

protoplanetary disks

demographics, structure, & evolution

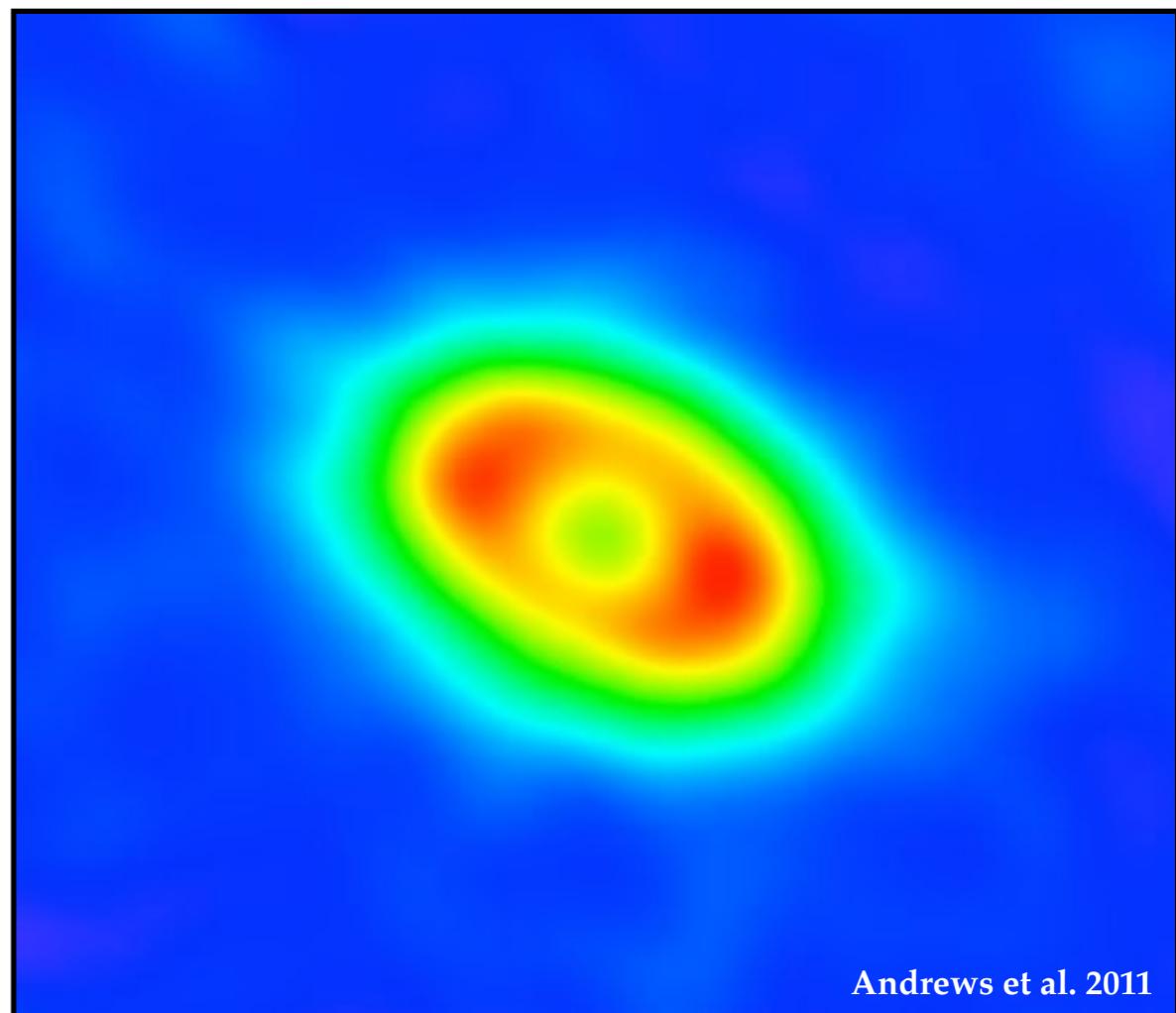
Sean Andrews (CfA)

Bally et al. 2000

Submillimeter Array: First Decade of Discovery



Heather Stanfield Wilkinson



Andrews et al. 2011

protoplanetary disk science with the SMA

- *very productive*

96 papers to date (15/year now)

7 PhDs; 4 more in progress

>7 postdocs; 5 as prize fellows

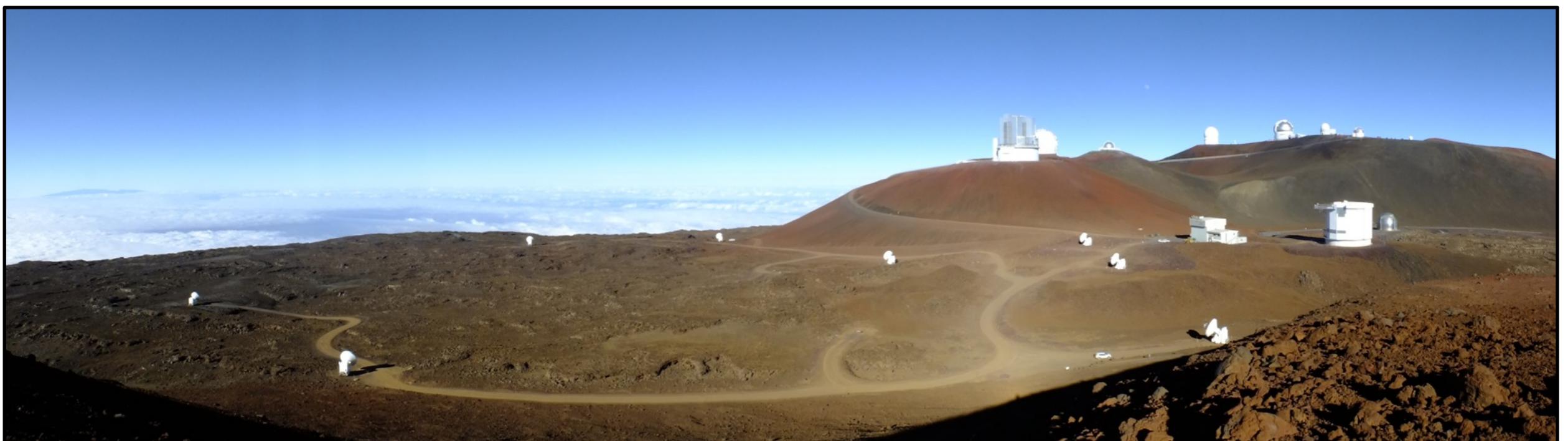
- *high impact*

~2900 citations

500-600 citations/year now

$h = 30$; 6 w/ >100 citations

- *key factors in success*



protoplanetary disk science with the SMA

- *very productive*

96 papers to date (15/year now)

7 PhDs; 4 more in progress

>7 postdocs; 5 as prize fellows

- *high impact*

~2900 citations

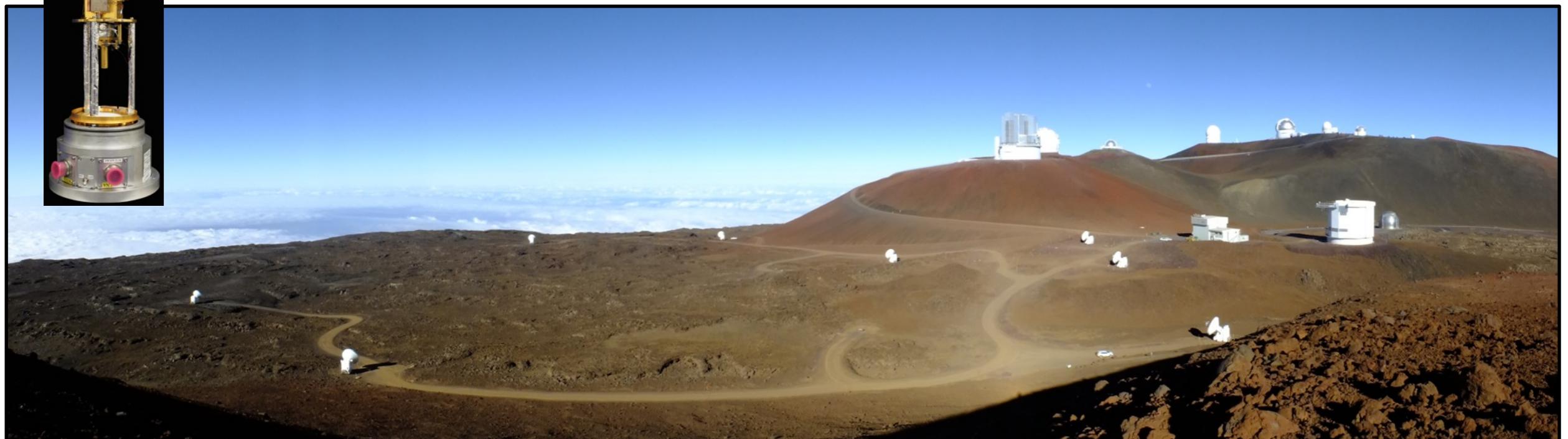
500-600 citations/year now

$h = 30$; 6 w/ >100 citations

- *key factors in success*



sensitivity (345 GHz) + broad bandwidth



protoplanetary disk science with the SMA

- *very productive*

96 papers to date (15/year now)

7 PhDs; 4 more in progress

>7 postdocs; 5 as prize fellows

- *high impact*

~2900 citations

500-600 citations/year now

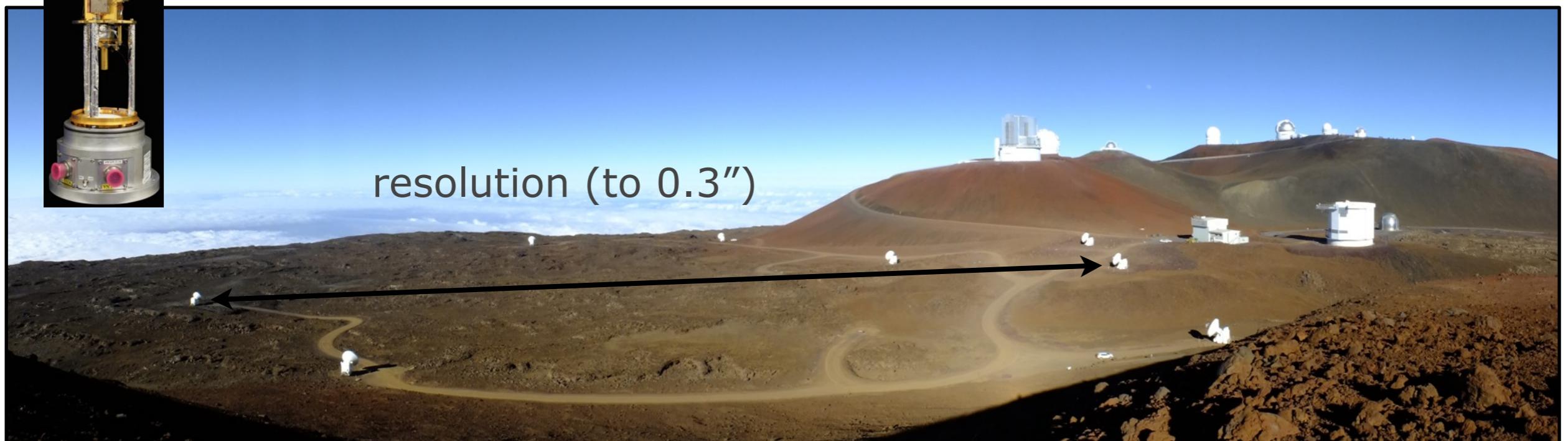
$h = 30$; 6 w/ >100 citations

- *key factors in success*



sensitivity (345 GHz) + broad bandwidth

resolution (to 0.3")



protoplanetary disk science with the SMA

- *very productive*

96 papers to date (15/year now)

7 PhDs; 4 more in progress

>7 postdocs; 5 as prize fellows

- *high impact*

~2900 citations

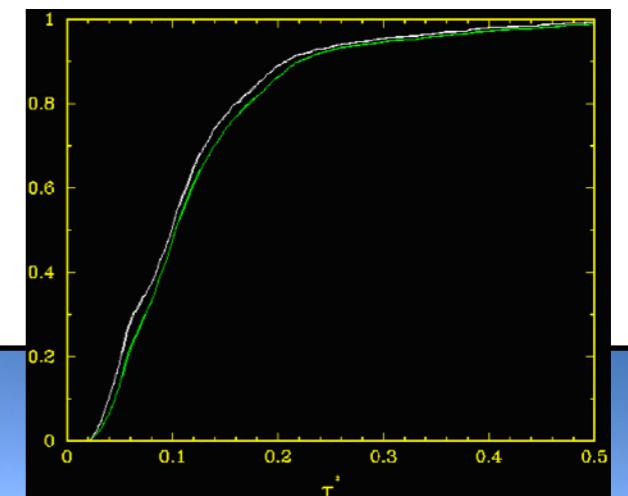
500-600 citations/year now

$h = 30$; 6 w/ >100 citations

- *key factors in success*

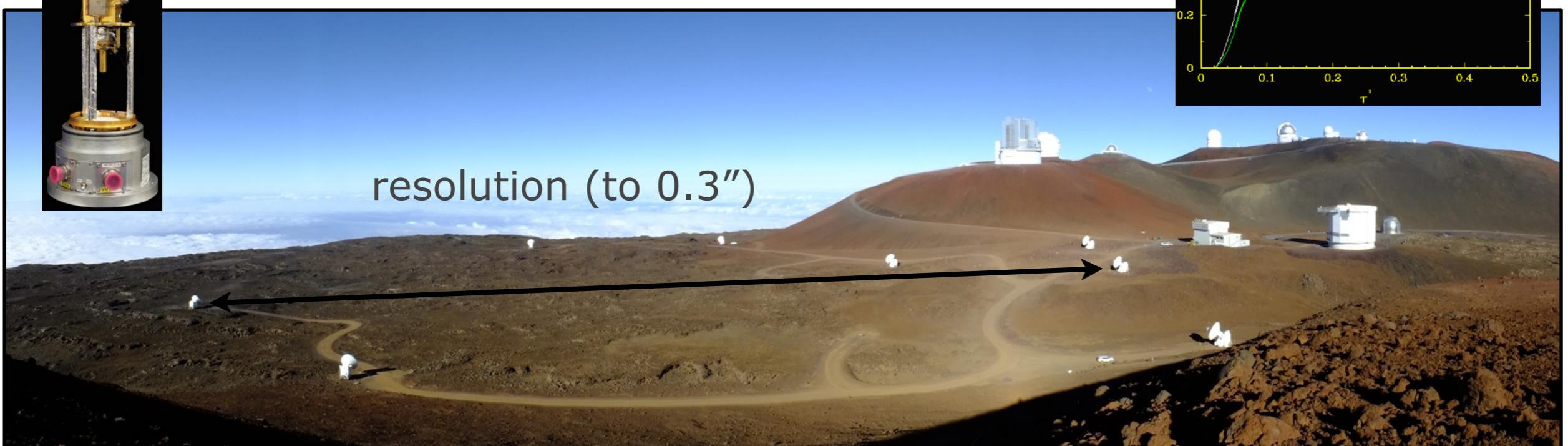


sensitivity (345 GHz) + broad bandwidth



great site (low pwv)

resolution (to 0.3")

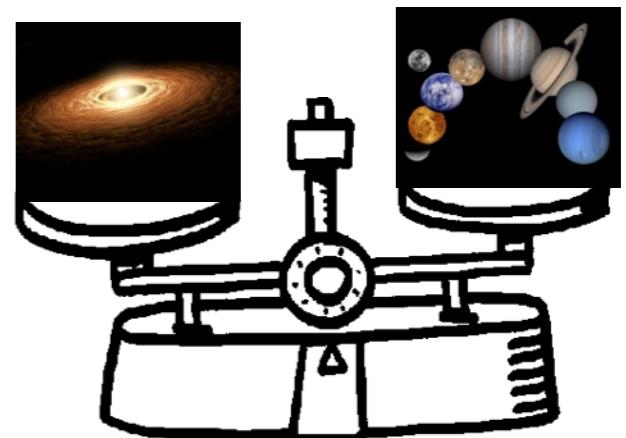


basic disk properties are tied to planet formation process

- demographics

what “external” factors influence disk masses?

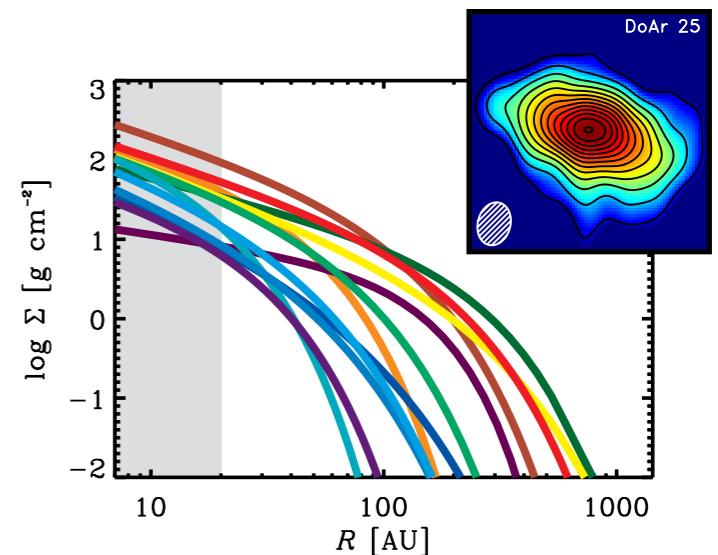
Williams et al. 2005, 2013; Lommen et al. 2007, 2010; Eisner et al. 2008; Cieza et al. 2008, 2010, 2012; Mann & Williams 2009a, b, 2010; Ricci et al. 2011; Lee et al. 2011; Harris et al. 2012; Meeus et al. 2012; Andrews et al. 2013; Williams & Best 2014



- structures

how is the mass spatially distributed in disks?

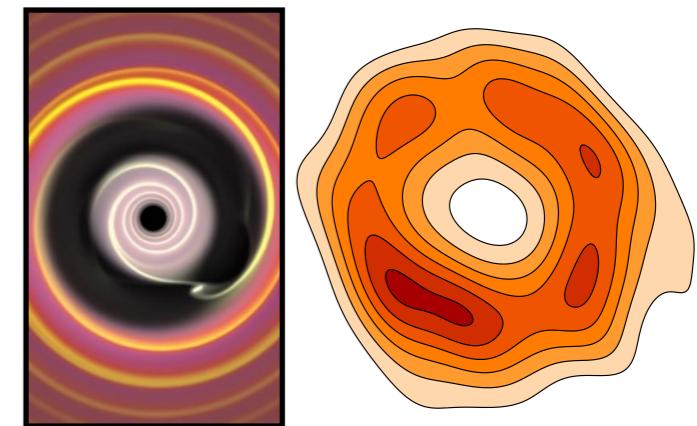
Qi et al. 2004, 2006, 2008, 2011, 2013a, b; Andrews & Williams 2005, 2007; Raman et al. 2006; Isella et al. 2007; Brinch et al. 2007; Wolf et al. 2008; Hughes et al. 2008, 2009, 2011, 2013; Andrews et al. 2008a, b, 2009, 2010a, b, 2012; Pinte et al. 2008; Panic et al. 2008, 2009; Sauter et al. 2009; Dai et al. 2010; Momose et al. 2010; Öberg et al. 2010, 2011, 2012; Rodríguez et al. 2010; Lee 2010, 2011; Takakuwa et al. 2012; Rosenfeld et al. 2012; Akimkin et al. 2012; Tobin et al. 2012, 2013; Gråfe et al. 2013; Forgan & Rice 2013; Favre et al. 2013



- evolution

how is disk material transformed or dissipated?

