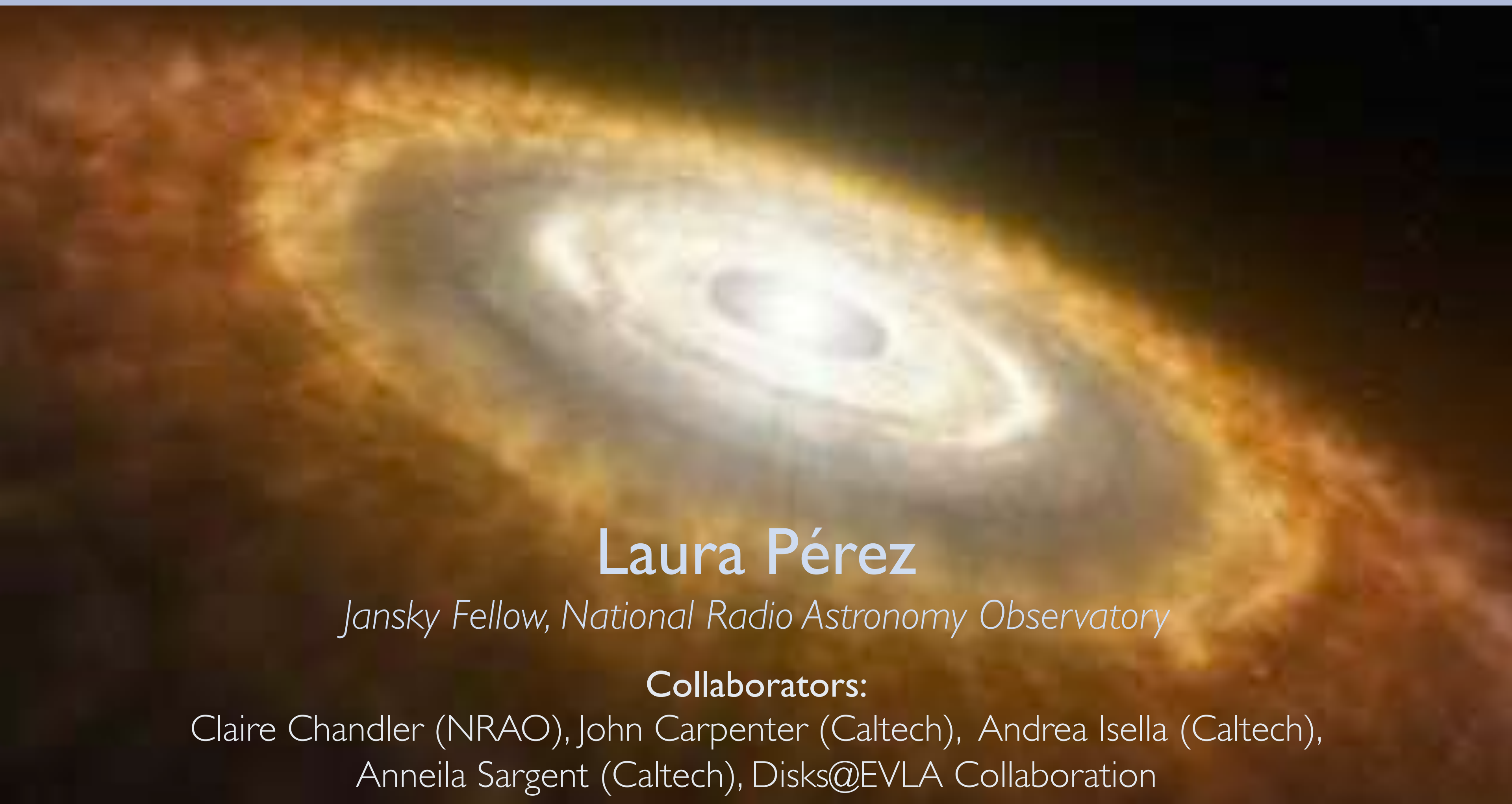
Studying the Origins of Stars and their Planetary Systems with ALMA & VLA

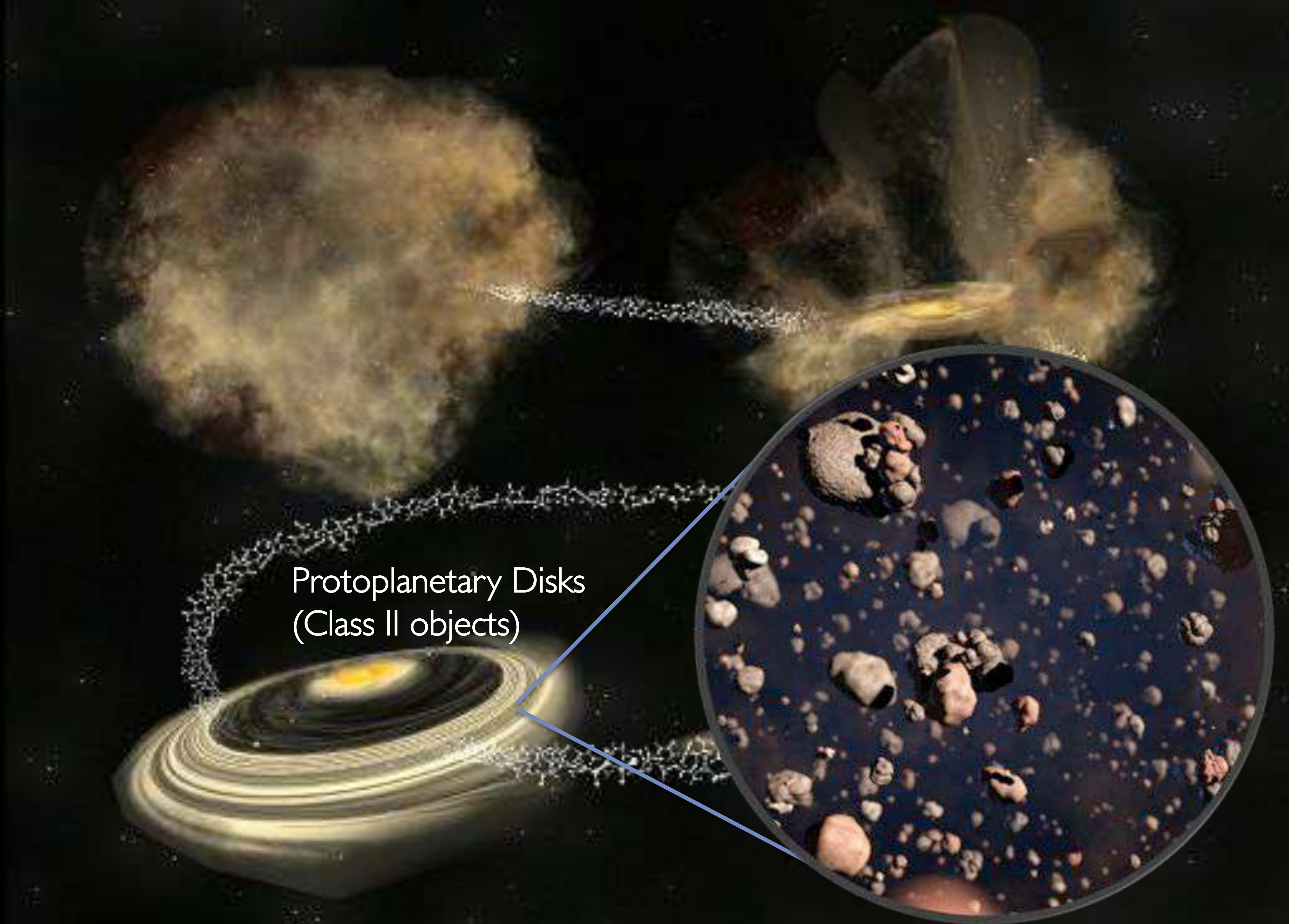
14th Synthesis Imaging Workshop



Laura Pérez

Jansky Fellow, National Radio Astronomy Observatory

Collaborators:
Claire Chandler (NRAO), John Carpenter (Caltech), Andrea Isella (Caltech),
Anneila Sargent (Caltech), Disks@EVLA Collaboration


Protoplanetary Disks
(Class II objects)

From ISM Dust to Planetary Systems

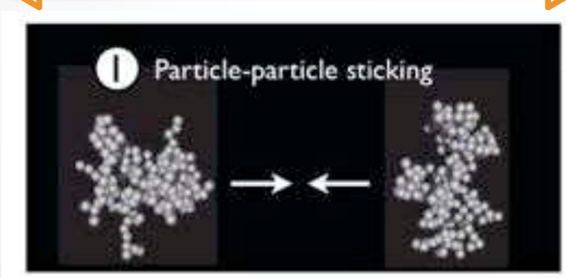
14 orders of magnitude growth !

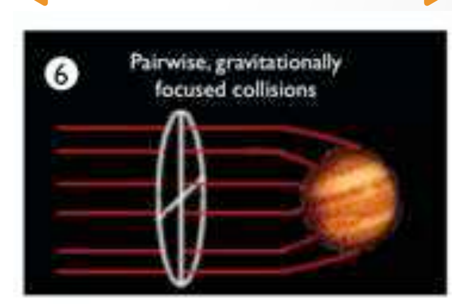
Size = μ m   mm   m   km   Mm

Interstellar Medium Dust

?

Planets

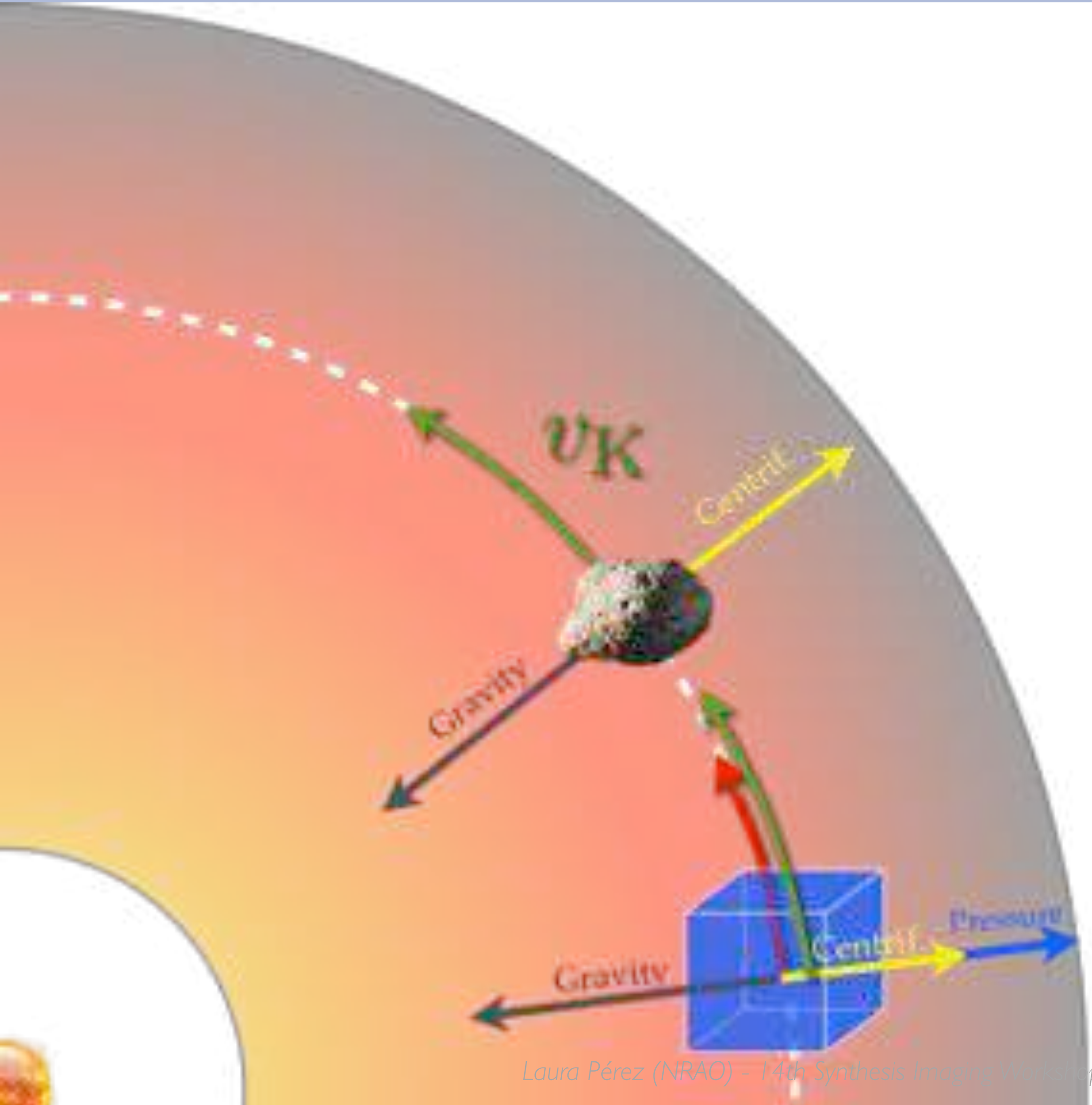




Adapted from Chiang & Youdin (2009)

