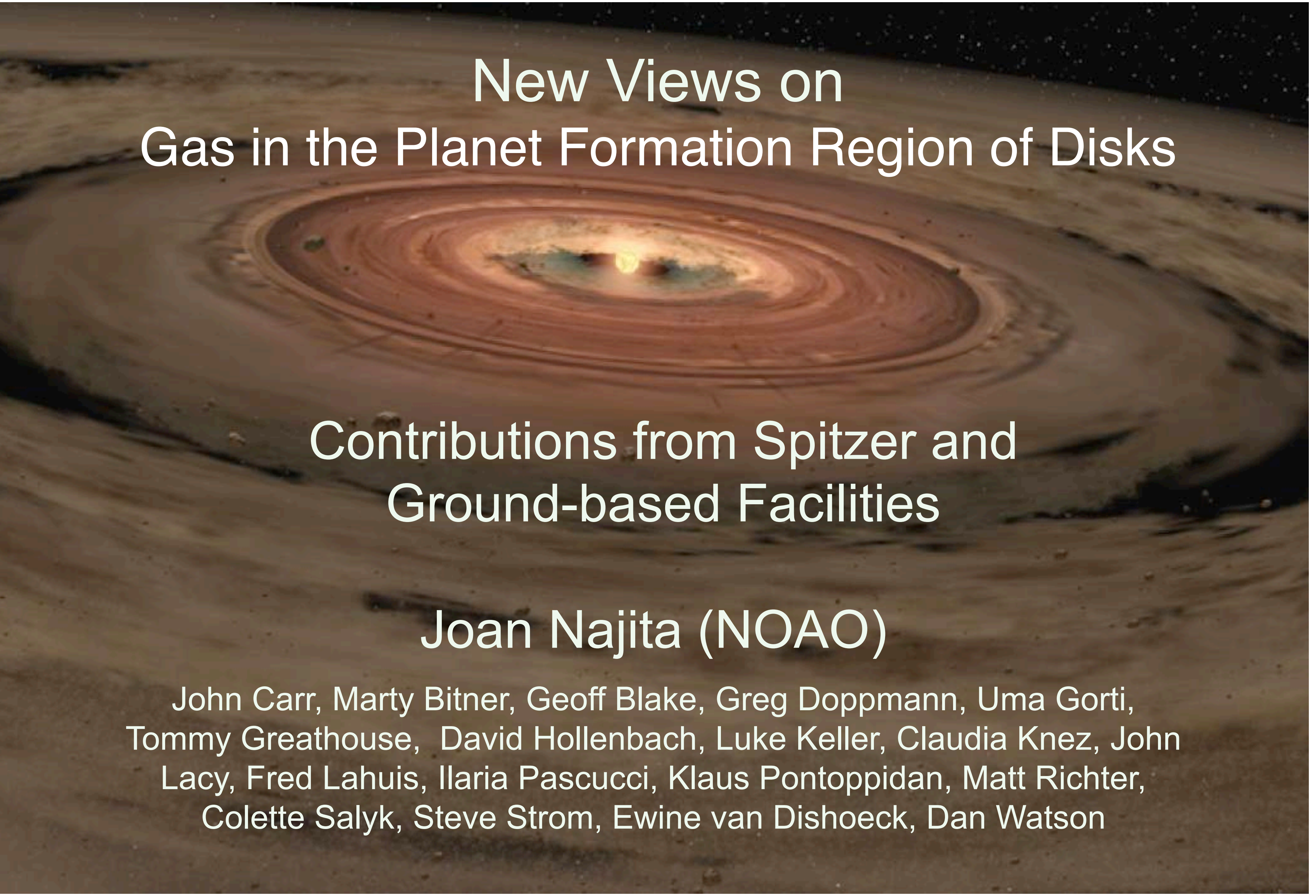


# New Views on Gas in the Planet Formation Region of Disks

## Contributions from Spitzer and Ground-based Facilities

Joan Najita (NOAO)

John Carr, Marty Bitner, Geoff Blake, Greg Doppmann, Uma Gorti, Tommy Greathouse, David Hollenbach, Luke Keller, Claudia Knez, John Lacy, Fred Lahuis, Ilaria Pascucci, Klaus Pontoppidan, Matt Richter, Colette Salyk, Steve Strom, Ewine van Dishoeck, Dan Watson

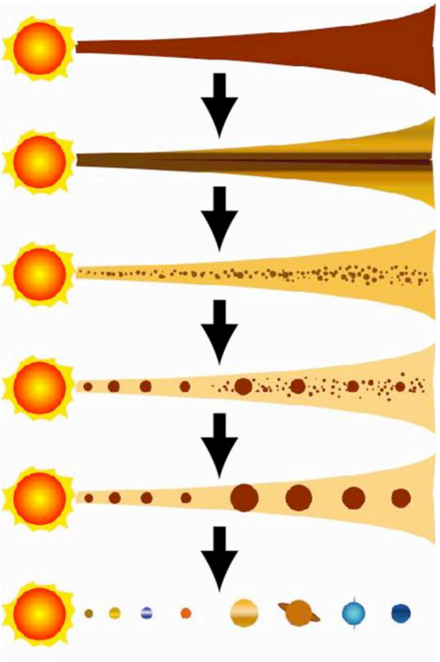
# Why Study Gaseous Disks?

## How did we get here?


What

kinds of disks make what kinds of planets?

**Test Planet Formation Theories**



**Diagnose Ongoing Planet Formation**

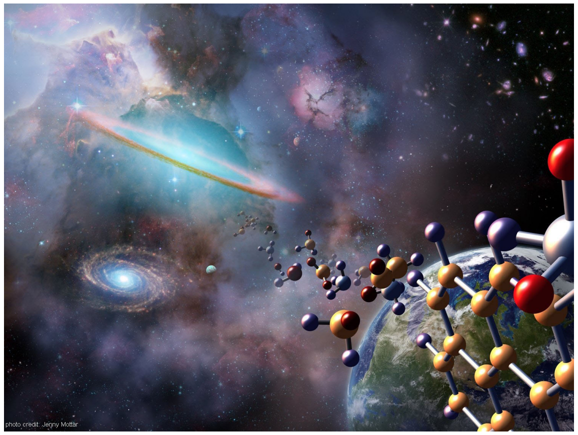


photo credit: Jenny Mottar

**Explore Astronomical Origin of Prebiotic Molecules and Life on Earth**

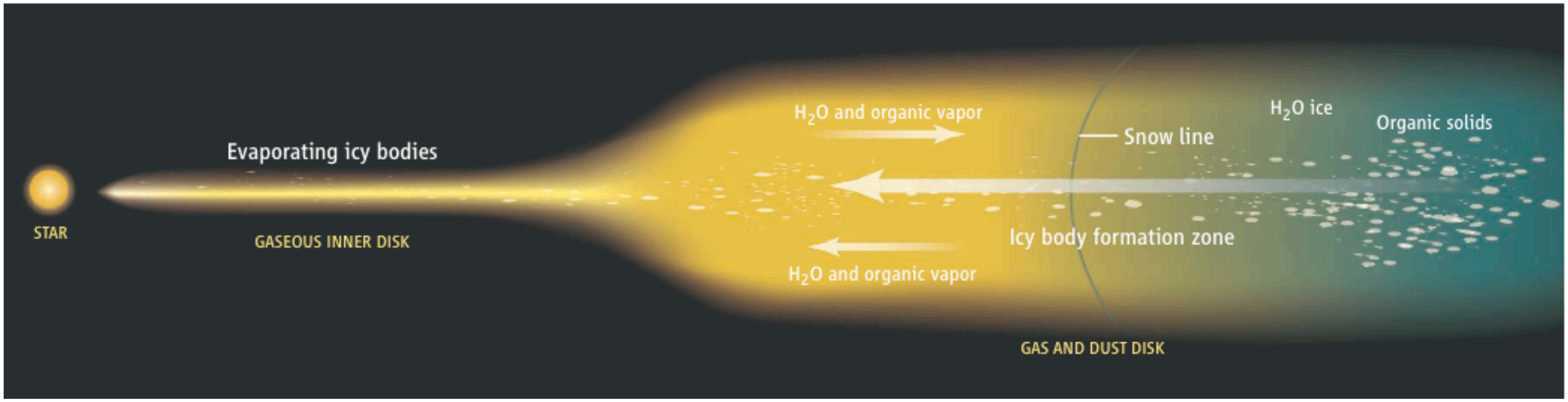
# Extra-terrestrial Origin of Prebiotic Molecules

Were the “chemical building blocks” of life synthesized in clouds and disks and delivered to Earth by asteroids and comets?

Amino acids present in meteorites

Organic molecules, from simple (CO) to complex ($HOCH_2CH_2OH$), detected in comets.

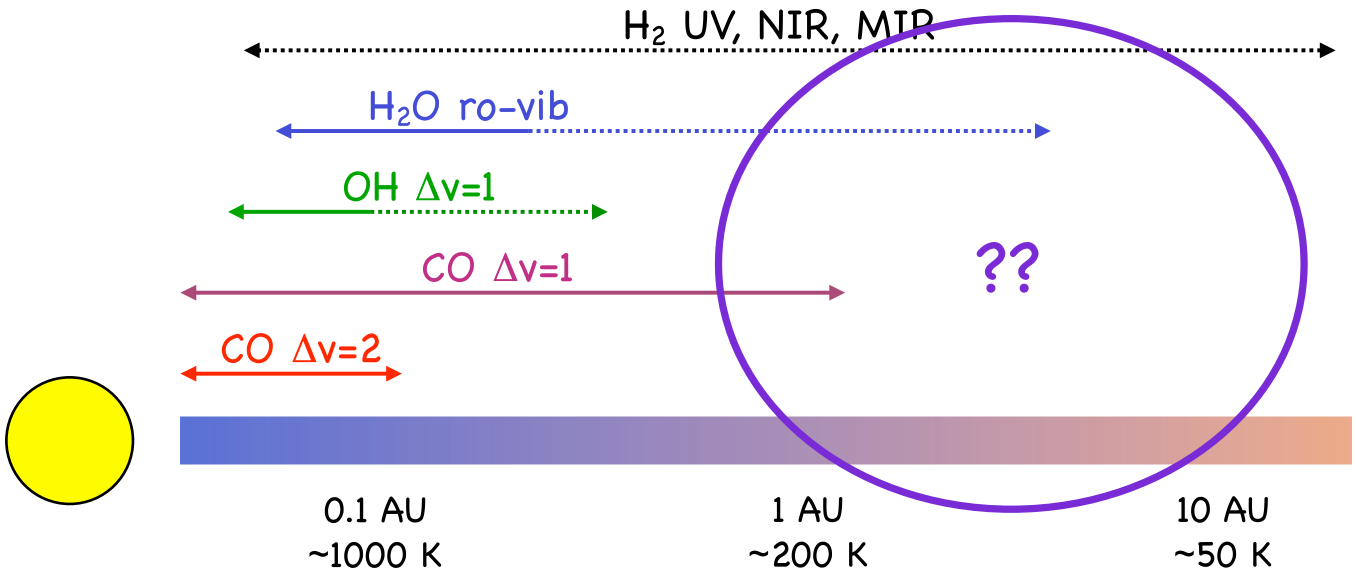
# What is Synthesized in Disks?



- Molecular abundances probe chemistry and transport
- Inner disk abundances (within the snow line) probe evaporation products from outer disk + inner disk chemistry.

# Gaseous Probes of Inner Disks

## (Pre-Spitzer)



$H_2$ UV, NIR, MIR

$H_2O$ ro-vib

OH Δv=1

CO Δv=1

CO Δv=2

??

