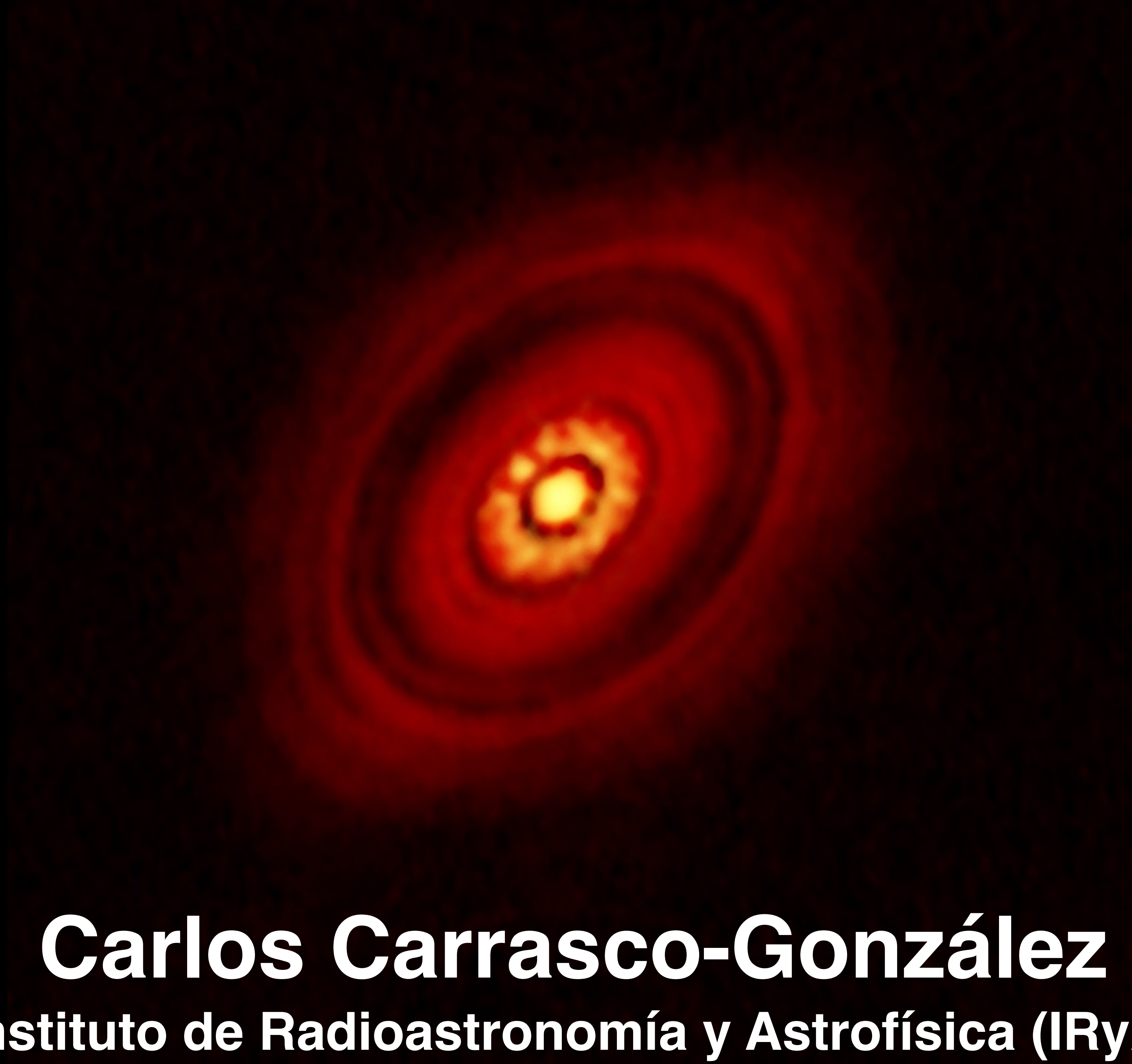
The VLA view of the HL Tau disk

Observing the earliest stages of planet formation



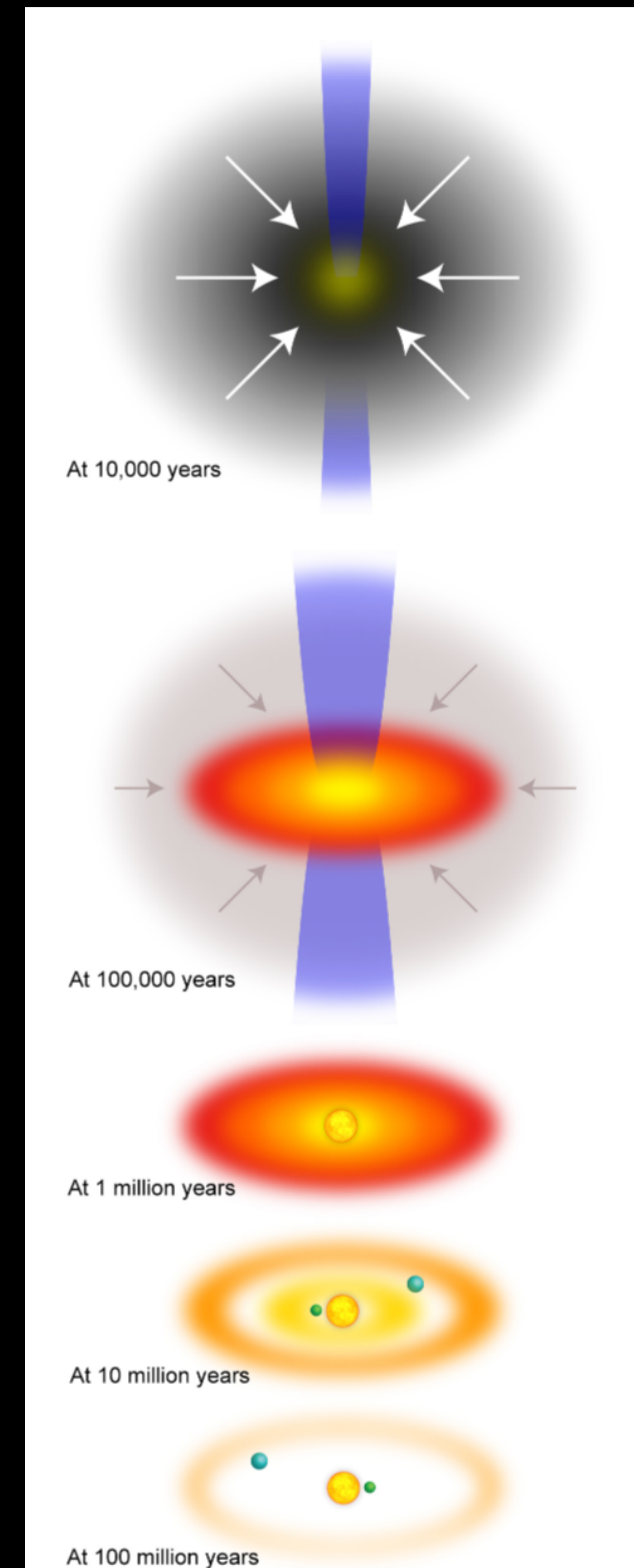
Carlos Carrasco-González

Instituto de Radioastronomía y Astrofísica (IRyA)

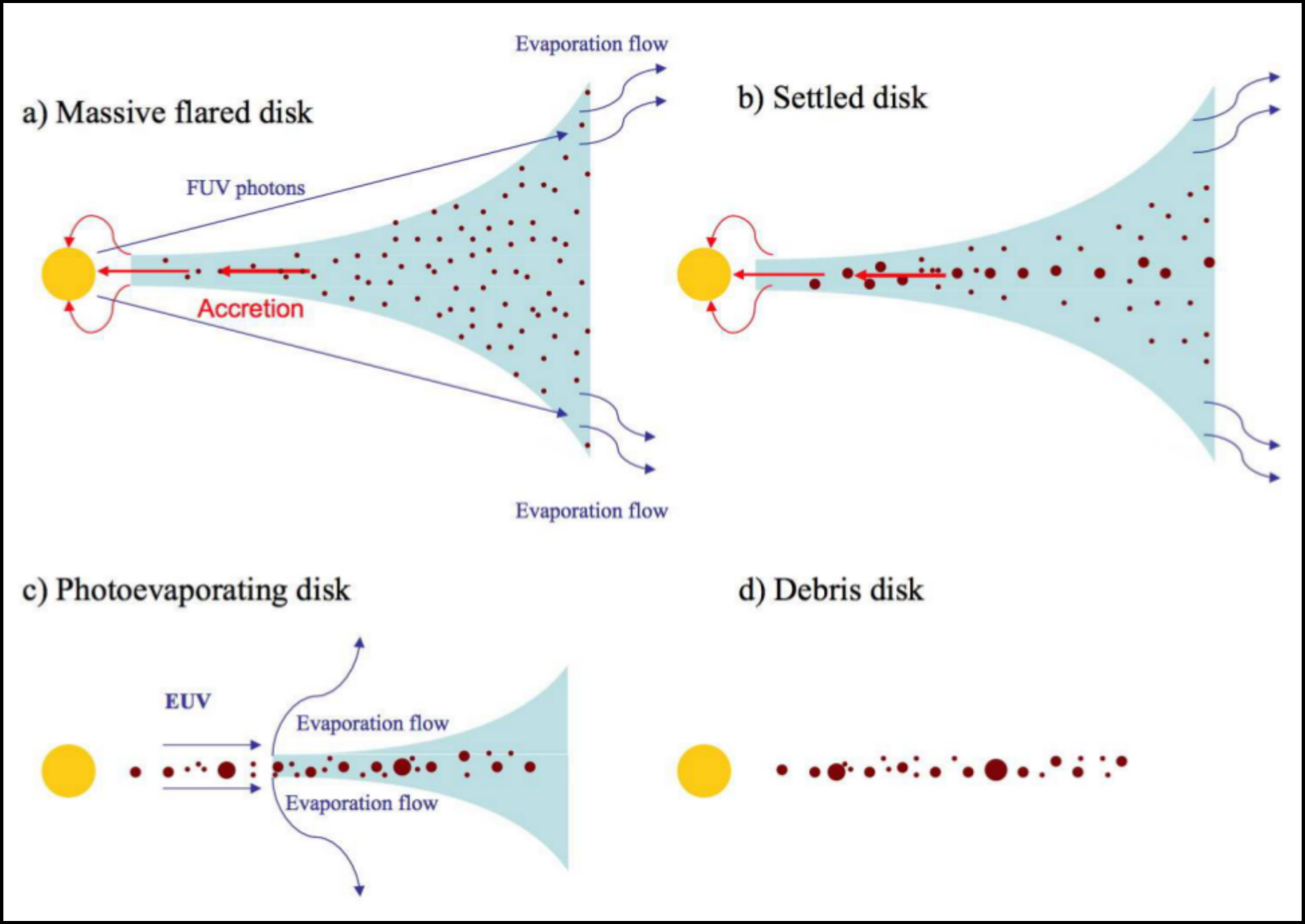
UNAM Campus Morelia (México)

Sharing data between two different groups

Star formation from parsecs to tens of AU

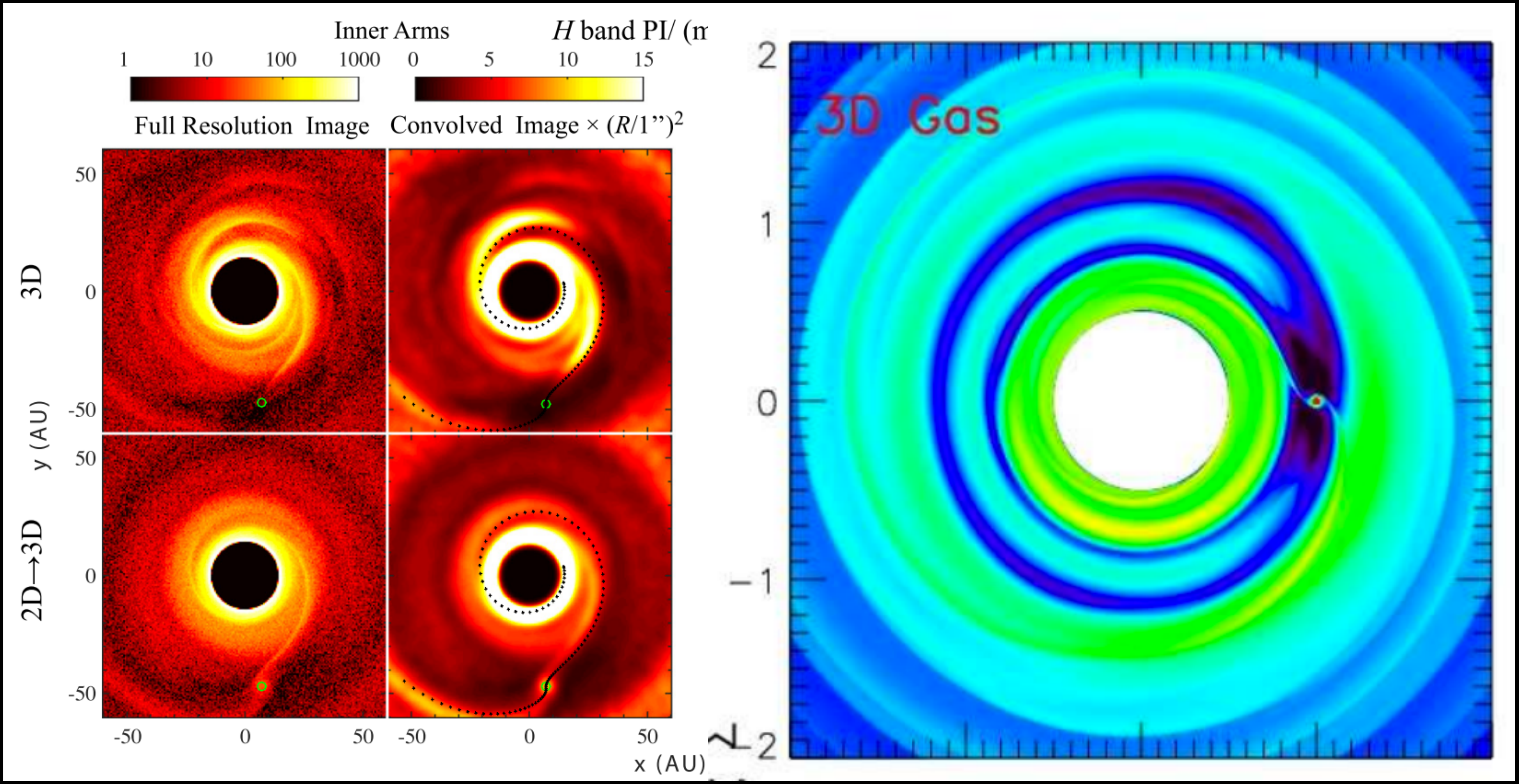


Disk Evolution



Processes that are taking place at scales of ~1 AU or less

Formation of planets shapes the disk
Protoplanets "clean" their orbits -> HOLES in the disk



Zhu+2015

The Astrophysical Journal, 693:L86–L90, 2009 March 10 doi:10.1088/0004-637X/693/2/L86

HIGH ANGULAR RESOLUTION RADIO OBSERVATIONS OF THE HL/XZ TAU REGION: MAPPING THE 50 AU PROTOPLANETARY DISK AROUND HL TAU AND RESOLVING XZ TAU S INTO A 13 AU BINARY

