The Evolution of Gas in Protoplanetary Disks

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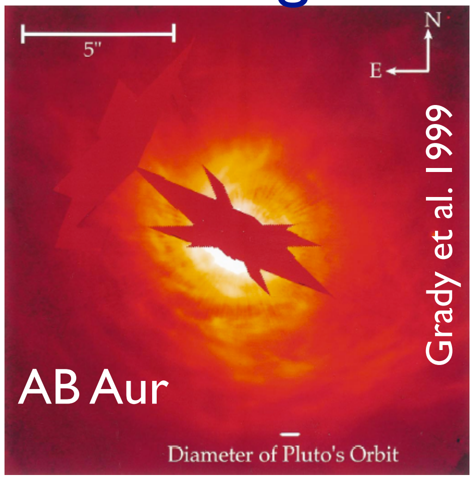
Outline

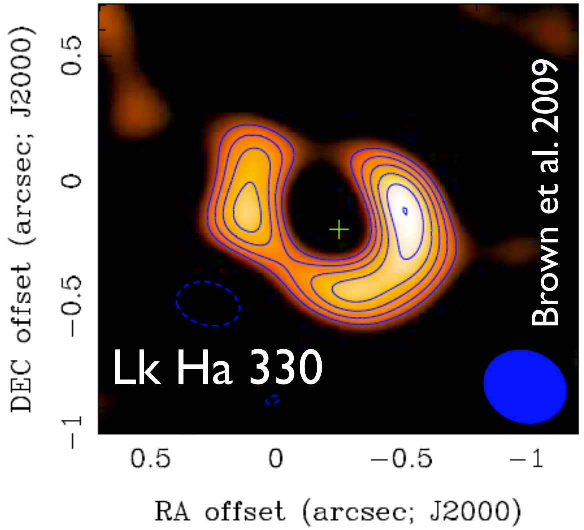
1. Motivate the study of gas in disks

2. Gas in protoplanetary disks

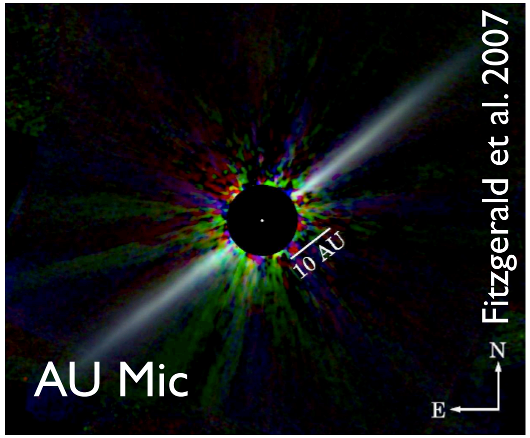
Young



Evolved



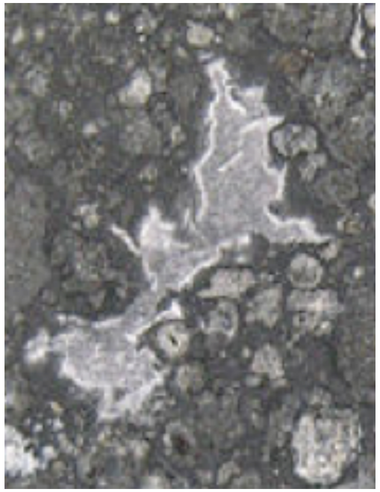
Debris



3. Herschel first results and key contributions

Gas in the protosolar nebula

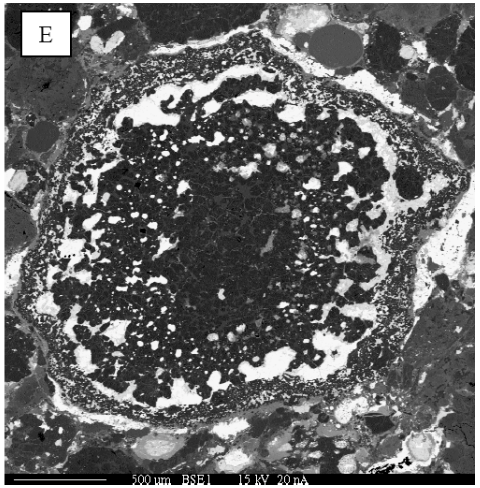
CAI



~2,000 K gas present

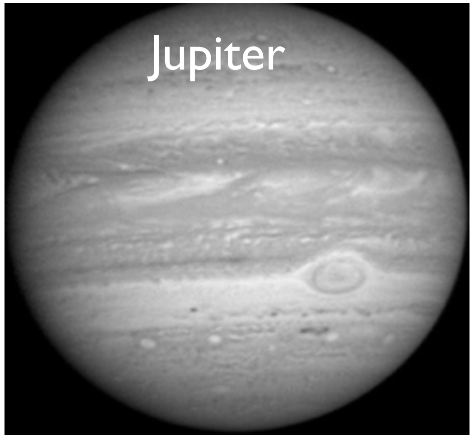
oldest solids

Chondrule

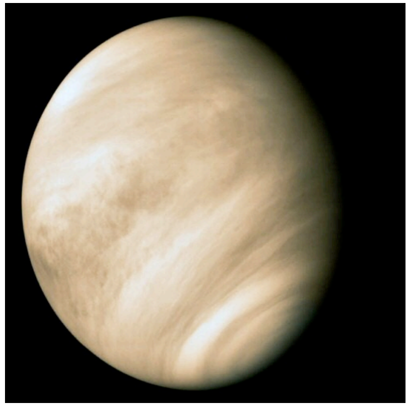


~ 2Myr

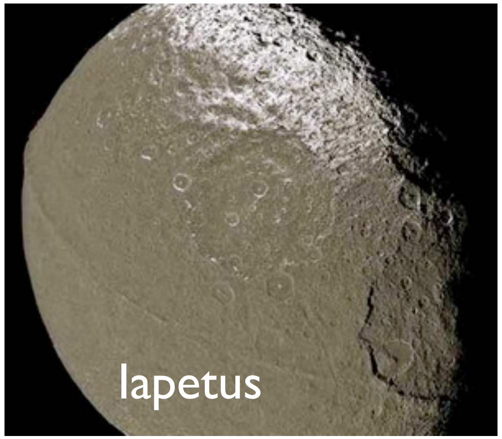
gas present



~ 5 Myr (?)



+50 Myr



photoevaporating nebula (?)

gas (?)

Pascucci & Tachibana 2010

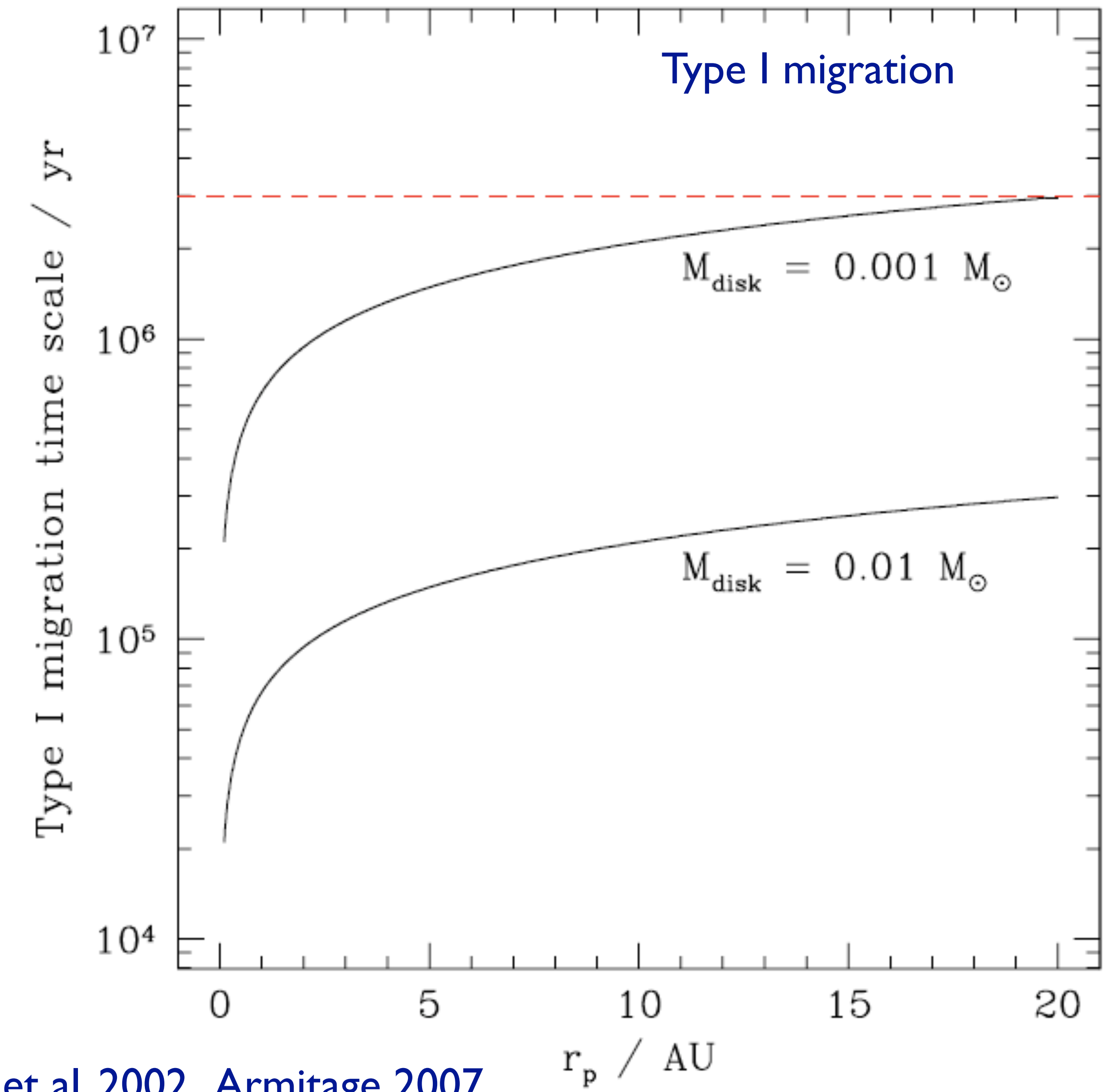
The evolution disk gas directly affects:

– when giant planets form and their atmosphere

– the final location of planets in the disk

– the habitability of terrestrial planets
(circular orbits and volatile delivery)

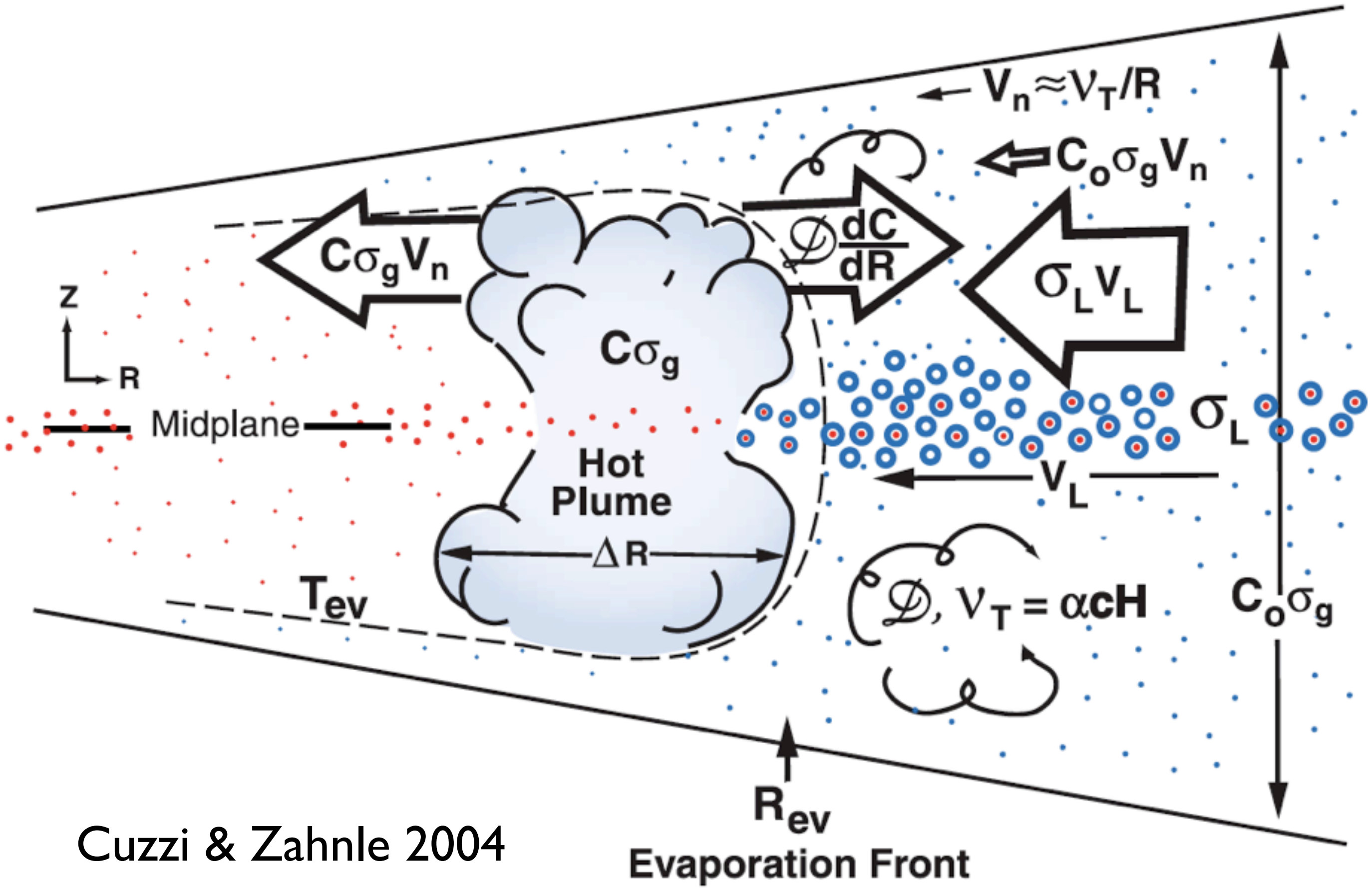
Planet migration and disk gas



Tanaka et al. 2002, Armitage 2007

Inward migration of planetesimals

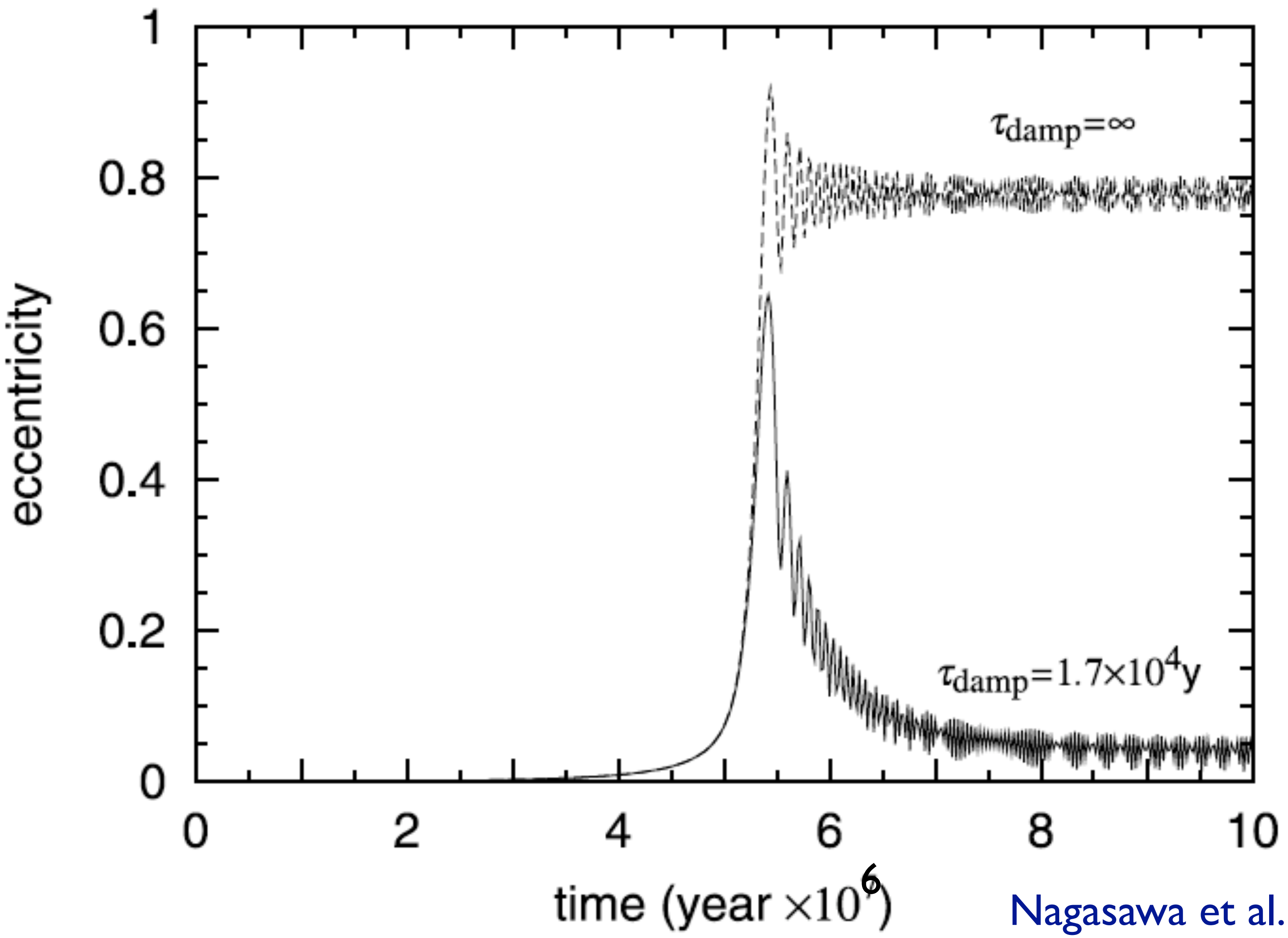
Nebular gas permits inward radial transport of icy solids that can replenish the terrestrial planet-forming region of volatiles (e.g. Ciesla & Lauretta 2005)



Cuzzi & Zahnle 2004

Formation of terrestrial planets: embryo-disk interaction

A small amount of gas (~1g/cm^2) may be needed to form terrestrial planets on circular orbits



Nagasawa et al. 2005

Key Questions:

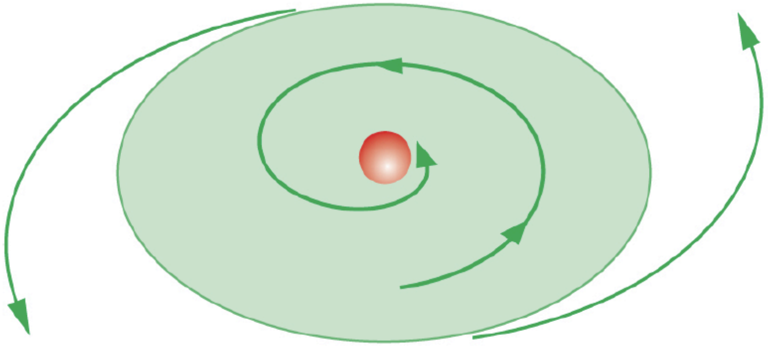
how does disk gas evolve as a function of time and radial distance from the star?

how does chemistry evolve with time?

which mechanisms clear out primordial disks?

