



# Orbits and dynamics of eccentric, long-period companions

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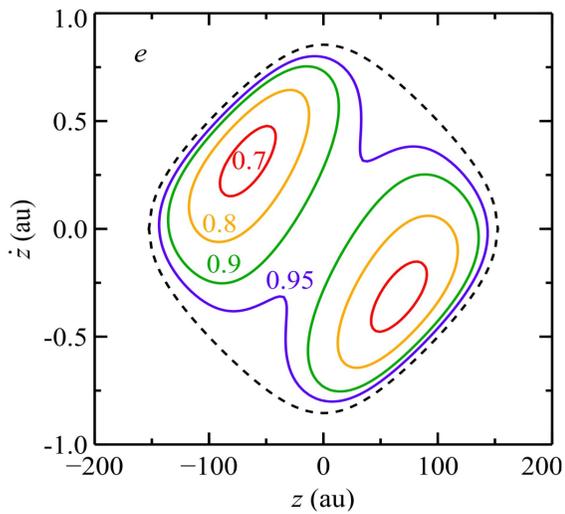
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## What constraints can we place on the orbits of directly imaged companions?

### The problem

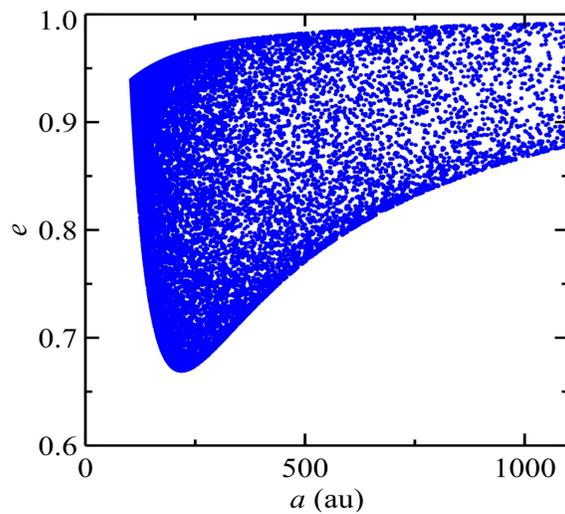
- Imaging a companion over a short orbital arc yields only four of the six coordinates required for unique orbit determination. The line of sight values ( $z, \dot{z}$ ) are unknown
- Probability distributions for orbital elements may be found by varying  $z$  and  $\dot{z}$  or by MCMC, but these are biased by the arbitrary choice of priors



Possible eccentricities of Fomalhaut b, a function of measured sky coordinates and the unknowns  $z$  and  $\dot{z}$

### Prior independent bounds

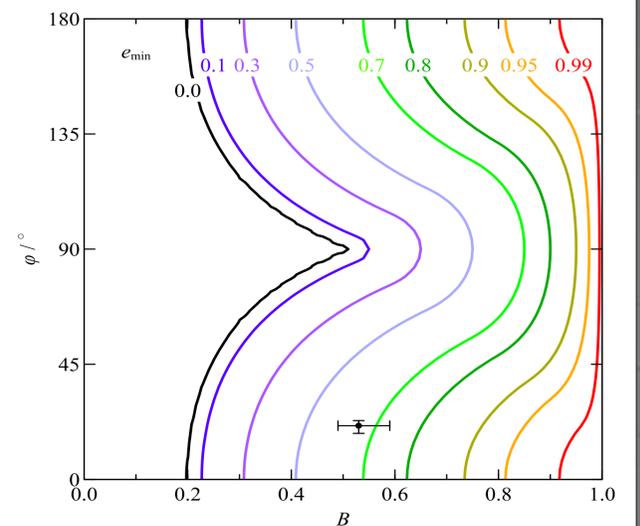
- Not all orbits are allowed; some orbital elements may only lie within certain bounds
- The bounds are set by sky coordinates and are *independent of priors*. Priors determine the probability distributions within the bounds, not the bounds themselves



Density of semi-major axis and eccentricity solutions for Fomalhaut b, assuming uniform priors on  $z$  and  $\dot{z}$

### Minimum eccentricity etc.

- The semi-major axis  $a$ , eccentricity  $e$ , inclination  $i$  and true anomaly  $f$  are bounded
- Extrema depend on two measurable quantities,  $\phi$  and  $B$
- Hence we find the minimum possible eccentricity of any imaged companion (and similarly bound  $a$ ,  $i$  and  $f$ ) using only sky plane coordinates

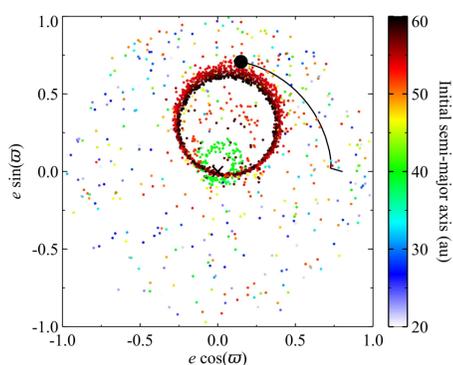


Minimum  $e$  of a general imaged companion, as a function of combinations of sky plane values. The point is Fomalhaut b