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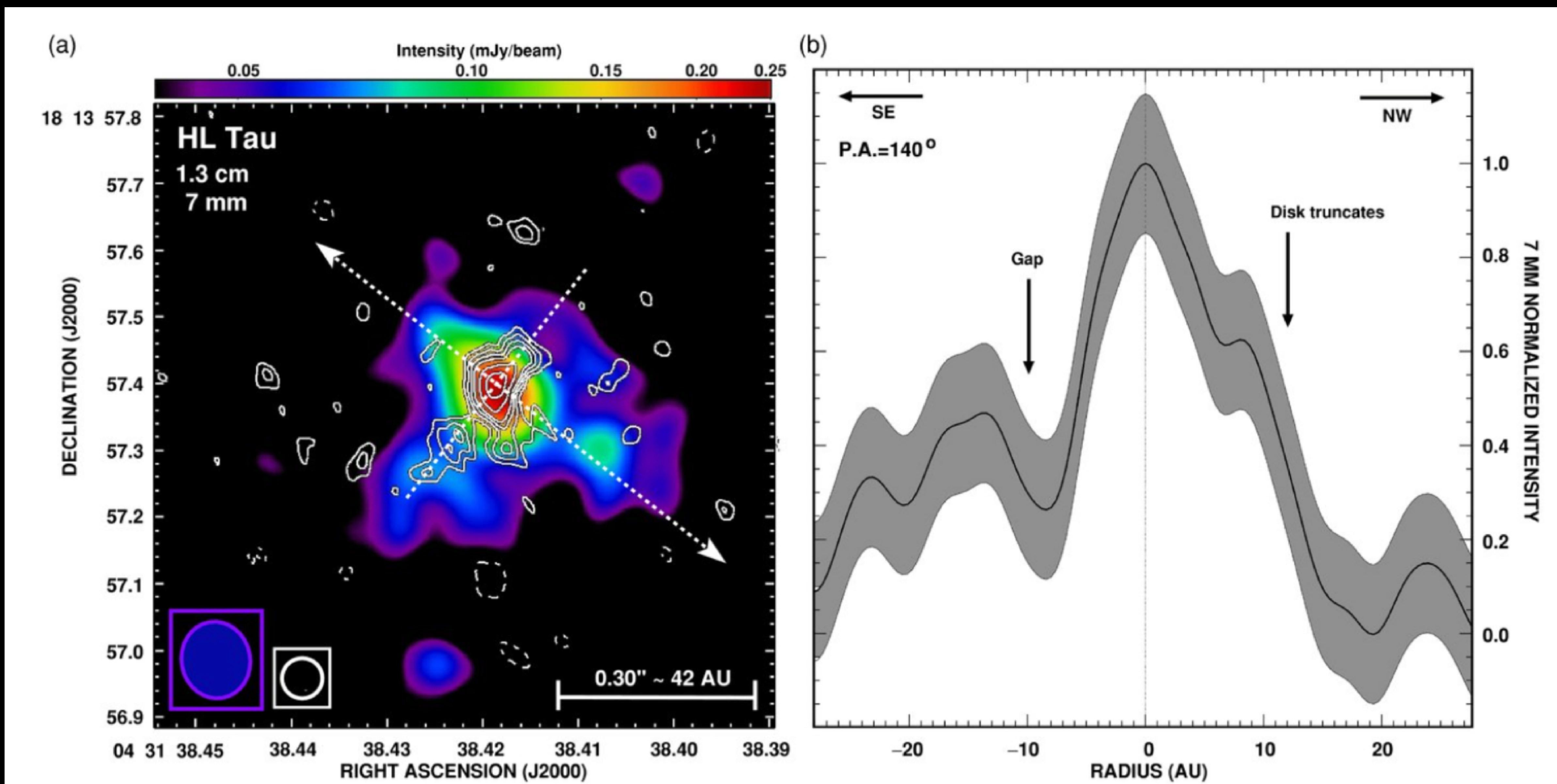
Received 2008 November 15; accepted 2009 January 23; published 2009 February 18



Carrasco-González et al. (2009)

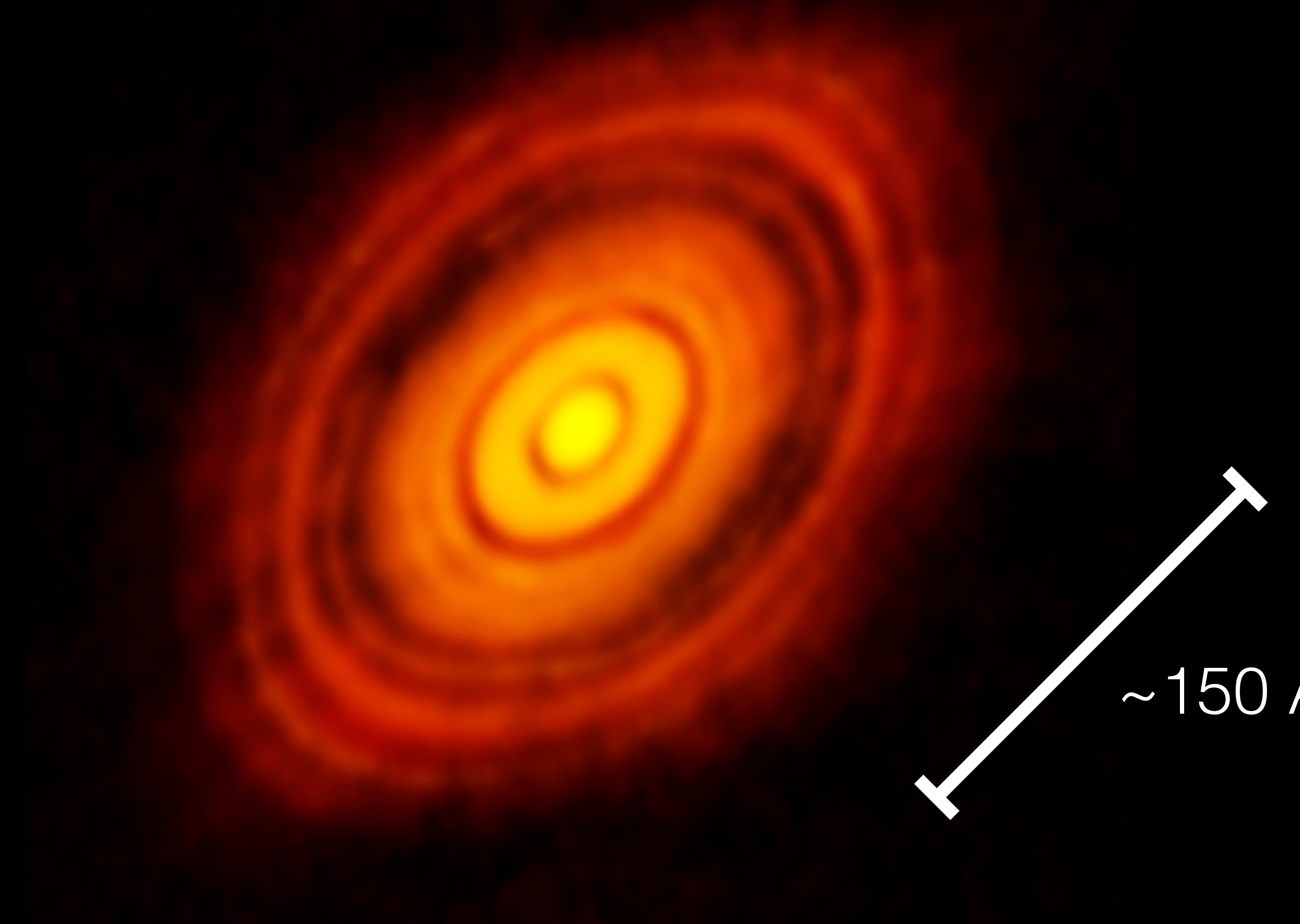
ALMA

The most powerful mm interferometer

High sensitivity (~microJy/beam)
High angular resolution (~mas)

Disk evolution and planet formation -> **Key project**

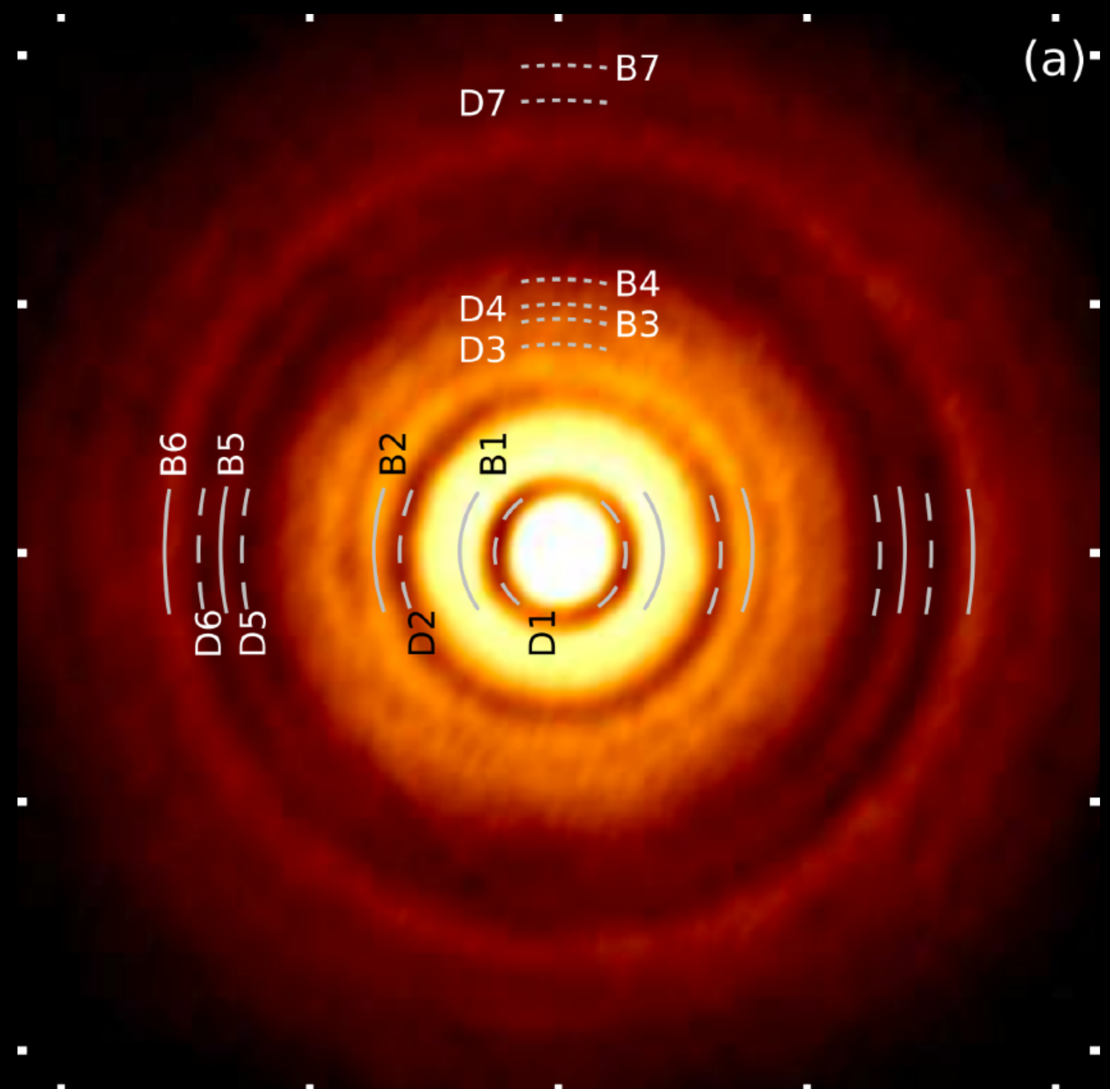
HL Tau @ ALMA 1.3 mm



The most detailed and highest quality image of a circumstellar disk ever obtained

