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Protoplanetary Disk Observations with ALMA

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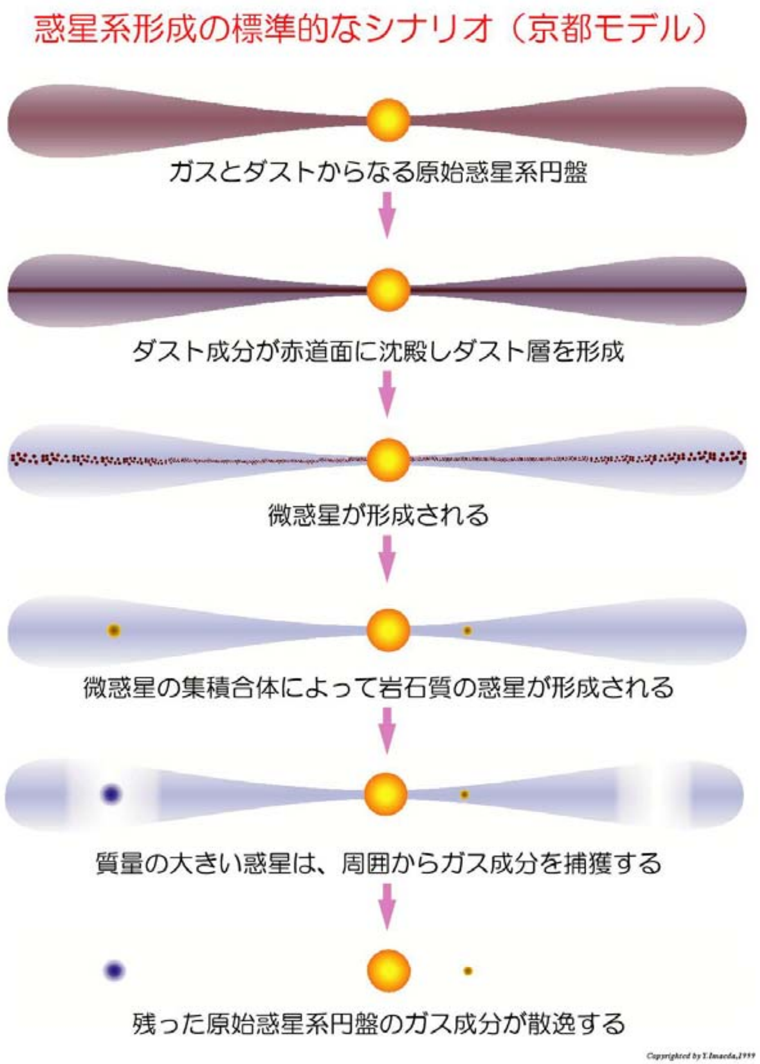
Contents

Disclaimer

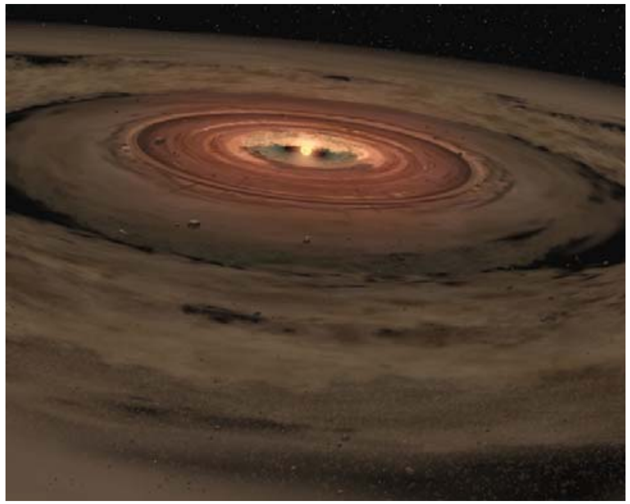
- I will cover:
  - Scientific motivations of observing with ALMA and a little bit of modeling work
  - A tiny fraction of recent observation (papers published in 2015-2016) results
- But I do NOT cover:
  - Chemistry (does not mean chemistry is less important)
  - Many theoretical works that try to connect observations with planet formation

- Introduction
- Survey of Protoplanetary Disks
- Imaging Observations of Individual Targets
- Polarization Observations
- Summary

Protoplanetary Disk and Planet Formation

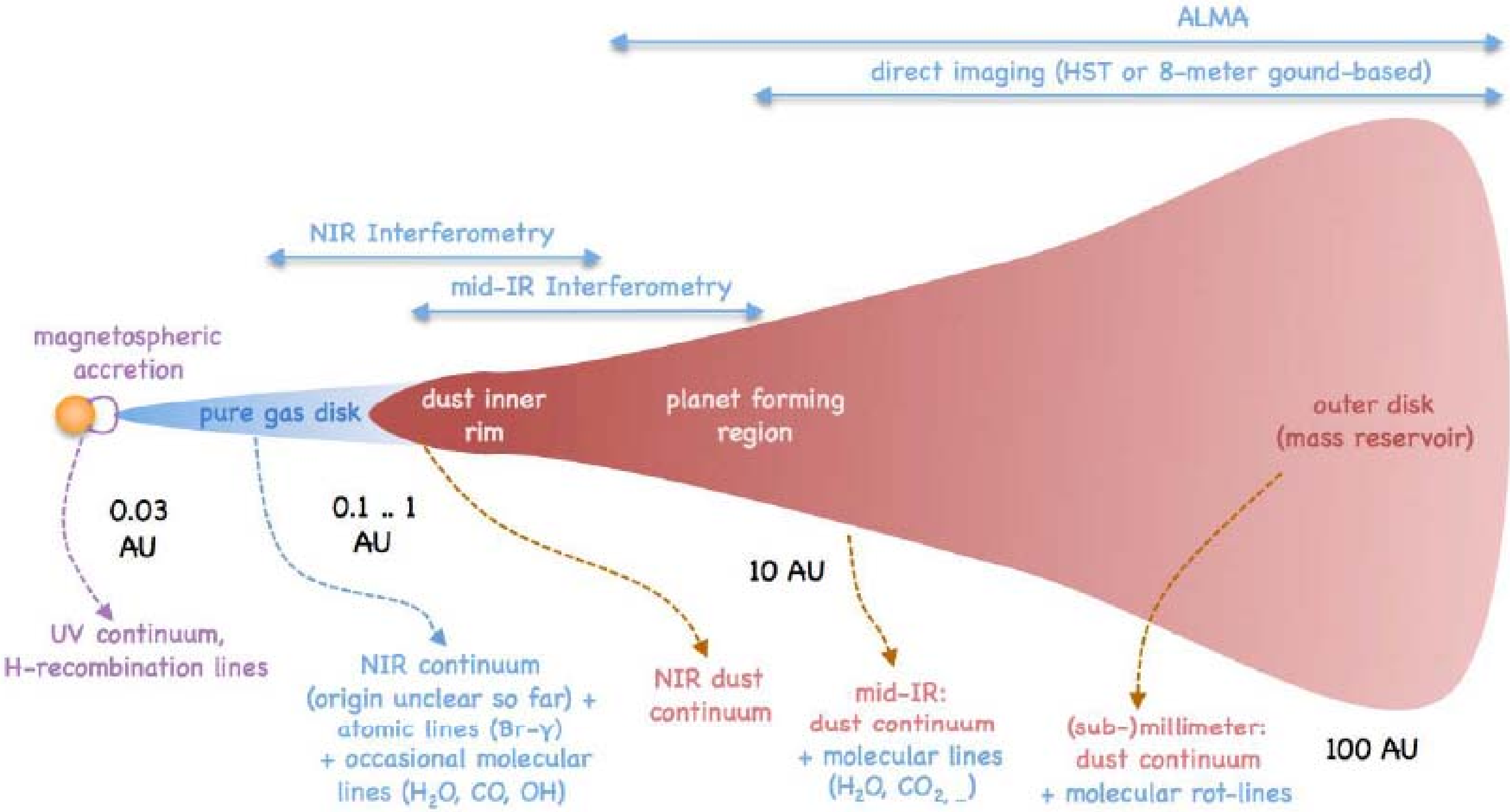


- Protoplanetary disks are birthplace of planets
- Mixture of gas and dust
- Dust grains grow to planets



From NASA

Overview of Protoplanetary Disk



- Cold, thin disk
- Many are located at >~140 pc (the closest one at ~50 pc)

Dullemond and Monnier 2010

Fundamental Questions

- What are protoplanetary disks?
  - Gas mass, dust mass, temperature, size …
- What happens in protoplanetary disks?
  - How do grains grow, in what time scale?
  - What happens when planets are form?
  - When and how does gas dissipate?

