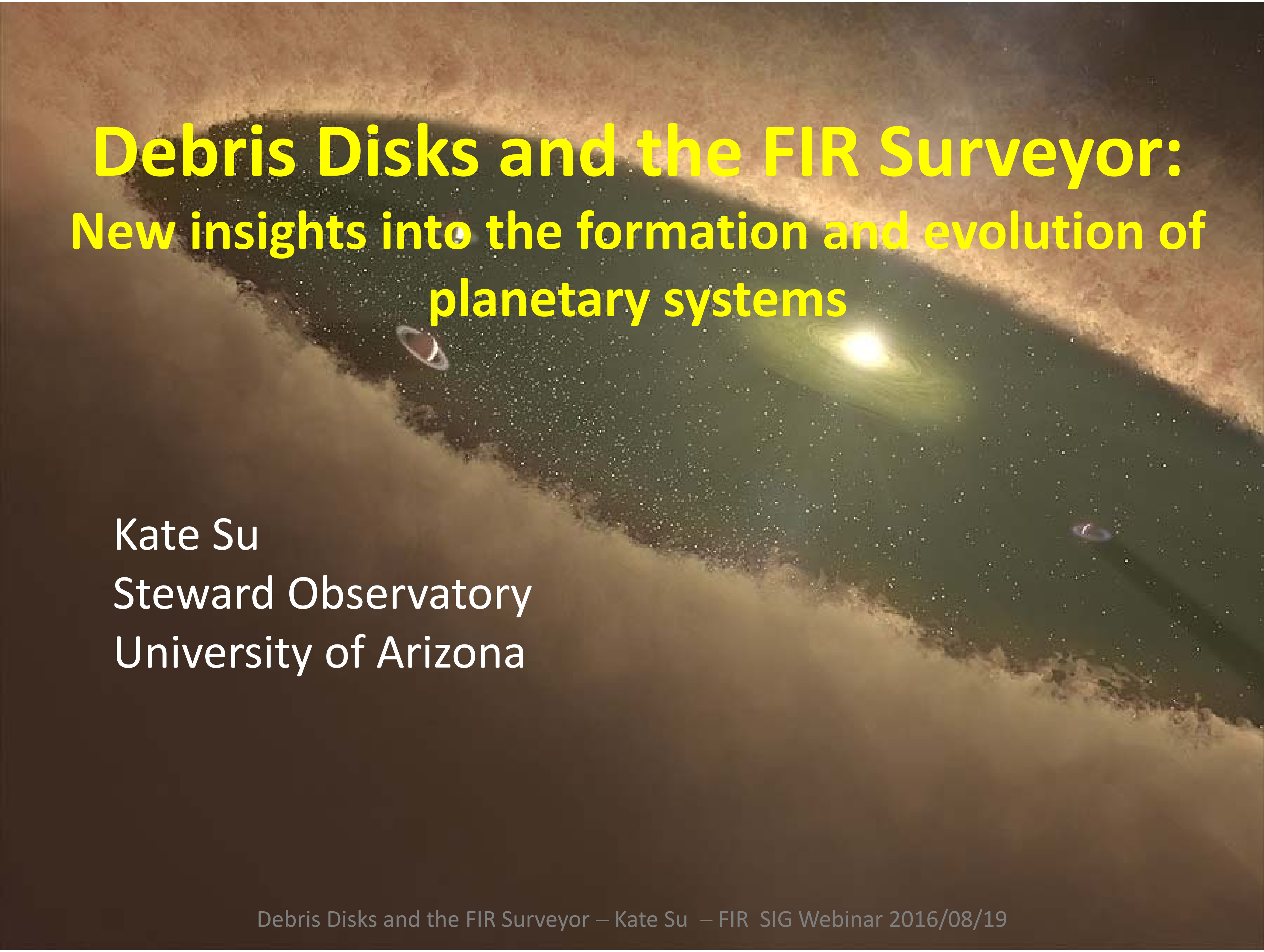


Debris Disks and the FIR Surveyor:

New insights into the formation and evolution of planetary systems

Kate Su
Steward Observatory
University of Arizona

Outline

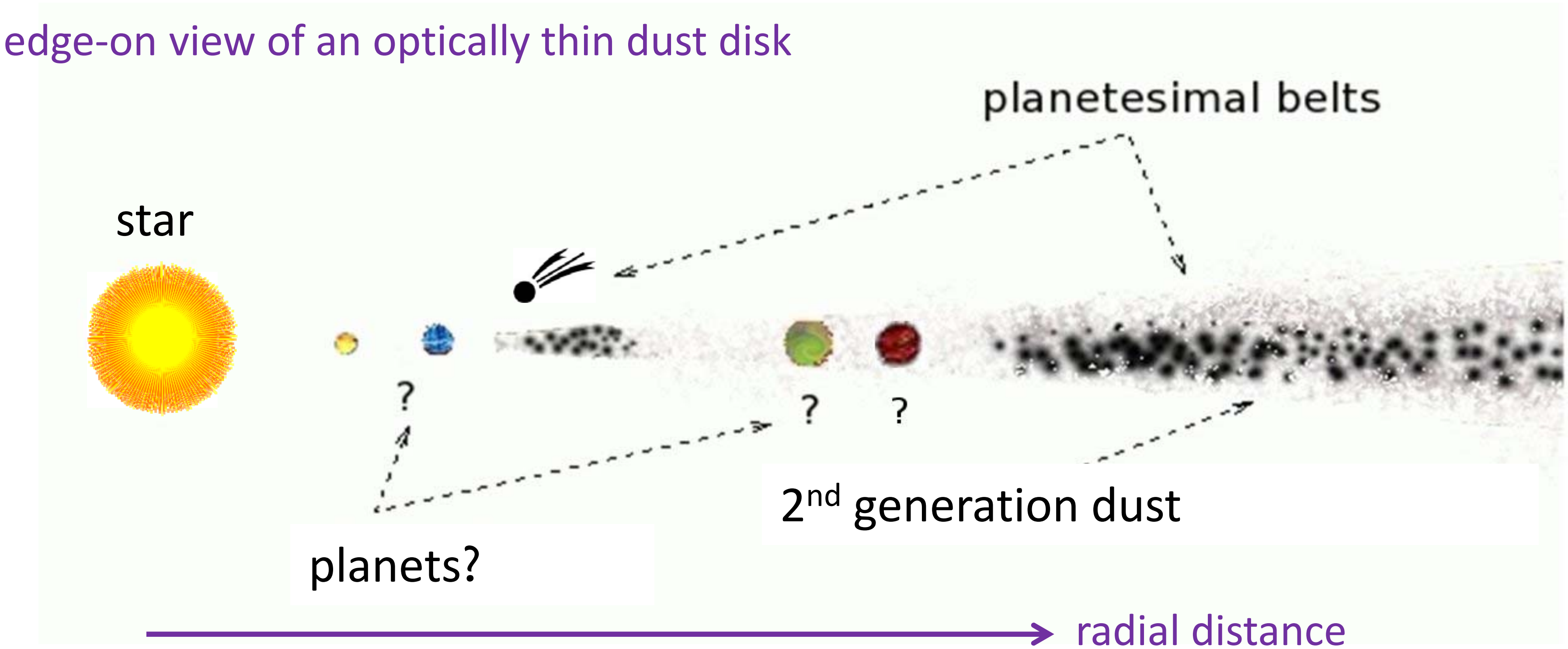
- What are debris disks and why study them?

  They are our best tools to study the full duration

  of planetary system evolution

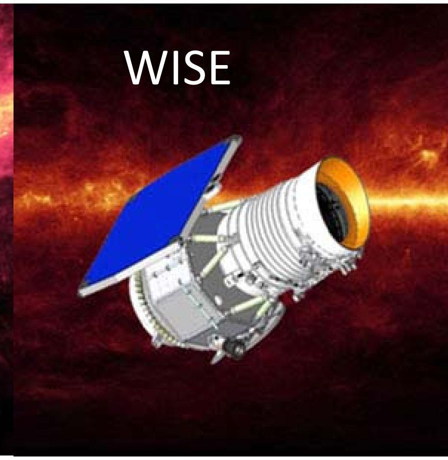
  - Good tracers of planet formation
- Planet-Disk Interaction – how to use disk structures to infer the properties of unseen planet(s)
- Potentials for the FIR Surveyor
- Summary of Debris Disk Science Theme

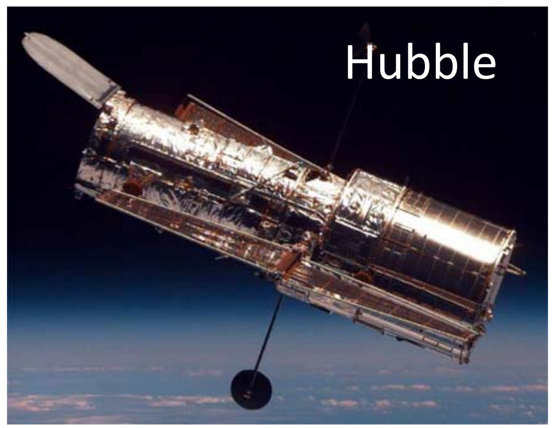
Definition of Debris Disks



- very little gas, mainly km-size solid material
- dust replenished by collisions or cometary activity
- forces/processes in play include: collisions, radiation blow out, drag forces (P-R drag, stellar wind drag…)

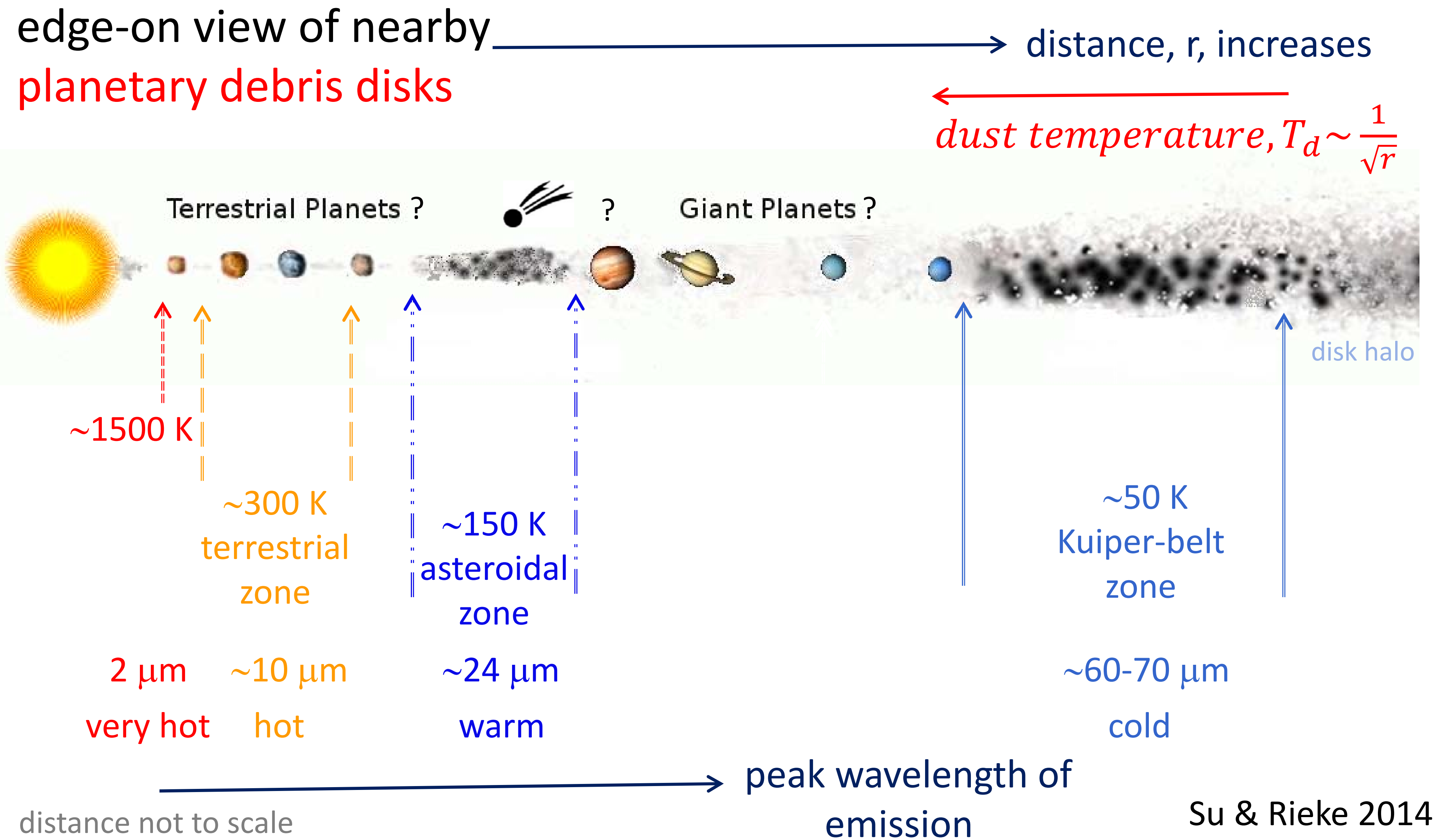
Great Facilities to Study Planetary Debris Disks





- More than ~400 debris disks known within ~100 pc.
- Most disks are unresolved (only a few dozens are resolved), and only broad-band Spectral Energy Distributions (SEDs) are available to determine the disk properties.

