The formation of planetesimals in proto-planetary disks, observed with the Jansky VLA

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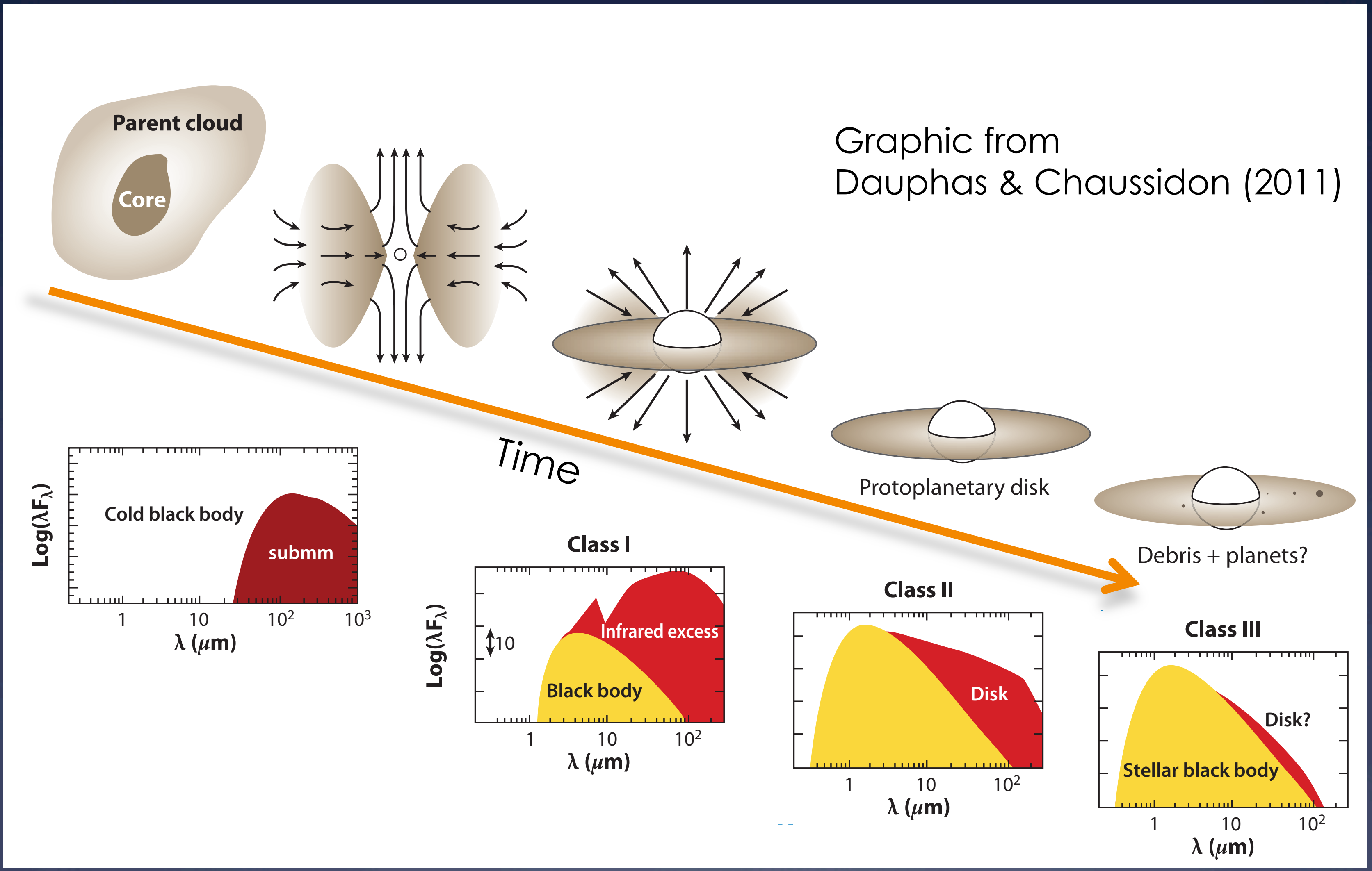
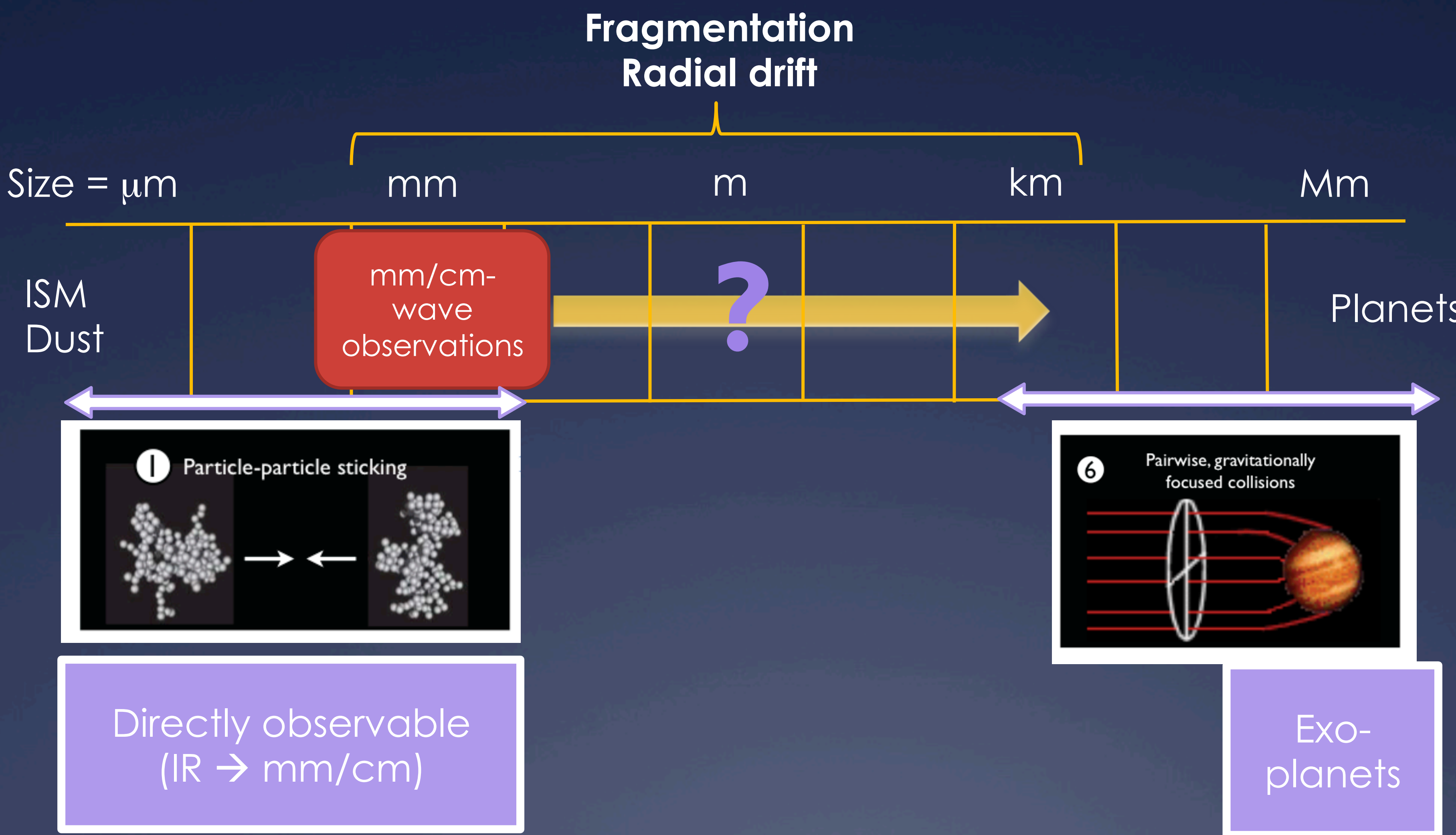
Disks: natural by-product of star formation



From ISM Dust to Planetary Systems

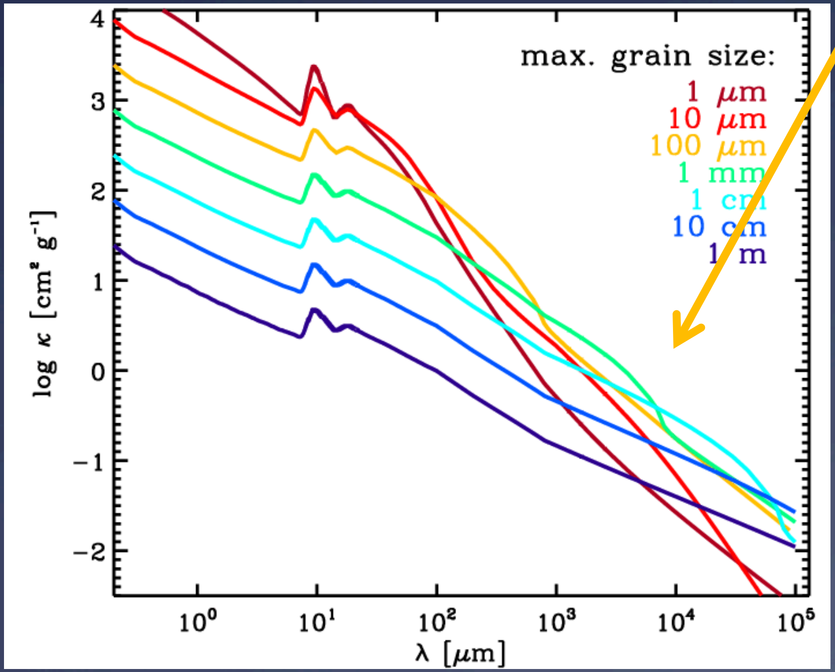


Adapted from Chiang & Youdin (2009)

