Evolution of Arrokoth
from a binary planetesimal into contact
via Kozai-Lidov oscillations and nebular drag

Wladimir Lyra

New Mexico State University

Funding

TCAN – 2020
NFDAP – 2019
XRP – 2016, 2018

AAG – 2010, 2020

NRAO - 2017

HST - 2016

Computational Facilities

Universidad de Concepcion, Apr 6nd, 2021

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Evolution of MU69 from a binary planetesimal into contact by Kozai-Lidov oscillations and nebular drag

W. Lyra [a], A.N. Youdin [b], A. Johansen [c]

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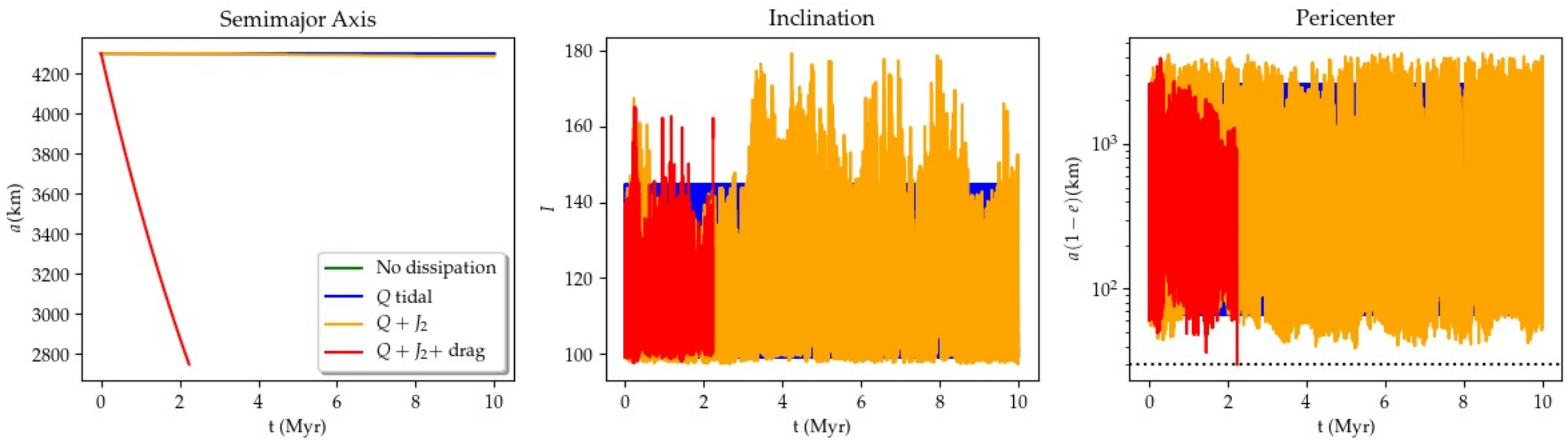
Highlights

- Solution of the hierarchical three-body problem with nebular drag implemented into a Kozai cycles plus tidal friction model.
- Contact is implausible via drag alone in the Kuiper belt because the gas drag is linear with velocity, not quadratic.
- The permanent quadrupoles of the pre-merger lobes make the Kozai

Effect of Drag

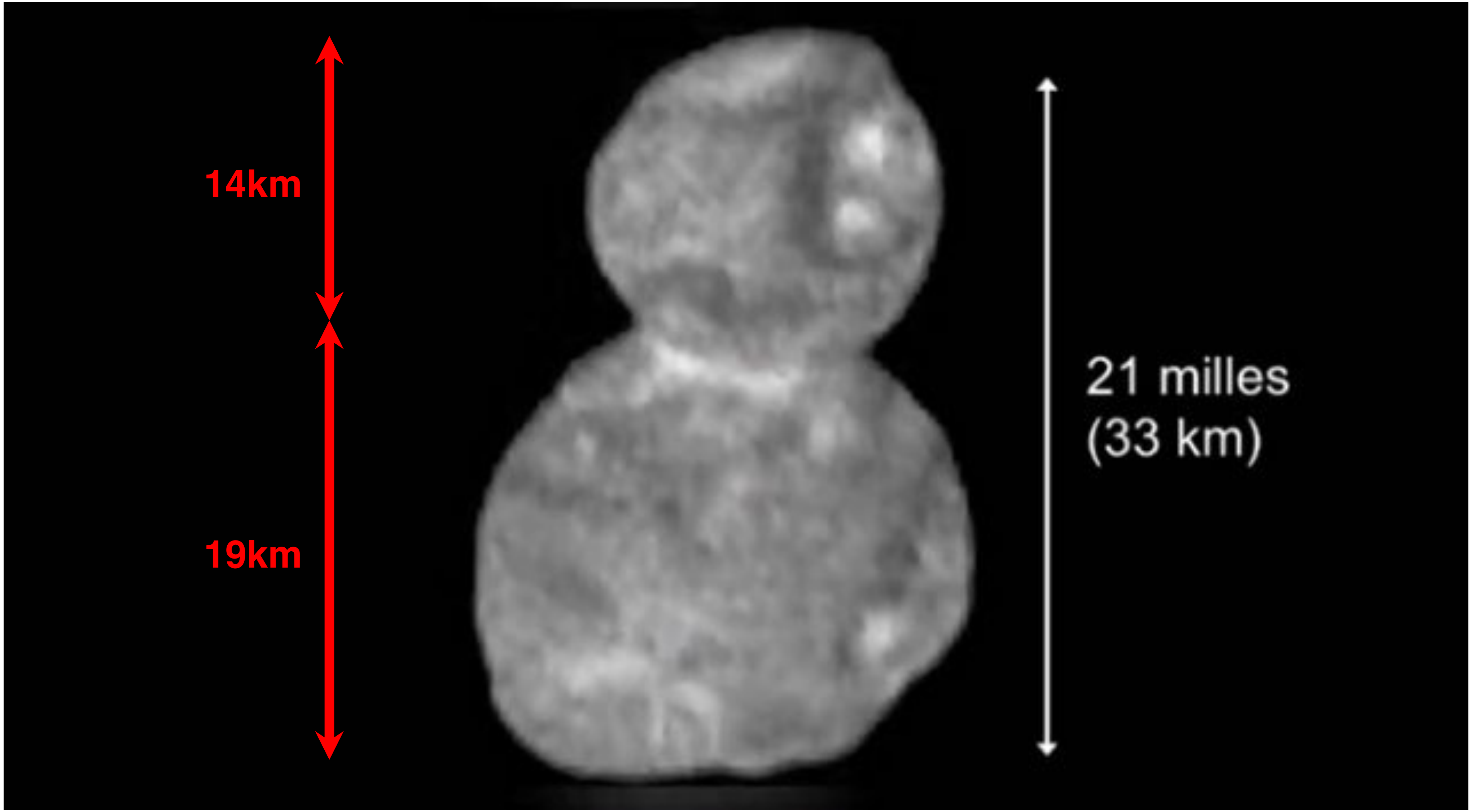


Lyra, Youdin, & Johansen (2021)

Arrokoth (MU_{69})

Lyra, Youdin, & Johansen (2021)

MU_{69}: Dimensions



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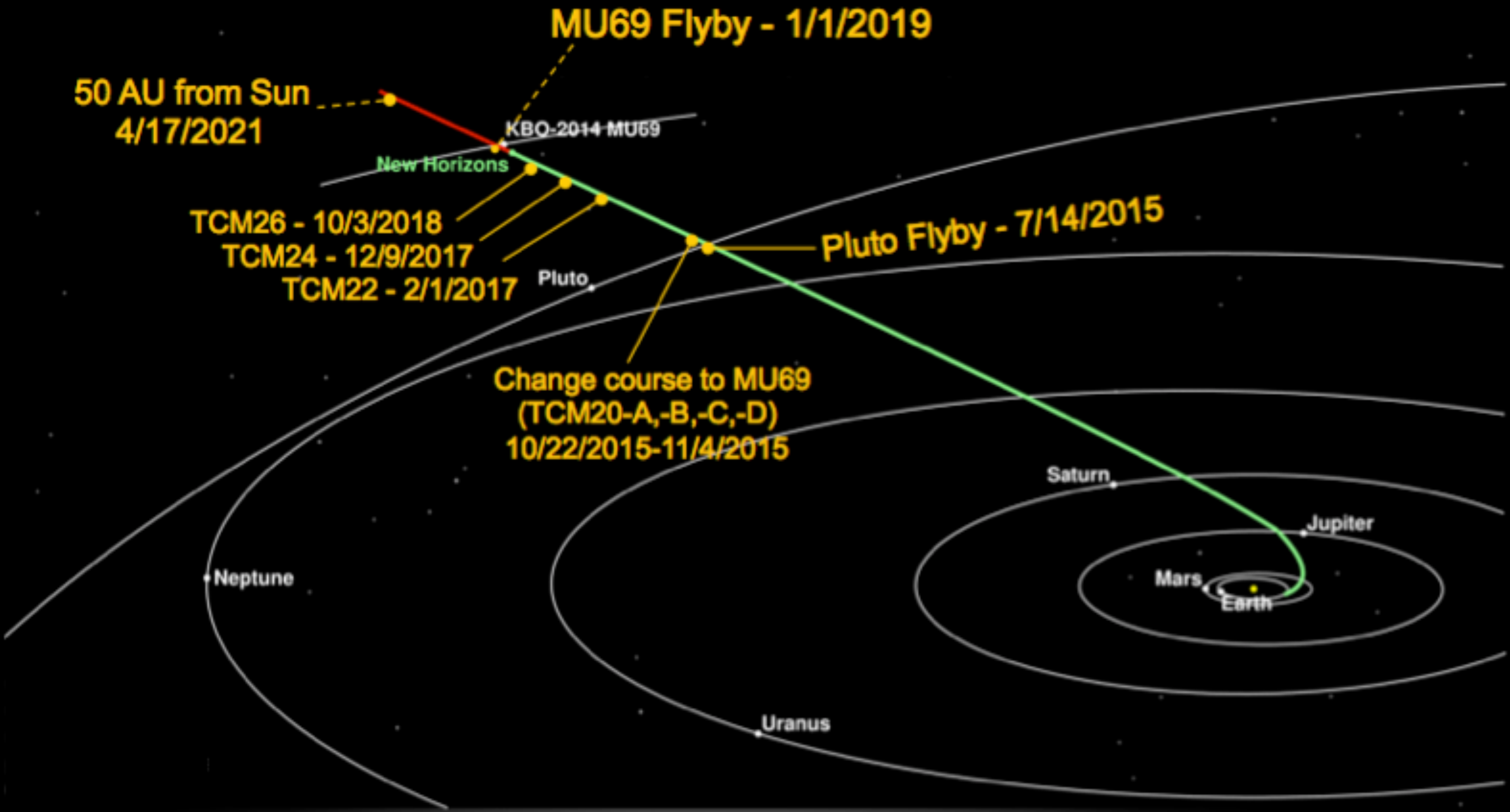
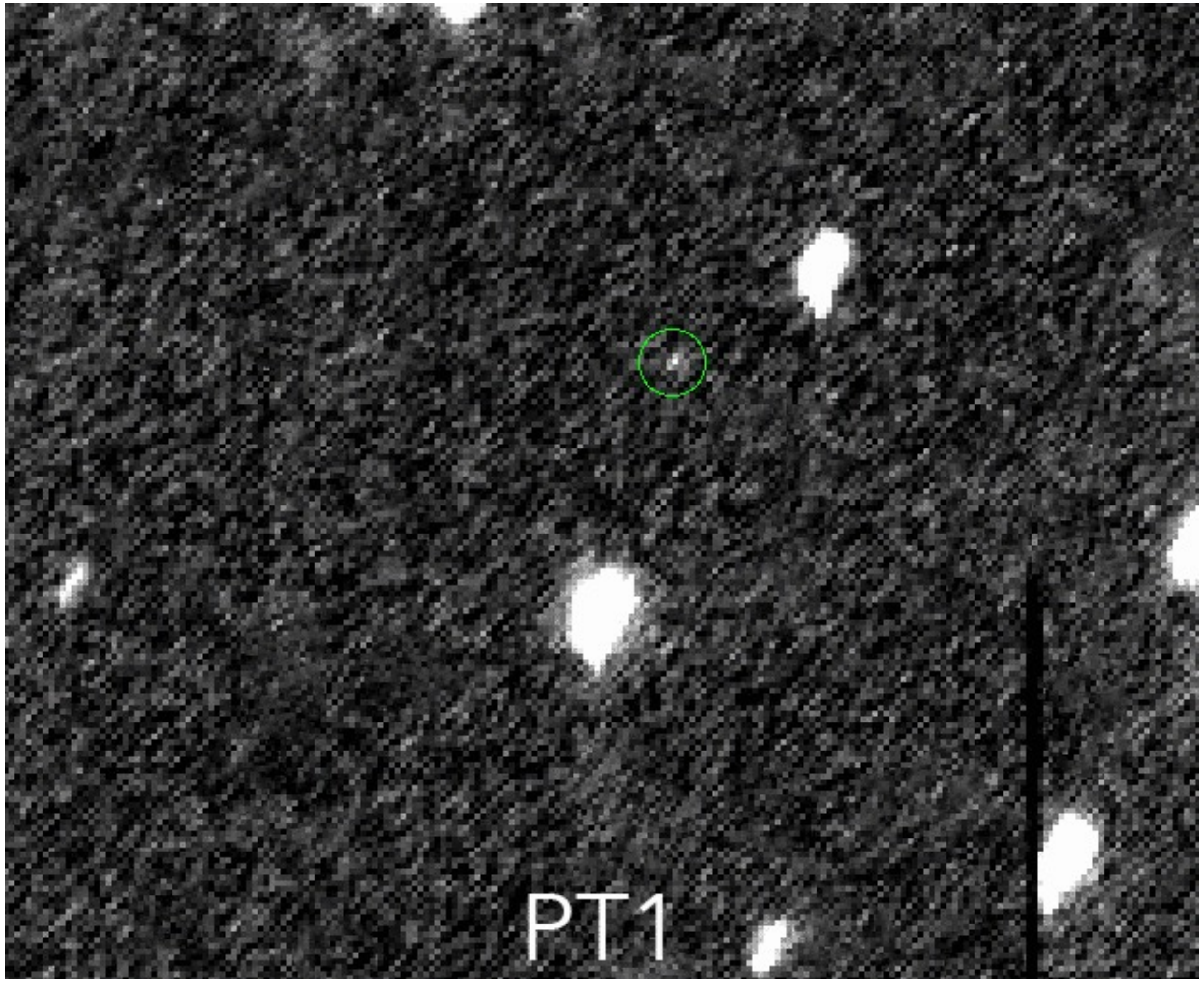
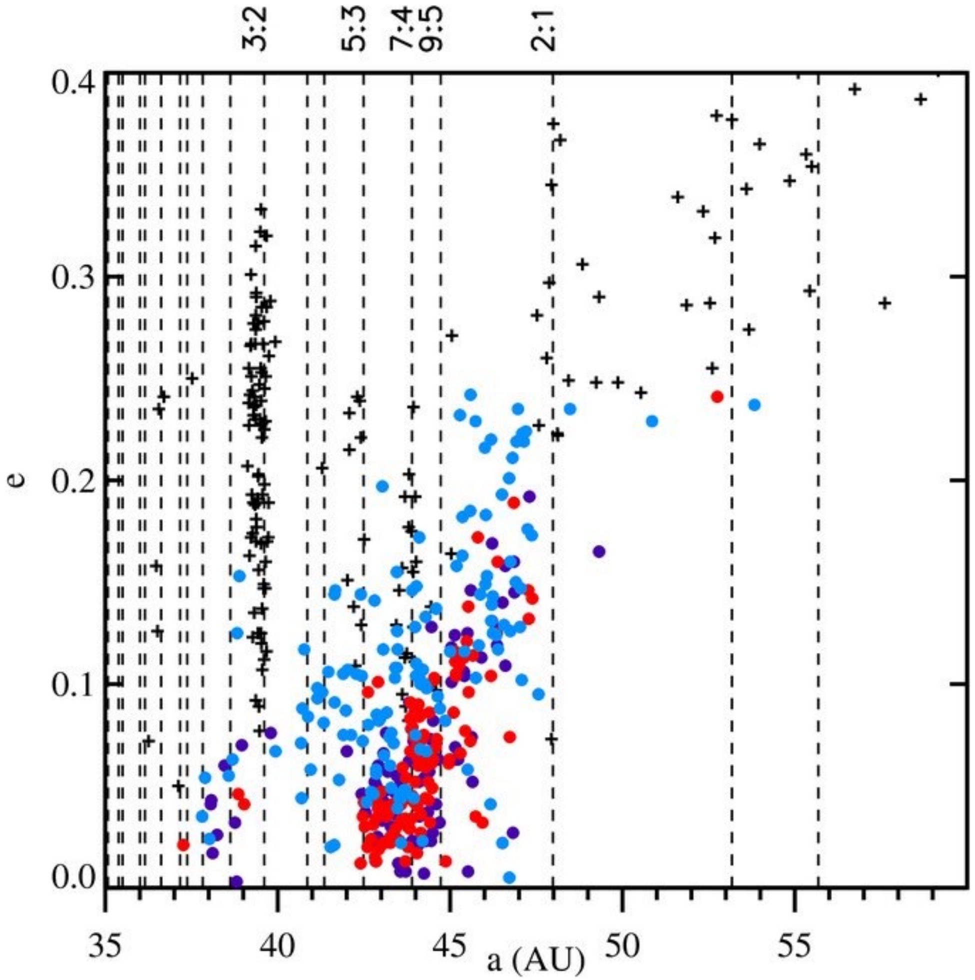
New Horizons Trajectory



2014 MU_{69}: Discovery



Cold Classical Kuiper Belt Object



+ Resonant and Scattered
Cold Classical *i*<2°
"Ambiguous" 2°<*i*<6°
Hot Classicals i>6°

Presumably pristine planetesimals

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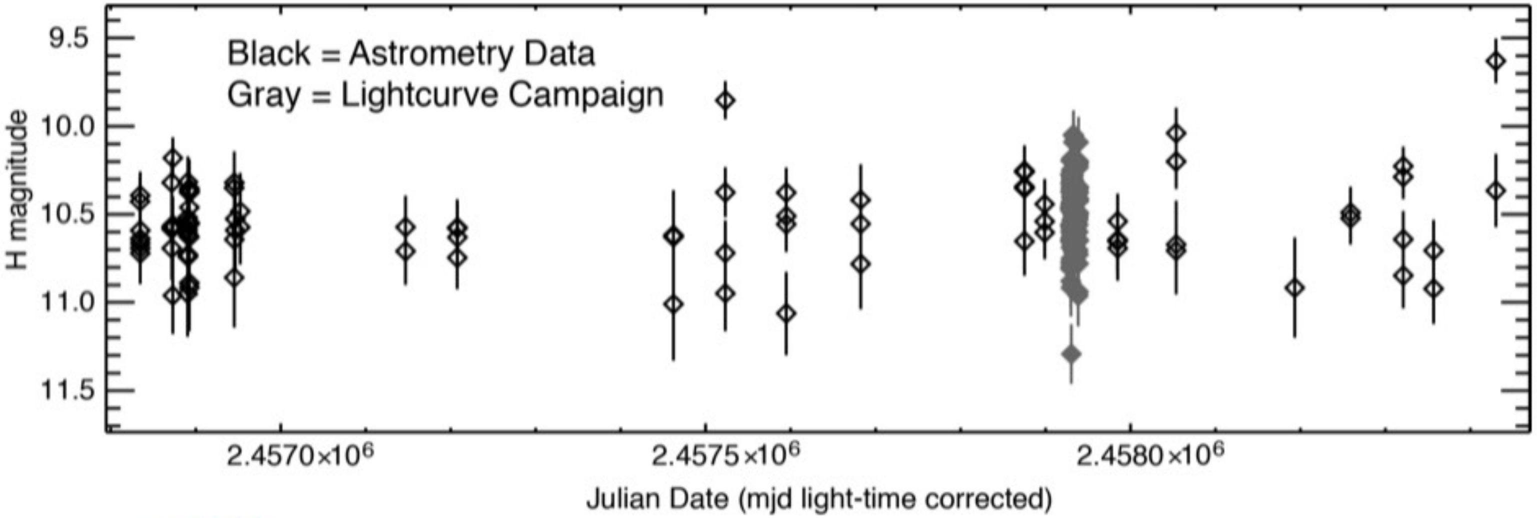
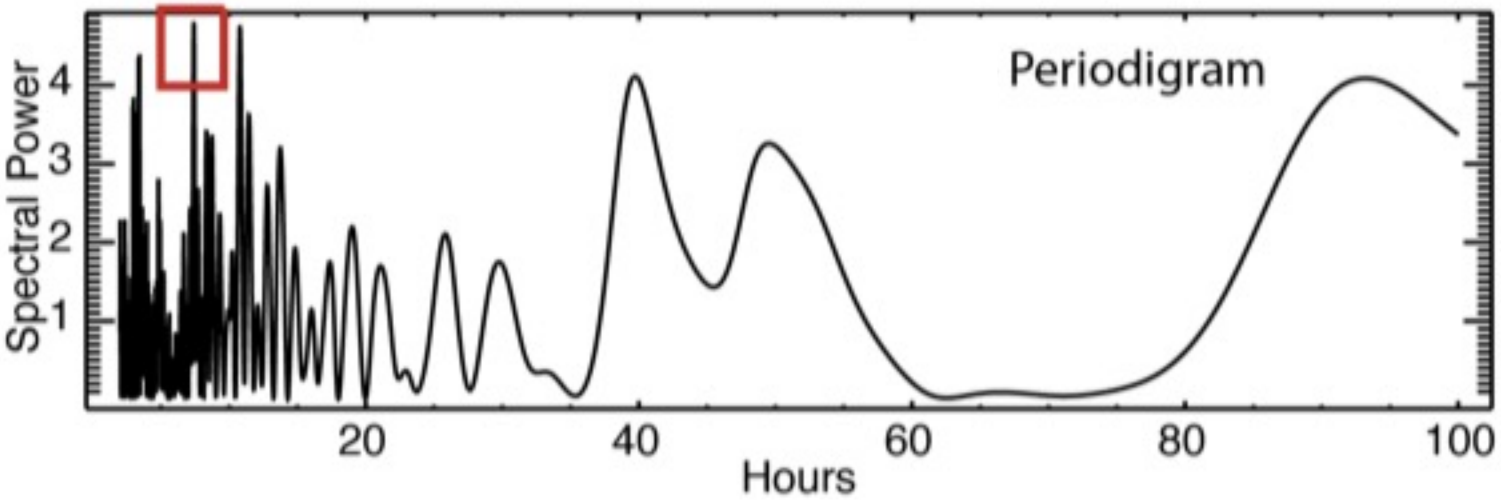
Gladman+ '08, Batygin+ '10, Dawson & Murray-Clay '12

THE HST LIGHTCURVE OF (486958) 2014 MU_{69}

S.D. Benecchi,[1] S. Porter,[2] M.W. Buie,[2] A.M. Zangari,[2] A.J. Verbiscer,[3] K.S. Noll,[4] S.A. Stern,[2] J.R. Spencer,[2] and A. Parker[2]