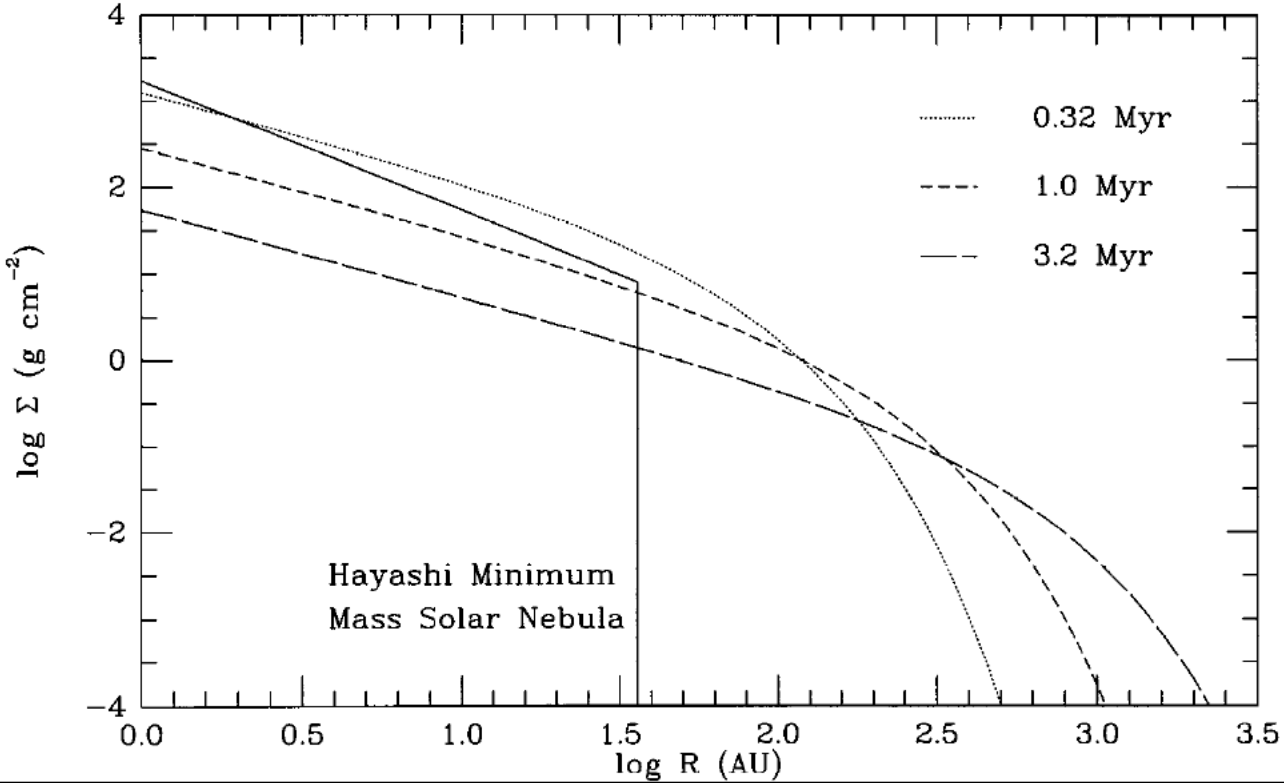
Viscous evolution: smooth decline in surface density

accretion of gas onto the central star and spreading outward



α – accretion disk : $\nu = \alpha\, c_s\, H$

(Shakura & Syunyaev 1973)

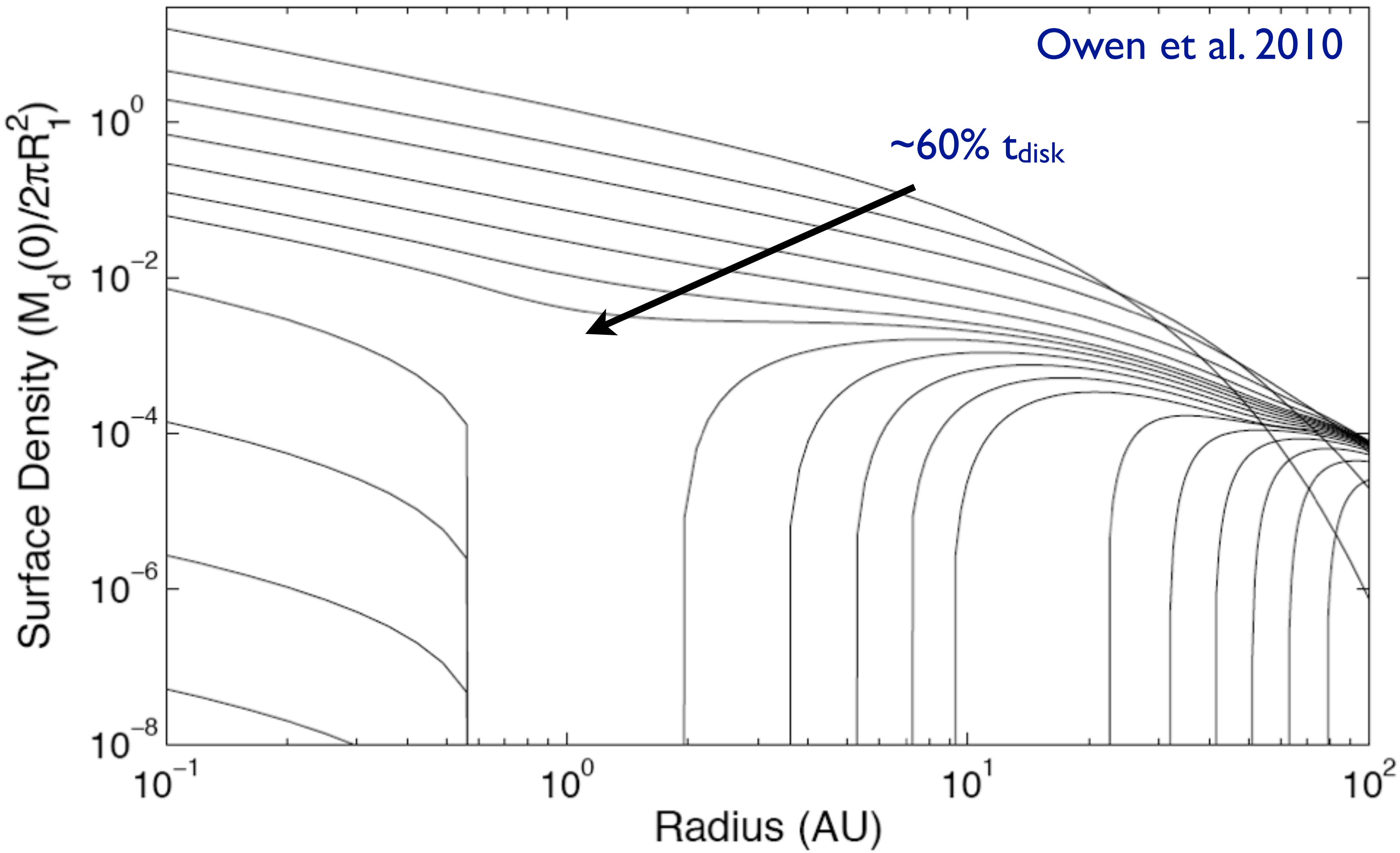


$\dot{M} \propto t^{-(3/2)}$

Hartmann et al. 1998

Photoevaporation: gap formation

→ talk by Uma Gorti



See also: Alexander et al. 2006; Gorti & Hollenbach 2009; Gorti et al. 2009; Ercolano et al. 2009

Key Questions:

how does disk gas evolve as a function of time and radial distance from the star?

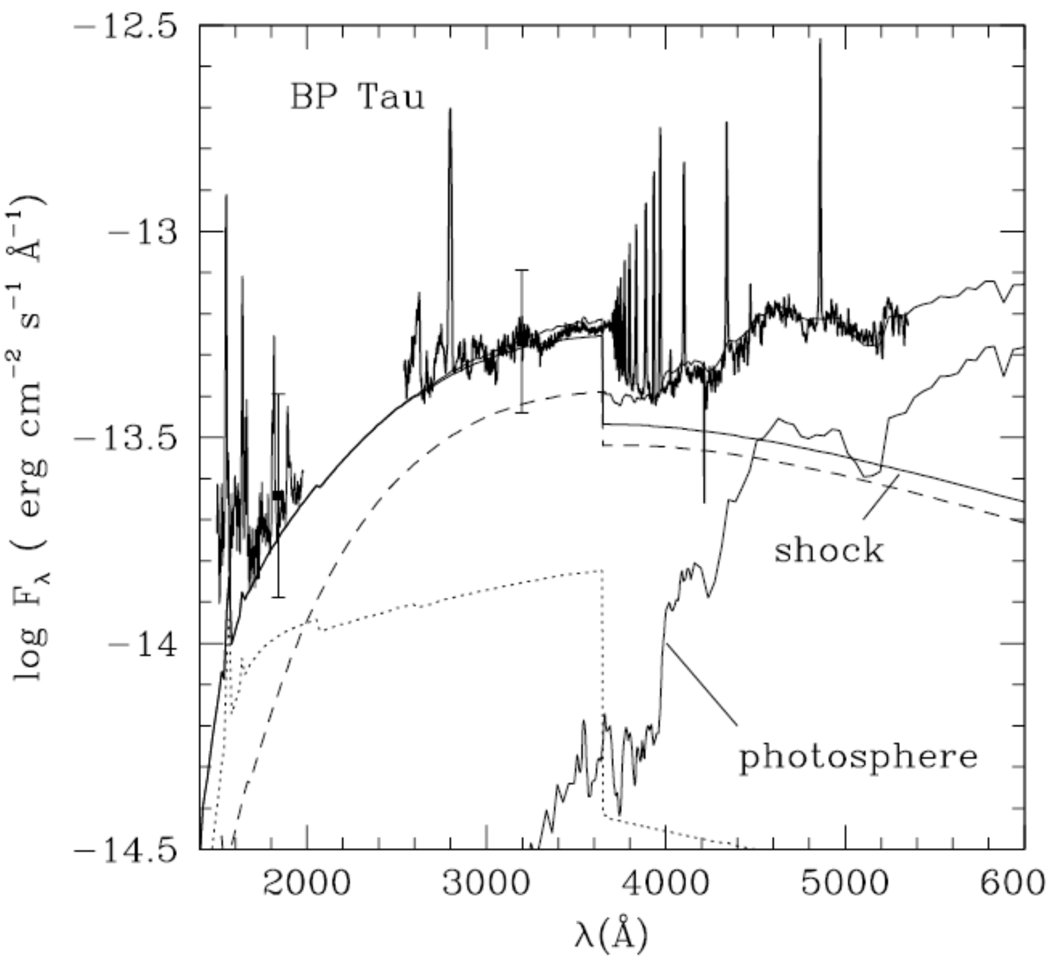
how does chemistry evolve with time?

which mechanisms clear out primordial disks?

What do we know about the evolution of disk gas?

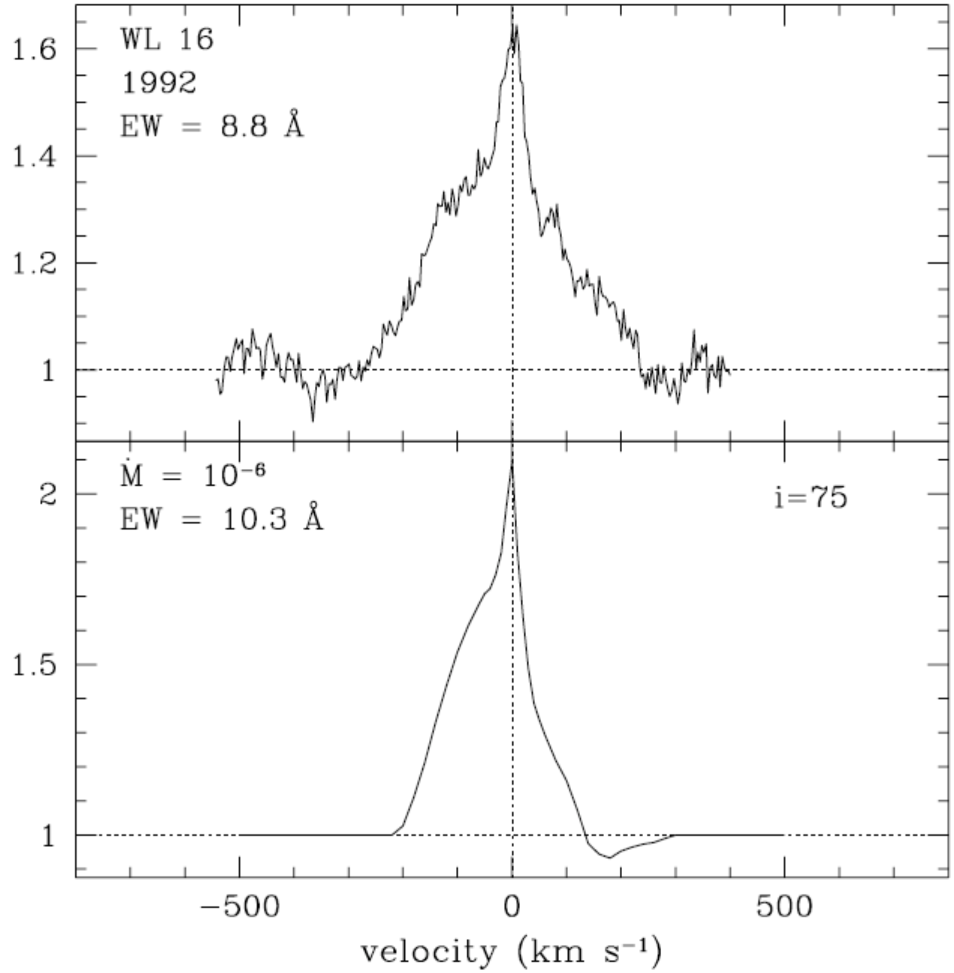
Diagnostics of gas accreting onto the star