- Need observational evidences

Recent ALMA Results (to be covered in this talk)

- Survey
- Individual Targets
  - High resolution observations
  - Gas and dust structures
- New science with new capability
  - Polarization

- Introduction
- **Survey of Protoplanetary Disks**
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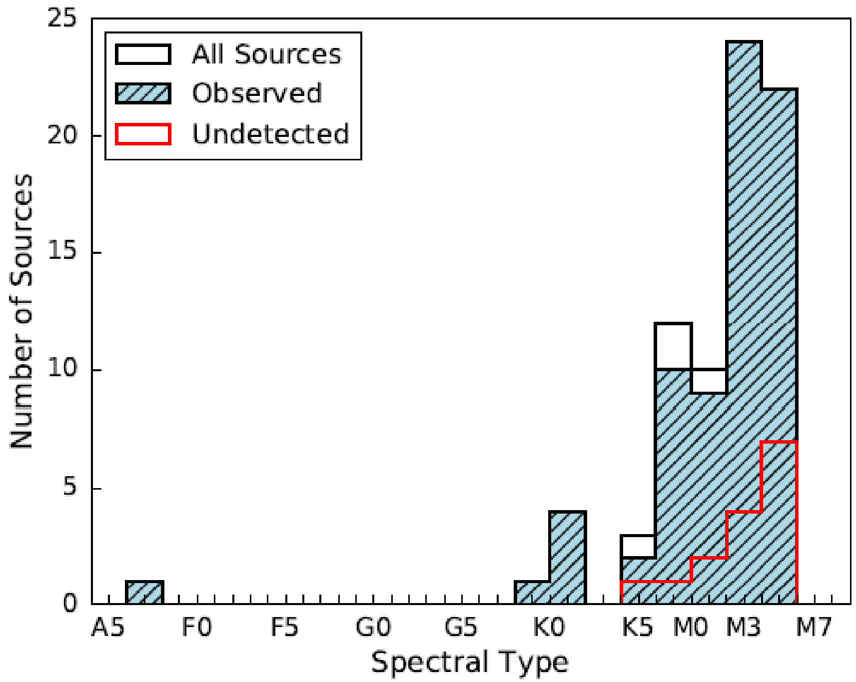
Survey

- What is the overall properties of protoplanetary disks?
  - Dust mass
  - gas mass
  - gas-to-dust ratio
- Lupus Survey (Ansdell et al. 2016)
  - Continuum + 13CO(3-2) + C18O(3-2)
- USco Survery (Barenfeldt et al. 2016)
  - Continuum + 12CO(3-2)

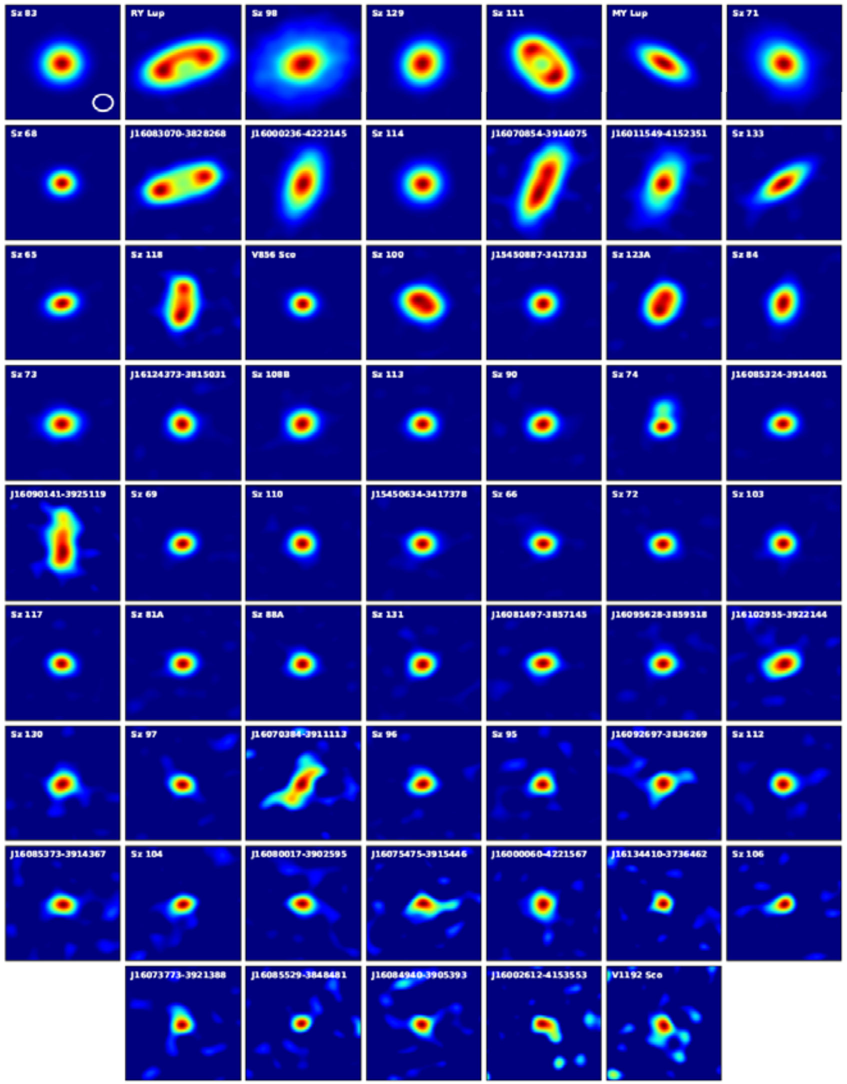
Lupus Survey Overview

- 89 sources in Lupus I-IV
- 0.3 asec resolution
  - 45 AU @ d=150 pc
- Sensitivity
  - ~0.3 Mearth dust
  - ~ 1MJ gas
- Only 30sec – 1min on source
- 62 detected in dust continuum
- 36 detected in 13CO, 11 detected in C18O



