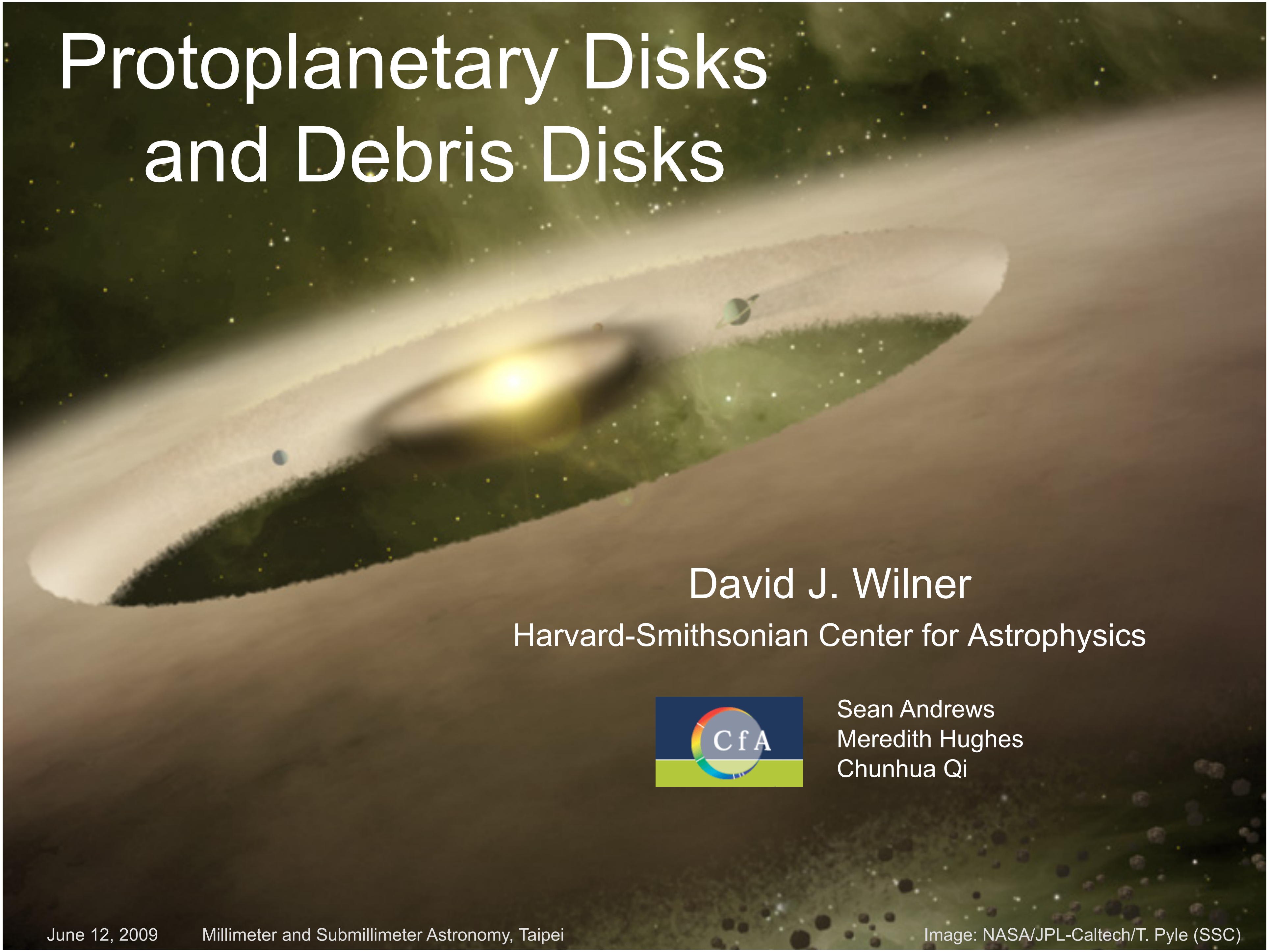

Protoplanetary Disks and Debris Disks

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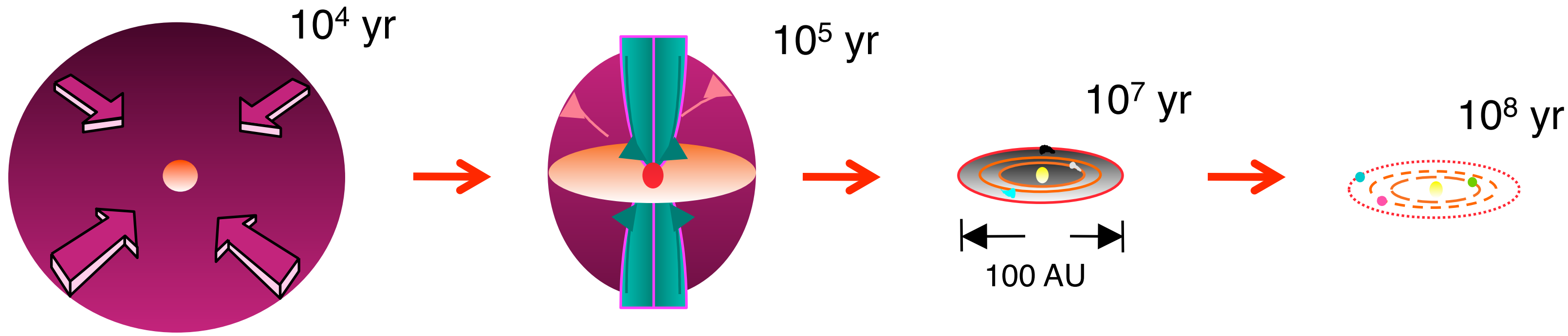
Sean Andrews
Meredith Hughes
Chunhua Qi

Image: NASA/JPL-Caltech/T. Pyle (SSC)

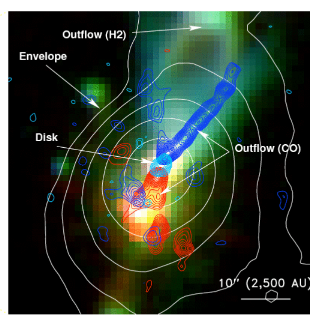
Circumstellar Disks

- inevitable consequence of gravity + angular momentum
- integral part of star and planet formation paradigm

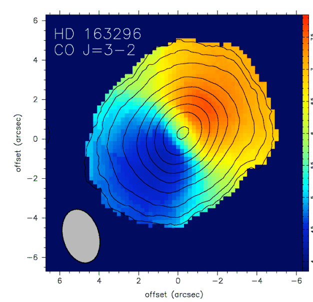


cloud collapse *protostar* ***protoplanetary disk*** *planetary system and **debris disk***

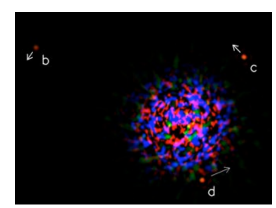
Alves et al. 2001



J. Jørgensen



Isella et al. 2007



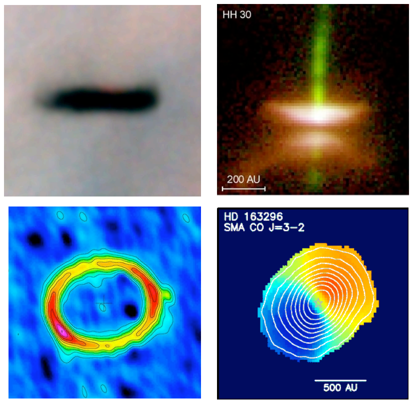
Marrois et al. 2008

This Talk

- context: “protoplanetary” and “debris” disks
- tool: submillimeter dust continuum emission
- some recent SMA studies and implications

1. high resolution ρ Oph disk imaging survey
   - *S. Andrews*, D. Wilner, A.M. Hughes, C. Qi, K. Dullemond (arxiv:0906.0730)
2. resolved disk polarimetry: TW Hya, HD 163296
   - *A.M. Hughes*, D. Wilner, J. Cho, D. Marrone, A. Lazarian, S. Andrews, R. Rao
3. debris disk imaging: HD 107146
   - D. Wilner, J. Williams, S. Andrews, A.M. Hughes, C. Qi

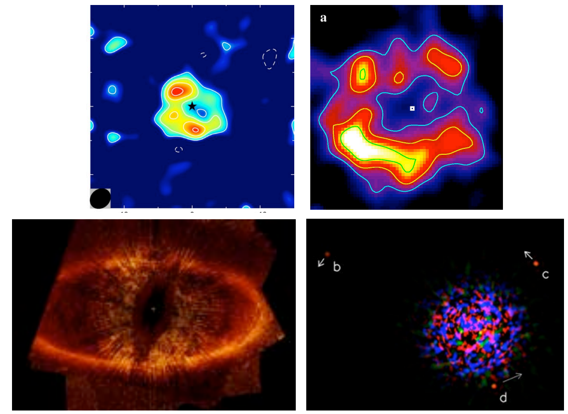
“Protoplanetary” → “Debris”



McCaughrean et al. 1995; Burrows et al. 1996
V. Pietu; Isella et al. 2007

- age ~1 to 10 Myr
- gas and trace dust
- dust particles are sticking, growing into planetesimals
- mass 0.001 to 0.1 $M_{\odot}$

