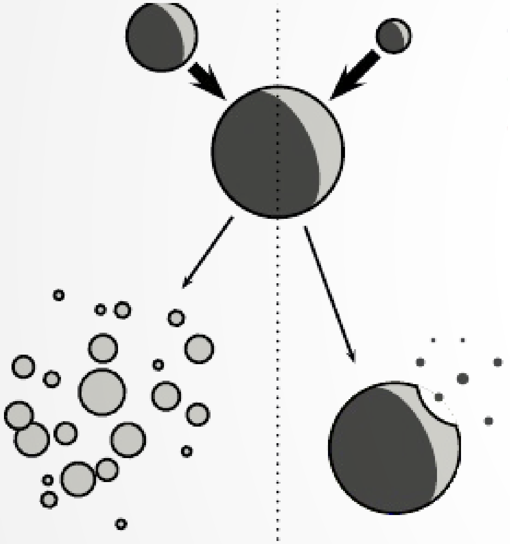
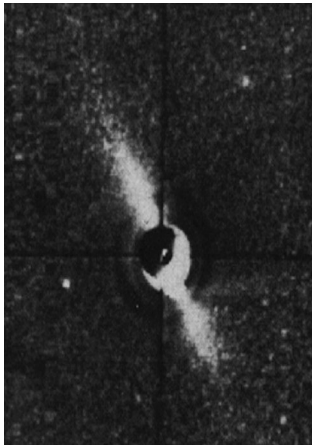
Debris Discs

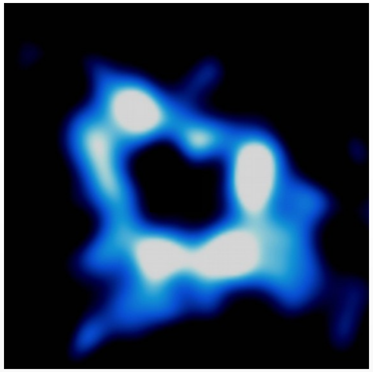
Mark Booth
Friedrich-Schiller
Universität Jena