0.1 AU
~1000 K

1 AU
~200 K

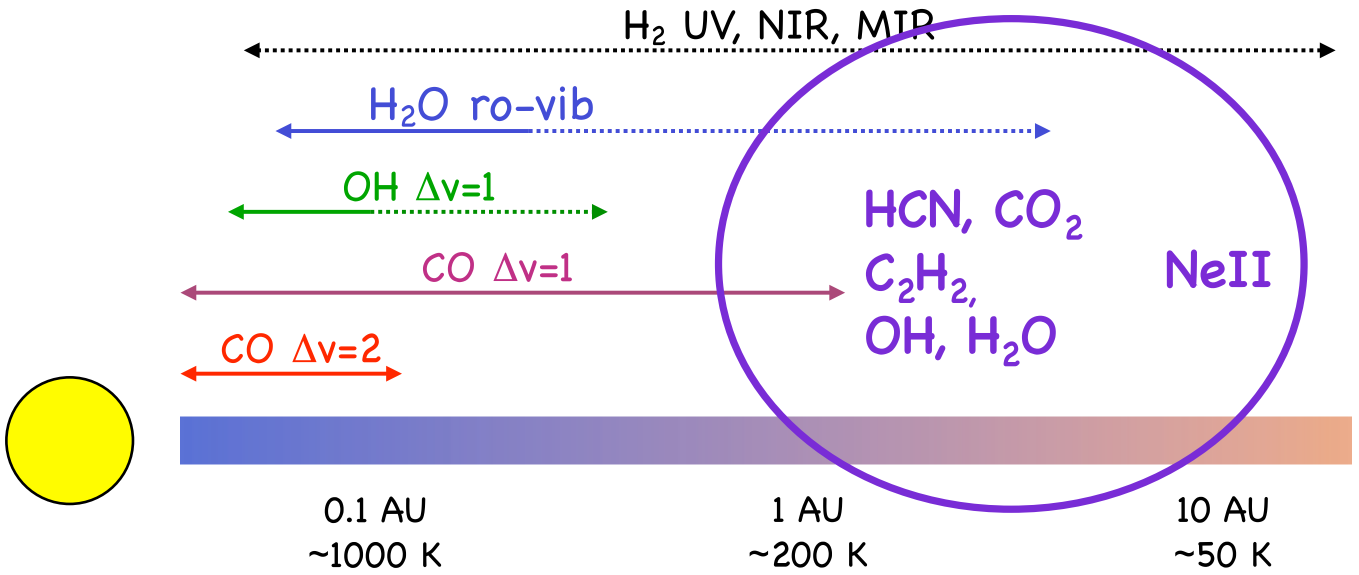
10 AU
~50 K

> 20AU:
CO, $HCO^+$,
CS, $N_2H^+$,
$H_2CO$, CN,
HCN, NHC,
etc

Possibilities:

- ISO: MIR $H_2$ detectable
- Ground: NIR $H_2$

# Gaseous Probes of Inner Disks



$H_2$ UV, NIR, MIR

$H_2O$ ro-vib

OH Δv=1

CO Δv=1

CO Δv=2

HCN, $CO_2$
$C_2H_2$,
OH, $H_2O$

NeII

0.1 AU
~1000 K

1 AU
~200 K

10 AU
~50 K

> 20AU:
CO, $HCO^+$,
CS, $N_2H^+$,
$H_2CO$, CN,
HCN, NHC,
$H_2D^+$, $DCO^+$,
DCN, etc

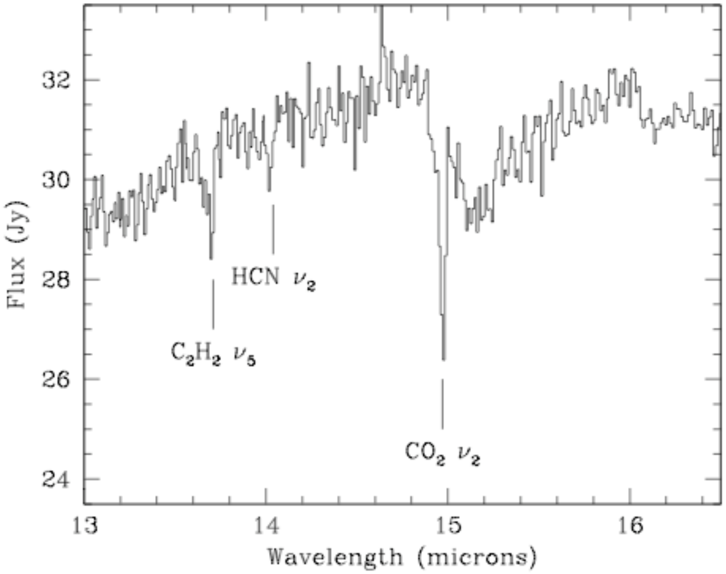
**New diagnostics from Spitzer:**
Water, organic molecules,
Atomics, e.g., NeII

# Organic Molecules in Absorption: GV Tau

## See also Lahuis et al. 2006 IRS 46

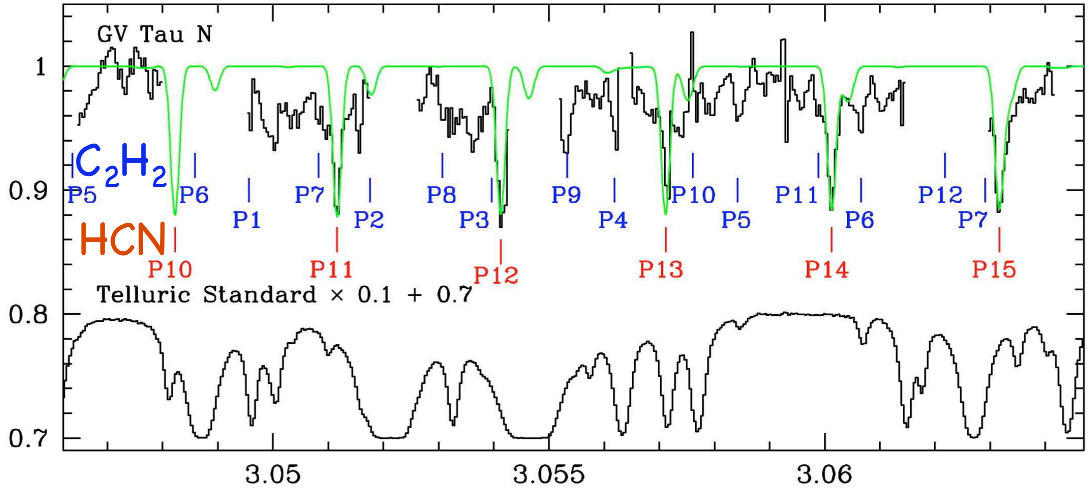
R=600

Spitzer Courtesy IRS GTOs



R=20,000

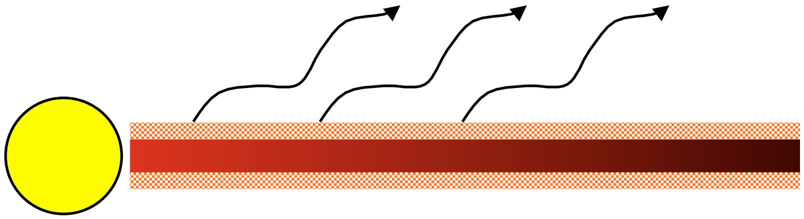
NIRSPEC 3μm: Doppmann et al. 2008;
see also Gibb et al. 2007



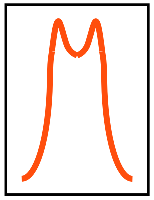
- $C_2H_2$, HCN, $CO_2$ detected in absorption (T=550 for HCN)
- 3μm HCN ~at cloud velocity; absorption in a disk atmosphere?
- Source is very bright in MIR; enables study of other molecules

