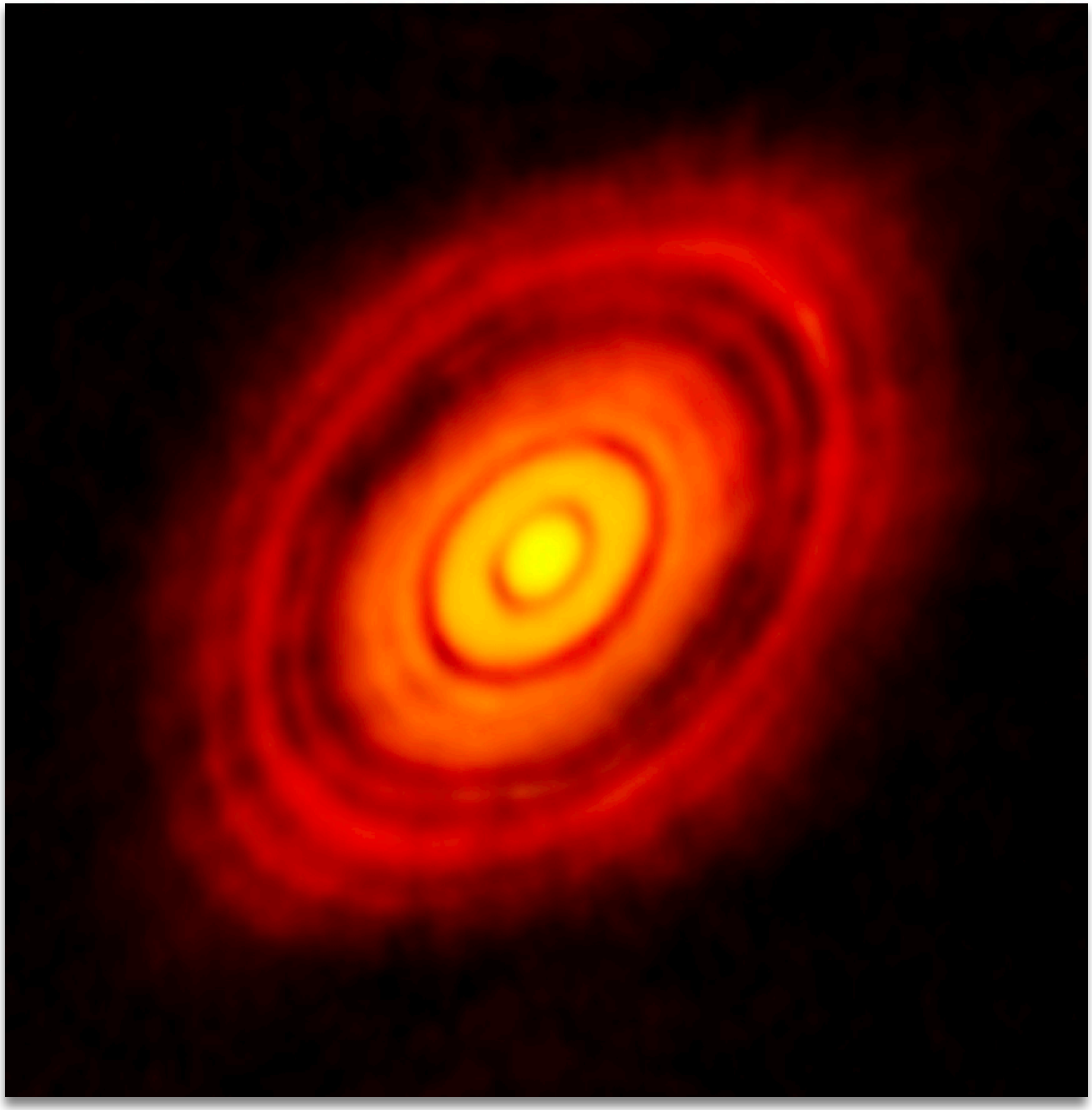
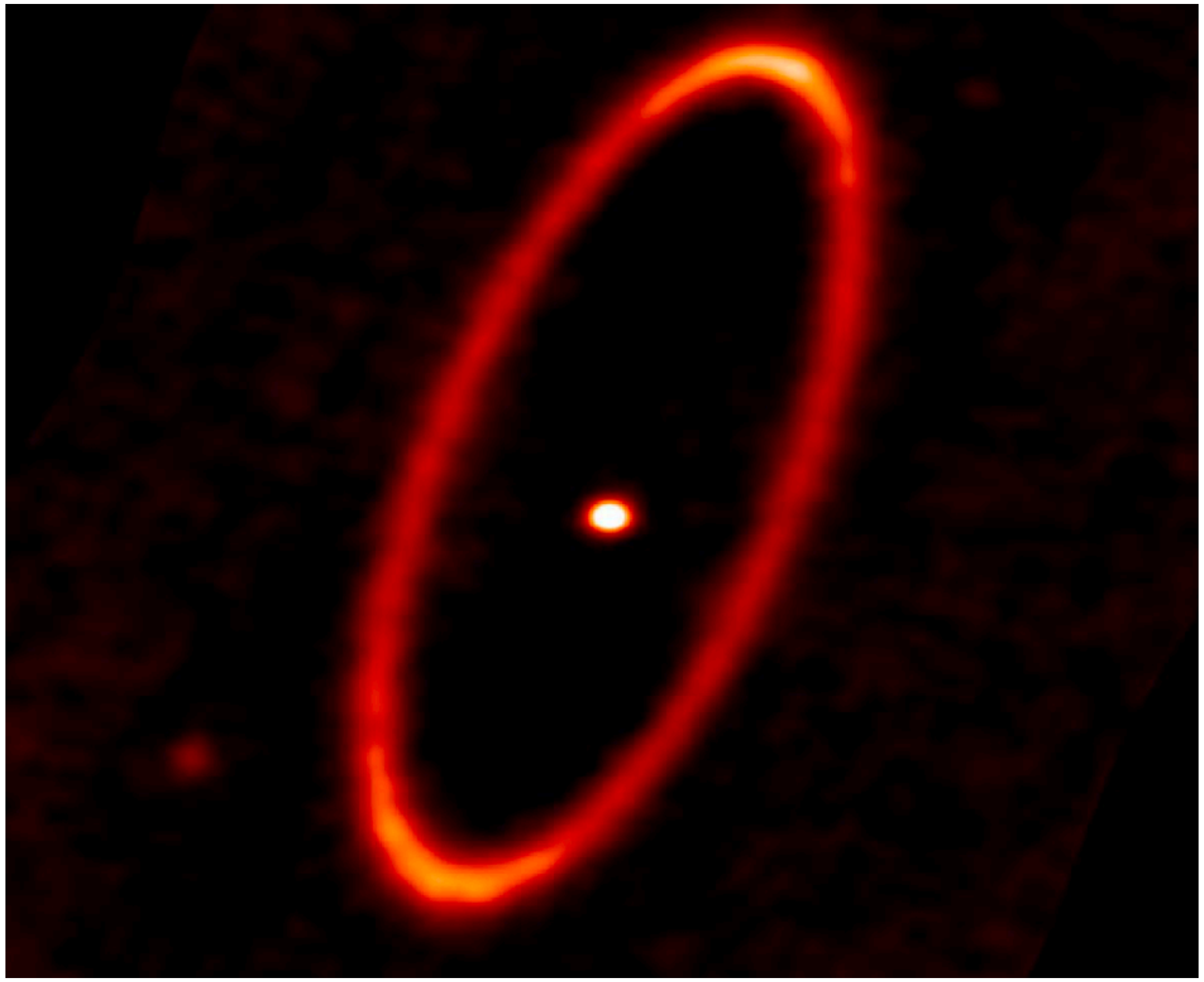
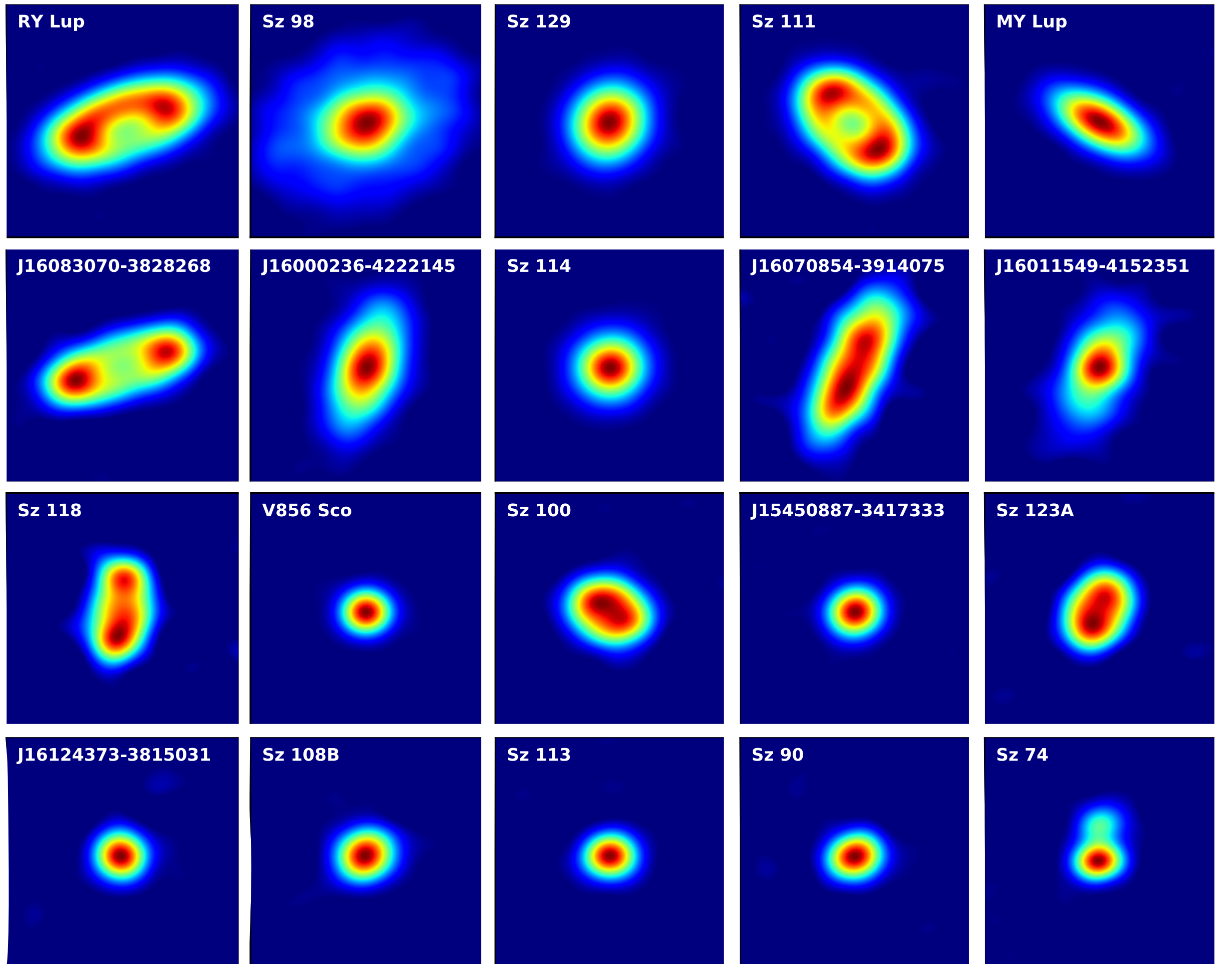
Protoplanetary Disks:
Updates from Observations

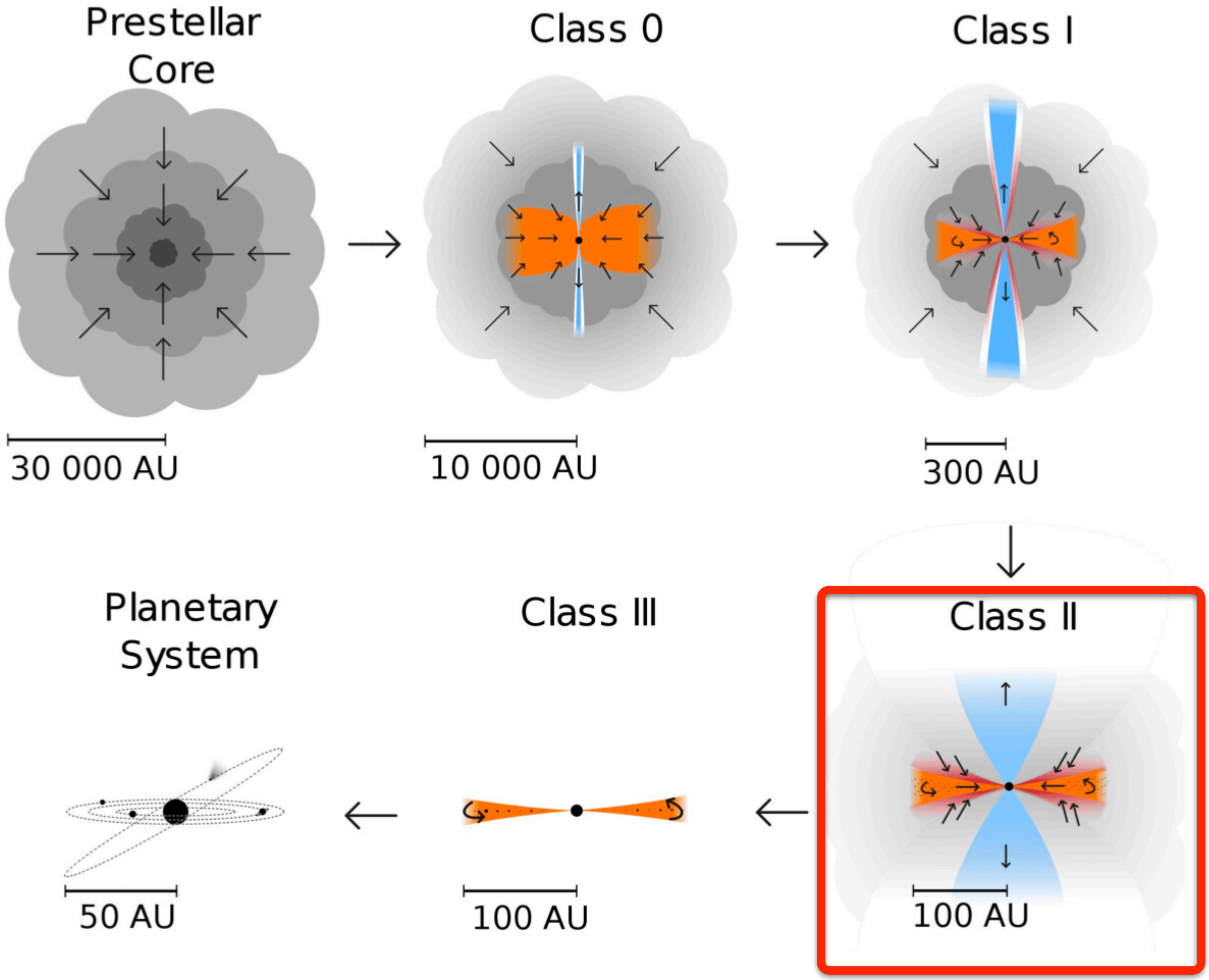
Megan Ansdell, UC Berkeley, 10/9/2017





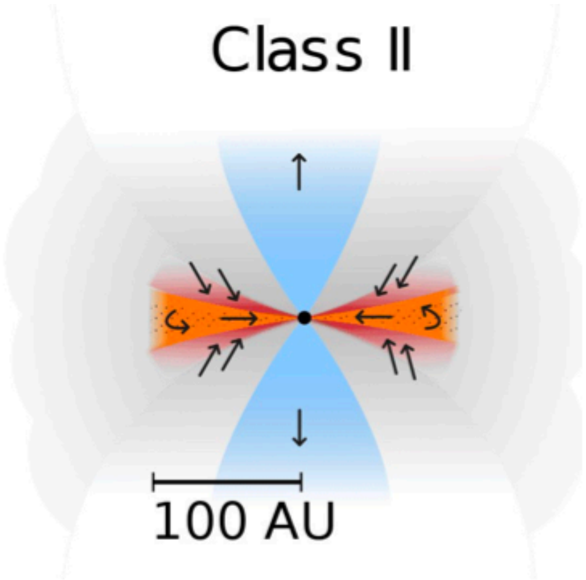


Protoplanetary Disks 101



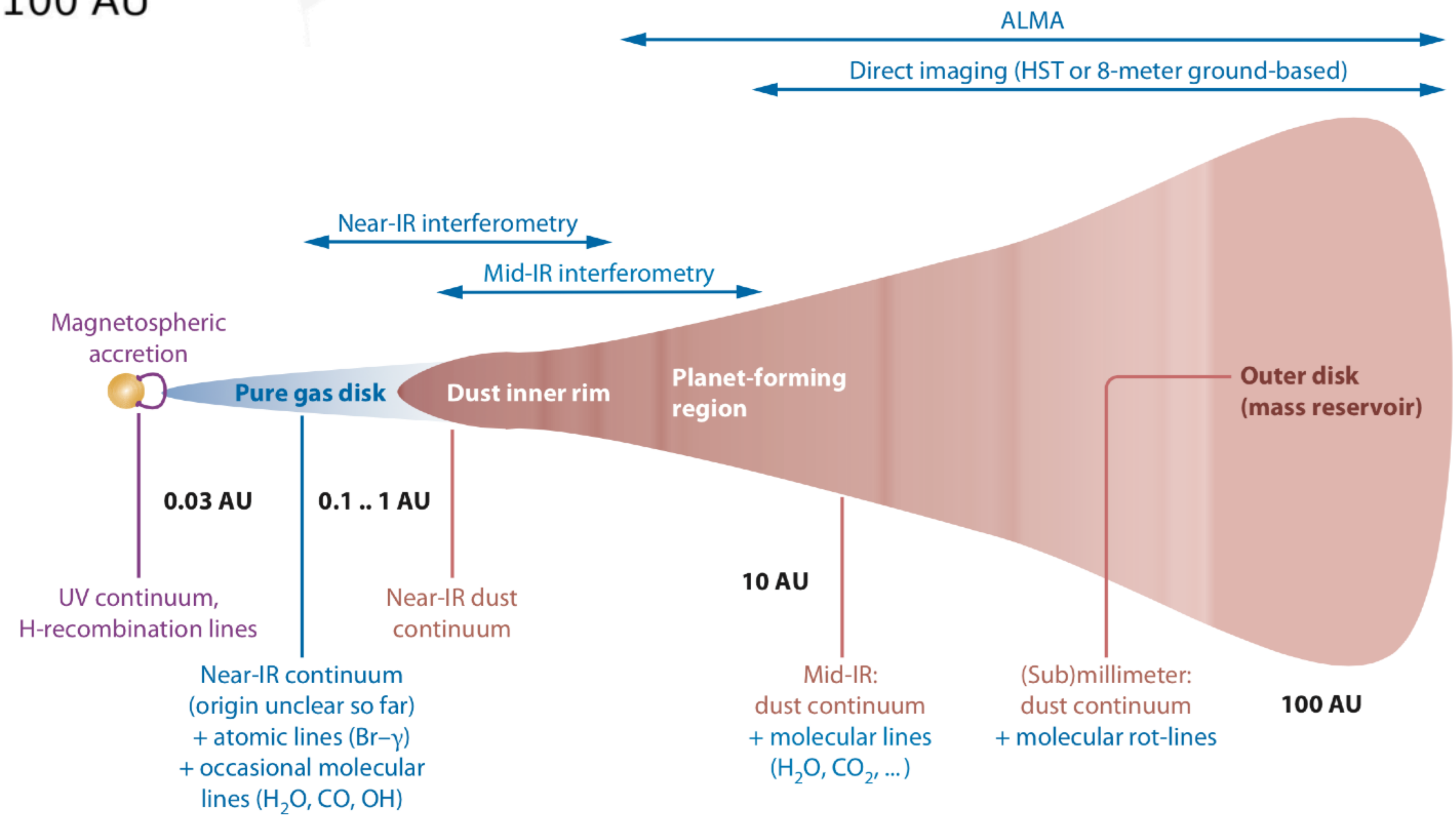
M. Persson

Protoplanetary Disks 101



Protoplanetary disks:

- Optically visible central stars
- 5 - 10 Myr lifetimes
- compact (100 AU), low-mass (0.01 $M_\odot$), cold (20 K)



ALMA

Direct imaging (HST or 8-meter ground-based)

Near-IR interferometry

Mid-IR interferometry

Magnetospheric
accretion

Pure gas disk

Dust inner rim

**Planet-forming
region**

**Outer disk
(mass reservoir)**

0.03 AU

0.1 .. 1 AU

10 AU

100 AU

UV continuum,
H-recombination lines

Near-IR continuum
(origin unclear so far)
+ atomic lines (Br–γ)
+ occasional molecular
lines (H_2O, CO, OH)

Near-IR dust
continuum

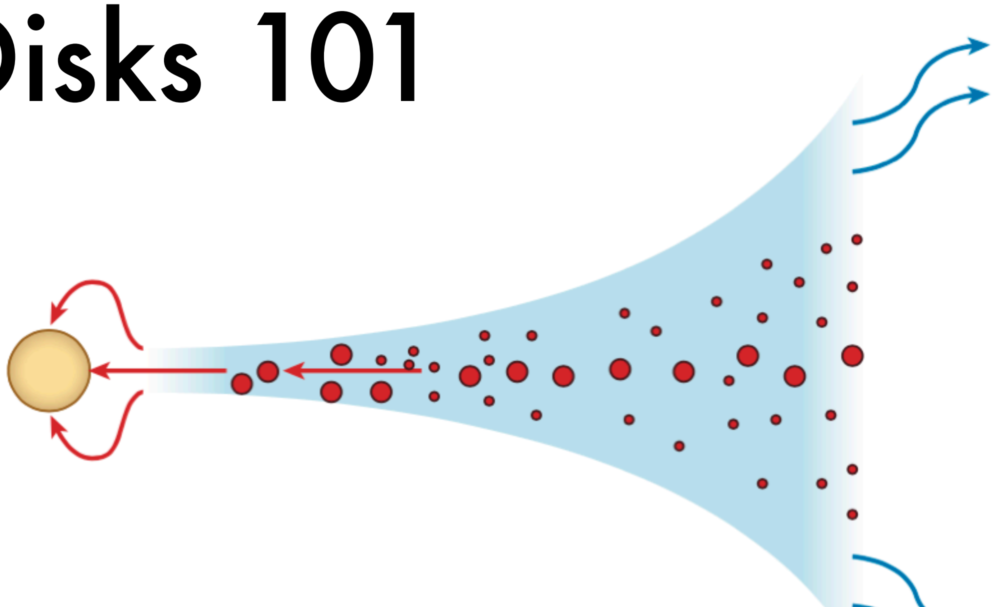
Mid-IR:
dust continuum
+ molecular lines
(H_2O, CO_2, ...)

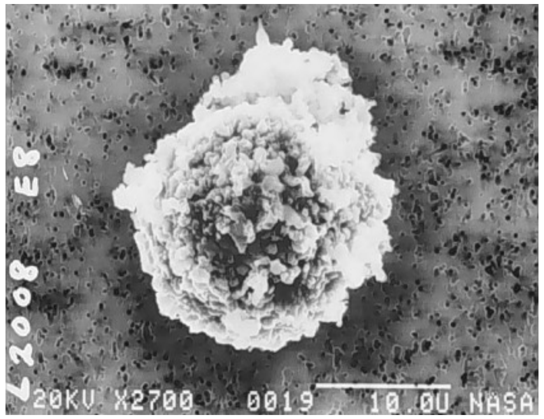
(Sub)millimeter:
dust continuum
+ molecular rot-lines

M. Persson

Protoplanetary Disks 101

- Disks are made of gas + dust
  - G/D = 100:1 in ISM
  - ratio must decrease in disks?





