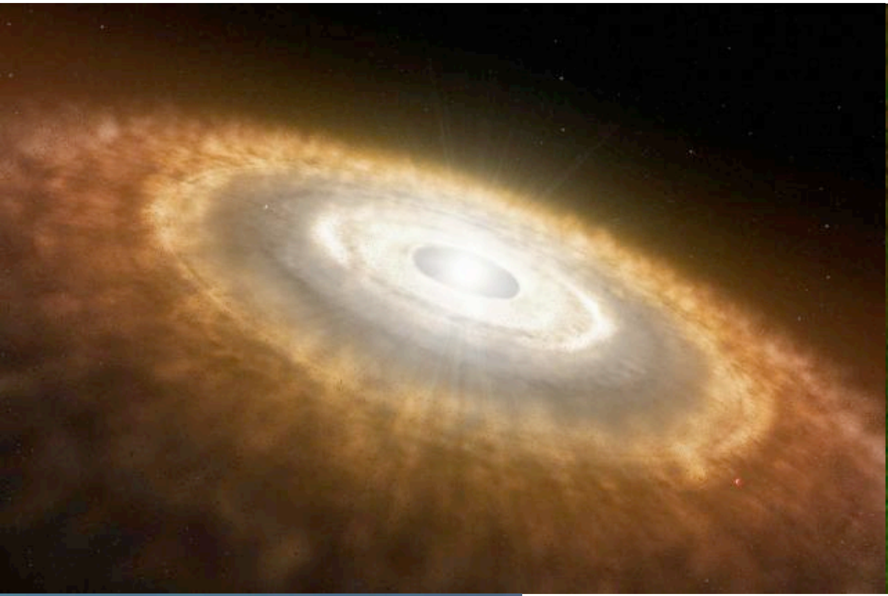
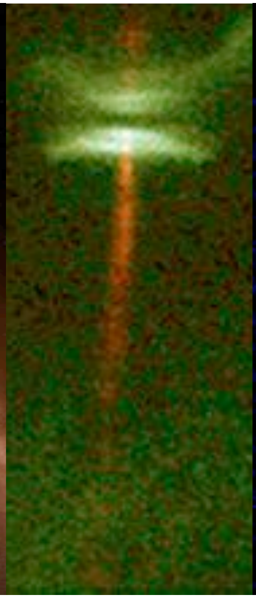
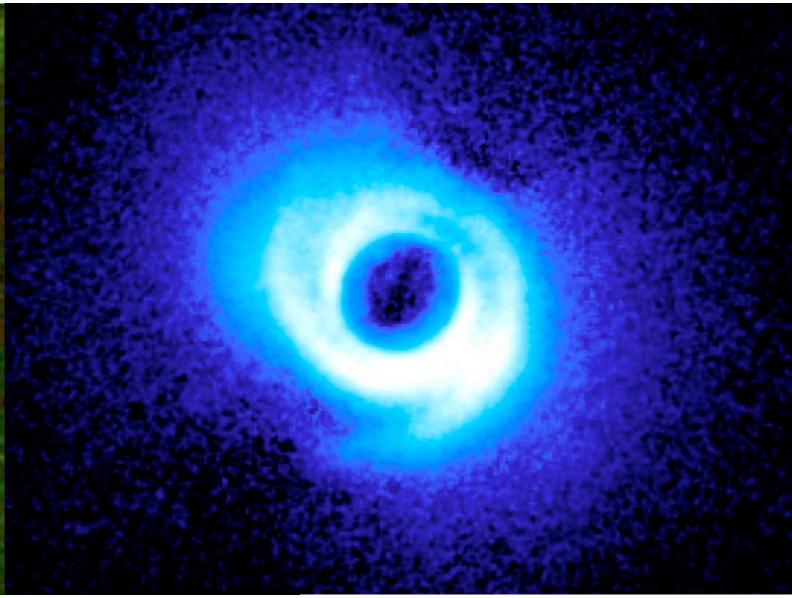
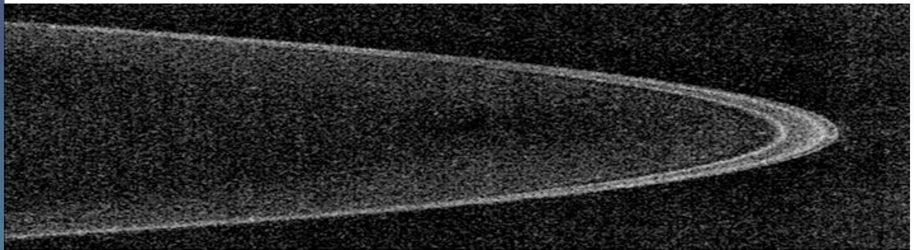
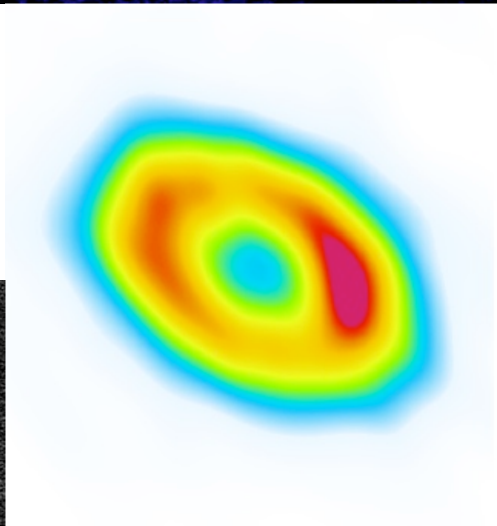
Observations of Protoplanetary Disks: DUST


Meredith Hughes
Wesleyan University


Disclaimer: I have a serious bias
towards radio observations

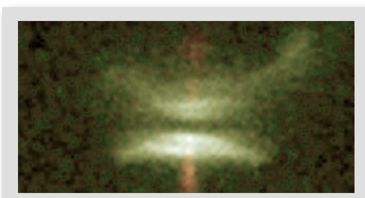
Dust vs. Gas

Protoplanetary

Pre-MS stars

Gas-rich

Primordial dust



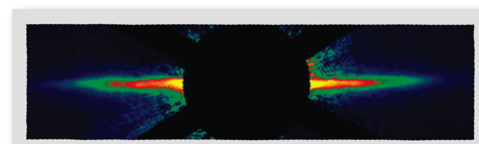
HH 30, Burrows et al. 1996

Debris

Main sequence

No (or very little) gas

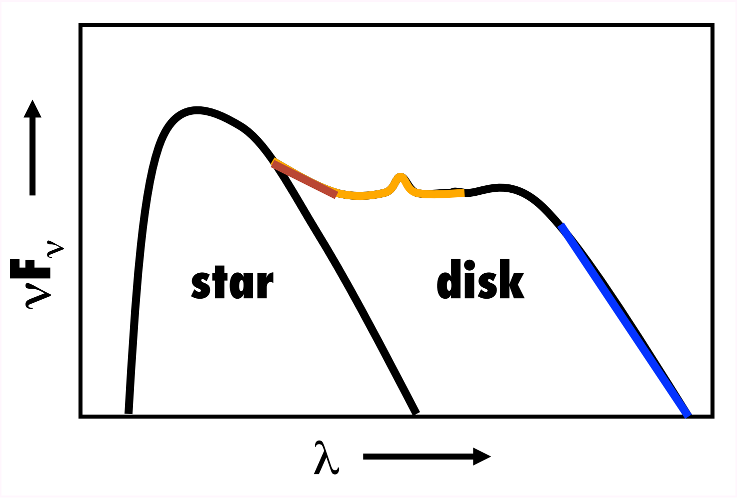
Dust must be replenished

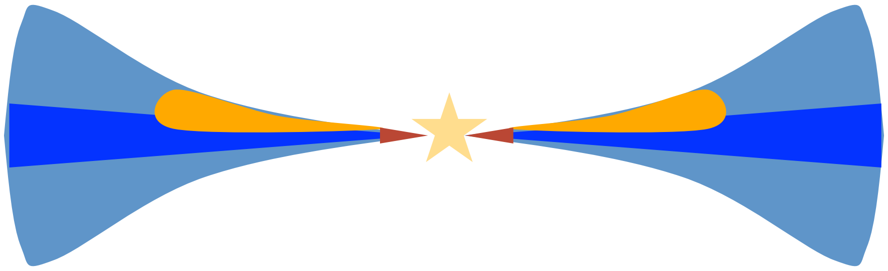


AU Mic, Liu et al. 2004

Protoplanetary Disks:
99% of the mass is in gas
Opacity dominated by dust
Gas dominates dynamics
Gas-dust interactions depend on grain size

Circumstellar Disk Structure





Optical/near-IR

Strong disk/star contrast

Optically thick dust

Aperture masking/interfer.