## How would an eccentric body interact with a debris disc in the system?

### Planets in the disc midplane

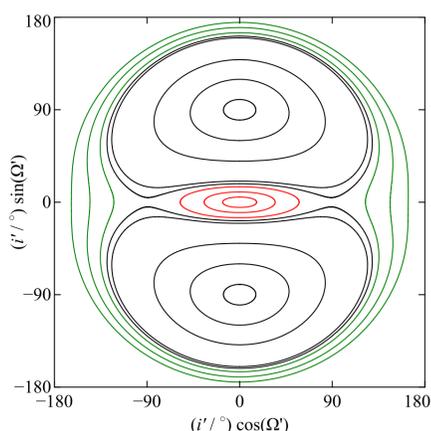
Secular effects dominate surviving non-resonant particles. Each orbit oscillates between a near circle and an ellipse aligned with the planet's orbit, forming an eccentric disc.



Coupled eccentricity - longitude of pericentre of the debris particles

### Planets inclined to the disc midplane

If the planet and disc planes are similar, debris planes circulate about the planet plane forming a puffed up eccentric disc. Otherwise they librate about a plane orthogonal to the planet's, and debris forms a hollow "bell"-shape.



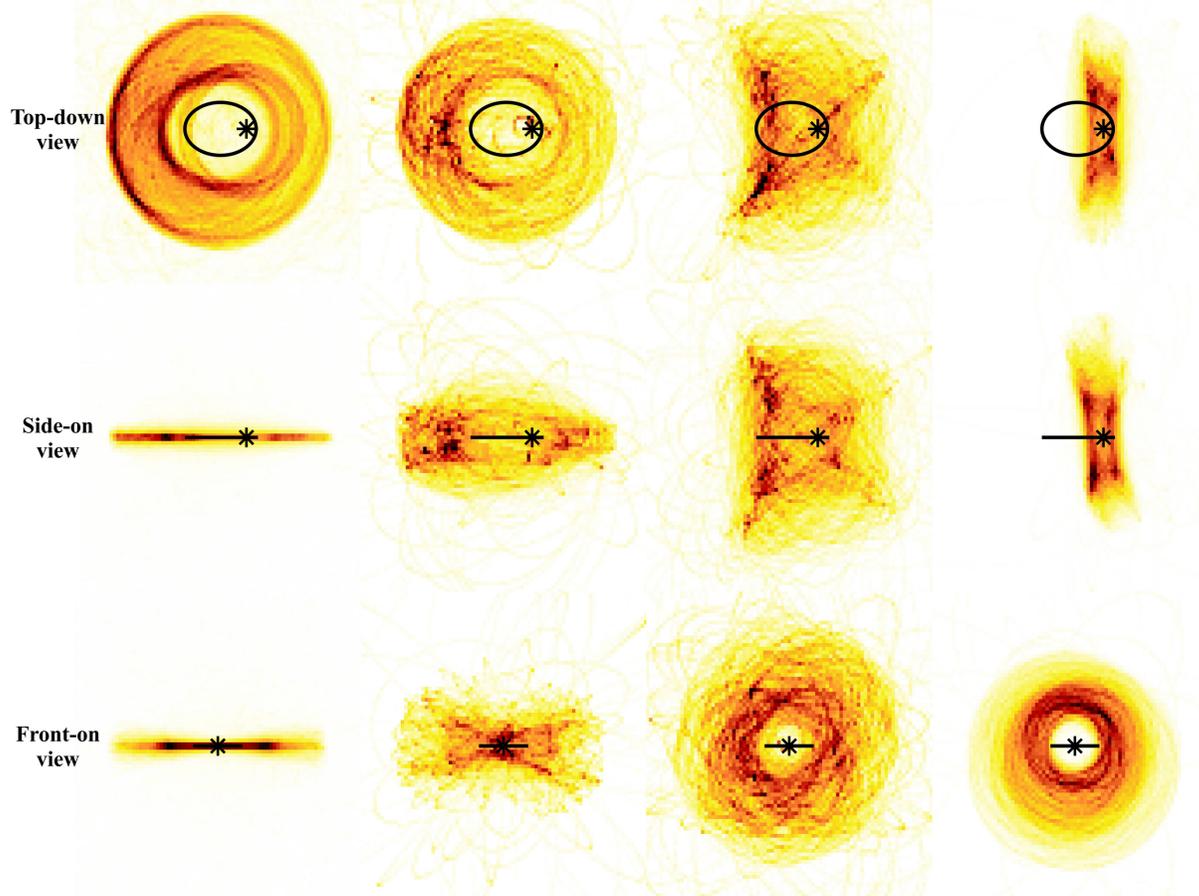
Evolution of test particle orbital planes, relative to the planet plane

### Planet in disc midplane ( $i_{\text{plt}} = 0^\circ$ )

### $i_{\text{plt}}$ small

### $i_{\text{plt}}$ moderate

### $i_{\text{plt}}$ large



### Evolution of the debris structure

Differing secular periods mean eventually all particles have different secular phases, and the debris structure assumes its final shape. This occurs after several of the outermost particle's secular times. Before then spirals may be present, and structures may not have aligned with the planet's orbit. An overdensity of scattered particles also exists around the planet's orbit early on.