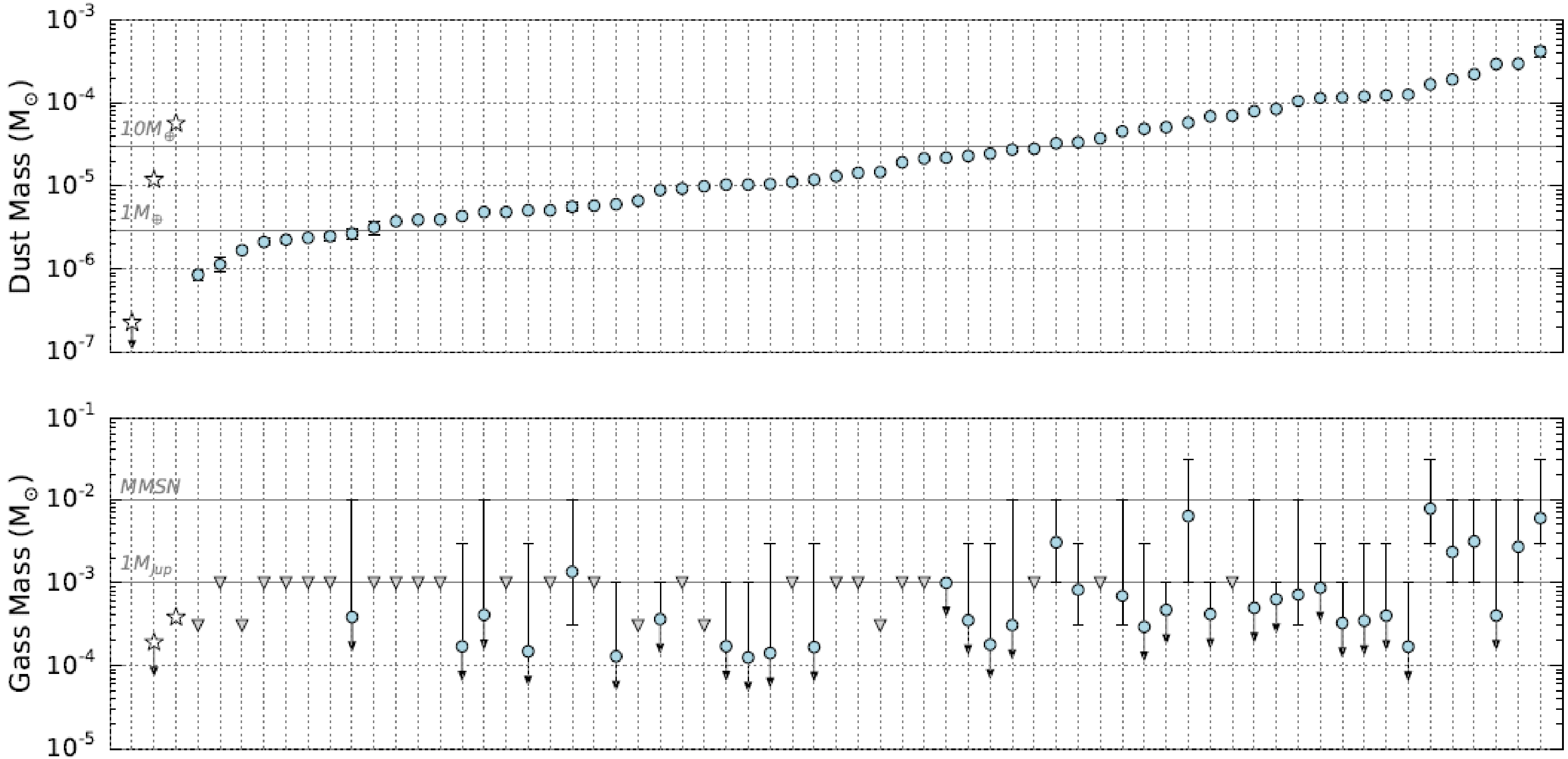
Ansdell et al. 2016

Lupus Continuum Image Gallery



Ansdell et al. 2016

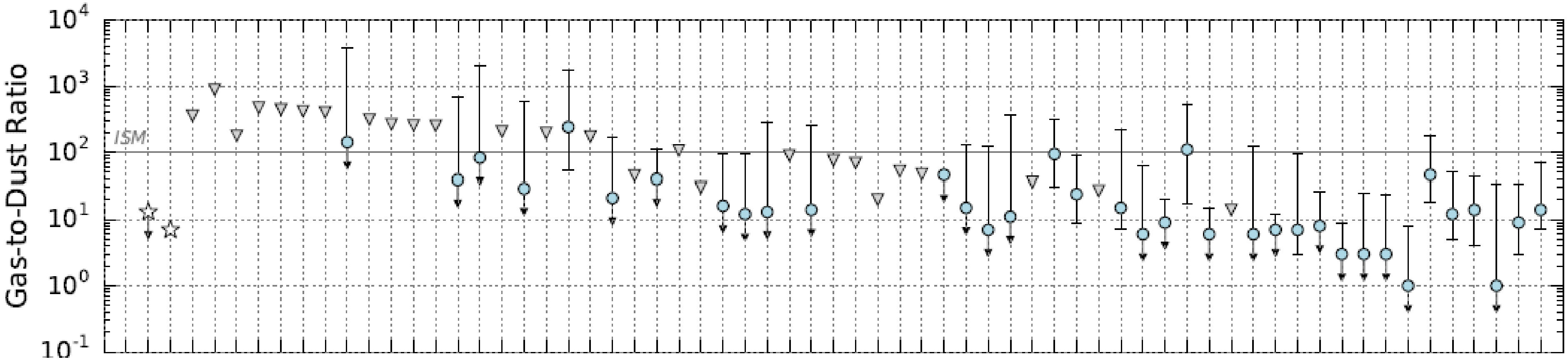
Dust and Gas Mass



- Dust mass spans over ~ 3 orders of magnitude
- Gas mass is typically ~1 MJ

Ansdell et al. 2016

Gas-to-Dust Ratio

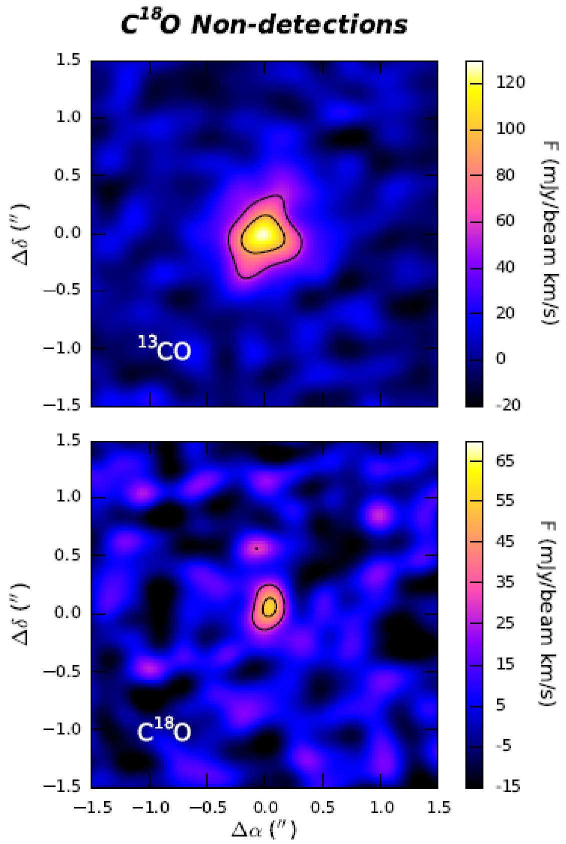


Significantly lower gas-to-dust ratio than ISM

Ansdell et al. 2016

Stacking of Non-Detections

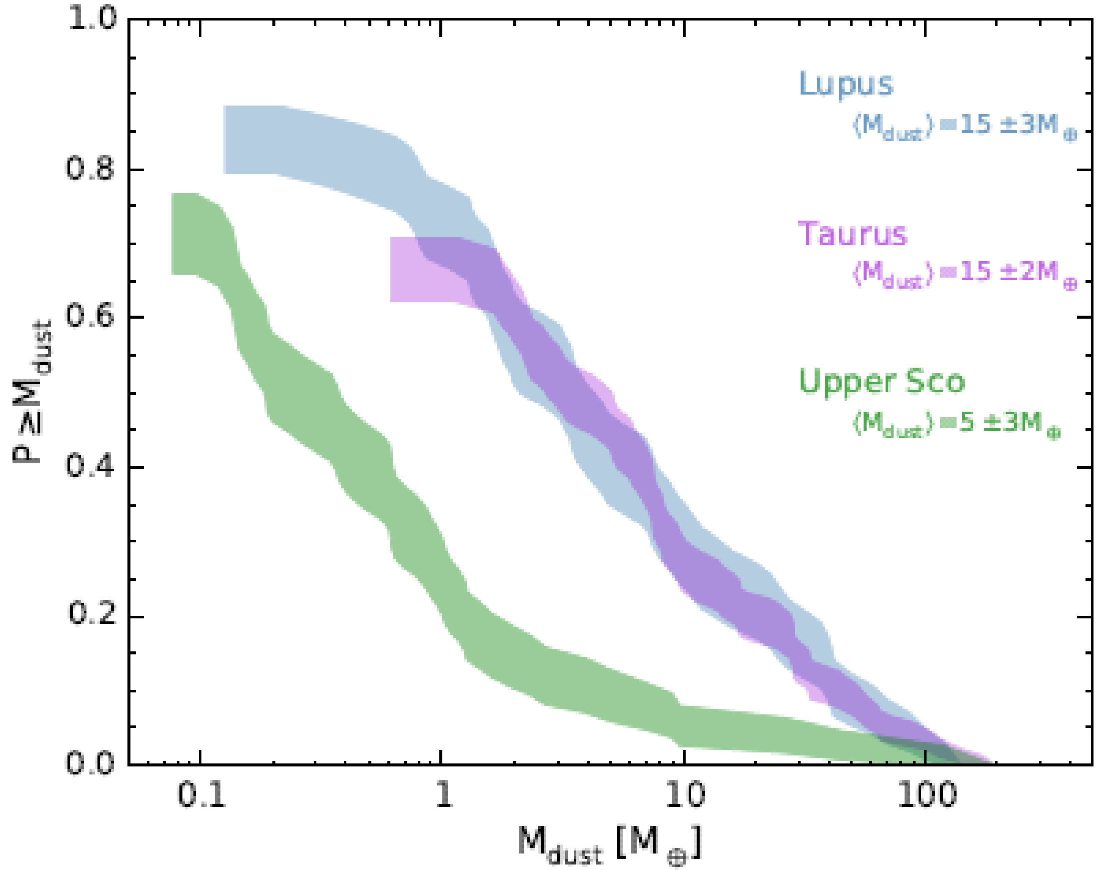
- Continuum Non-Detections
  – Non-detection even after stacking
  – (Dust mass) < 6 Lunar mass
- Gas Non-Detections
  – Gas-to-Dust <~ 10



•Quick evolution from protoplanetary to debris disk phase?
•Very small gas-to-dust ratio

Ansdell et al. 2016

Comparison with Other Region



- Lupus and Taurus are similar, while USco shows lower Mdust
- Similar distribution for three regions

Ansdell et al. 2016
Barenfeld et al. 2016

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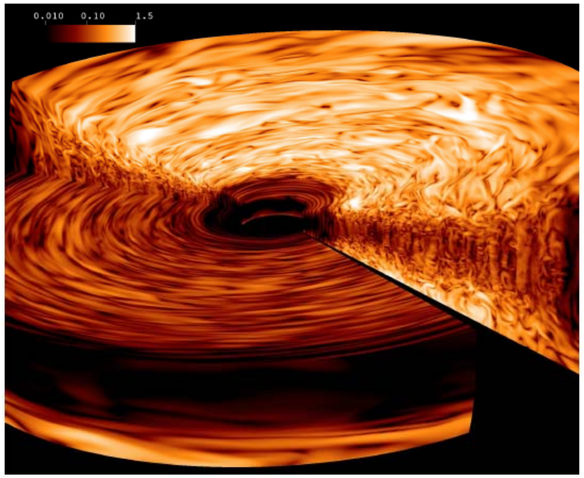
High Resolution Imaging Observations

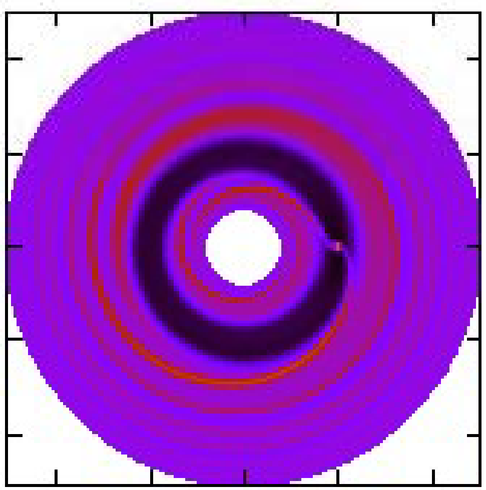
- "Ring World" revealed
  - High resolution (<0.1 asec) observations for dust continuum
    - HL Tau, TW Hya
  - Gas+dust rings
    - HD 163296
- And another spiral…
  - Elias 2-27

Why high resolution?