Long-λ dust emission

- Optically-thin ⇒ traces mass $F_\nu \approx \kappa(\nu) M_d B_\nu(T_d) d^{-2}$
- Long-λ ⇒ in Rayleigh-Jeans for typical disk temperatures

$$F_\nu \approx \frac{2k}{c^2}\nu^2 \kappa(\nu)\frac{M_d T_d}{d^2} \qquad \kappa(\nu) \propto \nu^\beta \qquad F_\nu \propto \nu^\alpha, \text{with } \alpha = 2+\beta$$

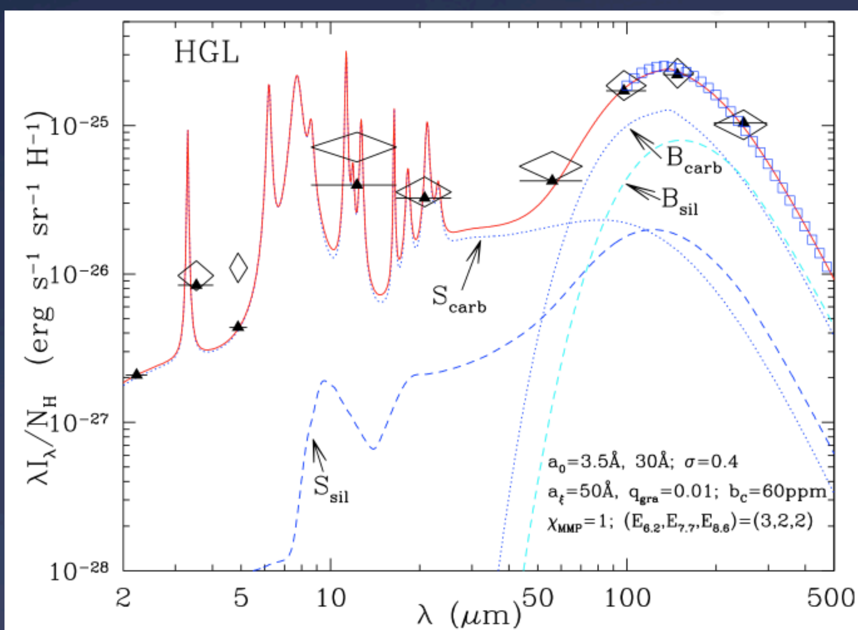


- Spectral index, β, is a measure of the size of the dust grains in a disk!
- Can be derived directly from α
- Need long-λ to measure big grains

Multi-λ observations constrain $\beta_{disks} < 1$

- Dust in the ISM
  - (diffuse and dark clouds)

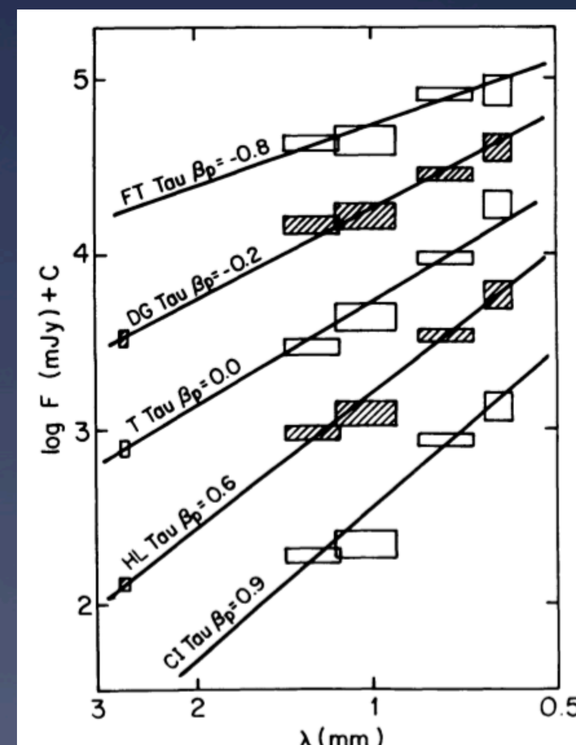
$\beta_{ISM} \approx 1.8 \pm 0.2$



E.g., Li & Draine (2001)

- Integrated disk spectra show flatter spectral index:

$2 < \alpha_{disks} < 3 \Rightarrow \beta_{disks} < 1$



E.g., Beckwith & Sargent (1991)

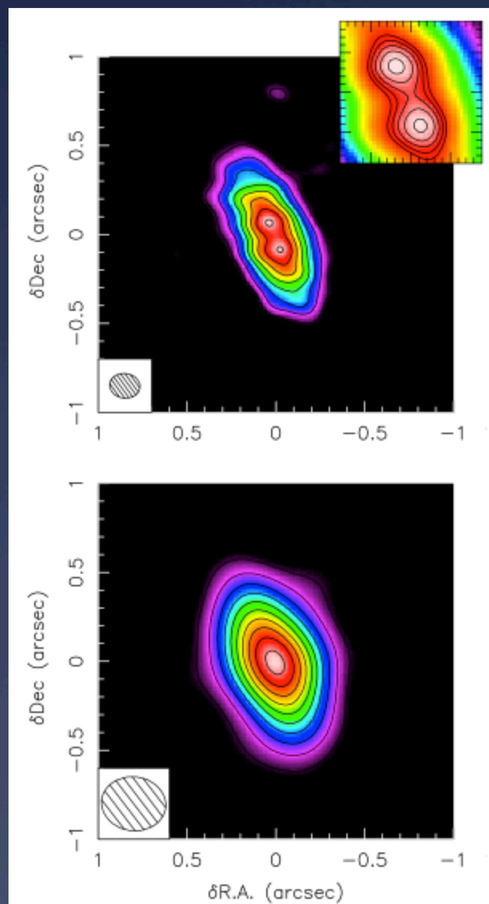
Expect spatial variations: observational constraints on radial variations of β

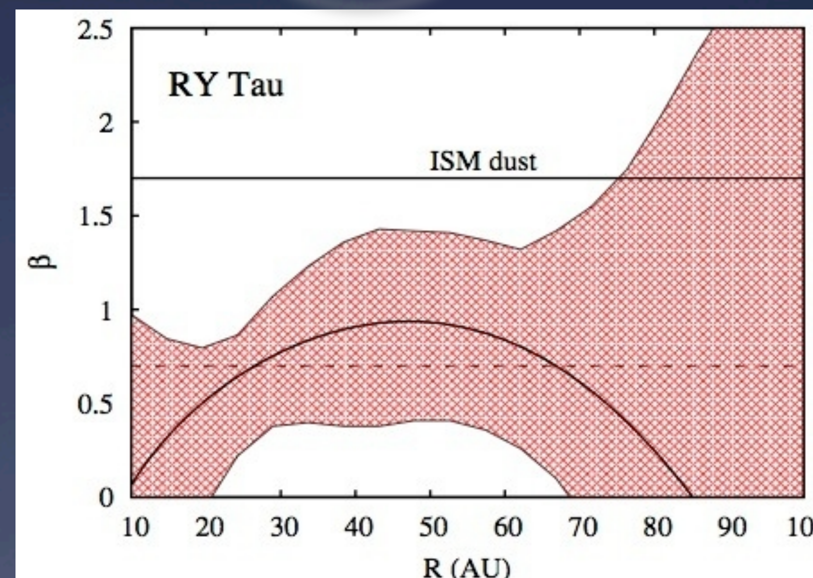
* **CARMA observations of RYTau**

$$\Delta\beta \sim \frac{1}{\log(\nu_1/\nu_2)\ln 10}\sqrt{\left[\frac{\Delta S_{\nu 1}}{S_{\nu 1}}\right]^2 + \left[\frac{\Delta S_{\nu 2}}{S_{\nu 2}}\right]^2}$$

1.3mm

2.7mm





Isella et al. (2010)
See also: Guilloteau et al. (2011)
Banzatti et al. (2011)

The Disks@EVLA project

* Survey statistically significant sample of protoplanetary disks (65 sources) at cm wavelengths with the VLA; goals:
  * Determine prevalence of grain growth to cm-sized particles in disks with ages 1-10 Myr from spectral indices
  * Use high resolution to image location of large dust grains in disks
  * Investigate dependence of particle populations on properties of the central stars, disk structure, and star forming environment

