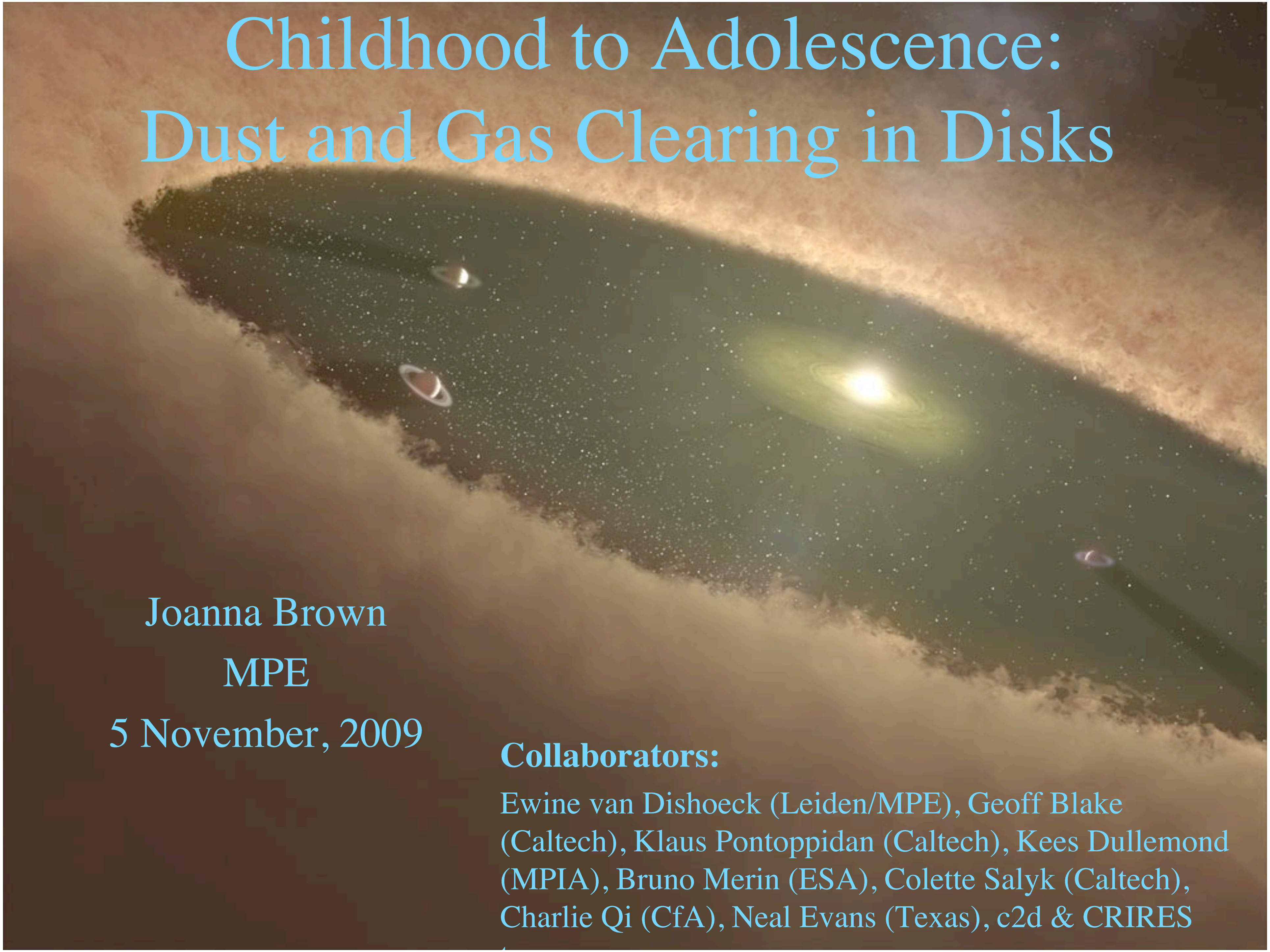

Childhood to Adolescence: Dust and Gas Clearing in Disks

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MPE

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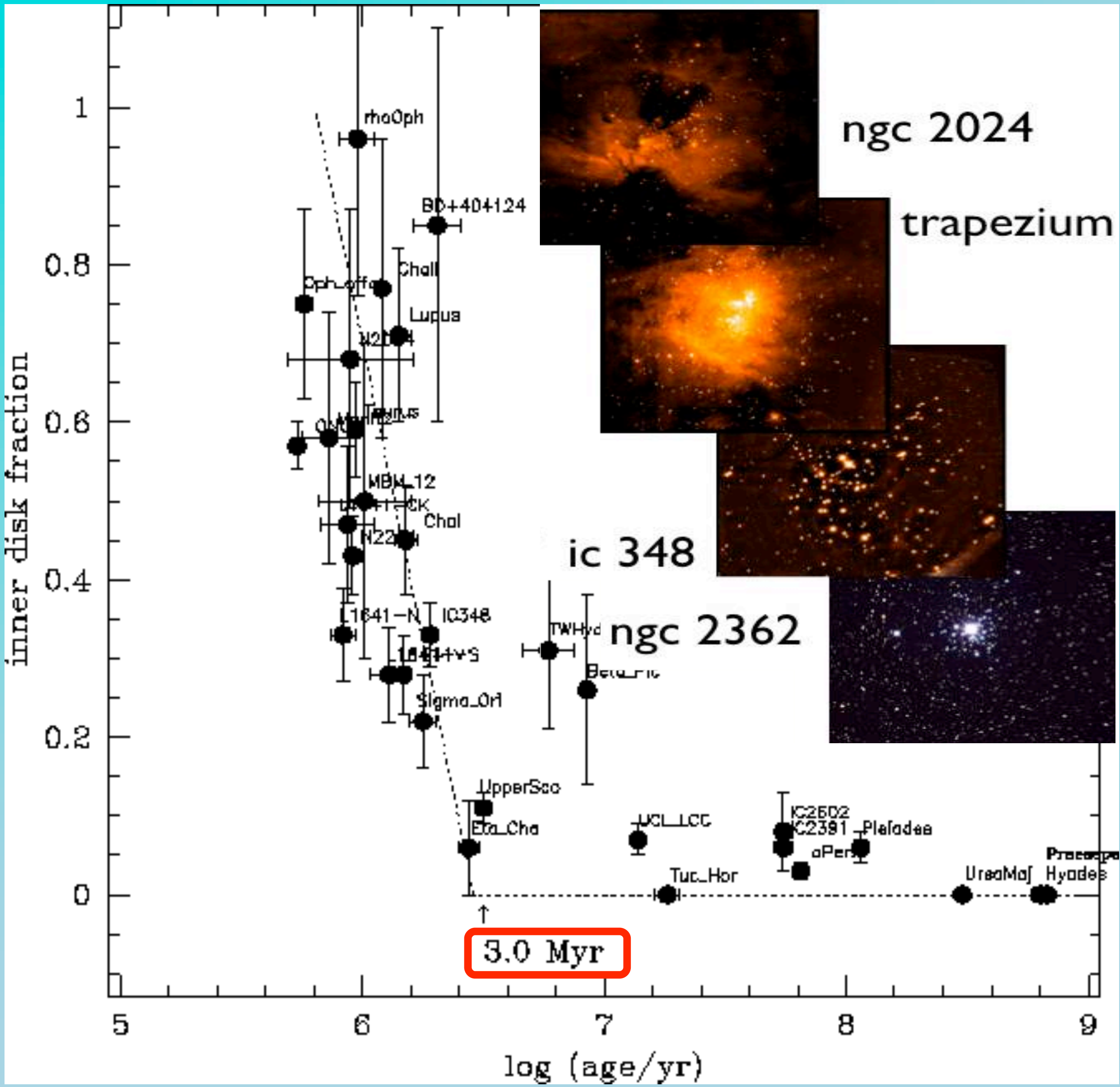
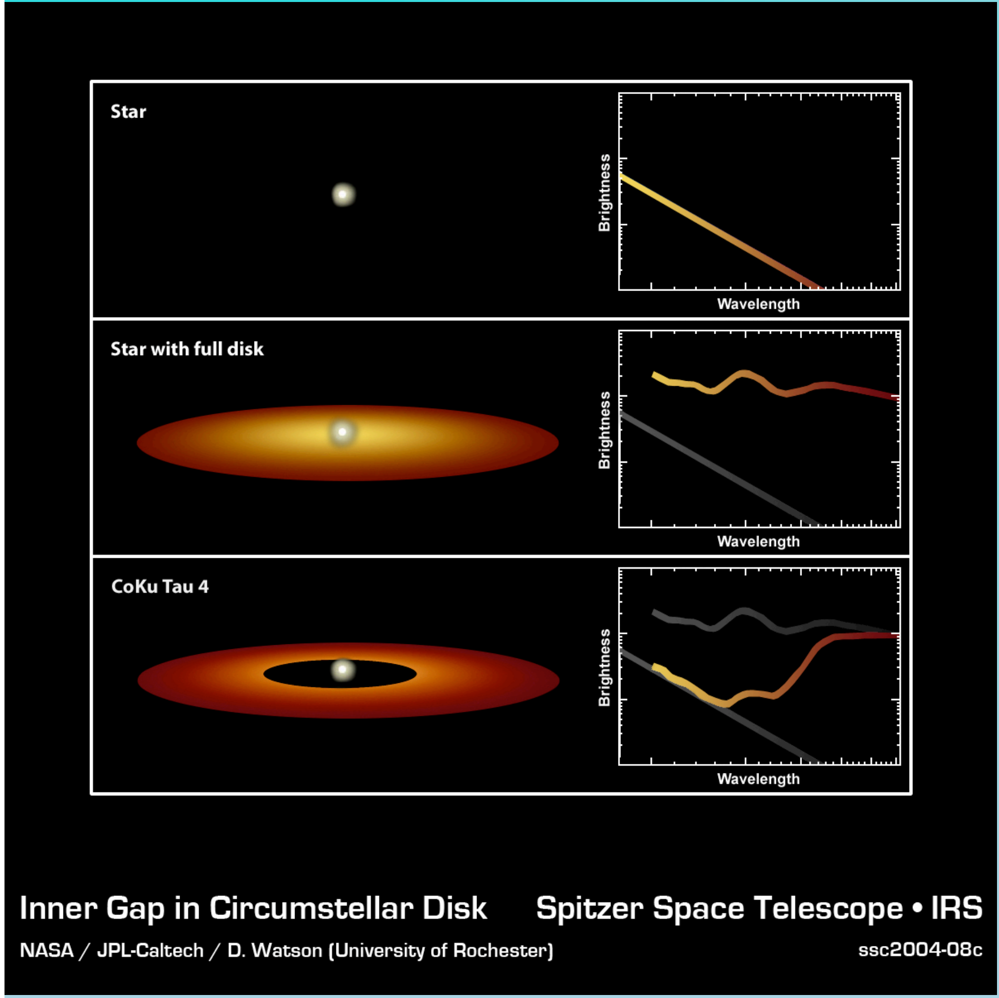


