Observational Constraints on the Process of Grain Growth and Evolution

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Observational Constraints on the Process of Grain Growth and Evolution *(inside protoplanetary disks)*

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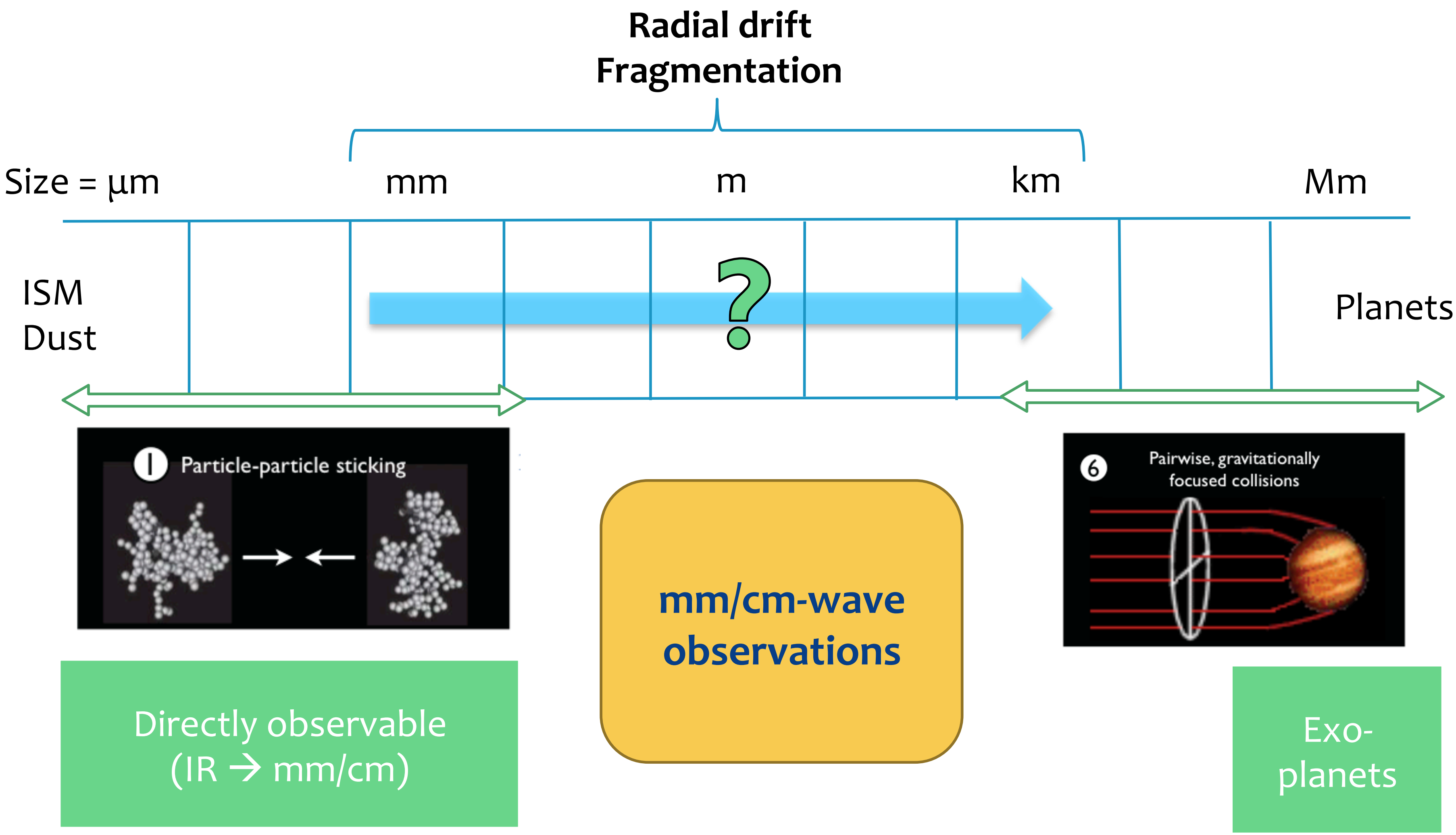
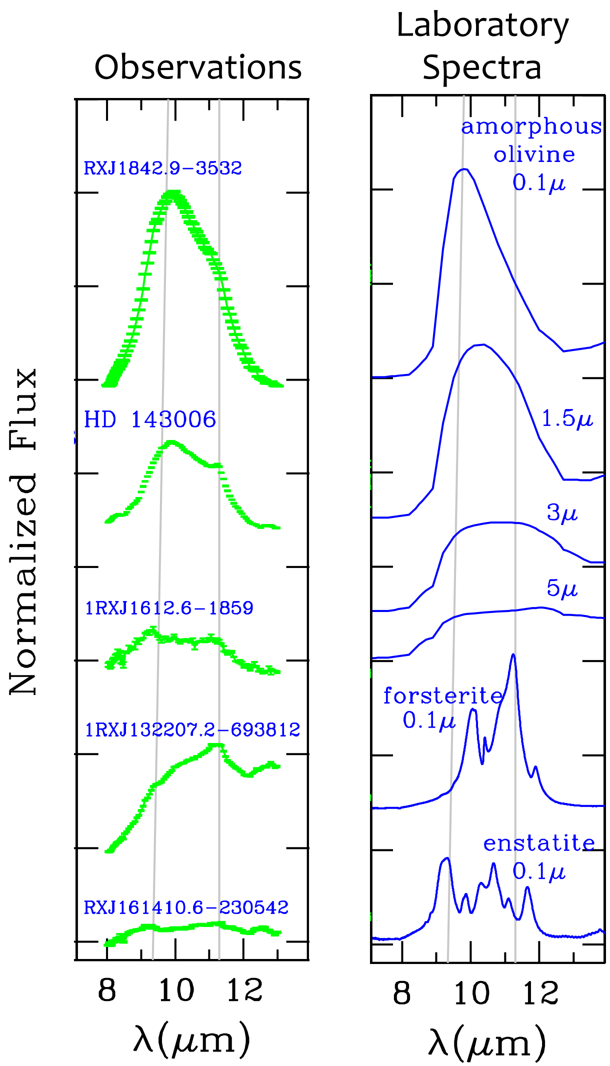
From ISM Dust to Planetary Systems



Adapted from Chiang & Youdin (2009)

Growth to μm-sizes: IR evidence

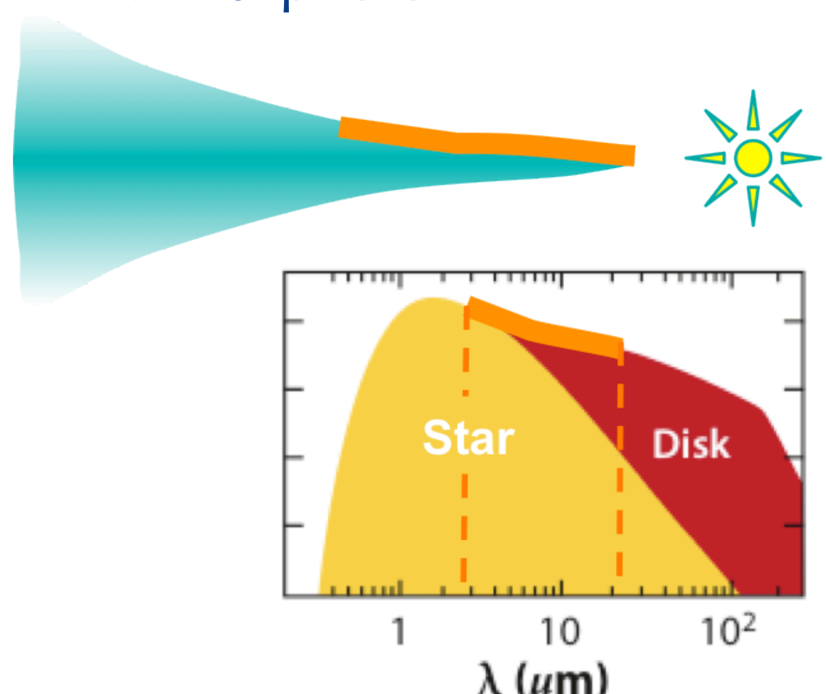


Natta et al. (2007)

- From IR spectroscopy of disks
  - e.g. 10 μm silicate feature

McClure's and Oliviera's talks

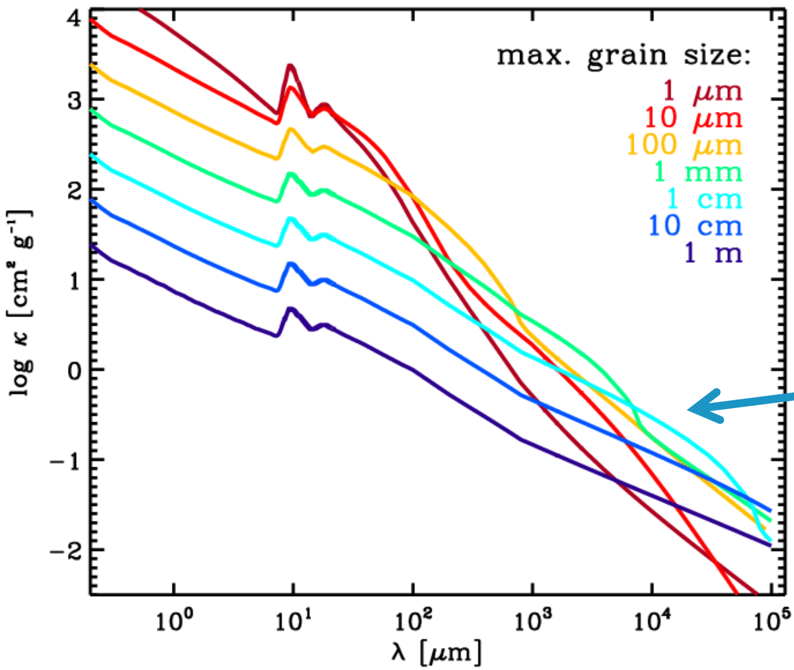
- However: IR emission traces warm disk "atmosphere"



Long-wavelength emission traces bulk of disk

- (Generally) optically thin
  - traces disk mass:

$$F_\nu \approx \kappa(\nu) M_d B_\nu(T_d) d^{-2}$$



- For long wavelengths/warm temperatures:
  - Rayleigh-Jeans limit (hν<< kT)

$$F_\nu \approx \frac{2k}{c^2} \nu^2 \kappa(\nu) \frac{M_d T_d}{d^2}$$

- At mm/cm wavelengths:
  - Dust opacity spectrum

$$\kappa(\nu) \propto \nu^\beta$$

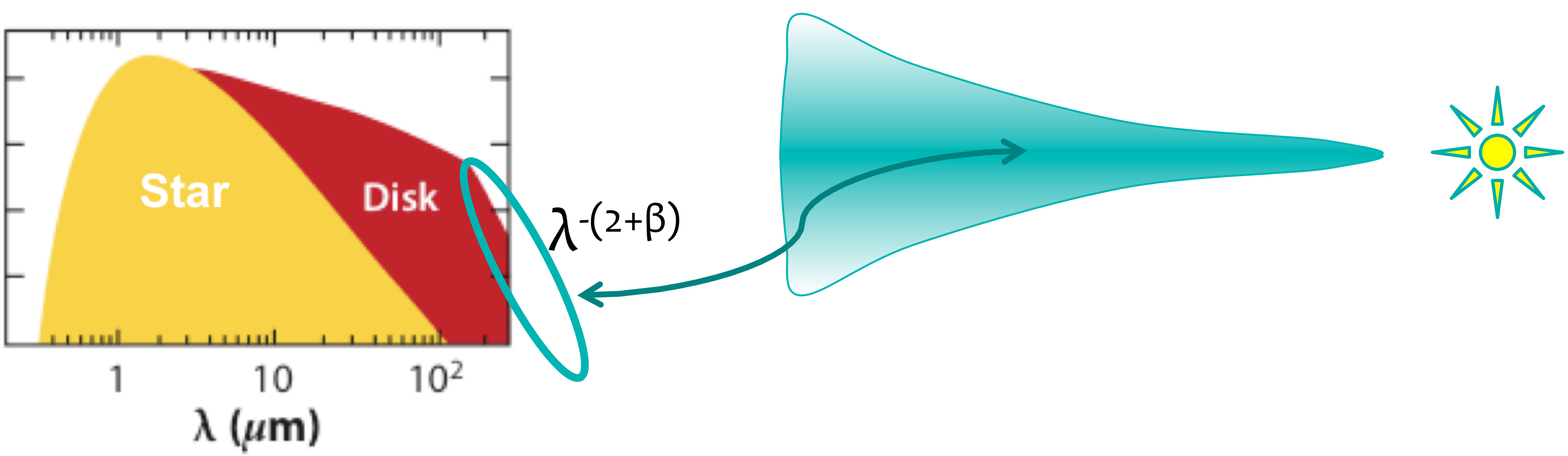
  - Dust emission spectrum is also a power law!

$$F_\nu \propto \nu^\alpha, \text{with } \alpha = 2 + \beta$$

Multiwavelength observations determine β

- Even if **absolute** opacity / temperature cannot be determined
- Multiwavelength observations in the **optically thin regime** can determine dust opacity spectrum

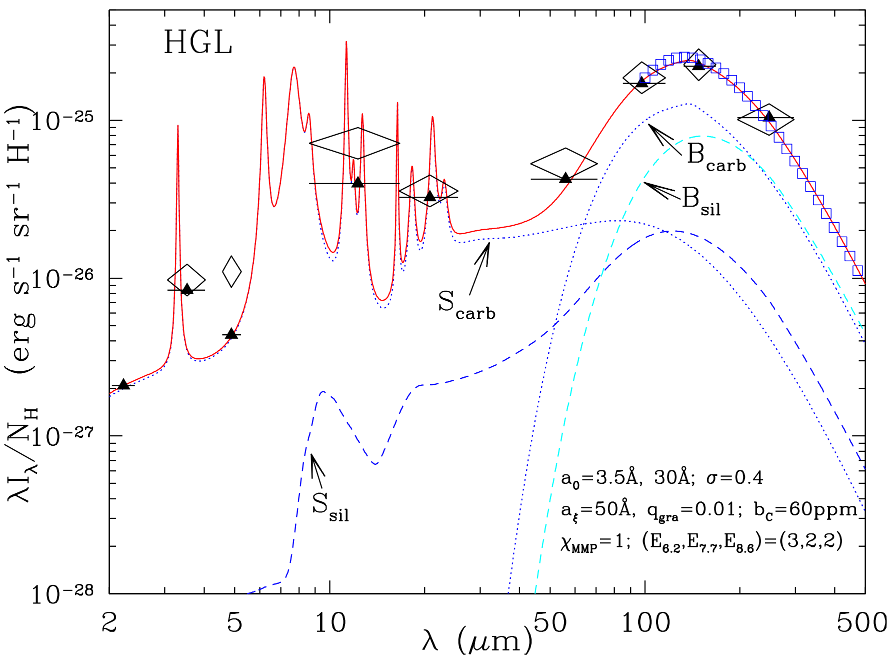
$$F_\nu \propto \nu^\alpha, \text{with } \alpha = 2 + \beta \quad \Rightarrow \quad \beta = \frac{\log_{10}(S_{\nu_1}/S_{\nu_2})}{\log_{10}(\nu_1/\nu_2)} - 2$$