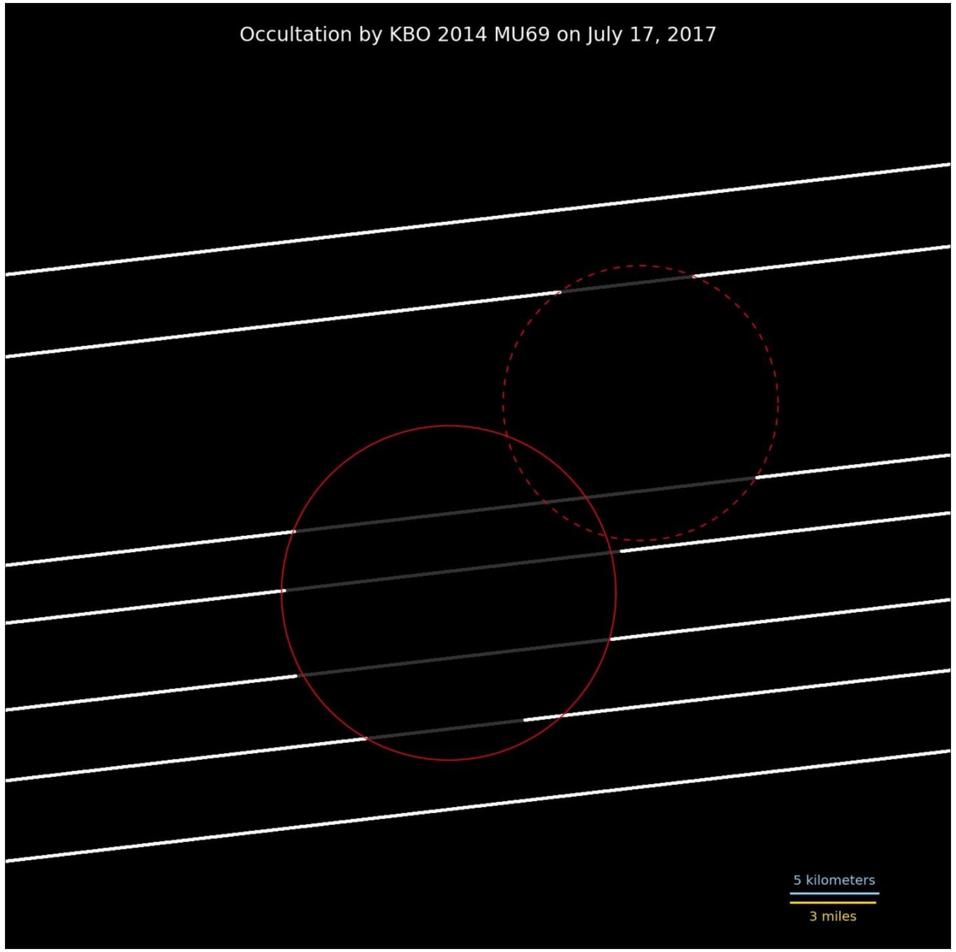


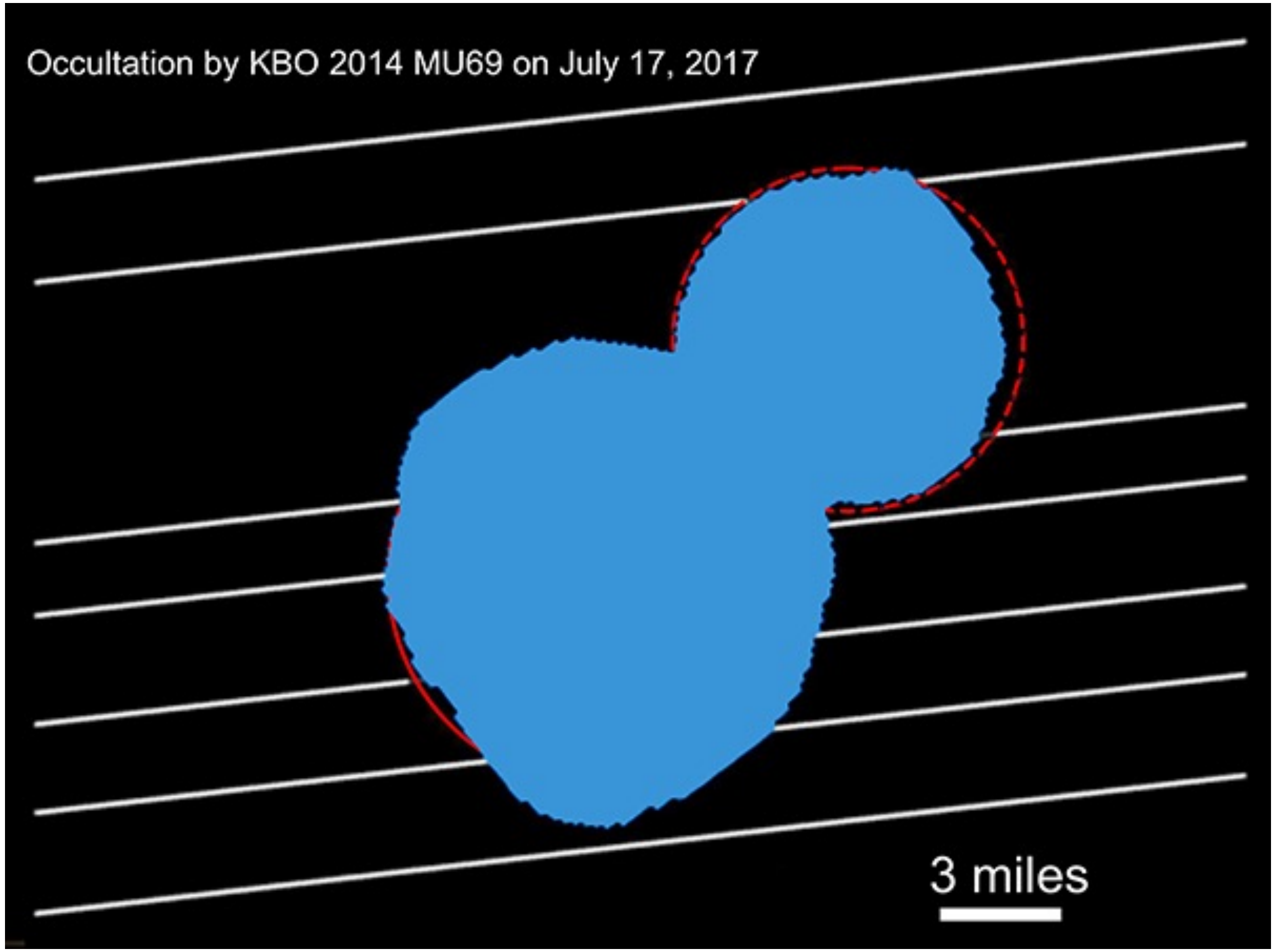


ABSTRACT

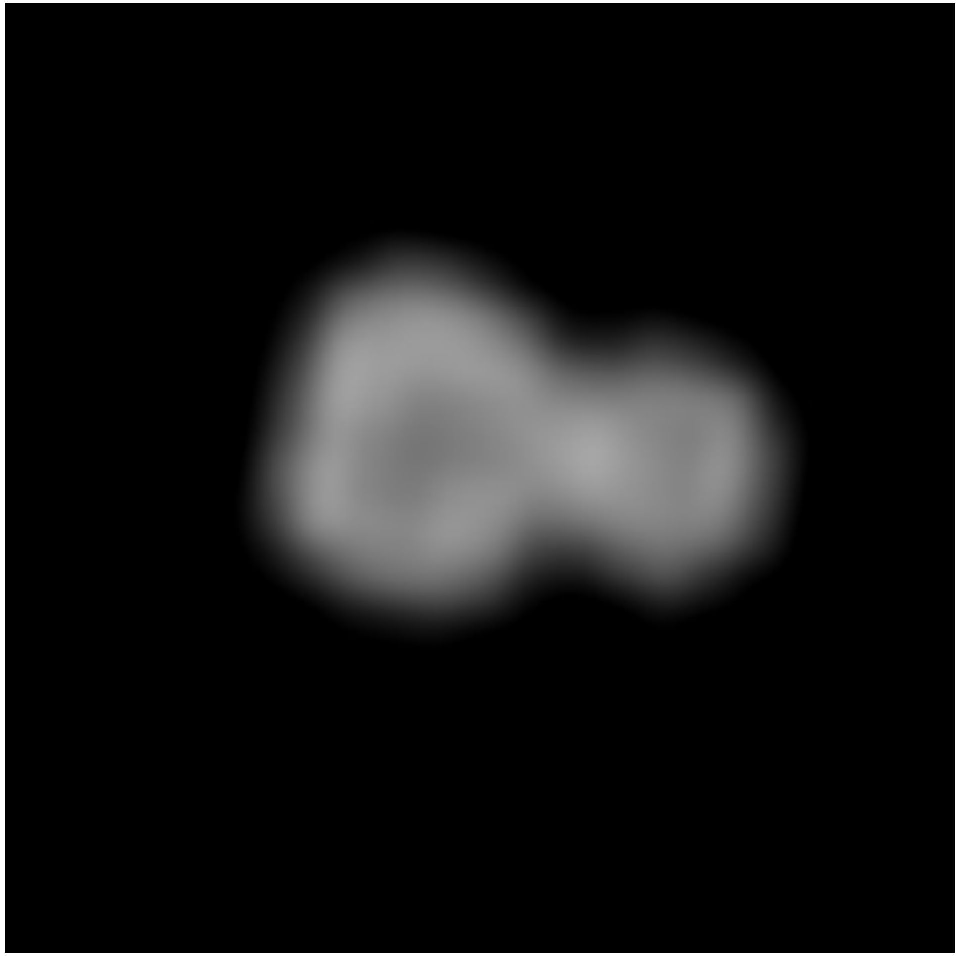
We report *Hubble Space Telescope* (HST) lightcurve observations of the *New Horizons* spacecraft encounter Kuiper Belt object (KBO) (486958) 2014 MU_{69} acquired near opposition in July 2017. In order to plan the optimum flyby sequence the *New Horizons* mission planners needed to learn as much as possible about the target in advance of the encounter. Specifically, from lightcurve data, encounter timing could be adjusted to accommodate a highly elongated, binary, or rapidly rotating target. HST astrometric (Porter et al. 2018) and stellar occultation (Buie et al. 2018) observations constrained MU69's orbit and diameter (21 - 41 km for an albedo of 0.15 - 0.04), respectively. Photometry from the astrometric dataset suggested a variability of ≥0.3 mags, but they did not determine the period or provide shape information. To that end we strategically spaced 24 HST orbits over 9 days to investigate rotation periods from approximately 2-100 hours and to better constrain the lightcurve amplitude. Until *New Horizons* detected MU69 in its optical navigation images beginning in August 2018, this HST lightcurve campaign provided the most accurate photometry to date. The mean variation in our data is 0.15 magnitudes which suggests that MU69 is either nearly spherical (a:b axis ratio of 1:1.15), or its pole vector is pointed near the line of sight to Earth; this interpretation does not preclude a near-contact binary or bi-lobed object.

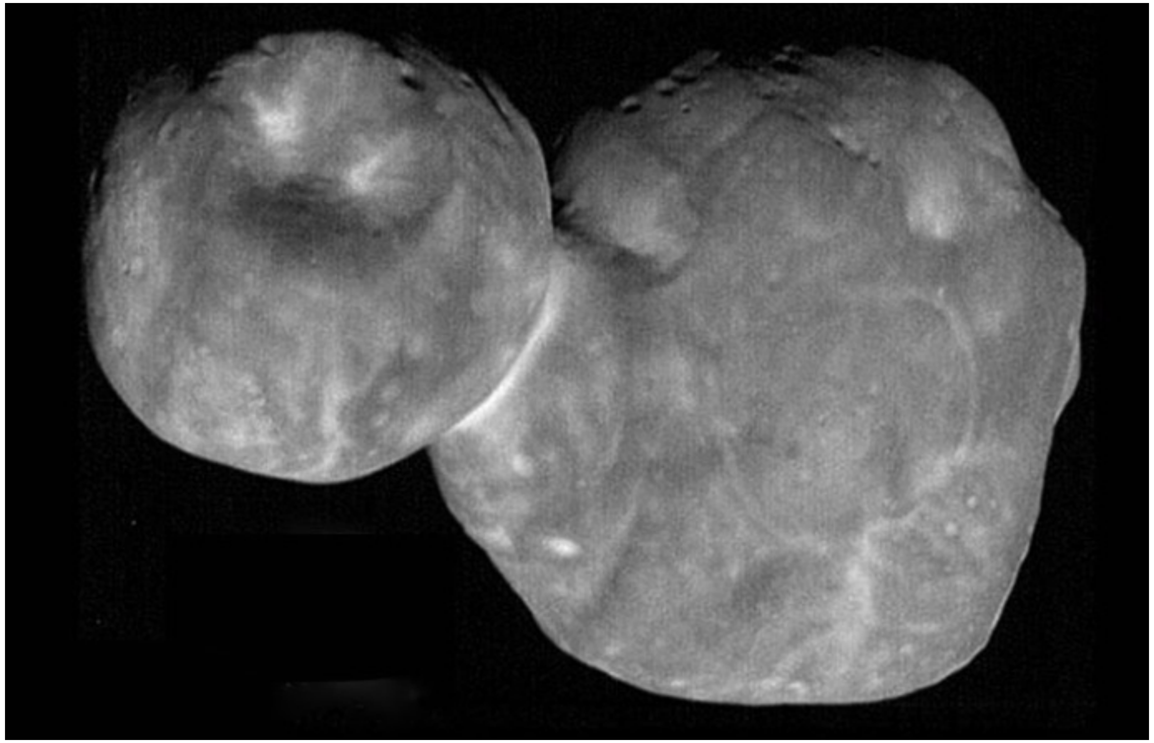
Occultation data suggests binary



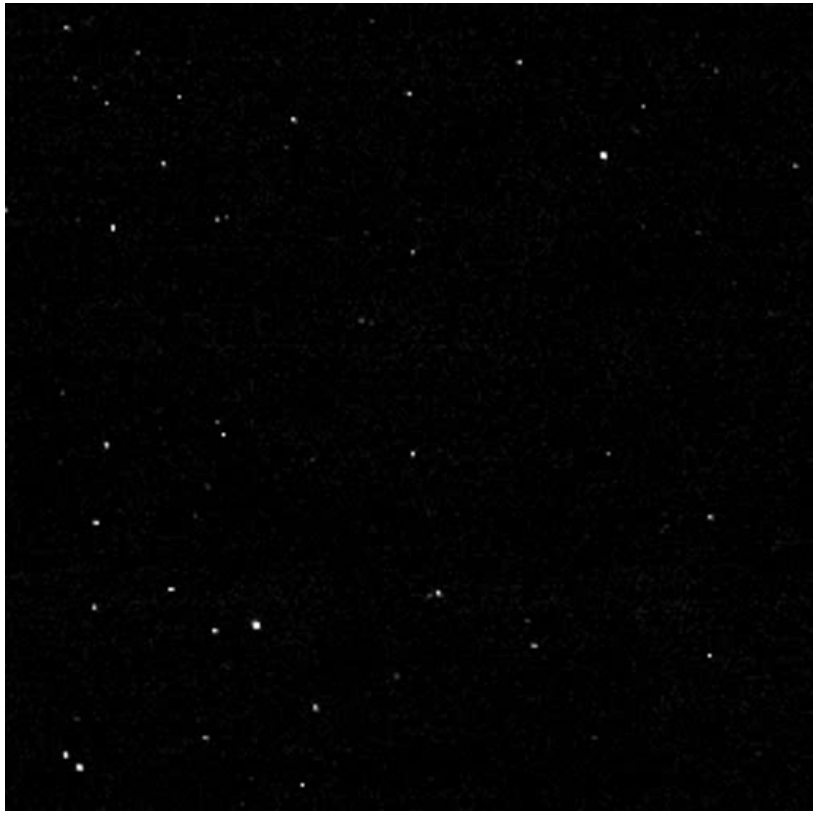


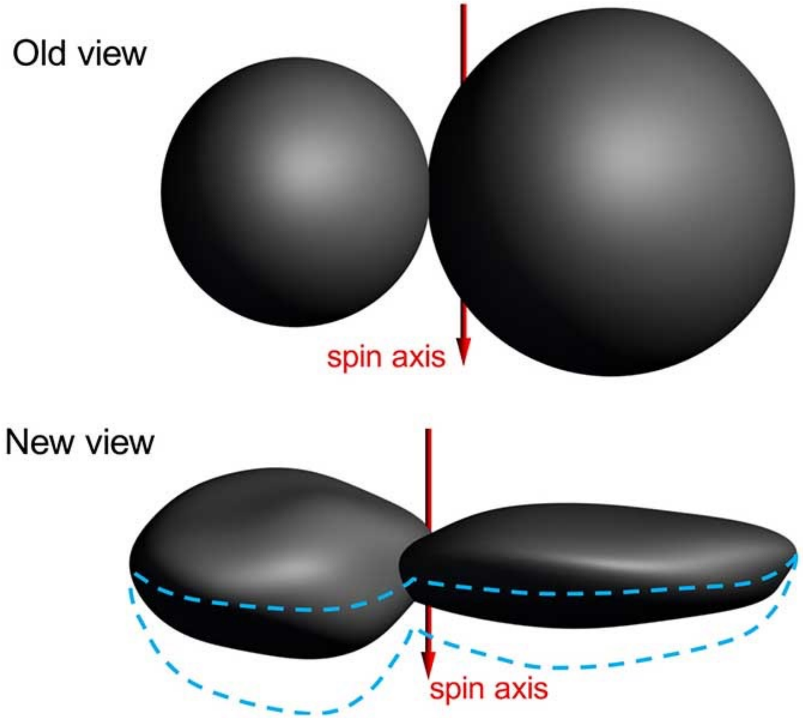
Approach sequence:
Contact binary at inclination 99.3º



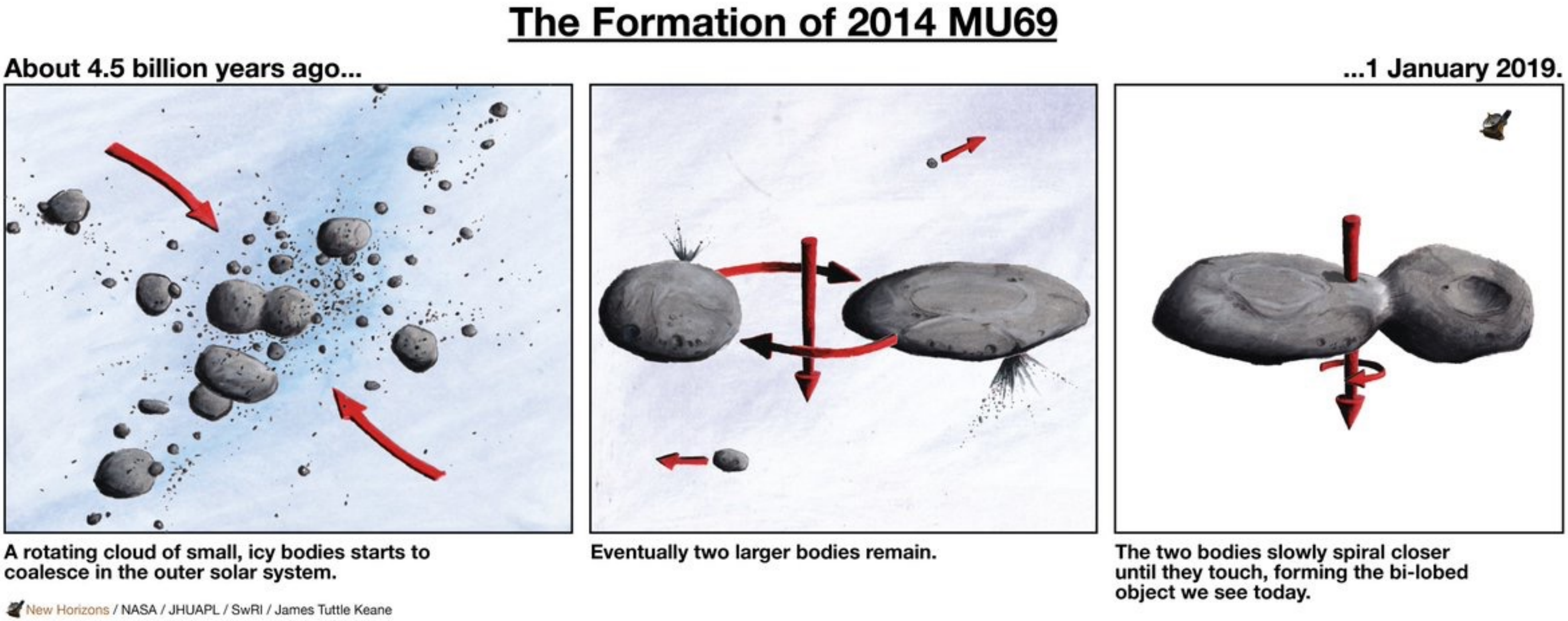


Departure sequence: Shape

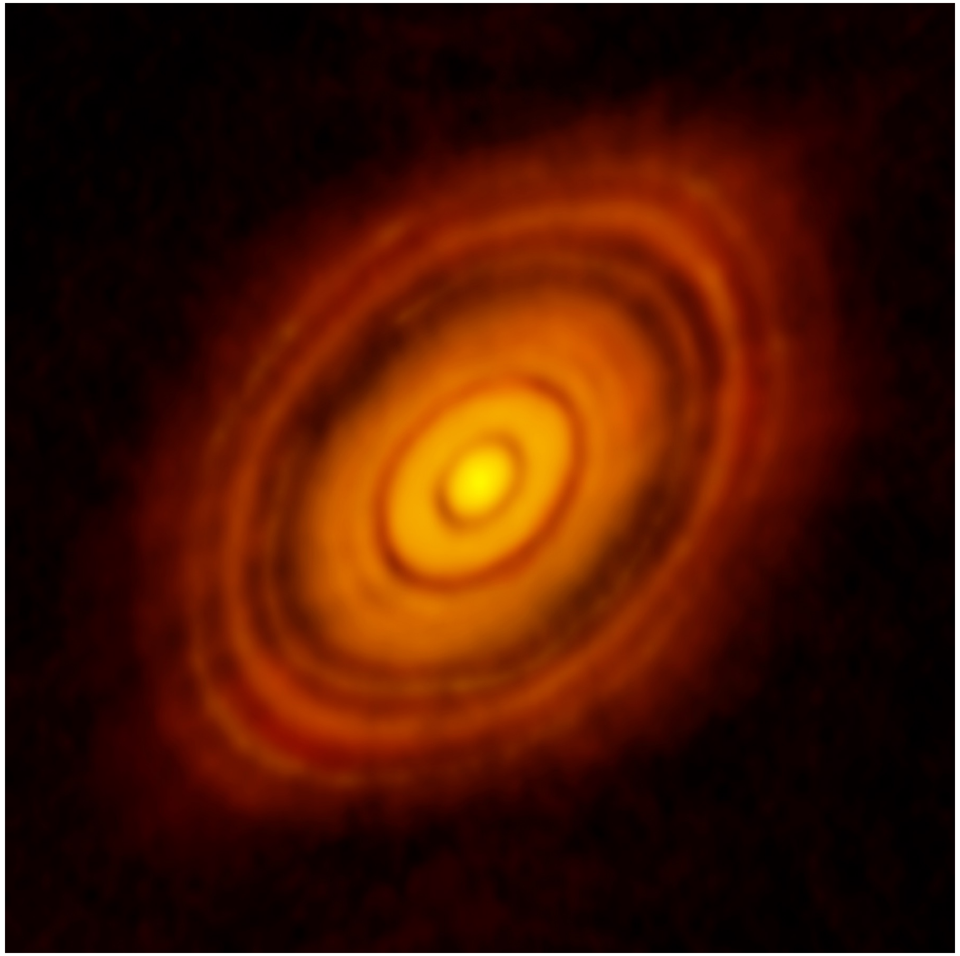




The Cartoon Image



Beyond the cartoon image



How?

