Future Directions for Interferometry:

Young Stellar Objects

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on behalf of YSO Working Group

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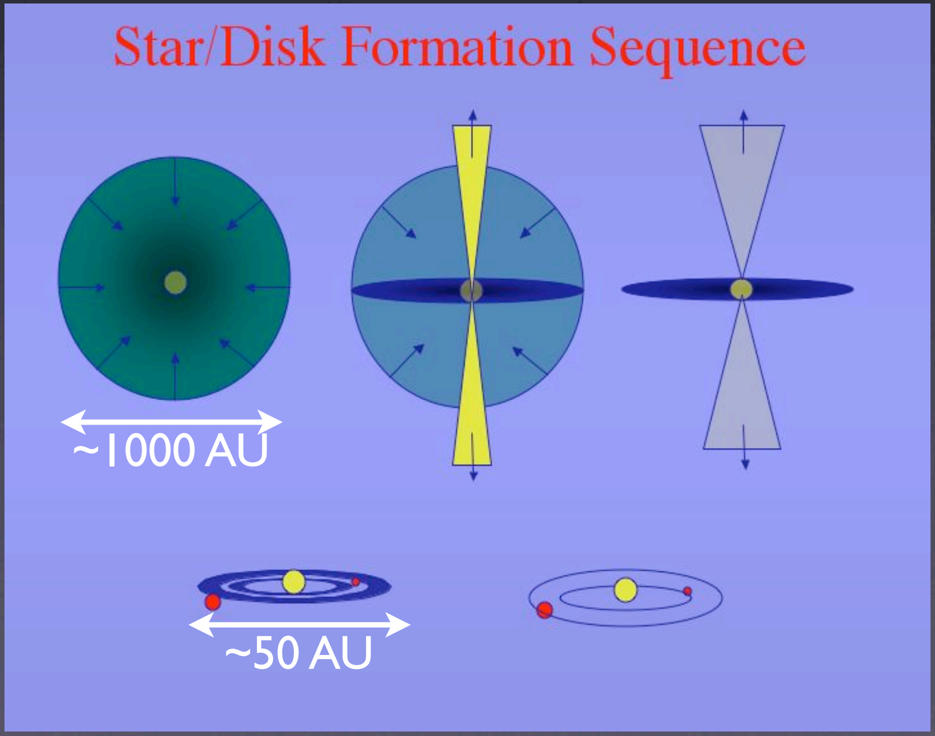
The Questions

- Big Picture: Origins
  - how do stars and planets form?
  - how did our system form? and is this mode of formation common?
  - how many exo-systems hospitable to life?

Star Formation

- Disks form during collapse of cloud to star
  - accretion through disk onto star
- envelope/halo contributions
  - infall signatures
- Jets
  - resolve launching region



Initial Conditions for Planets

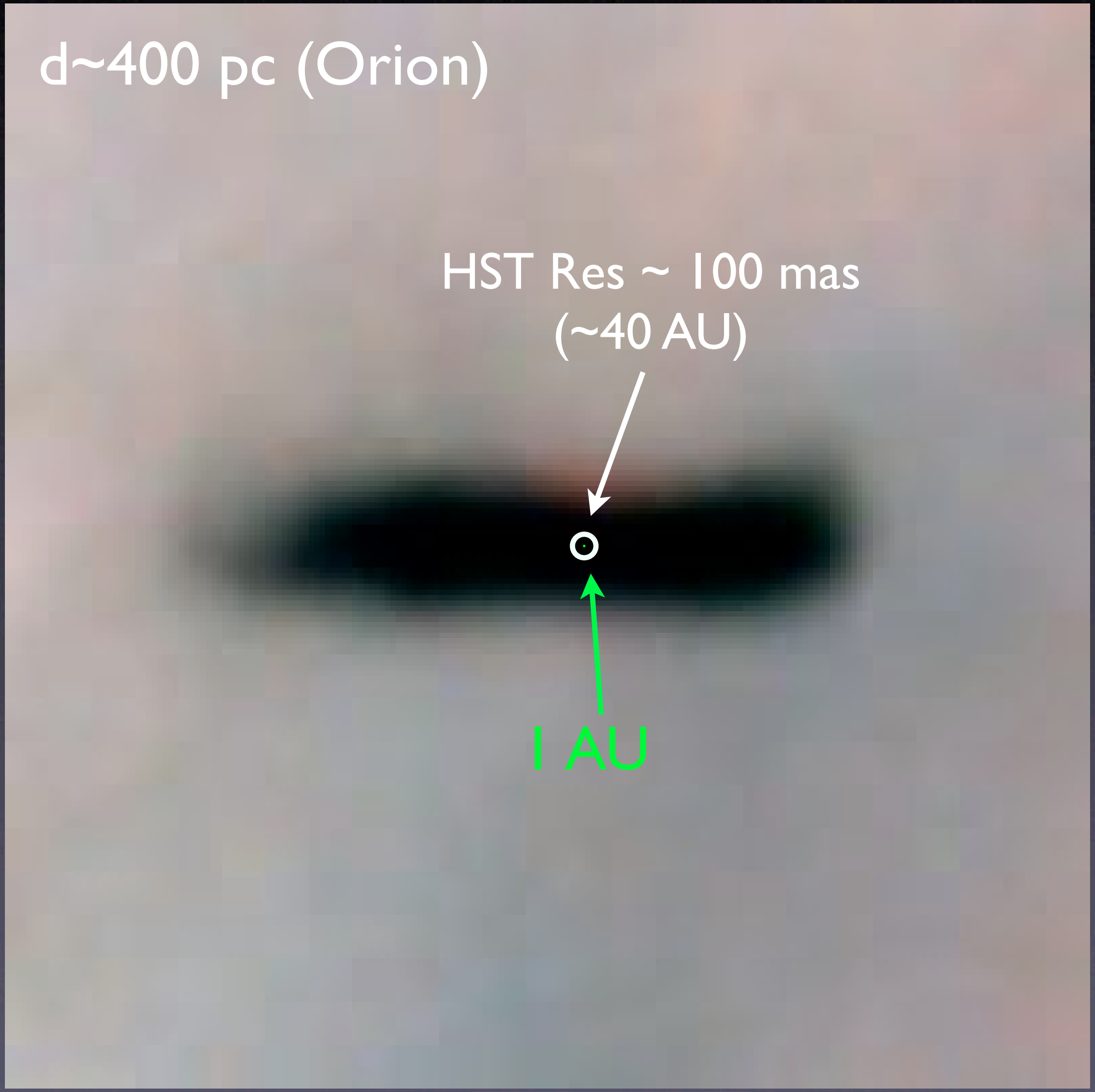
- Planets form in disks: how and when?
  - distribution, amount, chemistry, temperature of dust & gas in protostars, TTs, HAEBEs
  - disk structure from 10^5 to 10^7 yr
    - how do solids evolve?
    - what happens to gas?

Planetary Signposts

- Protoplanet blobs, gaps, variability in TTs
  - test when planets form, how they accrete, whether they migrate
- "Mature" planets in "transition"/debris disks
  - provide link between YSOs and RV planets
- Planets around MS stars
  - astrometry, differential phase

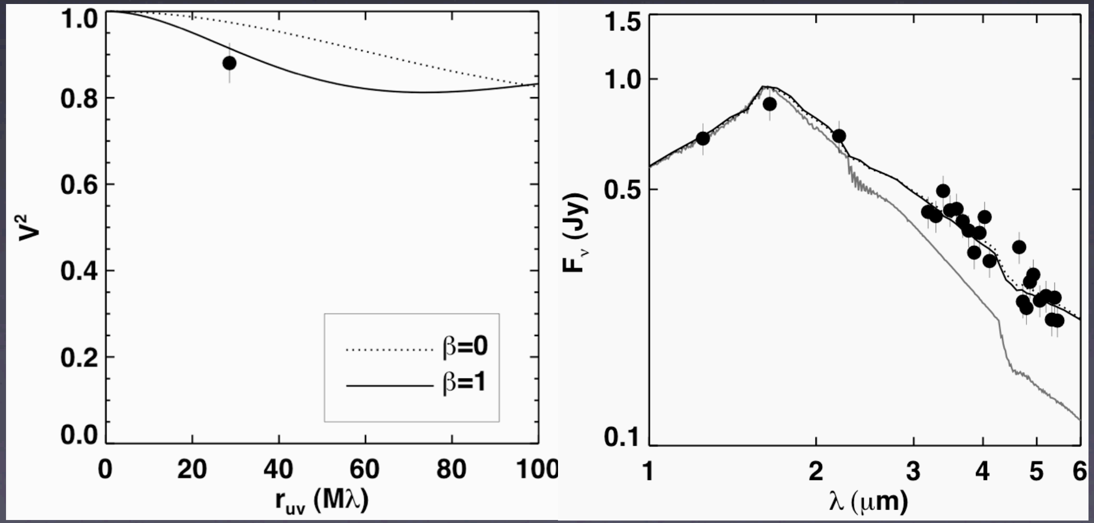
The Challenge

- Disks are small
- nearest star forming regions at100+ pc
  - 1 AU < 10 mas
- Available resolution
  - θ_{HST} ~ 100 mas
  - θ_{KeckAO} ~ 50 mas
  - θ_{TMT} ~ 20 mas