- Key to understand dynamical structure
  - Important scale: disk scale height
  - H ~ (sound speed) * (Kepler time) ~ 10 AU at r=100 AU
  - Need to resolve ~ 0.1 asec structures at d=140 pc

* If you really want to resolve “Earth-Forming” regions, you need much longer baseline

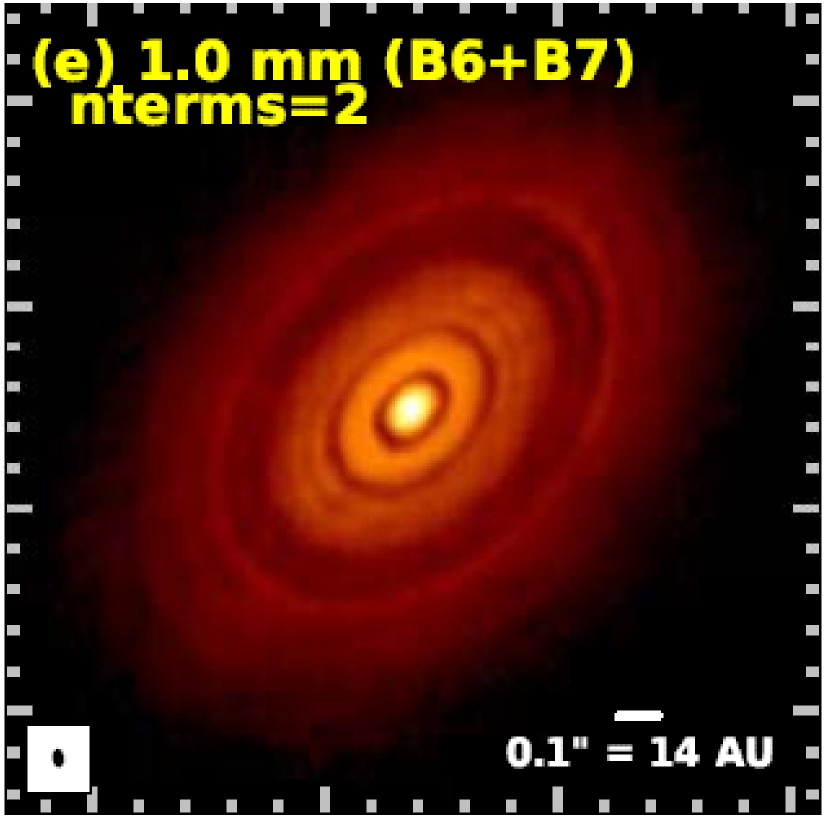




Flock et al. 2011
FARGO simulation

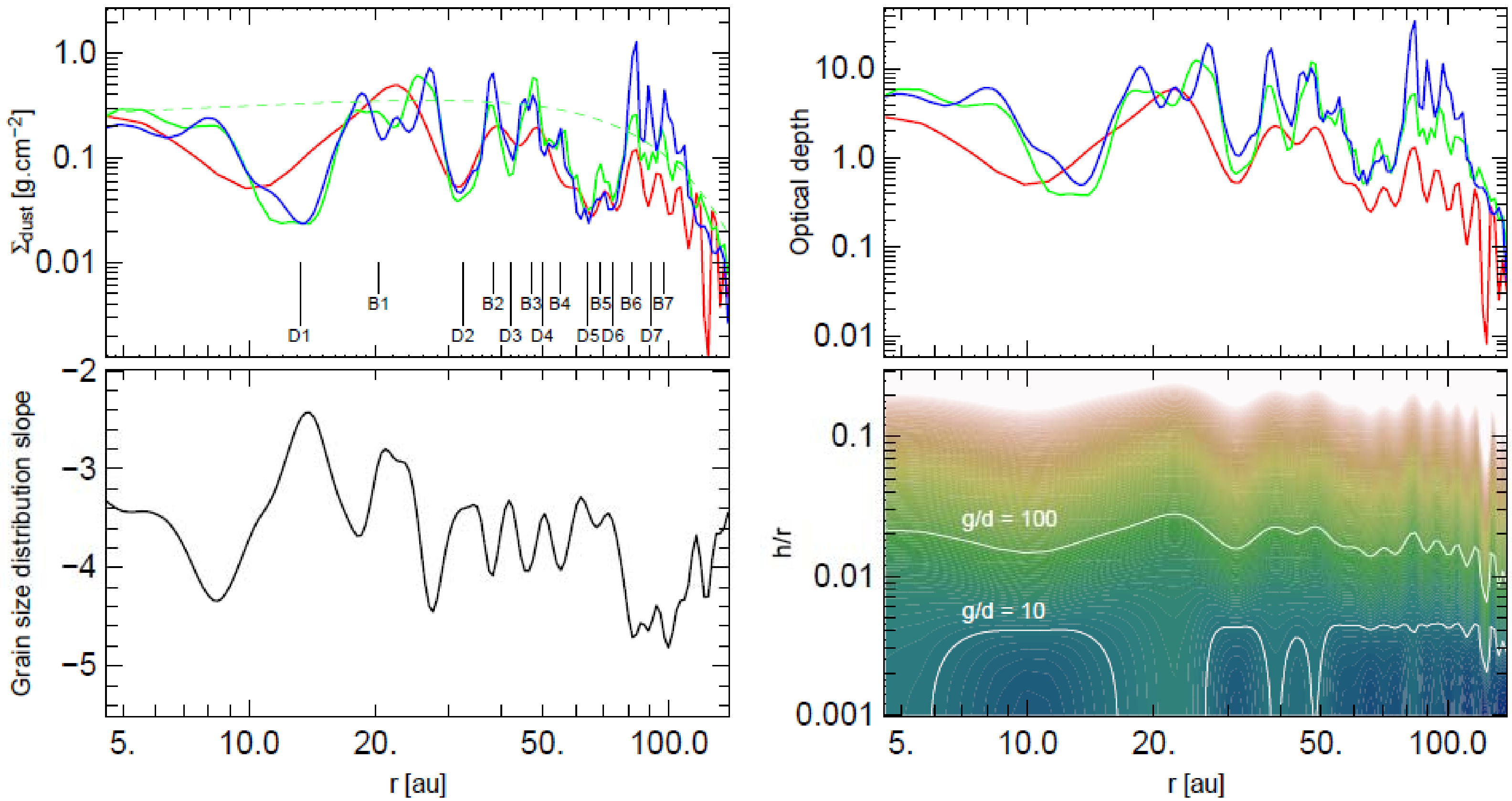
HL Tau

- ALMA long baseline campaign
- Multiple ring structure in dust continuum in B3, B6, B7
  - 0.025-0.075 asec resolution
- Gas emission also detected in HCO+
- 139 citations!