* See https://safe.nrao.edu/evla/disks/ for project information

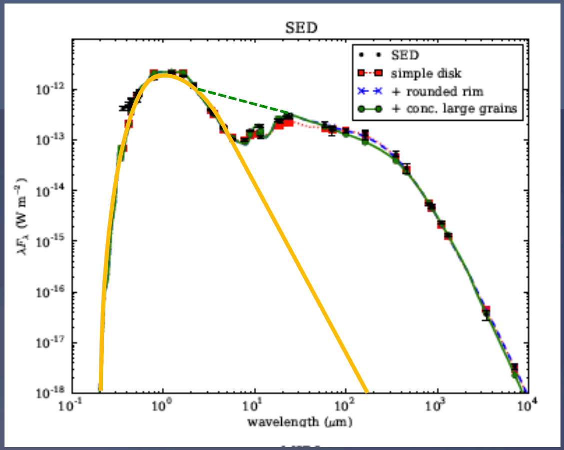
Sample

- Breakdown by type:
  - Taurus-Auriga 34
  - Ophiuchus 25
  - Isolated 6

  - Single 49
  - Multiple 16

  - "Classical" 50
  - "Transition" 15
- 49 sources imaged, 40 resolved

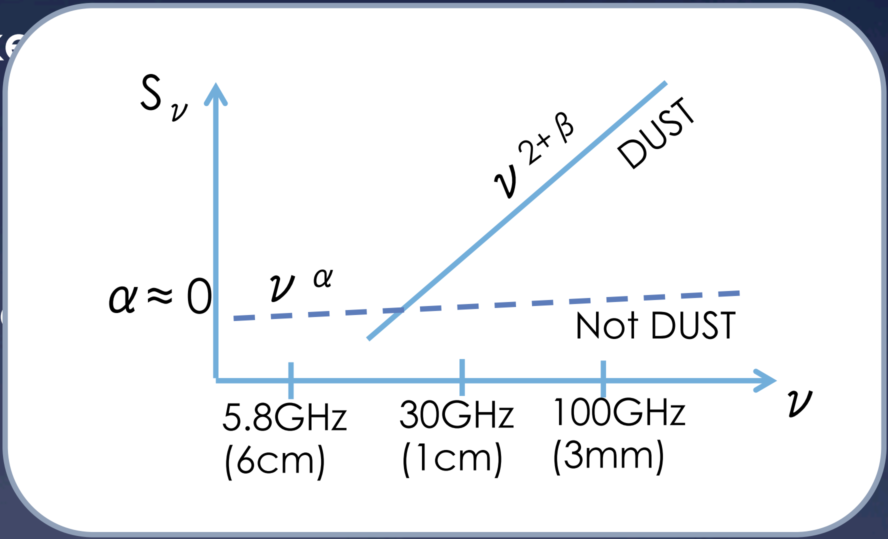
- Spectral type:
  - A 8
  - F 1
  - G 2
  - K 31 → K0-4 9, K5-8 22
  - M 18
  - ? 5



TWHya: Menu et al. (2013)

Observations

* Observations from July 2010 through December 2012
  * 376.5 hrs observed in 138 scheduling blocks, 10.5 TB raw data
  * First wide bandwidth data take
* New wide bandwidth capab
  * 1 GHz BW per IF, two IFs
  * Photometry at C/K/Ka/Q ban
  * Imaging at Ka/Q (+C) bands:



* Complications
  * First wide bandwidth data taken with the new EVLA hardware!
  * Early datasets are challenging
  * Most of the photometry data were taken first: focus on imaging results today
  * Some SBs observed with resolved calibrators → need to model

Observation/reduction summary

* **49 sources imaged, 27 at the highest resolution in A-config:**

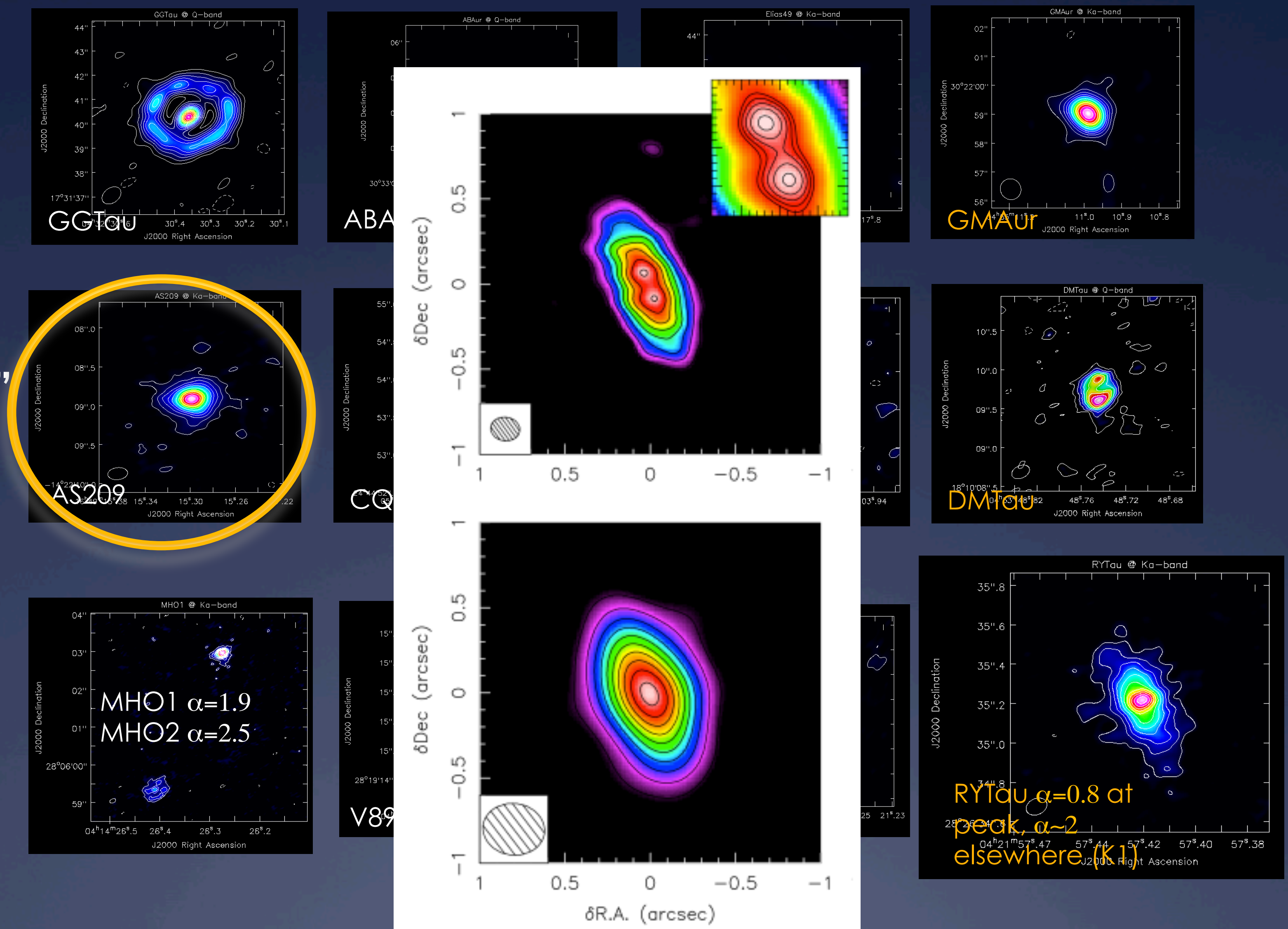
SFR	C/CnB	B/BnA	A
Taurus-Auriga	GGTau, Haro6-37, GMAur, ABAur, HD35187	FTTau, UXTau, DMTau, DNTau, HPTau, DRTau, UYAur, CQTau, *DLTau*	MHO1/2, CYTau, V892Tau, RYTau, UZTau*, MWC480, *TTau, DGTau, DGTauB, GVTau, HLTau, XZTau, Haro6-13, DOTau, DQTau*
TW Hydra Association			TWHya*, *HD98800*
ρ Ophiuchus	DoAr24, IRS41, WSB52, RNO90, RNO91, Elias49	WSB60, AS209*	AS205, GSS26, DoAr25, Elias24, Elias27, SR24, IRS51, WaOph6
Other isolated			HD142666, MWC275

Imaging: sensitivity

* Typical resolution of targets observed in A+B+C configs is 0.1 arcsec ~ 14 AU
* Typical rms noise is 10μJy/beam
* Brightness temperature:
  * In Rayleigh-Jeans, $S = 2\,k\,T_B\,\Omega\,/\,\lambda^2$, so if emission is resolved (no beam dilution) and detected at the 10-σ level (0.1 mJy/beam) the source brightness temperature is ~ 11 K
  * For source radiation temperature T_R the optical depth is then just $\tau = T_B/T_R$
    * To be detected at 10-σ dust emission from a disk must have optical depth ~0.1 to 1
    * Potential contamination from optically thin (and beam-diluted) free-free emission from ionized wind or jet close to star