- Disks dissipate in few Myr
- Lack of dust and gas stops planet formation
- How (and when) does an individual disk dissipate?
- Traces dust - gas?

Hillenbrand (2006)

Transitional or cold disks



WHAT?

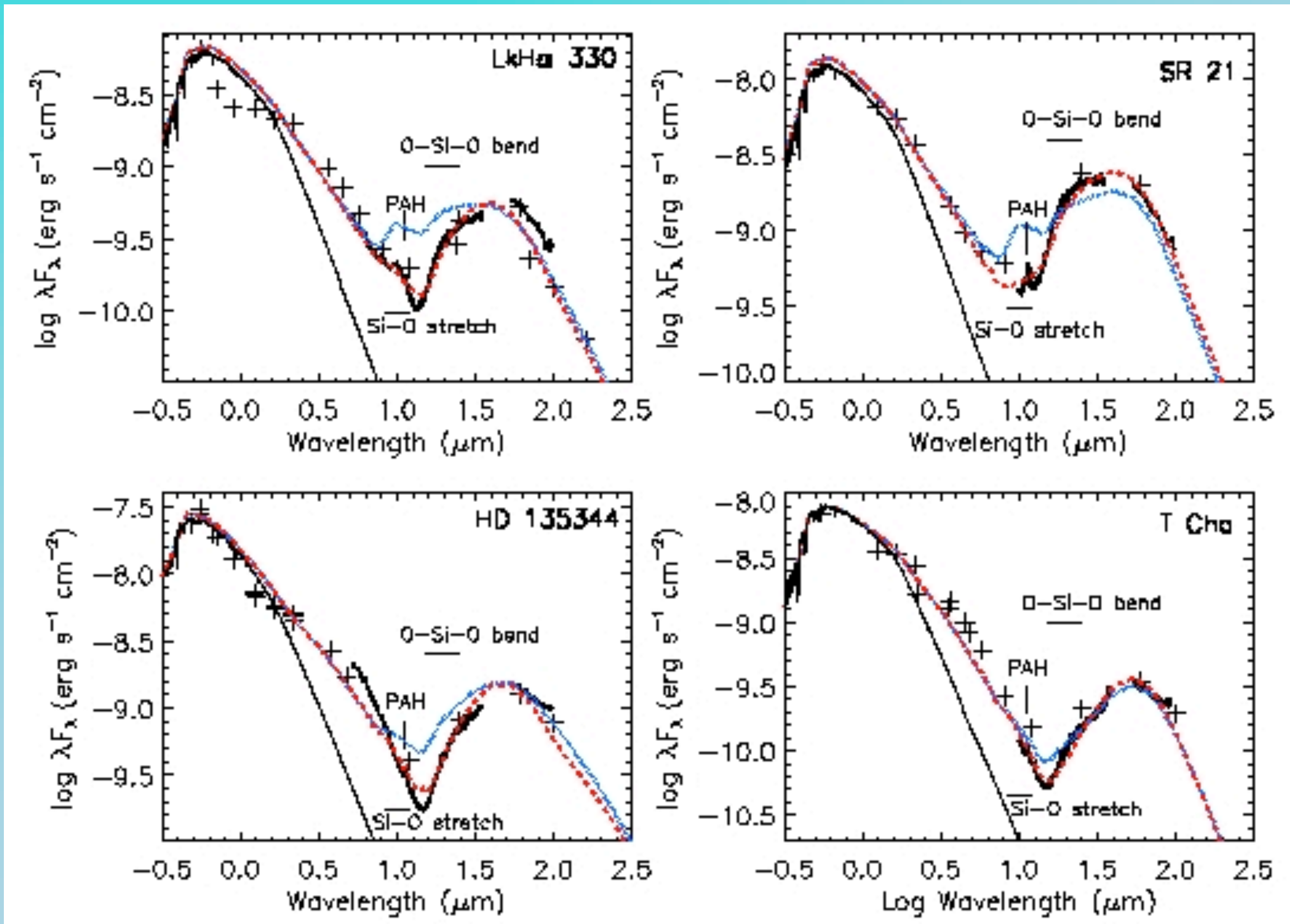
- Disks where dust clearing has begun
- Rare, presumably short-lived, phase between dusty protoplanetary disk and star with planetary system
- Identifiable through mid-IR photometry and spectroscopy (Spitzer)

WHY?