Wanted: Spatial resolution

- Interferometry constrains geometry
- Visibilities + fluxes (e.g., SEDs) give temperature structure, dust grain properties of star+disk systems
  - spectroscopic veiling very useful
  - SEDs alone cannot distinguish geometry, *T*, dust properties



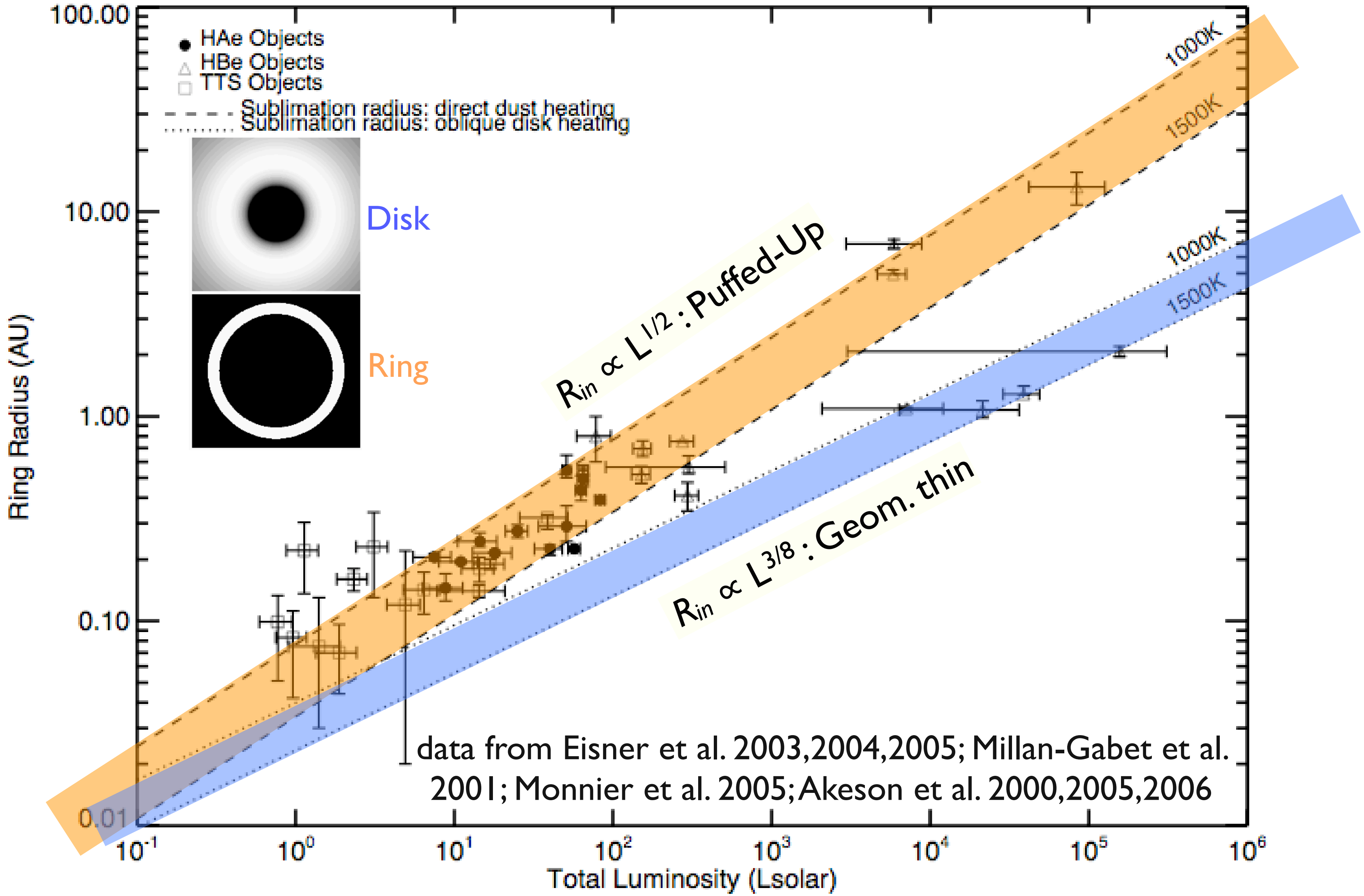
Eisner, Chiang, & Hillenbrand 2006

Lots of Progress

- Disks from ~1-100 Myr
  - size scales & geometries
  - temperature profiles
  - dust properties
  - gas: outflows
  - envelopes

