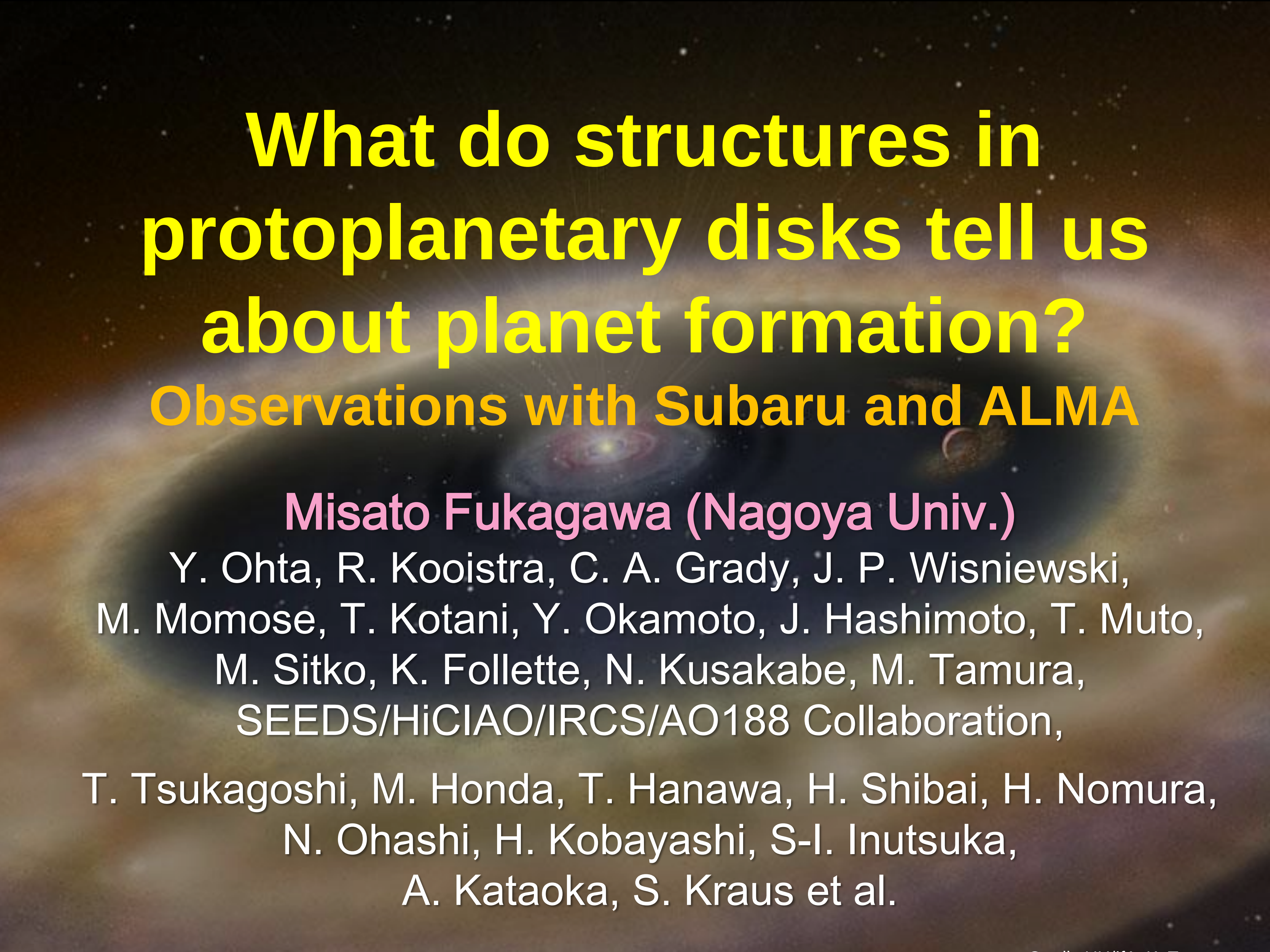
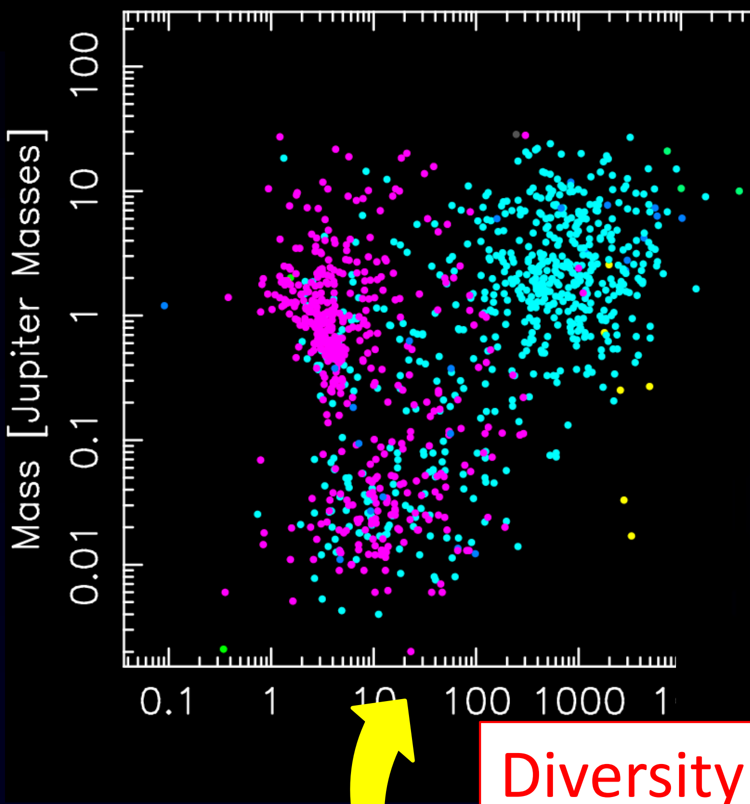


What do structures in protoplanetary disks tell us about planet formation?

Observations with Subaru and ALMA

Misato Fukagawa (Nagoya Univ.)
Y. Ohta, R. Kooistra, C. A. Grady, J. P. Wisniewski,
M. Momose, T. Kotani, Y. Okamoto, J. Hashimoto, T. Muto,
M. Sitko, K. Follette, N. Kusakabe, M. Tamura,
SEEDS/HiCIAO/IRCS/AO188 Collaboration,

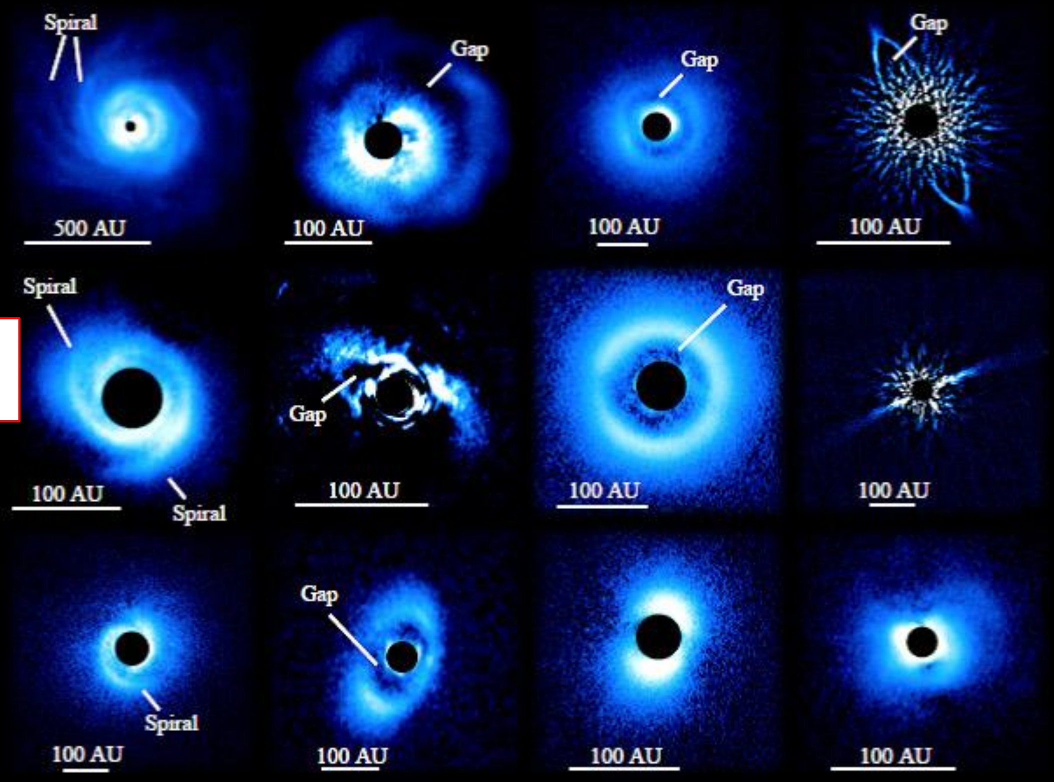
T. Tsukagoshi, M. Honda, T. Hanawa, H. Shibai, H. Nomura,
N. Ohashi, H. Kobayashi, S-I. Inutsuka,
A. Kataoka, S. Kraus et al.



1. Formation
2. Migration
   Interaction with a disk
   Interaction with other planets

Diversity

?

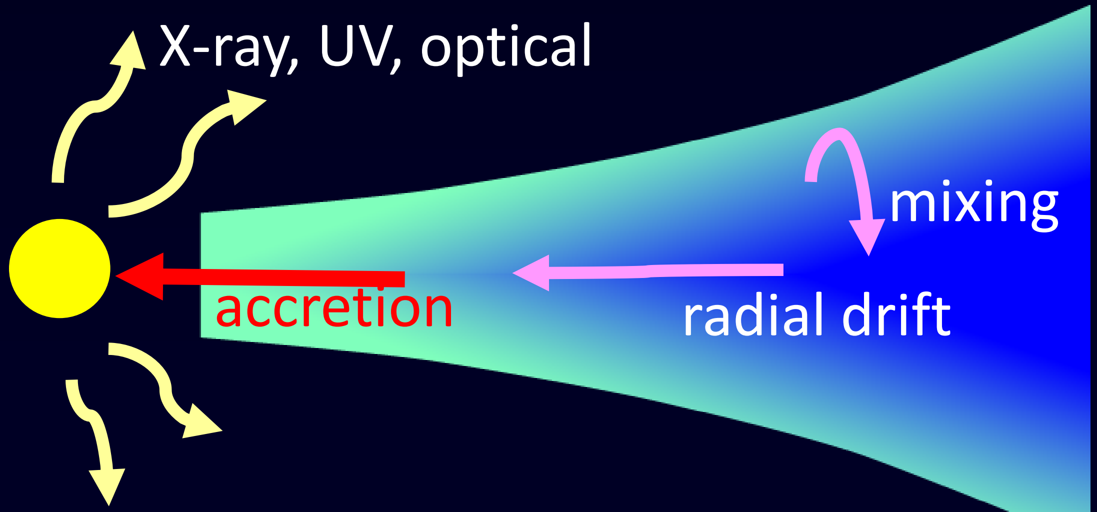


Credit: NAOJ

Disks provide initial condition of formation and control early orbital evolution of planets