- *mass distribution?*
- *accretion/dispersal physics?*

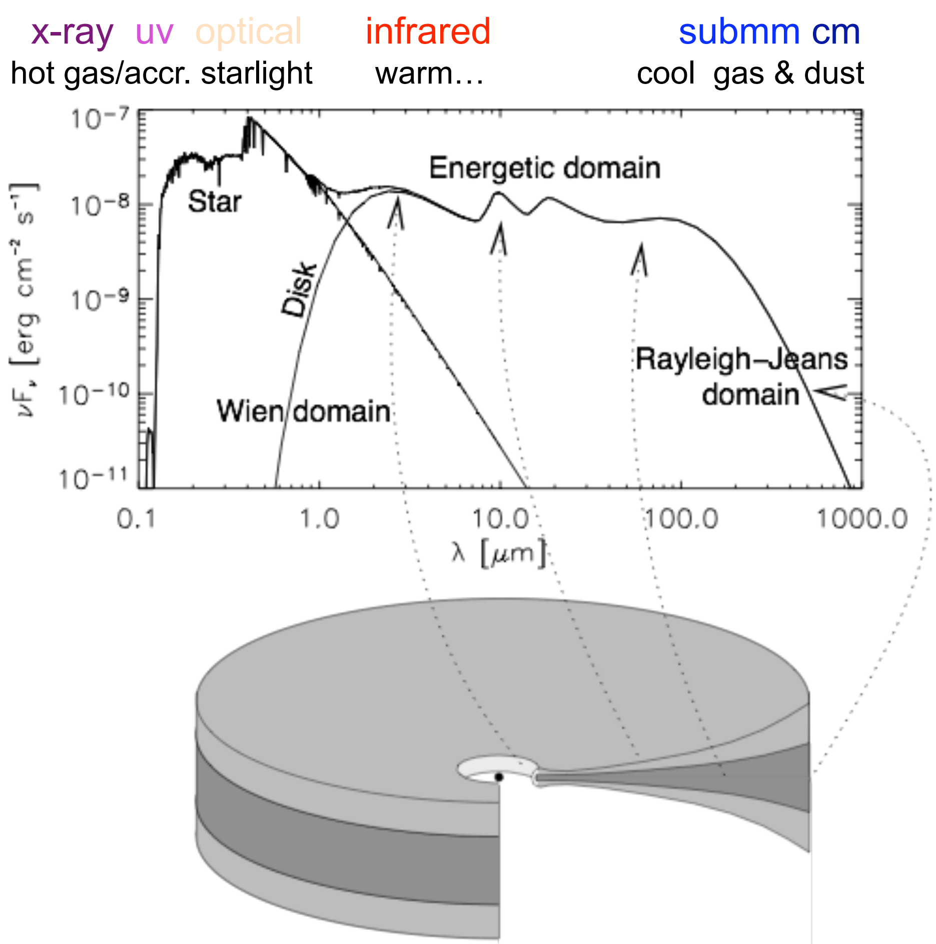


Corder et al 2009; Greaves et al. 2005
Kalas et al. 2008; Marois et al. 2008

- age up to Gyrs
- dust and trace gas
- planetesimals are colliding, creating new dust particles
- mass <1 M_{moon}

- *dust distribution → planets?*
- *dynamical history?*

Submillimeter Dust Emission



Dullemond et al. 2007

- sensitive to “cold” dust (*including mid-plane*)
- low opacity: $S \propto \kappa\, \Sigma\, T$
- no contrast problem with stellar photospheres
- high angular resolution using interferometry
- $\kappa(\lambda) \rightarrow$ dust diagnostic
- polarization $\rightarrow$ B field

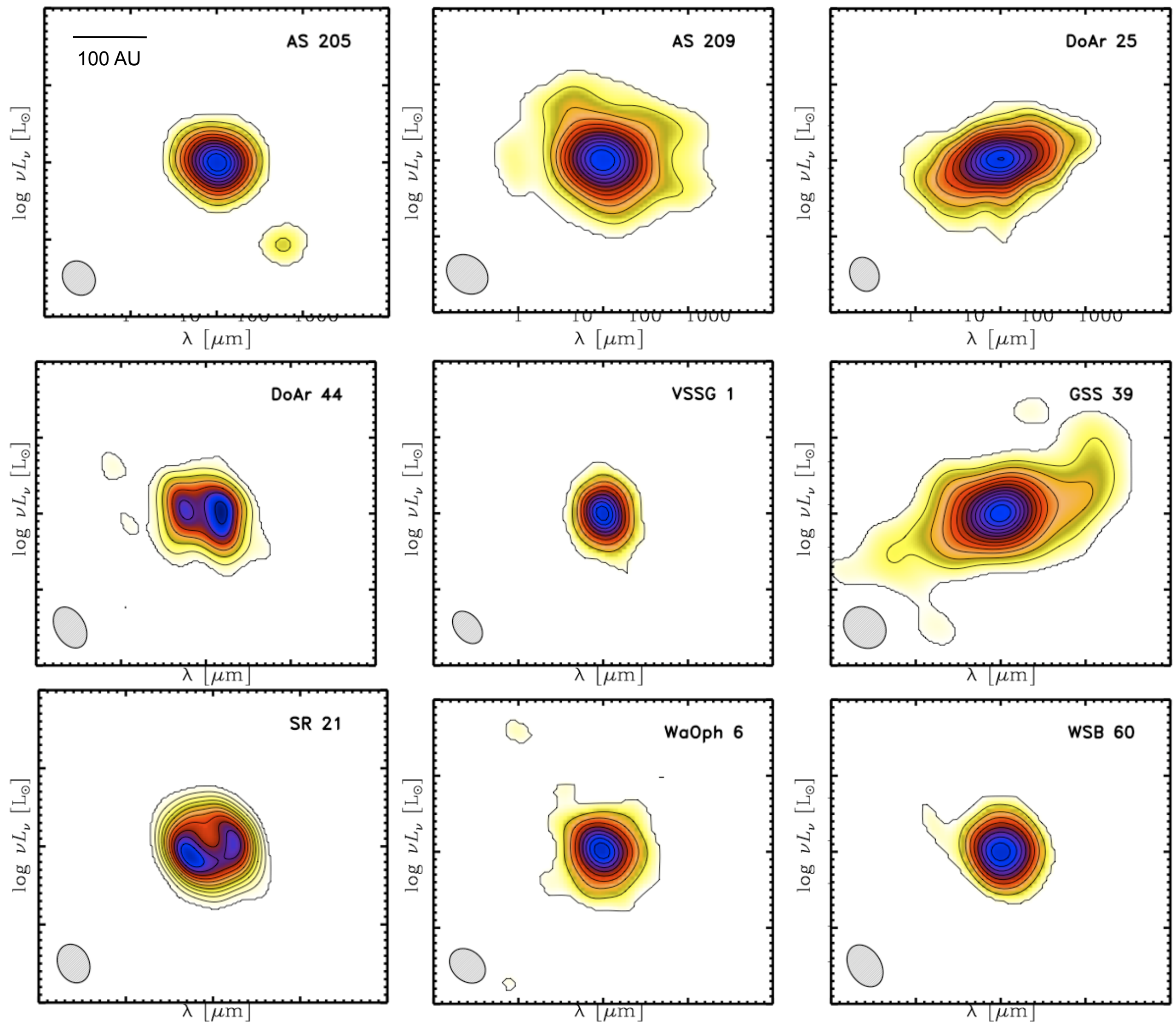
SMA ρ Oph Disk Survey

1 Myr old, d ~125 pc

870 μm , <0.3" = 40 AU

"flux limited" survey:

9 so far, 8 more



Andrews et al. 2009

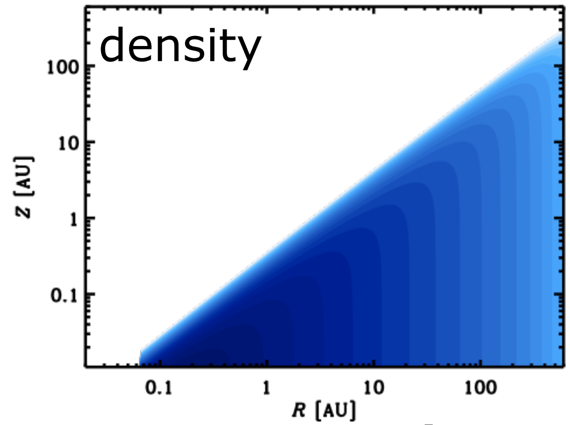
Modeling Disk Structure

parametric density structure

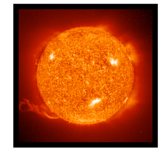
$$\rho(R,Z) = \frac{\Sigma}{\sqrt{2\pi}H} \exp\left[-\frac{1}{2}\left(\frac{Z}{H}\right)^2\right]$$

$$\Sigma(R) \propto \left(\frac{R}{R_c}\right)^{-\gamma} \exp\left[-\left(\frac{R}{R_c}\right)^{2-\gamma}\right]$$