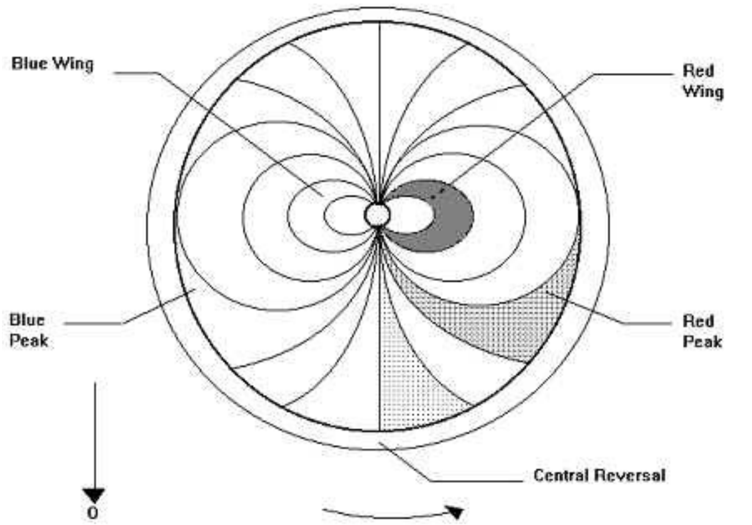
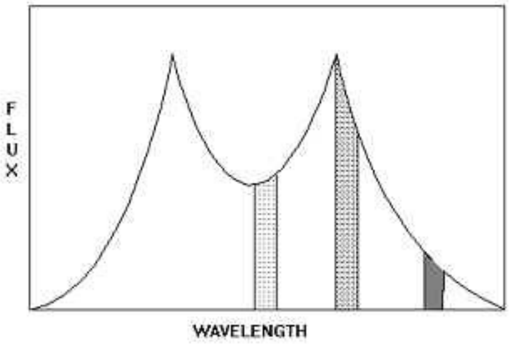


Figure 4a The characteristic 'dipole field' pattern created on the surface of a Keplerian disc by loci of points of constant radial velocity. The shaded areas correspond to emission in those parts of the line profile which are shown in Figure 4b

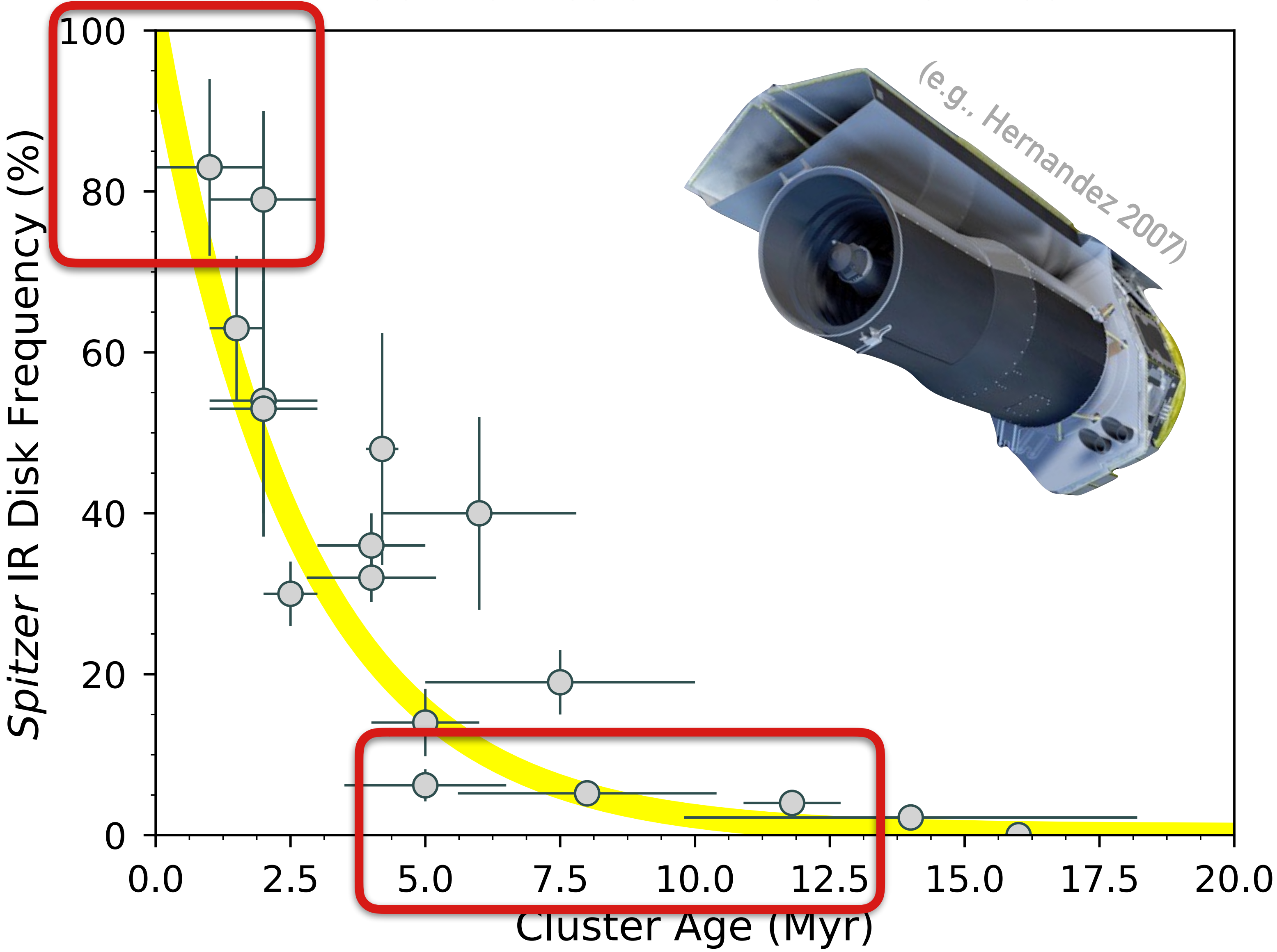


- Dust component:
  - sizes range from sub-µm to planets (?)
  - compositions likely vary (silicates, ices, graphite)
  - detection by continuum (thermal) emission

- Gas component:
  - vast majority of gas in H_2 (but also CO)
  - detected by line emission from molecules in disk

Protoplanetary Disks 101

IR continuum emission → disk lifetimes

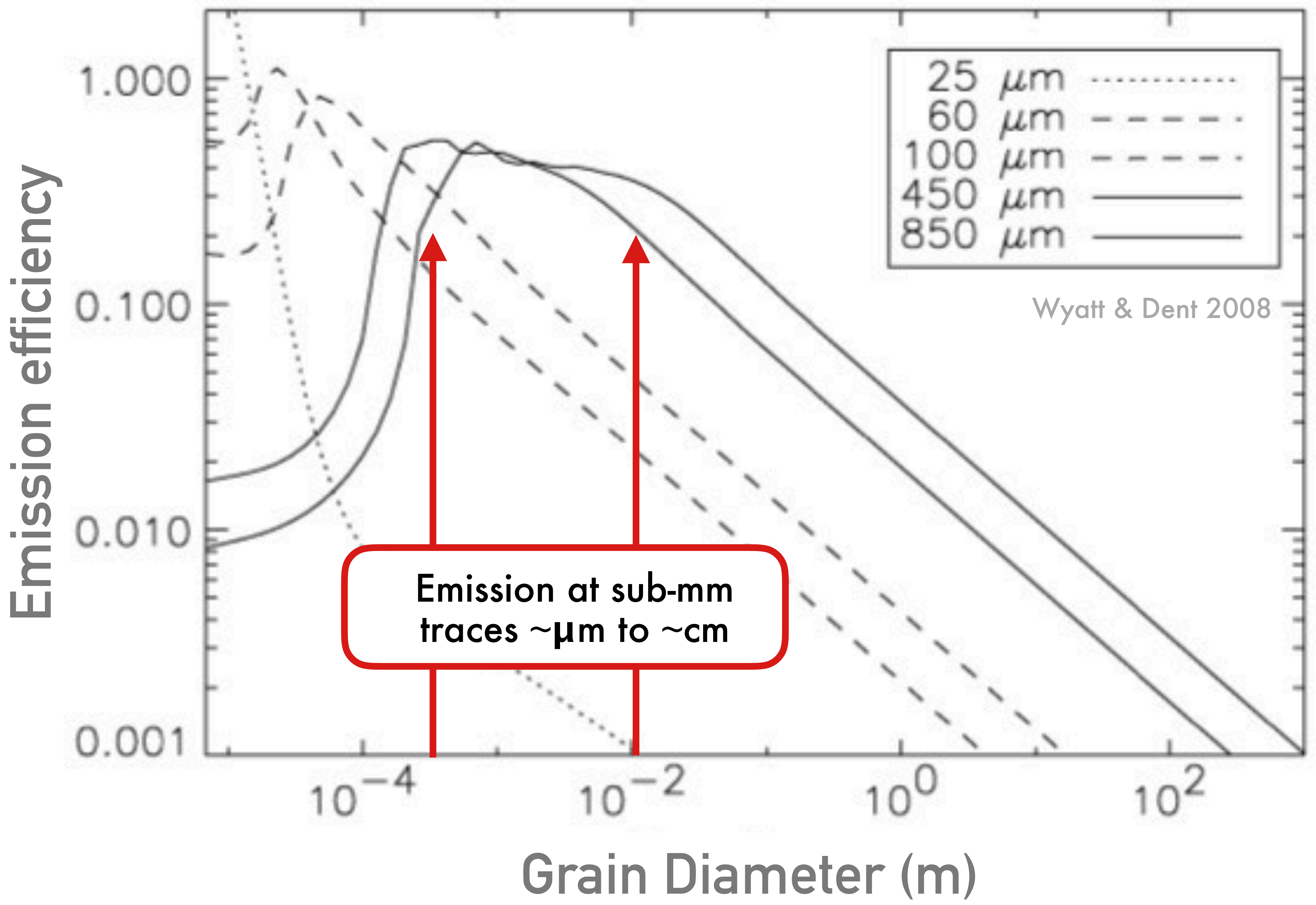


(e.g., Hernandez 2007)

- Disks are ubiquitous around young stars at ~1 Myr
- Disks lifetimes ~5-10 Myr

IR disk emission optically thick
→ good for identifying disks,
but poor tracer of disk mass

Obs. wavelength ~ grain size (λ>100μm)

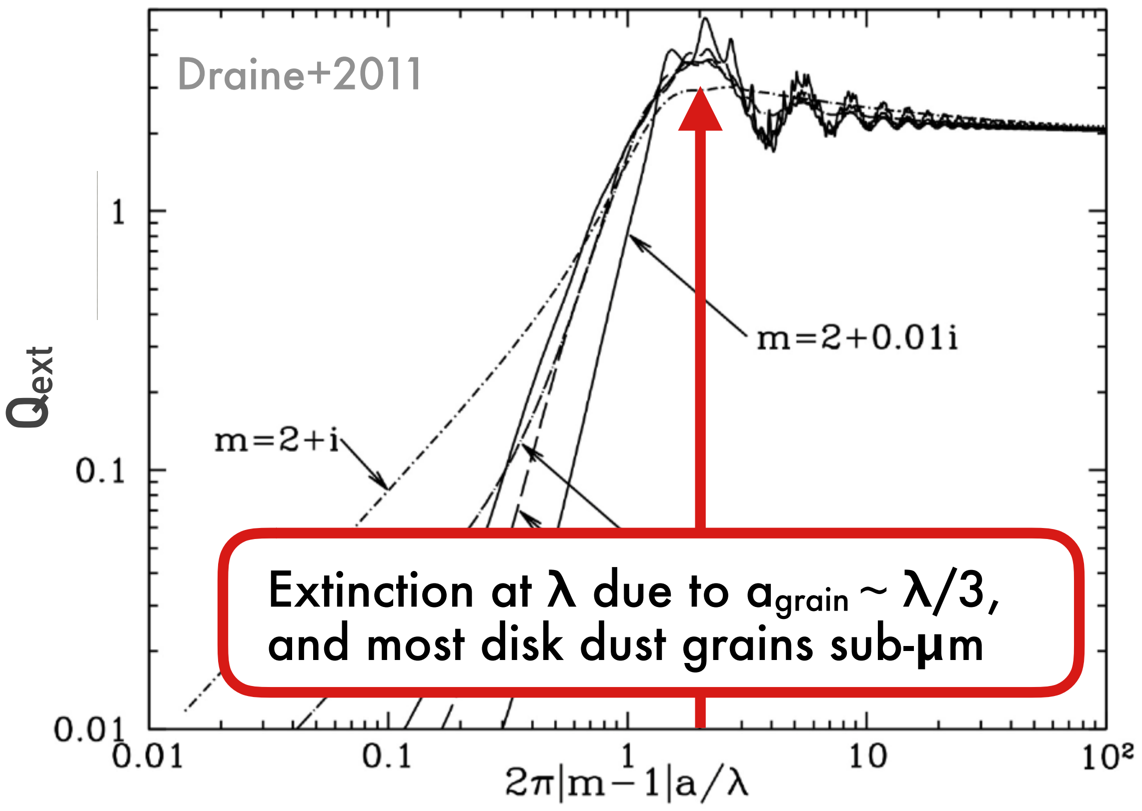


Wyatt & Dent 2008

Emission at sub-mm traces ~μm to ~cm

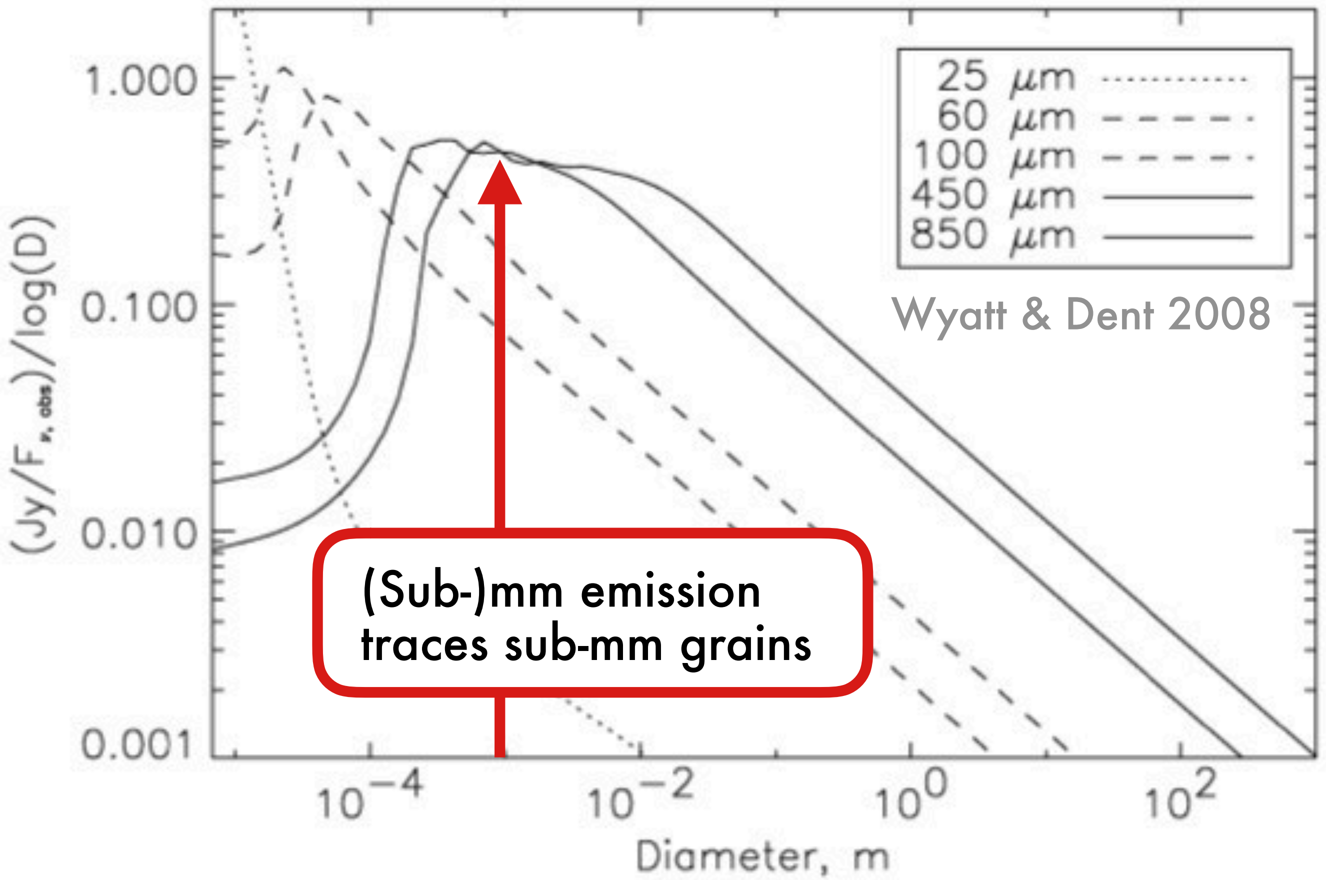
Why (sub-)mm Emission Traces Dust Mass

1. Sub-mm emission optically thin



Extinction at λ due to a_{grain} ~ λ/3, and most disk dust grains sub-μm

2. Dust emits at λ ~ a_{grain}



(Sub-)mm emission traces sub-mm grains

3. Mass locked in (sub-)mm grains

$$N(a) \sim a^{-3.5} \rightarrow \Sigma \sim a^{-1.5}$$

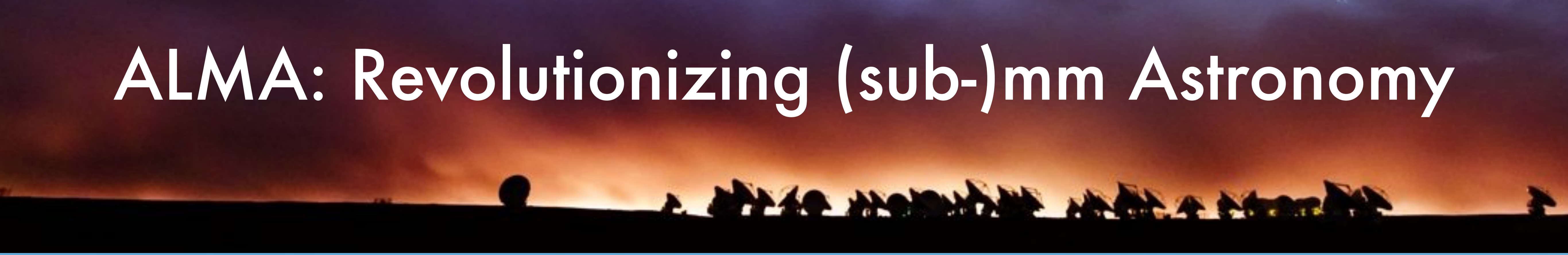
$$M \sim a^{+1.5}$$

Mathis+1977

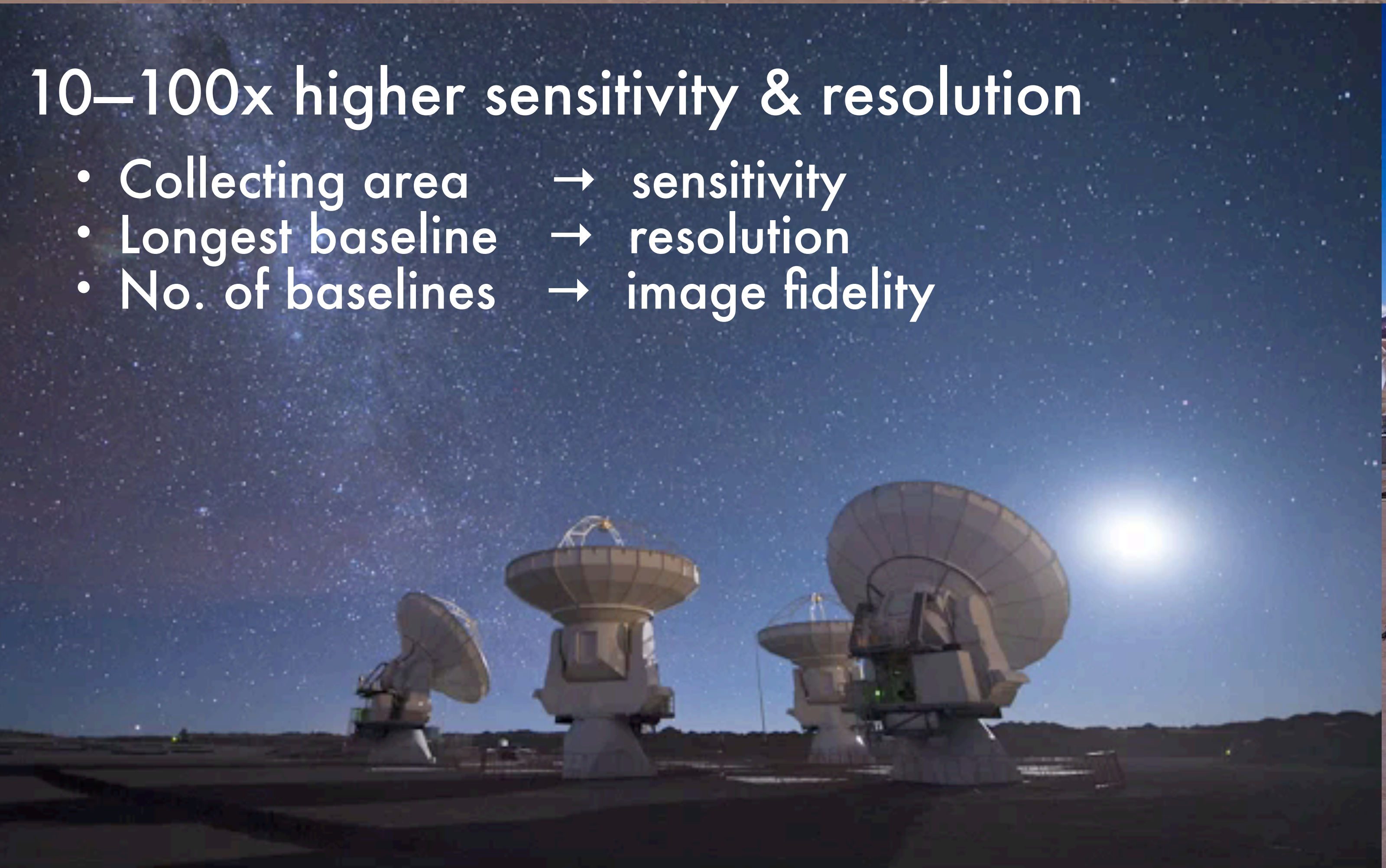
Most of dust mass located in larger (>> μm) grains

Thus (sub-)mm emission traces the amount of sub-mm to cm sized grains, which contain the bulk of the dust mass

ALMA: Revolutionizing (sub-)mm Astronomy



66 antennas at 16,500 ft
15 km baselines → 10 mas resolution
10 observing bands → (sub)-mm

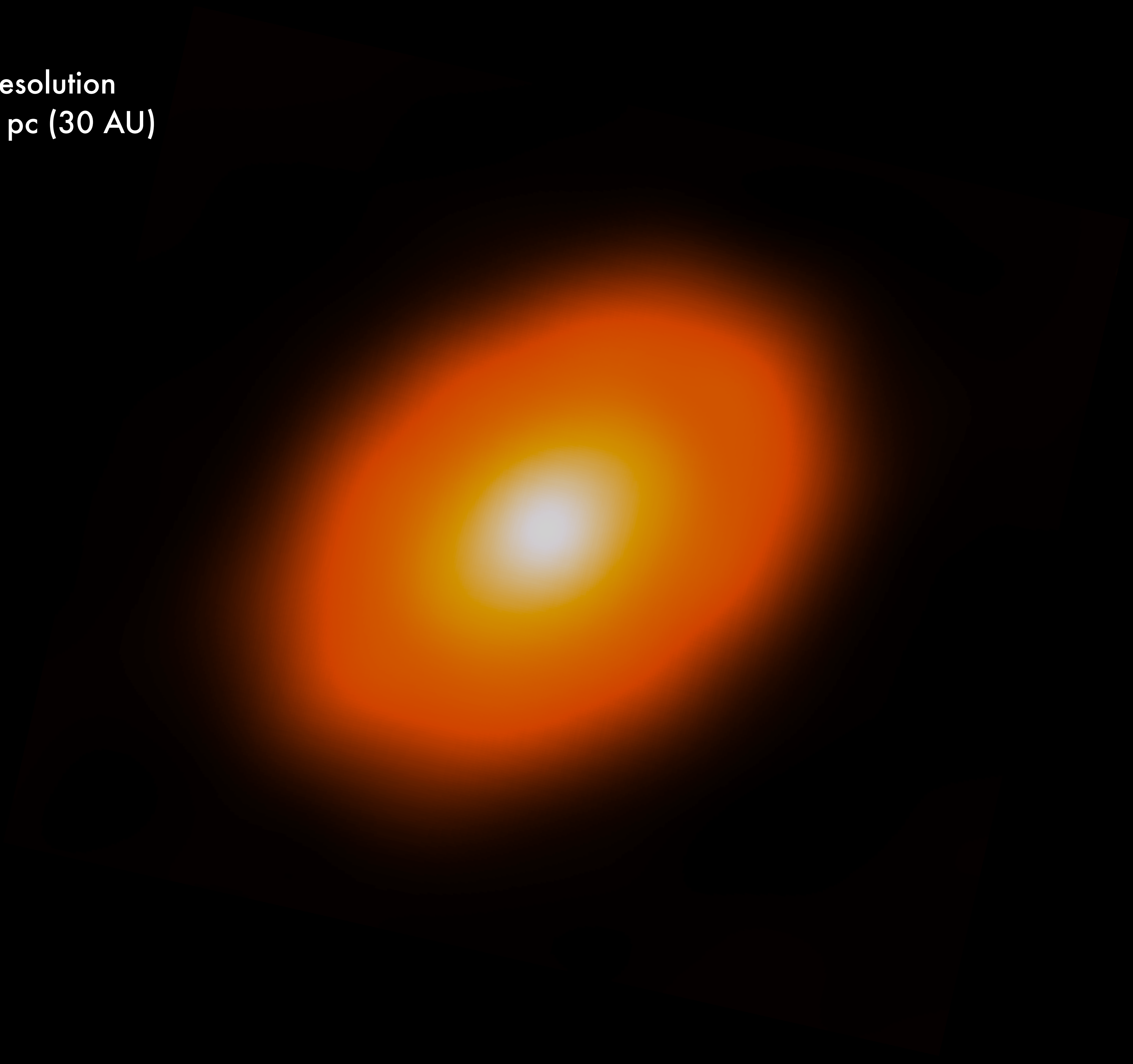


10–100x higher sensitivity & resolution

- Collecting area → sensitivity
- Longest baseline → resolution
- No. of baselines → image fidelity

