Substructures in Protoplanetary Disks through Radio Eyes

Wassily Kandinsky, 1913

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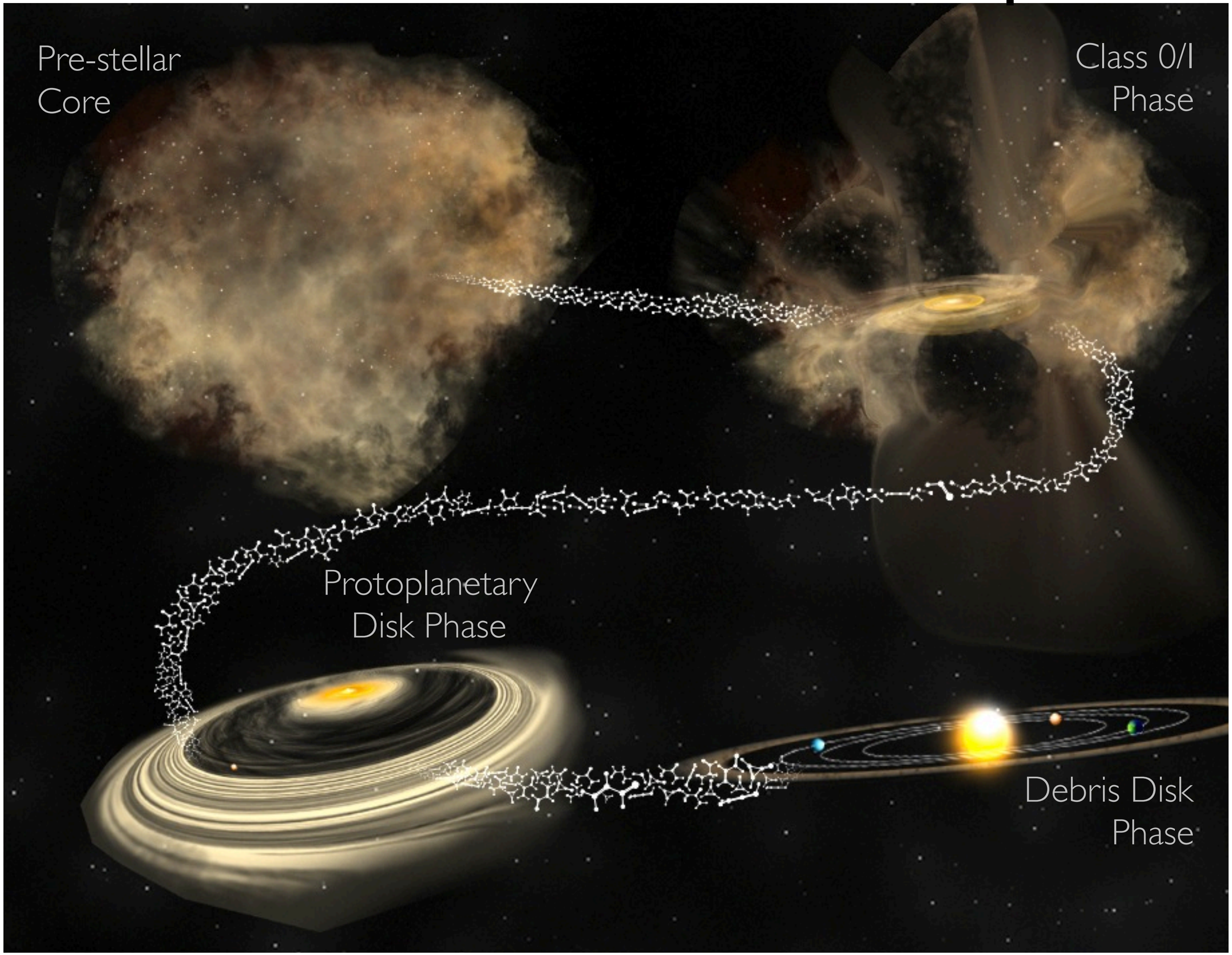
Our current view of the star* formation process



* Low mass stars

What do we learn about disks from radio continuum?

Rich set of information from sub-mm to cm wavelengths

Dust component
(thermal dust emission)

Generally optically thin at λ>mm

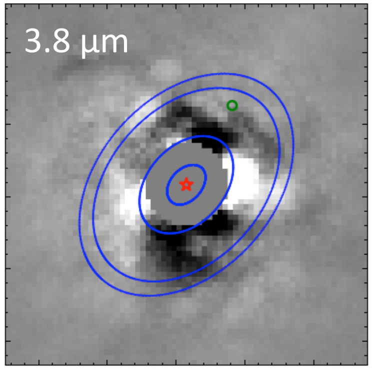
$$I_\nu \approx B_\nu(T_d)\tau_\nu \approx \kappa_\nu \Sigma_d T_d$$

Dust properties

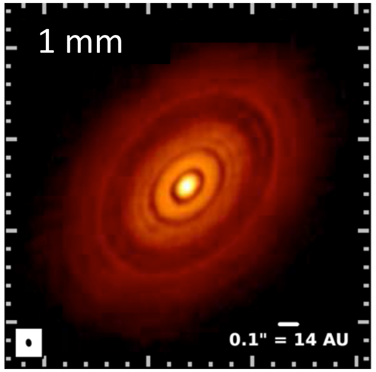
Mass available

Disk temperature

Contrast is not a problem!

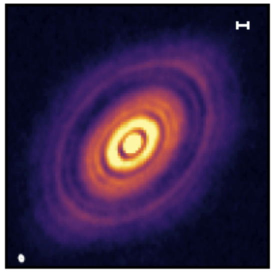


Testi et al. 2015

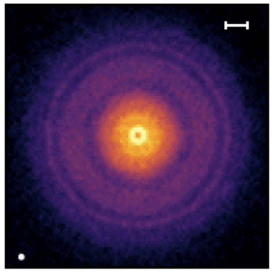


ALMA Partnership +LP et al. 2015

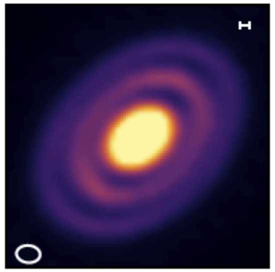
ALMA has been transformational to the field



