

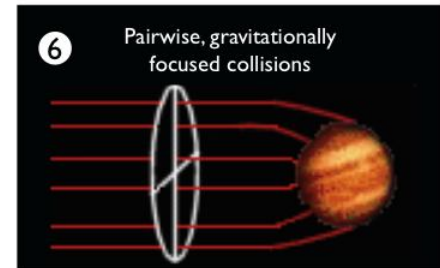
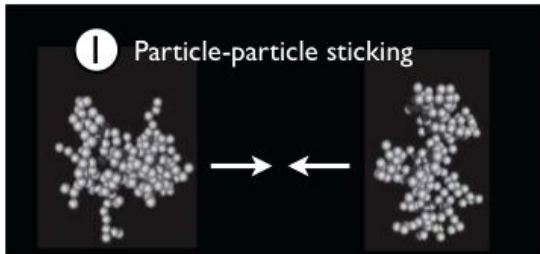
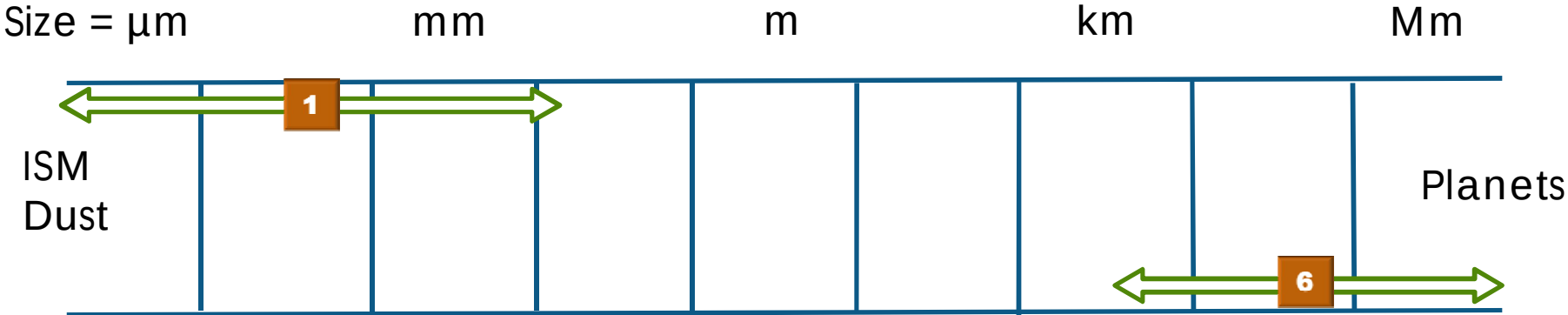
The Growth of Small Grains into Pebbles: Observational constraints of the First Steps of Planet Formation

Laura M. Pérez
California Institute of Technology

Collaborators:

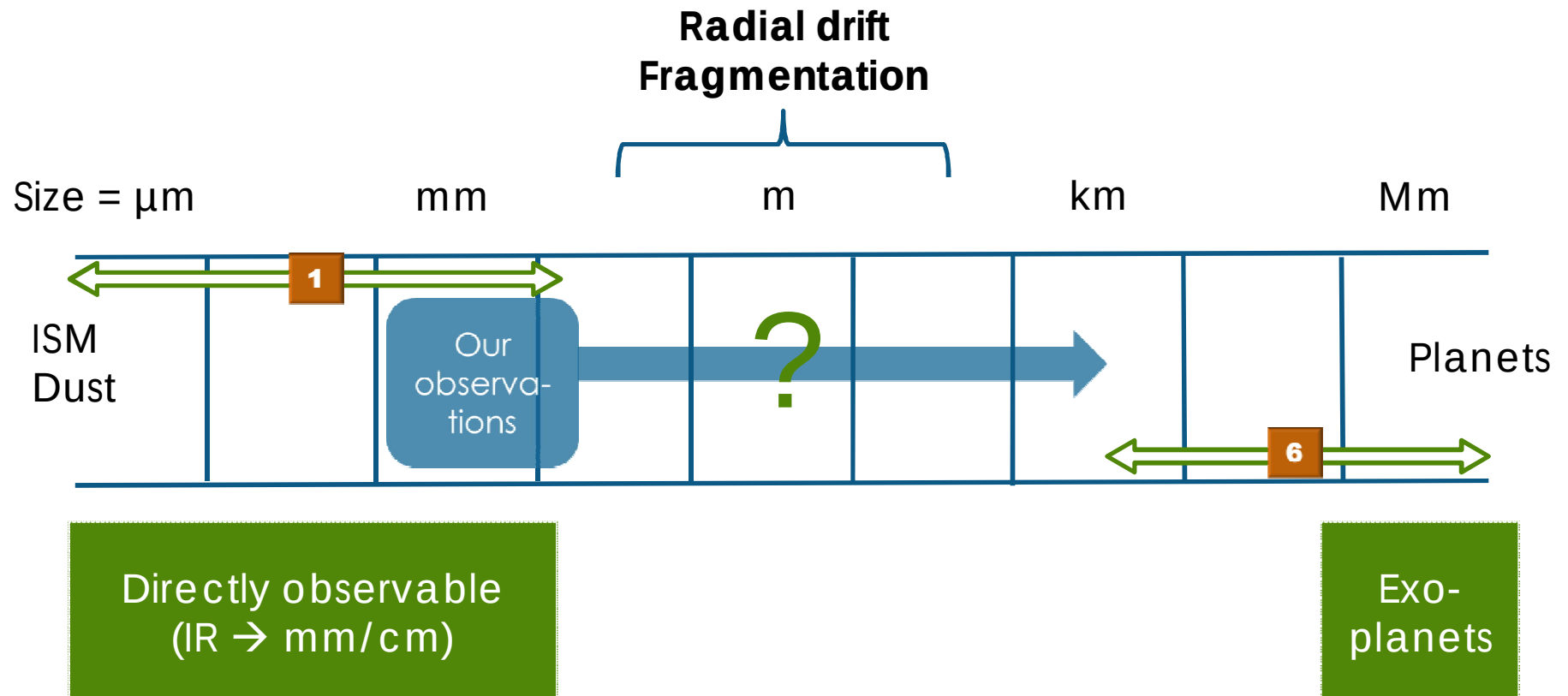
Andrea Isella, John Carpenter,
Luca Ricci, Anneila Sargent (Caltech)
Claire Chandler (NRAO) + Disks@EVLA Group

From ISM Dust to Planetary Systems



Adapted from Chiang & Youdin (2009)

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Observing Planetary Systems II - ESO Santiago - March 2012

Spectral Signatures of Grain Growth

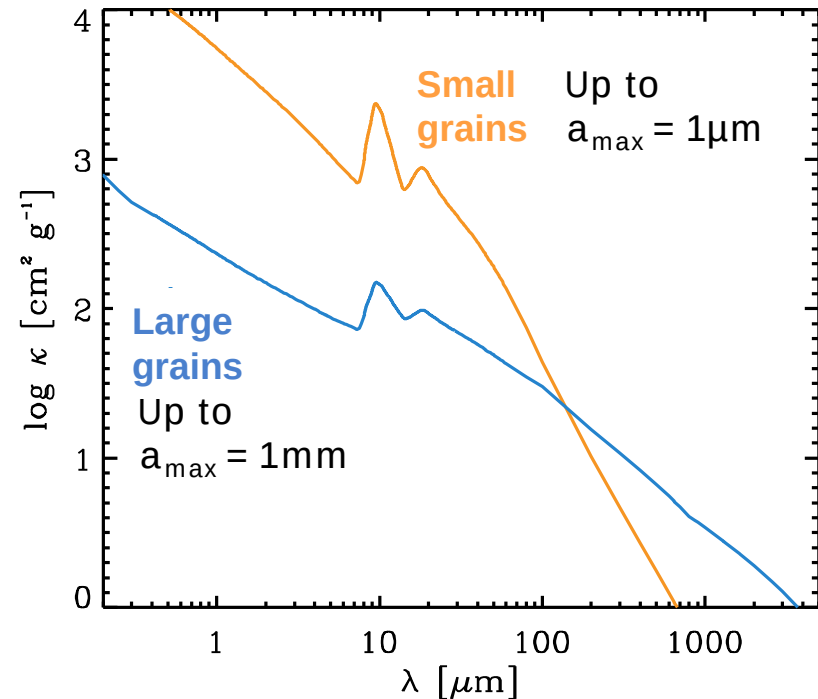
- Mm-wave observations probe bulk of dust emission

$$S_{\nu} \sim \kappa_{\nu} \nu^2 \quad (\text{opt. thin})$$

- Dust emissivity at mm/cm wavelengths:

$$\kappa_{\nu} \sim \nu^{\beta}$$

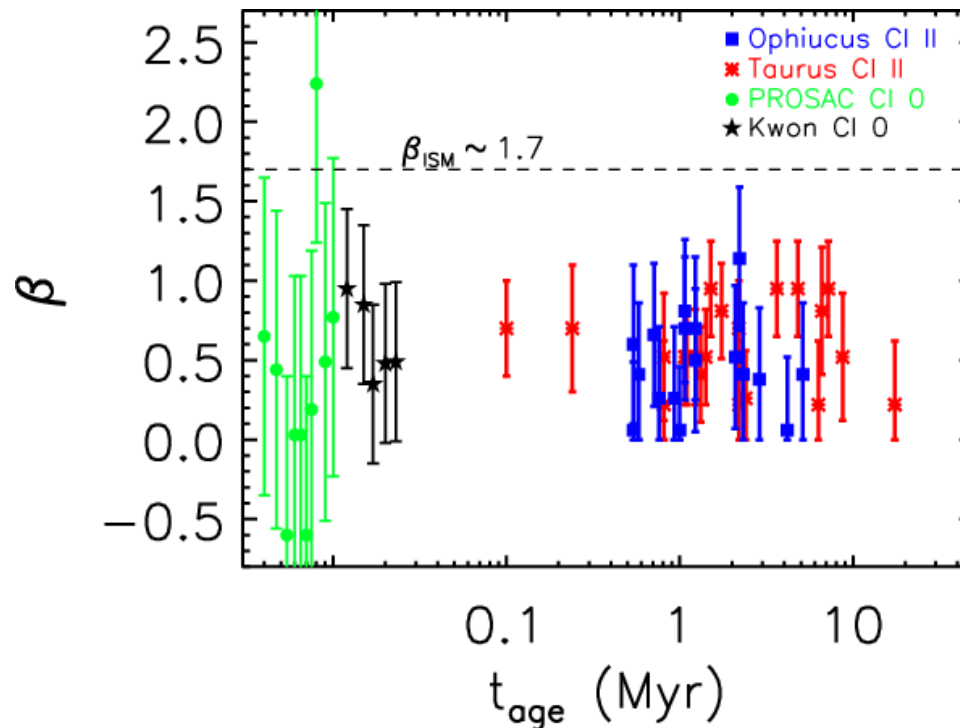
- Opacity spectral index β are diagnostic for:
 - Grain size distribution (a_{max})
 - Dust composition



Andrews et al. 2011a

Evidence for Grain Growth: “global” β

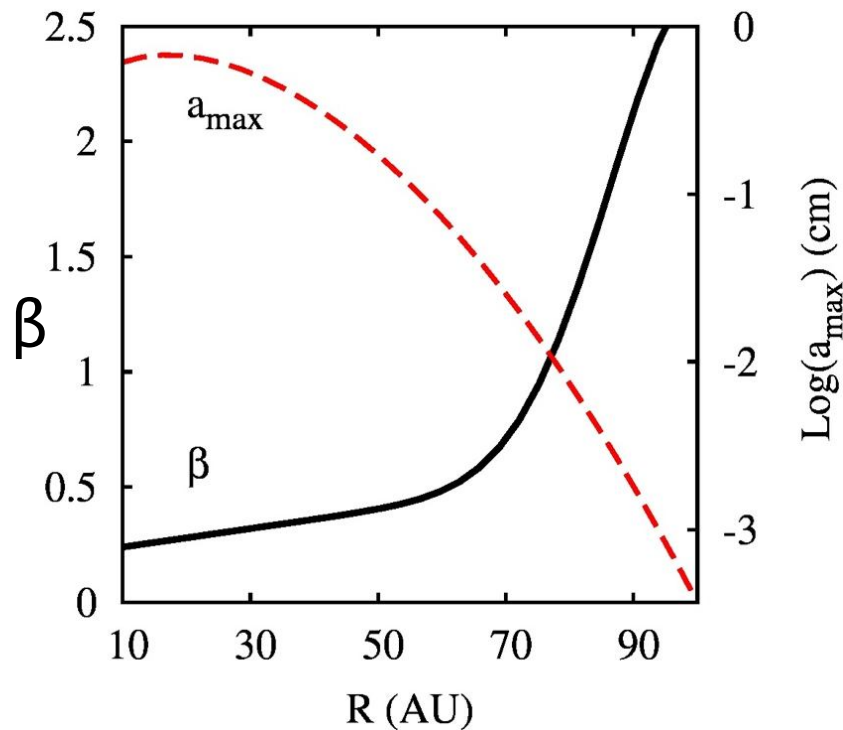
- Small values of β for a large sample of disks
 - Indicative of at least a 10^4 growth in particle size



Ricci et al. 2010, 2011

Beckwith & Sargent, 1991
Mannings & Emerson 1994
Testi et al. 2003
Andrews & Williams 2005, 2007
Wilner et al. 2005
Rodmann et al. 2006
Lommen et al. 2007
Kwon et al. 2009

Radial Variations of Grain Growth: $\beta(R)$

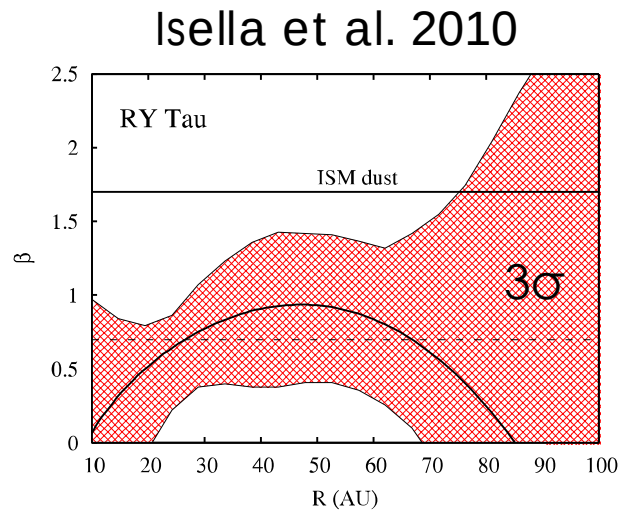


Birnstiel et al. 2010

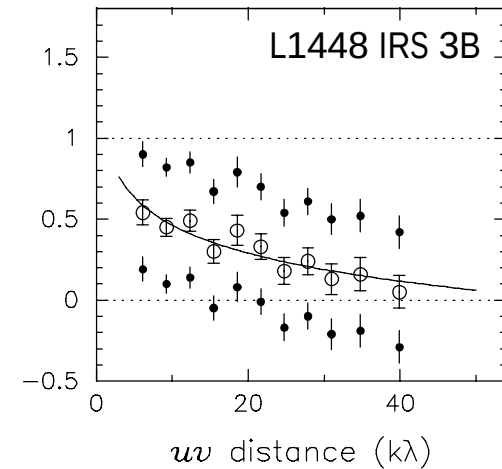
- Arise naturally from models of dust evolution
- What to do?
 - Spatially resolve disks at multiple mm/cm wavelengths
 - Solve for $\beta(R)$

Existing constraints on $\beta(R)$

CARMA
1 – 3 mm
observations

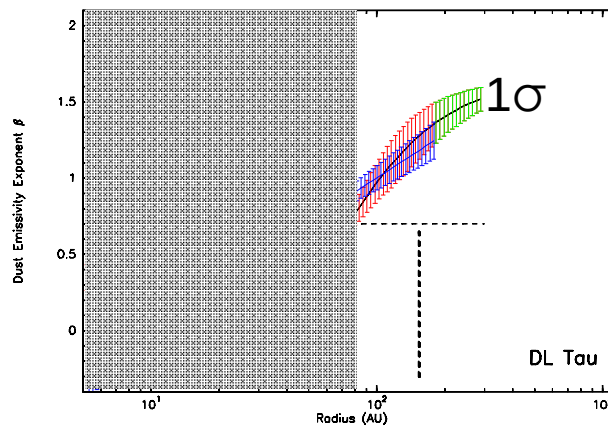


Kwon et al. 2009



PdBI
1 – 3 mm
observations

Guilloteau et al. 2011



Observational Constraints on Radial Variations of β

Improving $\beta(R)$ Constraints

- Require an increase in: wavelength coverage, sensitivity, & angular resolution of our observations

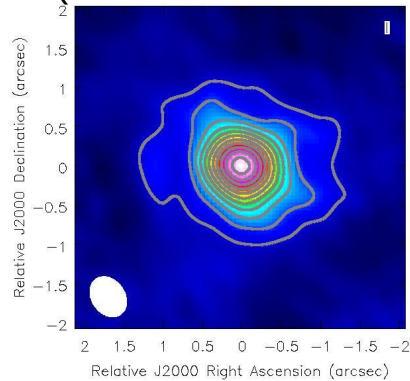


P.I. Claire Chandler

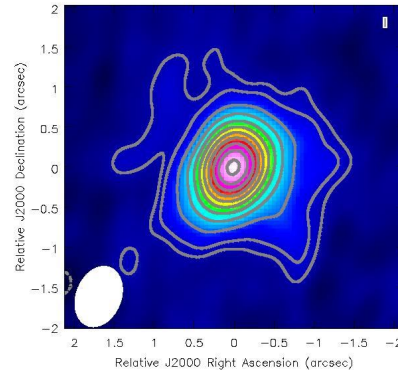
- Staged approach: photometry $\rightarrow$ imaging
- 66 disks observed from 7 mm to 6 cm (photometry)

