Star and Planet Formation: New Insights from Spatially Resolved Observations

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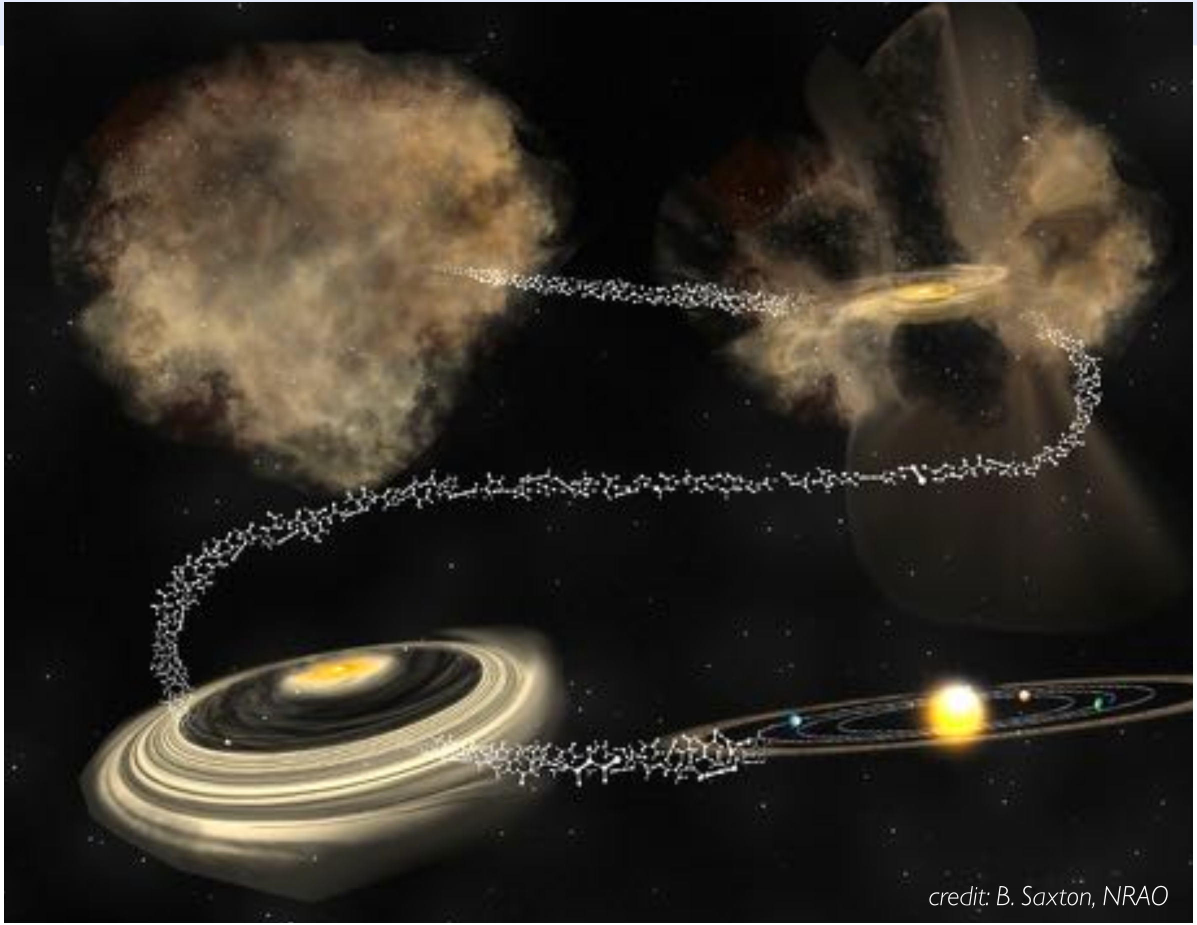
Setting the stage: Our current view of low-mass star and planet formation

Pre-stellar
Core

Class 0/I
object



Protoplanetary
Disk

Debris
Disk

Setting the stage: What do we learn about disks from radio-wave observations?

Rich set of information from sub-mm to cm wavelengths

Gas component
(molecular line emission)

I_ν {
- T_{gas}, abundances → chemistry
- Kinematics → $M_\star$, turbulence
- Distribution → sizes, geometry

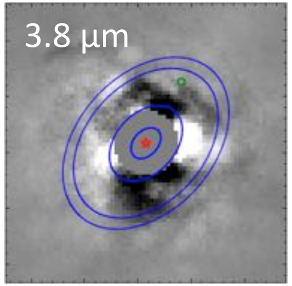
Dust component
(thermal dust emission)

Generally optically thin at λ>mm

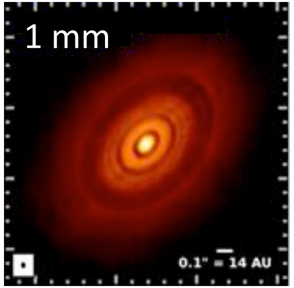
$$I_\nu \approx B_\nu(T_d)\tau_\nu \approx \kappa_\nu \Sigma_d T_d$$

- κ_ν → Dust properties
- Σ_d → Mass available
- T_d → Disk temperature

→ Contrast is not a problem!

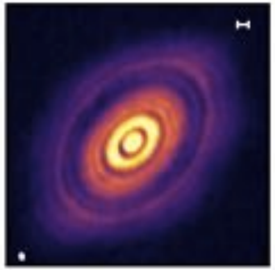


Testi et al. 2015

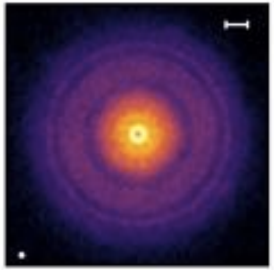


ALMA Partnership +LP et al. 2015

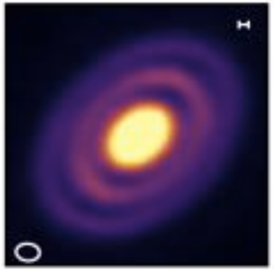
ALMA+VLA have been transformational to the field



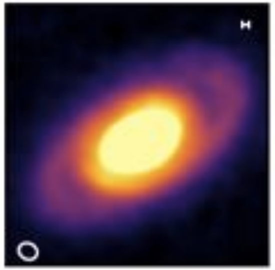
ALMA Partnership +2015



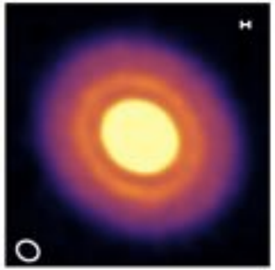
Andrews et al. 2016



Isella et al. 2016



Pérez et al. 2016



Dipierro et al. 2018

Setting the stage: From ISM dust to planetary systems

14 orders of magnitude growth

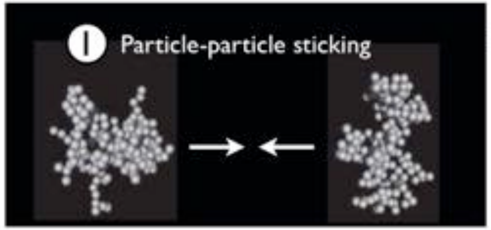
Size = μm — mm — m — km — Mm

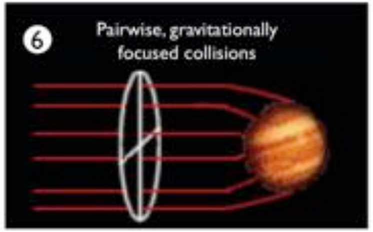
Interstellar Medium Dust

Last *direct detection* of solids before detecting Planets

?

