Gas dispersal in disks
observations and models

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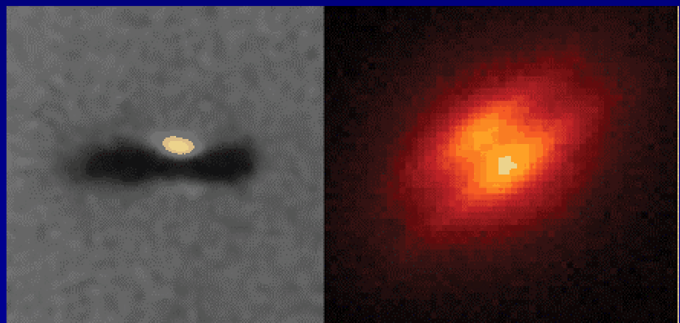


Outline

- Observations
  - CO millimeter
  - CO infrared
  - H_2 UV
  - H_2 mid-infrared
  - Other tracers
- Models
  - Viscous accretion and photoevaporation
  - Stellar EUV and FUV radiation
- Summary

Why gas important?

- **Affects dust dynamics**
  - **E.g., sharp dust density gradients**
- **Needed for formation gas giants**
  - **Constraints on formation timescales**
- **Affects outcome of planet formation through circularization planetesimal orbits**
  - **Mass and eccentricity of planets**
- **Affects planet migration**

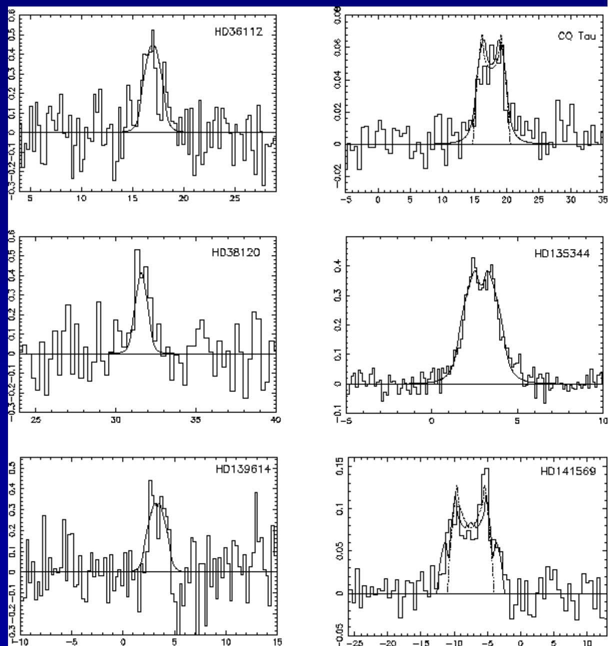
Gas important when M_{gas} ~10^{-2} M_{Jup} (10^{-5} M_{Sun}) or larger

CO millimeter: T Tauri stars

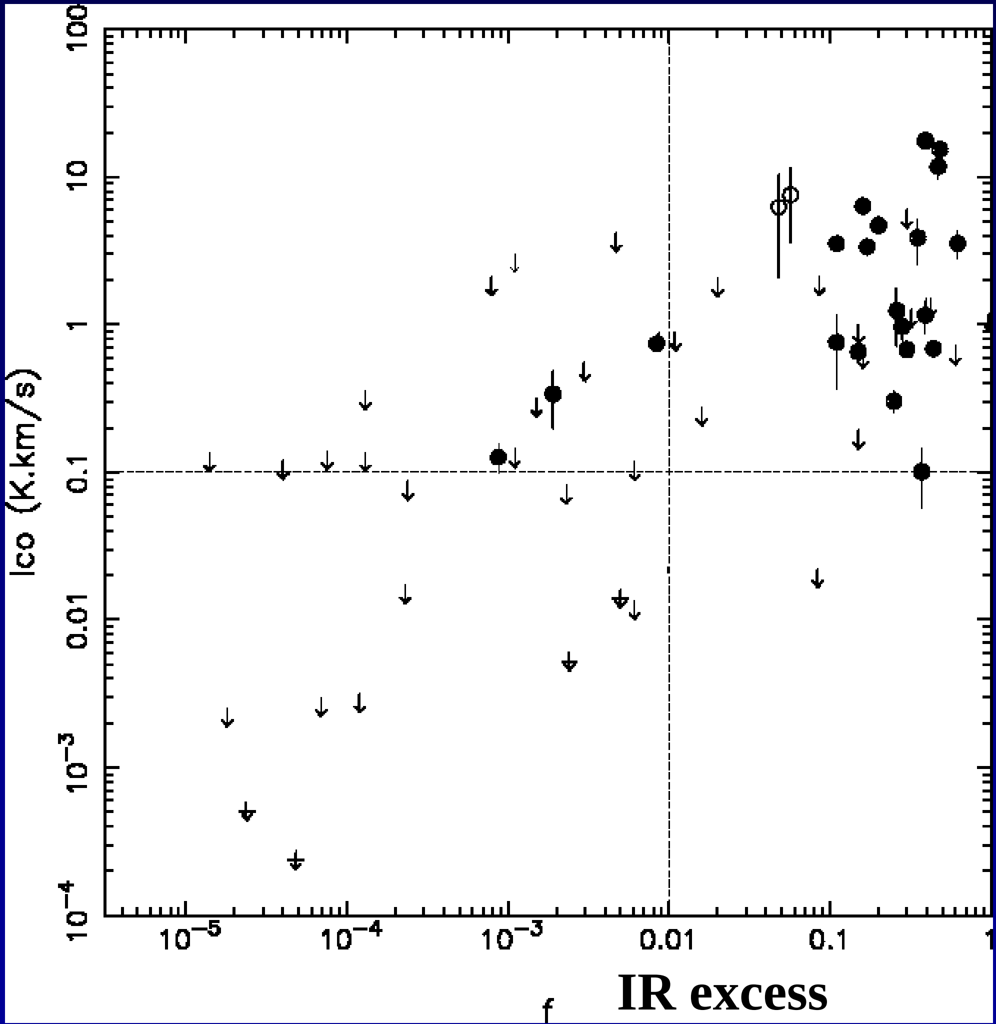
- Classical T Tauri stars (~40 objects up to ~10 Myr)
  - Koerner et al. 1995, Dutrey et al. 1996, 2003
  - Large fraction of detections: 60-100%
  - No trend with age
  - Young (<1 Myr) transitional objects found with little CO
    - BP Tau, V836 Tau
- Weak-line T Tauri stars (~15 objects up to 20 Myr)
  - Duvert et al. 2000
  - Small fraction of detections: ~10%

CO millimeter: Herbig + Vega excess

- Herbig Ae and IR excess stars (~50 stars up to 20 Myr)
  - Zuckerman et al. 1995, Mannings & Sargent 2000, Thi et al. 2001, Dent et al. 2005
  - Large fraction of detections (>60%) if f_{IR}>0.01 (disk opening angle >12°)
  - Small fraction of detections (~10%) if f_{IR}<0.01
  - Decrease of R_{out} with M_{disk} => time?
  - No correlation R_{out} with spectral type
  - Inner gap or cavity common?



