Ultima Thule (MU_{69})
Formation and binary hardening

Wladimir Lyra

New Mexico State University

In the shuffle from

California State University

Funding

Exoplanet Research Program
XRP - 2018

NRAO 2017

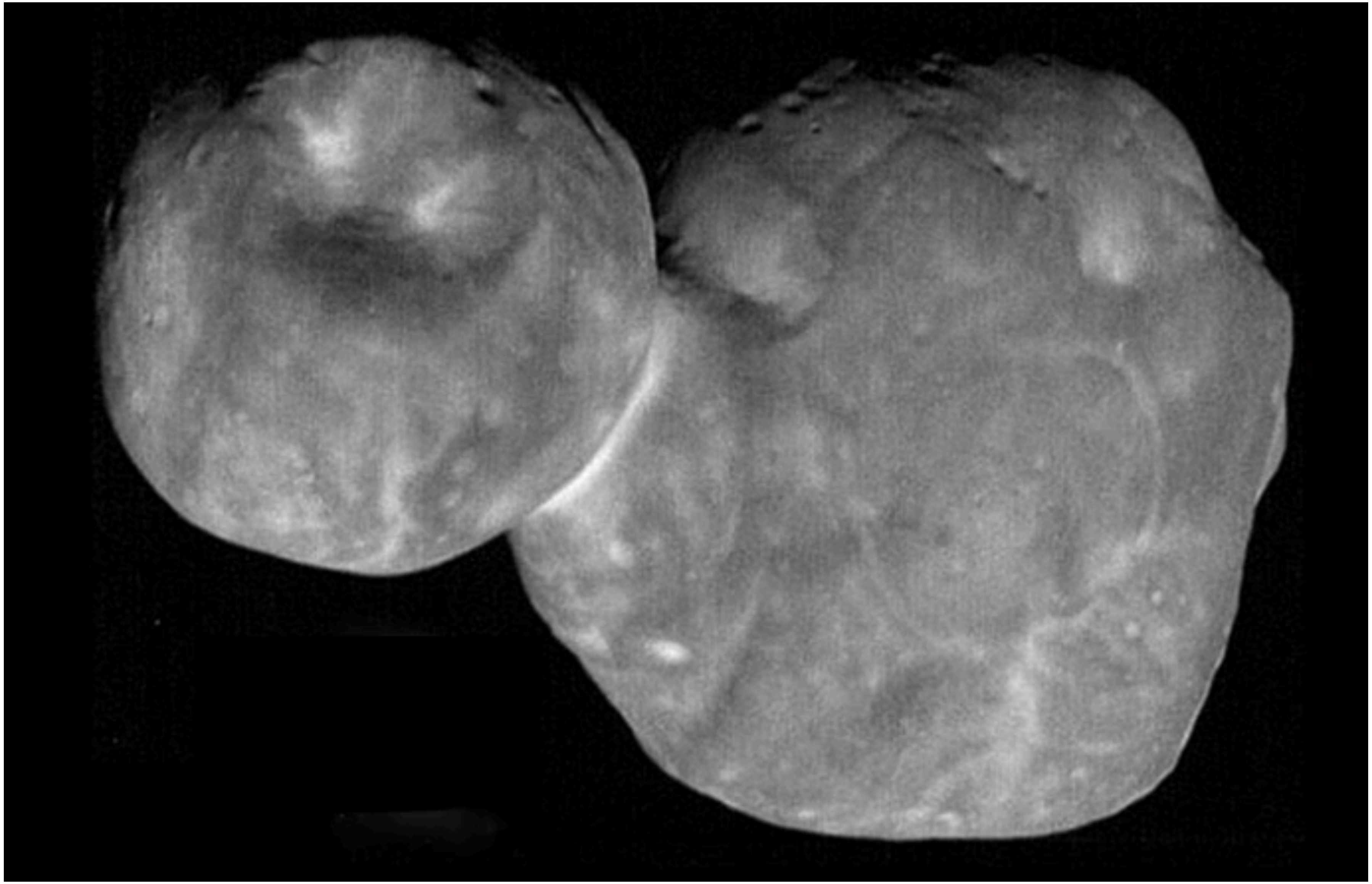
XRP - 2016

HST Cycle 24, 2016

Computational Facilities

MPIA, July 16th, 2019

Ultima Thule (MU_{69})



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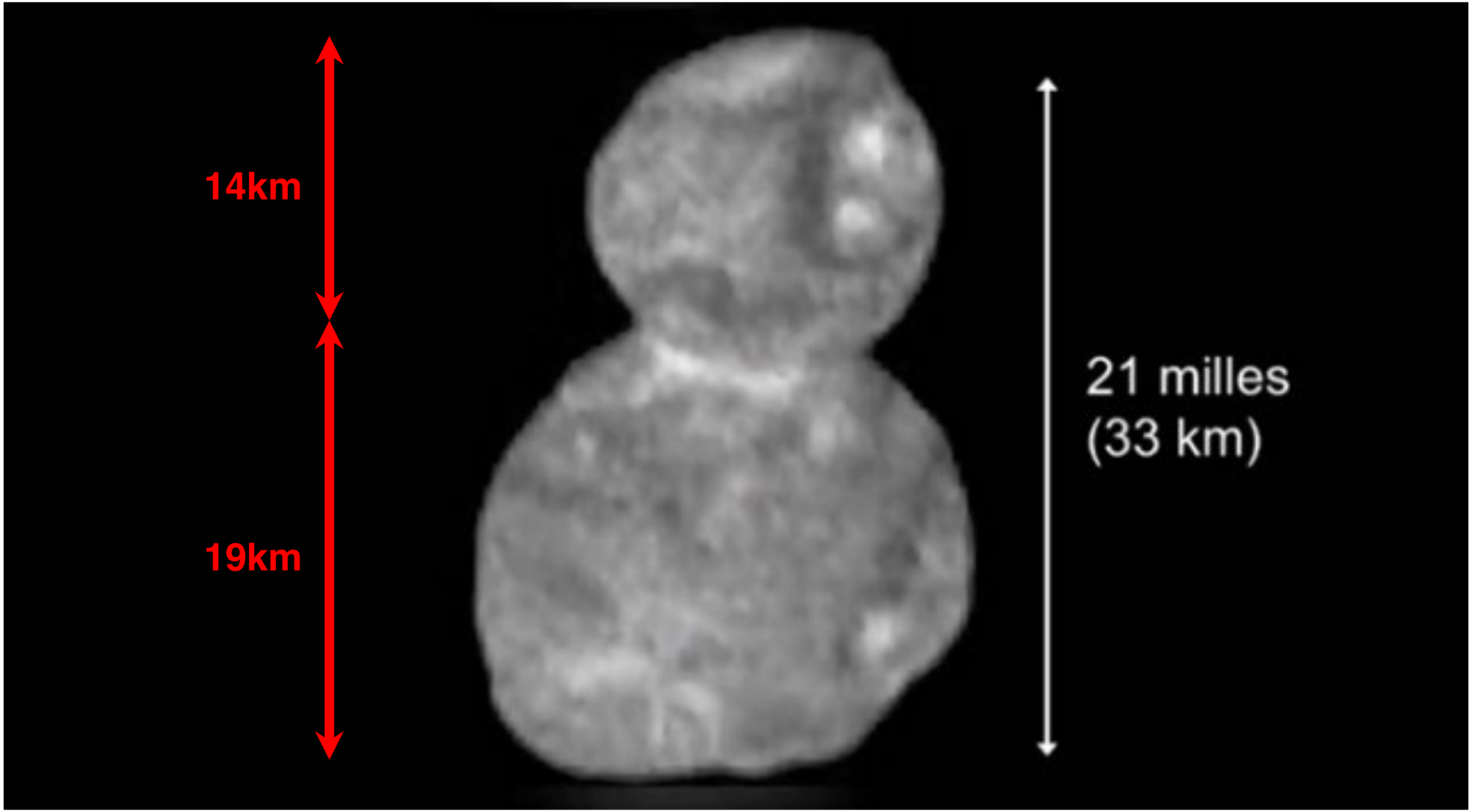
New Horizons Flyby, Jan 2019

MU_{69}: Dimensions



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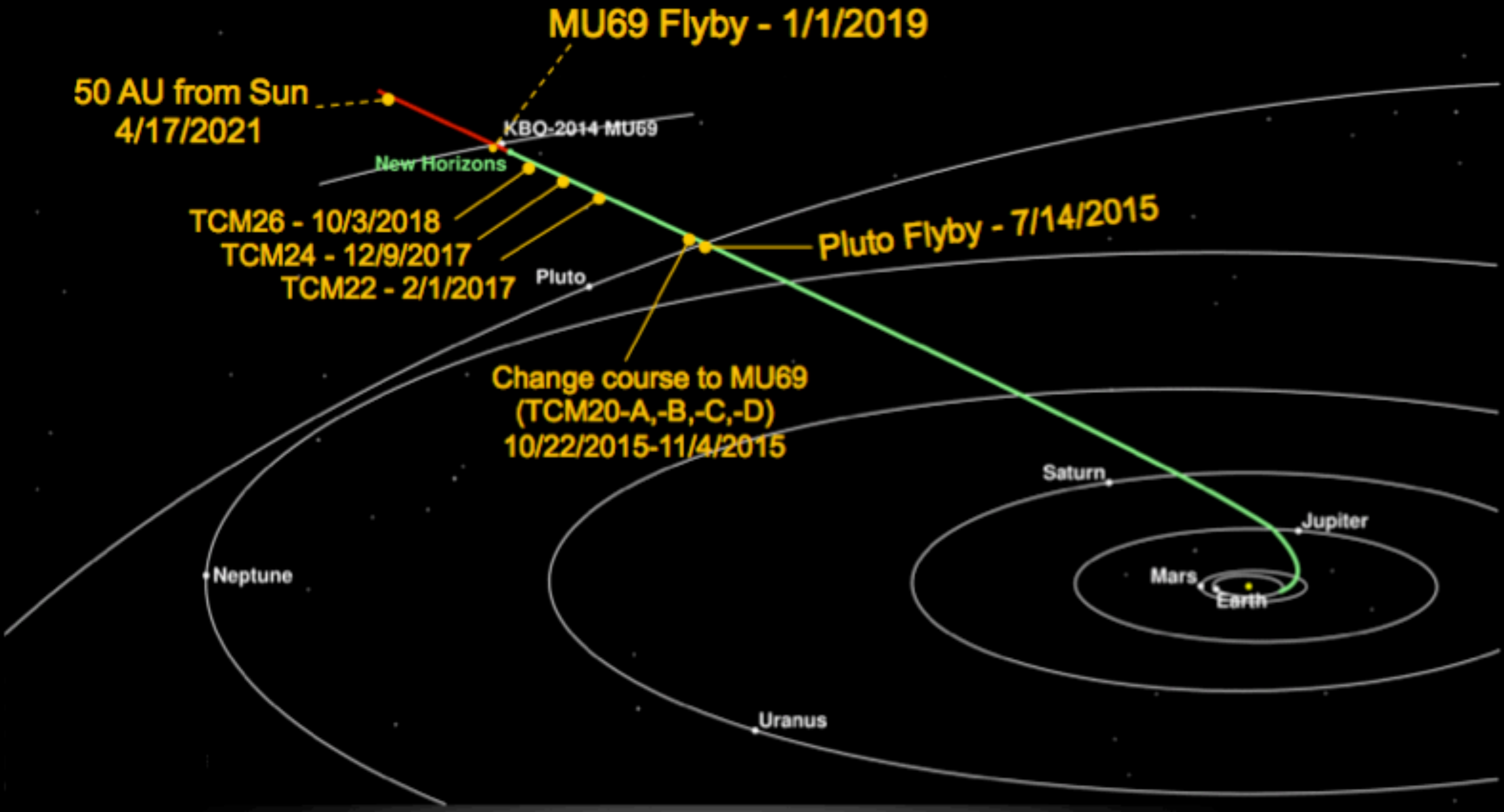
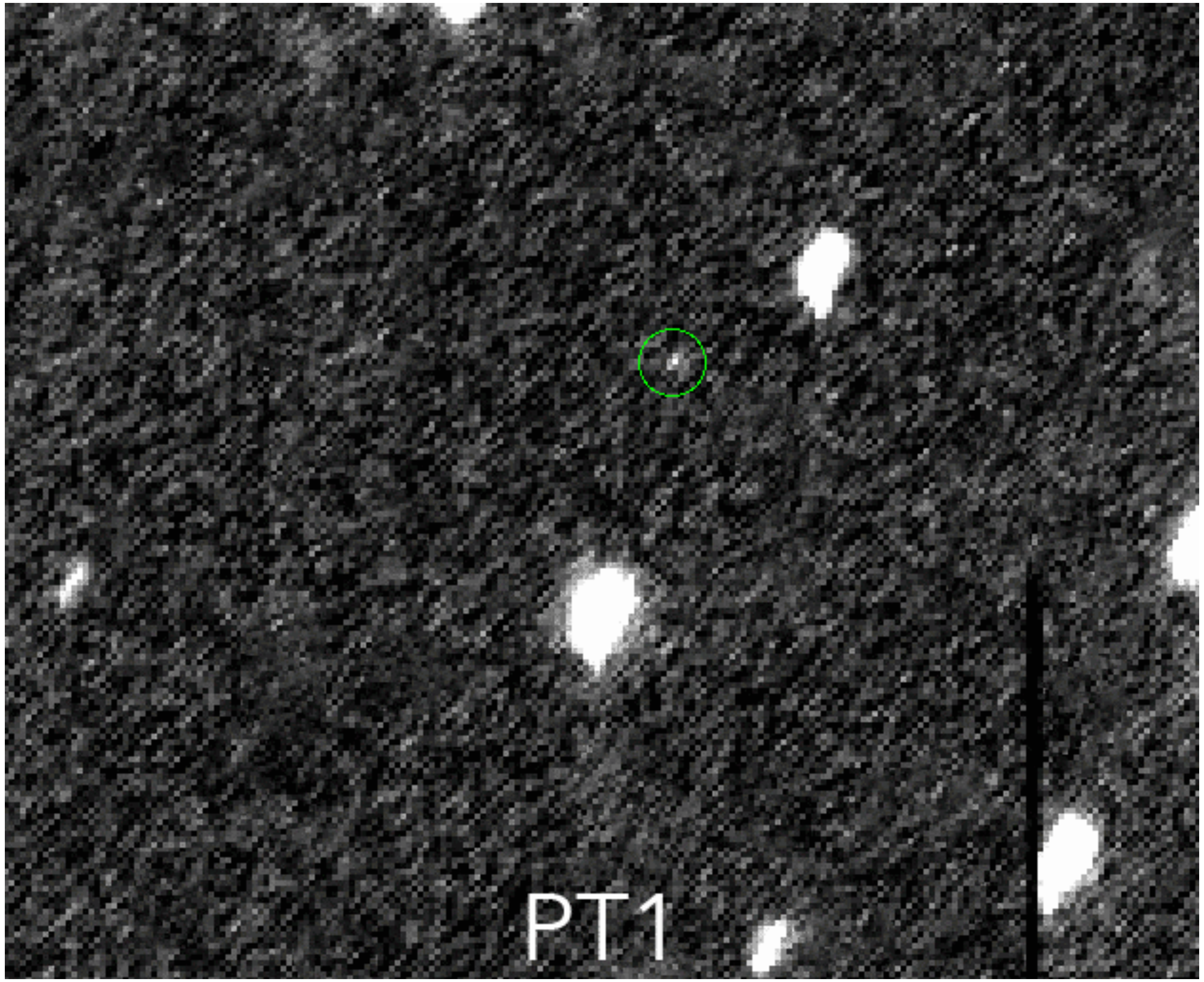
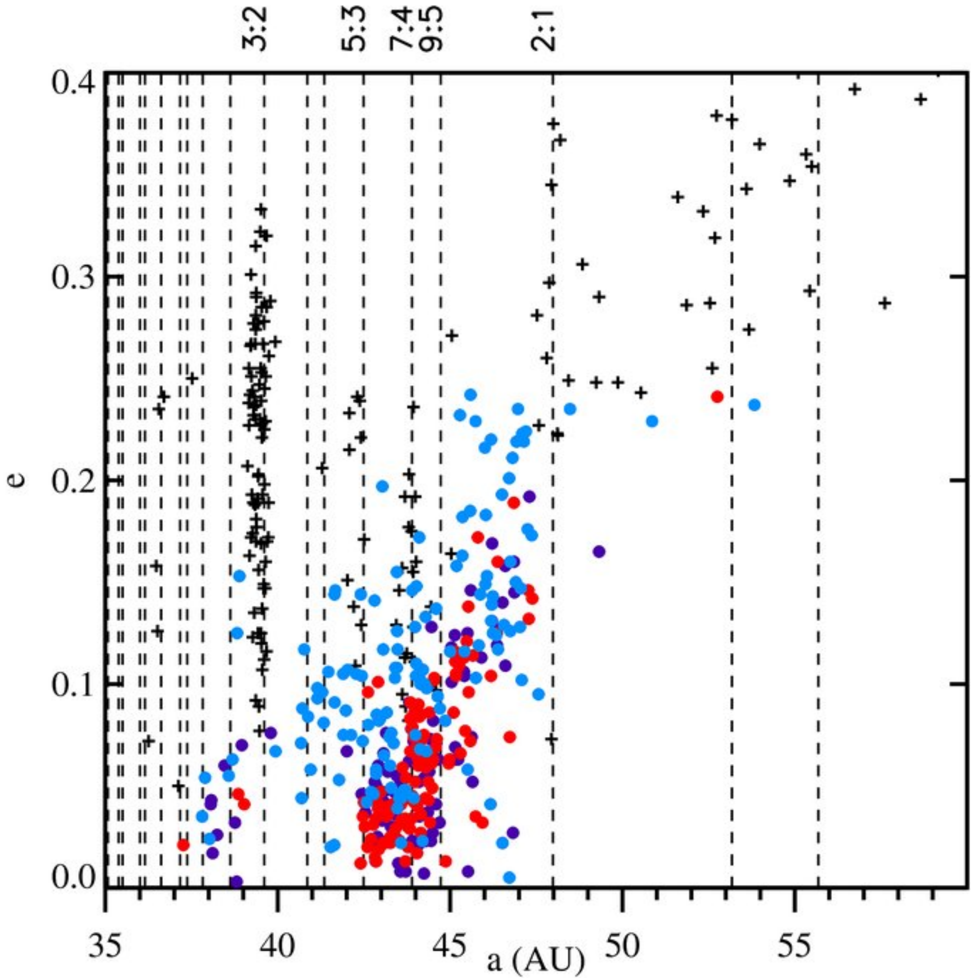
New Horizons Trajectory



2014 MU_{69}: Discovery



Cold Classical Kuiper Belt Object



+ Resonant and Scattered
Cold Classical $i<2^o$
"Ambiguous" $2^o<i<6^o$
Hot Classicals $i>6^o$

Presumably pristine planetesimals

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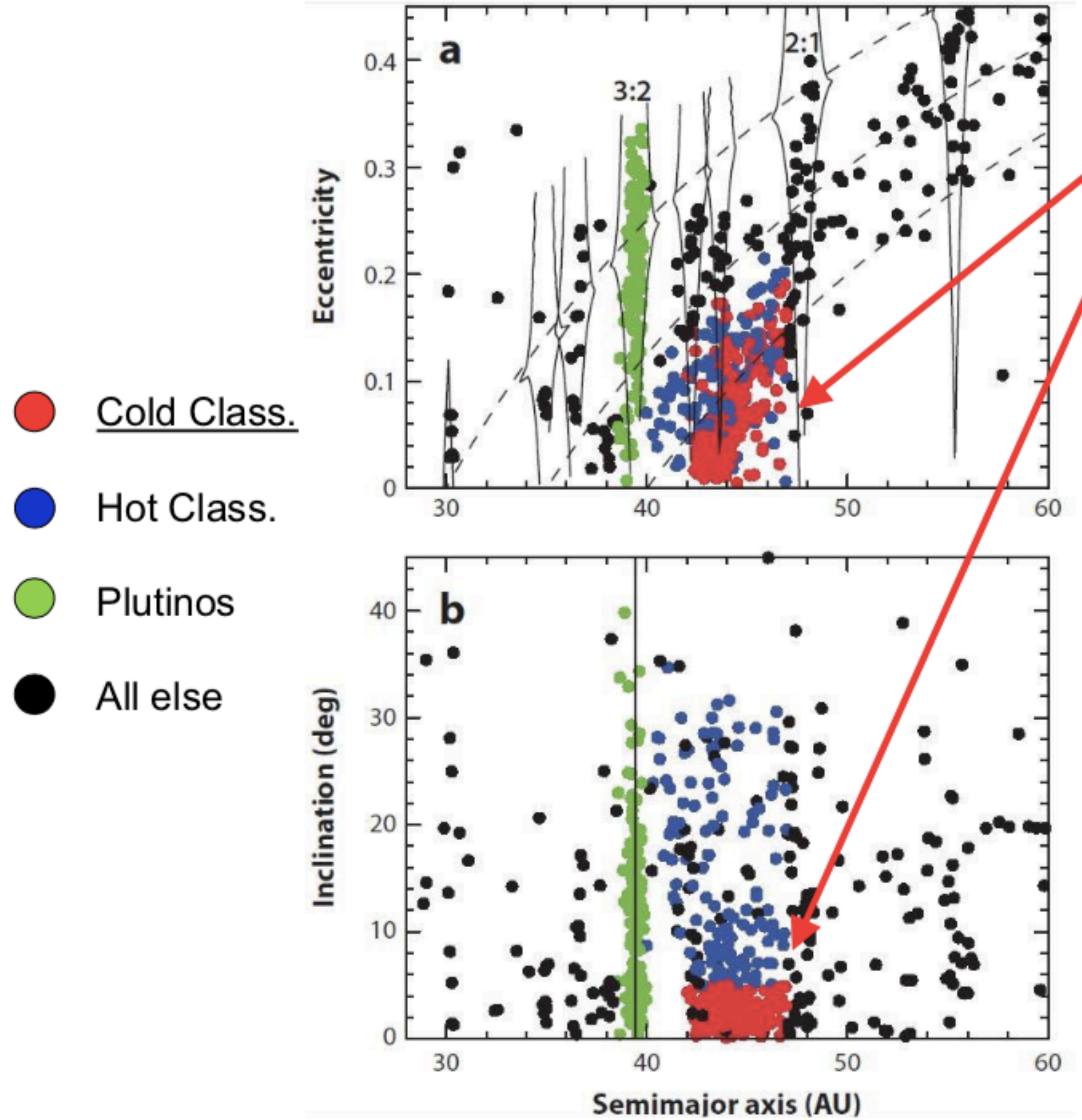
Gladman+ '08, Batygin+ '10, Dawson & Murray-Clay '12