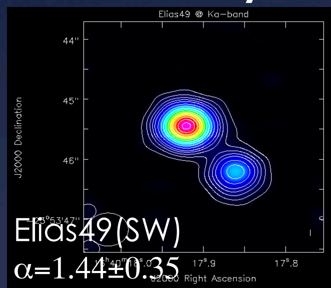
A protoplanetary disk picture gallery

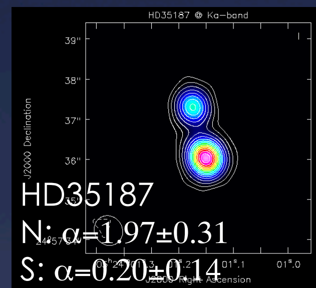
- θ_B~0.7"
  (100 AU)
- θ_B~0.25"
  (35 AU)
- θ_B~0.1"
  (14 AU)

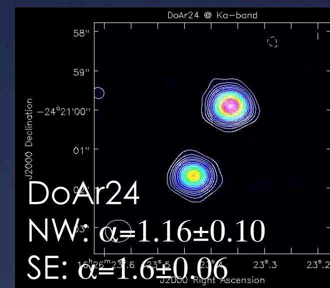


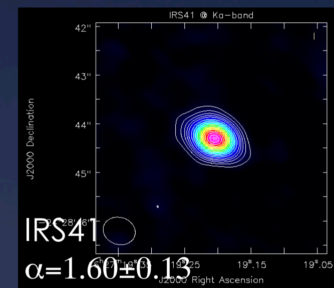
“Low” resolution images (θ_B~0.7”)

* Ka-band imaging provides spectral index information, even for unresolved sources: many consistent with contributions from dust; $S \propto \nu^{\alpha}$

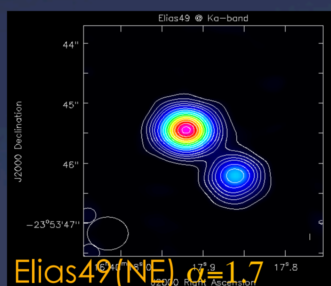


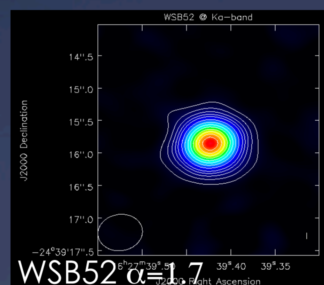


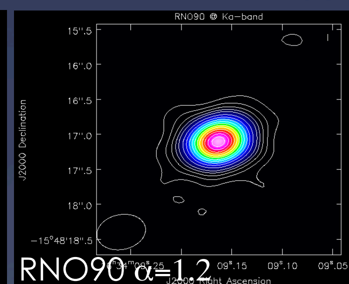


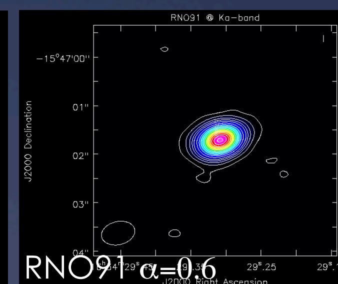


* Marginally resolved emission; transition disks denoted in GOLD

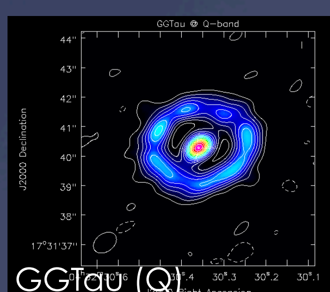


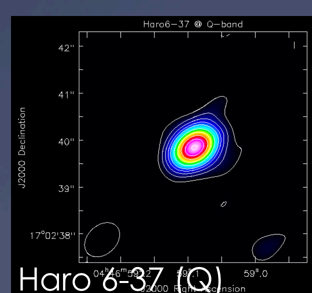


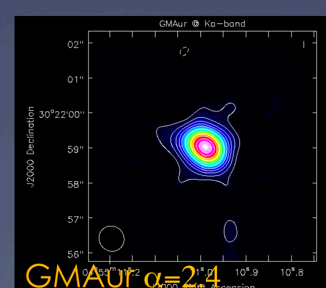


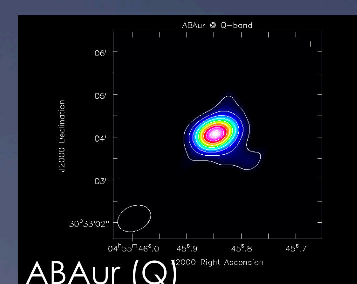


* Resolved sources: no spectral index info for those observed at Q-band



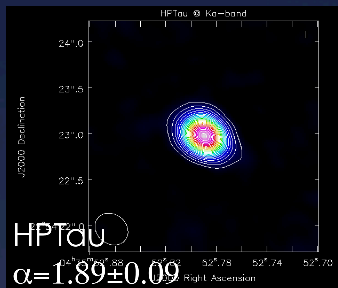


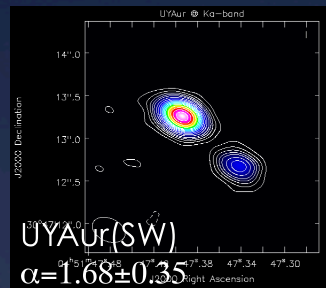


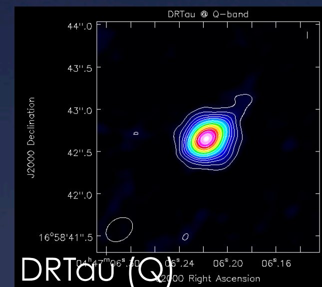


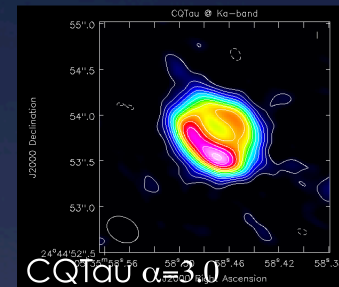
“Medium” resolution images (θ_B~0.25”)

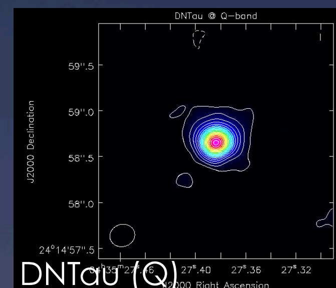
* Sources unresolved at 35AU resolution

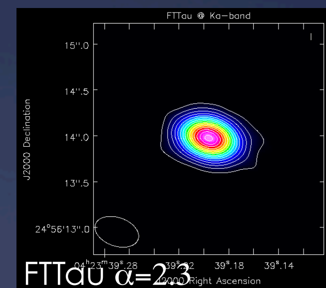




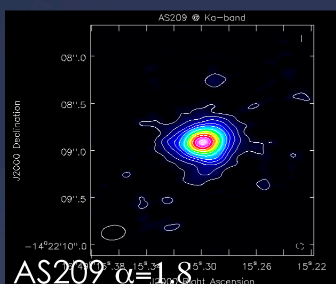


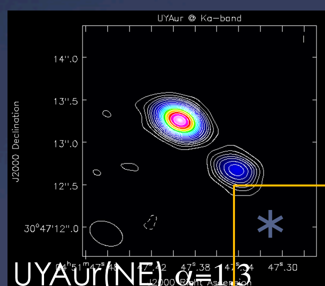




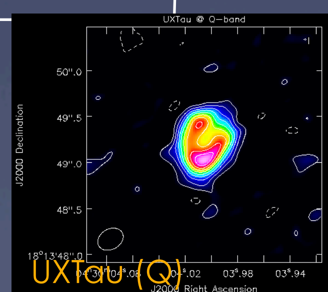


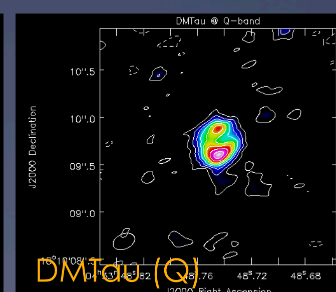
* Resolved sources: “classical” disks

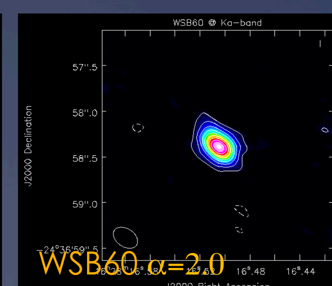




* Resolved sources: “transition” disks
* inner holes, spectral index consistent with dust emission