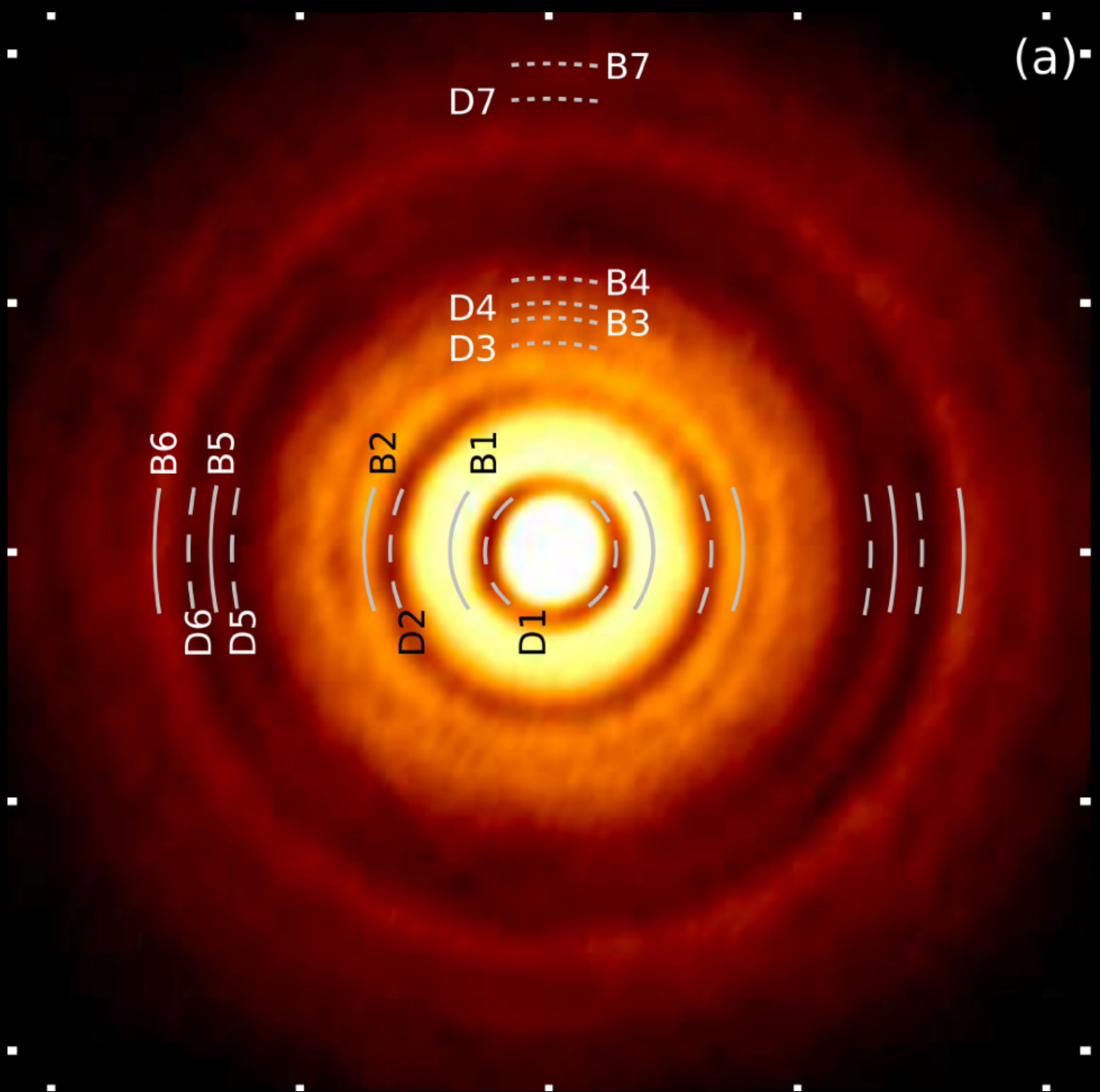
ALMA Partnership, Brogan+2014

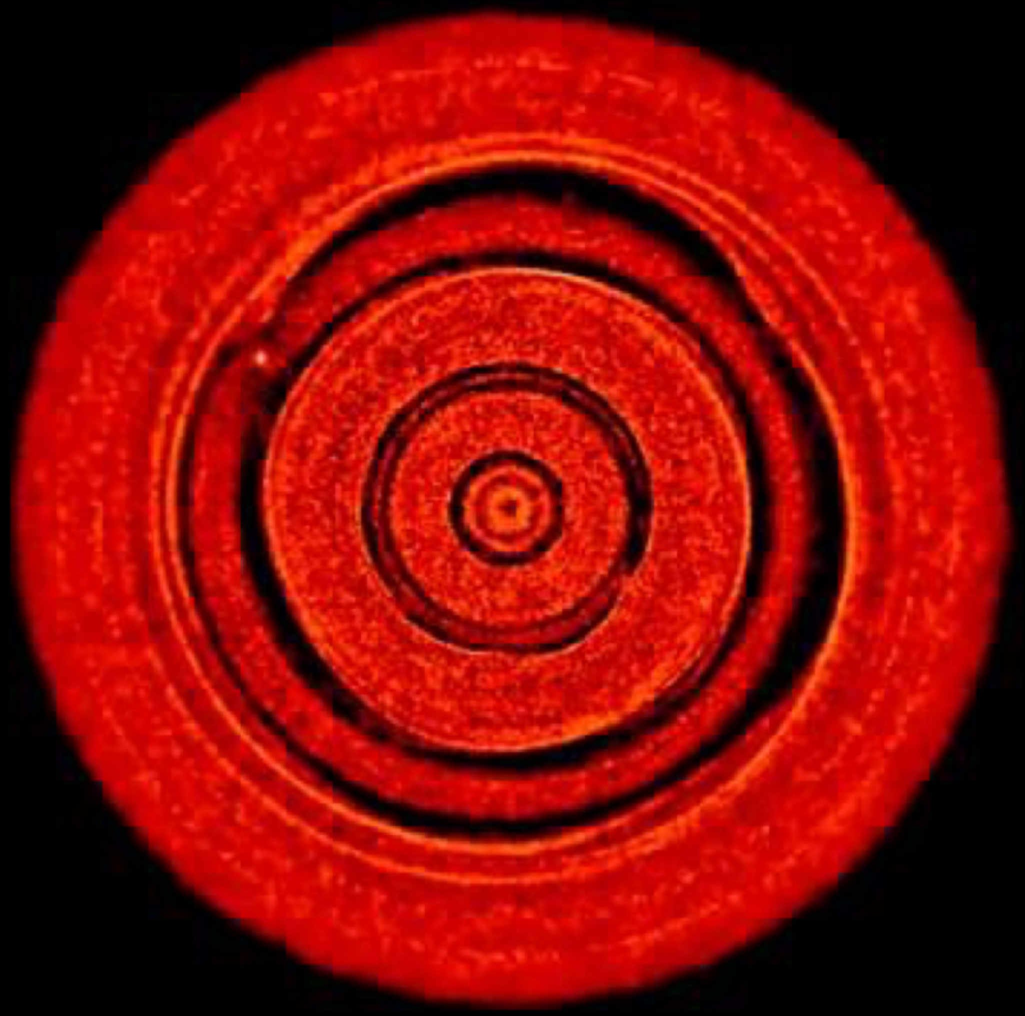
HL Tau @ ALMA 1.3 mm



7 pairs of BRIGHT and DARK rings

ALMA Partnership, Brogan+2014

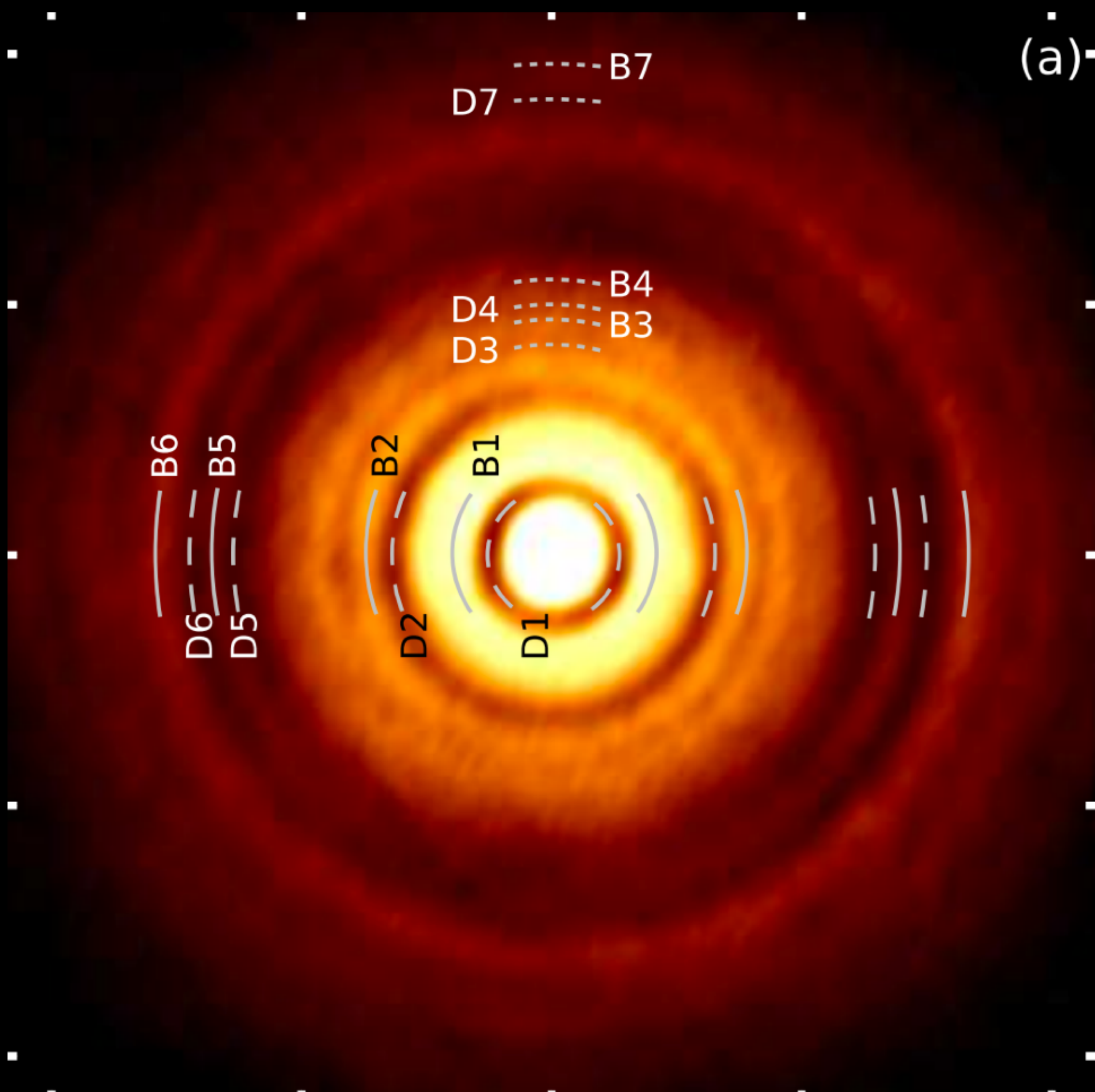


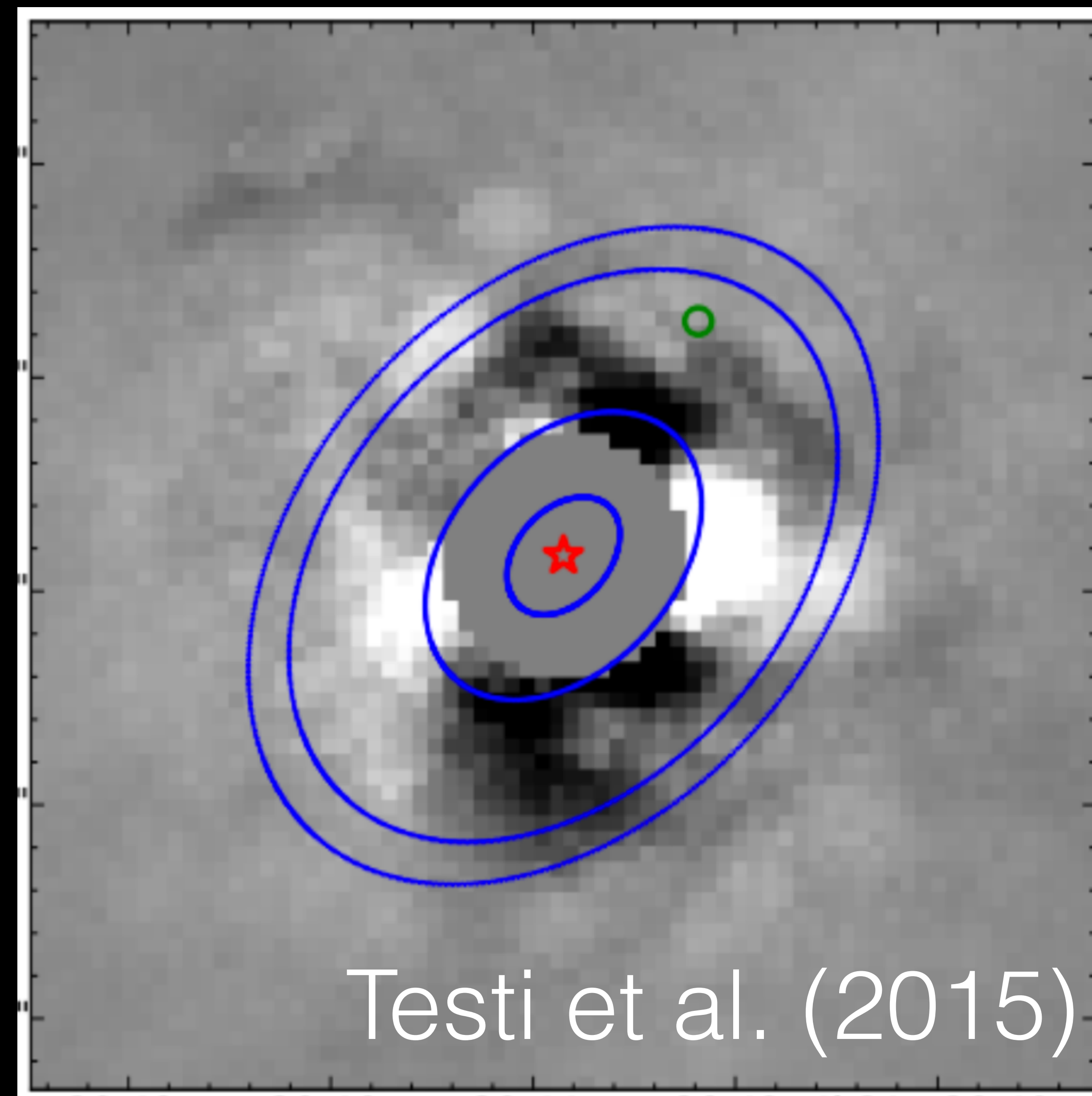


If, as commonly interpreted, gas are a consequence of planet formation, HL Tau would have a relatively **well formed planetary system.**

But HL Tau is a YSO with only 1,000,000 years… very soon

Planets begin to forms **very early** and they form **very fast??**





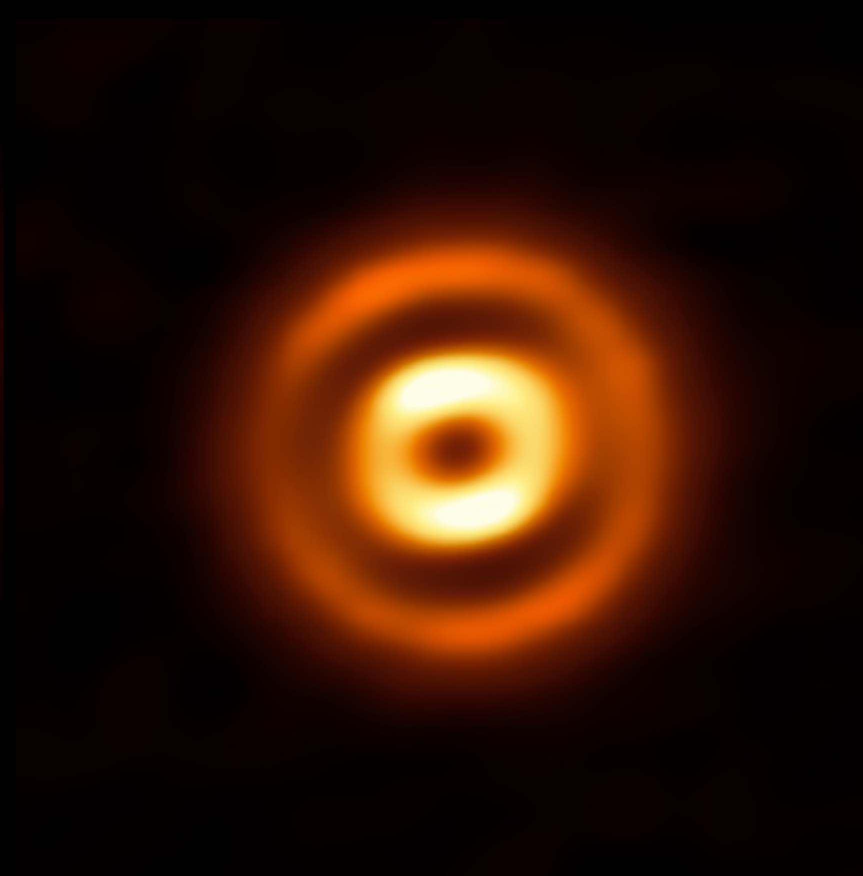
There are **no massive planets** (> 15 M_J)
at the **outer parts** of the disk (> 50 AU)

But, maybe **less massive planets** or in the **internal parts?**

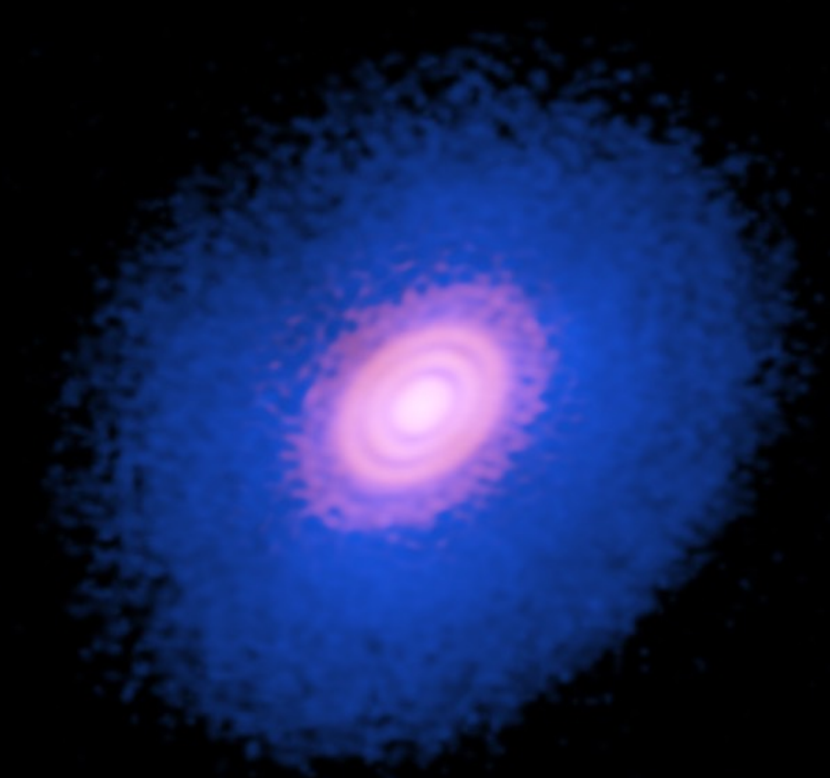
But, these structures seems to be more common than expected