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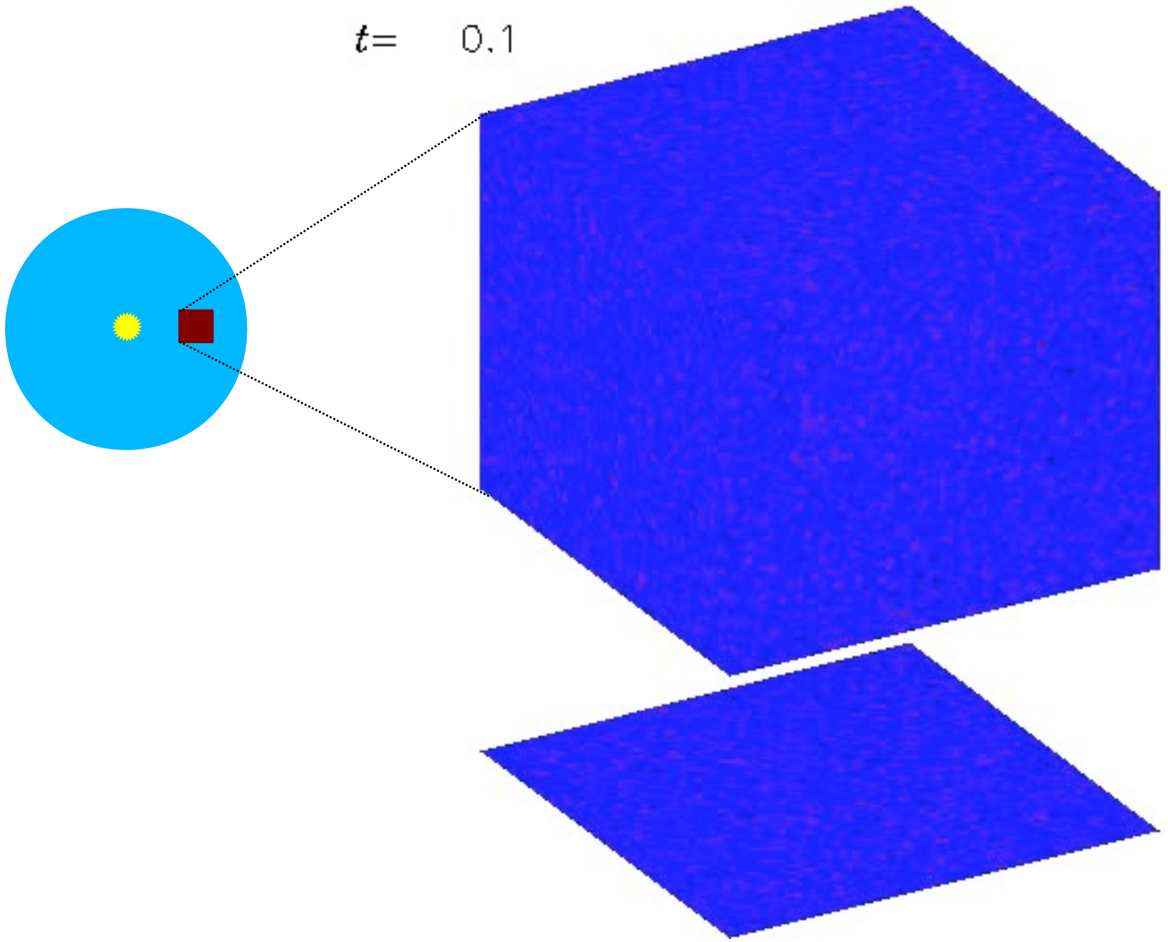
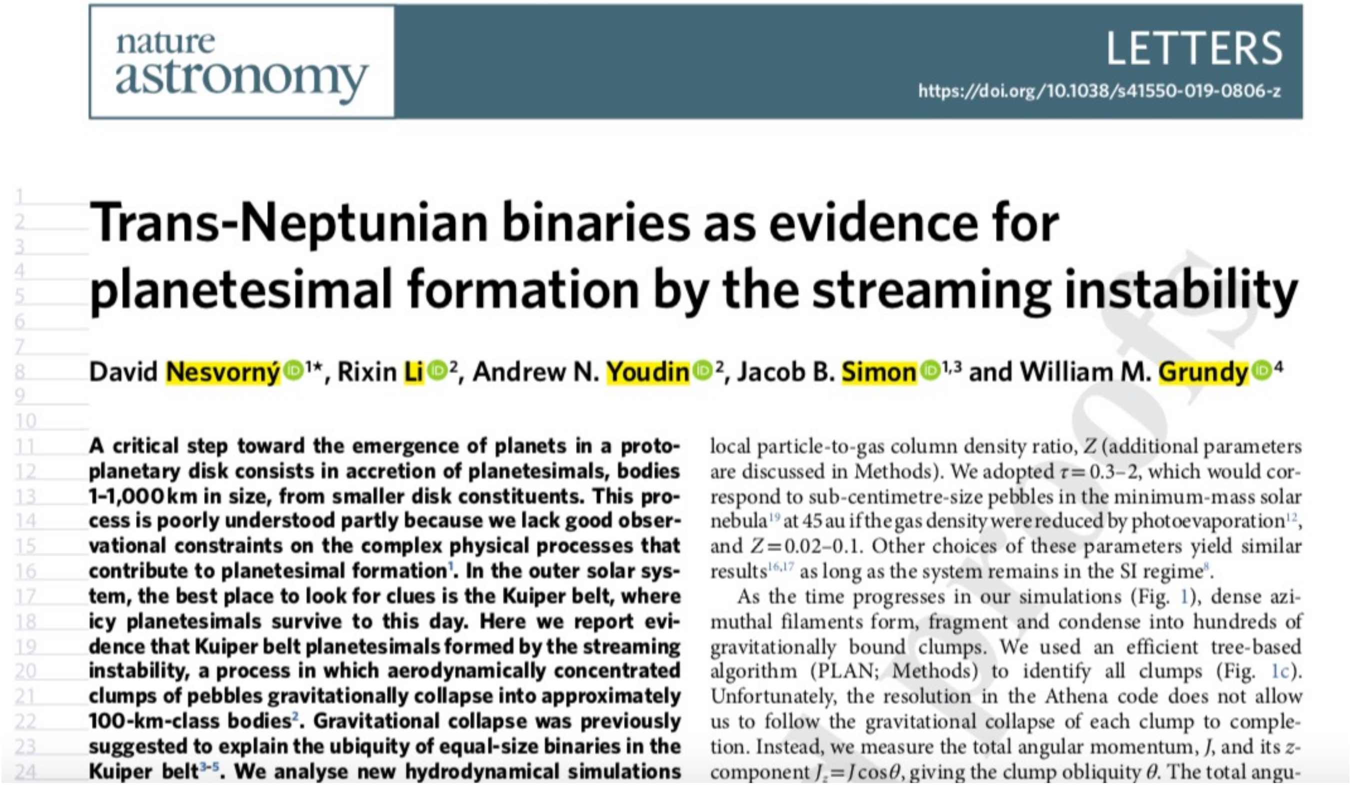
Streaming Instability

The dust drift is hydrodynamically unstable



Youdin & Goodman (2005), Johansen & Youdin (2007),
Youdin & Johansen (2007), Squire & Hopkins (2018)

In the lookout for binaries



nature astronomy

LETTERS

https://doi.org/10.1038/s41550-019-0806-z

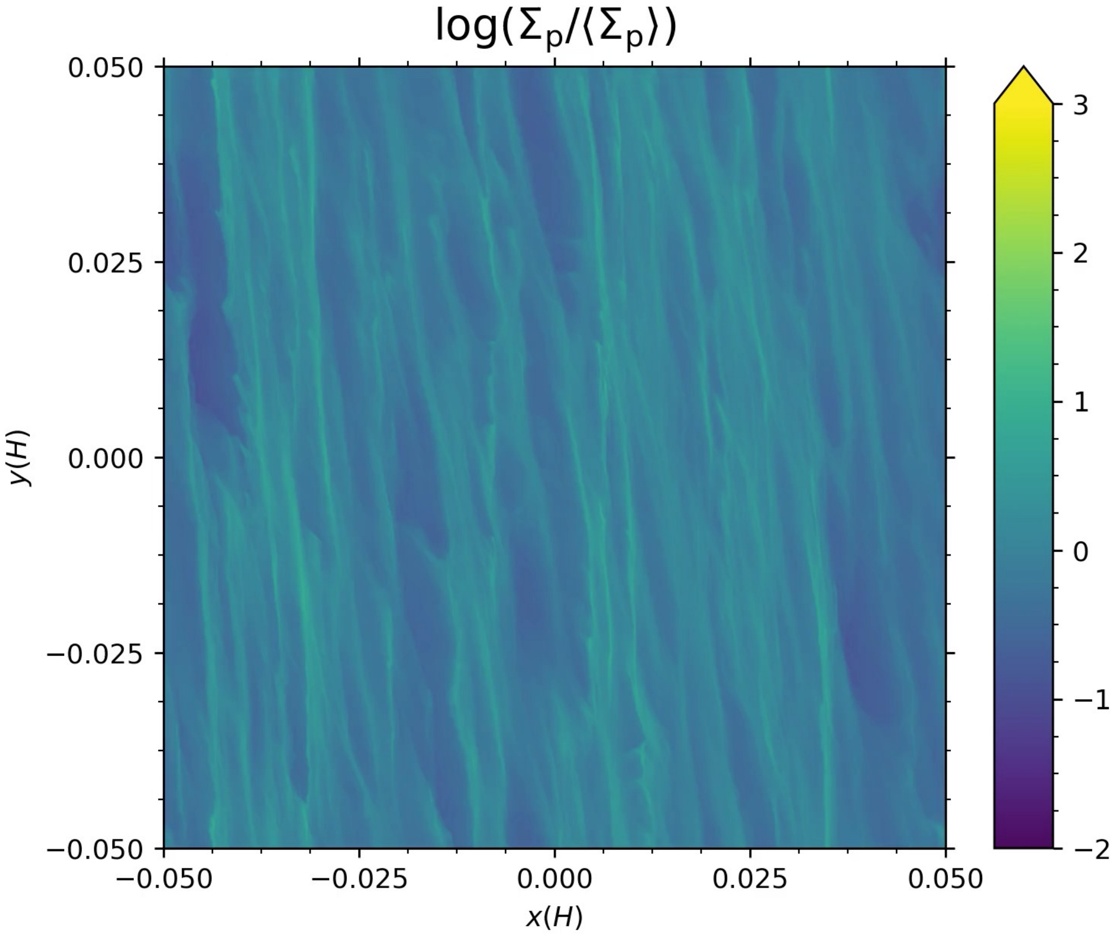
Trans-Neptunian binaries as evidence for planetesimal formation by the streaming instability

David Nesvorný[1*], Rixin Li[2], Andrew N. Youdin[2], Jacob B. Simon[1,3] and William M. Grundy[4]

A critical step toward the emergence of planets in a protoplanetary disk consists in accretion of planetesimals, bodies 1–1,000 km in size, from smaller disk constituents. This process is poorly understood partly because we lack good observational constraints on the complex physical processes that contribute to planetesimal formation[1]. In the outer solar system, the best place to look for clues is the Kuiper belt, where icy planetesimals survive to this day. Here we report evidence that Kuiper belt planetesimals formed by the streaming instability, a process in which aerodynamically concentrated clumps of pebbles gravitationally collapse into approximately 100-km-class bodies[2]. Gravitational collapse was previously suggested to explain the ubiquity of equal-size binaries in the Kuiper belt[3–5]. We analyse new hydrodynamical simulations

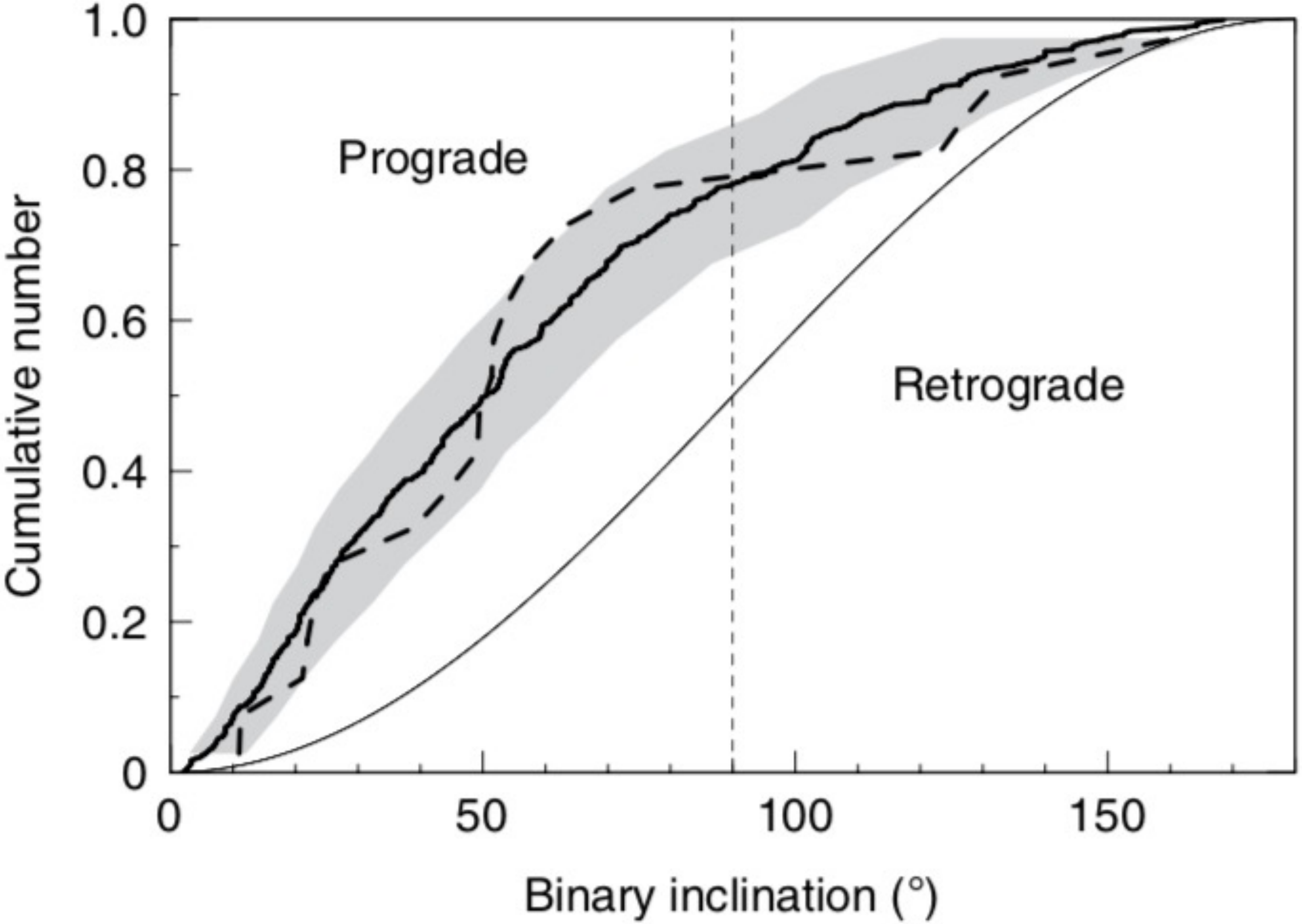
local particle-to-gas column density ratio, Z (additional parameters are discussed in Methods). We adopted $\tau = 0.3$–2, which would correspond to sub-centimetre-size pebbles in the minimum-mass solar nebula[19] at 45 au if the gas density were reduced by photoevaporation[12], and $Z = 0.02$–0.1. Other choices of these parameters yield similar results[16,17] as long as the system remains in the SI regime[8].

As the time progresses in our simulations (Fig. 1), dense azimuthal filaments form, fragment and condense into hundreds of gravitationally bound clumps. We used an efficient tree-based algorithm (PLAN; Methods) to identify all clumps (Fig. 1c). Unfortunately, the resolution in the Athena code does not allow us to follow the gravitational collapse of each clump to completion. Instead, we measure the total angular momentum, J, and its z-component $J_z = J\cos\theta$, giving the clump obliquity θ. The total angu-



Nesvorny+’19, model by Rixin Li

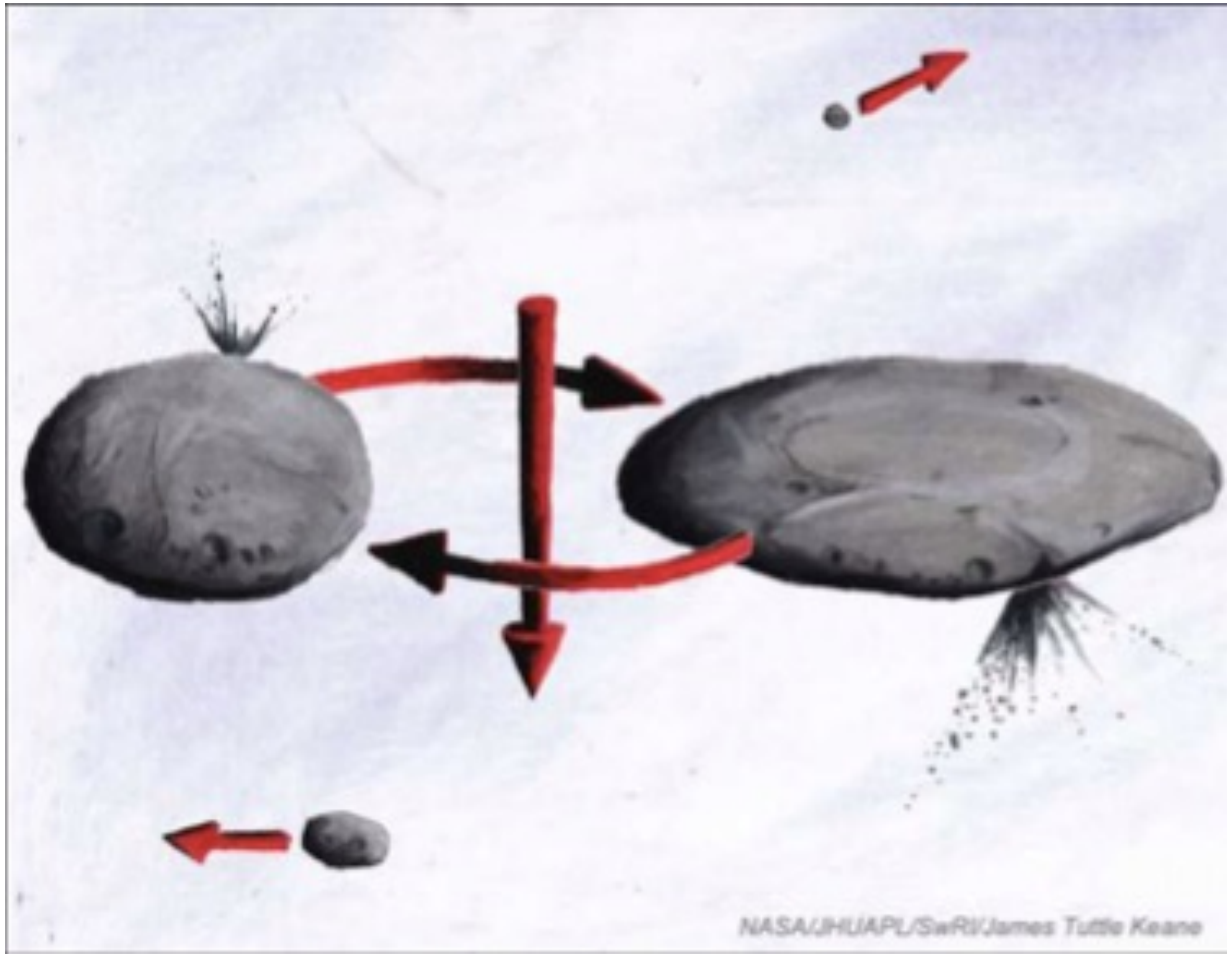
Preference for Prograde (~80%)



SI Model (solid)
KBOs (dashed)

Nesvorny+Li+Youdin ‘19

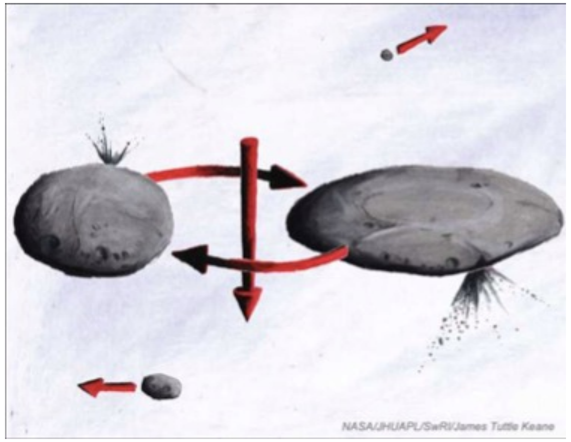
Hardening



Sketch by J.T. Keane

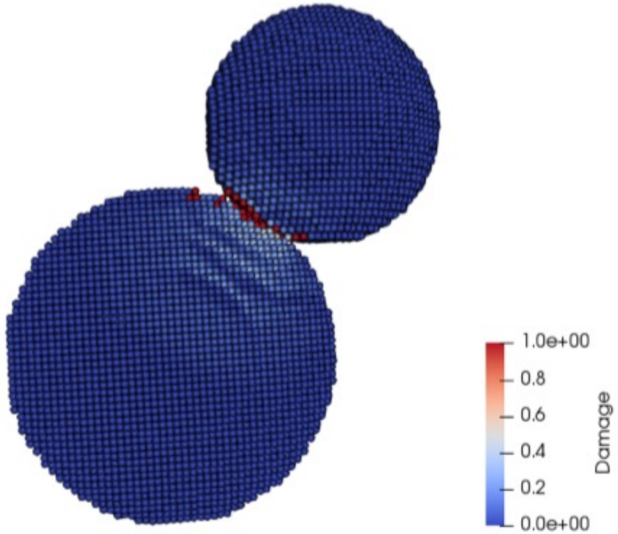
How was angular momentum lost?

Mutual orbit
(i.e., not captured)



Inferred from:
alignment of component minor axes,
small angular momentum,
similar colors.

