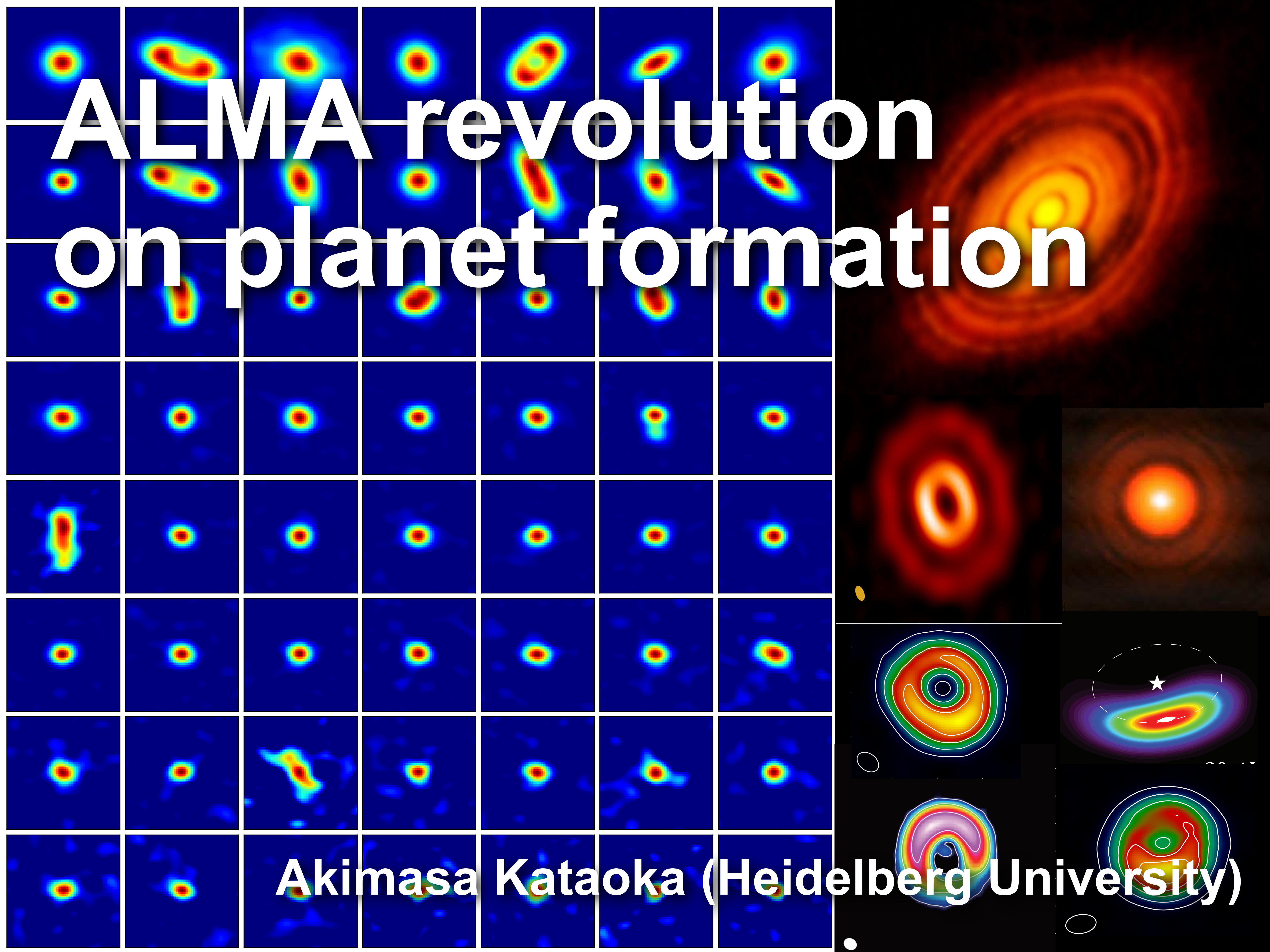
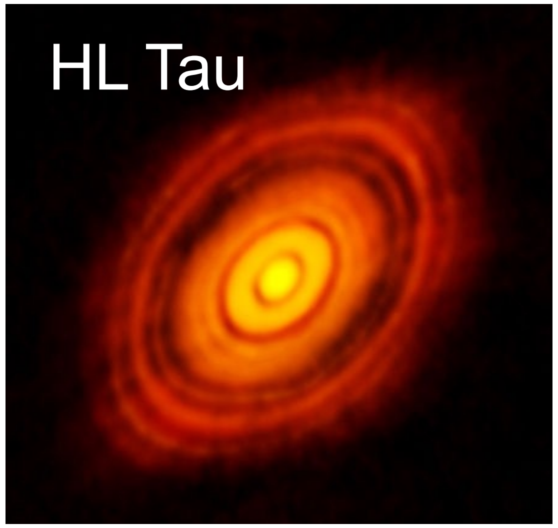
ALMA revolution on planet formation



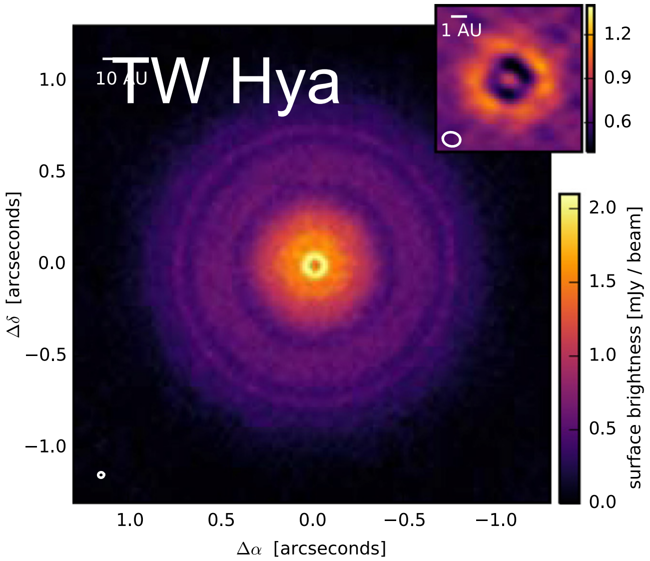
Akimasa Kataoka (Heidelberg University)

ALMA revolution

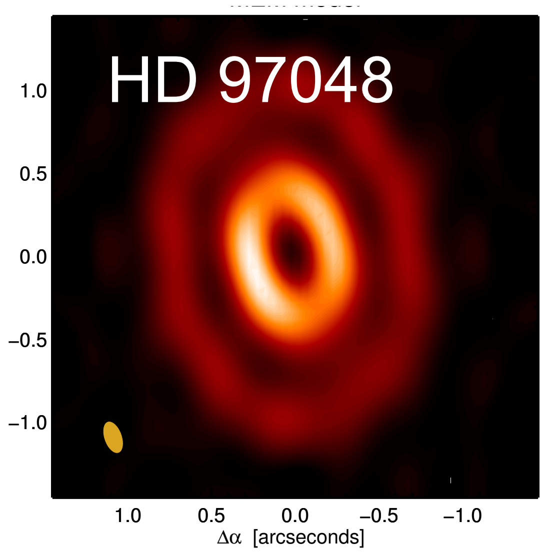
- High resolution studies - HL Tau, TW Hya, HD 97048



ALMA Partnership 2015

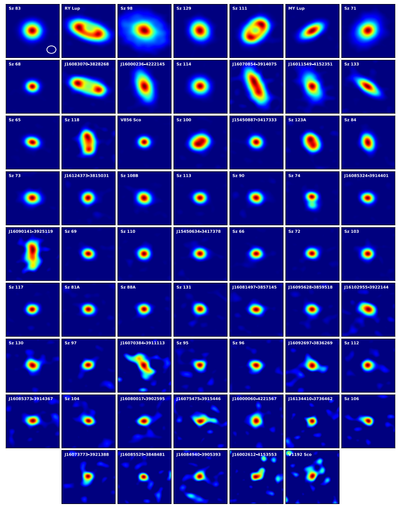


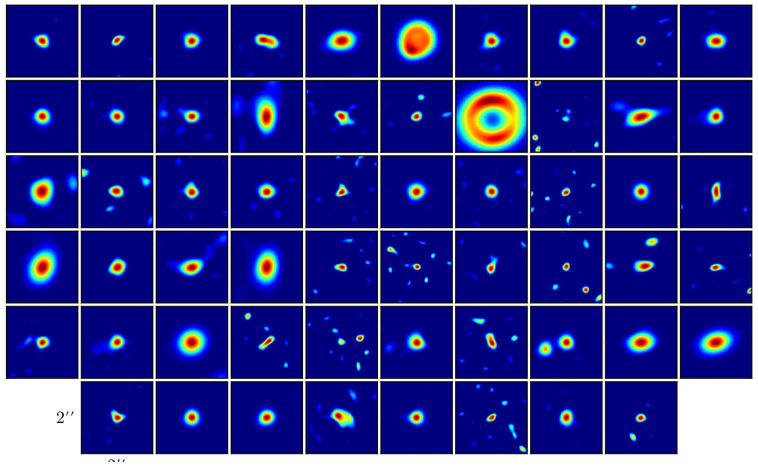
Andrews et al. 2016

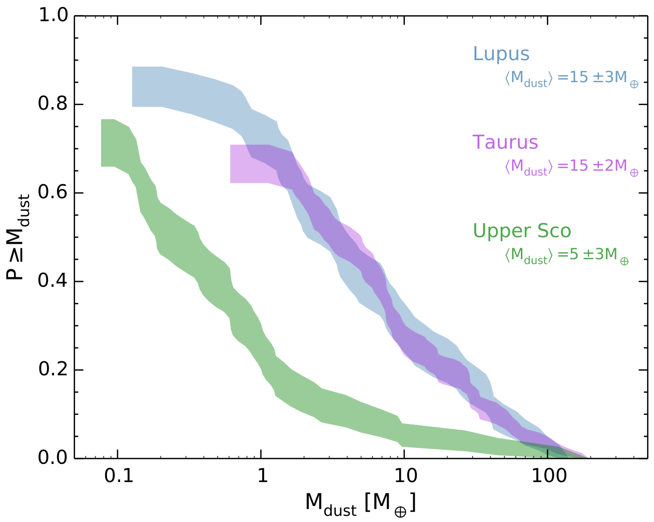


van der Plas et al. 2016

- Surveys on Upper Sco, Lupus, and Chameleon



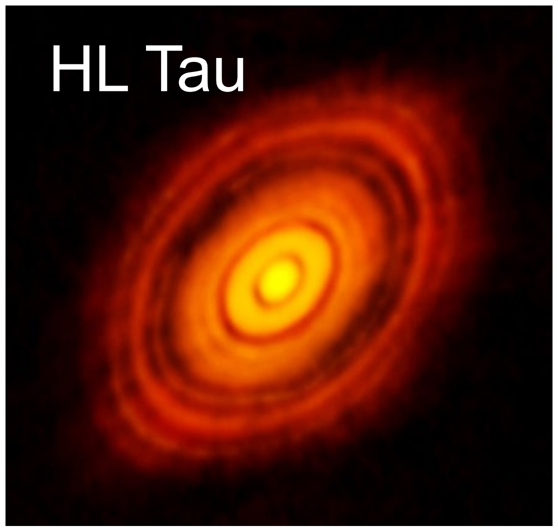




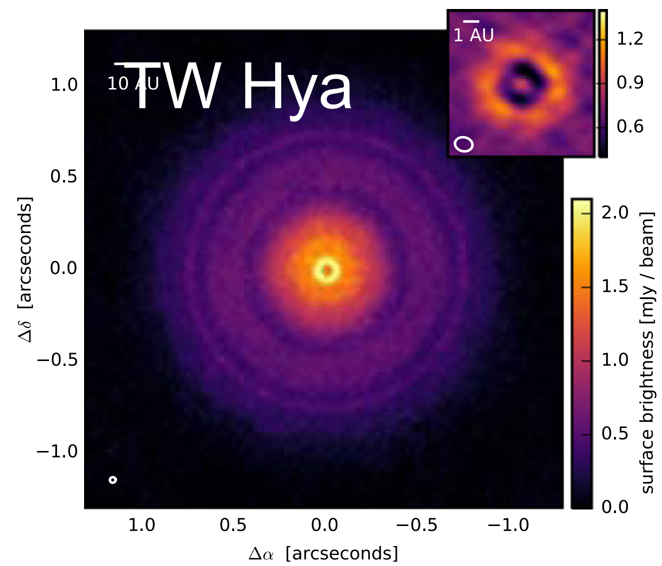
Barenfeld, et al. 2016, Andsell et al. 2016, Pascucci et al. 2016