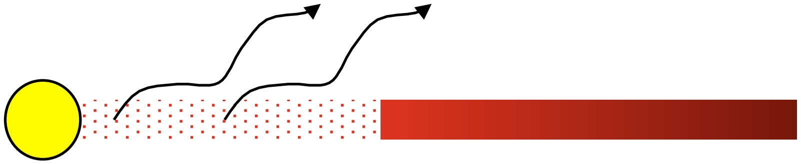
# Disk Spectral Lines

## Emission Lines



Temperature Inversion in
Optically Thick Disk

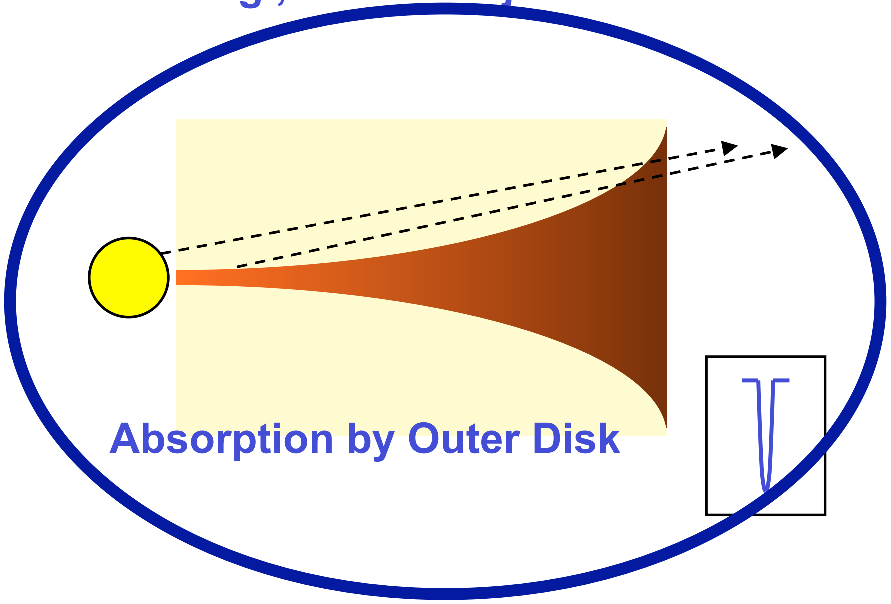




Optically Thin Disk, Hole or Gap

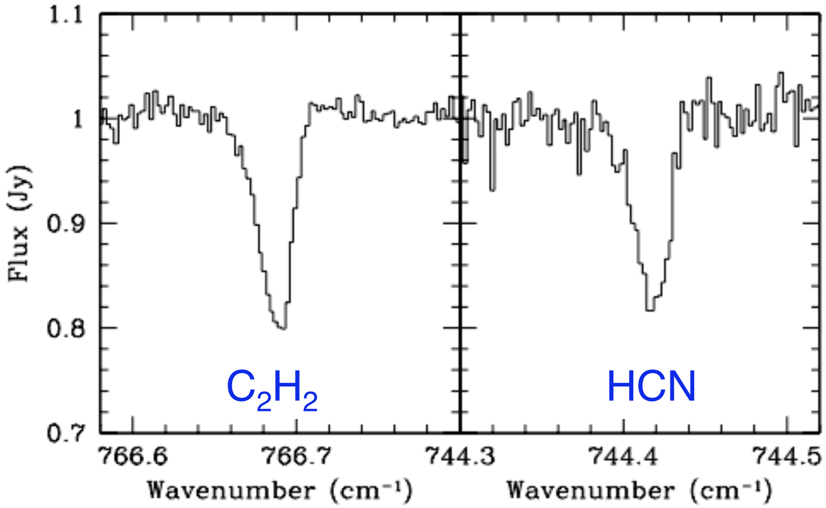
## Absorption Lines

Optically Thick, High $M_{acc}$
e.g., FU Ori object



Absorption by Outer Disk

# MIR Molecular Absorption at High Spectral Resolution

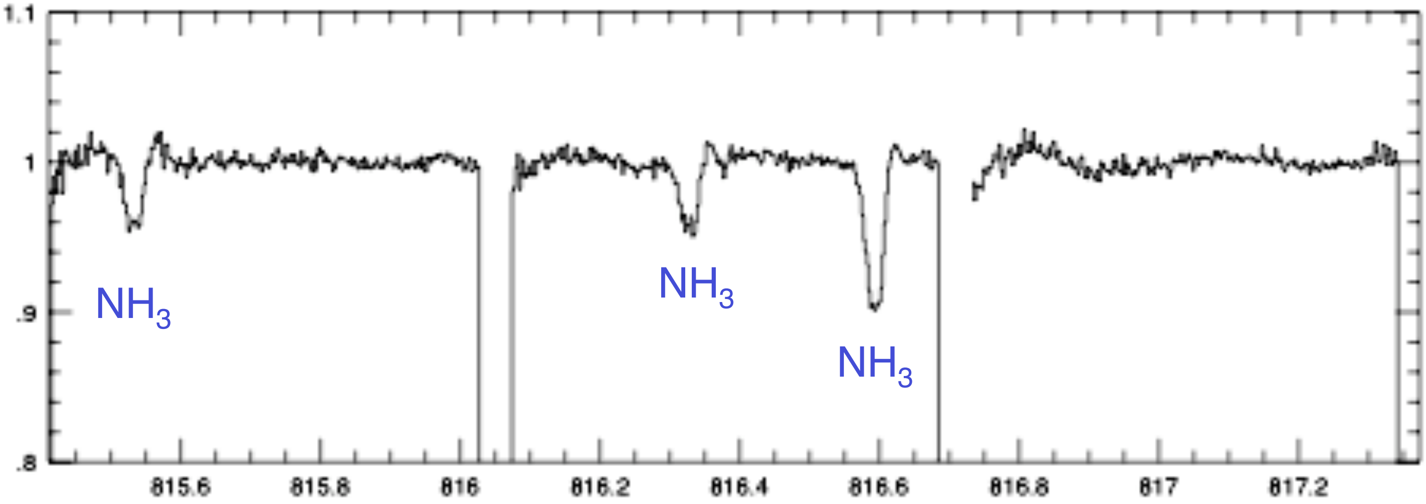


Gemini/TEXES (R=100,000)

FWZI ~ 20 km/s

Can detect molecules w/o strong bands that Spitzer does not detect.

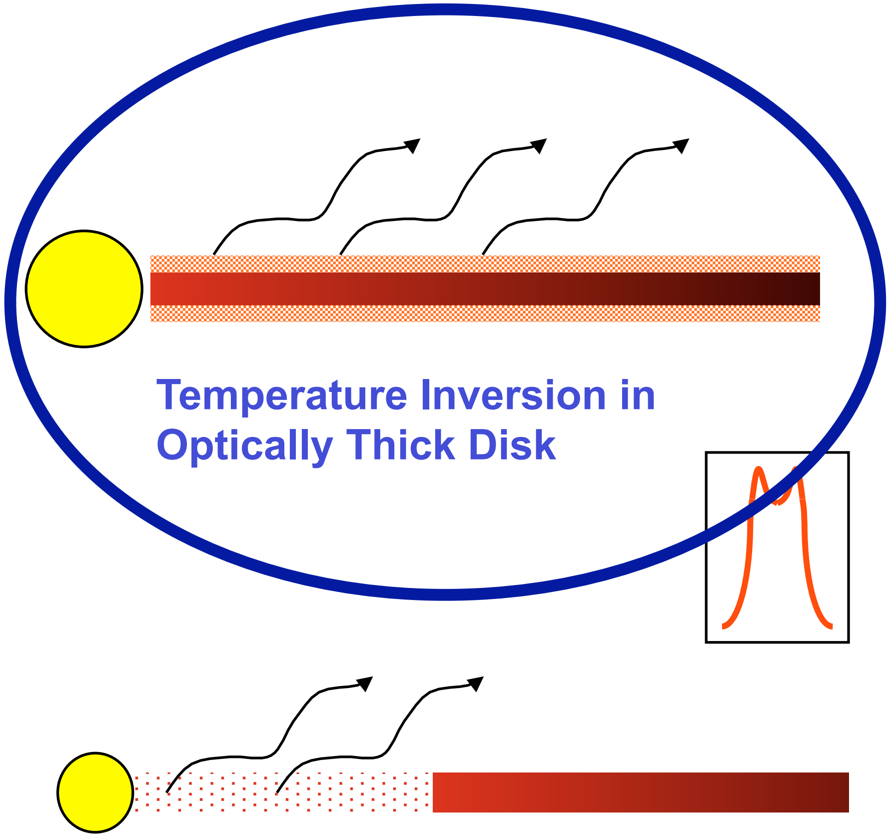
Study relative abundances in disk atmospheres.