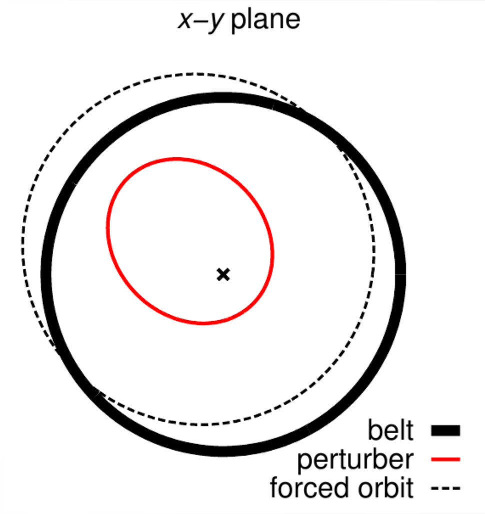
OVERVIEW



Collisions

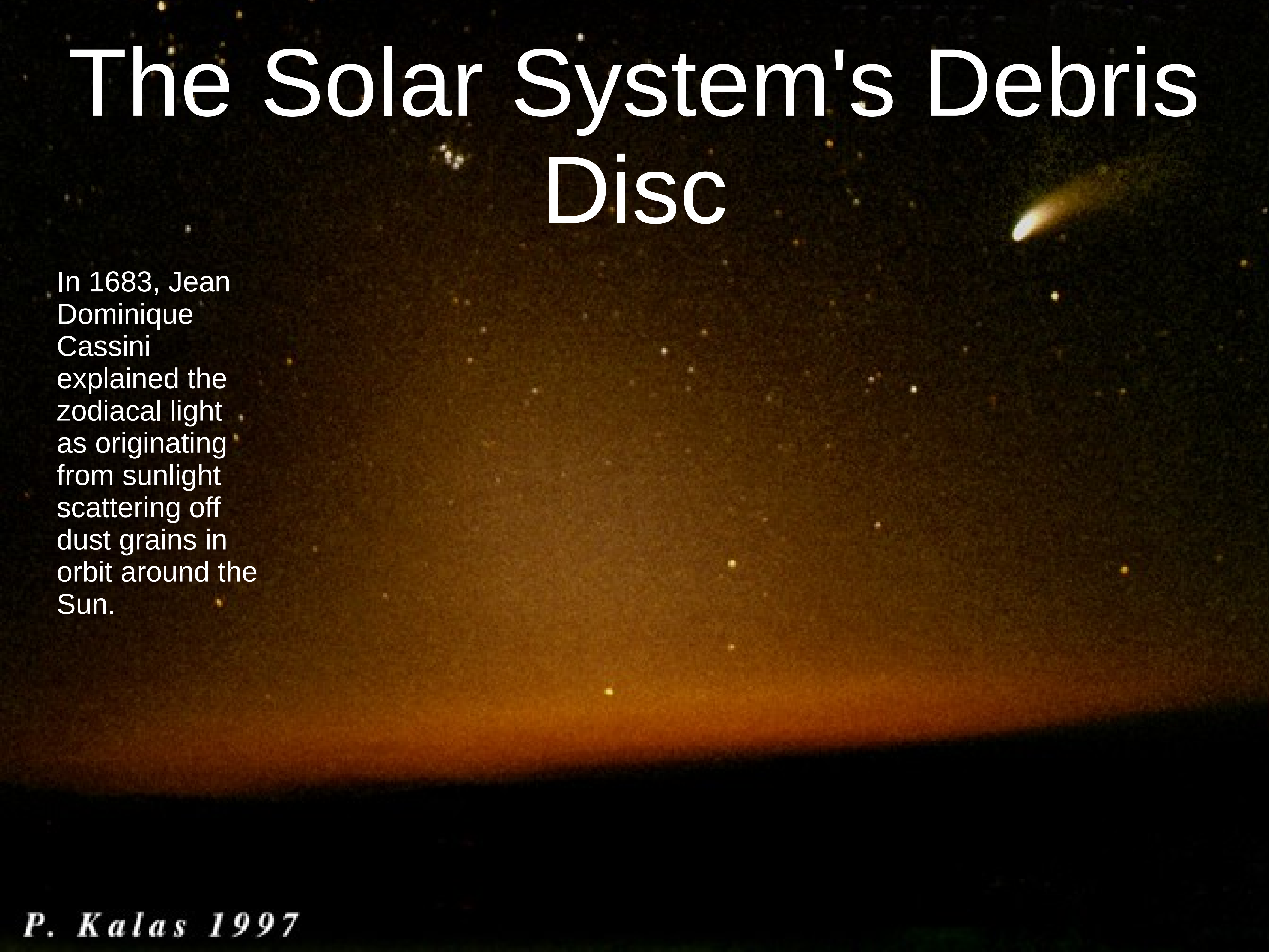






Planet Interactions

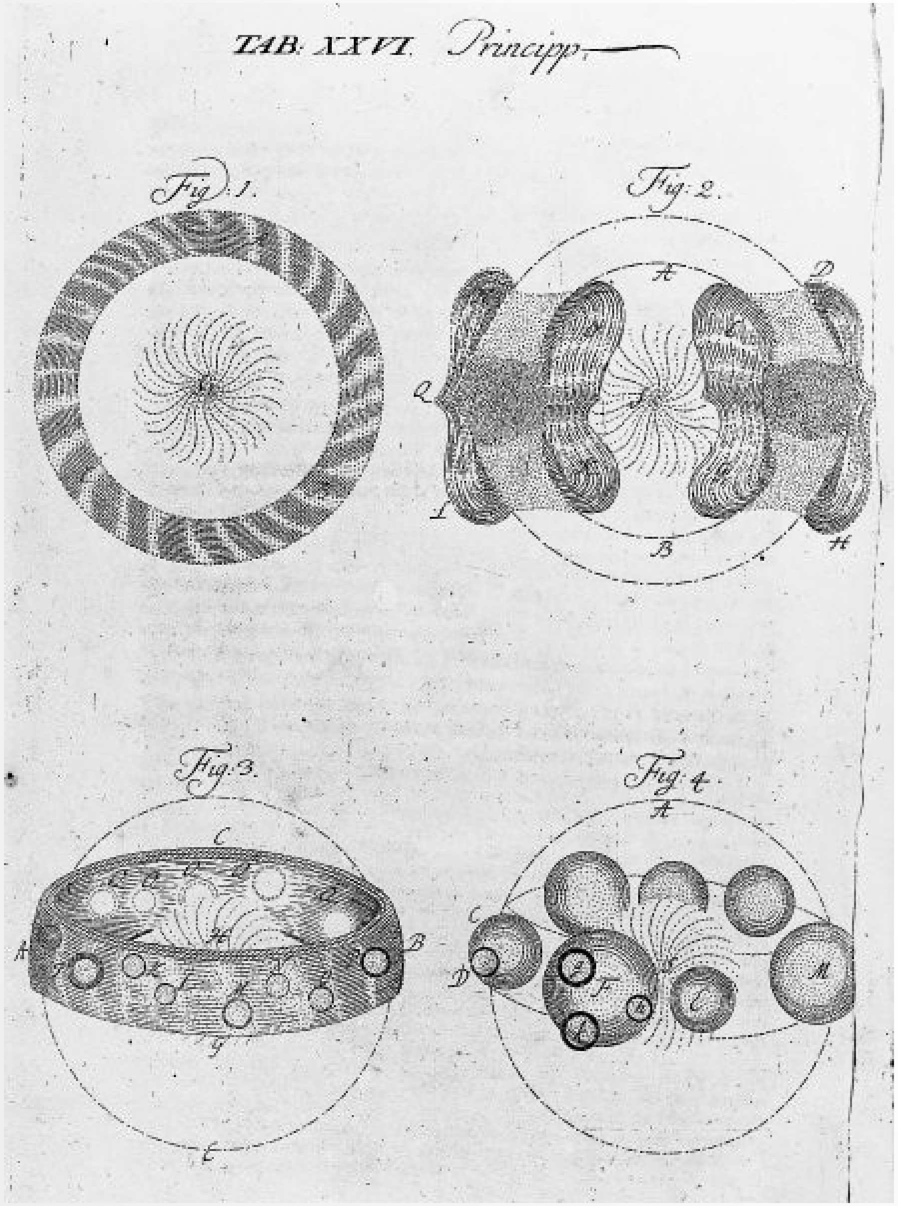
The Solar System's Debris Disc



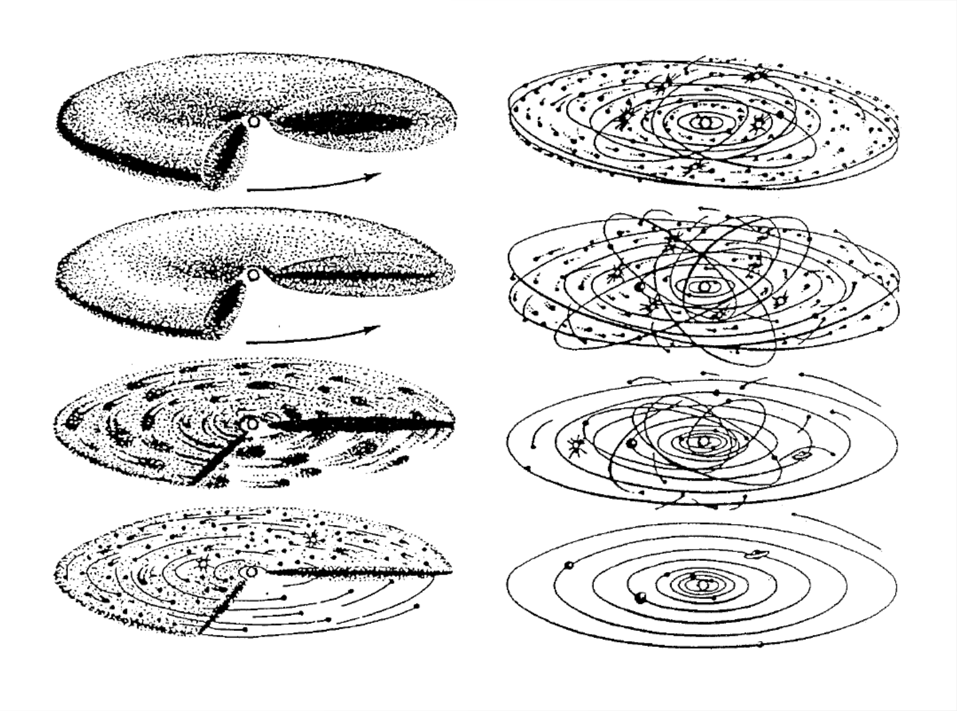
In 1683, Jean Dominique Cassini explained the zodiacal light as originating from sunlight scattering off dust grains in orbit around the Sun.

P. Kalas 1997

Formation of the Solar System

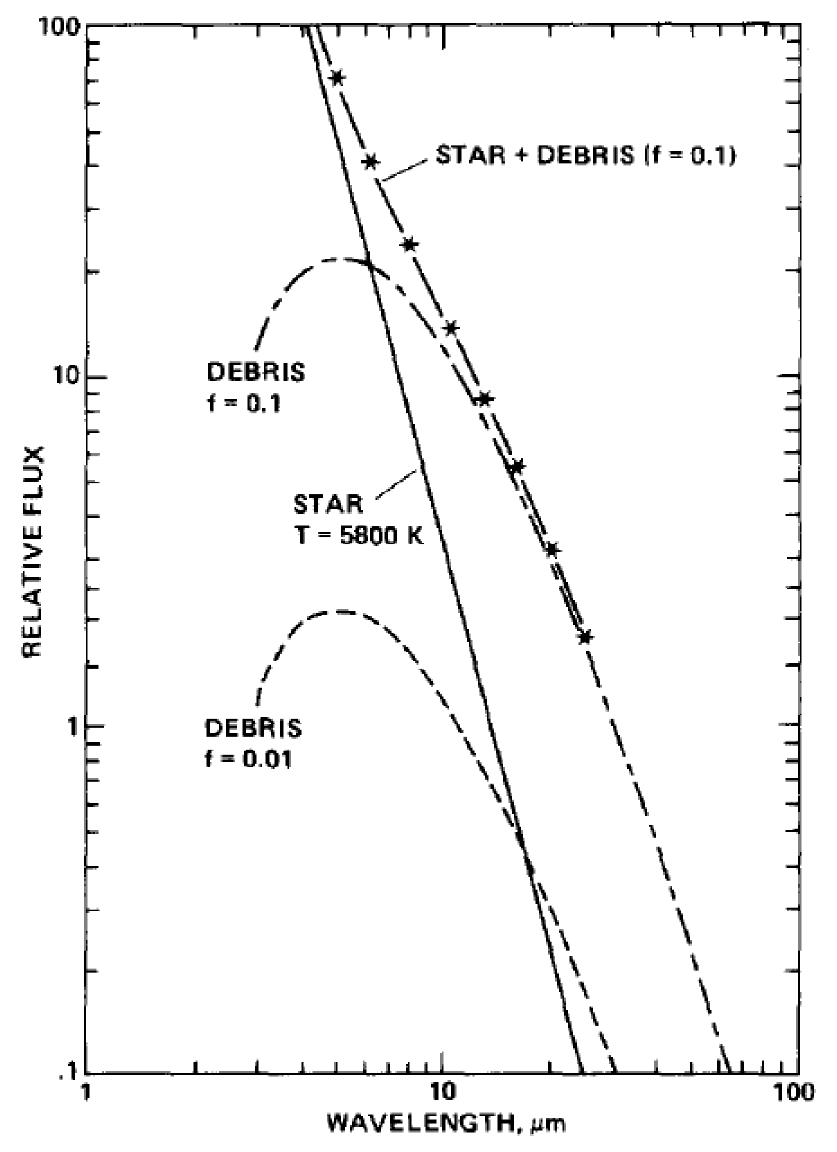


- Swedenborg 1734: The nebular hypothesis
- Revived and improved by Safronov, Wetherill and other in the 1970s



Prediction of Extrasolar Debris

- Inspired by these models of planetary system formation and the cratering history of the Moon, Witteborn et al. 1982 predicted infrared excesses due to 'debris clouds'.
- They assumed the planetesimals would follow the orbits of the planets, but otherwise the model was very similar to current debris disc models.



1984: The Vega Phenomenon

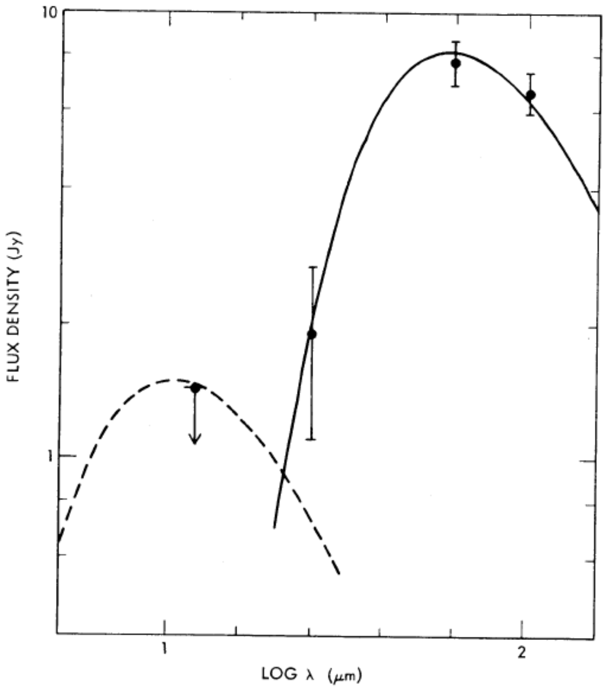


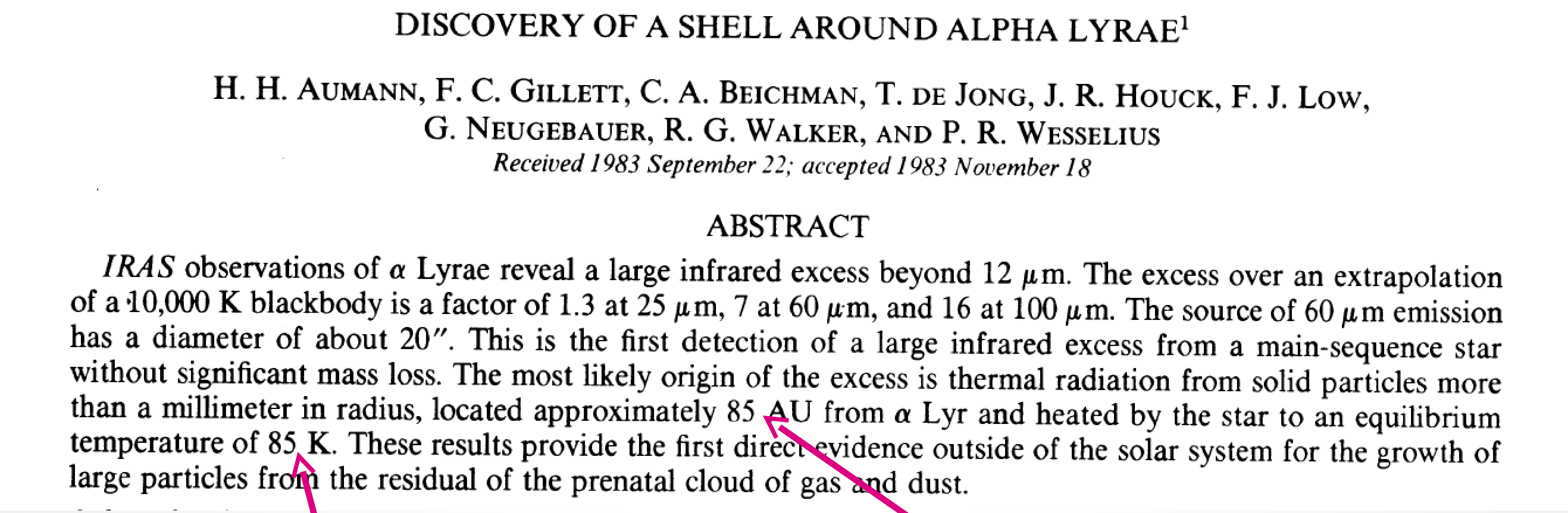
FIG. 1.—Energy distribution of the infrared excess from α Lyr. The error bars represent the 10% calibration uncertainty. The 12 μm upper limit indicates the effect of the 5% uncertainty in the absolute calibration at 12 μm. The solid line represents a 85 K blackbody spectrum with a solid angle of 7×10^{-13} sr fitted to the excess. The dashed line represents a 500 K blackbody spectrum with a solid angle of 6.3×10^{-16} sr arbitrarily fitted to the 12 μm upper limit.

Aumann et al. 1984

- IRAS discovers infrared access around a number of stars.
- A blackbody can be fit to this to estimate its temperature and infer the distance of the dust from the star.

1984: The Vega Phenomenon

Grain temperature gives radius from star where most of the dust resides, but distinguishing a shell versus disc architecture requires resolved imaging.