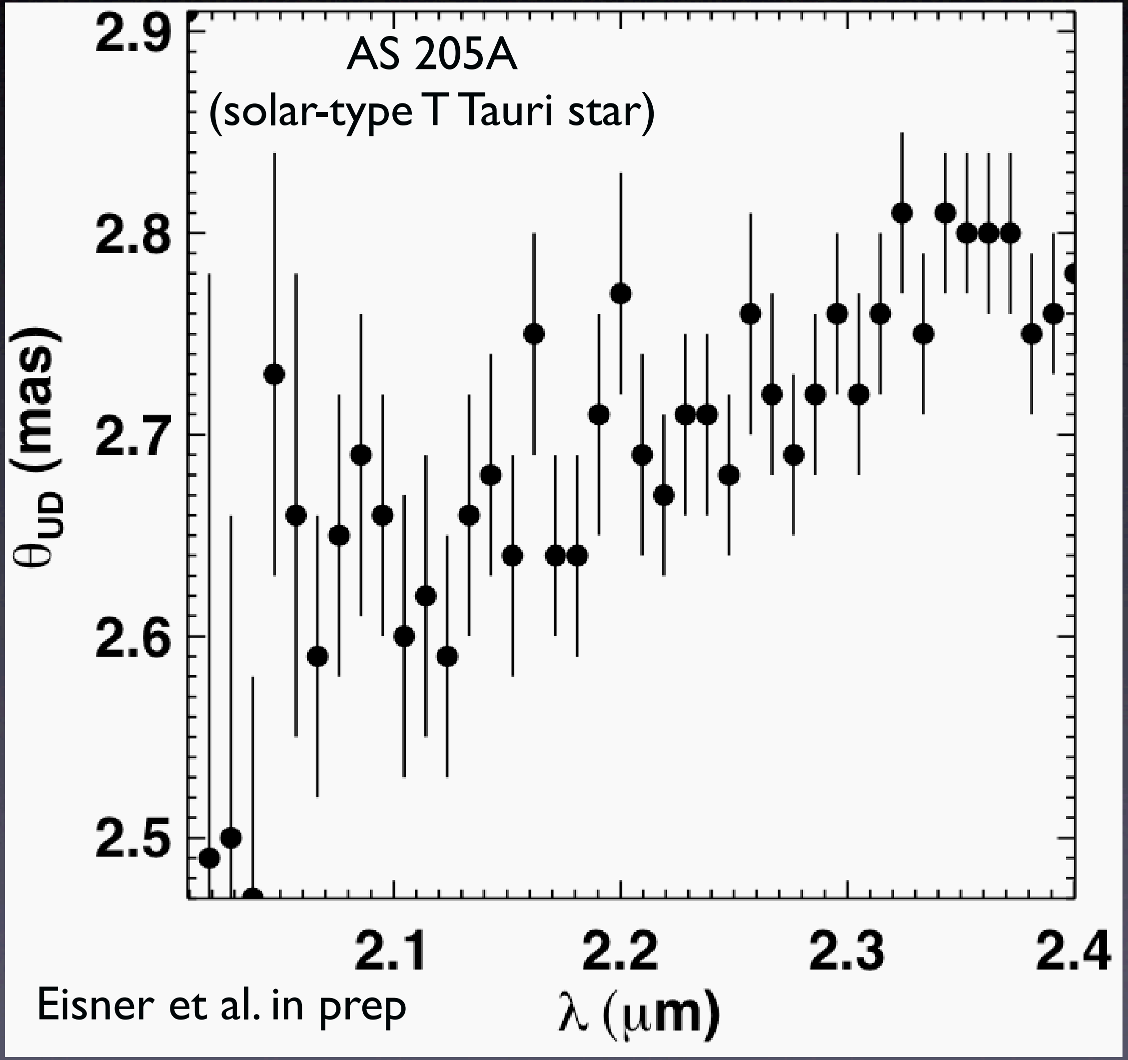
Inner Disk Radii

Adapted from Millan-Gabet et al. PPV Review

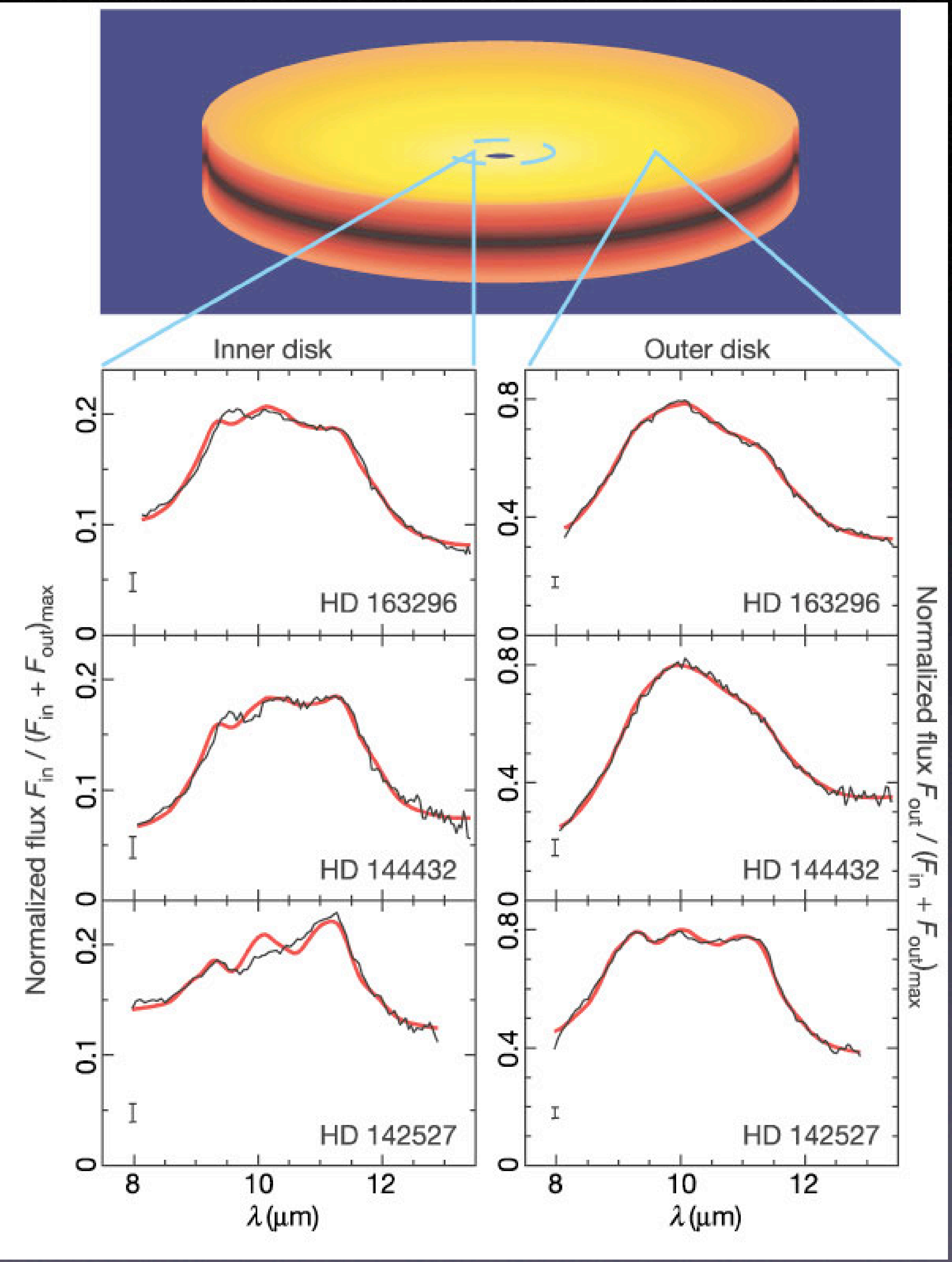


T(R) for a T Tauri Star: Keck-I Grism Data

- First Light obs. May 15-16, 2006
- 2.0-2.4 μm
- $\lambda/\Delta\lambda$ ~ 230
- model: *T(R)* ~ $R^{-\alpha}$ $\alpha \approx 0.5 \pm 0.05$



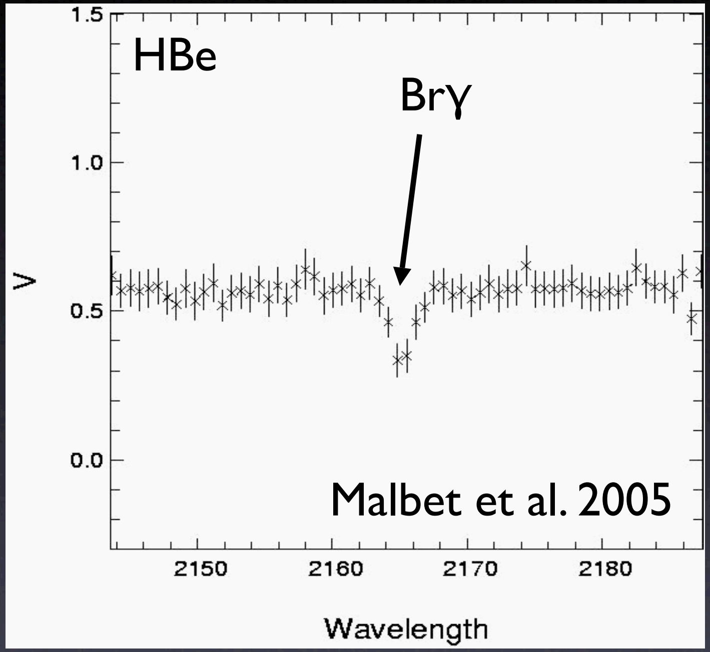
Dust Evolution

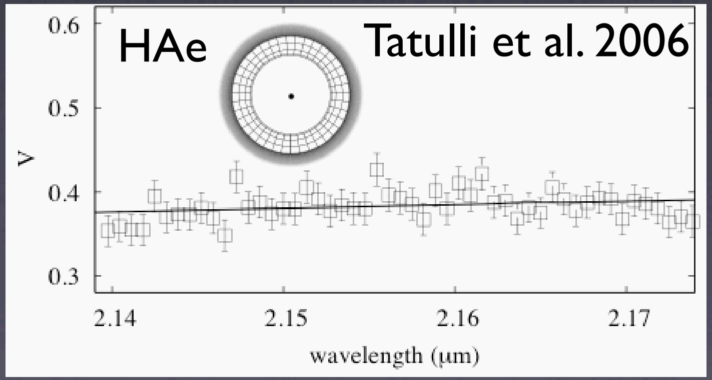


van Boekel et al. 2004
VLTI MIDI

Gas Infall/Outflow

- Brγ spatially, spectrally resolved
  - outflow (Malbet et al. 2005)
  - disk? see Tatulli et al. 2006
  - no infall signatures yet...

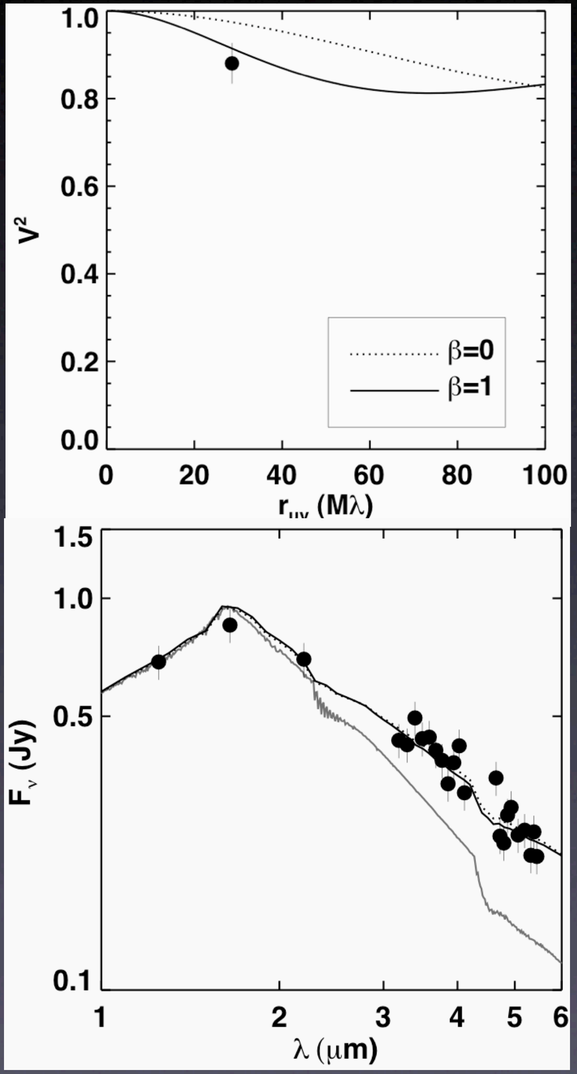




Resolving Transition Disks

- if no circumstellar dust, $V^2=1$ (central star unresolved)

