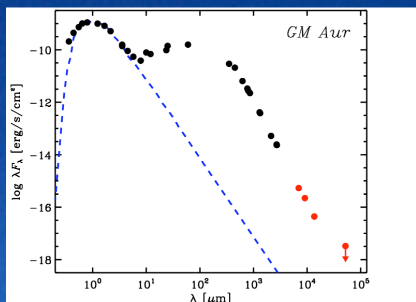
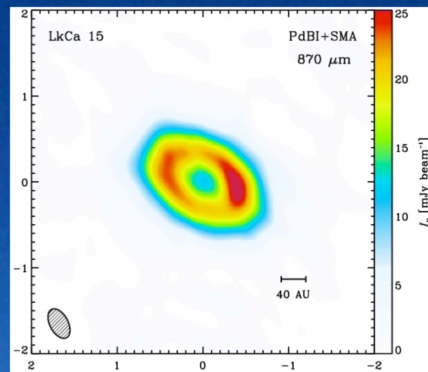
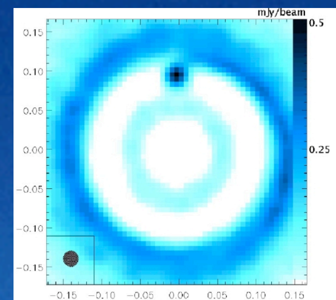
Submillimeter Imaging of Disks

David J. Wilner (Harvard-Smithsonian CfA)

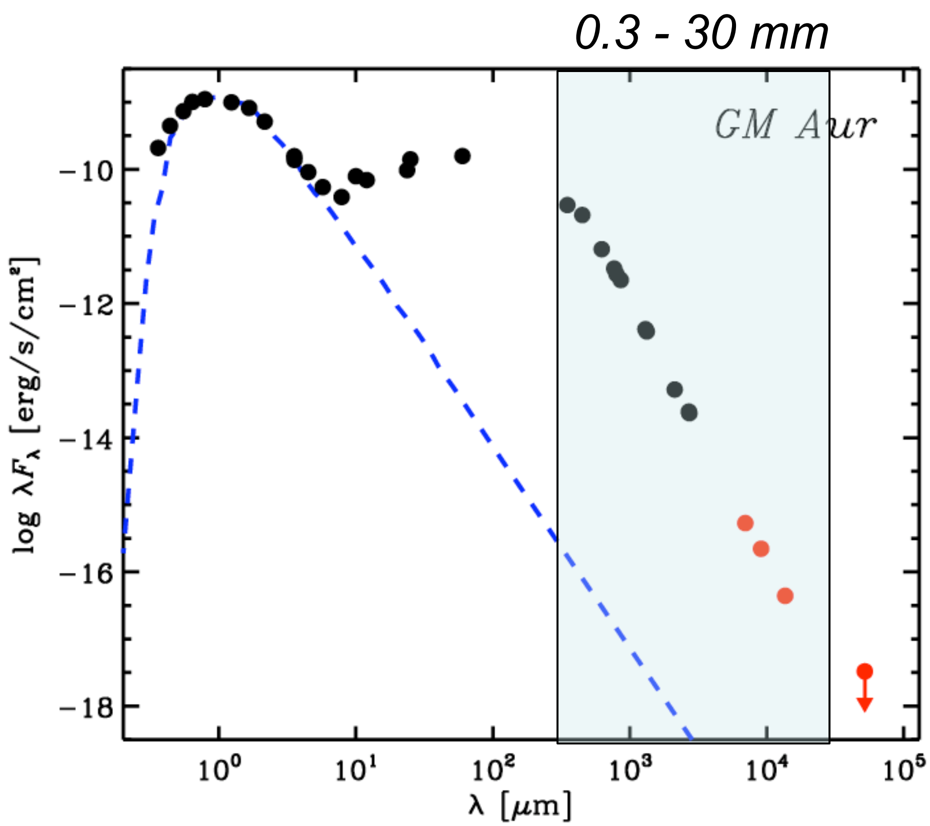






18 antennas at AOS on 13 August 2011, NAOJ

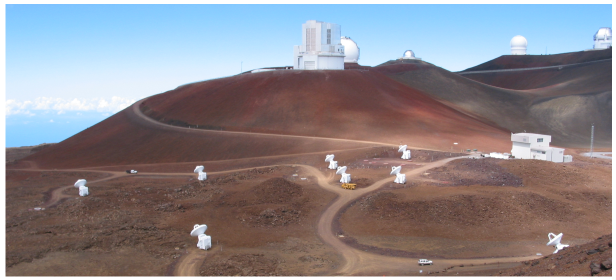
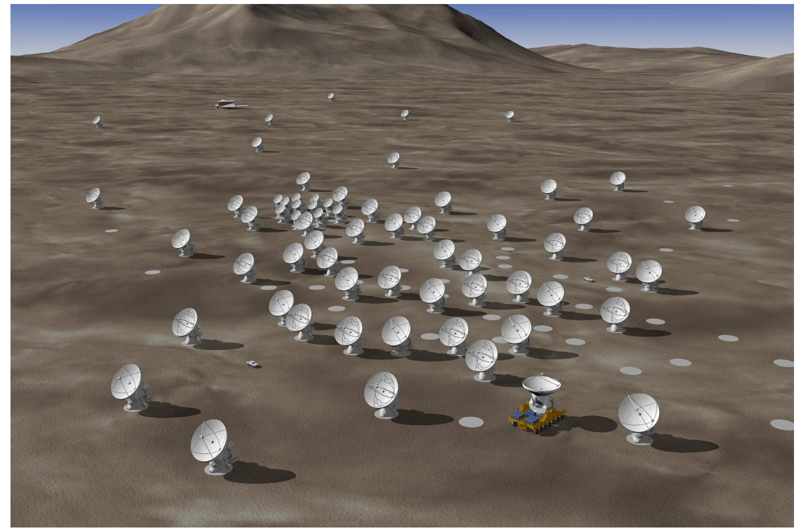
Relevance of Millimeter Regime



- avoid high dust opacities
  (dust) mass tracer
- sensitive to cold dust
  including mid-plane
- sensitive to large dust
  grain growth
- contrast with star
  planet-forming zone
- spectral lines, $R>10^7$
  kinematics, chemistry

- low T (and τ)
  need high sensitivity

Examples of Millimeter Telescopes

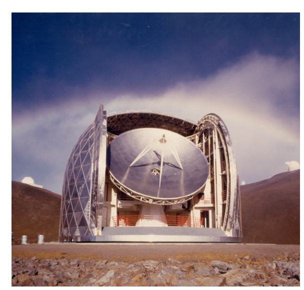
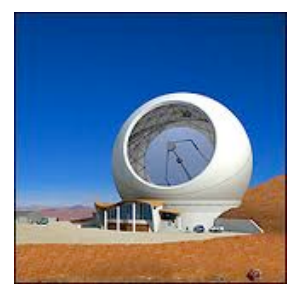






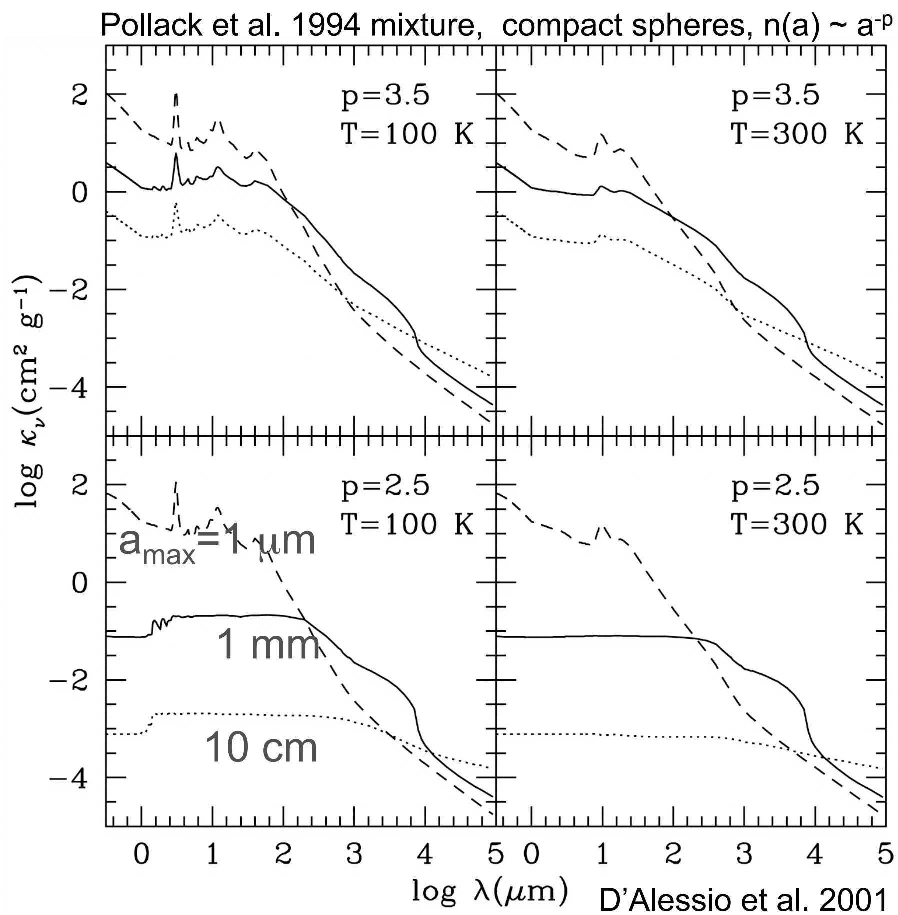


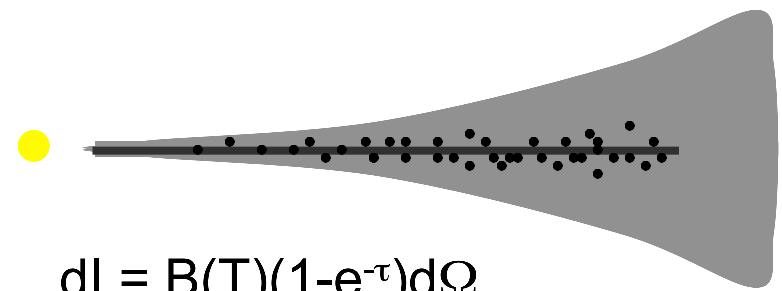




Disk Masses from Dust Emission? Really?





$dI = B(T)(1-e^{-\tau})d\Omega$

$\tau = \kappa\Sigma$

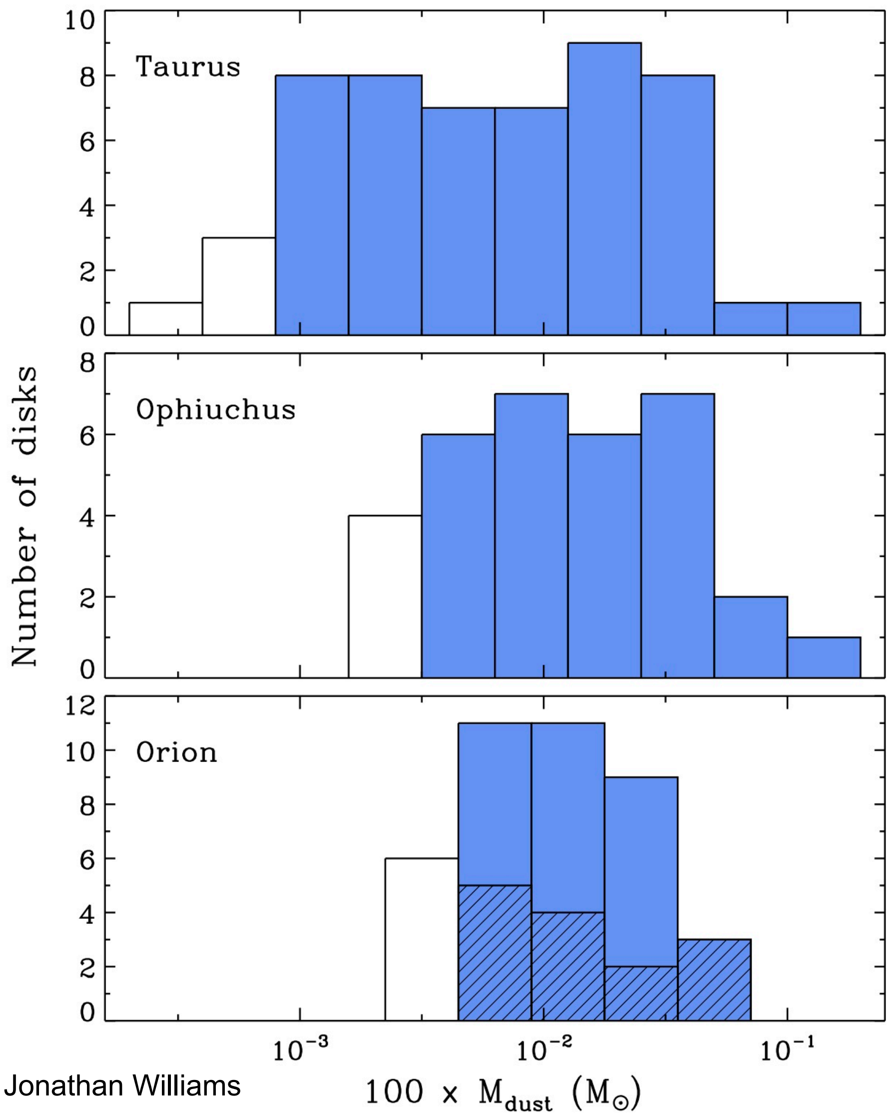
$\kappa_{mm} \approx \lambda^{-\beta}$

$F_{mm} = B(T)\ \kappa\ \Sigma\ A / D^2$

$\approx\ (2kT/\lambda^2)\ \kappa\ M / D^2$

- κ depends on dust properties and gas-to-dust ratio (both evolving!)
- dust masses → factor of few
- *total disk masses* highly uncertain