Zhang et al. (2015)

Pérez et al. (2016)

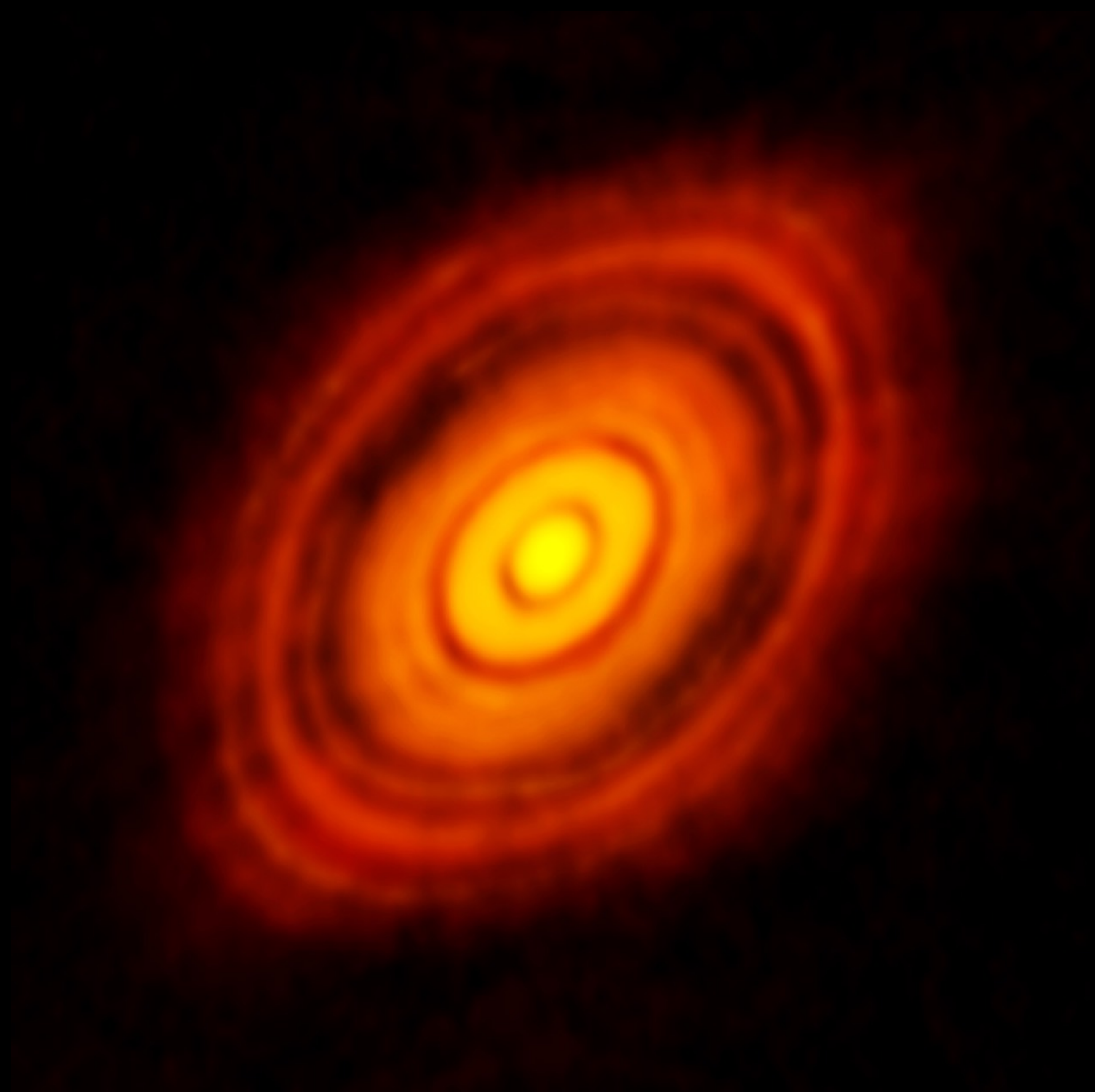


Fedele et al. (2017)



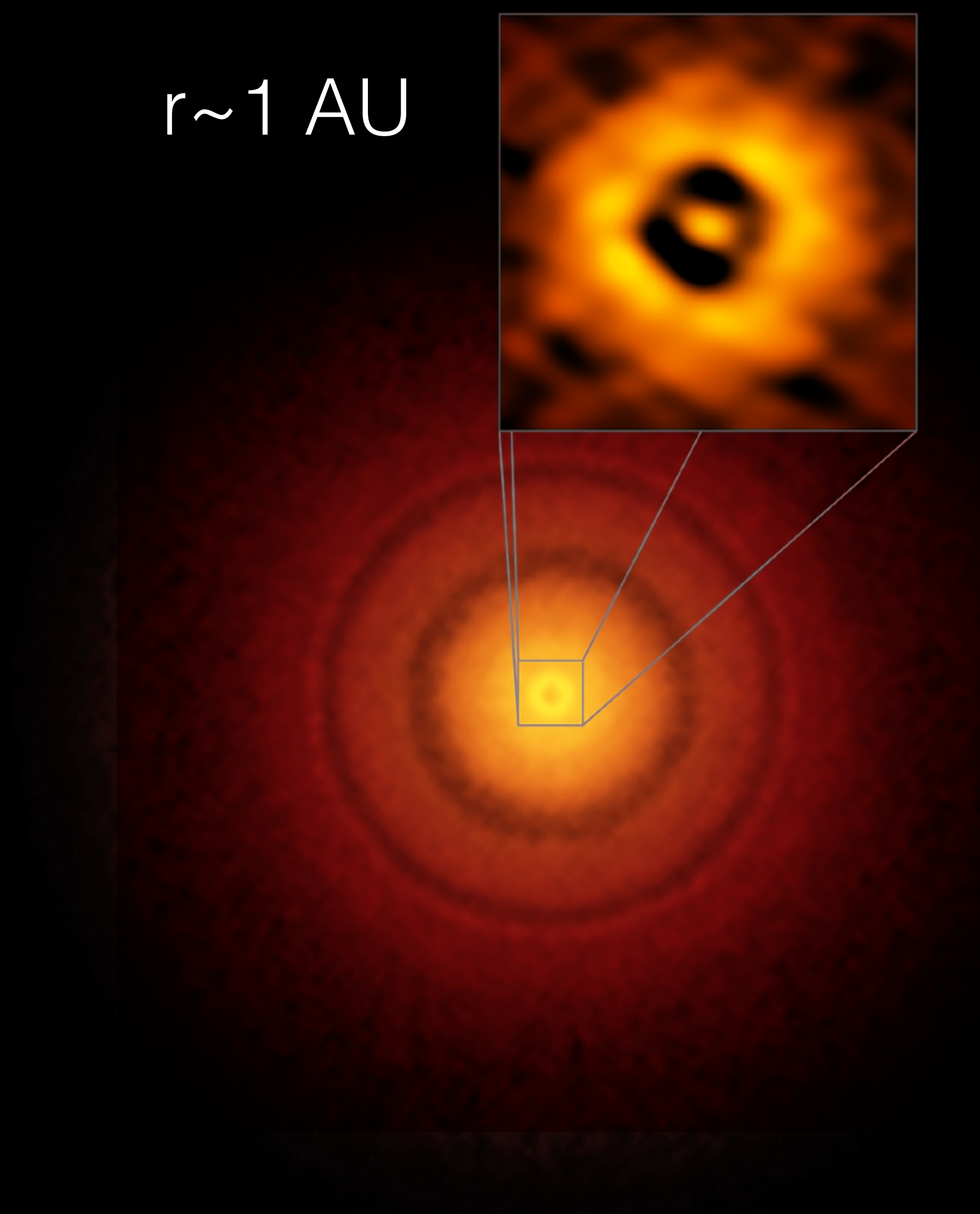
Isella et al. (2017)

HL Tau
~1 million years



Partnership, Brogan+2015

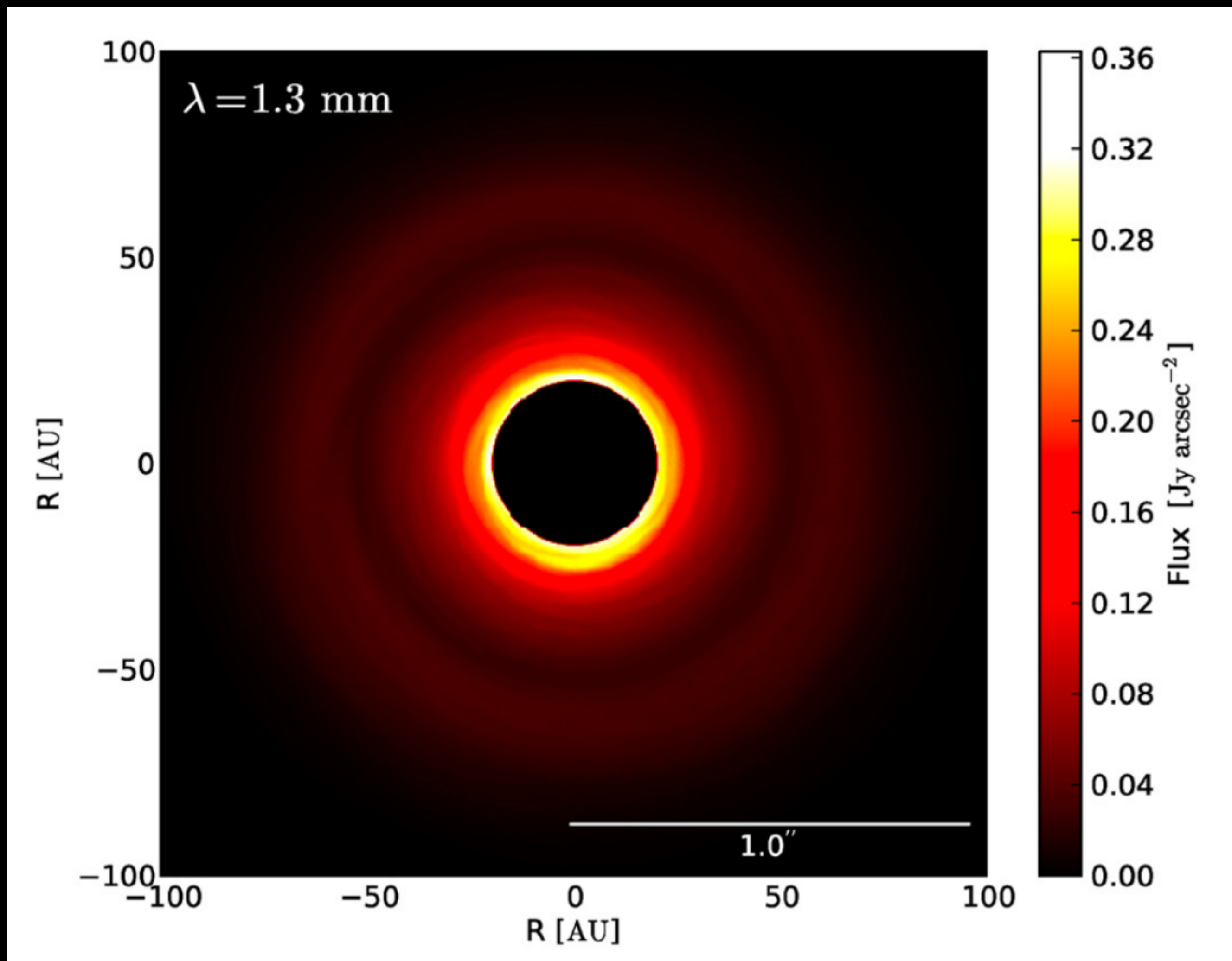
TW Hya
~10 million years

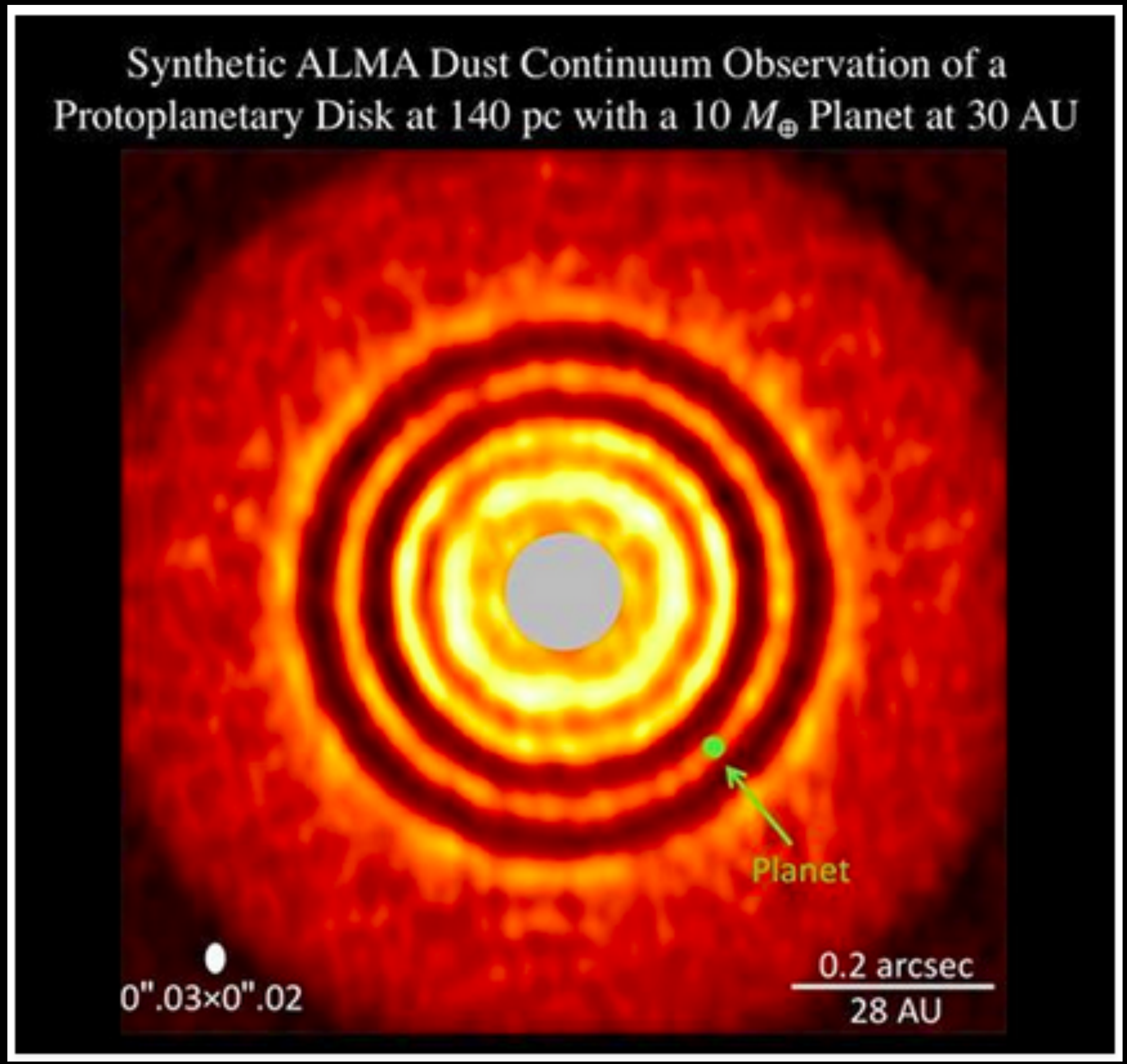


Andrews+2016

And, there are also alternative explanations for the formation of gaps…

Two examples:



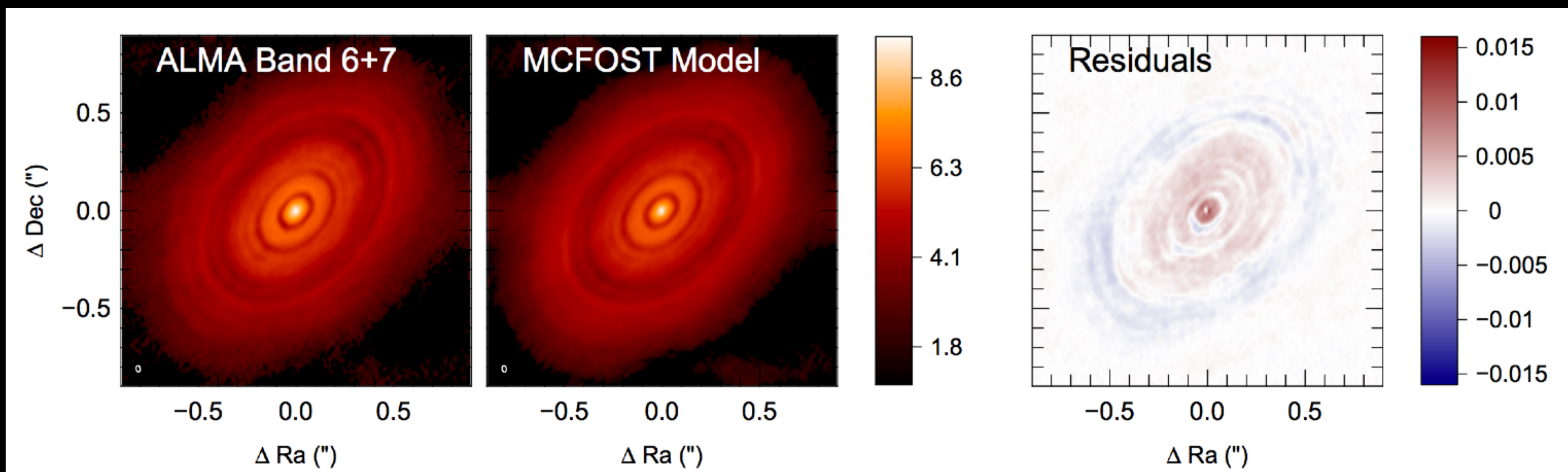


Magnetized disk
(Flock+2015)

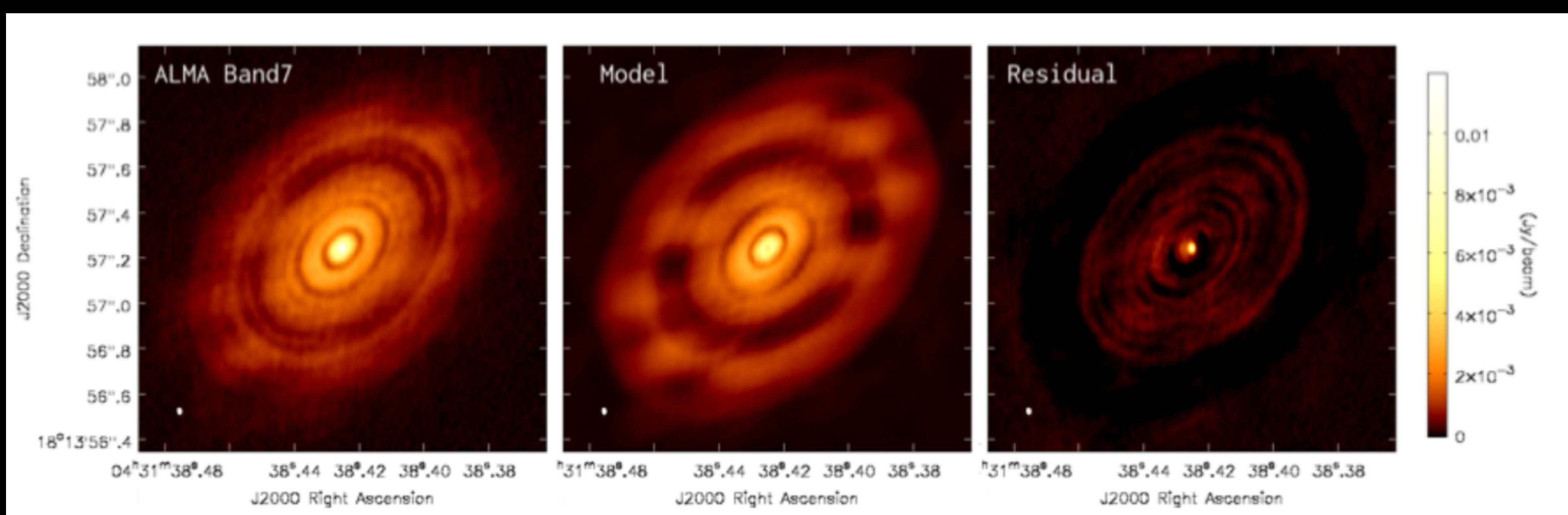
A single protoplanet
(Dong+2017)

Planets or not, these are the **most resolved and detailed images** of a circumstellar disk ever obtained

First time we can **model** details of the **substructure** in the disk

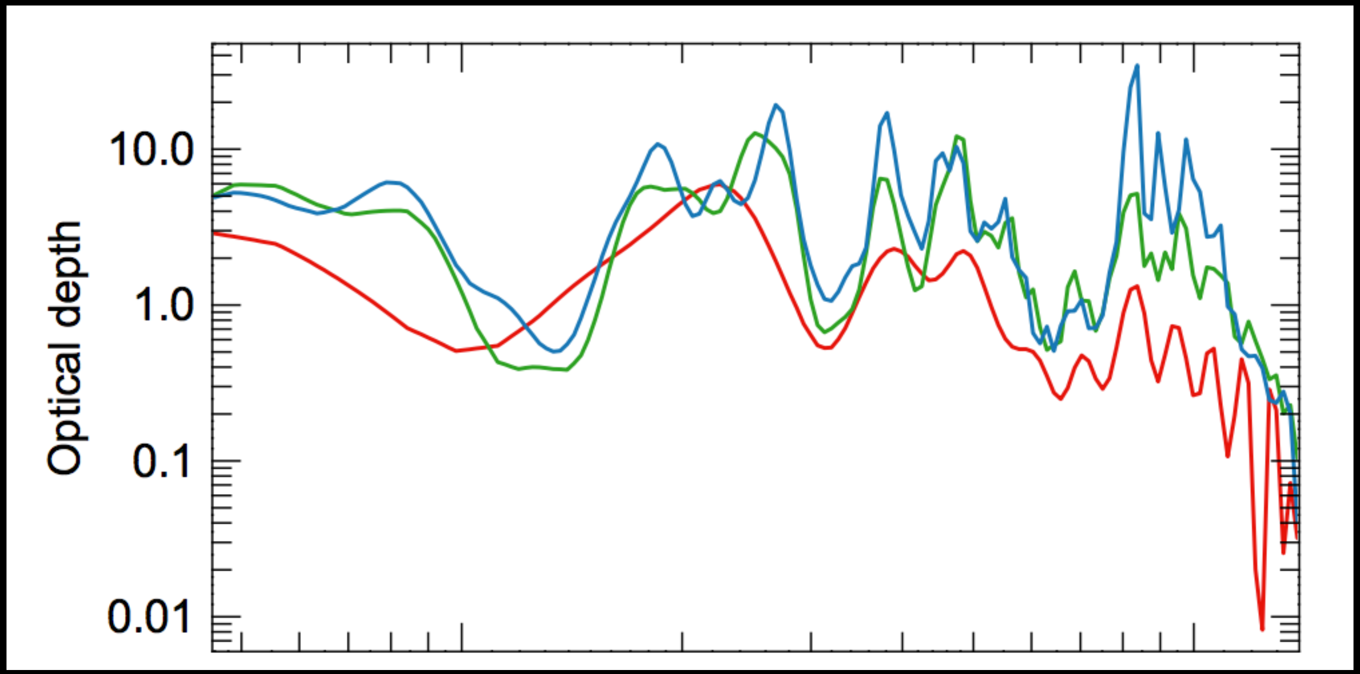


Pinte et al. (2016)

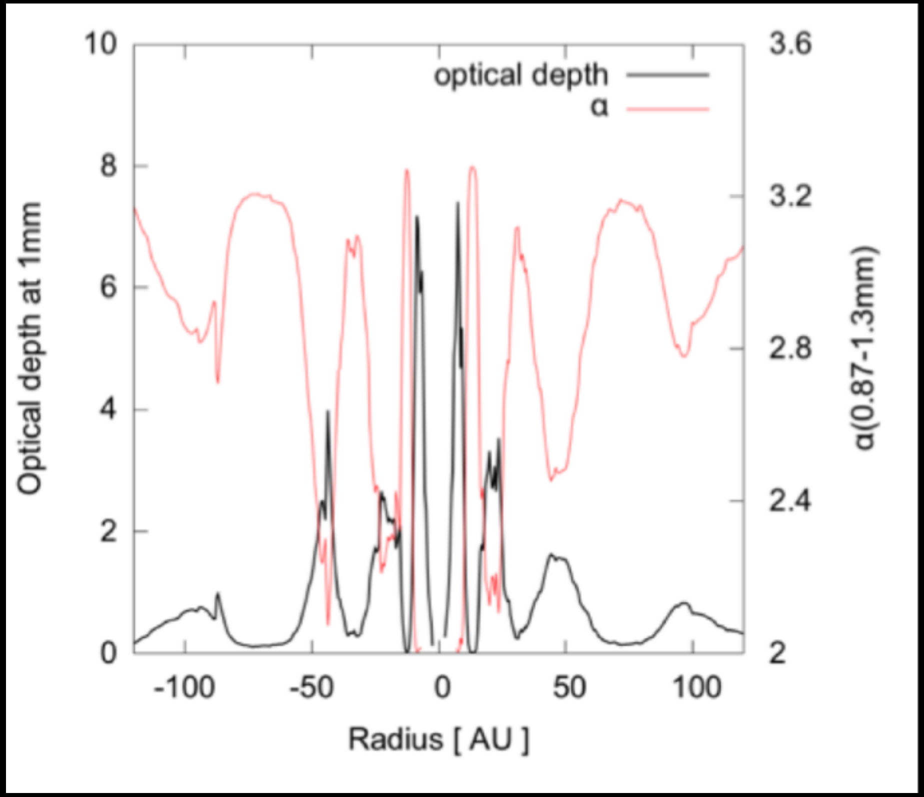


Jin et al. (2016)

Problem: Emission at all ALMA wavelengths is **optically thick**

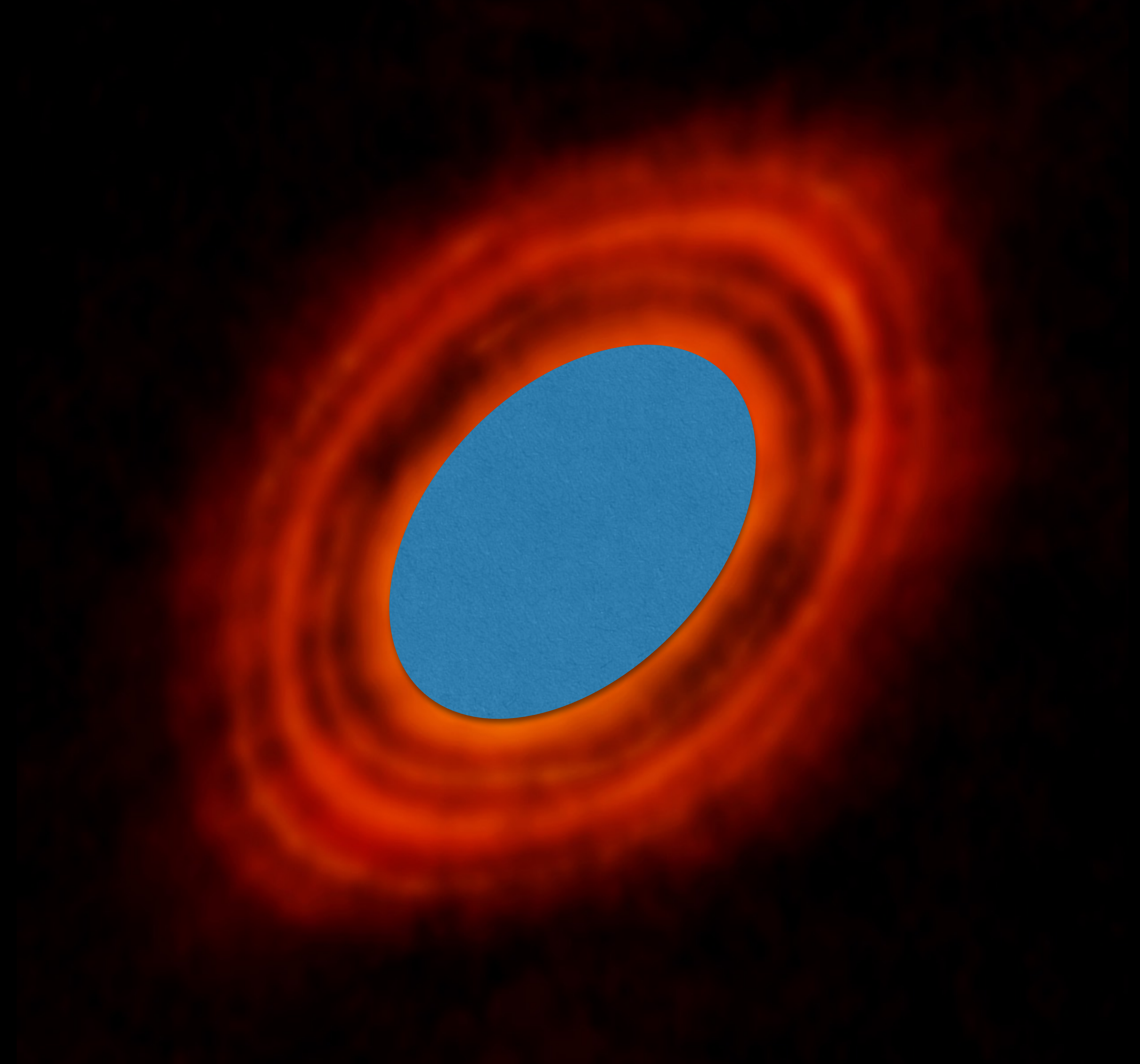


Pinte et al. (2016)



Jin et al. (2016)

ALMA emission is **optically thick** at the densest parts.
Specially the **internal disk** (<50 AU),
where **grain growth** is expected to be more important, and
terrestrial planets are expected to form.



The Very Large Array (VLA)

You may better know it as a cm wavelength interferometer
but it is **also a very powerful mm interferometer**….