Slow merger
(~2 m/s: human walking speed)

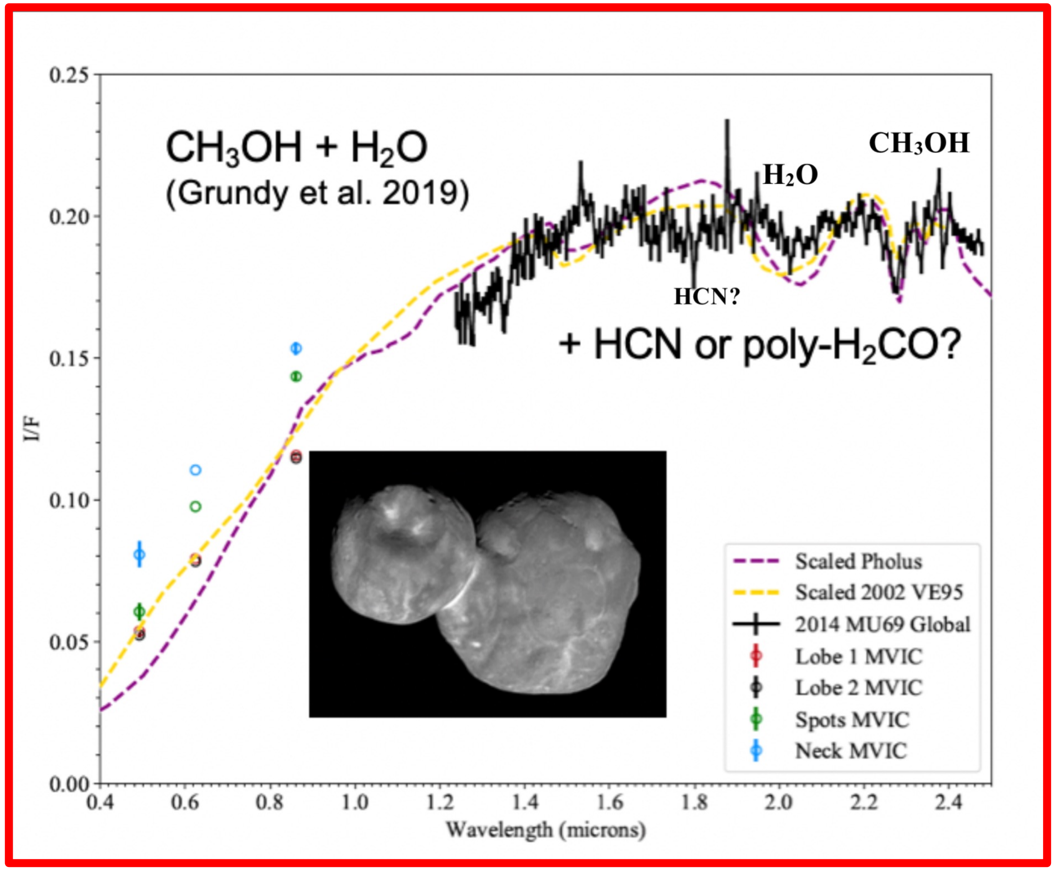


Inferred from:
Negligible evidence for impact damage

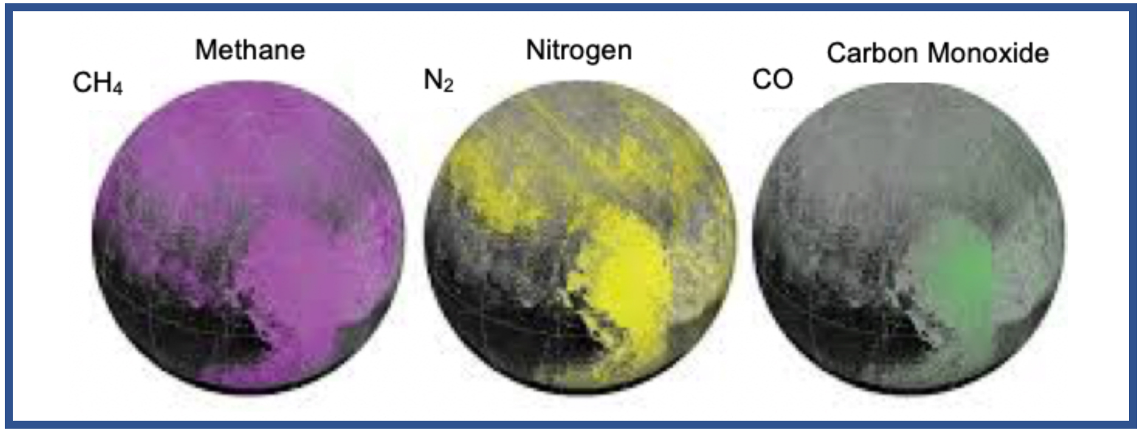
Tombaugh Regio / Sputnik Planitia – N_2 frost

MU69 and Pluto ices are different

MU69 : Methanol, H_20, HCN



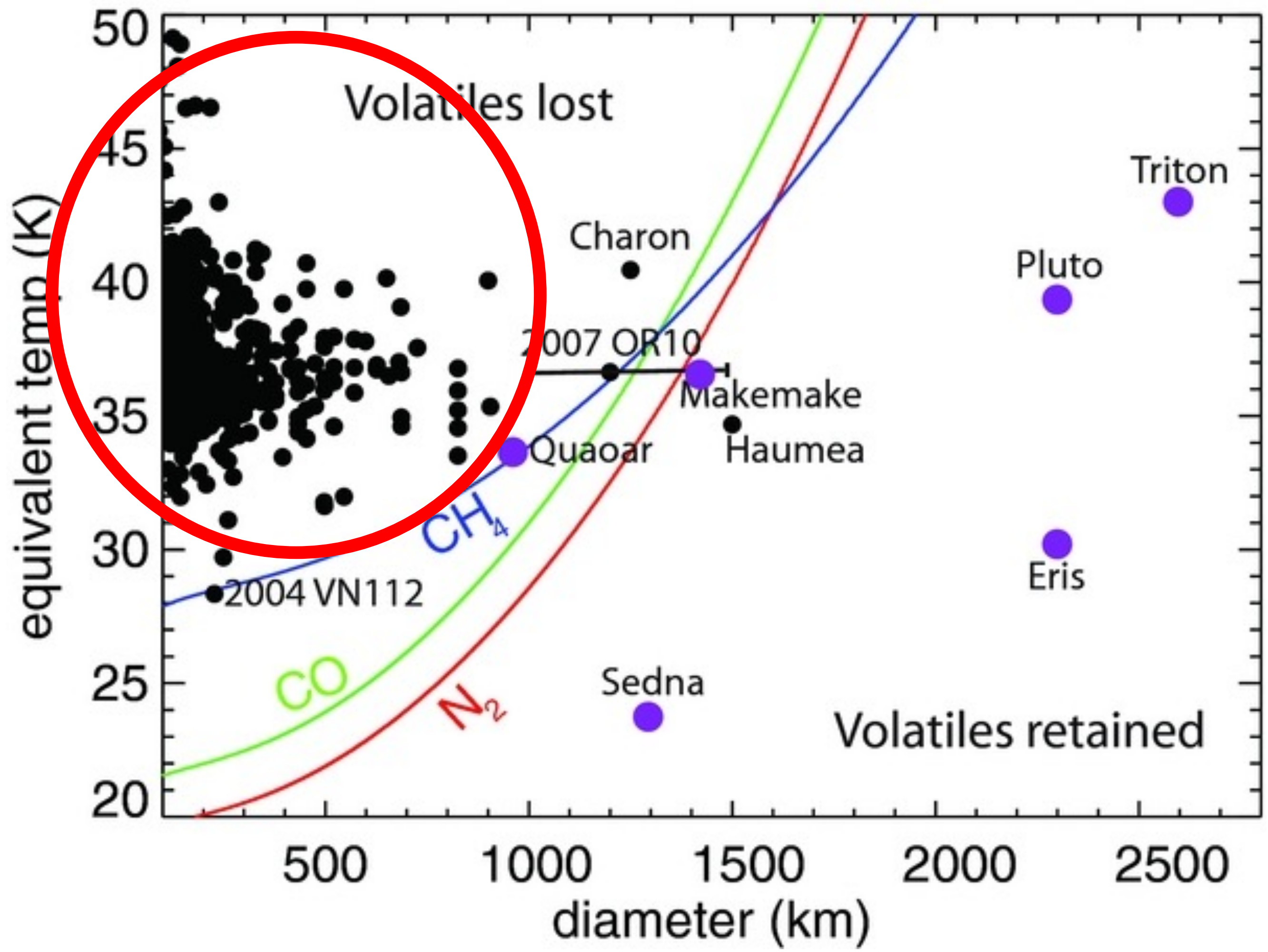
Pluto : CH_4, N_2, CO



Grundy+ '16, Lisse+Lyra '20

Retention of volatiles

If Pluto is formed from similar bodies to MU69, they must retain N_2



Needs shielding from the sunlight flambé.

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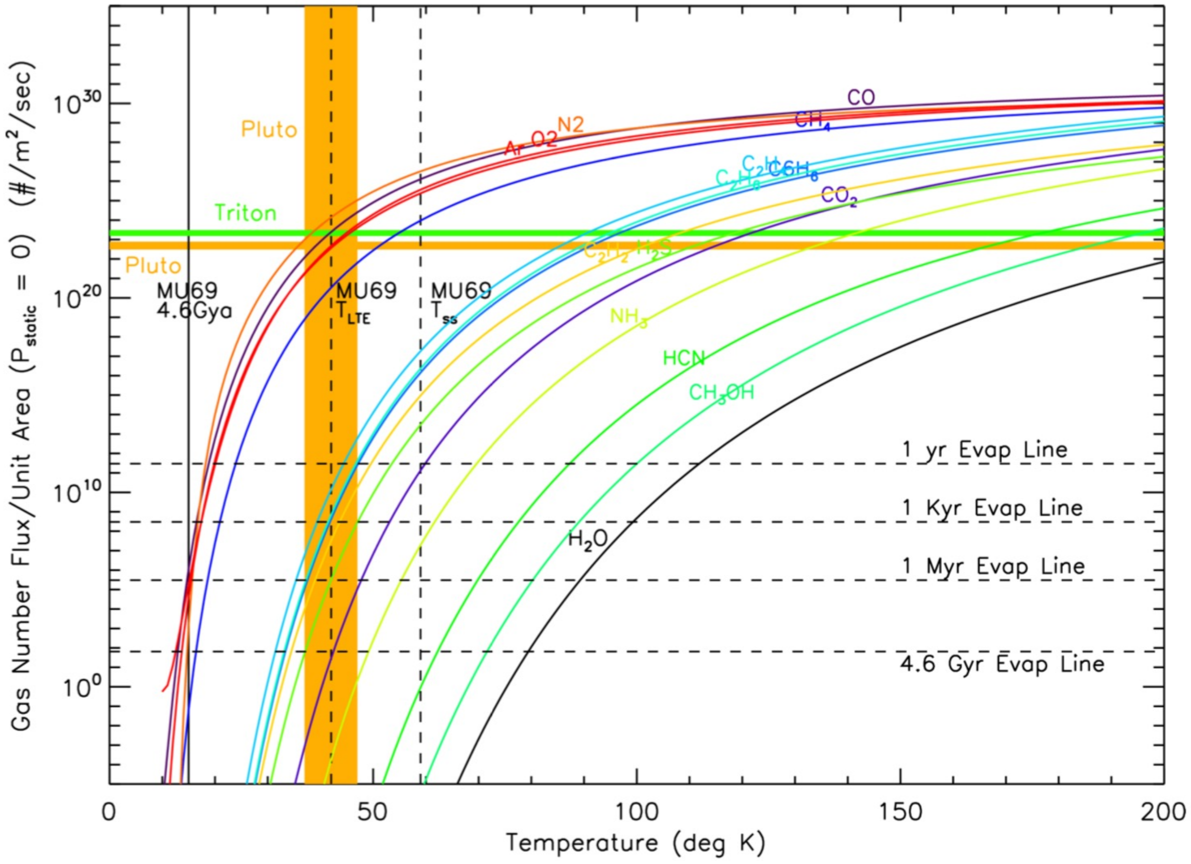
Brown, Burgasser, & Fraser (2011); Lisse+Lyra '20

Retention of volatiles



Hypervolatiles (CH_4 / CO / N_2) lost under vacuum pressure and microgravity in ~1 Myr for 40 K

Retained for long times if formed < 20K

Formation of MU69 in an optically thick disk keeps the interior cold enough to allow the volatiles to remain frozen.

Lisse+Lyra '20

Angular momentum loss via nebular drag

gravity

drag

$$\ddot{\boldsymbol{r}}_1 = -Gm_2 \frac{(\boldsymbol{r}_1 - \boldsymbol{r}_2)}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|^3} - \frac{\dot{\boldsymbol{r}}_1}{\tau_1}$$

$$\ddot{\boldsymbol{r}}_2 = -Gm_1 \frac{(\boldsymbol{r}_2 - \boldsymbol{r}_1)}{|\boldsymbol{r}_1 - \boldsymbol{r}_2|^3} - \frac{\dot{\boldsymbol{r}}_2}{\tau_2}$$

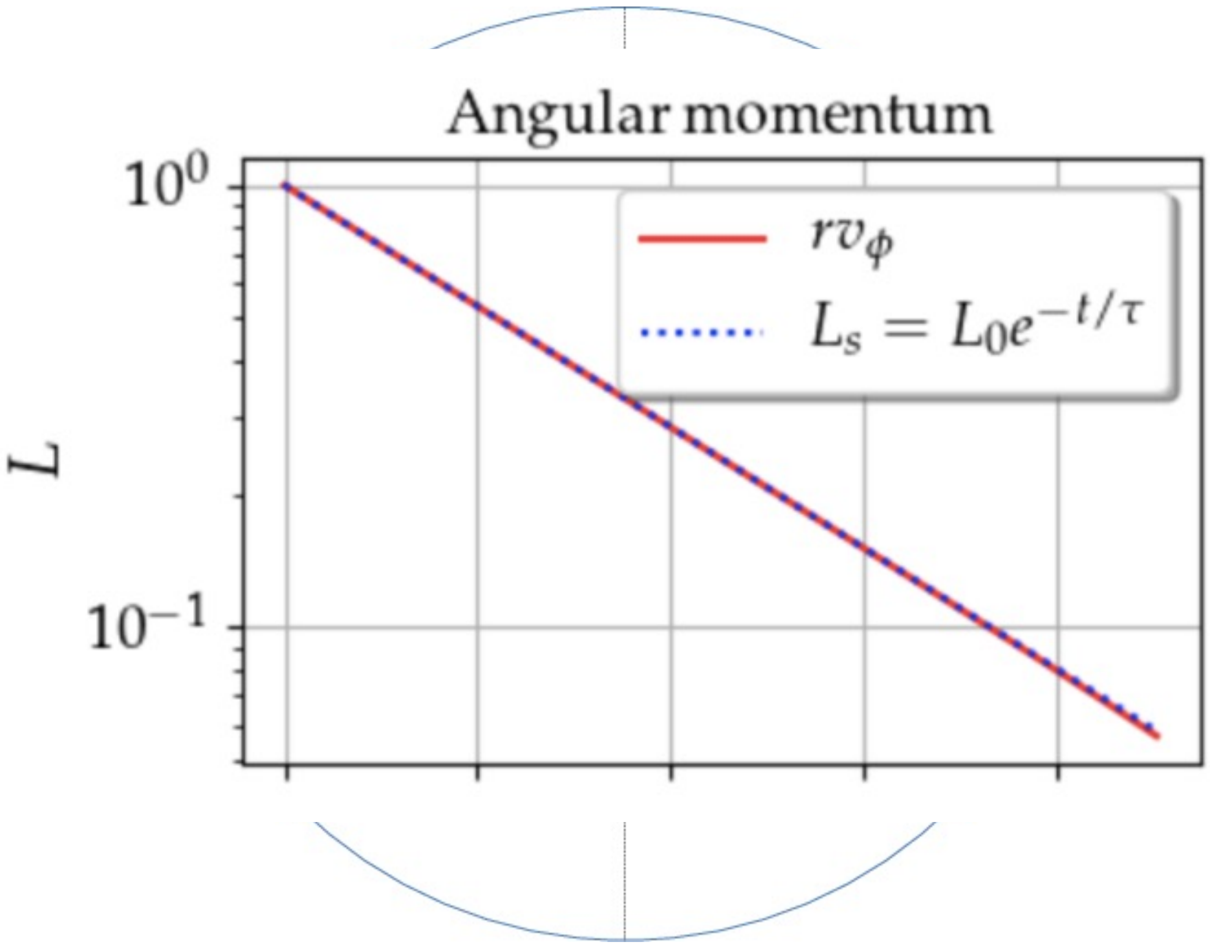
For equal mass:

$$r\ddot{\phi} + 2\dot{r}\dot{\phi} = -\frac{r\dot{\phi}}{\tau}$$

$$\frac{dh}{dt} = -\frac{h}{\tau}$$

Exponential decay of angular momentum !

$$\boxed{h = h_0 e^{-t/\tau}}$$



en the

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Lyra, Youdin, & Johansen (2021)

Hardening during disk lifetime

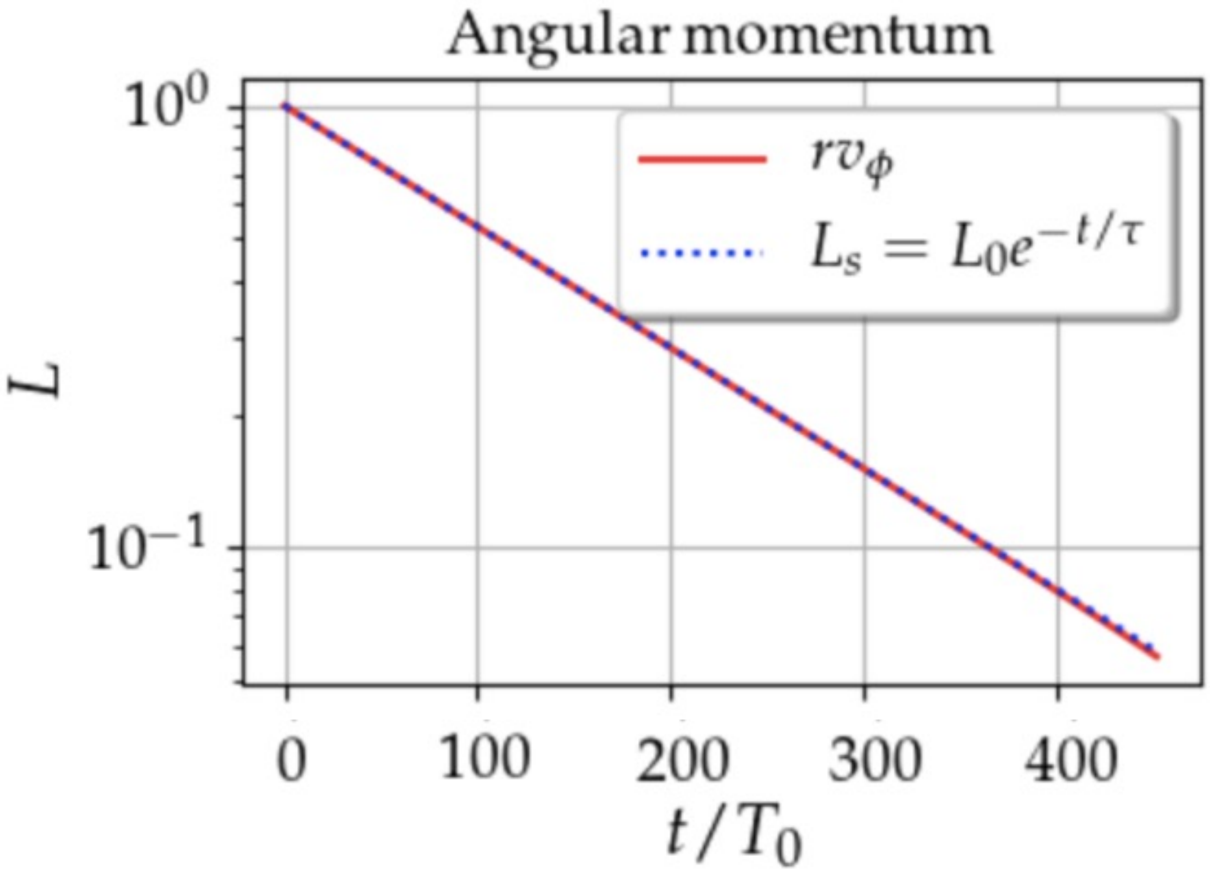
For unequal mass the physics is similar, the drag time is just replaced by an effective drag time:

Effective drag time

$$\boxed{\tau_{\rm eff} = (m_1 + m_2)\frac{\tau_1\tau_2}{\tau_2 m_2 + \tau_1 m_1}.}$$

Exponential decay of angular momentum

$$\boxed{h = h_0 e^{-t/\tau_{\rm eff}}.}$$

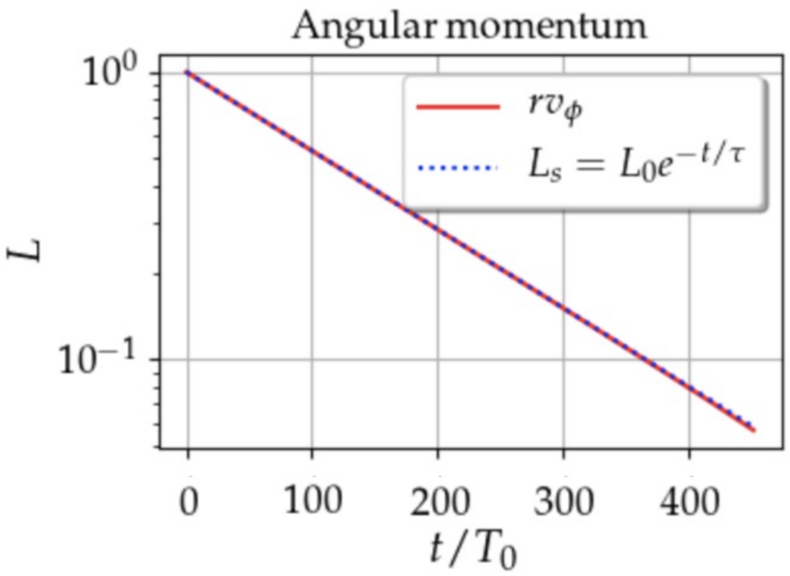


Lyra, Youdin, & Johansen (2021)

