Debris disks in nearby young moving groups in the ALMA era

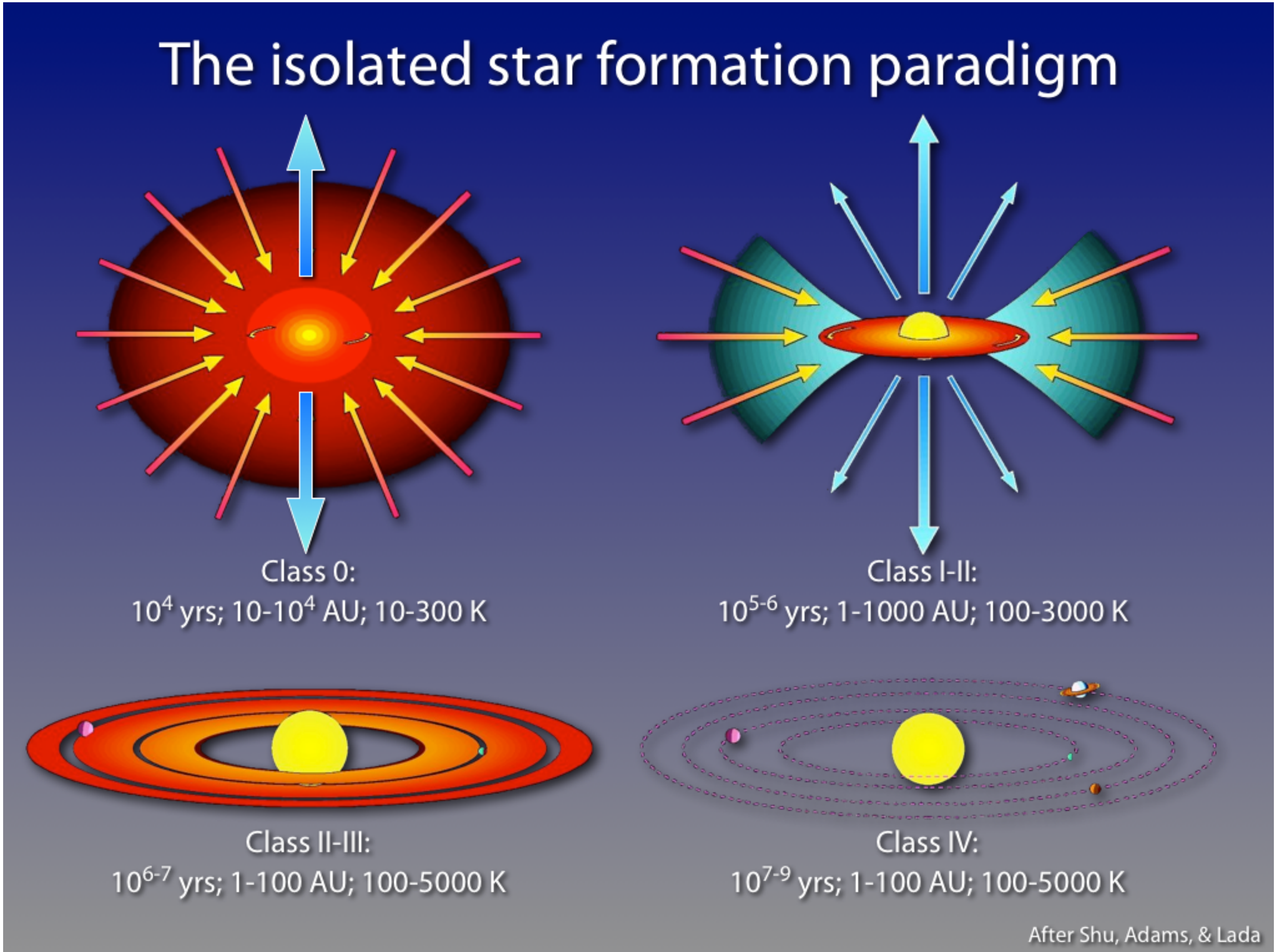
Ágnes Kóspál and Attila Moór
Konkoly Observatory, Budapest, Hungary

IAU Symposium 314, Young Stars and Planets Near the Sun, May 13, 2015

Structure of the talk

- Introduction to debris disks
- **Dust** in debris disks
  - pre-ALMA results
  - ALMA results
  - open questions
- **Gas** in debris disks
  - pre-ALMA results
  - ALMA results
  - open questions

Circumstellar disks



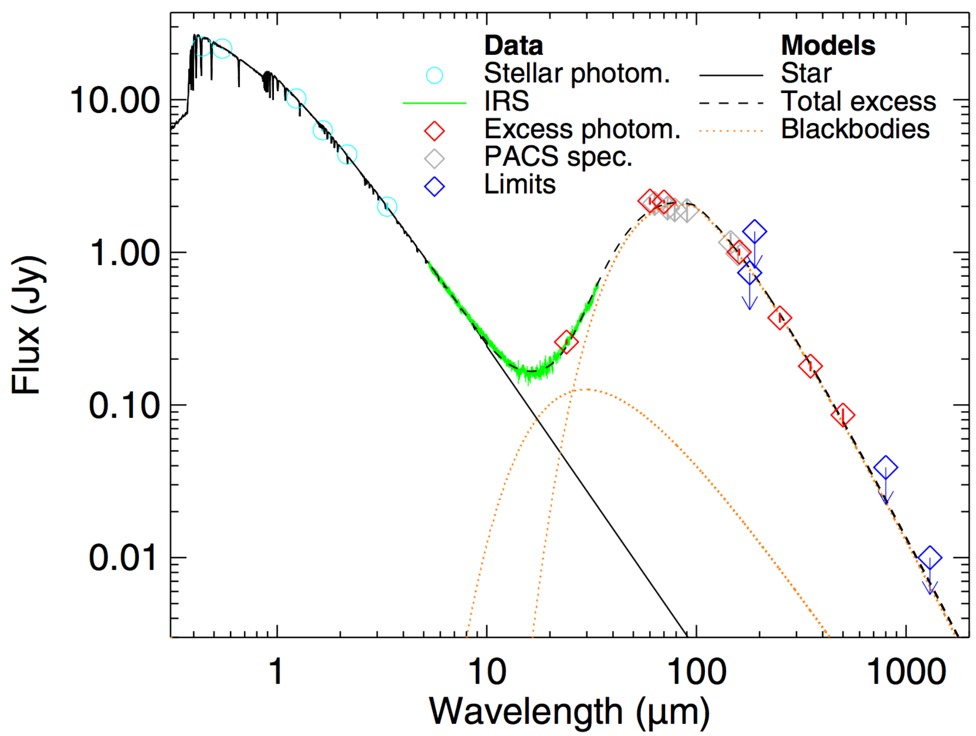
Circumstellar disks

	 Protoplanetary disk	 Debris disk
Age	< 10 Myr	10 Myr – 10 Gyr
Dust	primordial $> 10\ M_{\oplus}$ optically thick $L_{IR}/L_{bol} > 10^{-2}$	second generation $< 1\ M_{\oplus}$ optically thin $L_{IR}/L_{bol} < 5 \times 10^{-3}$
Gas	primordial gas/dust ratio = 100	secondary(?) very gas-poor
Geometry	broad disk	mostly narrow ring(s)

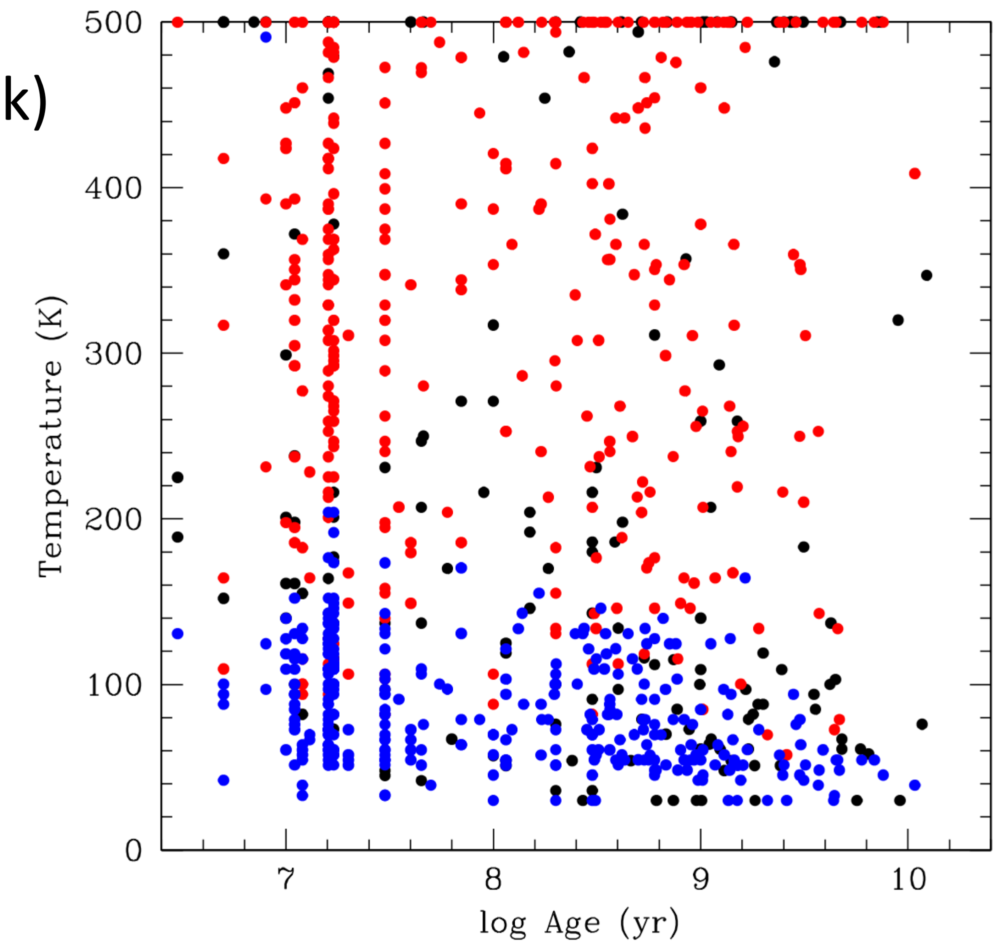
Characteristics of debris disks

- SED: single modified blackbody or two blackbodies
- Probably multiple dust belts

(see also G. Kennedy's talk)



(Roberge et al. 2013)