Lin et al. 2006; Espaillat et al. 2007, 2012; Brown et al. 2008, 2009, 2012; Hughes et al. 2009, 2010; Isella et al. 2010, 2013; Banzatti et al. 2011; Andrews et al. 2011; Lyo et al. 2011; Cieza et al. 2012; Mathews et al. 2012; Tang et al. 2012; Pérez et al. 2012; Follette et al. 2013; Rosenfeld et al. 2013; Tsukagoshi et al. 2014; Miotello et al. 2014

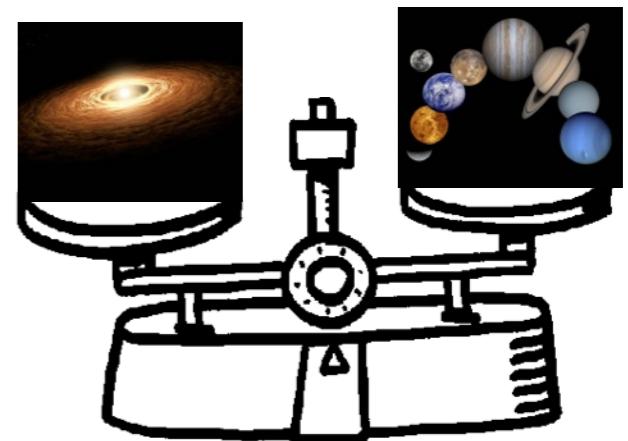


basic disk properties are tied to planet formation process

- demographics

what “external” factors influence disk masses?

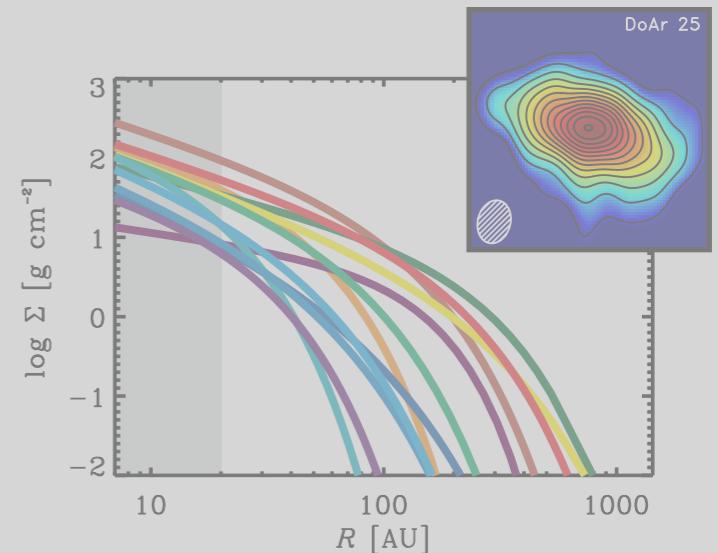
Williams et al. 2005, 2013; Lommen et al. 2007, 2010; Eisner et al. 2008; Cieza et al. 2008, 2010, 2012; Mann & Williams 2009a, b, 2010; Ricci et al. 2011; Lee et al. 2011; Harris et al. 2012; Meeus et al. 2012; Andrews et al. 2013; Williams & Best 2014



- structures

how is the mass spatially distributed in disks?

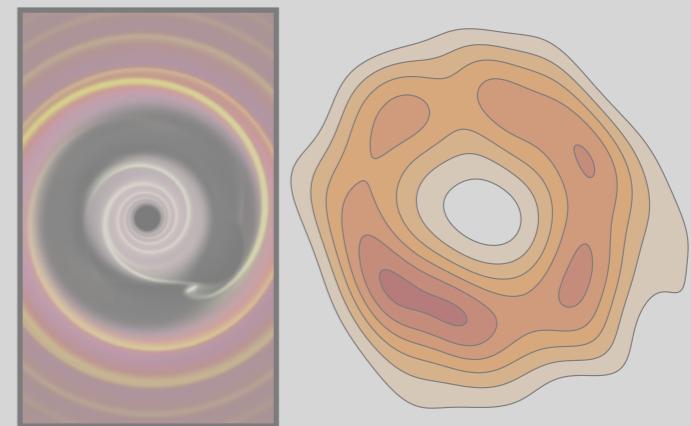
Qi et al. 2004, 2006, 2008, 2011, 2013a, b; Andrews & Williams 2005, 2007; Raman et al. 2006; Isella et al. 2007; Brinch et al. 2007; Wolf et al. 2008; Hughes et al. 2008, 2009, 2011, 2013; Andrews et al. 2008a, b, 2009, 2010a, b, 2012; Pinte et al. 2008; Panic et al. 2008, 2009; Sauter et al. 2009; Dai et al. 2010; Momose et al. 2010; Öberg et al. 2010, 2011, 2012; Rodríguez et al. 2010; Lee 2010, 2011; Takakuwa et al. 2012; Rosenfeld et al. 2012; Akimkin et al. 2012; Tobin et al. 2012, 2013; Gråfe et al. 2013; Forgan & Rice 2013; Favre et al. 2013



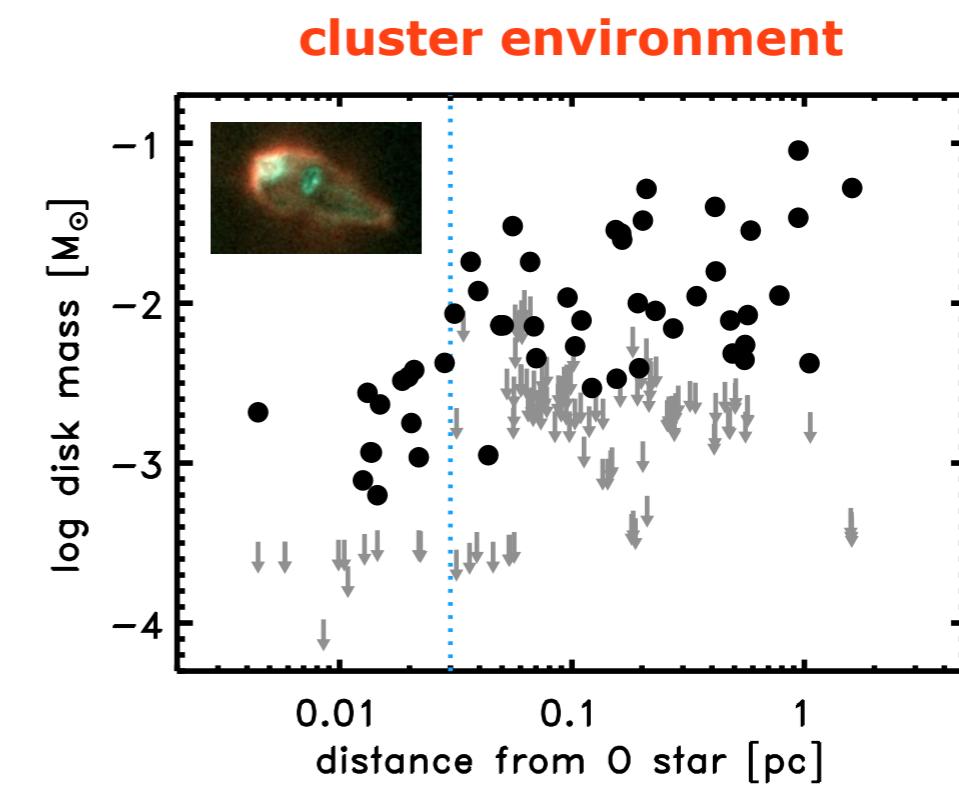
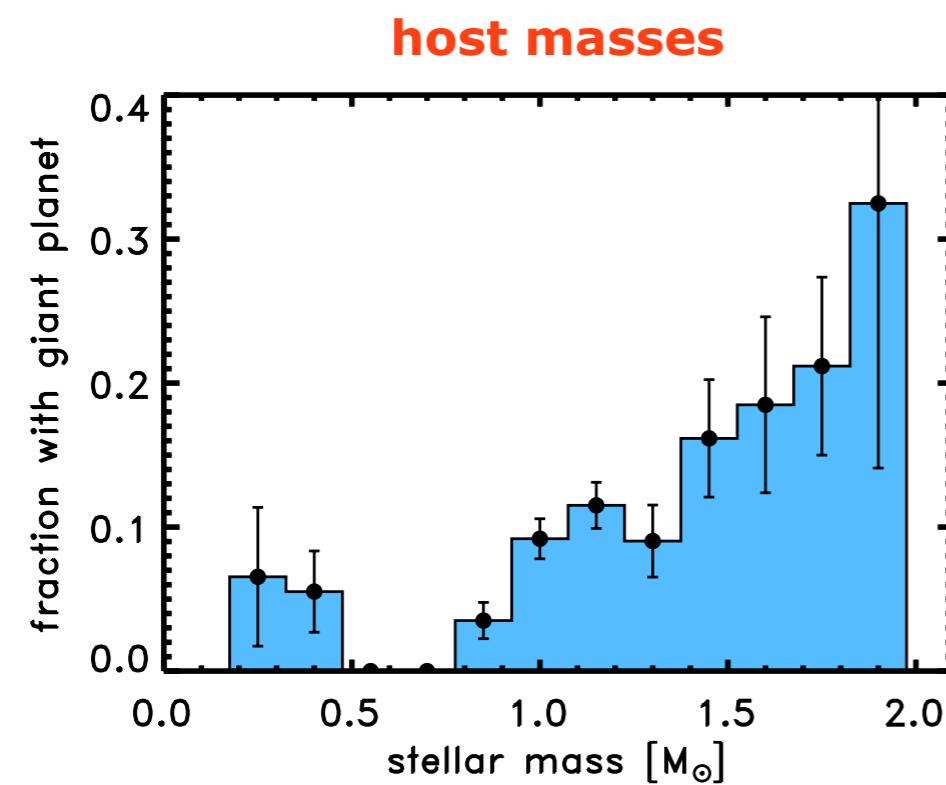
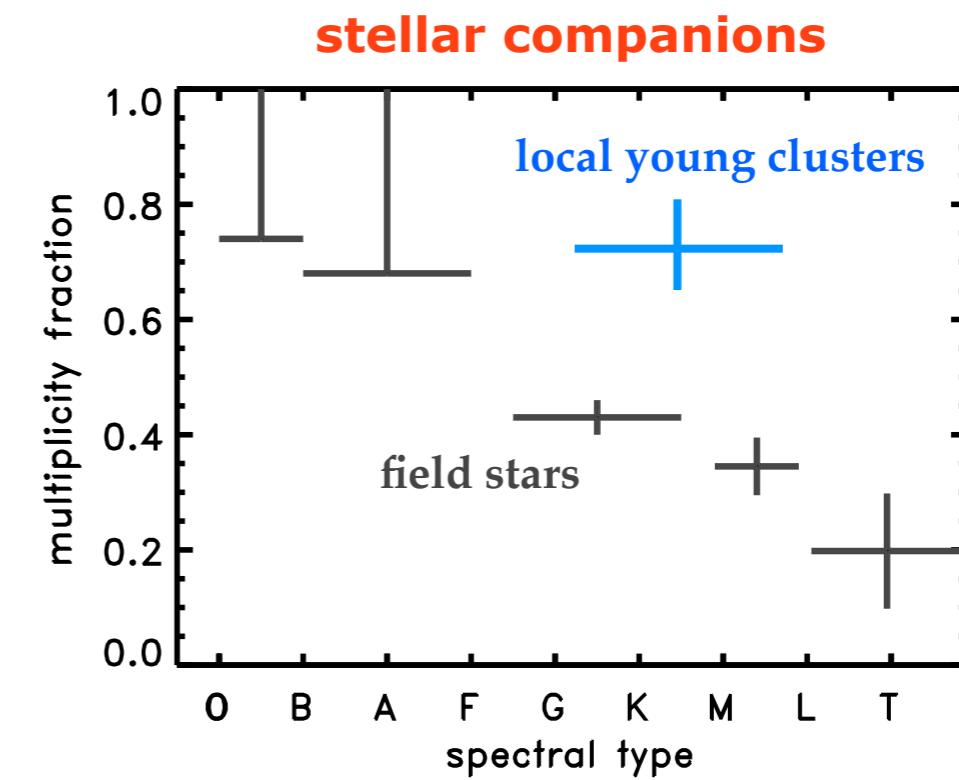
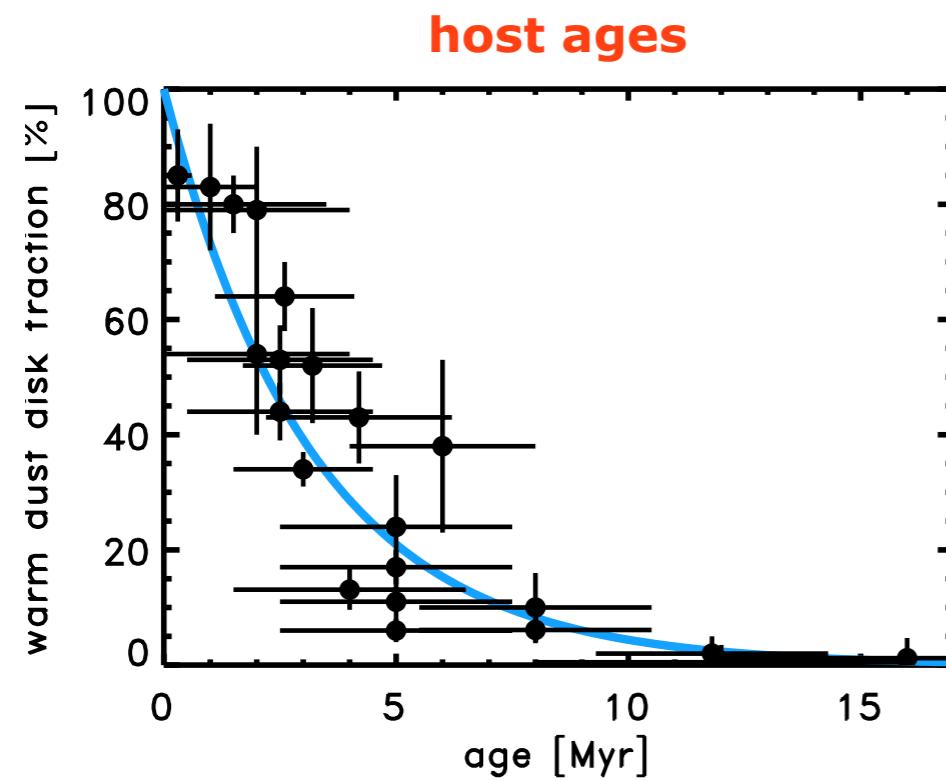
- evolution

how is disk material transformed or dissipated?