Dust Growth: Modulated by the Gas

Dust transport impacts its growth

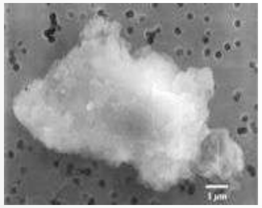


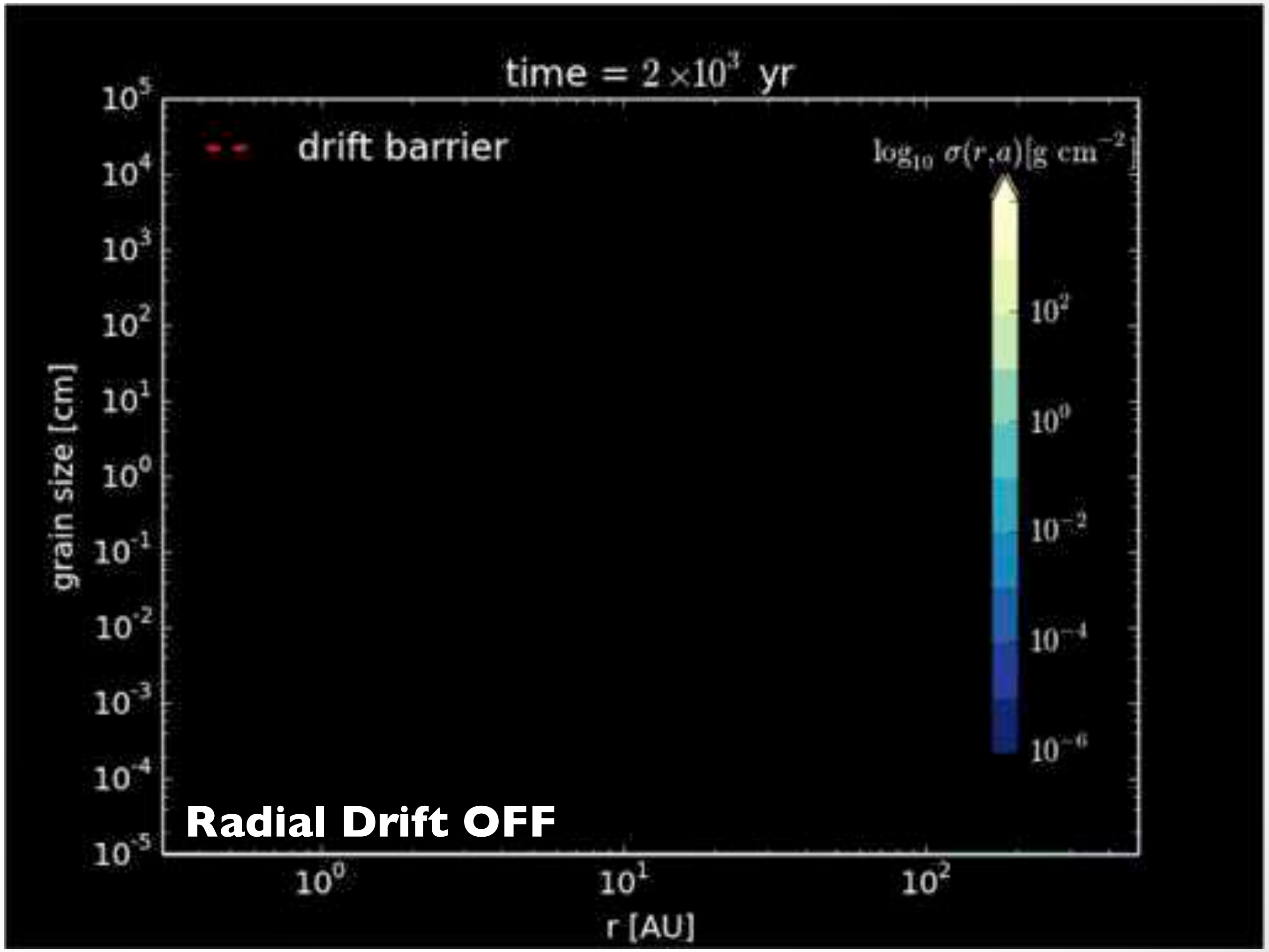
A problem:
The radial drift of solids

c/o T. Birnstiel

Trying to Model Dust Growth and Evolution

Without drift & fragmentation, growth proceeds to large bodies easily

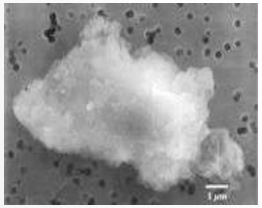




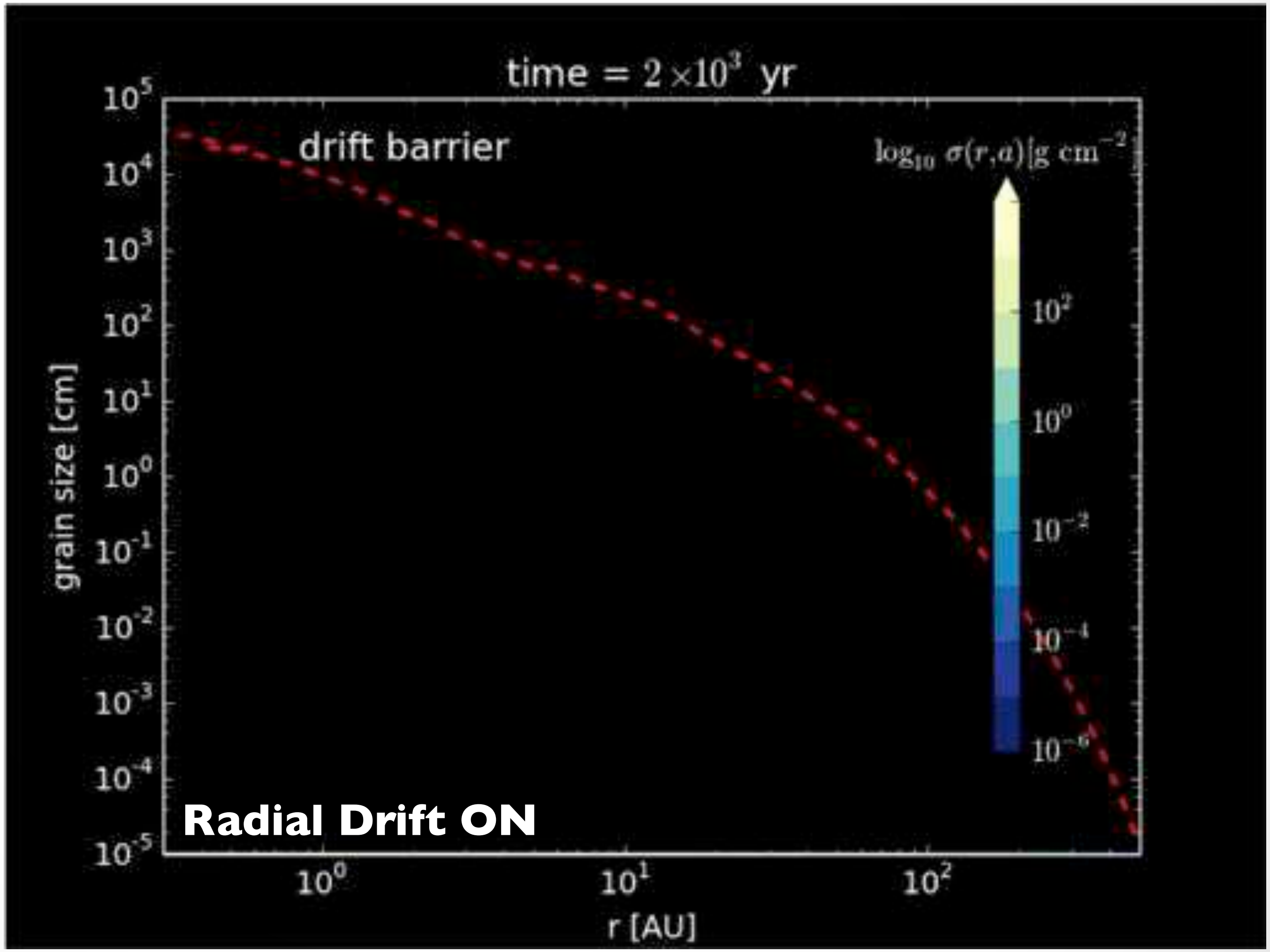
Birnstiel et al. (2010, 2012)

Trying to Model Dust Growth and Evolution

Radial drift limits population to < cm-size in a short timescale



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



Birnstiel et al. (2010, 2012)

From ISM Dust to Planetary Systems

14 orders of magnitude growth !

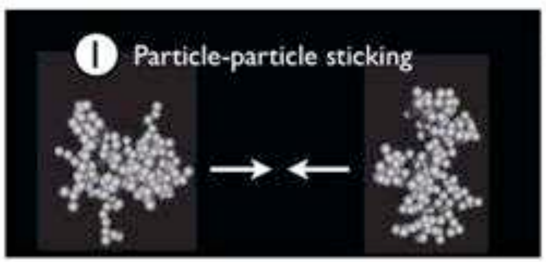
Size = μm — mm — m — km — Mm

ISM Dust

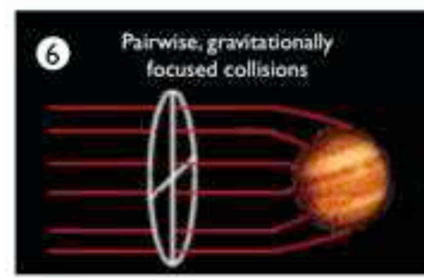
mm/cm observations

?

Planets

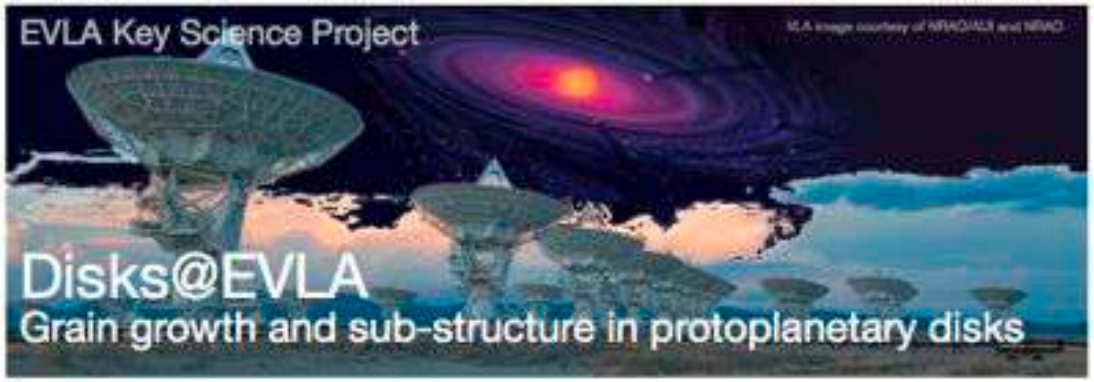


Radial drift barrier
&
Fragmentation barrier



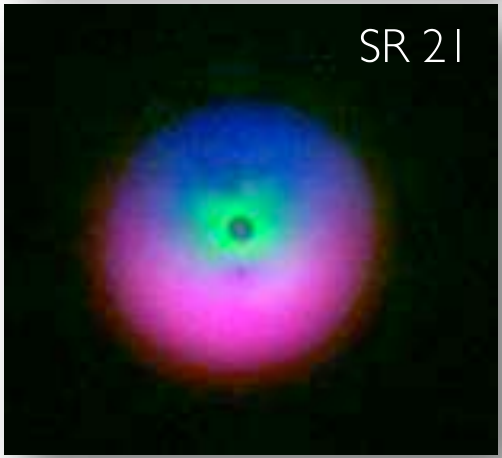
Adapted from Chiang & Youdin (2009)

Exploring this problem with ALMA & VLA



PI: Claire Chandler (NRAO)
S. Andrews (CfA)
N. Calvet (Michigan)
J. Carpenter (Caltech)
S. Corder (ALMA)
A. Deller (ASTRON)
C. Dullemond (MPIA)
J. Greaves (St. Andrews)
T. Henning (MPIA)
A Isella (Caltech/Rice)
W. Kwon (SRON)
J. Lazio (JPL)
H. Linz (MPIA)
J. Menu (MPIA)
L. Mundy (Maryland)
L. Pérez (NRAO)
L. Ricci (Caltech)
A. Sargent (Caltech)
S. Storm (Maryland)
L. Testi (ESO)
D. Wilner (CfA)

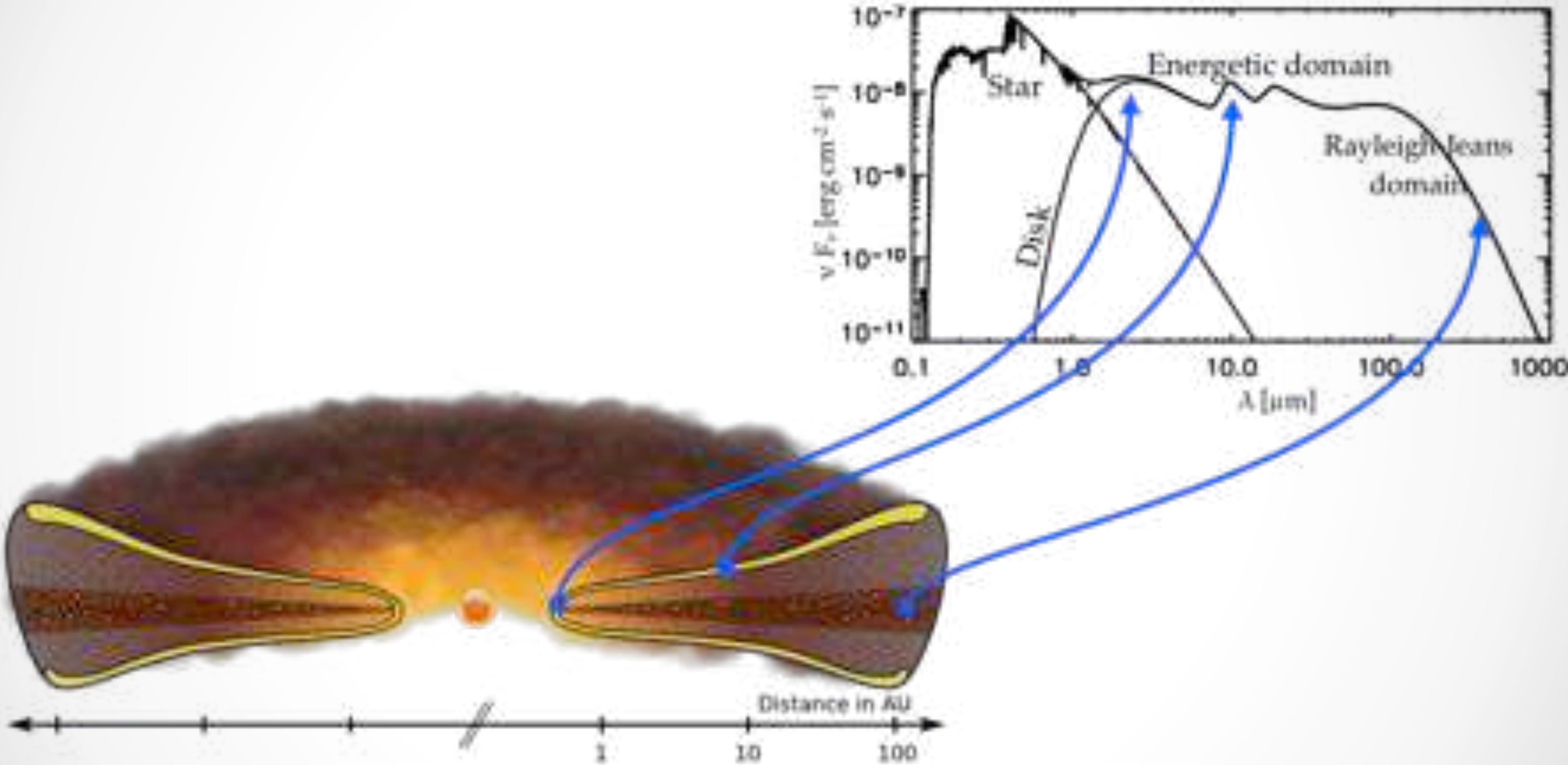
ALMA Cycle 0 observations



Observing Protoplanetary Disks at Radio-wavelengths

Different wavelengths probe different regions

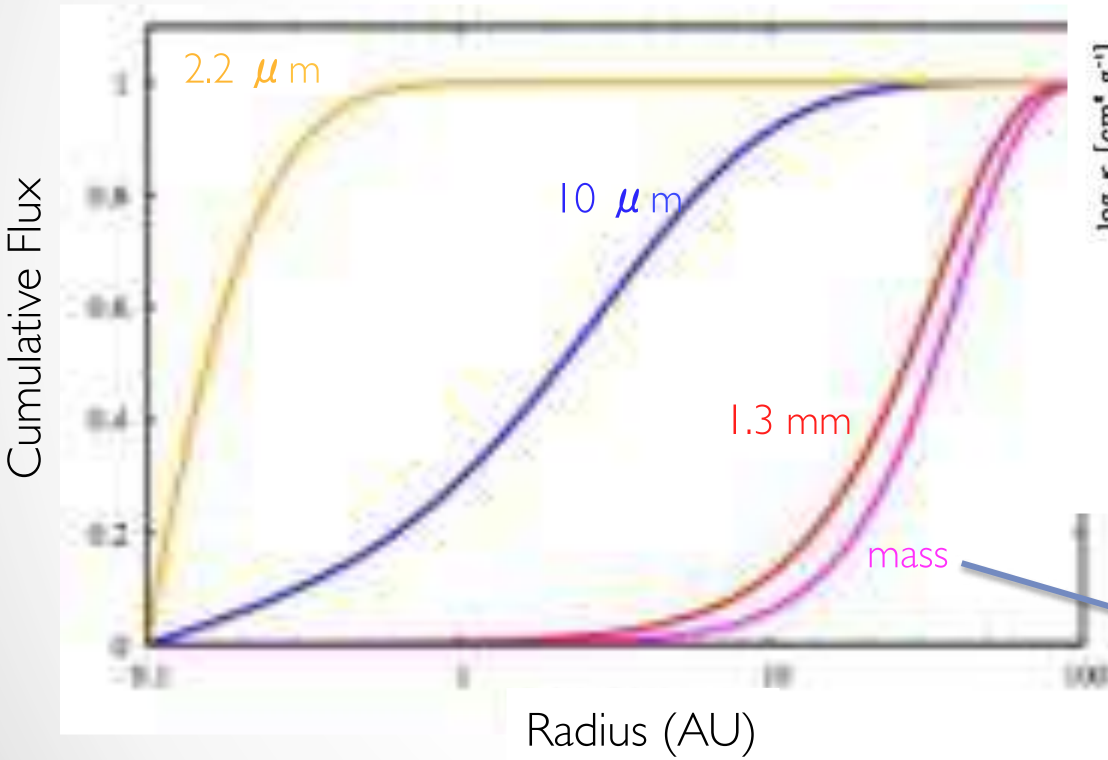
Full extent of disk is better probed at millimeter/centimeter wavelengths