Protoplanetary Disk Masses at 1 Myr



Jonathan Williams

"typical" $M_{disk} \approx 0.005\ M_\odot$

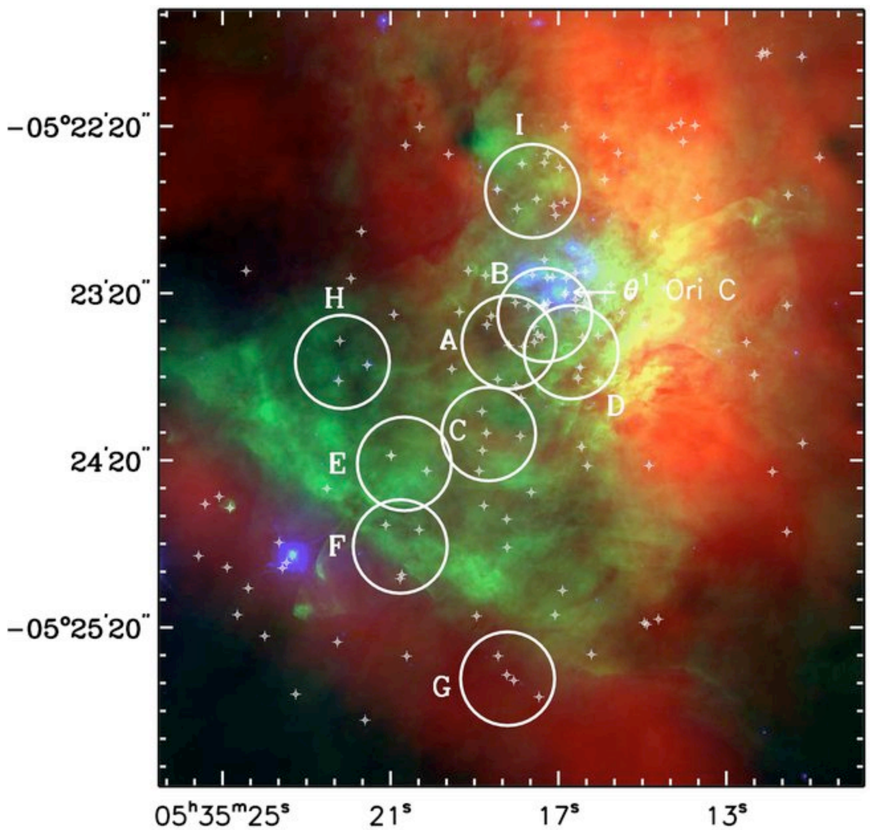
- planet forming potential
- $F_{850\ \mu m} \approx 80$ mJy at 140 pc (current facilities ~ 1 mJy)

at Orion and beyond, still hard to detect disks << MMSN

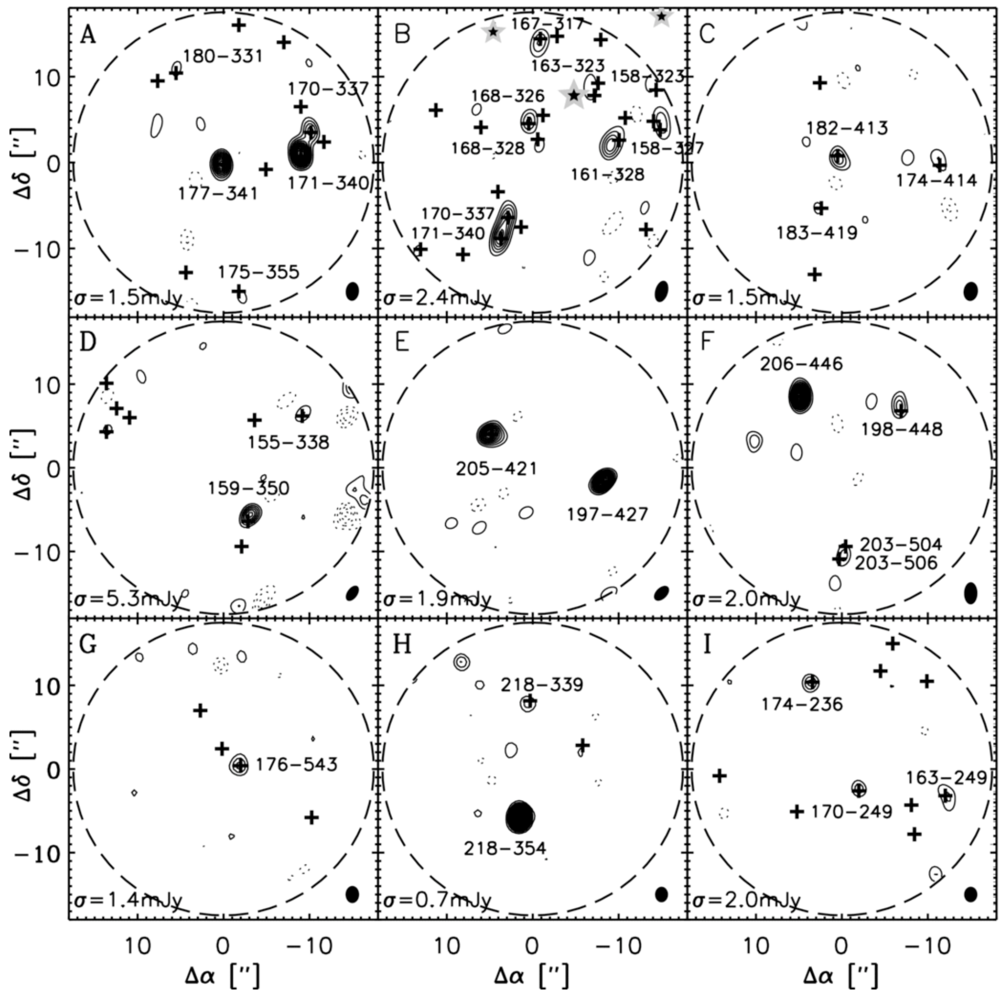
Andrews & Williams 2005
Andrews & Williams 2007
Mann & Williams 2010

(cf. Beckwith et al. 1990
Andre & Montmerle 1994)

Orion "Proplyds" in Submillimeter



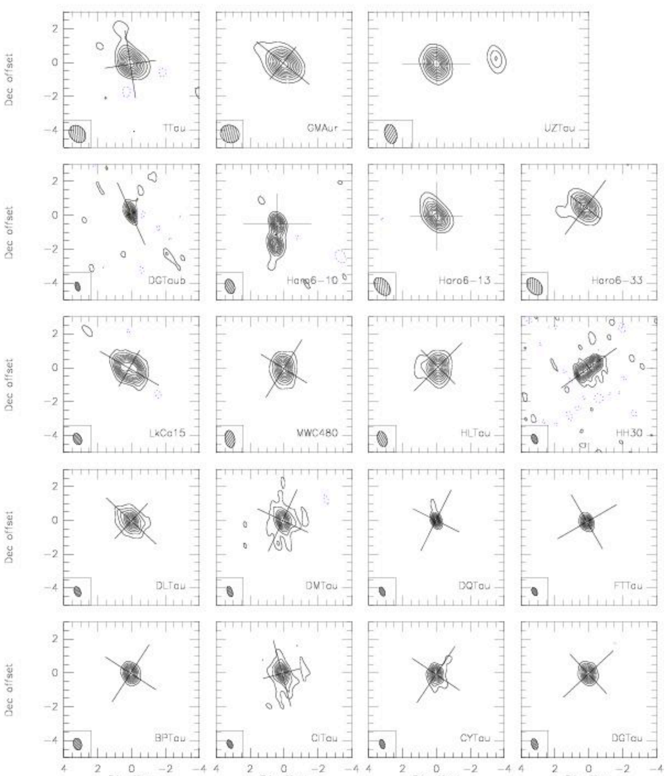
Mann and Williams 2009



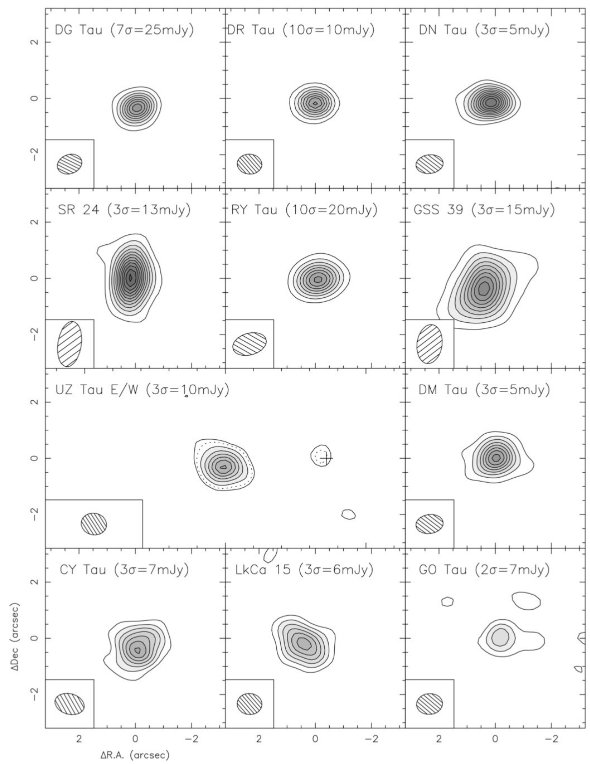
see also Williams, Andrews, Wilner 2005, Eisner et al. 2008

Protoplanetary Disk Structure at 1 Myr

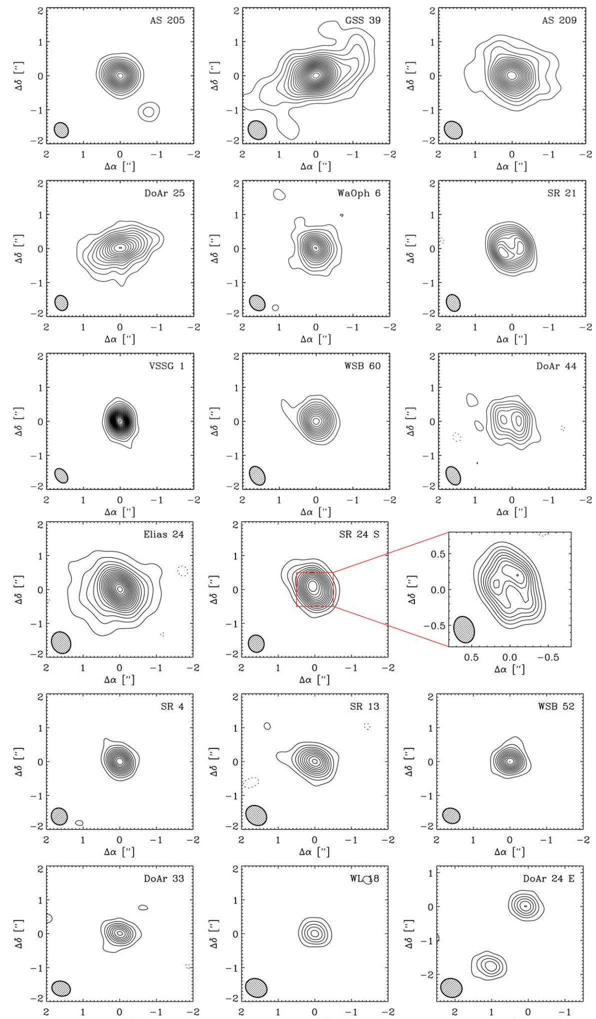
- many 10's of disks resolved by mid 2000's
- systematic 0.3 - 0.7 arcsec surveys of ~ 20 disks
  - SMA 870 μm Ophiucus Andrews et al. 2009/10
  - CARMA 1.3 mm Taurus Isella et al. 2009
  - PdBI 1.3/3 mm Taurus Guilloteau et al. 2011



Guilloteau et al. 2011

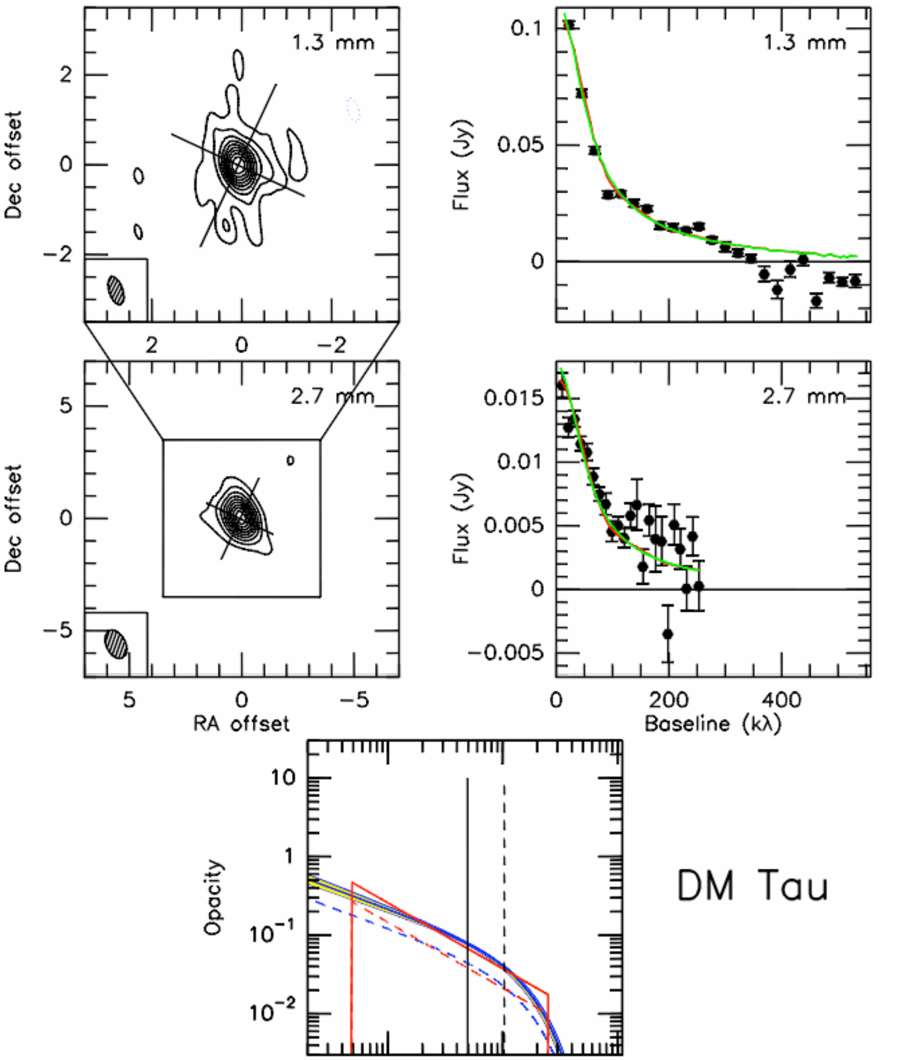


Isella et al. 2009



Andrews et al. 2009/10

Disk Structure Modeling



Guilloteau et al. 2011

$F_{mm} \sim \kappa \, \Sigma \, T$

density: parameterized, axisymmetric, radial structure, e.g.

