Debris Disks with ALMA

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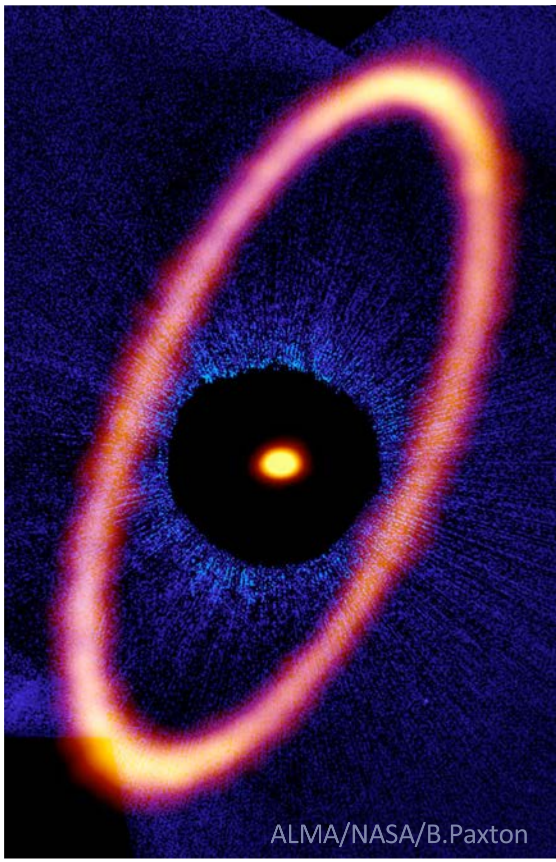
HARVARD & SMITHSONIAN



thanks to
M. MacGregor (Carnegie)
L. Matra (CfA)
+ many more collaborators

Planet-Forming Disks: A workshop to honor Antonella Natta. March 8, 2019

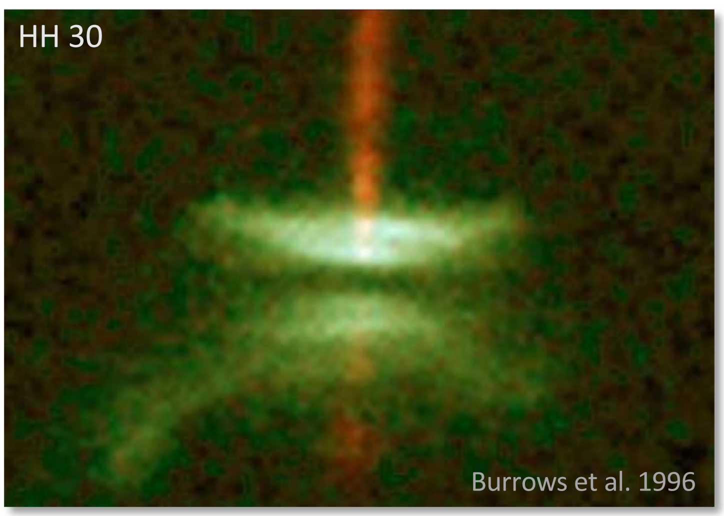
Planet-Forming → Debris Disk

Pre-Main Sequence (< 10 Myr)

Gas + Trace Dust

$L_{dust}/L_{*} \sim$ 10's of %

primordial dust colliding, growing planetesimals/planets

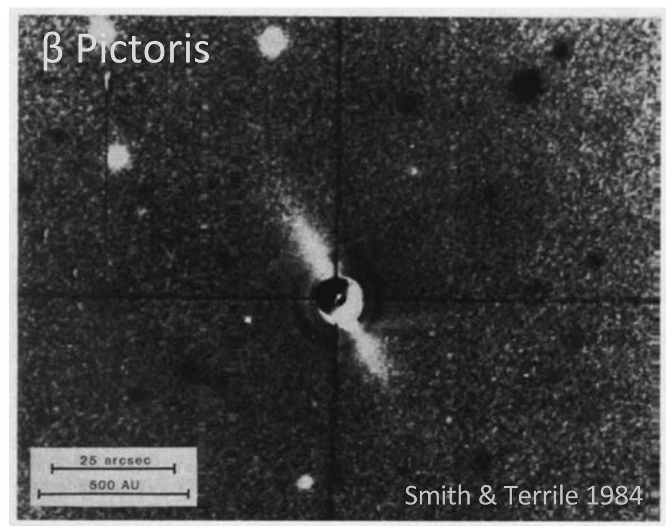


Main Sequence (to Gyrs)

Dust + Trace Gas

$L_{dust}/L_{*} <$ 0.1% (replenished!)

planetesimals colliding, generating secondary dust

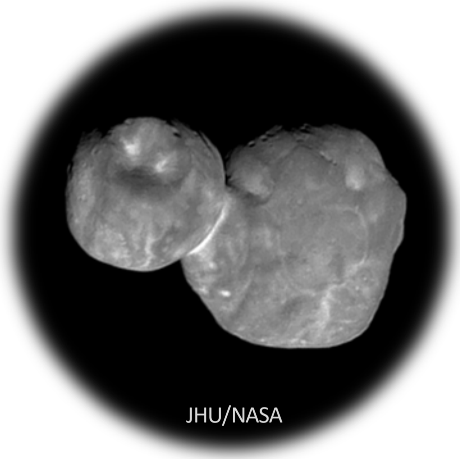


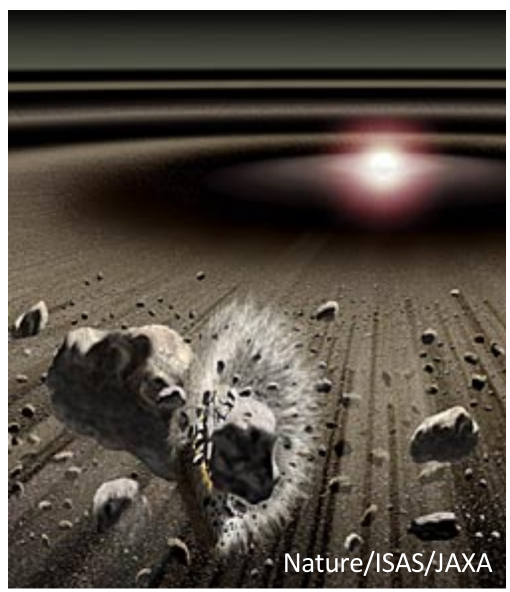
Relevance of Millimeter Regime

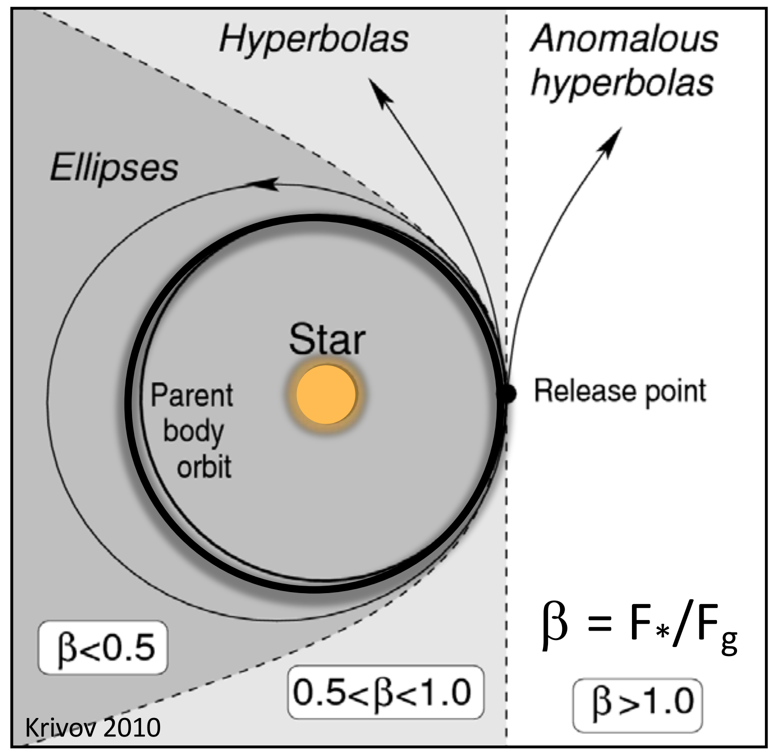
Collisional cascade creates fragments with a range of sizes