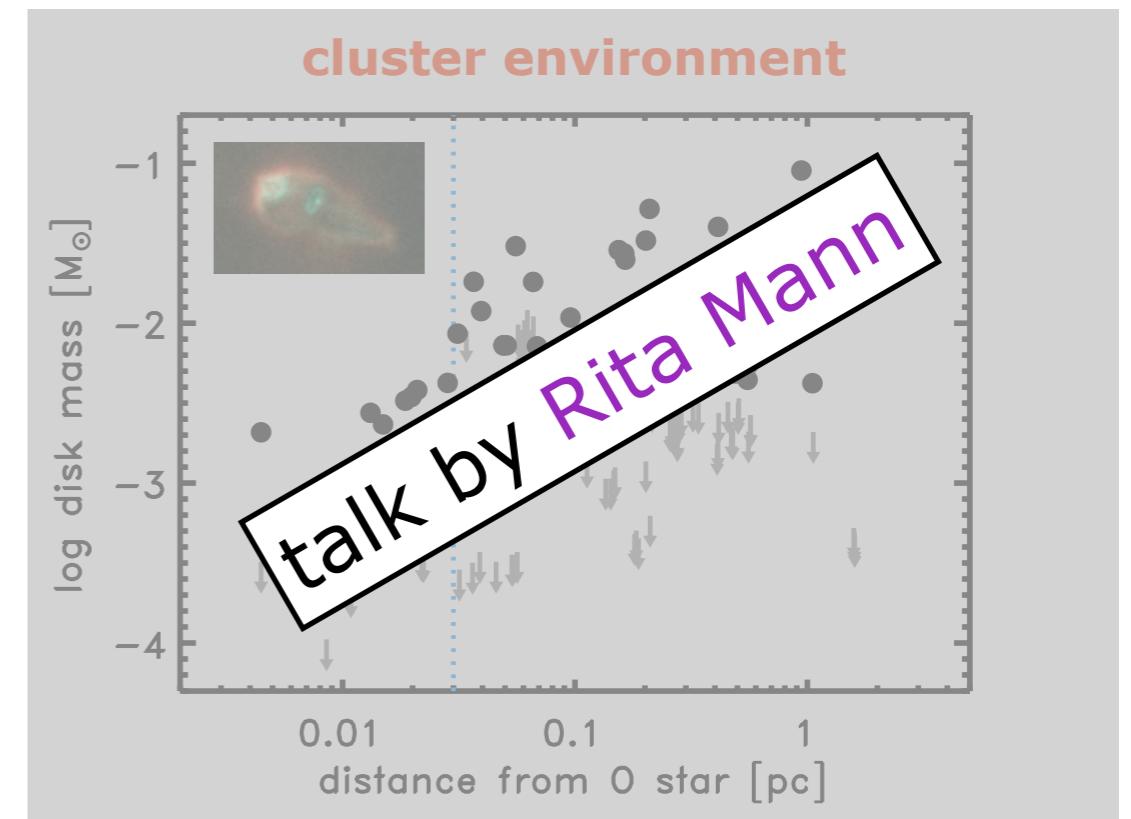
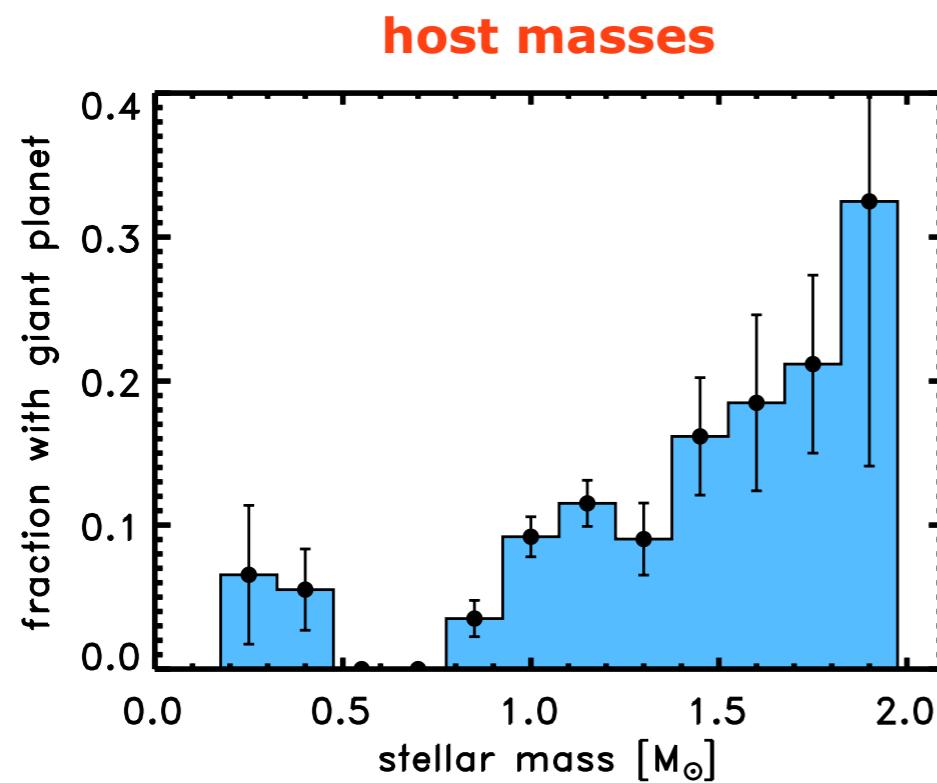
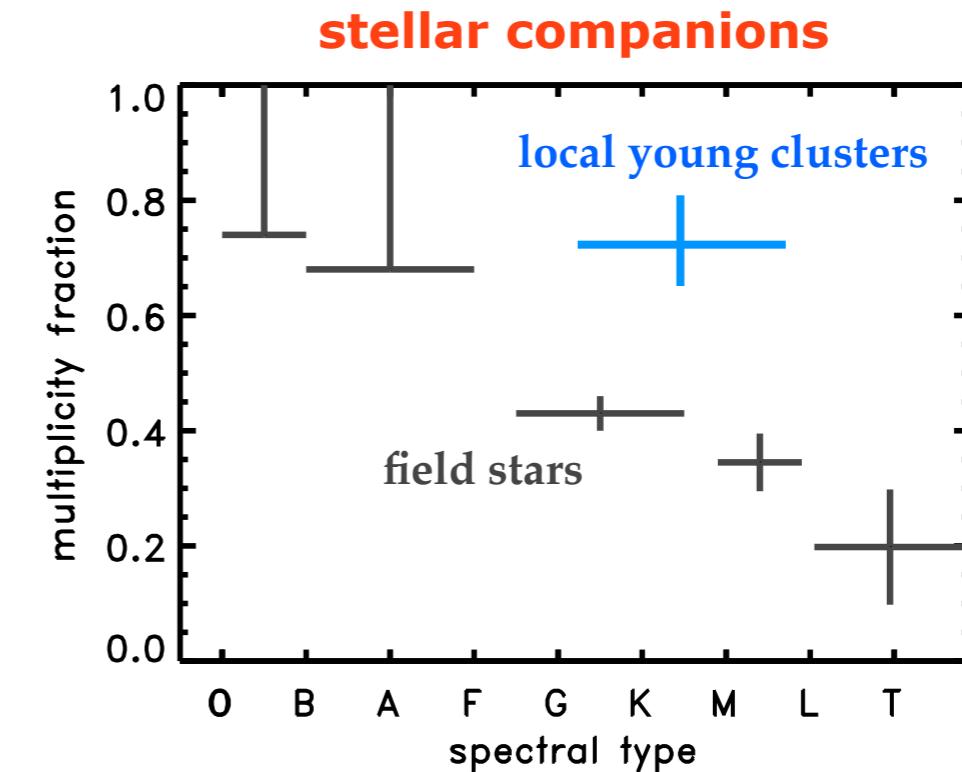
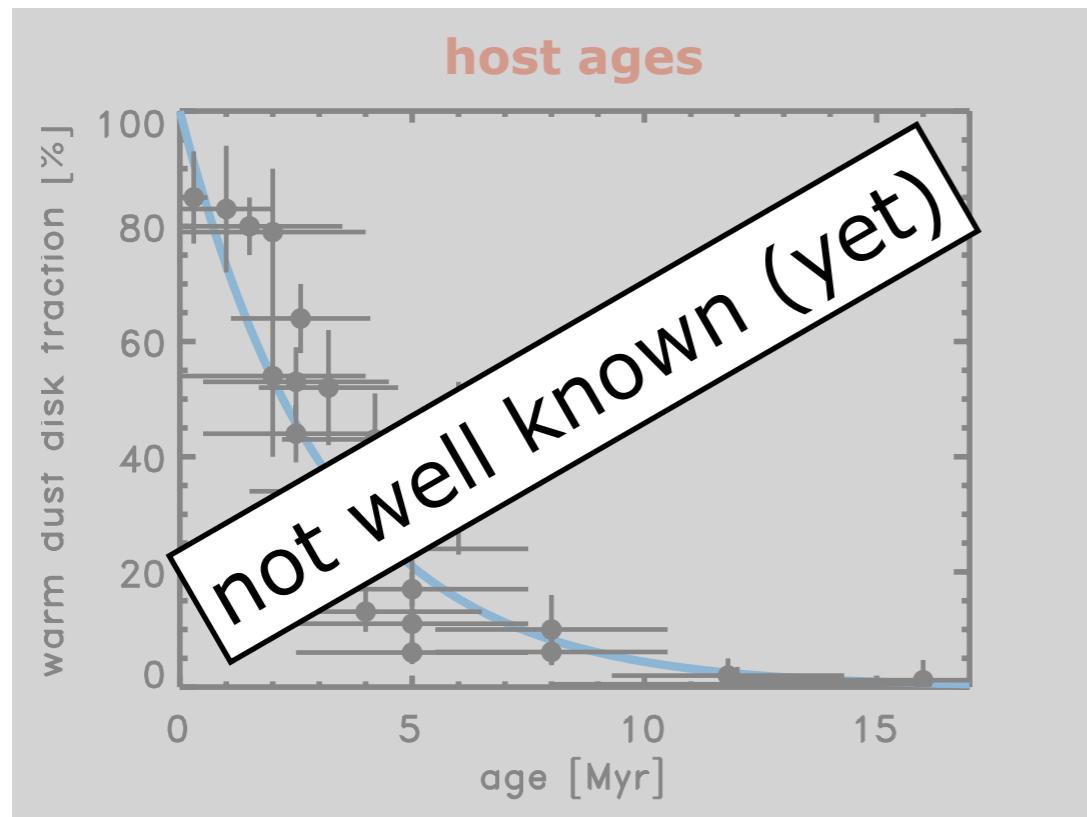
Lin et al. 2006; Espaillat et al. 2007, 2012; Brown et al. 2008, 2009, 2012; Hughes et al. 2009, 2010; Isella et al. 2010, 2013; Banzatti et al. 2011; Andrews et al. 2011; Lyo et al. 2011; Cieza et al. 2012; Mathews et al. 2012; Tang et al. 2012; Pérez et al. 2012; Follette et al. 2013; Rosenfeld et al. 2013; Tsukagoshi et al. 2014; Miotello et al. 2014



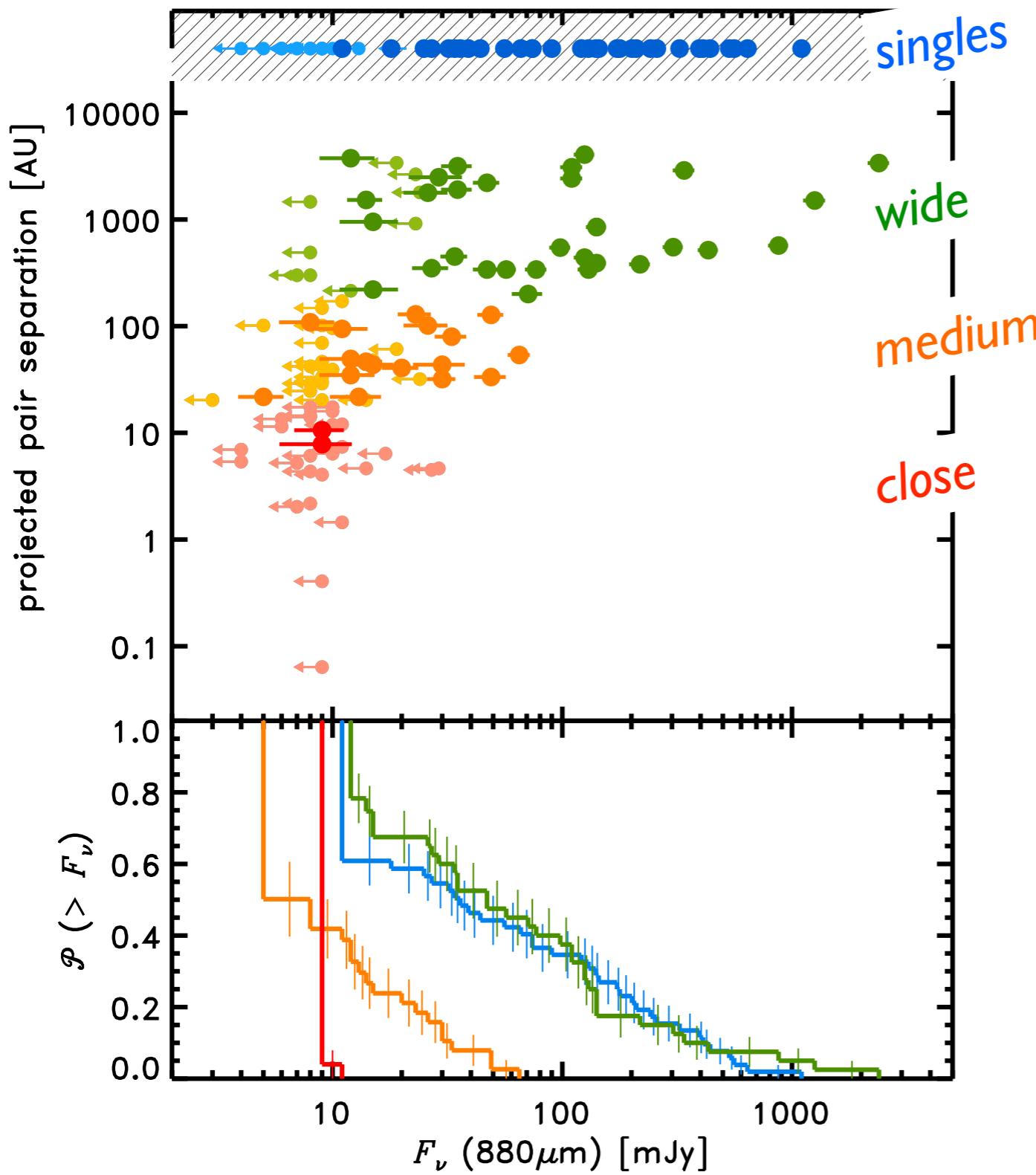
demographics: external factors that influence disk masses



demographics: external factors that influence disk masses

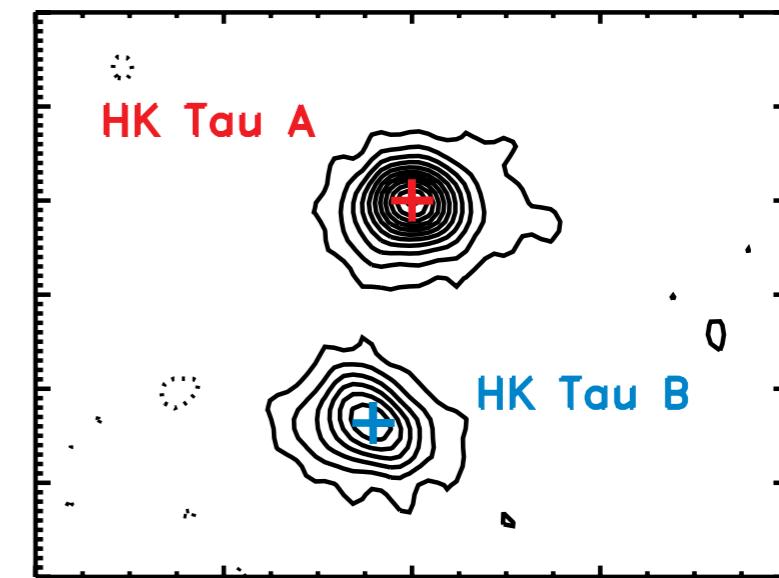


stellar companions can disrupt disks



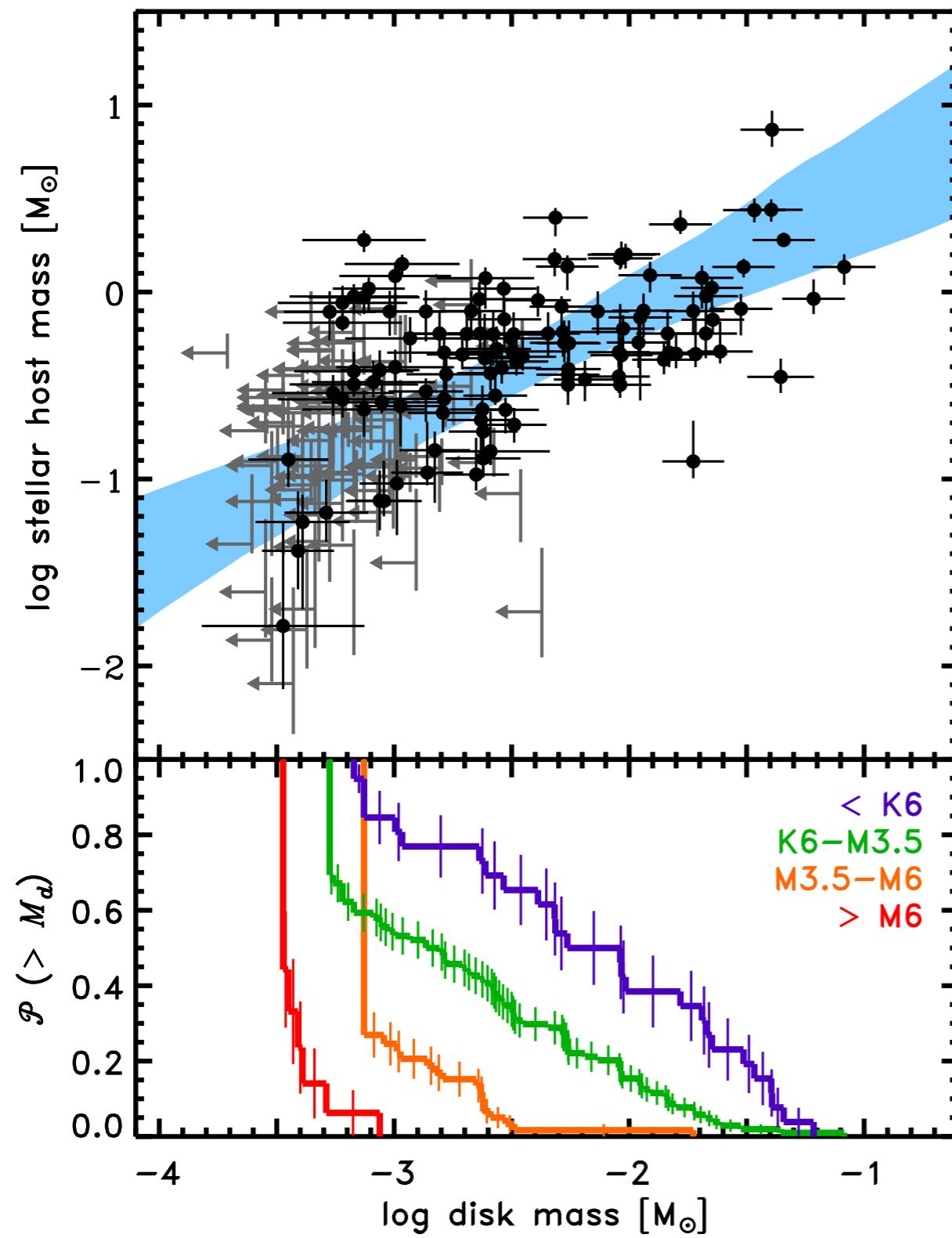
resolved SMA census of disks
in multiple star systems

Harris et al. 2012



wide pairs like singles
medium pairs: 5x less mass
close pairs rarely have disks
more mass around primaries

disk and stellar host masses are related



*mm-wave photometry census
of all Taurus disks (<M8.5)*

unbiased, complete to 3 mJy (3 σ)

Andrews et al. 2013

theorists assume linear scaling
between disk, host masses

consistent with $M_d \propto M_*$

typical mass ratio: 0.4%

scatter: FWHM factor of 40

(careful with comparisons)

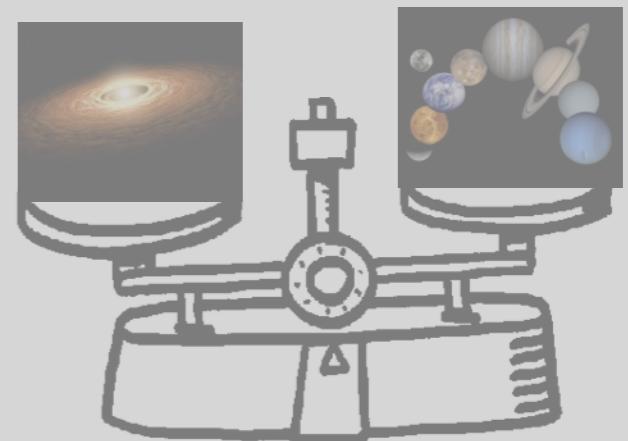
supports core accretion

basic disk properties are tied to planet formation process

- demographics

what “external” factors influence disk masses?

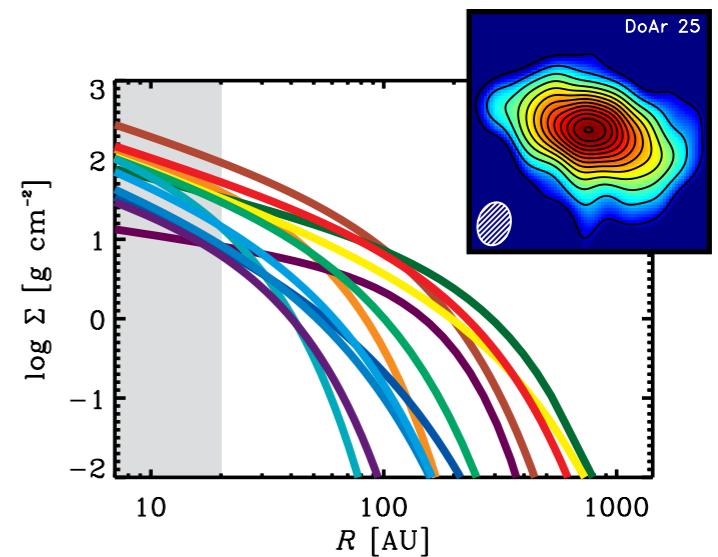
Williams et al. 2005, 2013; Lommen et al. 2007, 2010; Eisner et al. 2008; Cieza et al. 2008, 2010, 2012; Mann & Williams 2009a, b, 2010; Ricci et al. 2011; Lee et al. 2011; Harris et al. 2012; Meeus et al. 2012; Andrews et al. 2013; Williams & Best 2014



- structures

how is the mass spatially distributed in disks?