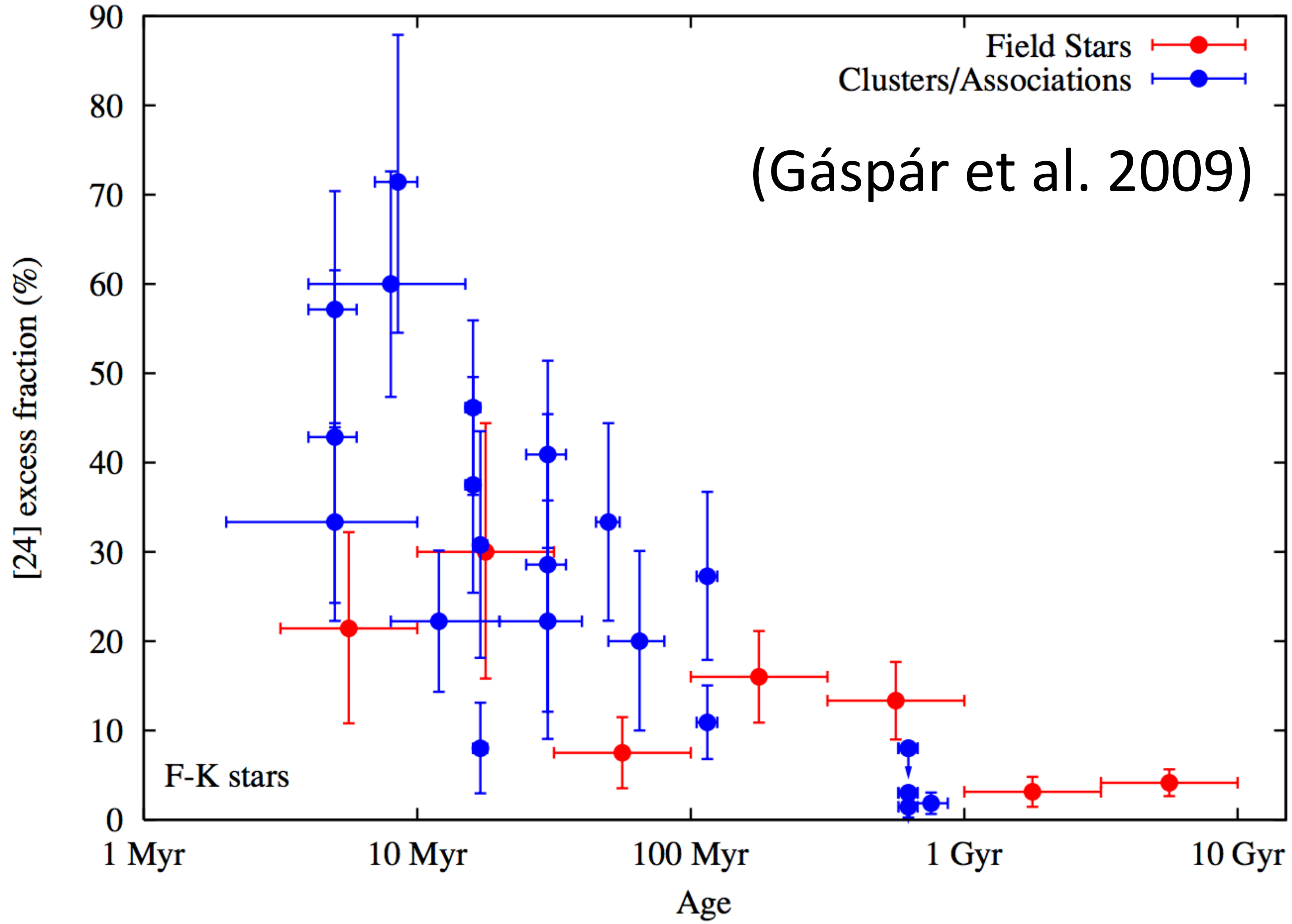


(Chen et al. 2014)

(Figure credit: Kate Su)

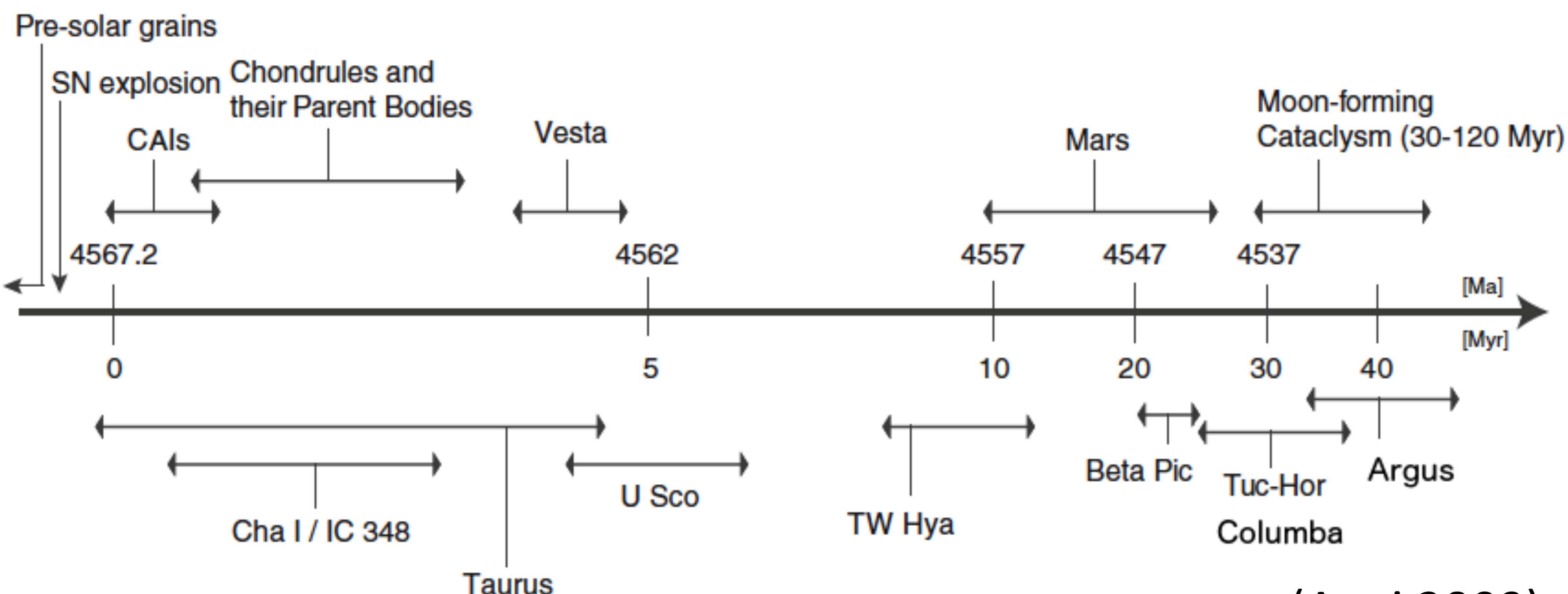
Debris disks in young moving groups

- Debris disks in YMGs are **more frequent and more massive** than around older field stars
- Many of the best studied debris disks are YMG members:
  HR 4796A (TWA)
  β Pic (BPMG)
  AU Mic (BPMG)
  49 Cet (Argus)
- They have precise, **reliable ages**, covering the 10–200 Myr range



YMGs: interesting evolutionary phase

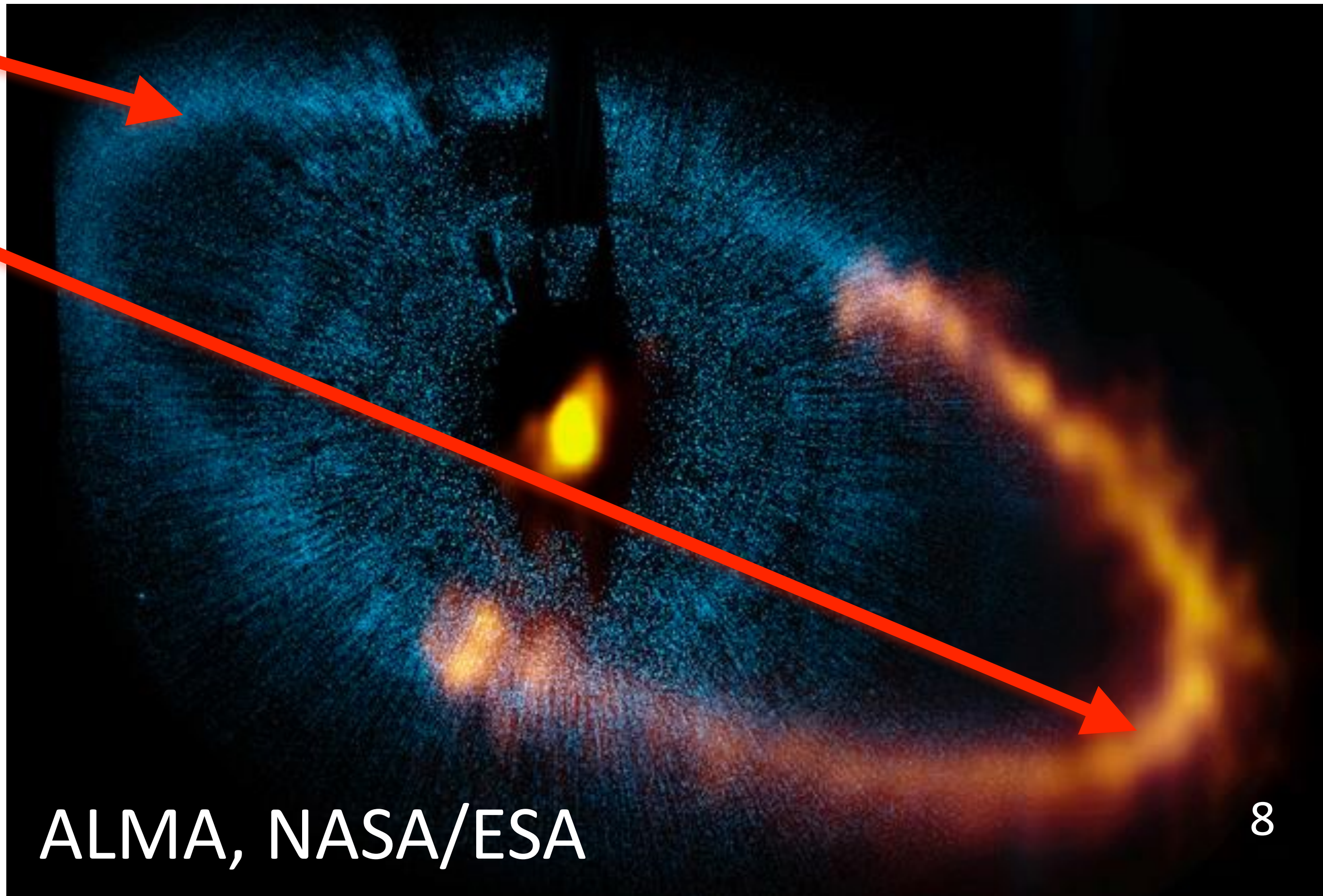
- Protoplanetary disks disappear
- Debris disks appear
- Terrestrial planets are forming (final accumulation)
- Coagulation of planetesimals in the outer region is on-going



(Apai 2009)

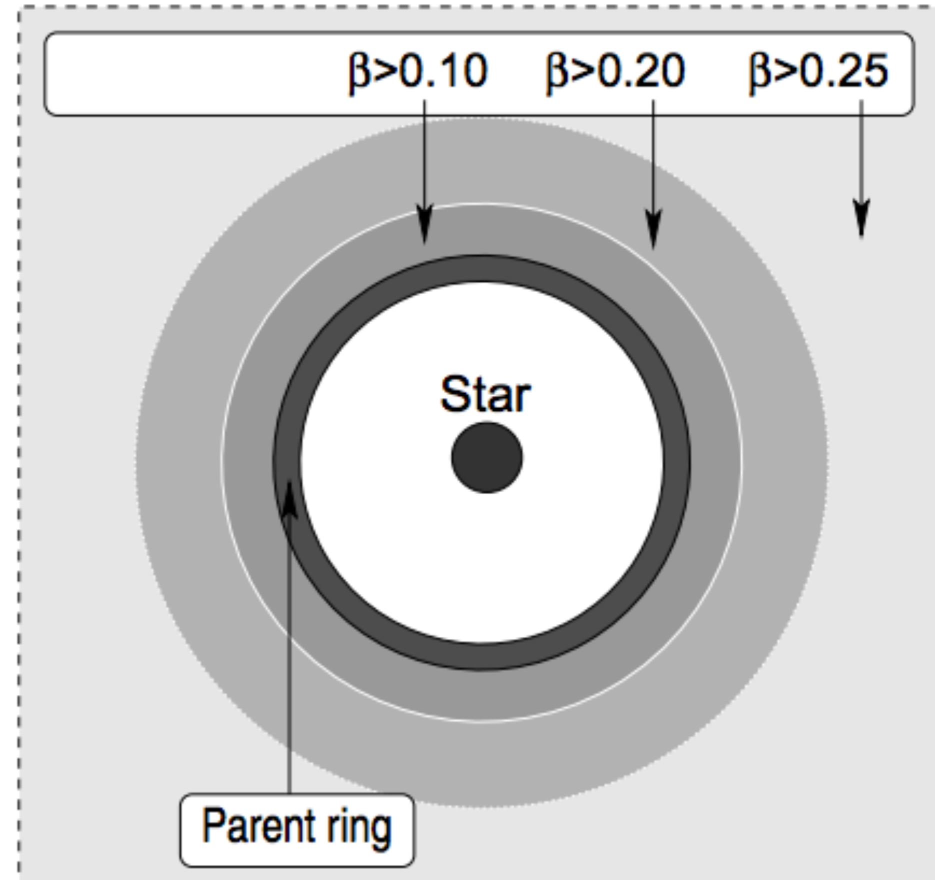
Spatially resolved data on debris disks

- Most debris disks are not spatially resolved → degeneracy in disk parameters
- Dust size + optical properties ↔ temperature ↔ radial location
- Resolved data on debris disks:
  - **scattered light** images
  - resolved **thermal emission**

