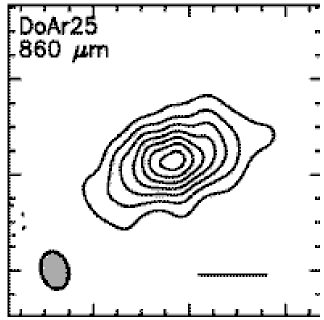


Protoplanetary Disks

David Wilner

SMA Protoplanetary Disk People

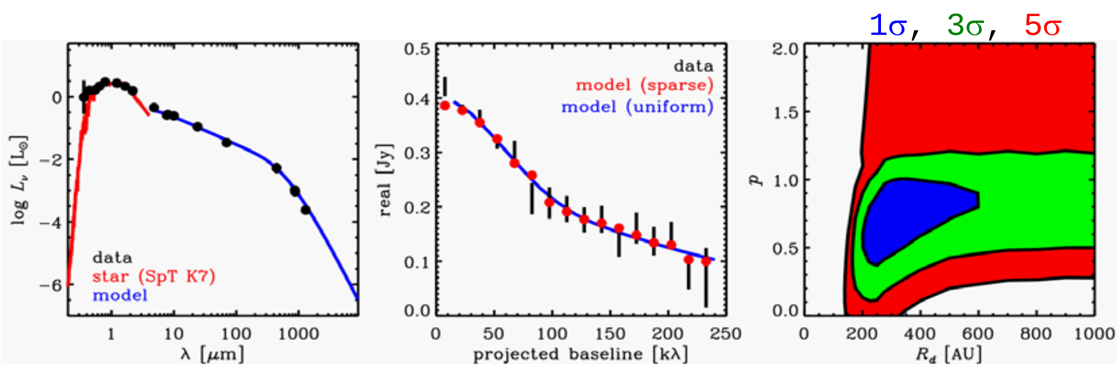
CfA	C. Qi, T. Bourke D. Wilner, *M. Hughes*
ASIAA	N. Ohashi, P. Ho, *S.-Y. Lin*
U. Hawaii	J. Williams, *S. Andrews*
Caltech	G. Blake, *J. Brown*
Leiden	M. Hogerheijde, *O. Panic*, E. van Dishoeck, *D. Lommen*
Arcetri	A. Natta, L. Testi, *A. Isella*
other notable (primarily theory)	N. Calvet, P. D'Alessio, E. Bergin, Y. Aikawa, I. Kamp

Why Submillimeter?

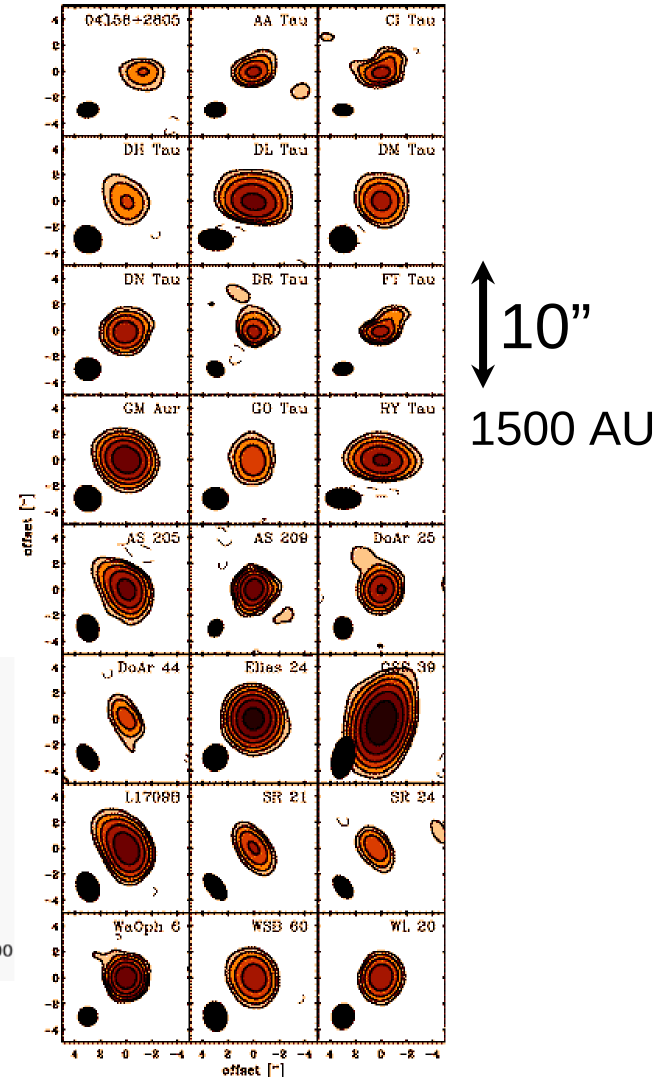
- bulk of disk material is “cold” molecular hydrogen
  - T ~ 30 K at r ~ 100 AU for a typical T-Tauri star
- dust continuum emission has low opacity
  - $dF = B(T)\,\kappa\Sigma dA$, detect every dust particle
  - submillimeter flux ≈ mass, weighted by temperature
- spectral lines of many trace molecules
  - heterodyne $R > 10^6$: kinematics, chemistry
- interferometry provides resolved information
  - 100 AU ~ 0.7 arcsec in nearest dark clouds
  - initial conditions for planet formation
  - disk evolution processes: viscous accretion, particle growth, photoevaporation

Imaging Survey of 24 Disks

- 12 disks in Tau-Aur,
  12 disk in Oph-Sco
- 1-2'' at 880 μm / 1.3 mm,
  $dF = B(T)\ \kappa\ \Sigma\ dA$,
- fit (simple) power-law models for homogenous sample of physical properties (T, Σ, R_{out})

