Grain Growth in Protoplanetary Disks

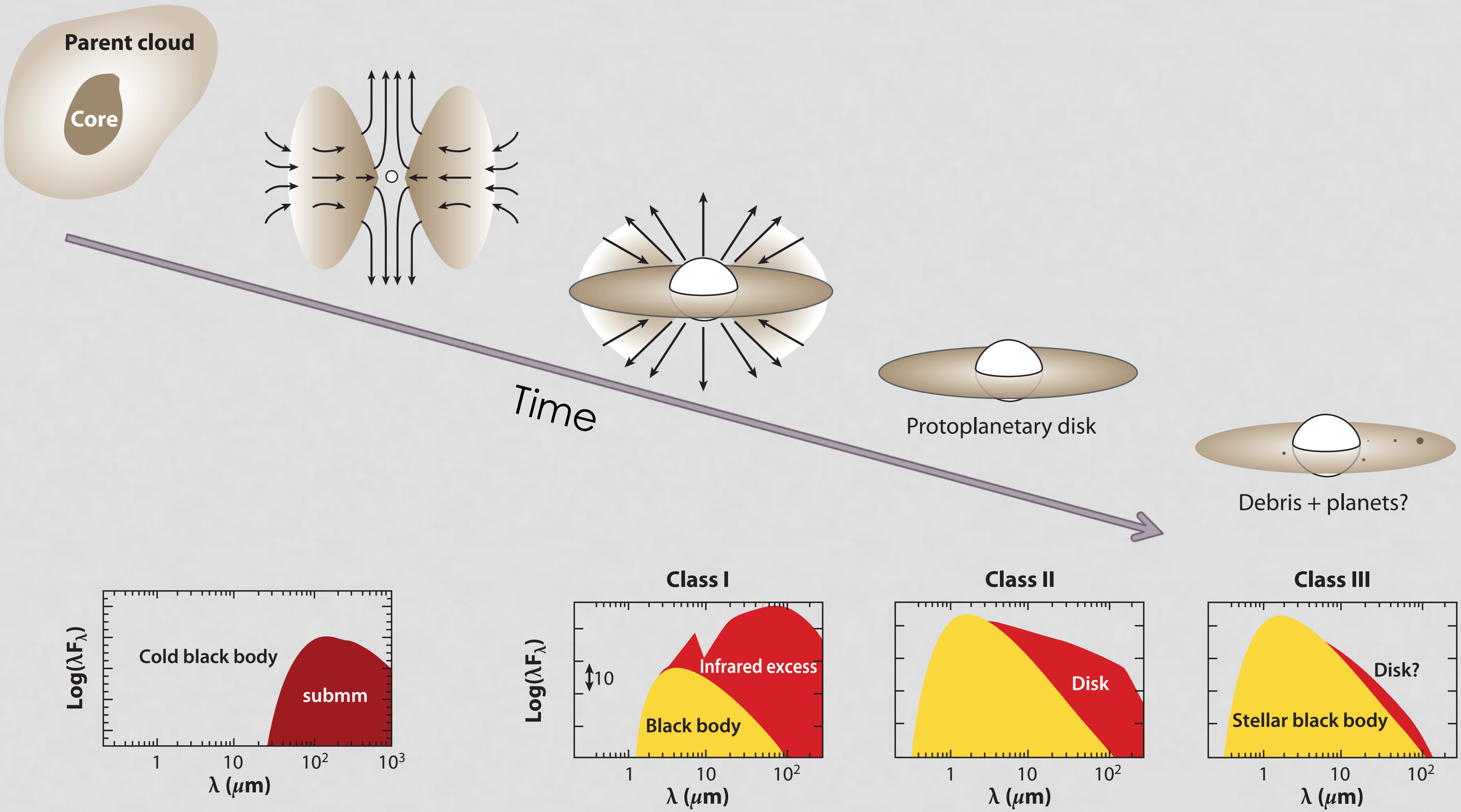
Laura M. Pérez

Collaborators:
John Carpenter (Caltech)
Andrea Isella (Caltech)
Claire Chandler (NRAO)
Anneila Sargent (Caltech)
Disks@EVLA KSP (PI: C. Chandler)

NRAO

Postdoc Symposium – April 28, 2013

Disks: natural by-product of star formation

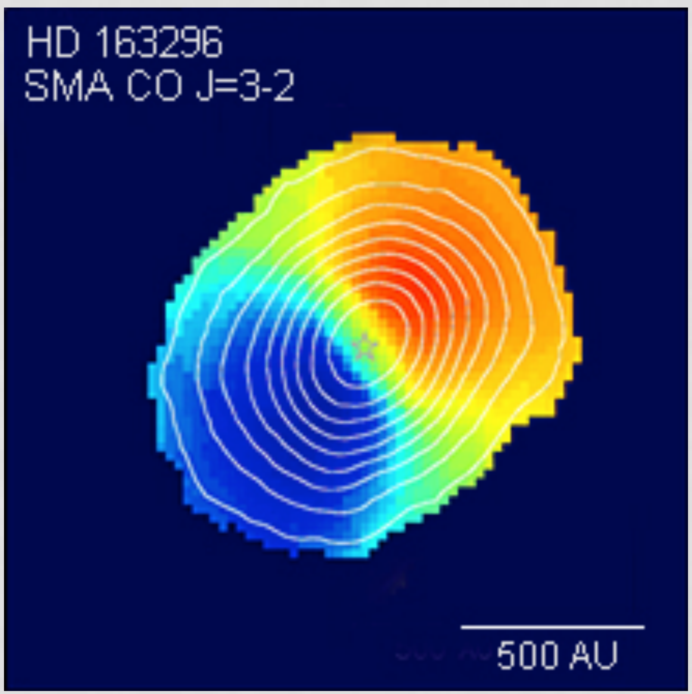


Dauphas & Chaussidon (2011)

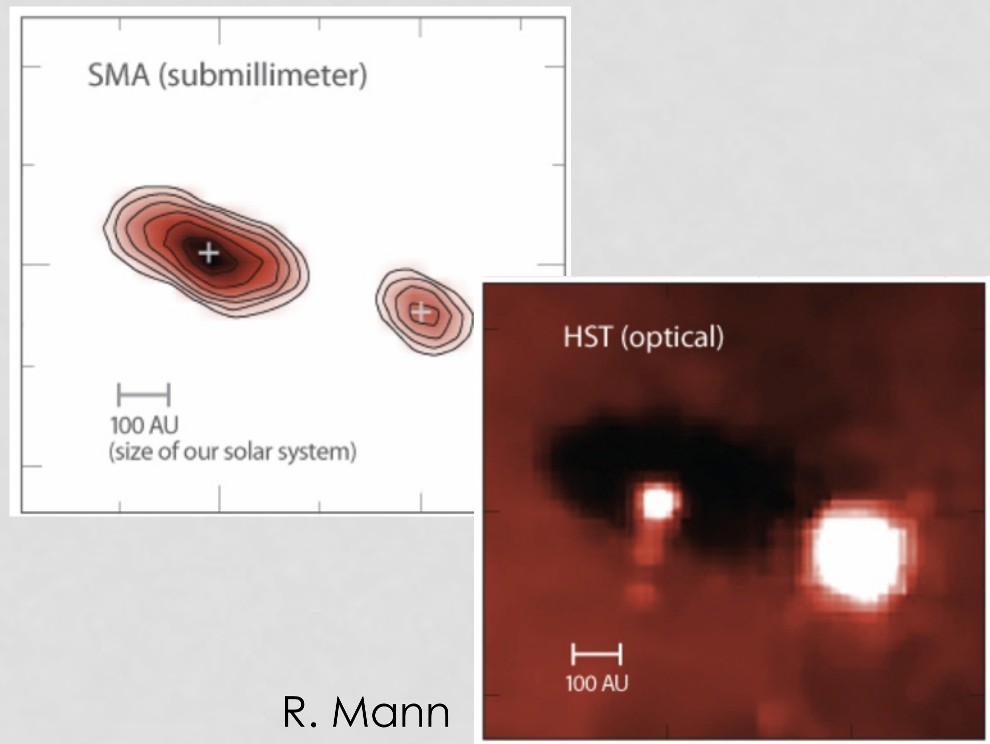
Disks studied through gas & dust

Gas emission → geometry, stellar mass, turbulence, disk extent

Dust emission/absorption → mass, composition, disk extent, lifetimes

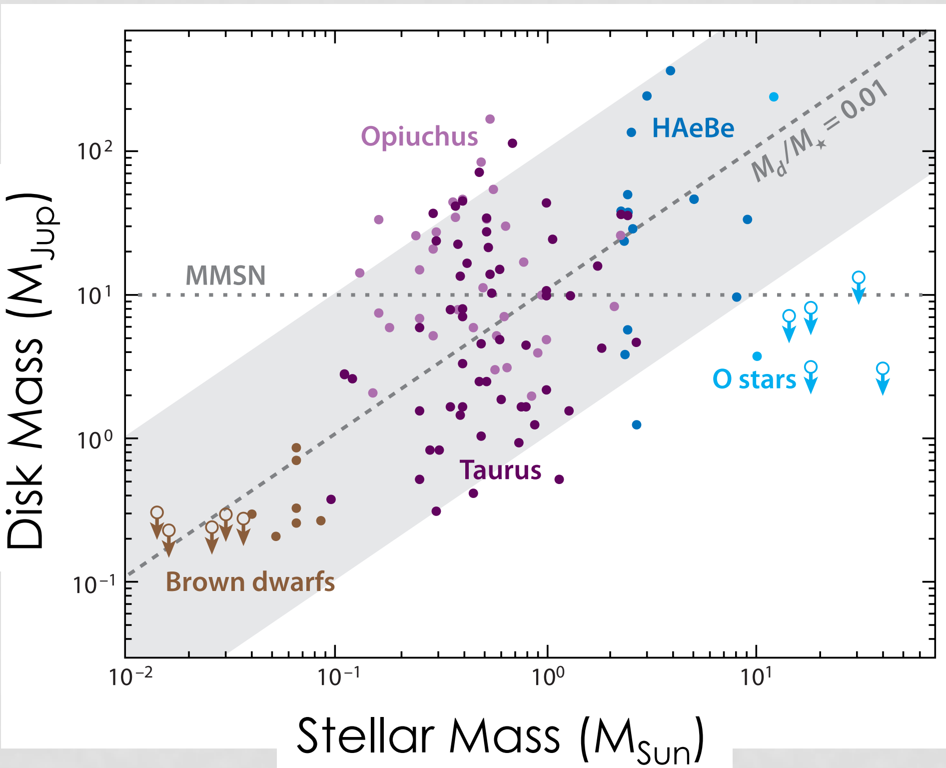


A. Isella

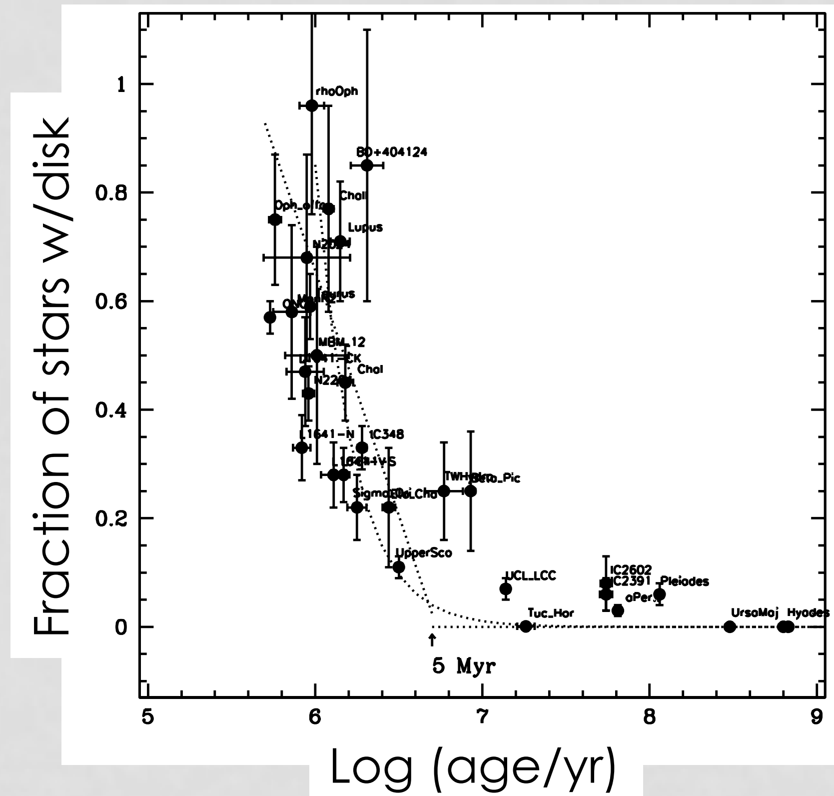


R. Mann

"Protoplanetary" since they are "capable" of forming planets



Williams & Cieza (2011)