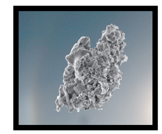
$$H(R) \propto R^{\psi}$$



+

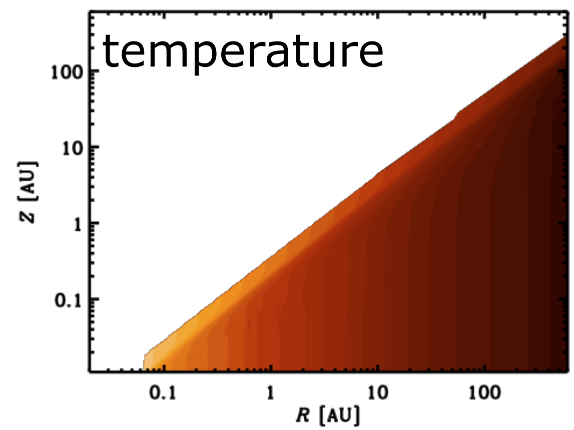


&

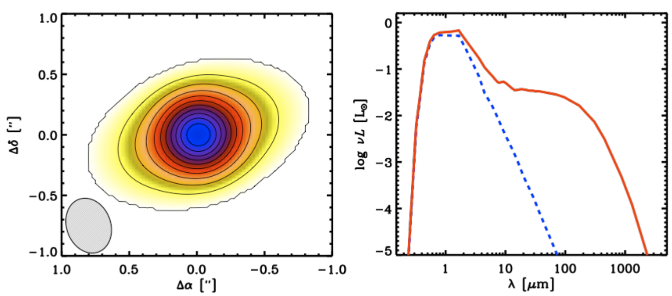


2-D Monte Carlo radiative transfer

Dullemond & Dominik 2004

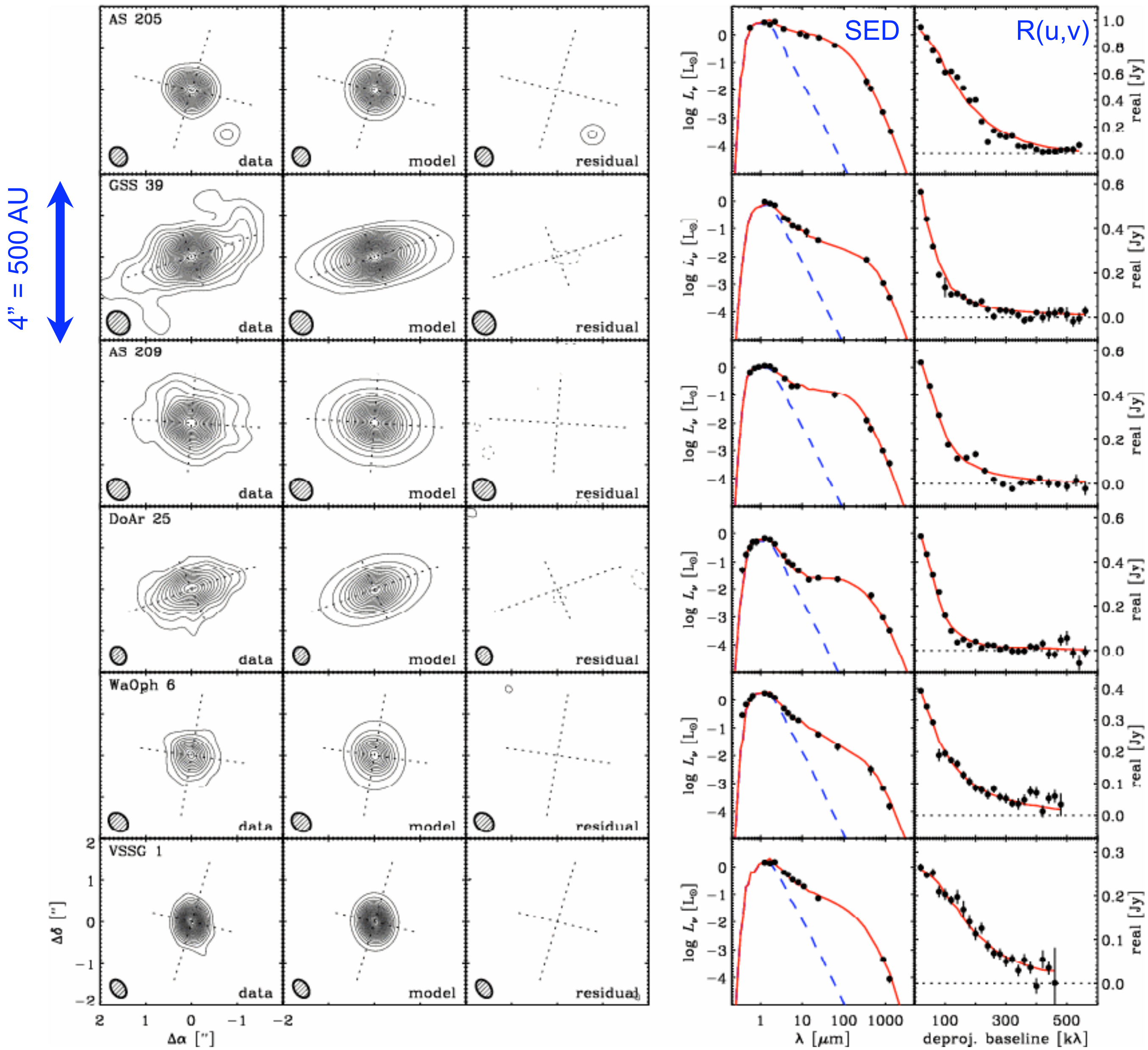


compare with data



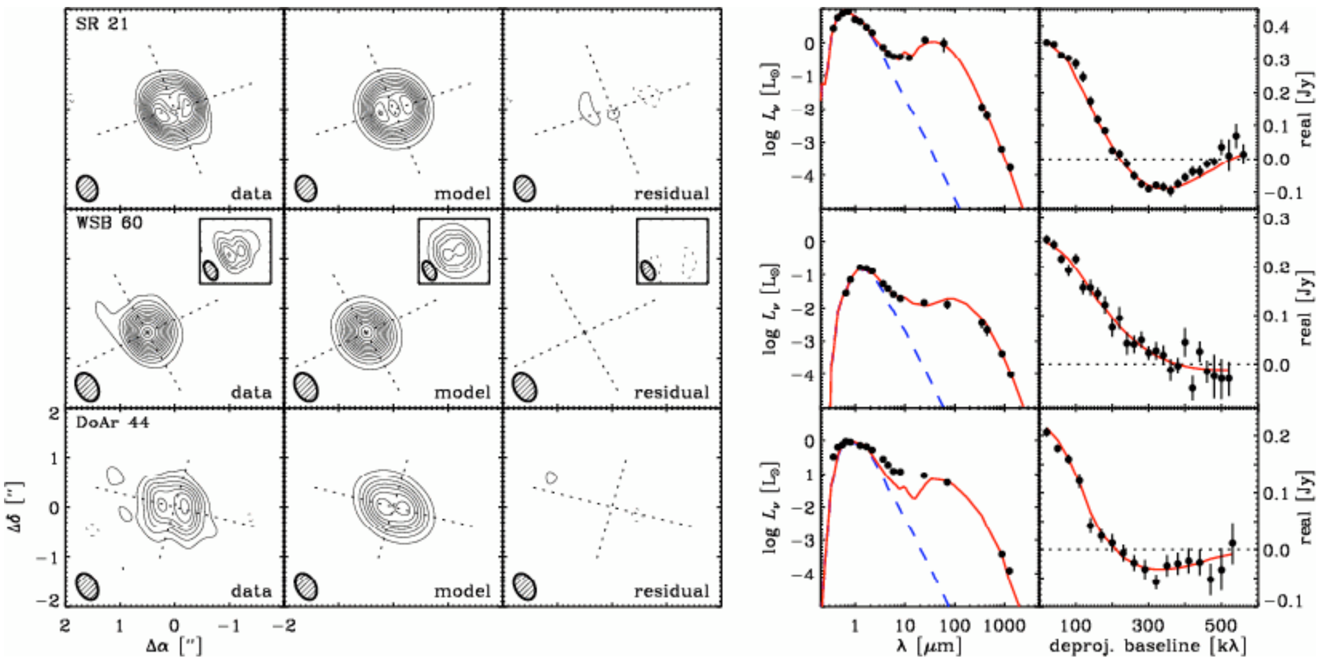
synthetic visibilities + SED

Modeling Results

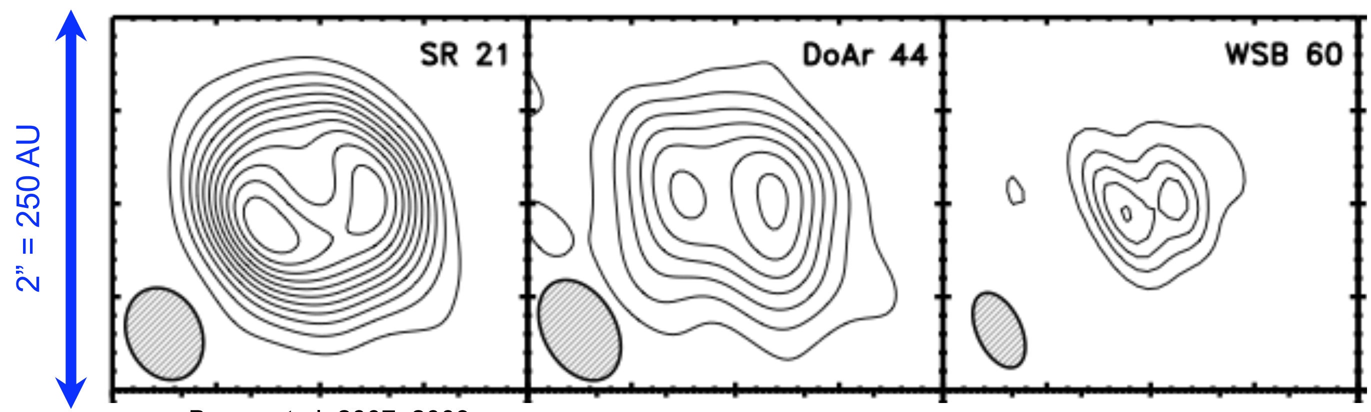


Andrews et al. 2009

Modeling Results: Holes



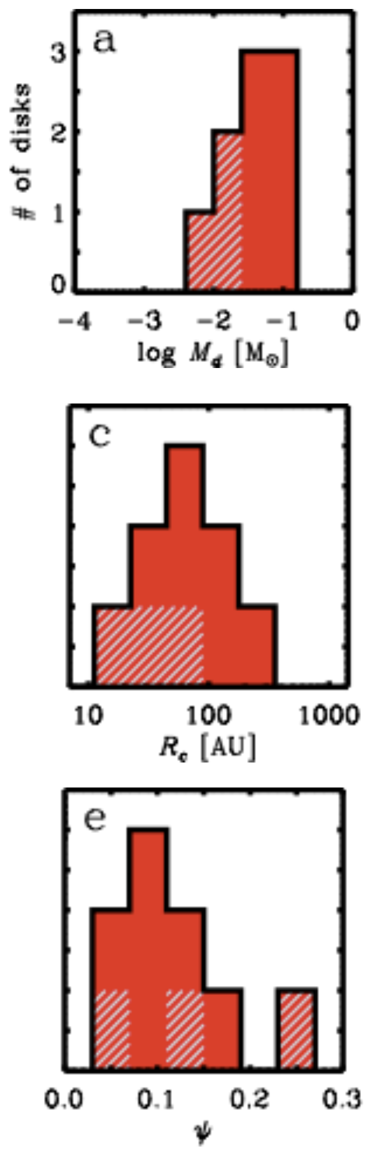
Andrews, et al. 2009

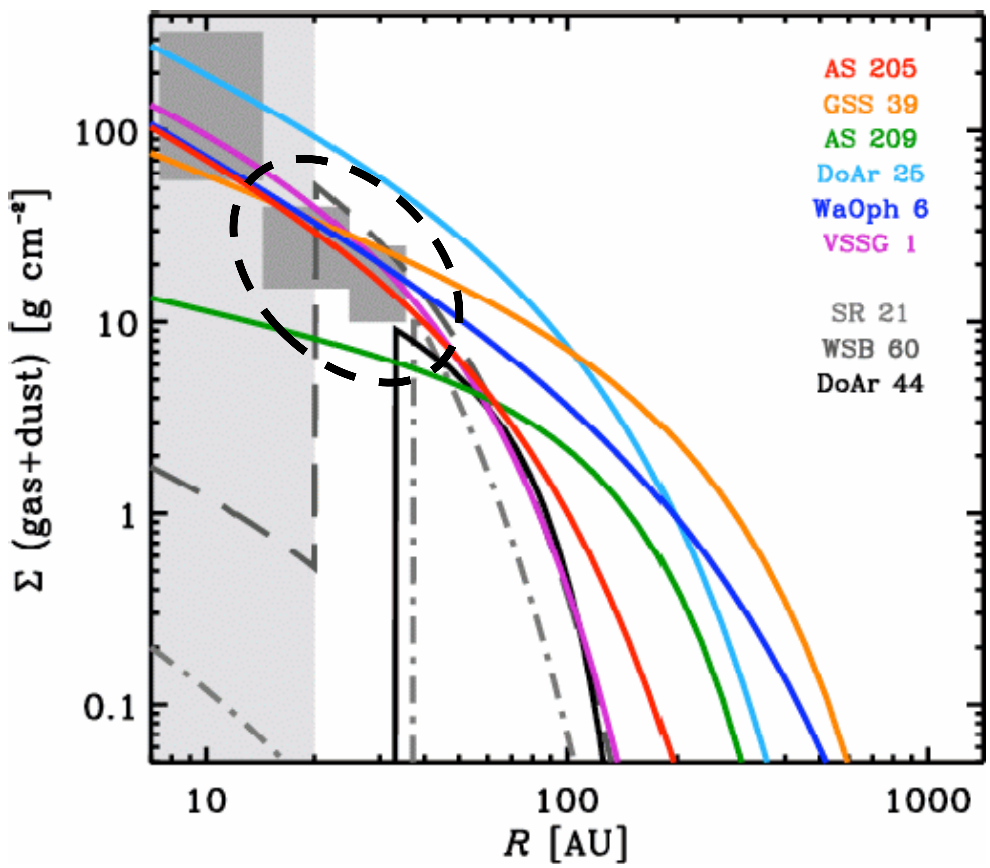


see Brown et al. 2007, 2009

pi disk, 2900-2200 BC

Modeling Results: Parameters





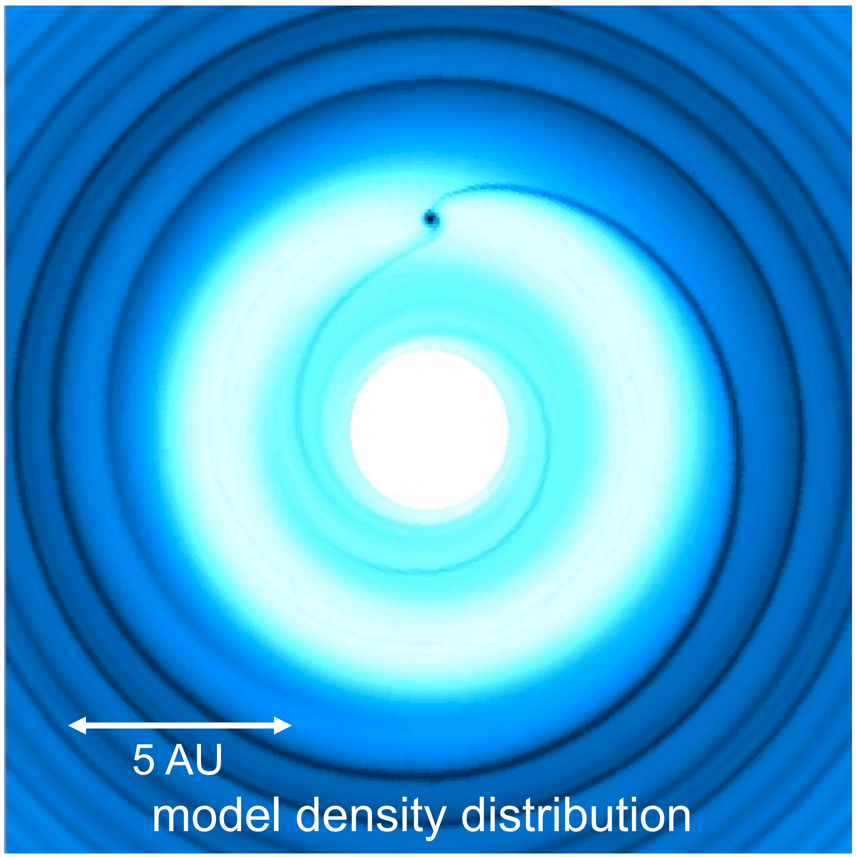
Andrews et al. 2009

Remarks

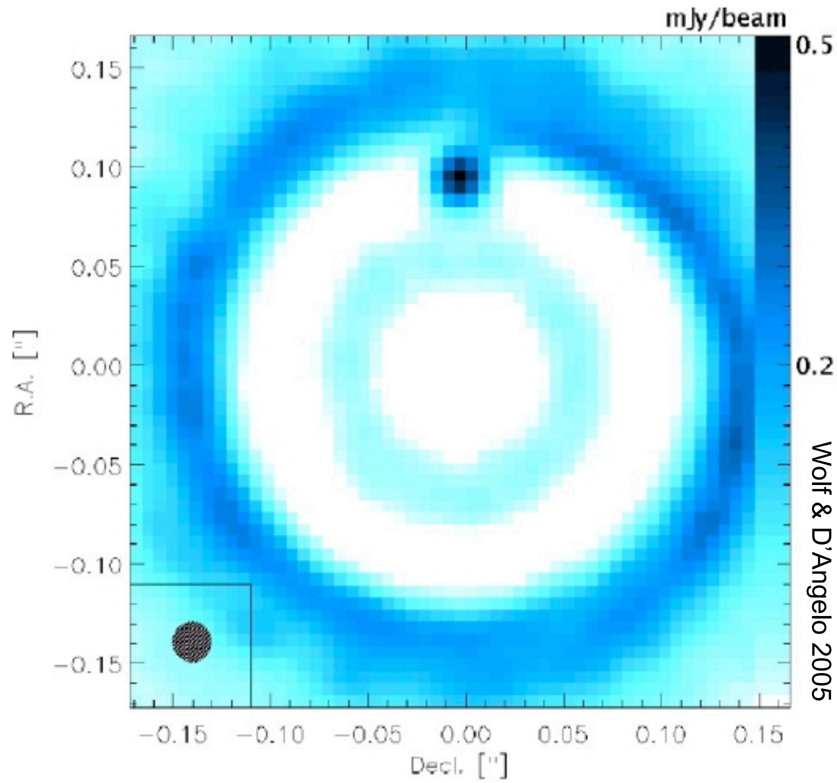
- densities comparable to “Minimum Mass Solar Nebula” for R ~ 10 to 40 AU (modulo our knowledge of κ)
- substantial mass reservoirs at R > 40 AU
- $\gamma \cong 1$, consistent w/structure set by viscous torques