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

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

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



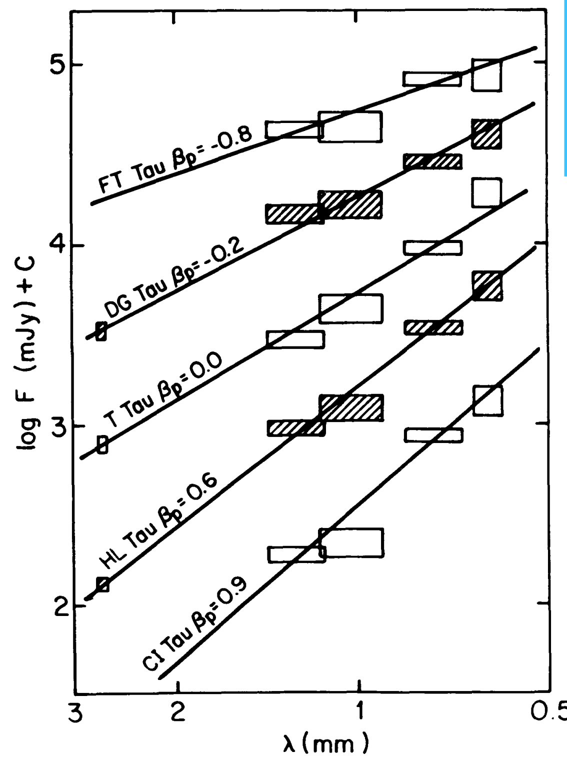
e.g., Li & Draine (2001)

- However, disks show flatter spectral index:

$2 < \alpha_{disks} < 3$

$\beta_{disks} < 1$

(Optically thin emission)



e.g. Beckwith & Sargent (1991)

What could make $\beta \neq \beta_{ISM}$? (and $\beta < 1$)

Grain Properties

- Dust composition very different from ISM
  - **Draine et al. (2006)** evaluated candidate materials: changes in composition cannot account for low β
- Or dust grains have a very "fluffy" grain structure
  - **Natta et al. (2004)** showed $\beta < 1$ for large fluffy grains: a_{max}>10cm

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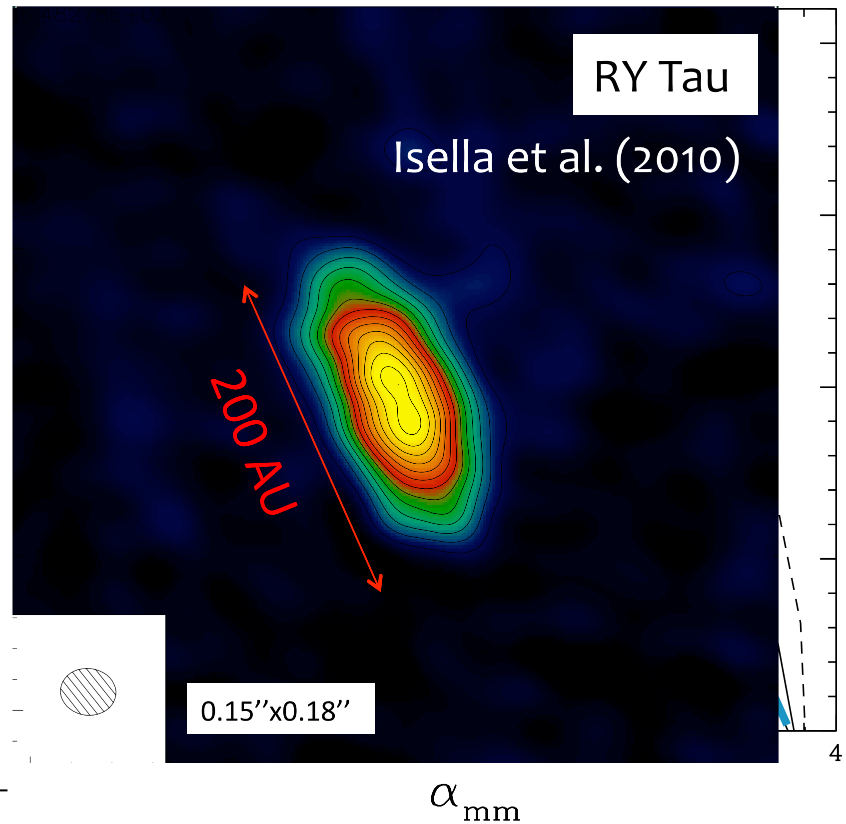
Emission Properties

- Dust emission in disks is optically thick



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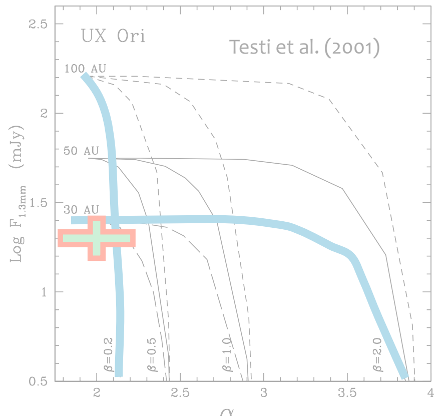
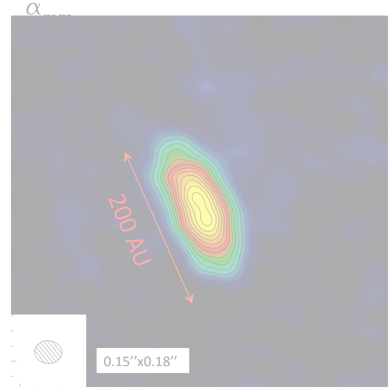
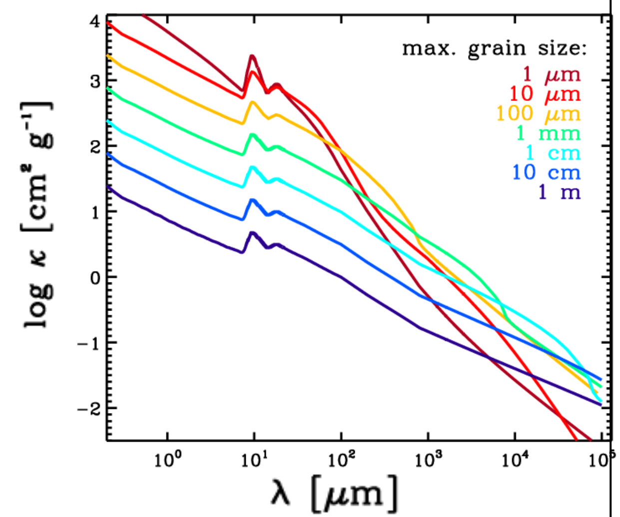




Isella et al. (2010)

Grain Growth

- Grains in disk are larger than ISM
- As grains grow:
  - their opacity ↓
  - opacity spectrum gets shallow, making β small



Observations at mm/cm wavelengths → growth

OVRO/CARMA

Beckwith & Sargent (1990, 1991)
Mannings & Sargent (1997,2000)
Ricci et al. (2011a, 2012)

JCMT/SMA

Mannings & Emerson (1994)
Andrews & Williams (2005, 2007)
Lommen et al. (2007)
Ricci et al. (2011b)

VLA

Wilner et al. (2000)
Calvet et al. (2002)
Testi et al. (2001,2003)
Natta et al. (2004)
Wilner et al. (2005)
Rodmann et al. (2006)
Ricci et al. (2011b)

PdBI/IRAM

Dutrey et al. (1996)
Natta et al. (2004)
Schaefer et a (2009)
Ricci et al. (2

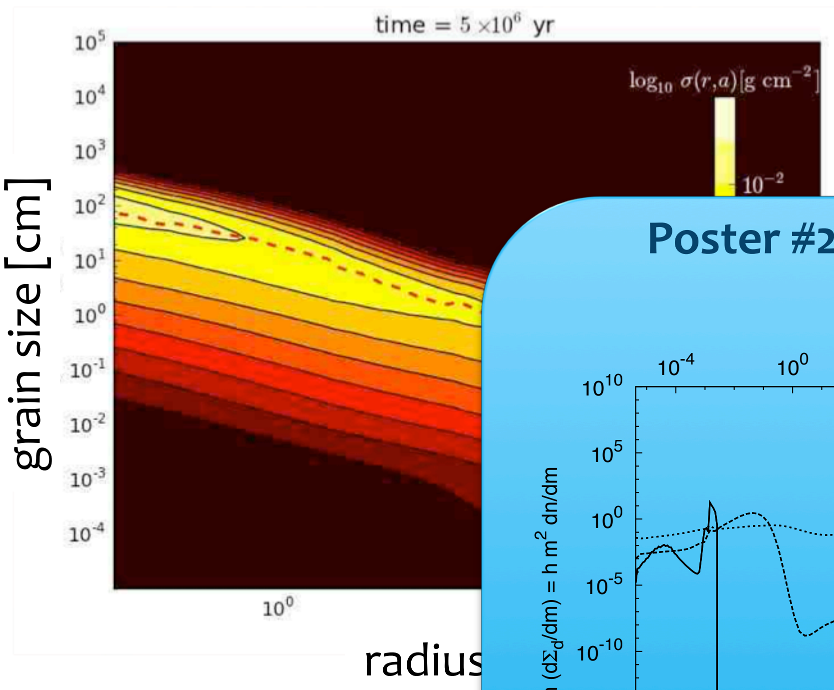
ATCA

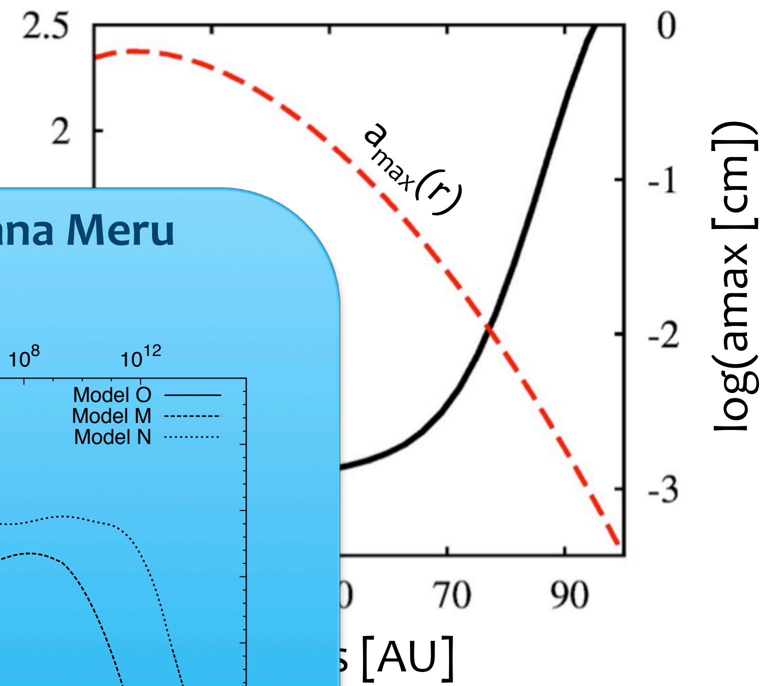
Poster #46
(C. Wright)
for HD 100546
- 3mm to 6cm SED
- Temporal monitoring

These observations infer small β's
Growth from ISM sizes (μm) to pebble sizes (cm)

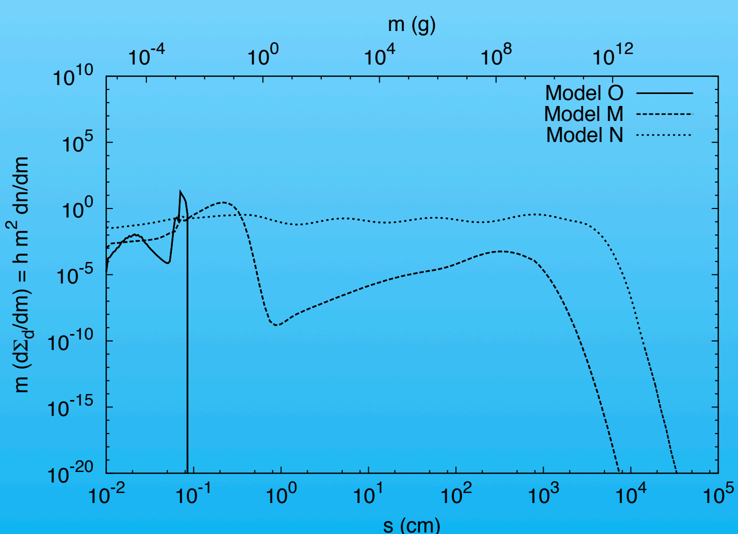
Grain growth vary with radius

- T. Birnstiel's talk:
- Observational signature in β(r)