- Surface density distribution
  → mass of solids and gas, location
- Chemical evolution of disk material
  → composition
- Disk gas lifetime, dissipation mechanisms
  → orbital evolution (migration)

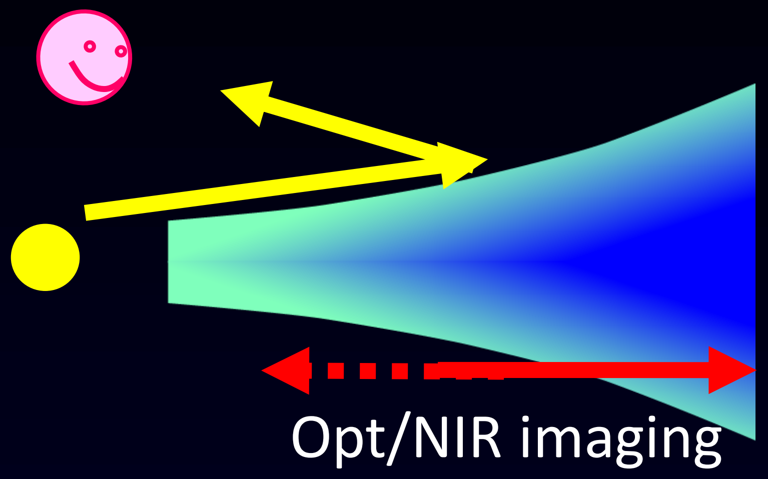
What we want to know:
Physical and chemical structure at various age
$\rho(r, z)$, $T(r, z)$, $X(r, z)$…



Imaging for dust in an optically thick disk

- Scattered light in NIR

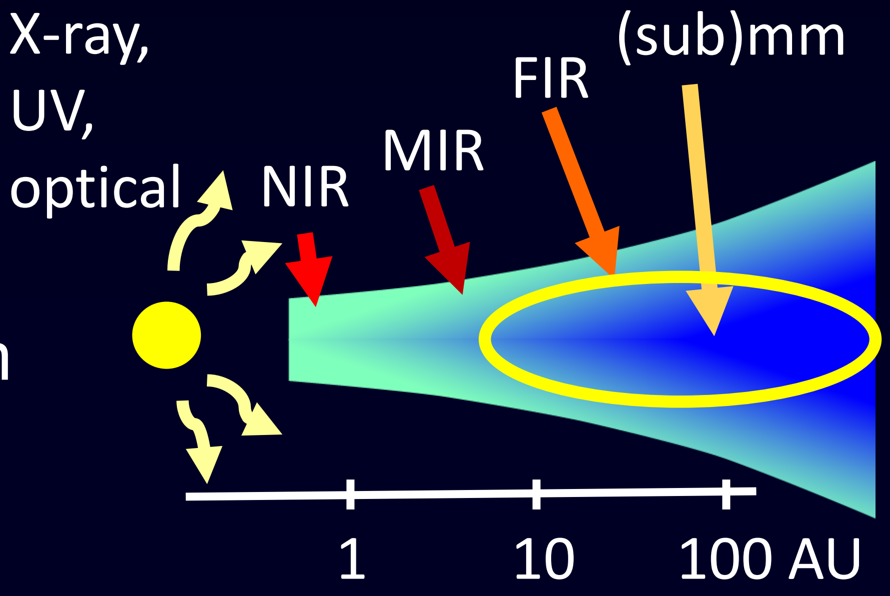
  sensitive to (sub)micron-sized grains in the upper surface of an optically thick disk



Subaru

- Thermal emission in (sub)millimeter

  mm-sized grains near the disk mid-plane efficiently detected in mm thermal observations



ALMA

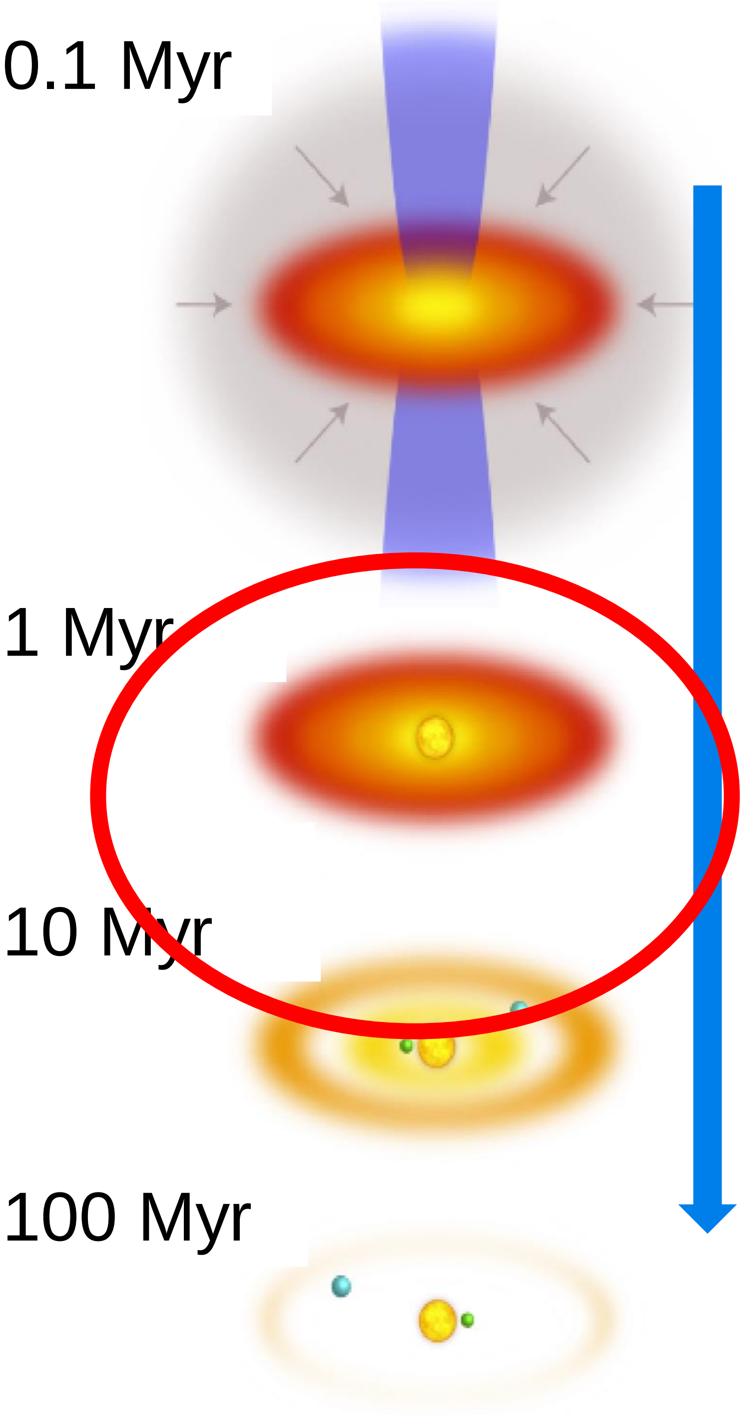
Proto-planetary disks in this talk

- age: 1—10 Myr
- optically thick ($L_{IR}/L_* \sim 0.1$), gaseous

- ~10 Herbig Ae stars (F, A-type)
  - T_{eff} = 6000—10000 K
  - $M_* \sim 2\ M_\odot$

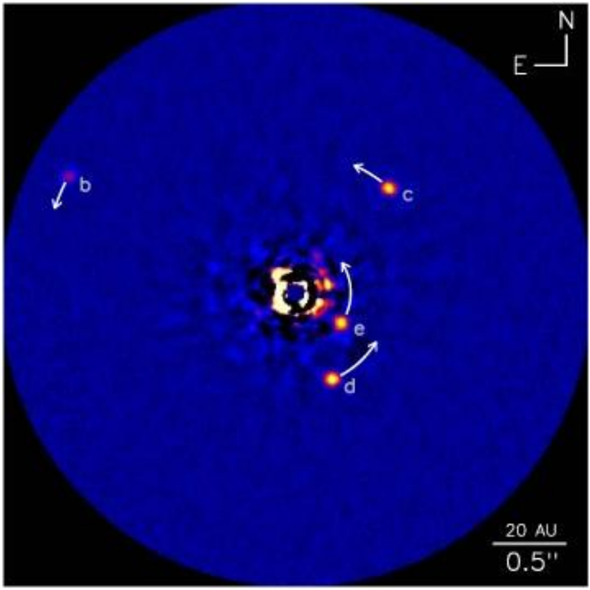
pros: bright

cons: not many in nearby

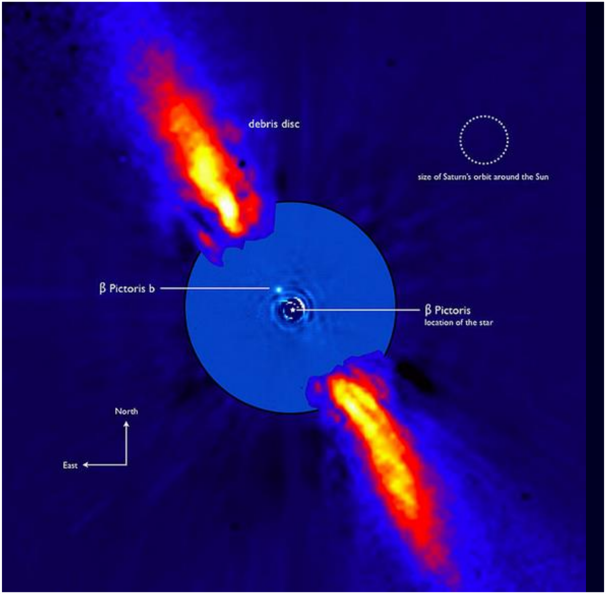


Proto-planetary disks in this talk: around ~2 solar-mass stars

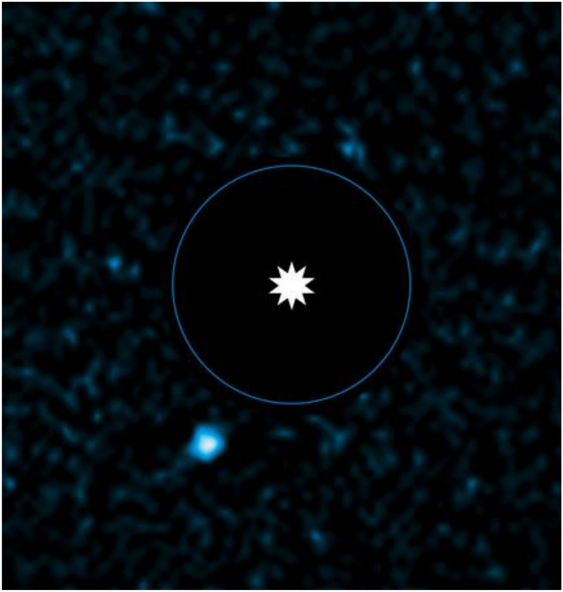
- Compared to <~ 1 $M_\odot$
  - Higher frequency of giant planets? (e.g., Bowler et al. 2010)
  - Planets detected in direct imaging: HR 8799, β Pic, HD 95086, 51 Eri, Fomalhaut