HL Tau

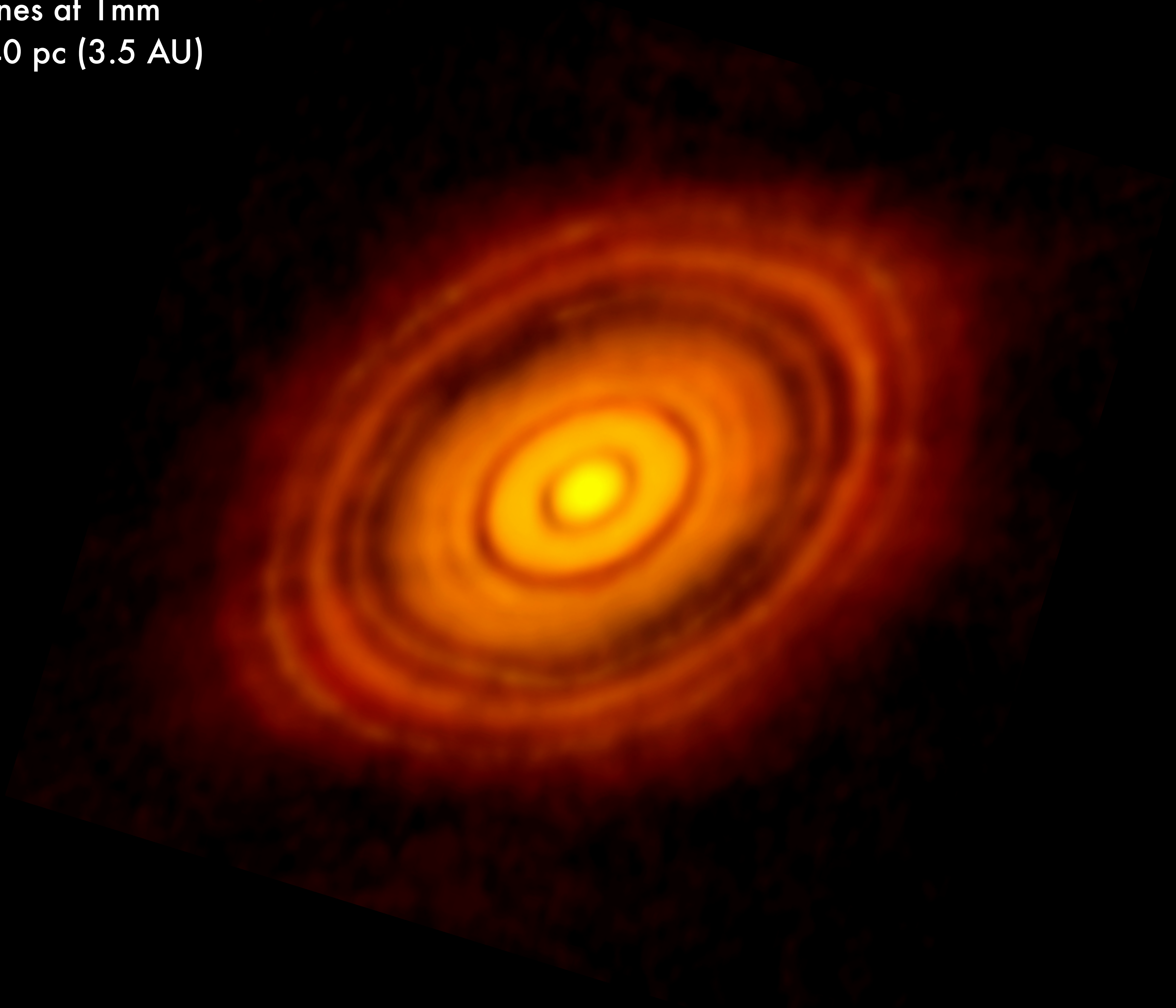
pre-ALMA resolution
0.2″ at 140 pc (30 AU)



HL Tau

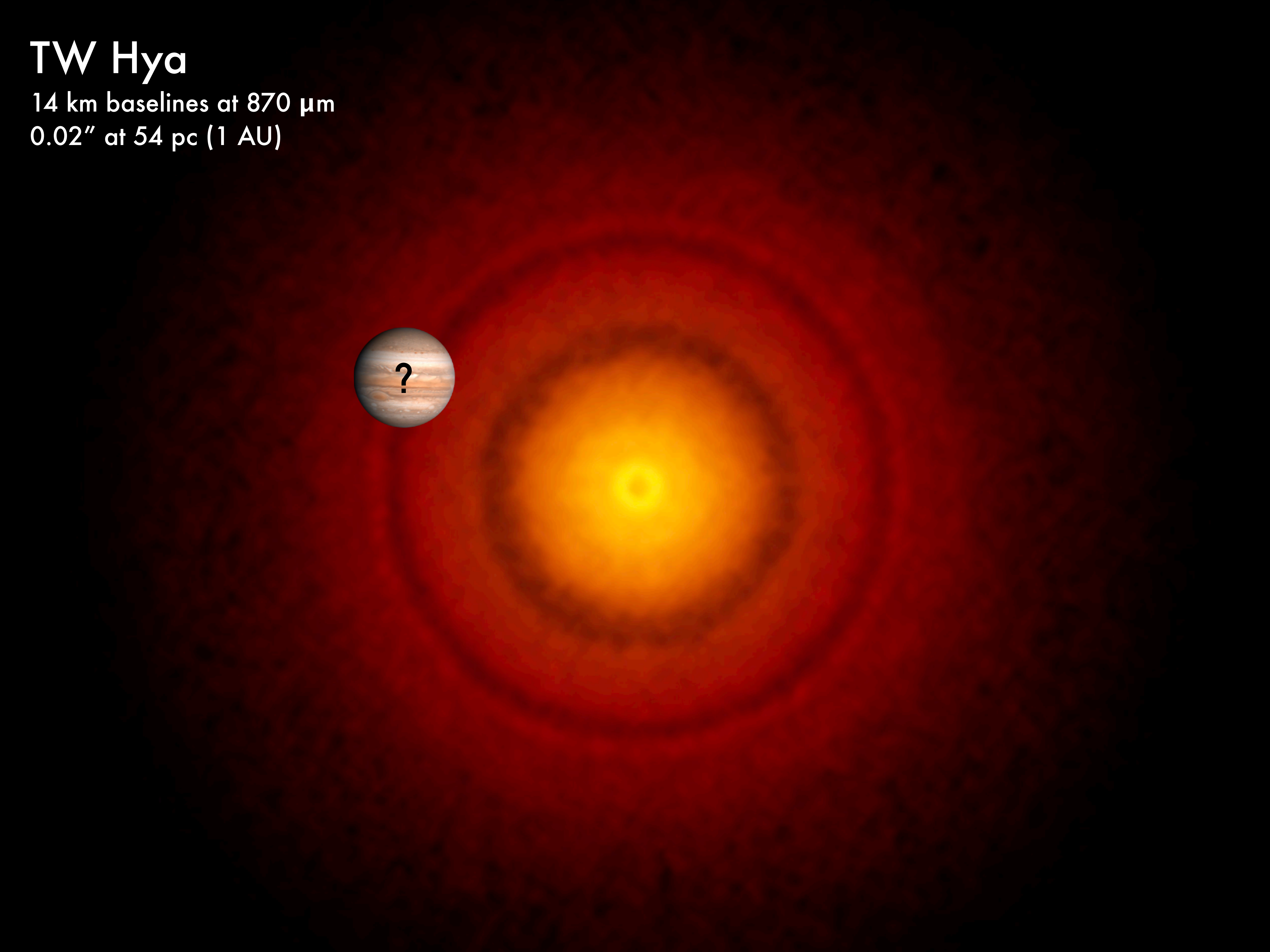
15 km baselines at 1mm

0.025″ at 140 pc (3.5 AU)



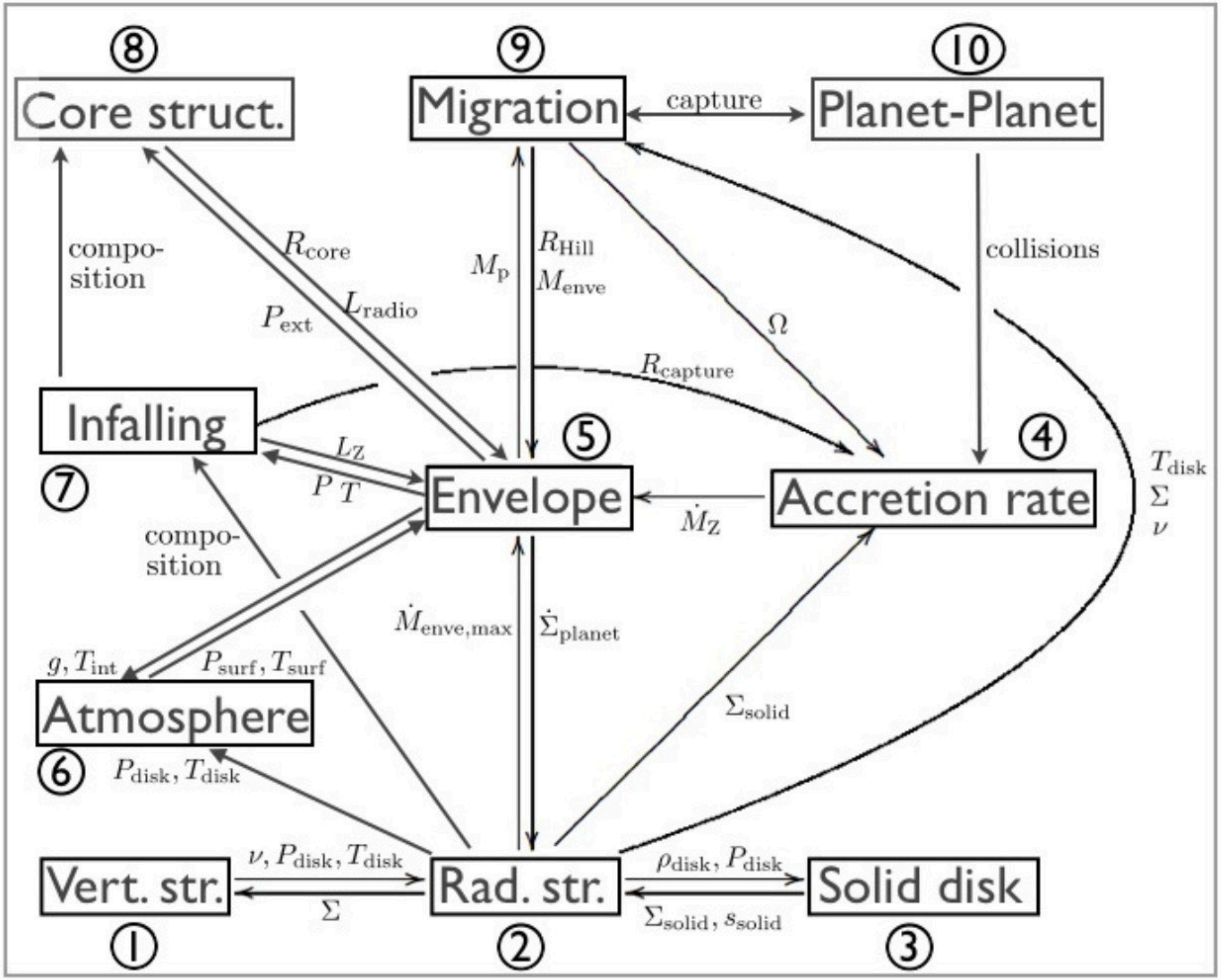
TW Hya

14 km baselines at 870 µm
0.02″ at 54 pc (1 AU)



Why Large Surveys?

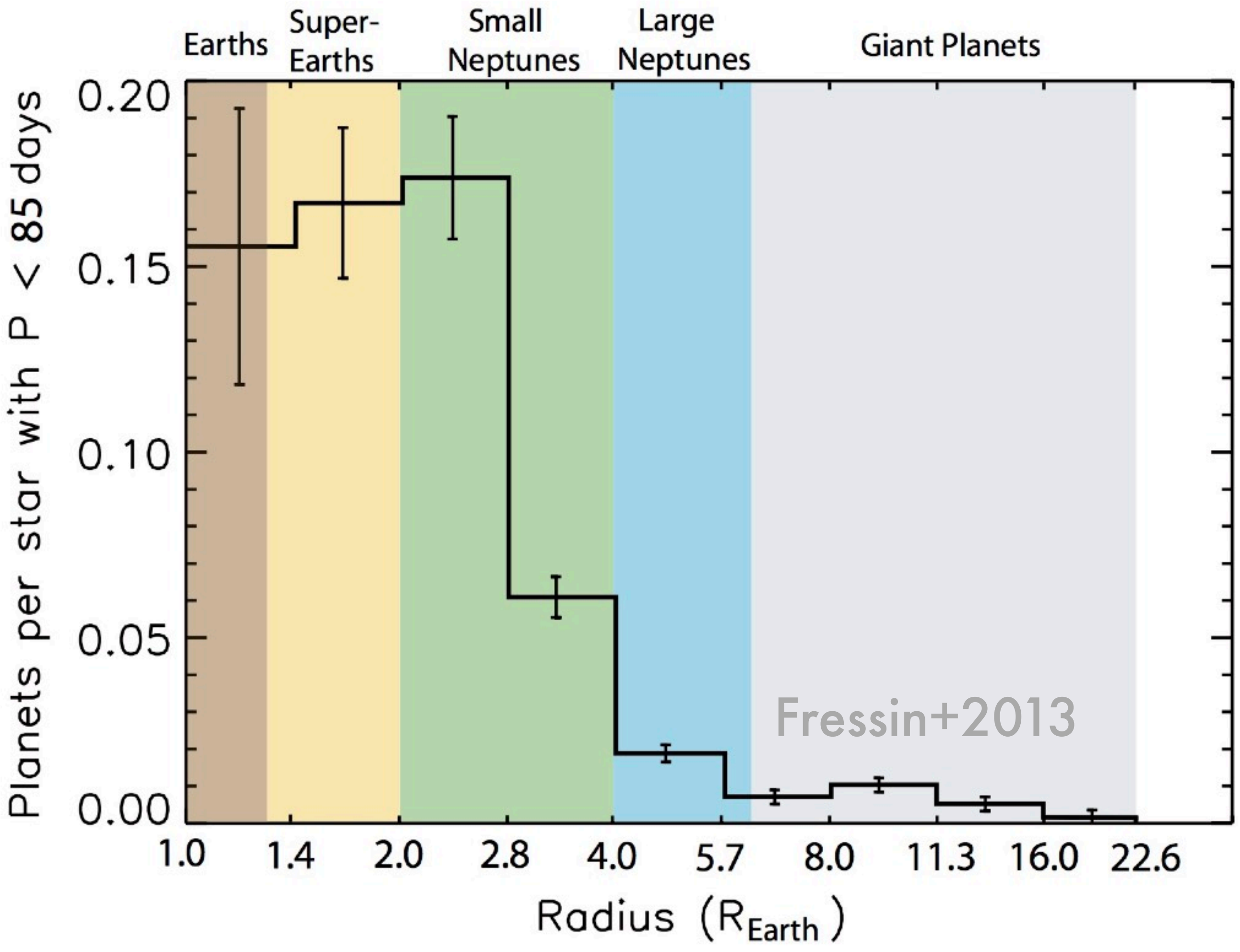
Protoplanetary disks evolution → initial conditions for planet formation

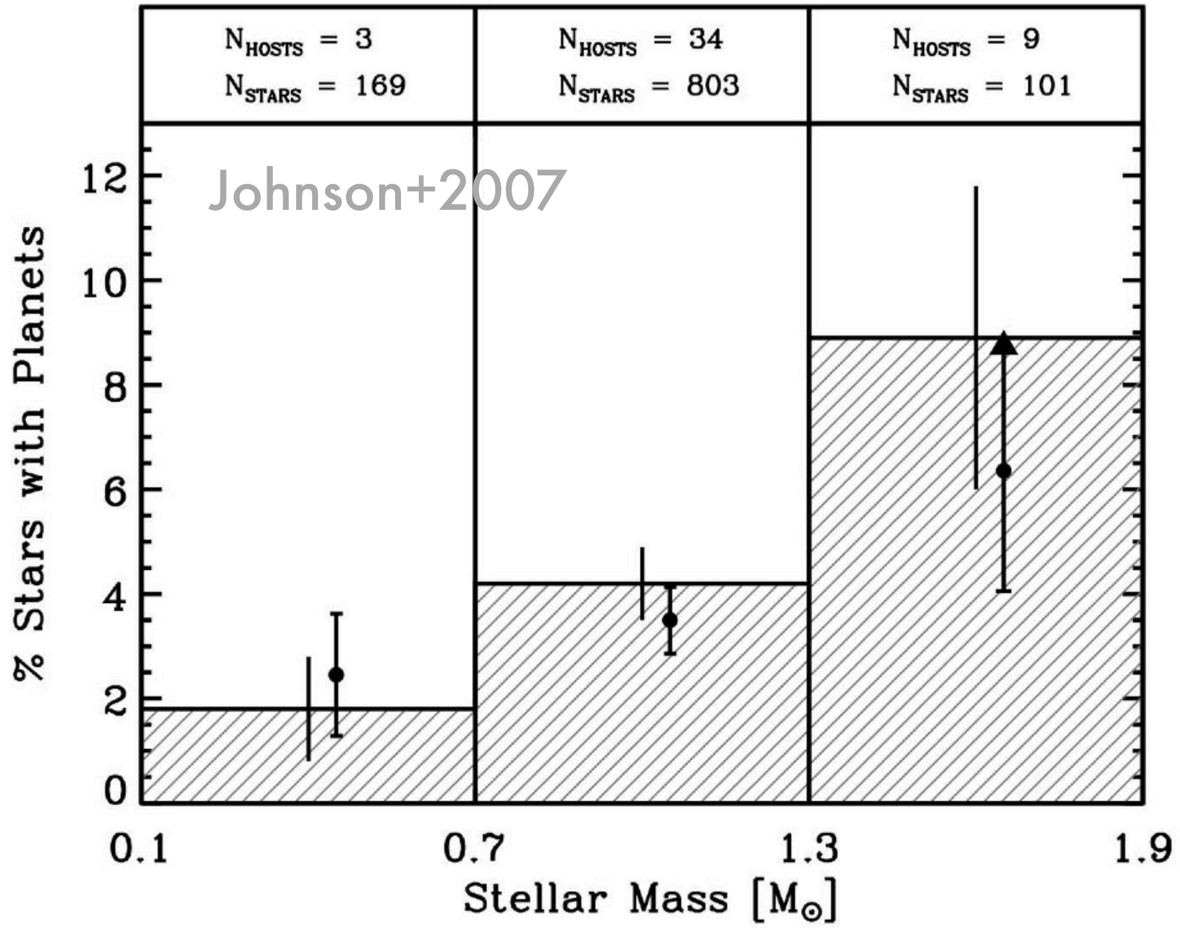


Benz+2014

Why Large Surveys?

Protoplanetary disks trends → explain exoplanet trends?





- Why are super-Earths so common?
- Why are Jupiters so rare?

- What are the origins of exoplanet trends with stellar mass?

ALMA Surveys of Bulk Dust & Gas Masses

- Tells us how much material is available for planet formation
- Can be measured efficiently with ALMA for large populations of disks

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DUST FROM SUB-MM CONTINUUM

Sub-mm flux density
(ALMA observations)

Source distance
(better with GAIA)

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

Hildebrand 1983

Single grain opacity
(10 $\mathrm{cm}^2\ \mathrm{g}^{-1}$ at 1000 GHz)

Isothermal disk dust
emission ($T_{\rm dust}$ =20 K)

ALMA Surveys of Bulk Dust & Gas Masses

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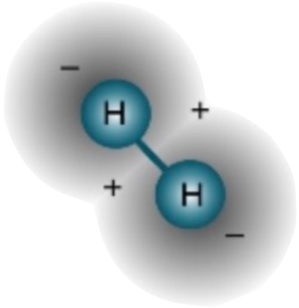
GAS FROM H_2



- Most abundant species in disks
- But symmetric molecule difficult to detect

(see Carmona+2008)

ALMA Surveys of Bulk Dust & Gas Masses

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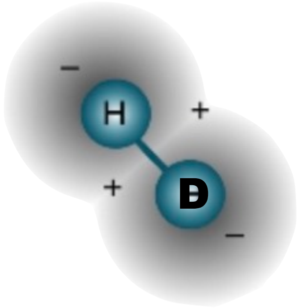
GAS FROM HD



- Good tracer of H_2
- Weak dipole moment allows detectable emission
- But emits in far-IR (need space-based observatory)

(see Bergin et al. 2013)

ALMA Surveys of Bulk Dust & Gas Masses

- Tells us how much material is available for planet formation
- Can be measured efficiently with ALMA for large populations of disks

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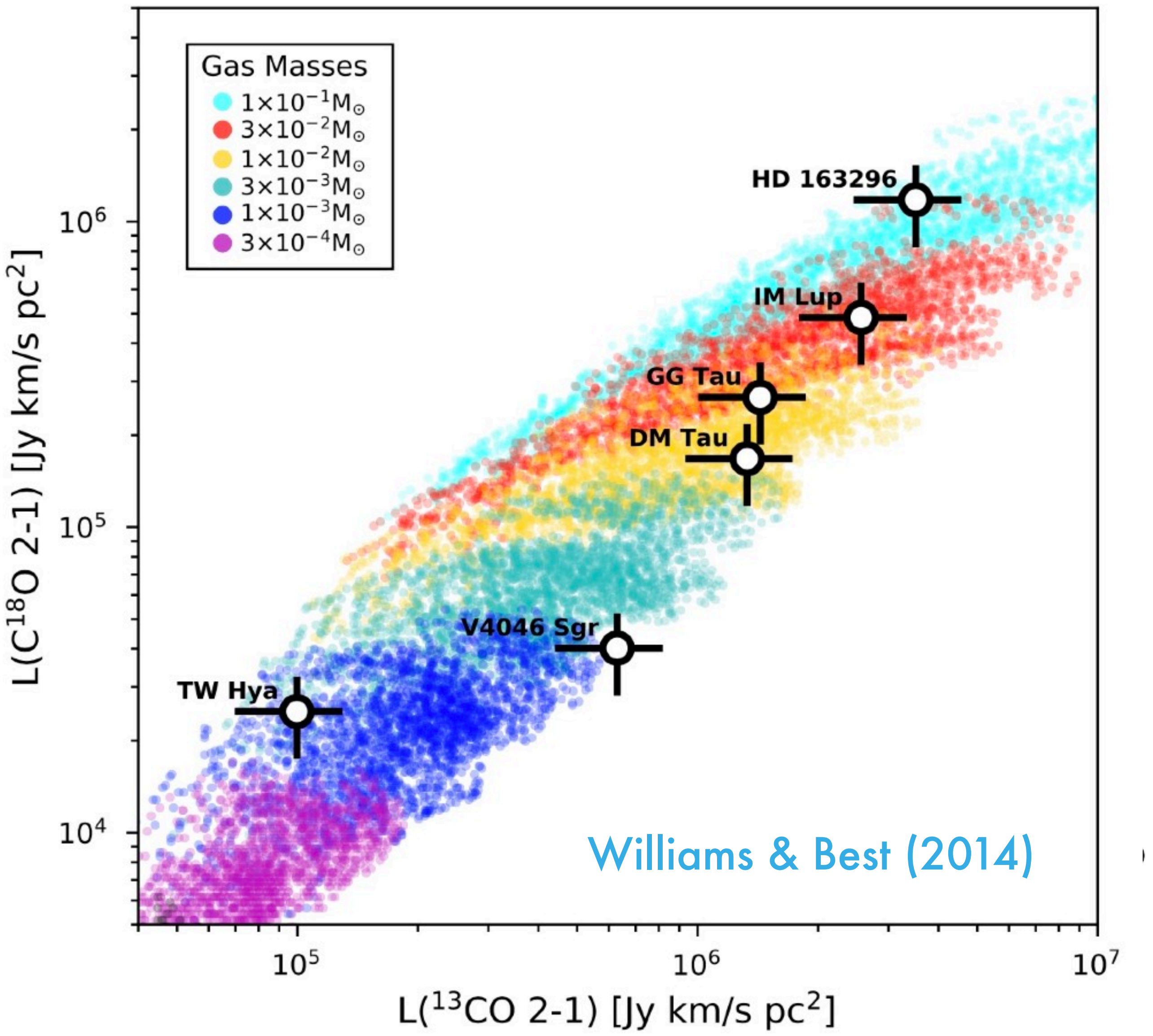
GAS FROM CO ISOTOPOLOGUES

- Detectable at sub-mm wavelengths
- Optically thin (traces total disk mass)

- Parametric models + radiative transfer
- Simple CO chemistry (freeze out + photodiss.)
- Efficient to get M_{gas} to within factor of 3



Williams & Best (2014)

ALMA Surveys of Bulk Dust & Gas Masses

- Measure dust & gas masses for complete populations of protoplanetary disks
- Indicative of how much material is available for planet formation
- Surveyed star-forming regions with distinct ages to study disk evolution

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DUST FROM SUB-MM CONTINUUM

Sub-mm flux density (ALMA observations)