Cold Classicals (CCs)

low inclinations: CCs not much affected by Neptune's migration

no very large bodies: accretion halted at sizes <300 km

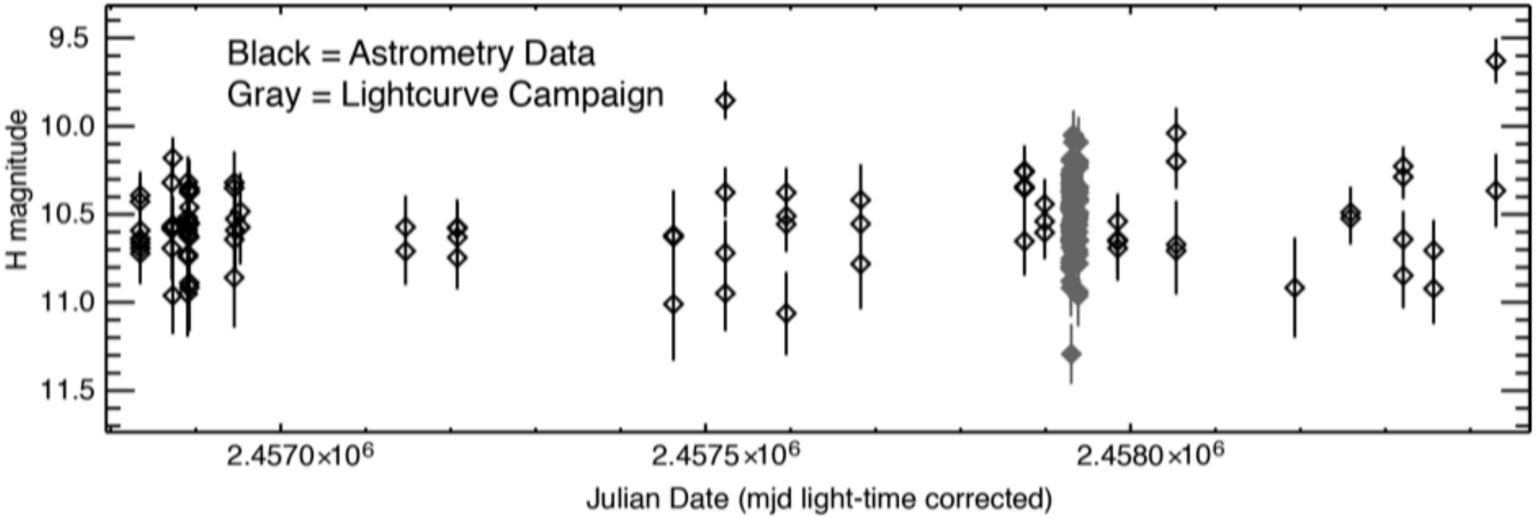
weakly bound binaries: CCs not affected by disruptive collisions

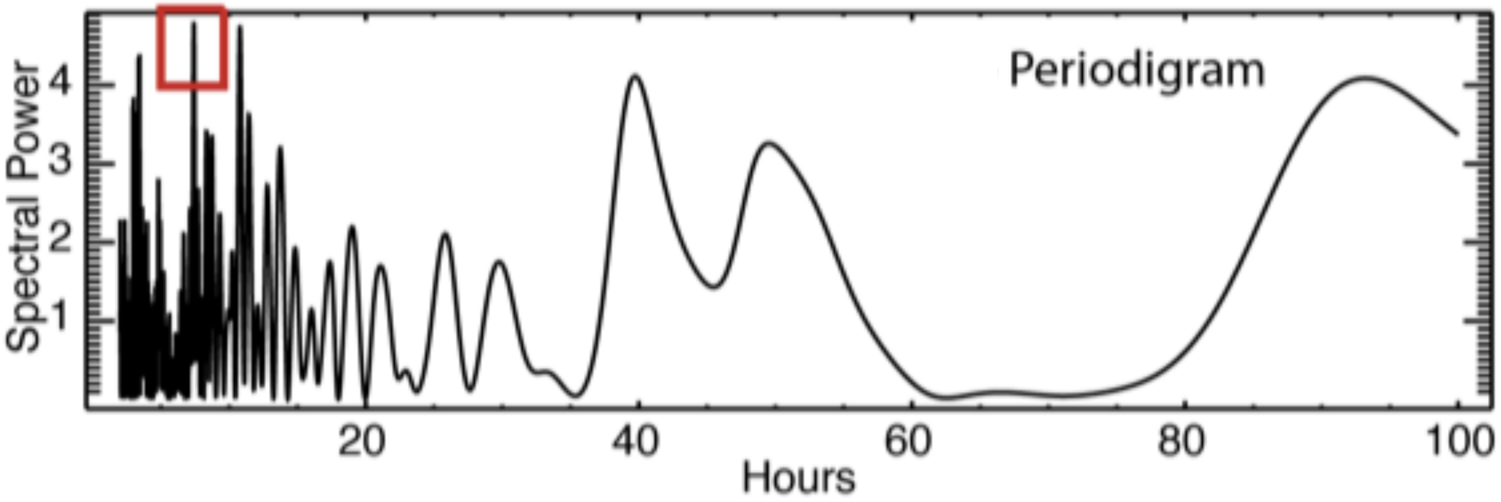
Implication: CCs formed at >40 au and survived relatively unscathed

Slide by David Nesvorny

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]

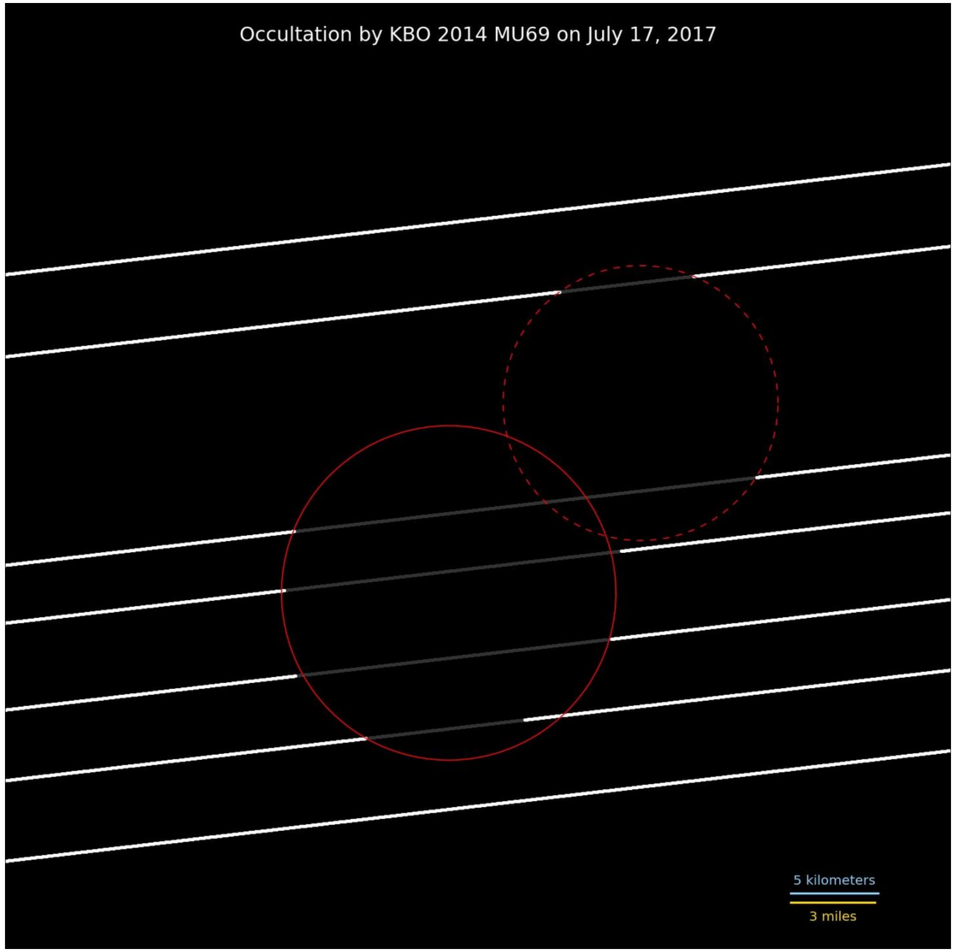


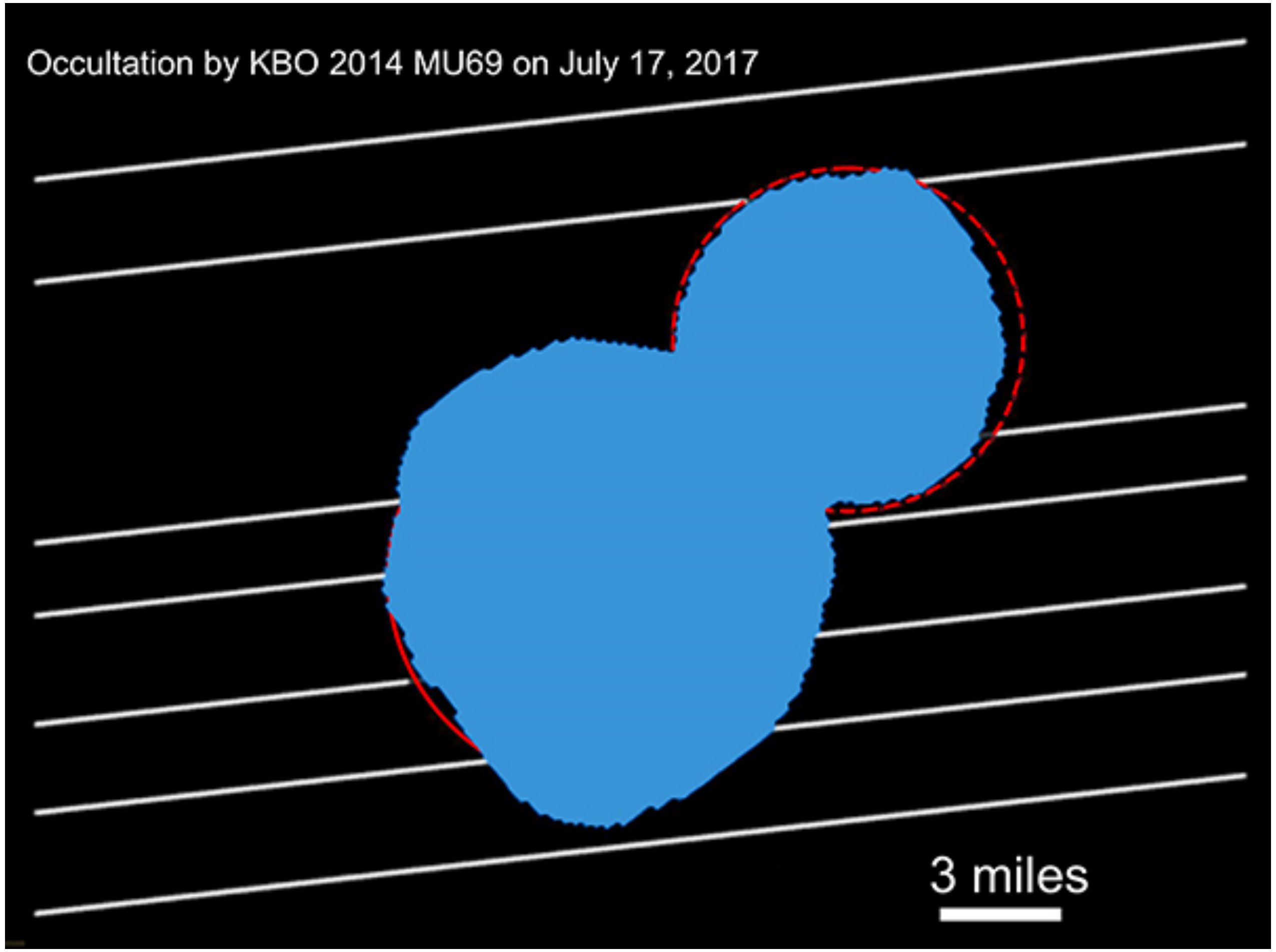


ABSTRACT

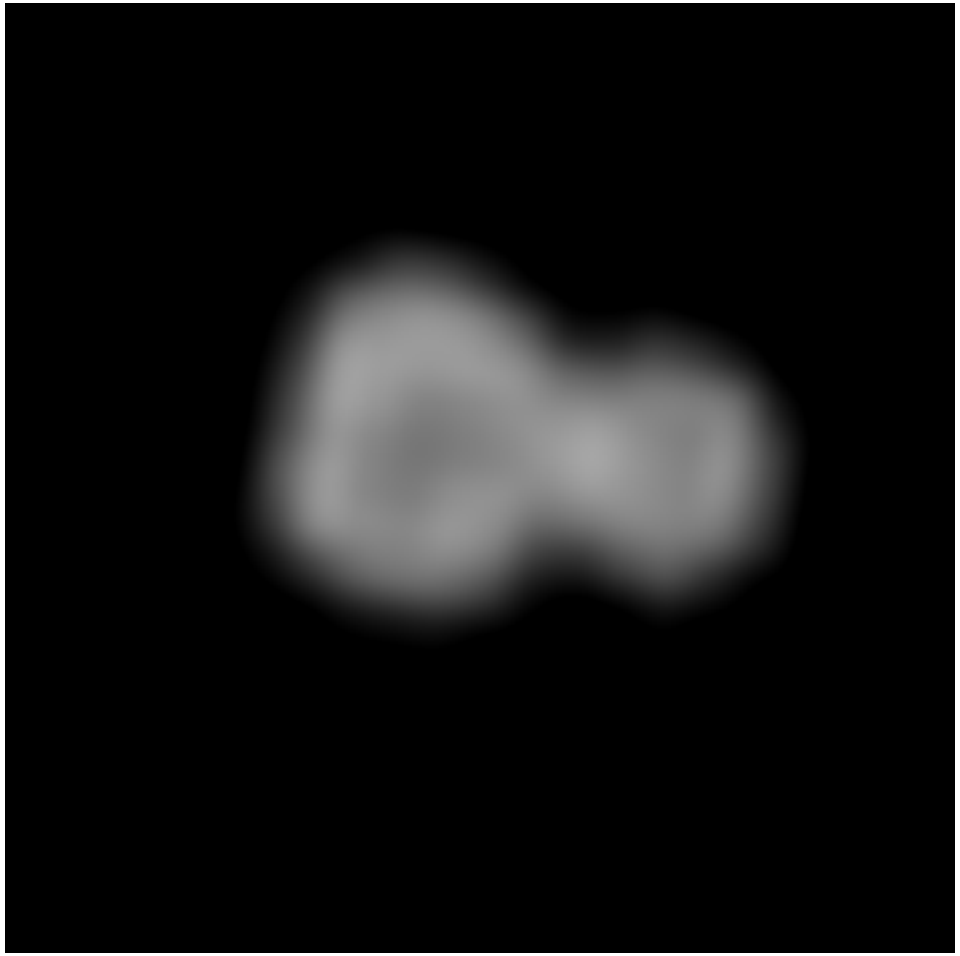
We report *Hubble Space Telescope* (HST) lightcurve observations of the *New Horizons* spacecraft encounter Kuiper Belt object (KBO) (486958) 2014 MU_{69} acquired near opposition in July 2017. In order to plan the optimum flyby sequence the *New Horizons* mission planners needed to learn as much as 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.

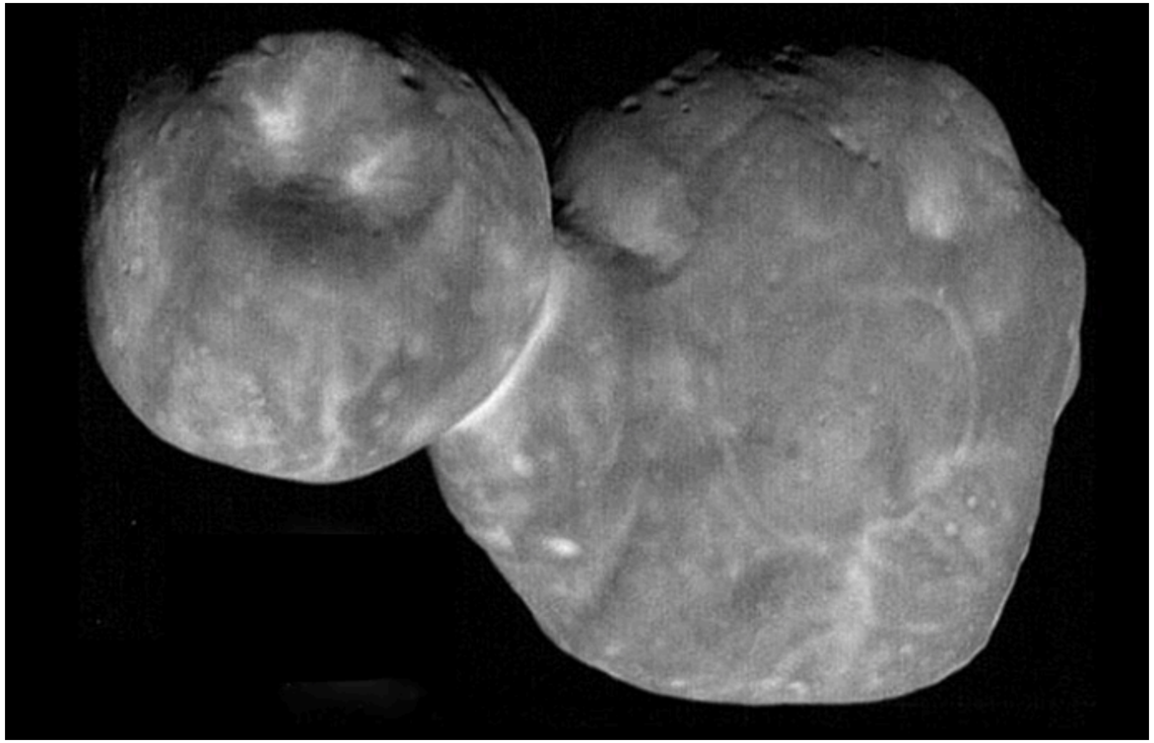
Occultation data suggests binary



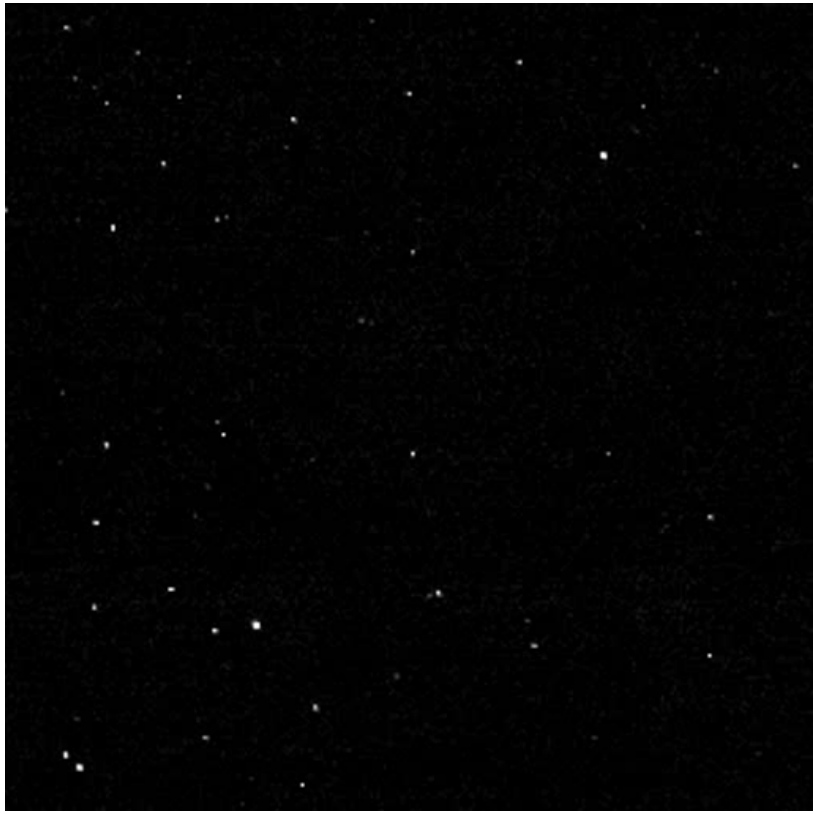


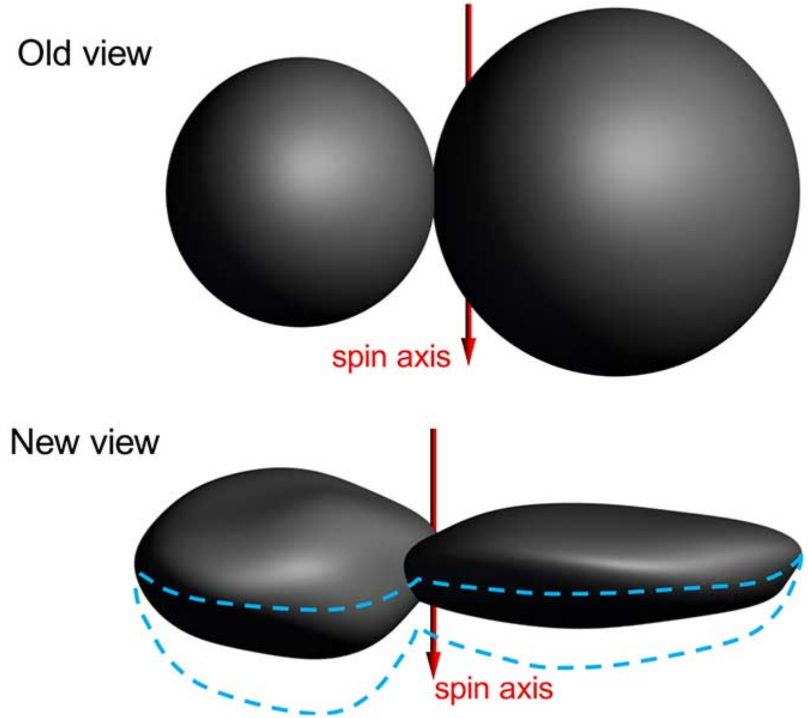
Approach sequence:
Contact binary at inclination 98 degrees