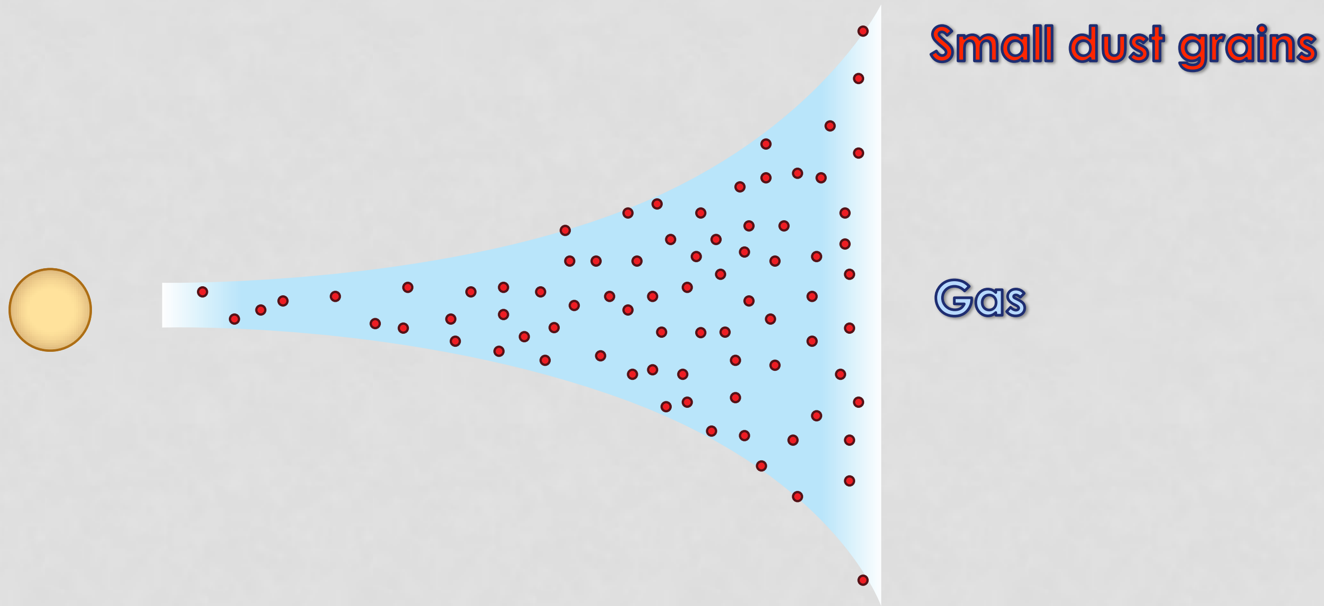


Hillenbrand (2005)

Earliest phase of planet formation: growth of small dust grains into "pebbles"

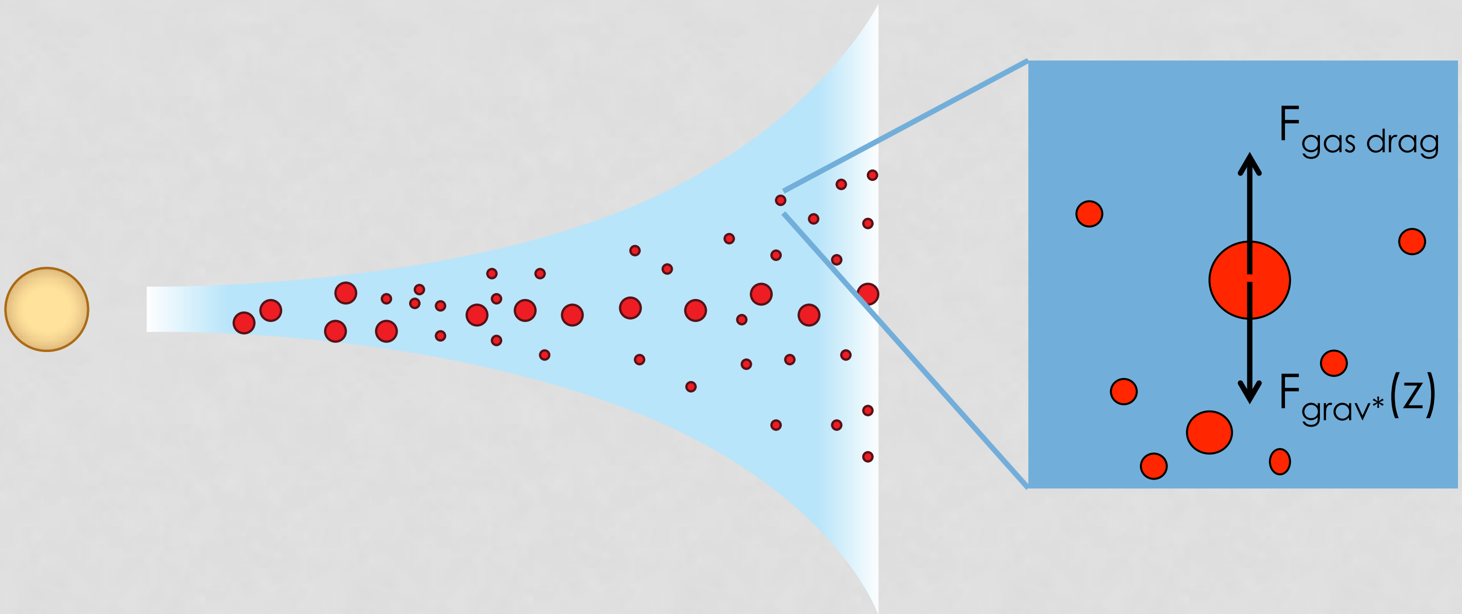
Growth of small grains: easy!

- Very small ISM dust grains coupled to the collapsing gas
- Initial (rapid) growth: Brownian motion



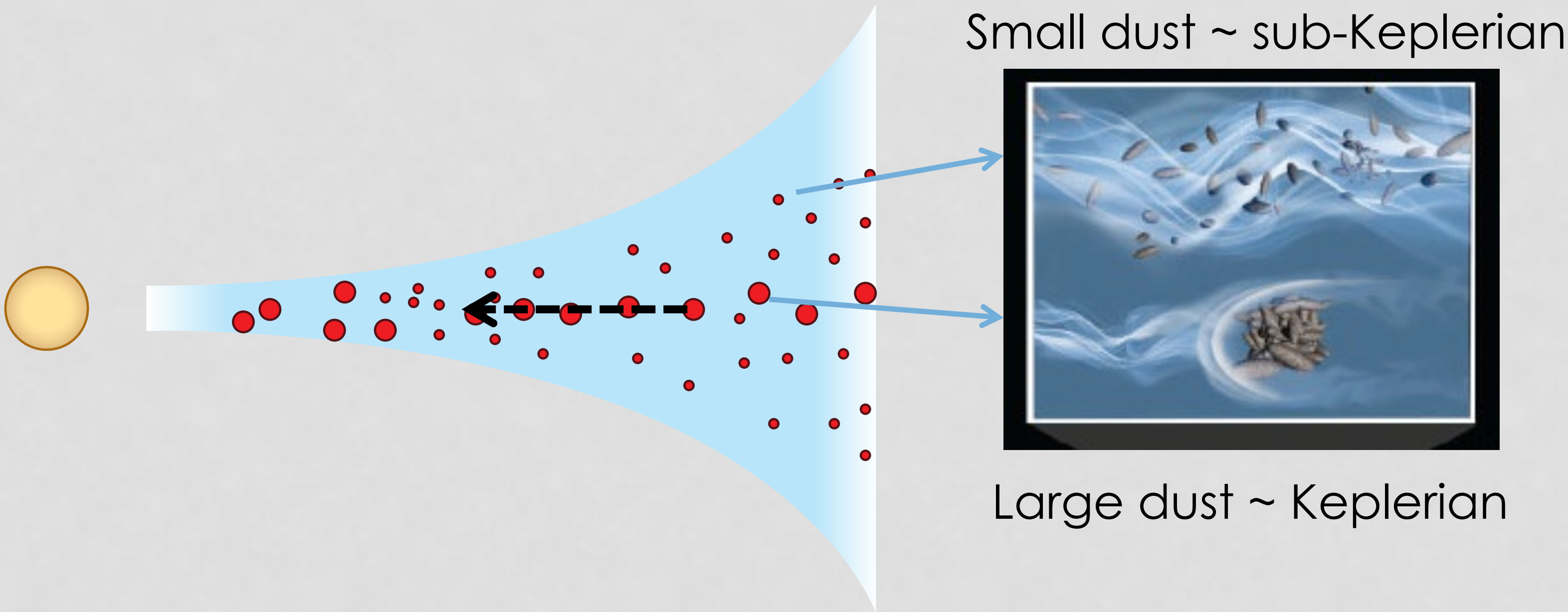
Growth of small grains: easy!

- Large particles decouple from gas
- Settling towards disk mid-plane
- Sweep up other particles → further growth

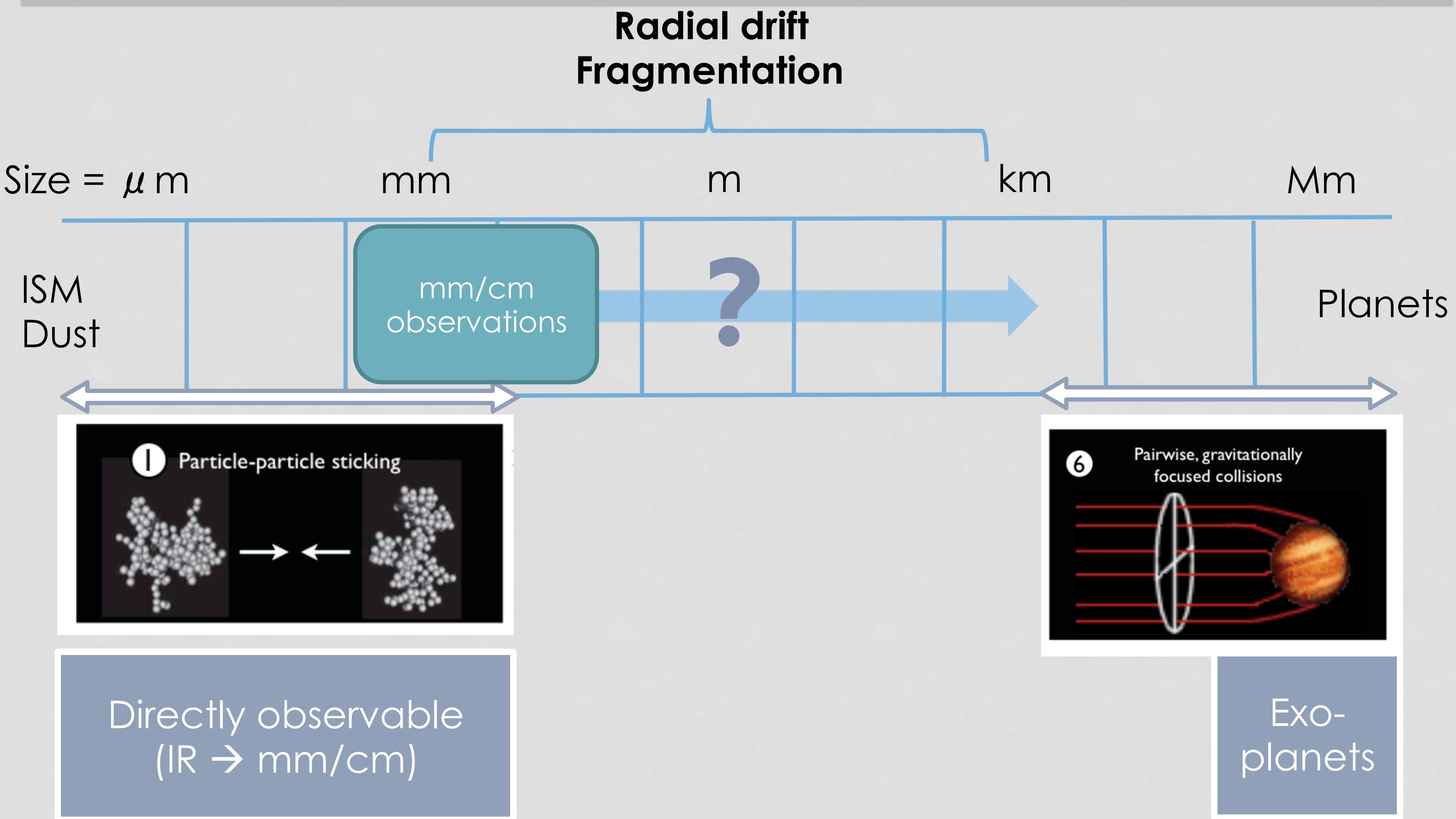


Grow of larger grains: it gets hard!