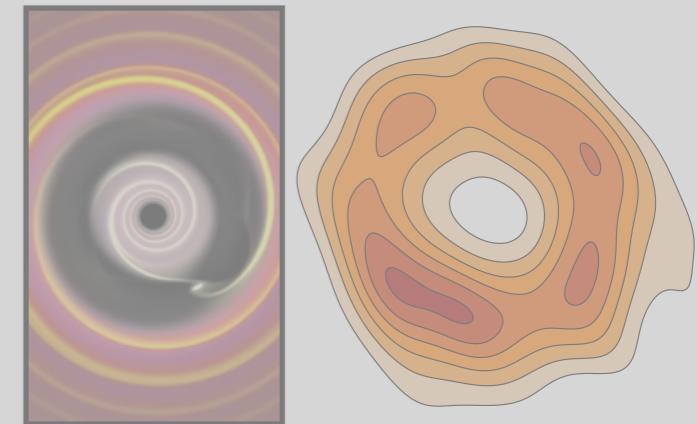
Qi et al. 2004, 2006, 2008, 2011, 2013a, b; Andrews & Williams 2005, 2007; Raman et al. 2006; Isella et al. 2007; Brinch et al. 2007; Wolf et al. 2008; Hughes et al. 2008, 2009, 2011, 2013; Andrews et al. 2008a, b, 2009, 2010a, b, 2012; Pinte et al. 2008; Panic et al. 2008, 2009; Sauter et al. 2009; Dai et al. 2010; Momose et al. 2010; Öberg et al. 2010, 2011, 2012; Rodríguez et al. 2010; Lee 2010, 2011; Takakuwa et al. 2012; Rosenfeld et al. 2012; Akimkin et al. 2012; Tobin et al. 2012, 2013; Gråfe et al. 2013; Forgan & Rice 2013; Favre et al. 2013



- evolution

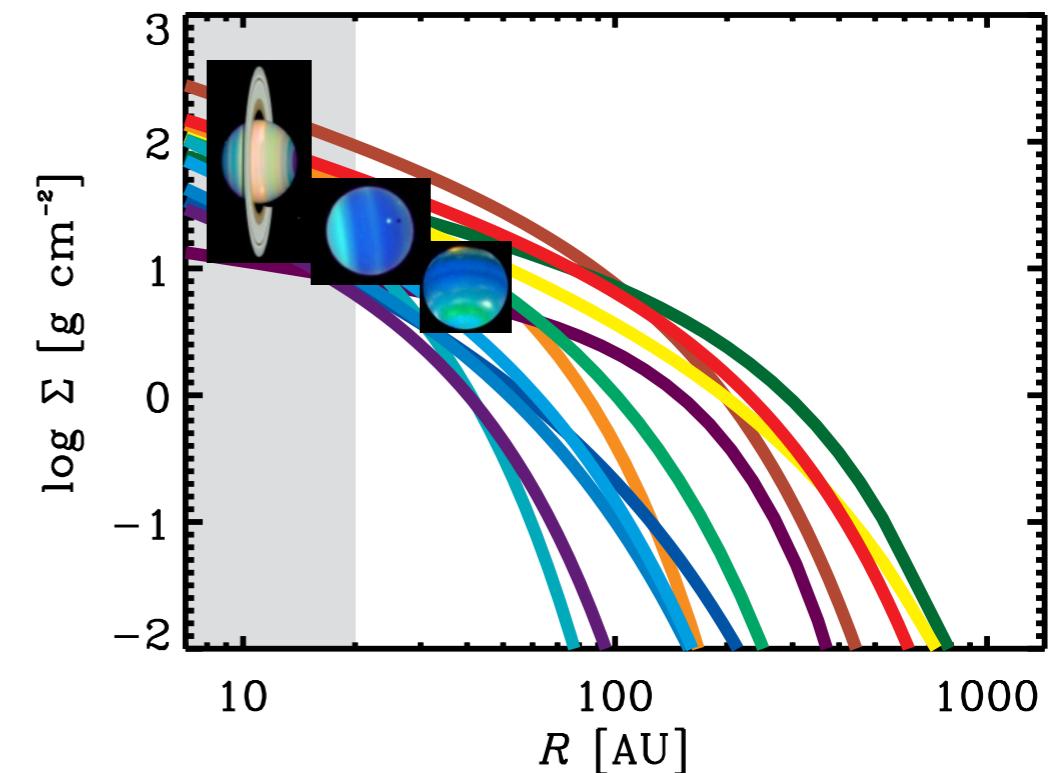
how is disk material transformed or dissipated?

Lin et al. 2006; Espaillat et al. 2007, 2012; Brown et al. 2008, 2009, 2012; Hughes et al. 2009, 2010; Isella et al. 2010, 2013; Banzatti et al. 2011; Andrews et al. 2011; Lyo et al. 2011; Cieza et al. 2012; Mathews et al. 2012; Tang et al. 2012; Pérez et al. 2012; Follette et al. 2013; Rosenfeld et al. 2013; Tsukagoshi et al. 2014; Miotello et al. 2014

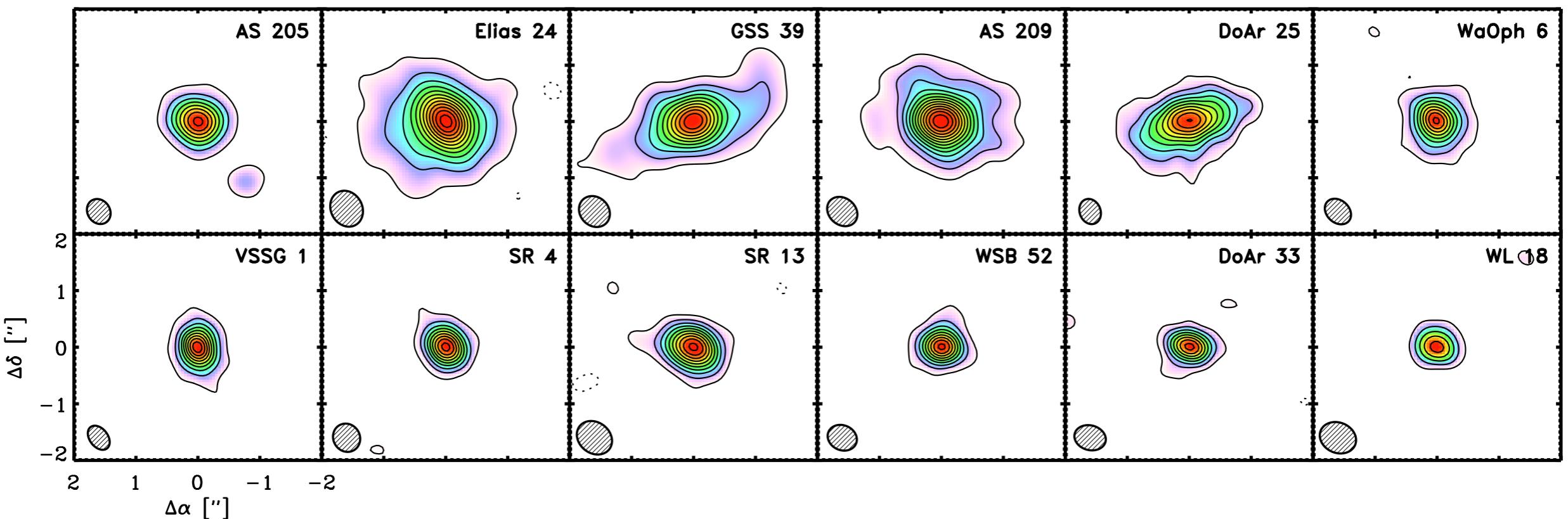


surface density profiles of disk “solids” (< few cm sizes)

- sensitive (340 GHz), high-res ($r \sim 20$ AU)
- forward model SED+visibilities;
3-D Monte Carlo radiative transfer
- radial density profiles **similar to MMSN**
- mass-radius or **luminosity-size correlation**

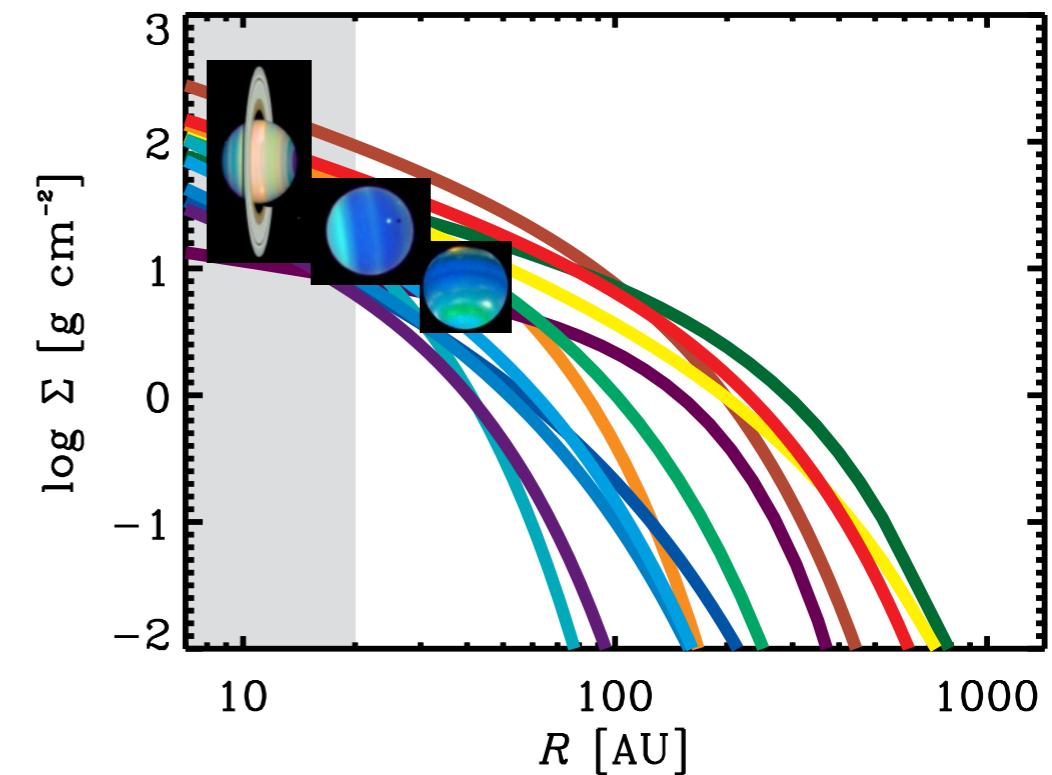


data

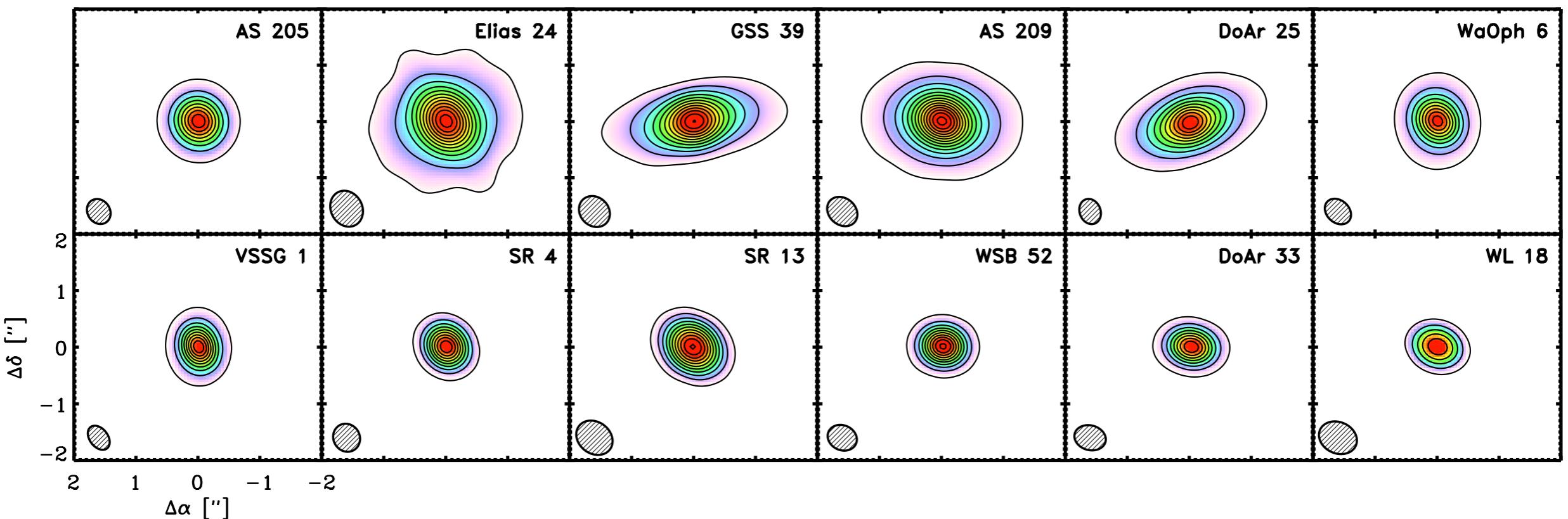


surface density profiles of disk “solids” (< few cm sizes)

- sensitive (340 GHz), high-res ($r \sim 20$ AU)
- forward model SED+visibilities;
3-D Monte Carlo radiative transfer
- radial density profiles **similar to MMSN**
- mass-radius or **luminosity-size correlation**

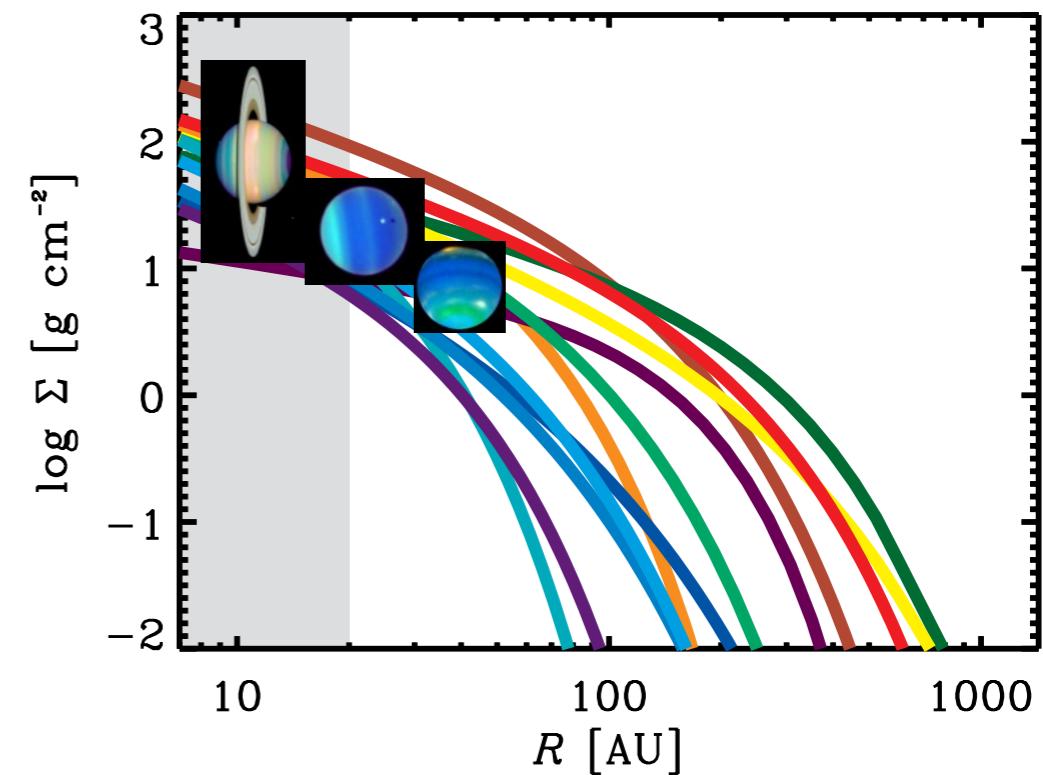


models

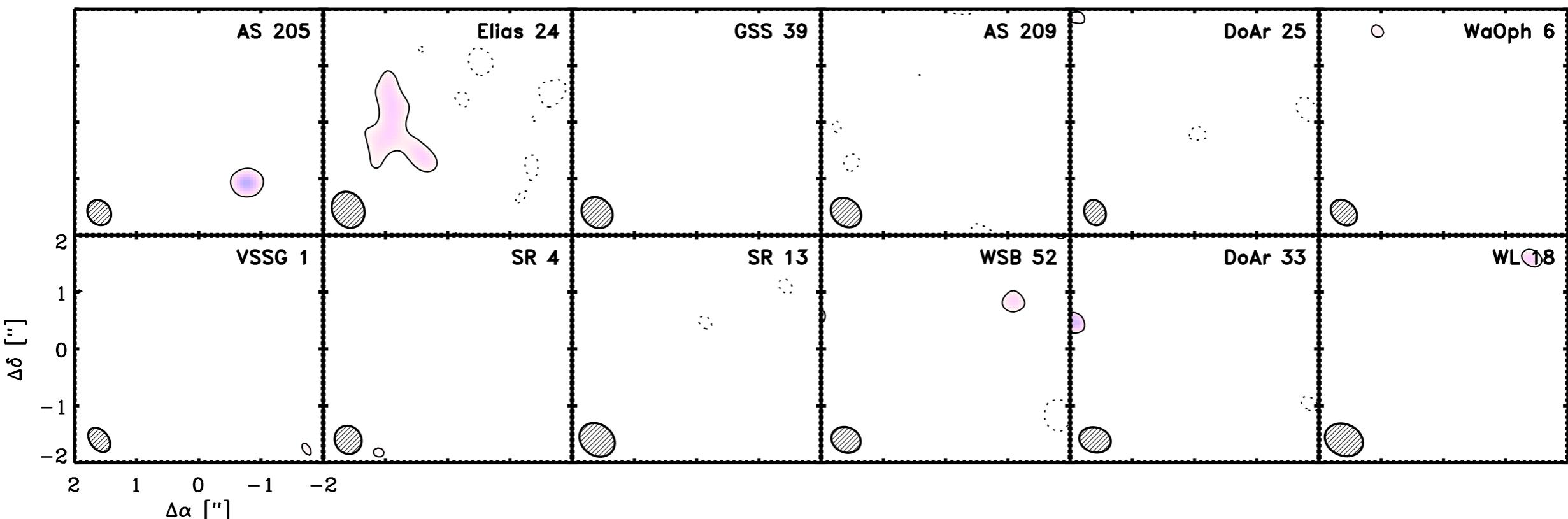


surface density profiles of disk “solids” (< few cm sizes)

- sensitive (340 GHz), high-res ($r \sim 20$ AU)
- forward model SED+visibilities;
3-D Monte Carlo radiative transfer
- radial density profiles **similar to MMSN**
- mass-radius or **luminosity-size correlation**