Diagnostic 1



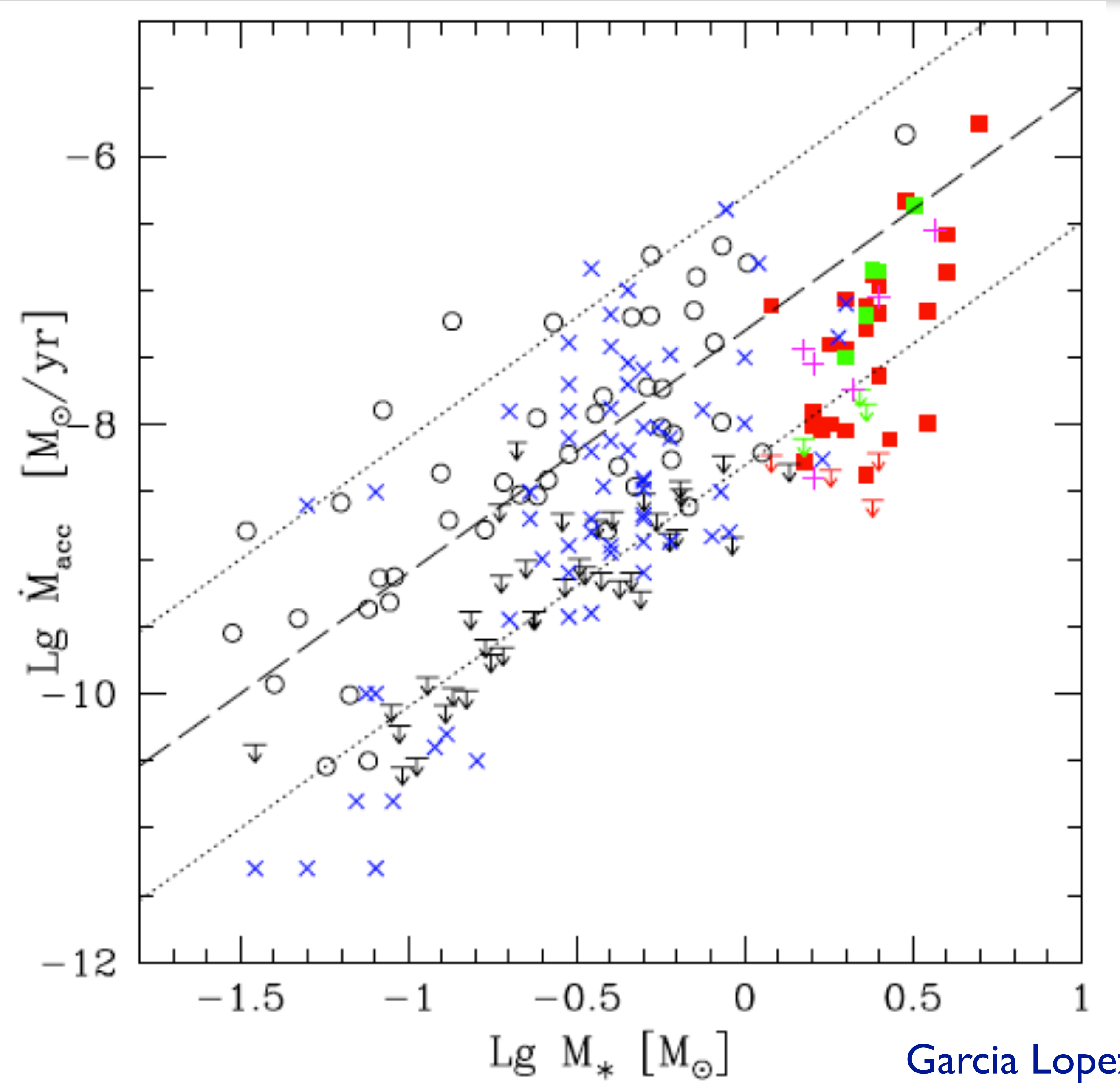
Gullbring & Calvet 2000

Diagnostic 2



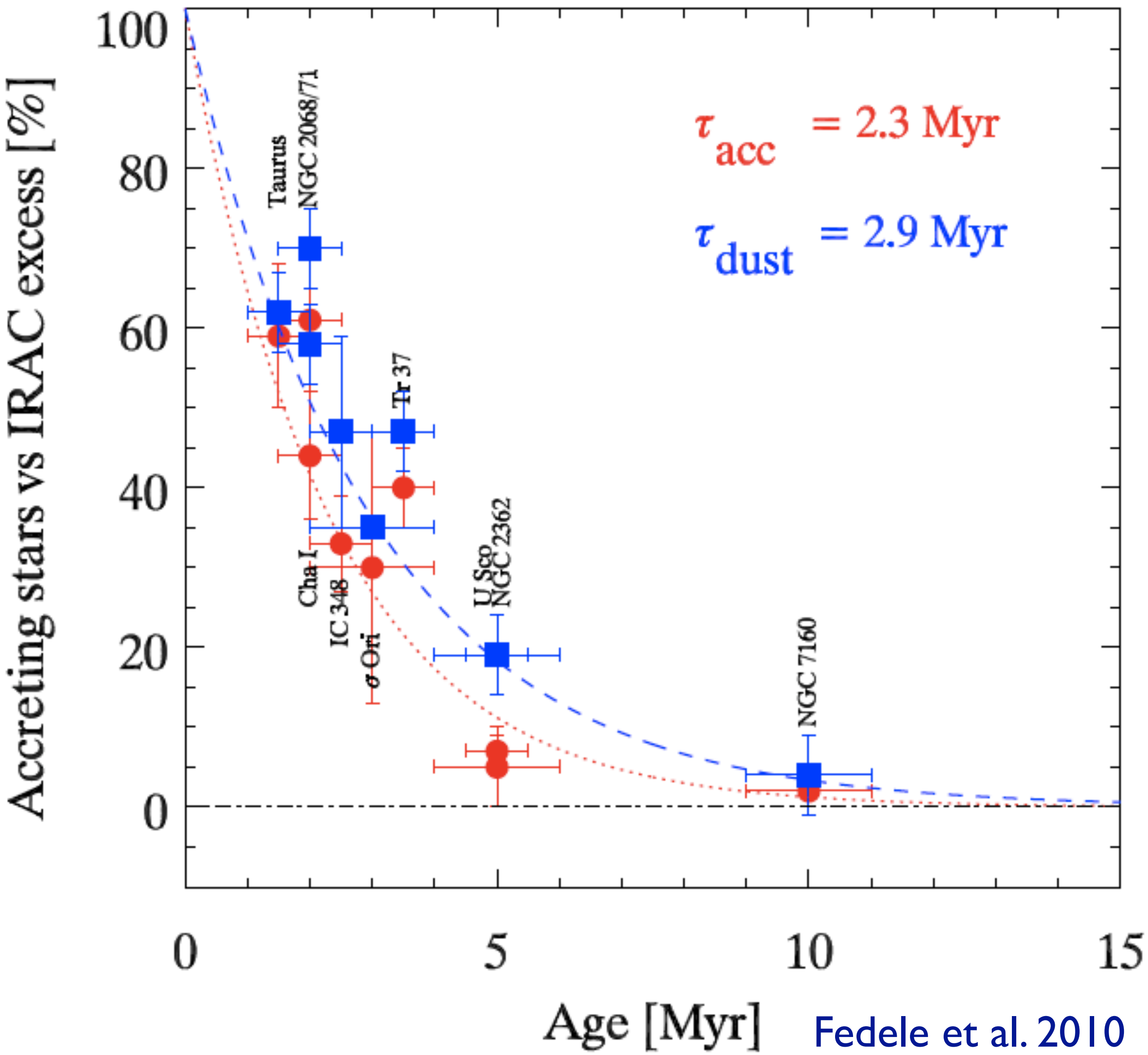
Muzerolle et al. 1998

Accretion rates from Herbig stars to brown dwarfs



Garcia Lopez et al. 2006

Dispersal of hot dust – end of accretion



Fedele et al. 2010

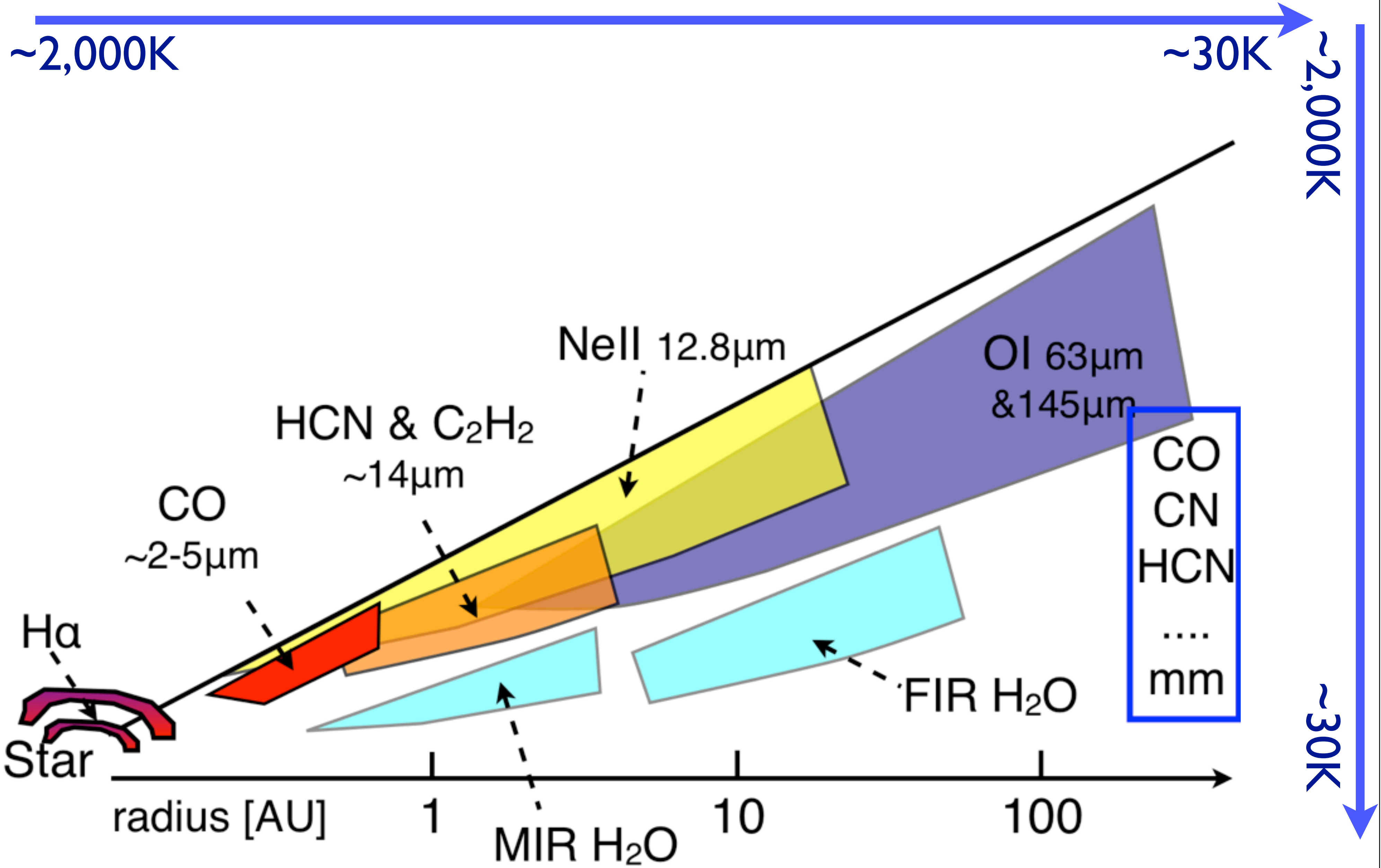
Accretion does not measure the gas disk mass

$$\dot{M} \simeq 7 \times 10^{-9} \left(\frac{\alpha}{0.01}\right) \left(\frac{T_{1\mathrm{AU}}}{100K}\right) \left(\frac{\Sigma_{1\mathrm{AU}}}{100\, g/cm^2}\right) \; [M_\odot/yr]$$

Hartmann (1998)

To use the equation above we need to know:
– viscosity parameter
– midplane disk temperature
– how surface density scales with radial distance
– is gas depleted because of other mechanisms
(e.g. photoevaporation)?

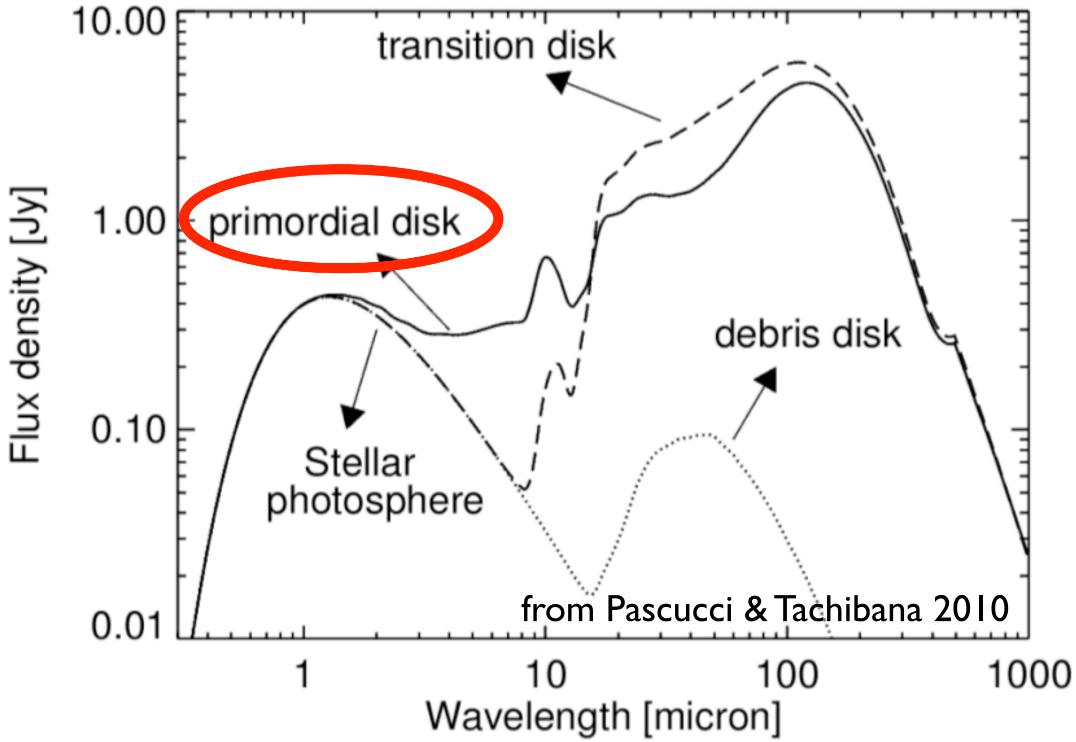
Panchromatic view of a protoplanetary disk



Gas in Young Protoplanetary Disks

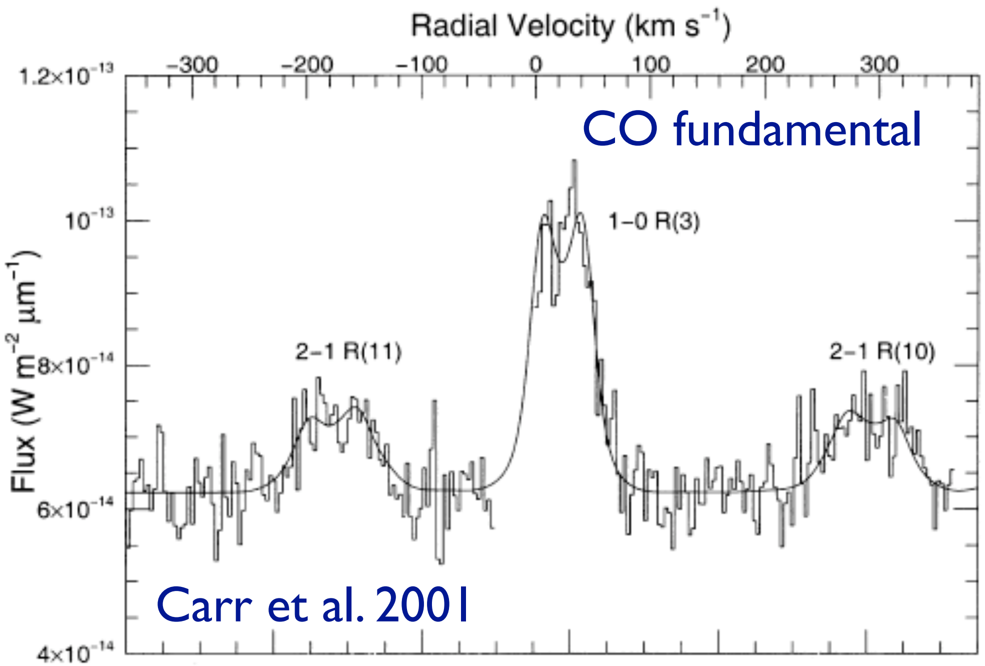
AB Aur

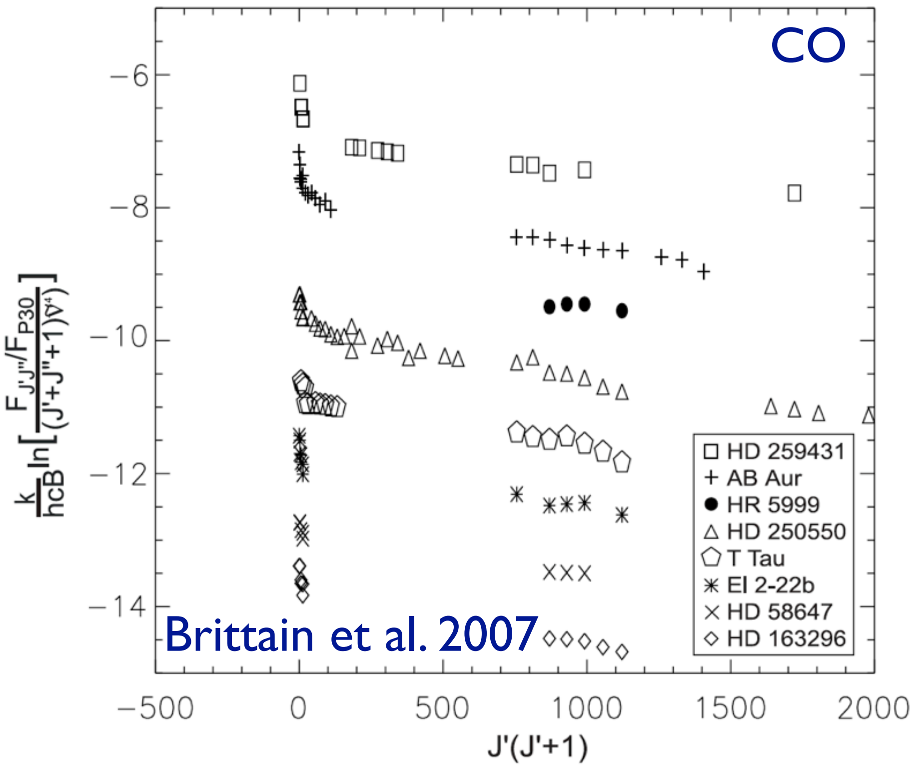
Grady et al. 1999

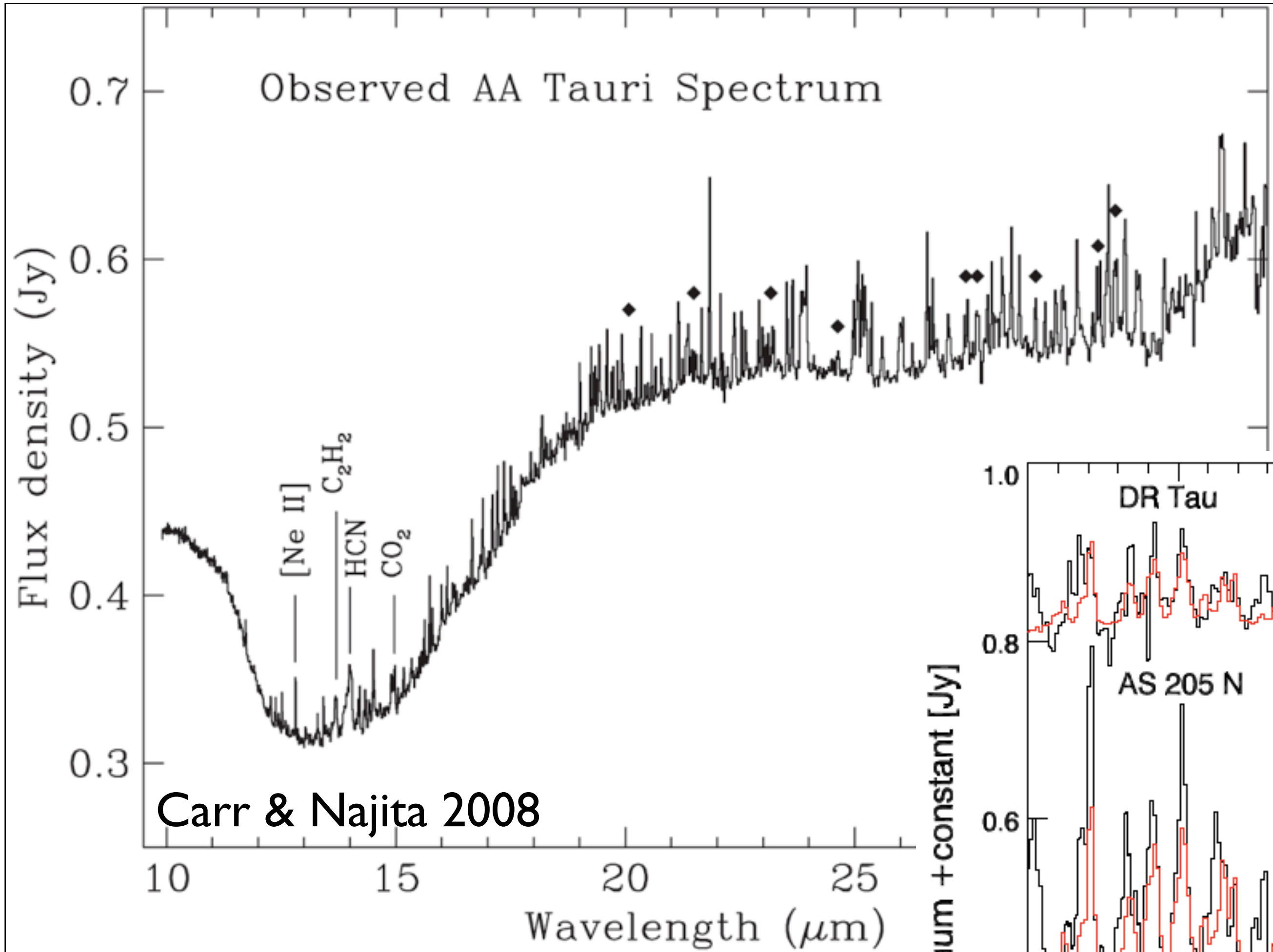


Simple (abundant) molecules detected

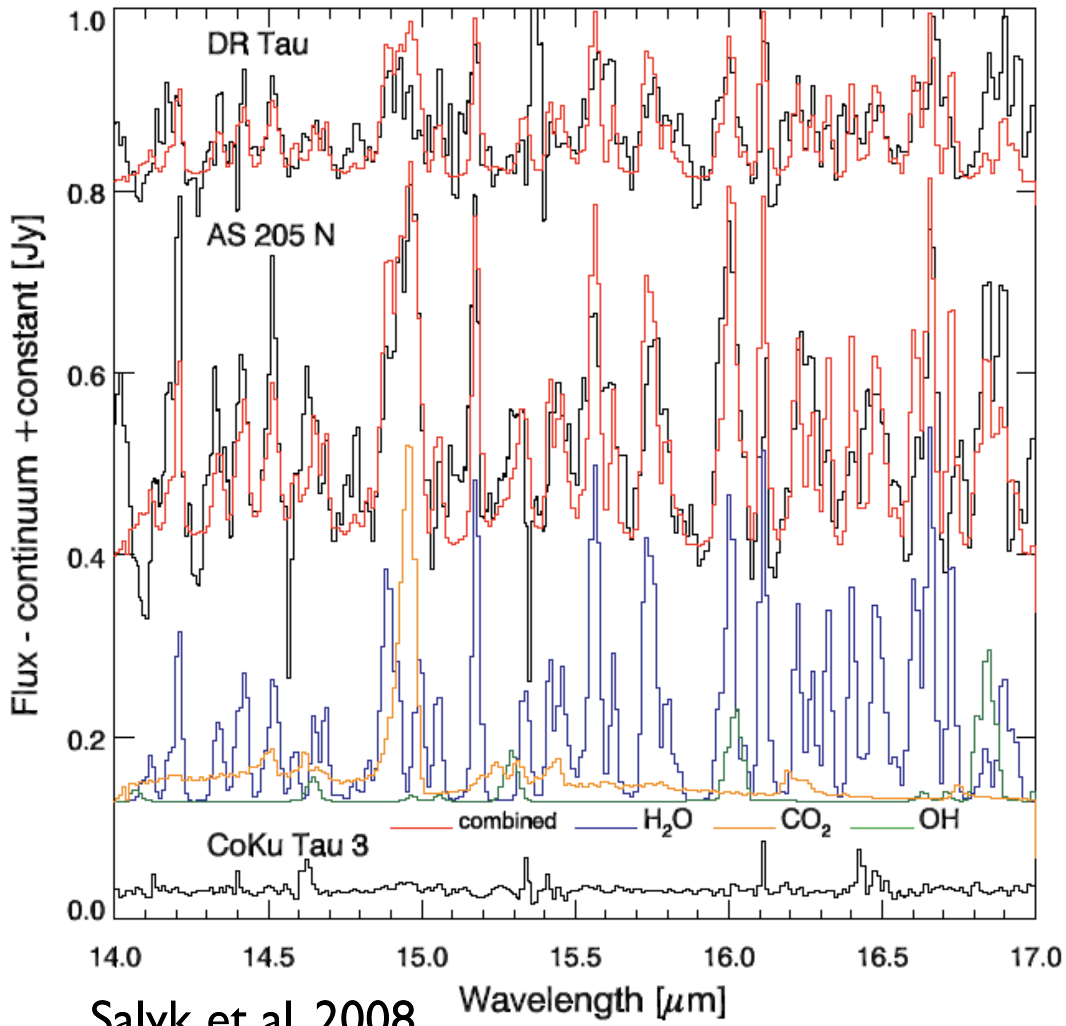
– CO overtone: ~1,000 K gas within < 0.3 AU rarely detected
– CO fundamental: cooler gas out to a few AU often detected
– H_2 NIR: disk surface ~1,000 K out to several AU (30% det. rate)
(reviews by Najita et al. 2007, Carmona 2010, Pascucci & Tachibana 2010 **+ poster 7**)