Results: The disk surrounding AS209

SMA - 0.88 mm
(Andrews et al. 2009)

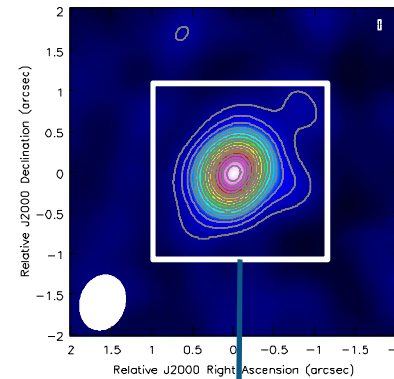


CARMA - 2.7 mm

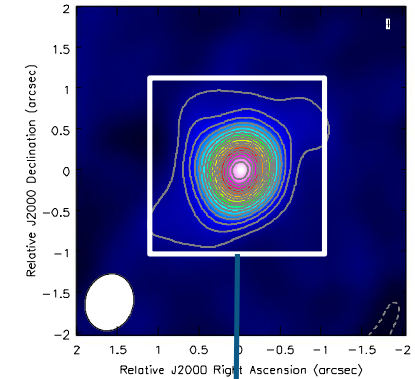


4" ~ 500 AU

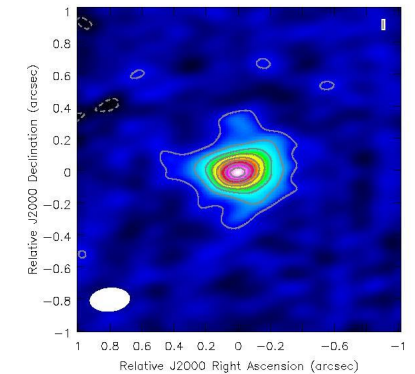
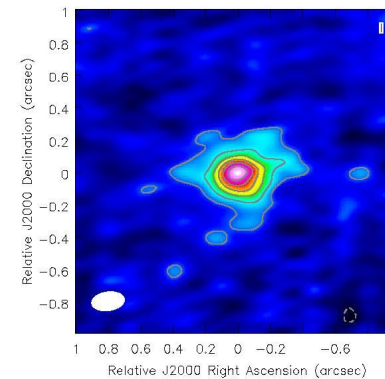
EVLA - 8 mm



EVLA - 10 mm



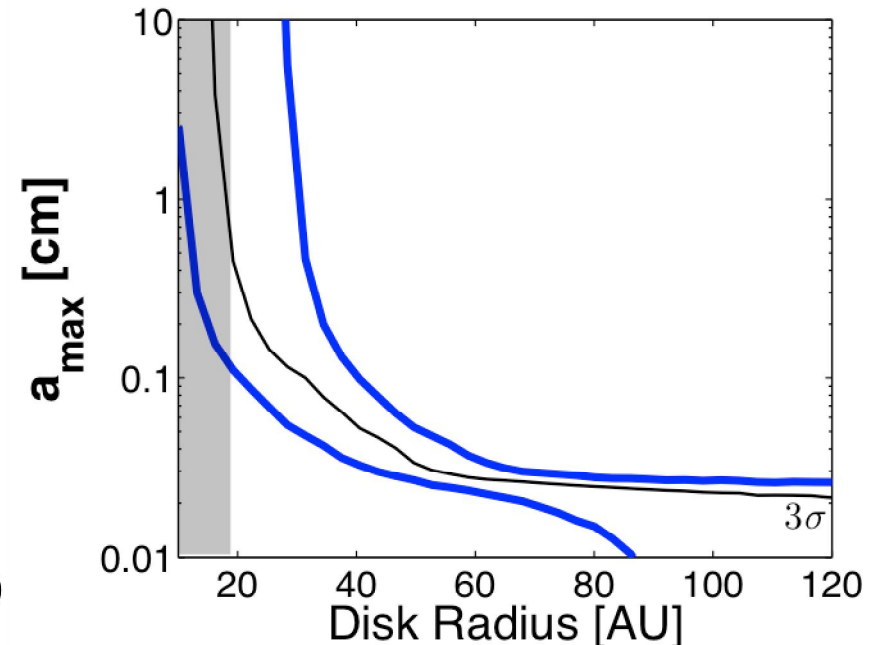
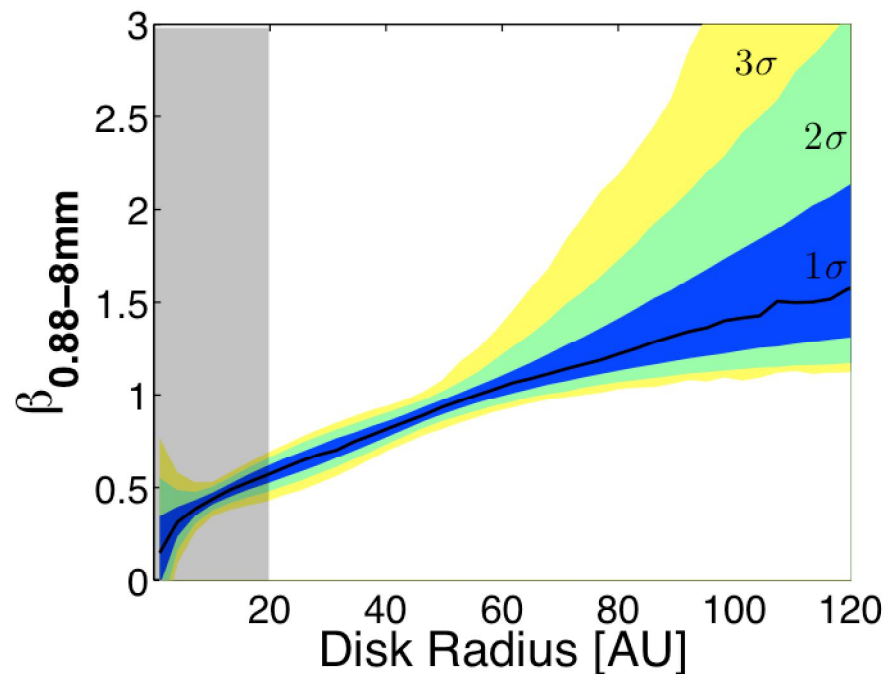
AS209: young K5 star located in rho-Oph (d ~ 125 pc, 0.9 M_{Sun}, 1.6 Myr)



Pérez et al. in prep.

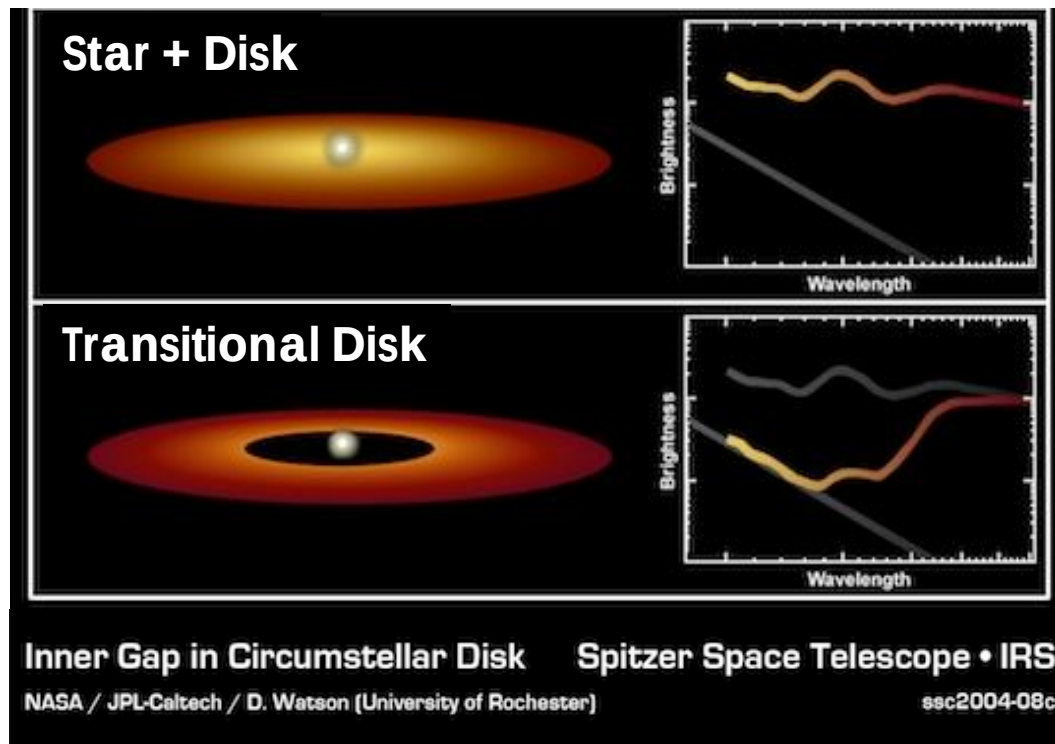
Results: The disk surrounding AS209

- Derive radial distribution by comparing observed emission with model visibilities (following Isella et al. 2009)
 - Σ : Similarity solution of viscous Keplerian disk (Lynden-Bell & Pringle, 1974)
 - T: “Two layer disk approximation” (Chiang & Goldreich, 1997)