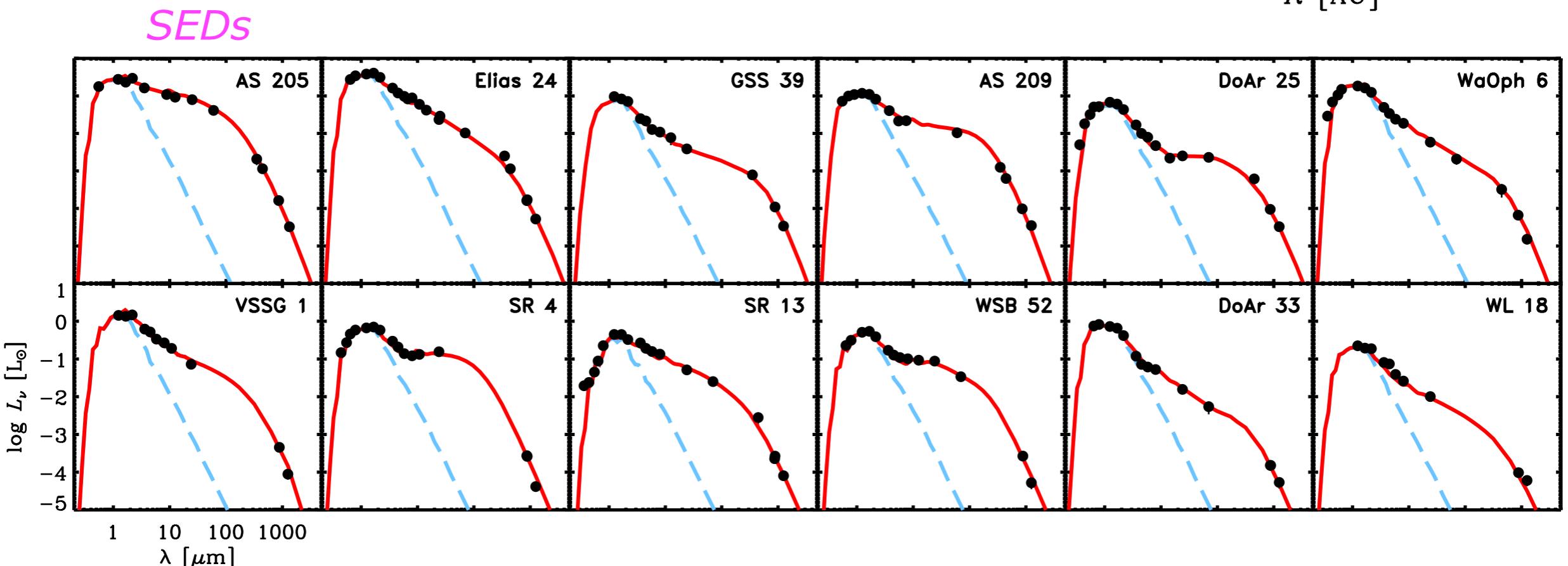
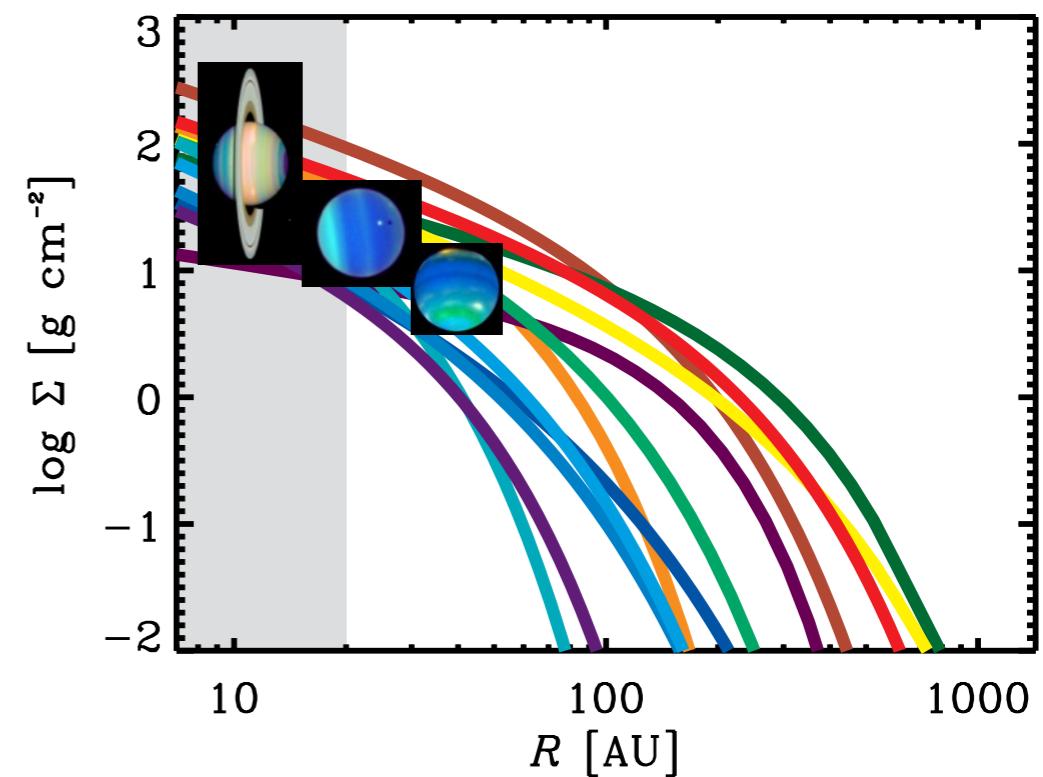


residuals



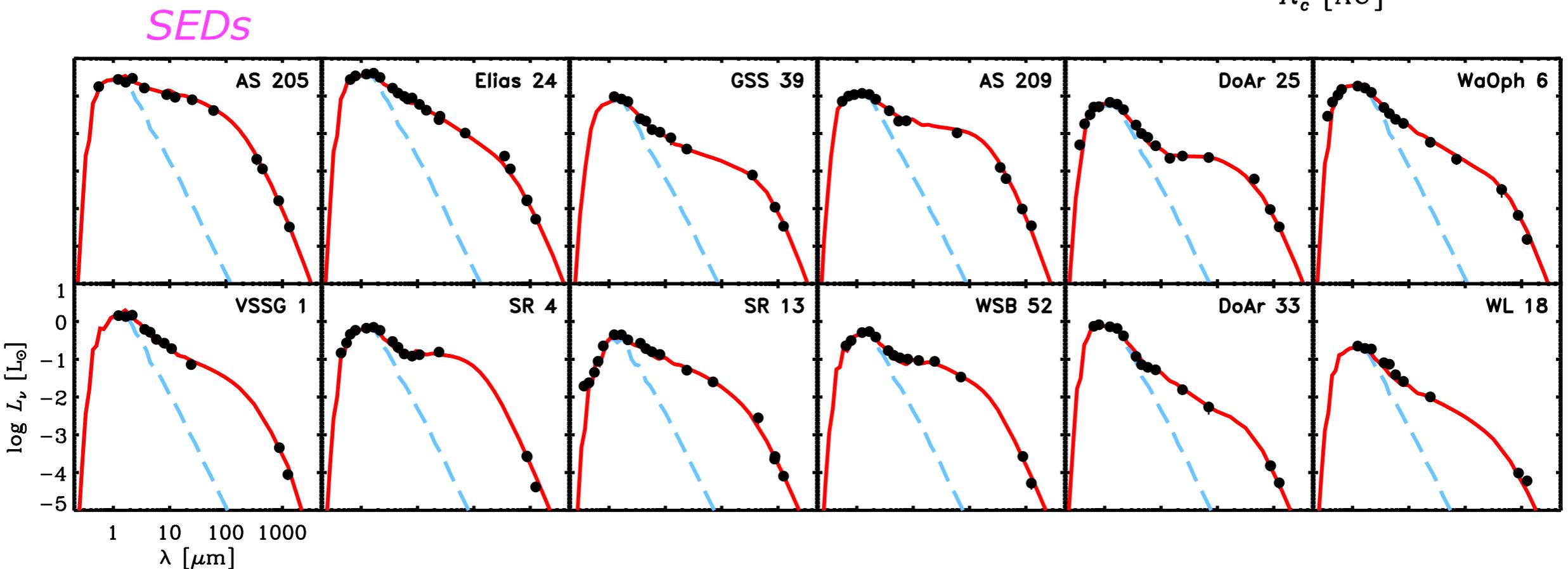
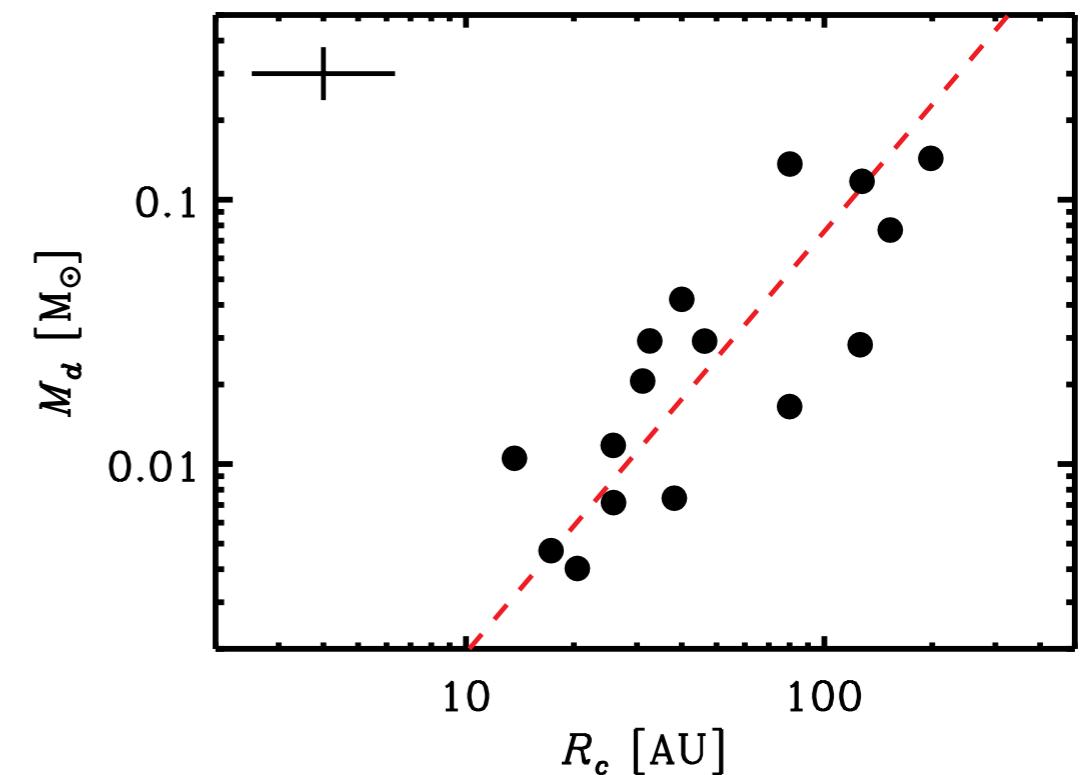
surface density profiles of disk “solids” (< few cm sizes)

- sensitive (340 GHz), high-res ($r \sim 20$ AU)
- forward model SED+visibilities;
3-D Monte Carlo radiative transfer
- radial density profiles **similar to MMSN**
- mass-radius or **luminosity-size correlation**

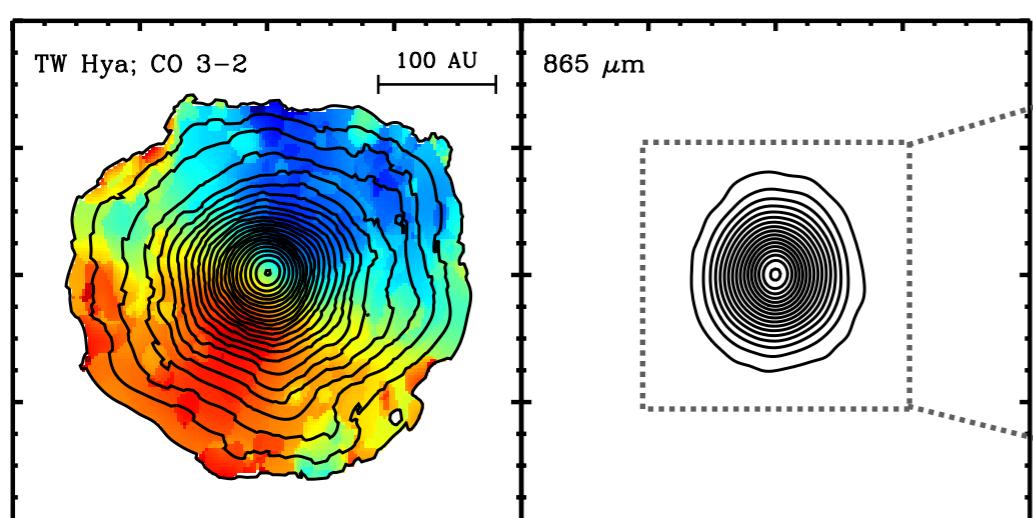
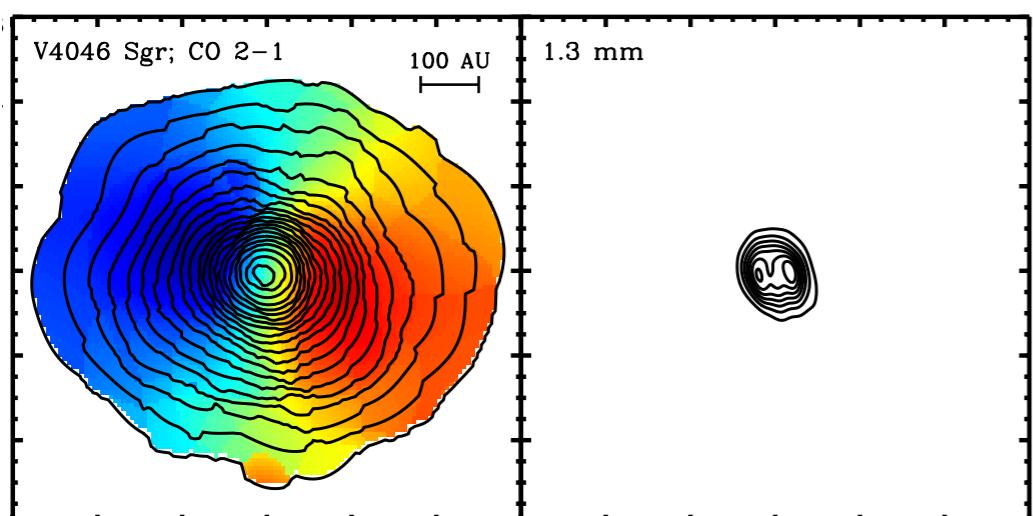
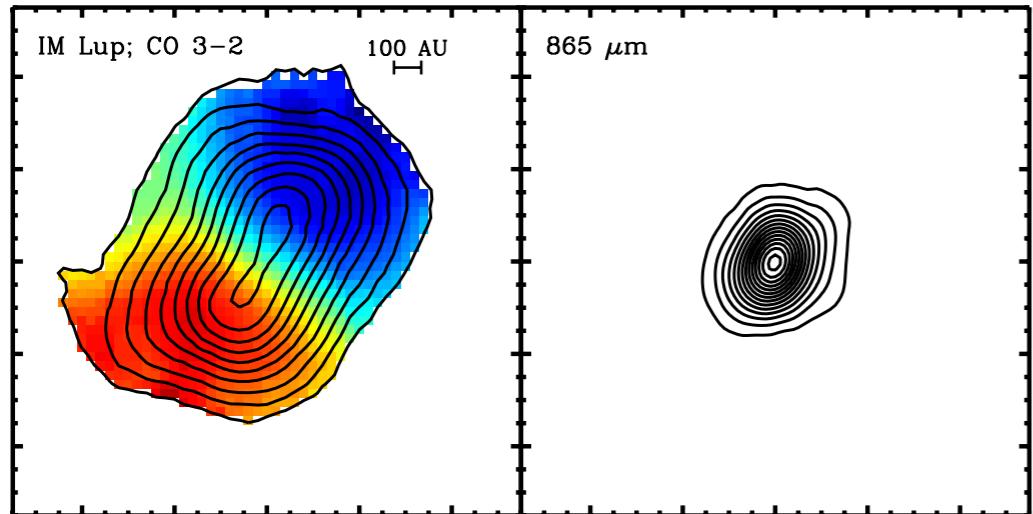


surface density profiles of disk “solids” (< few cm sizes)

- sensitive (340 GHz), high-res ($r \sim 20$ AU)
- forward model SED+visibilities;
3-D Monte Carlo radiative transfer
- radial density profiles **similar to MMSN**
- mass-radius or **luminosity-size correlation**



new evidence for the growth and migration of solids

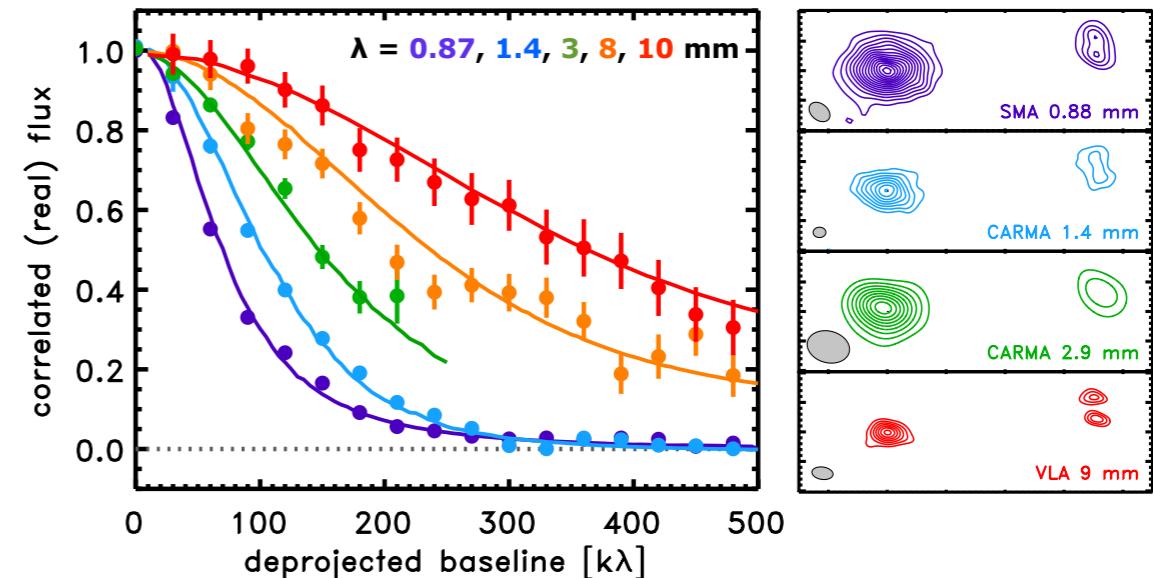


- disk size discrepancy: gas > solids

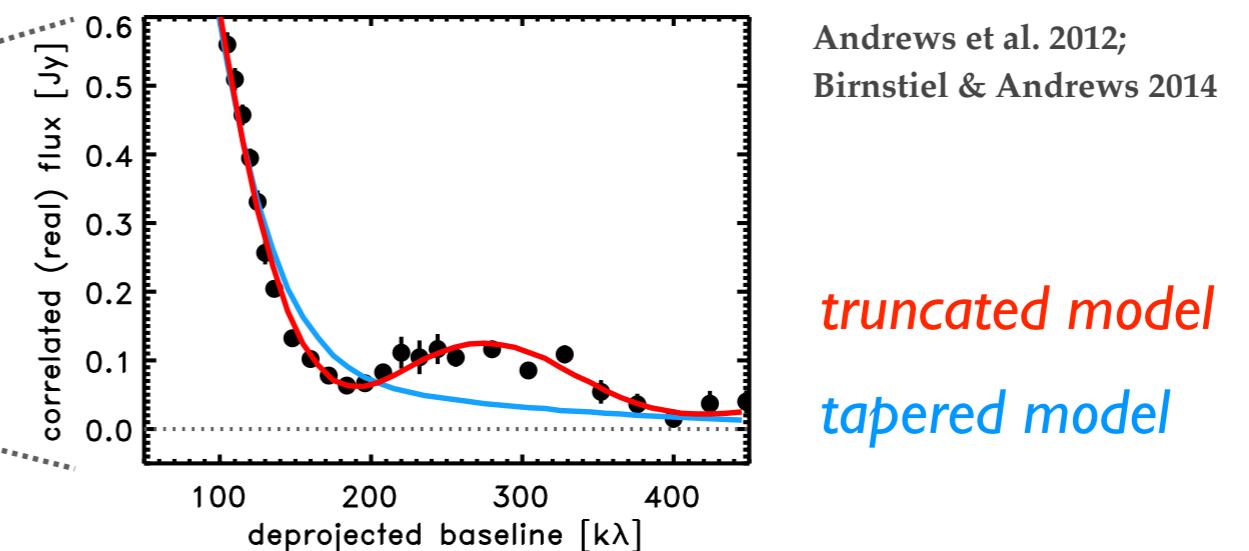
Hughes et al. 2008; Panic et al. 2009; Andrews et al. 2012; Rosenfeld et al. 2013

- dust size-wavelength anticorrelation

Banzatti et al. 2010; Pérez et al. 2012; Harris et al. (*in preparation*)



- sharp outer edge in dust distribution

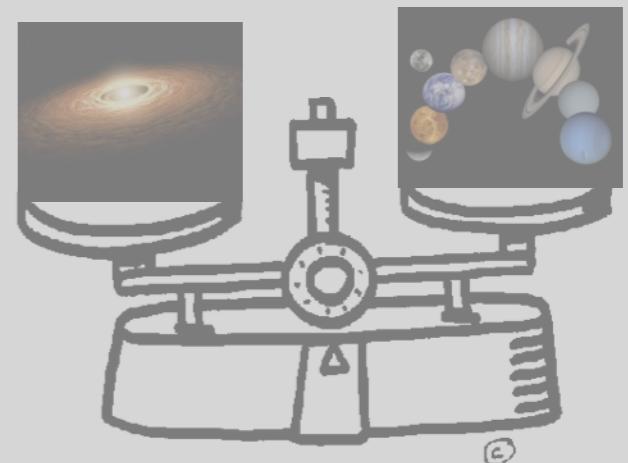


basic disk properties are tied to planet formation process

- demographics

what “external” factors influence disk masses?