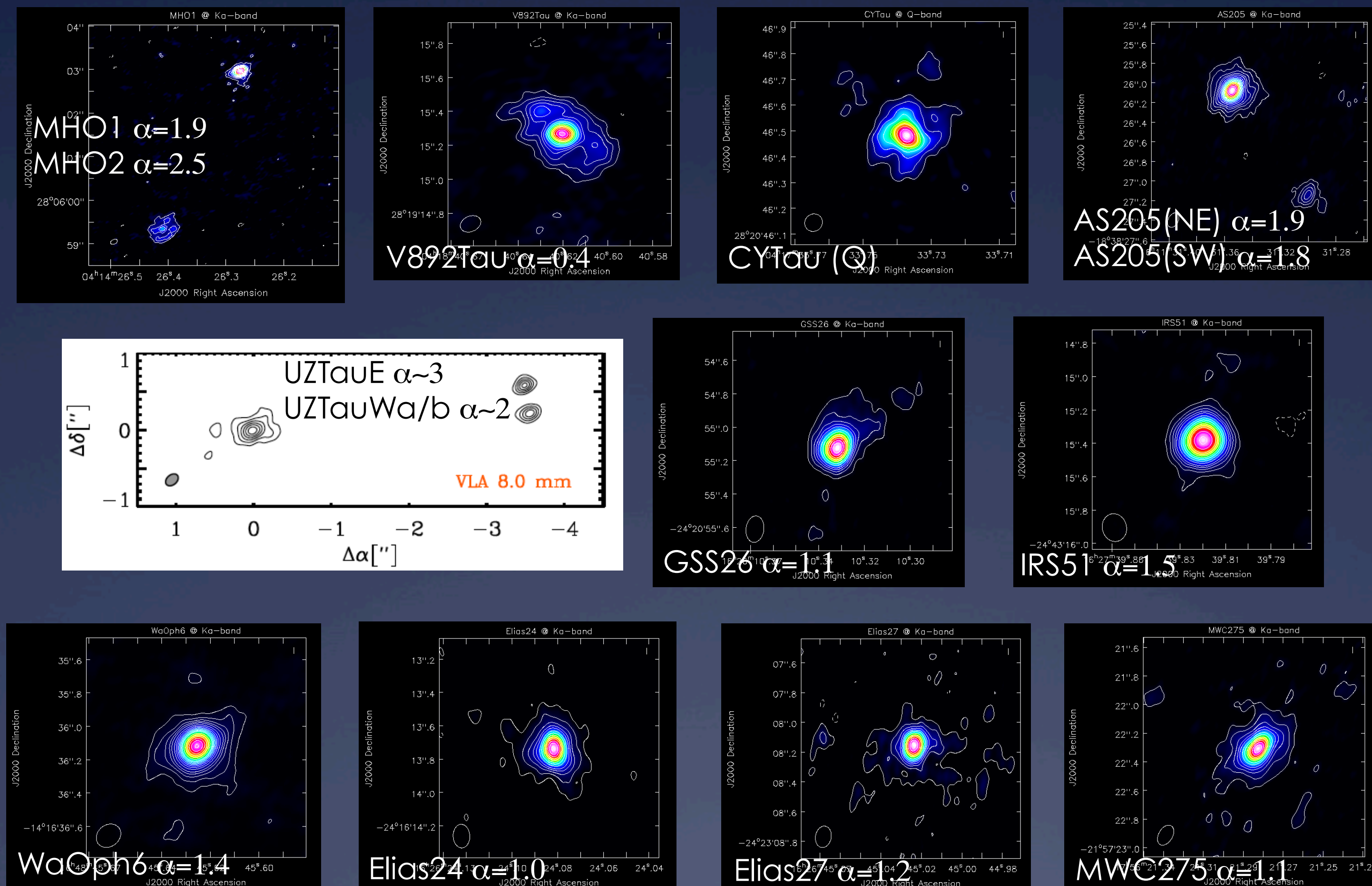






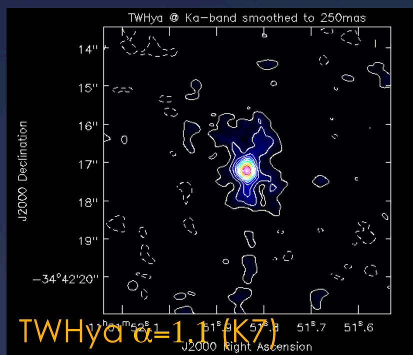
“High” resolution images (θ_B~0.1”)

* All sources resolved on these size scales; classical disks:

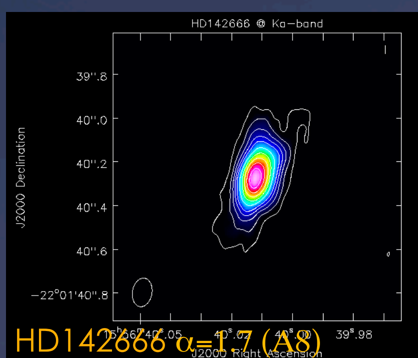


“High” resolution images (θ_B~0.1”)

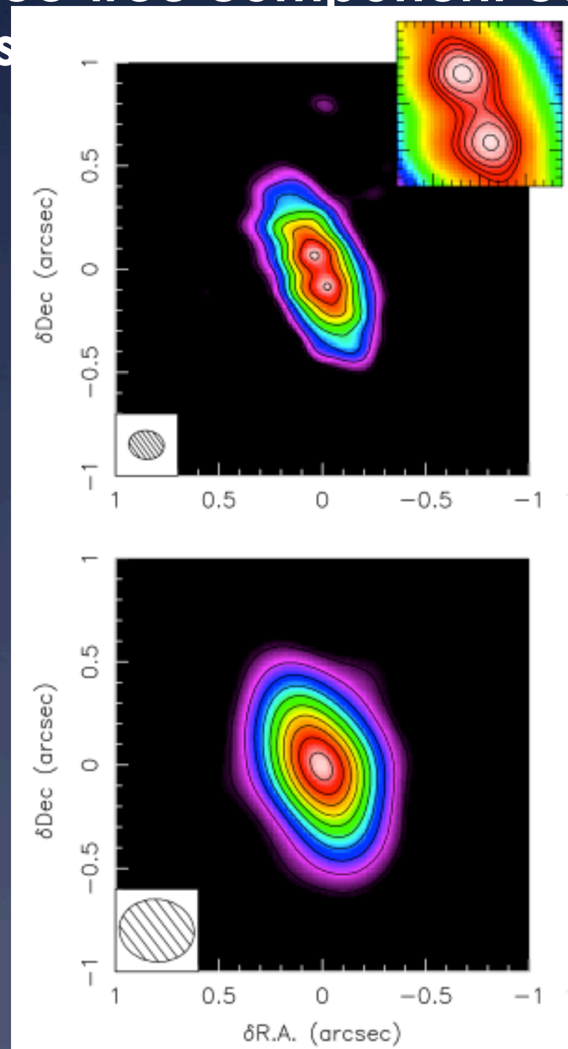
* Transition disks: free-free component coincident with star (all spectral types

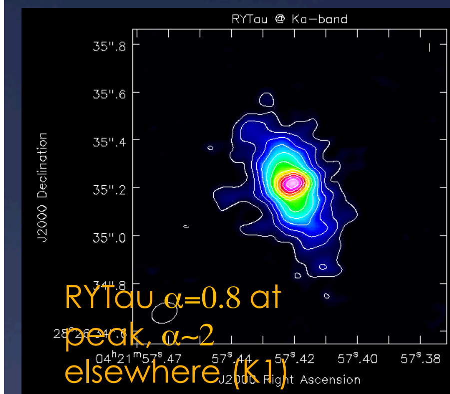


TWHya α=1.1 (K7)



HD142666 α=1.7 (A8)