Planets

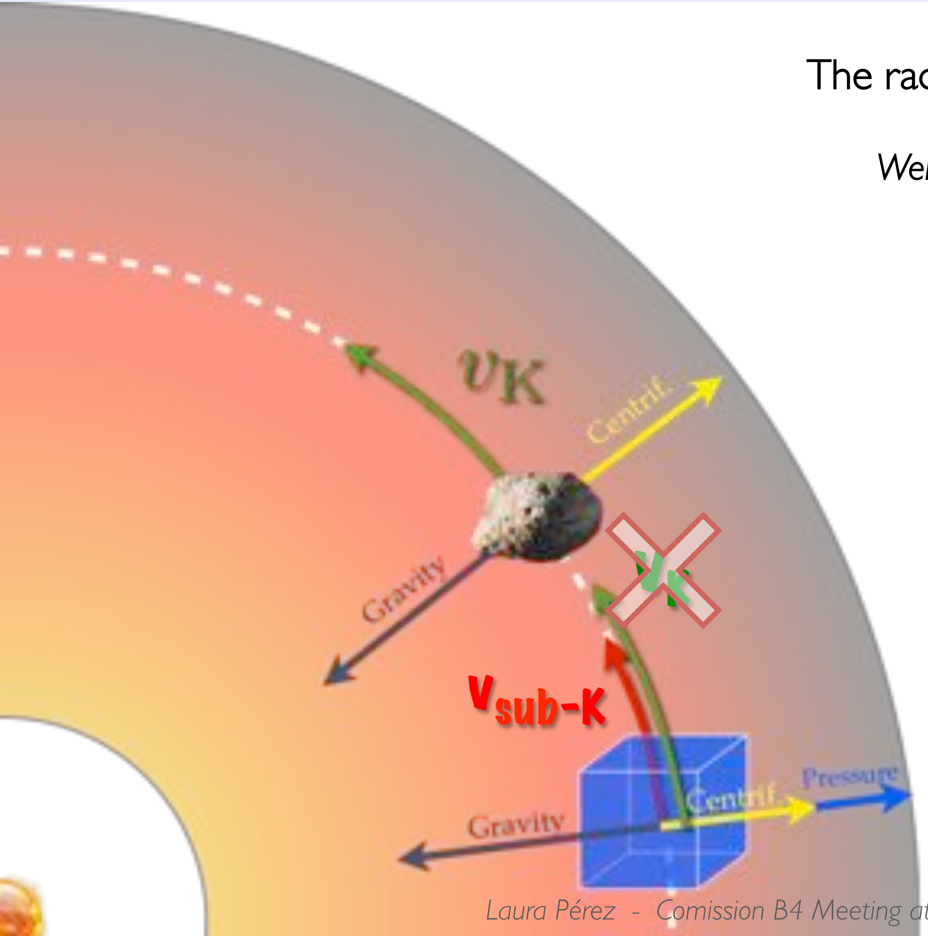




Adapted from Chiang & Youdin (2009)

The evolution of solids in disks: Modulated by the gas

Dust transport impacts its growth



The radial drift of solids
Whipple (1972)
Weidenschilling (1977)

Drift velocity of the dust:

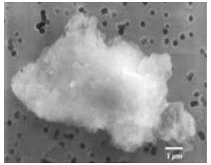
$$v_{r,\,dust} \propto \frac{dP}{dr}$$

→ Dust drifts toward P_{max}

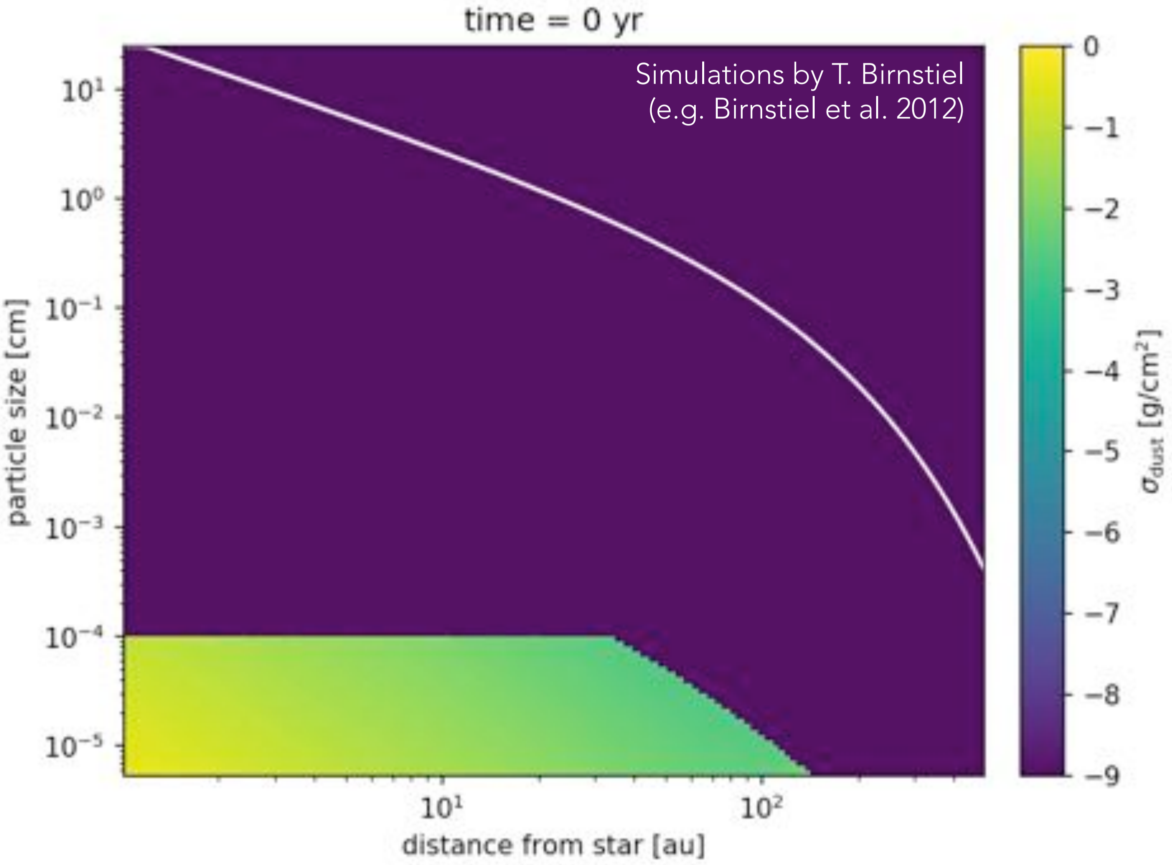
The evolution of solids in disks: Modulated by the gas

A disk *without substructure* will lose solids needed for planetesimal formation

Pebbles



ISM-like



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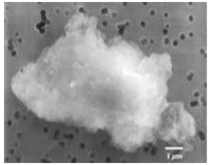