CO vs f_{IR}

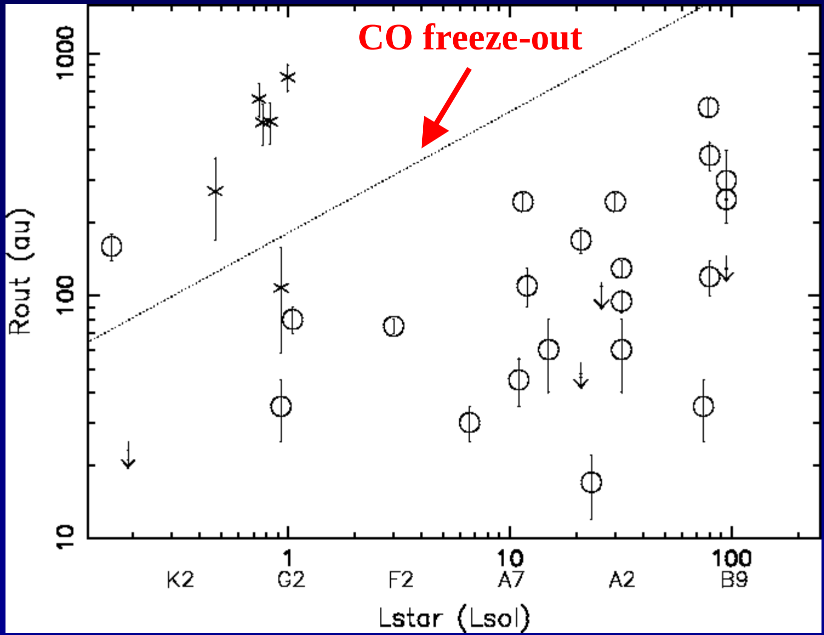


Dent et al. 2005

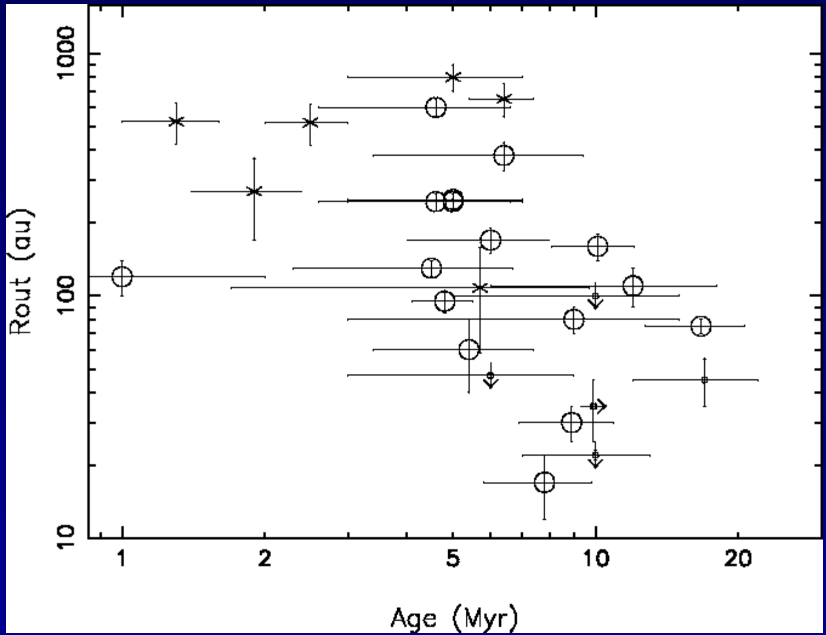
poster

Outer radius CO disk

No correlation with spectral type



Anti-correlation with age?

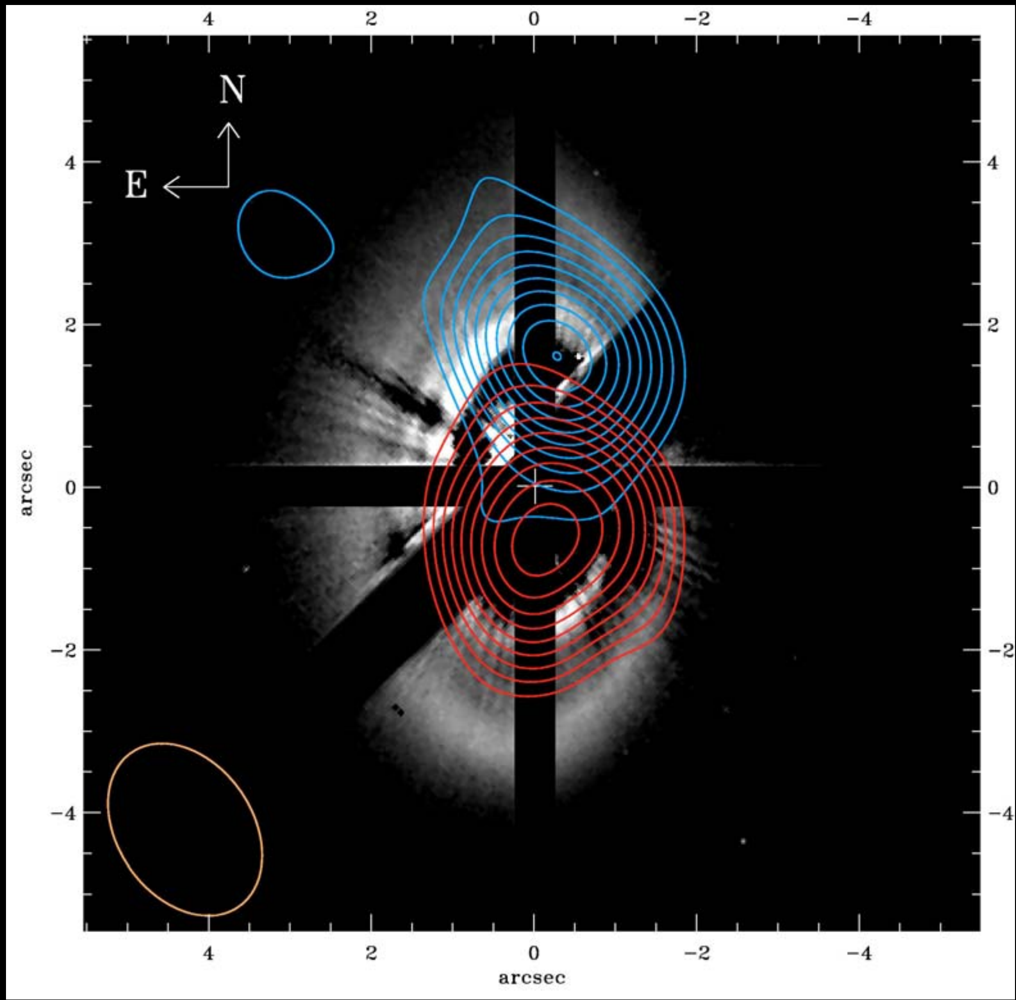


Dent et al. 2005

HD 141569 transitional disk: dust and gas

Massive gas-rich disk

Debris disk



IRAM PdB

^{12}CO 2-1

Superposed on HST-STIS

-Is there gas in dust hole?

-What is gas/dust ratio in rings?

Augereau, Dutrey et al. 2004, in prep

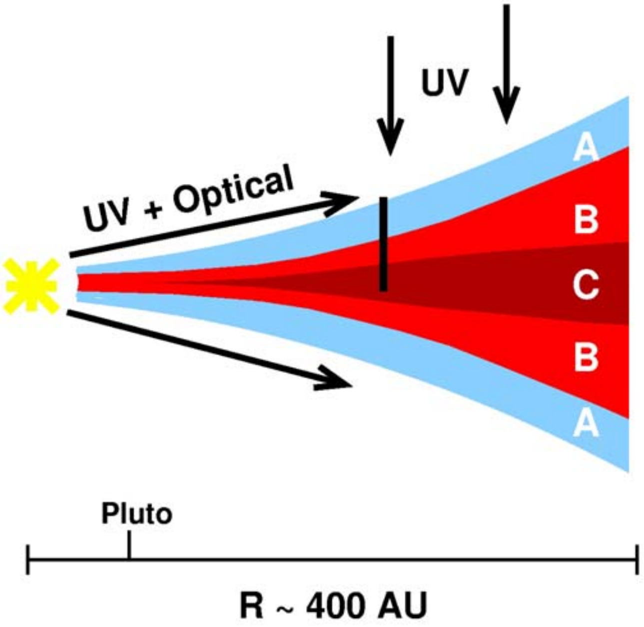
CO millimeter: main sequence stars

- **Main sequence stars with dust and A-G spectral type (~15 objects at ~1 Gyr)**
  - Yamashita et al. 1993, Dent et al. 1995, Greaves et al. 2000, Coulson et al. 2004
  - **No detections down to 10^{-7} M_{Jup} (10^{-10} M_{Sun})**
  - **Stars nearby (down to 3 pc) => larger sensitivity than for pre-main sequence stars (typically 150 pc)**

