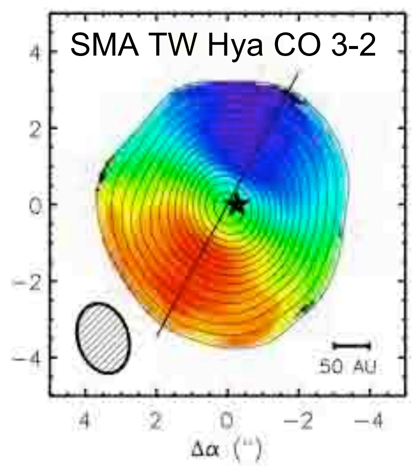
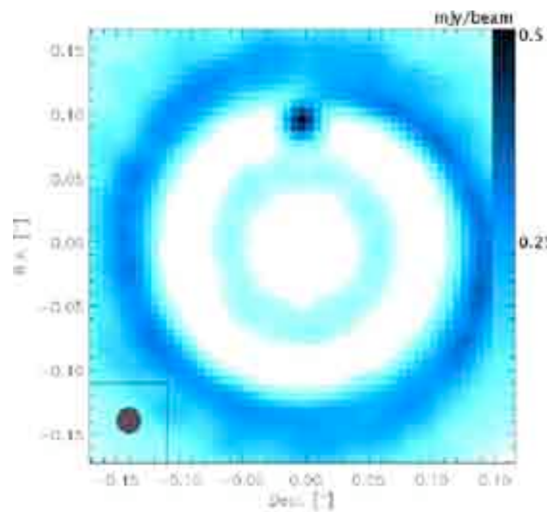
Spatially Resolved YSO Disk Studies: Present and Future

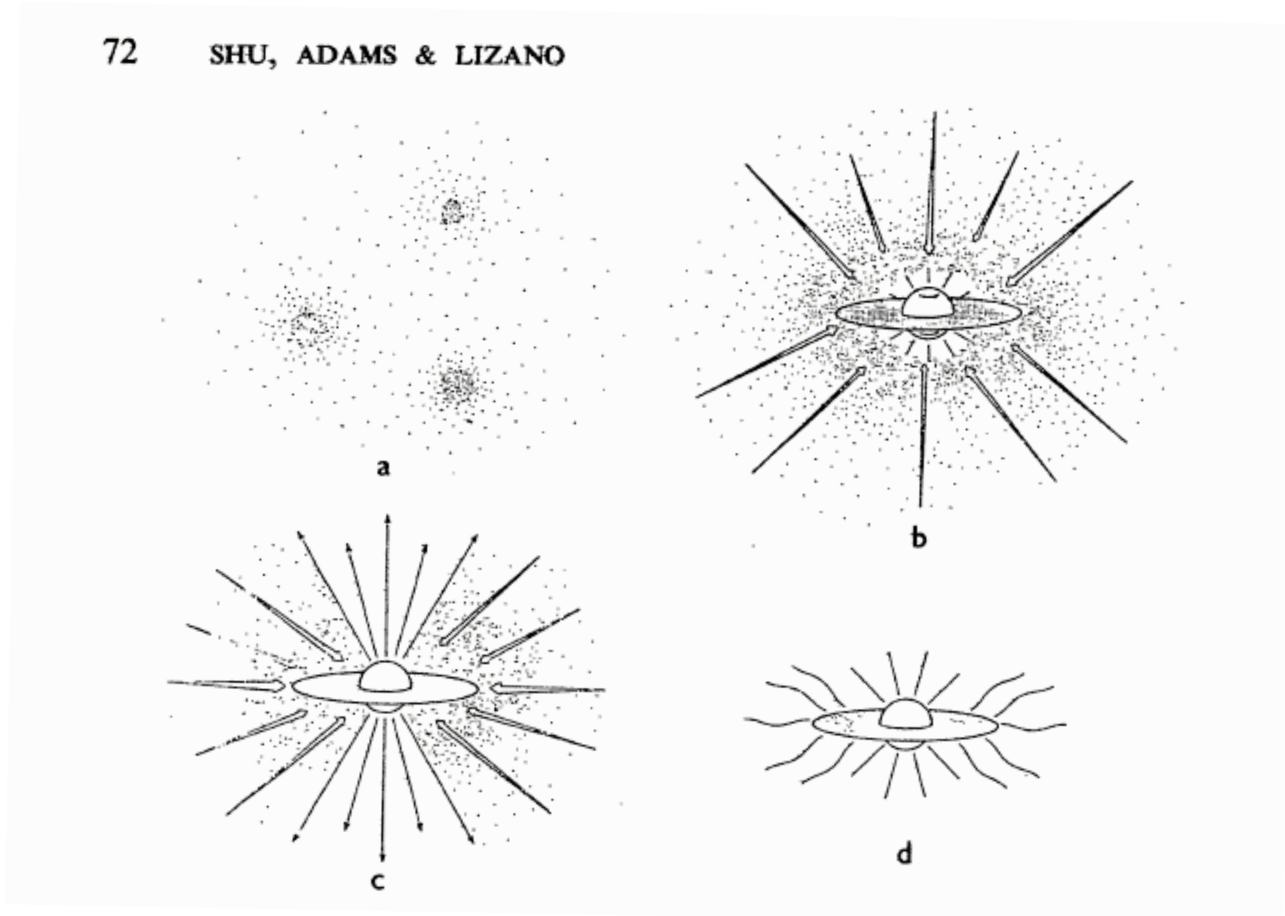
David J. Wilner





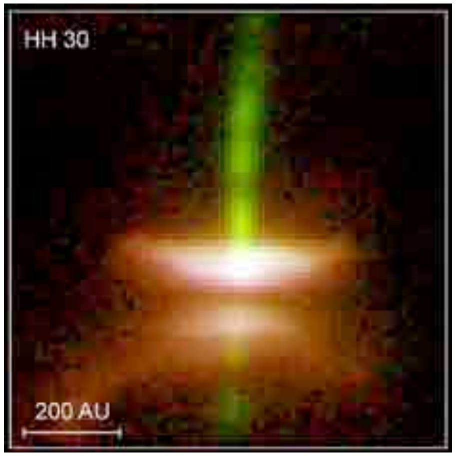
Disks around YSOs

- integral part of star formation paradigm before disks spatially resolved
  - inevitable consequence of gravitational collapse with angular momentum
  - fossil record of Solar System plane
  - preponderance of circumstantial evidence

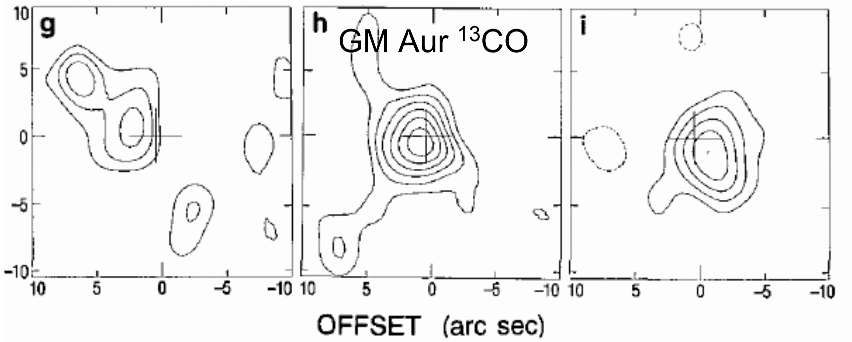


Utility of Resolved Studies

- confirm disk geometry
- break parameter degeneracies
- break model degeneracies
- insights into disk physics
- constrain disk properties
  - orientation, inclination
  - structure and kinematics: n,T, v… f(r,z,ϕ)
  - transitions: inner/outer edges
- reveal new phenomena



Burrows et al. 1996
Watson & Stapelfeldt 2004, 2007



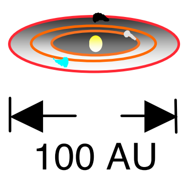
Koerner et al. 1993

Observational Challenges

- focus on nearby Class II objects
  - 100's at 125 - 200 pc, and a few closer
  - ages 1-5 Myr, low luminosities ($< 10^2 L_\odot$), low $M_* < 2.5 M_\odot$
  - optically revealed, no/little envelope

- bulk of YSO disk mass is cold (and dark) H_2
  - dust: thermal emission, scattered light
  - gas: trace species, subject to excitation and chemistry

- Solar System size scales
  - not so easy to image



100 AU ↔ 0.7 arcsec

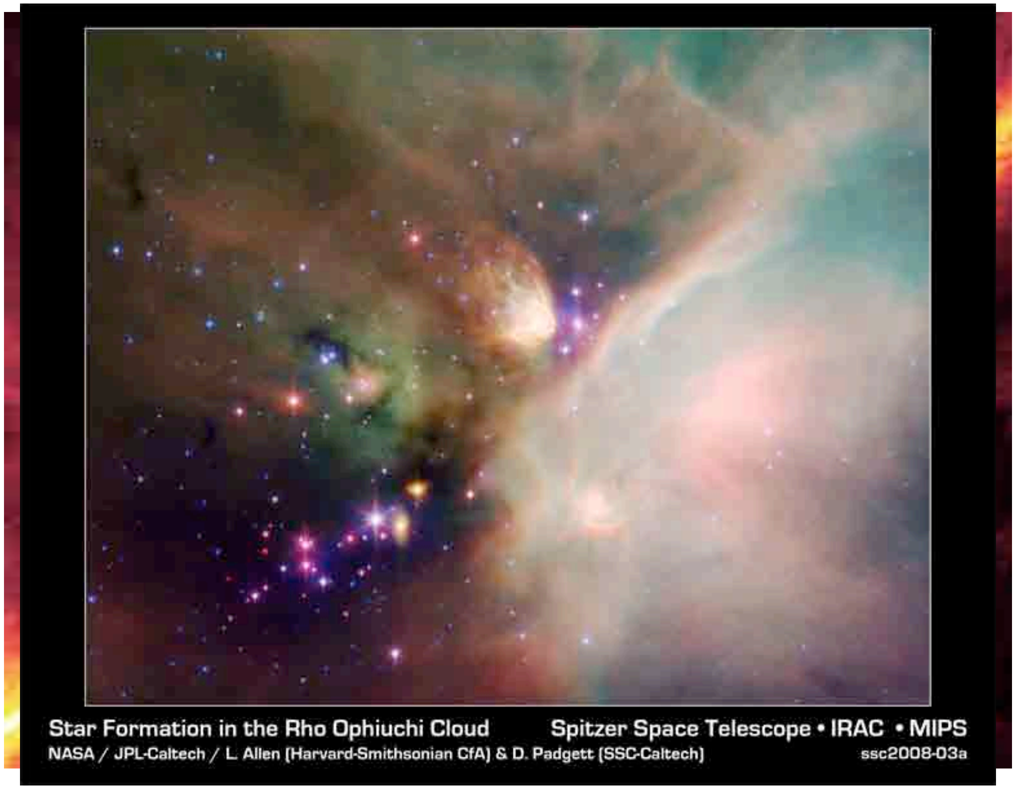
1 AU ↔ 7 milliarcsec

Spitzer Space Telescope

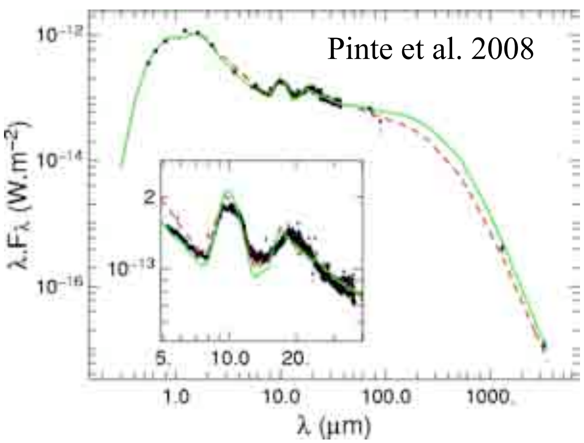
- unprecedented sensitivity
  - 3.6 to 24/70/160 μm photometry (IRAC/MIPS)
  - 5 to 40 μm R ~10^2 spectroscopy (IRS)

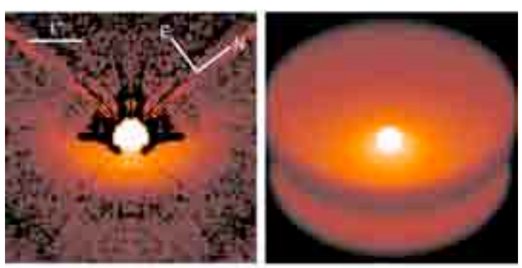
- (nearly) complete census of YSOs with circumstellar dust in nearby regions

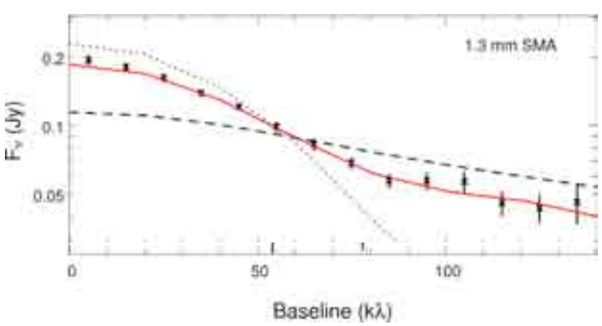
- but… 85 cm telescope
  - diffraction limit > 1 arcsec
  - disks not spatially resolved