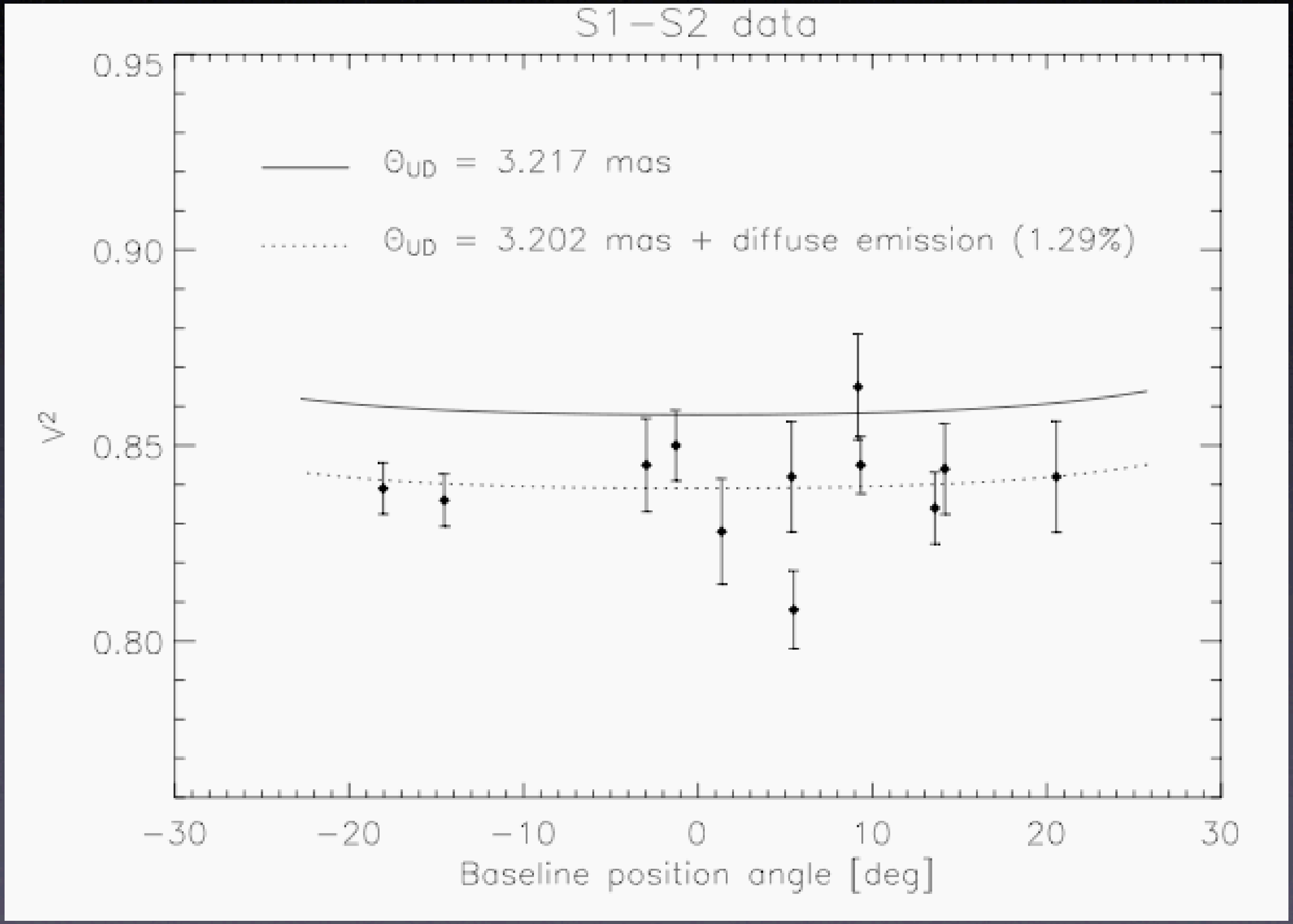
- KI obs: $V^2 < 1$ (at 2 μm)
  - Disk models with small dust grains
    - $\beta=1$ (or >1): submicron-sized dust
    - R_{in} = 0.06 AU, T_{in} = 1100 K