Dominated by inner ~1AU

Mid-IR

Moderate disk/star contrast

Optically thick dust/gas

Dust/gas spectral features

Dominated by ~10AU

Submm/Radio

Low disk/star contrast

Optically thin dust

Molecular lines (thick/thin)

Moderate spatial resolution

Whole disk

Adapted from Dullemond et al. (2007)

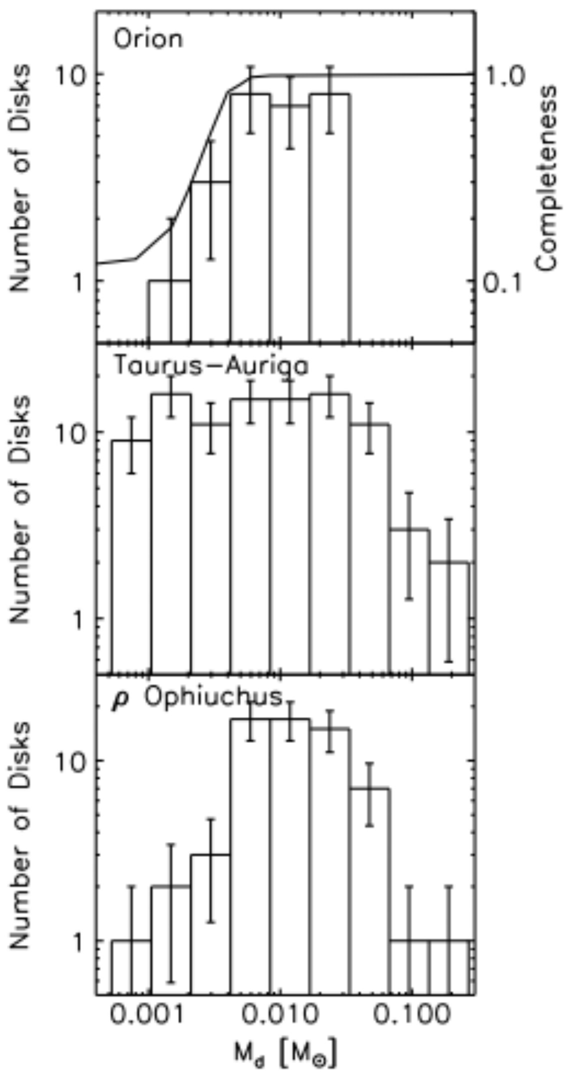
BIG QUESTIONS

about dust

1. Where is the mass, and how much?
2. How quickly do the grains grow?
3. When/why does the dust disappear?
4. What creates structure in dust?
5. What can dust tell us about planets?

1. Where is the mass? How much?

mm/radio measurements necessary because disk needs to be optically thin



Environment matters!

No massive disks in the center of the ONC (although there are on the outskirts)

Low-mass star-forming regions show broad distribution of disk masses, including both high- and low-mass tails.

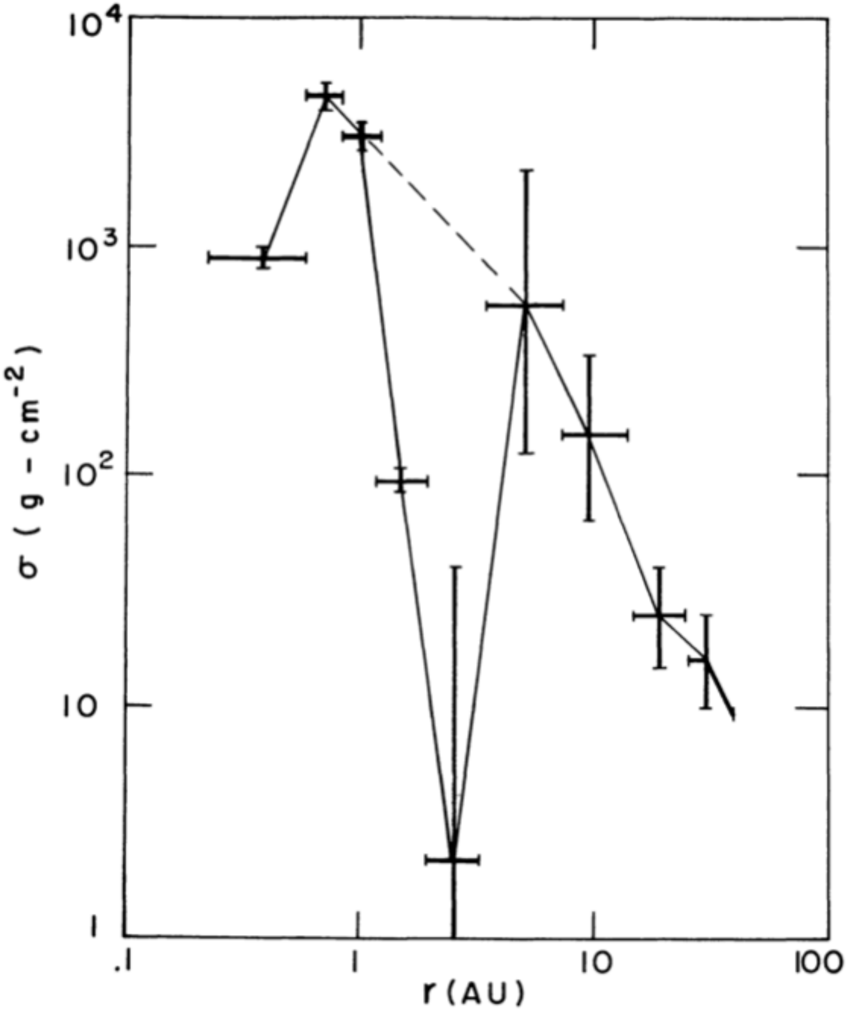
$$M_{disk} = \frac{F_{dust} d^2}{\kappa_\nu B_\nu(T)}$$

HUGE CAVEAT: Biggest uncertainty is mass opacity, κ_ν. Probably factor of ~4 wiggle room (Pollack et al. 1994; Ossenkopf & Henning 1994). An arbitrary amount of mass could be locked up in boulder-size objects.

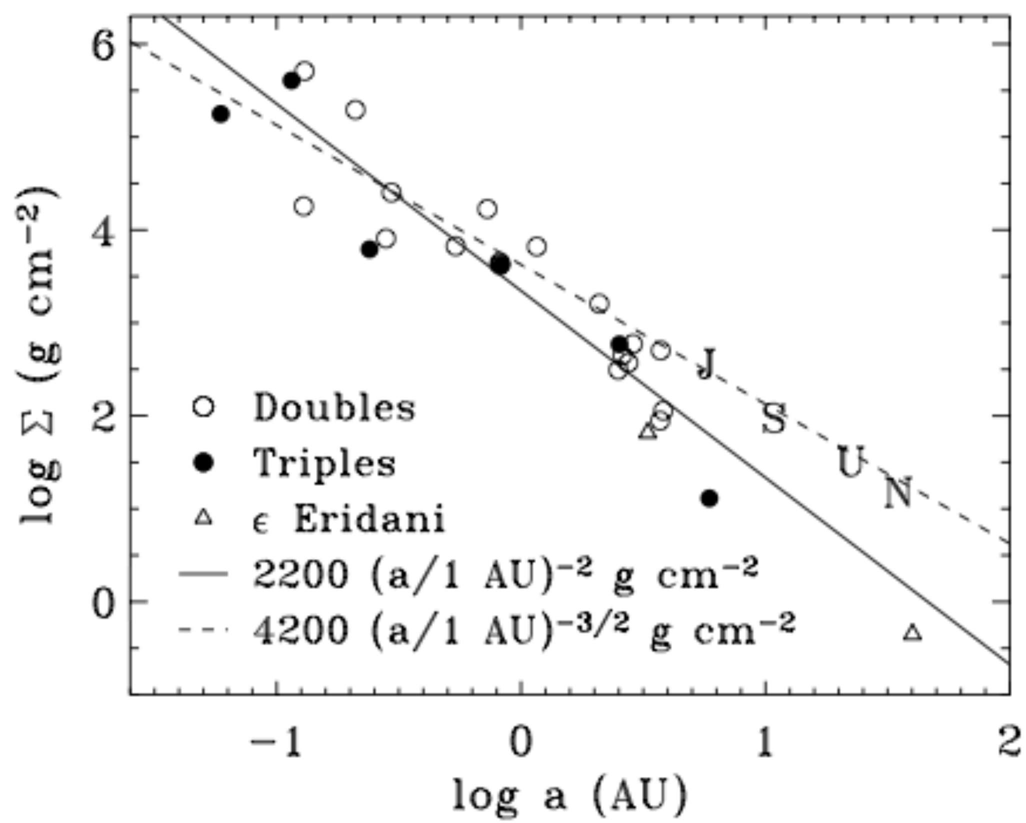
Mann et al. (2009)