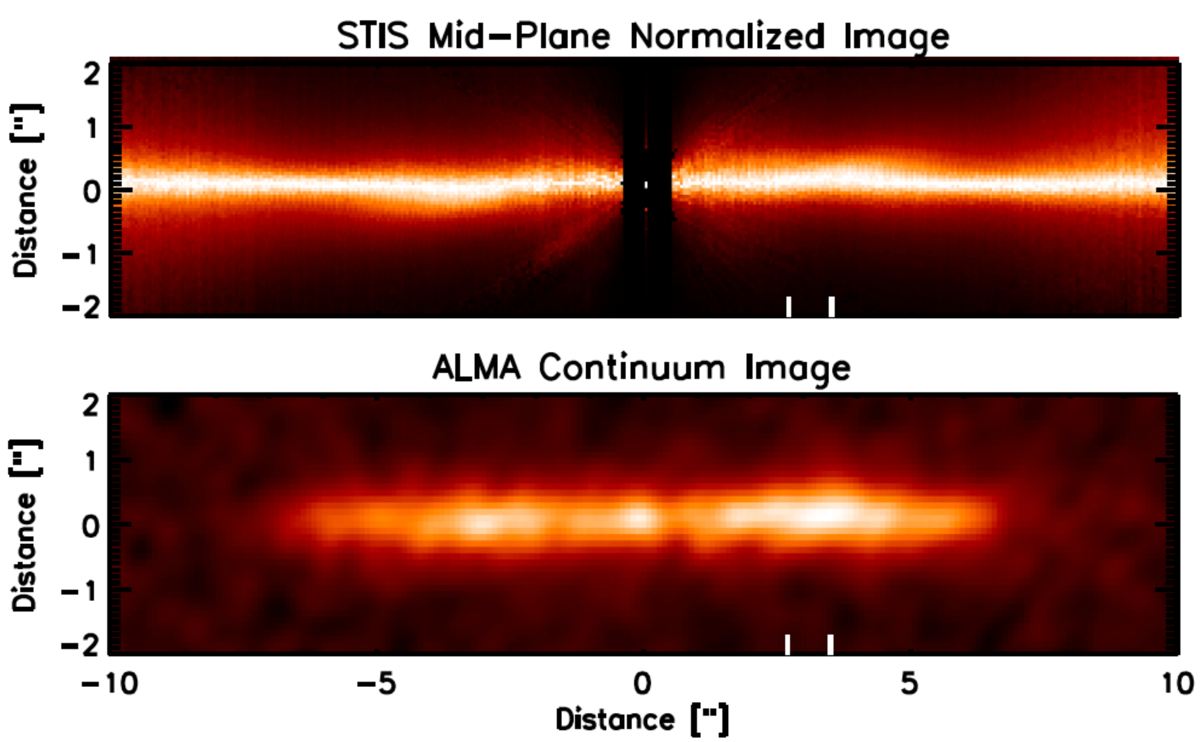


Scattered light vs. thermal emission

- **Scattered light**:
  sensitive to small dust →
  affected by radiation pressure
- **Millimeter emission**:
  trace mm-sized grains →
  trace the parent planetesimal belt



(Krivov 2010)



(Apai et al. 2015)

- Disk resolved in the mm before ALMA: only about a dozen, and not very well resolved

Atacama Large Millimeter/Submillimeter Array

Atacama Large Millimeter/Submillimeter Array

- 54 12m antennas + 12 7m antennas
- 0.4 - 3.1 mm (84 - 950 GHz)
- Spatial resolution: 0.03” - 3.4”
- Spectral resolution: 3.8 kHZ - 15.6 MHz (> 0.01 km/s)

ALMA and debris disks

- ALMA observations trace large dust grains → planetesimals
- ALMA can resolve debris disks in the close-by young moving groups
- Debris disks have low surface brightness, but ALMA is very sensitive
- Can detect both the continuum and line emission in one setup

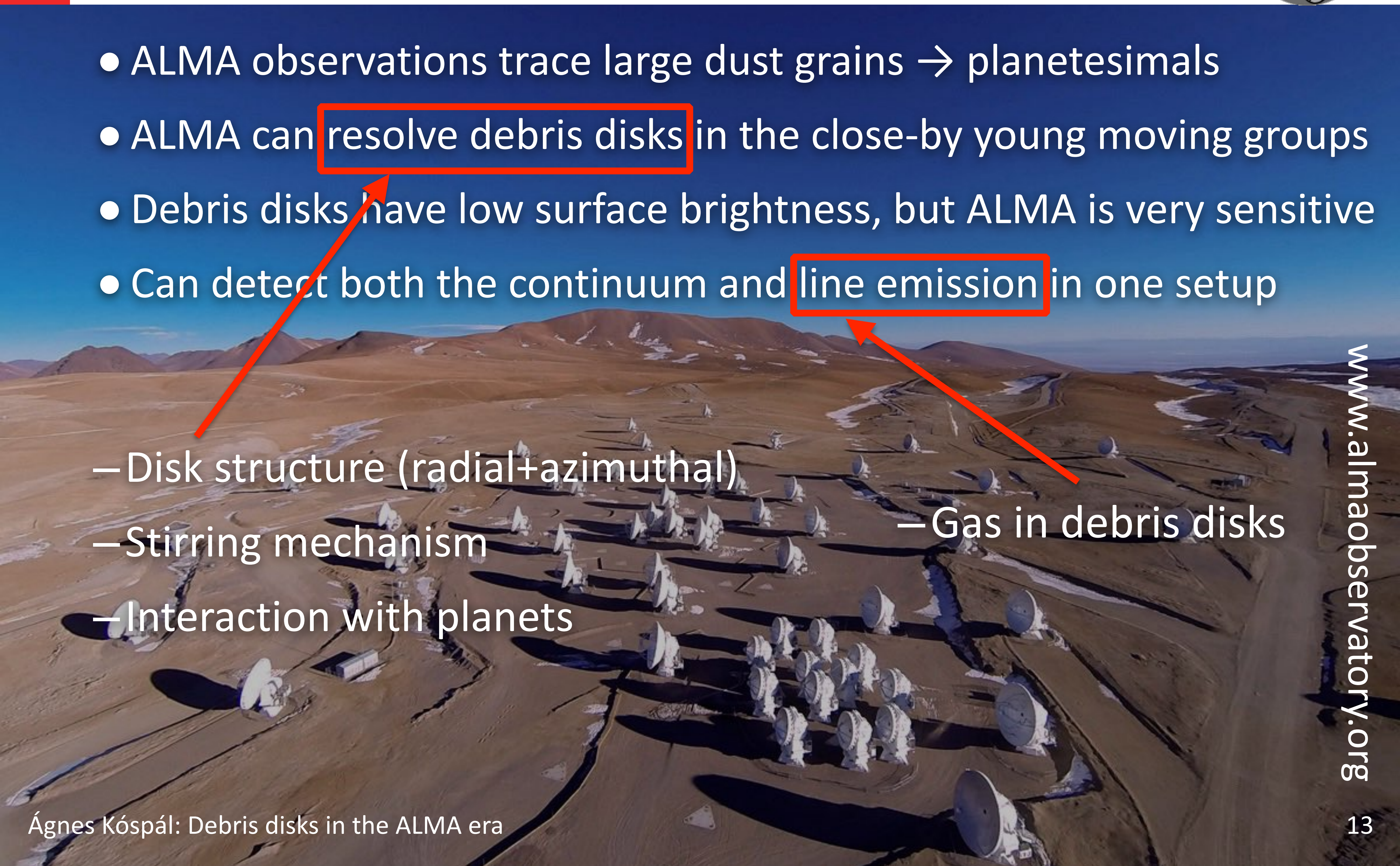
www.almaobservatory.org

ALMA and debris disks

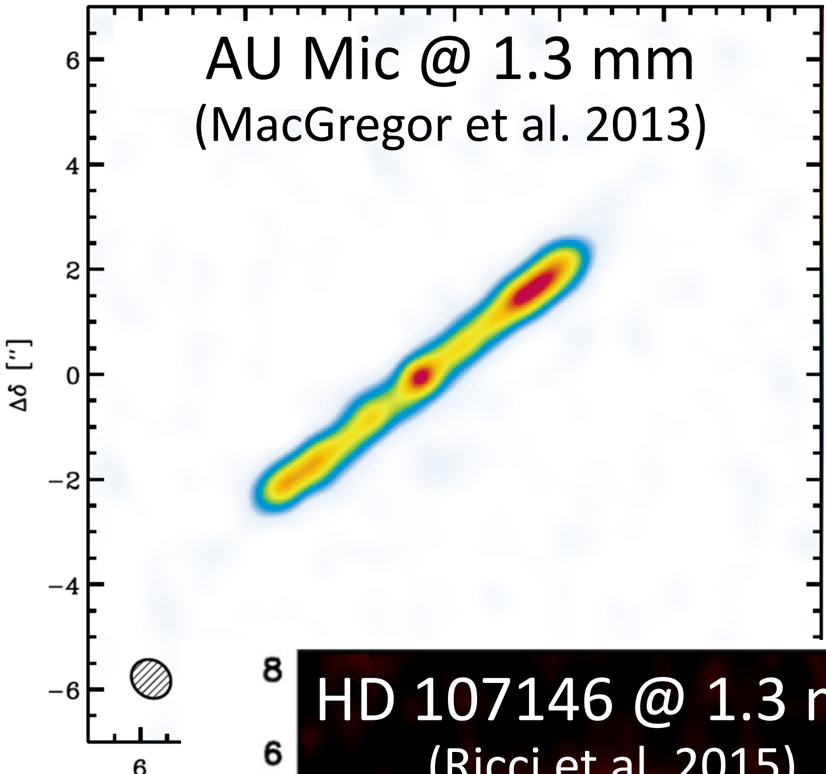
- ALMA observations trace large dust grains → planetesimals
- ALMA can resolve debris disks in the close-by young moving groups
- Debris disks have low surface brightness, but ALMA is very sensitive
- Can detect both the continuum and line emission in one setup

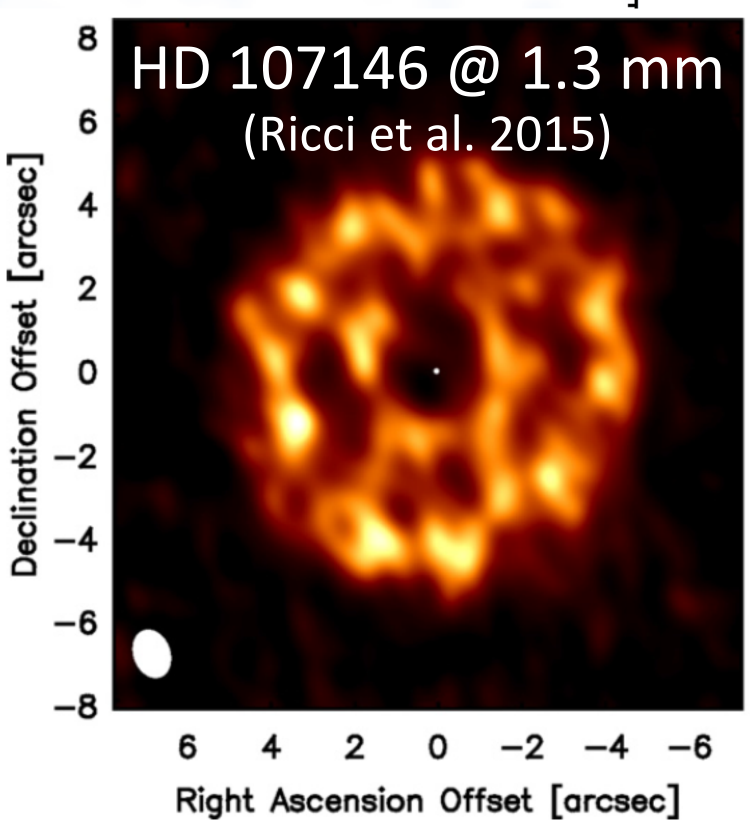
  – Disk structure (radial+azimuthal)
  – Stirring mechanism
  – Interaction with planets