ALMA Partnership 2015

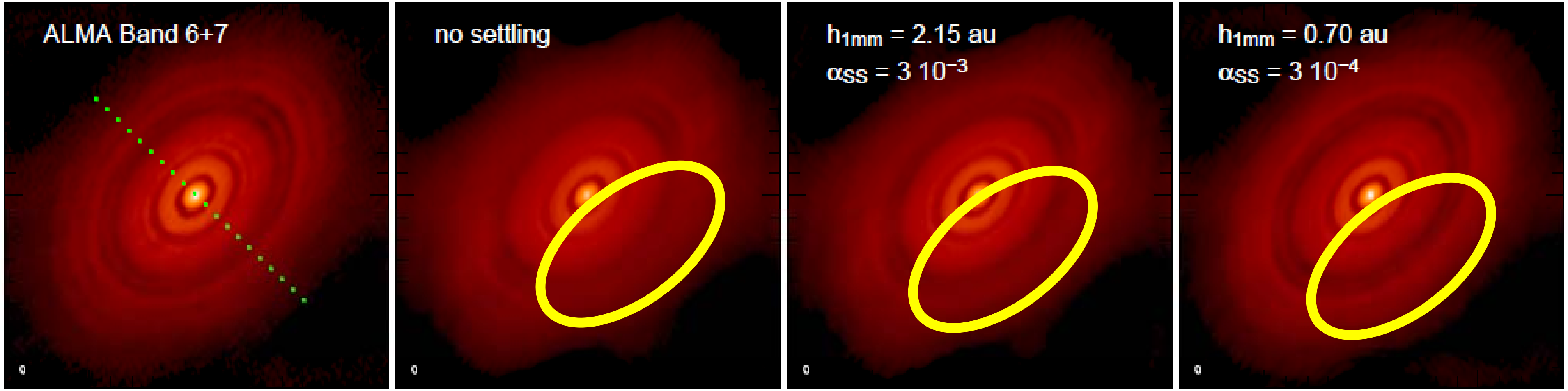
Dust + Gas Modeling



Dust settled in the disk midplane

Pinte et al. 2015

Morphological Signature of Dust Settling



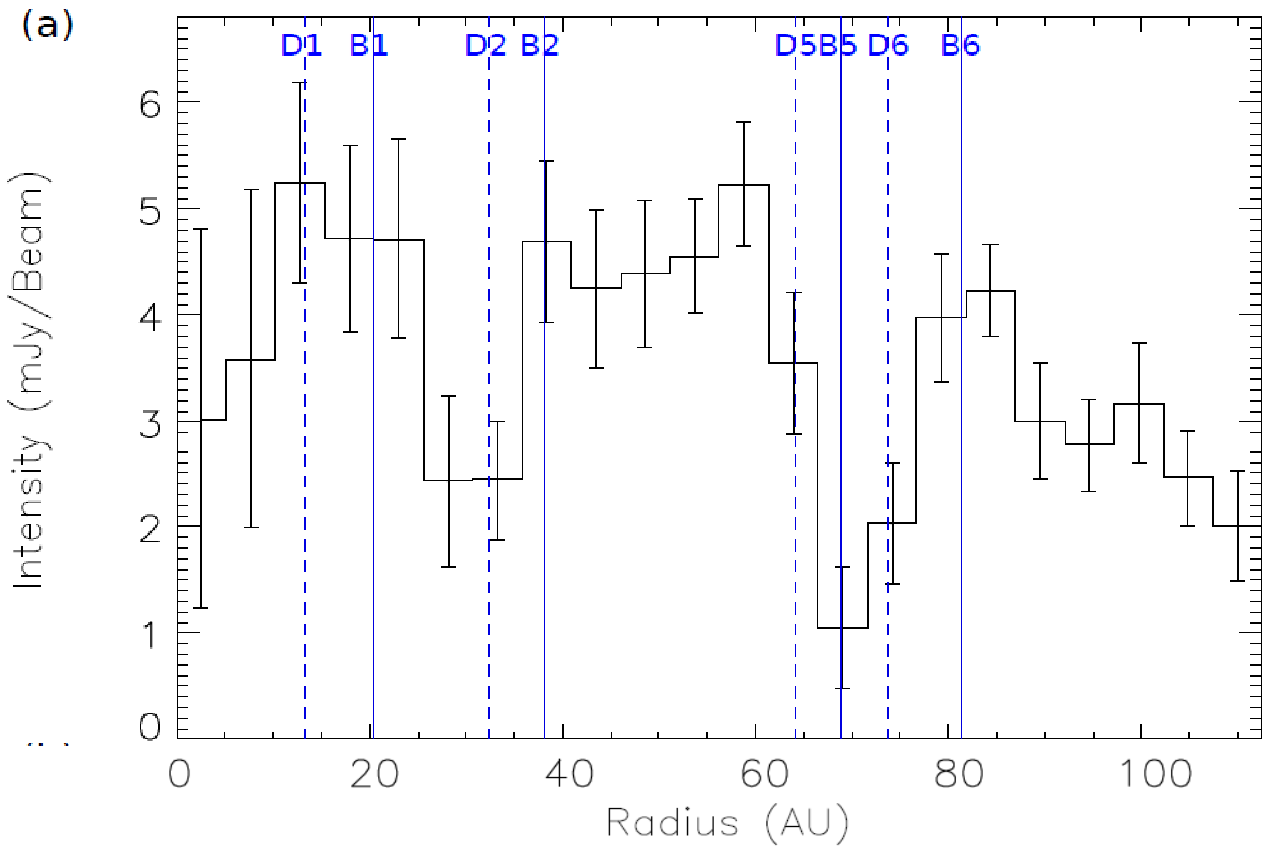
No settling   intermediate settling   Highly settled

Young (1-2 Myr) disk showing dust settling

Pinte et al. 2015

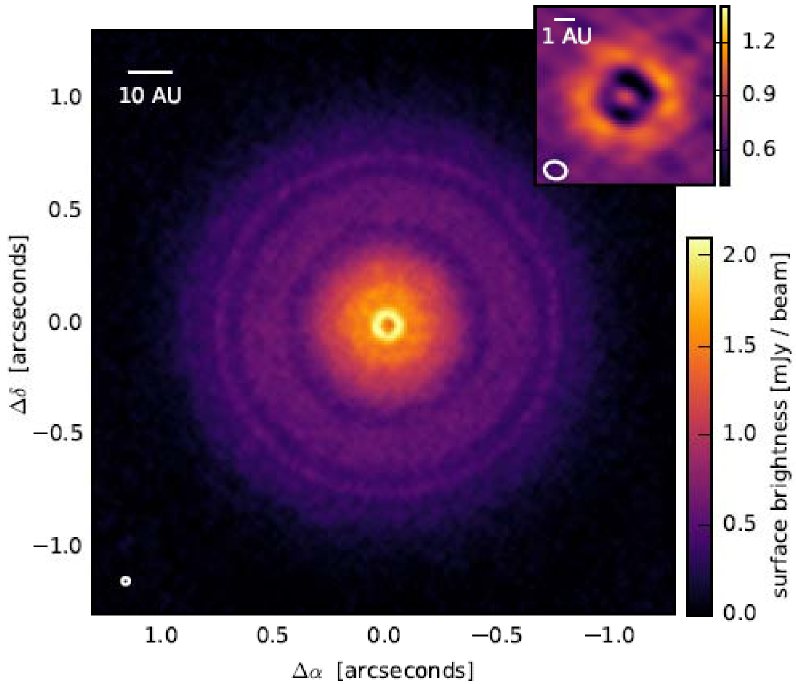
Gas Gaps?

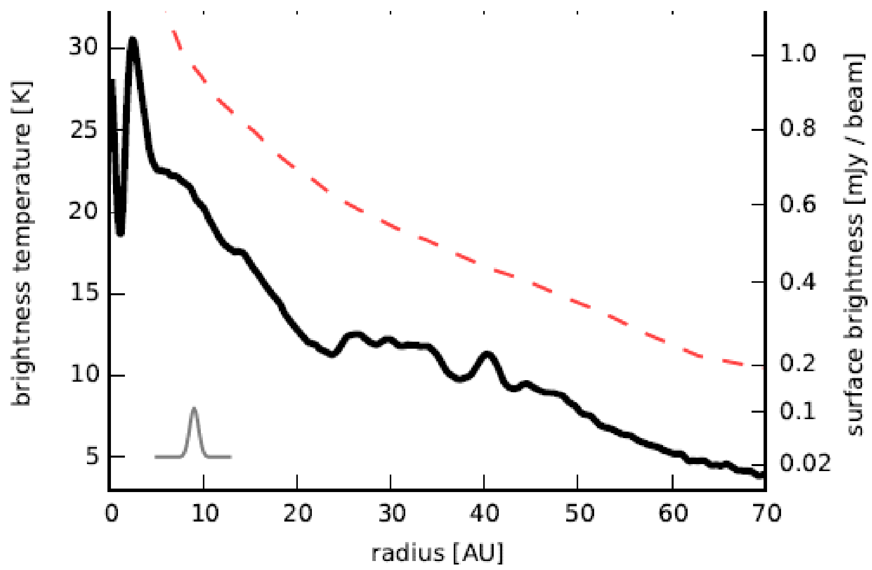
“integrated and azimuthally averaged” HCO+ profiles