µm-size grains blown out rapidly by radiation/winds into halo

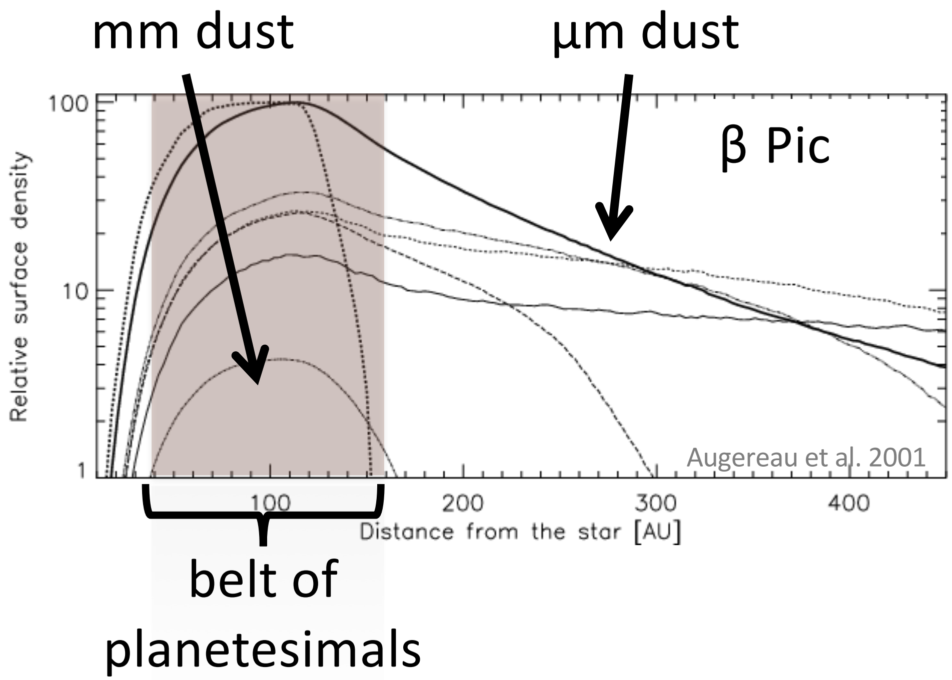
mm-size grains don't travel far → trace planetesimal orbits (and perturbations from planets, if present)

