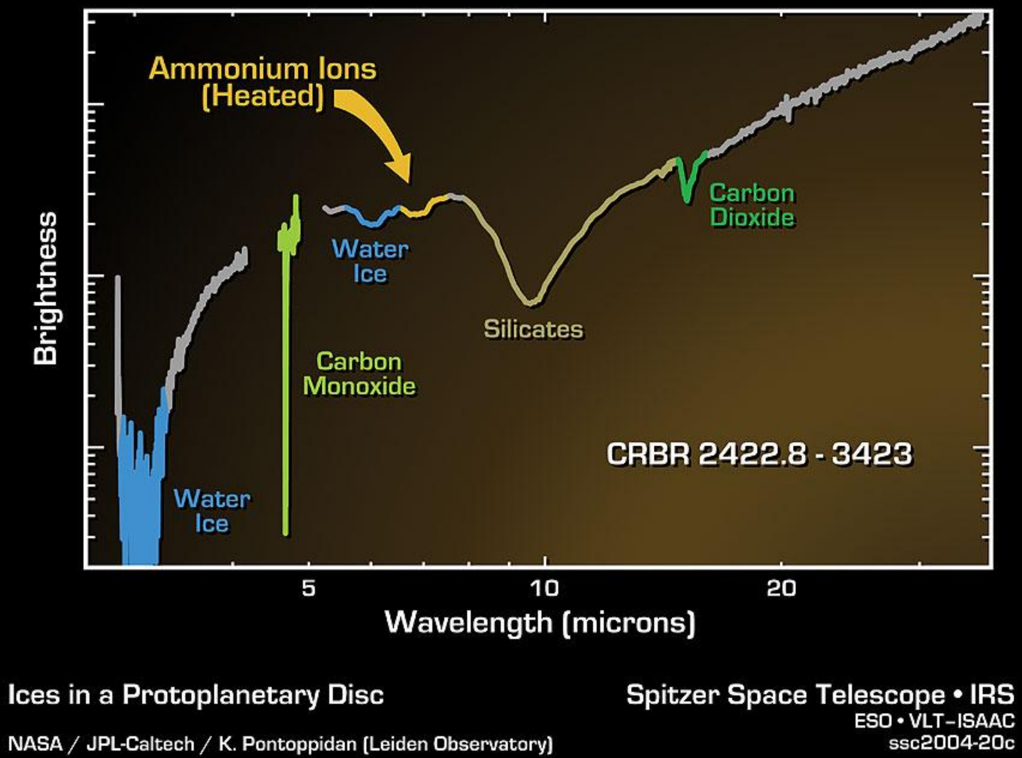
Silicate subtracted spectra: NH_3 and CH_3OH!

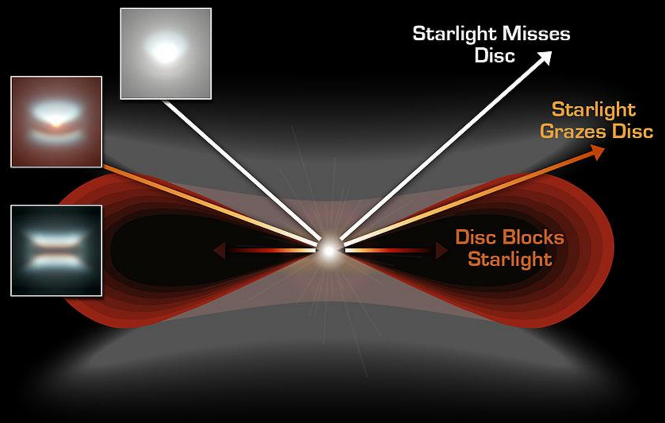


Ingredients for complex organics!

Heated ices in edge-on disk

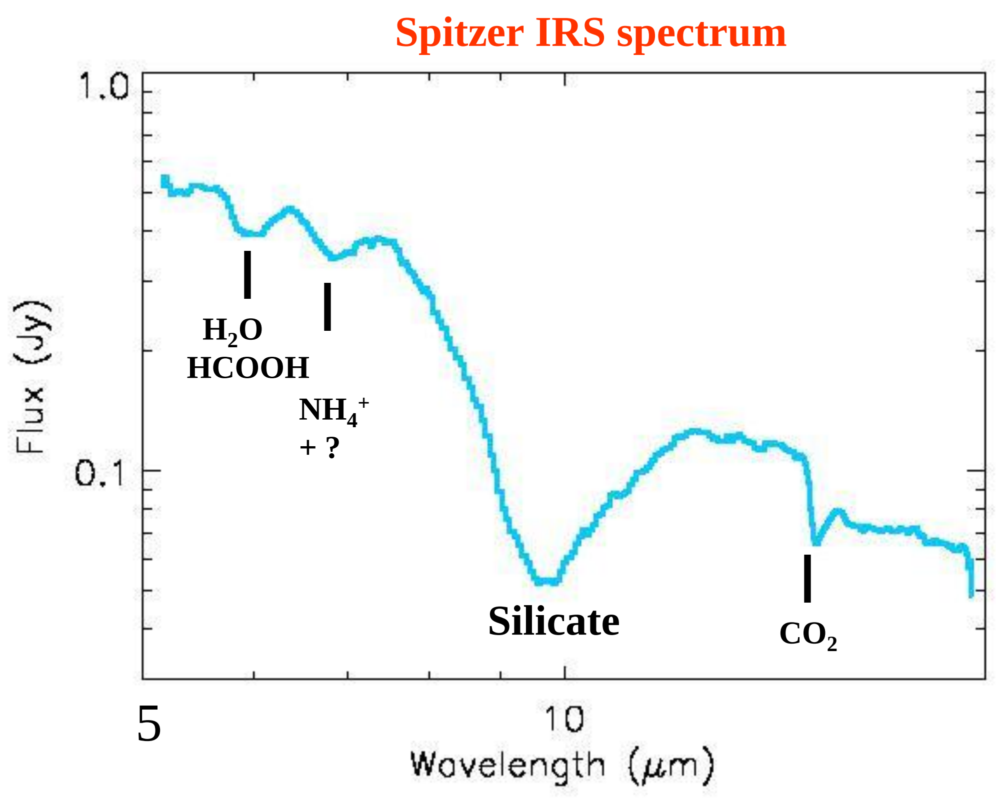
NASA press release Nov. 9, 2004



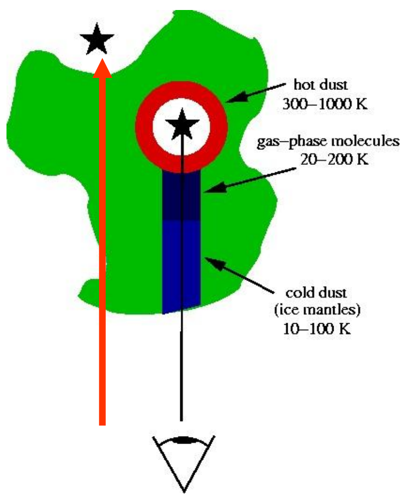


Pontoppidan, Dullemond et al. 2005

Ices are complex early on



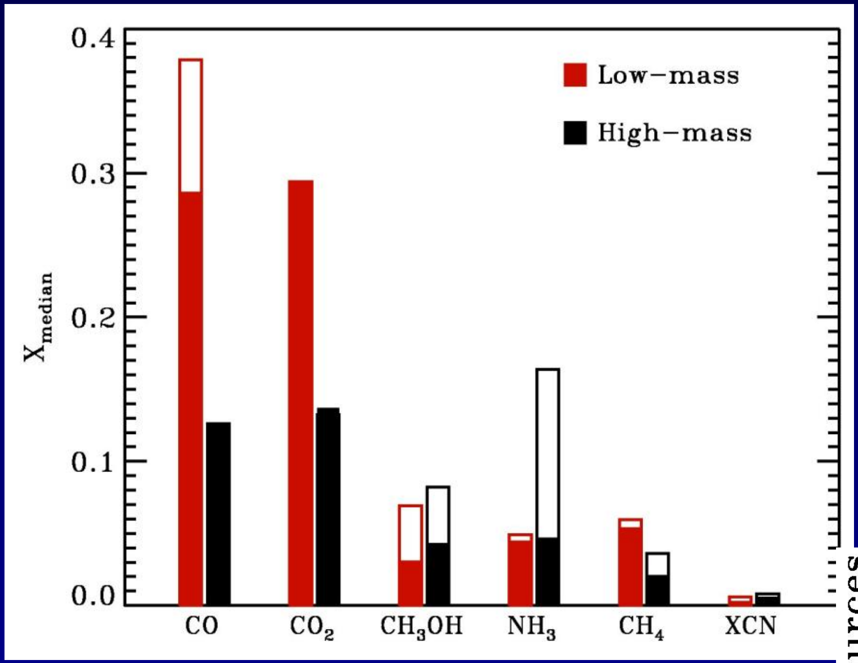
CK 2 behind Serpens cloud



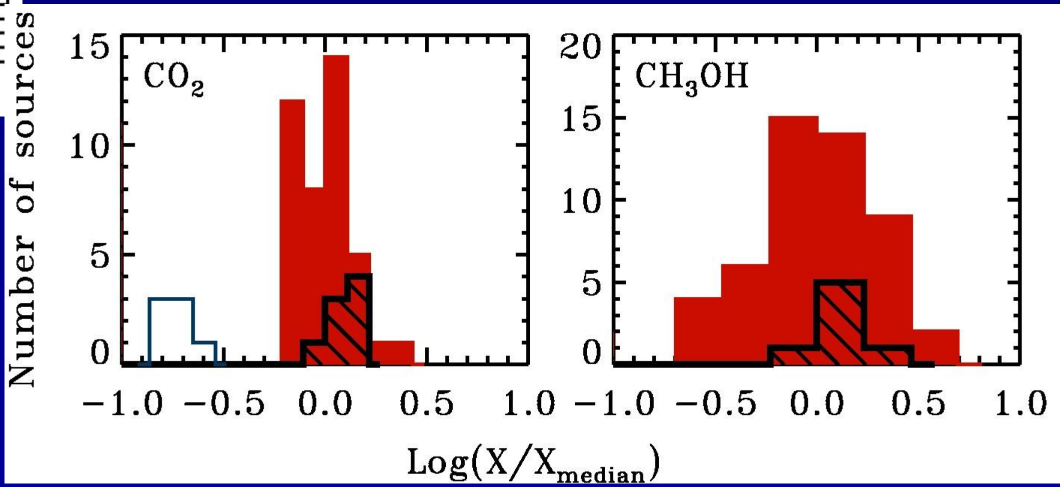
- Background stars: ices unaffected by heating and radiation from star
- Features same as seen as for YSOs, including 6.0 and 6.8 μm bands => do not require heating