H_2O, OH and other organic molecules

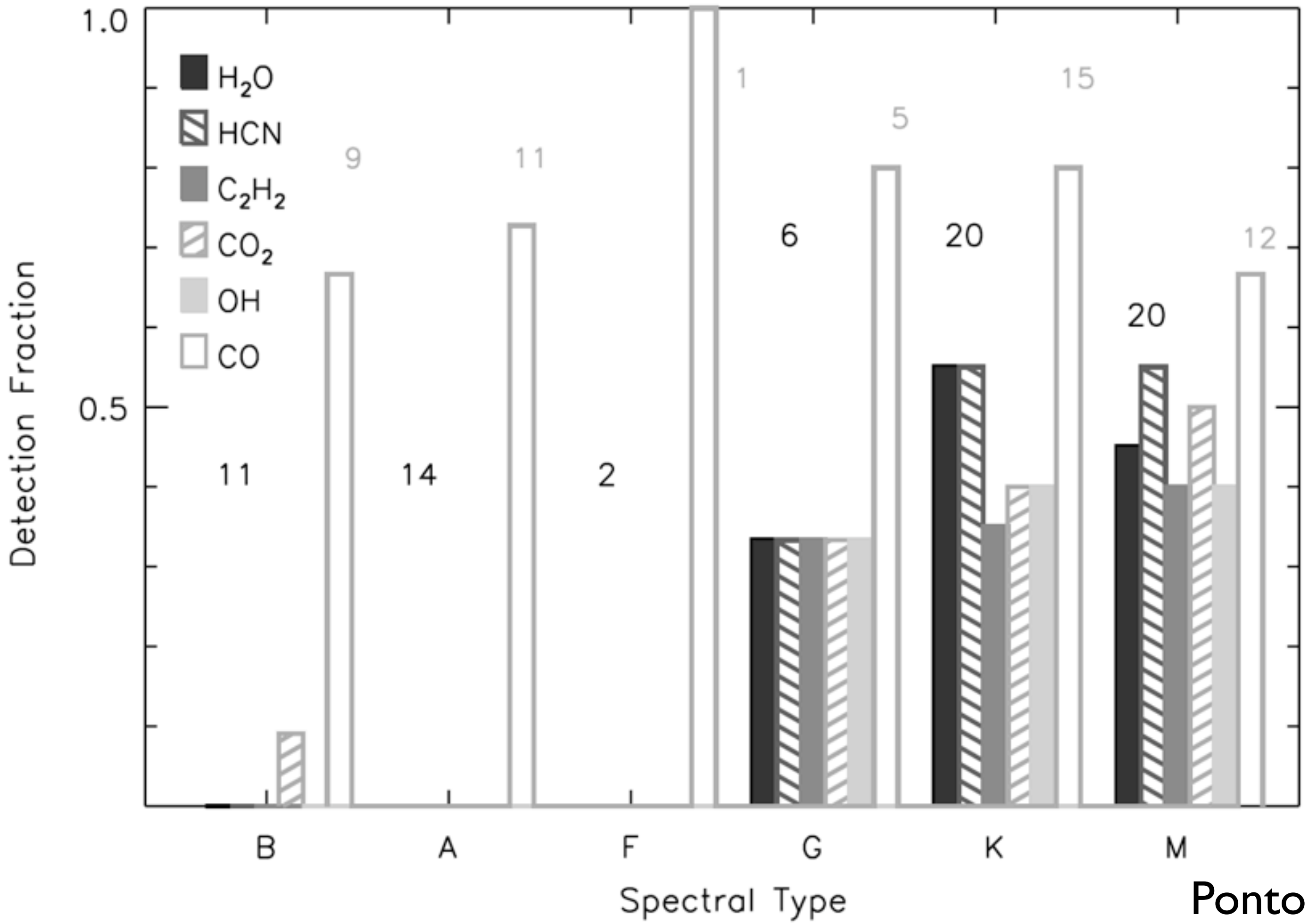


Salyk et al. 2008

LTE models suggest that these lines trace the terrestrial planet-forming region of disks
T ~ 600 K , R ~ 1AU

Gas line detections vs spectral type

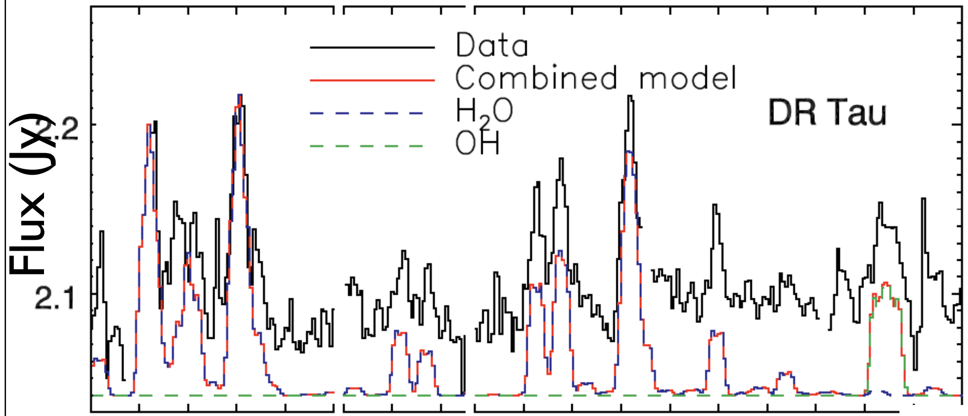
MIR spectra of intermediate-mass stars are not rich in molecular lines
UV photodestruction of molecules?



Pontoppidan et al. 2010

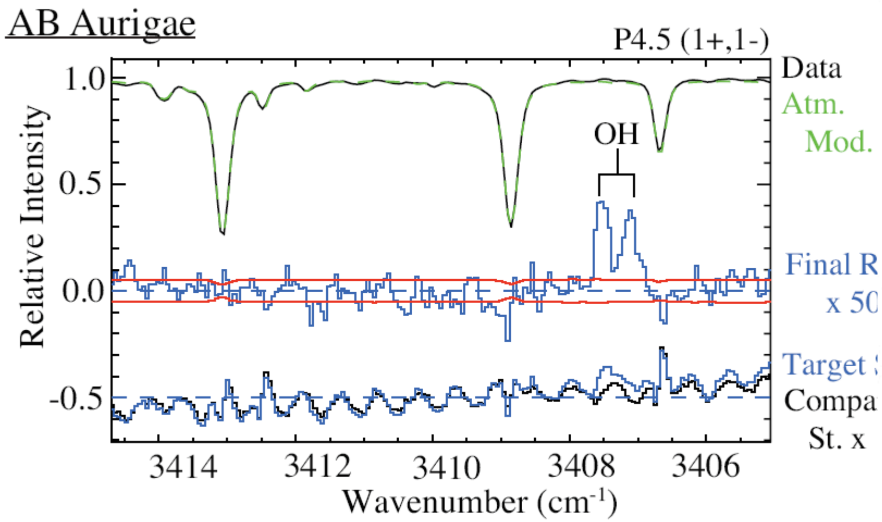
Lack of water lines but strong OH lines in Herbig

Salyk et al. 2008

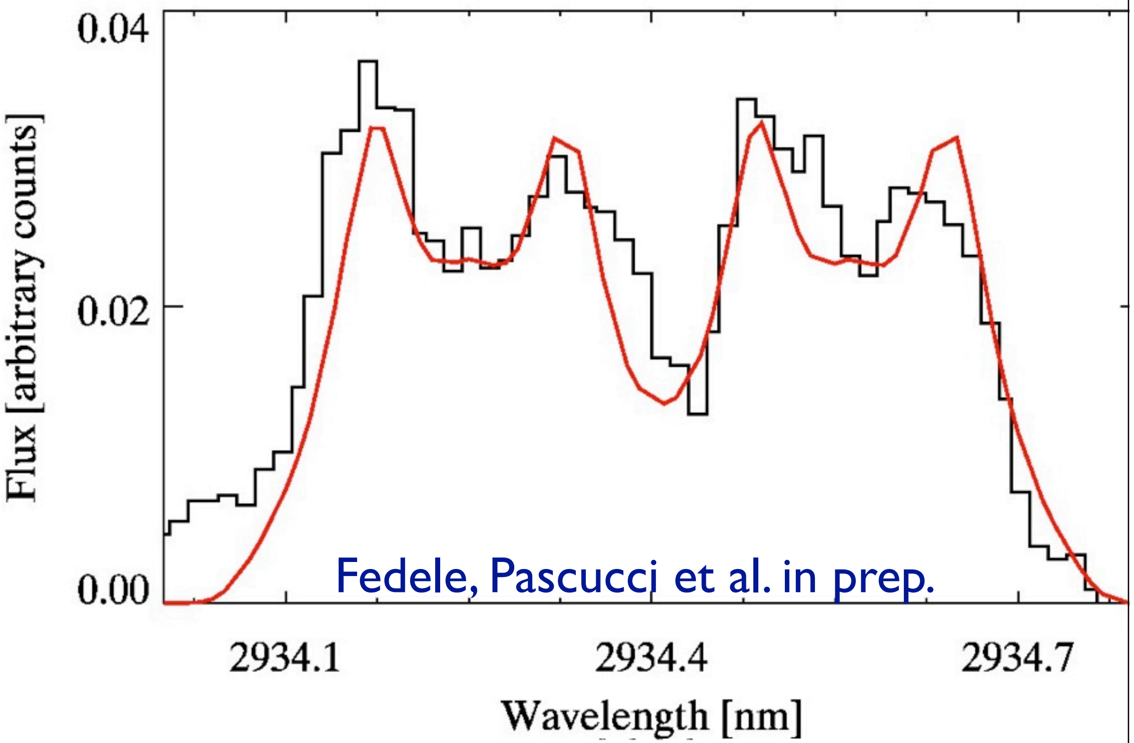


$$\mathrm{O} \underset{\mathrm{UV}}{\overset{\mathrm{H_2}}{\rightleftharpoons}} \mathrm{OH} \underset{\mathrm{UV}}{\overset{\mathrm{H_2}}{\rightleftharpoons}} \mathrm{H_2O}$$

Bethell & Bergin (2009)



Mandell et al. 2008



Fedele, Pascucci et al. in prep.

Chemically poor outer disks of Herbig stars

AB Aur vs DM Tau (Schreyer et al. 2008)

Molecule	χ^2-minimization method			Chemical model		DM Tau
	N $[cm^{-2}]$	1 σ error	$N/N(^{13}CO)^{(1*)}$	N $[cm^{-2}]$	$N/N(^{13}CO)^{(2*)}$	$N/N(^{13}CO)^{(1*)}$
H_2	$6\,10^{22}$	$1\,10^{22}$	$1.5\,10^{6}$	$5\,10^{22}$	$1.3\,10^{6}$	$1\,10^{7}$
$^{13}CO^{(*3)}$	$4\,10^{16}$	$5\,10^{15}$	1	$4\,10^{16}$	1	1
HCO^+	$6\,10^{12}$	$3\,10^{11}$	$1.5\,10^{-4}$	$1.5\,10^{13}$	$4\,10^{-4}$	$2\,10^{-3}$
HCN	$5\,10^{11}$	$3\,10^{11}$	$1.3\,10^{-5}$	$4\,10^{11}$	10^{-5}	$7\,10^{-4}$
CS	$3\,10^{12}$	$3\,10^{12}$	$< 8\,10^{-5}$	$2\,10^{11}$	$5\,10^{-6}$	$3\,10^{-4}$
C_2H	$2\,10^{13}$	$2\,10^{13}$	$< 5\,10^{-4}$	10^{10}	$2.5\,10^{-7}$	10^{-3}
CH_3OH	0	$7\,10^{15}$	$< 2\,10^{-1}$	0	0	0

supported by other studies: Chapillon et al. 2008, Henning et al. 2010, Oberg et al. 2010 → talk by K. Oberg

Effect of high UV field from intermediate-mass stars

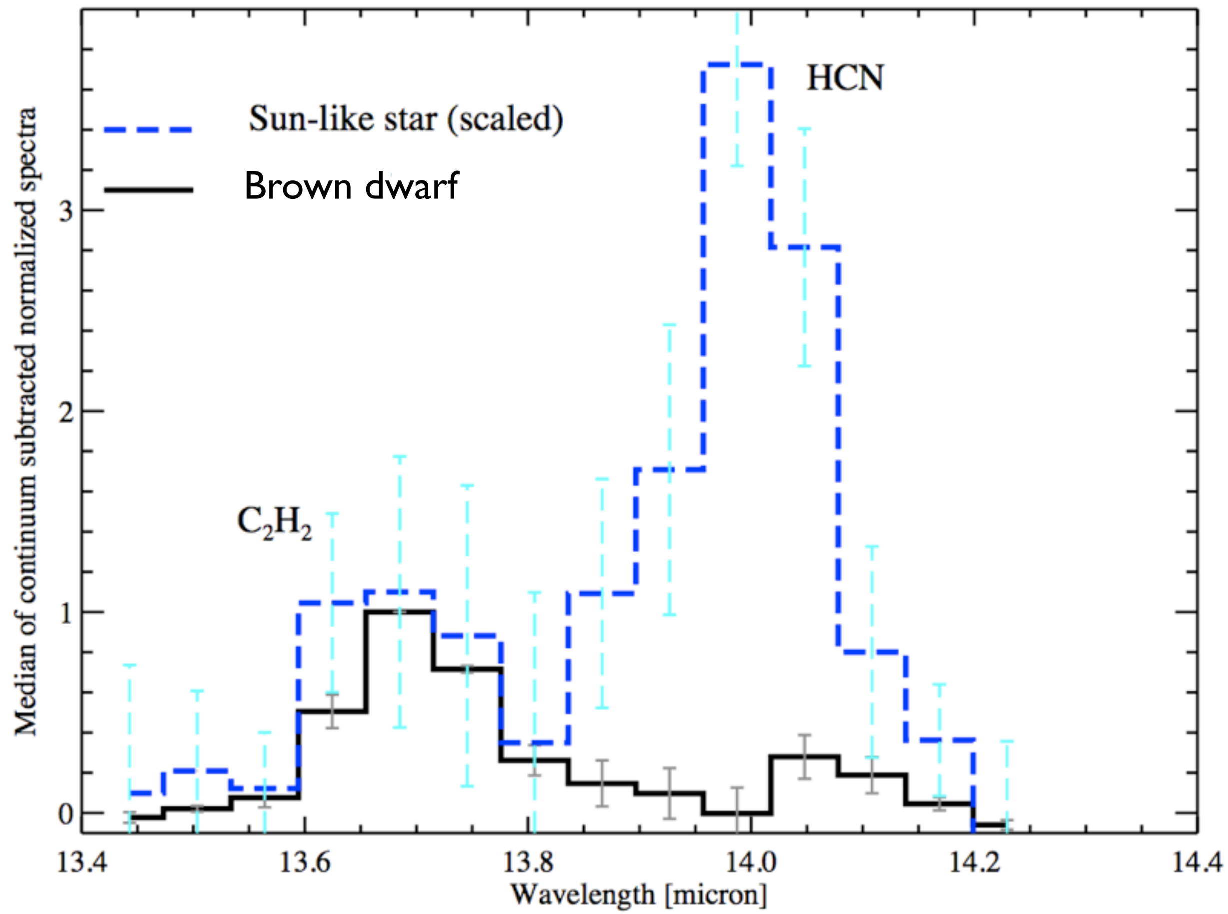
Different chemistry in disks around brown dwarfs

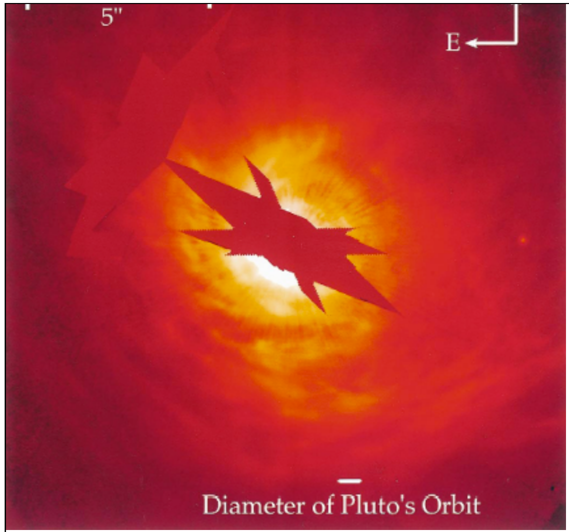
– IRS low-resolution spectra from a sample of 44 disks around sun-like stars and 17 disks around brown dwarfs

– 30% of the disks have HCN and/or C_2H_2 bands detected

LTE models suggest under-abundance of HCN in brown dwarf disks

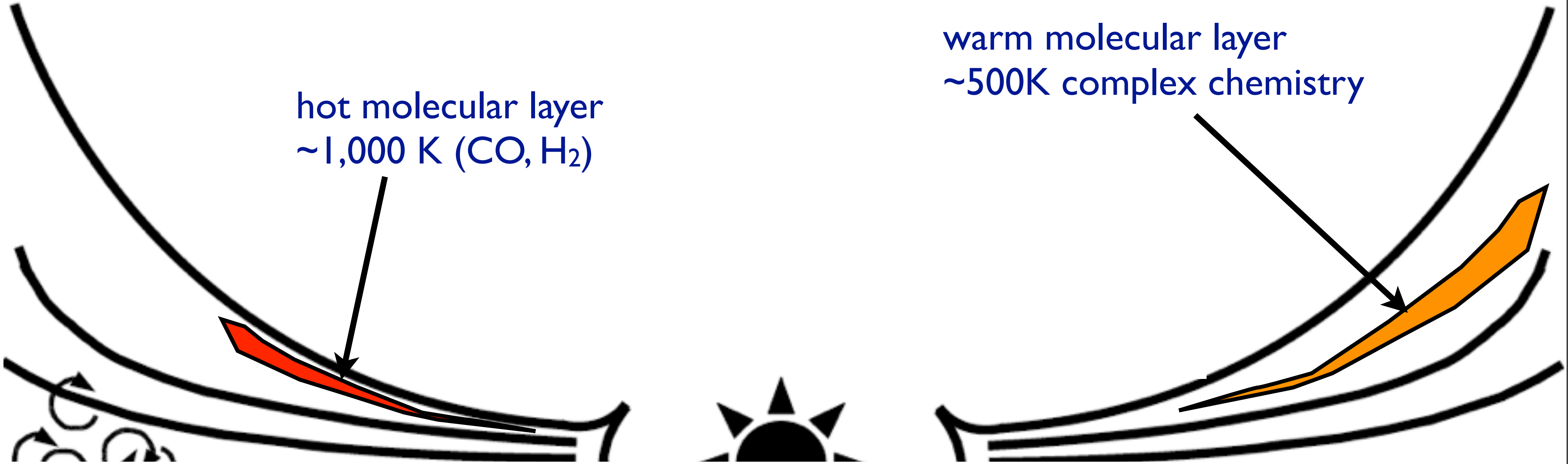
Pascucci et al. 2009



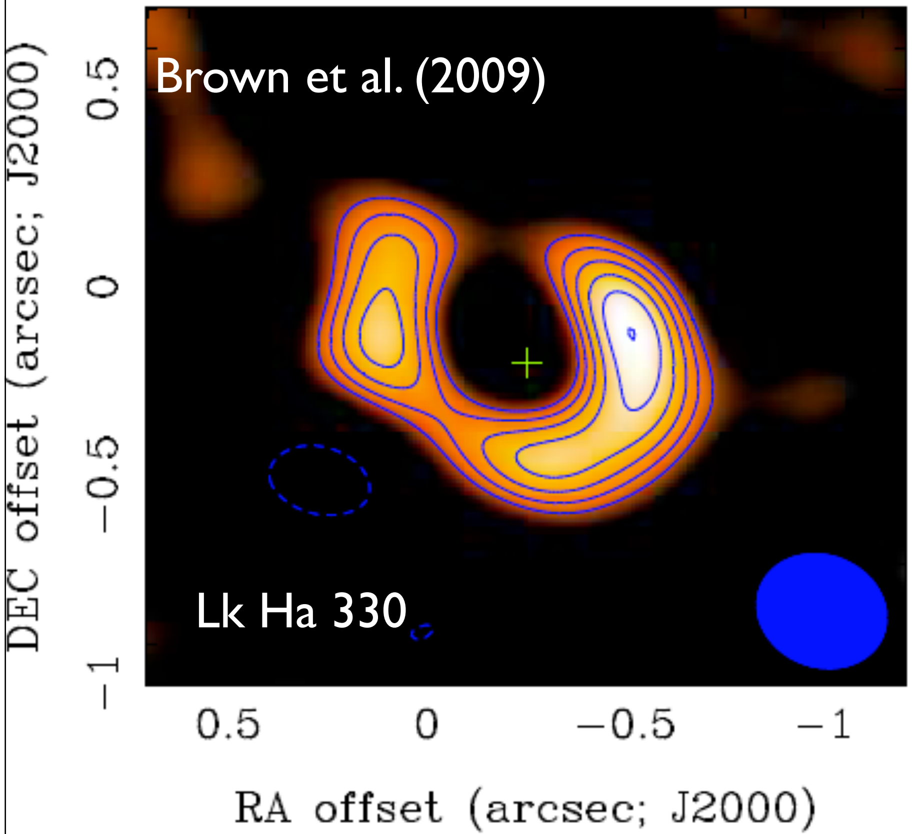


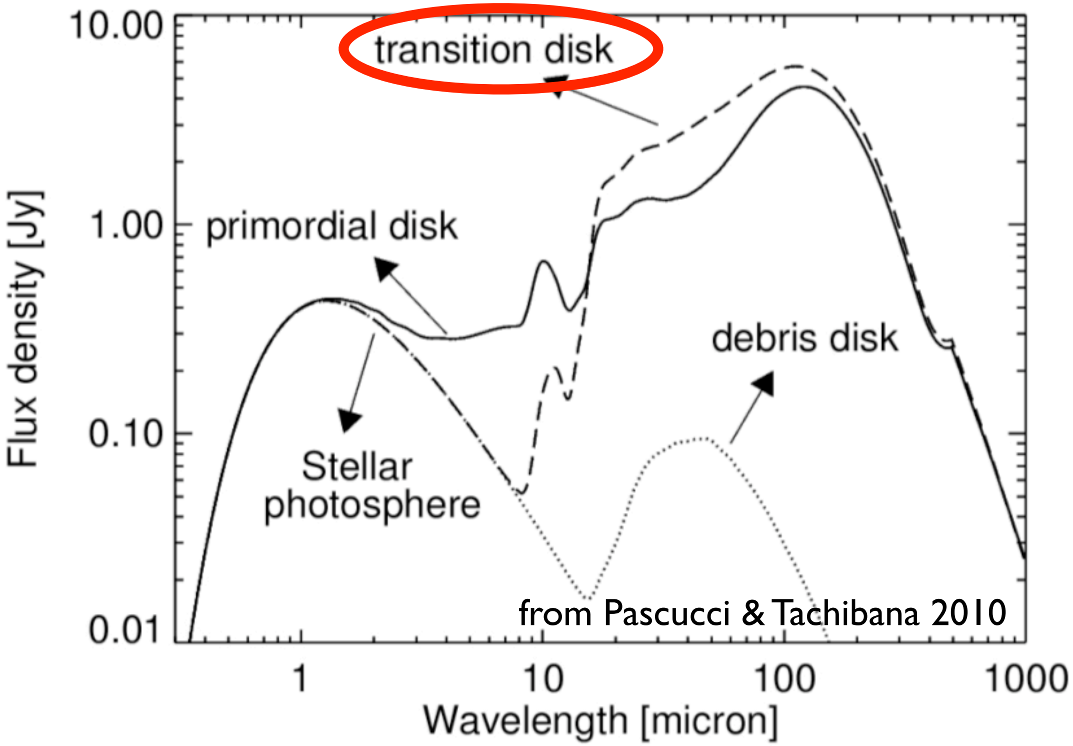
a multitude of diagnostics to trace gas from very close to the central star out to hundreds of AU

rich complex chemistry linked to the stellar radiation field
⇒ talk by V. Geers and P5+P9+P12