Flux vs. Disk Radius

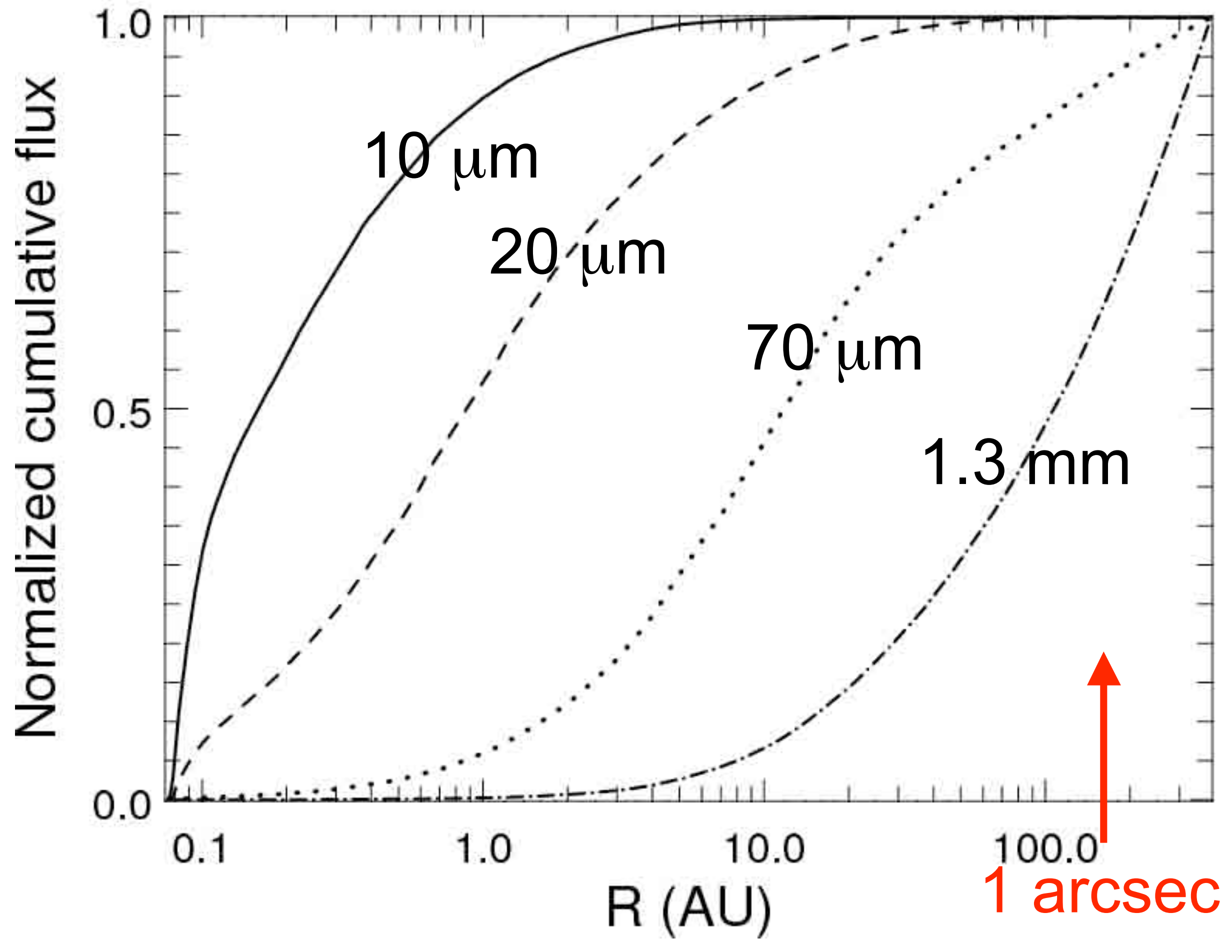






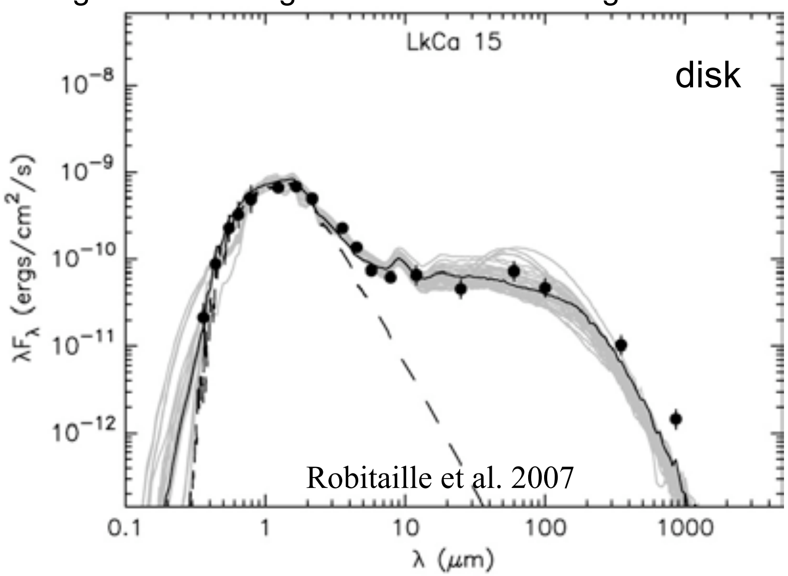
IM Lup

Poster #47,#49

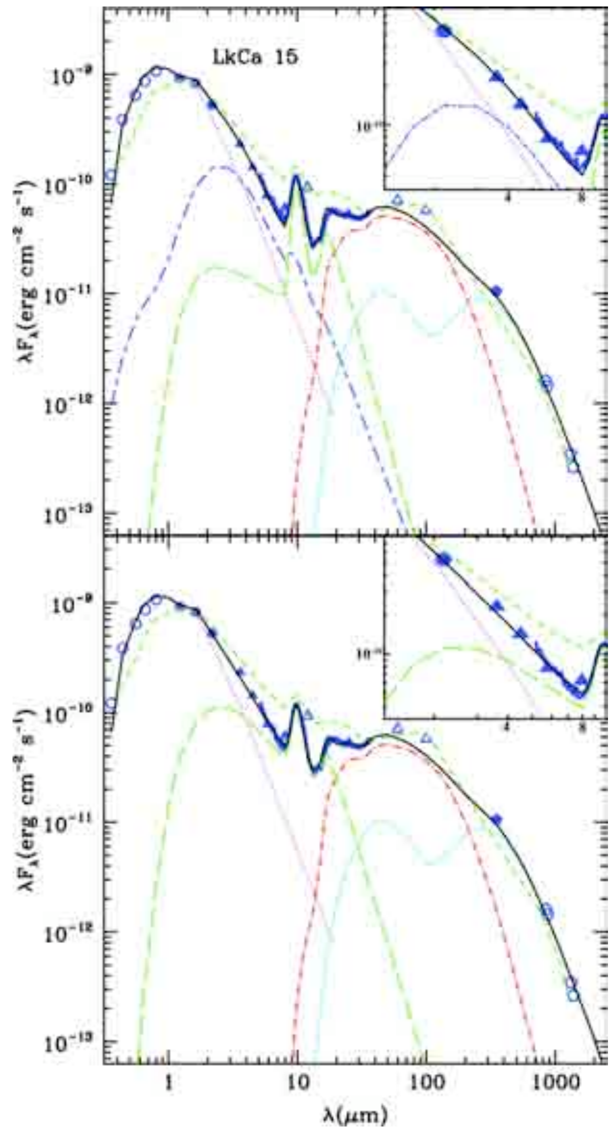


SED Models

x-ray uv optical mid/far-ir submm cm
hot gas/accr. starlight warm… cool gas & dust



- state-of-the-art
  - analytic parameterizations
  - physical models, e.g. steady accretion with radiative equilibrium, dust:gas, …



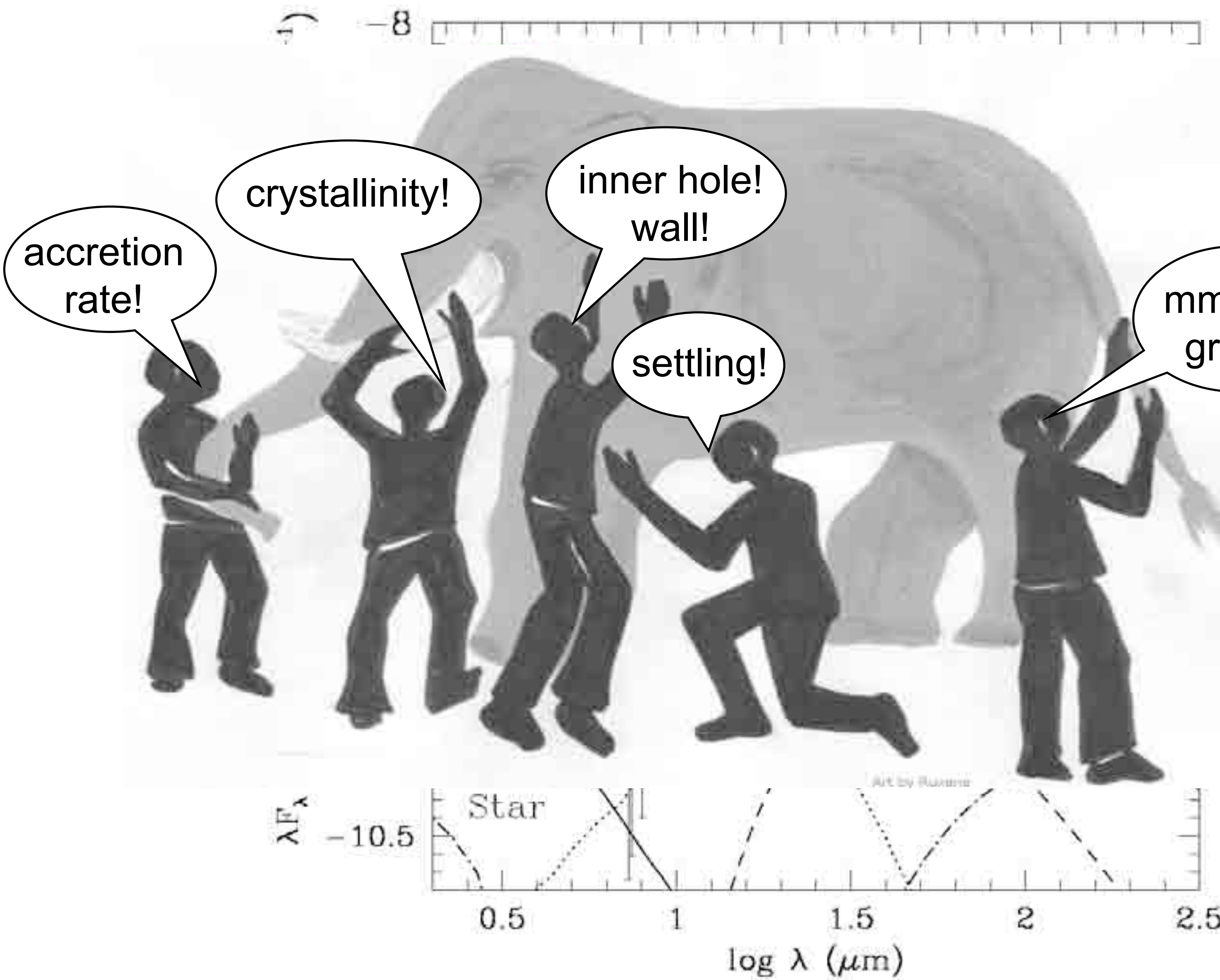
Espaillat et al. 2007
see Espaillat et al. 2008

46 AU truncation,
inner wall at 0.12 AU

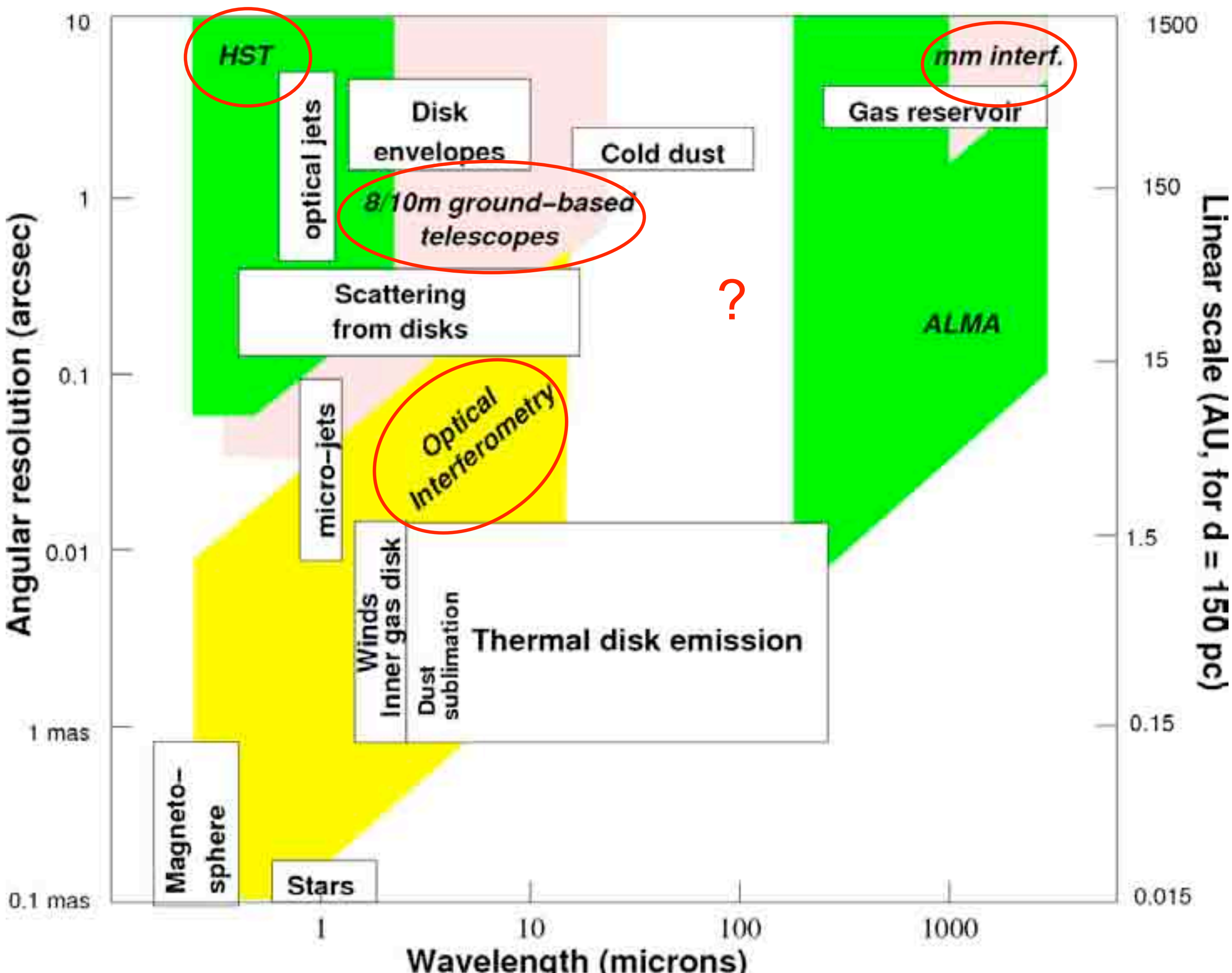
without inner wall

Poster #91

SED Models


accretion rate!
crystallinity!
inner hole! wall!
settling!
mm-size grains!
−8
−10.5
Star
λFλ
0.5
1
1.5
2
2.5
log λ (μm)

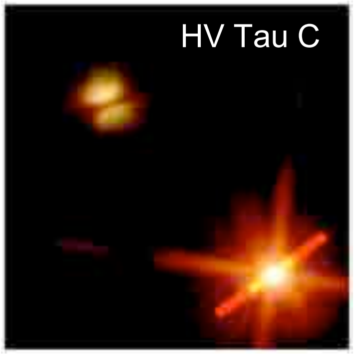
Instrumental Landscape



Millan-Gabet et al. 2007

Optical/Near-Infrared Imaging

- scattered light: contrast with star
- Hubble Space Telescope: WFPC2/NICMOS/STIS/ACS
  - 0.05 arcsec resolution, in to r ~0.3 arcsec
  - 0.5 to 2 μm colors
- visible central stars
  - psf stability, coronagraphy
- edge-on systems
  - natural coronagraph
- “proplyd” shadows
  - against nebular background