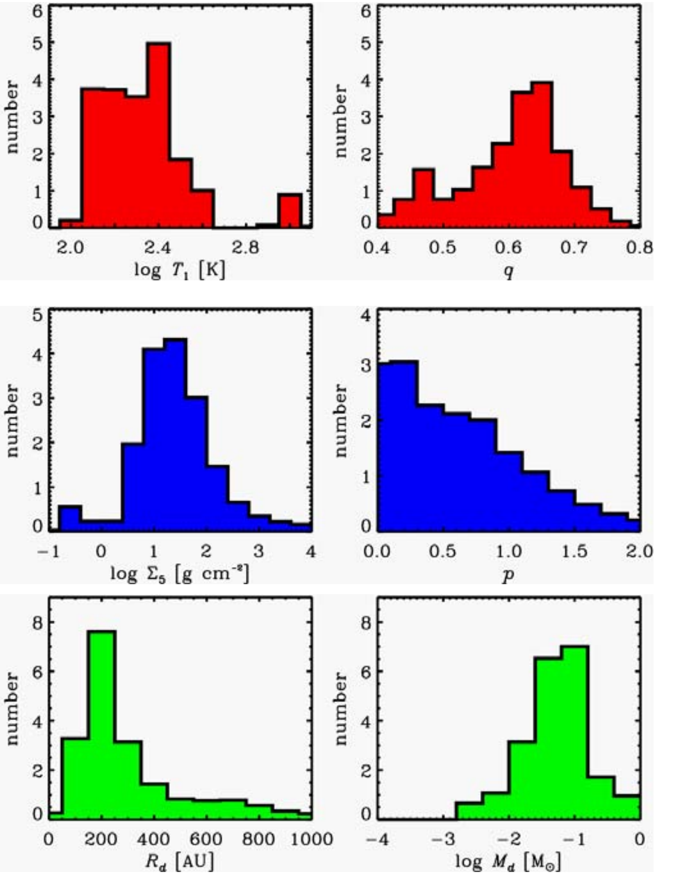


SED   visibilities χ^2



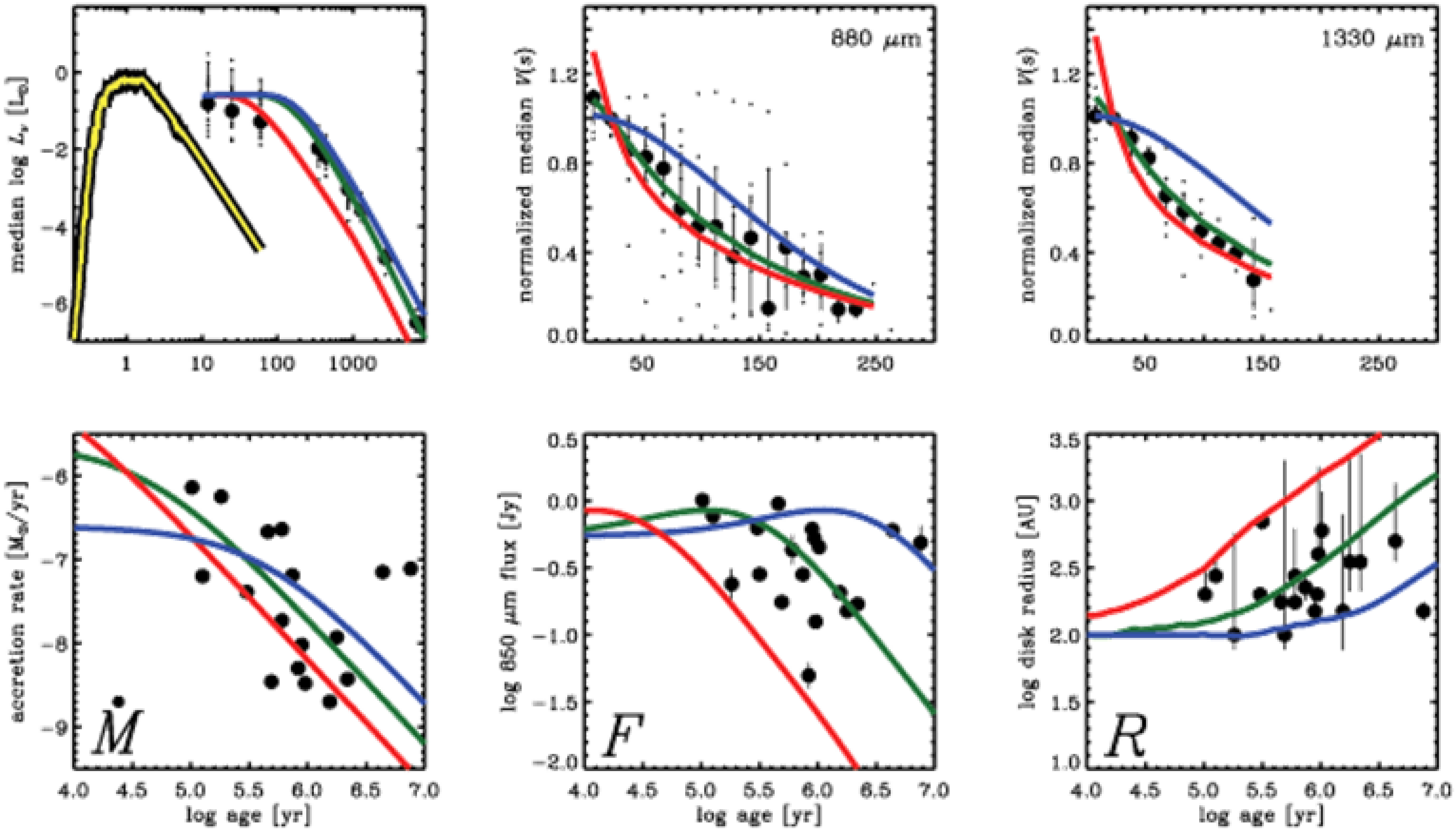
Imaging Survey of 24 Disks

- Temperatures: $T \propto R^{-q}$
  - median $q \approx 0.6$, 200 K at 1 AU
- Surface Densities $\Sigma \propto R^{-p}$
  - median $p \approx 0.7\text{-}1.0$, 150 g/cm^2 at 1AU
- Sizes and masses
  - median $R_d \approx$ 200 AU
  - median $M_d \approx 0.05$ solar masses
- Constrain
  - initial conditions for planet formation
  - disk evolution: viscous accretion, particle growth, photoevaporation