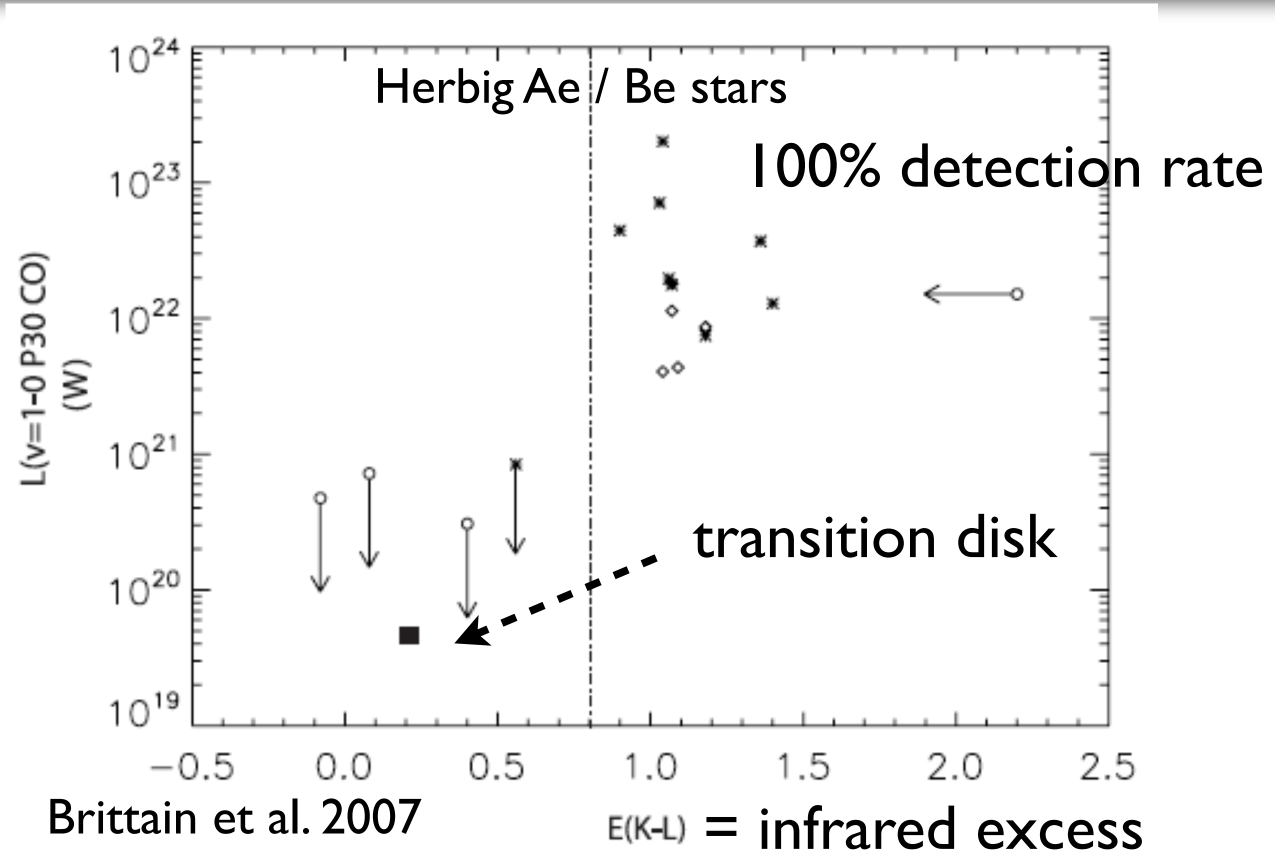


Evolved Protoplanetary Disks





Fewer CO rovibrational lines detected

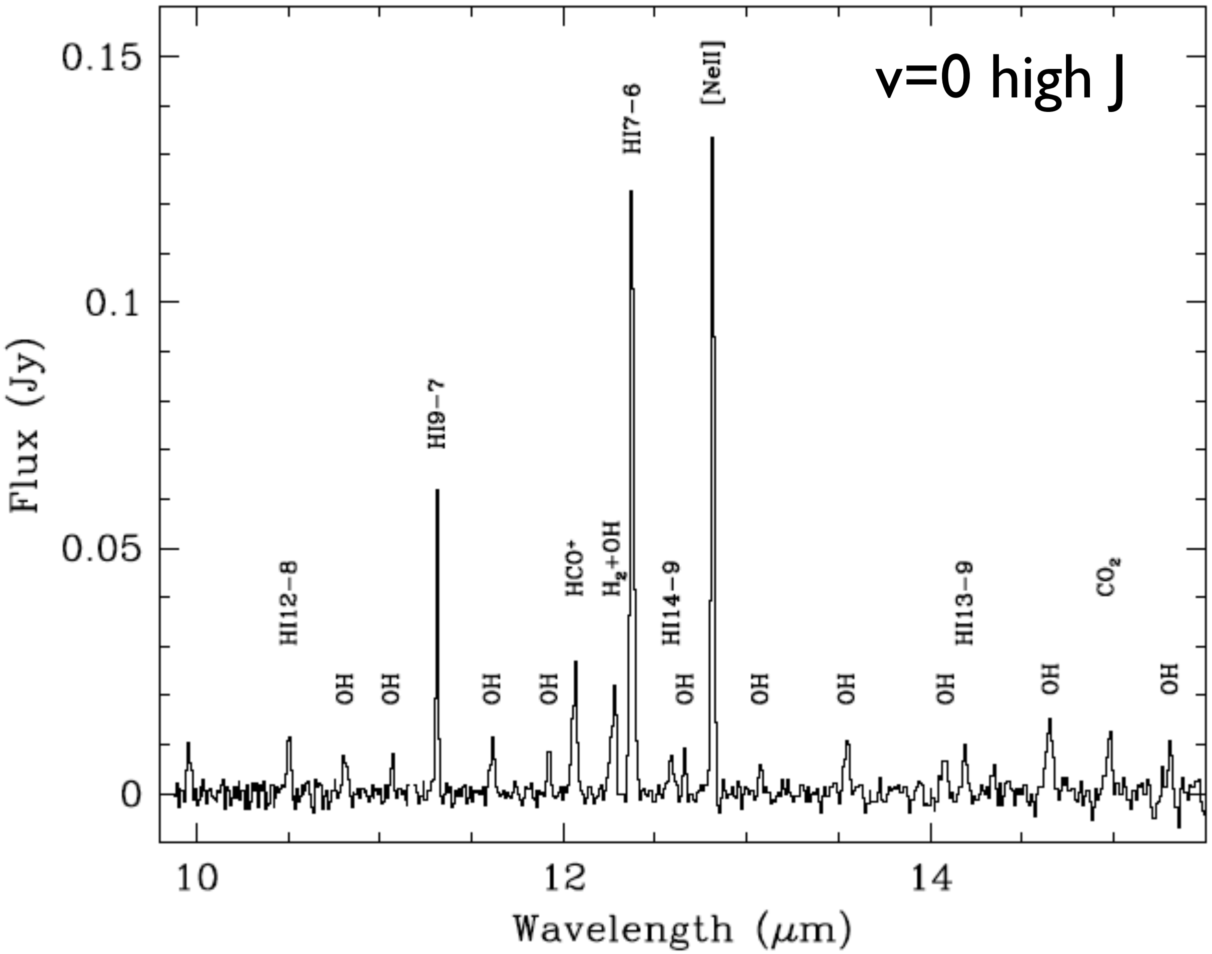


Brittain et al. 2007

– Sun-like Stars: CO detections in 9/14 transition disks, hot gas in the dust-depleted disk (Salyk et al. 2009)

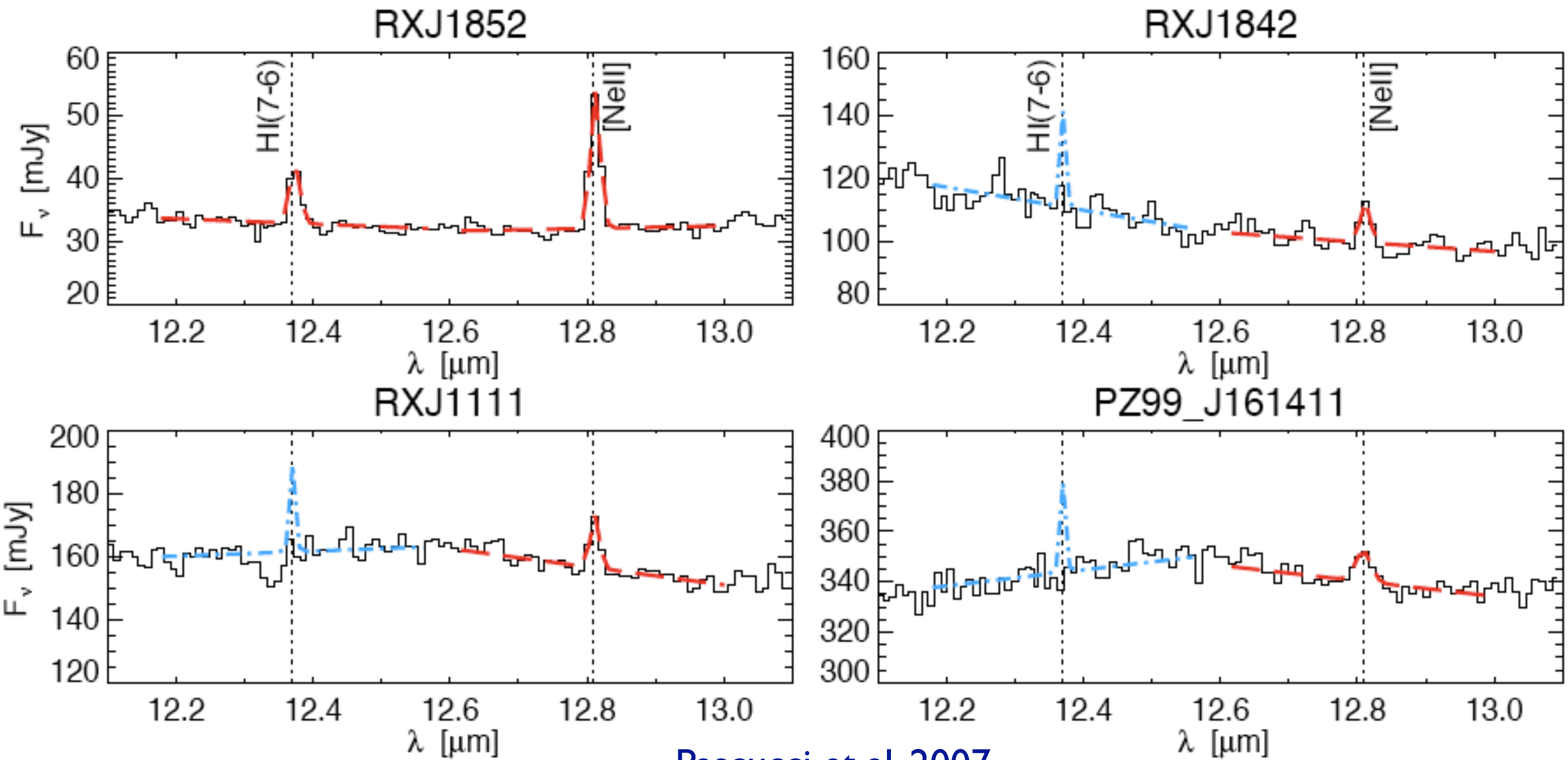
Lack of strong molecular lines in transition disks

OH produced via dissociation of water? (Tappe et al. 2008)
⇒ talk by Uma Gorti



Atomic lines in ‘oldish’ disks

disks in ~5Myr-old star-forming regions

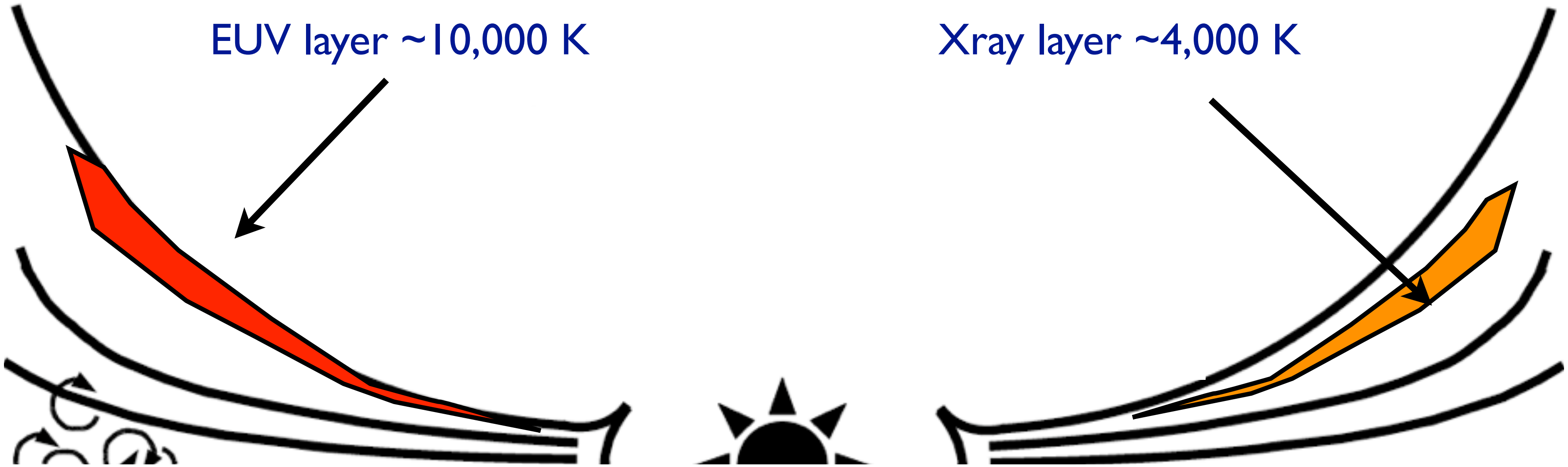


Pascucci et al. 2007

See Guedel et al. 2010 for the largest sample of [NeII] detections in young disks

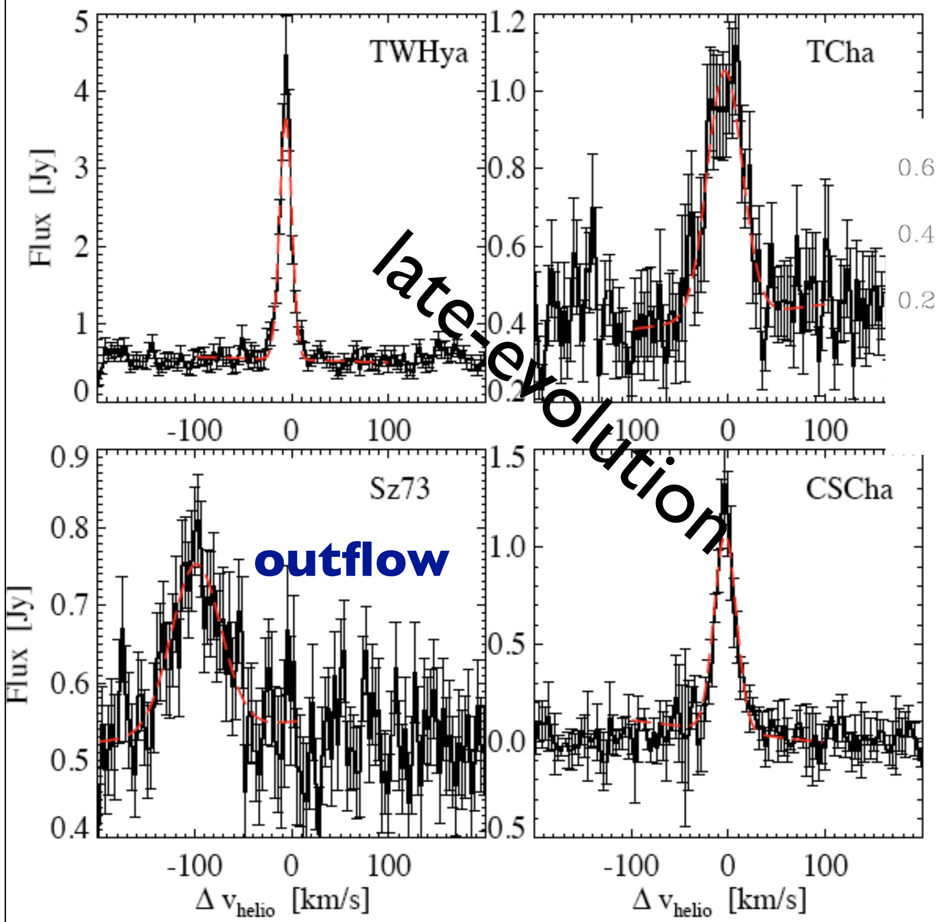
Ne^+: high-energy photons ionizing the disk surface

Measured L_{NeII} ~ a few 10^{-6} L_{sun} are consistent with both EUV and Xrays irradiated disks

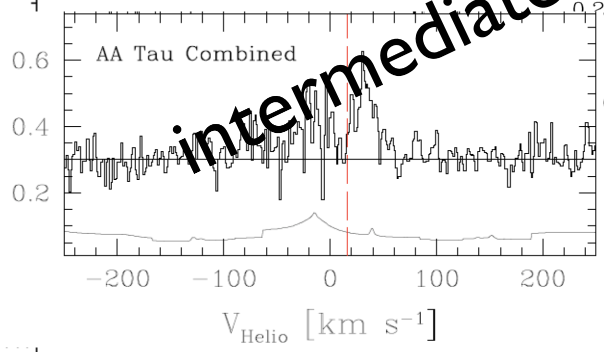


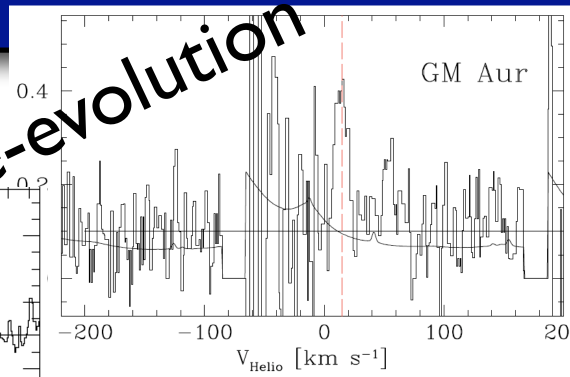
Glassgold et al. 2007, Meijerink et al. 2008, Ercolano et al. 2008, Hollenbach & Gorti 2010