- Particles ~ few cm: sticking efficiencies drop
    - v_{rel} > 1 m/s: fragmentation or bouncing
- Also: Radial drift problem (Weidenschilling 1977)
    - Timescale ~ 10^3-10^5 yr



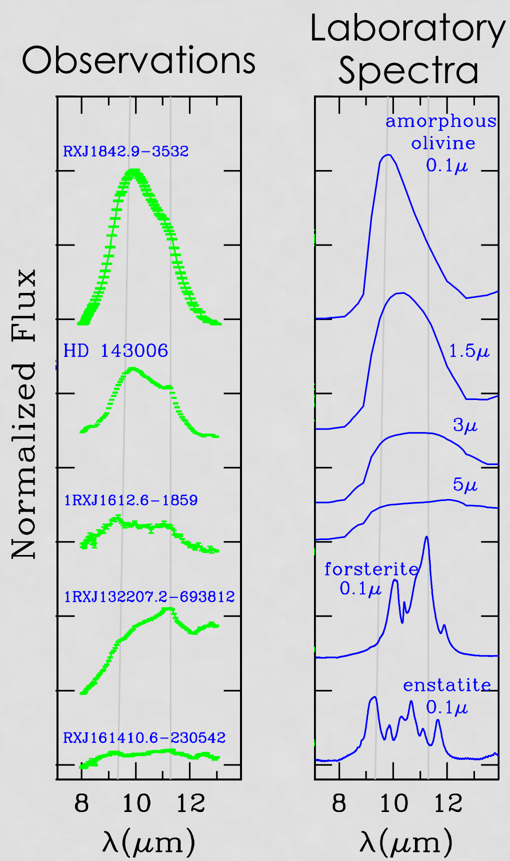
From ISM Dust to Planetary Systems



Adapted from Chiang & Youdin (2009)

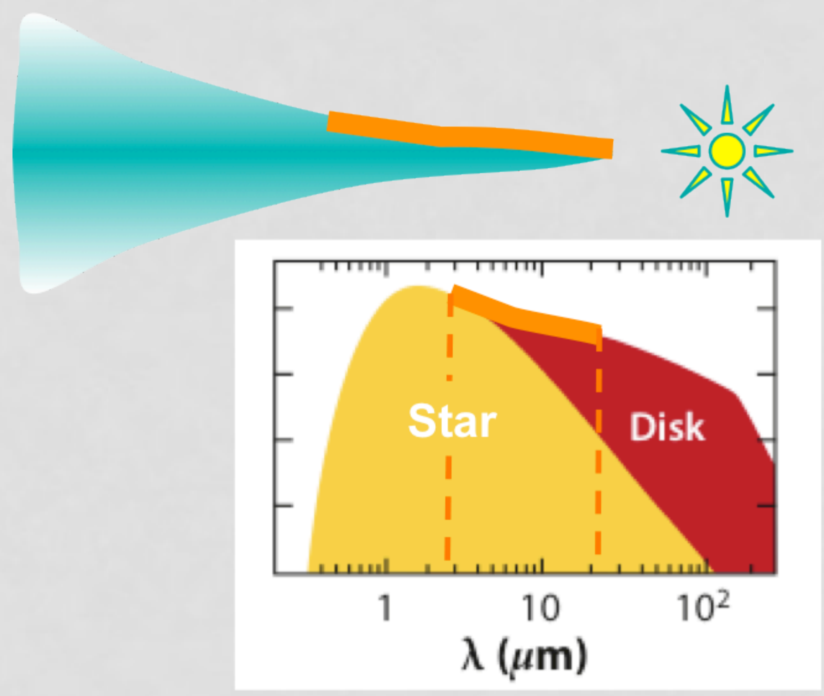
Observational Evidence for Grain Growth in PPDs

Growth to few micron-sizes: IR evidence



Natta et al. (2007)

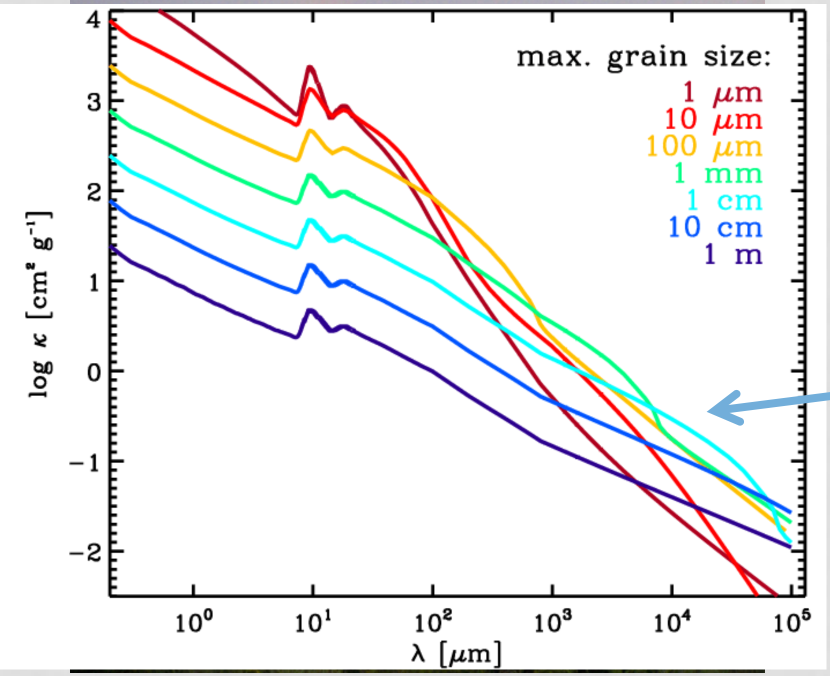
- IR spectroscopy of protoplanetary disks
  - E.g. 10 μ m silicate feature



Long-wavelength observations to the rescue!

Trace bulk of the mass

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



- At long wavelengths/warm temperatures
  - Raleigh-Jeans limit (hnu<< 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

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

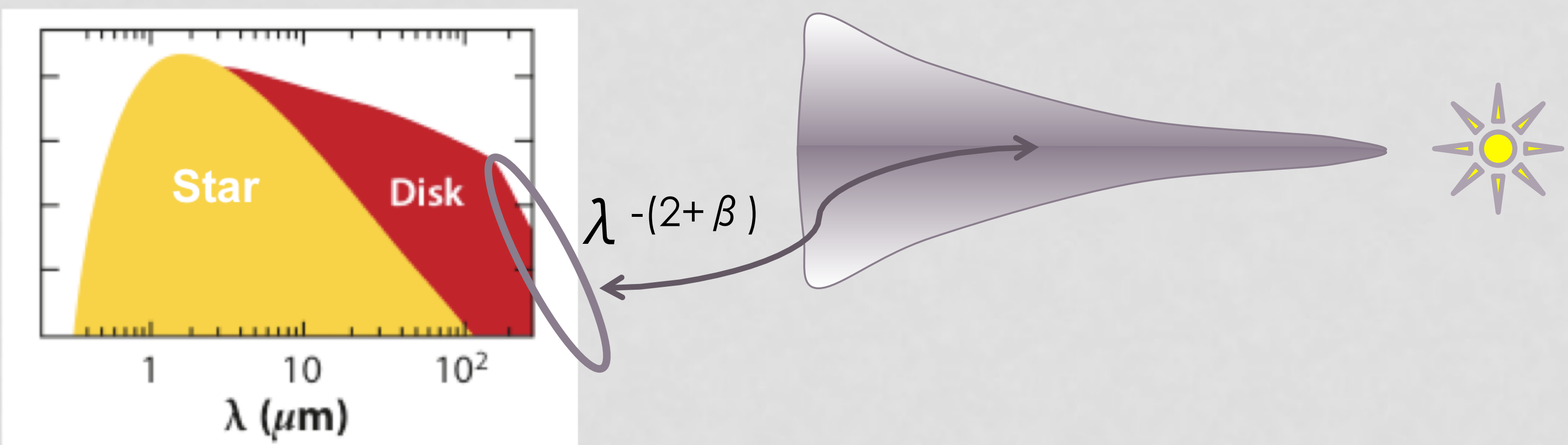
  - Dust emission spectrum is also a power law!

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

Multiwavelength observations determine β

- Even if **absolute** opacity / temperature cannot be determined
- Multiwavelength observations(*) determine dust opacity spectrum

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

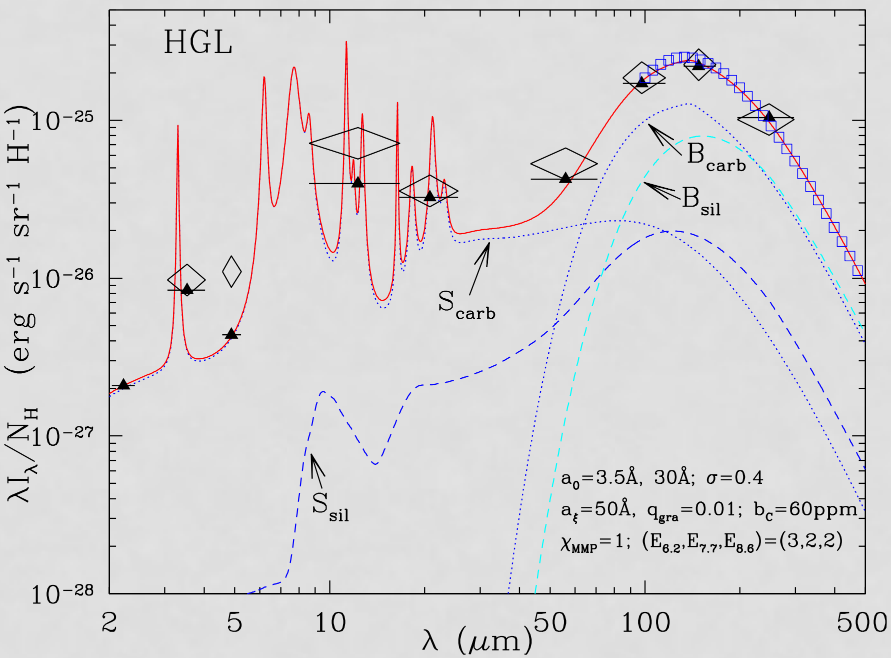


(*) in the **optically thin regime**

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

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

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



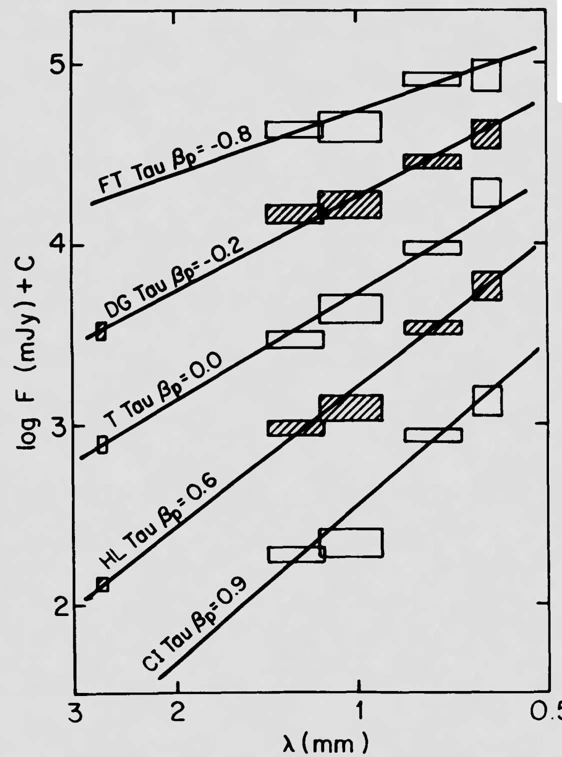
e.g., Li & Draine (2001)

