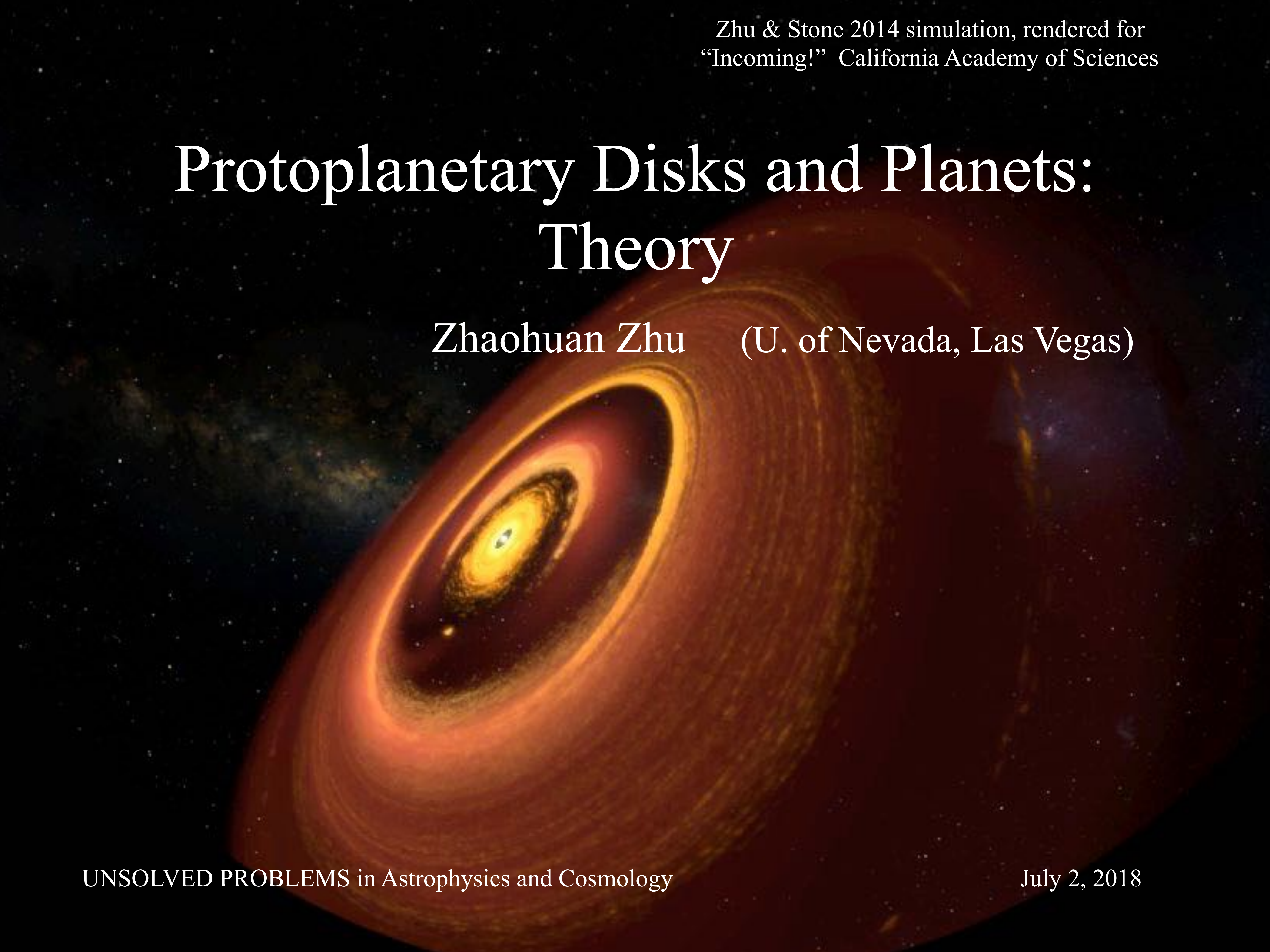


Zhu & Stone 2014 simulation, rendered for "Incoming!" California Academy of Sciences

Protoplanetary Disks and Planets: Theory

Zhaohuan Zhu (U. of Nevada, Las Vegas)

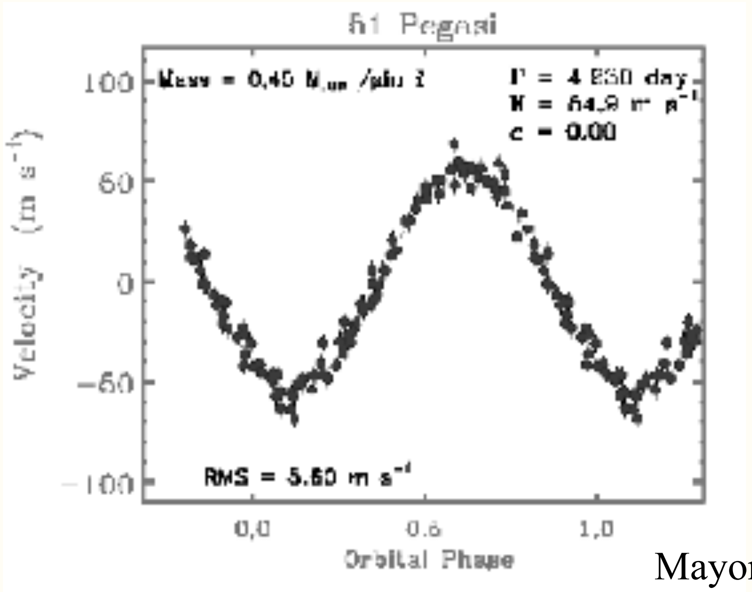
UNSOLVED PROBLEMS in Astrophysics and Cosmology

July 2, 2018

Now we are really good at finding mature planets

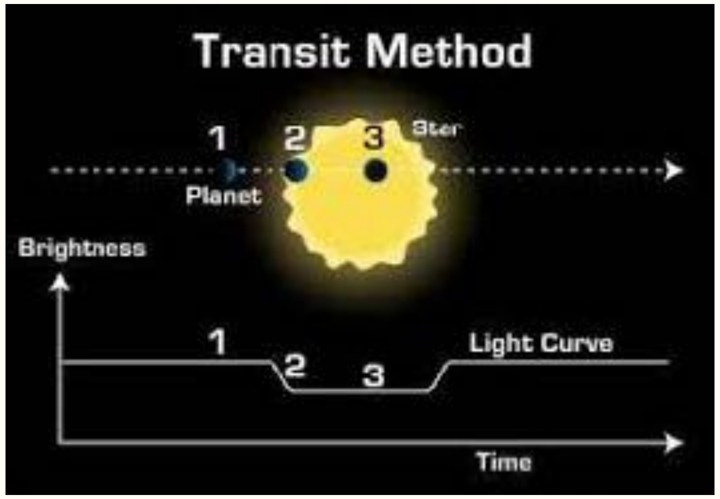
Two decades after 51 Pegasi b, we have 3800 exoplanets

1. Radial velocity:

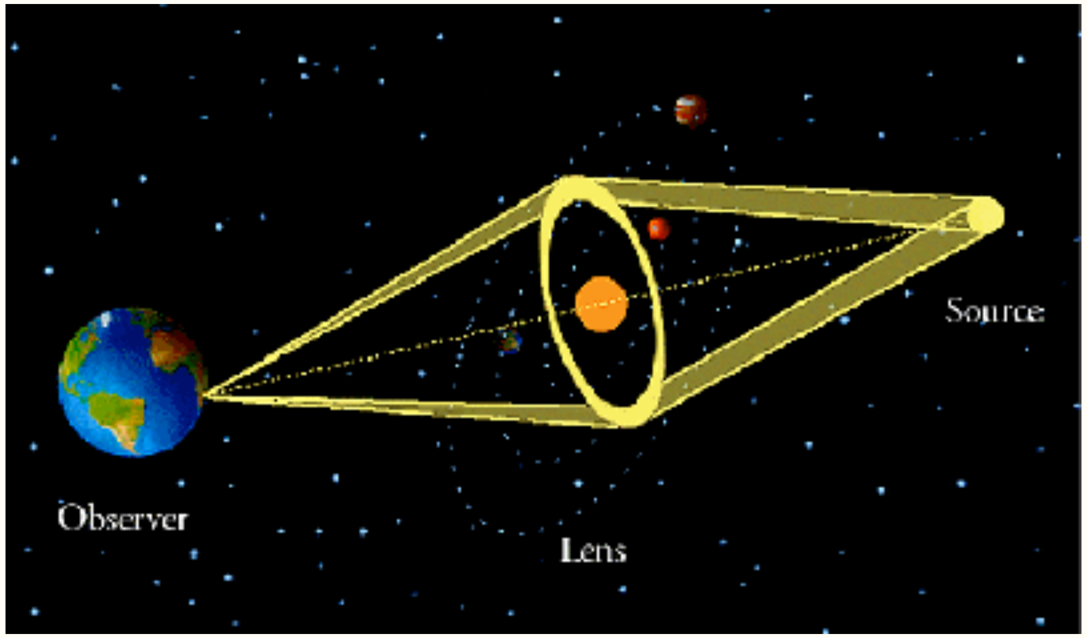


Mayor & Queloz 1995

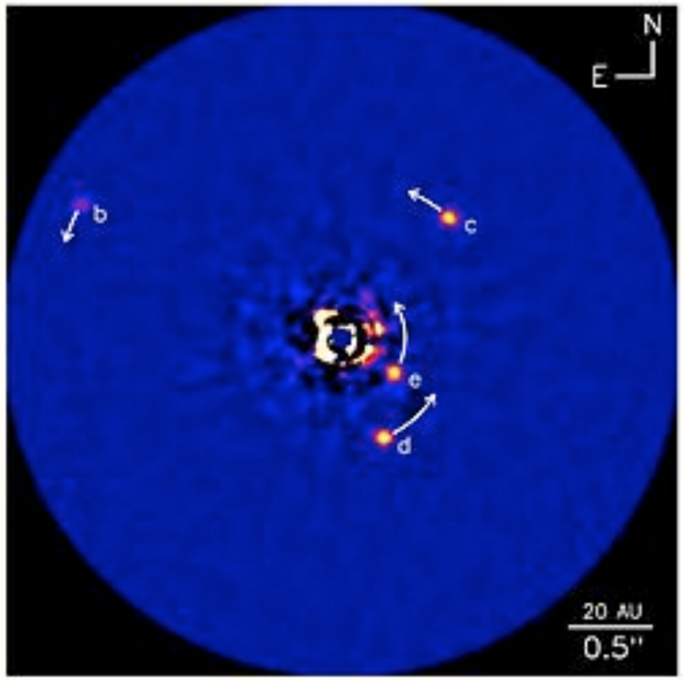
2. Transit:



3. Microlensing:



4. Direct Imaging:



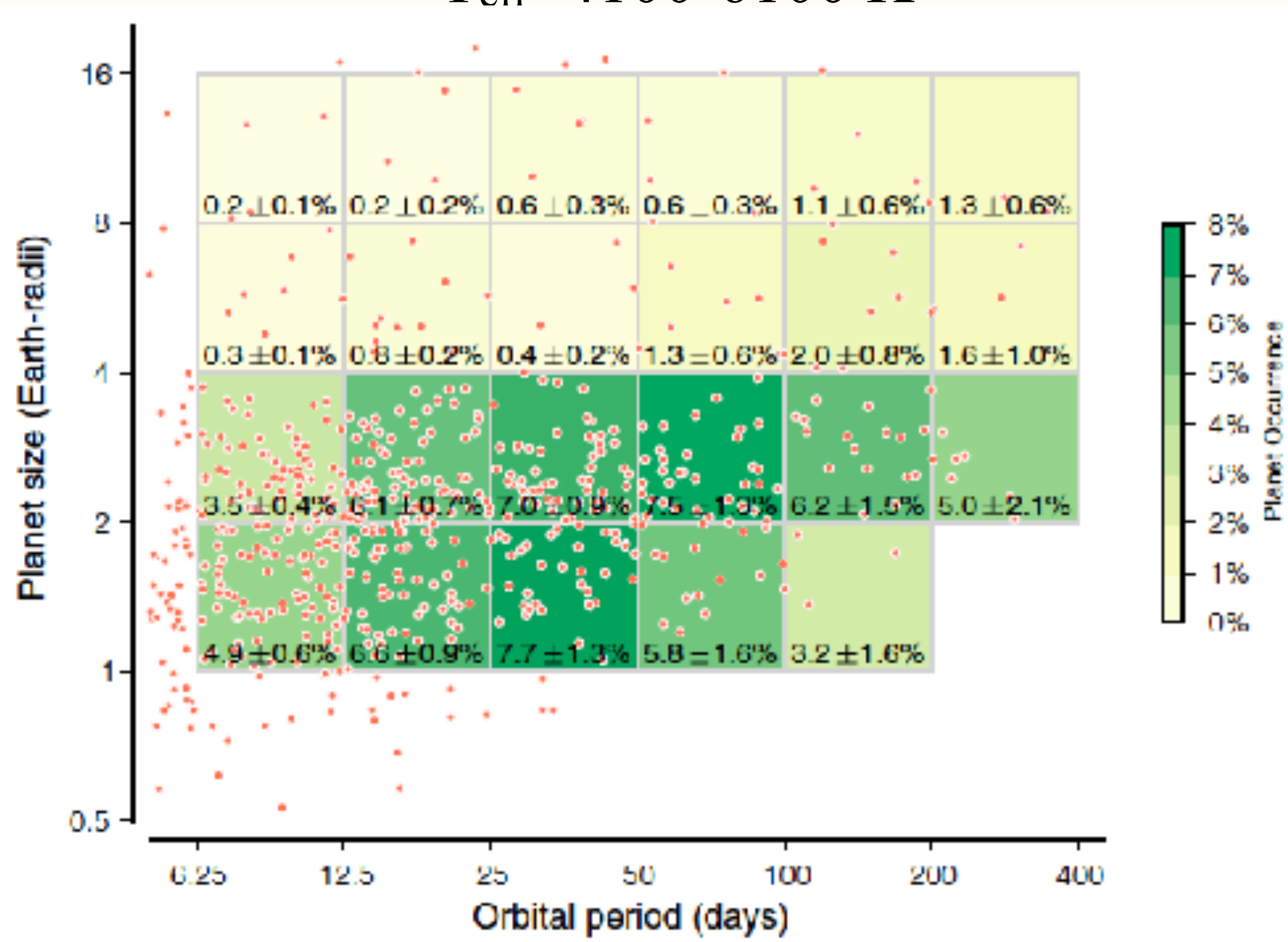
Credit: Marois

Planet statistics is robustly constrained: <1 AU

Kepler

GK Dwarf

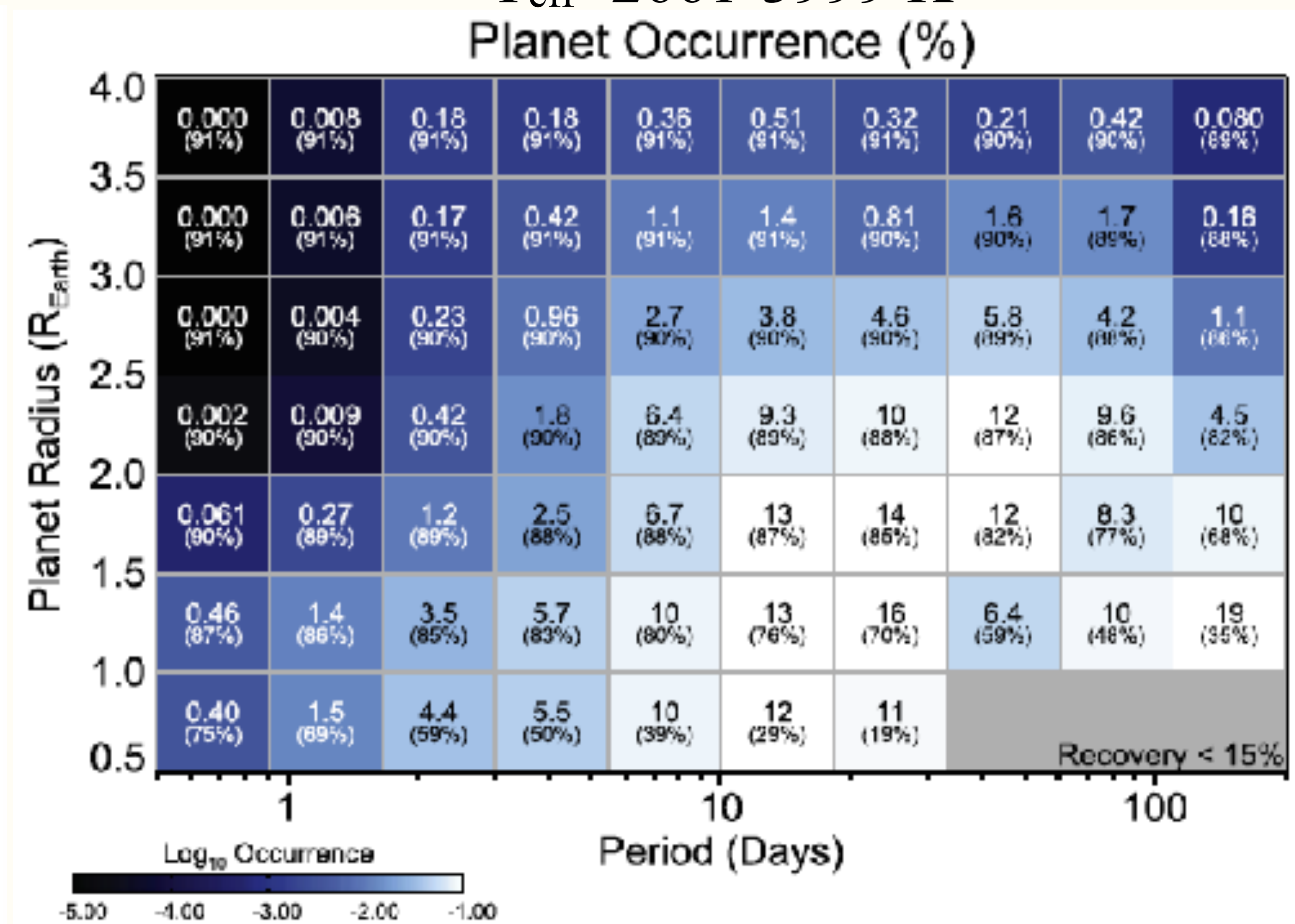
T_{eff}=4100-6100 K



Petigura et al. 2013

M Dwarf

T_{eff}=2661-3999 K



Dressing & Charbonneau 2015

Most planets are <4 $R_\oplus$

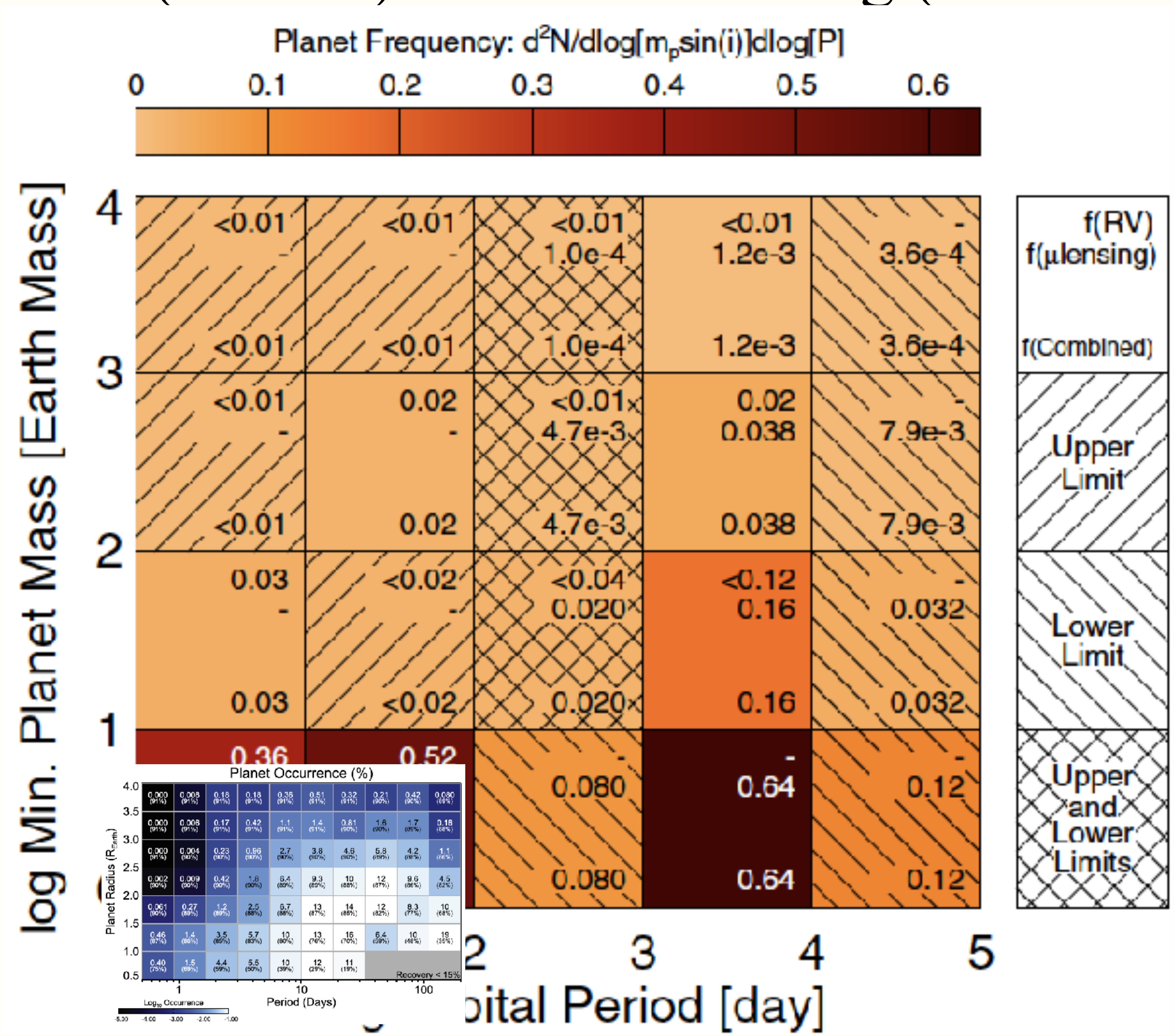
Most planets are <2.5 $R_\oplus$

0.6 planets at 1-4 $R_\oplus$ per GK dwarf

2.5±0.2 planets at 1-4 $R_\oplus$ per M dwarf

Within ~ 10 AU

RV (FGKM) and Microlensing (M dwarf):



Giant planets:

$0.1\ M_J < M_p \sin i$

$1 < P/\text{days} < 10^4$

M dwarf:

f=15%

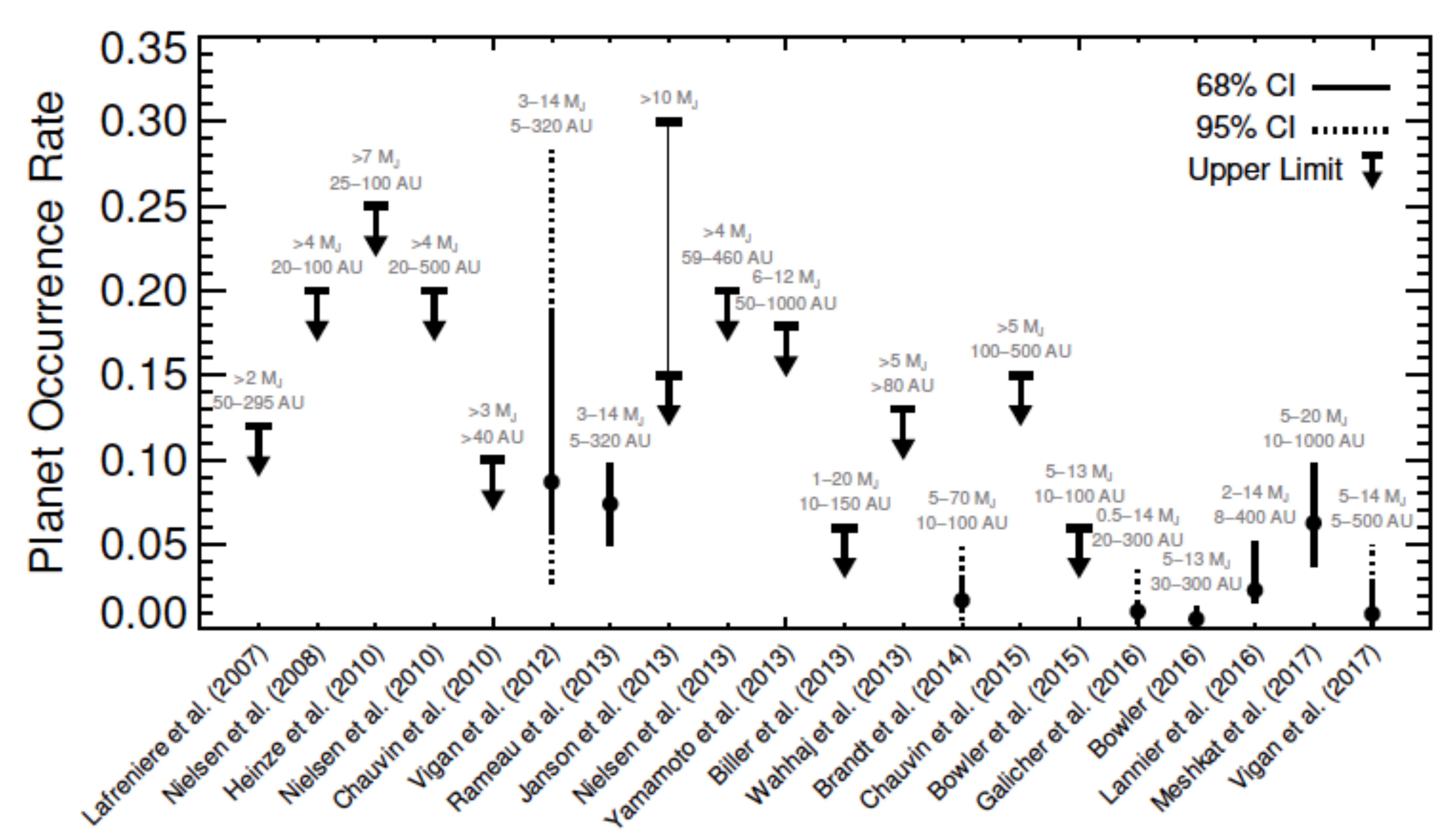
FGK stars:

f=31%

Clanton & Gaudi 2014

Beyond 10 AU

Direct imaging

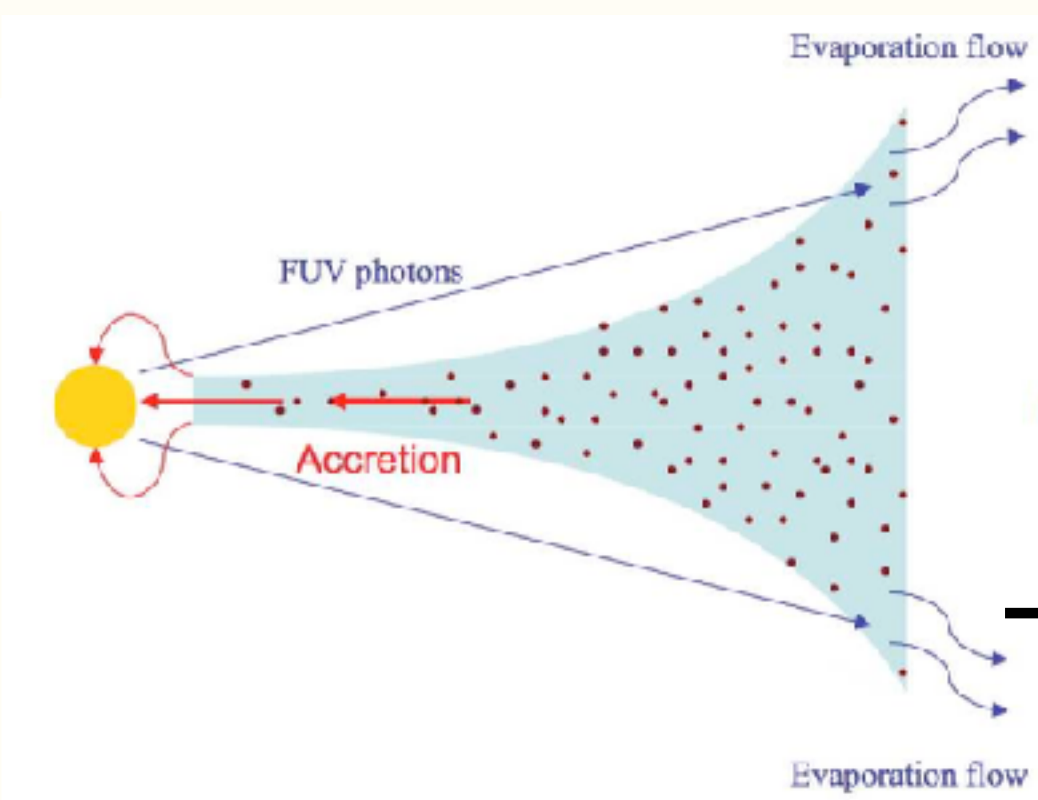


Bowler & Nielsen 2018

Why do we care?

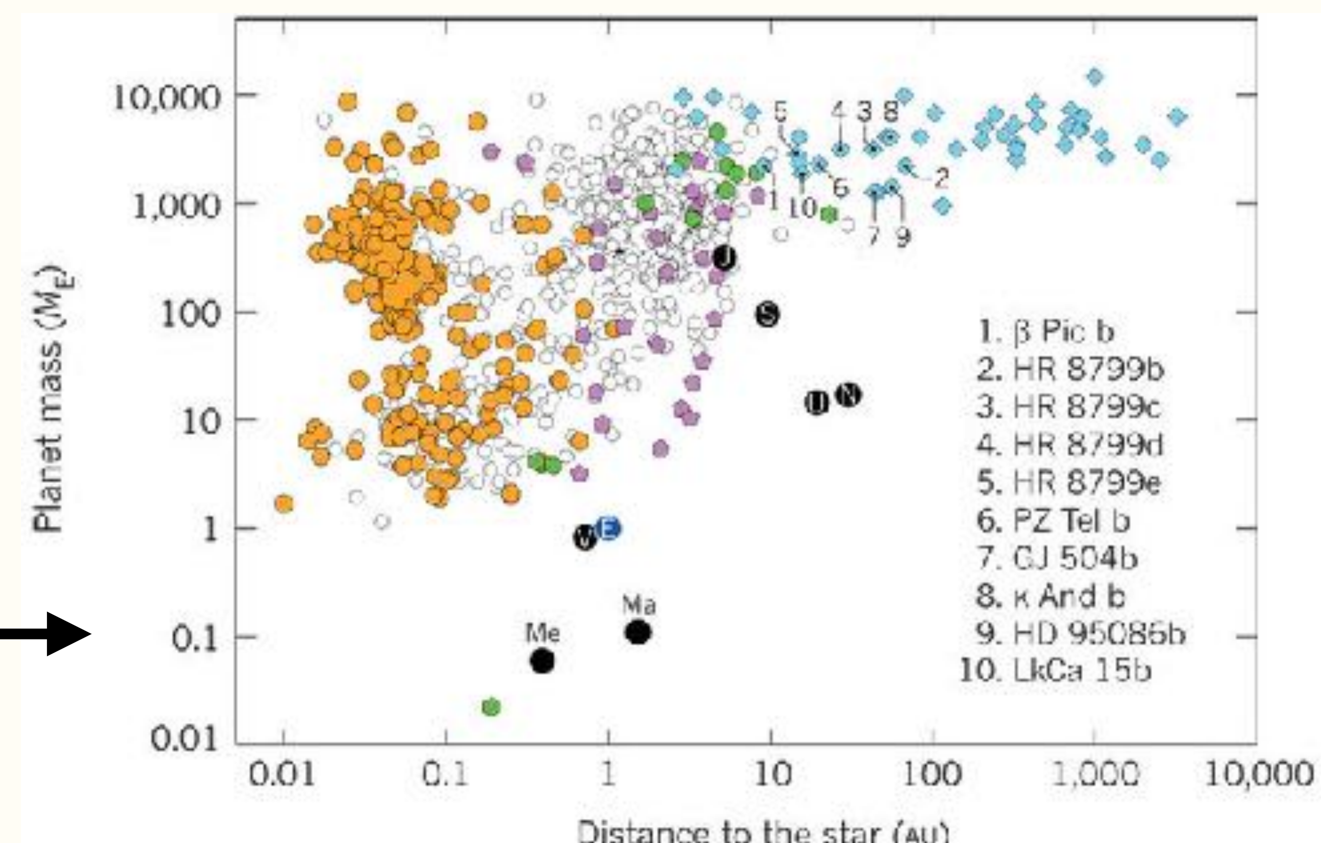
- Is our solar system special ?
- How do planets form ?

How do protoplanetary disks evolve to such diverse exoplanets?



© Williams & Cieza 2011

?



Pepe et al. 2014

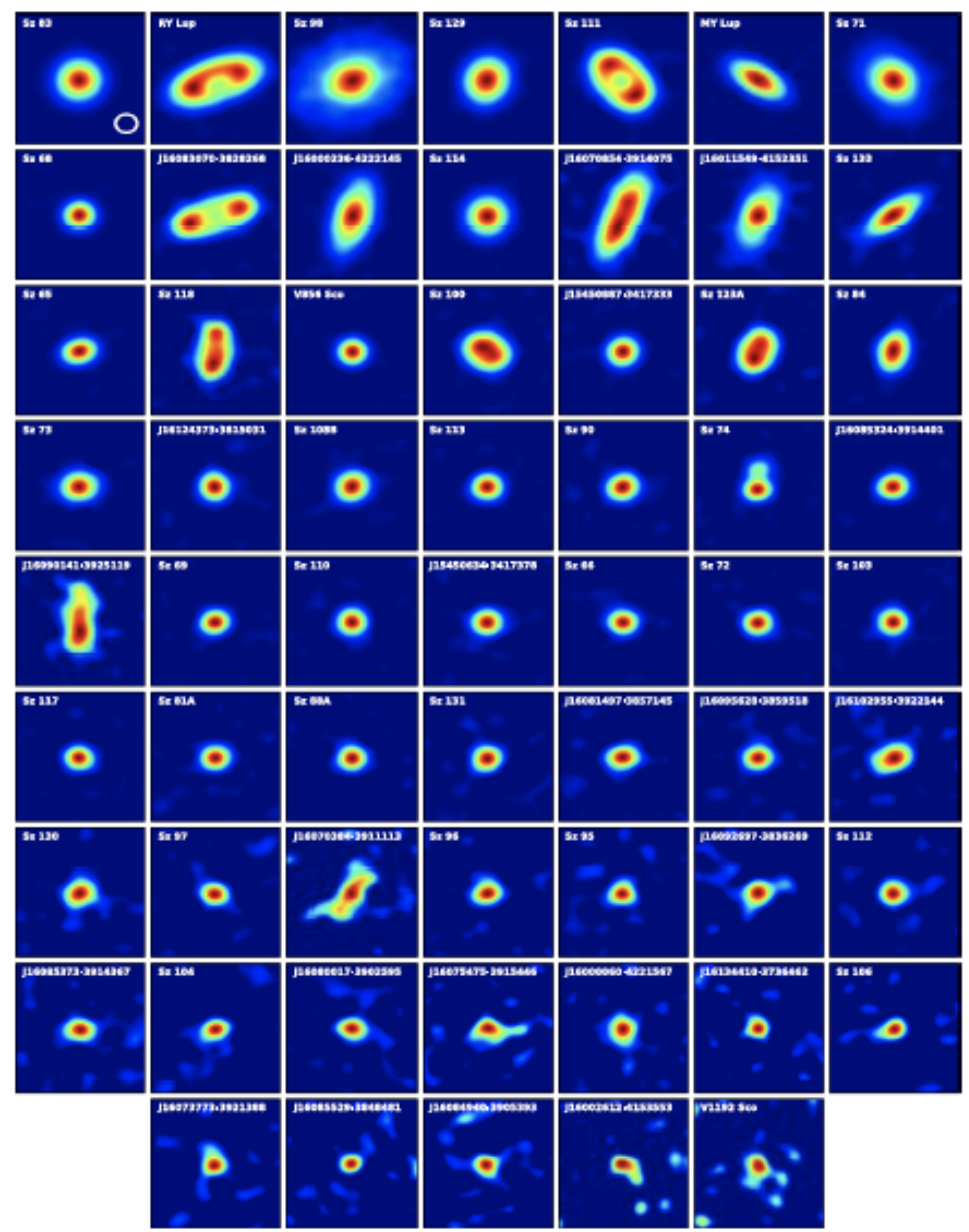
Protoplanetary disks => diverse exoplanets