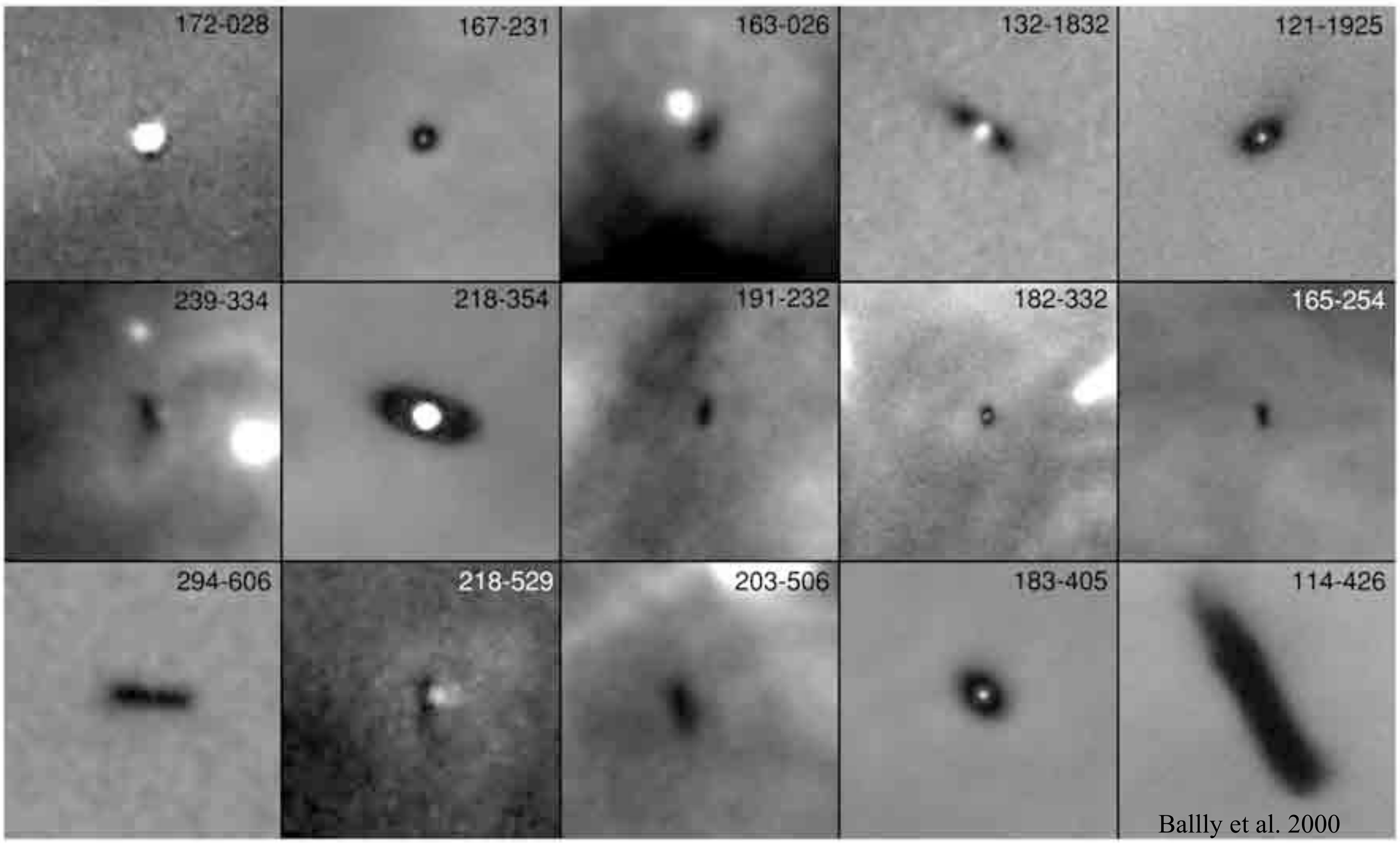
Stapelfeldt et al. 2003

Schneider et al. 2003

Throop et al. 2001

Orion "Proplyds"

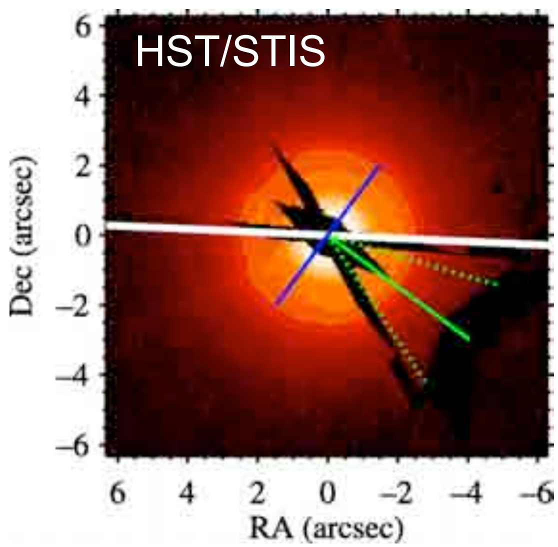
- diversity of disk sizes, r < 50 to > 500 AU



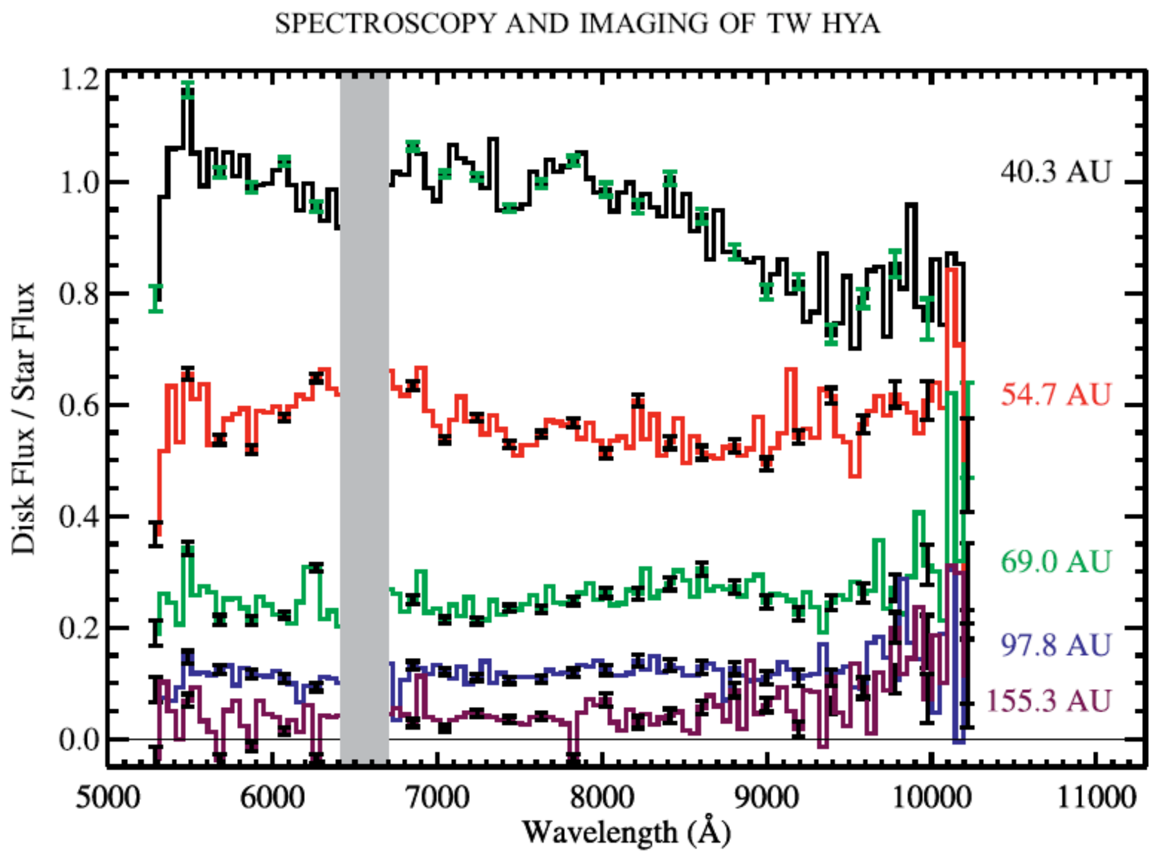
Ballly et al. 2000

Resolved Scattered Light

- TW Hya, nearly face-on T Tauri disk, unique at d ~ 50 pc
- gray colors: grain growth to size >> λ (1 μm)

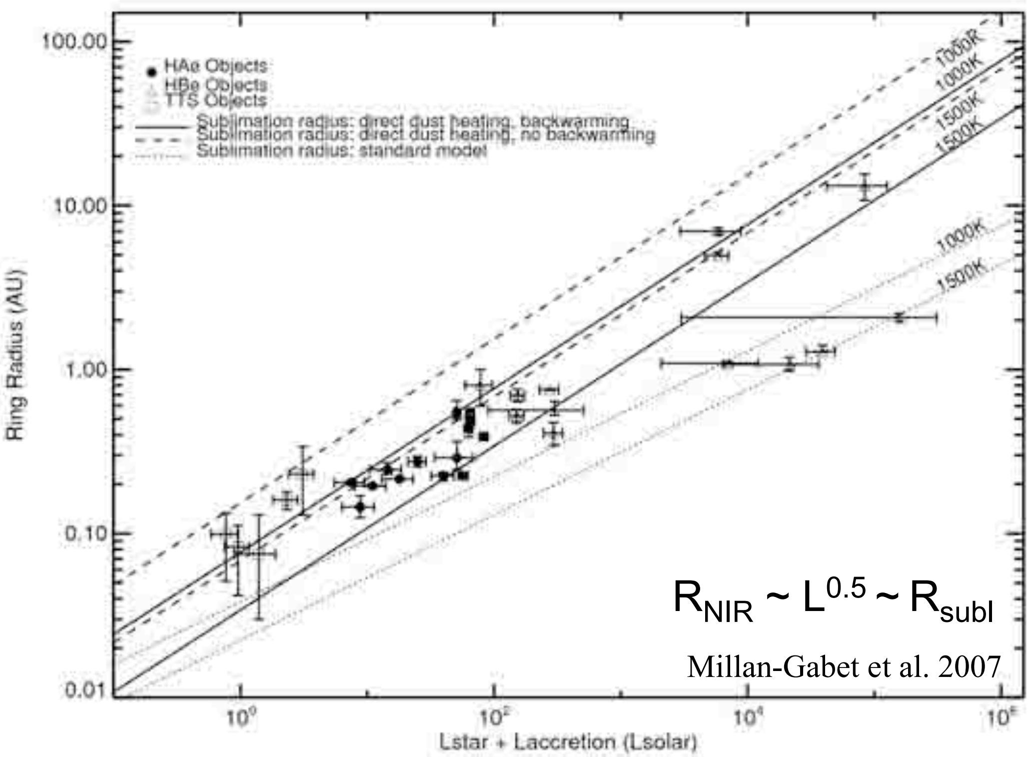


Roberge et al. 2005



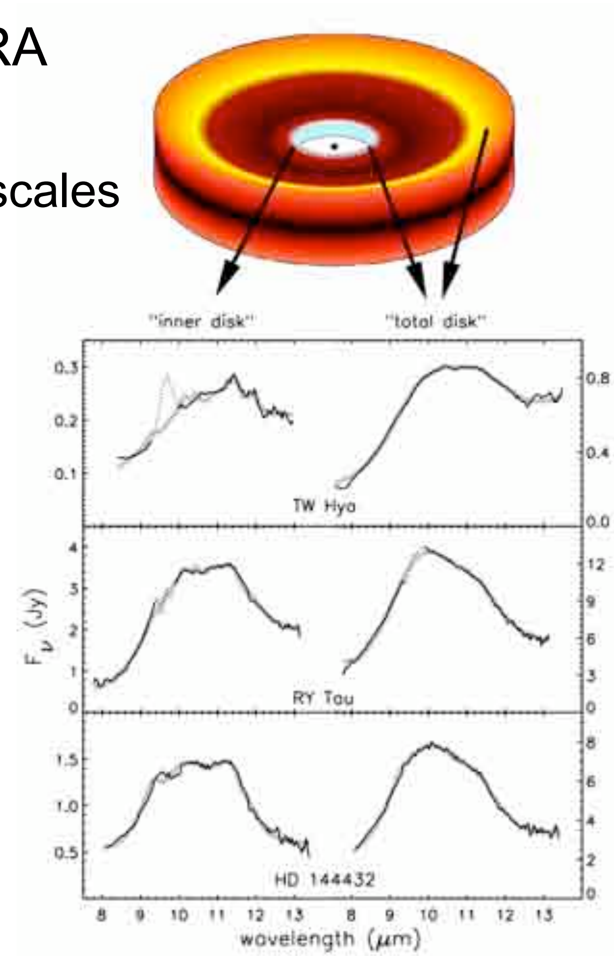
Infrared Interferometry

- 100 m baseline: 4 mas at 2 μm, 20 mas at 10 μm
- facilities: PTI, IOTA, Keck, VLTI, CHARA
  - few simultaneous visibilities
  - model fits, separate flux from different scales
  - capabilities improving rapidly



$R_{NIR} \sim L^{0.5} \sim R_{subl}$

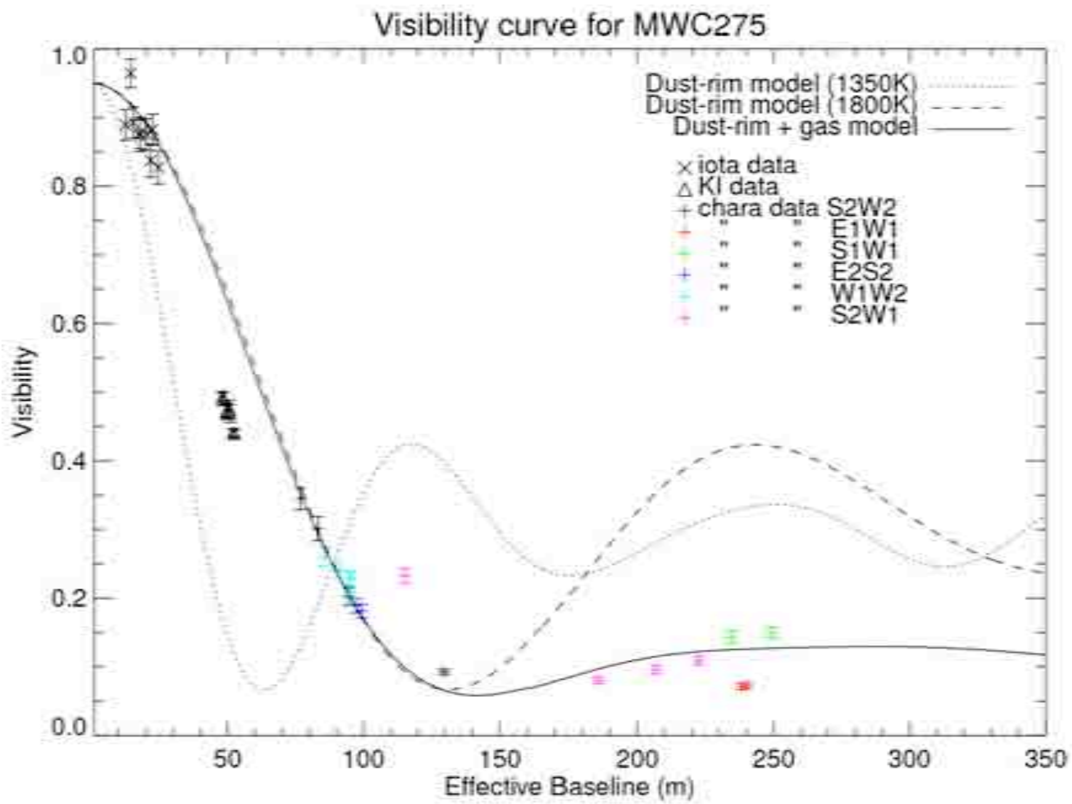
Millan-Gabet et al. 2007

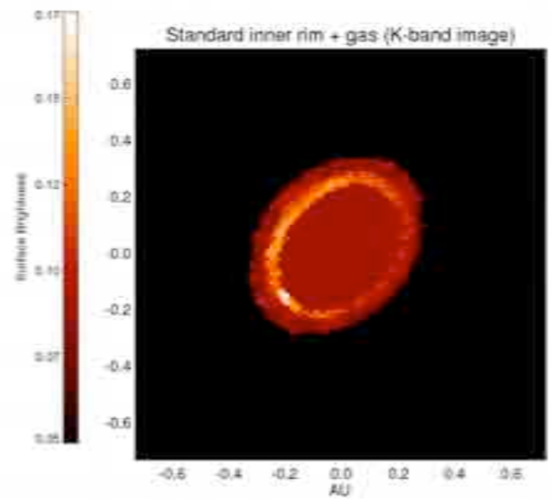


inner few AU vs. total disk

HD163296 Inner Edge Complexity

- simple dust rim fails to fit SED and resolved 2 μm data
  - requires opacity source inside sublimation radius (gas)
  - also note variability