- However, disks show flatter spectral index:

$2 < \alpha_{disks} < 3$

$\beta_{disks} < 1$

(Optically thin emission)



e.g. Beckwith & Sargent (1991)

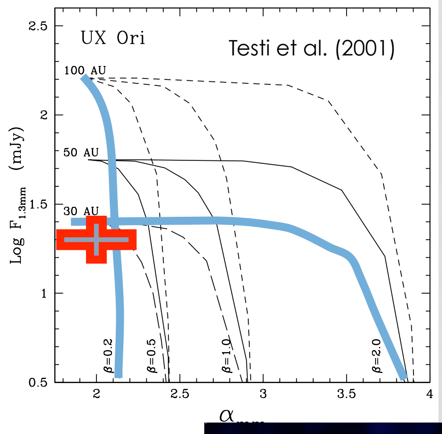
What could make $\beta \neq \beta_{ISM}$? (and $\beta < 1$)

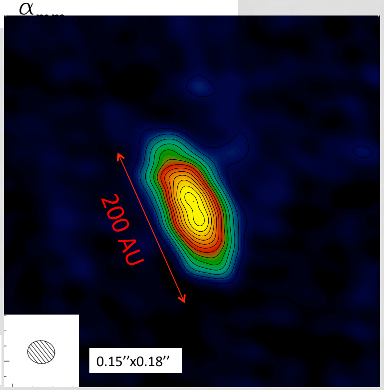
Grain Properties

- 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

Emission Properties

- Dust emission is optically thick

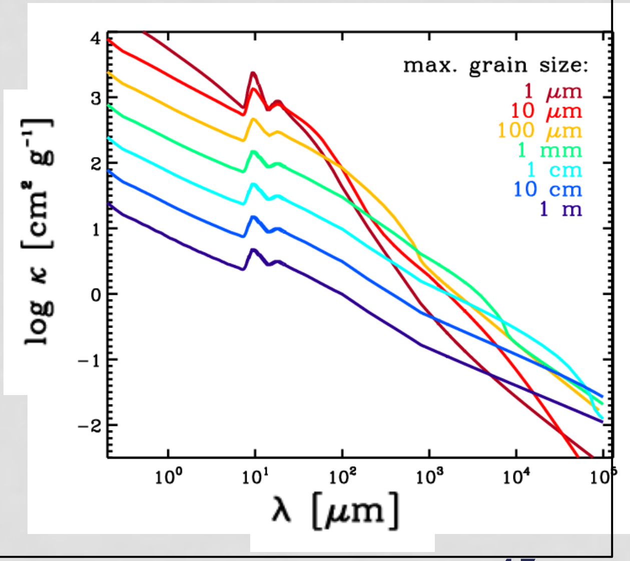




Isella et al. (2010)

Grain Growth

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



Observational Evidence for Grain Growth in PPDs (from mm-wave obs.)

A summary of many “global” studies…

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 al. (2009)
Ricci et al. (2010)

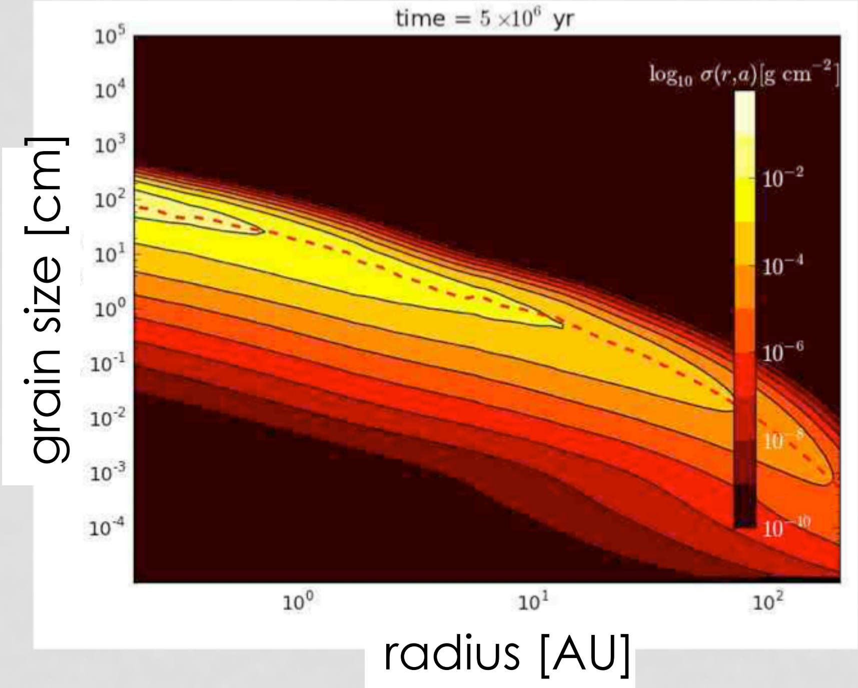
ATCA

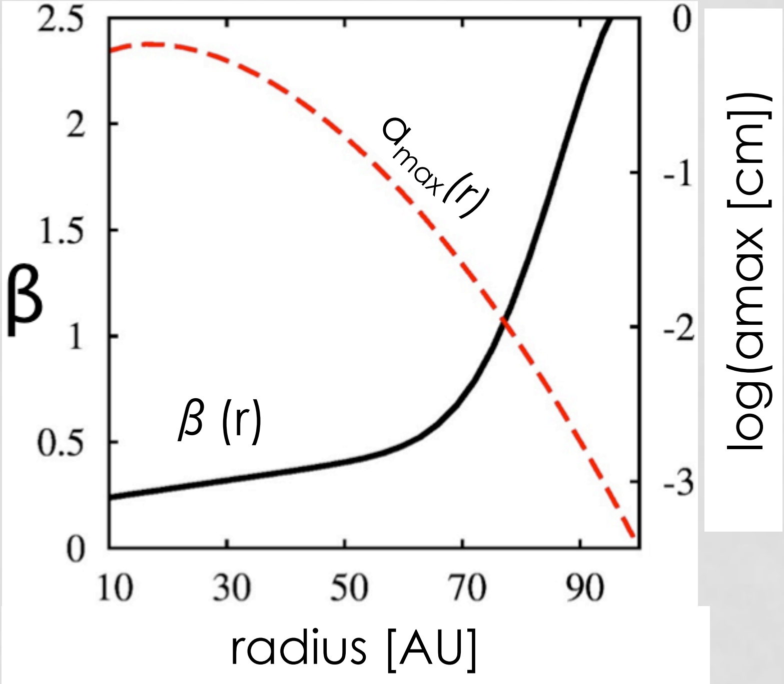
Lommen et al. (2007, 2009)
Ricci et al. (2010)
Ricci et al. (2011a)

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

Grain growth: both global and local

- Radial variations of grain size are expected
- Observational signature in β (r)





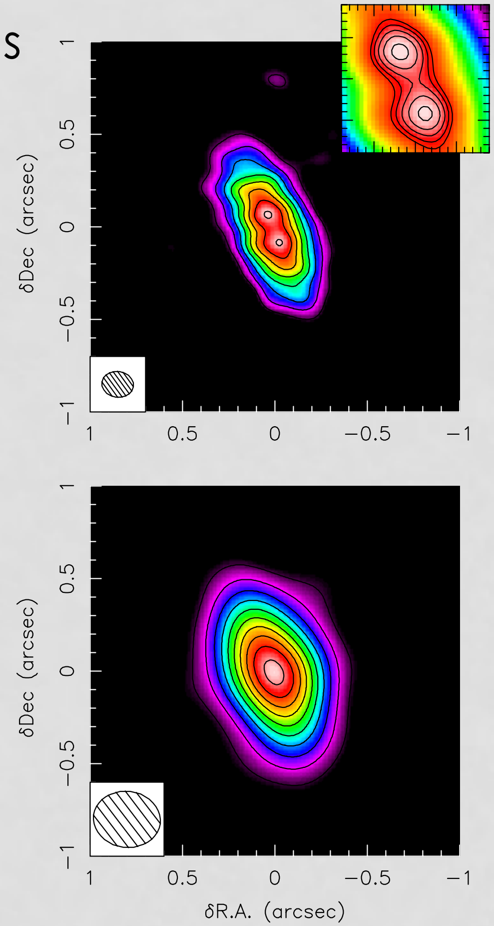
Dullemond & Dominik 2005
Birnstiel et al. 2010, 2012

Observational constraints on radial variations of β

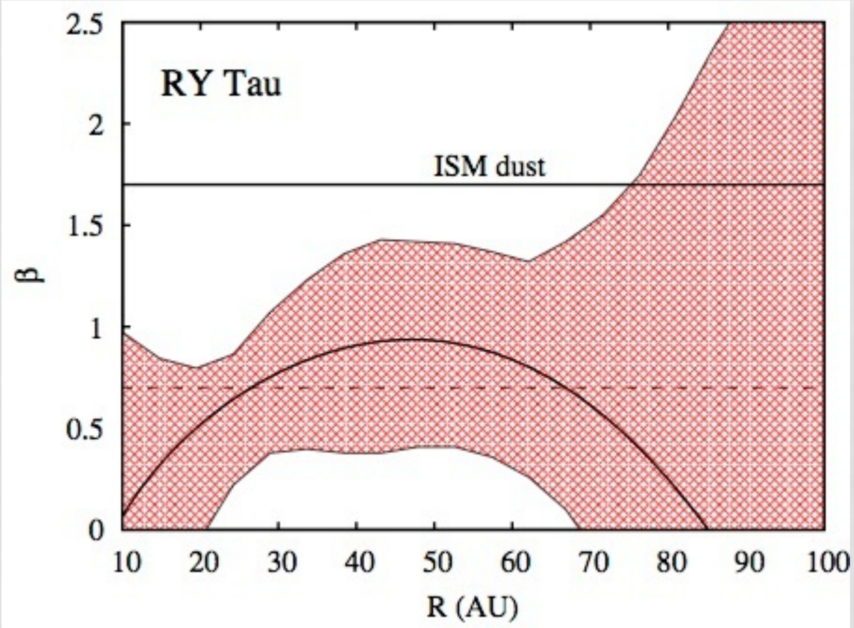
CARMA observations

1.3 mm

2.7 mm



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



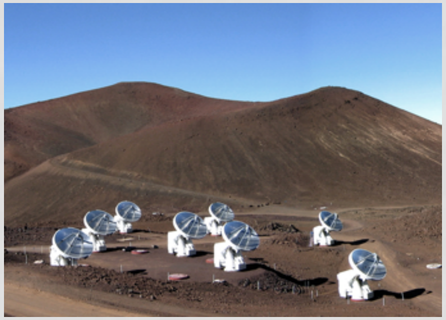
Isella et al. (2010)

See also: Guilloteau et al. (2011)

Banzatti et al. (2011)