1. Where is the mass? How much?

mm/radio measurements necessary because disk needs to be optically thin



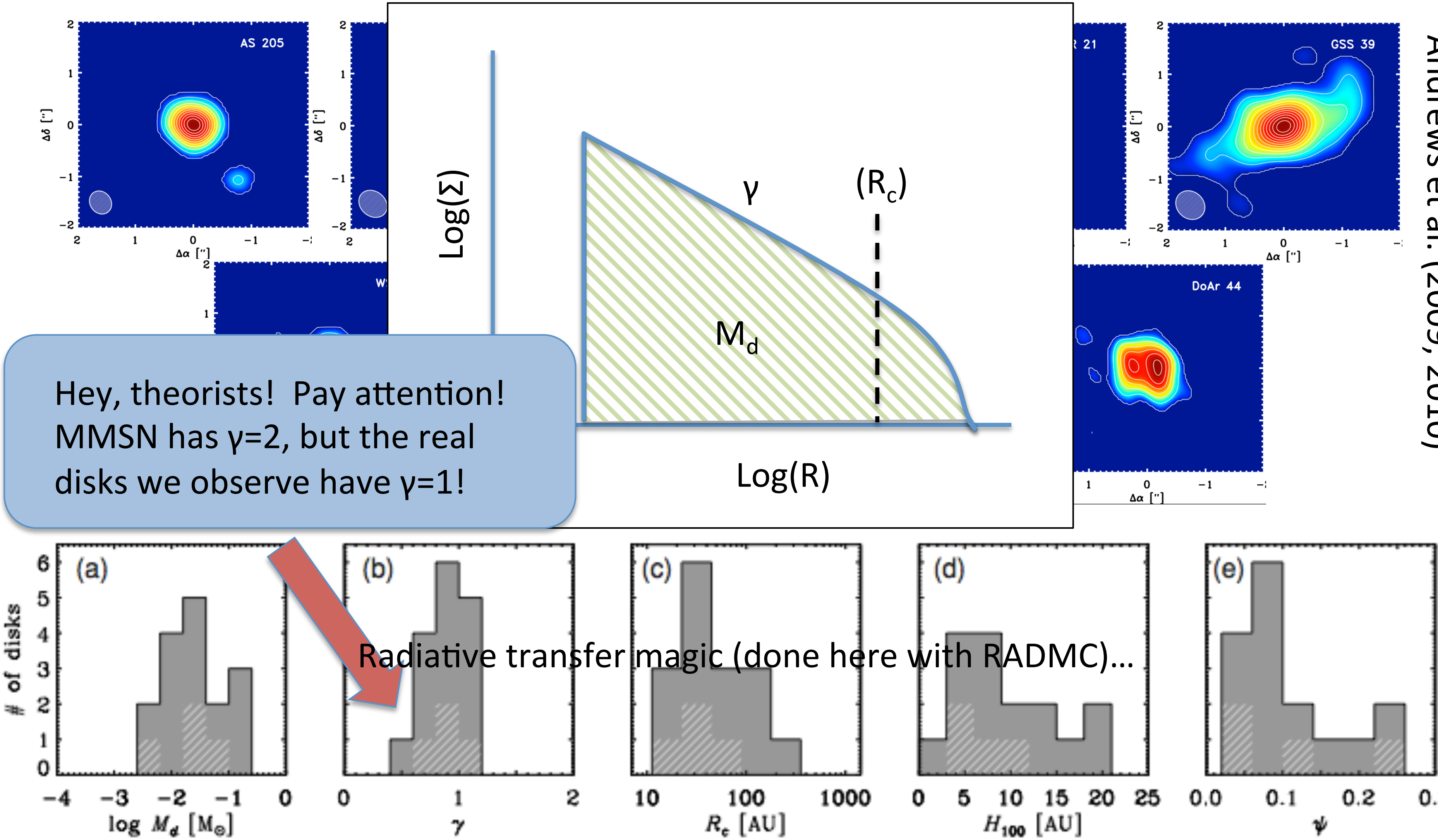
Weidenschilling et al. (1977) - MMSN



Kuchner et al. (2004) - MMEN

1. Where is the mass? How much?

mm/radio measurements necessary because disk needs to be optically thin

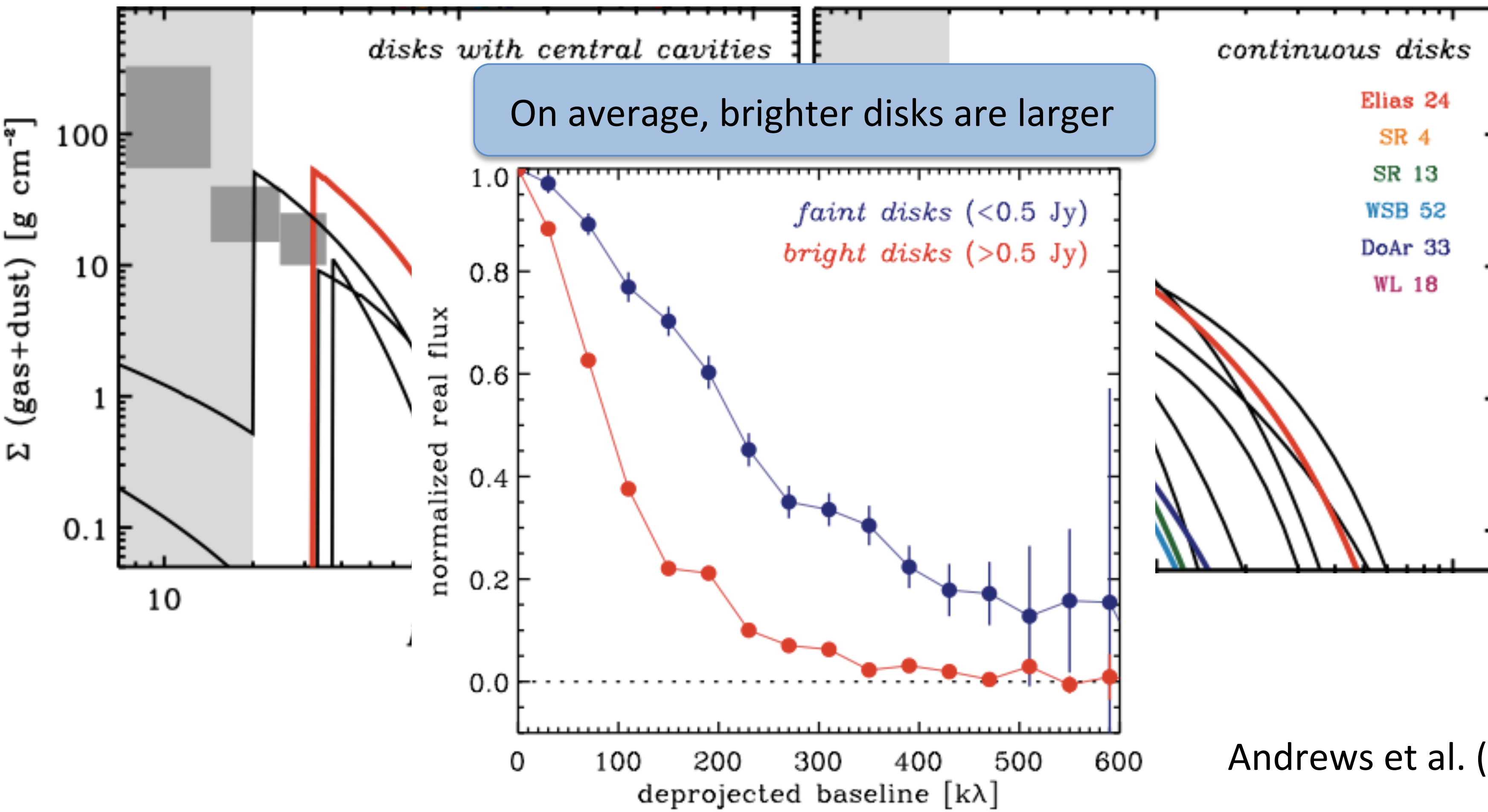


Andrews et al. (2009, 2010)

1. Where is the mass? How much?

mm/radio measurements necessary because disk needs to be optically thin

Using standard assumptions, most disks have roughly as much material as MMSN



Andrews et al. (2010)

2. How quickly do the grains grow?

Ideally, we would like to know size distribution as a function of position.