  – Gas in debris disks

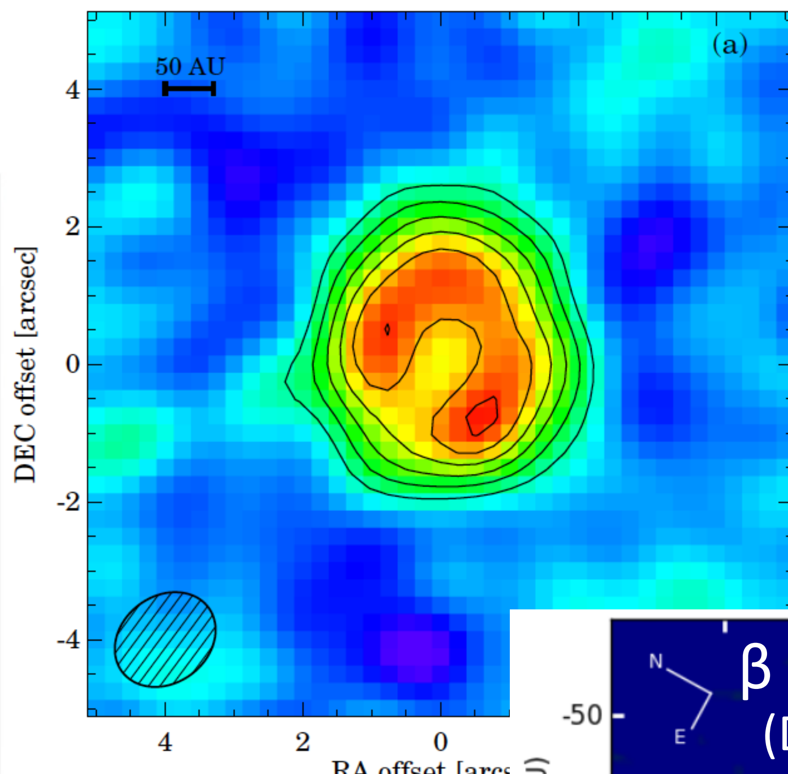


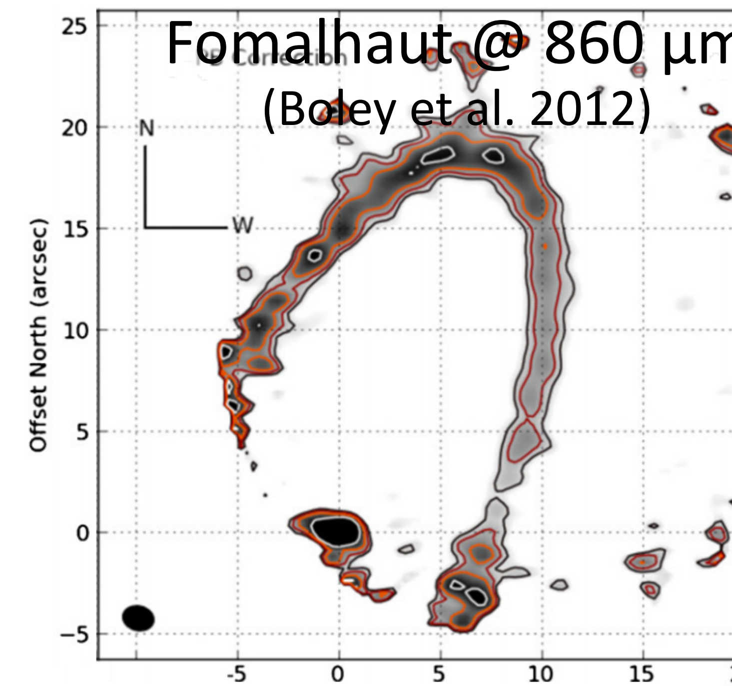
ALMA gallery of resolved debris disks

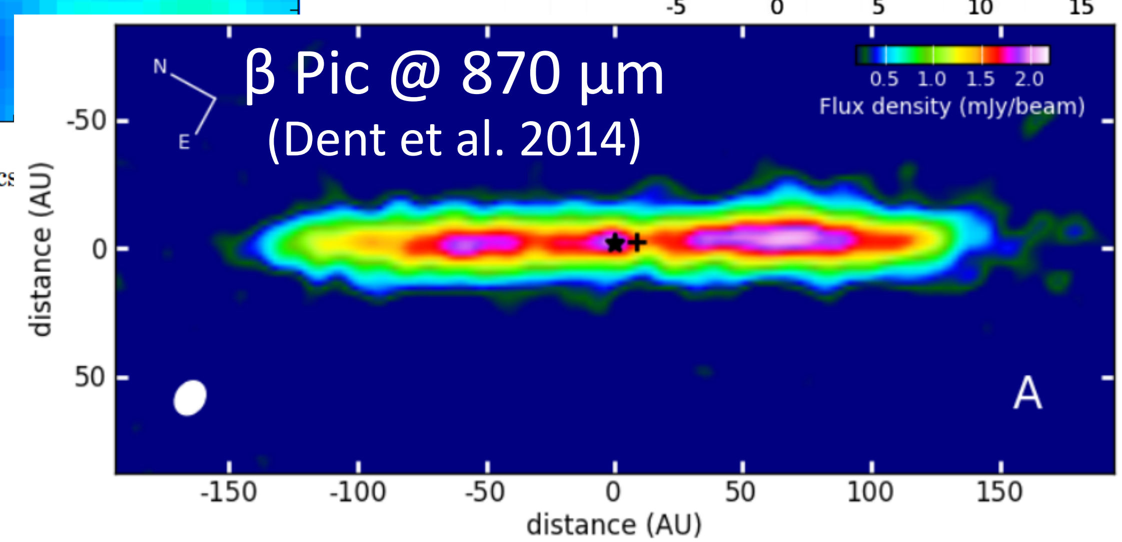




HD 21997 @ 890 μm
(Moór et al. 2013)





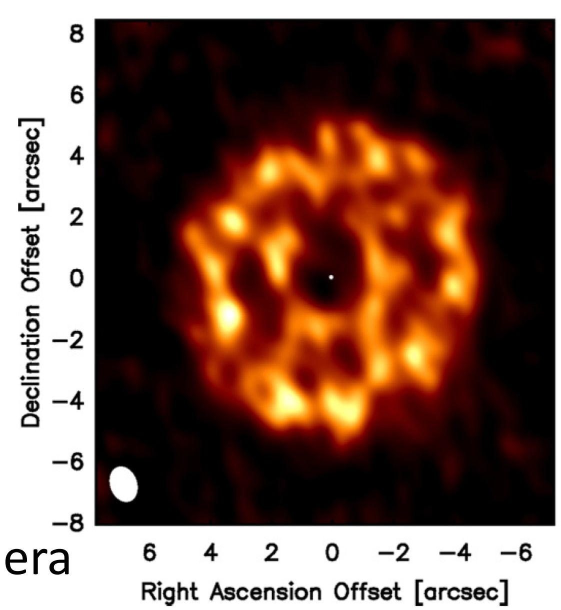


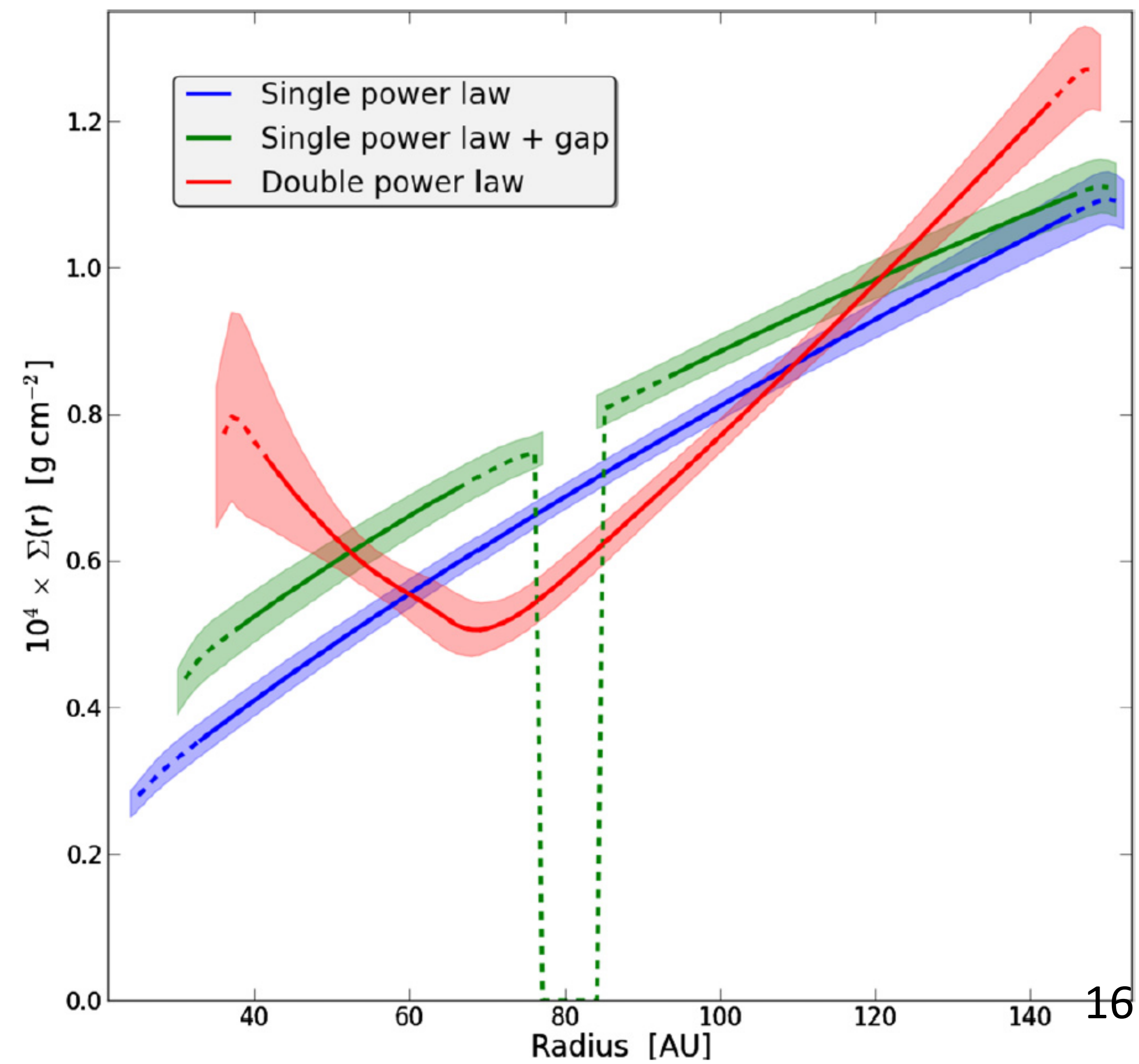
Dust production in debris disks

- The **lifetime** of debris dust grains is very short due to radiation pressure
- Dust grains are **continuously replenished** through collisions between planetesimals
- For **destructive collisions**, the collision velocity must exceed a certain critical value
- For such high velocities, the planetesimals need to be dynamically stirred
- Proposed **stirring** mechanisms:
  - self-stirring (Kenyon & Bromley 2004)
  - planetary stirring (Wyatt 2005, Mustill & Wyatt 2009)