Marois et al. (2010)



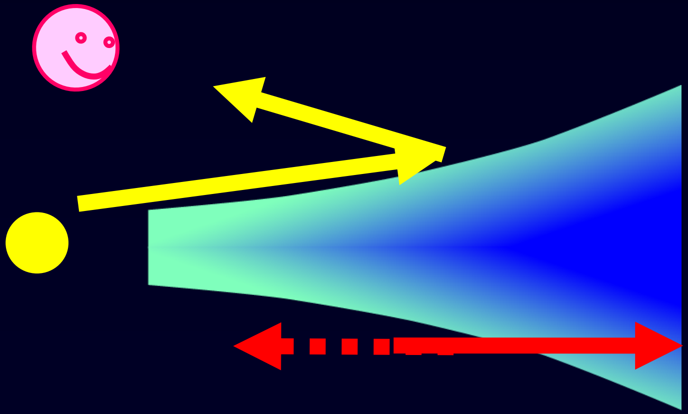
Lagrange et al. (2010)



Rameau et al. (2013)

Credit: NAOJ

Scattered light imaging with Subaru



Disk imaging in SEEDs project

(Strategic Explorations of Exoplanets and Disks with Subaru)

1. Higher angular resolution

Adaptive optics

→ ~0.07” at 1.6 μm = 10 au at 140 pc

= 28 au at 400 pc

2. Inner region

Polarization differential imaging

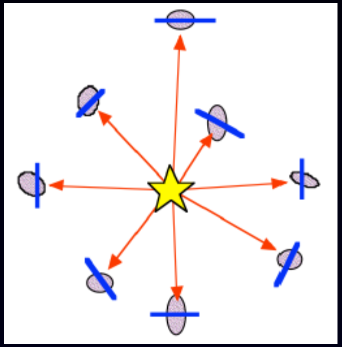
→ Inner working radius ~0.2”

= 28 au at 140 pc

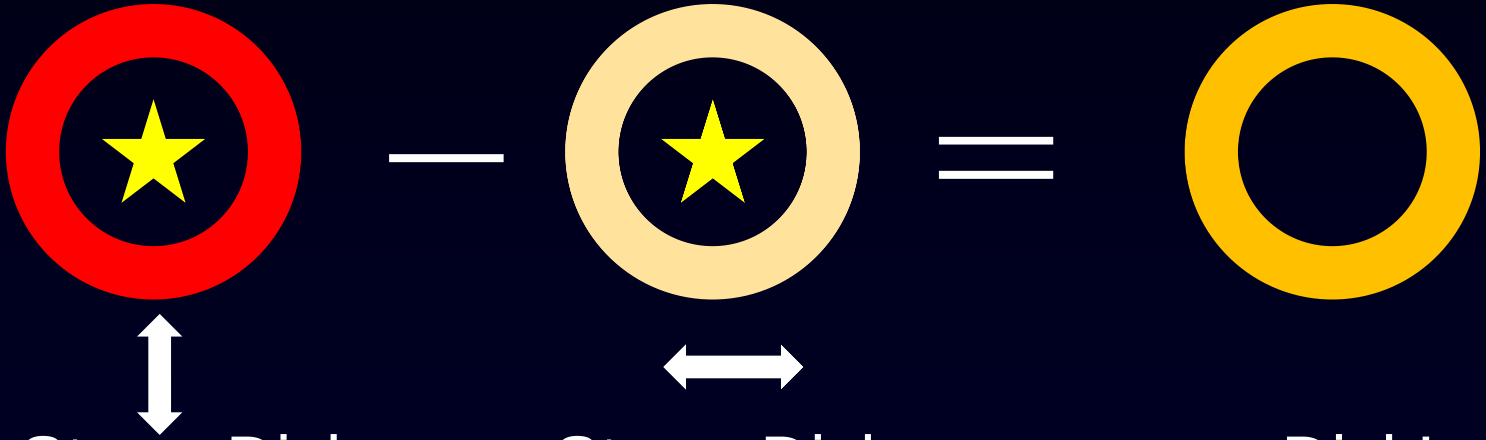
= 80 au at 400 pc

Current generation: VLT/SPHERE, Gemini/GPI, Subaru/SCExAO

Polarization Differential Imaging (PDI)



Scattered light is polarized,
while starlight is unpolarized.



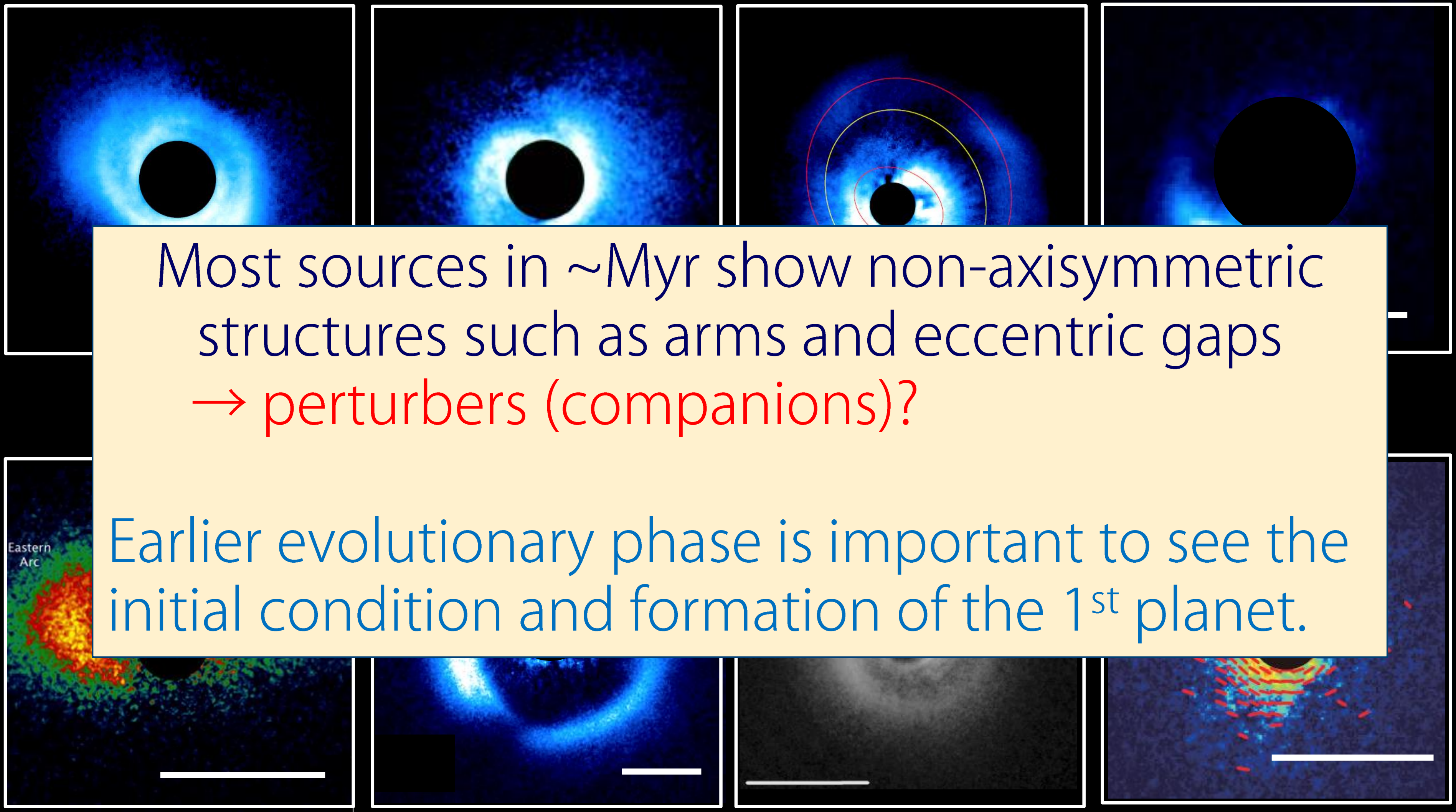
Star + Disk
(Target)

Star + Disk
(Target)

Disk!

need to obtain simultaneously → Rin ~ 0.15”

Observable: Polz intensity = (Intensity) × (Polz degree)



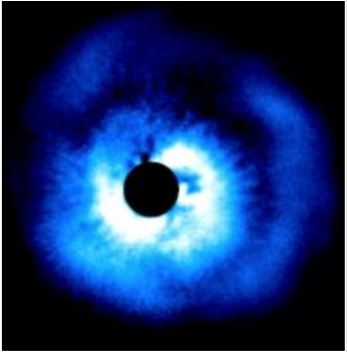
Most sources in ~Myr show non-axisymmetric structures such as arms and eccentric gaps

→ perturbers (companions)?

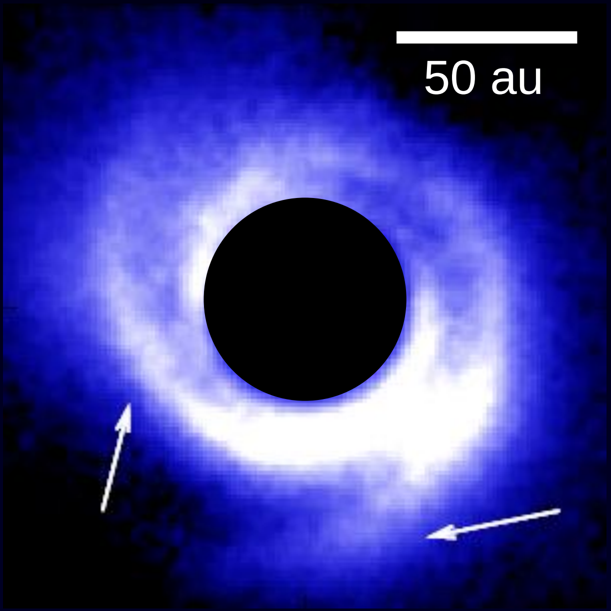
Earlier evolutionary phase is important to see the initial condition and formation of the 1st planet.