Dust Zones Revealed by Existing Observations



Su & Rieke 2014

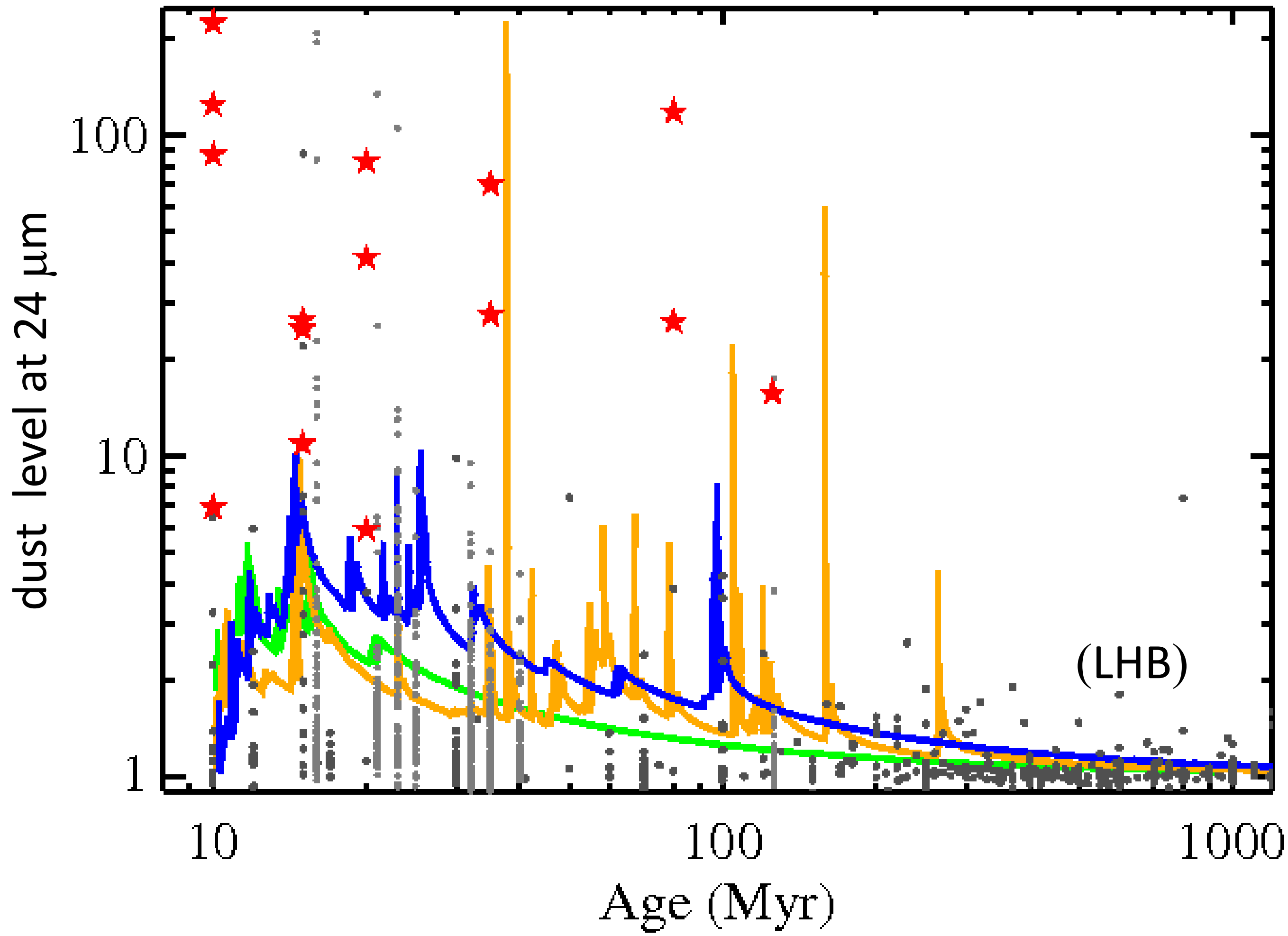
Debris Disks: Tracers of Planet Formation

Debris Disks trace a pattern of development similar to the Solar Systems:

1. A peak in inner debris disks activity at 10-20 Myr, when terrestrial planets are being built

2. Period of Late Heavy Bombardment (LHB)

3. Occasional major collisions such as the formation of our Moon and Pluto-Charon system

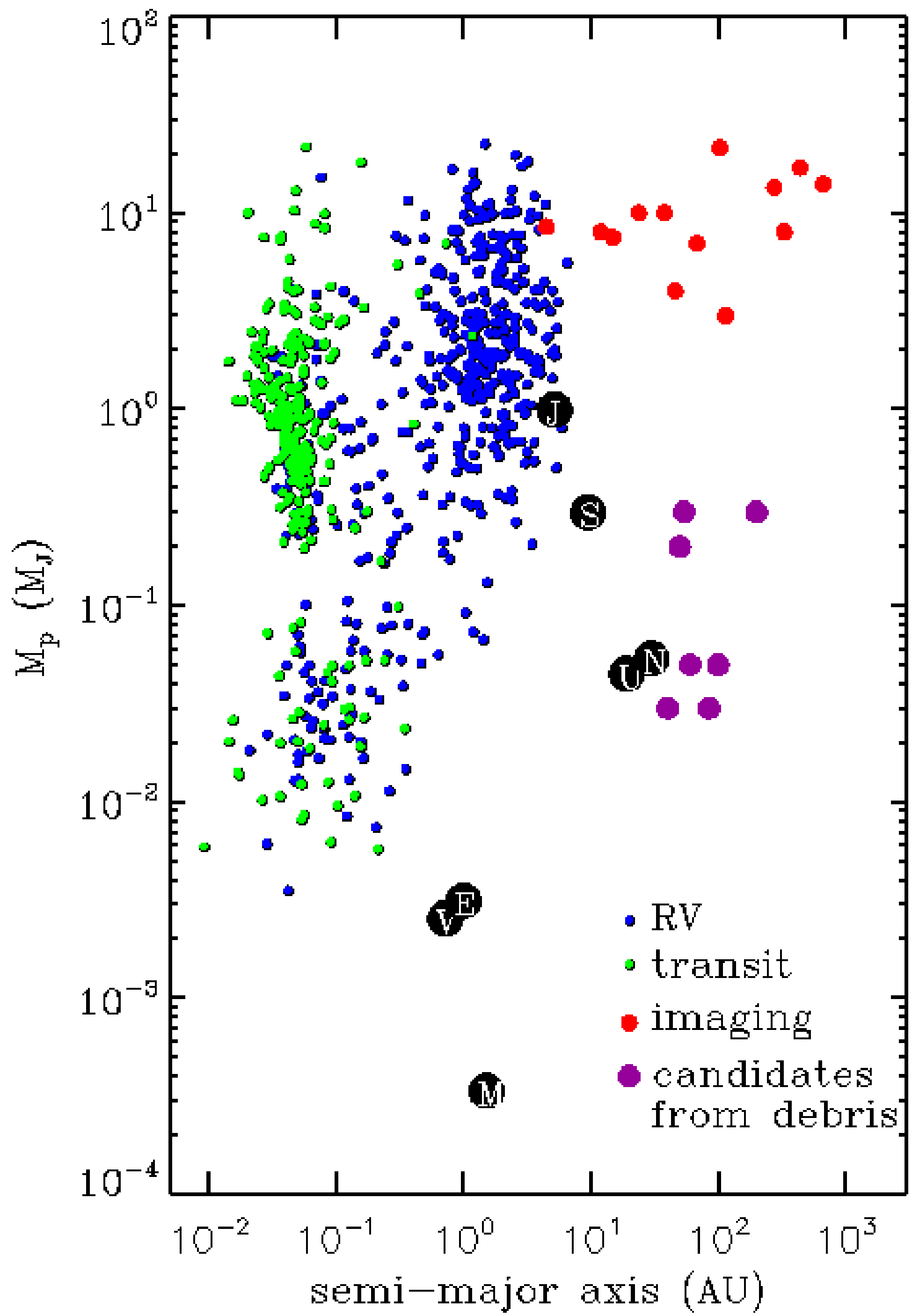


symbols: debris systems around stars in the field and clusters
lines: terrestrial planet formation models by Genda+2015

Signpost of Exoplanets

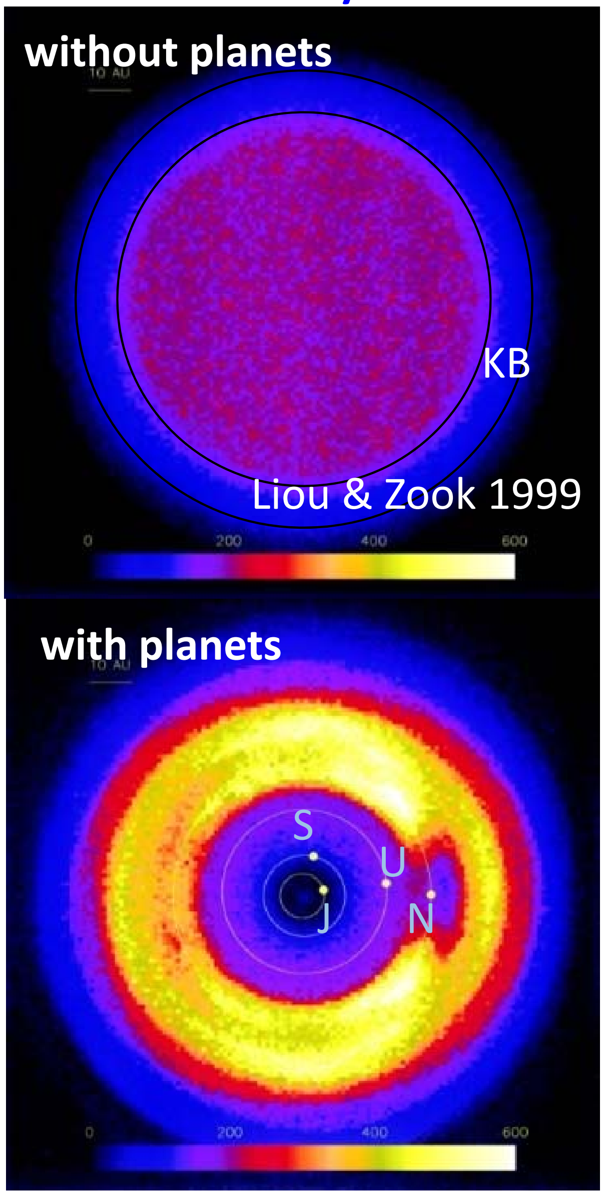
Current search methods are strongly biased.

Look for solar analogs that have giant planet at large radial distance. The existence of habitable terrestrial planets relies on gas giants remaining at large orbital radii.



Planet-Disk Interaction - structures created by planet(s)

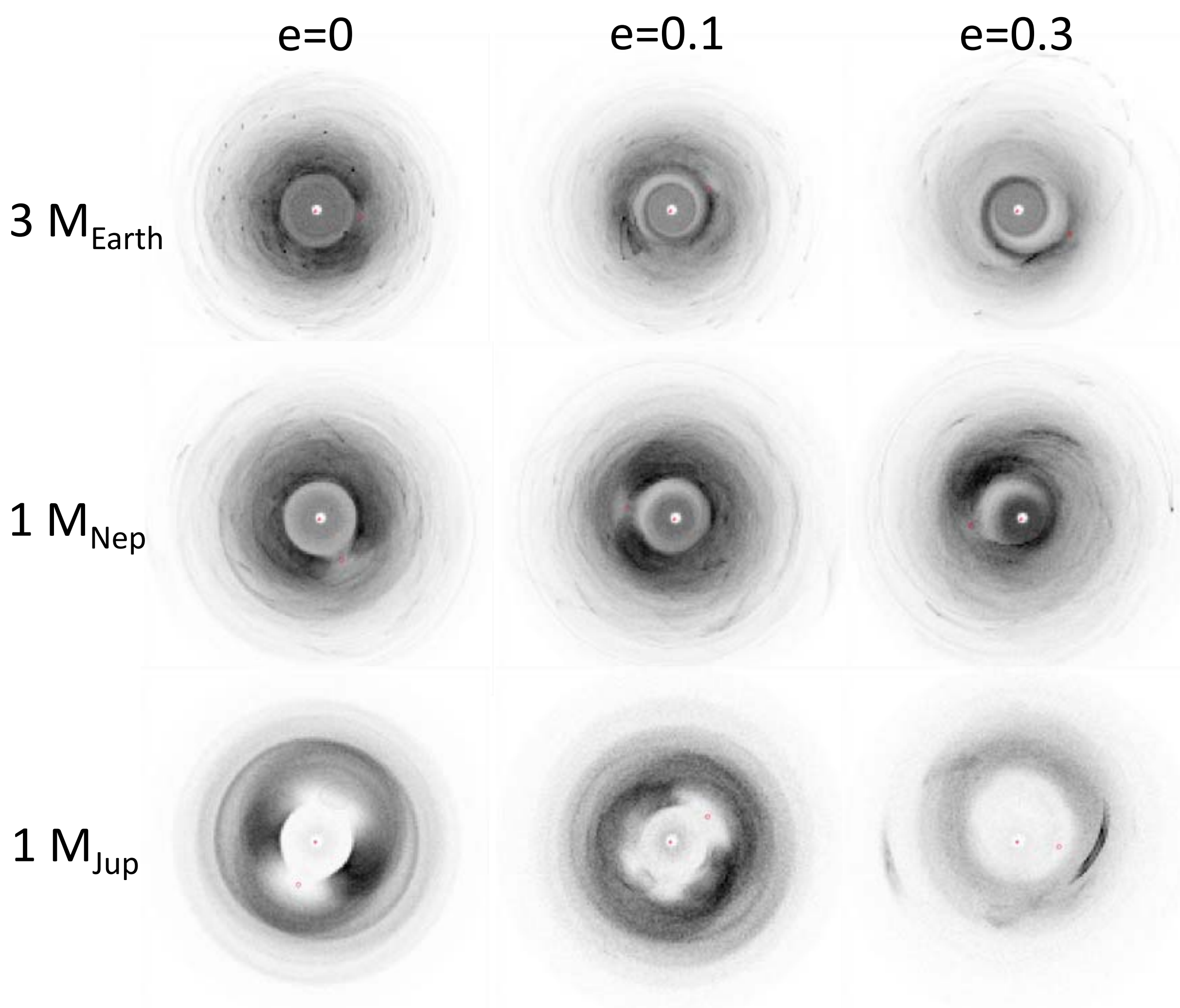
- Particle Distribution in the Solar System