First order: Long-wavelength SED slope

Want to

$$n(a) \propto a^{-q}$$

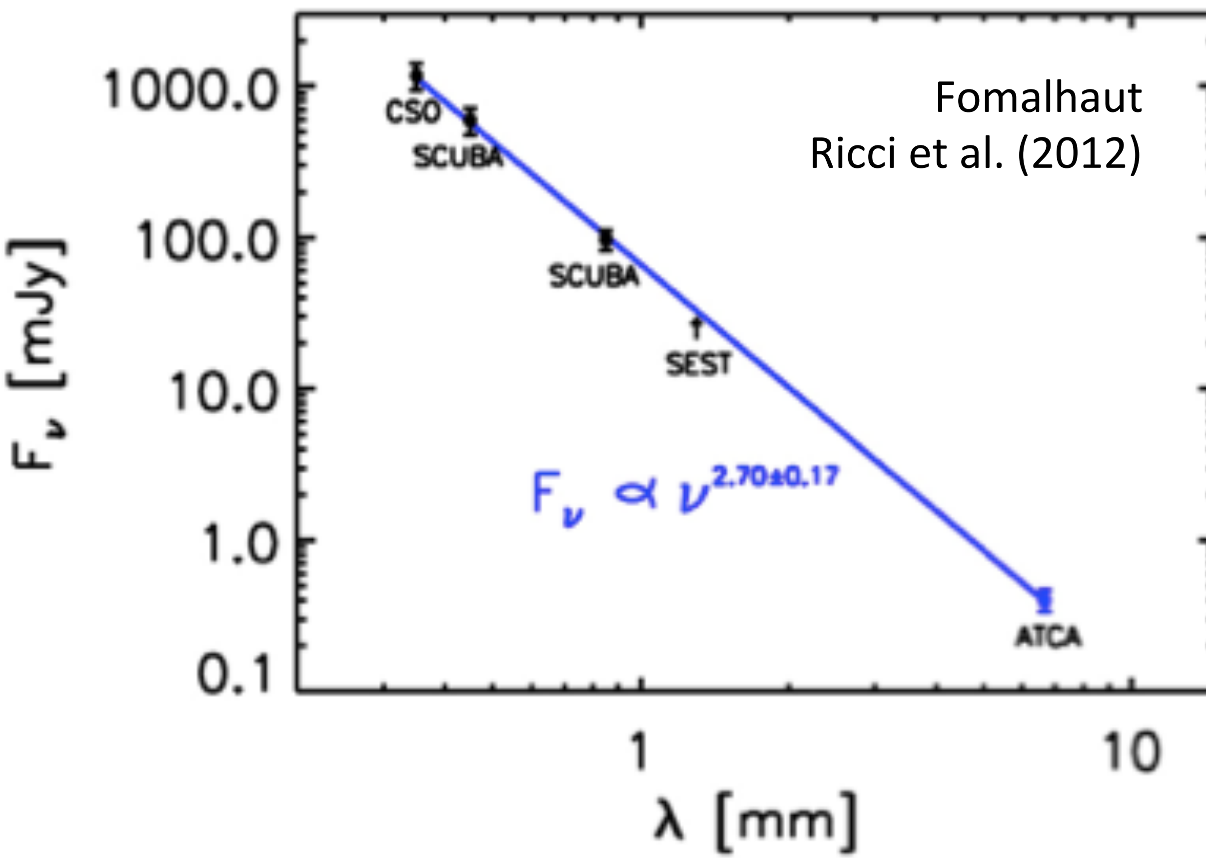
$$F_\nu \propto \frac{B_\nu(T_{dust})\kappa_\nu M_{dust}}{d^2}$$

Works for t

$$\kappa_\nu \propto \nu^\beta$$

D

$$\beta \propto (q-3)/\beta_s$$



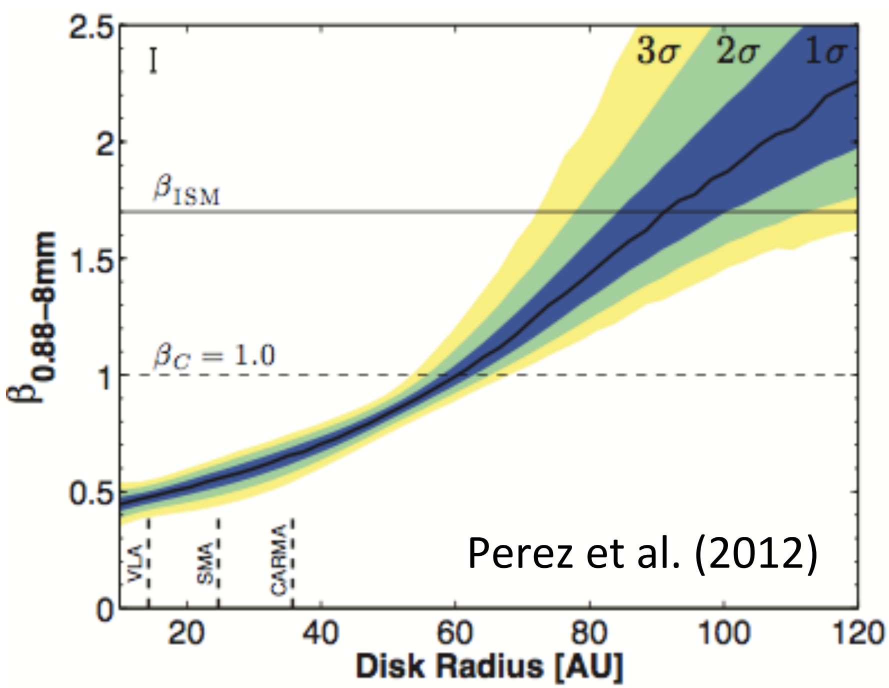
2. How quickly do the grains grow?

Ideally, we would like to know size distribution as a function of position.

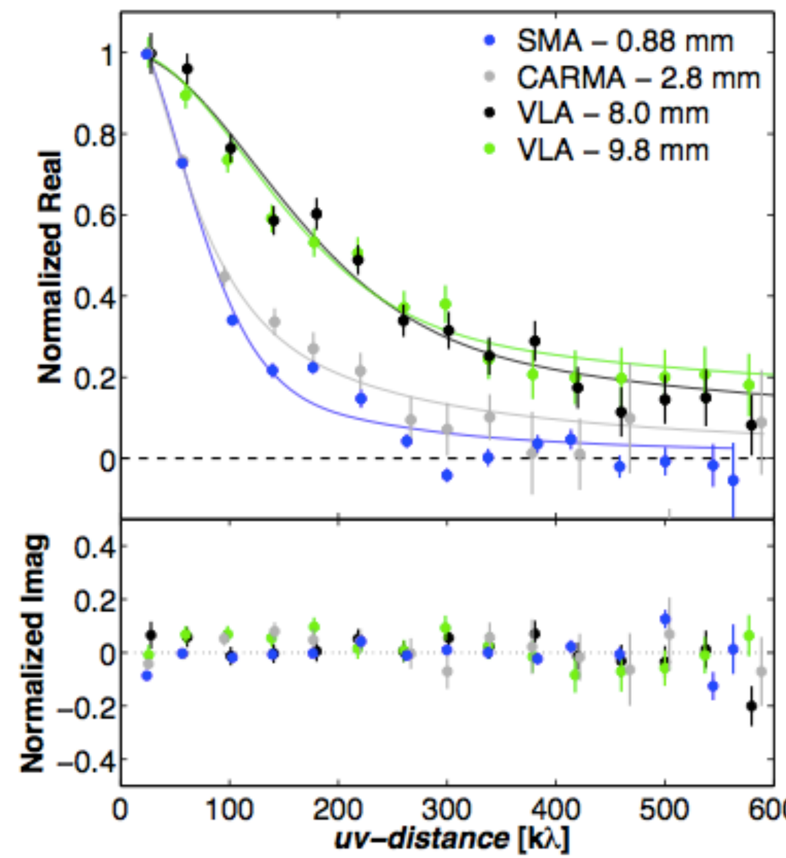
Second order: Radially resolved κ_ν

$$F_\nu \propto \frac{B_\nu(T_{dust})\kappa_\nu M_{dust}}{d^2}$$

$$\kappa_\nu \propto \nu^\beta$$



Perez et al. (2012)