DISCOVERY OF A SHELL AROUND ALPHA LYRAE[1]

H. H. AUMANN, F. C. GILLETT, C. A. BEICHMAN, T. DE JONG, J. R. HOUCK, F. J. LOW,
G. NEUGEBAUER, R. G. WALKER, AND P. R. WESSELIUS

Received 1983 September 22; accepted 1983 November 18

ABSTRACT

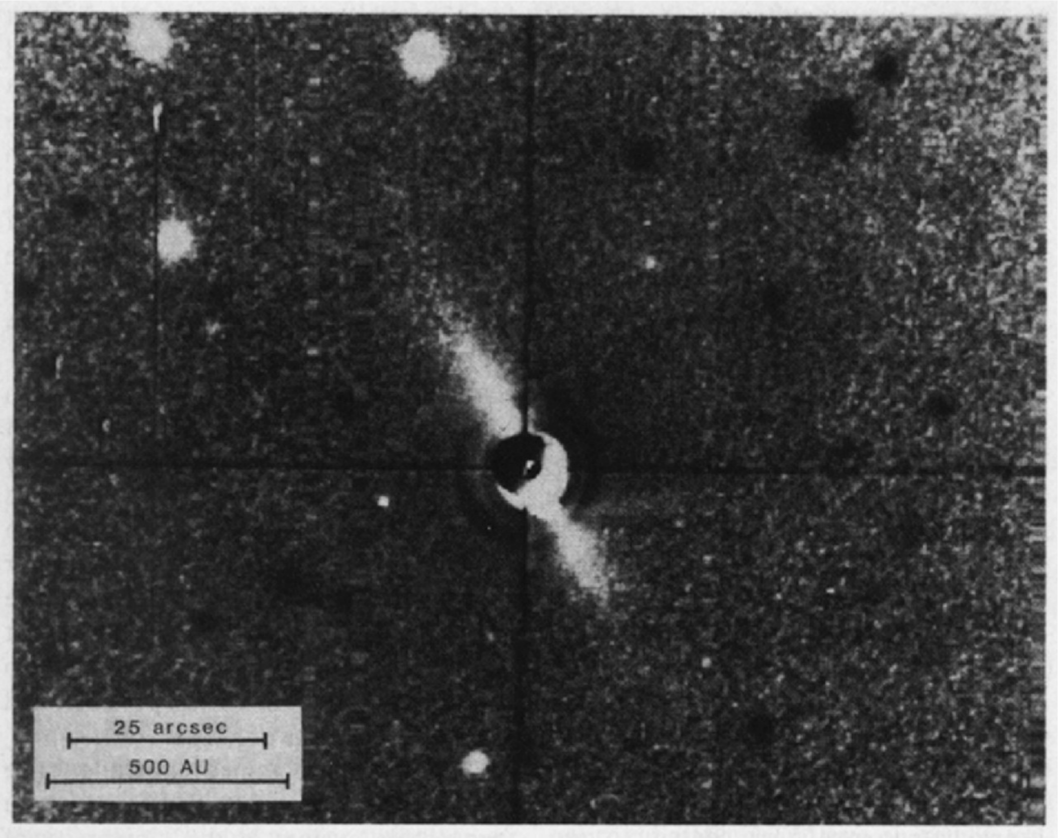
IRAS observations of α Lyrae reveal a large infrared excess beyond 12 μm. The excess over an extrapolation of a 10,000 K blackbody is a factor of 1.3 at 25 μm, 7 at 60 μm, and 16 at 100 μm. The source of 60 μm emission has a diameter of about 20″. This is the first detection of a large infrared excess from a main-sequence star without significant mass loss. The most likely origin of the excess is thermal radiation from solid particles more than a millimeter in radius, located approximately 85 AU from α Lyr and heated by the star to an equilibrium temperature of 85 K. These results provide the first direct evidence outside of the solar system for the growth of large particles from the residual of the prenatal cloud of gas and dust.

They discovered a cold exo Kuiper Belt/Shell, before the Kuiper Belt in our own Solar System was detected in 1992.

Resolving the beta Pic Disc

Smith & Terrile 1984

Resolving the beta Pic Disc



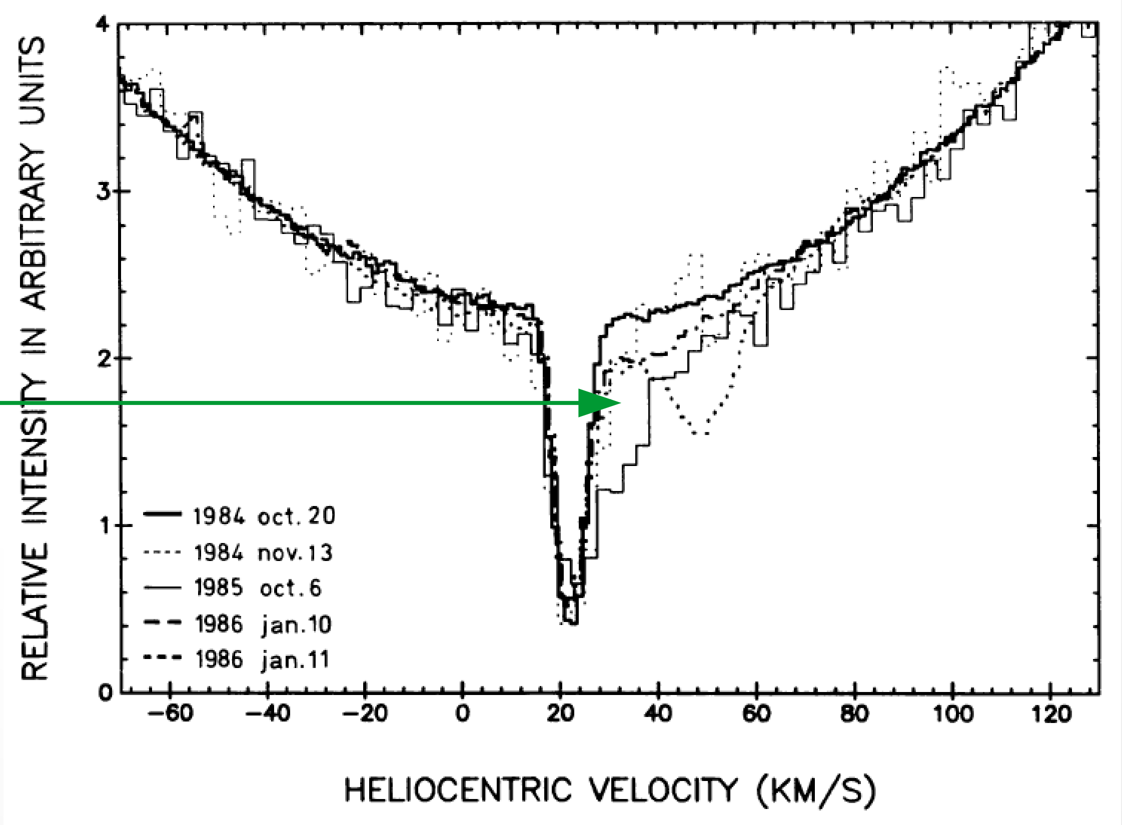
Smith & Terrile 1984

This made it clear that the dust was distributed as a disc not a shell.

Exocomets

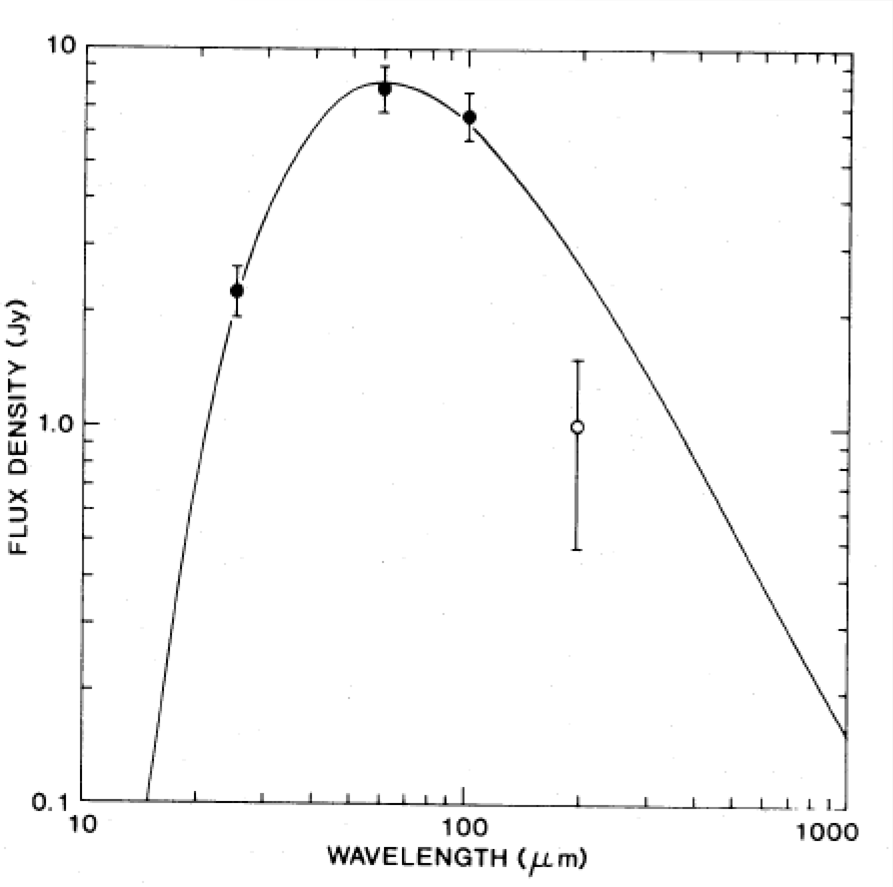
- Slettebok 1975, Kondo & Bruhweiler 1985, Hobbs + 1985, Vidal-Madjar 1986 all noted absorption lines showing that there must be gas in the beta Pic disc.

- In Ca II-K, Ferlet + 1987 also noted that the absorption spectrum was variable and suggested this was due to comets.

