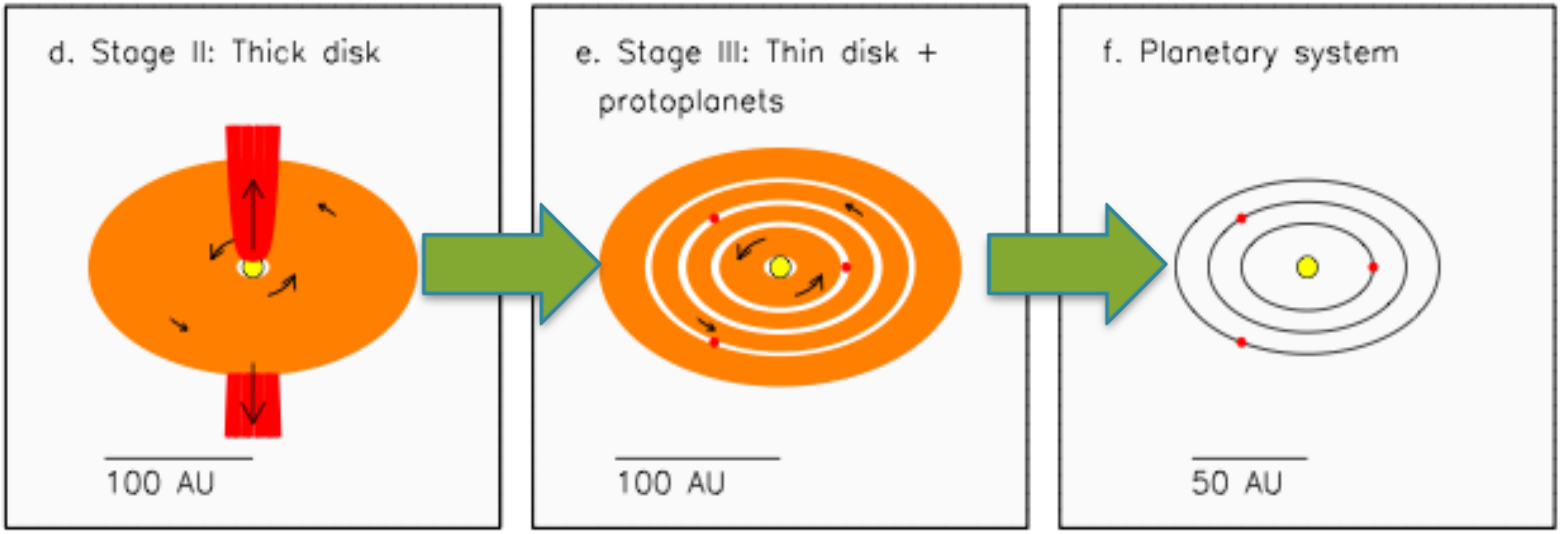
Infrared Observations of Gas Molecules in Protoplanetary Disks

Colette Salyk
Harlan J. Smith postdoctoral fellow
McDonald Observatory, The University of Texas at Austin

Protoplanetary disks are the birthplace of planets



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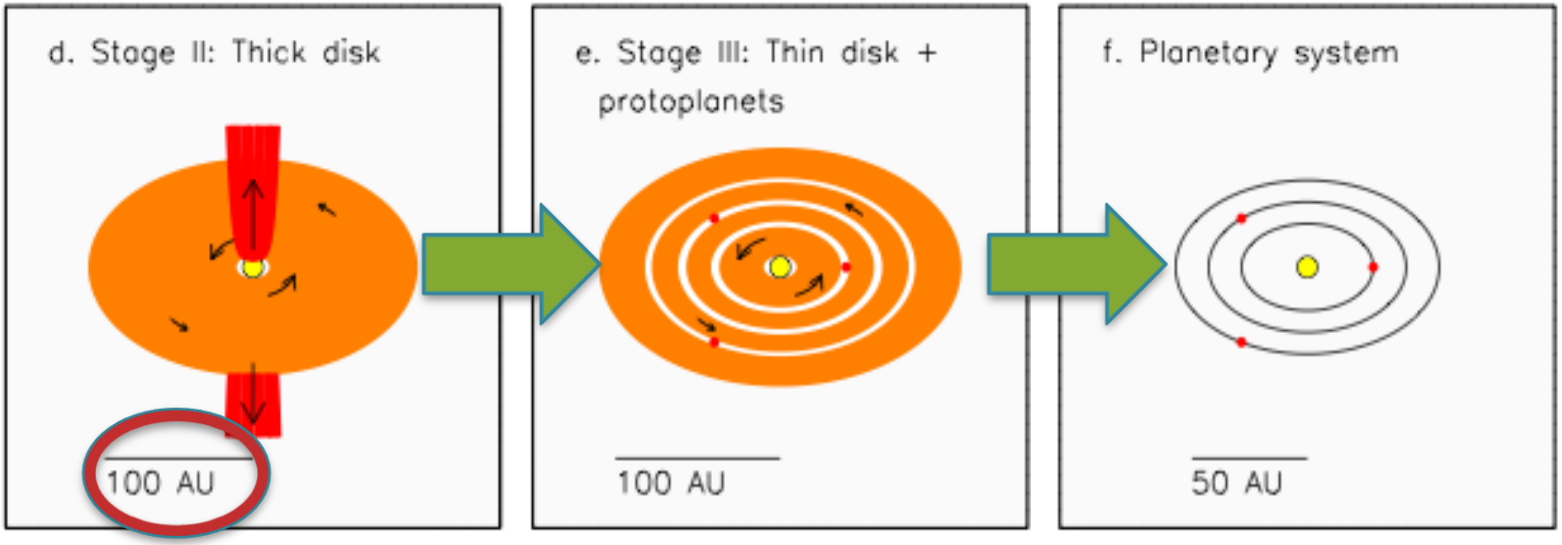
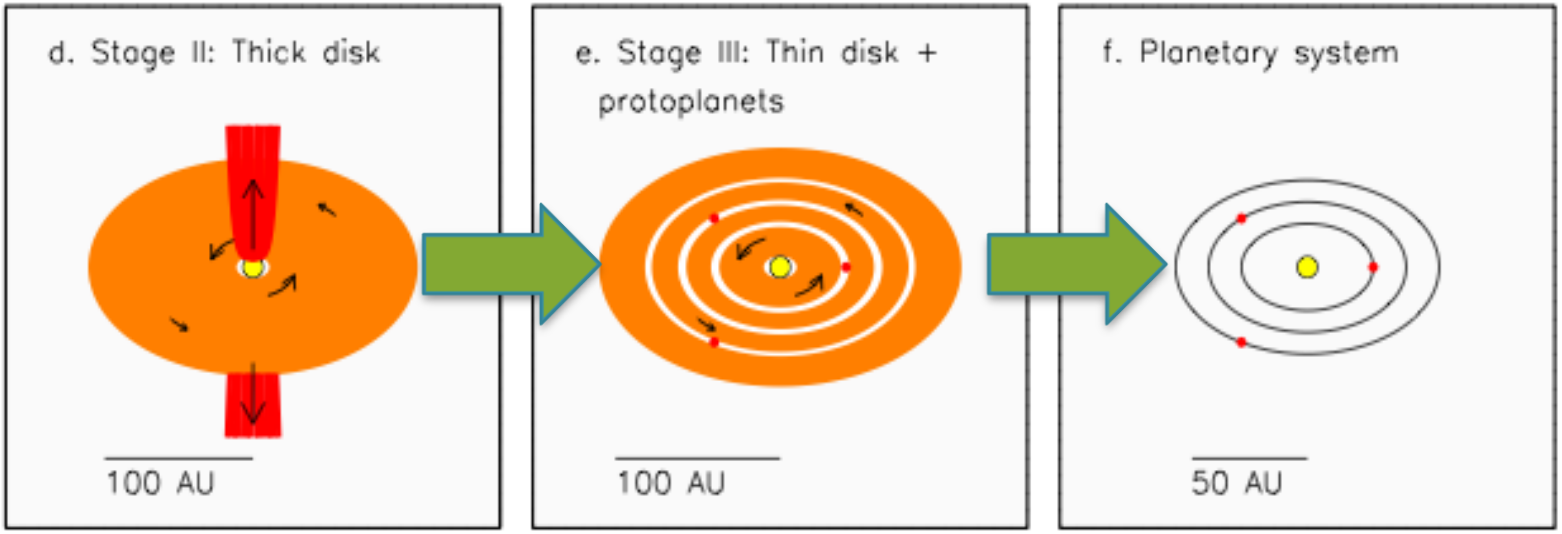


Advantages of IR spectroscopy



Provide very small-scale spatial information about gas
Provide tests of fundamental disk physics and structure
Provide abundances for testing chemical models

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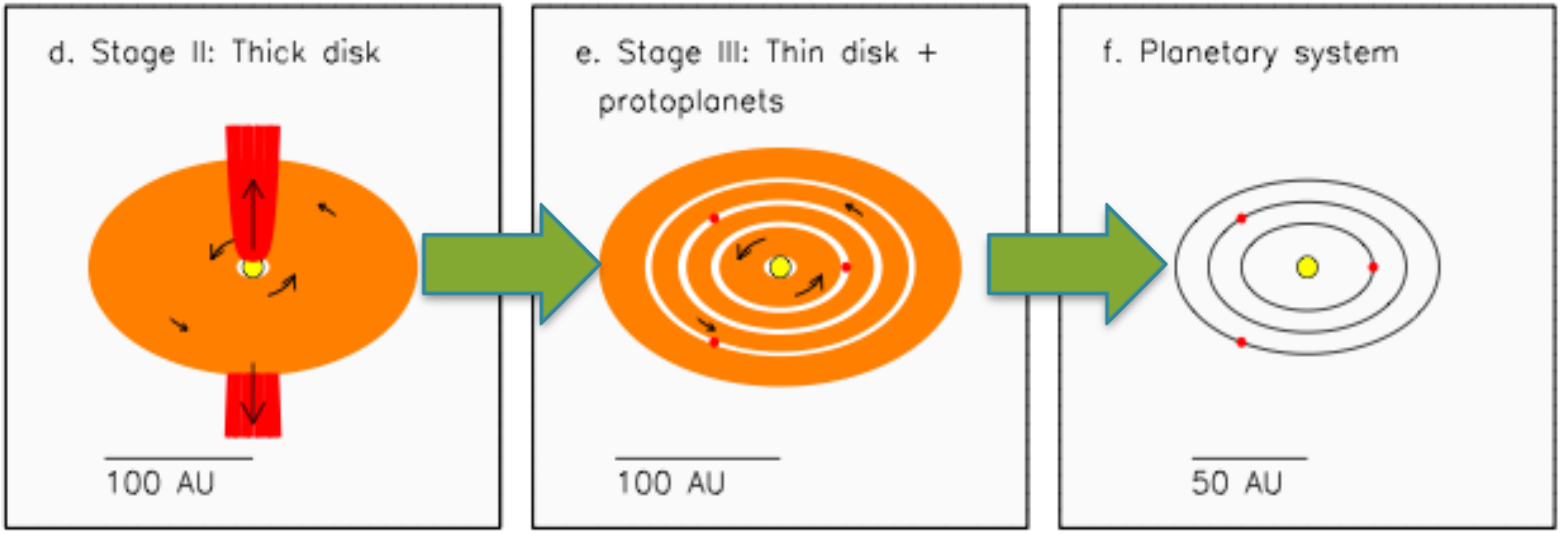
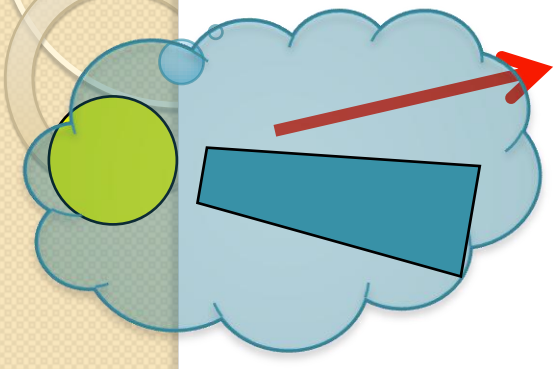
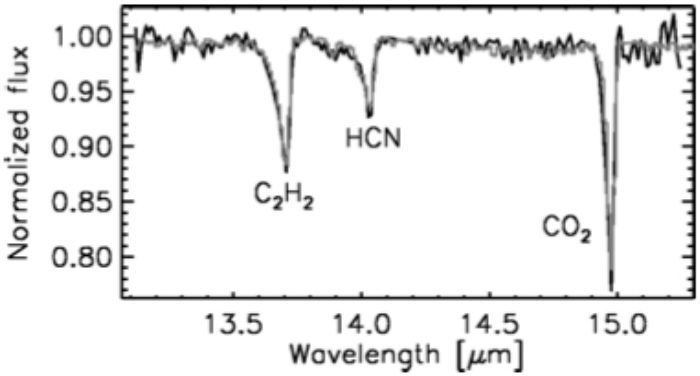


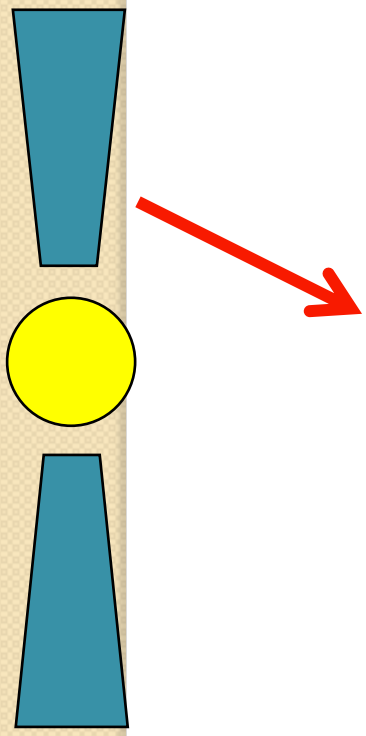
Provide very small-scale spatial information about gas
Provide tests of fundamental disk physics and structure
Provide abundances for testing chemical models***
*** Key to understanding the diversity of planetary systems

Basic geometry and spectra





Lahuis et al. 2006



CO p-branch

*** Usually limited to seeing upper atmosphere

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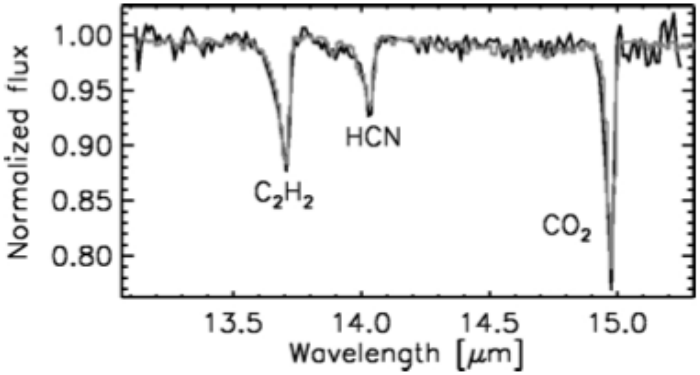

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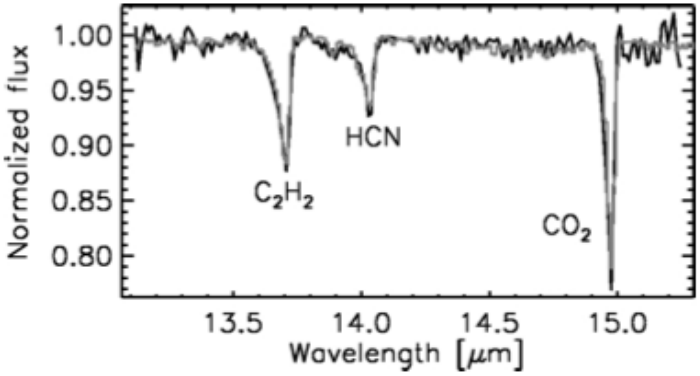

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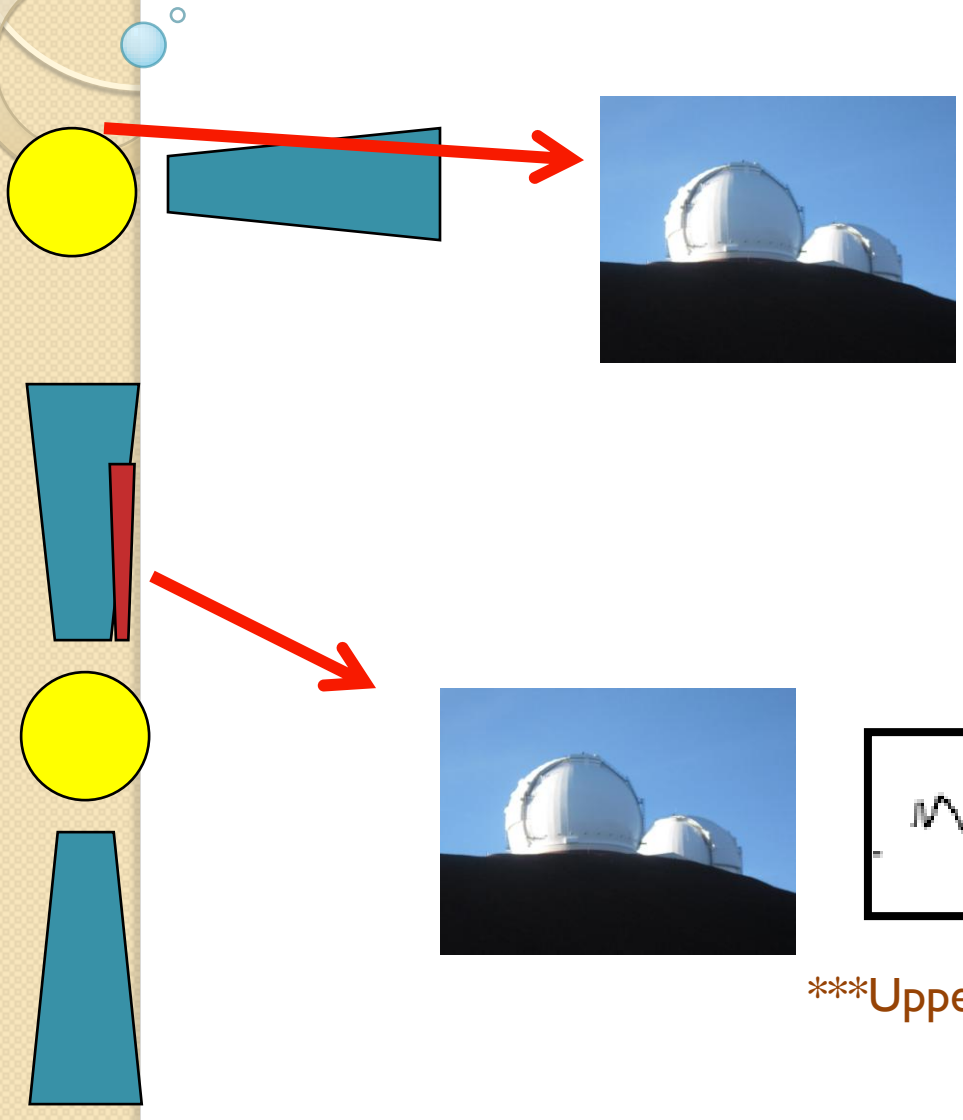