Yen et al. 2016

TW Hya

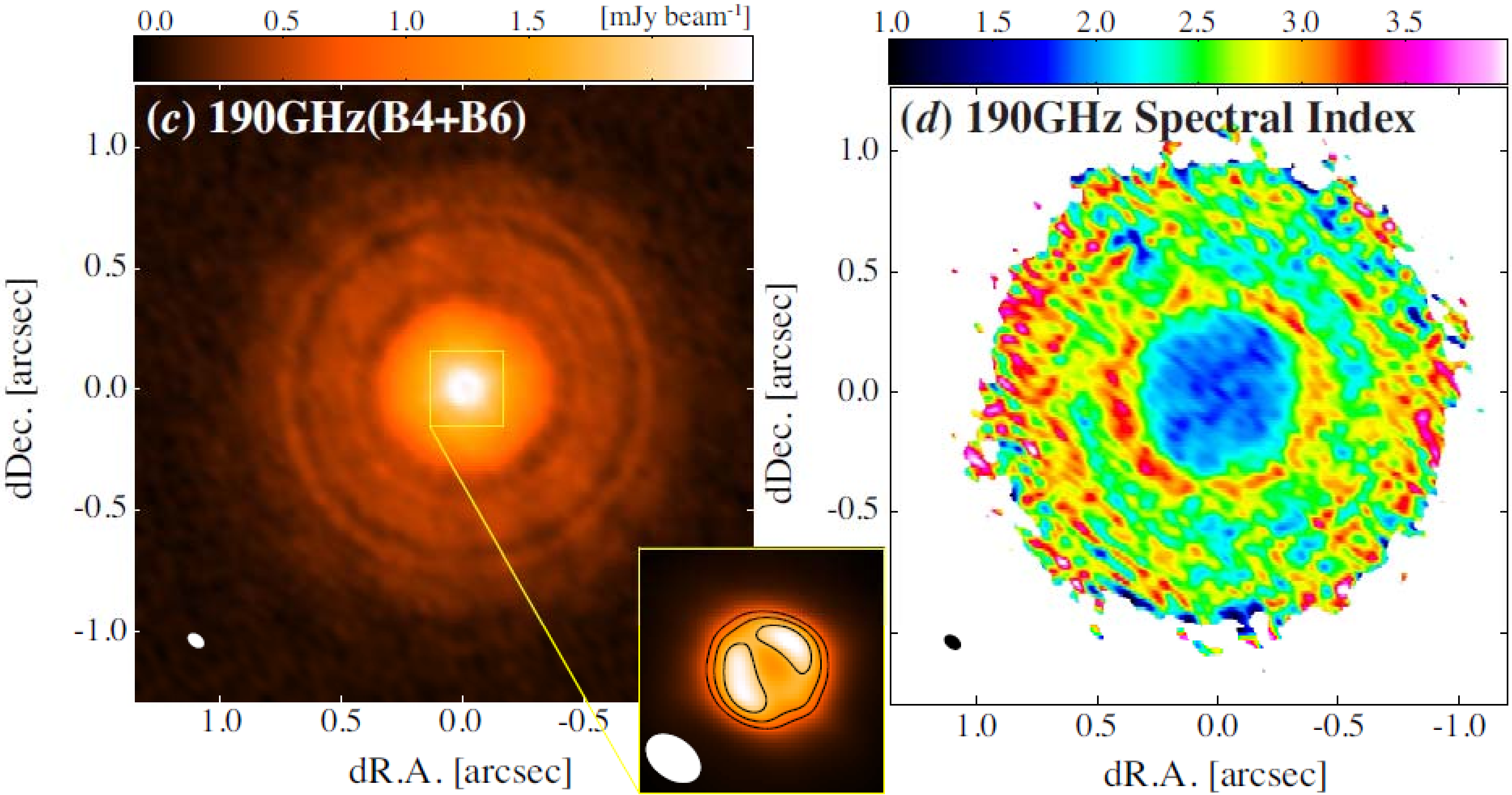




- 0.02 asec resolution in B7
  - ~1AU resolution due to its proximity to the Sun
- Inner hole + multiple rings

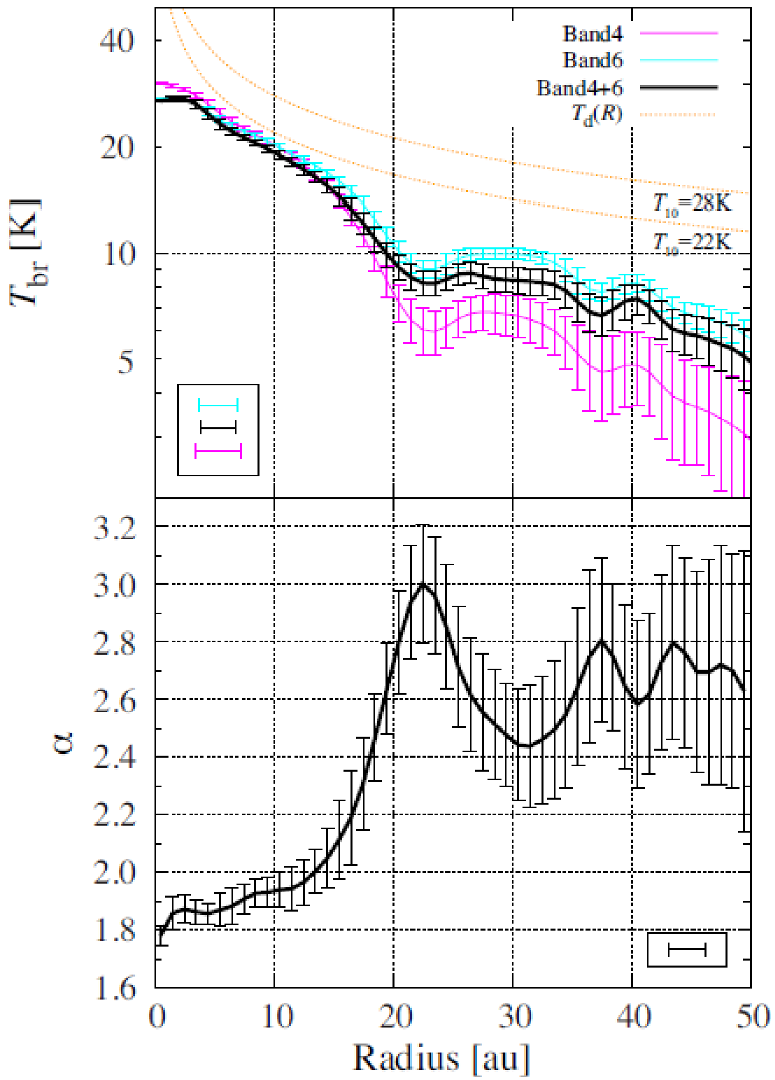
Andrews et al. 2016

TW Hya High-Res. Multiband



Tsukagoshi et al. 2016

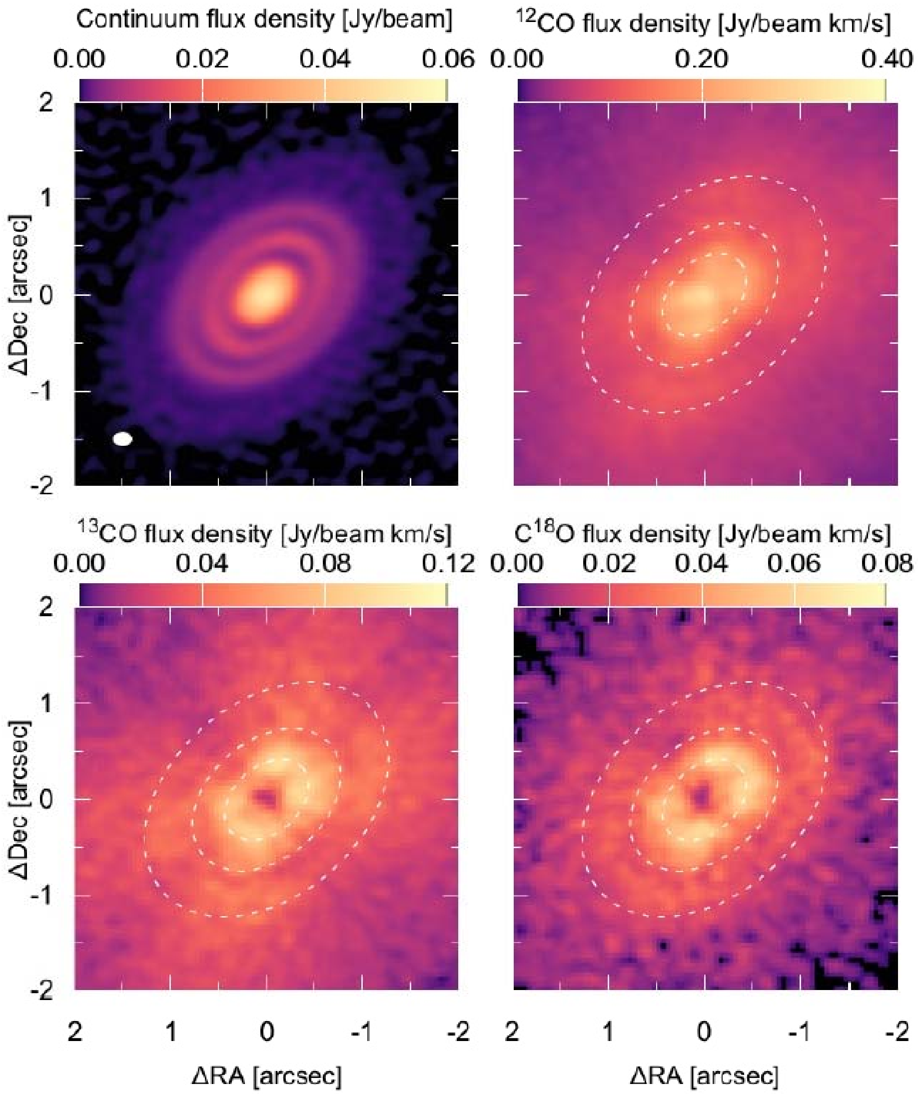
Gap and Grain Properties



- Reasonably optically thin emission
- Spectral index peaks inside the 20AU gap
  - "large grain deficit gap"