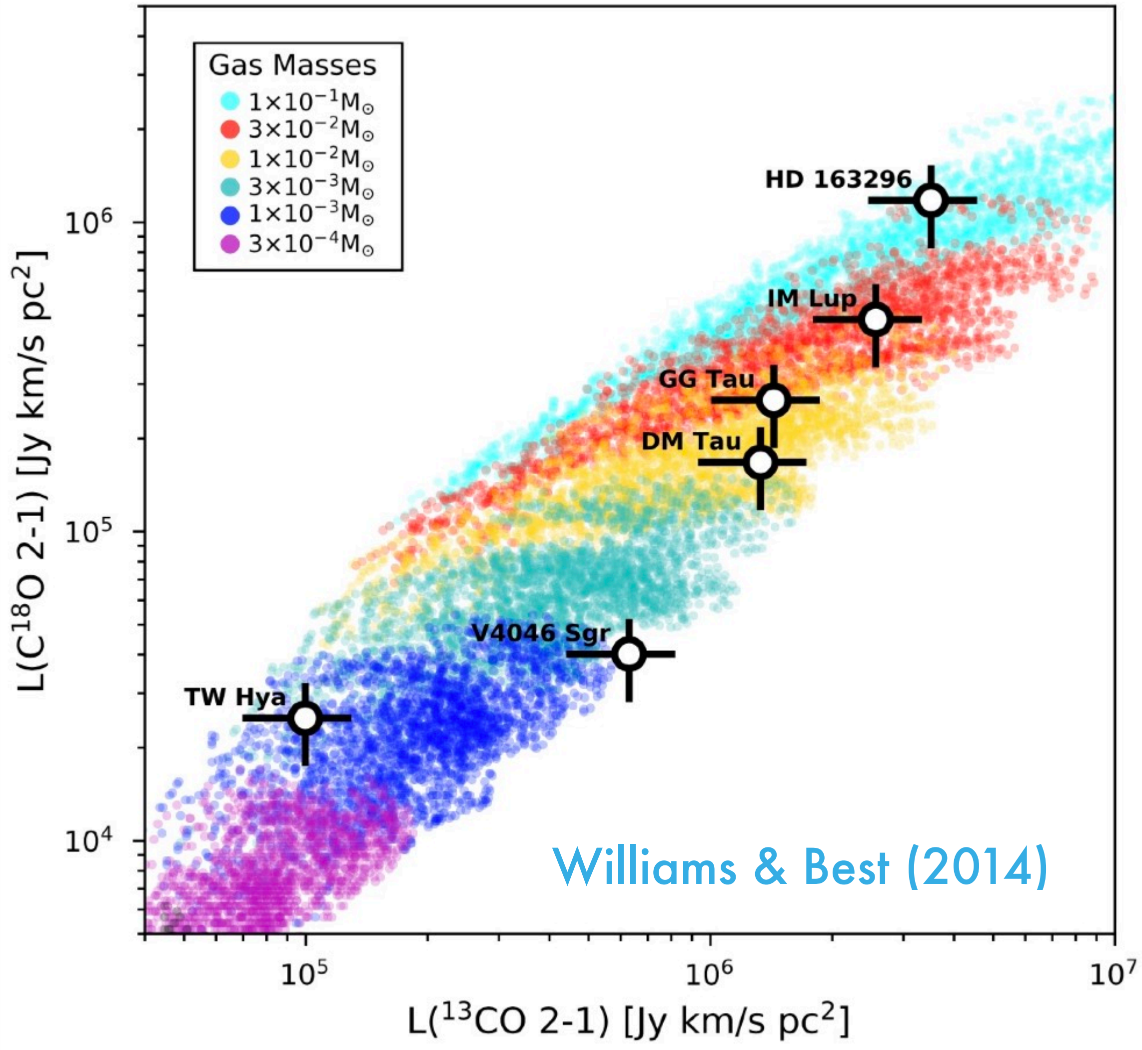
Source distance (150-200 pc)

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

Single grain opacity (10 cm^2 g^{-1} at 1000 GHz)

Isothermal disk dust emission ($T_{\text{dust}} = 20$ K)

GAS FROM CO ISOTOPOLOGUES



Williams & Best (2014)

ALMA Surveys of Bulk Dust & Gas Masses

Disk Evolution

Lupus Clouds

- Young (1–3 Myr)
- Nearby (150 pc)
- 95 protoplanetary disks

Ansdell+2016c

σ Orionis Cluster

- Middle-aged (3–5 Myr)
- Nearby-ish (385 pc)
- 92 protoplanetary disks

Ansdell+2017

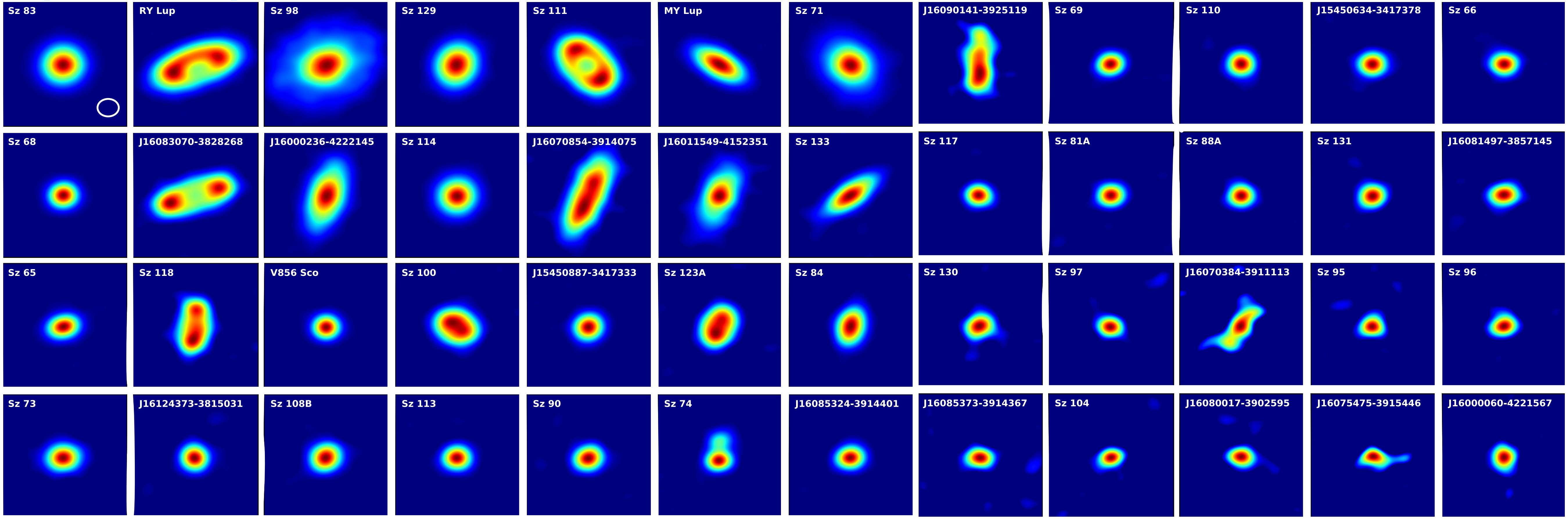
Upper Sco Association

- Evolved (5–10 Myr)
- Nearby (145 pc)
- 75 protoplanetary disks

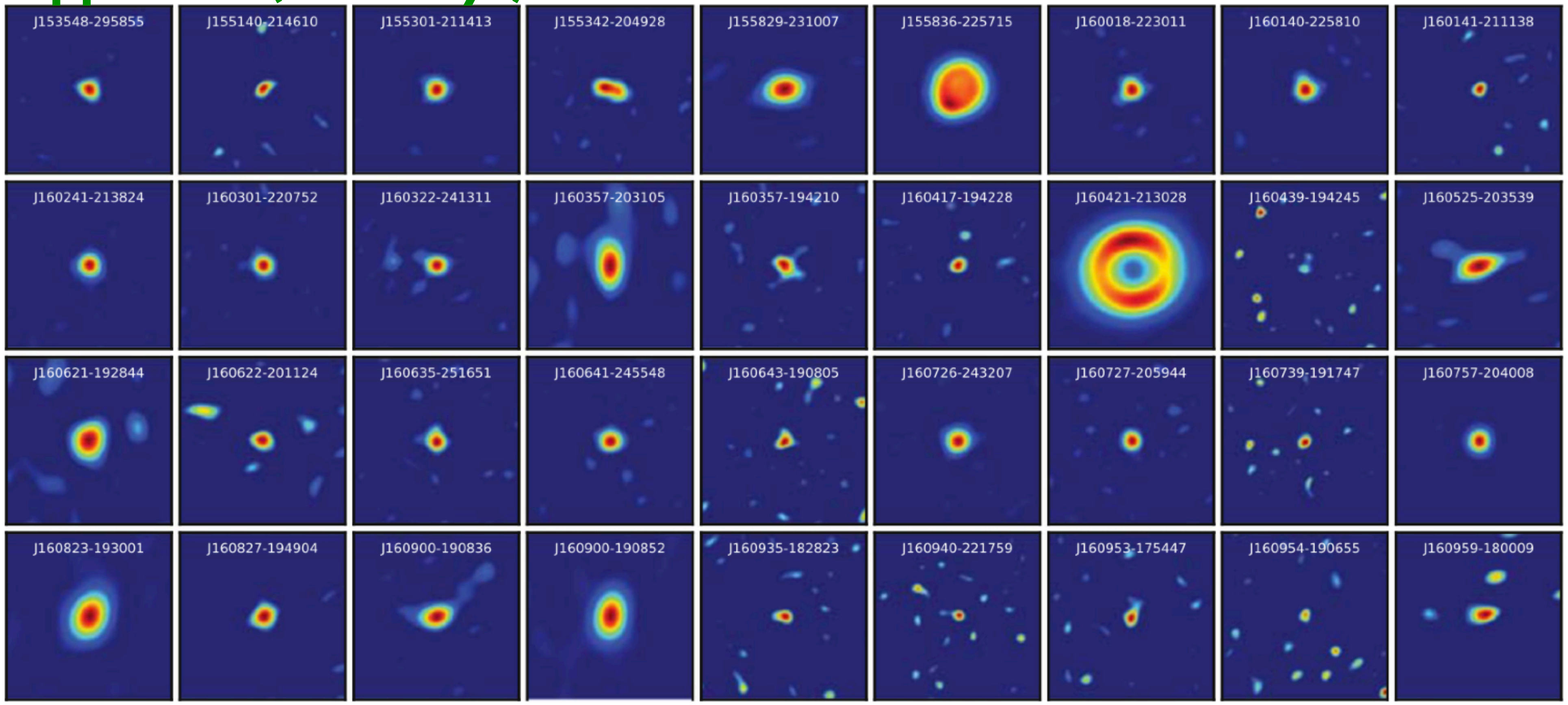
Barenfeld+2016

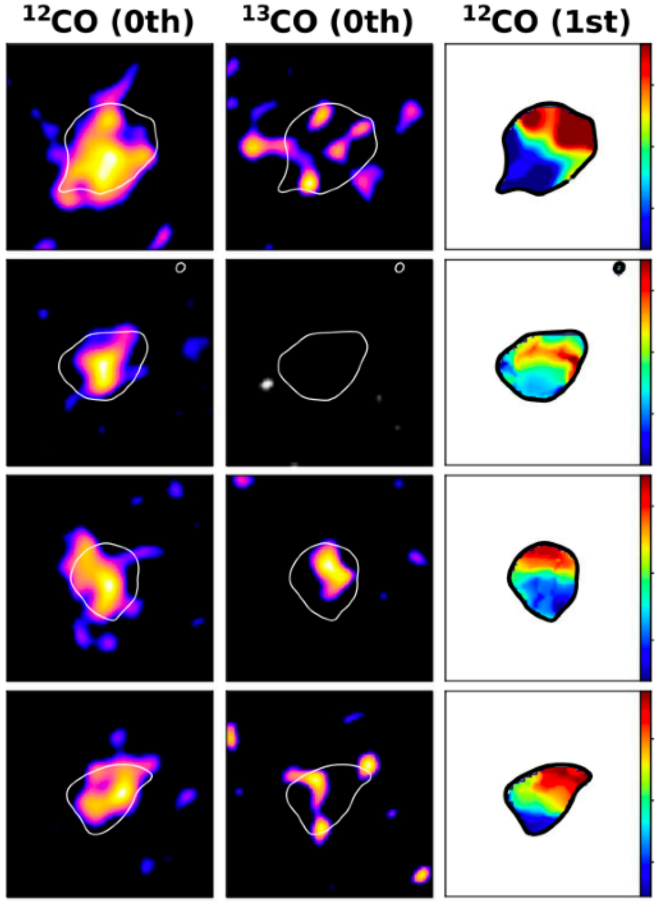
Protoplanetary Disk Zoo

Lupus (1–3 Myr)



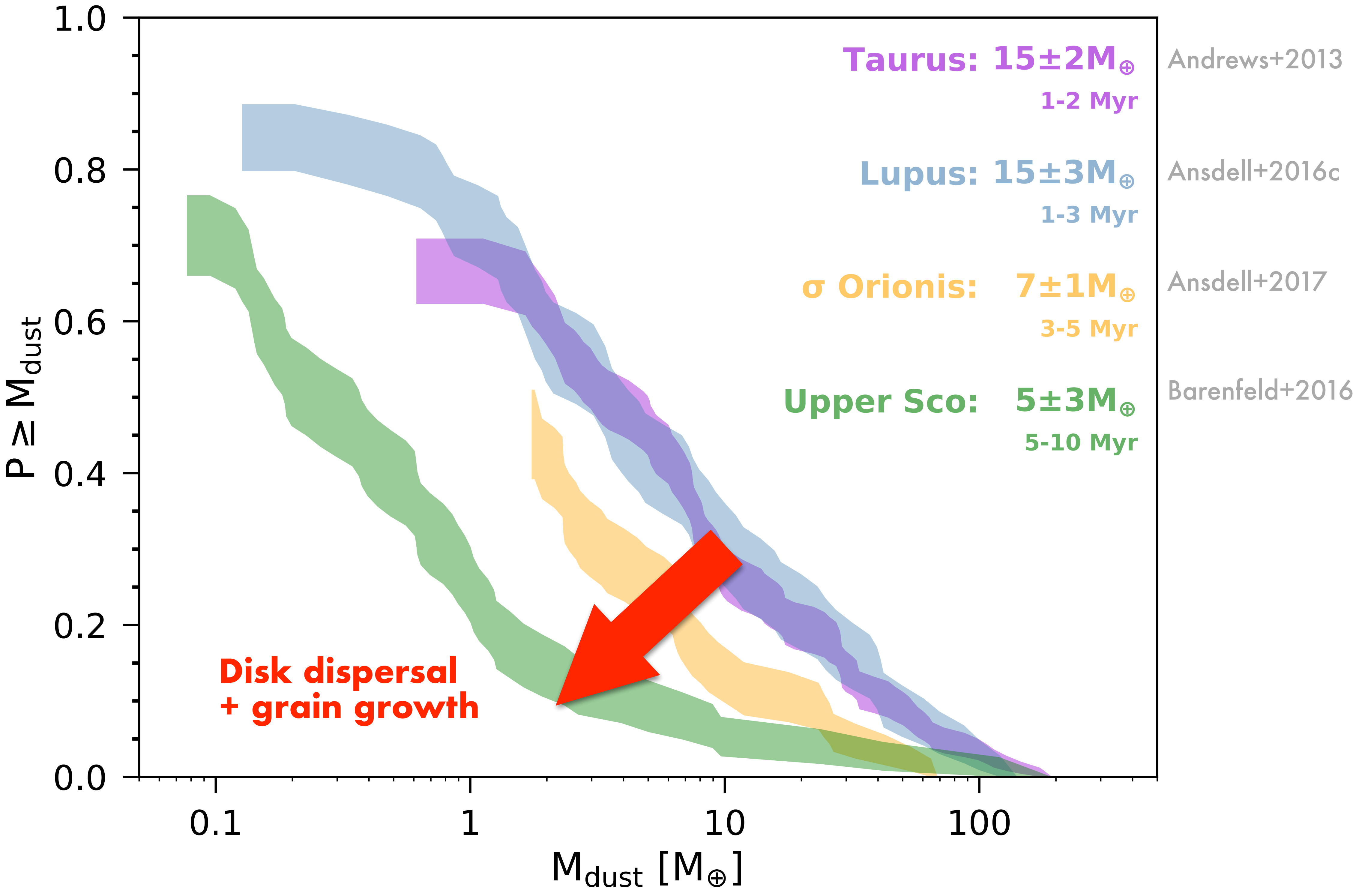
Upper Sco (5–10 Myr)





σ Orionis (3–5 Myr)

Declining Dust Distributions



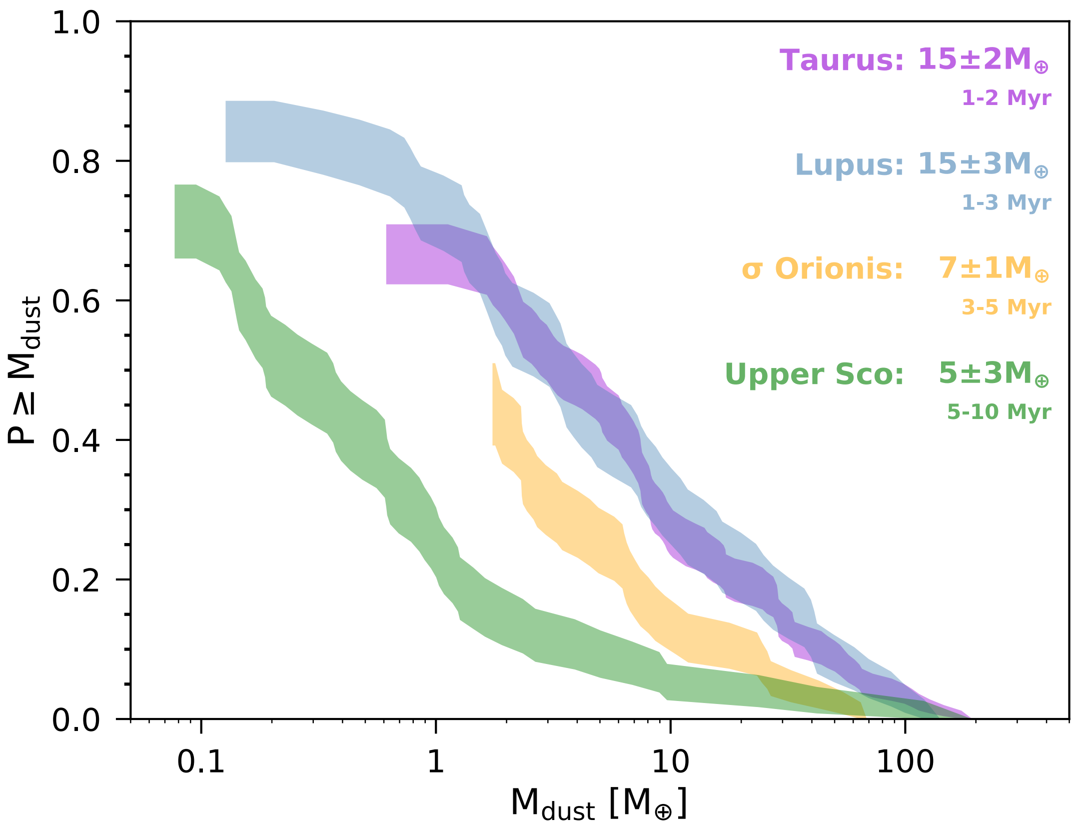
Disk dispersal + grain growth

Cumulative distributions calculated using Kaplan Meier Estimator
(to take into account upper limits)

Declining Dust Distributions

Disks that can form giant planet cores (10 $M_\oplus$) (unrealistically assuming 100% efficiency)

- 1-3 Myr: 25%
- 3-5 Myr: 13%
- 5-10 Myr: 5%



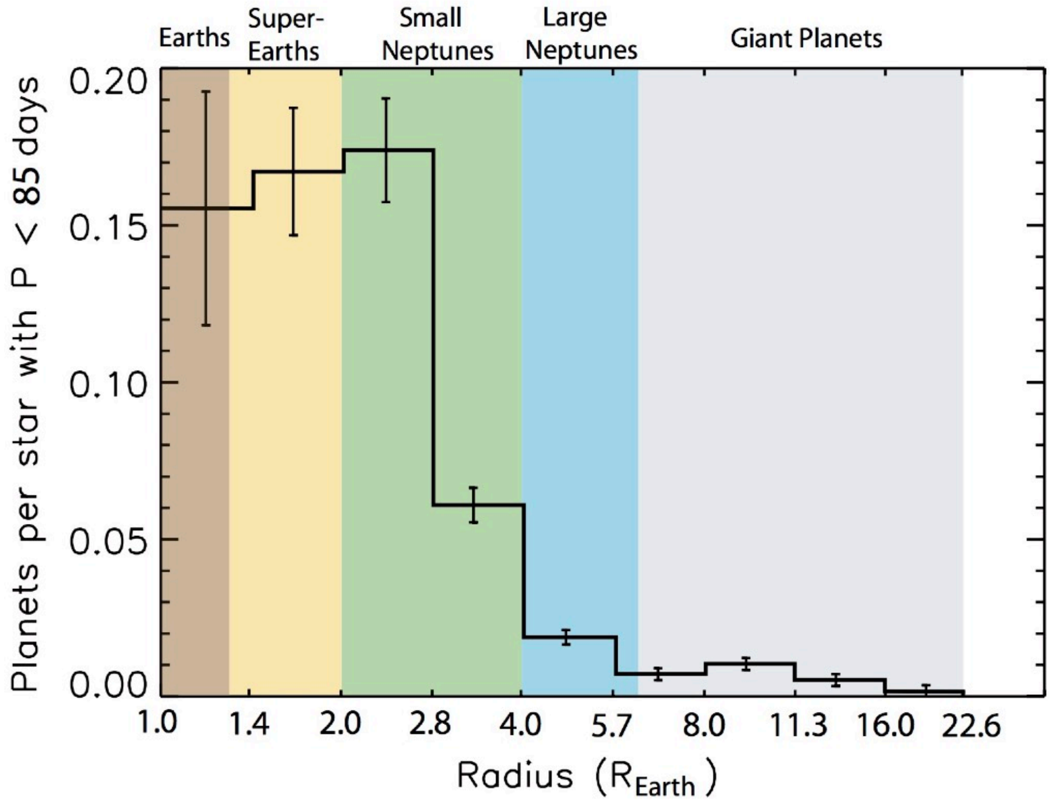
Giant planet formation well underway?

- Implies solids > cm already formed
- Evidence of overcoming "fragmentation barrier"

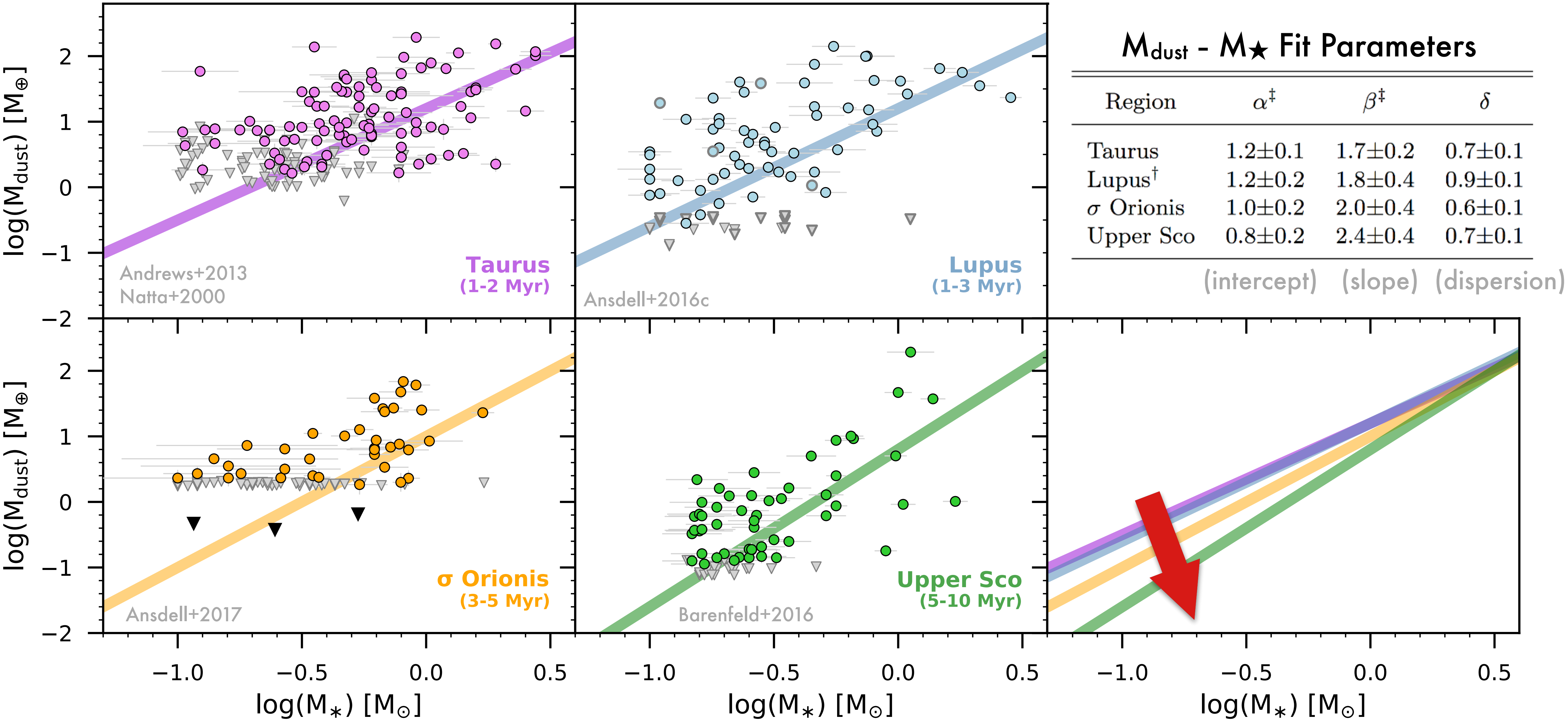
Giant planet formation rare?