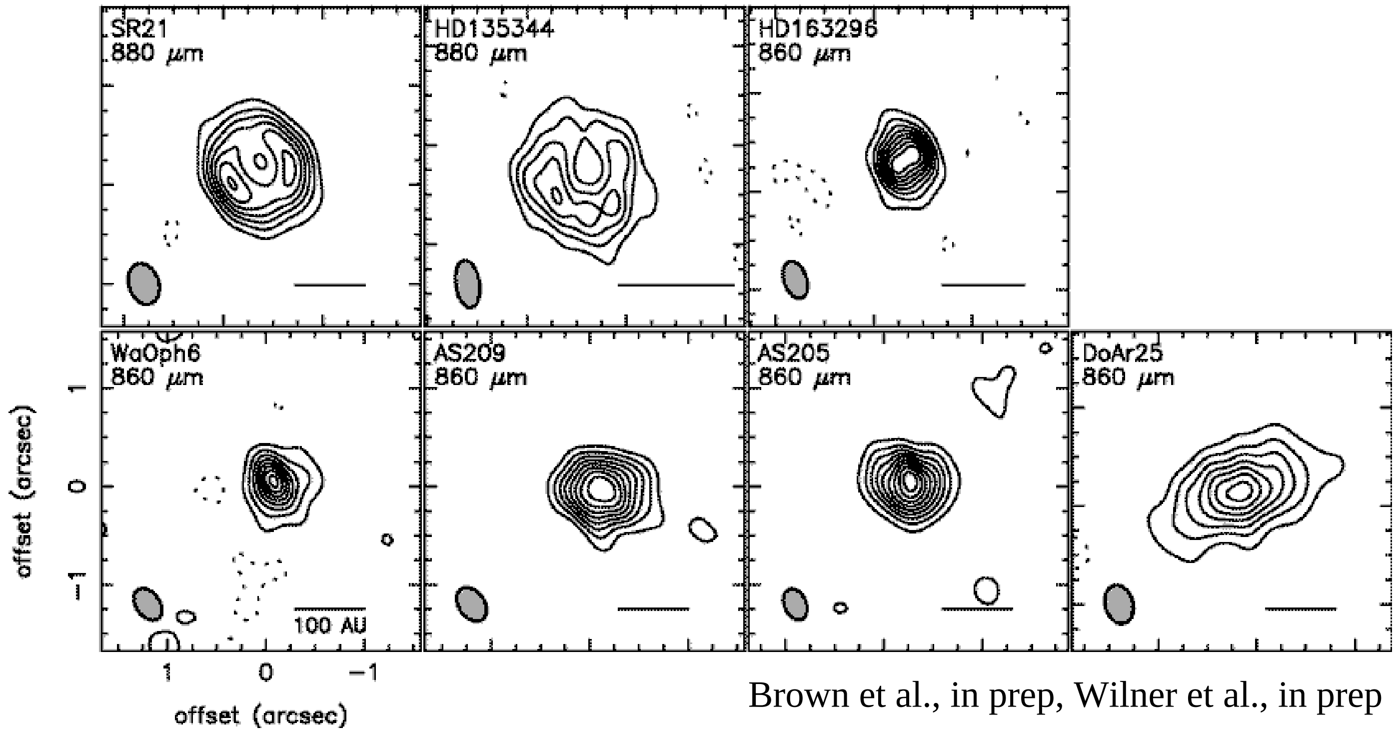
Imaging Survey of 24 Disks

- comparison with viscous accretion models, $\nu = \alpha c_s H$



α=0.001
α=0.01
α=0.1

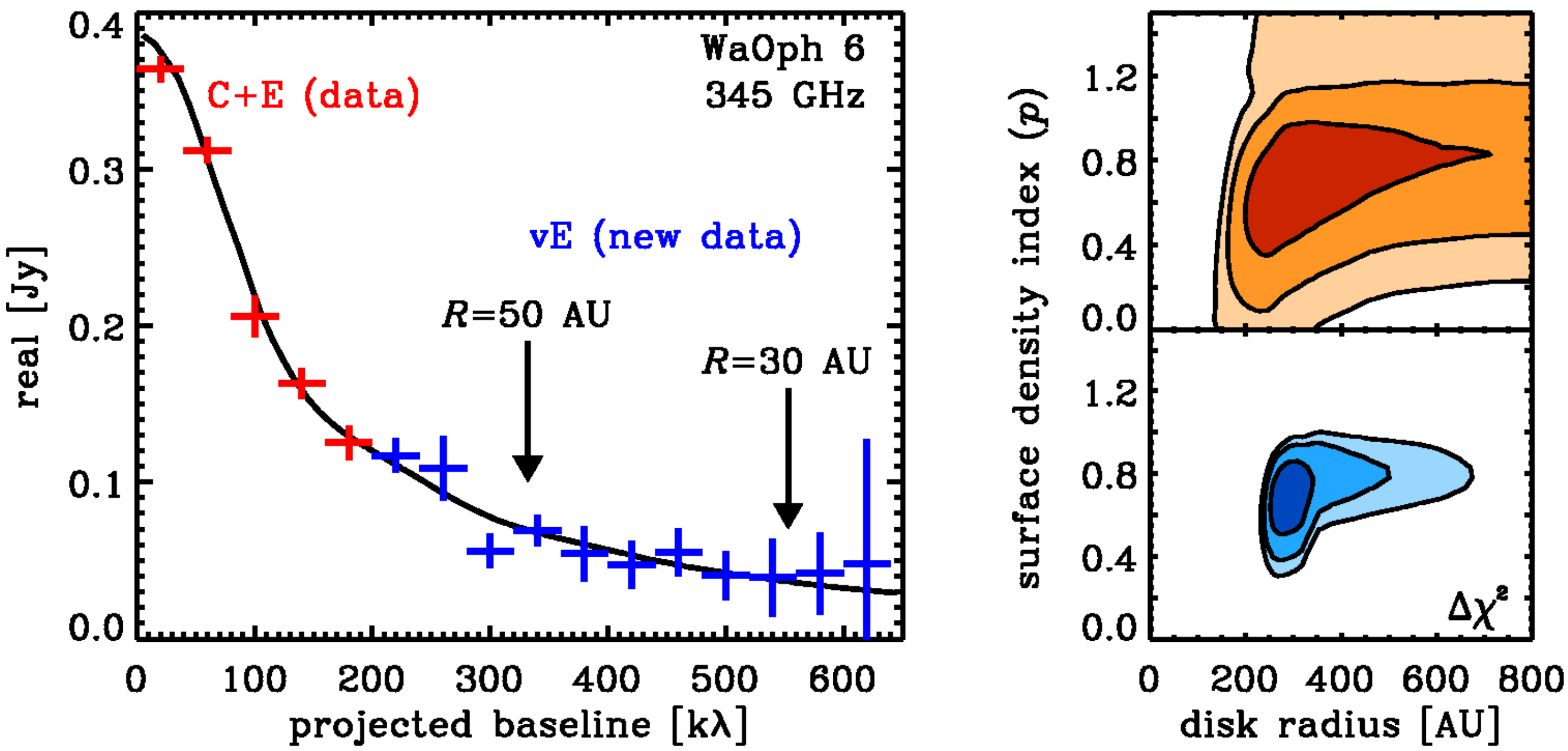
Structure at Higher Resolution



Brown et al., in prep, Wilner et al., in prep

- Starting to resolve sample of (mostly southern) disks at Solar System scales, 0.2" ~ 30 AU
- remarkable variety

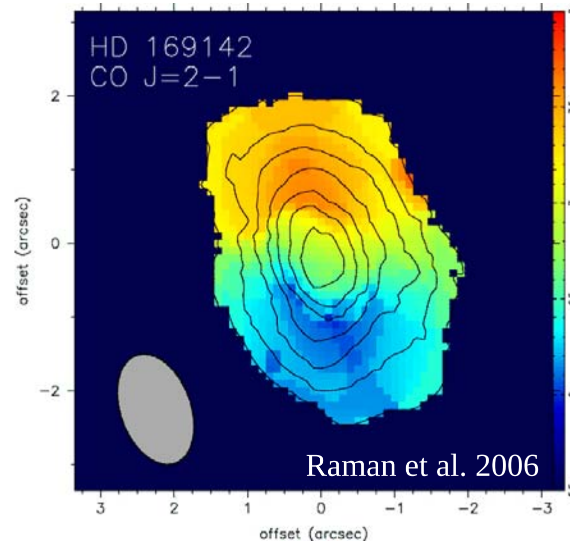
Structure at Higher Resolution

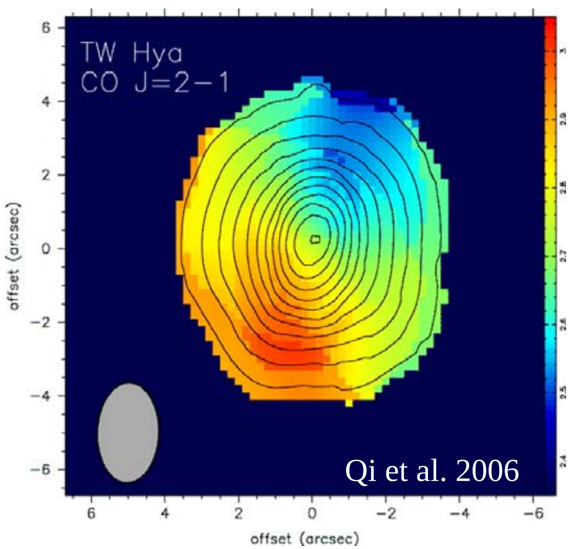


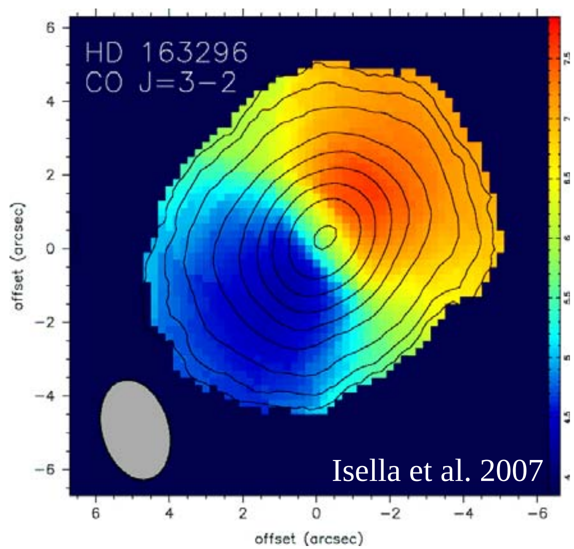
- Dramatically improved constraints with longer baselines

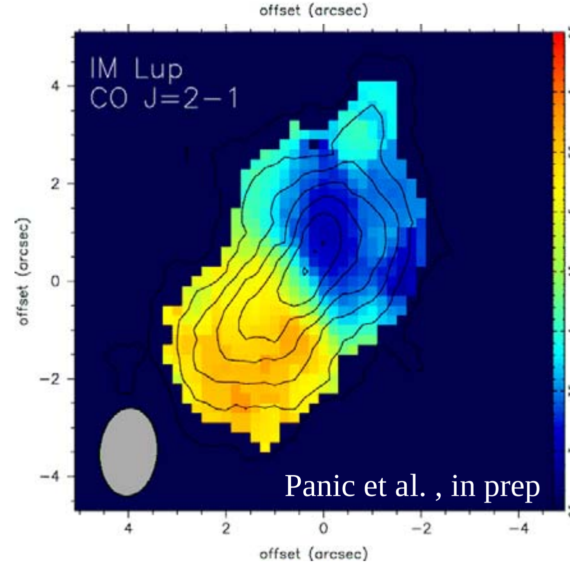
Spectral Line Observations

- CO, most abundant gas tracer of H_2
- disk kinematics, $R > 10^6$
  - Keplerian: $v(r/D) = (GM_*/r)^{0.5} \sin i$
  - constrain turbulence
- multiple lines probe n(r,z), T(r,z), excitation, abundance



