Planet formation and evolution in binary systems

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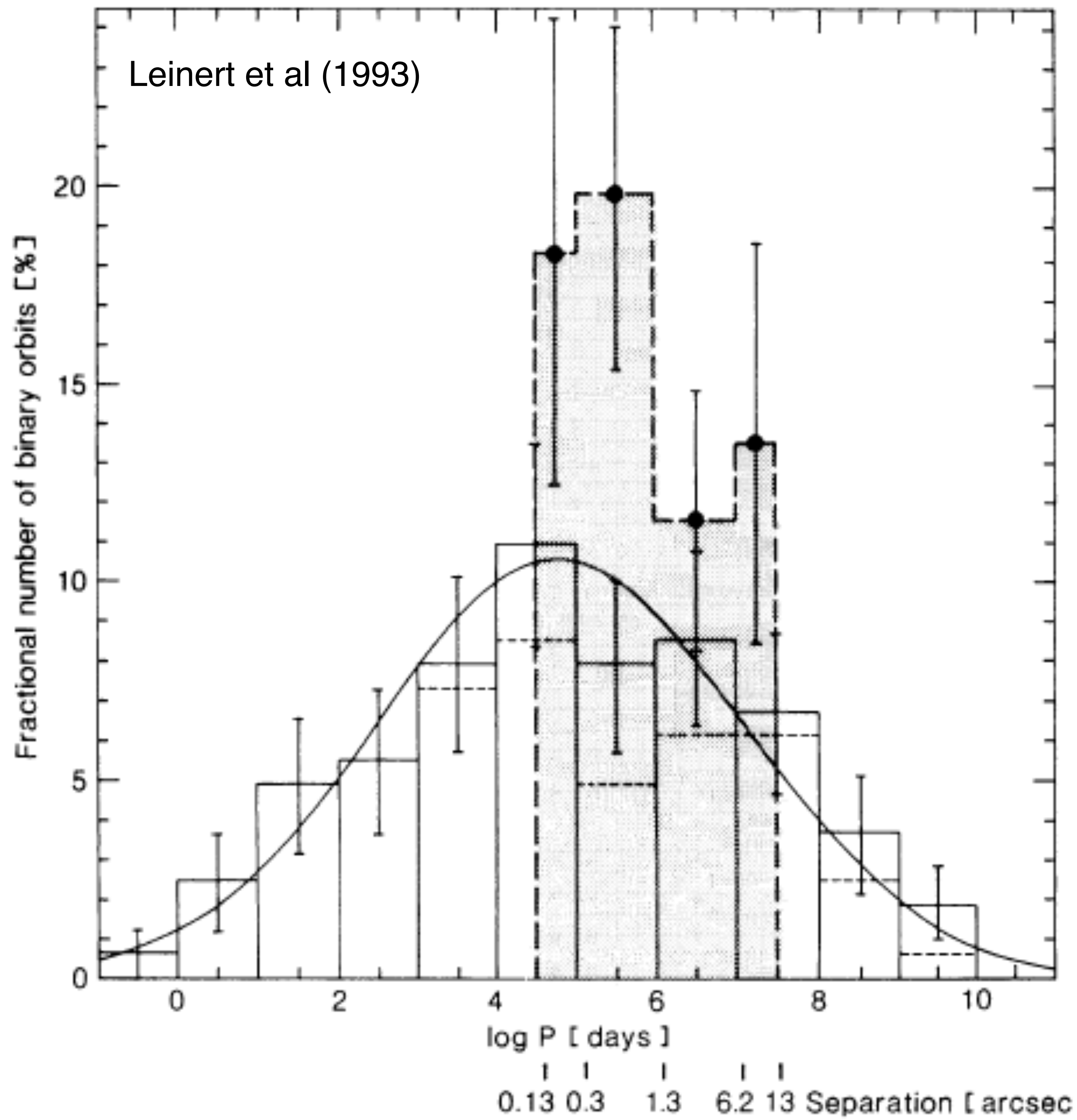
Observations of discs in external binaries

Approximately ~ 55% of field stars are members of binary star systems (Duquennoy & Mayor 1991; Raghavan et al 2010)

Approximately 65% of T Tauri stars are members of binary systems (Leinert et al 1993; Ghez et al 1993) with the peak in the distribution of separations occurring at ~ 30 AU.

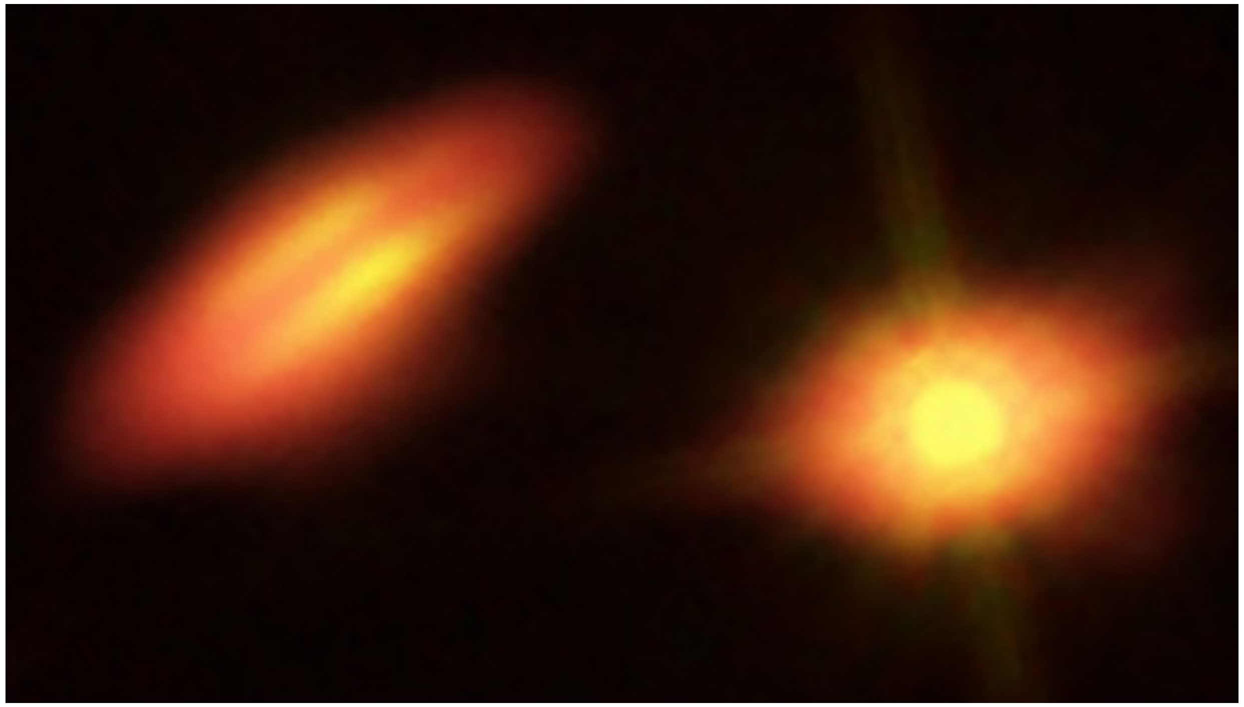
Approximately 20% of known exoplanet host stars are members of binary systems (Raghavan et al 2006). At least 3 exoplanet systems have binary companions with $a_b \sim 20$ AU (GJ 86, Gamma Ceph, HD41004)

ALMA observations show that discs in the binaries HK Tau and V2434 Ori are misaligned relative to the binary orbital plane (Jensen & Akeson 2014; Williams et al 2014)



Observations of discs in external binaries

Jensen & Akeson 2014



Approximately 60% of field stars are members of binary star systems (Duquennoy & Mayor 1991)

Approximately 65% of T Tauri stars are members of binary systems (Leinert et al 1993; Ghez et al 1993) with the peak in the distribution of separations occurring at ~ 30 AU.

At least 23% of known exoplanet host stars are members of binary systems (Raghavan et al 2006). At least 3 exoplanet systems have binary companions with a_b ~ 20 AU (GJ 86, Gamma Ceph, HD41004)

ALMA observations show that discs in the binaries HK Tau and V2434 Ori are misaligned relative to the binary orbital plane (Jensen & Akeson 2014; Williams et al 2014)

Observations of planets in external binaries

THE ASTROPHYSICAL JOURNAL, **331**:902–921, 1988 August 15

A SEARCH FOR SUBSTELLAR COMPANIONS TO SOLAR-TYPE STARS

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Received 1987 December 14; accepted 1988 February 4

p) HR 8974 (γ Cep).—Probable third body variation of 25 m s^{-1} amplitude, 2.7 yr period, superposed on a large velocity gradient. Status of astrometric perturbations is unknown.

Observations by Campbell et al (1988) hinted strongly at the presence of a planet in the binary system Gamma Cephei

Observations of planets in external binaries

THE ASTROPHYSICAL JOURNAL, 396: L91–L94, 1992 September 10

γ CEPHEI: ROTATION OR PLANETARY COMPANION?

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ABSTRACT

In 1988 we reported γ Cep as a single-line, long-period spectroscopic binary with short-term periodic ($P = 2.7$ yr) residuals which might be caused by a Jupiter-mass companion. Eleven years of data now give a 2.52 yr ($K = 27$ m s^{-1}) period and an indeterminate spectroscopic binary period of ≥ 30 yr. While binary motion induced by a Jupiter-mass companion could still explain the periodic residuals, γ Cep is almost certainly a velocity variable yellow giant because both the spectrum and $(R-I)$ color indices are typical of luminosity class III. $T_{\rm eff}$ and the trigonometric parallax give $R_* = 5.8\ R_\odot$ independently. The λ8662 Ca II emission line index varies in phase with the 2.52 yr period which, together with a low $v \sin i$ and the value of R_*, strongly implies that it is in fact the star's period of rotation.

Doubts about planetary status are expressed by Walker et al (1992)

Observations of planets in external binaries

THE ASTROPHYSICAL JOURNAL, 599:1383–1394, 2003 December 20

A PLANETARY COMPANION TO γ CEPHEI A

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Received 2003 April 30; accepted 2003 August 22

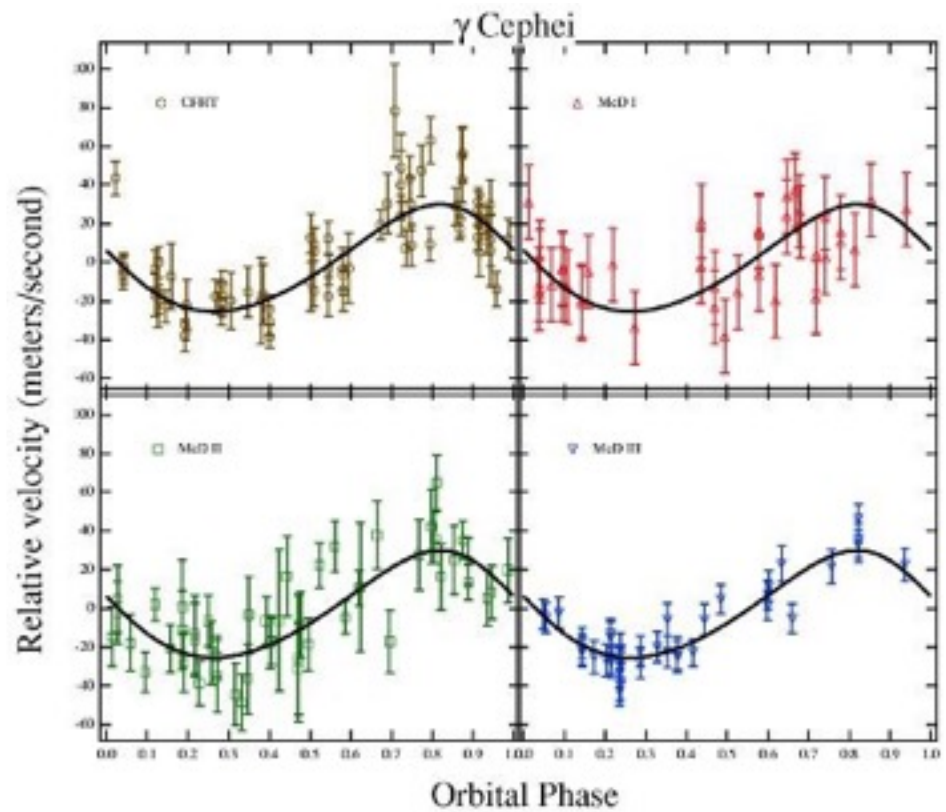
ABSTRACT

We report on the detection of a planetary companion in orbit around the primary star of the binary system γ Cephei. High-precision radial velocity measurements using four independent data sets spanning the time interval 1981–2002 reveal long-lived residual radial velocity variations superposed on the binary orbit that are coherent in phase and amplitude with a period or 2.48 yr (906 days) and a semiamplitude of 27.5 m s^{-1}.

Planet around Gamma Ceph confirmed by Hatzes et al (2003)

Observations of planets in external binaries

Gamma Ceph parameters from Hatzes et al (2003)



Binary Orbital Elements for γ Cep

Element	This Work	Griffin et al. 2002
Period (days)	20750.6579 ± 1568.6	24135 ± 349
T (JD)	248429.03 ± 27.0	248625 ± 210
Eccentricity	0.361 ± 0.023	0.389 ± 0.017
ω (deg)	158.76 ± 1.2	166 ± 7
K1 (km s^{-1})	1.82 ± 0.049	2.04 ± 0.10
$f(m)$ ($M_\odot$)	0.0106 ± 0.0012	0.0166 ± 0.0025
Semimajor axis (AU)	18.5 ± 1.1	20.3 ± 0.7
Reduced χ^2 (without planet)	4.36	...

Orbital Elements for Planet around γ Cep

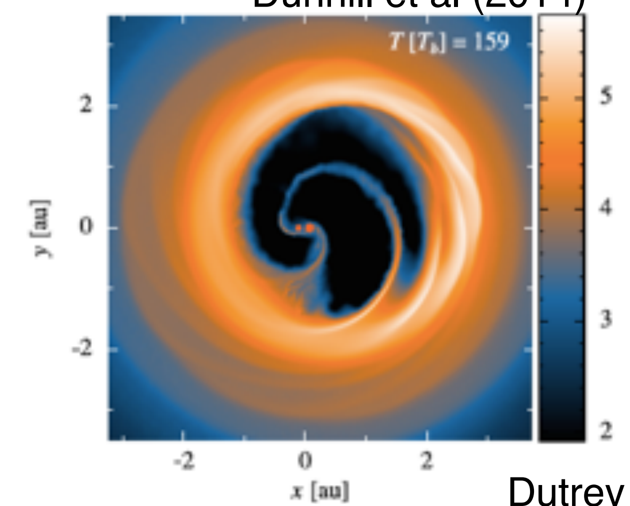
Element	Value
Period (days)	905.574 ± 3.08
T (JD)	253121.925 ± 66.9
Eccentricity	0.12 ± 0.05
ω (deg)	49.6 ± 25.6
K1 (m s^{-1})	27.50 ± 1.5
$f(m)$ ($M_\odot$)	$(1.90 \pm 0.3) \times 10^{-9}$
Semimajor axis (AU)	2.13 ± 0.05
Reduced χ^2	1.47
σ_{CFHT} (m s^{-1})	15.3
$\sigma_{\mathrm{Phase\,I}}$ (m s^{-1})	17.4
$\sigma_{\mathrm{Phase\,II}}$ (m s^{-1})	15.8
$\sigma_{\mathrm{Phase\,III}}$ (m s^{-1})	8.2

Note that stellar companion makes a closest approach of ~ 11.2 AU to primary star which hosts planet at a_p ~ 2.13 AU

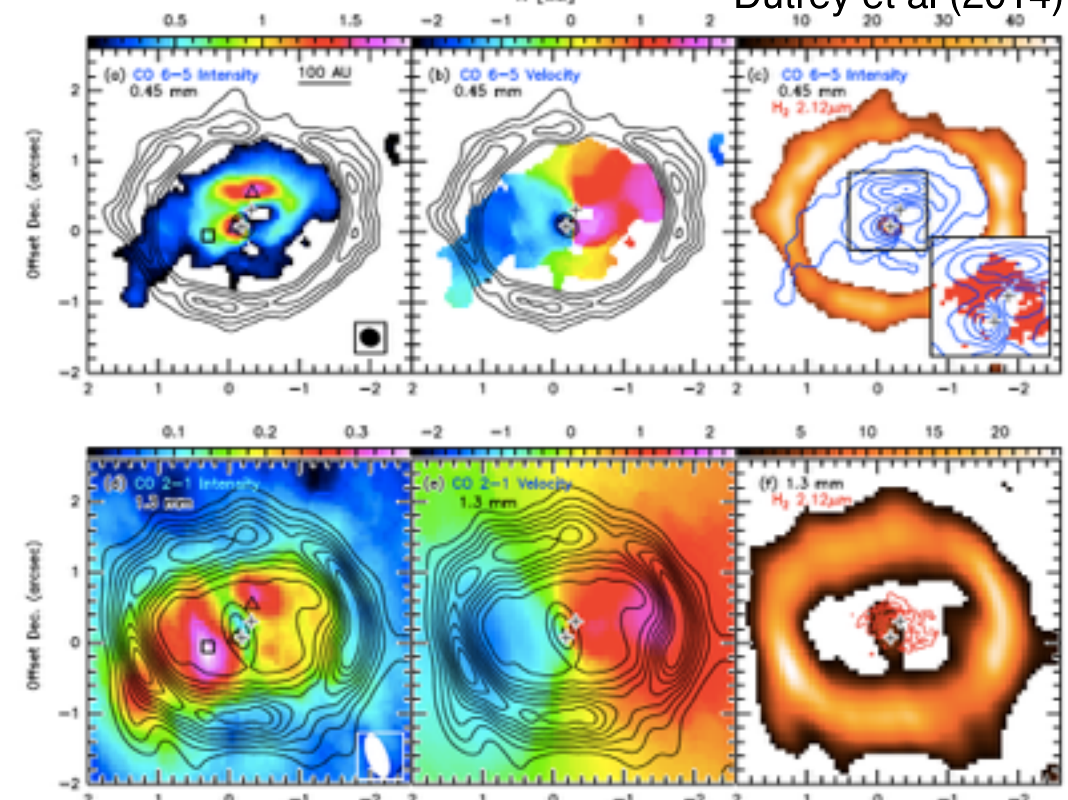
Observations of circumbinary discs

Herbig Ae/Be system HD 104237
Spectroscopic binary a_b=0.22 AU, e=0.6, T_b=20 days (Bohm et al 2004; Garcia et al 2013)

Dunhill et al (2014)

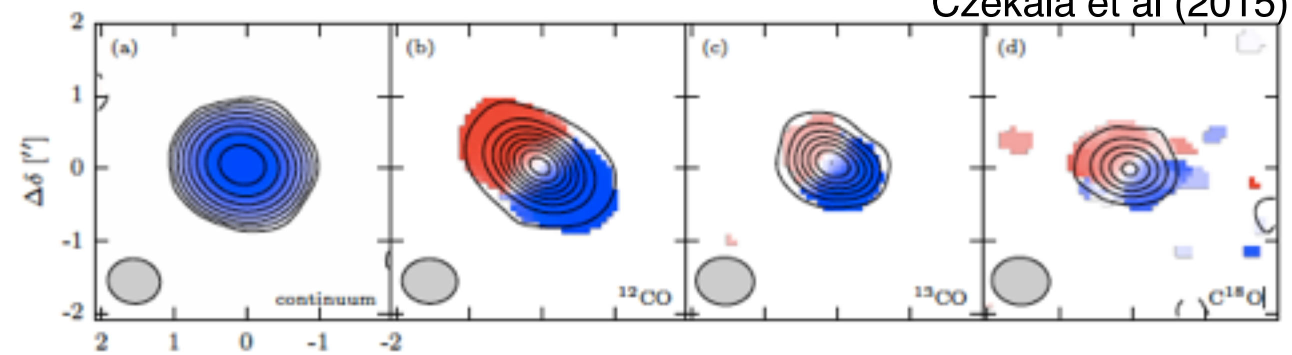


Dutrey et al (2014)



GG Tau - Hierarchical triple with a_b=35 AU and 4.5 AU surrounded by ring circumbinary with inner and outer radii ~ 190 and 240 AU (Dutrey et al 2014)

Czekala et al (2015)



AK Sco - 18 Myr old binary with two F5 stars on 13.6 day period and e_b=0.47 (Czekala et al 2015)

Observations of circumbinary planets

Confirmed circumbinary planets [edit]

Star system	Planet	Mass (M_J)	Semimajor axis (AU)	Orbital period (y)	Discovered	Ref	Discovery method
PSR B1620-26	b	2.5	23	100	2003		Pulsar timing
DP Leonis	b	6.28 ± 0.58	8.6	23.8	2009		Eclipsing binary timing
NN Serpentis	c	6.91 ± 0.54	5.38 ± 0.20	15.50 ± 0.45	2010		Eclipsing binary timing
NN Serpentis	d	2.28 ± 0.38	3.39 ± 0.10	7.75 ± 0.35	2010	[24]	Eclipsing binary timing
DT Virginis	c	8.5 ± 2.5	1168	33081	2010		Imaging
Kepler-16	b	0.333 ± 0.016	0.7048 ± 0.0011	0.6266 ± 0.0001	2011	[25]	Transit
NY Virginis	b	2.3 ± 0.3	3.3	7.9	2011	[26]	Eclipsing binary timing
RR Caeli	b	4.2 ± 0.4	5.3 ± 0.6	11.9	2012	[27]	Eclipsing binary timing
Kepler-34	b	0.220 ± 0.0011	1.0896 ± 0.0009	0.7908 ± 0.0002	2012	[28]	Transit
Kepler-35	b	0.127 ± 0.02	0.603 ± 0.001	0.3600 ± 0.1	2012	[28]	Transit
Kepler-38	b	≤ 0.38	0.4644 ± 0.0082	0.289	2012	[29]	Transit
Kepler-47	b	*unknown*	0.2956 ± 0.0047	0.136	2012	[30]	Transit
Kepler-47	c	*unknown*	0.989 ± 0.016	0.83	2012	[30]	Transit
Kepler 64	PH1	0.11 ± 0.3	0.634 ± 0.011	0.379	2012		Transit
ROXs 42B	ROXs 42Bb	10±4	140		2013		Imaging
FW Tauri	FW Tauri b	10±4	330		2013		Imaging
Kepler-413	b	0.21	0.3553	0.181	2014	[31]	Transit

Note that all Kepler circumbinary planets are sub-Jovian in mass

Observations of circumbinary planets - Kepler 16b

The Kepler-16 planetary system[5]

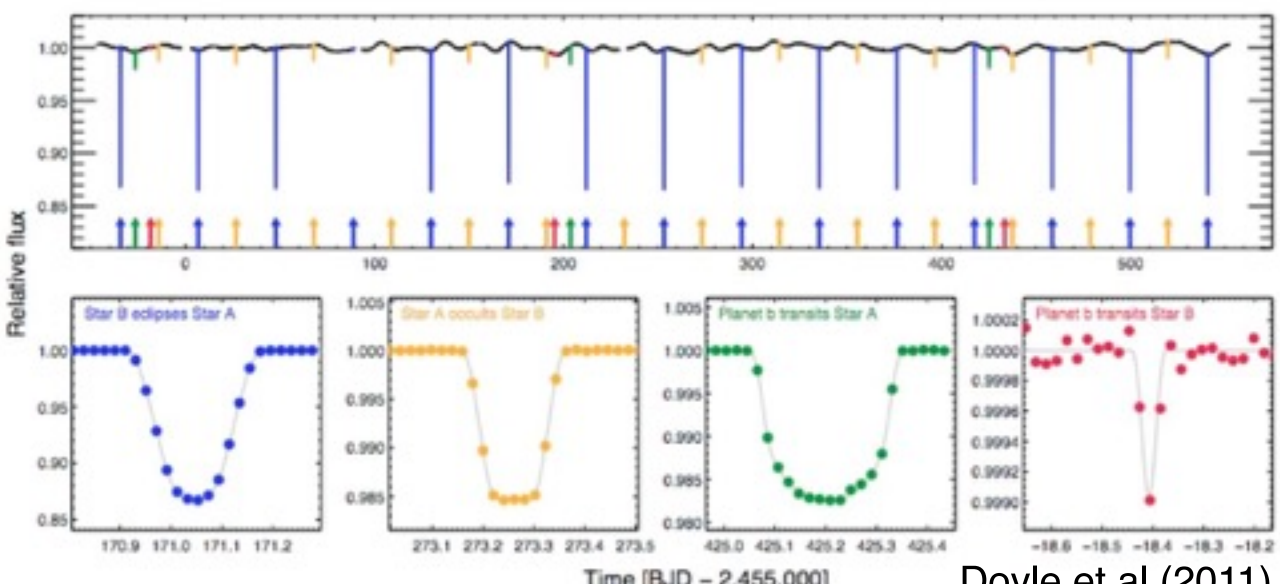
Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Inclination	Radius
b	0.333 M_J	0.7048	228.776	0.0069	90.032°	0.7538 R_J

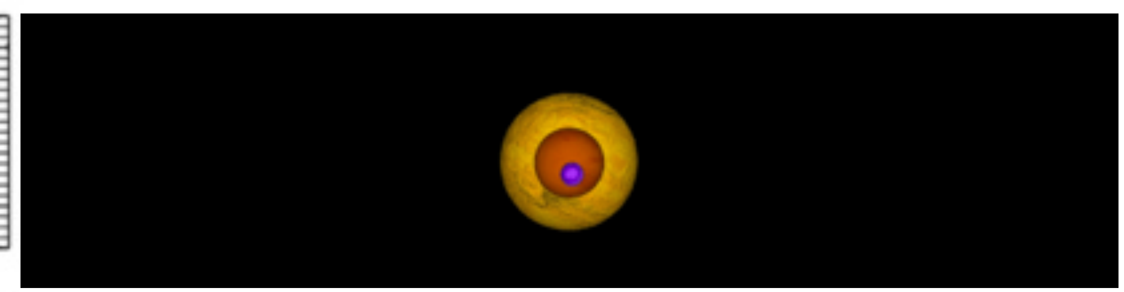
Orbit[2]

Primary	Kepler-16A
Companion	Kepler-16B
Period (P)	41.079220 (± 0.000078) d
Semi-major axis (a)	0.22431 (± 0.00035) AU
Eccentricity (e)	0.15944 (± 0.00062)
Inclination (i)	90.30401 (± 0.0019)°

Details

Kepler-16A	
Mass	0.6897 (± 0.0035) $M_\odot$
Radius	0.6489 (± 0.0013) $R_\odot$
Surface gravity (log g)	4.6527 (± 0.0017) cgs
Temperature	4450 (± 150) K
Metallicity [Fe/H]	-0.3 (± 0.2) dex
Rotation	35.1 ± 1.0 days[3]
Kepler-16B	
Mass	0.20255 (± 0.00065) $M_\odot$
Radius	0.22623 (± 0.00059) $R_\odot$





Doyle et al (2011)

Observations of circumbinary planets - Kepler 34b

The Kepler-34 planetary system

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Inclination	Radius
b	0.220 M_J	1.0896	288.822	0.182	90.355°	0.764 R_J

Orbit	
Primary	Kepler-34A
Companion	Kepler-34B
Period (P)	27.7958103 (± 0.0000016) d
Semi-major axis (a)	0.22882 (± 0.00019) AU
Eccentricity (e)	0.52087 (± 0.00055)
Inclination (i)	89.8584 (± 0.0080)°

Details	
Kepler-34A	
Mass	1.0479 (± 0.0033) $M_{\odot}$
Radius	1.1618 (± 0.0030) $R_{\odot}$
Temperature	5913 (± 130) K
Metallicity	-0.07 (± 0.15)
Kepler-34B	
Mass	1.0208 (± 0.0022) $M_{\odot}$
Radius	1.0927 (± 0.0030) $R_{\odot}$
Temperature	5867 K

Observations of circumbinary planets - Kepler 35b

The Kepler-35 planetary system

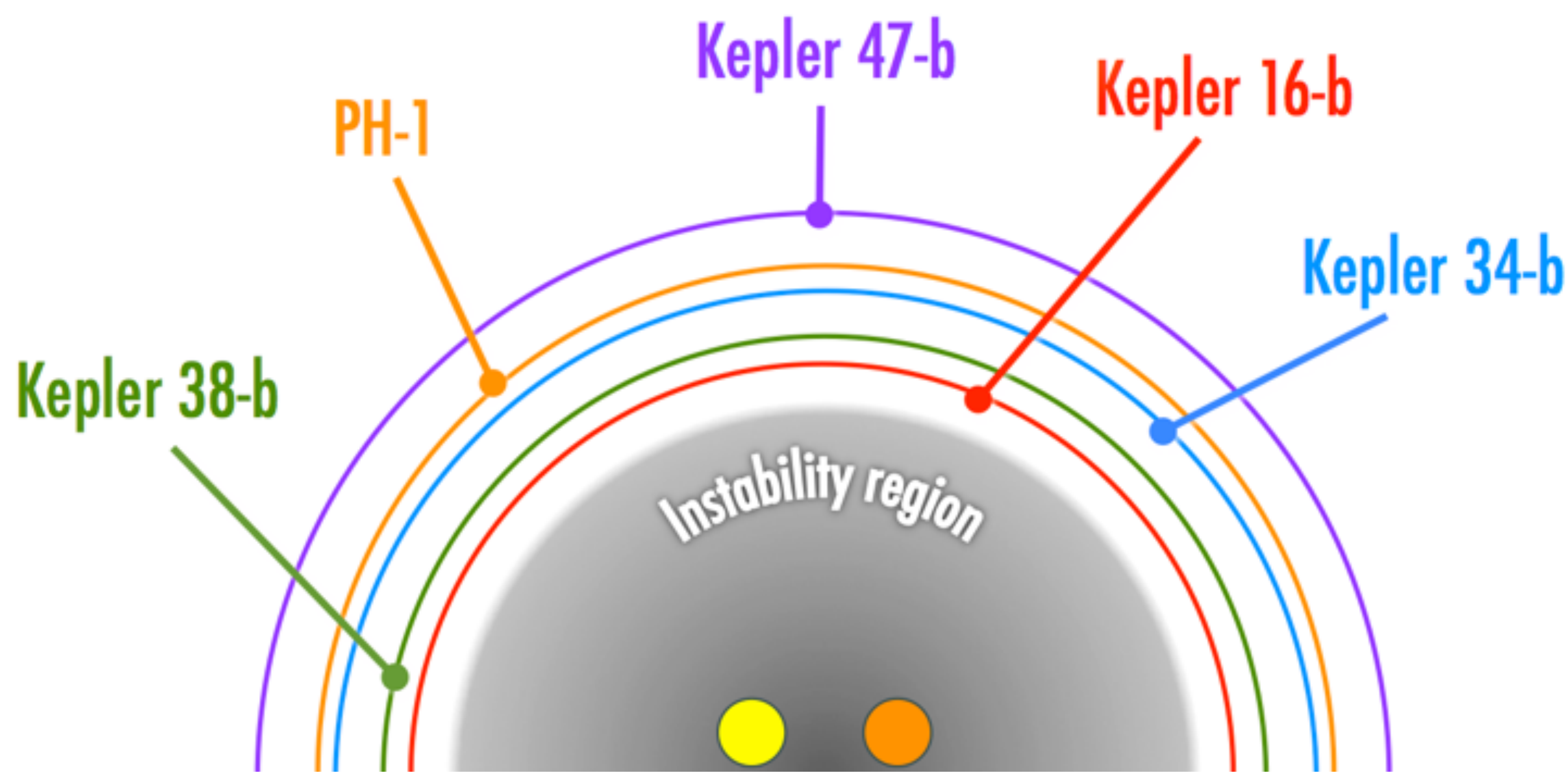
Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Inclination	Radius
b	0.127 M_J	0.60347	131.458	0.042	90.760°	0.728 R_J

Orbit	
Primary	Kepler-35A
Companion	Kepler-35B
Period (P)	20.73
Semi-major axis (a)	0.176

Details	
Kepler-35A	
Mass	0.8877 $M_\odot$
Radius	1.0284 $R_\odot$
Temperature	5606 K
Metallicity	-0.13
Kepler-35B	
Mass	0.8094 $M_\odot$
Radius	0.7861 $R_\odot$
Temperature	5202 K
Metallicity	-0.13

Observed circumbinary planets

(orbits normalized to the instability region)



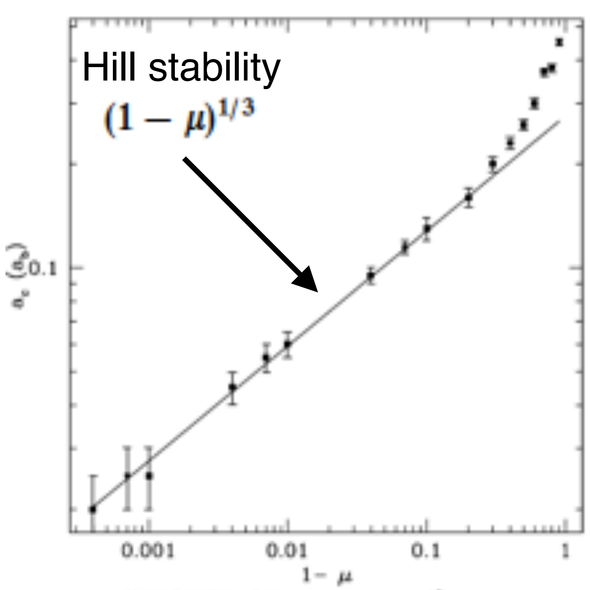
Orbital stability in binary systems

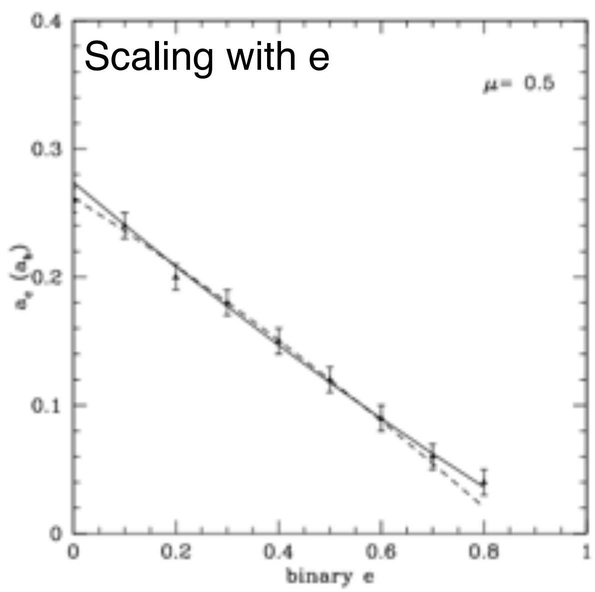
S-type orbits - planet orbits around one component (Holman & Wiegert 1999)
P-type orbits - planet orbits around both components

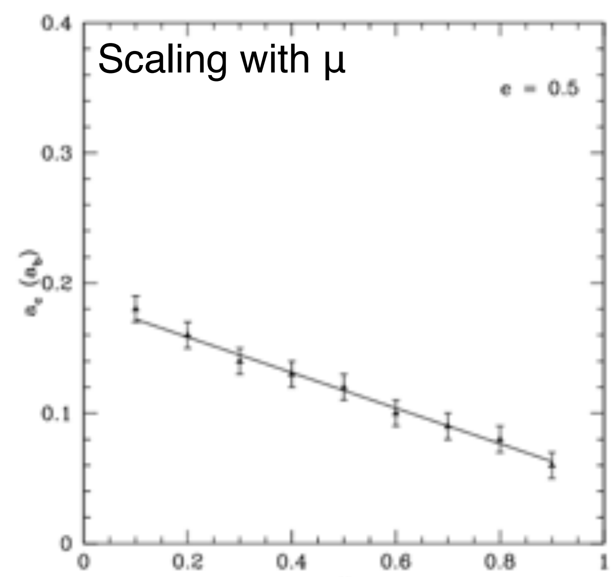
- N-body simulations conducted covering broad range of binary mass ratios and eccentricities using restricted elliptic 3-body approx.