Analytical solution

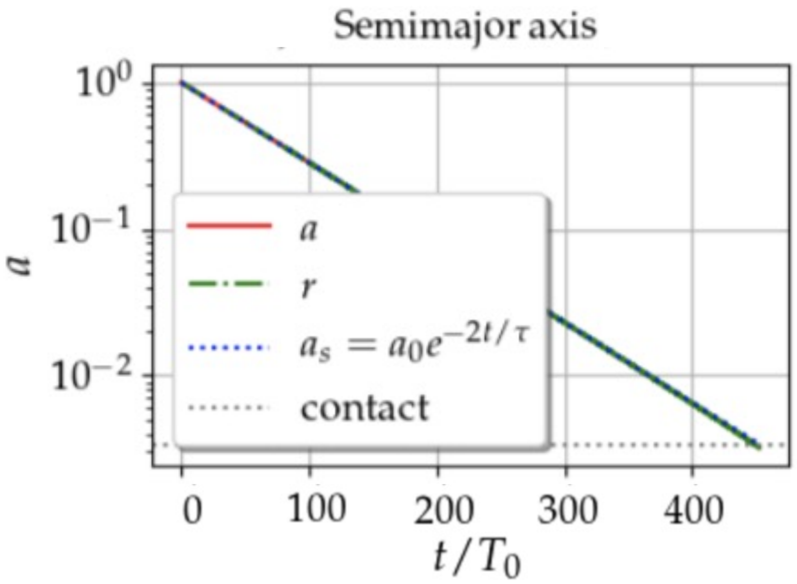
Exponential decay of angular momentum

$$\boxed{h = h_0 e^{-t/\tau_{\rm eff}}}$$



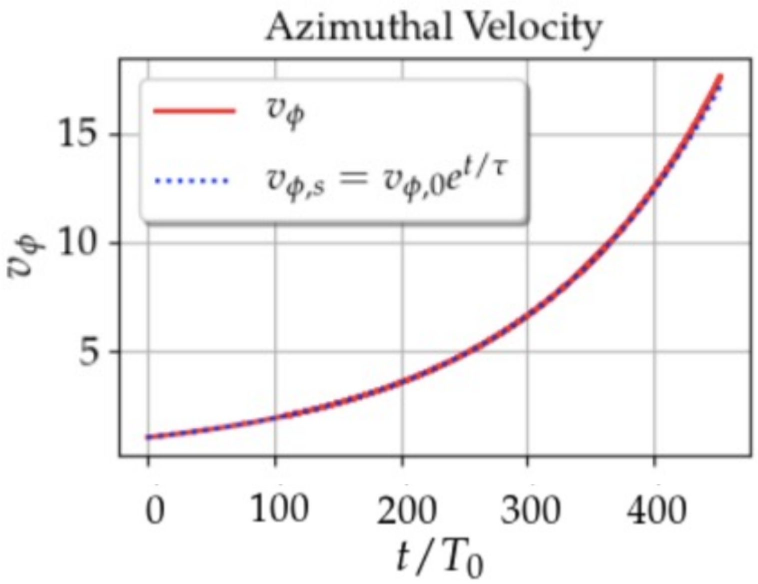
Exponential decay of semimajor axis

$$\boxed{a = a_0\, e^{-2t/\tau_{\rm eff}}}$$



Exponential increase of orbital velocity

$$\boxed{v_\phi = v_{\phi,0}\, e^{t/\tau_{\rm eff}}}$$



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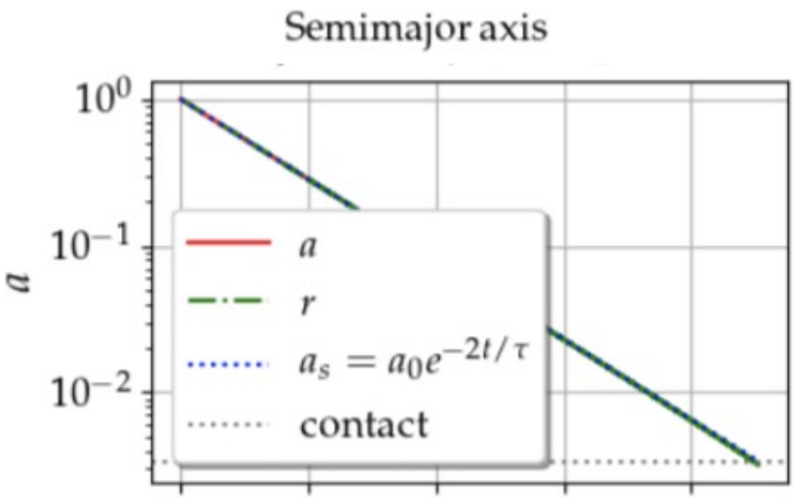
Analytical solution



Time until contact

$$t = \frac{\tau}{2} \ln \frac{a_0}{a}$$

For $a = 0.1\ r_H$ (6000 km), hardening to a_0=20km and $\tau\Omega$=10^7 …

t ~ 100 Myr

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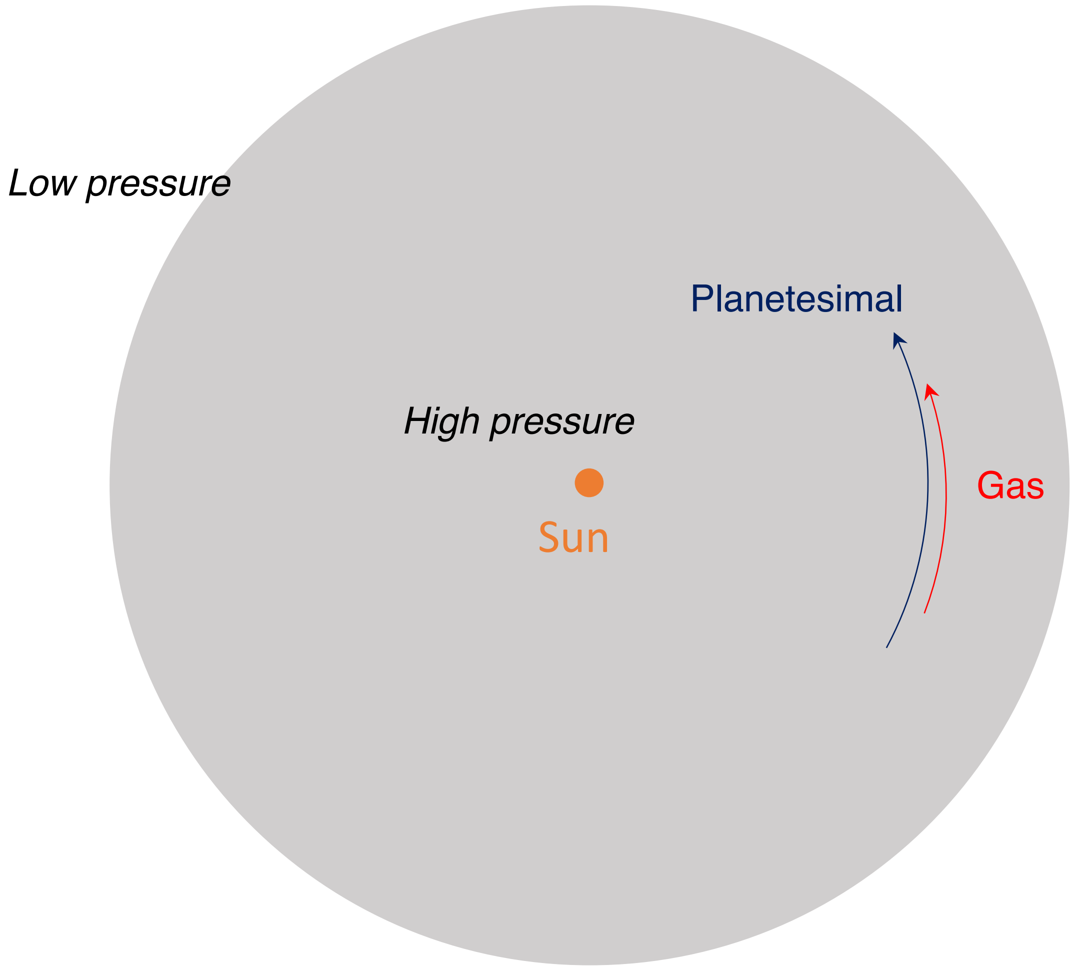
Wind



The gas has some pressure support.

The planetesimal has none.

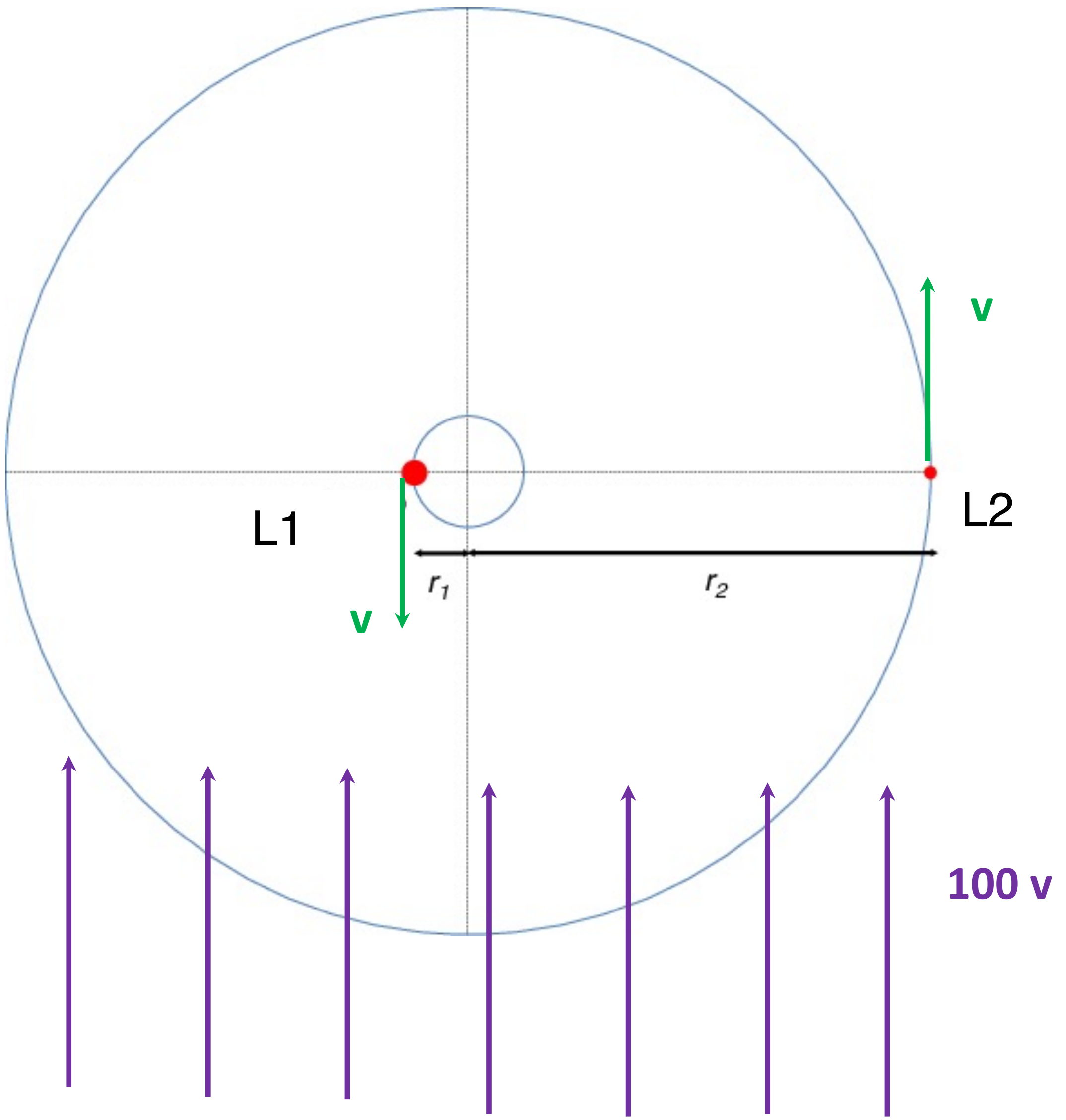
Wind

Binary orbital velocity **~ 10 cm/s**

Solar orbit velocity at 42AU **~ 4.5 km/s**

Subkeplerian pressure support
$\Omega = \Omega_k\,(1-\eta)$; **η~1% (50 m/s)**

Subkeplerian wind on the binary
= 100 times orbital velocity



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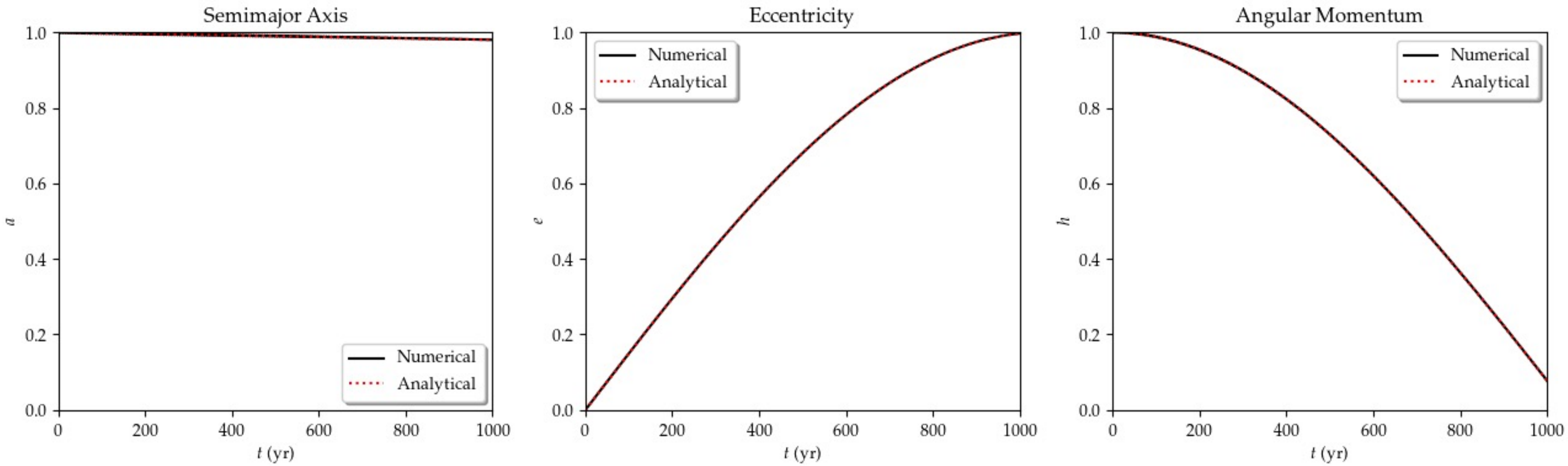
Wind solution



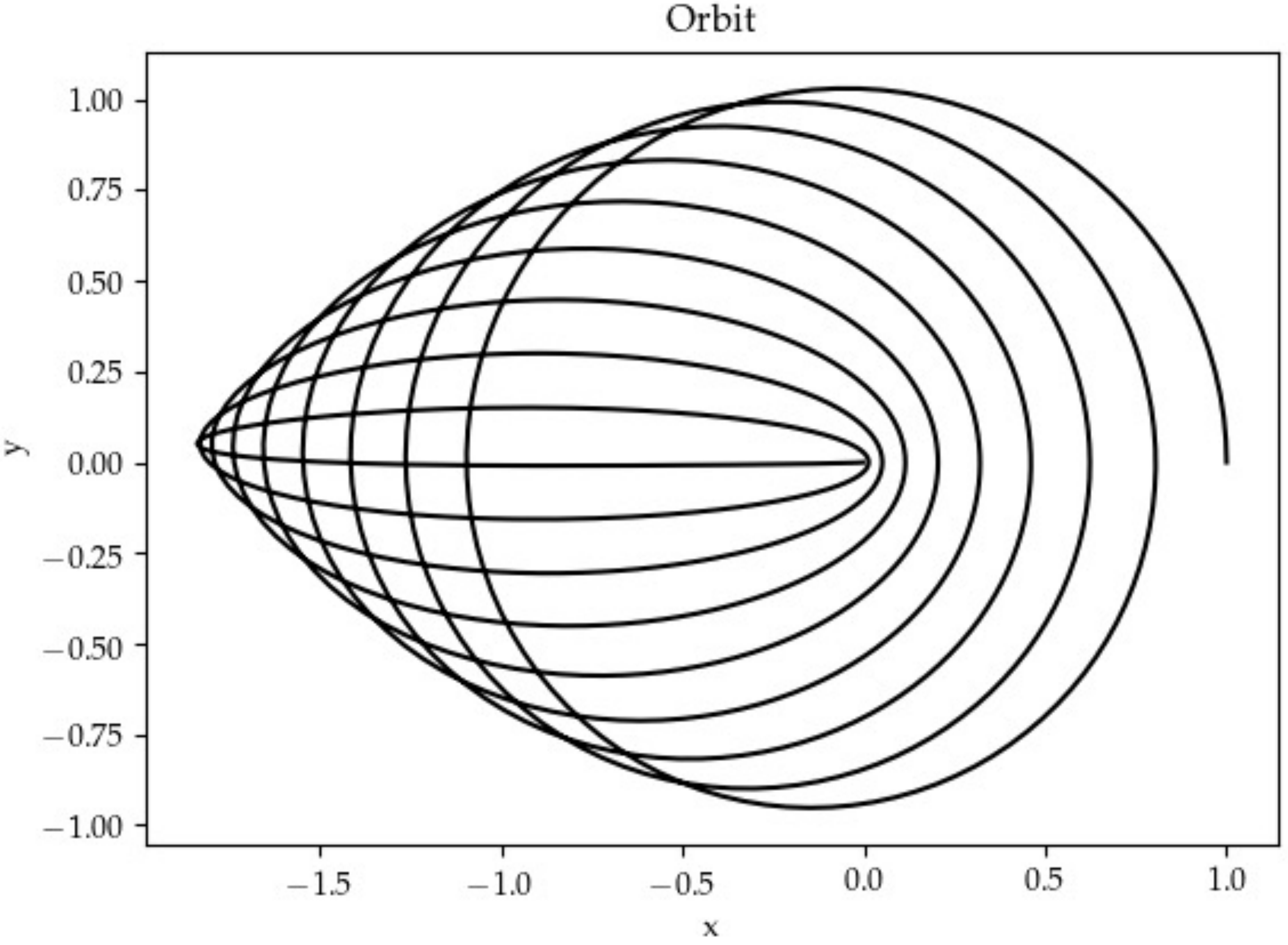
$$\langle a(t) \rangle = a_0 e^{-2t/\tau}$$

$$\langle e(t) \rangle = \cos\left[\cos^{-1} e_0 + \frac{3u}{2}\sqrt{\frac{a_0}{\mu}}\left(1 - e^{-t/\tau}\right)\right]$$

$$\langle h(t) \rangle = e^{-t/\tau}\left\{h_0 - 1 + \cos\left[\frac{3}{2}a_0 u\left(1 - e^{-t/\tau}\right)\right]\right\}$$

Lyra, Youdin, & Johansen (2021)

Wind solution



Angular momentum loss at constant energy.

Eccentricity increase at constant semimajor axis

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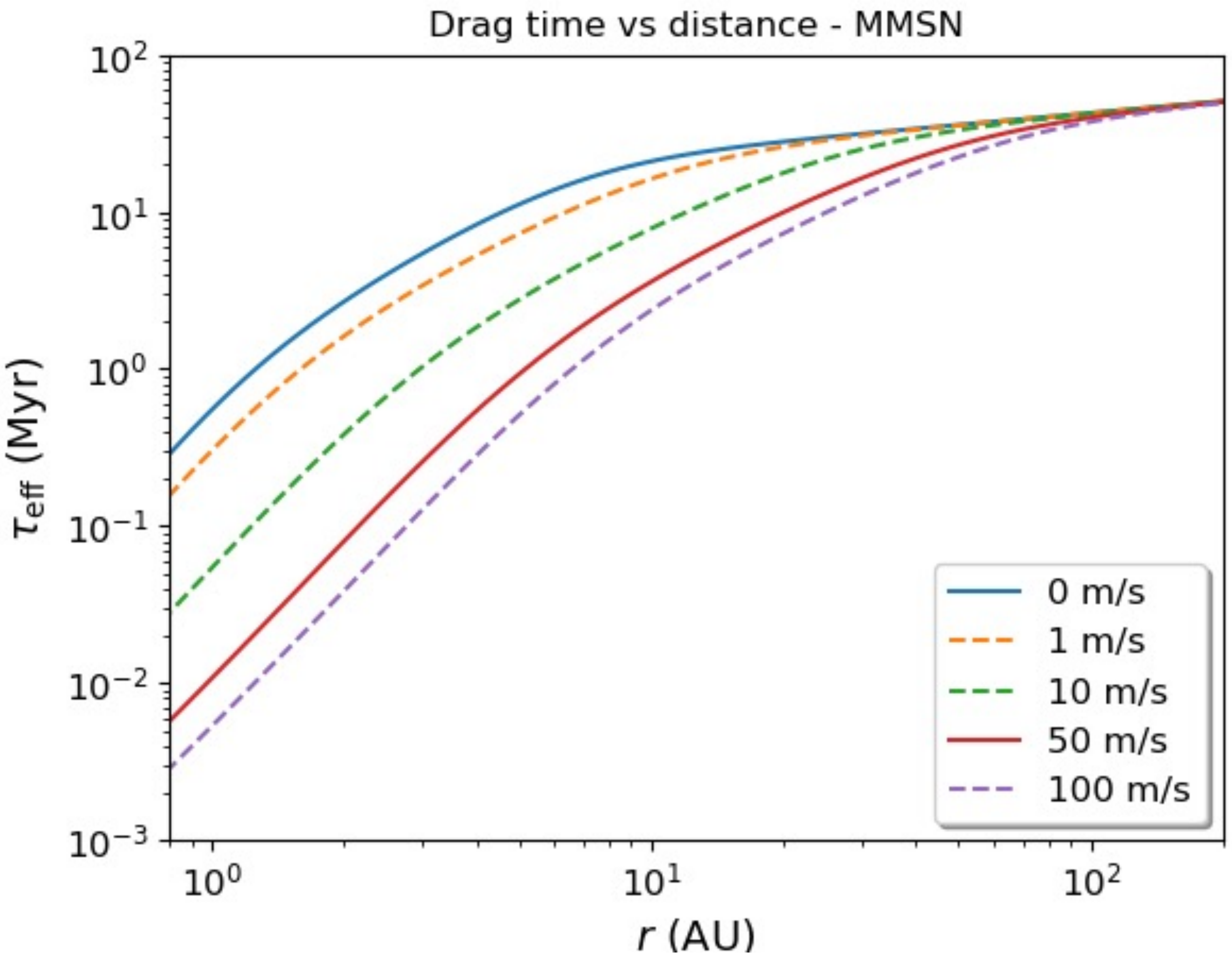
Timescales

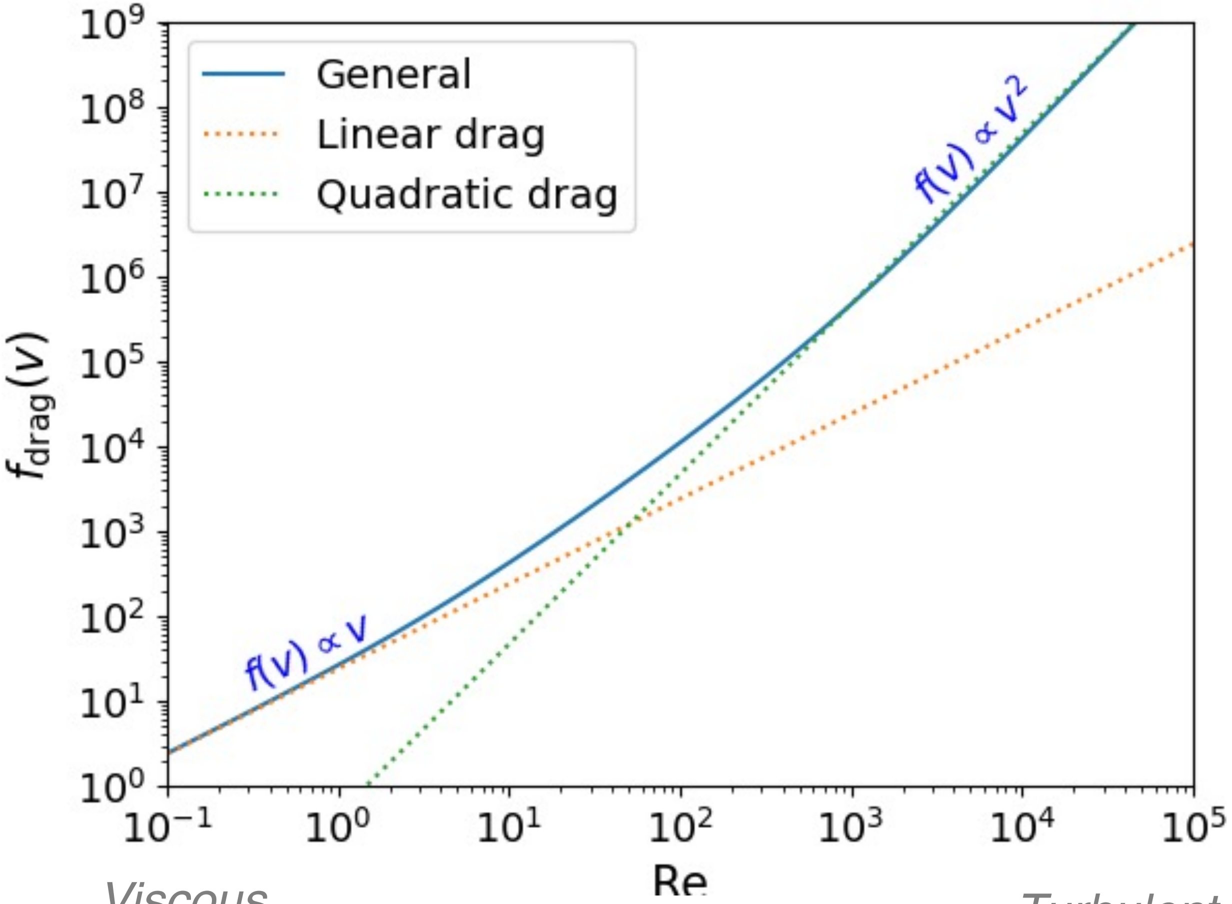


Wind has a strong effect in the distances of the asteroid belt.