- Potentially trace young/forming planets
- Look at how disks disperse

Spitzer disks with gaps

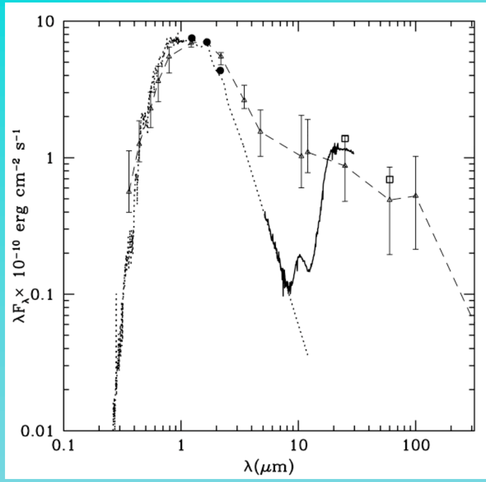
CoKu Tau 4 (Sargent et al. 2004, D'Alessio et al. 2005), DM Tau, GM Aur (Calvet et al. 2005), CS Cha, UX Tau, LkCa 15 (Espaillat et al. 2007)



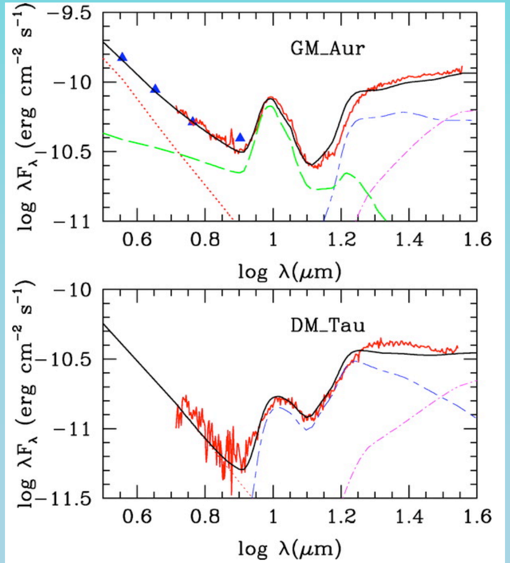
Brown et al. 2007

- •IRS spectra show sharp rise
- •Large gap radius implied, with sharp boundary
- •Strong near-IR excess with T~1500K