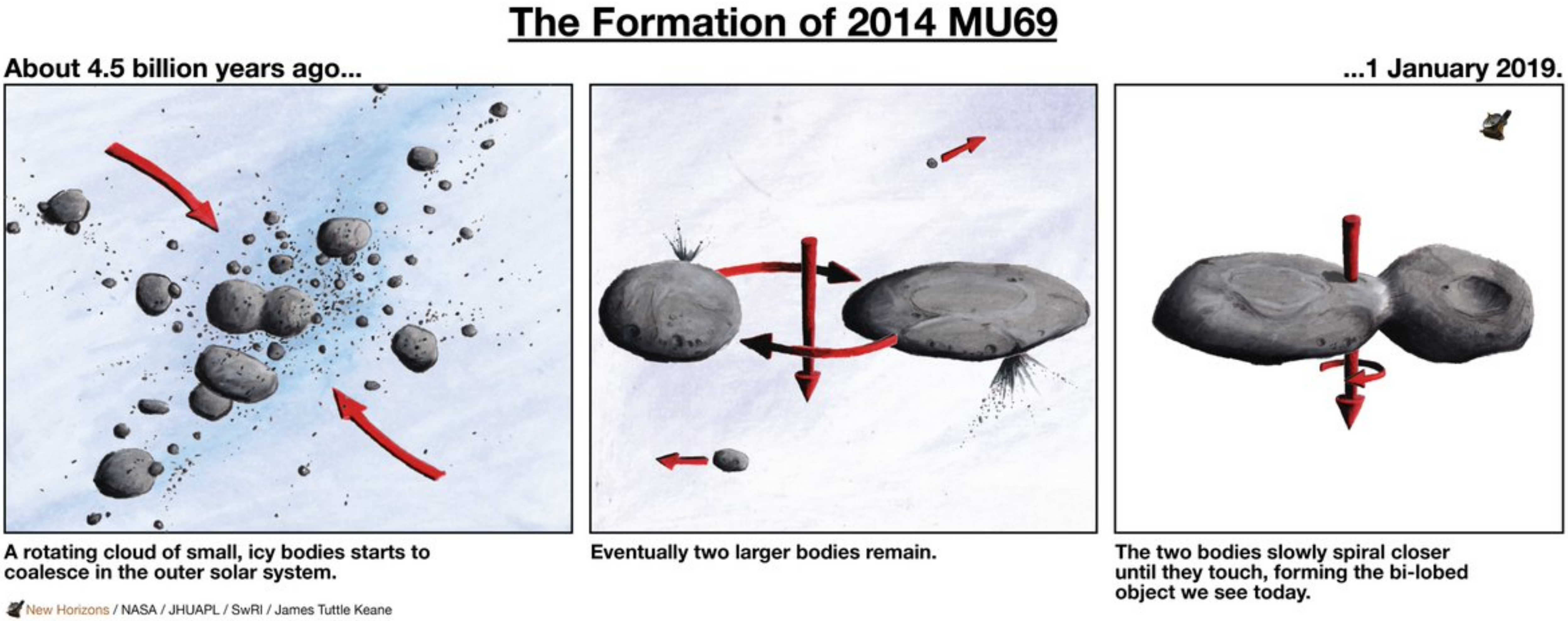


Departure sequence: Shape



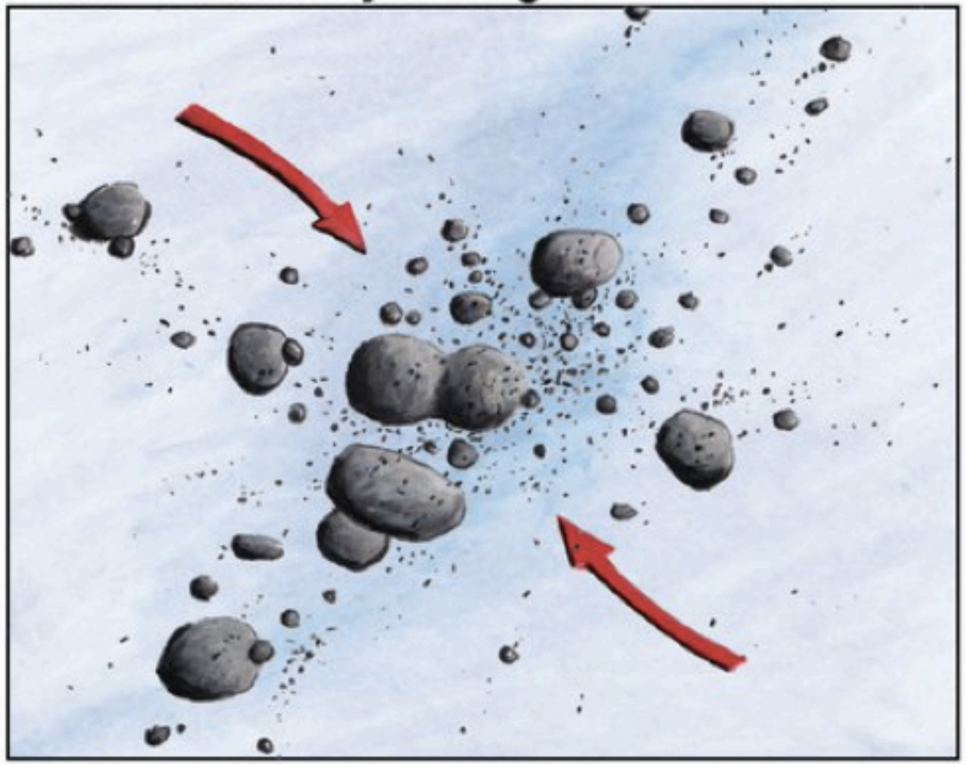


The Cartoon Image



Formation

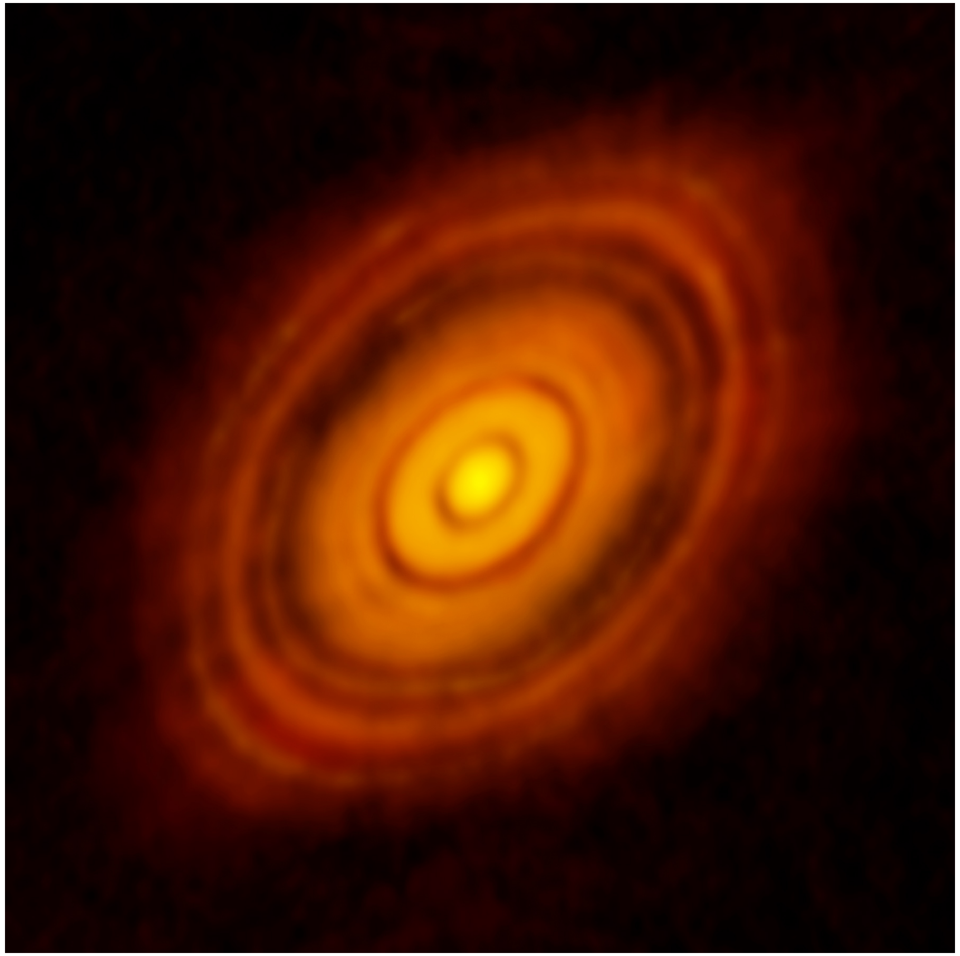
About 4.5 billion years ago...



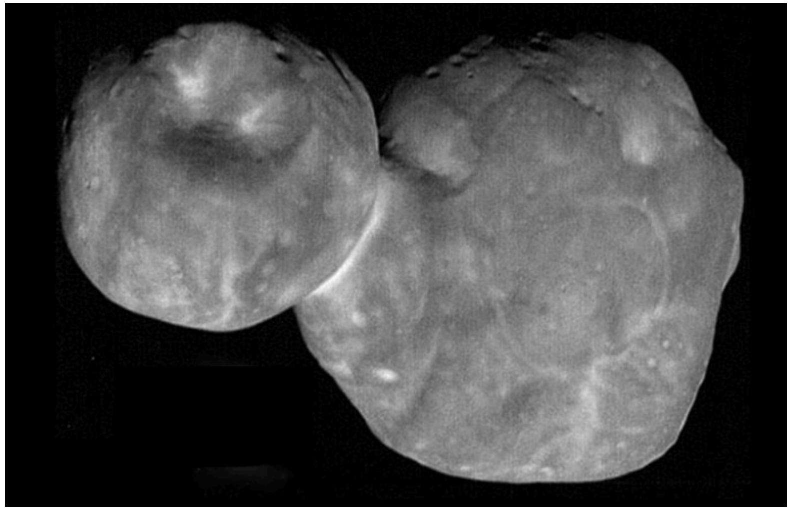
A rotating cloud of small, icy bodies starts to coalesce in the outer solar system.

Sketch by J.T. Keane

Beyond the cartoon image



How?



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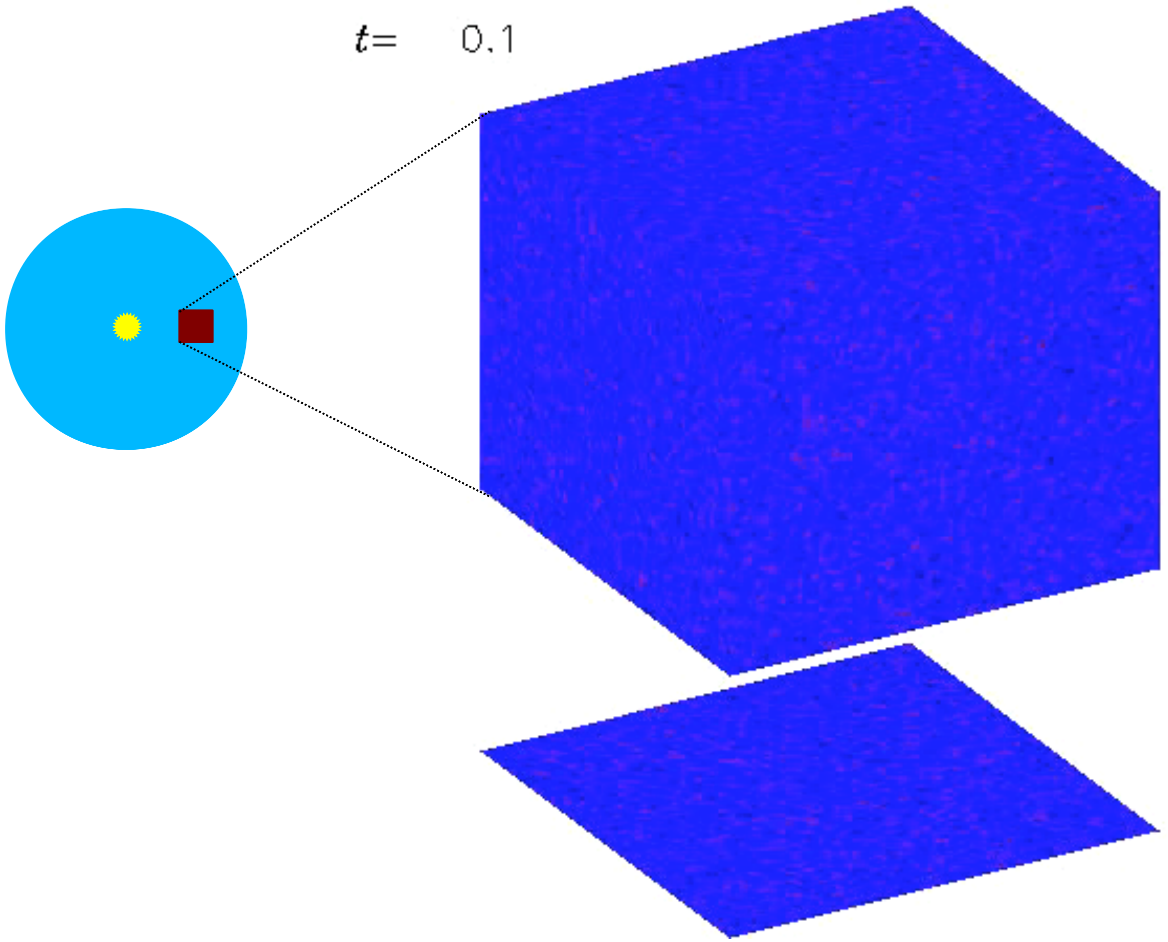
Streaming Instability

The dust drift is hydrodynamically unstable



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

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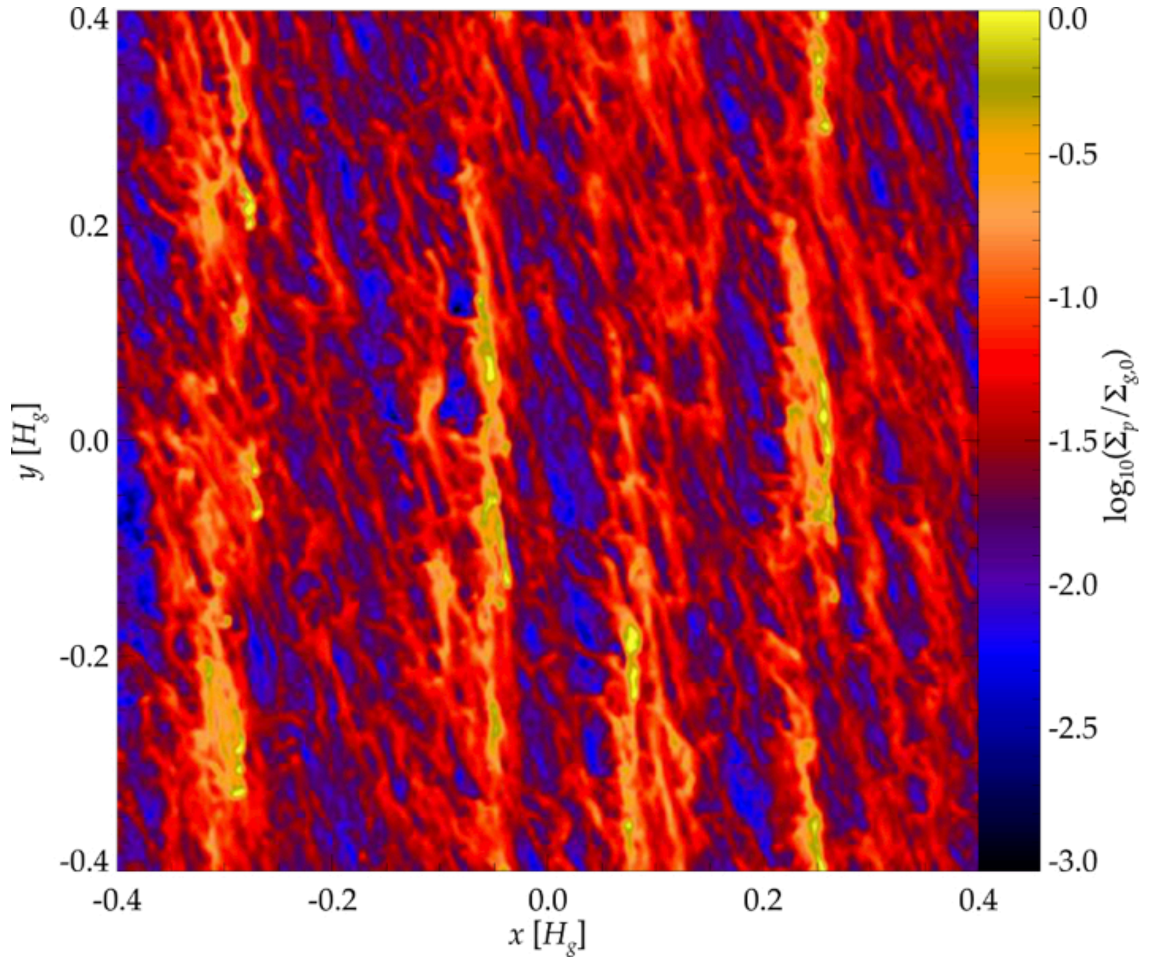
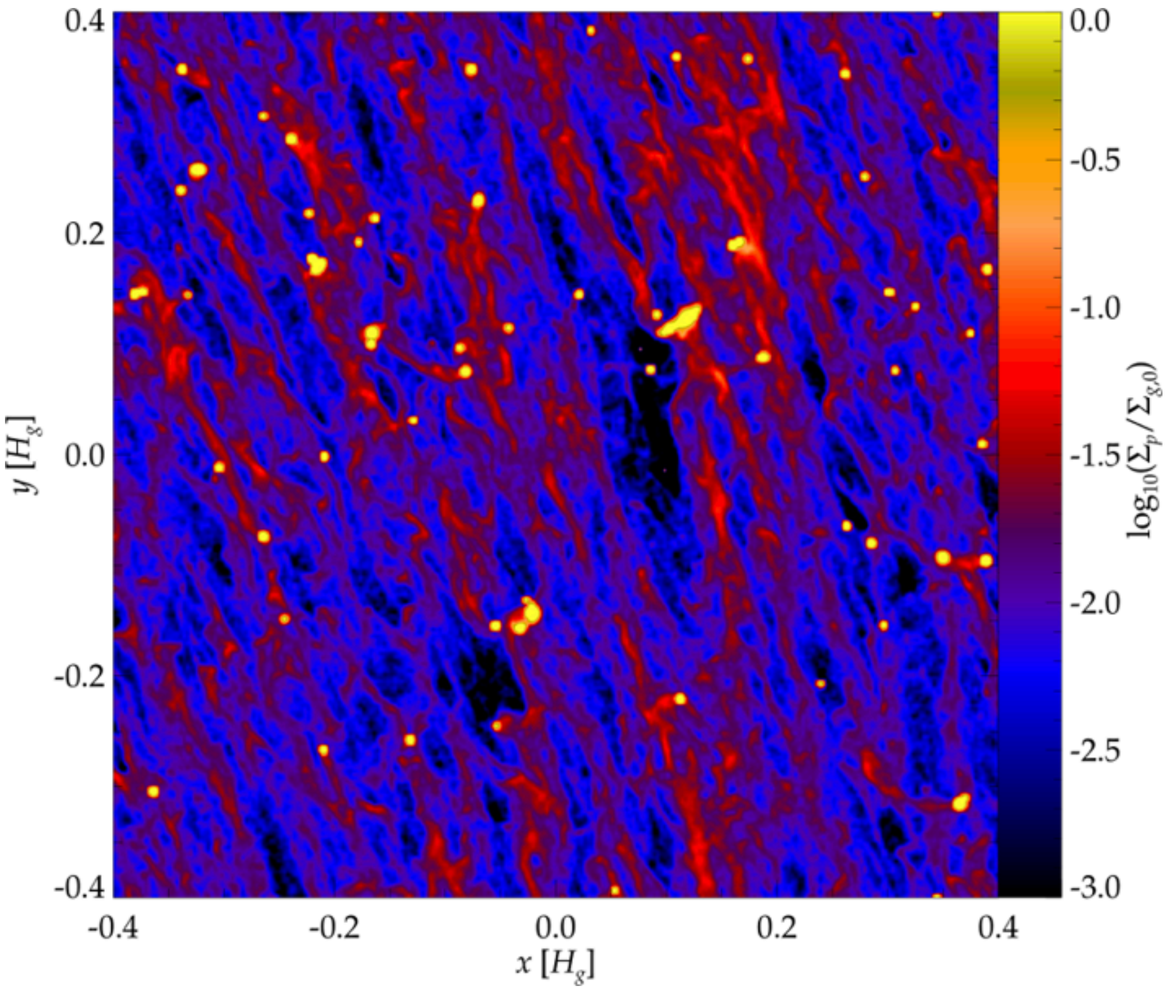
Planetesimal Formation





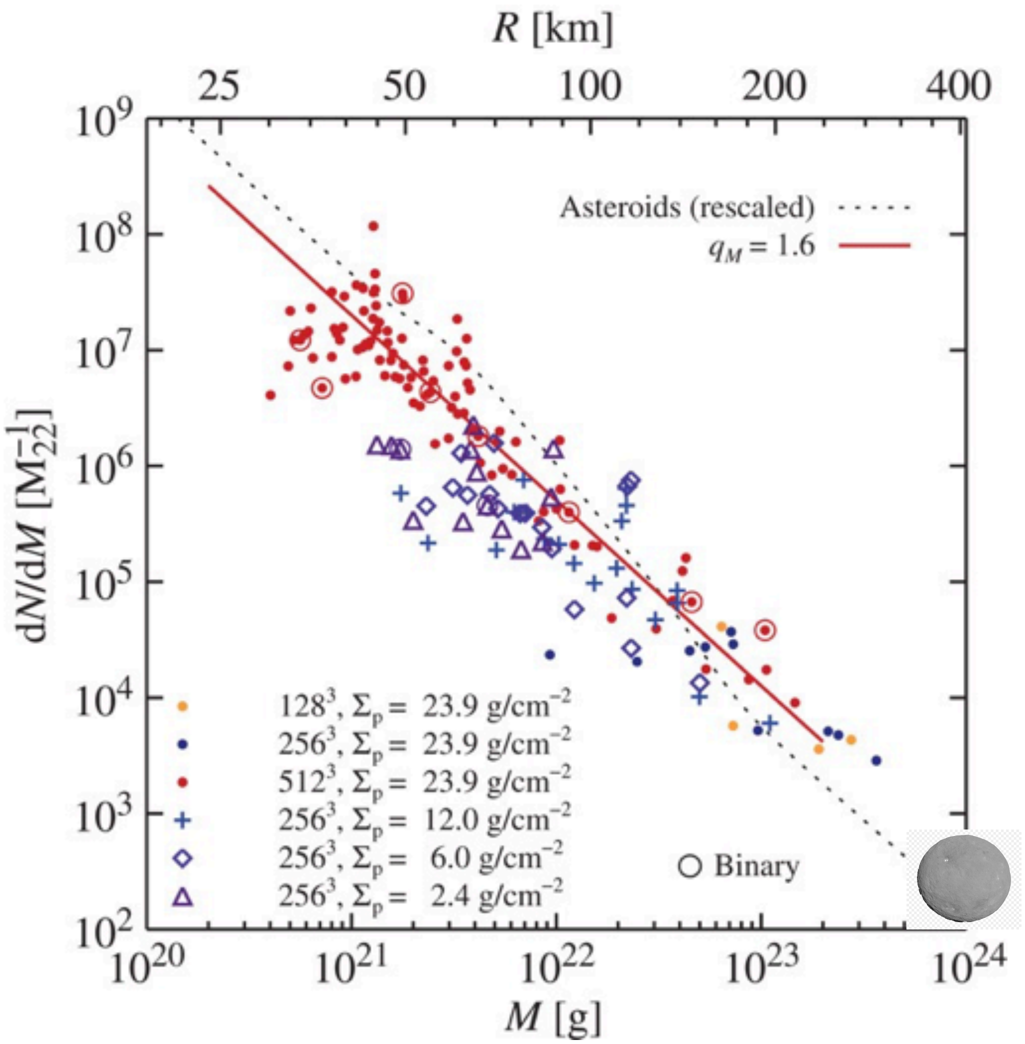
Emergence of zonal flows

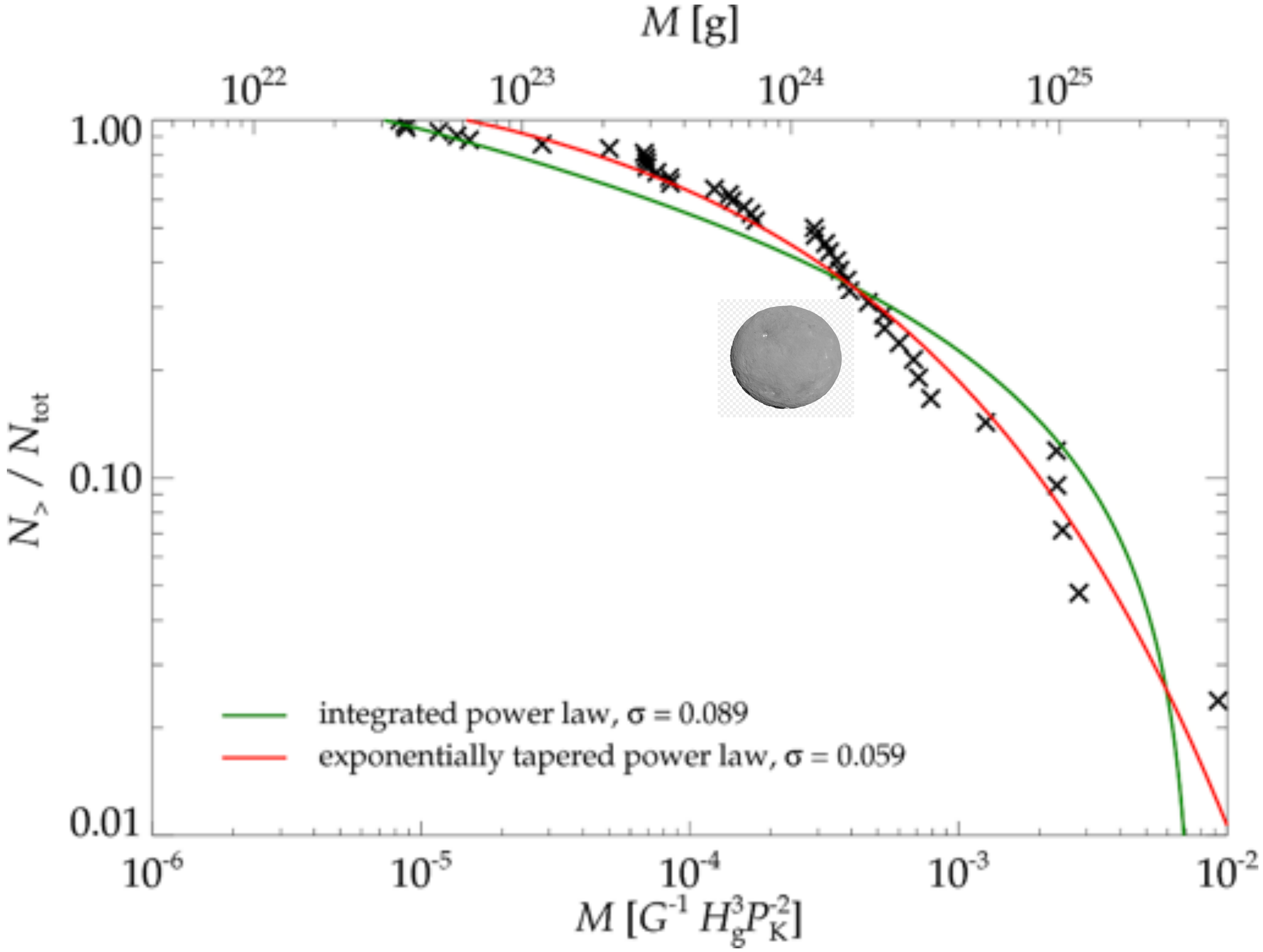
Larger planetesimals: planetary embryos formed