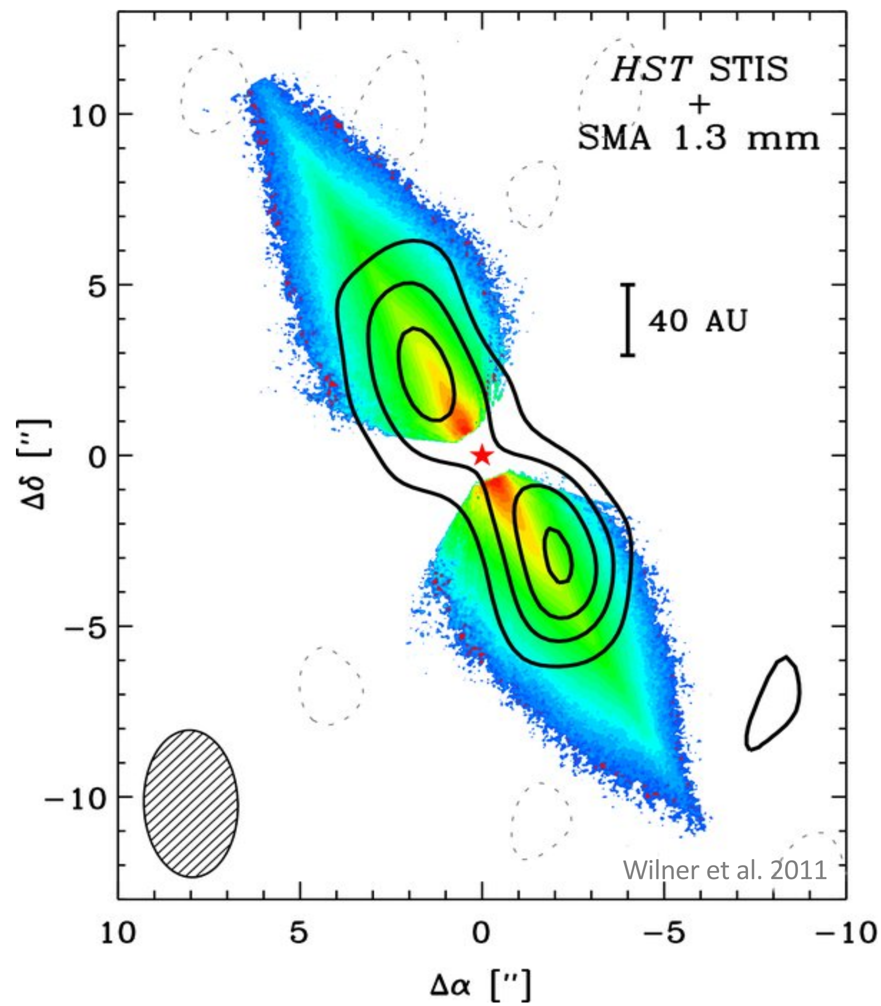






Size Dependent Dust Dynamics





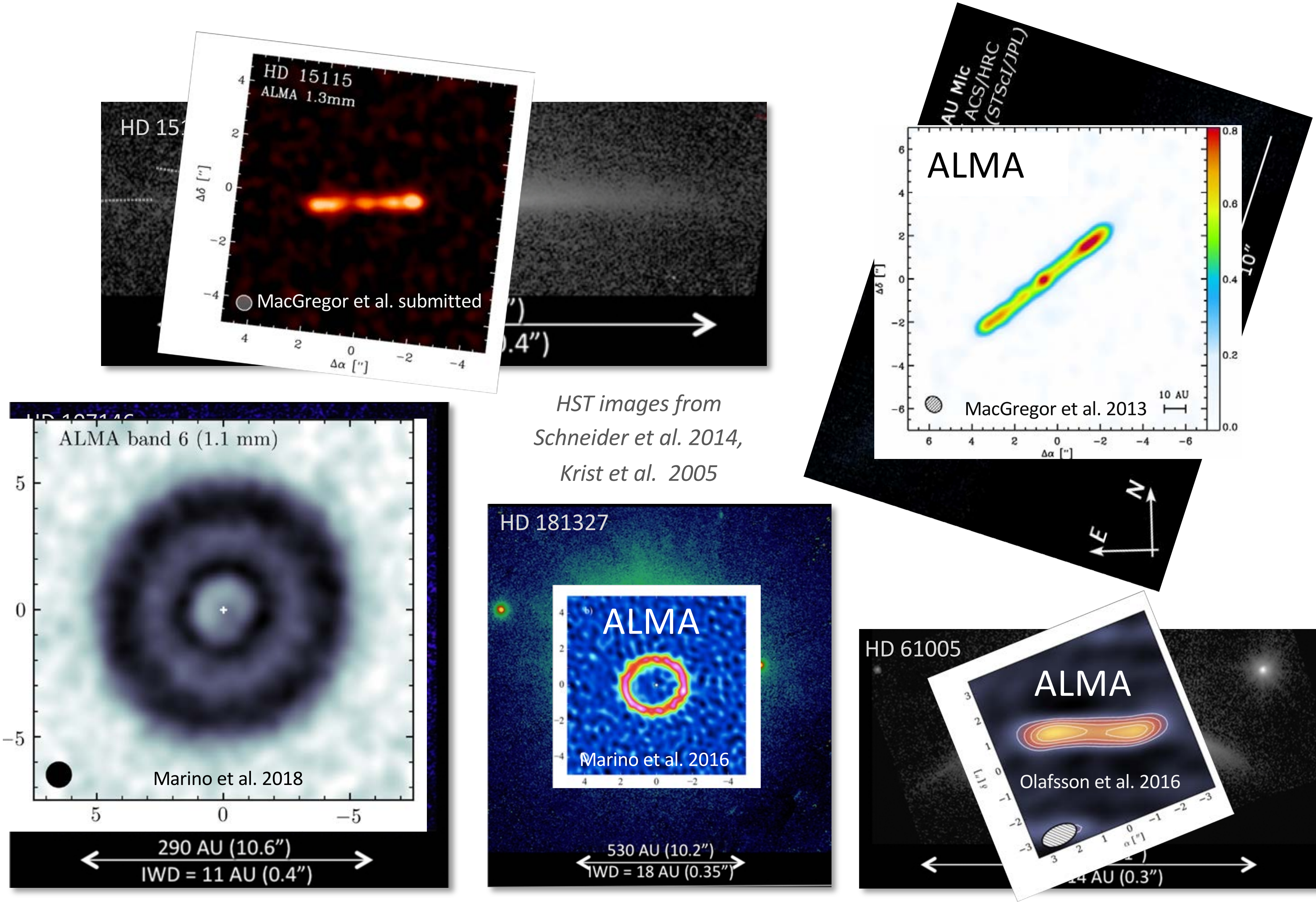
pre-ALMA millimeter-wave images revealed planetesimal belts, in accord with theoretical picture

e.g. β Pic (A6, 19.4 pc, ~23 Myr)

see also Maness et al. 2008, Corder et al. 2009, Hughes et al. 2011, 2012, Wilner et al. 2012, Ricarte et al. 2013