- Compare protoplanetary disks with exoplanets

- Look for young planets

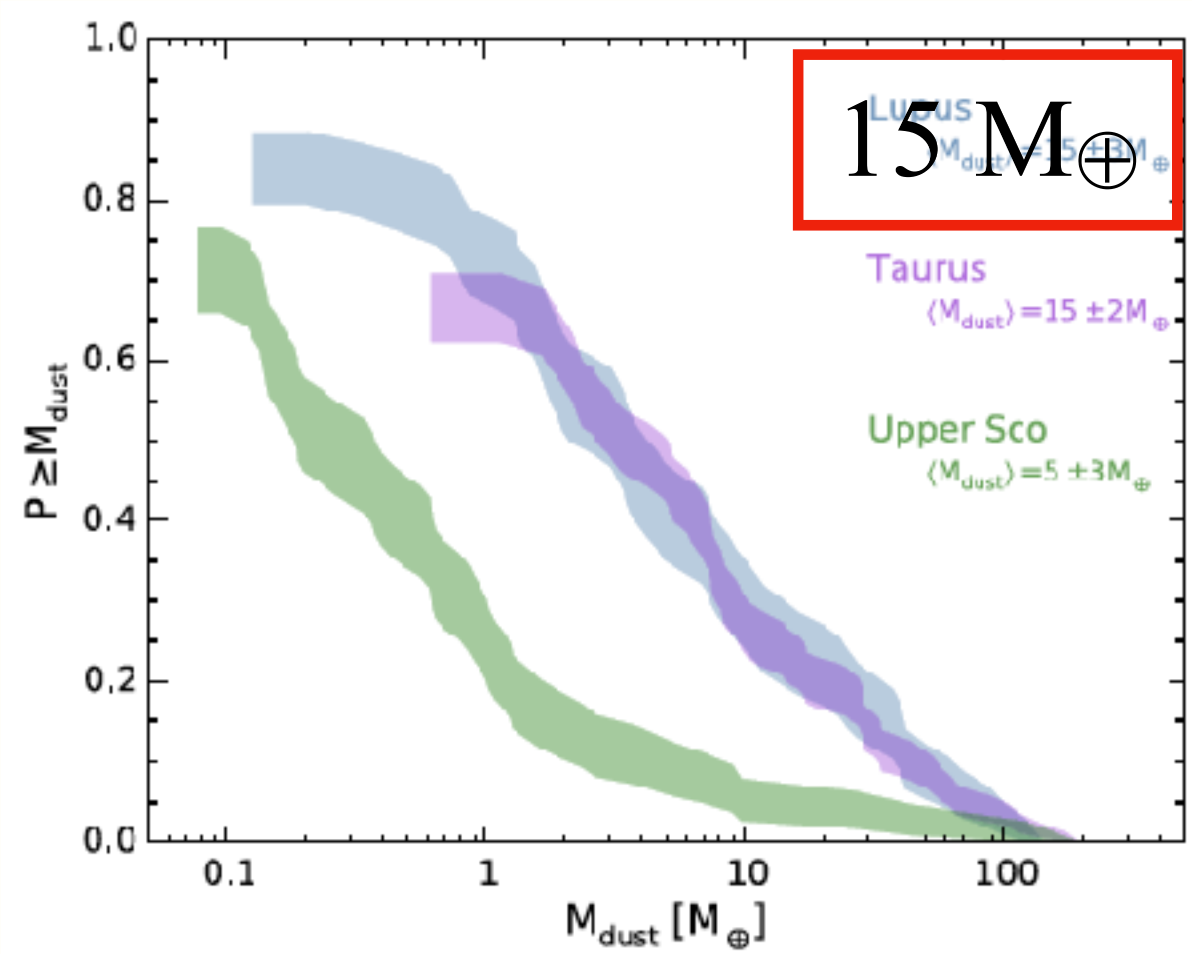
Protoplanetary disks VS exoplanets

Lupus ALMA cycle 2 Survey



Ansdell et al. 2016

Dust mass in disks by ALMA



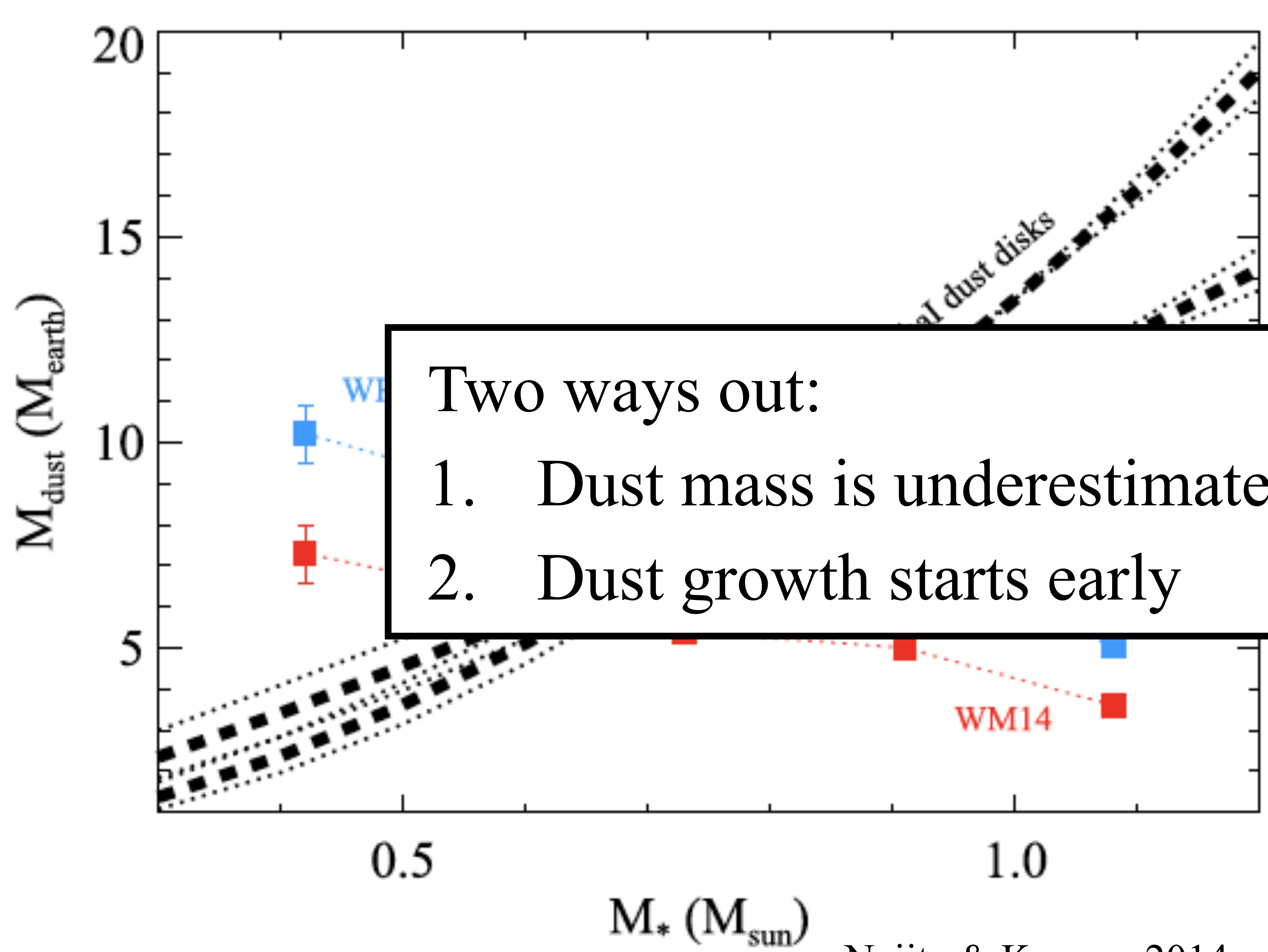
The mean solid mass in Kepler planets ~ 20 earth mass within 1 AU

Dong & Zhu 2013, Chiang & Laughlin 2013

There appears to be a **mass budget problem**:

Najita & Kenyon 2014

Mass budget problem



Two ways out:

1. Dust mass is underestimated
2. Dust growth starts early

Najita & Kenyon 2014
Pascucci et al. 2016

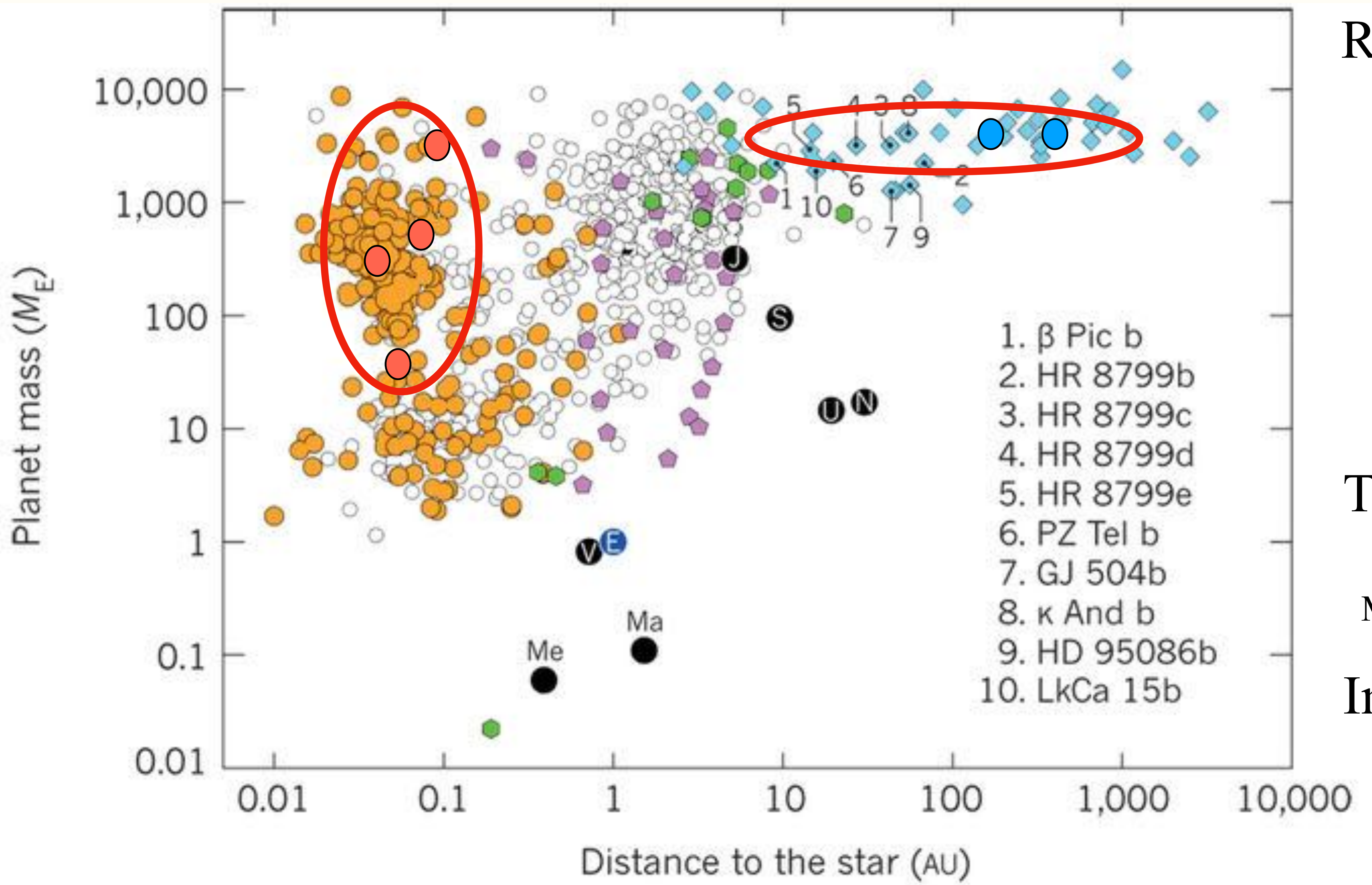
Protoplanetary disks => diverse exoplanets

- Compare protoplanetary disks with exoplanets

- Look for young planets

  Direct Methods:
  Indirect Methods:
    Dust features: Gaps, Spirals, Blobs
    Gas kinematics

Direct Detection



Pepe+ 2014

RV:

CI Tau b
Johns-Krull+ 2016

V 830 Tau b
Donati+ 2016

Tap 26 b
Yu+ 2017

Transit:

K2 33b
Mann+ 2016, David+ 2016

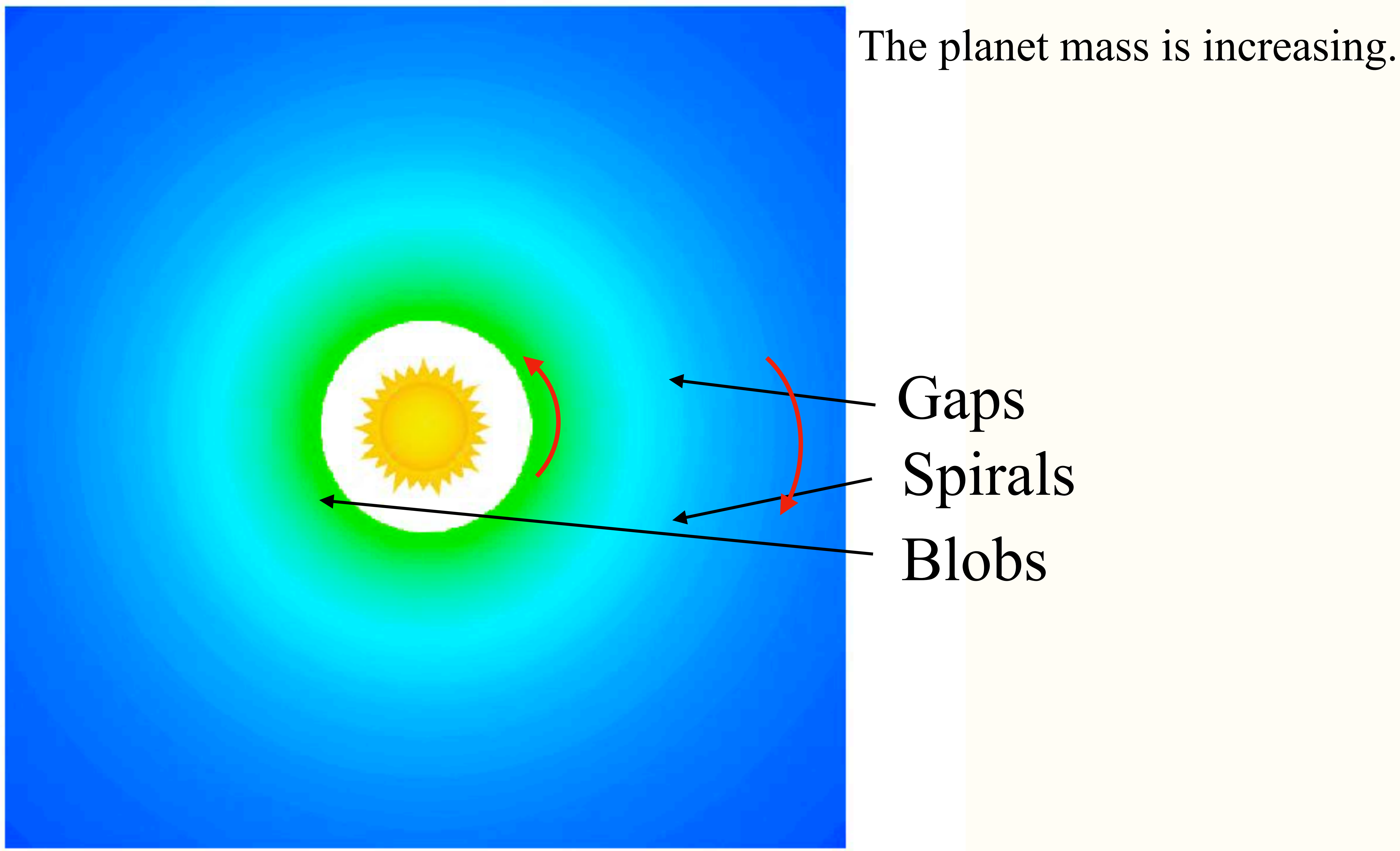
Imaging:

ROXs 42Bb
Currie+ 2014

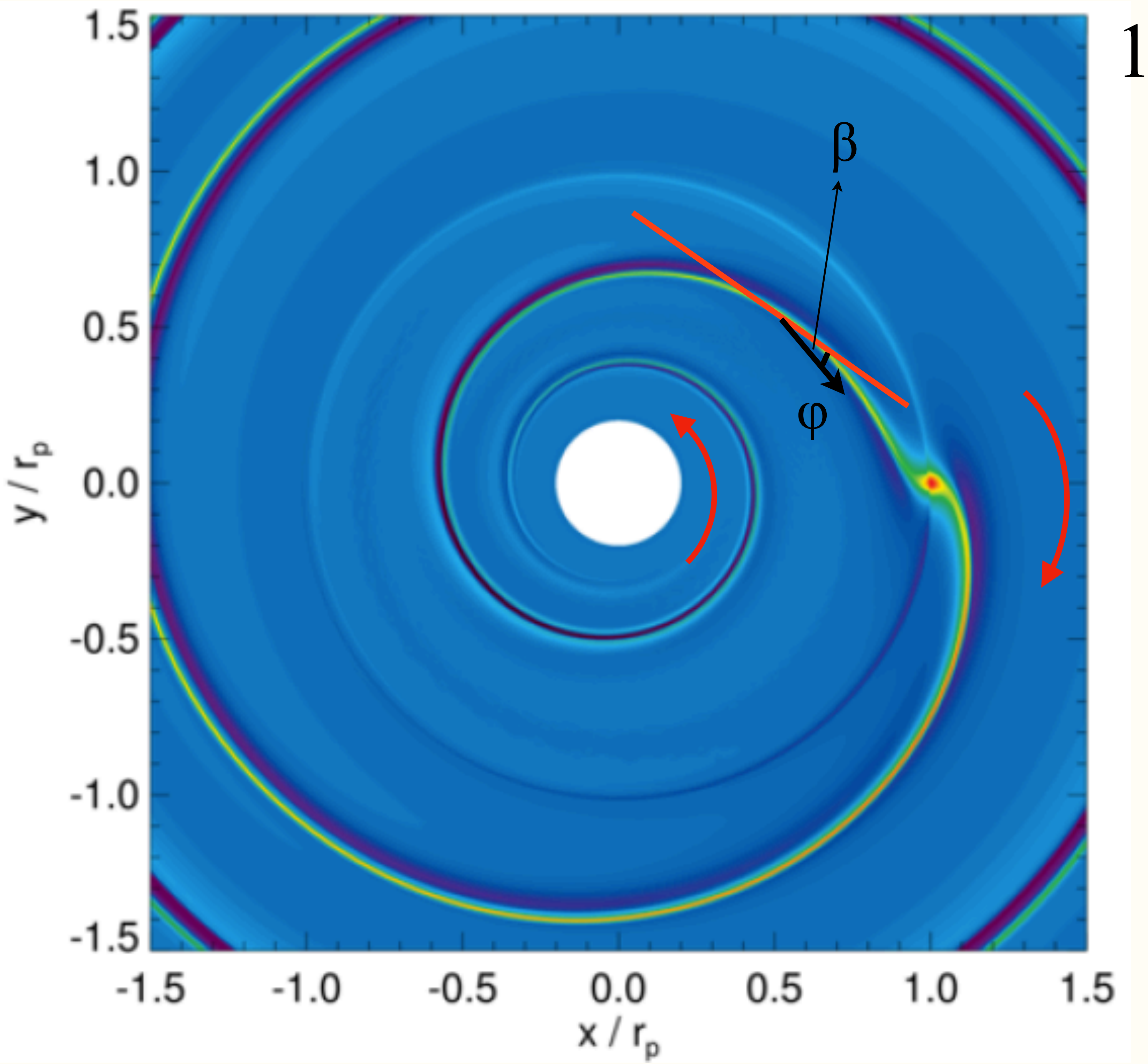
FW Tau b
Kraus+ 2014

LkCa 15 b
Kraus+ 2011

Indirect Detection using disk features



Planet-disk interaction



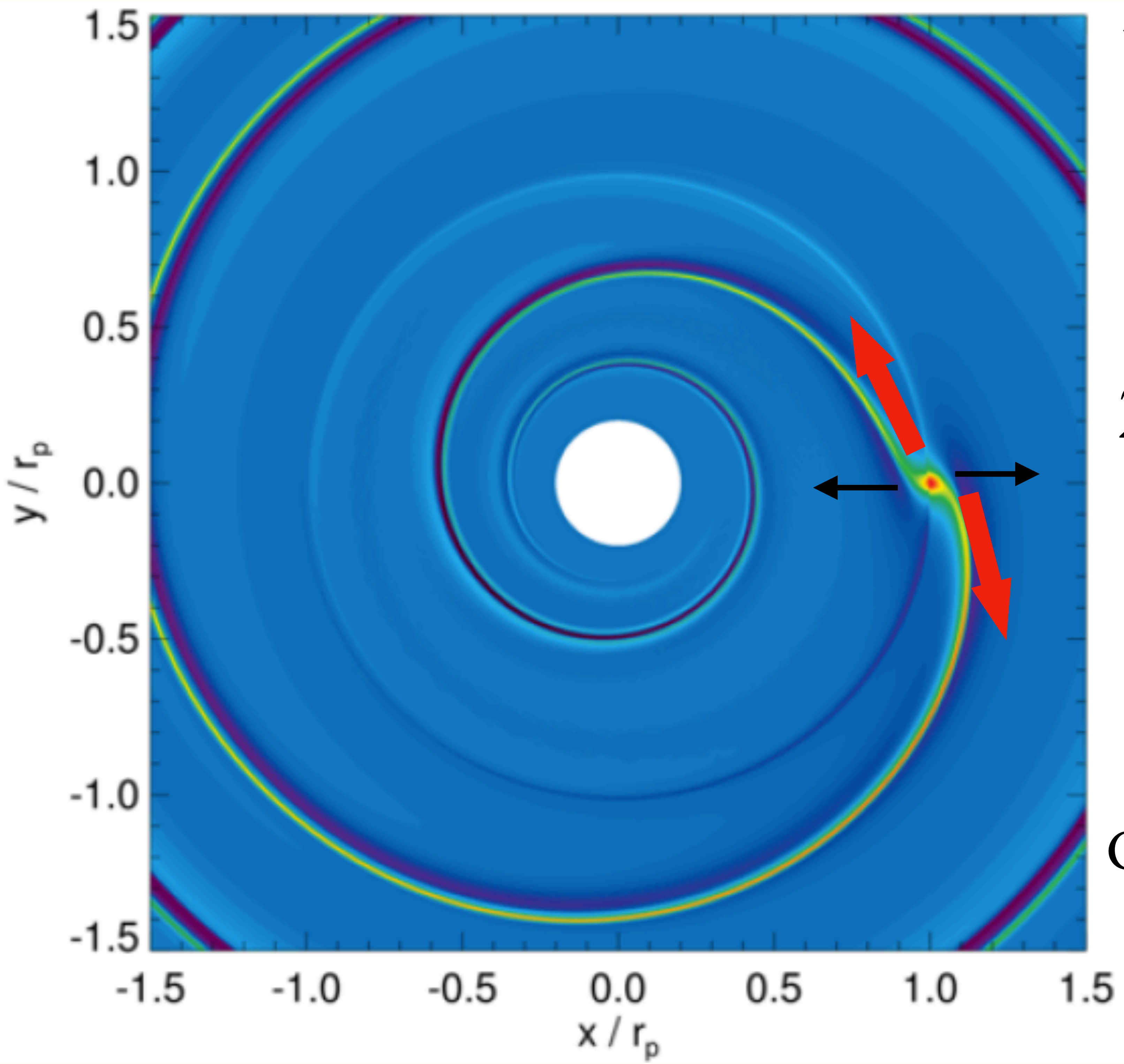
Baruteau+ 2014

1. Spirals

The pitch angle β

$$\tan \beta = \frac{c_s}{R\left|\Omega - \Omega_p\right|}$$

Planet-disk interaction



Baruteau+ 2014

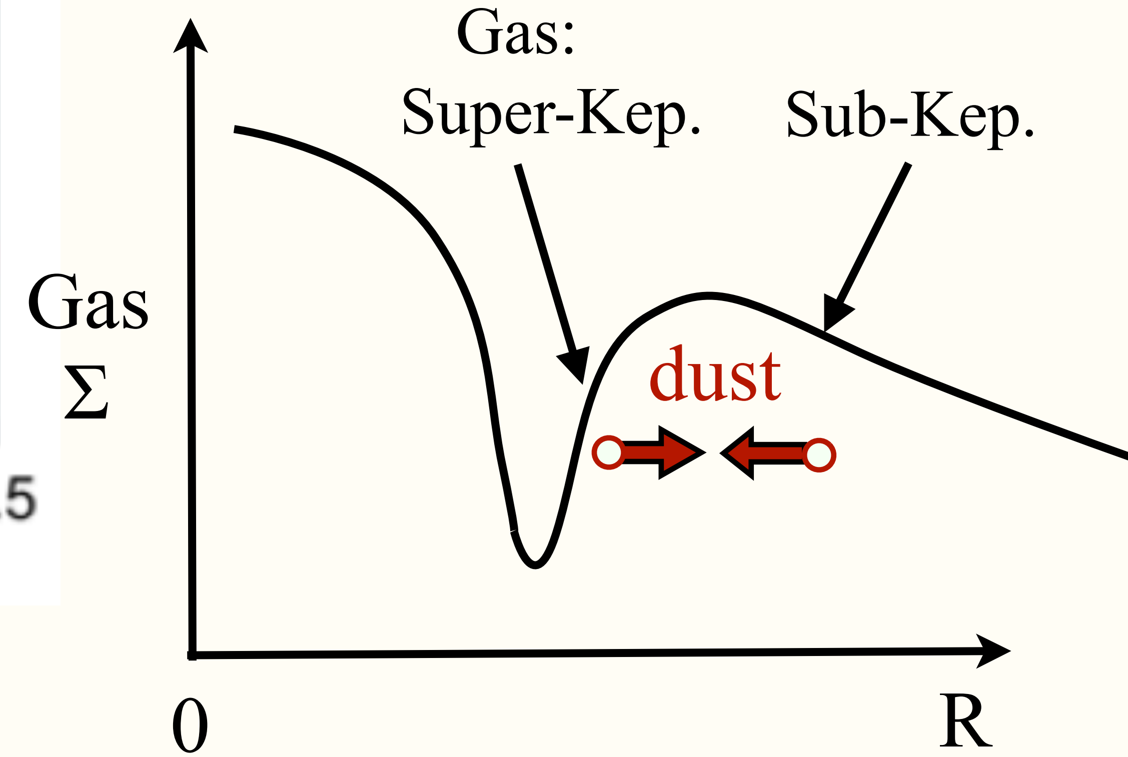
1. Spirals

The pitch angle β

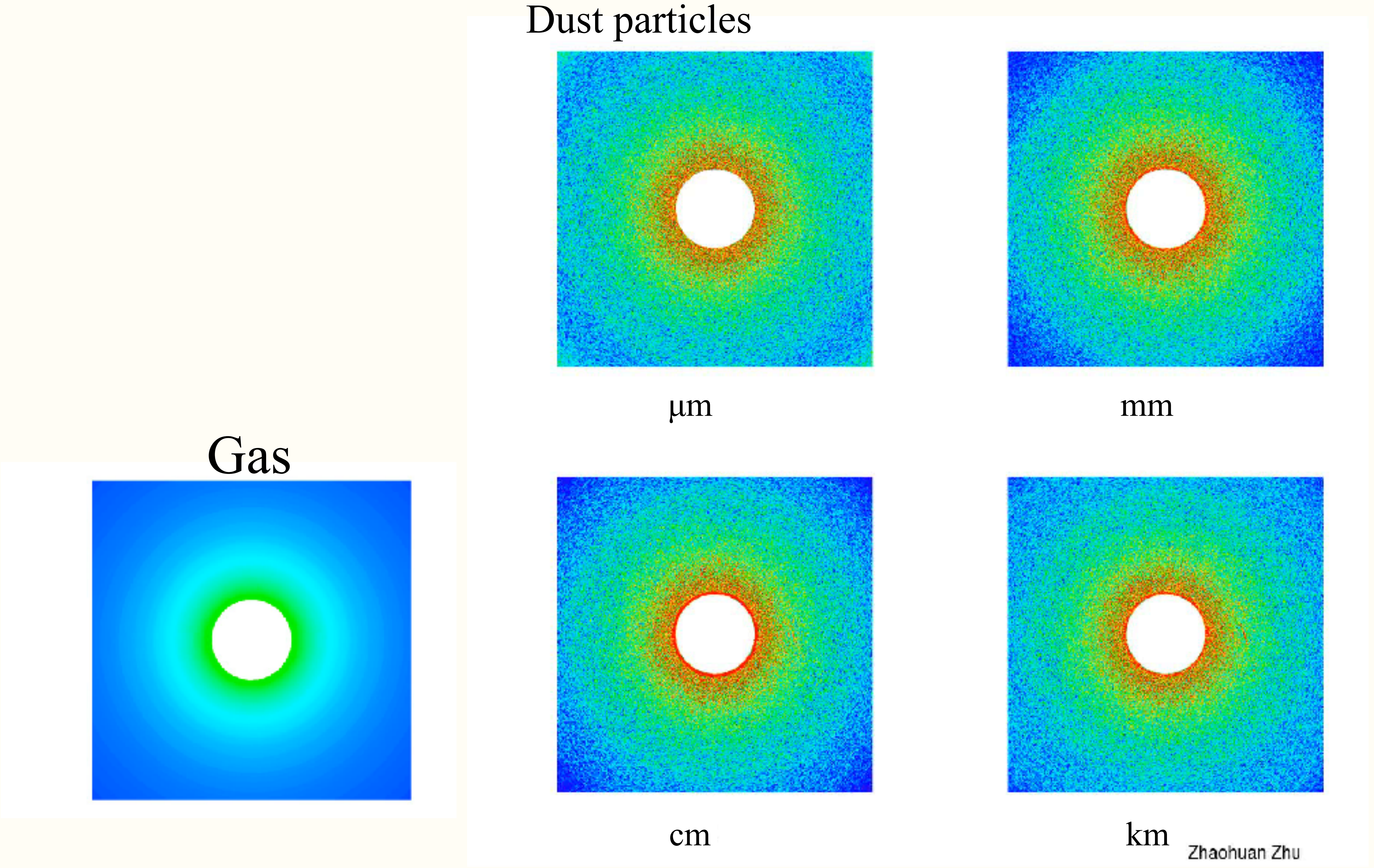
$$\tan\beta = \frac{c_s}{R|\Omega-\Omega_p|}$$

2. migration

3. gap opening



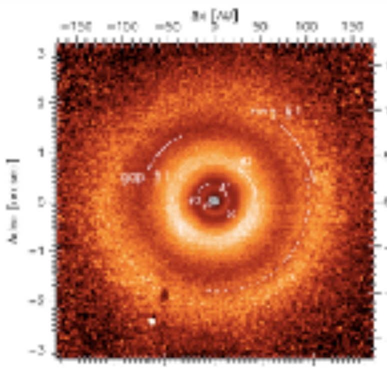
Indirect Detection diverse disk features: Dust