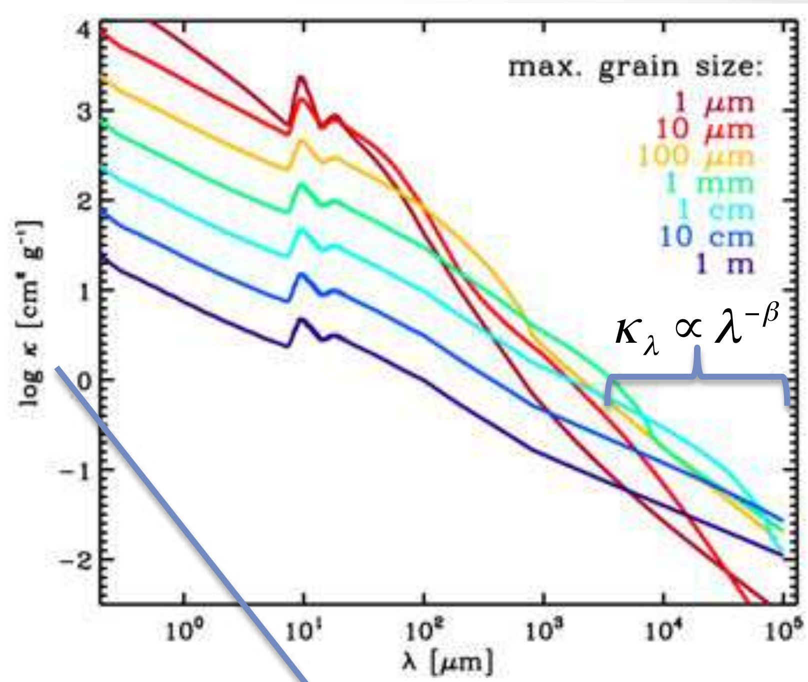


3.0 mm	ALMA
7.0 mm	VLA

Different wavelengths probe different regions

Direct observations of solids require mm/cm observations



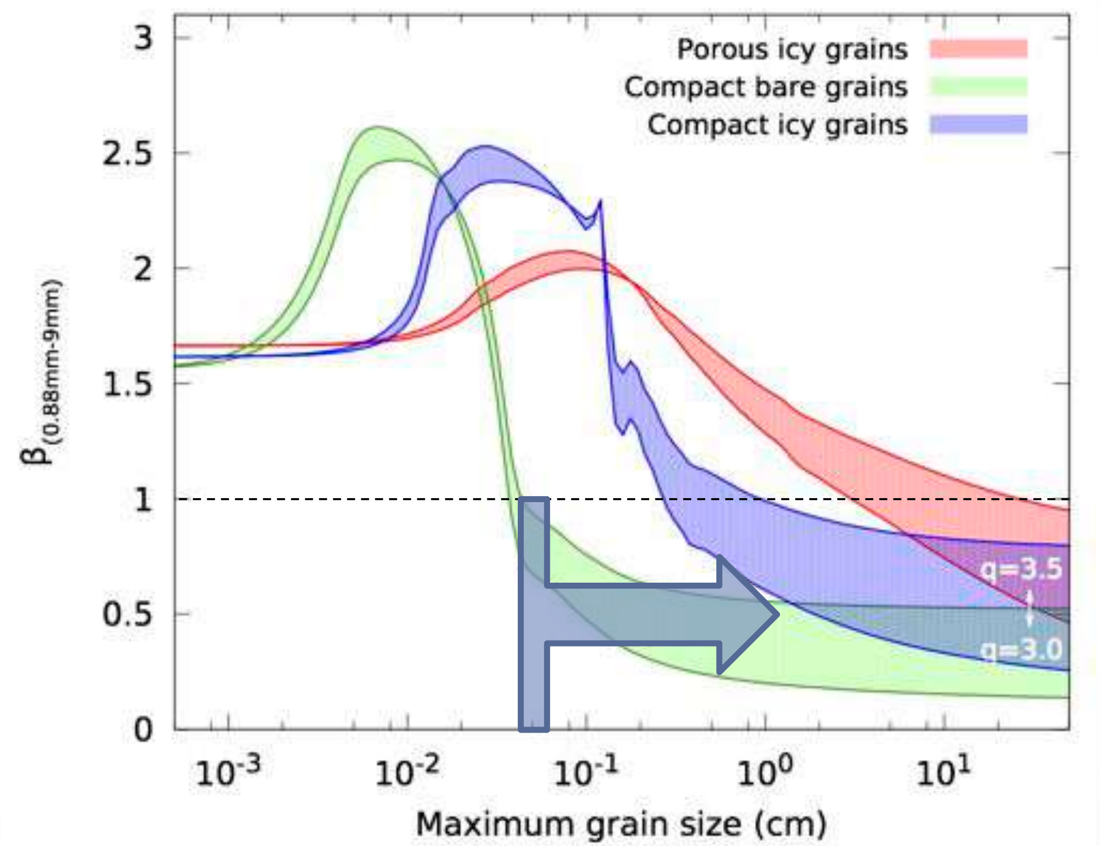


$$S_\nu = M_{disk} \frac{\kappa_\nu B_\nu(T_d)}{D^2}$$

$$\boxed{\Rightarrow S_\nu \propto \nu^{2+\beta}}$$

Emissivity spectral index β : a proxy for grain size

When dust population reaches large a_{max}, dust emission spectrum becomes shallow



Testi et al. (2014)

What do observations tell us about grain growth in protoplanetary disks?

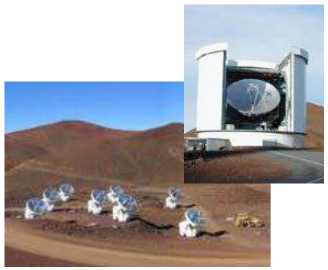
Multi-wavelength observations constrain $\beta_{disks} < 1$

These observations imply growth from ISM sizes (μm) to pebble sizes (cm)

OVRO/CARMA

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

JCMT/SMA/CSO



Beckwith & Sargent (1990, 1991)
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

Beckwith & Sargent (1990)
Dutrey et al. (1996)
Natta et al. (2004)
Schaefer et al. (2009)
Ricci et al. (2010)

ATCA

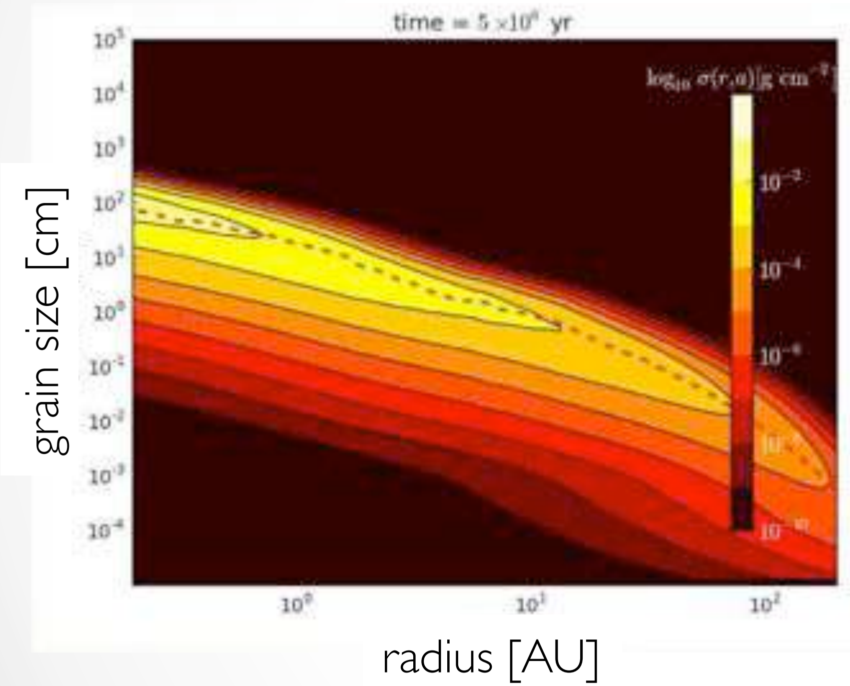
Lommen et al. (2007, 2009)
Ricci et al. (2010)
Ricci et al. (2011a)

… due to lack of angular resolution, these are *global* results.

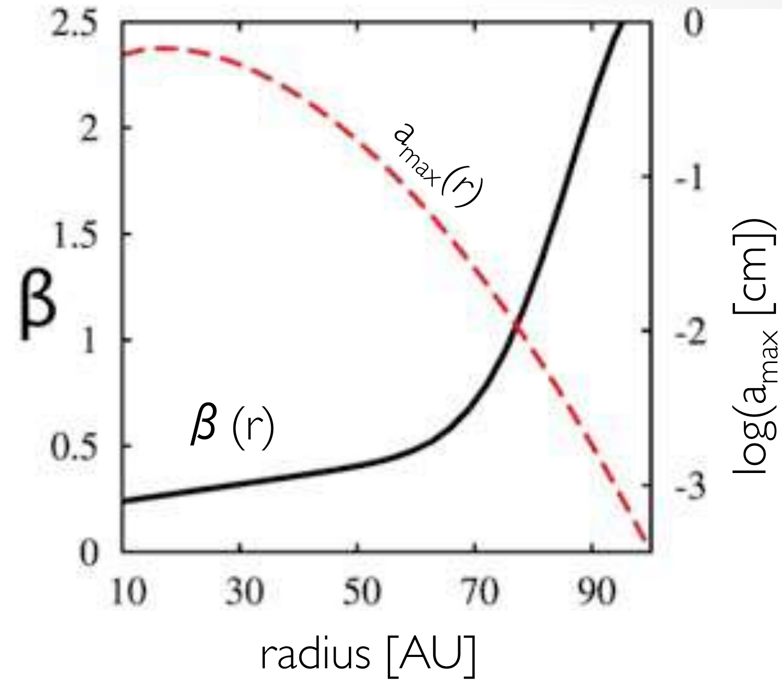
Expectation of radial variations of dust size

Whose observational signature is a gradient in β with orbital radius

Numerical Simulations



Observational Signature



Birnstiel et al. (2010)

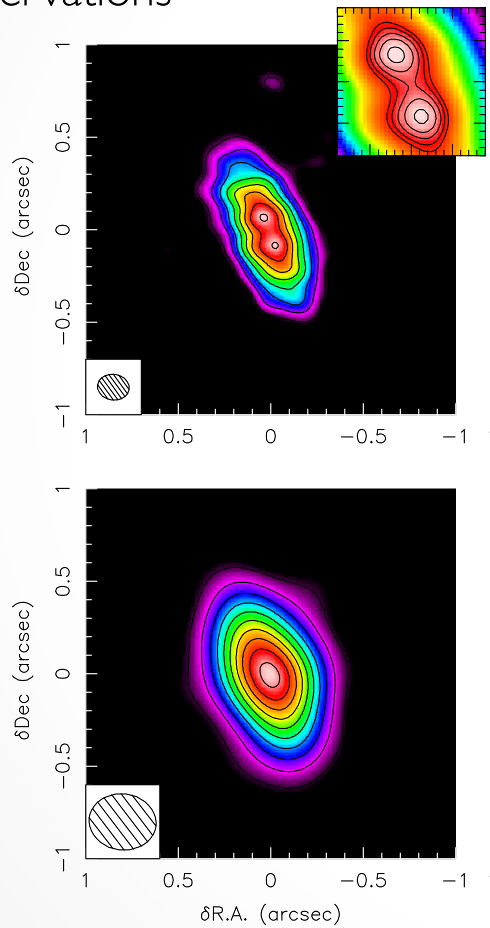
Measuring dust size vs. orbital radius

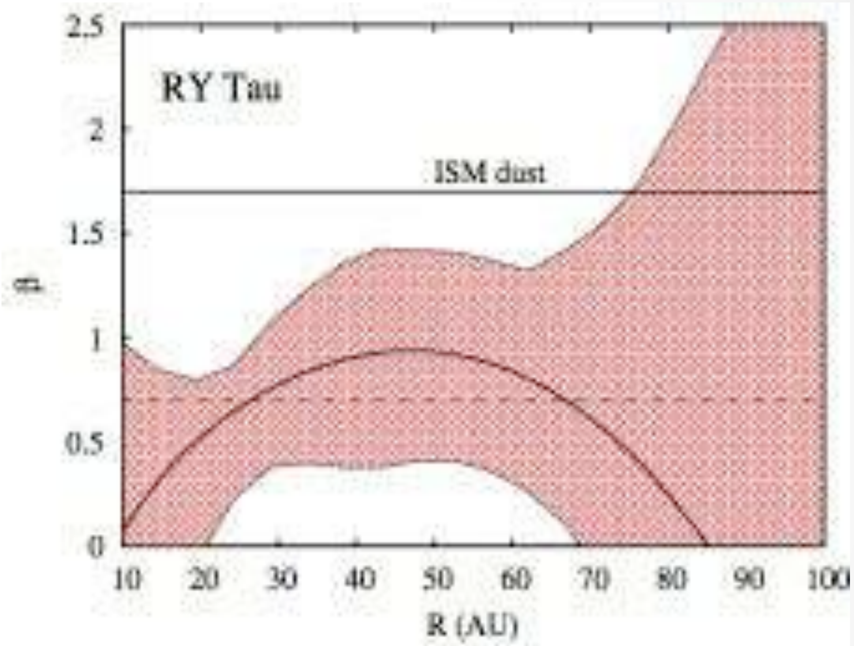
Observations with *good* resolution required to constrain β (R)