- Implies most disk just lack sufficient dust
- Consistent with exoplanet statistics

	Stellar mass	Orbital radius	Planet mass	Frequency
Micro-lensing	0.14 -1.0 $M_\odot$	0.5 -10 AU	0.3 -10 M_{Jup}	17% Cassan+2012
Direct Imaging	0.1 - 0.7 $M_\odot$	< 20 AU	1.0 -13 M_{Jup}	6.5% Montet+2014
	0.1 - 0.6 $M_\odot$	10 -100 AU	1.0 -13 M_{Jup}	<16% Bowler+2015



M_{dust} – $M_\star$ Correlation



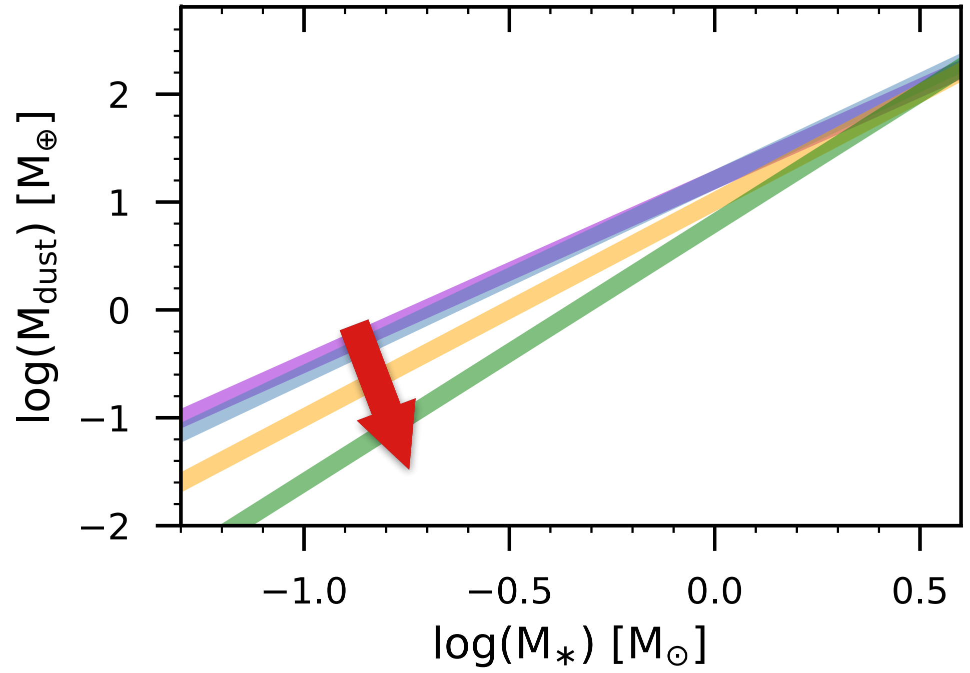
M_{dust} - $M_\star$ Fit Parameters

Region	$\alpha^\ddagger$	$\beta^\ddagger$	δ
Taurus	1.2±0.1	1.7±0.2	0.7±0.1
Lupus†	1.2±0.2	1.8±0.4	0.9±0.1
σ Orionis	1.0±0.2	2.0±0.4	0.6±0.1
Upper Sco	0.8±0.2	2.4±0.4	0.7±0.1

(intercept) (slope) (dispersion)

Linear fit from Bayesian Linear Regression method of Kelly 2007
(to take into account upper limits, errors on both axes, intrinsic scatter)

M_{dust} – $M_\star$ Correlation



The M_{dust} - $M_\star$ relation fundamentally explains the f_{giant} - $M_\star$ relation?

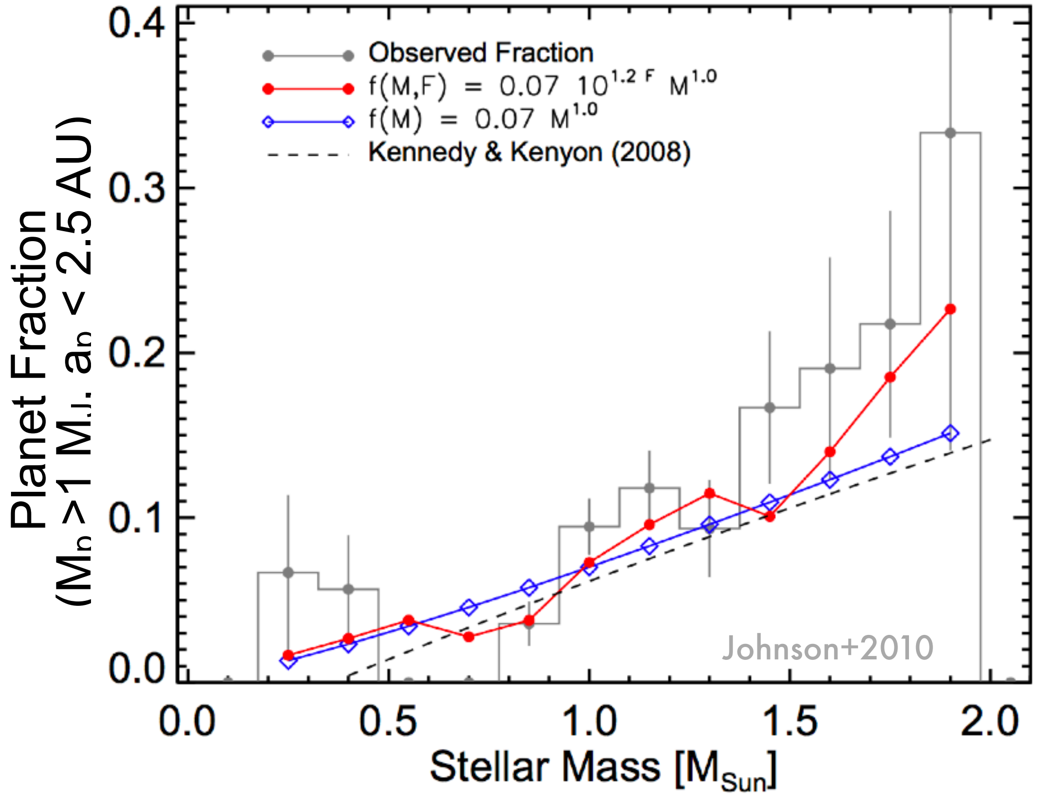
- Giant planets form more efficiently in higher-mass disks around higher-mass stars
- Due to higher Σ + faster T_{dym} → faster core growth and larger formation zones

(e.g., Ikoma+2000, Ida & Lin 2005, Kennedy & Kenyon 2008)

Steepening of M_{dust} - $M_\star$ relation points to different evolution around low-mass stars

- Growth of mm-size dust into > cm-sized bodies more efficient around low-mass stars?
- Inward drift of mm-size grains more efficient around lower-mass stars?

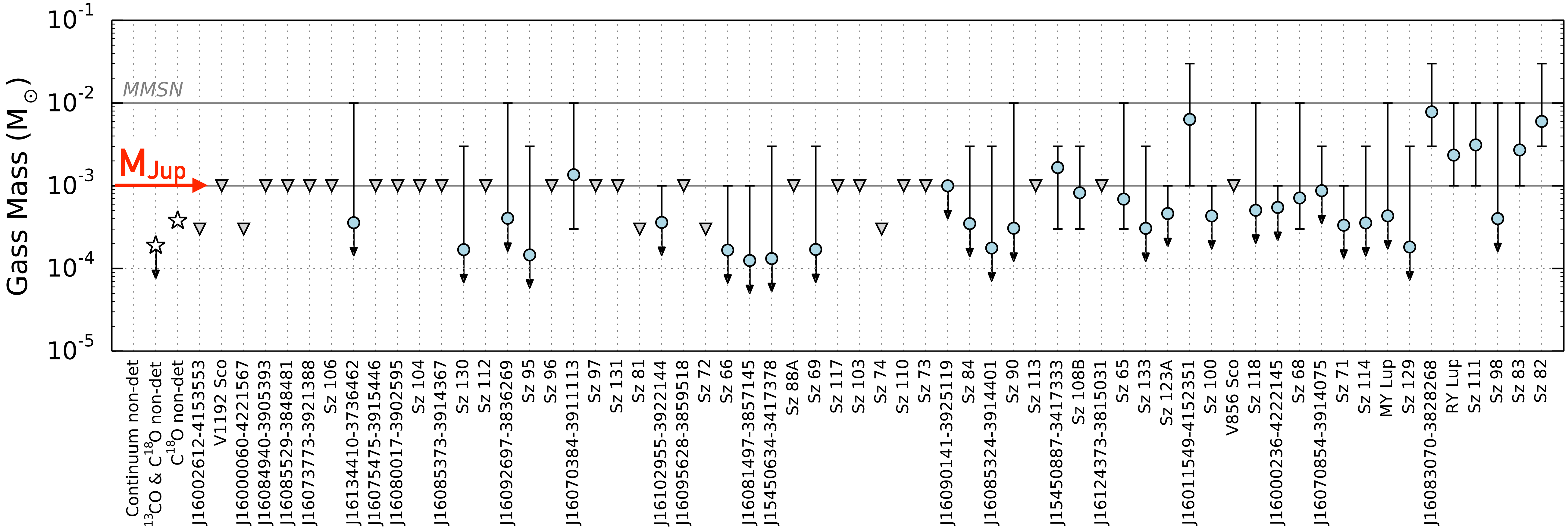
(e.g., Pascucci+2016)



Low Gas Masses

Typical gas masses $\lesssim 1$ M_{JUP} in Lupus (1-3 Myr)

- Explained by stratified nature of disks?
- Supports that giant planet formation is rare or rapid



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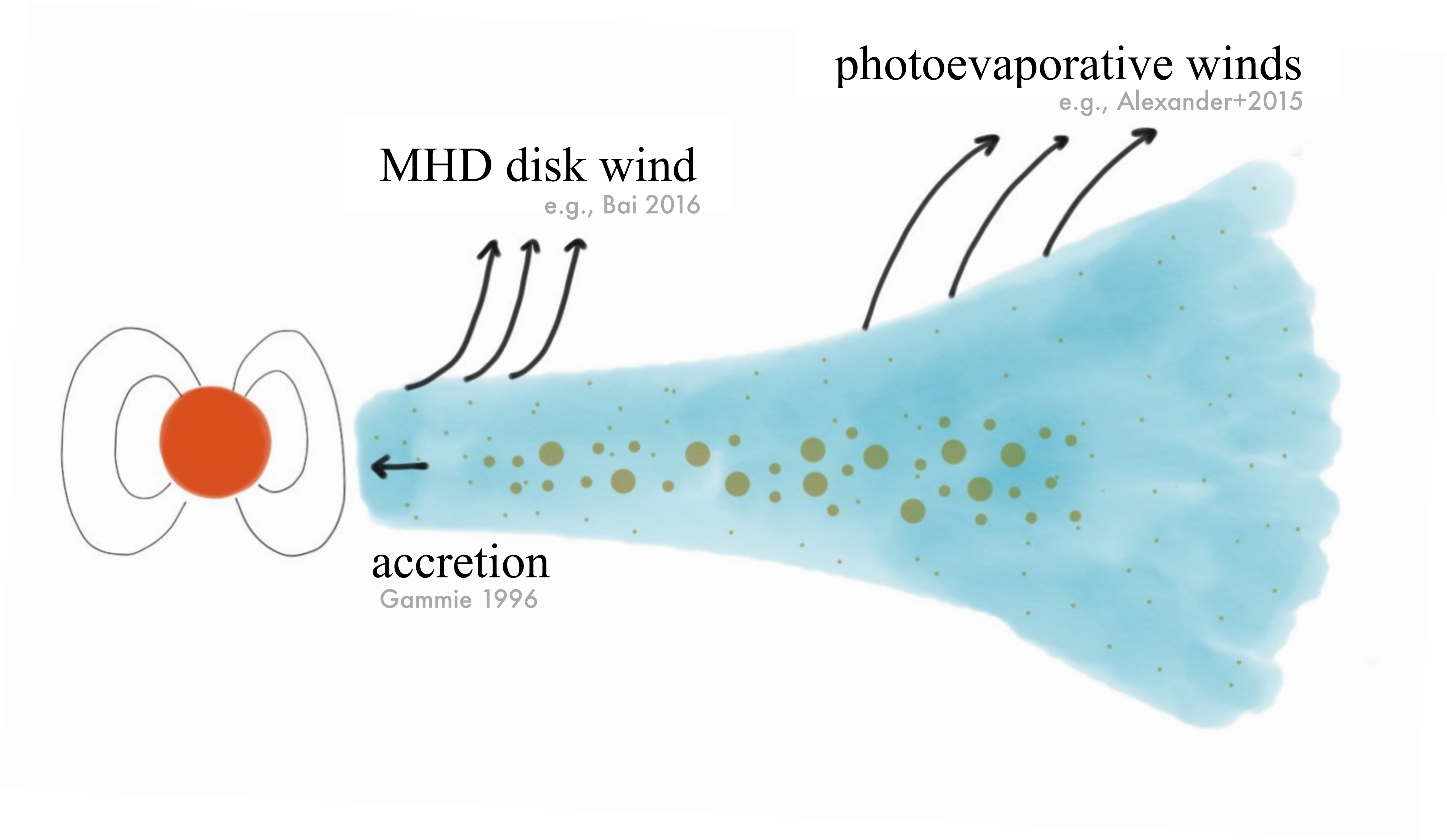

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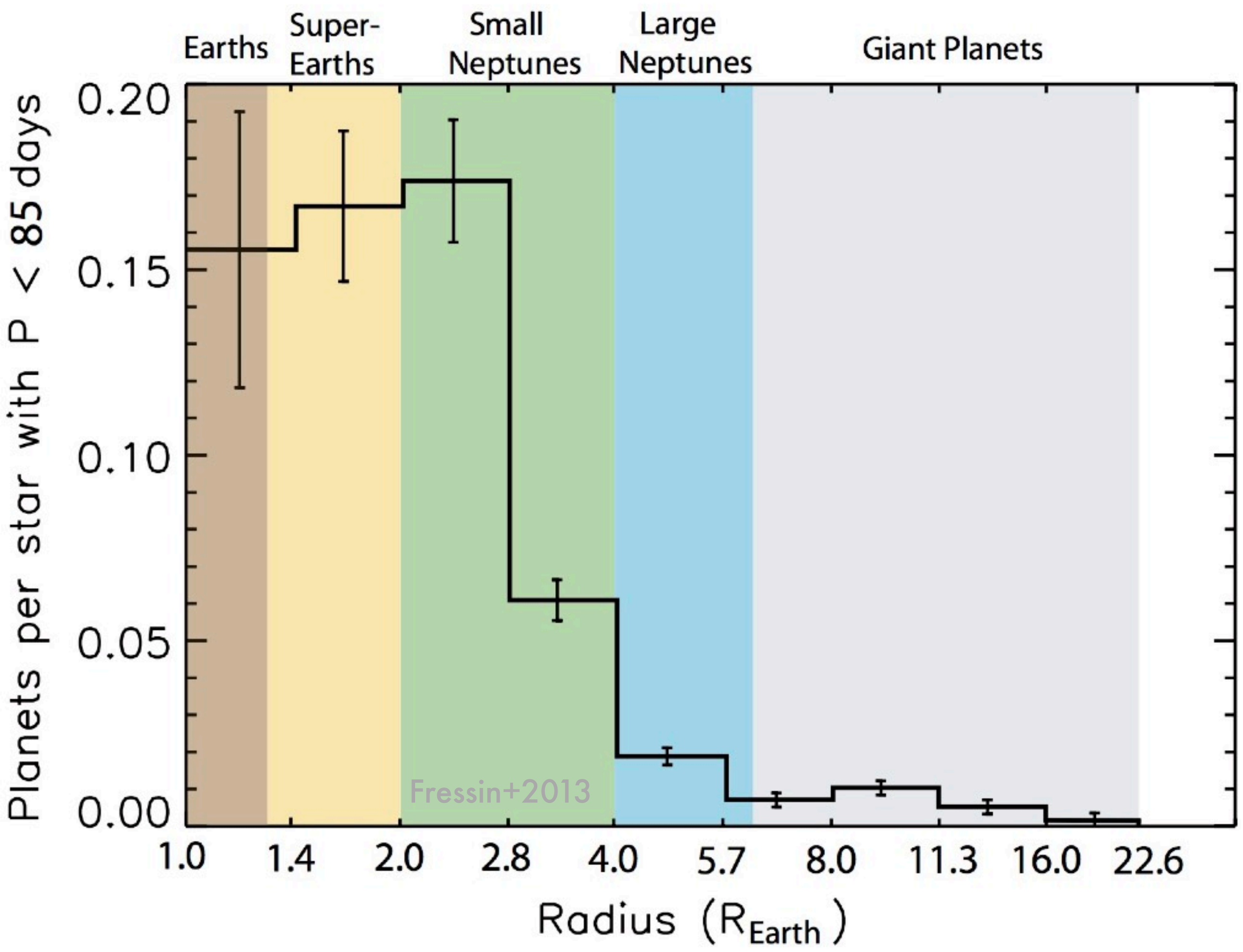
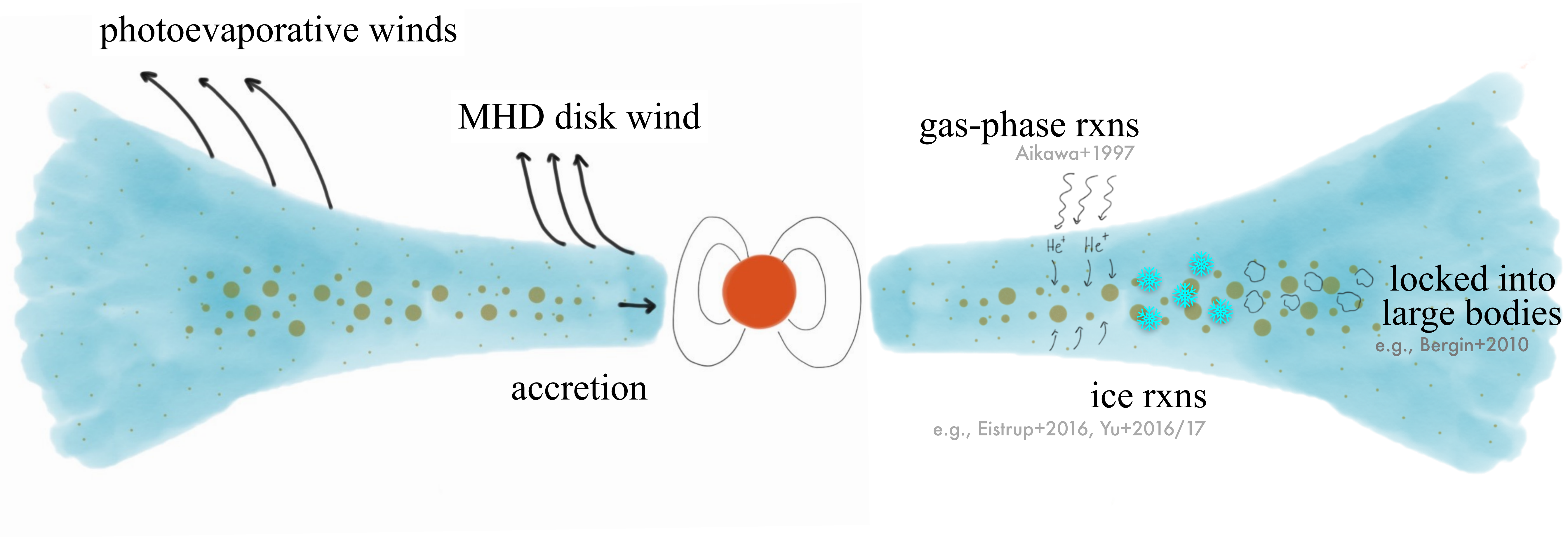


Low ^ Gas Masses

[CO-derived]



photoevaporative winds

MHD disk wind

accretion

gas-phase rxns
Aikawa+1997

ice rxns
e.g., Eistrup+2016, Yu+2016/17

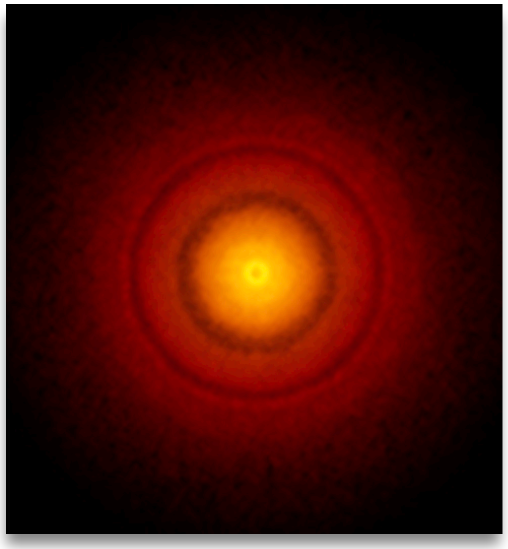
locked into large bodies
e.g., Bergin+2010

Removal of gas-rich atmosphere via winds?

Additional depletion of volatile carbon?

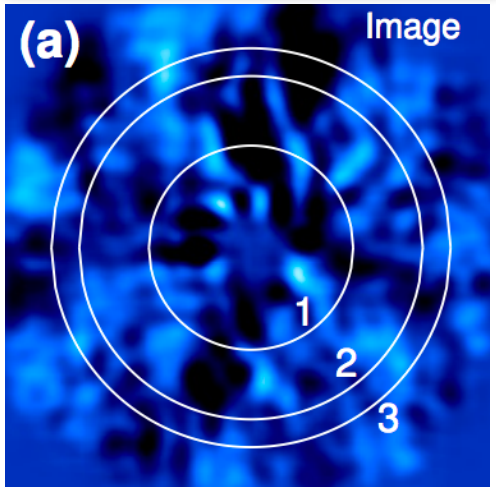
HD vs. CO Gas Masses

Andrews+2016



Different gas mass estimates for TW Hydrae:

- HD: $M_{gas} > 0.05\ M_\odot$
  Bergin+2013
- CO: $M_{gas} \approx 5\text{x}10^{-4}\ M_\odot$
  Williams & Best (2014)
- HD with updated vertical structure: $M_{gas} \approx 6\text{-}9\text{x}10^{-3}\ M_\odot$
  Trapman+2017



Ruane+2017

If 10 Myr with 50 M_{Jup} then where are the gas giants?
No non accreting Jupiter-mass planets found with direct imaging

Only two other gas masses from HD
(biased to brightest/massive disks)

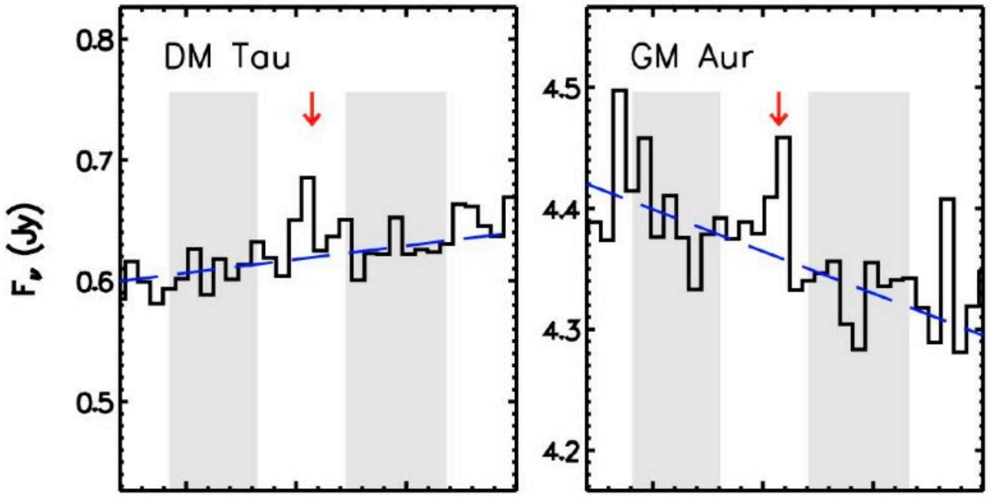
- GM Aur: $2.5\text{-}20.4\text{x}10^{-2}\ M_\odot$
- DM Tau: $1.0\text{-}4.7\text{x}10^{-2}\ M_\odot$

↑

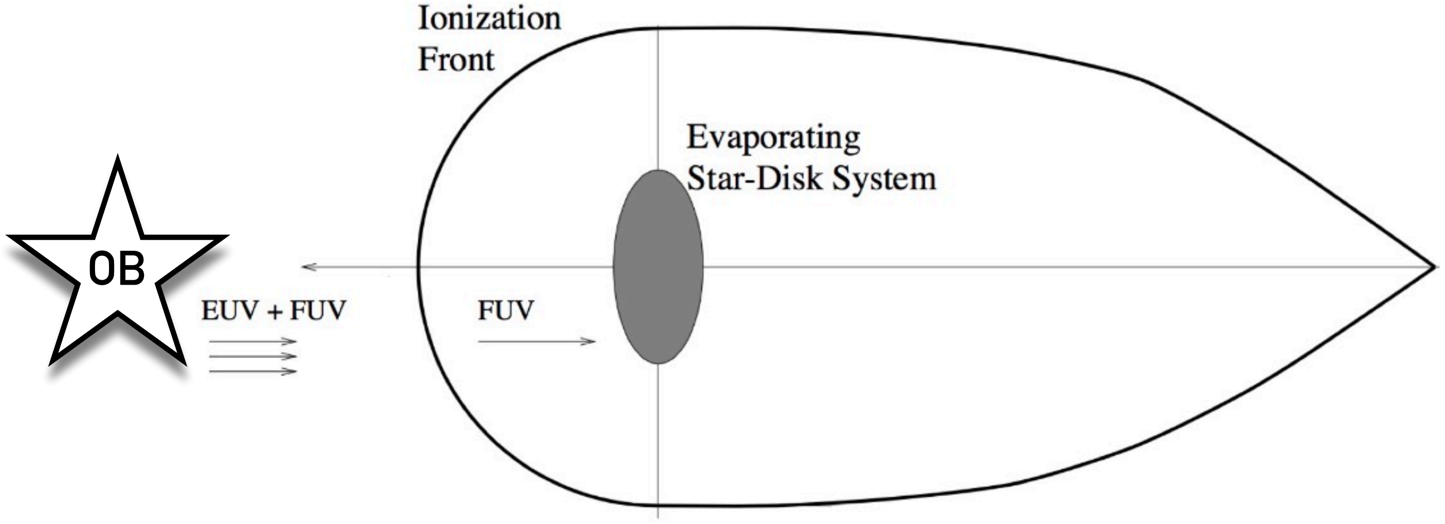
Consistent with CO mass
of $0.9\text{x}10^{-2}\ M_\odot$