Related results in Knez et al. (2009) for a disk around a high mass star

# Disk Spectral Lines

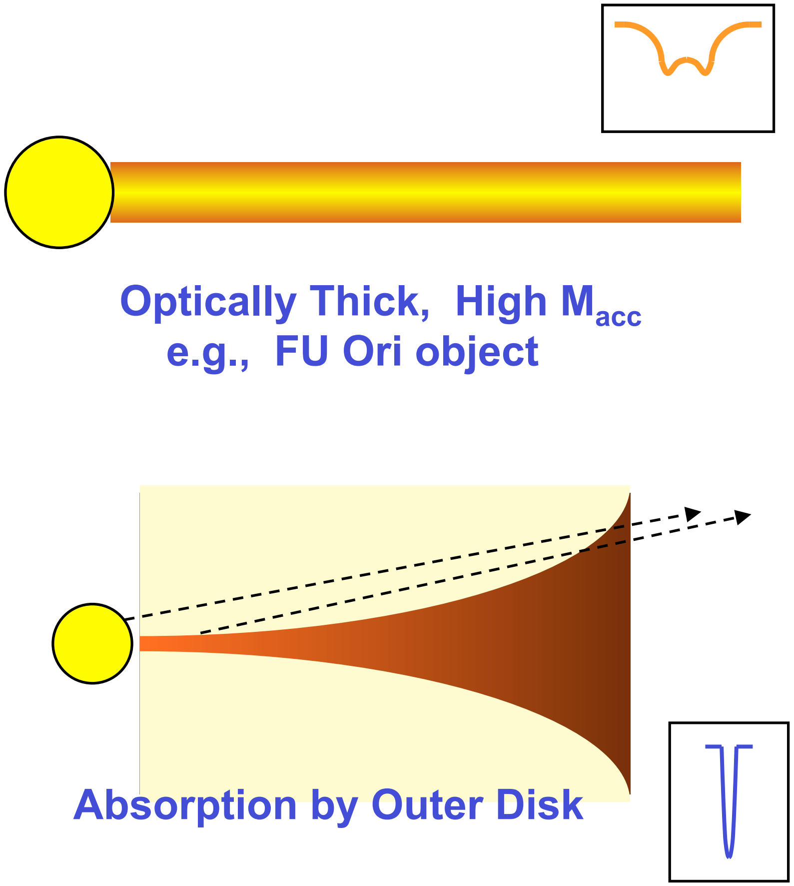
## Emission Lines



Temperature Inversion in
Optically Thick Disk

Optically Thin Disk, Hole or Gap

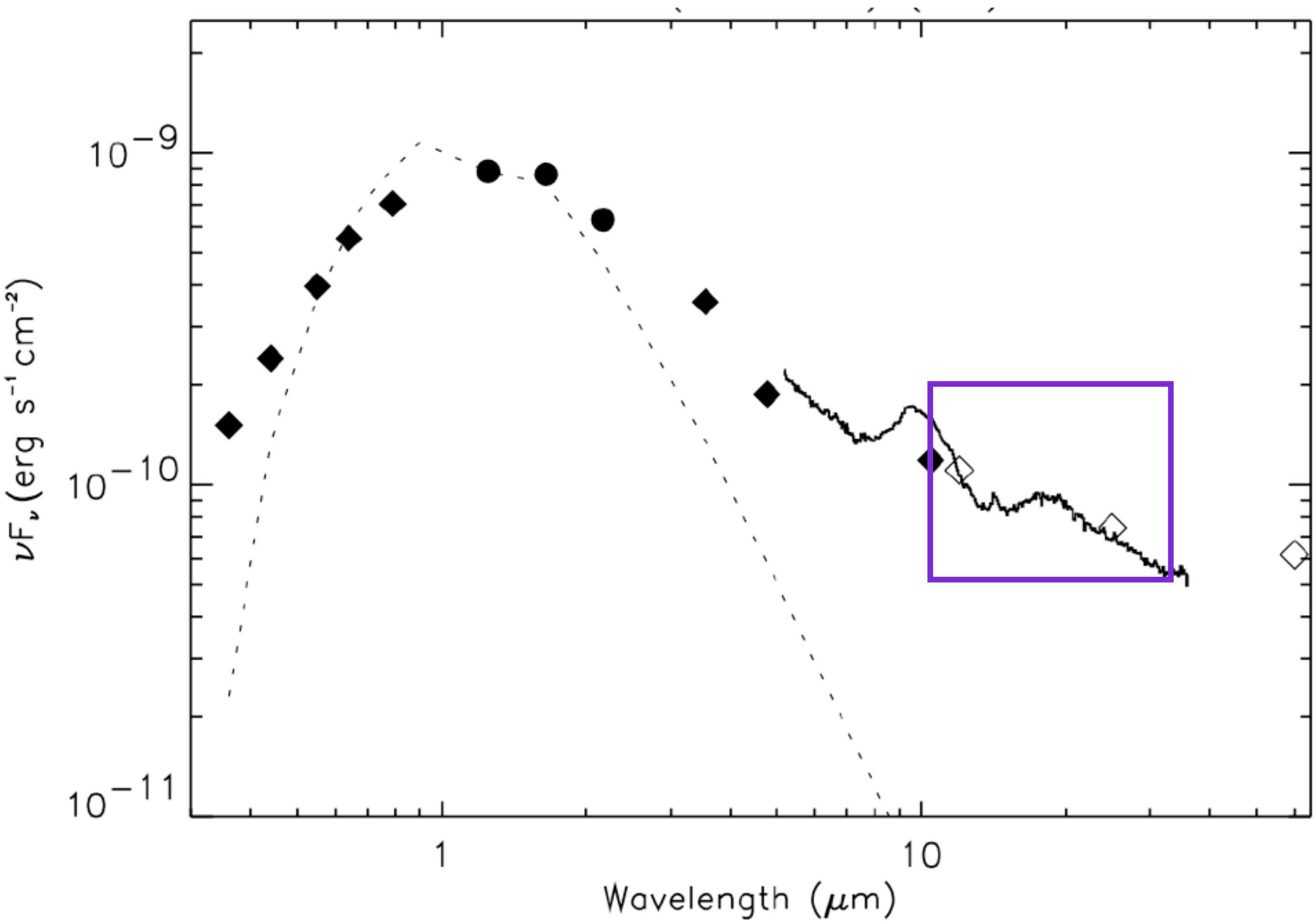
## Absorption Lines



Optically Thick, High $M_{acc}$
e.g., FU Ori object

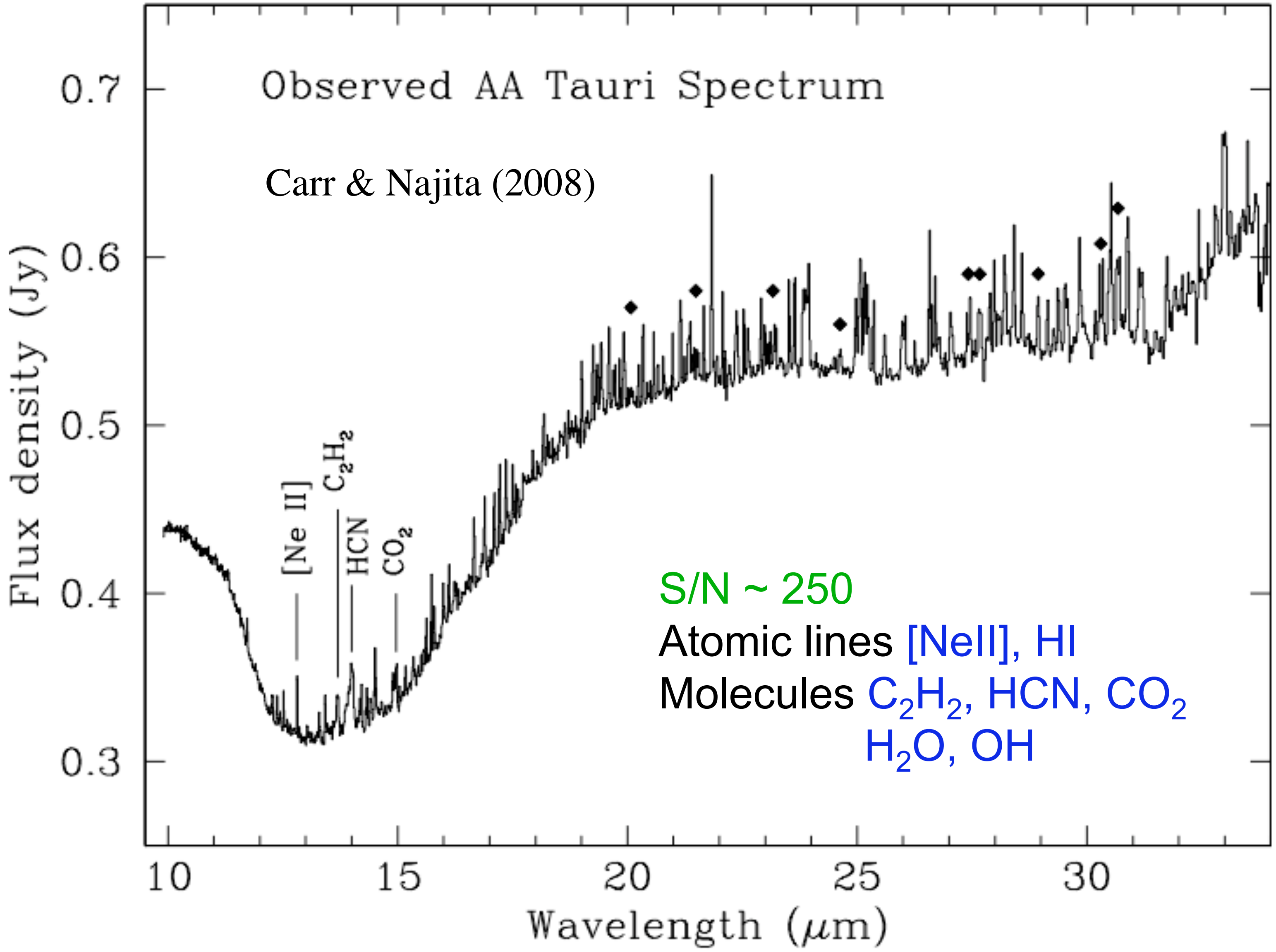
Absorption by Outer Disk

# Spitzer IRS Spectrum of a Typical T Tauri Star



Low resolution, modest s/n

# Spitzer IRS Spectrum of a Typical T Tauri Star



Carr & Najita (2008)

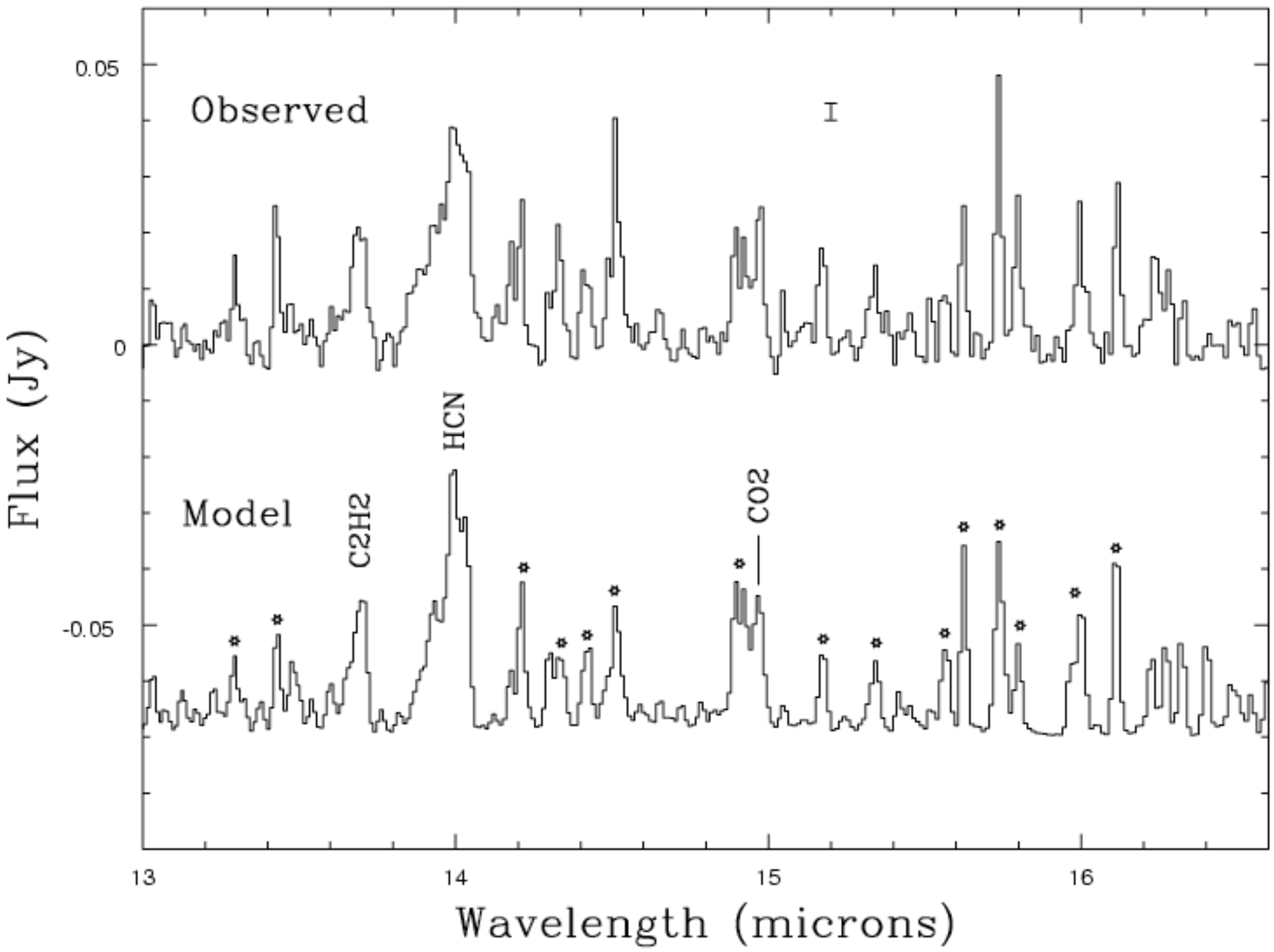
S/N ~ 250

Atomic lines [NeII], HI

Molecules $C_2H_2$, HCN, $CO_2$
$H_2O$, OH

**See also Salyk et al. (2008) on Spitzer detection of water in disks.**

# Continuum-subtracted T Tauri Star Spectrum



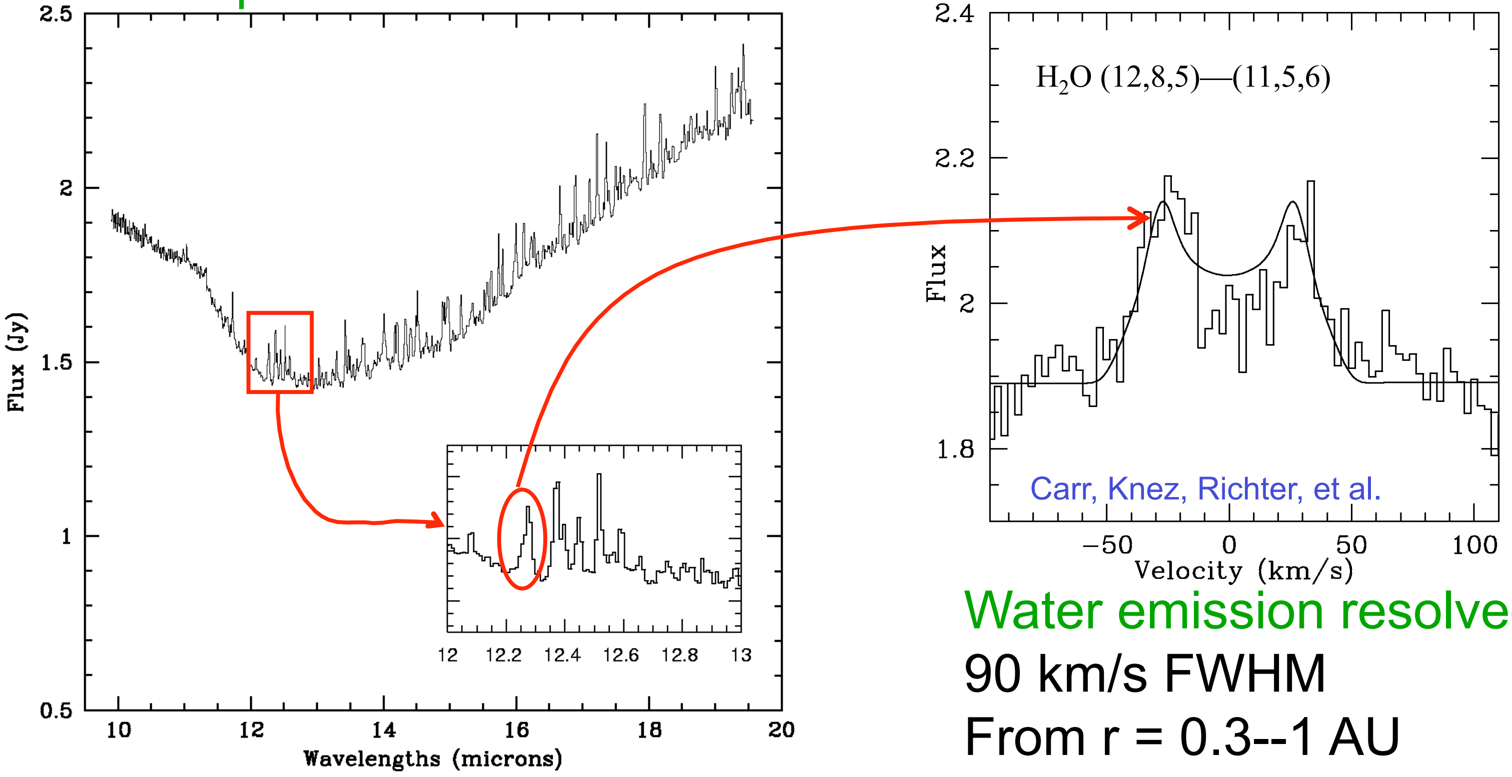
Lines of water throughout (*)

# Molecular Emission Properties

| Molecule | T (K) | N ($10^{16}$cm$^{-2}$) | R (AU) |
|---|---|---|---|
| $H_2O$ | 575 | 65 | 2.1 |
| OH | 525 | 8.1 | 2.2 |
| HCN | 650 | 6.5 | 0.6 |
| $C_2H_2$ | 650 | 0.81 | 0.6 |
| $CO_2$ | 350 | 0.2–13 | 1.2 |
| CO | 900 | 49 | 0.7 |

Temperatures and emitting areas consistent with an origin in the terrestrial planet region of the disk

# $H_2O$ Rotational Emission Line Resolved


Spitzer/IRS R=600

Gemini/TEXES R=100,000

Carr, Knez, Richter, et al.