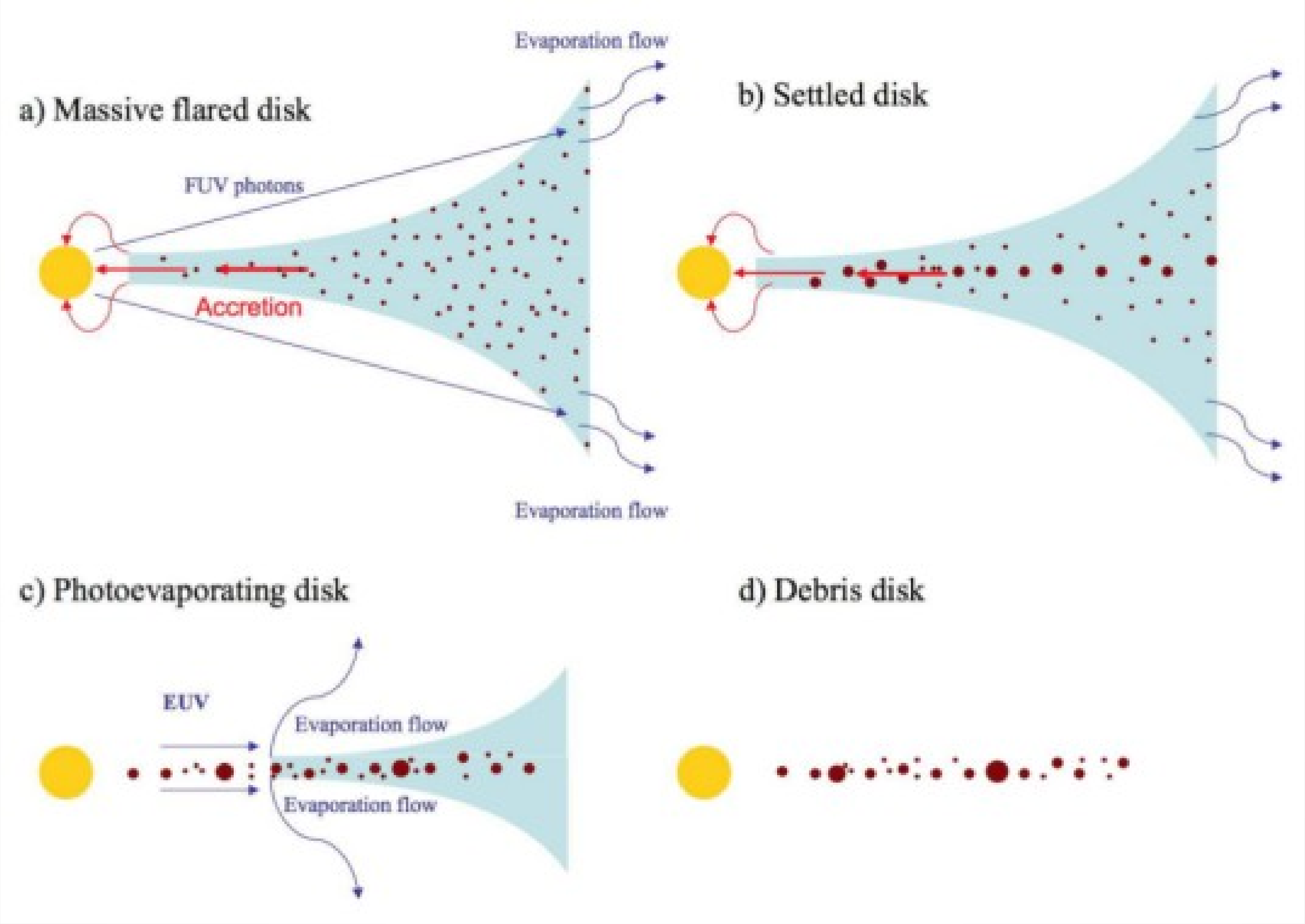


Collisional Cascade

- Realising that small grains are removed quickly by radiation pressure and Poynting-Robertson drag, Aumann et al. 1984 predicted that the dust excess must be due to mm grains.
- Harper et al. 1984 observed Vega at a longer wavelength and, along with Weissman 1984, concluded that small grains are necessary and must be continually replenished, likely through a collisional cascade.



Protoplanetary → Debris



Williams & Cieza 2011

Instigating the Collisional Cascade

- Gas in a protoplanetary disc keeps relative velocities low.
- Once this gas has (mostly) been removed, relative velocities can be increased and collisions become destructive.
- But what stirs them?

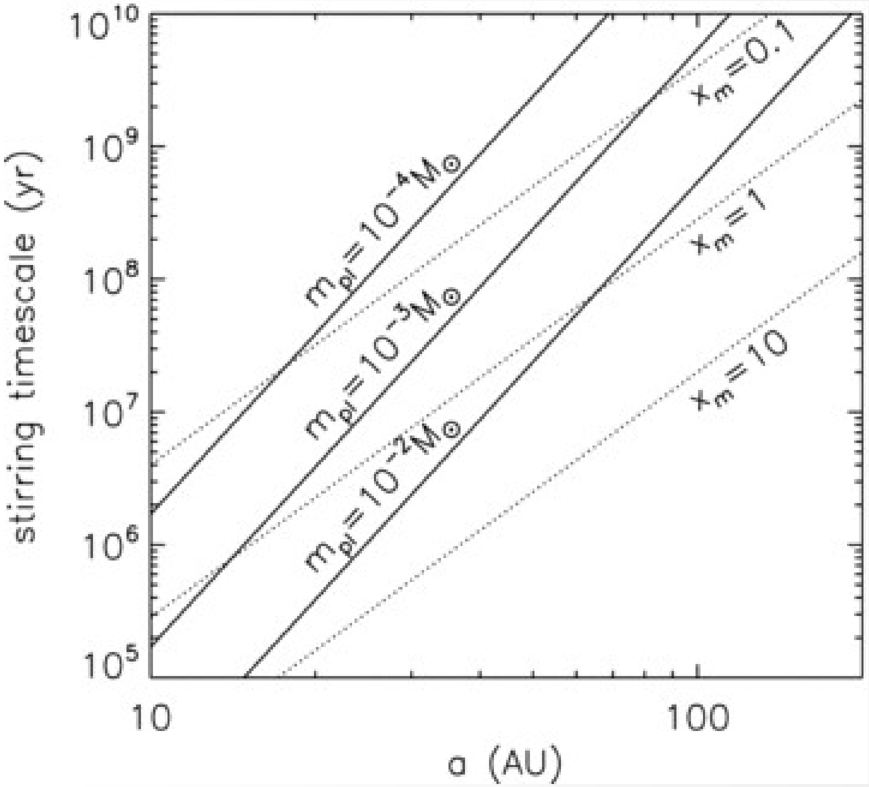
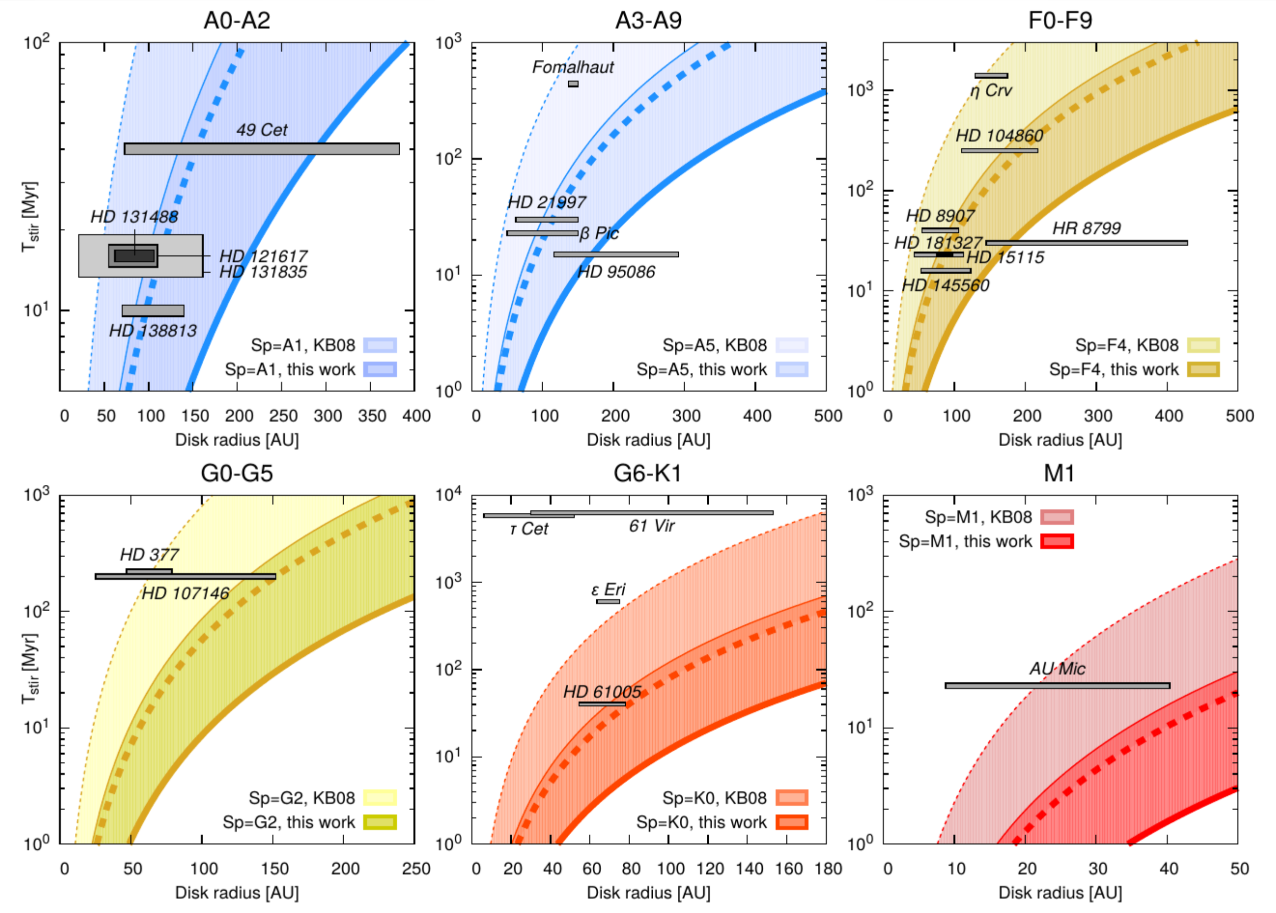


Figure from Mustill & Wyatt 2009
Solid lines: stirring due to a planet
Dotted lines: self-stirring due to Pluto sized bodies within the disc (based on Kenyon & Bromley 2008)