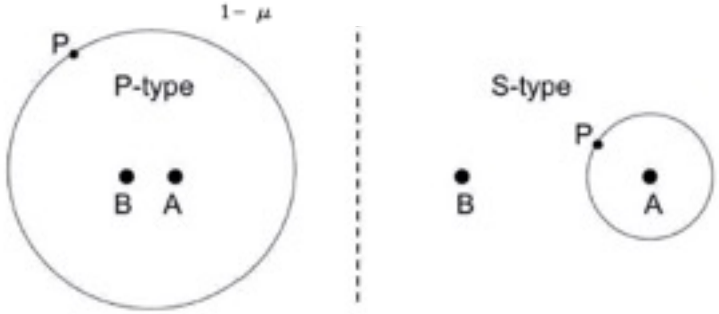
<u>S-type results:</u>

$$a_c = [(0.464 \pm 0.006) + (-0.380 \pm 0.010)\mu + (-0.631 \pm 0.034)e + (0.586 \pm 0.061)\mu e + (0.150 \pm 0.041)e^2 + (-0.198 \pm 0.074)\mu e^2]a_b$$









INITIAL CONDITIONS FOR THE BINARIES AND TEST PARTICLES

Inner Region		Outer Region
	Binaries	
	$a_b = 1.0$	
$0.1 \le \mu \le 0.9$		$0.1 \le \mu \le 0.5$
	$\Delta\mu = 0.1$	
$0.0 \le e \le 0.8$		$0.0 \le e \le 0.7$
	$\Delta e = 0.1$	
	Binary phase: periapse or apapse	
	Test Particles	
$0.02a_b \le a \le 0.5a_b$		$1.0a_b \le a \le 5.0a_b$
$\Delta a = 0.0025$–$0.01a_b$		$\Delta a = 0.1a_b$
	$e_p = i = \Omega = \omega = 0.0$	
	$M = 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°$	

NOTE.—The binary semimajor axis is a_b, its eccentricity is e, and its mass ratio $\mu = m_2/(m_1 + m_2)$. A test particle's initial semimajor axis, eccentricity, inclination relative to the binary plane, longitude of the ascending node, argument of perihelion, and mean anomaly are designated by a, e_p, i, Ω, ω, and M, respectively.

Holman & Wiegert (1999)

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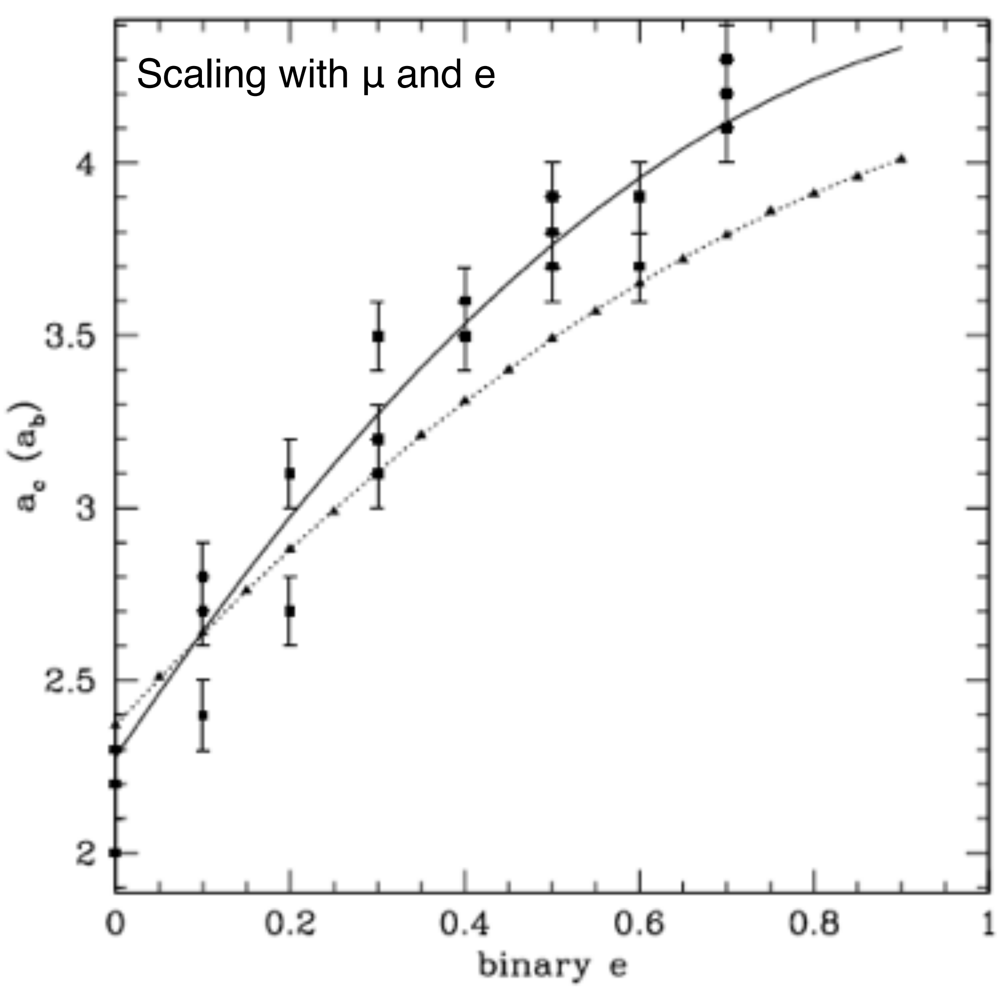
S-type orbits - planet orbits around one component (Holman & Wiegert 1999)
P-type orbits - planet orbits around both components

- N-body simulations conducted covering broad range of binary mass ratios and eccentricities using restricted elliptic 3-body approx.

<u>P-type results:</u>

$$a_c = (1.60 \pm 0.04) + (5.10 \pm 0.05)e + (-2.22 \pm 0.11)e^2 + (4.12 \pm 0.09)\mu + (-4.27 \pm 0.17)e\mu + (-5.09 \pm 0.11)\mu^2 + (4.61 \pm 0.36)e^2\mu^2 \,.$$



Initial Conditions for the Binaries and Test Particles

Inner Region		Outer Region
	Binaries	
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	$\Delta\mu = 0.1$	
$0.0 \le e \le 0.8$		$0.0 \le e \le 0.7$
	$\Delta e = 0.1$	
	Binary phase: periapse or apapse	
	Test Particles	
$0.02a_b \le a \le 0.5a_b$		$1.0a_b \le a \le 5.0a_b$
$\Delta a = 0.0025$–$0.01a_b$		$\Delta a = 0.1a_b$
	$e_p = i = \Omega = \omega = 0.0$	
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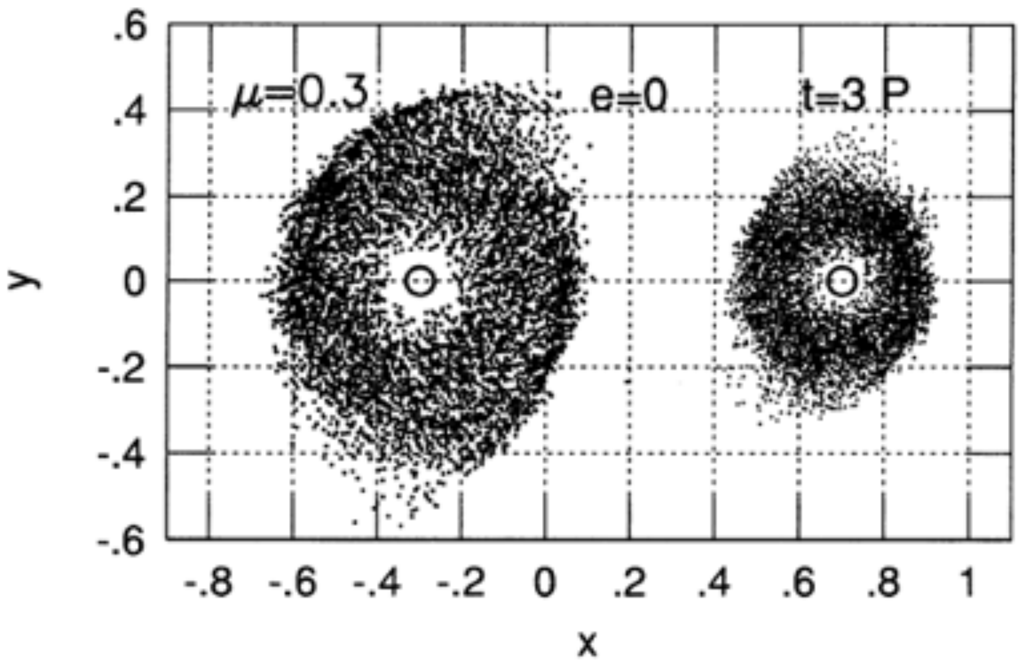
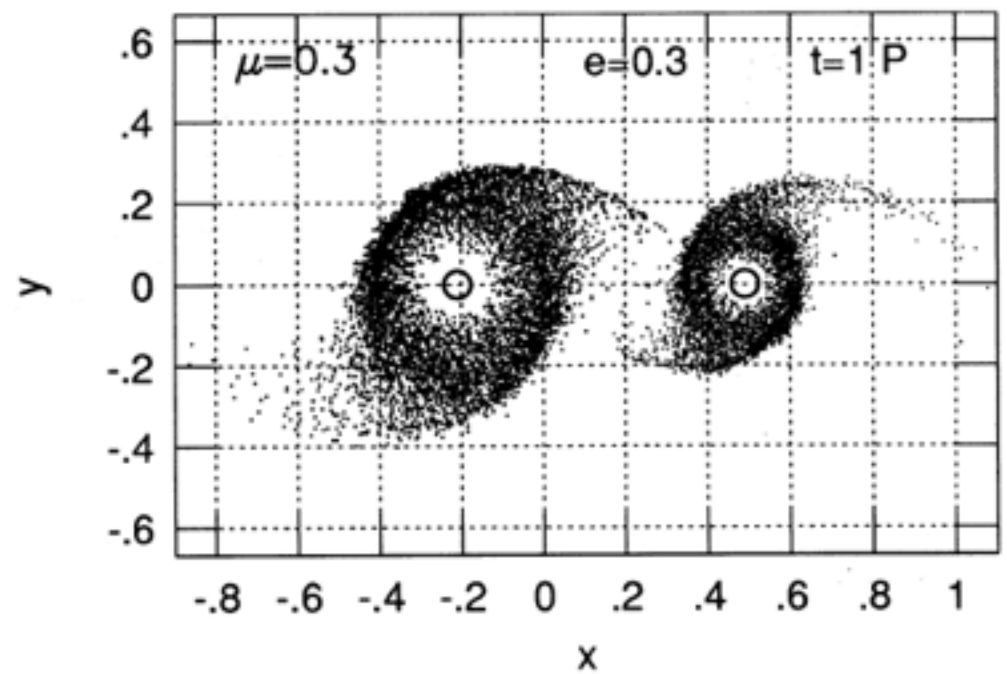
Note.—The binary semimajor axis is a_b, its eccentricity is e, and its mass ratio $\mu = m_2/(m_1 + m_2)$. A test particle's initial semimajor axis, eccentricity, inclination relative to the binary plane, longitude of the ascending node, argument of perihelion, and mean anomaly are designated by $a, e_p, i, \Omega, \omega$, and M, respectively.

External binaries - tidal truncation

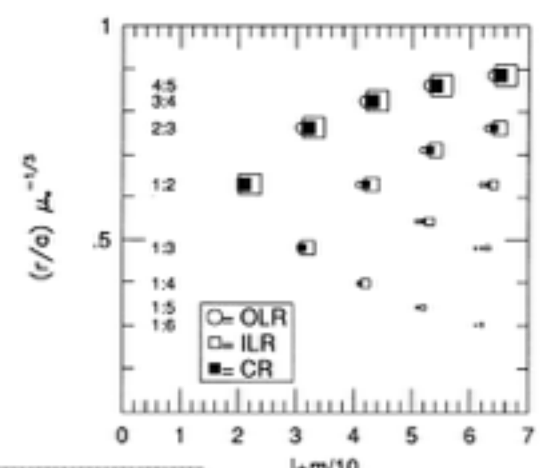




Eccentric binary excites spiral waves at Lindblad resonances that can truncate disc (Artymowicz & Lubow 2004)

Gap formation criteria extended to include torque from eccentric Lindblad resonances being balanced with viscous torque in disc

Calibrated using SPH simulations

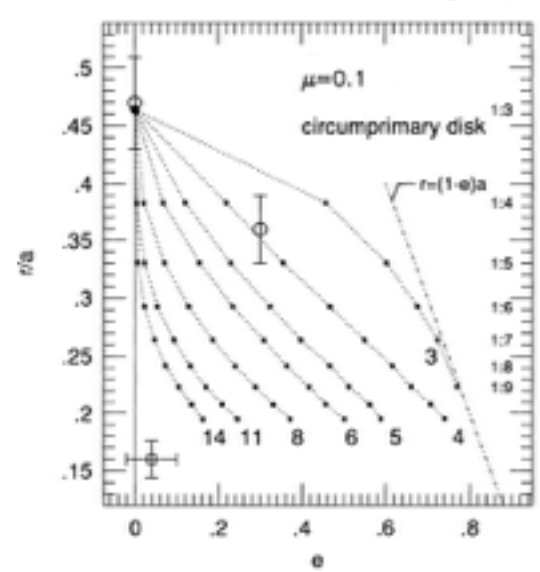


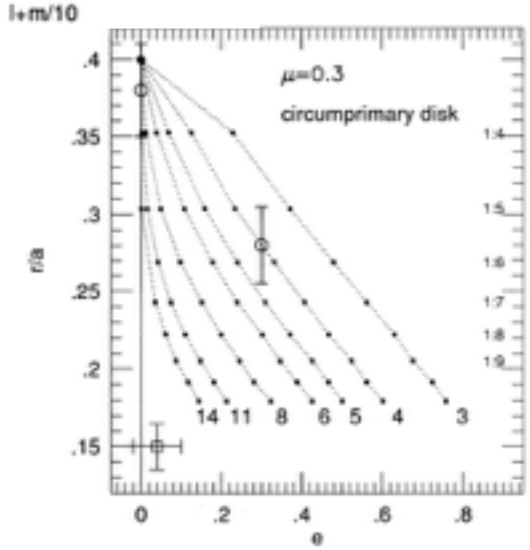
Note μ_* is mass parameter of the central star $m_1/(m_1+m_2)$

μ is mass parameter of secondary star

For stellar mass ratios $\mu > 0.1$ disc is not truncated by 2:1 ILR as it is not contained in Roche lobe. For circular orbit binary, truncation arises because of particle orbit crossing near edge of Roche lobe (Paczynski 1977)

For eccentric binaries the eccentric Lindblad resonances can truncate disc. For Reynolds number ~ 10^5 -10^6 and e ~ 0.4 disc is truncated at ~ 0.3a





External binaries - planetesimal accumulation

Secular evolution of planetesimals under influence of external binary companion on eccentric orbit first considered by Heppenheimer (1978) and more recently by Marzari & Scholl (2000)

In absence of gas drag predict that eccentricities and periastra oscillate with a frequency that increases with planetesimal semimajor axis.

Orbital de-phasing causes orbits of neighbouring planetesimals to cross and increases collisional velocities

$\longrightarrow$ catastrophic disruption

$$h = e \sin(\tilde{\omega})$$

$$k = e \cos(\tilde{\omega})$$

$$\frac{dh}{dt} = Ak - B \qquad A = \frac{3}{4}\frac{m_P}{n(1-e_B^2)^{3/2}}$$

$$\frac{dk}{dt} = -Ah\,, \qquad B = \frac{15}{16}\frac{ae_B}{(1-e_B^2)^{5/2}}\,,$$

$$\downarrow$$

$$h(t) = e_P \sin(At + \tilde{\omega}_0)$$

$$k(t) = e_P \cos(At + \tilde{\omega}_0) + \frac{B}{A}\,,$$

$$\frac{B}{A} = \frac{5}{4}\frac{ae_B}{(1-e_B^2)} \qquad A = \frac{3}{4}\frac{\sqrt{m_P}\,a^{3/2}}{(1-e_B^2)^{3/2}}$$

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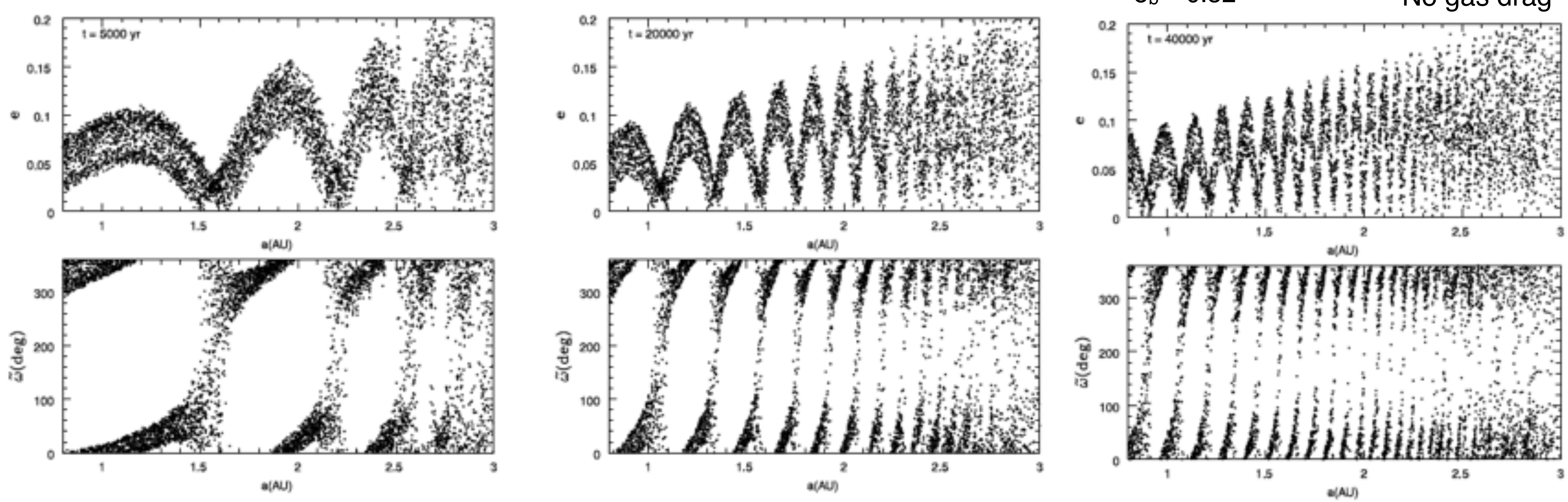
⟶ catastrophic disruption

Alpha Centauri A and B:
$a_b = 24$ AU
$e_b = 0.52$

No gas drag



Marzari & Scholl (2000)

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$$\downarrow$$

$$h(t) = e_P \sin(At + \tilde{\omega}_0)$$
$$k(t) = e_P \cos(At + \tilde{\omega}_0) + \frac{B}{A}\,,$$

$$\frac{B}{A} = \frac{5}{4}\frac{ae_B}{(1-e_B^2)} \qquad A = \frac{3}{4}\frac{\sqrt{m_P}\,a^{3/2}}{(1-e_B^2)^{3/2}}$$

Influence of gas drag can be incorporated into secular equations (drag force ~ e^2)

When D > B/A then longitude of pericentre halts circulation and approaches value 270^0 for increasing values of D/A
$\longrightarrow$ alignment of eccentric orbits reduces impact velocities

$$\frac{dh}{dt} = Ak - B - Dh(h^2 + k^2)^{1/2}$$
$$\frac{dk}{dt} = -Ah - Dk(h^2 + k^2)^{1/2}$$

External binaries - planetesimal accumulation

Secular evolution of planetesimals under influence of external binary companion on eccentric orbit first considered by Heppenheimer (1978) and more recently by (Marzari & Scholl 2000)

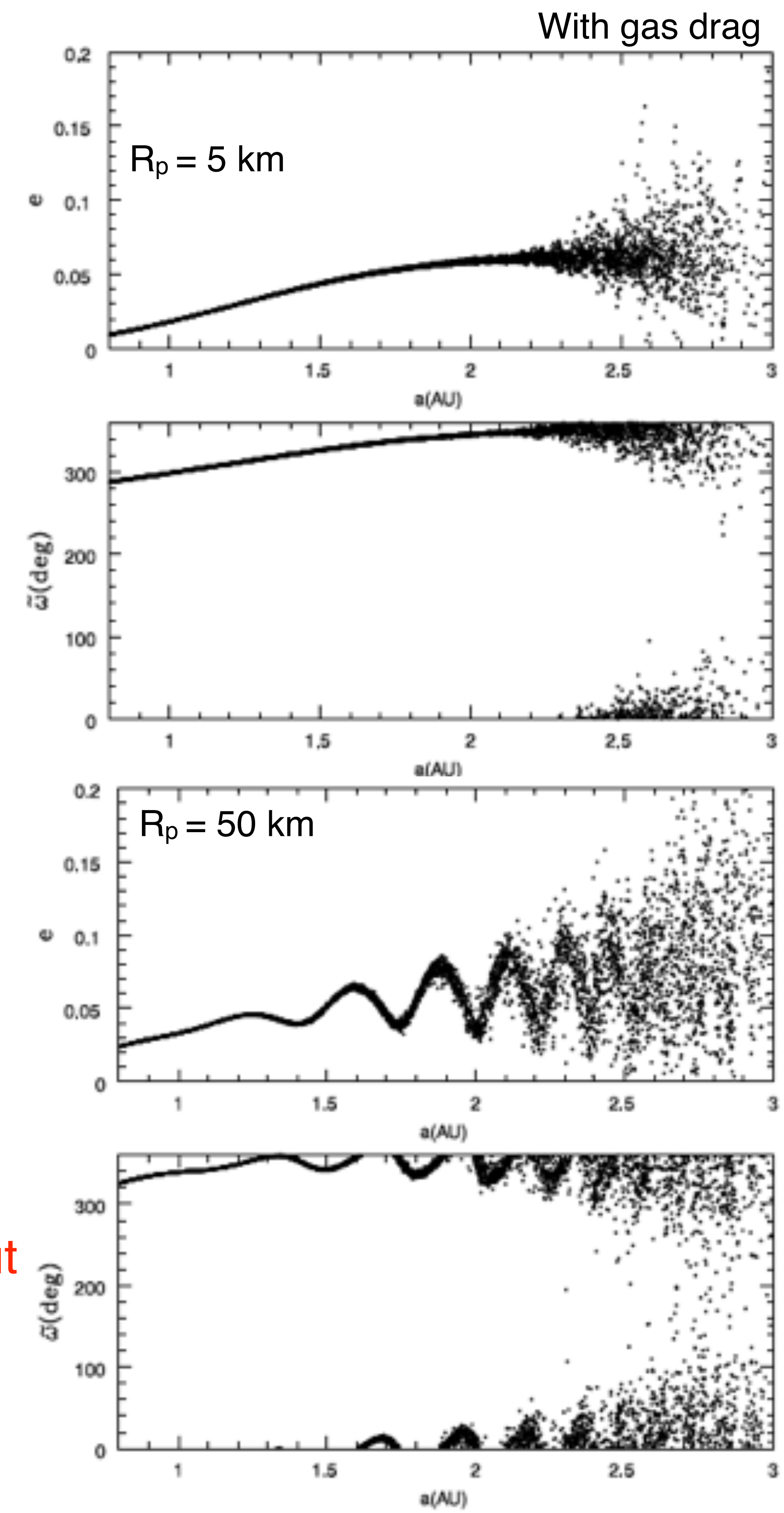
In absence of gas drag predict that eccentricities and periastra oscillate with a frequency that increases with planetesimal semimajor axis.