Knez et al. 2005
Bergin et al. 2005

Ice composition low vs high-mass



w.r.t H_2O



Volatile ices higher for low-mass YSOs

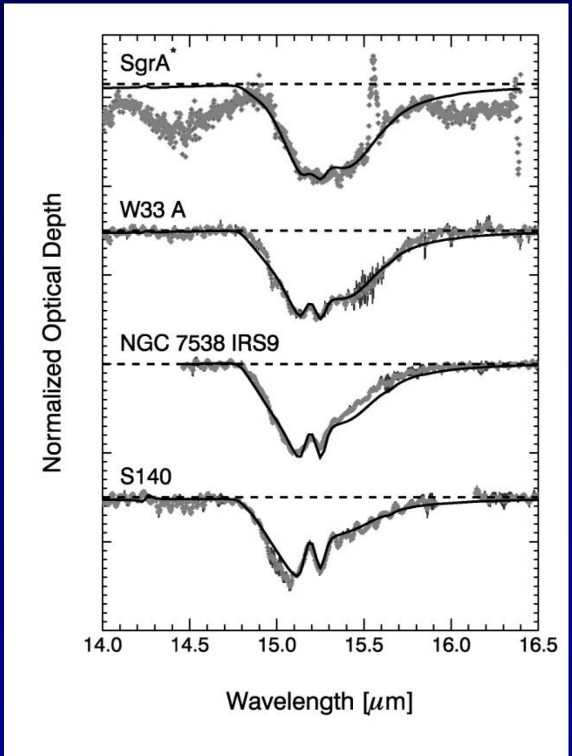
Öberg et al. 2011

Narrow distribution CO_2, broad CH_3OH

Full: upper limits included; Open: only detections

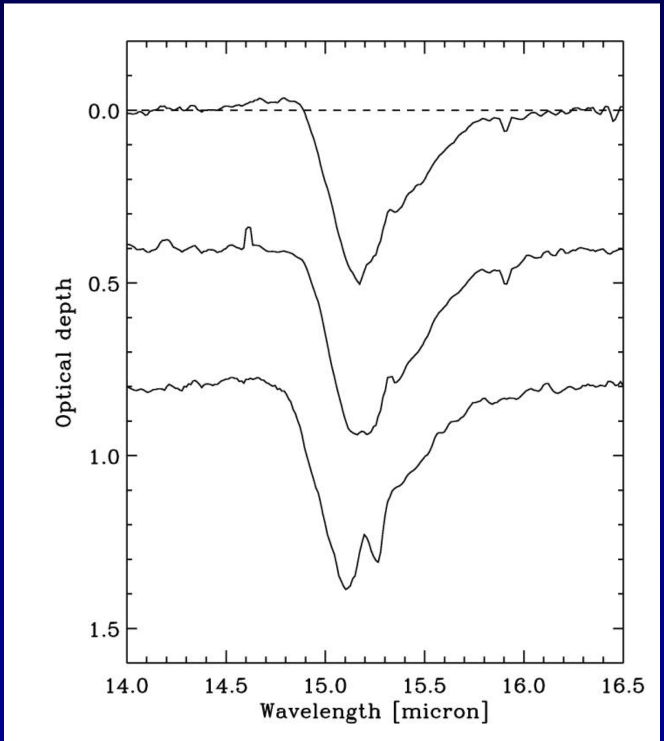
Heating of ices: segregation

High-mass: ISO



T

Low-mass: Spitzer

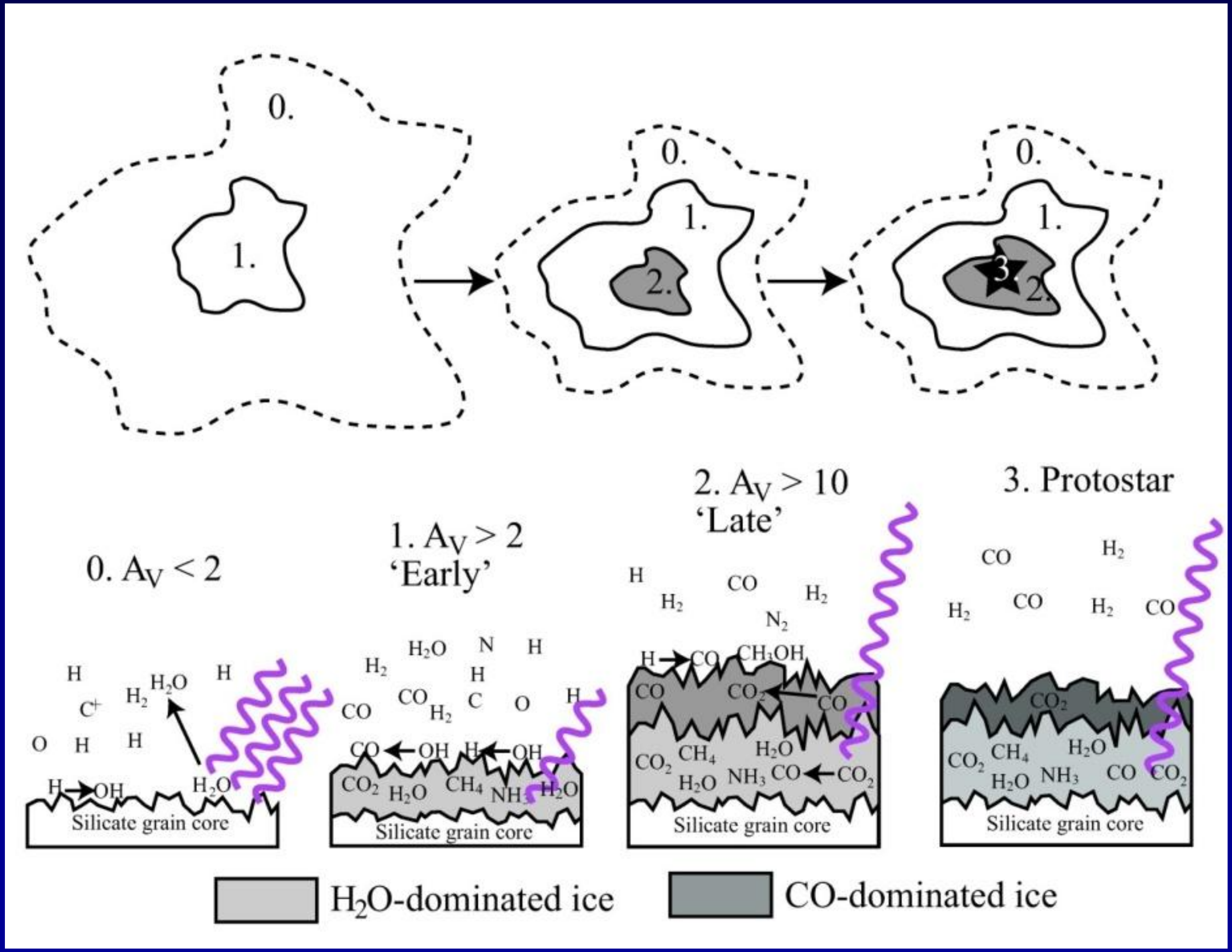


CO_2
15 μm

- Systematic trends in band profiles with increasing temperature (CO_2 15 μm, NH_4^+ 6.8 μm, gas/solid ratios …)
- Irreversible → trace heating events

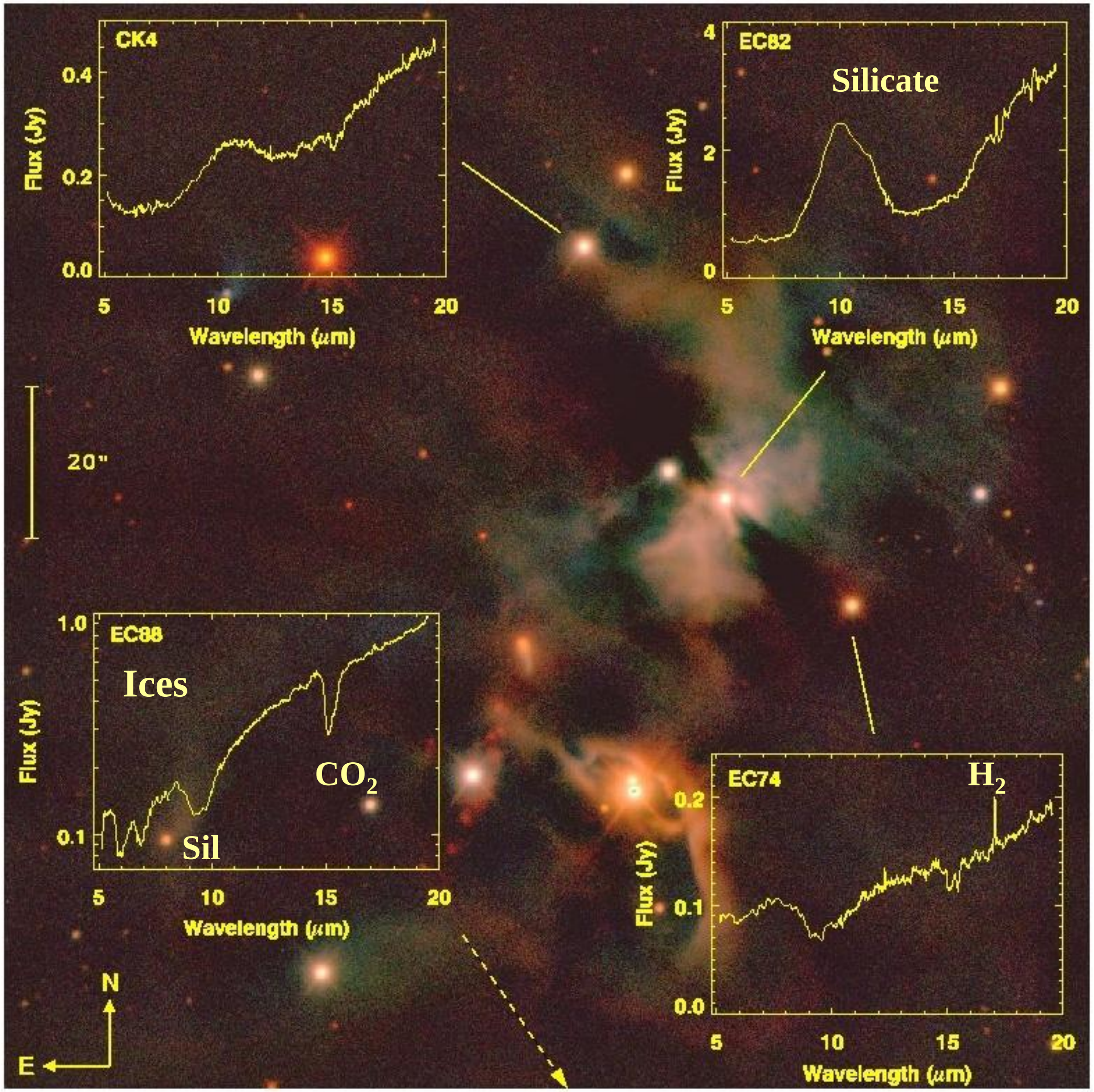
Gerakines et al. 1999,
Pontoppidan, Boogert et al. 2008
Kim et al. 2012