Grain Growth Signatures in the Disk Structure

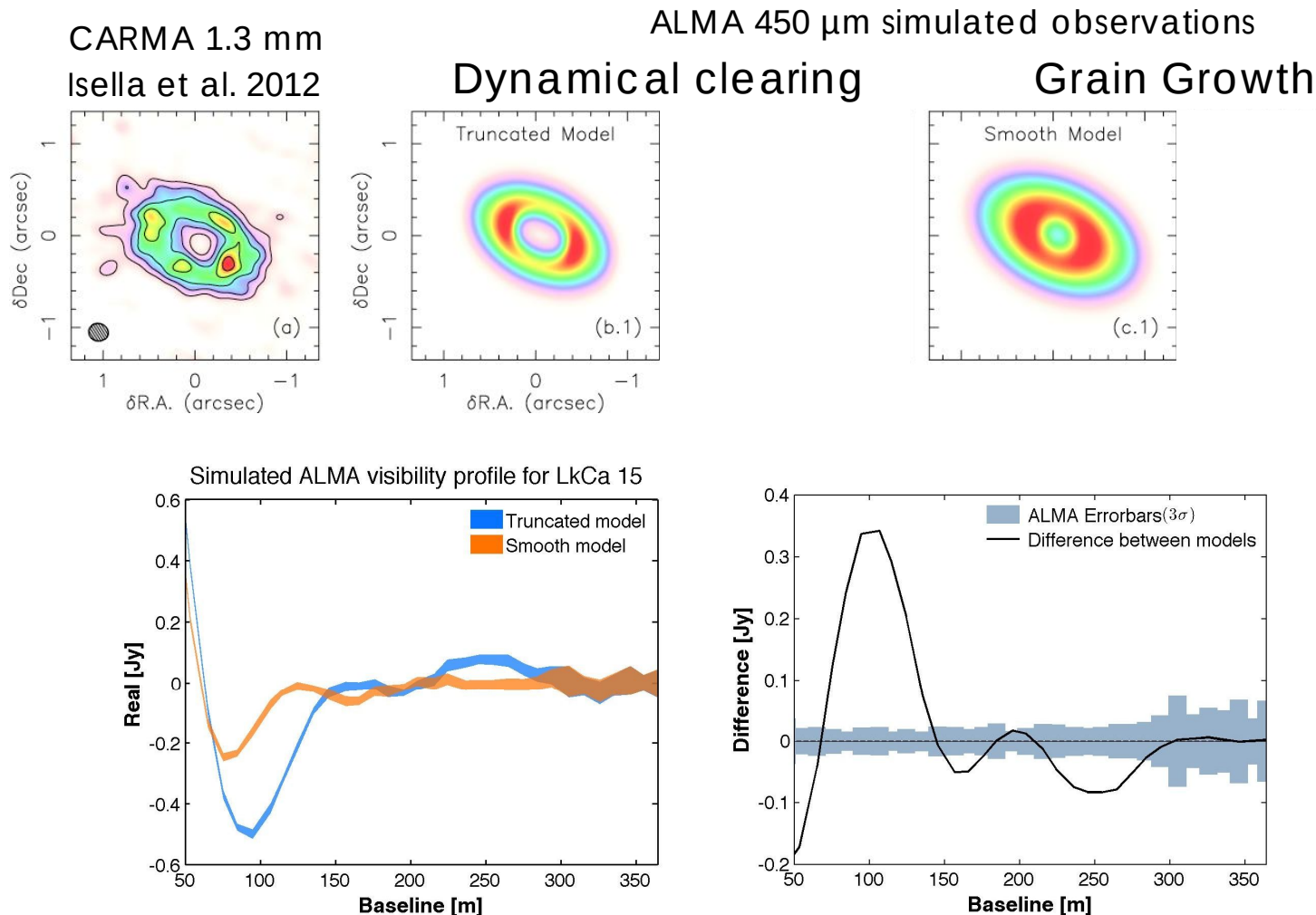
Transitional Disks



- SED signatures
- Possible origin for the inner cavity?
 - Grain growth to sizes where dust emission becomes inefficient
 - Dynamical Interactions with planets
 - Photoevaporation

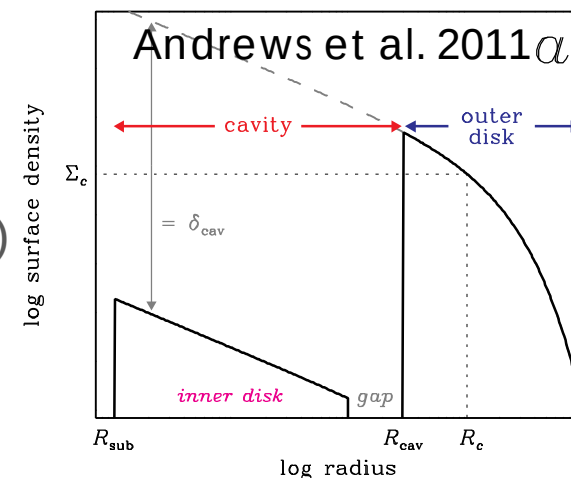
ALMA can distinguish these processes

Example: disk surrounding LkCa 15

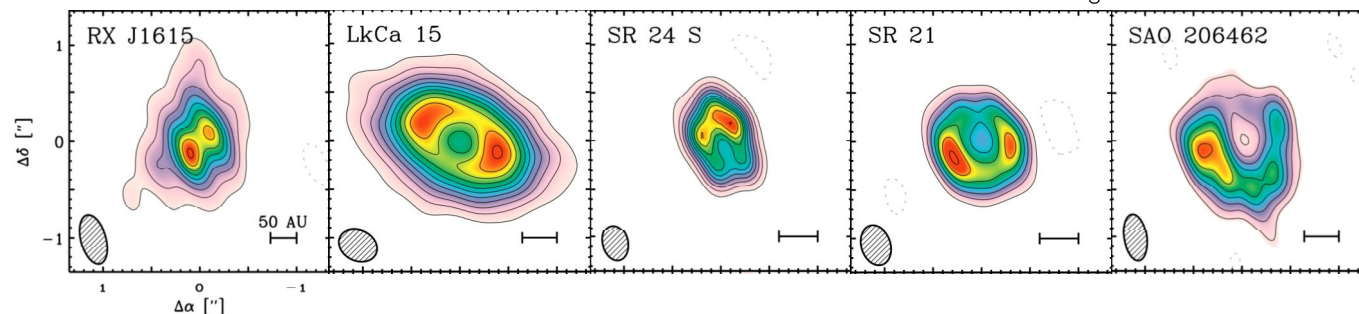


Upcoming ALMA Cycle-0 Observations

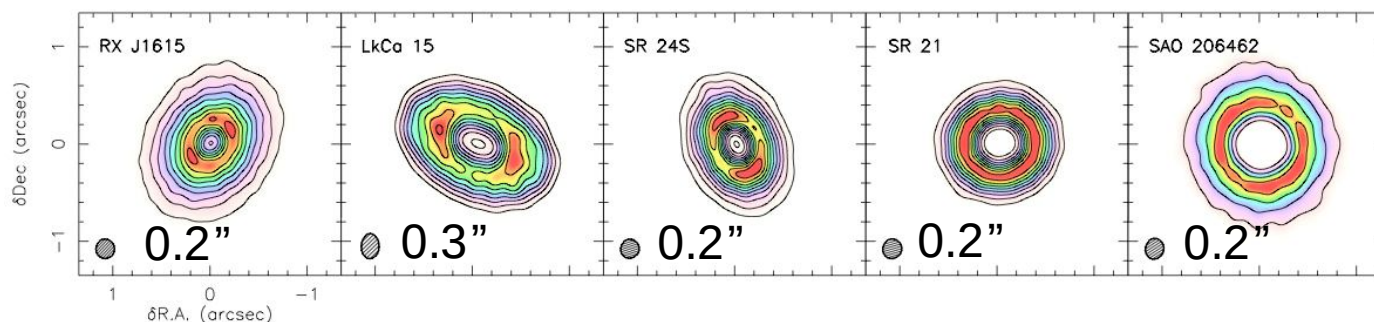
- Sample of 5 transitional disks
 - Large disk mass ($>0.01 M_{\text{sun}}$)
 - High accretion rate ($>\sim 10^{-9} M_{\text{sun}}/\text{yr}$)
 - Large cavities ($> \sim 20\text{AU}$)
 - PI: L. Pérez