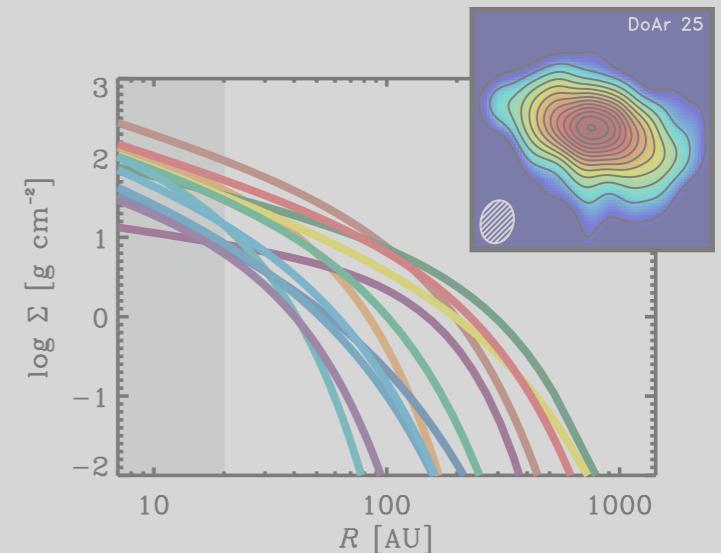
Williams et al. 2005, 2013; Lommen et al. 2007, 2010; Eisner et al. 2008; Cieza et al. 2008, 2010, 2012; Mann & Williams 2009a, b, 2010; Ricci et al. 2011; Lee et al. 2011; Harris et al. 2012; Meeus et al. 2012; Andrews et al. 2013; Williams & Best 2014



- structures

how is the mass spatially distributed in disks?

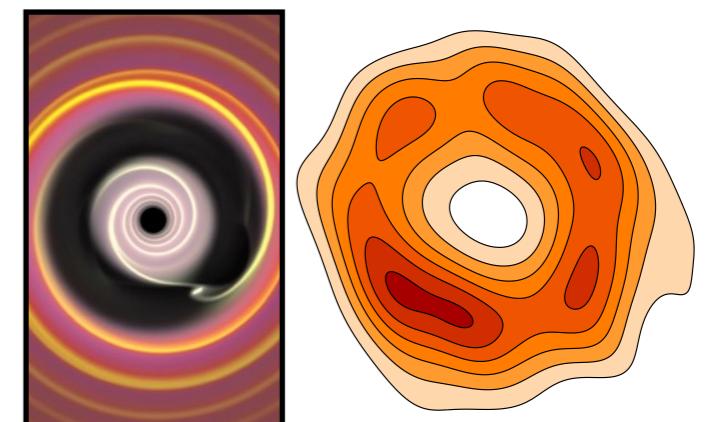
Qi et al. 2004, 2006, 2008, 2011, 2013a, b; Andrews & Williams 2005, 2007; Raman et al. 2006; Isella et al. 2007; Brinch et al. 2007; Wolf et al. 2008; Hughes et al. 2008, 2009, 2011, 2013; Andrews et al. 2008a, b, 2009, 2010a, b, 2012; Pinte et al. 2008; Panic et al. 2008, 2009; Sauter et al. 2009; Dai et al. 2010; Momose et al. 2010; Öberg et al. 2010, 2011, 2012; Rodríguez et al. 2010; Lee 2010, 2011; Takakuwa et al. 2012; Rosenfeld et al. 2012; Akimkin et al. 2012; Tobin et al. 2012, 2013; Gråfe et al. 2013; Forgan & Rice 2013; Favre et al. 2013



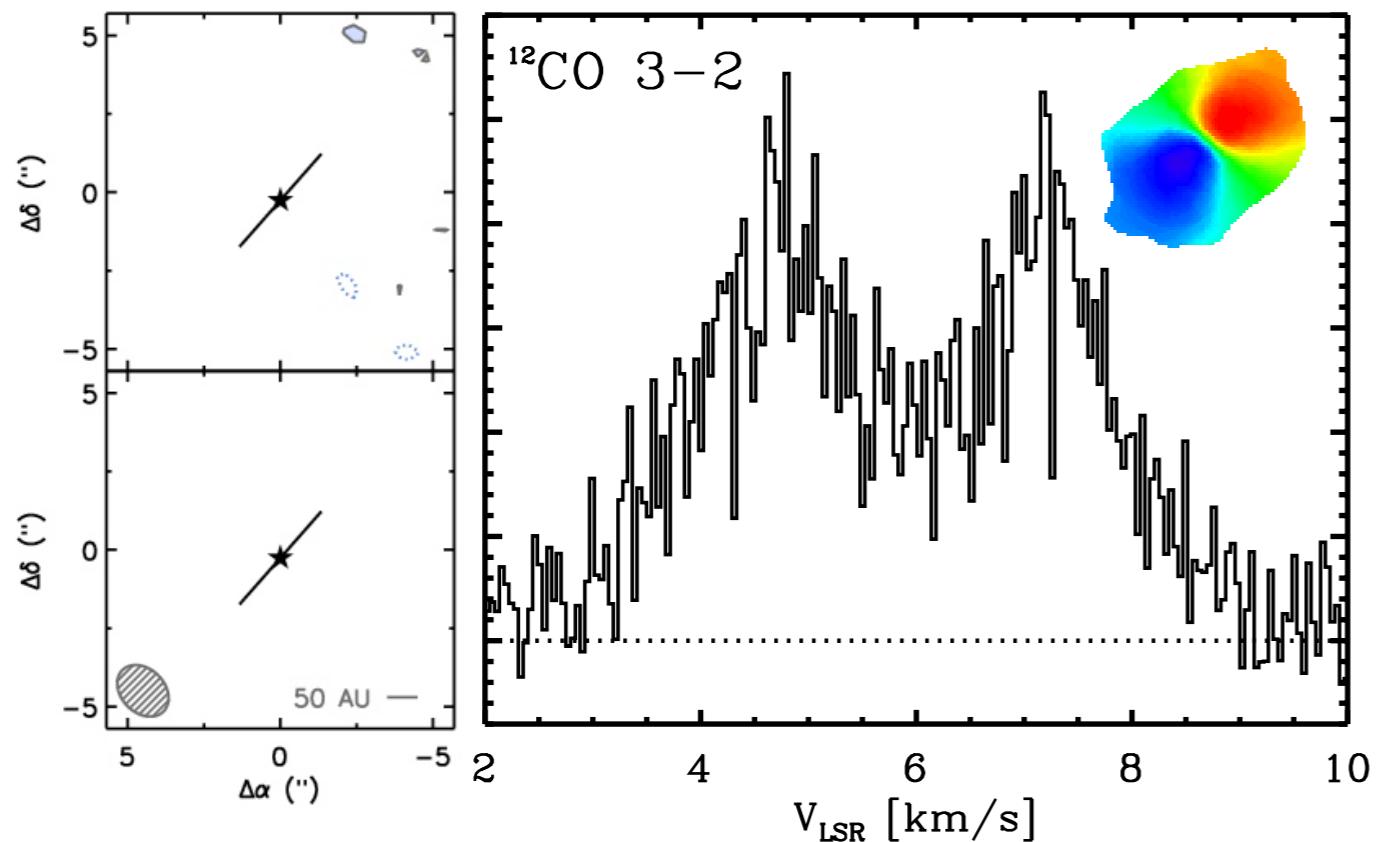
- evolution

how is disk material transformed or dissipated?

Lin et al. 2006; Espaillat et al. 2007, 2012; Brown et al. 2008, 2009, 2012; Hughes et al. 2009, 2010; Isella et al. 2010, 2013; Banzatti et al. 2011; Andrews et al. 2011; Lyo et al. 2011; Cieza et al. 2012; Mathews et al. 2012; Tang et al. 2012; Pérez et al. 2012; Follette et al. 2013; Rosenfeld et al. 2013; Tsukagoshi et al. 2014; Miotello et al. 2014



toward direct constraints on viscous evolution

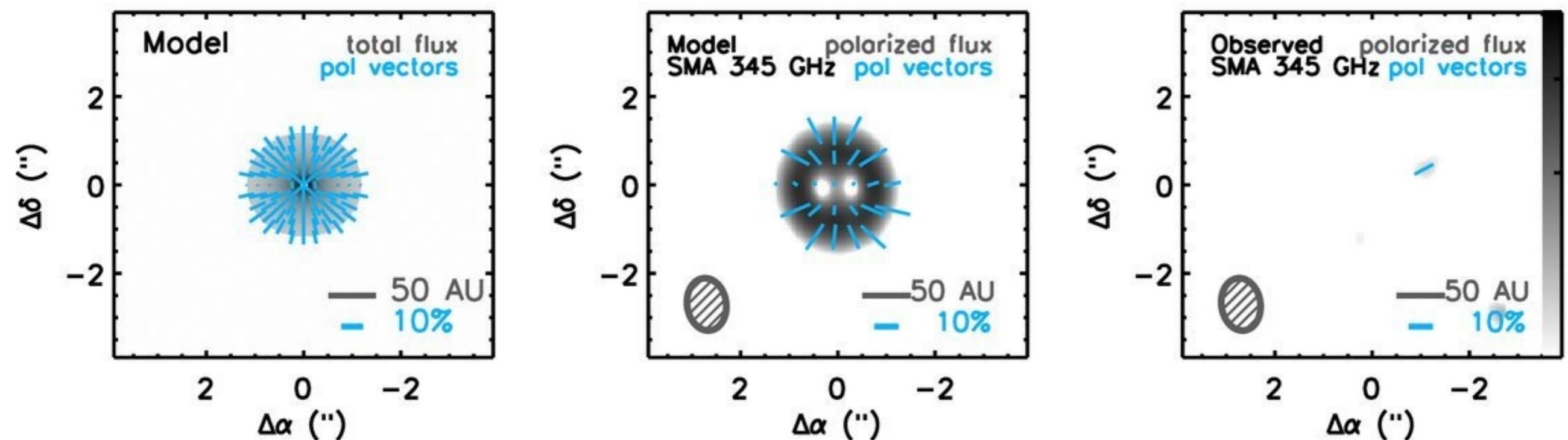


- resolved non-thermal linewidths
subsonic turbulence in atmosphere

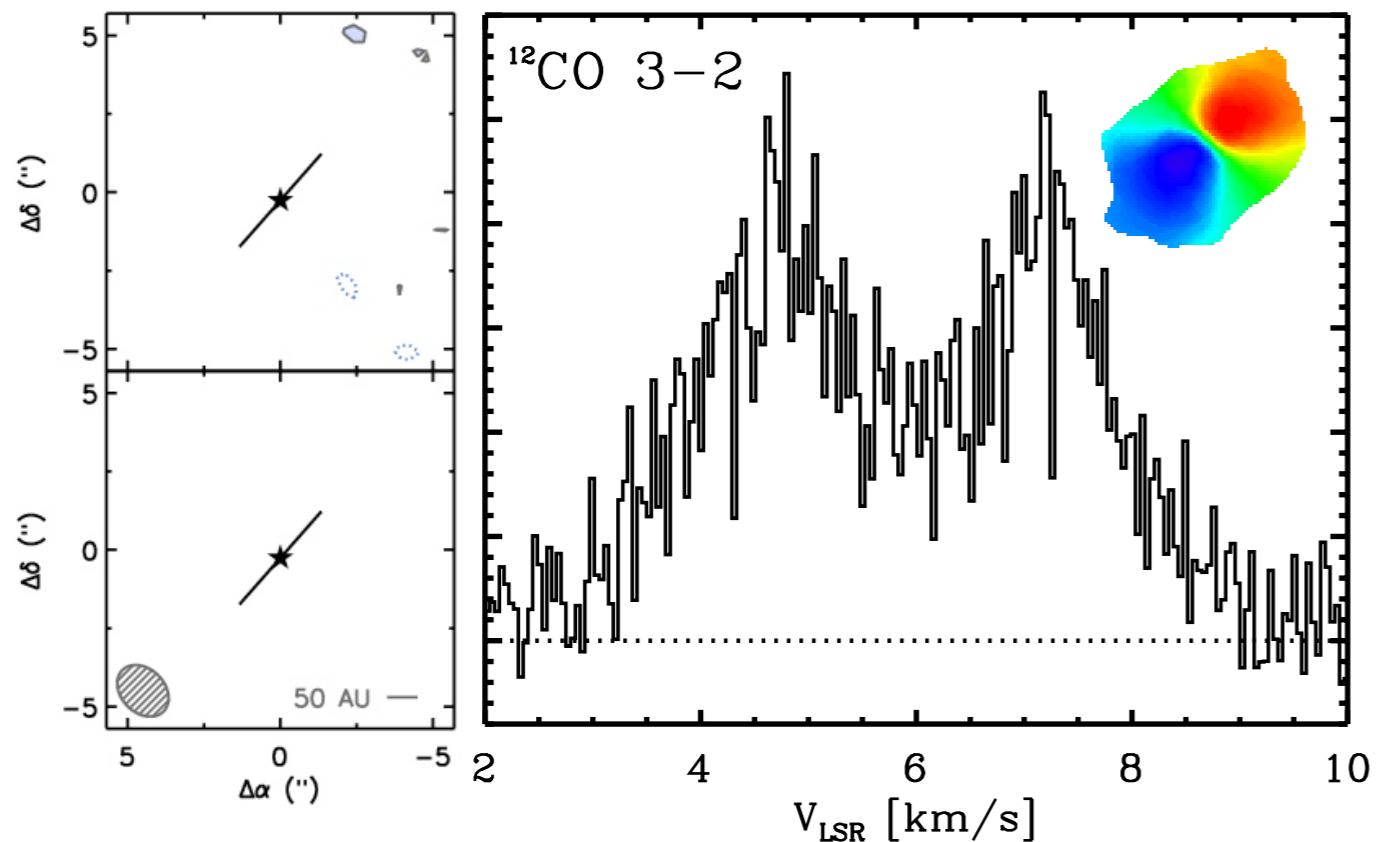
Hughes et al. 2011

- tight constraints on polarization
limits B-field strength/substructure

Hughes et al. 2009



toward direct constraints on viscous evolution

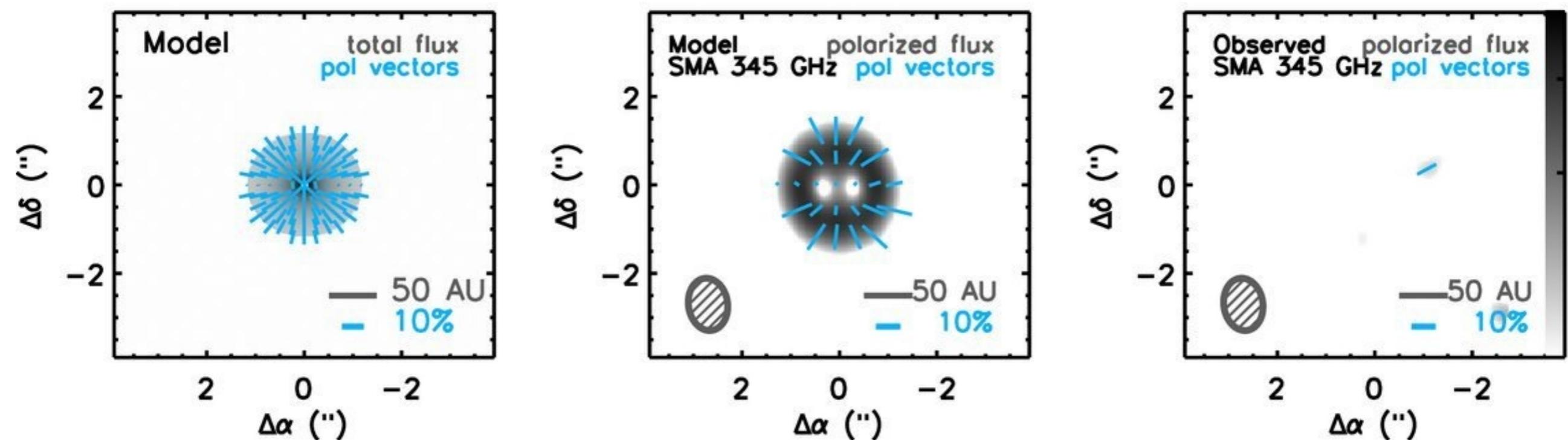


- resolved non-thermal linewidths
subsonic turbulence in atmosphere

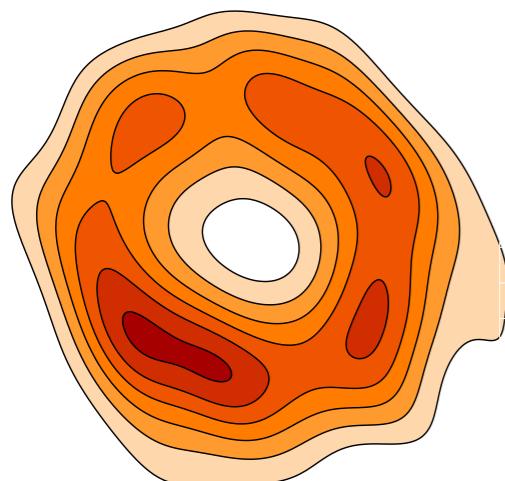
Hughes et al. 2011

- tight constraints on polarization
limits B-field strength/substructure

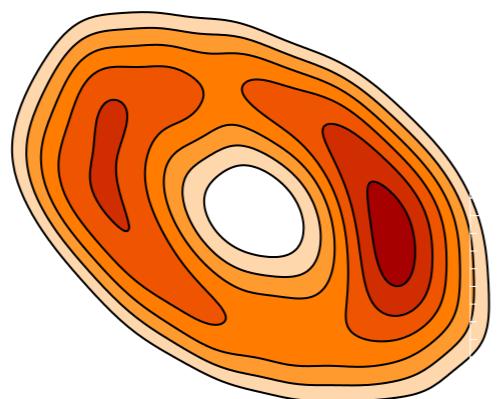
Hughes et al. 2009



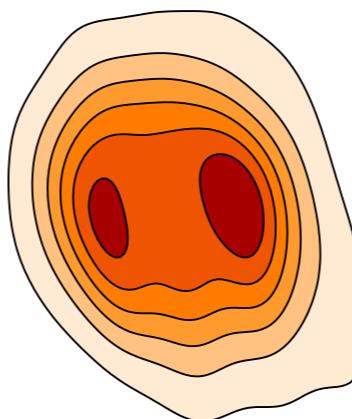
“transitional” evolution: evidence for young planets?