(Muto+12, Kusakabe+12, Grady+13, Hashimoto+11, Follette+14, Momose+15,Ohta+16)

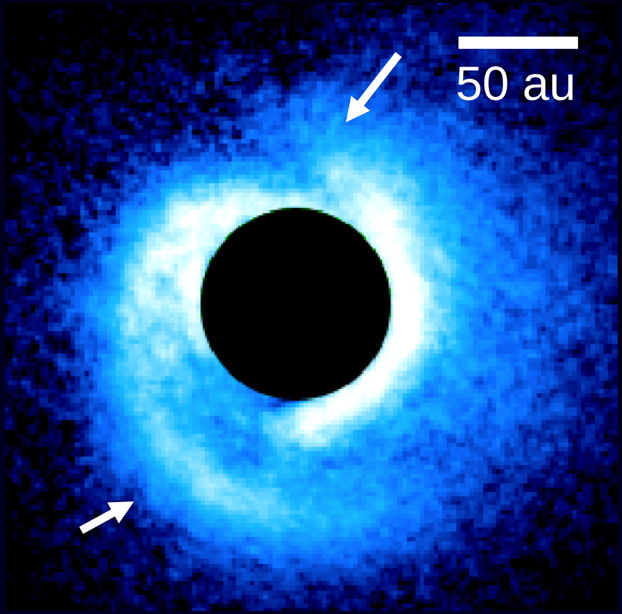
Spiral arms within ~100 au



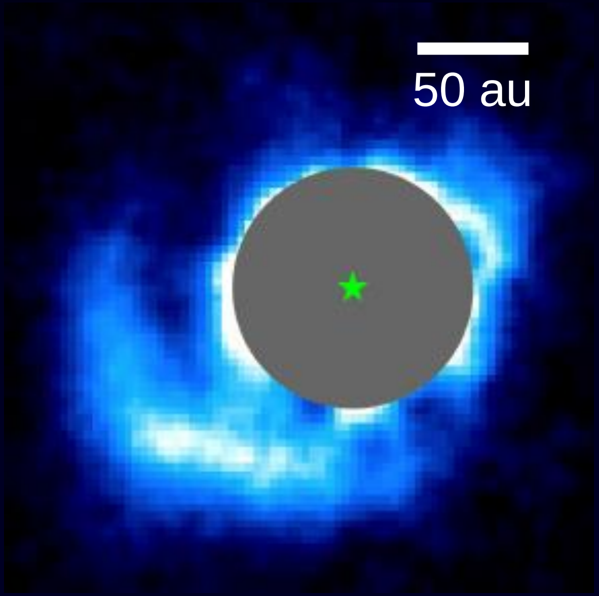
- Density wave (driven by a planet)?
- Two arms seem common.
- Spirals preferentially found for warm (>6000 K) disks?



Muto et al. (2012)



Grady et al. (2013)

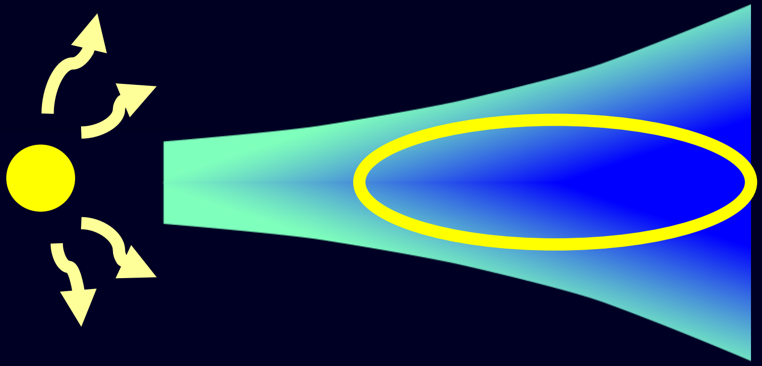


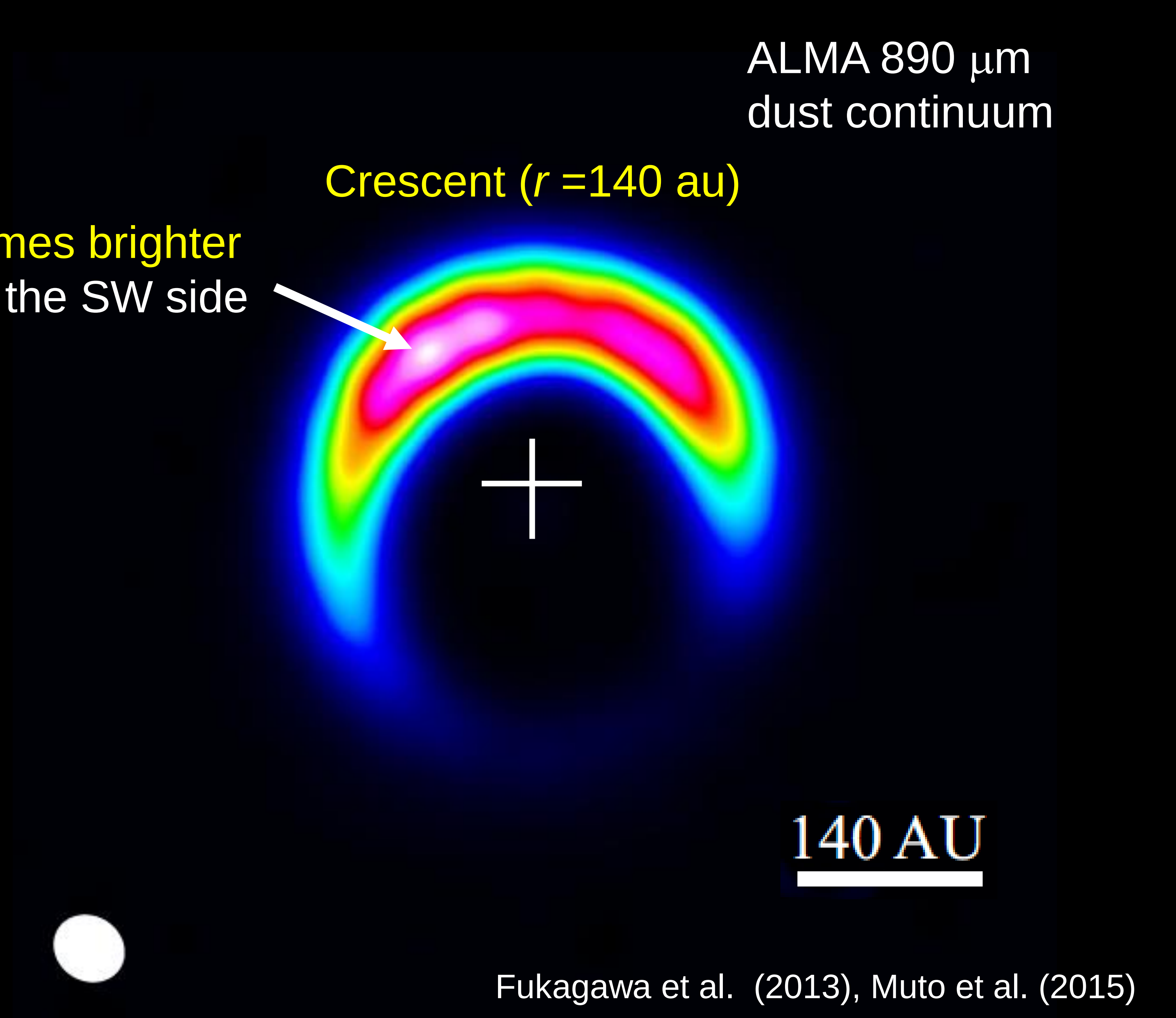
Ohta et al. (2016)

See also Akiyama et al. (2016)


Credit: NAOJ

Dust emission with ALMA



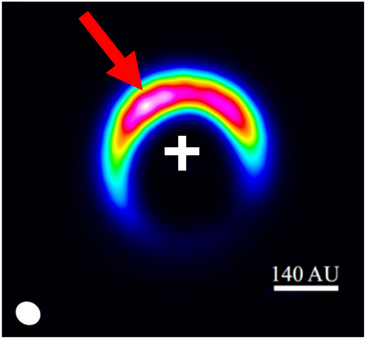


ALMA 890 μm
dust continuum

Crescent (*r* =140 au)

30 times brighter
than the SW side

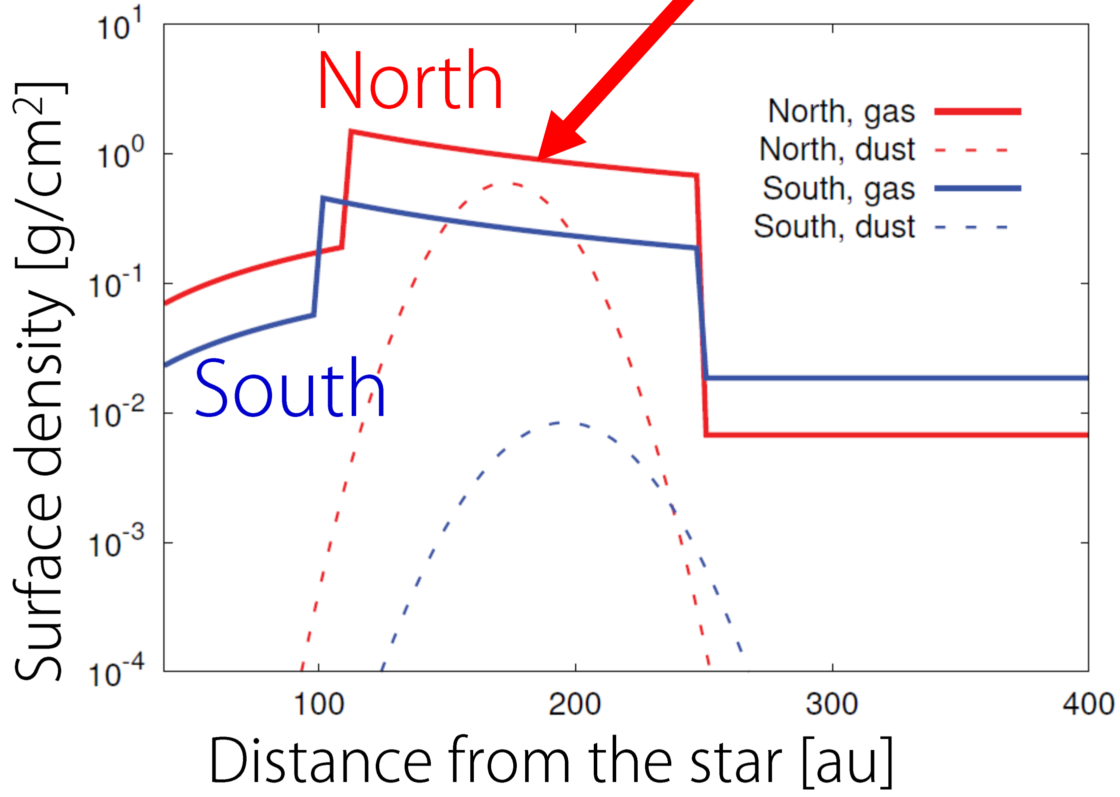
Fukagawa et al. (2013), Muto et al. (2015)