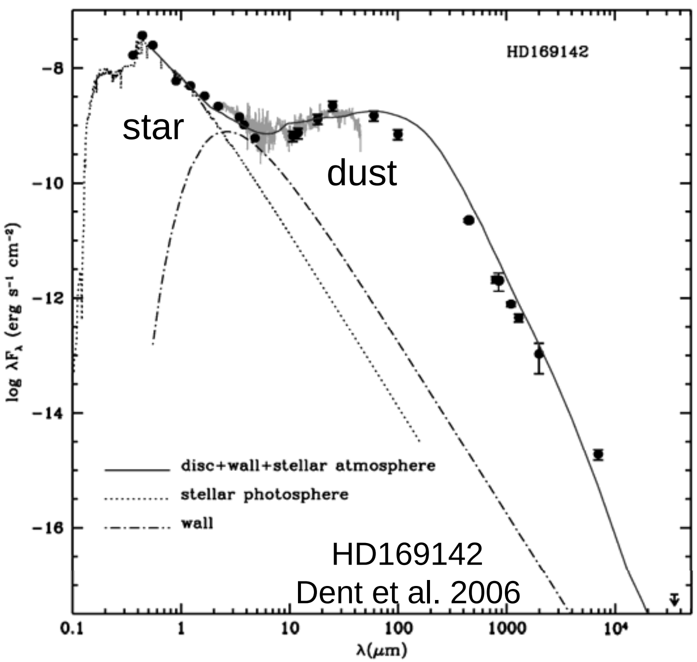


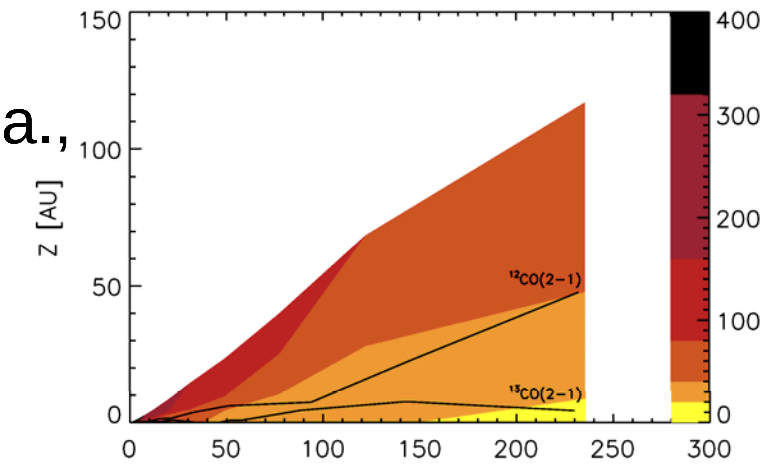


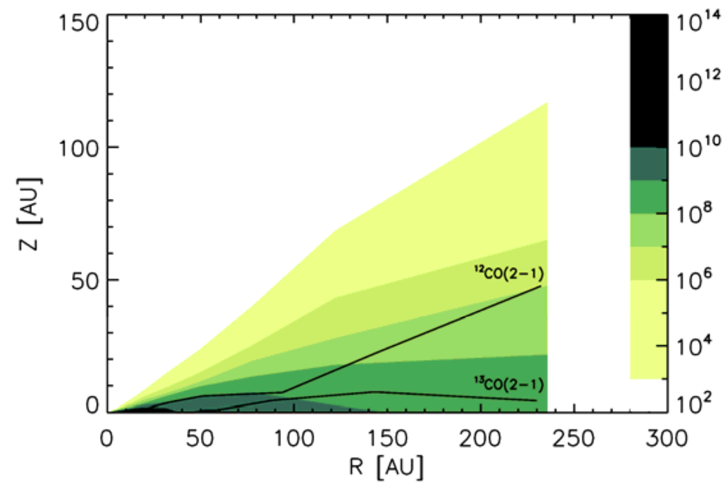


Spectral Line Modeling

- start with physical model f(r,z) that fits (dust) SED
- analyze with 2D rad. transfer and χ^2 minimization: R_{out}, i, p.a., M_*, δv_{turb}, X(CO), …