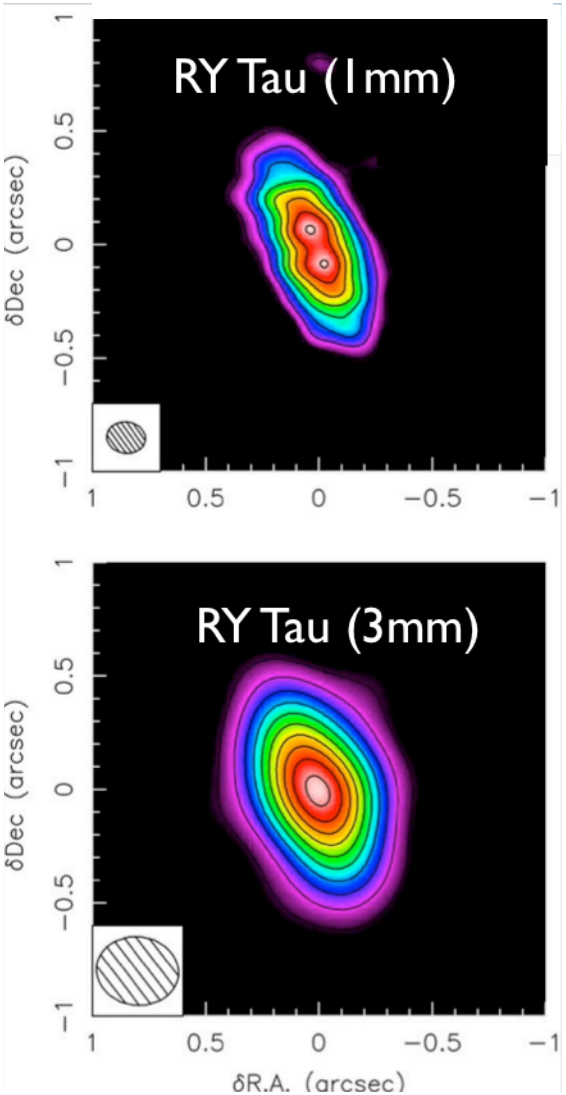




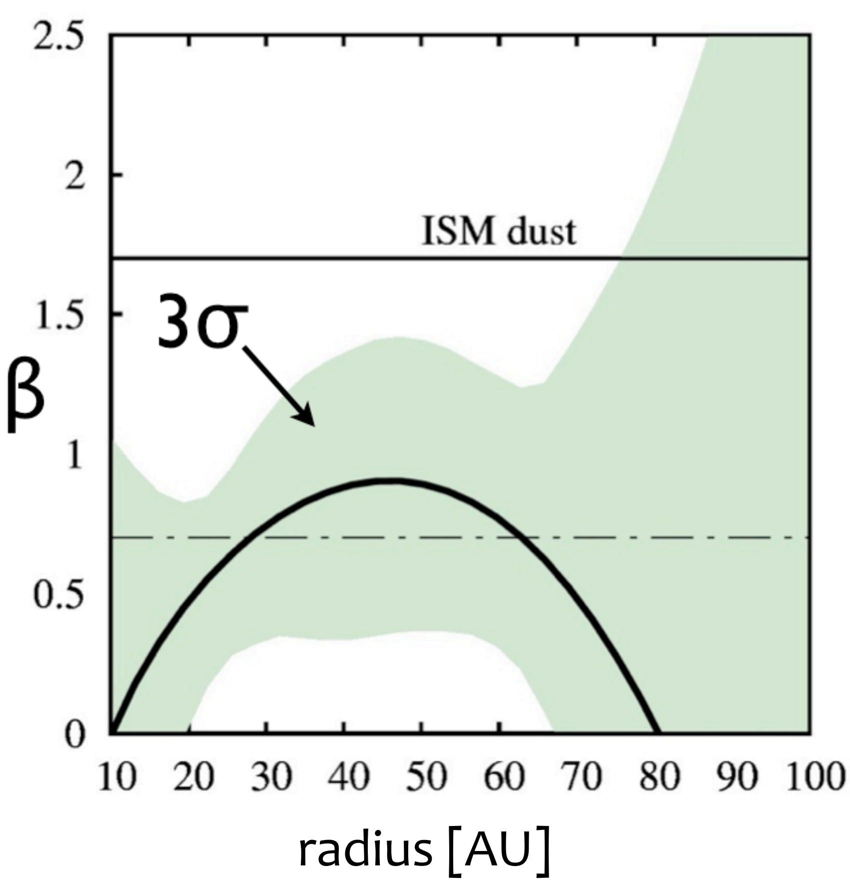
Poster #26 - Farzana Meru



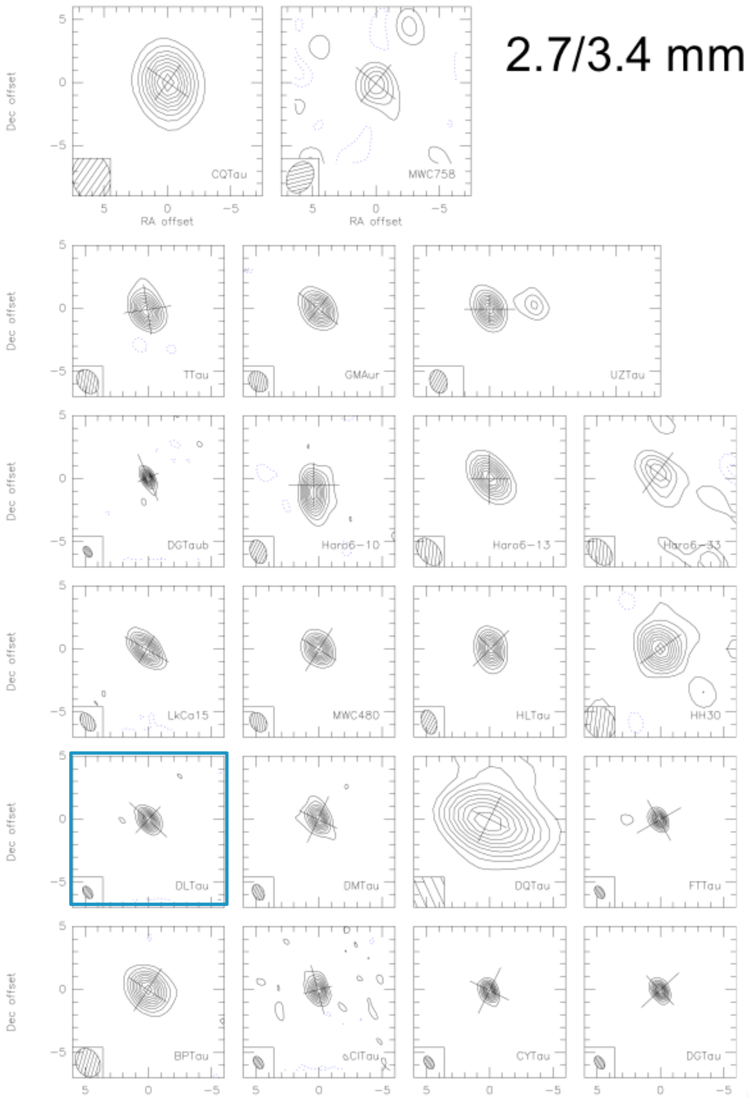
Radial variations of grain growth



- **Isella et al. (2010):** two disks observed with CARMA in 1 and 3 mm bands

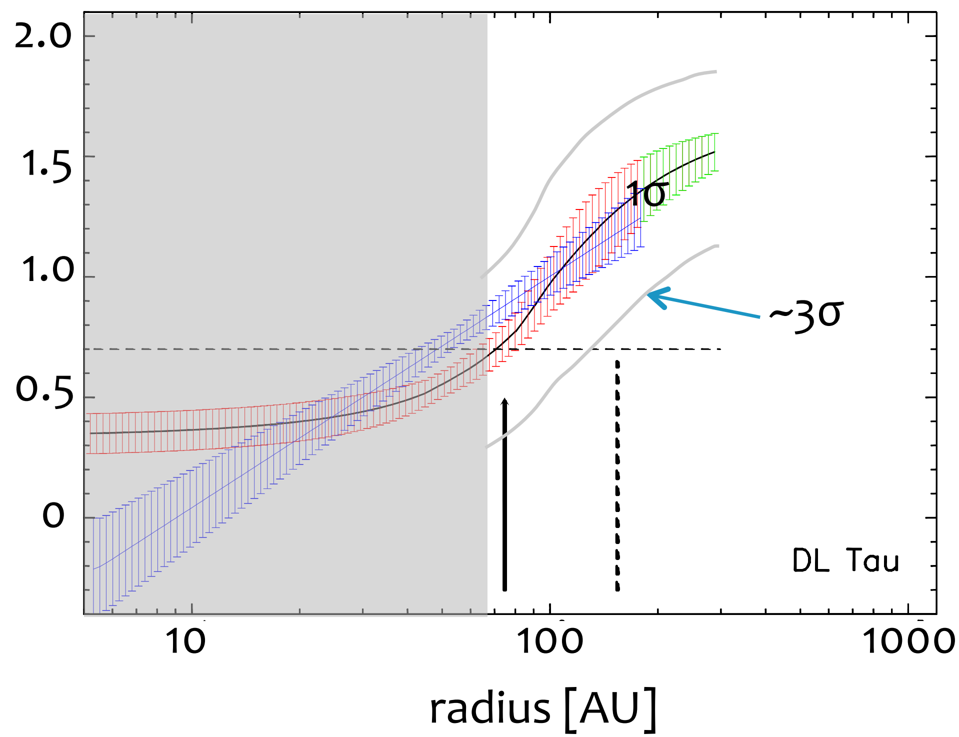


Radial variations of grain growth



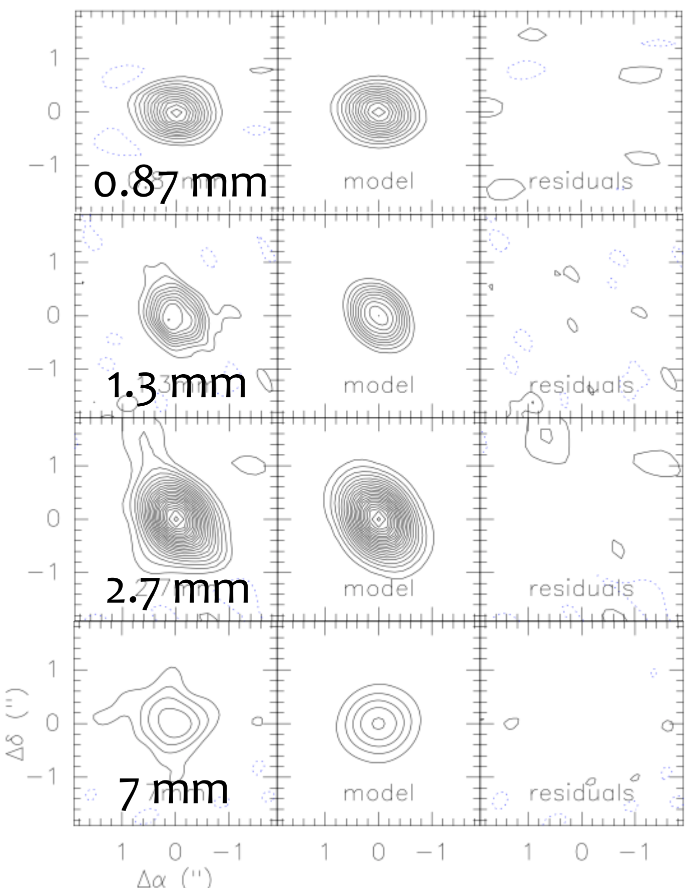
2.7/3.4 mm

- **Guilloteau et al. (2011):** Taurus survey with PdBI, also dual-wavelength obs.



Improve constraints on β(R) by…

- Increase wavelength coverage



CQ Tau
Banzatti et al. (2011)

$$\beta = \frac{\log_{10}(S_{\nu_1}/S_{\nu_2})}{\log_{10}(\nu_1/\nu_2)} - 2$$

"crude" error estimate

$$\Delta\beta = \frac{1}{\log_{10}(\nu_1/\nu_2)\ln 10}\left[\frac{1}{(\mathrm{SNR}_{\nu_1})^2} + \frac{1}{(\mathrm{SNR}_{\nu_2})^2}\right]^{0.5}$$