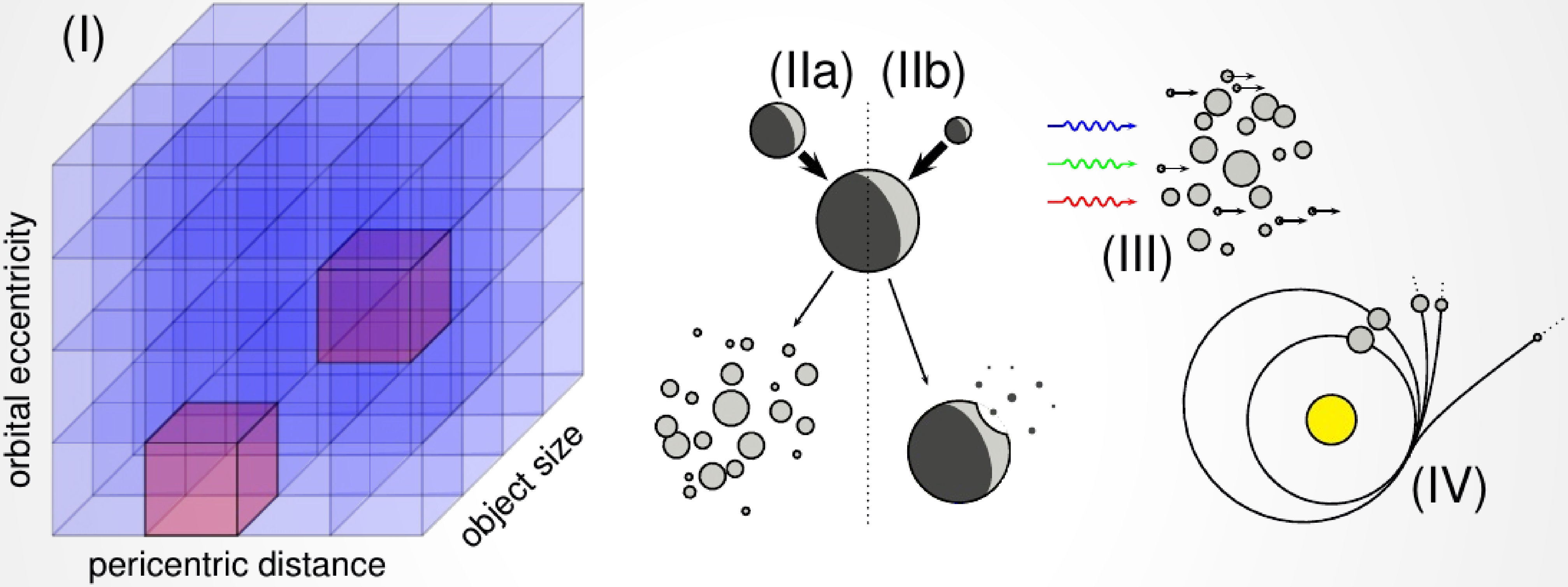
Origin of Stirring

Krivov & Booth 2018



If planetesimals form big through pebble concentration, then self stirring will be much more effective than previously thought.

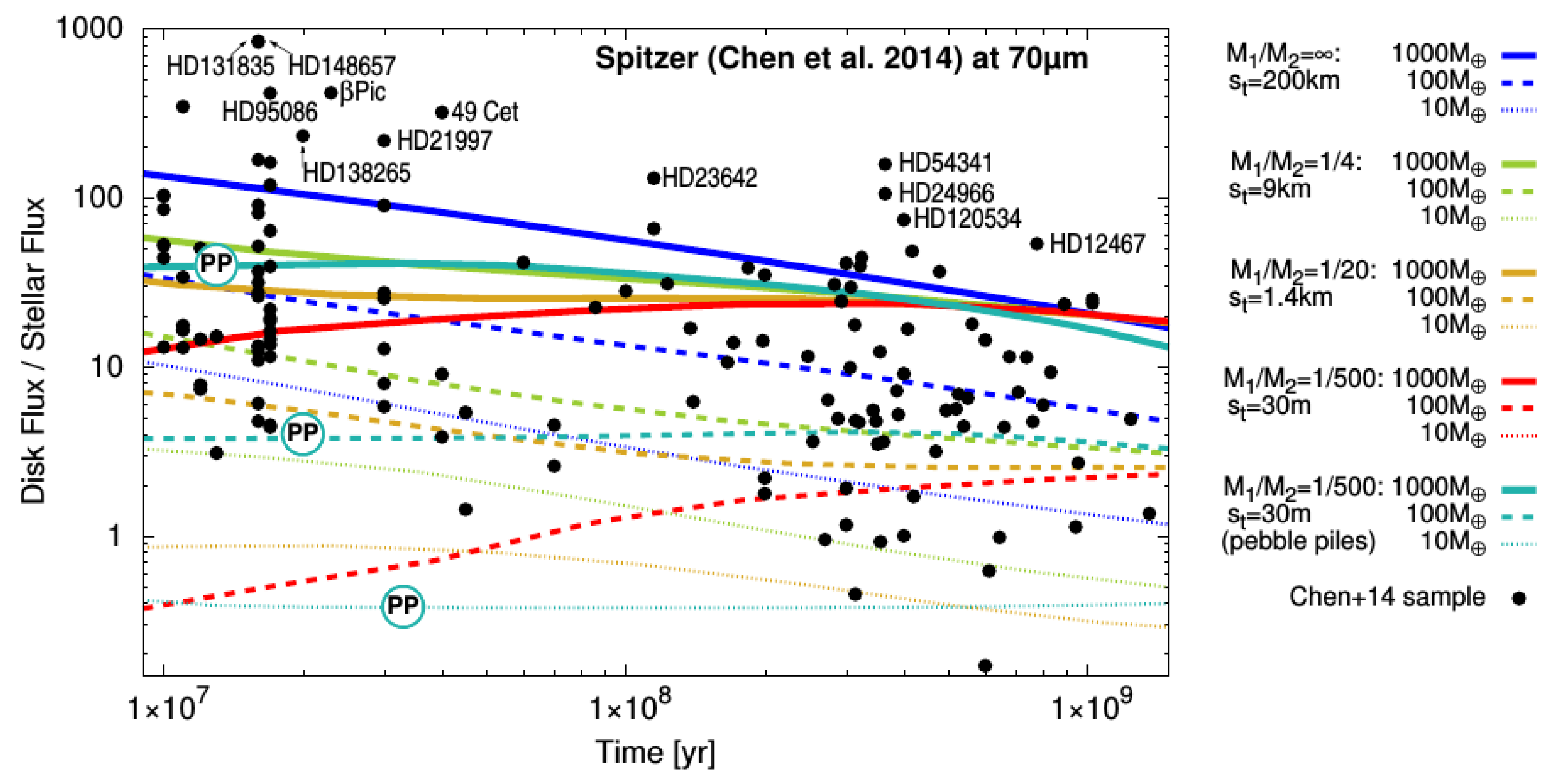
Collisional Evolution: ACE



- ACE: Analysis of Collisional Evolution (Krivov + 2005, 2006, Löhne + 2008, Reidemeister + 2011, . . .)
- binned parameter space of grain sizes and orbital parameters
- collision rates and outcomes based on local particle densities, velocities and masses
- radiation (and wind) pressure modify fragments’ orbits and result in drag

Collisional Evolution

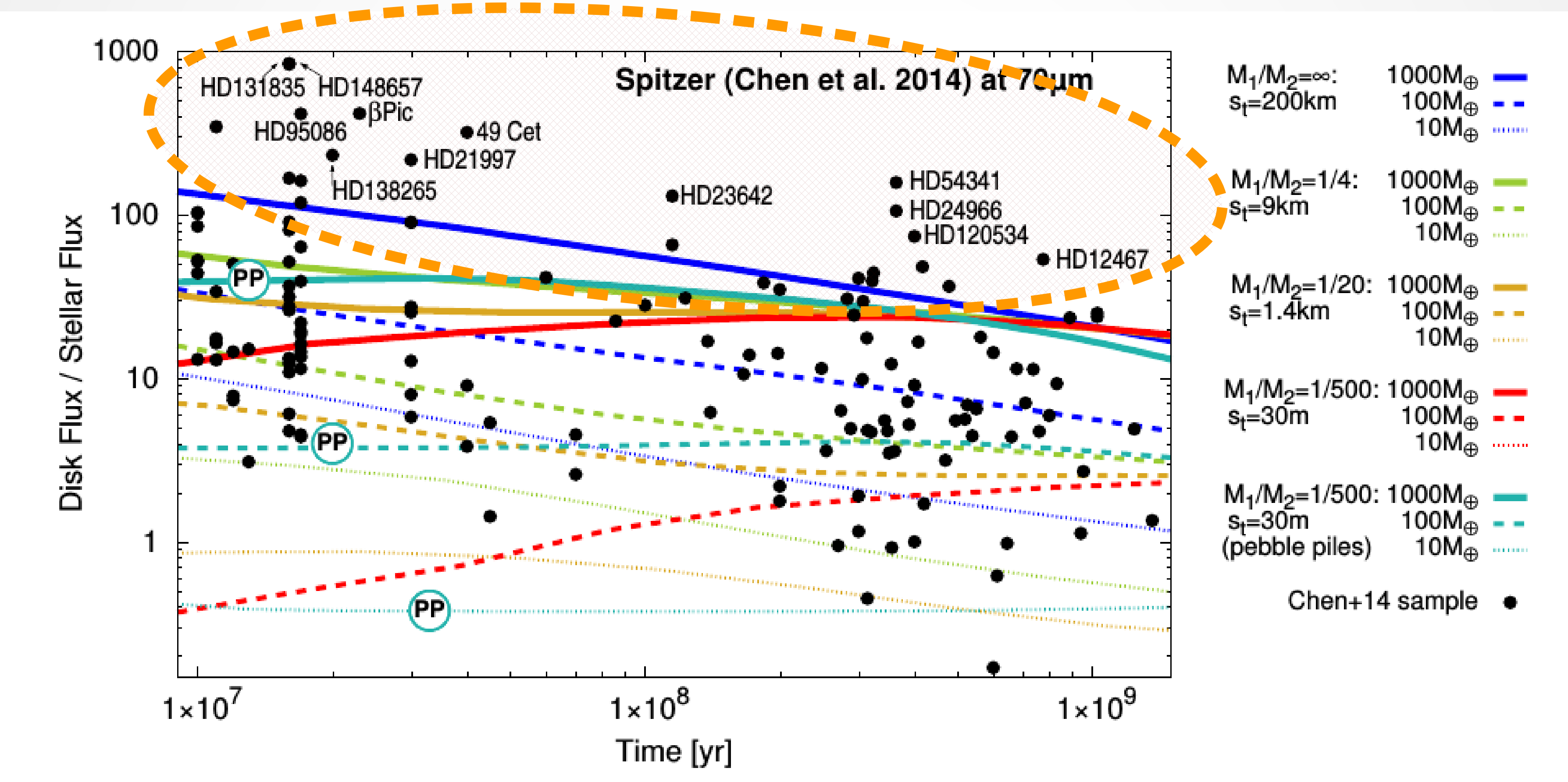
Krivov et al. 2018



Evolution of discs differs depending on whether planetesimals are formed through slow growth accretion or rapid concentration into pebble piles.