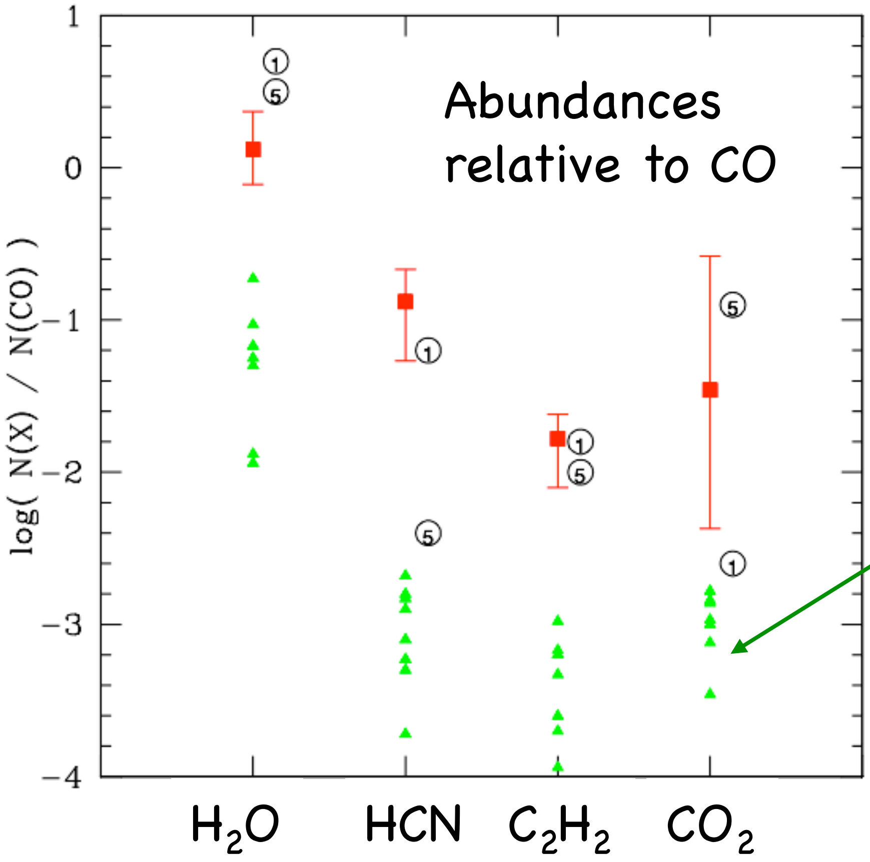
Water emission resolved:

90 km/s FWHM

From r = 0.3--1 AU

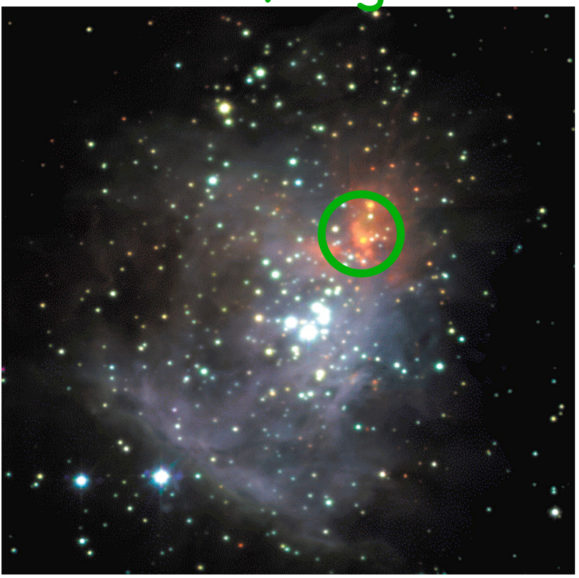
Line profiles, temperatures, and emitting areas indicate origin in planet formation region of disk

# AA Tau Molecular Abundances



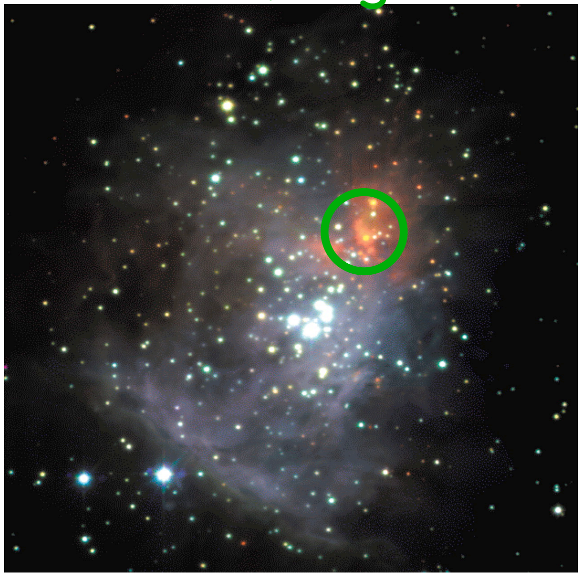
Higher abundances than hot cores
→Molecular synthesis in disks
→Similar chemistry to hot cores?