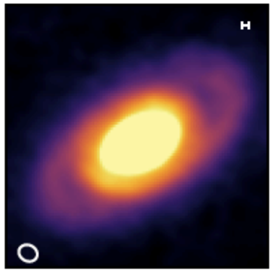
ALMA Partnership et al. 2015



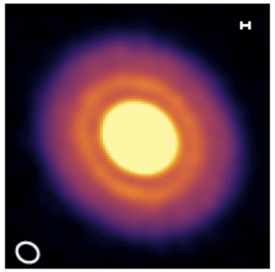
Andrews et al. 2016



Isella et al. 2016



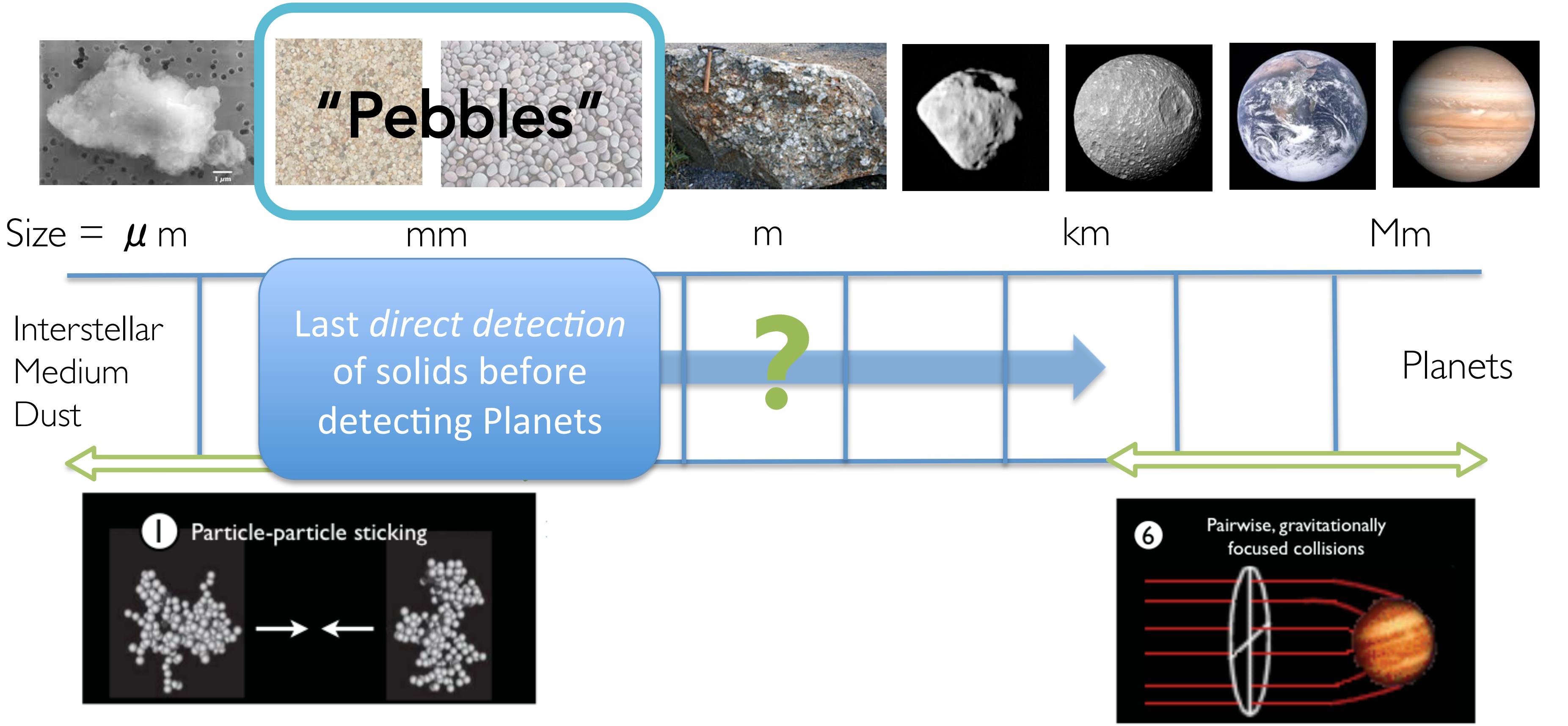
Pérez et al. 2016



Dipierro et al. 2018

From ISM dust to Planetary Systems

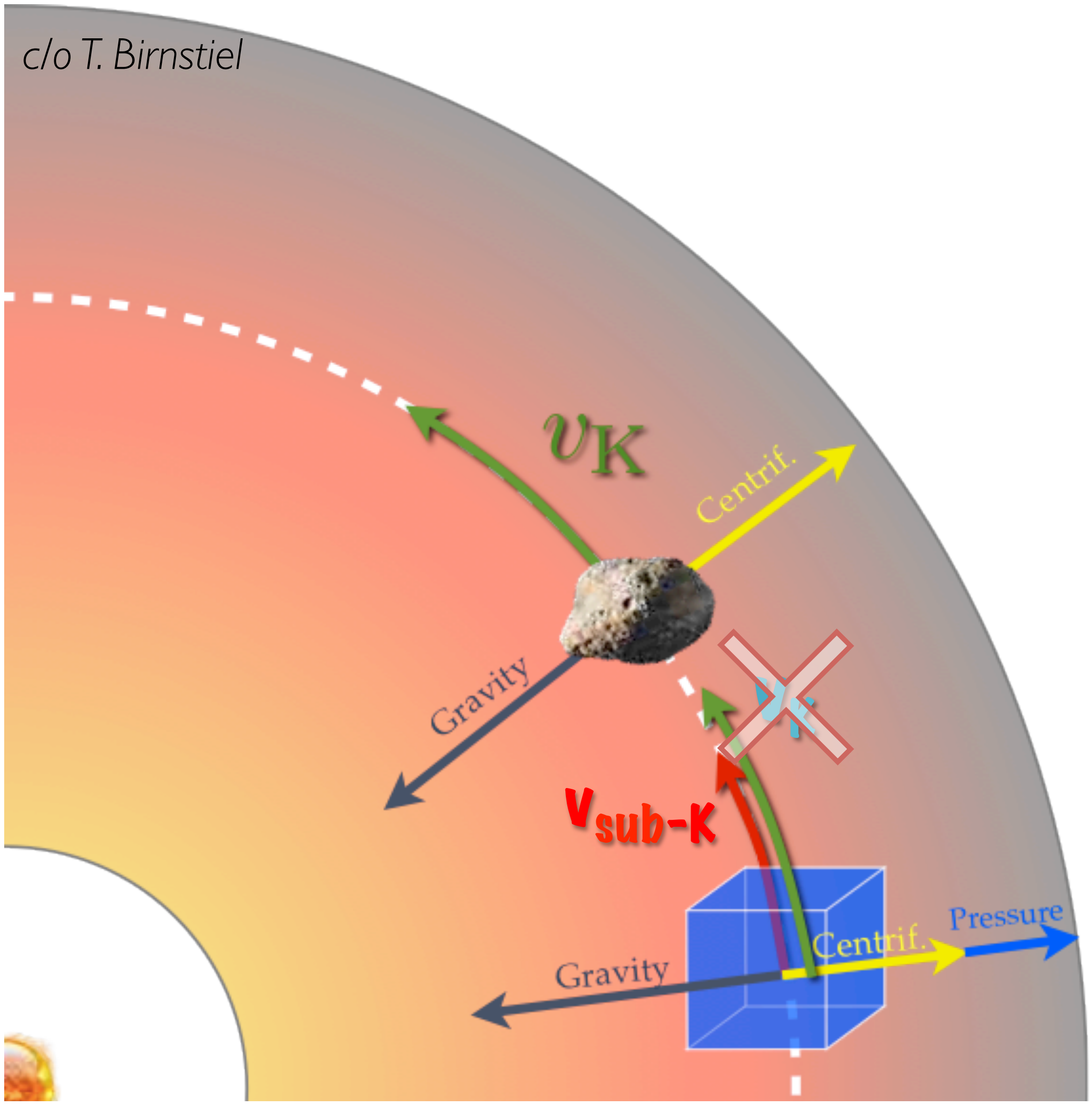
14 orders of magnitude growth !



Adapted from Chiang & Youdin (2009)

Solids Growth: Modulated by the Gas

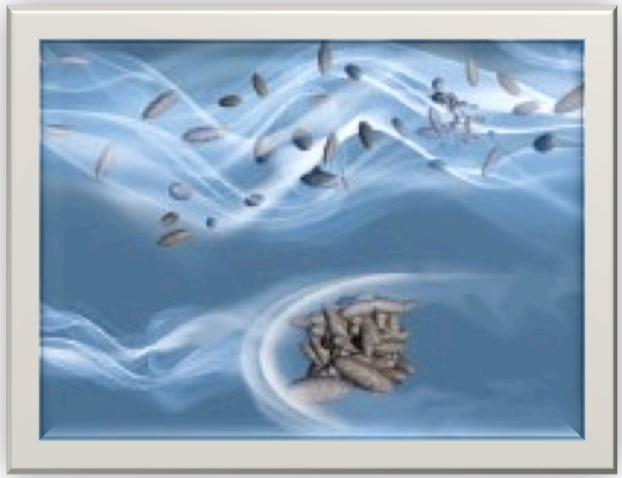
Dust transport impacts its growth



The radial drift of solids

Whipple (1972)

Weidenschilling (1977)



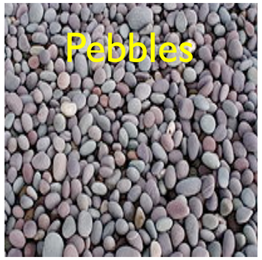
Drift velocity of the dust:

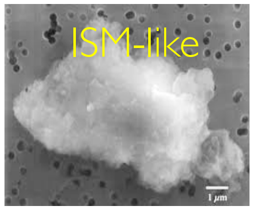
$$v_{r,\,dust} \propto \frac{dP}{dr}$$

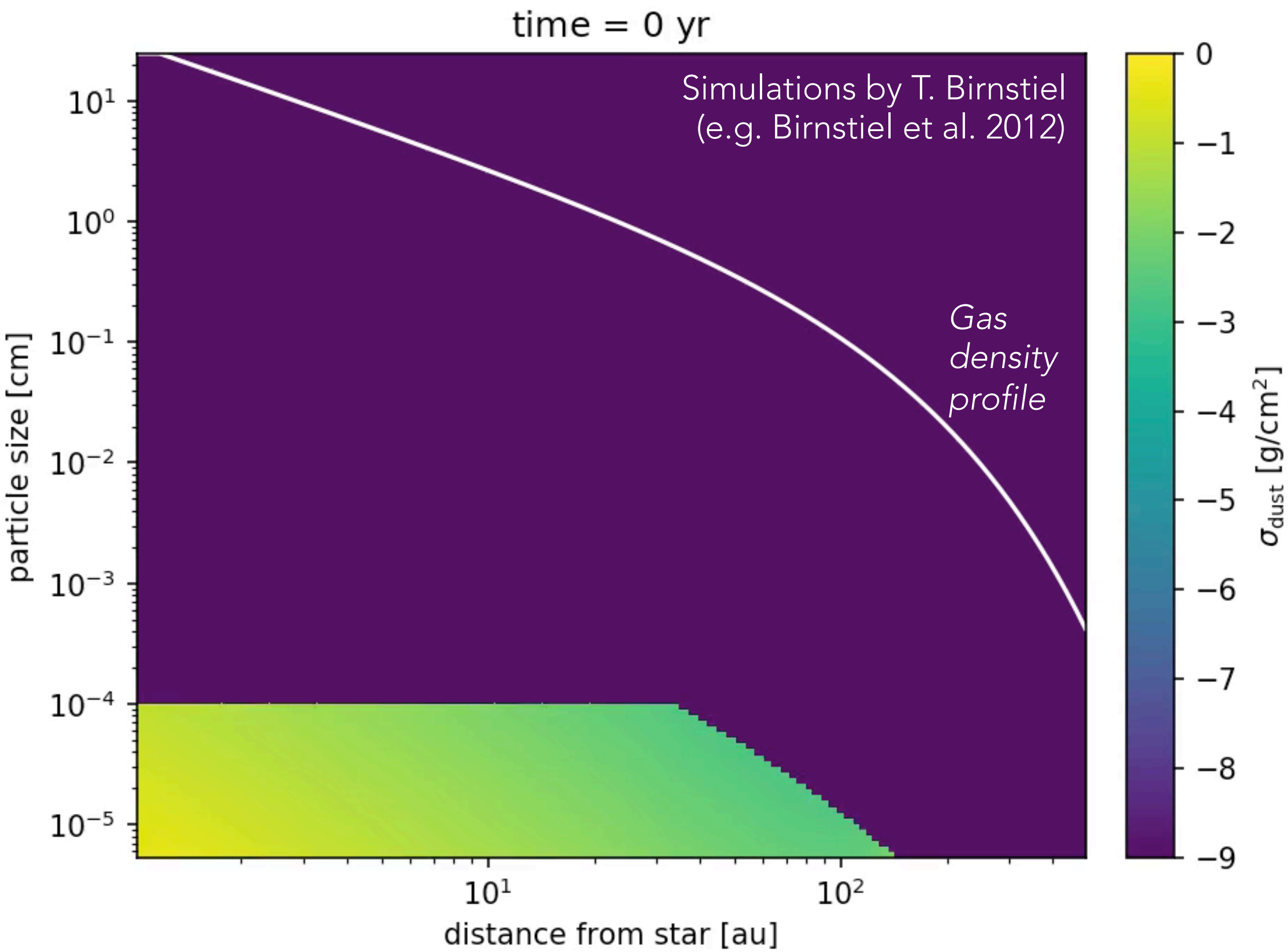
→ Dust drifts toward P_{max}

Solids Growth: Modulated by the Gas

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



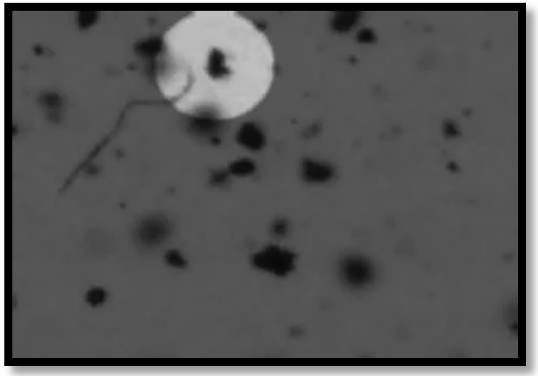




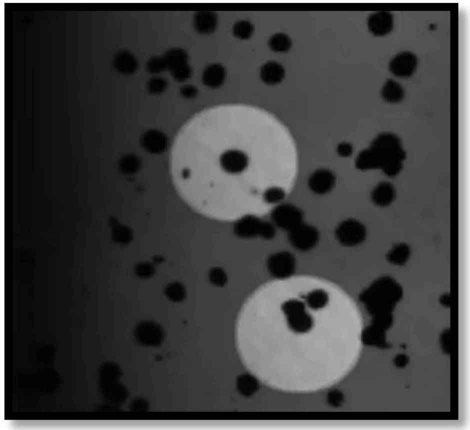
Solids Growth: Contingent on its Properties

e.g. outcomes of collissions depend on composition/structure of grains

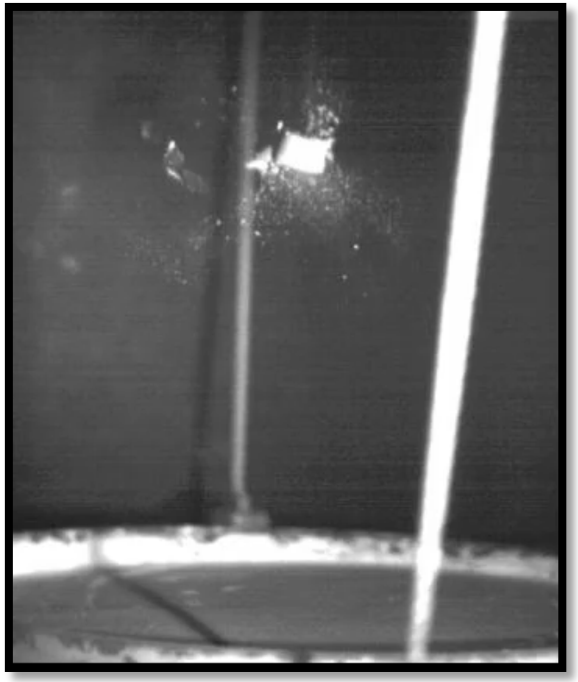
Sticking



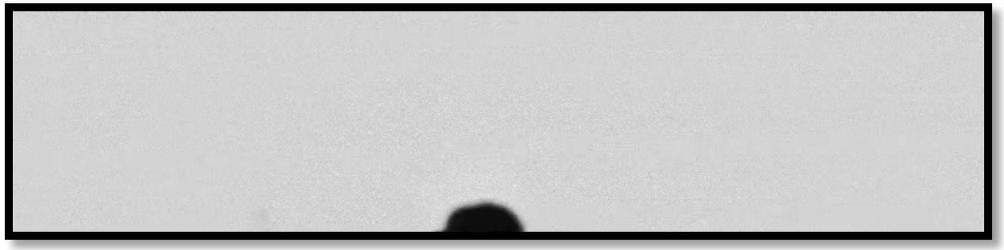
Bouncing



Fragmentation



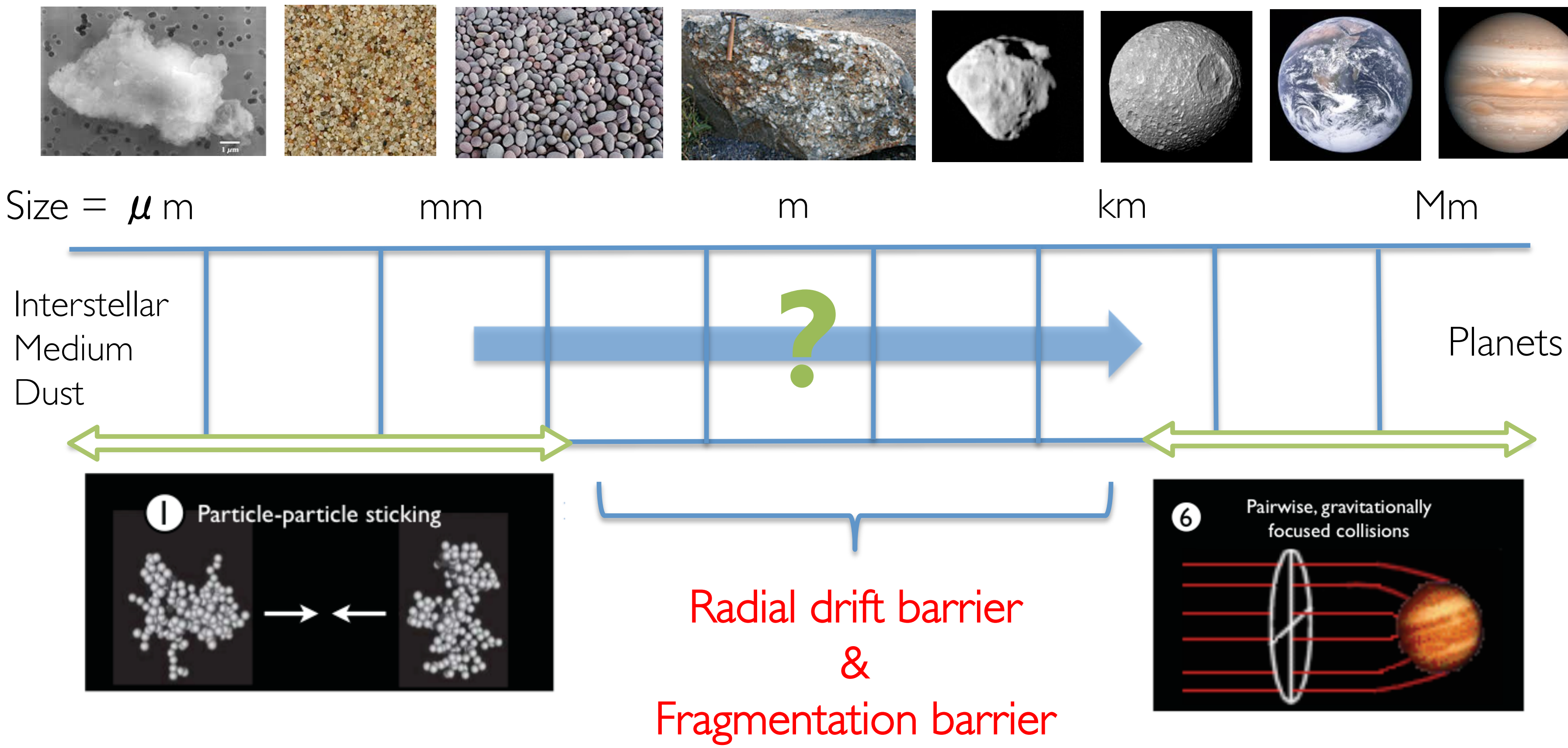
Mass Transfer



Experiments from J. Blum's Lab
Movies courtesy of J. Blum and collaborators,
see e.g. Blum & Wurm 2008, Güttler et al. 2010

From ISM dust to Planetary Systems

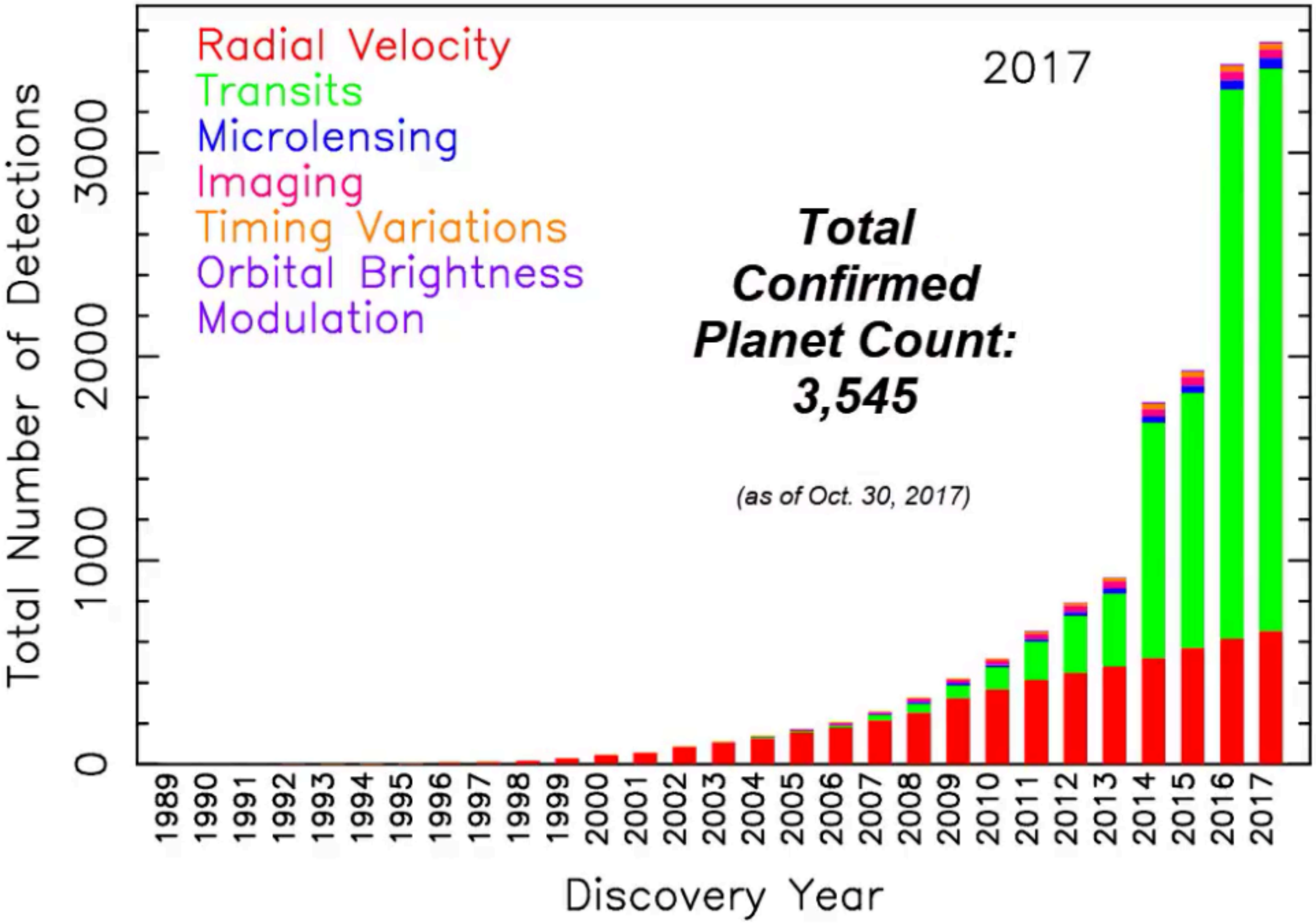
14 orders of magnitude growth !