Yang & Johansen (2014); Schäfer, Yang, & Johansen (2017)

Adapted from slide by Chao-Chin Yang

Planetesimals' Initial Mass Function



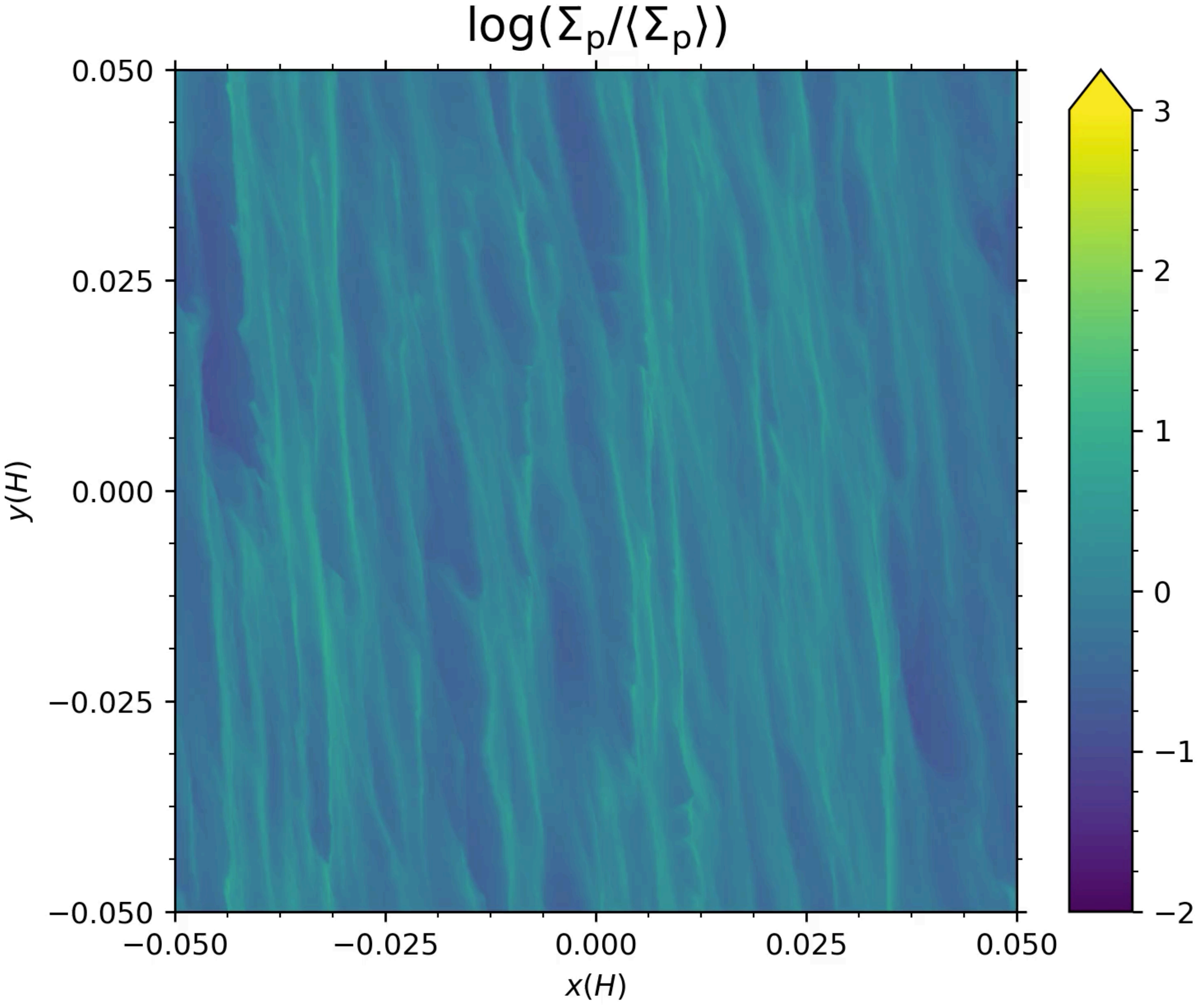


Convergence with resolution; slope 1.6

Johansen et al. (2015), Schäfer et al. (2017)

Adapted from slide by Chao-Chin Yang

In the lookout for binaries



Nesvorny+'19, model by Rixin Li

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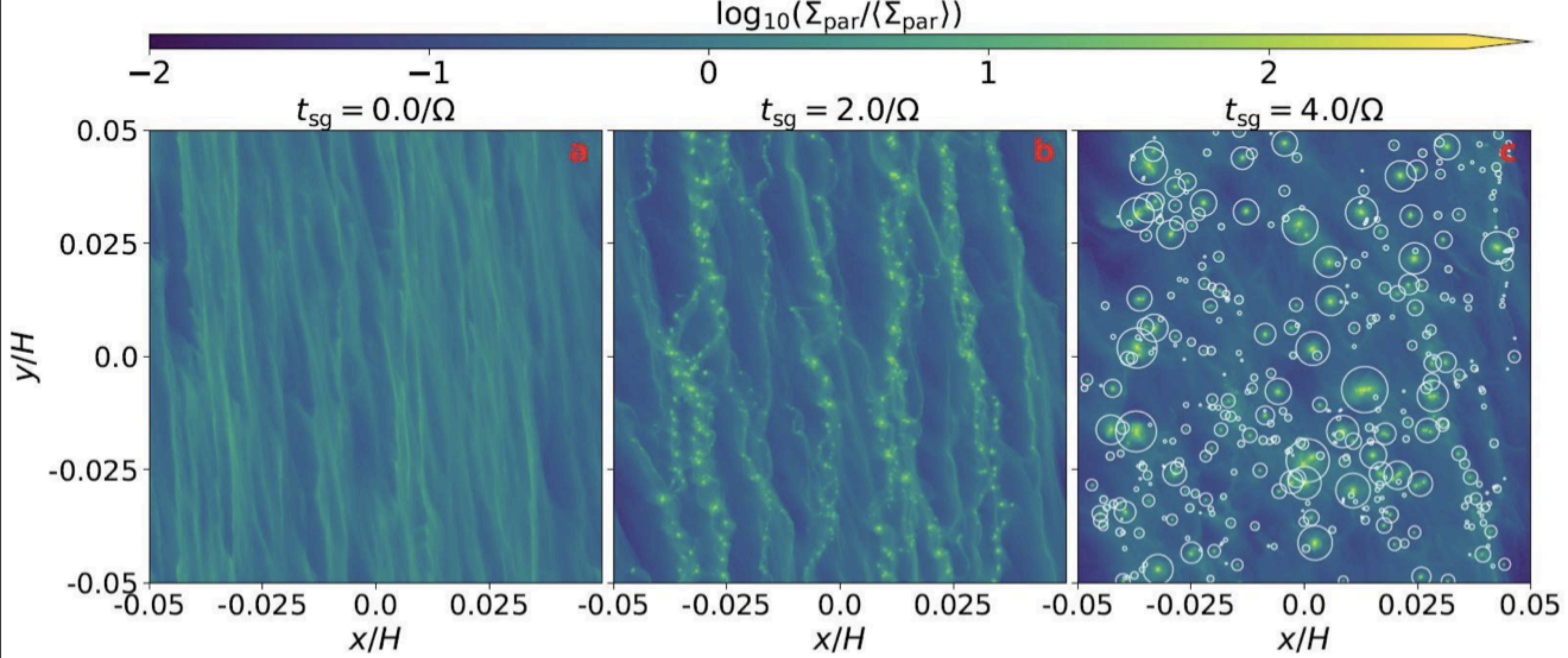
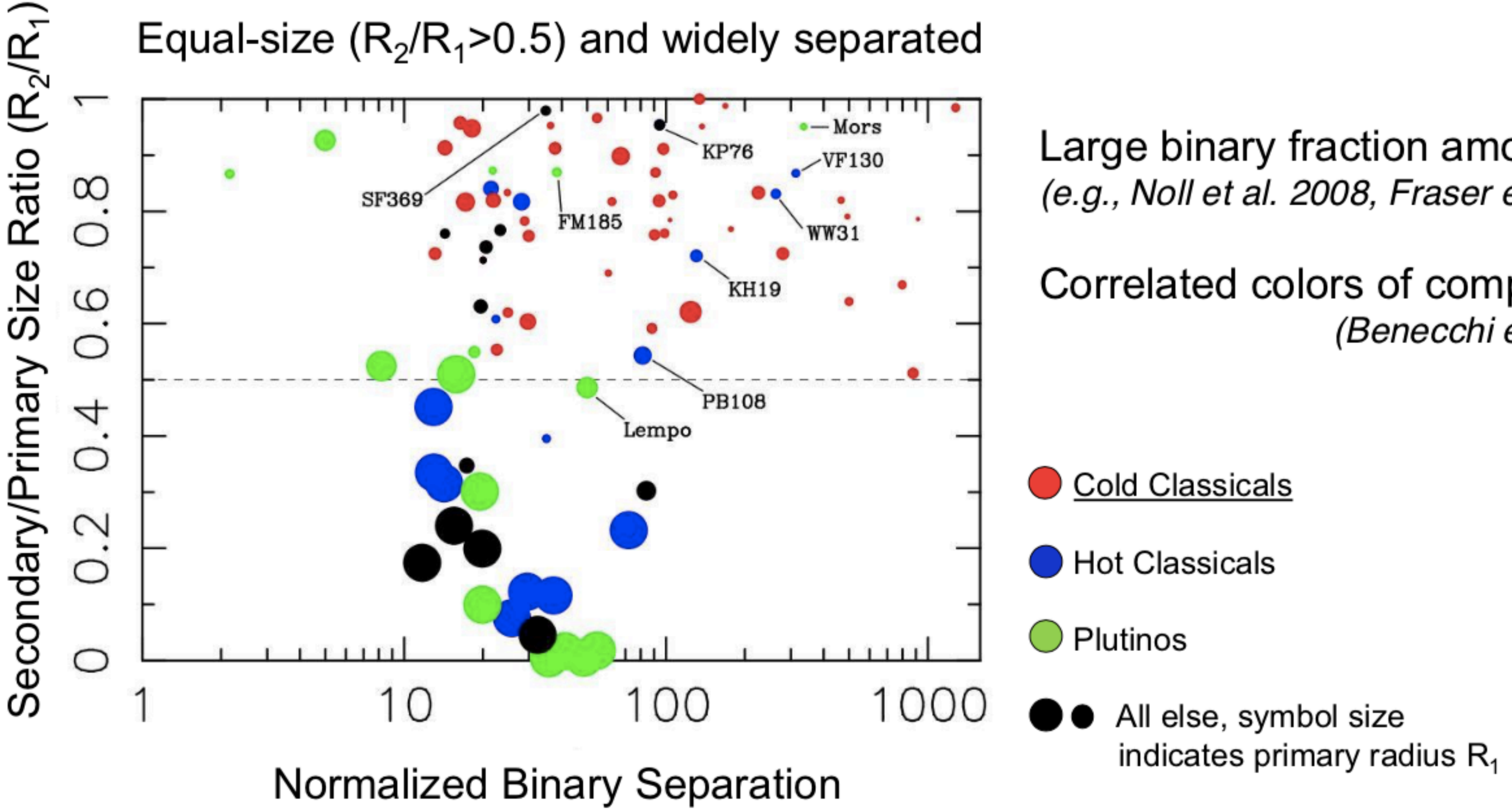
Filaments form and fragment into gravitationally bound clumps



Nesvorny+'19

Slide by David Nesvorny

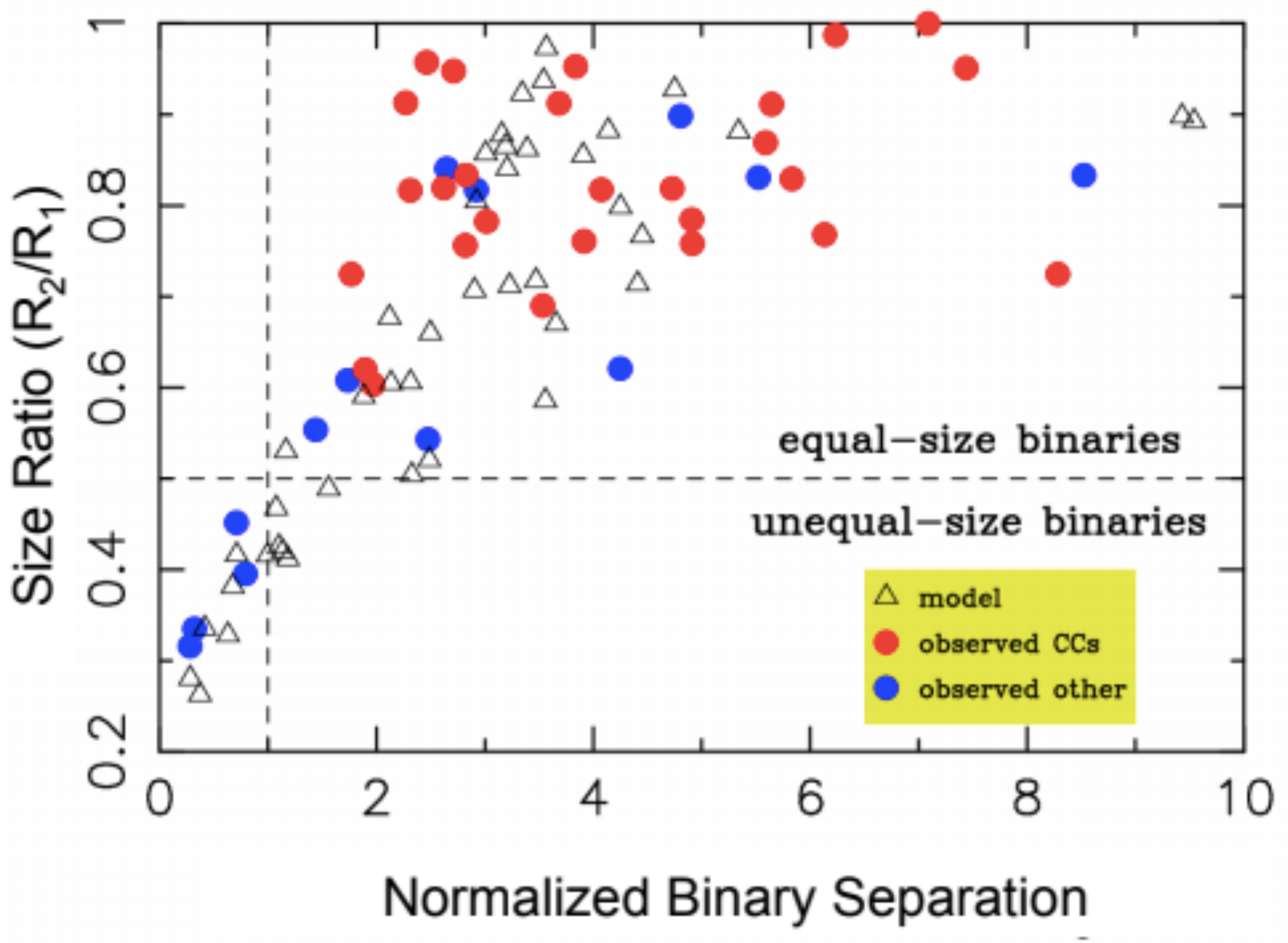
Cold Classical Binaries



Large binary fraction among CCs
(e.g., Noll et al. 2008, Fraser et al. 2017)

Correlated colors of components
(Benecchi et al. 2011)

Cold Classicals



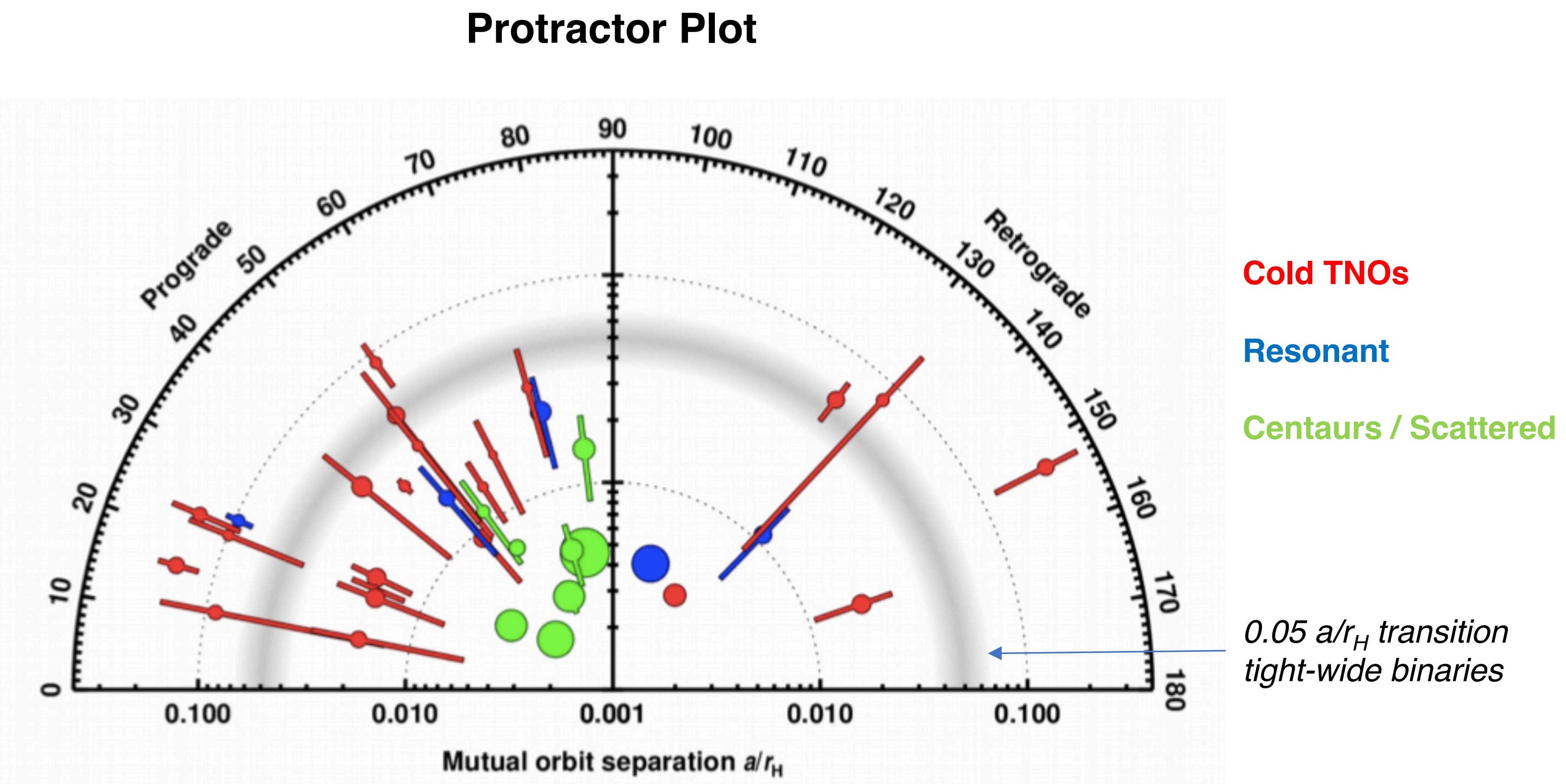
Nesvorny+'19

Ultima Thule is retrograde

Obliquity is ~98^{o}

Sketch by J.T. Keane

Angular Momentum: Prograde vs Retrograde



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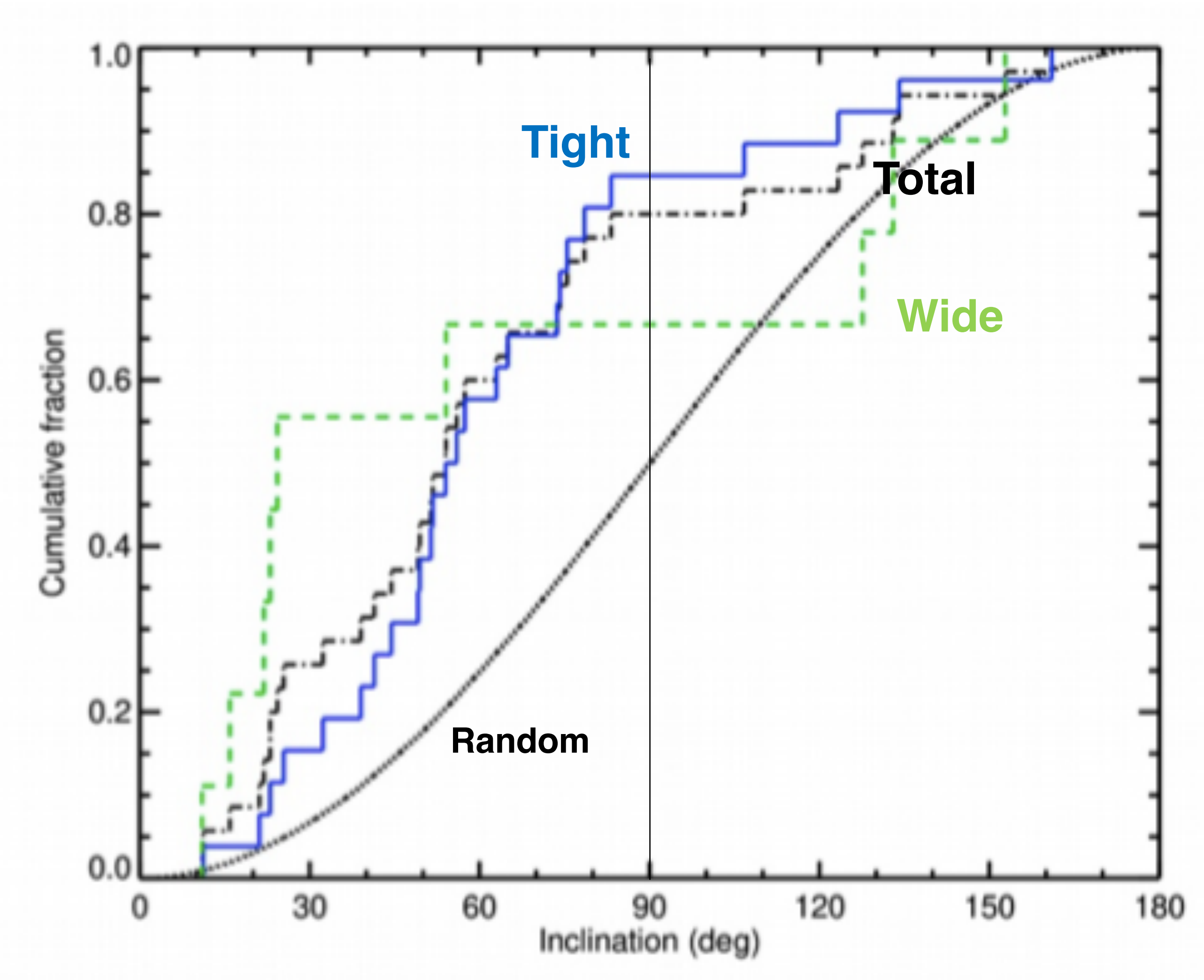
Noll+08, Grundy+19, Nesvorny+19