Mathews et al. 2012

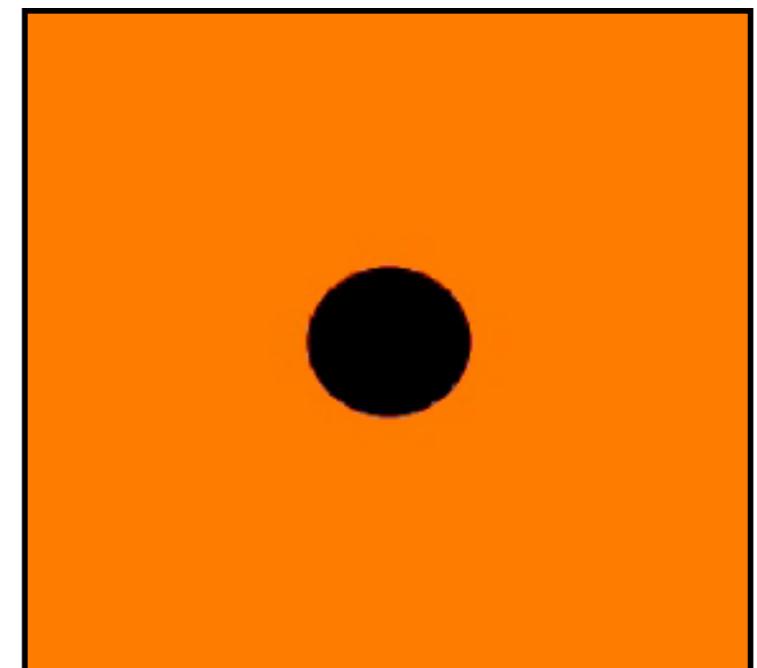


Andrews et al. 2011

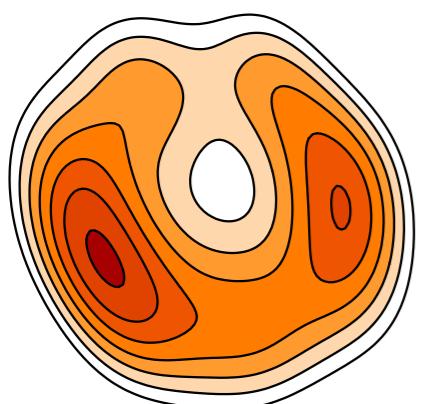


Rosenfeld et al. 2013

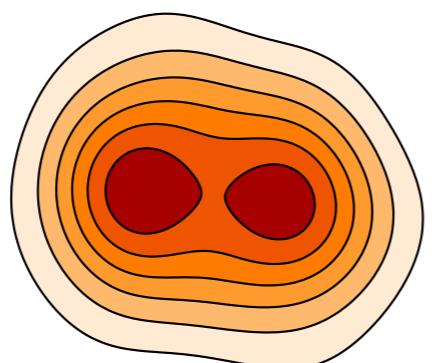
hydro simulation (gas density)



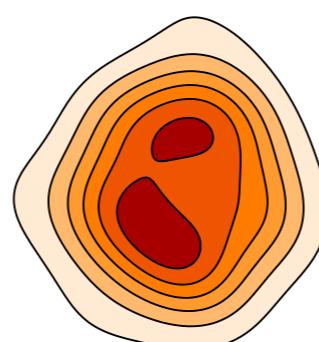
Masset 2002



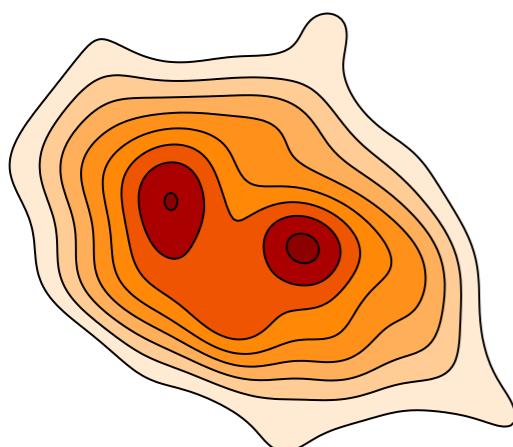
Brown et al. 2009



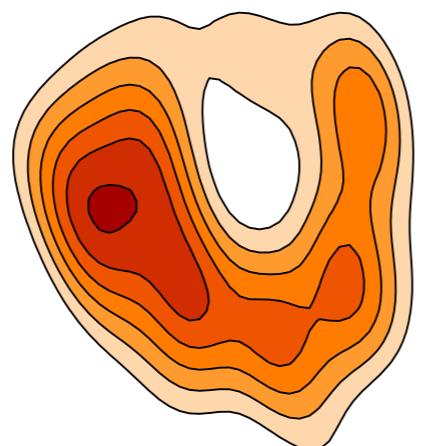
Cieza et al. 2012



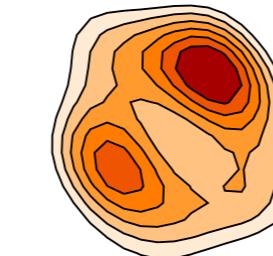
Andrews et al. 2011



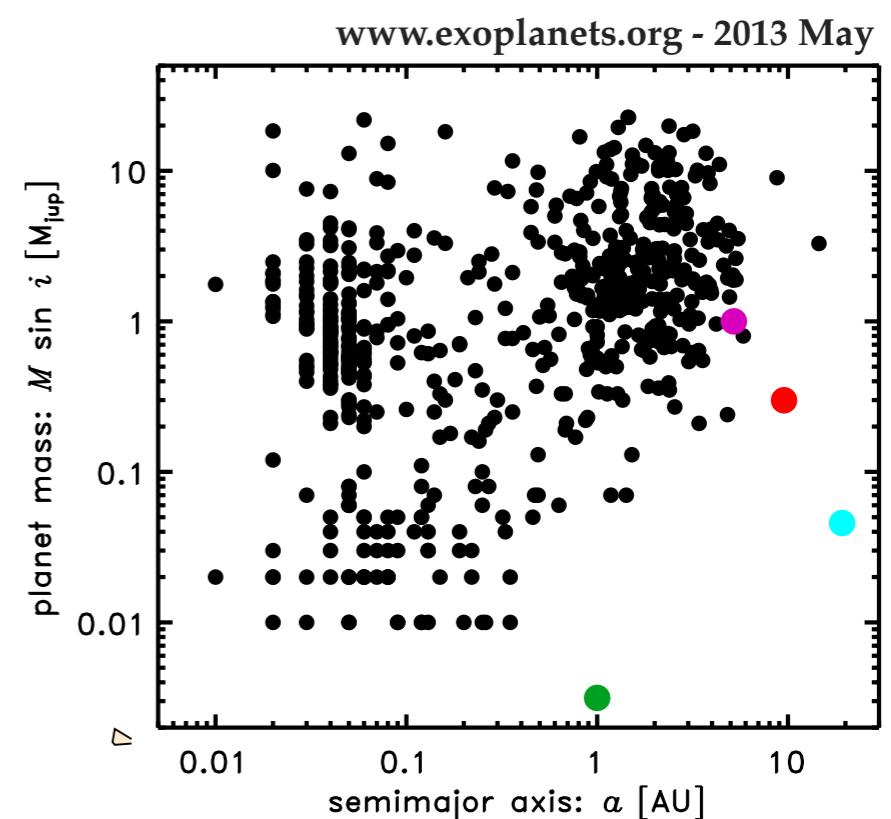
Hughes et al. 2009



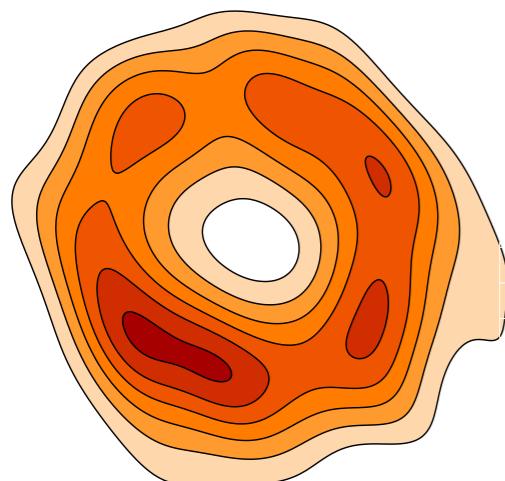
Brown et al. 2009



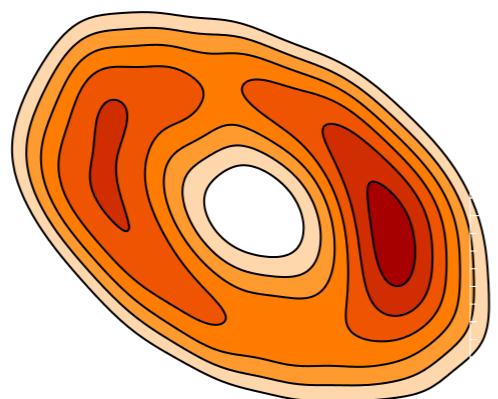
Espaillat et al. 2014



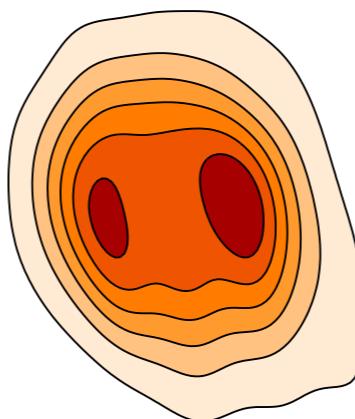
“transitional” evolution: evidence for young planets?



Mathews et al. 2012

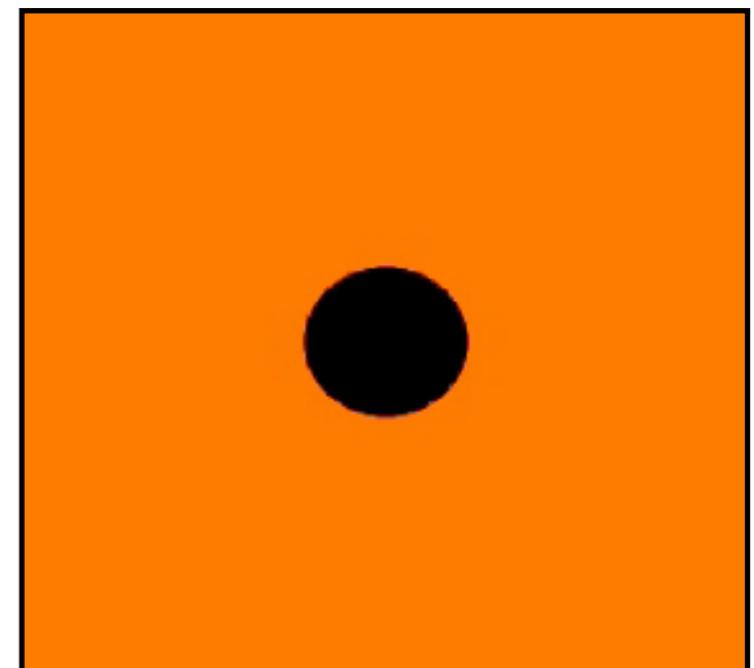


Andrews et al. 2011

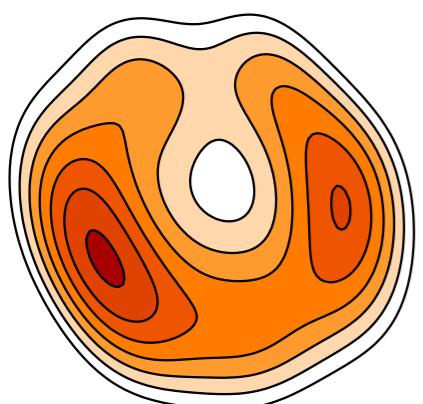


Rosenfeld et al. 2013

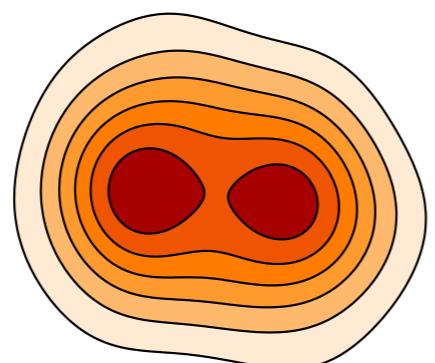
hydro simulation (gas density)



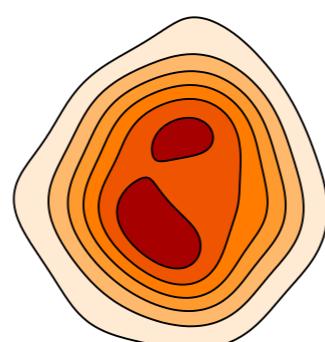
Masset 2002



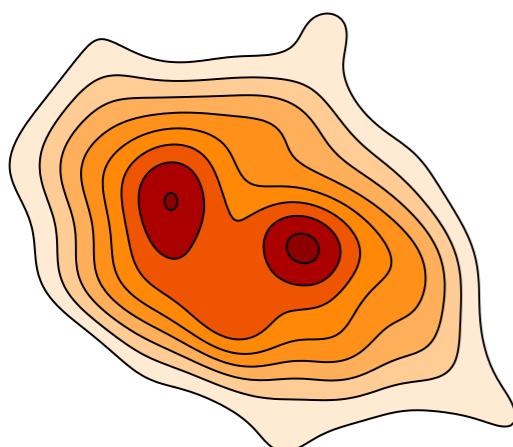
Brown et al. 2009



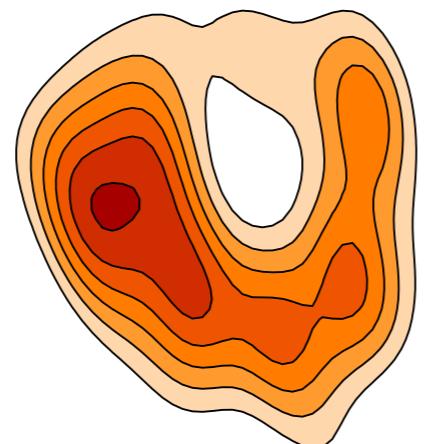
Cieza et al. 2012



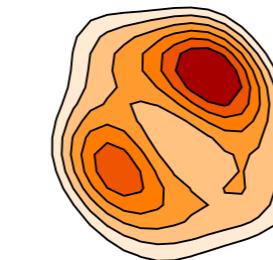
Andrews et al. 2011



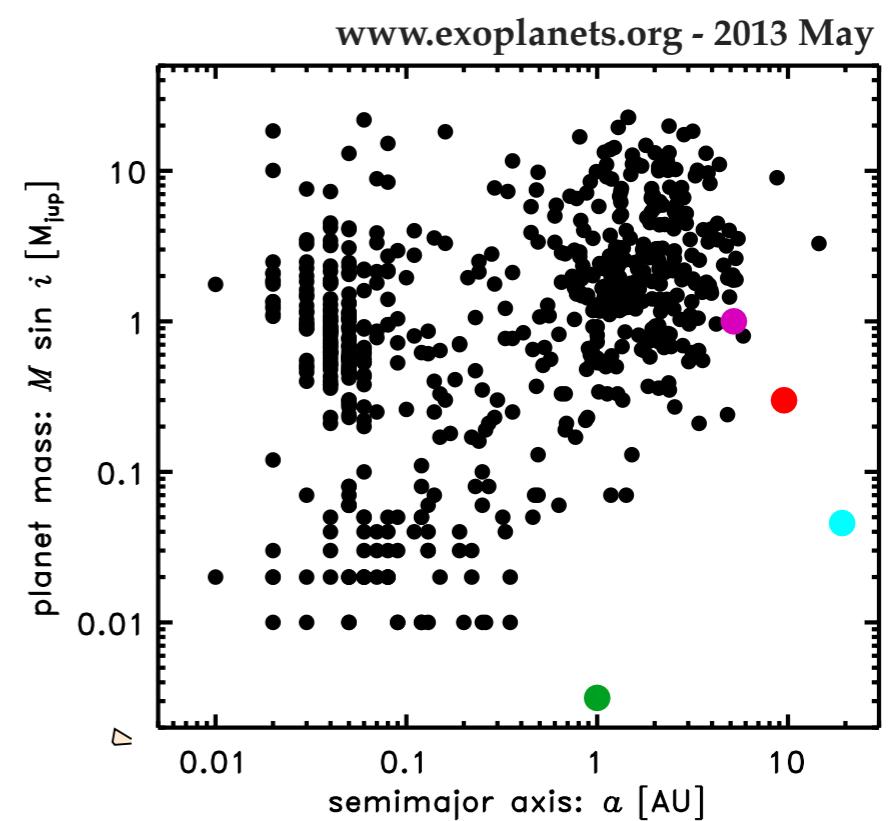
Hughes et al. 2009



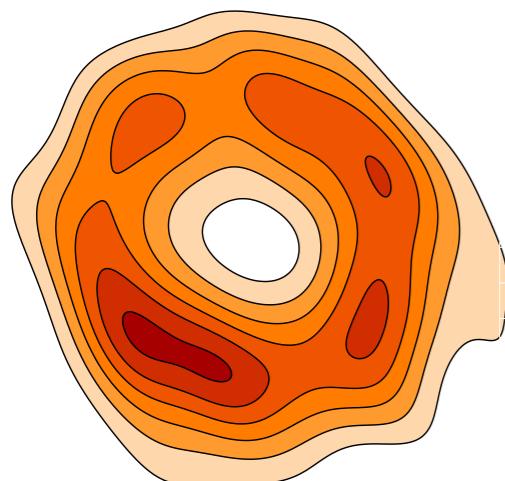
Brown et al. 2009



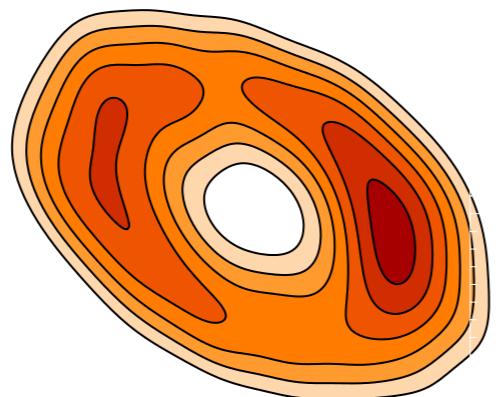
Espaillat et al. 2014



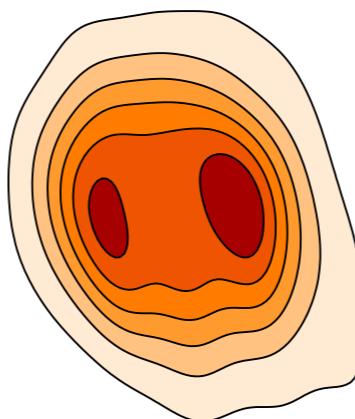
“transitional” evolution: evidence for young planets?