Orbital de-phasing causes orbits of neighbouring planetesimals to cross and increases collisional velocities
$\longrightarrow$ catastrophic disruption

Influence of gas drag can be incorporated into secular equations (drag ~ e^2)

When D > B/A then longitude of pericentre halts circulation and approached value 270^0 for increasing values of D/A
$\longrightarrow$ alignment of eccentric orbits reduces impact velocities

These results suggest planetesimal accumulation can occur without fear of disruption interior to 2 AU in disc around Alpha Cen A
(see also Thebault et al (2004) for Gamma Cephei case)



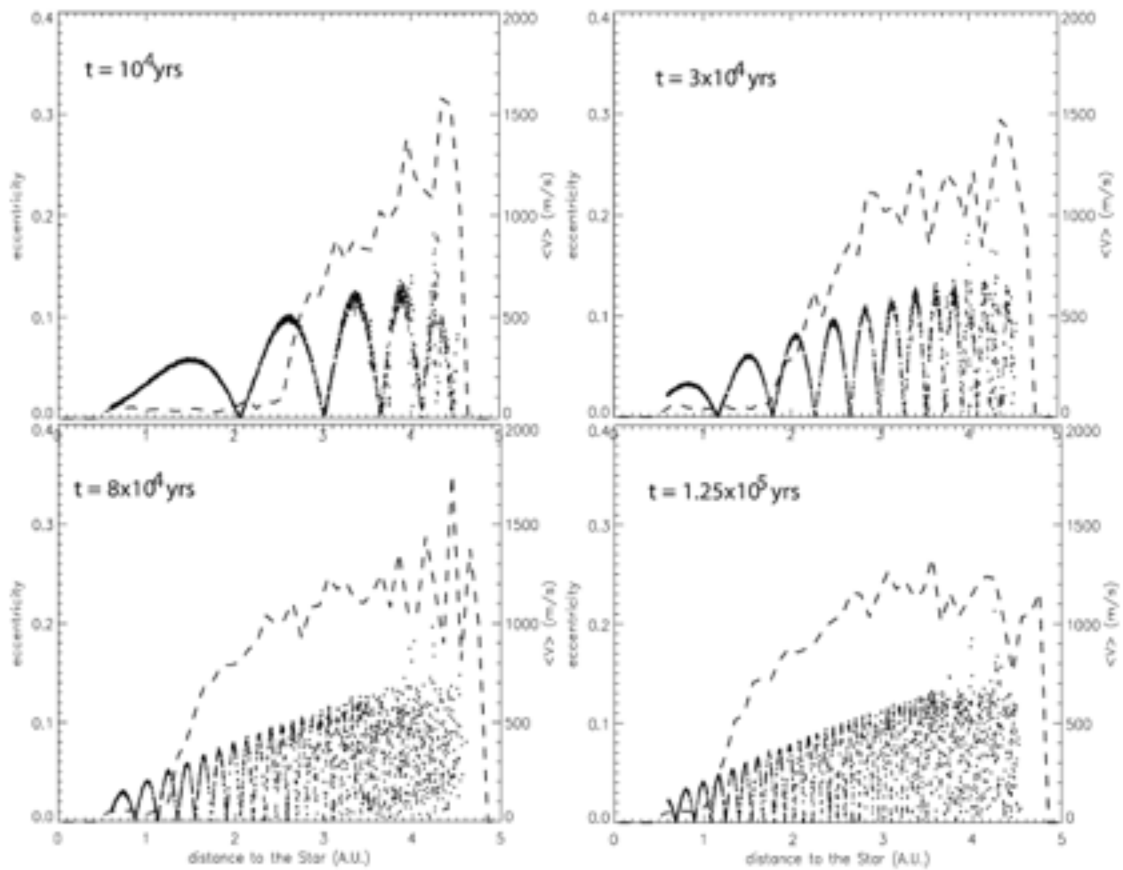
External binaries - planetesimal accumulation

Orbital phasing in presence of gas drag is size dependent

(Thebault et al 2006)

Planetesimals of different size may collide at high velocity leading to catastrophic disruption. Runaway growth difficult to achieve for $a_b < 50$ AU and $0.1 < e_b < 0.9$ at 1 AU

No gas drag



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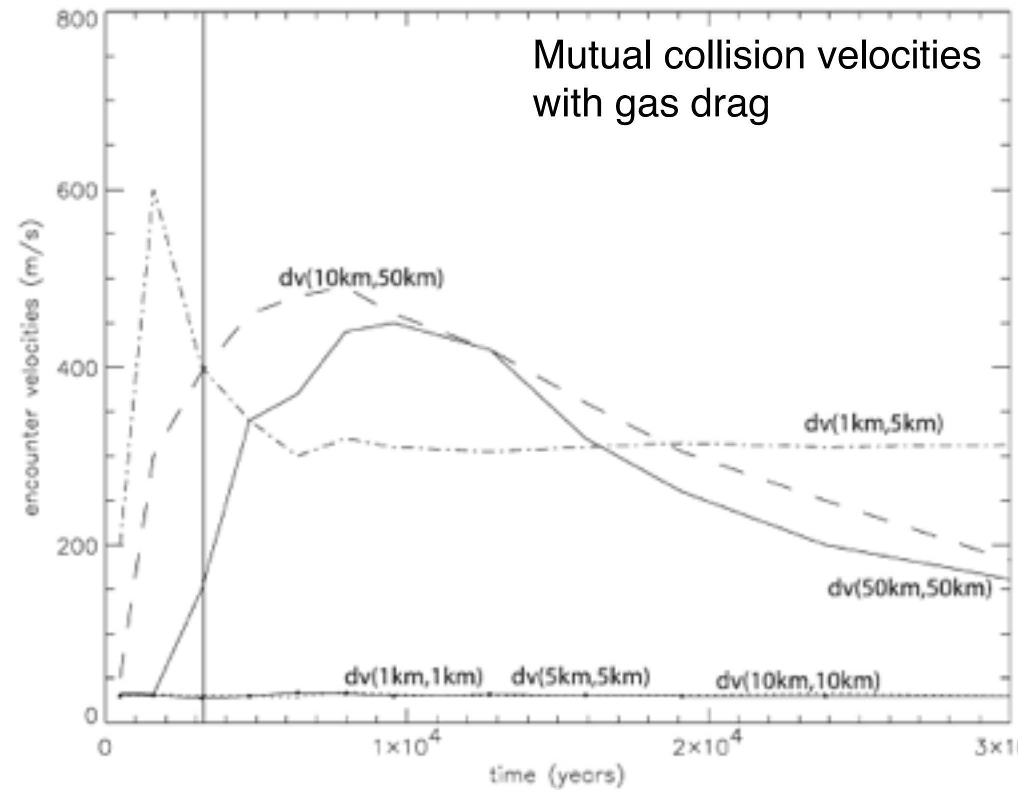

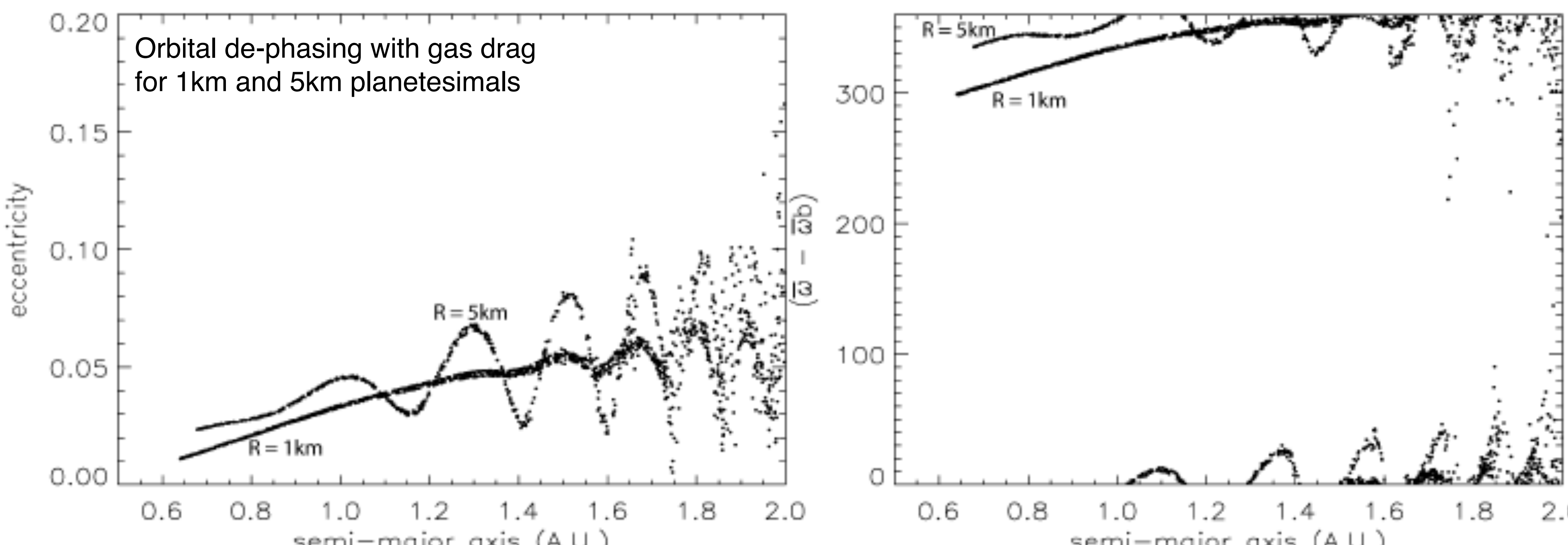

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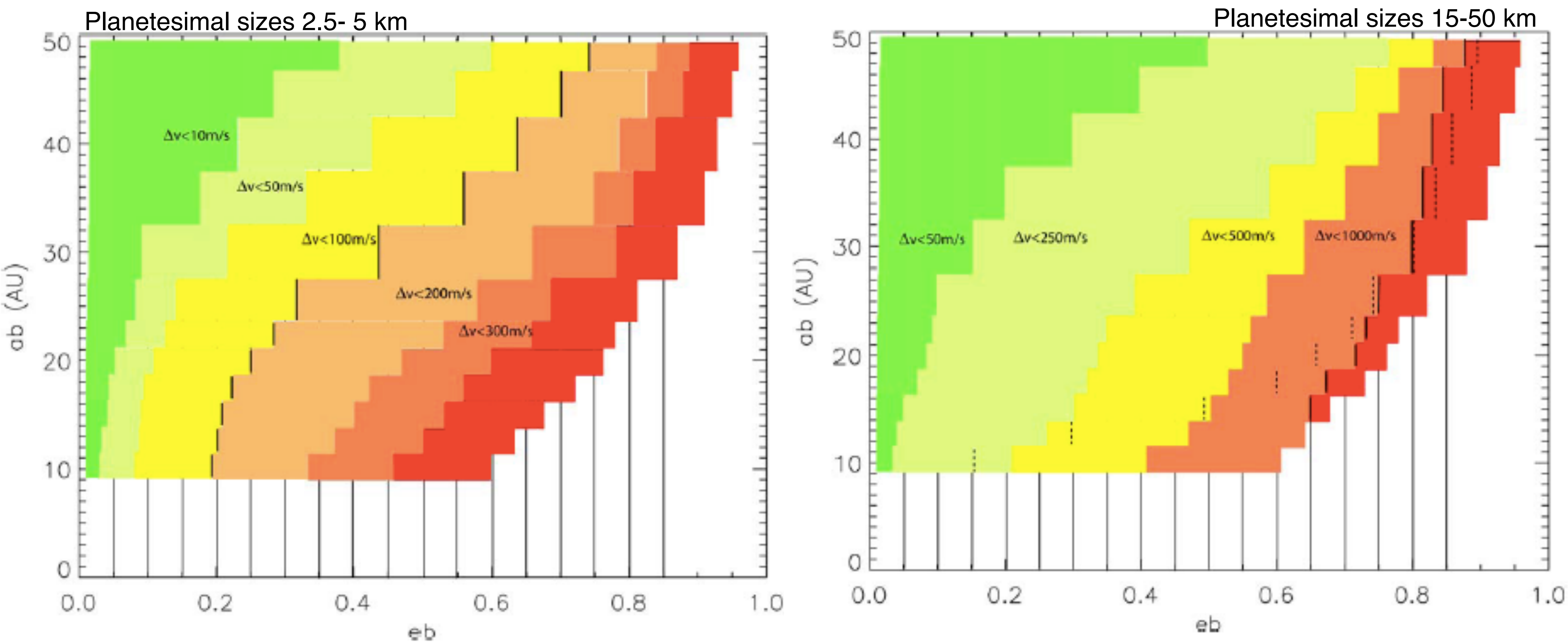

Collision velocities as function of binary semimajor axis and eccentricity. Regions of guaranteed catastrophic disruption shown by black outline for planetesimals located at 1 AU. Even if planetesimals don't disrupt the effective velocity dispersion is too high for runaway growth

External binaries - planetesimal accumulation

Orbital phasing in presence of gas drag is size dependent

(Thebault et al 2006)

Planetesimals of different size may collide at high velocity leading to catastrophic disruption. Runaway growth difficult to achieve for $a_b < 50$ AU and $0.1 < e_b < 0.9$ at 1 AU.

Planet formation in α Centauri A revisited: not so accretion friendly after all

P. Thébault,[1,2]★ F. Marzari[3] and H. Scholl[4]

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[2] *Observatoire de Paris, Section de Meudon, F-92195 Meudon Principal Cedex, France*
[3] *Department of Physics, University of Padova, Via Marzolo 8, 35131 Padova, Italy*
[4] *Laboratoire Cassiopée, Universit de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, B.P. 4229, F-06304 Nice, France*

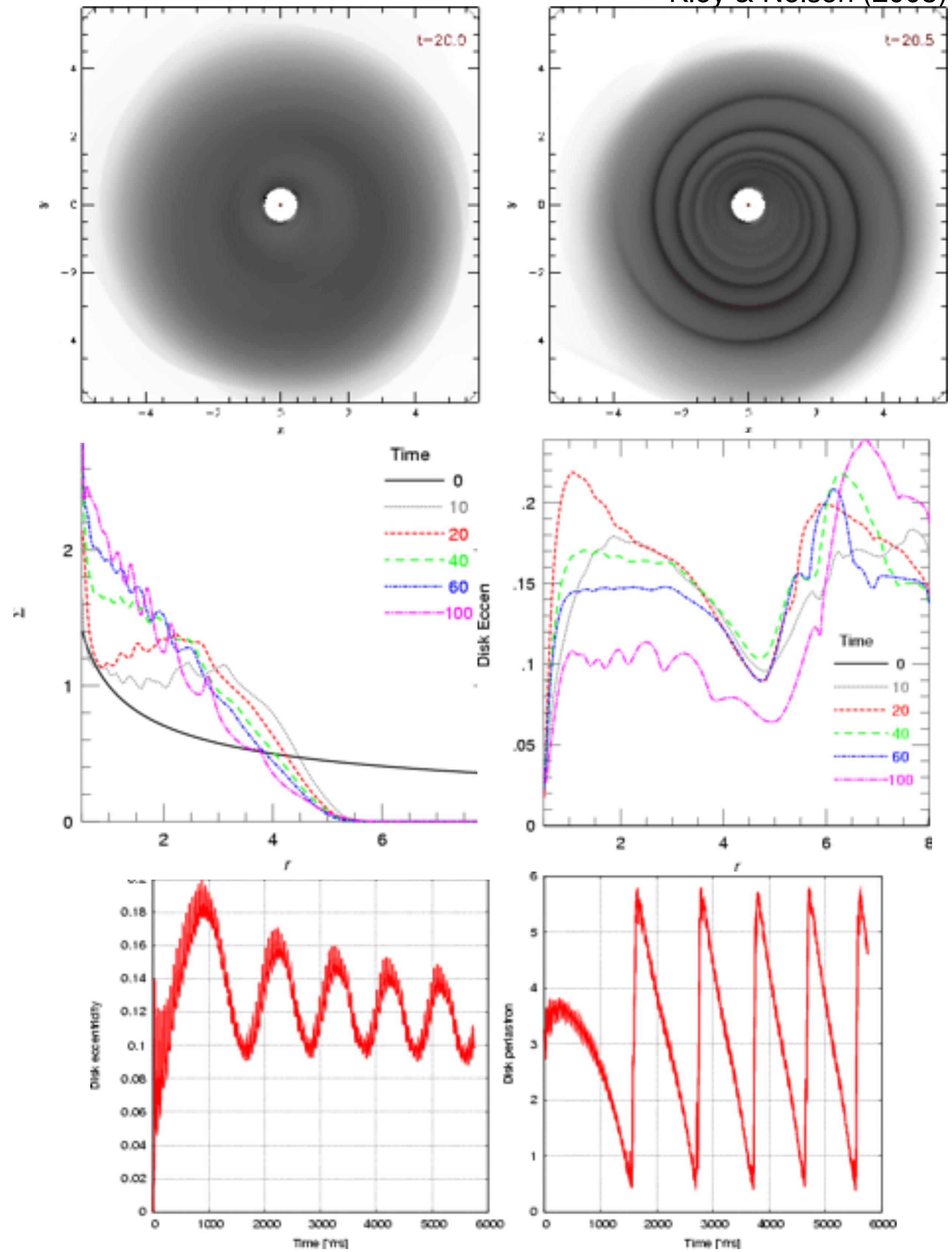
Thebault et al (2008)

External binaries - planetesimal accumulation

Kley & Nelson (2008)

Hydrodynamic simulations of discs in a binary with parameters that match Gamma Ceph indicate that the disc becomes truncated at ~ 5 AU and becomes eccentric
(Kley & Nelson 2007, 2008; Paardekooper et al 2008)

The disc undergoes long-term secular evolution due to interaction with binary, with oscillations in mean disc eccentricity being associated with mean disc precession angle



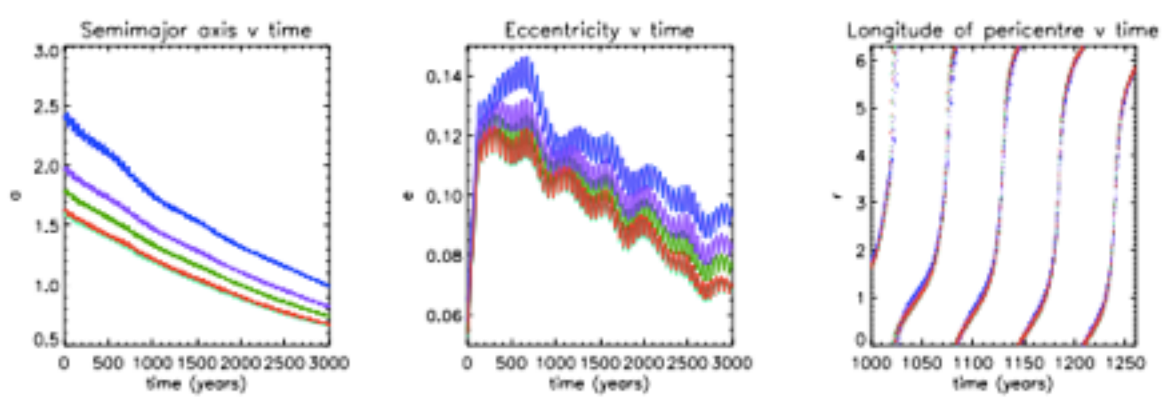
External binaries - planetesimal accumulation

Hydrodynamic simulations of discs in a binary with parameters that match Gamma Ceph indicate that the disc becomes truncated at ~ 4 AU and becomes eccentric
(Kley & Nelson 2007+2008; Paardekooper et al 2008)

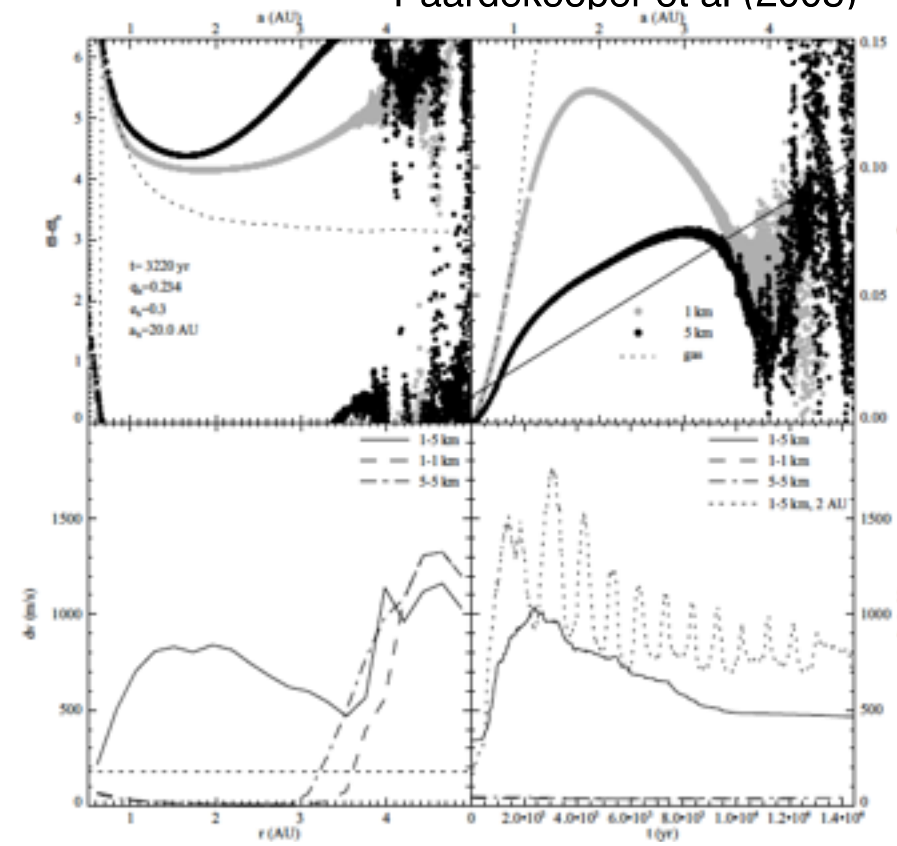
The disc undergoes long-term secular evolution due to interaction with binary, with oscillations in mean disc eccentricity being associated with mean disc precession angle

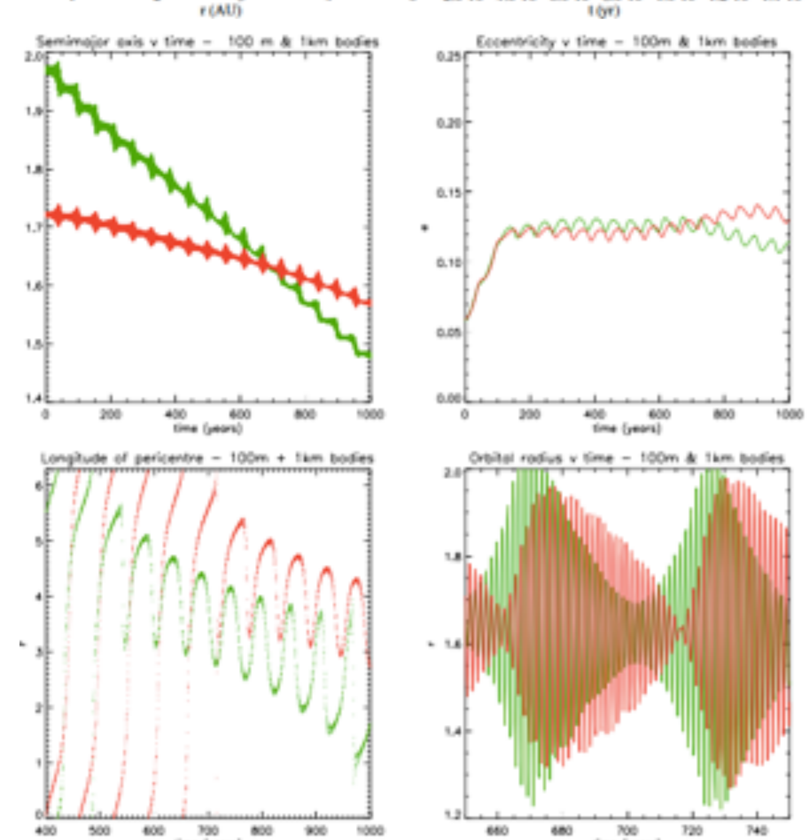
Different sized planetesimals observed to have large collision velocities even in absence of disc gravity acting on planetesimal orbits
(Paardekooper et al 2008)

Inclusion of disc gravity increases planetesimal eccentricities, giving rise to collision velocities ~ 2 km/s for 100m and 1 km-sized bodies
(Kley & Nelson 2007, 2010)



Paardekooper et al (2008)



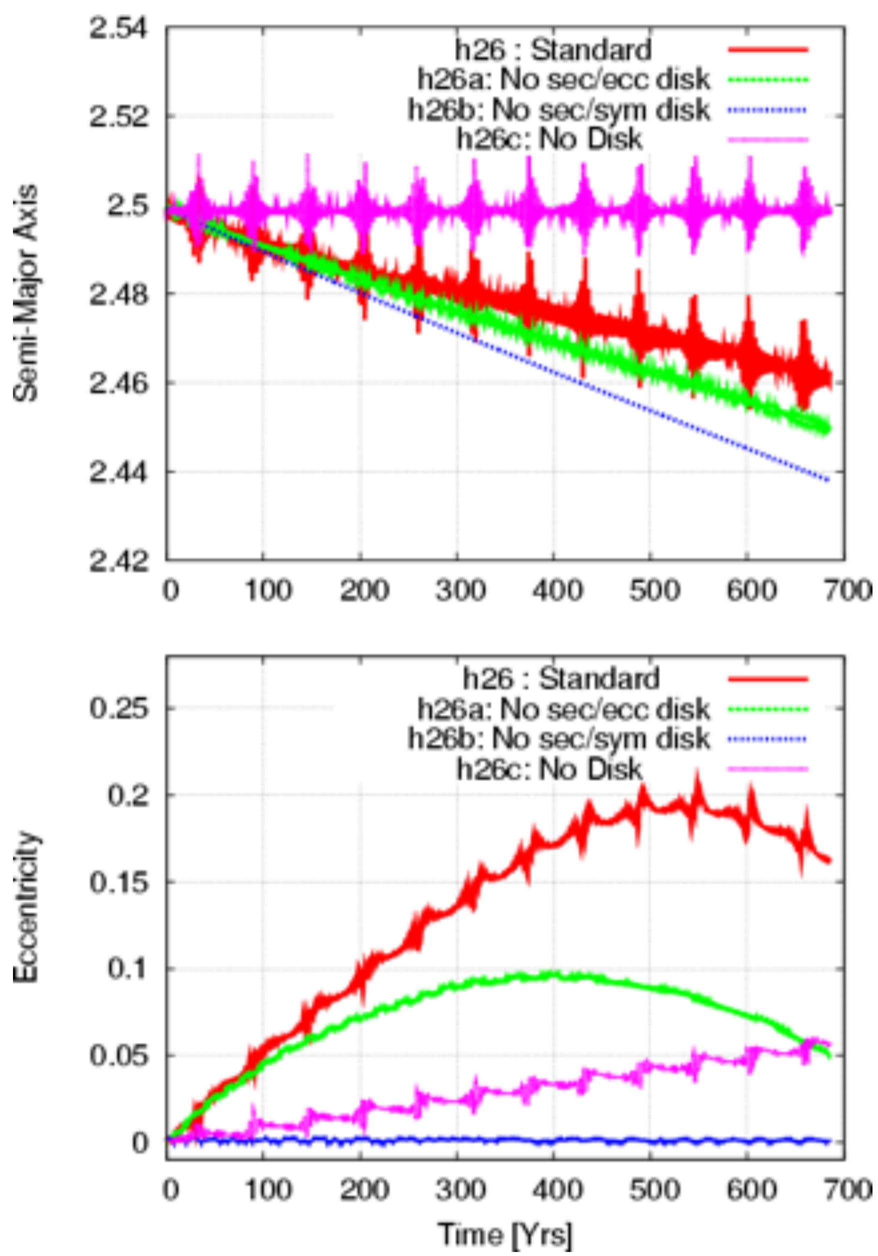


Kley & Nelson 2007

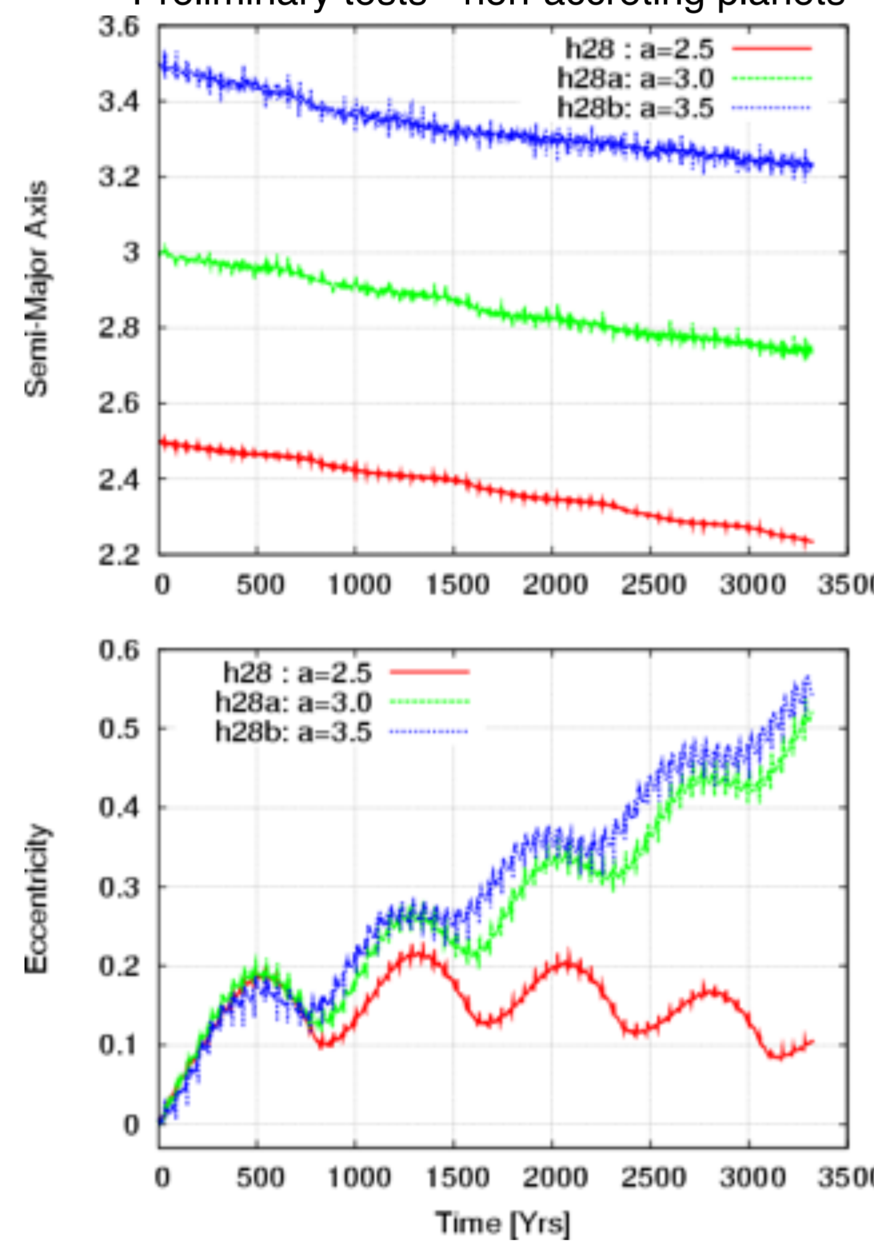
External binaries - giant planet formation

Hydrodynamic simulations of planetary migration
and growth performed by (Kley & Nelson 2008)
Application to Gamma Ceph system

Initial planet mass m_p = 36 M_{Earth}
Initial semimajor axis a_p=2.5 AU



Preliminary tests - non-accreting planets



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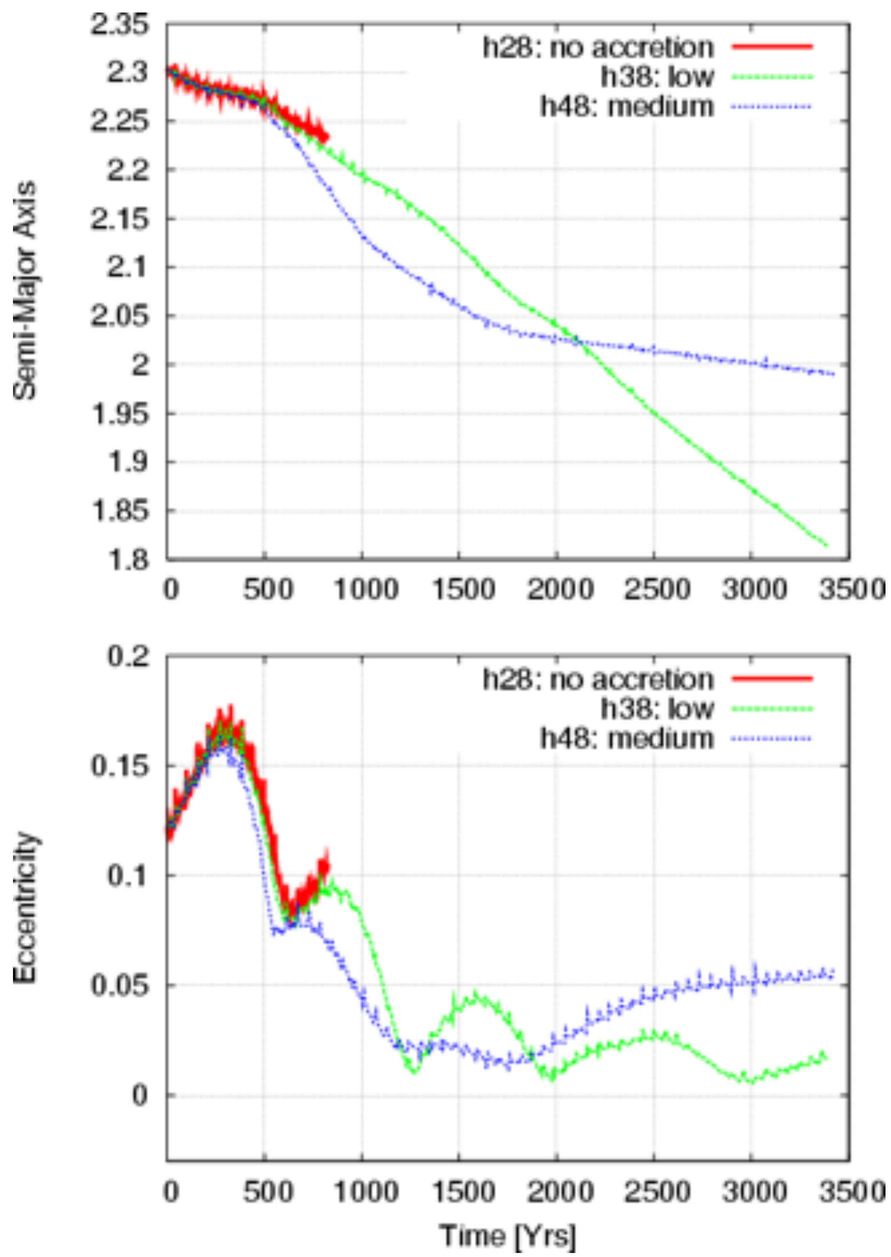
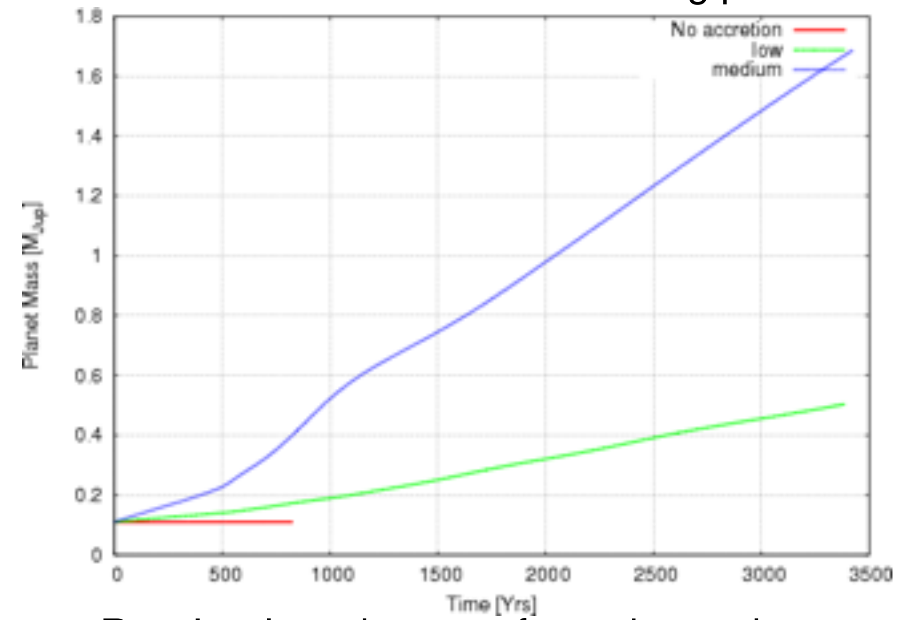


Accreting planets



Results show that core formation and gas accretion at ~ 2.5 AU can lead to planet with a_p ~ 2 AU and m_p ~ 1.6 M_{Jup} with e_p ~ 0.1 (eccentricity fit perhaps more difficult to achieve).