Predictions of stirring models I

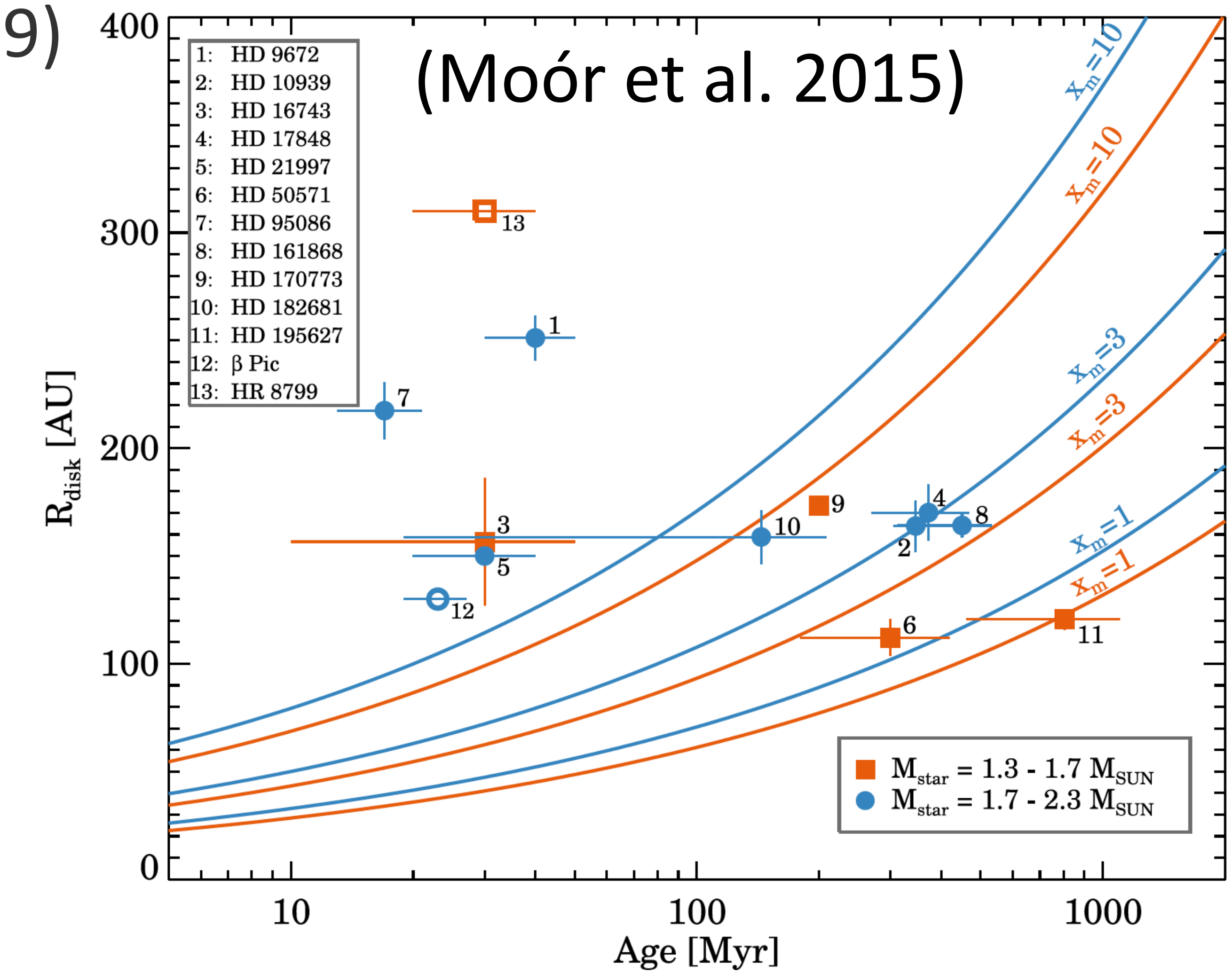
- Self-stirring & planetary stirring with an “inner” planet: collisional cascade is ignited in the inner disk first, propagates outwards → inside-out process
- Consequence: **rising surface density profile** (Kennedy & Wyatt 2010)
- ALMA observations confirm this:
  - AU Mic (BMPG, 20 Myr): $\Sigma \sim r^{2.8}$ (MacGregor et al. 2013)
  - HD 107146 (80-200 Myr): Ricci et al. 2015





Predictions of stirring models II

- Self-stirring model: the pace of outward propagation of collisional cascade is **faster** for more massive disks
- Consequence: existence of dust-producing planetesimals at large radii in a young system requires very large initial disk masses → check the "feasibility" of self-stirring with ALMA (see also L. Vican's poster #3.09)
- **Too large disks are good candidates for planet searches**
  - HR 8799 (Columba)
  - HD 95086 (LCC)
  - β Pic (BPMG)

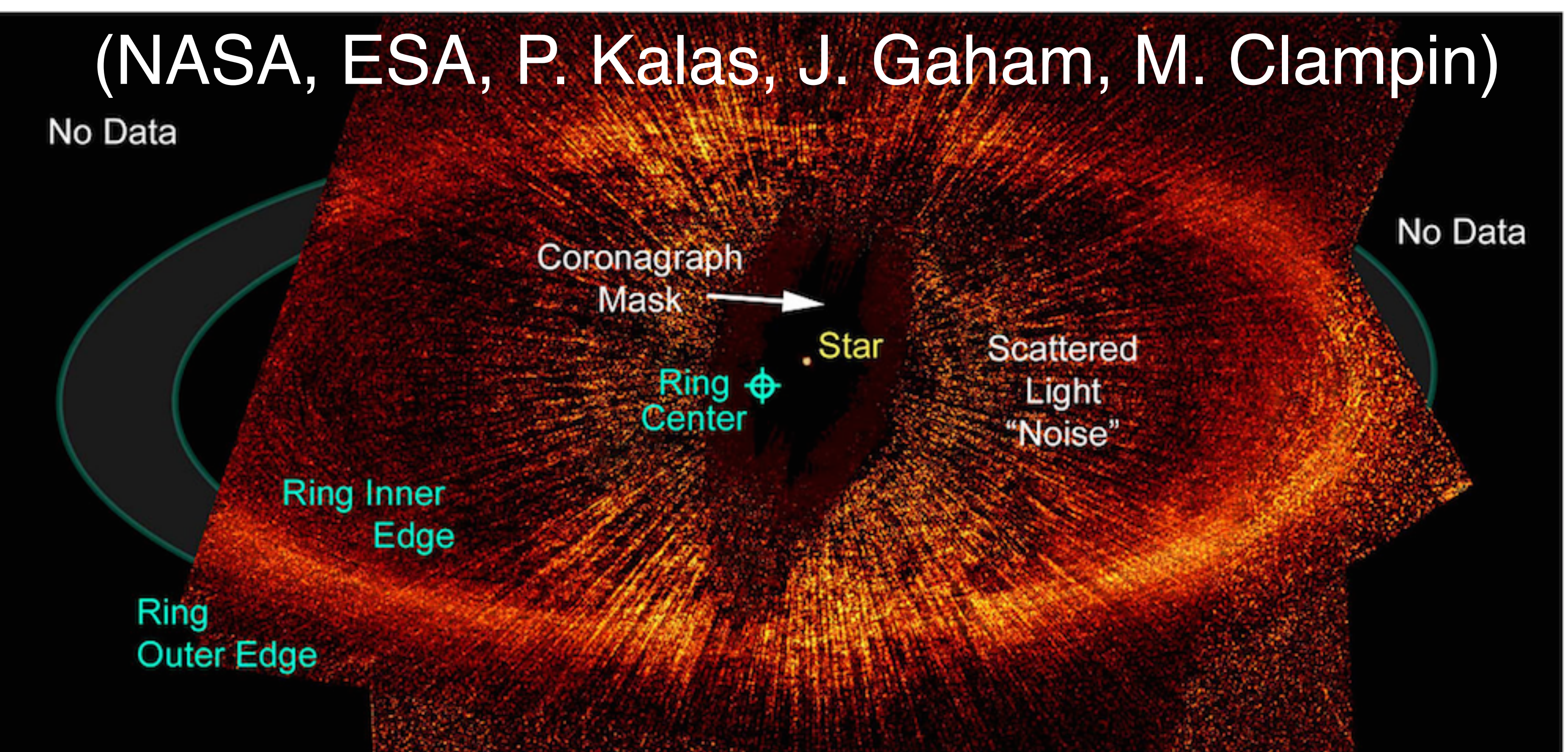


Planet-disk interactions

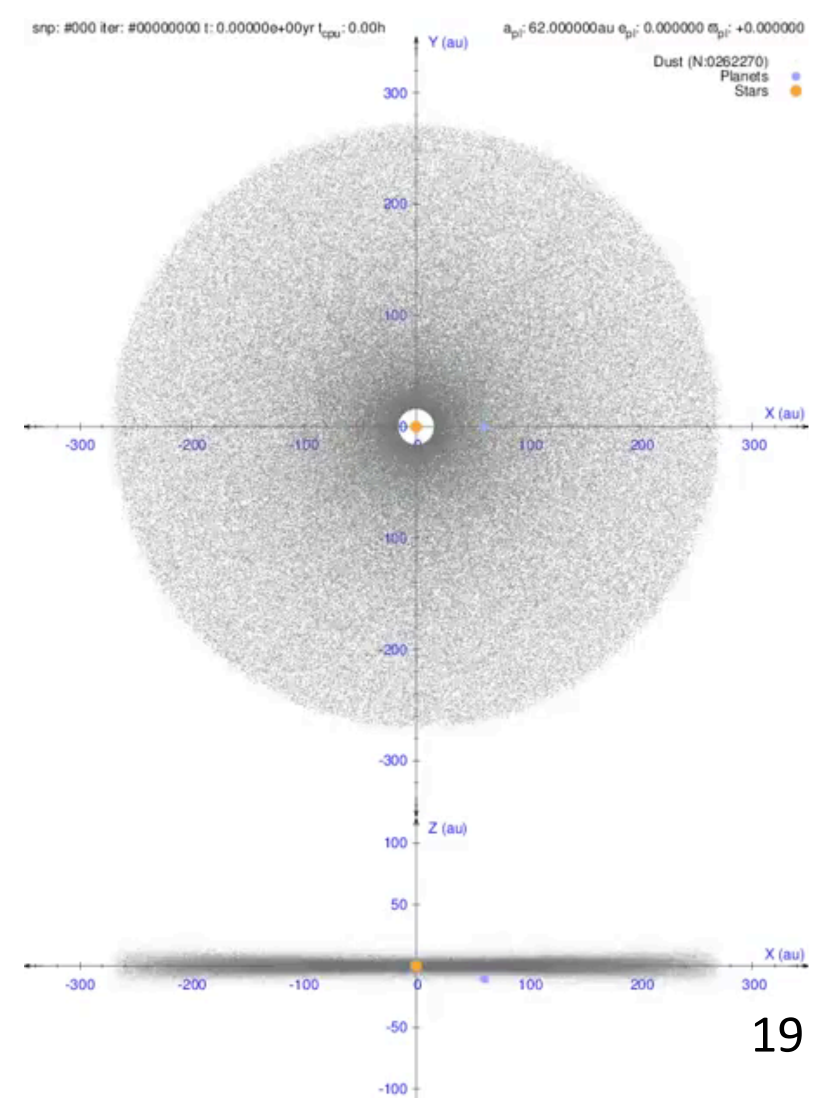
- In the planetary stirring model, the planets exert secular perturbations on the planetesimals → leads to stirring
- Other perturbations that have observable effects on the disk structure:
    - **Secular perturbations**
    - **Resonant perturbations**

Secular perturbations

- **Eccentric** planet causes: tightly wound spiral in the disk; eccentric debris ring
- **Inclined** planet causes: spiral + warp in the disk
- Disk structure can be used to deduce the planet’s **orbital parameters**