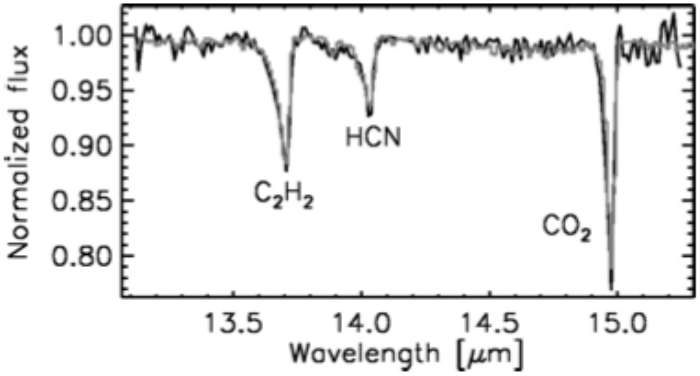

Lahuis et al. 2006

CO p-branch

***Upper disk atmosphere, ~<10 AU

Inner disk tracers prior to 2008

Species	$\lambda(\mu m)$	Transition	E_u (K)	Radius Probed
H_2	0.10 - 0.15	Lyman-Werner bands	10^5	r $<$ 1 AU
H_2	2.12	$v = 1 - 0$ S(0)	6471	r $\sim$ 10 – 40 AU
CO	2.23	$v = 2 - 0$	6300	r $\sim$ 0.05 – 0.3 AU
CO	4.6	$v = 1 - 0$	3000	r $\sim<$ 0.1 – 2 AU

From Bergin 2009

with interesting exceptions:

Carr et al. 2004 – H_2O overtone emission from energetic young star + disk

Lahuis et al. 2006 – HCN, C_2H_2, CO_2 absorption from an edge-on disk

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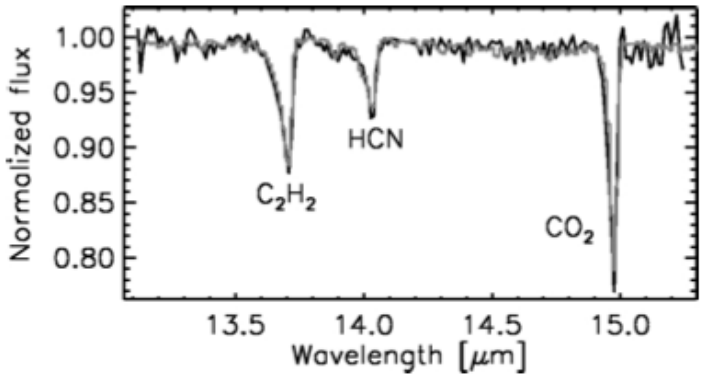
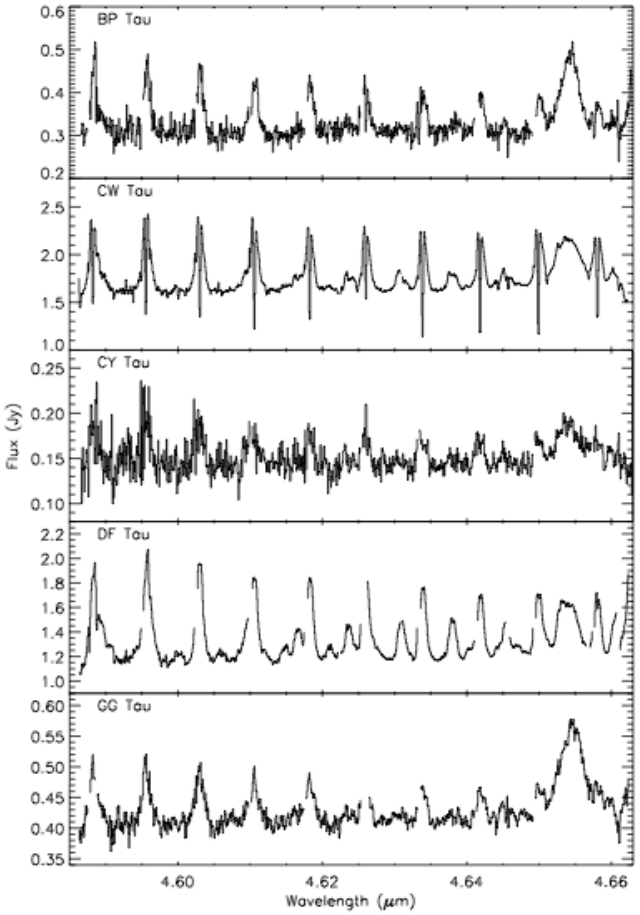
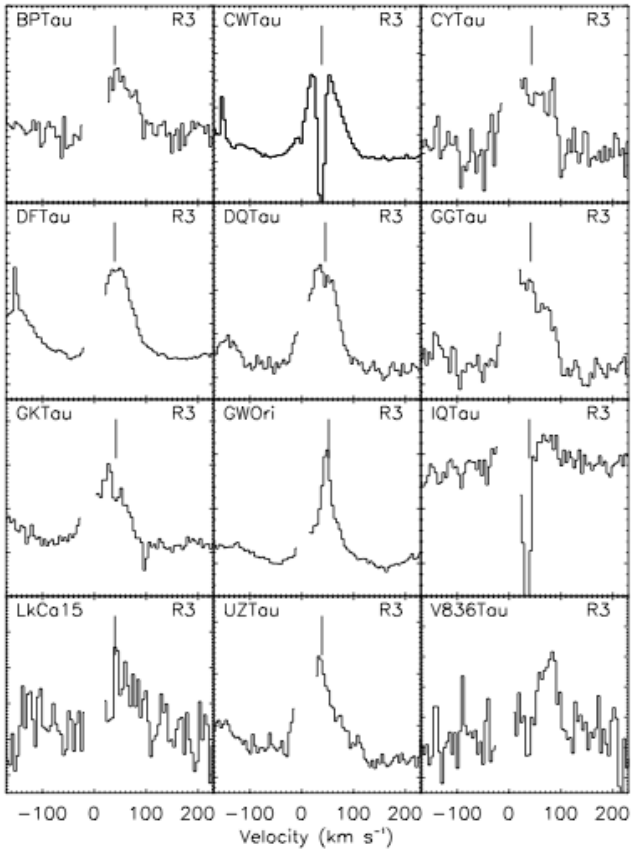


Lahuis et al. 2006

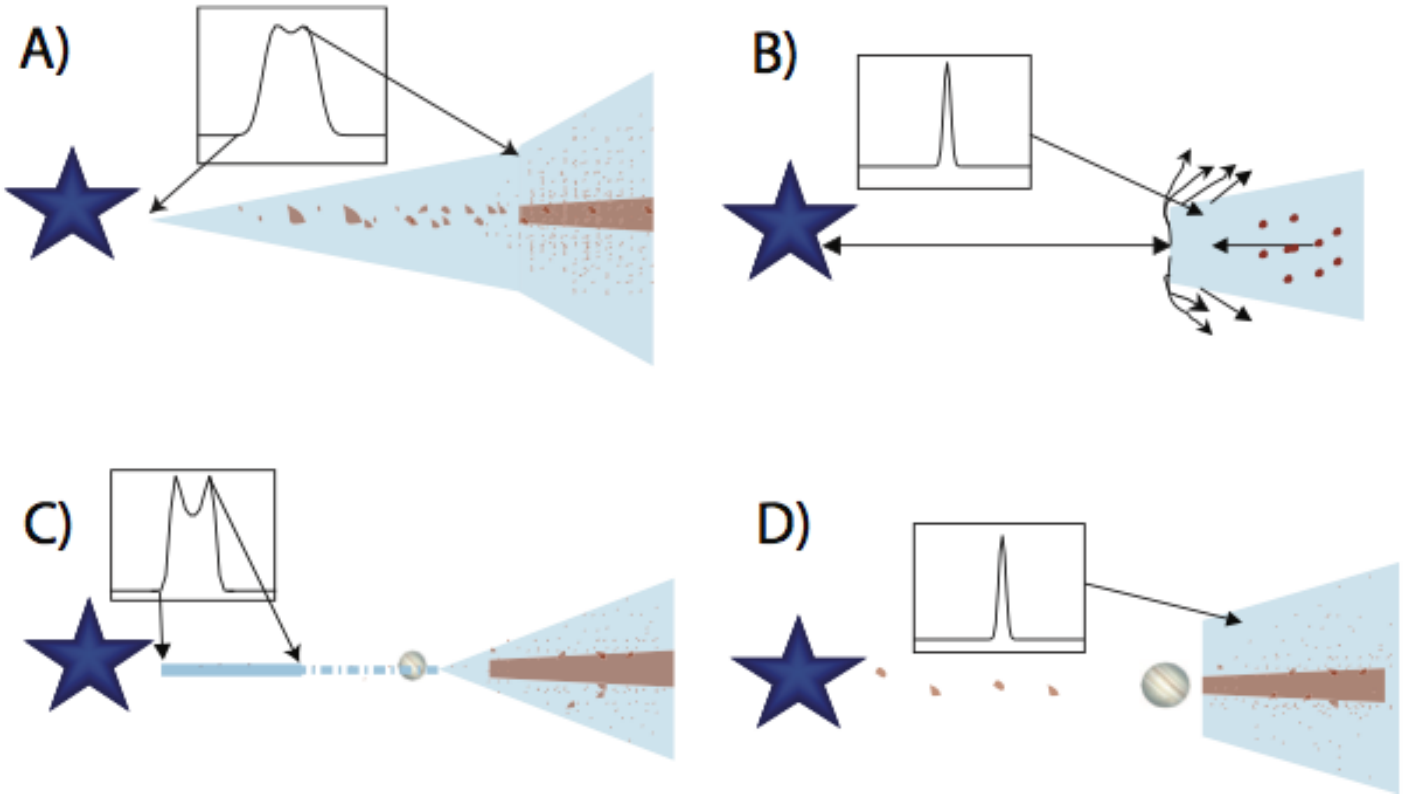
CO: Evidence for warm inner disk atmospheres





Najita et al. 2003

CO: The origin of transitional disks



Brittain et al. 2009

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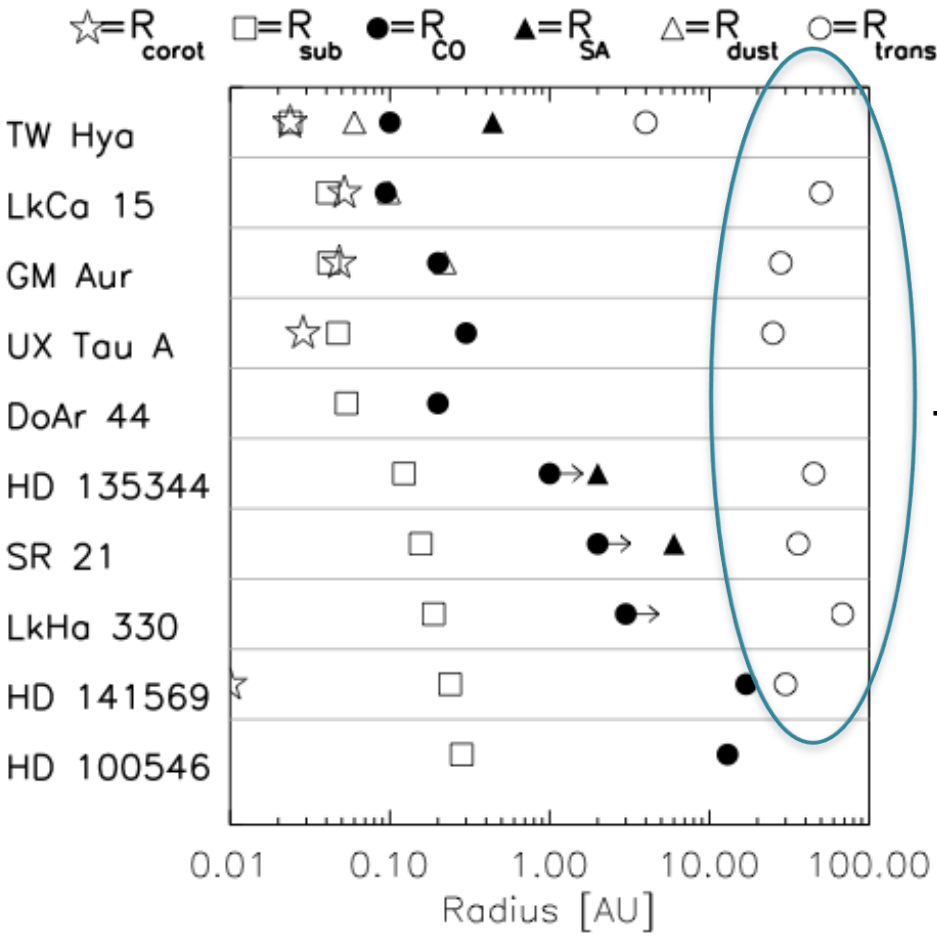

Transition radii

Salyk et al. 2009, 2011; Brittain et al. 2003, 2009

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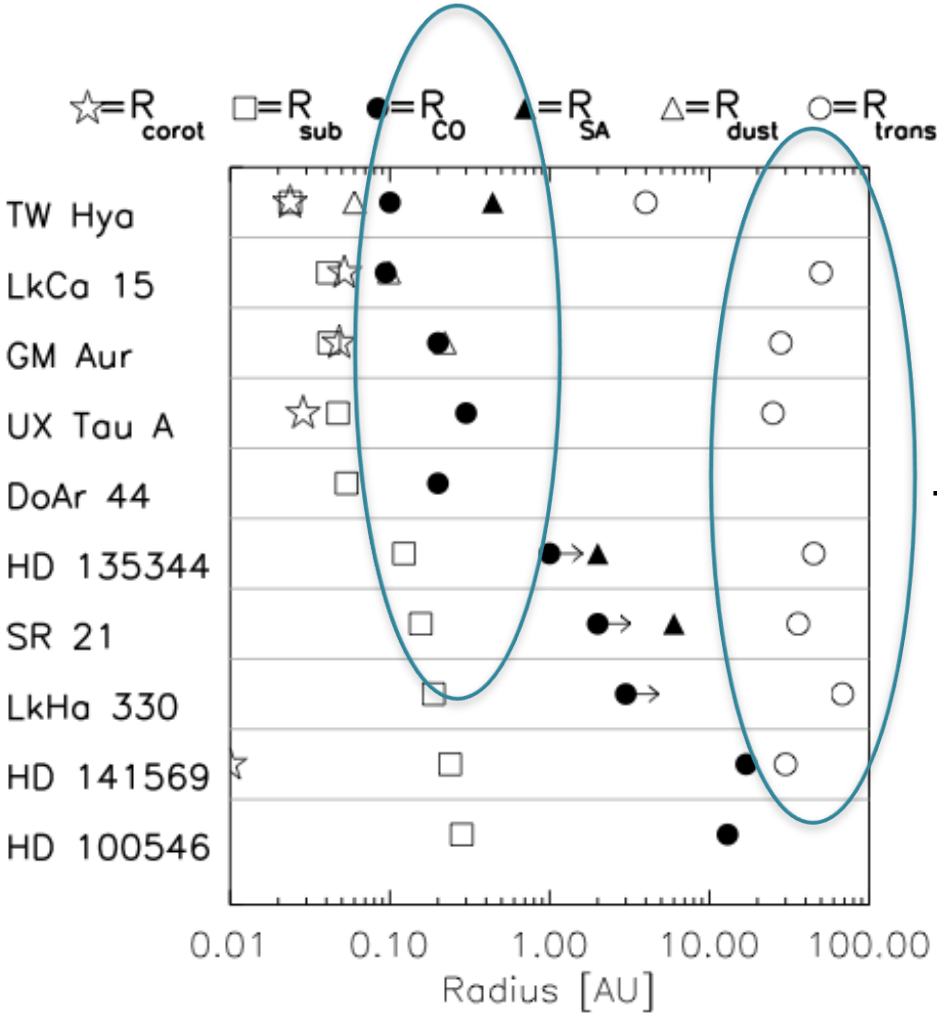