Proposed ice evolution



Öberg et al. 2011

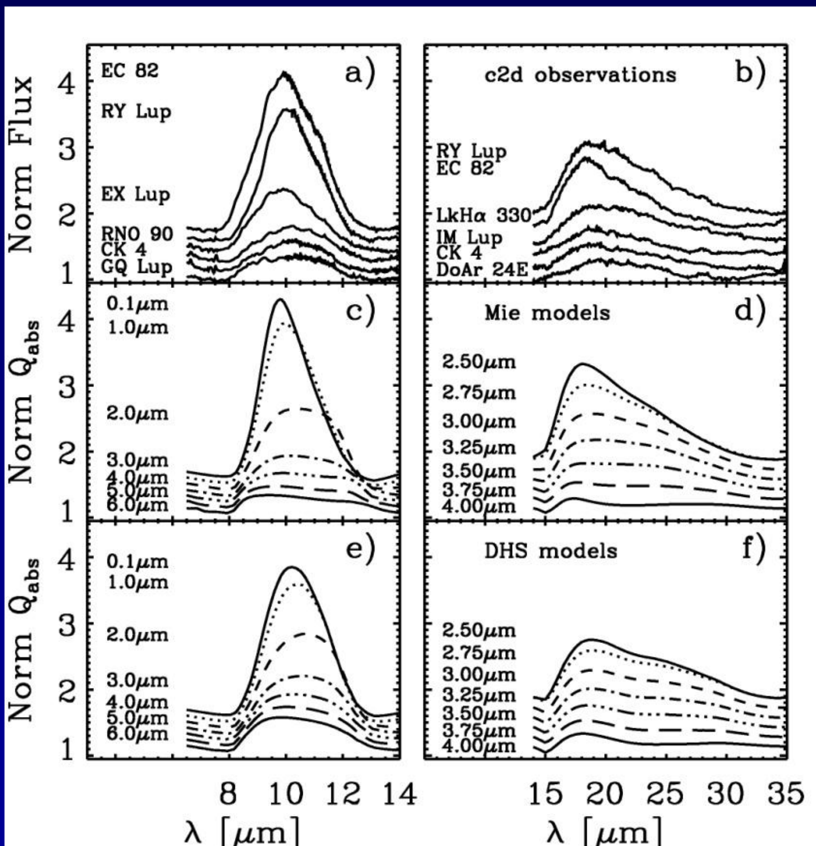
Spitzer spectra of low-mass YSO's
Serpens core

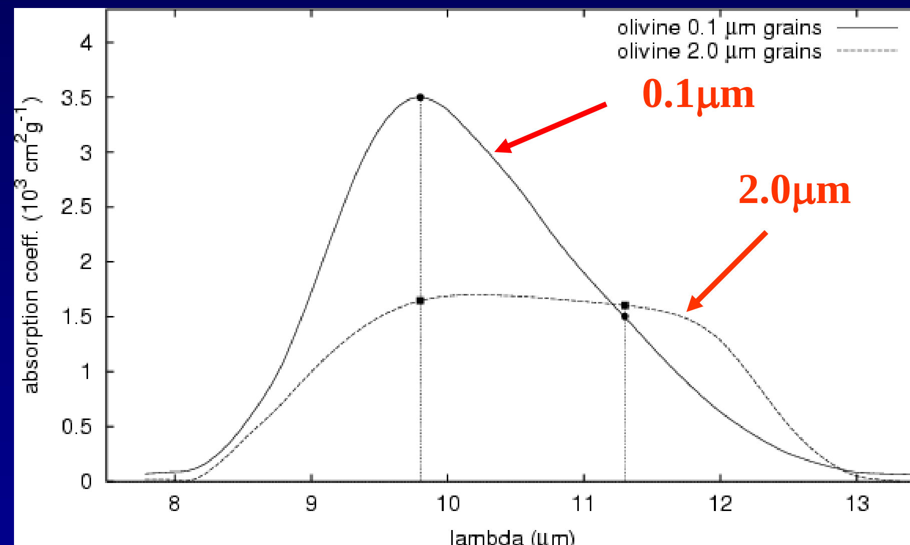


VLT-ISAAC
J, H K image

c2d team
data

Grain growth and crystallization inner disk
Silicate features





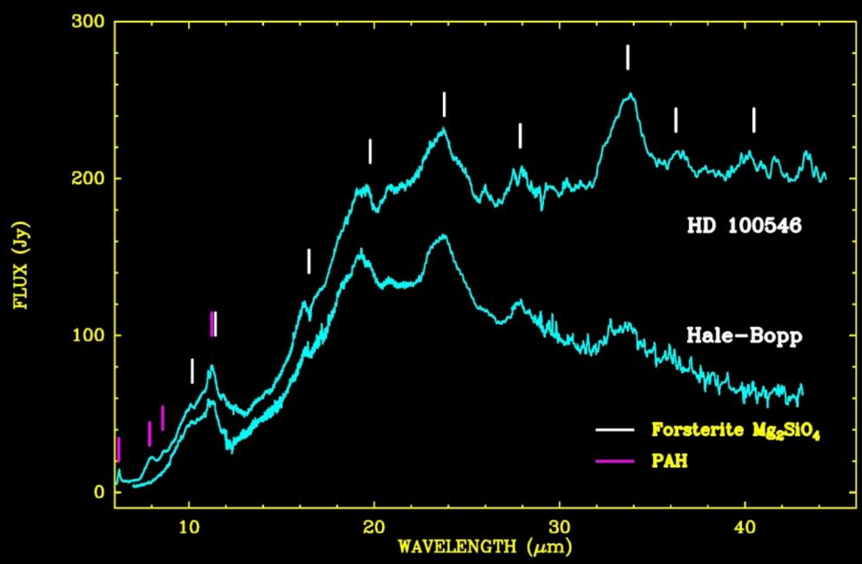
Also: van Boekel et al. 2005, Furlan et al. 2006
Bouwman et al. 2008
Watson et al. 2009, Juhasz et al. 2010
Sturm et al. 2010, 2013 (Herschel-DIGIT)

Kessler-Silacci et al. 2006
Olofsson et al. 2009, 2010
Oliveira et al. 2010

Grains grow to μm size in surface layers

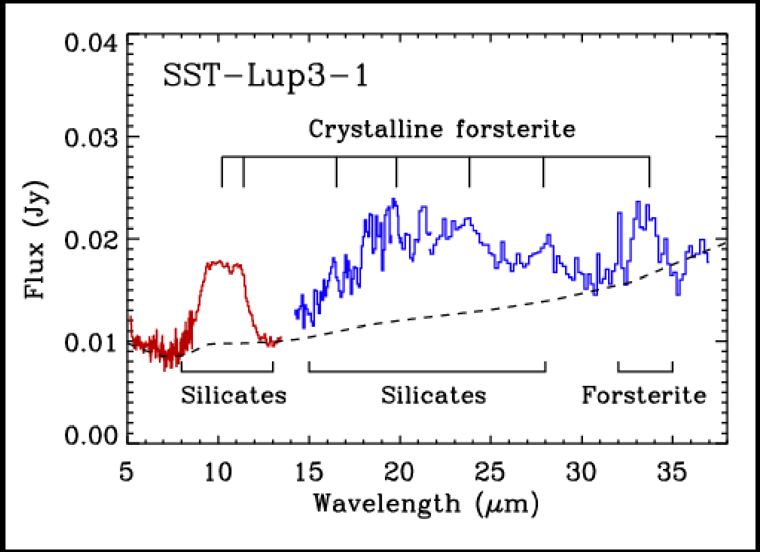
Crystallinity

ISO: Herbig stars



Malfait, Waelkens et al. 1998

Spitzer: T Tauri stars and Brown Dwarfs

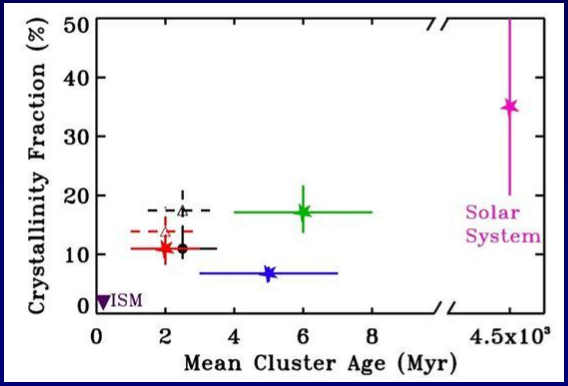


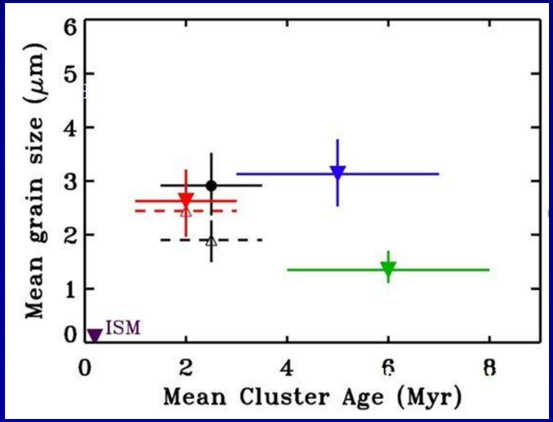
Apai et al. 2005, Merin et al. 2007
Olofsson et al. 2009,2010, Bouwman et al. 2008
Sturm et al. 2010, 2013 69 μm (DIGIT)