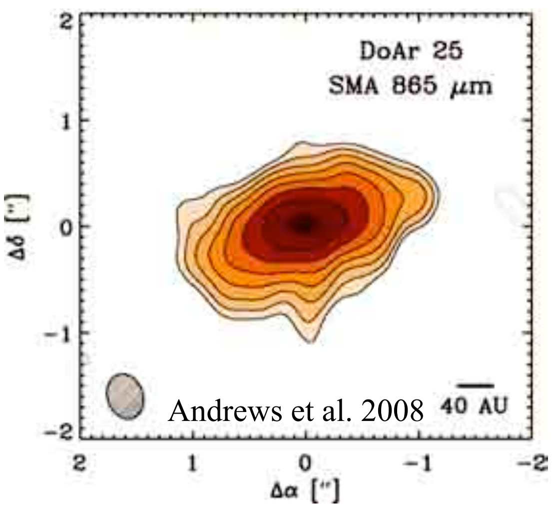


Tannirkulam et al. 2008

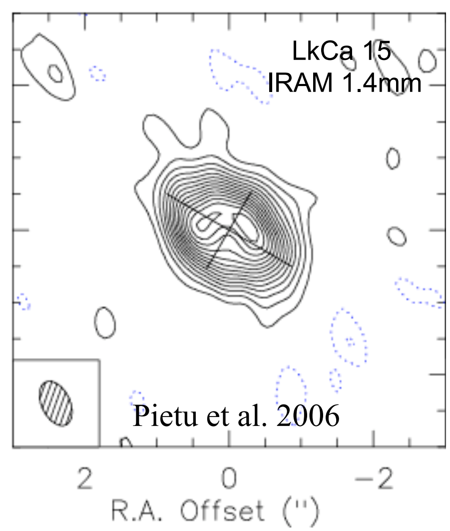
Poster #65

Millimeter Interferometry

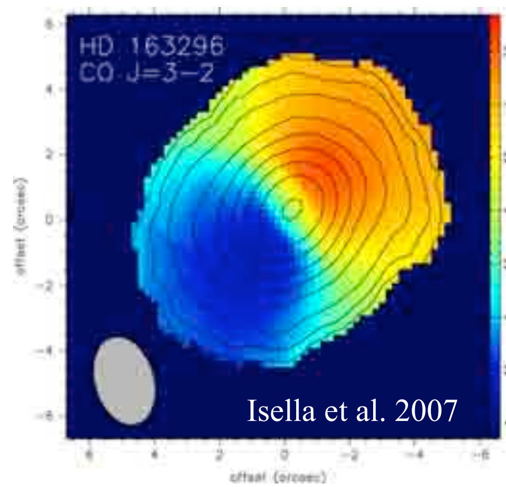
- no contrast problem with starlight
- facilities: ATCA, CARMA, IRAM PdBI, SMA, VLA
  - 450 μm to 7 mm, to 0.25 arcsec (to 0.025 arcsec at 7 mm)
- thermal dust emission: (mostly) optically thin and R-J
  - intensity $\propto B_\nu(T)(1 - e^{-\tau})\, d\Omega \approx \kappa_\nu \Sigma\, T$
- spectral lines of many molecules, heterodyne R $>10^6$



Andrews et al. 2008



Pietu et al. 2006

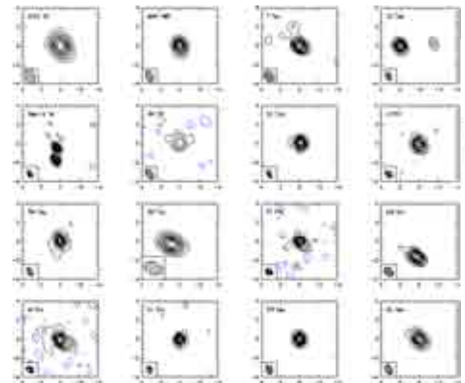


Isella et al. 2007

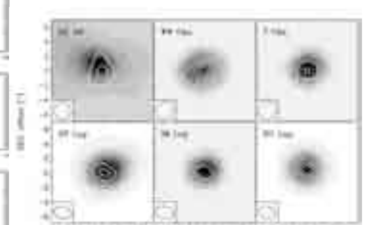
Resolved Millimeter Observations

- routine imaging >0.7 arcsec
  - about 40 disks observed and resolved so far
  - frontier < 0.3 arcsec

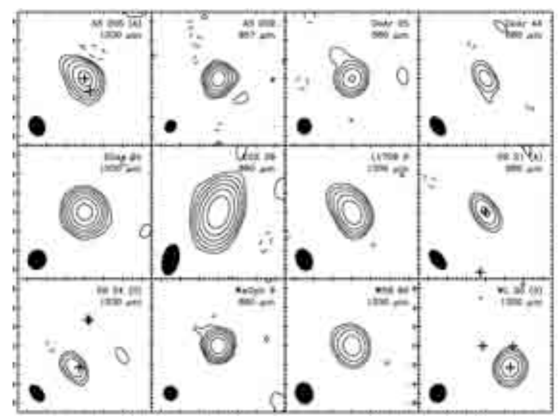
- intensity ≈ $\kappa_\nu \Sigma$ T
- access $\Sigma(r)$ “directly”
  - $\kappa_\nu(r,z)$? constant? theory/experiment/hope
  - need stellar properties
  - use full SED information
  - proper radiative transfer



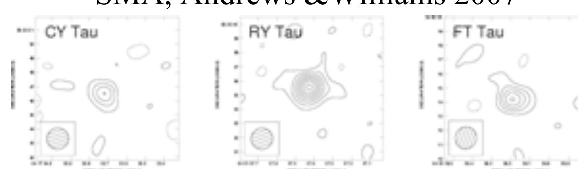
IRAM PdBI, Dutrey et al. 2001



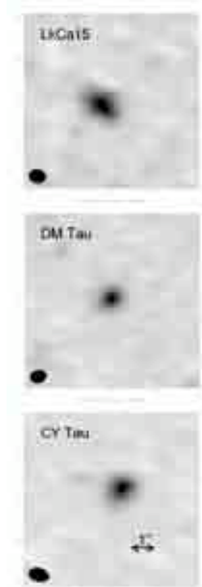
ATCA, Lommen et al. 2006



SMA, Andrews &Williams 2007



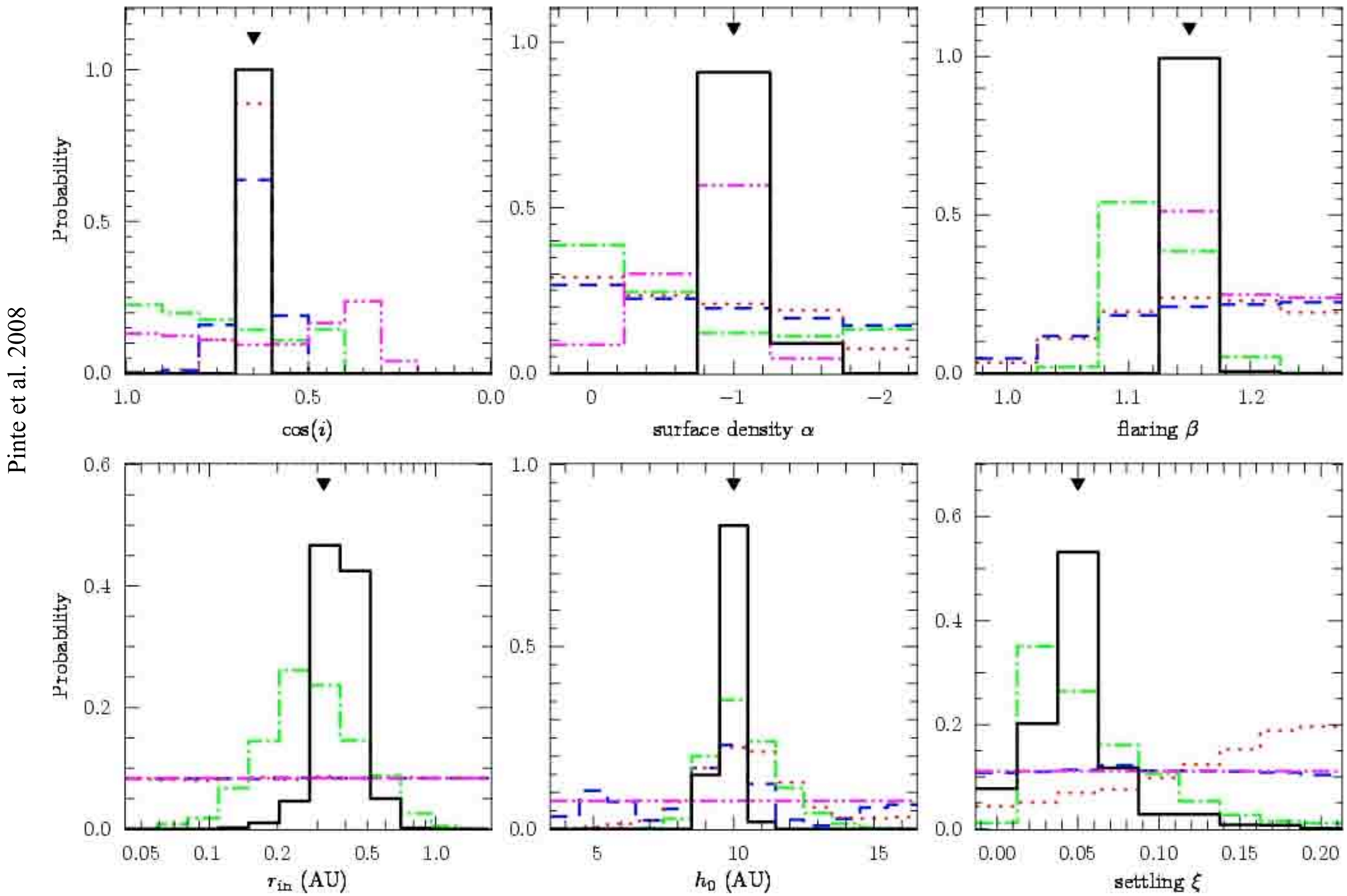
VLA, Rodmann et al. 2006



CARMA, courtesy A. Isella

IM Lup: A Bayesian View

0.6 μm scattered light 1.6 μm scattered light SED 1.3 mm visibilities all data



Surface Density Distributions

"Minimum Mass Solar Nebula"

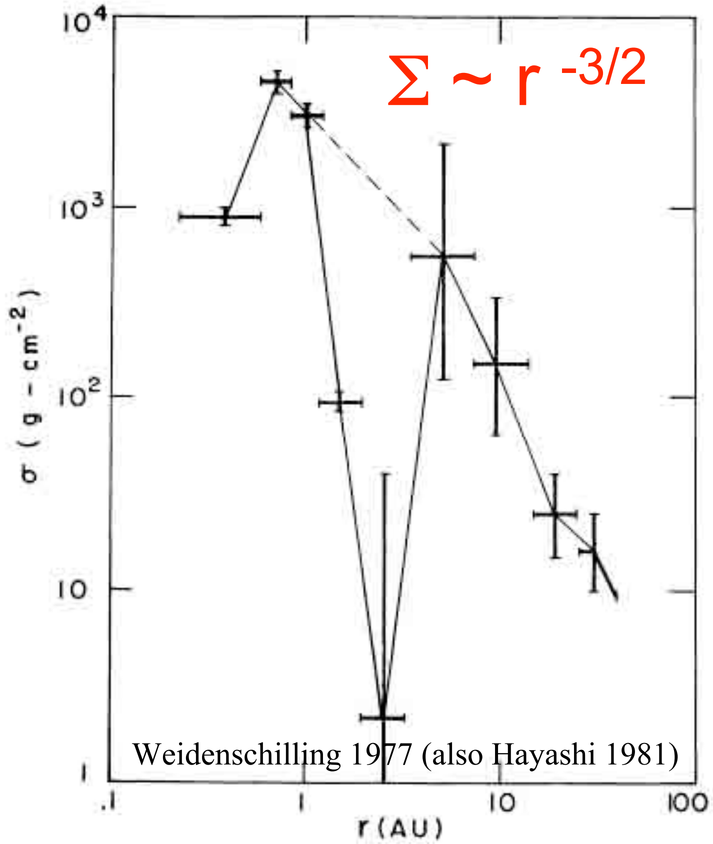
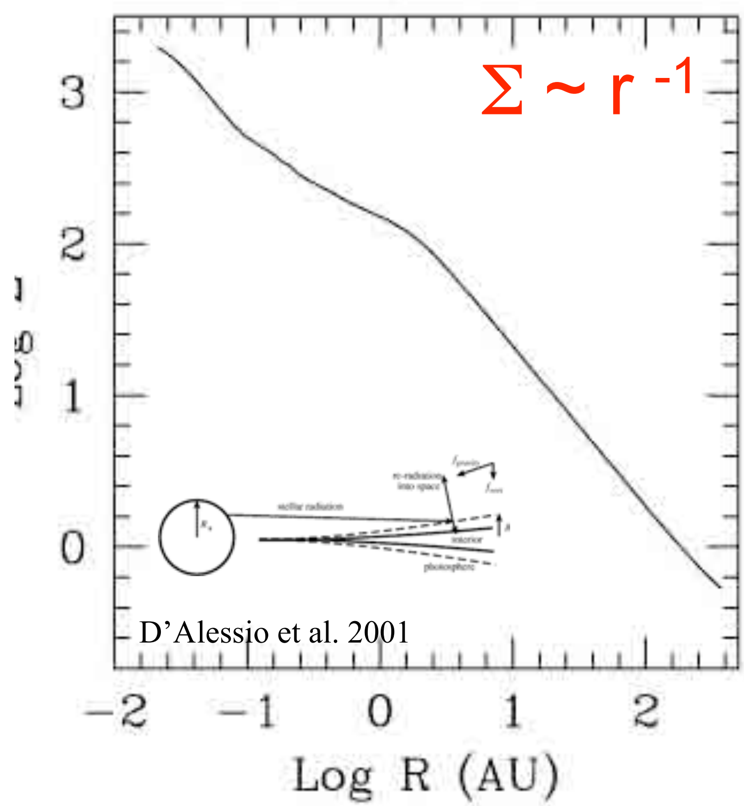


Fig. 1. Surface densities, σ, obtained by restoring the planets to solar composition and spreading the resulting masses through contiguous zones surrounding their orbits. The meaning of the 'error bars' is discussed in the text.