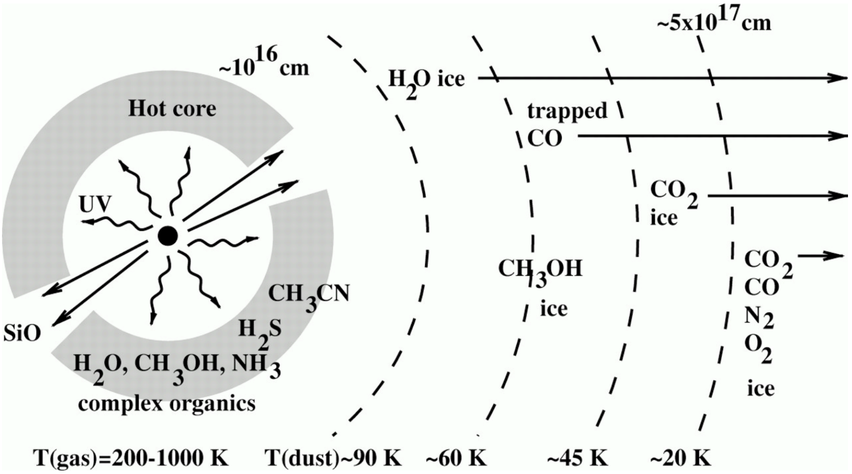
“Hot core”, e.g. Orion

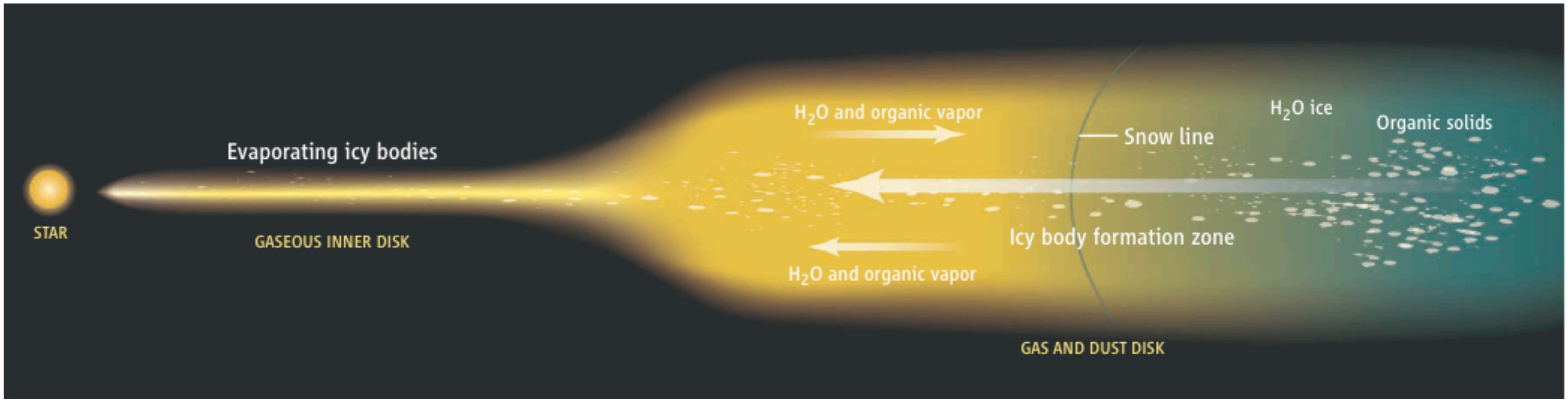


# Hot Core and Disk Chemistry

"Hot core", e.g. Orion

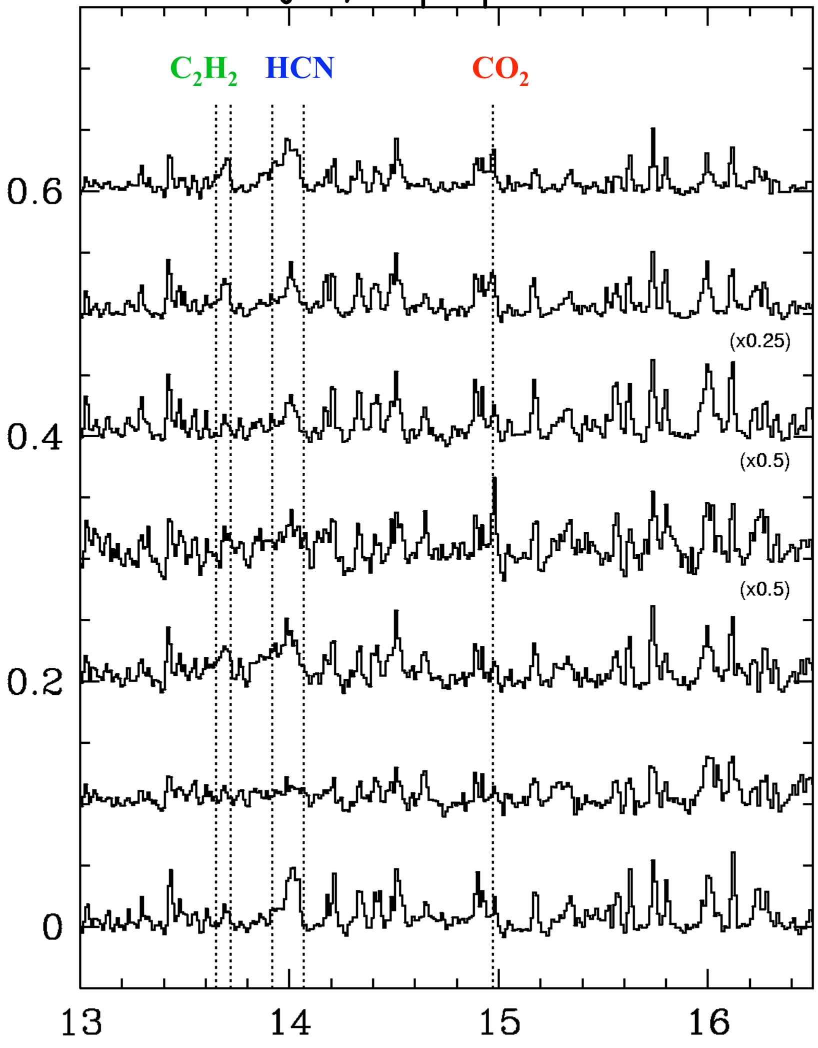






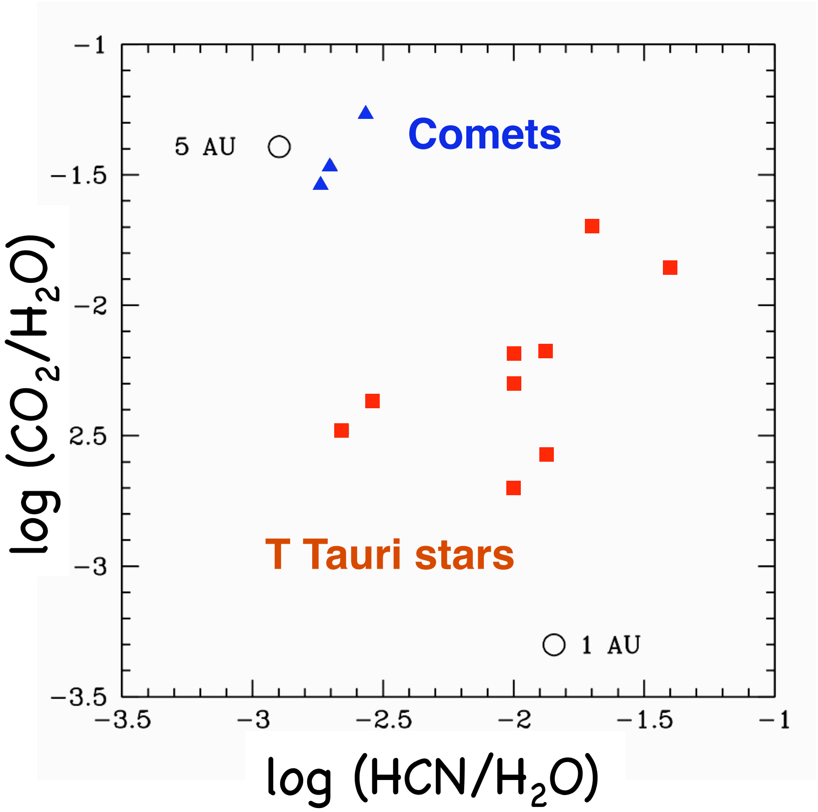
# Molecular Emission is Common, Diverse

Carr & Najita, in prep.



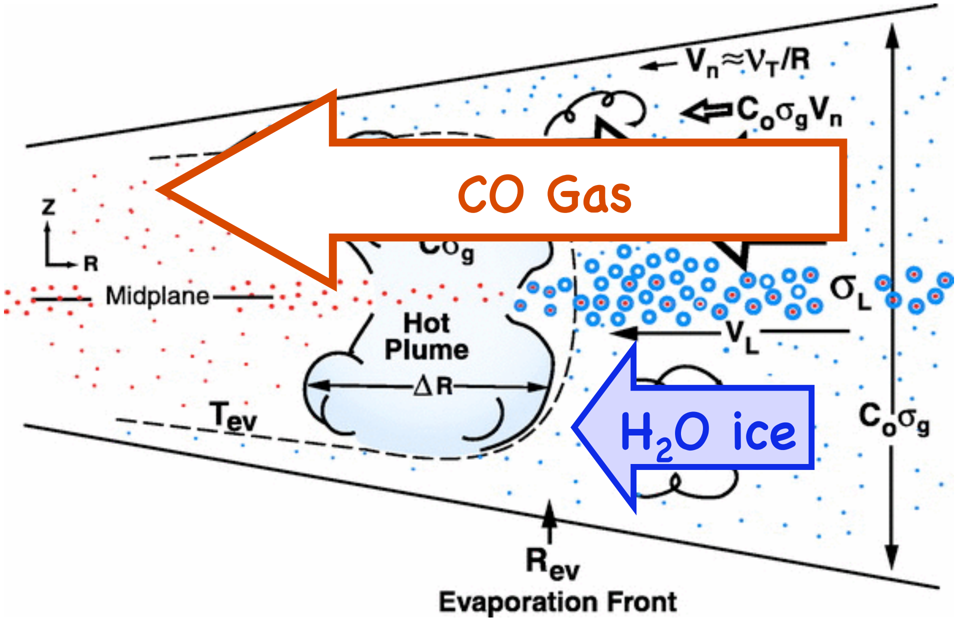
See also Salyk et al. (2008)

- Relative strengths of molecular features vary.
- Abundances are diverse.



# Can Abundances Probe Icy Bodies?

Problem: planetesimals (~1 km) and protoplanets (~$M_{Mars}$) are too small to open gaps. How to detect them?



Cuzzi & Zahnle 2004
Ciesla & Cuzzi 2007

Large (> 1km), non-migrating bodies dehydrate inner disk (low $H_2O$); increases C/O; enhances organic molecules?

# What Can We Learn from Surface Abundances?

**May be affected by:**

- Irradiation (UV, X-rays)
- Radial & vertical mixing
- Accretion
- Grain growth & settling
- Planetesimal migration
- etc.

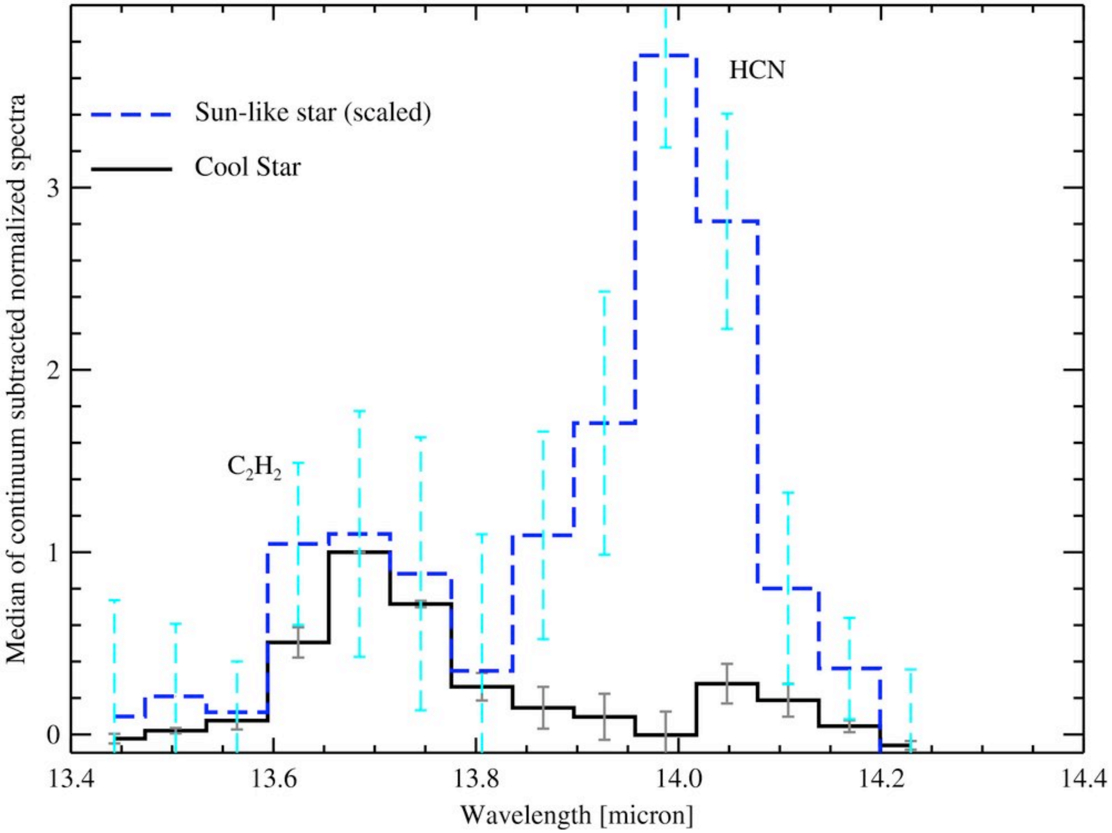
**Measurable demographics:**

- $L_X$, $L_{UV}$
- Mdot
- SED shape
- Silicate feature morphology
- Crystallinity

**Need a big survey:** Carr, Blake, van Dishoeck, Pontoppidan, Salyk, Lahuis, & Najita (GO5)

# Different Abundances vs. Stellar Mass?

(Pascucci et al. 2008)



T Tauri stars

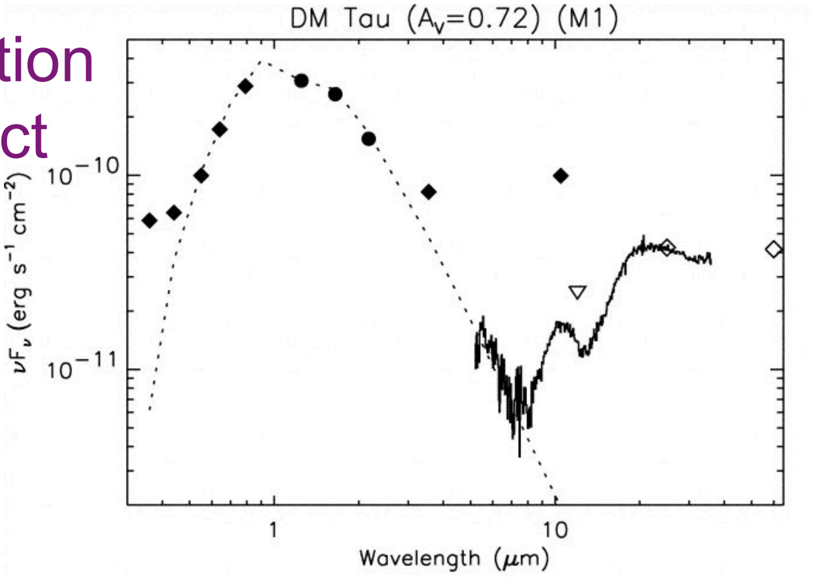
(HCN > $C_2H_2$)

Brown dwarfs

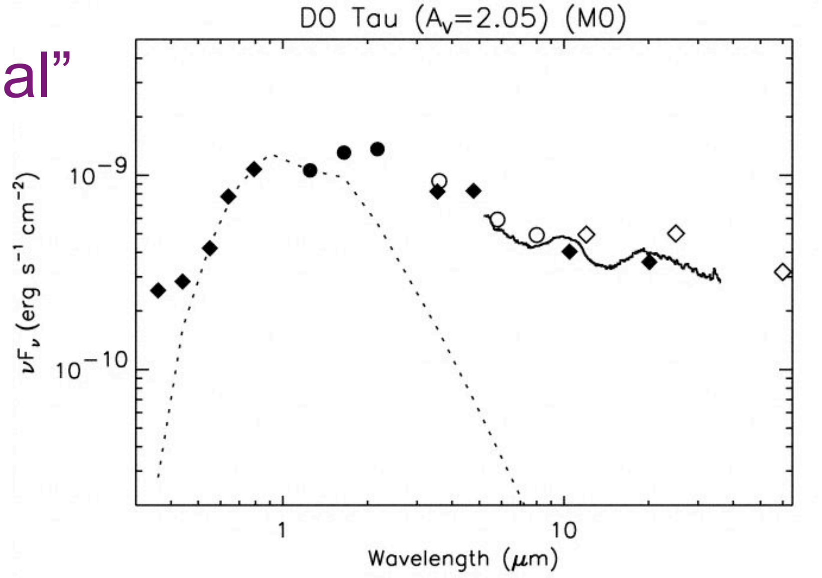
($C_2H_2$ > HCN)