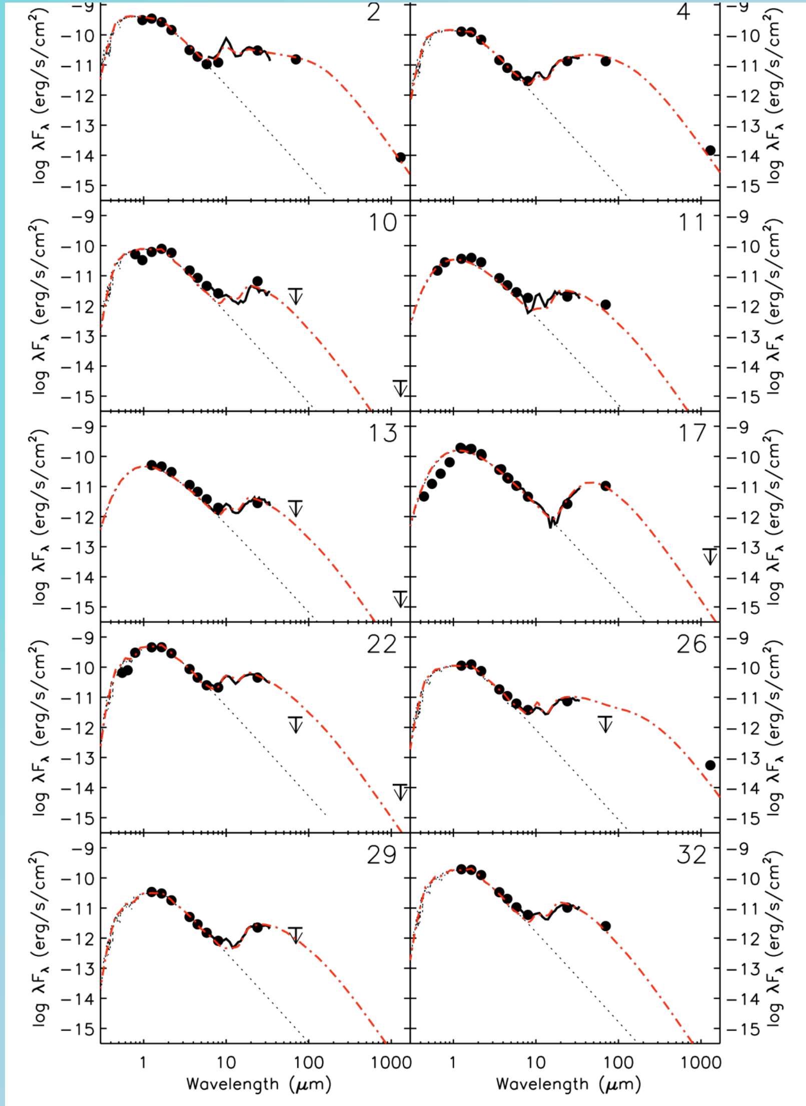
Many transitional disks now known



D'Alessio et al. 2004



Calvet et al. 2005

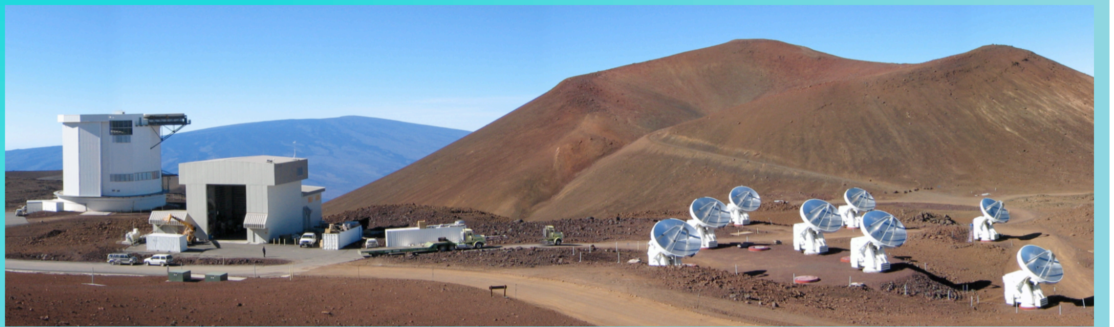


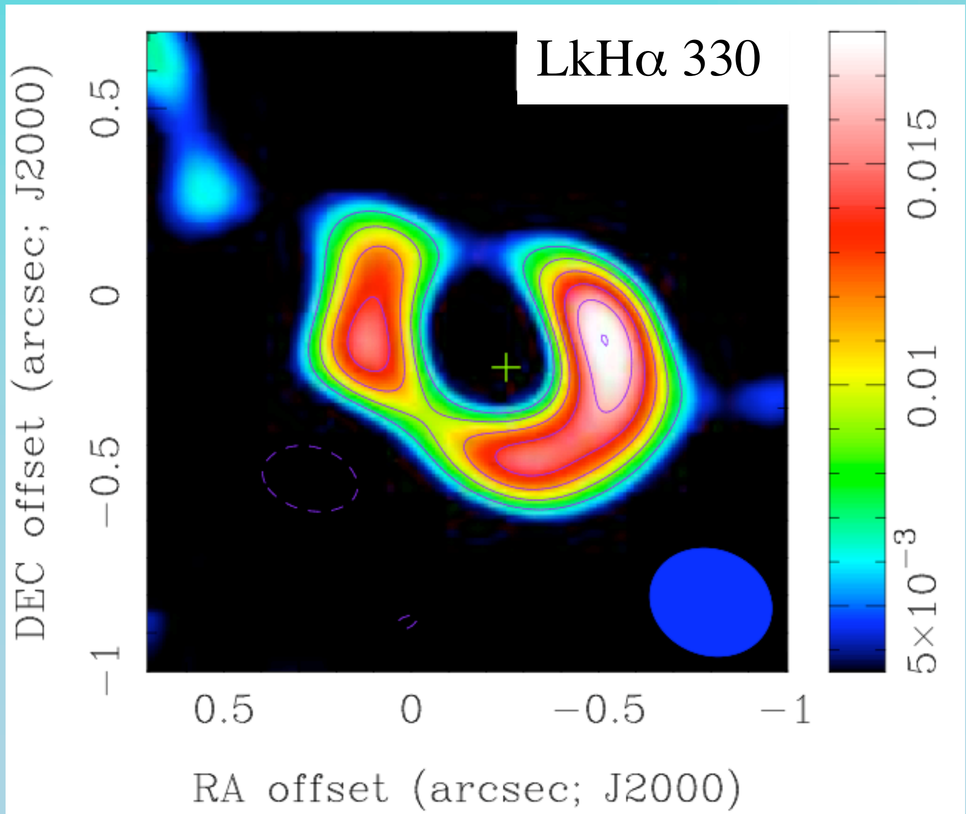
Merin, Brown et al., 2010

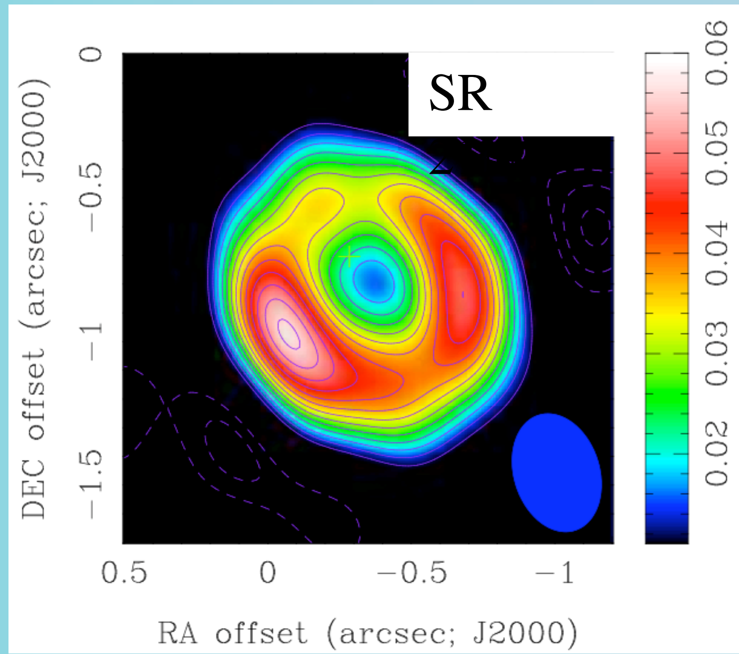
BUT many different SED shapes observed

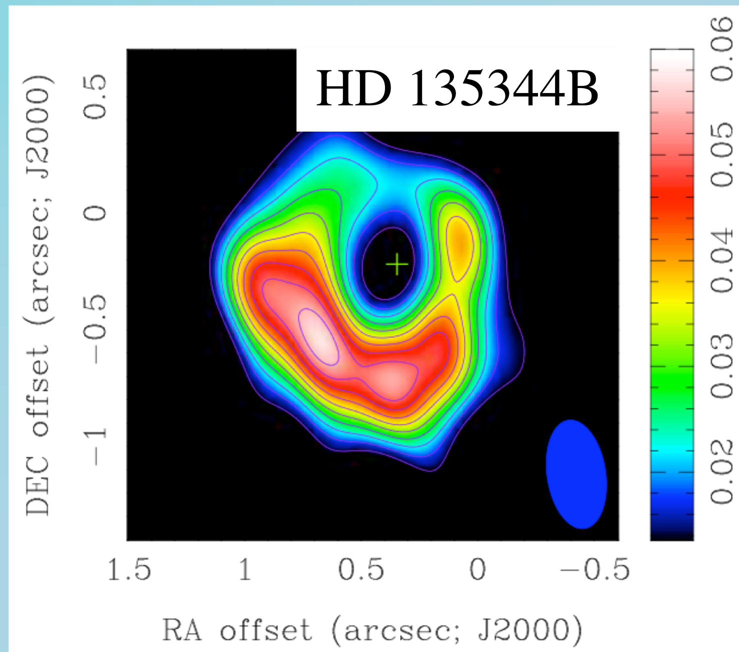
Is it a hole?