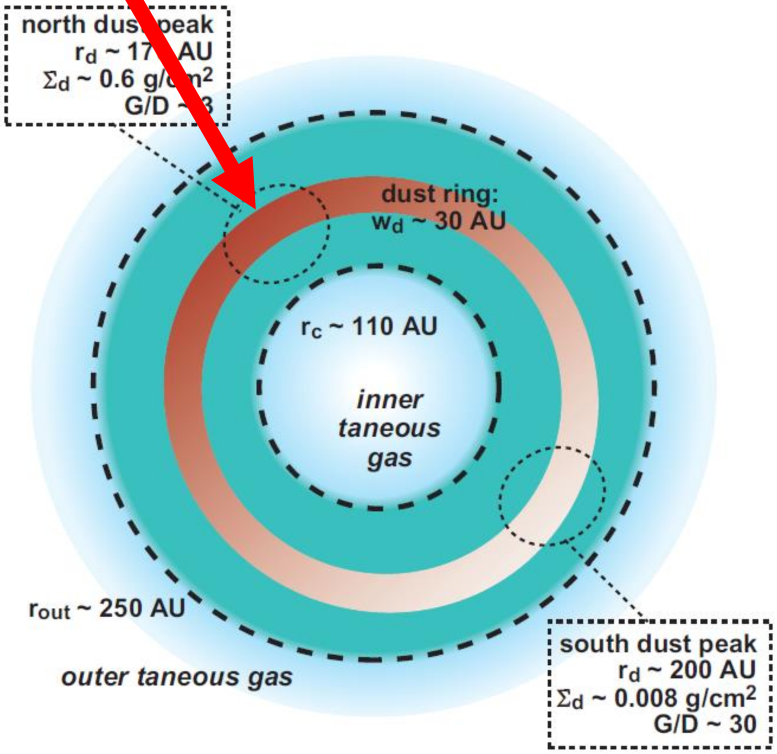


Density distribution of dust

Radiative transfer (Muto et al. 2015)

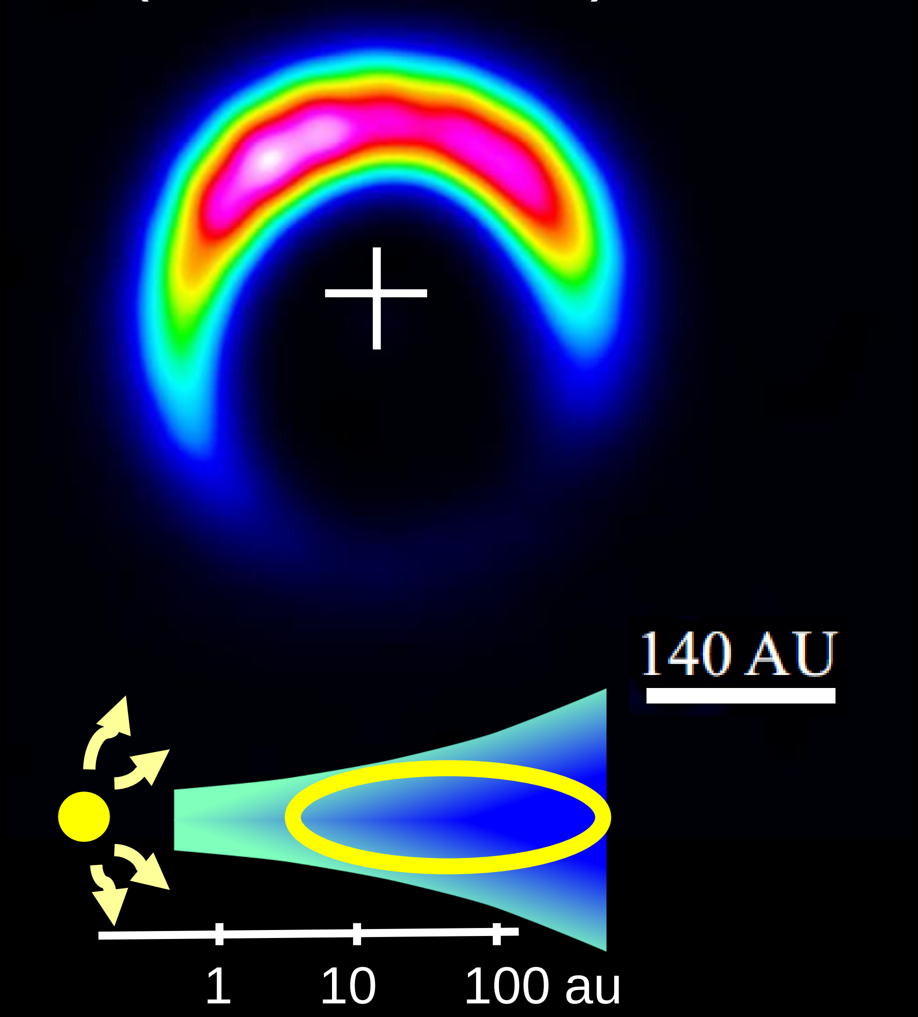
Gas:dust mass ratio in the north ~3
(↔ 100 for ISM) = concentration of solids



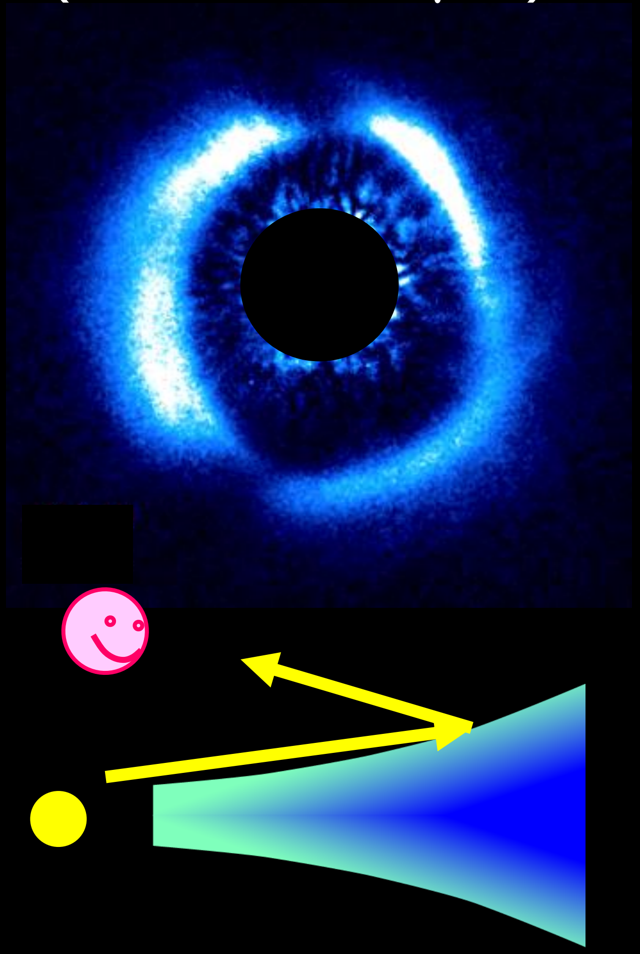


Sign of grain growth

Large grains
(ALMA, ~1 mm)

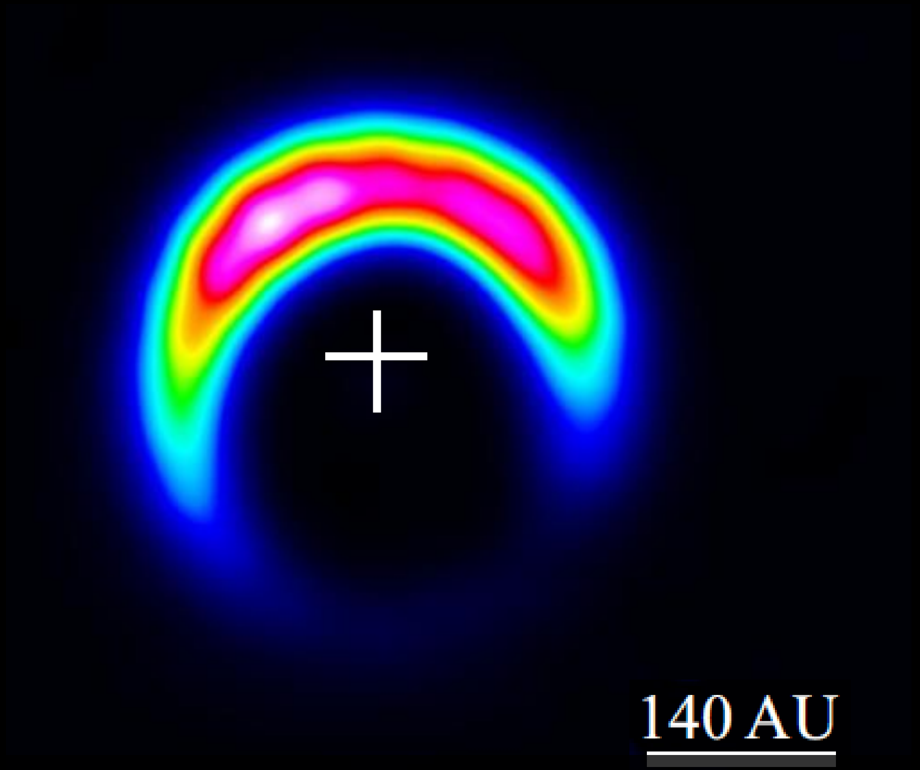


Small grains
(Subaru, ~1 μm)

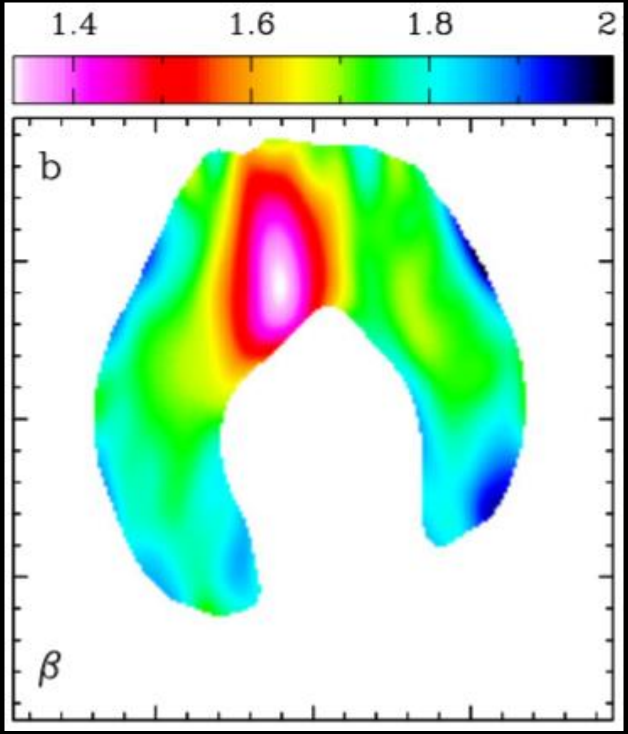


Sign of grain growth

Large grains
(ALMA, ~1 mm)