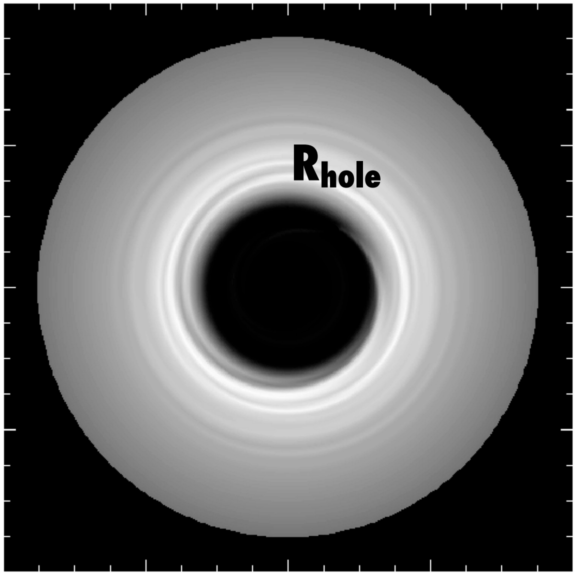
# Transition Object SEDs imply evolution

Transition
Object



“Normal”





Optically thin inner region

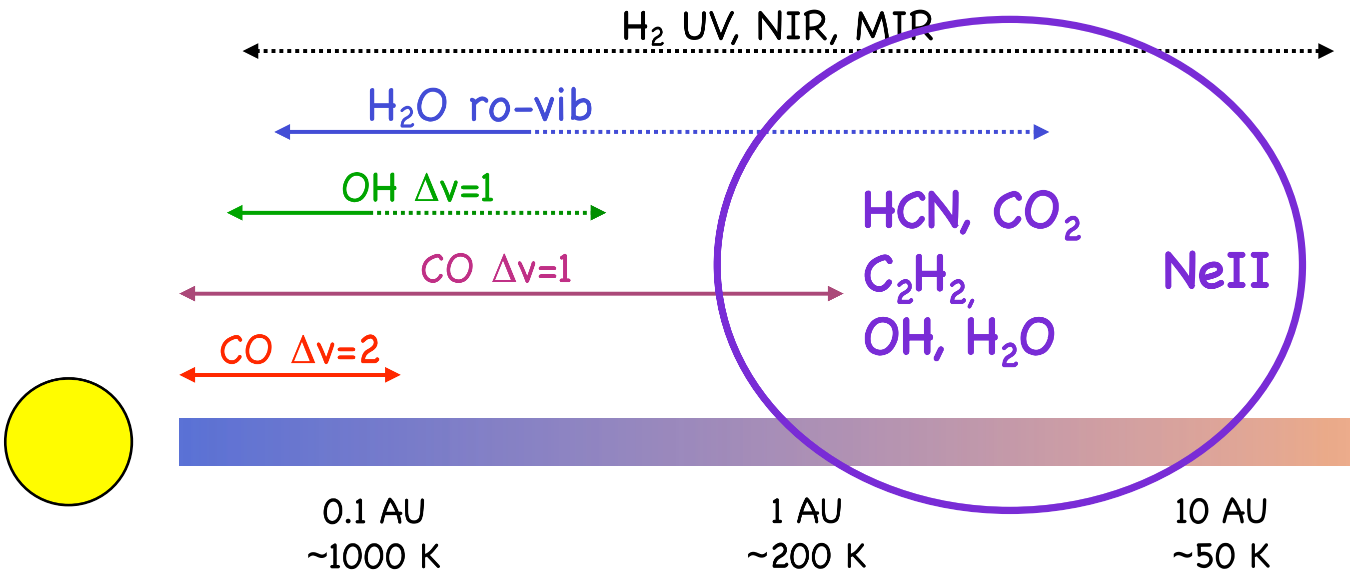
(< $R_{hole}$ = 1-50 AU)

Optically thick outer disk

(> $R_{hole}$)

Are they forming giant planets?

# Probing Gaseous Disks of Transition Objects



$H_2$ UV, NIR, MIR

$H_2O$ ro-vib

OH $\Delta v=1$

CO $\Delta v=1$

CO $\Delta v=2$

HCN, $CO_2$

$C_2H_2$,

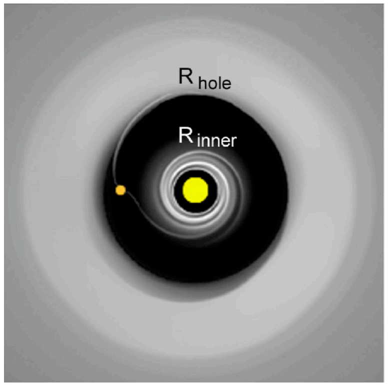
OH, $H_2O$

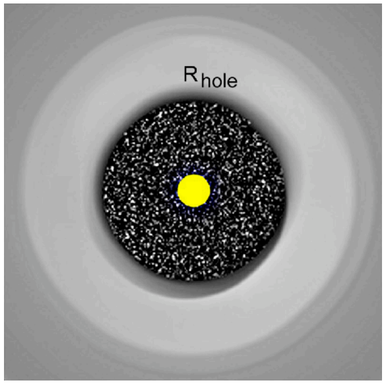
NeII

0.1 AU
~1000 K

1 AU
~200 K

10 AU
~50 K

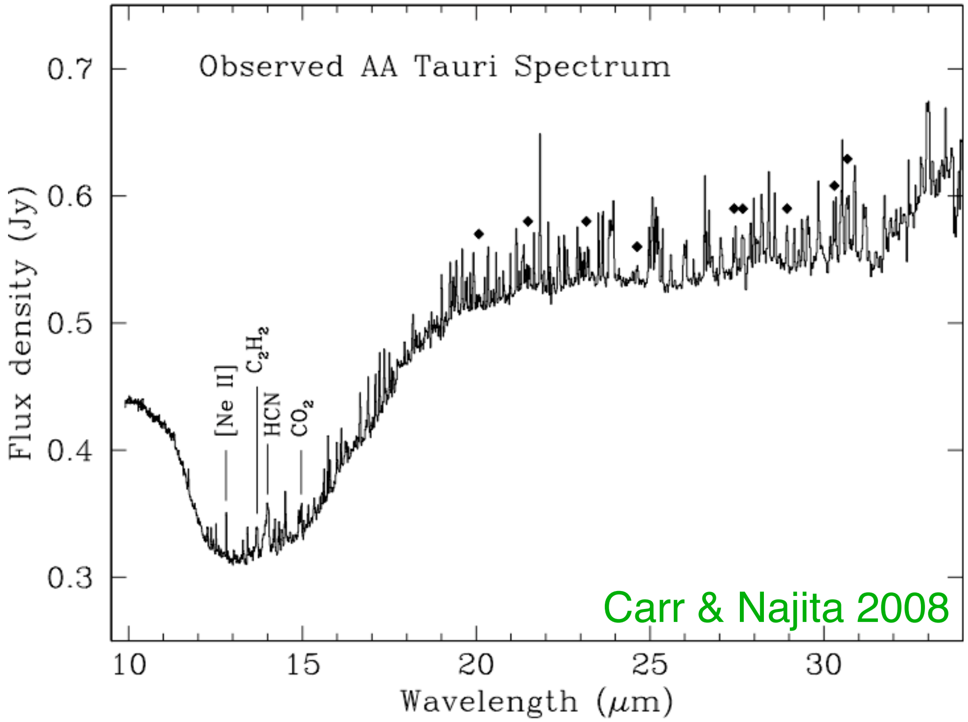




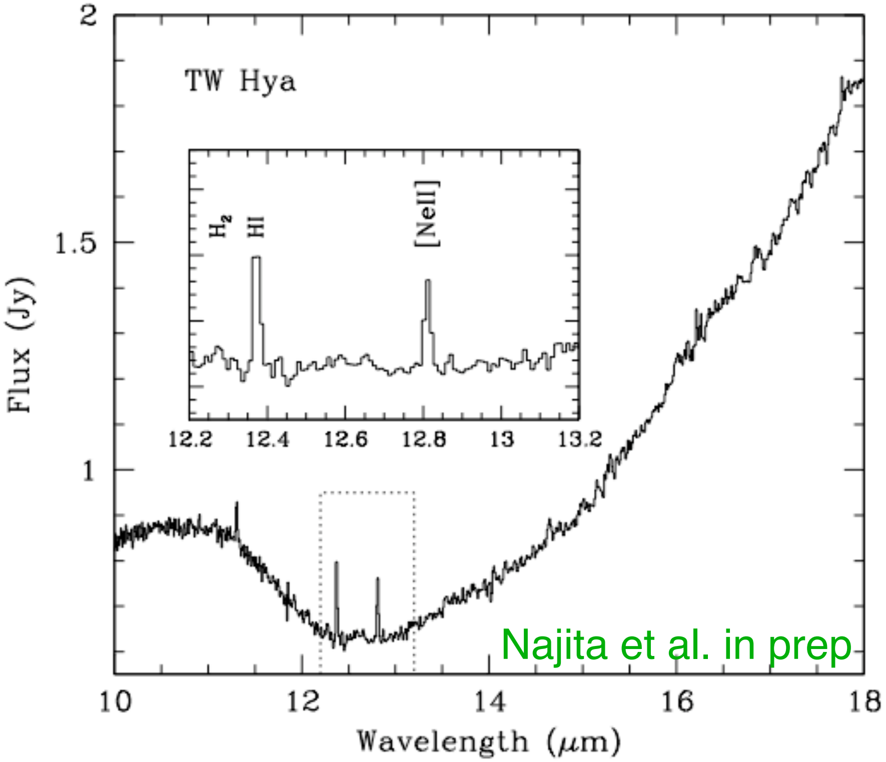
Transition objects with massive outer disks (many $M_J$) typically show stellar accretion, signatures of an inner gaseous disk (CO, UV $H_2$).

(Najita et al. 2003; Bergin et al. 2004; Rettig et al. 2004; Herczeg et al. 2006; Salyk et al. 2007, 2009)

# A typical CTTS and a Transition Object



Carr & Najita 2008

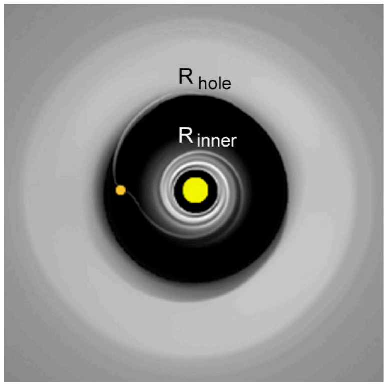


Najita et al. in prep

TOs lack strong molecular emission at 10-20μm

- Gap created by an orbiting giant planet?
- Different inner disk chemistry or excitation?

Need theory…or empirical approach?