Angular Momentum: Prograde vs Retrograde

~80% of TNO binaries are prograde



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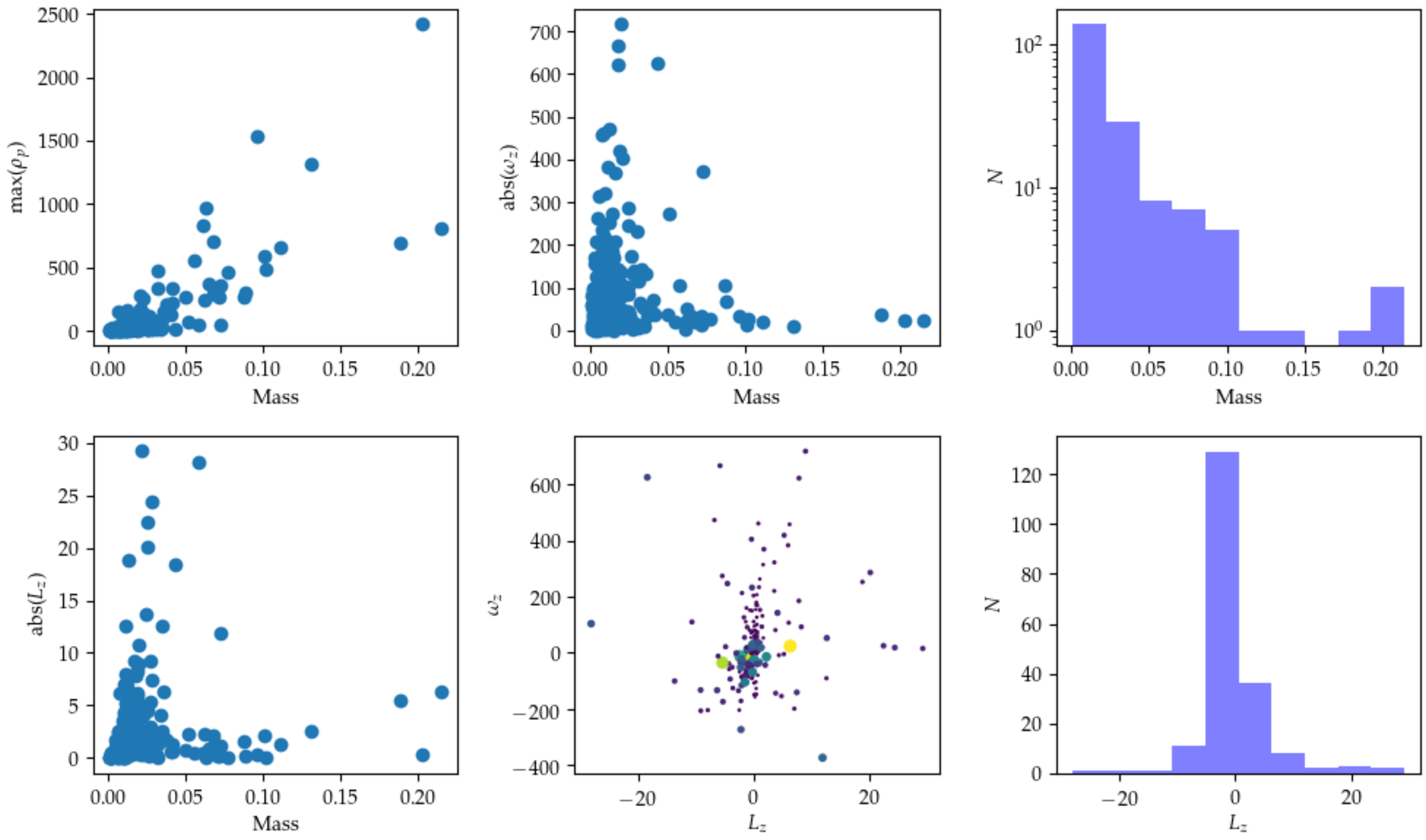
Grundy+19, Nesvorny+19

Simulation results from YJ14



Data from Yang & Johansen (2014)

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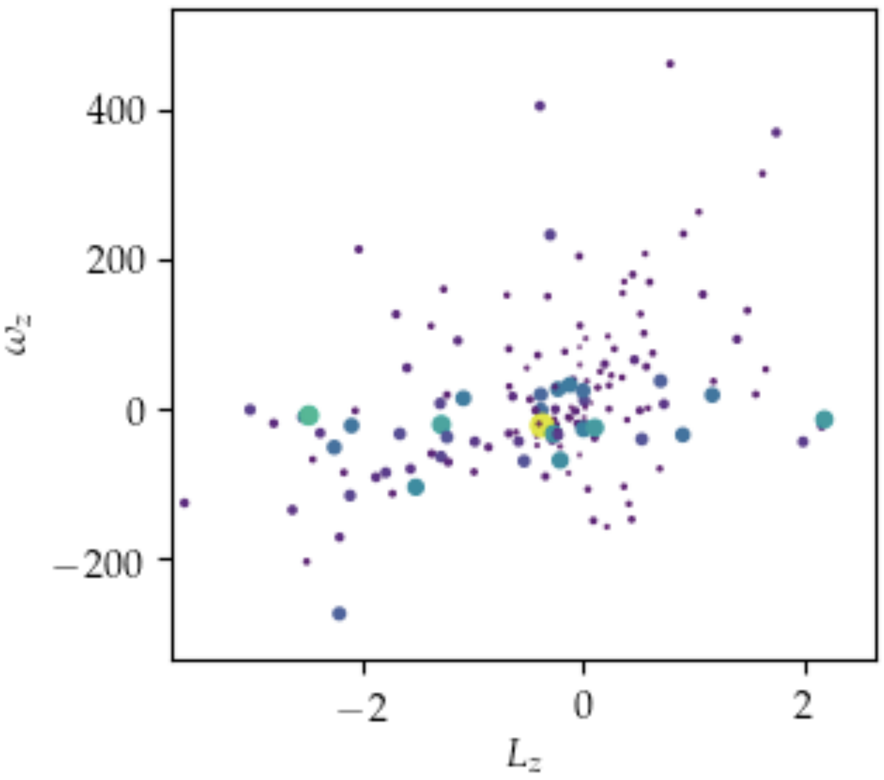
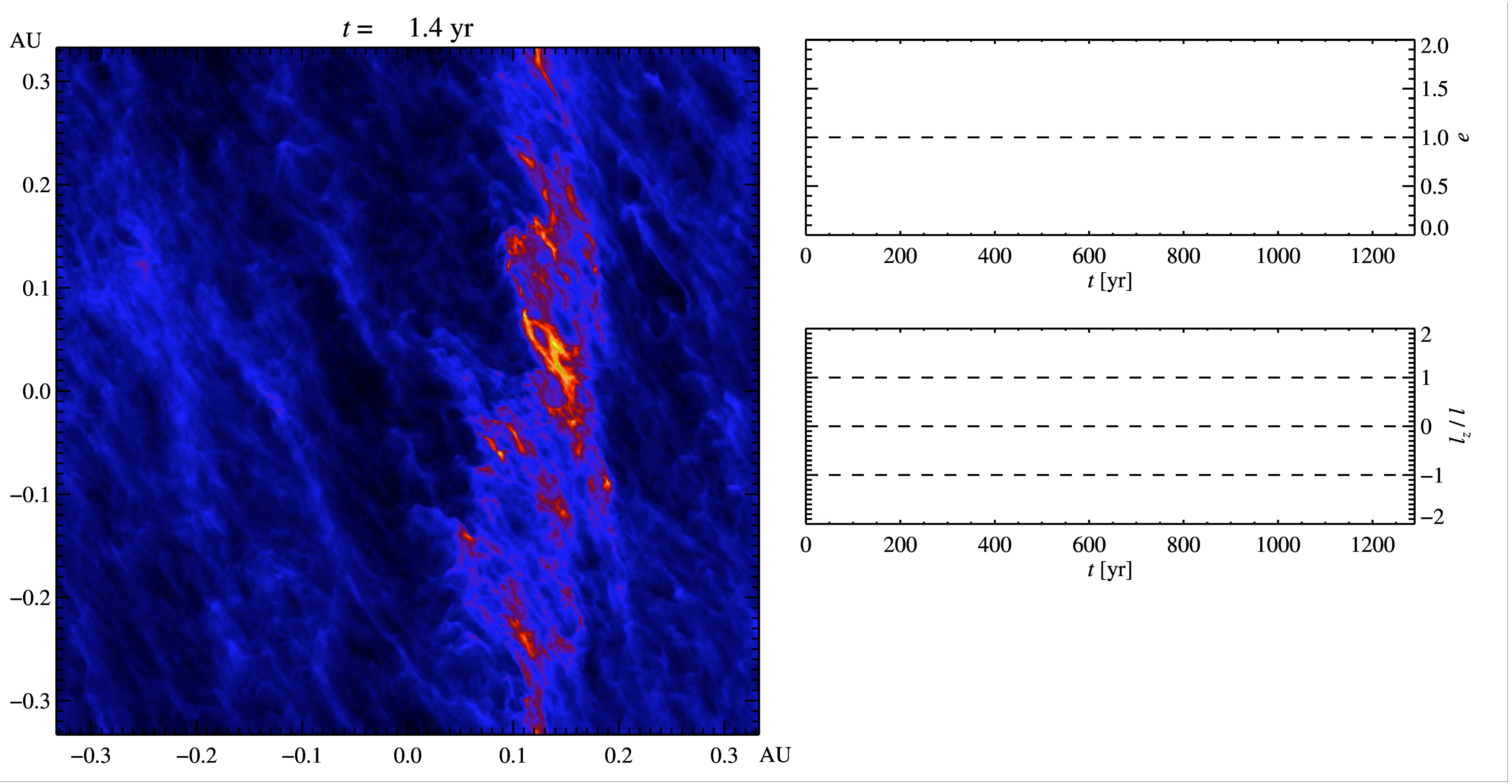
Gas vorticity and clump angular momentum



No strong correlation
No preference for prograde or retrograde

Data from Yang & Johansen (2014)

Effect of Gravity: Preference for Prograde (~80%)



Data from A. Johansen (private communication)

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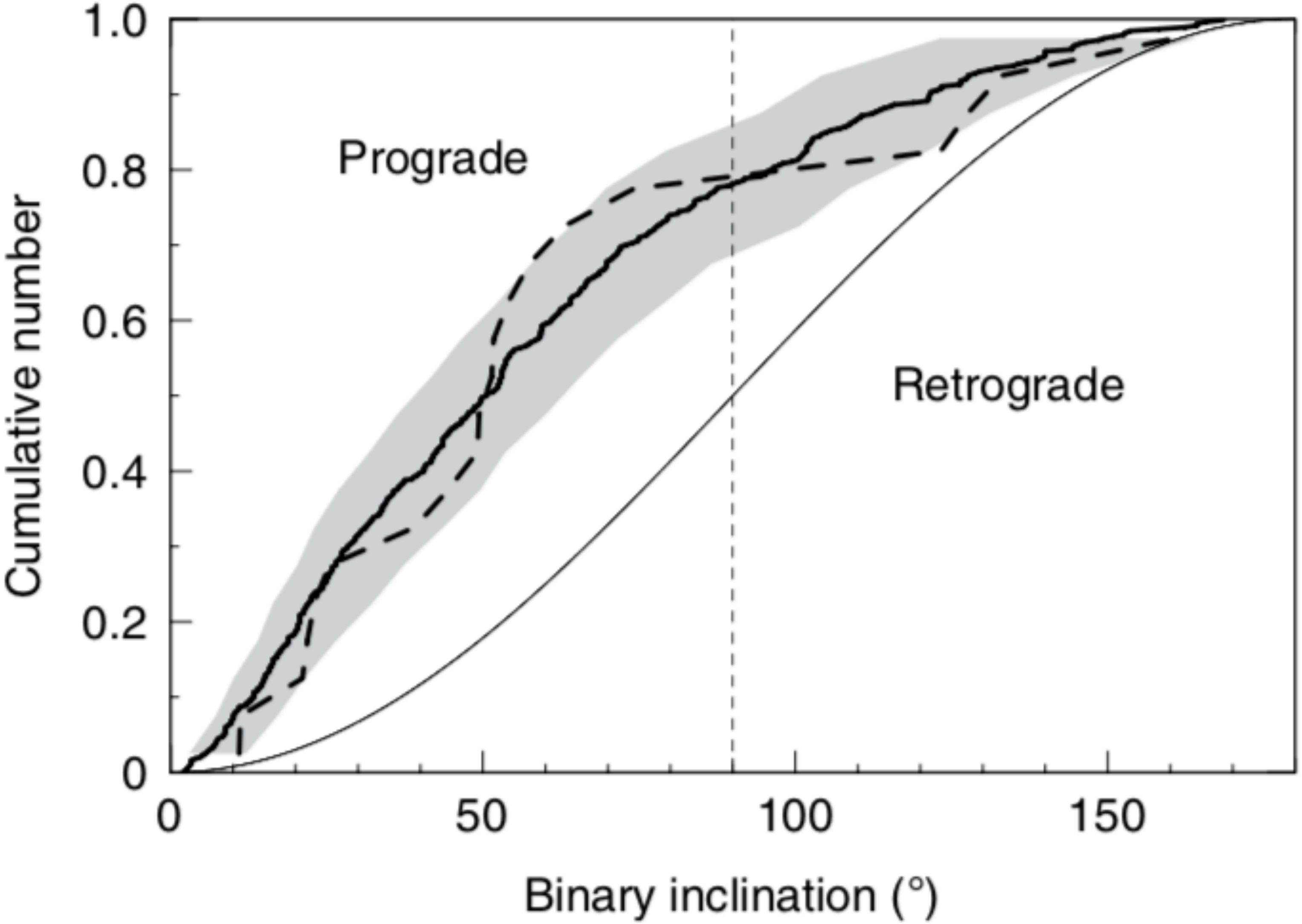
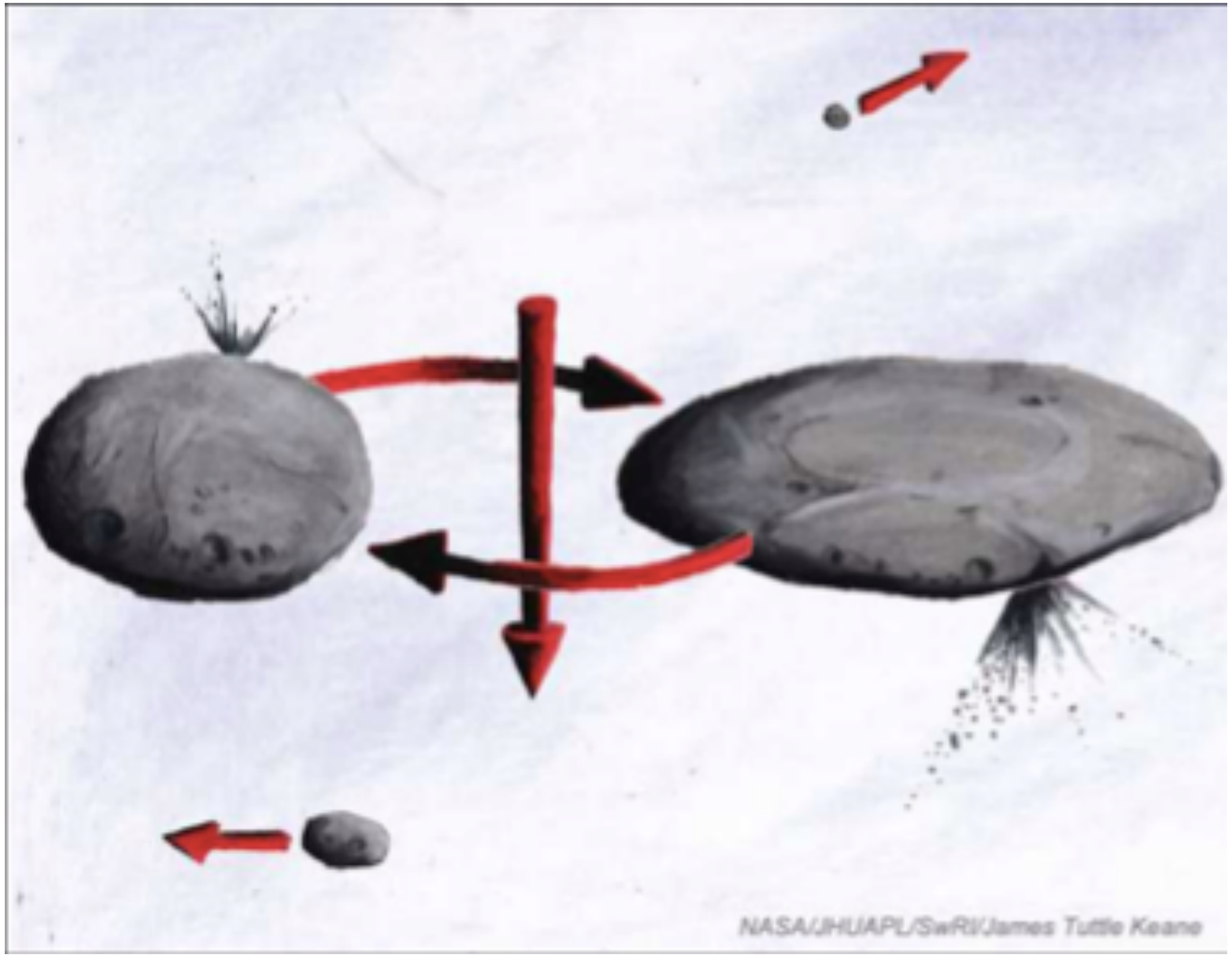
Preference for Prograde (~80%)



SI Model (solid)
KBOs (dashed)

Nesvorny+19

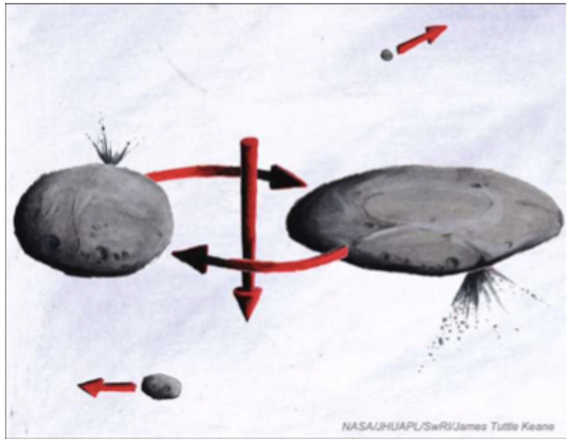
Hardening



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.

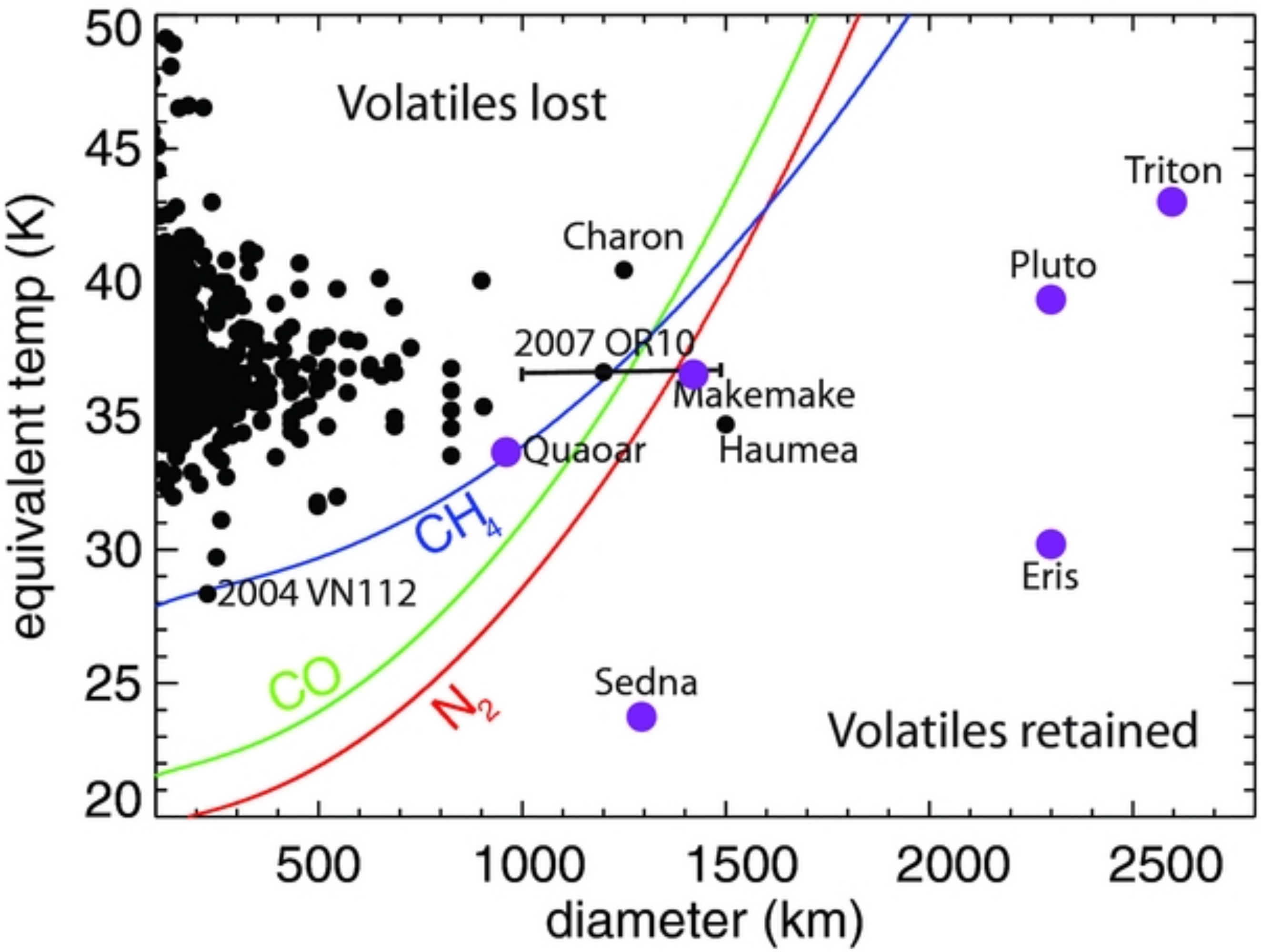
Slow merger
(~ 2 m/s: human walking speed)

Inferred from:
Negligible evidence for impact damage

Sputnik Planitia –N_2 frost

Retention of volatiles

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



MU69 equilibrium temperature ~ 40K

N_2 should be gone too early
unless temperature is kept under 20K

Needs shielding from starlight!!