- good planet formation potential by core accretion
- gravitationally stable at all radii
- significant fraction show large central holes: 3/9
  - sizes ~20 to 40 AU, density contrast > 20 to 100
  - outer disk densities comparable to the continuous disks
  - most likely due to *unseen companions*: brown dwarf/planet (cf. Pietu et al. 2006, Hughes et al. 2007, 2009, Brown et al. 2008, 2009)
  - the oldest stars in the sample (a clue?)

At the Limits of ALMA

hypothetical giant planet in the disk around TW Hya



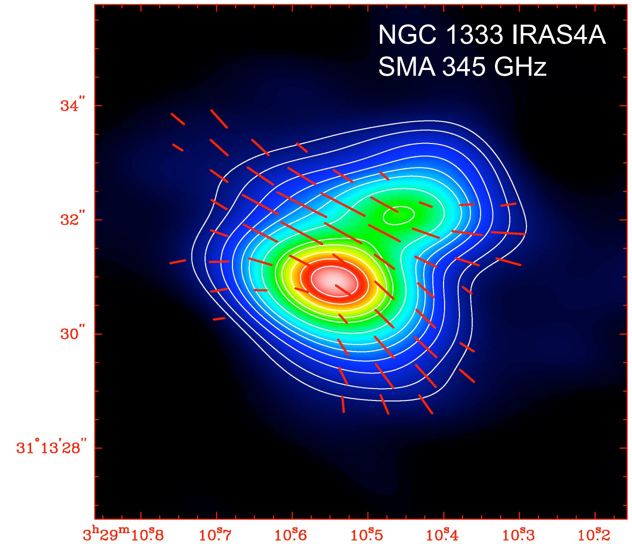
simulated ALMA image of 0.3 mm dust continuum emission



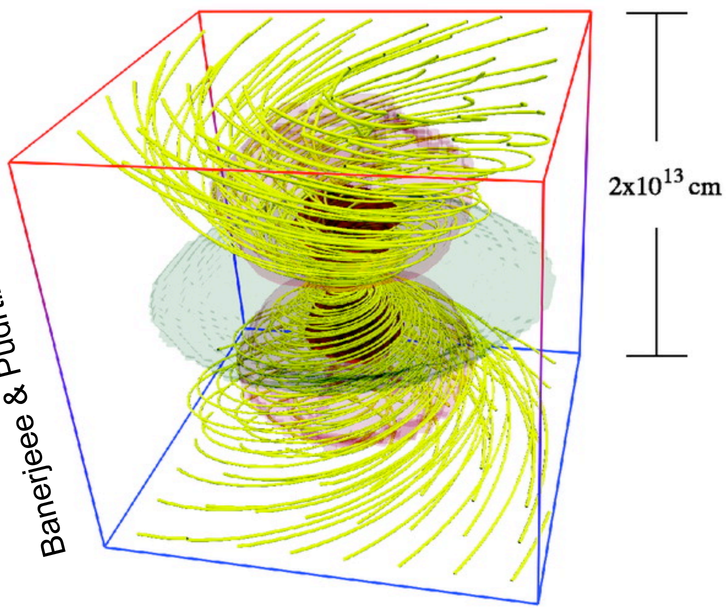
Wolf & D'Angelo 2005

Disk Magnetic Fields

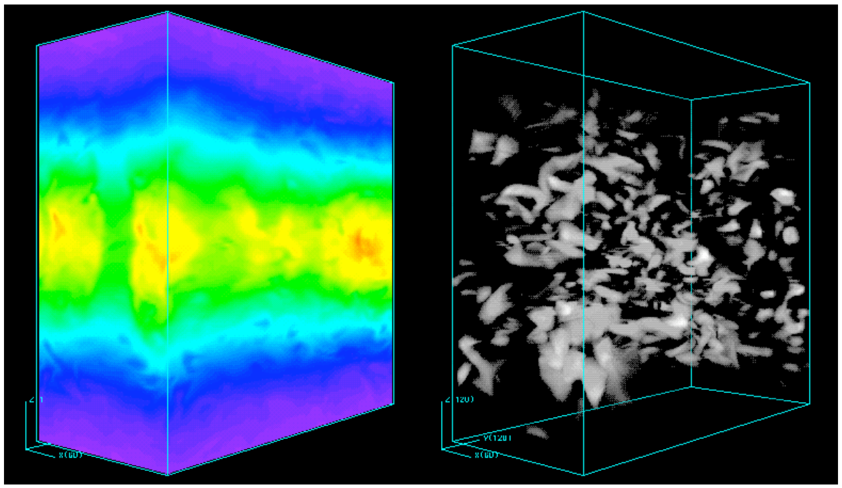
- B fields present (and probably important) in clouds and cores
- B field required for MRI-driven turbulence: viscosity source, enhance/inhibit grain growth, chemical mixing, …