No effect in the Kuiper belt.

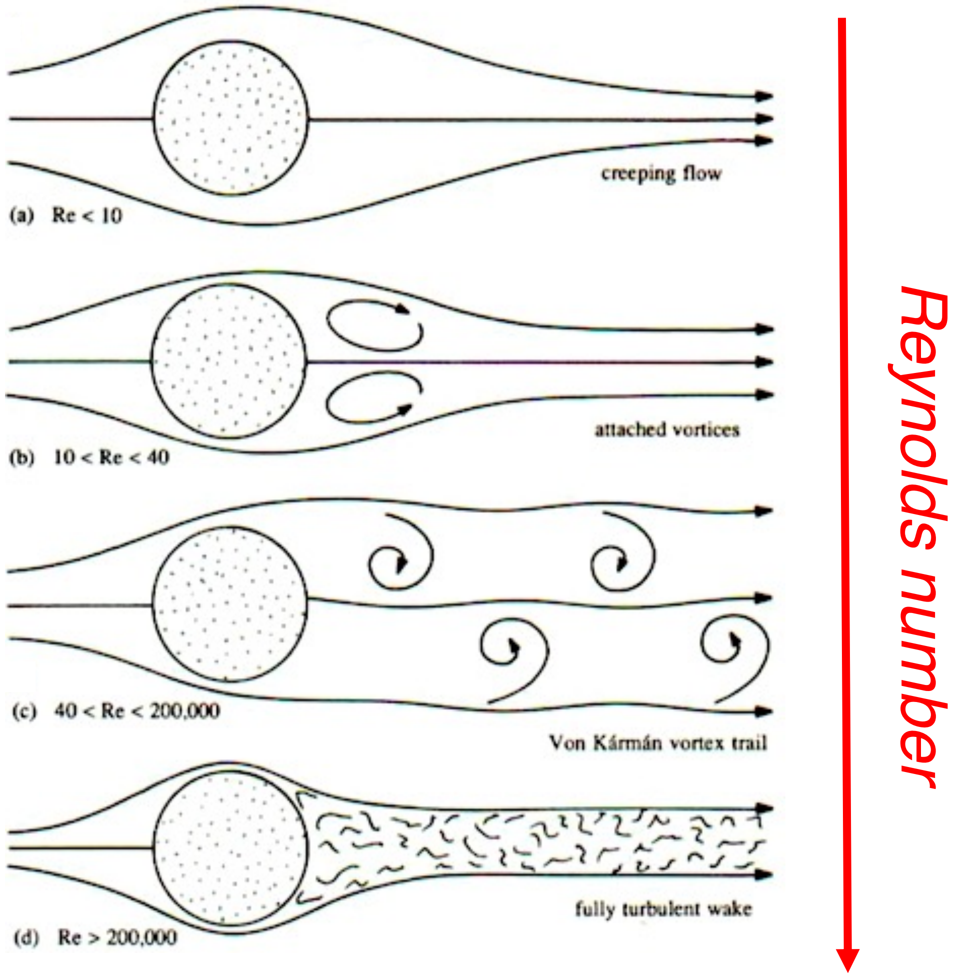
Lyra, Youdin, & Johansen (2021)

Linear vs quadratic drag



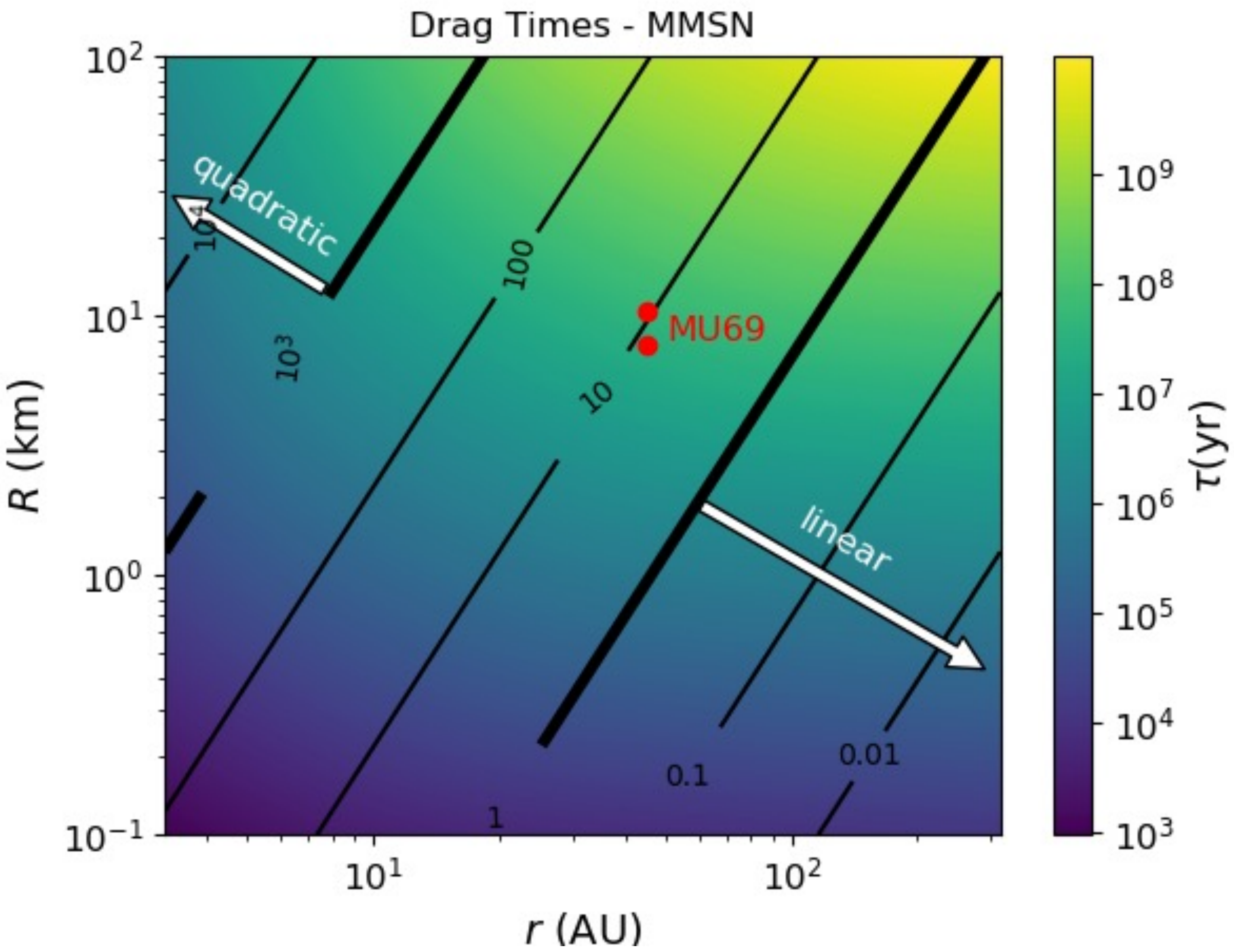
Viscous

Turbulent



Lyra, Youdin, & Johansen (2021)

Linear vs quadratic drag



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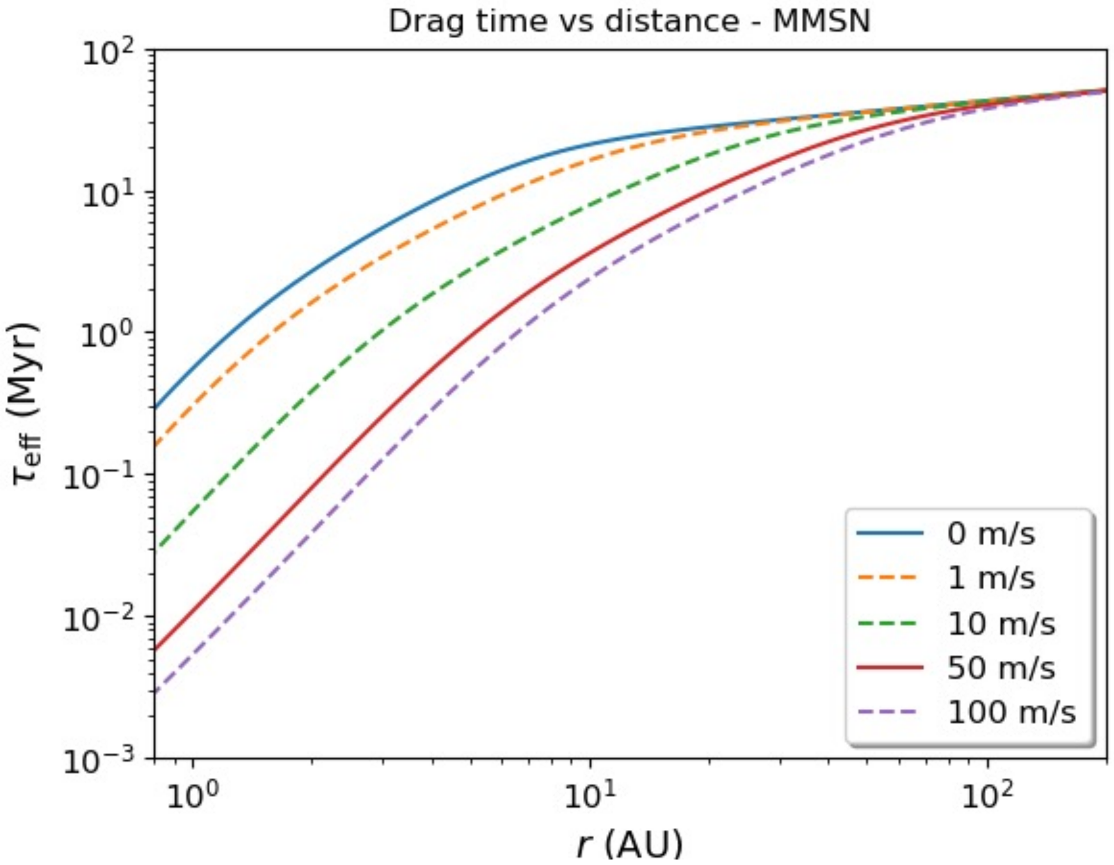
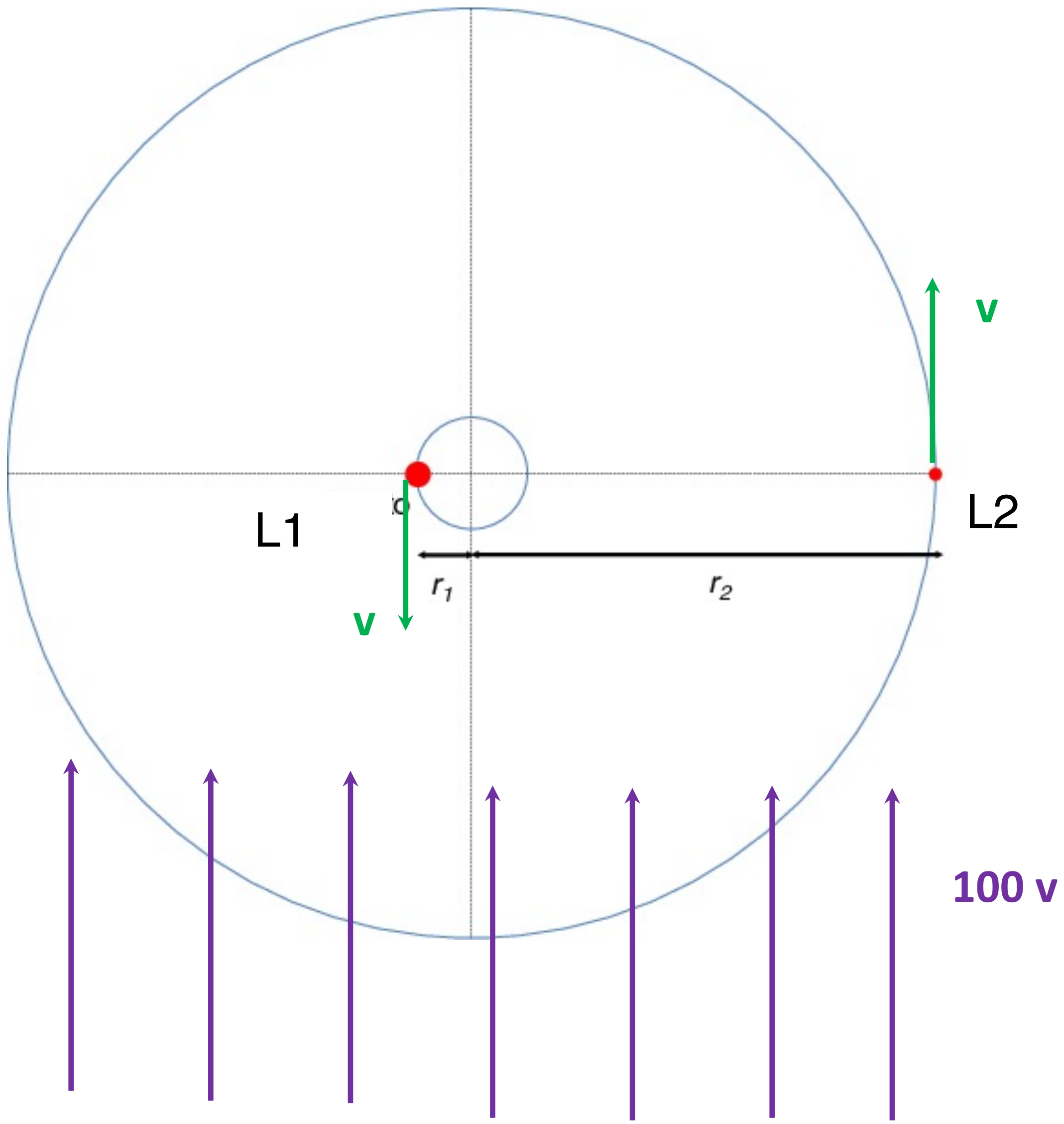
Linear vs quadratic drag





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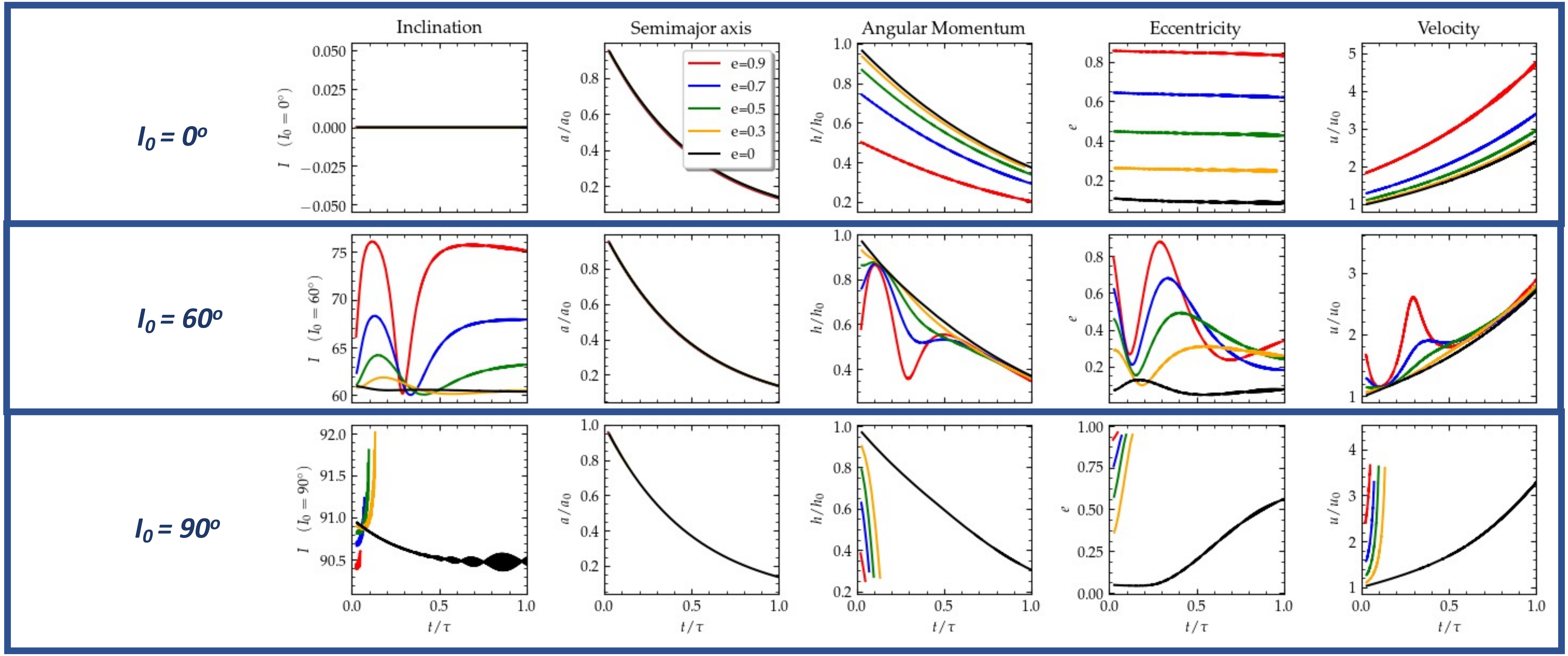
Effect of Inclination



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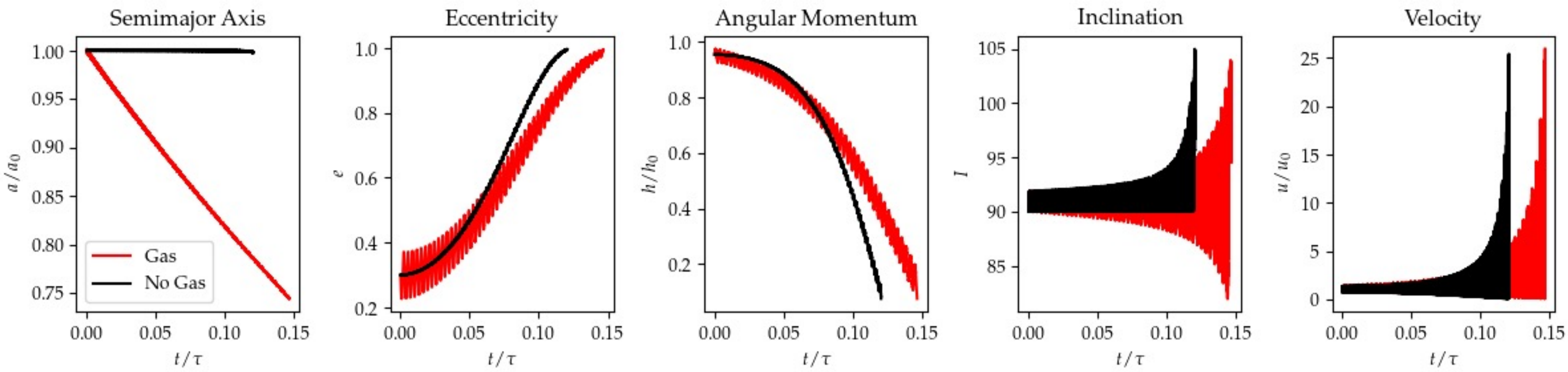
$I_0 = 90^o$ inclination