$\Sigma(r) \sim (r/R_c)^{-\gamma} \exp[-(r/R_c)^{2-\gamma}]$

or $(r/R_{out})^{-p}$

temperature: varying sophistication

accurate stellar properties

proper radiative transfer

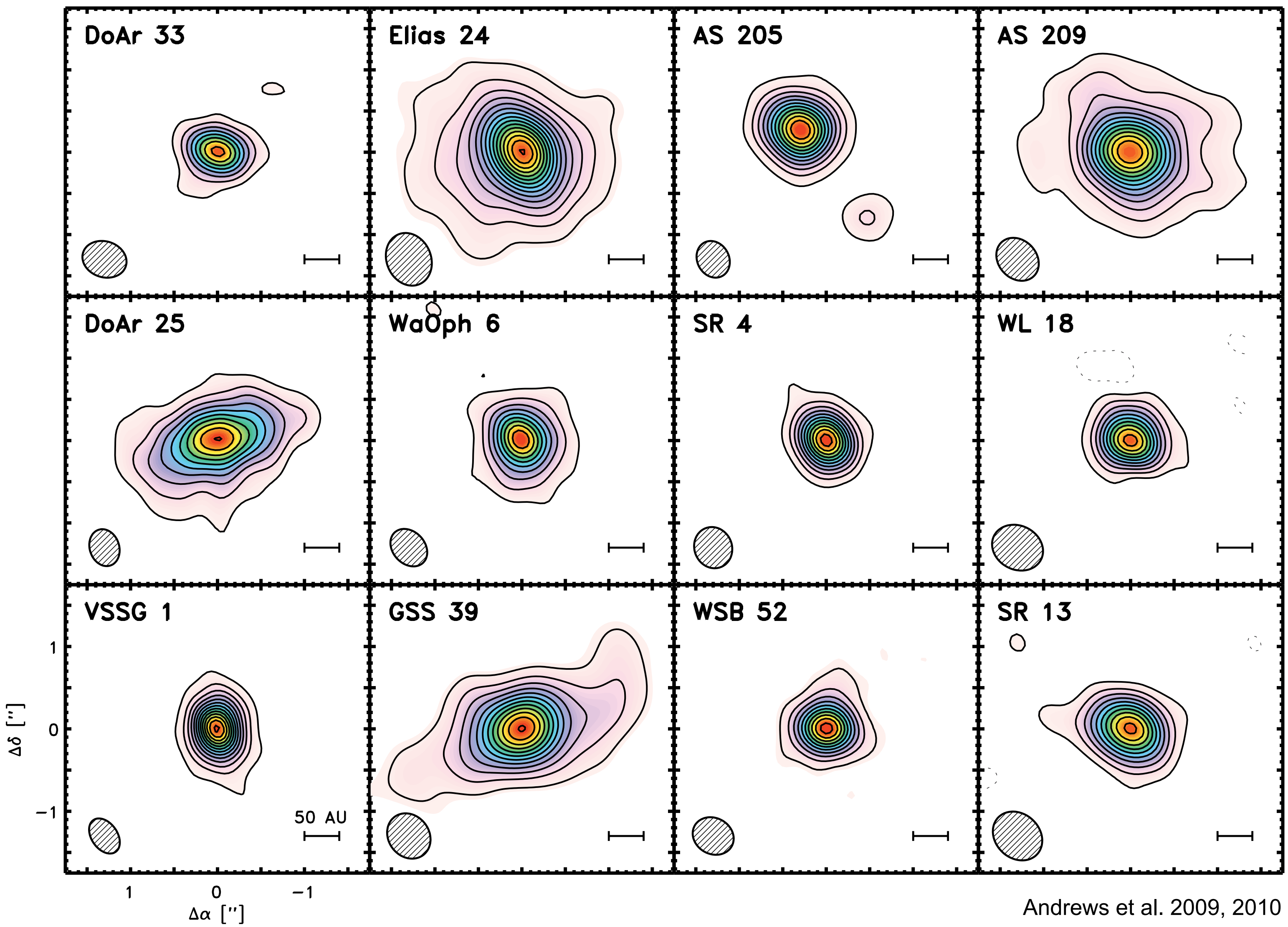
full SED information

opacity: $\kappa(r)$ = constant

max grain size mm → min Σ

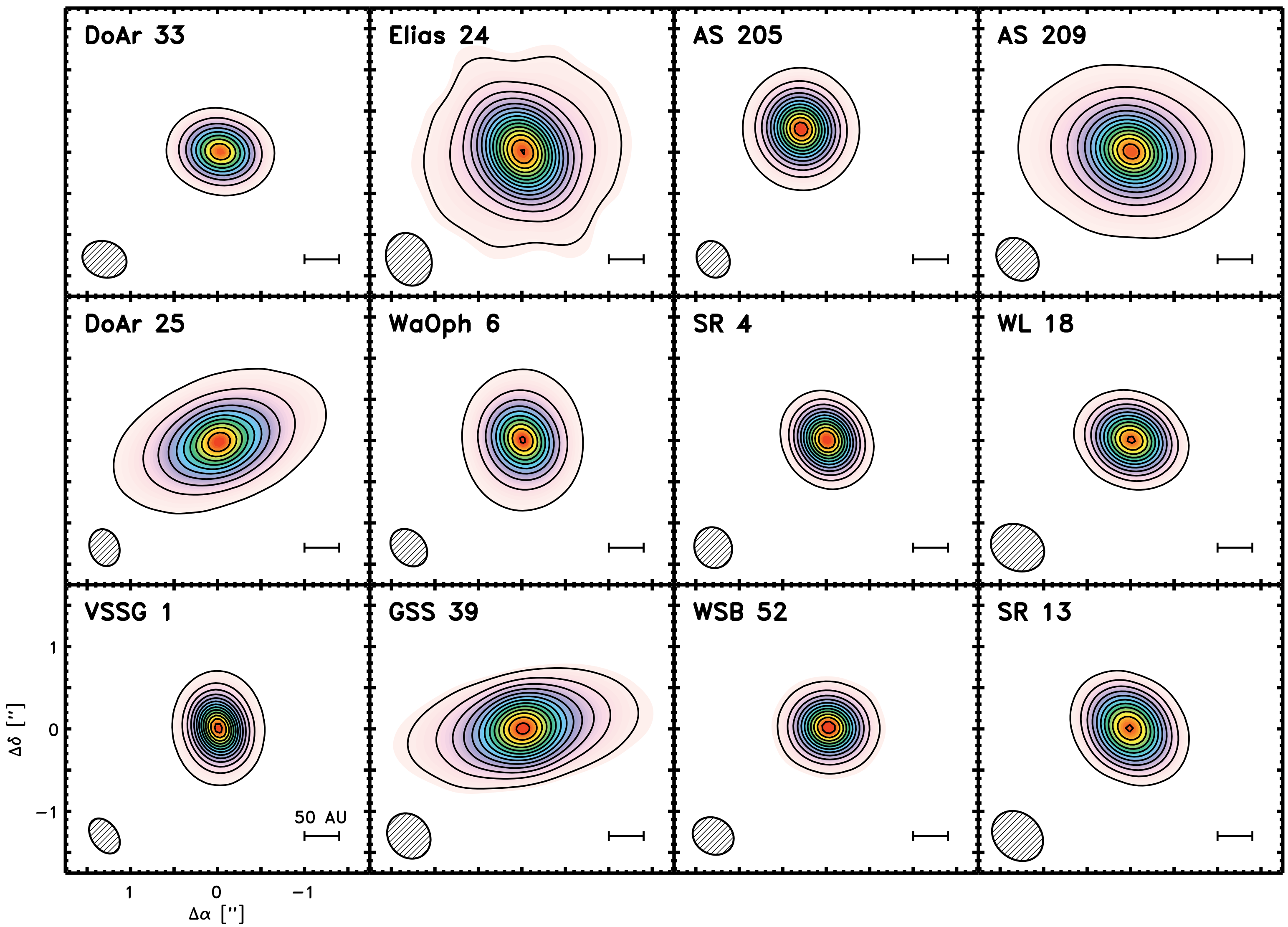
if multiple λ's, then fit for $\beta(r)$

SMA Oph Survey Disk Data and Models



Andrews et al. 2009, 2010

SMA Oph Survey Disk Data and Models



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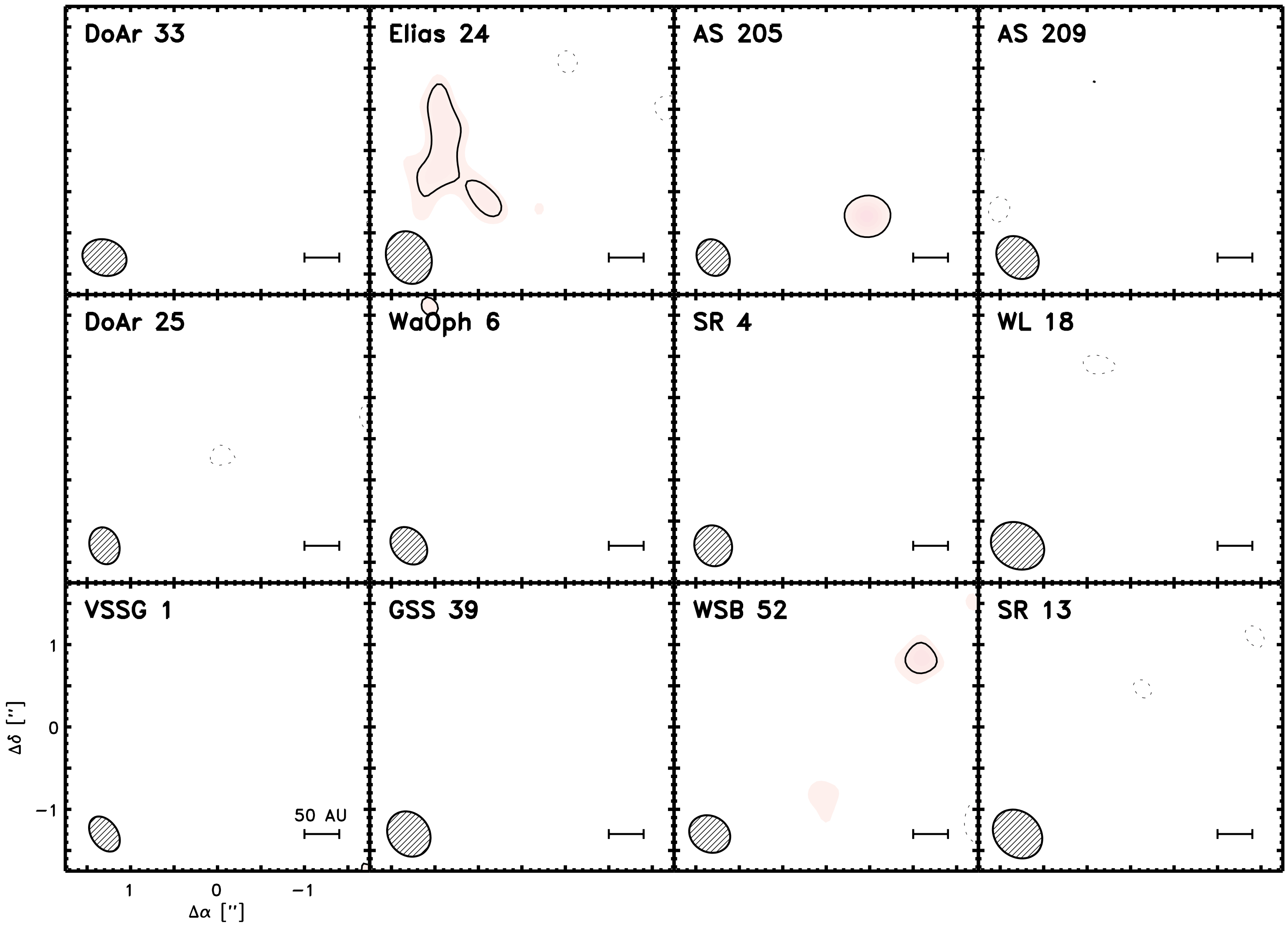
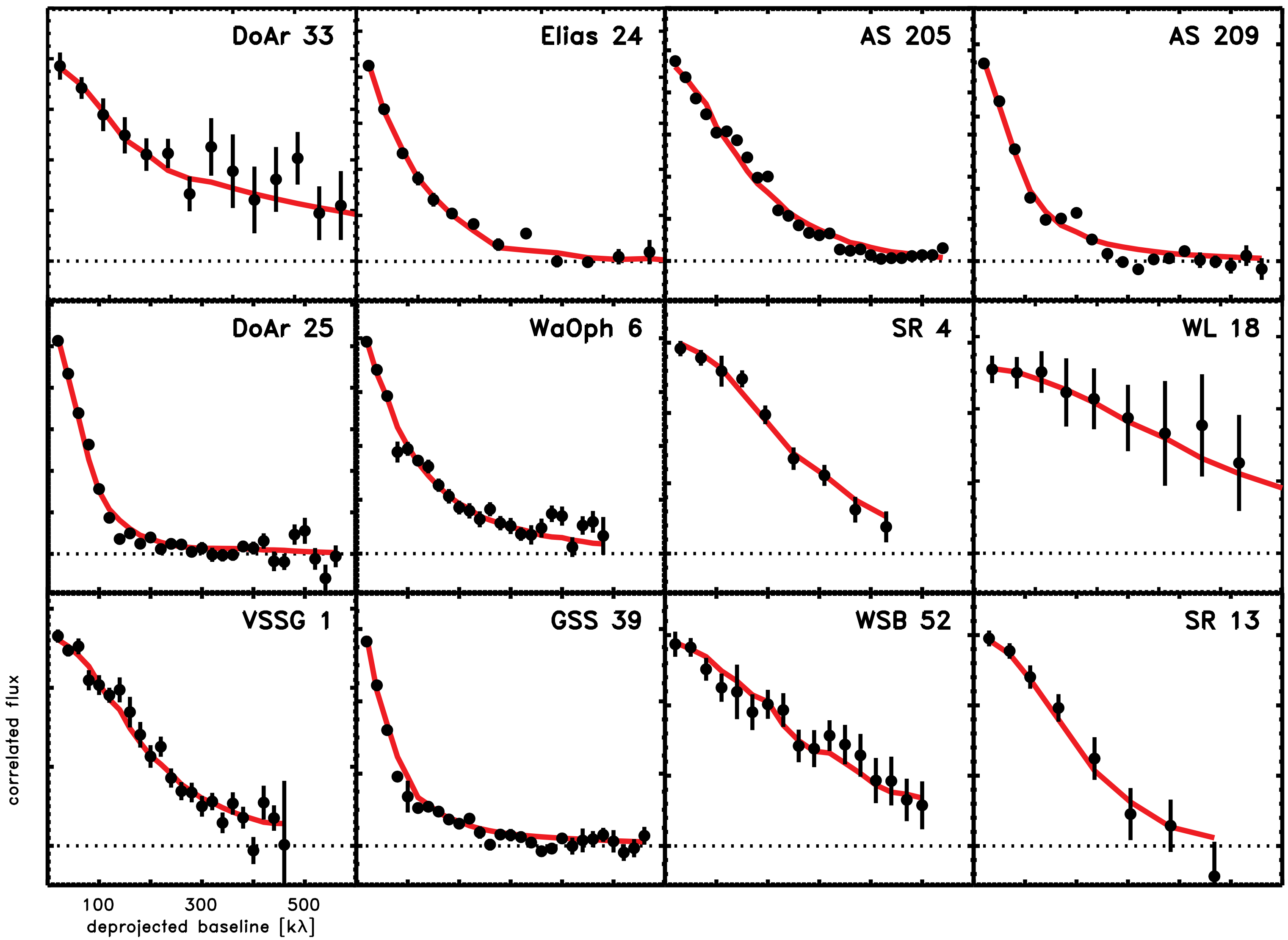