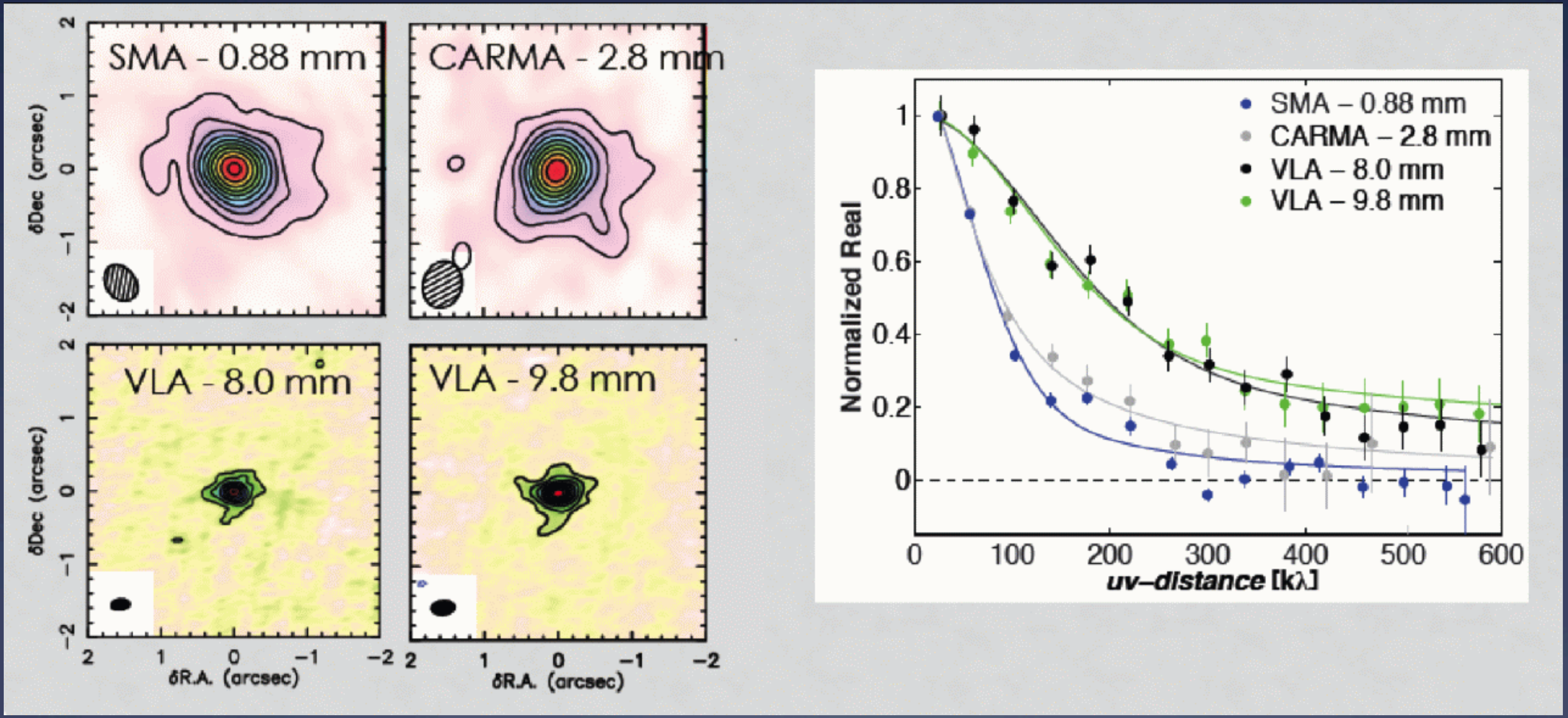




RYTau α=0.8 at peak, α~2 elsewhere (K1)

Constraints on grain growth

- **AS209: Pérez et al. (2012): combine SMA+CARMA+VLA**
  - Increase lever arm for measuring slope of dust opacity
  - Extends sensitivity to *large* dust grains

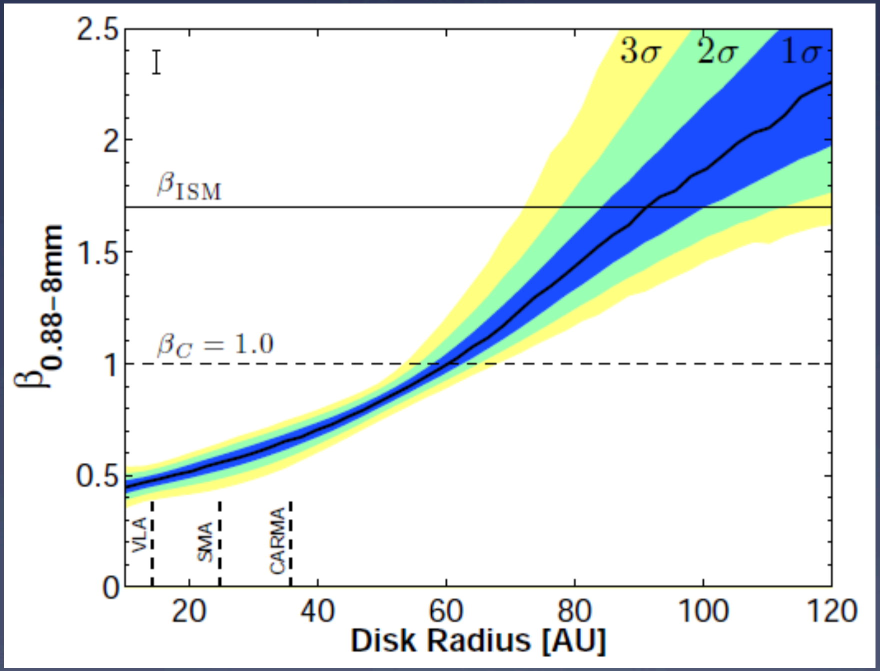


Dust emissivity index, β

- $\tau_\lambda(R) = \kappa_\lambda(R)\,\Sigma(R)$, dust emissivity usually modeled as $\kappa_\lambda \propto \lambda^{-\beta}$
- Turn measurement of $\tau_\lambda(R)$ into constraint on $\beta(R)$
  - Inconsistent with a constant value of β as a function of radius!