Eisner, Chiang, & Hillenbrand 2006

Debris Disks

- Constrain excess in inner regions
- Implications for particle sizes

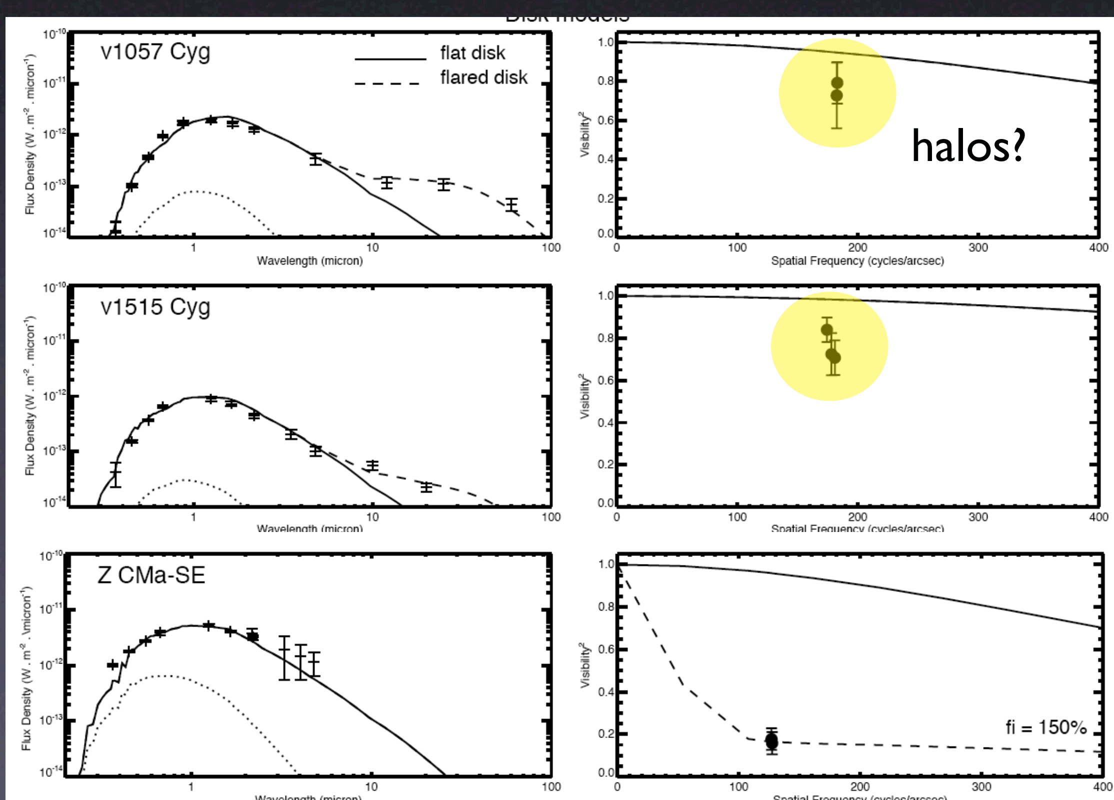


Absil et al. 2006: Vega

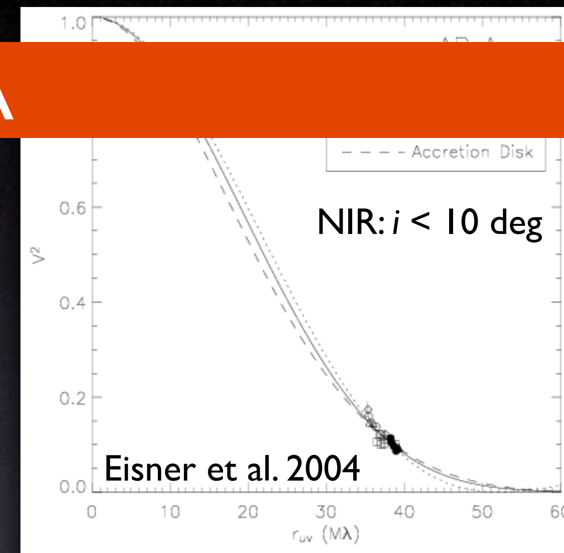
Small & Large Scales

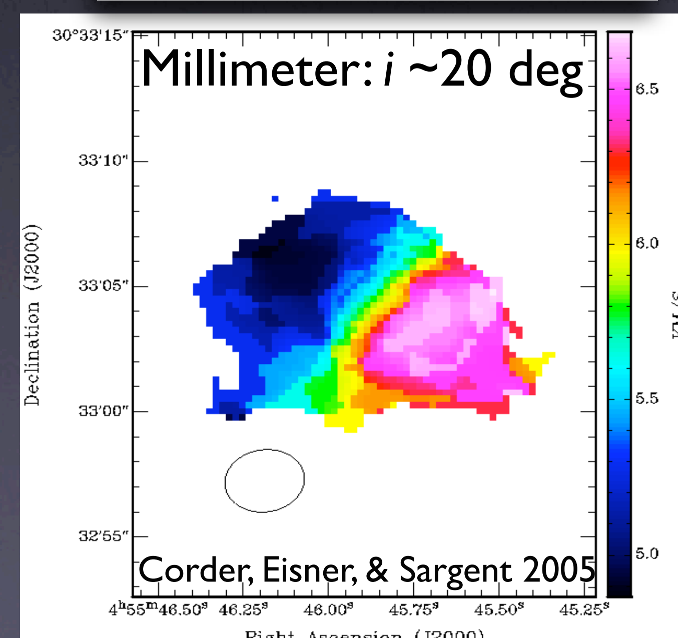
synergy with ALMA

- disk/envelope contributions



Millan-Gabet et al. 2006



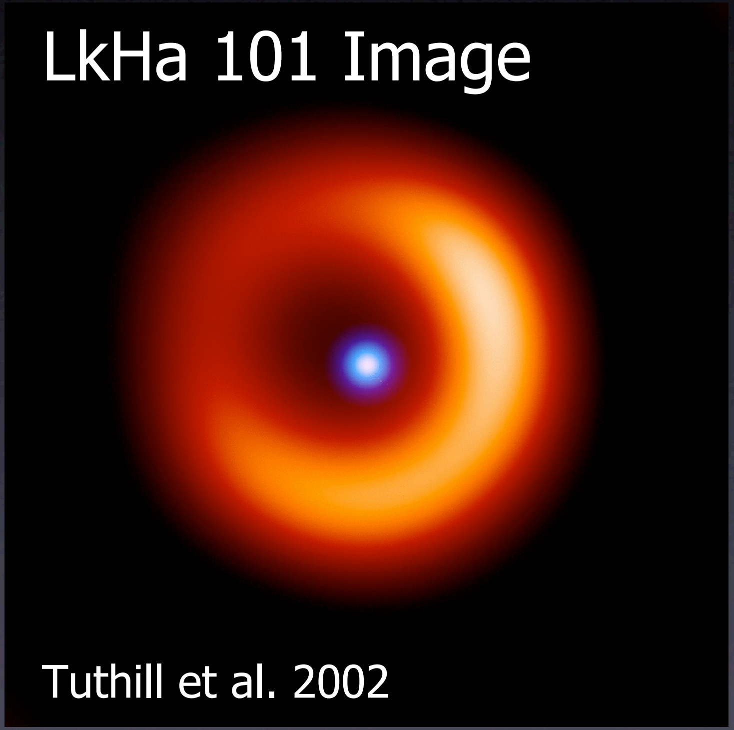


Going Forward

- Investigate detailed disk structure
  - imaging, spectroscopy, polarization
- Accretion and Outflow
  - need spectroscopy; imaging helpful
- detect gaps, planets, other indicators
  - high dynamic range, long baselines

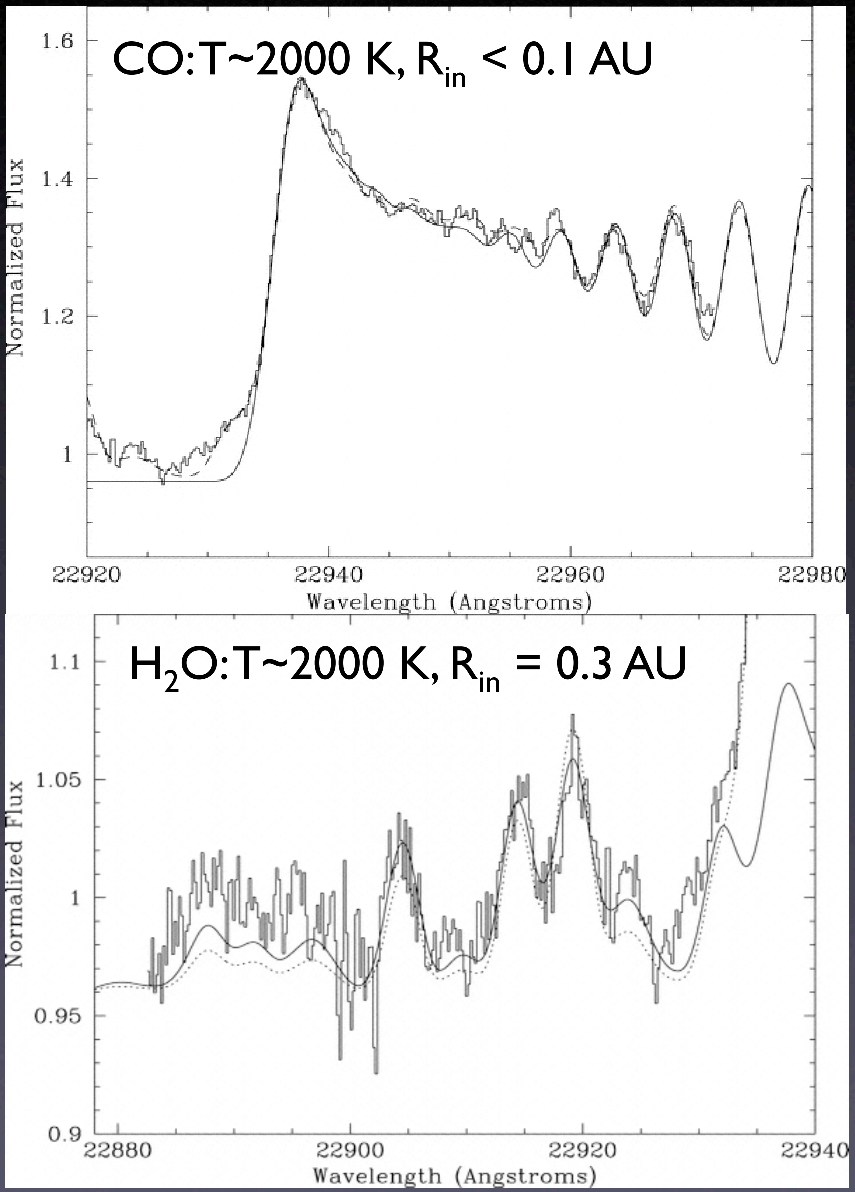
Imaging

- Lots of baselines allow imaging (see aperture masking results!)
- test complex structures, including asymmetries



Kinematics

- preliminary results from VLTI
- want other tracers (disk, infall)
- resolved line profiles of multiple transitions trace infall, rotation, surface density, etc.