SMA Oph Survey Disk Data and Models



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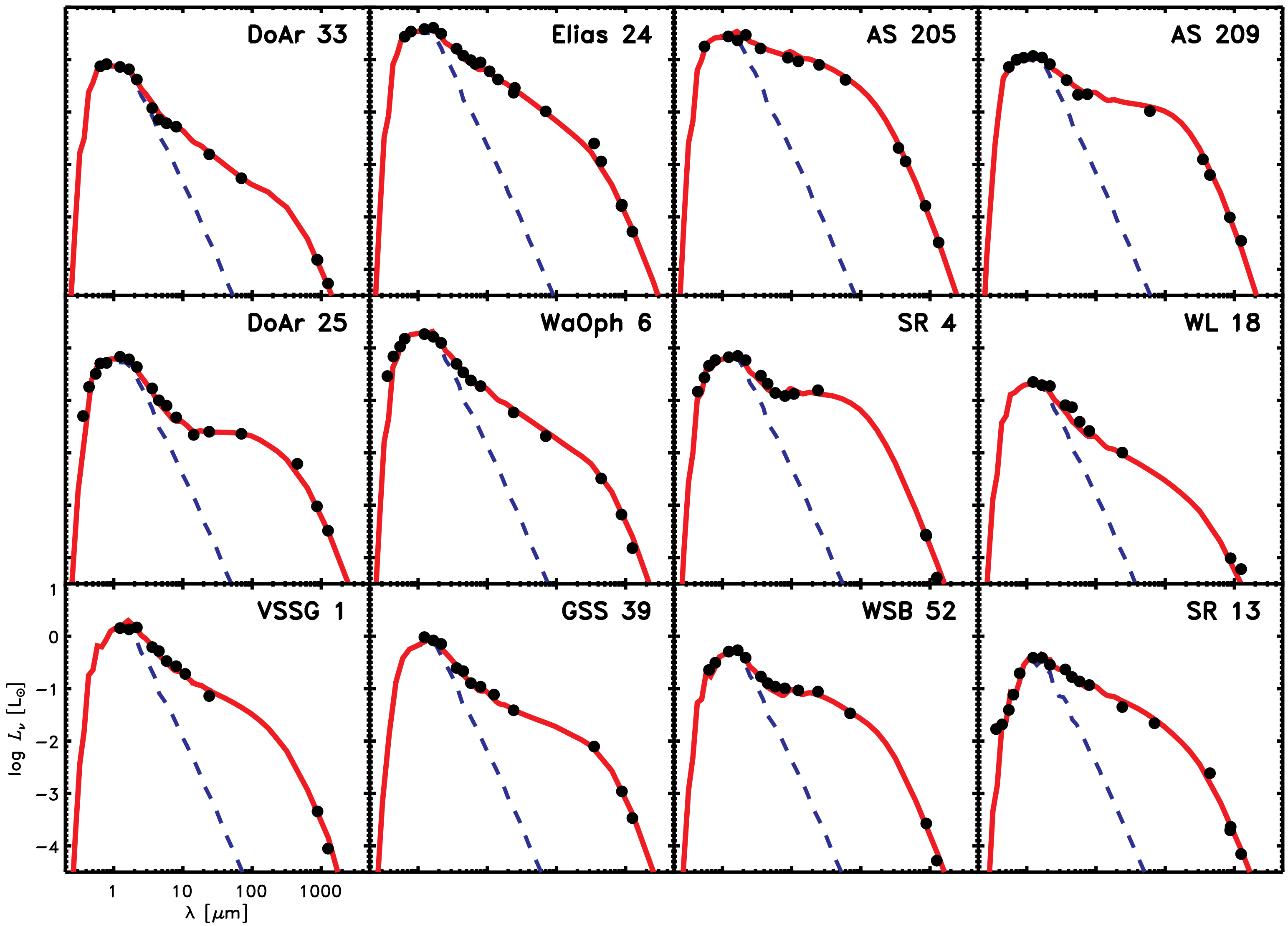
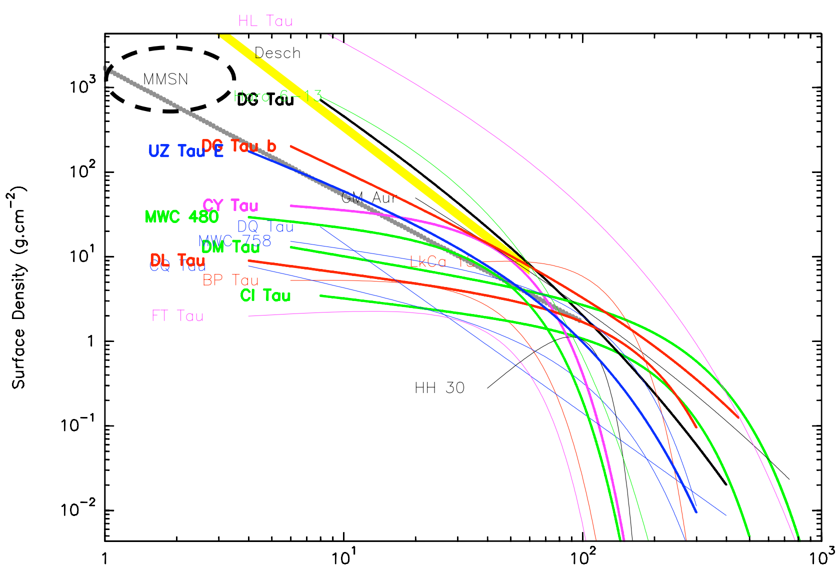
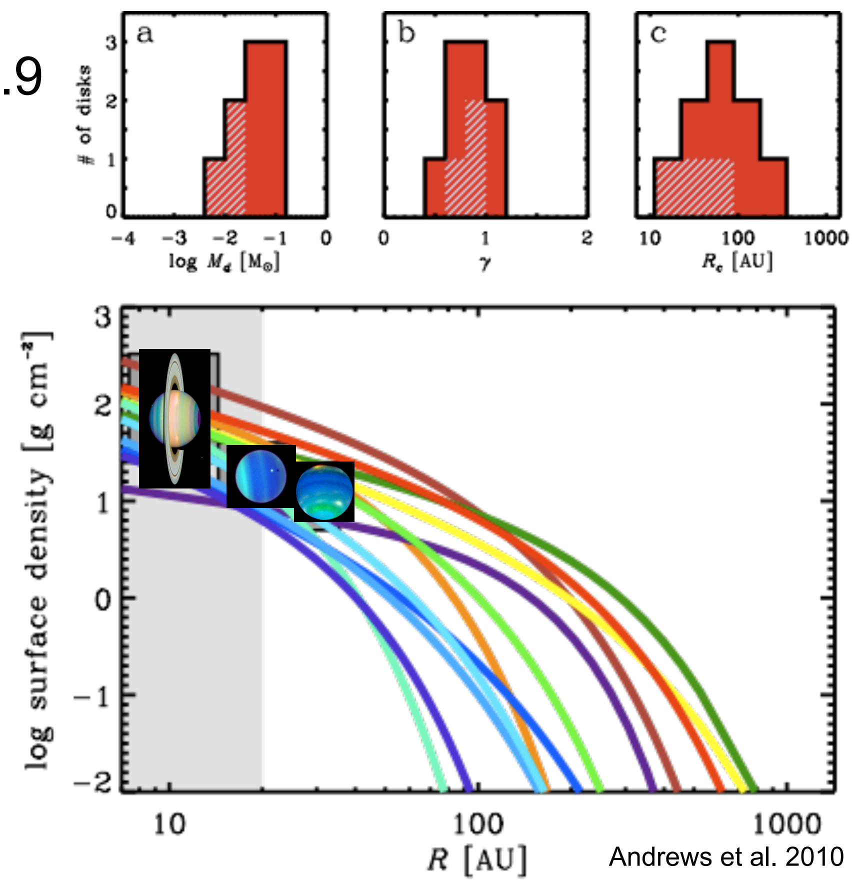


Protoplanetary Disk Structure Results

- *fundamental assumption: dust traces gas*
- Σ < 20 AU compatible with MMSN
- range of disk sizes: R_c ~ 10 - 200 AU (fainter disks are smaller)
- range of density gradients: $\langle\gamma\rangle$ ~0.9
- Toomre stable at all radii



Guilloteau et al. 2011



Andrews et al. 2010

HL Tau

Kwon et al. 2011

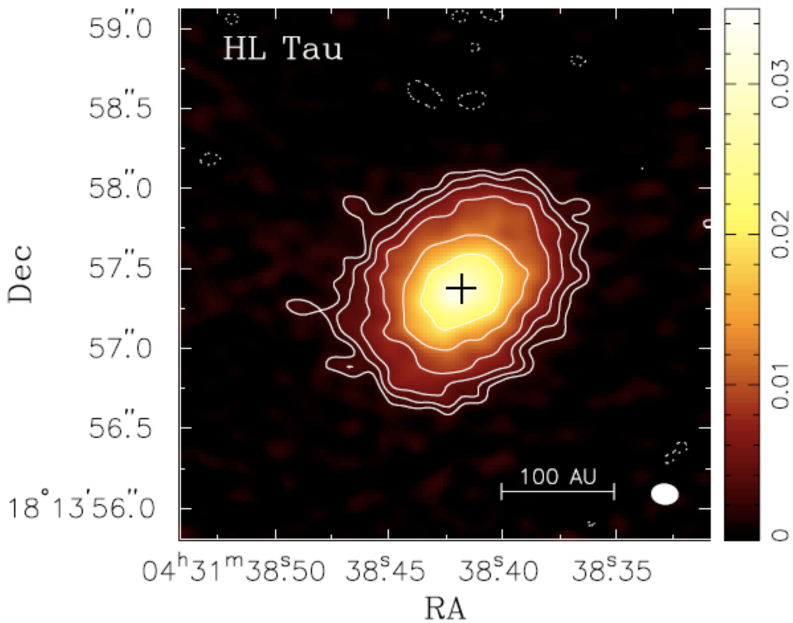
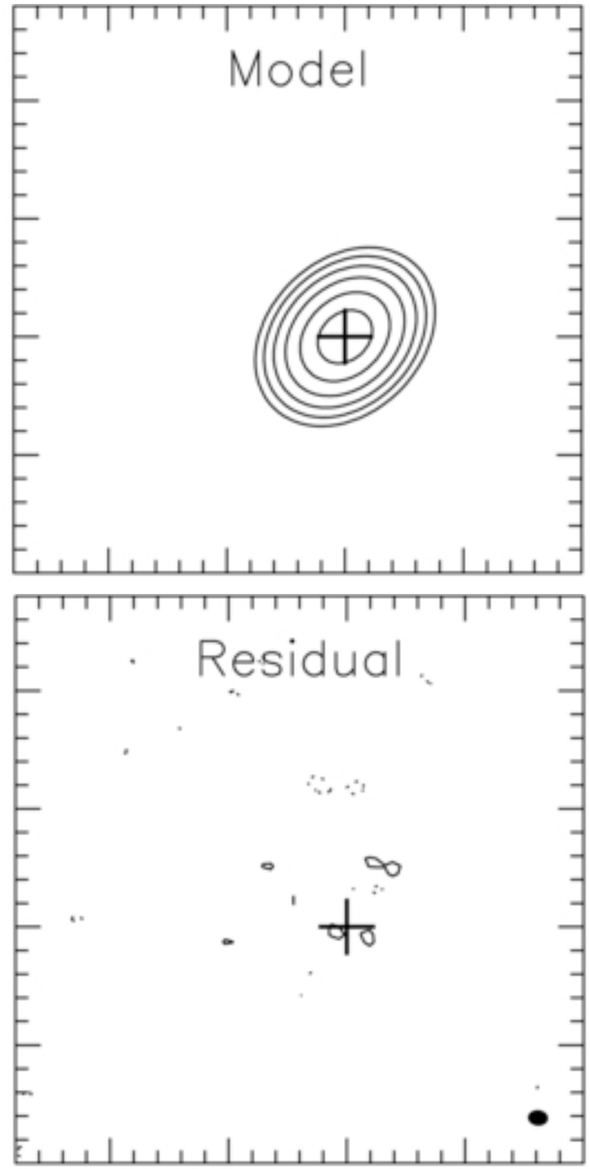


Figure 1. HL Tau in the $\lambda = 1.3$ mm continuum. The image is the combined of CARMA A, B, and C configurations, and the synthesized beam is $0\farcs17 \times 0\farcs13$ (P.A. = 85°) corresponding to 18 AU. The contour levels are 2.5, 4.0, 6.3, 10, 16, 25, and 40 times $\sigma = \pm 0.8$ mJy beam^{-1}.

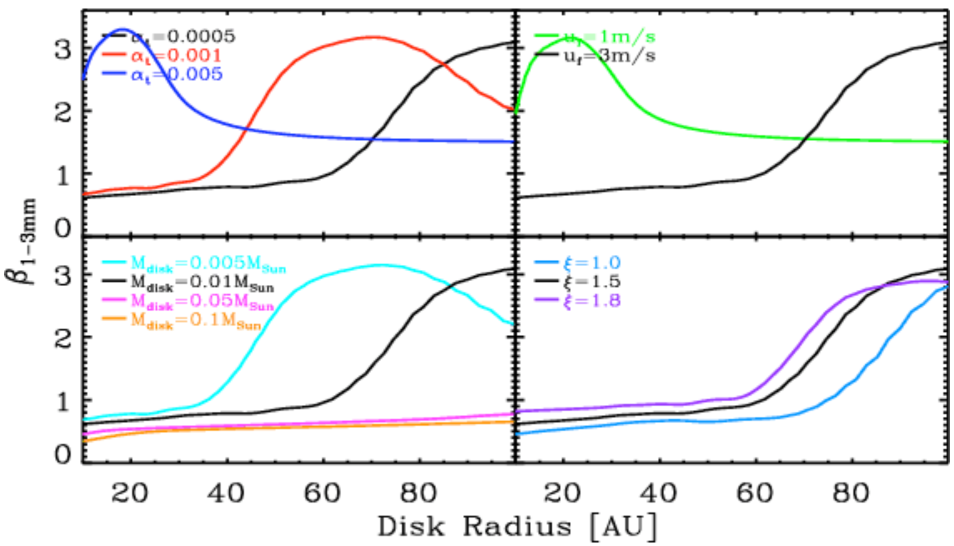


no significant asymmetries/clumps

Radial Dependence of Grain Properties?

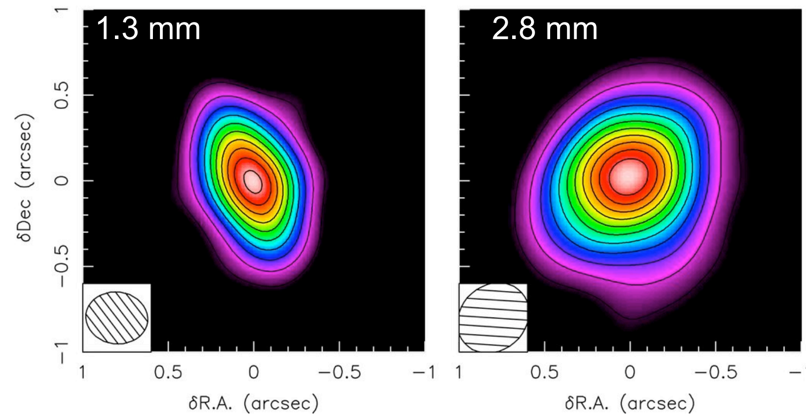
models couple viscous evolution of gas structure and size/space evolution of solids