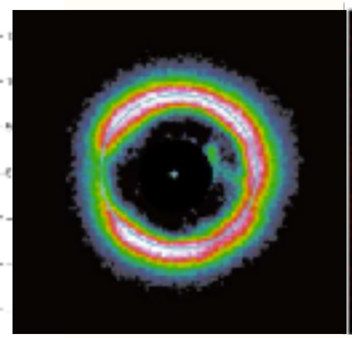
Diverse disk features

Rings
m=0

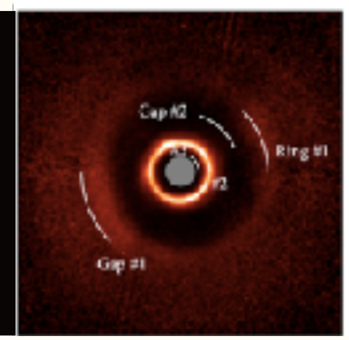
Optical/Near-IR



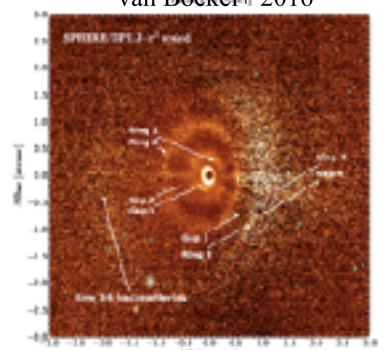
van Boekel+ 2016



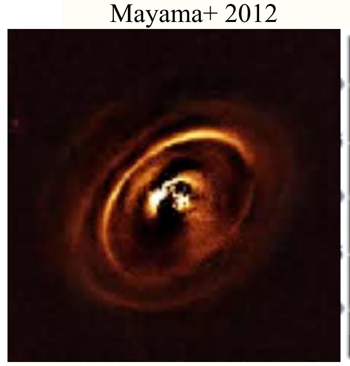
Mayama+ 2012



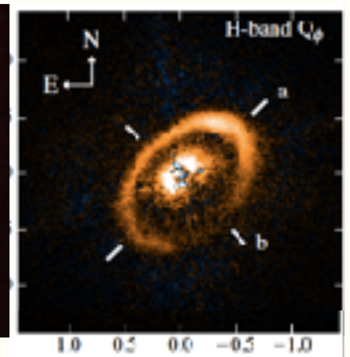
Pohl+ 2017



Ginski+ 2016

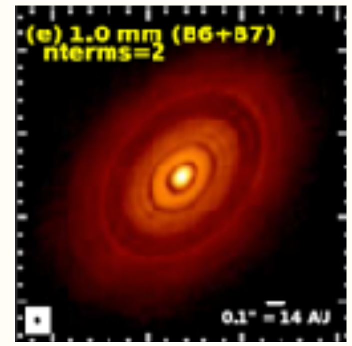


De Boer+ 2016

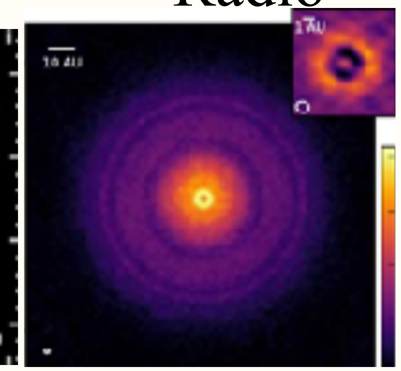


Muro-Arena+ 2018

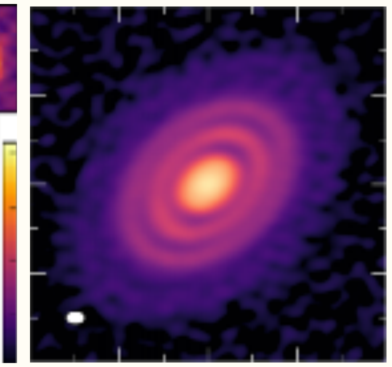
Radio



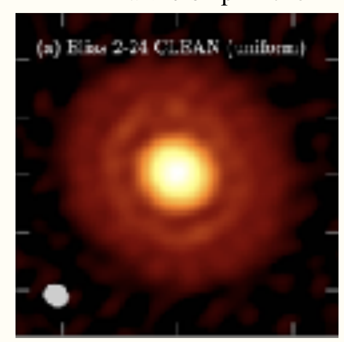
ALMA Partnership+ 2015



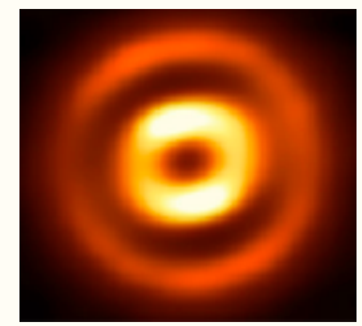
Andrews+ 2016



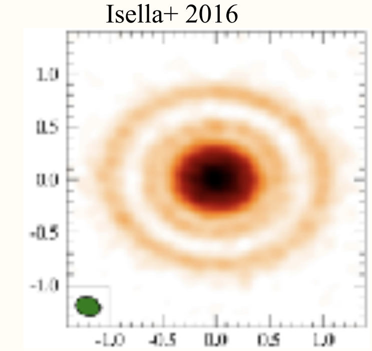
Isella+ 2016



Cieza et al. 2017



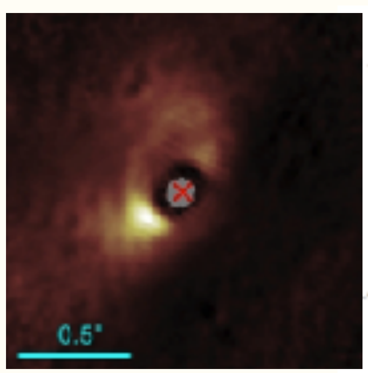
Fedele+ 2017



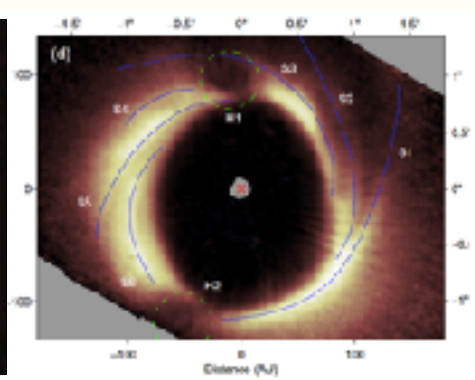
Fedele+ 2017

Lopsided
structure

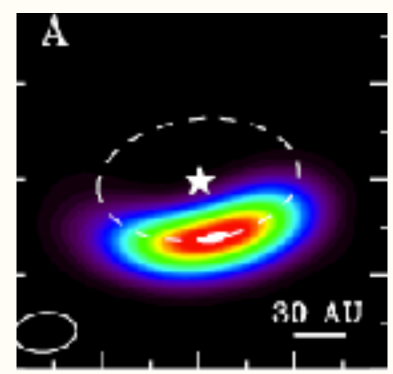
m=1



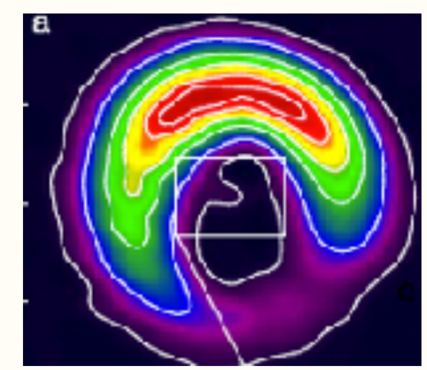
Avenhaus+ 2014



Avenhaus+ 2014



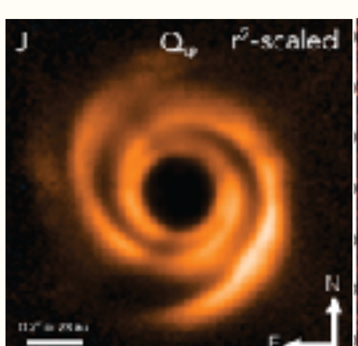
van der Marel+ 2013



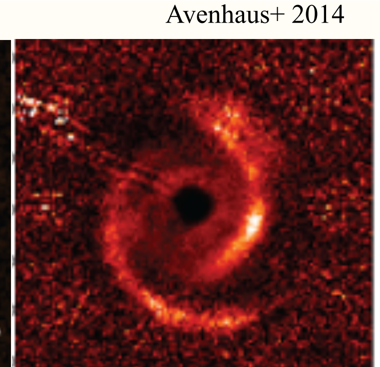
Casassus+ 2013

Spirals

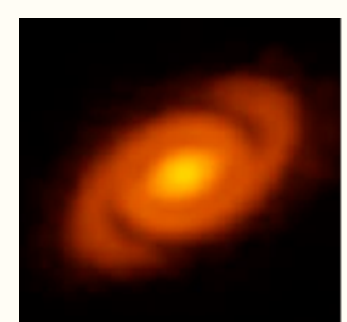
m=2



Garufi+ 2015



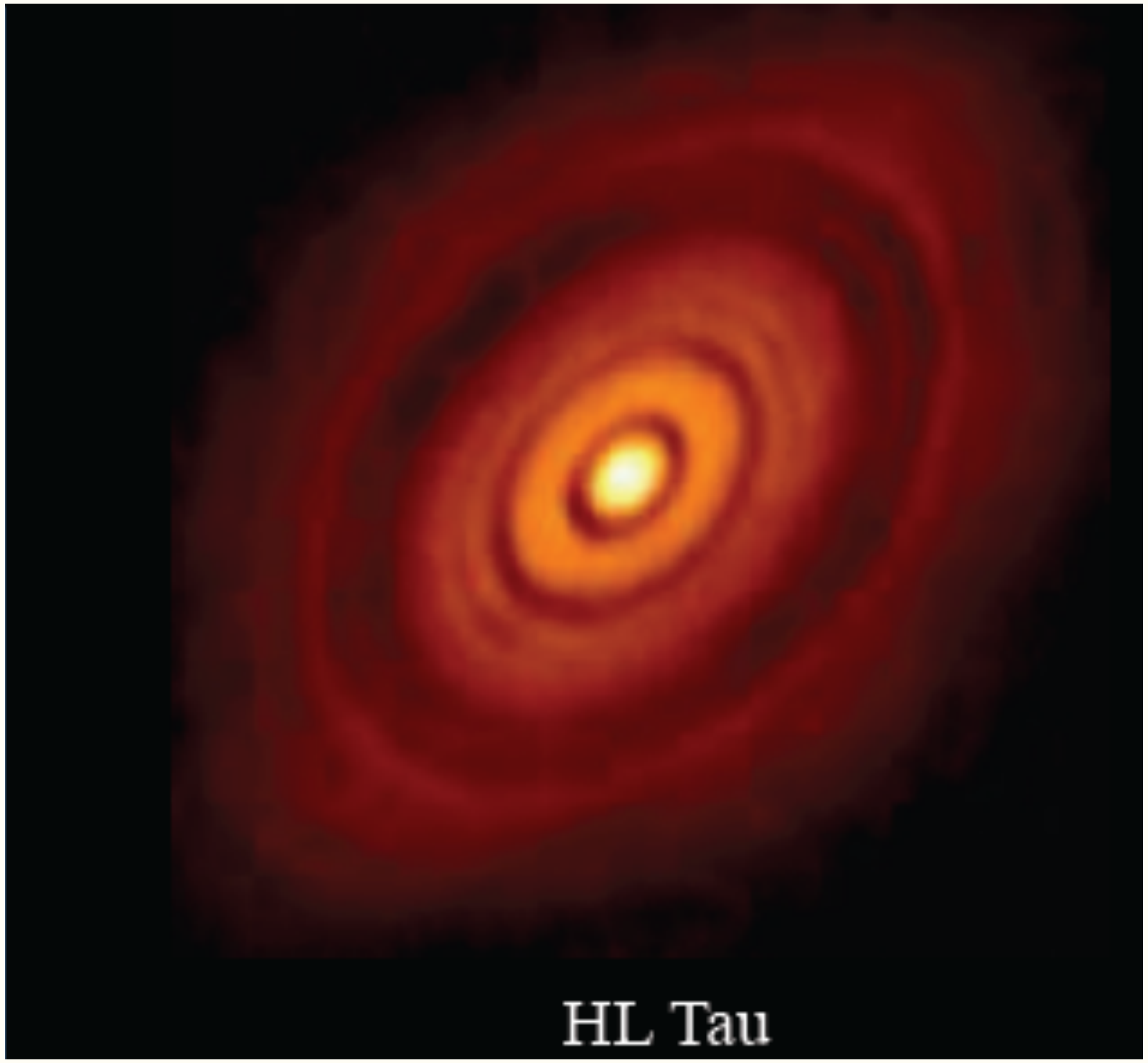
Benisty+ 2015



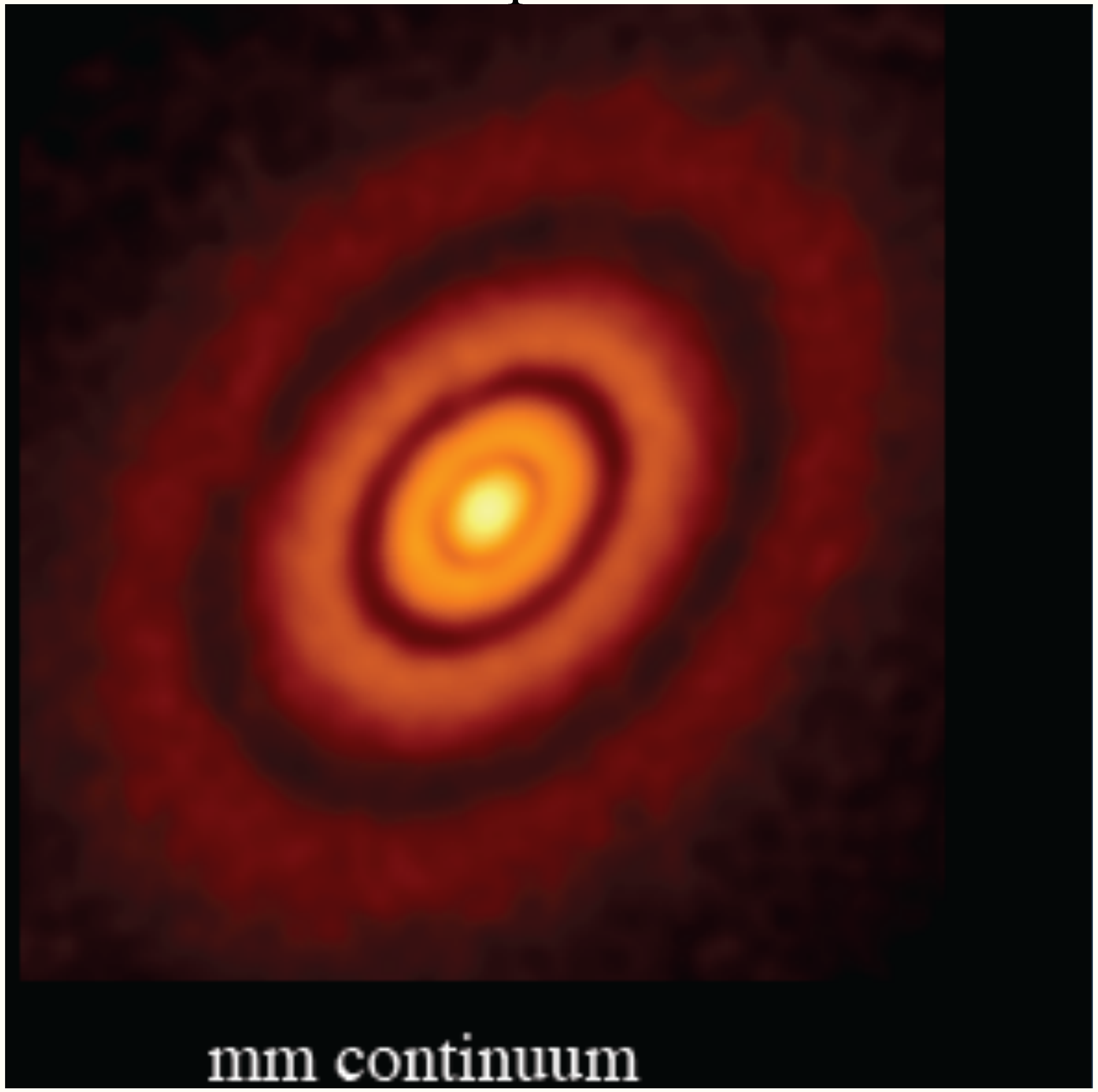
Pérez+ 2016

Dust: Rings

Observations