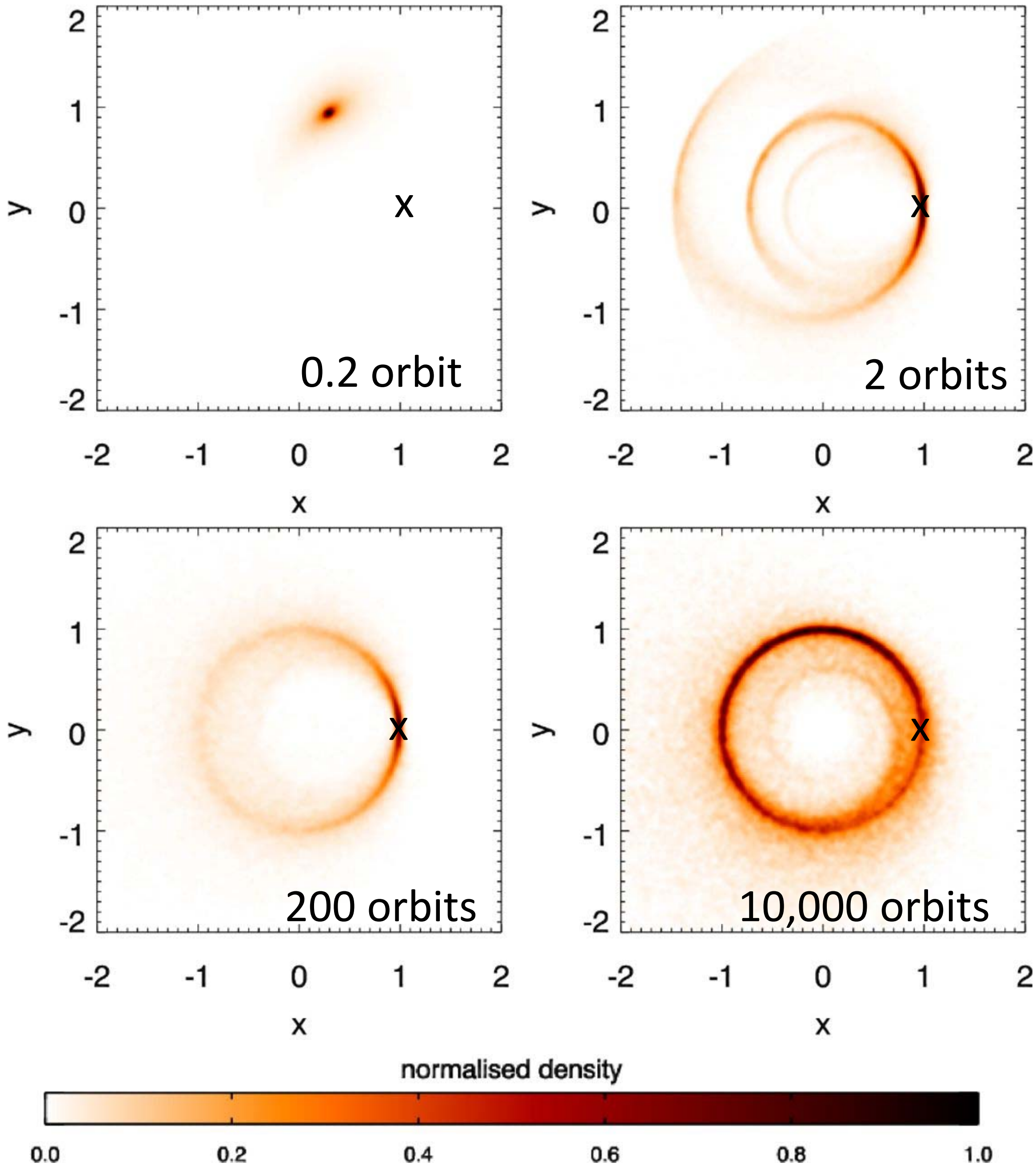
- Expected Dust Density Distribution in the presence of a Planet

planet: mass, eccentricity and inclination

Deller & Maddison (2005)

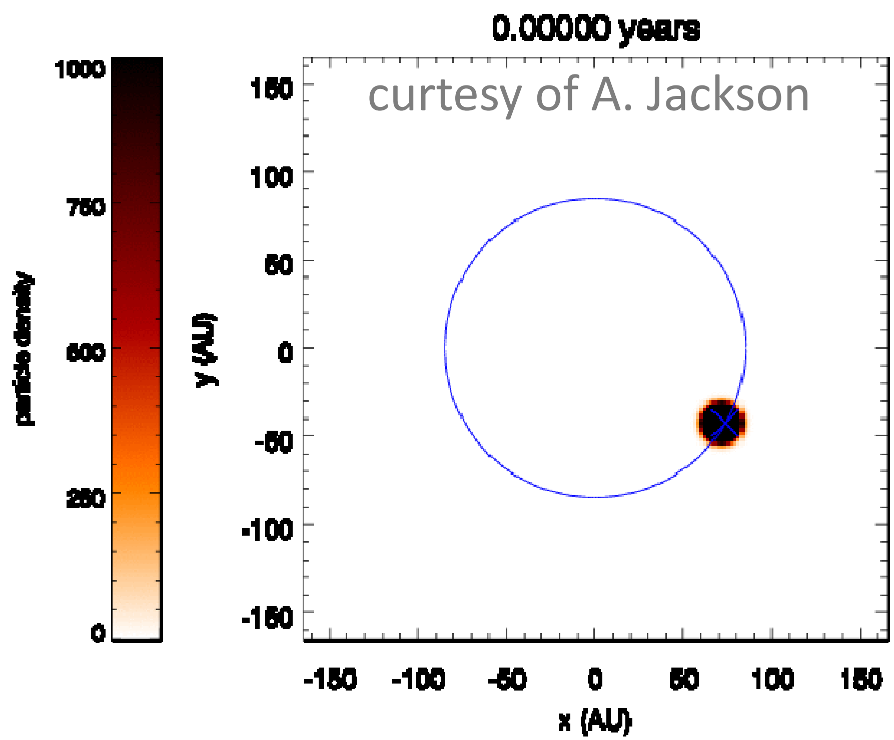


Debris/Fragments Evolution due to a Large Impact



Jackson et al. (2014)

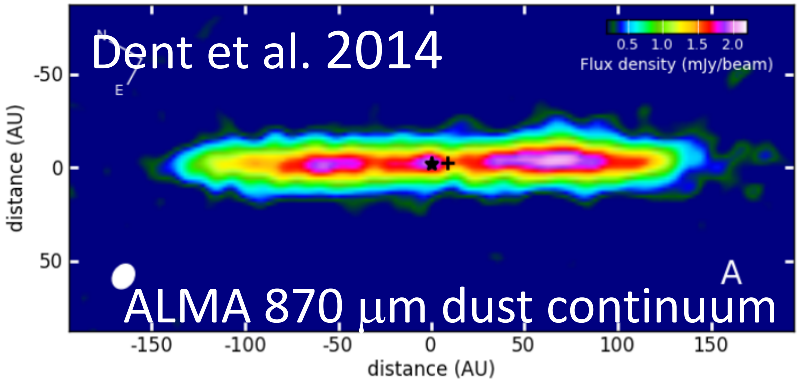
- 1st orbit – clump
- ~2-10 orbits – spiral
- After ~10 orbits – smooth asymmetric disk lasting for ~1000 orbits

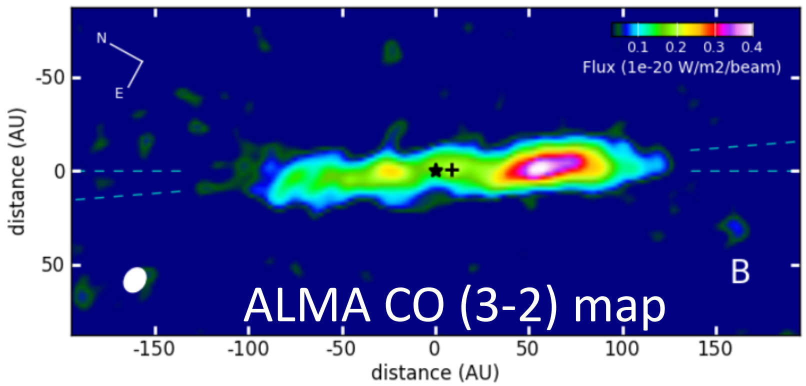


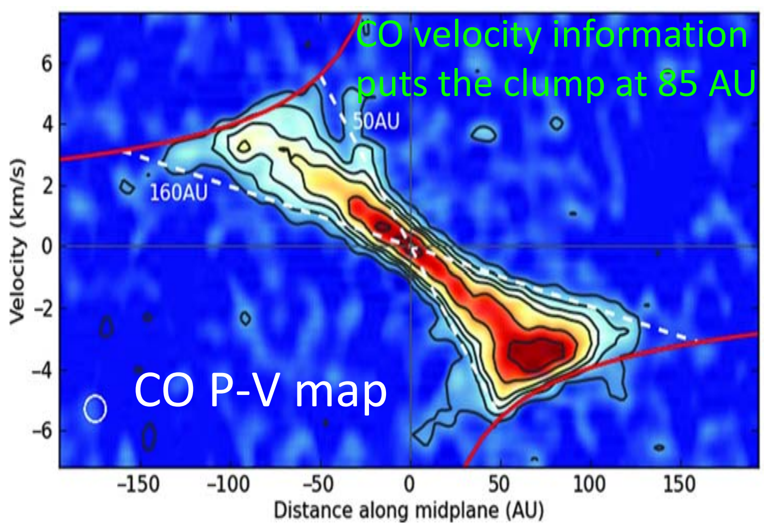
consistent with varable disk emission in extreme debris disks (Meng, Su+2014)

The β Pic Disk – clump

A clump first detected at mid-IR (Telesco+2005) is detected at 870 μm dust continuum and CO (3-2) line