CO millimeter

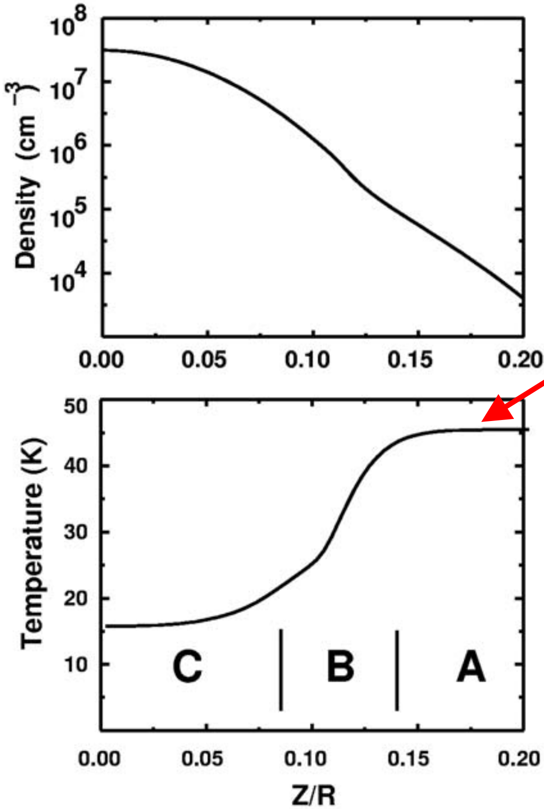
- Strengths
  - Sensitive to low gas masses: 10^{-3} M_{Jup} (10^{-6} M_{Sun}) at 150 pc
  - Optically thin in dust continuum
  - Line profiles resolved
  - Imaging with interferometers
- Weaknesses
  - Lines often optically thick
  - CO abundance affected by freeze-out + photodissociation => difficult to infer gas masses
  - Confusion from surrounding cloud => interferometers
  - Only sensitive to outer disk >50 AU

CO chemistry in disks



M_d~0.01 M_{Sun}

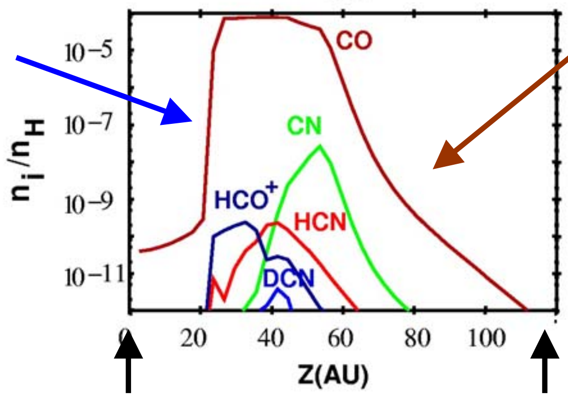
R=200 AU



T_{gas} is larger

Freeze-out

Photodissociation



midplane

surface

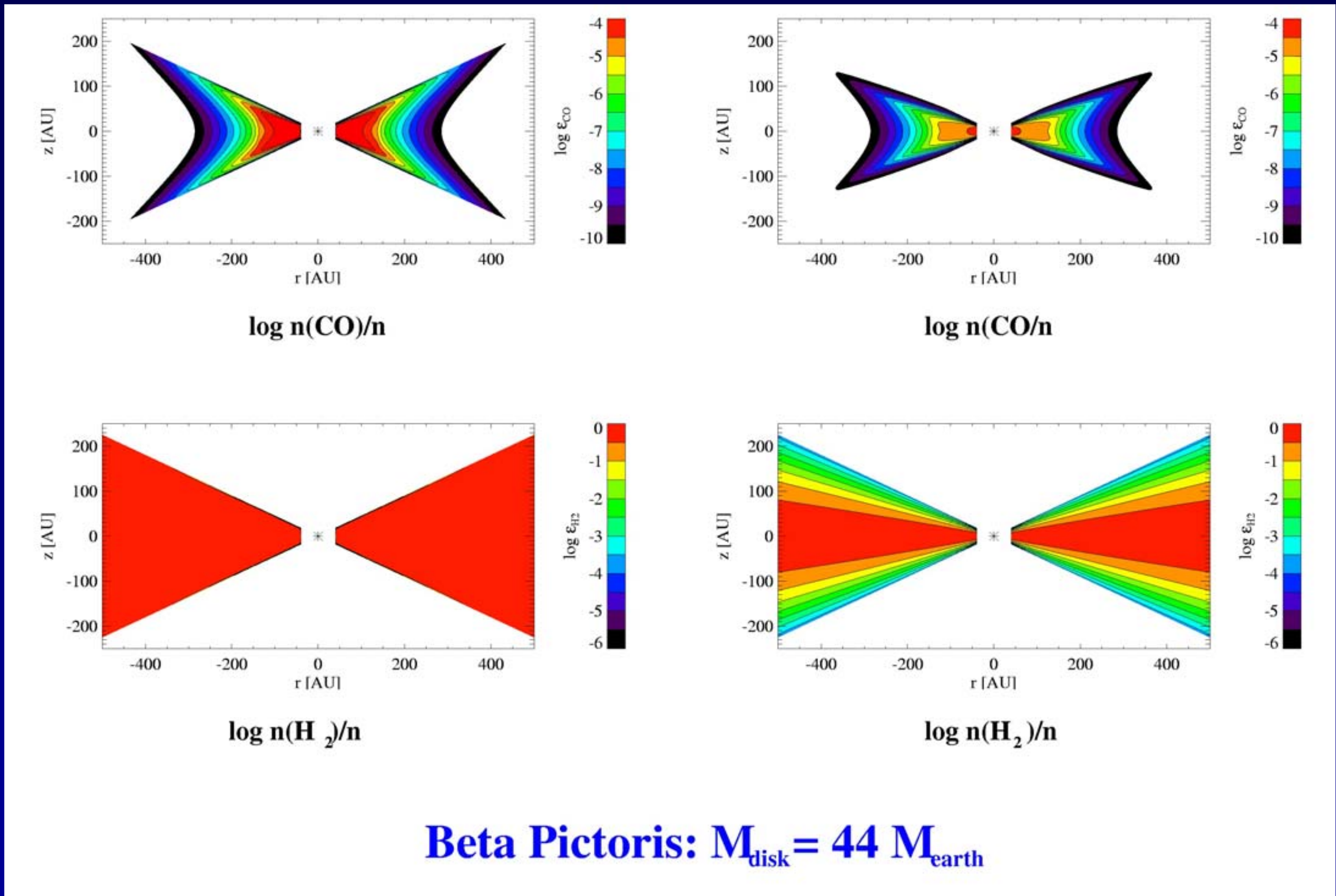
Disk-averaged CO abundance not ~10^{-4}; can be as low as 10^{-7} or less

Aikawa et al. 2002
Van Zadelhoff et al. 2003

Absence of CO does not mean absence of H_2

Stellar UV

Stellar + interstellar UV



CO p.d.

H_2 self-shielding

Note: both CO and H_2 are only dissociated at 912-1100 Å

Kamp & Bertoldi 2000

CO infrared (4.7 μm)

- T Tauri + Herbig Ae stars (~20 objects)
  - Najita, Carr et al. 2003, Brittain & Rettig 2003, Blake & Boogert 2004
  - Large fraction (>80%) detected, including transitional objects V836, BP Tau

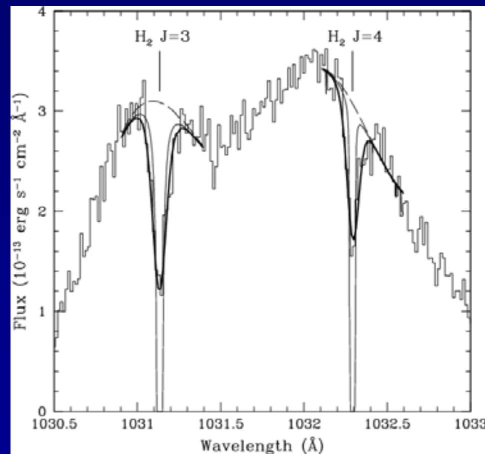
Q: how many sources detected in both CO IR and mm?