Simulations+MCRT:
3x0.2 M_J planets

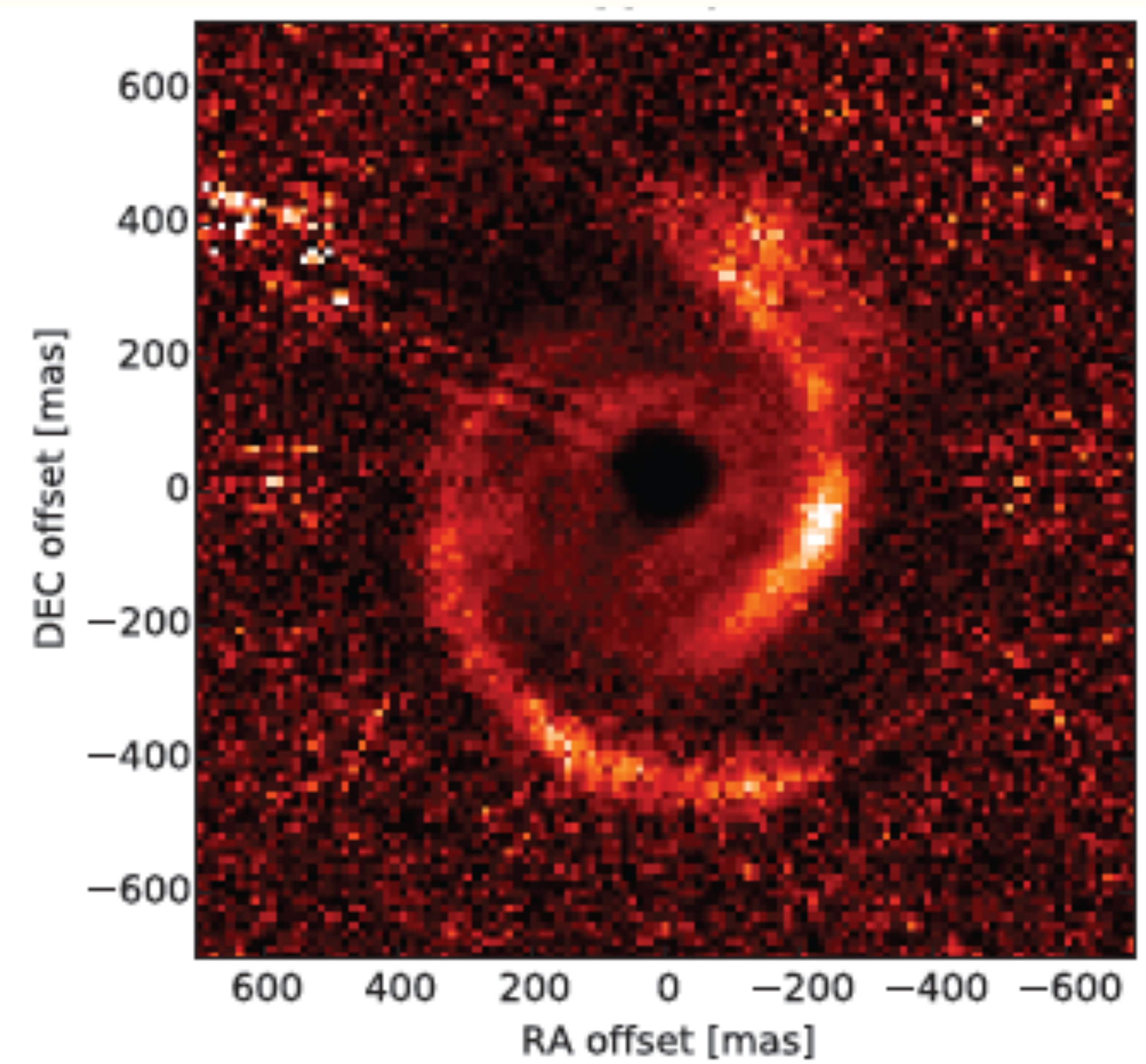


Dong, Zhu et al. 2015a, Dipierro et al. 2016

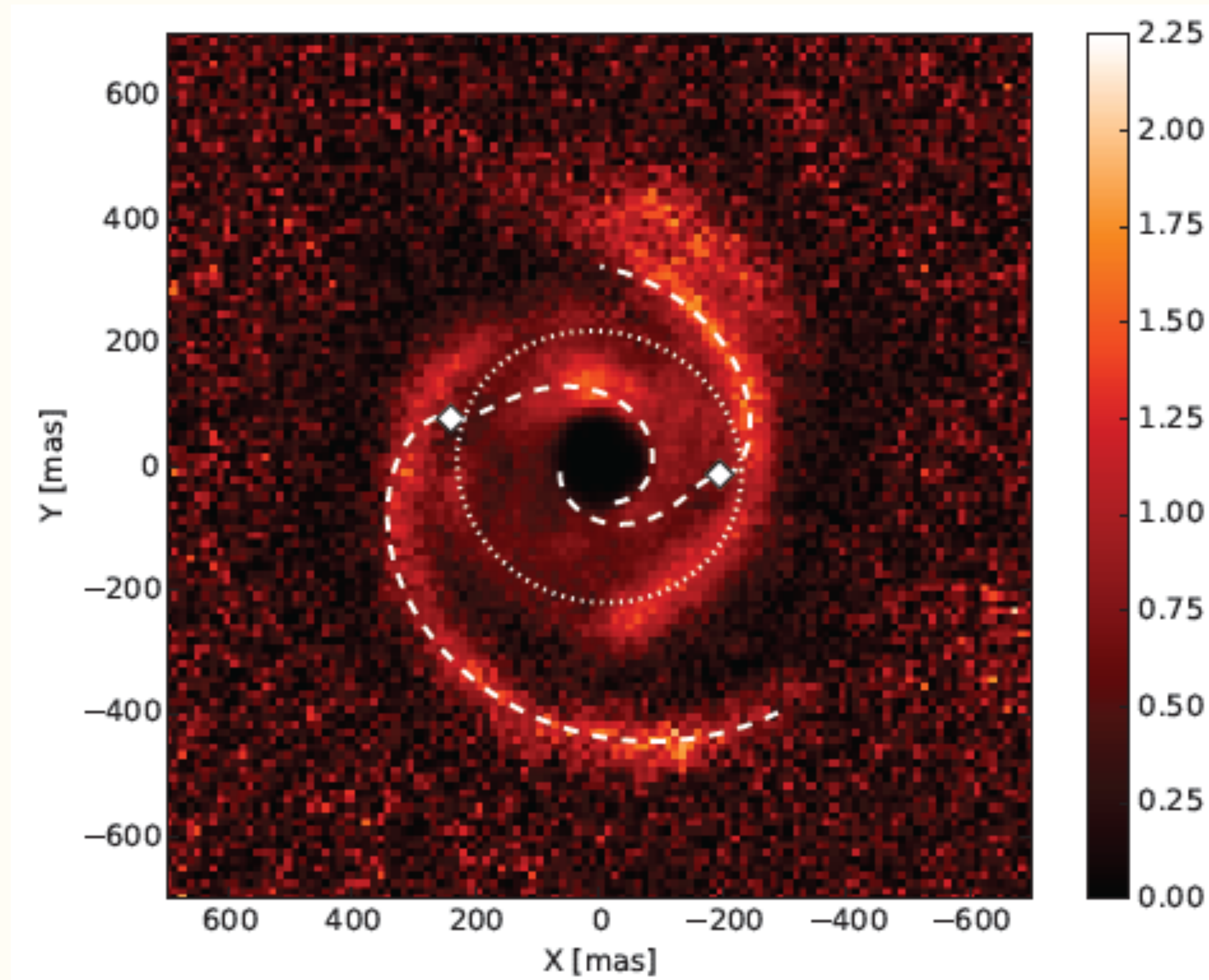
Dust: Spirals

Fitting the pitch angle suggests a too hot disk

MWC 758



At 50 AU, T~300 K

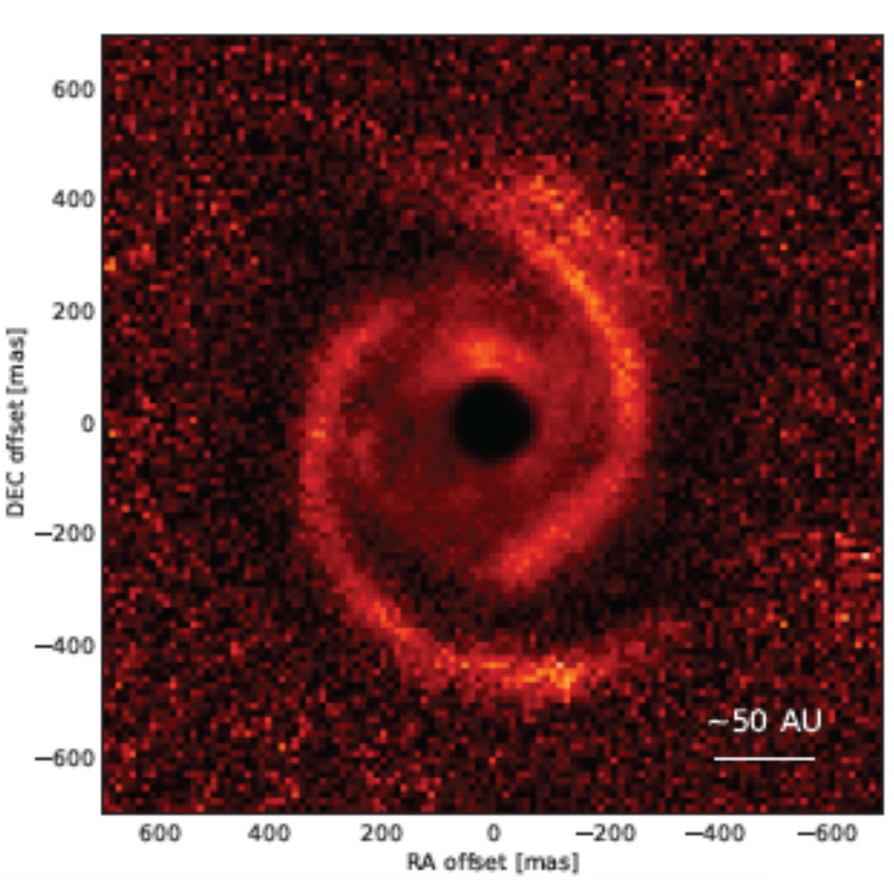


Benisty et al. 2015

Spirals: Grand design

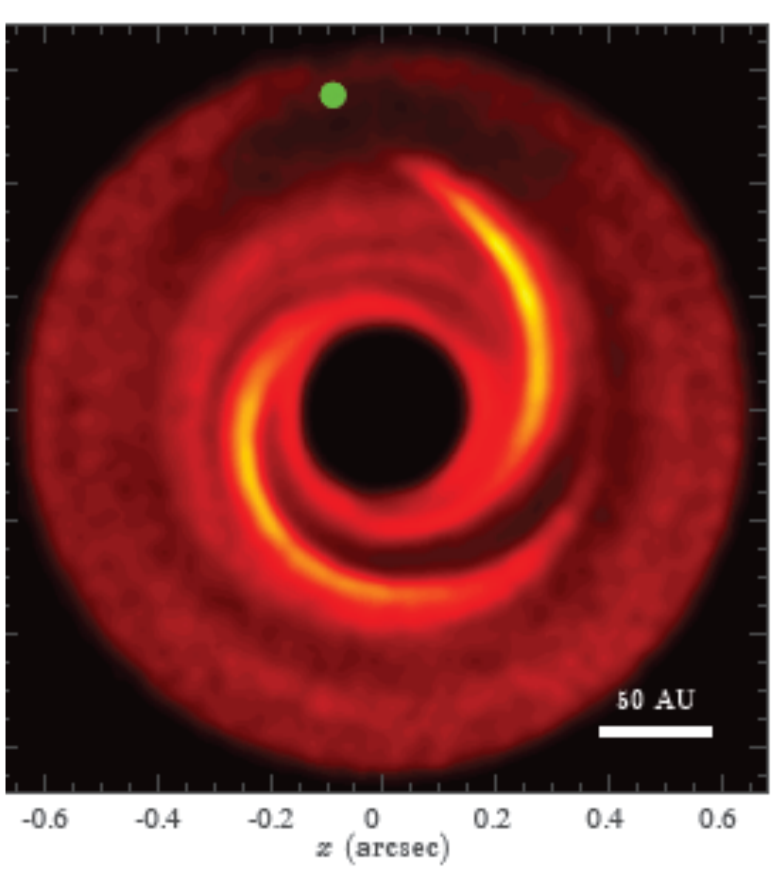
M51

Observation



Benisty et al. 2015

Simulation

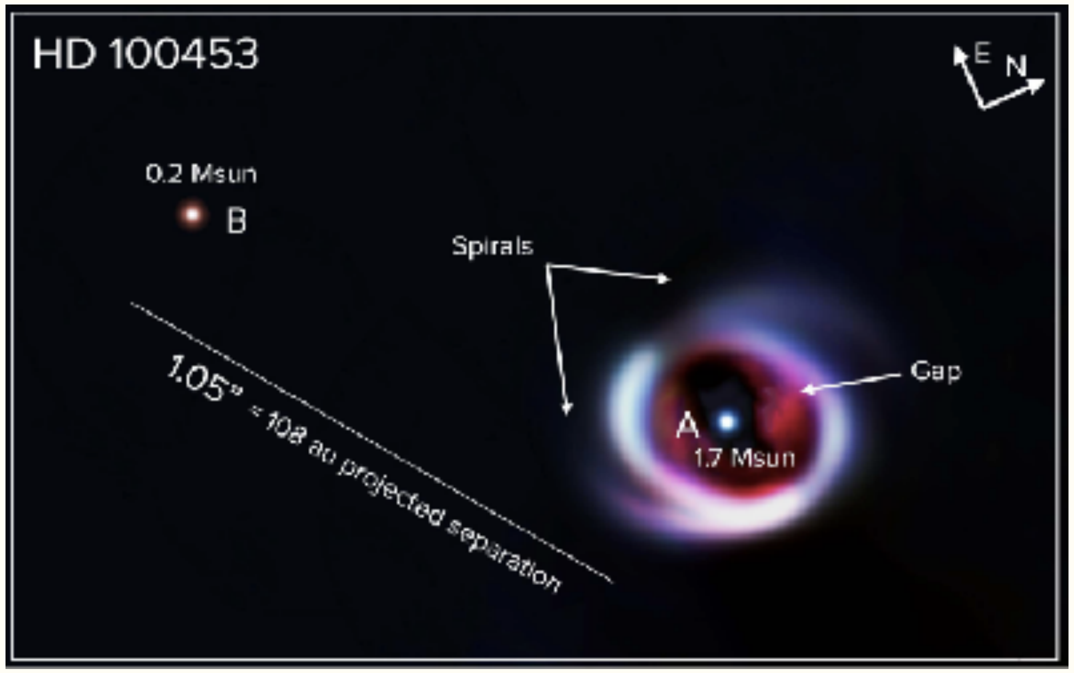


Dong, Zhu et al. 2015b
Zhu, Dong et al. 2015

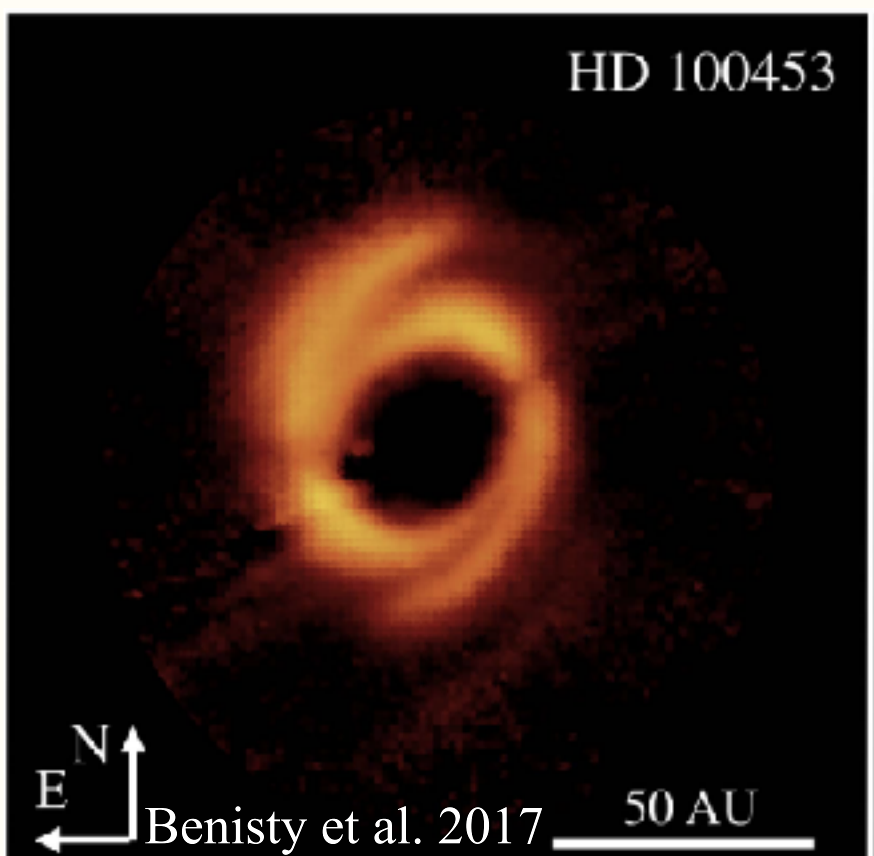
6 M_J planet

How to test the theory?

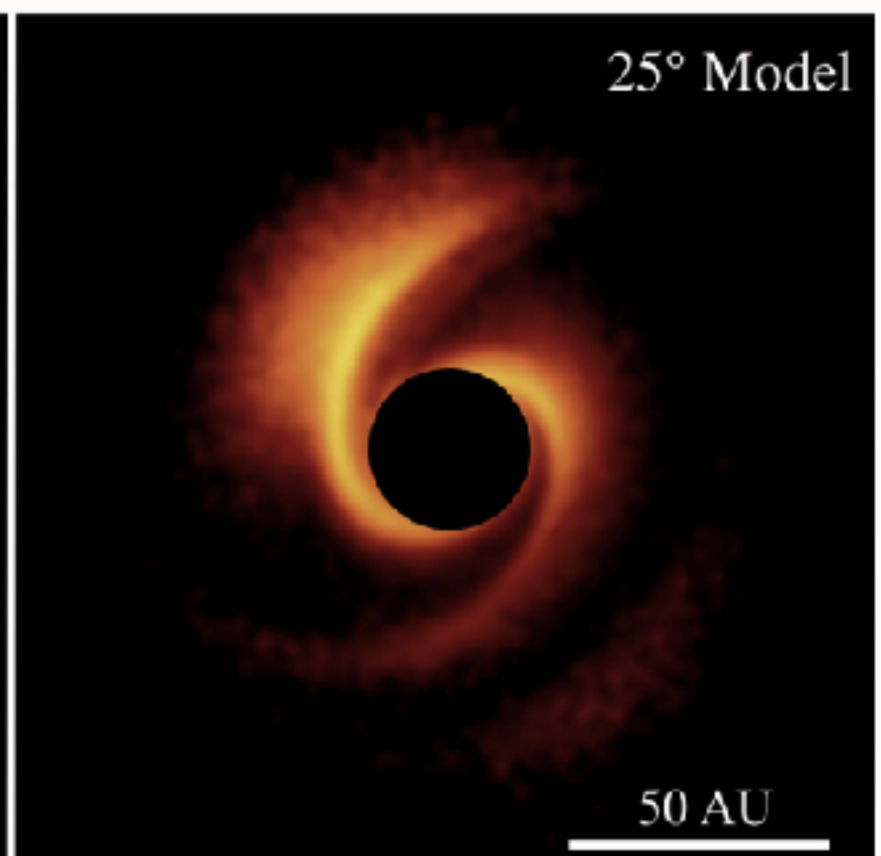
1. Use binaries as a test



Wagner et al. 2015



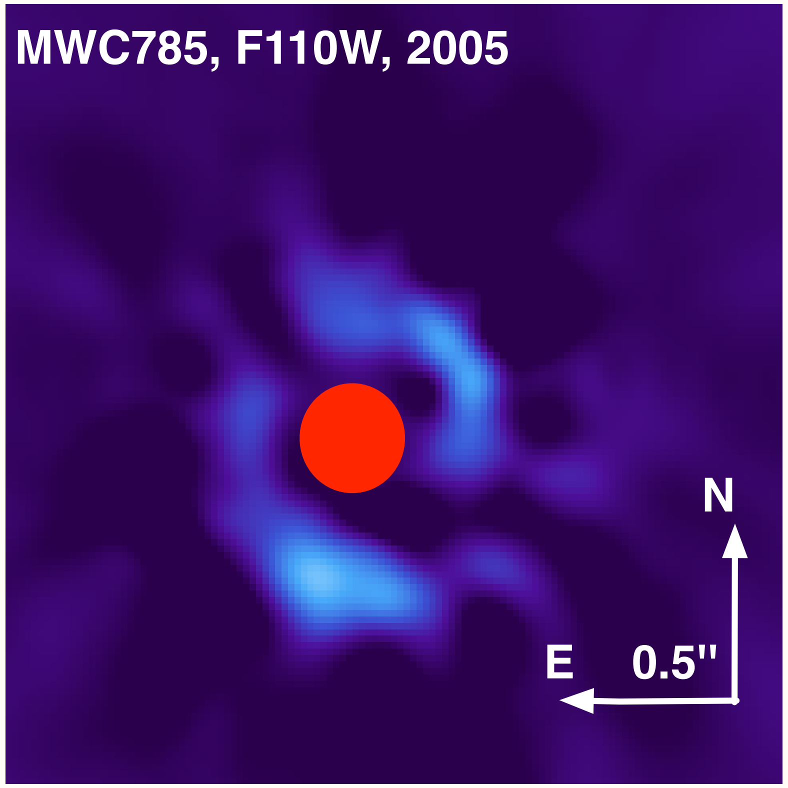
Benisty et al. 2017



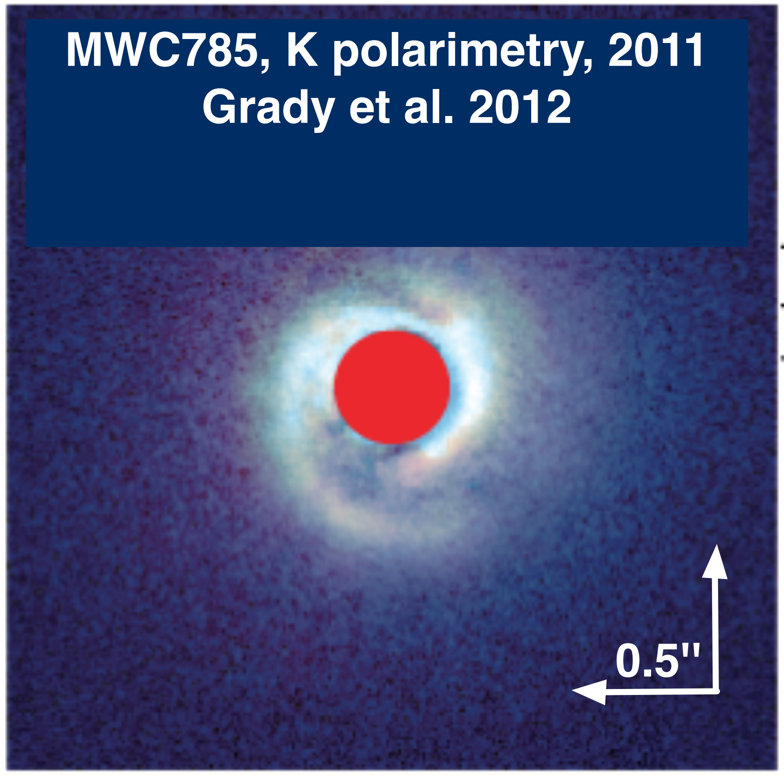
Wagner et al. 2018

How to test the theory?

2. Spiral Patterns over Time

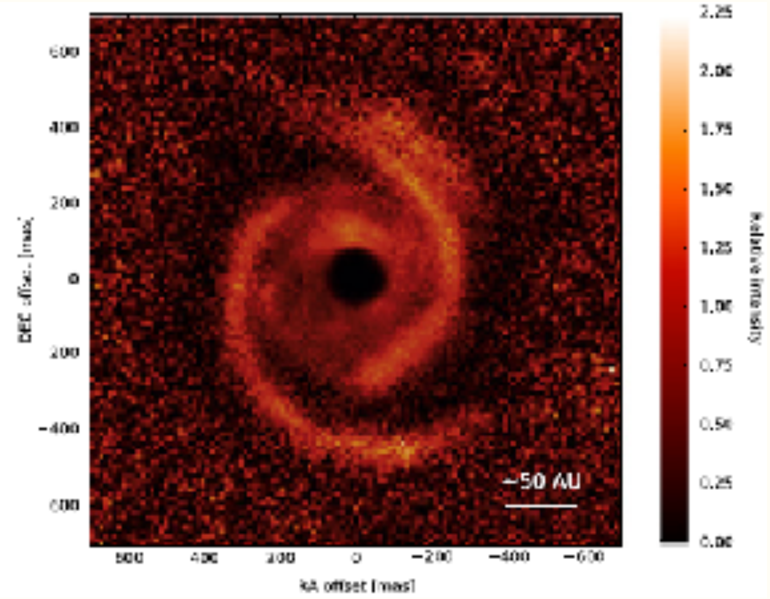


2005 Hubble observation

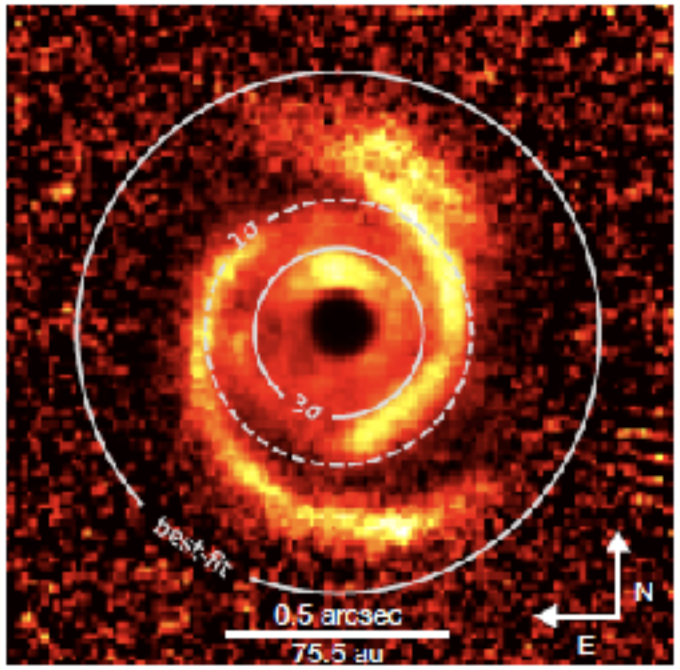


2012 Subaru observation
by Grady et al. 2012

MWC 758



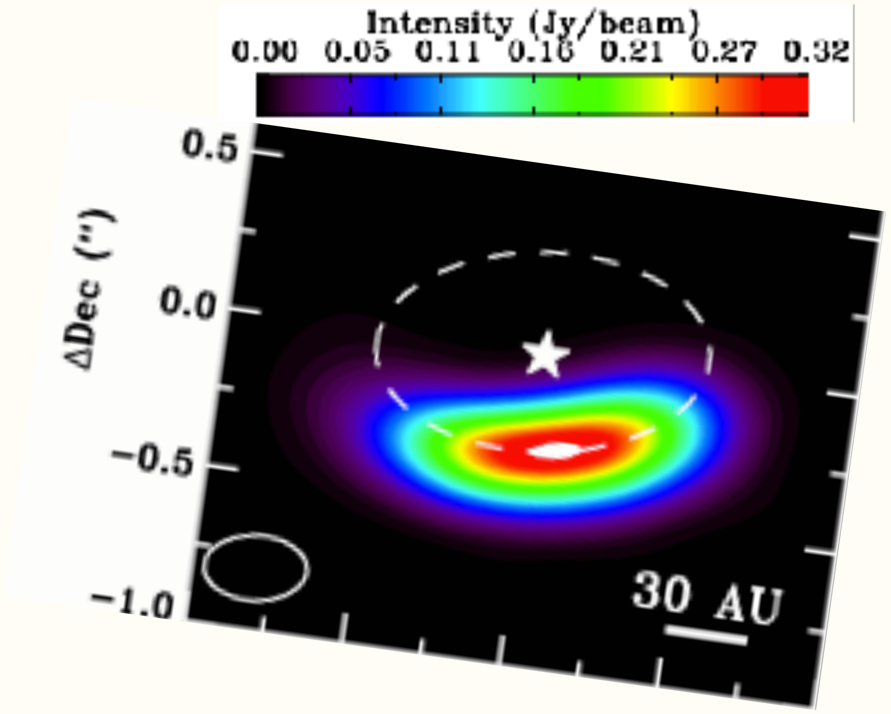
VLT Observations
by Benisty et al. 2015

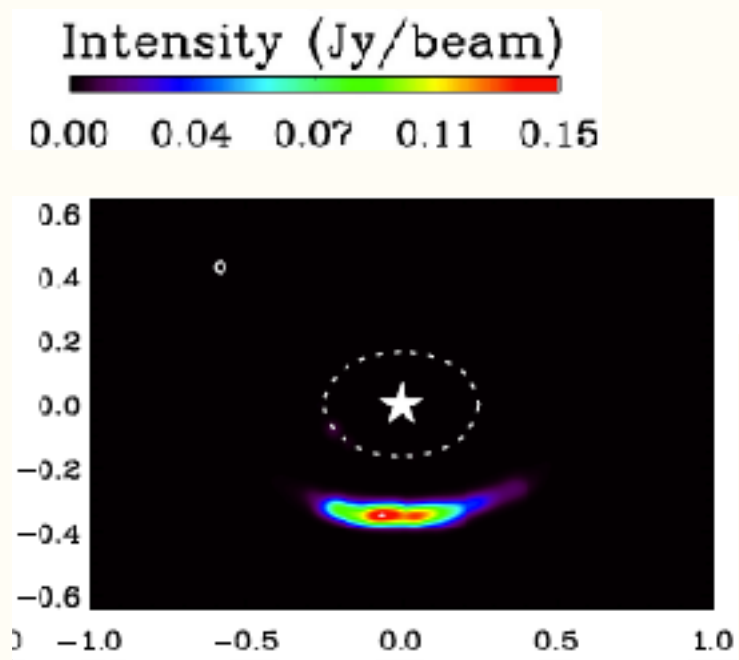


Ren + 2018

Planets at 30 AU, 10 years, rotates 30°
Planets at 150 AU, 10 years, rotates 2.7°