Mathews et al. 2012

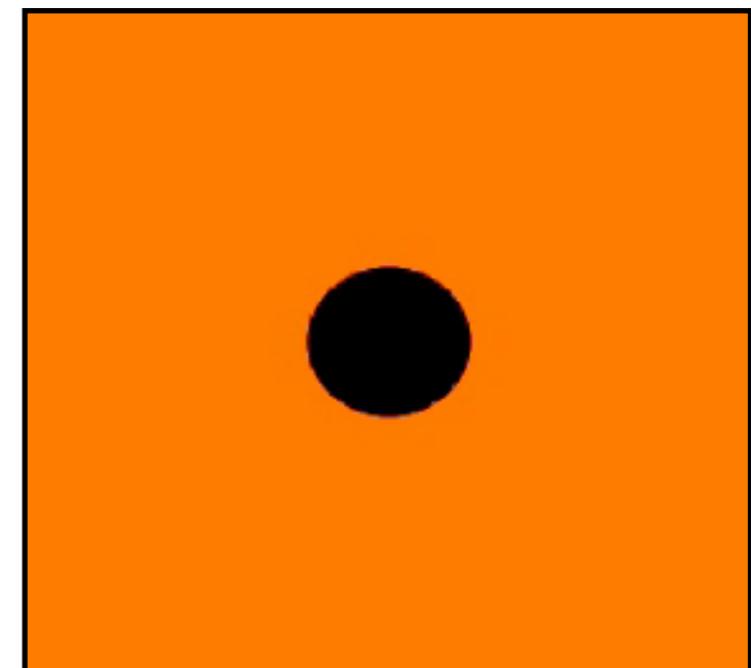


Andrews et al. 2011

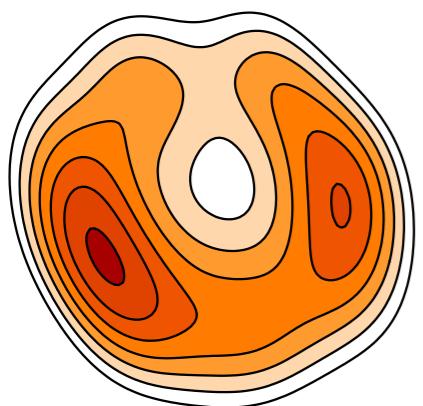


Rosenfeld et al. 2013

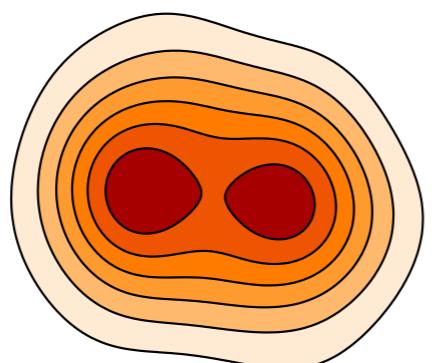
hydro simulation (gas density)



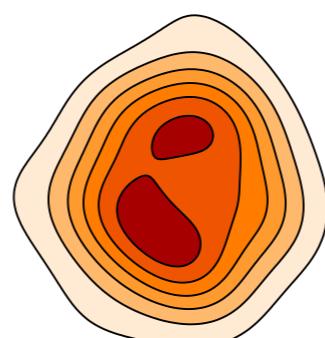
Masset 2002



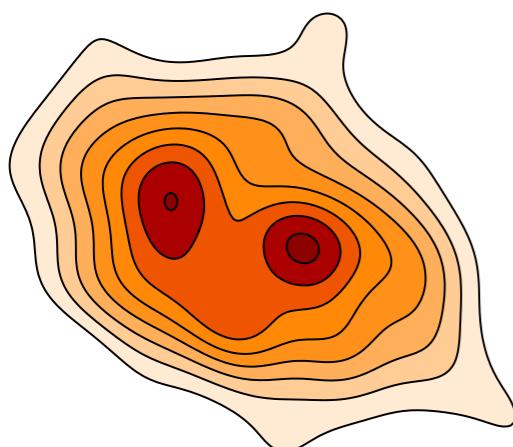
Brown et al. 2009



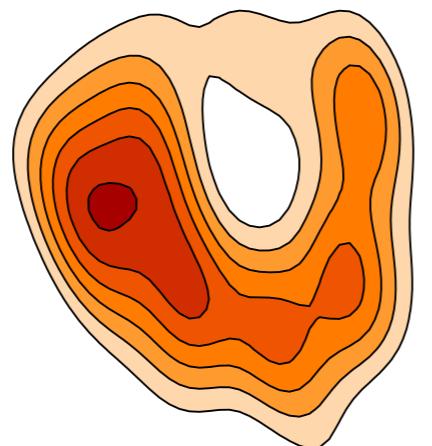
Cieza et al. 2012



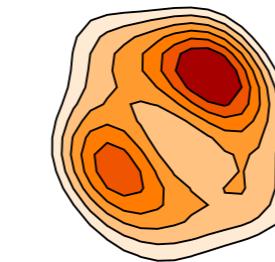
Andrews et al. 2011



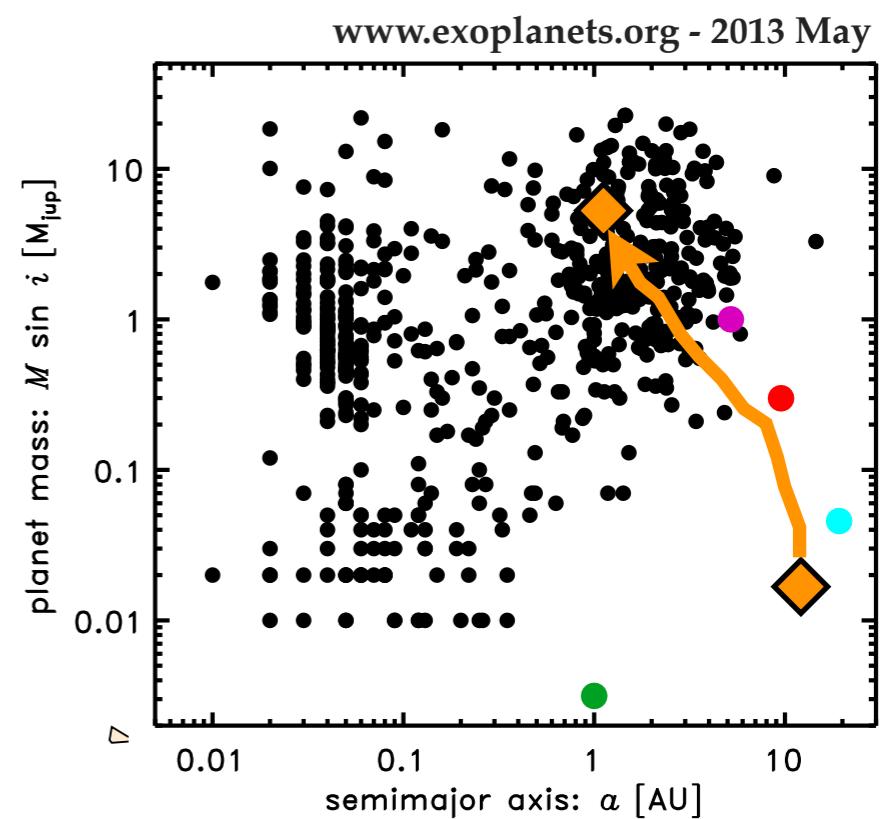
Hughes et al. 2009



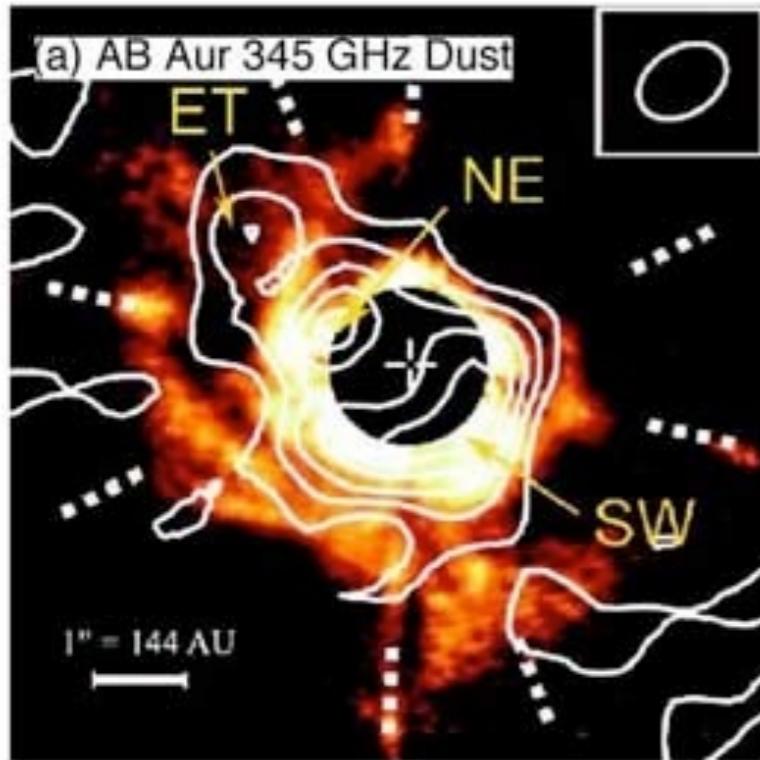
Brown et al. 2009



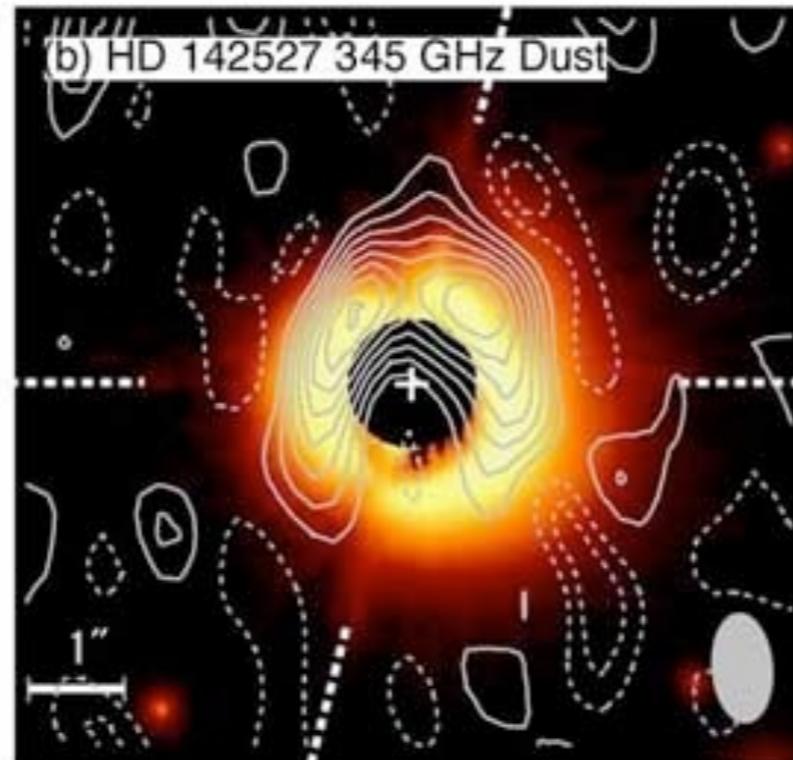
Espaillat et al. 2014



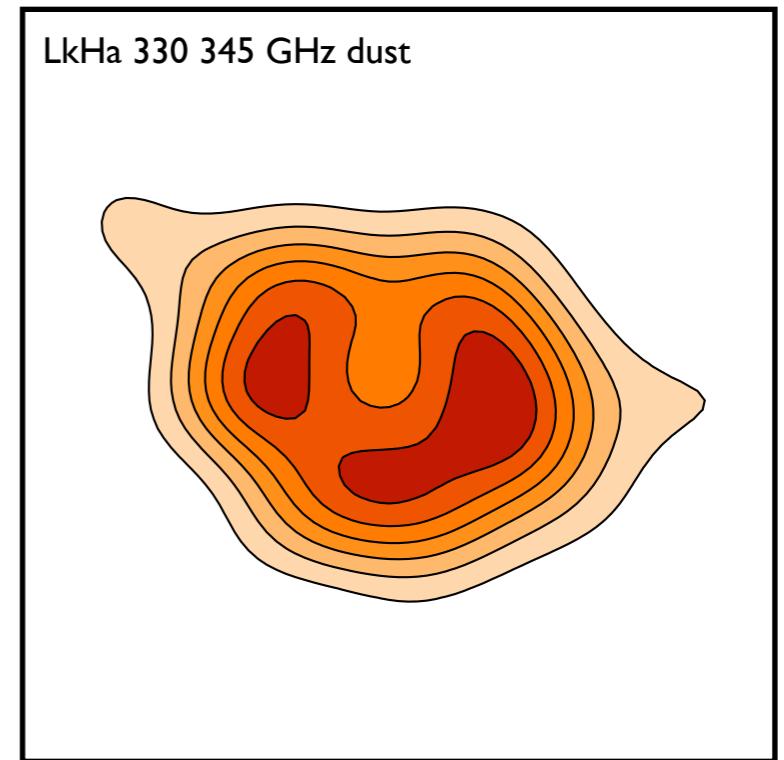
low-level substructure: signature of vortex trapping?



Lin et al. 2006

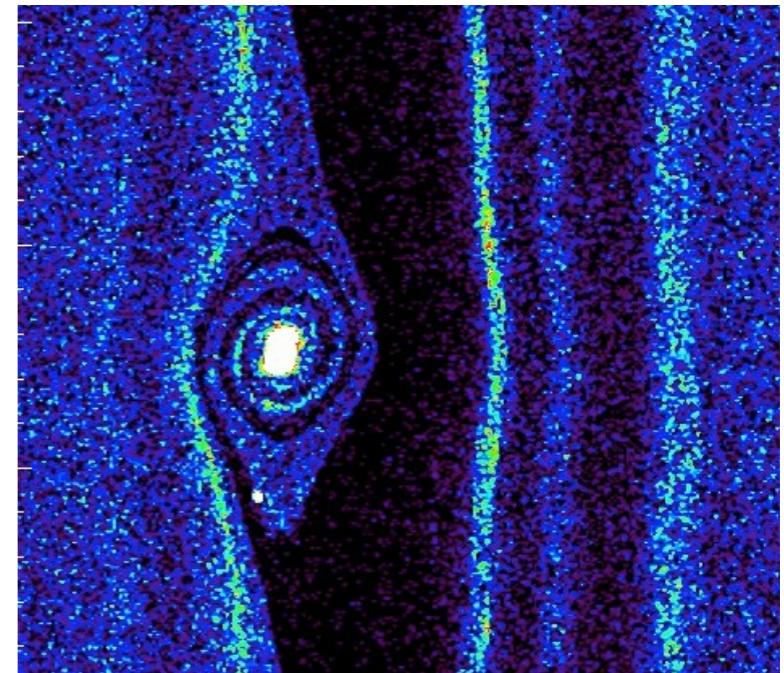


Ohashi et al. 2008



Isella et al. 2013

- “rings” sometimes show azimuthal asymmetry
solids trapped in gas pressure maxima
concentration in hydrodynamic instability (vortex)



Dittrich et al. 2013

extremely productive instrument; new era of observational planet formation

demographics: mass depletion as function of

age (in progress)

multiplicity (M_{disk} down 5x per loga bin)

cluster environment (*R. Mann*)

host mass ($M_{disk} \propto M_{star}$)

constraints on spatial distributions of solids

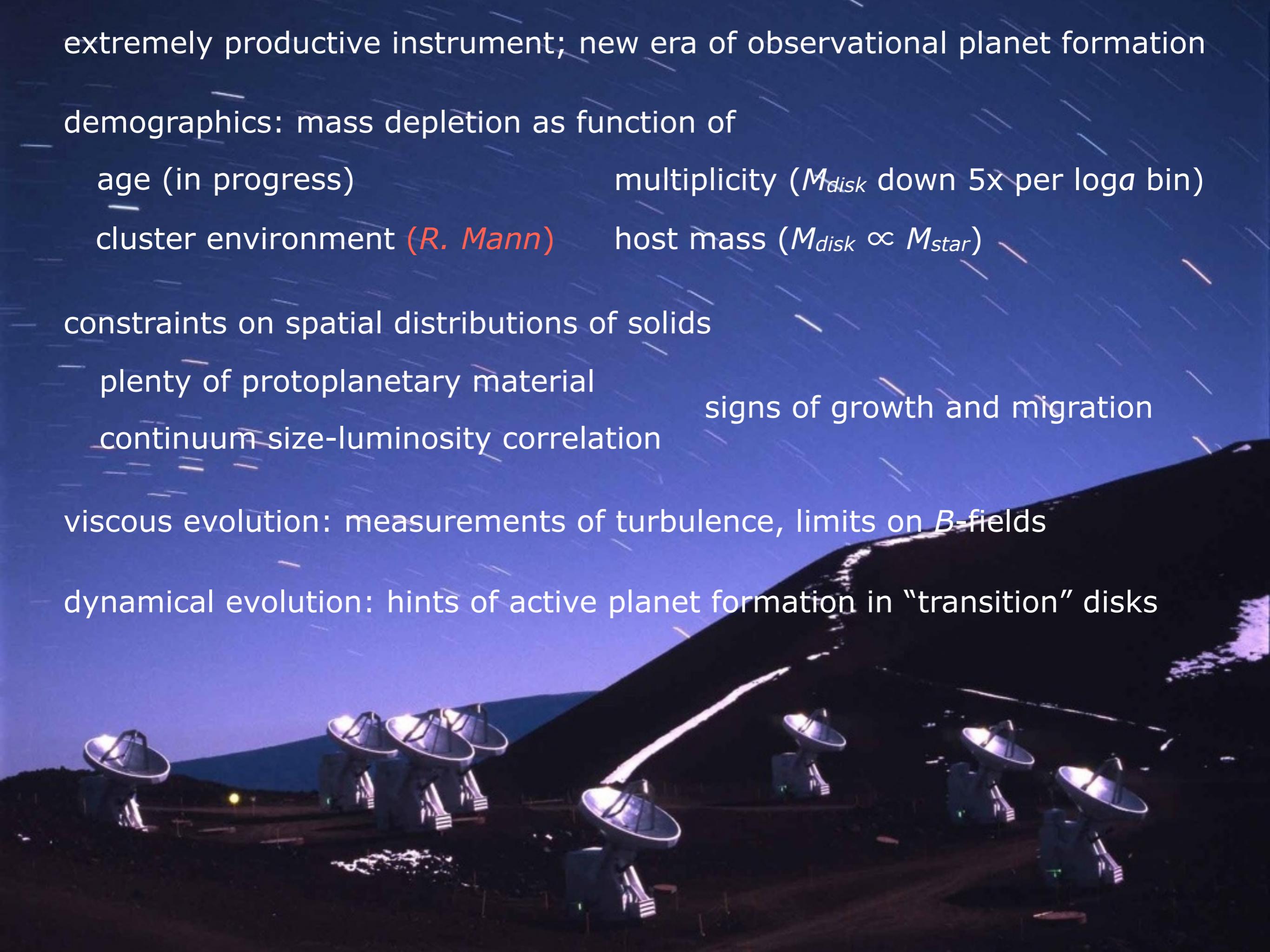
plenty of protoplanetary material

signs of growth and migration

continuum size-luminosity correlation

viscous evolution: measurements of turbulence, limits on B -fields

dynamical evolution: hints of active planet formation in “transition” disks



disk-based, dynamical estimates of stellar host masses

goal: measure stellar mass from gas disk rotation

problems: complex radiative transfer +
at least 14 free parameters (!)

empirical calibration test: disk + SB2 host

- * 2 independent dynamical mass estimates agree: 3-5% precision
- * disk-stellar orbits coplanar within <0.1 degrees
- * mass prior: more precise ages from H-R diagram

Rosenfeld et al. 2012; Czekala et al. in preparation