SMA very extended configuration

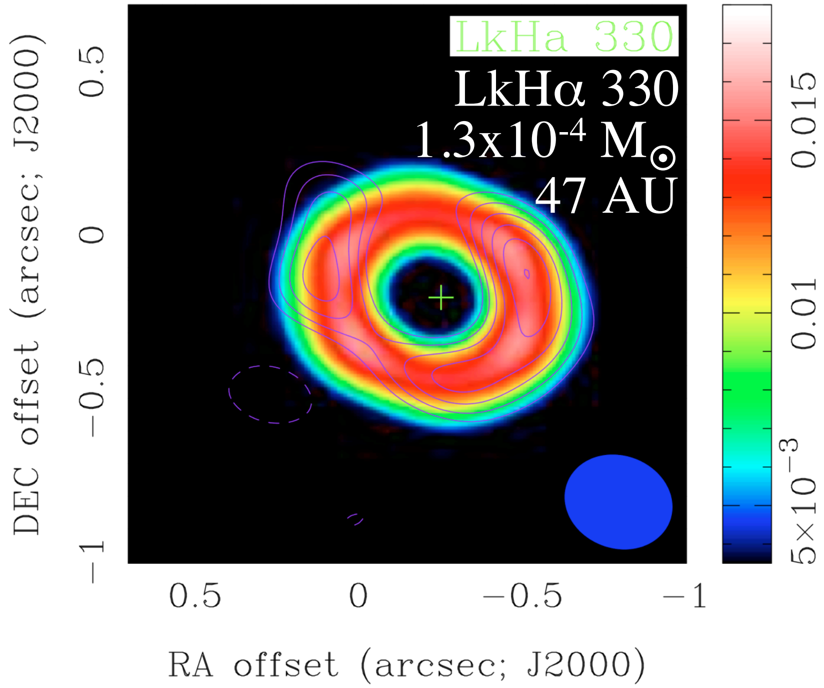






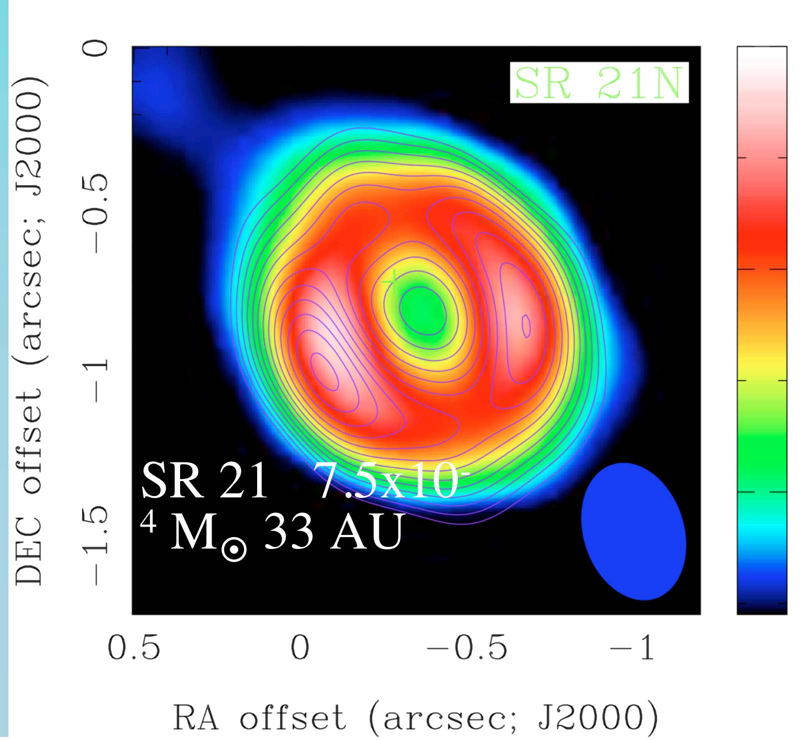


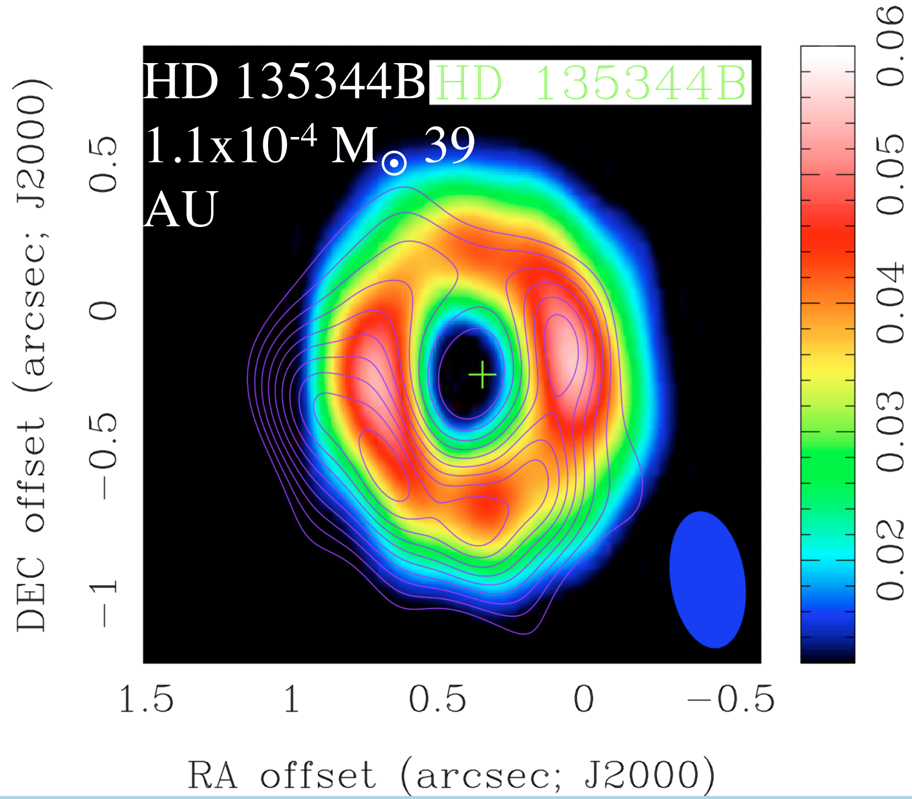
Brown et al. 2008, 2009



Simultaneous modeling of submm images, visibilities, and SEDs

SED interpretation supported by imaging

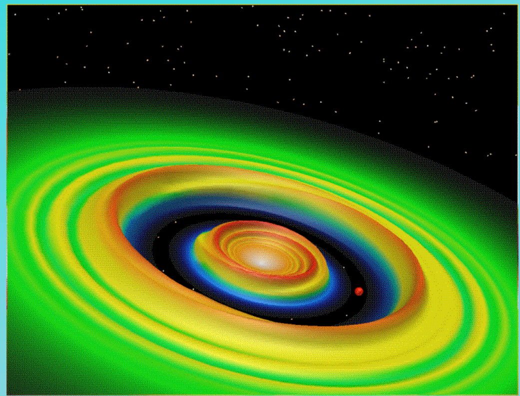




Causes of holes

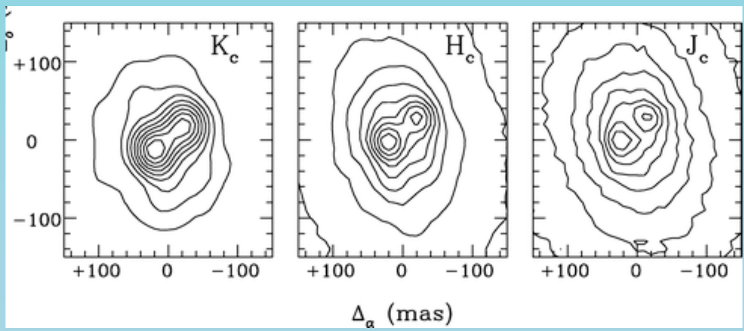
Companion

Planet:



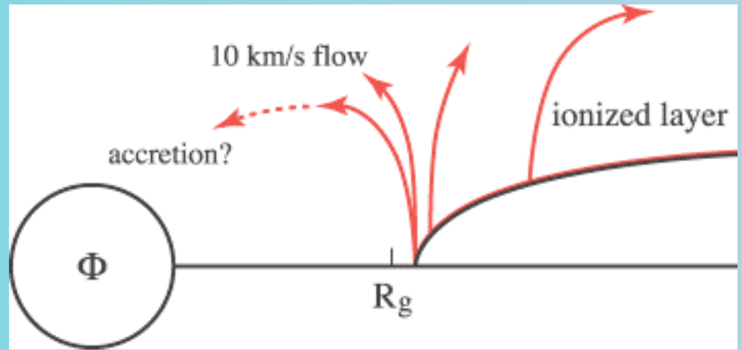
Simulation G. Bryden (JPL)

Star: e.g. Coku Tau 4



Ireland & Kraus 2008

Photoevaporation



Alexander et al. 2006

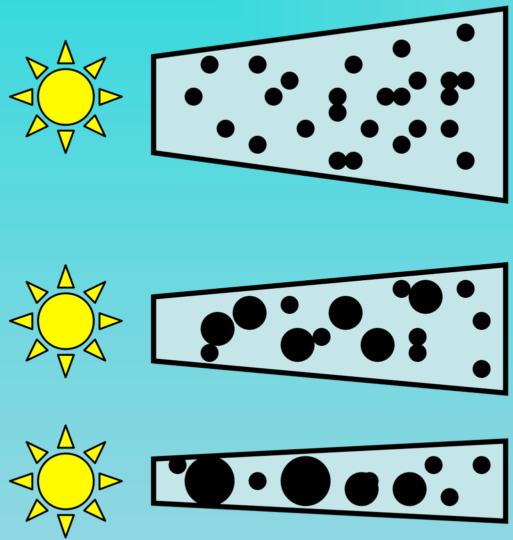
Radiation creates ionized surface layer

Ionized gas is unbound outside gravitational radius and flows away at sound speed

Cannot resupply inside R_g -> Hole

Causes of holes

Grain growth



e.g. Dullemond& Dominik 2005,

Brauer et al. 2008

Disk viscosity

Disk viscosity decreases with orbital radius (γ<0) leading to depleted inner region

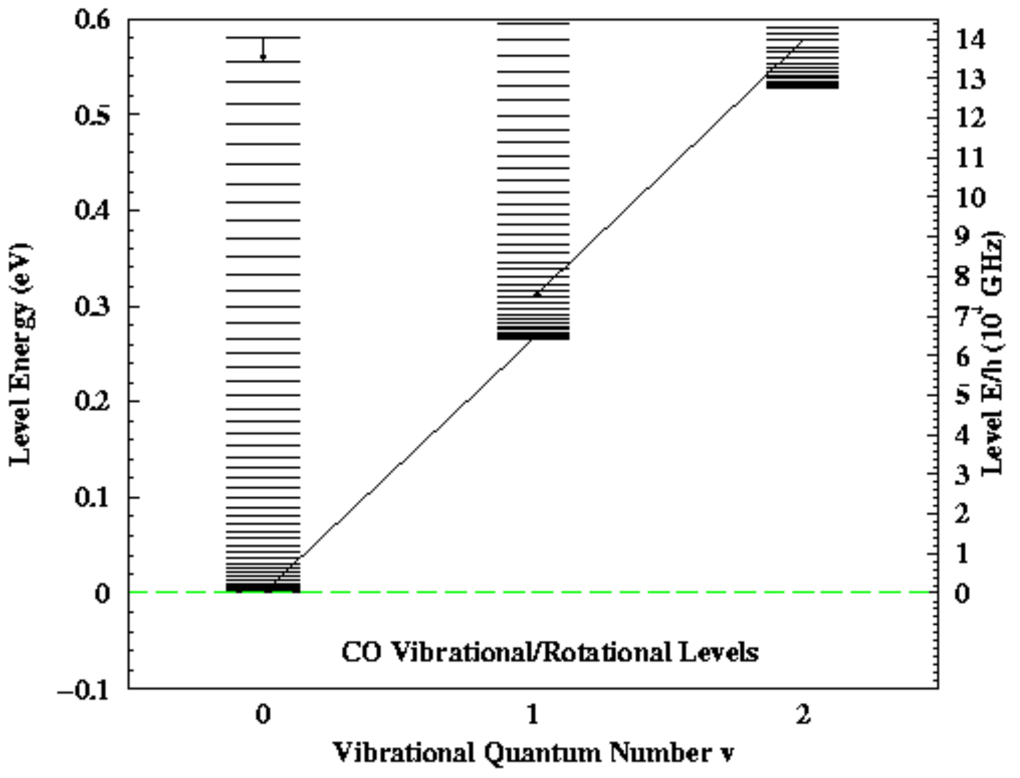
Works best when depleted region is large fraction of total disk radius

Isella et al. 2009

Should be distinguishable by gas signatures from within hole

Scenario	Warm gas present?
Planetary companion	Maybe - depends on companion size & orbit
Stellar companion	
Photoevaporation	No
Dust grain growth	Yes
Disk viscosity	Reduced

How to look for gas in the holes?