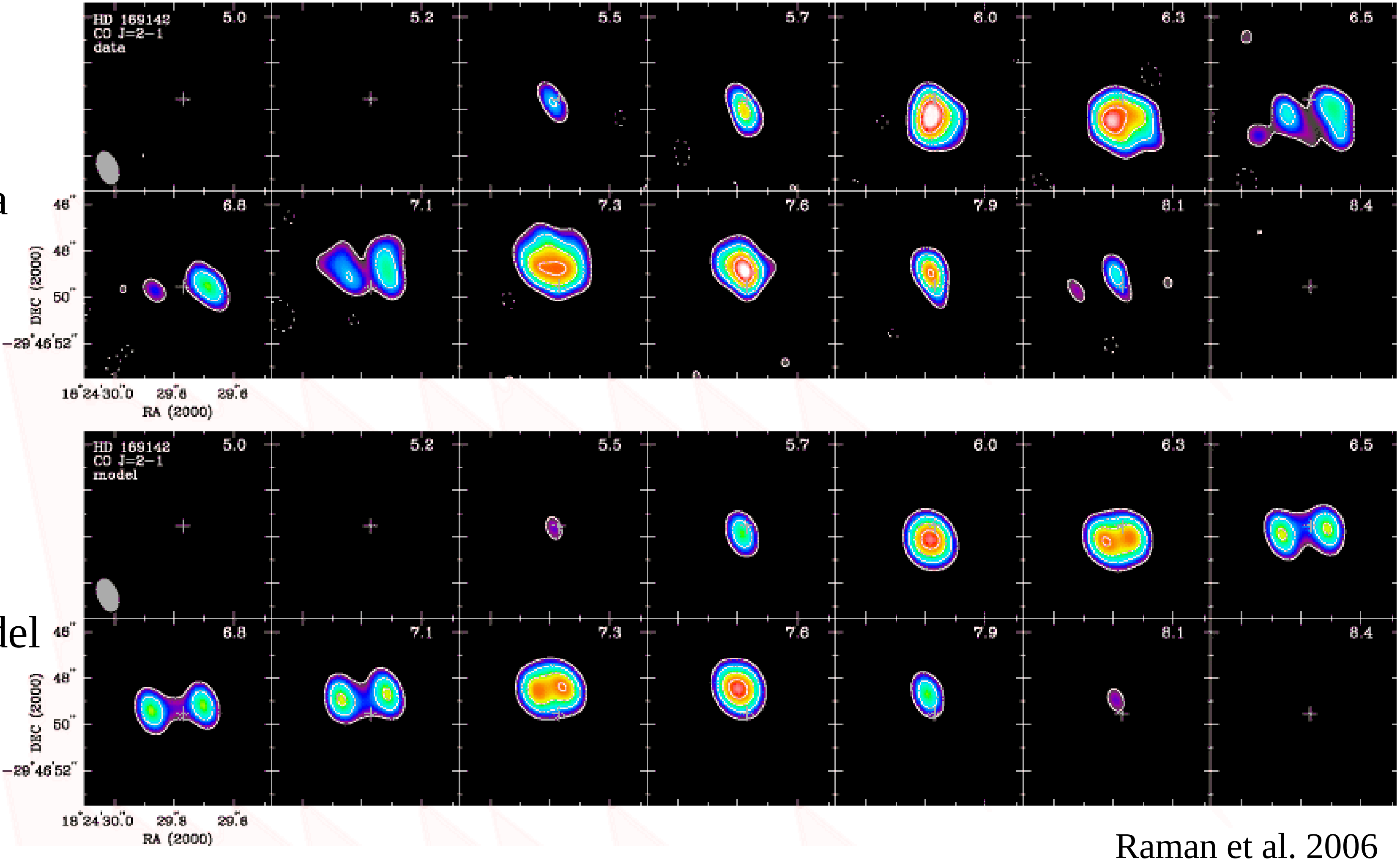




Example: HD 169142

Data

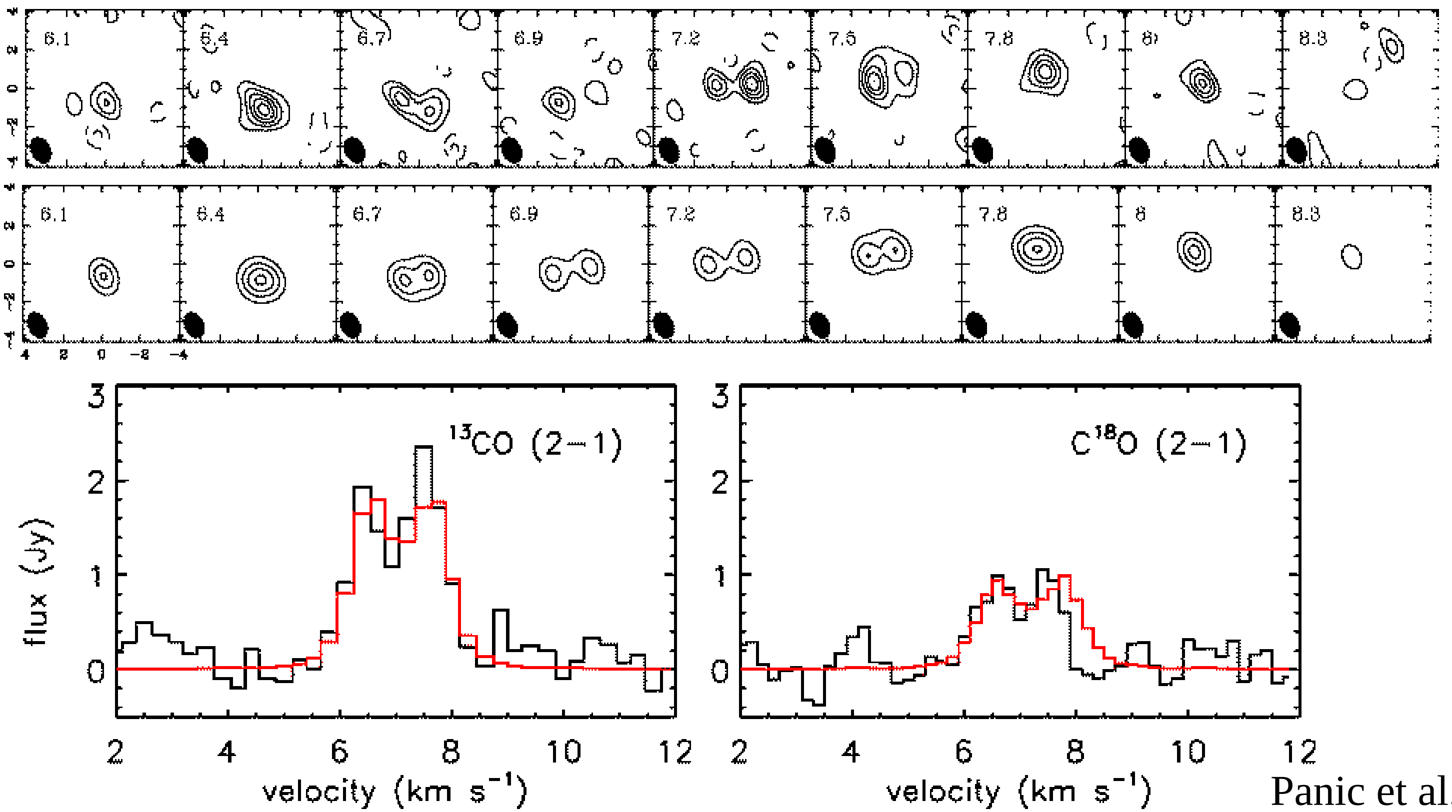
Model



Raman et al. 2006

Example: HD 169142

- opacity range of ^{12}CO, ^{13}CO, $C^{18}O$ J=2-1 lines provide vertical resolution on ~7-20 AU scales

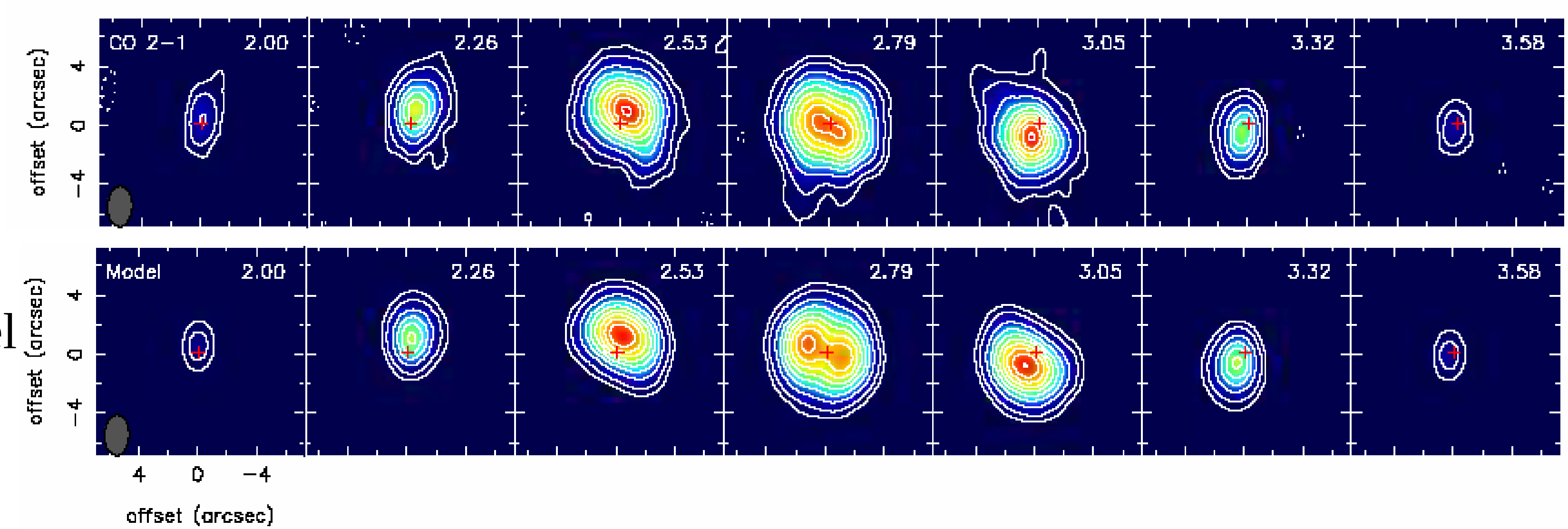


Panic et al., in prep

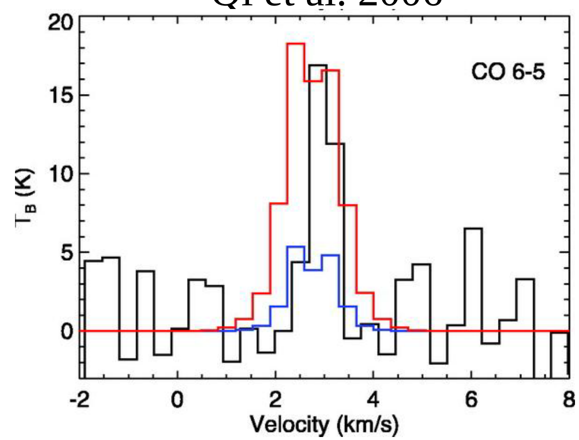
Example: TW Hya

Data

Model



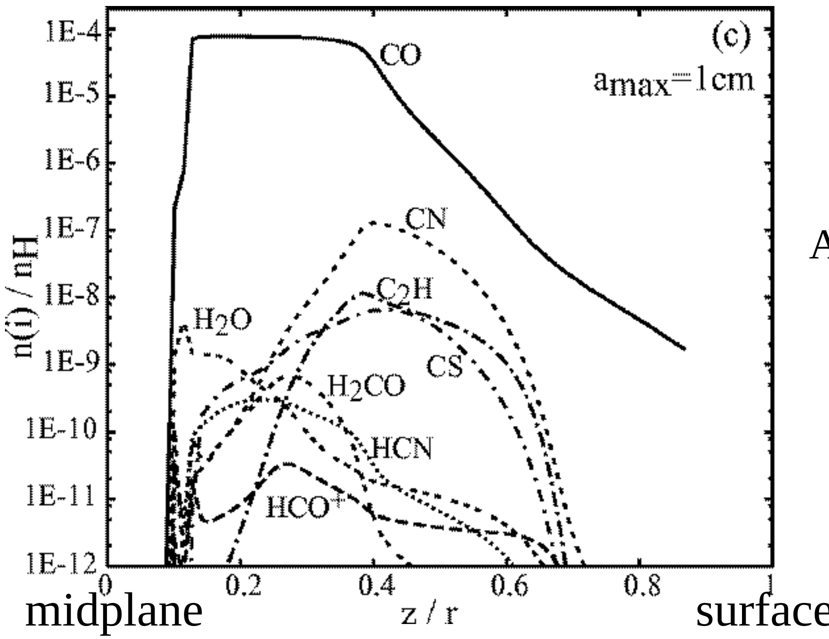
Qi et al. 2006



- unique at 56 pc, 2.5x closer
- nearly face-on viewing geometry
- detailed tests of model constructs, e.g. dust vs. gas temperature, selective photodissociation