Dust: lopsided structure



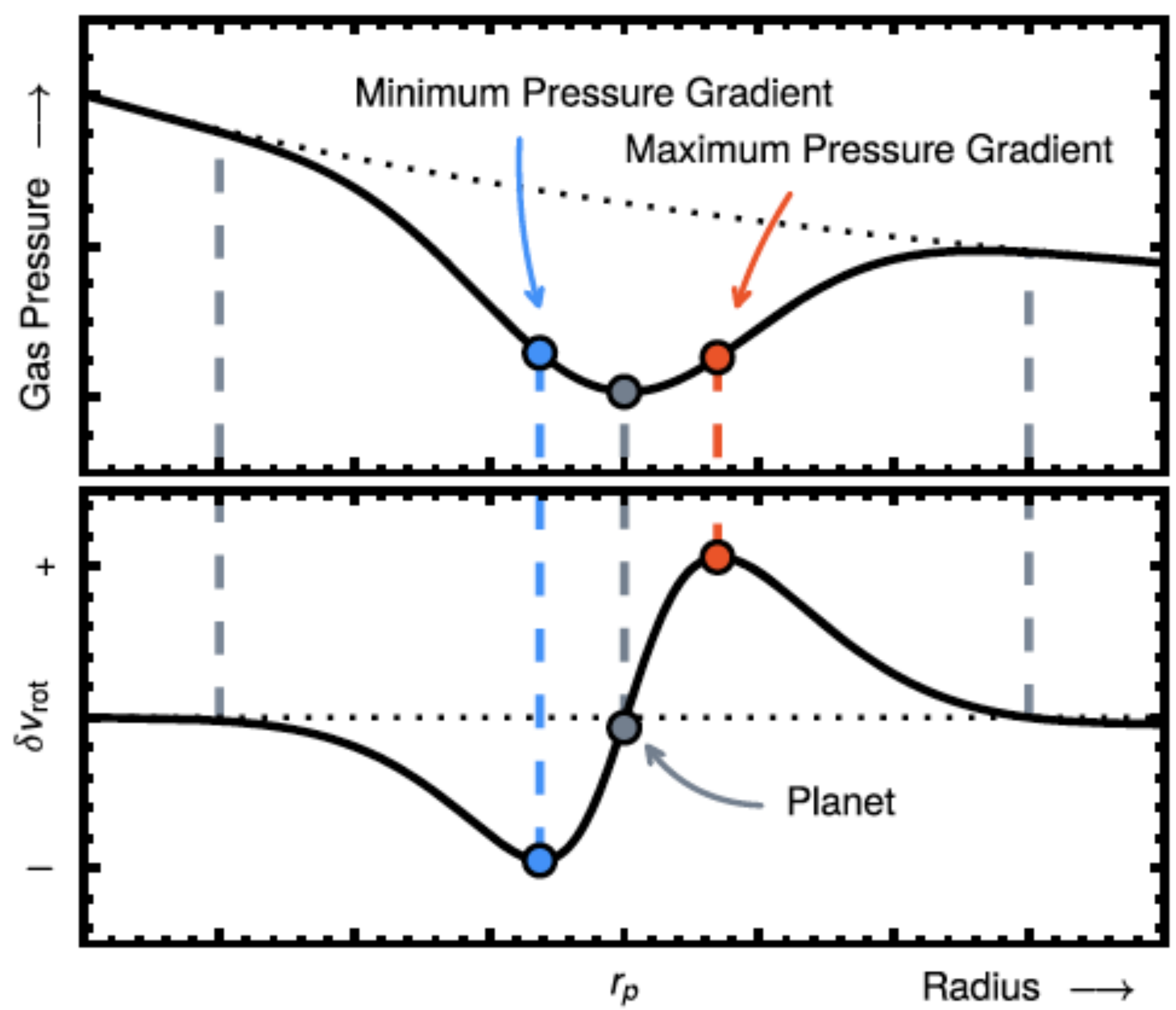


Cycle 3

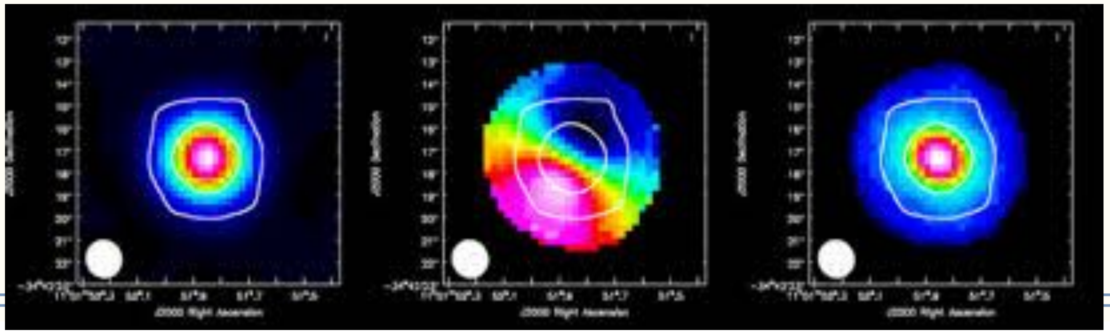
Zhu & Stone 2014

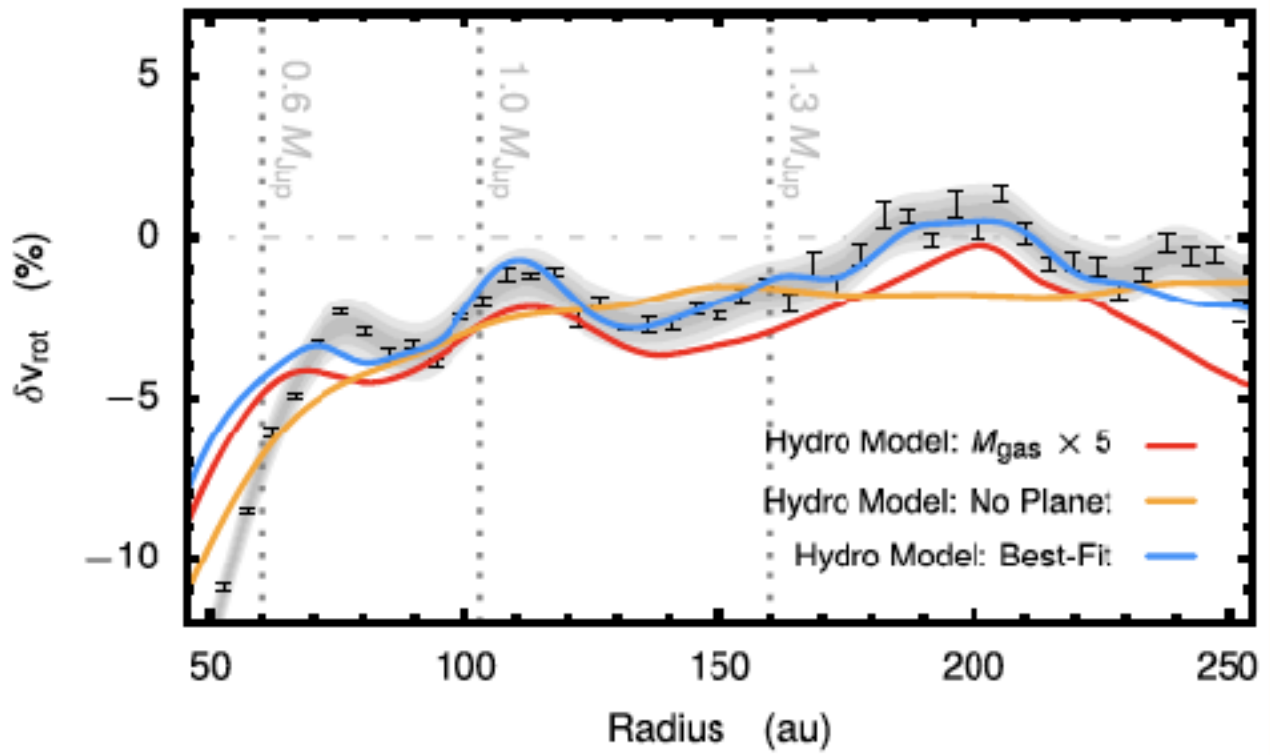
See also Lyra & Lin 2013, Barge et al. 2017

Gas dynamics: Rings

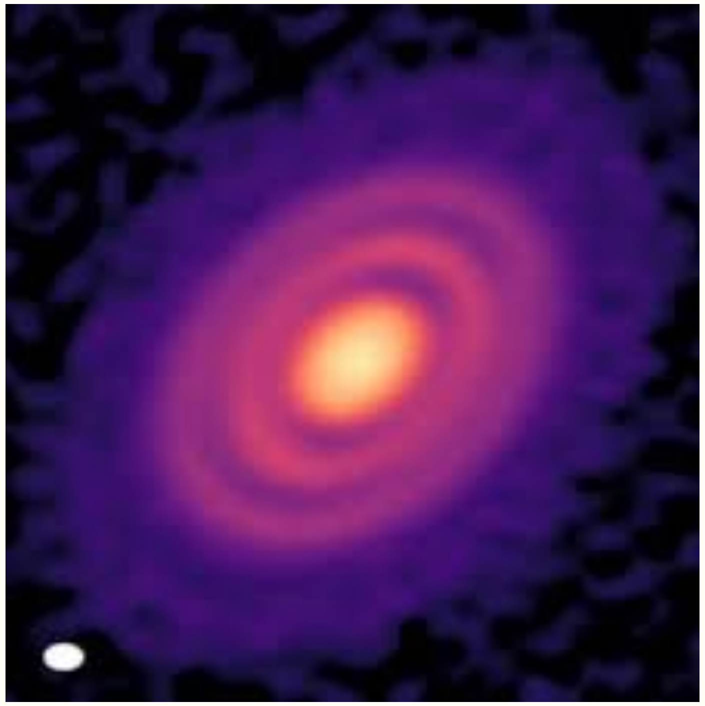


Teague et al. 2018

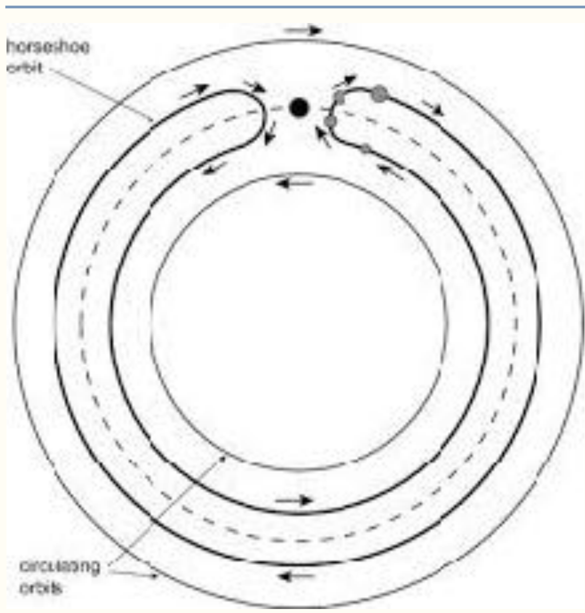


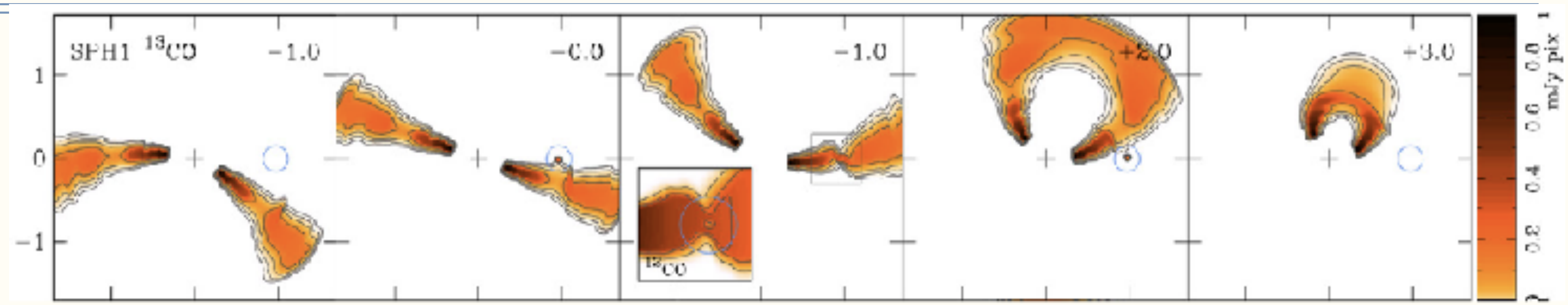


0.6, 1.0, 1.3 M_J



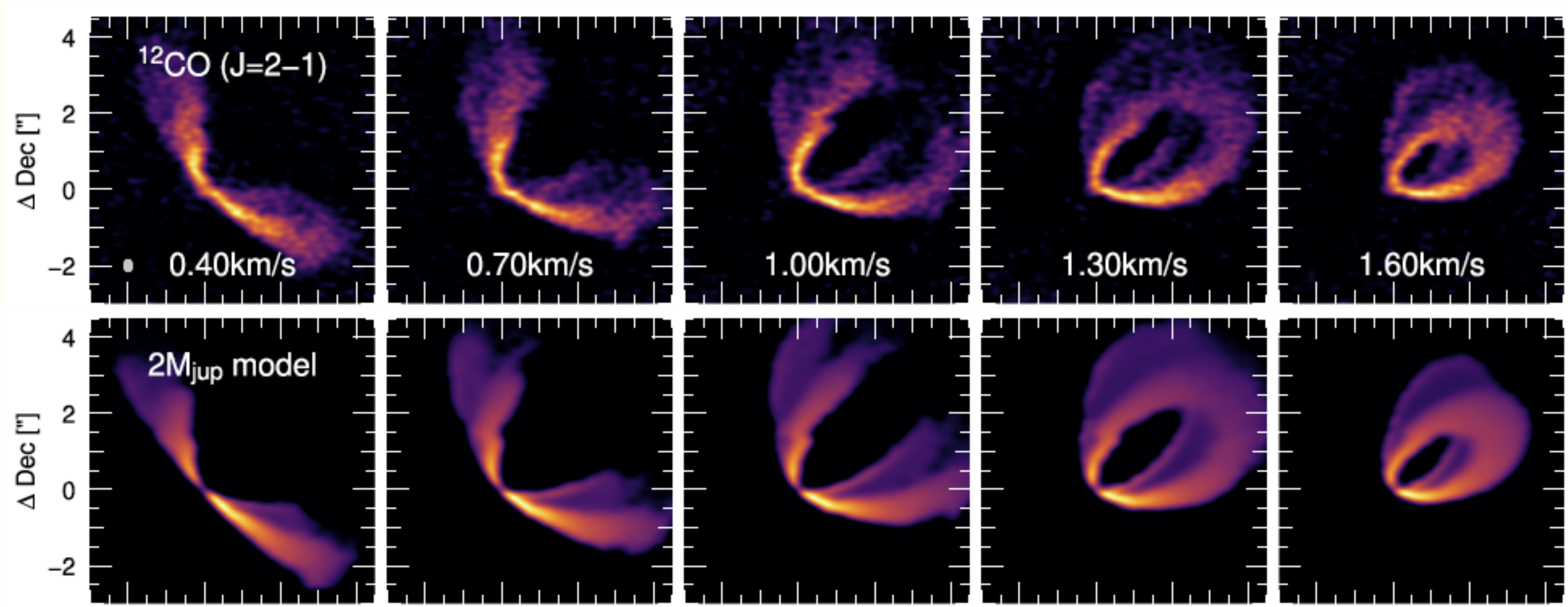
Gas kinematics: horseshoe around the planet





Perez et al. 2015

A 2 M_J planet at 260 AU



Pinte et al. 2018

Summary

- Planet statistics is being nailed down

- Compare protoplanetary disks with exoplanets

  Mass budget problem

  More comparisons to be made

- Look for young planets

  Direct Methods:

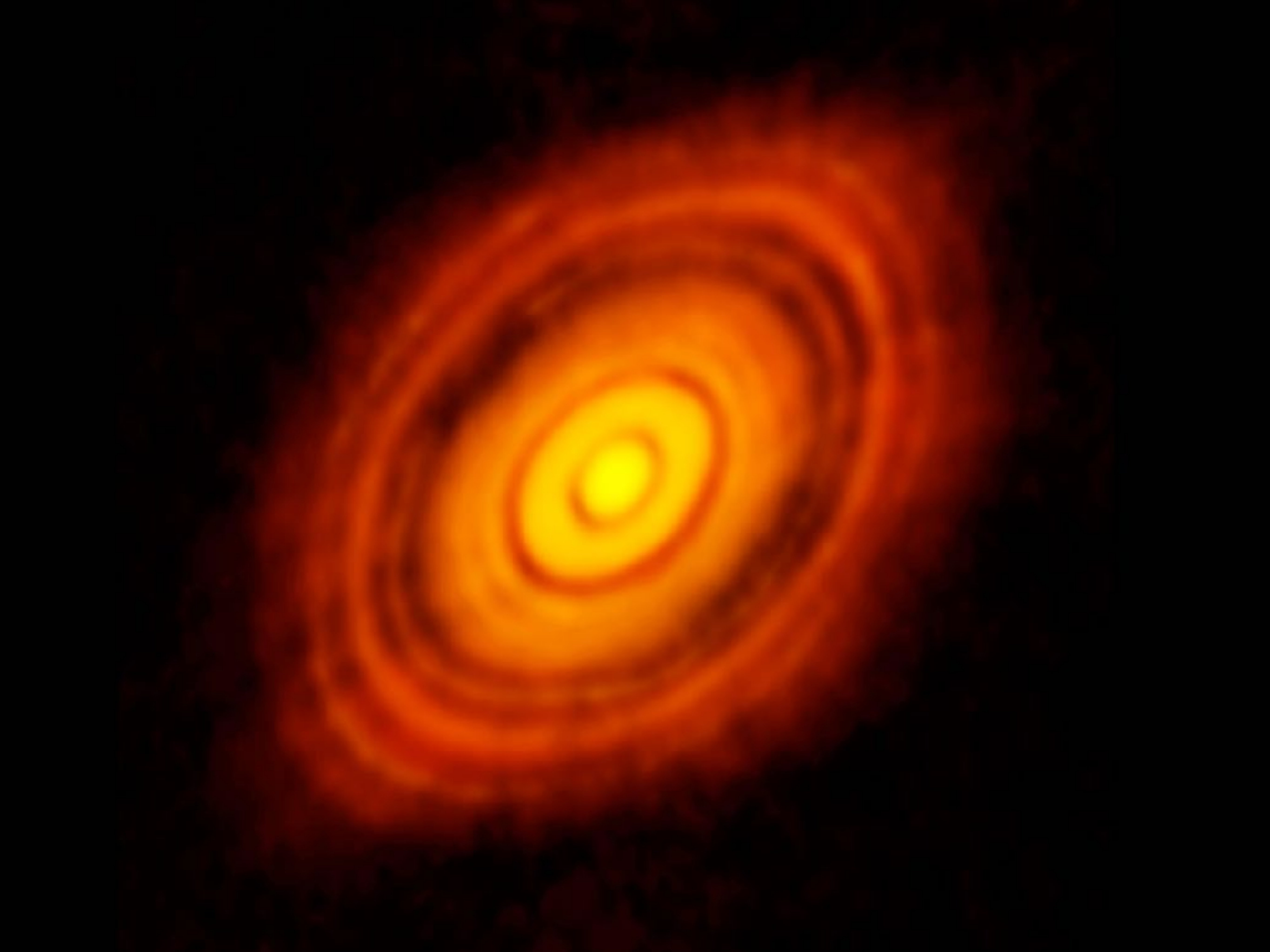
  Indirect Methods:

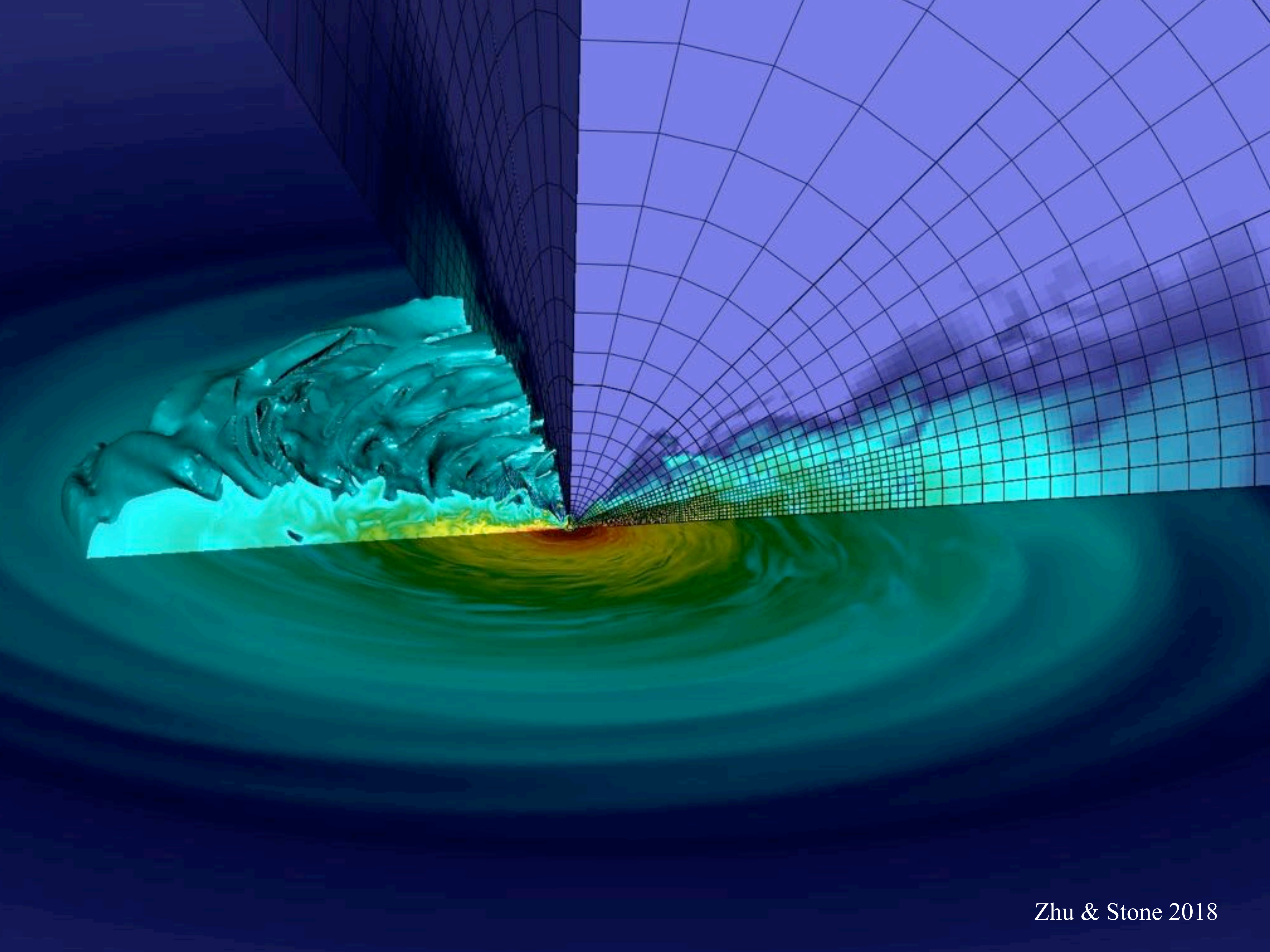
    Dust features: Gaps, Spirals, Blobs

    Gas kinematics

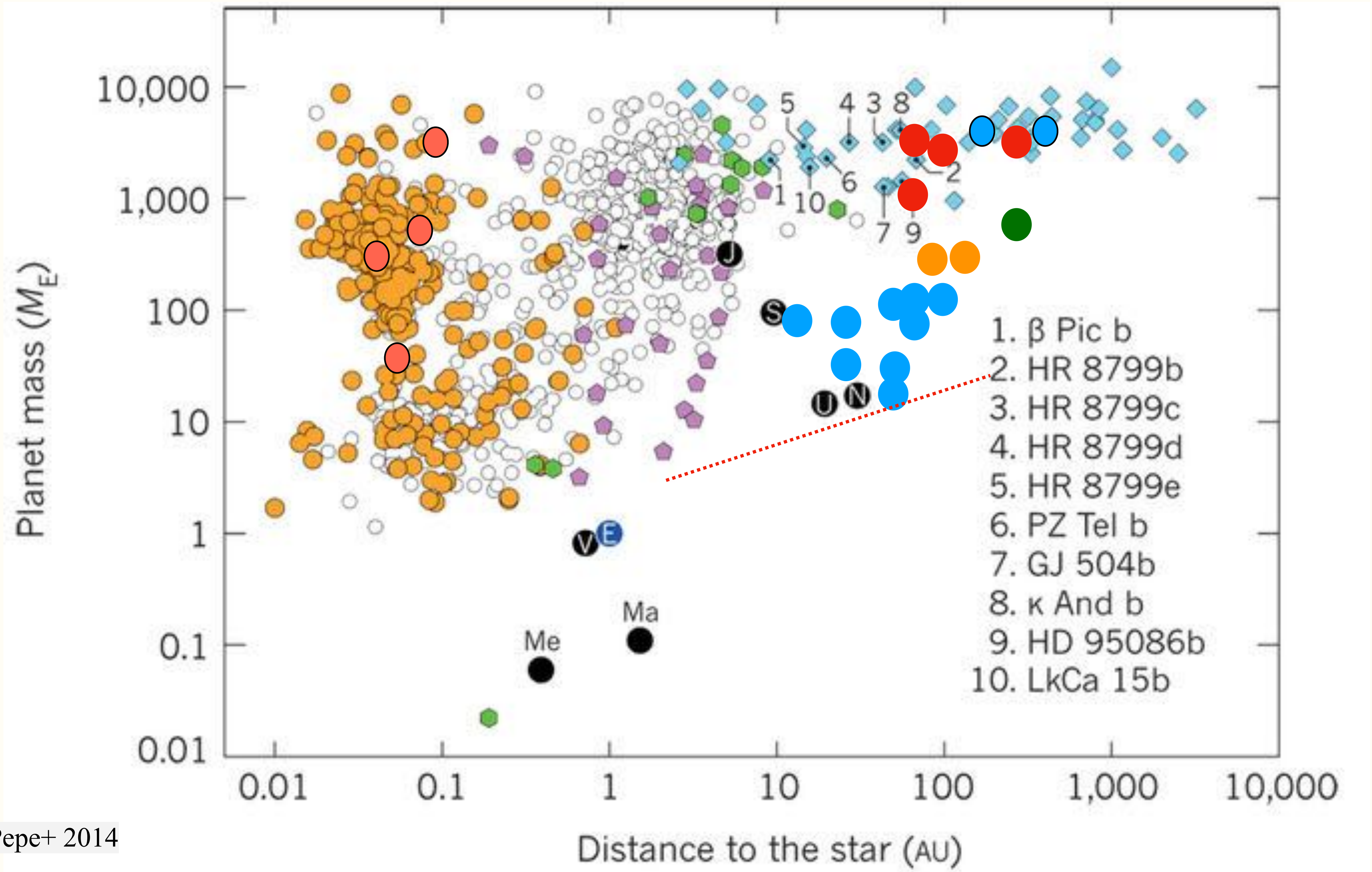
  Are we sure that disk features are due to planets?

  How to break the degeneracy?



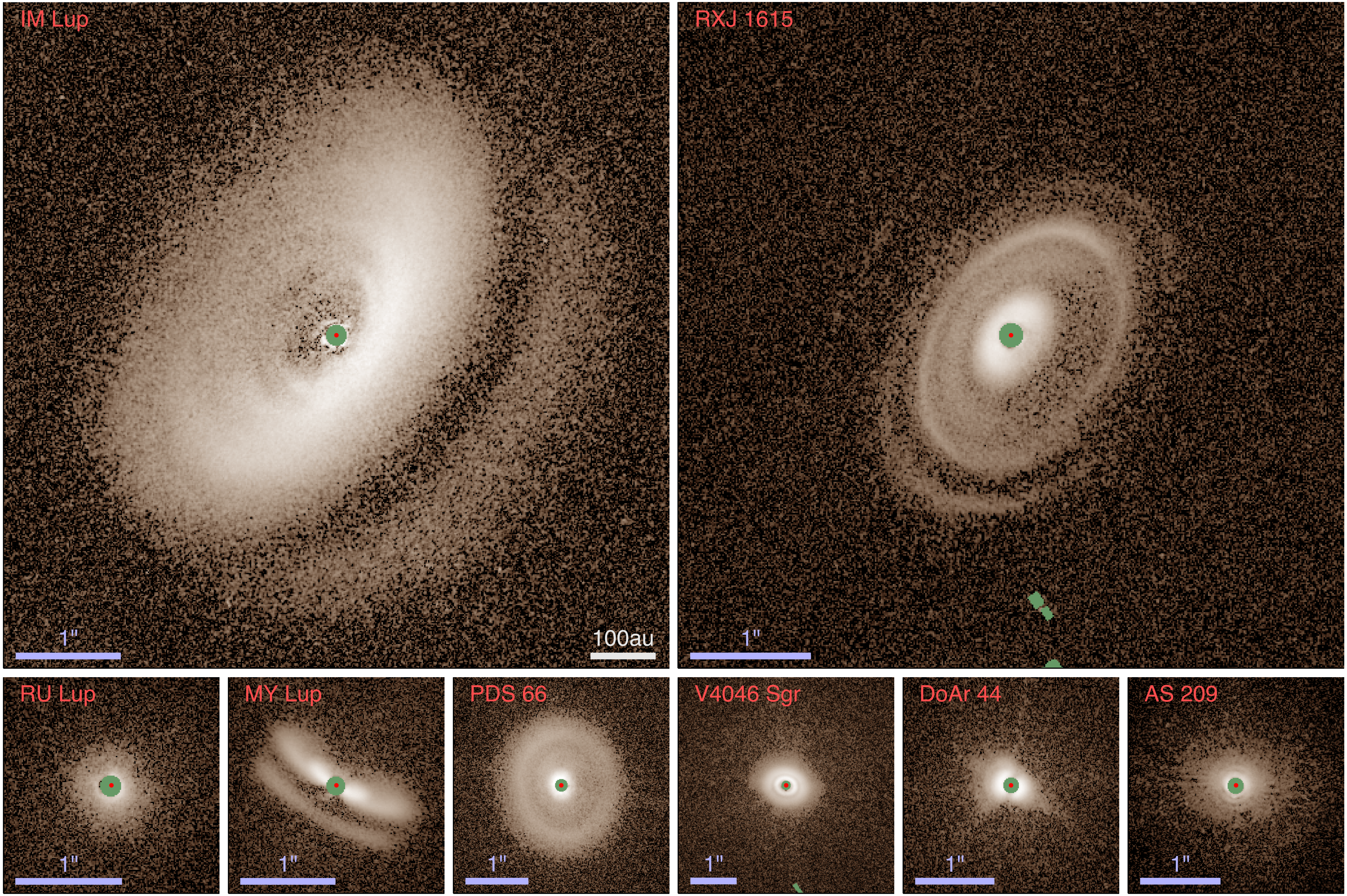


Zhu & Stone 2018



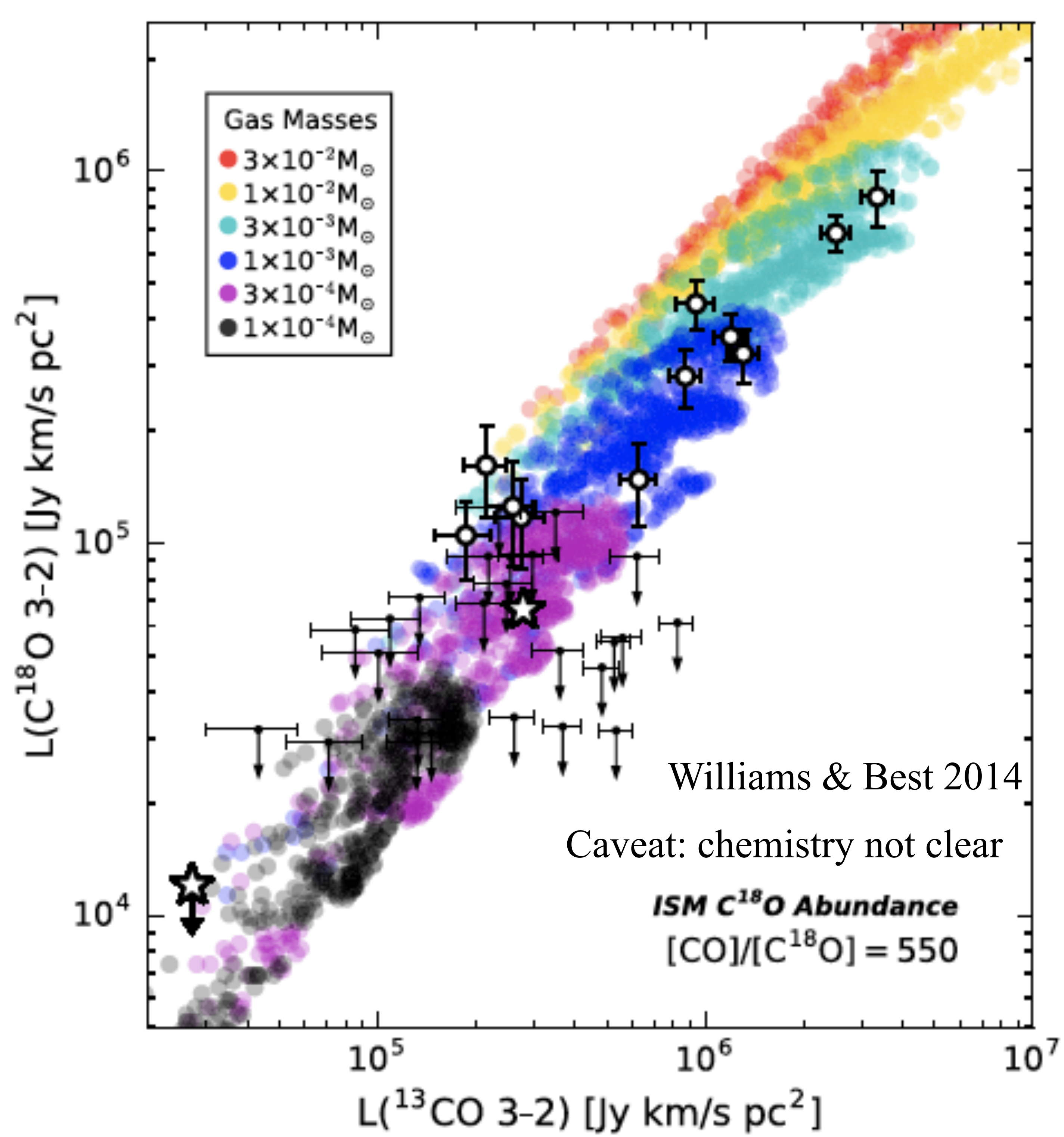
Pepe+ 2014

Dong+ 2015, Bae+ 2016, Isella+ 2016 Meru+ 2017, Dipierro+ 2018, Fedele+ 2018, Teague+ 2018, Pinte+ 2018



Avenhaus et al. 2018

Using CO to estimate the gas mass



Williams & Best 2014

Caveat: chemistry not clear

Ansdell et al. 2016

Most disks have mass less than M_J

There appears to be a mass budget problem:

Najita & Kenyon 2014

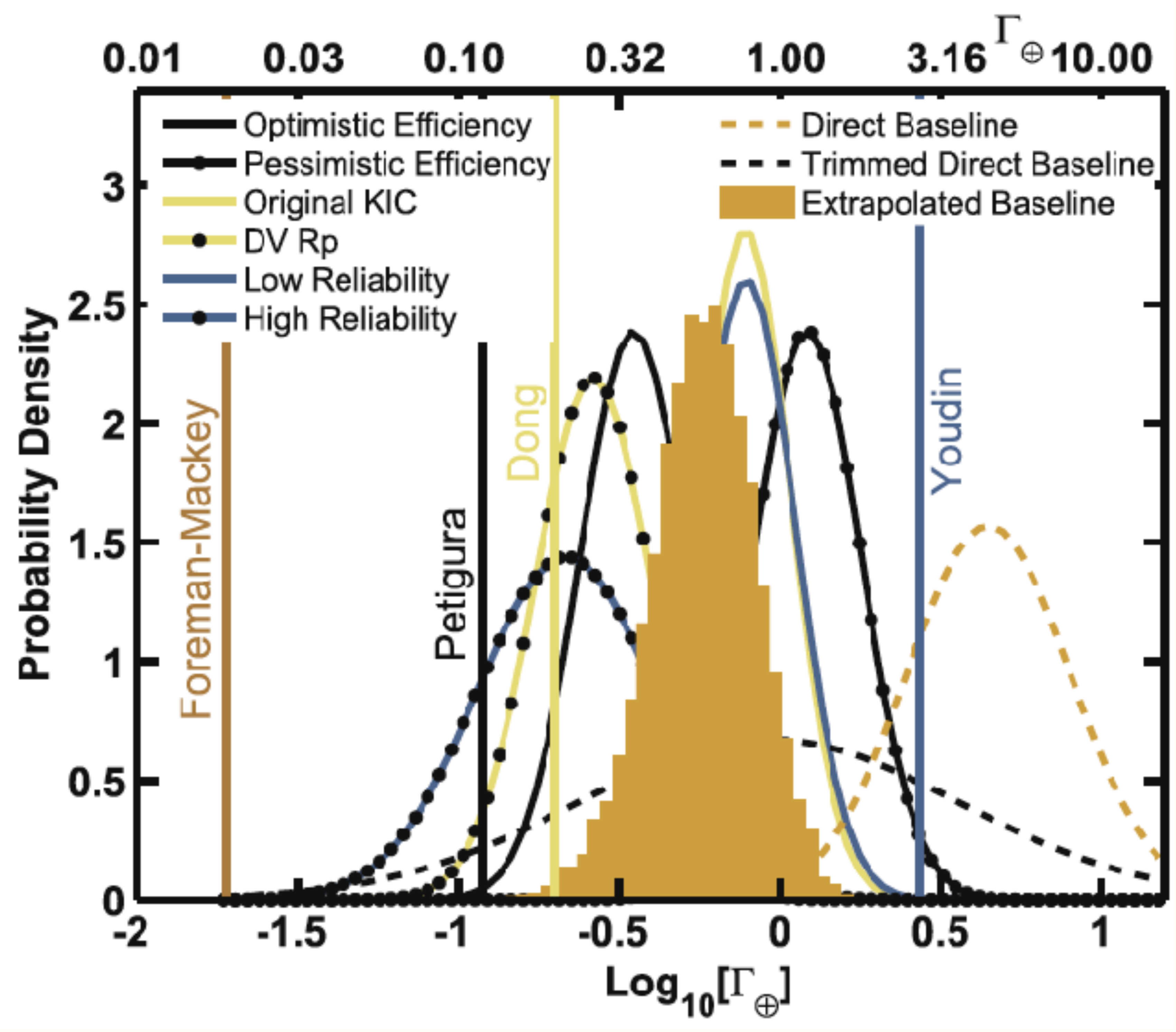
The mean solid mass in Kepler planets ~ 10 earth mass within 1 AU

Dong & Zhu 2013, Chiang & Laughlin 2013

10% FGK star have Jupiter or super-Jupiter

Earth analog fraction, $\eta_\oplus$

Extrapolated!!!! 1-2 $R_\oplus$, 300-700 days



Burke et al. 2015