Molecular hydrogen abundant but hard to see

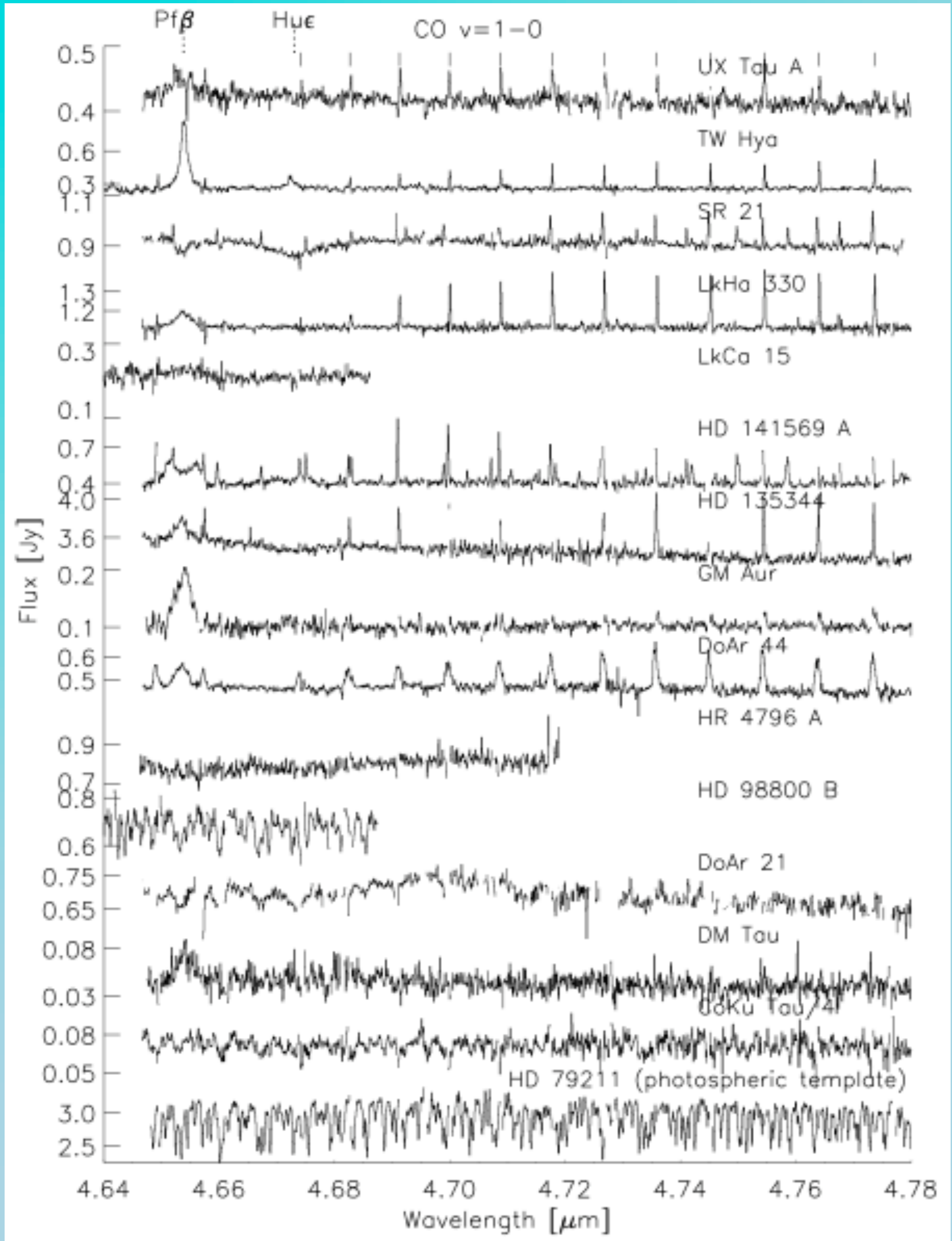
Carbon monoxide (CO) - abundant in young disks

Rovibrational (v=1-0) band at 4.7 μ m

Probes gas ~1000K and rovibrational nature means traces a range of energies

R=10,000-100,000 (30-3 km/s) echelles (NIRSPEC, PHOENIX,TEXES, CRIRES)
on 8-10 m telescopes can now probe "typical" T Tauri/Herbig Ae stars

High Resolution CO Spectroscopy



Salyk et al. 2009

9/14 (~65%) transitional disks have hot CO emission

Of 5 with no gas, 2 are close binaries

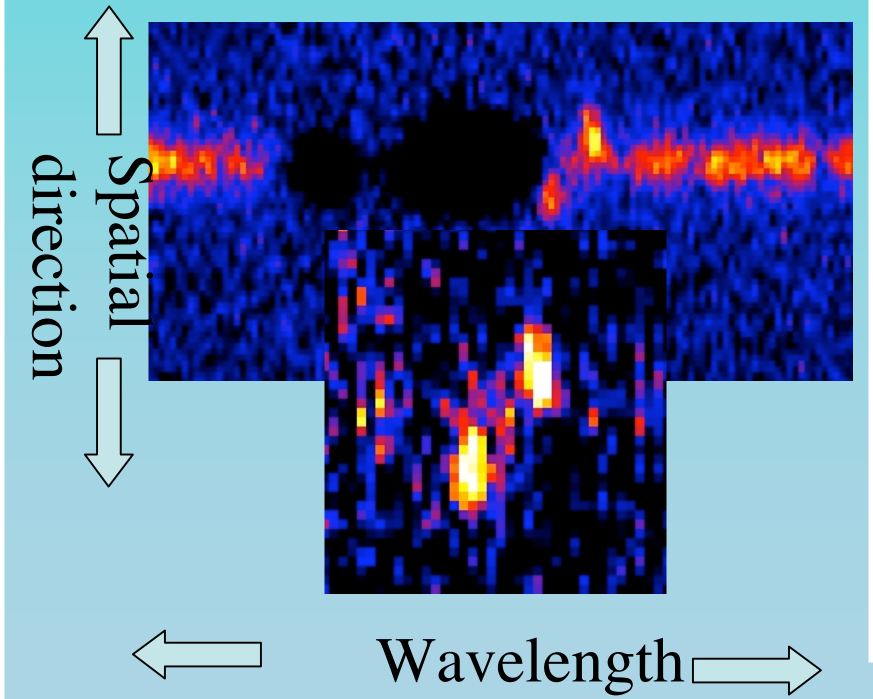
With gas generally still accreting, high degree veiling (~600 K dust) and higher disk masses