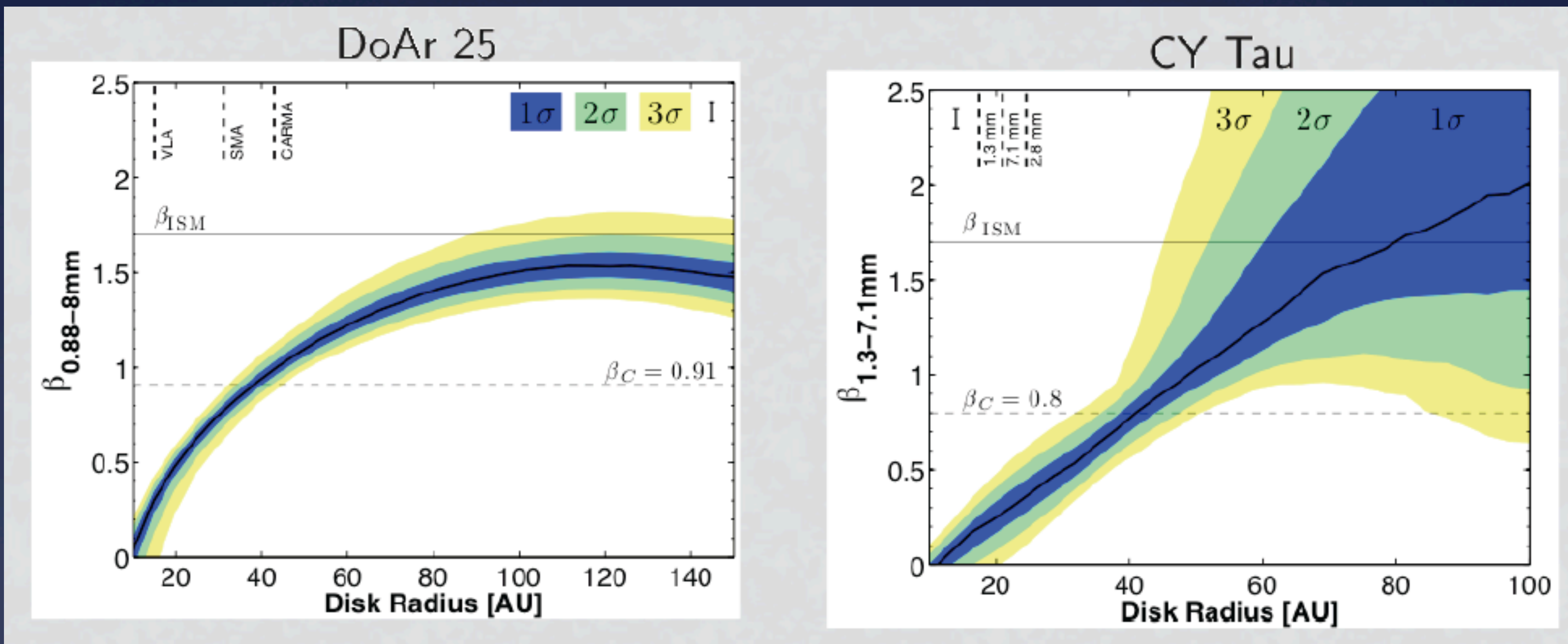
Small grains →

Big grains →



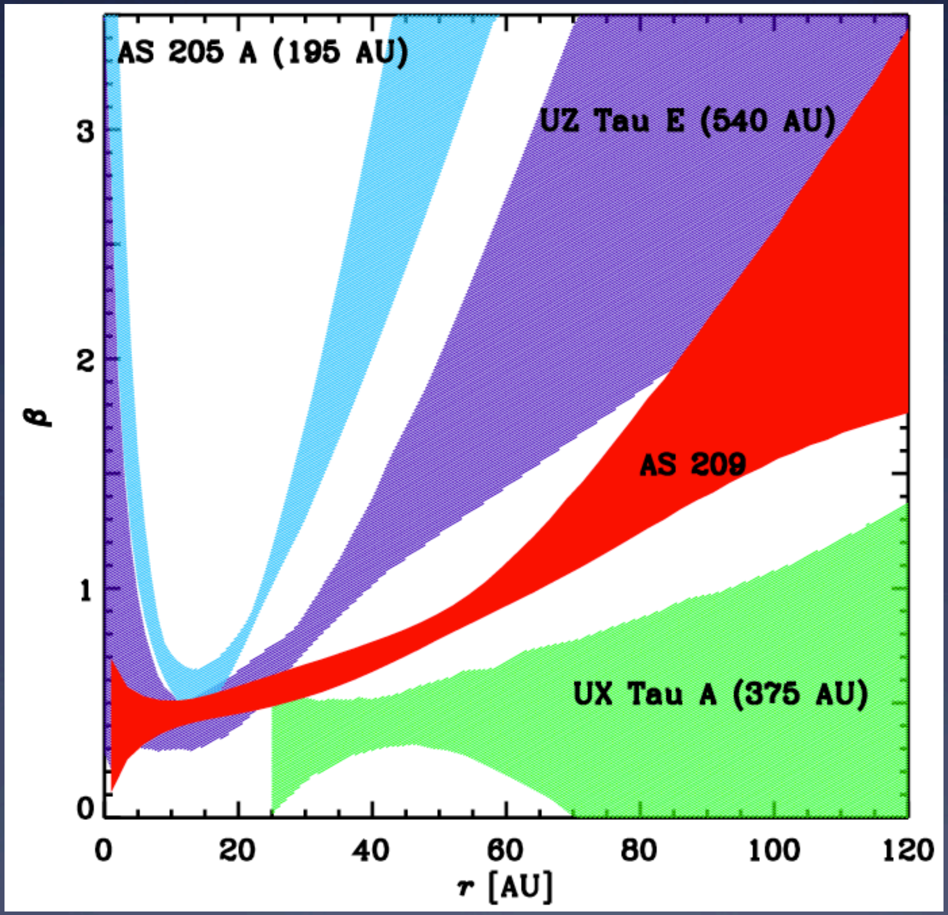
Results for other sources

* Pérez (2012, PhD Thesis)



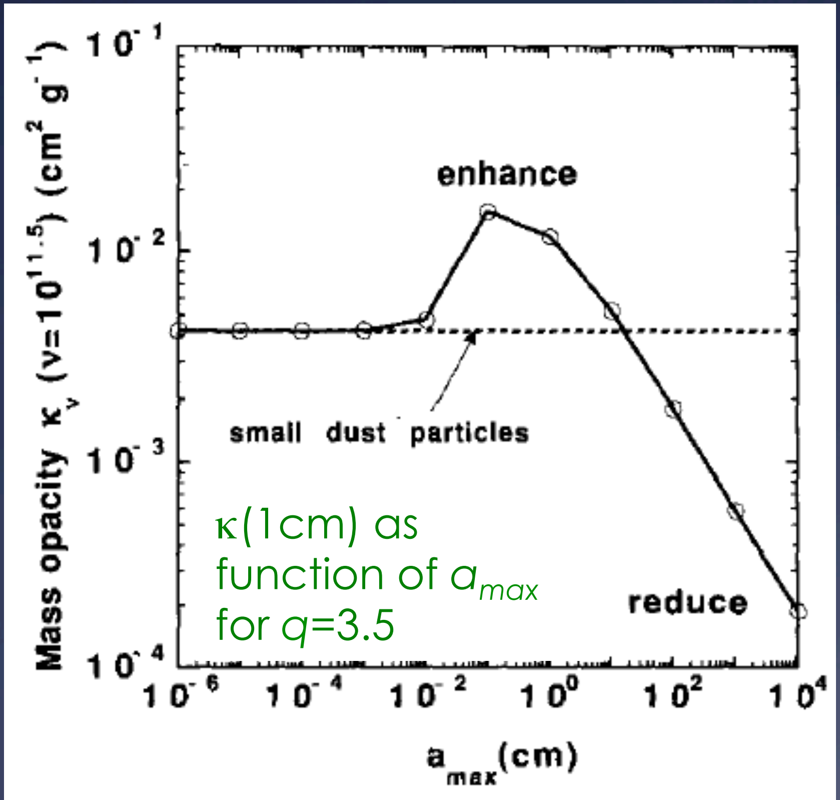
Multiple systems: UZTau, UXTau, AS205

- Harris (2013, PhD Thesis): dust properties similar to single systems

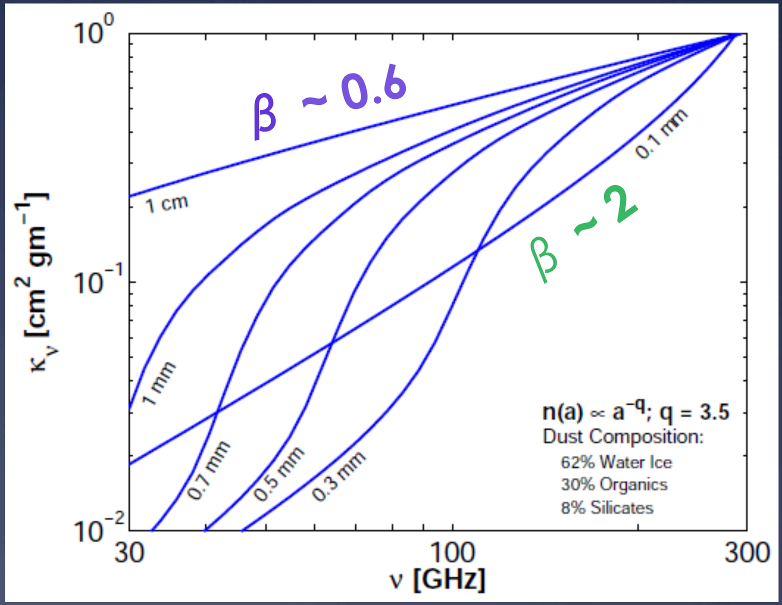


What does κ tell us about the grain size?

* Assume grain size distribution $n(a) \propto a^{-q}$ up to max grain size a_{max}; use models of κ_λ to constrain a_{max}



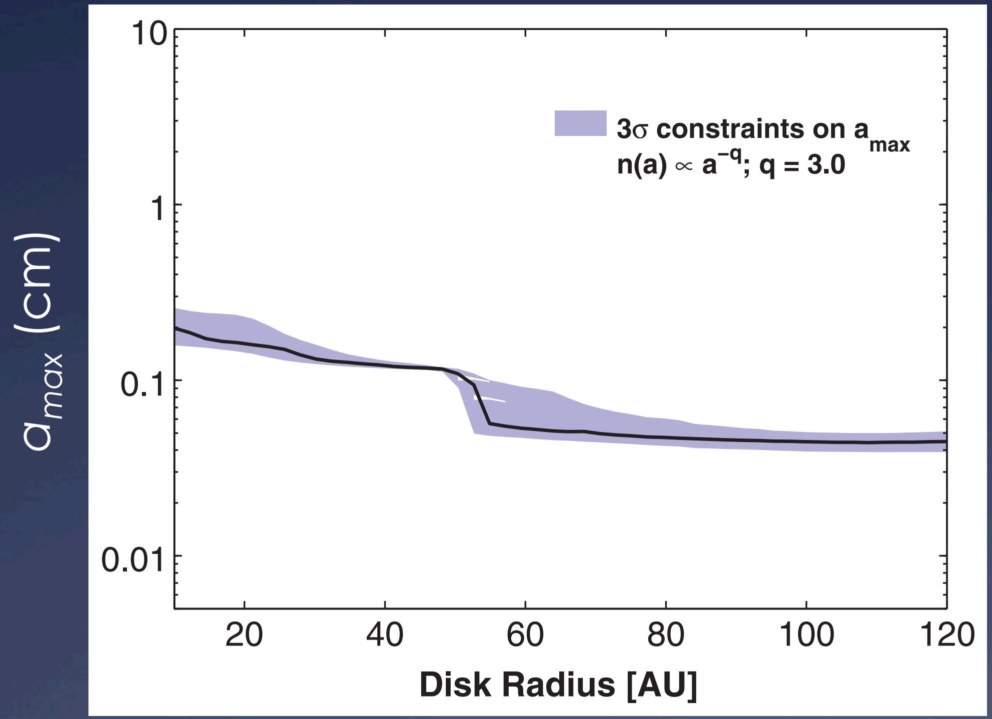
Miyake & Nakagawa (1993)



κ as function of ν for various values of a_{max} (Pérez et al. 2012)

a_{max} vs. radius for AS209

- Find a_{max} that reproduces multi-wavelength emission, $F_\nu \sim \kappa(\nu) M_d B_\nu(T_d) d^{-2}$