Disc Mass Problem

Krivov et al. 2018

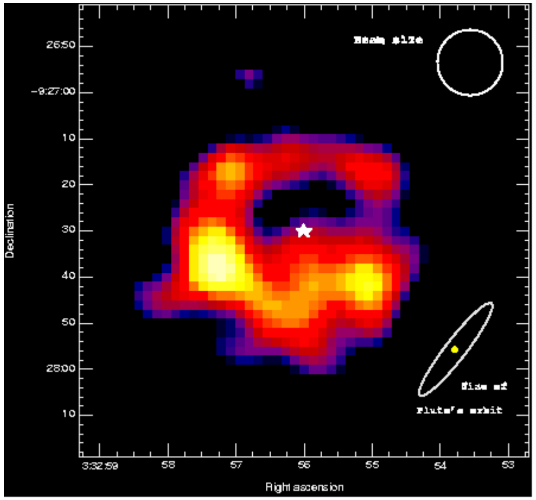


By considering the collisional evolution of debris discs, it is found that many of the brightest discs require a mass of >1000 Mearth. This high mass appears to be inconsistent with expected available mass in solids.

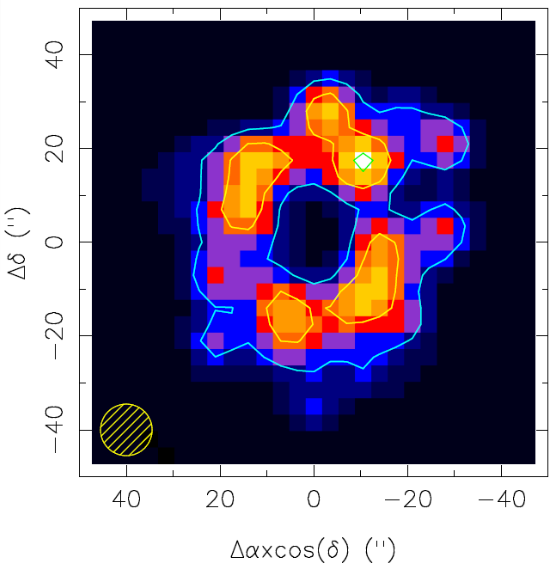
eps Eri

Closest debris disc so far detected around another star – only 3.2pc away.