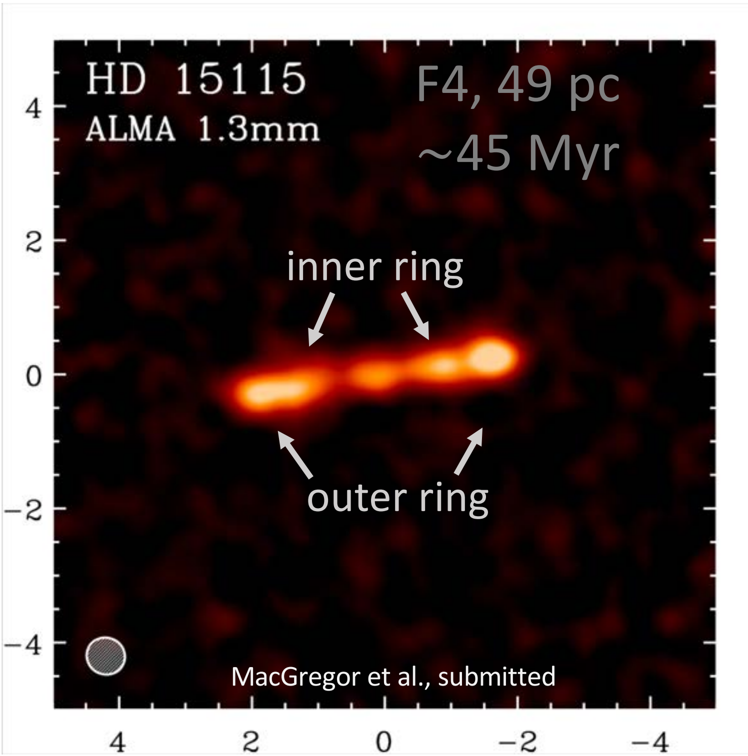

ALMA
image by Ariel Marinkovic / X-Cam

ALMA Reveals Planetesimal Belts

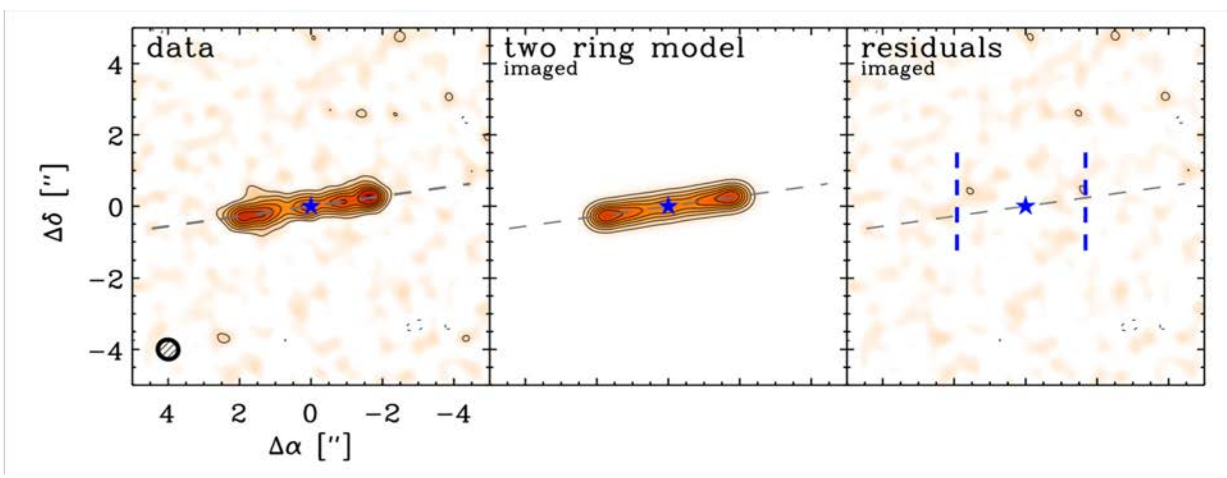


HST images from Schneider et al. 2014, Krist et al. 2005

Multiple Rings of Millimeter Emission

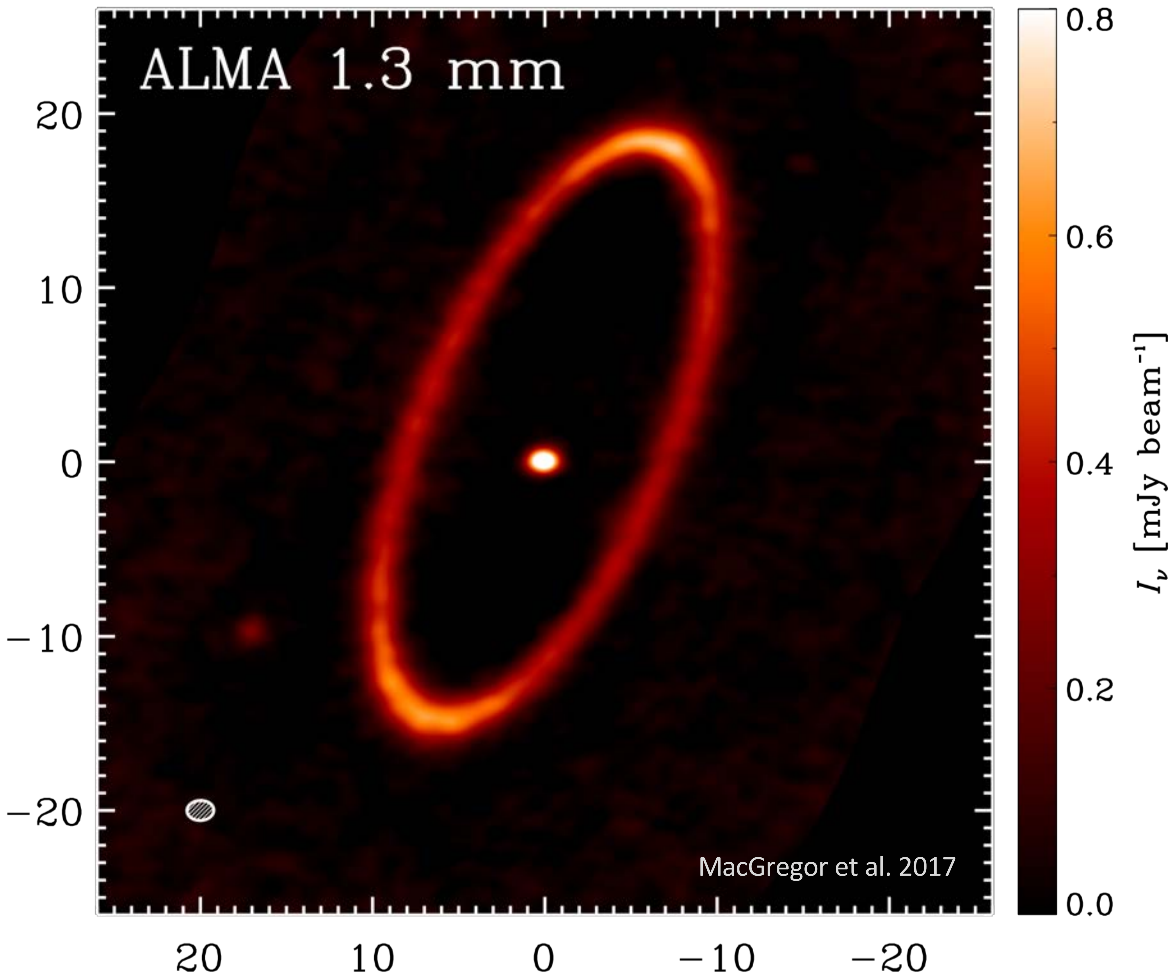


Parameter	Description	Two Ring Model
$R_{\mathrm{in},1}$	Ring 1 inner edge [AU]	44.6 ± 4.5
$R_{\mathrm{out},1}$	Ring 1 outer edge [AU]	50.9 ± 8.8
x_1	Ring 1 power law gradient	-0.95 ± 64
$R_{\mathrm{in},2}$	Ring 2 inner edge [AU]	65.7 ± 4.5
$R_{\mathrm{out},2}$	Ring 2 outer edge [AU]	92.8 ± 3.1
x_2	Ring 2 power law gradient	-0.65 ± 0.78
F_{disk}	Total disk flux density [mJy]	1.95 ± 0.04
F_{pt}	Central point source flux density [mJy]	0.04 ± 0.01
$\Delta\alpha$	RA offset of star from disk centroid [″]	0.10 ± 0.05
$\Delta\delta$	DEC offset of star from disk centroid [″]	-0.05 ± 0.05
i	Disk inclination [°]	86.3 ± 0.4
PA	Disk position angle [°]	278 ± 1



15 AU wide gap
@58 AU
→
0.2 M_{Jup} planet?

Departures from Axisymmetry



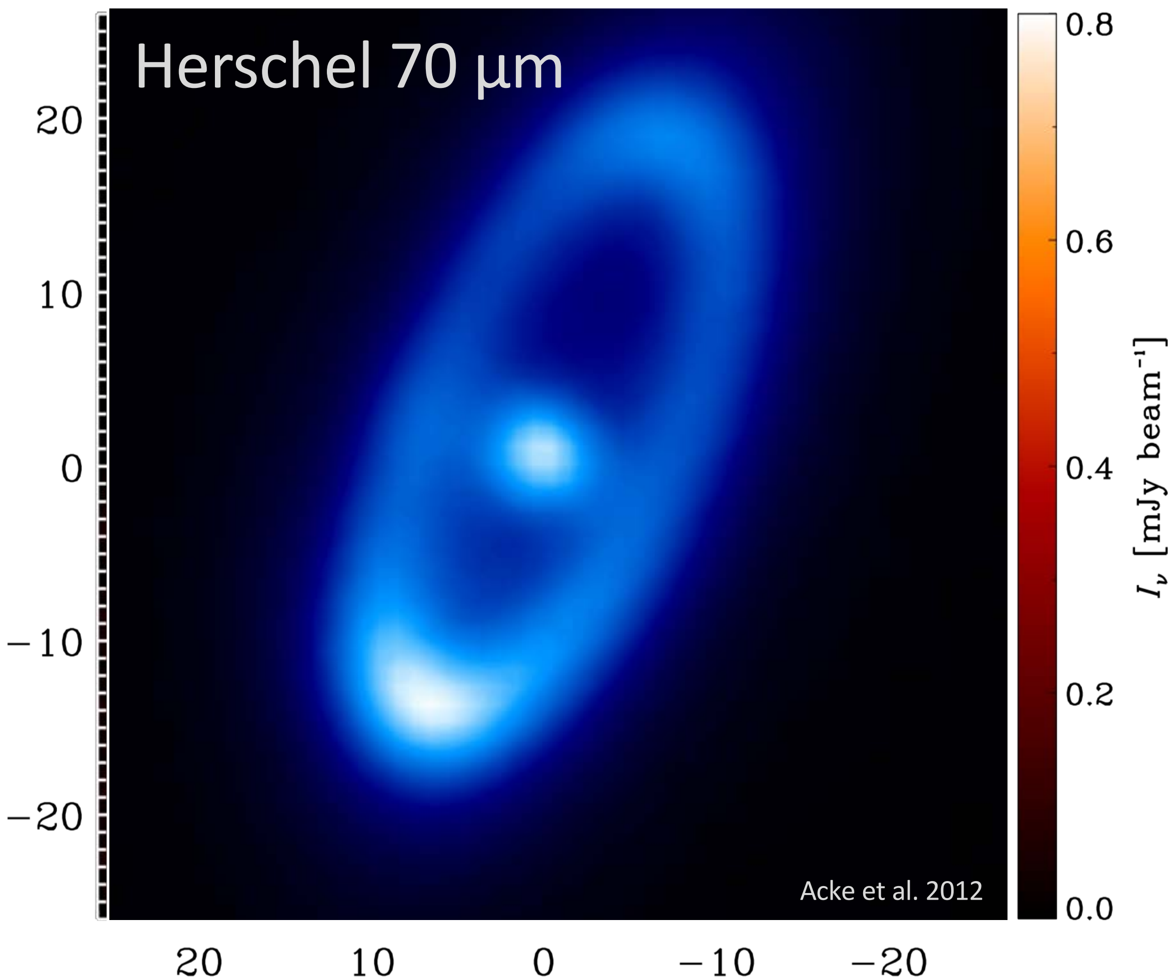
Fomalhaut
A3, 7.76 pc, 440 Myr

no azimuthal structure at 10 AU resolution

eccentricity = 0.12 ± 0.01

1.3 mm "apocenter glow"
vs.
70 μm "pericenter glow"