Tsukagoshi et al. 2016

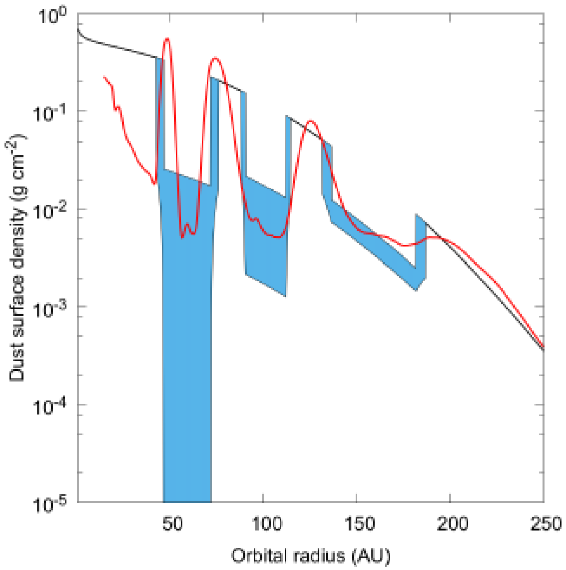
HD 163296



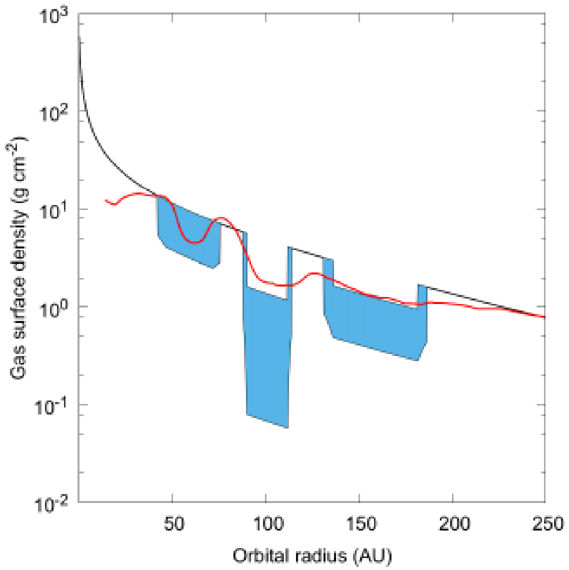
- Continuum + 12CO + 13CO + C18O
  - ~ 0.2 asec resolution
- Ring structures in dust
- No prominent ring in gas, but yet no-gas-gap model does not fit the observations

Isella et al. 2016

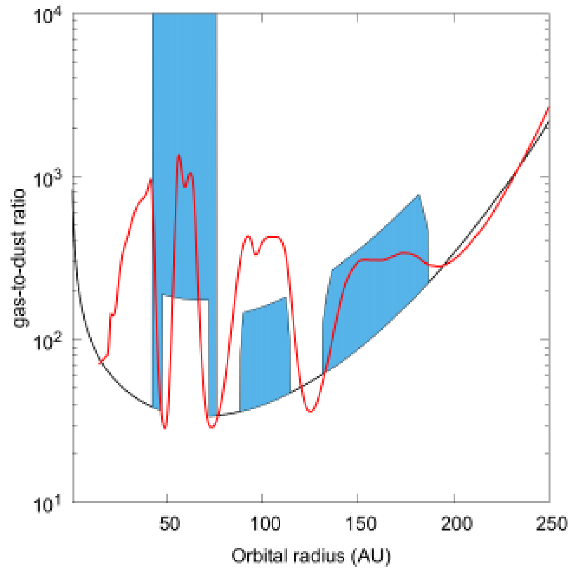
G/D Ratio Estimates Based on Simple Modeling