Orbital Elements for Planet around γ Cep

Element	Value
Period (days)	905.574 ± 3.08
T (JD)	253121.925 ± 66.9
Eccentricity	0.12 ± 0.05
ω (deg)	49.6 ± 25.6
K1 (m s^{-1})	27.50 ± 1.5
$f(m)$ ($M_\odot$)	$(1.90 \pm 0.3) \times 10^{-9}$
Semimajor axis (AU)	2.13 ± 0.05
Reduced χ^2	1.47
$\sigma_{\rm CFHT}$ (m s^{-1})	15.3
$\sigma_{\rm Phase\ I}$ (m s^{-1})	17.4
$\sigma_{\rm Phase\ II}$ (m s^{-1})	15.8
$\sigma_{\rm Phase\ III}$ (m s^{-1})	8.2

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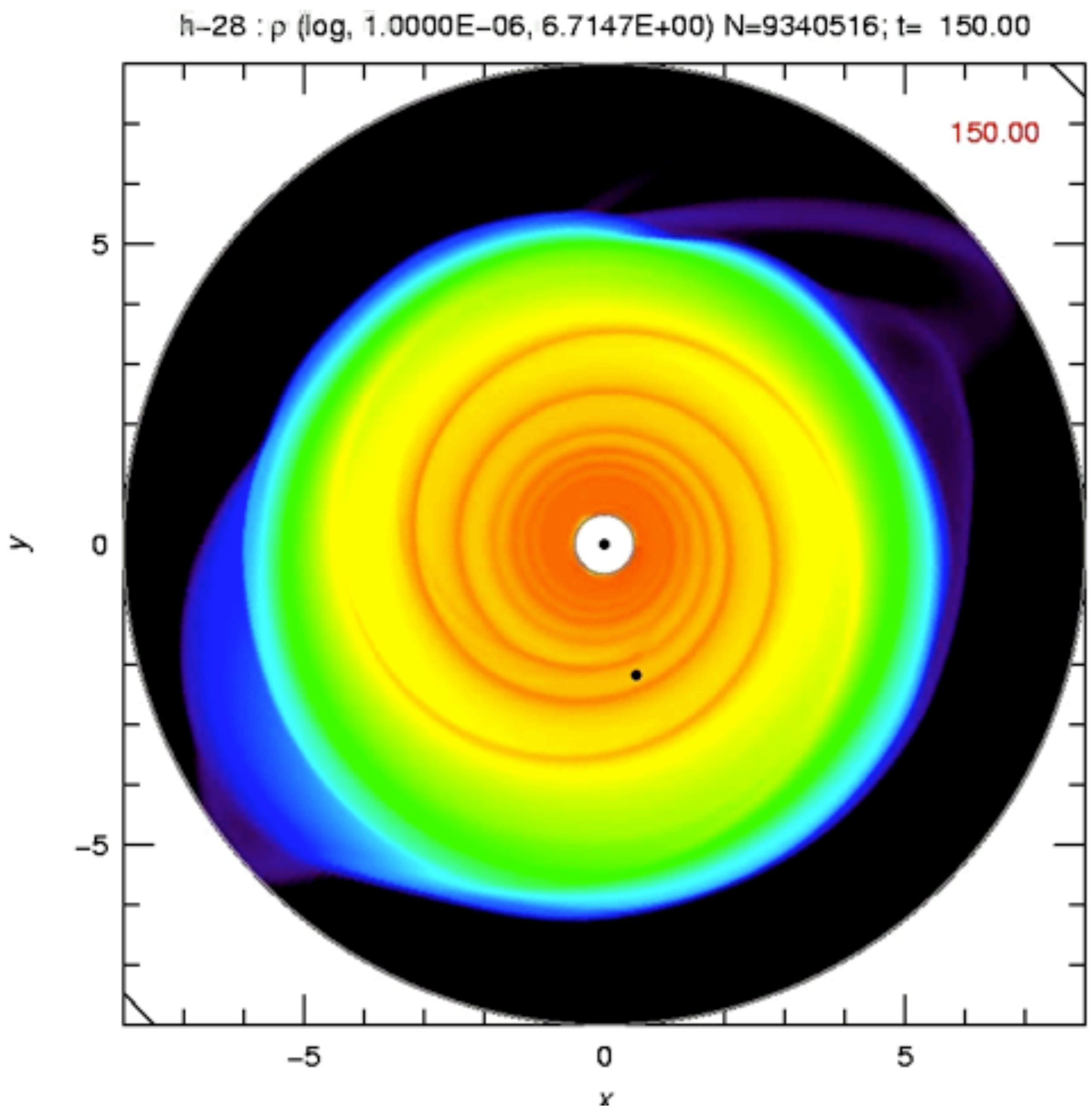
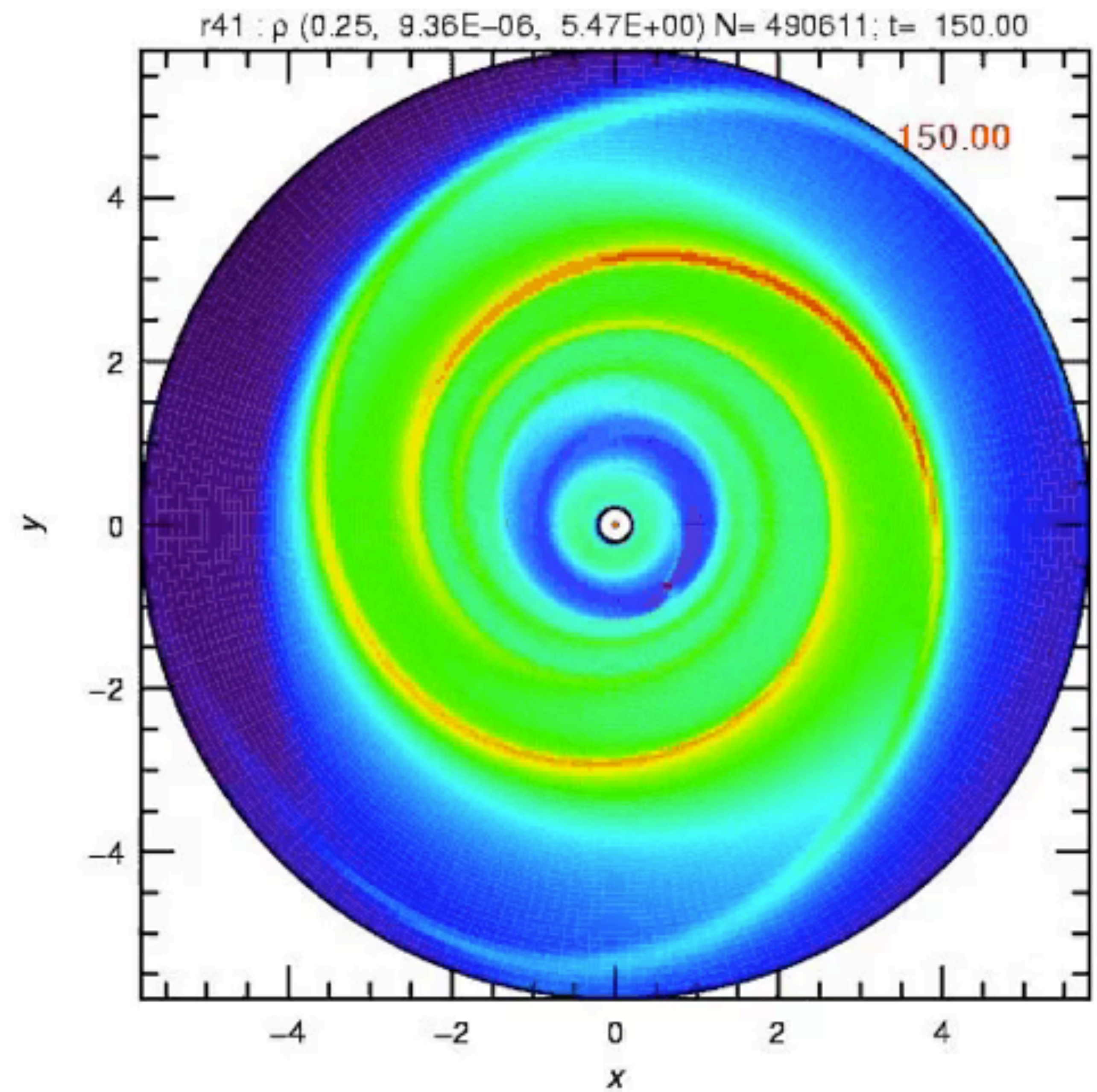
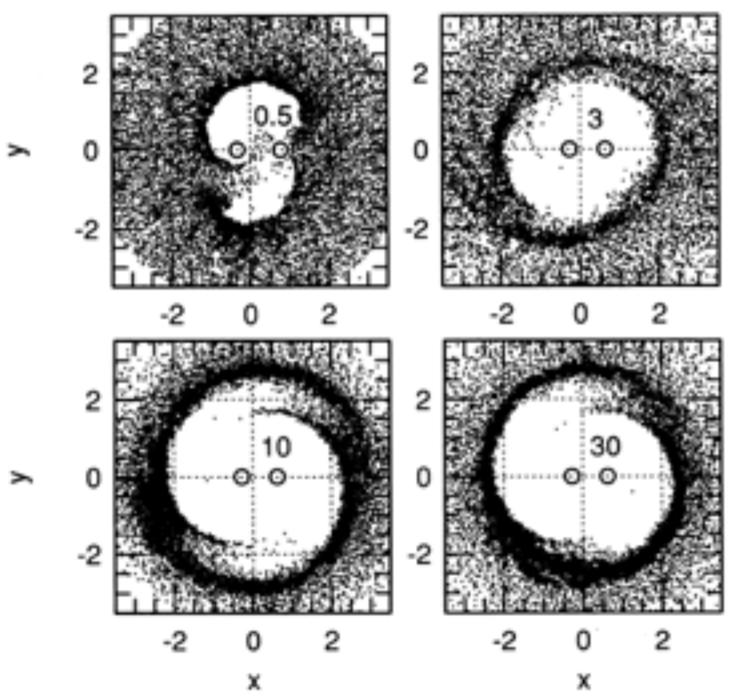
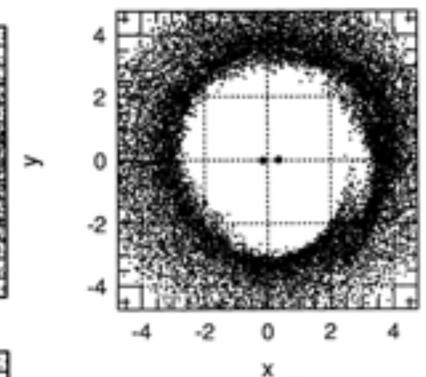


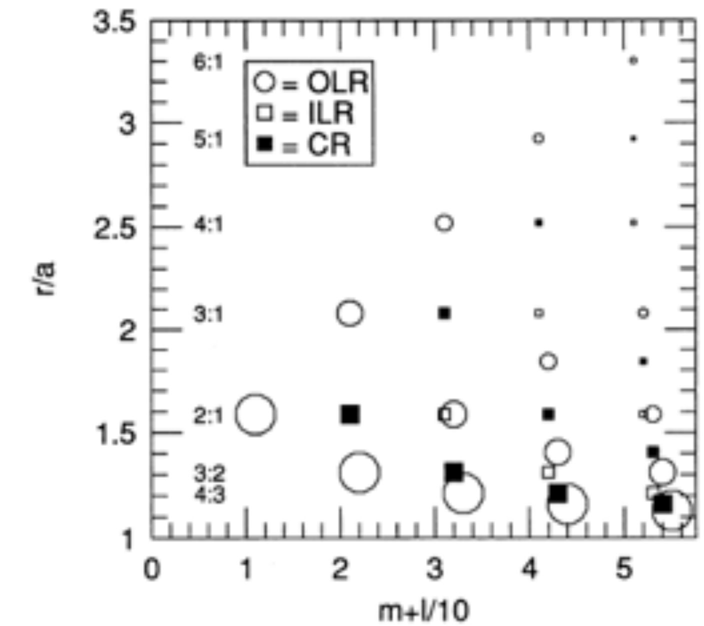


Circumbinary discs - tidal truncation





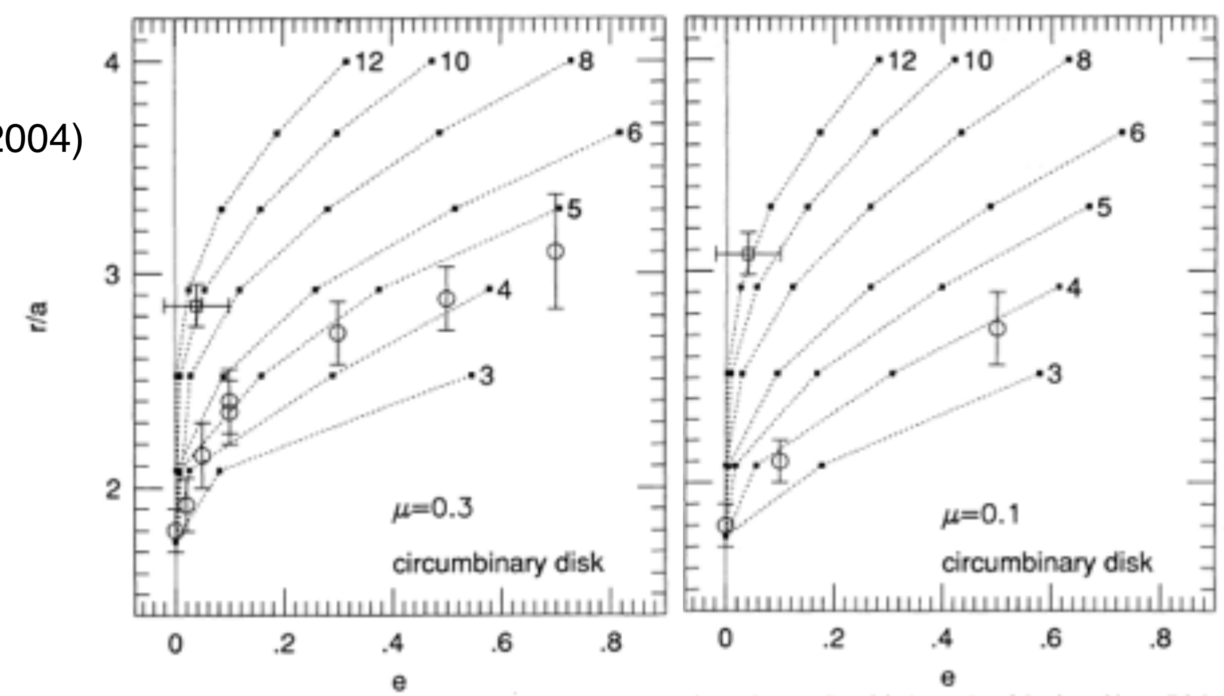
$e_B = 0.1$ and $e_B = 0.5$ with $\mu = 0.3$. Higher order resonances open a larger gap for higher eccentricity
- up to some limit



Eccentric binary excites spiral waves at Lindblad resonances that can truncate disc (Artymowicz & Lubow 2004)

Gap formation criteria extended to include torque from eccentric Lindblad resonances being balanced with viscous torque in disc

Calibrated using SPH simulations



Circumbinary discs - planetesimal accumulation

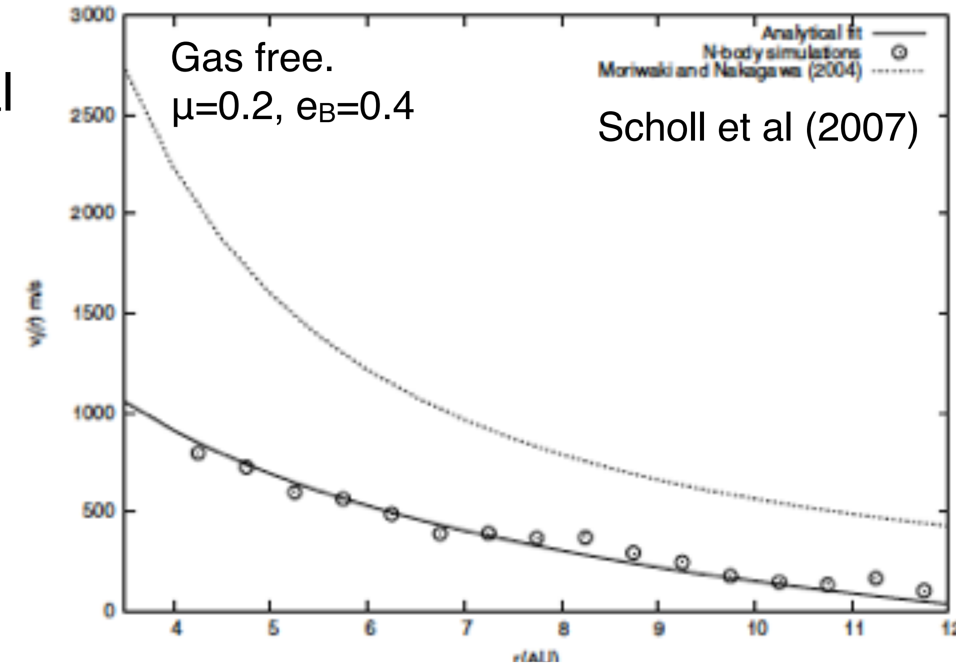
First attempt to examine planetesimal collision velocities in gas free scenario by (Moriwaki & Nakagawa 2004)

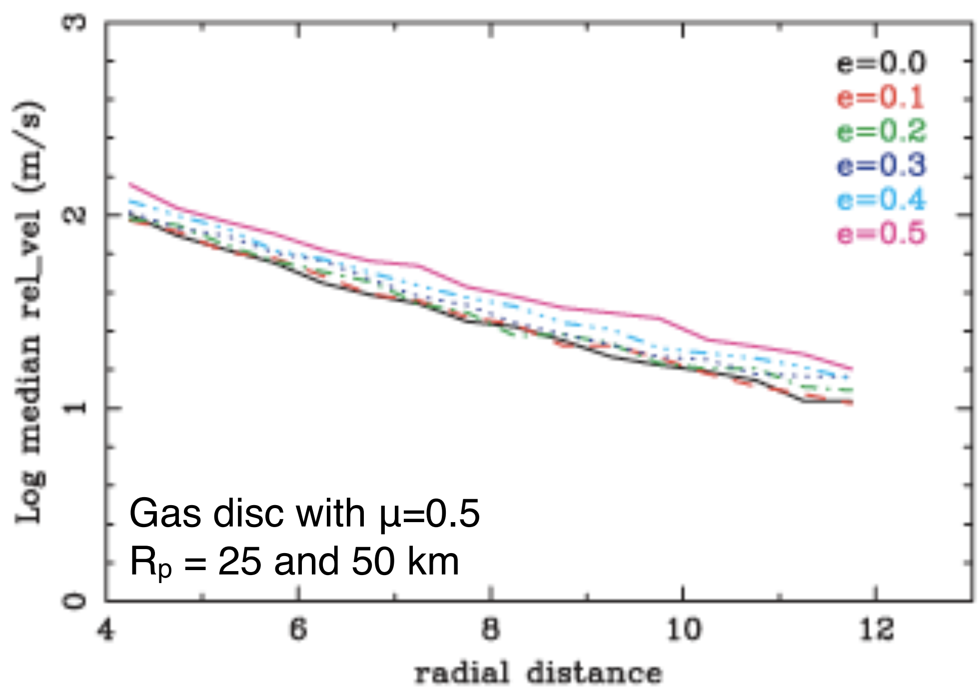
Inert gas disc model with gas drag and different planetesimal sizes considered by (Scholl et al 2007). Also calculate collision velocities directly using 10,000 particles.

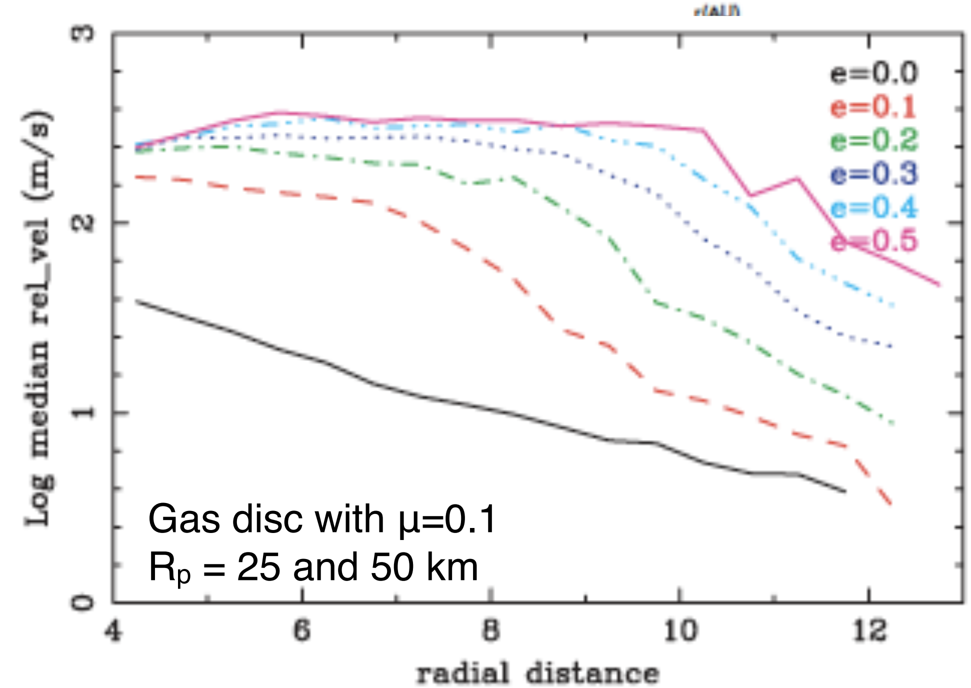
For $a_B = 1$ AU, accretion zone for 25-50 km planetesimals > 6 - 10 AU (depending on e_B and μ)

Accretion friendly binary systems have $e_B = 0$ and $\mu = 0.5$: $e_{forced} = 0$

$$e_{\rm forced} = \frac{B}{A} = \frac{5}{4}(1-2\mu)\frac{a_B}{a}e_B\left[\frac{1+(3/4)e_B^2}{1+(3/2)e_B^2}\right]$$







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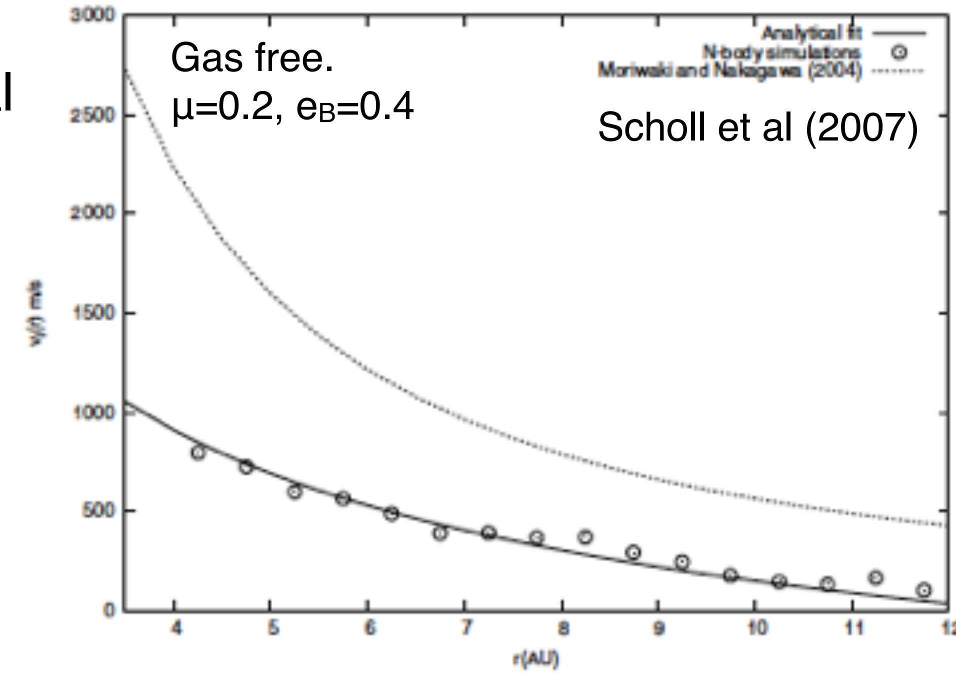

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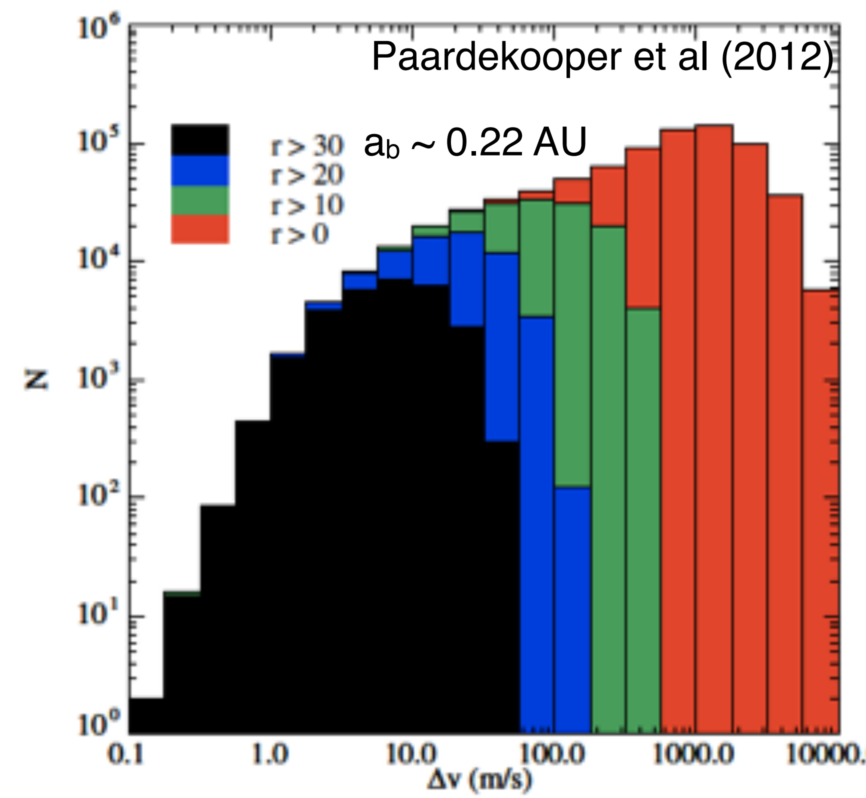
Accretion friendly binary systems have $e_B = 0$ and $\mu = 0.5$: $e_{\rm forced} = 0$

Paardekooper et al (2012) note that short period oscillations in eccentricity are also generated by binary that cannot be damped by gas drag.