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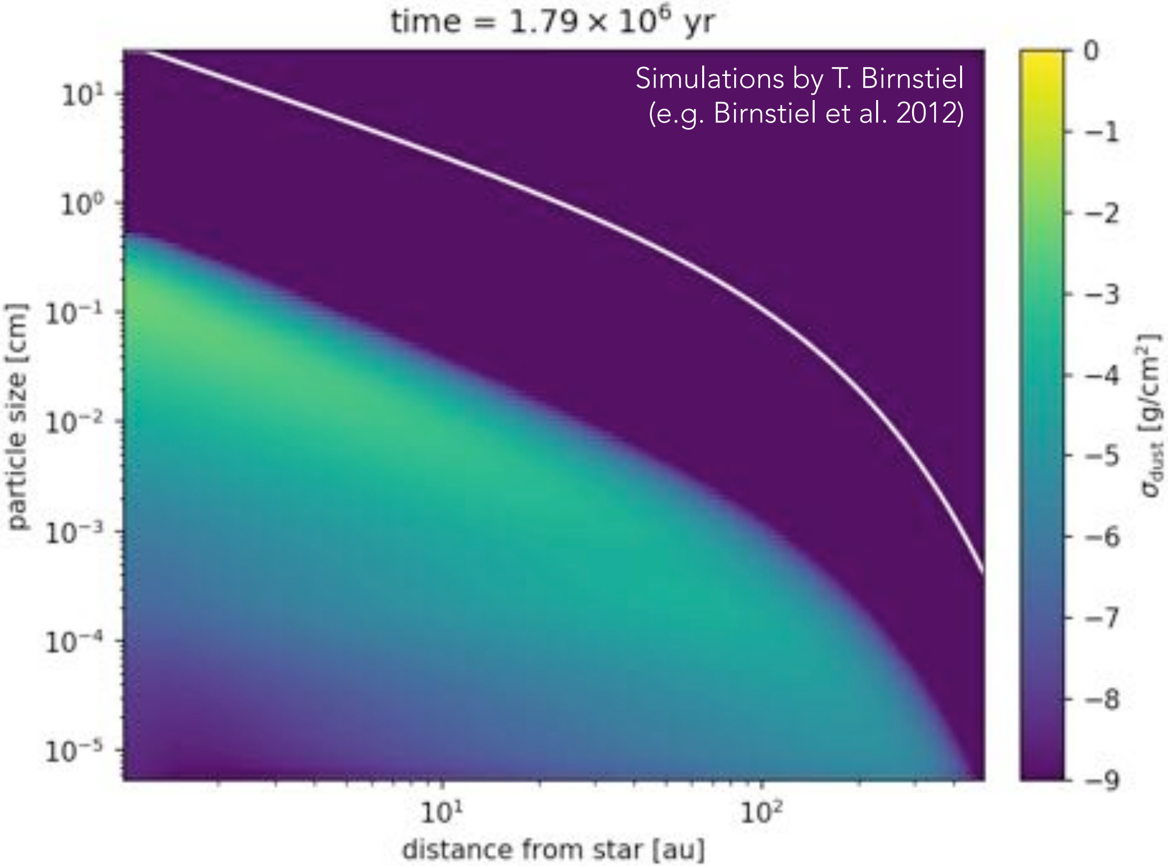
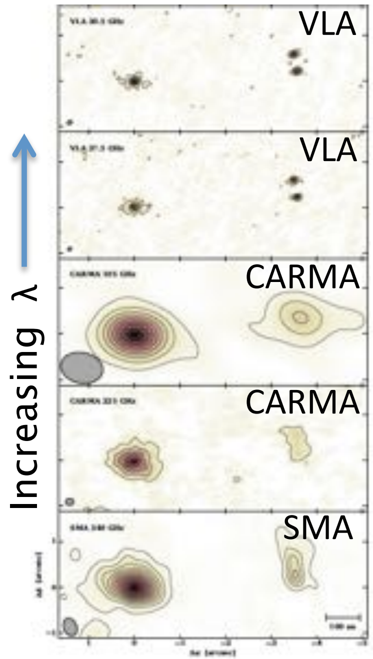
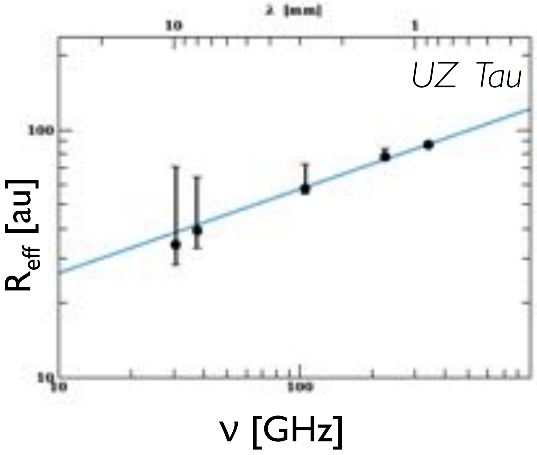


The evolution of solids in disks: what do observations tell us?

Inferring particle-size distribution in disks from multi-wavelength observations

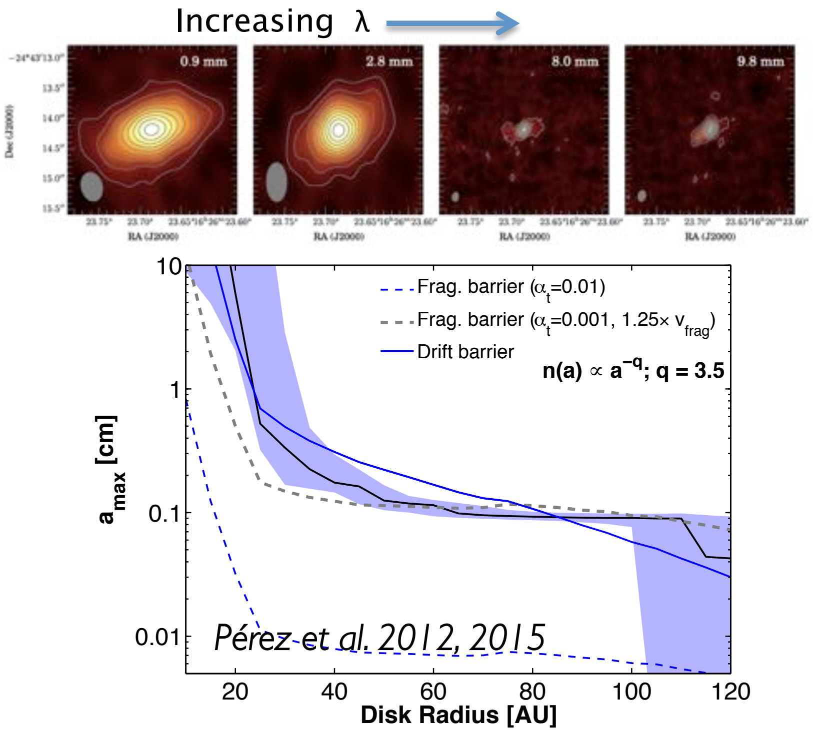
Disks get "smaller" with increasing λ





Tripathi +LP et al. 2018

Particles are "smaller" at increasing R

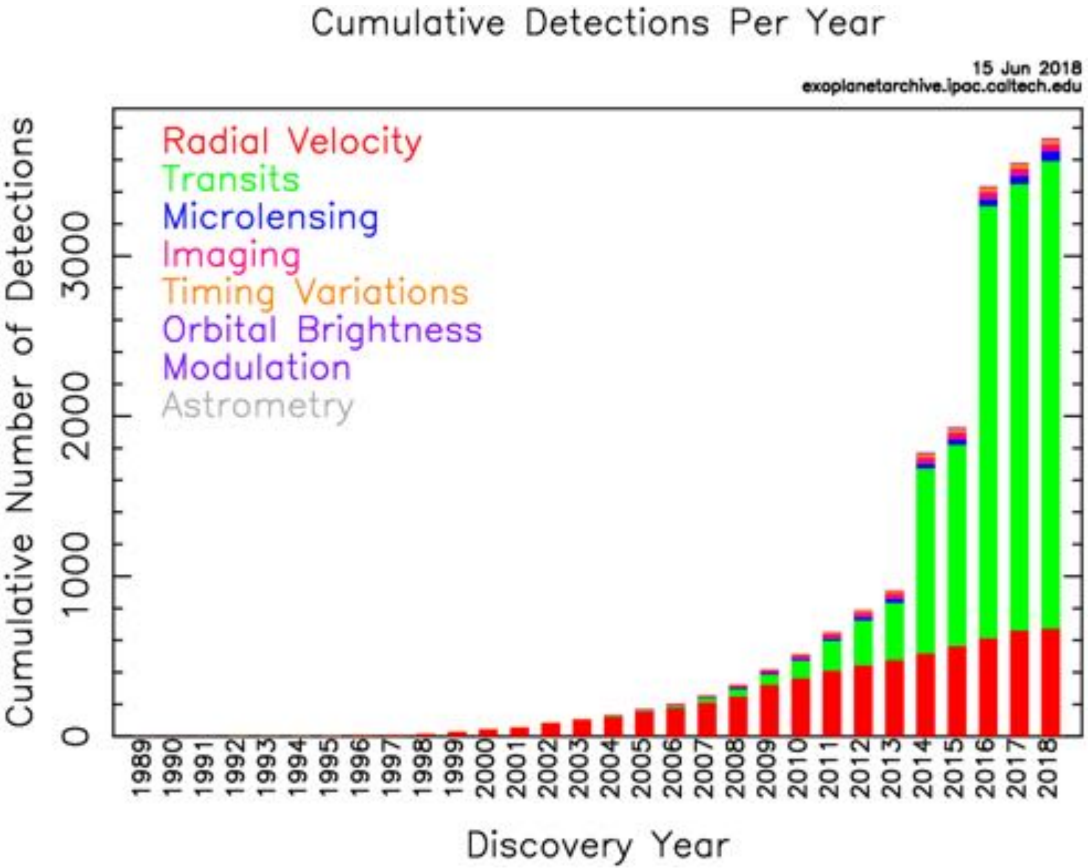


Pérez et al. 2012, 2015

Nature somehow overcomes these growth barriers

… after all, planets exist!