- ALMA Polarization

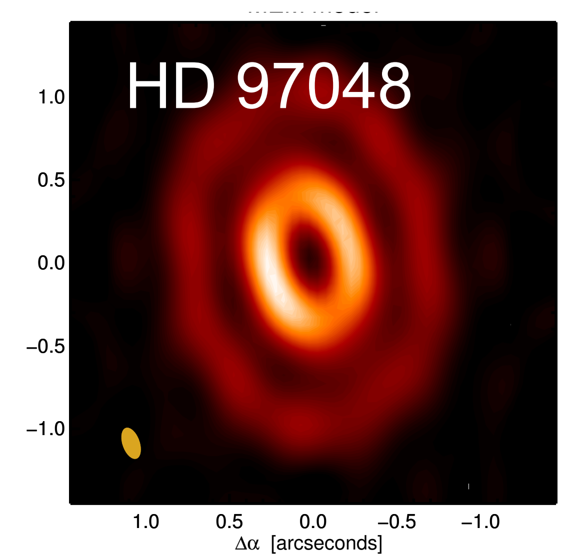
High resolution studies



ALMA Partnership 2015



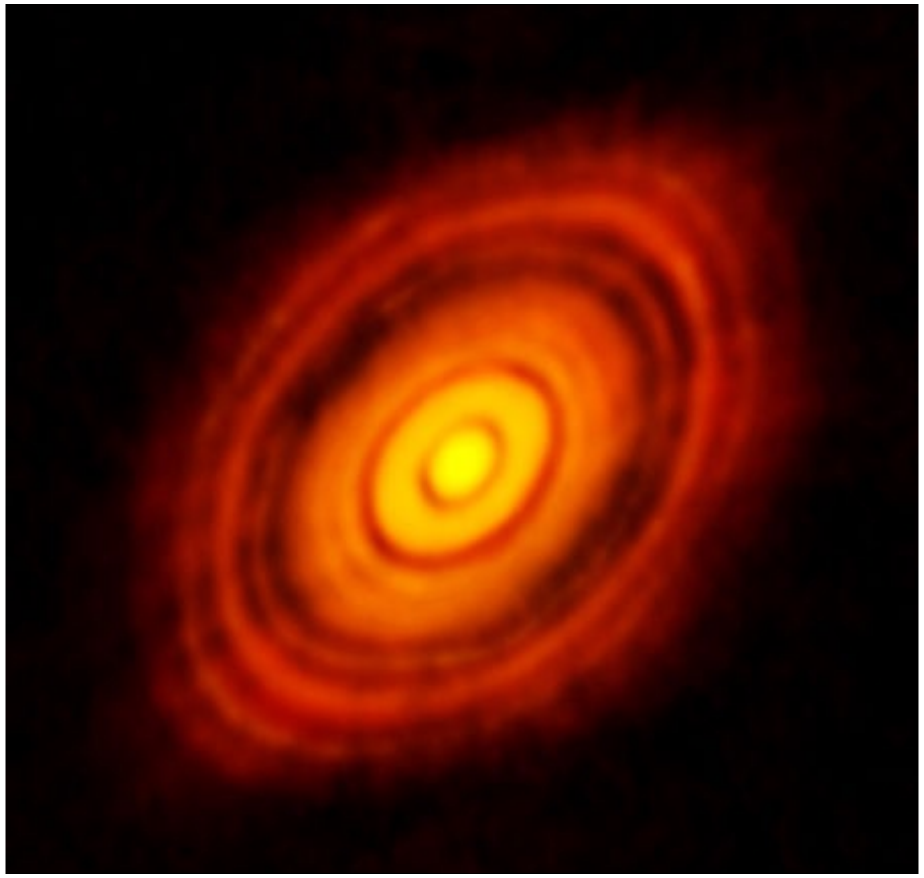
Andrews et al. 2016



van der Plas et al. 2016

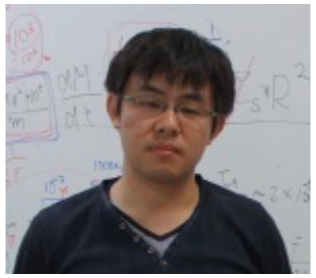
- Rings are common in dust:
    - Dust rings appear for any stages (HL Tau: <1-2 Myr, HD 97048: 3 Myr, TW Hya: 10 Myr)
    - Are there gaps also in gas?
    - Grain growth at rings/gaps?
    - Comparison with IR images?

Ring formation mechanisms



ALMA Partnership 2015

- Planet-inducing gaps (e.g., Kanagawa et al. 2015, see his talk)



- Enhanced growth at snowlines (Zhang et al. 2015)

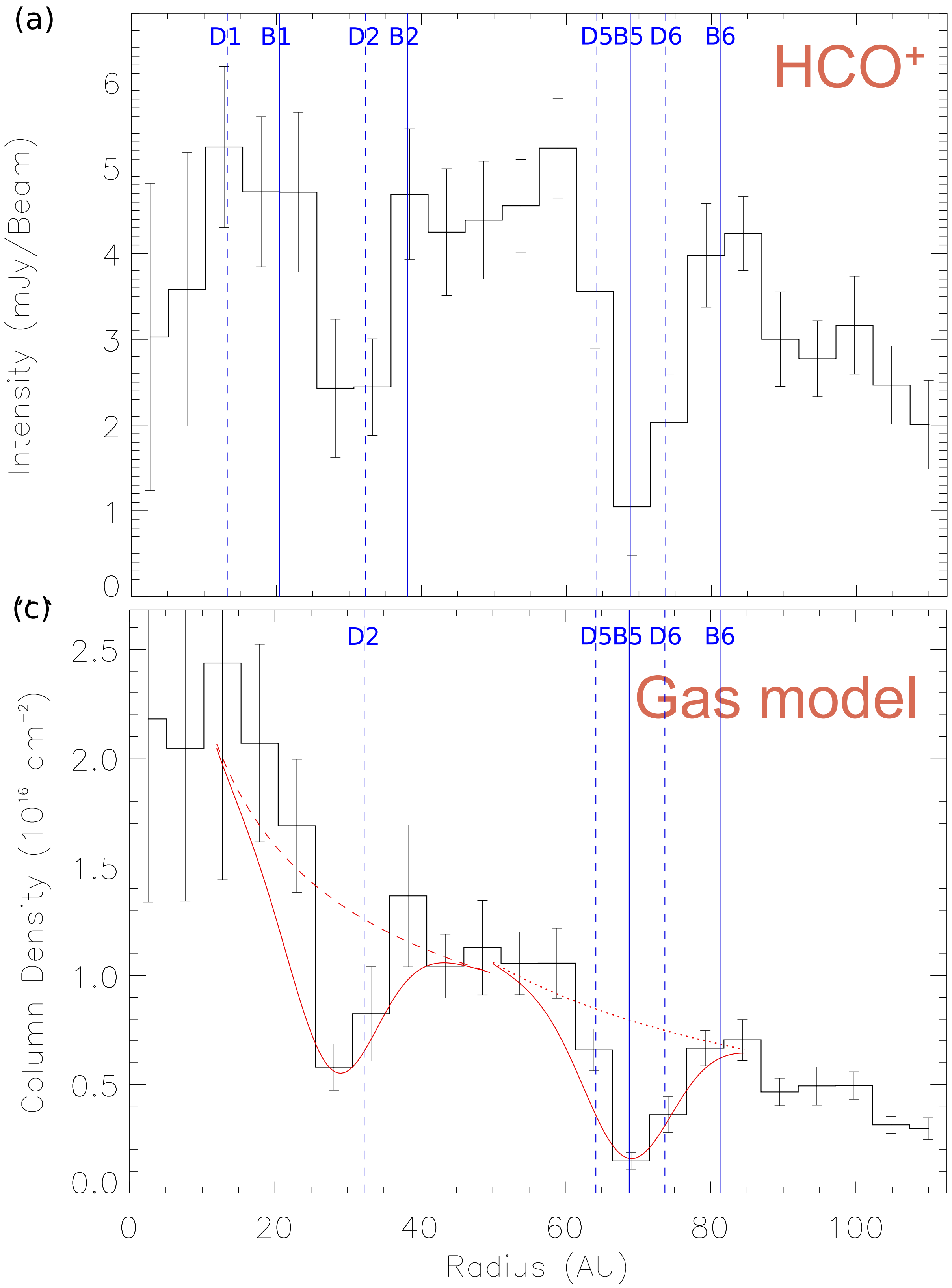
- Sintering-induced fragmentation of dust grains at snowlines (Okuzumi et al. 2016, see his talk)

- MHD instabilities (e.g., Flock et al. 2015, see talk by H. Klahr)

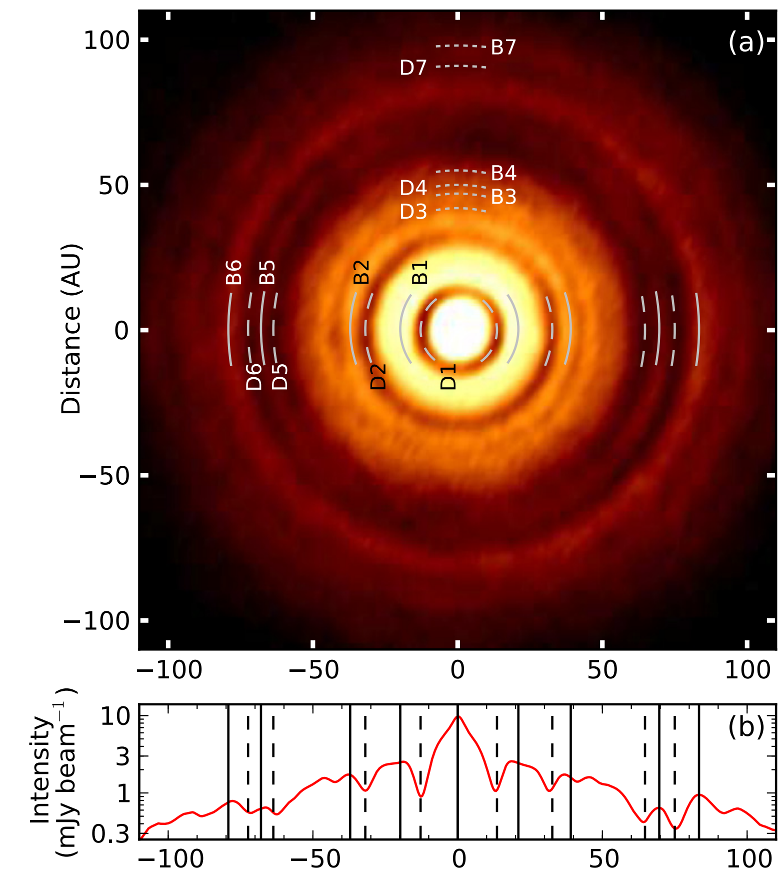
- Secular gravitational instability (Takahashi and Inutsuka 2014, 2016, see his talk)

Gas gaps?

HL Tau



ALMA Partnership 2015

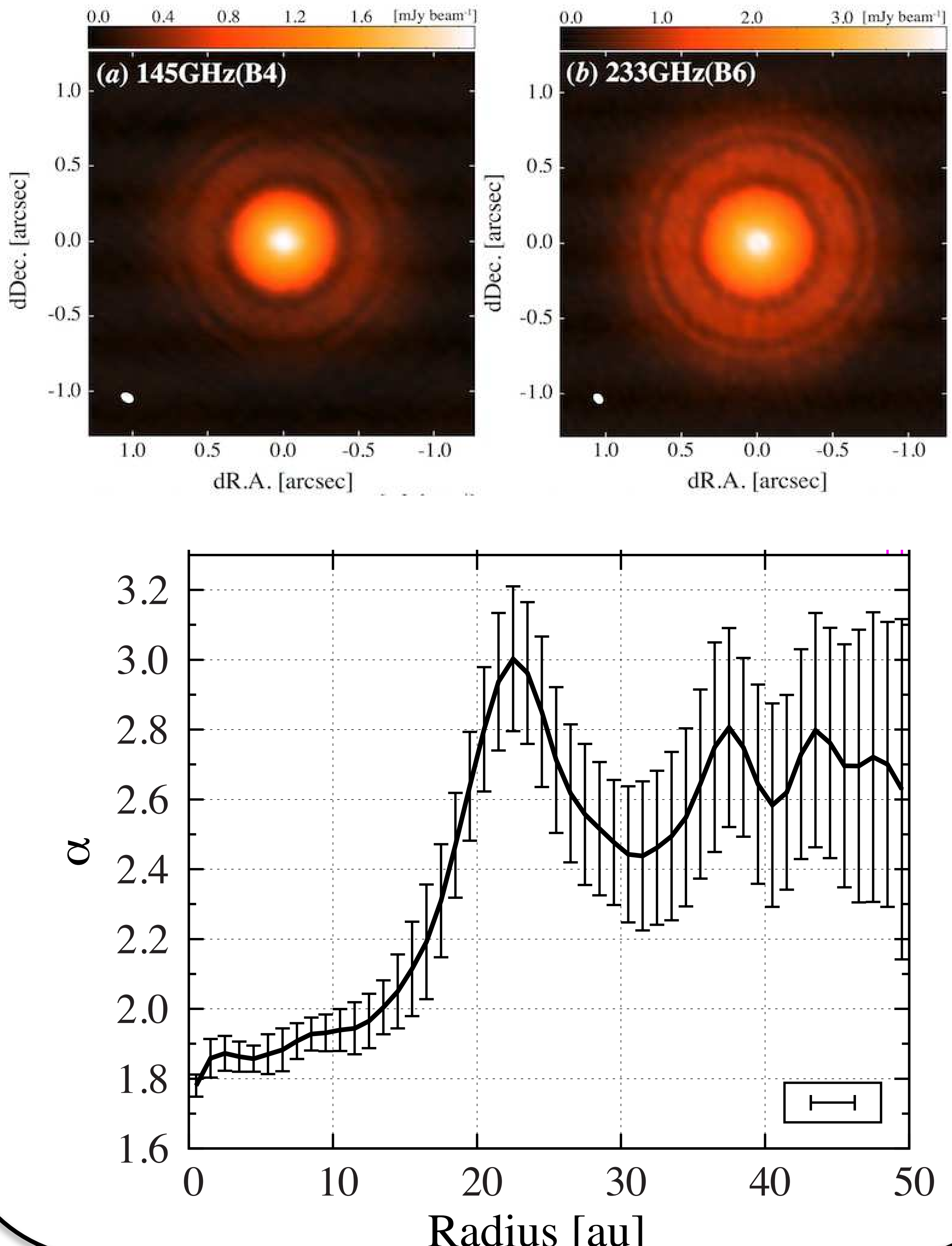


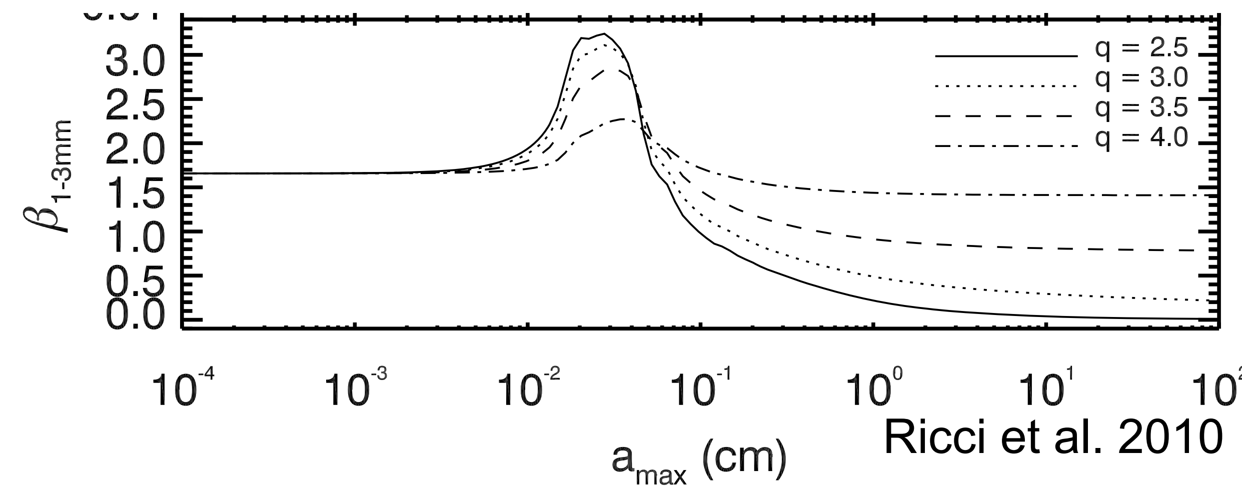
- Correlation between the dust and gas gaps
  - Is HCO^+ really trace the gas?
  - Is there too much continuum subtraction?