Steady Irradiated α Disk

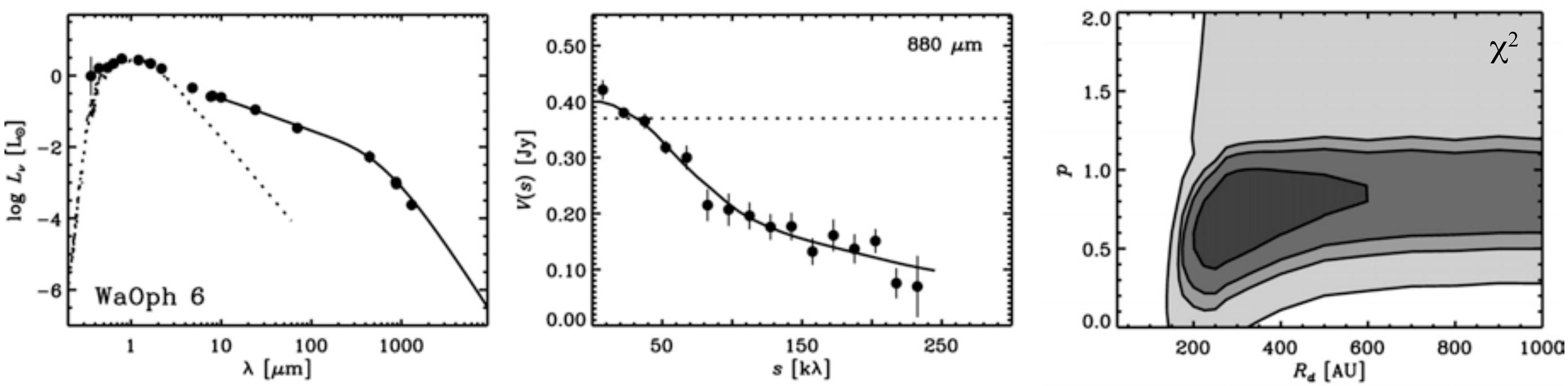


$\nu \sim \alpha c_s H$ (Shakura & Sunyaev 1973)

$\Sigma \sim (dM/dt)/3\pi\nu \sim (r^{1.5}T)^{-1} \sim r^{-1}$

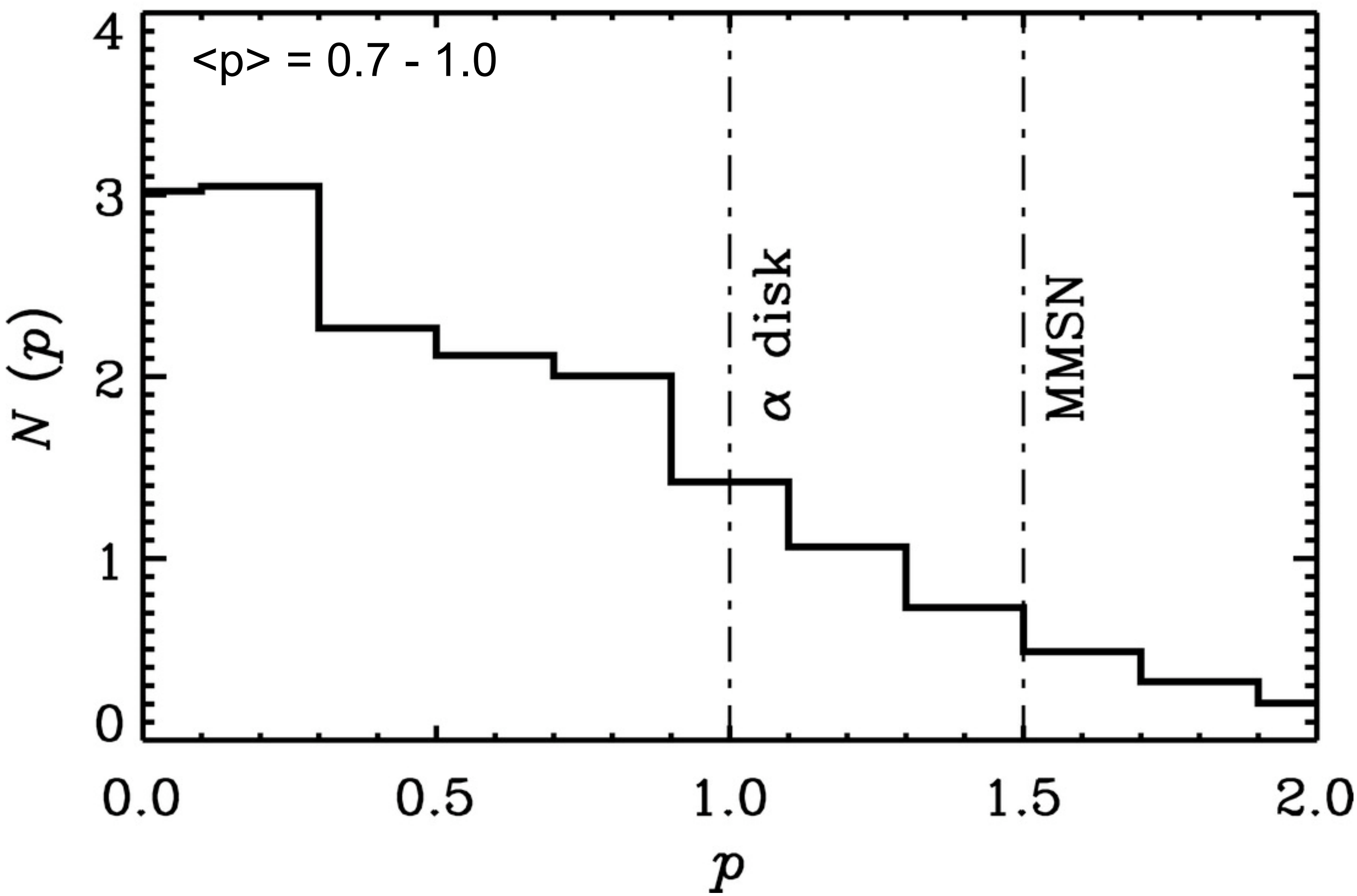
Dust Surface Densities

- SMA survey of 24 disks
  - 12 in Taurus, 12 in Oph
  - 0.87/1.3 mm, 1 - 2 arcsec
  - homogeneous sample
- fit SED and submm visibilities with (simple) power-law models
  - $T \propto r^{-q}$, $\Sigma \propto r^{-p}$, M_d, R_d
  - p to 50%



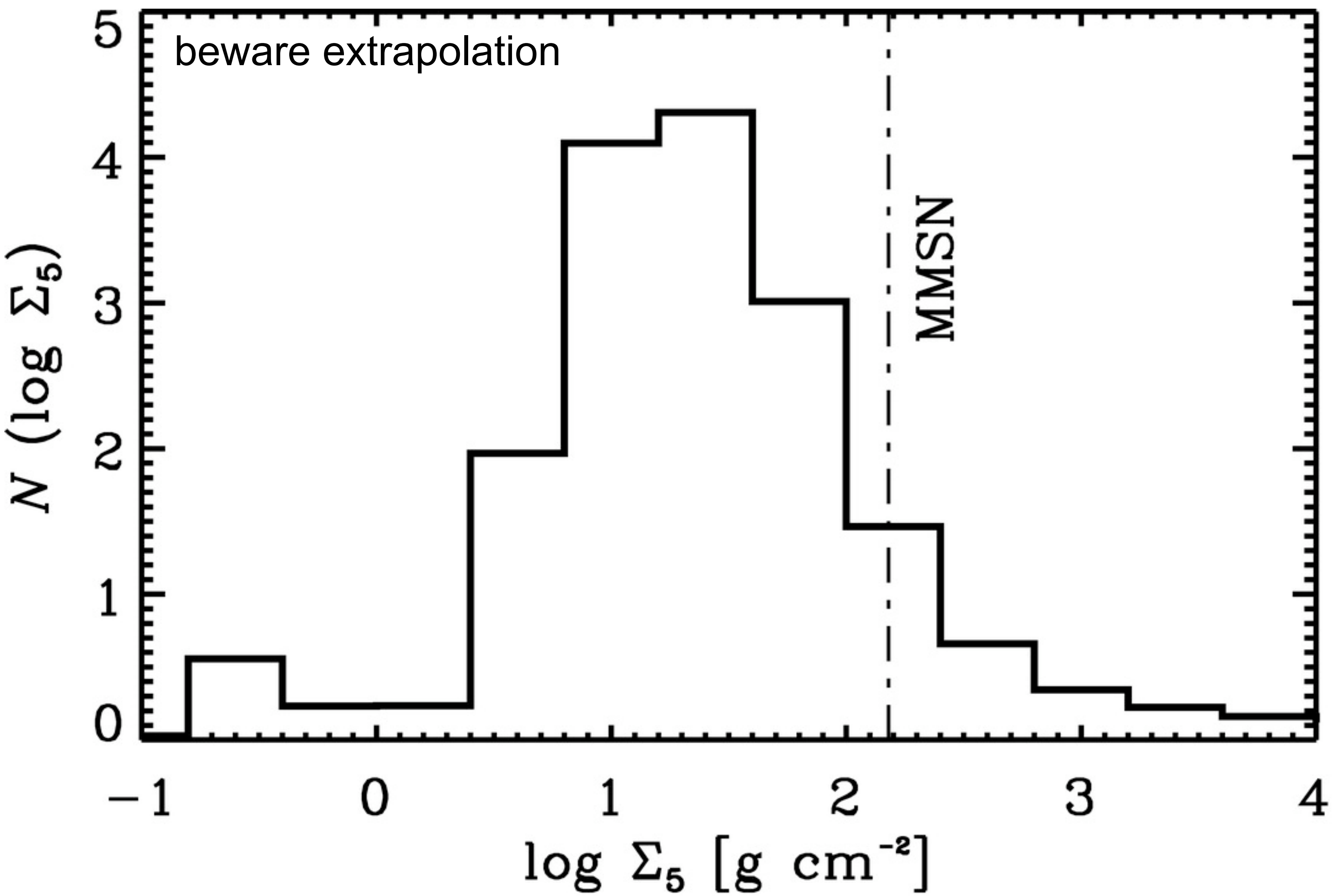
Andrews & Williams 2007

Dust Surface Densities



Andrews & Williams 2007

Dust Surface Densities

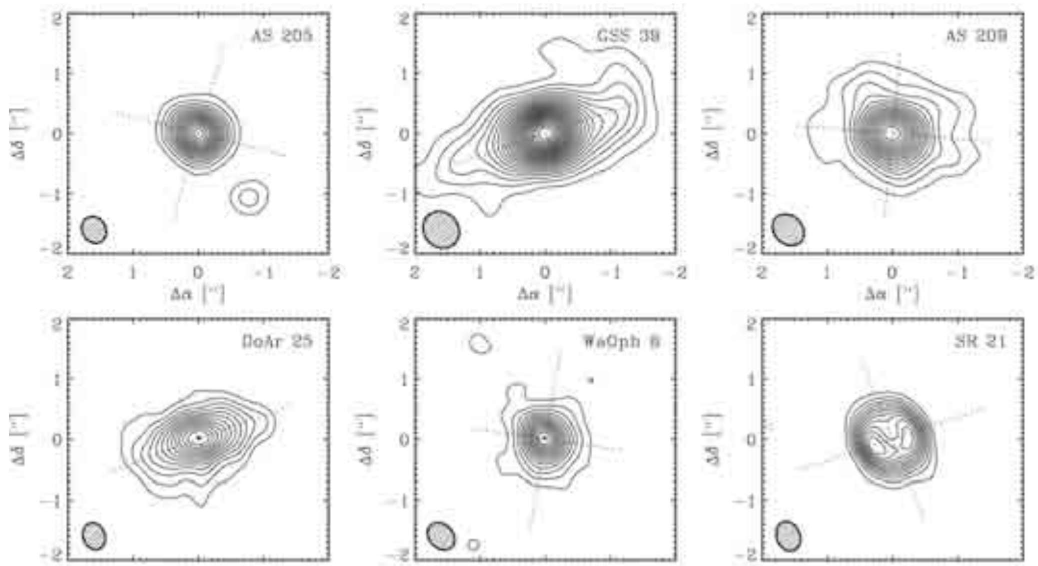


Andrews & Williams 2007

Dust Surface Densities

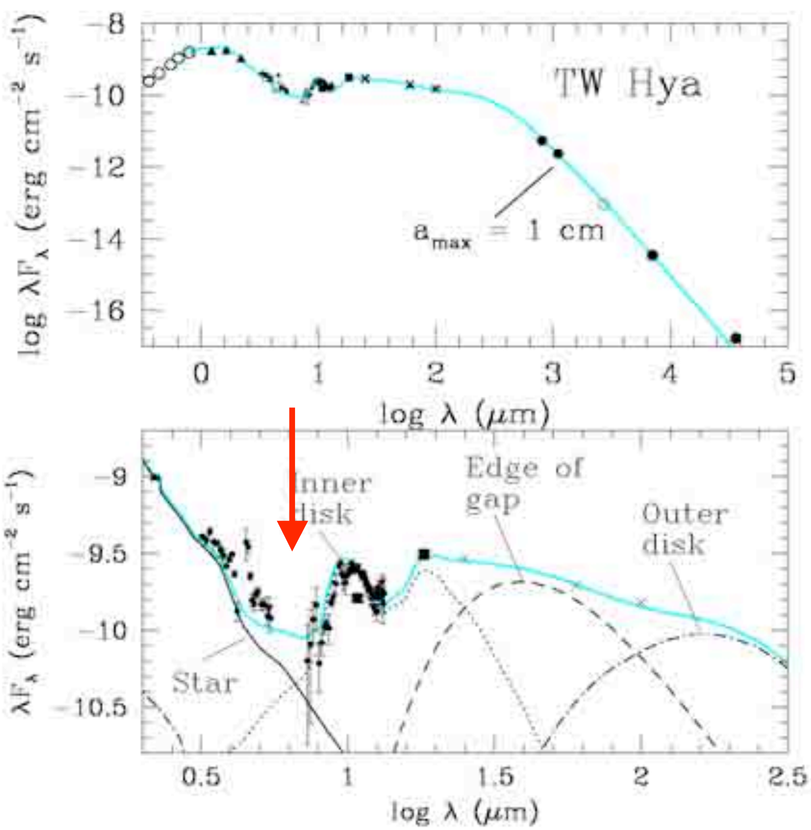
- higher resolution (sub)millimeter data
  - improved spatial dynamic range
  - sample inner disk, $r < 20$ AU
  - better radiative transfer modeling
  - tighter Σ constraints
- rely on good “seeing”