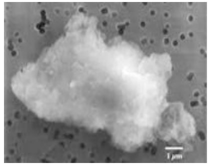
Solar system + exoplanet detections



What promotes solid concentration?

A disk *with substructure* will concentrate solids needed for planetesimal formation

Pebbles



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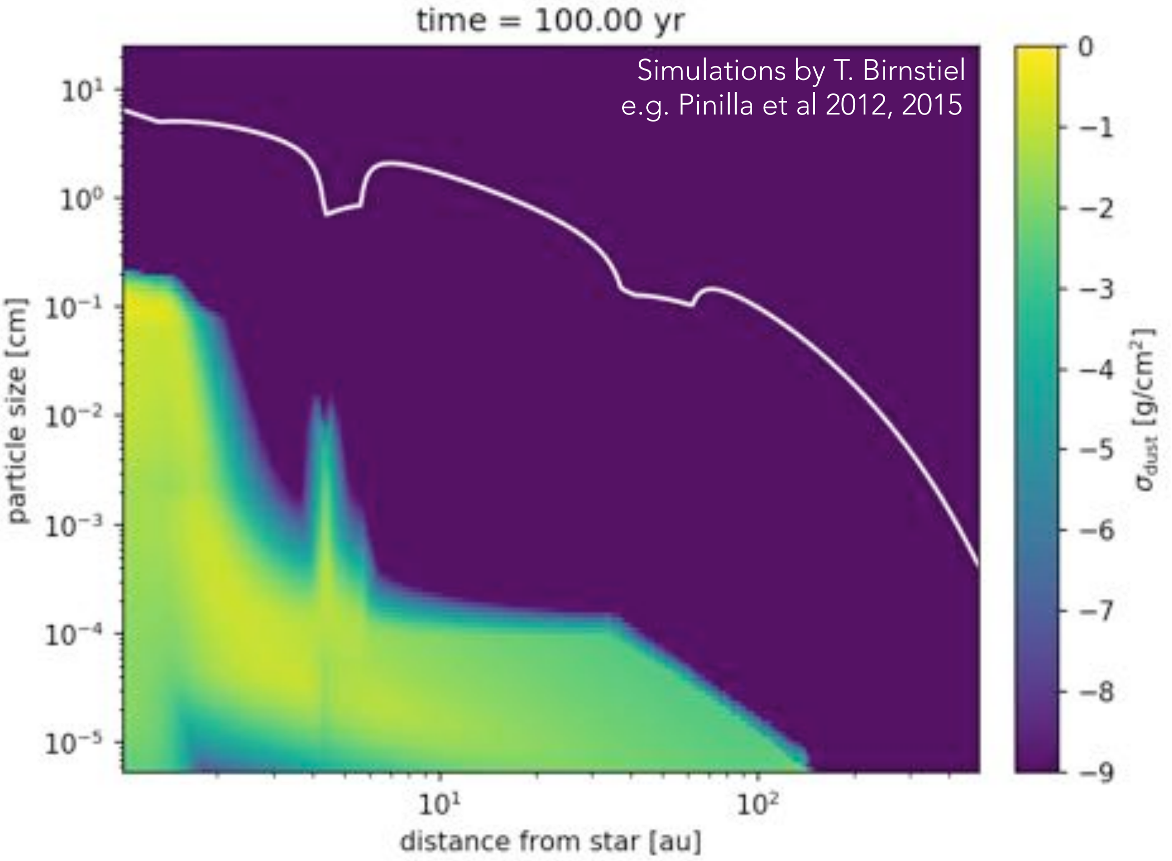

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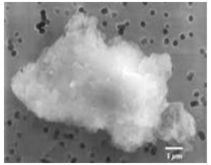

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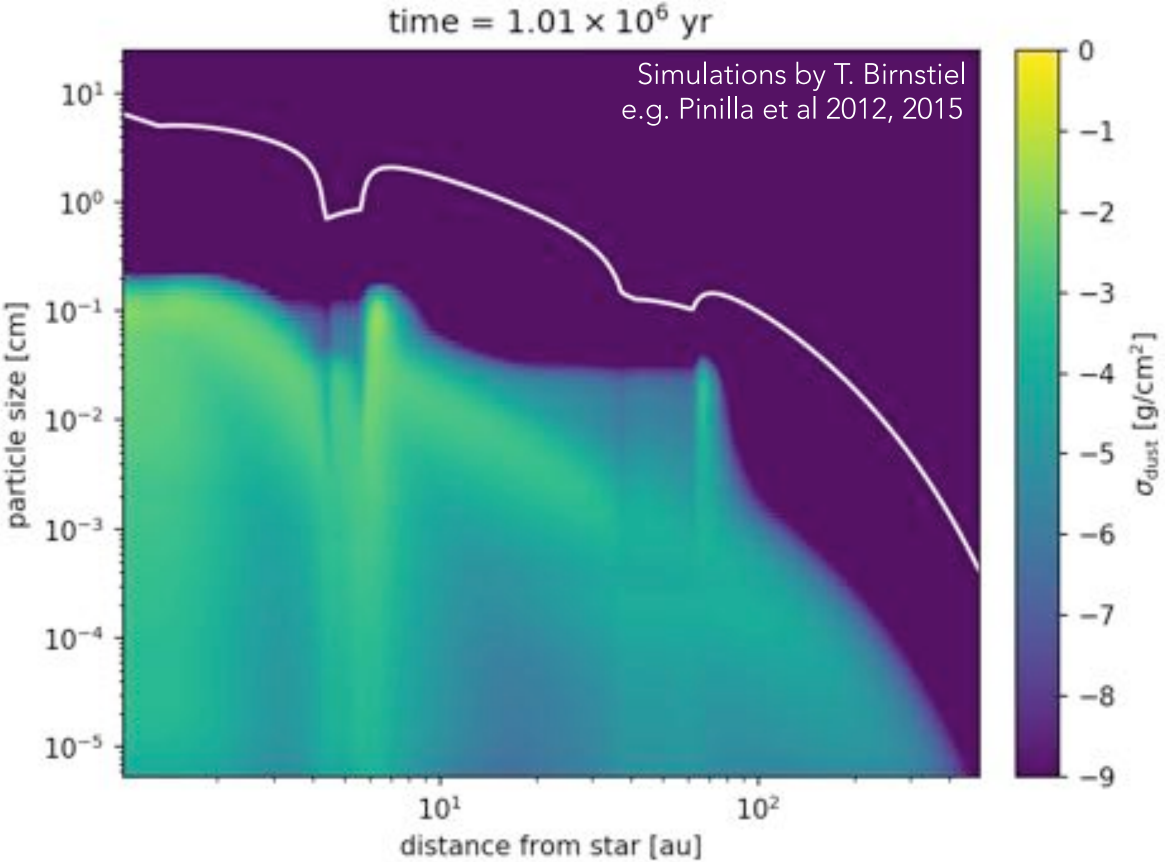
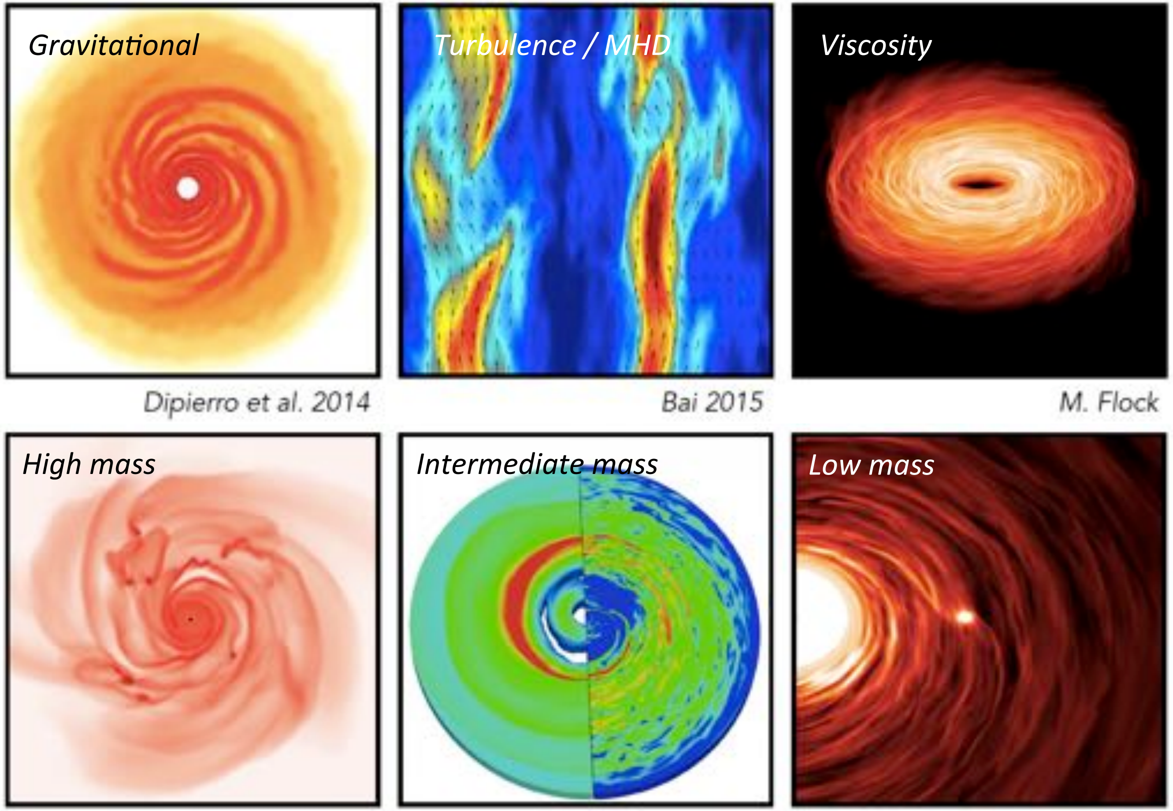