Departures from Axisymmetry



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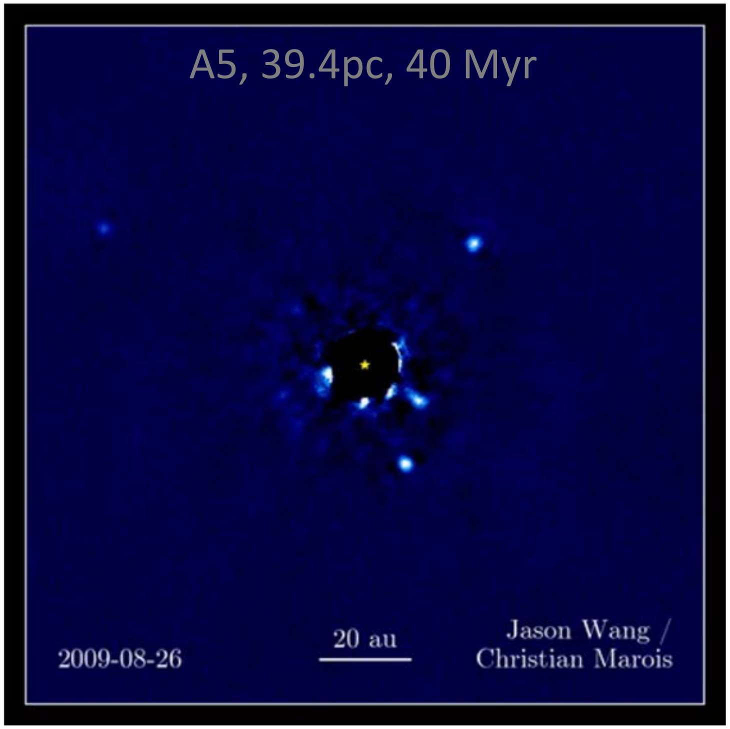
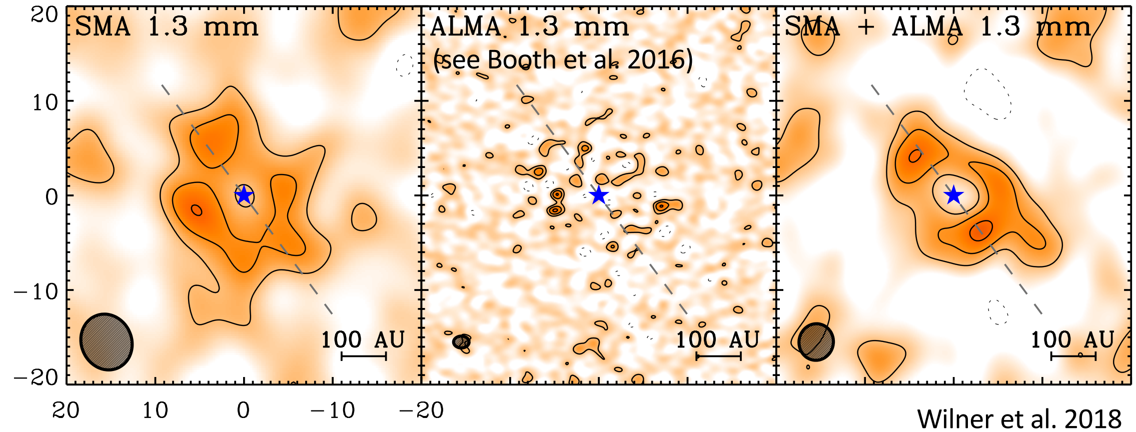
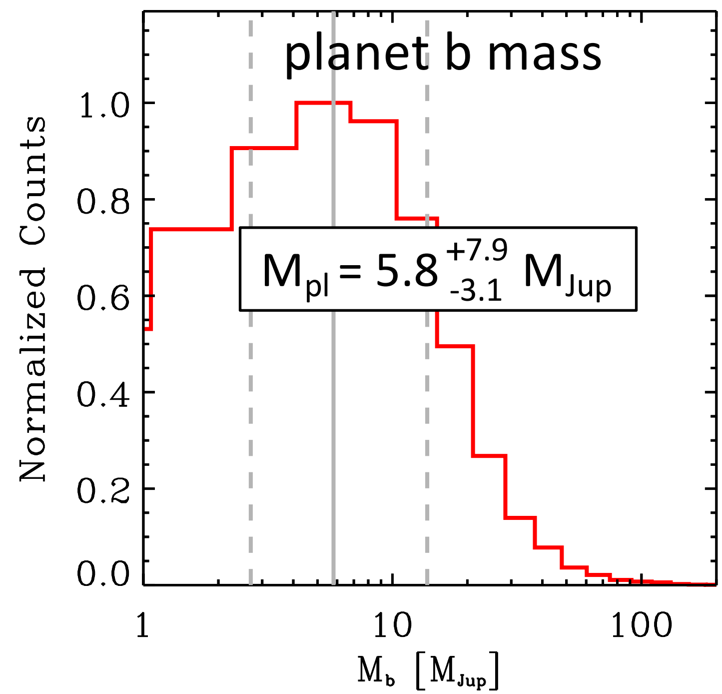
HR 8799b Mass from Disk Truncation





Wilner et al. 2018

(truncated) inner edge of planetesimal belt consistent with ir photometry and "hot start" cooling models that indicate planet masses in range of 4 to 9 M_{Jup}