Hsi-Wei Yen et al., 2016

Grain size variation in gaps

TW Hya observed with ALMA





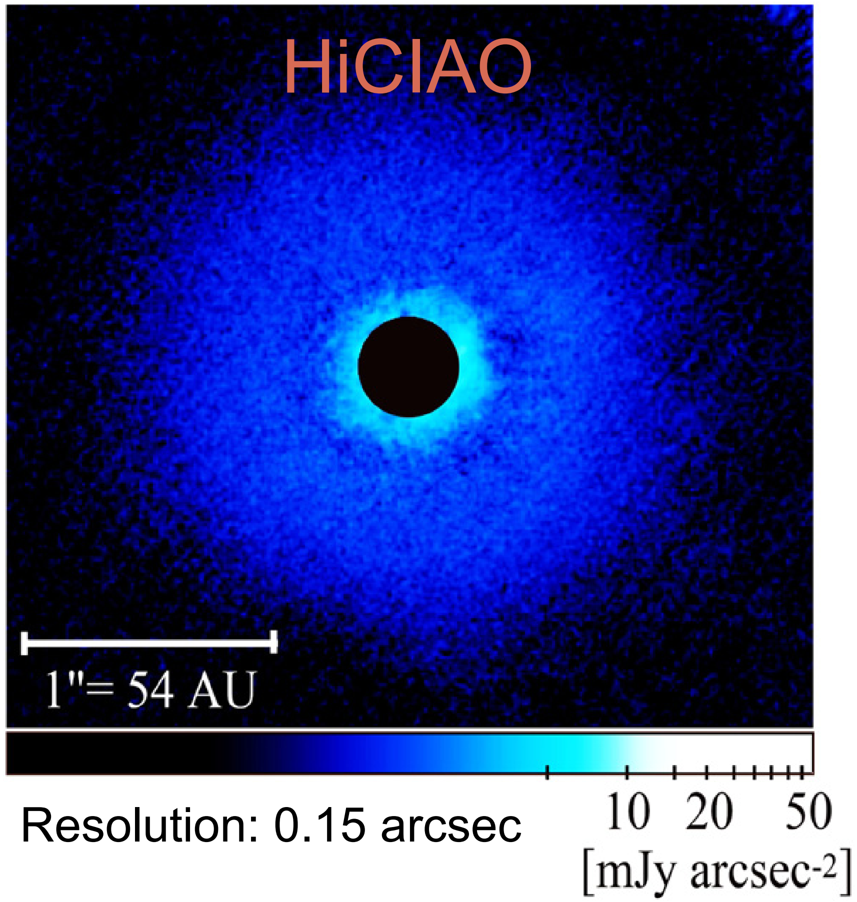
Ricci et al. 2010

- Two-band, high resolution observation
- Spectral index is low at dust gaps : grain size is smaller at the gaps.

Tsukagoshi, Nomura, Muto et al., 2016

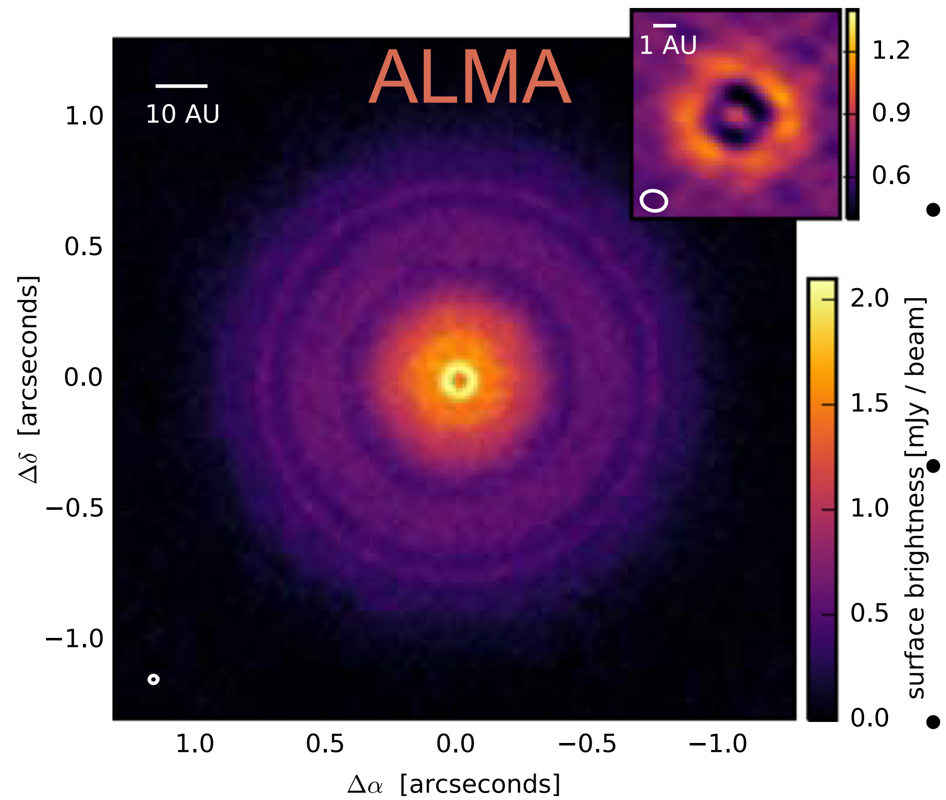
See also Nomura et al. 2016, Andrews et al. 2016

Comparison with IR obs.



Resolution: 0.15 arcsec

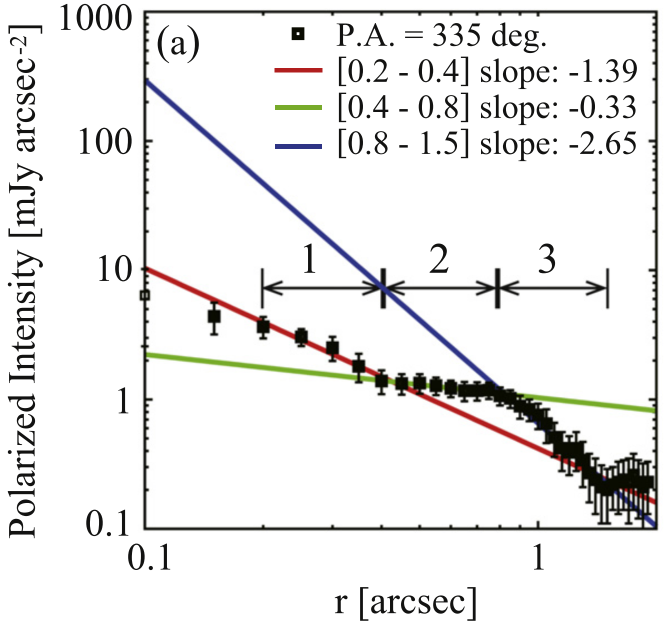
Akiyama et al. 2015

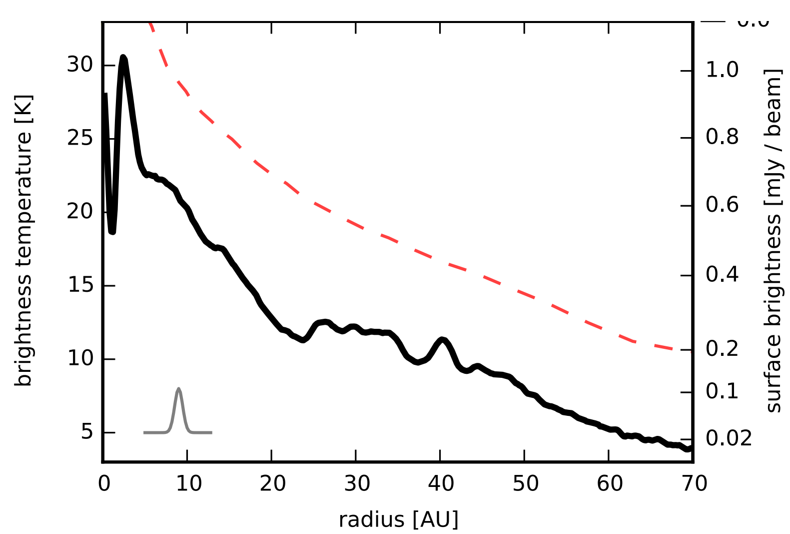


Resolution: 0.03 arcsec

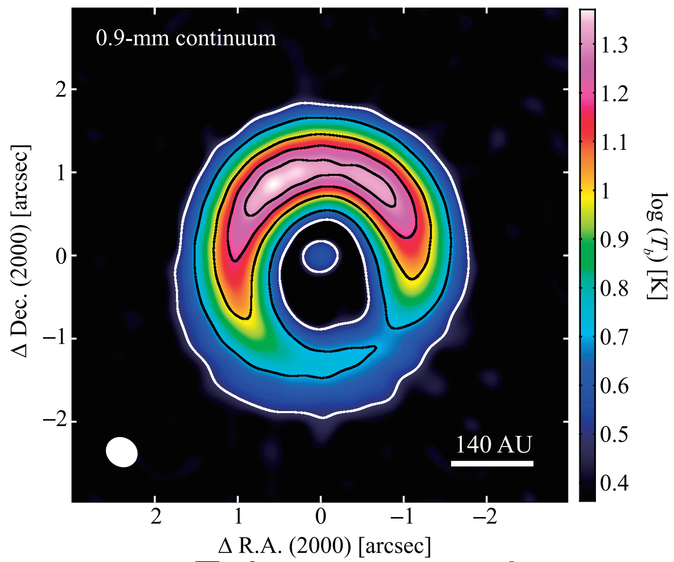
Andrews et al. 2016

- IR traces the surface layer
- Is there any correlation?
- (see talk about SPHERE results by Roy van Boekel)

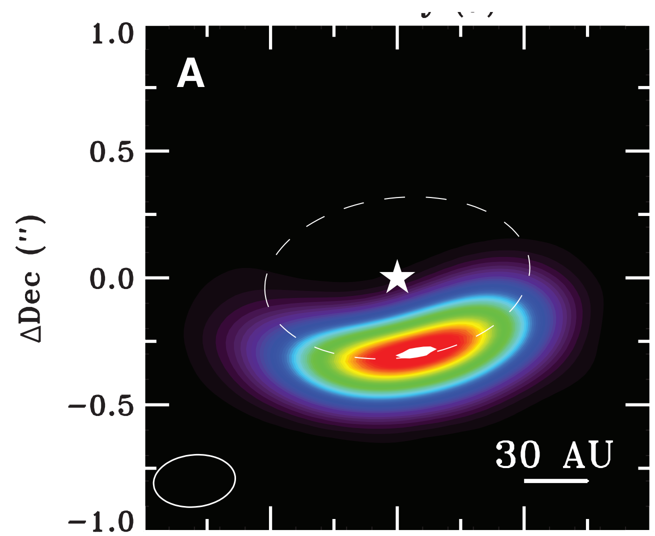




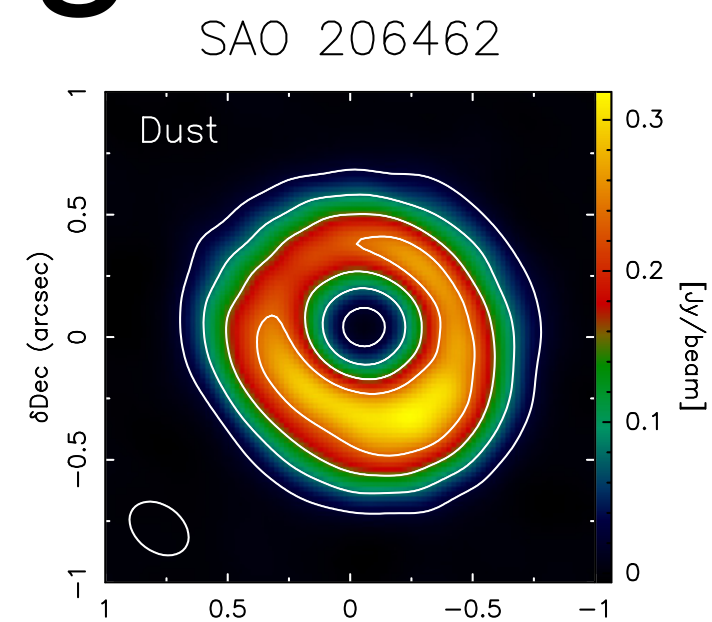
Lopsided or rings?