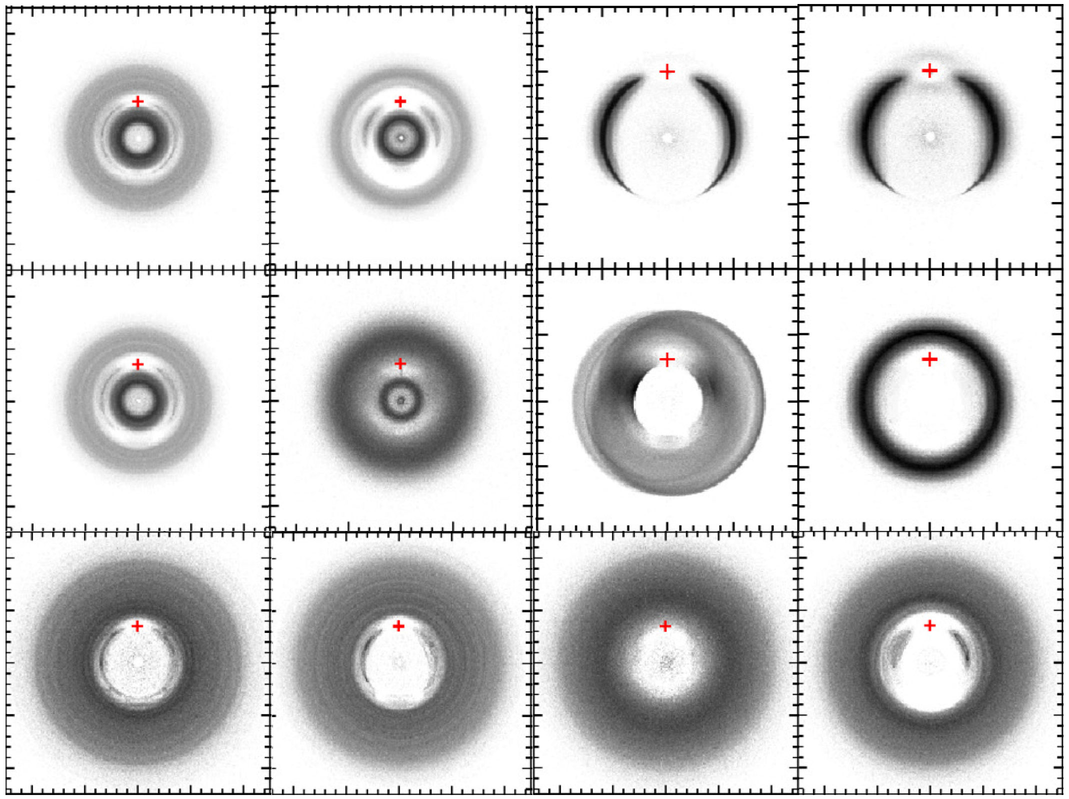
(NASA, ESA, P. Kalas, J. Gaham, M. Clampin)



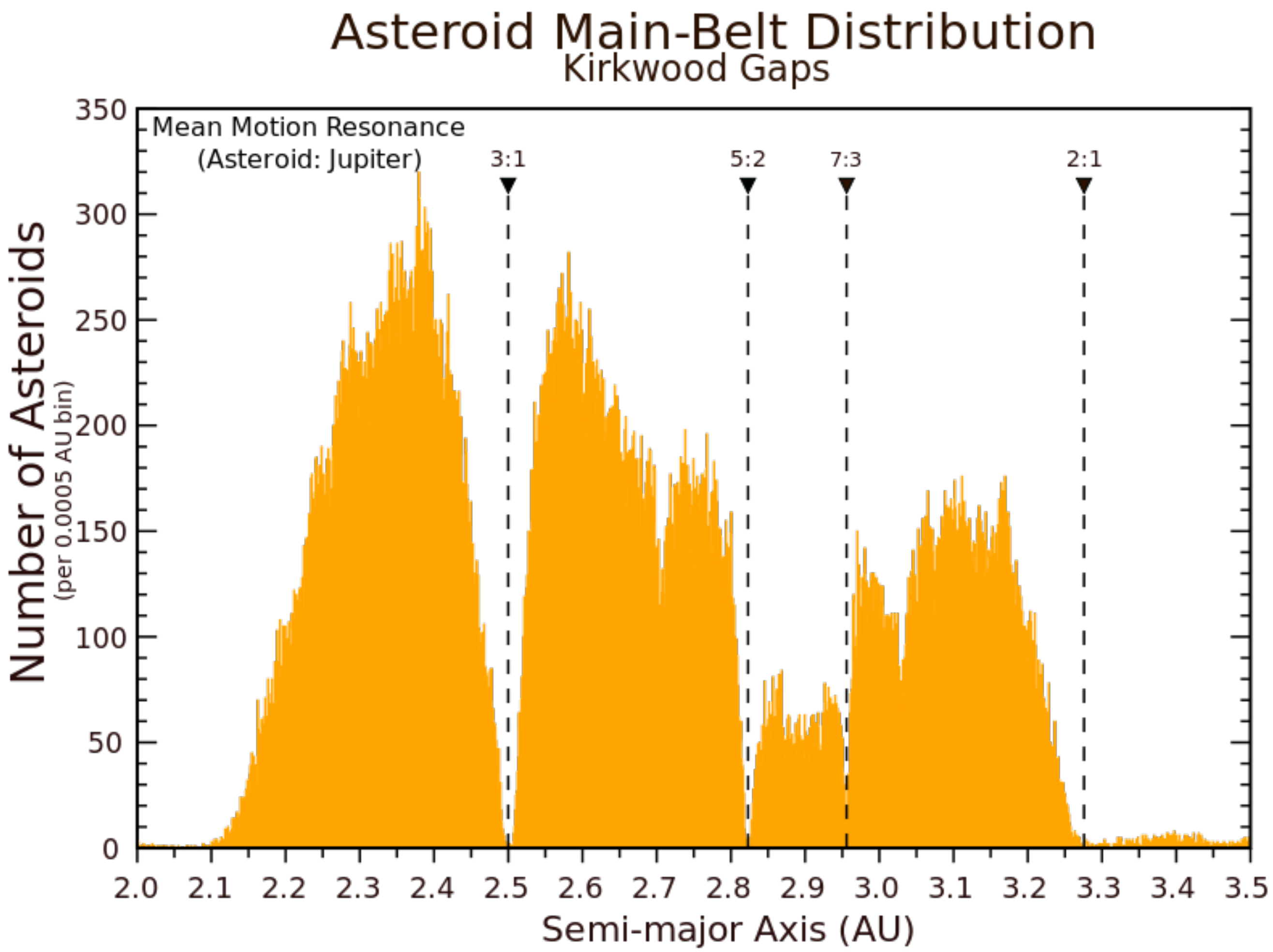
(Movie credit: Zs.Regály)

Resonant perturbations

- May lead to **structures** like the Kirkwood gaps in the Solar System
- Certain zones are empty, others collect planetesimals
- Can cause sharp inner edge
- Can cause special patterns



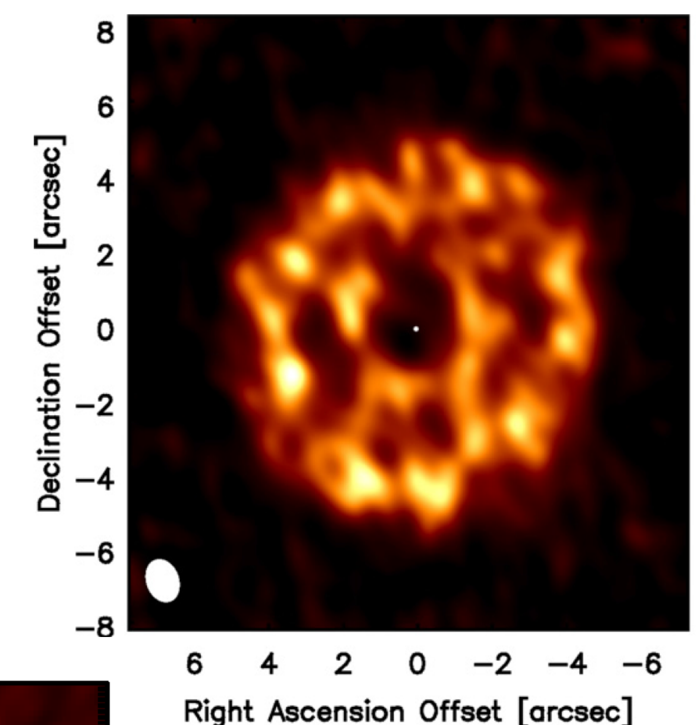
(Ertel et al. 2012)



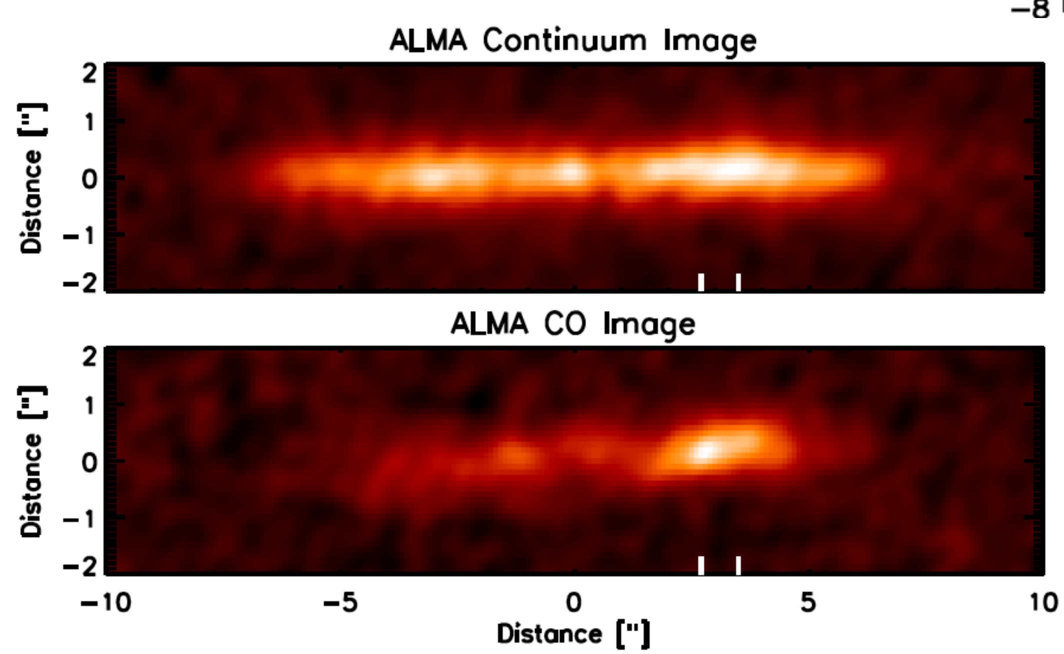
(Figure credit: A. Chamberlain)

Observational evidence for interactions?

- **Clumpy structure** is often observed (pre-ALMA)
- In some cases these couldn't be confirmed (e.g. Vega, Marsh et al. 2006, Hughes et al. 2012)
- In other cases, the observed structures may be robust (ε Eri, Lestrade & Thilliez 2015)
- ALMA results:
  - possible gap in HD 107146
  - clump in β Pic



(Ricci et al. 2015)



(Apai et al. 2015)

Open questions about the dust

- Are debris rings / planetesimal belts really narrow in most cases?
- Are the measured location, width, radial density profile of debris rings consistent with the predictions of different stirring models? What's the dominant stirring mechanism?
- What fraction of debris disks show signs of planet-disk interaction? Does it depend on stellar parameters? What kind of interactions are dominant?
- For systems with known directly imaged planet, are the planet parameters consistent with what the observed disk structure implies? Are the planetesimal belts always wide?

Gas in debris disks

- Debris disk ↔ dust grains
- Debris disk = gas-poor disk (but how poor is poor?)
- Icy planetesimals are expected to release gas when they collide or migrate into warmer regions!
- Not much volatiles, not very efficient production mechanisms → not much gas production
- Very few gaseous debris disks are known
- For a long time, the only example had been **β Pic** (circumstellar gas first suspected by Slettebak 1975)

β Pictoris.—The spectrograms show a normal, fairly rapidly rotating ($v \sin i = 120$ km s^{-1}) A5 IV star, but with very strong, sharp, and deep absorption components of Ca II H and K centered within the normal, broadened H and K lines. The spectrum is similar to that of α Oph, in which interstellar Ca II K was pointed out by Münch and Unsöld (1962), but the sharp absorption components are much stronger in β Pic than in α Oph. They are evidently of interstellar or circumstellar origin. Dr. Arlo Landolt very kindly measured *UBVRI* colors for β Pic in 1974 April, and these correspond to the colors of a normal A5 star.