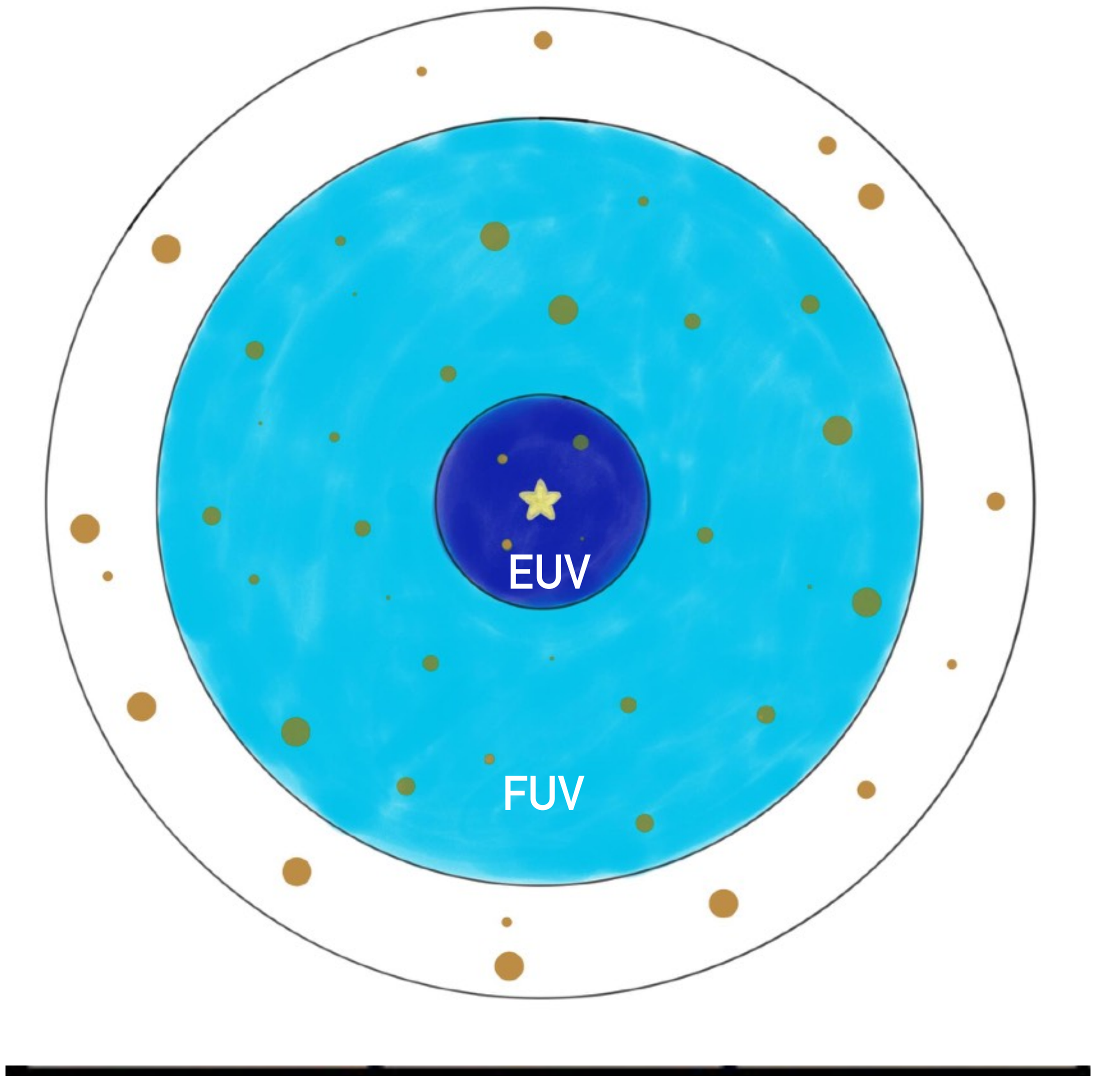
Williams & Best (2-14)

McClure+2016

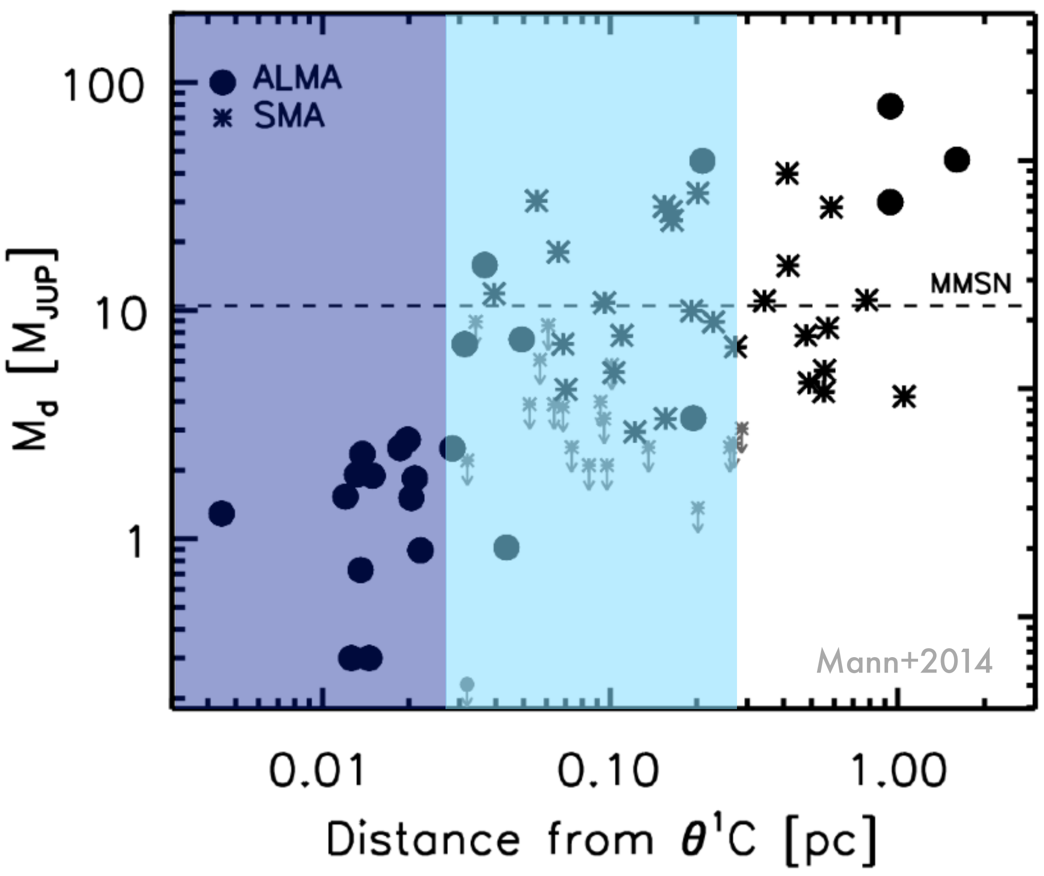


External Photoevaporation



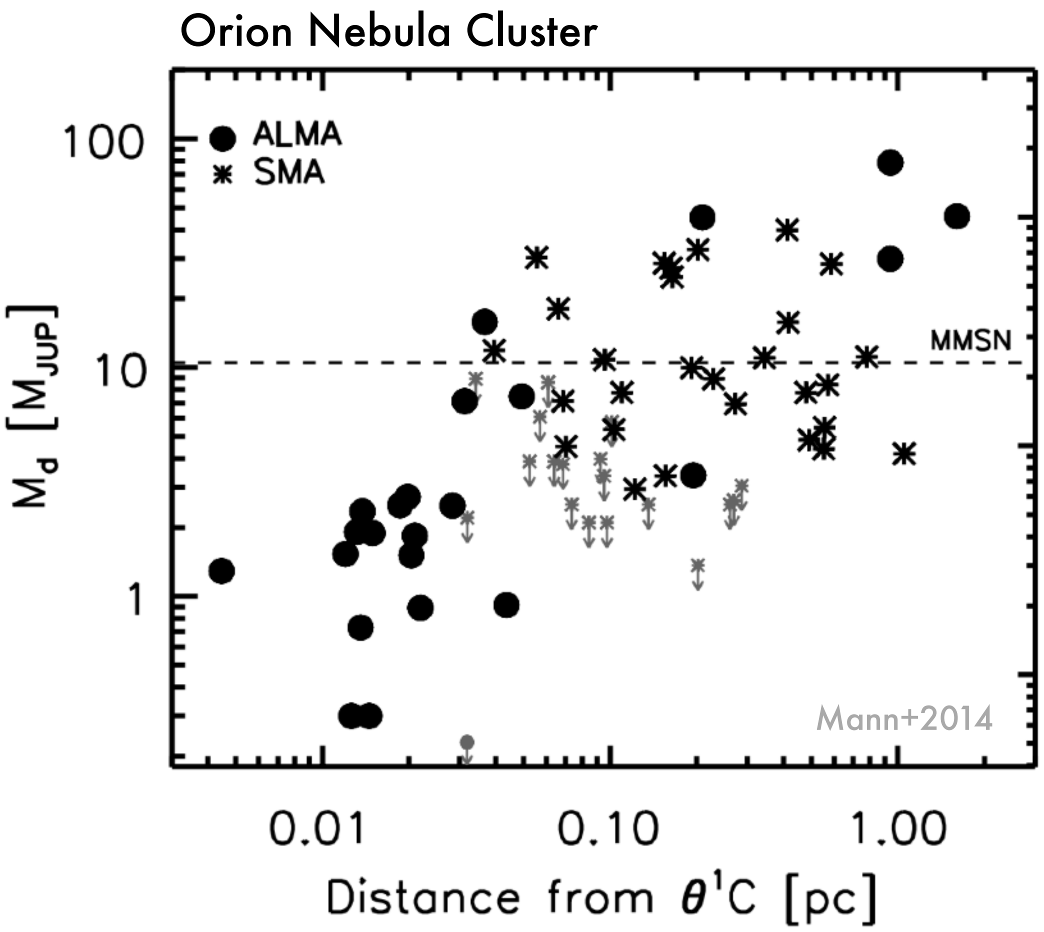


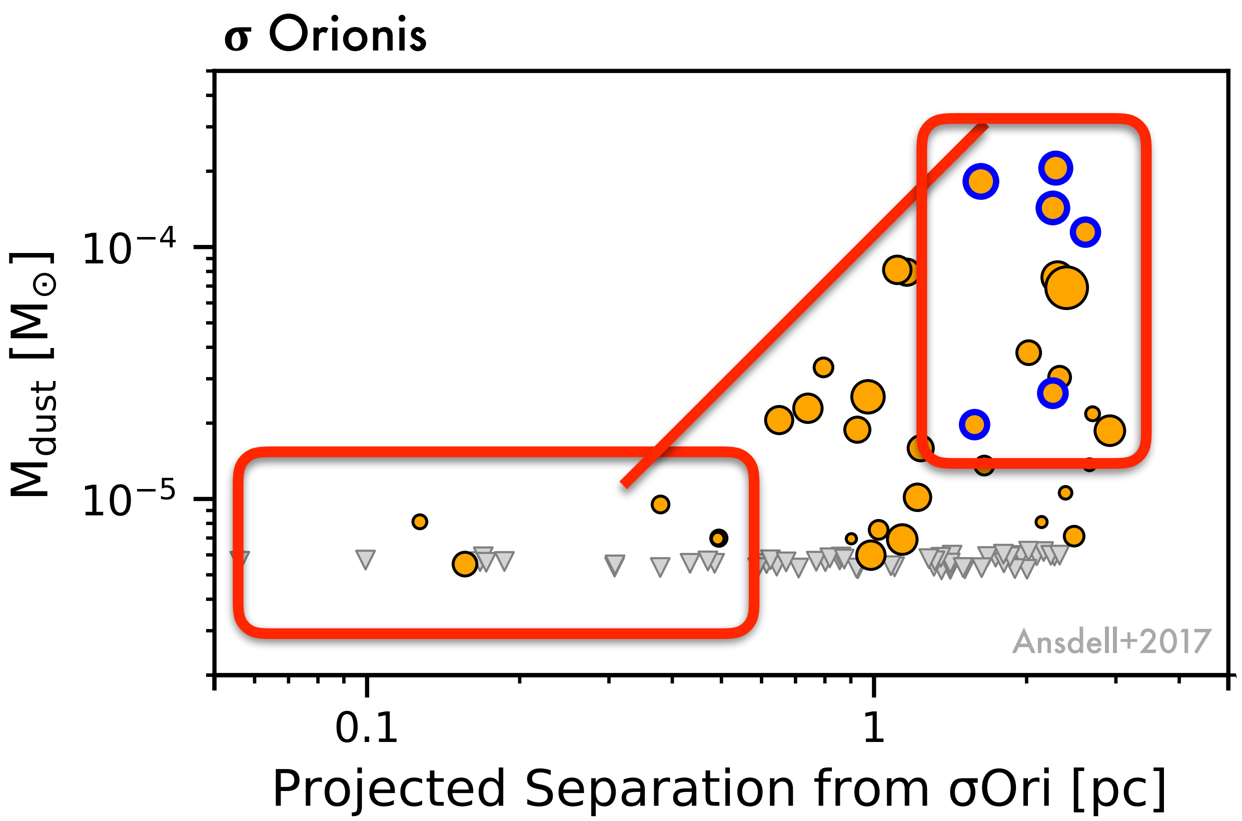
Orion Nebula Cluster



- No massive (>9$M_\oplus$) disks at < 0.03 pc (EUV)
- Normal at 0.03-0.30 pc (FUV) and beyond

External Photoevaporation


Orion Nebula Cluster

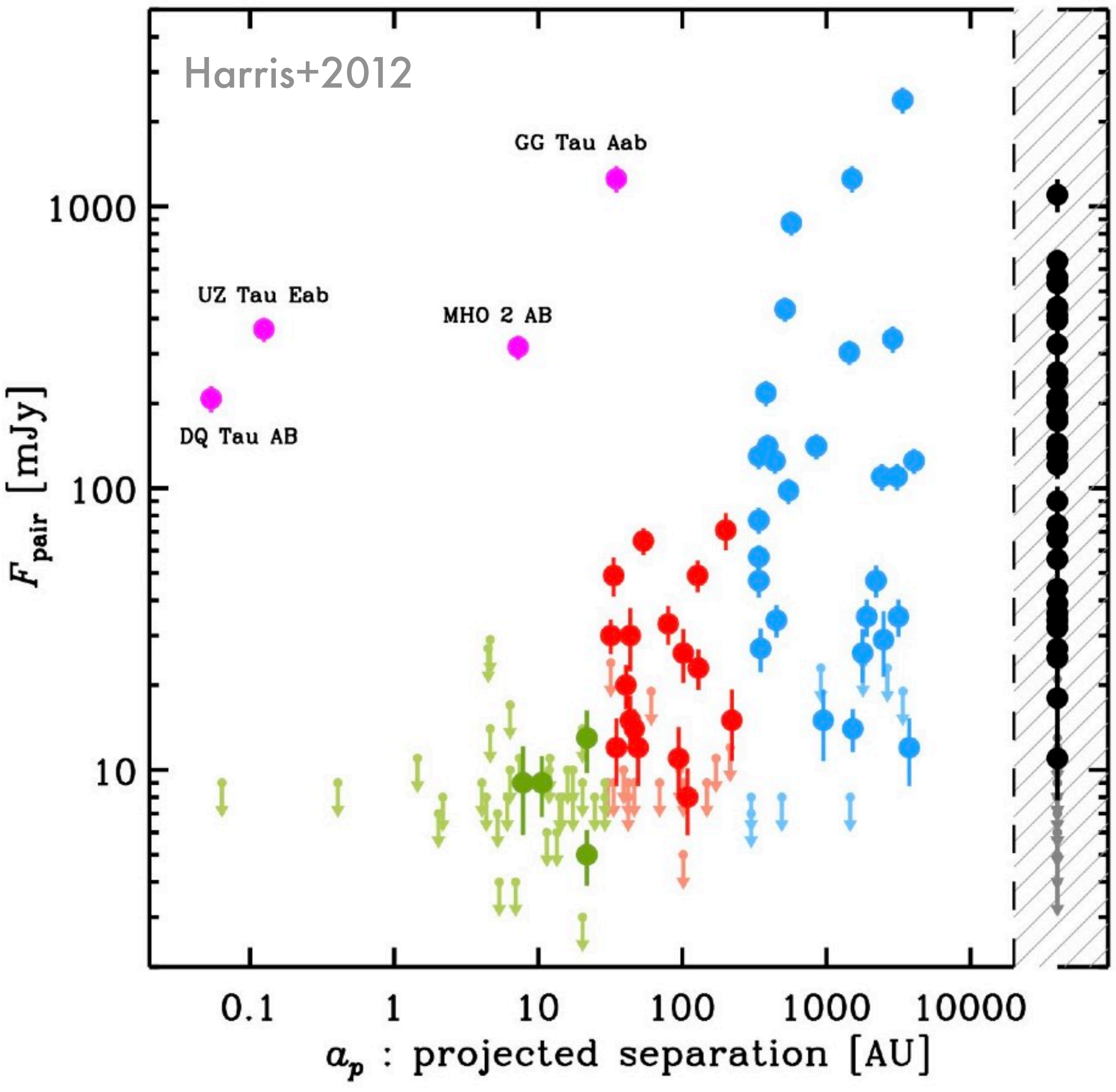

σ Orionis

- No massive (>9$M_\oplus$) disks at < 0.03 pc (EUV)
- Normal at 0.03-0.30 pc (FUV) and beyond

- No massive (>3$M_\oplus$) disks at <0.5 pc
- Smooth trend <0.5 pc to cluster edge
- Gas detections at edges of cluster

External photoevaporation effects
disks throughout OB clusters

Close (-ish) binaries inhibiting planet formation?

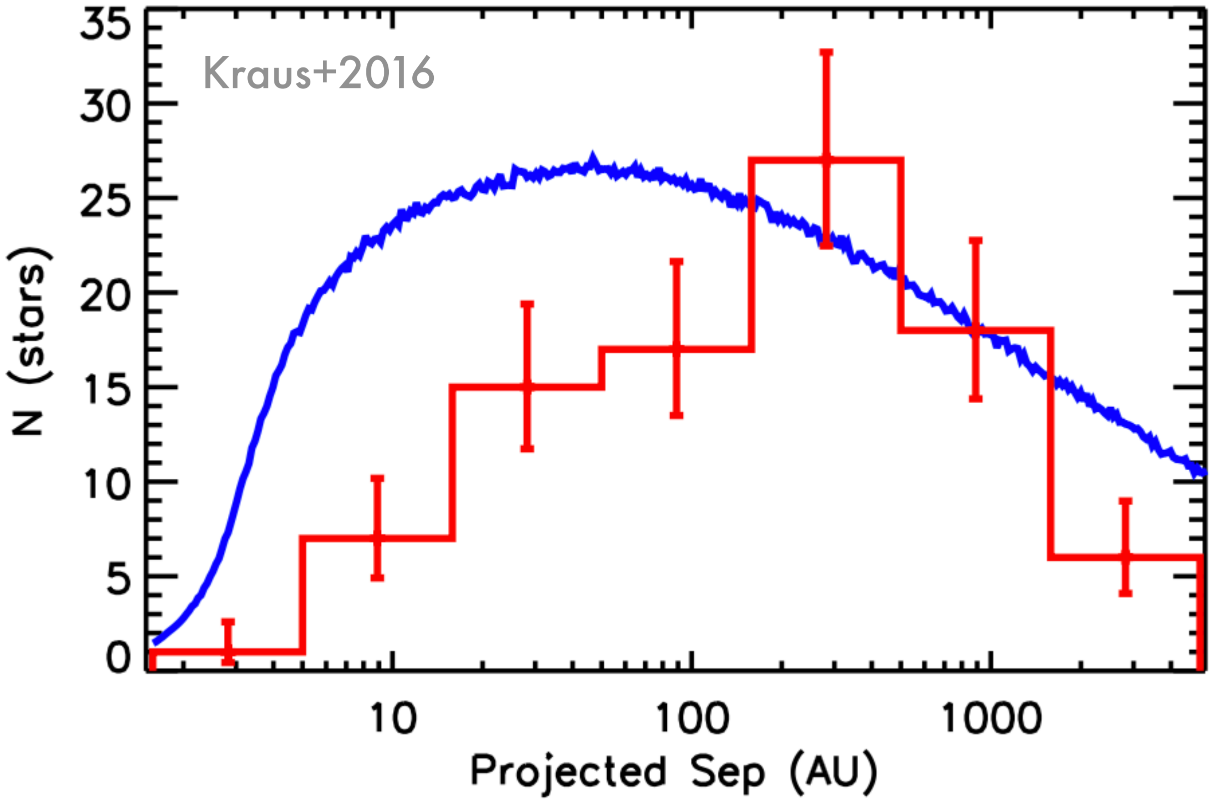


The (Taurus) disk view:

- a > 300 AU → same as isolated stars
- a = 30–300 → 5x fainter
- a < 30 → 25x fainter
- circumbinary → same as isolated stars

The (Kepler) exoplanet view:

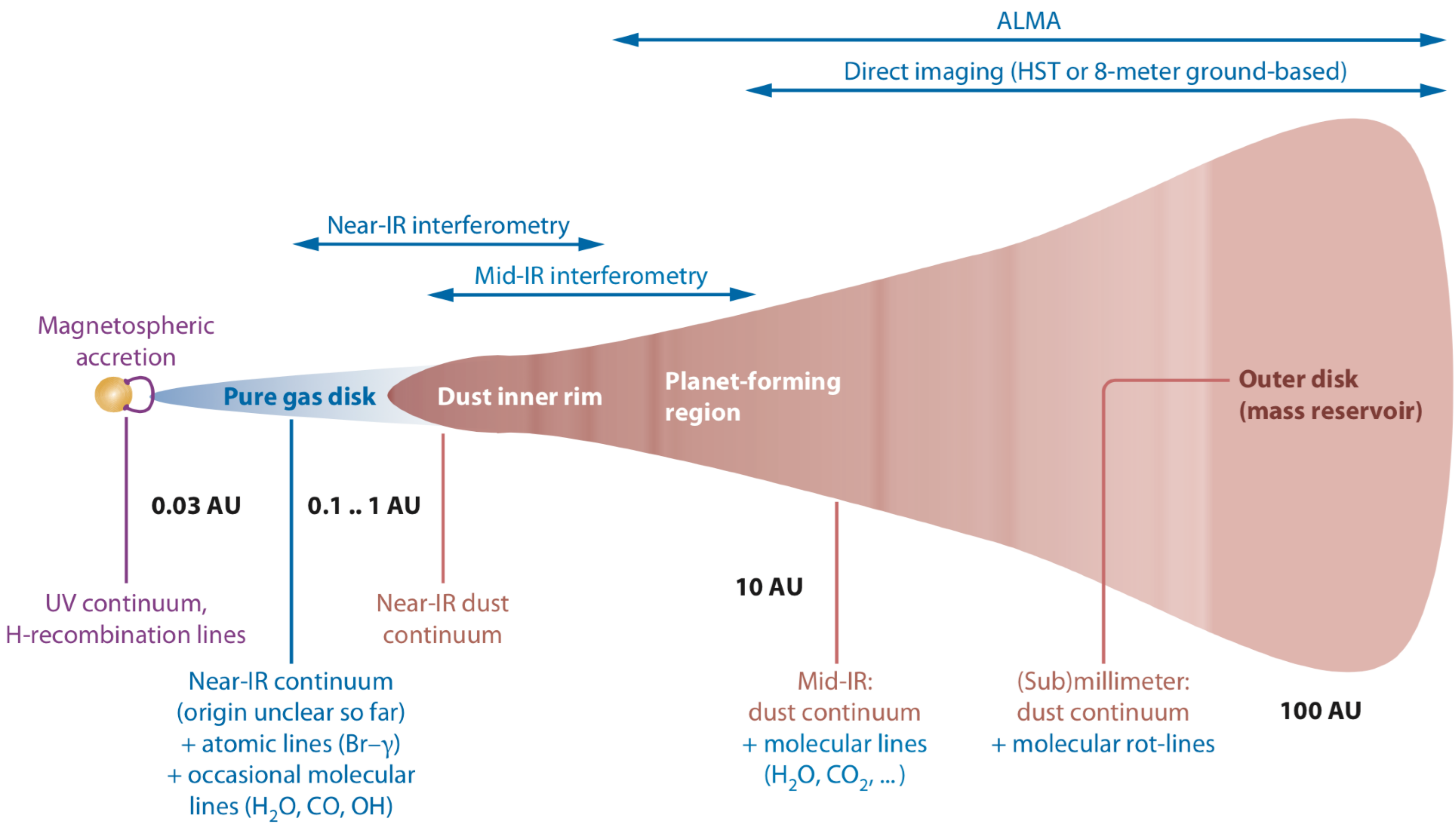
- a < 100 AU → planet-hosting binaries rarer than "field" binary population



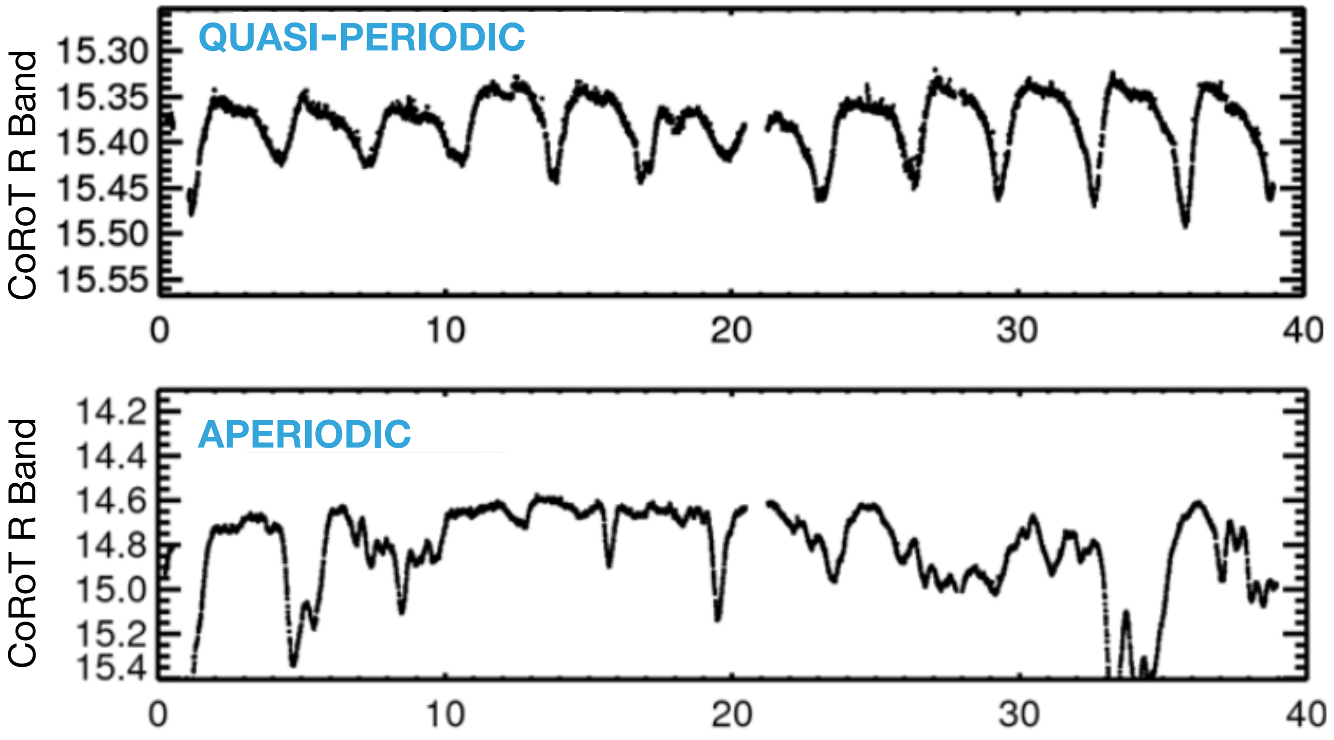
Close (<100 AU) binaries inhibit planet formation, but very close (<1 AU) binaries may not

What about the inner disk?