Girart et al. 2007



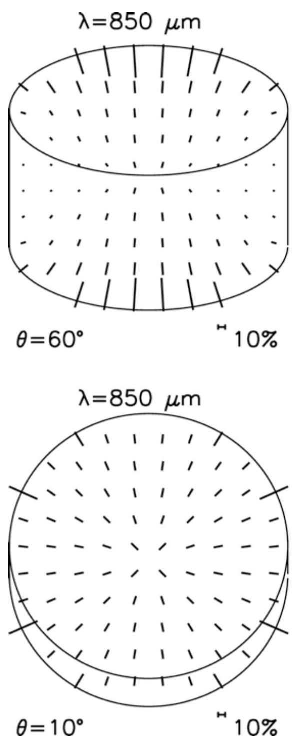
Banerjeee & Pudrtiz 2006

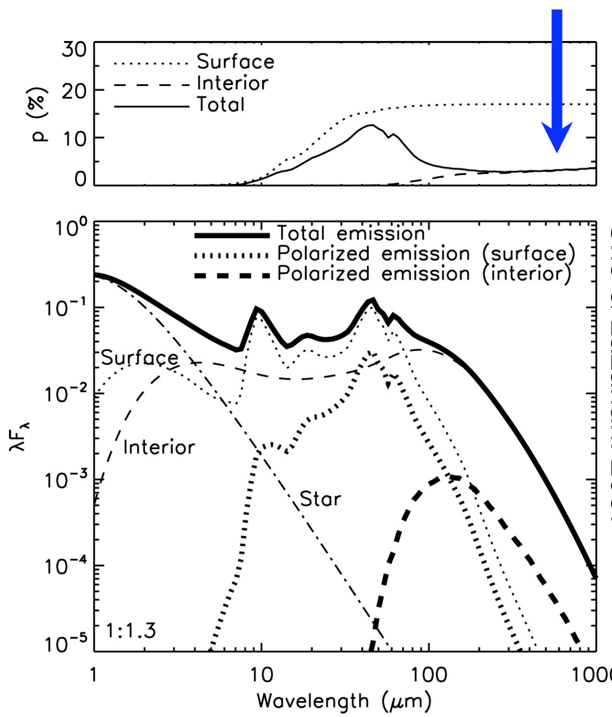


Stone et al. 1996

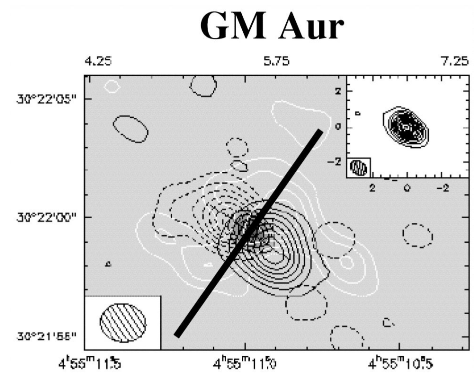
Polarized Disk Dust Emission

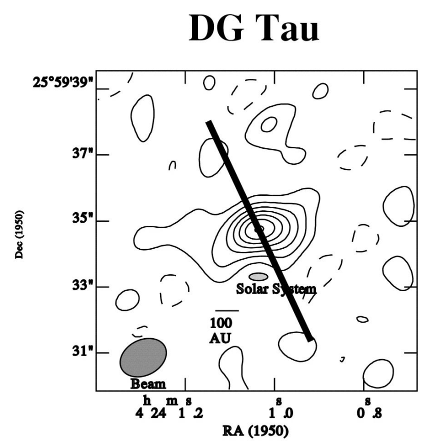
- two tentative (3σ) detections of ~3% linearly polarized dust emission (JCMT)
  - toroidal B field geometry
- first realistic models of polarized dust emission predict 2-3% pol. in submm
  - grain alignment by radiative torques