Gaseous debris disks

Name	Spectral type	Age	Membership	Fractional luminosity	Detected lines
β Pic	A6	20 Myr	β Pic	2.6×10^{-3}	CO, CII, CI, OI, …
49 Cet	A1	40 Myr	Argus	1.1×10^{-3}	CO, CII, CI
HD 21997	A3	30 Myr	Columba	5.7×10^{-4}	CO
HD 172555	A7	20 Myr	β Pic	7.4×10^{-4}	OI
HD 32297	A0	15-500 Myr	Field	4.4×10^{-3}	CII
eta Tel	A0	20 Myr	β Pic	2.4×10^{-4}	CII
HD 131835	A2	16 Myr	UCL	3.0×10^{-3}	CO

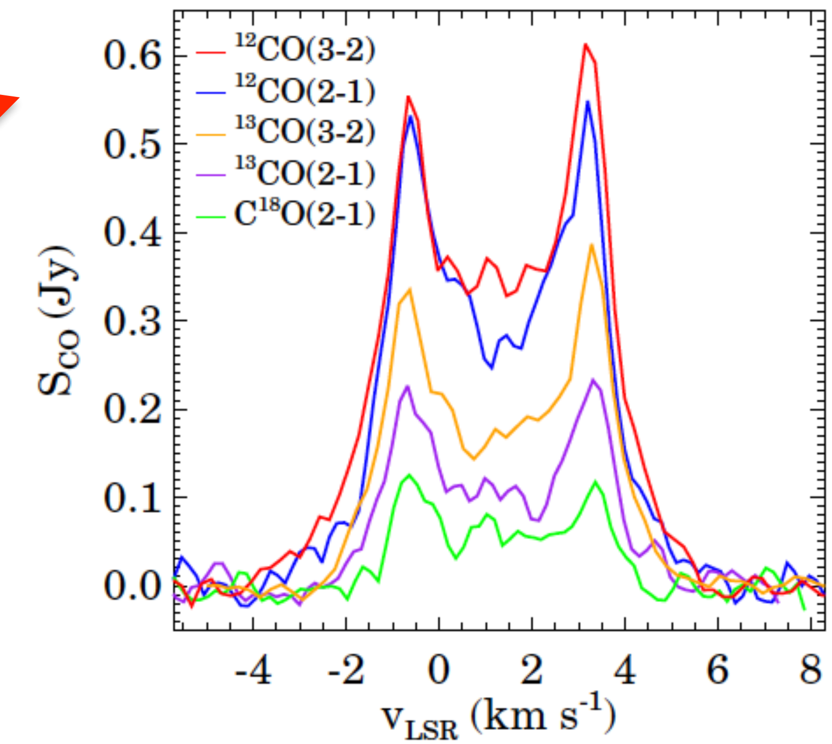
Gaseous debris disks

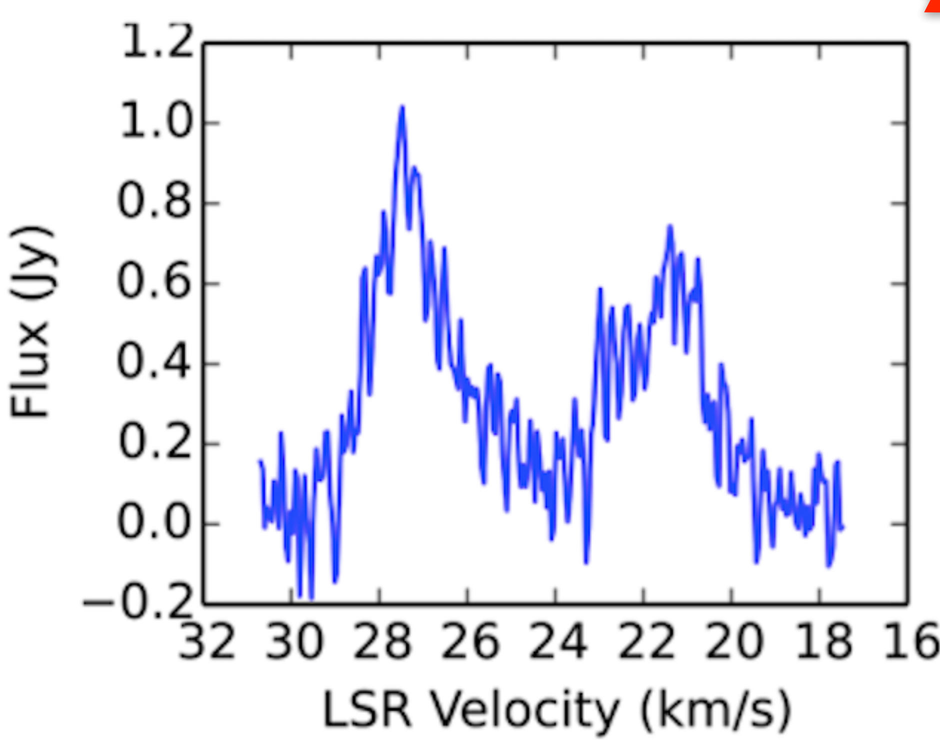
Pre-ALMA results:

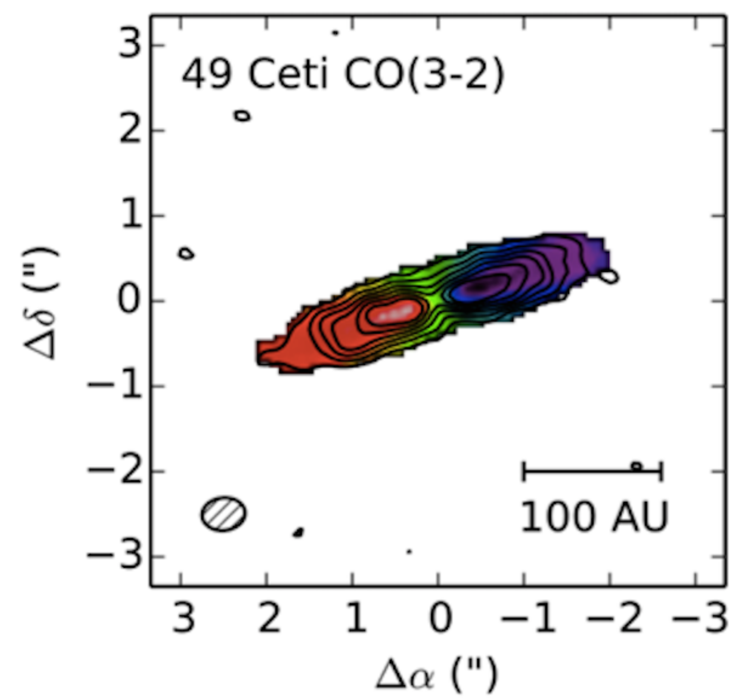
- All stars are young
- All stars have A spectral type
- With one exception, all have high (> 5×10^{-4}) fractional luminosity
- Within 125 pc, there are 9 young, A-type stars with bright ($L_{IR}/L_{bol} > 5 \times 10^{-4}$) debris disks, 6 of them contain gas
- β Pic, Columba, Argus moving groups' brightest members all contain gas
- **Gas in young massive debris disks around A-type stars is frequent**

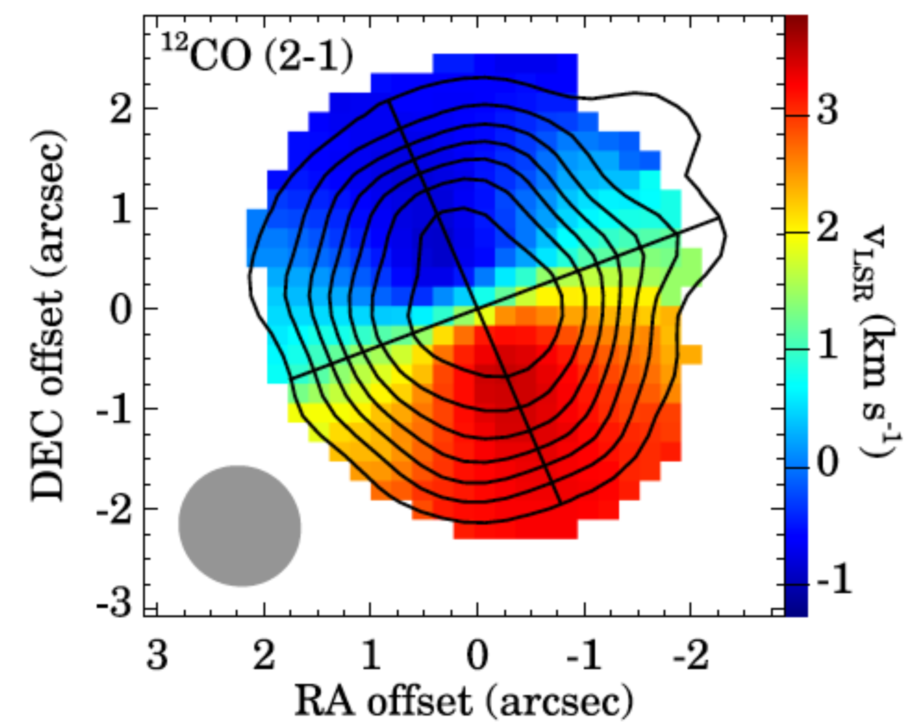
ALMA survey of young debris disks I

- **2011.0.00780 (PI: Á. Kóspál)**
  - HD 21997
- **2012.1.00195 (PI: M. Hughes)**
  - 49 Cet









ALMA survey of young debris disks II

- **2012.1.00688 (PI: J. Carpenter)**
  - 23 BAF-type stars in Sco-Cen
  - 3 detected in gas (CO J=2−1)
- **2012.1.00437 (PI: D. Rodriguez)**
  - 10 debris disks in nearby moving groups
  - No detection
- **2013.1.00457 (PI: D. Rodriguez)**
  - 15 low-mass members of TWA
  - One detected in gas (CO J=2−1)

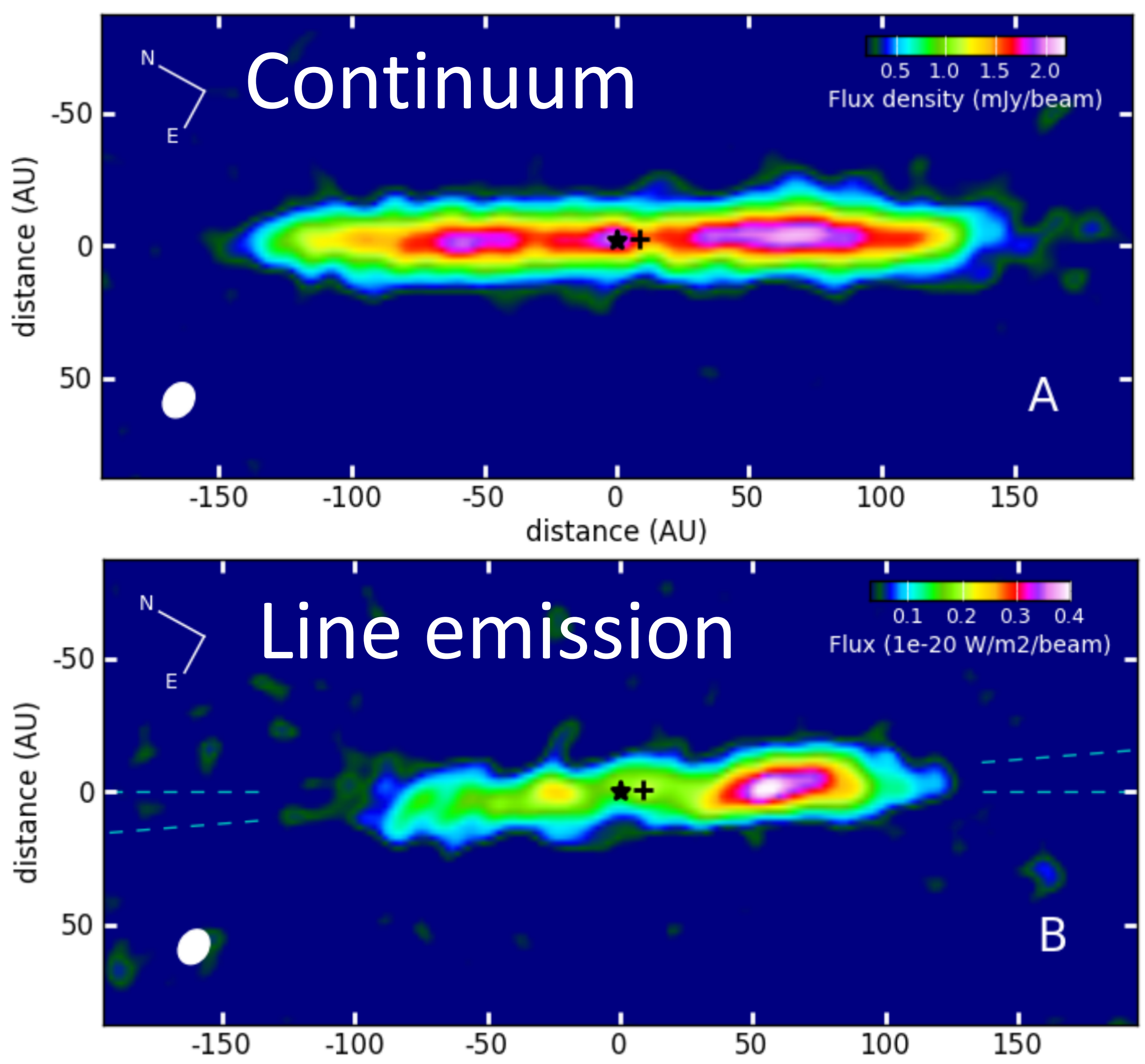
(see also D. Rodriguez' poster #1.13)