Adapted from Chiang & Youdin (2009)

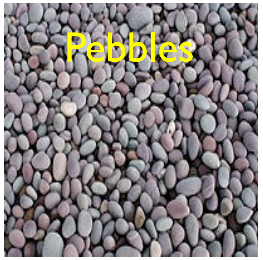
Nature somehow overcomes these barriers

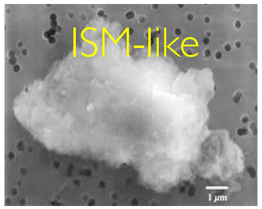
… after all, planets exist!

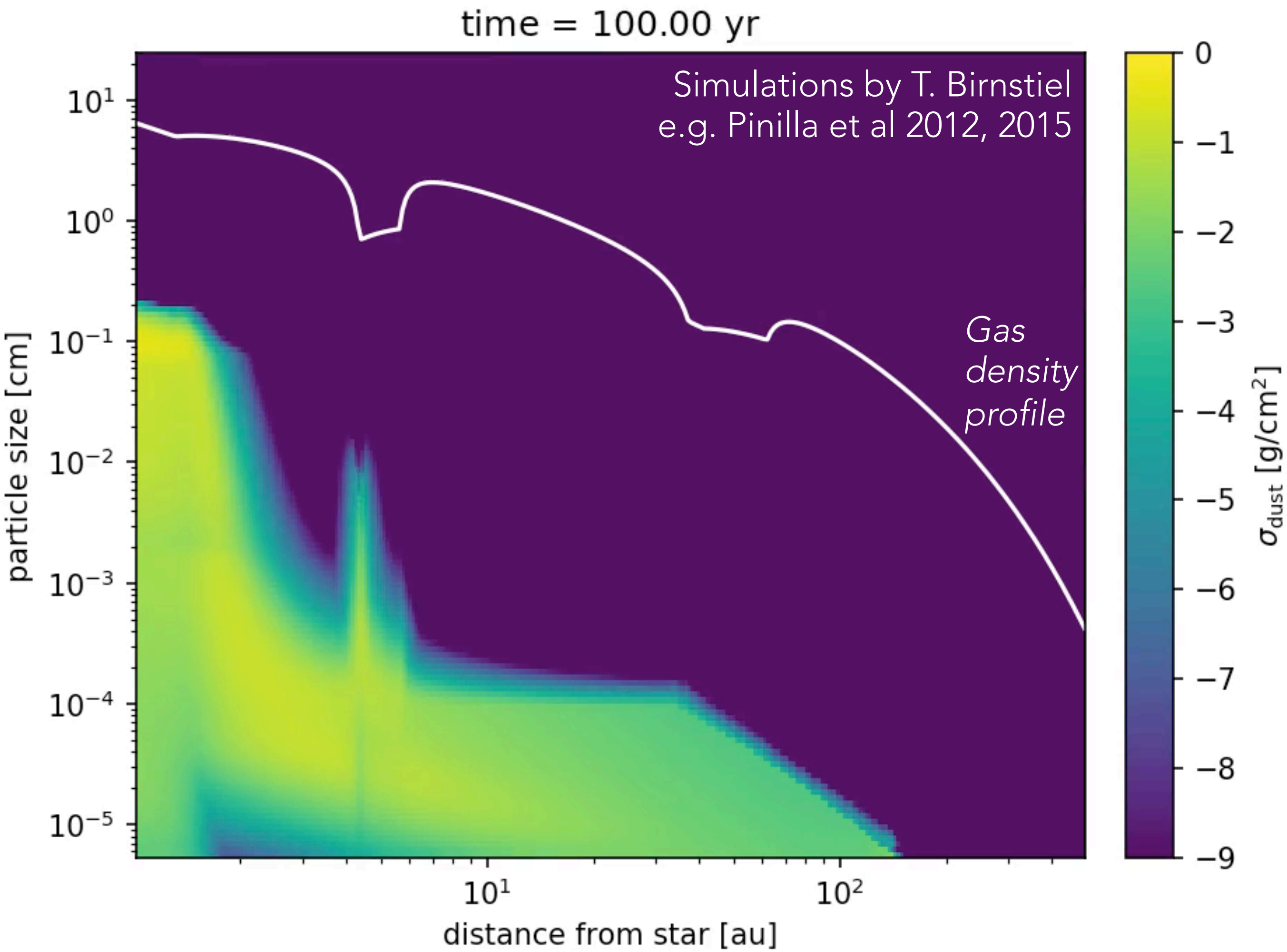


What promotes solid concentration?

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



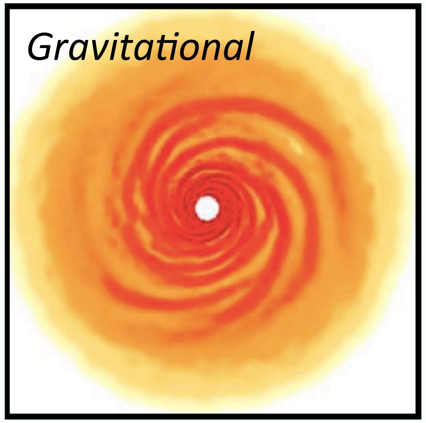




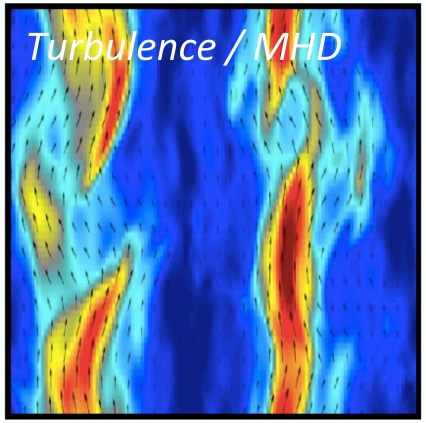
How is substructure created?

There are plenty of ways!