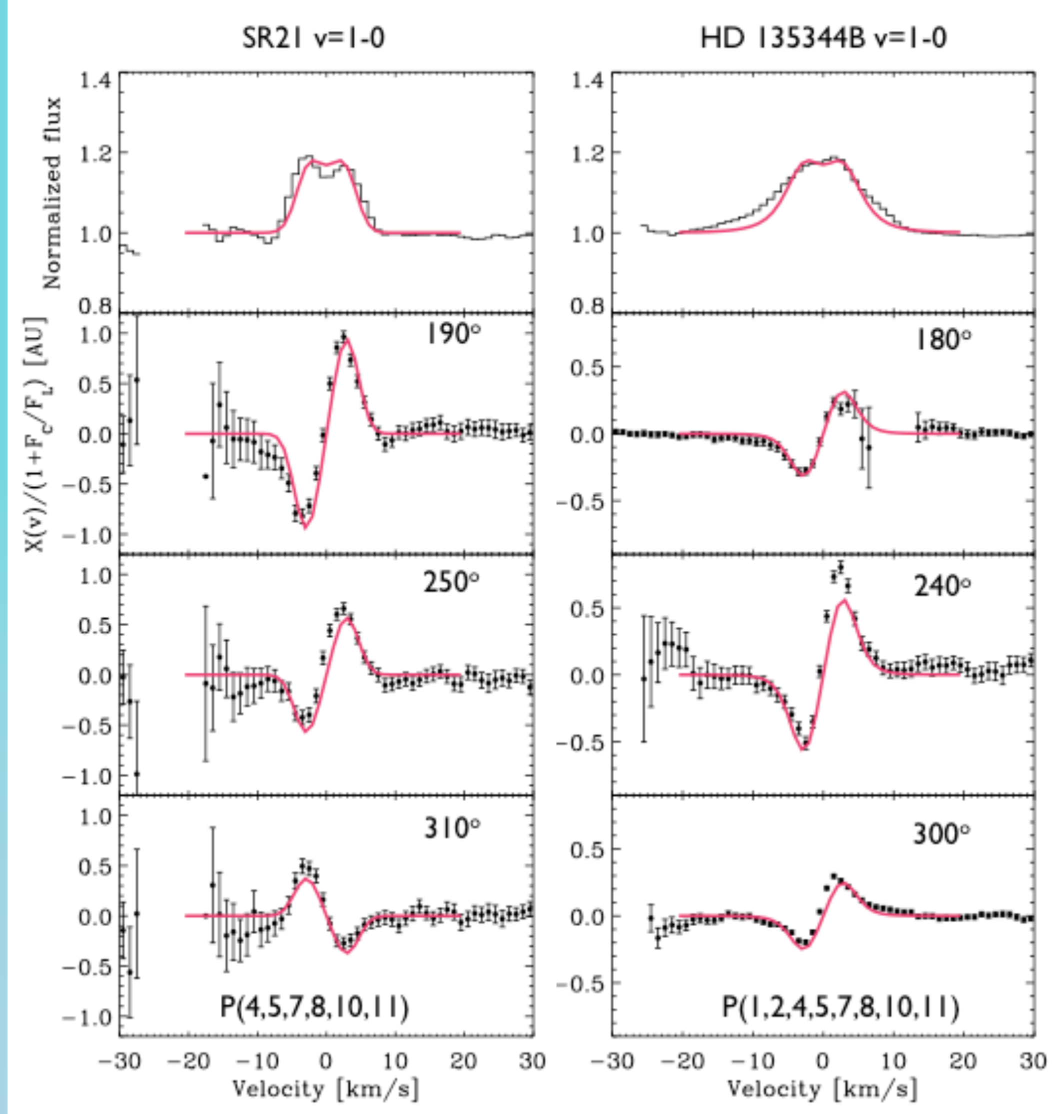
However, several exceptions and much diversity in CO column densities

Gas location via spectroastrometry

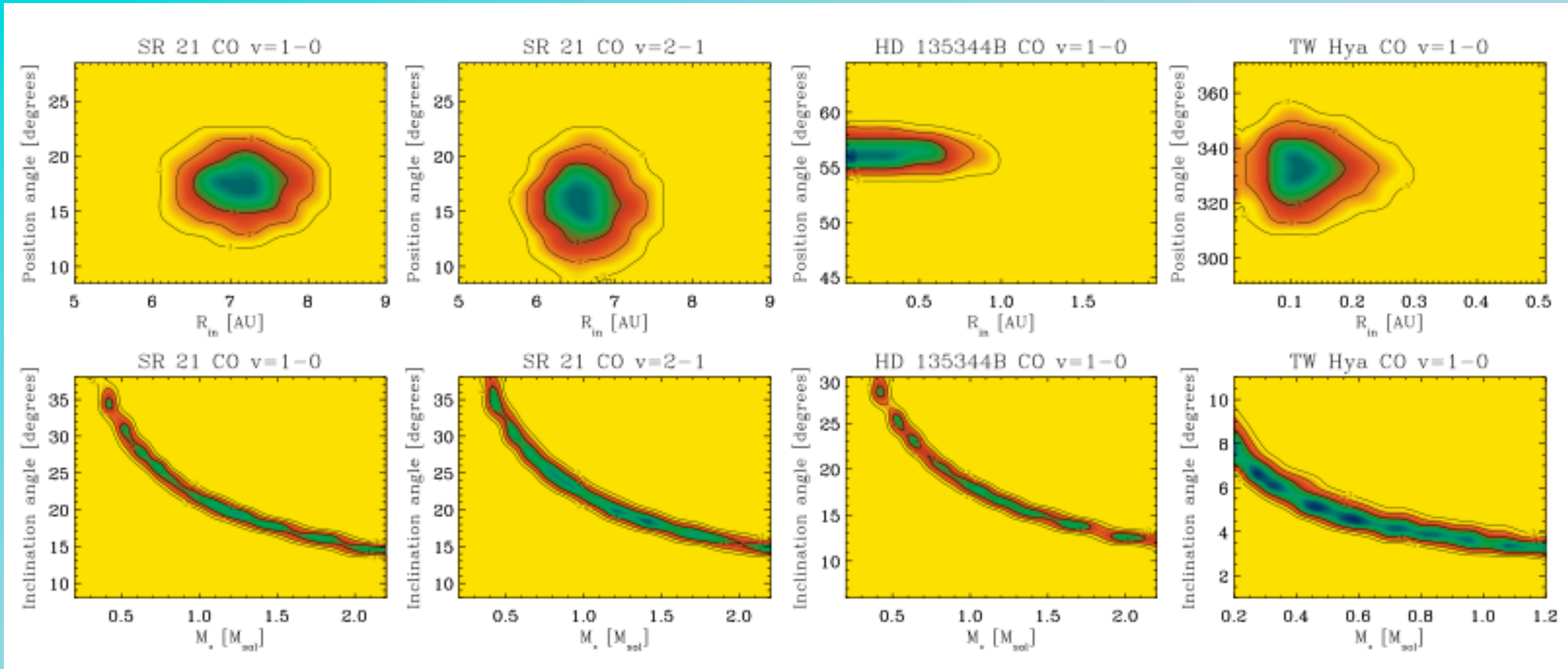
VLT CRIRES (R=100,000) is behind AO so lines can sometimes be seen to be spatially extended