SMA 880 μm
observations
(Andrews et al.
2011)

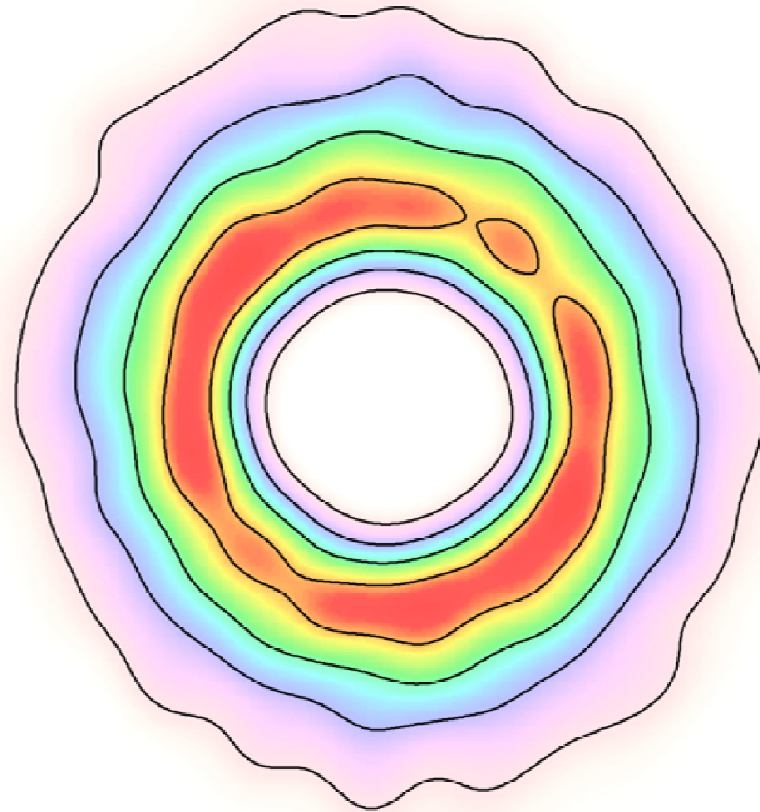


ALMA 450 μm
simulated
observations
(extended
configuration)



ALMA Observations: SAO 206462

SAO 206462

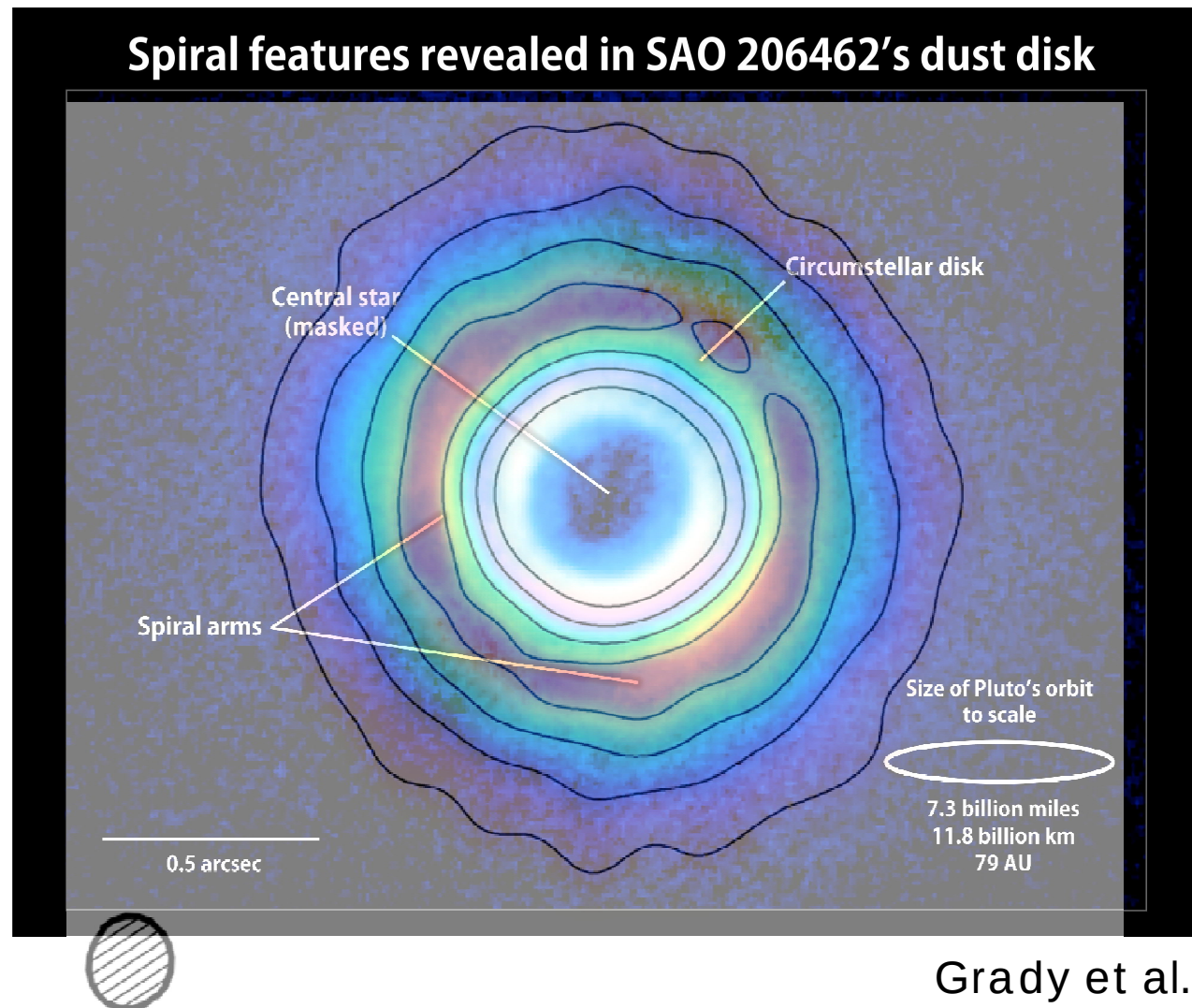


Grady et al.

Signposts of Planets Meeting, Oct 19 2011

Observing Planetary Systems II - ESO Santiago - March 2012

ALMA Observations: SAO 206462



Grady et al.
Signposts of Planets Meeting, Oct 19 2011

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Concluding Remarks

Summary

- The study of the first steps toward planet formation requires:
 - High angular resolution
 - Multi-wavelength coverage
 - High sensitivity
 - Hence, we will tremendously benefit from ALMA!
- Preliminary constraints on variations of dust opacity slope across the disk found for AS209 and LkCa 15
 - Inner disk: $a_{\text{max}} \sim 1\text{cm}$; Outer disk: $a_{\text{max}} \sim 100\ \mu\text{m}$
 - More coming with EVLA collaboration!
- Disk dissipation mechanisms: don't forget about grain growth!
 - More coming with ALMA Early Science observations!

Stay tuned!



Dust emission model: Isella et al. 2009

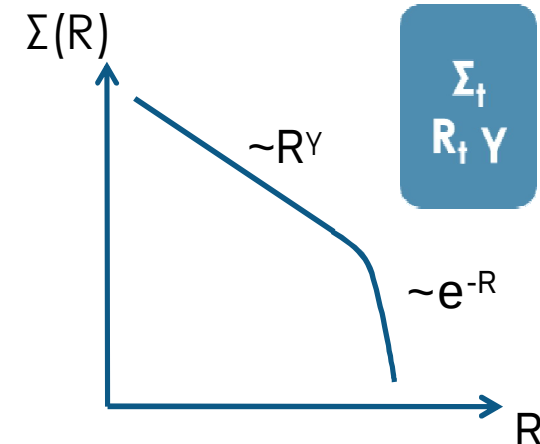
$$S_\nu(R) \propto \kappa_\nu(R) \Sigma(R) \nu^2 T_d(R)$$

Dust opacity

$$\kappa_\nu = \frac{\int_{a_{min}}^{a_{max}} n(a) \sigma_{abs}(a, \nu) da}{\int_{a_{min}}^{a_{max}} n(a) (4\pi/3) \rho a^3 da}$$

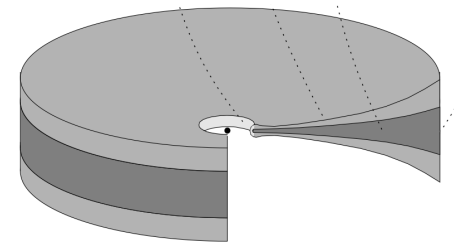
Dust
composition,
 a_{min} , a_{max} , $n(a)$

Surface density
profile



(Lynden-Bell & Pringle 1974)