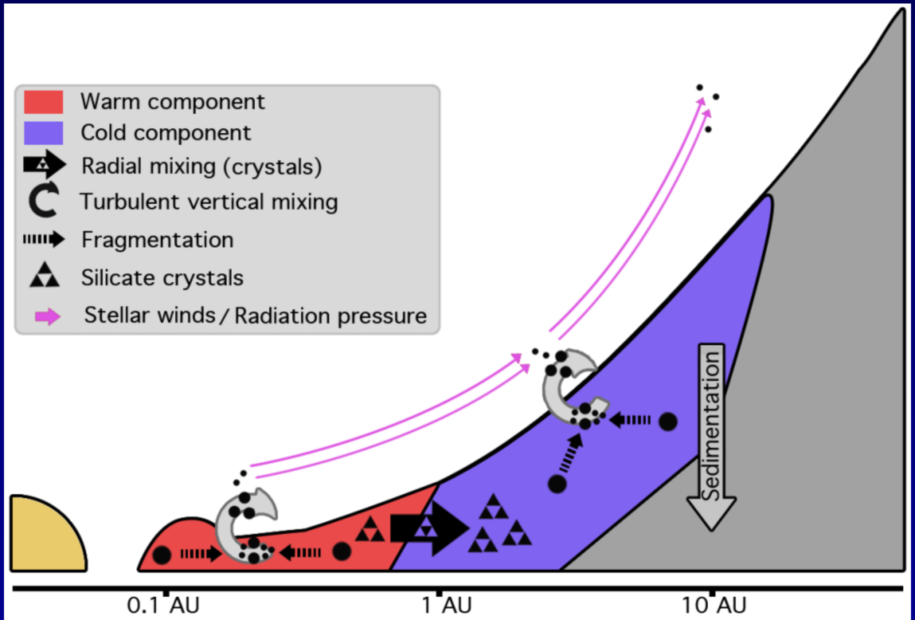
- Crystallinity seen in large fraction of T Tauri + BD disks (>50%)
- Interstellar silicates amorphous => crystallization at > 800 K must have occurred in inner disk
  => provides constraints on efficiency of heating and mixing processes

Grain processing occurs early

Hundreds of sources Spitzer



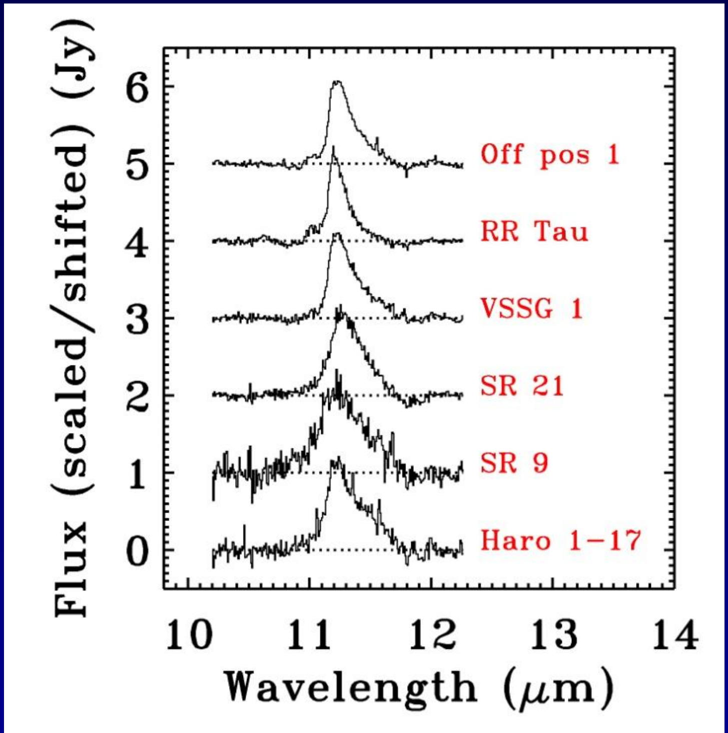




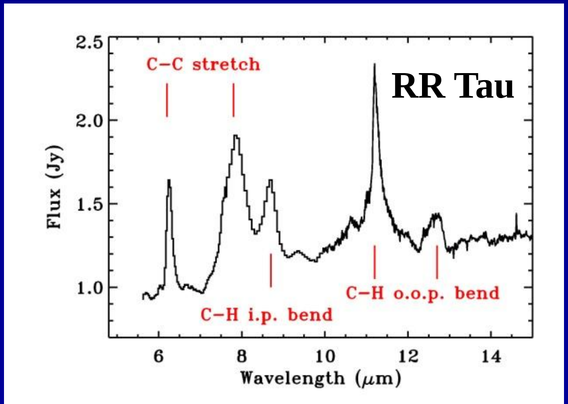
Oliveira et al. 2011, Olofsson et al. 2010

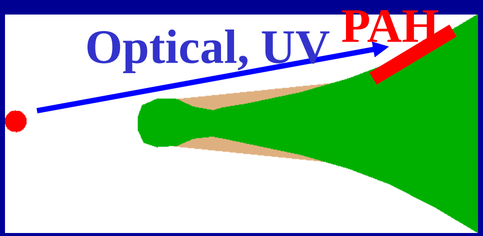
- Grain growth and crystallinity are established early (≤ 1 Myr) and maintained by continuous growth and destruction until disk dissipation

PAHs are rare in T Tau disks



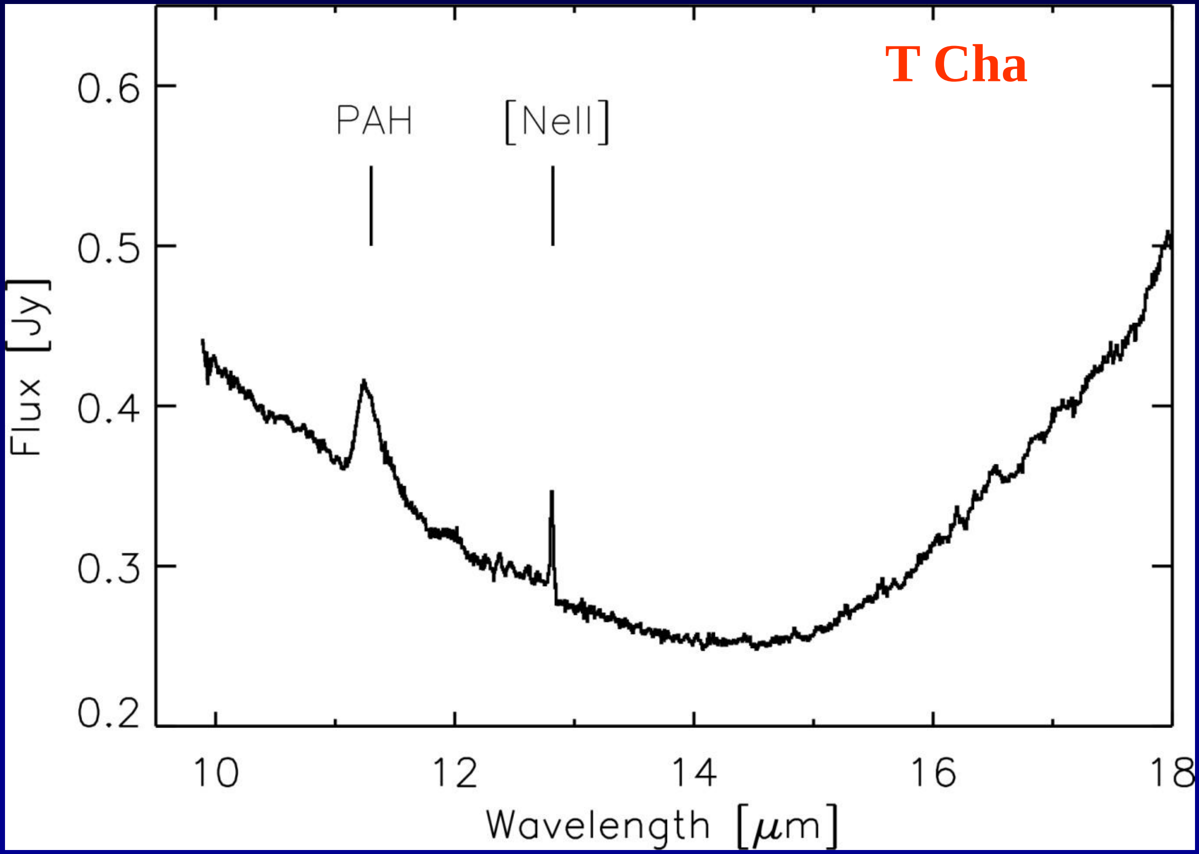
- Few % T Tauri stars show PAH
  - Mostly G stars detected, not K
- No PAHs detected embedded YSOs
- Absence in majority objects due to low PAH abundance
  - PAHs frozen into ices in pre-+ protostellar phase?