Improved constraints can be obtained by …

- Increasing wavelength coverage



SMA: 0.88mm

CARMA: 1.3, 2.7 mm

VLA: 7mm, 1cm

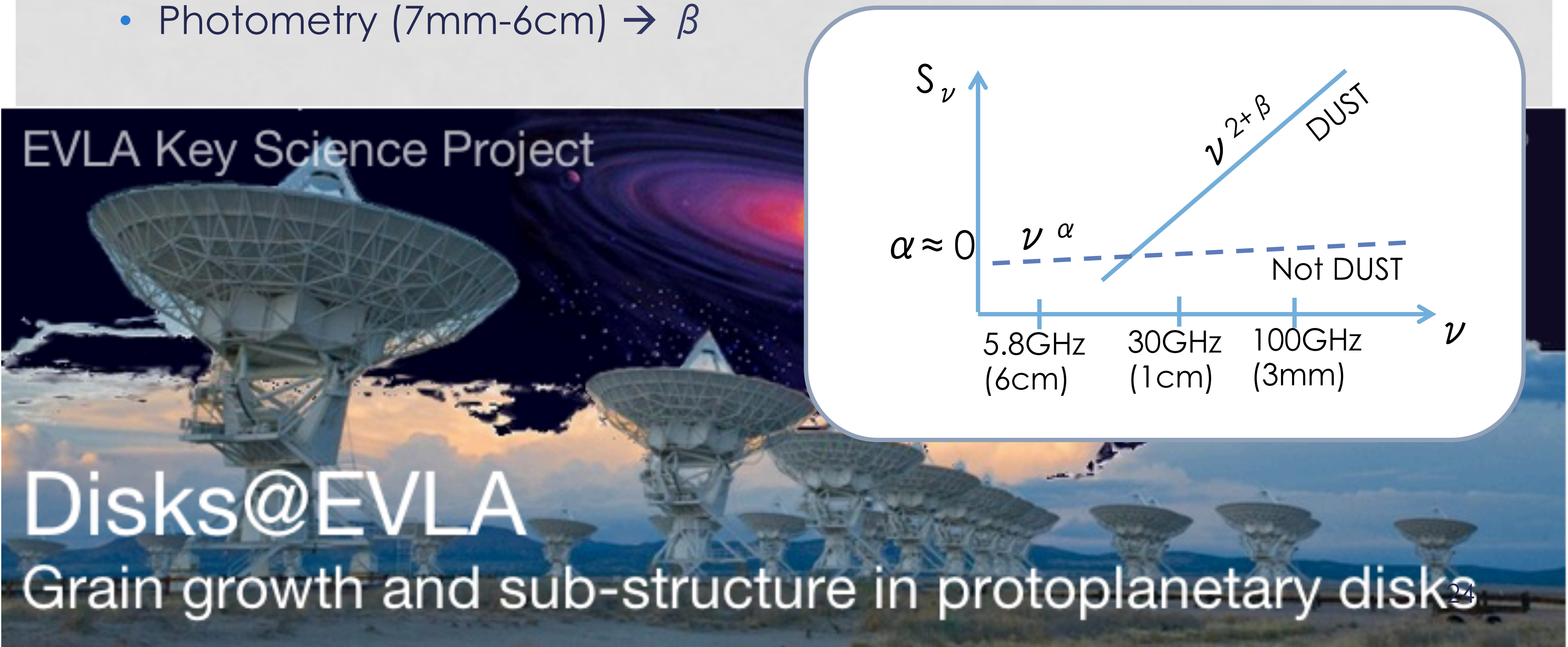
- Increasing sensitivity of our observations
  - Correct for atmospheric radio seeing with CARMA → bring forward the C-PACS system (Pérez et al. 2010)
  - Take advantage of VLA upgrade → EVLA Residency program
- BTW: High angular resolution is a must (0.2'' ~ 20-30 AU)

Observational Constraints of Grain Growth in Protoplanetary Disks
Pérez et al. (2012)

Disks@EVLA collaboration

PI: Claire Chandler

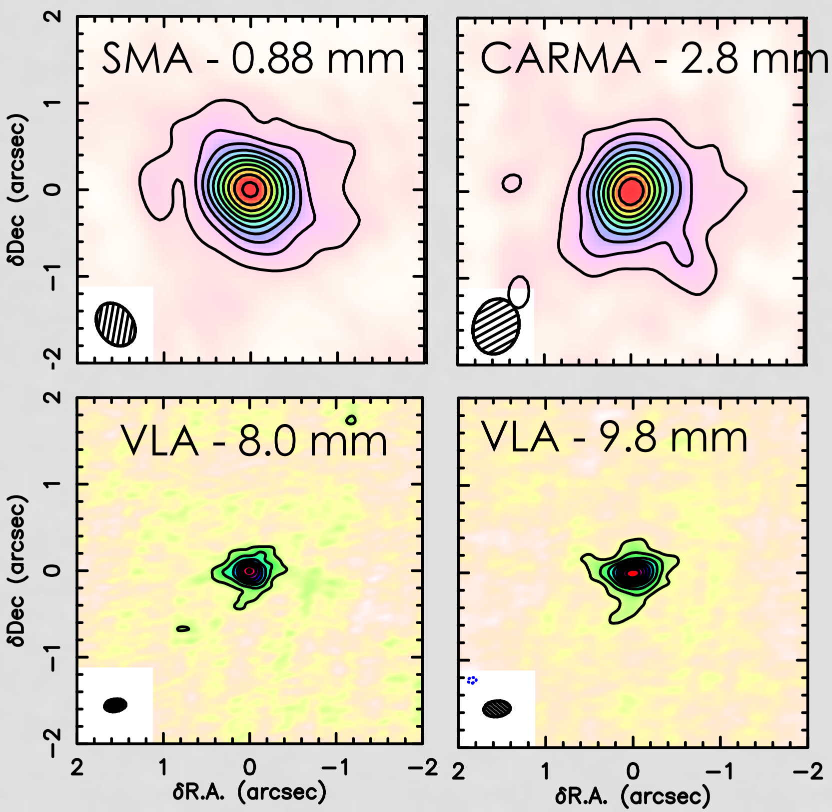
- Determine prevalence of grain growth to cm-sized particles
  - 66 stars (ages ~ 1-10 Myr old)
  - Photometry (7mm-6cm) → β
- Determine location of large grains in disks
  - Sub-sample imaged with ~0.2" res. at 7mm/1cm and 6cm



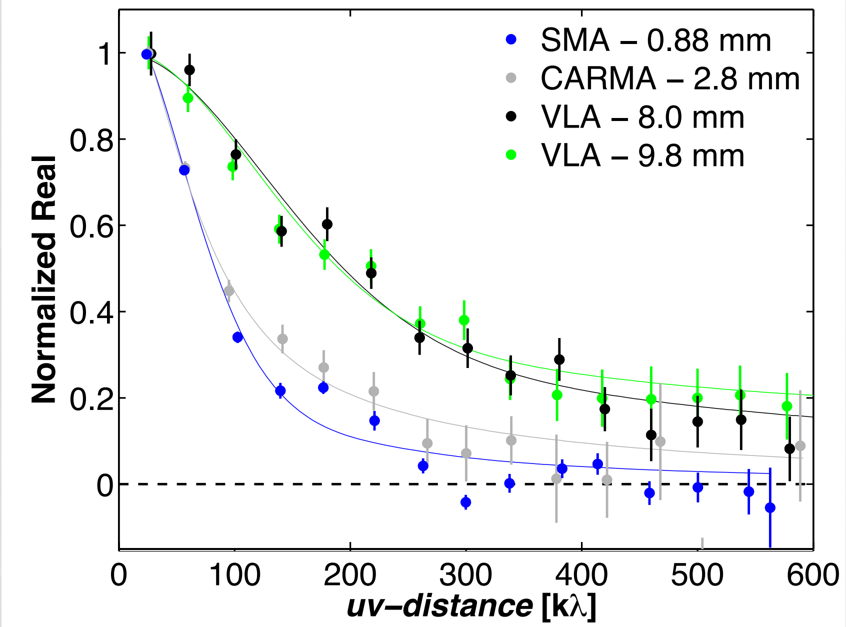
Constraints in Radial Variations of Grain Growth

- Increased wavelength coverage and sensitivity

AS 209 disk; Pérez et al. (2012)

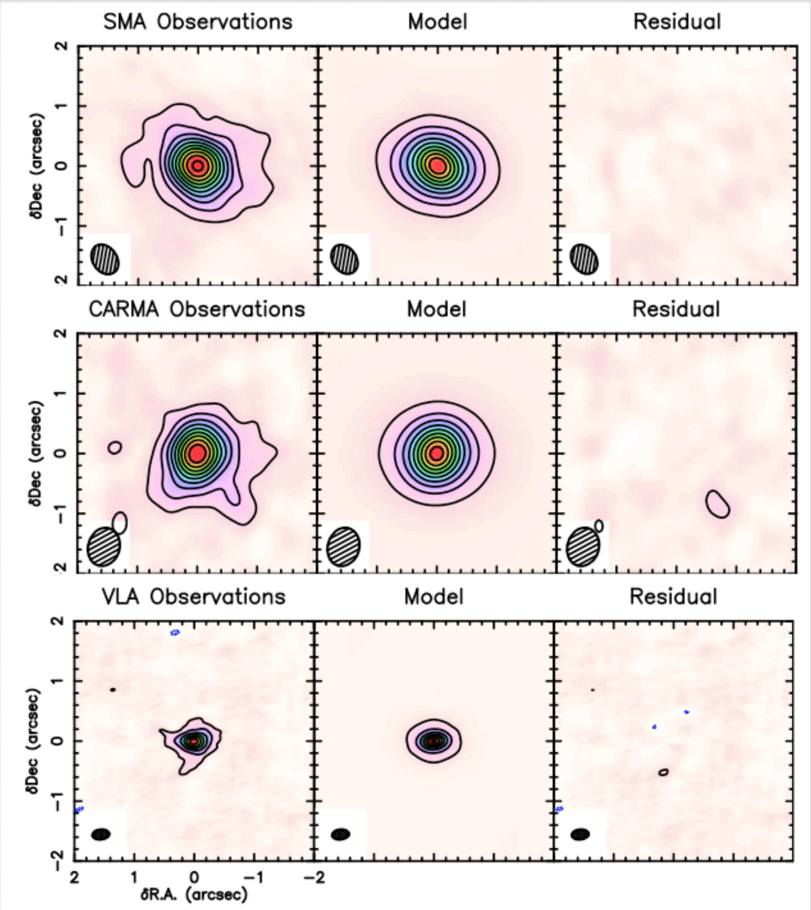


- Allow us to infer wavelength-dependent disk structure



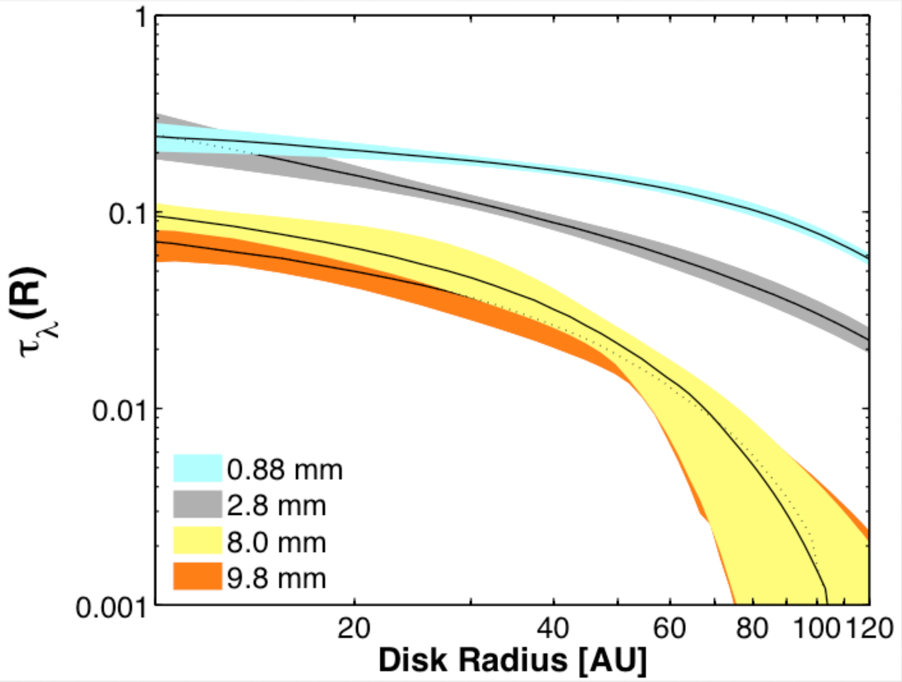
Constraints in Radial Variations of Grain Growth