“Two layer disk
Approximation”
(Chiang &
Goldreich, 1997)



L_* , R_*

Constraining Radial Variations of β

- Modeling of disk observations to constrain disk $\Sigma(R)$:

$$S_v \sim \kappa_v(R) T(R) \Sigma(R)$$

- In principle find parameterization for $\kappa_v(R)$ or $\beta(R)$

- Our approach:

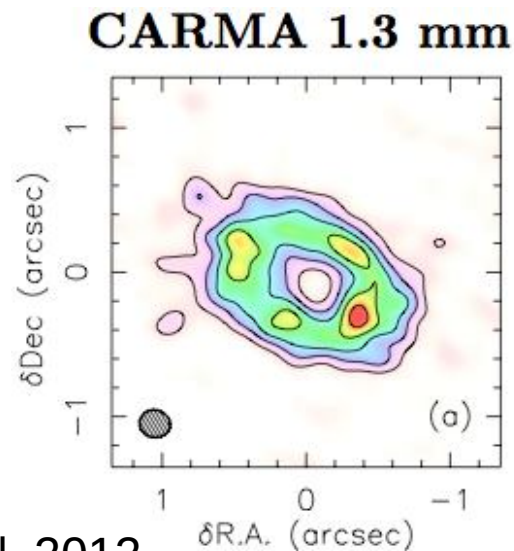
$$S_v \sim \kappa_0 T(R) \underbrace{v^{\beta(R)} \Sigma(R)}_{\Sigma(R,v)}$$

$\Sigma(R,v)$: contains information on radial variation of β

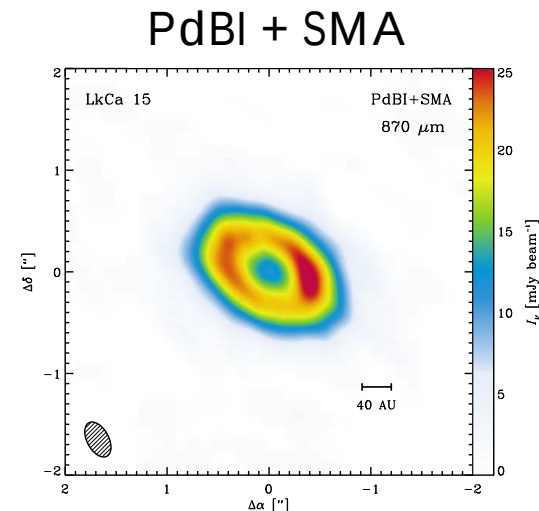
$$\kappa_v \sim v^\beta \rightarrow \beta(R) \sim \log (\Sigma(R,v_1) / \Sigma(R,v_2))$$

The disk surrounding LkCa 15

- Young star (~ 2 Myr; Kraus & Hillenbrand 2009), in Taurus SFR (~ 145 pc), massive disk ($55 M_{\text{jup}}$; Andrews & Williams 2005)
- Inner cavity/gap inferred:
 - mm-wave resolved observations (Piétu et al. 2006)
 - Mid-IR SED (Espaillet et al. 2007, 2008)
 - Reflected light from inner edge of disk (Thalmann et al. 2010)