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

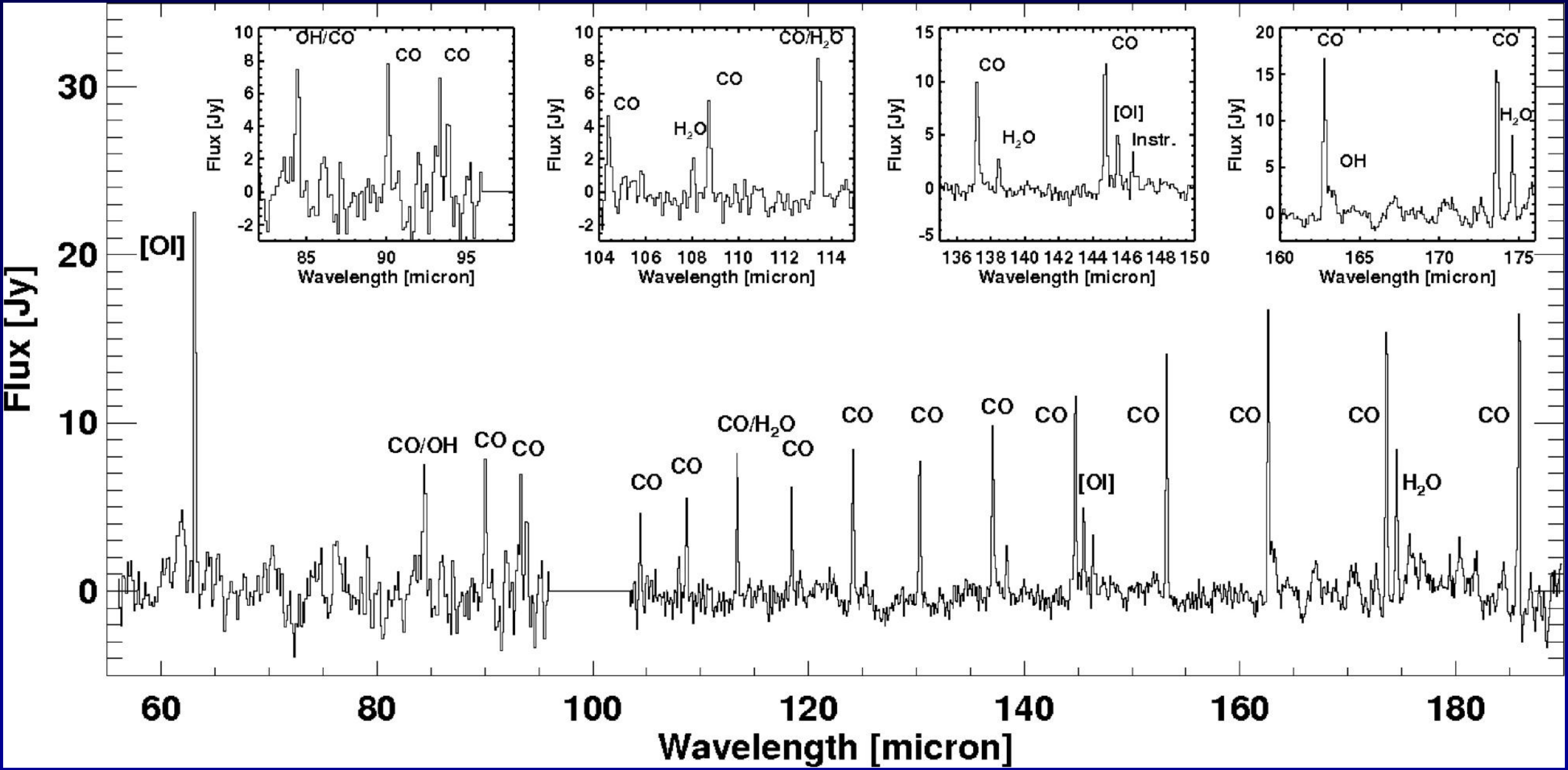
[Ne II] in disks: tracer of X-ray/EUV radiation?



- Detected in at least 20% of sources
- Some cases associated with jets
- Fluxes consistent with recent models of X-ray irradiated disks

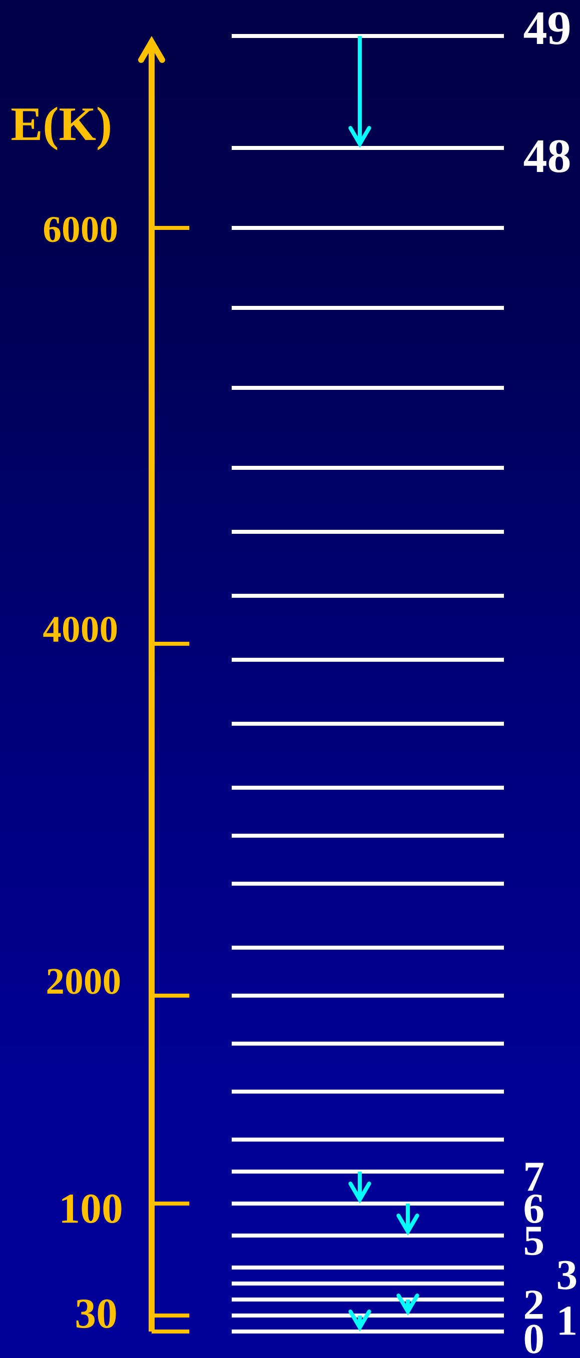
Lahuis et al. 2007, Pascucci et al. 2007
Guedel et al. 2010