How is substructure created?

There are plenty of ways!

Instabilities

Companions



Dipierro et al. 2014 | Bai 2015 | M. Flock

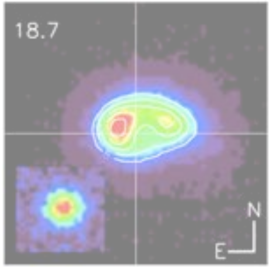
Lichtenberg & Schleicher 2015 | Z. Zhu | C. Baruteau

slide c/o S. Andrews

For many disks, we already knew about substructure

Transition Disks: substructure was already known even without an image! (SED modeling)

IRS Oph 48



IR

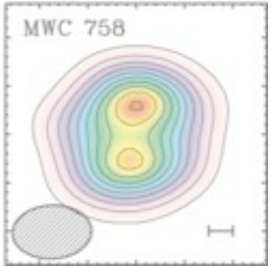
Geers et al. 2007

HD 142527

IR

Fukagawa et al. 2006

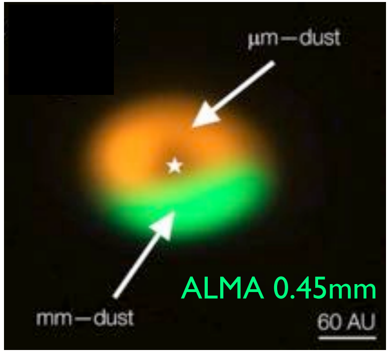
MWC 758



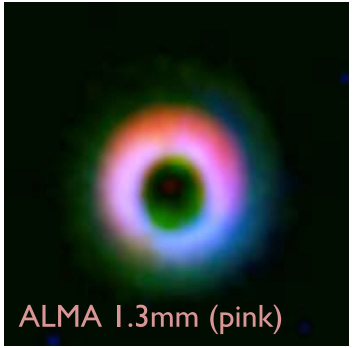
SMA

Andrews et al. 2011

Radio's view



Van der Marel et al. (2013)



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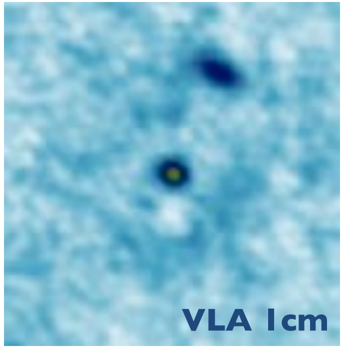
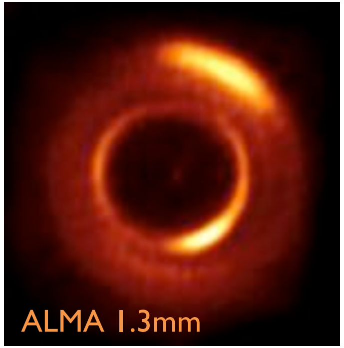
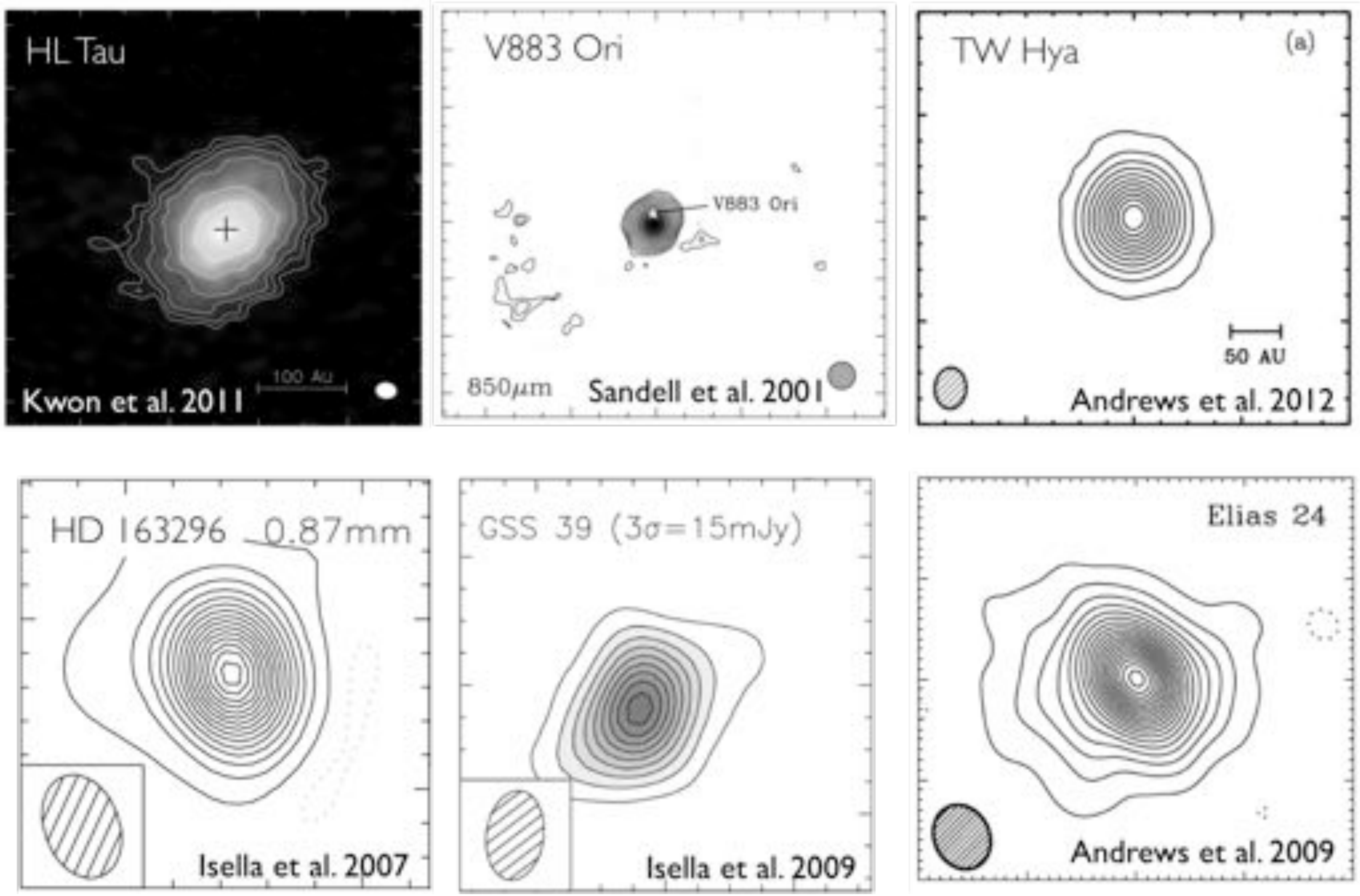