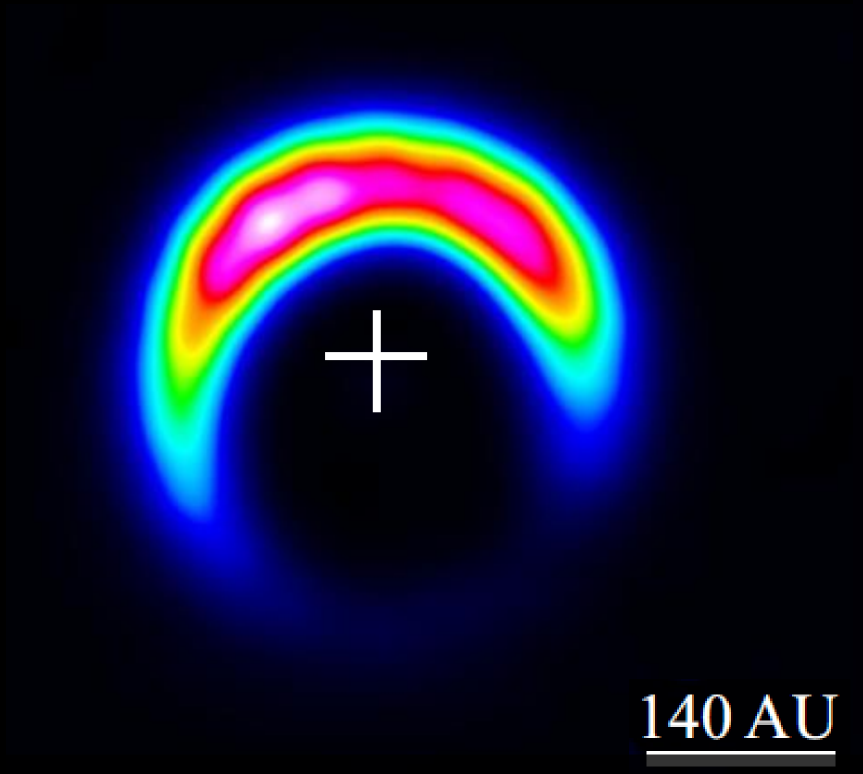
Spectral index
(Cassasus et al. 2015)



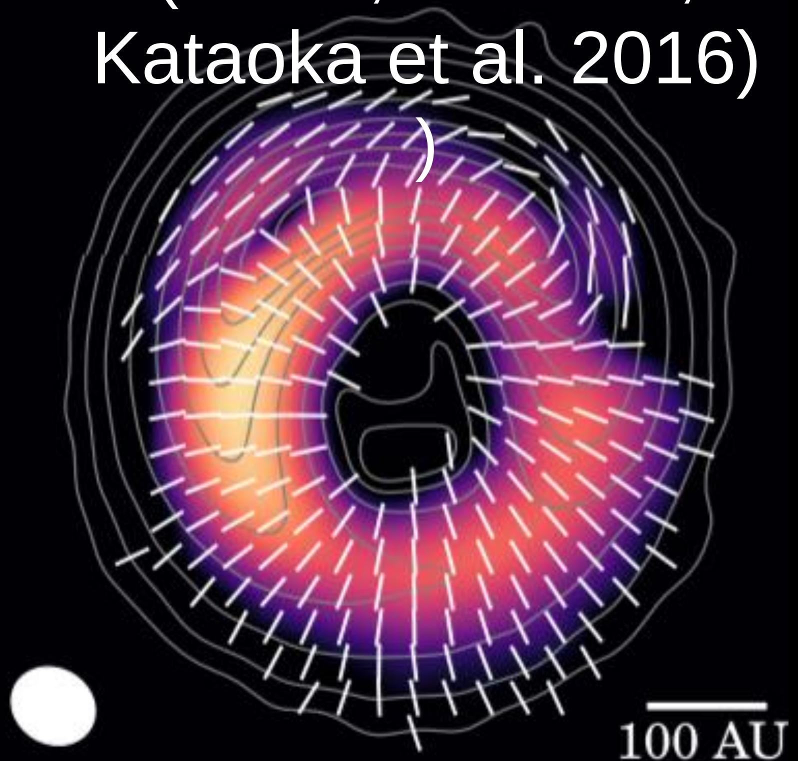
Only large grains are localized in a disk,
location of efficient grain growth? wide-orbit planets?

Sign of grain growth

Large grains
(ALMA, ~1 mm)



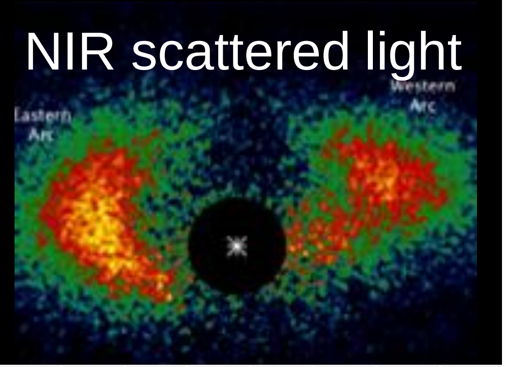
Scattering by large grains
(ALMA, ~0.2 mm;
Kataoka et al. 2016)
)



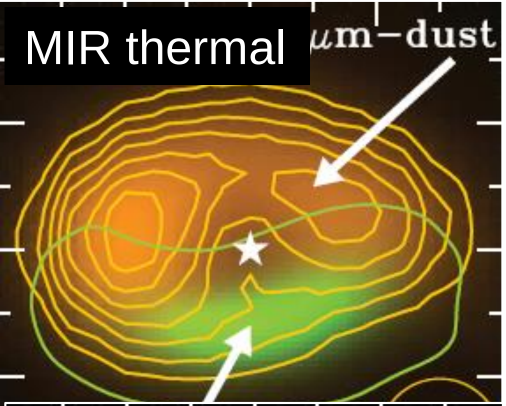
Only large grains are localized in a disk,
location of efficient grain growth? wide-orbit planets?

“Dust trap”

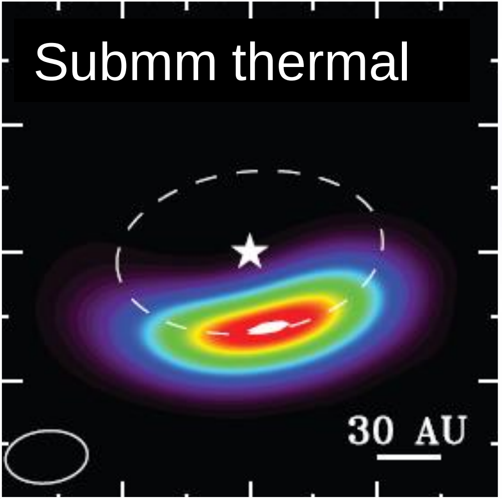
by van der Marel et al. (2013)