Far-IR spectroscopy: CO ladder

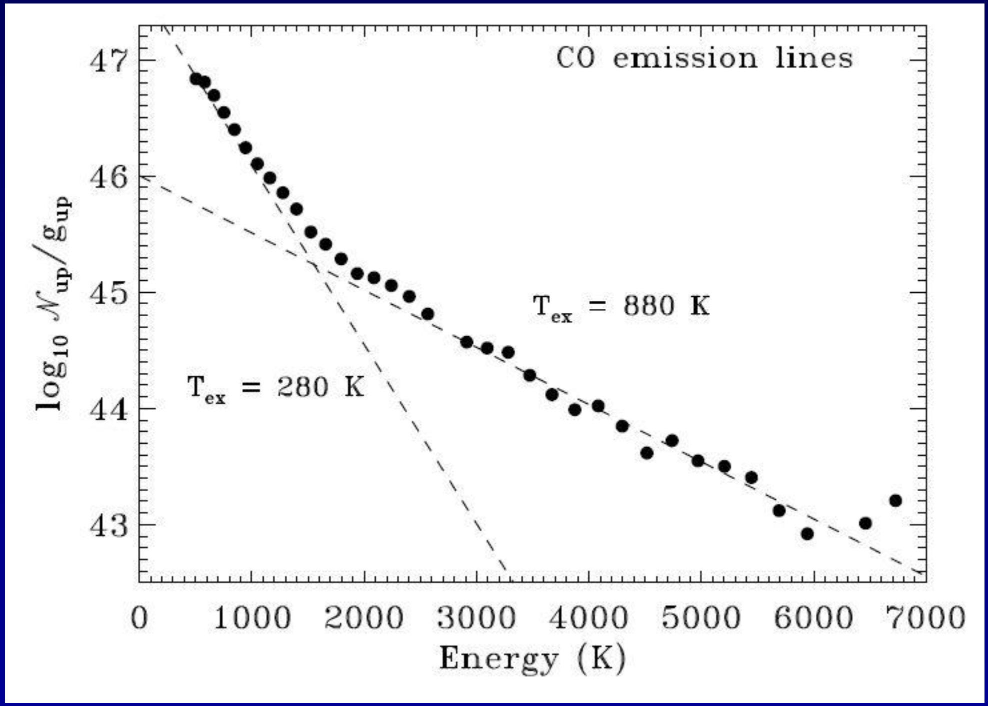


Van Kempen + DIGIT team 2010
Green et al. 2013

The CO ladder as a physical probe

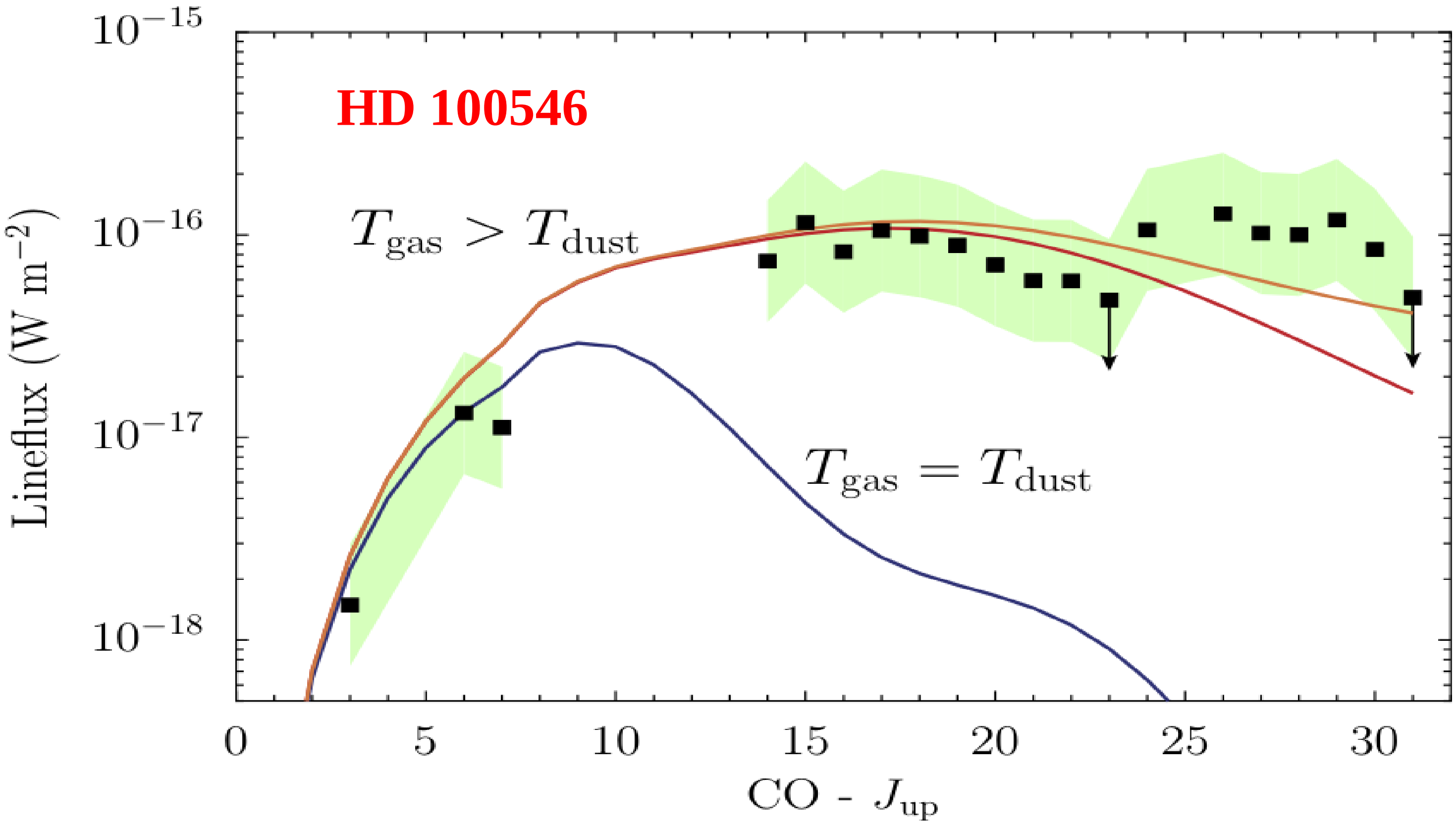


Not to scale



Herczeg et al. 2012
Goicoechea et al. 2012
Karska et al. 2013
Green et al. 2013
Dionatos et al. 2013
Lee et al. 2013