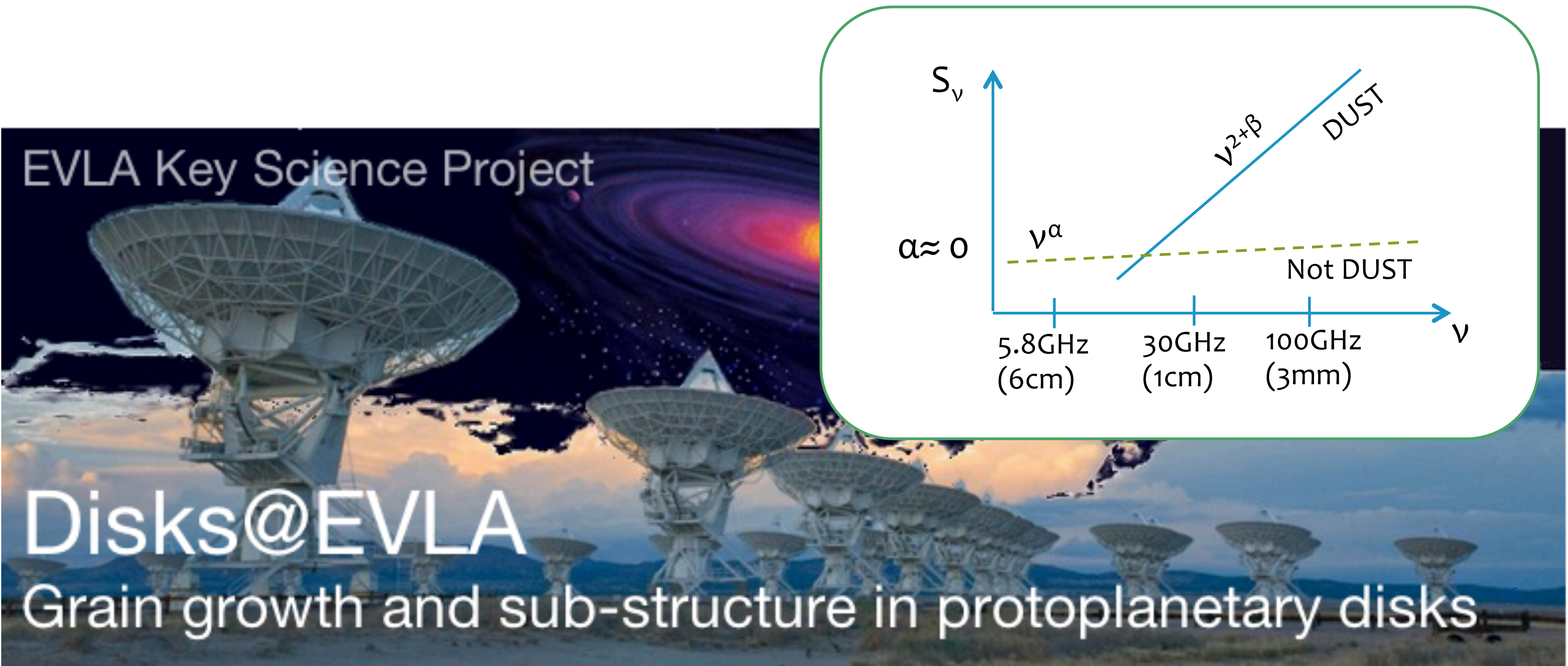
Increase sensitivity of observations

… particularly at long wavelengths

Disks@EVLA collaboration

PI: Claire Chandler

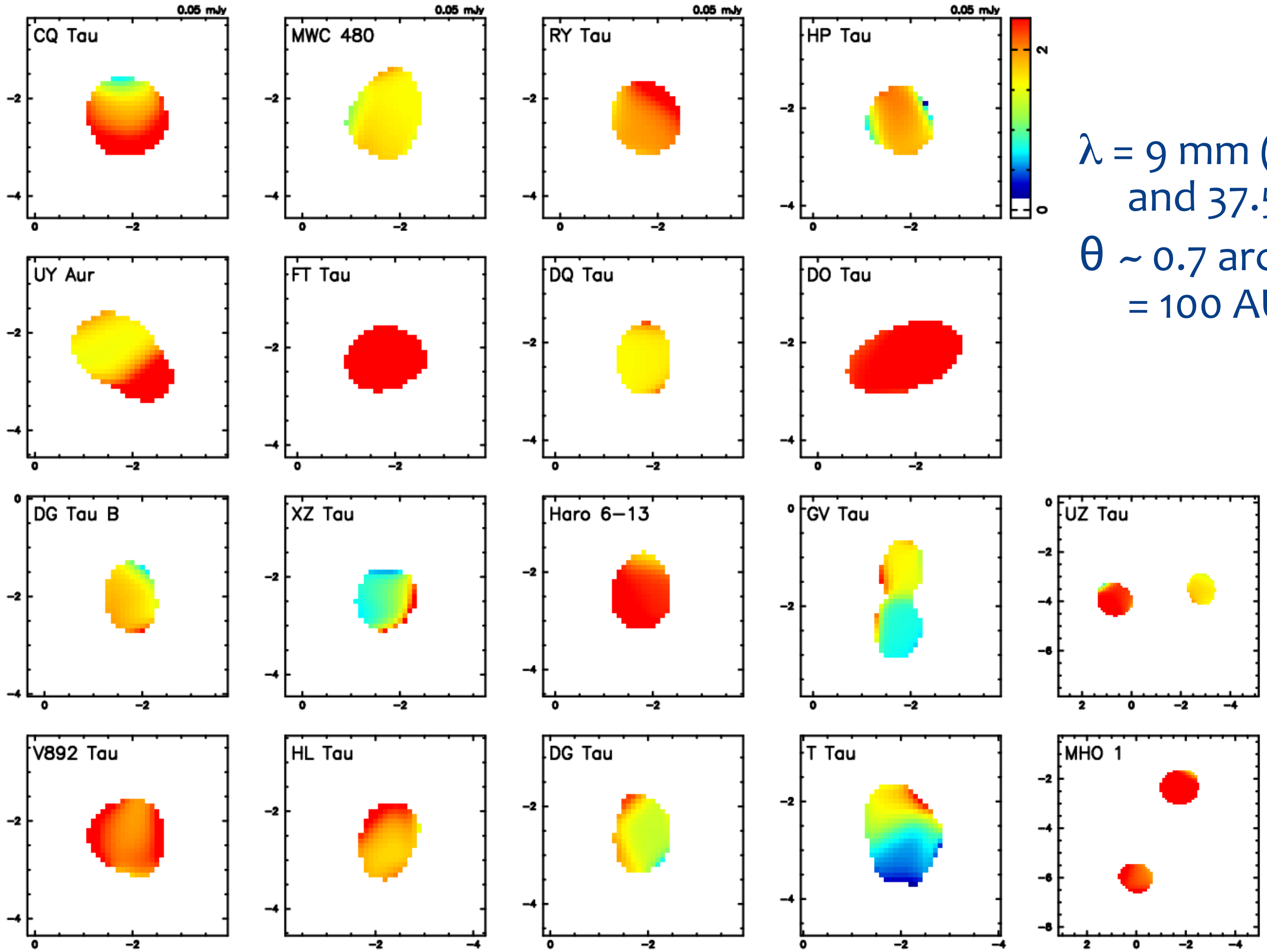
- Determine prevalence of grain growth to cm-sized particles
  - 66 stars (ages ~ 1-10 Myr old)
  - Photometry (7mm-6cm) → β
- Determine location of large grains in disks
  - Sub-sample imaged with ~0.2" res. at 7mm/1cm and 6cm



Disks@EVLA collaboration

PI: Claire Chandler

Maps of spectral index α



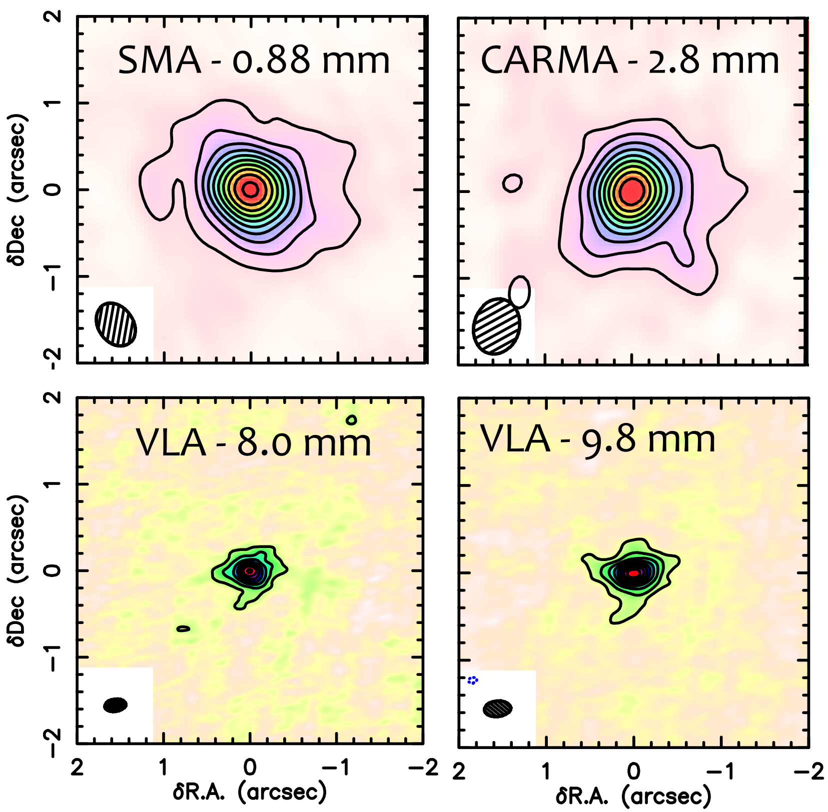
λ = 9 mm (30.5 and 37.5 GHz)

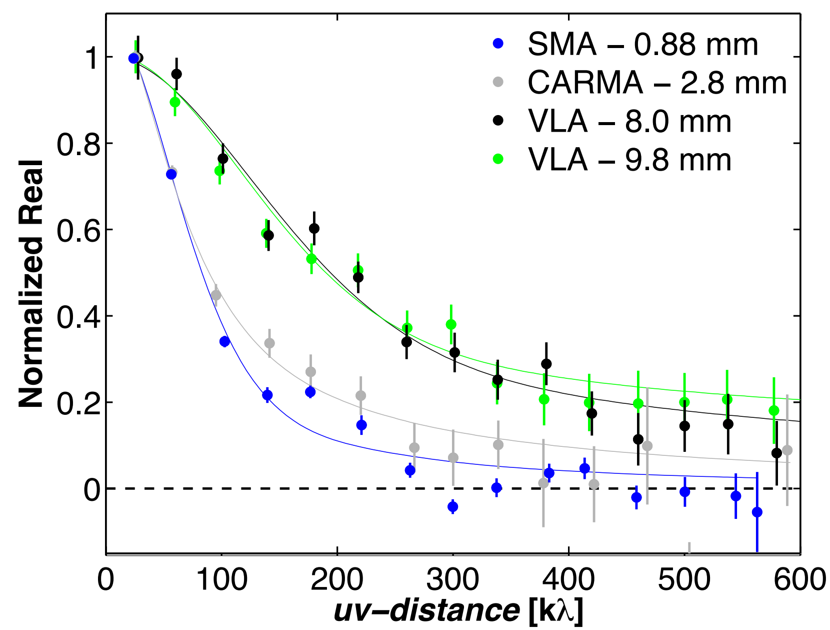
θ ~ 0.7 arcsec = 100 AU

Constraints in Radial Variations of Grain Growth

- Increased wavelength coverage and sensitivity of observations
- Allow us to infer wavelength-dependent disk structure

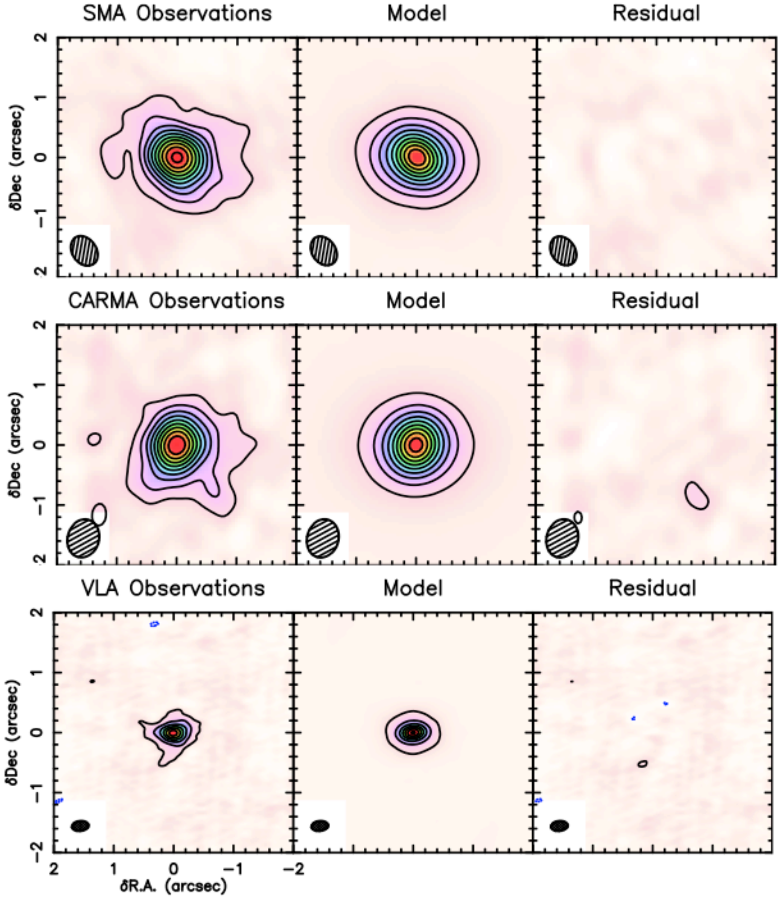
AS 209 disk; Pérez et al. (2012)