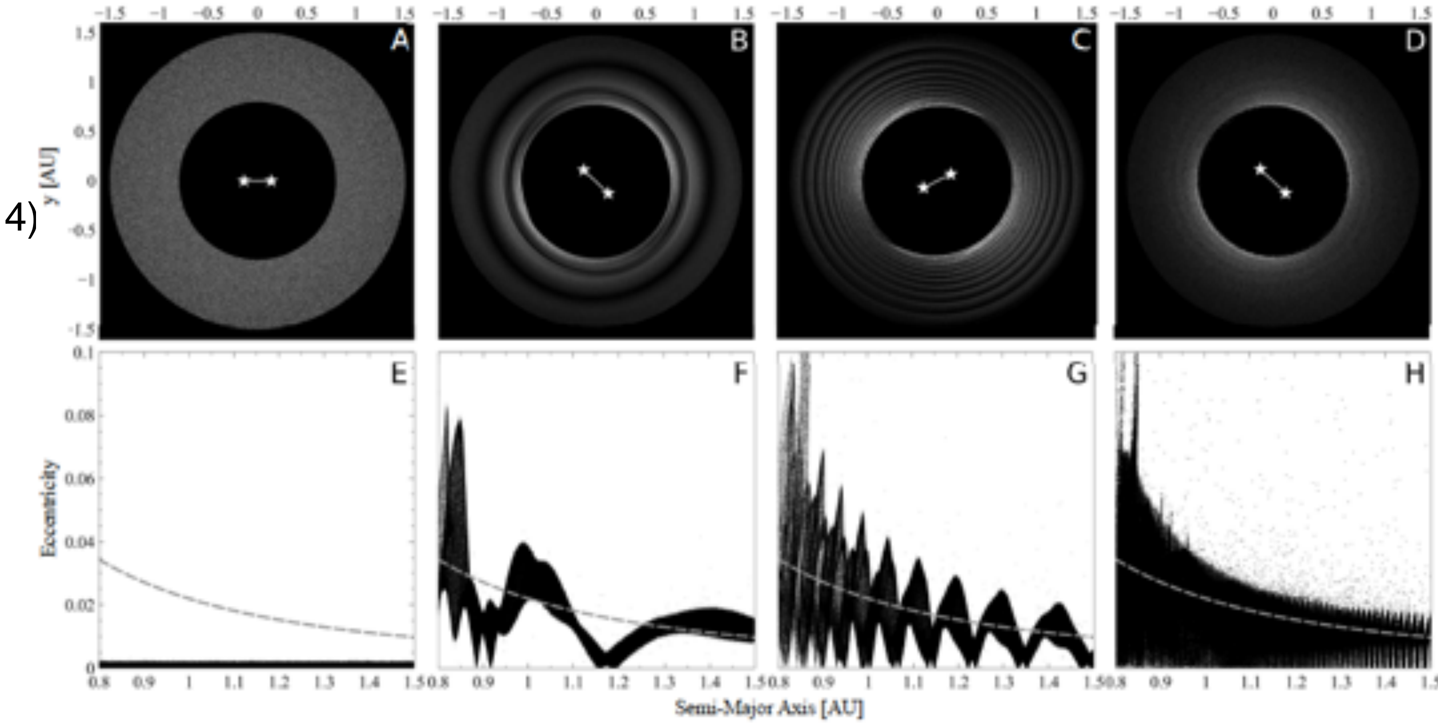
$$e_{\rm ff} = \frac{3}{4}\frac{M_A M_B}{M_*^2}\left(\frac{a_{\rm b}}{a}\right)^2\sqrt{1+\frac{34}{3}e_{\rm b}^2}$$



Model with static gas disc, planetesimal + dust accretion/destruction fails to generate Kepler 16, 34 and 35 planets *in situ.* Accretion zone found to be beyond 4 AU (Paardekooper et al 2012)

Circumbinary discs - planetesimal accumulation

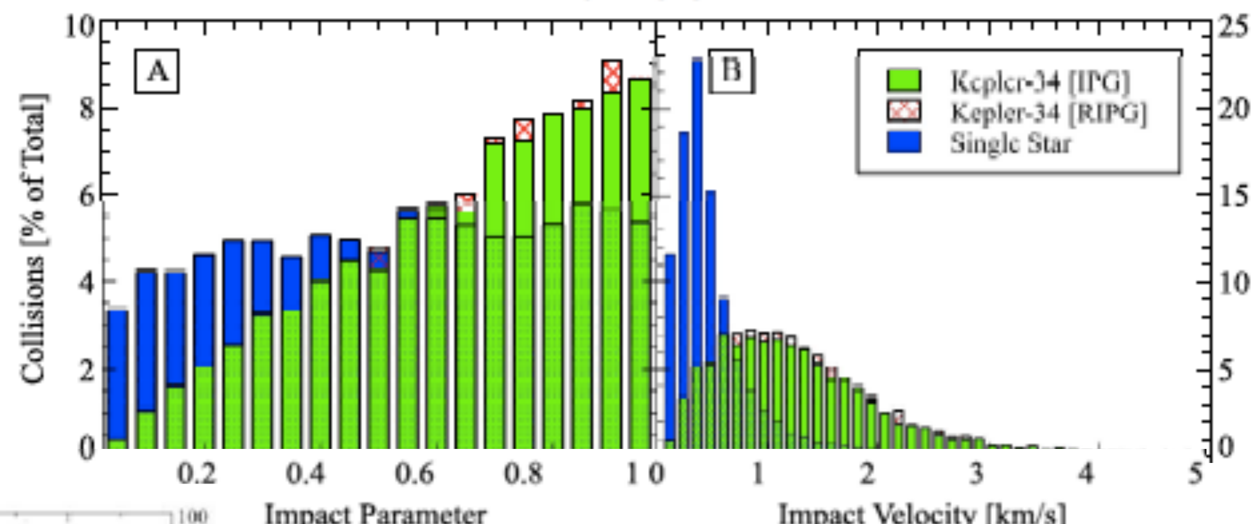
Simulation of self-gravitating planetesimal disc with 10^6 particles and sophisticated collision model (from Leinhardt & Stewart 2012) undertaken by Lines et al (2014) for Kepler 34 AB(b)



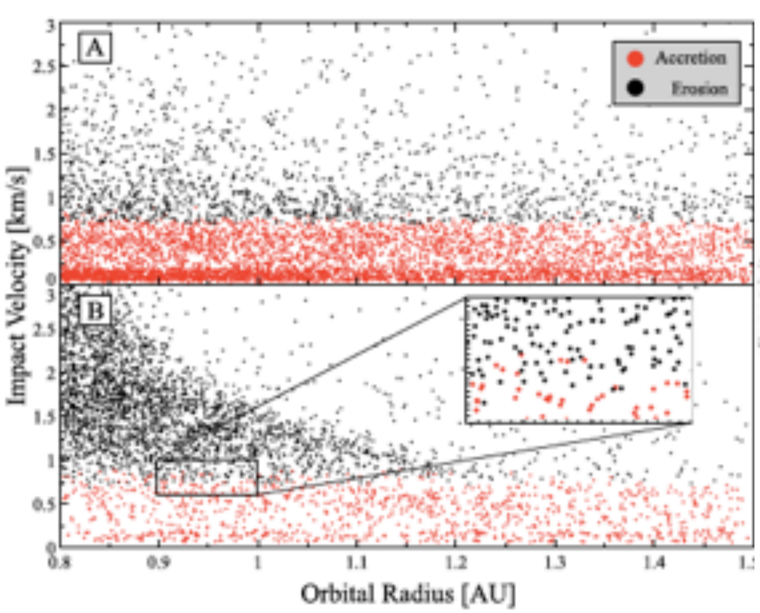
Effects of gas disc neglected completely

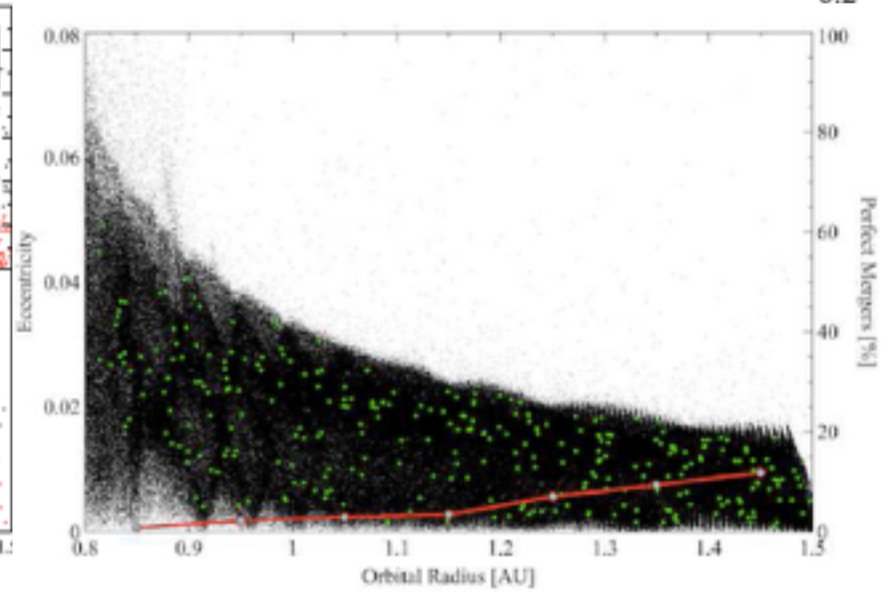
Forced eccentricity causes almost all collisions to be erosive at location of Kepler 34b

$$e_{\rm ff} = \frac{3}{4}\frac{M_A M_B}{M_*^2}\left(\frac{a_{\rm b}}{a}\right)^2\sqrt{1+\frac{34}{3}e_{\rm b}^2}$$



Conclude that *in situ* formation for all Kepler circumbinary planets unlikely except for Kepler 47c



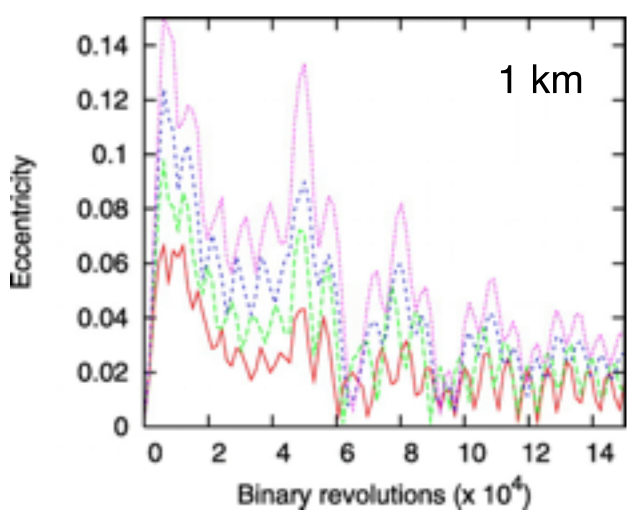


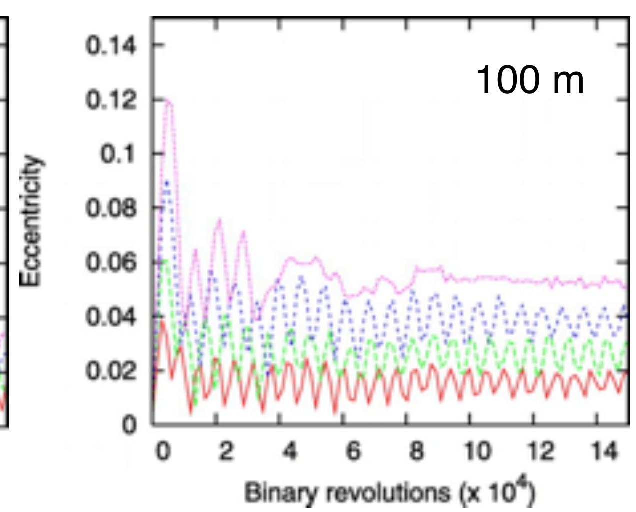
Circumbinary discs - planetesimal accumulation

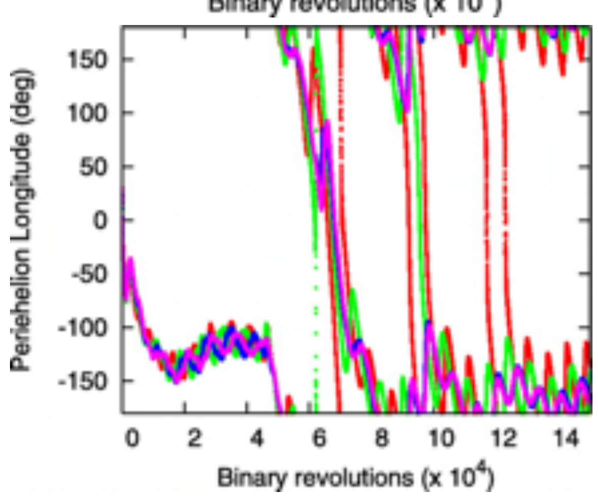
Hydrodynamic simulations with 100 m and 1 km planetesimals performed by (Marzari et al 2008) showing formation of eccentric disc

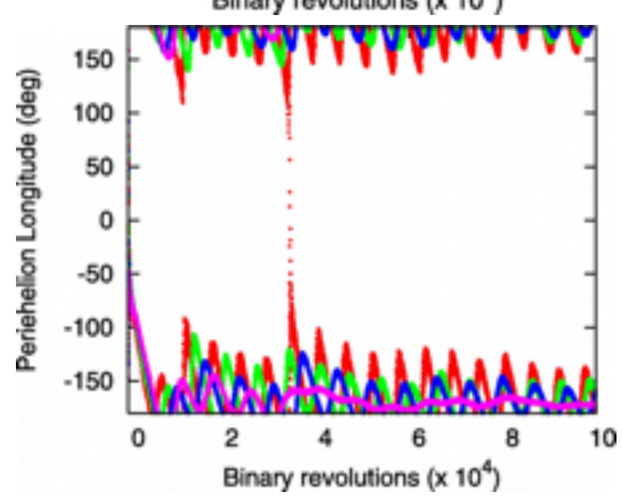
FARGO simulations with disc gravity acting on planetesimals

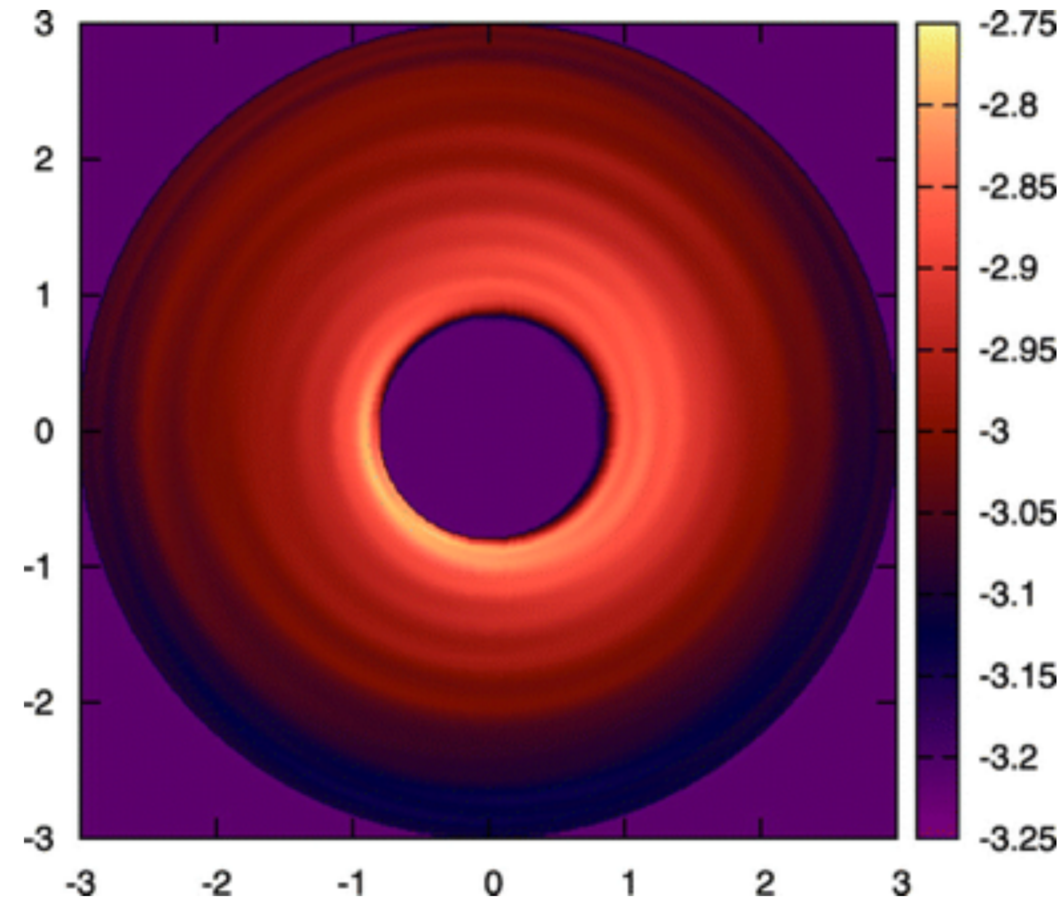
Conclusions: eccentric disc increases planetesimal eccentricity and increases de-phasing of planetesimal orbits - bad for accretion!

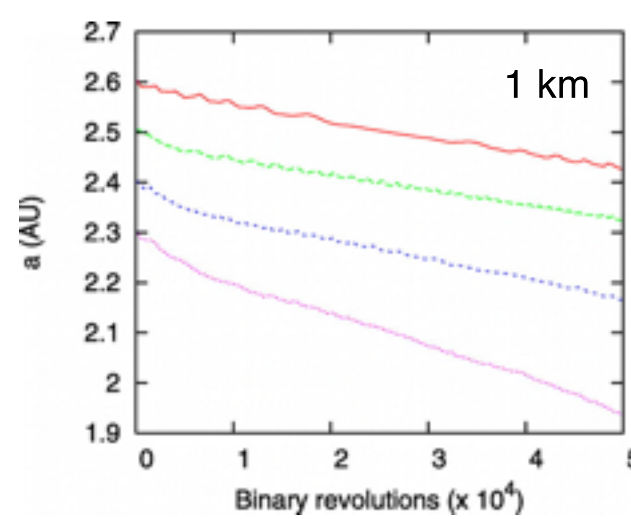


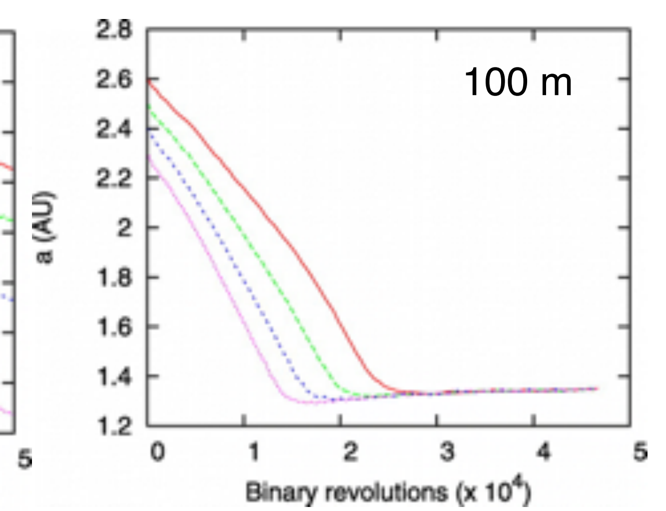












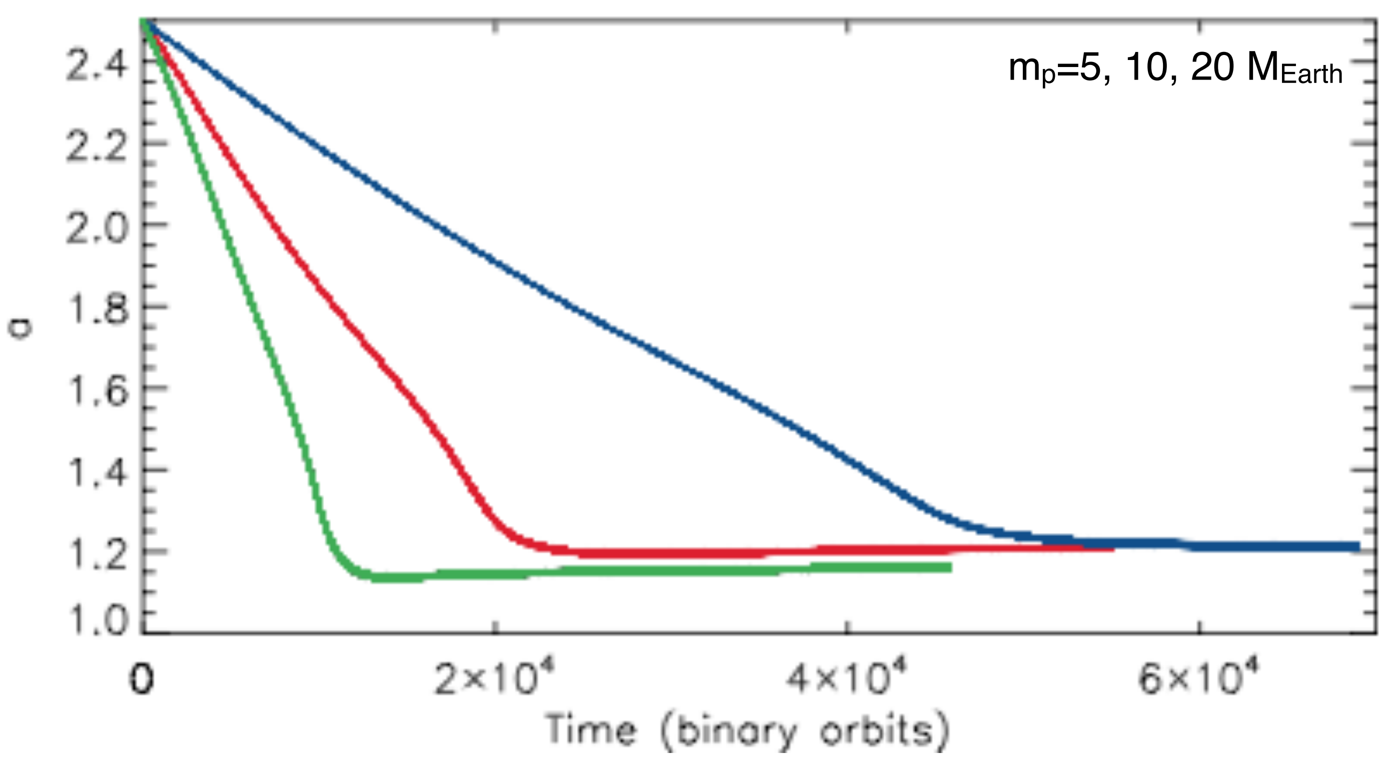
It’s very difficult (impossible?) to explain the Kepler circumbinary planets through *in situ* formation!

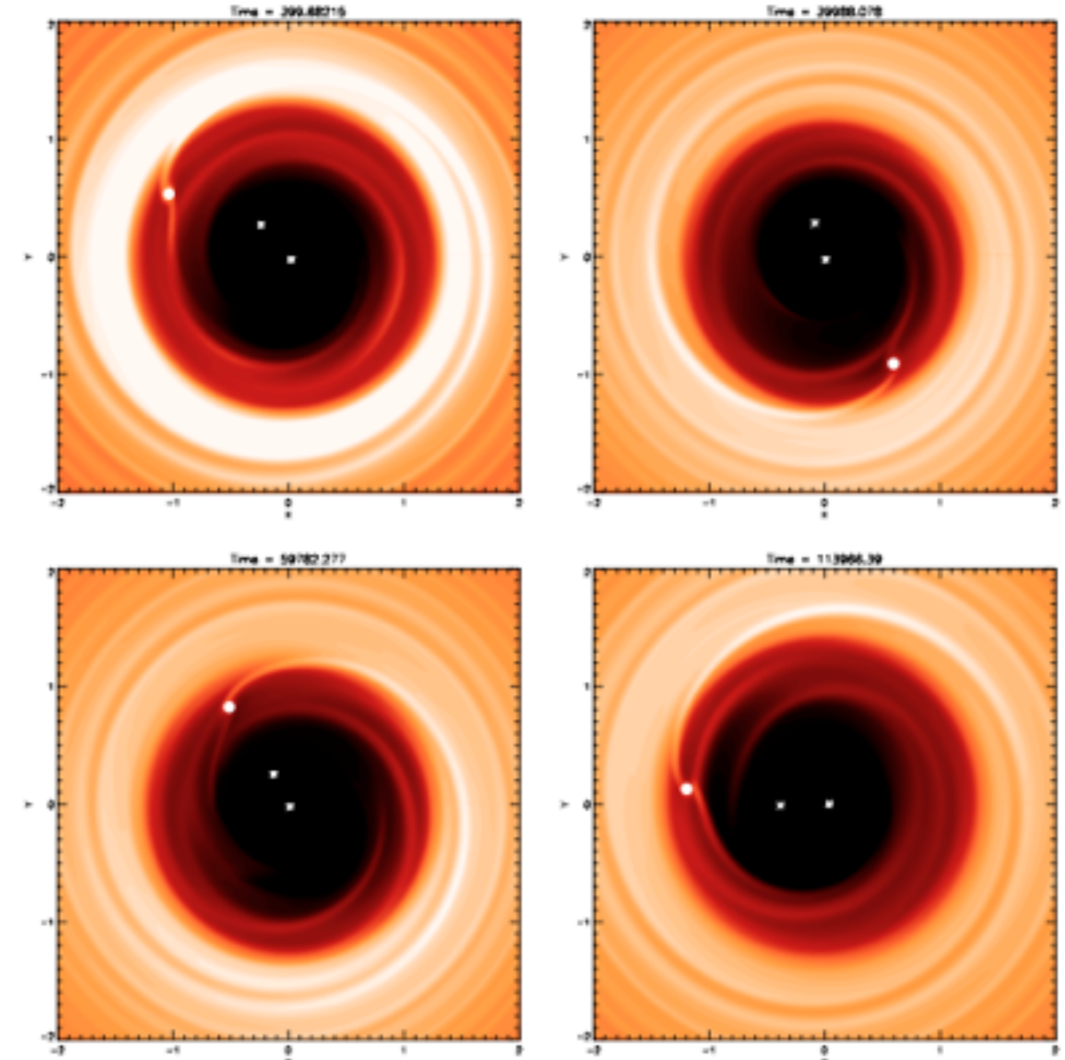
Circumbinary discs - migrating planets

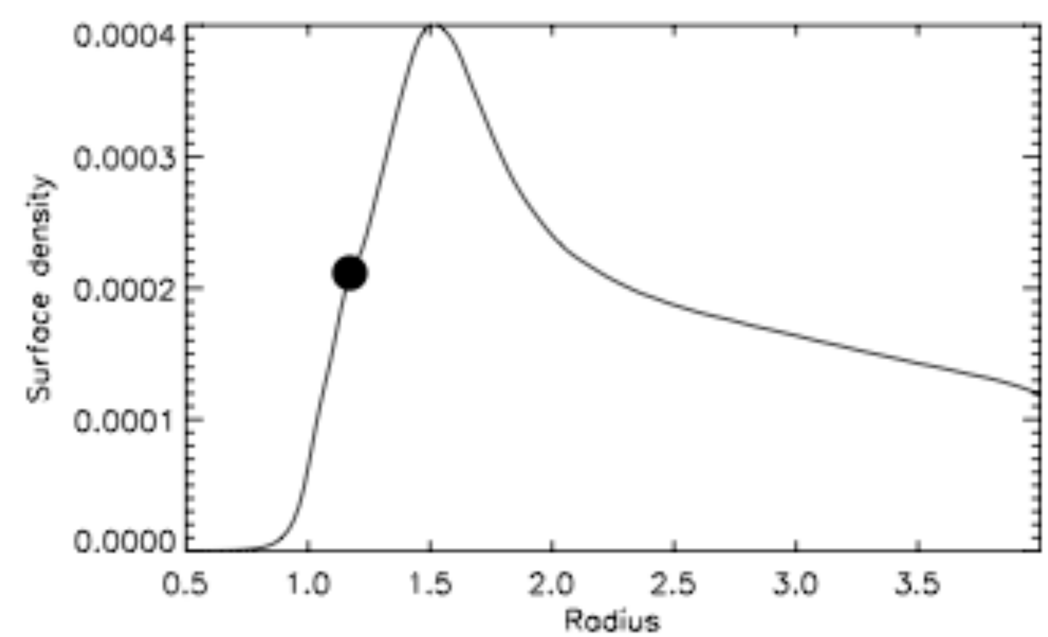
Hydrodynamic simulations of migrating circumbinary planets performed by (Nelson 2003; Pierens & Nelson 2007, 2008ab, 2013)

Test hypothesis that circumbinary planets forms at large distance and migrate in towards central binary.

Question: what happens as planet approaches binary?
Answer: If $m_p < 1\ M_{Jup}$ planet gets trapped at cavity edge







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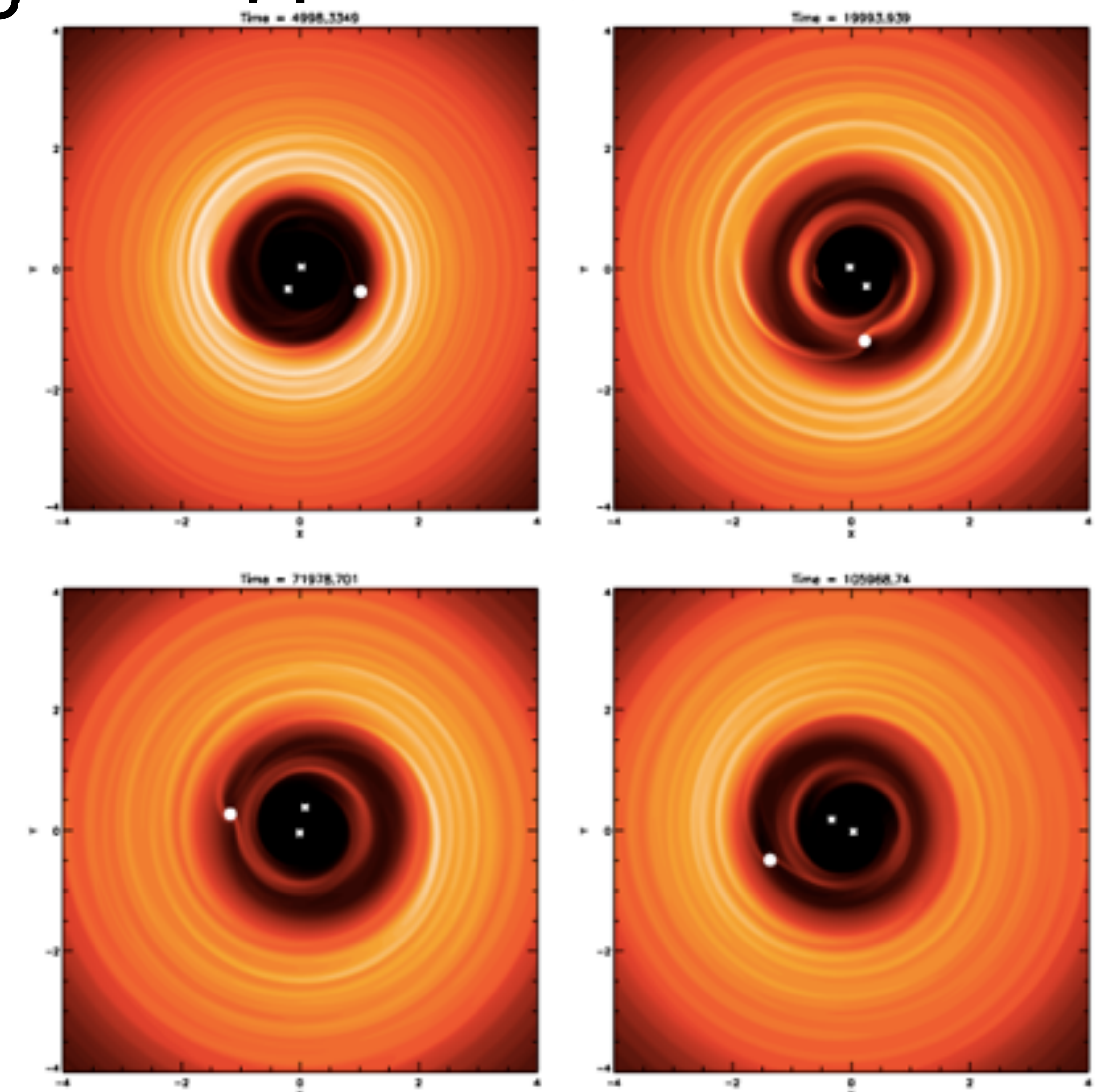
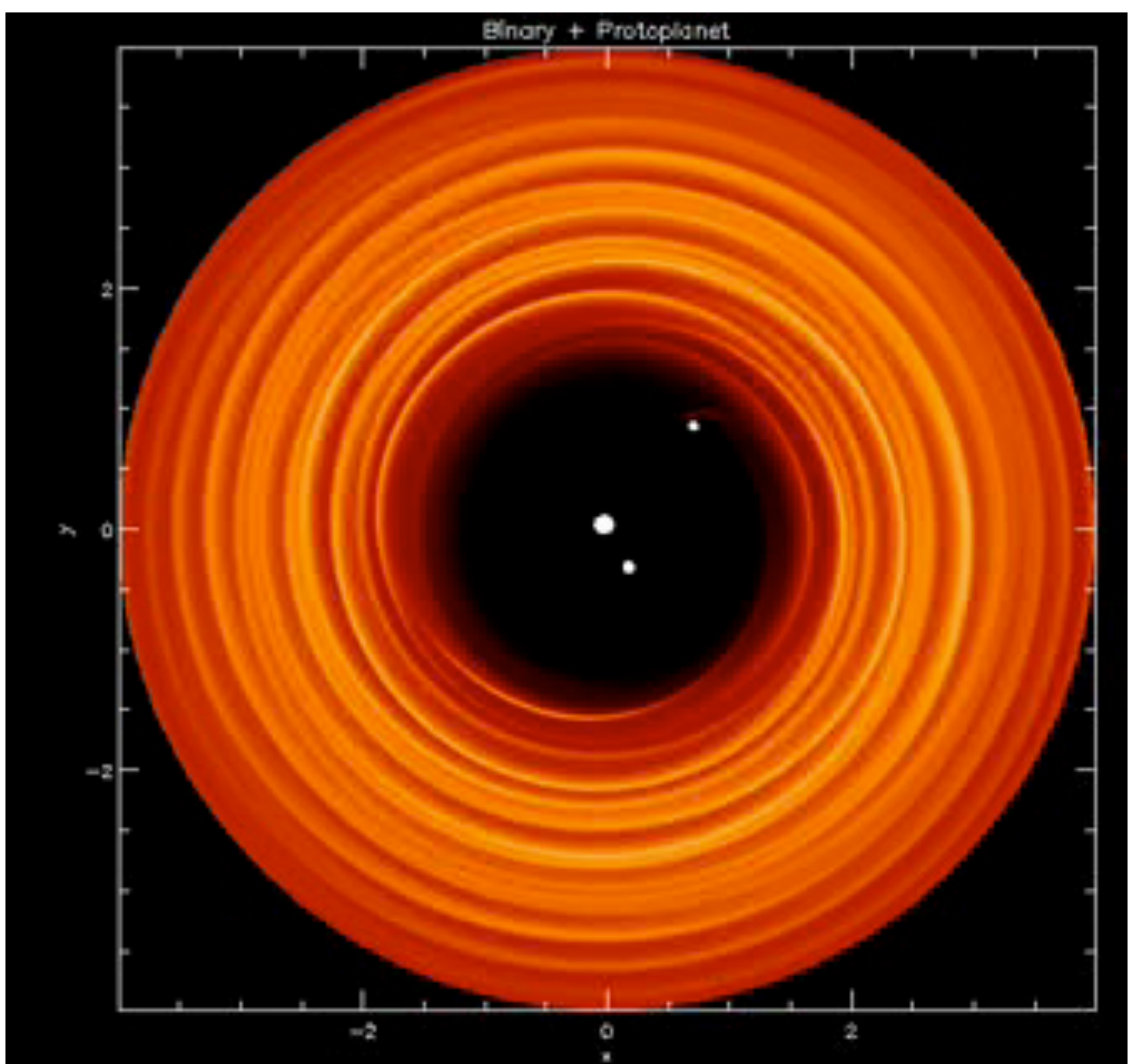
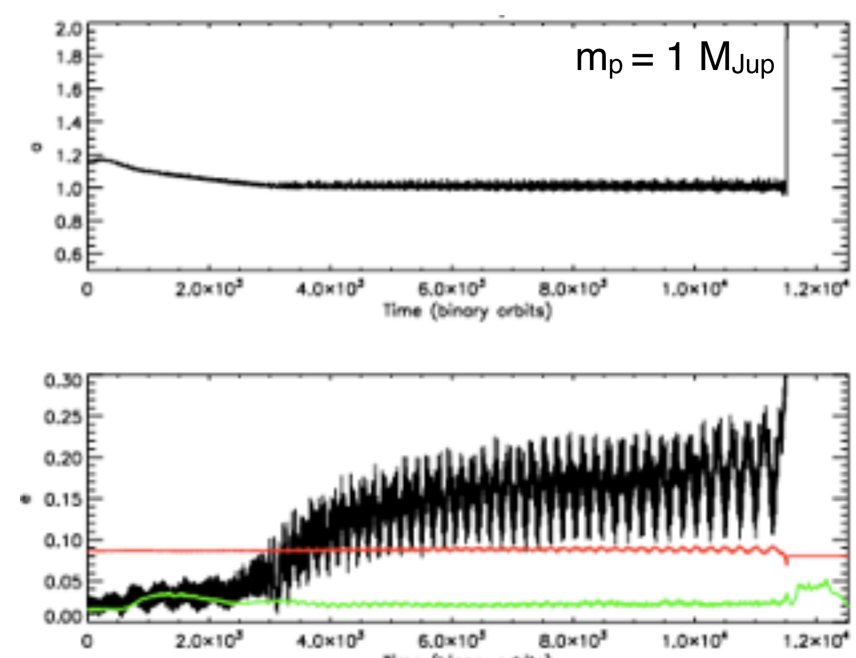
If $m_p > 1\ M_{Jup}$ planet gets ejected - eccentricity excitation by 4:1 mean motion resonance