- Simple disk model reproduces our observations



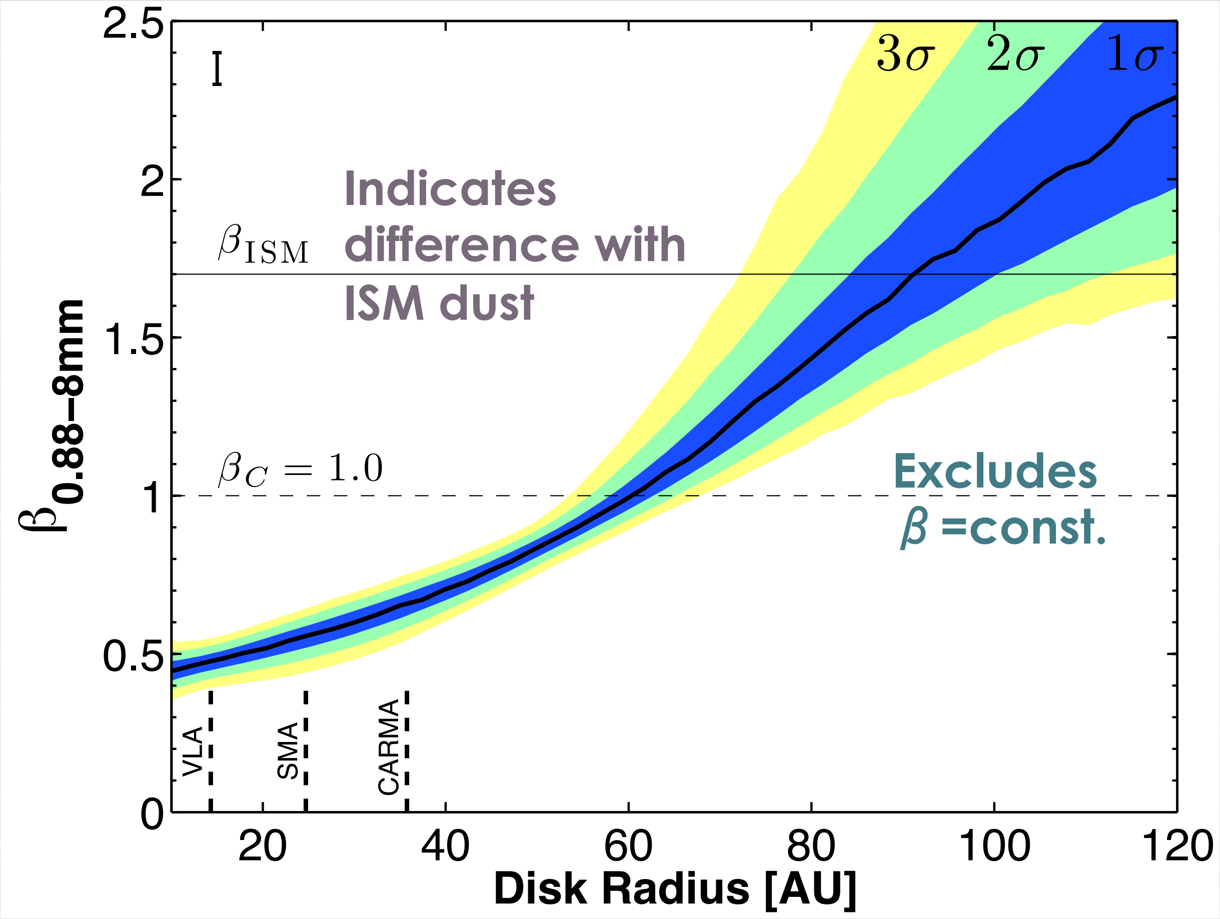
- Allow us to infer

$$\tau_\lambda(R) = \kappa_\lambda \times \Sigma(R)$$



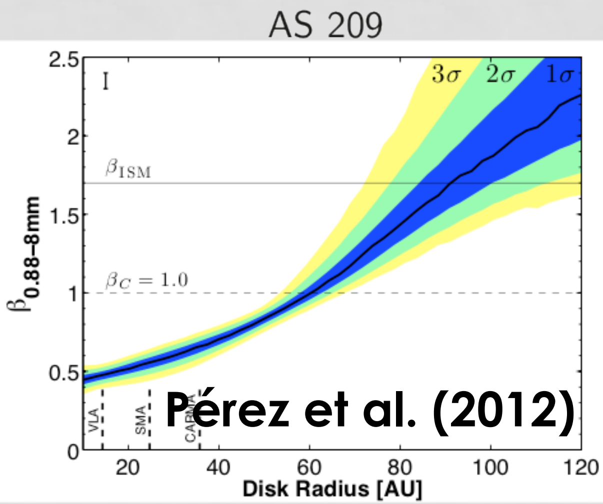
Wavelength-dependent disk structure

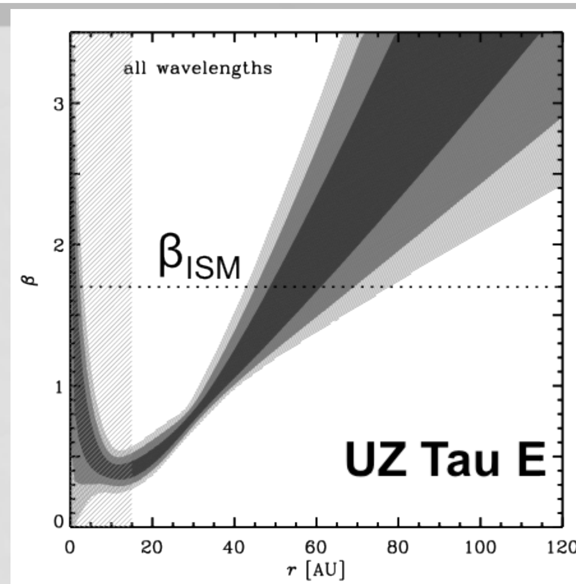
Constraints in Radial Variations of Grain Growth



Pérez et al. (2012)

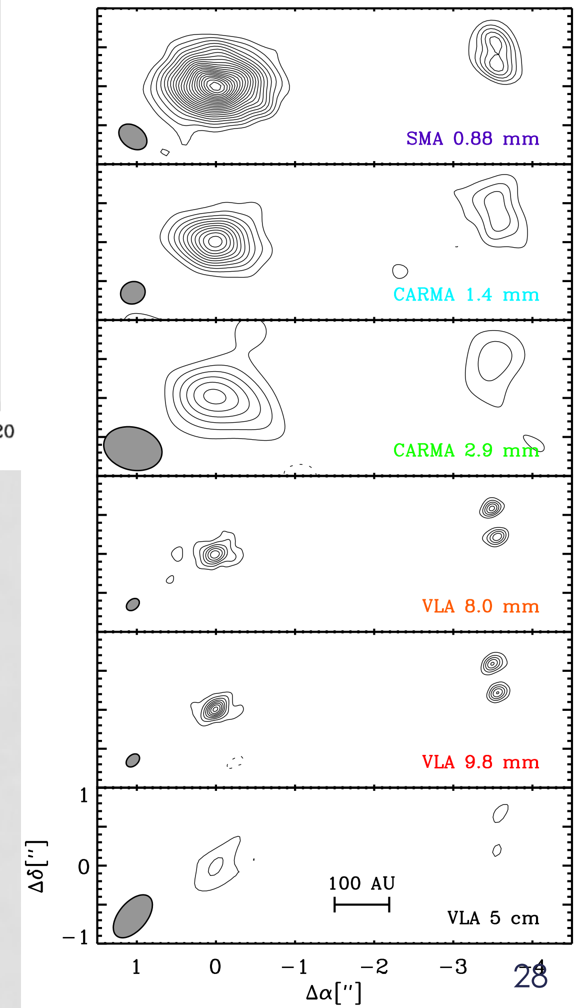
Similar constraints in many different disks

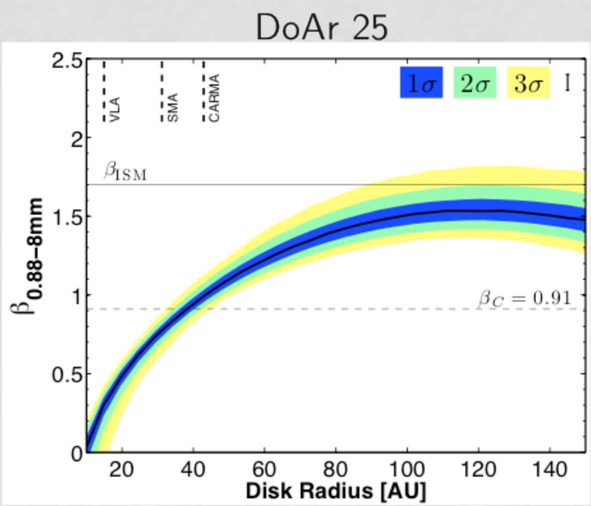


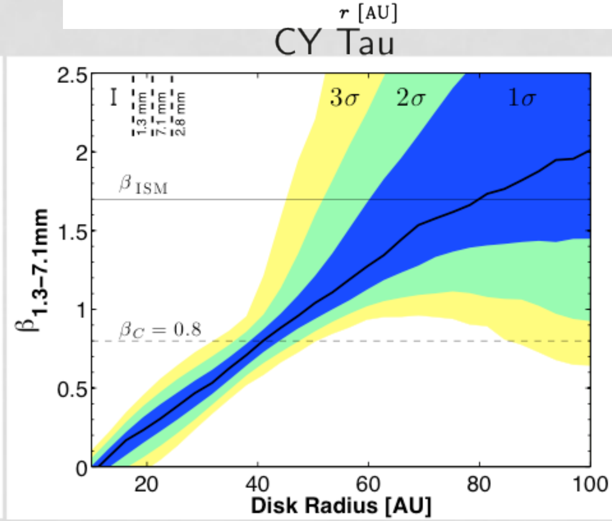


Harris et al. (subm.)

UZ Tau Quadruple system



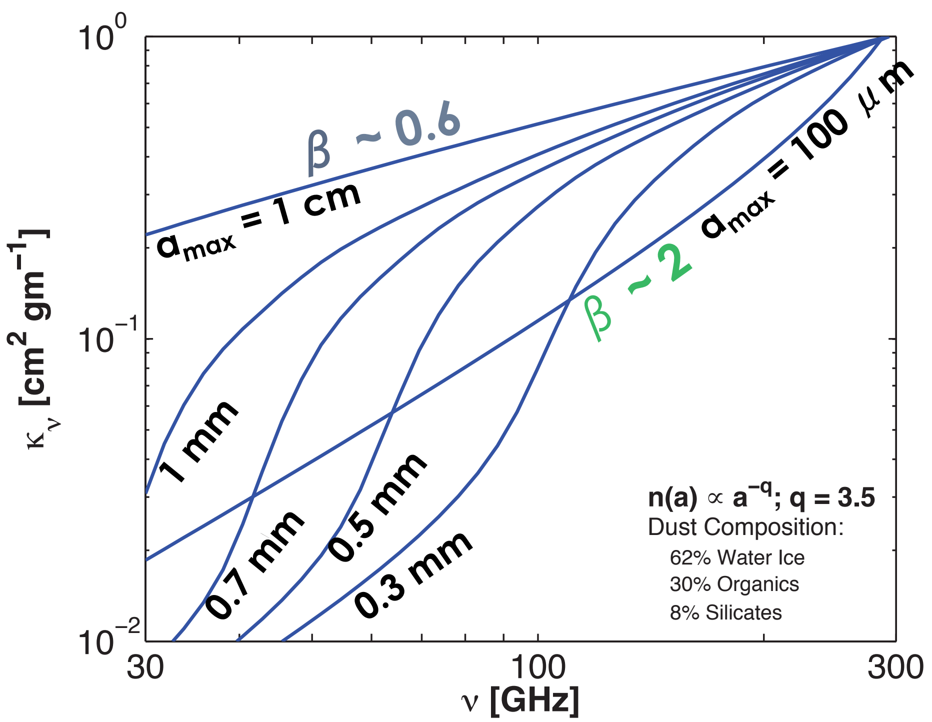




Pérez et al. (in prep.)