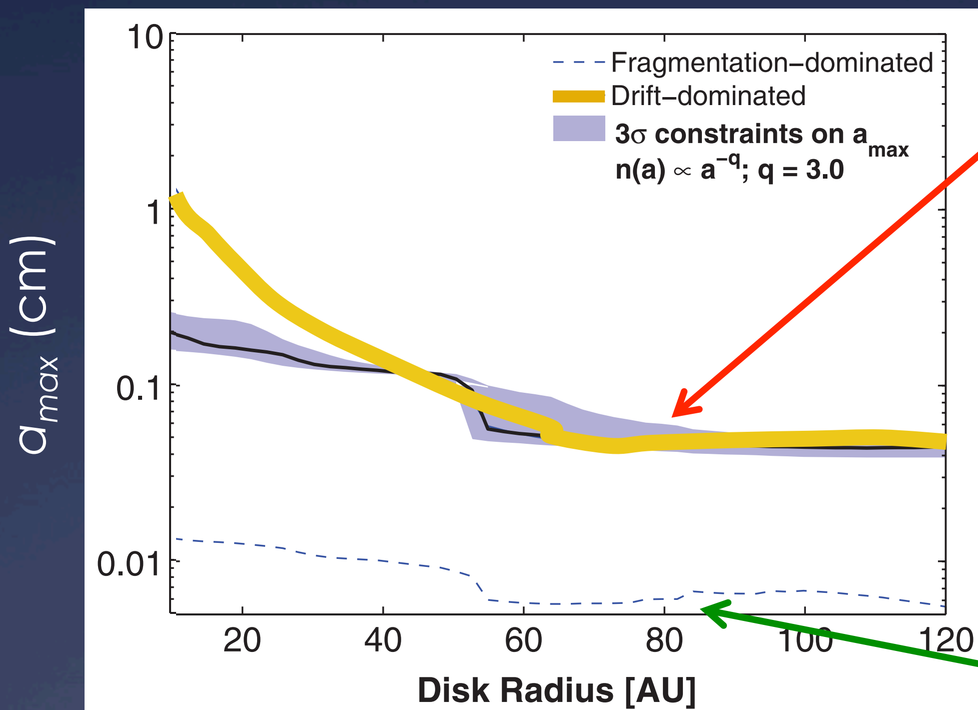


Pérez et al. (2012)

What about the barriers to grain growth?

- **Physical barriers to grain growth: fragmentation and radial drift (Birnstiel et al. 2012)**

$$a_{drift} \propto \Sigma_{dust} \frac{v_{Kep}^2}{c_s^2}$$

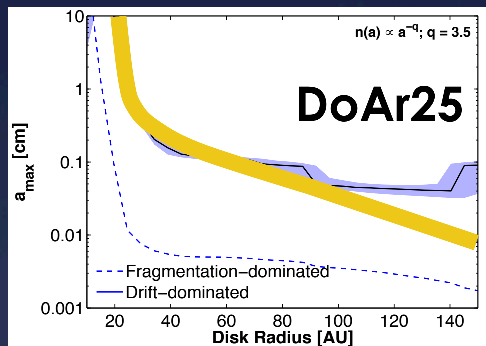


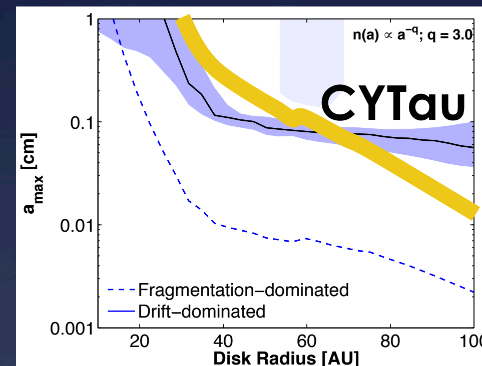
$$a_{frag} \propto \frac{\Sigma_{gas}}{\alpha_t} \frac{u_{frag}^2}{c_s^2}$$

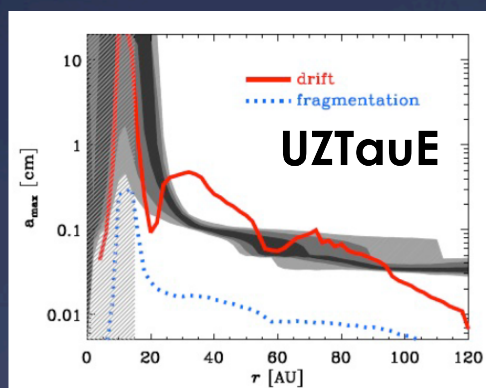
Pérez et al. (2012)

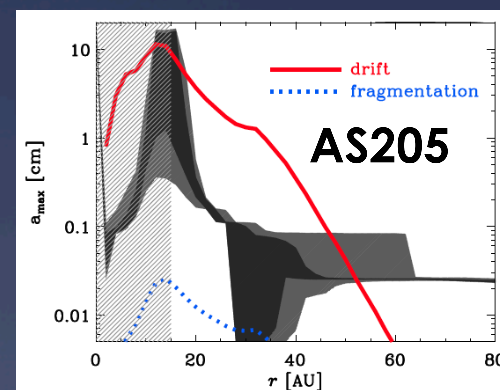
(α=0.01)

Results for other sources







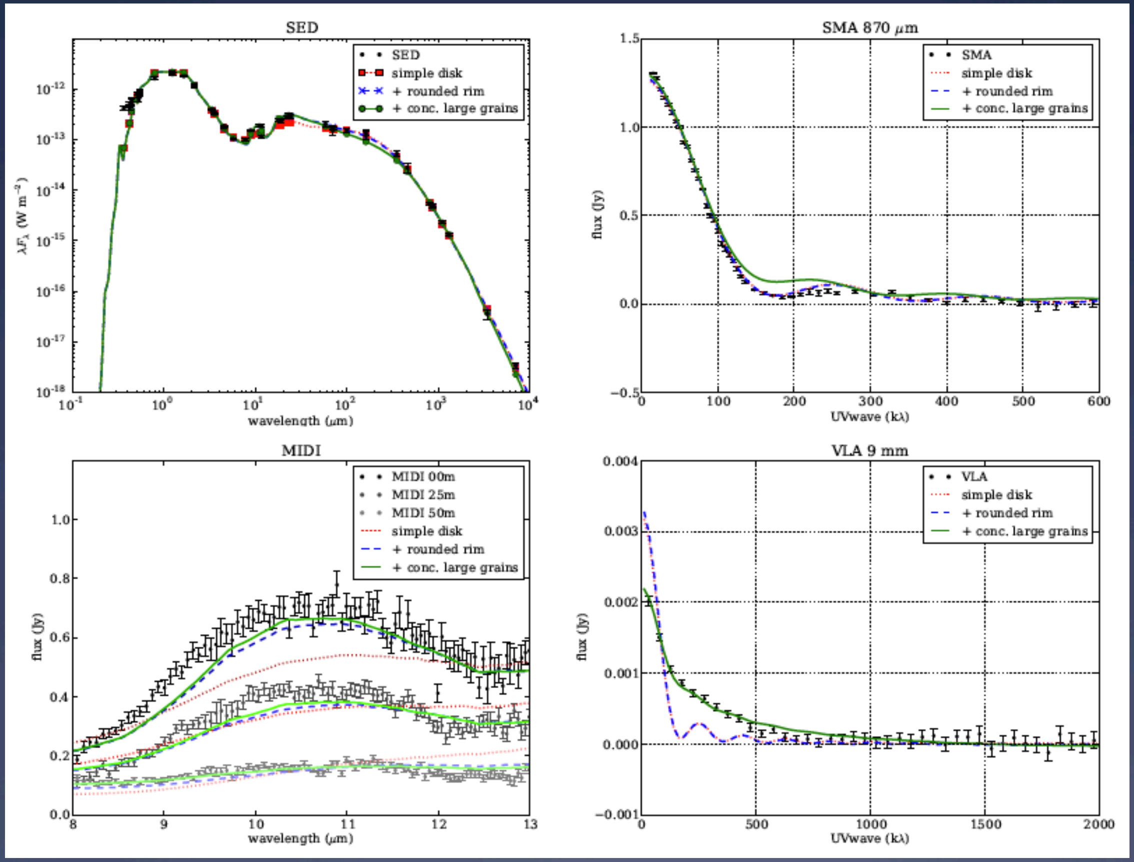


- All have a_{max} larger than can be explained by fragmentation-dominated particle sizes for "standard" viscosity parameter α=0.01, but instead are consistent with a_{max} limited by drift

  $\Rightarrow$ disks are not very turbulent (tentative conclusion!)

TWHydra

* Similar conclusion for the transition disk around TW Hya (Menu et al. 2013, submitted): a concentration of large grains in the center of the disk is needed to explain the submm/mm/cm data



Conclusions

* Evidence for growth to cm-sized particles in inner regions of protoplanetary disks from detailed modeling of 6 sources
* Max. particle size consistent with drift-dominated size distribution, suggests low turbulence (otherwise a_{max} would be lower due to collisional fragmentation)
* Full sample comprises 40 sources with resolved cm emission that will be used to study dust properties vs. stellar properties (multiplicity, spectral type, SF environment, …)
  * So far, dust properties of disks in multiple systems same as single systems
* The VLA is a powerful tool for studying grain growth and the formation of planetesimals; highly complementary to ALMA