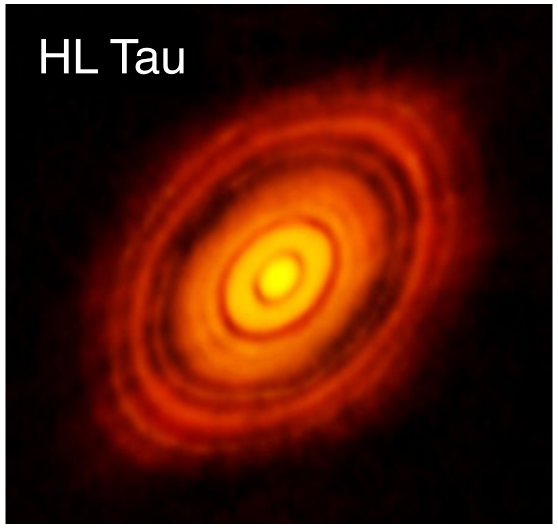
Fukagawa et al. 2013



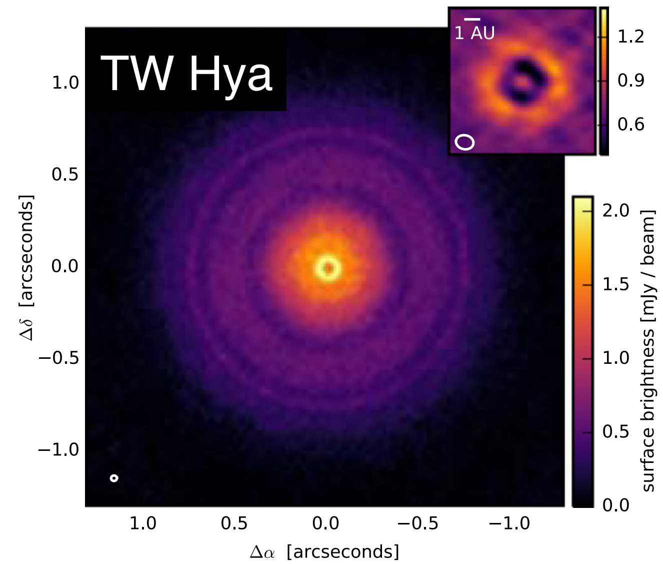
van der Marel et al. 2013



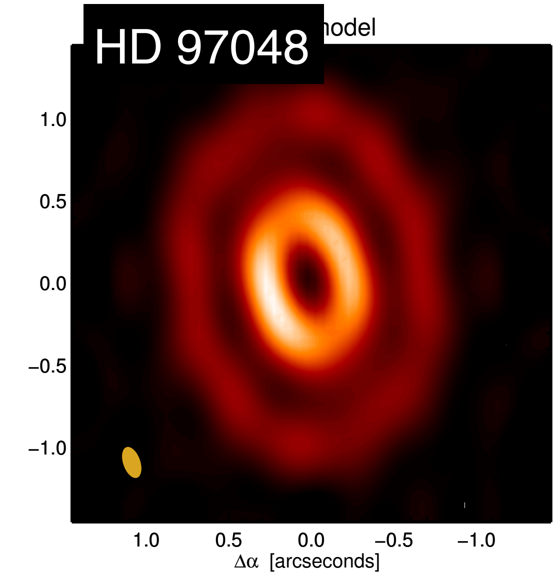
Perez et al. 2014



ALMA Partnership 2015



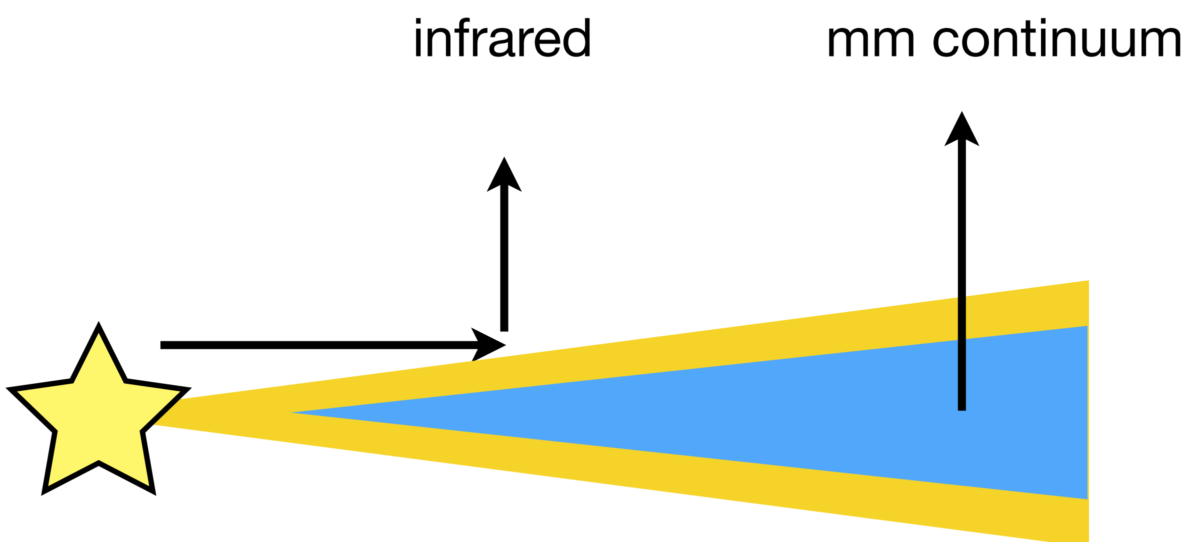
Andrews et al. 2016



van der Plas et al. 2016

- What physical mechanism does make this difference?

How to measure dust and gas mass?

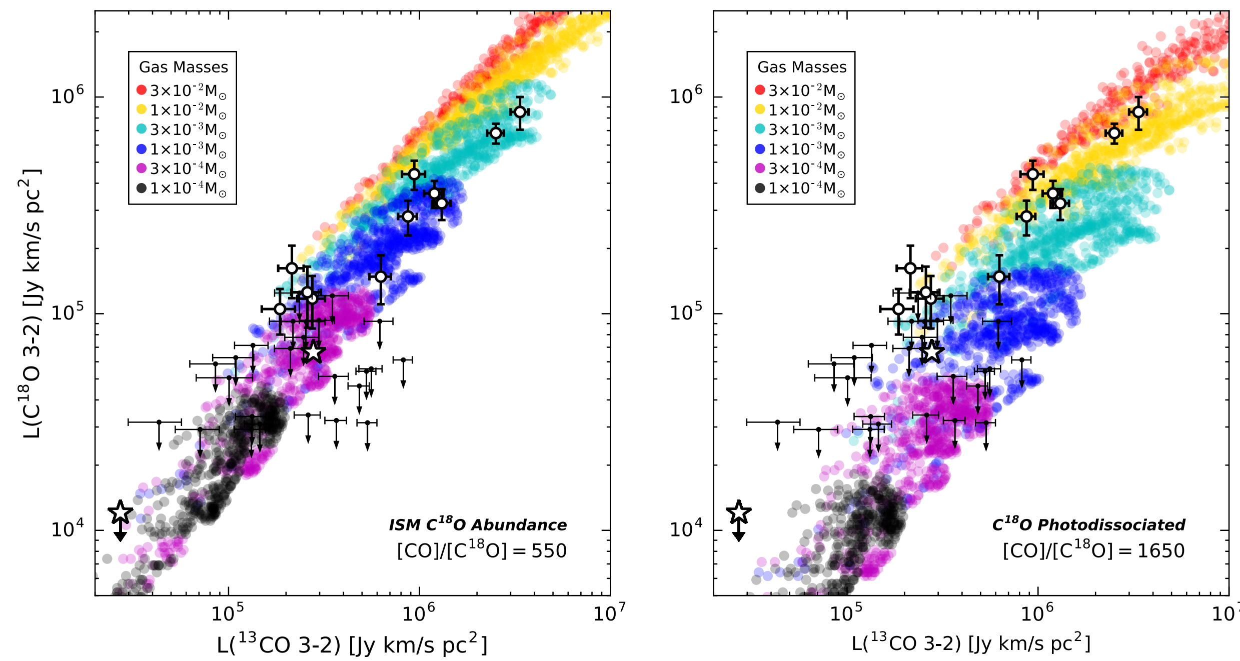


Dust mass

$$M_{\rm dust} = \frac{F_\nu d^2}{\kappa_\nu B_\nu(T_{\rm dust})}$$

- Flux (observed value)
- distance (fixed)
- Opacity (taken single value)
- Temperature (assumed to be isothermal or related to L_*)

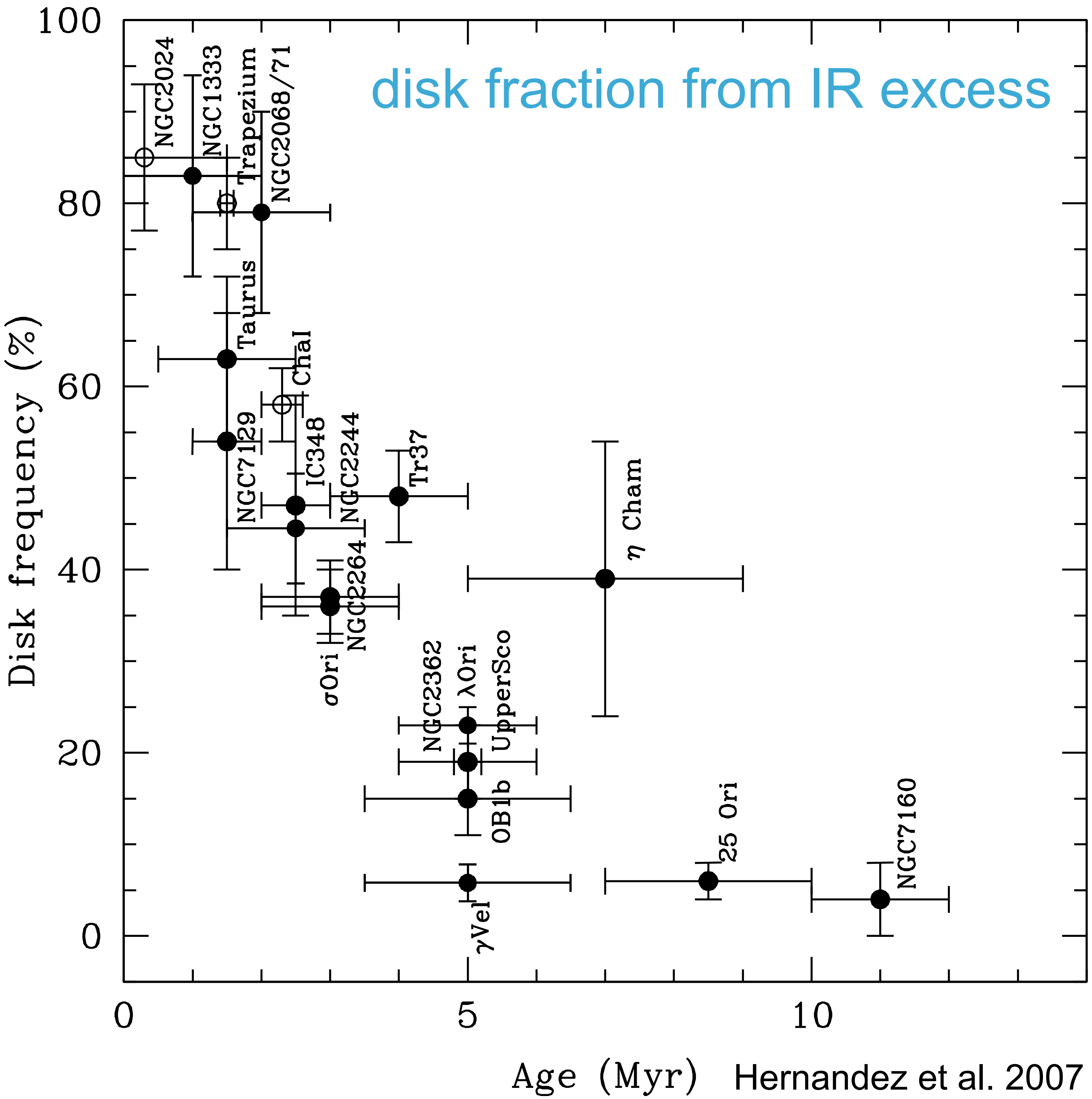
Gas mass



Williams and Best 2014, Ansdell et al. 2016

- If we can measure H_2, of course that's the best…
- CO is used as a tracer of the gas
- conversion: a factor of 3 lower than ISM.