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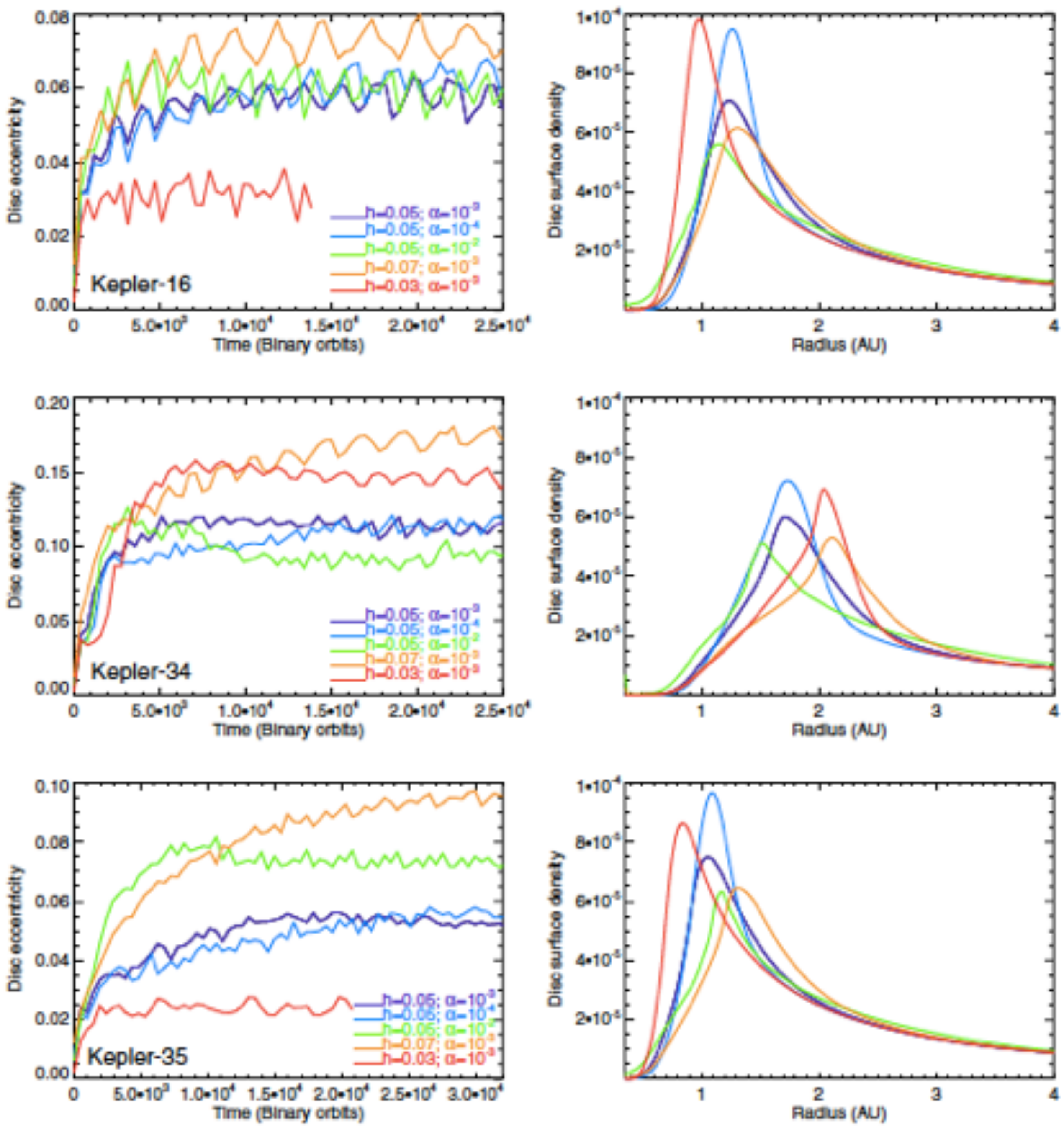
Fitting the Kepler 16, 34 and 35 systems (Pierens & Nelson 2013)



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M_A ($M_\odot$)	0.69	1.05	0.89
M_B ($M_\odot$)	0.20	1.02	0.81
m_p (M_J)	0.33	0.22	0.13
$q_b = M_A/M_B$	0.29	0.97	0.91
$q = m_p/M_*$	3.7×10^{-4}	1.1×10^{-4}	7.5×10^{-5}
a_b (AU)	0.22	0.23	0.18
a_p (AU)	0.7	1.09	0.6
e_b	0.16	0.52	0.14
e_p	0.069	0.18	0.04

Disc structure shows wide variation as a function of physical parameters (H/R and viscosity)

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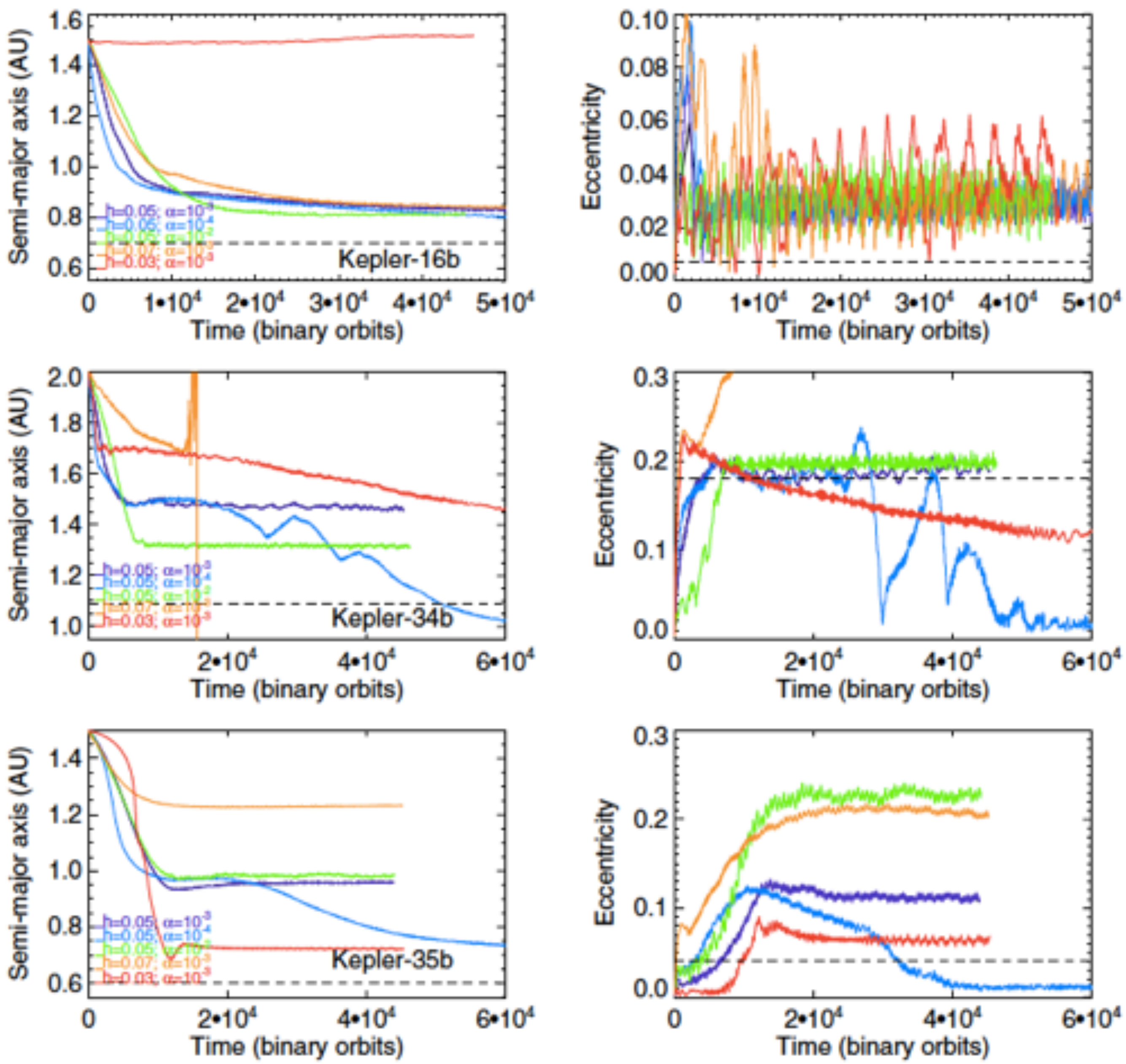

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Disc structure shows wide variation as a function of physical parameters (H/R and viscosity)

Planets with masses equal to those inferred from Kepler data show a range of stopping locations and orbital elements in the different disc models

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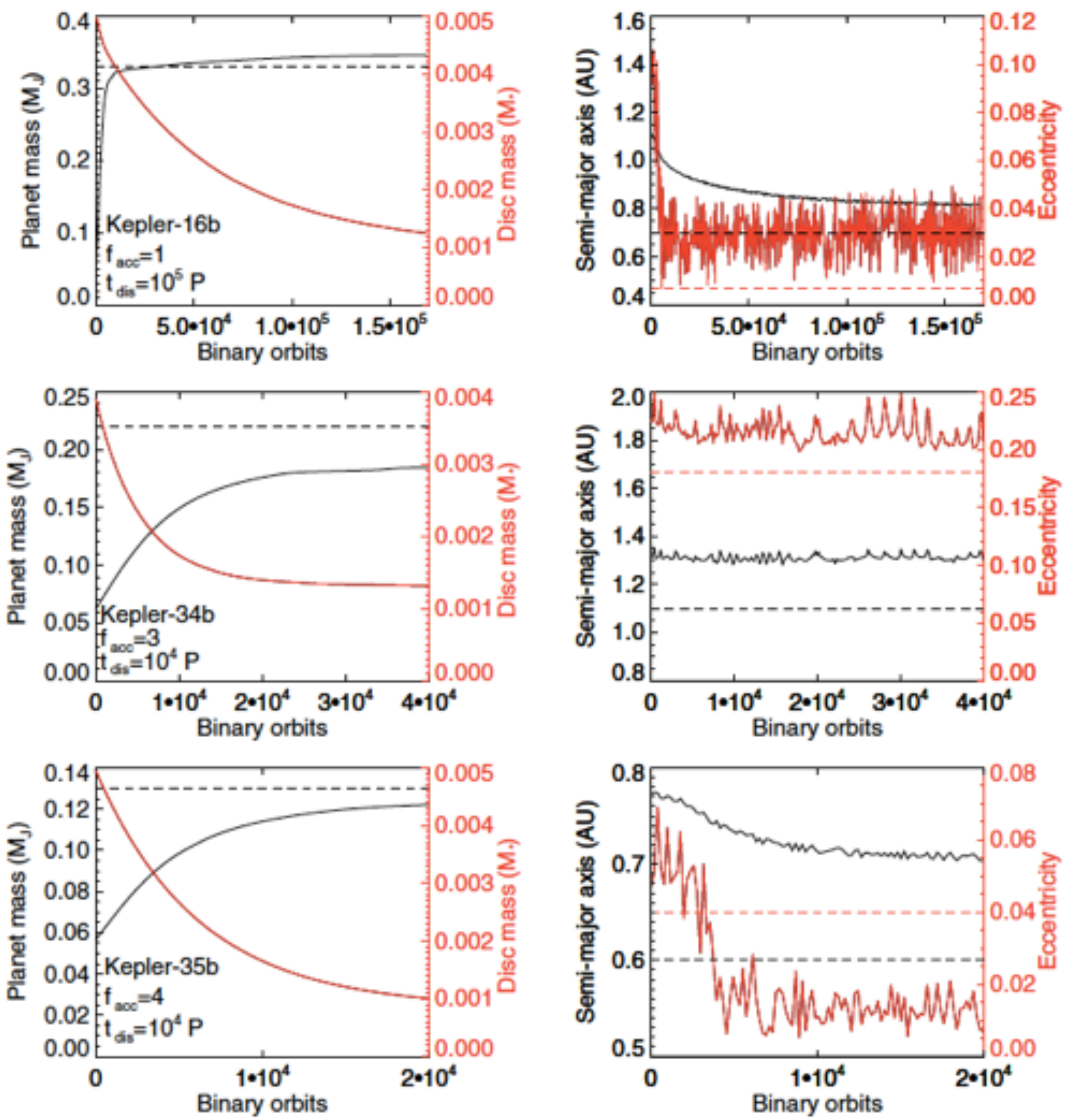
e_b	0.16	0.52	0.14
e_p	0.069	0.18	0.04



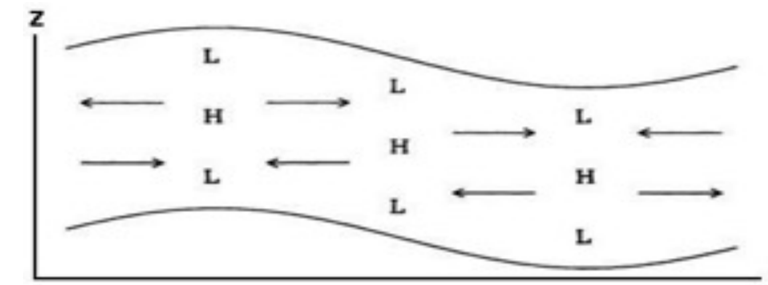
Disc structure shows wide variation as a function of physical parameters (H/R and viscosity)

Planets with masses equal to those inferred from Kepler data show a range of stopping locations and orbital elements in the different disc models

Best fit models for migrating and accreting cores (start with 20 M_{Earth} core) with disc dispersal provide reasonable fits, but more work needed! (see also Kley & Haghihighpour 2014 & 2015)

Inclined binary systems - warped discs

An inclined binary companion will introduce perturbations that cause out-of-plane motions in the disc. The disc will become locally inclined (warped) and a key question is by what means do these tilt perturbations propagate in discs and on what time scale.



Vertical displacement of the disc leads to radial pressure imbalance that then drives vertical shearing motions in the disc. This is a key ingredient in understanding how pressure acts during the propagation of bending waves.
In the diffusive regime ($\alpha > h$) the viscosity acts to strongly damp the vertical shear motion.
As such, it is the *r-z* component of the viscous stress tensor that determines the rate of warp diffusion rather than the usual *r-ϕ* component normally encountered in accretion disc theory.

<u>Motivation</u>: Binary stars have ~ aligned spin and orbital angular momentum vectors for $a_b < 40$ AU, but are inclined for $a_b > 40$ AU (Hale 1994).
HK Tau binary is observed to be inclined (Stapelfeldt et al. 1998; Jensen & Akeson 2014)

<u>Basic theory of warped discs</u>

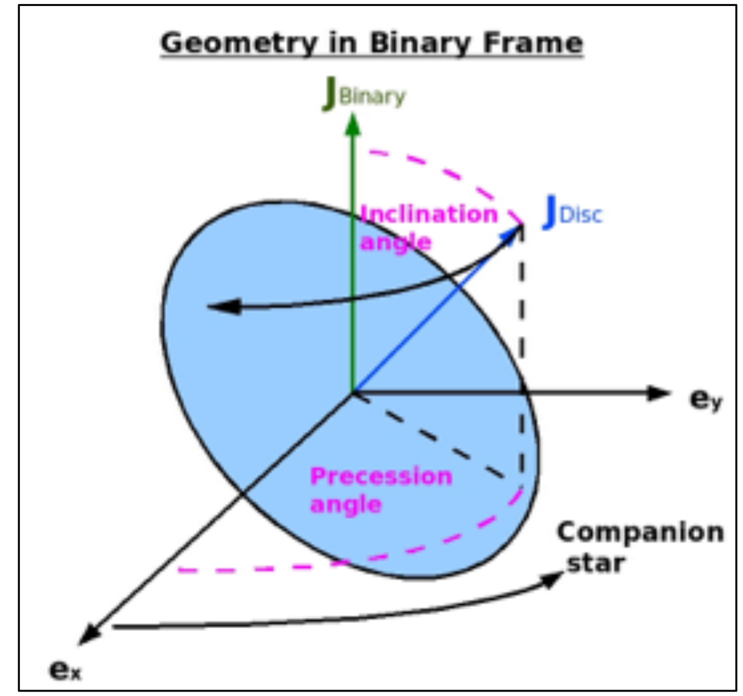
For $\alpha > h$ (where $h=H/R$) warps propagate diffusively with diffusion coefficient $D = \nu/(2\alpha^2)$ (where ν is kinematic viscosity) (Papaloizou & Pringle 1983)

Time scale for warp disturbance to diffuse distance R: $\tau_{warp} \sim R^2 / D$

For $\alpha < h$ warps propagate as bending waves with speed $v_{warp} \sim c_s / 2$ (Papaloizou & Lin 1995)

Time scale for warp wave to propagate distance R: $\tau_{warp} \sim 2R / c_s$

Inclined binary systems - warped discs



The presence of an inclined companion star (with mass M_s, distance from central star D and inclination δ) leads to both secular and time dependent perturbations in the disc (Papaloizou & Terquem 1995)

The secular component of the perturbing potential leads to a free-particle precession frequency $\boldsymbol{\omega}_z$ given by

$$2\Omega\omega_z = -\frac{3GM_s}{4D^3}(3\cos^2\delta - 1)$$

which depends on radial position in the disc through the local disc angular velocity Ω - i.e. the companion tries to twist the disc up through differential precession

Linear theory and numerical simulations indicate that the disc can precess as a rigid body if:

The warp propagation time across the disc < precession time

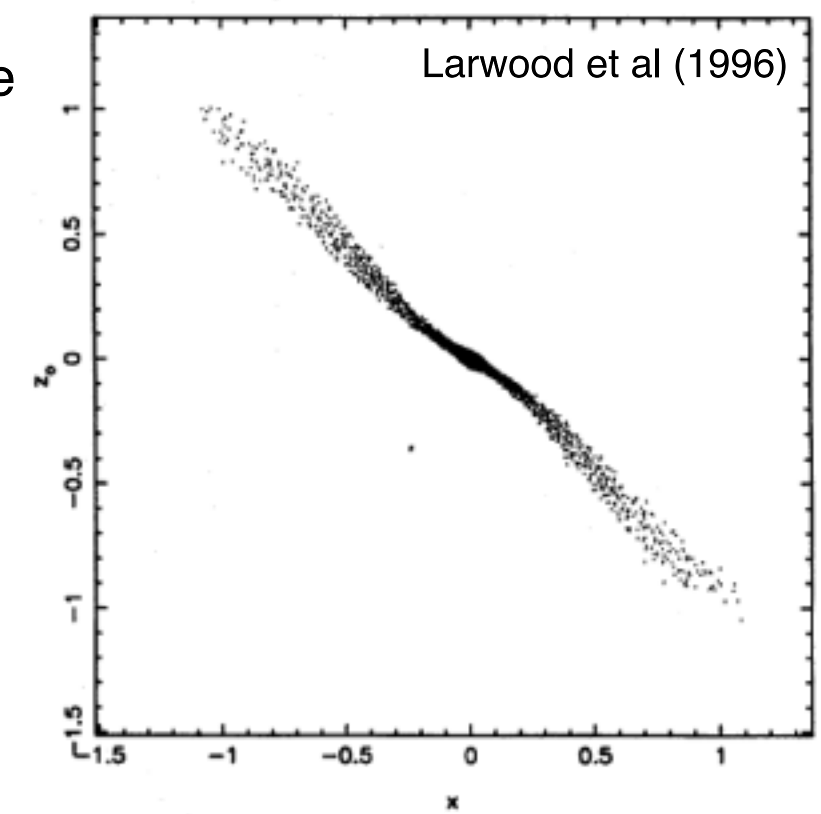
This condition approximates (within factors of order unity) to

$$\frac{H}{R} > \frac{|\omega_p|}{\Omega(R)}$$

for a disc in which bending waves propagate

Inclined binary systems - warped discs

Hydrodynamic simulations of discs in inclined binary systems conducted by (Larwood et al 1996) using SPH and (Fragner & Nelson 2010) using the grid-code Nirvana

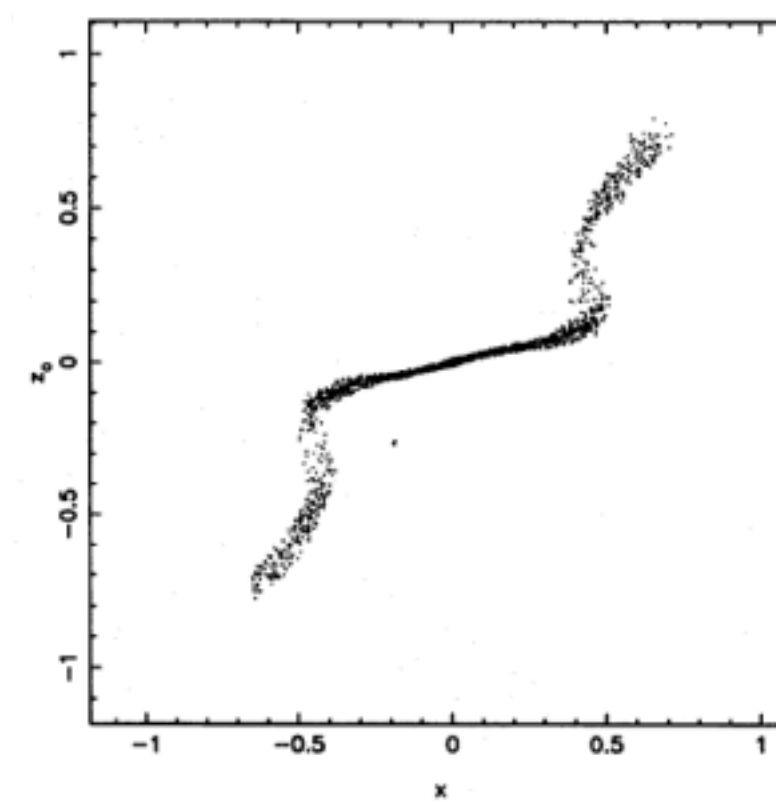


Basic agreement that discs precess as rigid bodies when bending disturbances propagate efficiently either through waves or diffusion

Note that for protoplanetary discs we expect $\alpha < h$ so that warps propagate as waves

Now present a few results from Fragner & Nelson (2010)

<u>Definitions</u>:
Consider the disc to consist of a set of concentric rings.
We define a **warp** to arise if the inclination between the disc local angular momentum vector and the binary angular momentum vector varies with radius



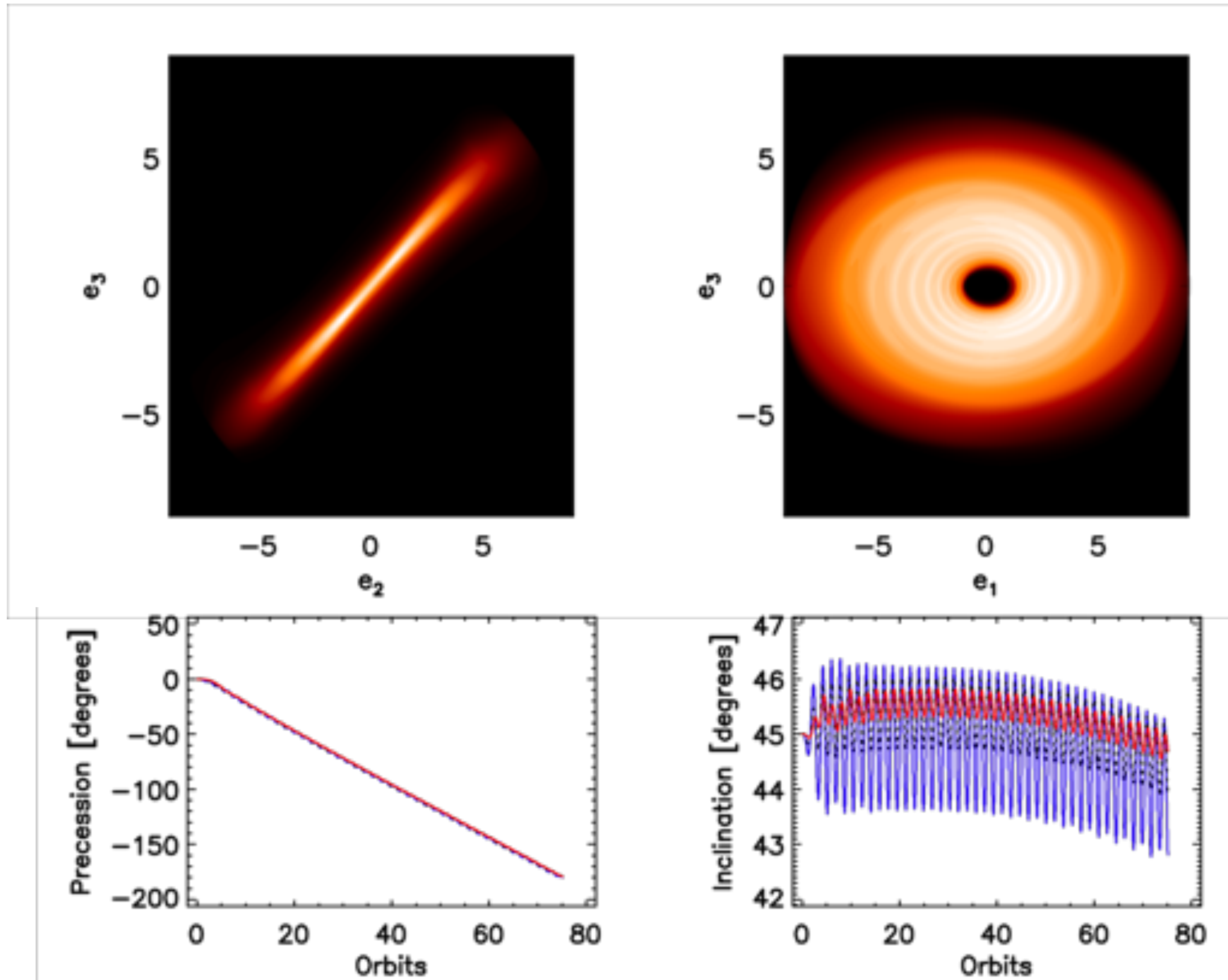
We define a **twist** to arise if the precession angle of the disc varies with radius

Inclined binary systems - warped discs

Model label	h	α	γ_F	R	Frame	τ_W	τ_P	Predicted behaviour
1	0.05	0.025	45	9	precessing	5.43	48.01	rigid precession
2	0.05	0.1	45	9	precessing	10.87	47.60	rigid precession
3	0.03	0.015	45	9	precessing	9.05	43.90	rigid precession
4	0.03	0.1	45	9	precessing	30.19	47.02	rigid precession
5	0.03	0.1	25	9	precessing	30.19	36.37	rigid precession
6	0.01	0.005	10	8	binary	22.77	33.87	rigid precession
7	0.01	0.1	10	8	binary	227.7	36.25	disrupted/broken
6a	0.01	0.005	10	10	binary	31.83	21.48	disrupted/broken
7a	0.01	0.1	10	10	binary	318.32	19.12	disrupted/broken

Run parameters from Fragner & Nelson (2010)