Birnstiel et al. 2010

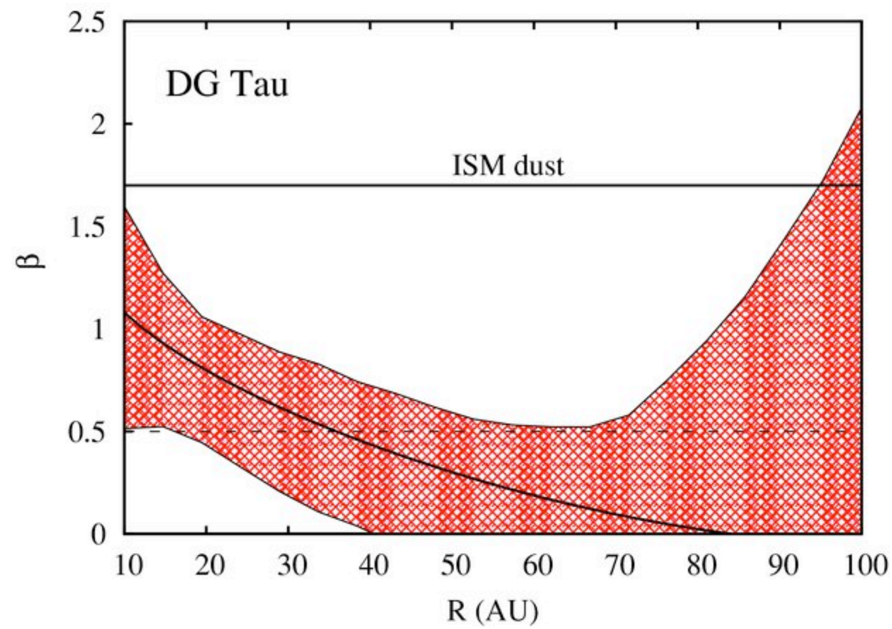


β (and κ) *should* vary with *R*

observational evidence is marginal



Isella et al. 2010



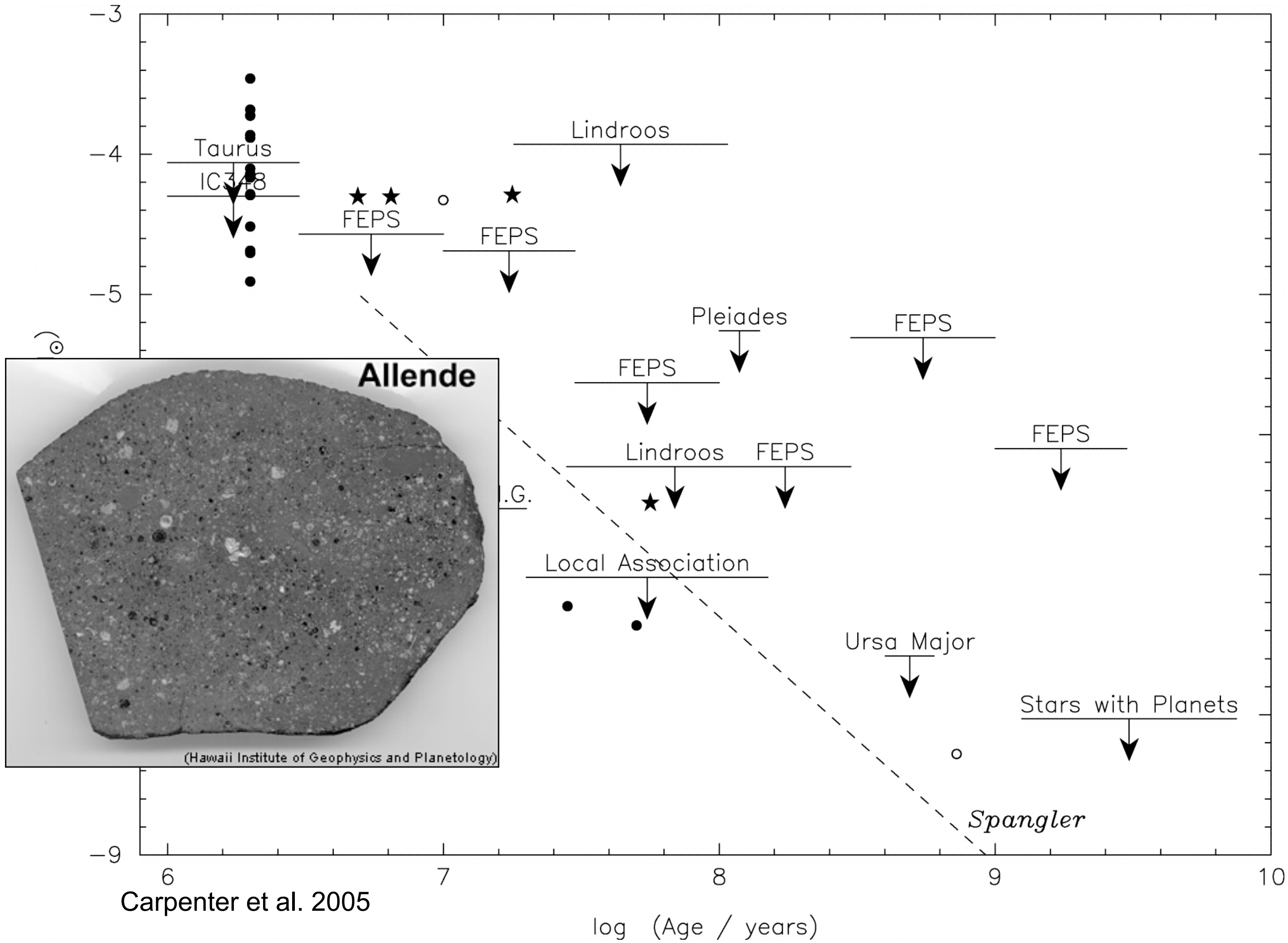
Evolution of Millimeter Emission

1 Myr
<0.005 $M_{\odot}$>

2-3 Myr
down by >10x
(e.g. IC348, Lee et al. 2011)

10 Myr
few outliers

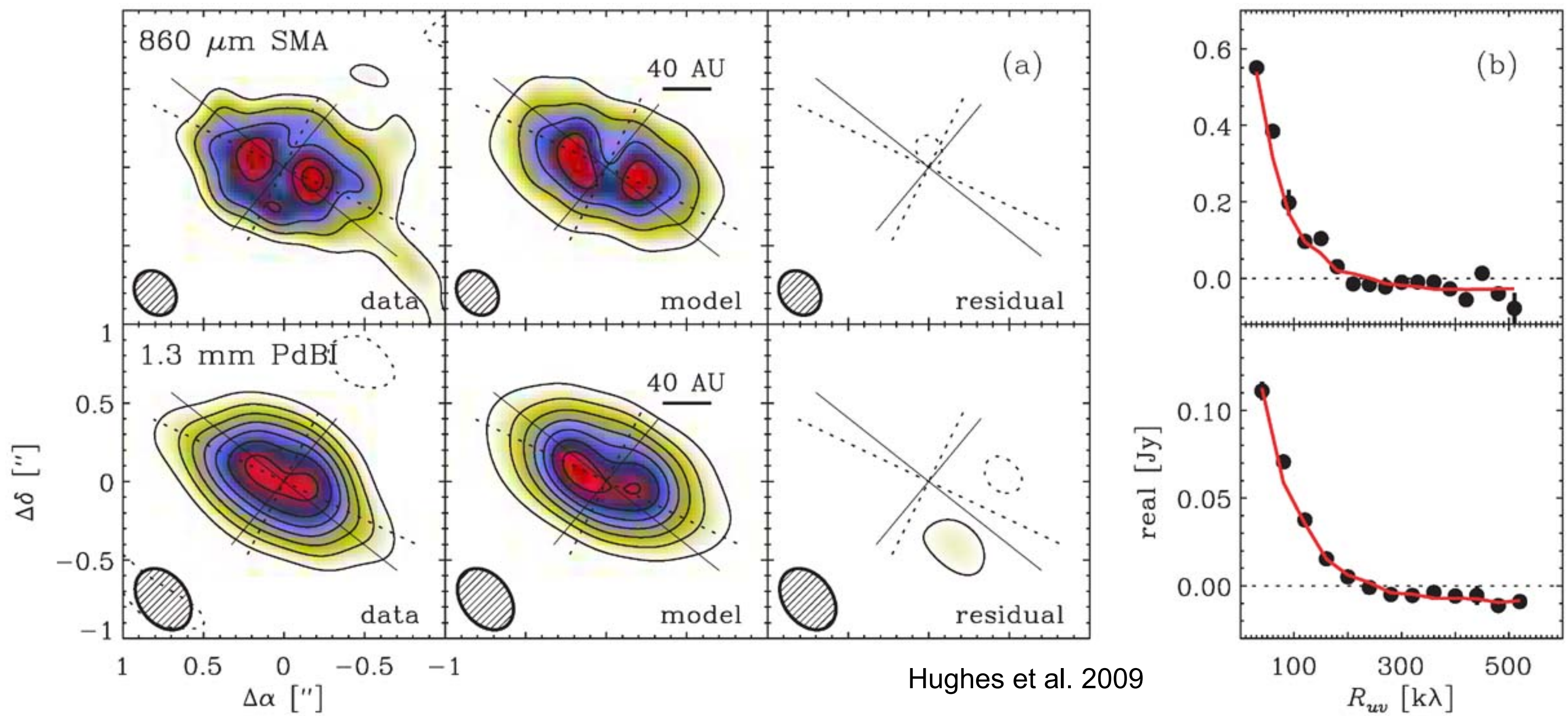
debris disks



Carpenter et al. 2005

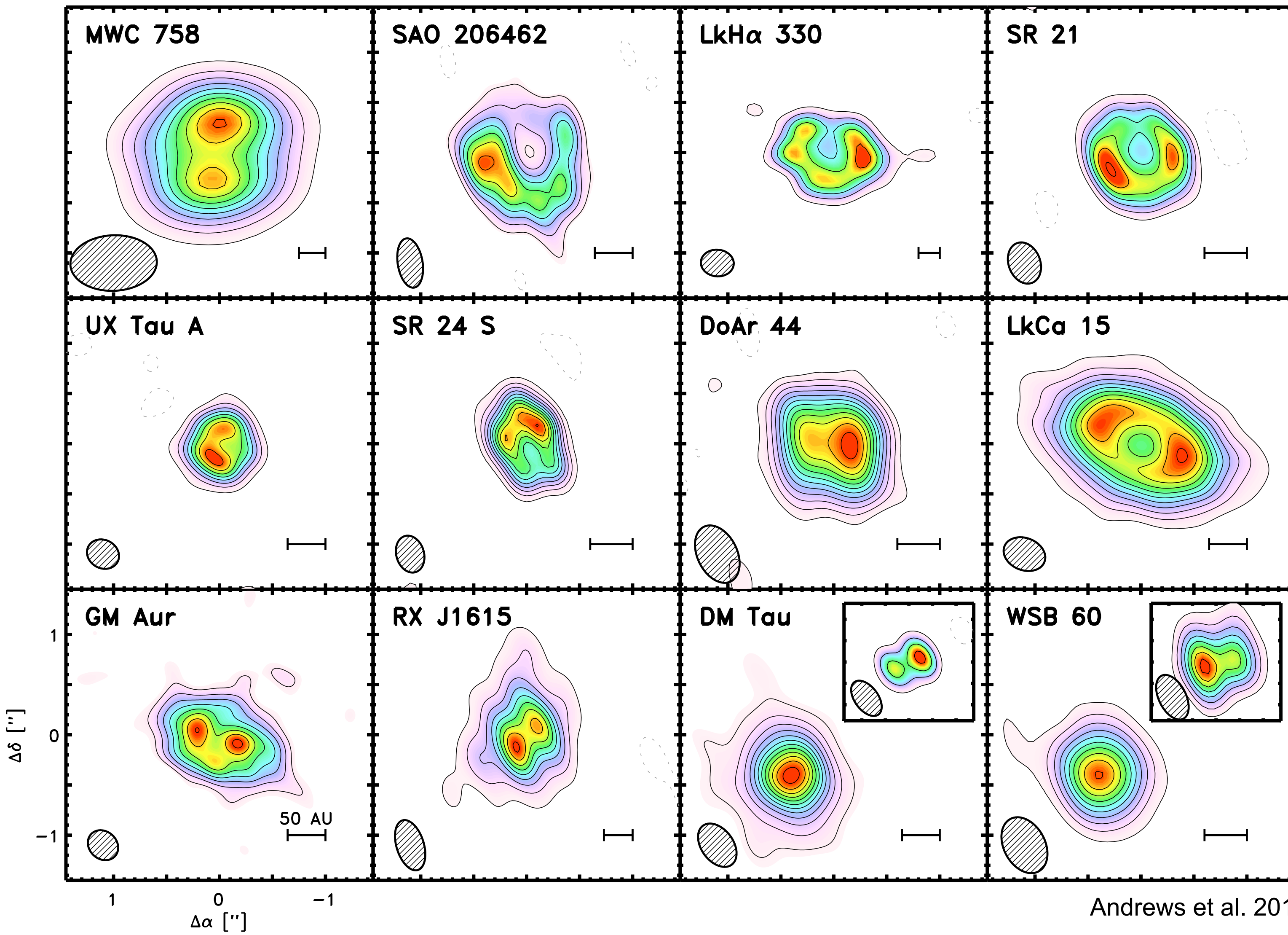
Evolution of Disk Structure

- millimeter images reveal central cavities of “transition” disks
  - LkCa 15 (Pietu et al. 2006), TW Hya (Hughes et al. 2007), LkHα 330 (Brown et al. 2008), GM Aur (Hughes et al. 2009), SR21N, HD135344B (Brown et al. 2009), MWC 758 (Isella et al. 2010), …