CARMA observations

1.3 mm

2.7 mm



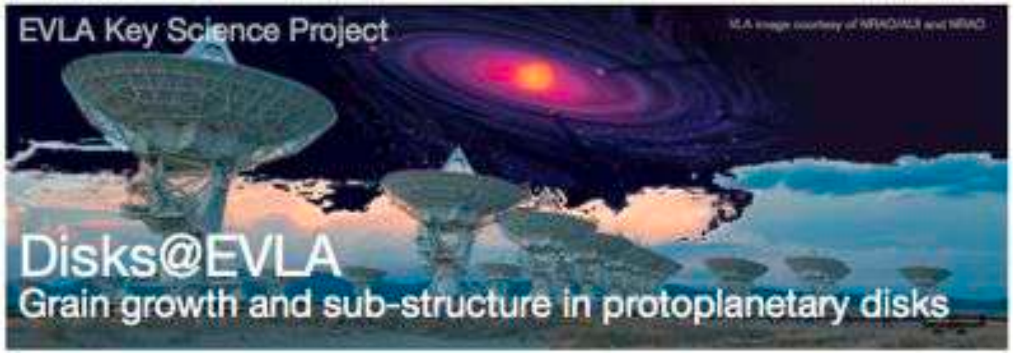


Isella et al. (2010)
see also: Guilloteau et al. (2011),
Banzatti et al. (2011)

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

Disk@EVLA: Measuring dust size vs. orbital radius

Going to longer wavelengths is important to constrain β (R)



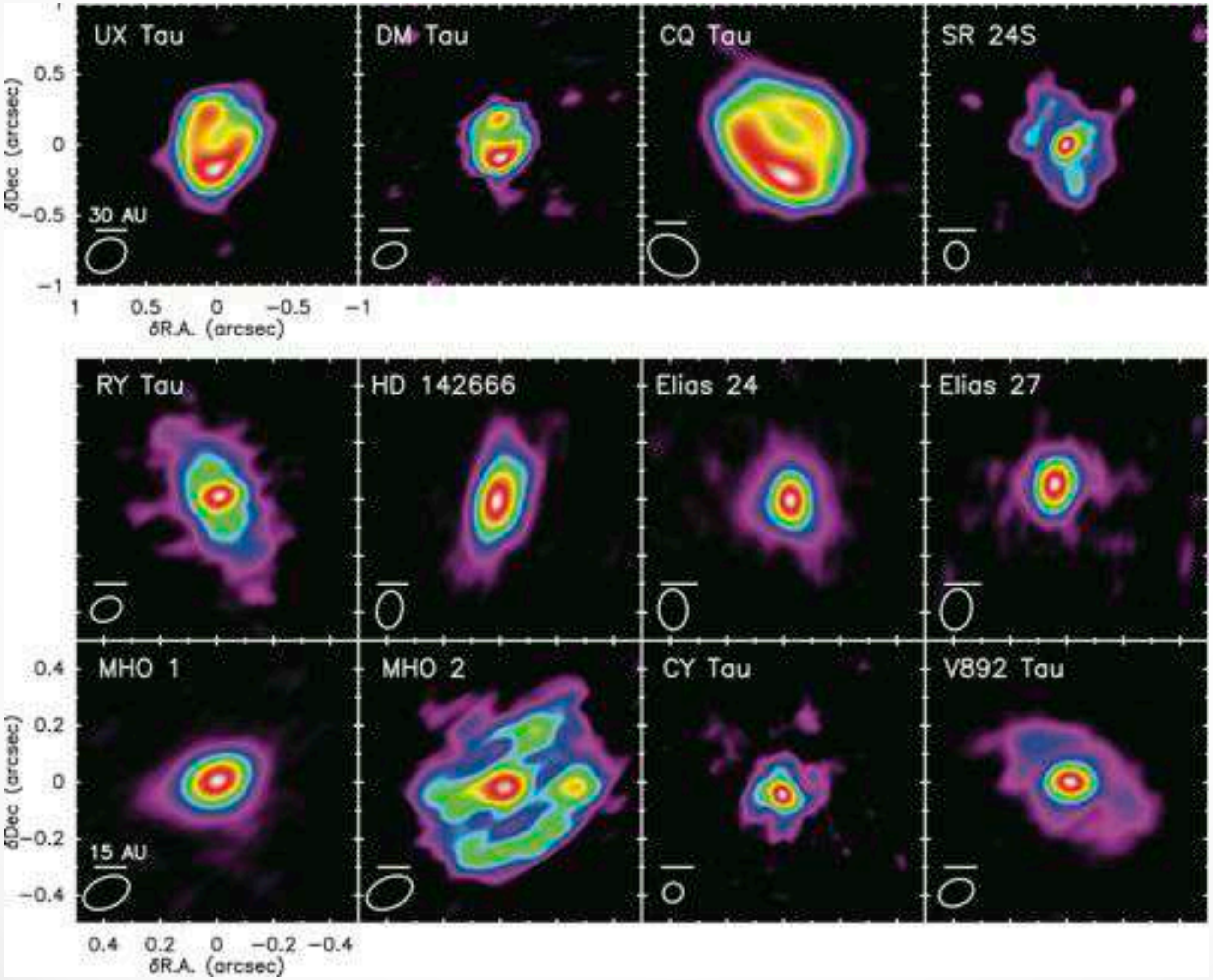
PI: Claire Chandler(NRAO)

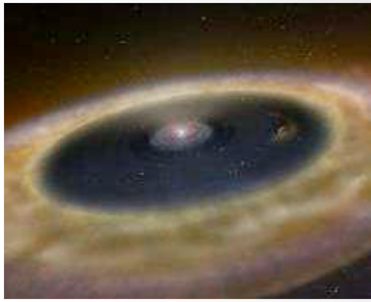
- Determine prevalence of grain growth to cm-sized particles
  - 66 stars (ages ~ 1-10 Myr old)
  - Bright and in nearby star - forming regions (d ~140 pc)
  - Photometry (between 7mm - 6cm) → global β

- Determine the location of large grains in disks
  - Sub-sample imaged with ~0.04" resolution
  - At 7mm/1cm, and at 6cm

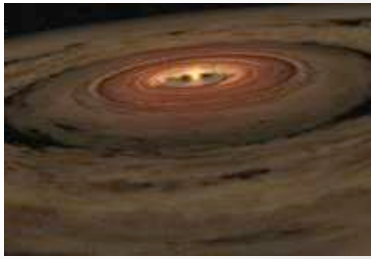
Disk@EVLA: Measuring dust size vs. orbital radius

7 mm/1cm observations with the VLA





Transitional disks

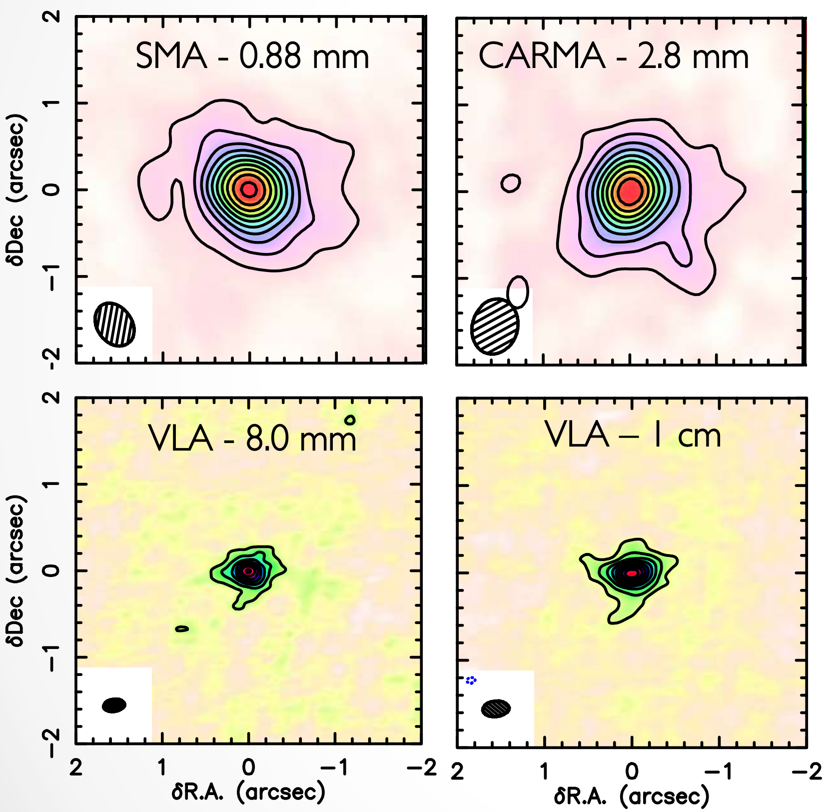


"Full" disks

Grain Growth in the AS 209 disk

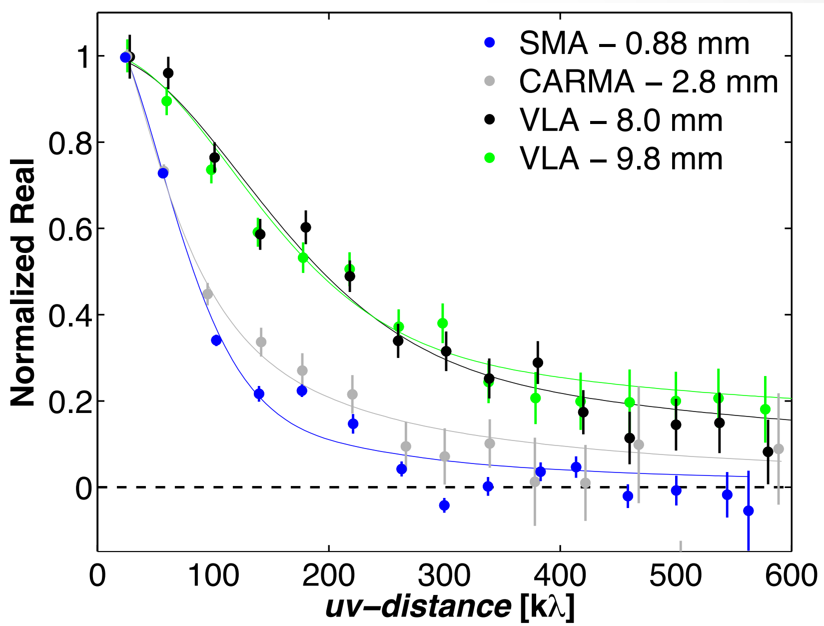
Wavelength-dependent disk structure in AS 209

Image domain



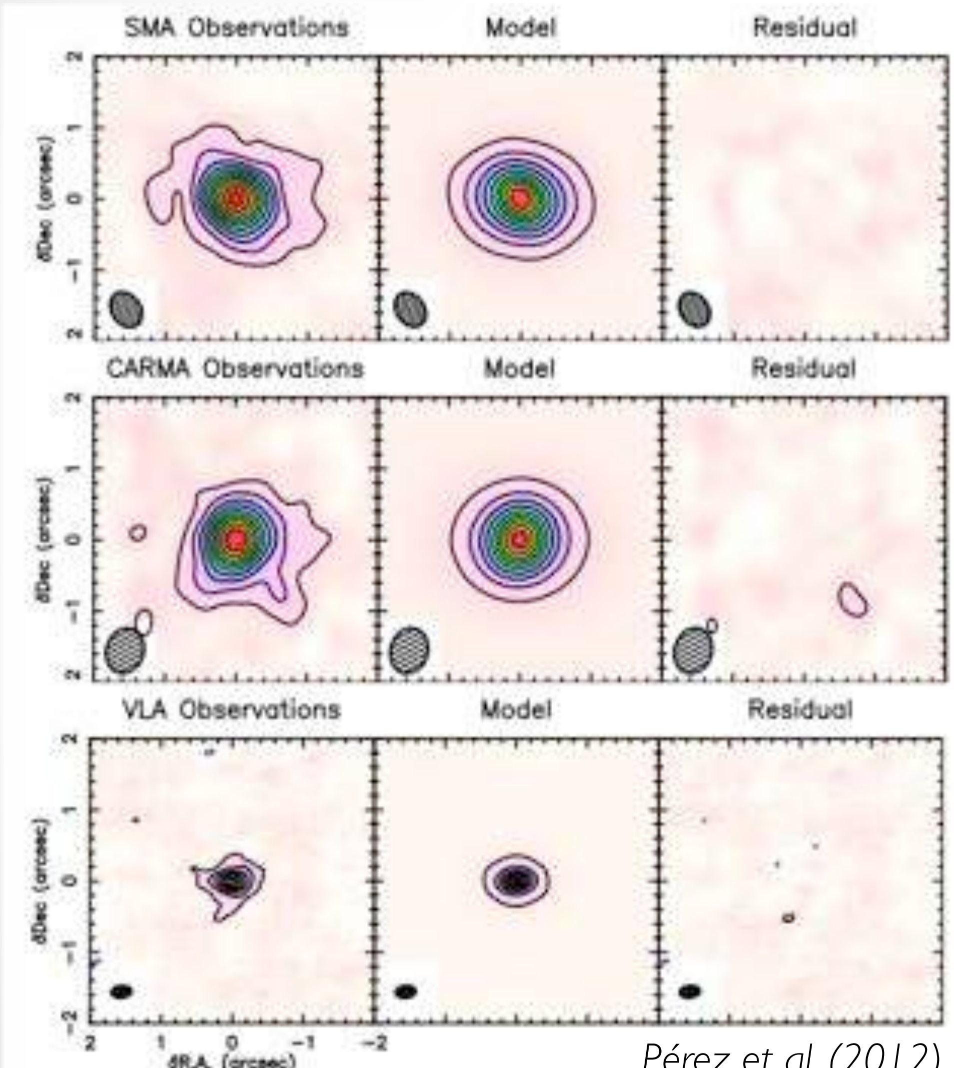
Pérez et al. (2012)