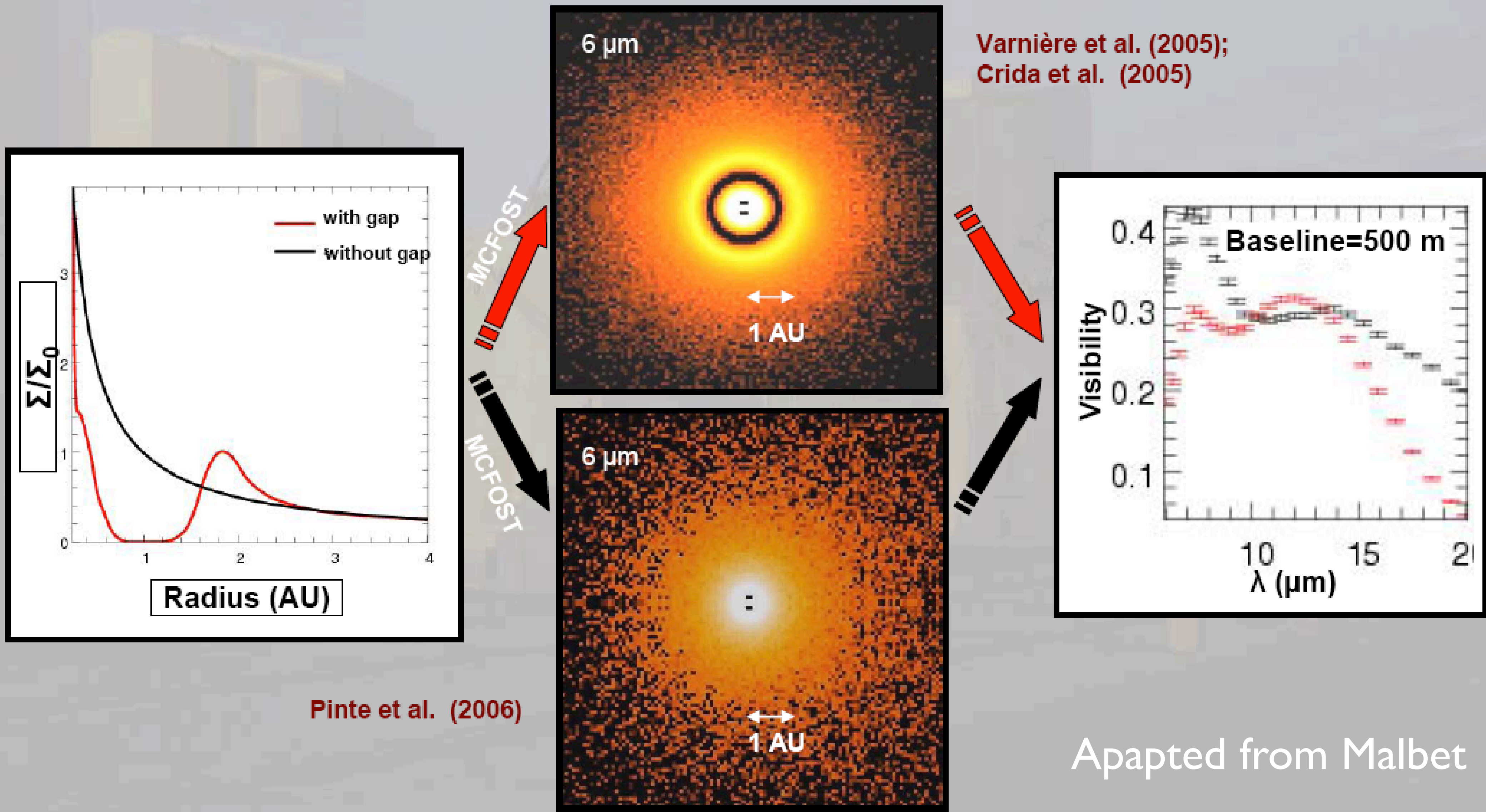


Carr, Tokunaga, & Najita 2004

Planetary Signatures

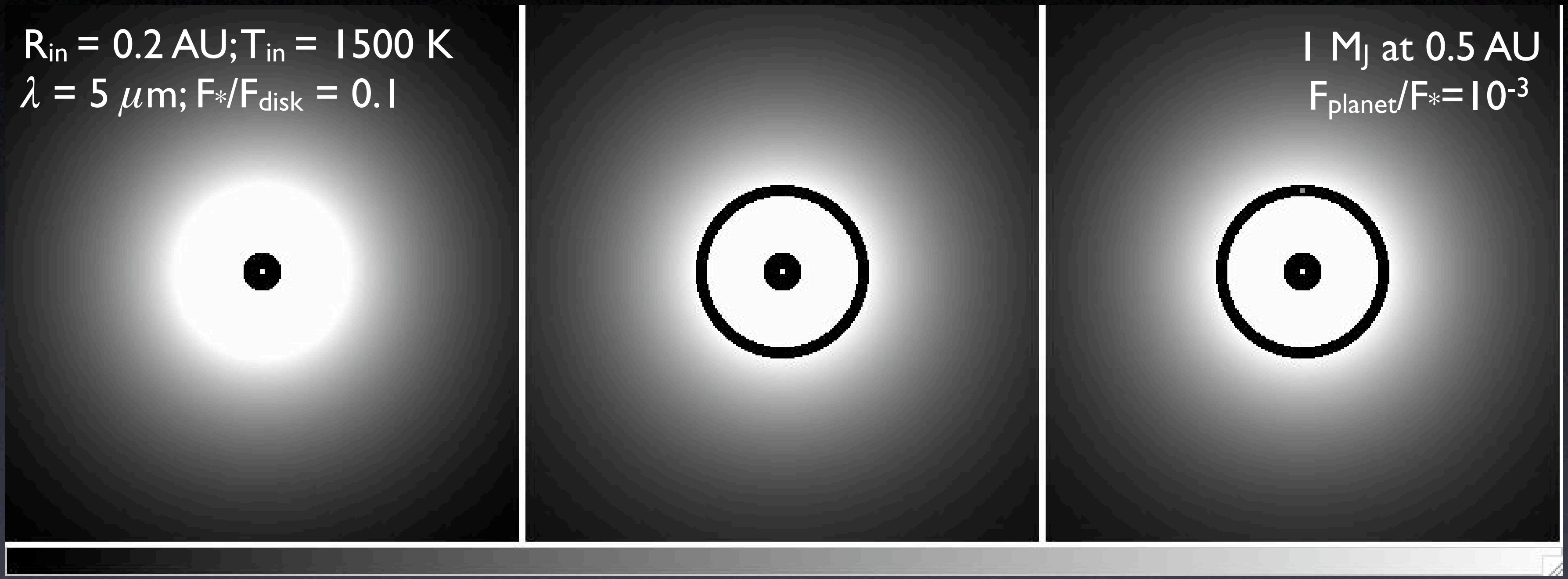
- gaps and protoplanets
  - need long baselines to resolve; difficult for TMT-type instruments
  - probably need amplitude & phase to measure protoplanets
  - nulling useful
  - variability on expected planet t_{dyn}?
  - astrometric wobble/DP: planet M, i

Gap Detection



Apapted from Malbet

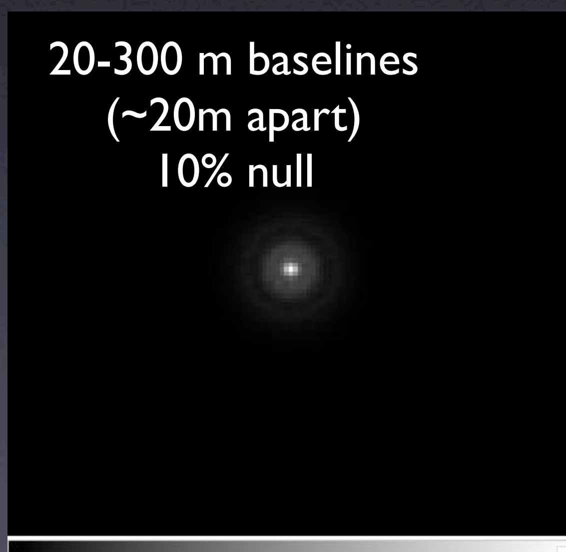
Toy Models

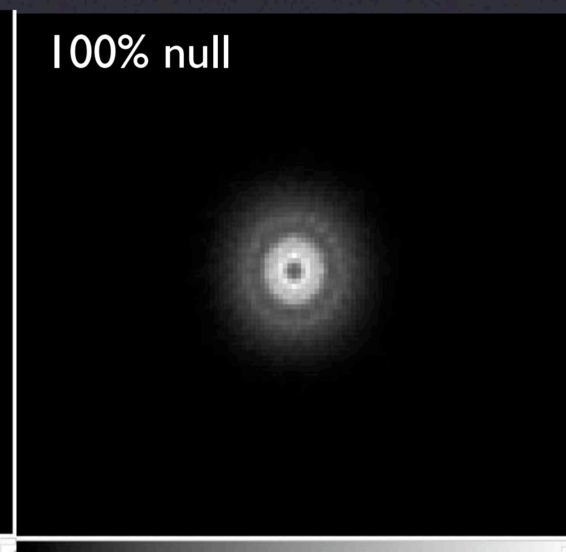


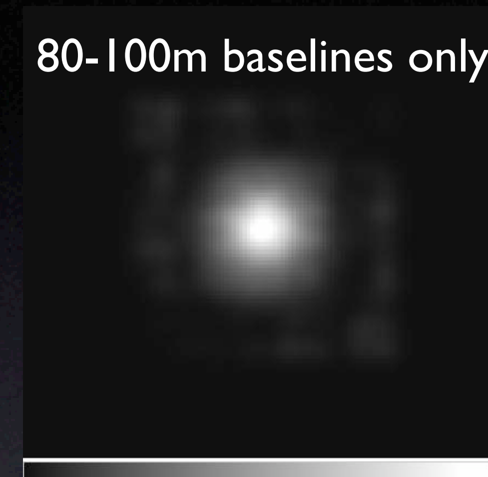
What do we need to detect these features?

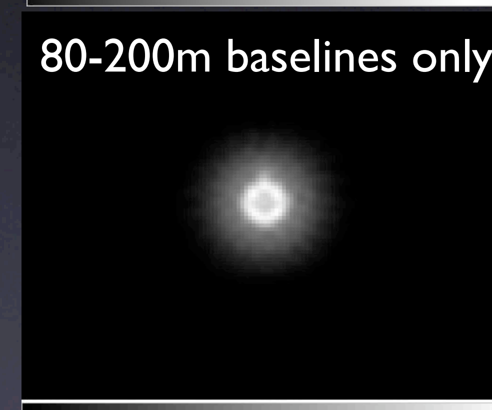
Dense Interferometer

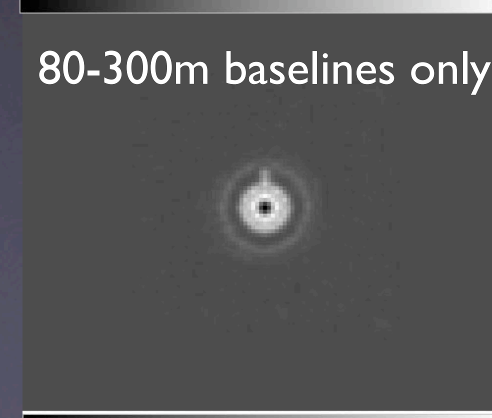
- Few rotating baselines (space) or many-element ground-based