Can determine gaussian centroid more accurately than width





Pontoppidan et al 2008

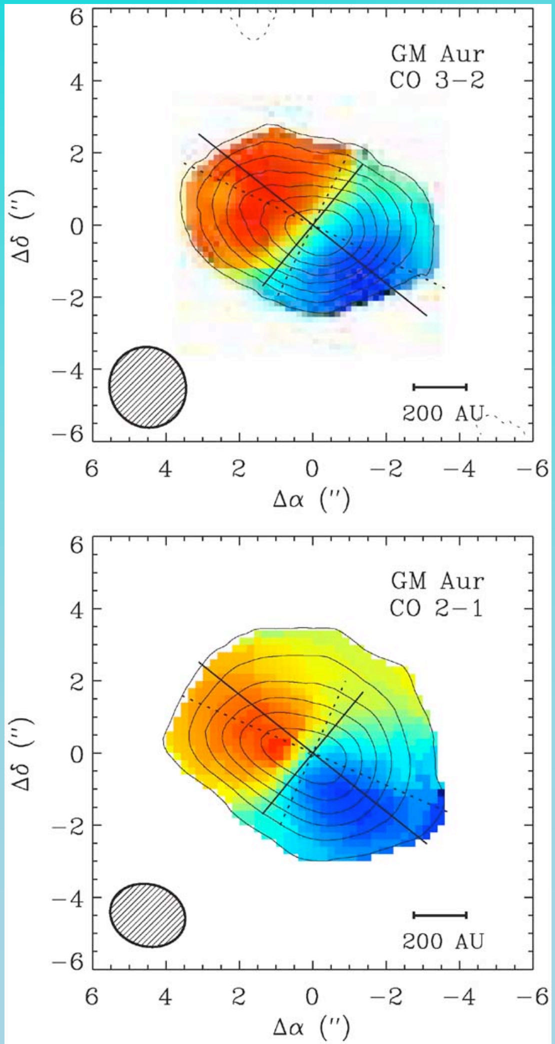


Spectroastrometry sensitive down to 0.1 AU regime

Confirms presence of CO **within** dust holes

Gas distribution is different in different disks

Millimeter gas detections



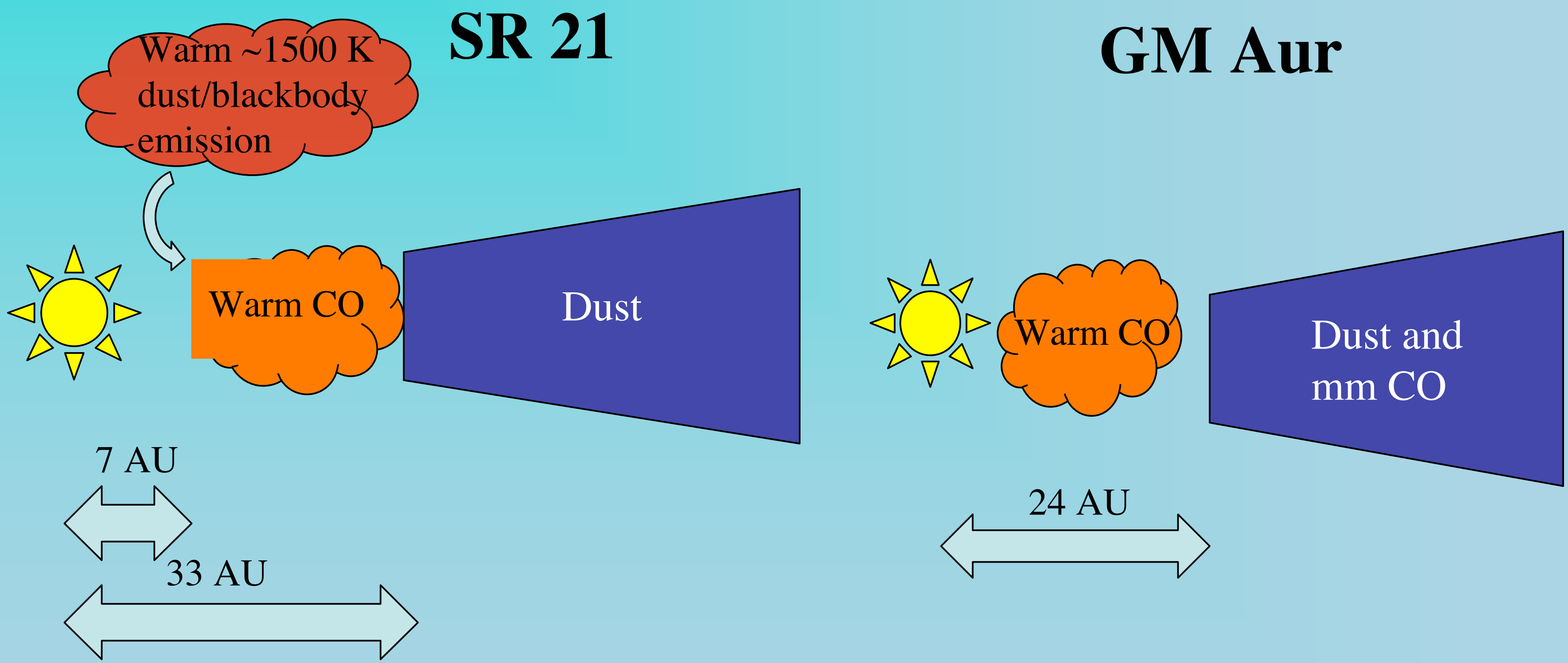
Hughes et al. 2009

Difficult to get sensitivity to spatially resolve submm gas lines

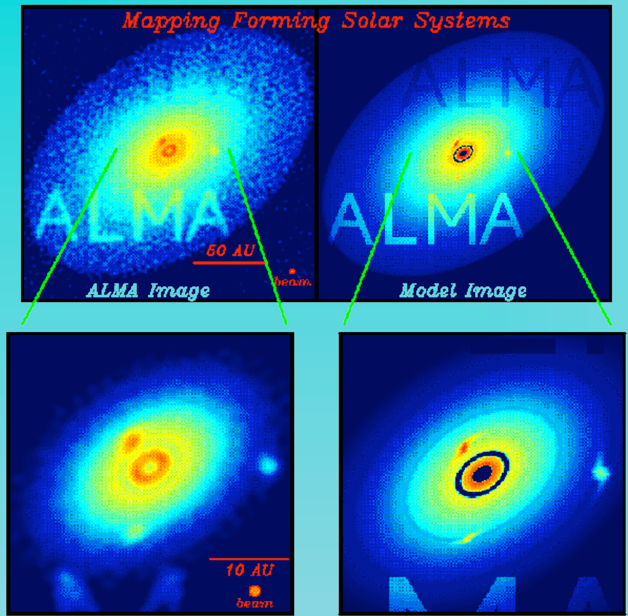
BUT at high spectral resolution, inner hole leads to narrower line shape because fastest rotating gas is absent (GM Aur, Dutrey et al. 2008)

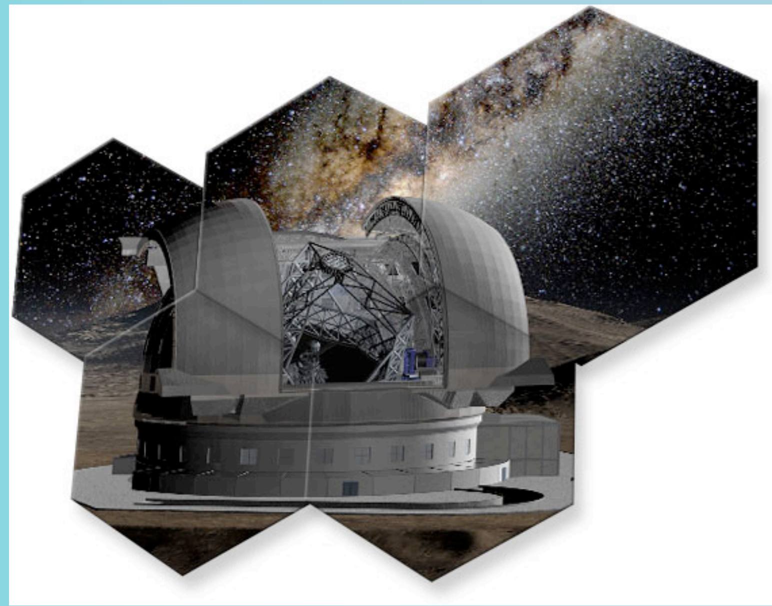
GM Aur also shows offset between continuum and gas rotation axis -- disk structures may be more complicated (e.g. warps) when seen at even higher resolution

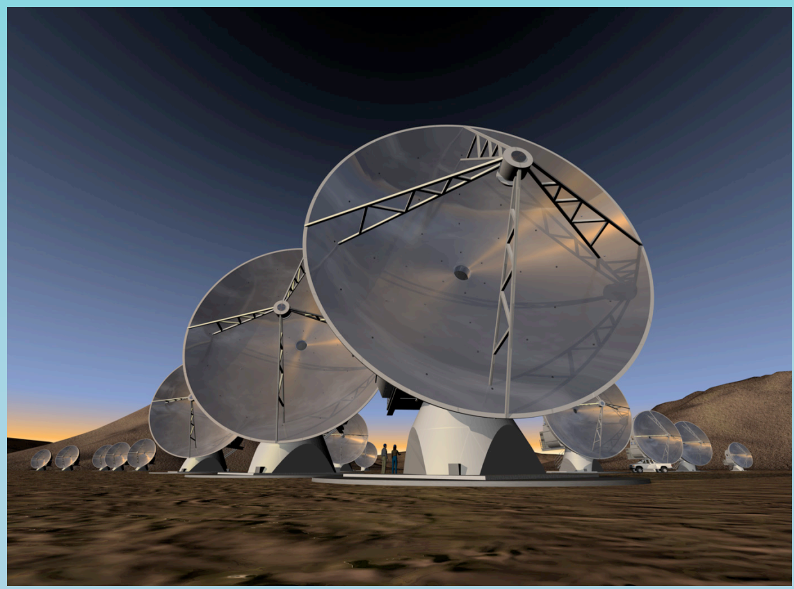
Case studies



Future of Disk Observations







European-Extremely Large Telescope (E-ELT) – METIS high resolution spectrograph

ALMA - direct submillimeter imaging

Conclusions

- Spitzer photometry /spectra reliably isolates disks with decreased dust emission over the 1-40 AU region.
- Spatially resolved (sub)mm imaging confirms that these disks do have holes with low dust content.
- Many disks show evidence of hot dust and gas, limiting hole formation mechanisms.
- CO M-band spectroastrometry can spatially constrain gas in the inner disk.
- Higher resolution reveals increasingly complex structure and diversity in transitional disks