Visibility domain

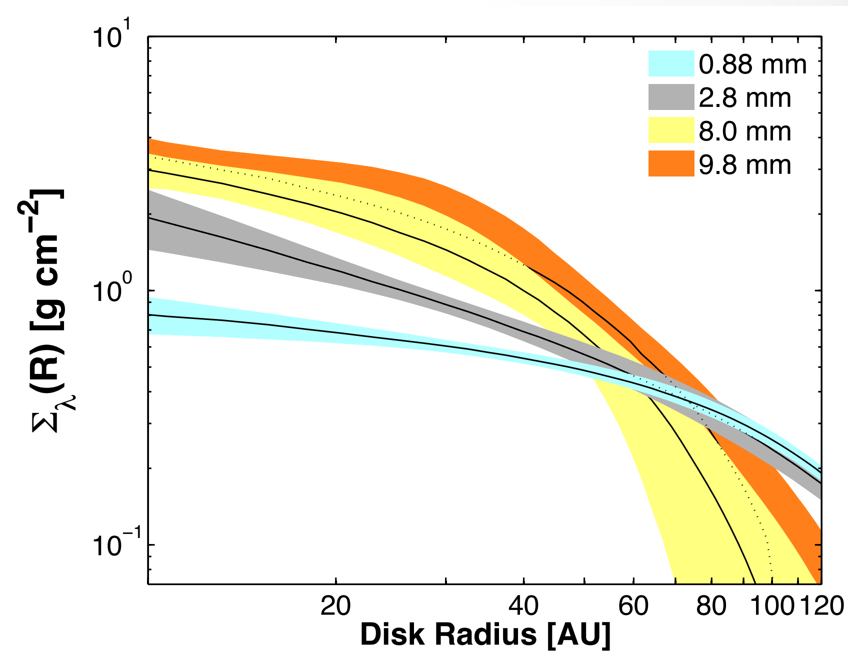


Grain Growth in the AS 209 Disk

Physical disk model constrains $\kappa_\nu(R)$ ←→ $\beta(R)$

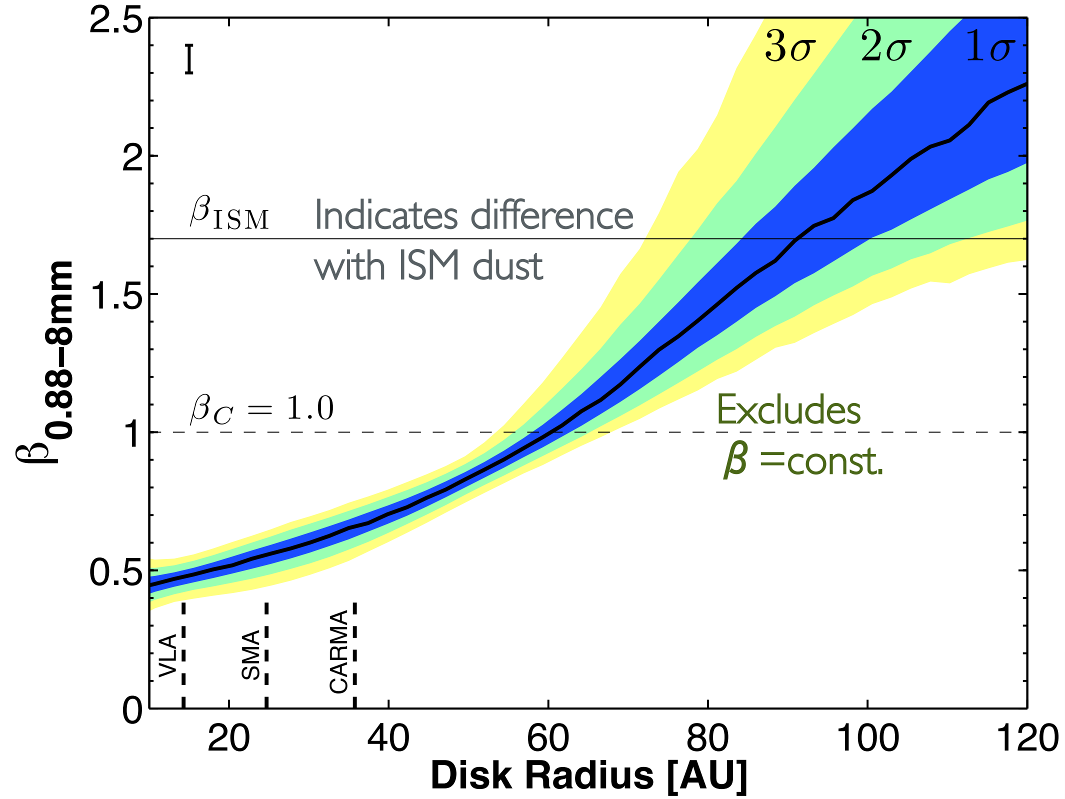


Pérez et al. (2012)



Grain Growth in the AS 209 Protoplanetary Disk

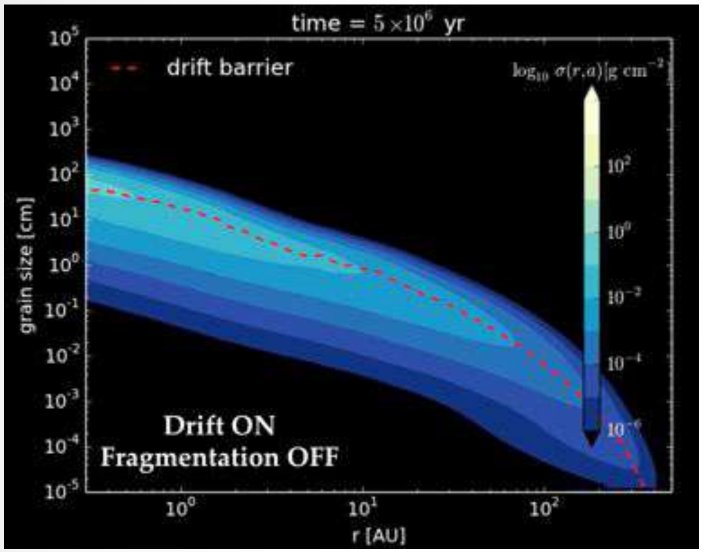
Dust grains in the inner disk are different from those in the outer disk

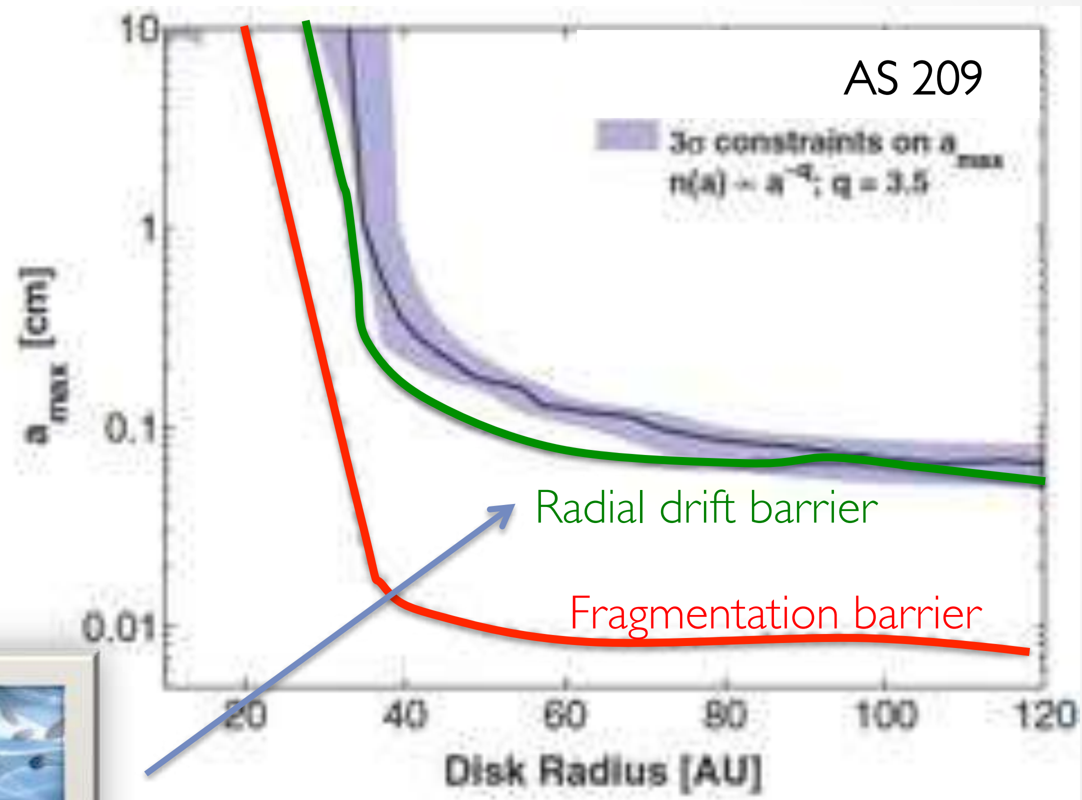


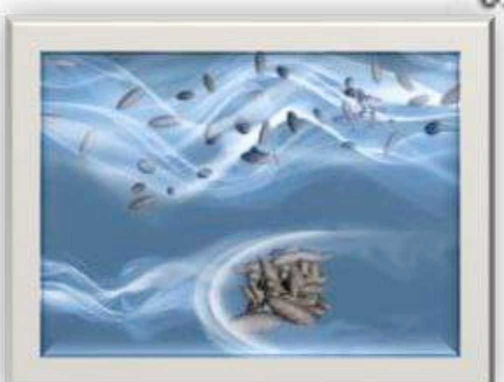
Pérez et al. (2012)

Constraint on Grain Size vs. Orbital Radius

Maximum grain size consistent with a population *limited* by Radial Drift





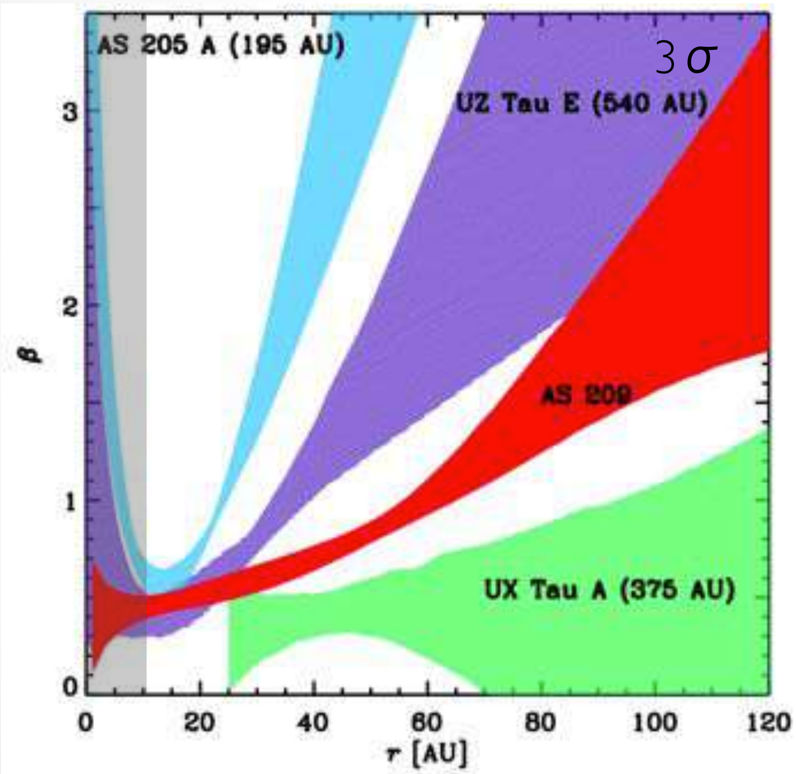


Pérez et al. (2012)

Grain Growth Measured in Many Disks

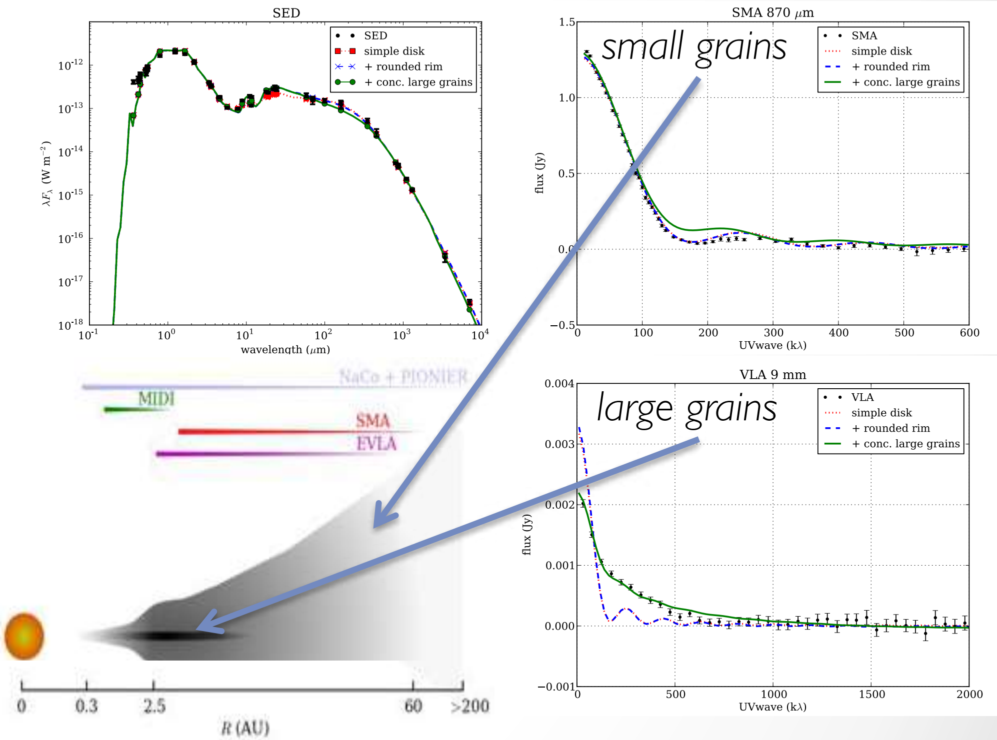
Dust grains in the inner disk are different from those in the outer disk

Disks in binary systems

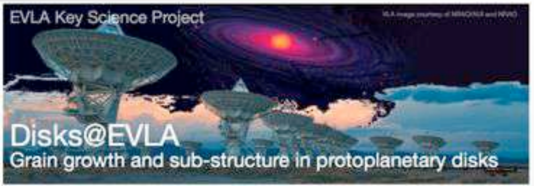


R. Harris PhD Thesis (2013)

TW Hya

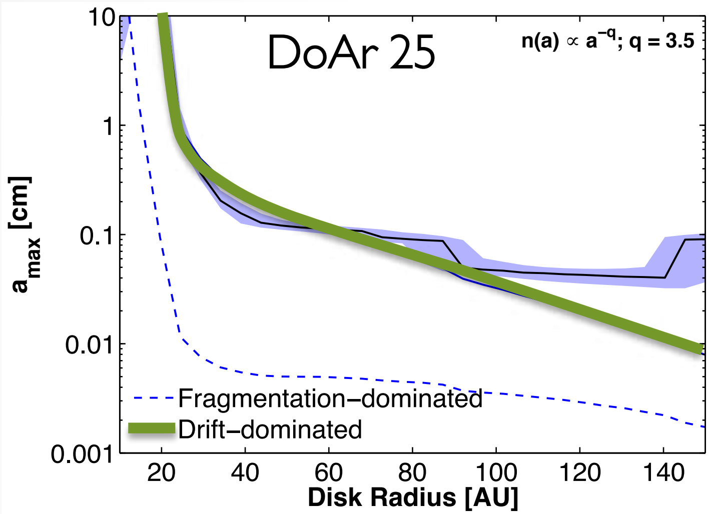


Menu et al. +LP (2014)

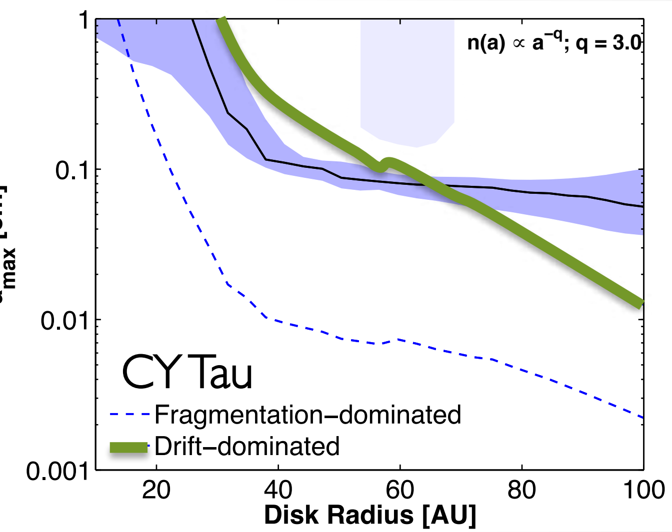


Similar grain size constraints for different disks

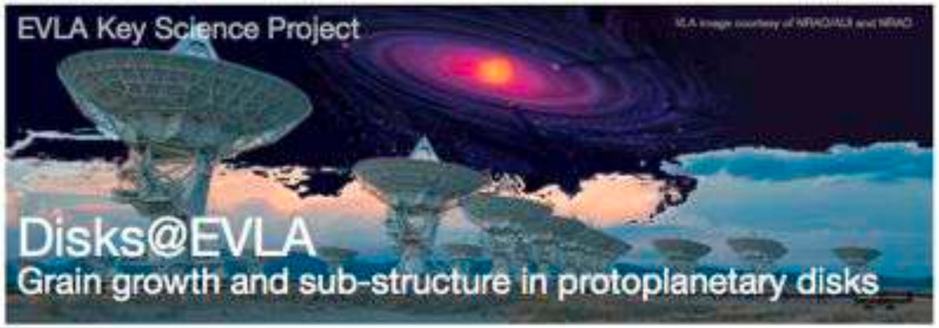
Maximum grain size consistent with a population *limited* by Radial Drift