Hot disk atmosphere probed by CO



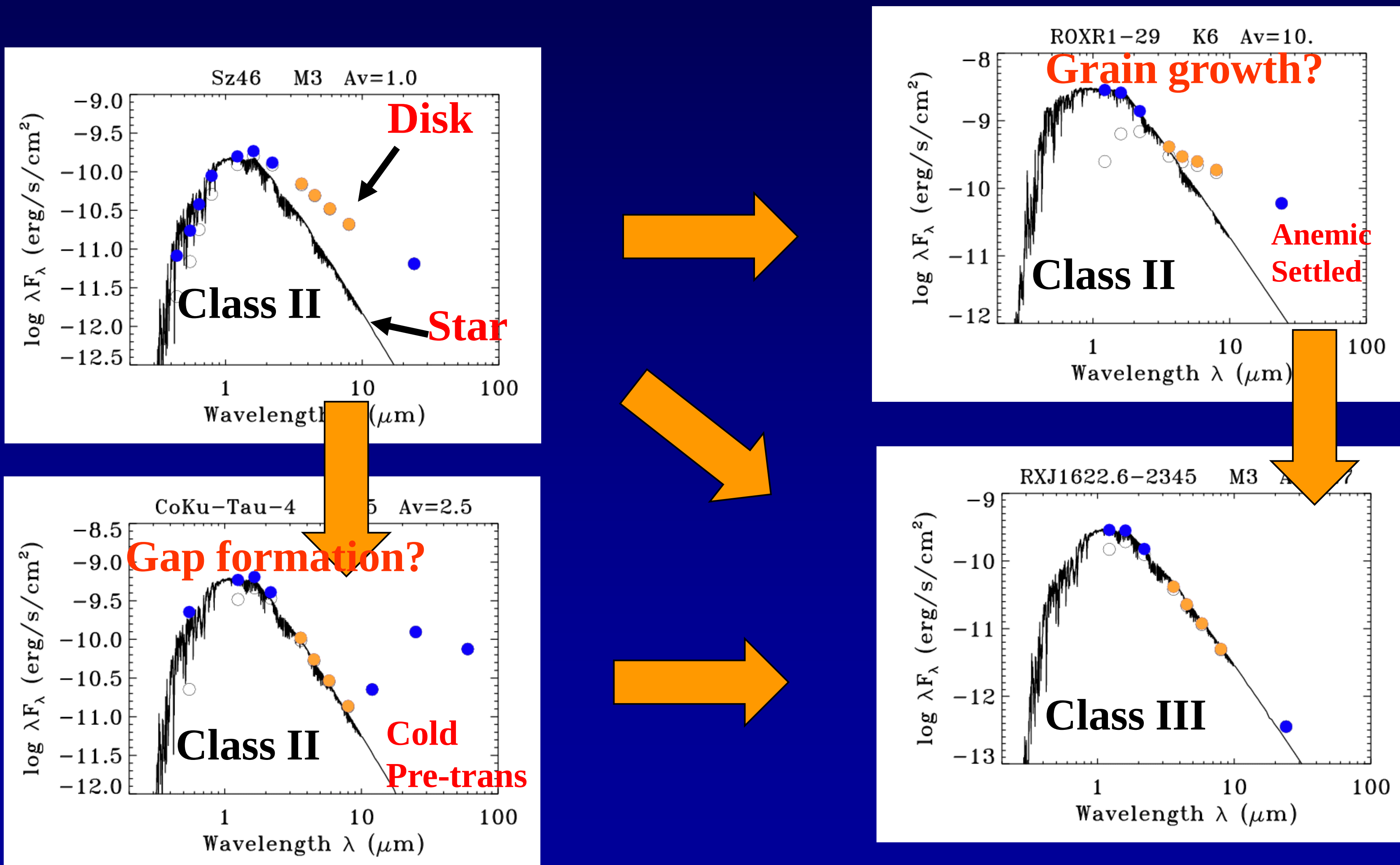
Bruderer et al. 2012

CO excitation requires $T_{gas} >> T_{dust}$

Guiding c2d and DIGIT: finding the right path

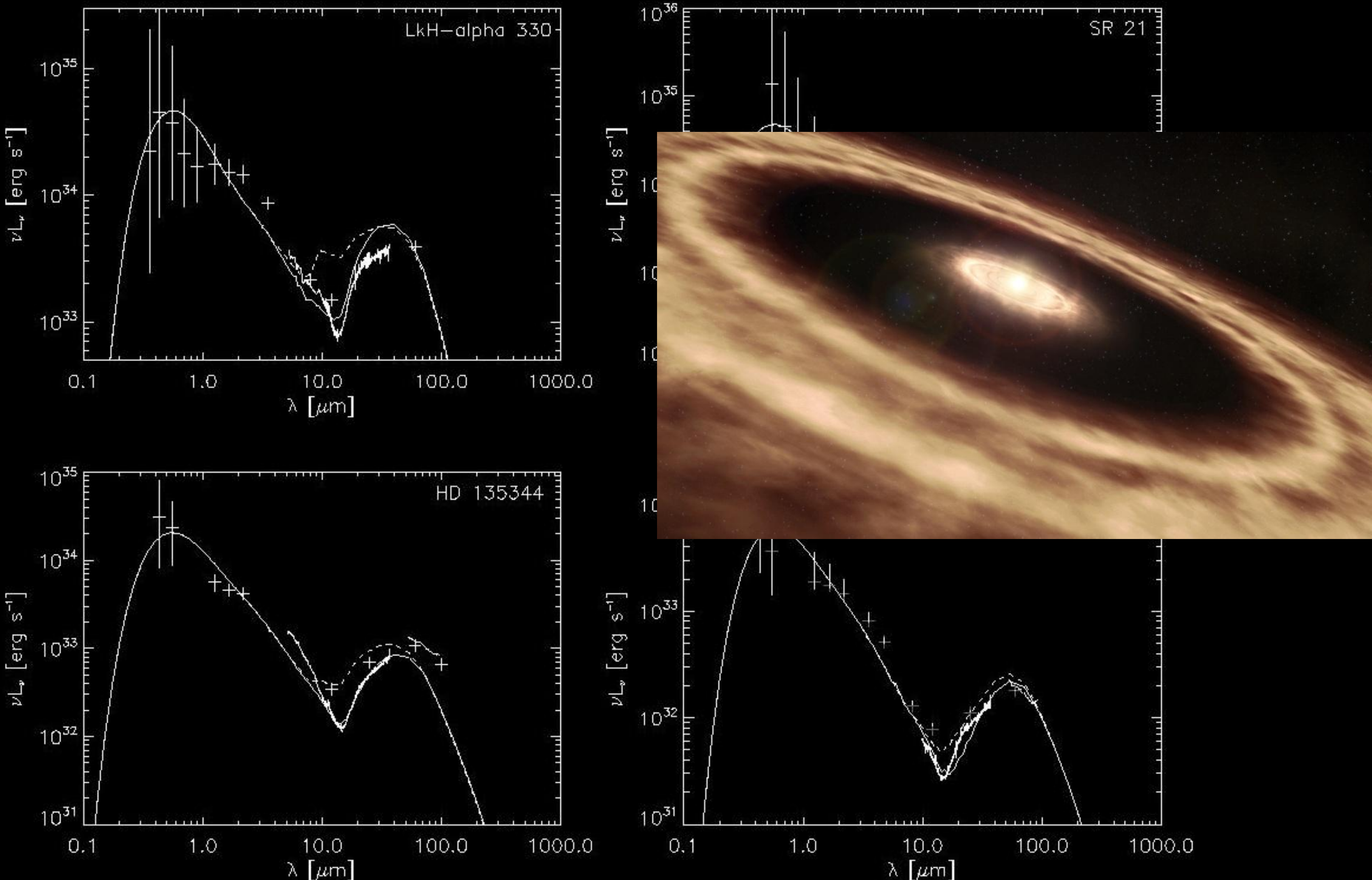
Disk evolution

There are multiple paths from protoplanetary to debris disks



Cieza et al. 2007, Merin, Brown et al. 2010

Transitional disks

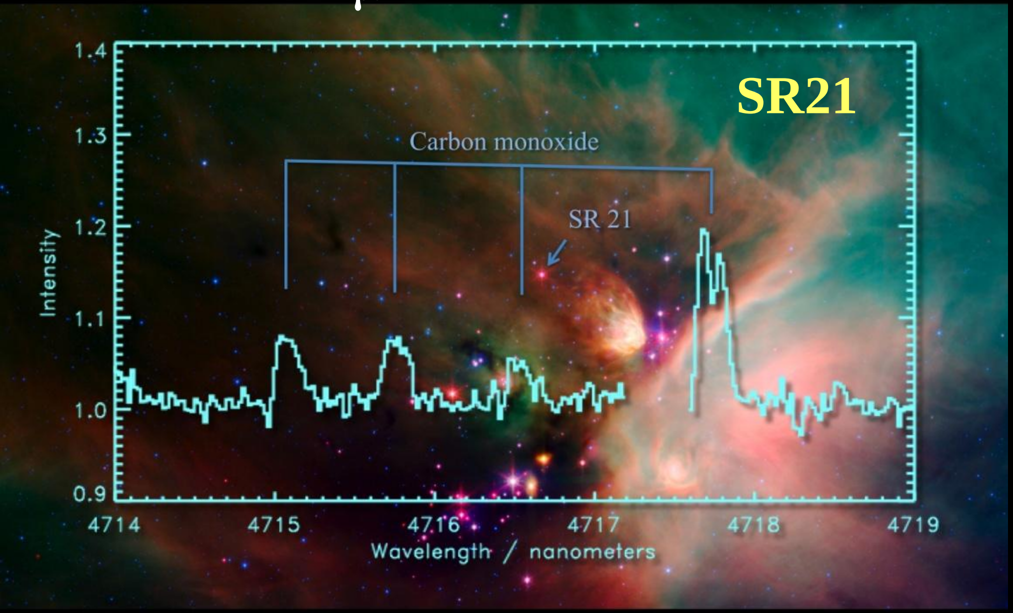


Estimated outer radii are >20 AU

Brown et al. 2007, 2008
Merin, Brown et al. 2010

Resolving dust cavities

CO 4.7 μm v=1-0 VLT-CRIRES

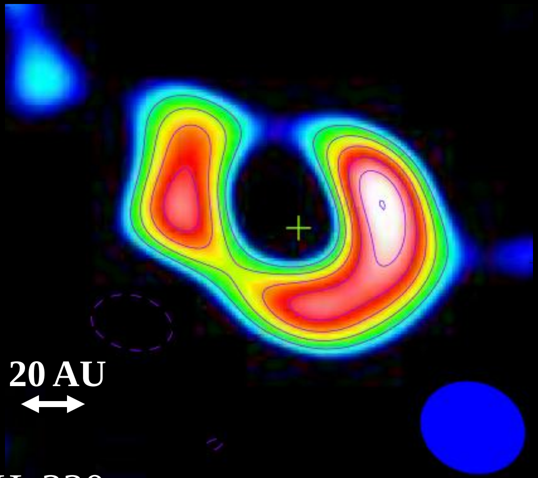


Pontoppidan et al. 2008

- SMA imaging resolves dust gap of ~20 AU

  Brown et al. 2007

- Spectroastrometry of near-IR lines allows to pinpoint gas well inside gap



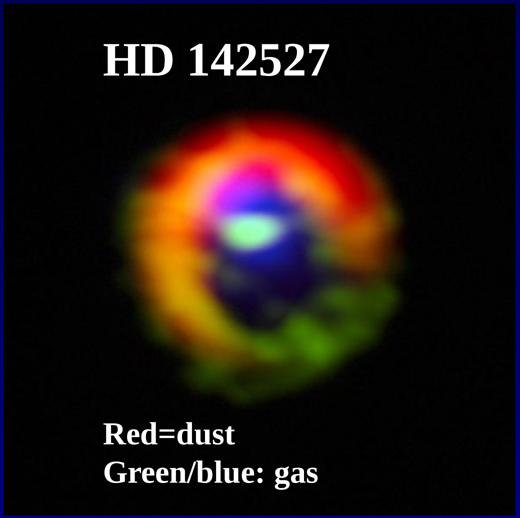
LkHa330

ALMA images of disks with cavities

HD135344B

Under embargo

Perez et al.



Gas streams across gap

Casassus et al. 2013, Fukugawa et al. in prep.

- **Asymmetries in dust and gas point to dust traps**

- **Traps triggered by planets?**

IRS48

Under embargo

Van der Marel et al. subm.

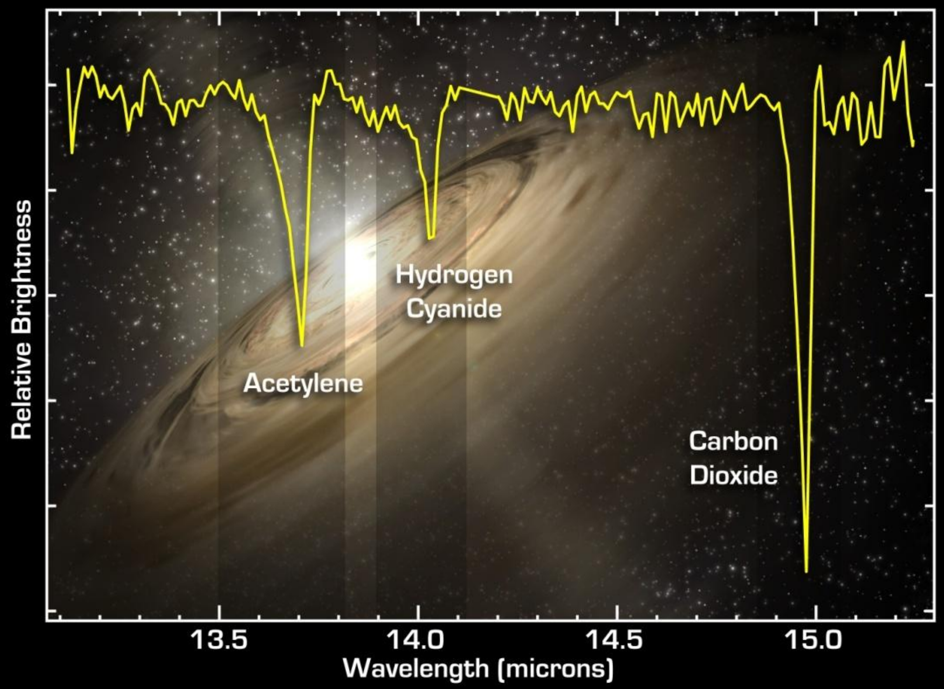
Neal and ALMA

ASAC September 2001

First ASAC Leiden March 2009

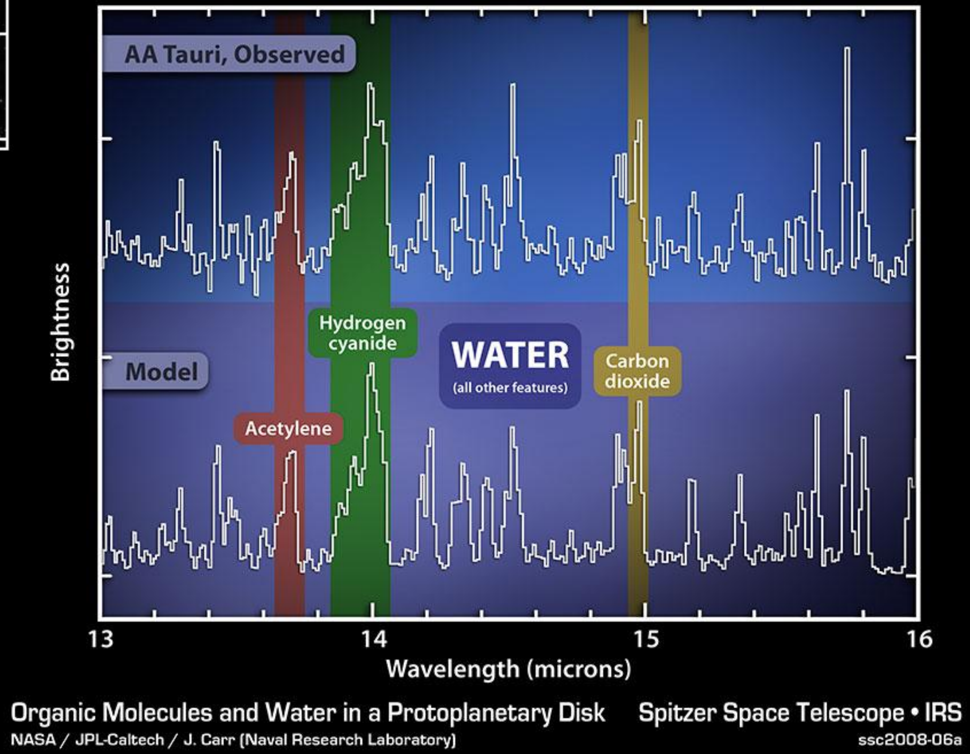
How about molecules in protoplanetary disks?