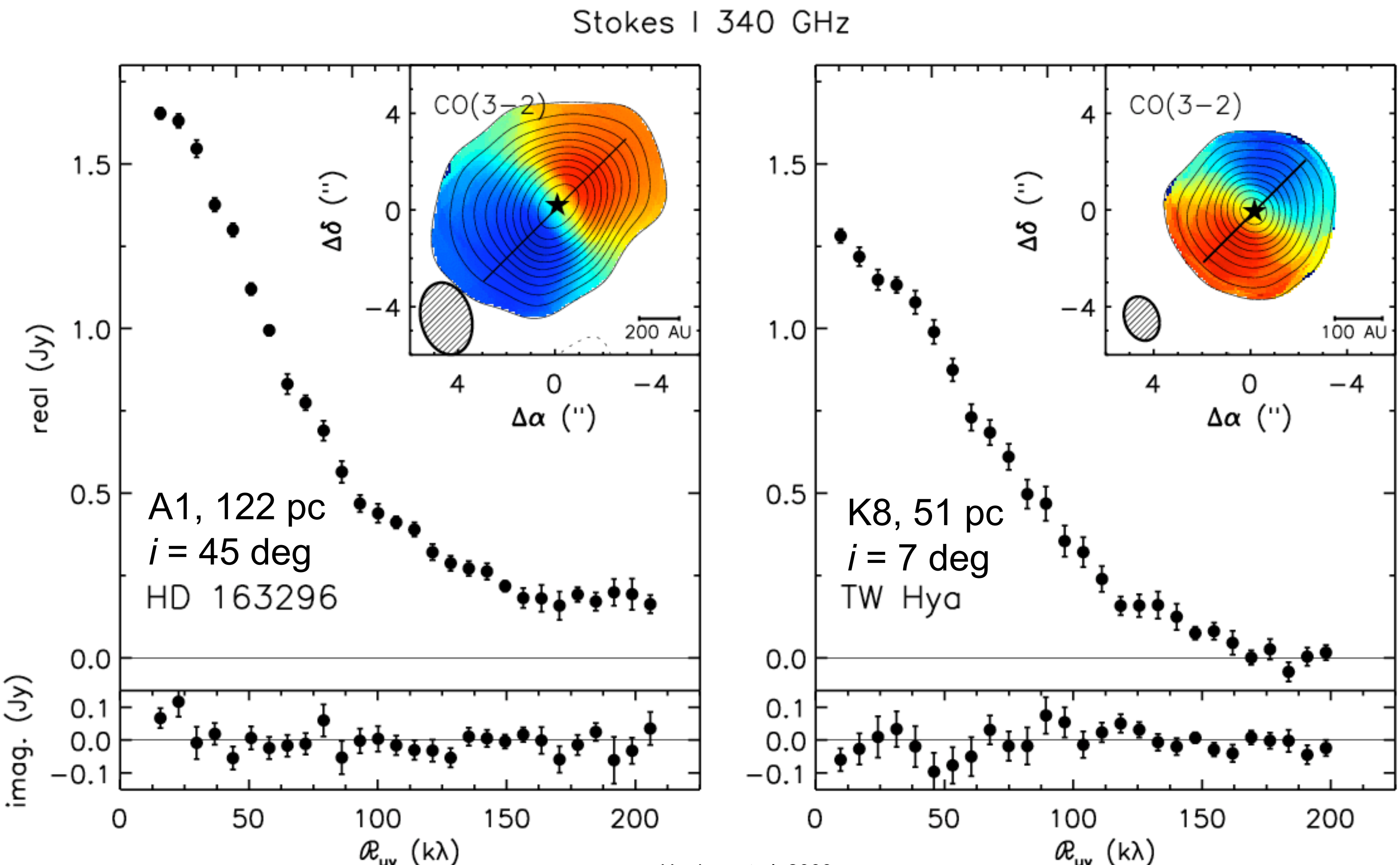
Cho & Lazarian. 2007





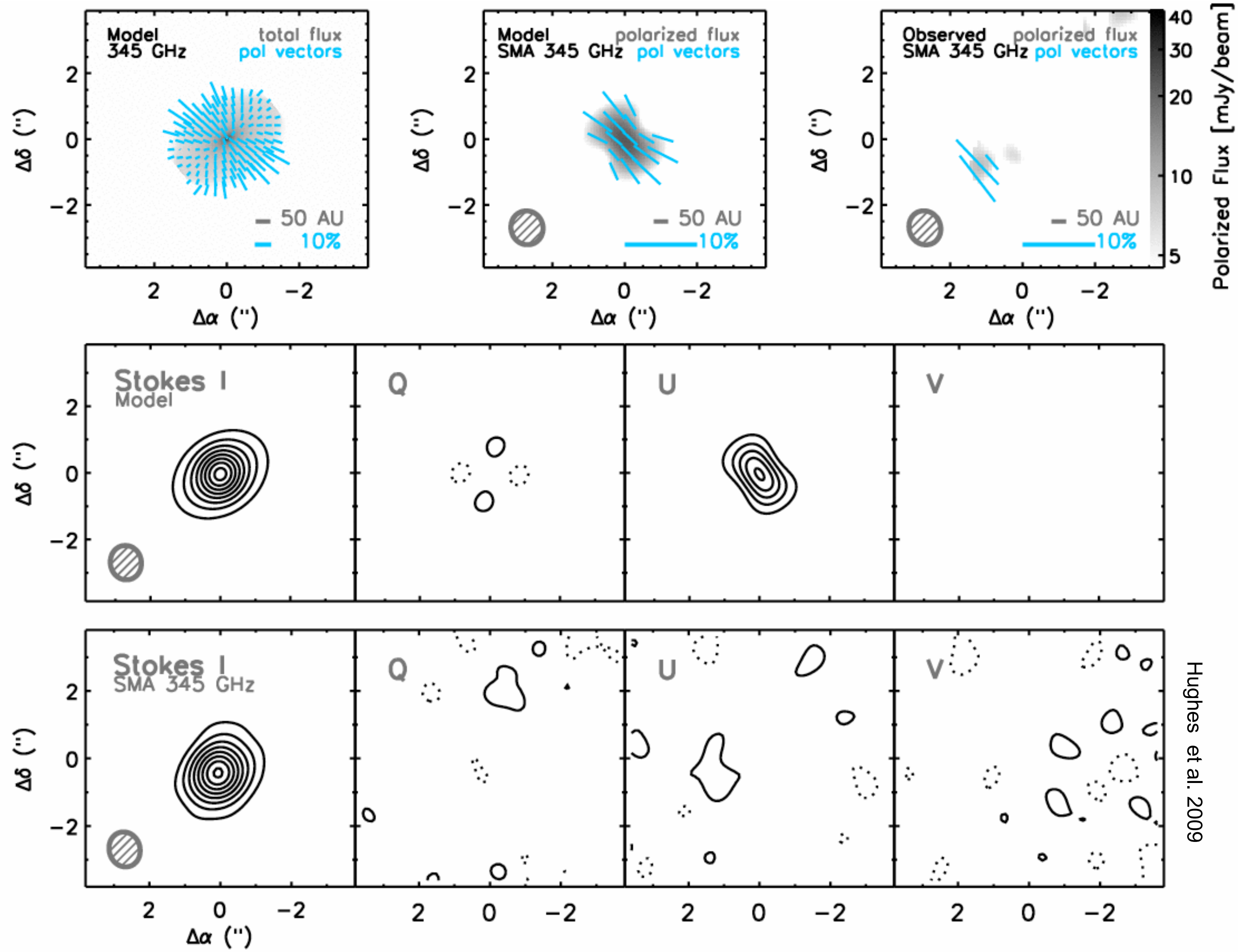
Tamura et al. 1999

SMA: Two Large, Bright Disks



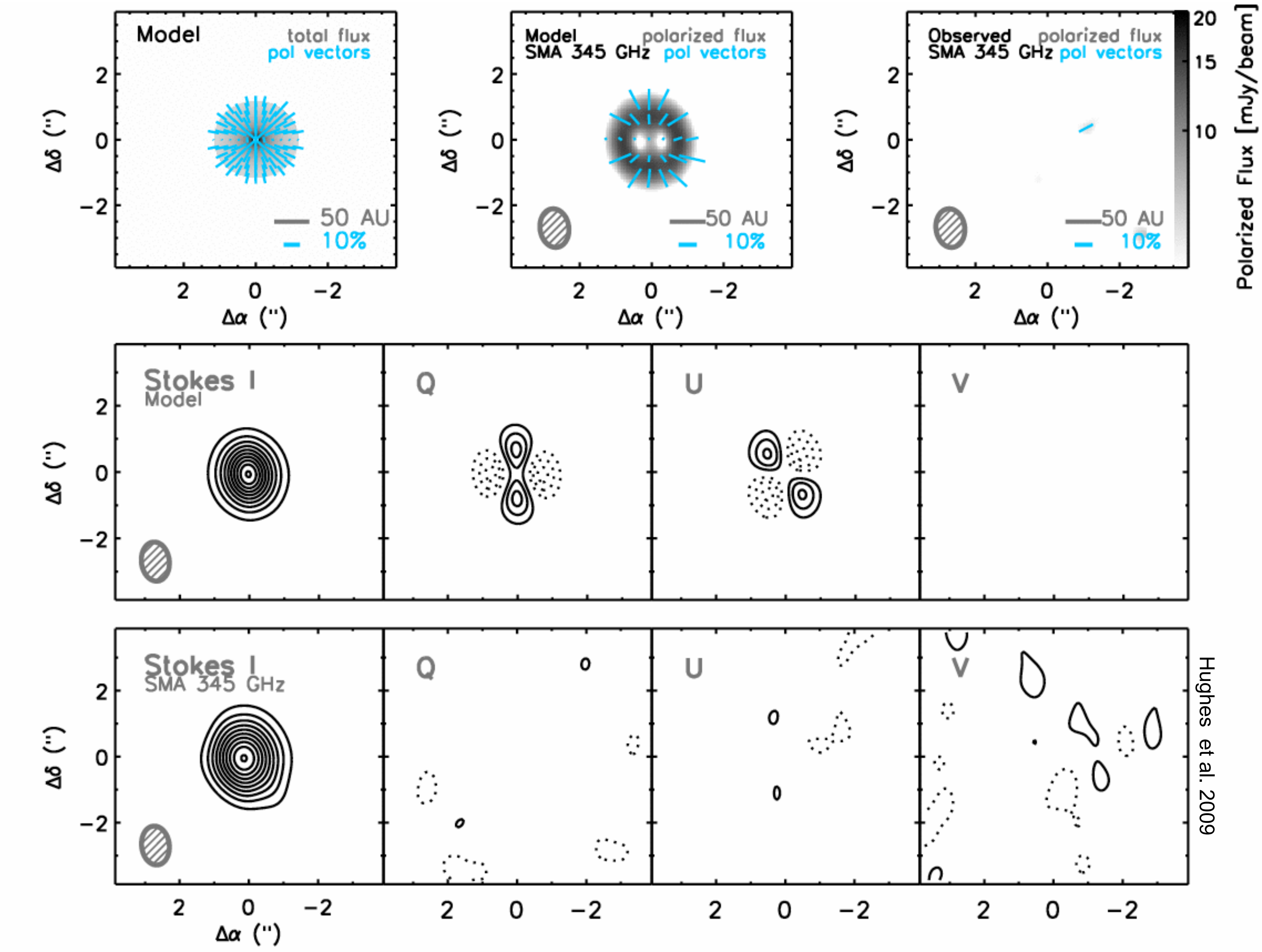
Hughes et al. 2009

HD 163296



Hughes et al. 2009

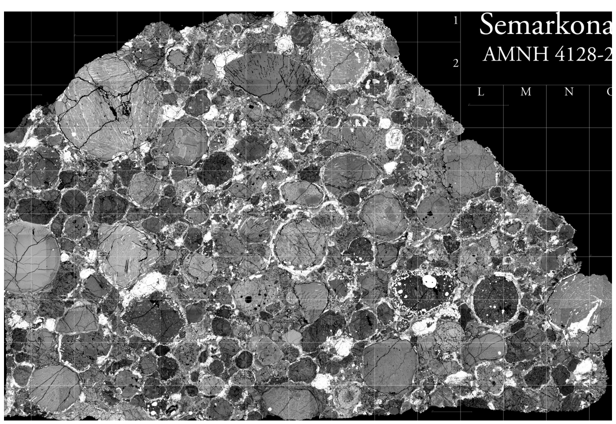
TW Hya

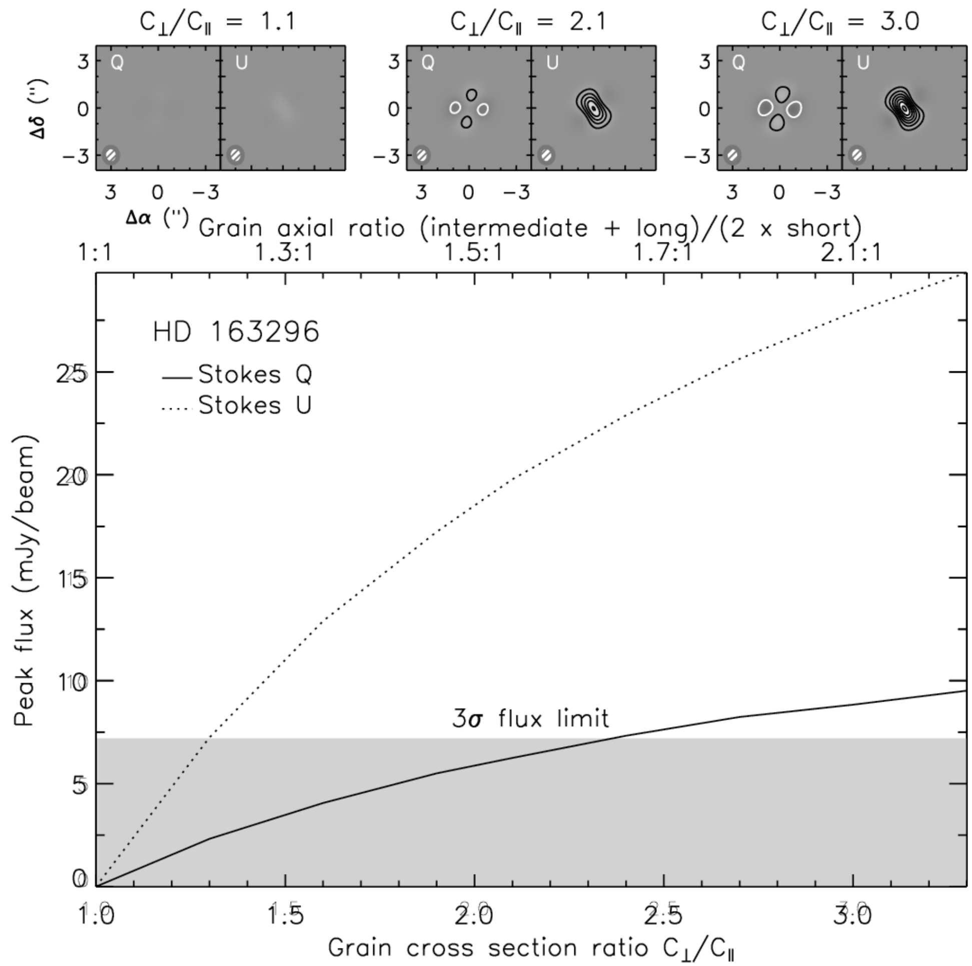


Hughes et al. 2009

Modeling Polarization

- fiducial model is ruled out at 10-12σ level
- parameters that affect polarization
  - grain elongation
  - alignment criterion
  - B field orderliness
  - B field strength
  - scattering
  - …