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Brown, Burgasser, & Fraser (2011); Lisse'+19

Retention of volatiles

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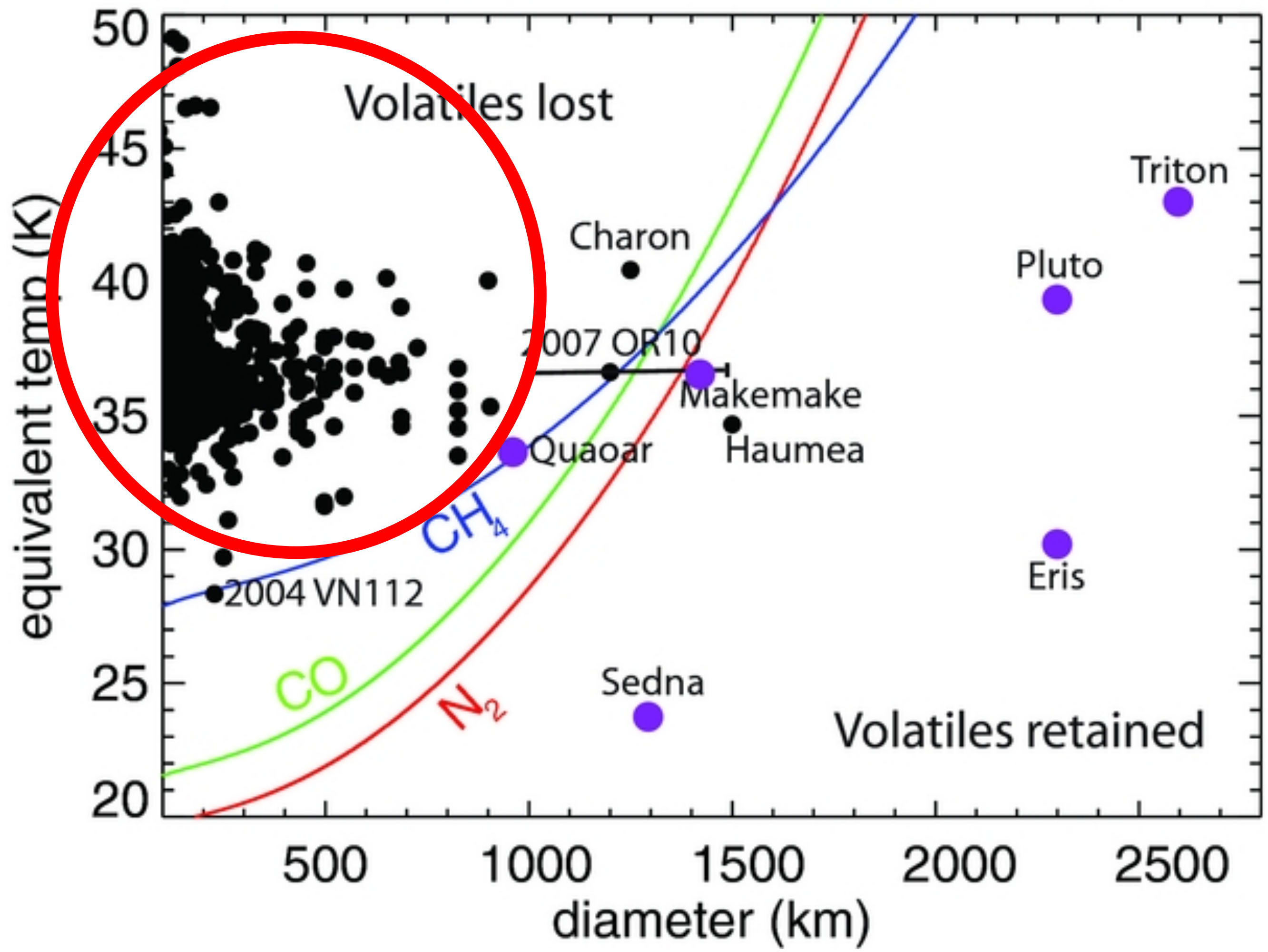
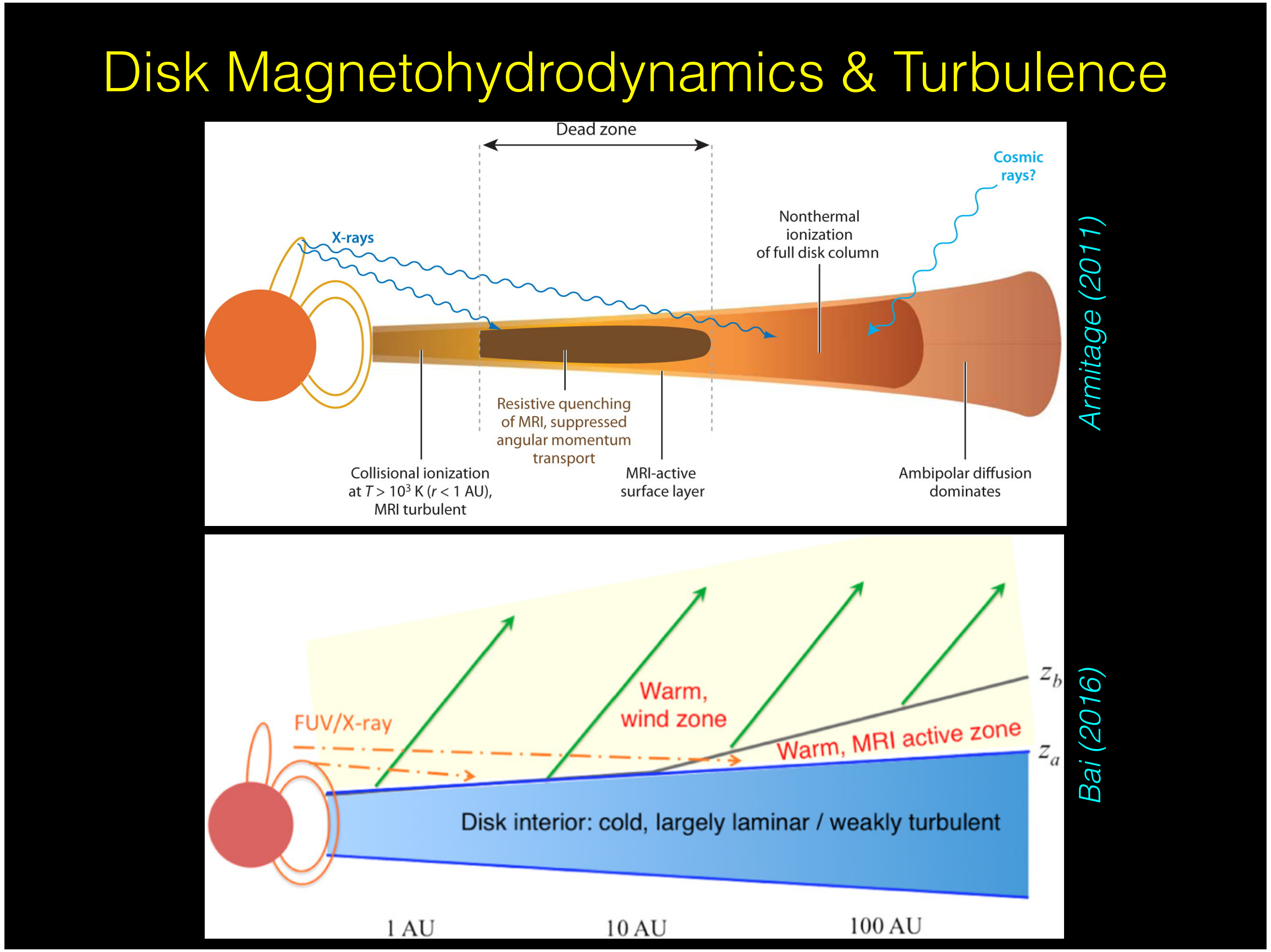


Needs shielding from the starlight flambé.

Brown, Burgasser, & Fraser (2011); Lisee+'19

Retention of volatiles



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

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Slide by
Chao-Chin Yang

Angular momentum loss via nebular drag

gravity

drag

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

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

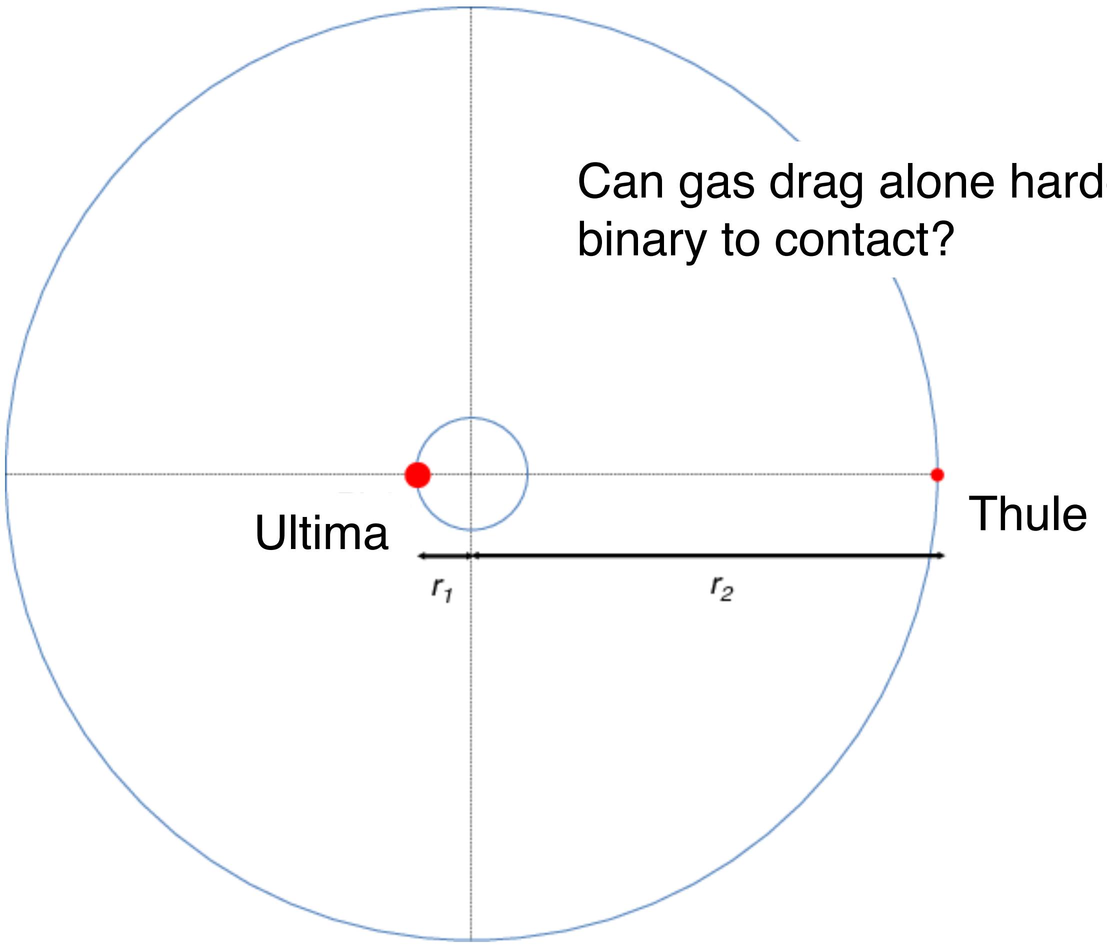
For equal mass:

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

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

Exponential decay of angular momentum !

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



Lyra+ in prep

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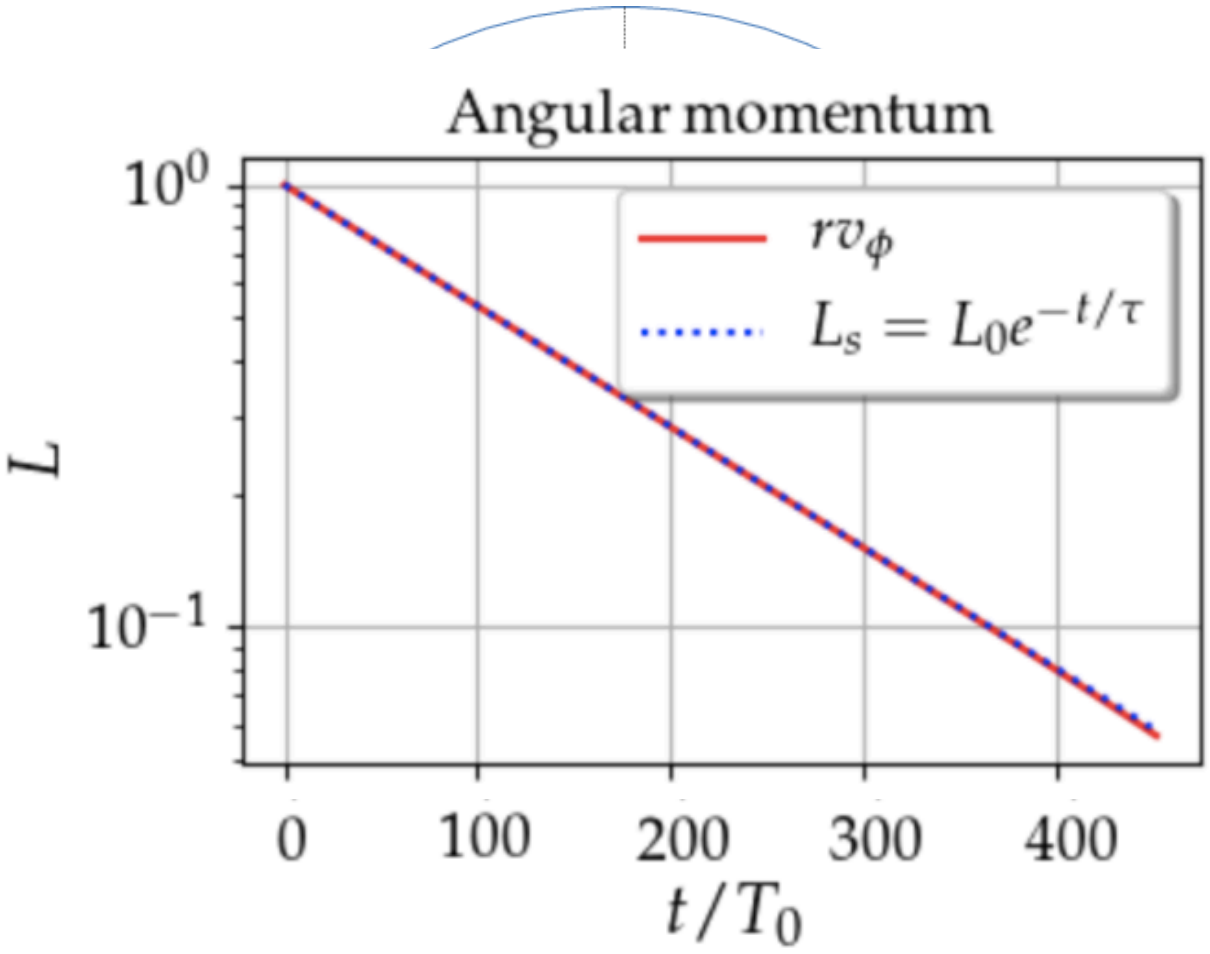


Hardening during disk lifetime

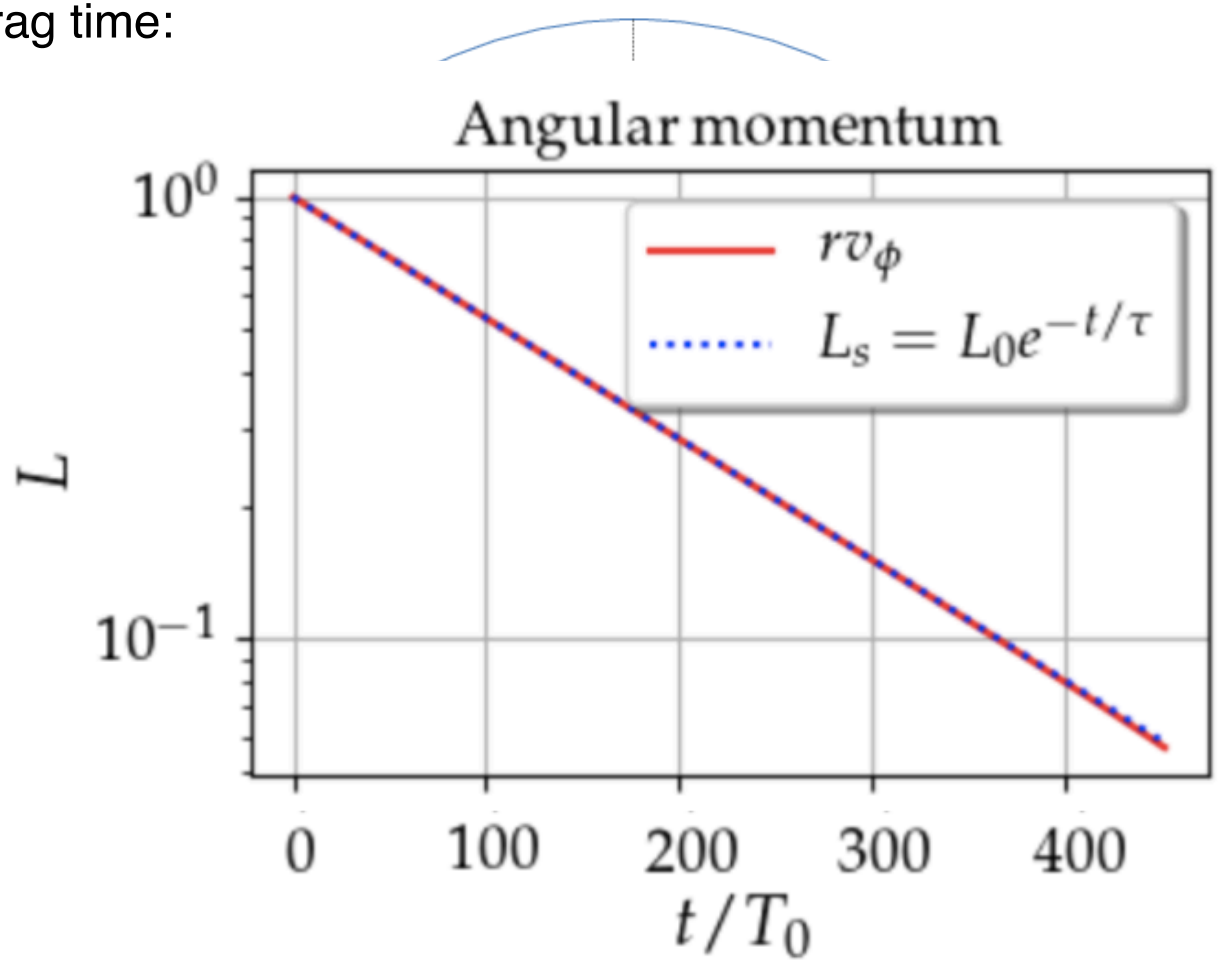
For unequal mass the physics is similar, the drag time is just replaced by an effective drag time:

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

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



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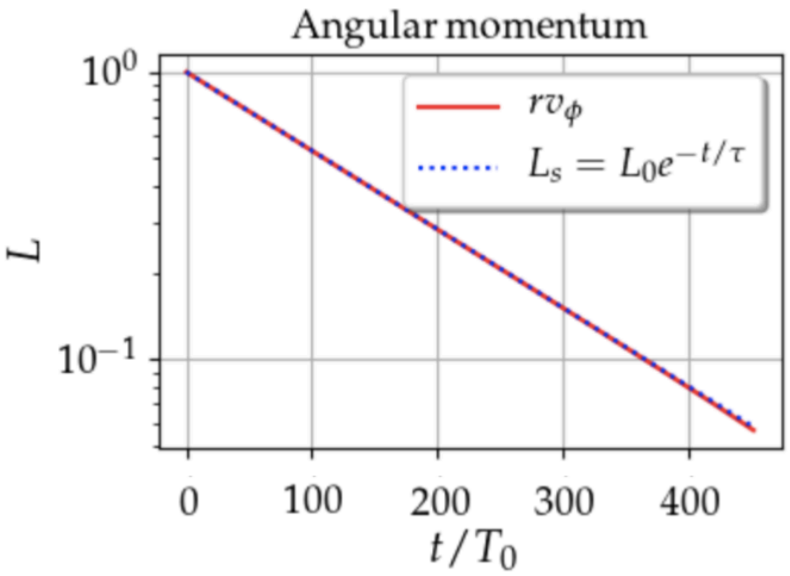
Analytical solution