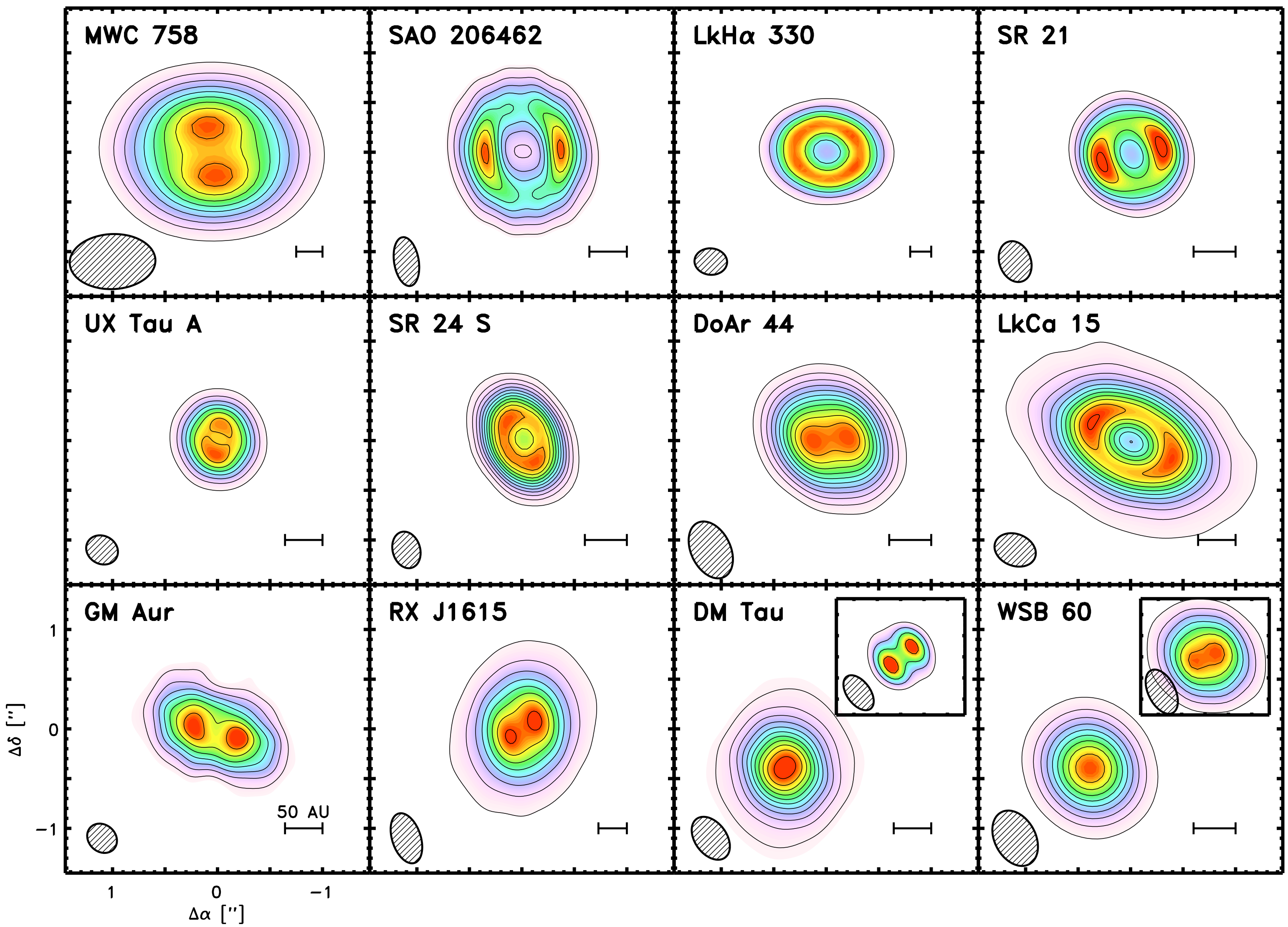
Hughes et al. 2009

Resolved Images of Large Cavities

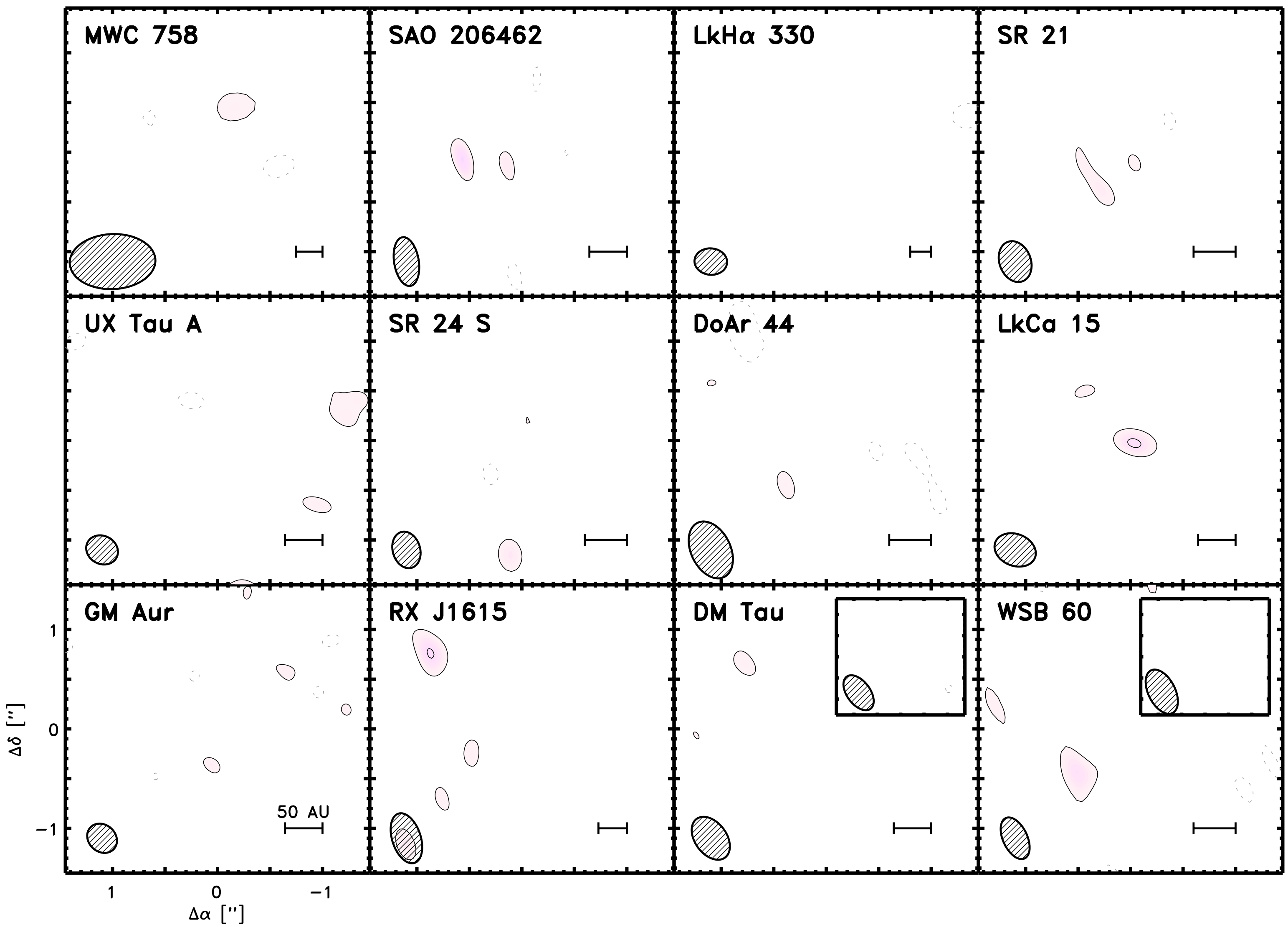


Andrews et al. 2011

Resolved Images of Large Cavities



Resolved Images of Large Cavities



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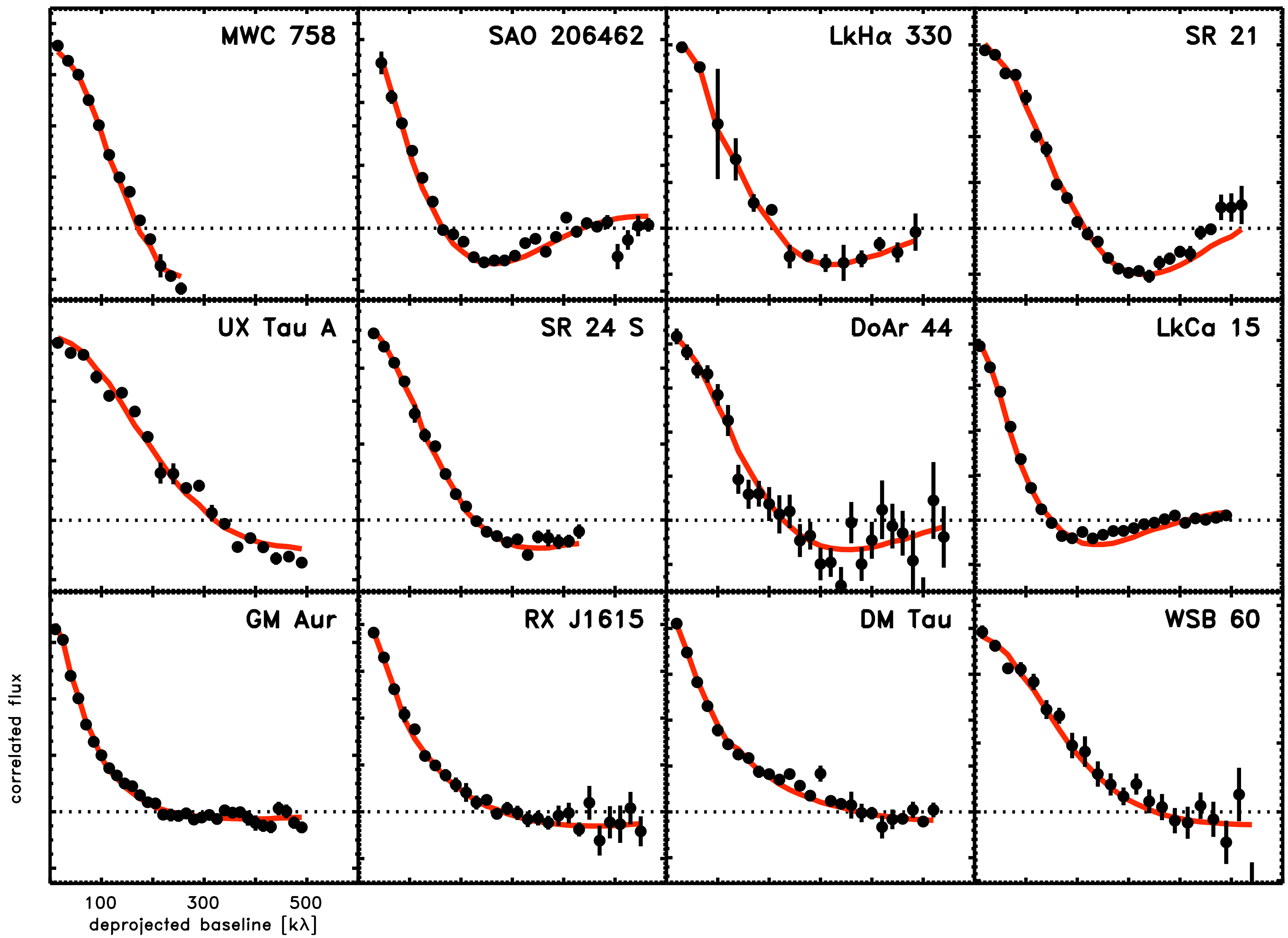
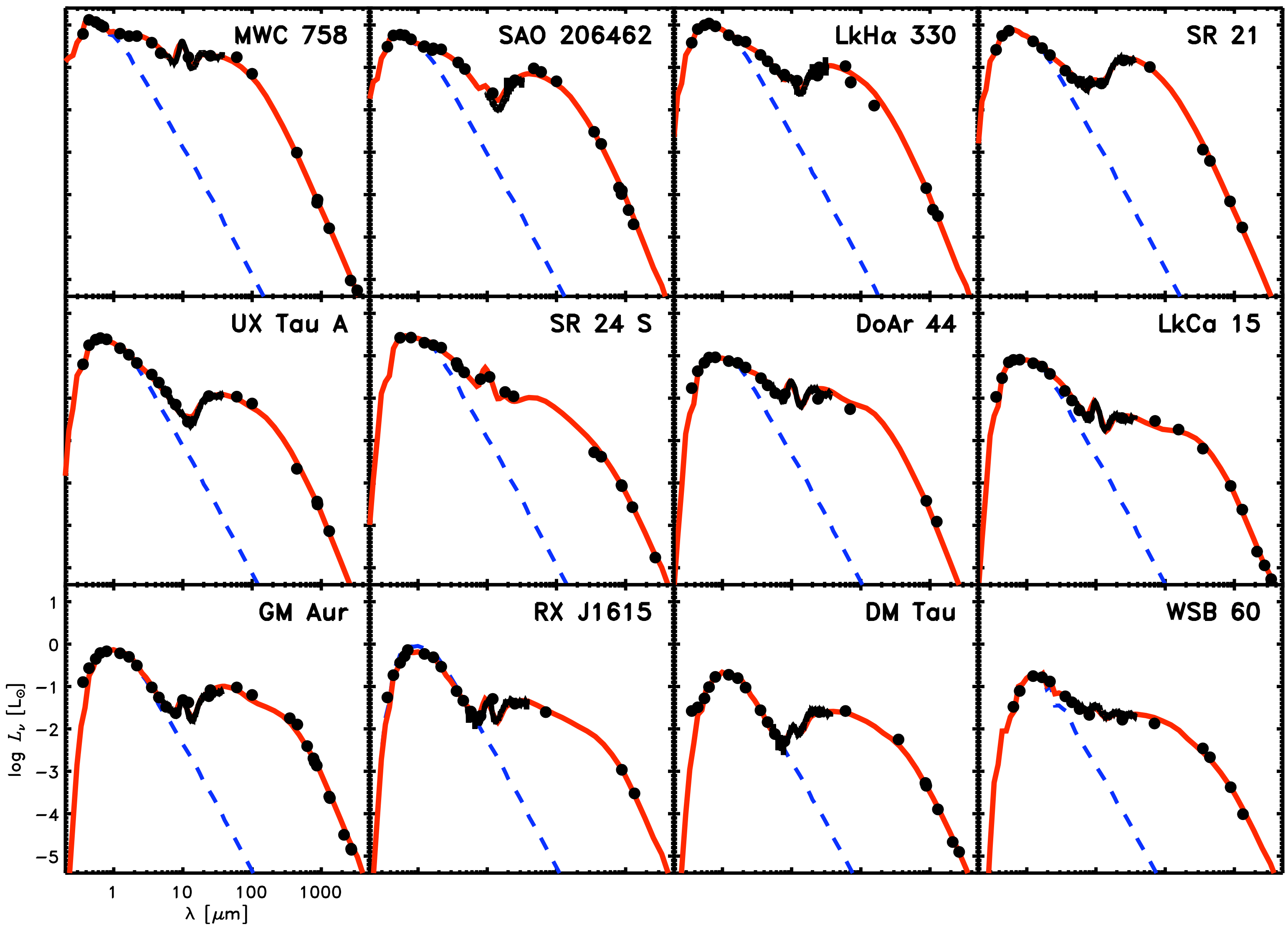
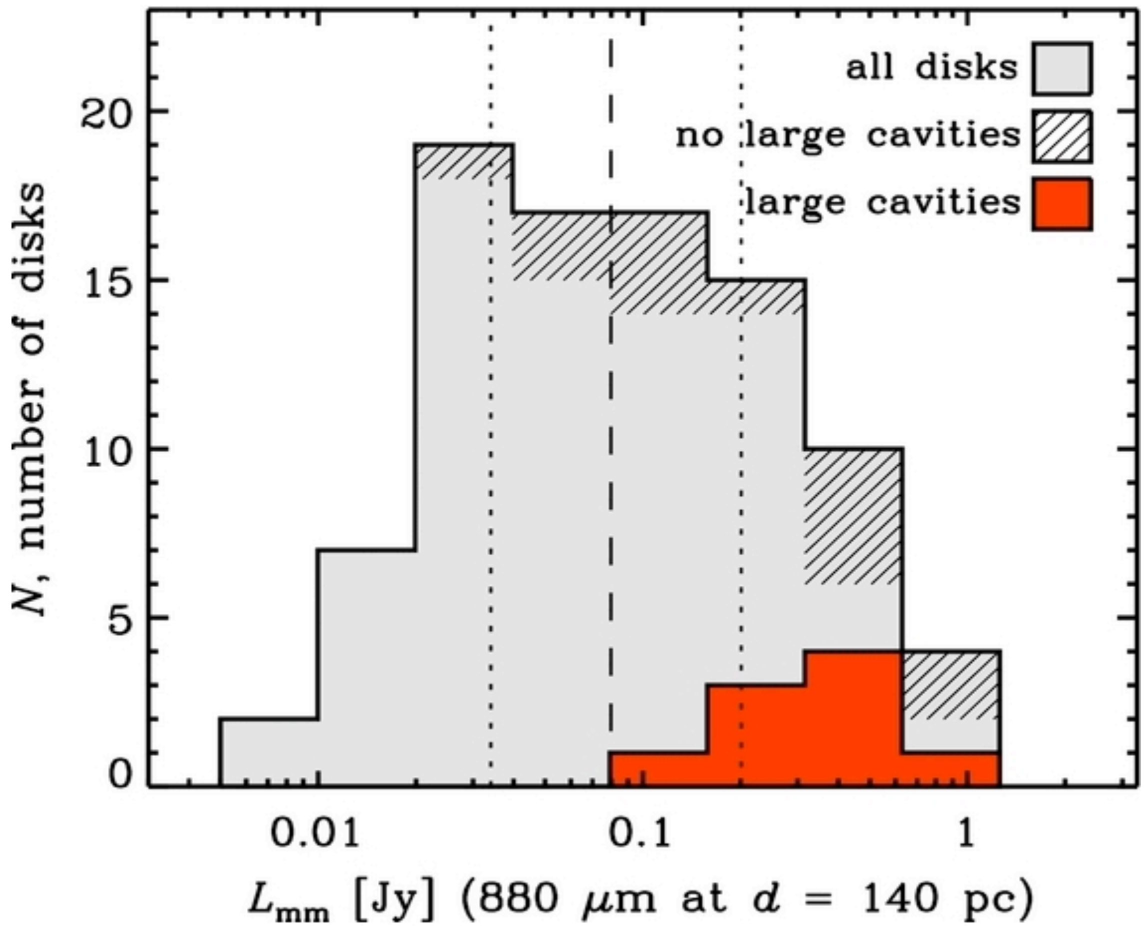