CO infrared

- **Strengths**
  - **Sensitive to very small gas masses: 10^{-8} M_{Jup} (10^{-11} M_{Sun})**
  - **Probes inner disk/planet-forming zones (<5 AU), as well as colder outer disk**
- **Weaknesses**
  - **IR continuum optically thick => need vertical T structure or (dynamically cleared) gaps**
  - **Limited velocity resolution (~10 km/s)**
  - **Probes only hot gas or surface layer=>no direct determination of total gas mass**

H_2 UV

- H_2 UV absorption (~18 sources)
  - Lecavelier-Estangs et al. 2003, Martin et al. in prep (poster)
  - Absorption against continuum or OVI
  - T_{ex}=400-700 K, N=10^{16}-10^{22} cm^{-2} => enormous sensitivity to small columns
  - Decrease of N with age?
- H_2 UV emission (~13 sources)
  - Herzceg et al. 2002, in prep
  - T_{ex}~2500 K, R<2 AU, pumped by Ly α

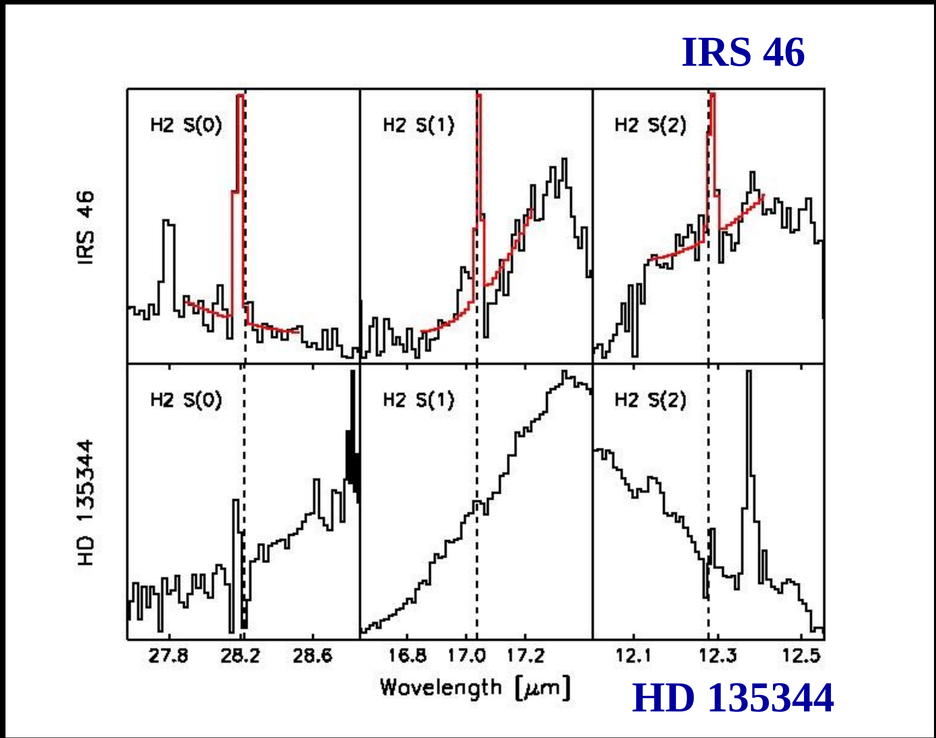


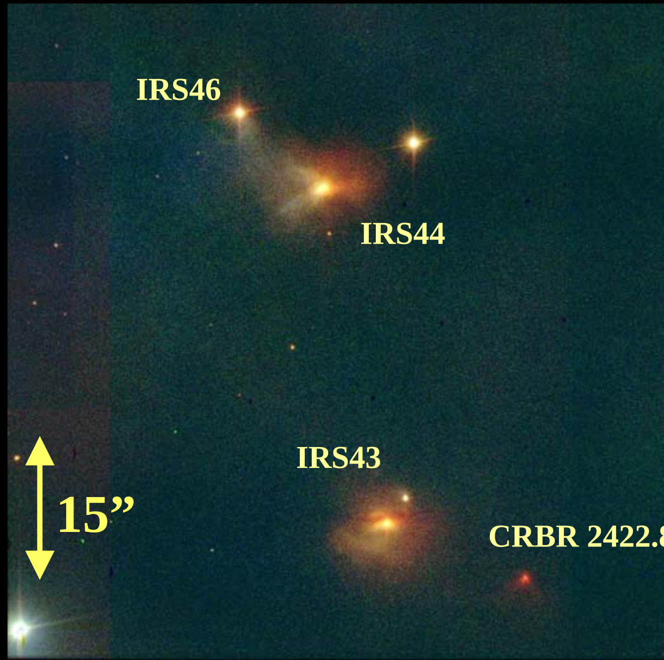
Direct probe of presence or absence of H_2, but no mass estimate

H_2 near + mid-IR

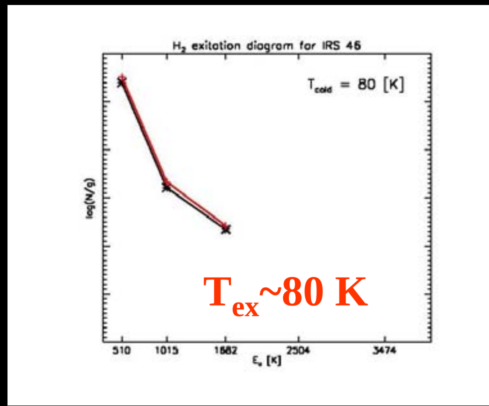
- H_2 2.1 μm vibration-rotation lines, ~10 objects?
  - Weintraub et al. 2000, Bary et al. 2003, in prep
  - Probes hot (~2000 K) gas in inner disk
- H_2 mid-IR pure rotation lines, ~10 objects
  - Thi et al. 2001, Richter et al. 2002
  - Tentative detections in large aperture by ISO, but not confirmed by subsequent observations
  - Direct probe of bulk *warm* (~100 K) gas in disks down to ~0.1 M_{Jup} at 150 pc
  - Requires high spectral resolution to get line/continuum ratio

H_2 mid-IR with Spitzer





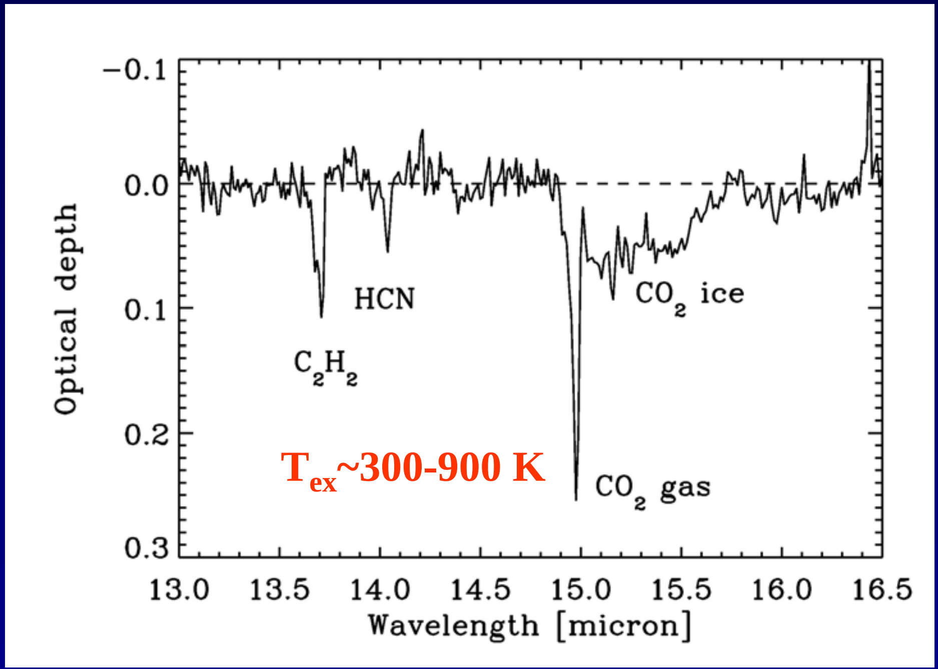
- H_2 emission seen toward ~1/4 of c2d objects, but may be largely extended
- Strengths and excitation temperatures comparable to those at off positions => need map
- H_2 not seen toward some transitional objects (HD 135344, β Pic, FEPS targets?)