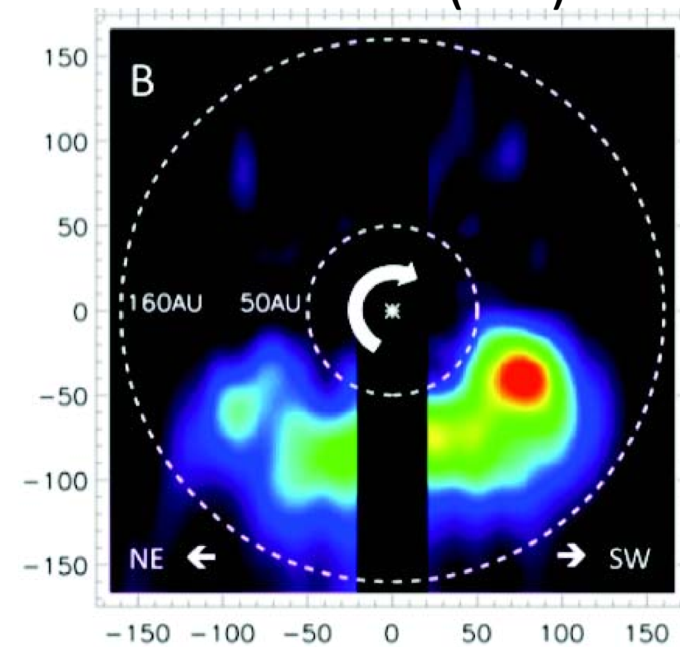






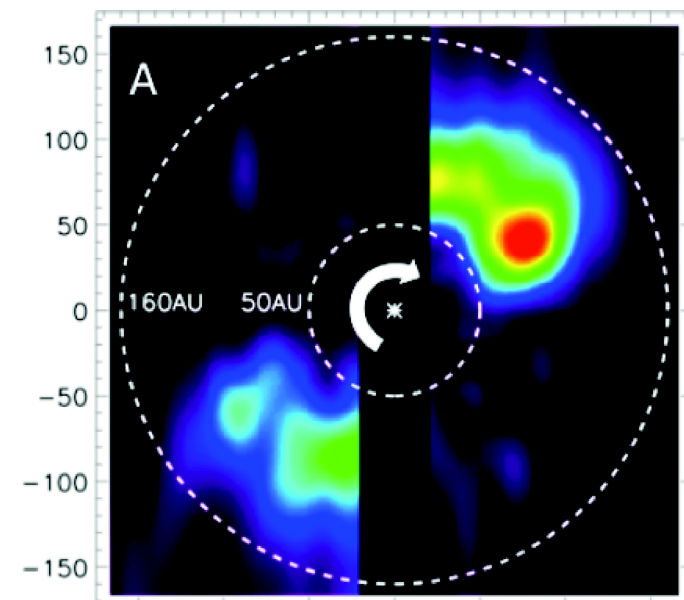
I: Giant impact

A planet with a few Mars mass



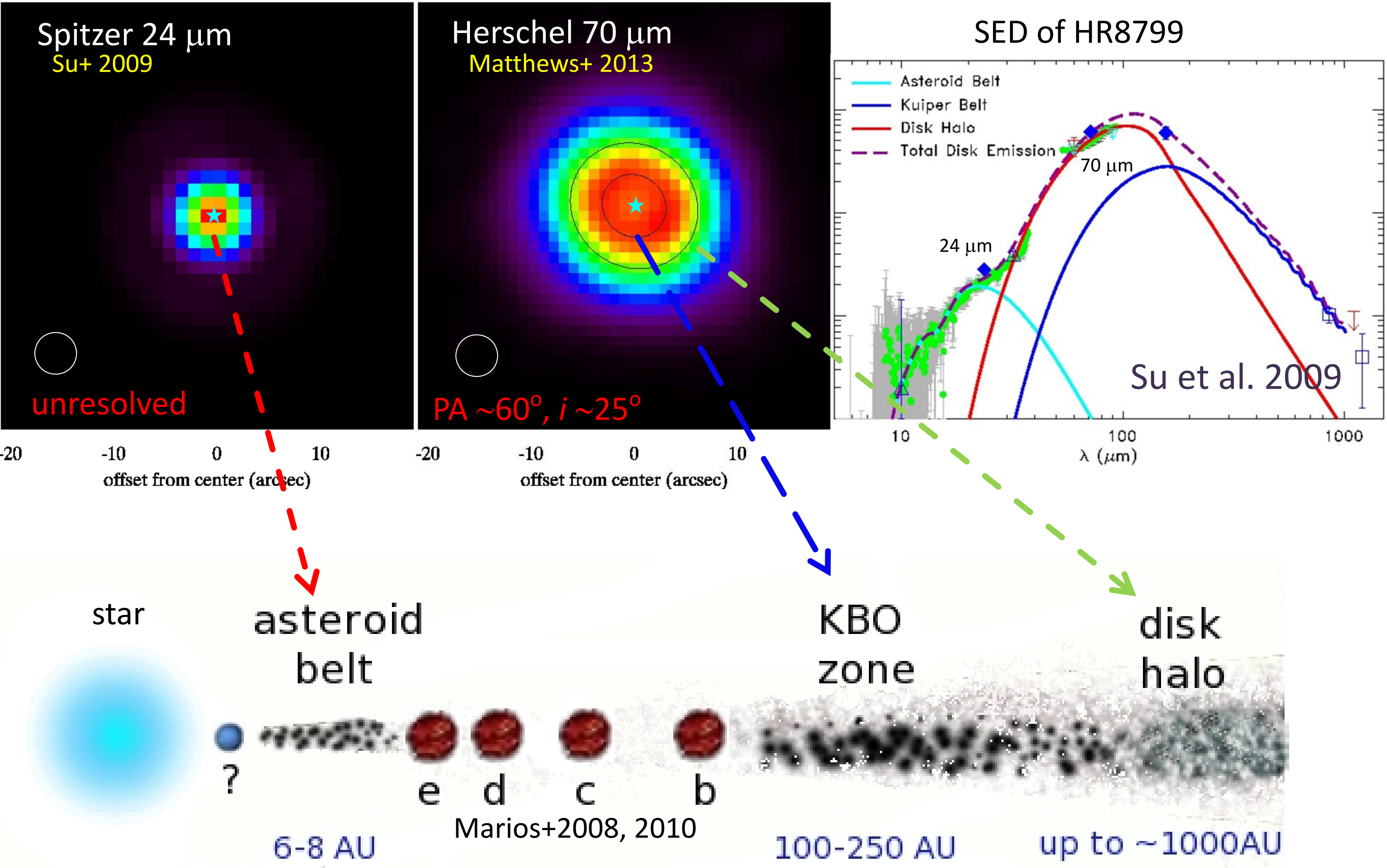
II: Resonance due to unseen planet

$>10\ M_\oplus$ planet at 54 AU

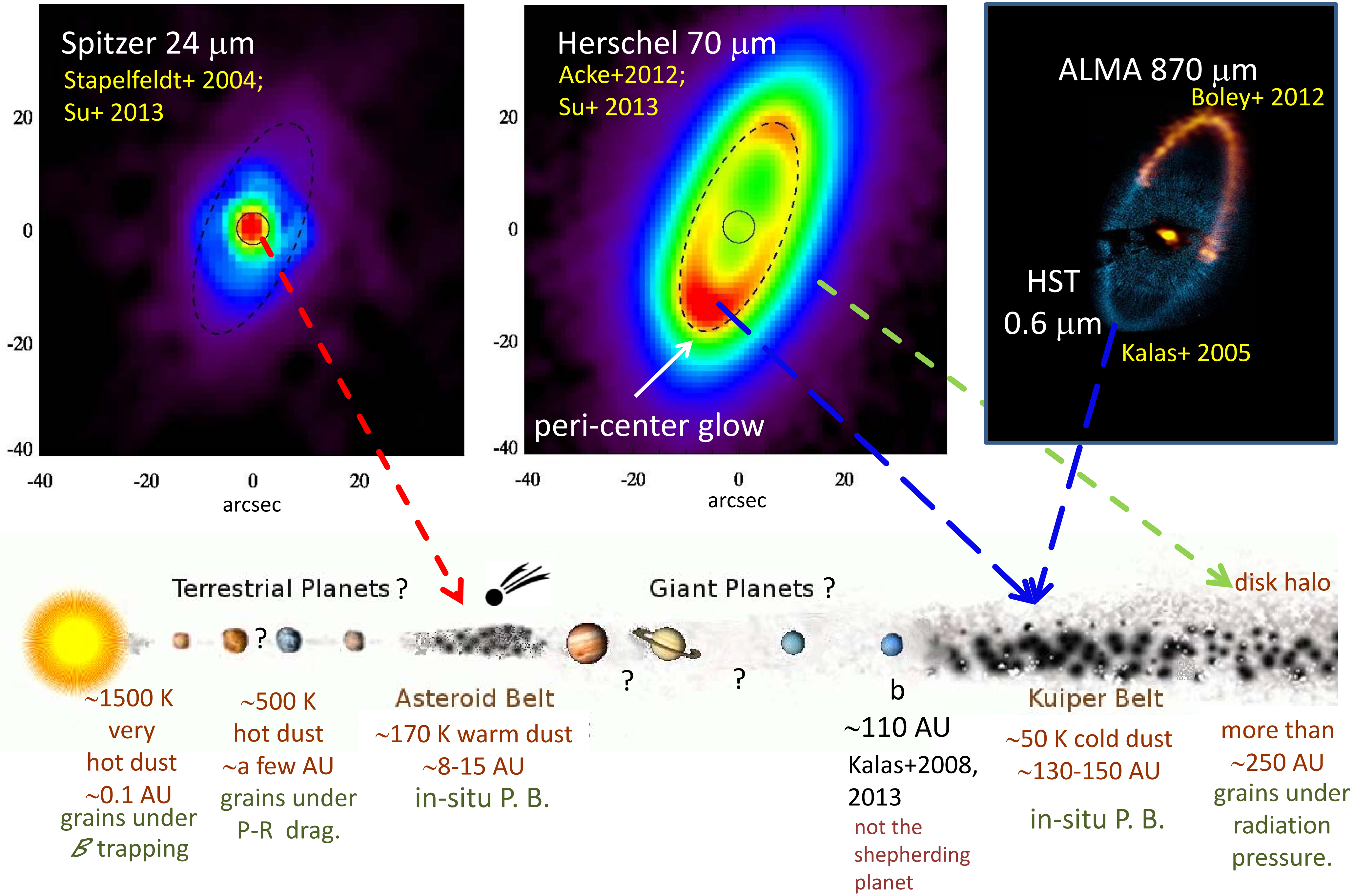


Nearby Debris Disk Structures: Signposts for Multiple Planets beyond the Ice Line

HR 8799 Debris Disk and its Four Giant Planets

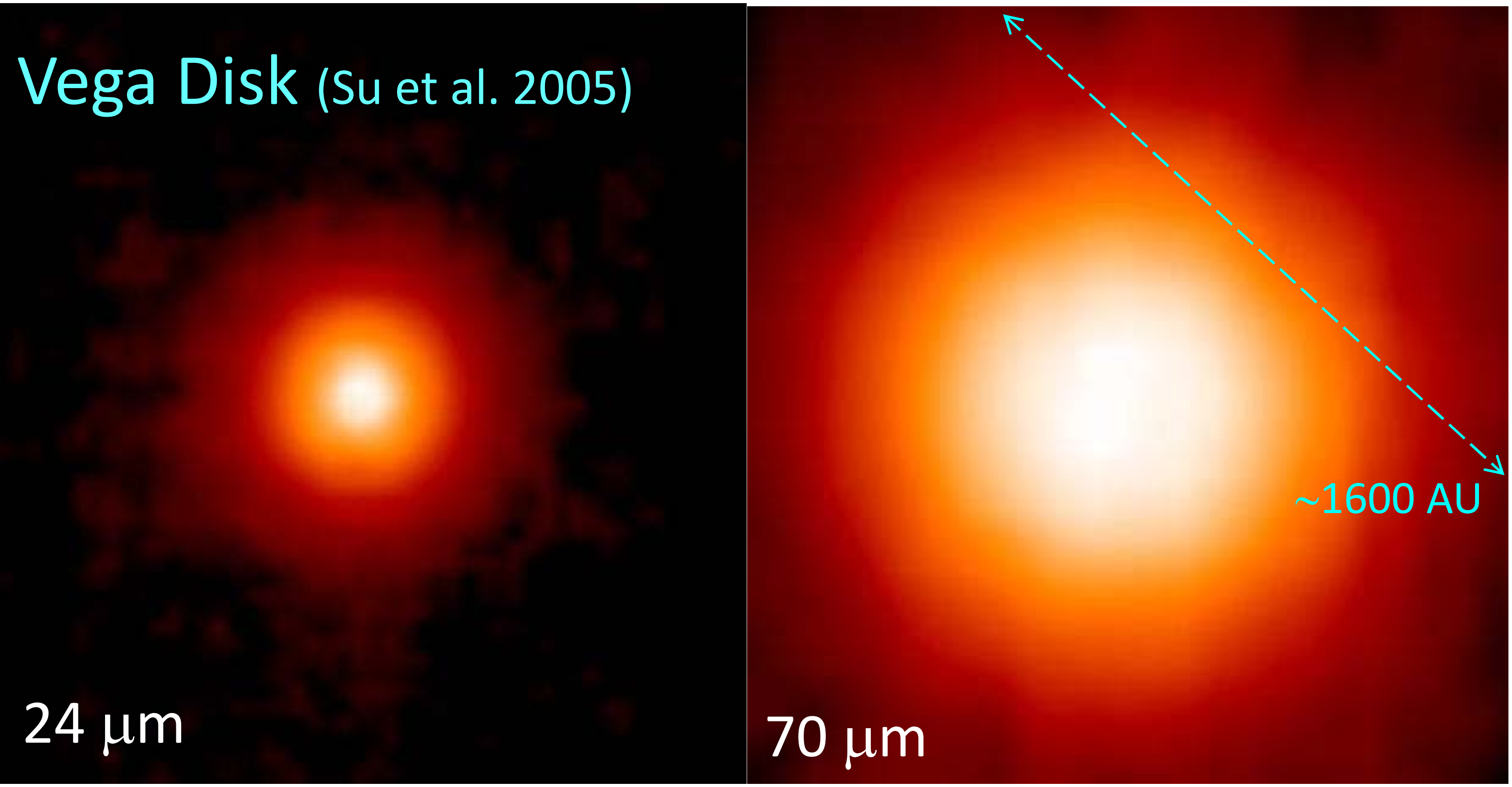


The Fomalhaut Debris Disks

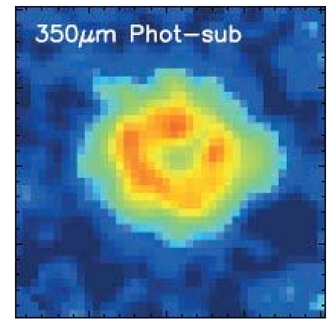


A Large Disk Halo around Vega

A big surprise from Spitzer!



all images are in same orientation and physical scale

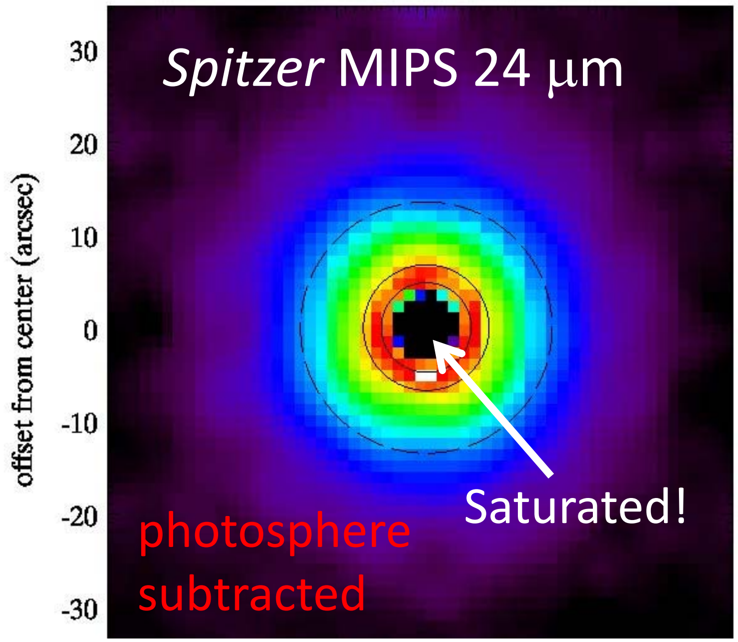


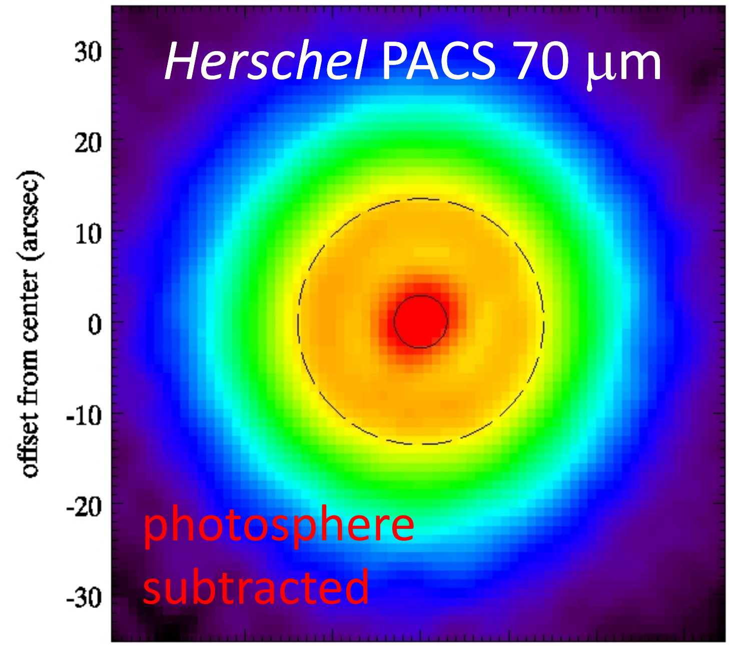
350 μm (Marsh et al. 2006)