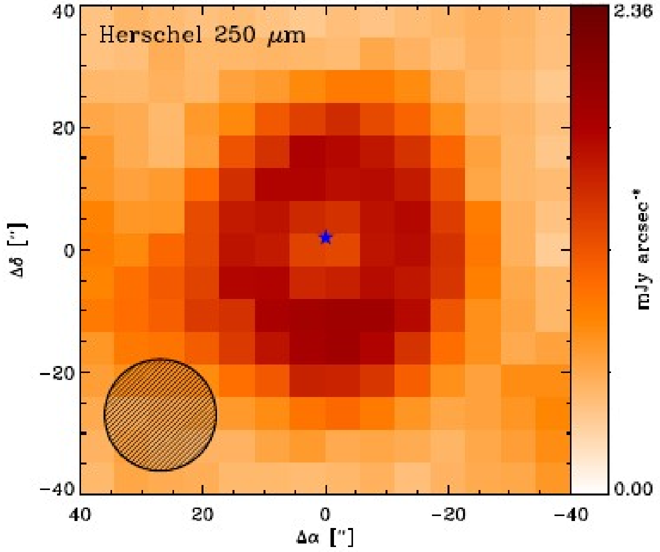
SCUBA – Greaves et al. 1998



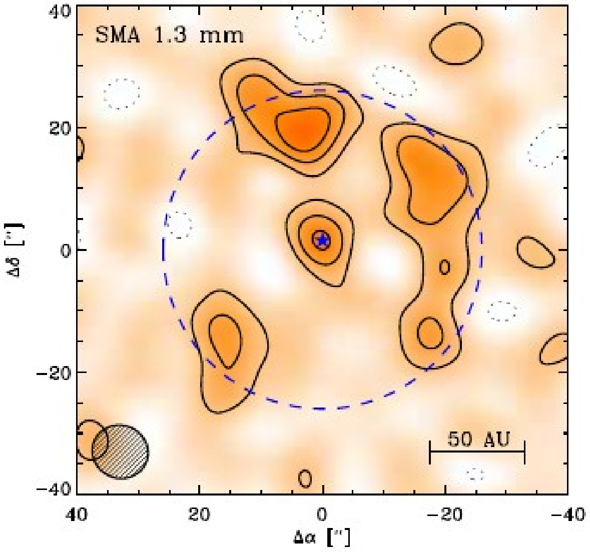
MAMBO – Lestrade & Thillez 2015



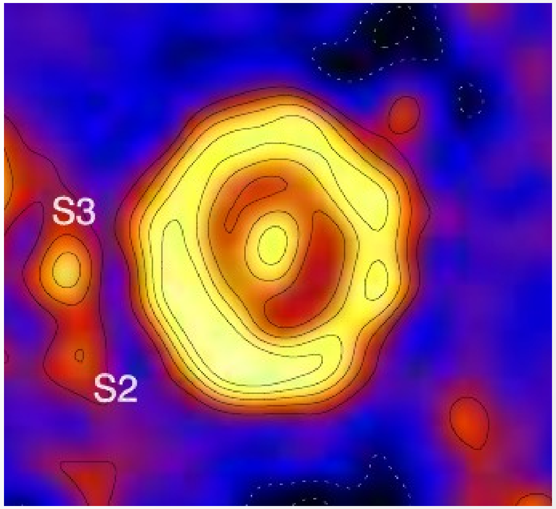
Herschel – Greaves et al. 2014



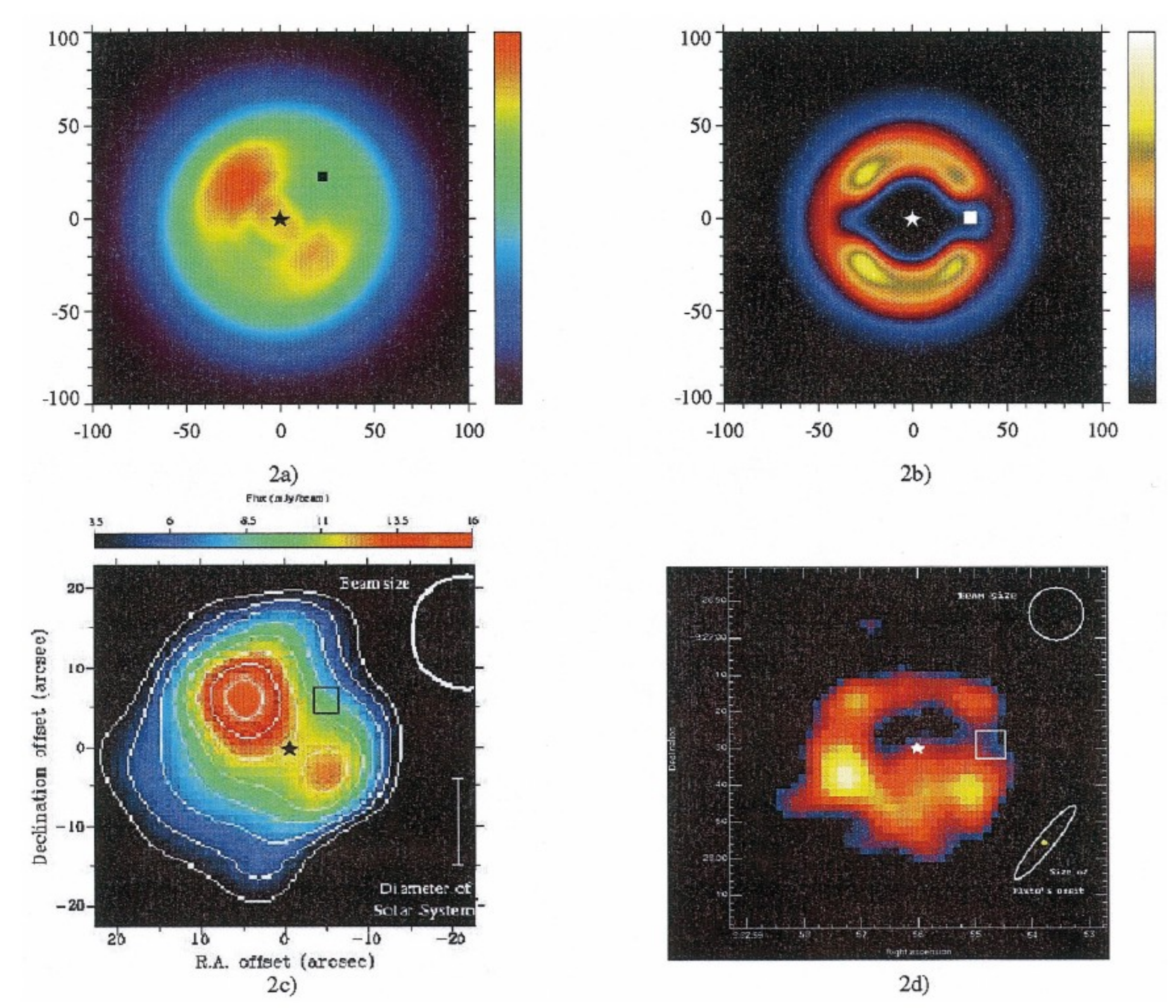
SMA – Macgregor et al. 2015



LMT – Chavez-Dagostino et al. 2015

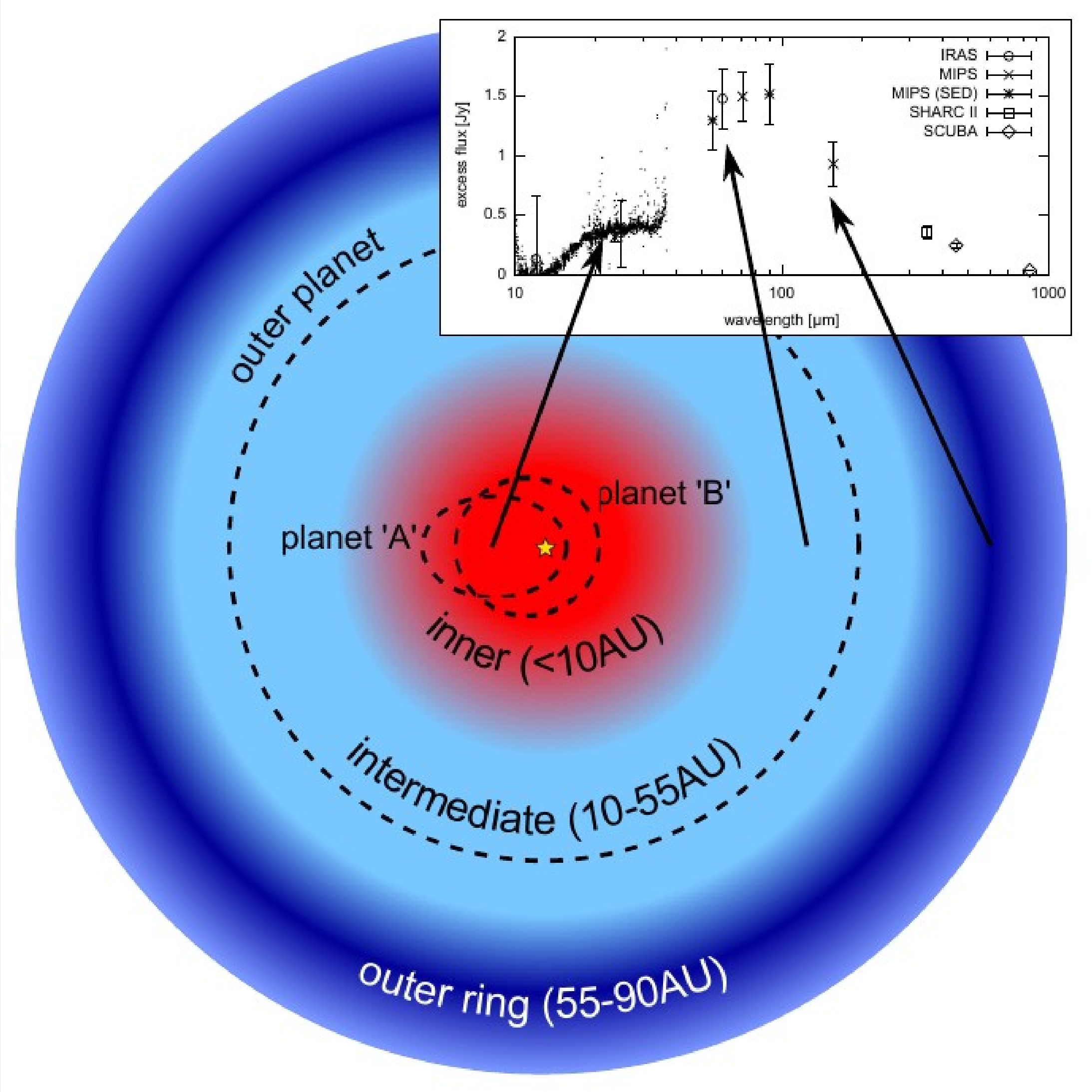


Clumps



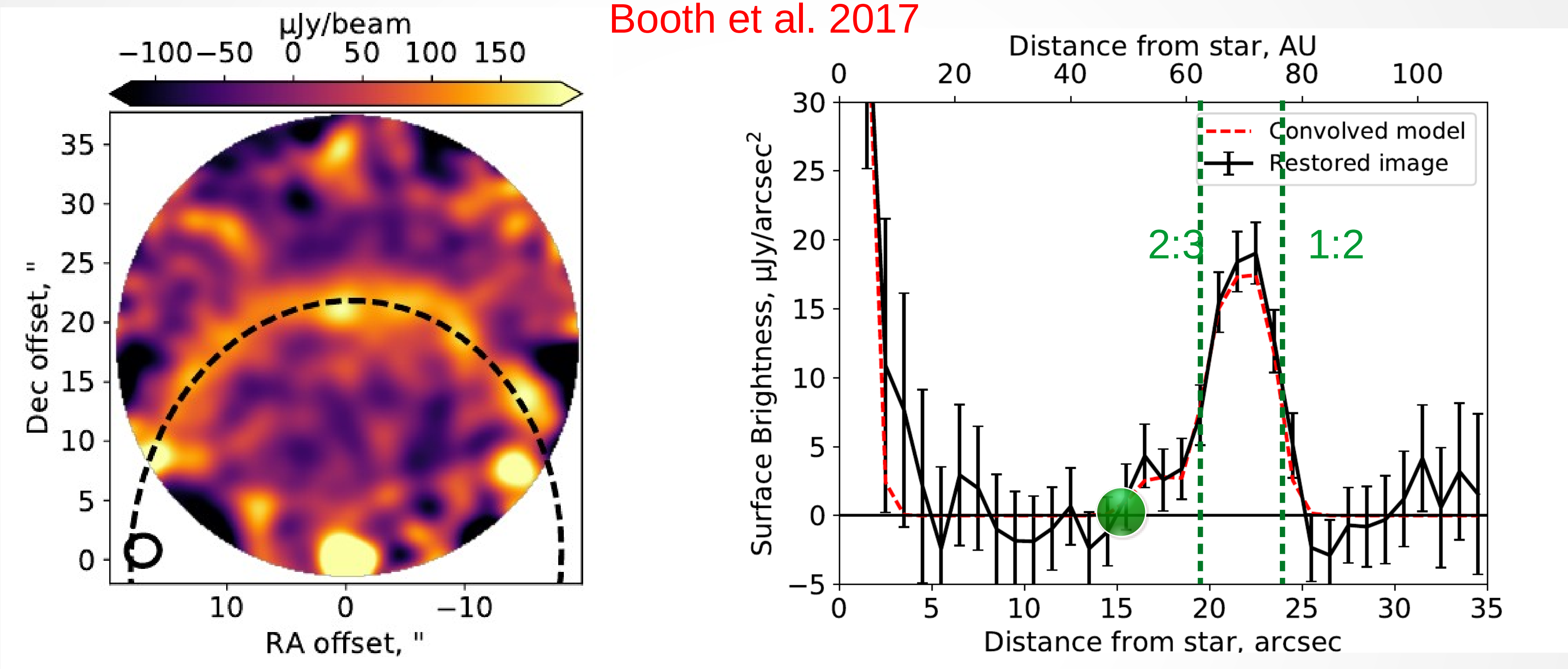
- Ozernoy et al. 2000 (see also Quillen & Thorndike 2002, Wyatt 2003...)
- Planets can trap planetesimals and dust in resonances

Dust Evolution around eps Eri



- Reidemeister et al. (2011) proposed that the warm dust seen by Spitzer (Backman et al. 2009) could be grains under the influence of Poynting-Robertson drag.
- Herschel (Greaves et al. 2014) also shows dust interior to the main ring.

eps Eri ALMA Image



Booth et al. 2017

13 AU wide belt. Inner and outer edges match with 2:3 and 1:2 resonances of a hypothetical planet at 48 AU.

HR 8799

Reidemeister et al. 2009

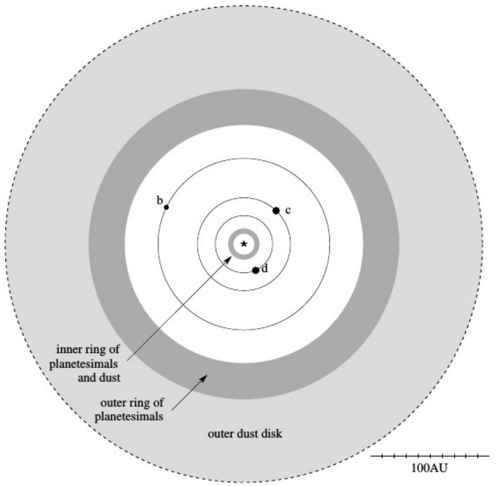
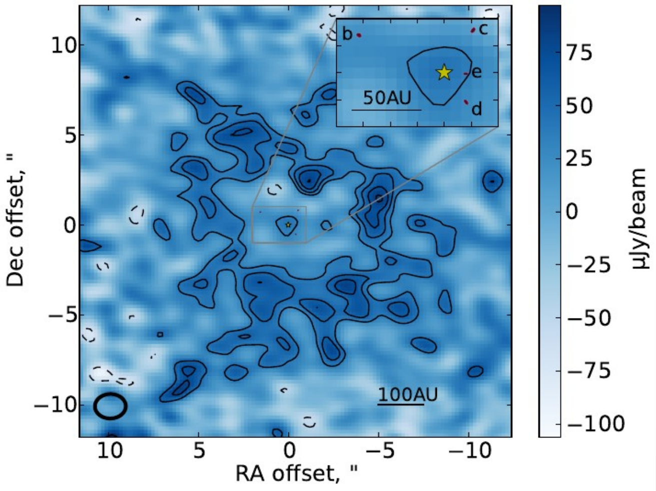


Fig. 14. A schematic view of the system HR 8799.

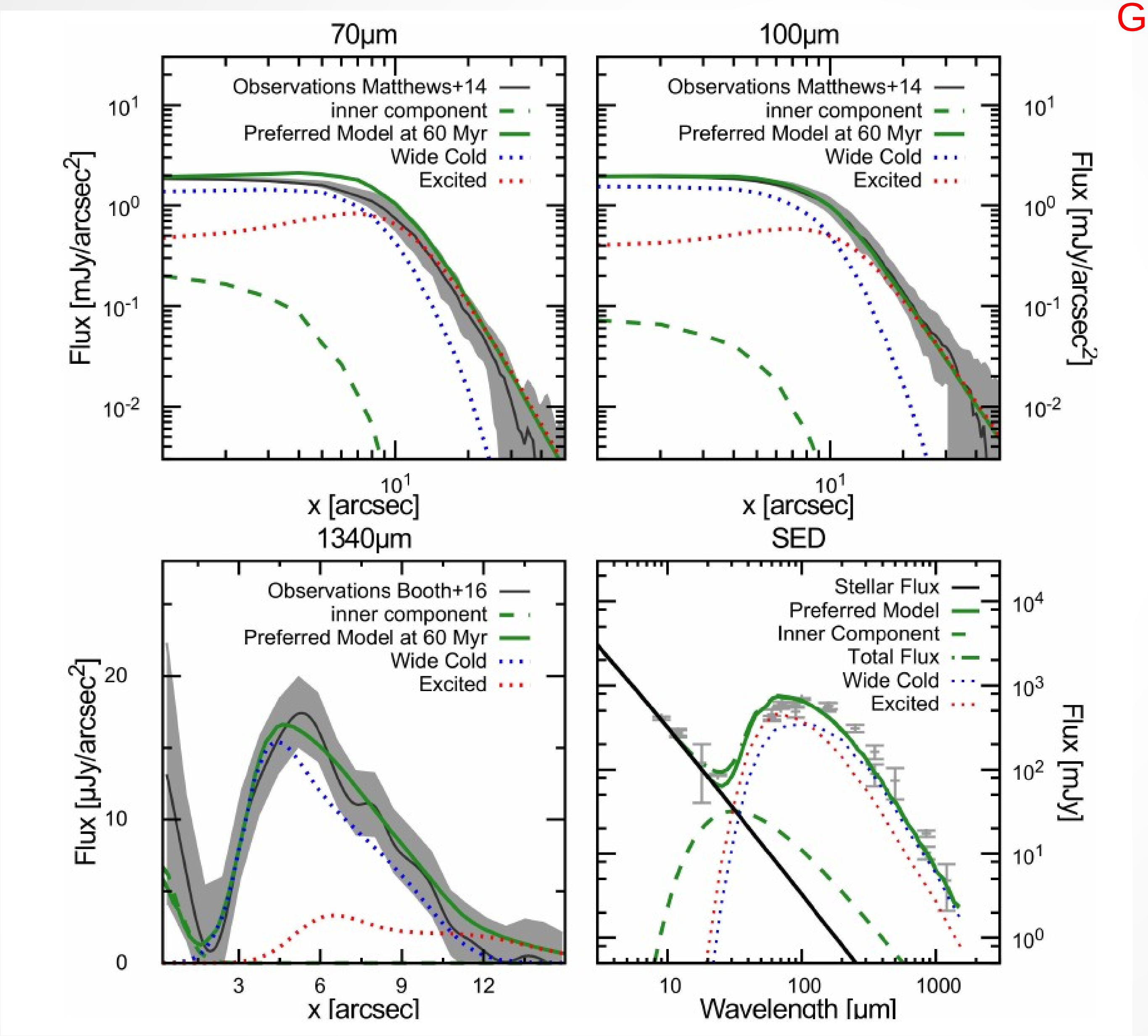


Booth et al. 2016

- Discovered by IRAS. (Sadakane & Nishida 1986)
- 4 directly imaged planets (Marois et al. 2008, 2010)
- Resolved at 24 µm with Spitzer. (Su et al. 2009)
- Warm component also detected.
- Inclination of 26° measured by Herschel (Matthews et al. 2014)
- ALMA observations show room for a 5th planet outside the known planets (Booth et al. 2016, although disputed by Wilner et al. 2018).