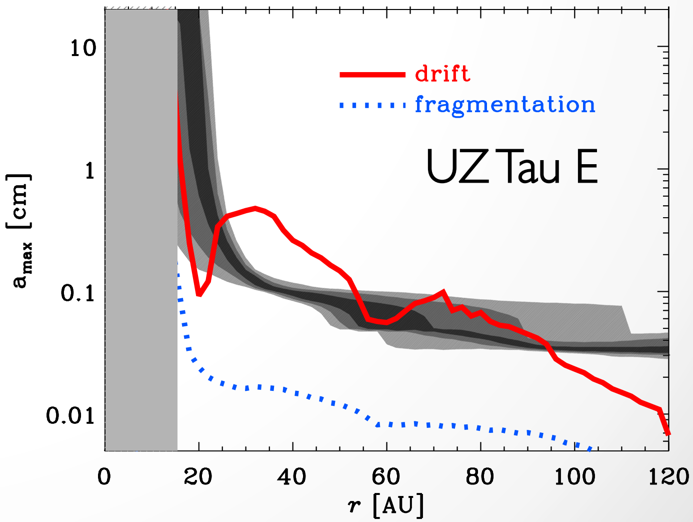


Pérez et al., in prep



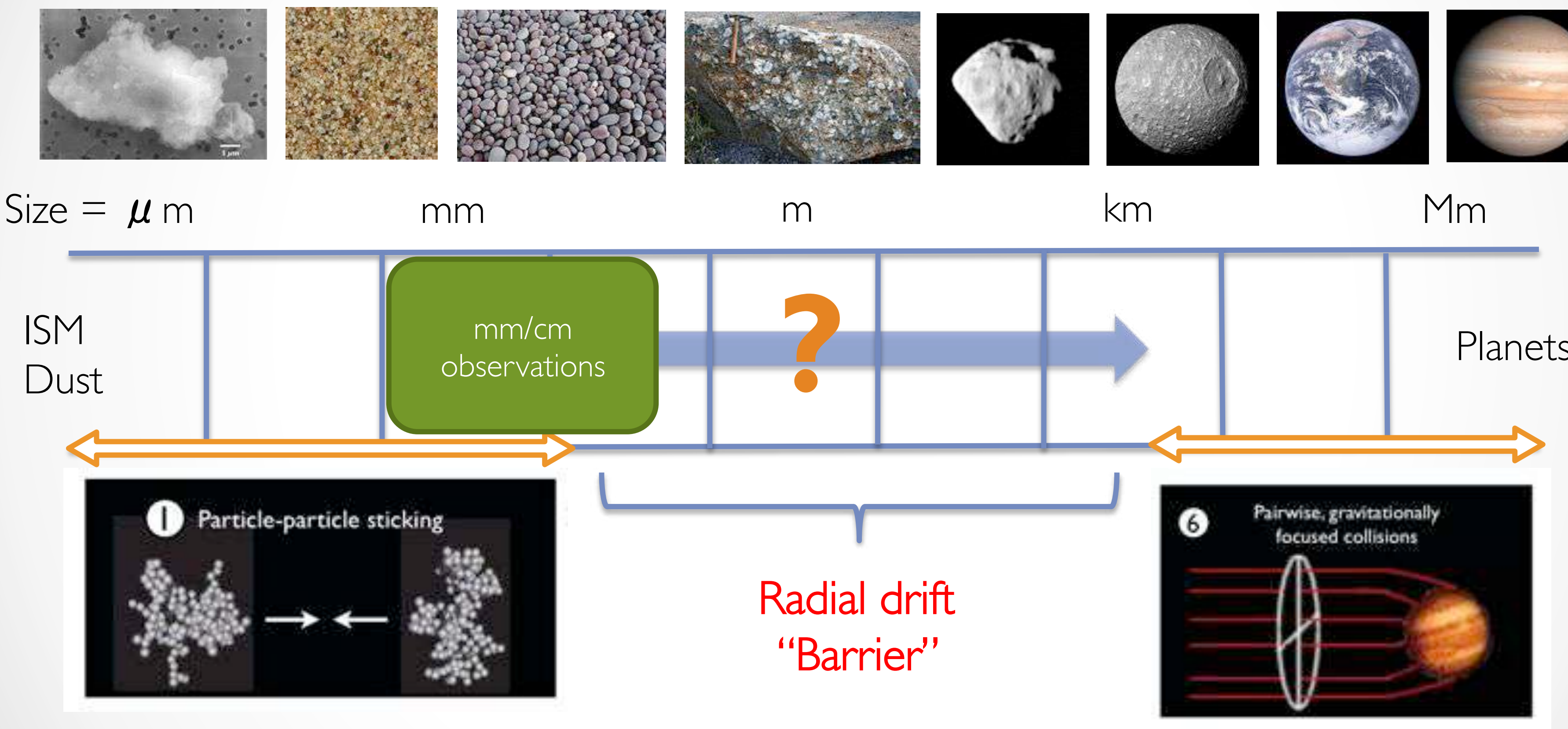
Pérez et al., in prep





From ISM Dust to Planetary Systems

14 orders of magnitude growth !



Adapted from Chiang & Youdin (2009)

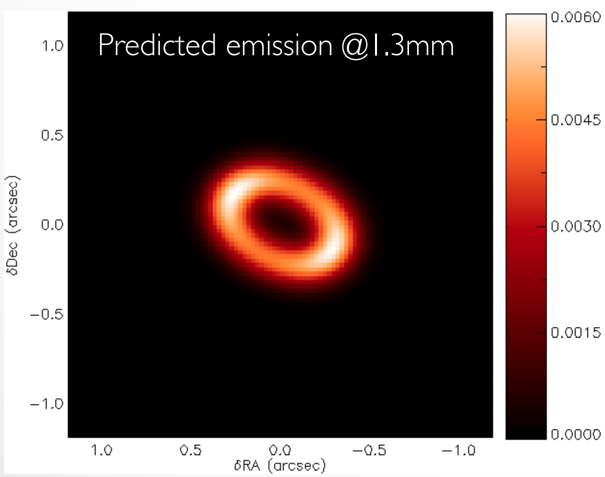
How to overcome the radial drift barrier?

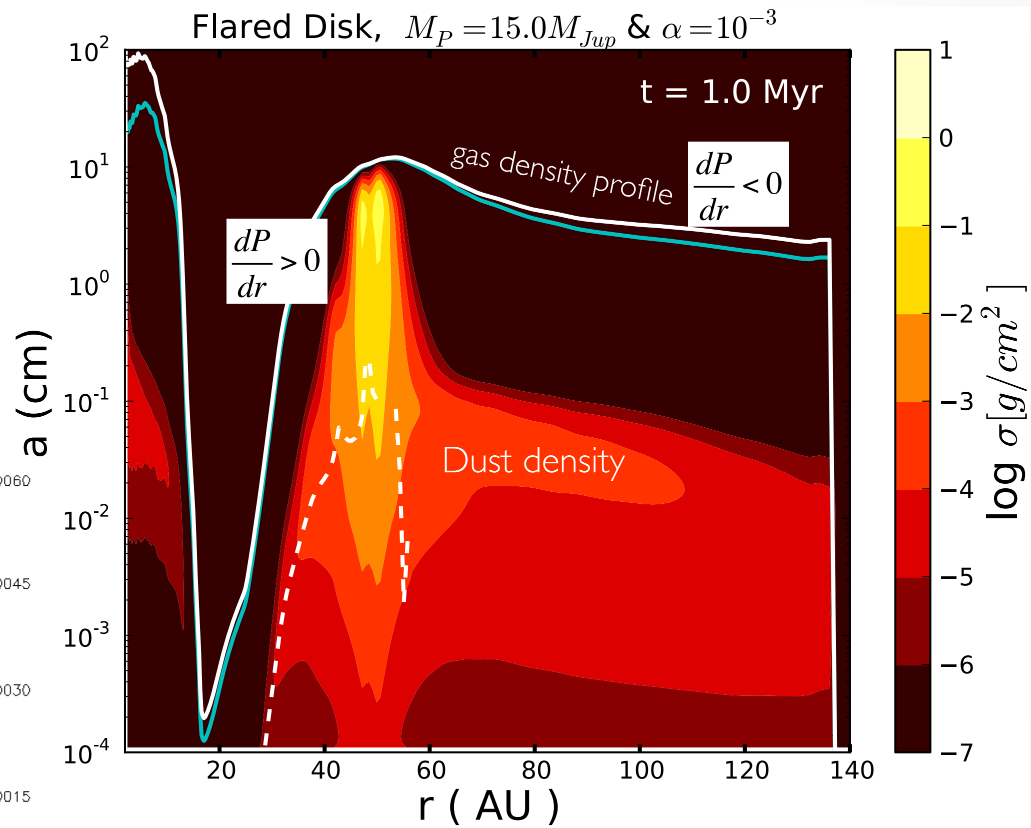
How to overcome the radial drift barrier?

Dust drifts toward pressure maxima → further growth may be possible there

Drift velocity of the dust:

$$v_{r,\,dust} \propto \frac{dP}{dr}$$





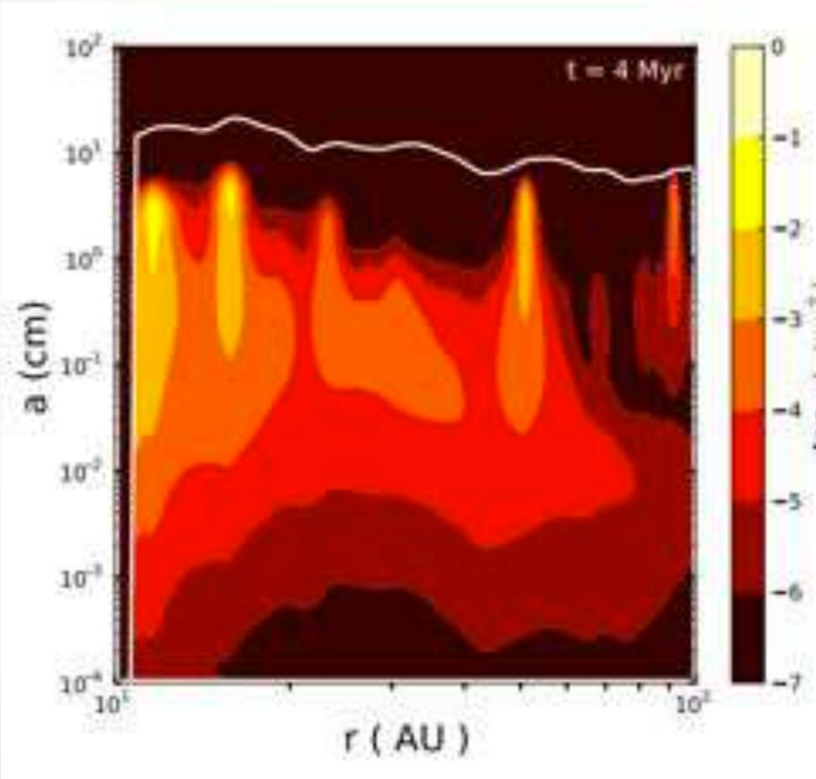
Pinilla et al. (2012a), Birnstiel et al. (2012)

Enhancements in gas density take many forms

Dust drifts toward pressure maxima → further growth may be possible there

Locally

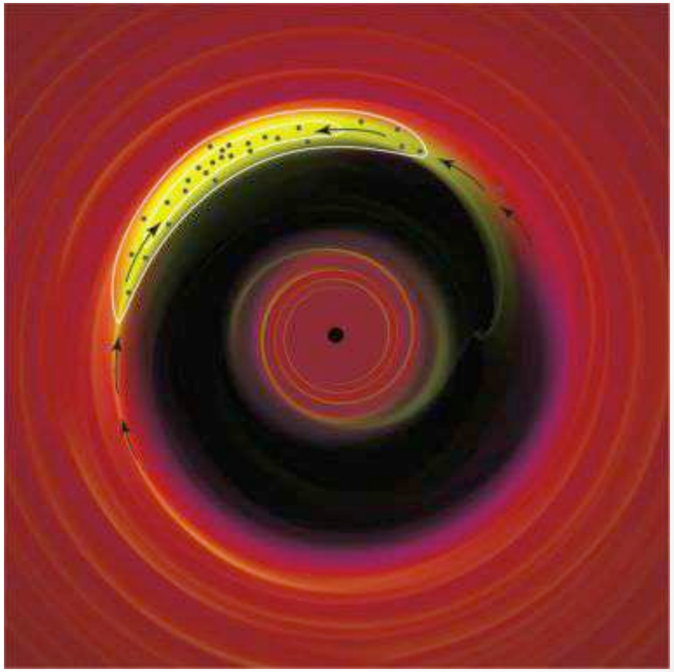
e.g. overdensities from turbulence



Pinilla et al. (2012b)

Globally

e.g. overdensities from sharp boundary that generates instability → vortices

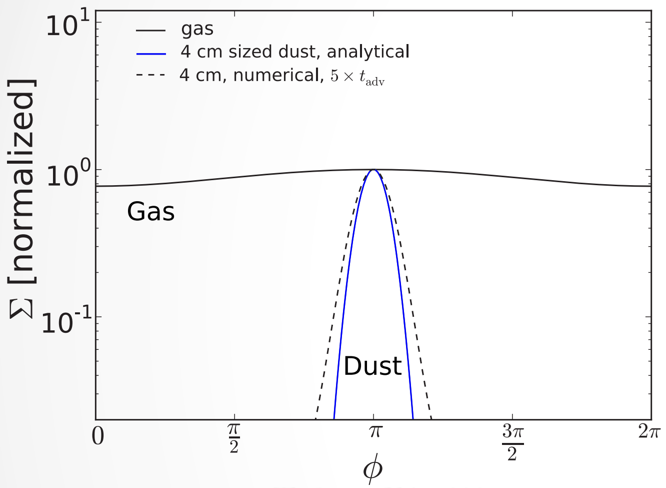


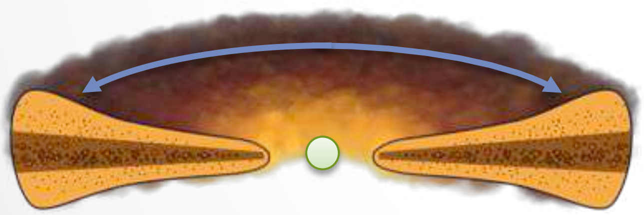
Armitage (2013)

Azimuthal density gradients also trap dust!