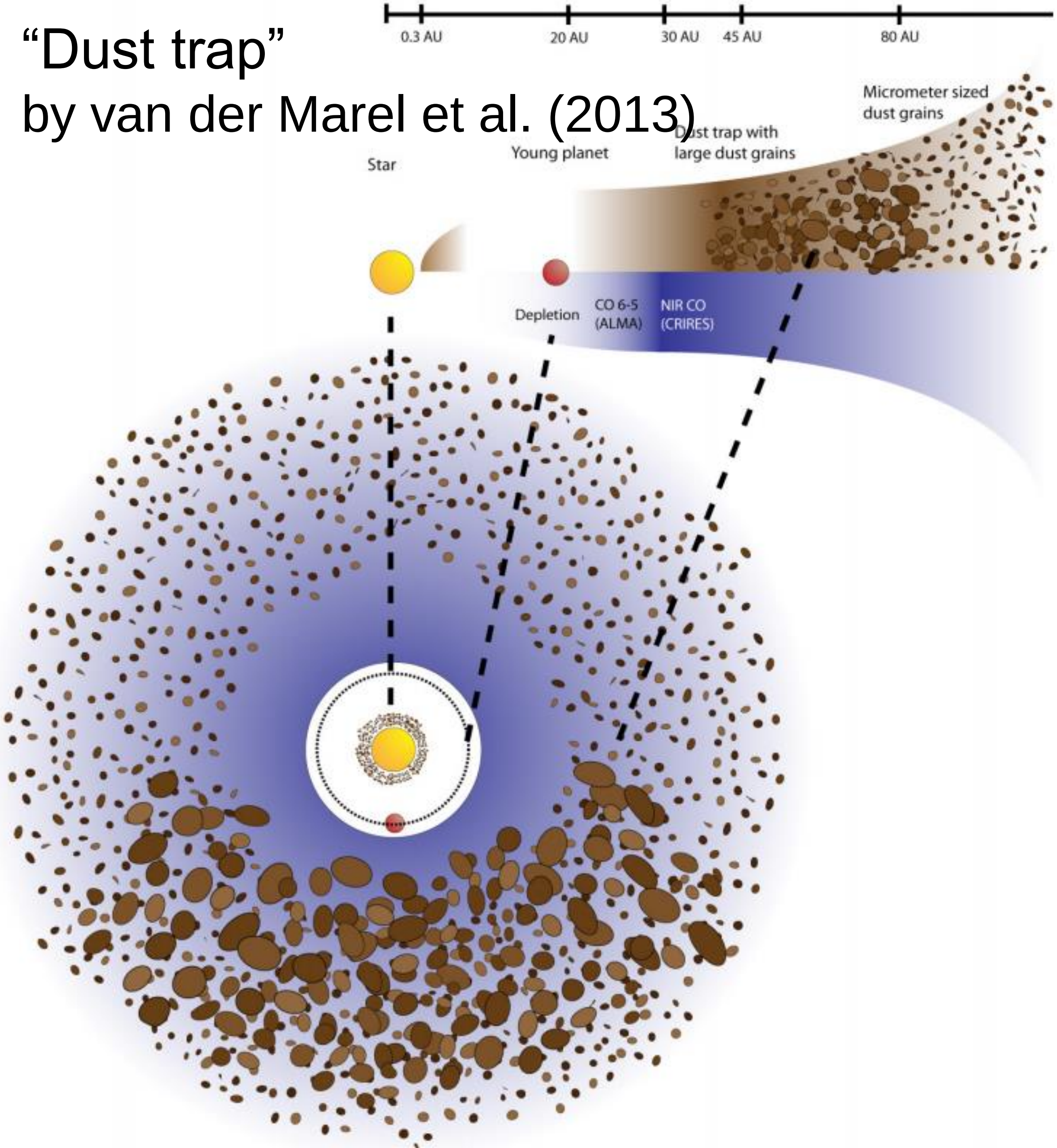
NIR scattered light



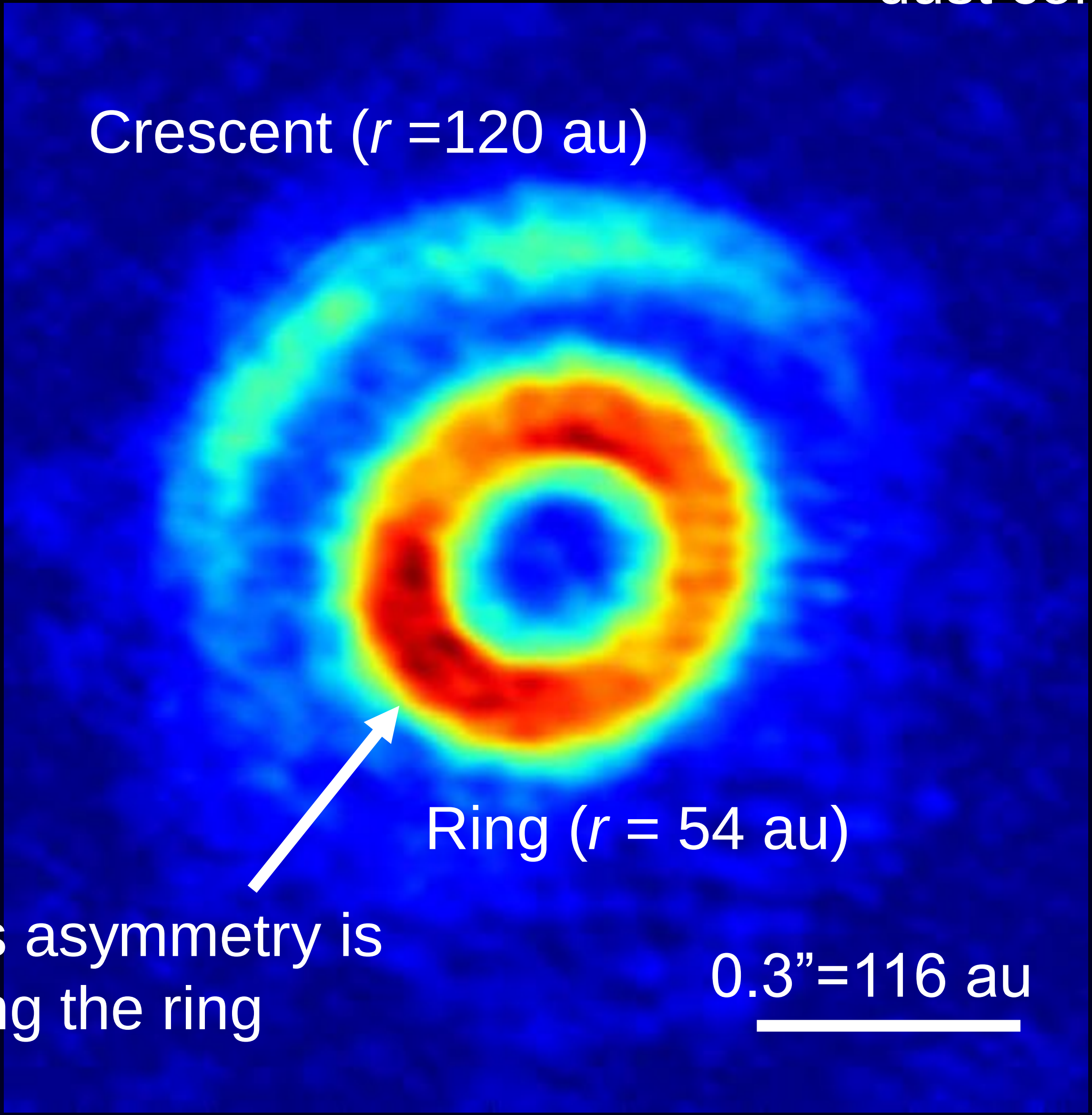
MIR thermal



Submm thermal



ALMA 870 μm dust continuum



Crescent (*r* =120 au)

Ring (*r* = 54 au)

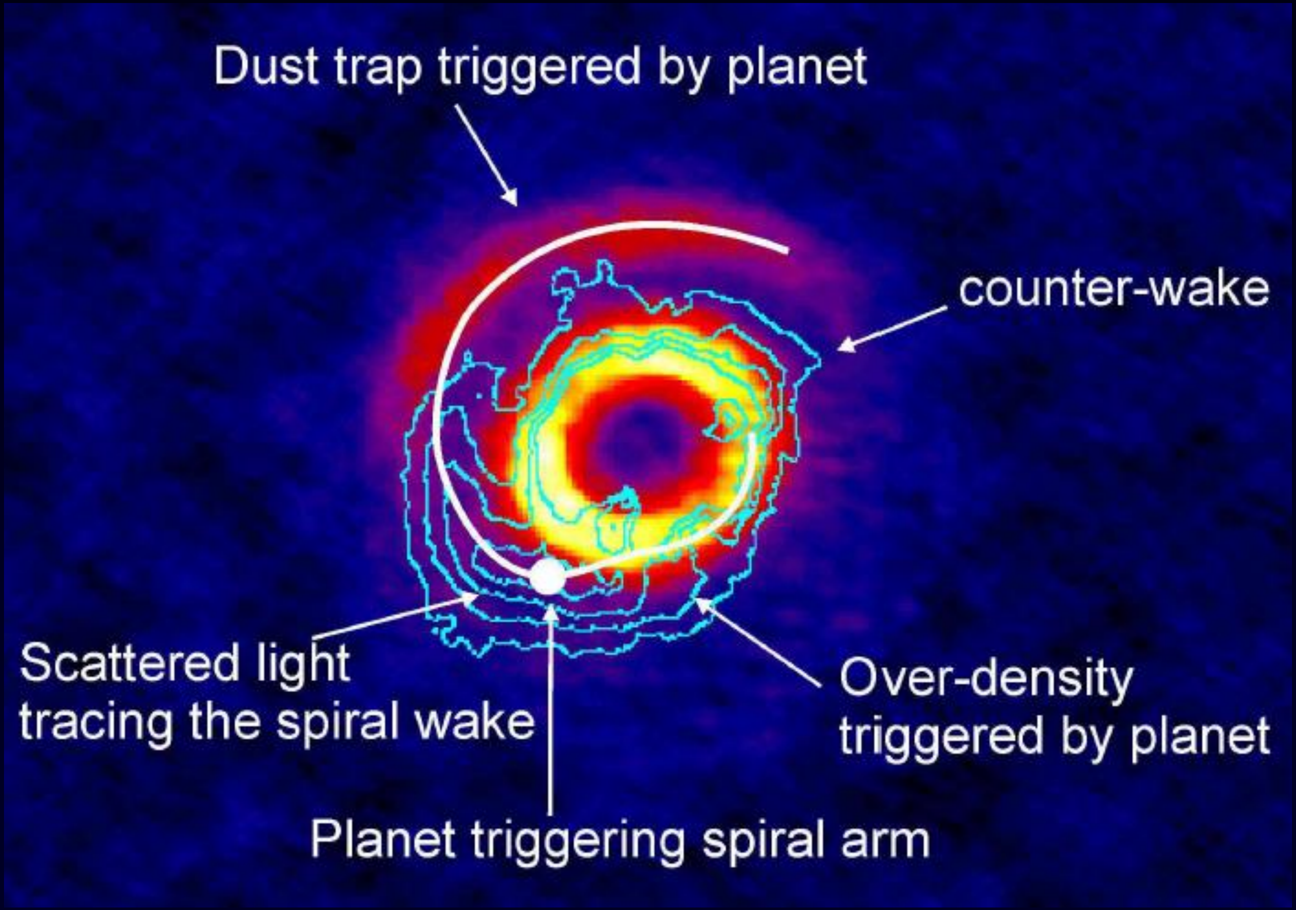
Brightness asymmetry is ~30% along the ring

0.3”=116 au

Kraus, ... Fukagawa et al. (2017)

Comparison with scattered light

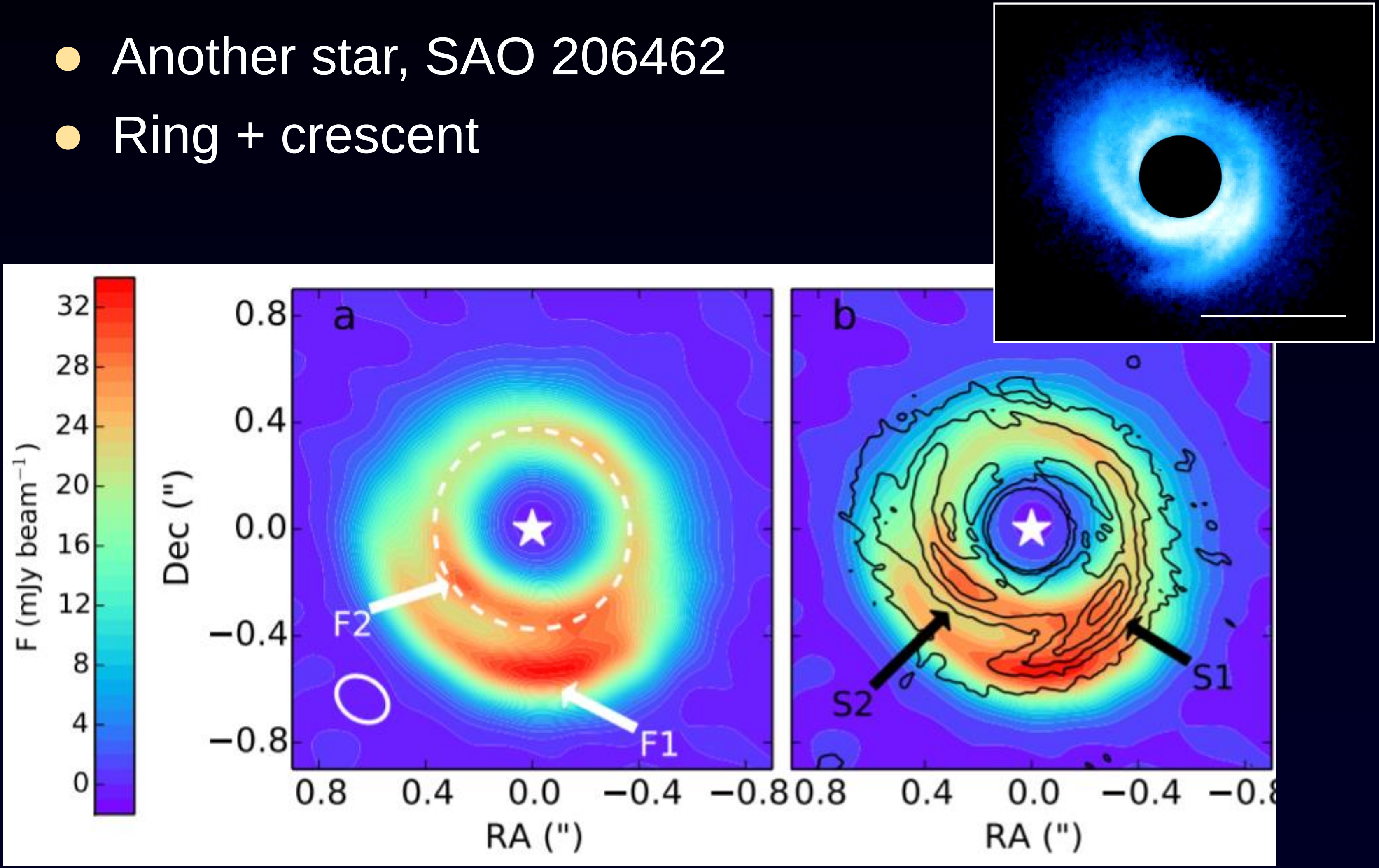
- An arm in scat light connects the ring and inner edge of the crescent