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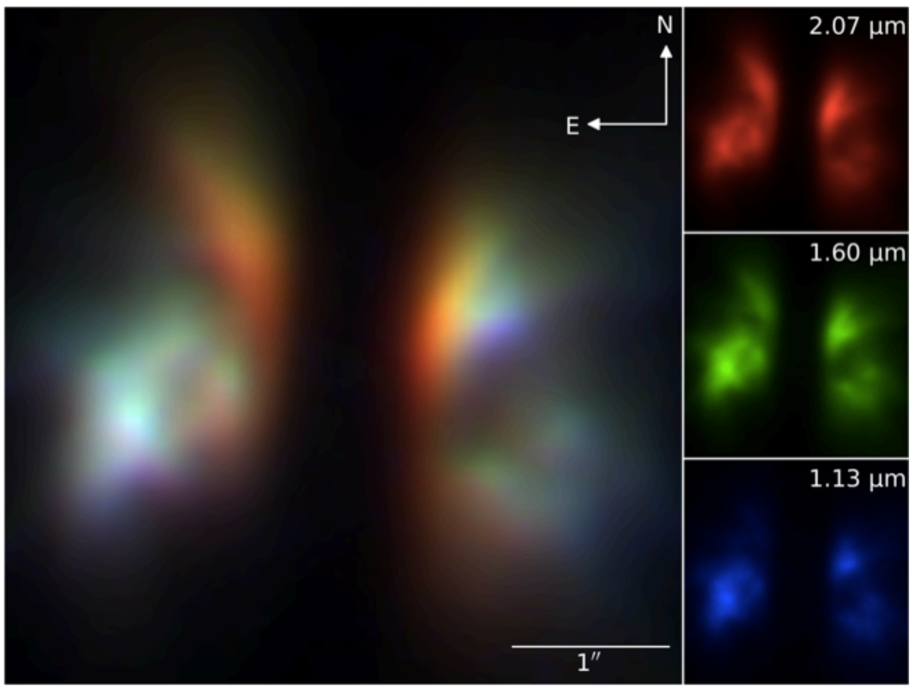
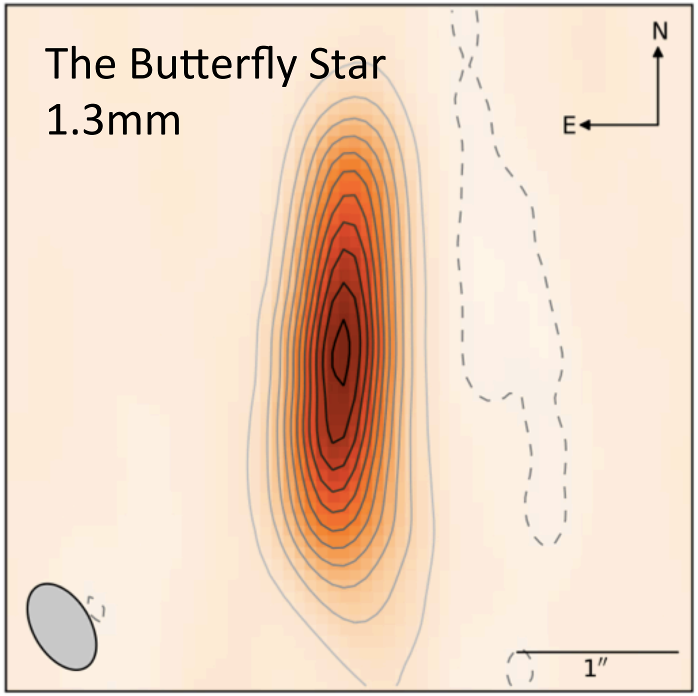
Ideally, we would like to know size distribution as a function of position.

Another dimension: edge-on disks



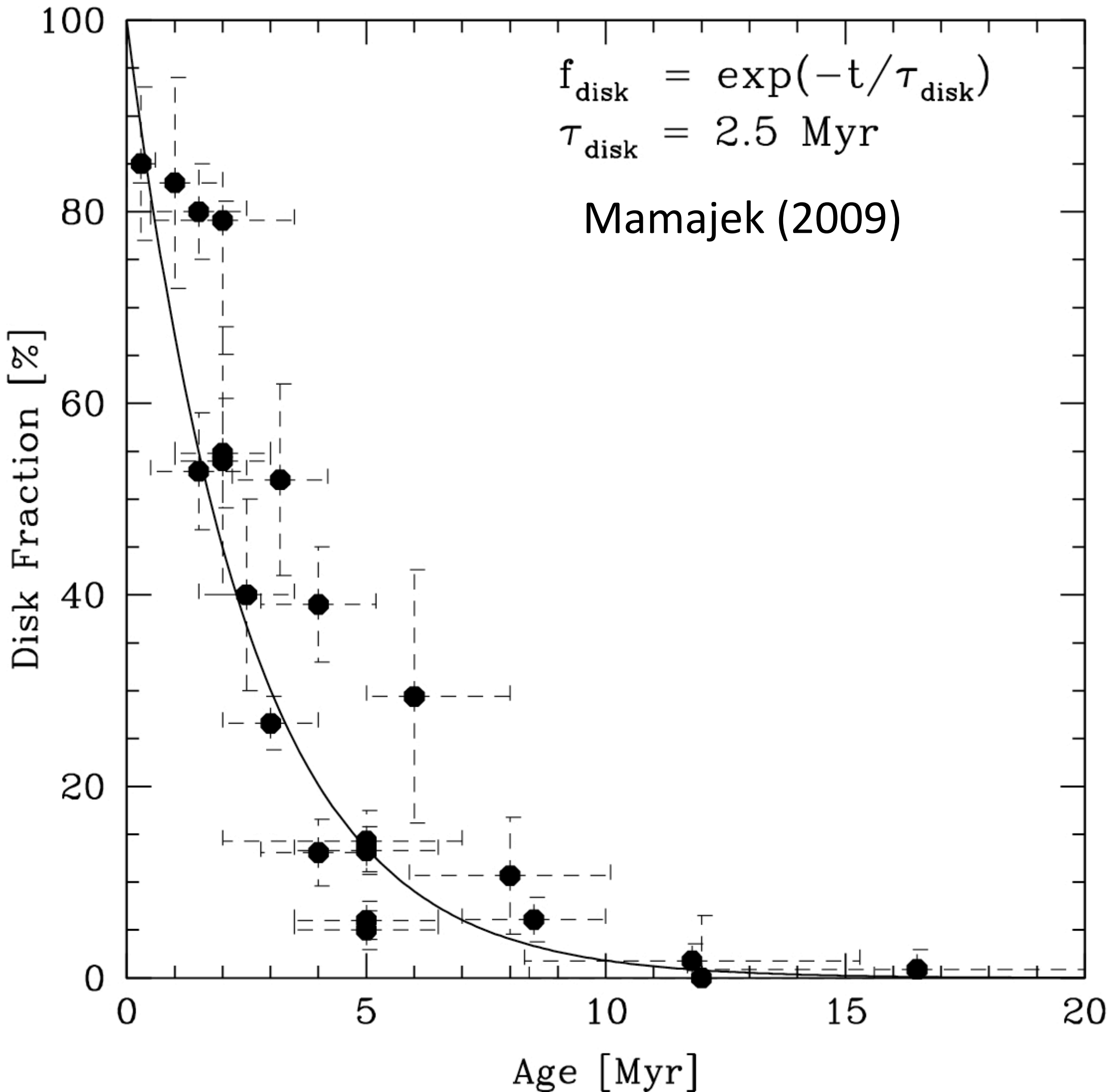


Grain growth to 100μm, vertical settling, and radial segregation

Gräfe et al. (2012)

3. When/why does the dust disappear?

Dissipation timescales and resolved imaging



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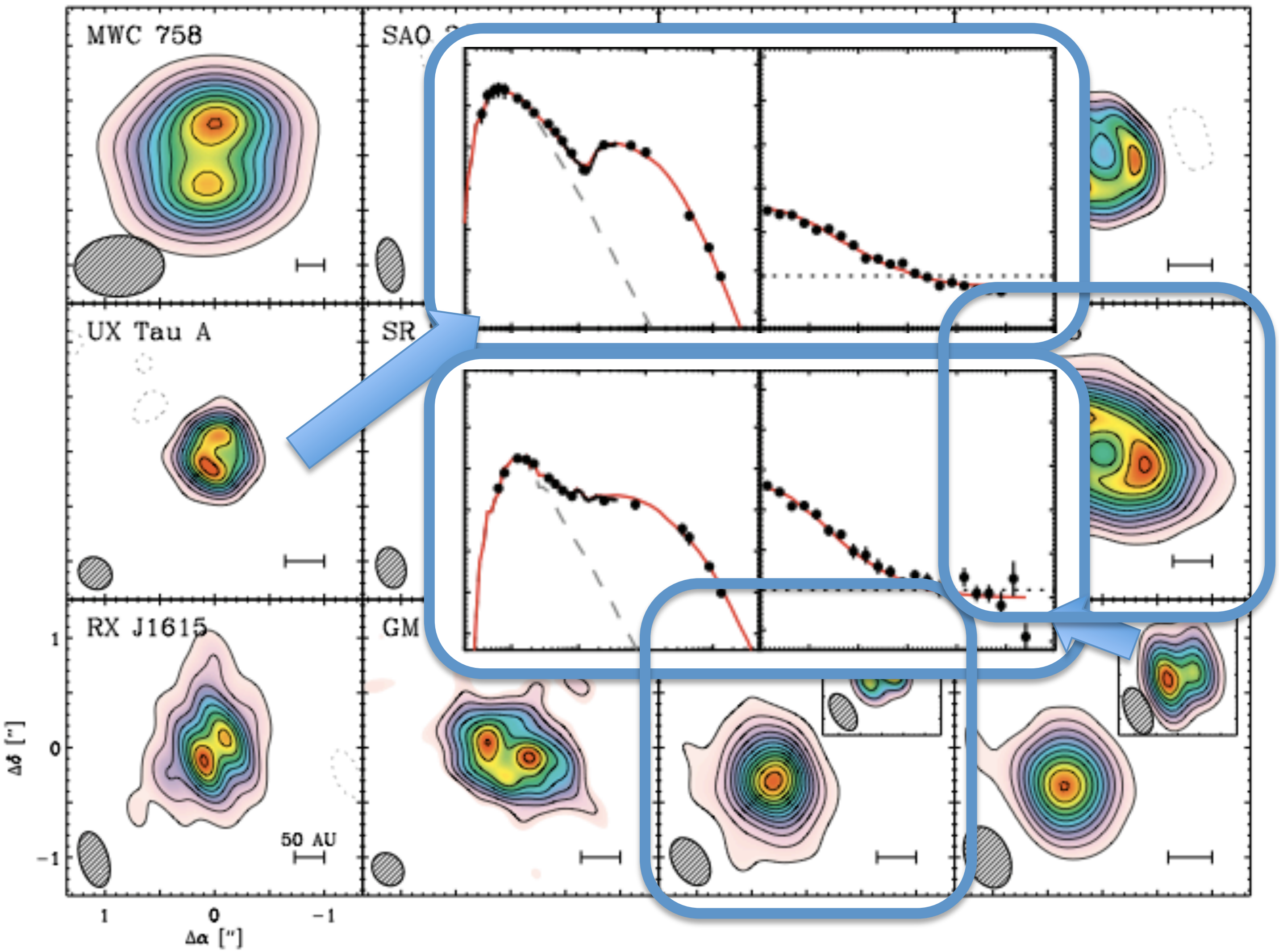
Dissipation timescales and resolved imaging