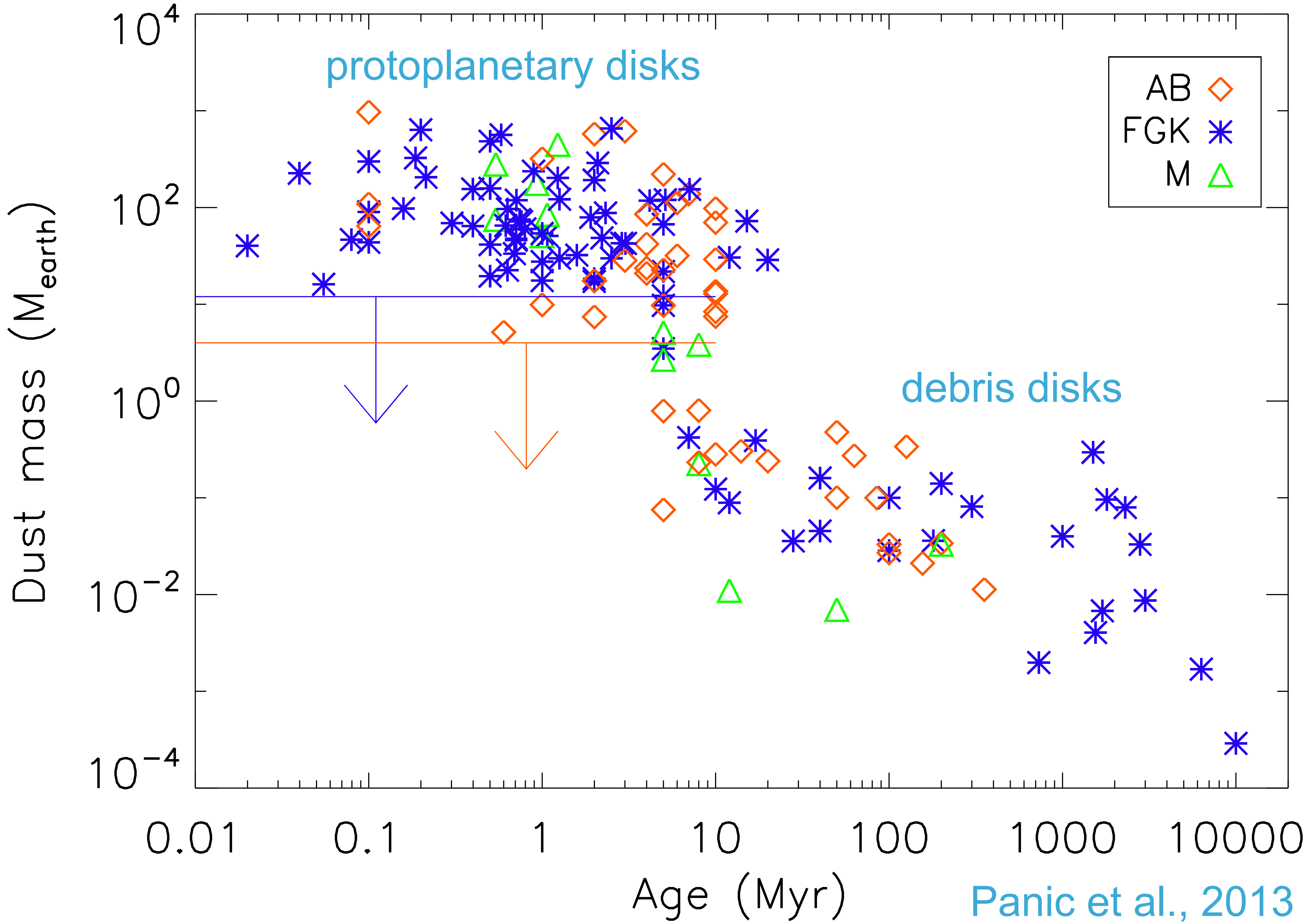
Disk surveys



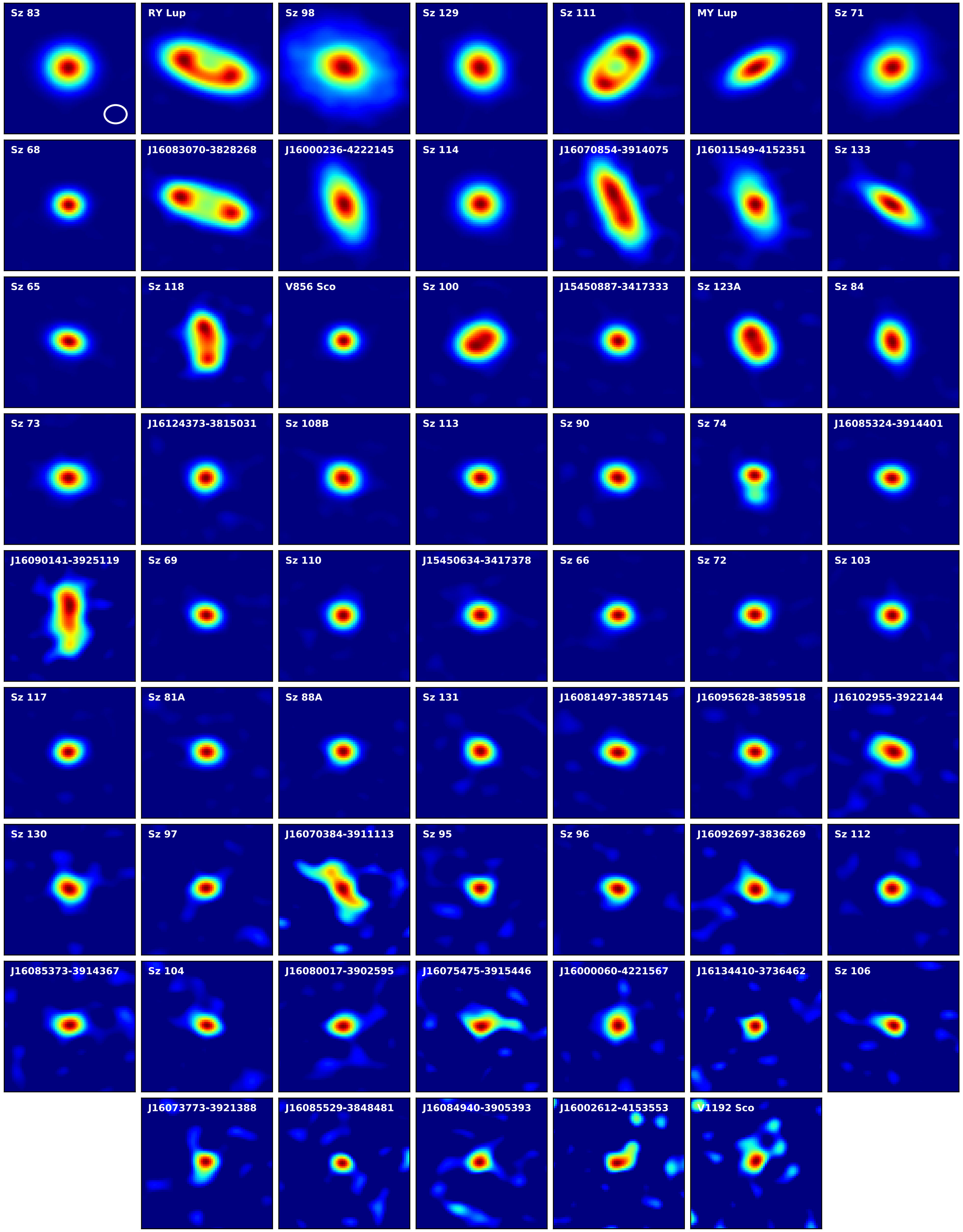
Hernandez et al. 2007

- Today's talk is based on the results of
  - Taurus (1-3Myr, SMA survey) by Andrews et al. 2013
  - Lupus (1-2 Myr) by Ansdell et al. 2016
  - Chameleon (2 Myr) by Pascucci et al. 2016
  - Upper Sco (5-11 Myr) by Barenfeld et al. 2016

Time evolution of dust mass



Panic et al., 2013

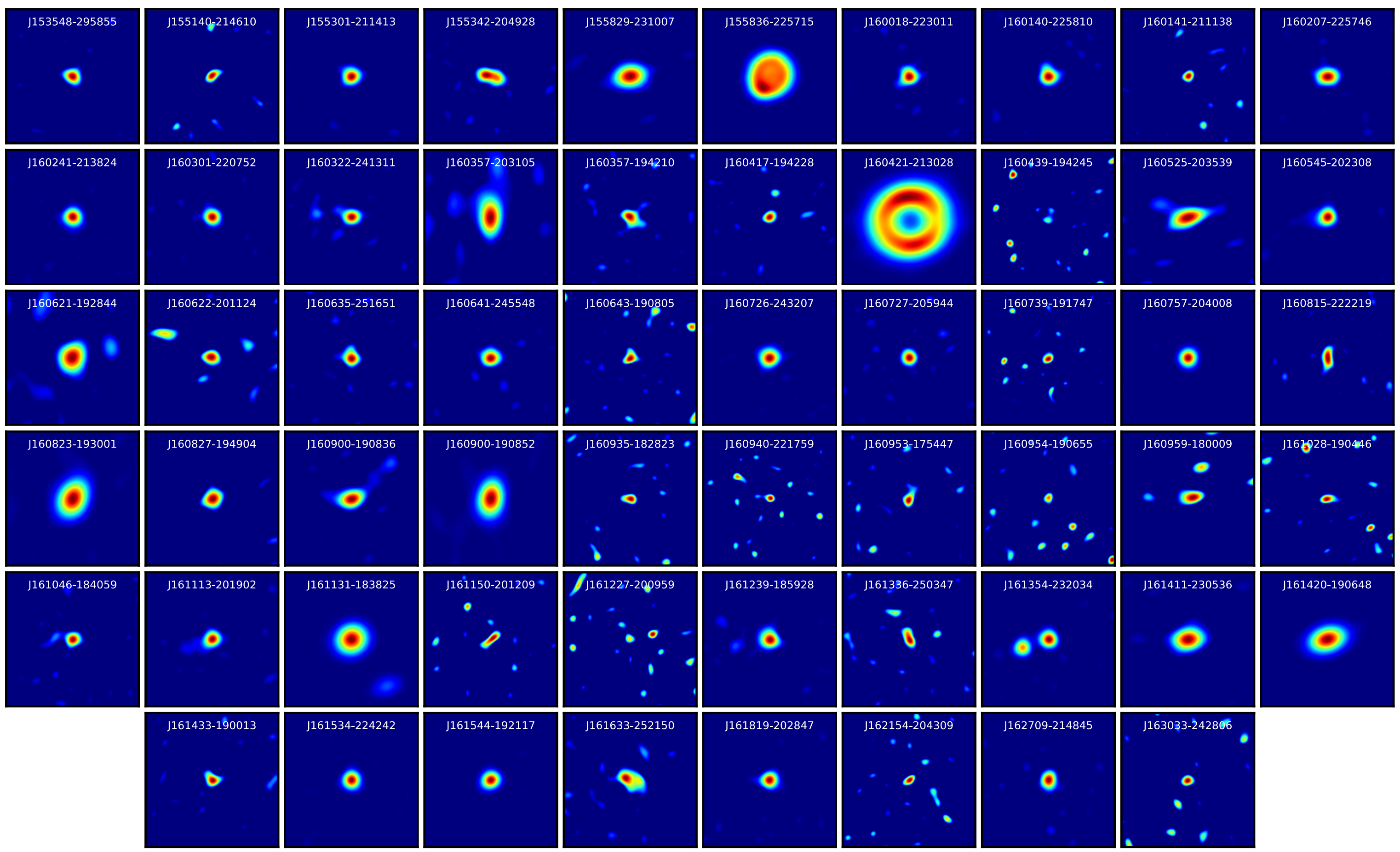


Lupus survey

- 89 disks observed (96% complete)
- 62 continuum detections
- 35 ^{13}CO detections
- 11 $C^{18}O$ detections
- 0.3" beam (50 AU)
- 0.3 Mearth of dust

Ansdell et al., 2016

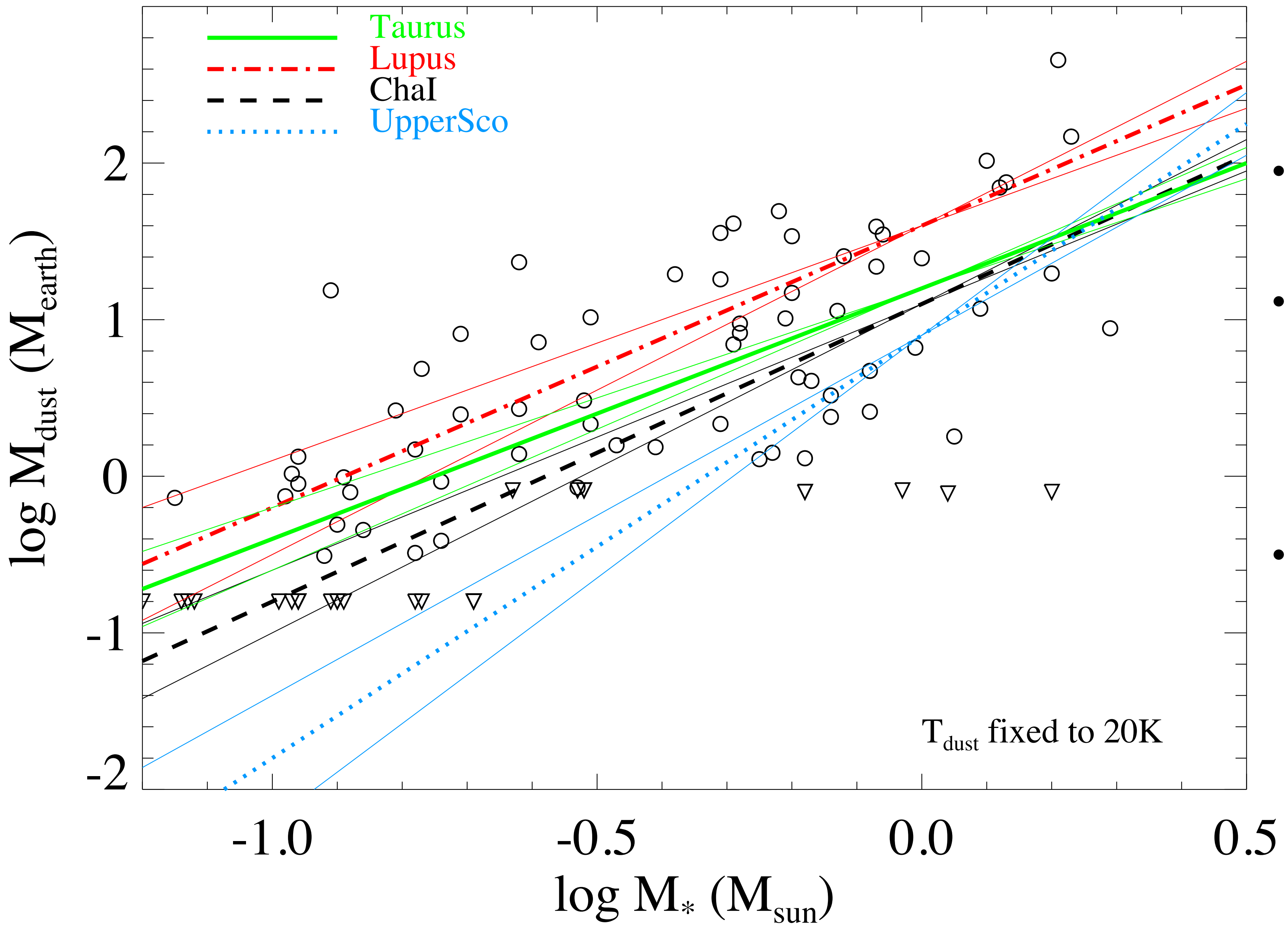
Survey of Upper Sco



Barenfeld et al., 2016

- 106 disks observed
- continuum detections
  - 53 of 75 primordial disks
  - 5 of 31 debris/evolved disks
- ^{12}CO detections
  - 26 of 76 primordial disks
  - 0 of 31 debris/evolved disks
- 0.34" beam (50 AU)
- 0.1 Mearth of dust

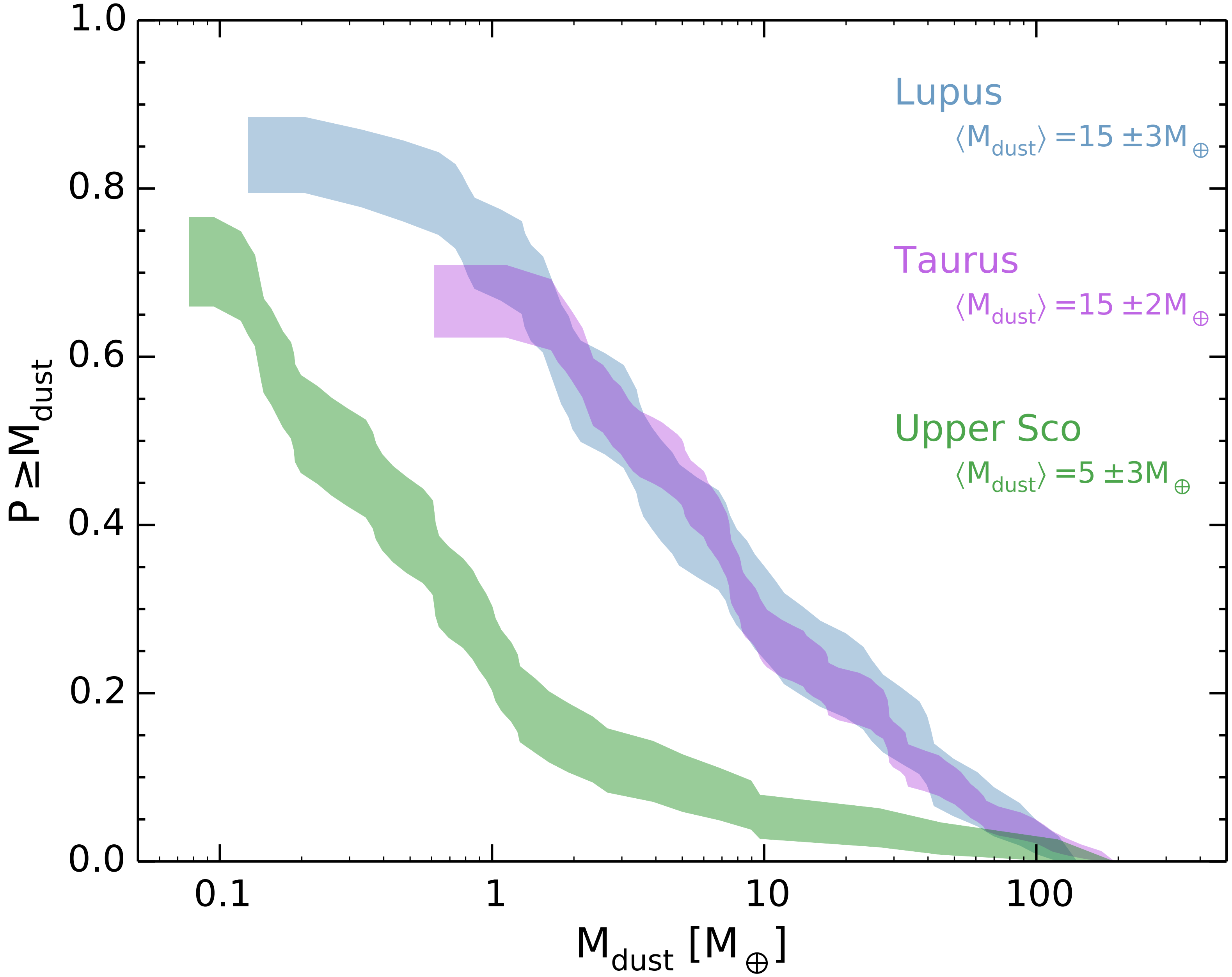
Stellar mass - dust mass relation



- Mdust ∝ $M_*^{1.3-1.9}$
- Taurus, Lupus, and Chamaeleon I (1-3 Myr) share the same relation
- Upper Sco (5-11 Myr) has steeper relation