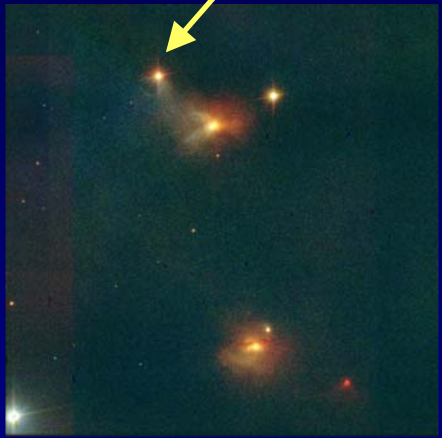


Lahuis et al. in prep

Other gas tracers: hot molecules

Low-mass: IRS46

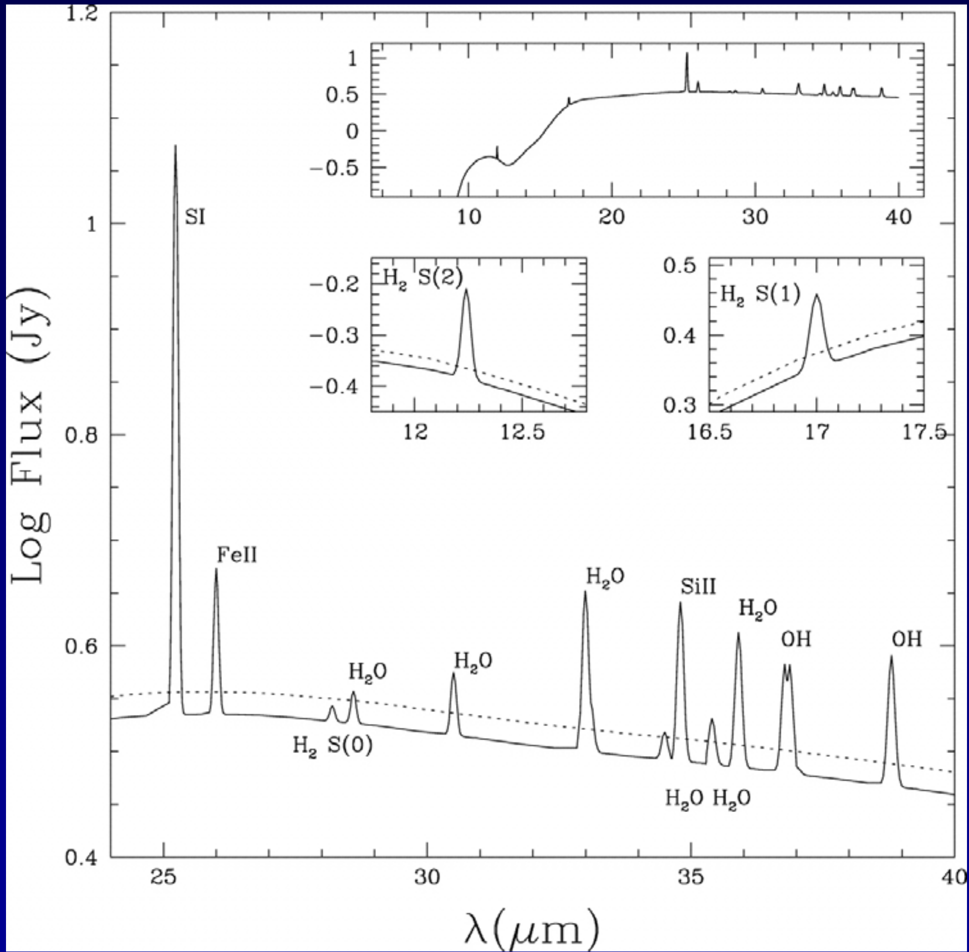




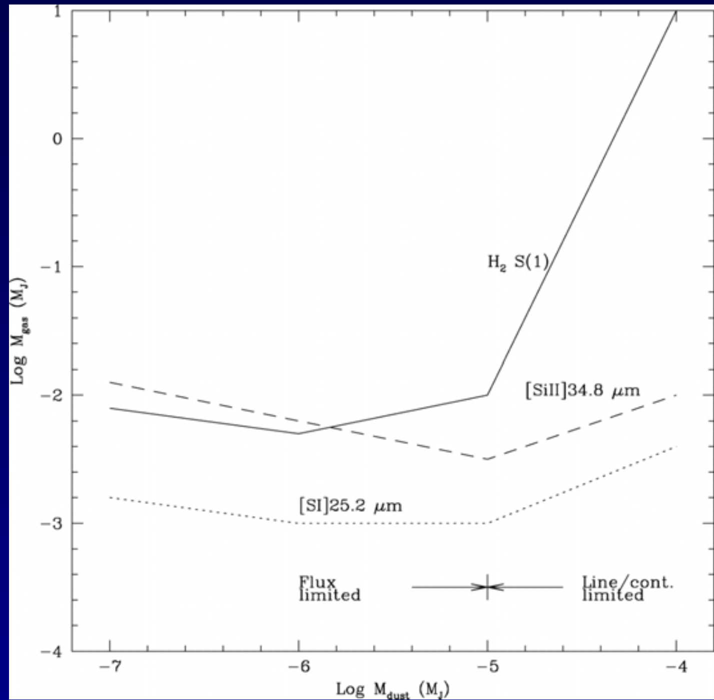
Lahuis et al.., in prep

- Spitzer can detect gas-phase lines in spite of low spectral resolution!
- IRS 46 does not have envelope or hot core => hot gas must arise in warm layers of inner disks (within 10-20 AU)

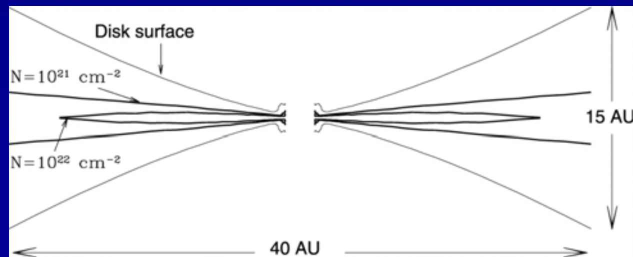
Other gas tracers: IR



Gas mass



Dust mass (M_{Jup})