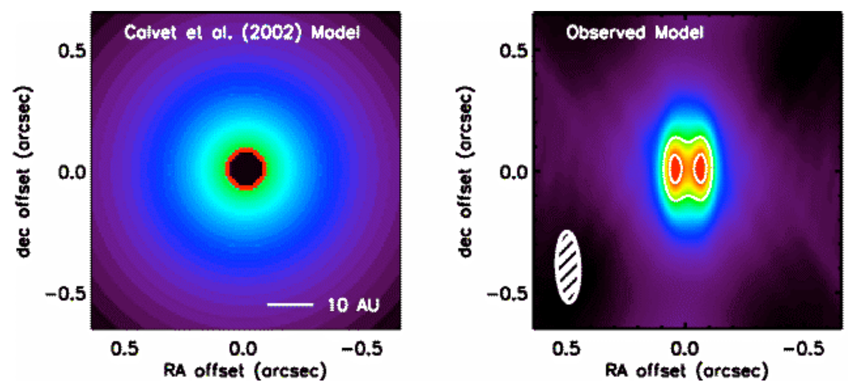
- $\Sigma \propto r^{-p}$, $p \approx 1$?
- stay for last talk

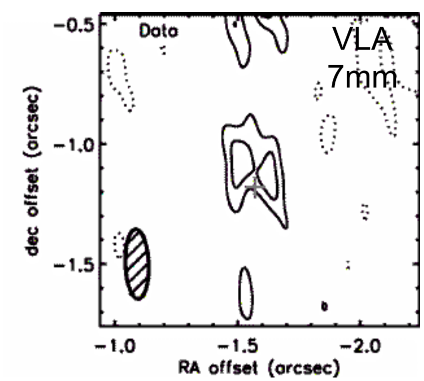


Resolved Central Holes

- TW Hya: classic “cold” disk SED with mid-infrared deficit
  - VLA 7 mm imaging confirms r ≈ 4 AU low opacity hole, wall



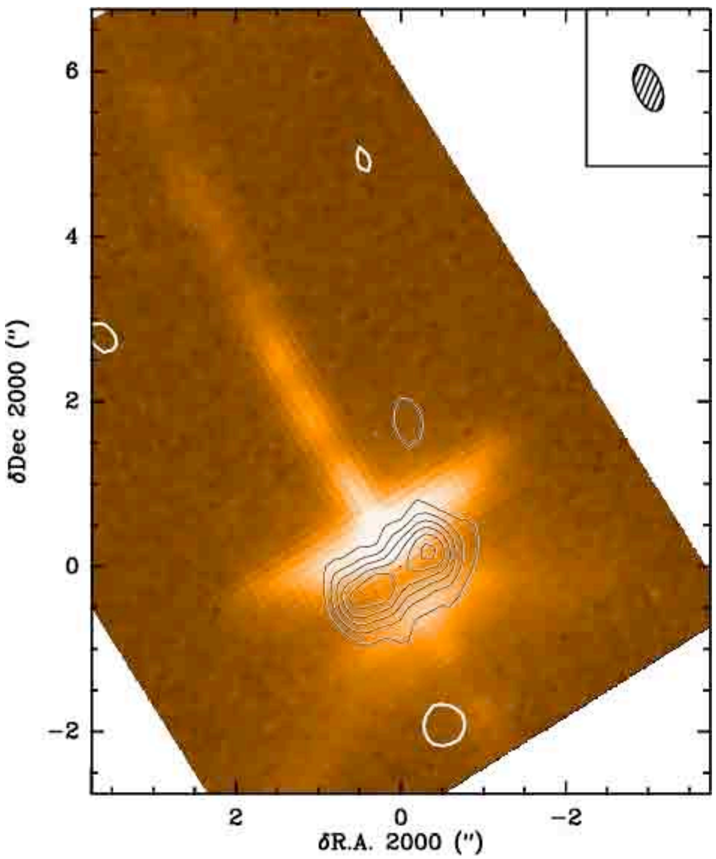




Hughes et al. 2007

More Central Holes

- growing sample of disks with resolved central holes r > 10 AU
  (e.g. Pietu et al. 2006, Brown et al. 2008)
  - binary/planetary companions? photo-evaporation? opacity illusions?

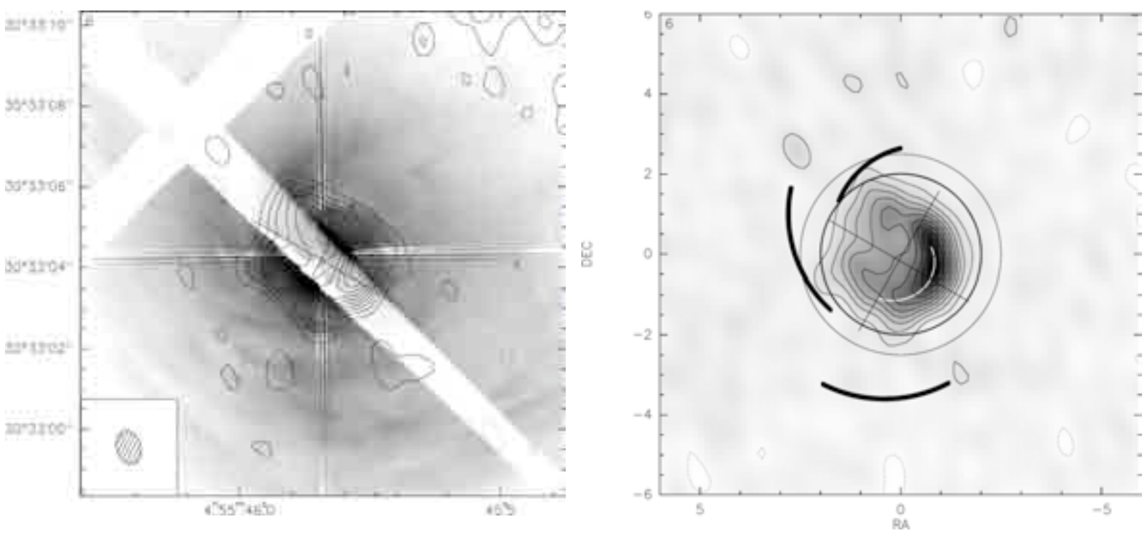


- HH30 system
  - IRAM PdBI: cavity at 1.3 mm
  - inner edge r ~ 40 AU
  - wiggling jet (Anglada et al. 2007)
  - tidal clearing by a binary
  - two stars → younger, 1-2 Myr

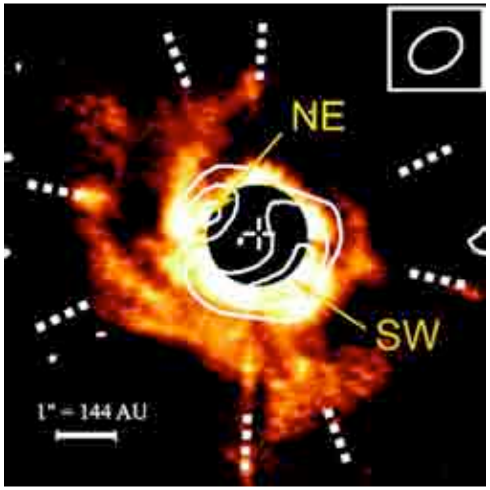
Guilloteau et al. 2008

Non-Axisymmetric Structure

- AB Aur: Herbig Ae star + disk + remnant envelope
- resolved in scattered light and millimeter emission
  - "spiral" structure
  - not a surface phenomenon
  - disk instabilities? unseen companion?



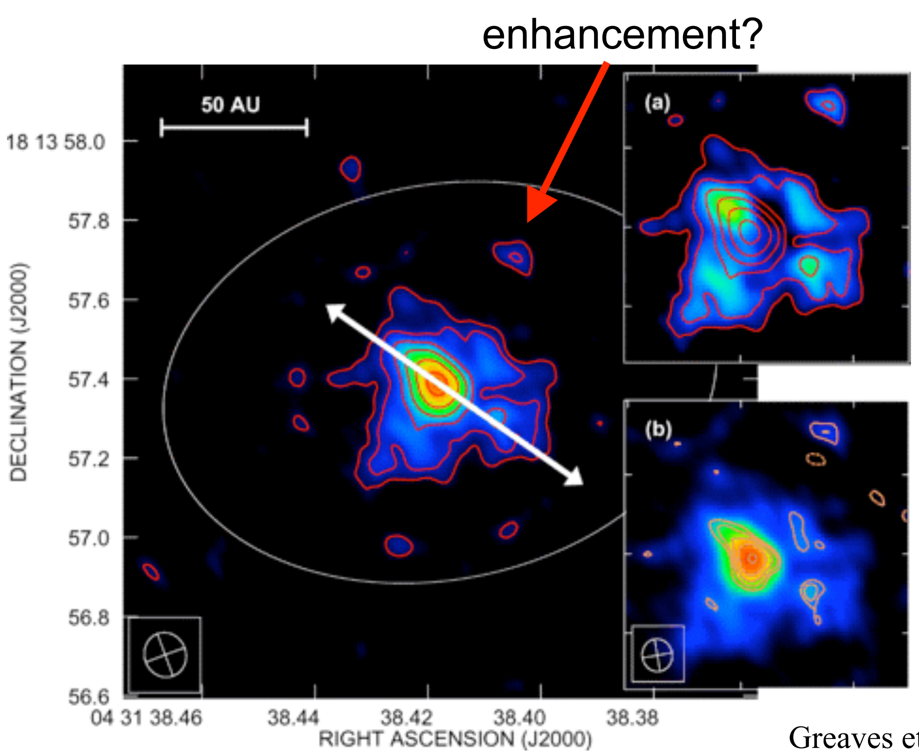
IRAM PdBI/ HST Pietu et al. 2005

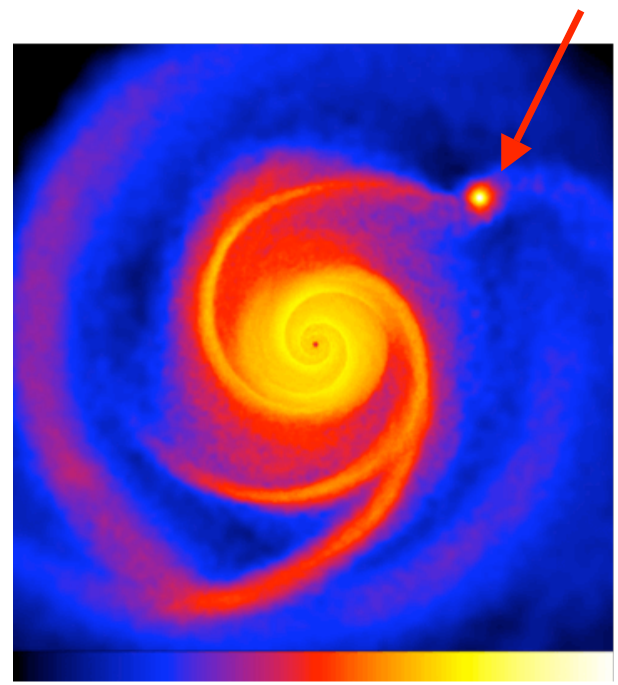


SMA/ Subaru Lin et al. 2006

HL Tau: Forming Companion?

- HL Tau: T Tauri star + disk + remnant envelope
- VLA 1.3 cm image: dust (disk) *and* ionized (jet) gas emission
  - compact 4.5σ feature at 65 AU, 14 M_{Jup}
  - gravitational instability?

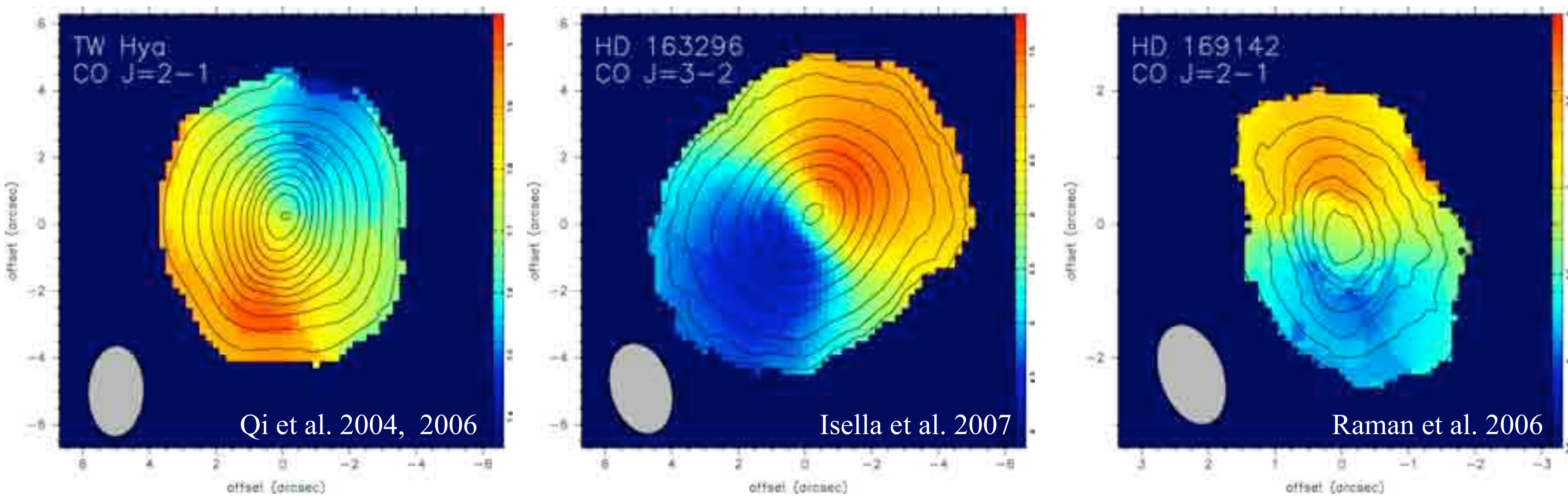




Greaves et al. 2008

Resolved Spectral Line Emission

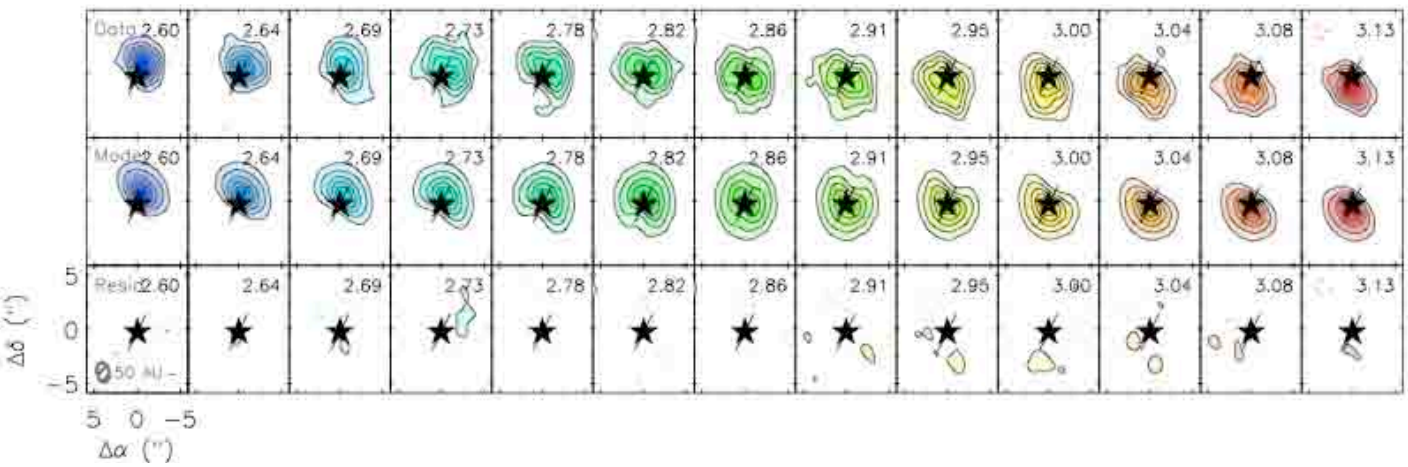
- CO is most abundant gas tracer of cold H_2
  (e.g. Koerner et al. 1993, Mannings et al. 1997, Dutrey et al. 1997, Simon et al. 2000, …)
  - low J lines collisionally excited, thermalized, optically thick
  - confusion with ambient cloud material can be a major problem