Casassus et al. (2018)



Dong et al. (2018)

A mm-wave gallery of "classical" disks pre-ALMA



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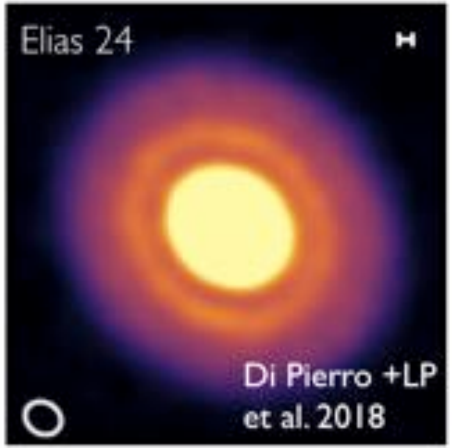


DSHARP:
Disks Substructures at High Angular Resolution Project

coPIs: Andrews (Harvard/SAO), Pérez (U. Chile), Isella (Rice), Dullemond (U. Heidelberg)

Graduate Students: J. Huang (Harvard/SAO), N. Troncoso (U. Chile), E. Weaver (Rice)

Collaborators: Guzman (ALMA), Carpenter (ALMA), Wilner (Harvard/SAO), Zhu (UNLV), Birnstiel (LMU Munich), Hughes (Wesleyan), Oberg (Harvard/CfA), Bai (IASTU/THCA), Ricci (CSUN), Benisty (UMI/U. Chile)

Data:
- 1.3 mm (Band 6) observations of 20 classical disks
- Angular resolution ~ 5 AU
- Sensitivity ~ 12-20 microJy/beam

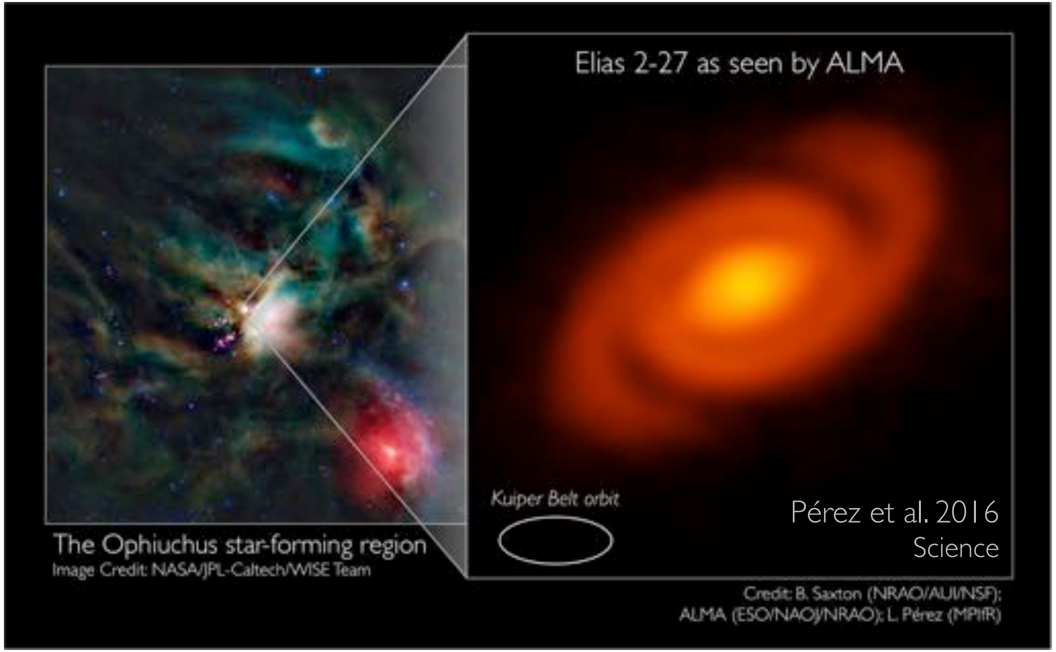
Goals:
Understand prevalence, forms, scales, spacings, symmetry, amplitudes, etc. of substructures in a representative sample of classical disks

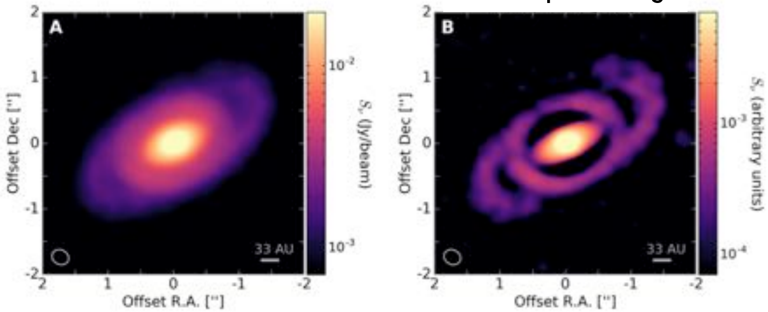
Analysis ongoing:
Look for 8+ papers (with data product release) in the fall