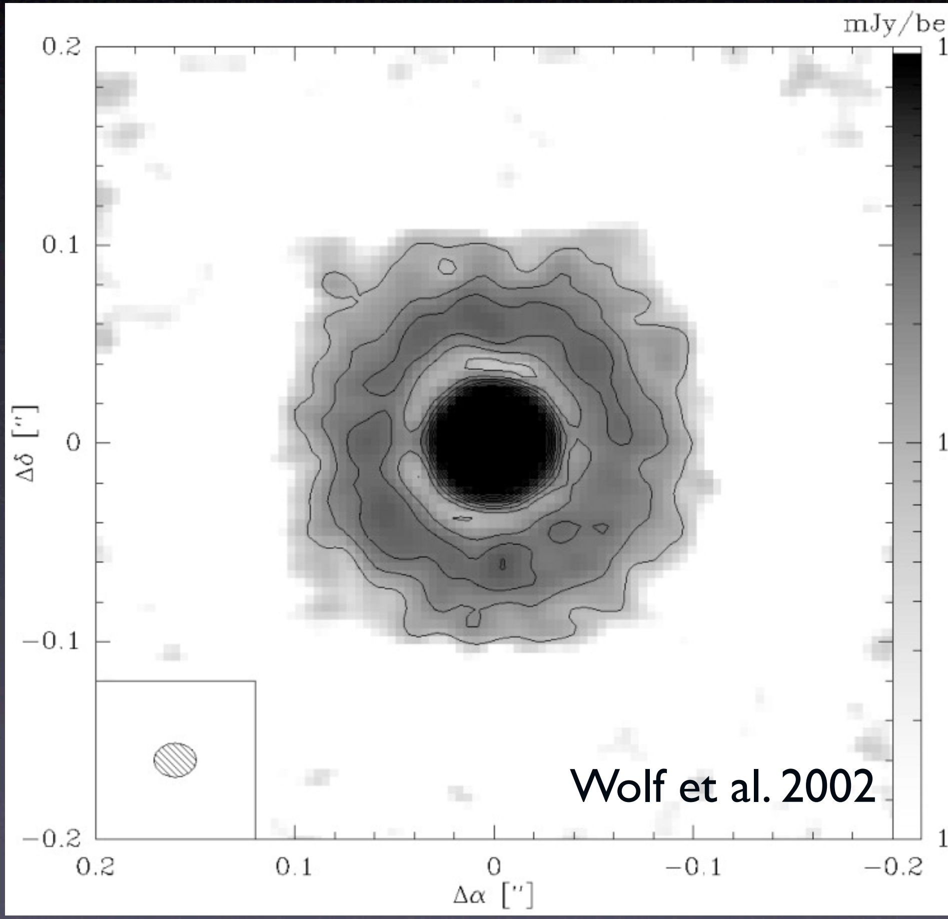




Images courtesy of Jayadev Rajagopal

Comparison to ELT/ALMA

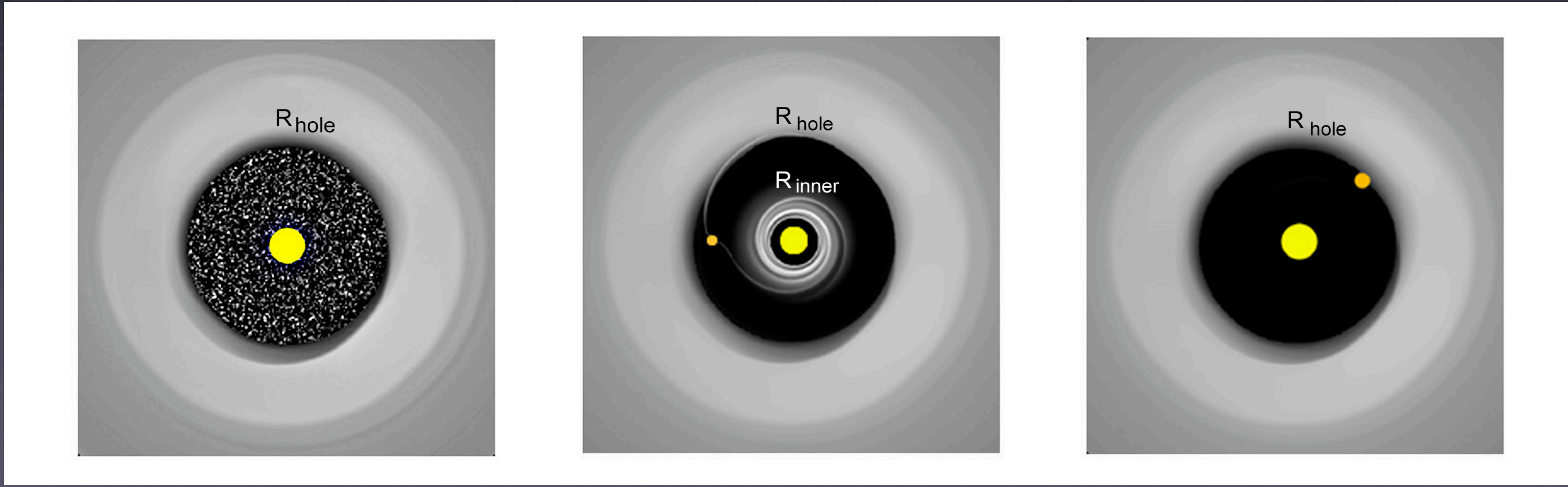
- Planets at larger radii more easily accessible with ALMA
  - at 5 AU, T~100 K; λ_{max}~30 μm
- Scattered light images with ELTs can also find gaps/ planets at >AU radii



Gaps/Holes

- "Transition objects" found by Spitzer
  - apparent inner clearings: planets?
  - evolutionary stage: gas dispersed?

Planetesimals Low-mass giant planet High-mass giant planet

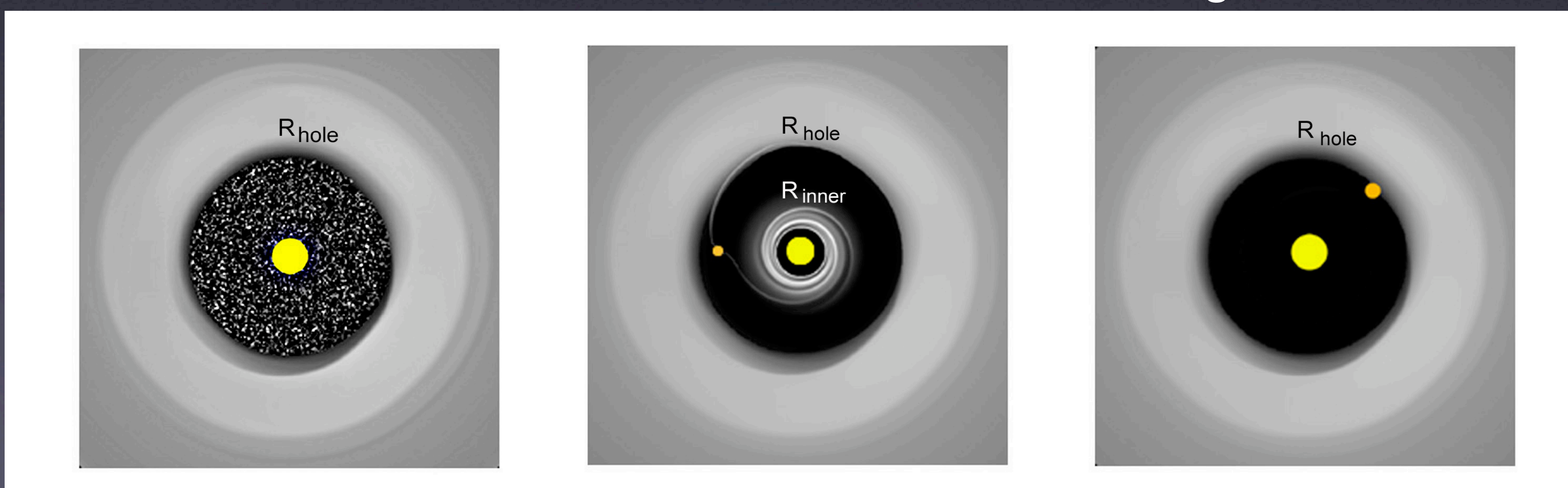


images courtesy of Joan Najita

Gaps/Holes & Gas

- Spatial distribution of gas can diagnose evolutionary stage

Gas within R_{hole} | Gas within R_{inner} | No gas within R_{hole}



Instrument Questions

- What resolution do we need?
  - e.g., for gaps, >100m baselines required
- What uv coverage do we need?
  - dynamic range for planet detection
  - complex geometries...
- What sensitivity do we need?
  - dictates aperture size and/or sky coverage