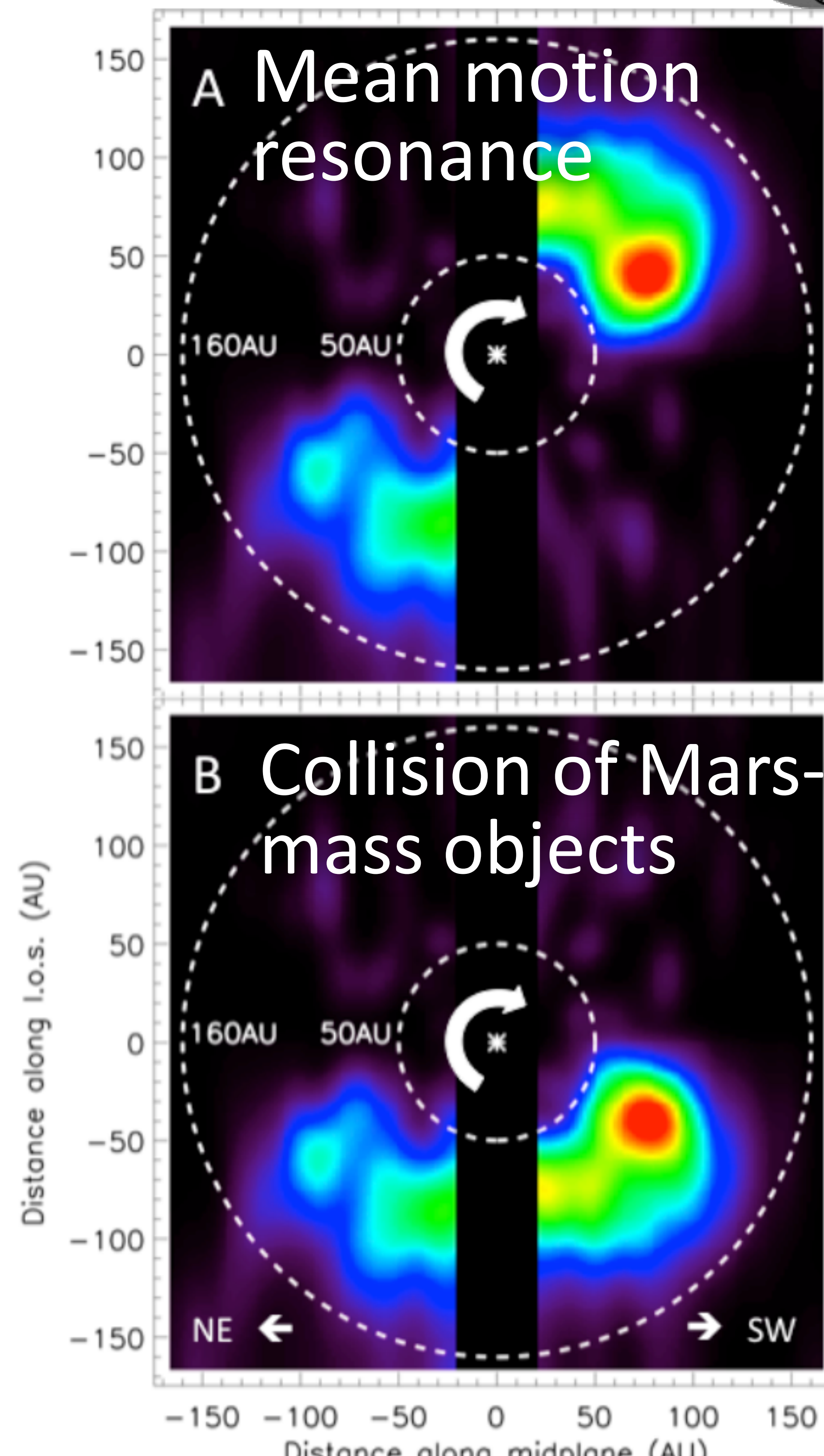
Origin of gas in young debris disks

- Gaseous debris disks are young → information about the protoplanetary/debris transition, and the very beginning of the debris disk evolution
- Gas can be **secondary**
  - sublimation of planetesimals, photodesorption from dust grains, vaporization of colliding dust particles, collision of comets or icy planetesimals
  - examples: β Pic, HD 172555, eta Tel, HD 32297
- Gas can be **primordial**
  - hybrid disks
  - example: HD 21997

Secondary gas: β Pic (Dent et al. 2014)

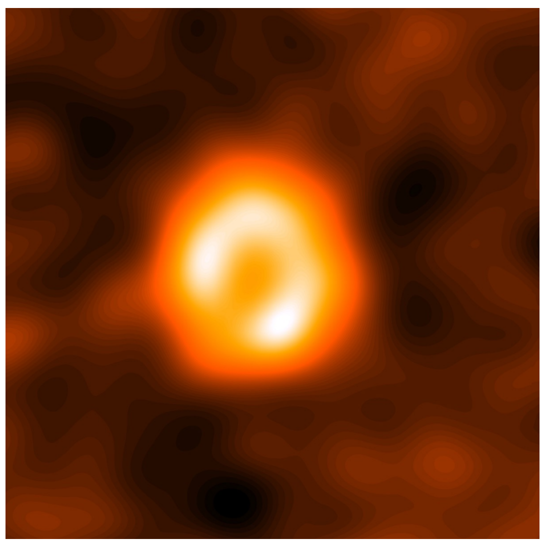
- Dust mass: 6.4 M_{Moon}
- CO gas mass: 0.003 M_{Moon}
- 30% of gas in a **clump**



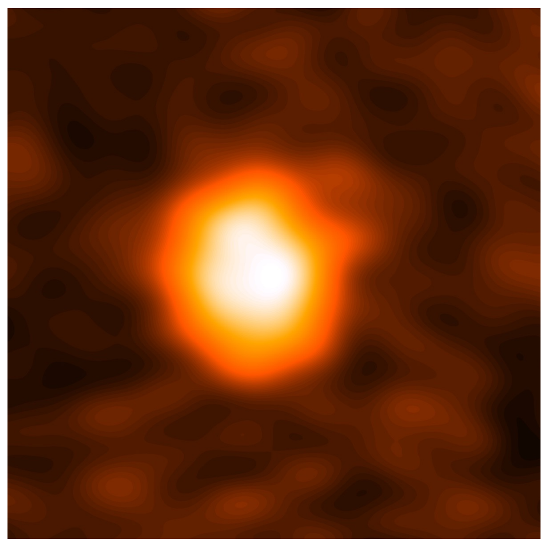


Hybrid disk: HD 21997 (Kóspál et al. 2013, Moór et al. 2013)

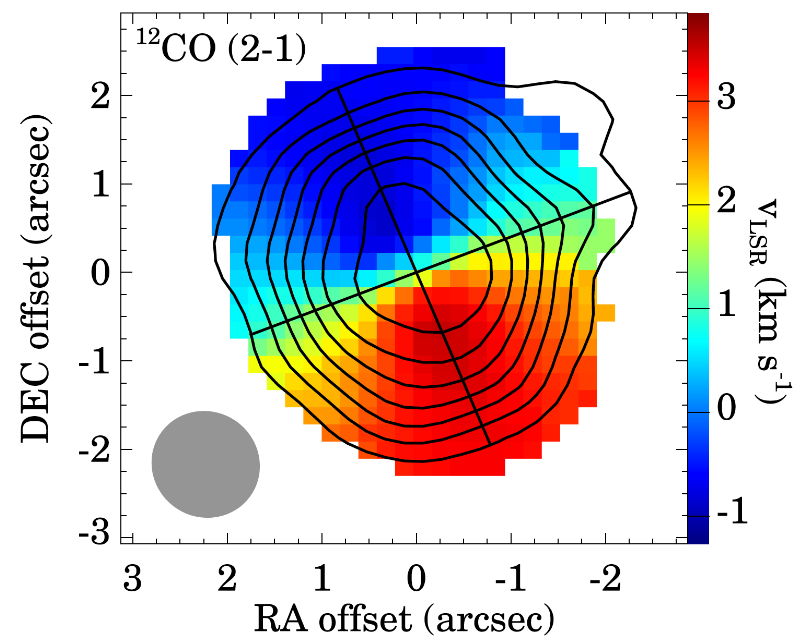
880 μm dust continuum



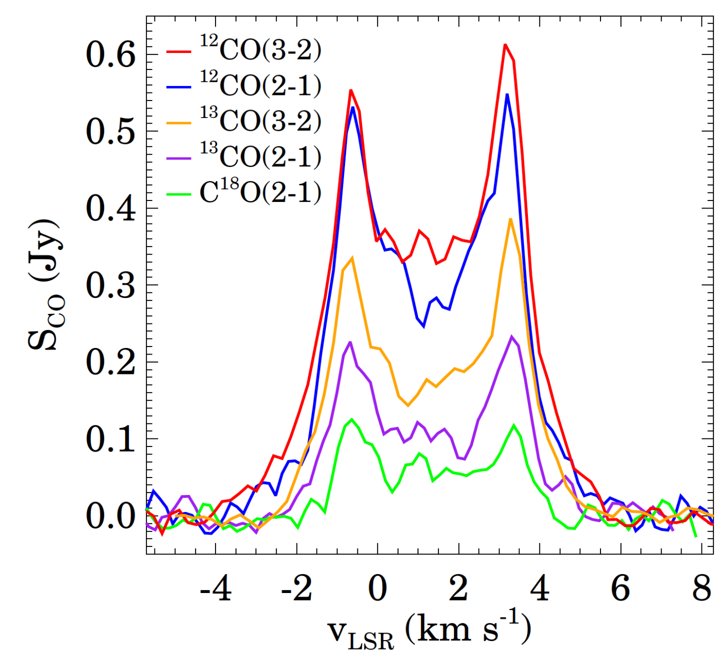
^{12}CO(2-1) gas line



gas velocity field



integrated line profile



- Dust mass: 7.3 M_{Moon}
- CO gas mass: 4.9 M_{Moon} (based on optically thin $C^{18}O$ detection)
- Secondary gas scenario: gas production rate needs to be too high
- Primordial gas scenario: possible;
  total gas mass: 40 $M_{\oplus}$ (3250 M_{Moon})

Gas in older debris disks?

- **HD 107146** (Ricci et al. 2015)
  - 80-200 Myr
  - search for gas lines with ALMA – no detection
  - upper limit for CO mass: 0.00015 M_{Moon}
  - CO-to-dust mass ratio: < 10^{-5} → smaller than even in β Pic
- **Fomalhaut** (Matrà et al. 2015)
  - 440 Myr
  - search for gas lines with ALMA – no detection
  - upper limit for CO mass: 0.0002 M_{Moon}
  - CO-to-dust mass ratio: < 10^{-4} → smaller than even in β Pic

Open questions about the gas

- Is there gas only around A-type stars? If yes, why?
- What is the frequency of hybrid disks? How long can the primordial gas last?
- What is the composition of the gas? Other molecules (HCN, HCO^+)?
- What is the dominant gas production mechanism in case of secondary gas?
- How does the gas evolve?

→ **Lots of work for ALMA!**