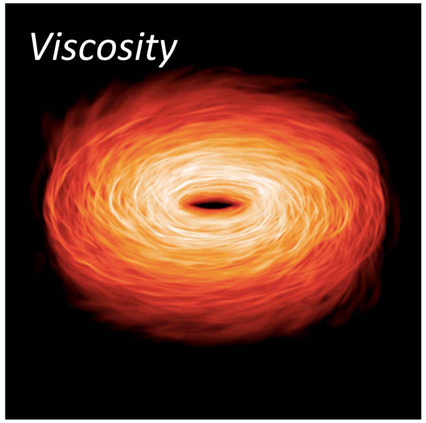
Instabilities



Dipierro et al. 2014

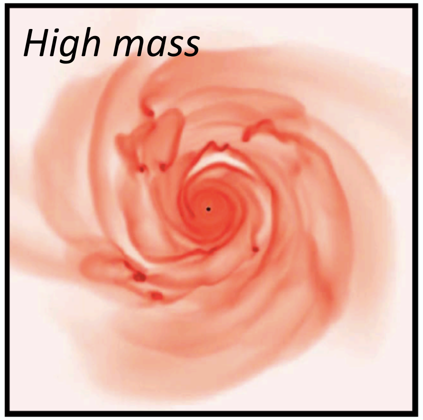


Bai 2015

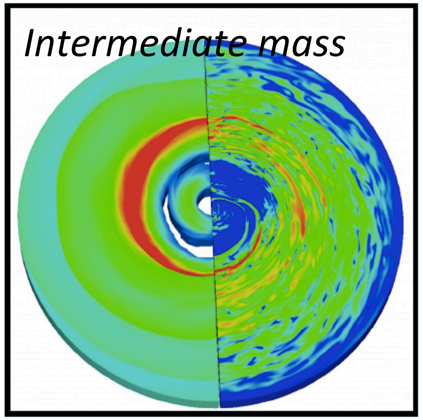


M. Flock

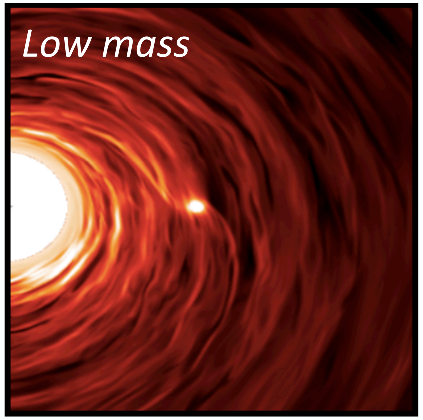
Companions



Lichtenberg & Schleicher 2015



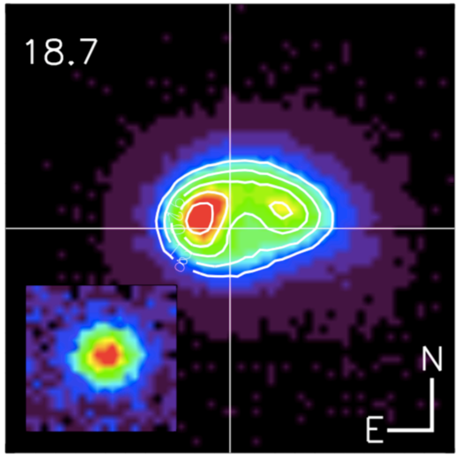
Z. Zhu



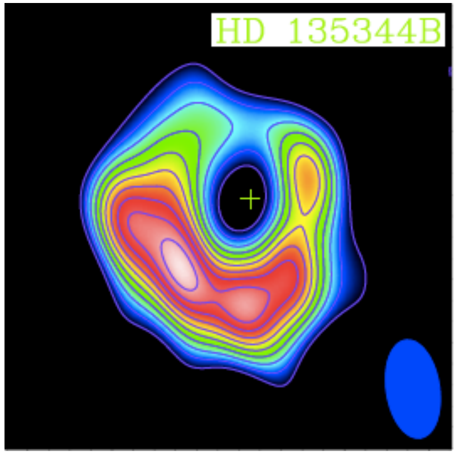
C. Baruteau

For many disks, we already knew about substructure

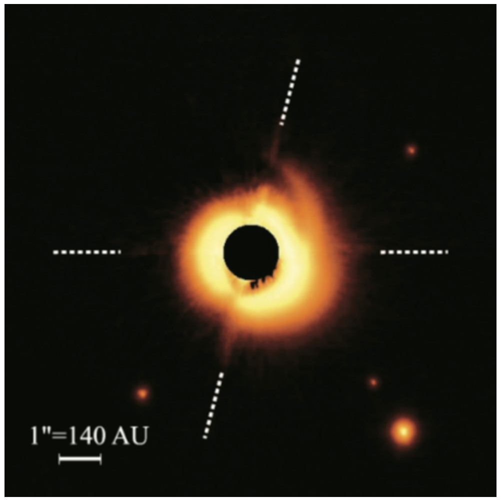
… even before ALMA, sometimes even without an image! (SED modeling)



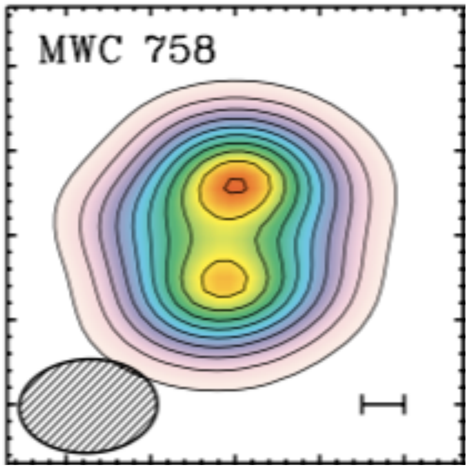
IRS 48, Geers et al. 2007



SAO 206462, Brown et al. 2009



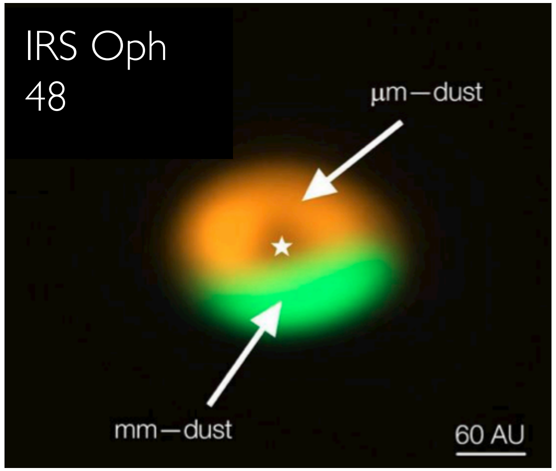
HD142527, Fukagawa et al. 2006



MWC758, Andrews et al. 2011

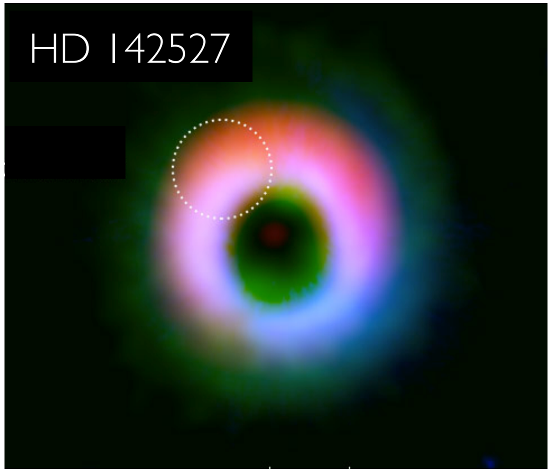
ALMA had a huge impact in the field of transition disks

Now asymetries, kinematics, gas and dust depletion can be studied in great detail

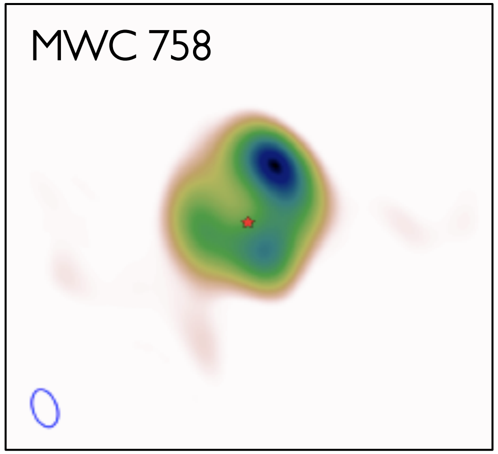


Van der Marel et al. (2013)

Pérez et al. (2014)

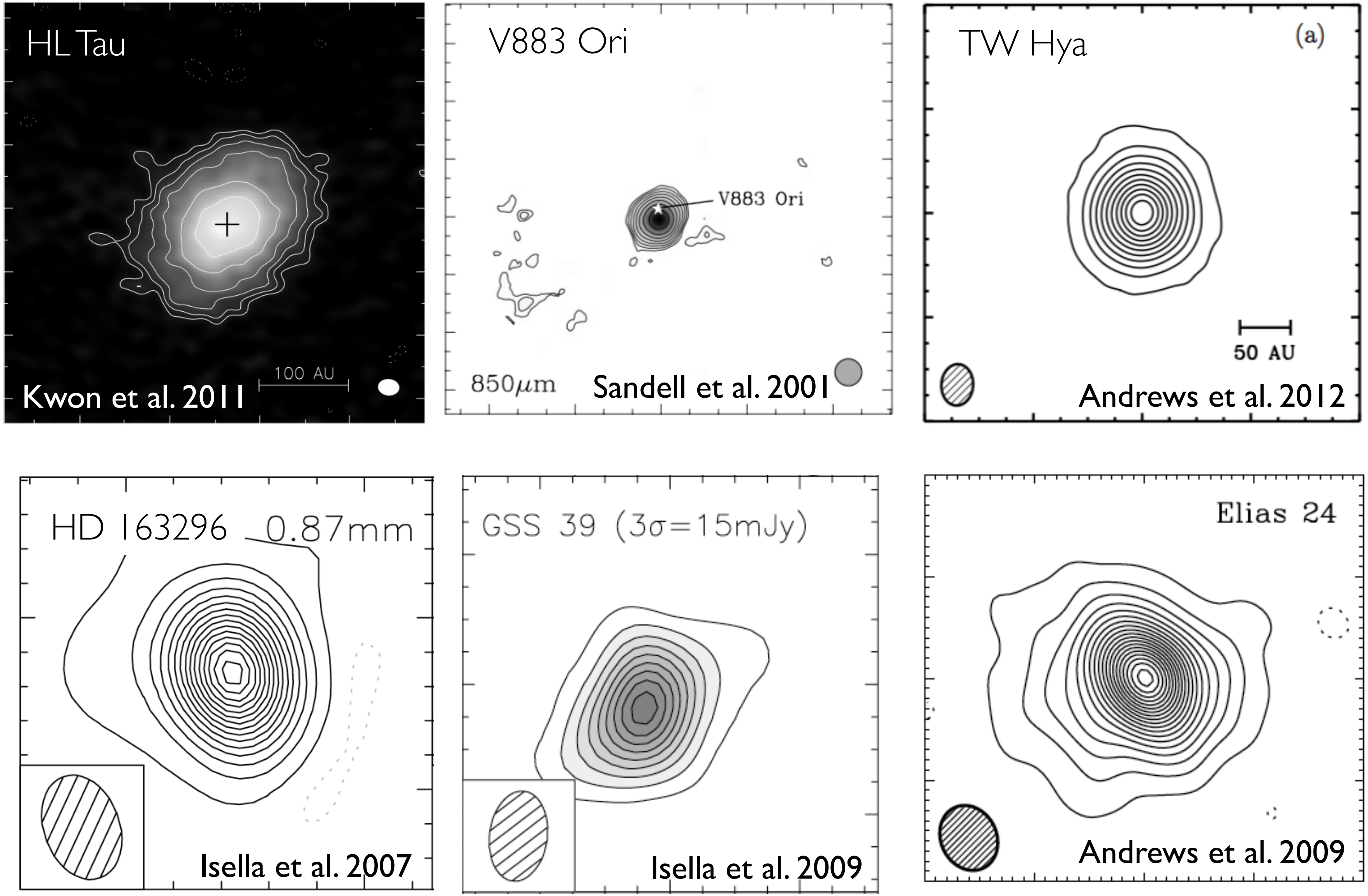


Casassus et al. (2013)