Spatial Resolution

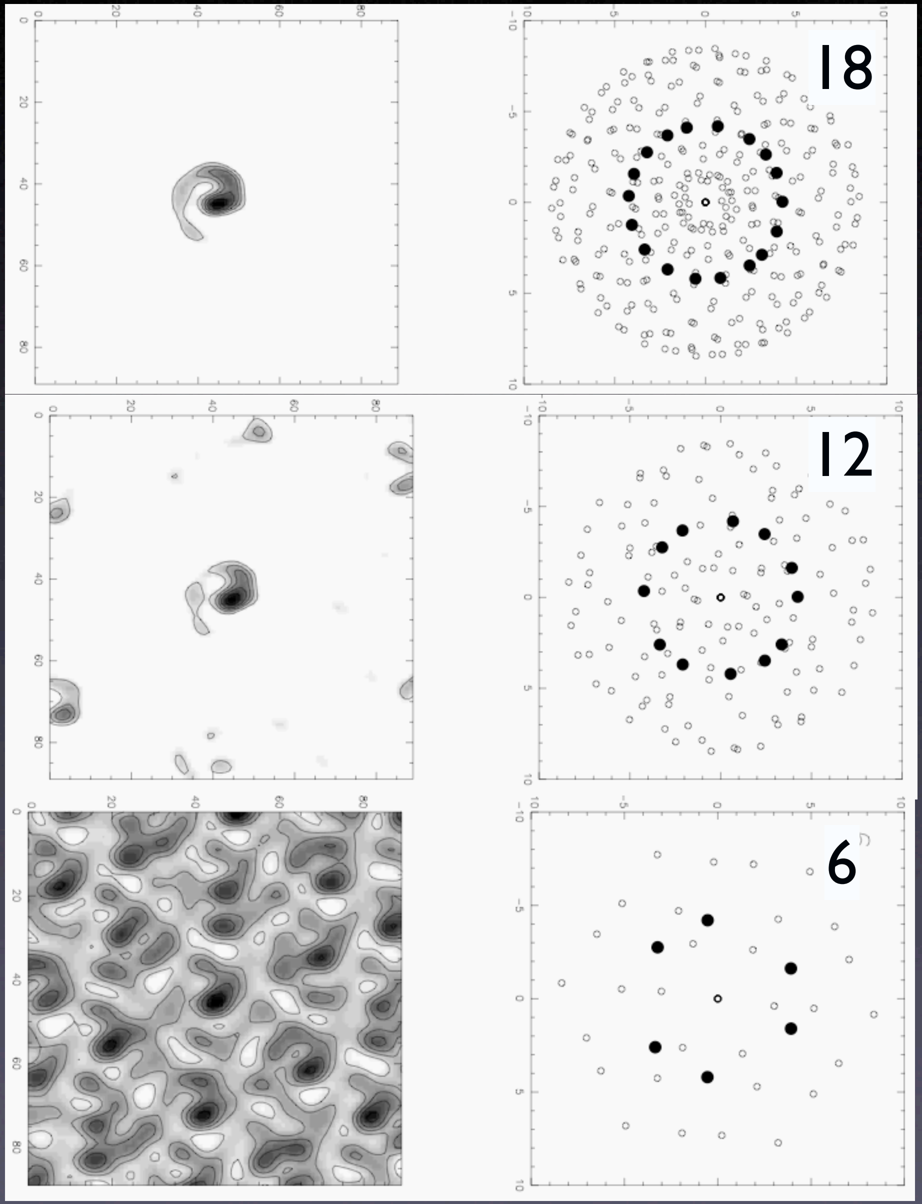
- 1 AU at Taurus: ~10 mas at 2 μm
  - ~100m baselines to resolve inner disk
- gap widths for M_J planet ~ 0.03 AU
  - >300m baselines to resolve gaps
- astrometry
  - $\sigma \sim \lambda$/B: longer baselines better

Spectral Resolution

- Disk Keplerian speeds ~1-10 km/s (similar for jets/infall)
  - want R~2000-20000 to resolve lines
- Dust/PAH features
  - R~1000 sufficient?

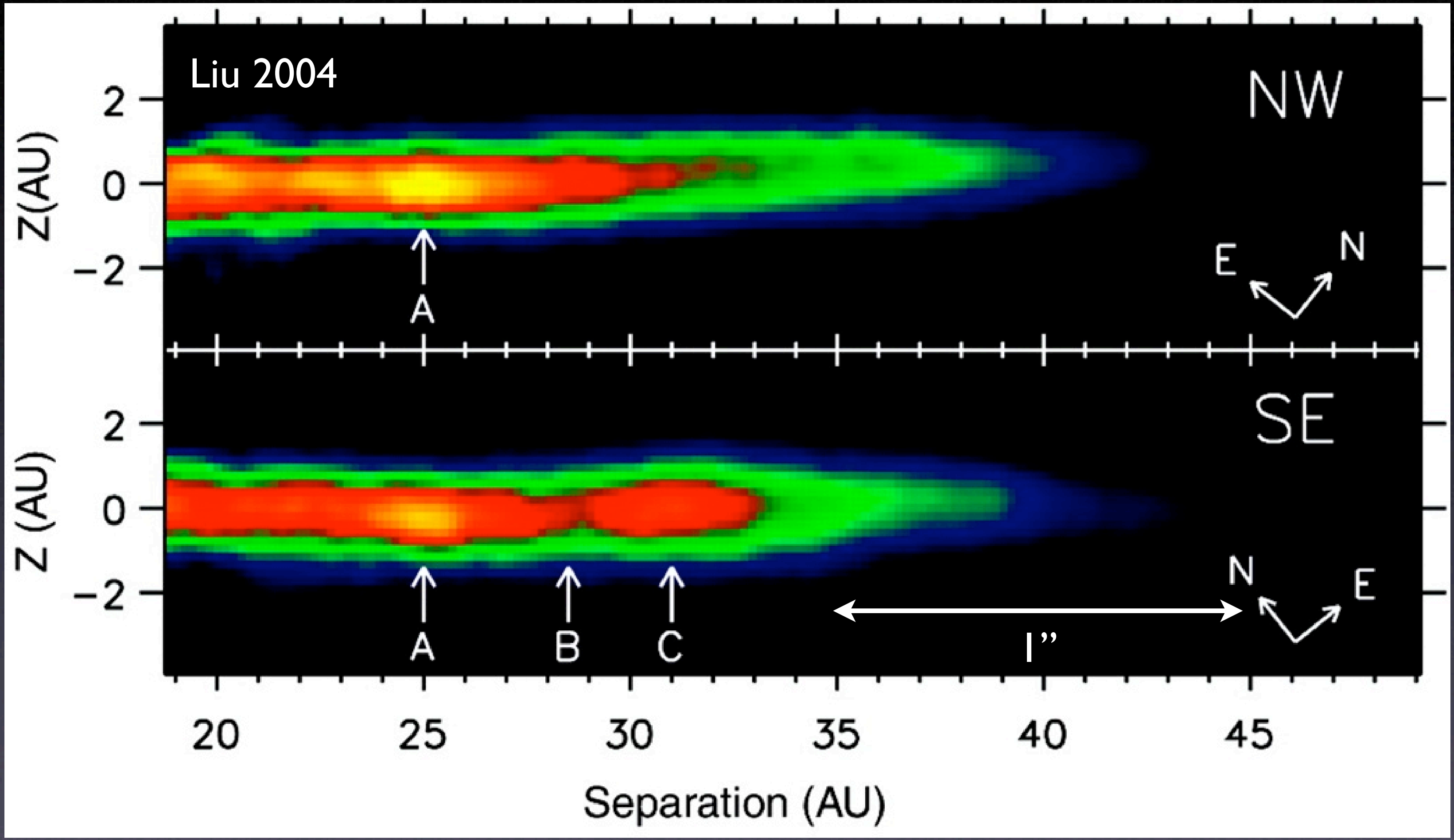
uv coverage

- Basic imaging
  - closure relations: 3-4 tels
  - more phase info w/ more tels
- High dyamic Range
  - Old disks: $F_{disk}/F_* < 0.01$
  - Planets: $F_{planet}/F_* < 10^{-3}$
  - need >10 elements
- Size scales: 0.01 - 10 AU
  - sparse or filled array?



Tuthill & Monnier 2000

Field of View



- large scales at high resolution
- Astrometry

Sensitivity

- hundreds of YSOs brighter than K~11; but often very red, V~15

- current limits- KI: K~10, V~12; VLTI: K~3, V~12 (?)
  - worse for smaller apertures
  - longer integratons (better sites) and/or phase referencing buys K sensitivity
  - LGS-AO or IR-AO is essential for YSO studies!

Prioritized Requirements?

- sub-mas resolution
  - unique capability of interferometers
- imaging
  - good dynamic range (>10^3 for planets)
  - nulling, espcially for more evolved systems where $F_*/F_{disk}>100$
- spectroscopy (and sensitivity)
  - v_{gas} ~1-100 km/s: R~1000-10000
- near to mid-IR: range of disk radii & processes