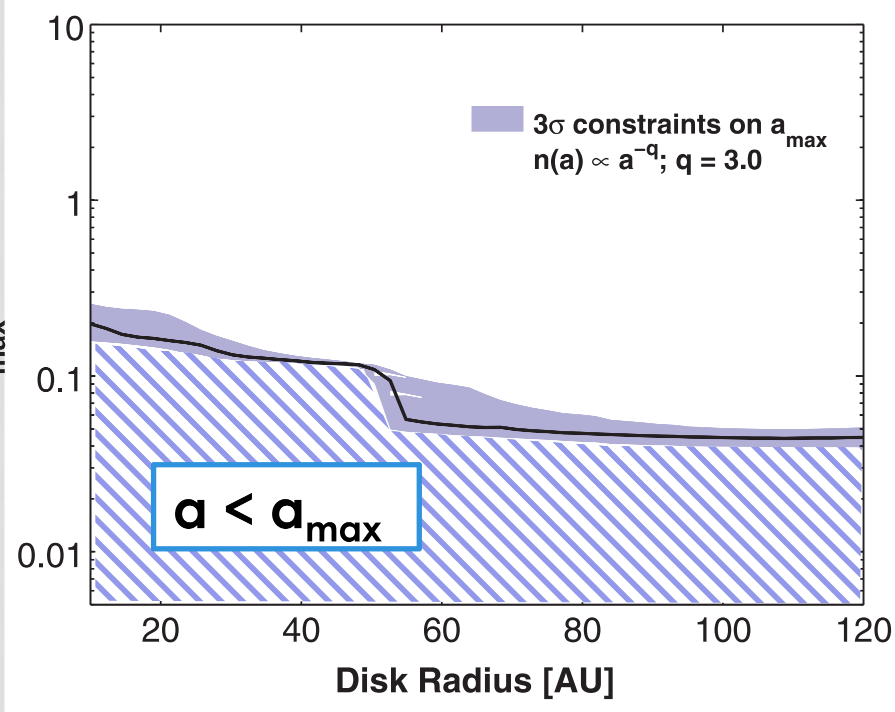
From radial variations of dust opacity to $a_{max}(R)$

- Dust opacity depends on particle-size distribution



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

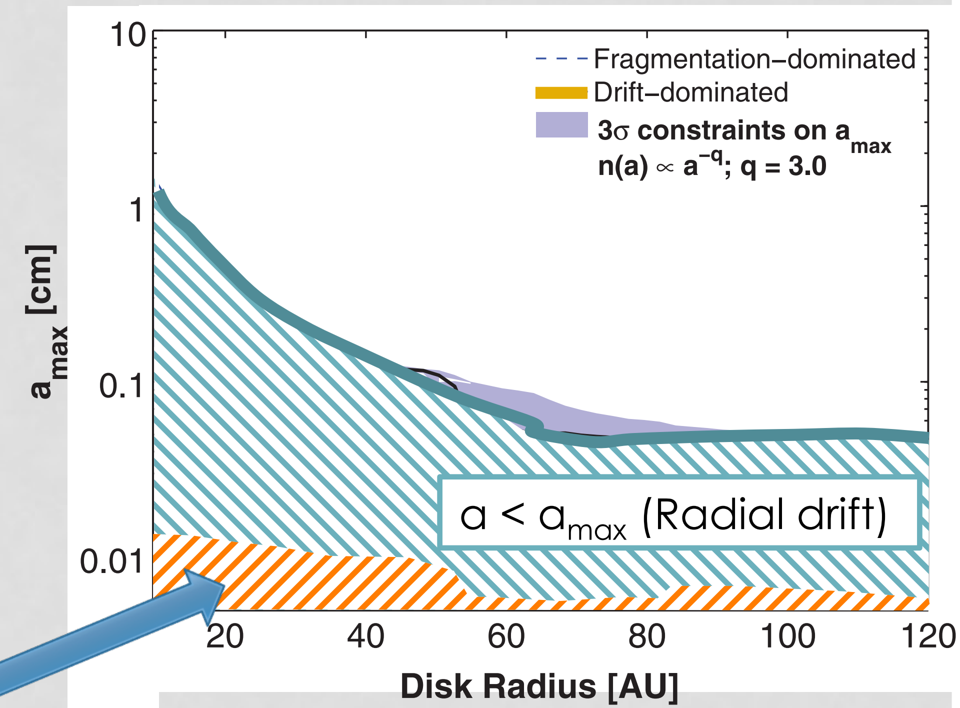
$$F_\nu \approx \kappa(\nu) M_d B_\nu(T_d) d^{-2}$$



Pérez et al. (2012)

Limit to particle growth: radial drift of solids

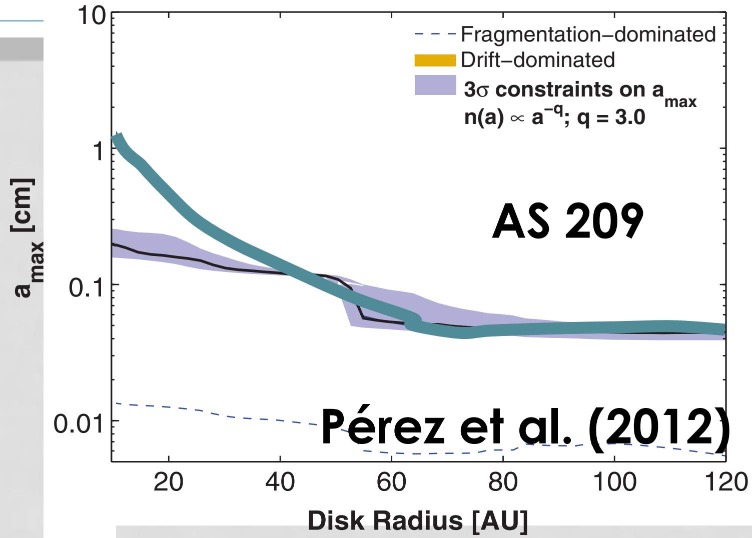
- Compare with physical barriers to further growth:
  - Fragmentation $a_{frag} \propto \frac{\Sigma_{gas}}{\alpha_t} \frac{u_{frag}^2}{c_s^2}$
  - Radial drift $a_{drift} \propto \Sigma_{dust} \frac{v_{Kep}^2}{c_s^2}$

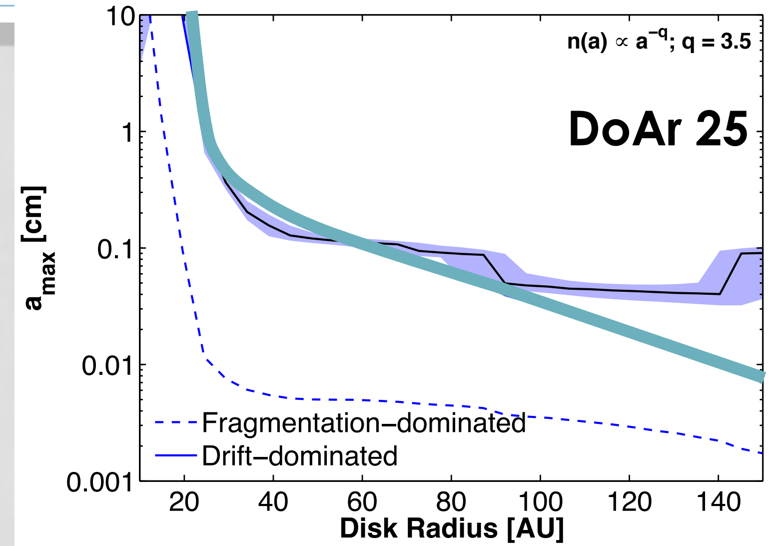


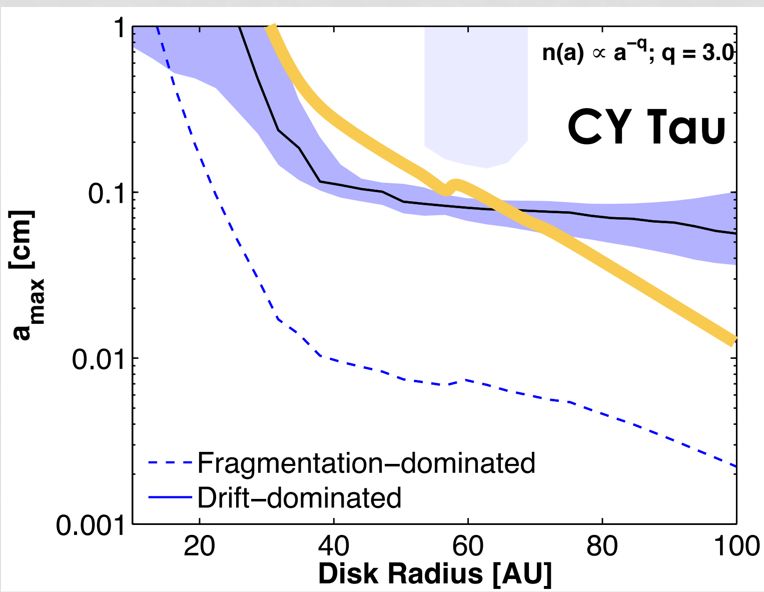
a < a_{max} (Fragmentation)

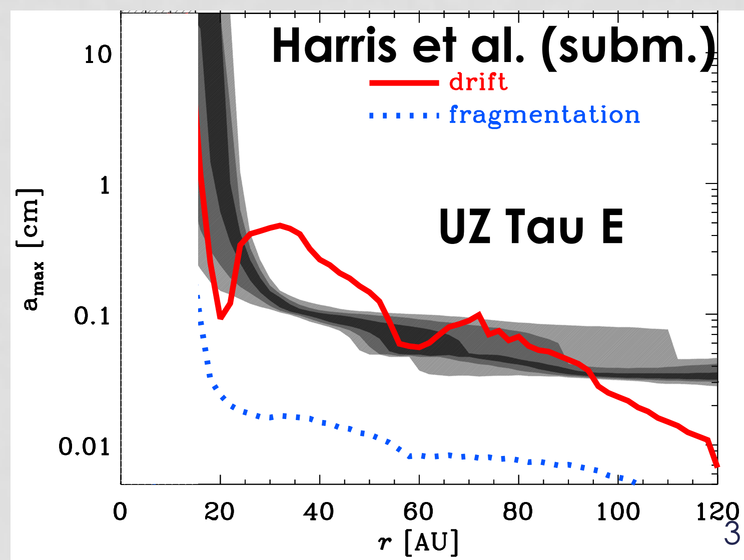
Pérez et al. (2012)

Similar constraints in many different disks









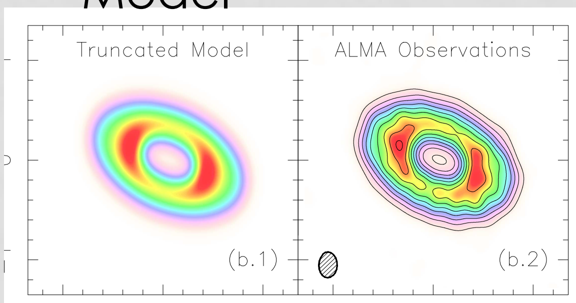
Some Future Work with ALMA

Future work: Transitional Disks

Truncated Model

Simulation

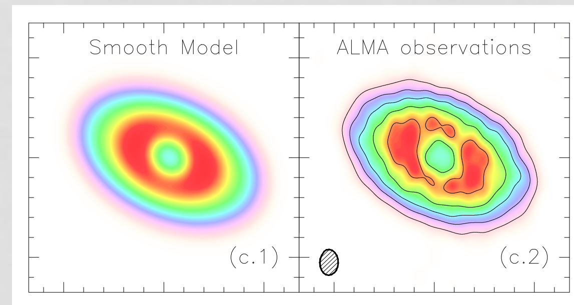
Planets!