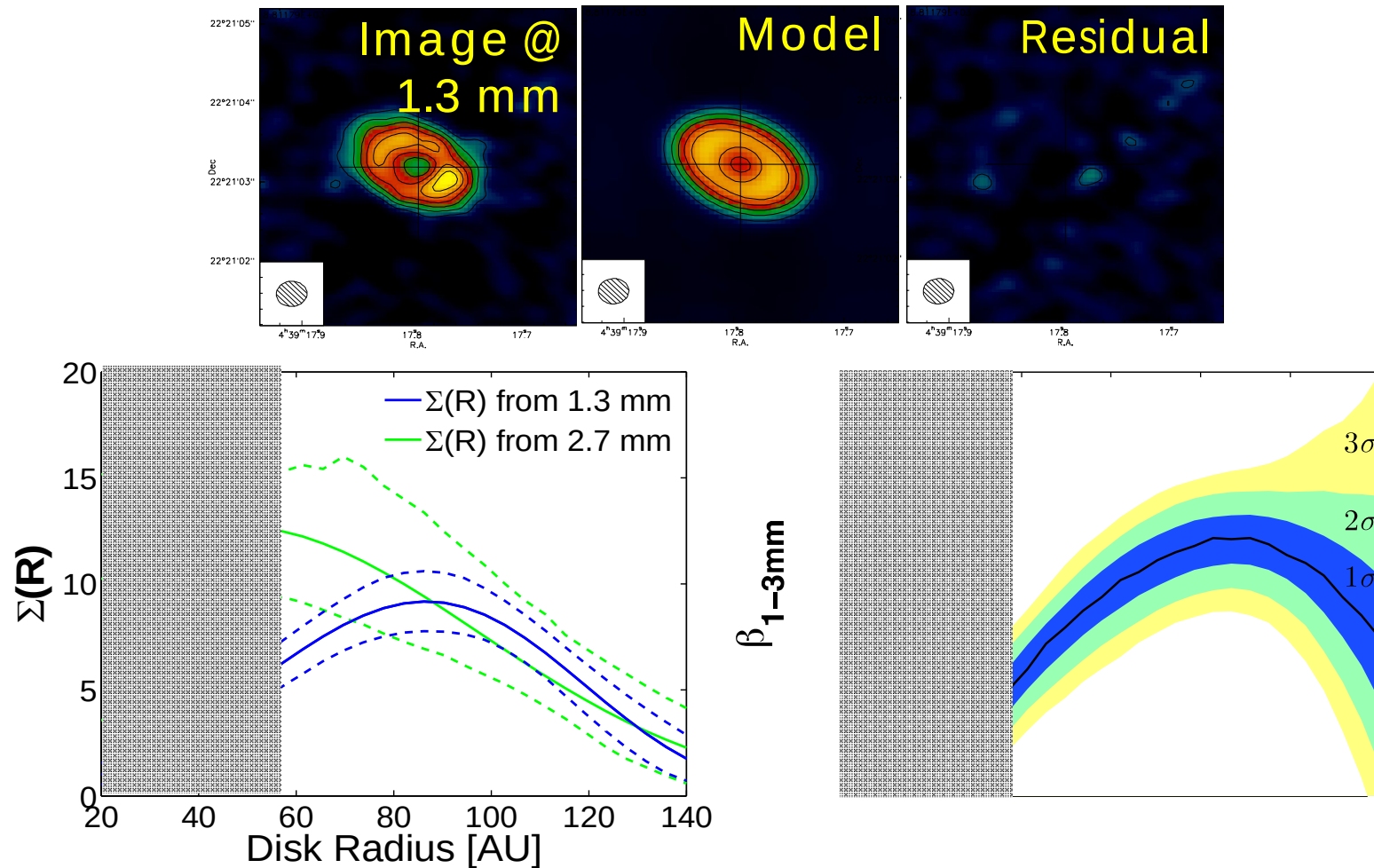
Isella et al. 2012



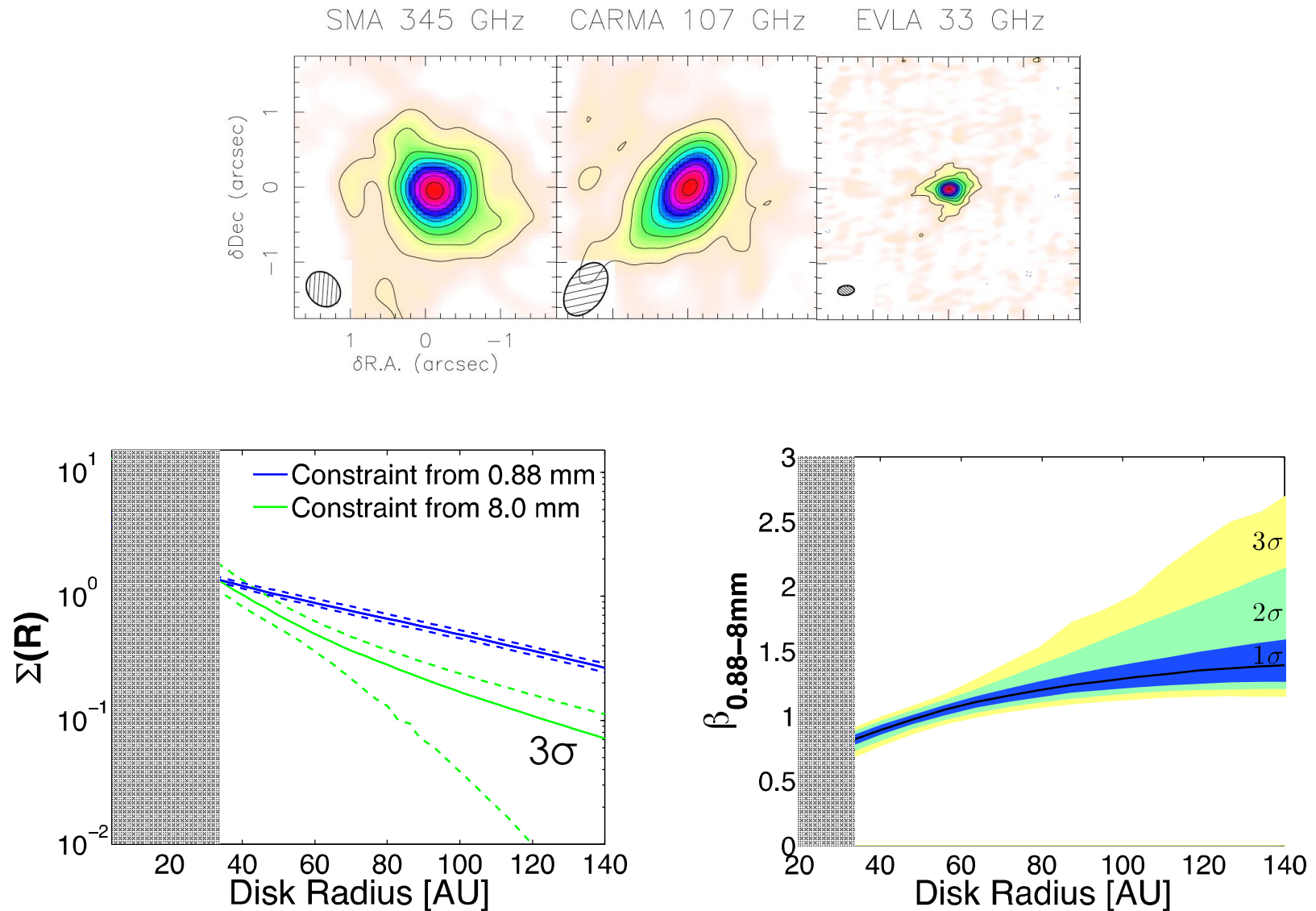
Andrews et al. 2011

Results: The Disk Surrounding LkCa 15

▣ CARMA observations at 1.3 and 2.7 mm

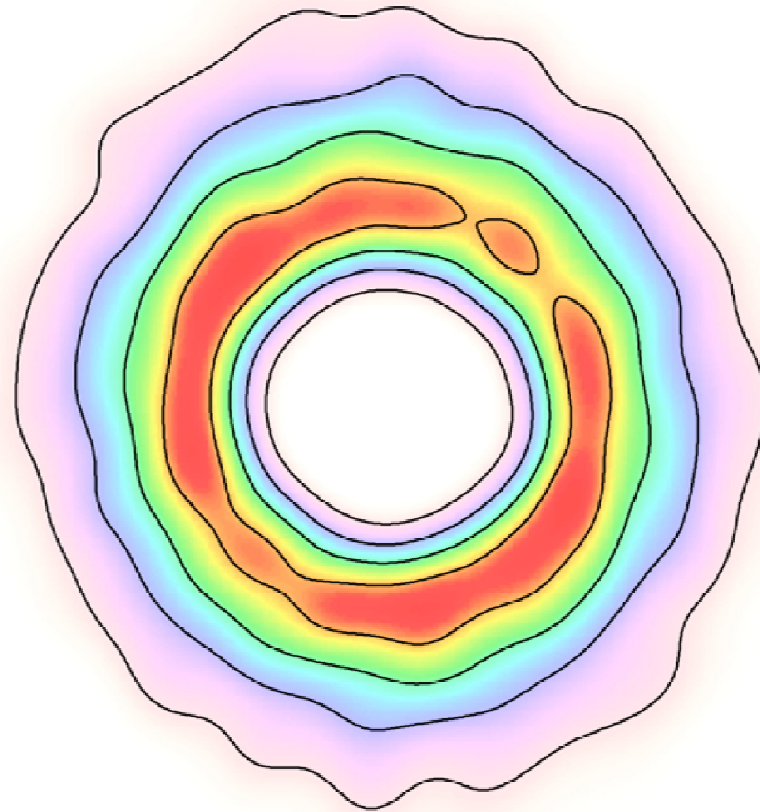


Results: The disk surrounding AS209



ALMA Observations: SAO 206462

SAO 206462



Grady et al.

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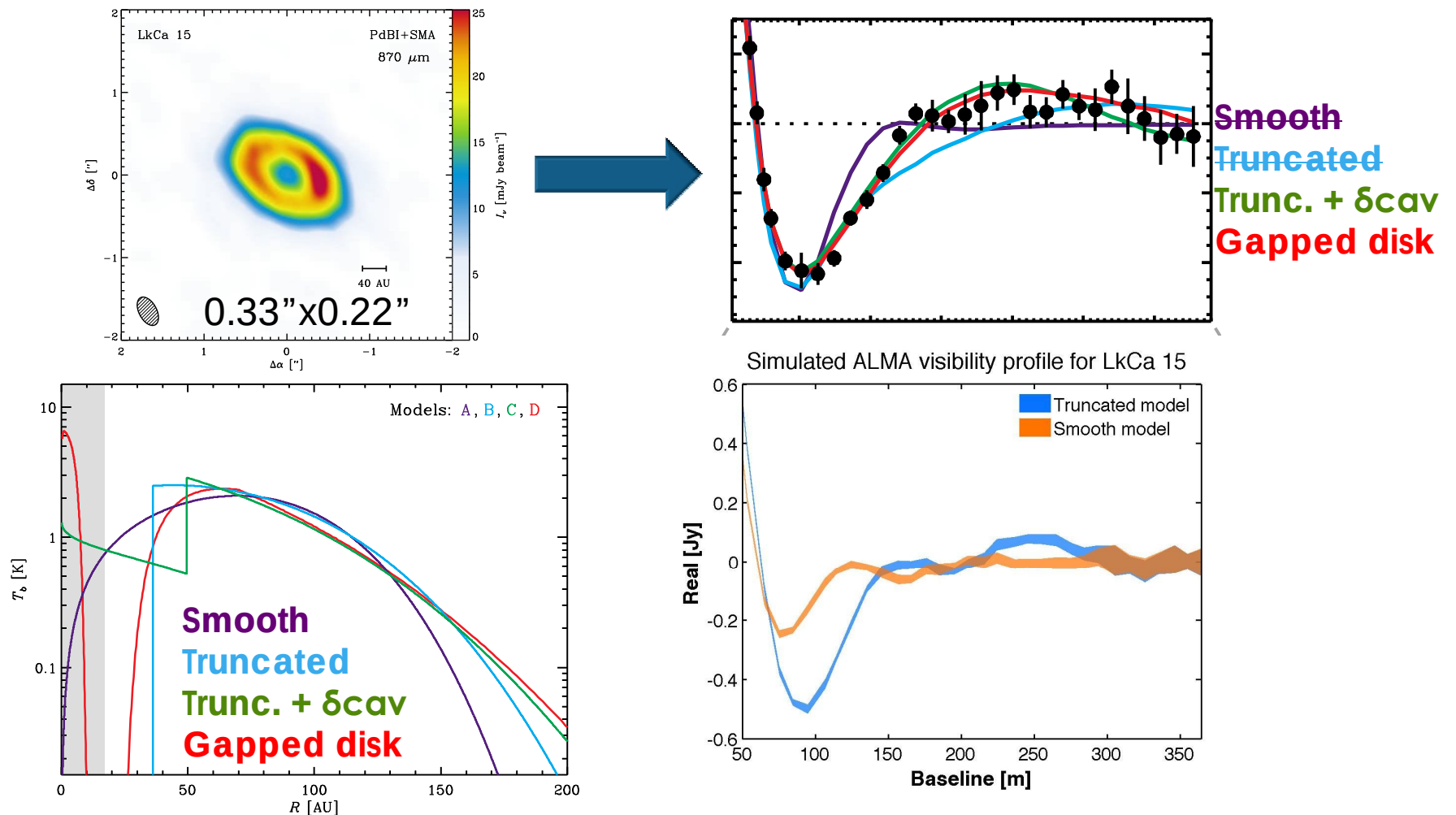
$$S_v \sim \kappa_0 T(R) \underbrace{v^{\beta(R)} \Sigma(R)}_{\text{dependent on } R \text{ and } v}$$

$v^{\beta(R)} \Sigma(R)$: contains information on radial variation of β

$$\kappa_v \sim v^\beta \rightarrow \beta(R) \sim \log (\Sigma(R, v_1) / \Sigma(R, v_2))$$