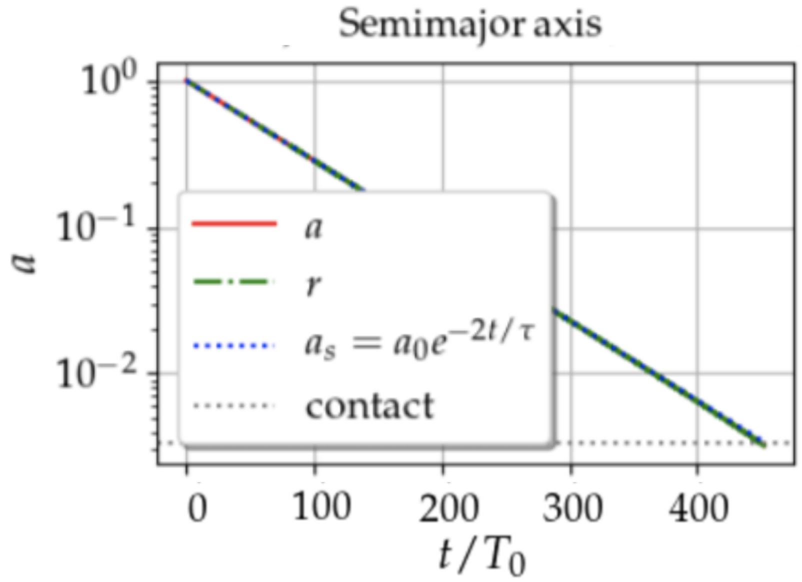
Exponential decay of angular momentum

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



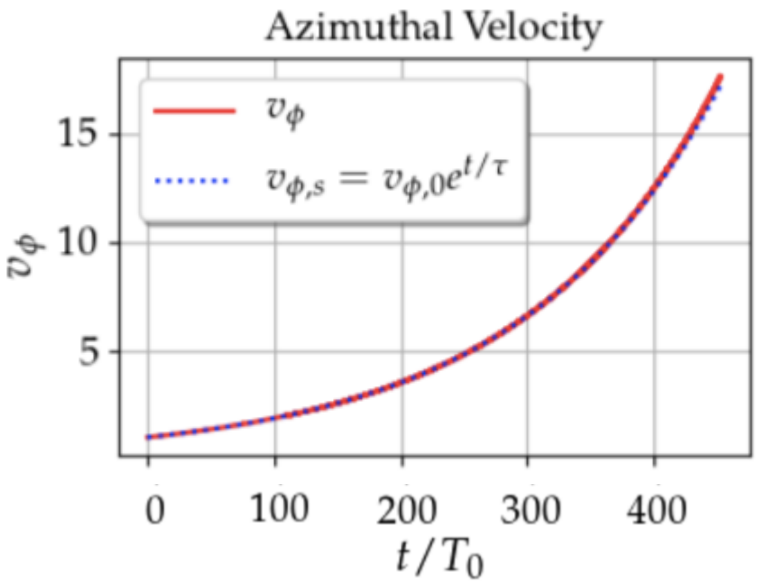
Exponential decay of semimajor axis

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

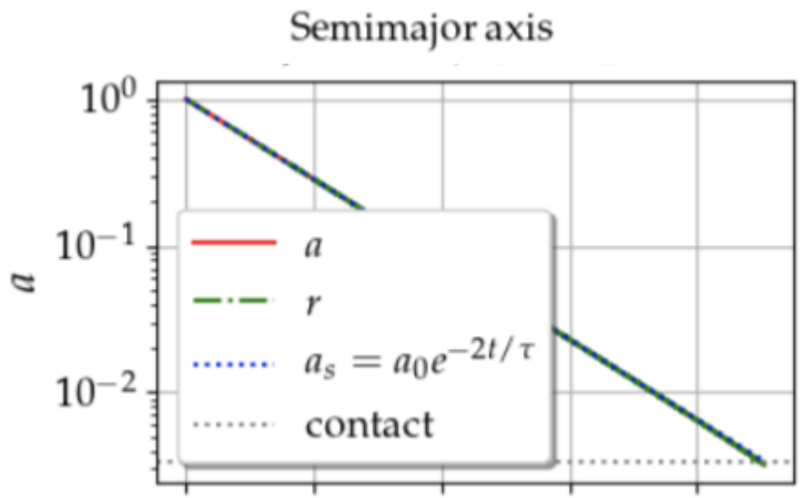


Exponential increase of orbital velocity

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



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 …

$t \sim 100$ Myr

Lyra+ in prep

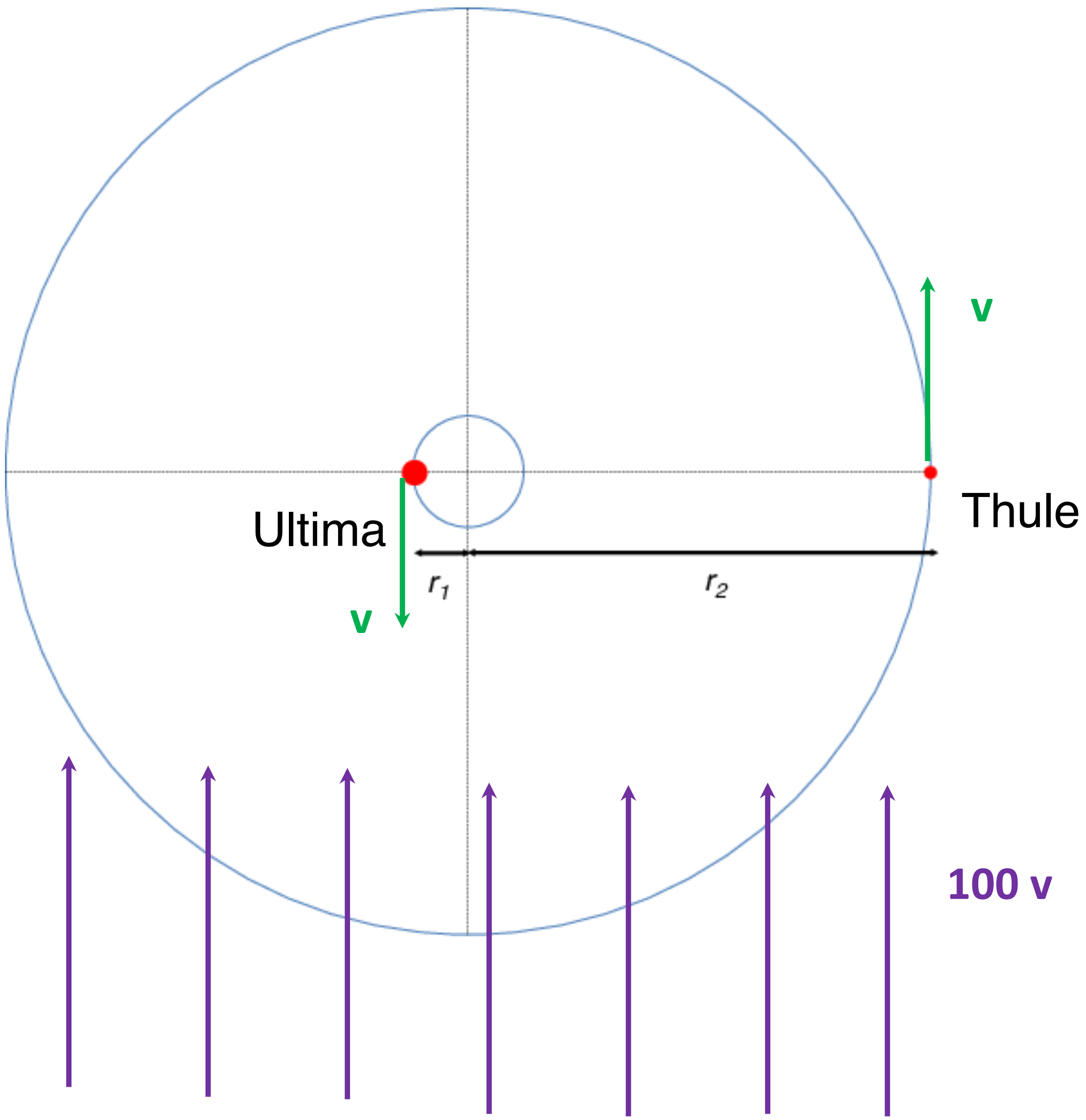
Wind

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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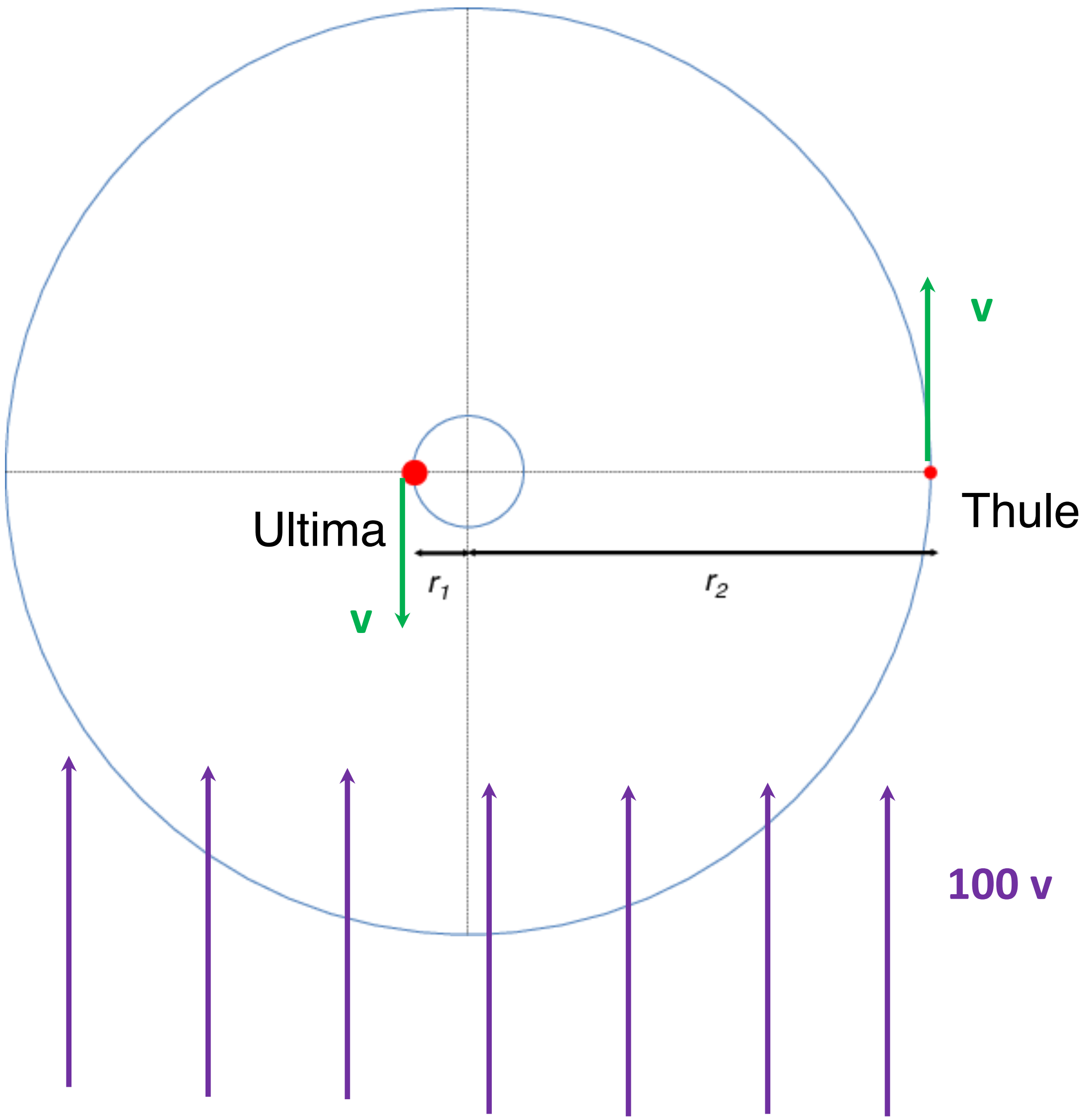
Subkeplerian wind on the binary
= 100 times orbital velocity

$$\frac{d\langle a\rangle}{dt} = -\frac{2\langle a\rangle}{\tau}$$

$$\frac{d\langle e\rangle}{dt} = \sqrt{\langle a\rangle\,\mu^{-1}(1-\langle e\rangle^2)}\,\frac{3u}{2\tau}$$

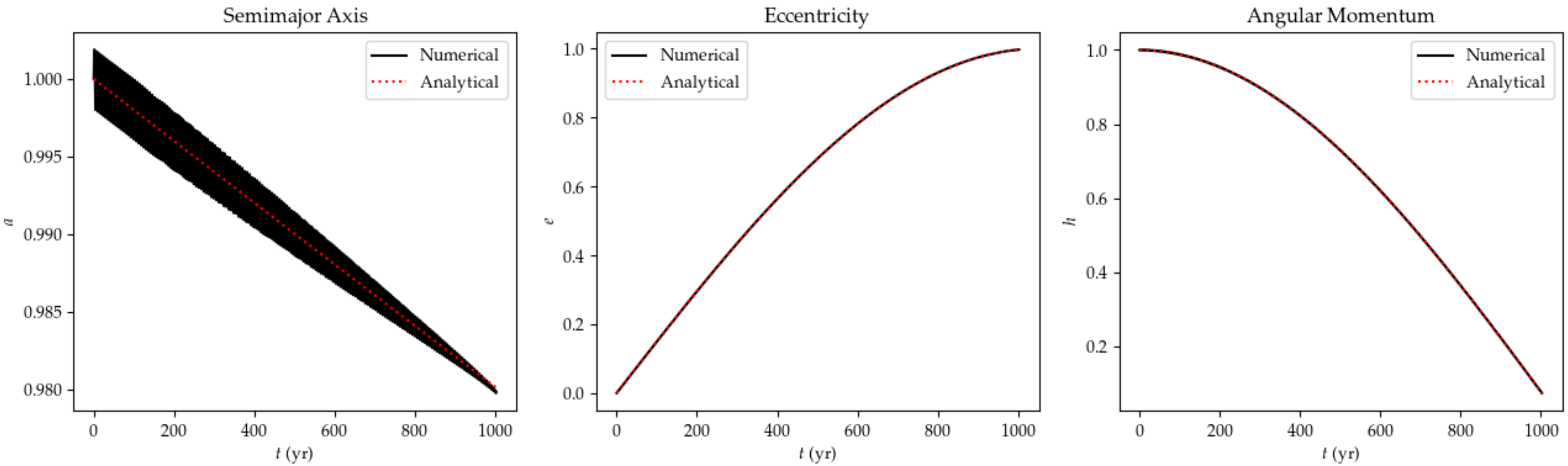
$$\frac{d\langle h\rangle}{dt} = -\frac{\langle h\rangle}{\tau} - ae\frac{3u}{2\tau}$$

Wind



Lyra+ in prep

Wind solution

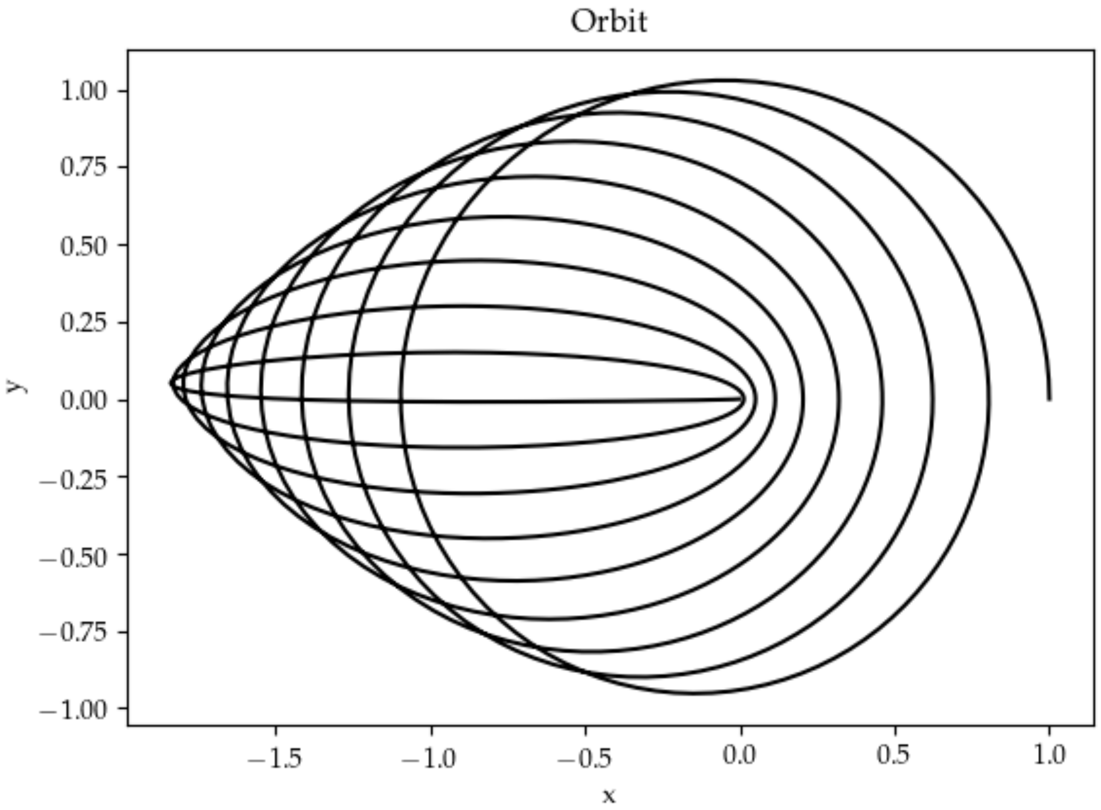


$$\langle a(t)\rangle = a_0 e^{-2t/\tau}$$

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

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

Wind solution



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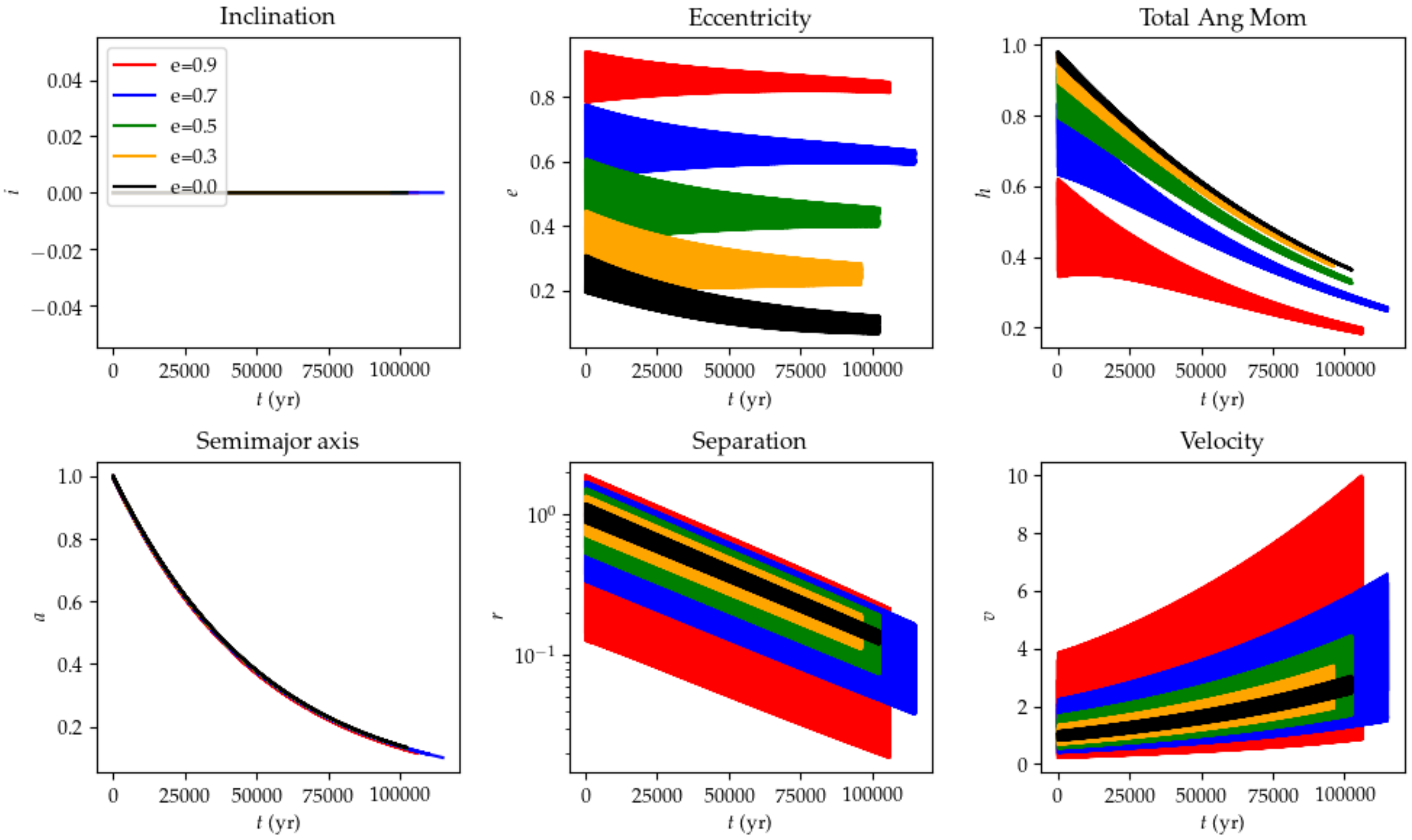
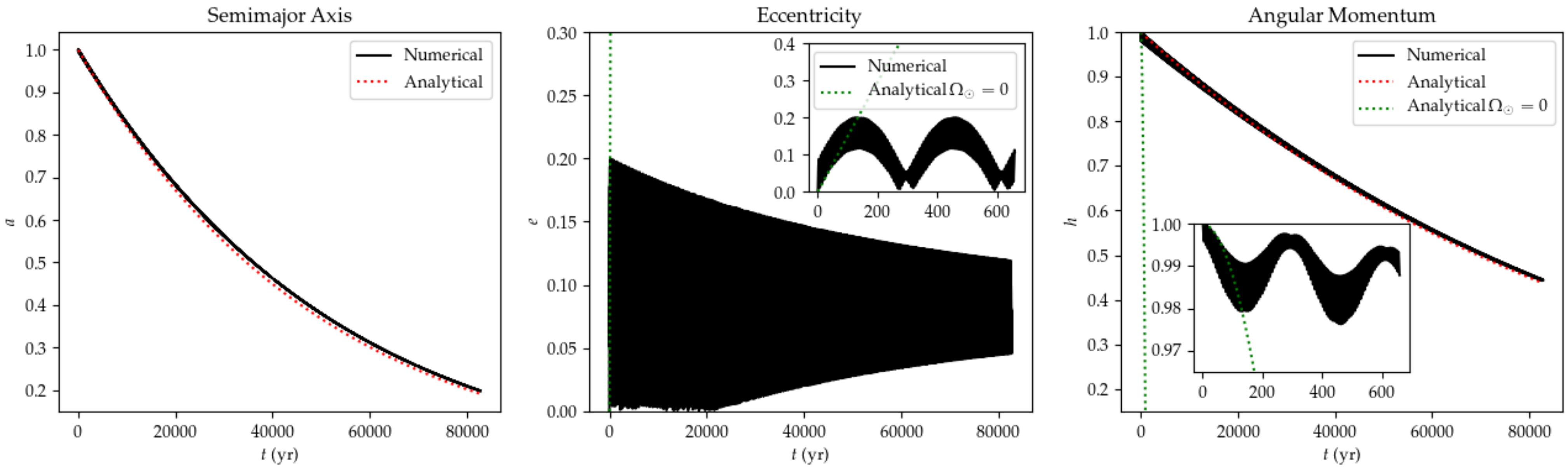
$$\langle h(t)\rangle = e^{-t/\tau}\left\{h_0 - 1 + \cos\left[\frac{3}{2}a_0 u\left(1 - e^{-t/\tau}\right)\right]\right\}$$

Coriolis force



Coriolis force – "Precession"