Pascucci et al., 2016

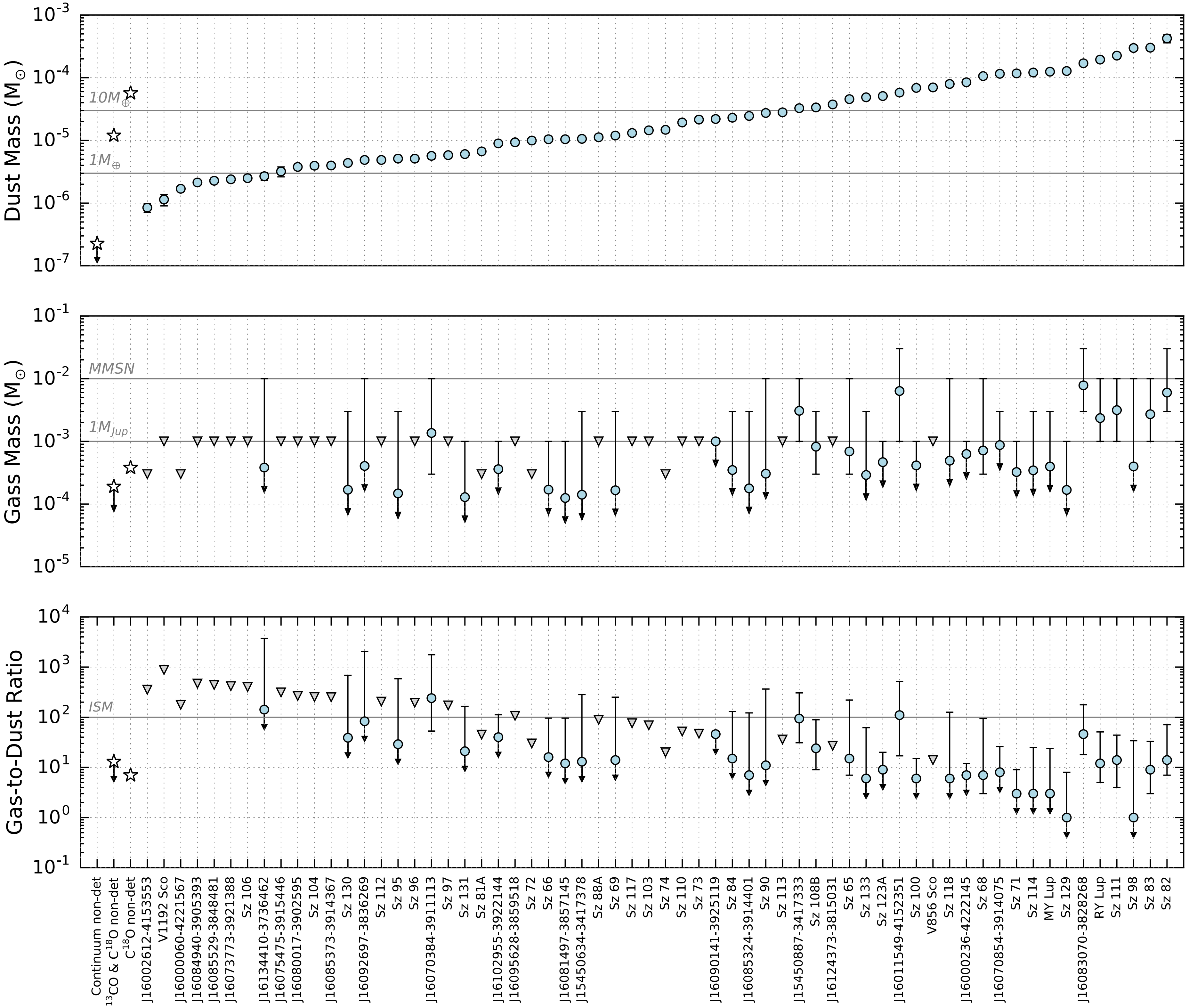
Dust mass of disks



- Lupus and Taurus (1-3 Myr) share the same dust mass range
- Lupus and Taurus (15 M_{earth}) has 3× higher mass than Upper Sco (5 M_{earth}, 5-11 Myr)

Gas-to-dust ratio

Lupus survey

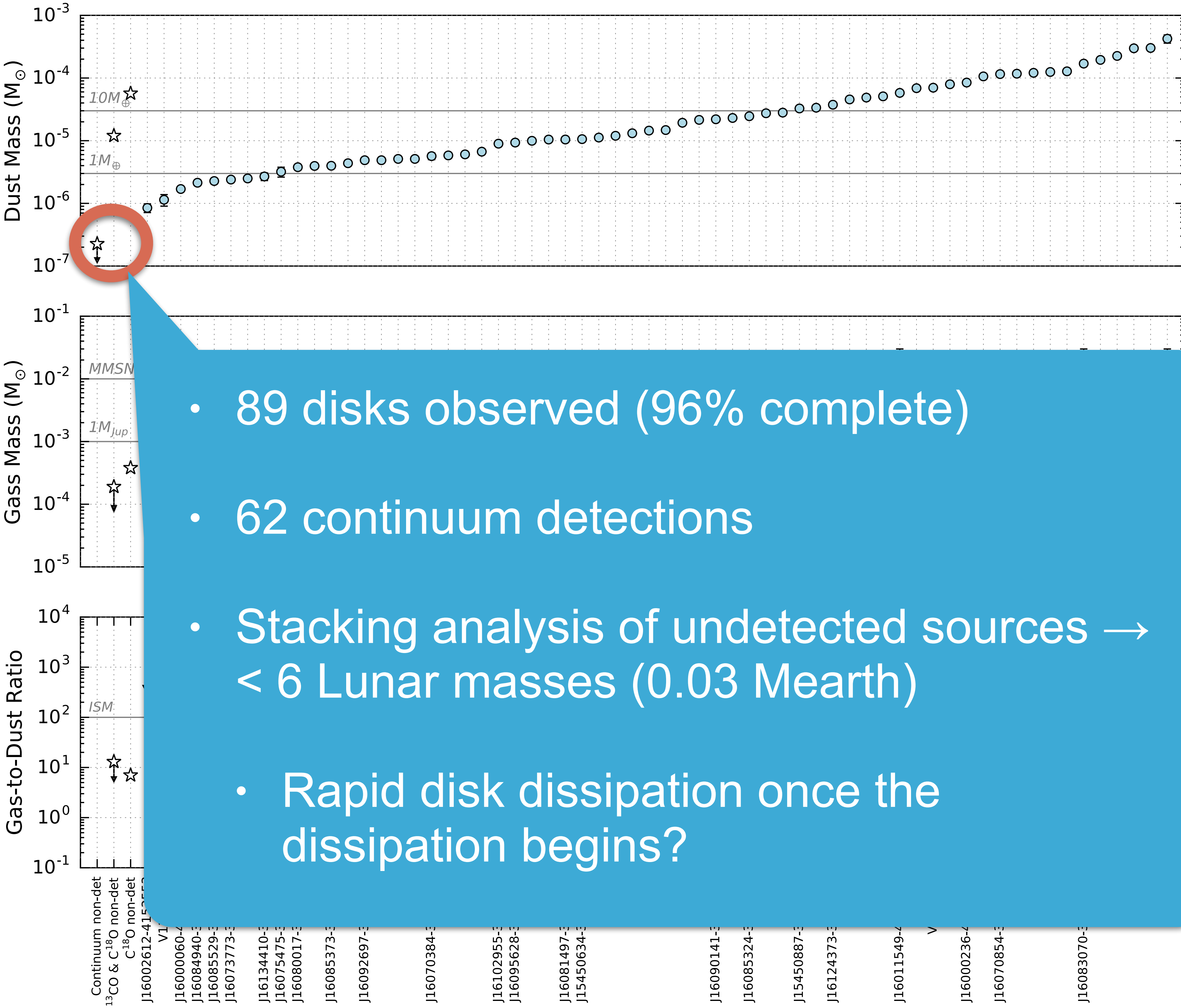


- Gas-to-dust ratio varies from 1 to 100
- Typical g/d ratio is ~10 (cf. ISM ~ 100)
- Quick gas dissipation or CO depletion?

Ansdell et al., 2016

Gas-to-dust ratio

Lupus survey



- 89 disks observed (96% complete)
- 62 continuum detections
- Stacking analysis of undetected sources → < 6 Lunar masses (0.03 Mearth)
    - Rapid disk dissipation once the dissipation begins?

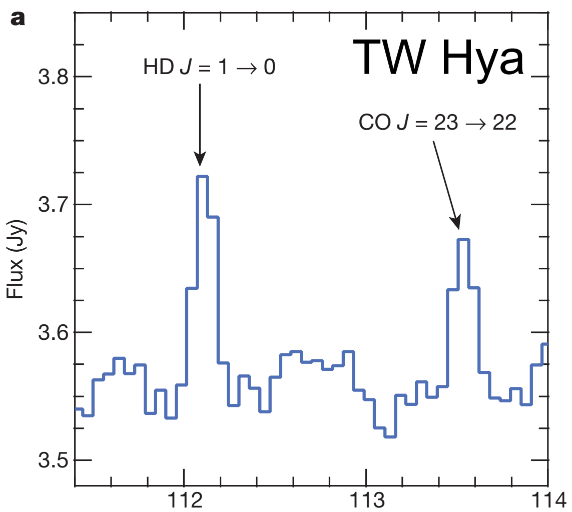
- Gas-to-dust ratio varies from 1 to 100
- Typical g/d ratio is ~10 (cf. ISM ~ 100)
- Quick gas dissipation or CO depletion?

*g/d is affected by grain growth (Tsukamoto et al. 2016) See his talk

Ansdell et al., 2016

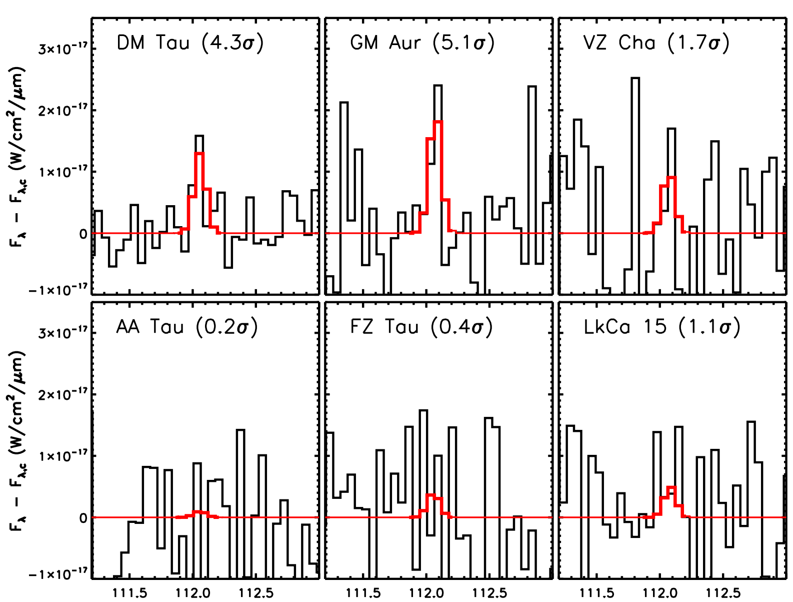
Gas mass measurement

HD line @ 112 μm
observed with Hershel



	HD measured	CO measured
TW Hya	> 5.0×10^{-2} M_{sun}	4.7×10^{-4}-6×10^{-2} M_{sun}*
DM Tau	1.0-4.7×10^{-2} M_{sun}	1.4×10^{-3} M_{sun}*
GM Aur	2.5-20.4×10^{-2} M_{sun}	< 0.35×10^{-3} M_{sun}*