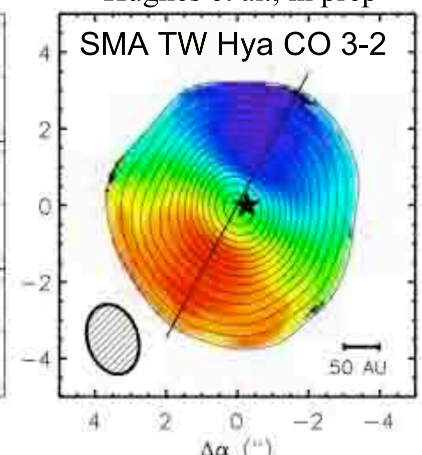
- many other (much weaker) species
  - rich nebular chemistry: ion-molecule, deuteration, photo, organics
  - HCO^+, DCO^+, HCN, CN, DCN, CS, H_2CO, CH_3OH, …

Resolved Velocity Fields

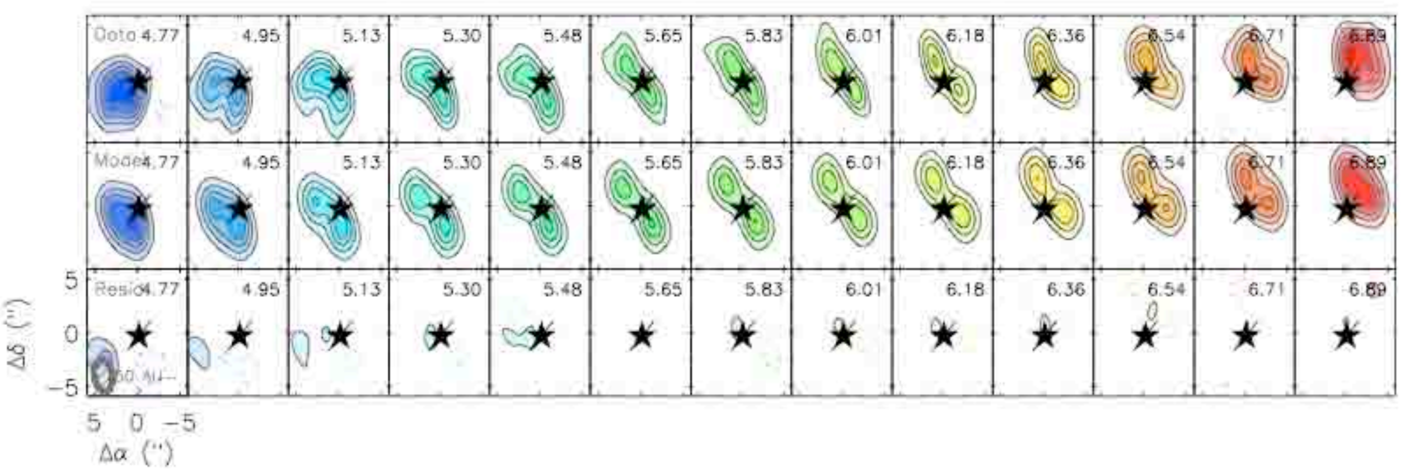
- outer disks show Keplerian rotation: $v(r/D) = (GM_*/r)^{1/2} \sin i$
- turbulent linewidths are subsonic (global value), if present

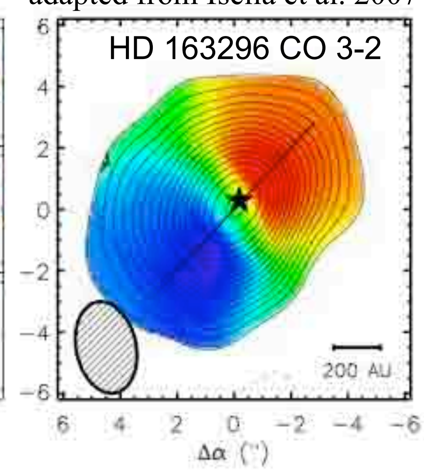


Hughes et al., in prep



adapted from Isella et al. 2007

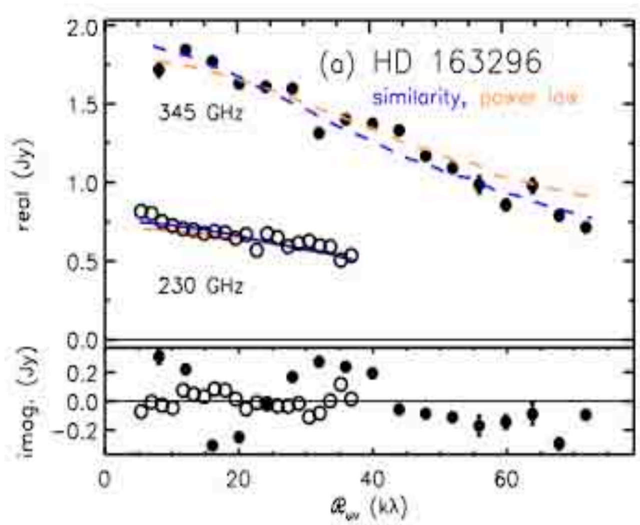




Outer Edge Complexity

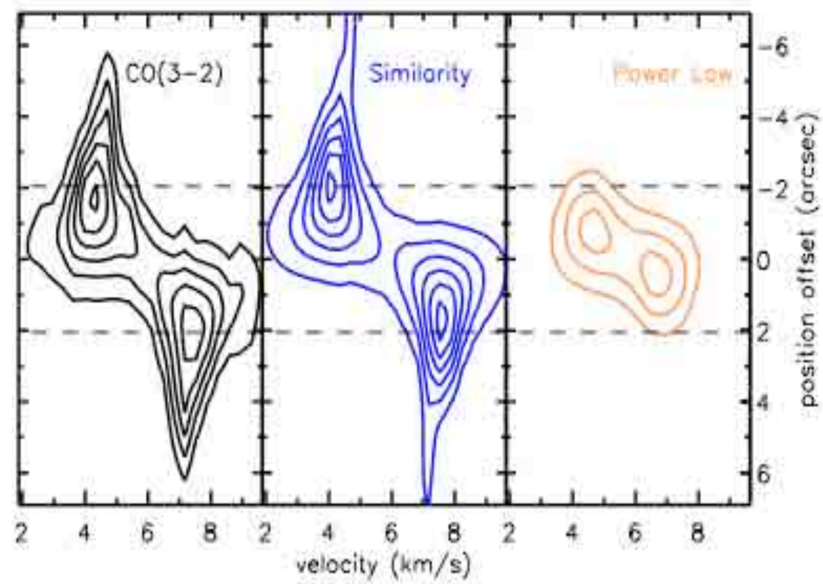
- power law models do not match observed extent of dust and CO emission
  - HD 163296: 200/600 AU?
  - not limited sensitivity
  - dust opacity change in outer disk? (Isella et al. 2007)

- accretion disk paradigm includes exponential edge
  - helps reconcile dust and gas sizes with same model



SMA 1.3/0.87 mm
CO J=3-2
Hughes et al. 2008

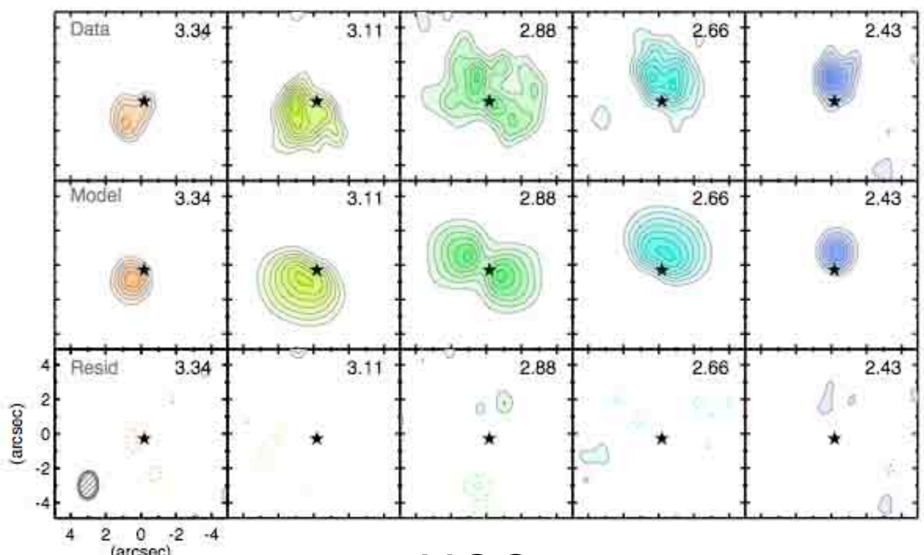
Poster #56



TW Hya DCO^+/HCO^+

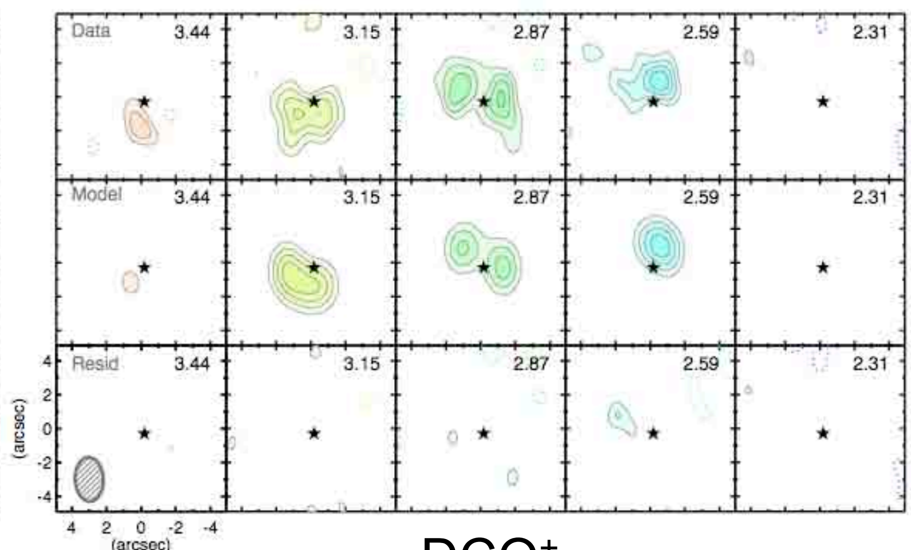
- D/H enhanced substantially at low T
- pristine cometary material: “interstellar” or “nebular”?
- TW Hya: resolve radial distribution of DCO^+ , HCO^+ J=3-2 emission
  - D/H ratio ↑ from 0.01 to 0.1 from r<30 to 70 AU
  - *in situ* fractionation is important