Transition disks look like protoplanetary disks with their middles cut out.

Some have centers depleted of small grains, and others don't (noticeably).

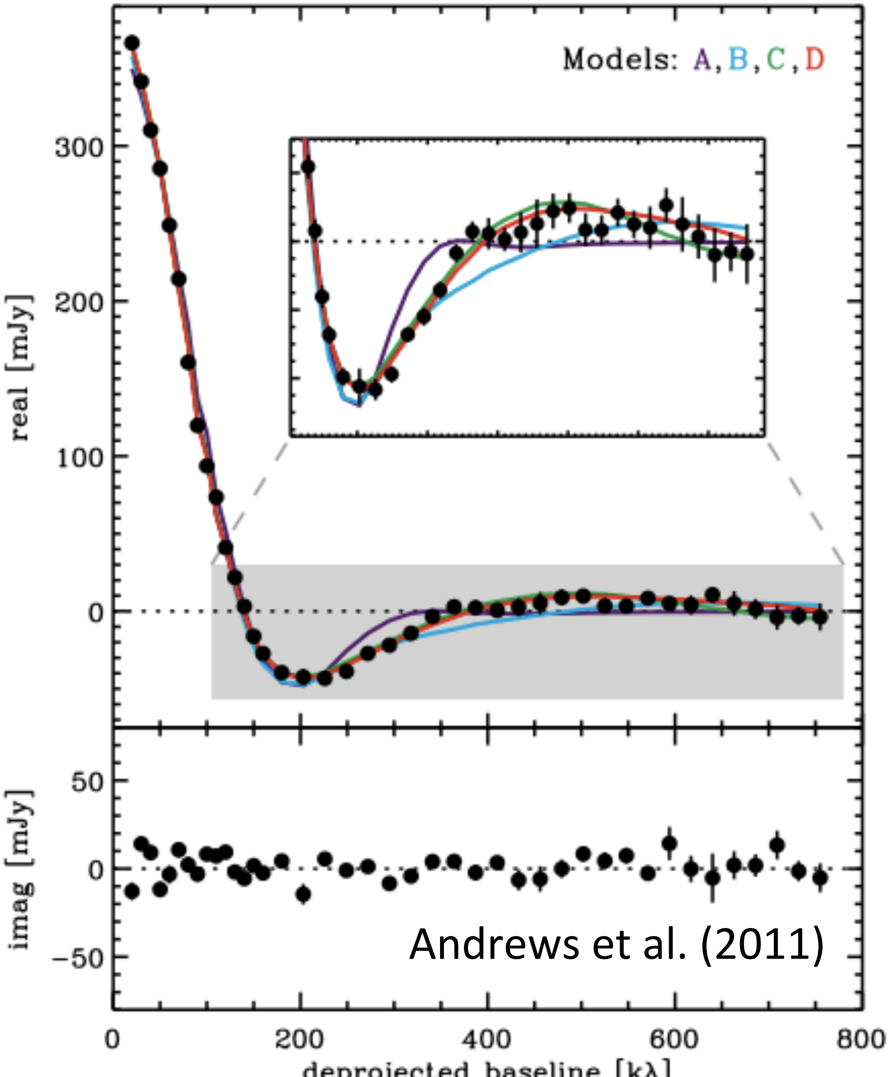
Don't believe size estimates based on SED alone

Probably not photoevaporation

Andrews et al. (2011)

3. When/why does the dust disappear?

Dissipation timescales and resolved imaging



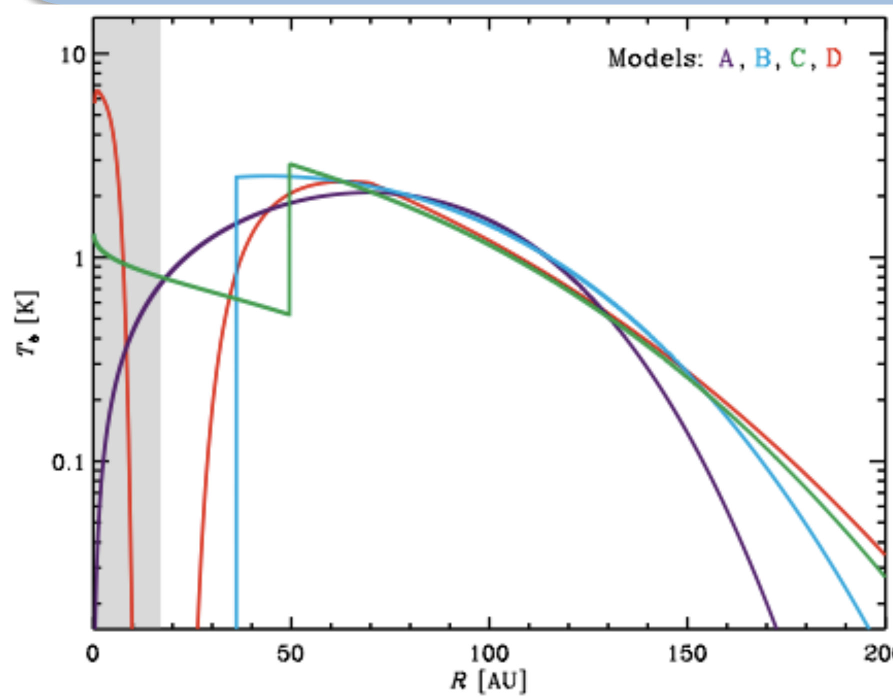
Andrews et al. (2011)

Scattered light imaging of LkCa 15 matches expectations from SED modeling and mm imaging.

Some large grains must be in the cavity.

Best fit to mm data matches predictions for a planet carving out a gap in the dust disk.

Also shows slight offset of star from disk center.