- [S I] 25 μm potential tracer of tenuous disks

Gorti & Hollenbach 2004

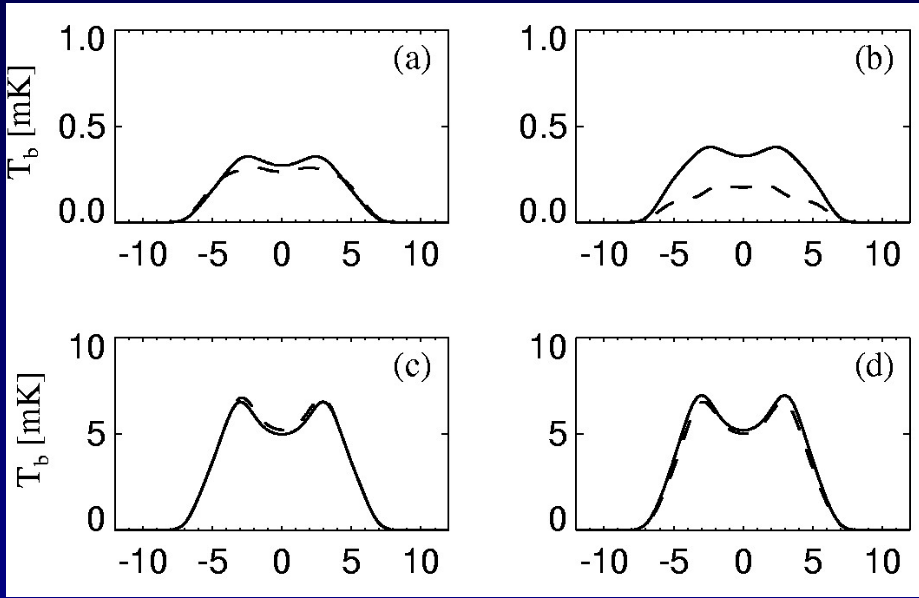
Other gas tracers: C and C^+

V_{drift}=max V_{drift}=0

βPic

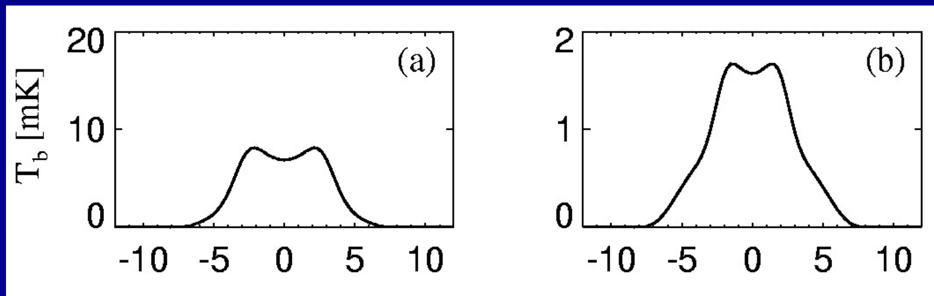
$0.2\ M_{Earth}$

$2\ M_{Earth}$



[C I]
490, 810 GHz

$2\ M_{Earth}$ $0.2\ M_{Earth}$



[C II]
158 μm

- Lines can be searched for with APEX, Herschel, SOFIA

Kamp et al. 2003

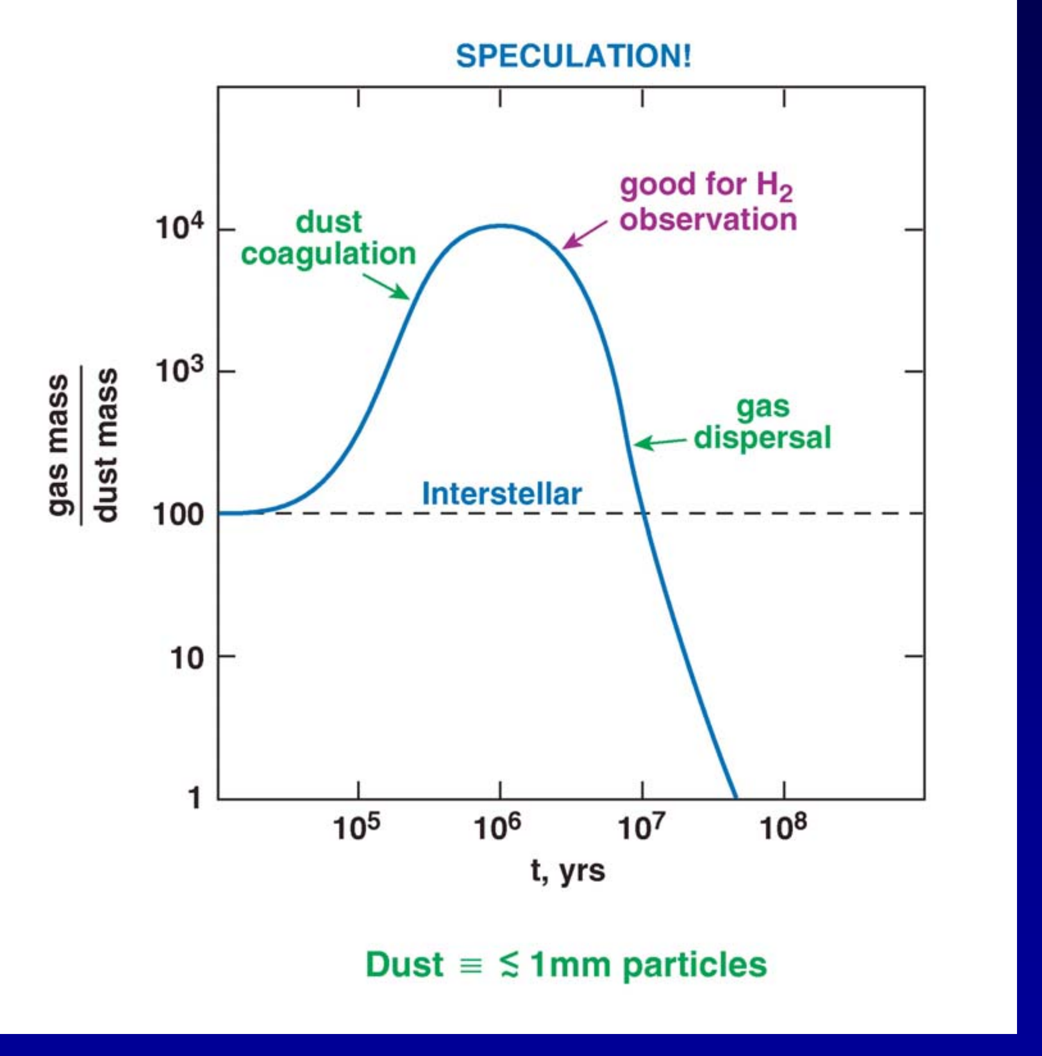
Conclusions + questions observations

- **Gas disks can persist up to 20 Myr**
- **Large range in gas disk dissipation time scales (<1 Myr to 20 Myr)**
  - **Related to initial conditions, environment, binarity?**

- **Do gas and dust disks disappear at the same time?**
  - **Difficulty in determining gas masses, proper gas tracers**
- **Do inner and outer disk disappear at the same time?**
  - **Search for CO mm and IR in the same objects**
- **Is disappearance a gradual process or abrupt, within ~10^5 yr?**
  - **Search for transitional objects**

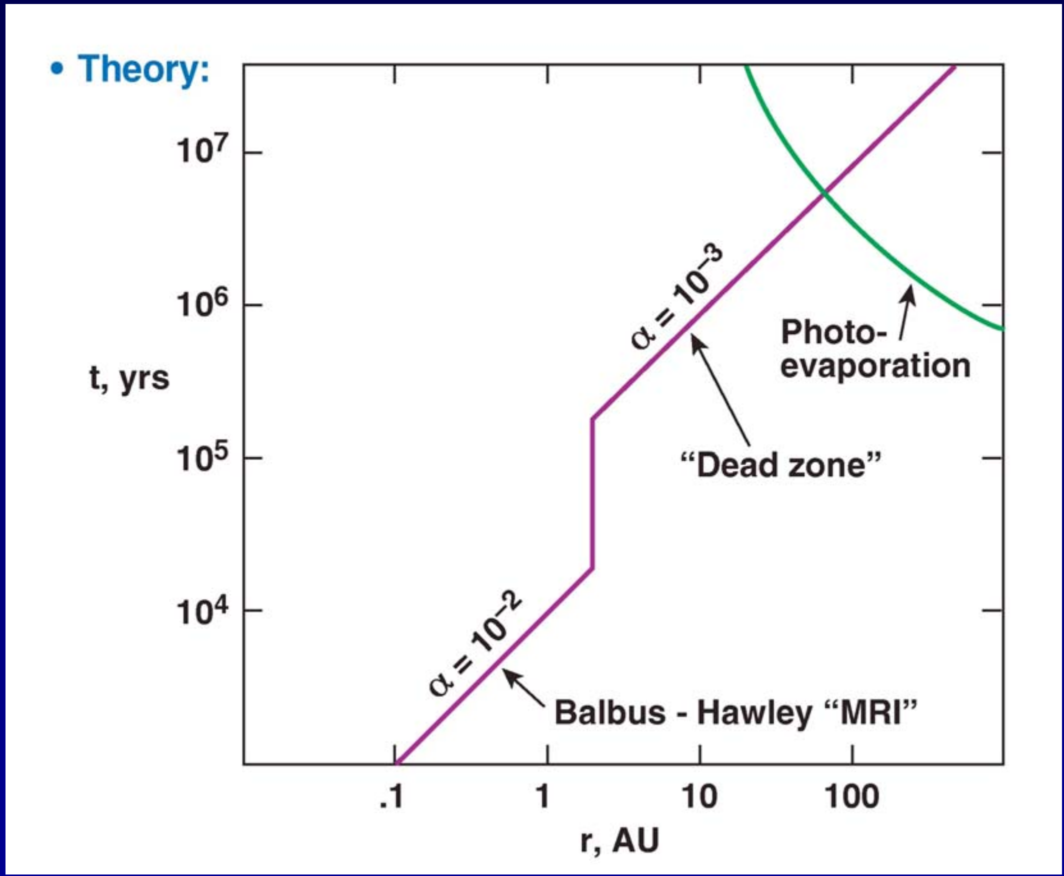
Need statistics on larger samples!

Gas/dust mass evolution



Hollenbach 2004

Models of gas disk dispersal

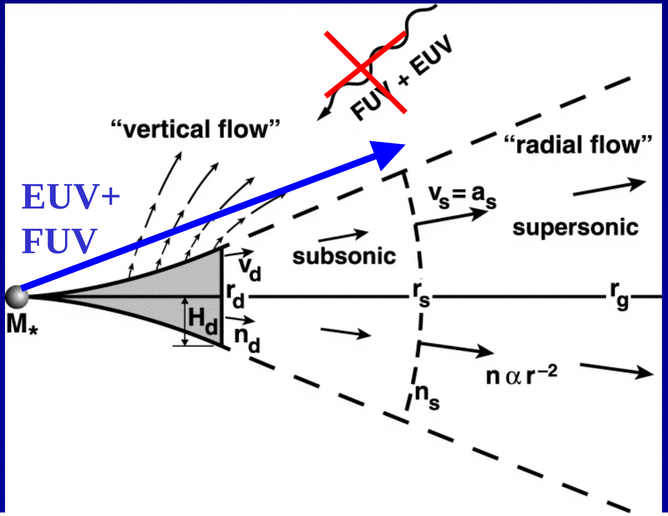


-Ignore in this talk stellar encounters, dynamical clearing by binaries, stellar winds, planet formation and strong external EUV/FUV as in Orion