dust distribution



gas distribution

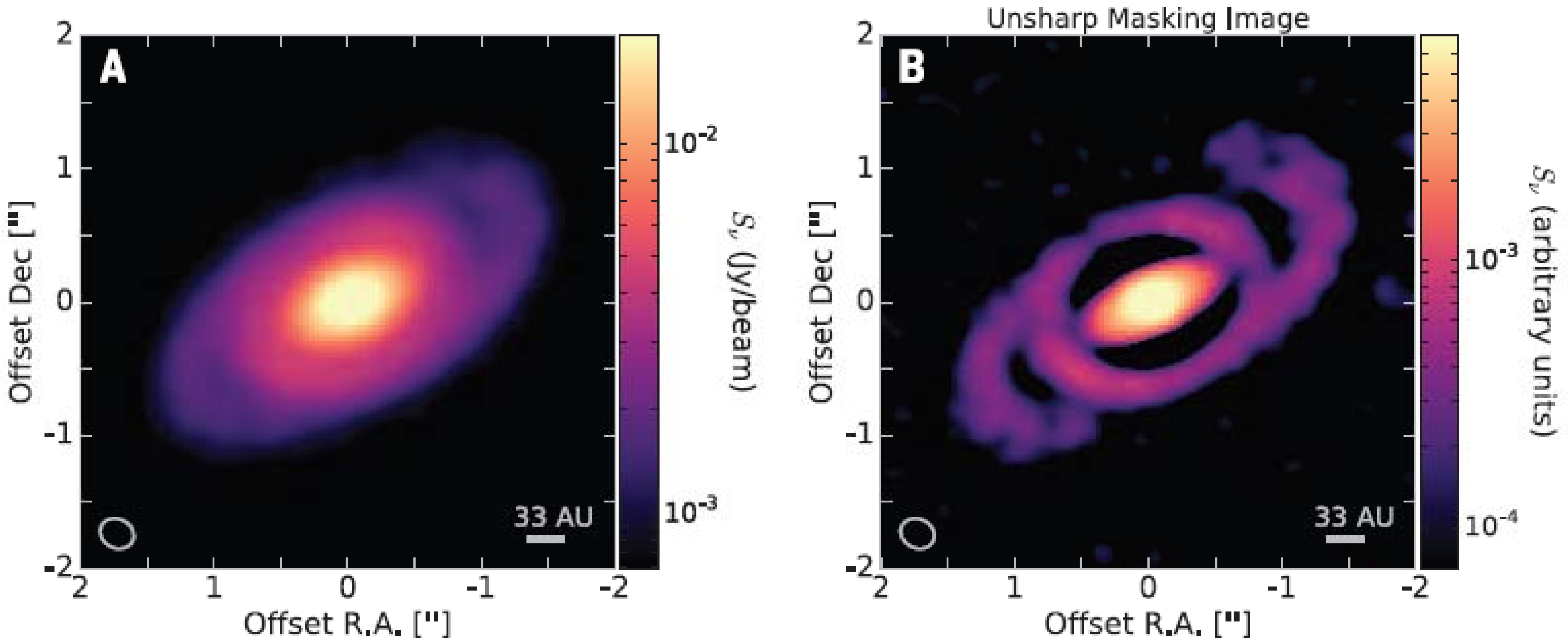


g/d ratio

- Both dust and gas gaps are necessary
- G/D ratio is not constant over the disk

Isella et al. 2016

Spiral in Elias 2-27



- Spiral-like structures in a young massive disk

Perez et al. 2016

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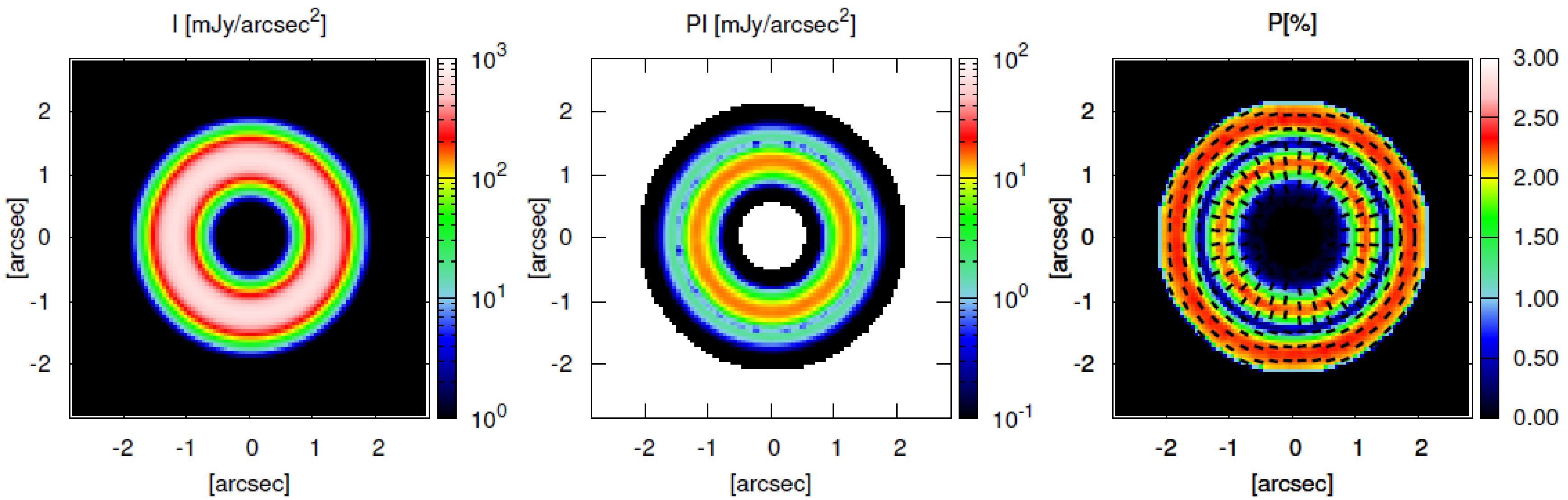
Polarization

- New features in ALMA
- Can be used to observe:
  - Magnetic field structures
  - Dust size when ring-like structures are present

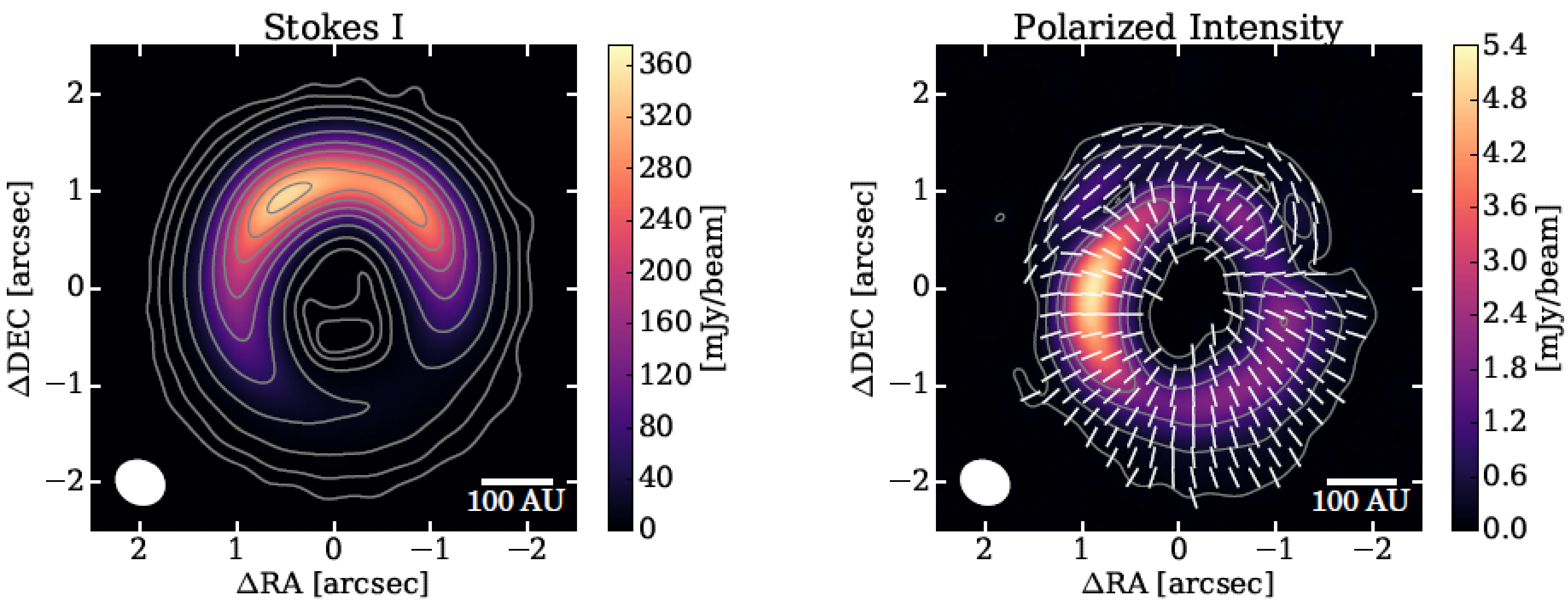
Dust Self-Scattering

- Dust thermal radiation scattered by dust particles
- Requires:
  - Ring-like structure and/or inclination
  - Dust particles with appropriate size
  - Relatively large amount of dust (optical depth ~ 1)
- Polarization can be a measure of dust grain size



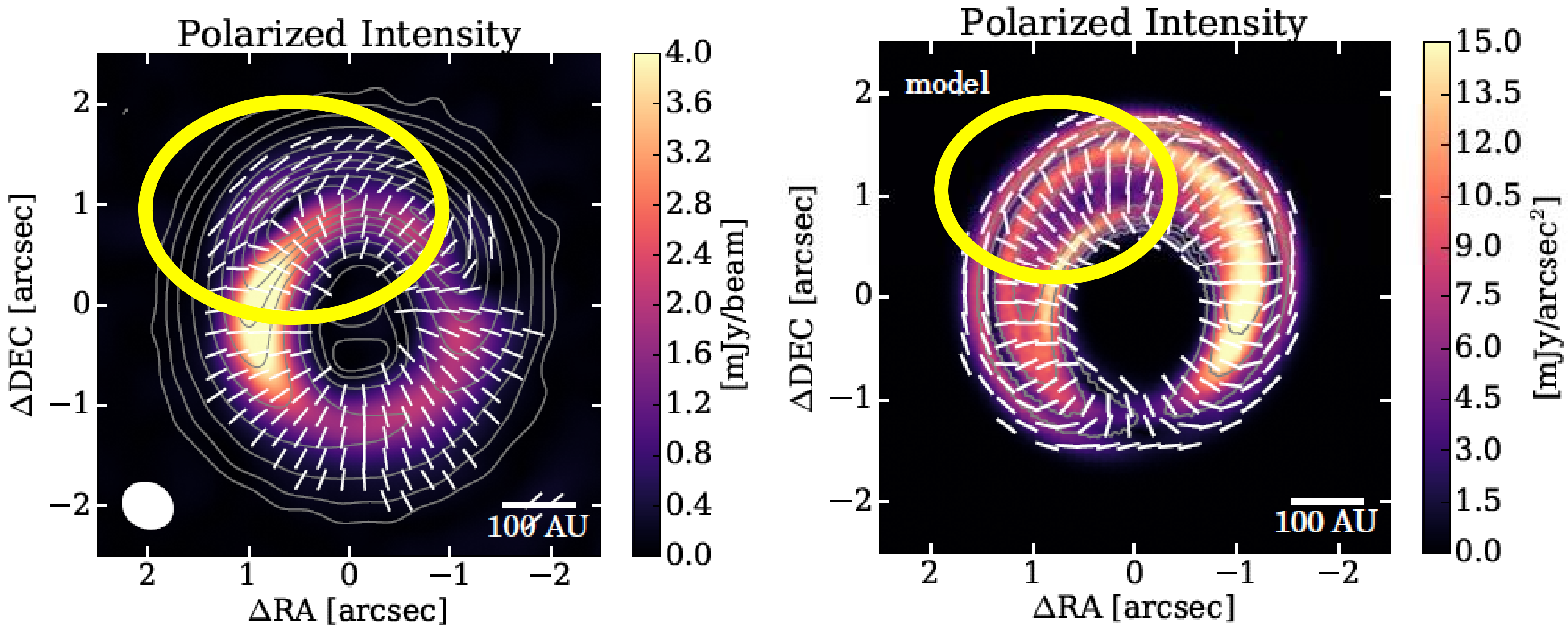
Kataoka et al. 2015

Polarization Image of HD 142527



Kataoka et al. 2016

Polarization Flip



- Polarization flip occurs
  - when a ring-like dust distribution is present
  - when dust size is appropiate (150 um in this case)

Kataoka et al. 2016

Summary and Outlook

- ALMA is revealing (and will reveal) the nature of protoplanetary disks with great details
  - Survey is indicating gas-to-dust ratio is different from that of ISM
  - High resolution observations are revealing ring and spiral like structures both in gas and dust
  - Polarization observations may constrain the state of grain growth
- New ideas of interpreting the data?
- How do we integrate the data to construct a planet formation scenario BASED ON OBSERVATIONS?