Modeling Polarization

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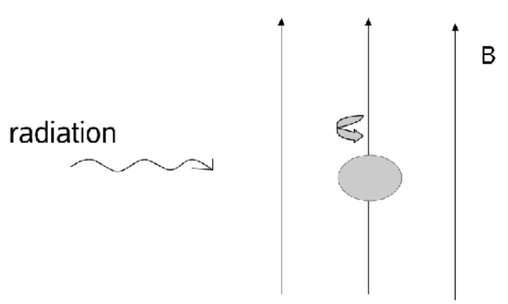
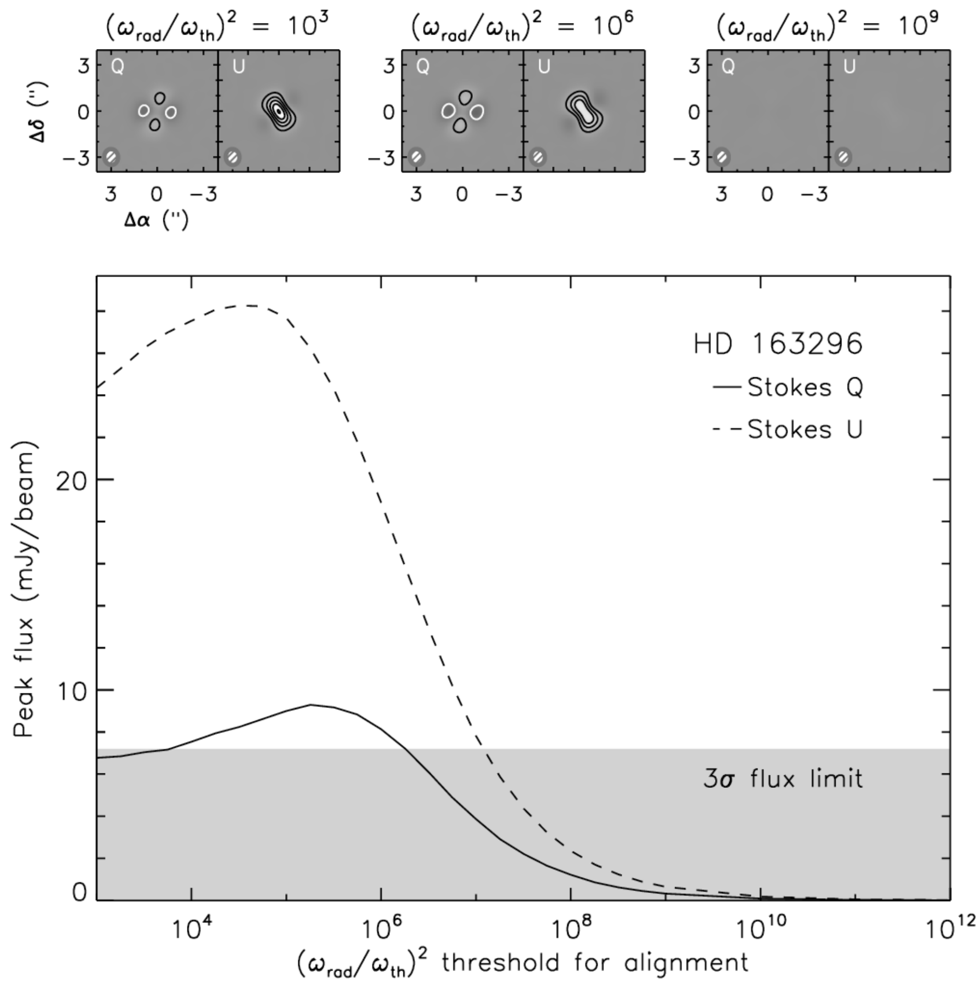


condition for alignment = fast rotation



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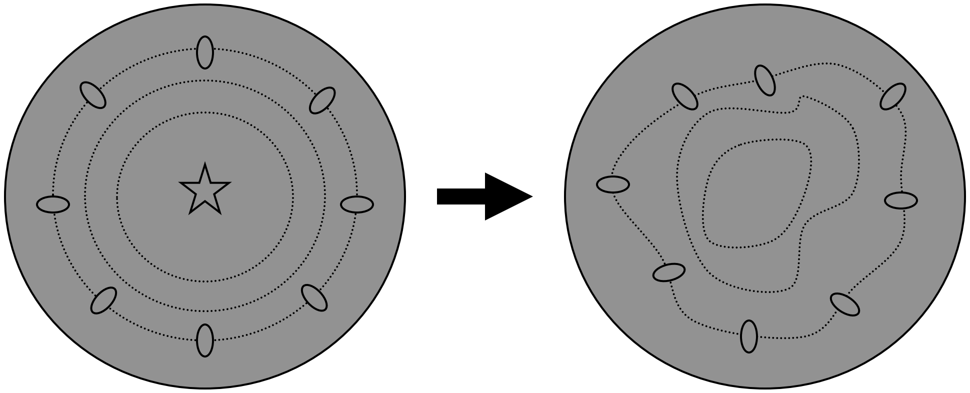

$$F = 3/2(\langle \cos^2 \theta \rangle - 1/3)$$

Modeling Polarization

- fiducial model is ruled out at 10-12σ level
- parameters that affect polarization
  - grain elongation
  - alignment criterion
  - B field orderliness
  - B field strength
  - scattering
  - …

$$\tau_{Larmor} < \tau_{damp}$$

$$\rightarrow B_{crit} \sim 10\ \mathrm{mG}$$

lower limit, see Lazarian & Hoang 2008

Modeling Polarization

- fiducial model is ruled out at 10-12σ level
- parameters that affect polarization
  - grain elongation
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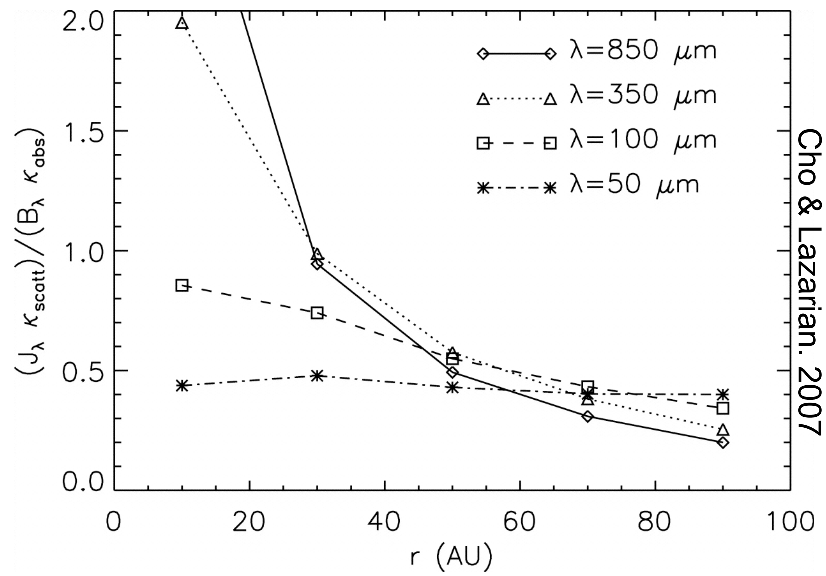
  - B field orderliness
  - B field strength
  - scattering
  - …

$$J_\lambda \, \kappa_{scatt} < B_\lambda \, \kappa_{abs}$$

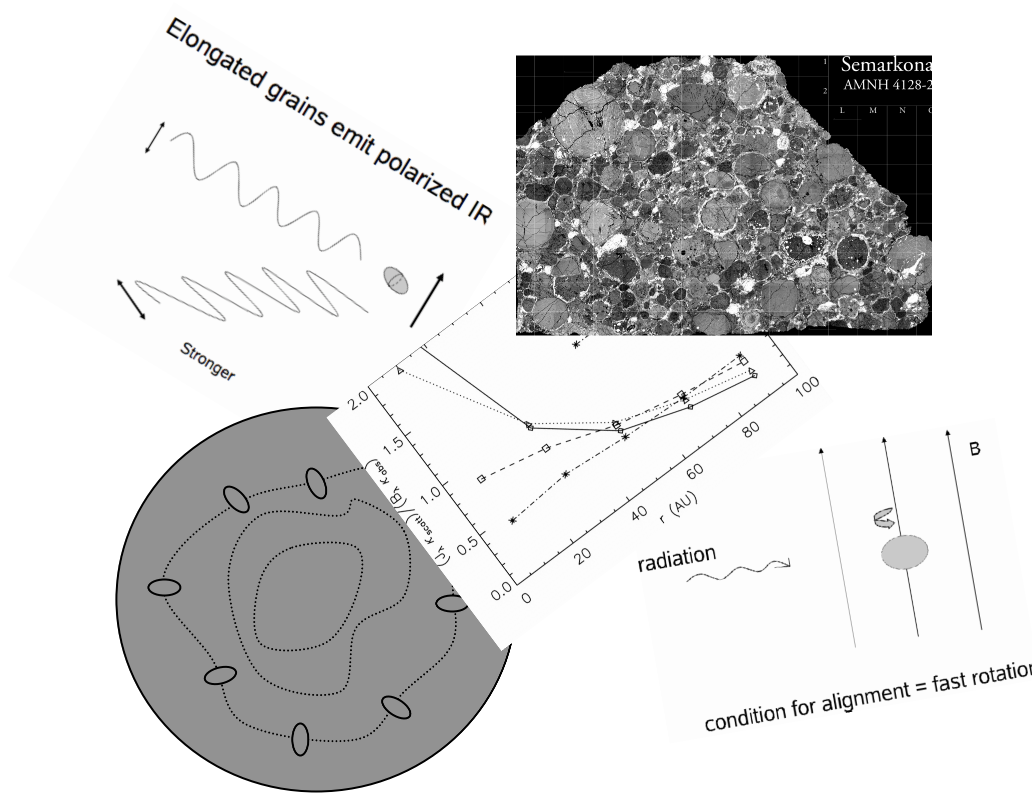


Cho & Lazarian. 2007

(n.b. scattering pol. direction in disk perpendicular to emission pol. direction)

Modeling Polarization

- fiducial model is ruled out at 10-12σ level
- parameters that affect polarization
  - grain elongation
  - alignment criterion
  - B field orderliness
  - B field strength
  - scattering
  - …
  - combinations



Modeling Polarization

- fiducial model is ruled out at 10-12σ level
- parameters that affect polarization
  - grain elongation
  - alignment criterion
  - B field orderliness
  - B field strength
  - scattering
  - …
  - combinations

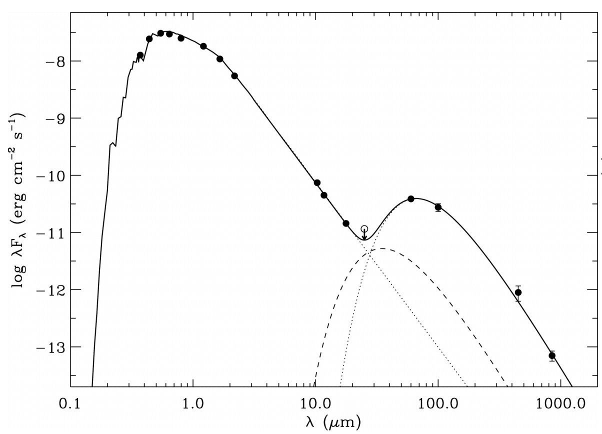
noise comparable to "leakage" correction uncertainty at ~0.2% level