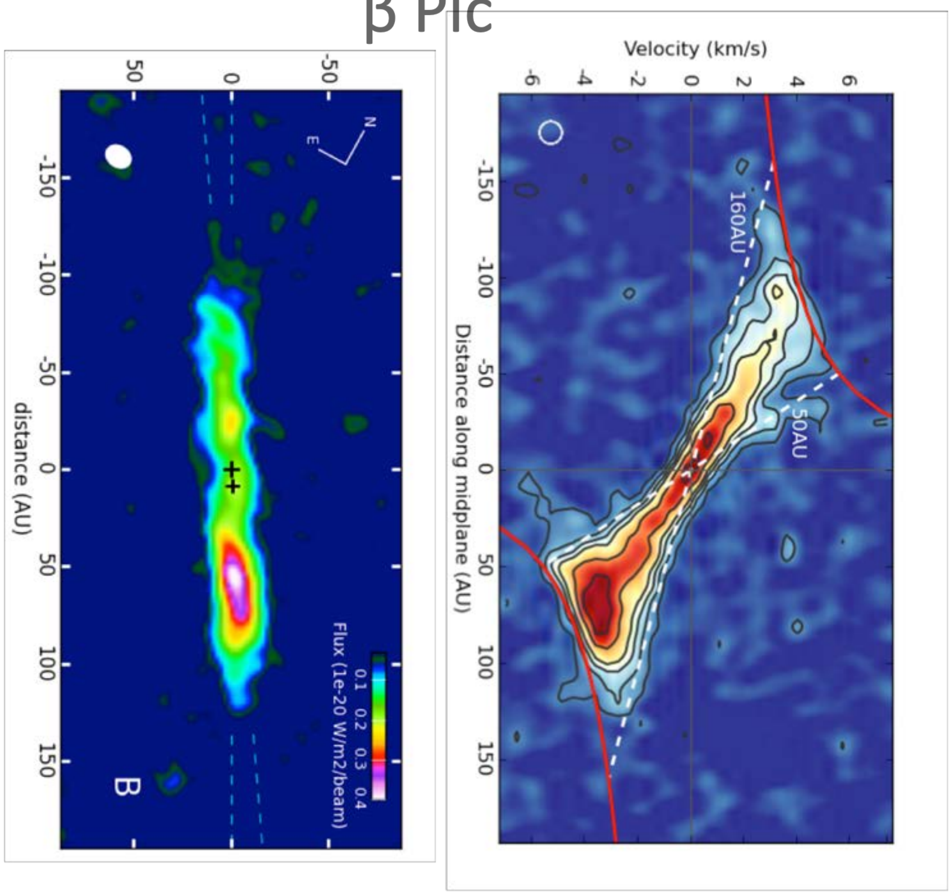


Secondary Molecular Gas in Debris

Surprise! ALMA detects CO disk emission

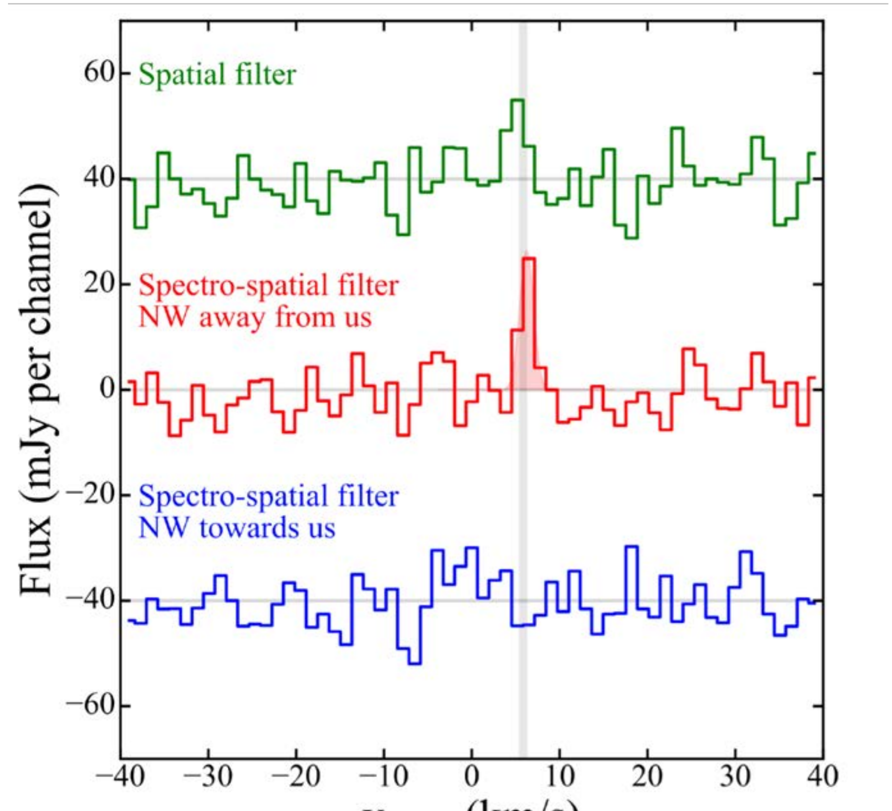
$M_{CO} \sim 10^{-5} - 10^{-7}\,M_{\oplus}$ → volatile release from icy exocomets

β Pic



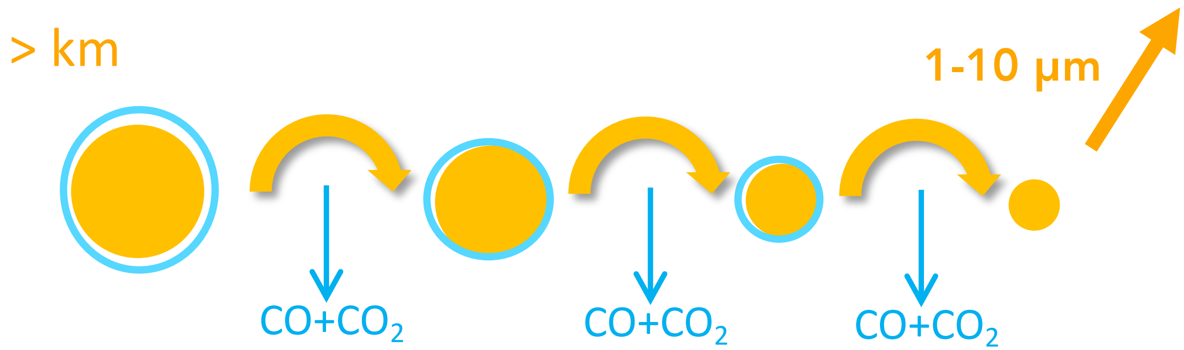
Dent et al. 2014

Fomalhaut

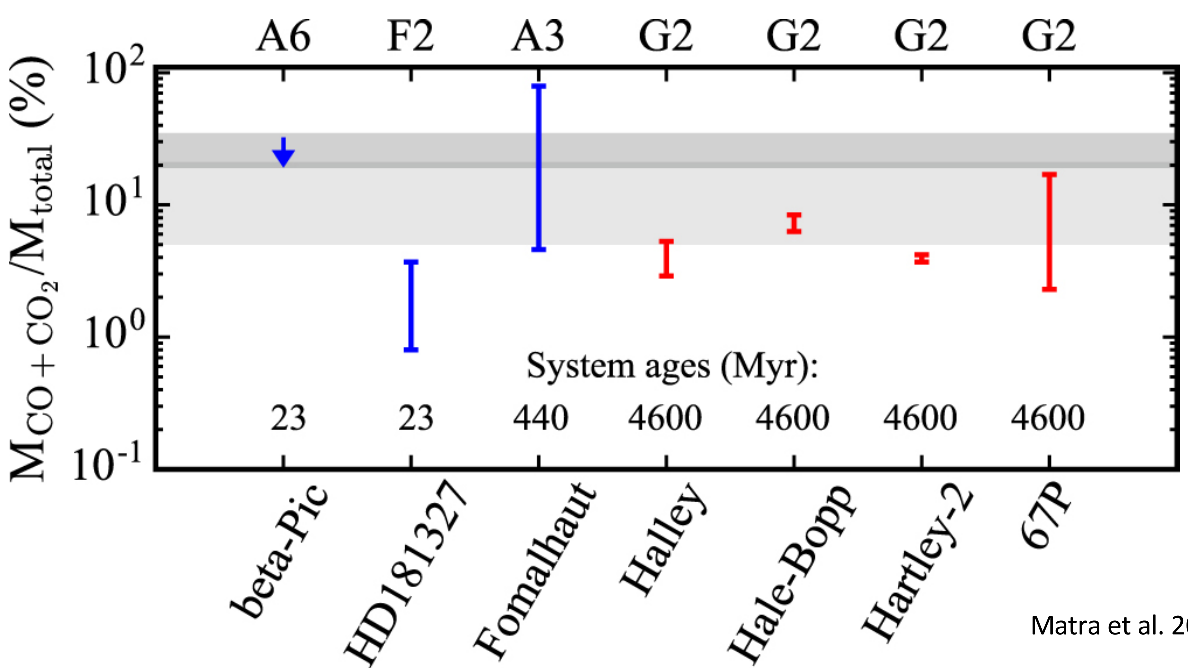


Matra et al. 2017

Access Exocomet Composition



Steady-state mass loss rate of solids (from dust) and of CO (NLTE + fluorescence) → volatile mass fraction