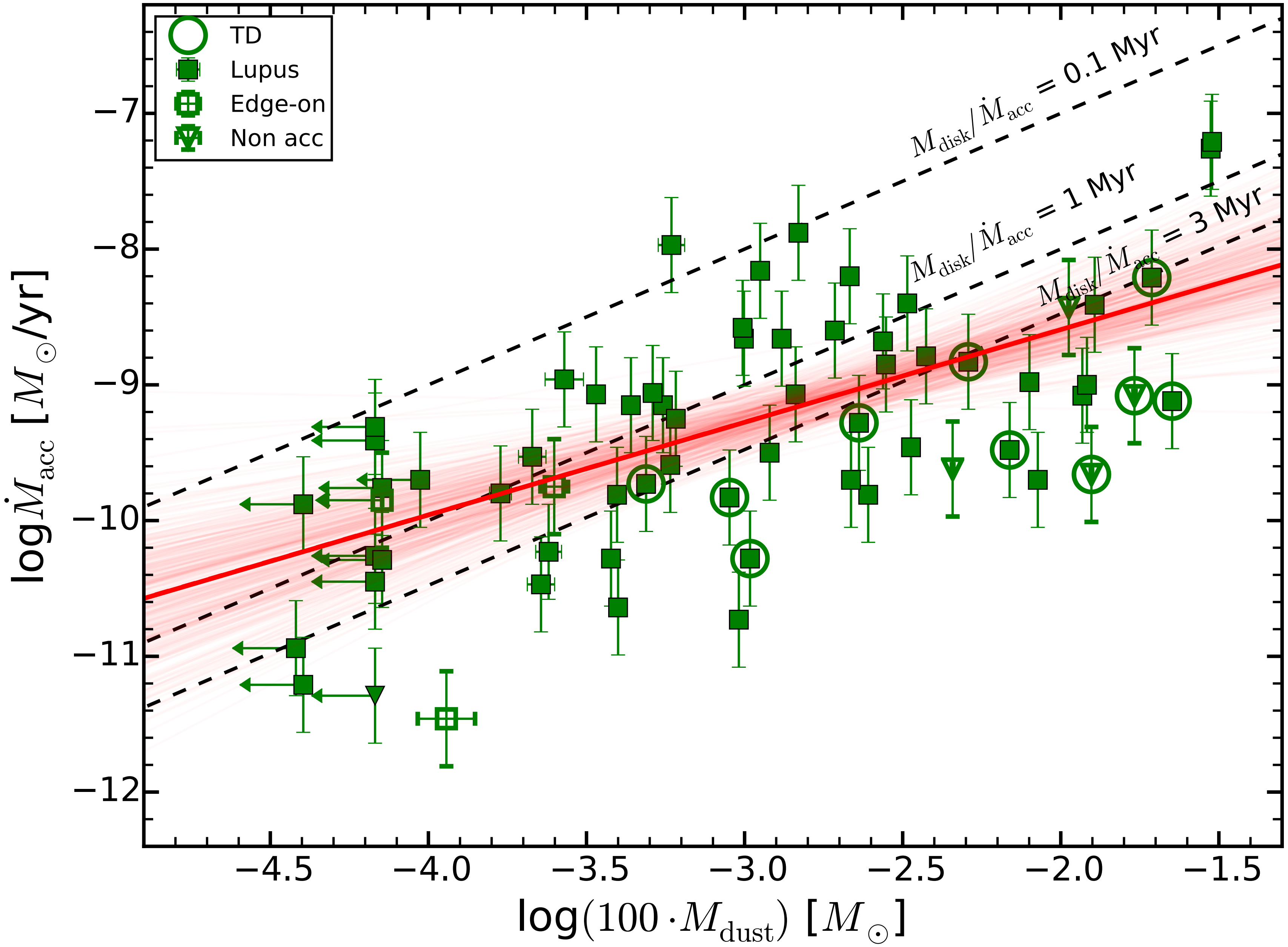
*Thi et al. 2010, Gorti et al. 2011, Dutrey et al. 1996



- HD line : good tracer of gas mass
- HD-measured gas mass > CO-measured gas mass
- CO freeze-out, photodissociation, or chemical depletion

Bergin et al. 2013, McClure et al. 2016

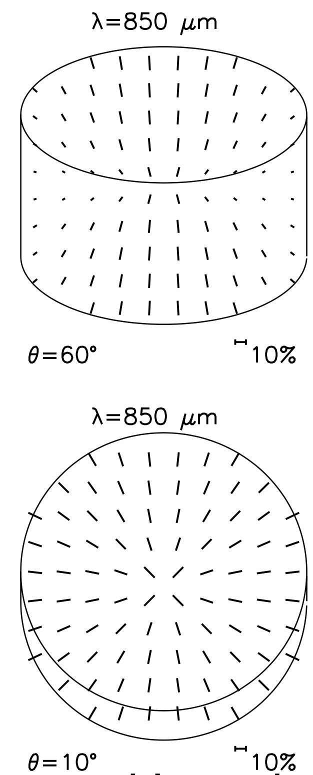
M_{acc}(X-shooter) vs. M_{dust} (ALMA)



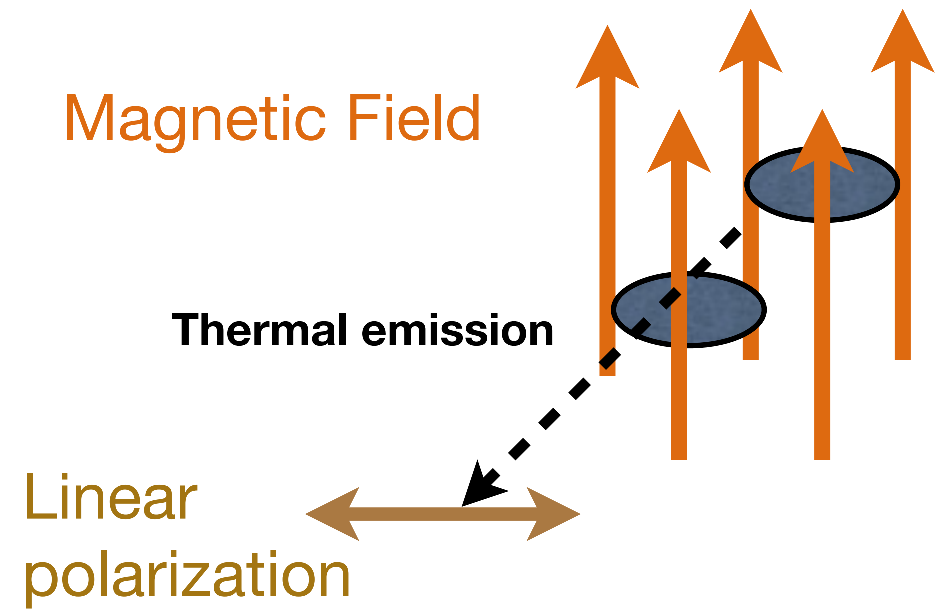
- Accretion rate from UV excess in VLT/X-Shooter
- g/d is assumed to be 100
- Consistent with the viscous accretion theory
- Transition disks have lower Macc.

Manara et al. 2016

mm-wave polarization of disks



Cho and Lazarian 2007

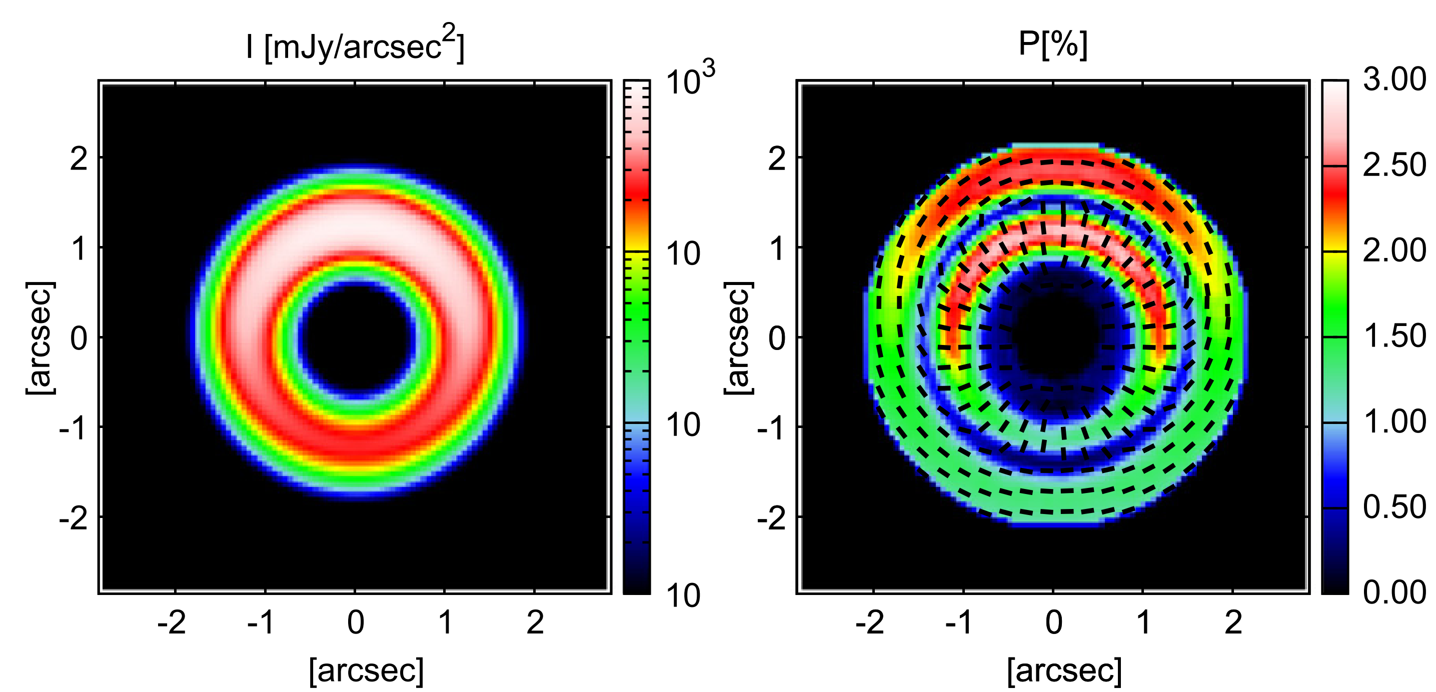


1. Thermal emission from elongated dust grains aligned with magnetic field

   → a probe of the magnetic field structure

2. Self-scattering of thermal dust emission

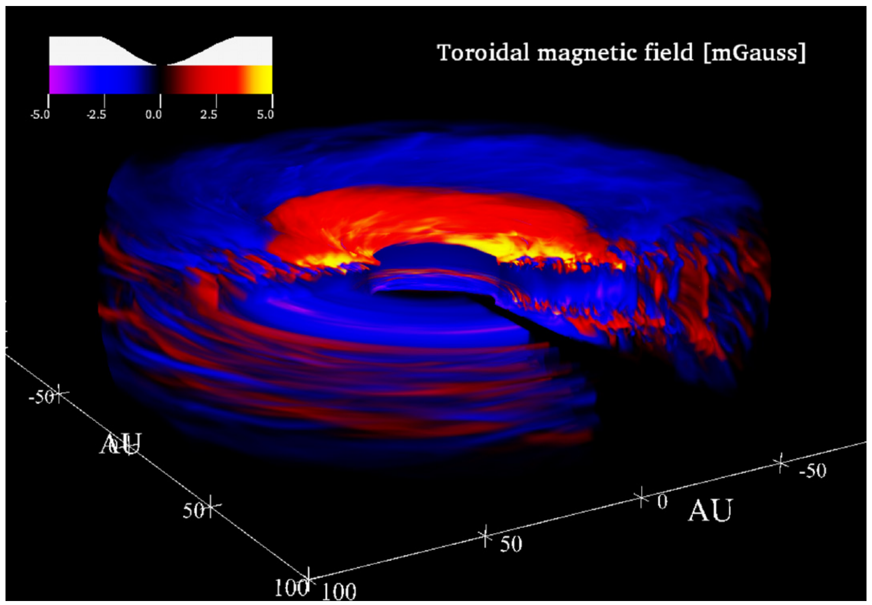
   → measuring the grain size at midplane