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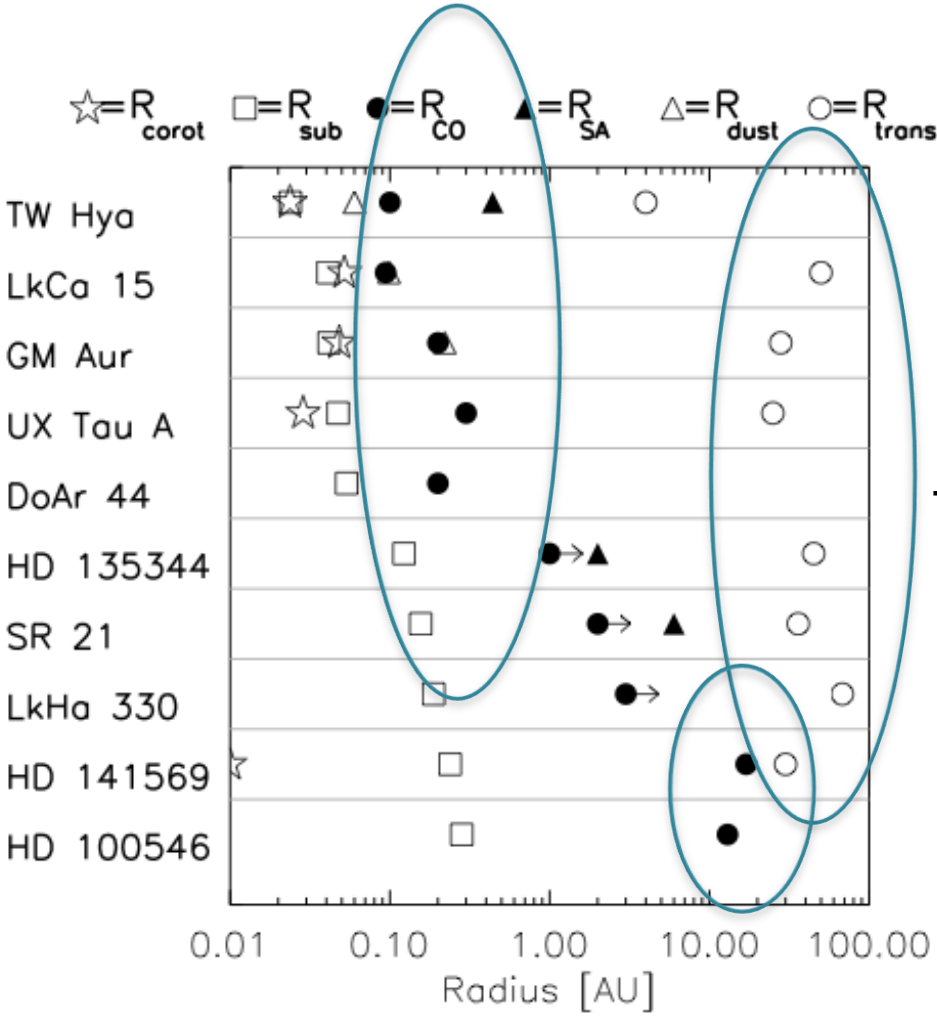

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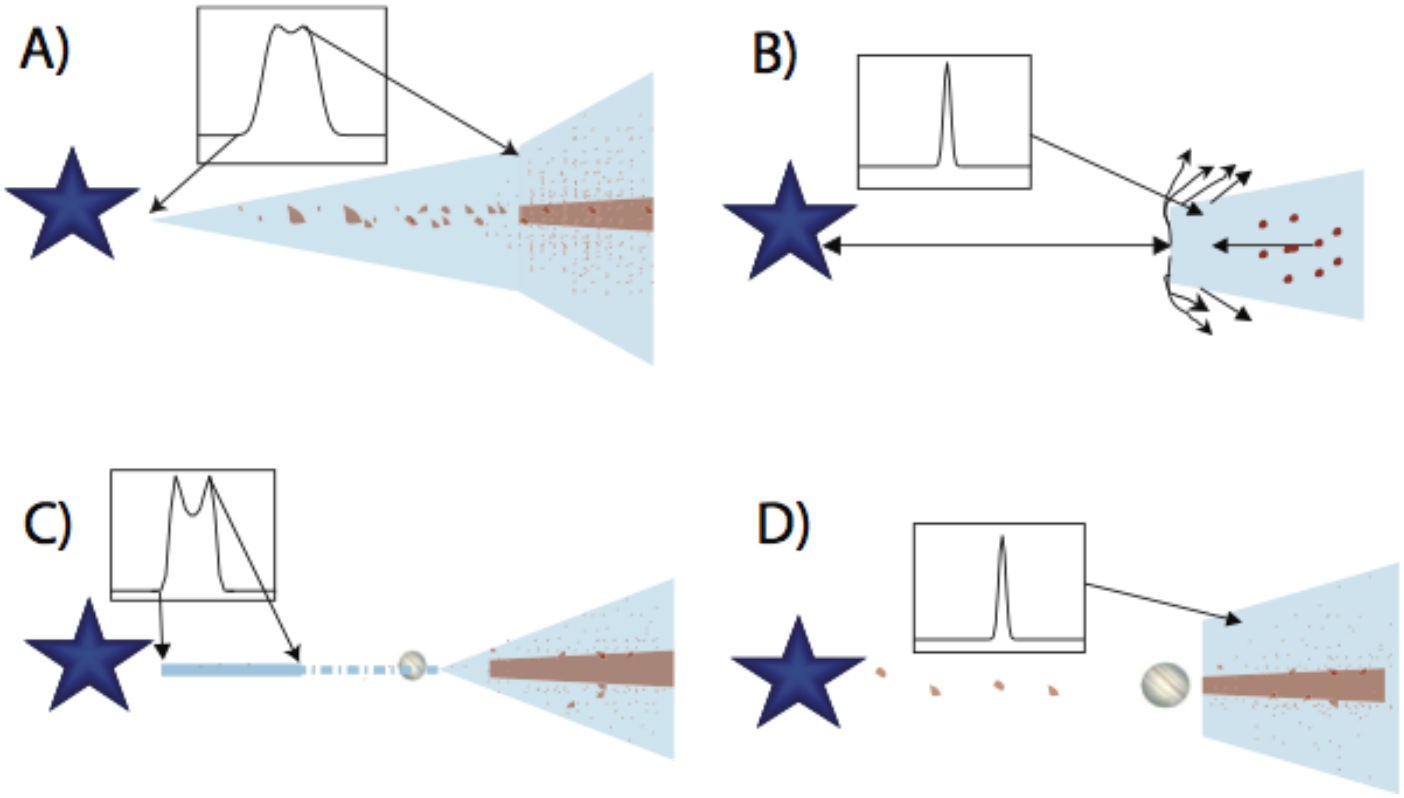
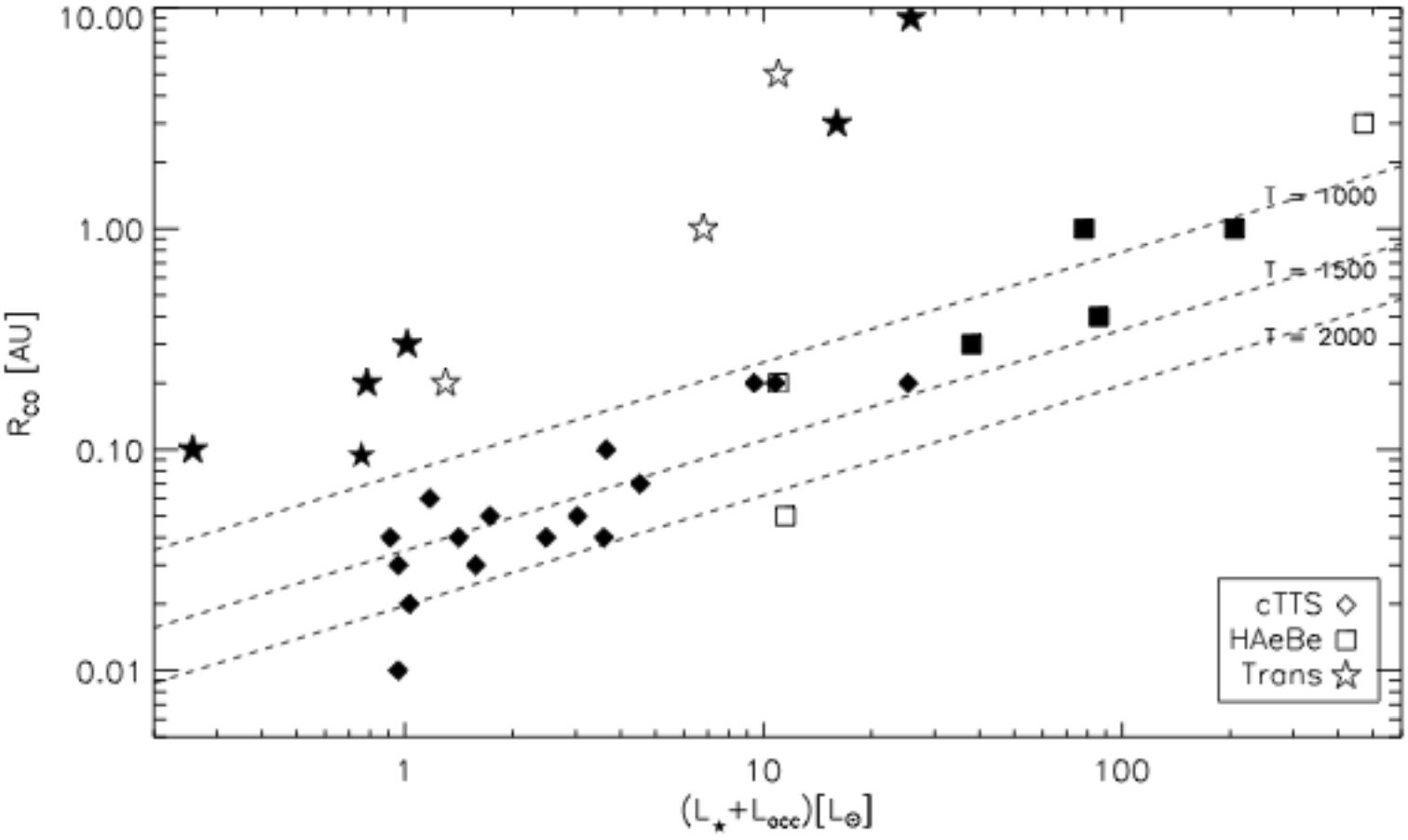


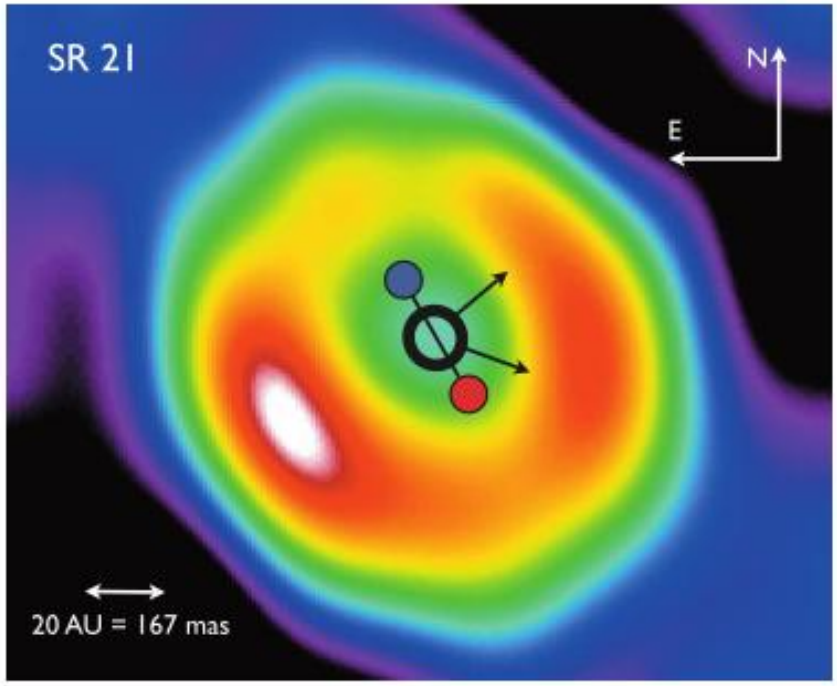
Brittain et al. 2009

CO: Inner disk sublimation fronts



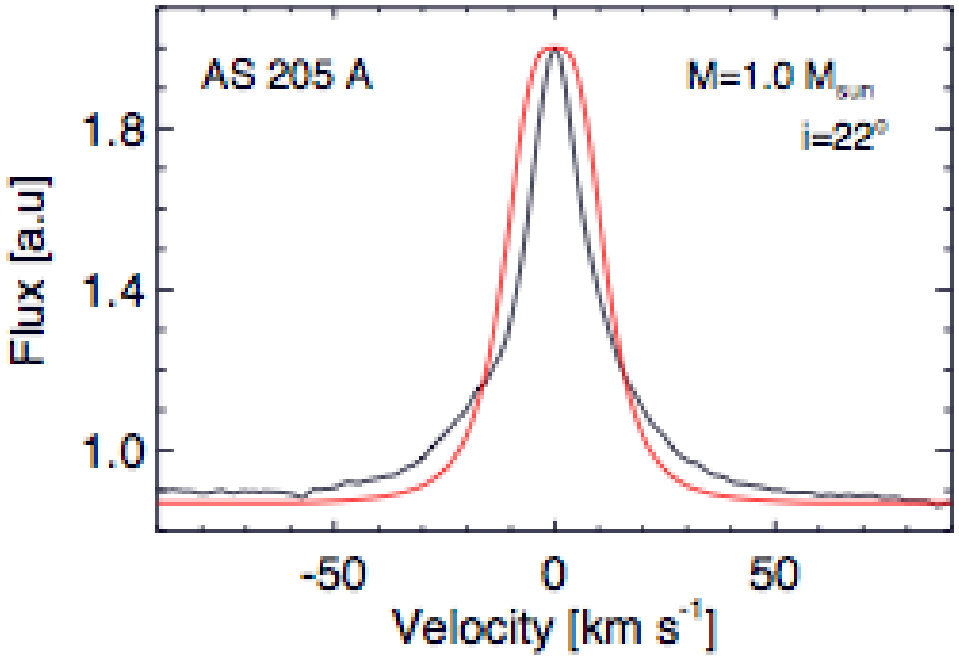
Salyk et al. 2011, submitted

CO: Spectro-astrometry reveals warps and aymmetries



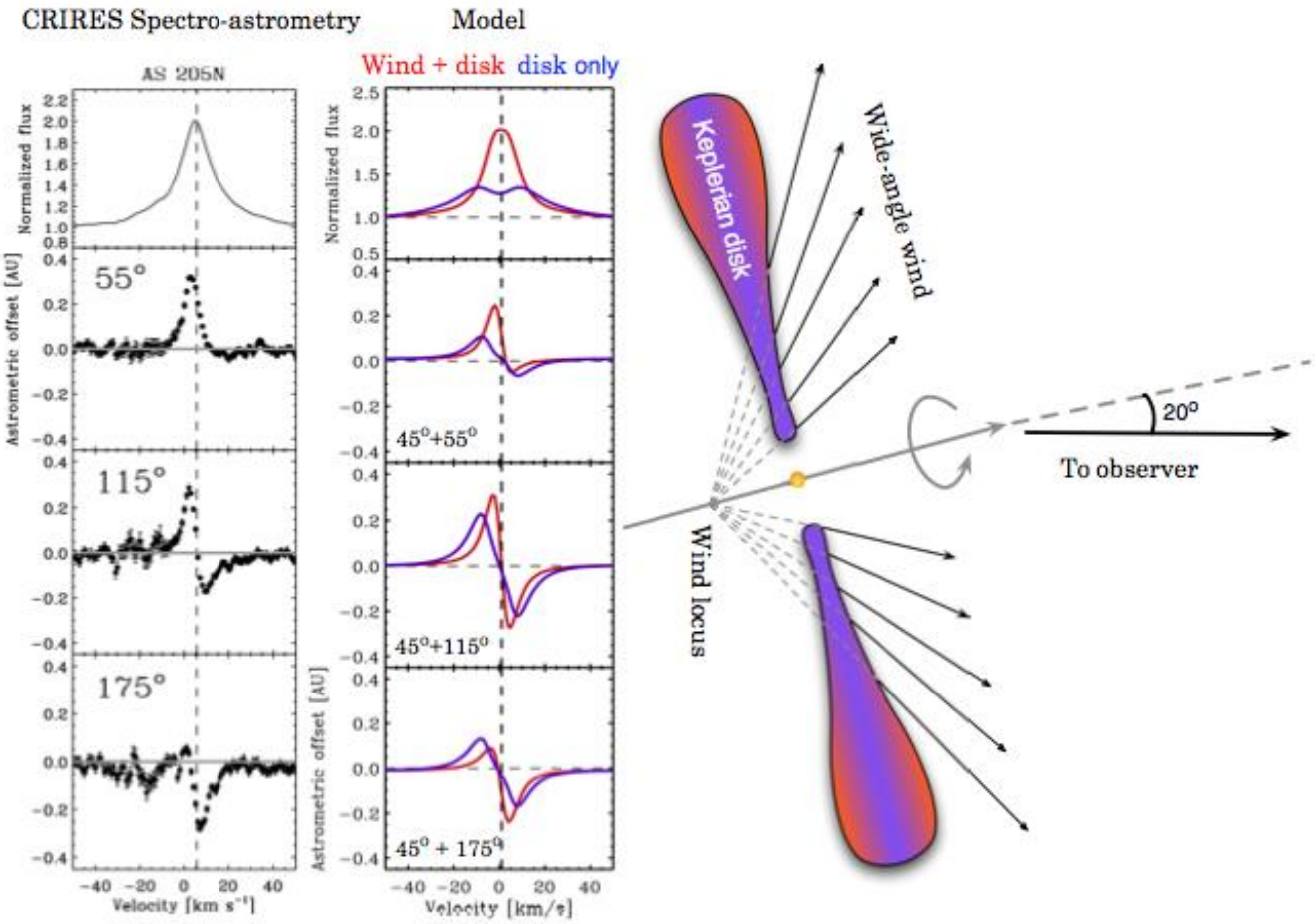
Pontoppidan et al. 2008
(SMA image from Brown et al. 2009)