Surprise: Hot water and organics in inner few AU of disks



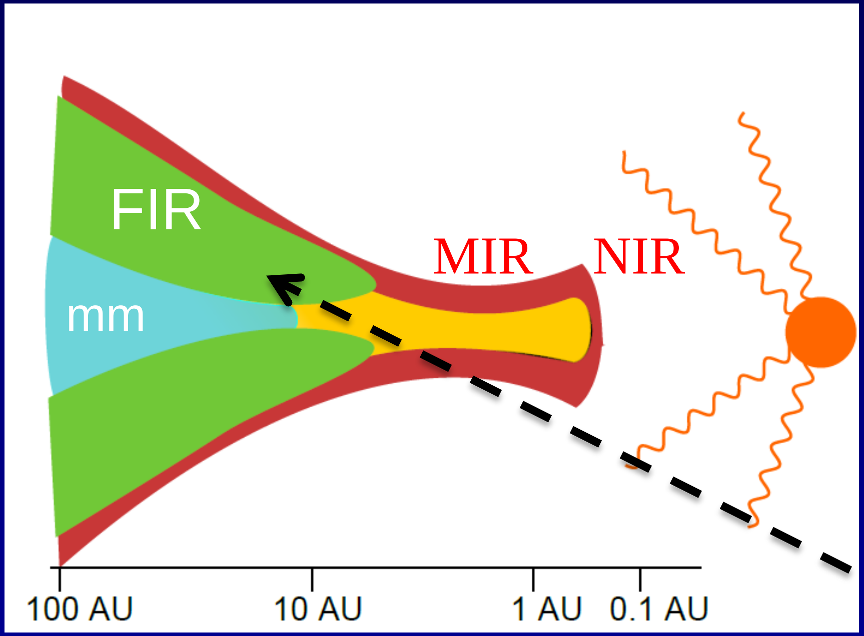
Lahuis et al.
2006

T Tau disks are molecule rich,
Herbig disks molecule poor

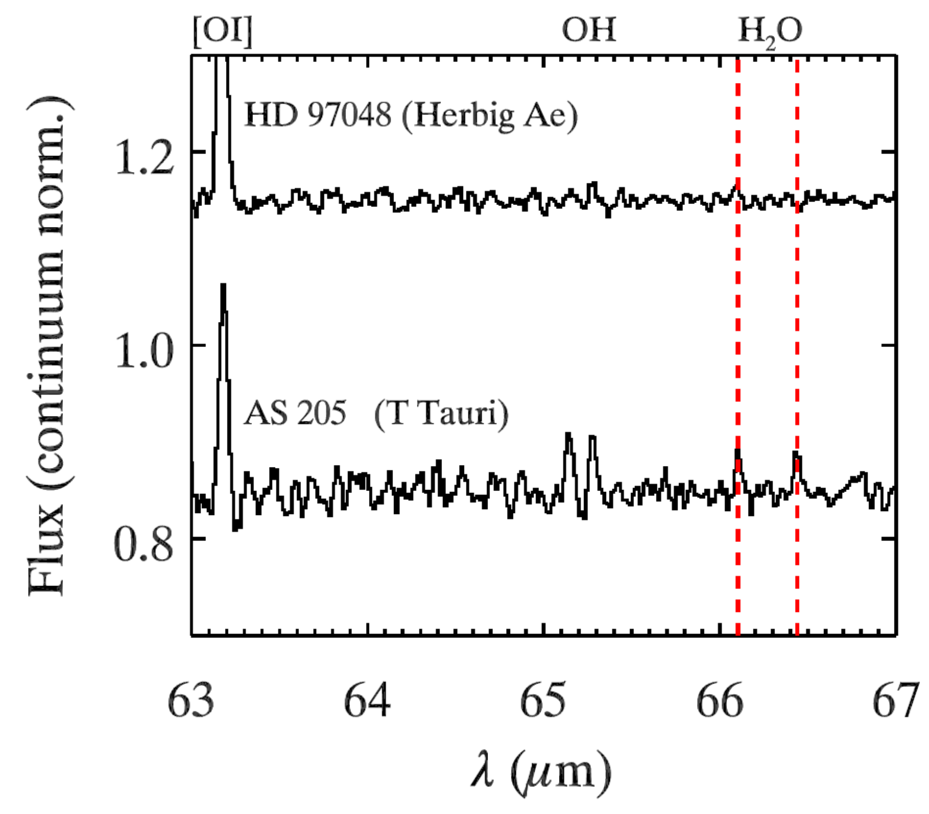


Carr & Najita 2008
Salyk et al. 2008
Pontoppidan et al. 2010
Salyk et al. 2011

Probing the entire disk surface



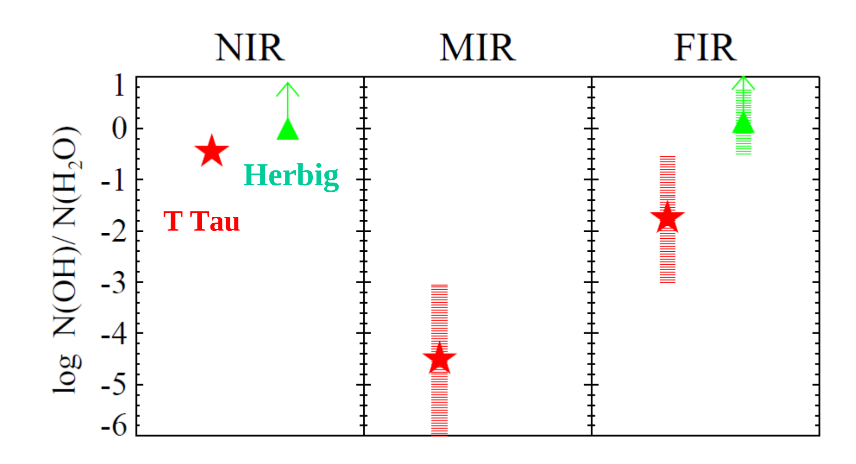
Importance of UV: OH/H_2O



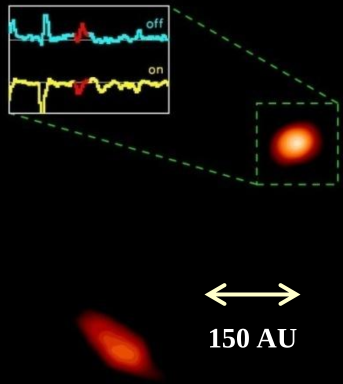
Fedele, Meeus et al. 2013
Salyk et al. in prep.
Zhang et al. 2013

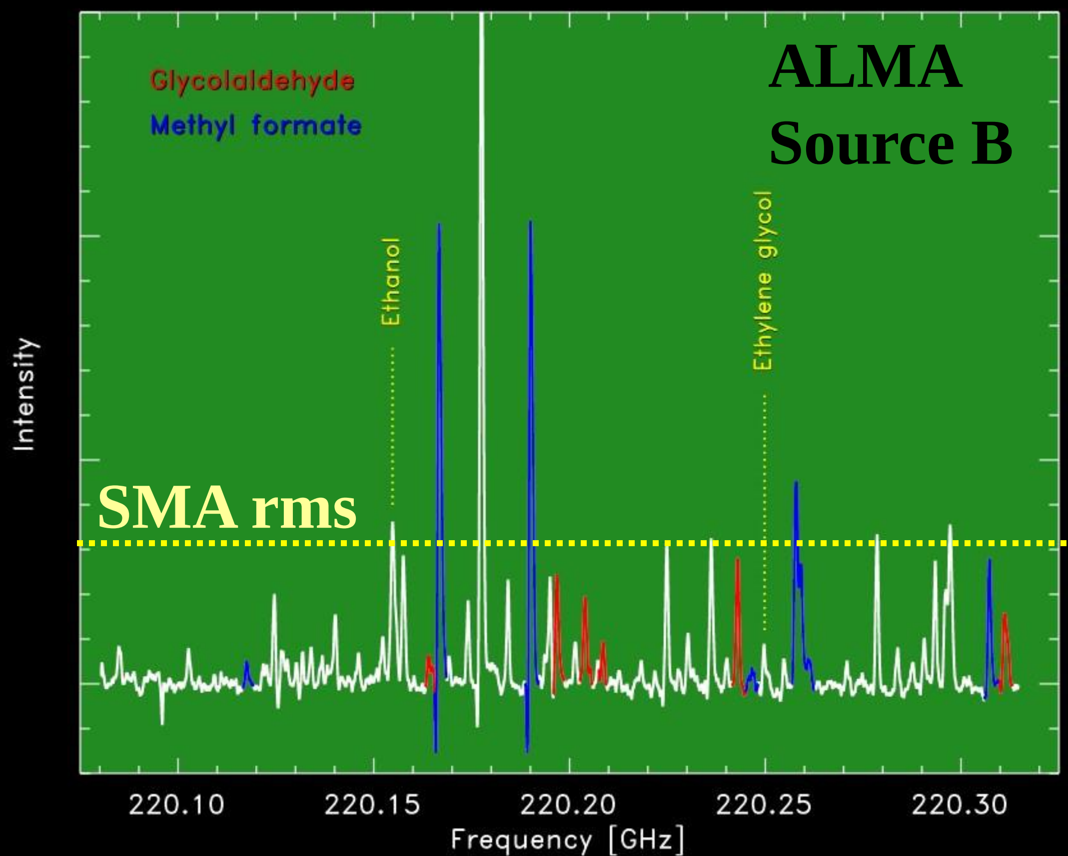
- Far-IR H_2O detected in T Tau disks, but hardly in Herbig disks

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

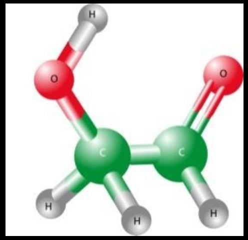


Complex molecules in young disks
ALMA test data of IRAS 16293-2422





Band 6



- Simple sugar detected toward low-mass YSO
- Imaged on ~0.2" scale, 25 AU radius!

Jørgensen et al. 12

Thanks to Neal!

Greetings from the ESO DG