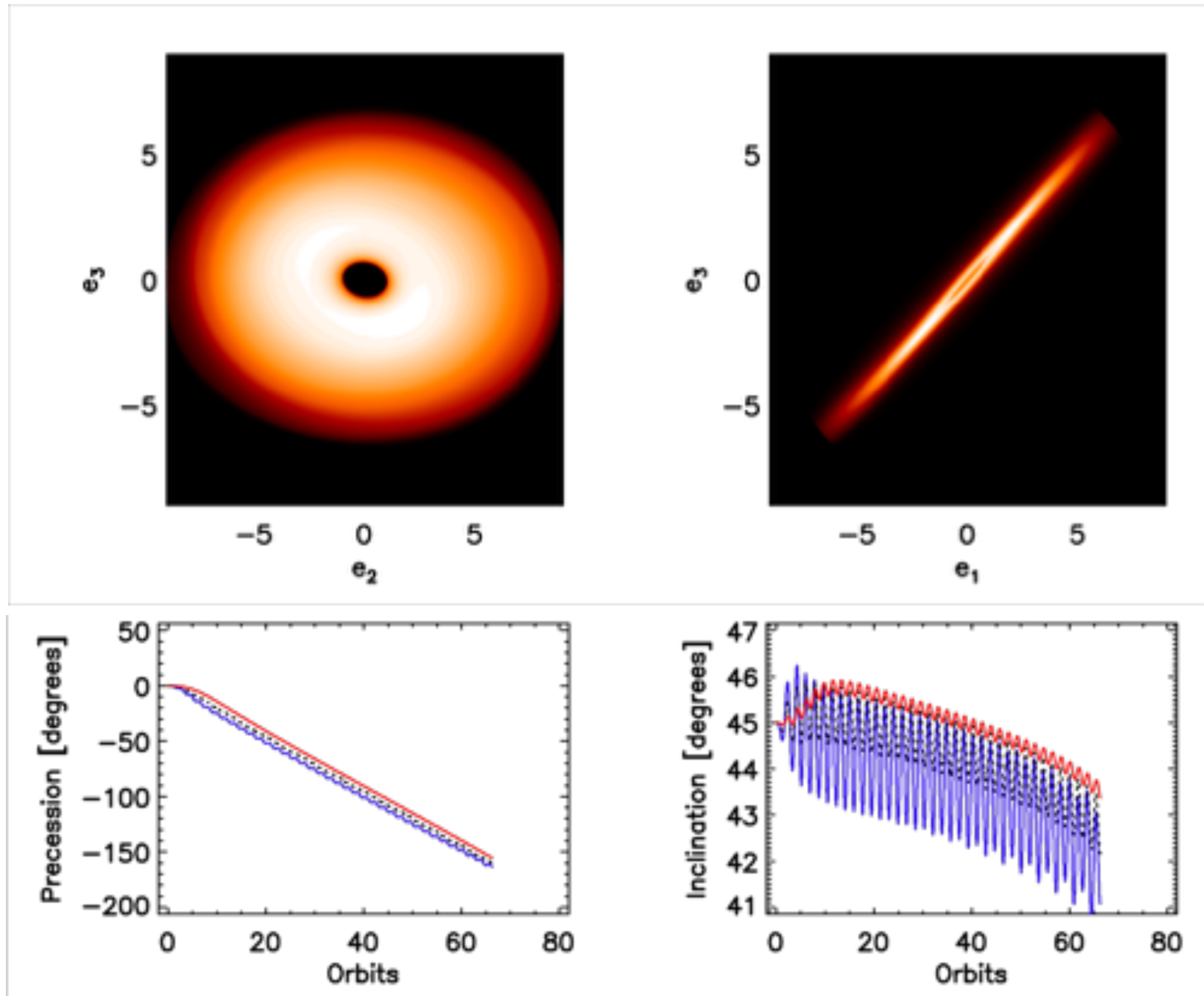
Inclined binary systems - warped discs



Model: h = 0.05, α = 0.025, binary inclination 45^o

Disc precesses as a rigid body with essentially zero twist and very mild warp. Disc re-aligns with binary on the global viscous evolution time scale

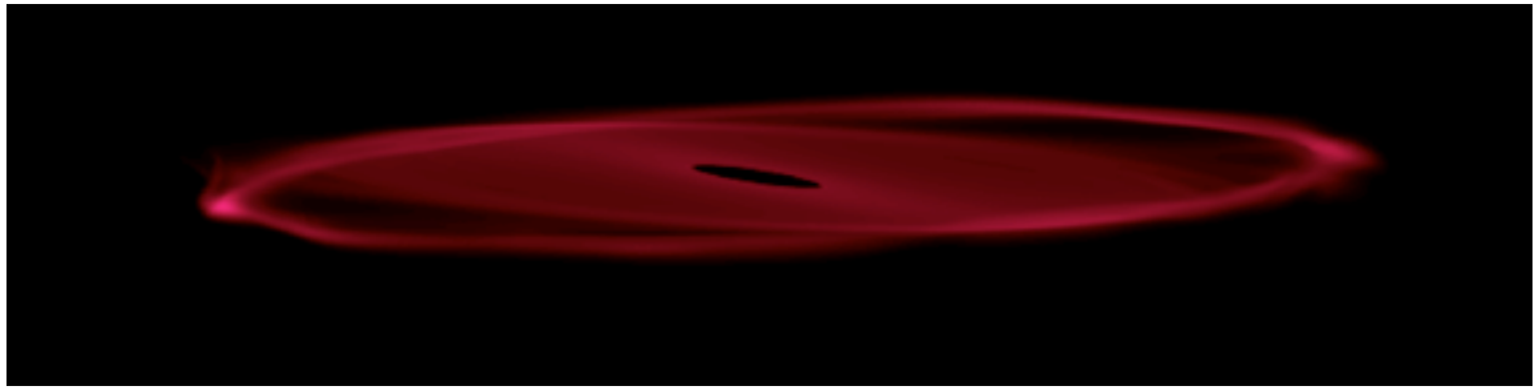
Inclined binary systems - warped discs

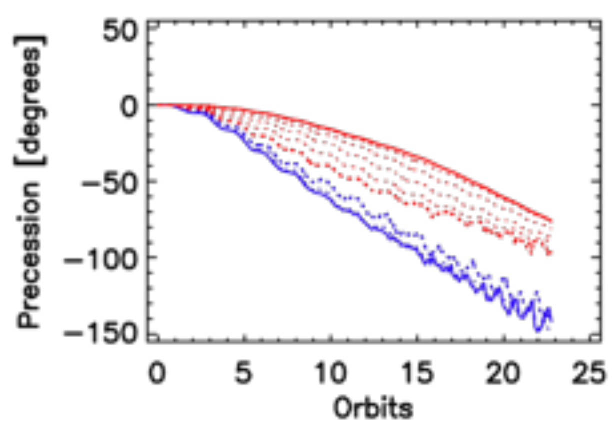


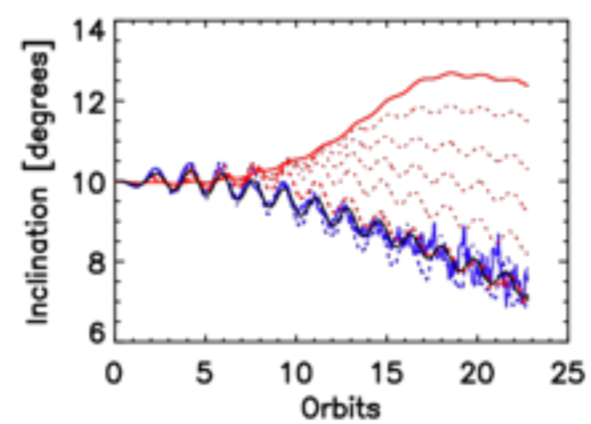
Model: $h = 0.03$, $\alpha = 0.1$, binary inclination 45^o

Disc precesses as a rigid body with a moderate twist and a warp of $\sim 1^o$. Disc re-aligns with binary on the global viscous evolution time scale

Inclined binary systems - warped discs

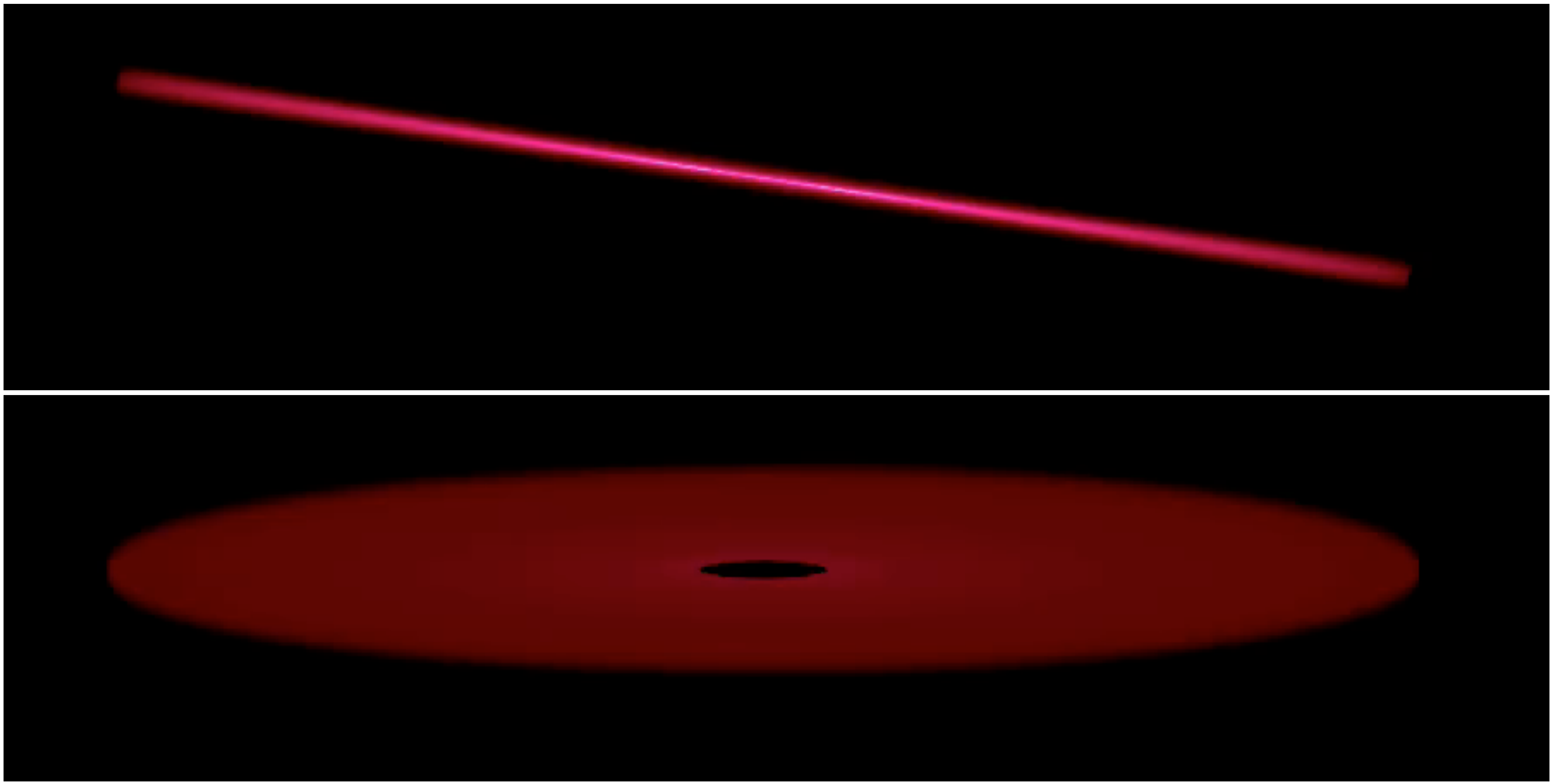




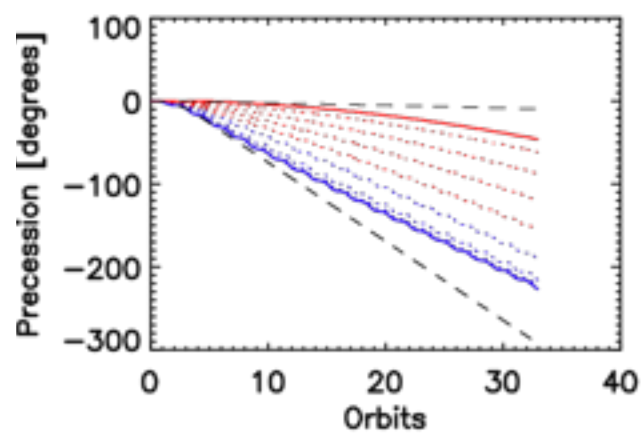


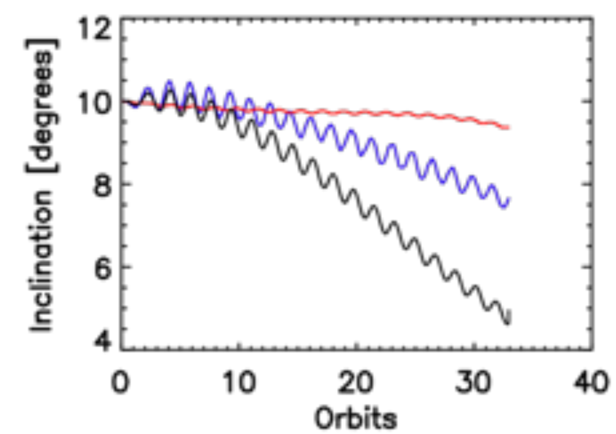
Model: h = 0.01, α = 0.005, binary inclination 10^o

Disc breaks at outer edge and inner regions precess as a rigid body with a significant twist and a large warp. Disc re-aligns with binary on a rapid time scale < viscous time



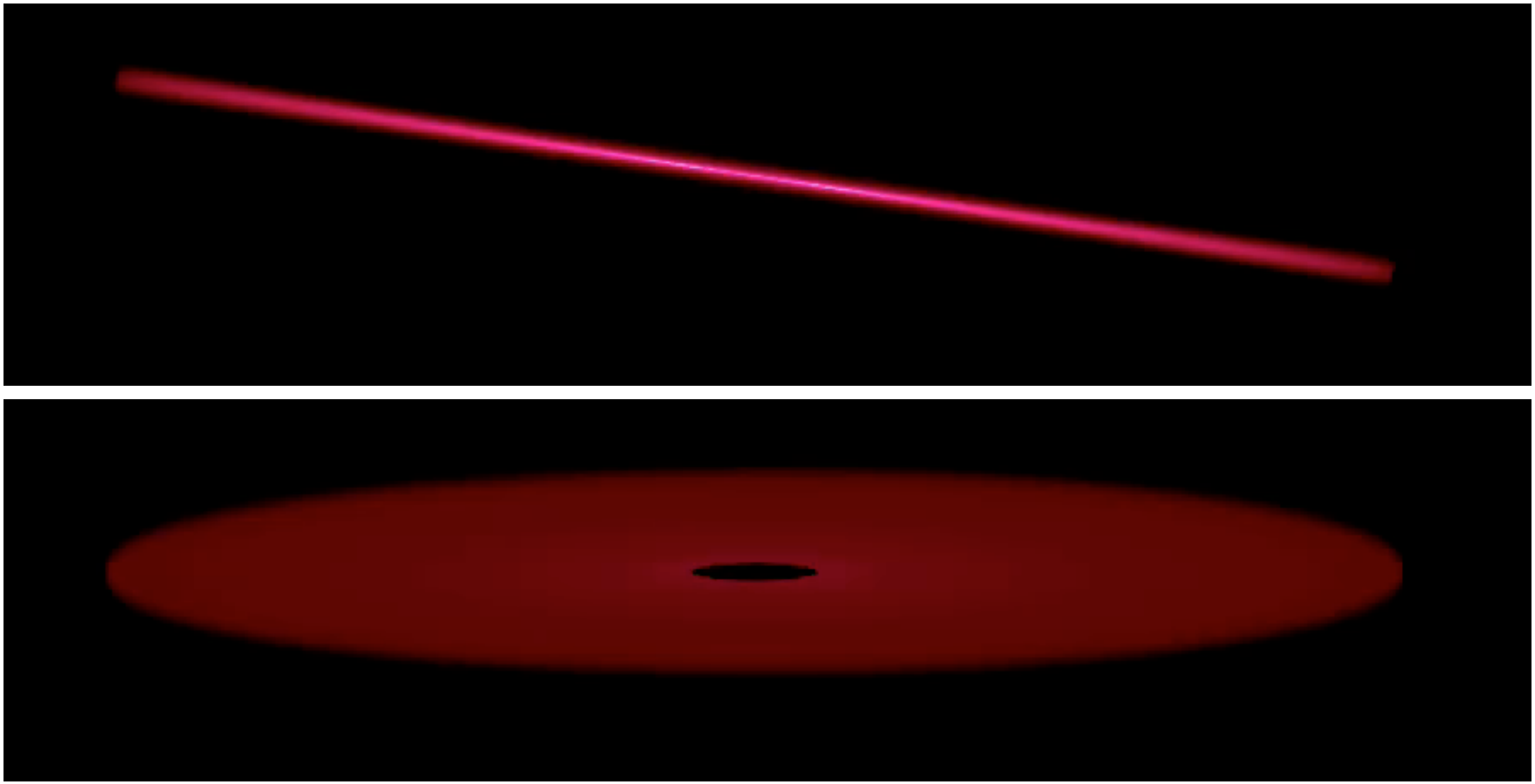
Inclined binary systems - warped discs



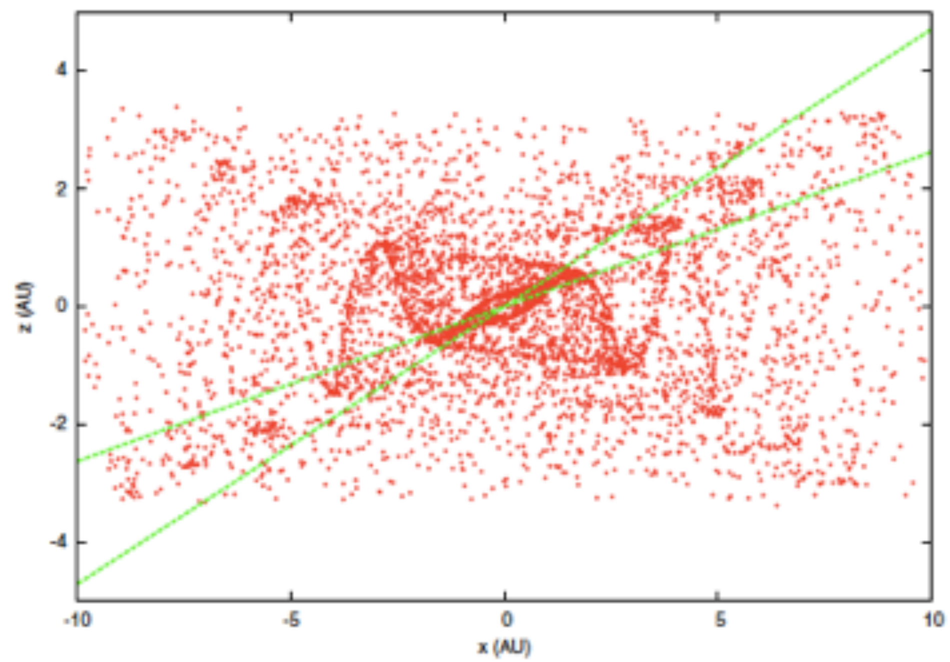


Model: h = 0.01, α = 0.1, binary inclination 10^{o}

Disc undergoes very strong differential precession but does not break - structure is smoothed by large viscosity. Disc realignment occurs on short time scale < viscous time



Inclined binary systems - planetesimal accumulation

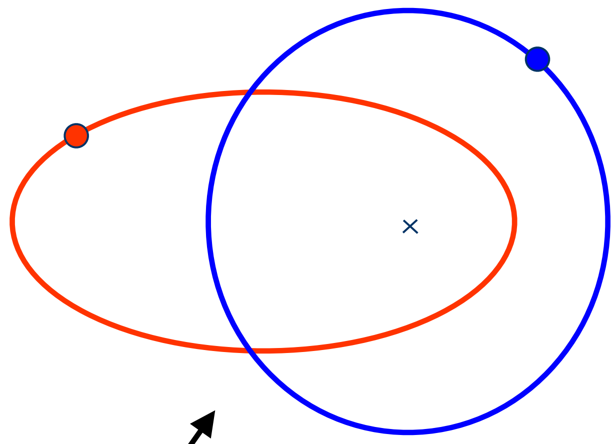


Earlier work

Marzari et al (2009) ignored gas disc and showed that differential nodal precession leads to highly destructive collisions in habitable zone when $a_b < 70$ AU. Kozai effect observed for $i_b > 40^o$ leading to highly destructive collisions

Xie & Zhou (2009) included static gas disc and showed that earlier results on orbital phasing of aligned pericentres applies to inclined orbits: aligned nodes Suggested that gas drag may lead to accretion friendly encounters when $i_b < 10^o$

Inclined binary systems - planetesimal accumulation



More recent work

Fragner et al (2011) presented 3D hydrodynamic simulations of 10km, 1km and 100m planetesimals in discs with inclined companions (i_b=25^o and i_b=45^o) with a_b=60 AU and disc radius ~ 18 AU.

Disc model: h=0.05; α=0.025

Planetesimals evolve under effects of:
(i) gravity due to binary components
(ii) disc gravity and gas drag forces

- Planetesimals assumed to be distributed along the orbits of a small number of test planetesimals (50 test particles used for each size)
- Orbit intersections used to determine collision velocities
- Collision velocities for neighbouring planetesimals arise because of: eccentricity differences; apsidal phasing; inclination differences; nodal phasing

$$\Delta v^2 = v_K^2 \left(\Delta e^2 + e^2 \Delta\omega^2 + \Delta\alpha^2 + \sin^2(\alpha)\Delta\Omega^2\right)$$

Inclined binary systems - planetesimal accumulation

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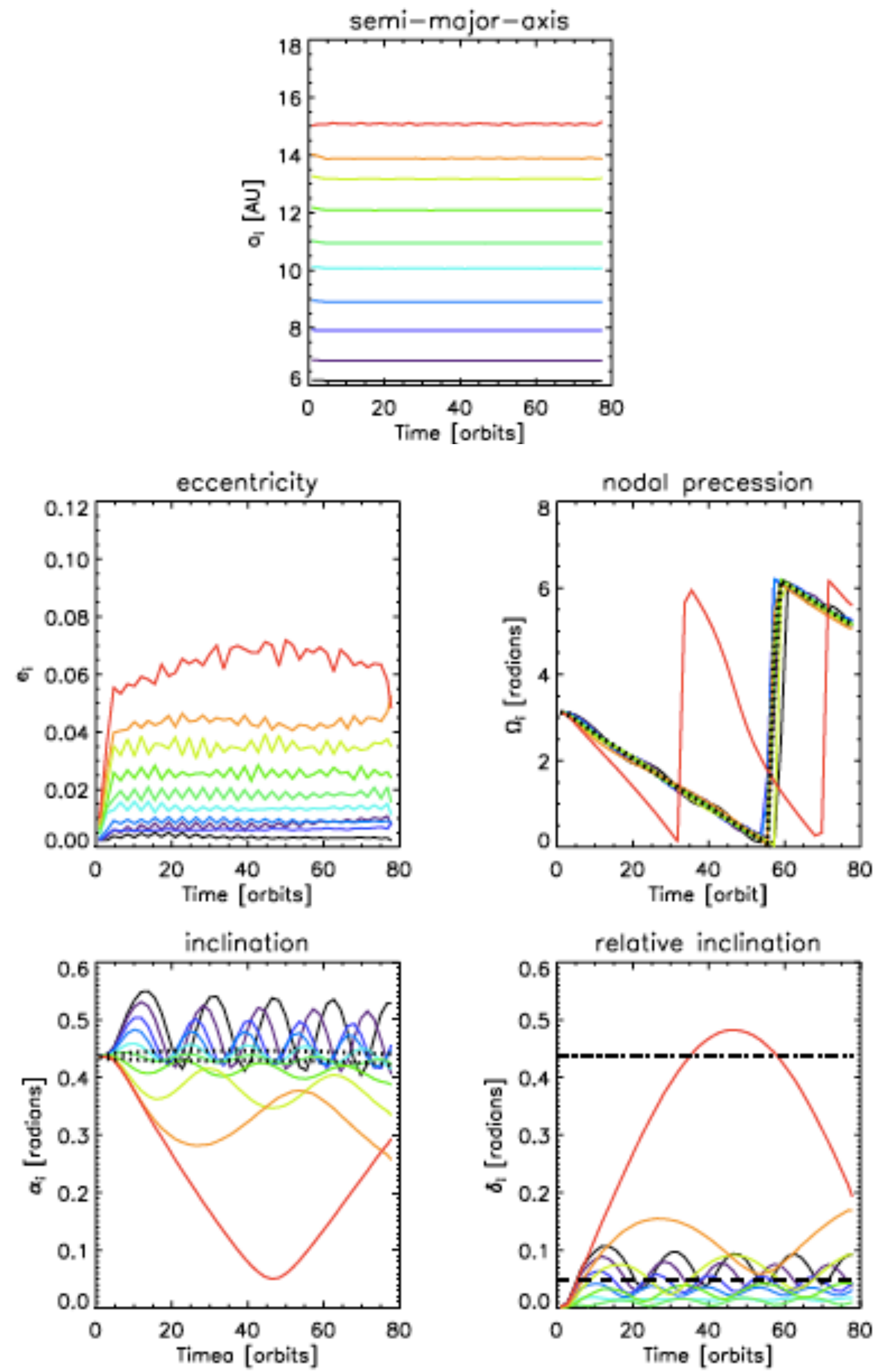
Disc model: h=0.05; α=0.025

<u>Planetesimal dynamics for $i_b=25^o$ - role of disc gravity</u>

- Large planetesimals (10 km) feel weak gas drag forces
- Disc undergoes solid body precession at rate that corresponds to free particle rate at ~ 11.5 AU
- Binary companion attempts to drive differential nodal precession of planetesimals
- Outer planetesimals precess relative to the disc
- Inner planetesimals (a_p < 14 AU) ~ precess with the disc due to disc gravity being dominant



Inclined binary systems - planetesimal accumulation

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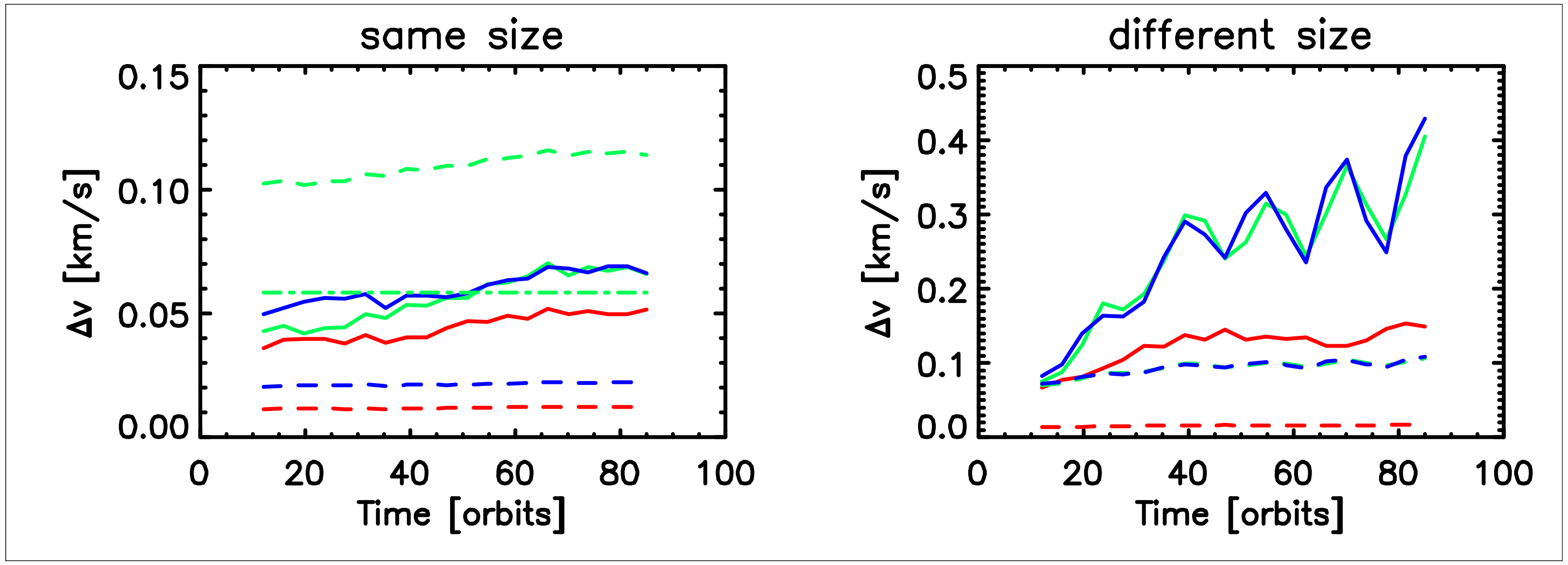
Disc model: h=0.05; α=0.025

<u>Collision velocities for i_b=25^o</u>

- Planetesimals at a_p ~ 10 AU develop collision velocities > catastrophic disruption threshold



10km – 10km
1km – 1km
100m – 100m

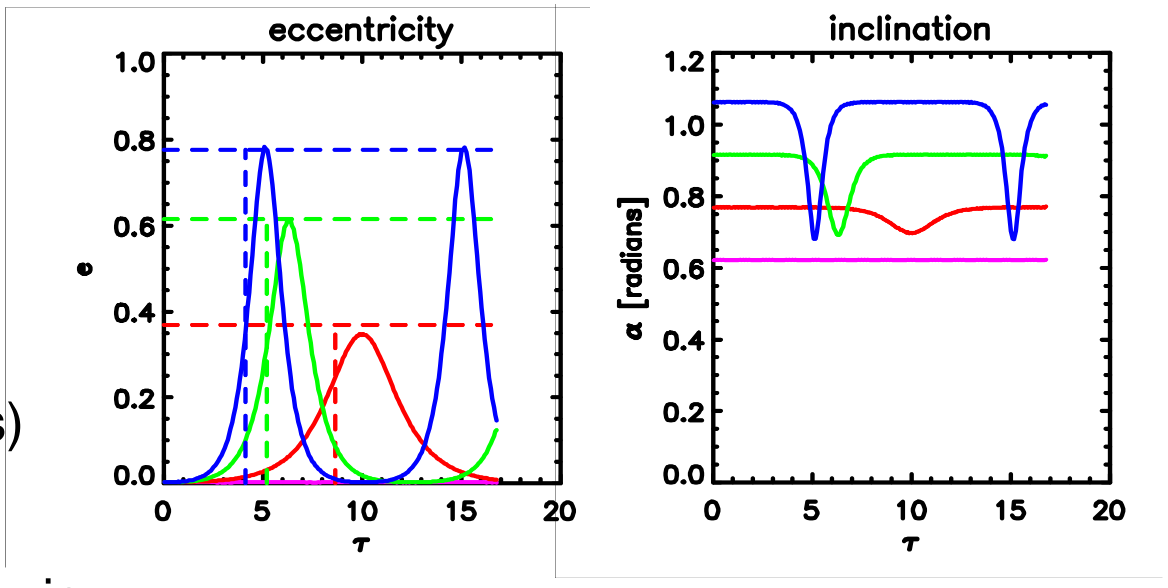
10km – 1km
10km – 100m
1km – 100m

Disruption limit (strong rock)
Disruption limit (weak rock)

Stewart & Leinhardt 2009, Housen & Holsapple 1990, 1999, Benz & Asphaug 1999

Inclined binary systems - planetesimal accumulation

Fragner et al (2011) presented 3D hydrodynamic simulations of 10km, 1km and 100m planetesimals in discs with inclined companions (i_b=25^o and i_b=45^o) with a_b=60 AU and disc radius ~ 18 AU.



Disc model: h=0.05; α=0.025

<u>Planetesimal dynamics for i_b=45^o - Kozai-Lidov effect</u>

- Kozai-Lidov effect switches on for i_b > 40^o (0.68 rads) (Kozai 1962; Lidov 1962)

- This is a secular effect derived for an inclined companion perturbing a test particle

$$\frac{\partial e_i}{\partial \tau} = \frac{15}{4} \sin^2(\alpha_{i0}) \sin(\omega_i) \cos(\omega_i) e_i$$
$$= \frac{15}{4} e_i \sqrt{\frac{2}{5}\left[\sin^2(\alpha_{i0}) - \frac{2}{5}\right]}.$$

Exponential growth of eccentricity switches on for critical value of the initial inclination, here denoted by α_{i0}.