CO: Some line profiles not fit by Keplerian disk alone



Bast et al. 2011

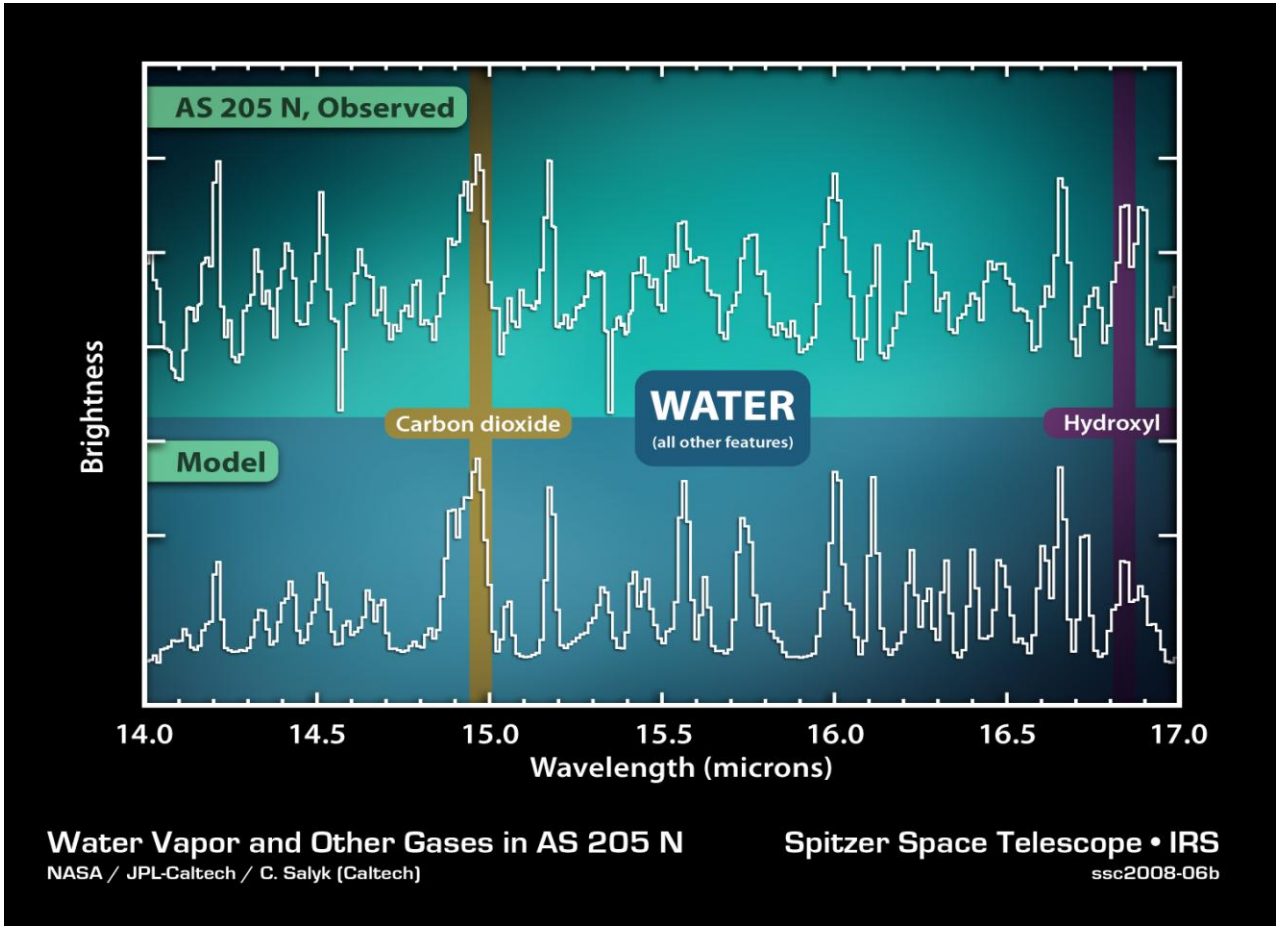
CO: Disk wind?



Pontoppidan et al. 2011

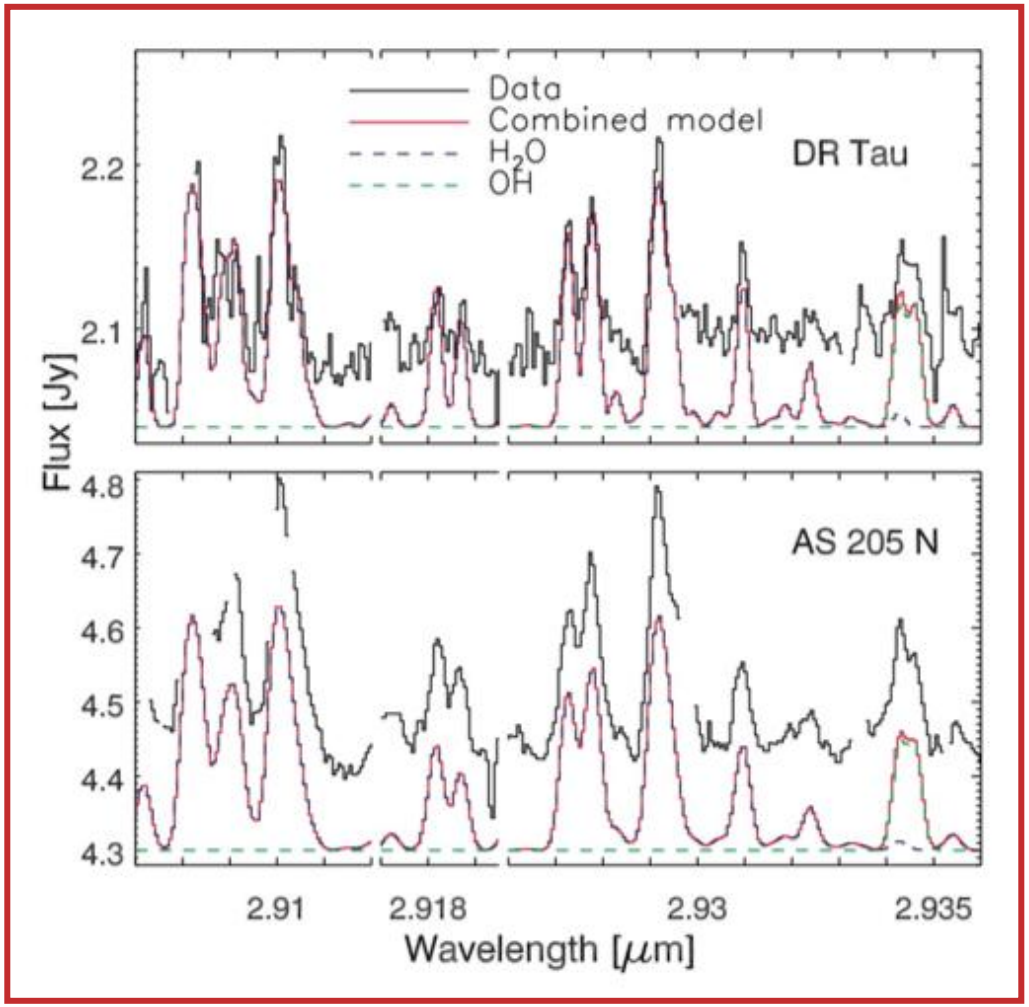
Discovery of molecular emission with IRS

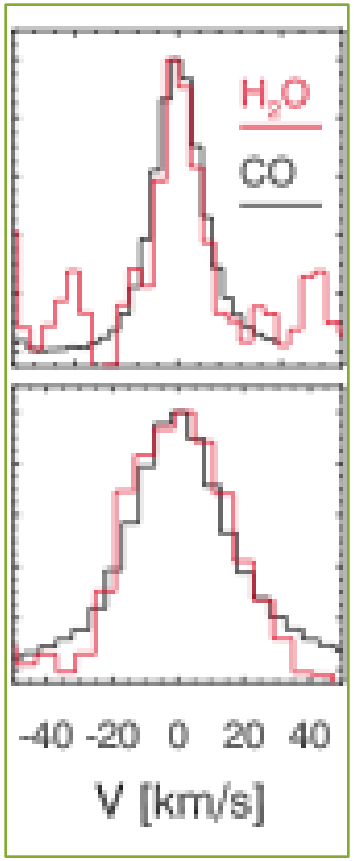
H_2O, OH, HCN, CO_2, C_2H_2



Carr &Najita 2008, Salyk et al. 2008

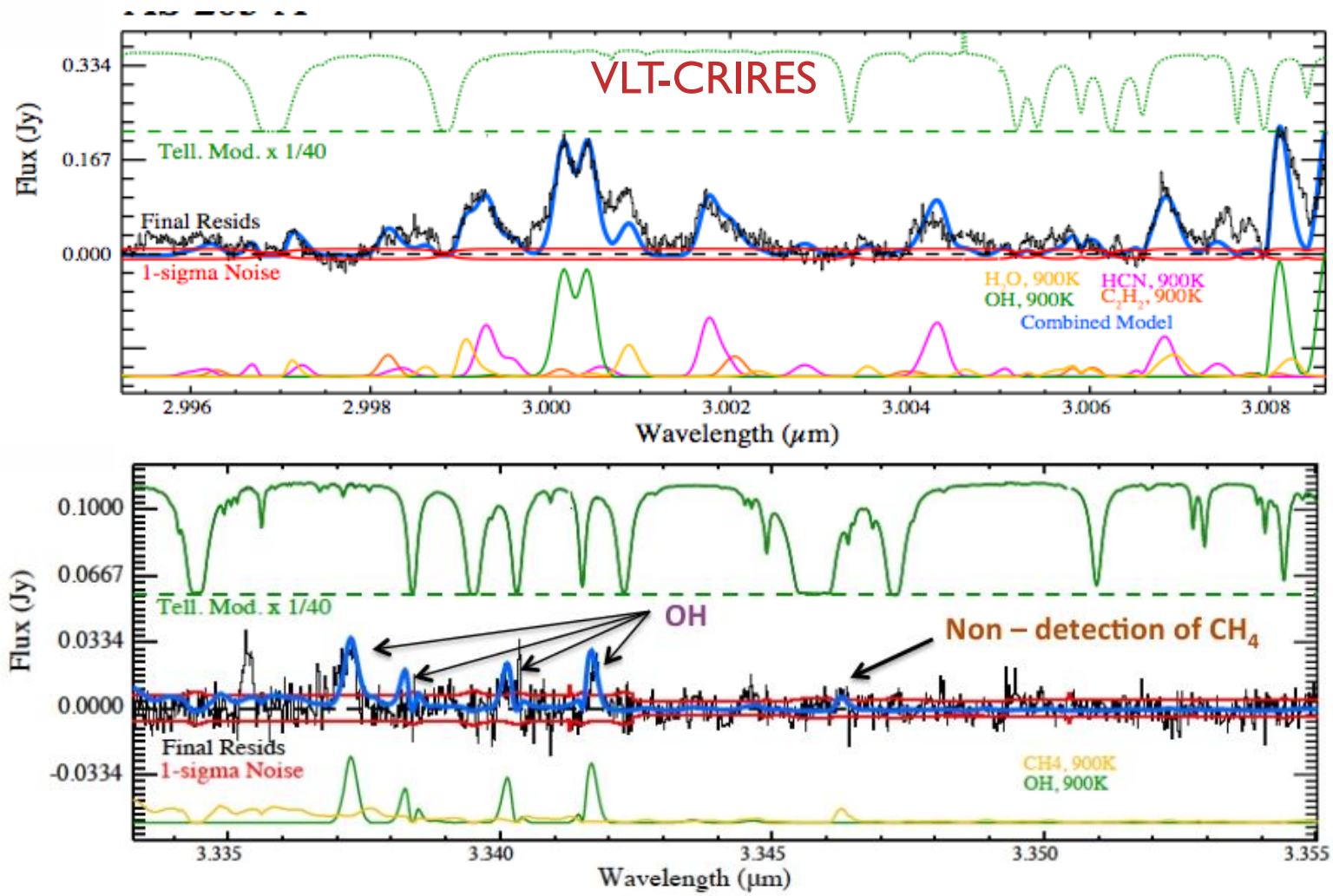
H_2O: Resolved lines in near-IR point to inner disk*
(*few AU or smaller = terrestrial planet-forming region)





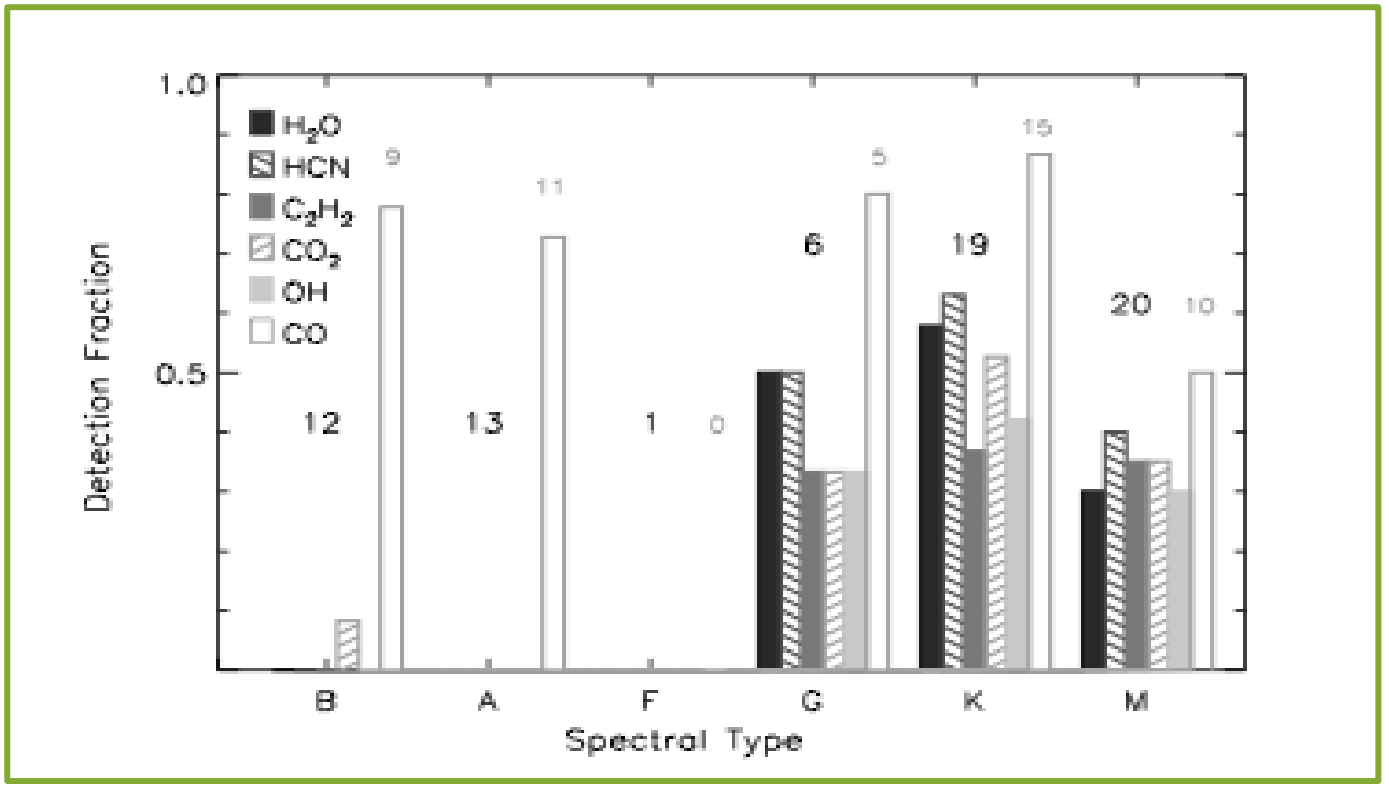
rovibrational lines with Keck-NIRSPEC; Salyk et al. 2008

…and probe additional molecules



Mandell et al., in prep

H_2O and organics: Profound differences between disks around low-mass and mid-mass stars