DSHARP

ALMA Observations of Elias 2-27: evidence of disk instability in a young disk

Providing a unique benchmark for planet formation studies



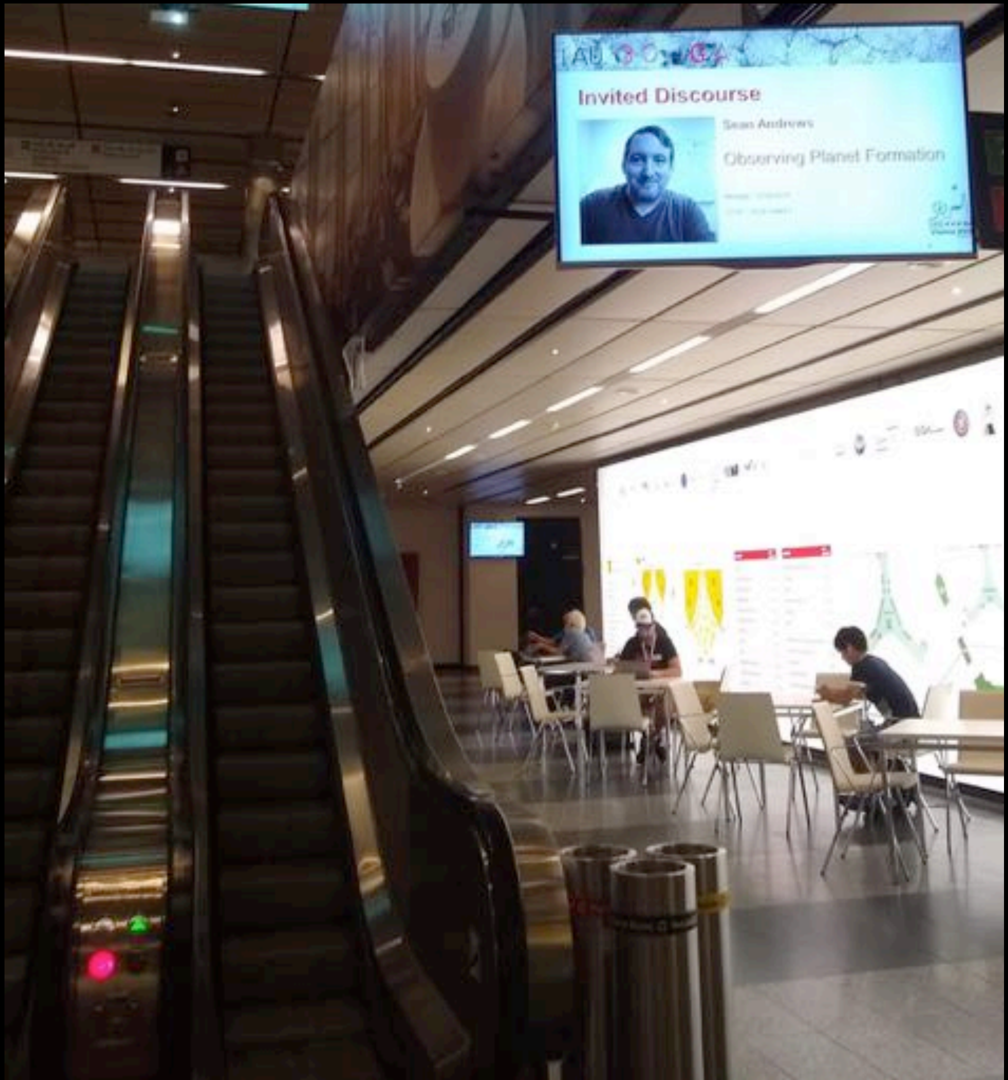


A snowball effect of theory papers from a single observation!
e.g. *Meru et al. 2017; Tomida et al. 2017; Bae & Zhu 2017; Juhazs & Rosotti 2017; Forgan et al. 2018*

DSHARP

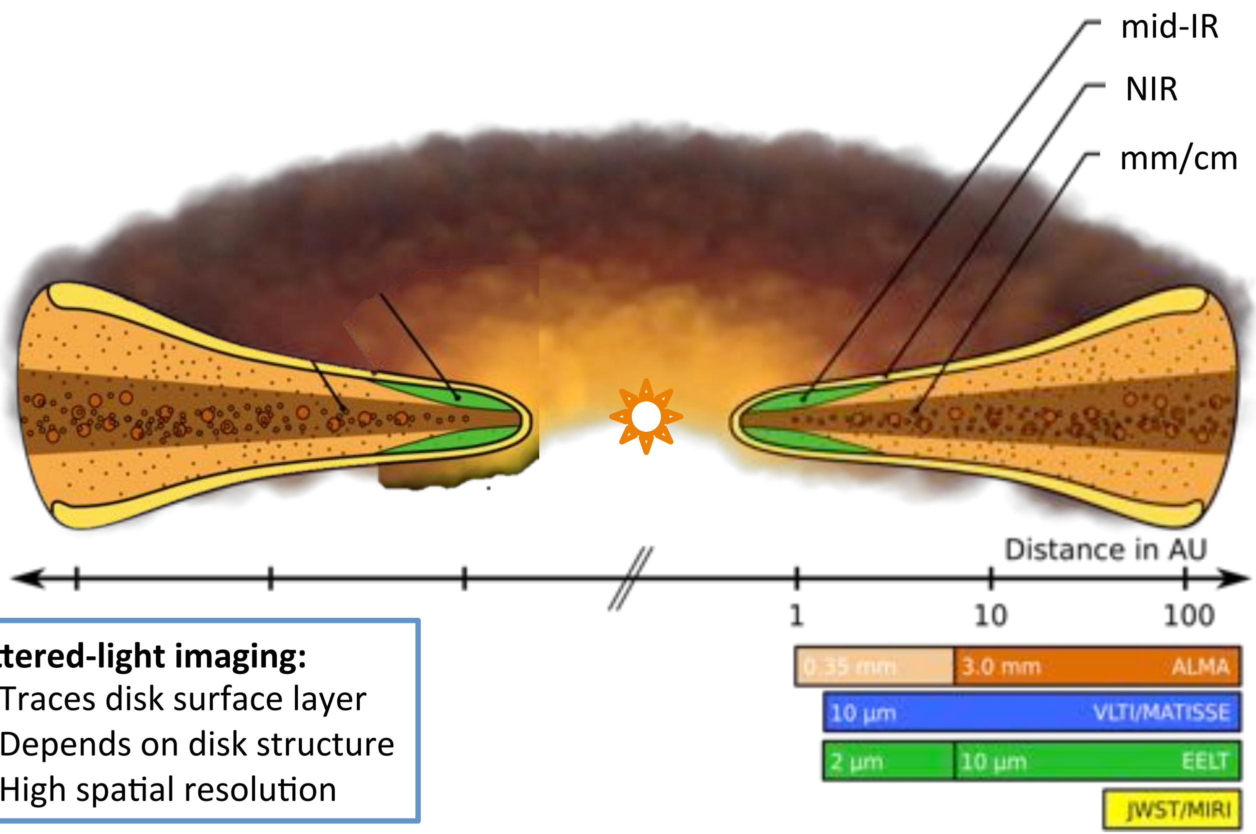
INVITED DISCOURSE:

Sean Andrews
Monday, August 27
@17:15



Observing substructures at multiple wavelengths

What can we learn from studying the same object at multiple wavelengths?



adapted from Testi et al. (2014)

Scattered-light imaging:

- Traces disk surface layer
- Depends on disk structure
- High spatial resolution

Substructures at multiple wavelengths

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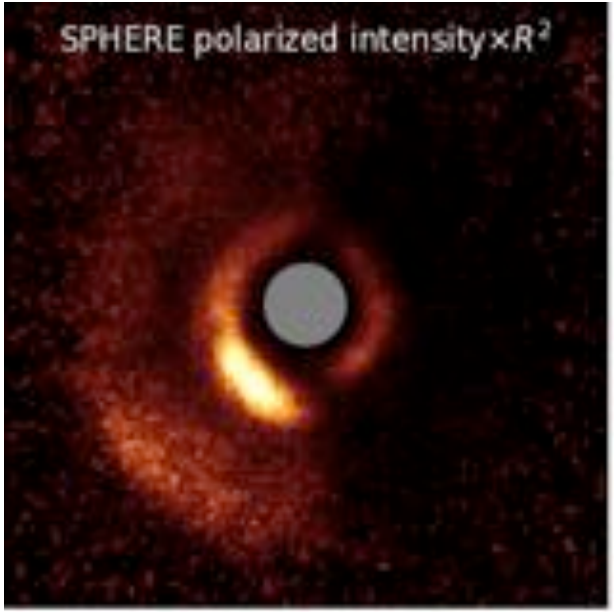
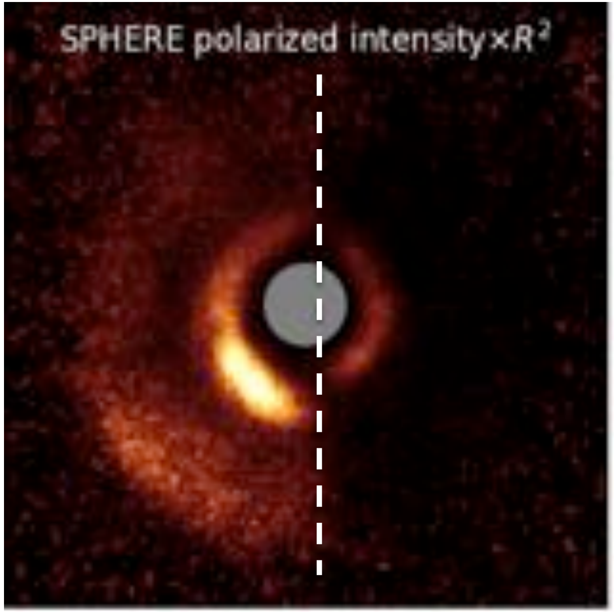


SPHERE J-band (40mas)
Benisty et al. (submitted)

Shadows in scattered light: a different probe of disk substructure?