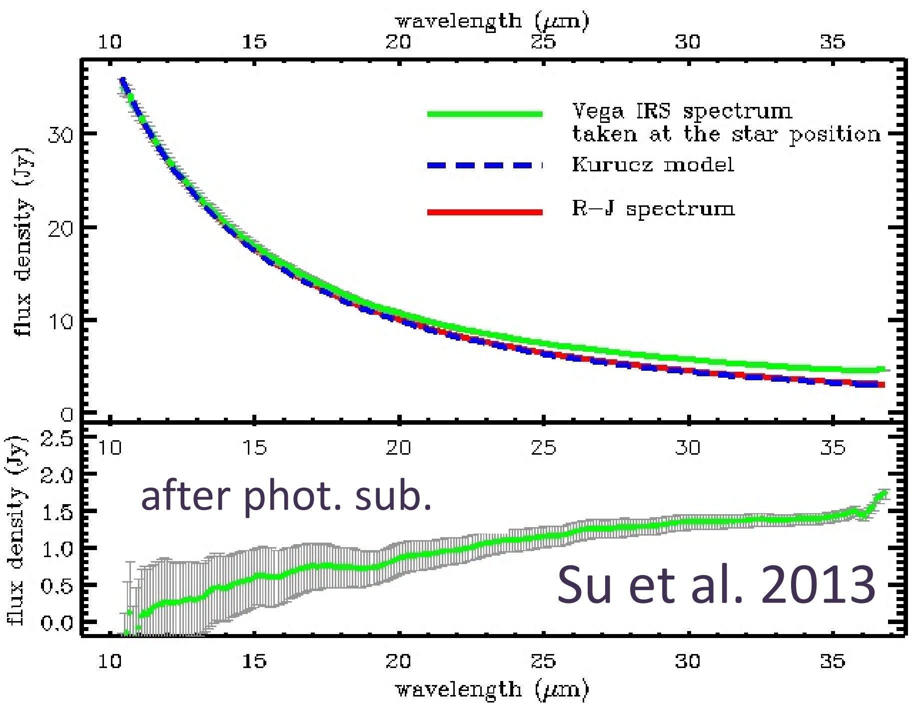
Different Grain Populations:

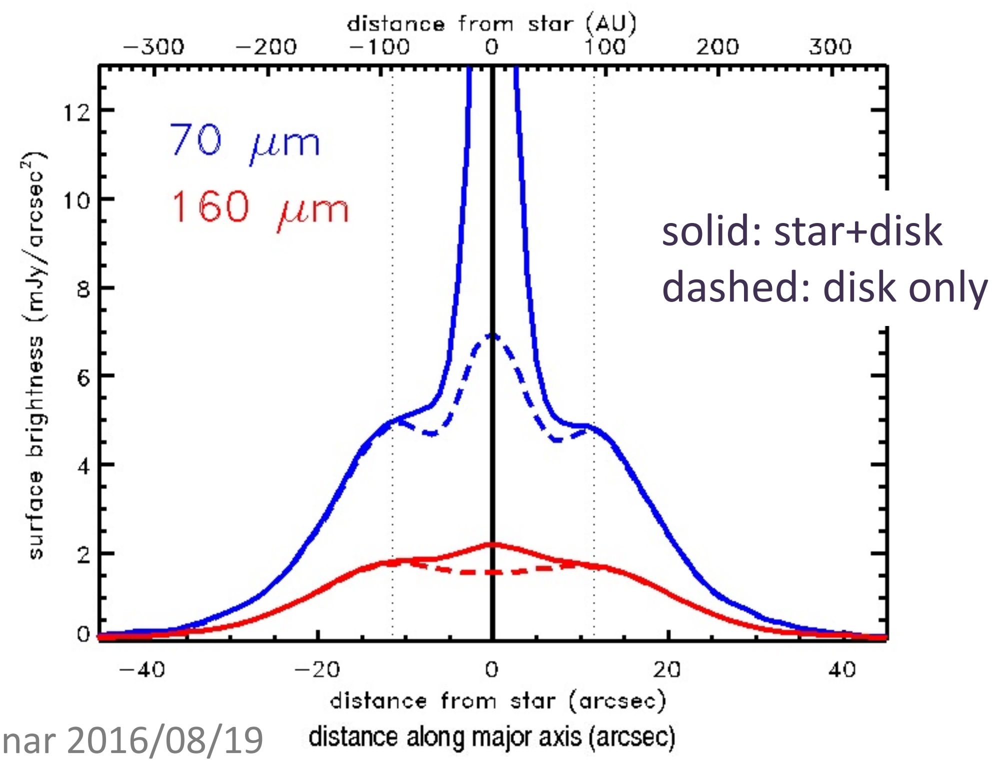
- a parent-body belt confined in a birth ring
- small grains driven outward by radiation pressure forming an extended disk halo

Vega also has a central Warm Component

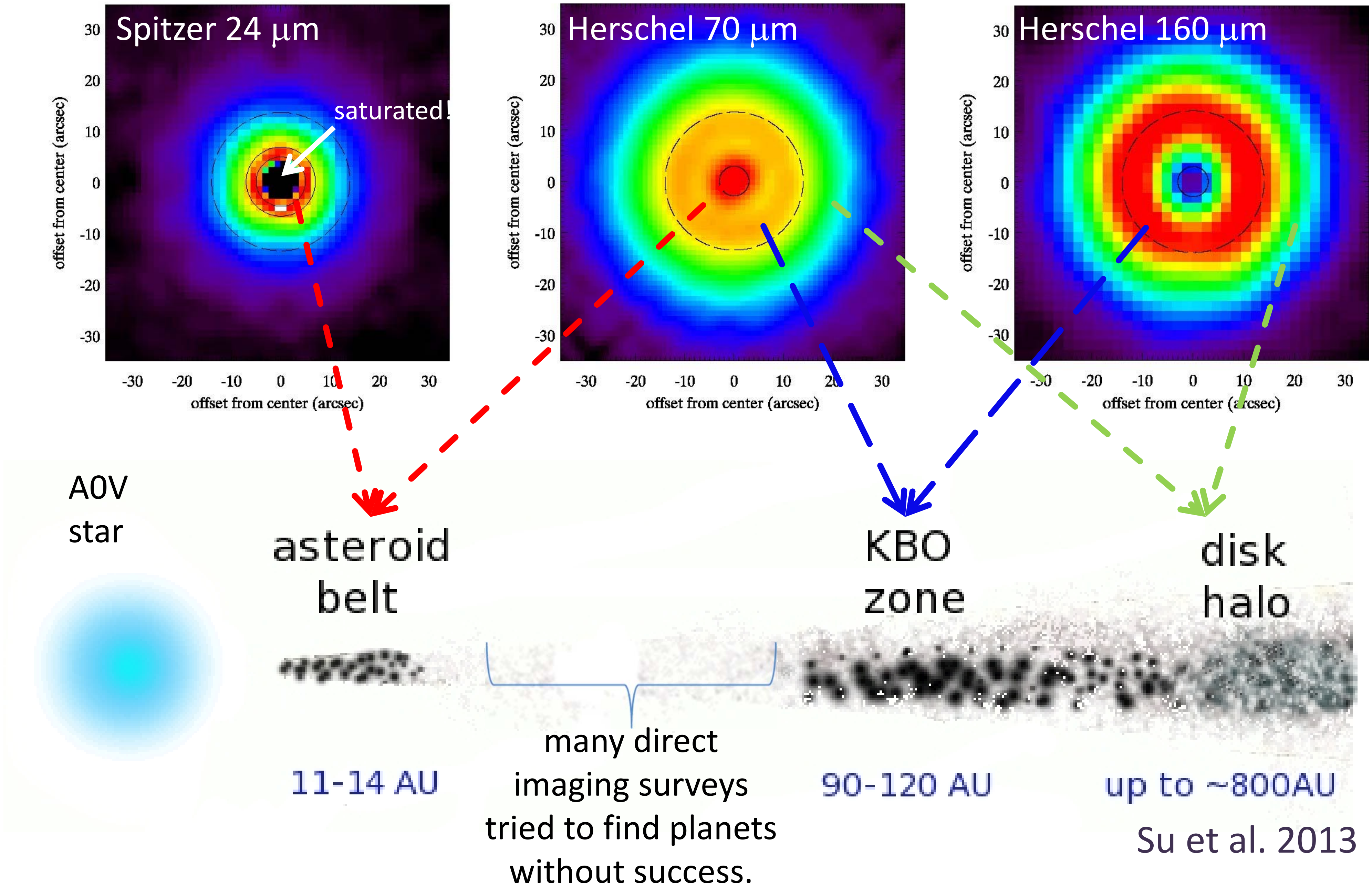






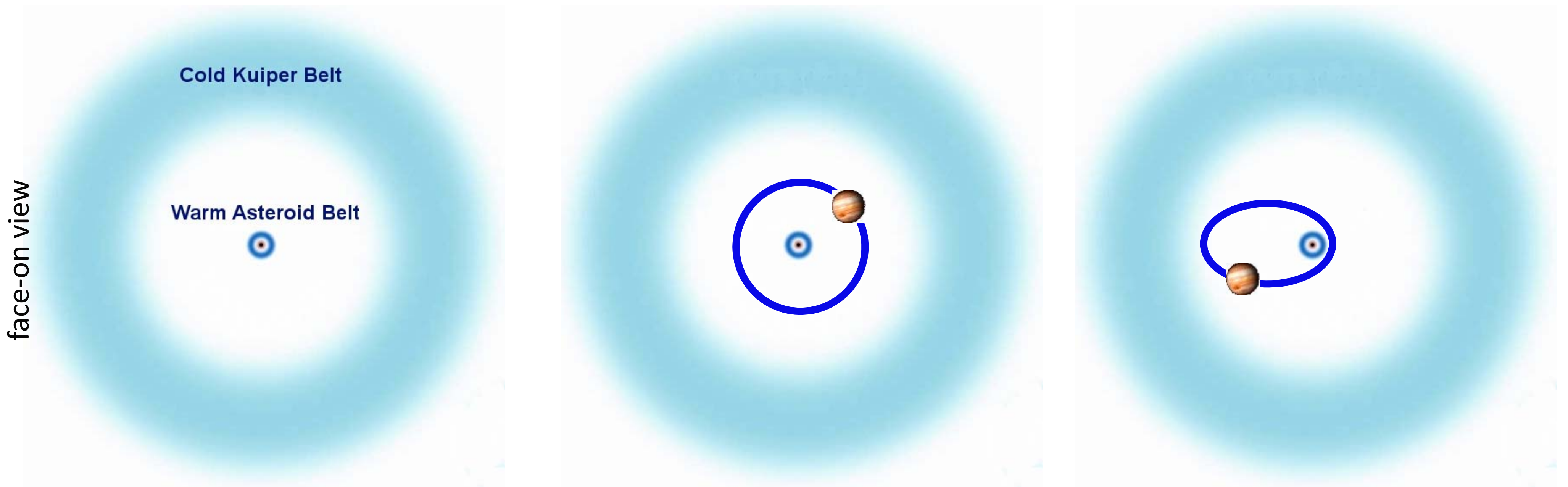


The Vega Debris Disk



Su et al. 2013

Implication - the Structure of Vega's Debris Disk



- A large dust-free zone between belts may be maintained by one or multiple planet-mass objects.
- Chaotic zone formulae:

$\Delta a \sim 1.5\ a\ \mu^{2/7}$ circular orbit

$\Delta a \sim 1.8\ a\ e^{1/5}\ \mu^{1/5}$ eccentric orbit

$$\mu = \frac{M_{planet}}{M_{star}}$$

One single object on a circular orbit
$\rightarrow M_{planet} \geq 100\ M_J$

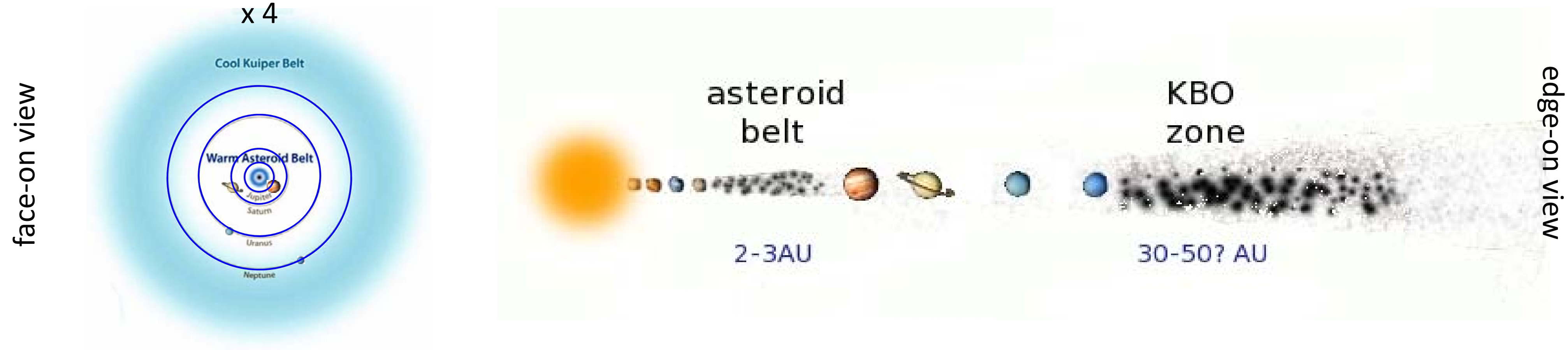
One single object on an eccentric orbit
$\rightarrow e_{exp} \sim 0.8$
$\rightarrow e_{obs} \ll 0.1$