Pontoppidan et al. 2010

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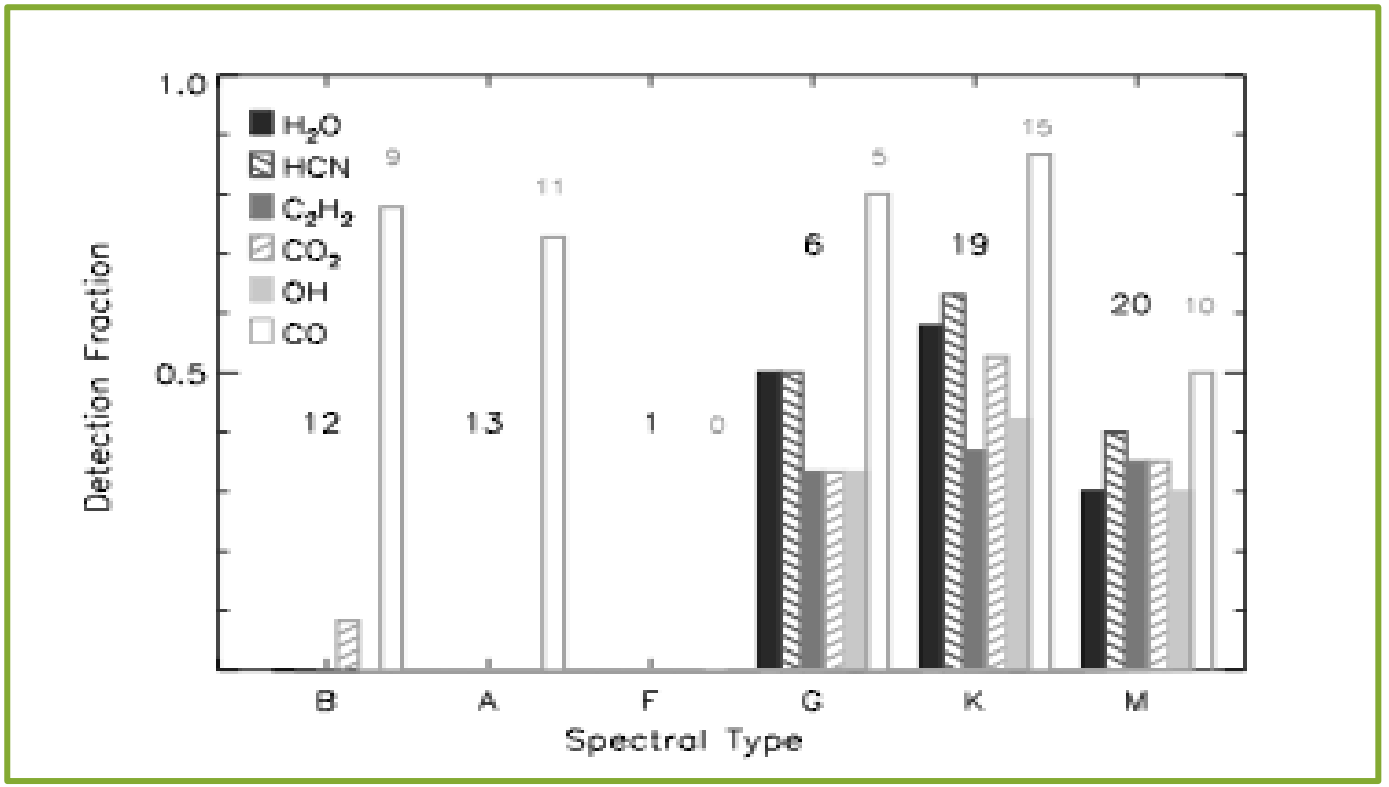


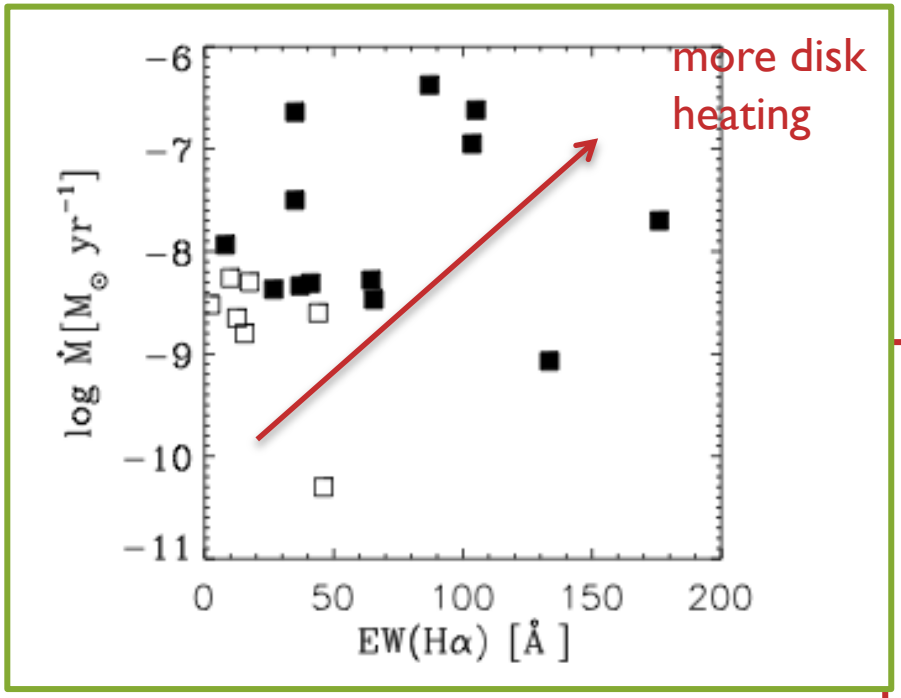
Does this imply different chemistry, or just different excitation?

Pontoppidan et al. 2010

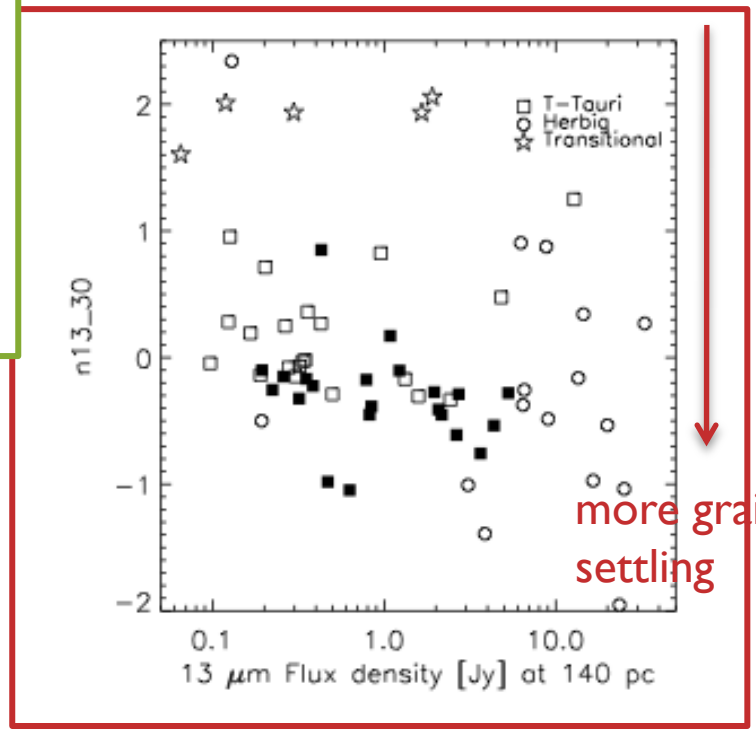
H_2O: Detections related to accretion rate and disk color

= H_2O detected

= H_2O un-detected

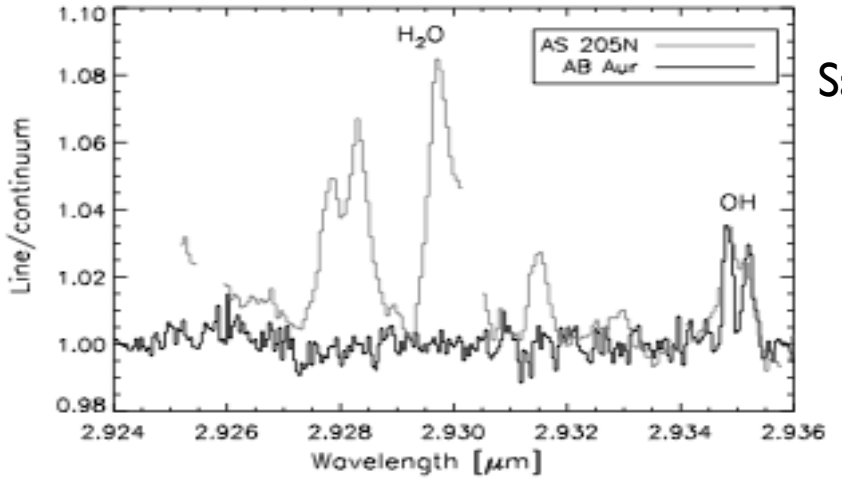


Salyk et al. 2011



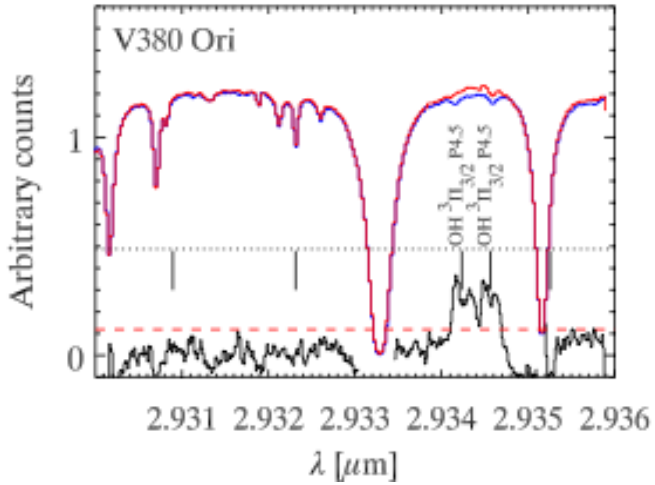
H_2O: OH line ratio differences consistent with photochemical destruction

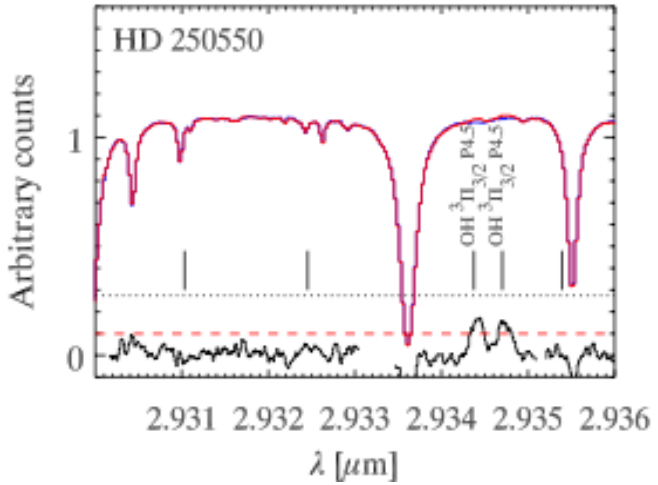
(Bethell and Bergin 2009)



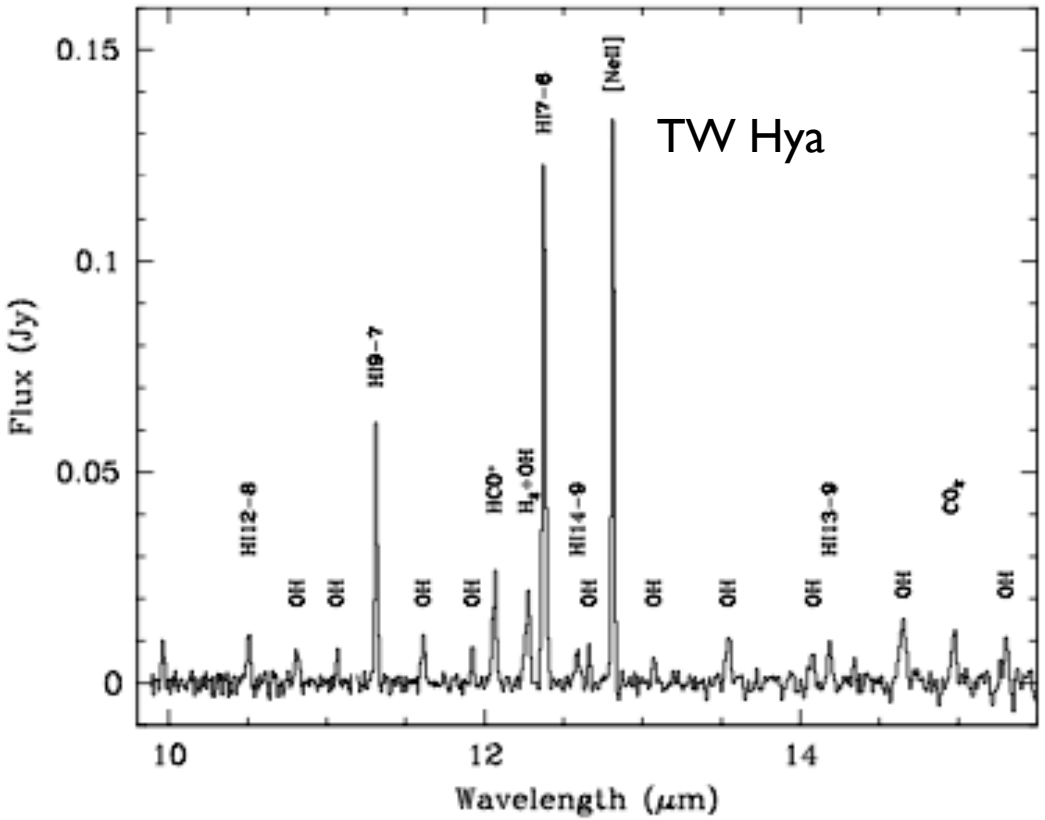
Salyk et al. 2008/Mandell et al. 2008

OH: 4/11 H_2O: 0/11
Fedele et al. 2011





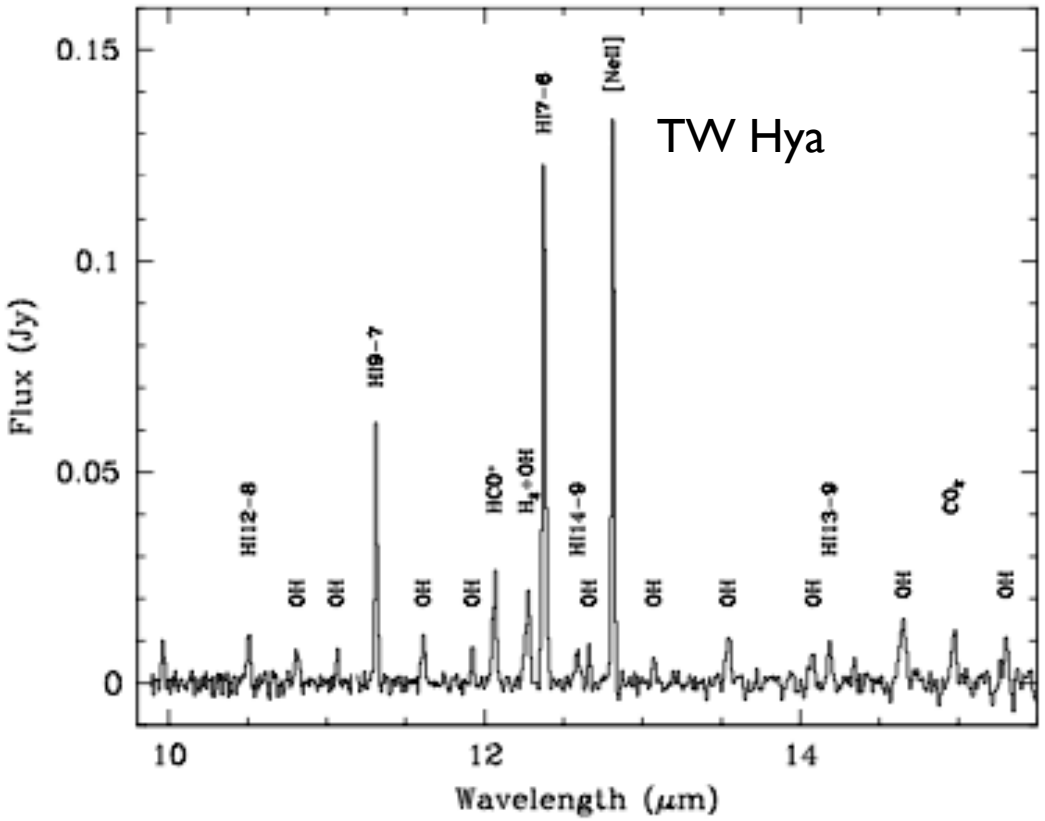
H_2O: Dissociation products consistent with photochemical hypothesis



Najita et al. 2010

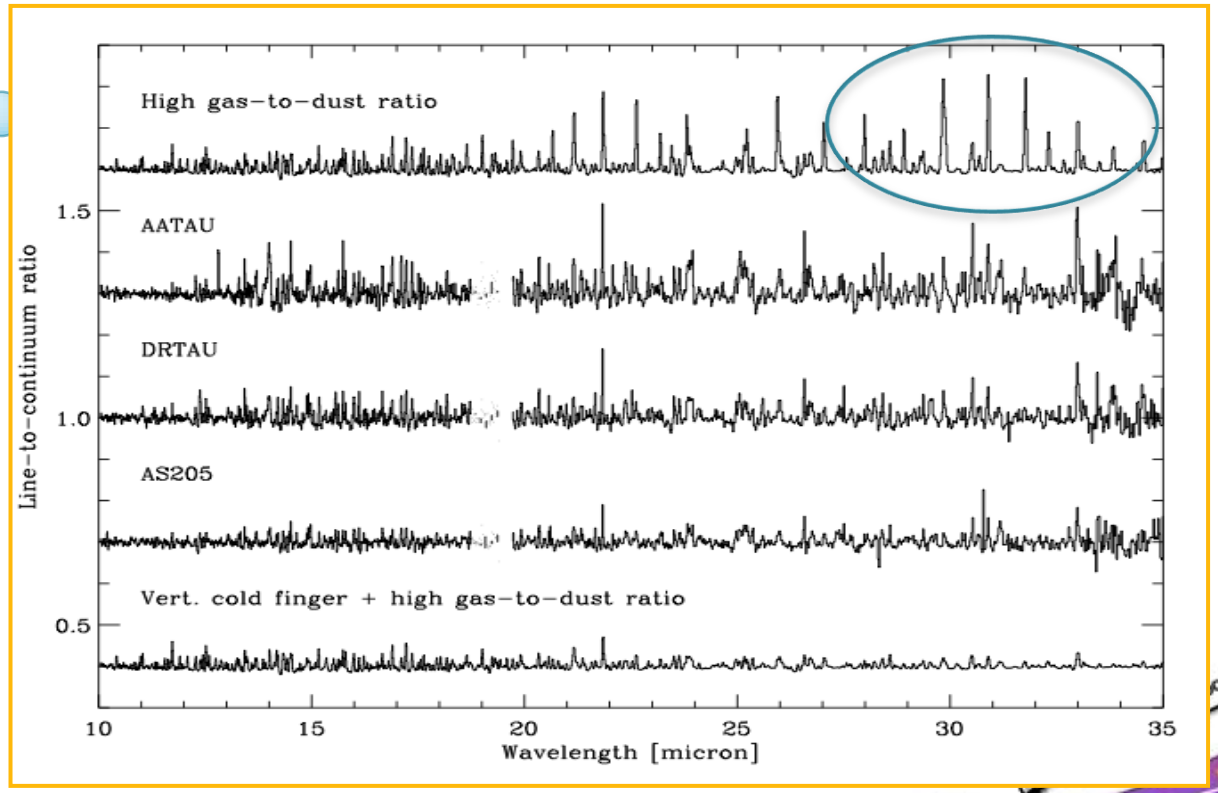
Potential for significant chemical differences between disks around low-mass and mid-mass stars