Resolved Images of Large Cavities



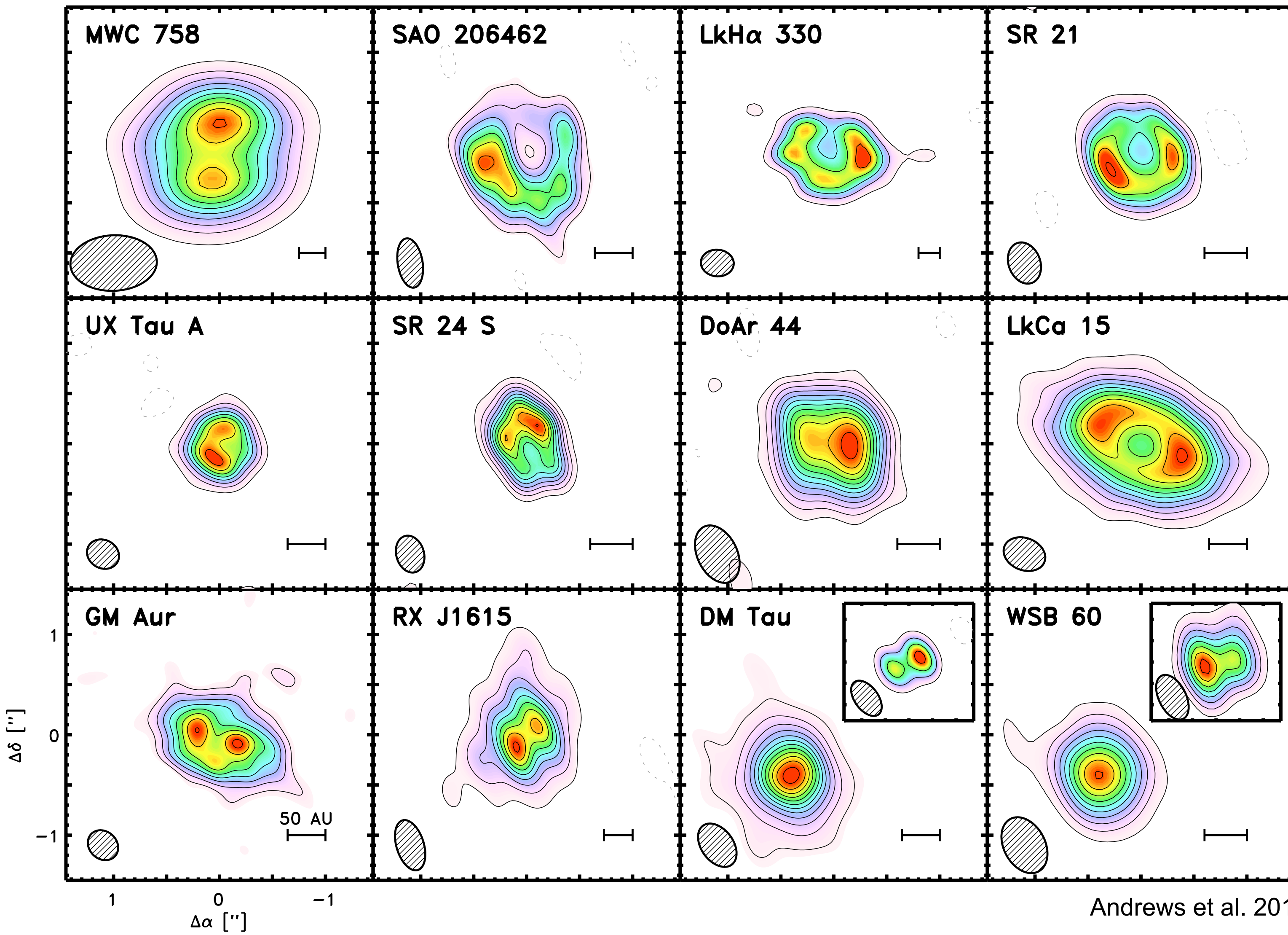
Large Cavities are Common



Andrews et al. 2011

at least 20% of bright half of millimeter luminosity (= disk mass) distribution!

Large Cavities = Signposts of Planets?



Andrews et al. 2011

Bewildering signs

Boston's Charles Circle is an example of the many confusing signs in the city.

A driver entering Charles Circle from the Longfellow Bridge will come across this sign with four arrows and four lines of directions.

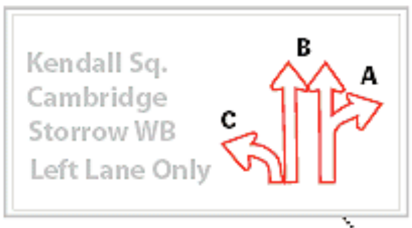
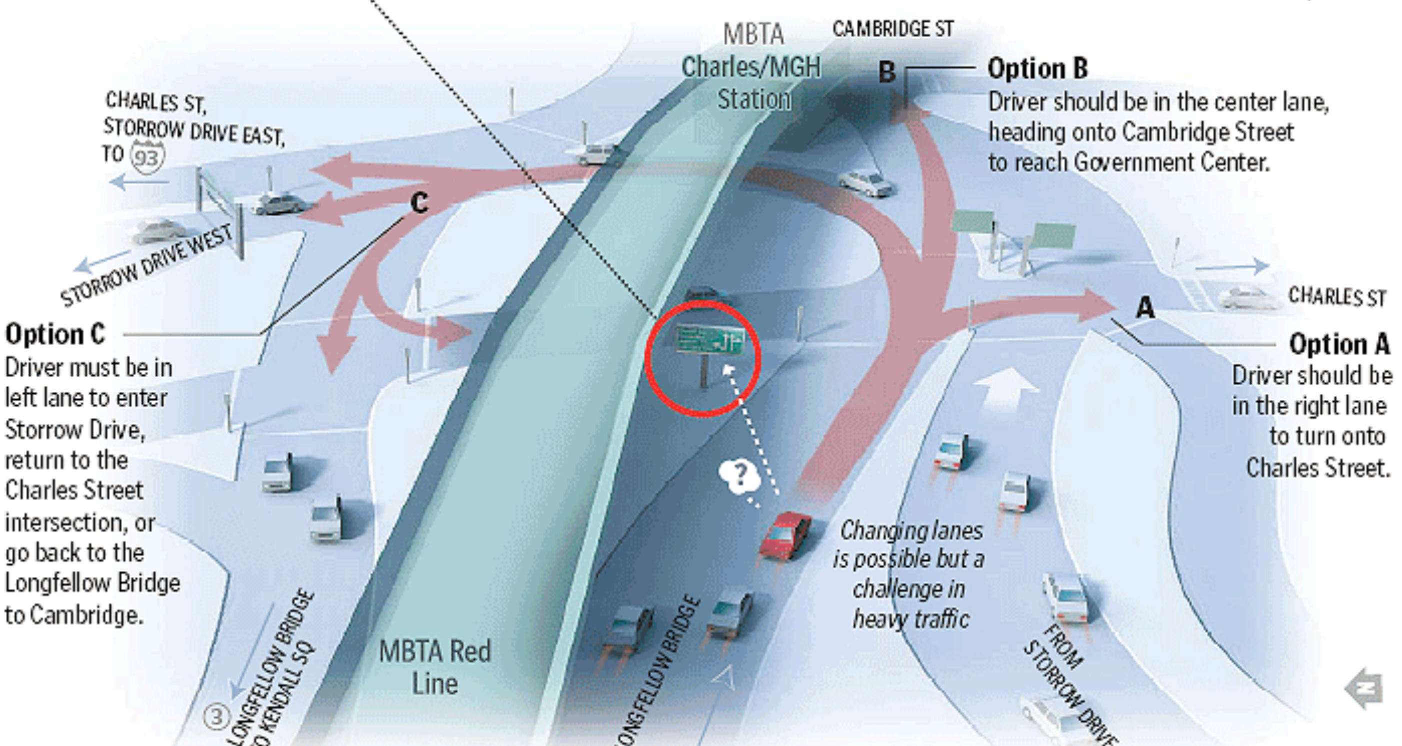


PHOTO: MARK WILSON/GLOBE STAFF

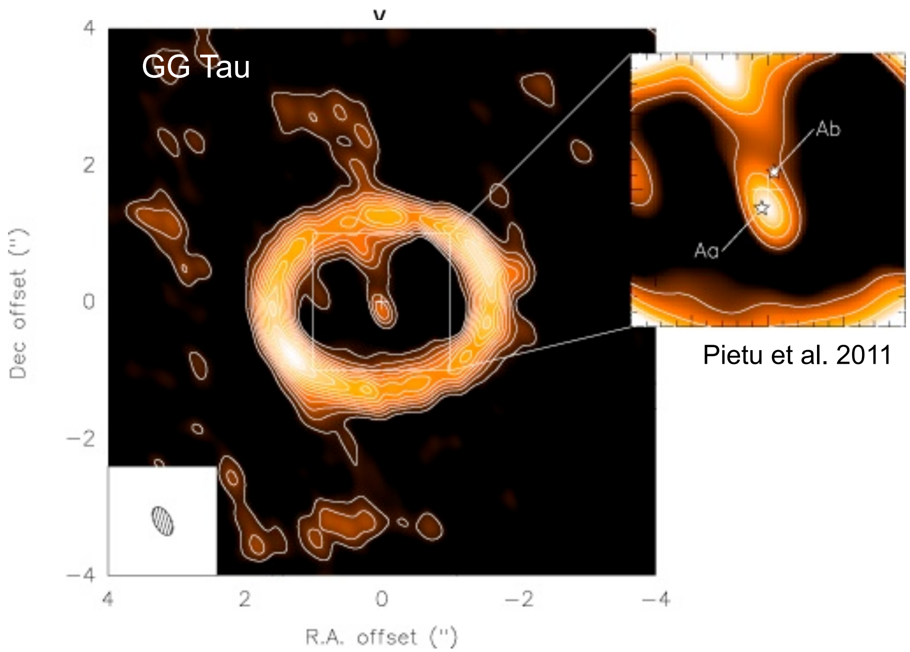


SOURCE: Globe reporting

AARON ATENCIO AND JAVIER ZARRACINA/GLOBE STAFF

Stellar Companions?

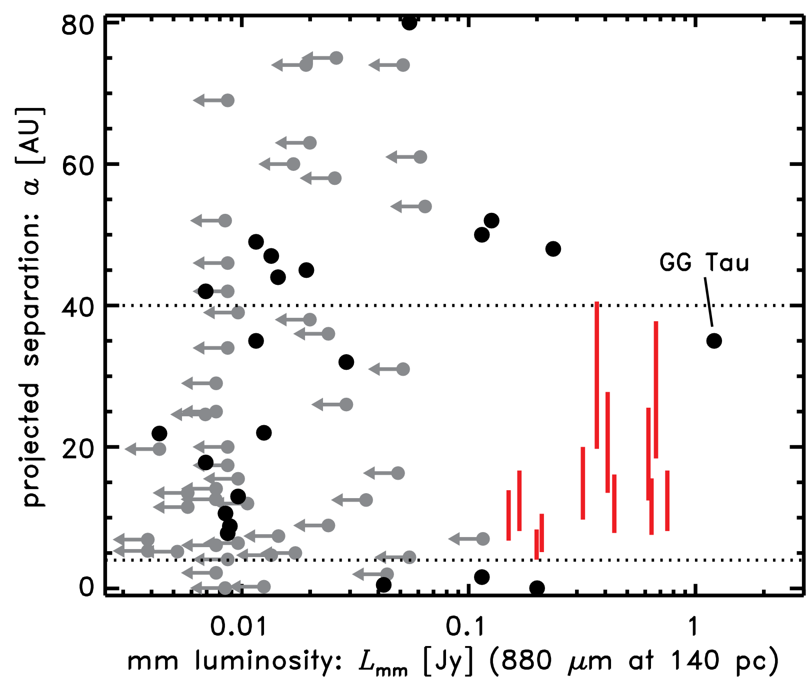
- circumbinary disk truncation at R = 2-3a, implies a = 4-40 AU



Pietu et al. 2011

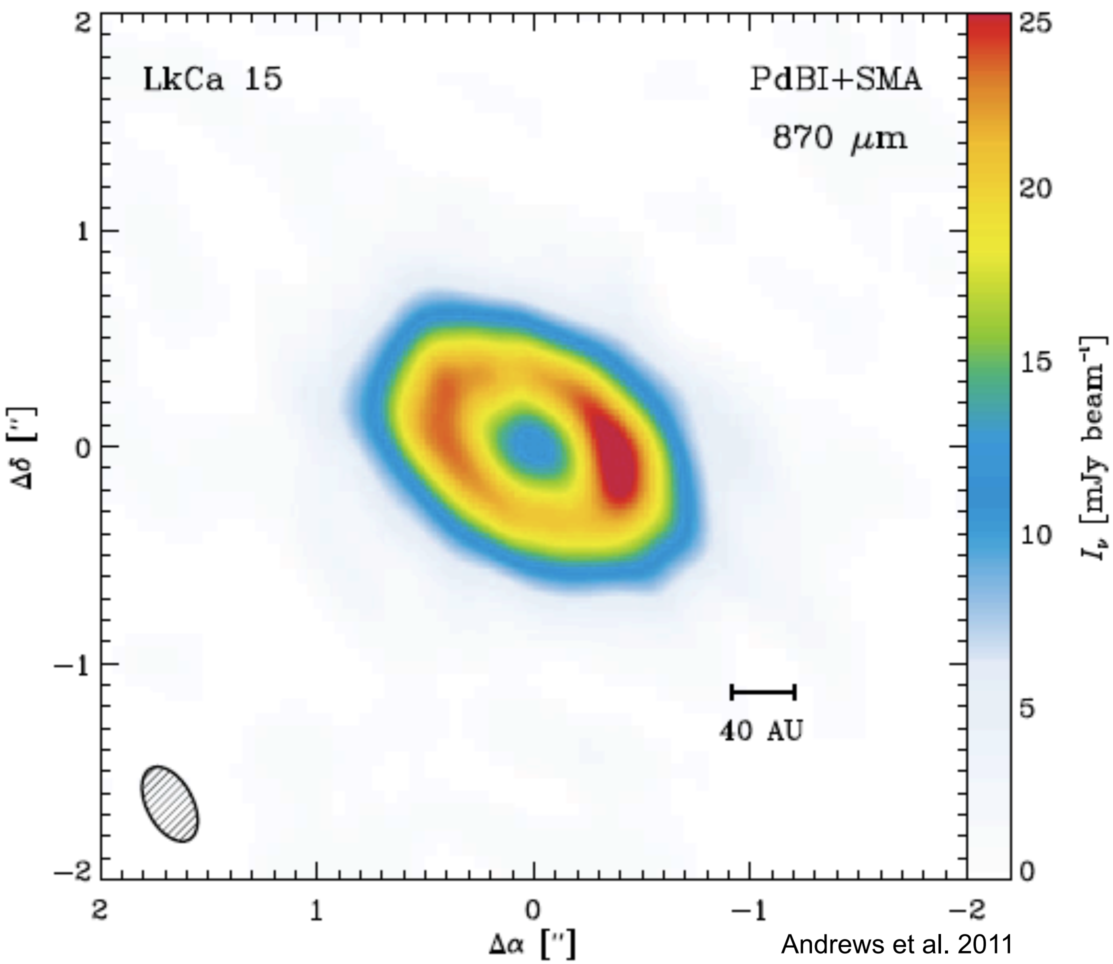
- stellar companions ruled out in many (but not all) systems by direct optical/infrared searches