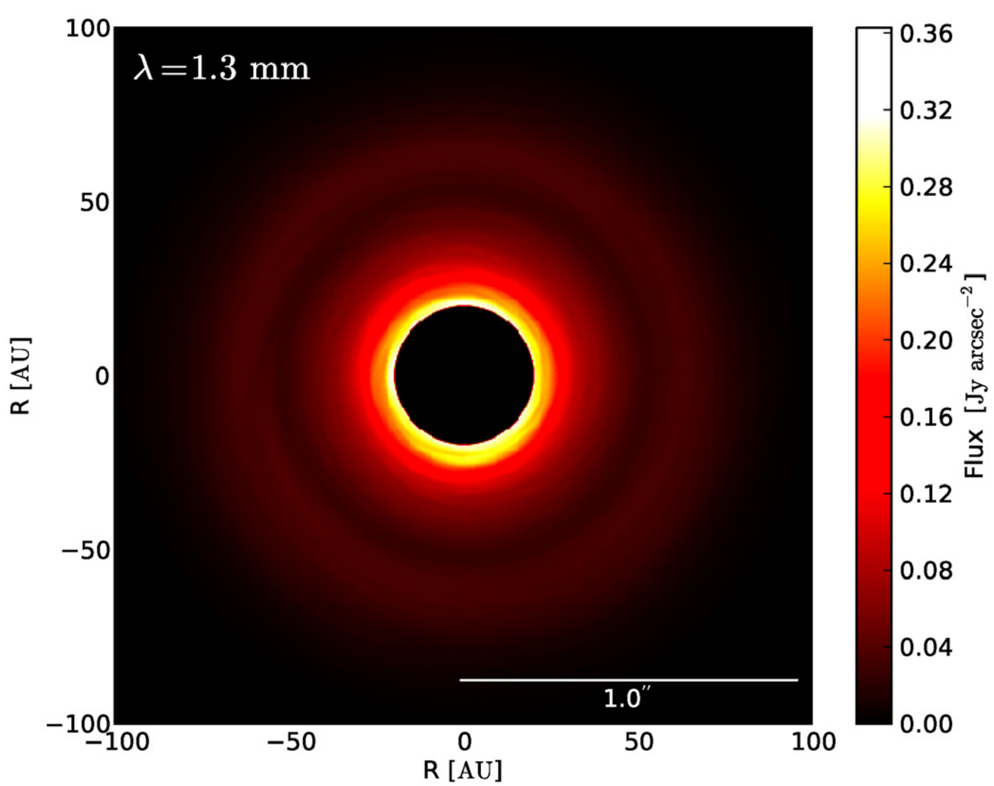


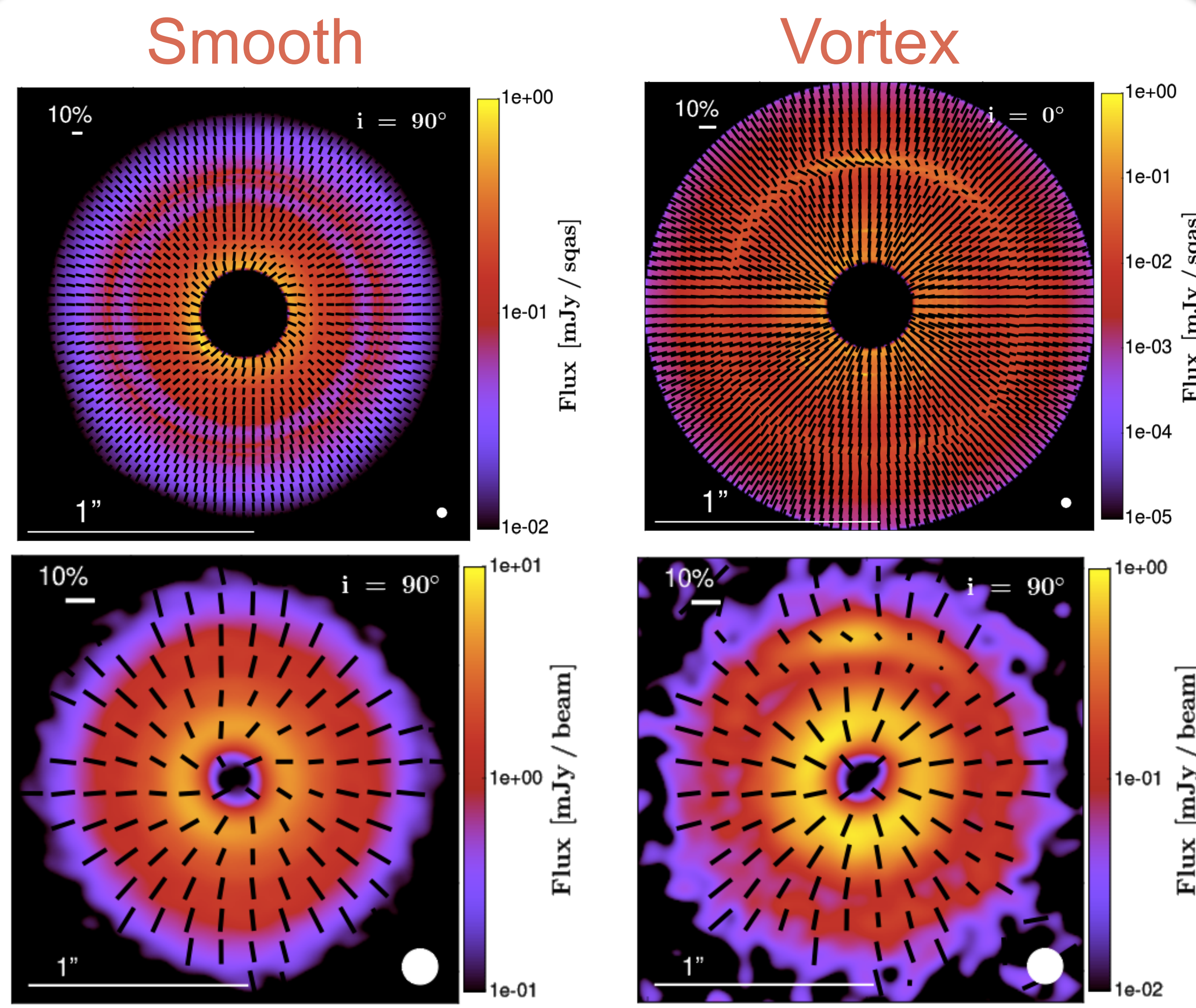
Kataoka et al., 2015

Synthetic Observations

1.Thermal emission from elongated dust grains aligned with magnetic field



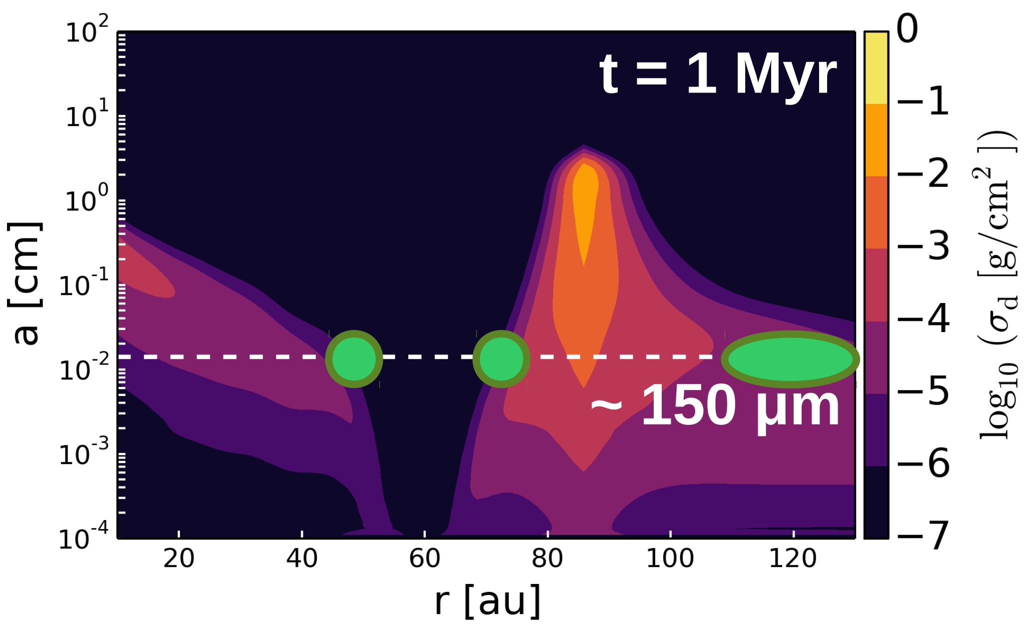




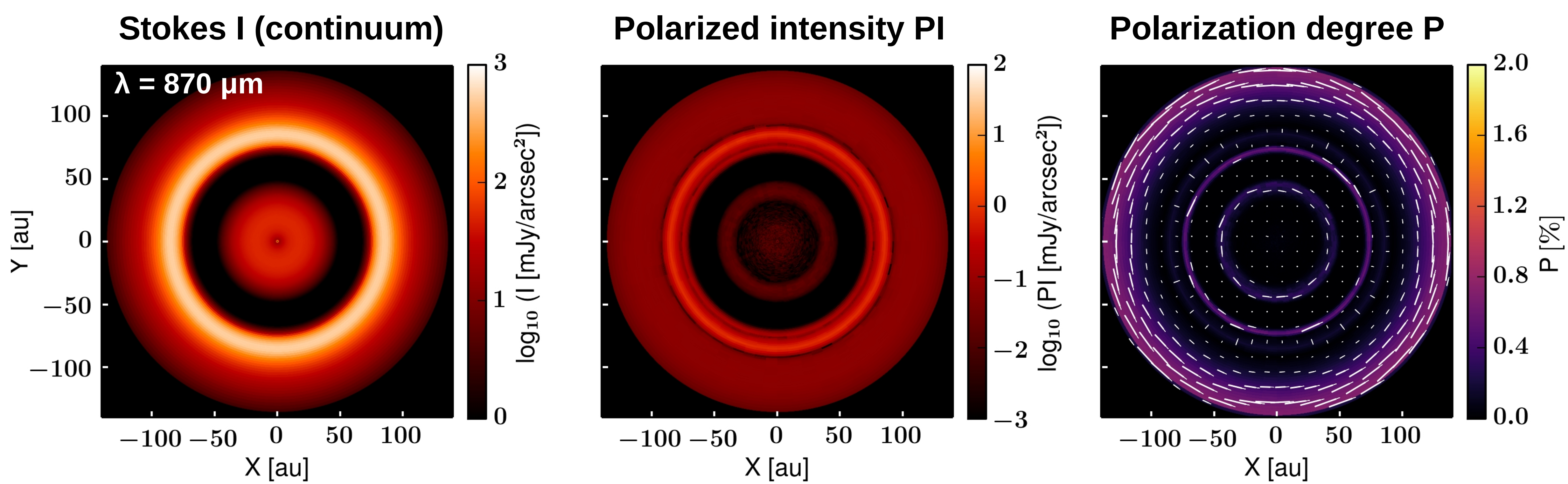
Bertrang, Flock, and Wolf 2016

Synthetic Observations

2.Self-scattering of thermal dust emission



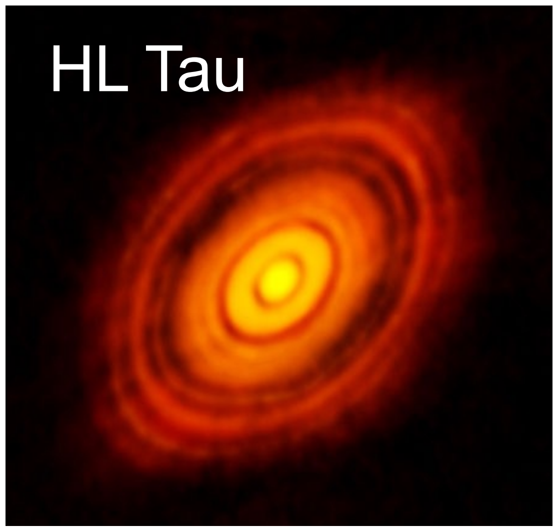
- Polarization is emitted only from locations where a_{max} = 150μm (λ=870 μm)
- In a disk with a planet, three polarization rings are expected.



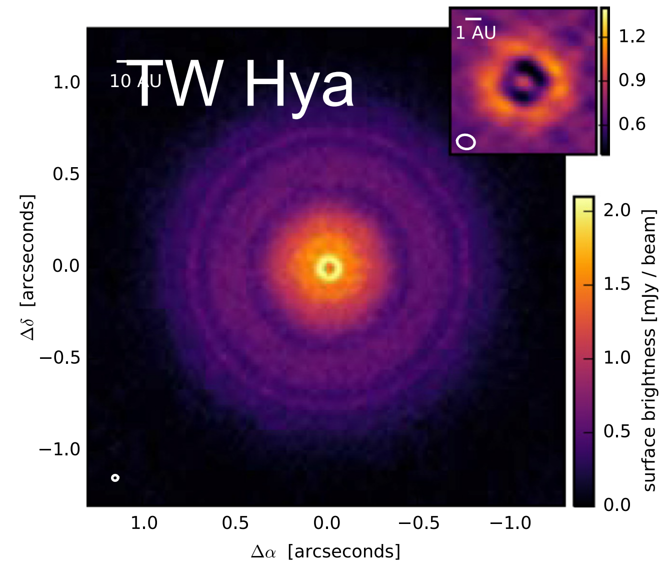
Pohl, Kataoka, et al., 2016

Summary

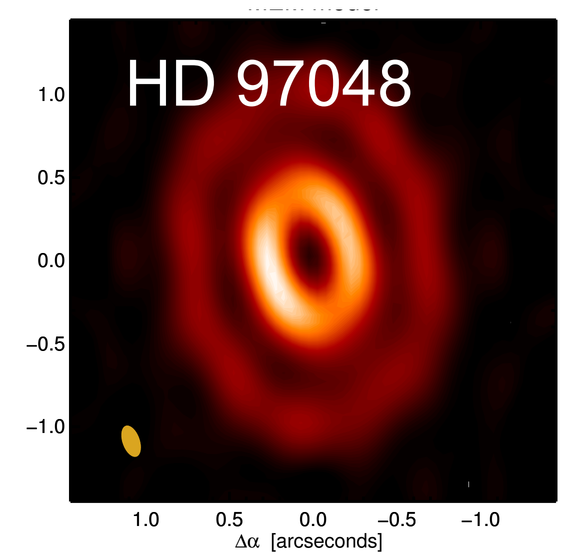
- There are rings and lopsided disks.



ALMA Partnership 2015

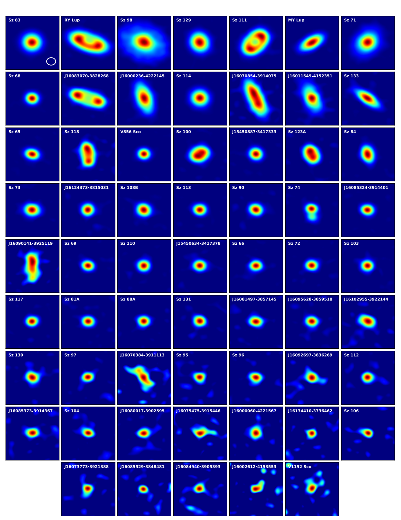


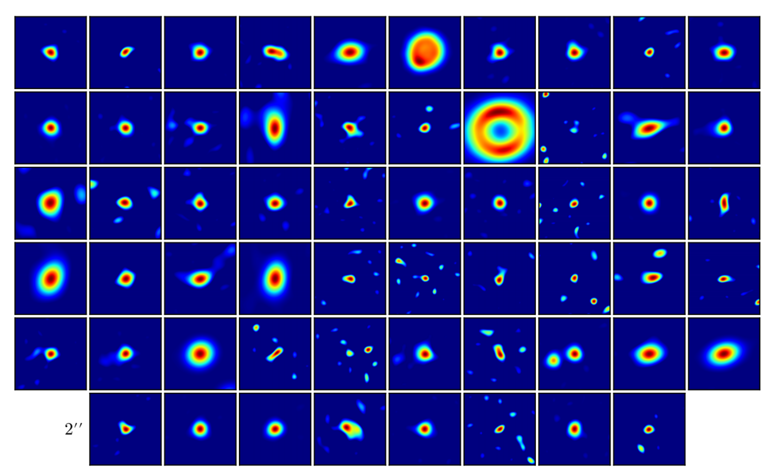
Andrews et al. 2016

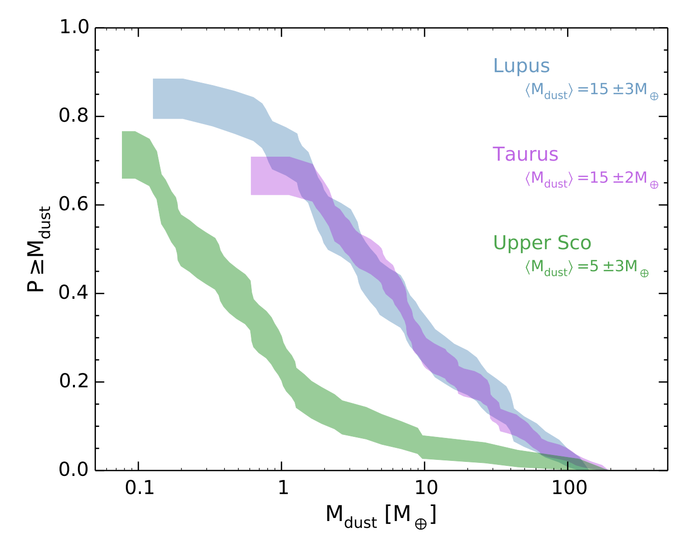


van der Plas et al. 2016

- Surveys show the disk evolution in Myr time scale







Barenfeld, et al. 2016, Andsell et al. 2016, Pascucci et al. 2016

- ALMA polarization as a new tool of measuring grain growth