Poster #41



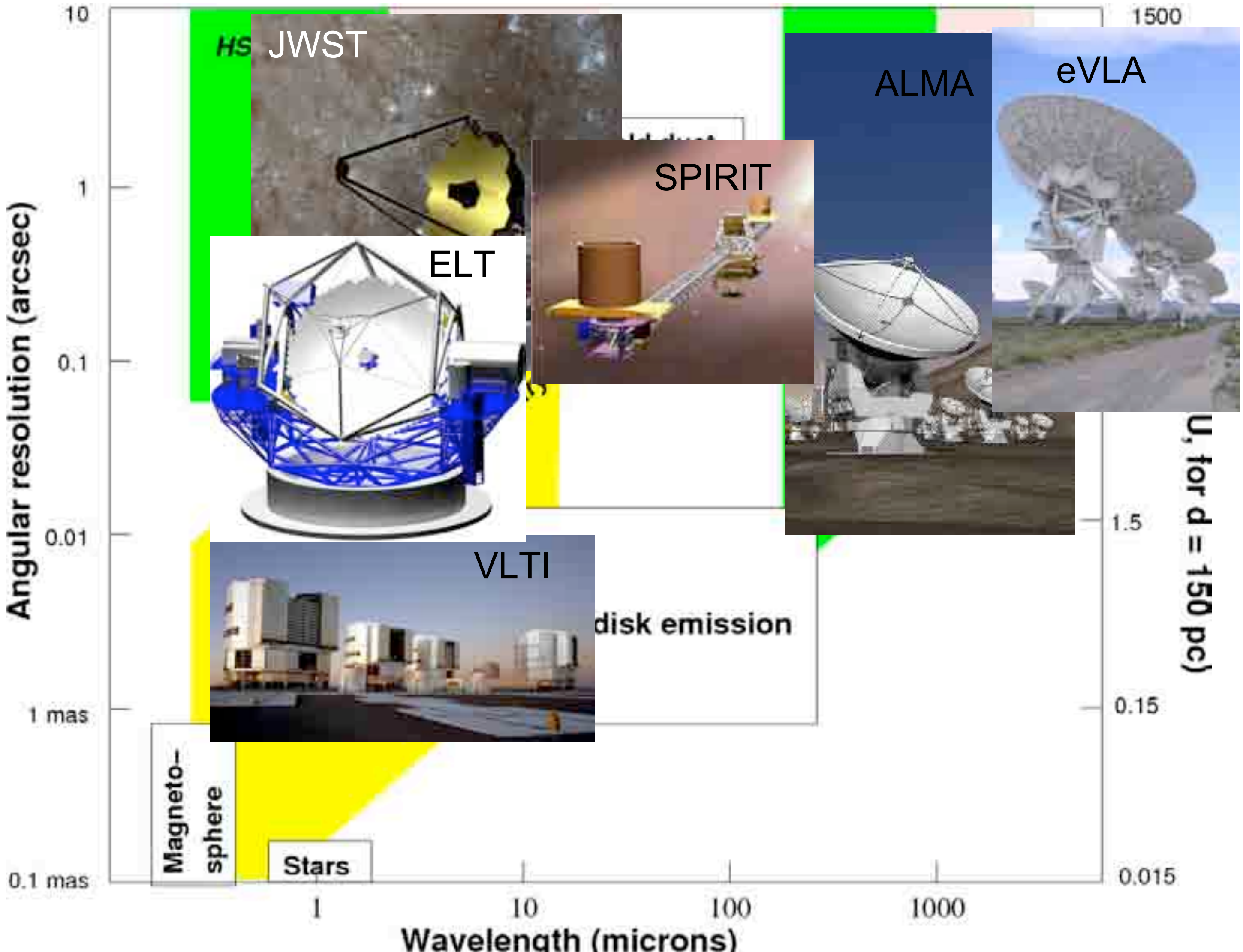
HCO^+

Qi et al. 2008



DCO^+

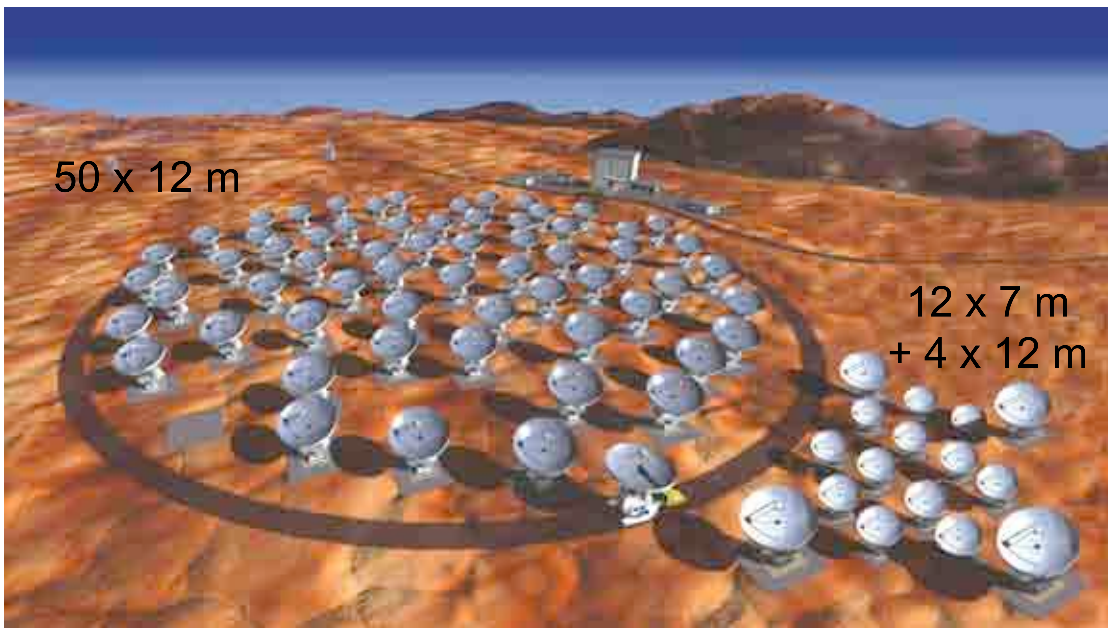
Next Generation Facilities



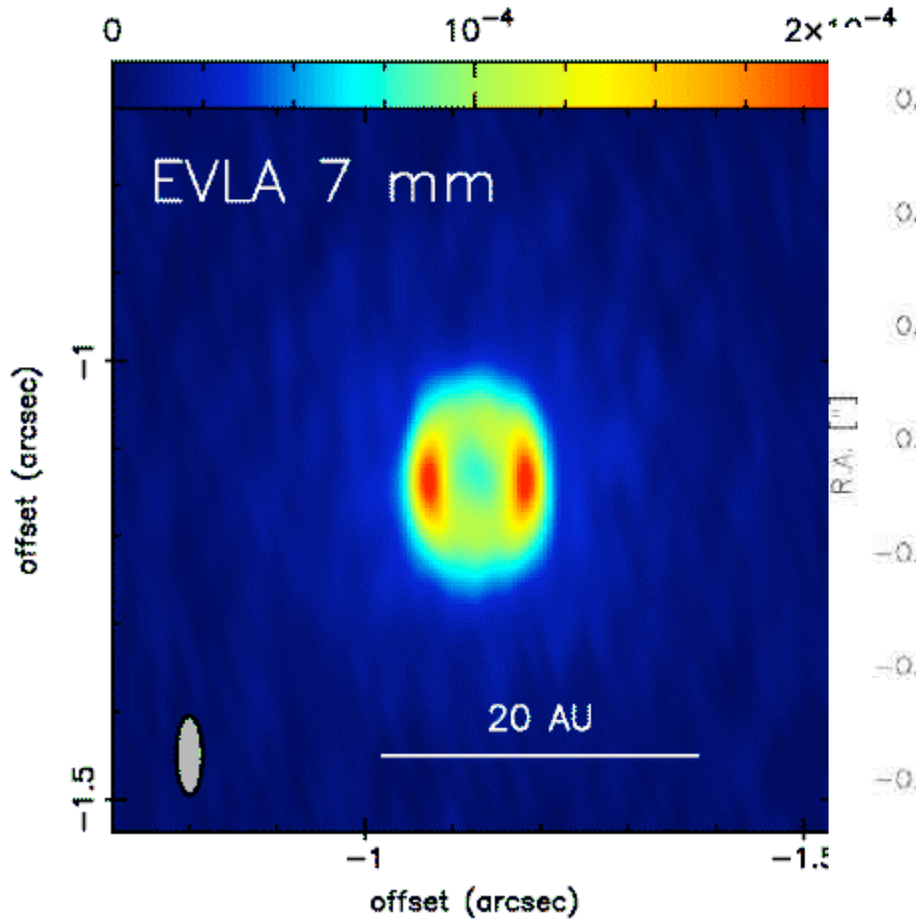
Millan-Gabet et al. 2007

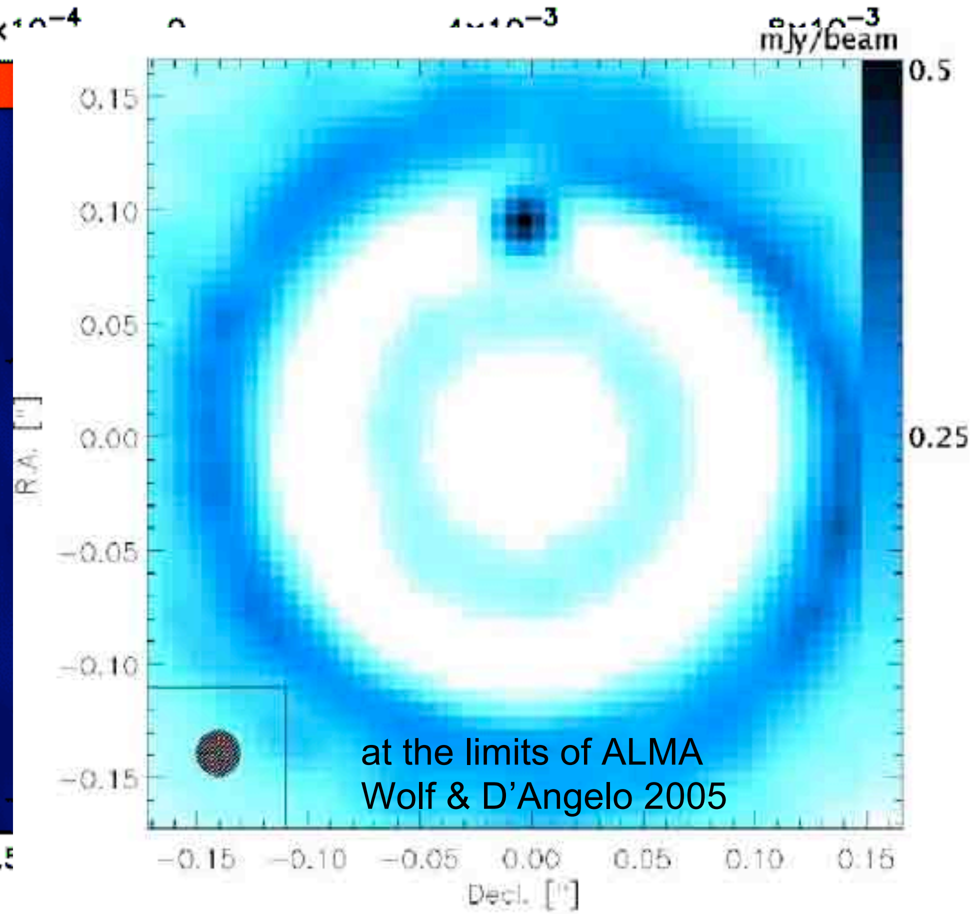
Atacama Large Millimeter Array

- 10-100x sensitivity, resolution, image quality; 0.3 to 3 mm
  - global partnership to fund >$1B construction
  - 50+ x 12 m antennas, best site, best receivers
  - current schedule: early science 2011, full operation 2013
- Key Science Goal I. Image protoplanetary disks, to study their physical, chemical, and magnetic field structures, and to detect tidal gaps...



TW Hya: eVLA and ALMA

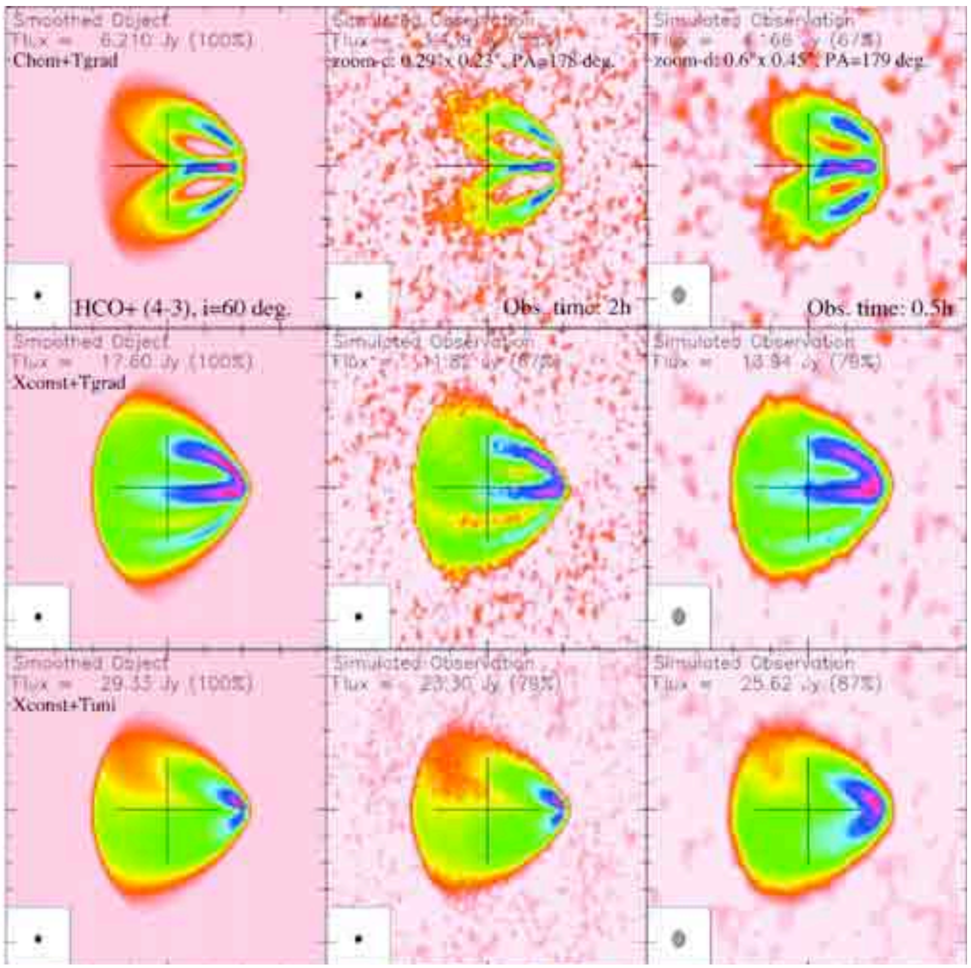




at the limits of ALMA
Wolf & D'Angelo 2005

Chemistry and Structure

ALMA: disentangle excitation and abundance gradients at 0.25 arcsec



– assume D'Alessio accretion disk structure

– HCO^+ J=4-3 uniform abundance vs. chemical network

– GILDAS ALMA simulator (2 configs)

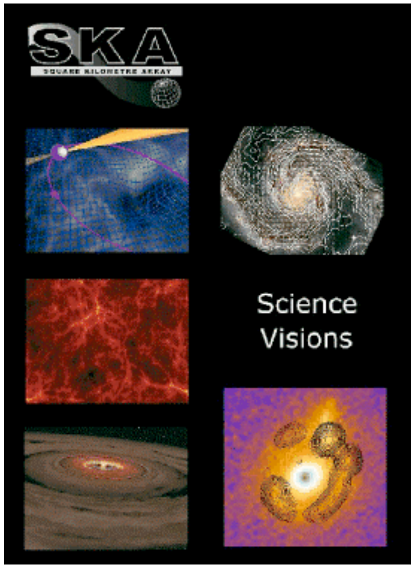
Semenov et al. 2008

New Territory for an SKA

- Square Kilometer Array
  - short λ centimeter capability and ~1000 km baselines
  - image thermal emission at 1 mas resolution

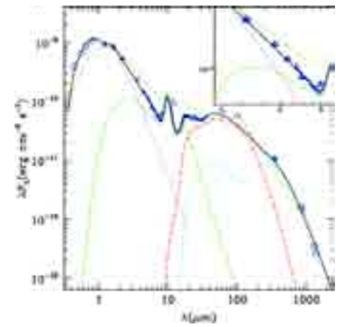
- unprecedented sub-AU views
  - low opacity, even in terrestrial planet zone
  - direct detection of tidal gaps
  - orbital timescales of inner disk ~ 1 year
    → track secular changes ("movies")

- track grain growth in inner disk to pebbles
  - radial gradients, settling
  - concentrations of pebbles? vortices?

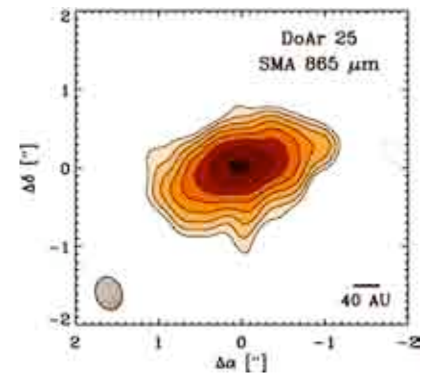


Summary

- YSO disks are small for Spitzer, but not too small for resolved
  - optical/infrared scattered light
  - infrared interferometry
  - millimeter dust/gas emission



- resolved studies of disks
  - reveal geometry
  - validate model constructs
  - constrain surface density (→ planet formation)
  - small samples, so far



- major new facilities on horizon
  - statistics, confront complexity