Q Band (43 GHz; **7 mm**)
K Band (23 GHz; **13 mm**)

Ka Band (33 GHz; 10 mm)

27 antennas separated by **30 km**

angular resolutions ~ **30-100 mas**

sensitivity (<2010) ~ 100 microJy/beam
sensitivity (>2010) ~ **1 microJy/beam**

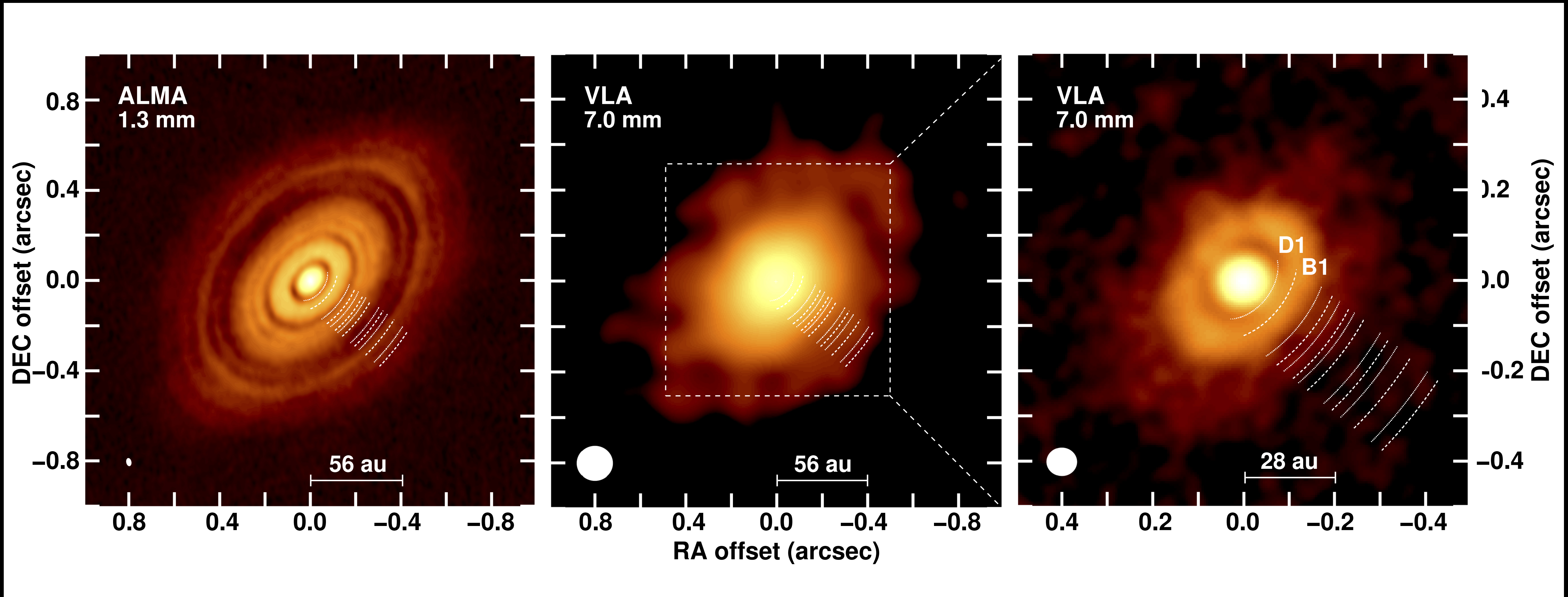
VLA multi-configuration, wide band, high sensitive, high angular resolution observations at 7 mm

Table 1. Summary of VLA observations at Q band

Obs. Date	Project Code	Conf.	On-source total time
2014-Dec-07	14B-485	C	1.7 h
2015-Feb-15	14B-485	B	1.6 h
2015-Aug-13	14B-487	A	1.1 h
2015-Aug-25	14B-487	A	1.1 h
2015-Sep-16[a]	14B-487	A	1.1 h
2015-Sep-19	14B-487	A	1.7 h
2015-Sep-20	14B-487	A	2.2 h
2015-Sep-20	14B-487	A	1.5 h
2015-Sep-21	14B-487	A	1.7 h
2015-Sep-21	14B-487	A	1.7 h

>15 hr of observation at Q band with excellent atmospheric conditions

VLA multi-configuration, wide band, high sensitive, high angular resolution observations at 7 mm

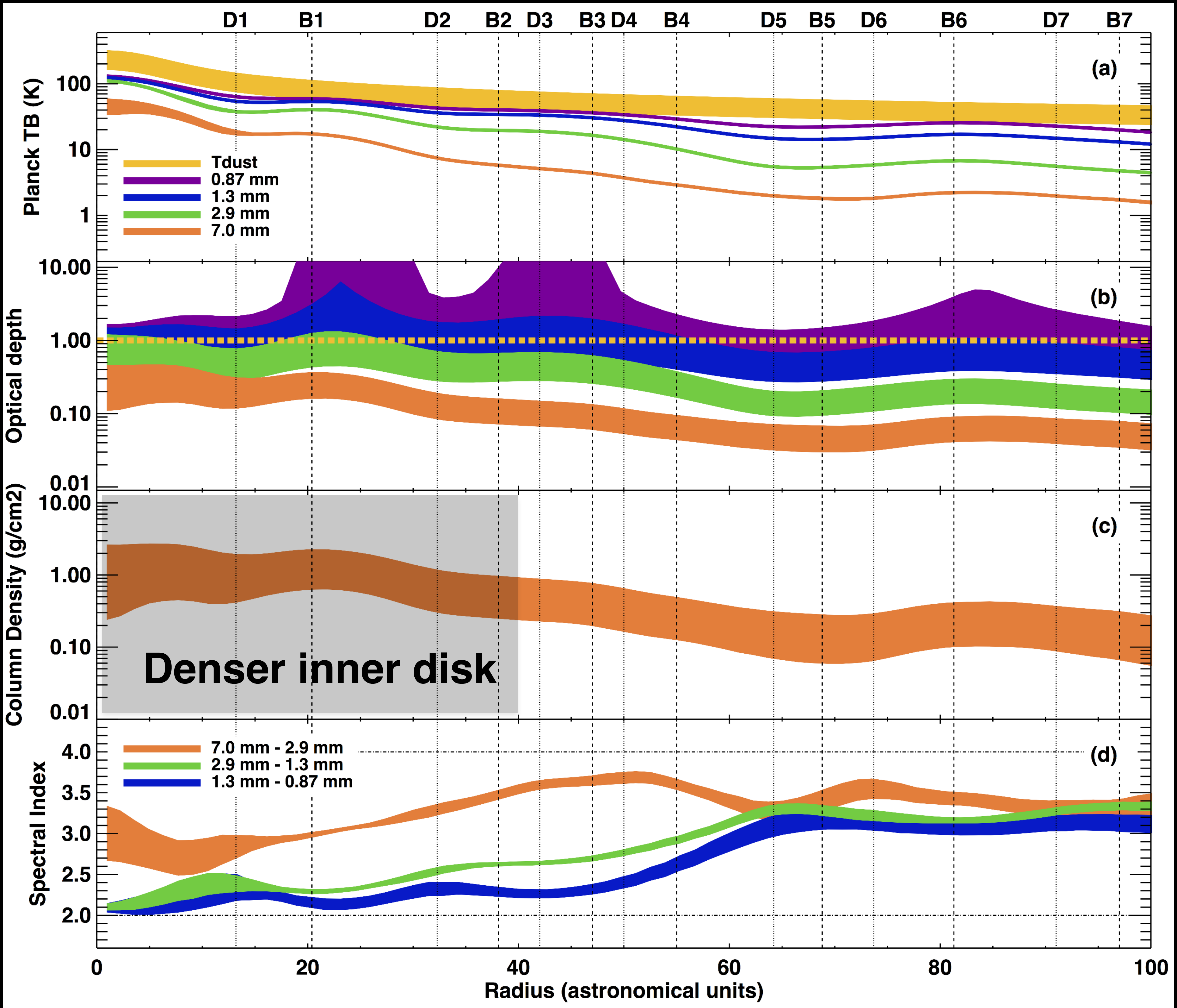


Now, THIS is a very nice image of a disk a long mm wavelengths

up to **~40 mas (5 AU!)** of resolution, **~3.5 microJy/beam** rms noise

Emission at **7 mm is optically thinner** than ALMA images

1. Mass distribution in the disk



1. Mass distribution in the disk

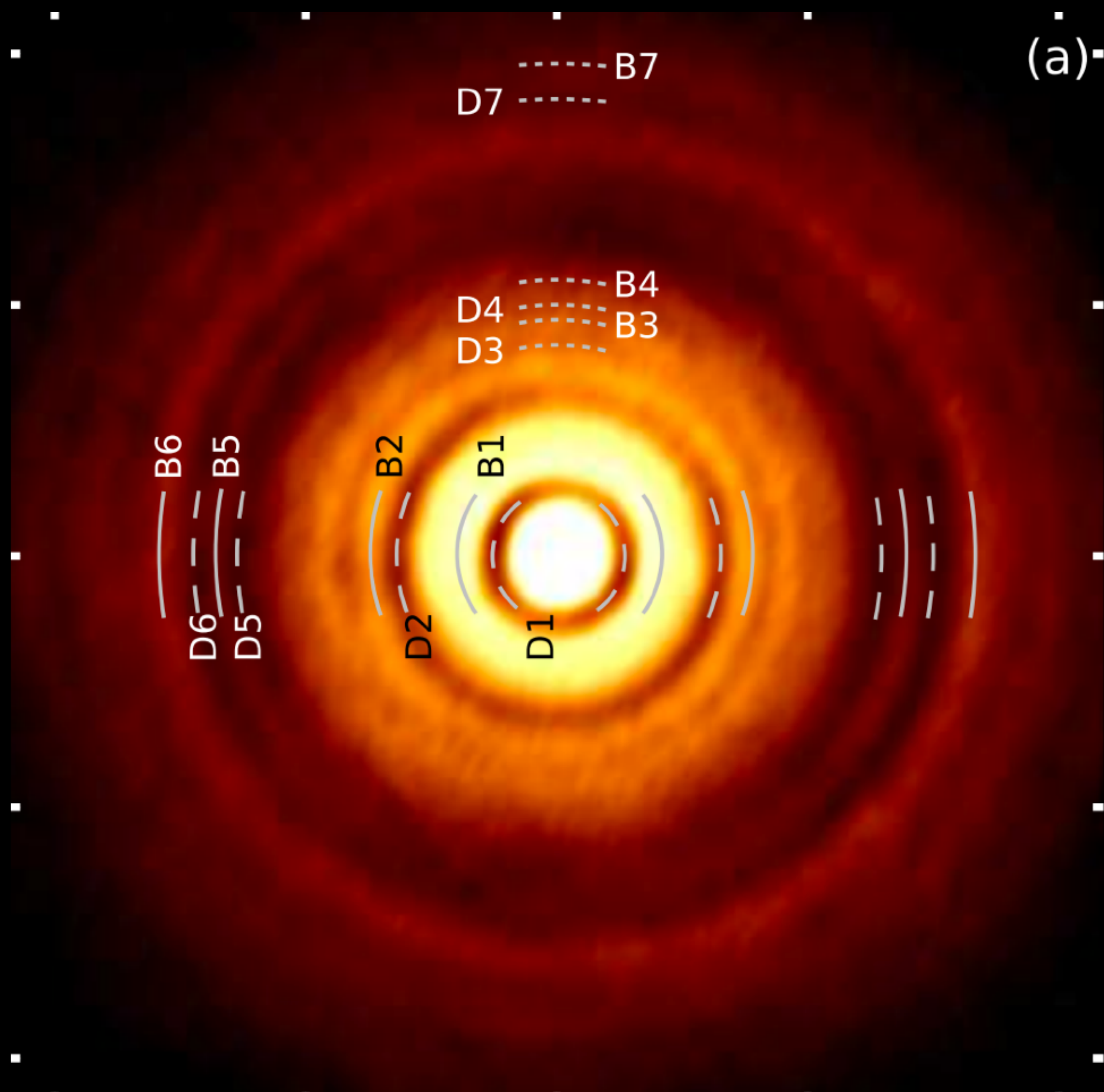


Table 2. Dust masses for the inner disk and bright rings

Disk Feature	Radius (au)	Dust Mass ($M_\oplus$) This paper[a]	Pinte et al.[b]
ID	<13	10 - 50	>2.3
B1	13 - 32	70 - 210	>47
B2	32 - 42	30 - 90	30 - 69
B3	42 - 50	20 - 80	14 - 37
B4	50 - 64	30 - 90	40 - 82
B5	64 - 74	10 - 50	5.5 - 8.7
B6	74 - 90	40 - 140	84 - 129

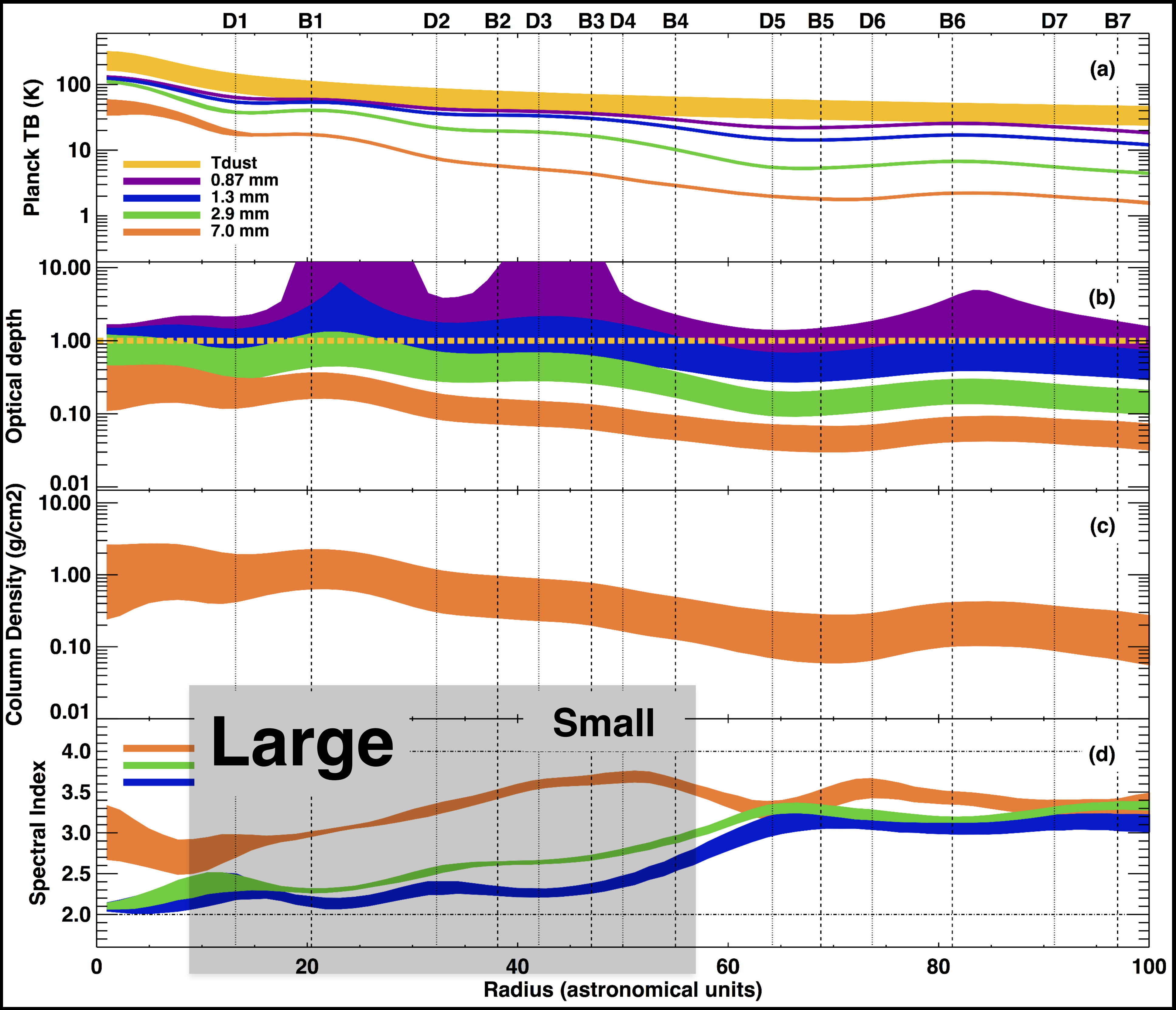
The most **internal features** of the disk seems to be **more massive** than previously inferred