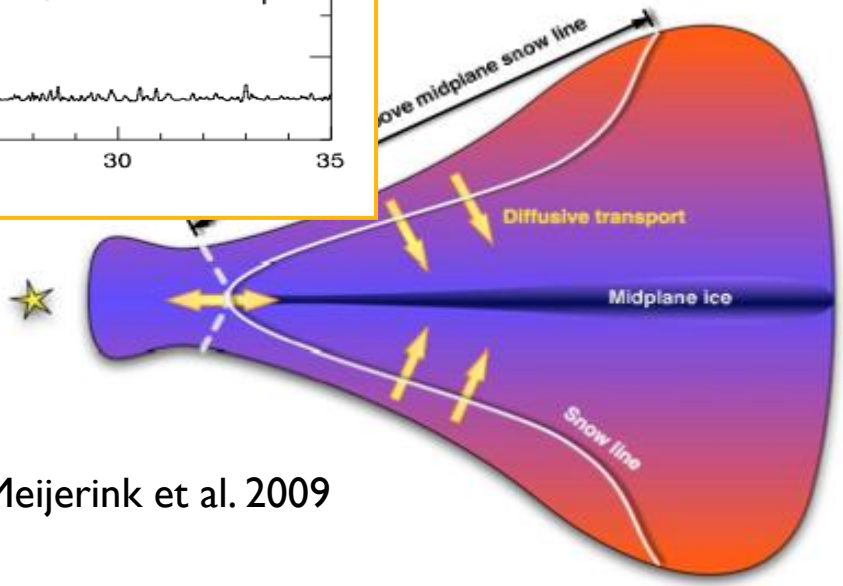
H_2O: Dissociation products consistent with photochemical hypothesis



Najita et al. 2010

H_2O: Locating the snow line

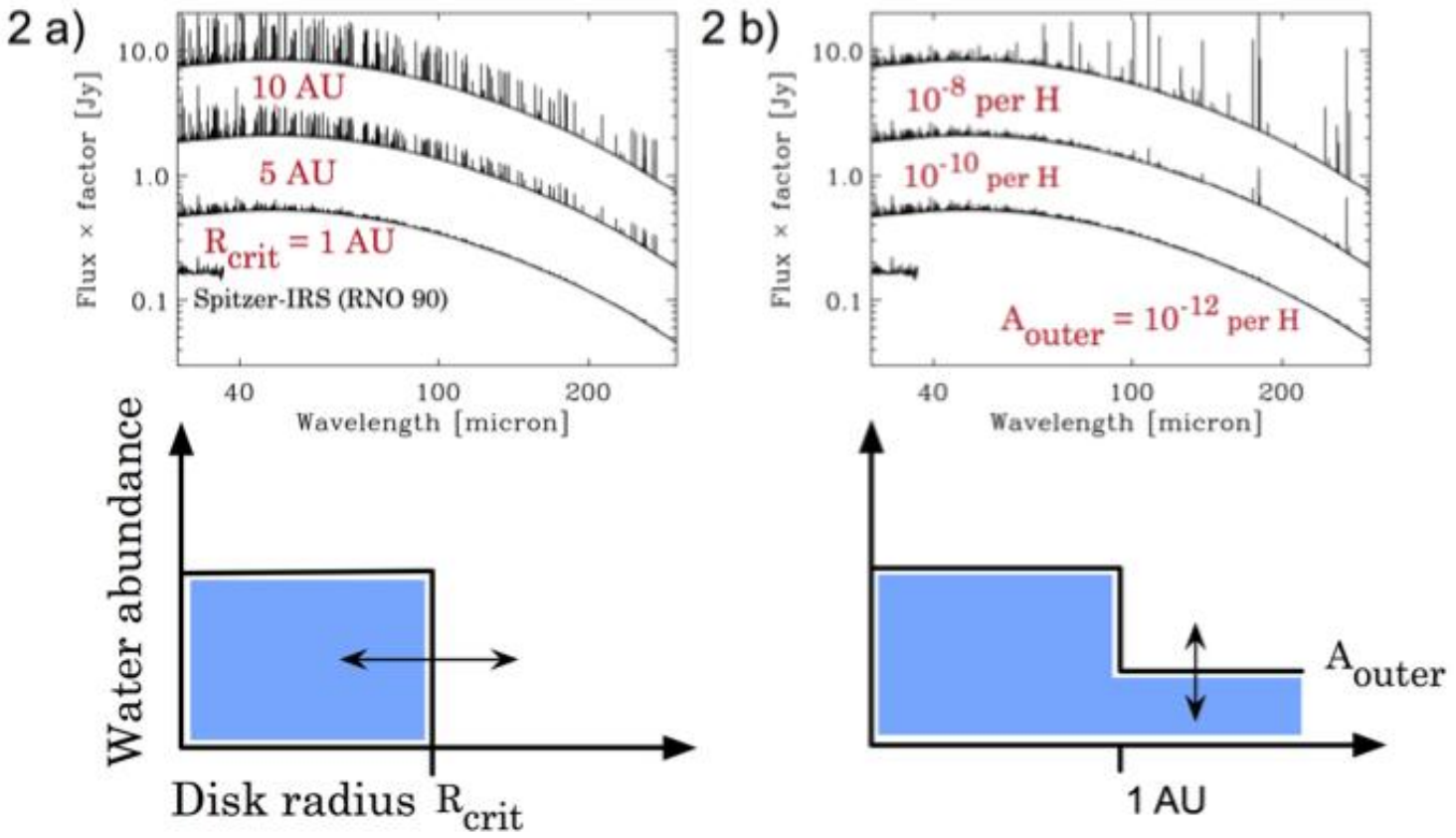




Meijerink et al. 2009

H_2O: Cool Herschel/Hot Spitzer: The distribution of water in protoplanetary disks

(K. Pontoppidan, C. Salyk, G.A. Blake, J. Carr, J. Najita)



Starting to connect inner and outer disk

Inner disk tracers to date

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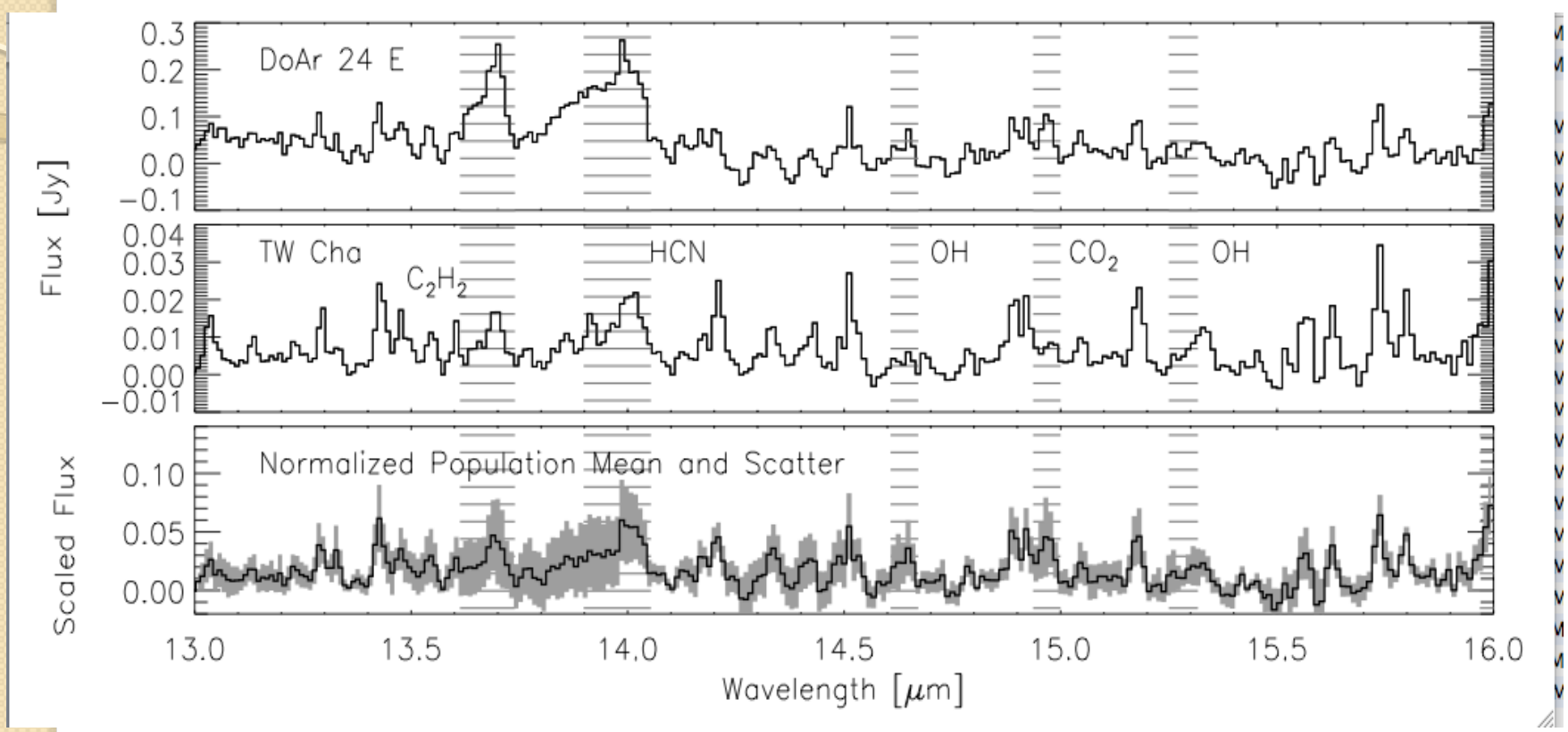
CO	2.23	$v = 2 - 0$	6300	r ~ 0.05 – 0.3 AU
H_2O	~ 2.9	$v_3 = 1 - 0$	5000 - 10000	r ~ 1 AU
OH	~ 3	$v = 1 - 0$ P branch	> 5000	r ~ 1 AU
CO	4.6	$v = 1 - 0$	3000	r ~< 0.1 – 2 AU
H_2	8.0 – 17.0	$v = 0 - 0$ S(1), S(2), S(4)	1015 – 3474	r ~ 10 – 40 AU
H_2O	10 – 30	$J > 4$	> 500	r ~ 1 – 2 AU
C_2H_2	~ 13.7	$v_5 = 1 - 0$ Q branch	1000	r ~ 1 AU
HCN	~ 14	$v_2 = 1 - 0$ Q branch	1000	r ~ 1 AU
CO_2	14.98	$v_2 = 1 - 0$ Q branch	1000	r ~ 1 AU

From Bergin 2009

Also: HCO+ and possibly CH_3 in TW Hya (Najita et al. 2010)

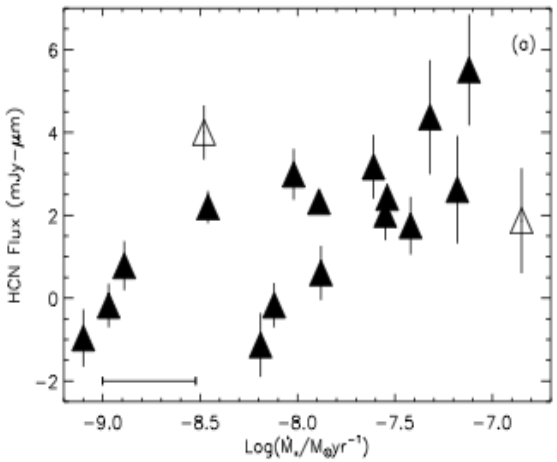
Observations of inner disk chemistry truly possible

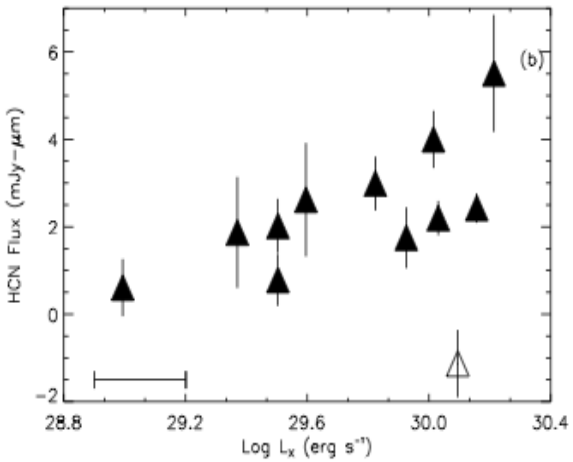
Organics: Variation observed, but what is its cause?



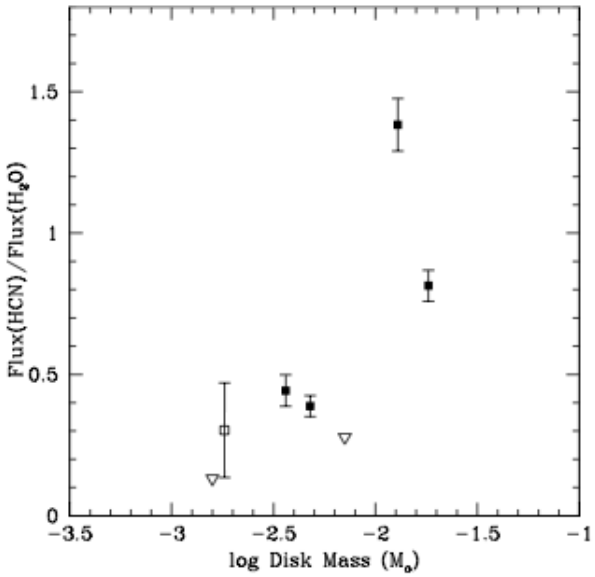
Salyk et al. 2011

Organics: Variation observed, but no clear cause yet.





Teske et al. 2011



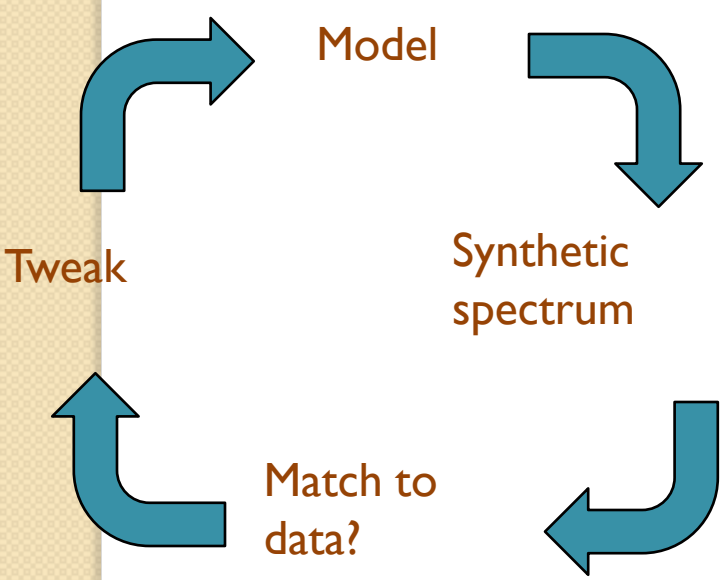
Carr &Najita 2011

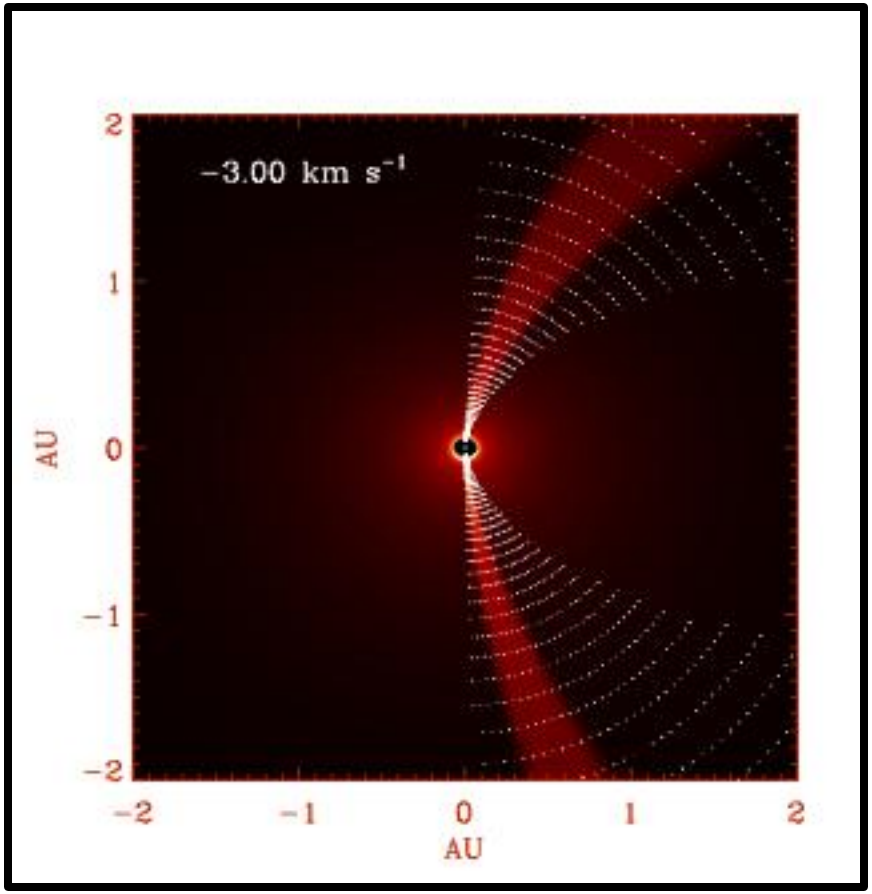
Looking towards the future…

- IR spectra of molecules in disks: probe of structure, physics, chemistry
- Data rich field (and growing! Herschel, SOFIA, SA with Keck, JWST…)
- Simple analysis thus far; complex analysis tools in place and ready to go – expect exciting new insights into disk chemistry
- Soon to have radial profiles of chemistry, by combining IR and millimeter with ALMA