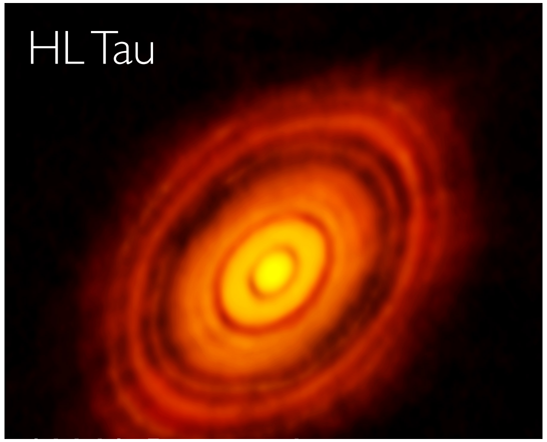


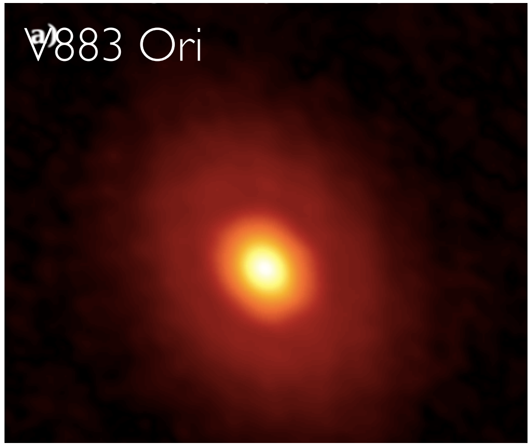
Marino et al. (2015)

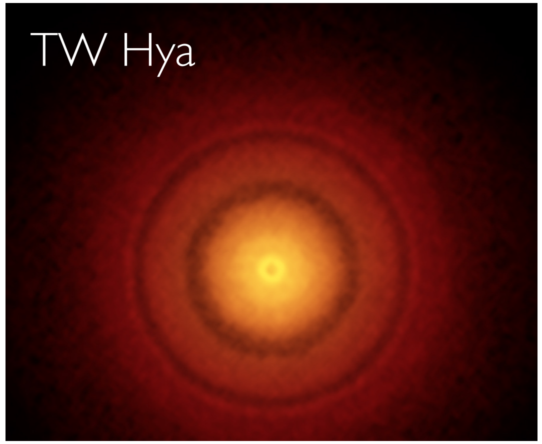
A mm-wave gallery of protoplanetary disks **pre-ALMA**



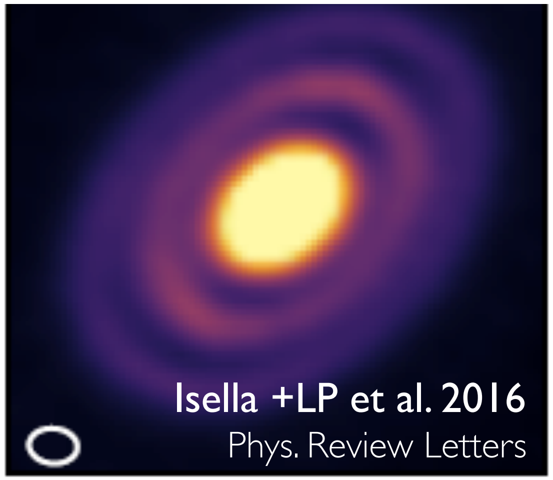
A mm-wave gallery of protoplanetary disks post-ALMA

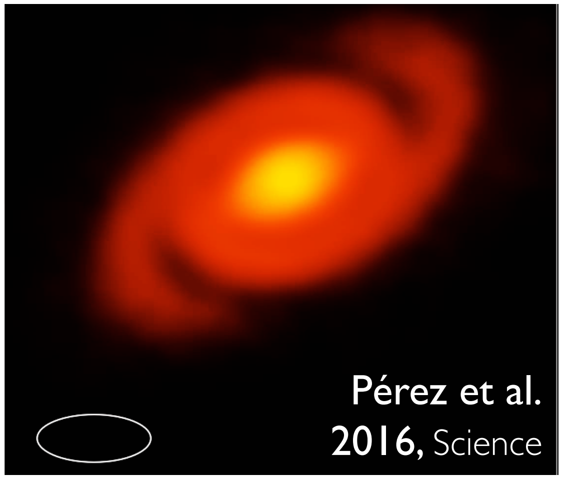


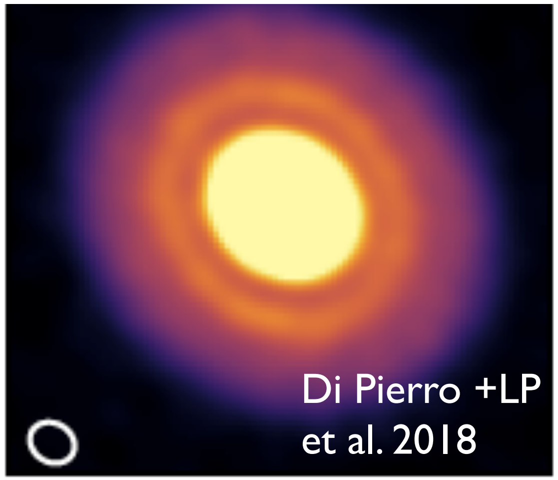




Motivate the need for an homogeneous sample!







ALMA Large Program in Protoplanetary Disks

"Small-scale substructures in Protoplanetary Disks"

Plan:

- 240 GHz (Band 6) observations of 20 classical disks
- Angular resolution ~ 5 AU
- Sensitivity ~ 17 microJy/beam

Goals:

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

Observational Status:

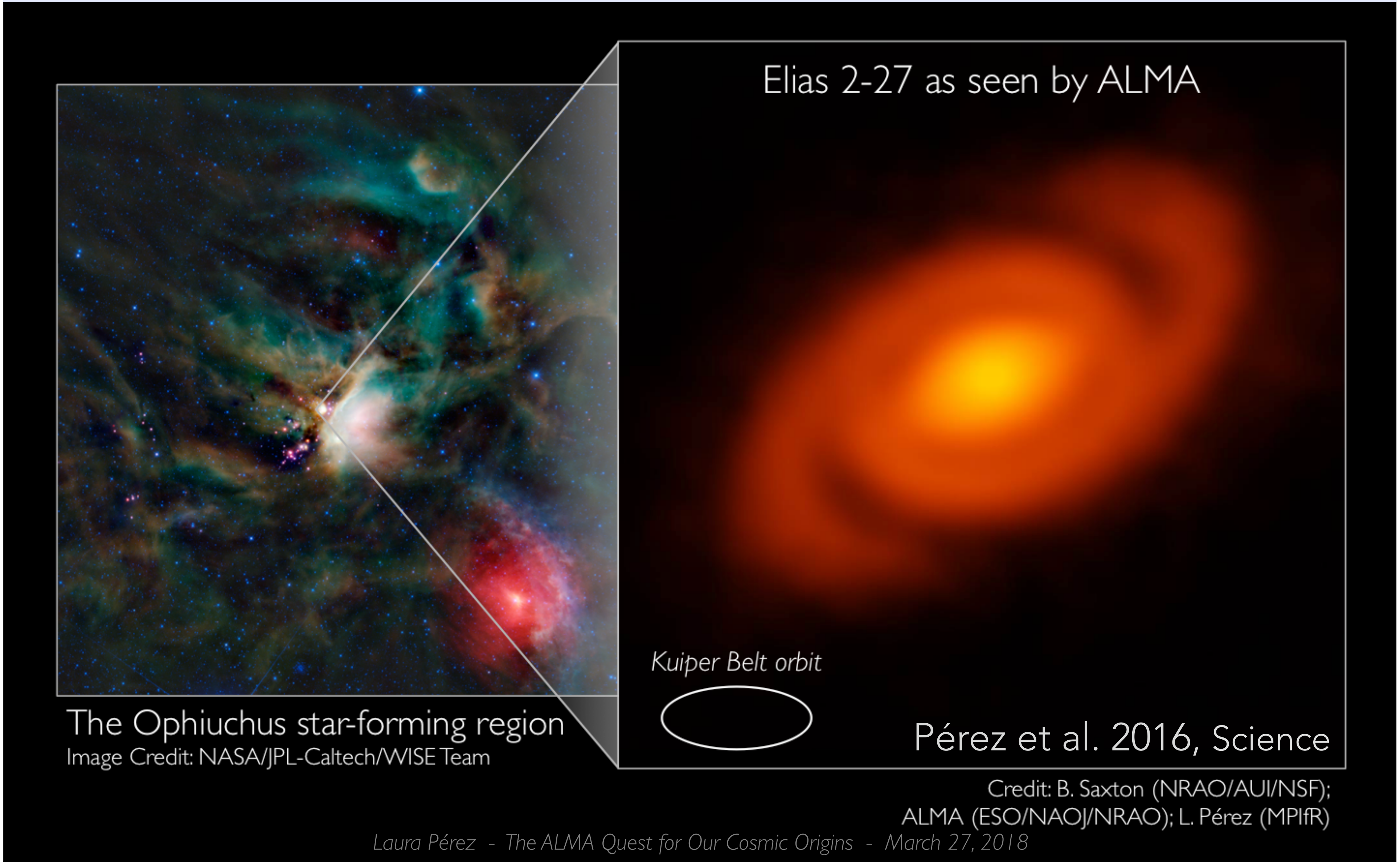
43.5/46 EBs completed; very preliminary images on the next slide!