Difficult to observe < 1 AU scales: small angular scales and bright host star



The "dipper" stars

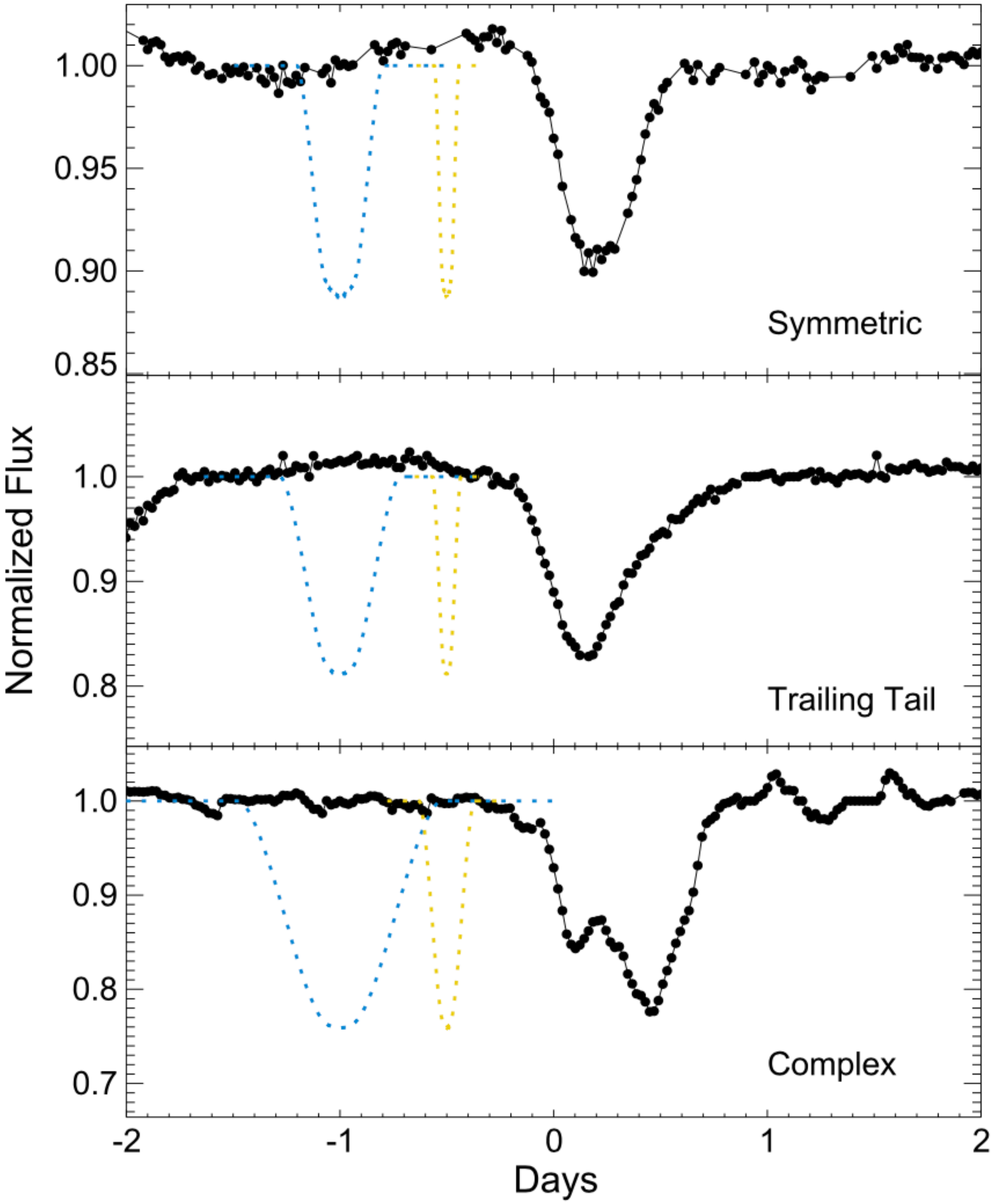


Cody+2014

- Dip periods < 1 week
- Dip durations ~0.5-2 days
- Dip depths up to ~60% in flux

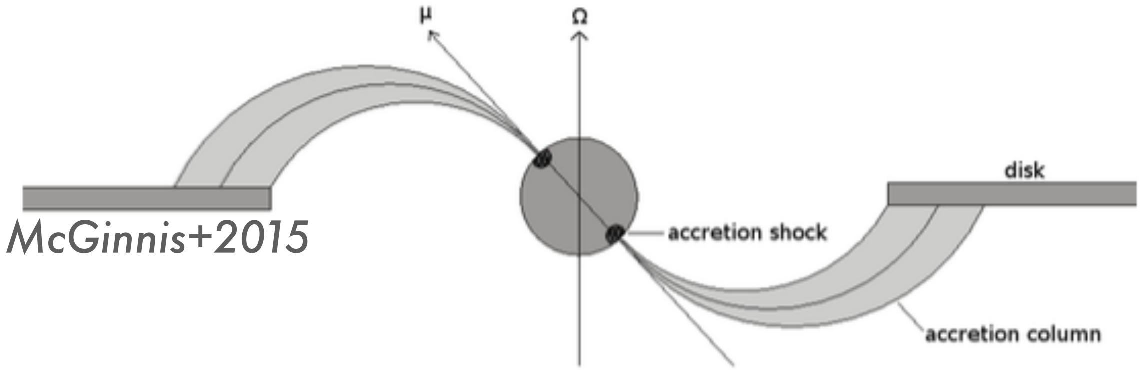
Not planetary!

- Young (<10 Myr) stars with disks
- Exhibit dimming events in optical LCs
- Quasi-periodic or aperiodic behavior



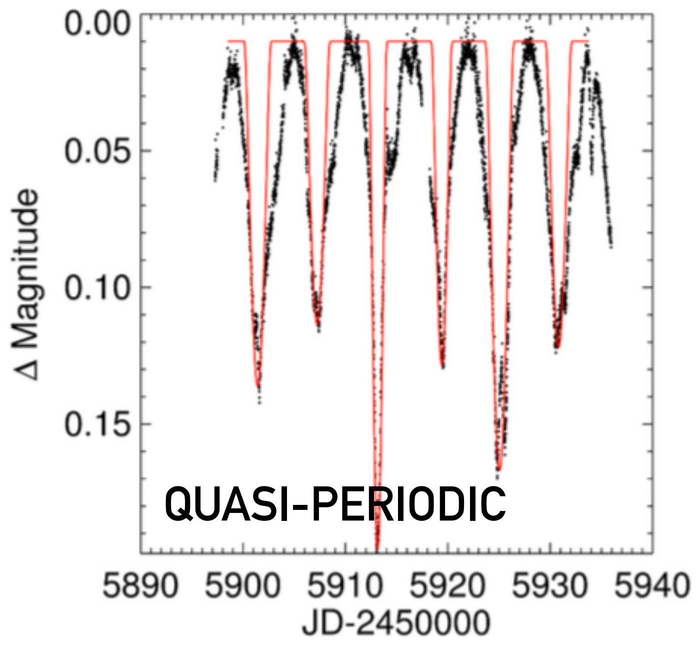
What is causing the “dipper” phenomenon?

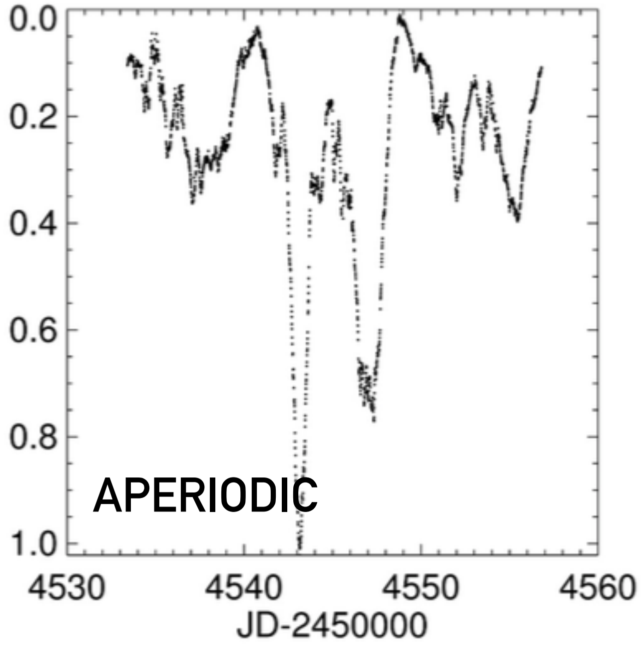
Inner dusty warps in nearly edge-on disks passing along line of sight



McGinnis+2015

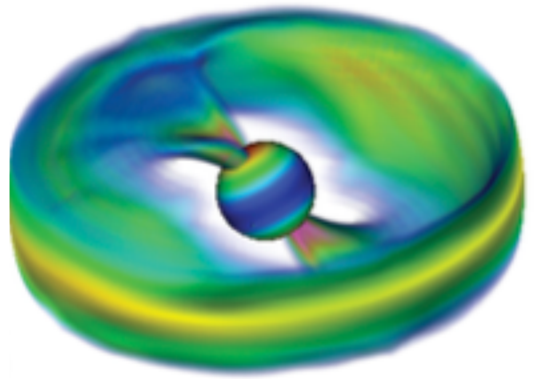
Are dippers too common (20-30% of disks) for edge-on disk scenario?

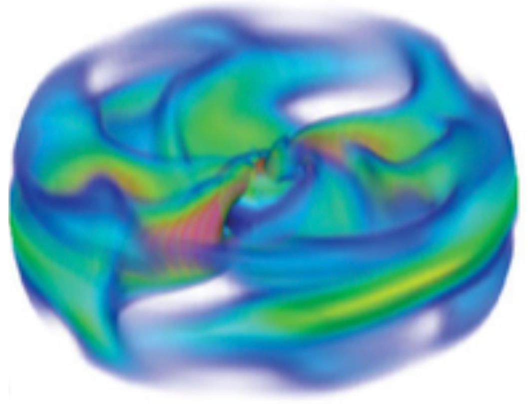




STABLE ACCRETION

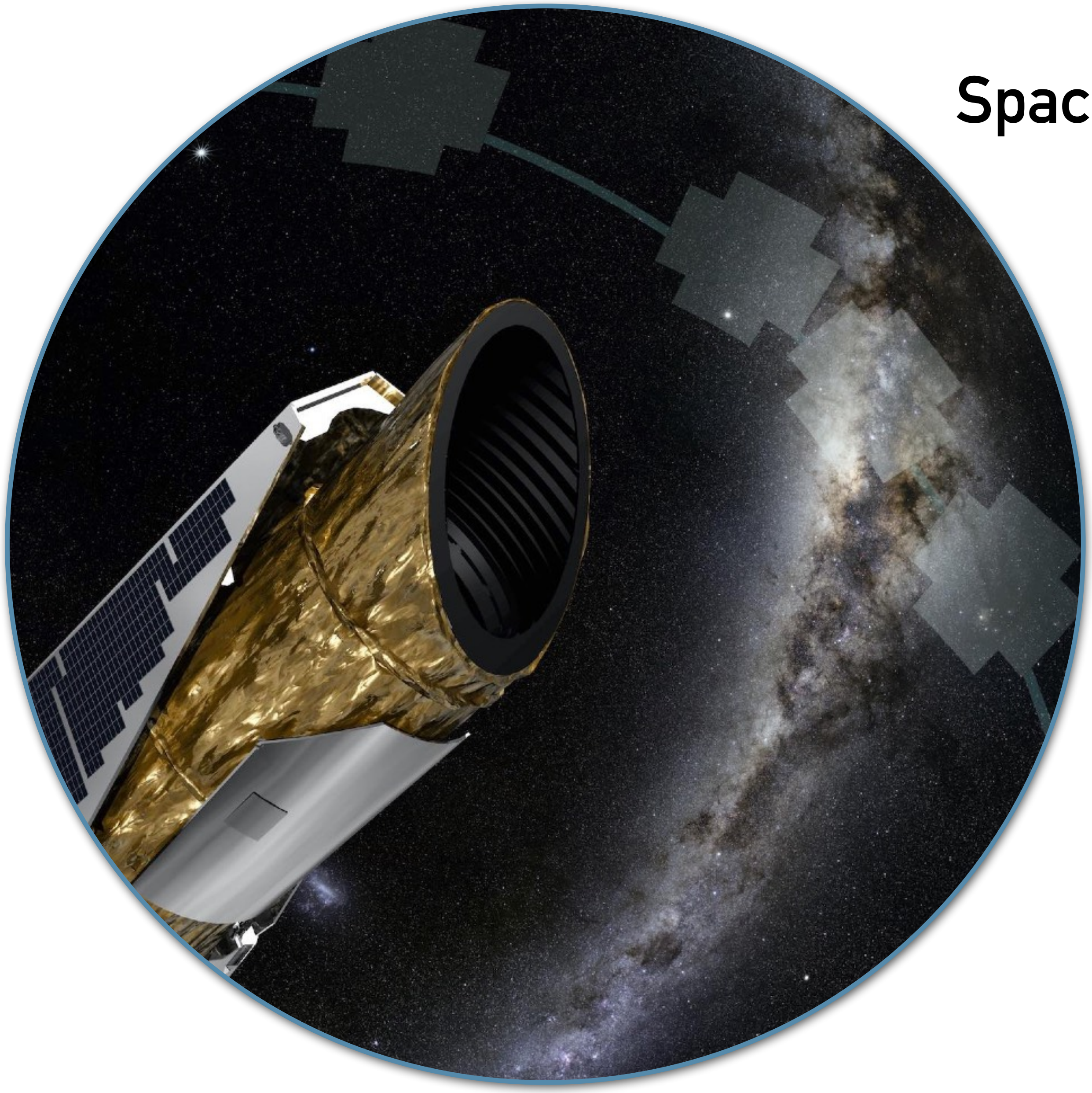
UNSTABLE ACCRETION





Kurosawa & Romanova 2013

K2: New Insights Into Dippers



Space-based optical photometry along ecliptic

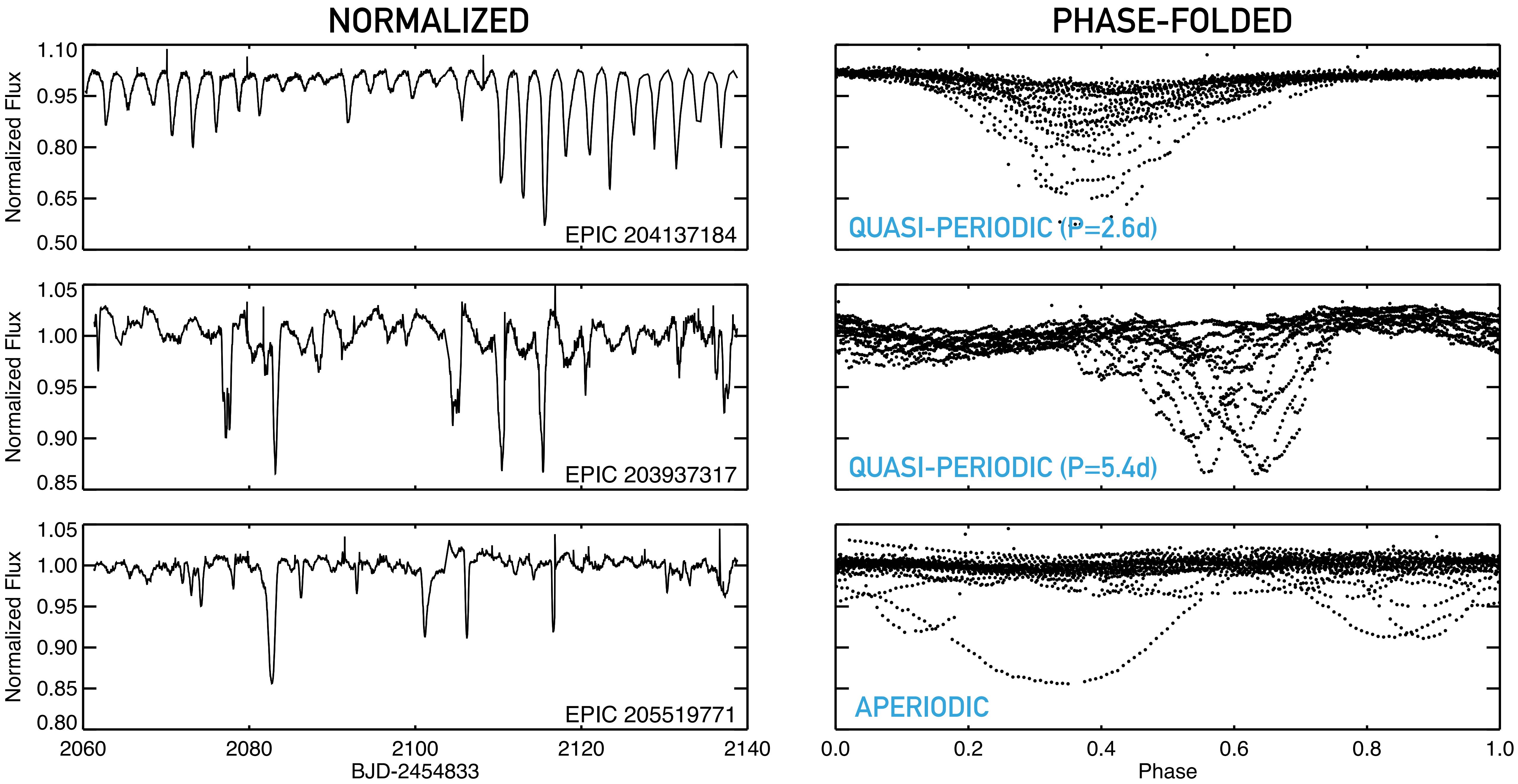
- High precision (~mmag)
- High cadence (~30 min)
- Long-term (~80 days)

K2/C2 observed closer + older SFRs

Ansdell+2016

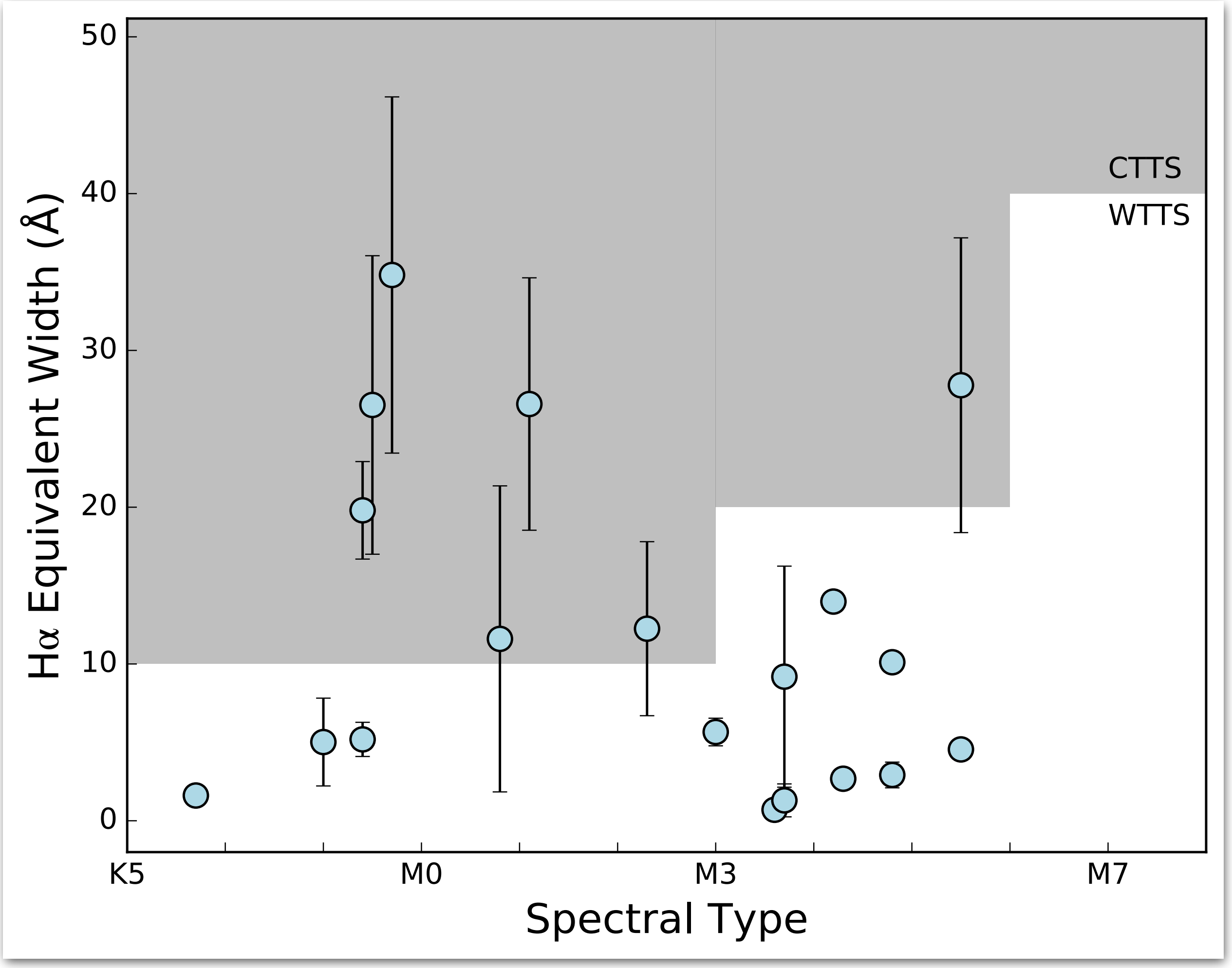
- USco (10 Myr @ 140 pc)
- ρ Oph (2 Myr @ 120 pc)

K2: New Insights Into Dippers

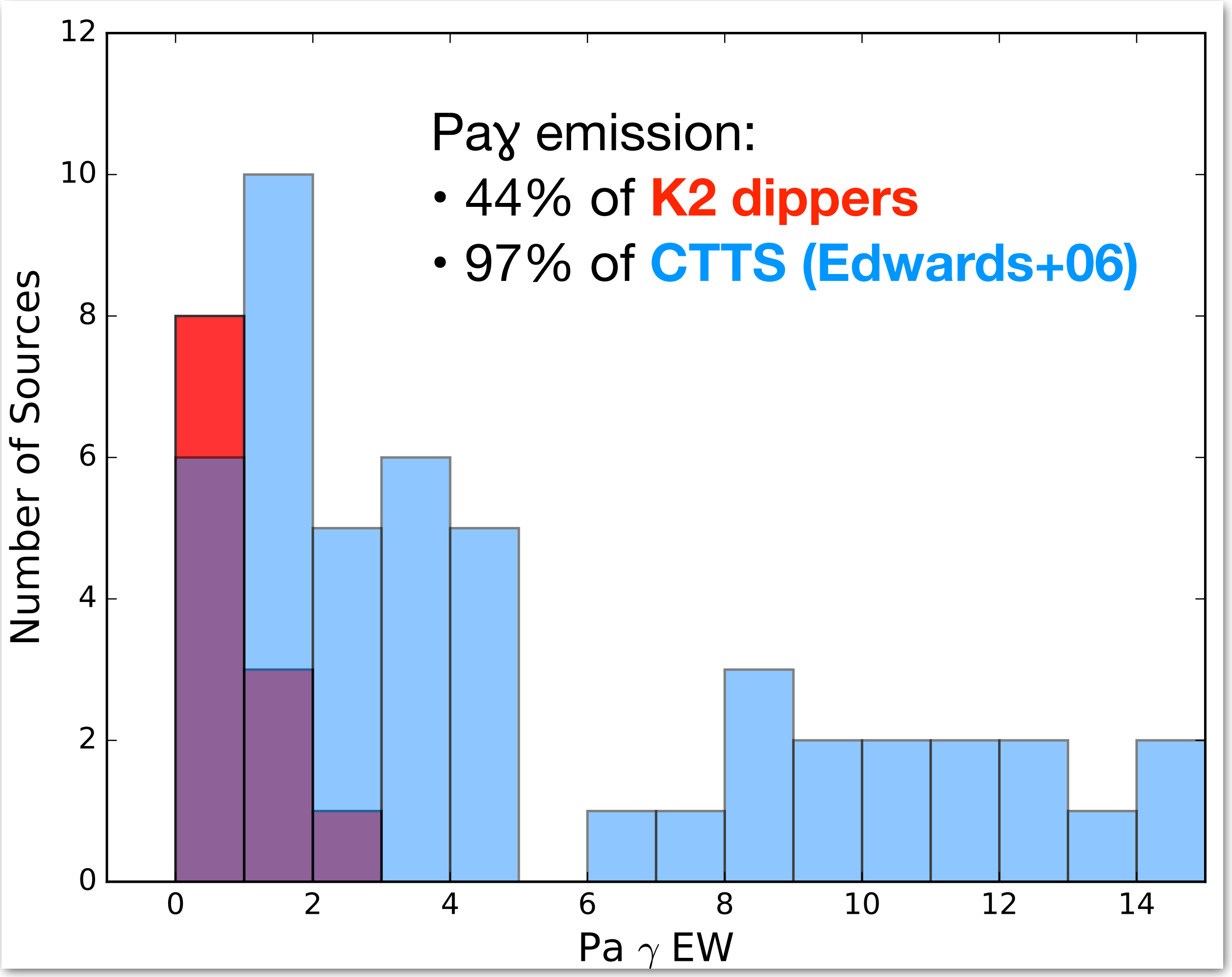


Ansdell+2016a

Non-accreting Dippers?