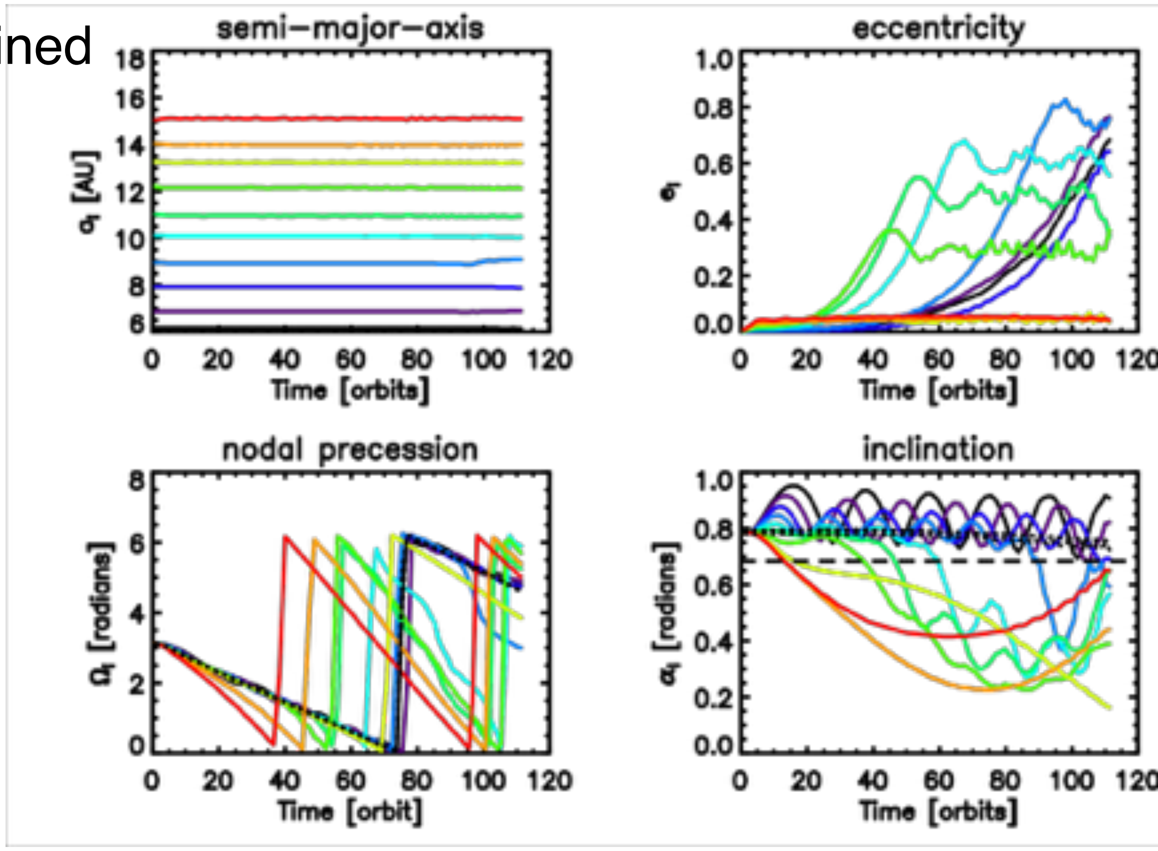
- The angular momentum of the planetesimal projected along the binary angular momentum vector is a constant of the motion (a consequence of assuming the binary has a circular orbit)

$$D_i = \sqrt{a_i(1-e_i^2)} \cos(\alpha_i).$$

- The semimajor axis is constant in secular theory so we have oscillations in the eccentricity and inclination (as shown in diagram)

Inclined binary systems - planetesimal accumulation

Fragner et al (2011) presented 3D hydrodynamic simulations of 10km, 1km and 100m planetesimals in discs with inclined companions (i_b=25^o and i_b=45^o) with a_b=60 AU and disc radius ~ 18 AU.



Disc model: h=0.05; α=0.025

<u>Planetesimal dynamics for i_b=45^o - Kozai-Lidov effect</u>

- Planetesimals that precess closely with the disc experience Kozia-Lidov effect
- For planetesimals that do not closely follow the disc, their inclinations can fall below the critical value required for Kozai for a period of time
- Large eccentricities are generated that lead to very large collision velocities

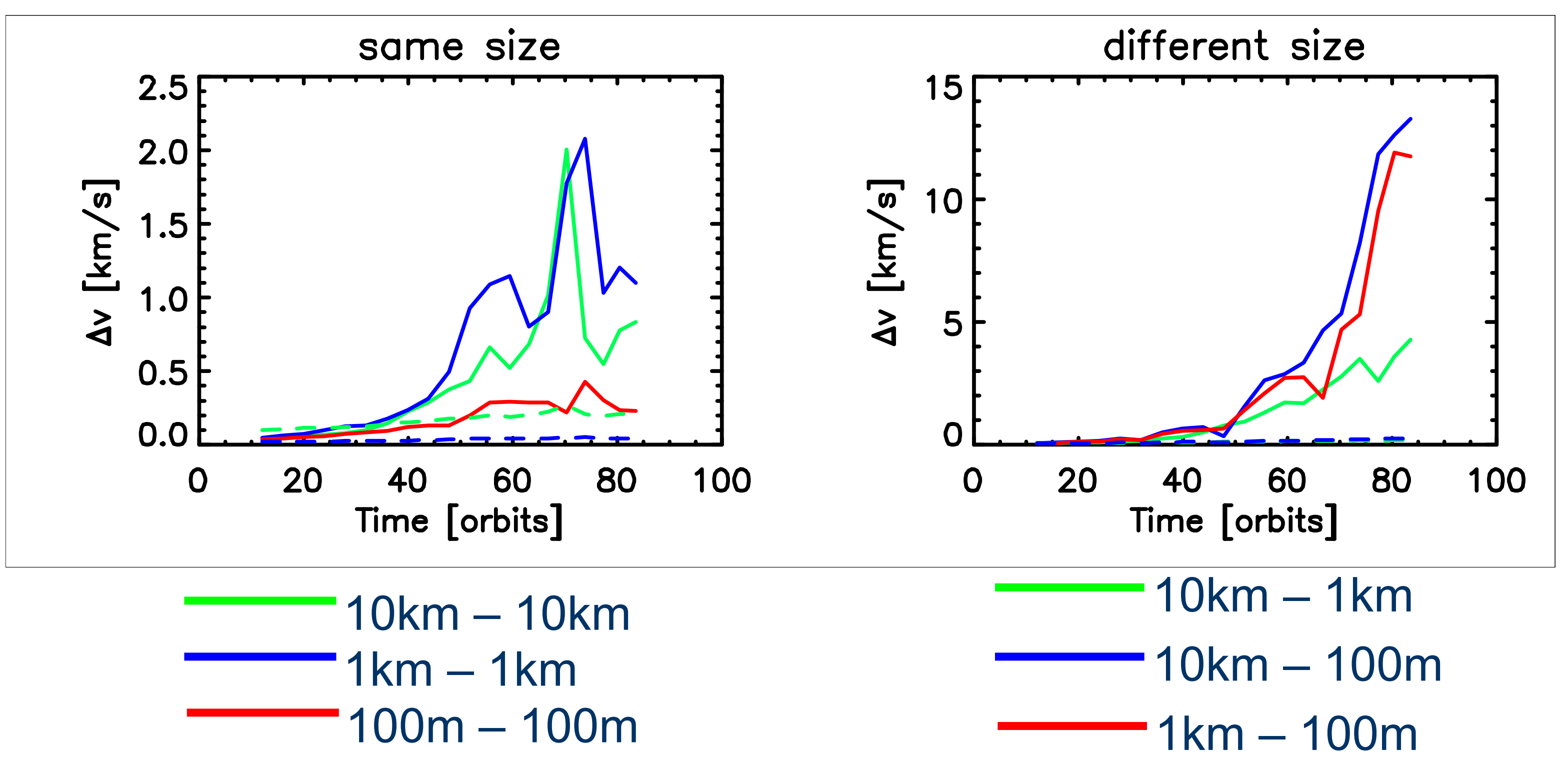
Inclined binary systems - planetesimal accumulation

Fragner et al (2011) presented 3D hydrodynamic simulations of 10km, 1km and 100m planetesimals in discs with inclined companions (i_b=25^o and i_b=45^o) with a_b=60 AU and disc radius ~ 18 AU.

Disc model: h=0.05; α=0.025

<u>Planetesimal dynamics for i_b=45^o - Kozai-Lidov effect</u>

- Large eccentricities are generated that lead to very large collision velocities - and catastrophic disruption
- Growth of planets through planetesimal accretion looks to be impossible in presence of Kozai



Inclined binary systems - planetesimal accumulation

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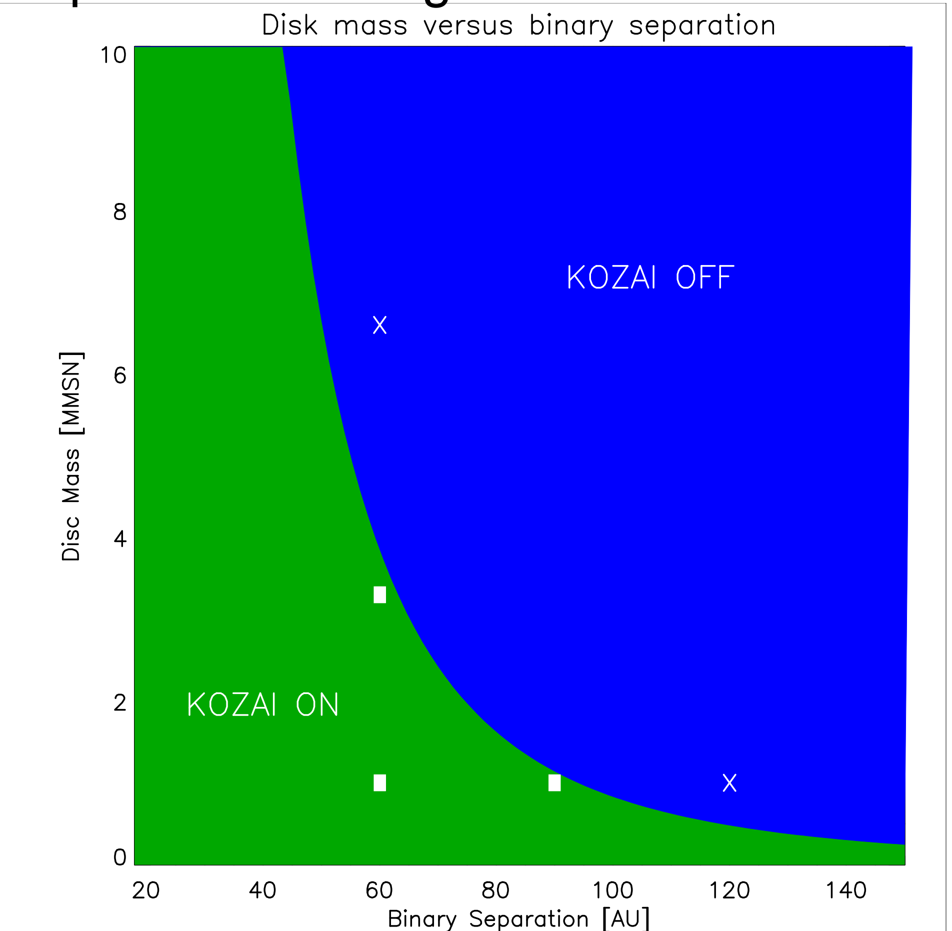
Disc model: h=0.05; α=0.025

<u>Planetesimal dynamics for i_b=45^o - Kozai-Lidov effect</u>

- Kozai effect can be switched off:
  if precession rate induced by companion < precession rate induced by disc
  i.e. move companion onto larger orbit or increase disc mass



Inclined binary systems - evolution of planets in discs

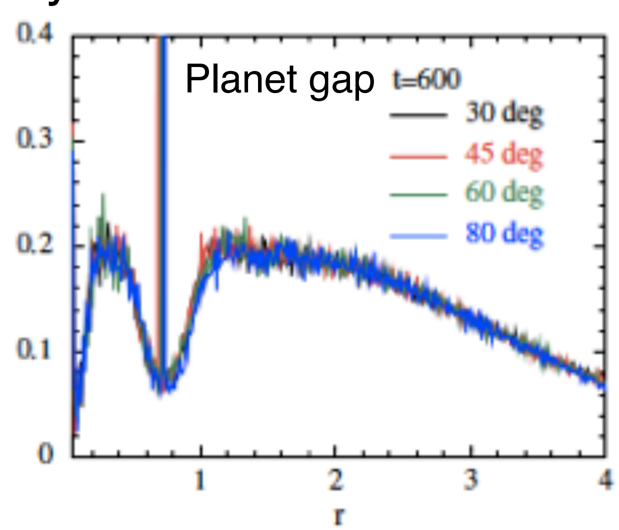
Batygin (2012) and Xiang-Greus & Papaloizou (2014) considered evolution of planet embedded in protoplanetary disc with inclined binary to explain planetary misalignment discovered through the Rossiter-McCaughlin effect

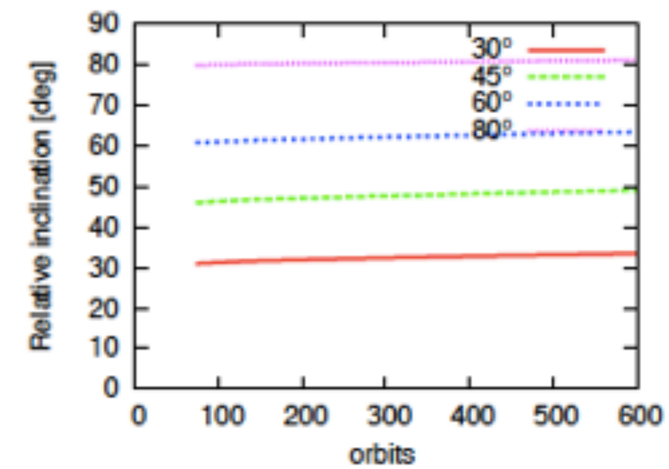
Protoplanetary disc precesses as a solid body either through self-gravity (Batygin 2012) or pressure (bending waves) (Xiang-Greuss & Papaloizou 2014)

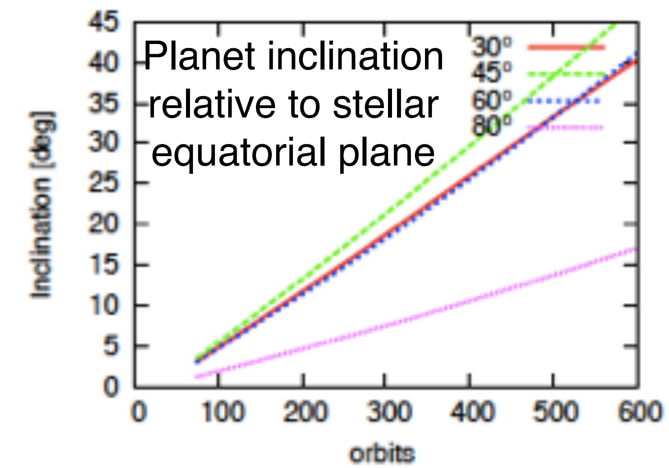
Planet precesses with the disc as observed for planetesimals for range of disc masses. Note that a binary inclination of 45^o can give rise to a maximum misalignment of 90^o with stellar spin axis so very large misalignment angles can be generated

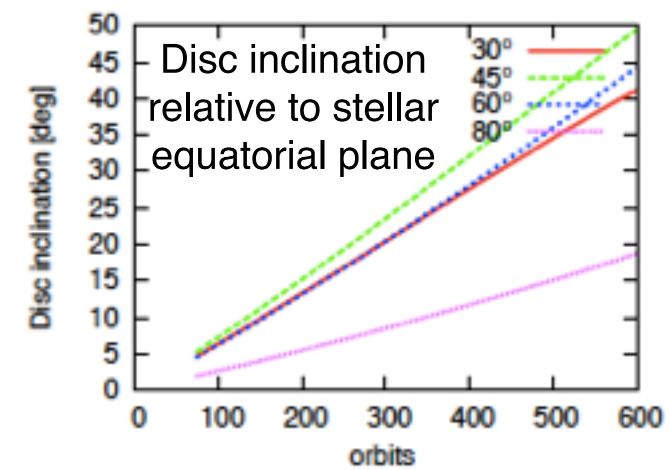
<u>Results</u>

1. SPH simulations presented by Xiang-Greuss & Papaloizou (2014) show that 2 M_{Jup} planet precesses with the disc while forming gap for a range of binary inclinations









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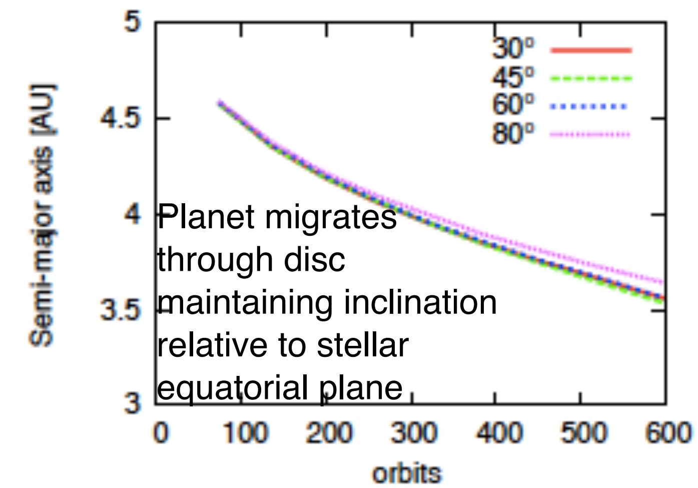

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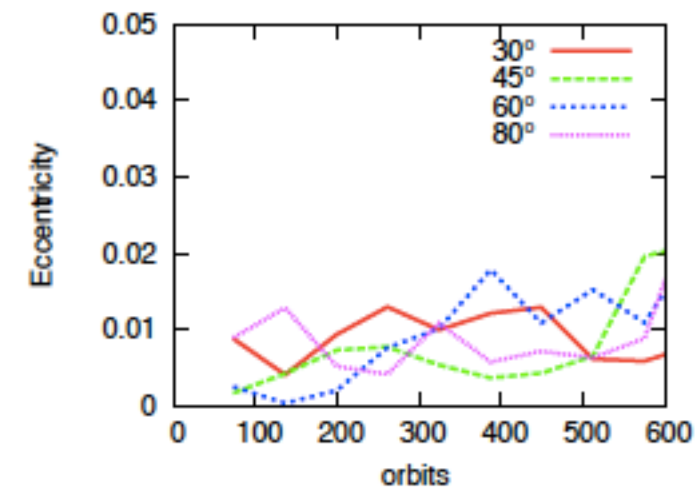
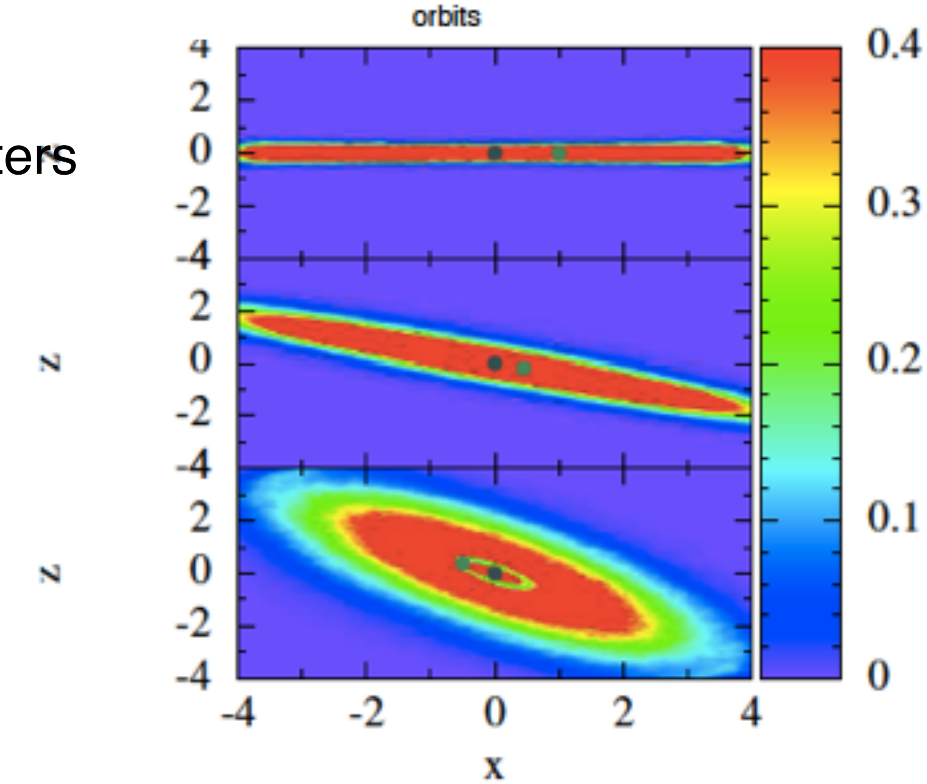


Planet precesses with the disc as observed for planetesimals for range of disc masses. Note that a binary inclination of 45° can give rise to a maximum misalignment of 90° etc so very large misalignment angles can be generated

<u>Results</u>

2. For range of inclinations the planet migrates through the disc maintaining small eccentricity - can form inclined hot Jupiters



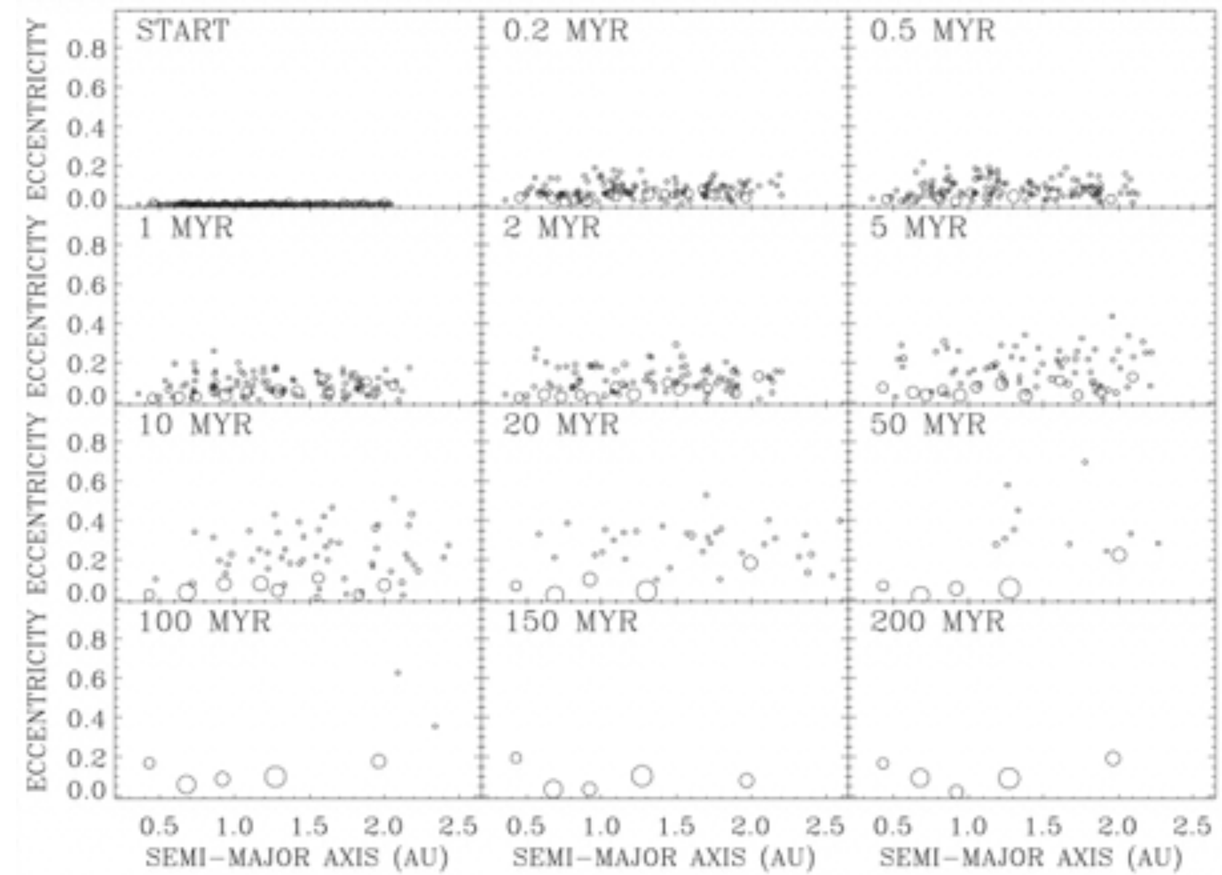
Terrestrial planet formation in binary systems

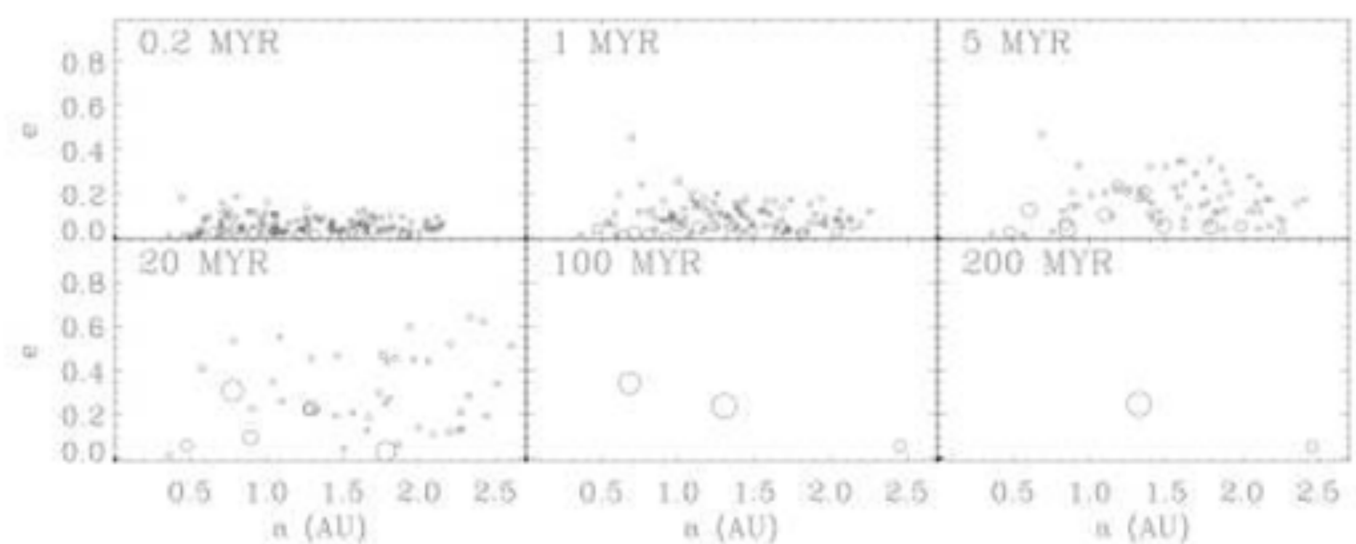
Quintana et al (2002) and Quintana & Lissauer (2006) considered terrestrial planet formation in the Alpha Cen system and in circumbinary discs

<u>Alpha Cen A & B</u>
a_b = 23.4 AU, e_b=0.52, M_A~ 1.1 M_{sun}, M_B ~ 0.91 M_{sun}
For $i < 60^{o}$ typically form 3 - 5 planets
For $i > 60^{0}$ most material falls into star (Kozai-Lidov!)

<u>Circumbinary</u>
For stellar apocentres $Q_B \equiv a_B(1 + e_B) \lesssim 0.2$ AU
results similar to those obtained with single stars

Larger apocentre values $\longrightarrow$ sparser planets



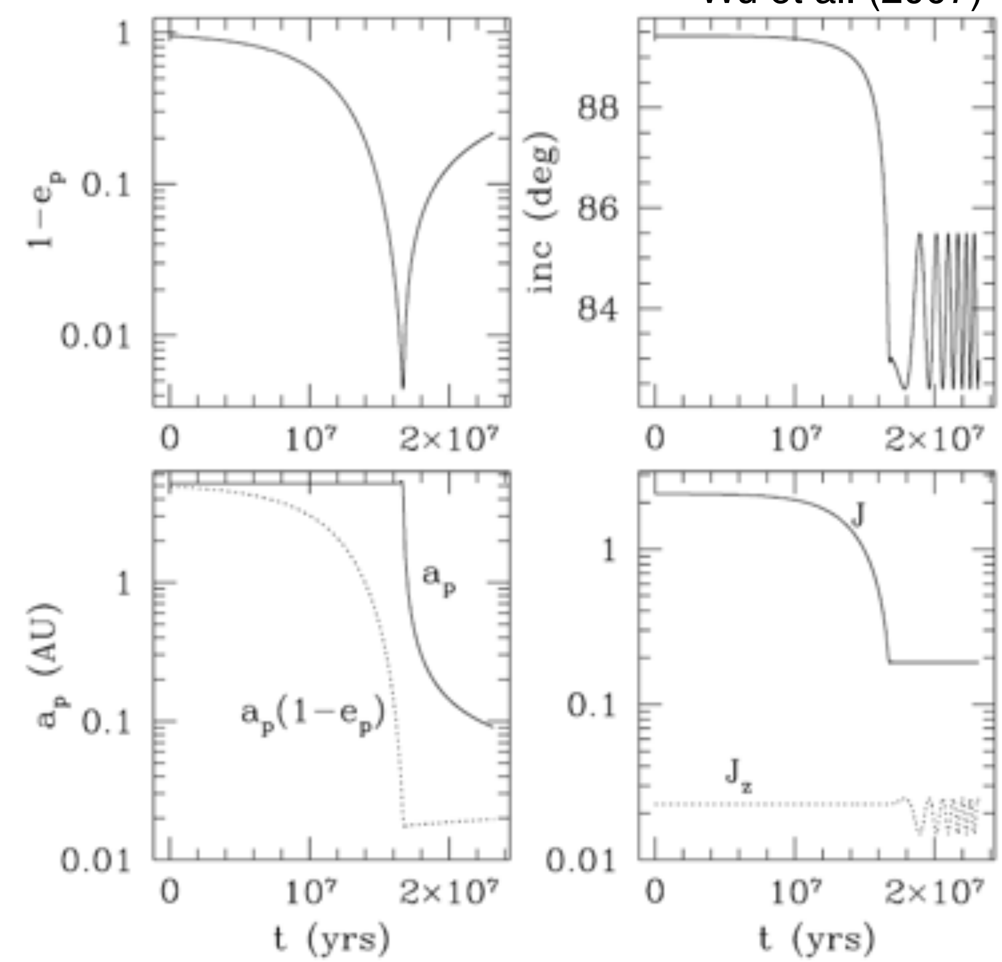


a_b=0.075, e_b=0.33

Inclined binary systems - Kozai migration

The Kozai-Lidov effect may provide a mechanism for producing hot Jupiters with circular, inclined orbits (Wu & Murray 2003; Wu et al. 2007; Fabrycky & Tremaine 2007; Naoz et al (2011; 2012)

Wu et al. (2007)



Binary systems with stellar companions on highly inclined orbits may drive planetary orbits to high eccentricity. When pericenter distance r_{peri} ~ 0.02 AU tidal circularisation can prevent further growth of eccentricity through the Kozai-Lidov effect and circularise the orbit.

Tidal circularisation at ~ constant angular momentum leads to $a_p \sim 2 \times r_{peri}$ if eccentricity ~ 1

Large misalignments between the host star spin axis and planetary orbit can arise because planet angular momentum vector precesses around binary angular momentum vector during evolution

<u>Recent developments</u>

The original Kozai-Lidov mechanism applied to a system with a circular binary orbit and a test particle. The eccentric Kozai-Lidov effect (EKL) relaxes these assumptions, producing qualitatively different behaviour such as orbital "flipping" from nearly coplanar configurations to generate retrograde orbits (Naoz et al 2011, 2012; Li et al 2014)

Concluding remarks

- Observations indicate that planets form in unexpected environments (e.g Gamma Cephei) - and that planet formation is a robust process
- These systems provide excellent testbeds for our theories of planetary formation
- Difficulties in forming Kepler circumbinary planets *in situ* provide strong evidence for disc driven migration - the models made predictions before the discoveries