Analysis ongoing:

Look for first papers (with data product release) in the fall

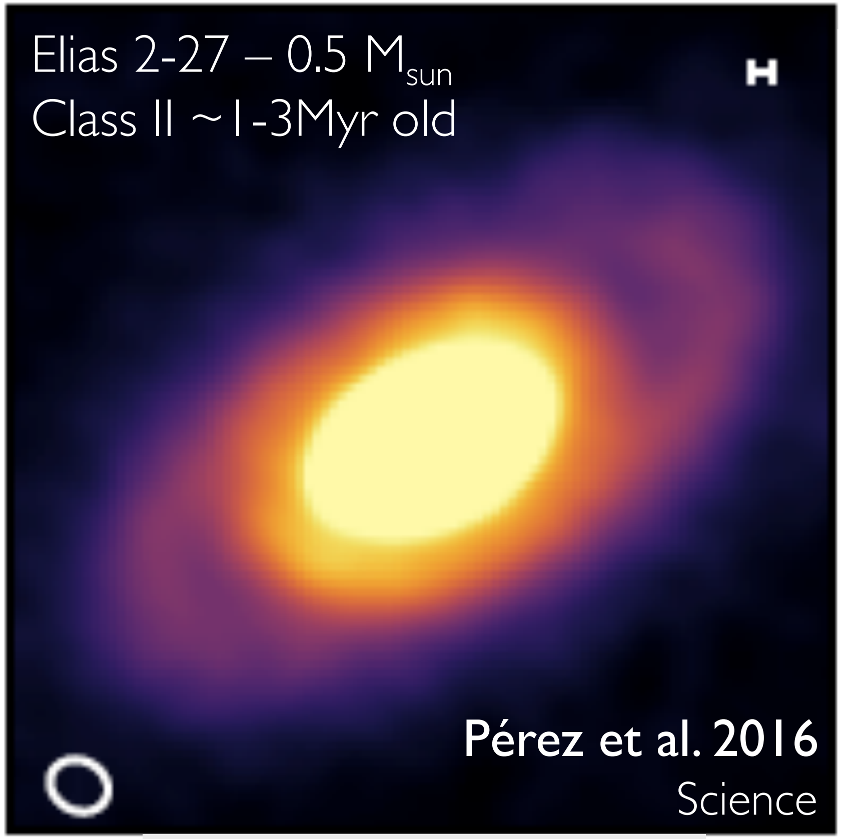
Our old friend … Elias 2-27

Spiral arms in the radio continuum observed for the first time

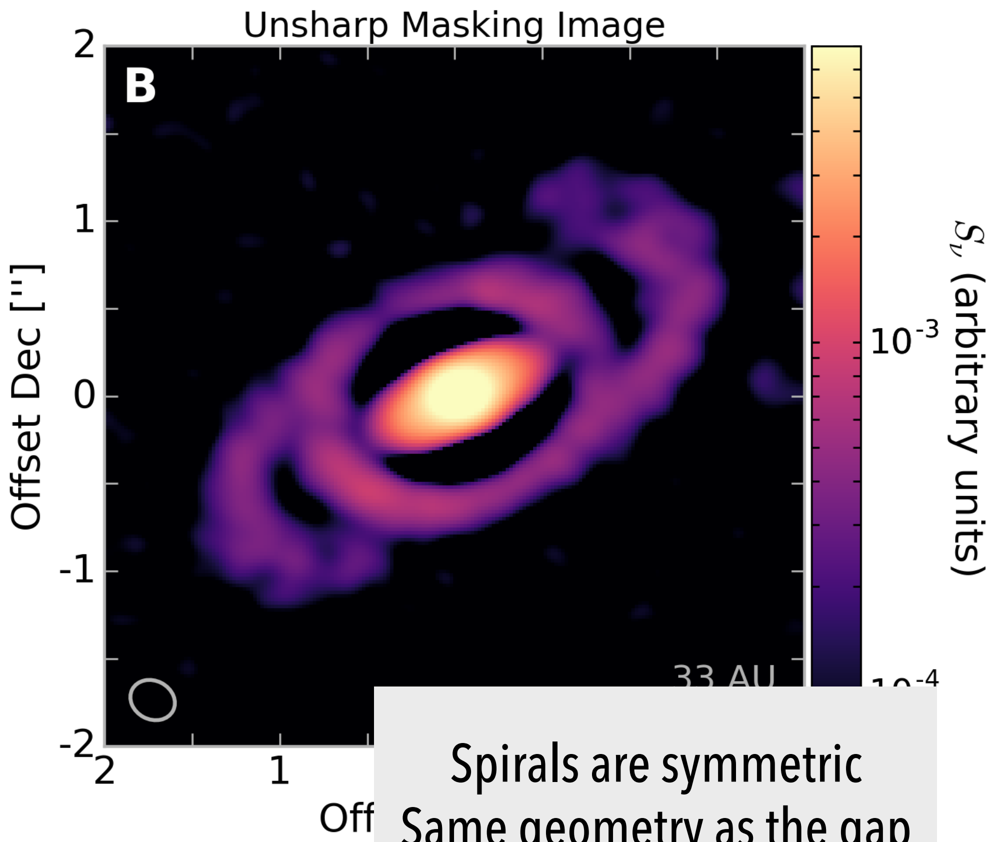


First direct evidence of disk instability in a young disk

Provides a unique benchmark for planet formation studies



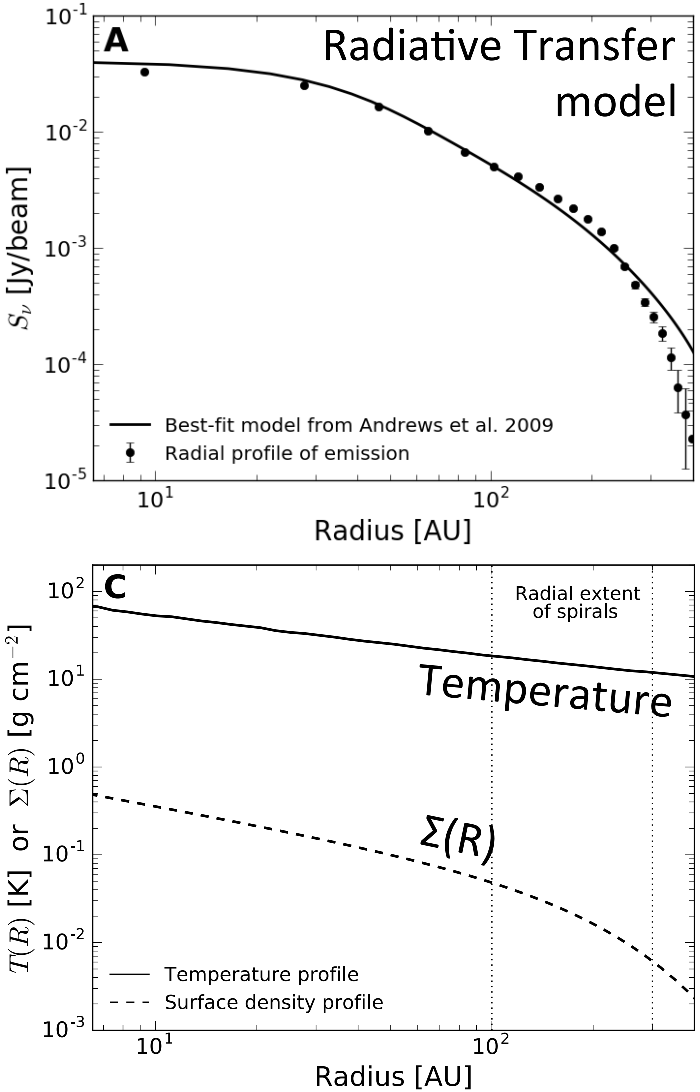
ALMA 1.3mm observations
~30 AU resolution