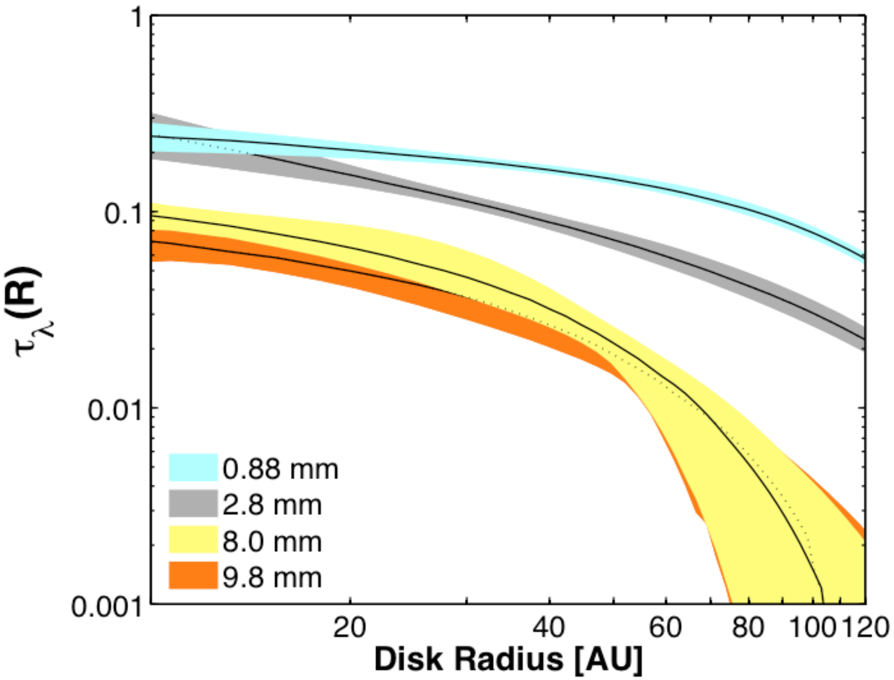


Constraints in Radial Variations of Grain Growth

- Simple disk model reproduces our observations

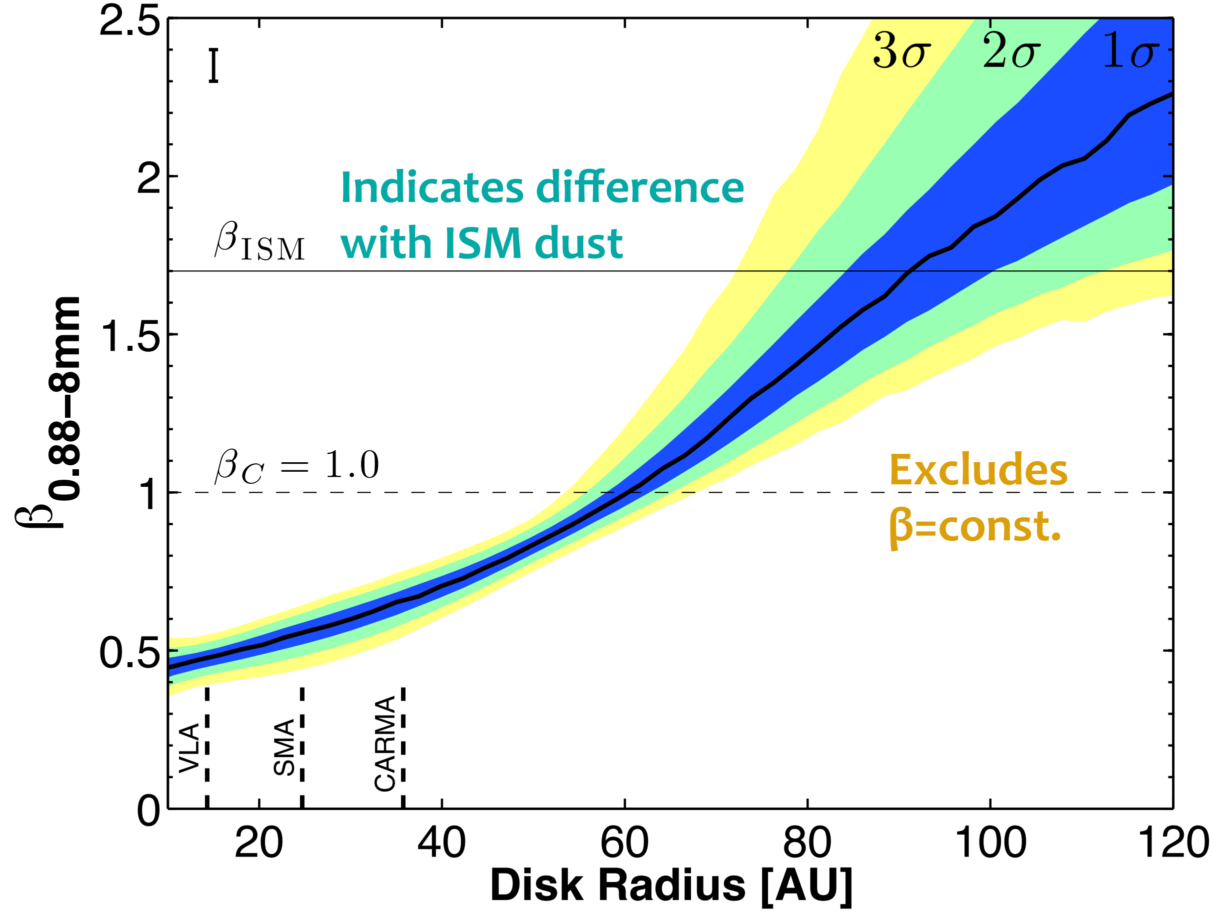


- Allow us to infer $\tau_\lambda(R) = \kappa_\lambda \times \Sigma(R)$



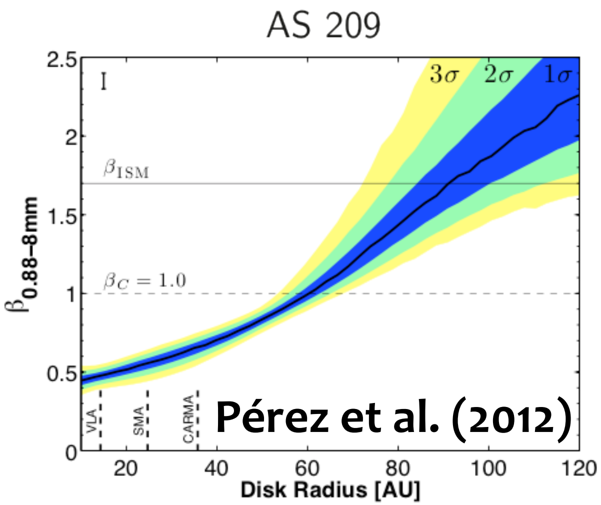
Wavelength-dependent disk structure

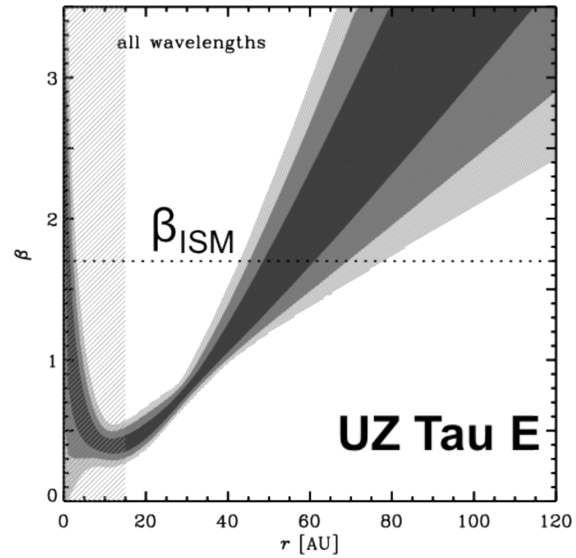
Constraints in Radial Variations of Grain Growth



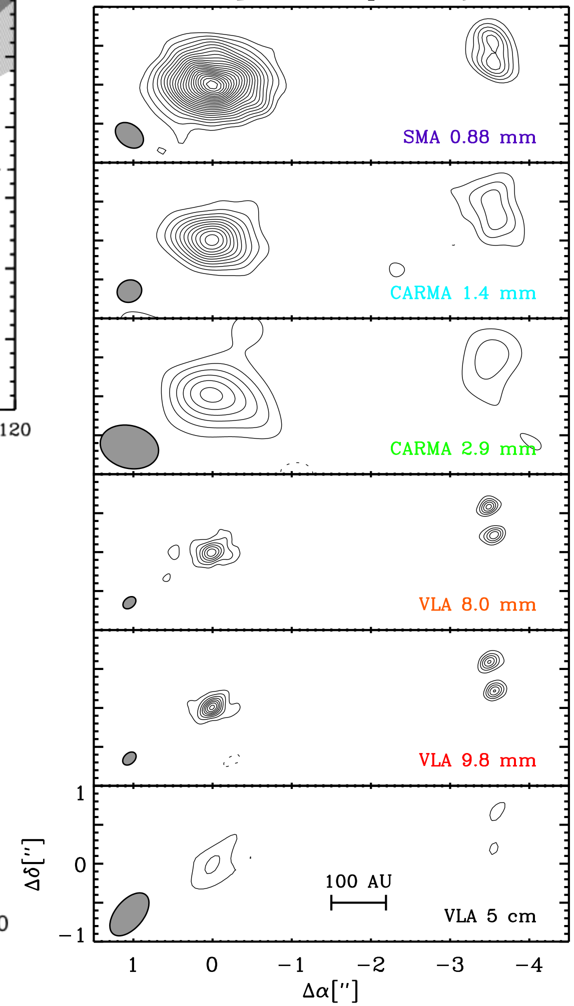
Pérez et al. (2012)

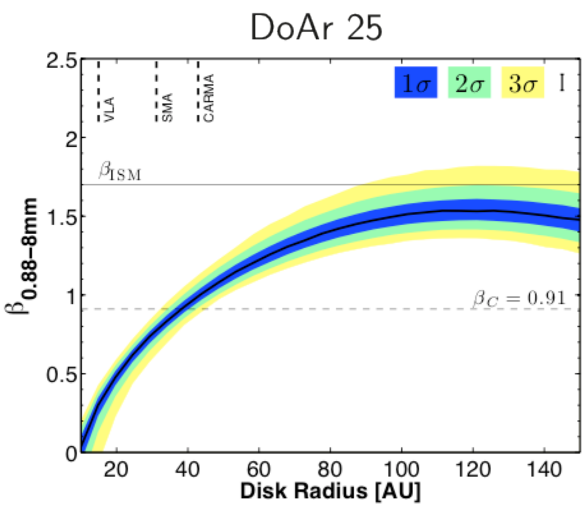
Similar constraints in many different disks

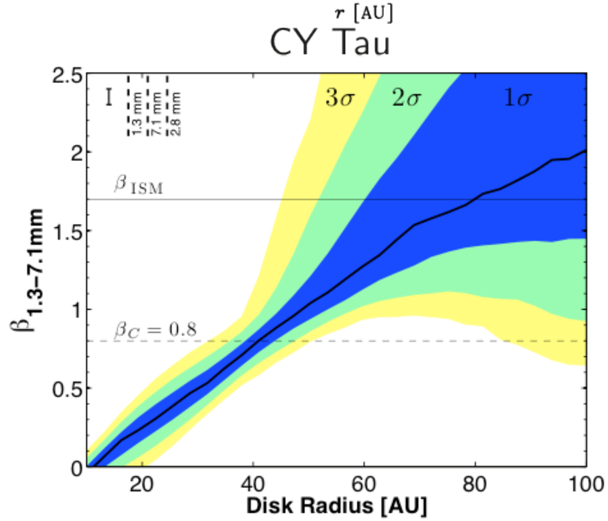




Harris et al. (subm.)
UZ Tau Quadruple system



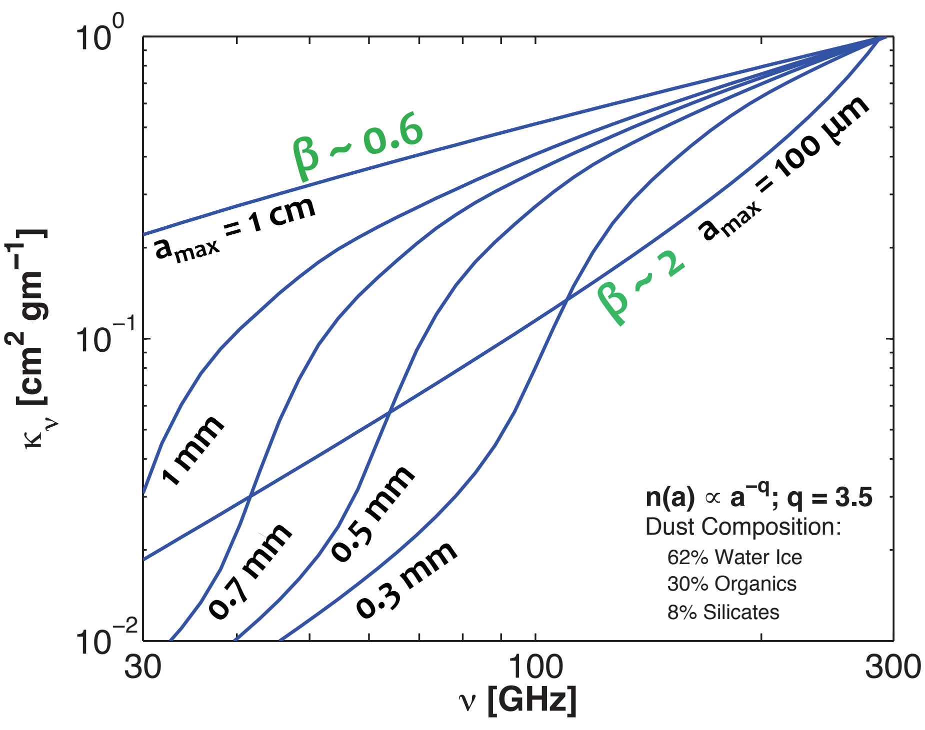




Pérez et al. (in prep.)

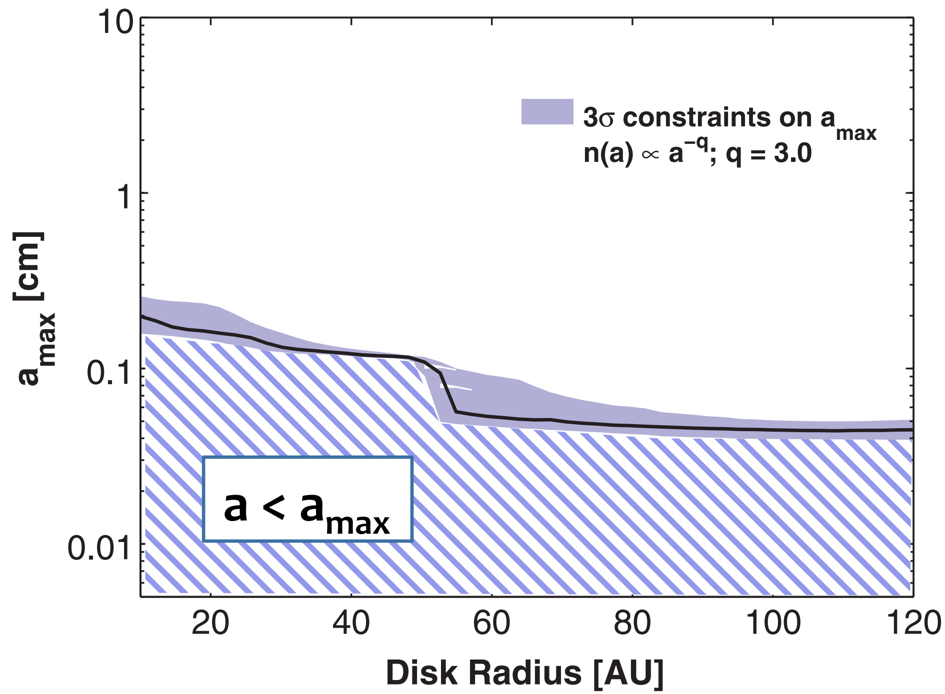
From radial variations of dust opacity to $a_{max}(R)$

- Dust opacity depends on particle-size distribution



- Find a_{max} that reproduces multi-wavelength emission:

$$F_\nu \approx \kappa(\nu) M_d B_\nu(T_d) d^{-2}$$



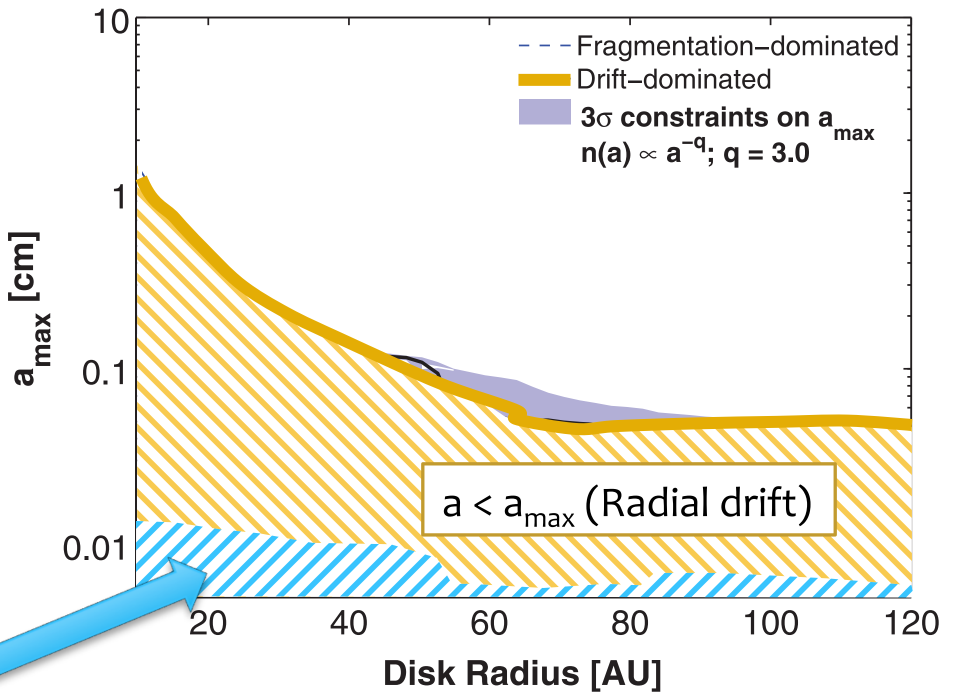
Pérez et al. (2012)