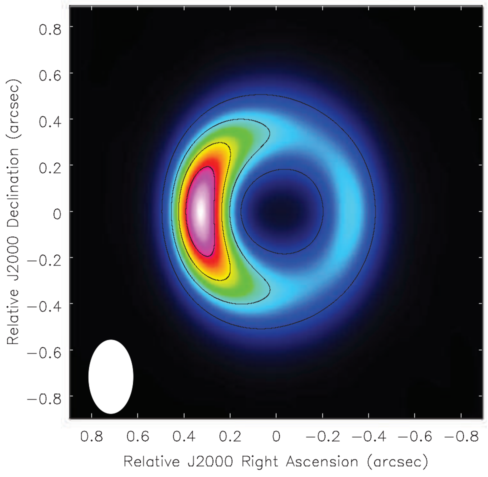
Dust drifts toward pressure maxima → further growth may be possible there

Birnstiel et al. (2013)

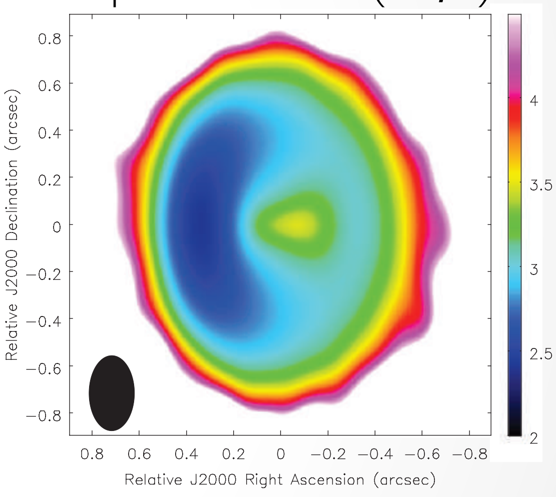




Simulated emission



Simulated spectral index (~ β)



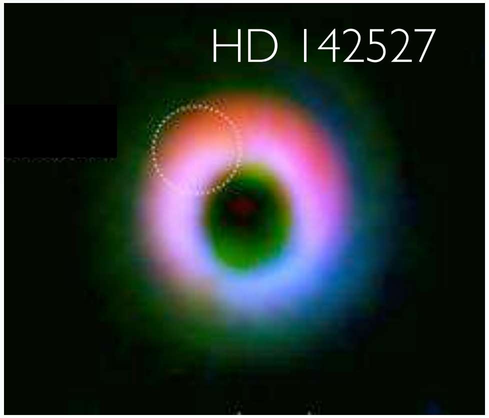
Birnstiel et al. (2013)

Atacama Large Millimeter/sub-millimeter Array is already revolutionizing this field!

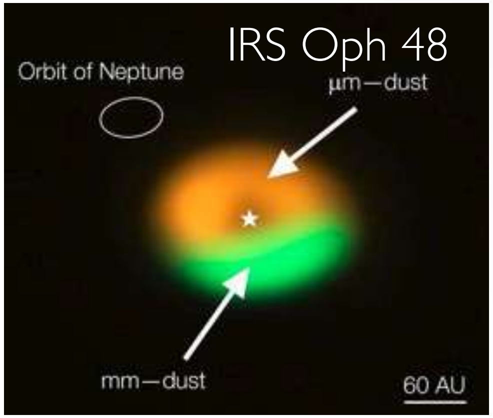
© ALMA Observatory

ALMA reveals asymmetrical structure for mm-dust

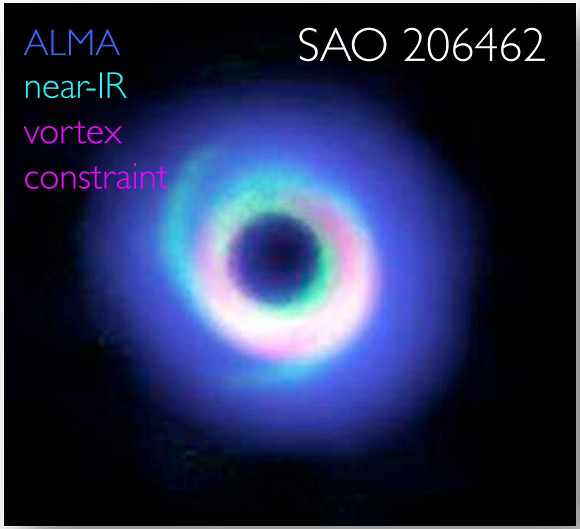
Only possible now thanks to increased sensitivity and phase stability

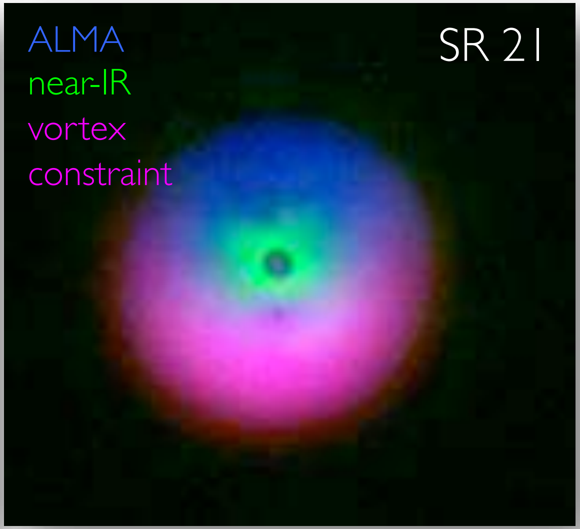


Fukagawa et al. (2013)



Van der Marel et al. (2013)



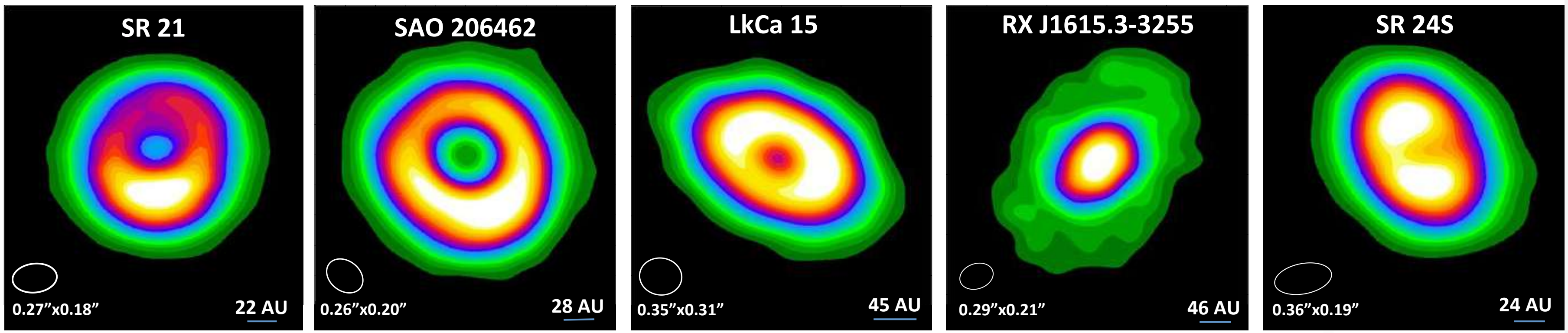


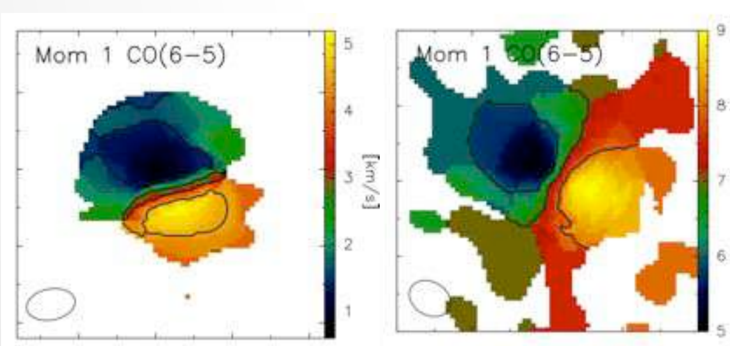
Pérez et al. (2014)

ALMA Survey of disks with cavities

(otherwise known as Transitional Disks)

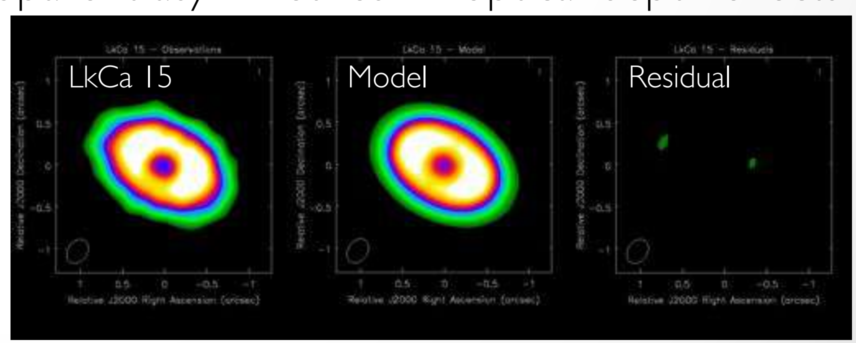
ALMA Cycle 0 observations – 0.45 mm (PI: L. Pérez)





Velocity field → geometry

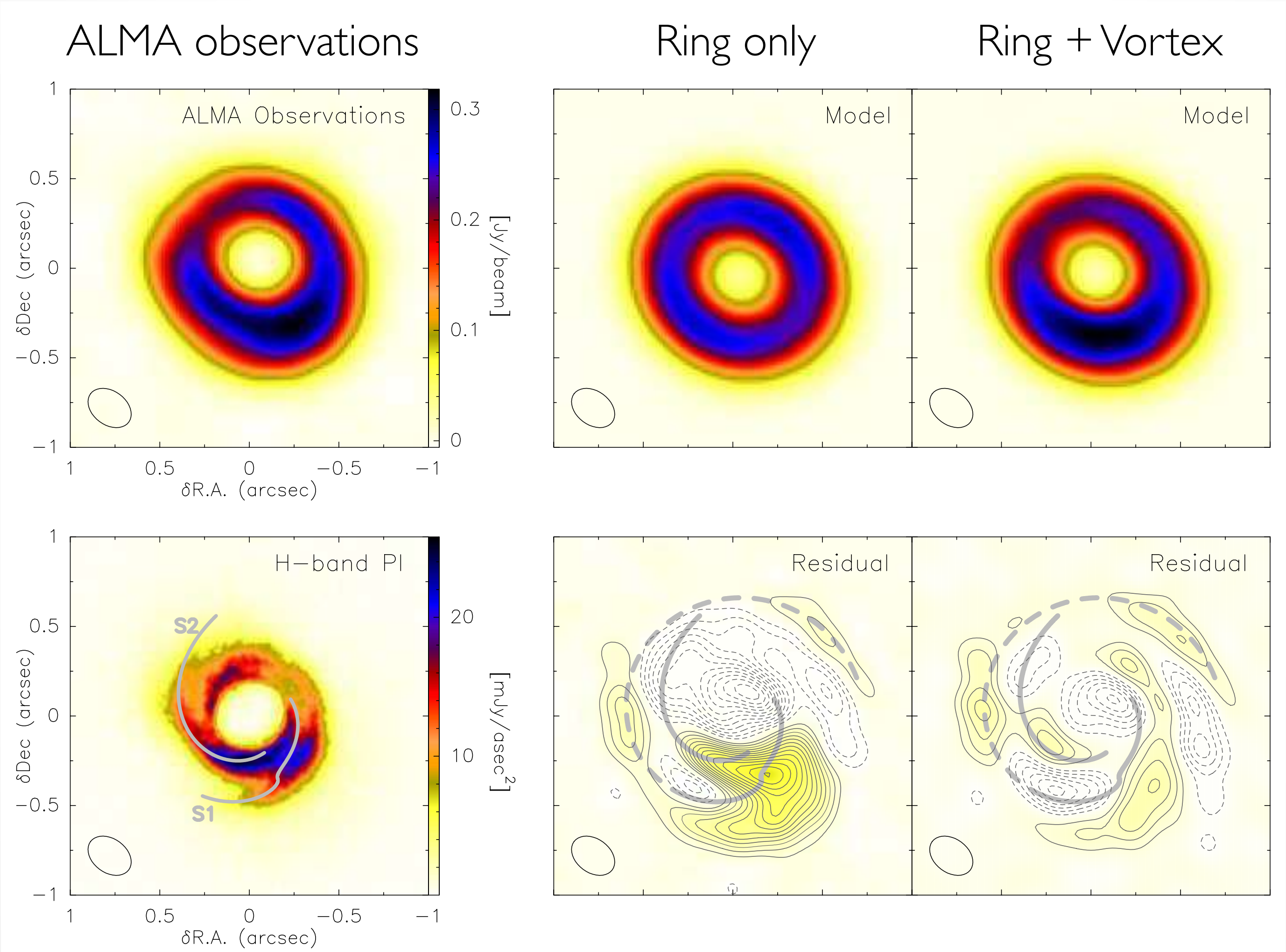
Apparent asymmetries → optical depth effects



Constraining observed Asymmetries

A ring alone is not a good enough fit

SAO 206462



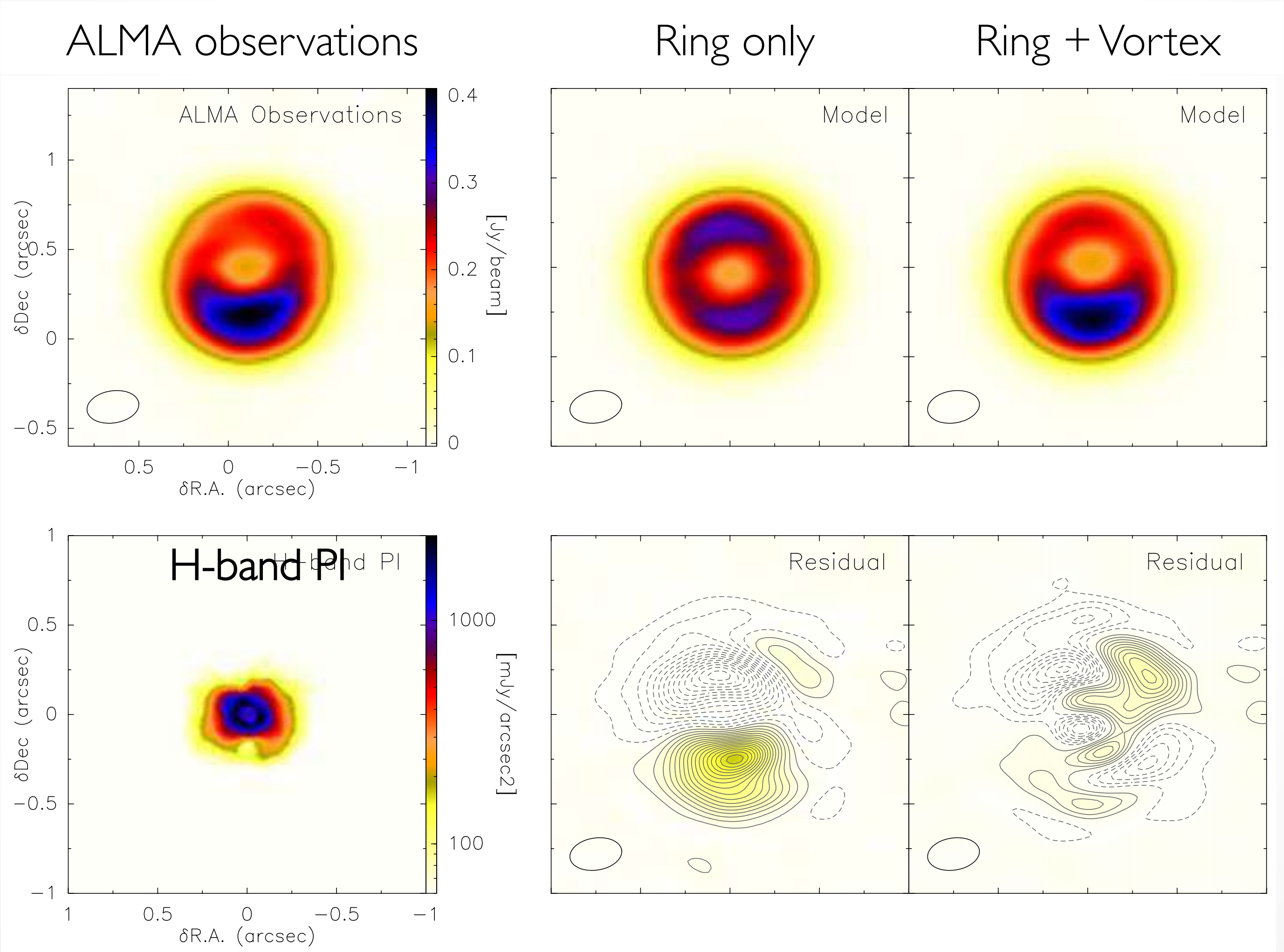
Motivated by steady- state vortex solution from Lyra & Lin (2013)