HR 8799

Geiler et al. 2018, submitted

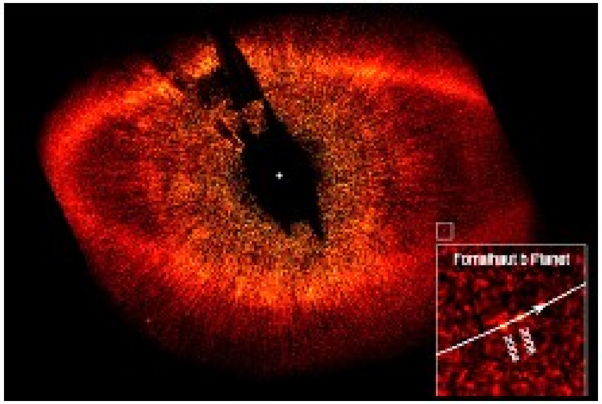


Using a physically motivated model including collisional evolution (ACE), we find that the ALMA + Herschel data requires a warm inner component, a cold belt, a scattered disc and a blowout halo.

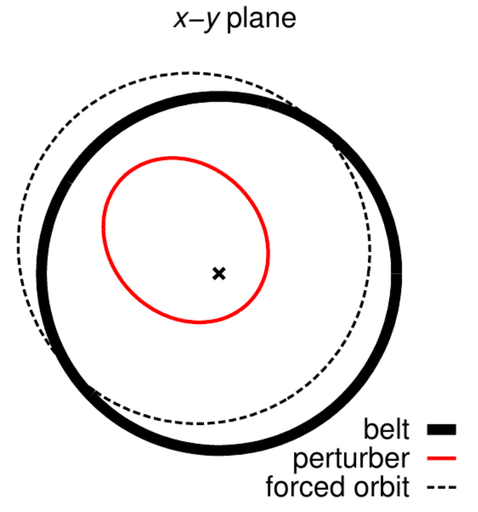
Eccentric Rings

- Eccentric planets induce a forced eccentricity in planetesimals.
- Eccentric rings are seen around a number of stars including Fomalhaut, HR 4796, HD 202628.
- This led to the discovery of Fom b – although this is now known to not be the main perturber in the Fomalhaut system (Kalas et al. 2013, Beust et al. 2014, Pearce & Wyatt 2015).

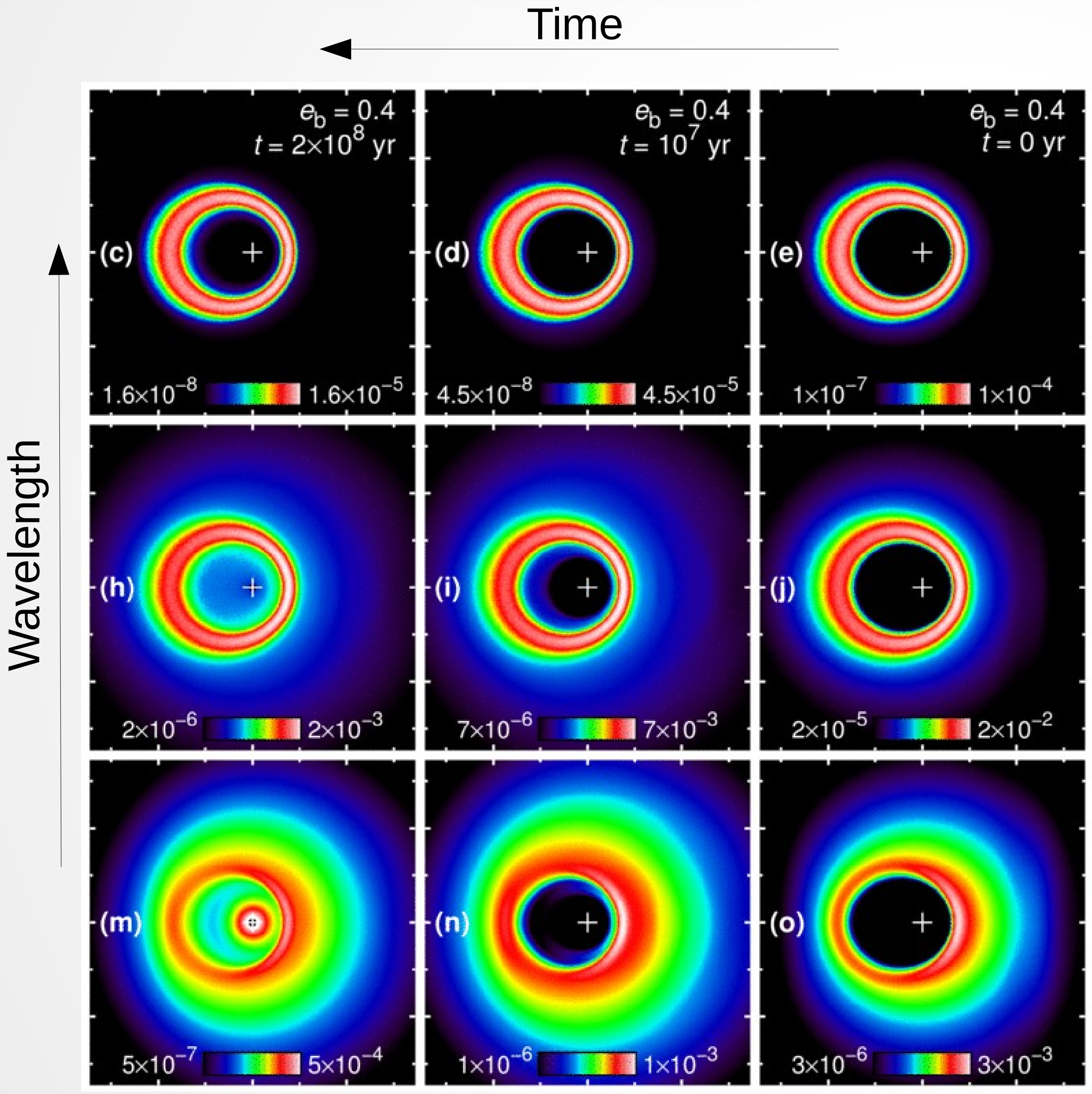
Fomalhaut, 440 Myr, $e = 0.11$



Kalas et al. (2008)



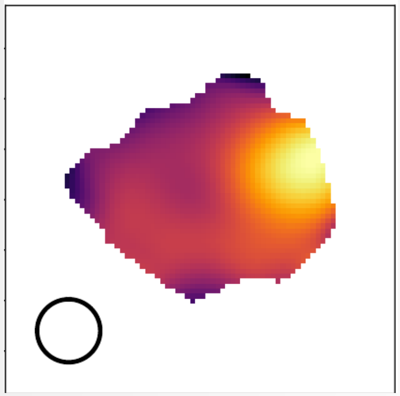
Collisional Evolution in Eccentric Rings



Löhne et al. 2017,
Kim et al. 2018
Sende et al. in prep.

- ACE can now model azimuthal asymmetries
- When predicting the observational properties of an eccentric ring, it is import to consider effect of collisions and transport forces

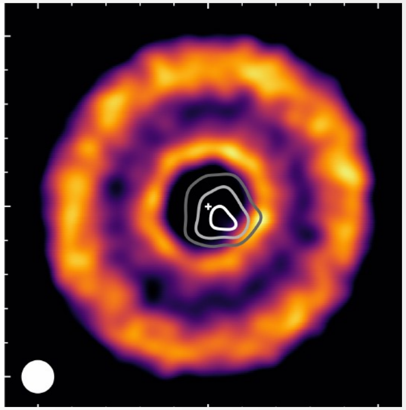
Take Home Message



Booth et al. 2018

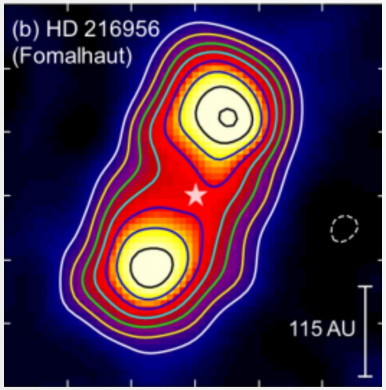
Debris discs are a key component of planetary systems that allow us to:

- *predict locations of planets and their properties*
- *determine the evolutionary history of the system*

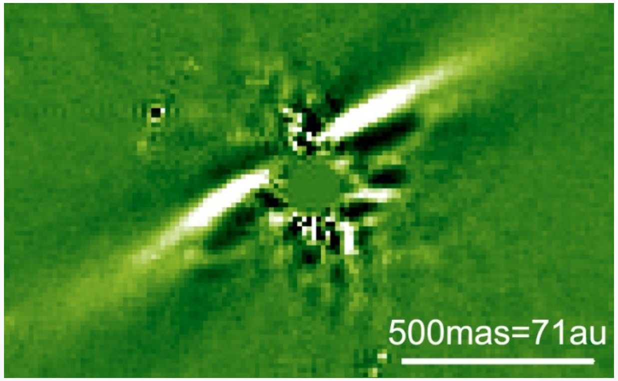


Marino et al. 2018

Holland et al. 2017



Matthews et al. 2017



Choquet et al. 2017