Spectrally resolved [NeII] emission lines

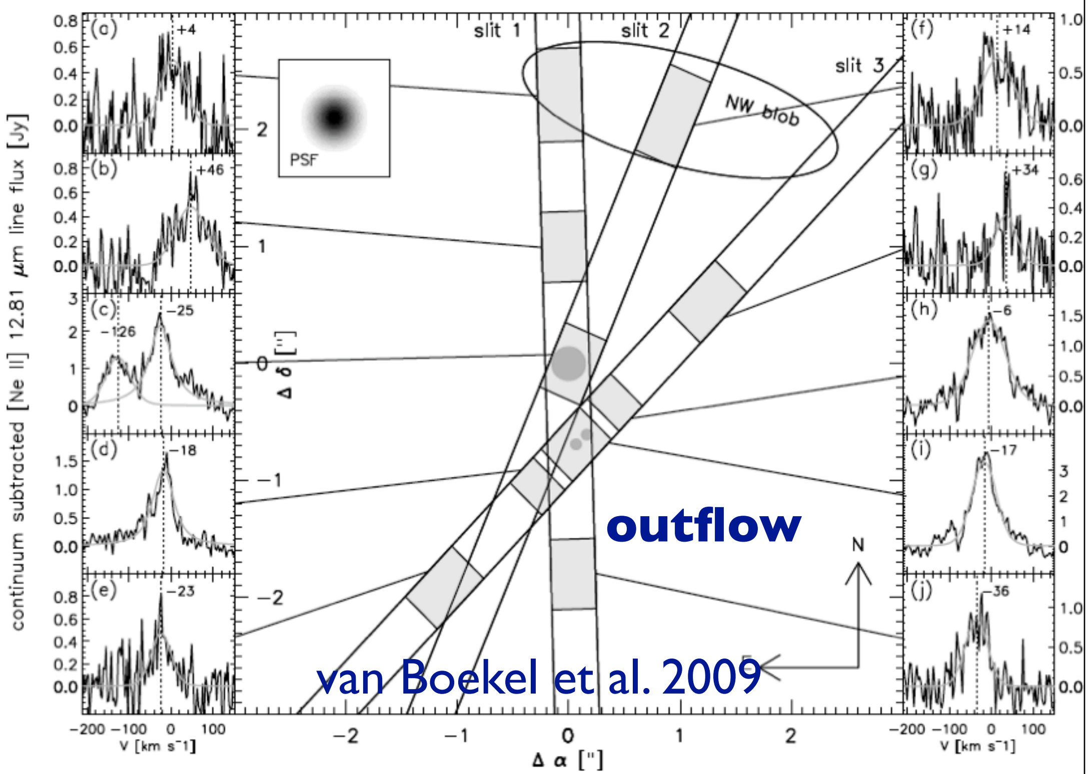


Pascucci & Sterzik 2009



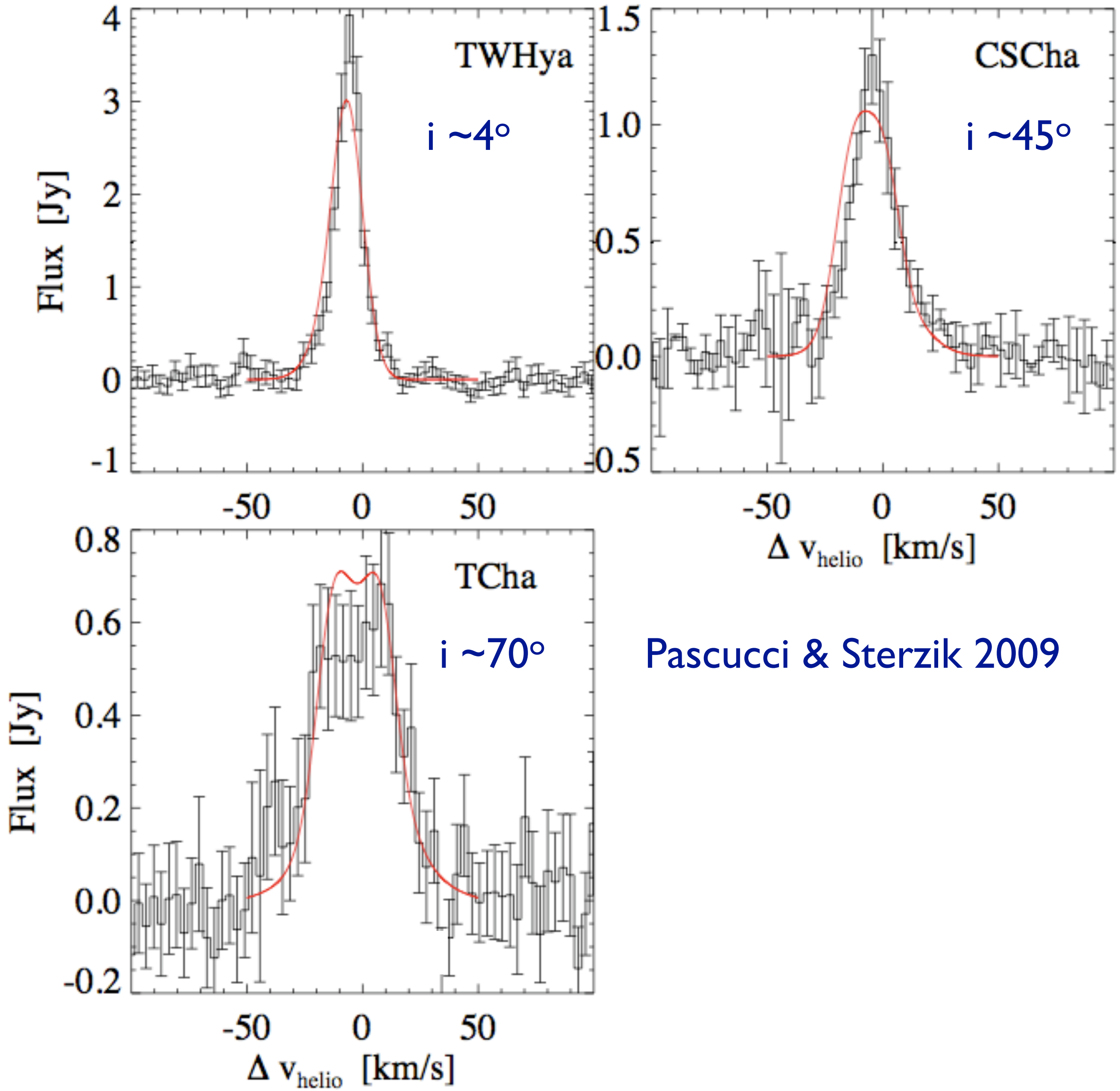


Najita et al. 2009



van Boekel et al. 2009

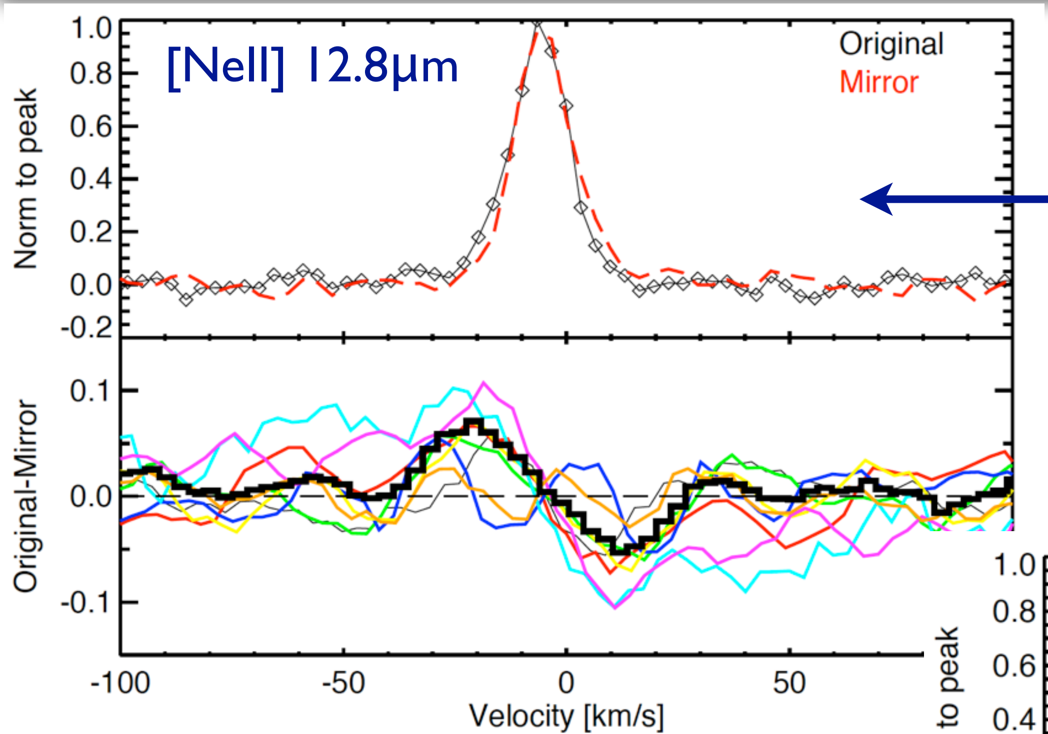
Ongoing photoevaporation in transition disks



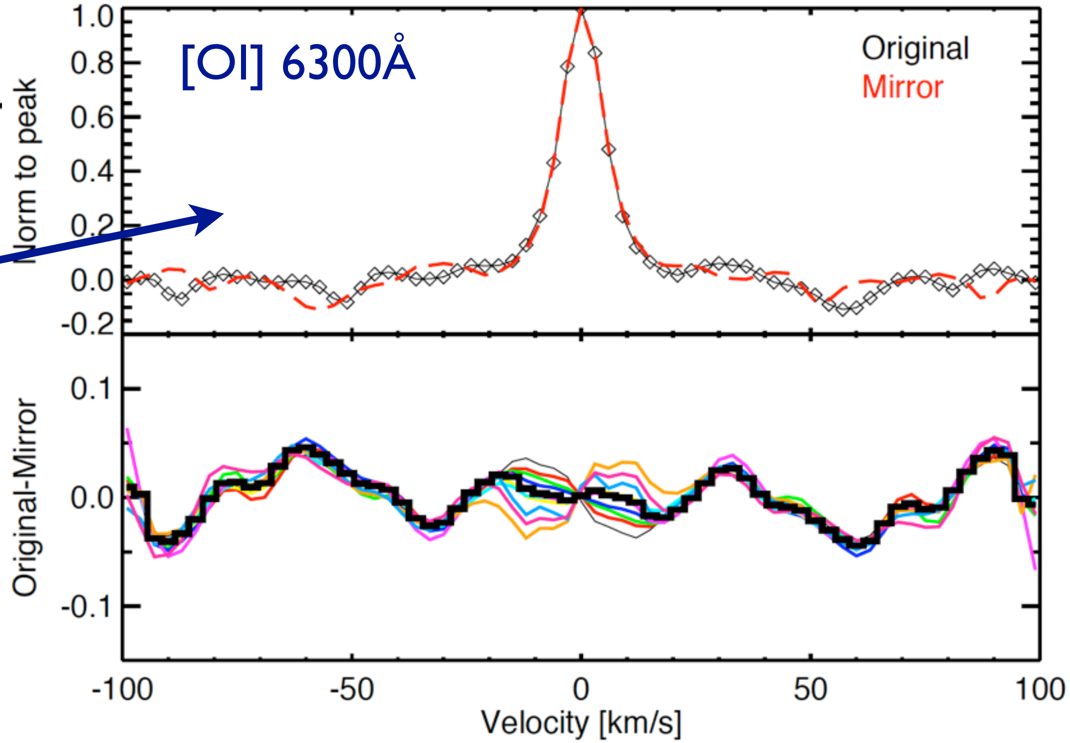
– small blueshifts in the peak emission

Pascucci & Sterzik 2009

The photoevaporative disk wind is mostly ionized

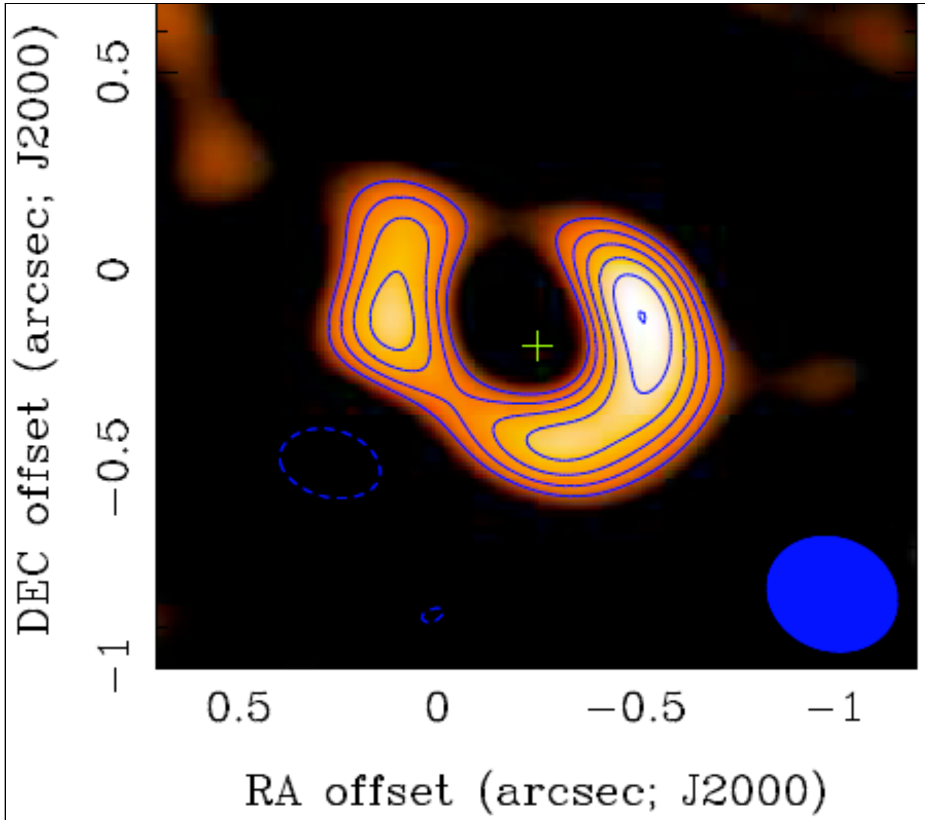


asymmetric/blueshifted line
(expected from models for
optically thick inner gas disk)



symmetric/centered line

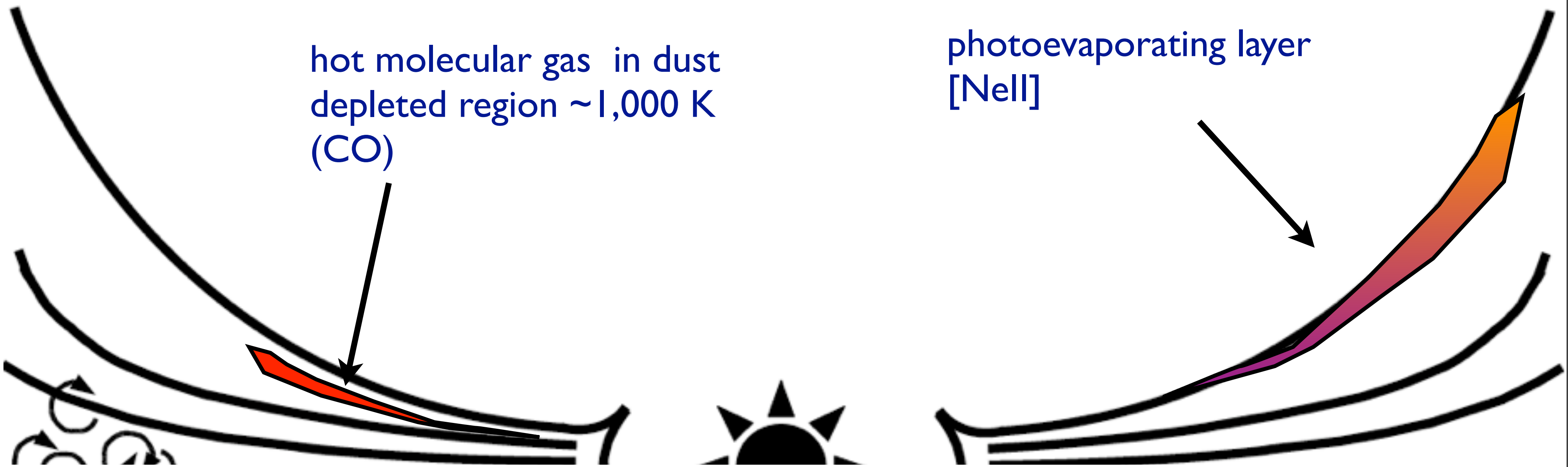
Pascucci et al. in prep.



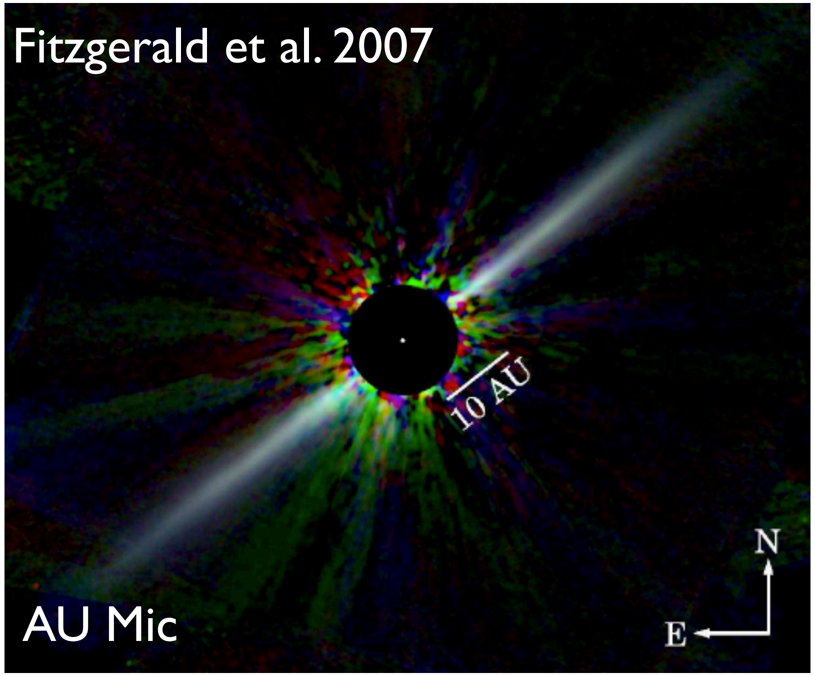
predominantly atomic gas (in the inner disk)