Towards Nebular Chemistry

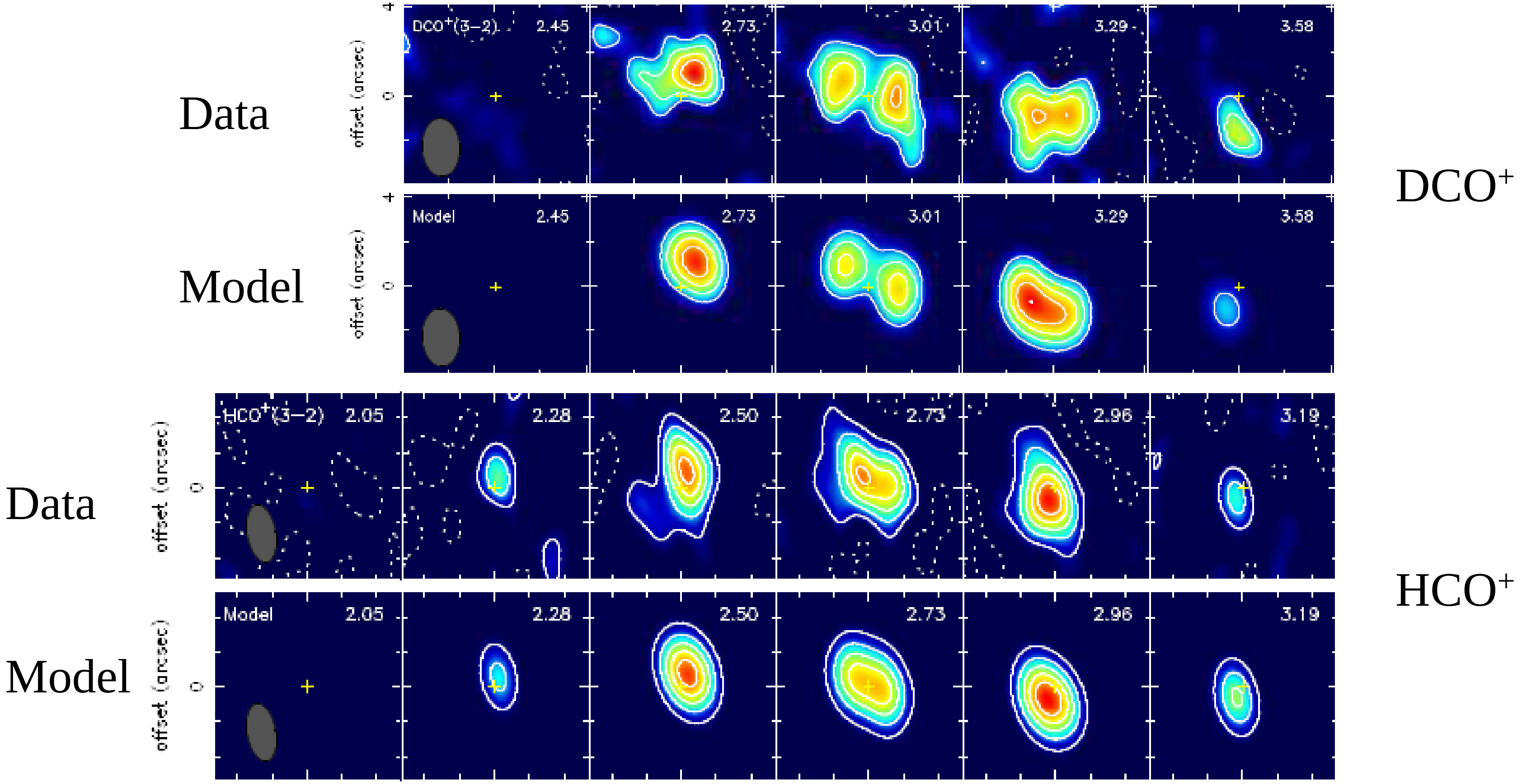
- simple species detected in a few disks, rich chemistry
  - depletions 5 to >100 x
  - photochemistry
  - ion-molecule reactions
  - deuteration
  - organics



Aikawa 2006

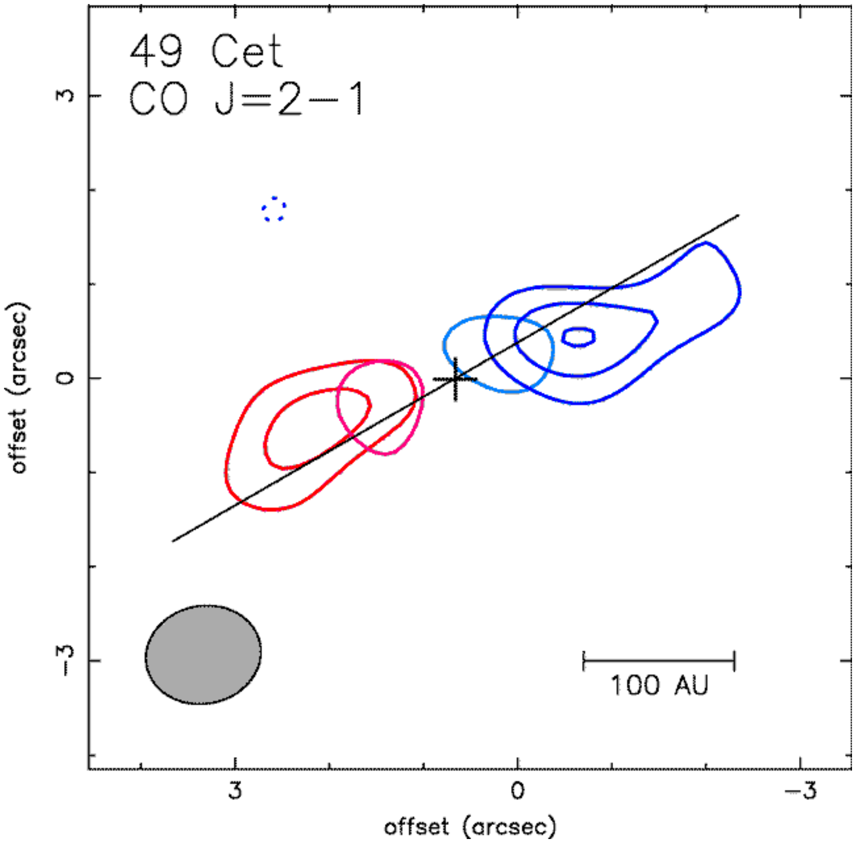
- SMA focus: TW Hya
  - CO, ^{13}CO, $C^{18}O$
  - HCN, CN, DCN
  - HCO+, $H^{13}CO+$, DCO+
  - H_2CO, N_2H^+, C_2H
  - HDO, H_2D^+, D_2H^+, CH_3OH and CS ?

TW Hya: DCO^+ vs. HCO^+

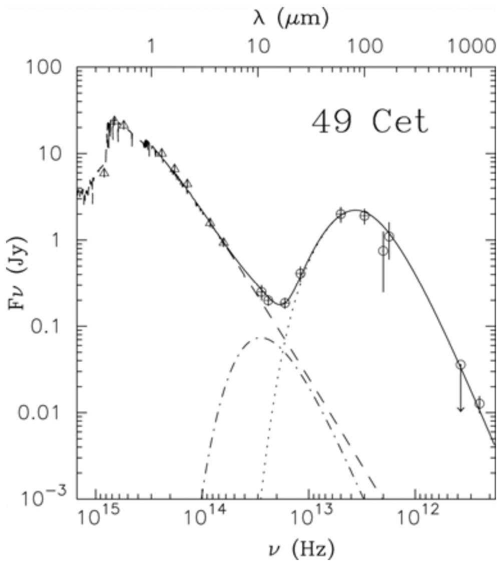


- DCO^+ abundance increases to 70 AU, doesn't follow HCO^+

49 Cet: A Transitional Gas Disk



Hughes, Wilner et al., in prep



$L_{IR}/L_{*} \sim 0.001$

$M_{dust} \sim 0.1\ M_{Earth}$

- no evidence for disk accretion, but ∴gaseous outer disk
- late stage photoevaporation?