Matra et al. 2017

Composition similar to Solar System comets

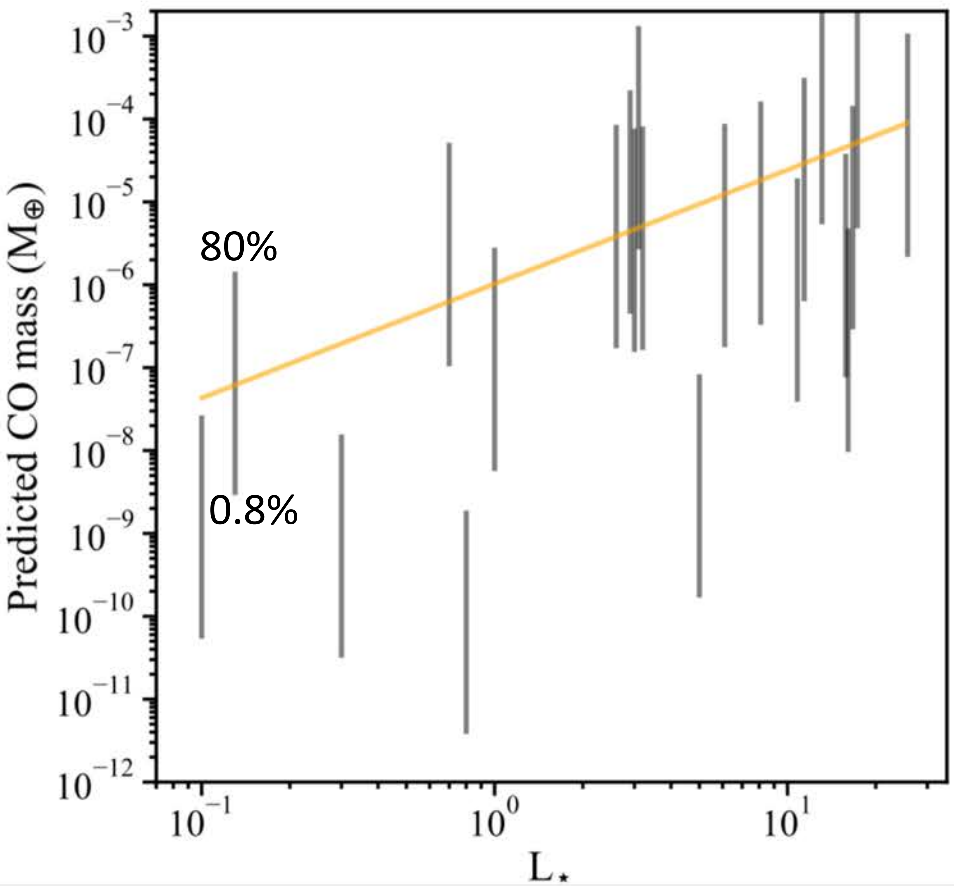
Exocomets scattered inward could deliver volatiles to otherwise dry terrestrial planets

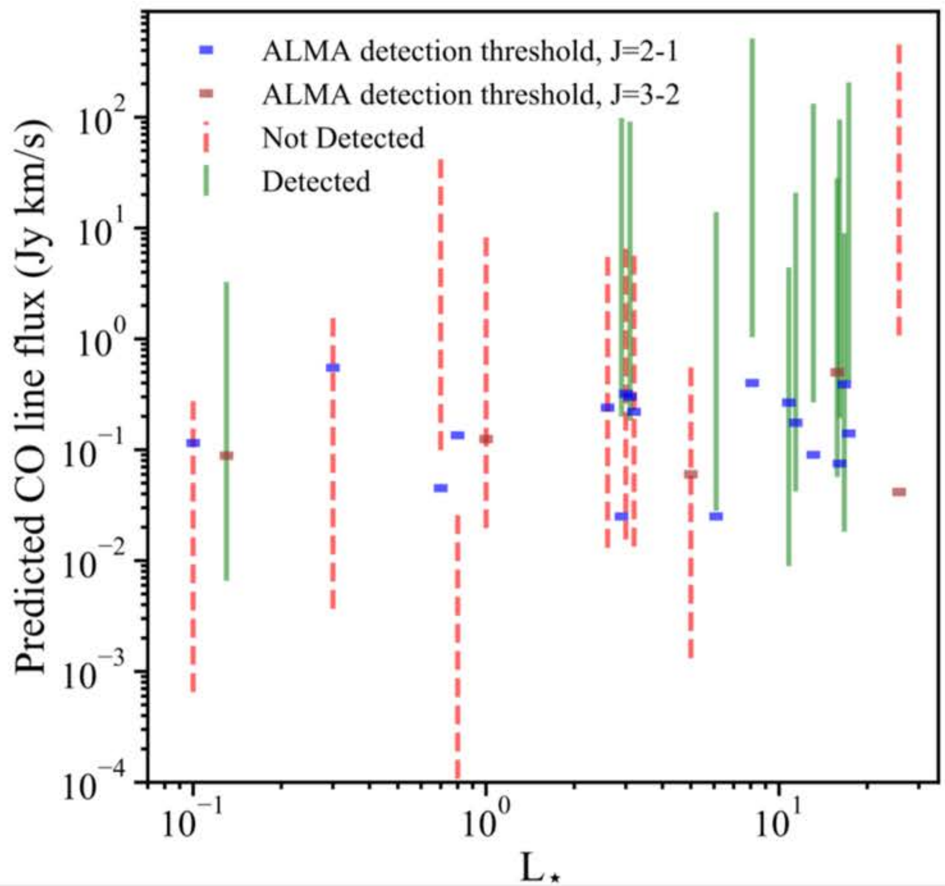
Exocometary CO is Nearly Ubiquitous

$$M_{\rm CO} = \underbrace{1.2 \times 10^{-3} R^{1.5} \Delta R^{-1} f^2 L_\star M_\star^{-0.5}}_{\text{mass loss rate of blow-out grains}} t_{\rm phd} \frac{f_{\rm CO+CO_2}}{1 - f_{\rm CO+CO_2}}$$

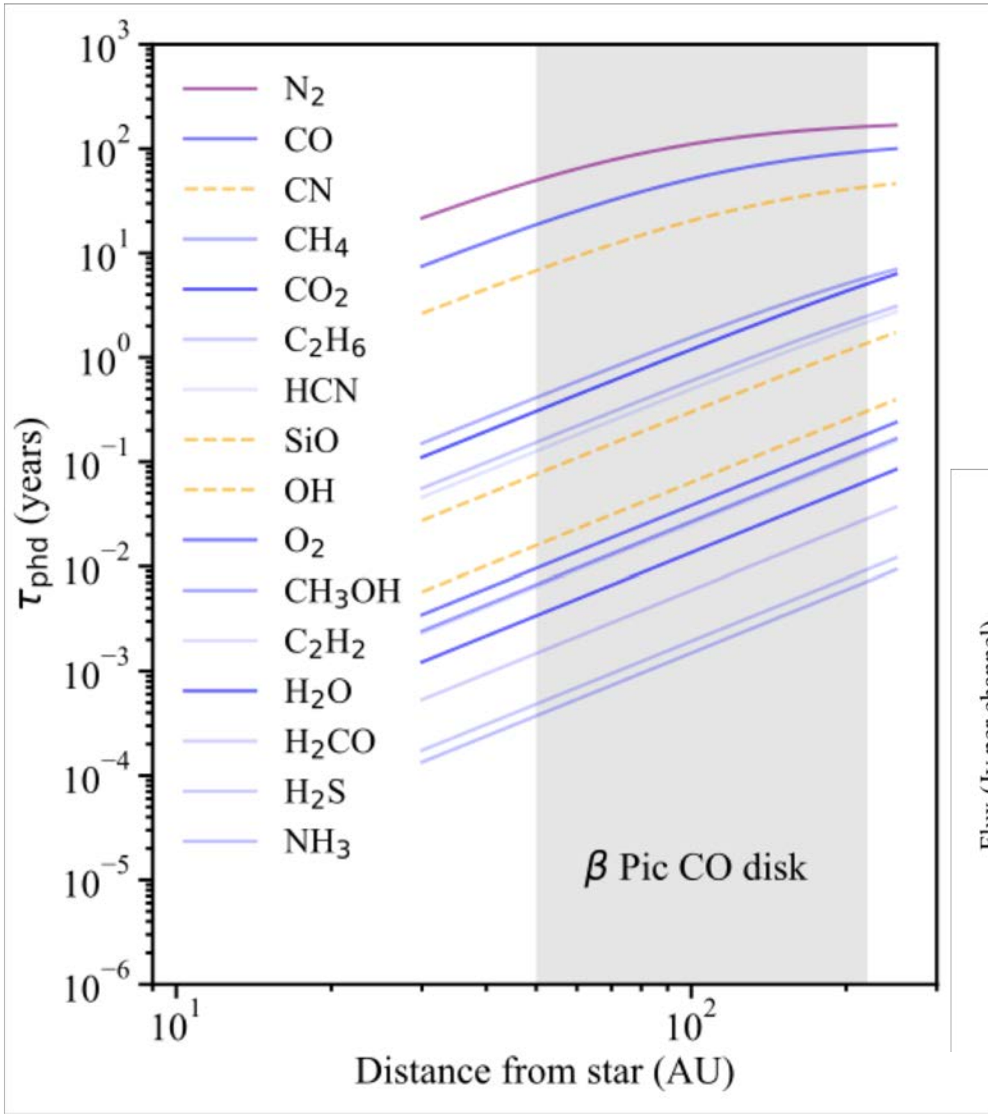
Matra et al. 2019
(see Kral et al. 2016)