- disks in binary systems generally less massive than transition disks



Andrews et al. 2011

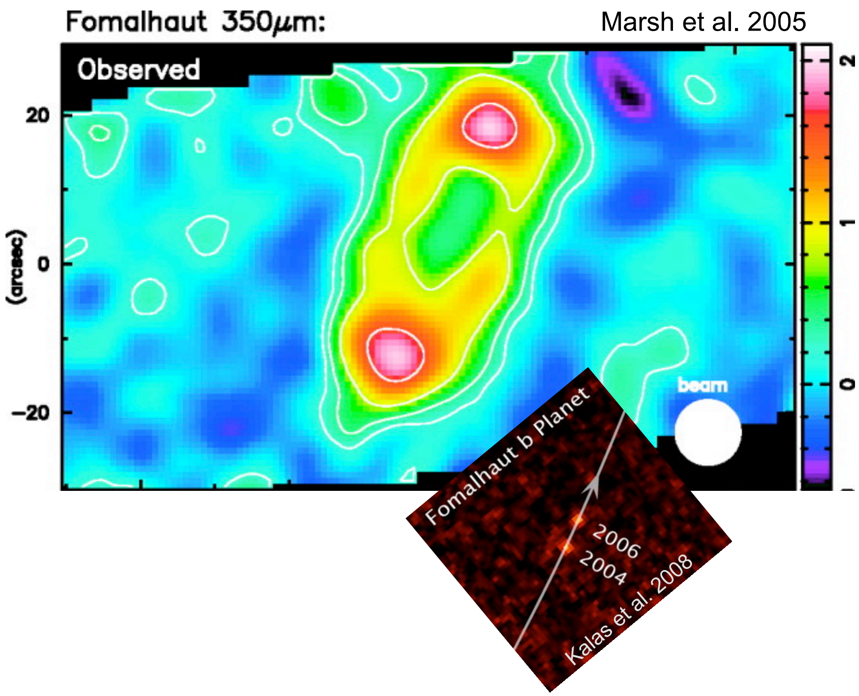
Substellar/Planetary Companions?

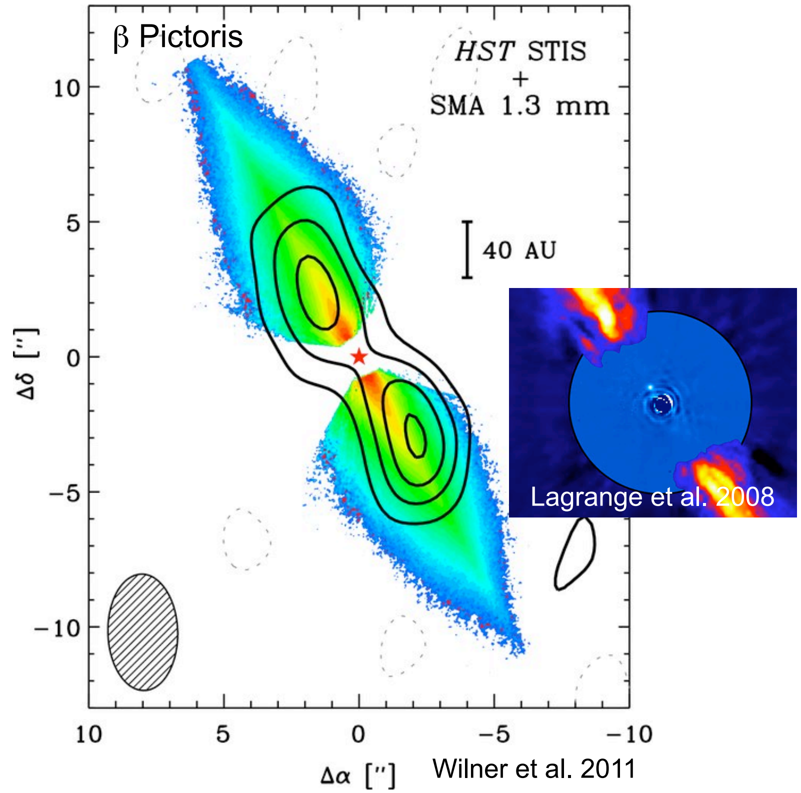


Andrews et al. 2011

- LkCa 15: substellar companion detected directly *within* the disk (Krauss and Ireland 2011)
- 870 μm data from SMA augmented by new PdBI A configuration data → enhance resolution 50%
  - emission inside cavity
- constrain M_s/M_* with gap? (Crida et al. 2006)

Debris Disk Analogs with Planets

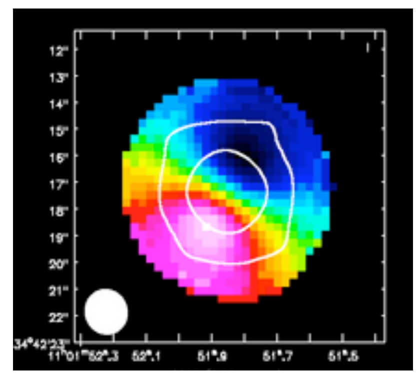




Were these giant planets formed at 1 Myr?

Atacama Large Millimeter Array

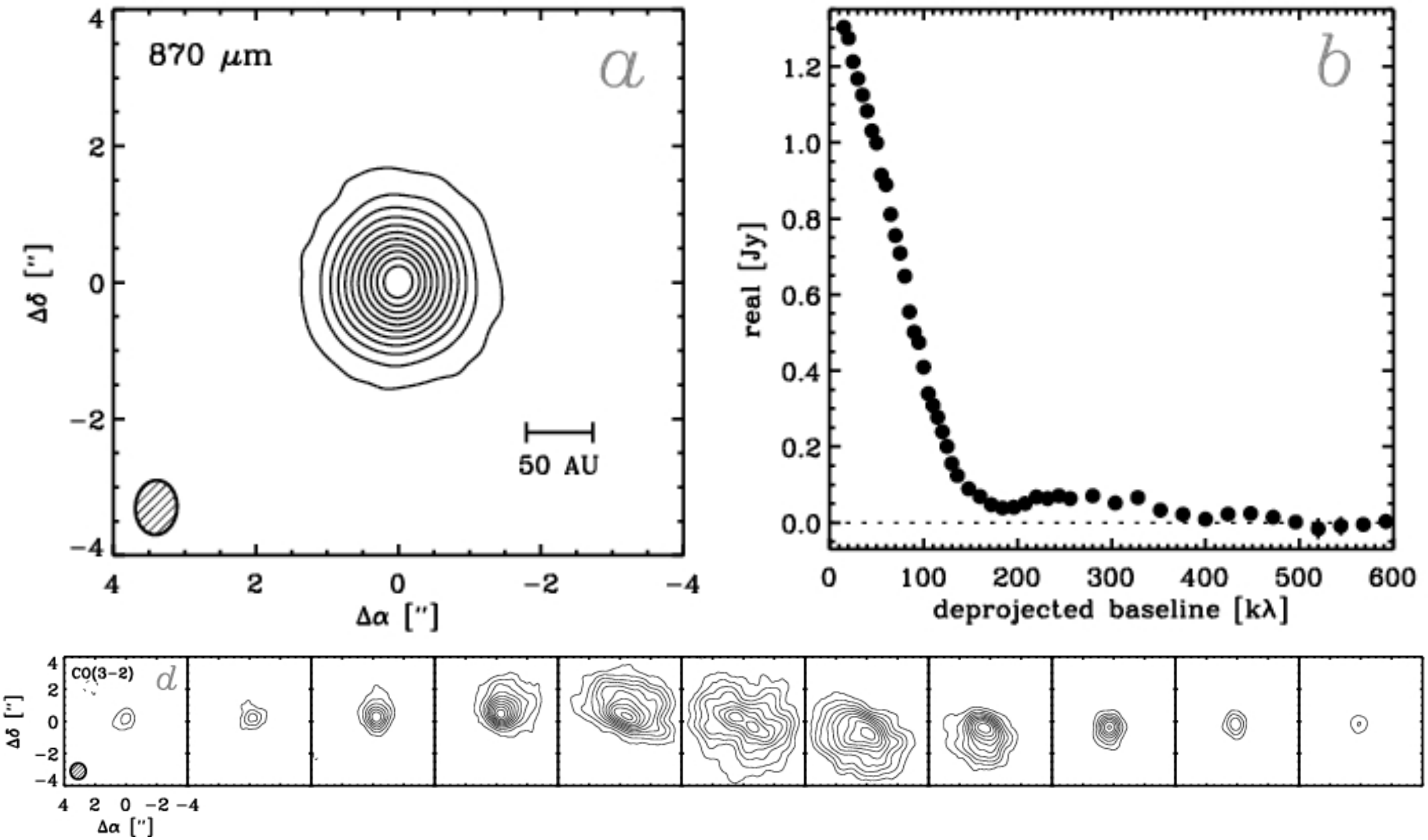
- 10 - 100x better sensitivity, resolution, image quality
- global partnership to fund $1.3B construction
- best antennas, best rx's, best site, 5000 m in Chile
- "Cycle 0" early science underway with 16 antennas
  - 20% protoplanetary/debris disk projects
- full operation with 50 antennas + ACA , 2013+



TW Hya HCO+ 4-3, science verification

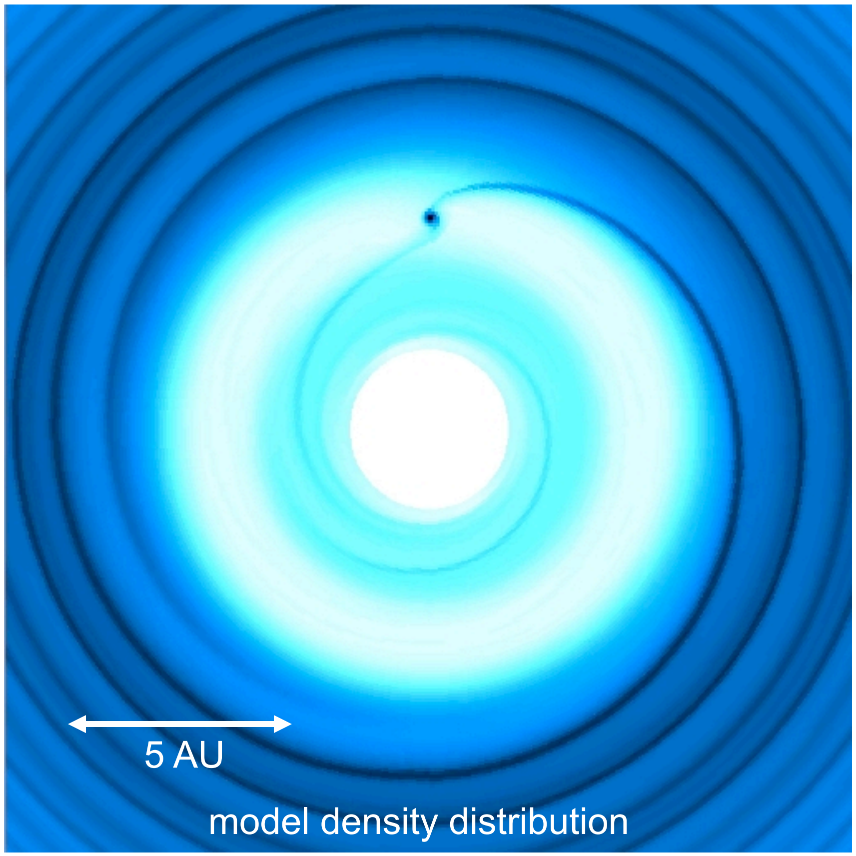
→ *much deeper* individual spectro-imaging studies *and* statistical views

TW Hya, c. 2011

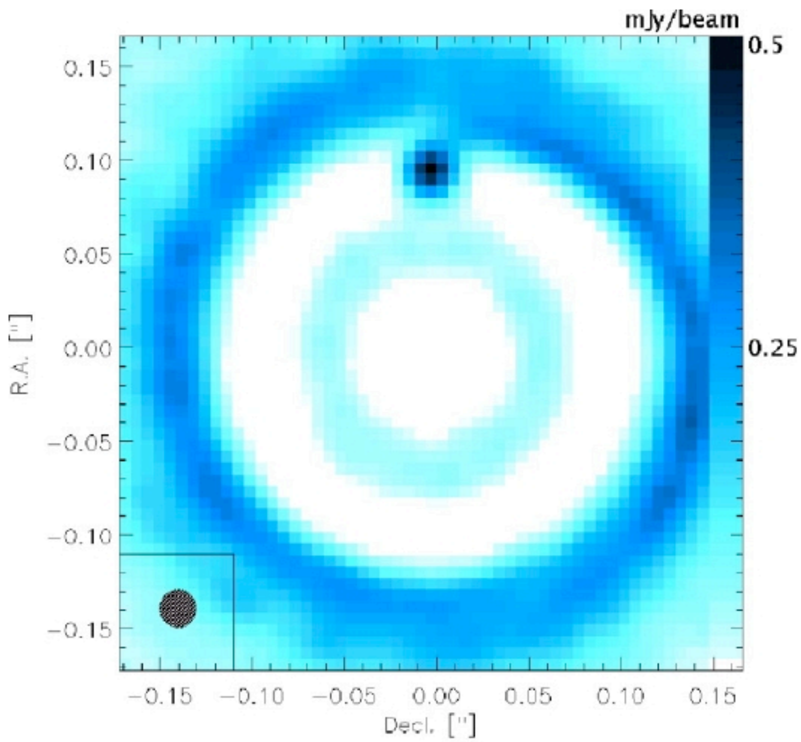


(challenging to reconcile dust and gas structure with simple models)

TW Hya at the Limits of ALMA, c. 2013?

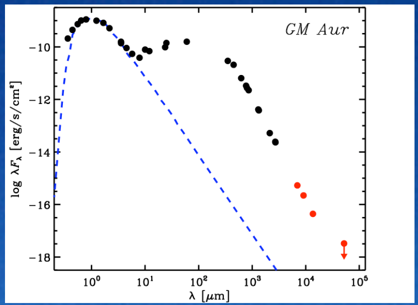


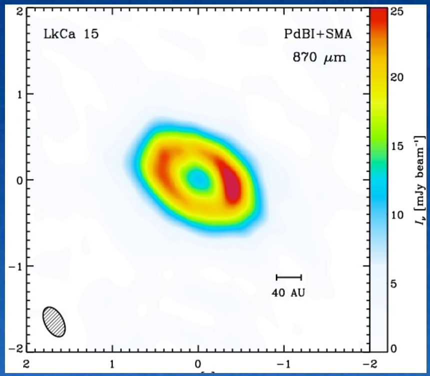
simulated ALMA image of 333 μm dust continuum emission, 8 hours

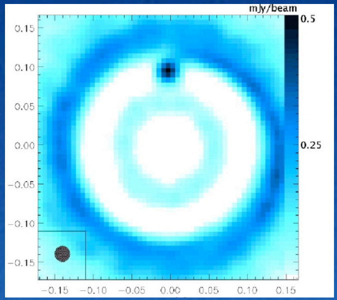


Wolf and D'Angelo 2005

Summary







18 antennas at AOS on 13 August 2011, NAOJ