Limit to particle growth: radial drift of solids

- Compare with physical barriers to further growth: **(T. Birnstiel's talk)**

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

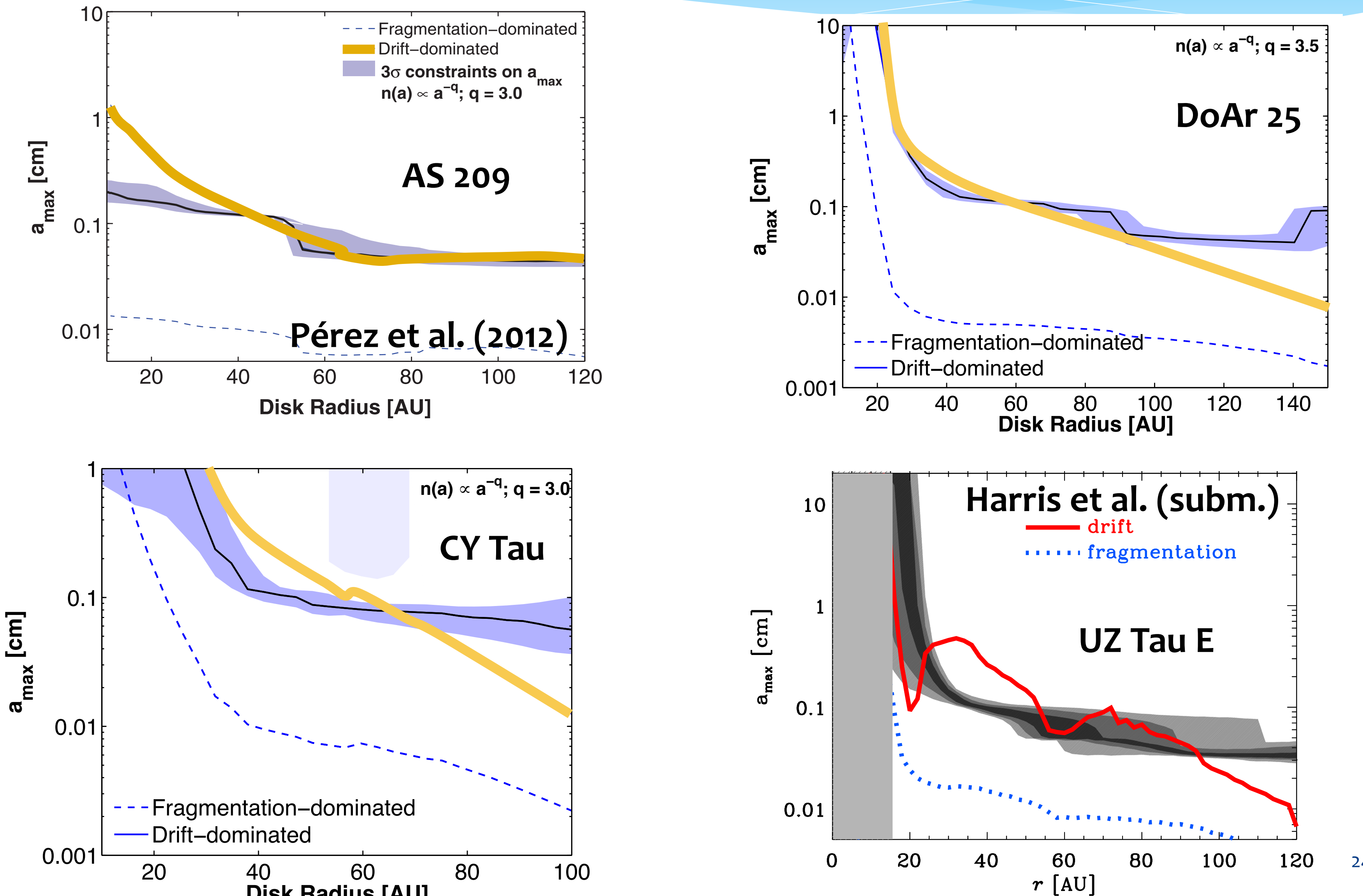
  - Radial drift $a_{drift} \propto \Sigma_{dust} \frac{v_{Kep}^2}{c_s^2}$



a < a_{max} (Fragmentation)

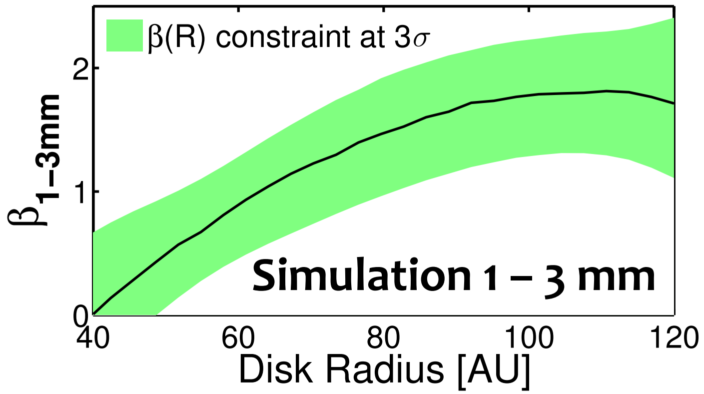
Pérez et al. (2012)

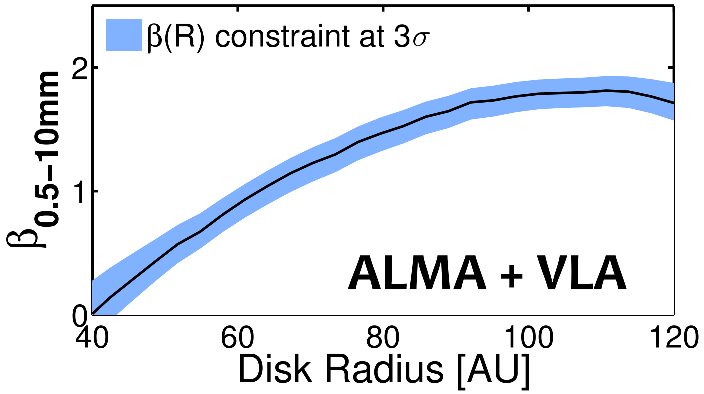
Similar constraints in many different disks



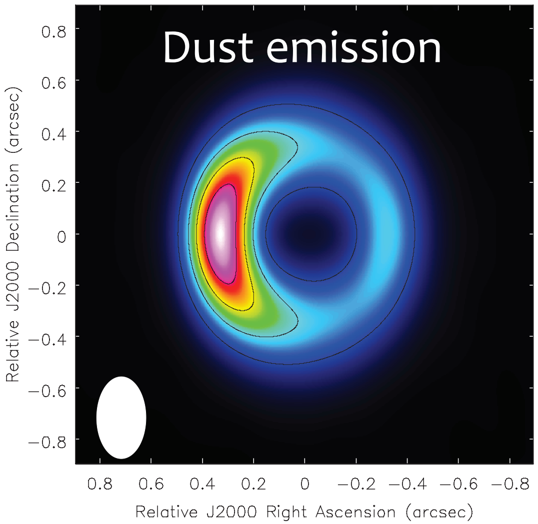
The future with ALMA and VLA

- Significant improvement in current constraints



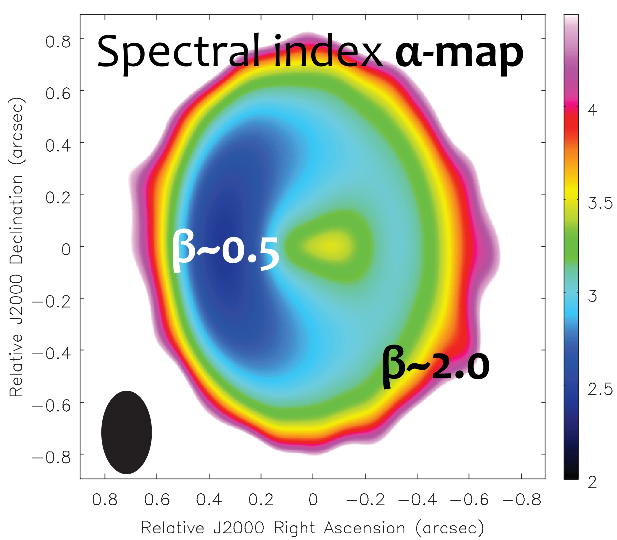


The future with ALMA and VLA



Azimuthal dust trapping

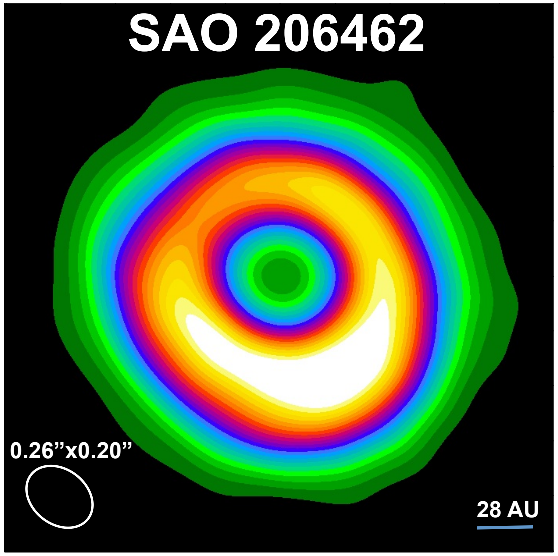
Birnstiel et al. (2013)



- Dust trapping mechanisms:
  - e.g. planet opening a gap
  - expect asymmetries
- Prediction: grain growth should occur within asymmetries
- Expect segregation of dust particle size: radially (Pinilla et al., 2012) and azimuthally (Birnstiel et al. 2013)
  - 2D constraints on β(R)

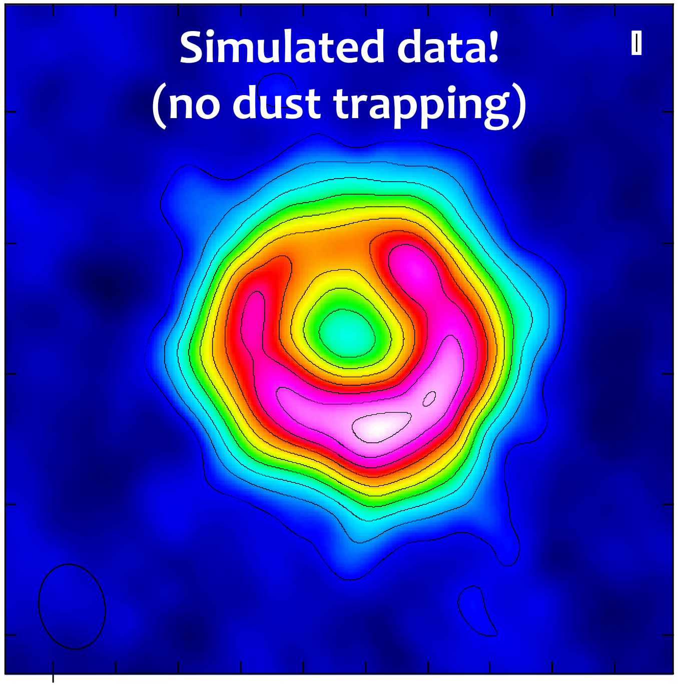
The future with ALMA and VLA

- **ALMA** observations at 0.45 mm



(see **A. Isella**’s talk)

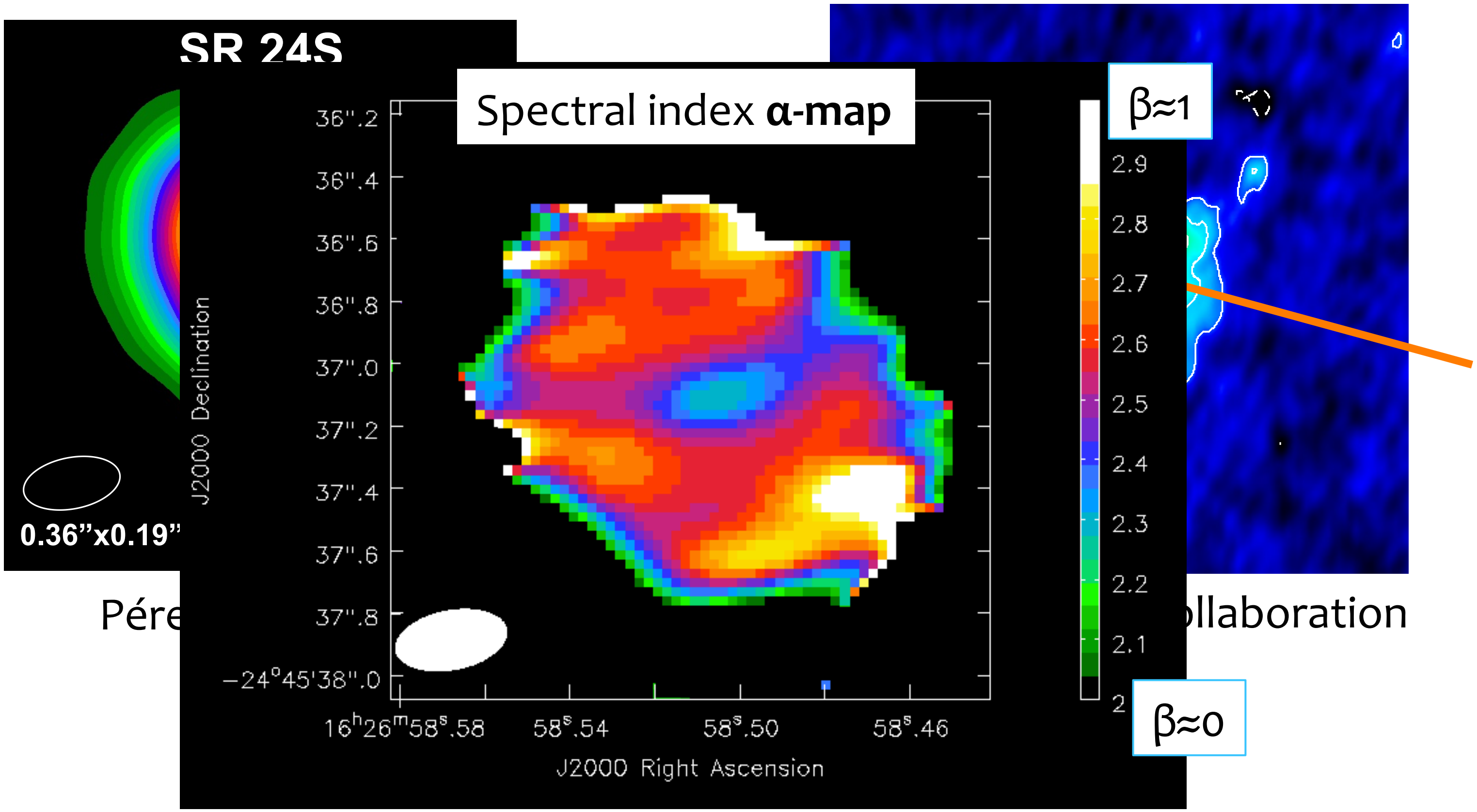
- Observational test of particle trapping with the **VLA**



  - 6hrs, CnB-config: 0.5”
  - 8 hrs, BnA-config: 0.2”

And the future is here!