Disk seems to be **more massive** than previously inferred:

7 mm —> ~(1-3) x 10^{-3} Msun

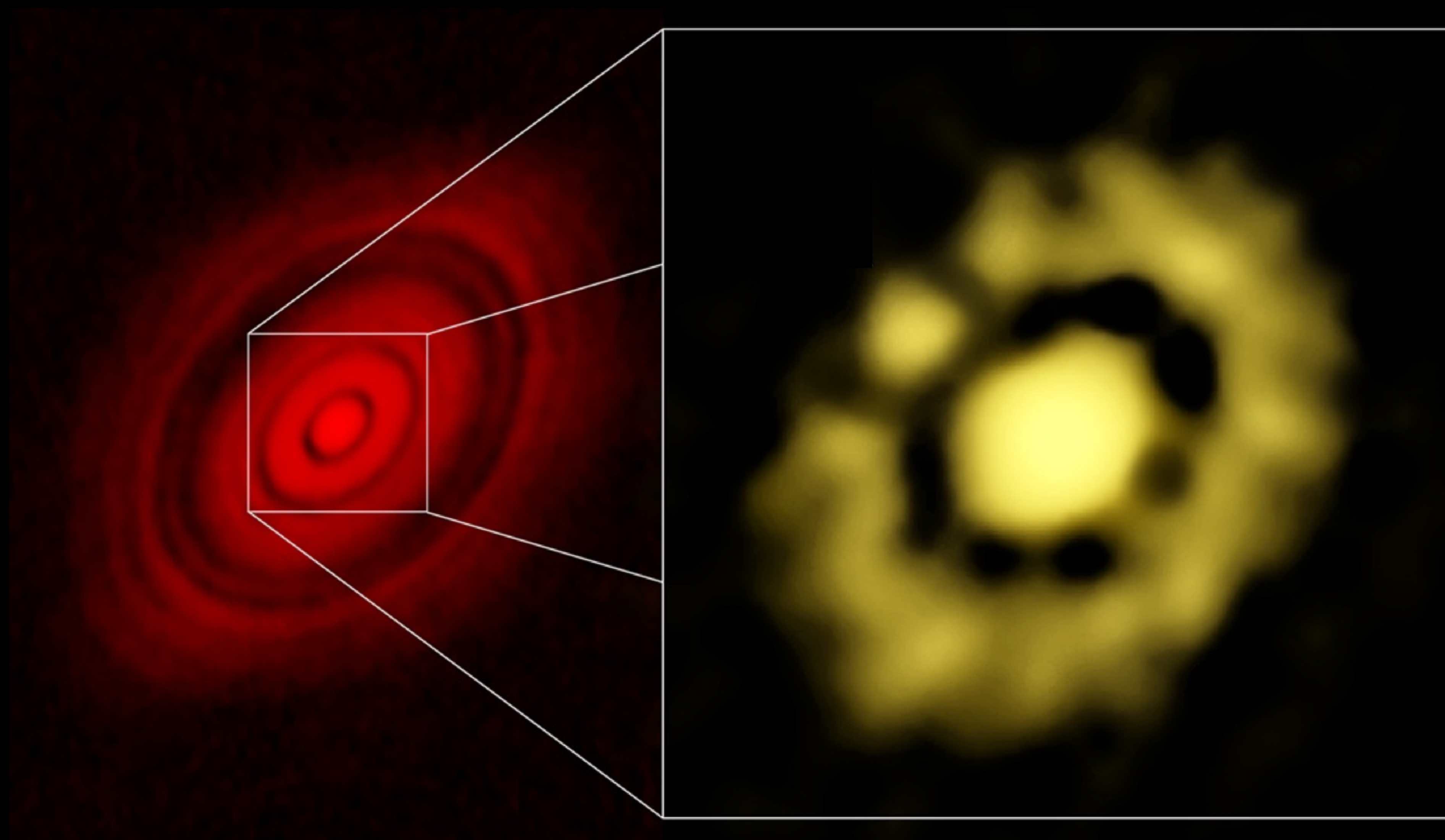
ALMA Modeling —> ~(0.3-1) x 10^{-3} Msun

2. Grain Size Distribution



Dust in the HL Tau disk is already growing at the most internal parts (<50 AU)