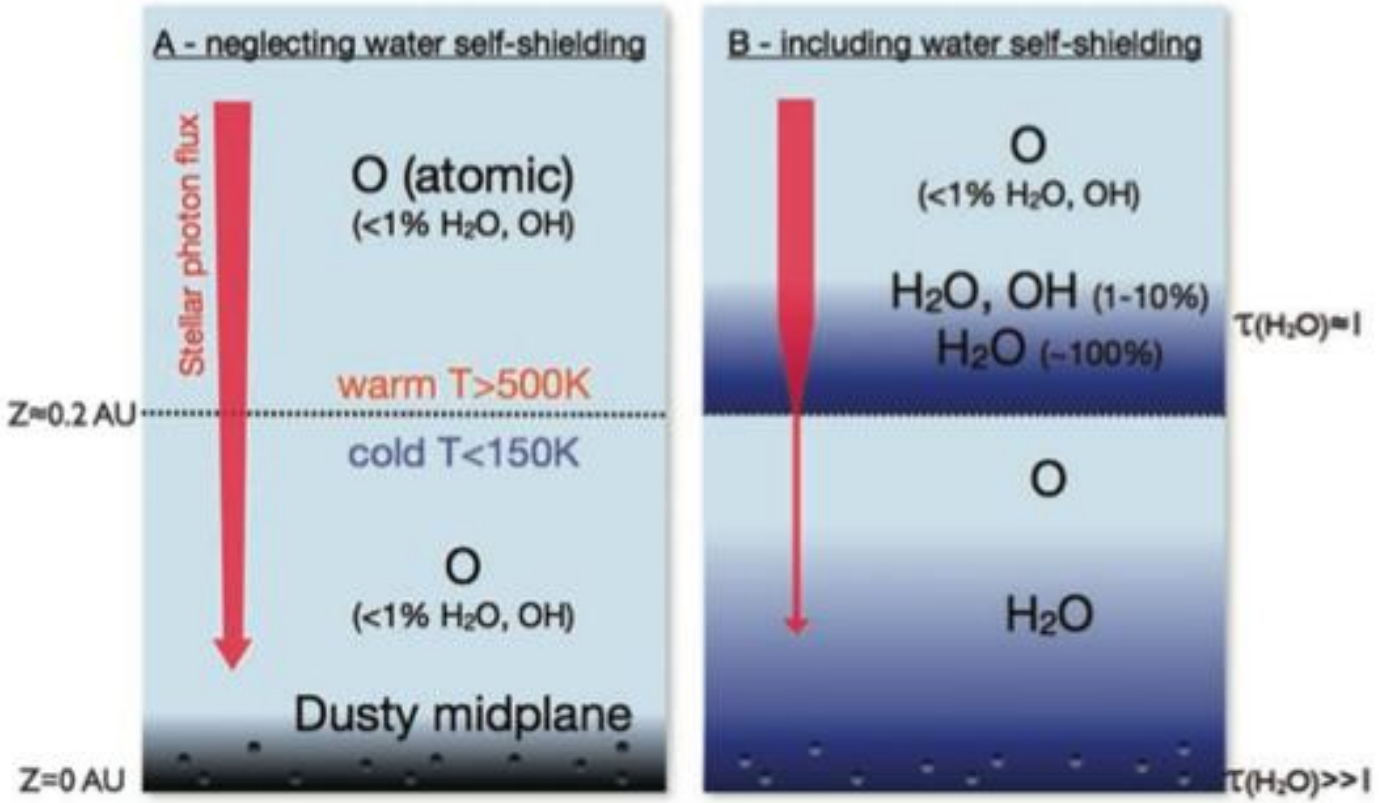
Basic tools: Complex (disk geometry, line radiative transfer, non-LTE, etc.) models

-More closely represent "reality"





Consistent with water self-shielding?



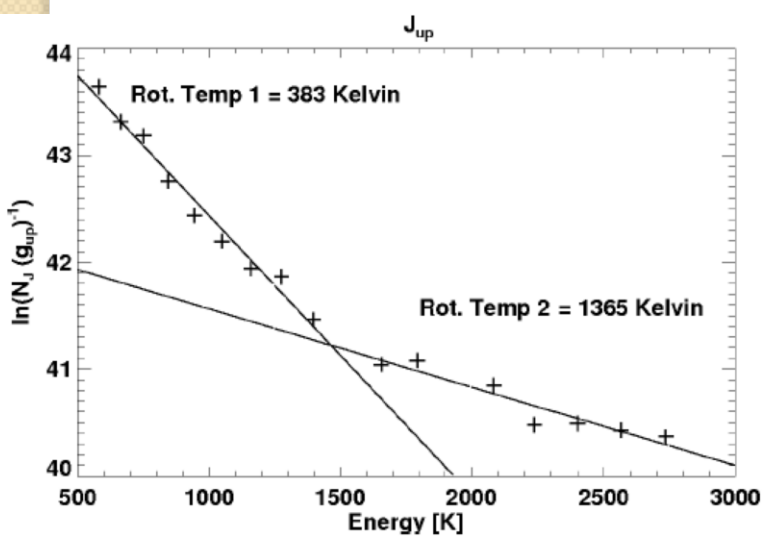
Bethell and Bergin 2009

Relevant Posters

- 1.06 Bast et al. New probes of the chemistry in the inner regions of planet-forming disks
- 1.10 Brown et al. A VLT-CRIRES 4.7 micron survey of CO emission from young protoplanetary disks
- 1.31 Gibb et al. New observations of molecular absorptions toward GV Tau N
- 1.48 Lockwood et al. Non-LTE infrared emission from protoplanetary disks surfaces
- 1.60 Nomura et al. Observations of near-infrared line ratios of molecular hydrogen emission to diagnose dust evolution in protoplanetary disks
- 1.82 Smith et al. Observational signatures of 12CO-13CO partitioning in ice and gas towards young stellar objects and molecular clouds
- 1.93 Troutman et al. Search for a spectro-astrometric signal from molecules in circumstellar disks

Basic tools: Simple (LTE slab) models

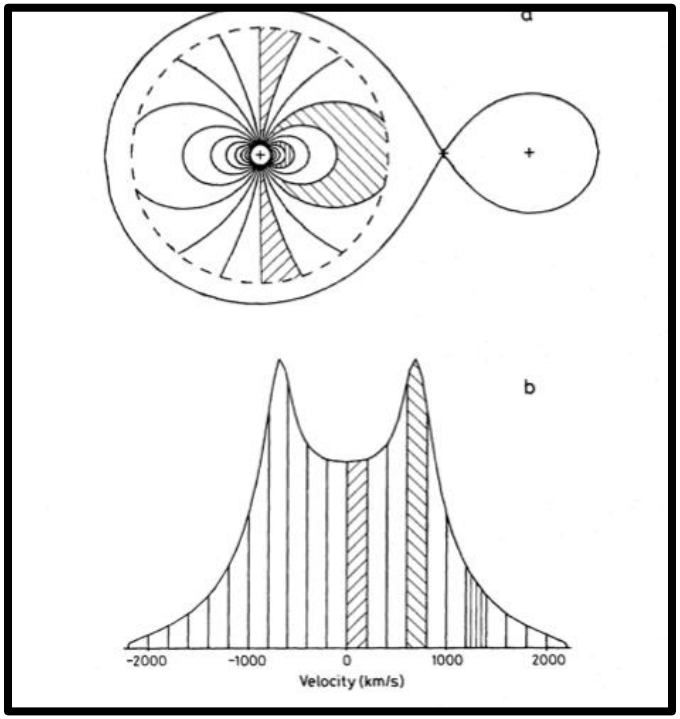
-Level populations follow a Boltzmann distribution
-Single T, column density, size
-"Rotation diagrams": tool primarily for optically thin limit
-Analysis: start with spectrum, back out information (T,N,A)



T, N

based on Herschel PACS data (J. Green)

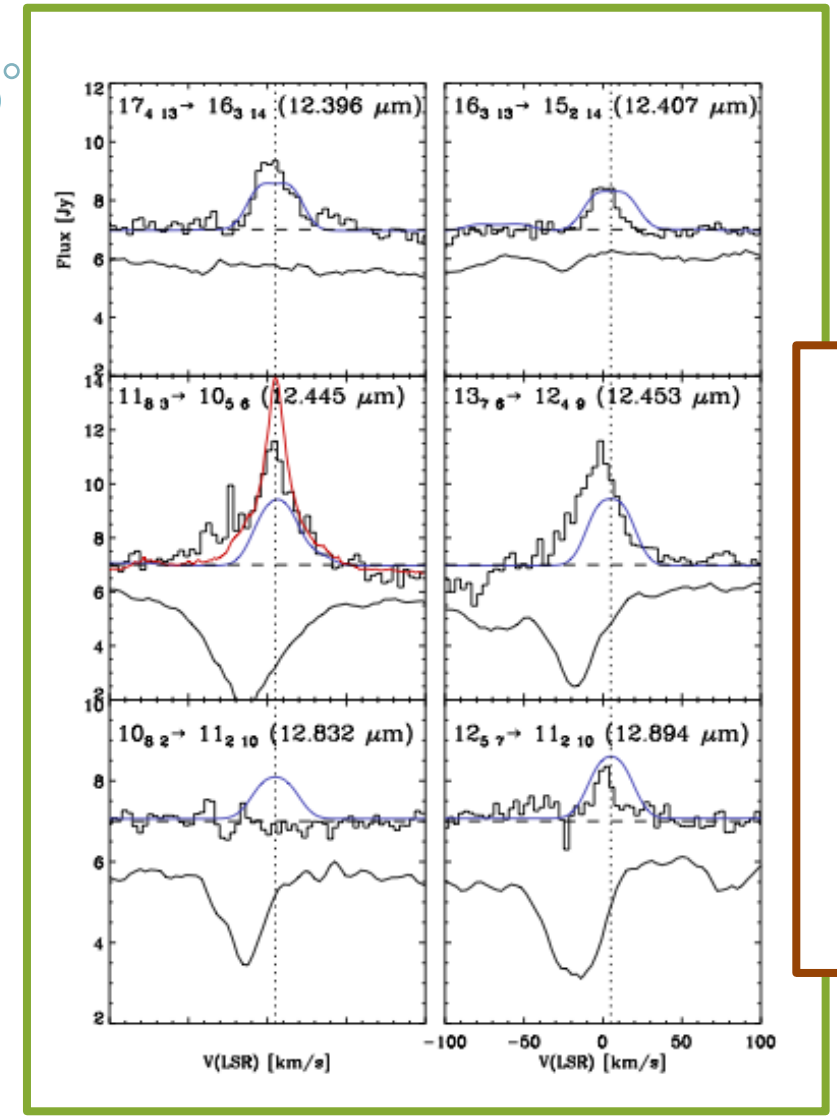
Basic tools: Kinematic analyses of line shapes

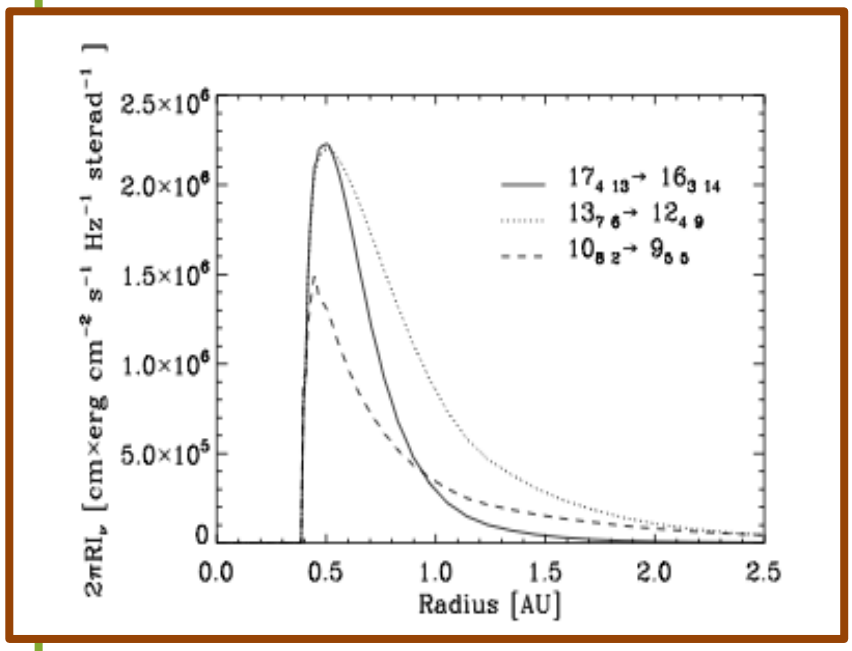


-Star/disk interface: accretion
-Inner disk: Keplerian orbital motion
-Outer disk: turbulence

Horne & Marsh 1986

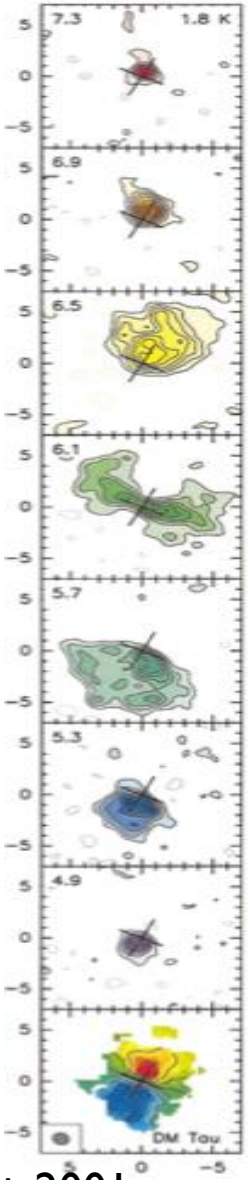
Resolved lines point to inner disk*
(*few AU or smaller = terrestrial planet-forming region)





rotational lines with VLT-VISIR; Pontoppidan+ 2010

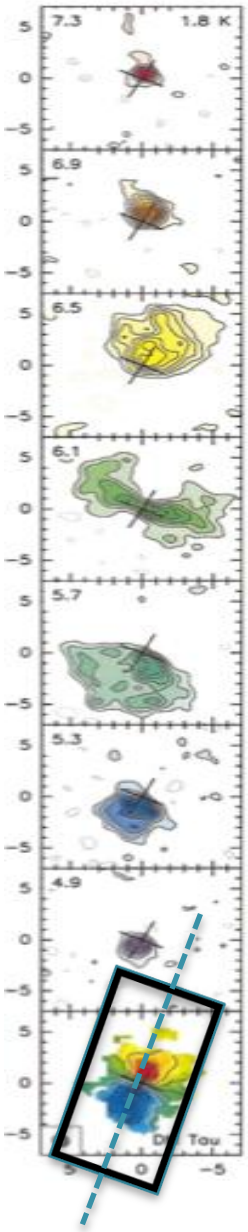
Spectro-astrometry



velocity

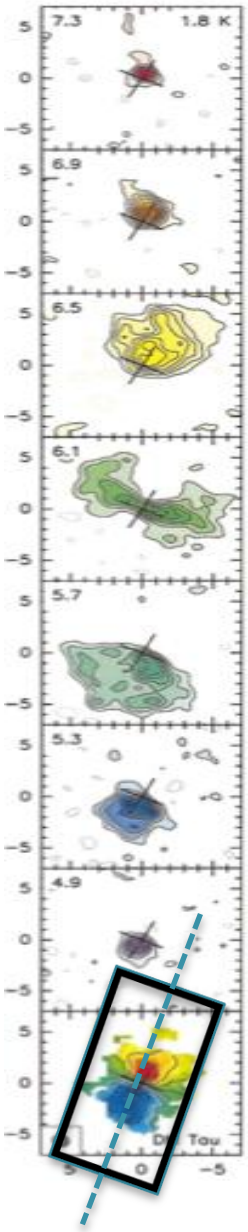
Simon+ 2001

Spectro-astrometry



velocity

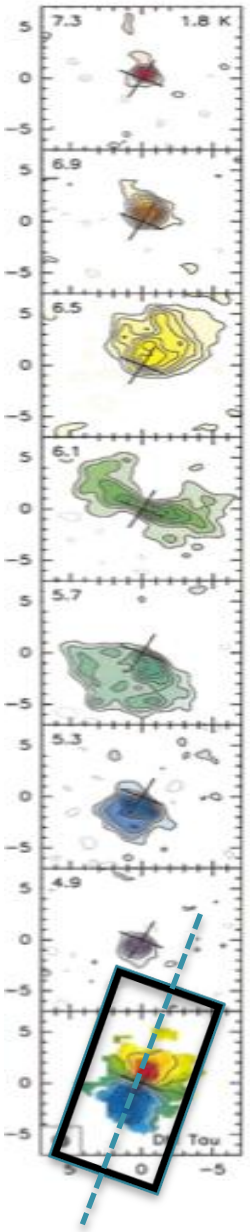
Spectro-astrometry



SA signal
(centroid)