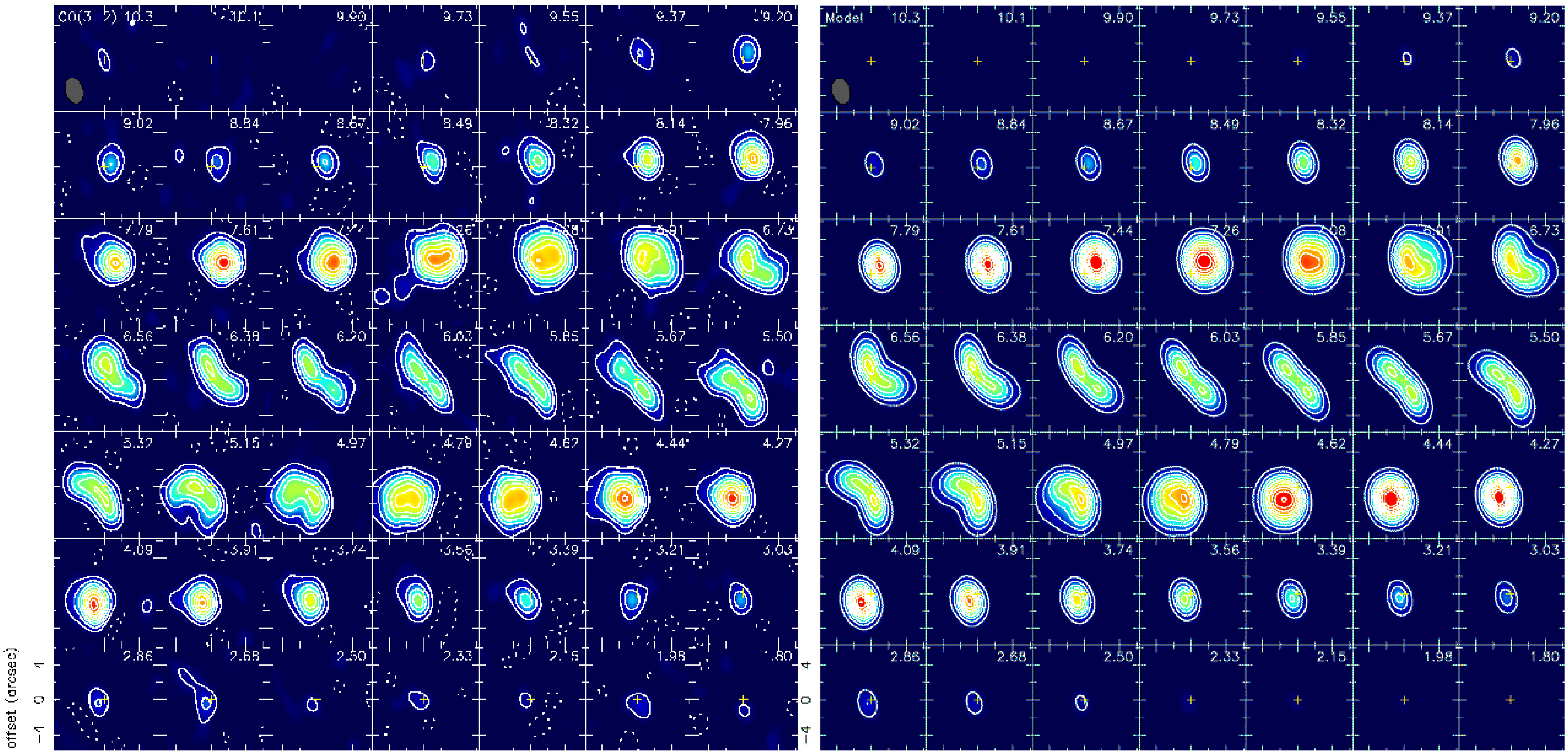
Alexander & Armitage 2007

Concluding Remarks

- SMA is ideal for protoplanetary disk studies
  - complementary approaches: surveys, case studies
- resolved submm continuum data is opening new regime for disk structure studies
- resolved line emission is showing radial and vertical abundance variations in key species
- close ties to accretion disk modelers and interstellar chemists, provide framework for physical interpretation
- focus on southern sky, prepare for ALMA

END

Example: HD 163296



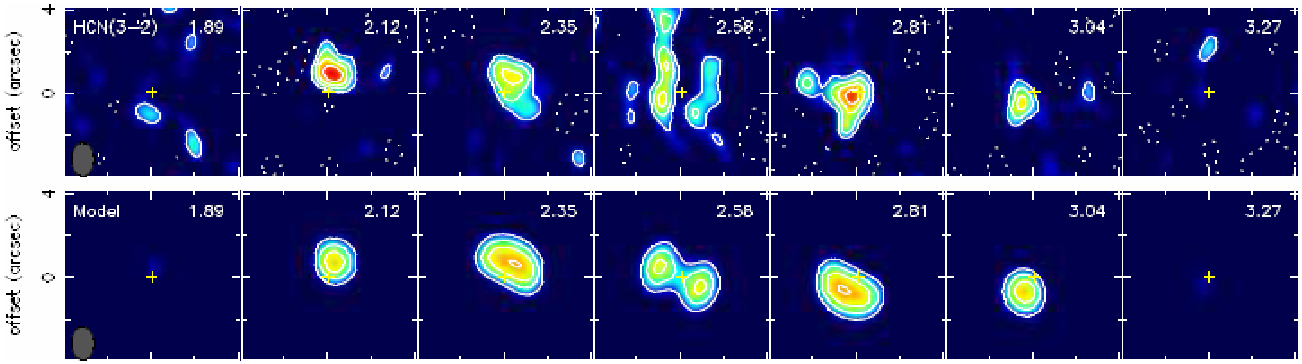
This is a Sample Slide

- The font is Arial (40 pt at top, 28 pt here)
- The slide master contains
  - the SMA Logo
  - a footer with the date and page number
- The slide background is white

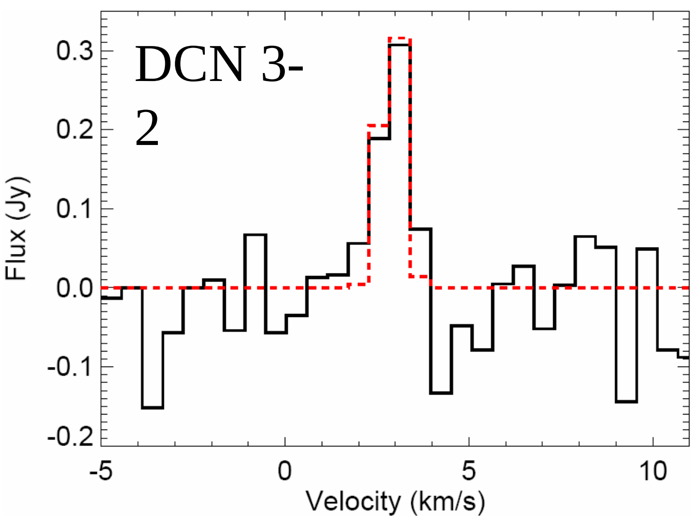
TW Hya: HCN and DCN

Data

Model

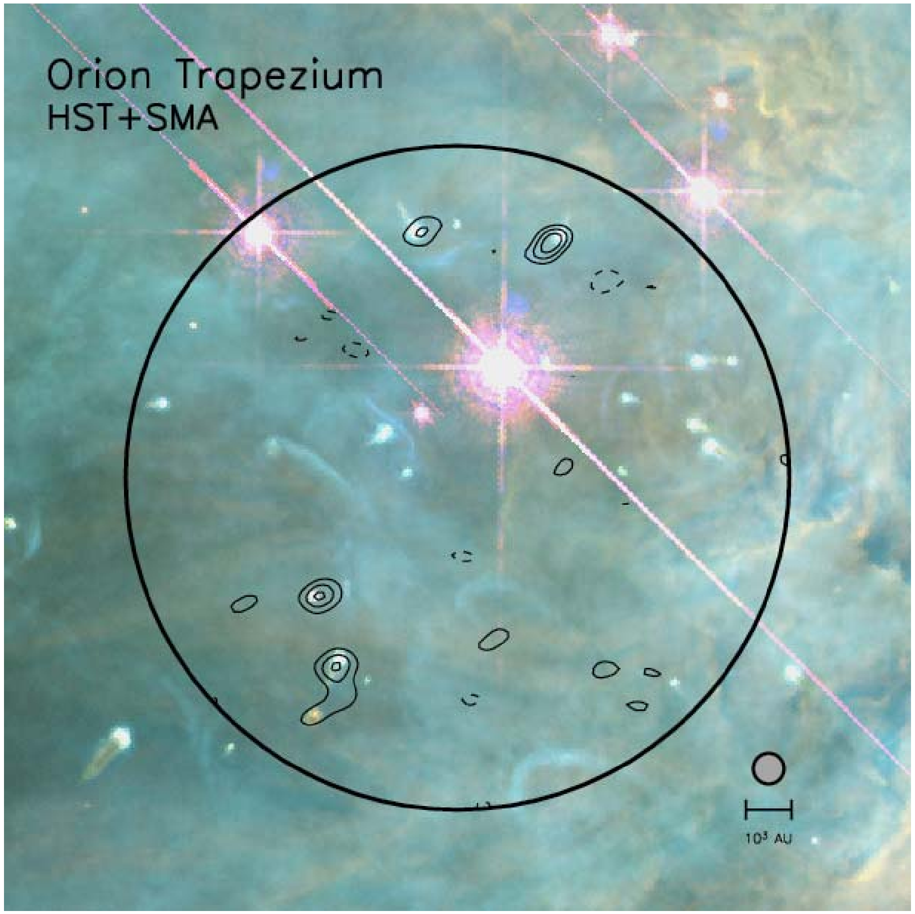


HCN 3-2



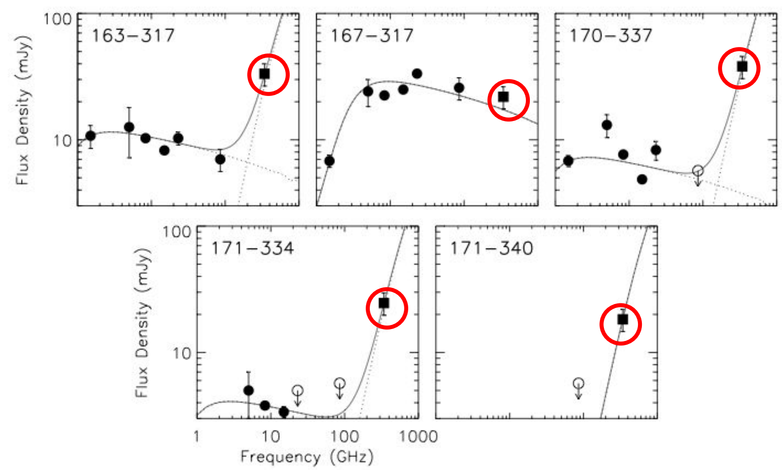
- First detection of DCN emission in a disk
- DCN/HCN ≈ 2×10^{-3} , consistent with comets