- **ALMA** observations at 0.45 mm
- **VLA** observations at 9 mm



From ISM Dust to Planetary Systems

Radial drift
Fragmentation

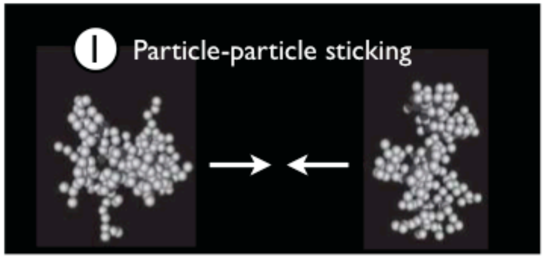
Size = µm | mm | m | km | Mm

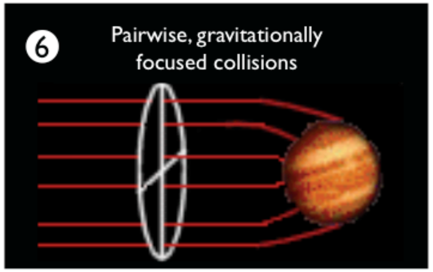
ISM Dust

mm/cm-wave observations

?

Planets





Directly observable (IR → mm/cm)

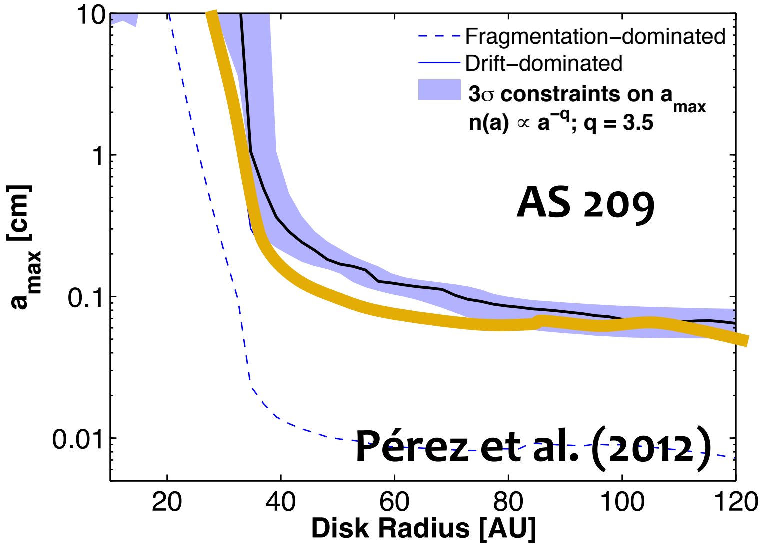
Exo-planets

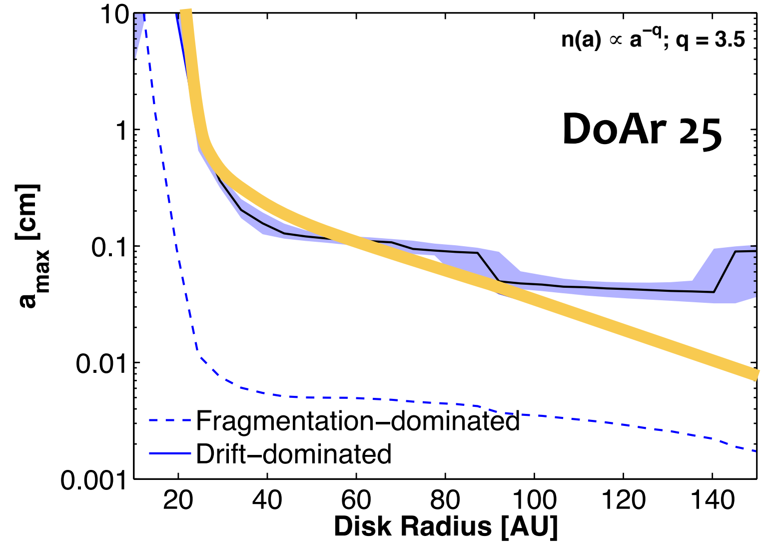
Adapted from Chiang & Youdin (2009)

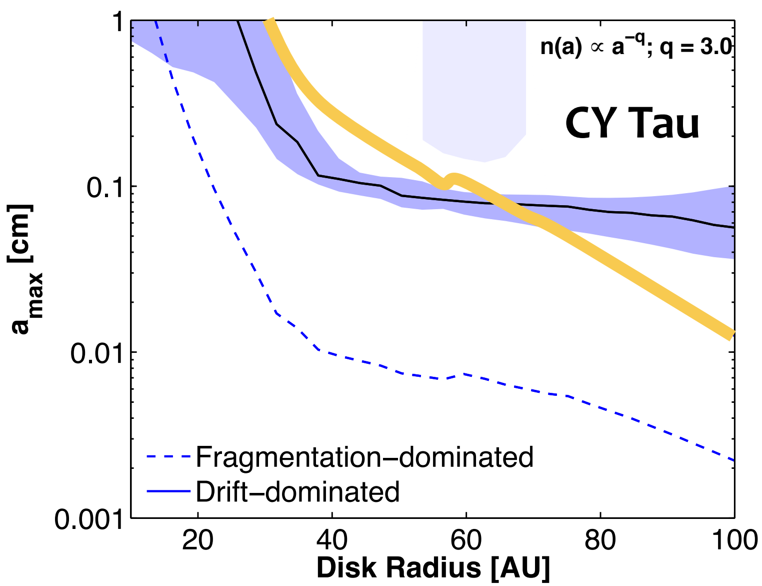
Summary

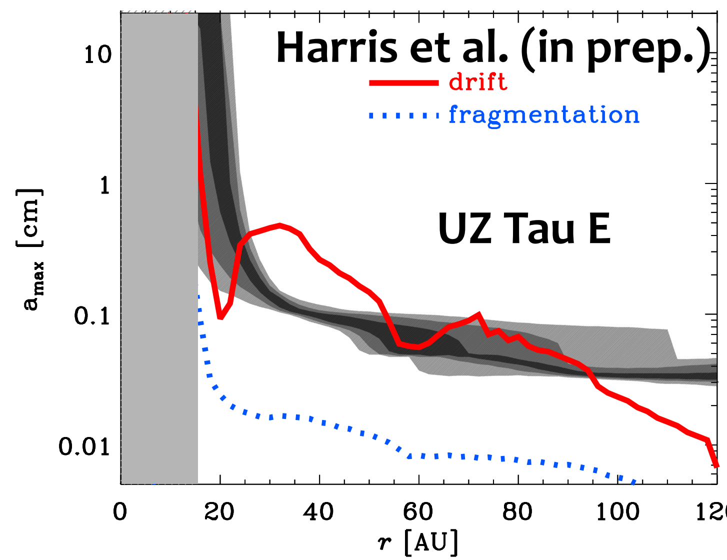
- Observational constraints of dust growth require multi-wavelength observations:
  - High angular resolution and high SNR
  - Future with new instruments like ALMA and VLA looks **rock solid!**
- Protoplanetary disks (generally) have $\beta < 1$ at mm/cm wavelengths
  - Compelling evidence for **grain growth in disks**
- Spatially resolved observational constraints inform us:
  - Disentangle optical depth effects from grain growth
  - Main limitation for further particle growth → **radial drift of solids**
- A way to overcome this problem: **dust trapping** of large particles
  - Radially, azimuthally
- These predictions can be **currently tested** with ALMA and VLA

Similar constraints in many different disks

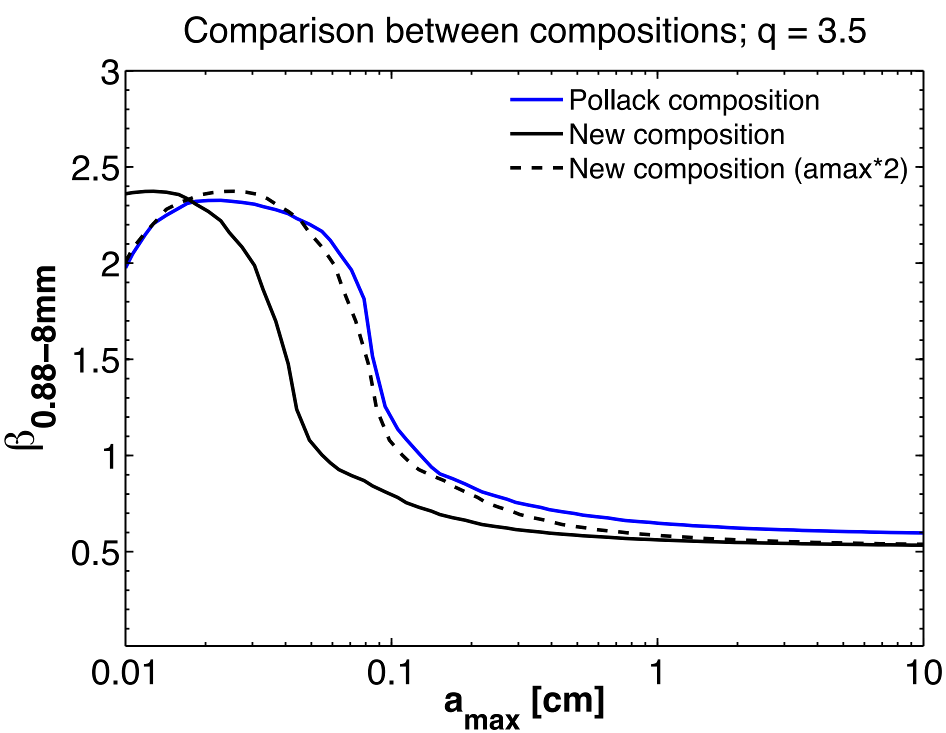


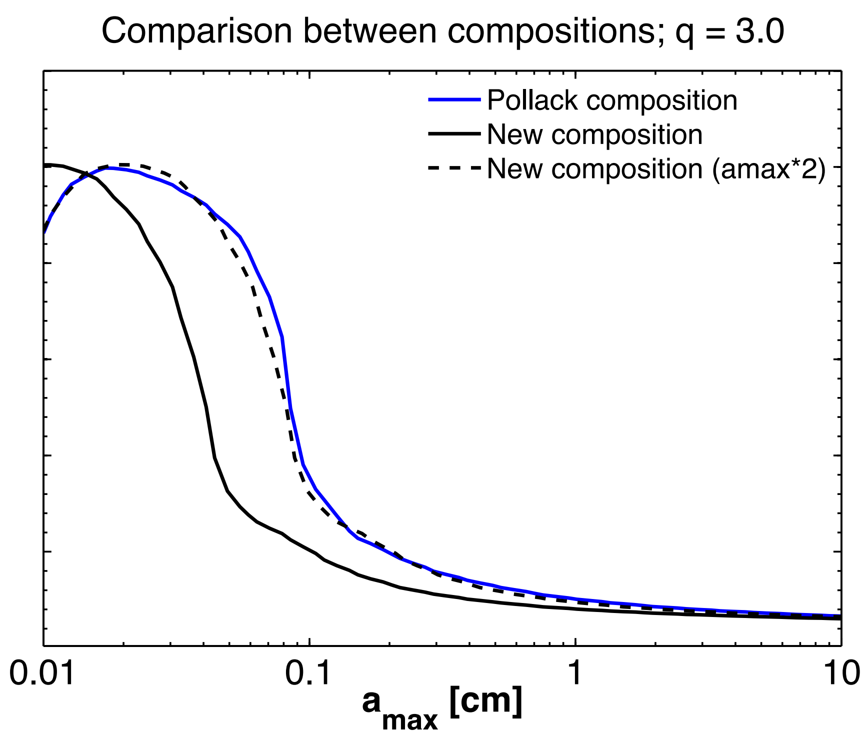






Different Compositions





Pérez et al. (2012)

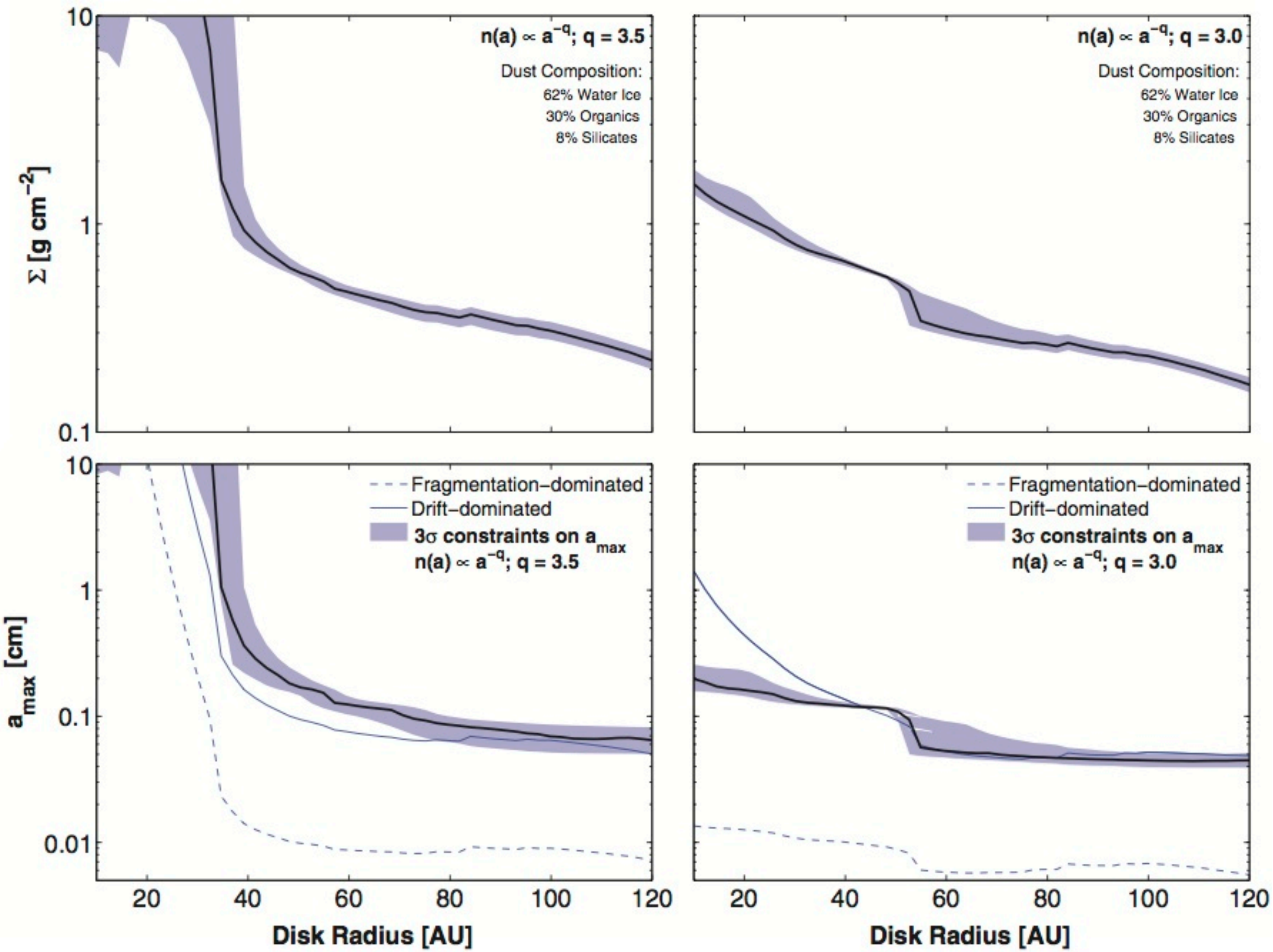
Pollack et al. (1994) composition:

8% silicates, 30% organics, 62% water ice

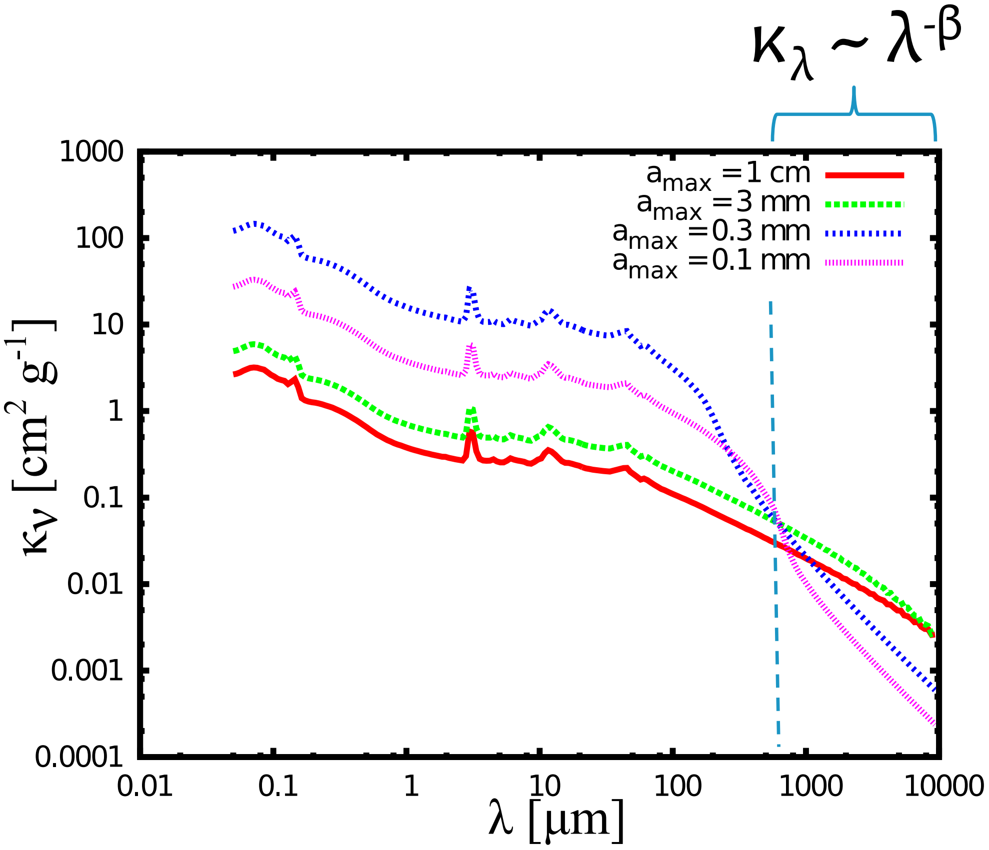
New Composition:

12% silicates, 44% organics, 44% water ice

Constraints on Σ(r)

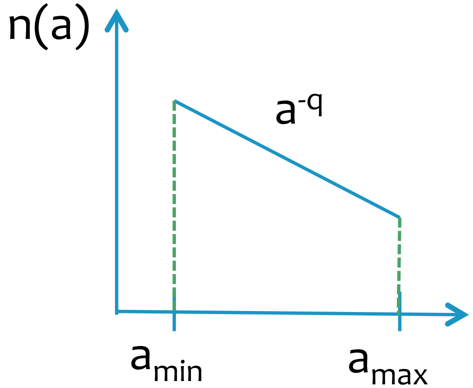


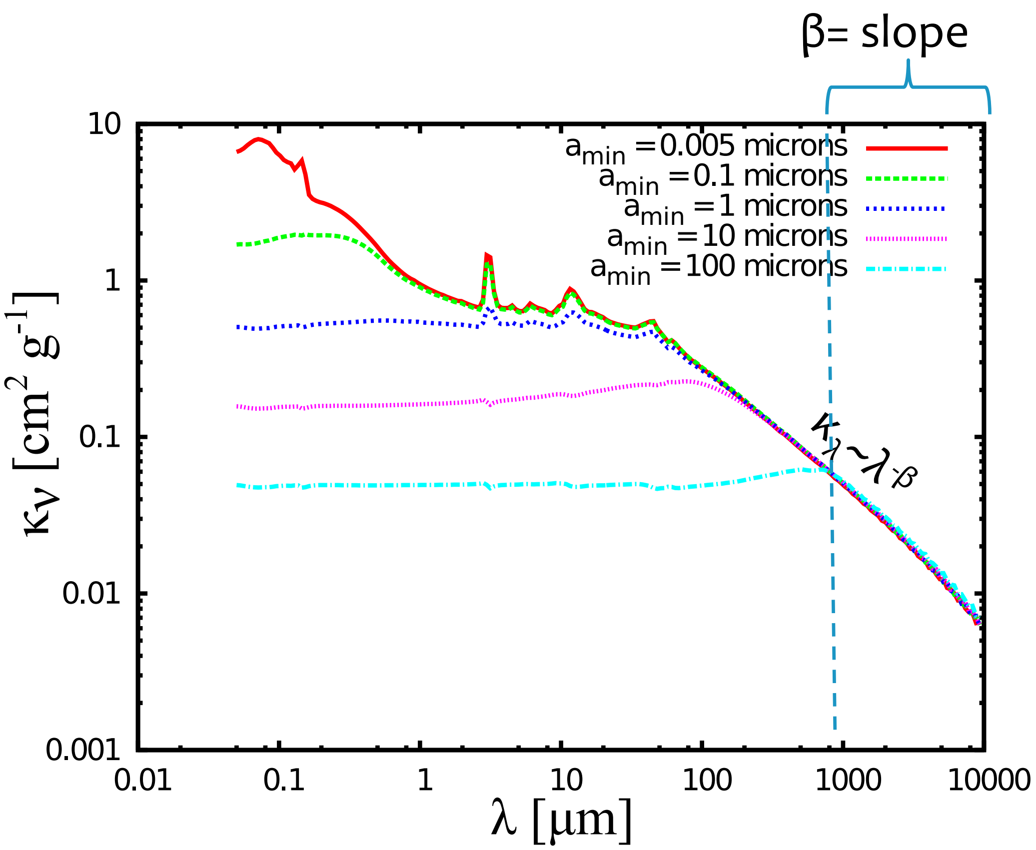
Dust opacity slope relates to grain growth



Dust opacity spectral index β

- Not influenced by a_{min}



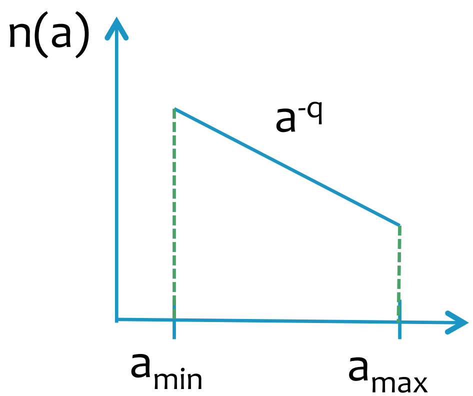


Dust opacity spectral index β

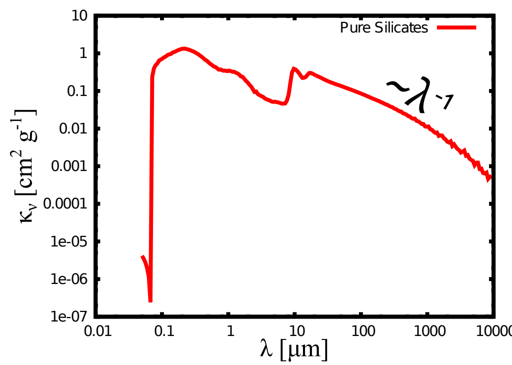
- Not influenced by a_{min}

$$a_{min} = 0.005\ \mu m.$$

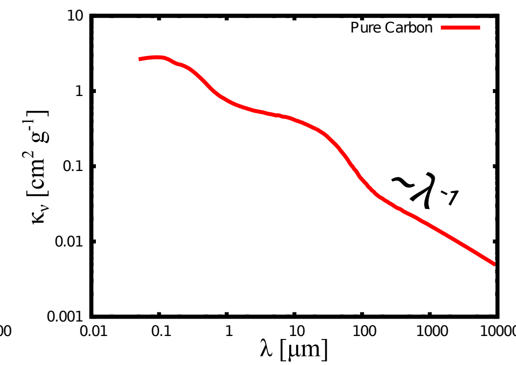
- **Influenced by:**
  - **Composition (slightly)**
  - a_{max}
  - Grain size distribution slope $n(a) \sim a^{-q}$

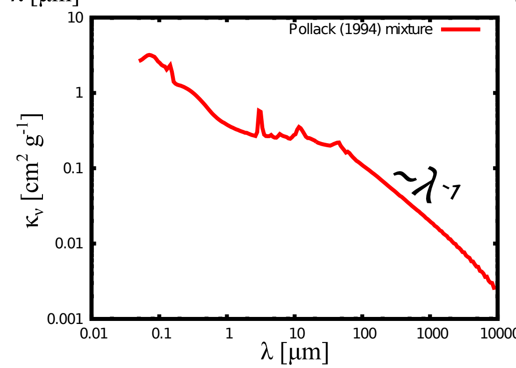


Silicates



Carbon

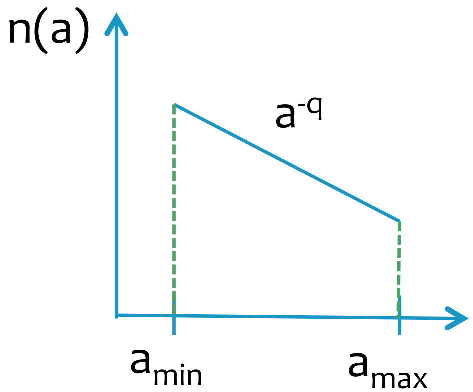




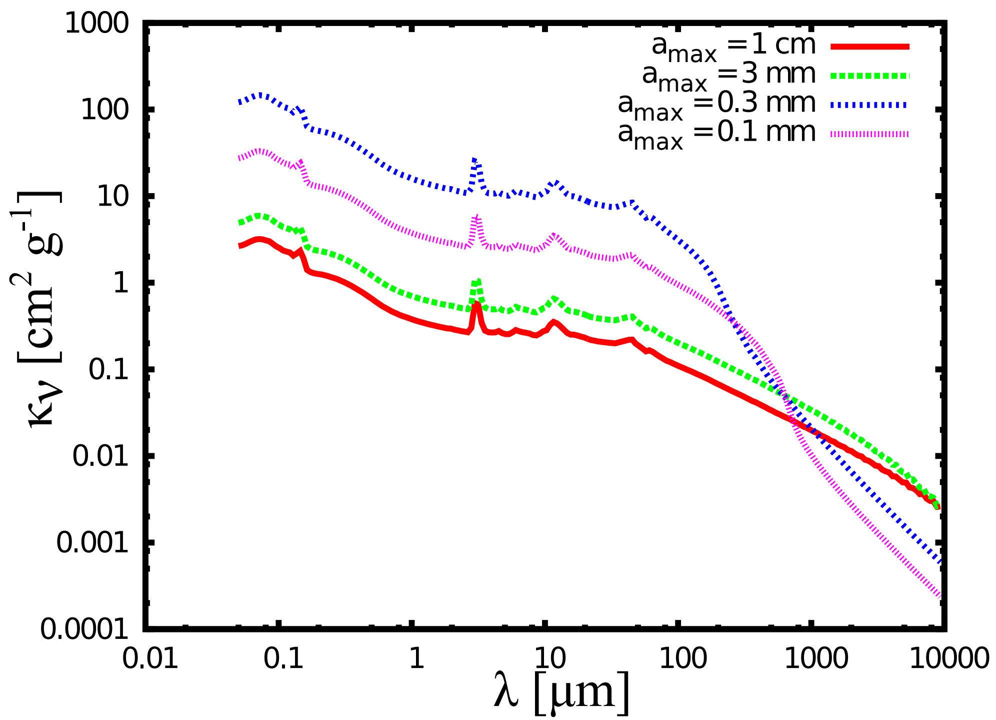
Dust mixture (Sil+C+Ices)

Dust opacity spectral index β

- Not influenced by a_{min}
- **Influenced by:**
  - Composition
  - $\mathbf{a_{max}}$
  - Grain size distribution slope $n(a) \sim a^{-q}$



$n(a) \propto a^{-q}$ with $a_{min} = 0.005\ \mu$m, $q = 3.5$



β as a proxy for a_{max}

- Not influenced by a_{min}
- **Influenced by:**
  - Composition
  - a_{max}
  - **Grain size distribution slope $n(a) \sim a^{-q}$**