velocity

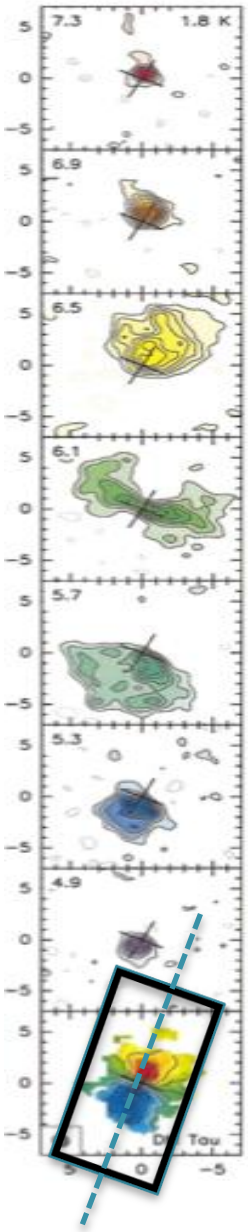
Spectro-astrometry



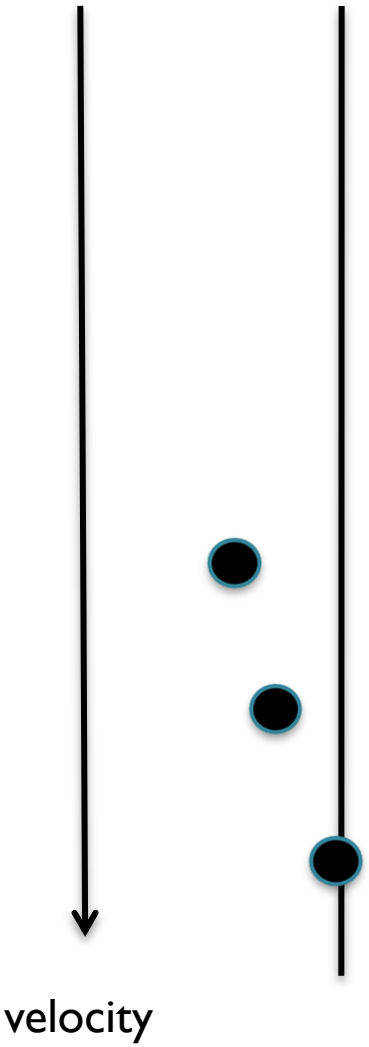
SA signal
(centroid)

velocity

Spectro-astrometry

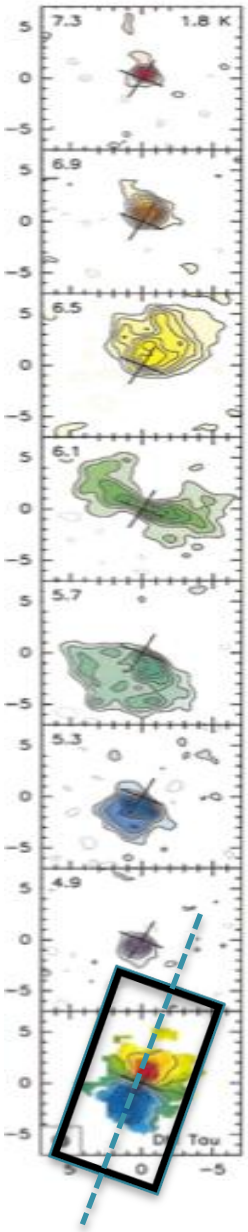


SA signal
(centroid)

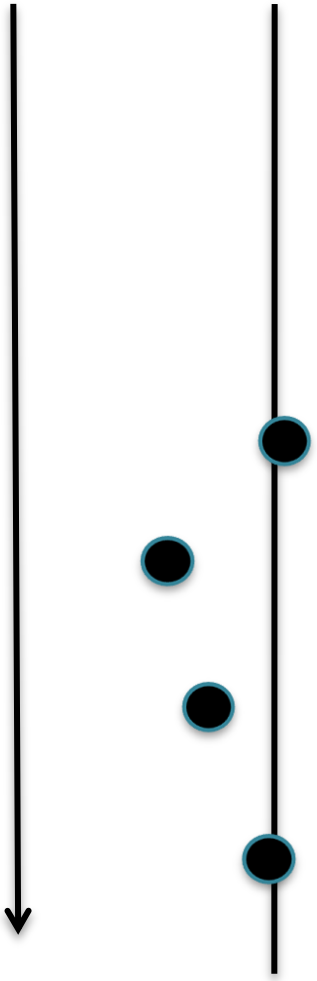


velocity

Spectro-astrometry

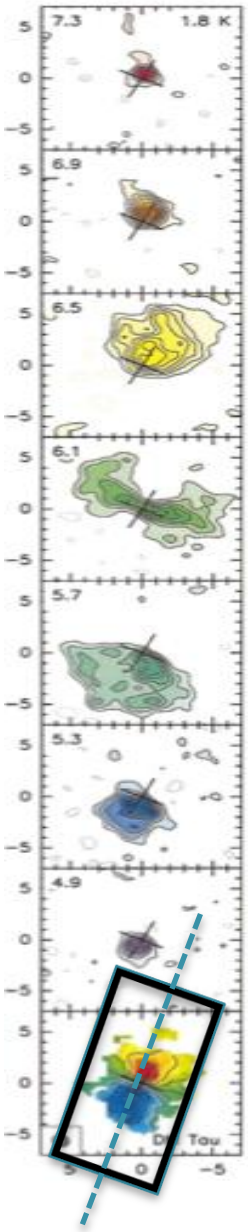


SA signal
(centroid)



velocity

Spectro-astrometry



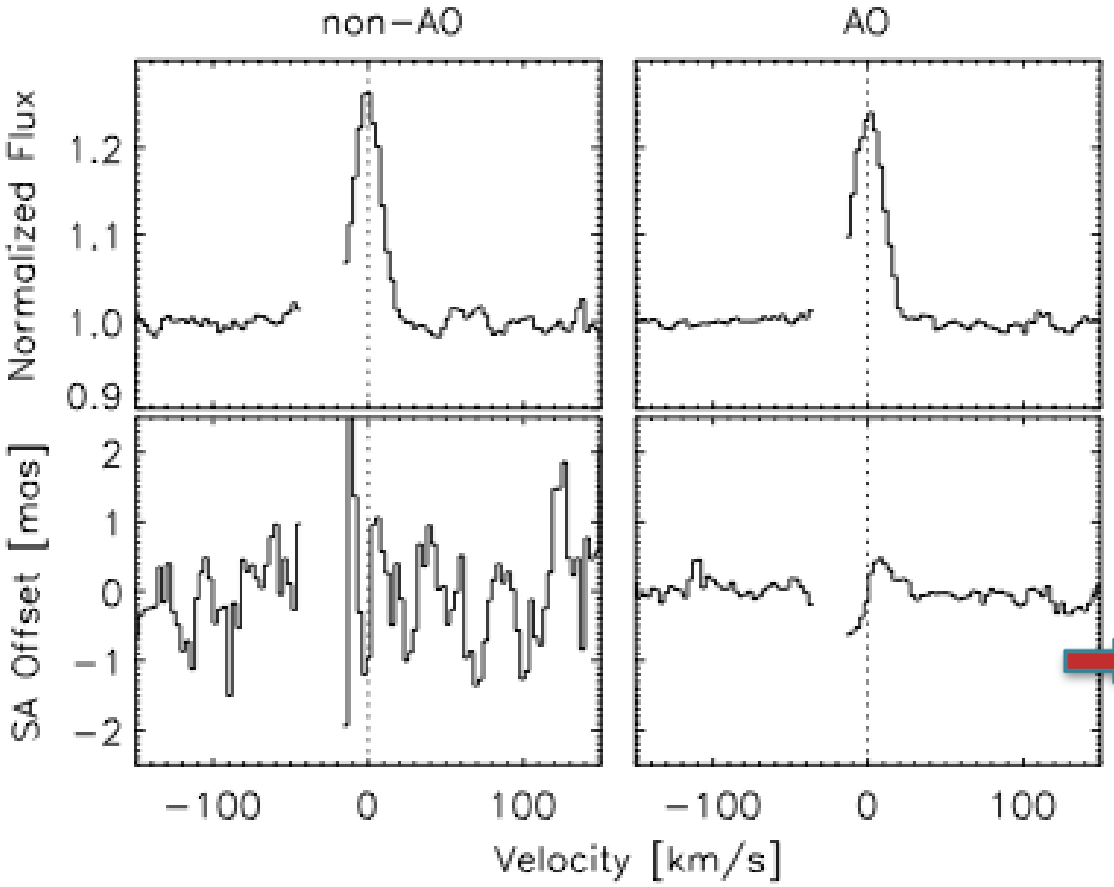
SA signal (spectral centroid)

velocity

infer a Keplerian disk

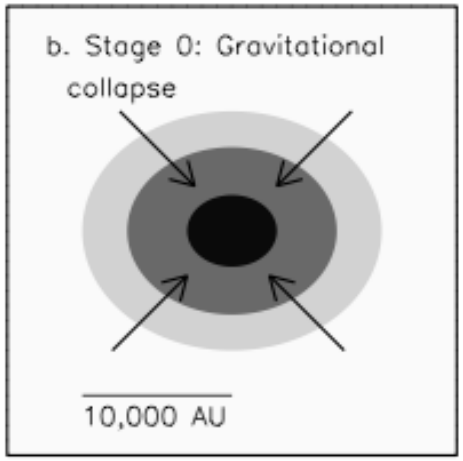
*Spatial resolution much smaller than instrument resolution

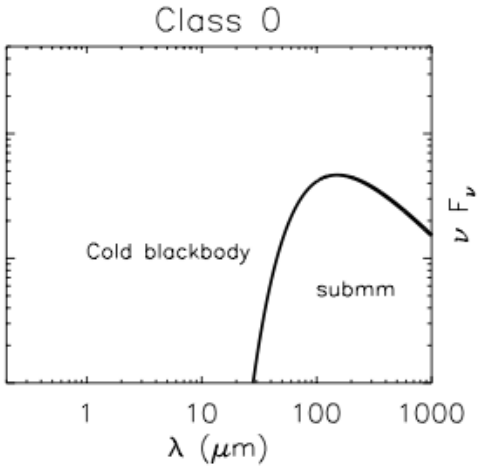
Spectro-astrometry now possible with Keck-NIRSPEC (thanks to AO availability in L and M bands)

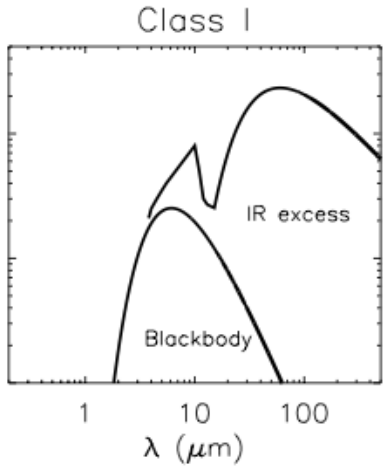


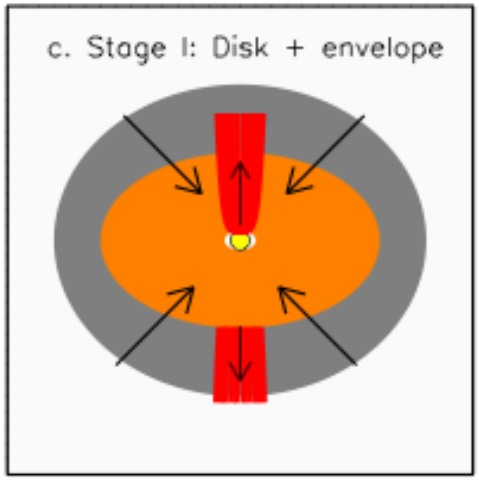
Infer a Keplerian disk

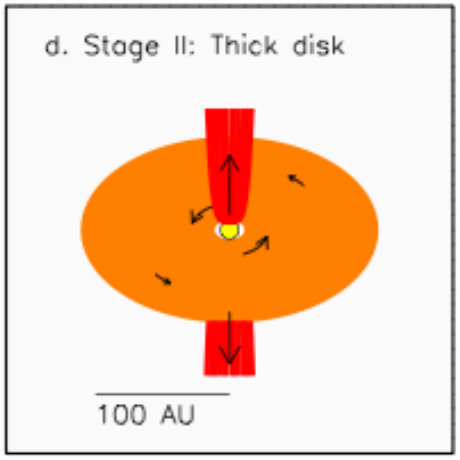
(see Keck newsletter)

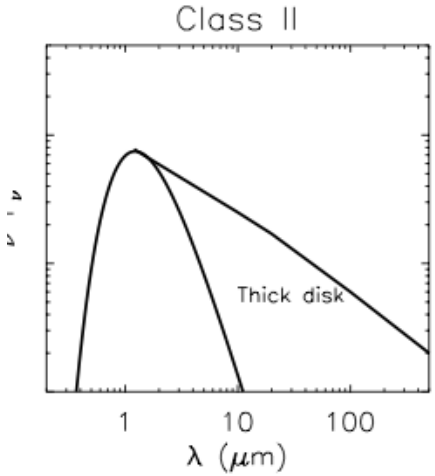

b. Stage 0: Gravitational collapse
10,000 AU

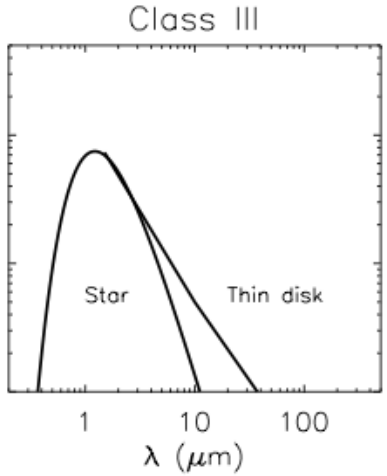

Class 0
Cold blackbody
submm
1
10
100
1000
λ (μm)

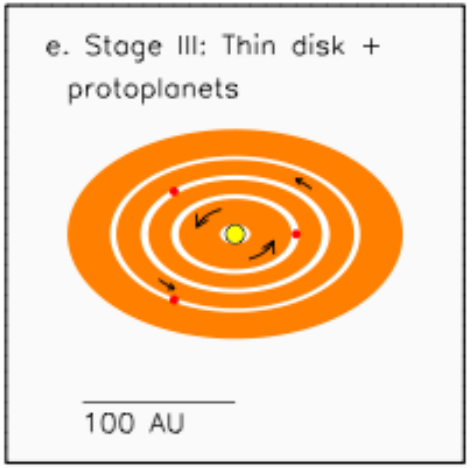

Class I
IR excess
Blackbody
ν F_ν
1
10
100
λ (μm)

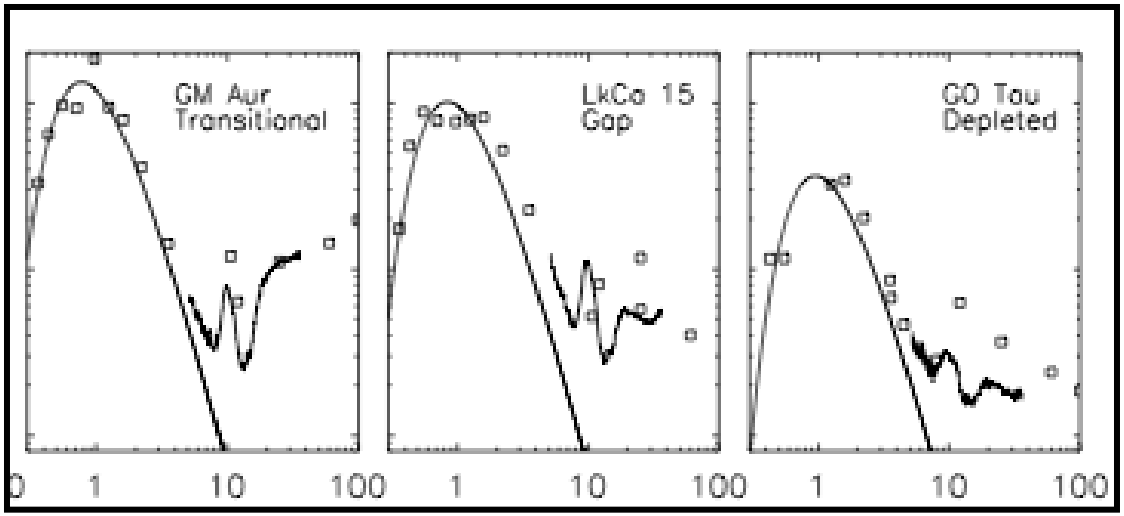

c. Stage I: Disk + envelope


d. Stage II: Thick disk
100 AU


Class II
Thick disk
ν F_ν
1
10
100
λ (μm)


Class III
Star
Thin disk
ν F_ν
1
10
100
λ (μm)


e. Stage III: Thin disk + protoplanets
100 AU


GM Aur
Transitional
LkCa 15
Gap
GO Tau
Depleted
0
1
10
100
1
10
100
1
10
100


d. Stage II: Thick disk
100 AU
e. Stage III: Thin disk +
protoplanets
100 AU