CO photodissociation time

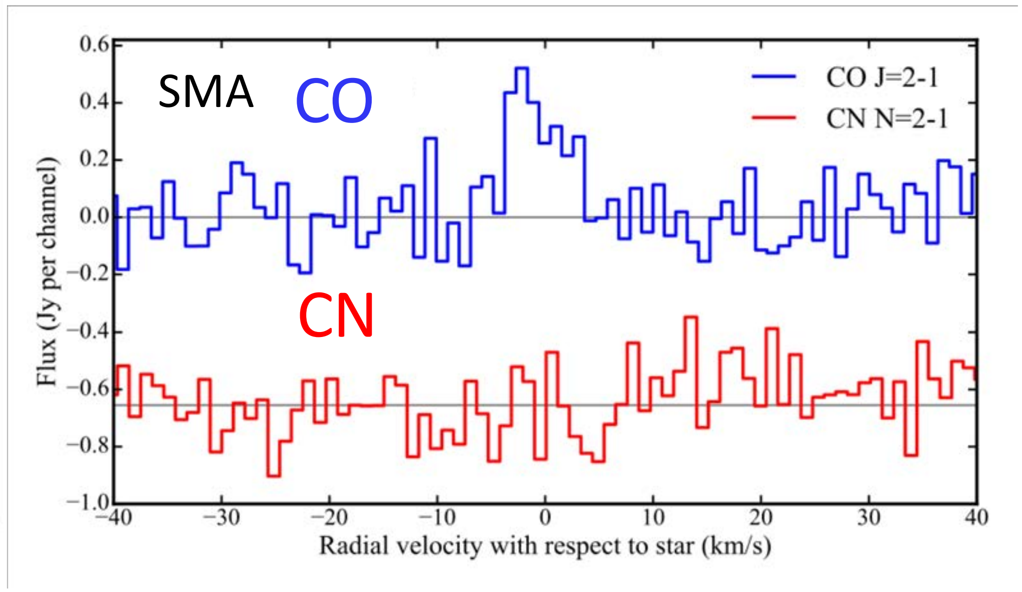




β Pic Molecular Line Reconaissance

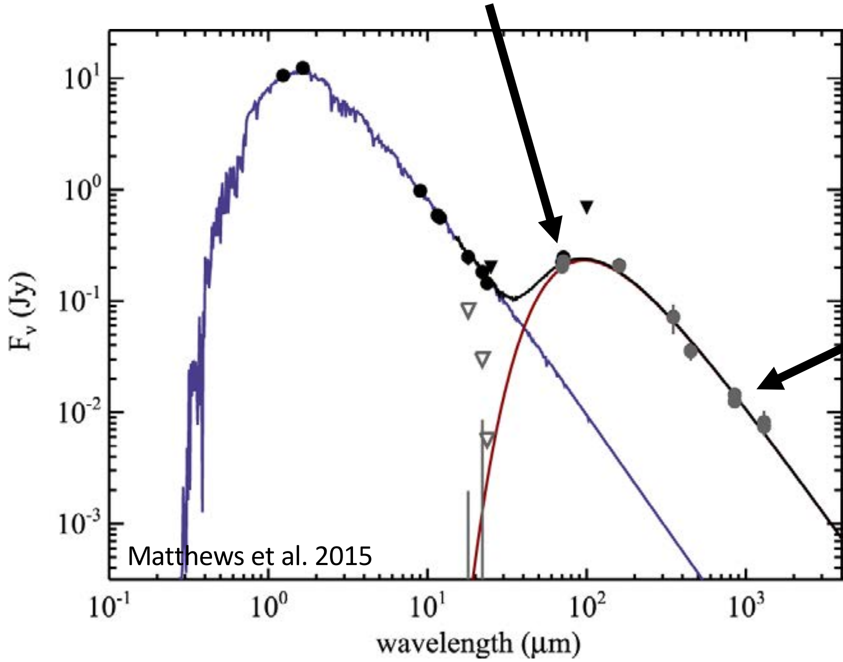


Only observable species with survival time against photo-dissociation comparable to CO is CN (HCN daughter product)



Typical Path to ALMA for Debris Disks

1. Far-ir excess (IRAS, ISO, Herschel) ~ 300

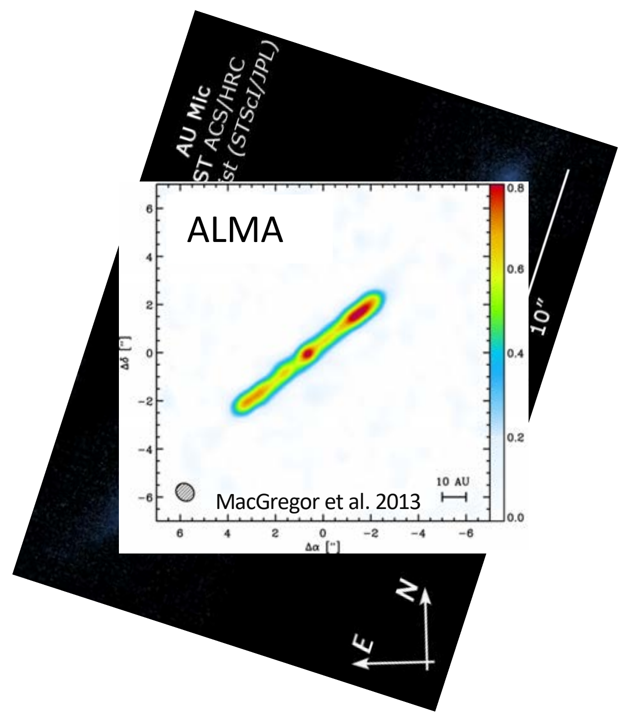


2. single dish mm photometry

~ 50 > few mJy @850 μm

3. (optional) scattered light features

~ 20



Looking to the Future with ALMA

Nearly all ~ 50 debris disks > few mJy at 850 μm have had a first look with ALMA (in numerous individual programs + *Resolved ALMA and SMA Observations of Nearby Stars*, REASONS, PI: Matra) → R, ΔR

A handful of bright systems have been the subject of more intensive studies with > few hours of ALMA time → detailed structure + gas

What's next?

1. Invest the necessary effort in the known bright systems

2. ALMA must become it's own discovery machine for debris disks

sensitivity: more/new targets (esp. missed by Herschel)

colder dust: debris around M stars? brown dwarfs? white dwarfs?

Summary

Debris disks are descendants of planet-forming disks

ALMA millimeter continuum emission reveals the location of colliding planetesimals within debris disks, including possible planetary perturbation features

CO line emission is nearly ubiquitous in debris disks, opening up access to the composition of exocomets

Next: improved imaging and new (cold) debris disks