Hollenbach et al. 1994, 2000, 2004

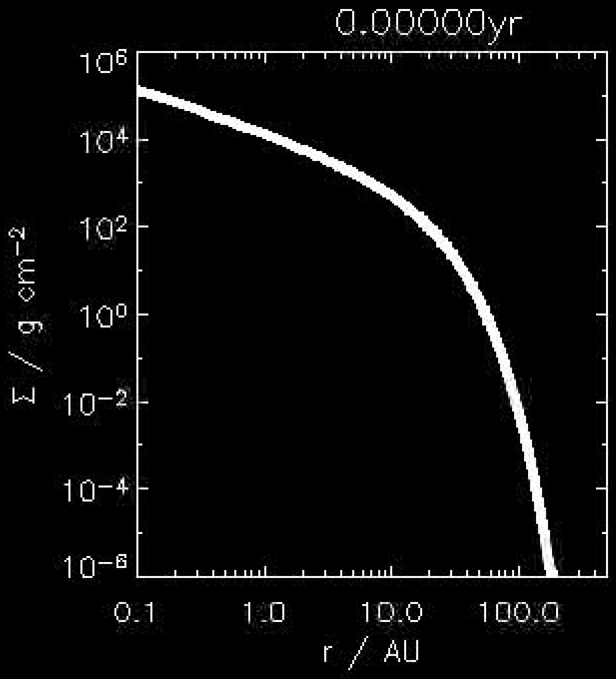
Disk dispersal

- Mass loss through
  - Accretion onto central star
  - Photo-evaporation
- Clarke et al. (2001) and Matsuyama et al. (2003) models
  - Viscous evolution of disk
  - Photoevaporation at $R>R_g$ where gas is no longer gravitationally bound
    - R_g~few AU for EUV photons, >20 AU for FUV photons
  - Opening of gap at R_g when $(dM/dt)_{accr}=(dM/dt)_{p.e.}$
  - Rapid draining of material within R_g
  - Gradual dispersal of material outside R_g

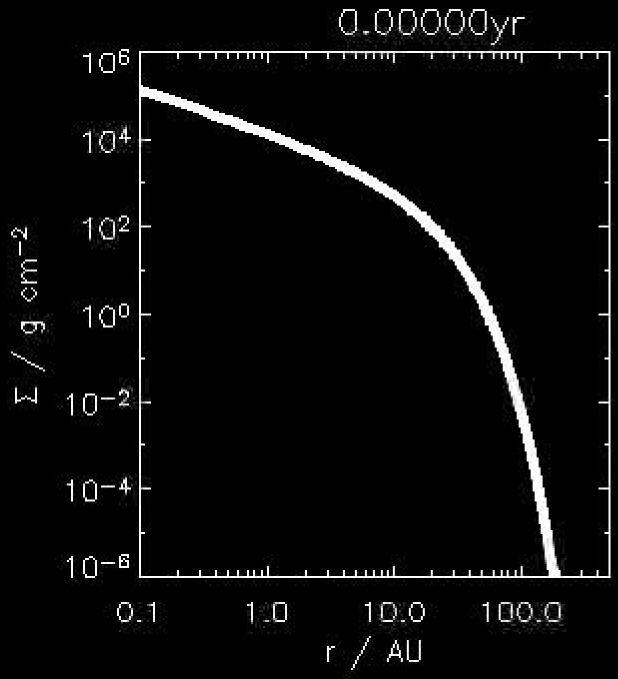


UV switch model

No p.e.



With p.e.



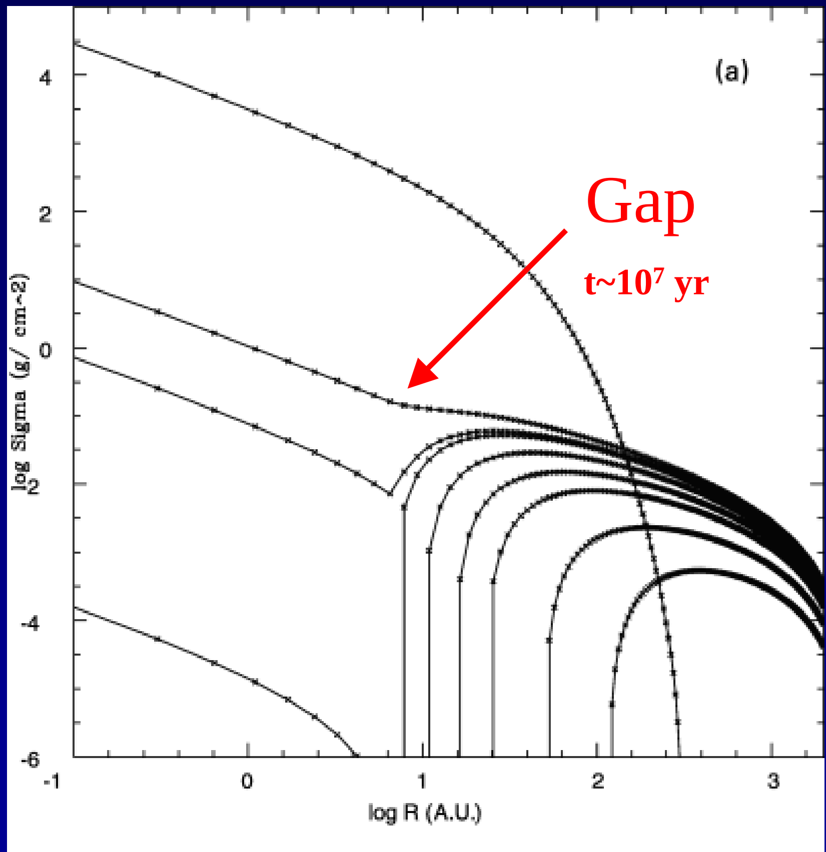
$M=1\ M_{sun}$, $M_d=0.1\ M_{sun}$,
$(dM/dt)_{accr,0}=4.2\ 10^{-7}\ M_{sun}/yr$
$(dM/dt)_{p.e.}=4\ 10^{-10}\ M_{sun}/yr$
$F_{EUV}=10^{41}\ s^{-1}$

- Main question: is EUV flux high enough to drive photoevaporation?

Clarke et al. 2001

Evolution of disk structure

Surface density



Clarke et al. 2001

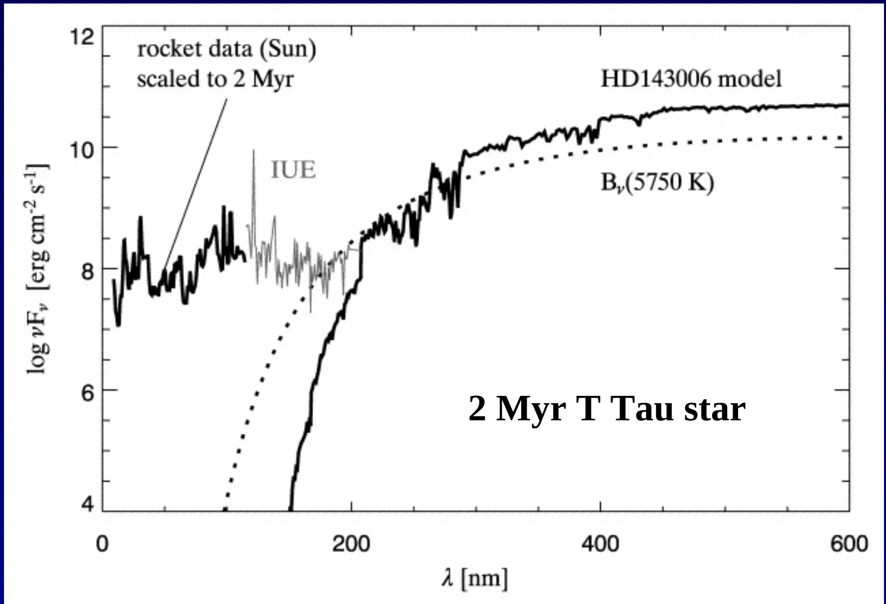
Origin EUV ionizing flux

- EUV from accretion shock
  - Absorbed by accreting column
- EUV from coronal X-rays
  - Not large enough
- EUV from chromospheres of magnetically active stars
  - Limited data but use He II/CIV as diagnostic