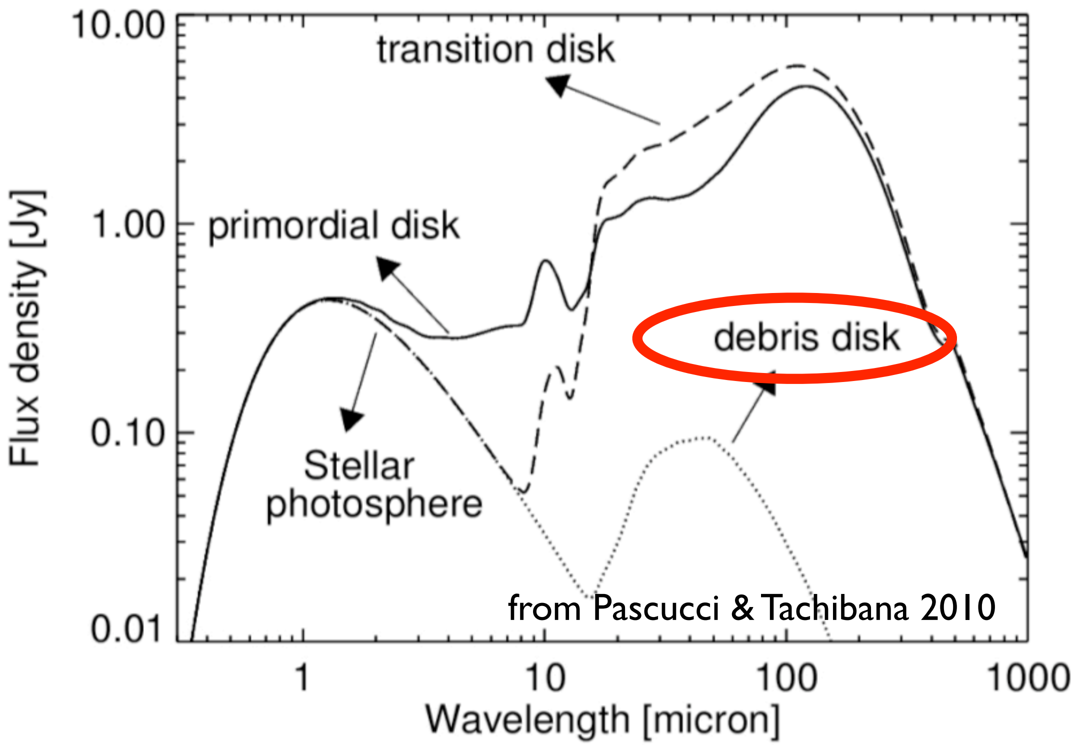
weak molecular lines

photoevaporation



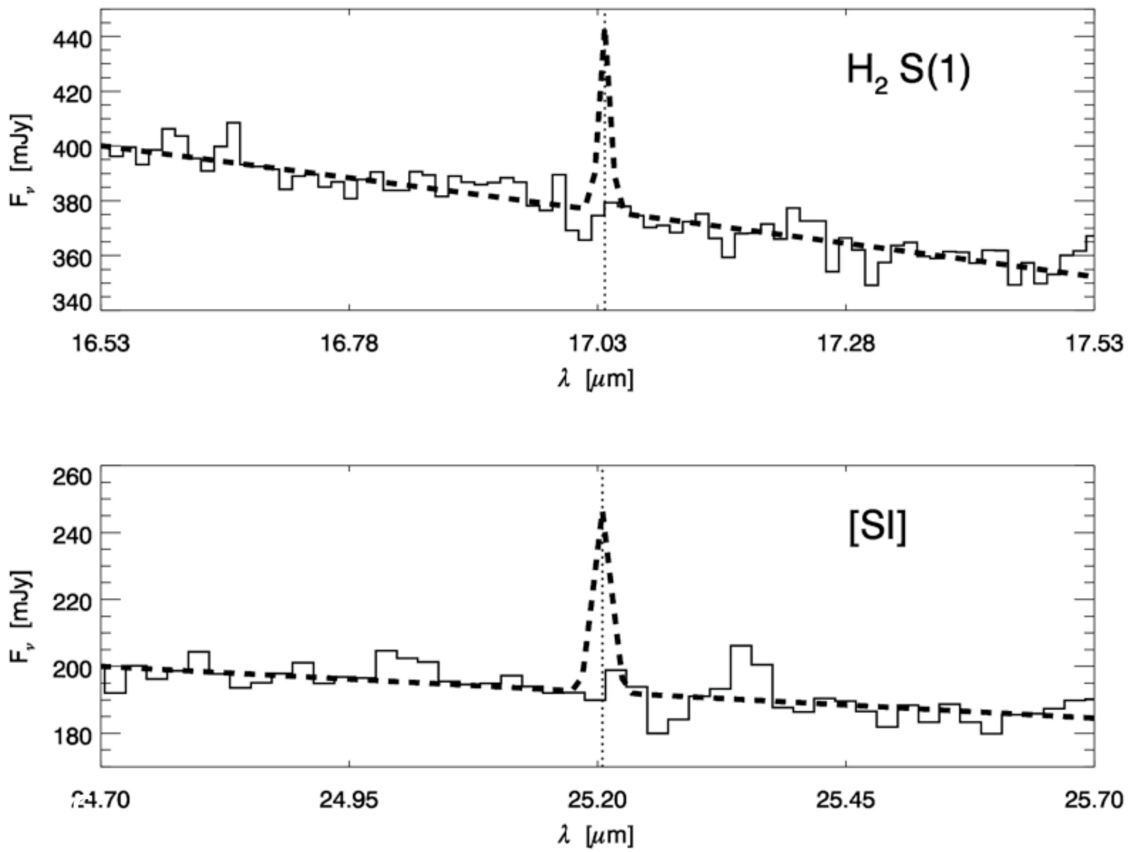
Gas in Debris Disks





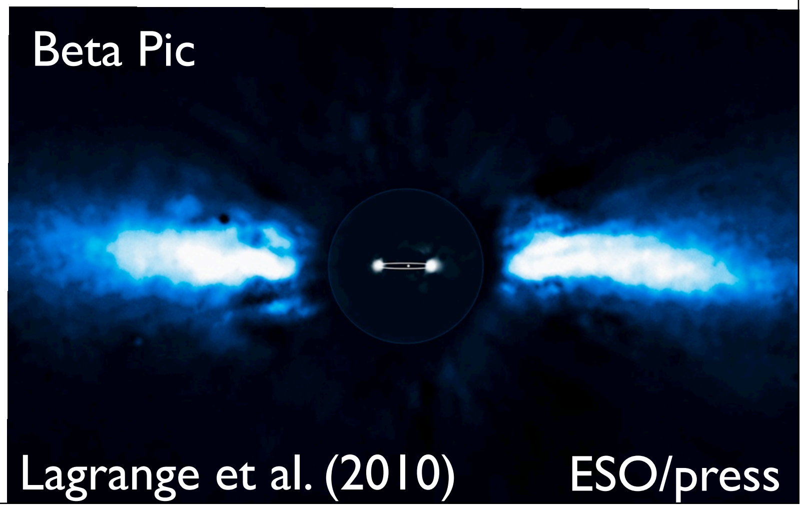
Most of the primordial gas mass is dispersed early

FEPS (PI M. Meyer): Survey of 32 solar analogs (26 non-accreting stars)



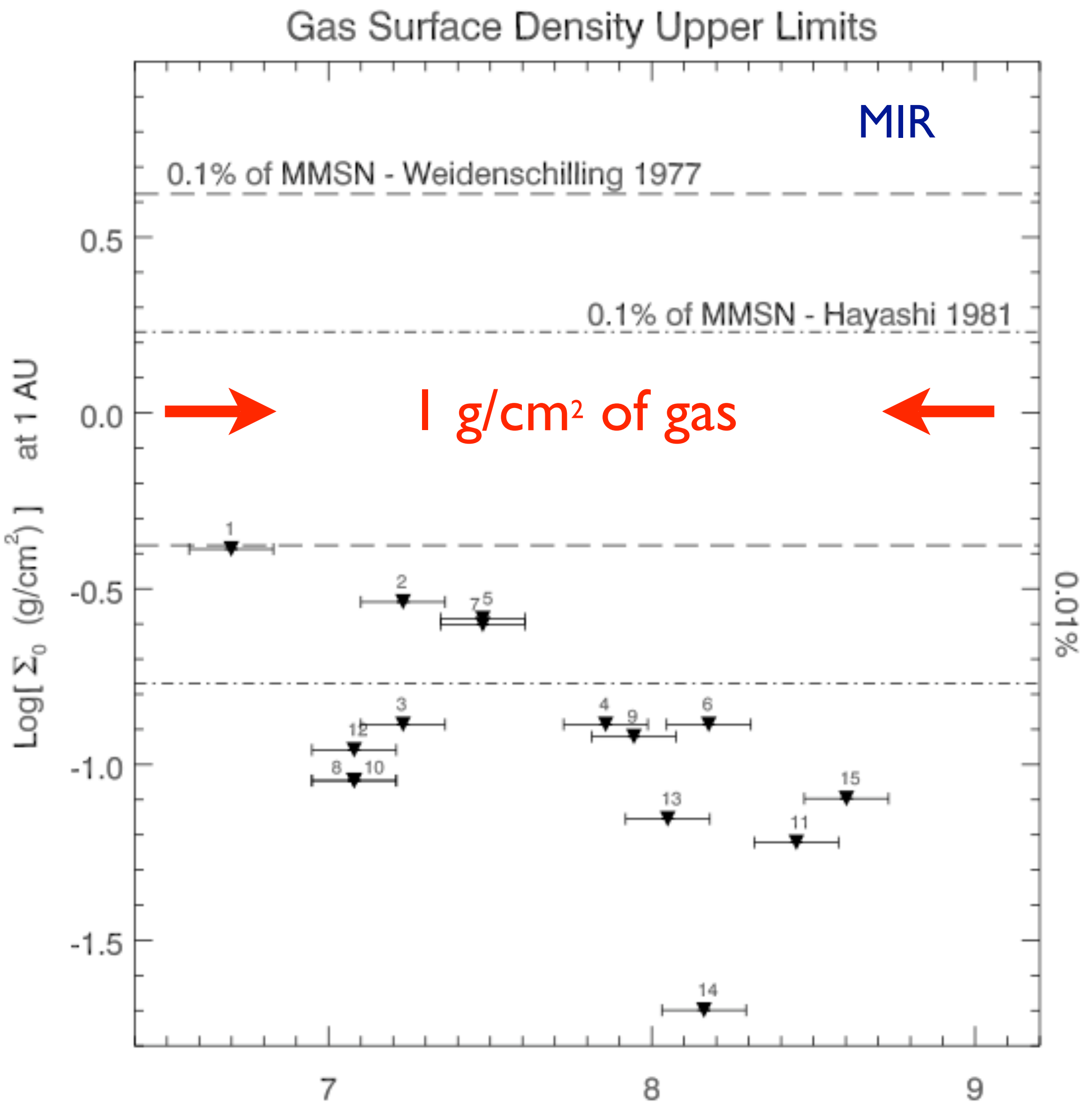
Pascucci et al. 2006

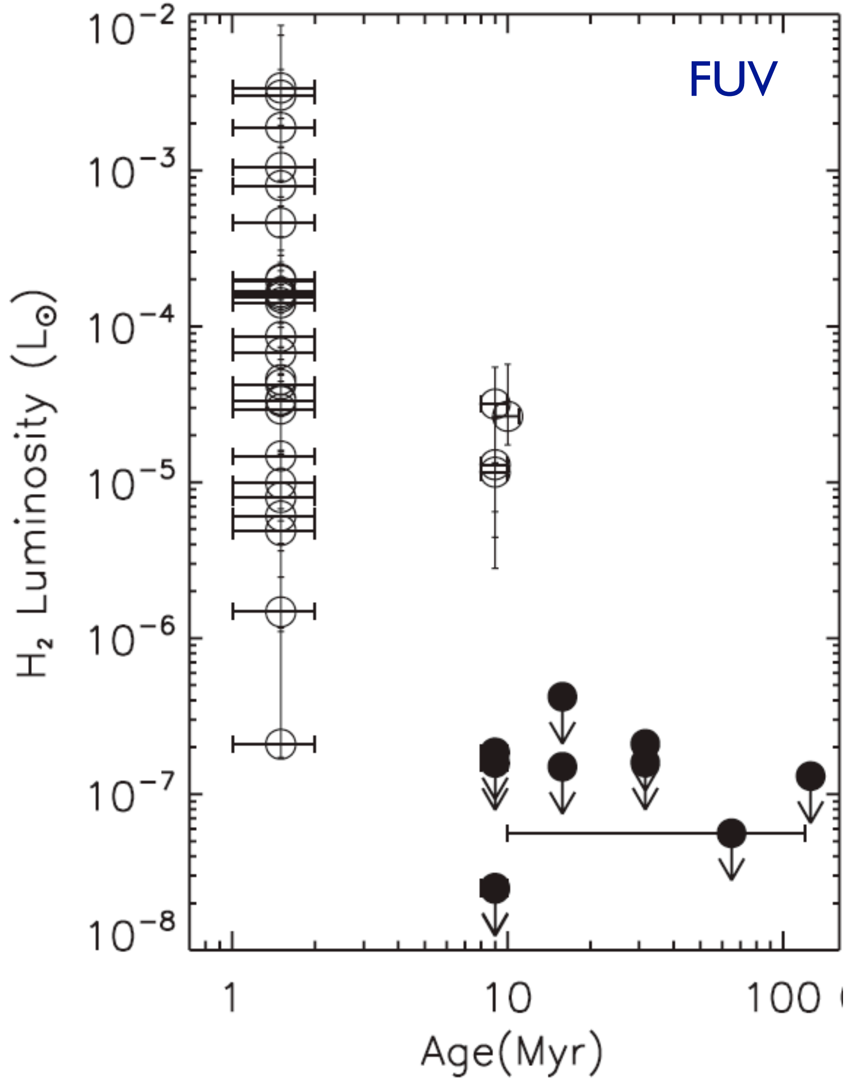
Post-accretion disks do not have enough mass to form Jupiter- or Saturn-like planets



modeling from Gorti & Hollenbach 2004

Little gas to circularize terrestrial planet orbits

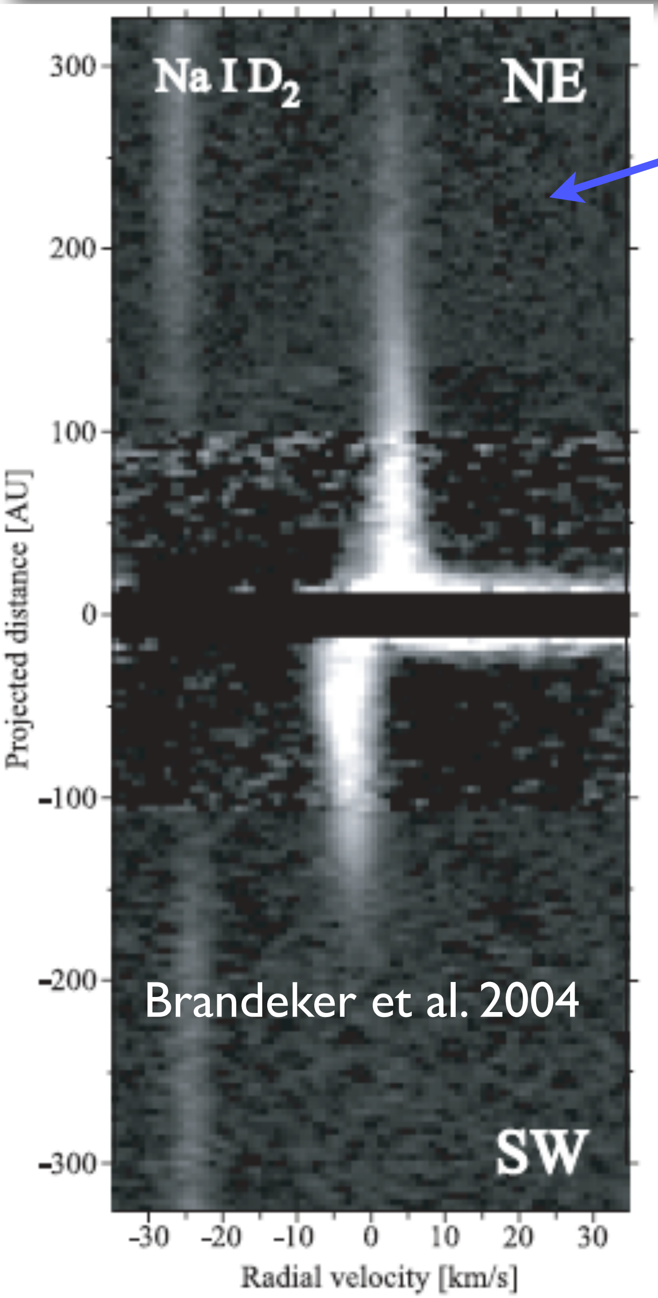




Pascucci et al. 2006

Ingleby et al. 2009

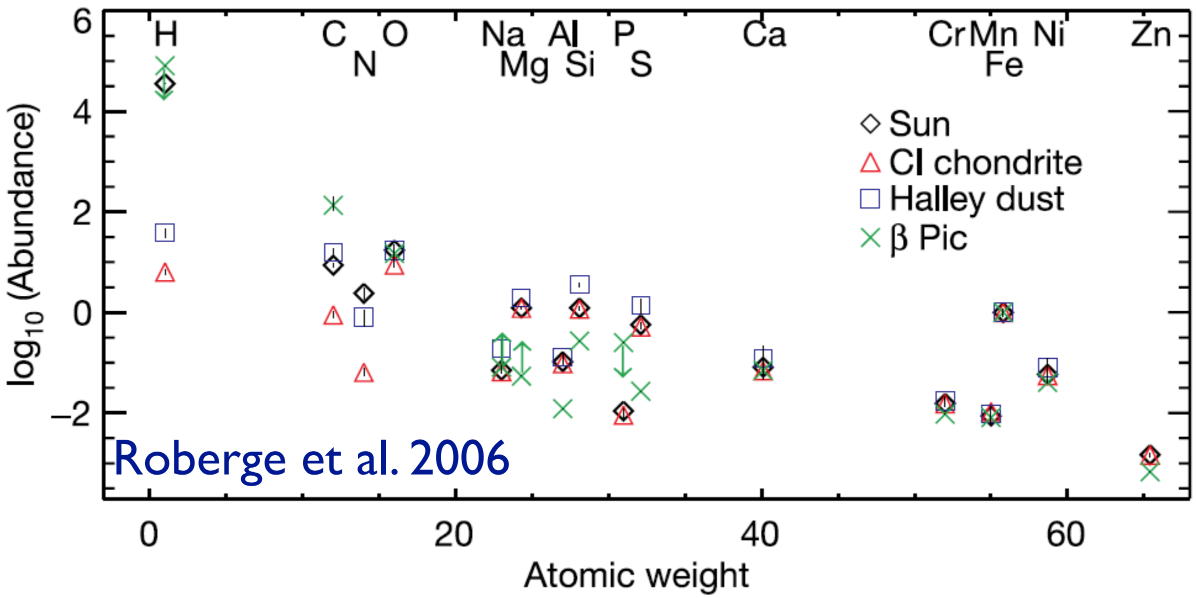
Second-generation gas in the disk of Beta Pic



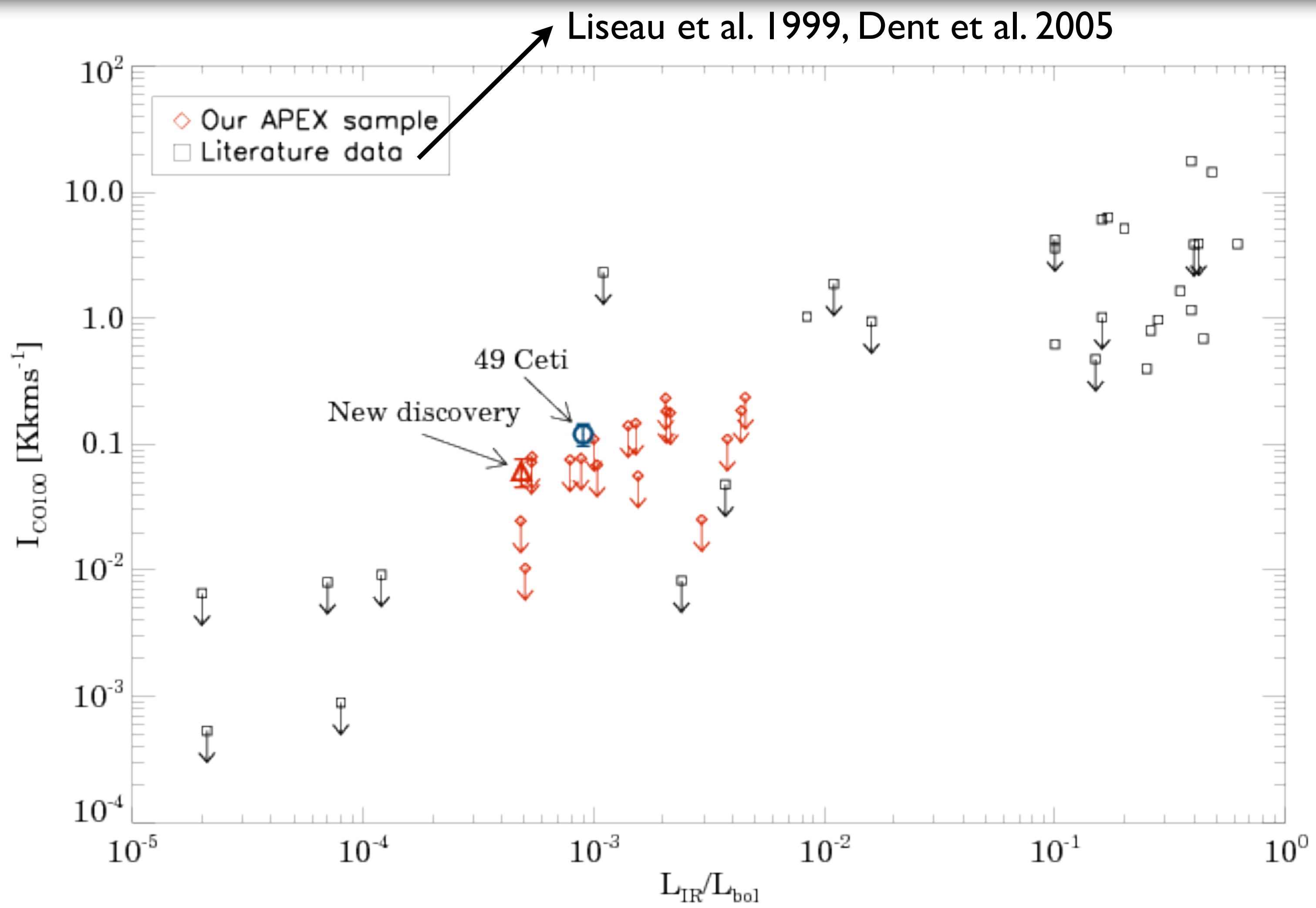
extended emission from Fe I, Na I, Ca II, Ni I .....

also [CII]157μm detected with Herschel (P15)

overabundance of C relative to other elements
outgassing of planetesimals?