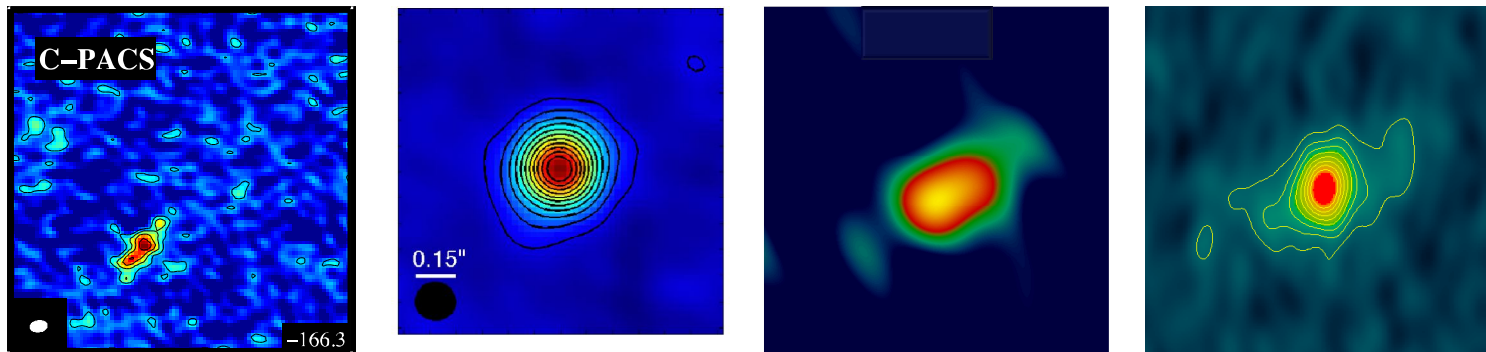
ALMA Observations

- Andrews et al. recently took “A closer look at LkCa 15 [...]”



Summary

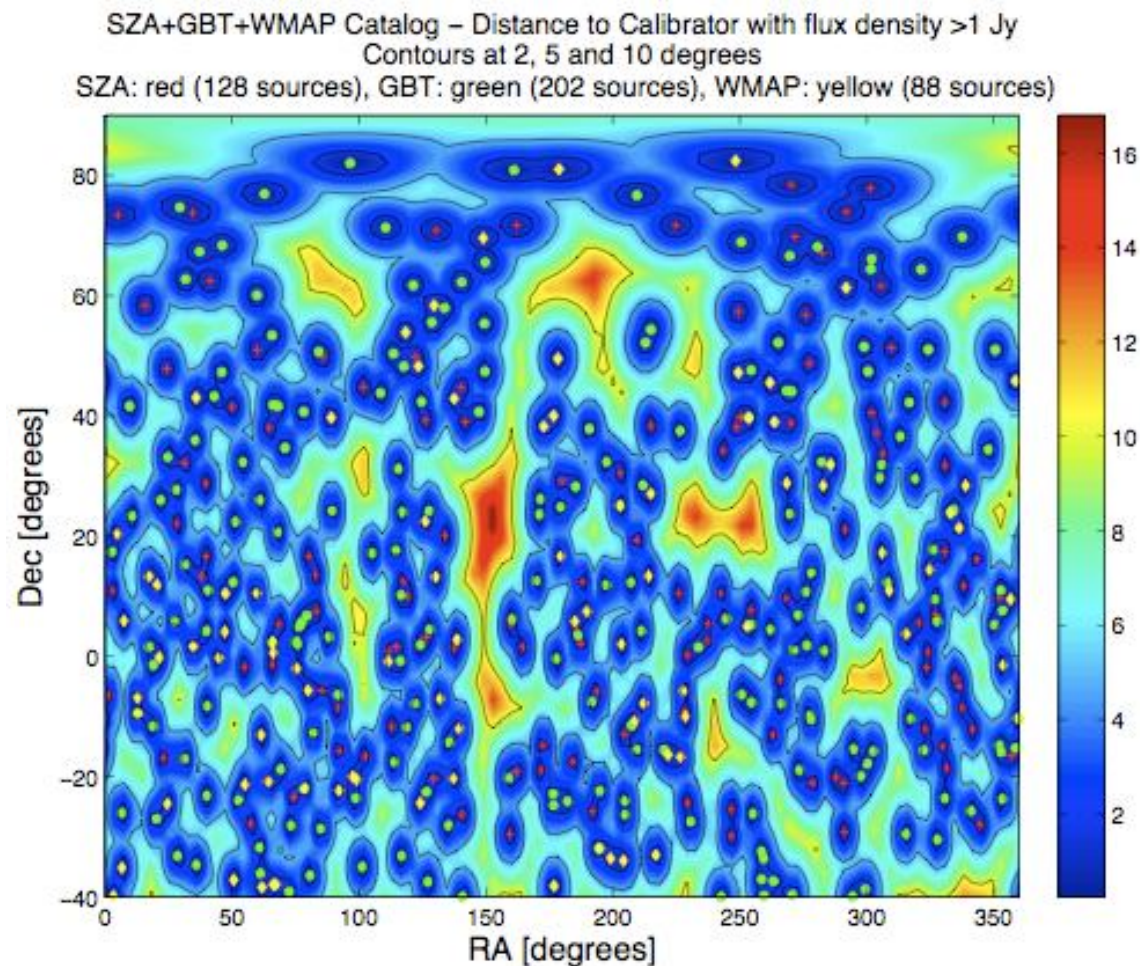
- ▣ Spatially resolve protoplanetary disks
 - ▣ Atmospheric phase fluctuations limit the ability of an interferometer to obtain high angular resolution images
 - ▣ C-PACS can correct for atmospheric “radio-seeing”
 - ▣ Separation and strength of atmospheric calibrator limit C-PACS



Some C-PACS users: Alatalo et al. 2010, Enoch et al. 2010, Kwon et al. 2010, Pérez et al. 2010, Salter et al. 2010, Zauderer et al. 2011, etc.

C-PACS restrictions

- Distance to calibrator and brightness of calibrator



Dust emission

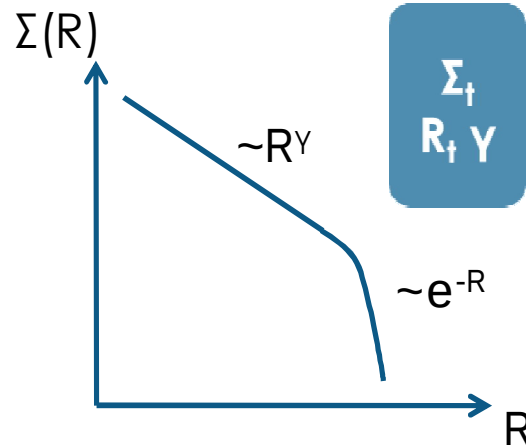
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Dust opacity

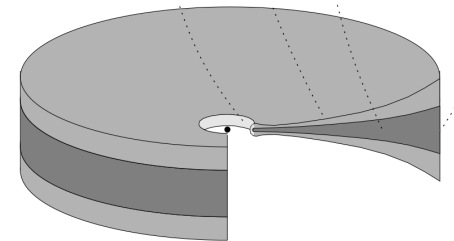
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Dust
composition,
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L_* , R_*

Dust opacity

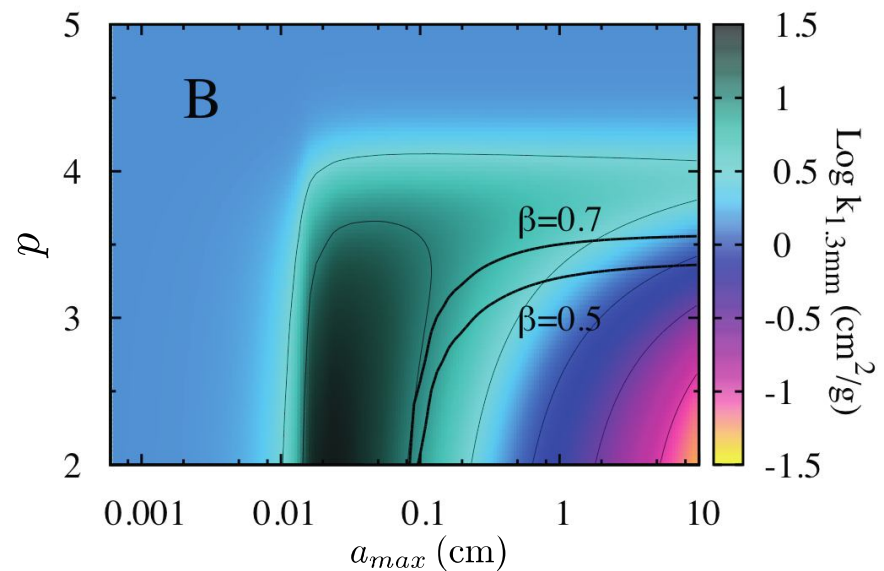
- Particle Size Distribution
 - Approximated by a power-law

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

- Opacity depends on choice of:

$$\{p, a_{min}, a_{max}\}$$

Measurements of β
set lower limit on a_{max}



Spherical grains (astronomical silicates, organic carbonates and water ices, mass ratio 1:1:0.7), $a_{min} = 0.005 \mu\text{m}$ (Isella et al., in preparation).