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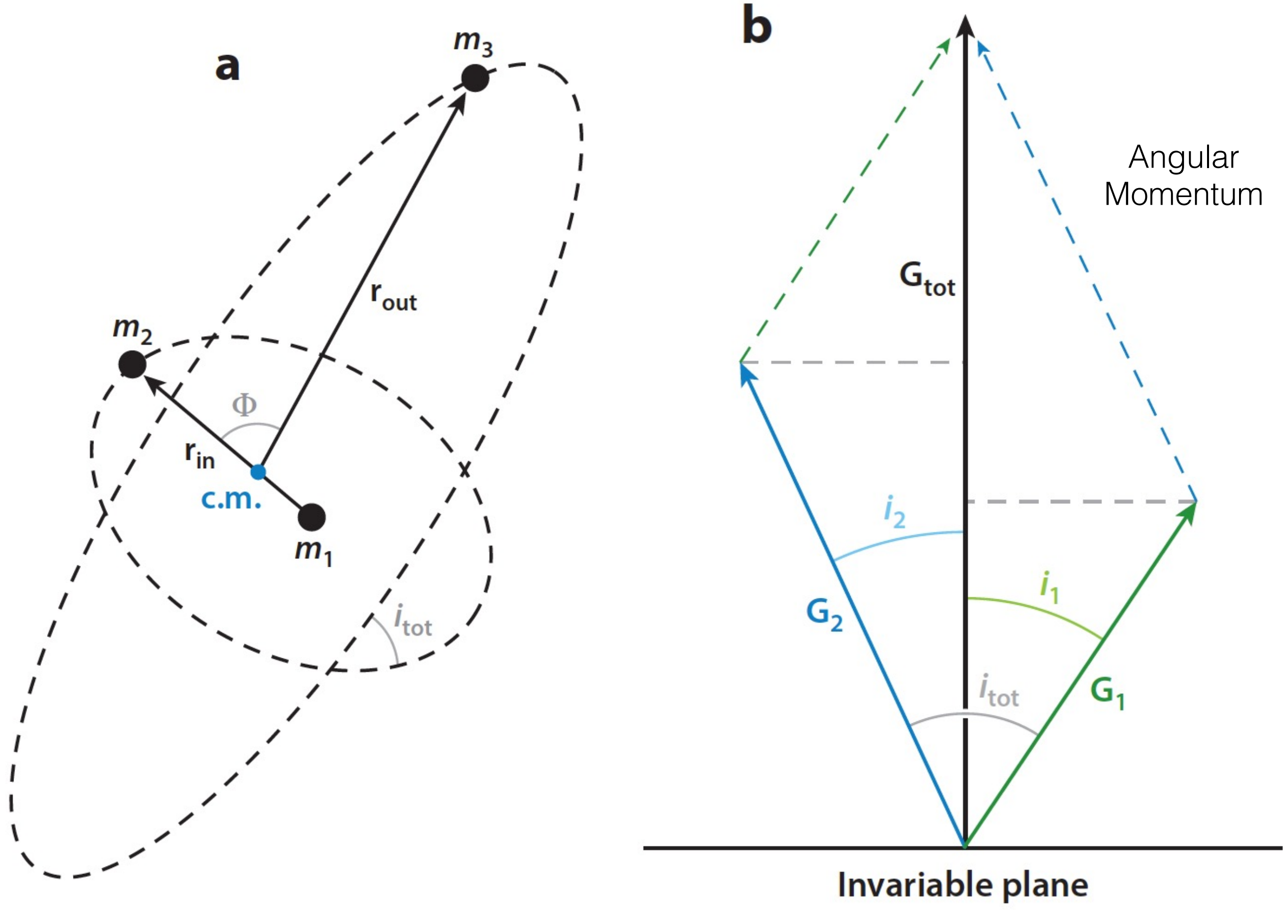
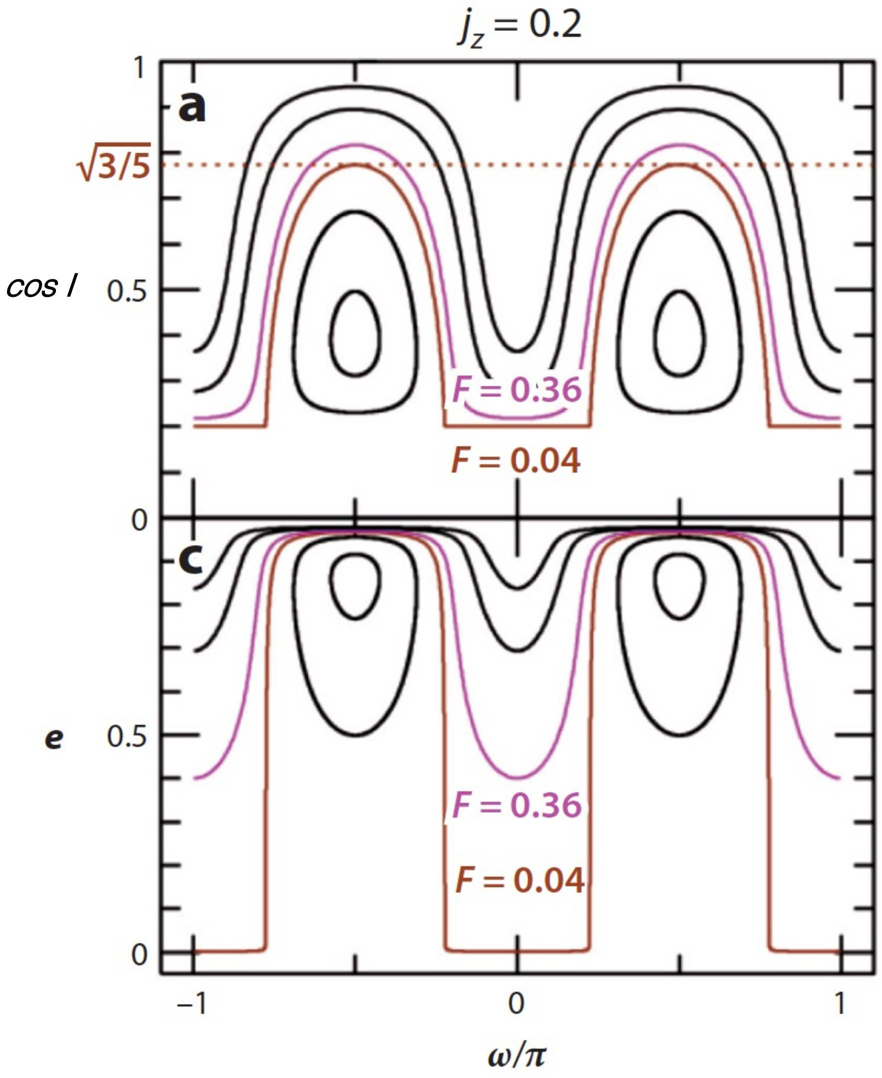
Kozai-Lidov Oscillations



Conserved quantity is not angular momentum, but vertical angular momentum

Naoz 2016

Kozai-Lidov Oscillations



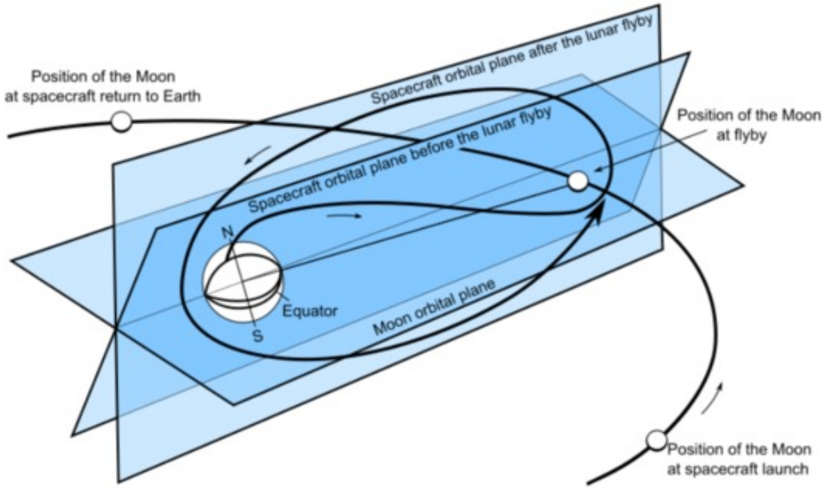
Conserved quantity is not angular momentum, but vertical angular momentum

$$j_z = (1-e^2)^{1/2} \cos I$$

Cycles of inclination and eccentricity.

Naoz 2016

Kozai-Lidov Oscillations



Planet. Space Sci., 1962, Vol. 9, pp. 719 to 759. Pergamon Press Ltd. Printed in Northern Ireland

THE EVOLUTION OF ORBITS OF ARTIFICIAL SATELLITES OF PLANETS UNDER THE ACTION OF GRAVITATIONAL PERTURBATIONS OF EXTERNAL BODIES

M. L. LIDOV

Translated by H. F. Cleaves from *Iskusstvennye Sputniki Zemli*, No. 8, p. 5, 1961.

Until recently, in works devoted to the evolution of the orbits of artificial satellites, investigations have been made in detail of the influence, on the orbit of the satellite, of the difference of the gravitational field of the Earth and the central and the influence of the braking of the satellite in the Earth's atmosphere. In some works the finer effects of evolution, connected with the rotation of the Earth's atmosphere have also been taken into account. The change in the parameters of the orbits of artificial Earth satellites on account of the gravitational attraction of the Moon and Sun only has been evaluated. Estimations have shown that, when near the Earth, artificial satellites experience the slight influence of other heavenly bodies, which is in practice difficult to observe with present-day means of measurement. However for the American satellite Vanguard I radio-technical means of measurement have already proved to be sufficiently accurate in this respect. The treatment of the results of measurement, in the course of two years of this satellite's existence, has shown(1) that it is impossible to explain the observed evolution of the parameters of the orbit without taking into account the gravitational influence of the Moon and Sun (and also pressure of light).

SOVIET ASTRONOMY – AJ VOL. 6, NO. 3 NOVEMBER-DECEMBER, 1962

CHRONICLE

CONFERENCE ON GENERAL AND APPLIED PROBLEMS OF THEORETICAL ASTRONOMY

E. A. Grebenikov

Translated from Astronomicheskii Zhurnal, Vol. 39, No. 3, pp. 562-564, May-June, 1962
Original article submitted January 29, 1962

In accordance with a resolution of the Presidium of the USSR Academy of Sciences, a Conference on General and Applied Problems of Theoretical Astronomy convened in Moscow on November 20–25, 1961. The Conference was held in the auditorium of the Sternberg State Astronomical Institute at Moscow State University. About 200 scientists participated in the sessions, including about 80 from out of town. Representatives were present from various scientific research institutes, universities, and other institutions of higher education in Moscow, Leningrad, Kharkov, Novosibirsk, Tiflis, Kazan, Odessa, Riga, Rostov-on-Don, Kalinin, Vologda, Tallin, and Saransk.

Several scientists from abroad also participated in the Conference: W. Cowla (United States), Y. Kozai (United States), J. Kovalevsky (France), K. Schmidt (East German), E. Tengström (Sweden), and G. Järnefelt (Finland).

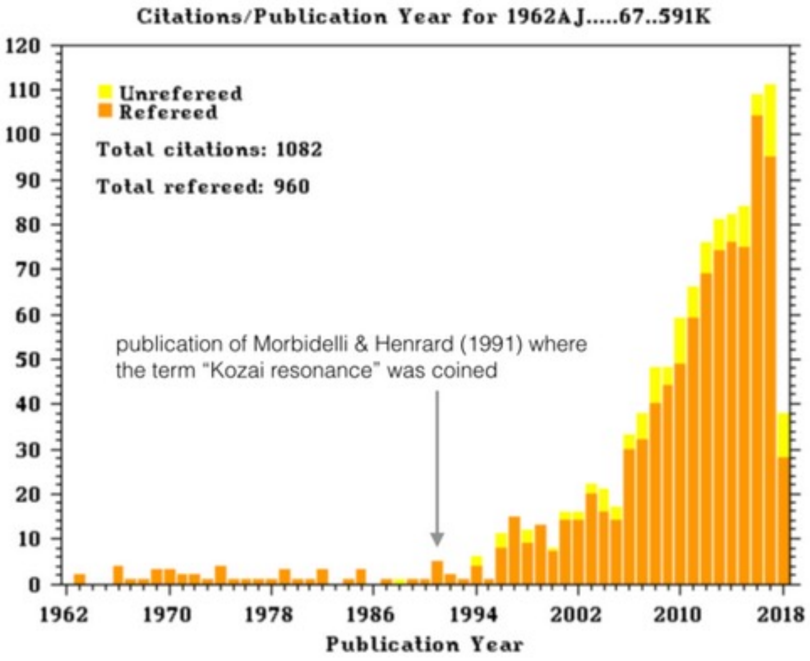
man used the method of compiling finite-difference equations, and obtained conditions for the stability and instability of the periodic solutions of a canonical system stable in the first approximation.

Arnol'd demonstrated the stability of an area-preserving transformation of a plane into itself in the neighborhood of a fixed point of general elliptic type. This fact has many applications in celestial mechanics. For example, it implies that the Lagrange periodic solutions of the restricted three-body problem are stable. Poincaré has shown that because of small divisors that appear as a result of integrating the equations of celestial mechanics in series, the series diverge. Arnol'd has now been able to construct a converging variant for the theory of perturbations even in the degenerate case with the aid of a modification of Newton's method.

Alkseev's paper gave a thorough and complete sur-

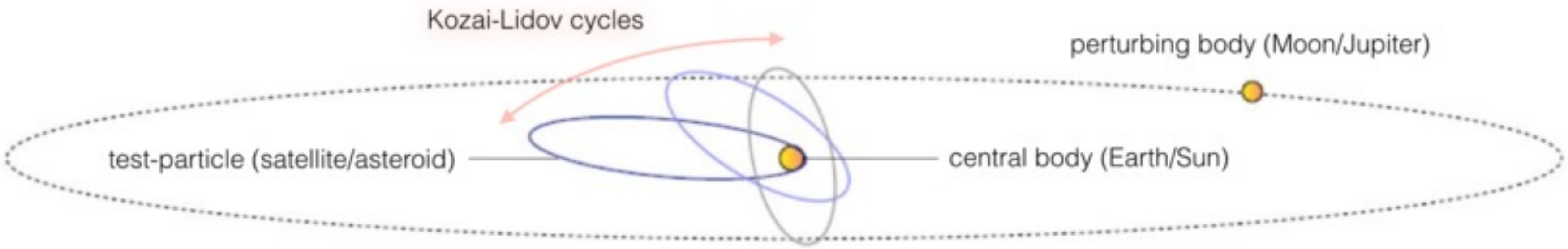
Yoshihide Kozai (1928-2018)

Secular Perturbations of Asteroids with High Inclination and Eccentricity



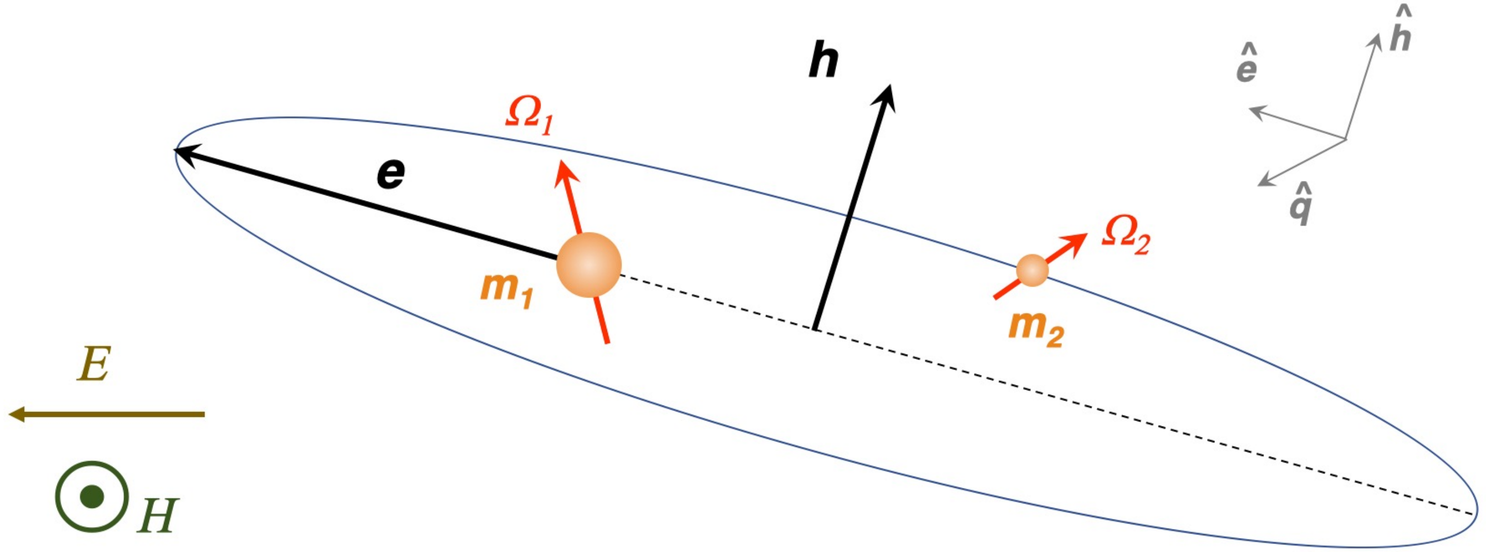
REFERENCES TO "KOZAI RESONANCE"

Kozai-Lidov Oscillations

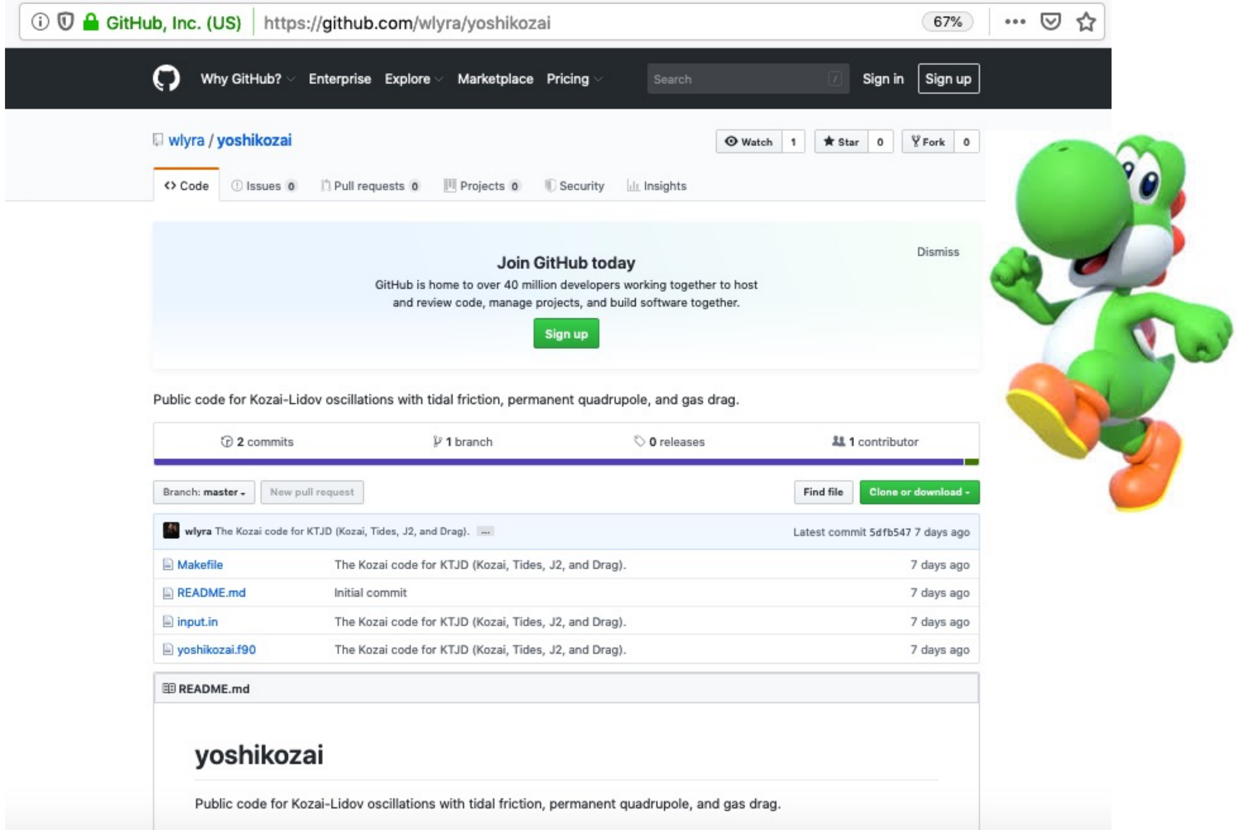


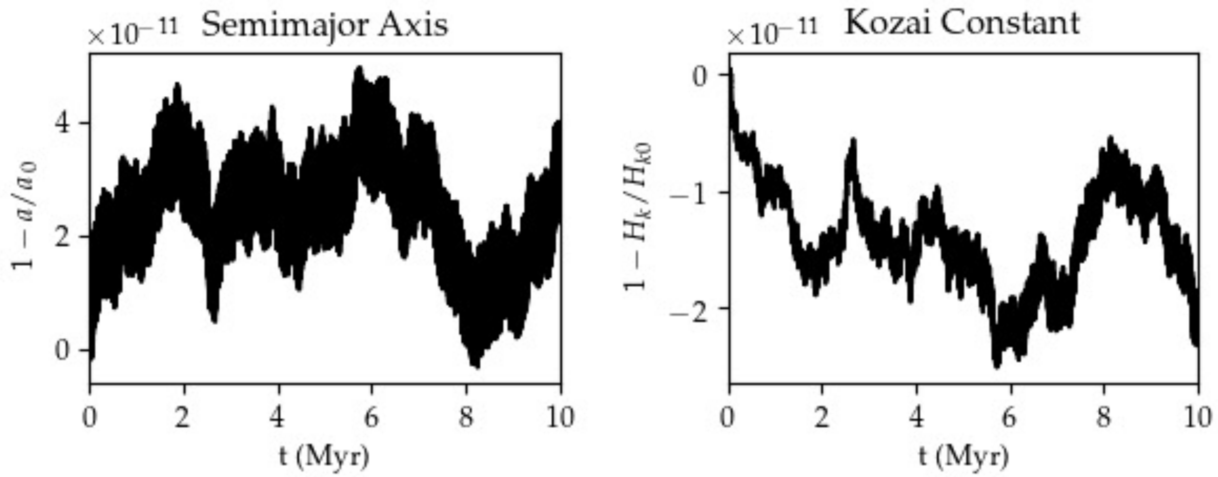
Kozai + Tidal Friction + Drag

$$\frac{de}{dt} = -e\left[V_1 + V_2 + V_d + 5\left(1-e^2\right)S_{eq}\right],$$
$$\frac{dh}{dt} = -h\left(W_1 + W_2 + W_d - 5e^2 S_{eq}\right),$$
$$\frac{d\hat{\boldsymbol{e}}}{dt} = \left[Z_1 + Z_2 + \left(1-e^2\right)\left(4S_{ee} - S_{qq}\right)\right]\hat{\boldsymbol{q}} - \left[Y_1 + Y_2 + \left(1-e^2\right)S_{qh}\right]\hat{\boldsymbol{h}},$$
$$\frac{d\hat{\boldsymbol{h}}}{dt} = \left[Y_1 + Y_2 + \left(1-e^2\right)S_{qh}\right]\hat{\boldsymbol{e}} - \left[X_1 + X_2 + \left(4e^2+1\right)S_{eh}\right]\hat{\boldsymbol{q}},$$
$$\frac{d\boldsymbol{\Omega}_1}{dt} = \frac{\mu_r h}{I_1}\left(-Y_1\hat{\boldsymbol{e}} + X_1\hat{\boldsymbol{q}} + W_1\hat{\boldsymbol{h}}\right),$$
$$\frac{d\boldsymbol{\Omega}_2}{dt} = \frac{\mu_r h}{I_2}\left(-Y_2\hat{\boldsymbol{e}} + X_2\hat{\boldsymbol{q}} + W_2\hat{\boldsymbol{h}}\right).$$