Millimeter results confirm low gas masses

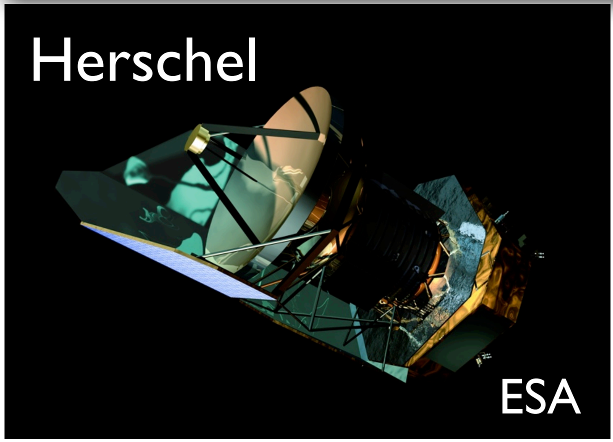


Moor et al. in prep.

APEX CO(3-2) survey of 19 (10-50 Myr) massive debris disks

First Results from the Herschel Space Observatory

Tracing the dispersal of nebular gas



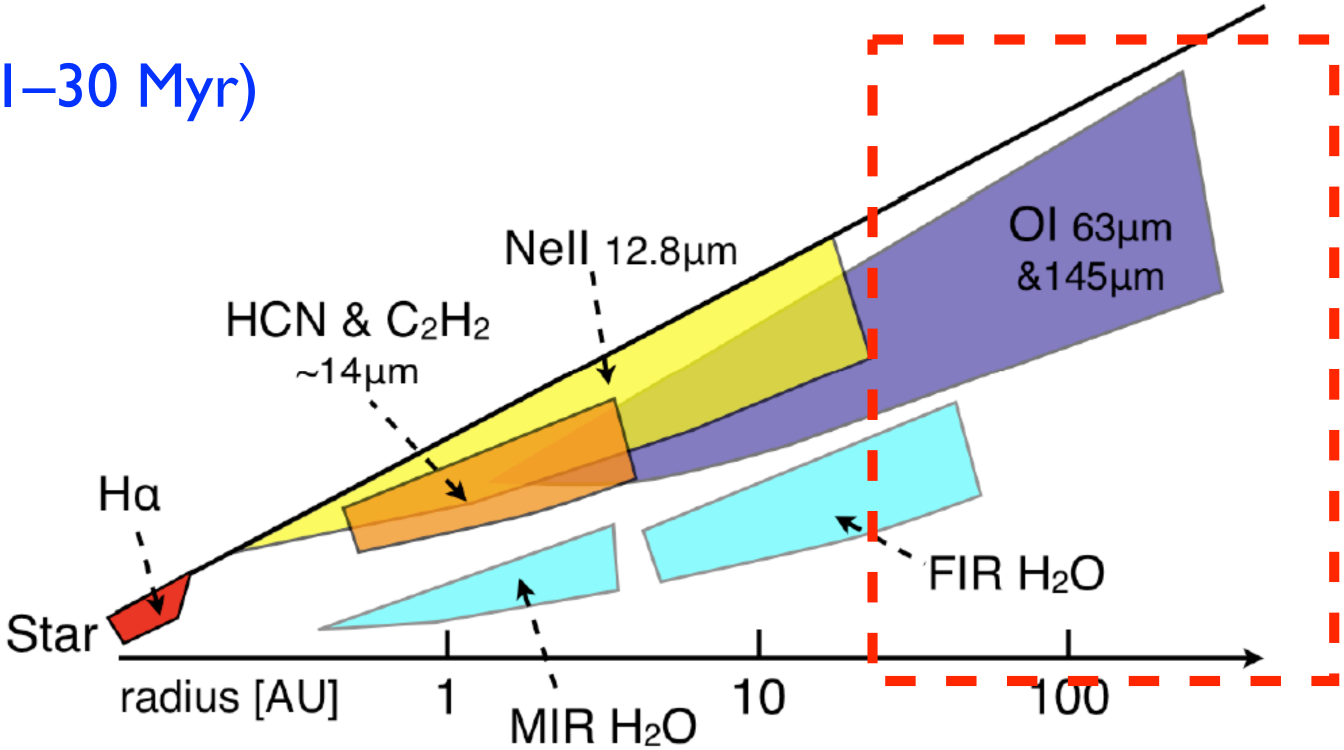
Gas in Protoplanetary Systems
– Herschel Key Program
(PI W. Dent)

GASPS

Sample of ~200 disks (1–30 Myr)

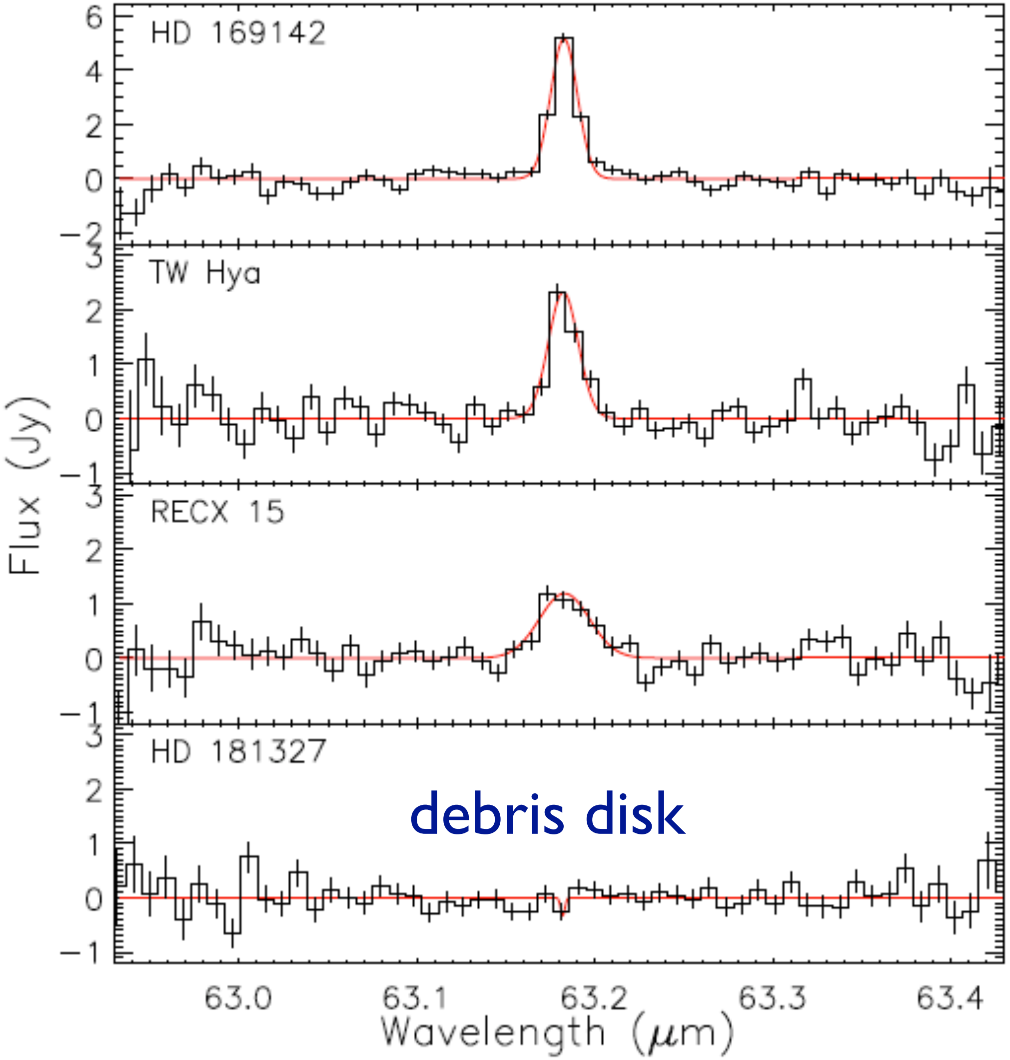
Key Tracers:
[OI], [CII], H_2O, CO

+extensive modeling
(Woitke et al. 2009,2010
Kamp et al. 2010)



Herschel Space Observatory – First results

[OI] 63 µm



4 Science Demonstration targets:

A) [OI] detected in 3 accreting stars
– not detected in a non-accreting star
– emission spatially unresolved
– line unresolved

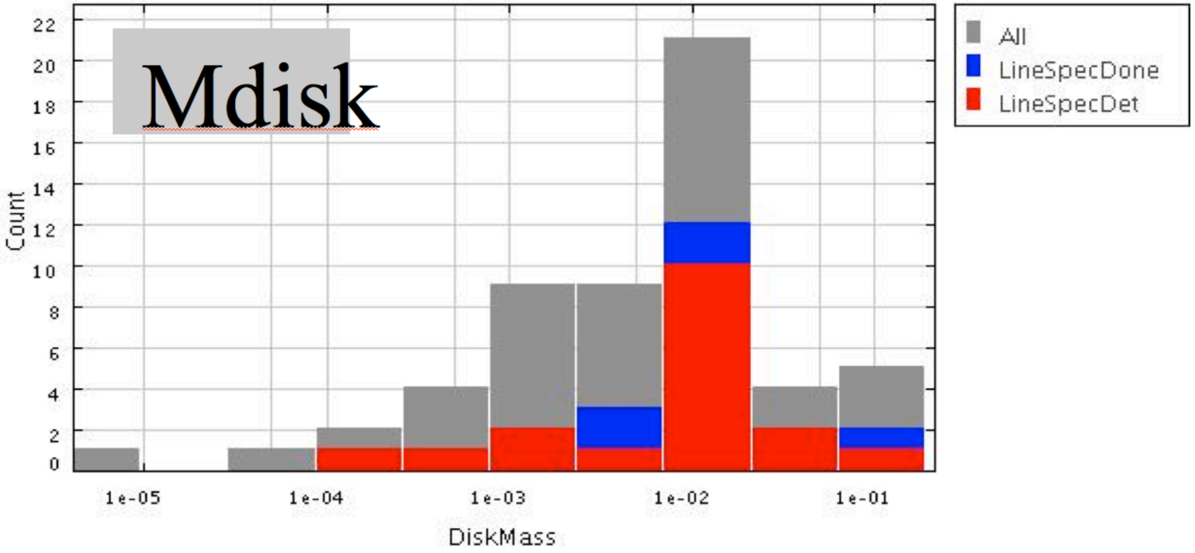
B) [CII] 157 not detected, lower than predicted

C) tentative detections of other lines

Mathews et al. 2010

Herbig Ae/Be stars → talk by G. Meeus

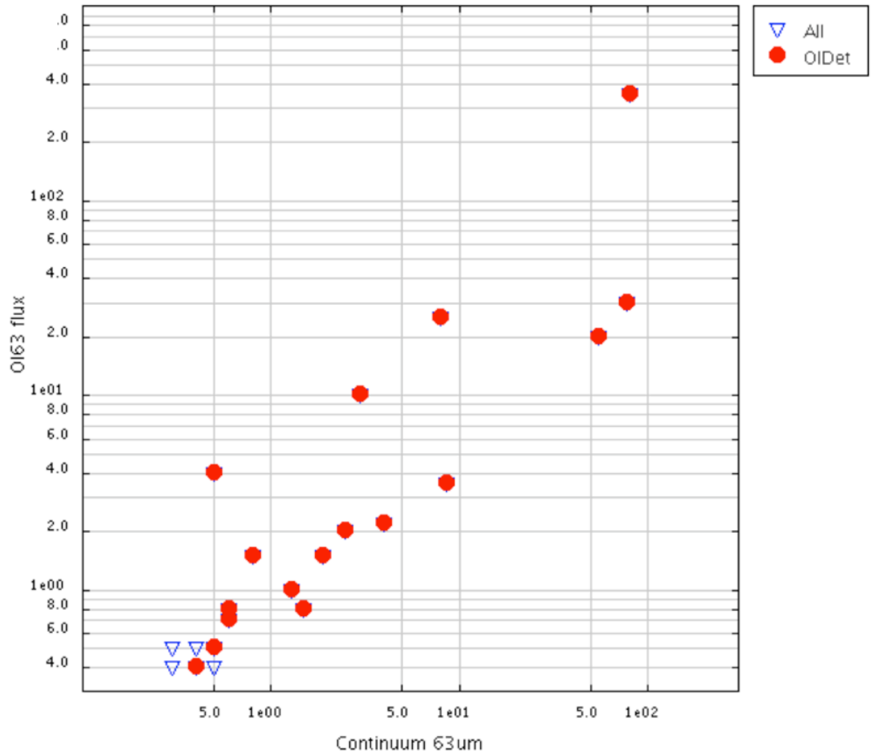
[OI] 63 µm detected in most sources



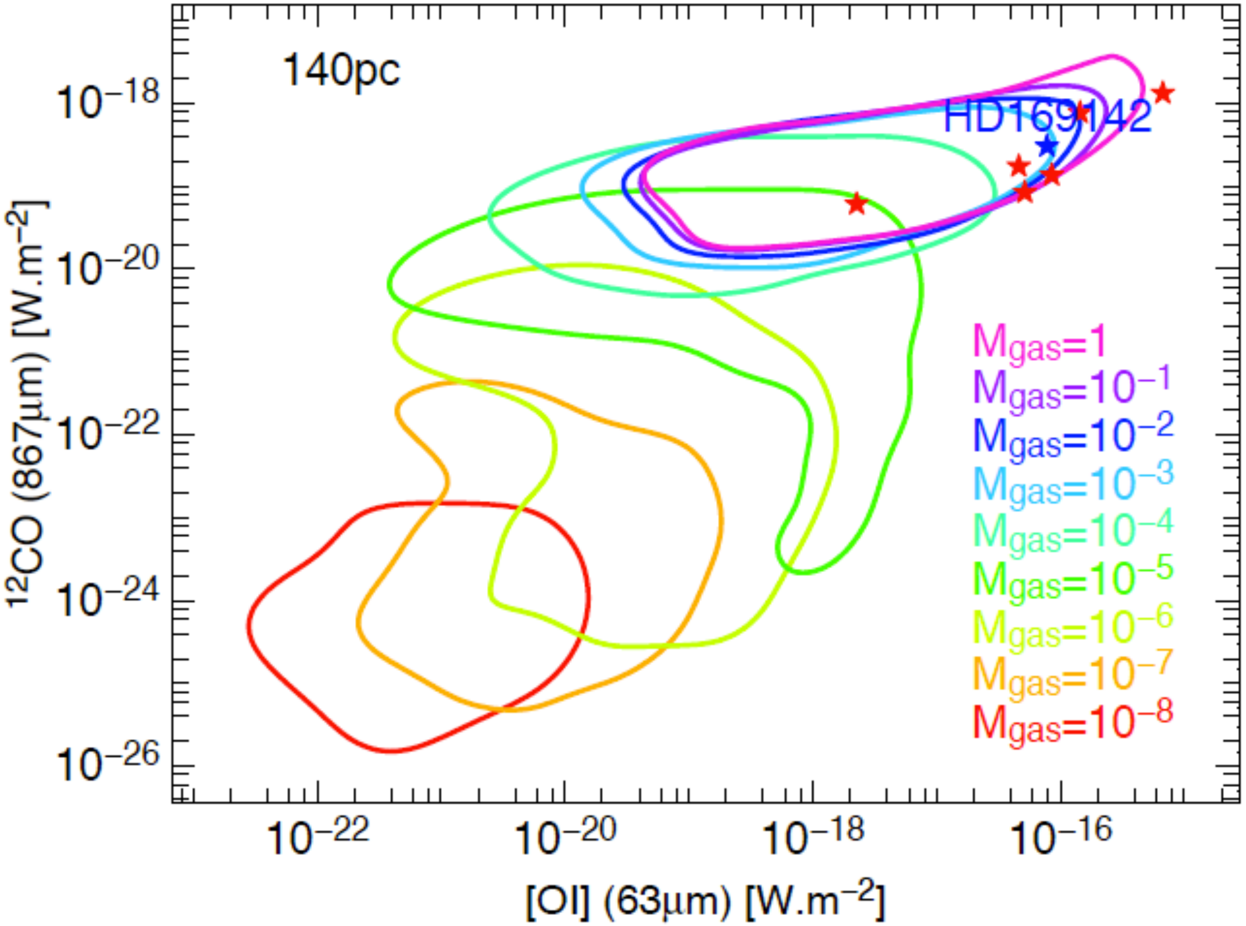
outflow sources → talk by L. Podio

Correlation between [OI] 63 µm flux and nearby continuum

dust and gas from similar disk radii



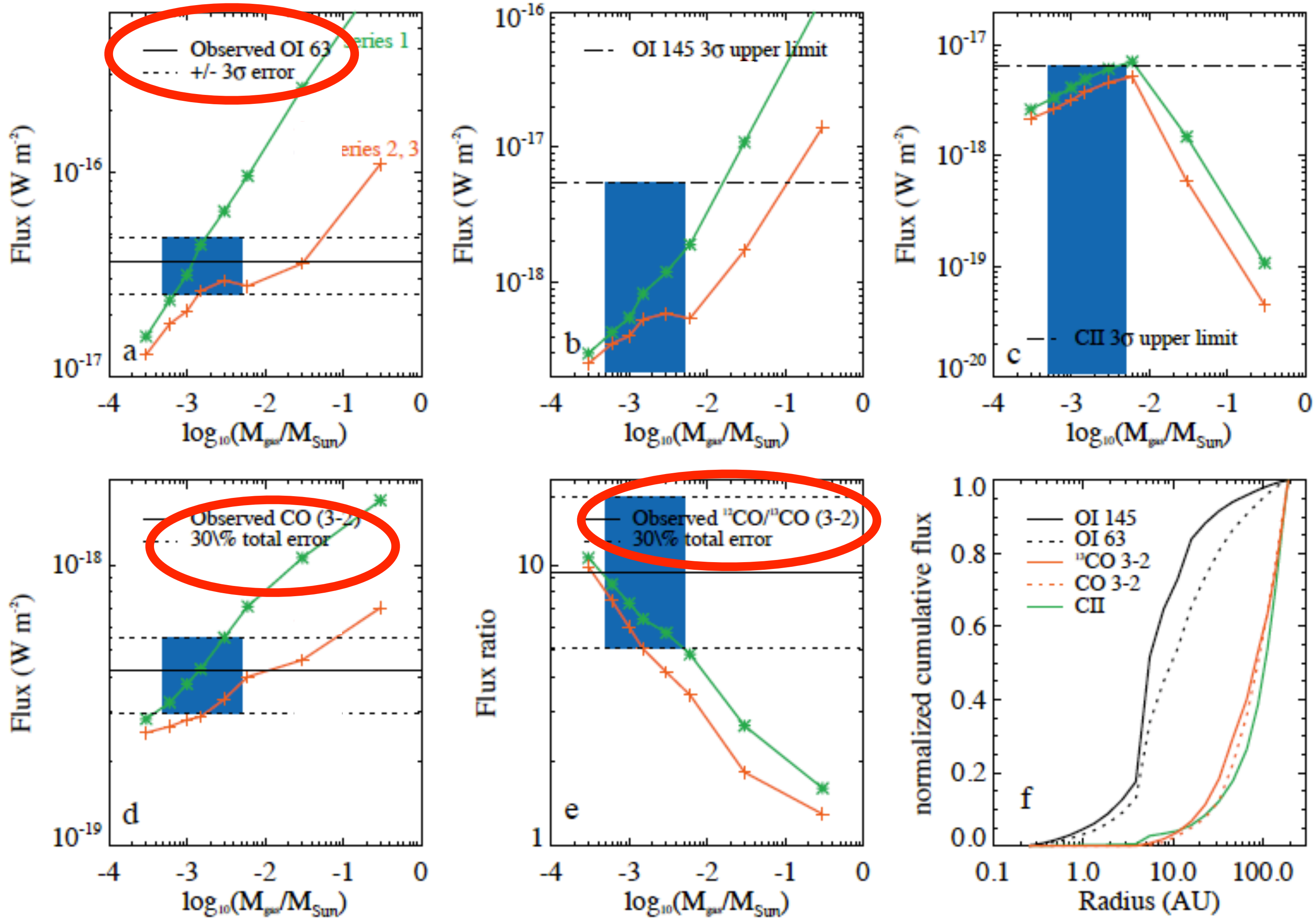
FIR + mm lines to measure the gas disk mass



Pinte et al. 2010 based on 300,000 disk models by Woitke et al. 2010

Indications on gas/dust disk mass ratios

TW Hya: gas/dust mass ratio < 100 → photoevaporation?



Thi et al. 2010

Summary

- Spectra of young accreting disks are rich in molecular emission lines
→ complex chemistry stellar-mass dependent

- Spectra of evolved disks lack strong molecular lines but have atomic emission lines (photodestruction of molecules by UV field)

- Ongoing photoevaporation in some evolved/transition disks

- Debris disks do not have enough mass to form giant planets

- Herschel key contributions on :
1) determination of gas masses as a function of stellar age
2) indications on gas/dust mass ratios → disk dispersal mechanisms