Environment: Orion "Proplyds"

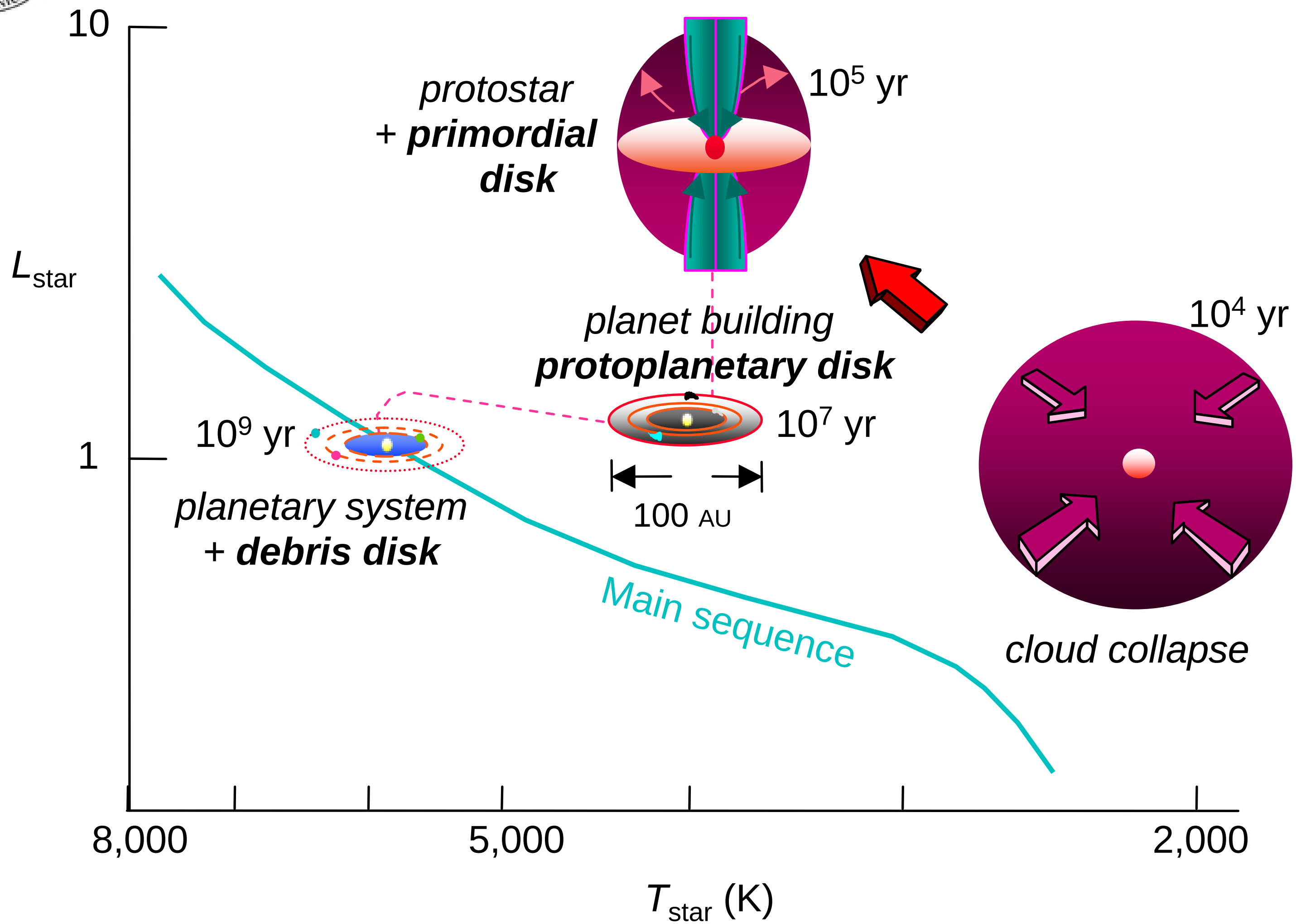


Williams, Andrews, Wilner 2005

- clusters are the common star formation environment
- proplyds ionized by θ^1 Ori C
- SMA observations
  - 4 disks, M > 0.01 $M_\odot$
  - 18 limits, <M> ~0.001 $M_\odot$
- are proplyds truncated?

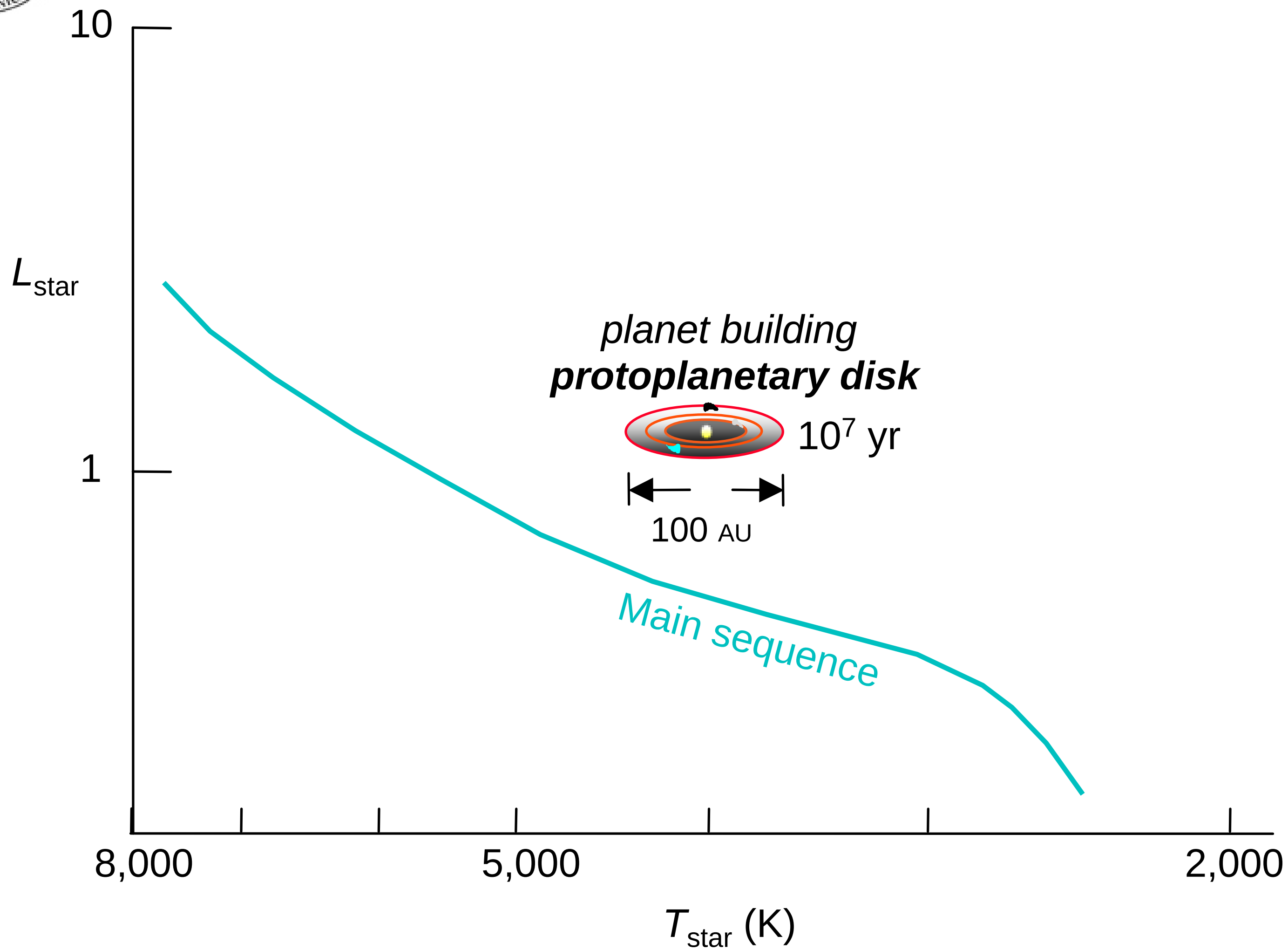


Schematic Disk Evolution



adapted from Beckwith & Sargent 1996, Nature, 383, 139

Schematic Disk Evolution



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