Pérez et al. (2014)

Constraining observed Asymmetries

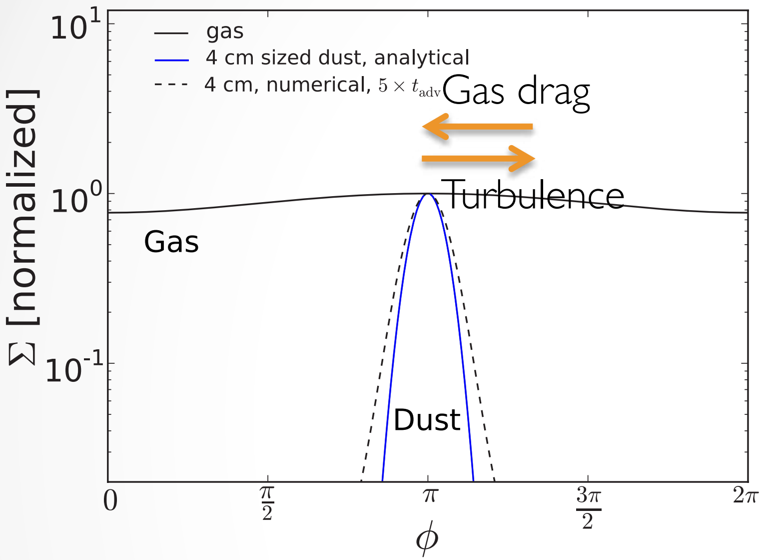
A ring alone is not a good enough fit

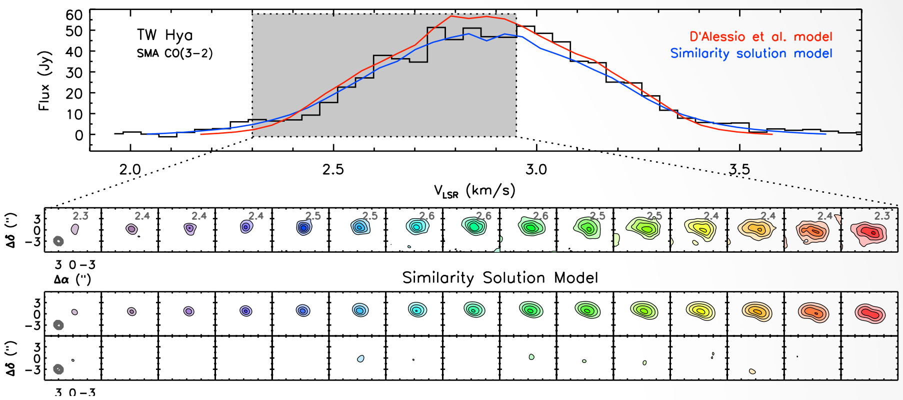
SR 21



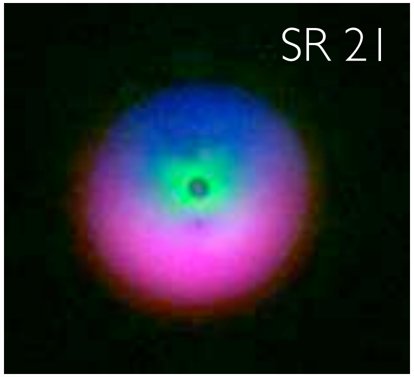
Pérez et al. (2014)

Dust trapping vs. turbulence: who will win?





TW Hya upper limit v_{turb} < 10% sound speed
Hughes et al. 2011
(see also: Piétu et al. 2007, Isella et al. 2007)



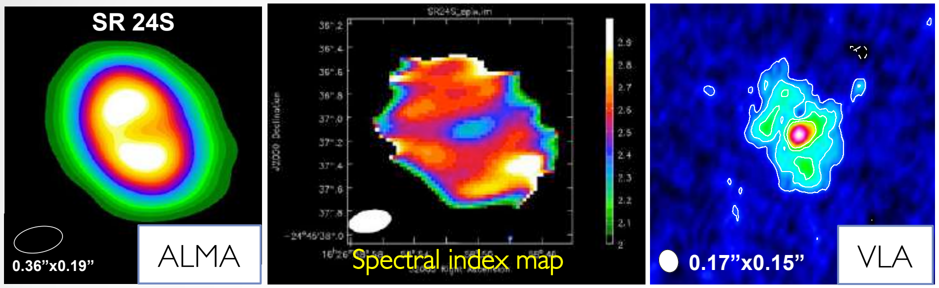
Vortices location in pink

Pérez et al. (2014)
To drive these azimuthally-wide vortices:

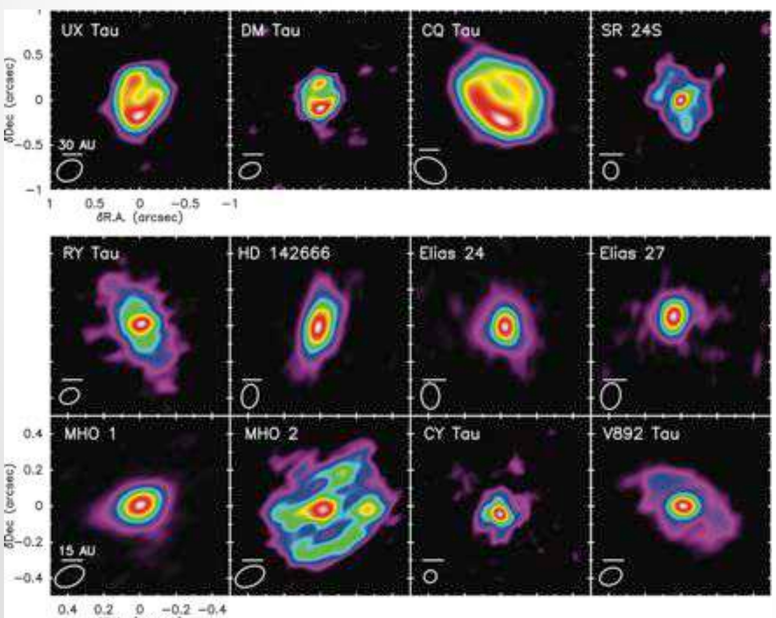
v_{turb} ~ 20% sound speed
in SAO 206462 and SR 21

Studies to come in the near future…

Studying grain growth with ALMA + VLA



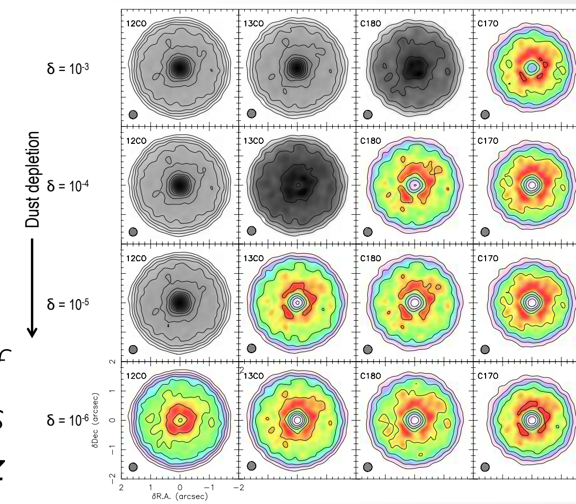
VLA 2013b + ALMA Cycle 0 sample
PI: L. Pérez



ALMA Cycle 2 observations of VLA sample
PI: L. Pérez

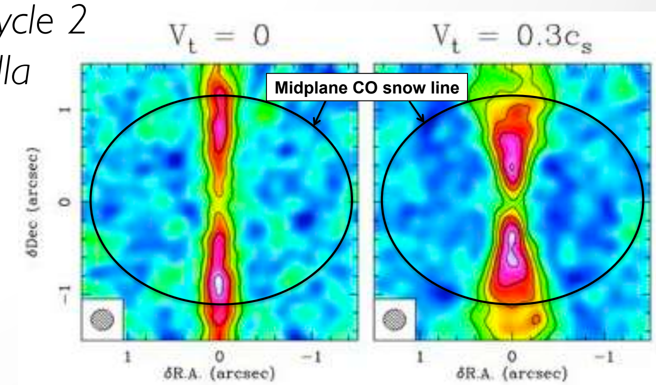
Studying gas depletion…

ALMA Cycle 1 observations of disks with cavities
PI: L. Pérez

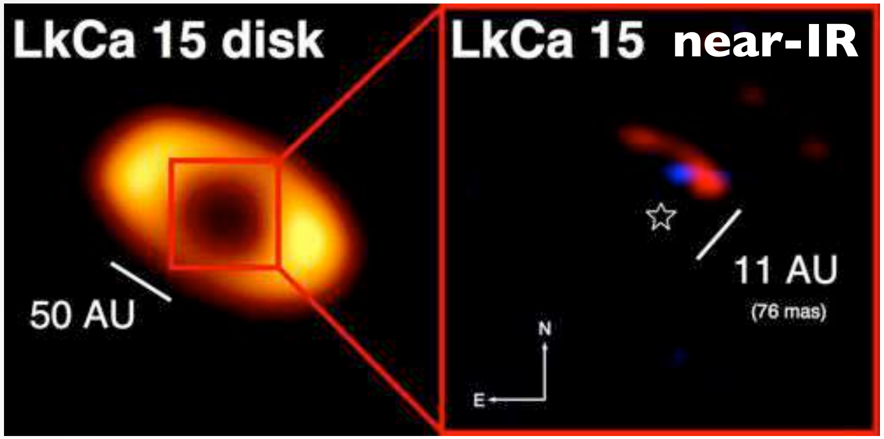


Studying turbulence…

ALMA Cycle 2
PI: A. Isella

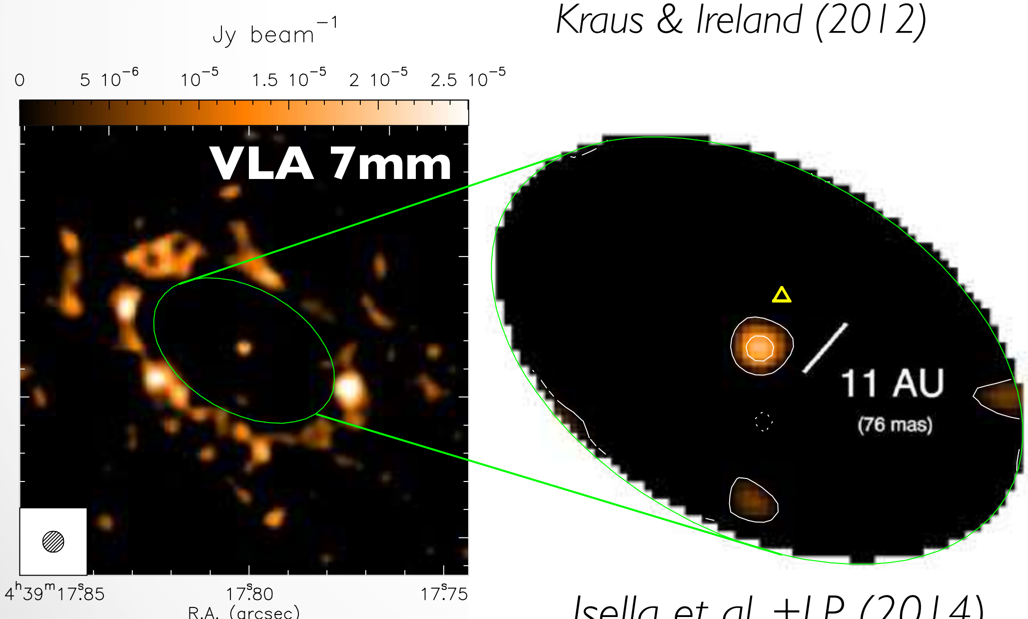


The Future: Studying Planets as they Form



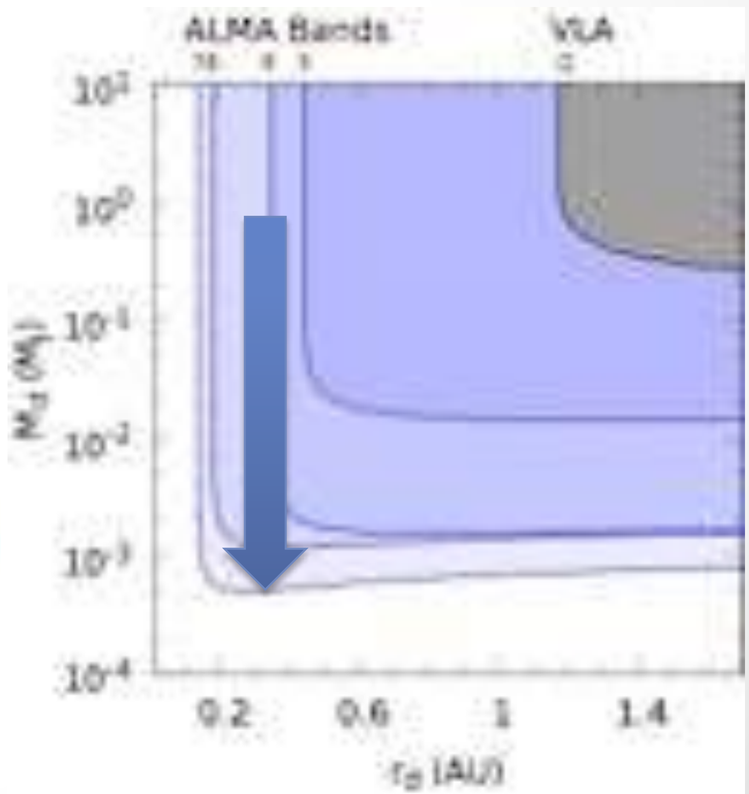
A young exoplanet?

Kraus & Ireland (2012)



Isella et al. +LP (2014)

Studying circum**planetary** disks



Summary

- Compelling evidence that **grain growth** takes place in disks
  - **Radial drift of solids** hinders further dust growth
  - A way to overcome this problem: **dust trapping** of large particles
  - Dust traps may occur radially in "**rings**", azimuthally in "**vortices**"

- *These predictions are currently being* ***tested*** *with ALMA & VLA!*