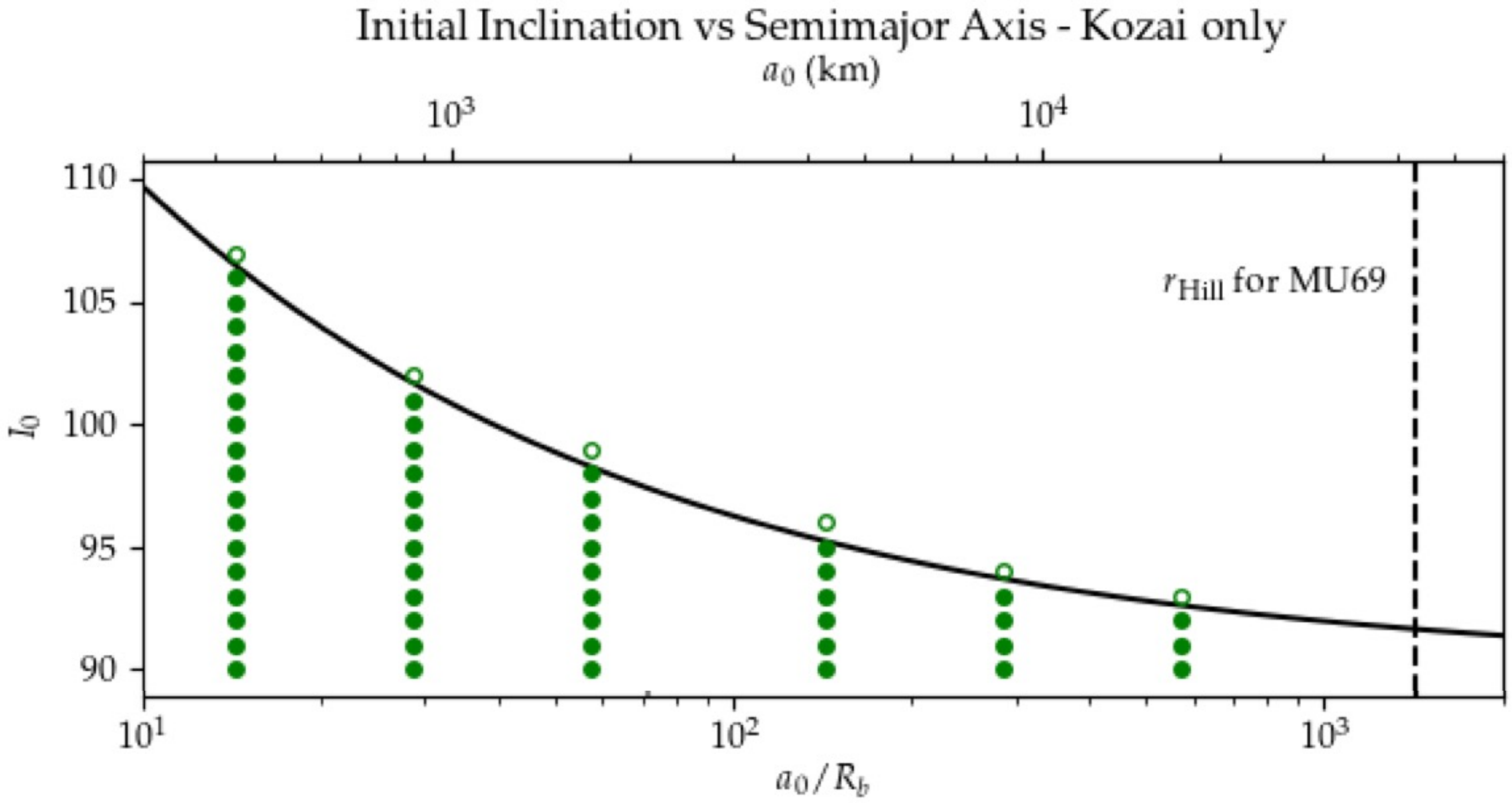
Lyra, Youdin, & Johansen (2021)





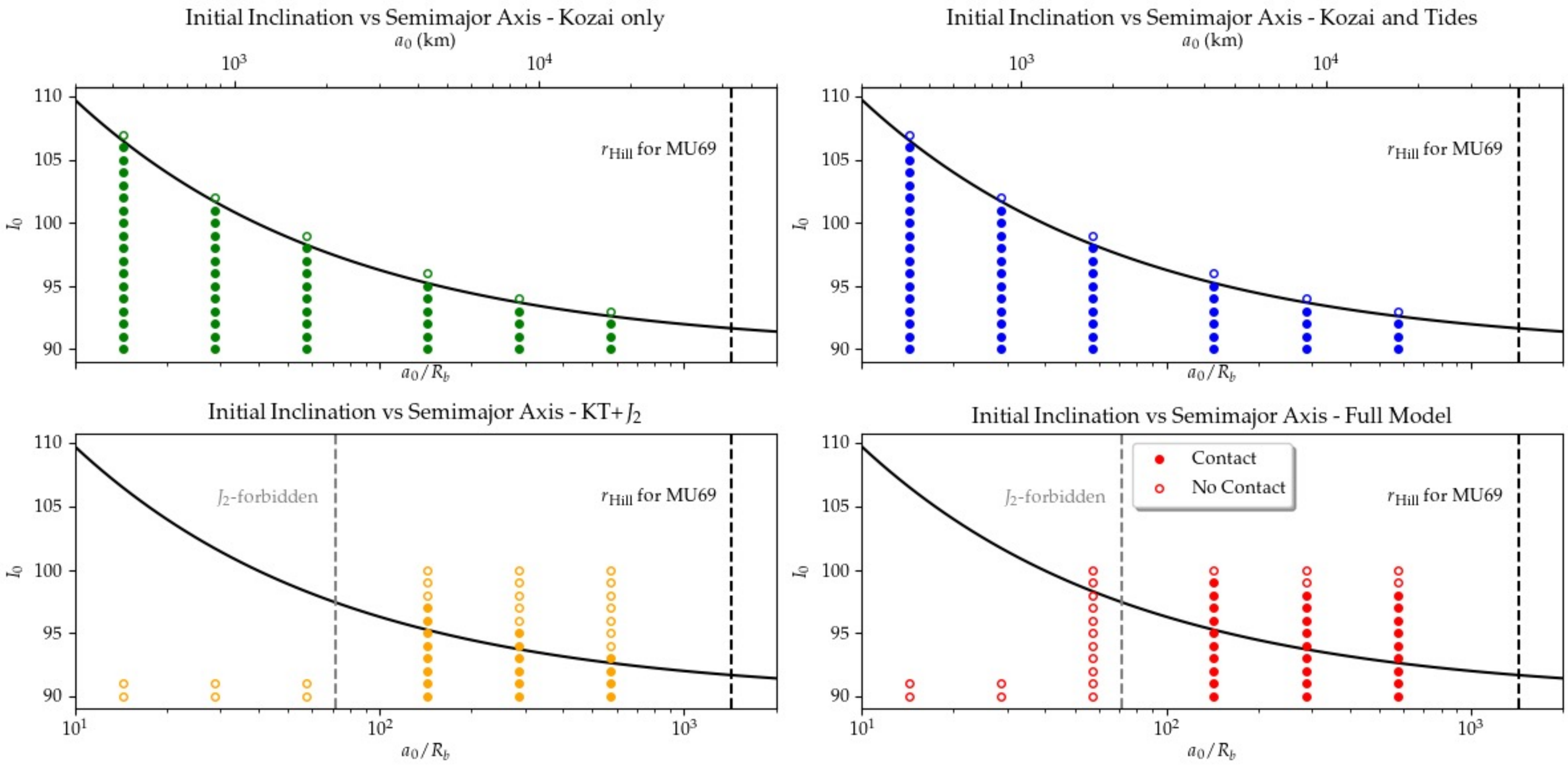
Lyra, Youdin, & Johansen (2021)

Critical Inclination



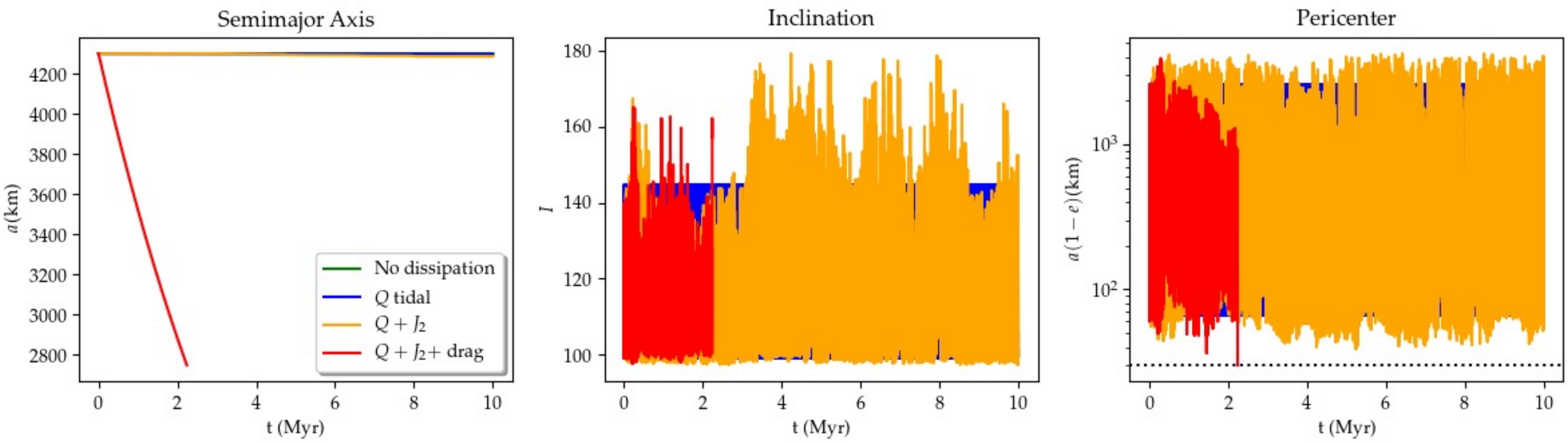
Lyra, Youdin, & Johansen (2021)

Kozai + Tidal Friction + Drag



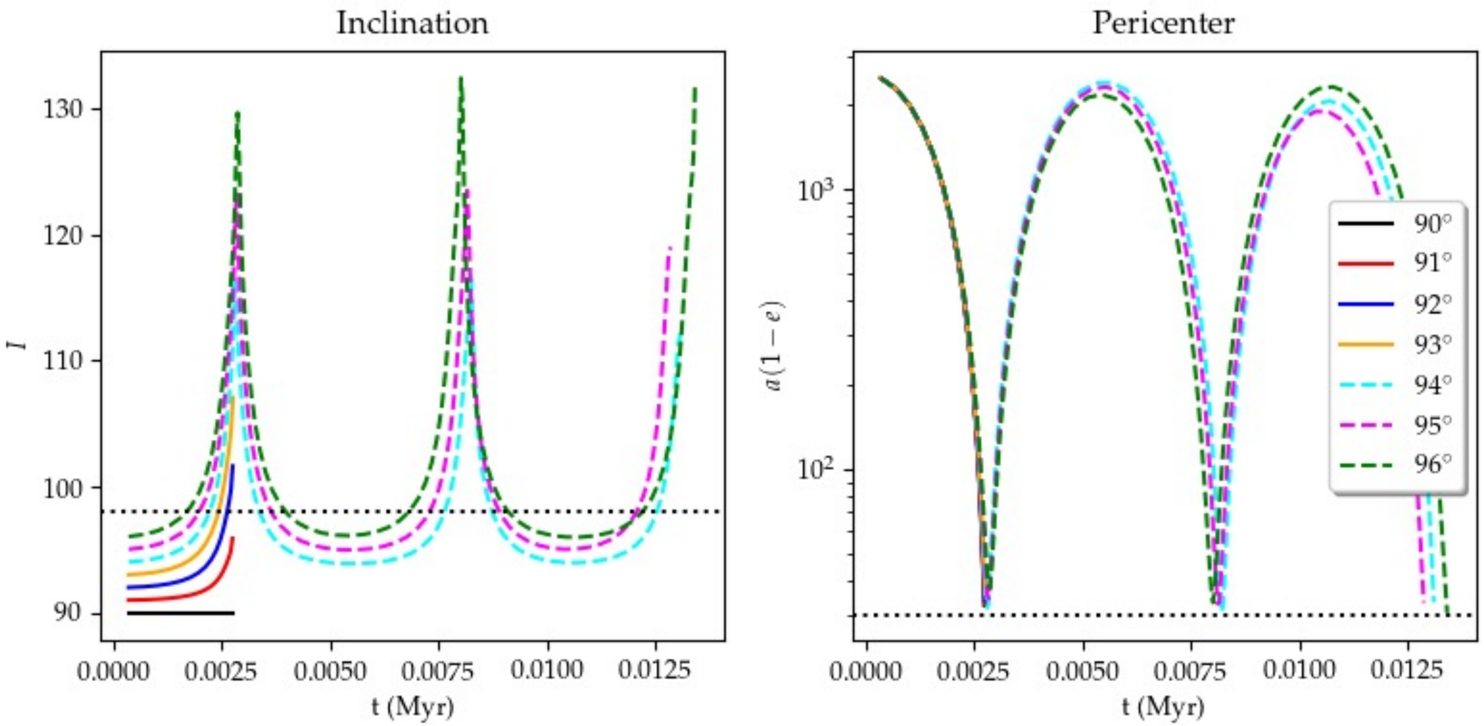
Lyra, Youdin, & Johansen (2021)

Effect of Drag

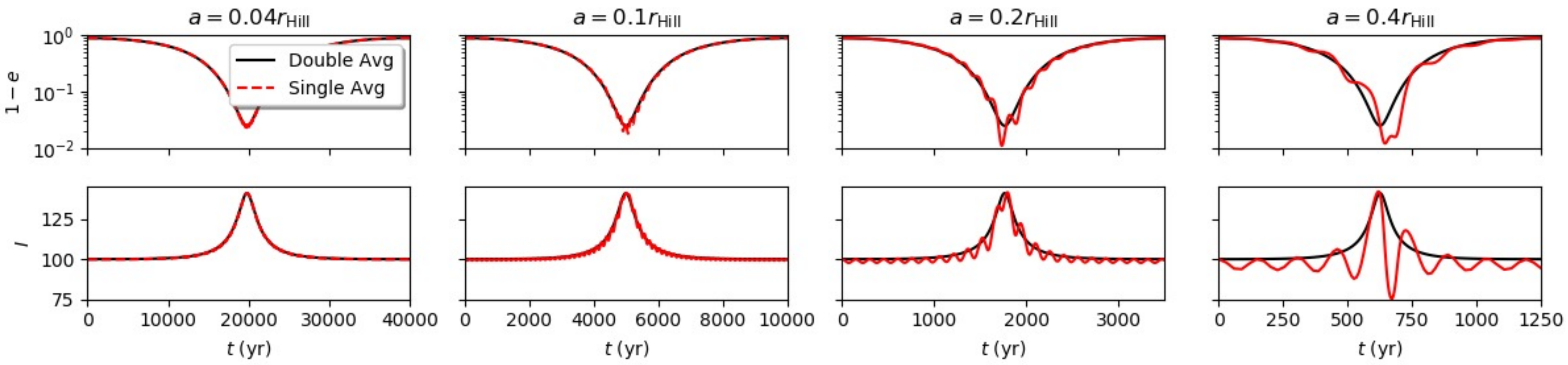


Lyra, Youdin, & Johansen (2021)

Fine Tuning of Initial Inclination



Double-Averaged vs Single-Averaged



Lyra, Youdin, & Johansen (2021)

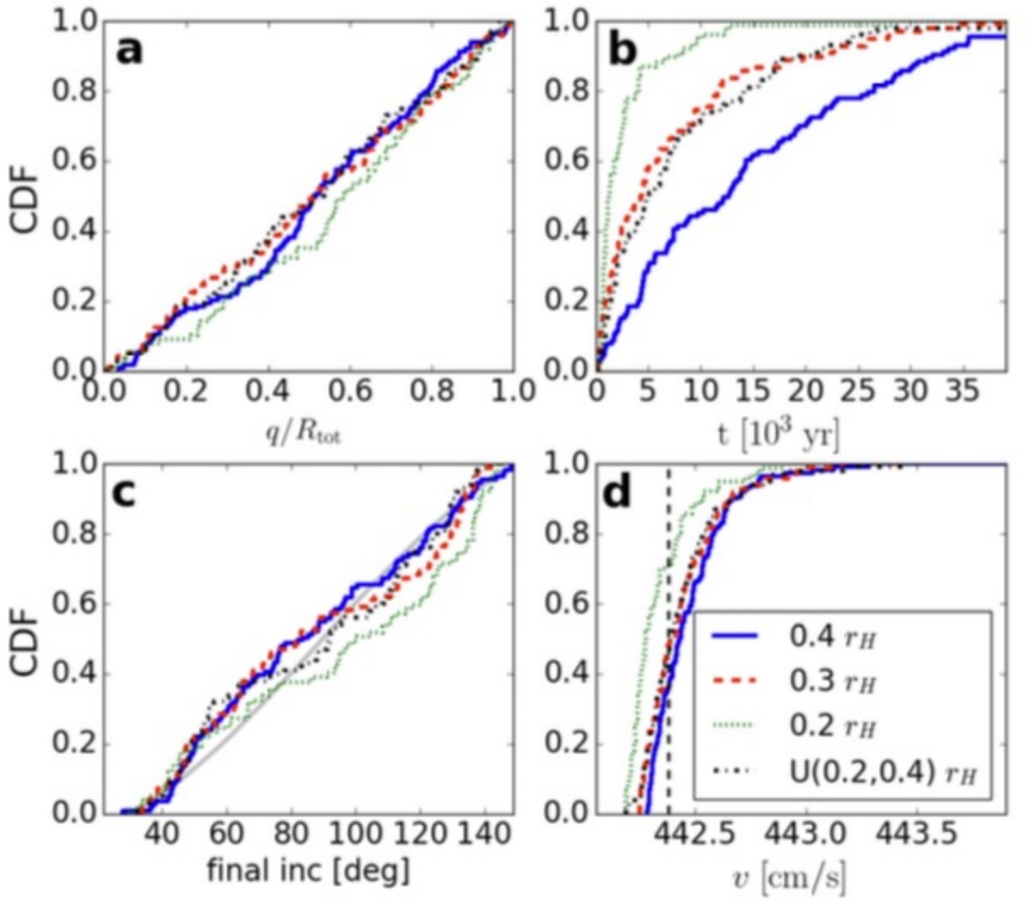
N-body simulations (no tides, J2, or drag)

Pericenter

Time to contact

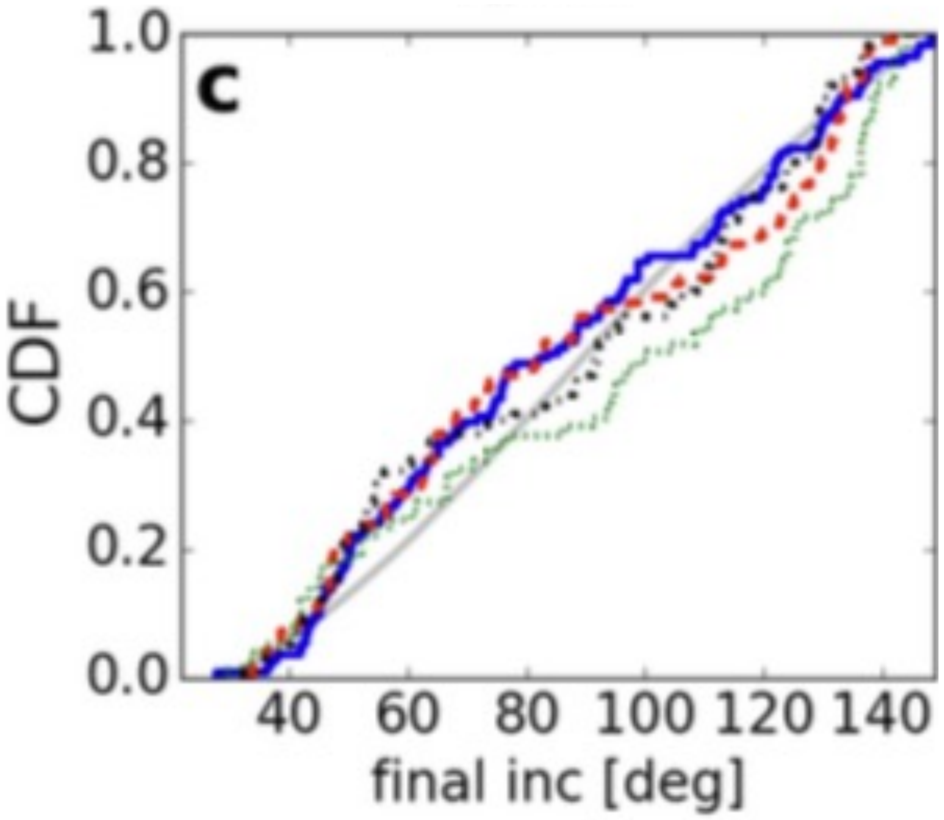
Inclination at contact

Speed at contact



Grishin et al. (2020)

N-body simulations (no tides, J2, or drag)

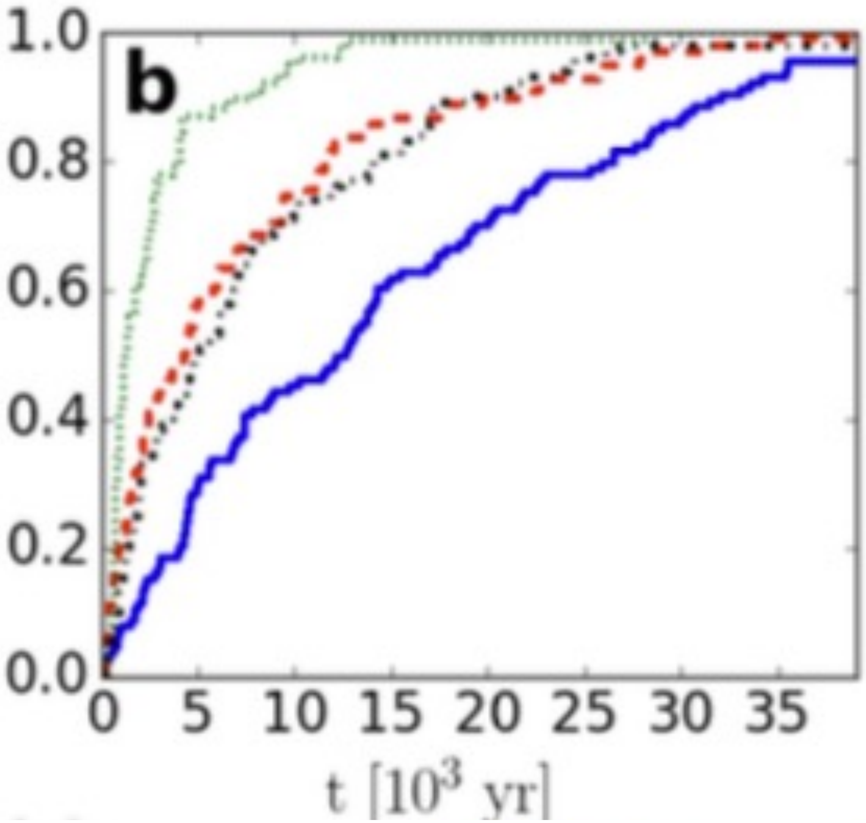


Inclination at contact

Uniform
any inclination (from 40^{o} to 140^{o}) equally likely

Grishin et al. (2020)

N-body simulations (no tides, J2, or drag)



Time to contact

Too short to allow for alignment

Grishin et al. (2020)

Conclusions

- Solved the binary planetesimal problem with gas drag
- Implemented the solution into a Kozai plus tidal friction code
- Contact possible in the asteroid belt within 0.1 Myr (depleted of binaries)
- Contact via Kozai cycles in the Kuiper belt, orbits become grazing
- Window of contact increased by J_2 and drag
- Enough time for the bodies to come to alignment
- Model predictions:
  - ~ 10% of KBCC binaries should be contact binaries
  - Velocities at contact should be about 3-4 m/s
- Open questions:
  - Single-averaged (or N-body) needed to reproduce final inclinations
  - Combine our model with single-averaged Kozai (or N-body)

...1 January 2019.

The two bodies slowly spiral closer until they touch, forming the bi-lobed object we see today.

Sketch by J.T. Keane

Lyra, Youdin, & Johansen (2021)