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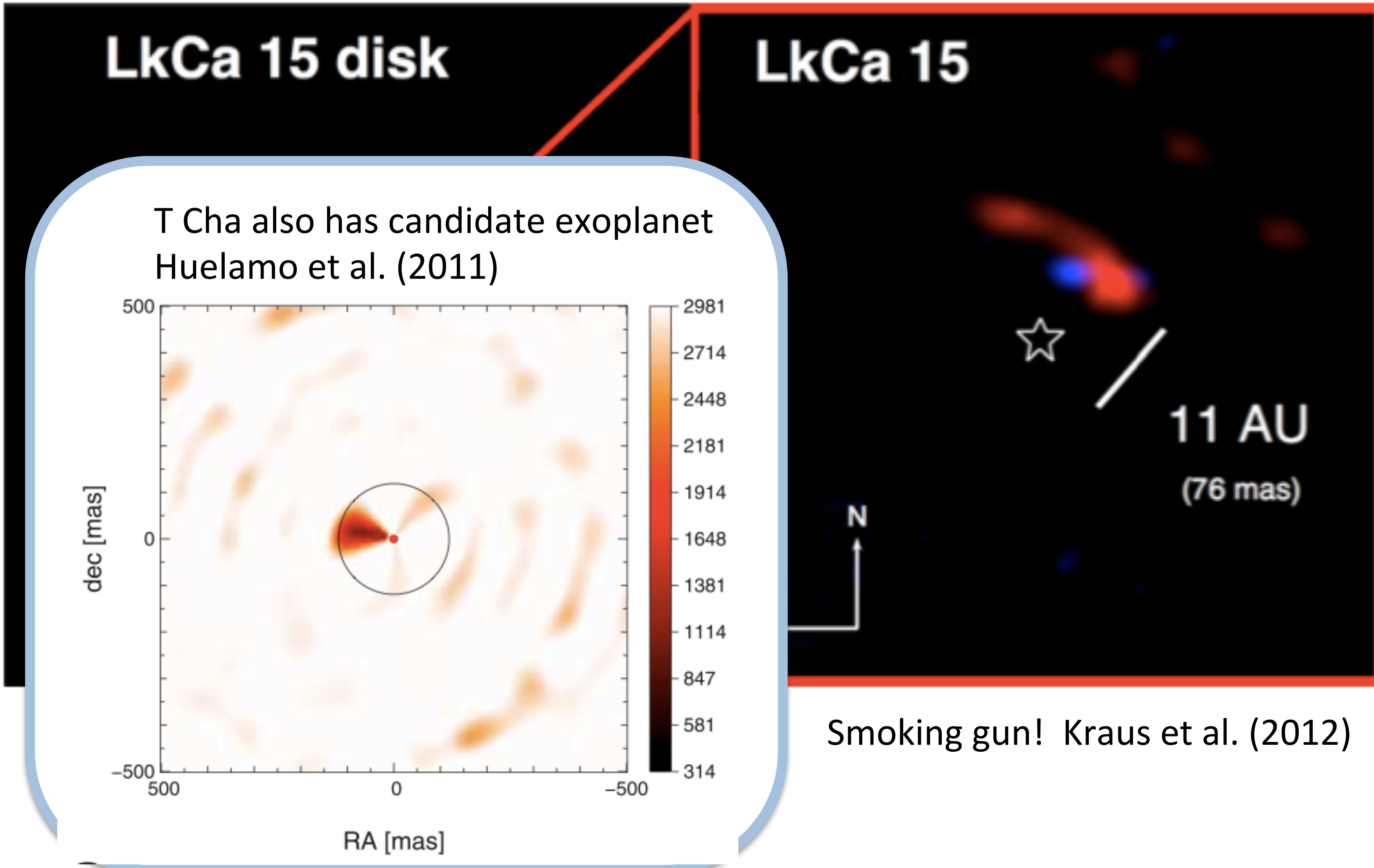


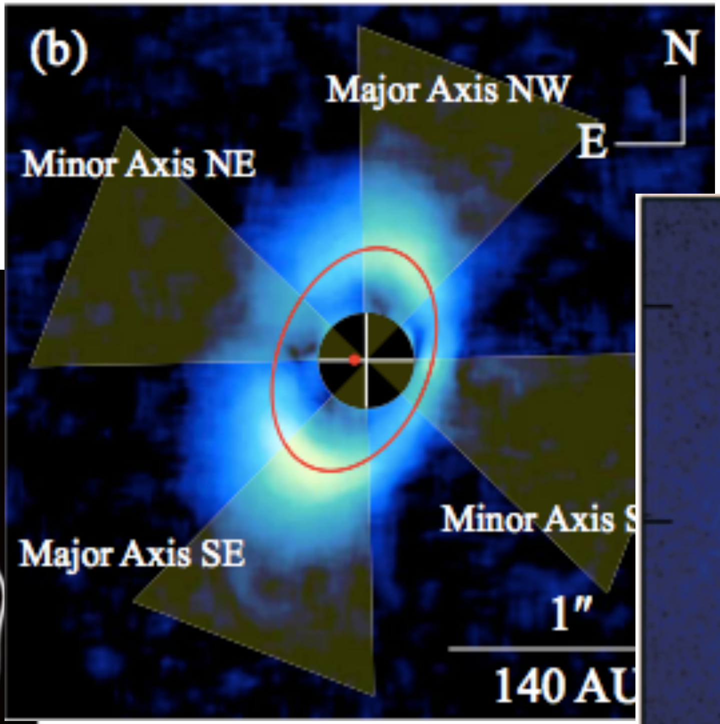
T Cha also has candidate exoplanet
Huelamo et al. (2011)

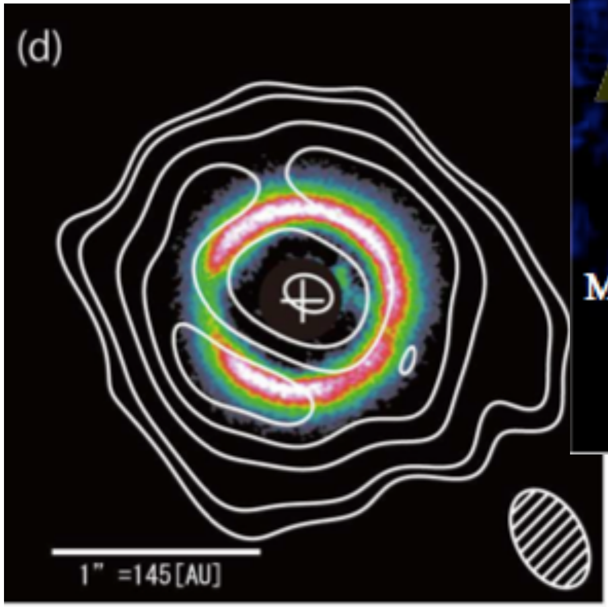
Smoking gun! Kraus et al. (2012)

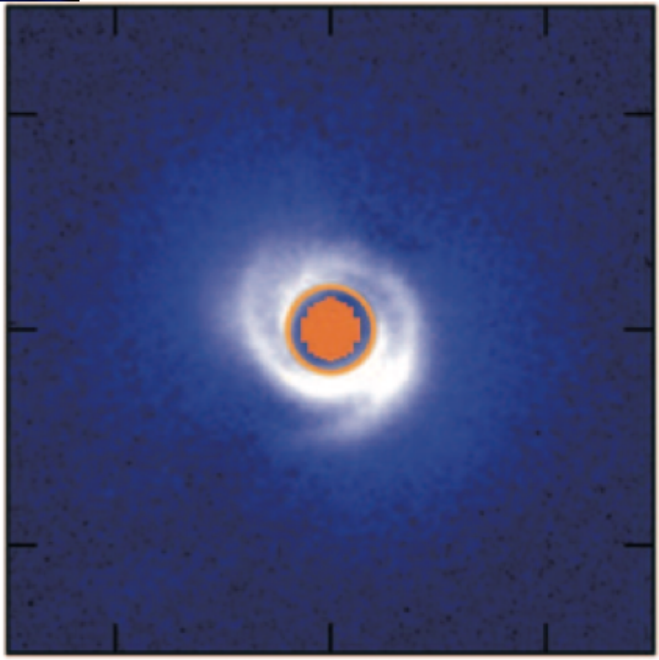
3. When/why does the dust disappear?

Dissipation timescales and resolved imaging

More results from SEEDS…







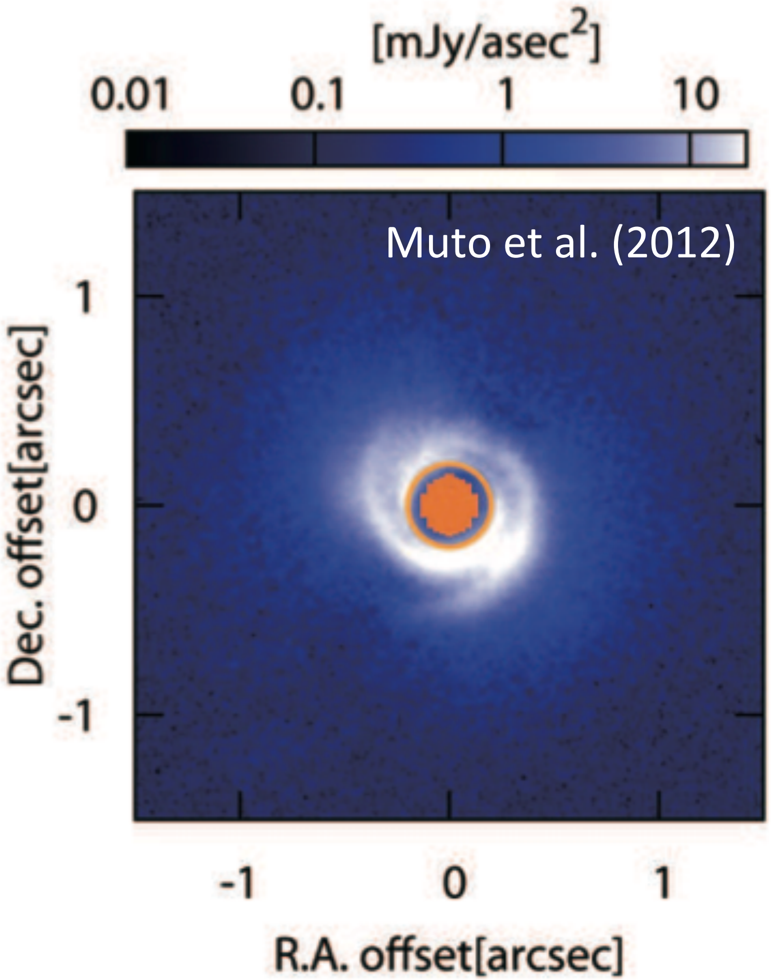
Hashimoto et al. (2012)
Gap discovery in PDS70