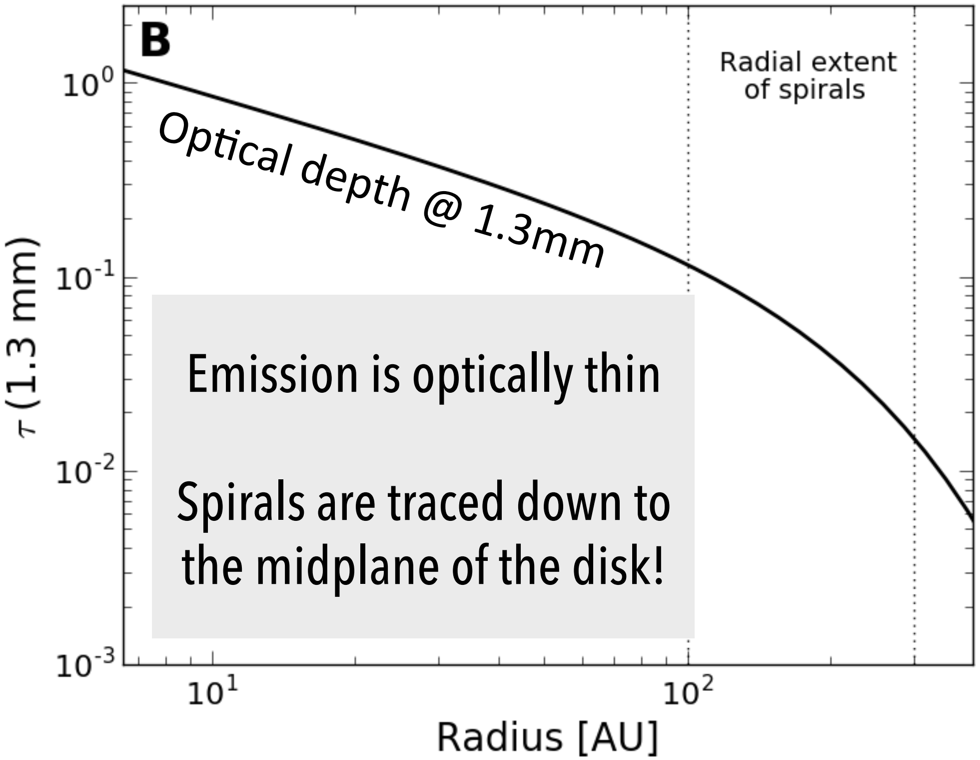


Spirals are symmetric
Same geometry as the gap
Trailing w.r.t disk rotation

Spirals @ 1.3mm can be traced down to disk midplane

Unlike spiral features from scattered-light observations

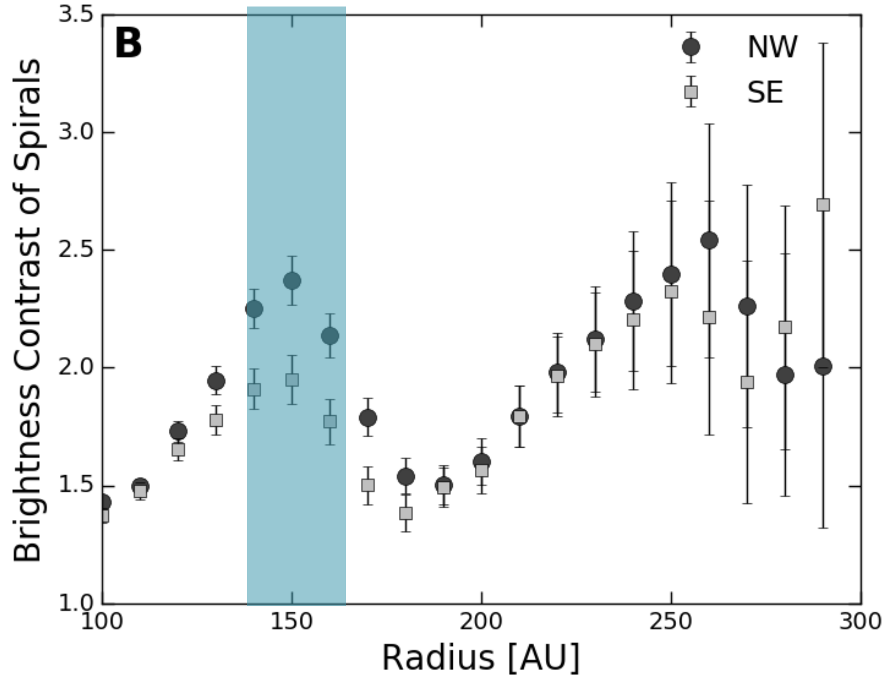




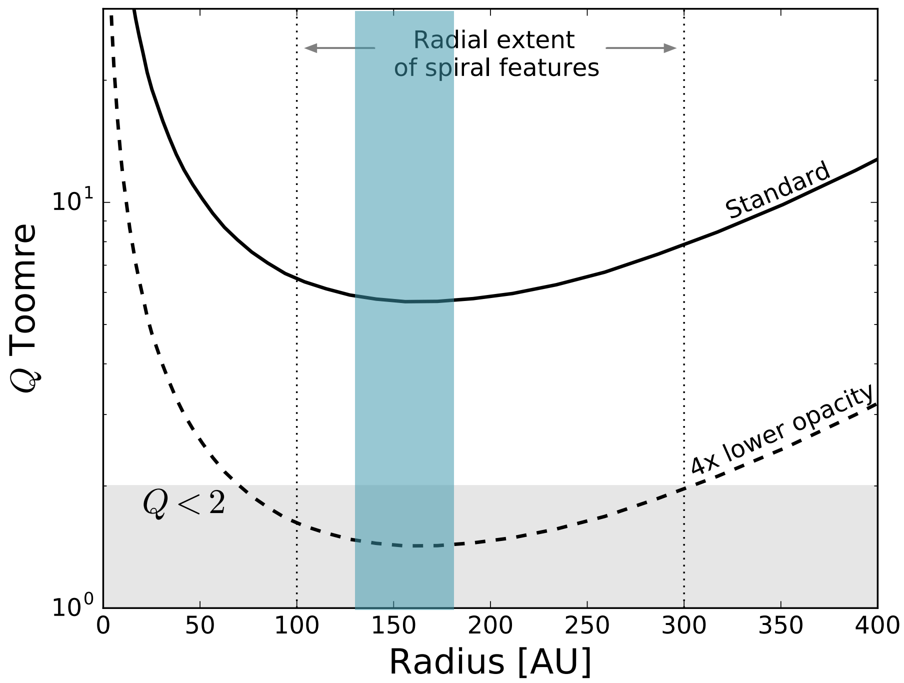
Spirals: low contrast and in stable regime

Unless dust properties are quite different in this disk!

Contrast of the spiral arms



Toomre Q analysis

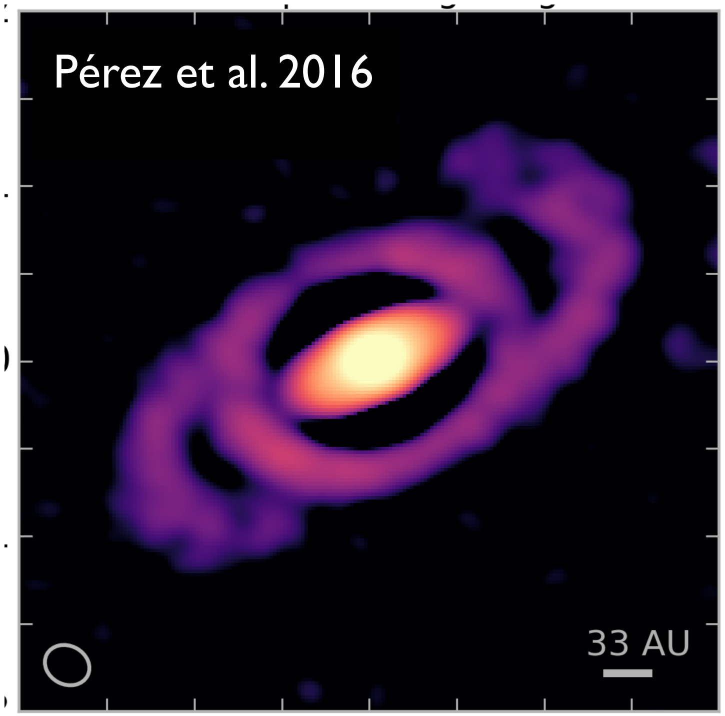


Spirals have contrast of ~1.2 - 2.5

Max. contrast occurs where gravity dominates over thermal pressure and shear forces

These observations trace shocks of spiral density waves

As in the case of galaxies, material arms will dissipate in a short timescale (~1000yrs)



What is the origin of these spirals?

Planet-disk interactions?

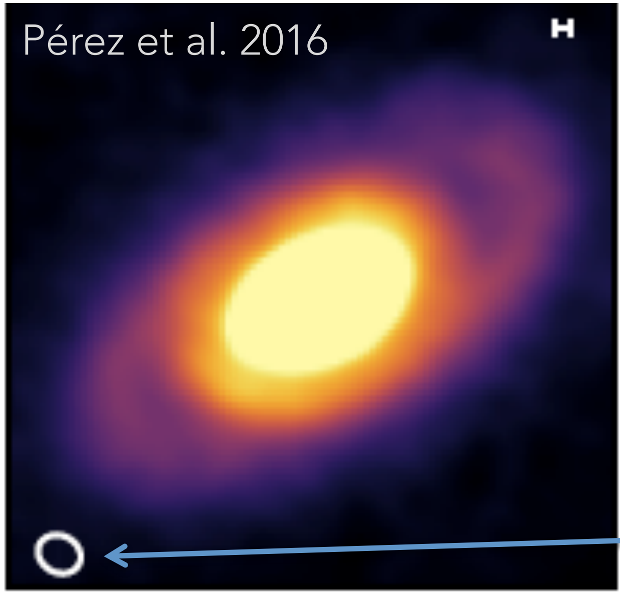
Gravitational Instabilities?

FUTURE: ALMA observations of this disk at longer wavelengths to check for dust trapping at spirals. Also gas!
(PI: L. Pérez)

Our old friend … Elias 2-27

Spiral arms observed in the radio continuum for the first time

Elias 2-27 star ~ 0.5 M_{sun}
Class II ~1-3Myr old



ALMA Large Program

PRELIMINARY IMAGE!

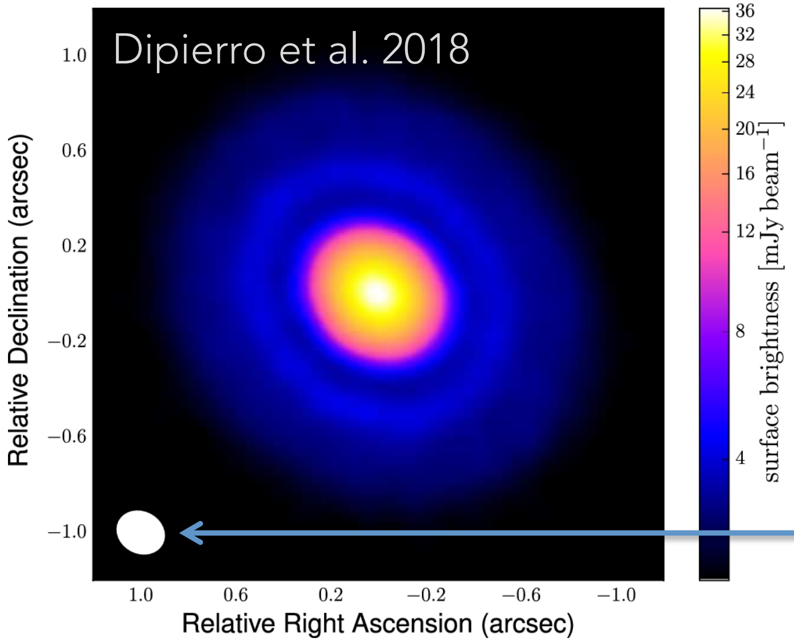
Spirals are not unique to this object!

P R E L I M I N A R Y !

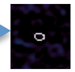
Our newer friend … Elias 24

Rings and gaps in the disk revealed by ALMA

Elias 24 disk ~ 0.1 Msun
Class II ~1 Myr old



ALMA Large Program



PRELIMINARY IMAGE!

See also:
Cox et al. 2017
Cieza et al. 2017

Rings are not unique to this object!

ALMA Large Program will provide new insights into processes that transform the disk reservoir into a planetary system

Structure?

Substructure is needed to prevent solids from drifting, so we can form planets and planetesimals

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

Evolution?

We are getting to understand basic disk evolution from mm-wave disk observations

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