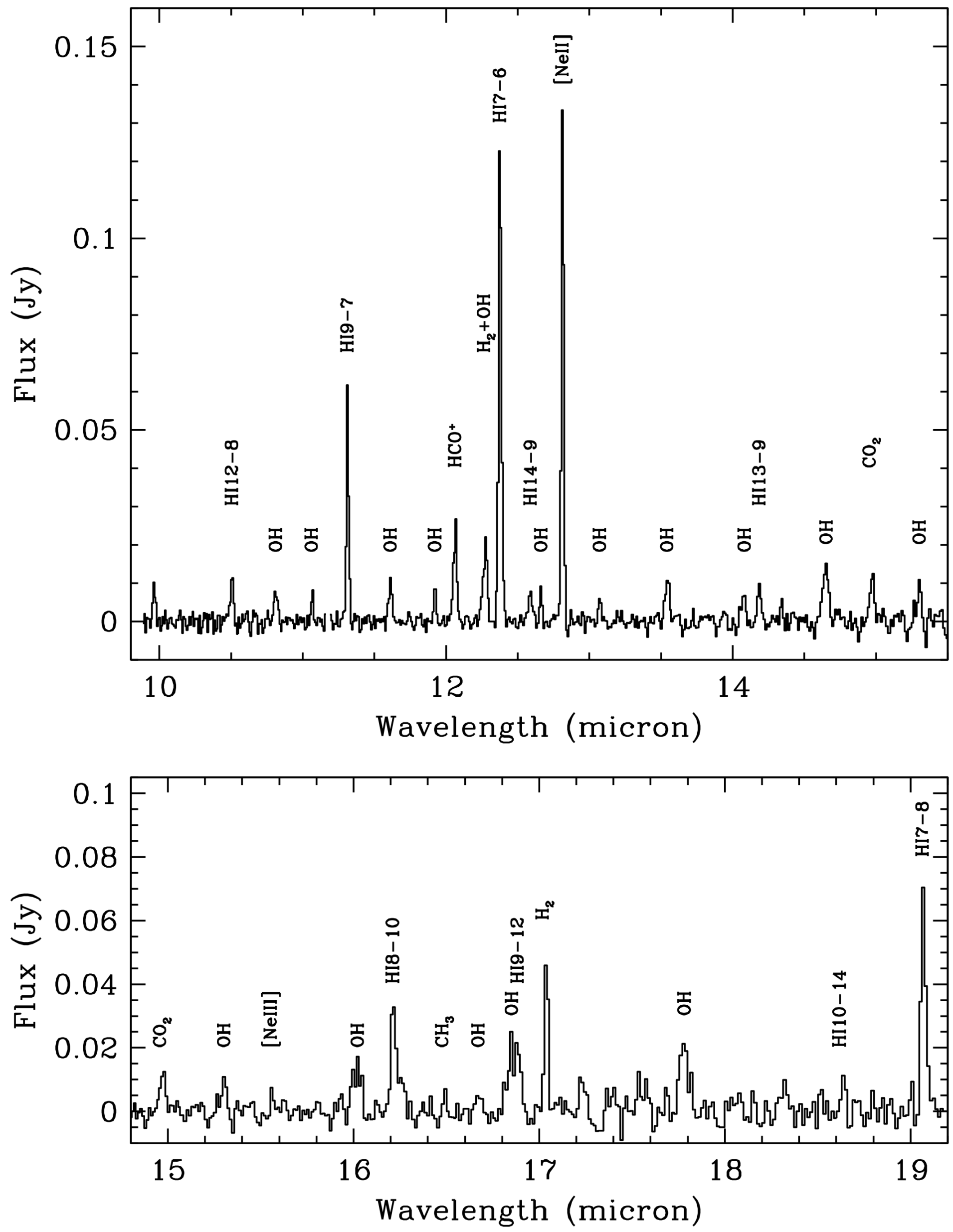
# Theories of Gaseous Disk Atmospheres

| Species | Studies |
|---|---|
| Atomic, $H_2$, CO, $H_2O$ | Glassgold et al. 2004, 2007, 2009<br>Meijerink et al. 2007, 2009 |
| | Kamp & Dullemond 2004+<br>Jonkheid et al. 2004+ |
| | Gorti & Hollenbach 2008, 2009 |
| Focus on $H_2$ | Nomura & Millar 2005,<br>Nomura et al. 2007, 2009 |
| Focus on Atomic | Ercolano et al. 2008+ |
| Water and Organics | Markwick et al. 2002<br>Agundez et al. 2008<br>Woods & Willacy 2008 |

Note: different assumptions about heating processes, chemistry, gaseous hydrostatic equilibrium.

# Rich (but Weak) Emission from a Transition Object

Najita et al. (2009)



**Qualitatively New:**

HI recombination lines

NeII, NeIII

$H_2$ rotational

Hot OH

Do these probe

A tenuous disk atmosphere?

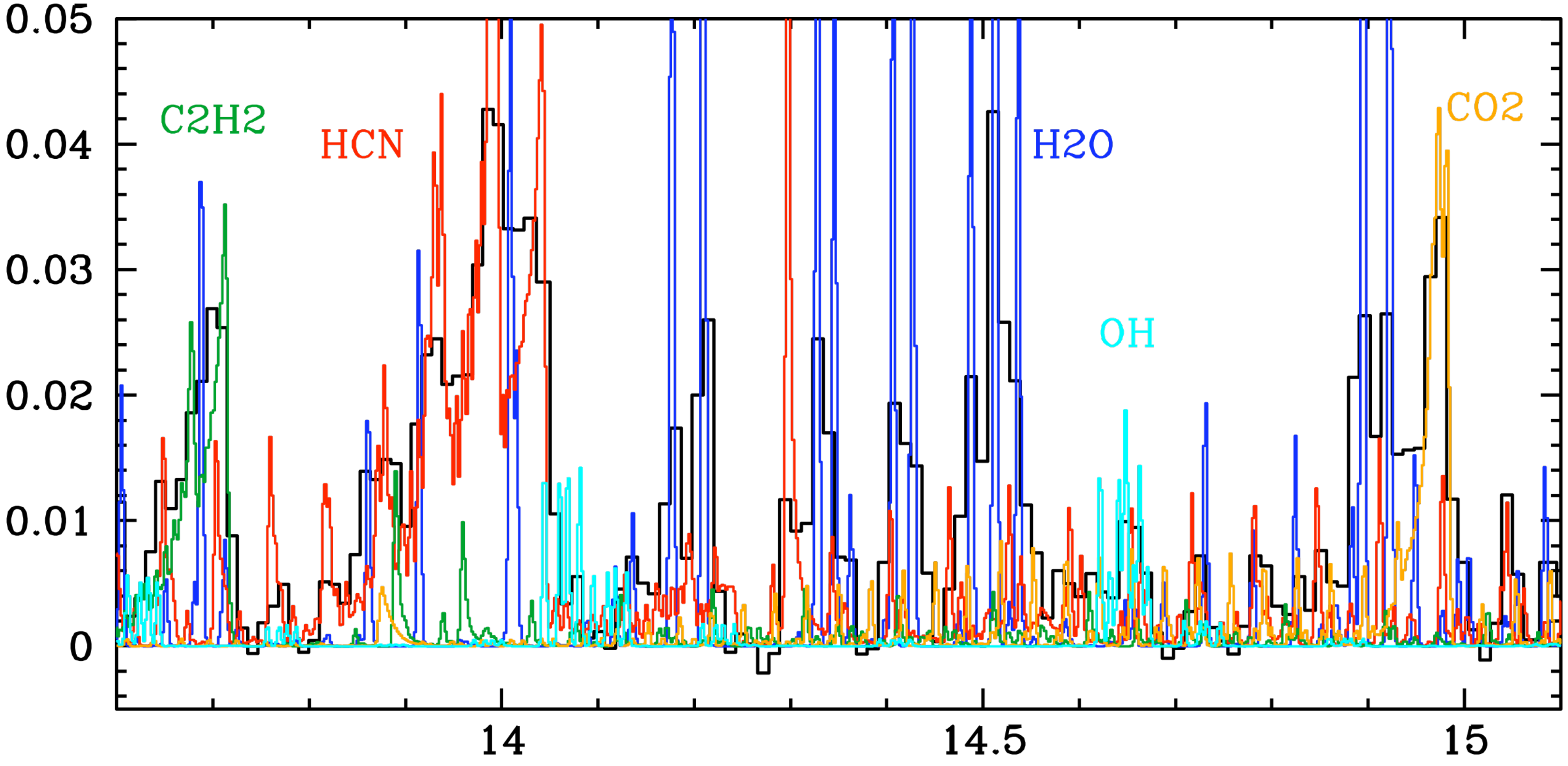
A disk photoevaporative flow?

(Ercolano, Hollenbach/Gorti)

Possible insights into disk dissipation and lifetimes

Are these present in normal T Tauri stars as well?

# JWST/MIRI



- Higher sensitivity than Spitzer/IRS, over 5-30μm
- Higher resolution (R=3000) resolves more blends (not velocity structure).
- Detect and characterize more species, measure average N and T.
- GSMT (R=100,000): resolve velocity structure, measure N(r) and T(r).

# New Window on Disk Chemical Evolution

**Planet Formation Region of Disks:**

**Emission**: probe typical sources

**Absorption**: probe large column densities, rare species

Spitzer, JWST,
8-30m telescopes

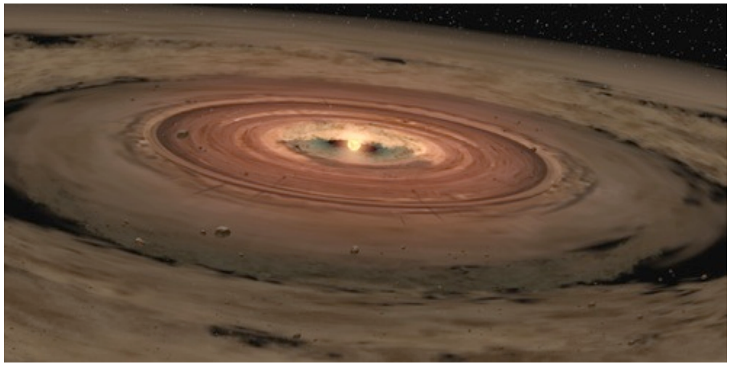
ALMA

**Results indicate that disks are chemically active**

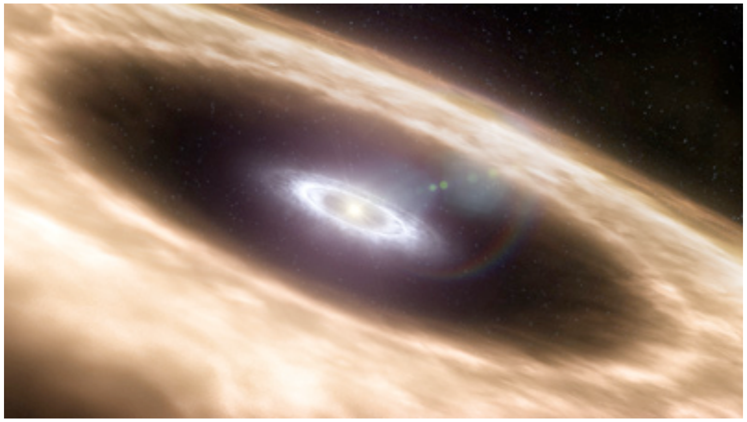
**Anticipate exciting results from Spitzer, JWST, GSMT**

# New Window on Planet Formation Environments

## Abundances are Diverse



- Clues to processes governing physical and chemical evolution of disks (irradiation, transport, accretion, grain growth, planetesimals)



## Spectra of Possible Planet-forming Systems Differ from Normal T Tauri stars

- Consistent with giant planet formation, but possibly different chemistry or excitation?