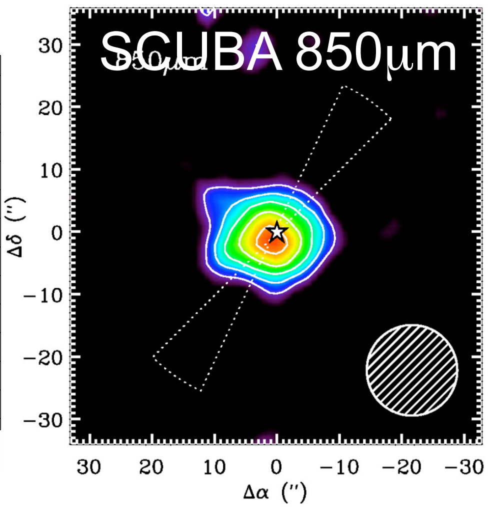
$\rightarrow$ *at limiting instrumental precision of SMA (ALMA?)*

HD 107146 Debris Disk

G2V, 28.5 pc, age 80-200 Myr: close analog of young Sun

Williams et al. 2004



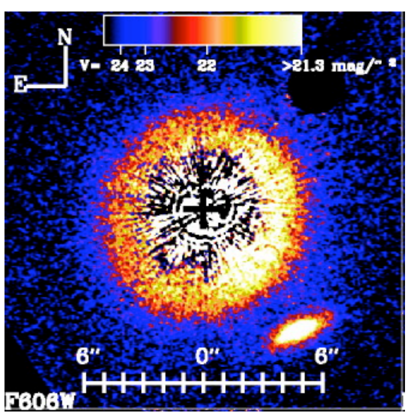


properties

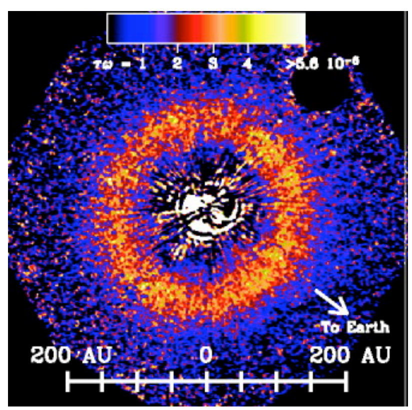
$L_{IR}/L_* = 10^{-3}$

i = 20 deg, R > 210 AU

R < 70 AU cleared



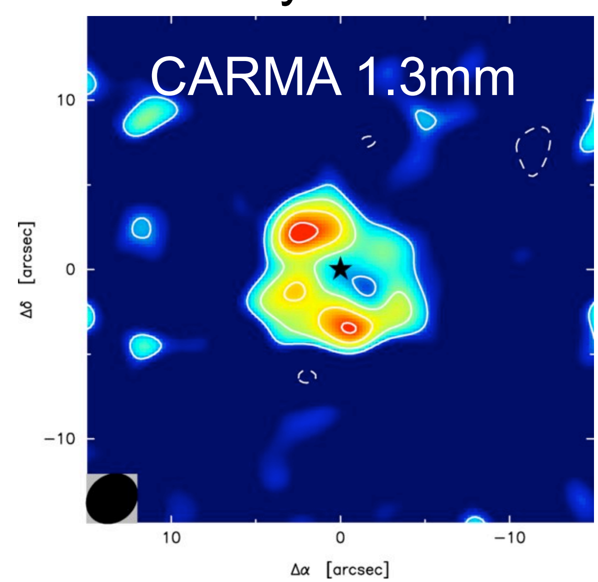
HST 0.6 μm



optical depth x albedo

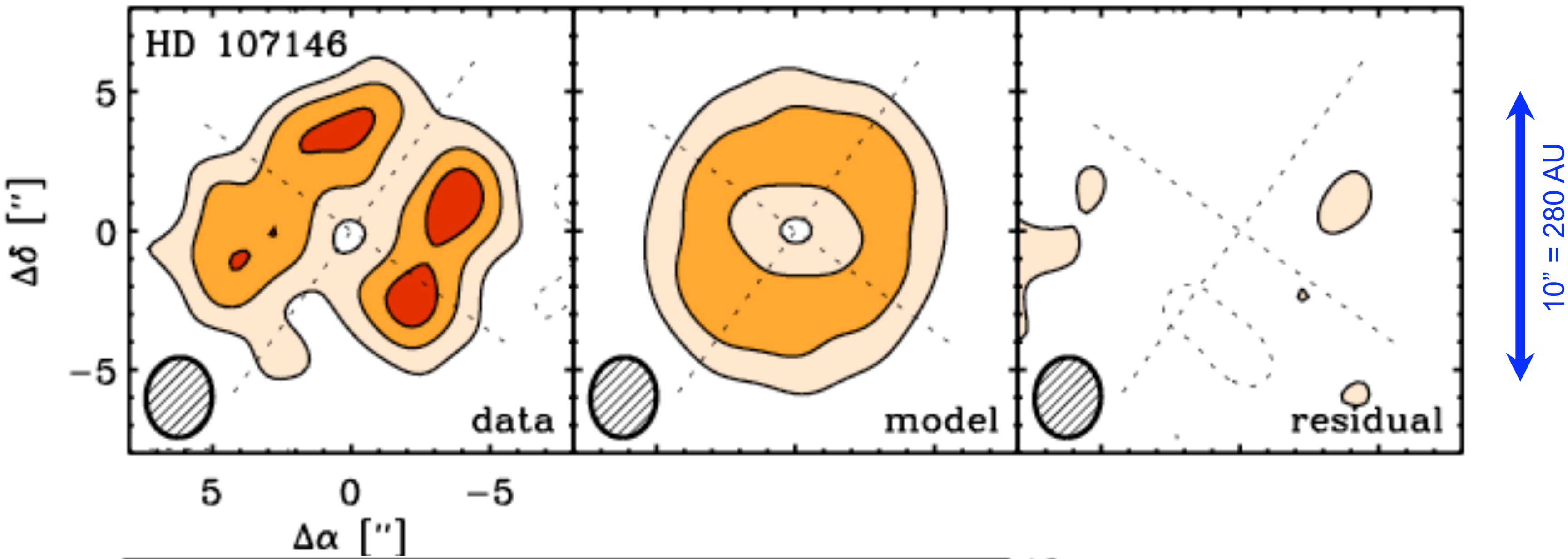
Ardila et al. 2004

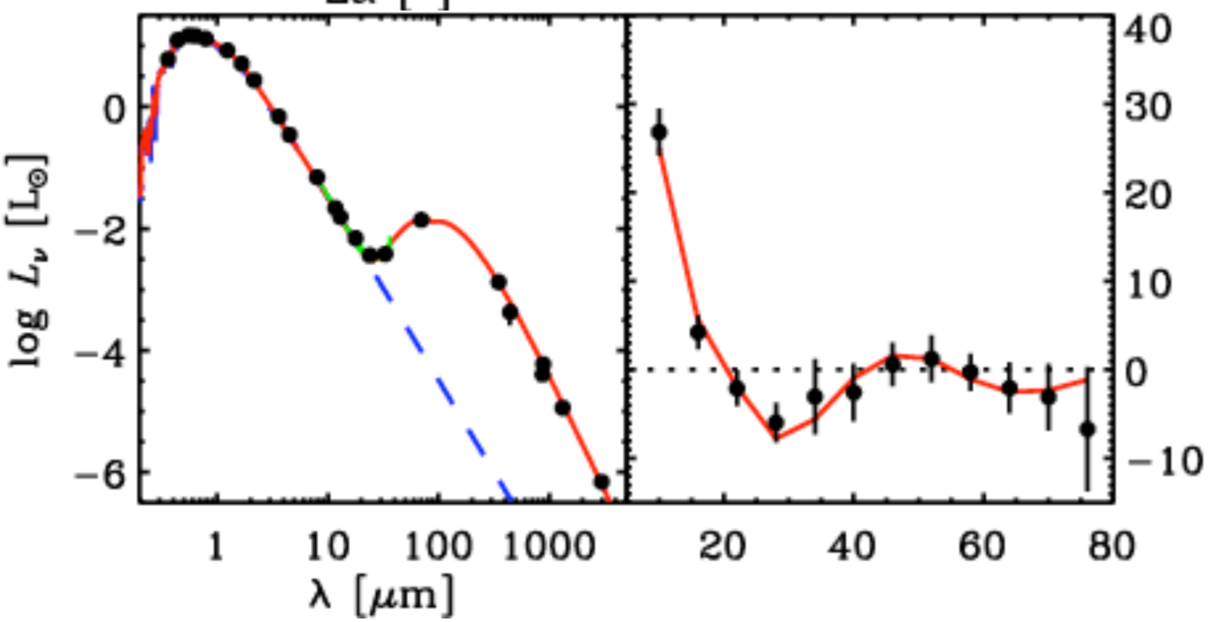
az. asymmetries?



Corder et al. 2009

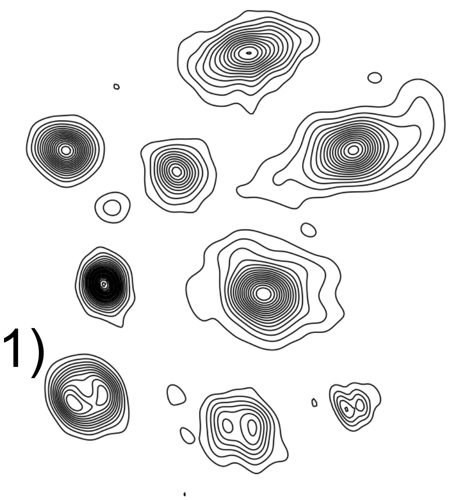
HD 107146 SMA 870 μm



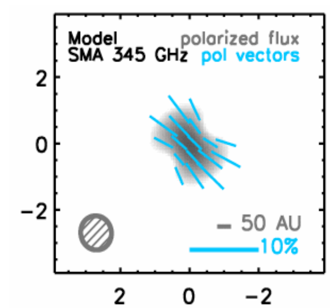


- emission extended, difficult to image
- R ~ 70 AU hole (SED: not empty)
- 3 zone model
- *no significant clumps*

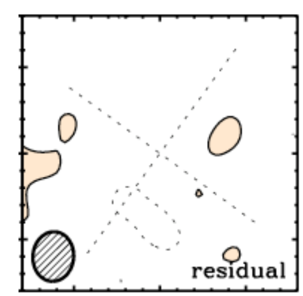
Summary



1. high resolution ρ Oph disk imaging survey
   - surface density constraints to $R \sim 20$ AU
   - consistent with steady accretion disk models ($\gamma \sim 1$)
   - (large) central holes common: planet formation?



2. disk polarimetry: TW Hya, HD 163296
   - daunting upper limits on linear polarization
   - spherical grains? poor alignment? tangled B fields?



3. debris disk imaging: HD 107146
   - challenging extended, low brightness emission
   - no evidence for structure due to planets