Ground-based high-contrast imaging searches (Marois et al. 2006; Heinze et al. 2008) should have fount it! (current mass limit $\sim 3\ M_J$)

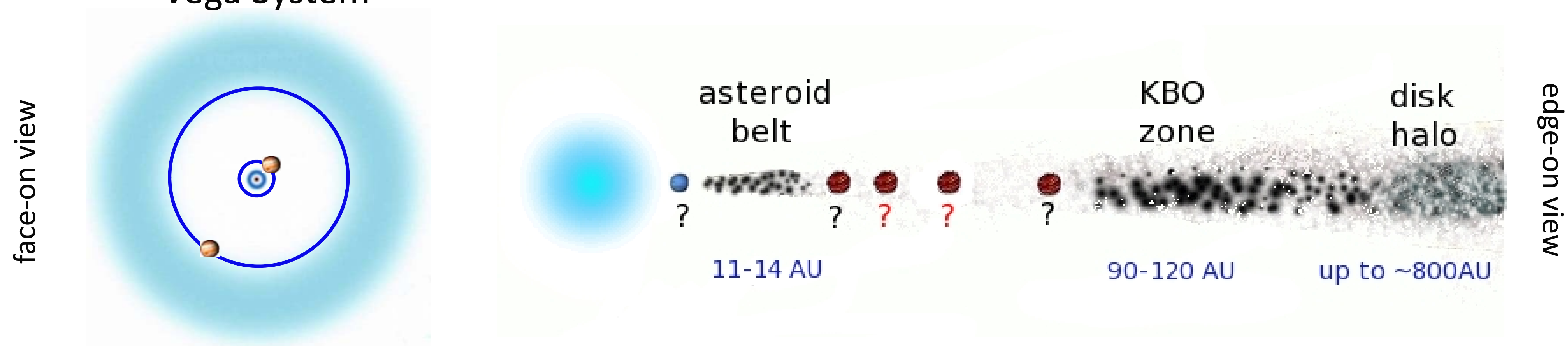
The gap is too large to be explained by one single circular perturber!

Implication - the Two-Component Debris Disks

Solar System
x 4



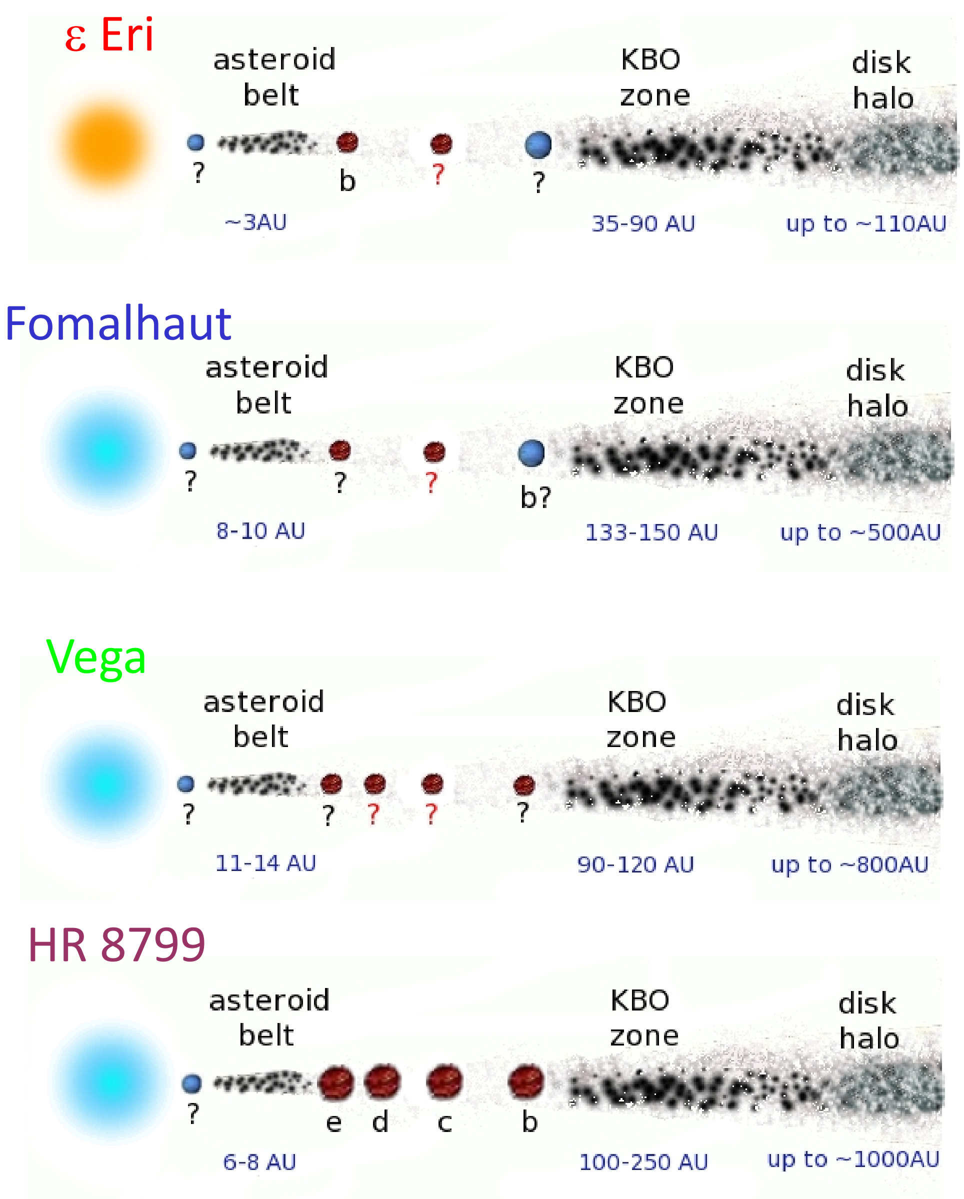
Vega System

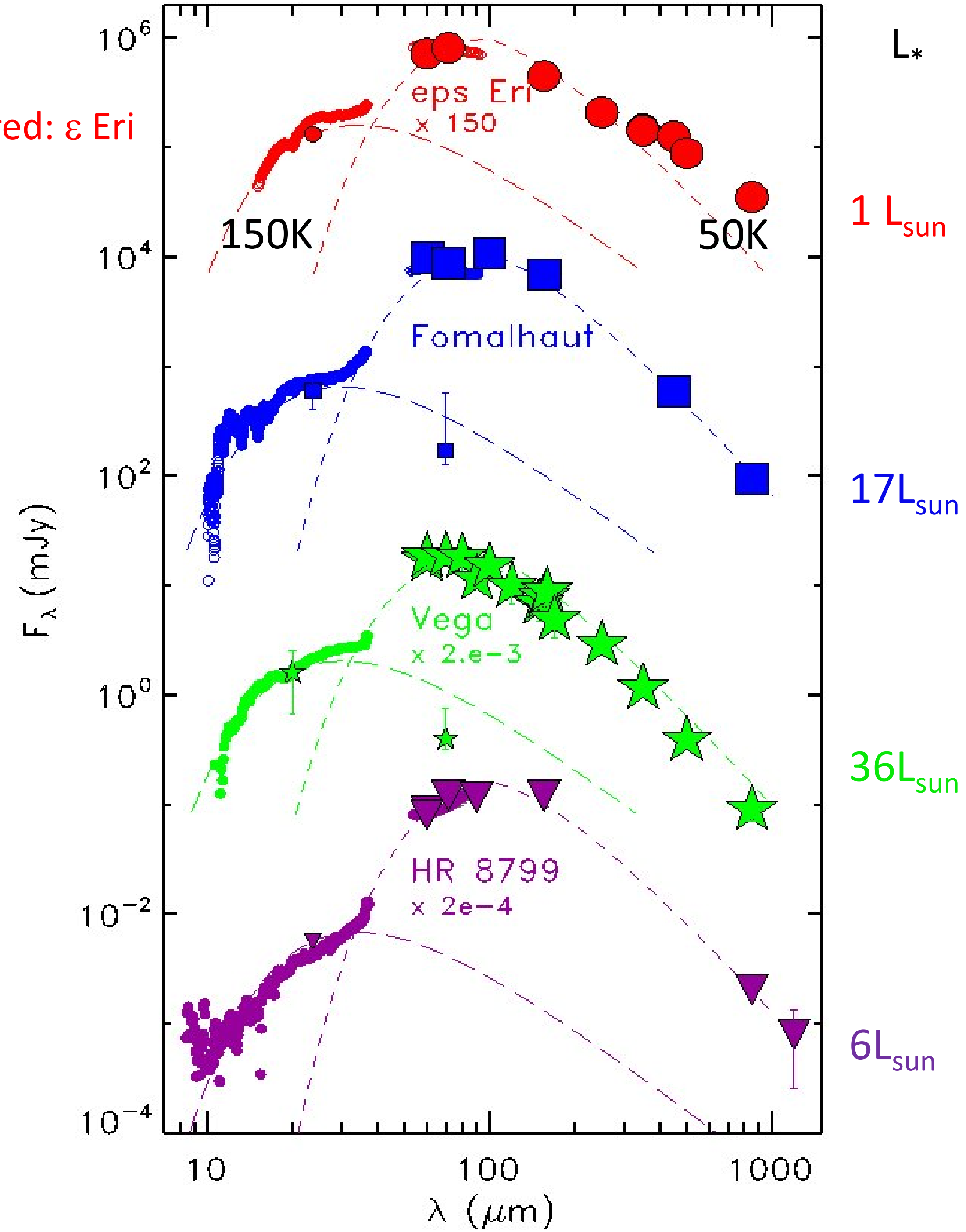


Outer dust belt has low eccentricity, so at least two low-mass planets are needed to maintain mostly circular dust belts: one just interior the cold outer belt, and one just outside the warm inner belt.

Signposts for Multiple Planets beyond the Ice Line

Detailed Excess SEDs + Resolved Images:
Symbols: observations
purple: HR 8799; green: Vega; blue: Fomalhaut; red: ε Eri

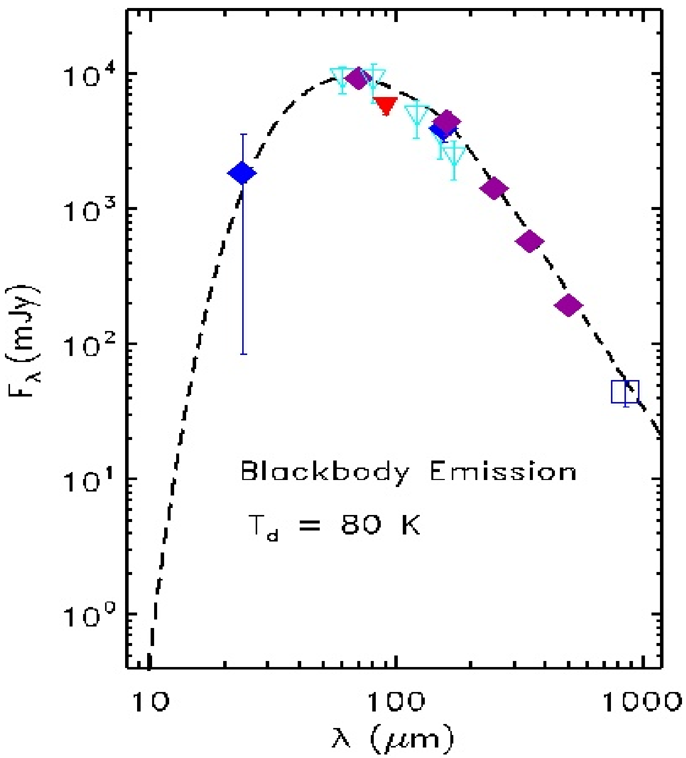




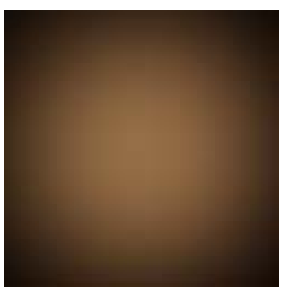
How Much We Learn from New Capabilities

IRAS + ISO era

cold Kuiper belt

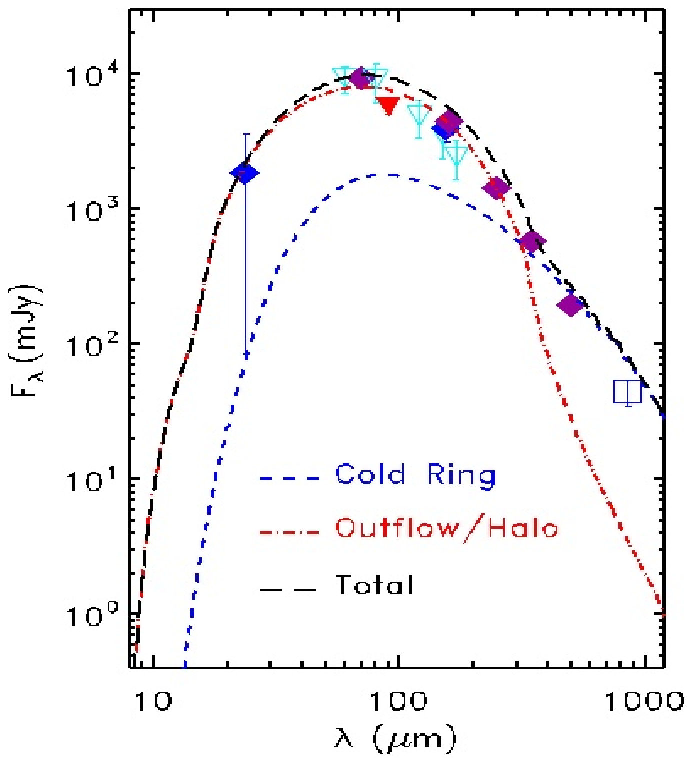


point source (1983)