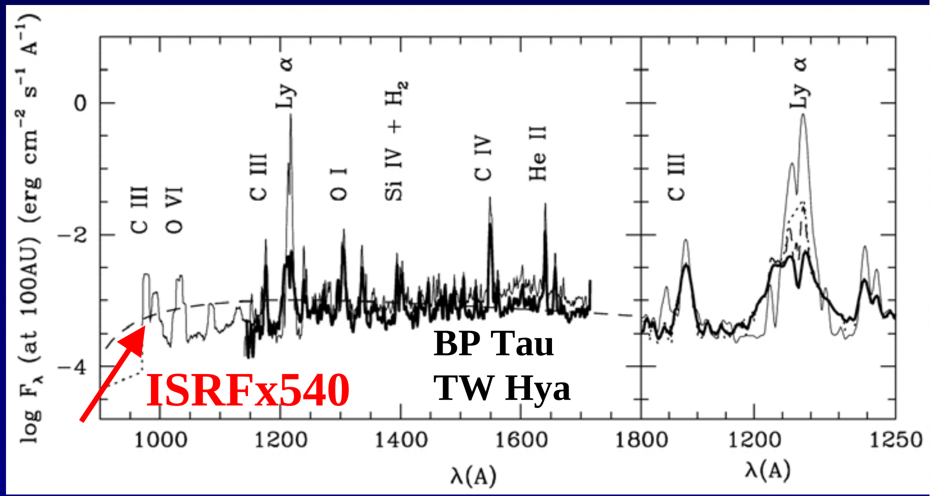
=> Consider FUV heating

Alexander et al. 2004, 2005, poster

FUV flux T Tauri stars



STIS/FUSE data



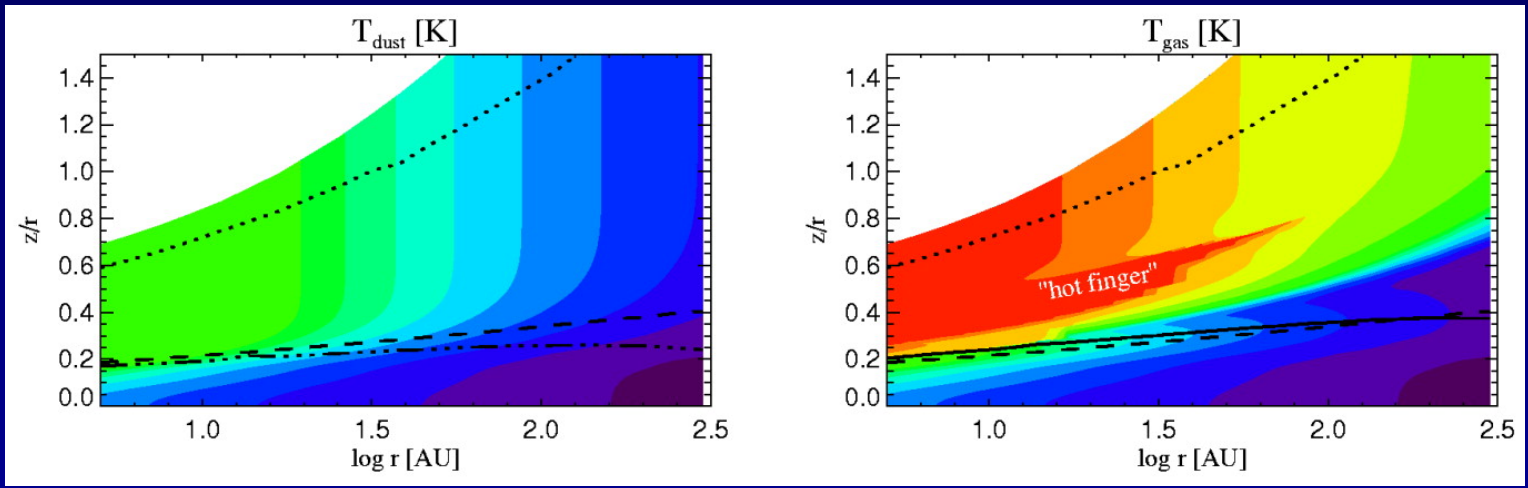
Much of the flux is in Lyα
H_2 and CO photodissociated only at 912-1100 Å

- Few direct measurements
- Enhancements w.r.t. interstellar field: I_{UV}~10^5 at 10 AU, 10^3 at 100 AU
- UV excess decreases with time as t^{-1}?
- Need I_{UV}~3000 to shrink disk on ~10 Myr timescale (Adams et al. 2004)

Kamp & Sammar 2004
Bergin et al. 2003
Van Zadelhoff et al. 2004

FUV heats gas in surface layers

- Gorti & Hollenbach 2004, 2005: inner disk 0.5-20 AU
- Jonkheid et al. 2004, : outer disk 50-400 AU
  Kamp & Dullemond 2004

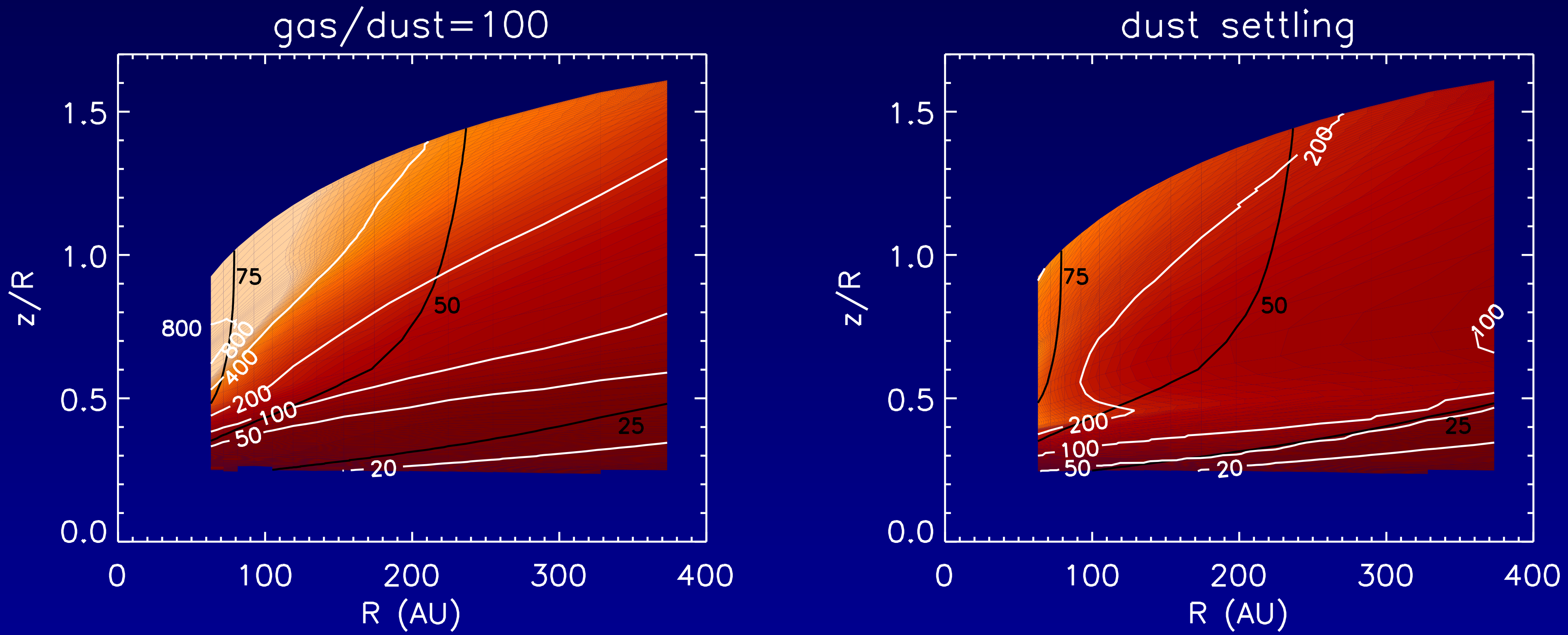


Red= 2000 K
Green= 100 K
Blue= 30 K

- $T_{gas} >> T_{dust}$ at surface, up to few thousand K
- Presence or absence of PAHs affects temperature
- Wind can be launched, even inside R_g; stronger in outer disk
- Density ~10^6 cm^{-3} at base => dM/dt~10^{-9} M_{sun}/yr at 20 AU

Kamp & Dullemond 2004

Gas temperature in flaring disk: effects of dust settling



-Black lines: T(dust) contours
-White lines: T(gas) contours
-Colors: T(gas)

- Dust settling results in lower gas temperatures at surface, but warm gas extends to deeper in the disk

Jonkheid et al. 2004

Conclusions

- No direct observational tracers of total (warm + cold) gas mass
  - Need to test various gas tracers against models, especially in transitional stage
- Some gas disks can persist up to 20 Myr, but large range in lifetimes
- Better observational statistics needed to
  - Constrain lifetime inner + outer gas disk
  - Compare lifetimes gas + dust disks
- Accretion + photoevaporation *may* explain disk lifetimes of 1-10 Myr, but model results depend critically on adopted EUV and FUV fields