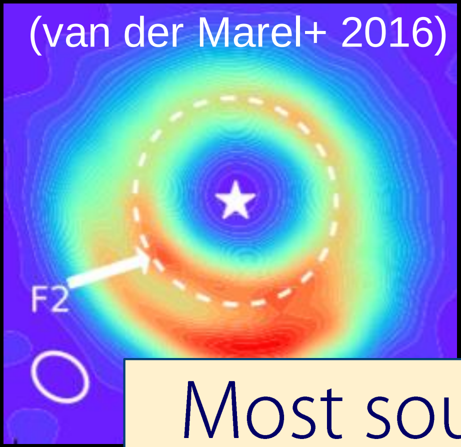
Kraus, ... Fukagawa et al. (2017)

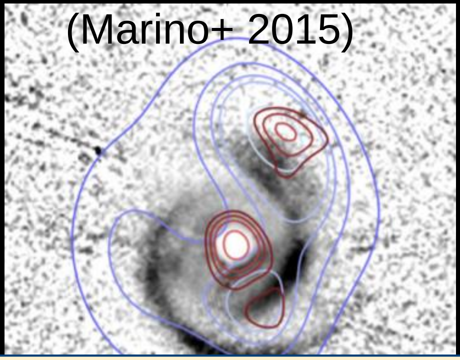
Similar case (crescent + ring)?

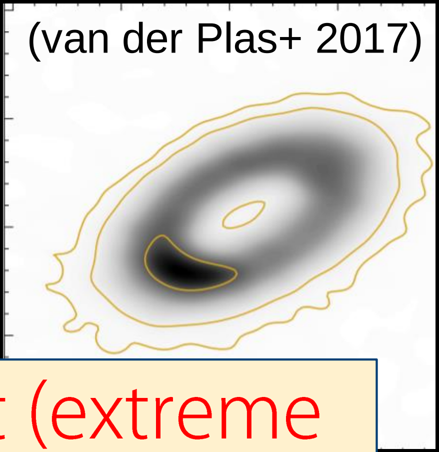
- Another star, SAO 206462
- Ring + crescent

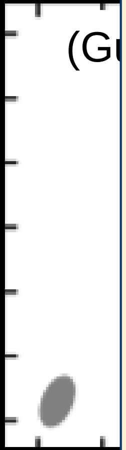


van der Marel et al. (2016)





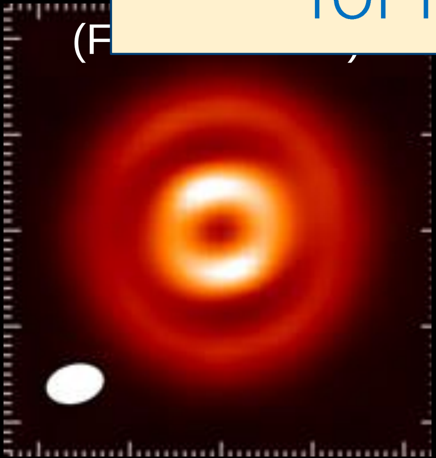


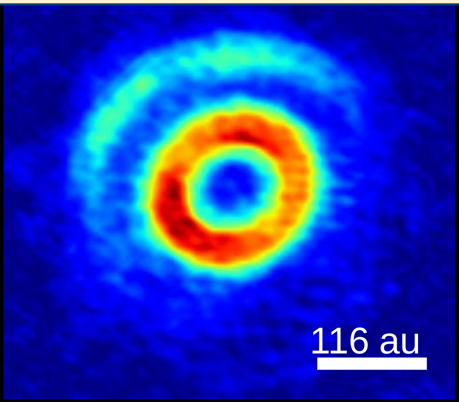


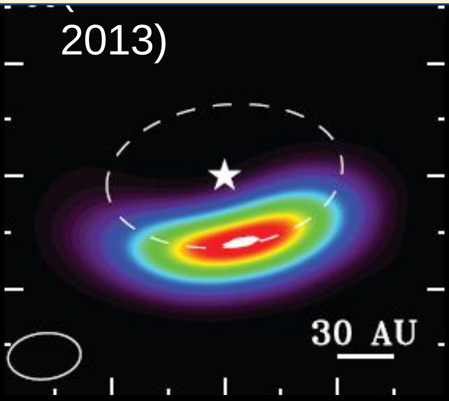
Most sources in ~Myr show a crescent (extreme asymmetry), crescent+ring, ring, rings (relatively symmetry).

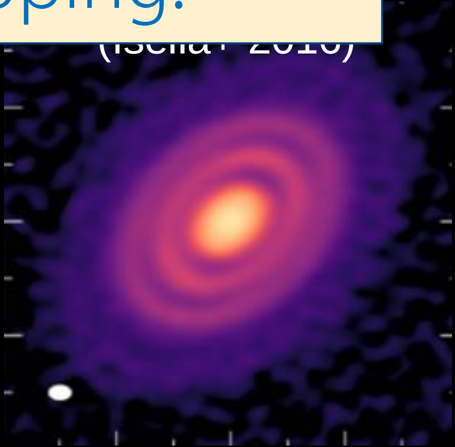
Grain growth (“dust traps”) is suggested from observations.

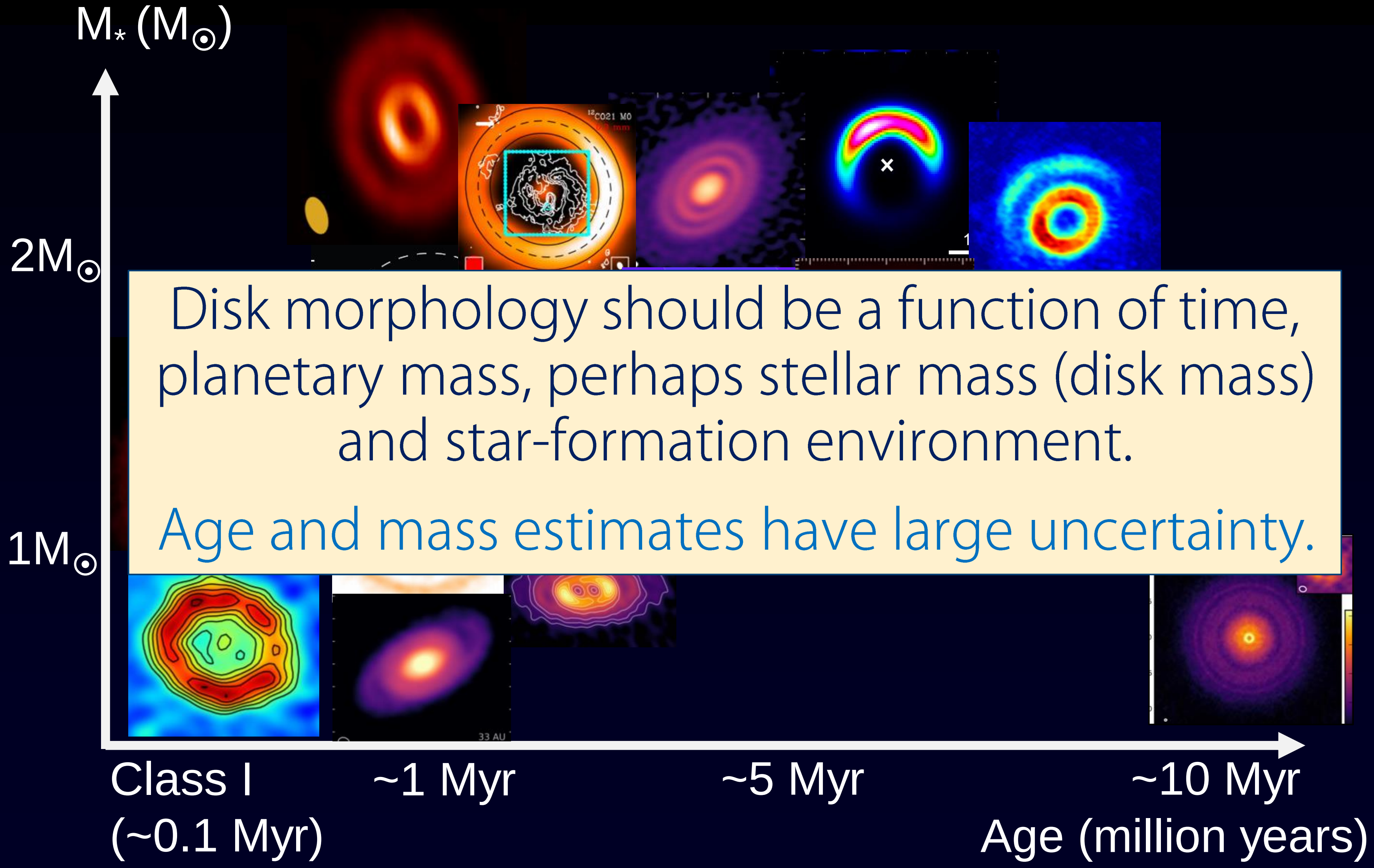
There are exceptions (smooth disks), but waiting for higher-angular resolution mapping.











Disk morphology should be a function of time, planetary mass, perhaps stellar mass (disk mass) and star-formation environment.

Age and mass estimates have large uncertainty.

ALMA Partnership+15, Pérez+16, Andrews+16, Loomis+17, Isella+16, van der Marel+16, Sheehan+17, Tang+17, van der Plas+17, Fedele+17, Kraus+17

Summary

- Most disks in Myr show non-axisymmetric structures such as arms and eccentric gaps, suggesting the presence of companions with extreme mass-ratio (incl. giant planets) already formed in disks.
- Disks often exhibit concentration of dust emission at submm/mm wavelengths, while small grains are more homogeneously extended (with gas). Those are ideal lab to study grain growth.
- Disk morphology shows a variety although those may be connected through evolution.

- We need to perform extensive observational study for gas and dust at various wavelengths to know the ‘mechanism’ of dust traps.
- We need to greatly improve ‘statistics’.