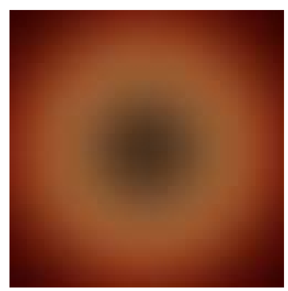


Spitzer era

cold Kuiper belt + disk halo

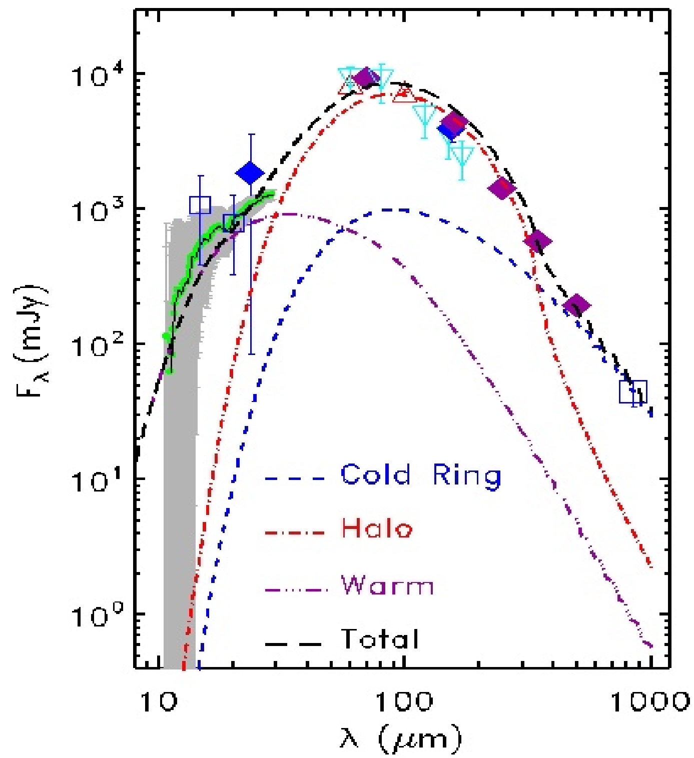


large disk (2005)

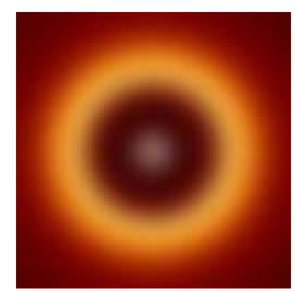


Spitzer/Herschel era

cold Kuiper belt + warm Asteroid belt + disk halo

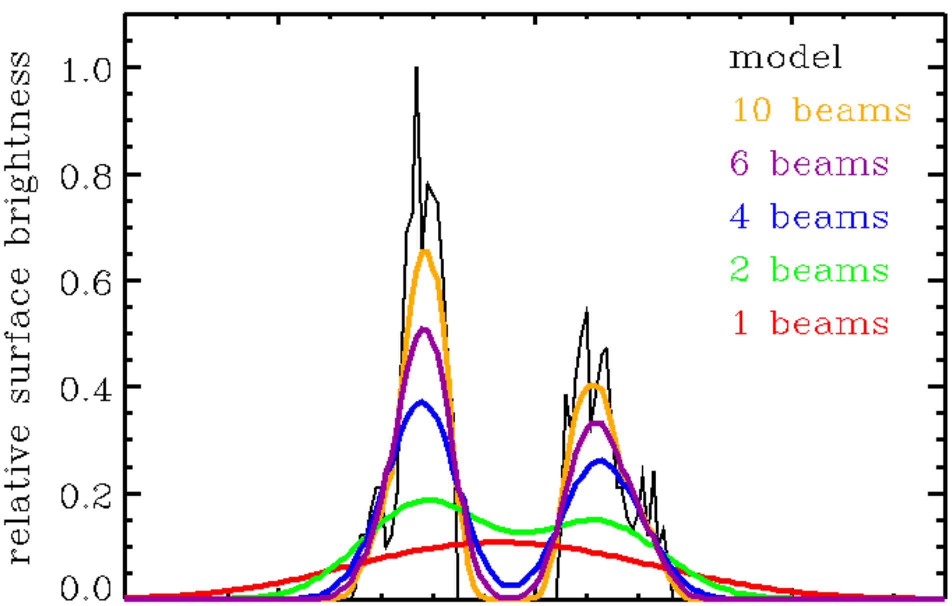


multiple components (2013)



How Much Information can be Extracted?

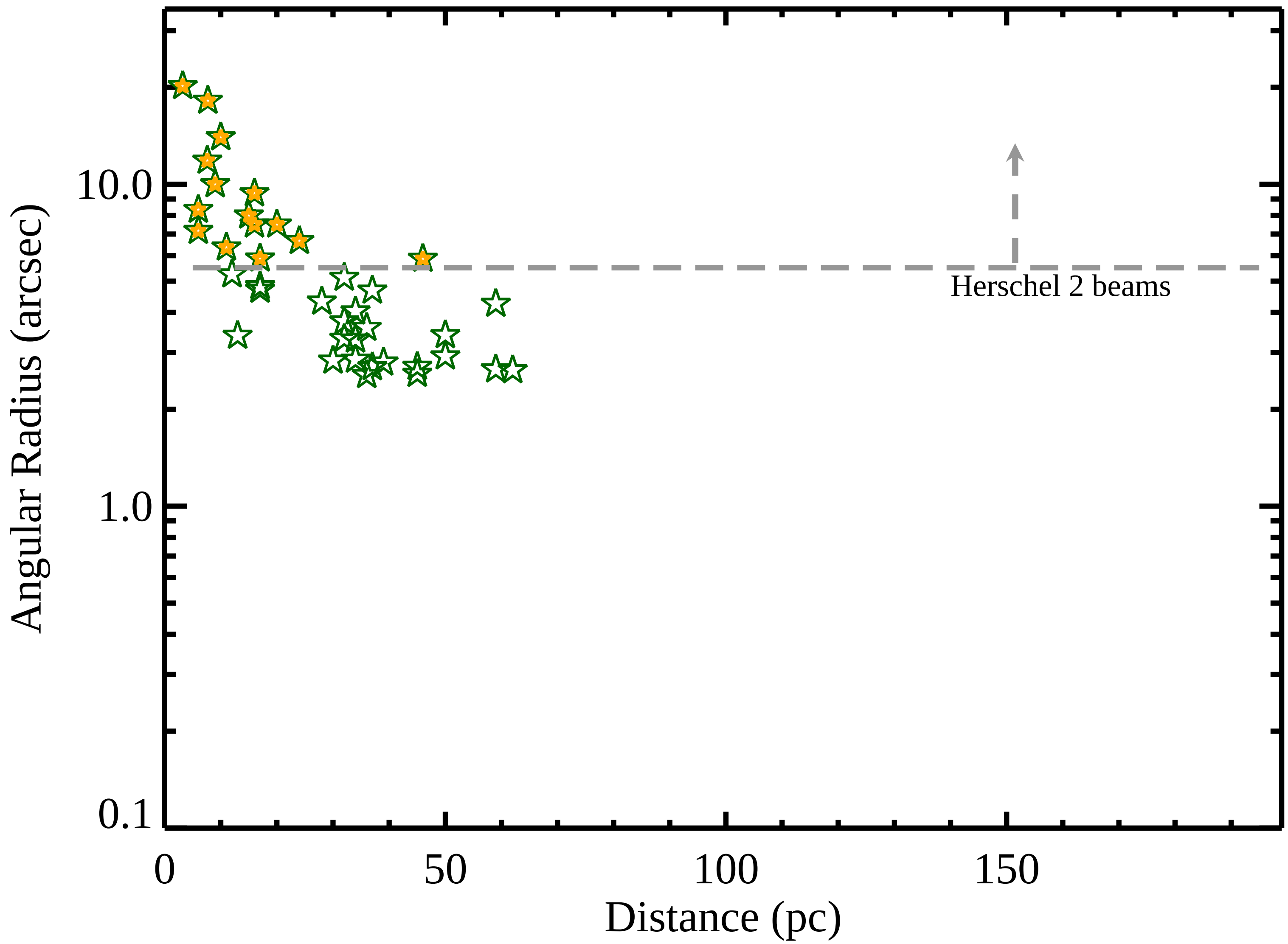
Resolability = Diameter / FWHM of the Beam



Resolved by
2 beam: minimum to detect modest asymmetry in the disk
4 beam: minimum to pin down the belt location and the sharpness of the belt
⇒ Put strong constraints on the mass of the sculpting planet

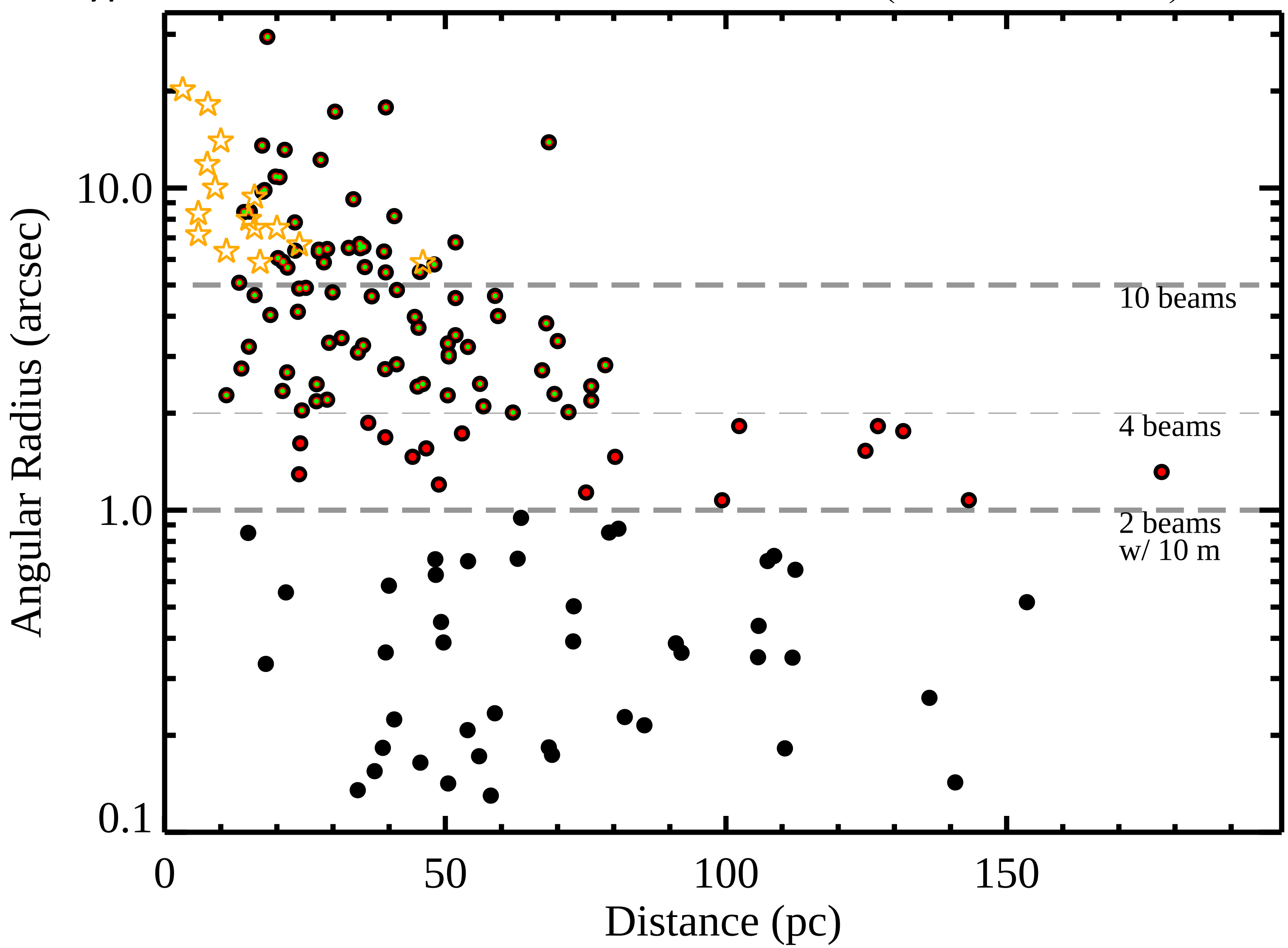
Herschel Resolved Disks

~2-3 dozens of debris disks are resolved by Herschel/PACS at 70/100 μm
(~1 dozens of them are resolved by more than 2 beams.)