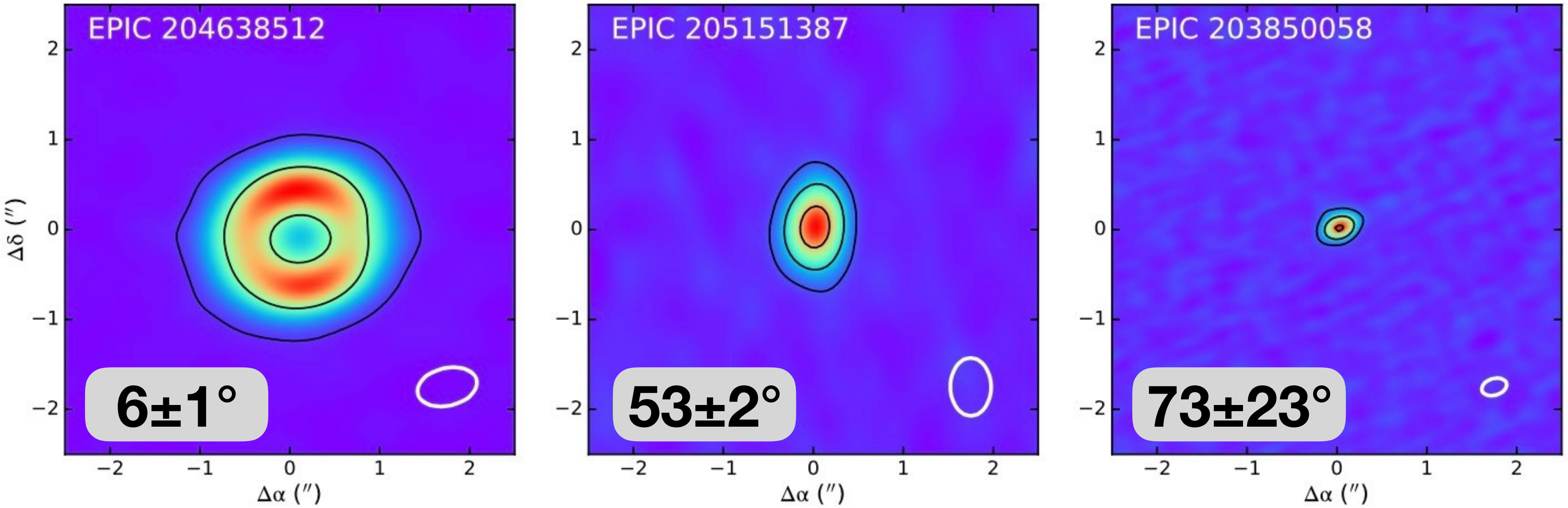
Mostly WTTS when using Hα emission to identify CTTS (White & Basri 2003)

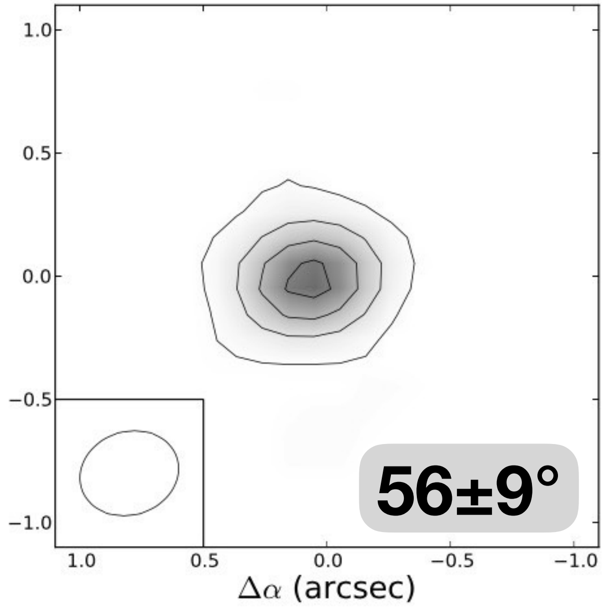

Paɣ emission:

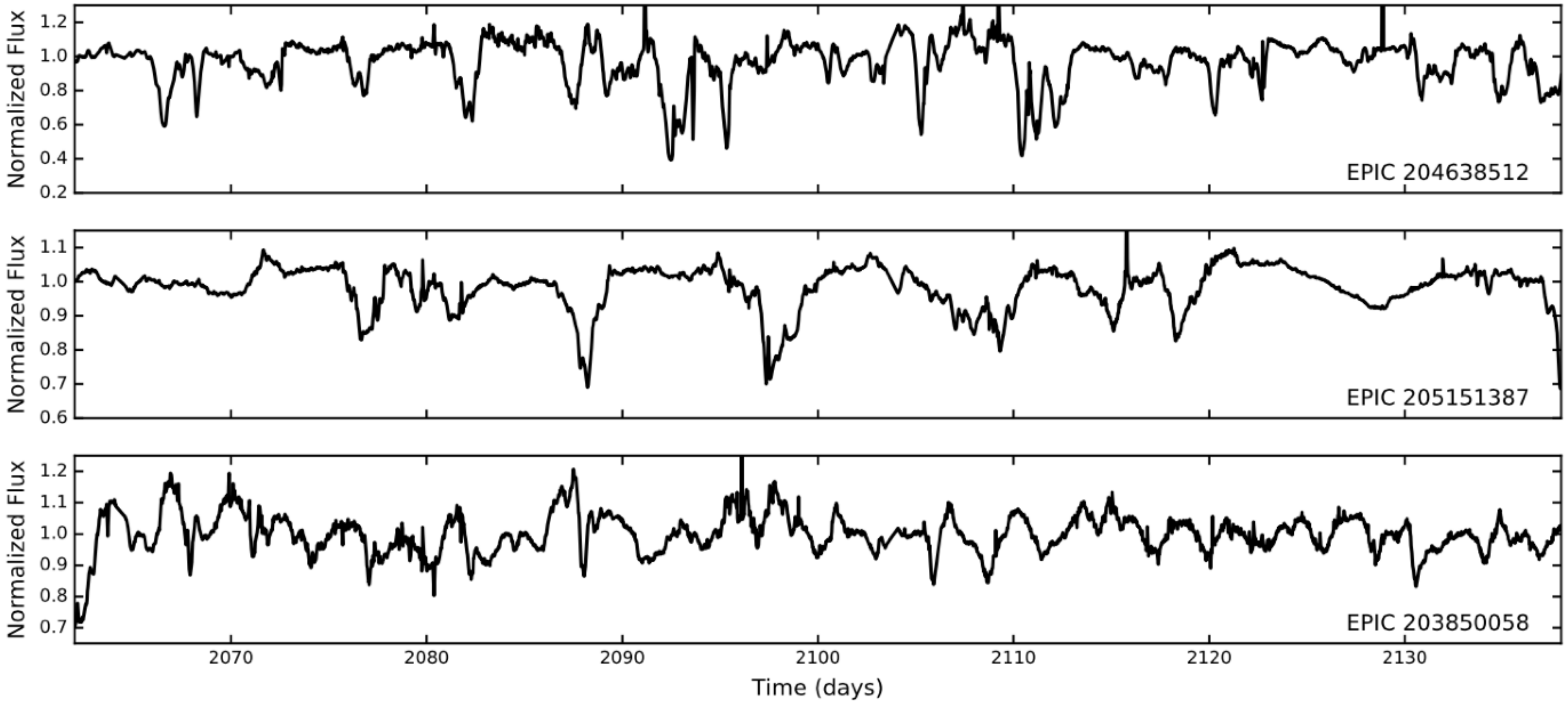
- 44% of **K2 dippers**
- 97% of **CTTS (Edwards+06)**

Weak or no accretion when using Paɣ emission as tracer of accretion

Dipper Disks Not Inclined to Edge-on Orbits...

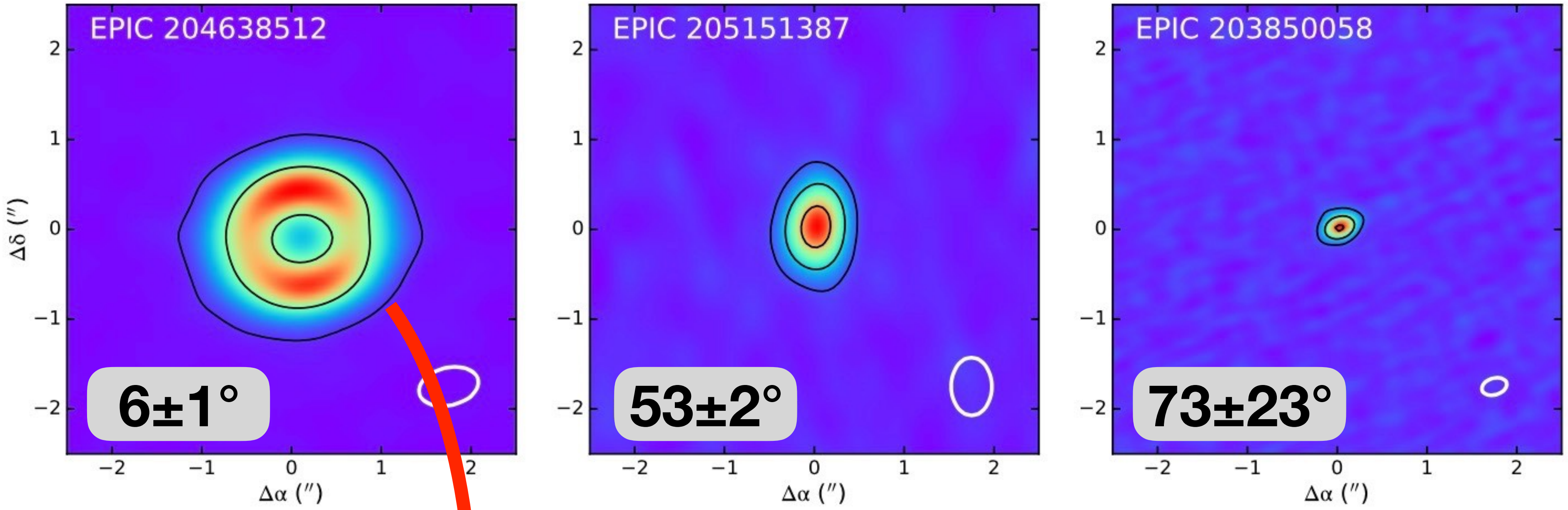

Ansdell+2016c


Scaringi+2016



Dippers not inclined toward edge-on orbits?

Dipper Disks Not Inclined to Edge-on Orbits...

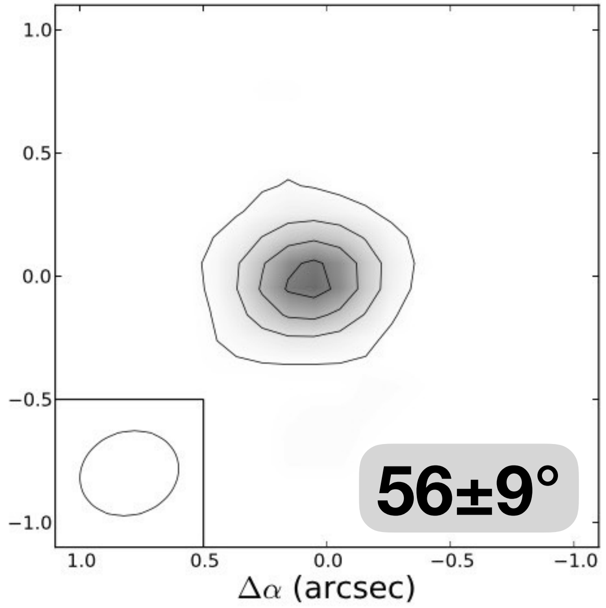


6±1°

53±2°

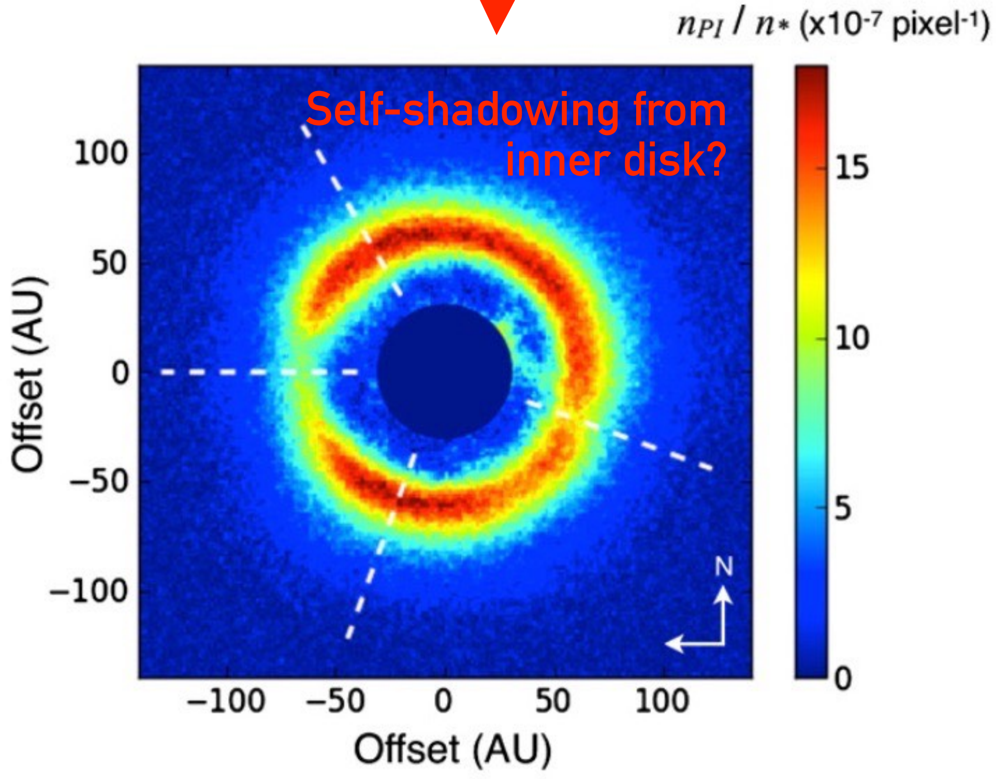
73±23°

Ansdell+2016c



56±9°

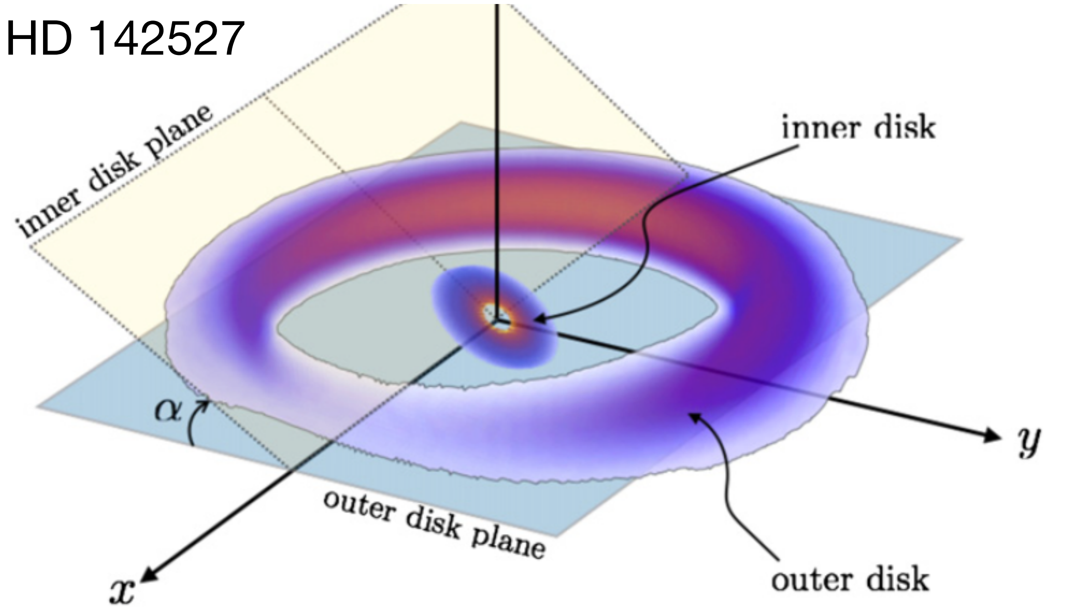
Scaringi+2016



Self-shadowing from inner disk?

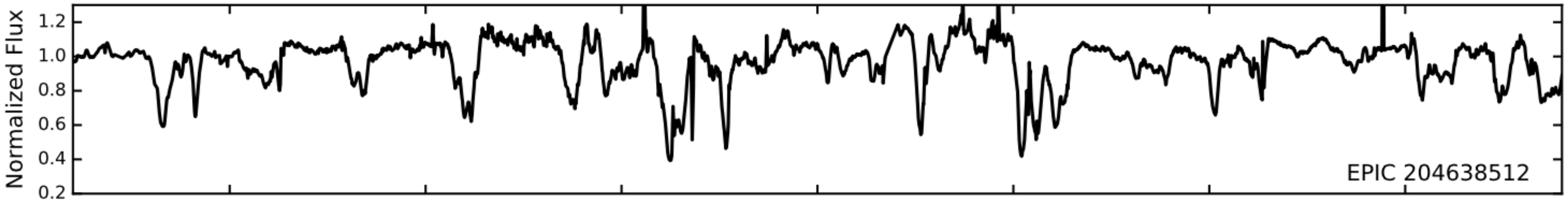
Takami+2014

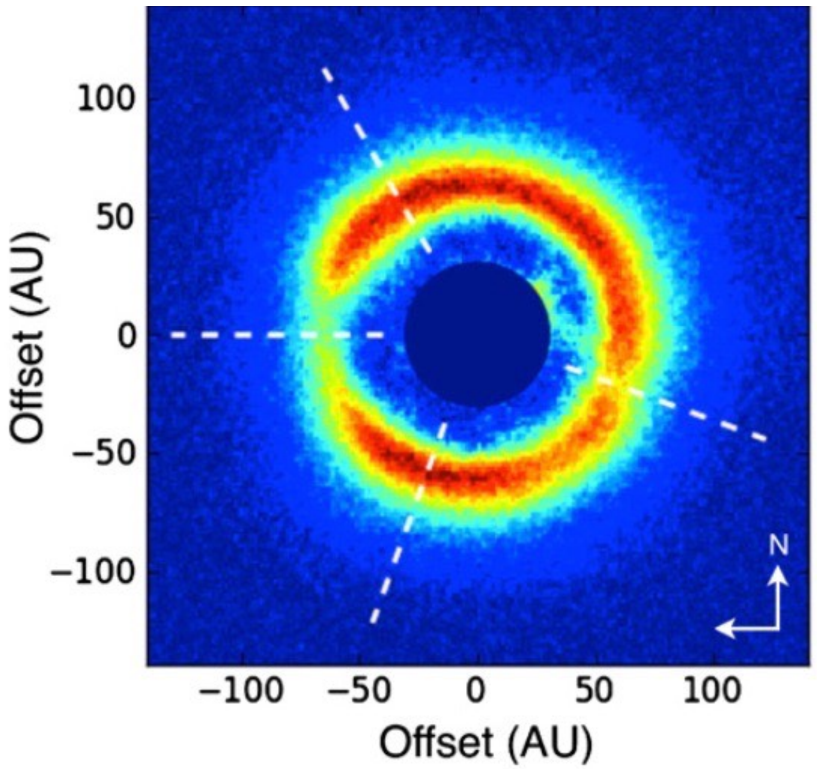
- Inclined inner disk source of dipper activity?
- Warped by companion orbiting in dust gap



Marino+2015

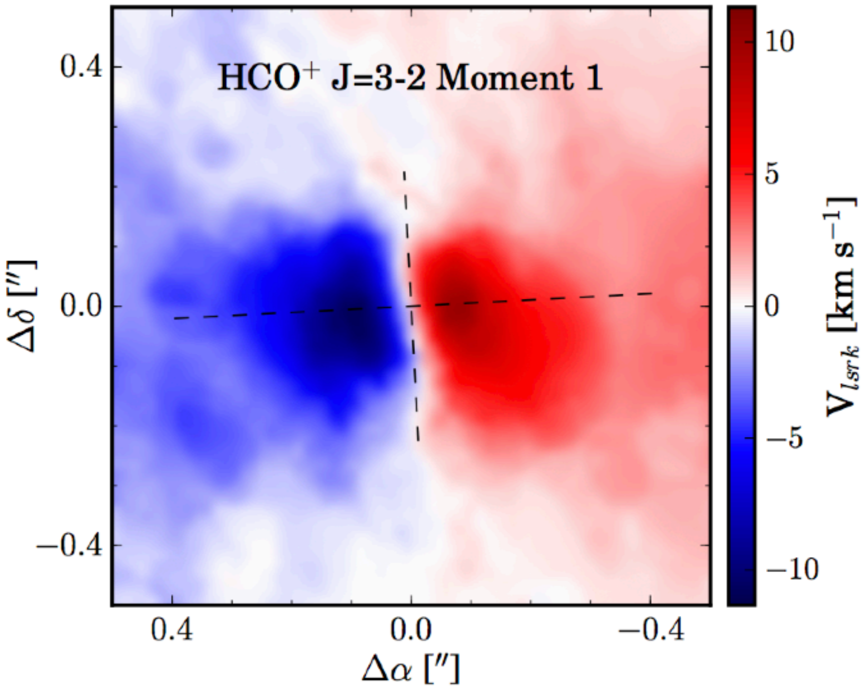
Increasing Evidence for Warps in Inner Disk

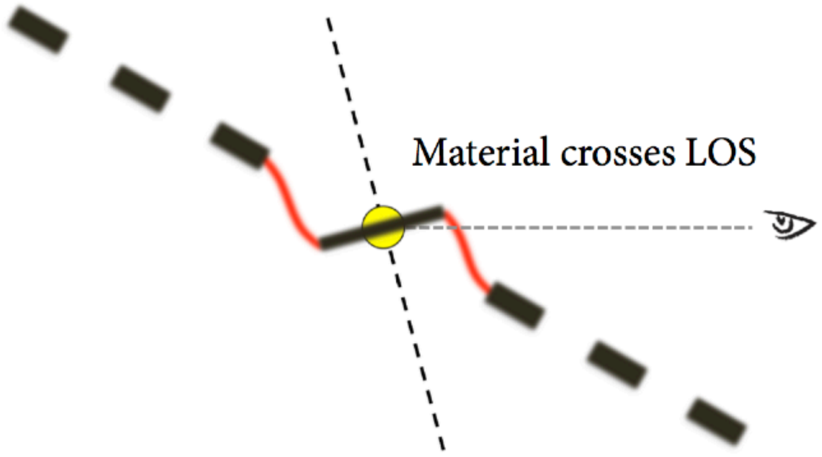




Many dippers with resolved disks are moderately inclined

Face-on disks show self-shadowing from inner disk





AA Tau (the original dipper) is not edge on!

Evidence for warps from HCO+ velocity profile