Muto et al. (2012)
No gap, despite mm obs

Mayama et al. (2012)
J1604-2130 – asymmetry in polarized light

4. What creates structure in the dust?

Spiral arms, eccentricity, and vortices



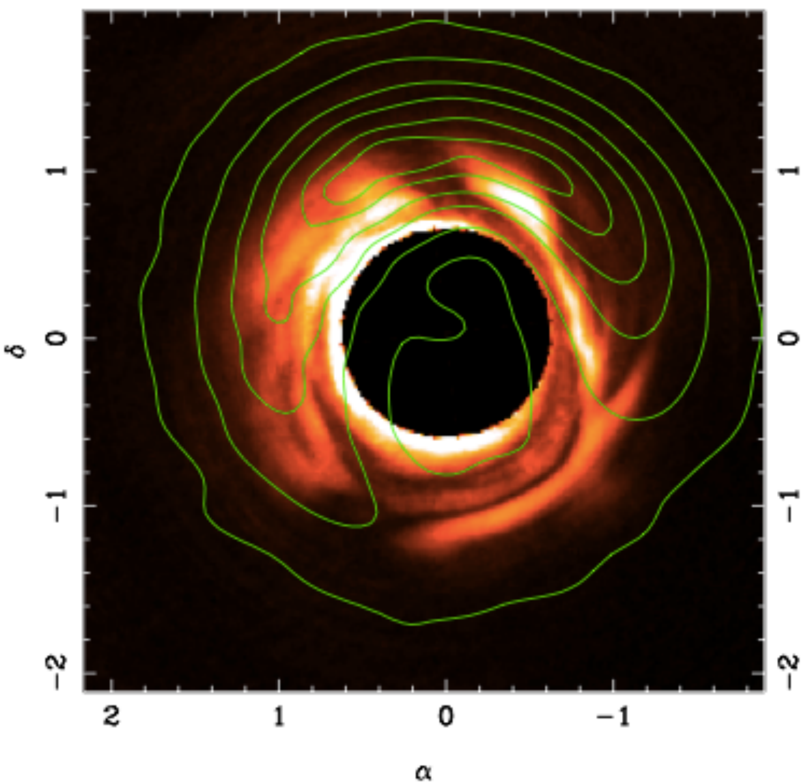
HD 135344B

- Two spiral arms clearly indicated, extending inside gap observed at mm wavelengths
- Cause is inconclusive; planets are plausible
- Can watch evolution of spirals over 10-20 yrs

4. What creates structure in the dust?

Spiral arms, eccentricity, and vortices

Casassus et al. (2013)



HD 142527

- Clumpy scattered light
- Millimeter horseshoe
- Contrast too extreme for eccentricity alone
- (More on the gas tomorrow)

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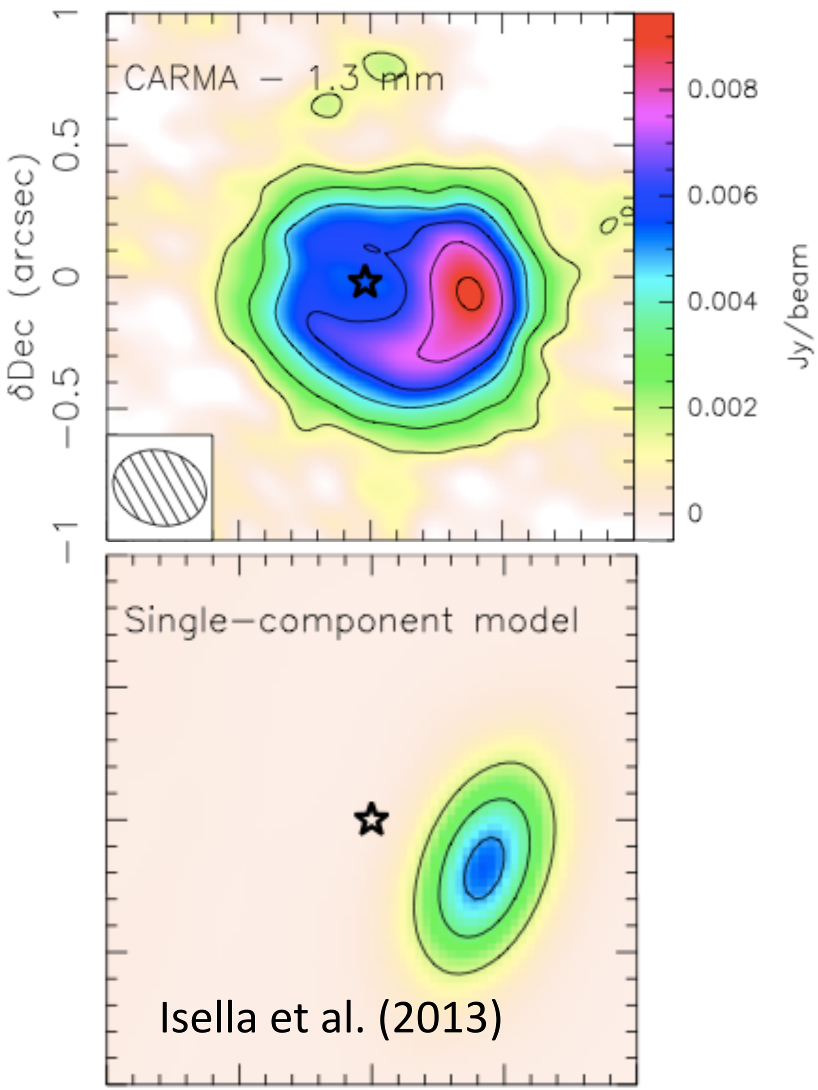
Spiral arms, eccentricity, and vortices



Isella et al. (2013)

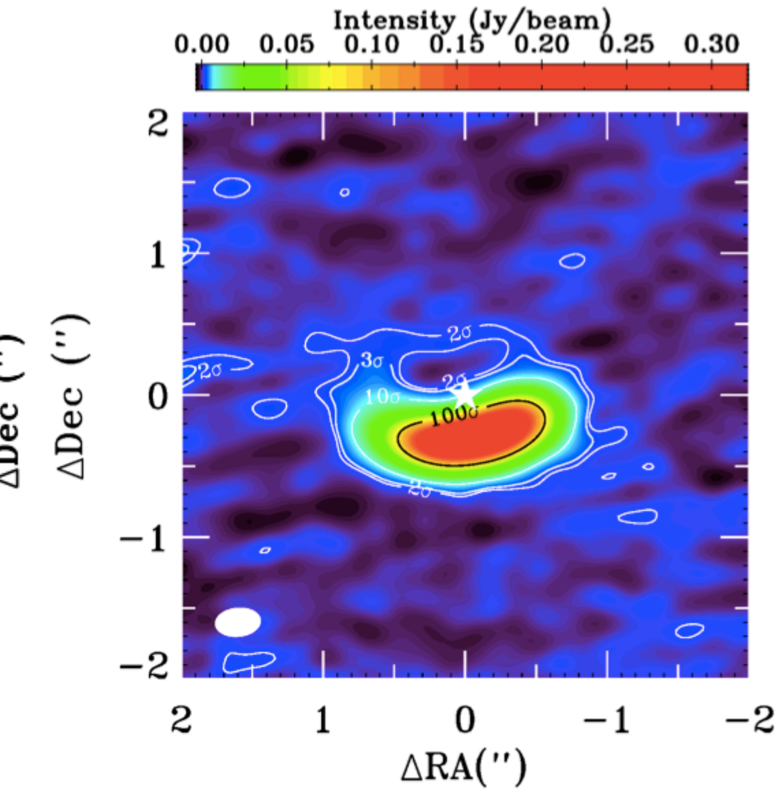
LkHα 330

- Adding fuel to the asymmetry fire!
- Asymmetry in the mm grains
- Simulations show that companions could trap the dust; Rossby wave and Baroclinic instabilities are unlikely in outer disk

4. What creates structure in the dust?

Spiral arms, eccentricity, and vortices

van der Marel et al. (2013)



IRS 48

- CO(6-5) and 18.7 μm VISIR emission unremarkable
- Asymmetry in the mm grains
- Far more pronounced and significant than any other source observed so far

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