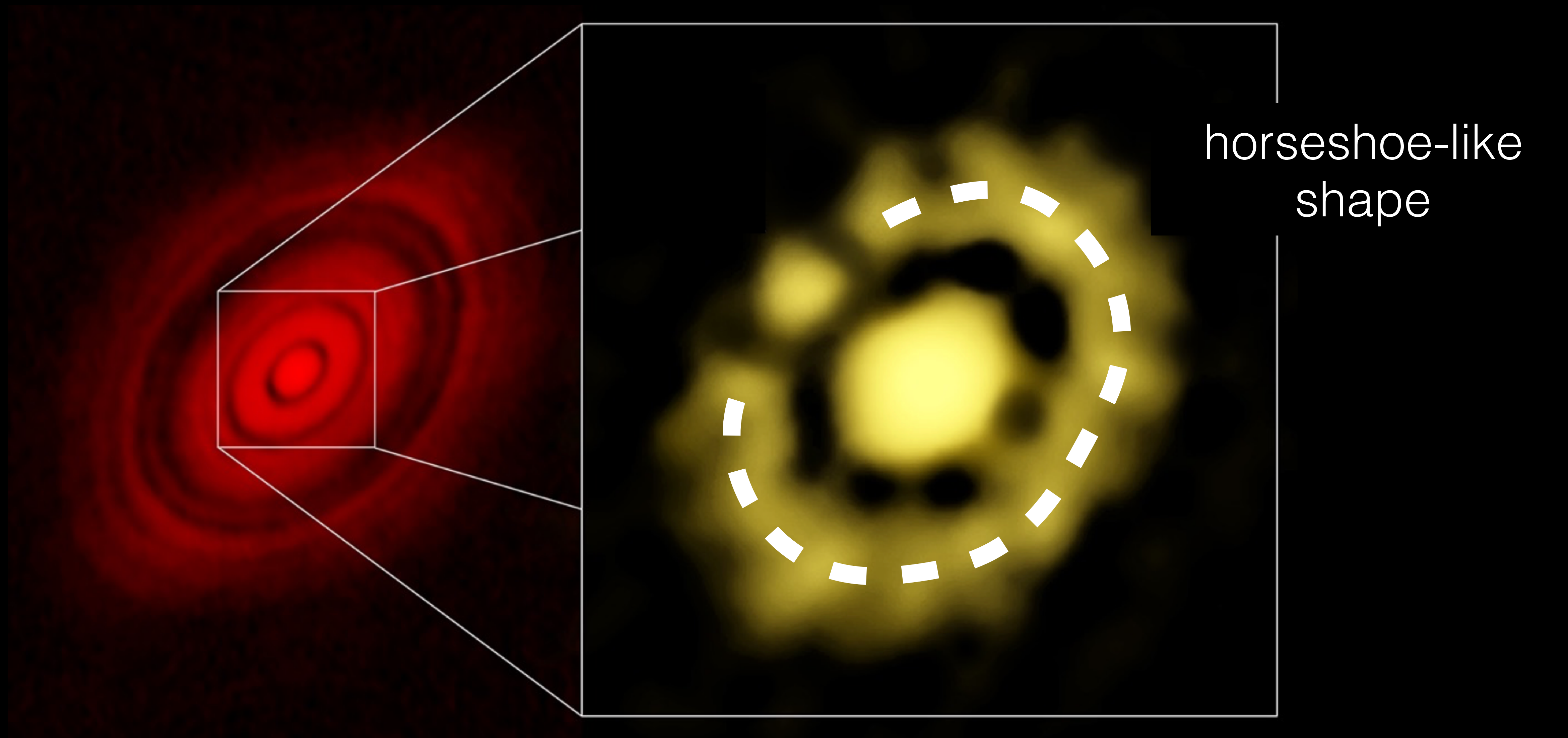
3. Substructure Within the Rings



ALMA@
1.3 mm

VLA@
7 mm

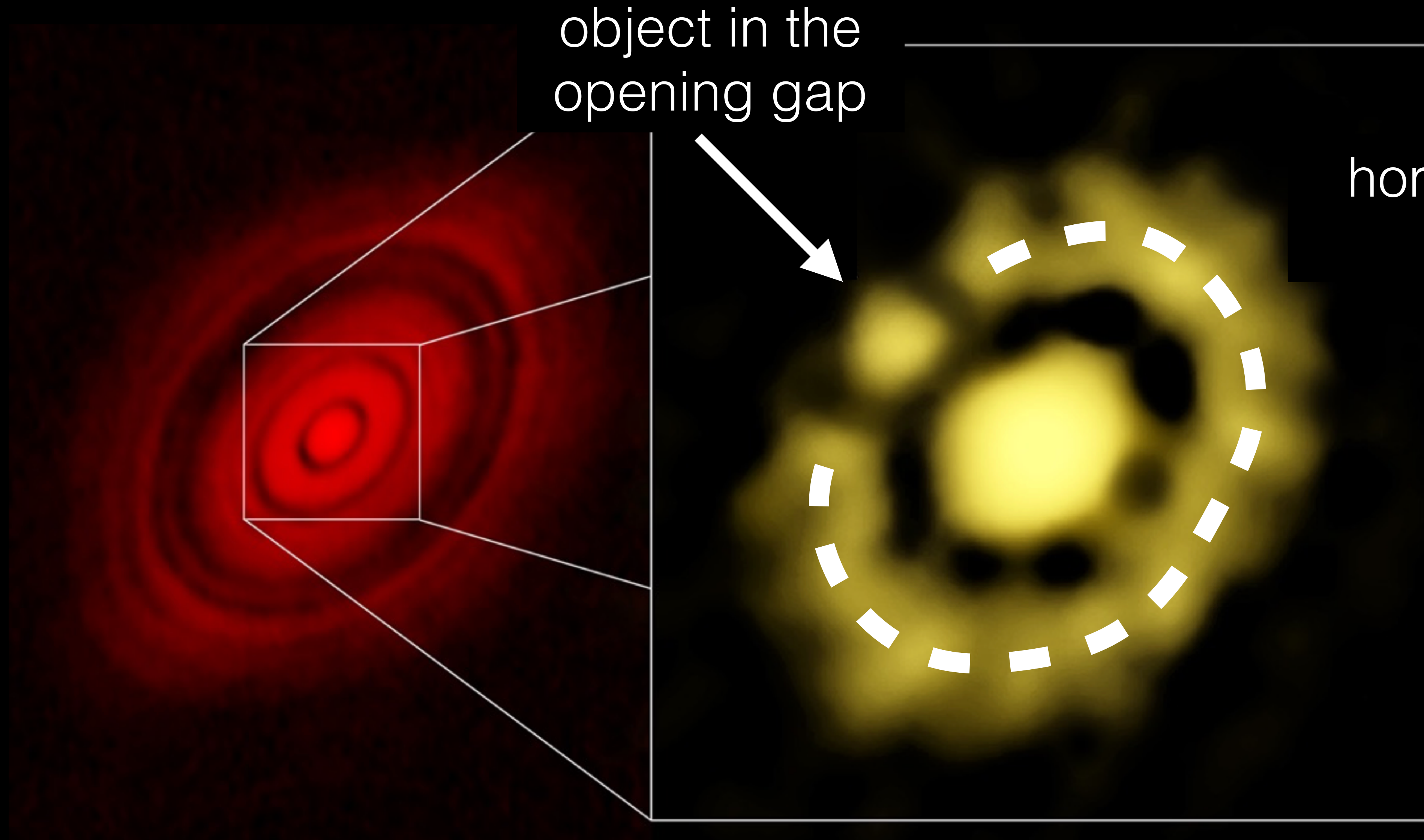
3. Substructure Within the Rings



ALMA@
1.3 mm

VLA@
7 mm

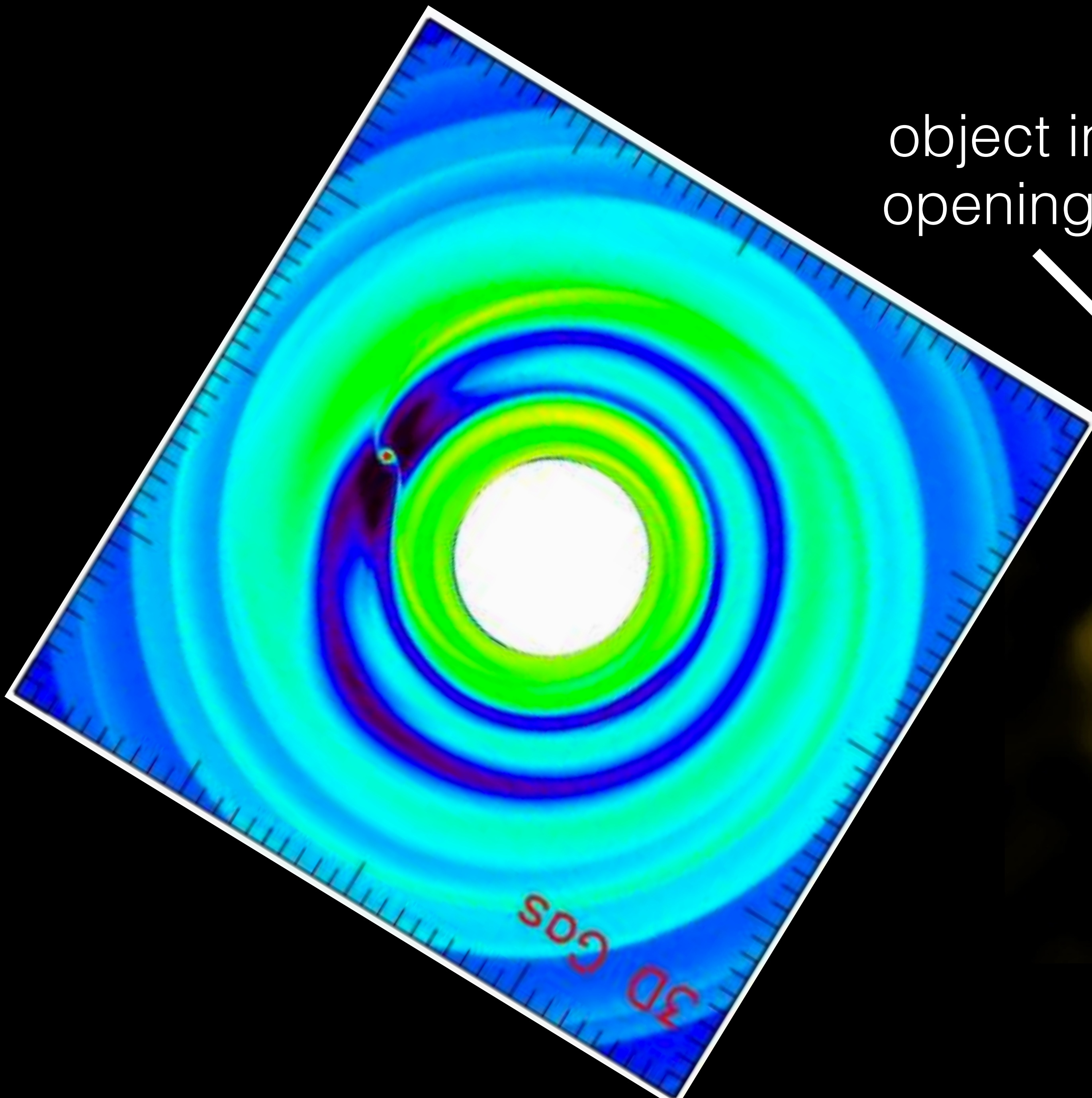
3. Substructure Within the Rings



ALMA@
1.3 mm

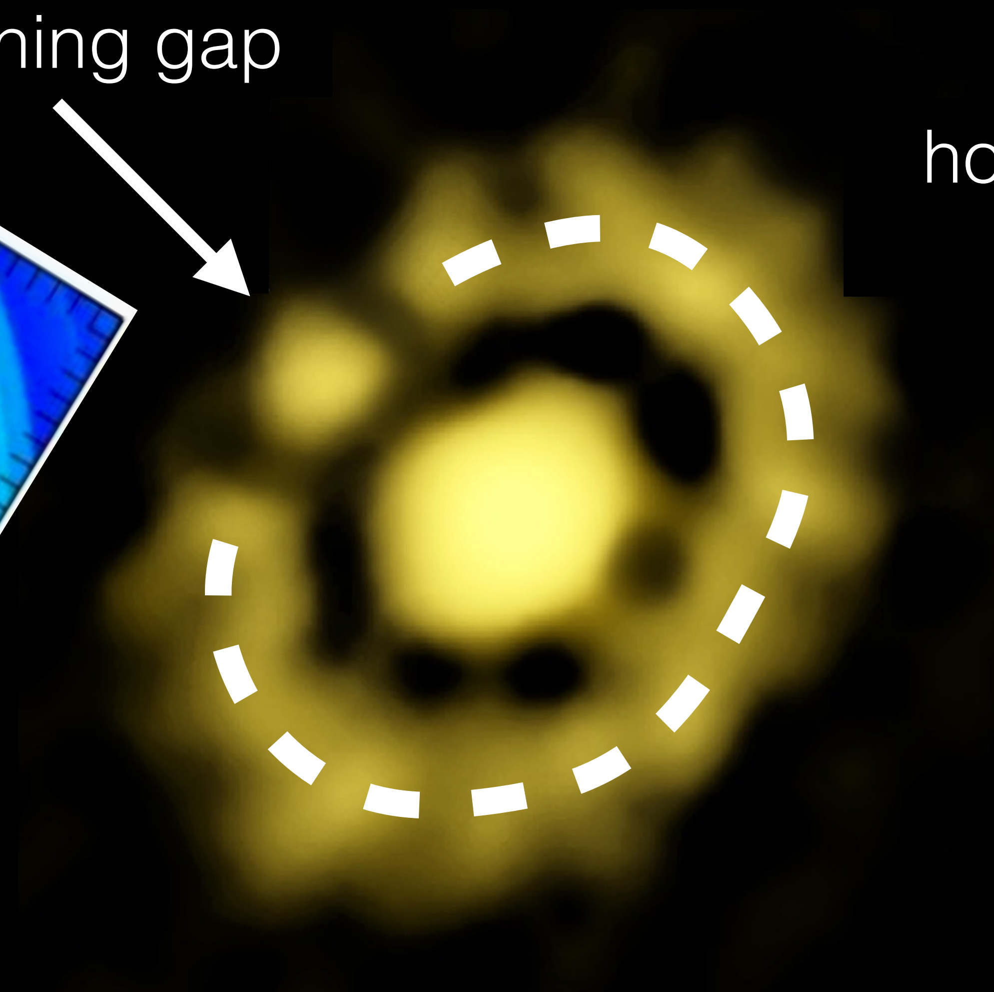
VLA@
7 mm

3. Substructure Within the Rings



Simulation

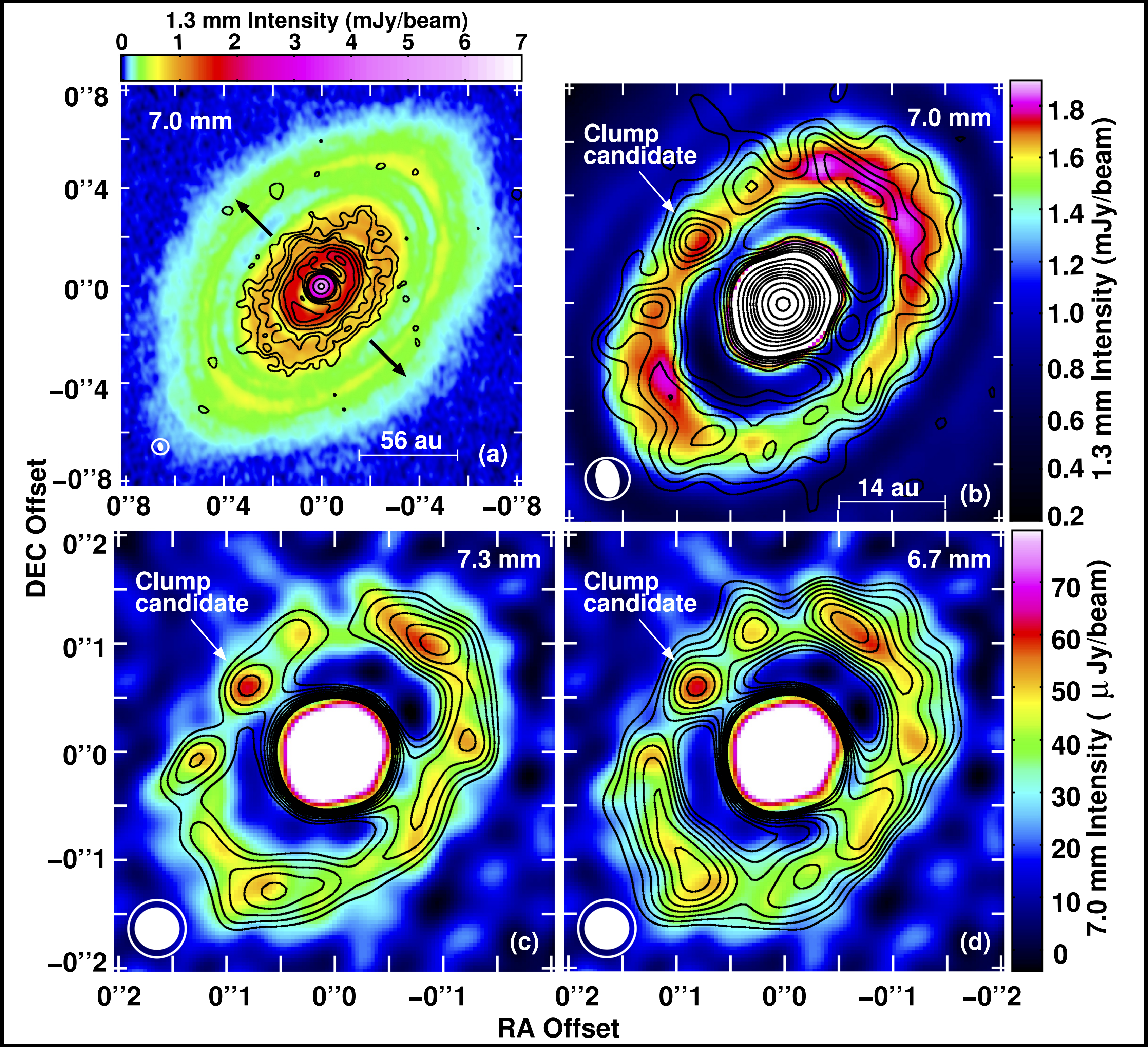
object in the opening gap



horseshoe-like shape

VLA@ 7 mm

3. Substructure Within the Rings

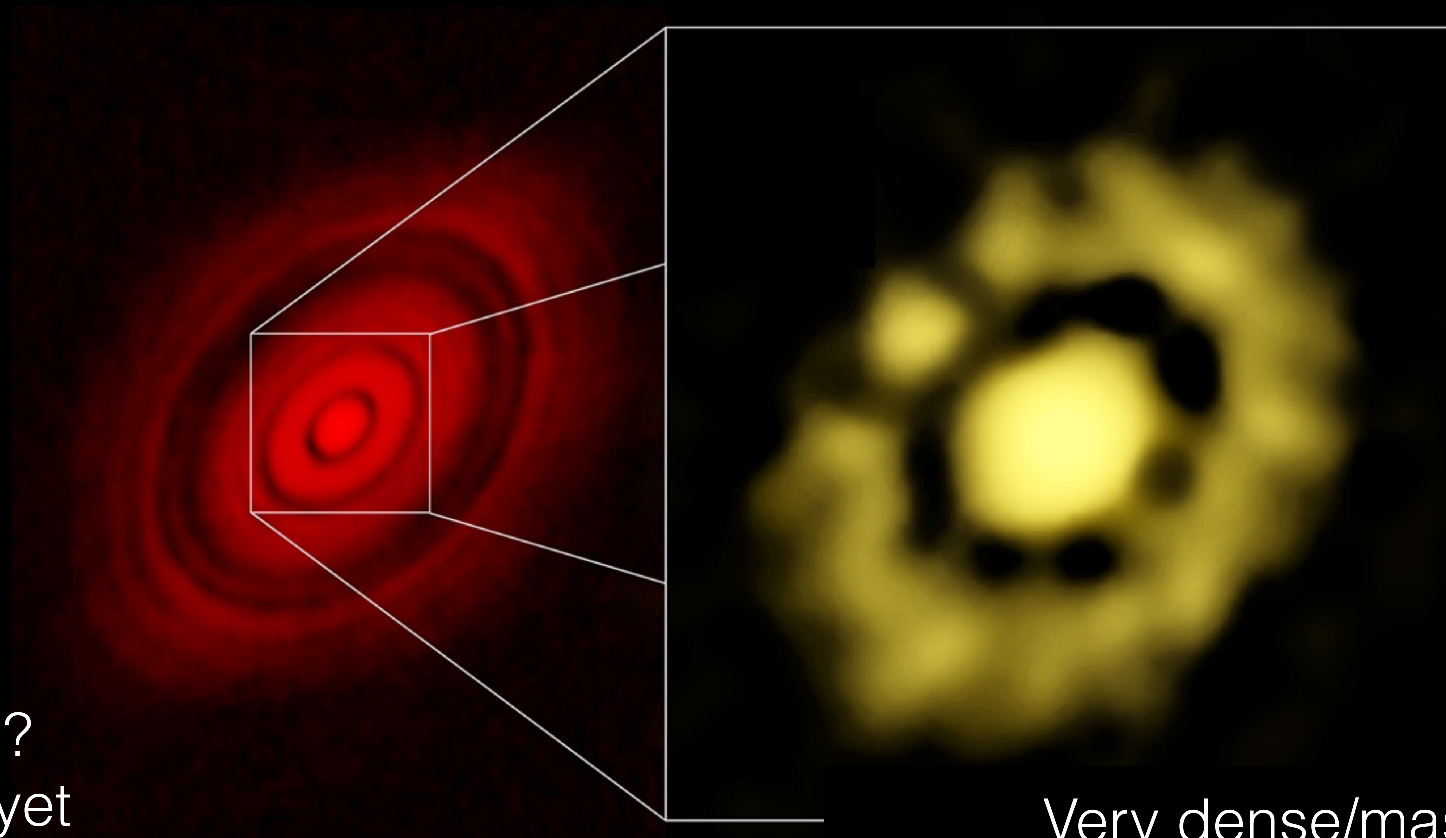


Looks like a **dense clump** in the densest and most massive ring

Estimated dust mass ~3-8 Mearth

On planet formation in HL Tau

ALMA@
1.3 mm



VLA@
7 mm

7 gaps -> 7 planets?
Not more evidences yet
Alternative explanations
HL Tau is VERY young

Very dense/massive inner disk
Dust grains are growing at densest parts
Probably, clumps are starting to form in
DENSE RINGS

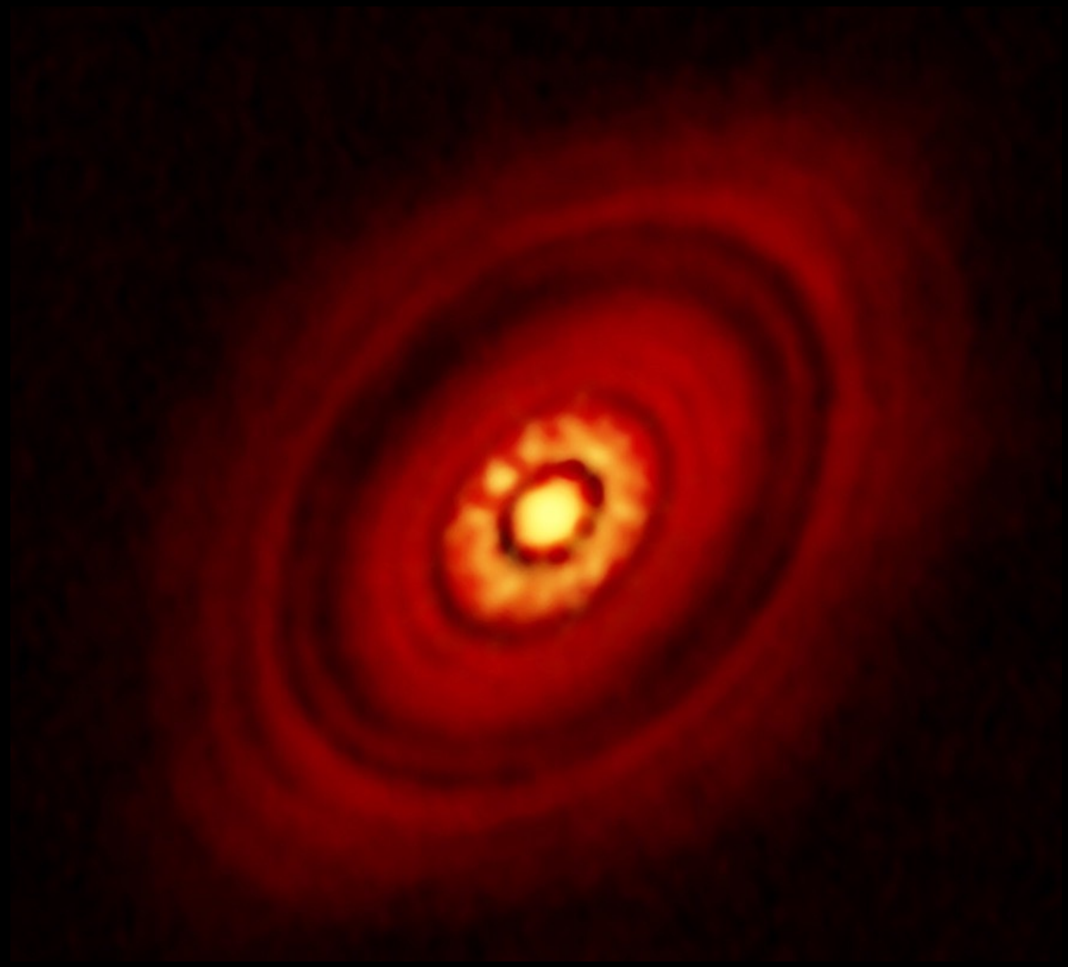
Our proposal:

Gaps (dark rings) are NOT formed by planets. They are common and appear very early on disks. Once formed, dense parts (bright rings) can suffer from instabilities/fragmentation and form planetary embryos

The dense rings in HL Tau can actually represents the very early stage of planet formation.

READ OUR PAPER:
Carrasco-González et al. 2016, ApJ Letters 821, 16

Remarks



HL Tau @ ALMA+VLA

We are in a very exciting epoch for the study of planet formation

ALMA is producing very detailed images of protoplanetary disks.

But, there is still a need for observation at longer wavelengths, were dust emission is optically thinner. At the moment, VLA is the best instrument to solve this.

Future: ALMA Band 1, ngVLA