Scattered light observations are very sensitive to the illumination pattern



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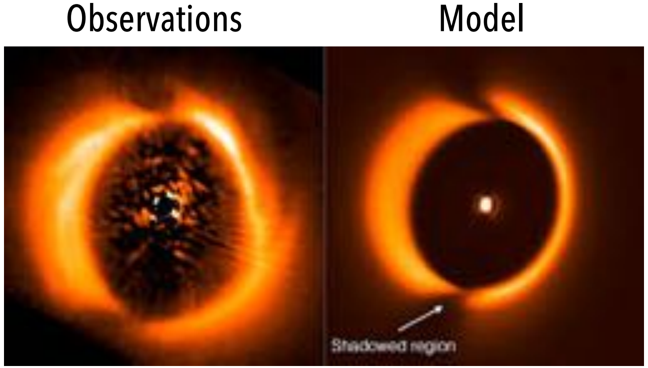
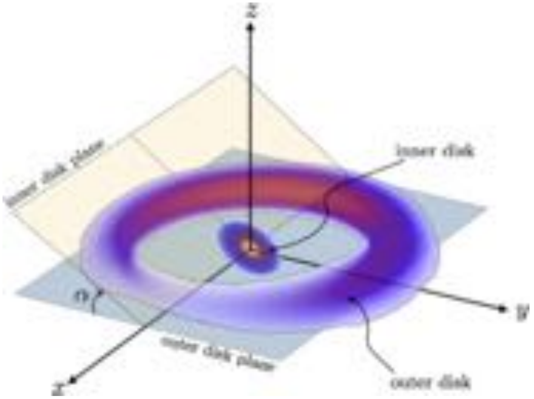


HD 142527
Marino et al. 2015



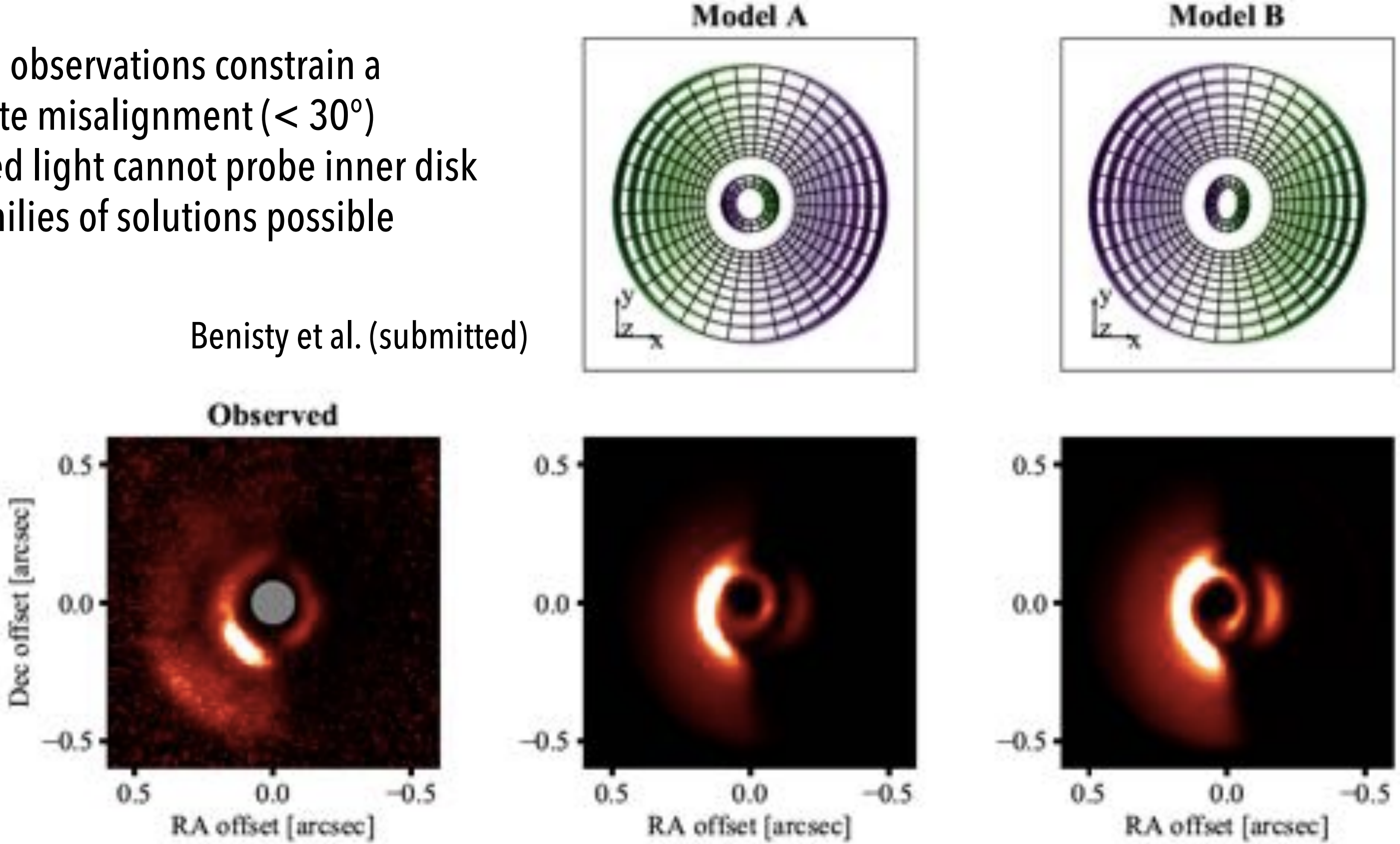
Highly misaligned inner disk cast <u>narrow</u> shadows on the outer disk

Not narrow shadows: an East-West broad shadow

A less pronounced misalignment can produce broad shadows in scattered light

- SPHERE observations constrain a moderate misalignment (< 30°)
- Scattered light cannot probe inner disk
- Two families of solutions possible

Benisty et al. (submitted)



What do the new DSHARP observations tell us?

New information about kinematics, gas emission, and dust continuum emission

Solids

Gas

Kinematics

ALMA (50mas)
Pérez et al. in prep

What do the new DSHARP observations tell us?

New information about kinematics, gas emission, and dust continuum emission

ALMA (50mas)
Pérez et al. in prep

Kinematics:
assuming no misalignment, significant residuals remain

Solids:
inner disk is misaligned w.r.t. the outer disk by ~ 6º (!!)

What do the new DSHARP observations tell us?

New information about kinematics, gas emission, and dust continuum emission

ALMA (50mas)
Pérez et al. in prep

Spatially resolved radio observations provide new insights into processes that transform the disk reservoir into a planetary system

Structure?

Substructure is needed to prevent solids from drifting and to form planets

A multitude of structures: new detections pave the way to understand star & planet formation

Radio Power?

We are getting to understand basic disk evolution from high resolution disk observations, particularly at mm wavelengths

We can now test if features predicted in disk evolution are present in most disks