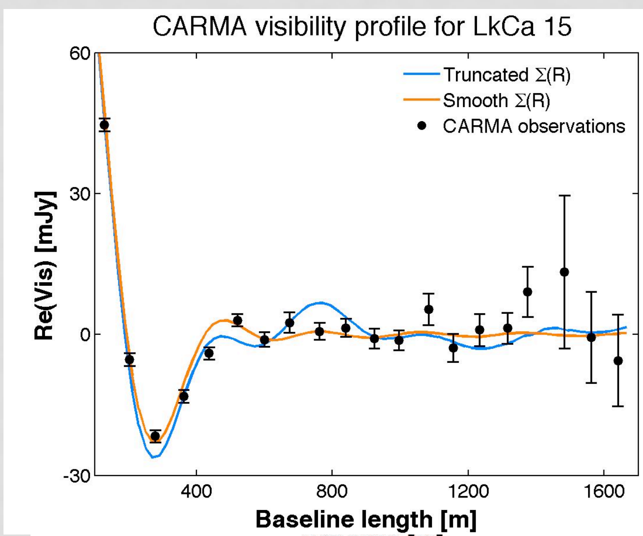


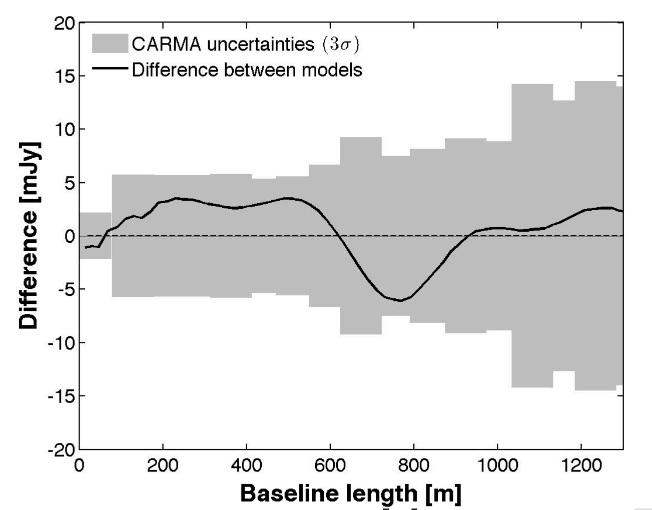
Smooth Model

Simulation

Grain growth!

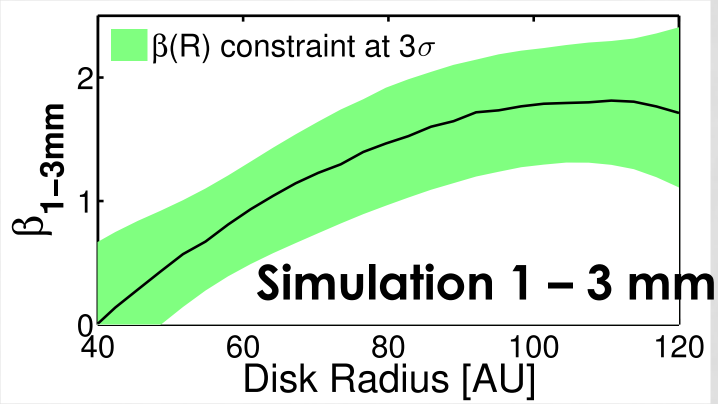


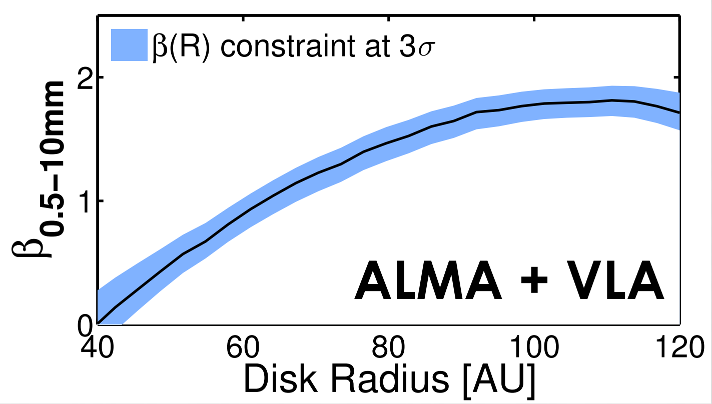




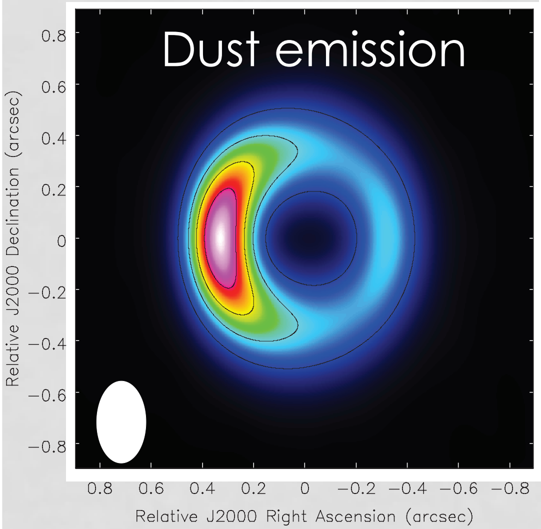
The future with ALMA and VLA

- Significant improvement in current constraints



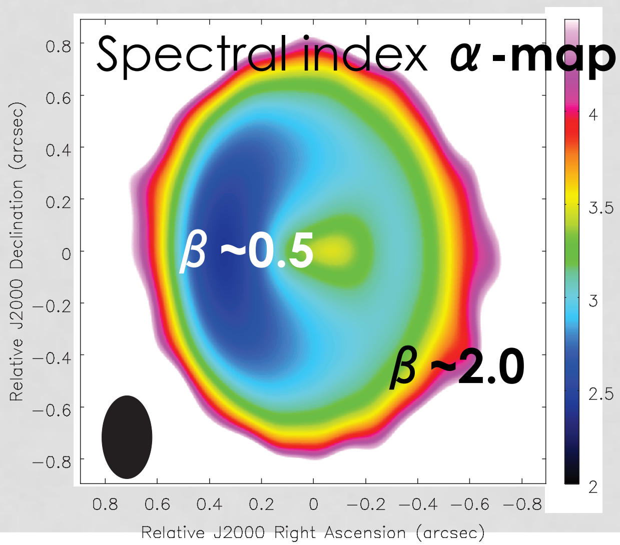


The future with ALMA and VLA



Azimuthal dust trapping

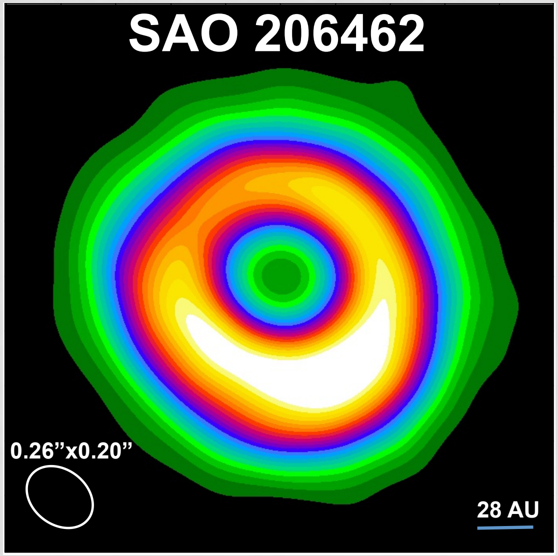
Birnstiel et al. (2013)



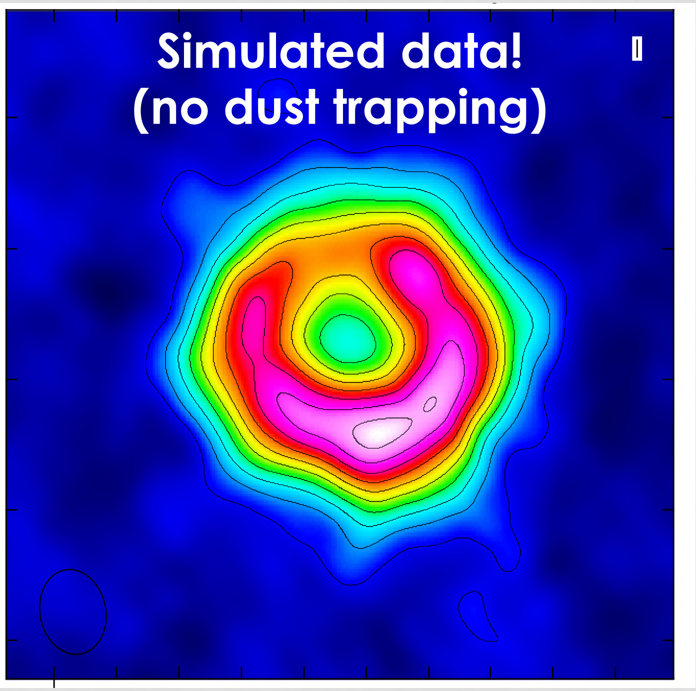
- Dust trapping mechanisms:
  - e.g. planet opening a gap
  - expect asymmetries
- Prediction: grain growth should occur within asymmetries
- Expect segregation of dust particle size: radially (Pinilla et al., 2012) and azimuthally (Birnstiel et al. 2013)
  - 2D constraints on β (R)

The future with ALMA and VLA

- **ALMA** observations at 0.45 mm



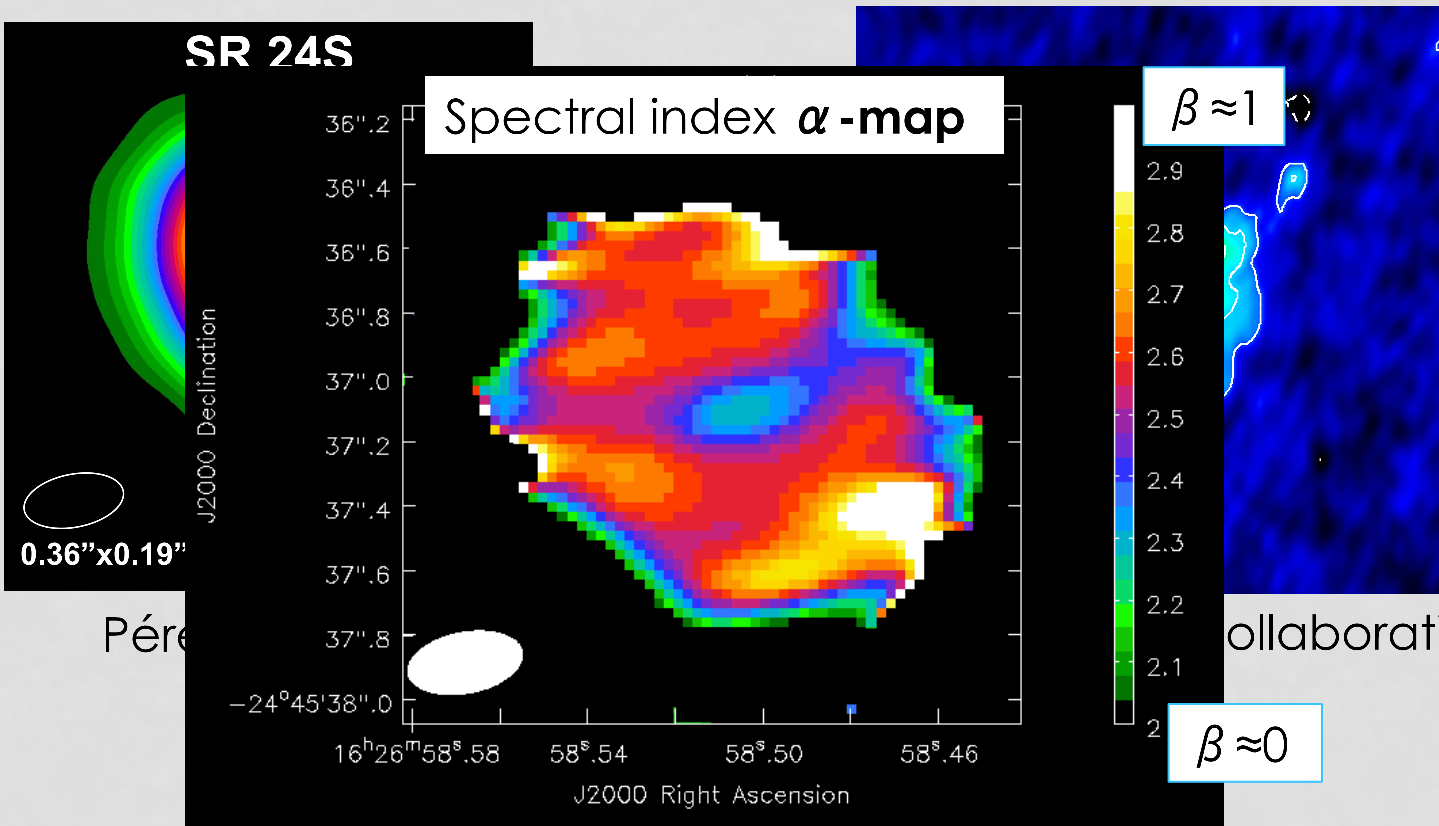
- Observational test of particle trapping with the **VLA**



  - 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



Pére

ollaboration

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 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