Expected Disk Sizes from Known Debris Disks

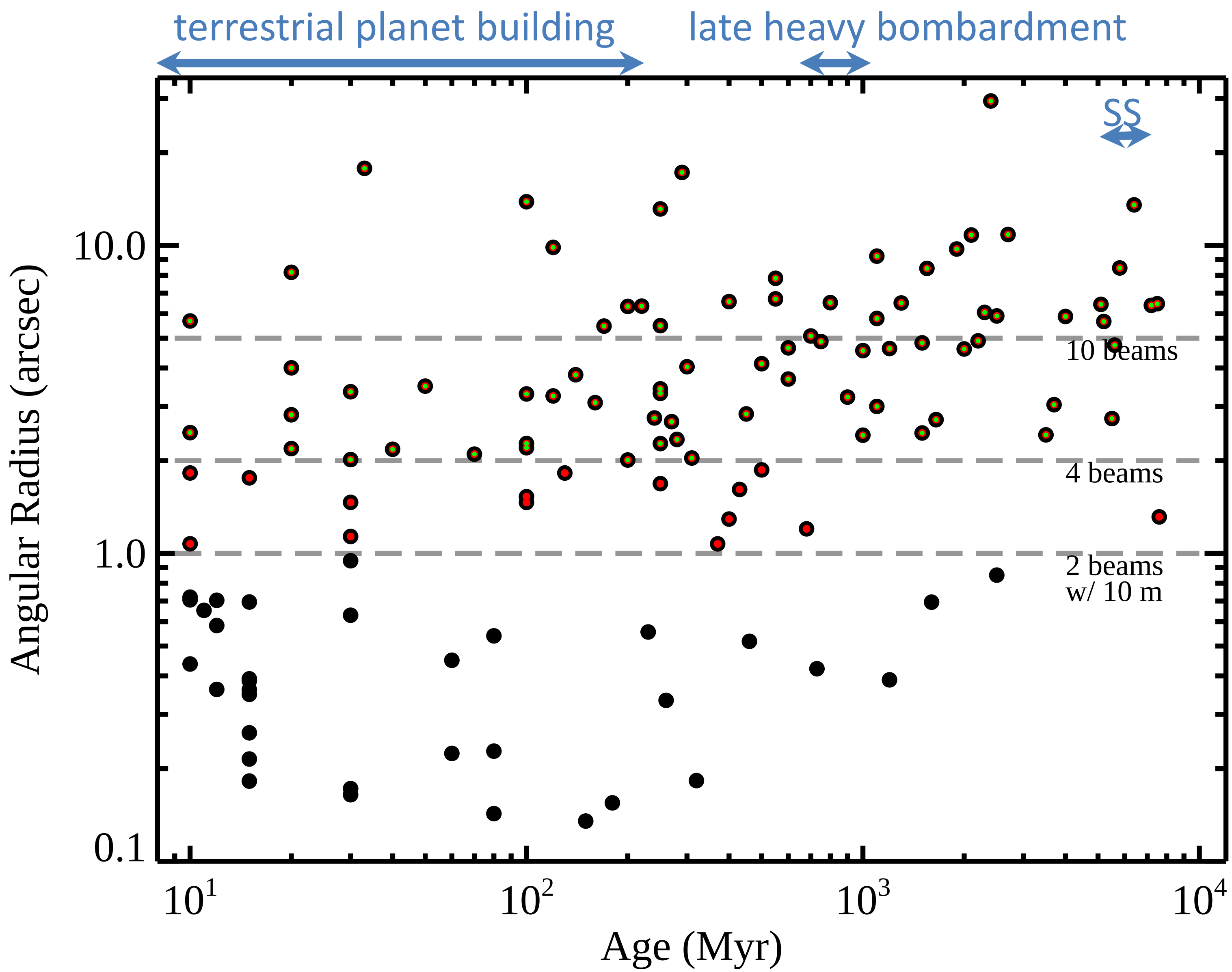
Disk sizes are estimated by a relationship between the observed dust temperatures and spectral types of stars, derived from Herschel results (Pawellek+2014).



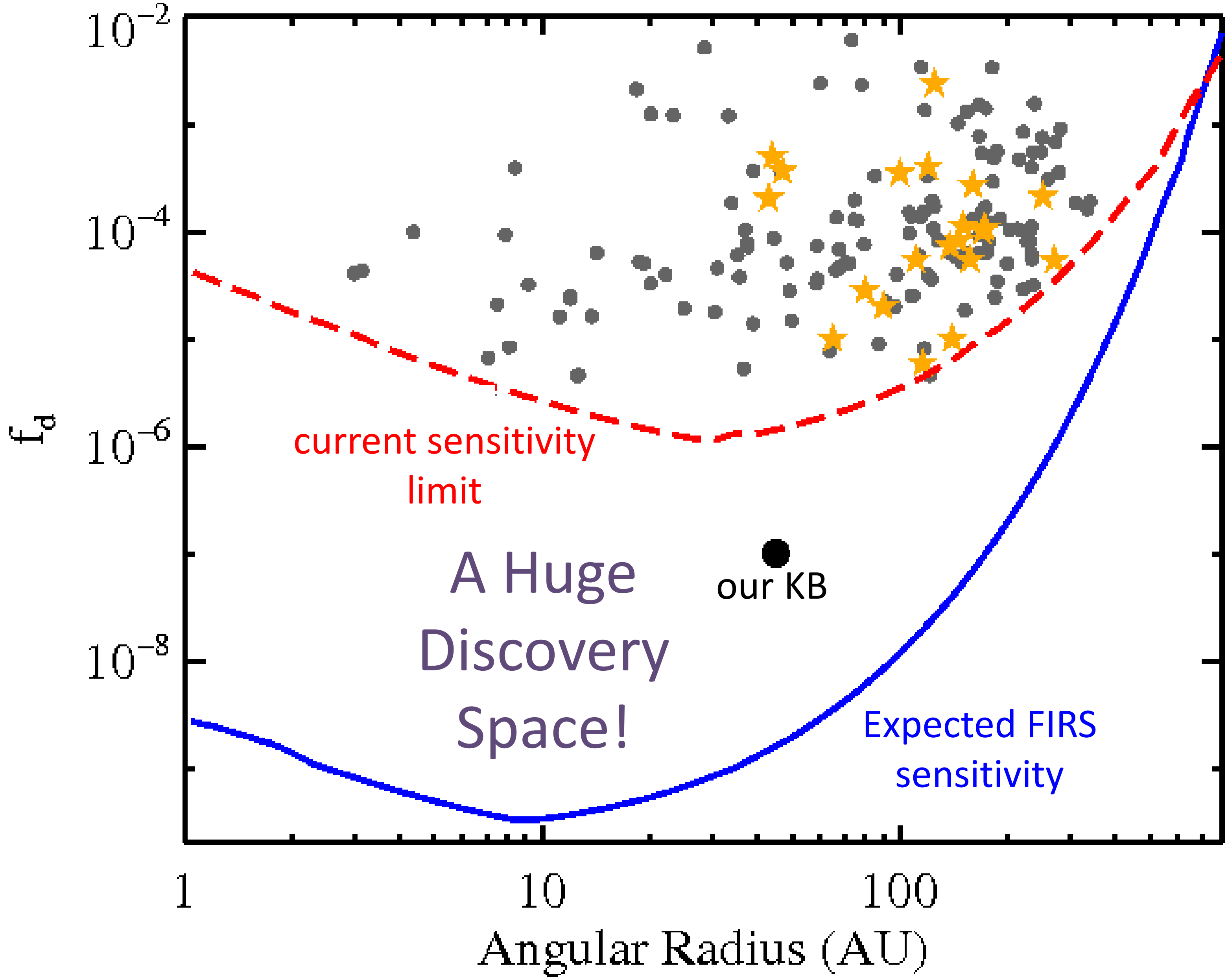
A beam size of 1”, FIRS can easily resolve nearby ~150 disks by more than 2 beams, and ~50 disks by more than 10 beams, i.e., 10 times more than what Herschel has done.

Expected Disk Sizes from Known Debris Disks

Disk sizes are estimated by a relationship between the observed dust temperatures and spectral types of stars, derived from Herschel results (Pawellek+2014).



Known Debris Disks are the Tip of the Iceberg

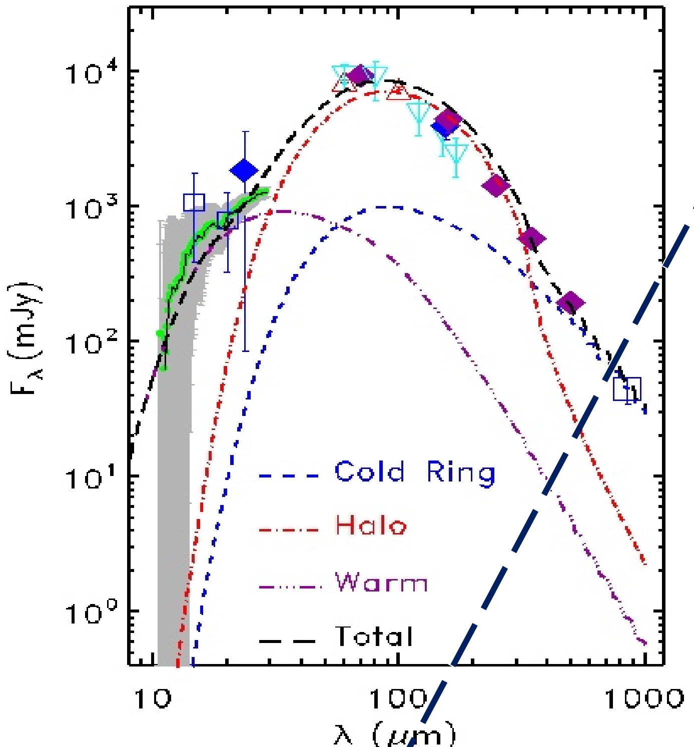


A large, cryogenic cold telescope can discover more debris disks and provide a census of true KB analogs, putting our SS into context.

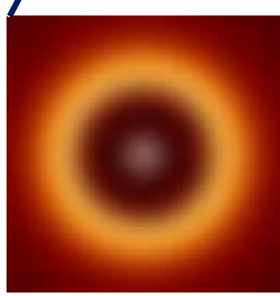
How Much We Learn from New Capabilities

Spitzer/Herschel era

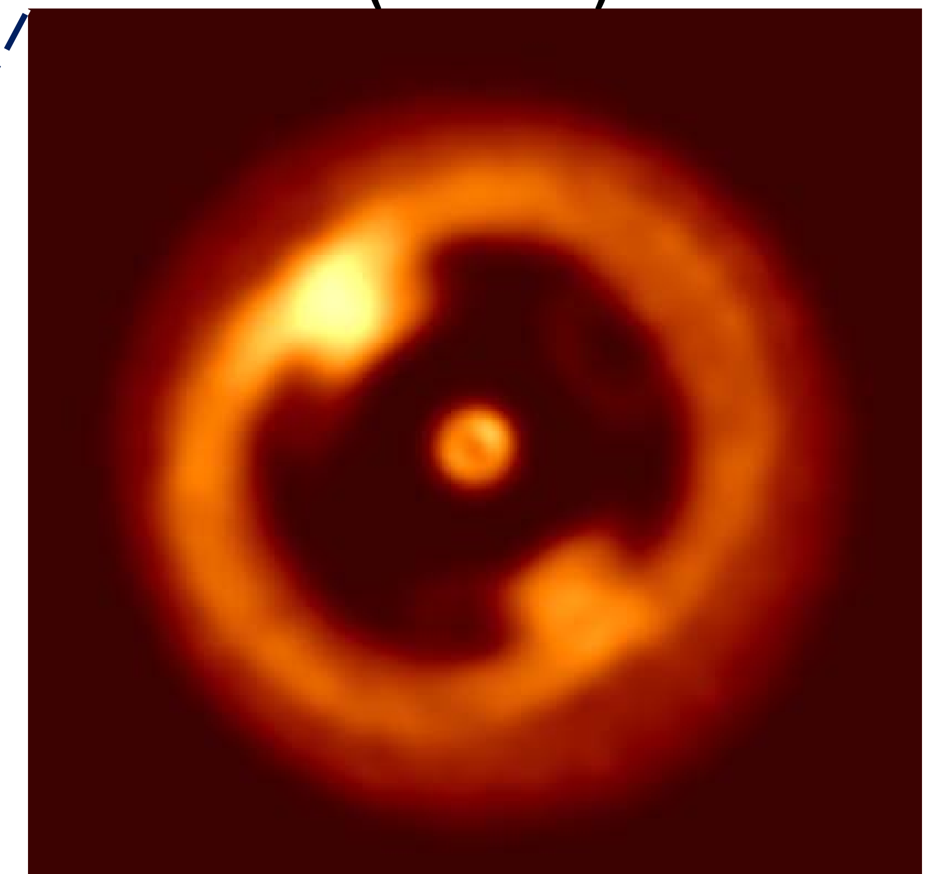
cold Kuiper belt +
warm Asteroid belt +
disk halo



multiple components



future image with FIR Surveyor (2035?)



Debris Disk Science Theme

- Planetary Architecture – Is our Solar System an Outlier?
  - Use debris disk structures to find and characterize the masses and orbits of exoplanets not found by ~2030 with other measurement technique
  - Use debris disk structures to constrain planet formation and migration history
  - Demographic studies of debris disks (disk brightness vs. other parameters: spectral type, metallicity, presence of known planets, stirring mechanisms)
- Composition in Debris Disks
  - Gas in debris disks – origins? composition of exo-comets
  - Dust mineralogy – silicates, ices, and calcites…etc, hydro-material?

    formation and transportation history, link to protoplanetary disks
- Planetary Systems beyond Main Sequence
  - Detecting the reservoir of surviving asteroids and KBOs

FIR Surveyor Science Themes

- **Tracing the signatures of life and the ingredients of habitable worlds:** trace the trail of water from interstellar clouds, to protoplanetary disks, to small bodies in the Solar System in order to understand the abundance and availability of water for habitable planets
- **Rise of Metals, Dust, and the First Galaxies:** trace the dust and metal enrichment history of the University, and probe the first cosmic sources of dust, the properties of the earlies star formation, and the birth of galaxies
- **Revealing the interplay between stars, black holes, and interstellar matter over cosmic time:** understand the connection between BH growth and SF, obtain a comprehensive view of the multiphase ISM, and measure the feedback from SF and AGN over cosmic time

STDT website: http://asd.gsfc.nasa.gov/firs/ Wiki website: https://firsurveyor.atlassian.net/