$u \rightarrow u \cos \omega$



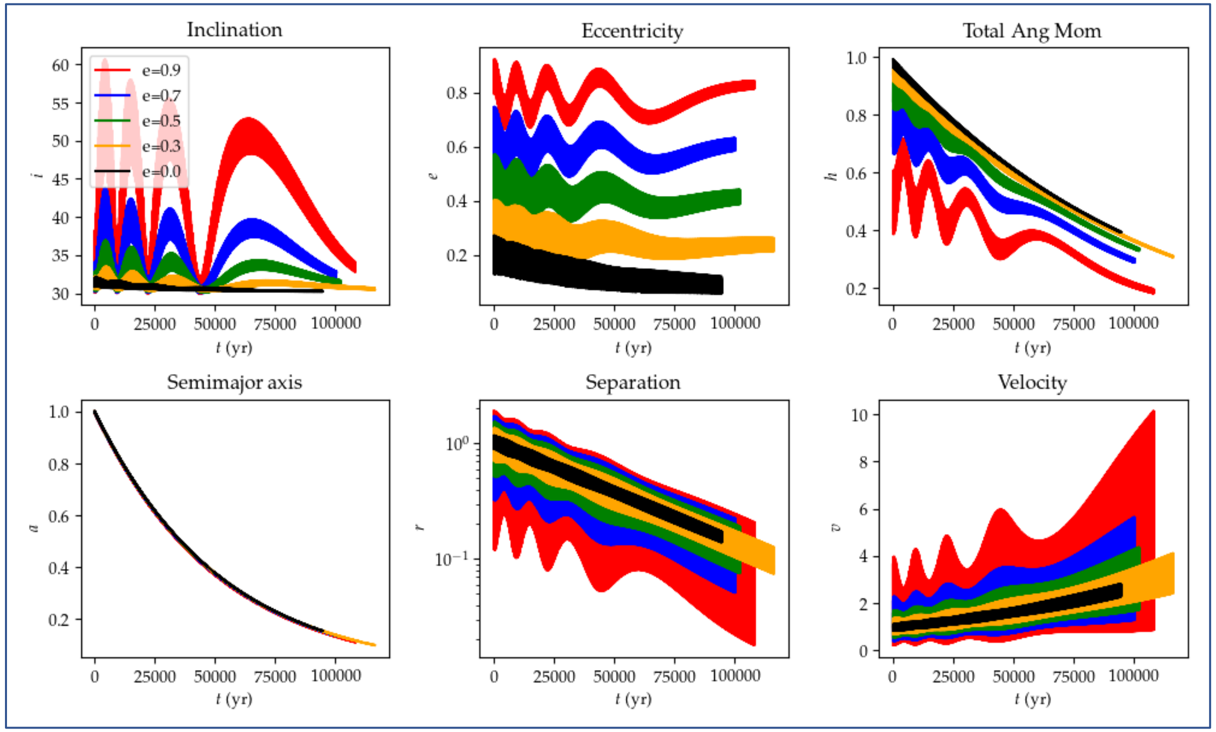
$$\frac{d\langle a\rangle}{dt} = -\frac{2\langle a\rangle}{\tau}$$

$$\frac{d\langle e\rangle}{dt} = \sqrt{\langle a\rangle \mu^{-1}(1-\langle e\rangle^2)}\frac{3u}{2\tau}\cos\omega$$

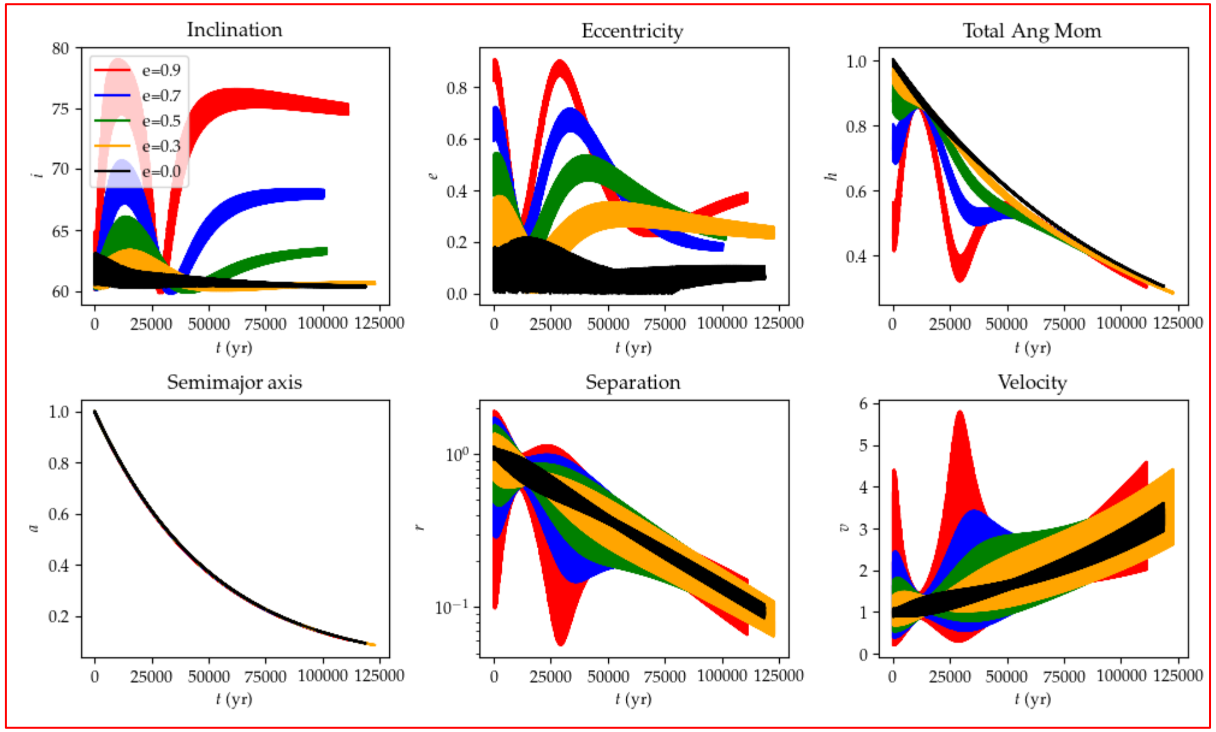
$$\frac{d\langle h\rangle}{dt} = -\frac{\langle h\rangle}{\tau} - ae\frac{3u}{2\tau}\cos\omega$$

Inclination

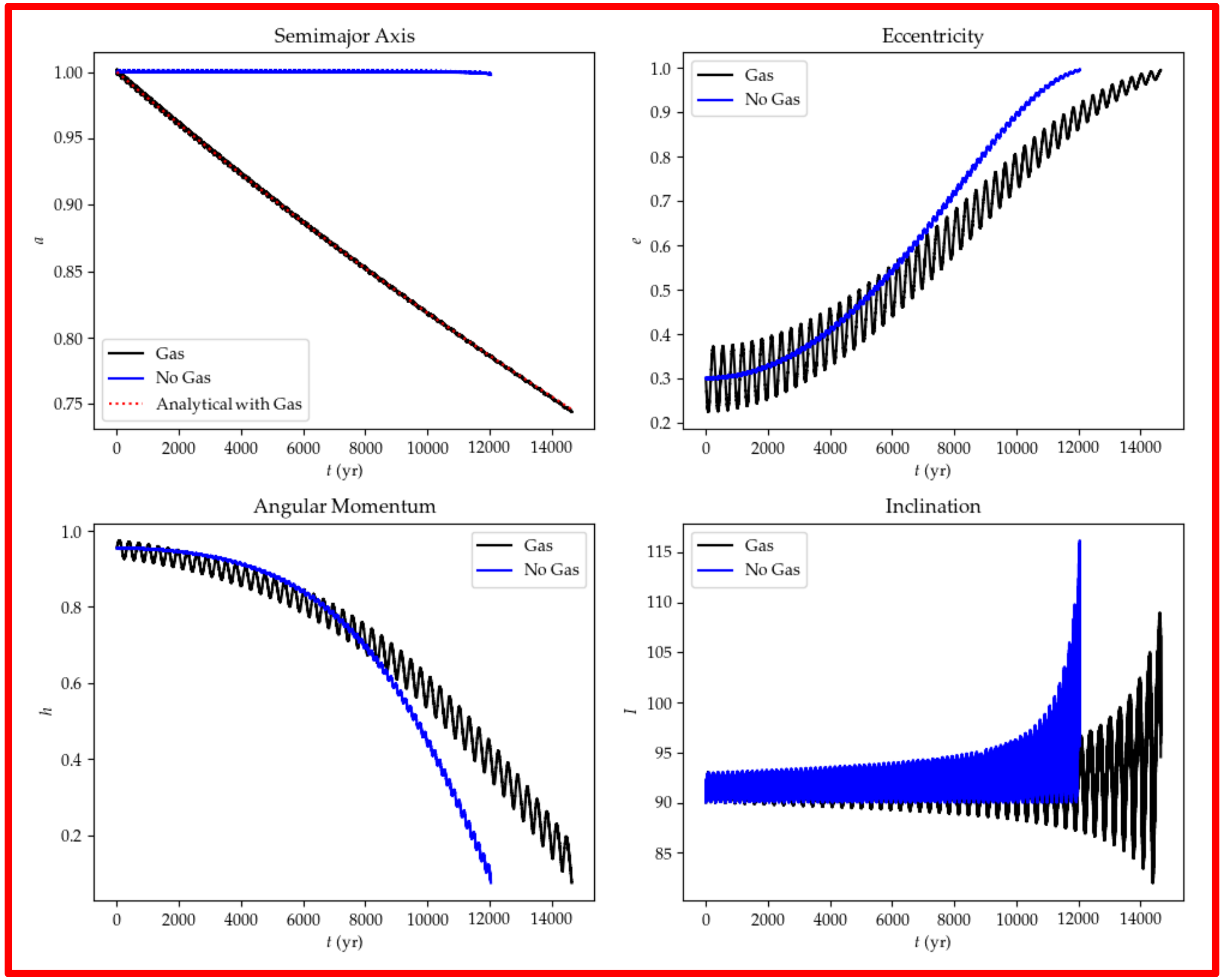
I=30°



I=60°



Kozai-Lidov



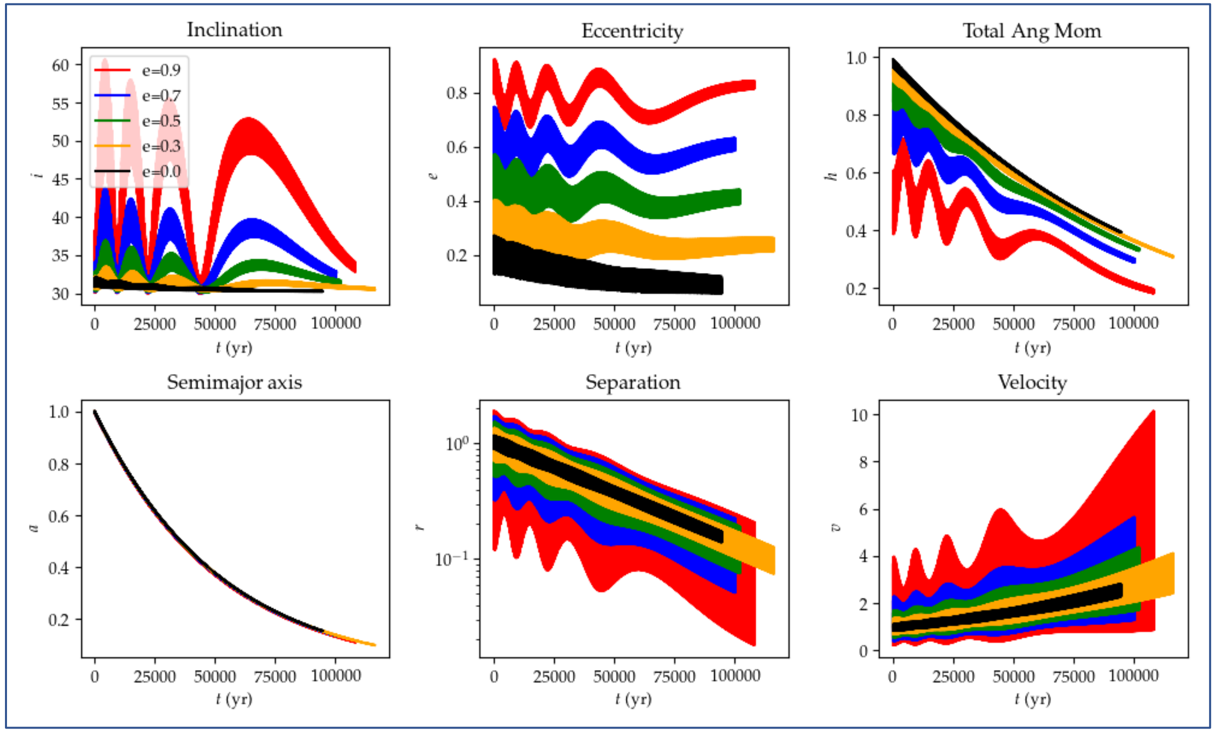
Conserved quantity is not angular momentum, but vertical angular momentum

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

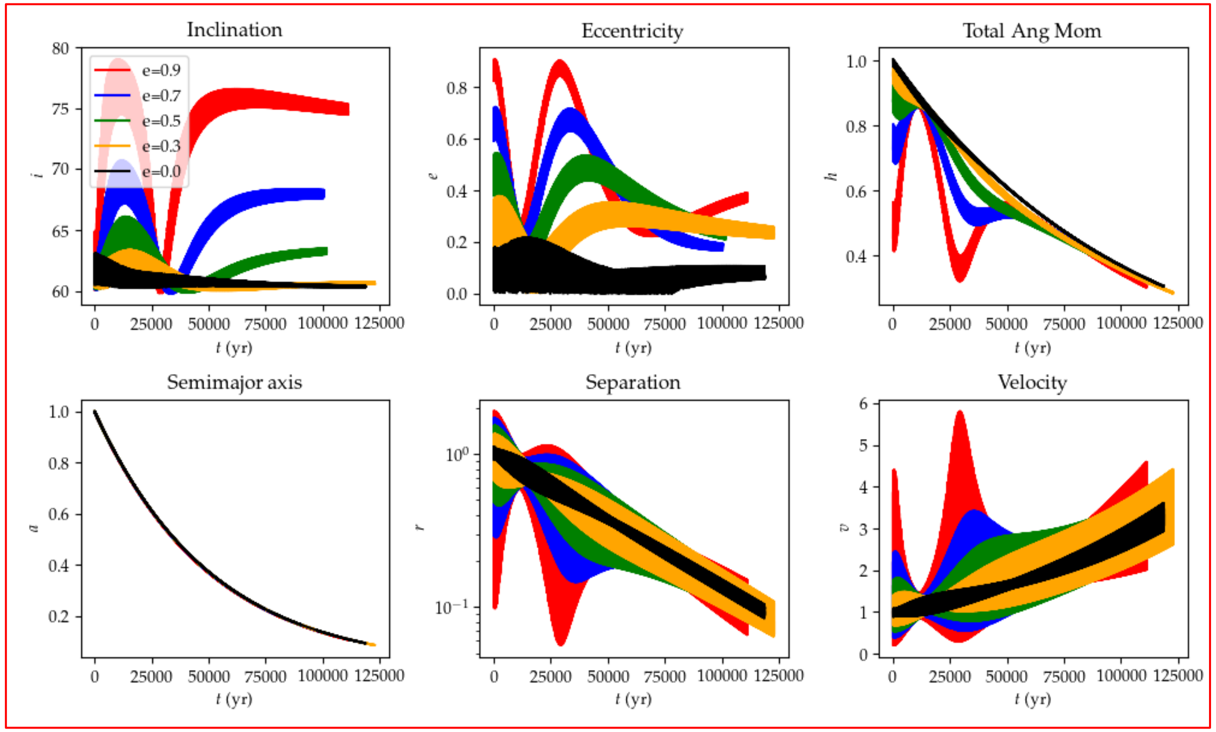
Inclination

Kozai-Lidov cycles!

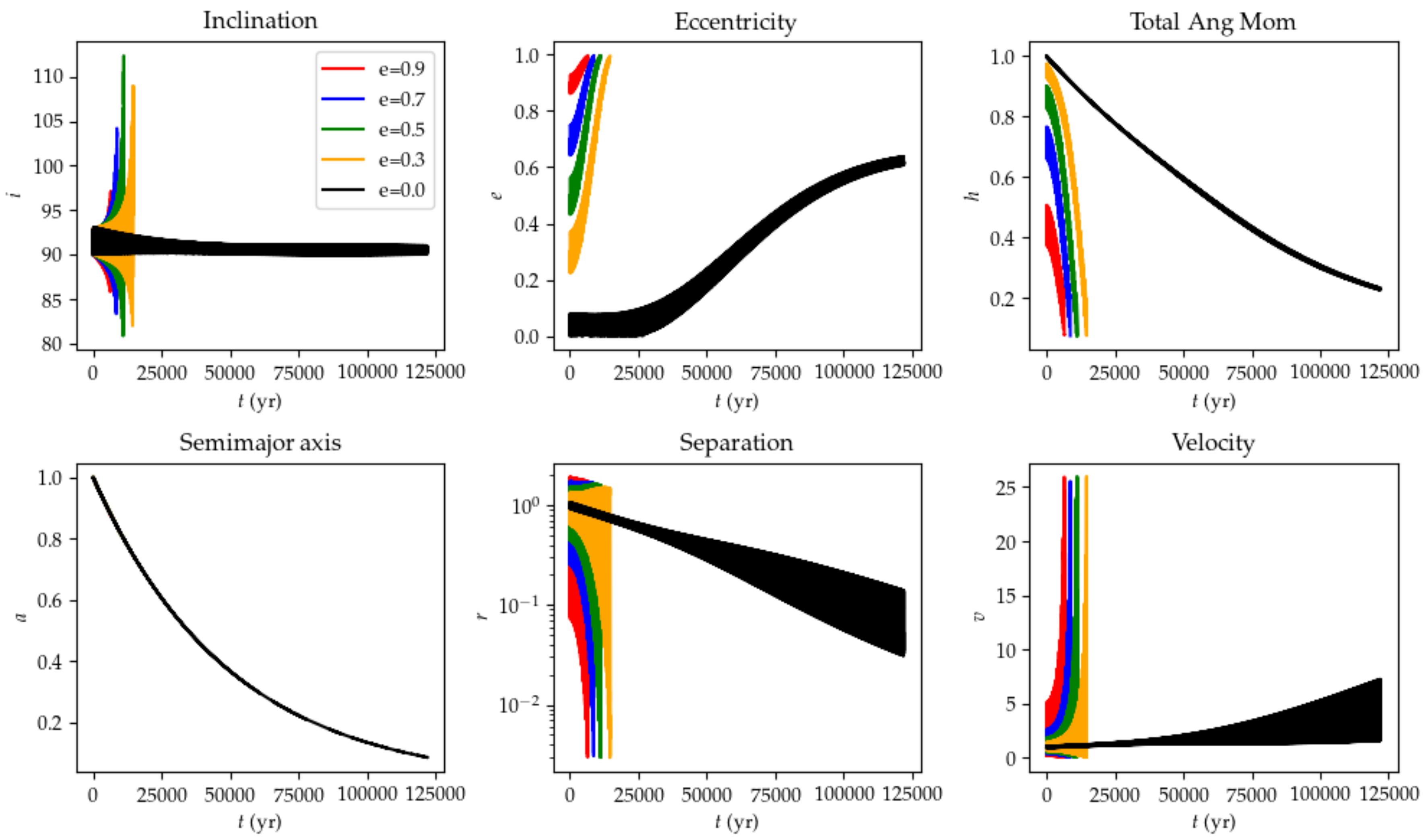
I=30°



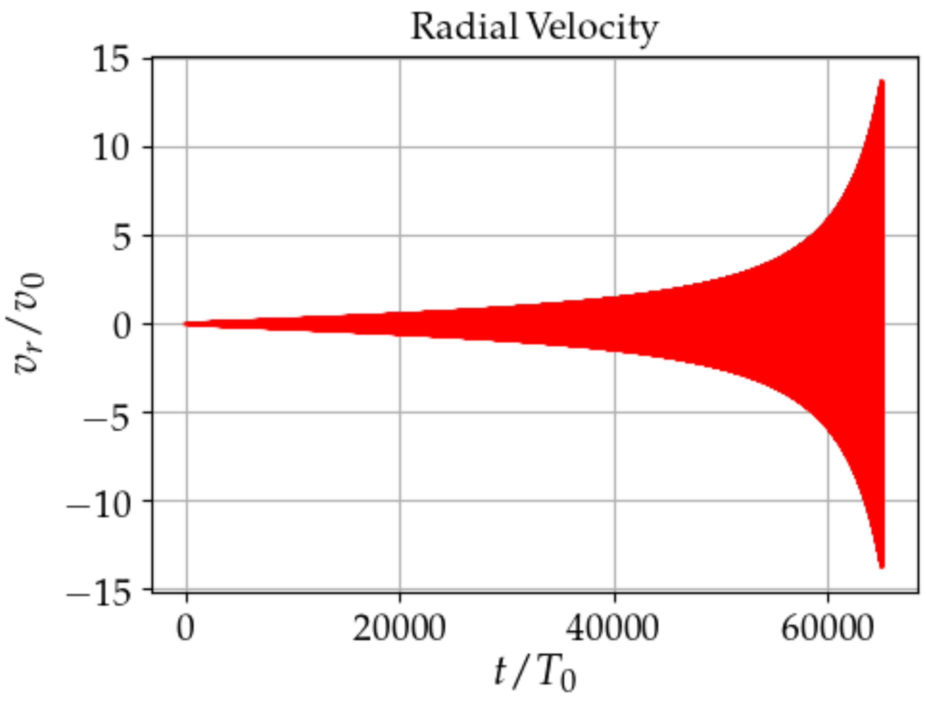
I=60°

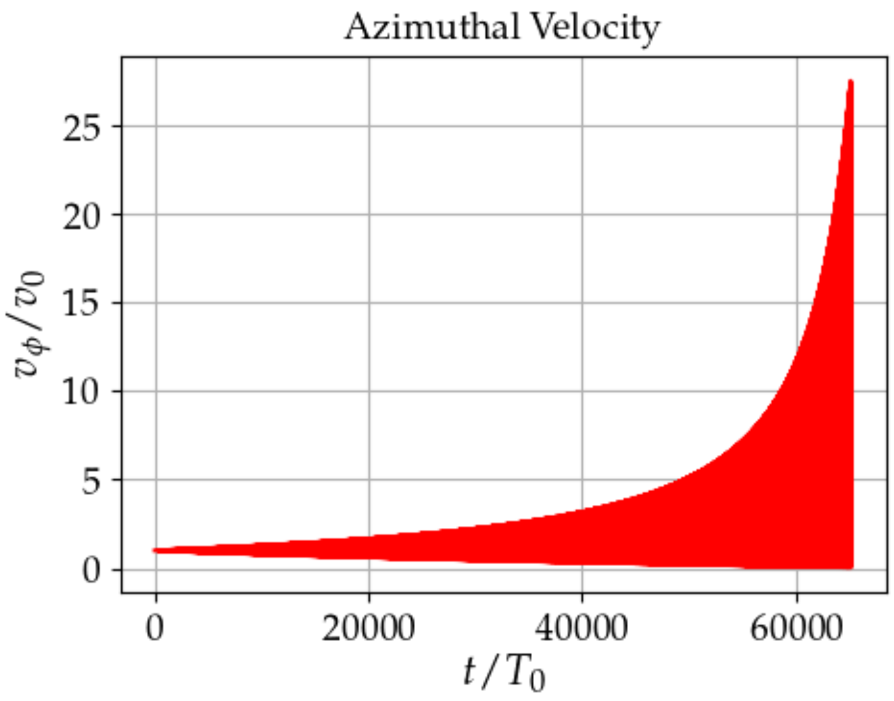


Inclination 90º
Kozai-led collapse

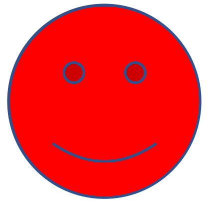


Kozai-Lidov “hardening”



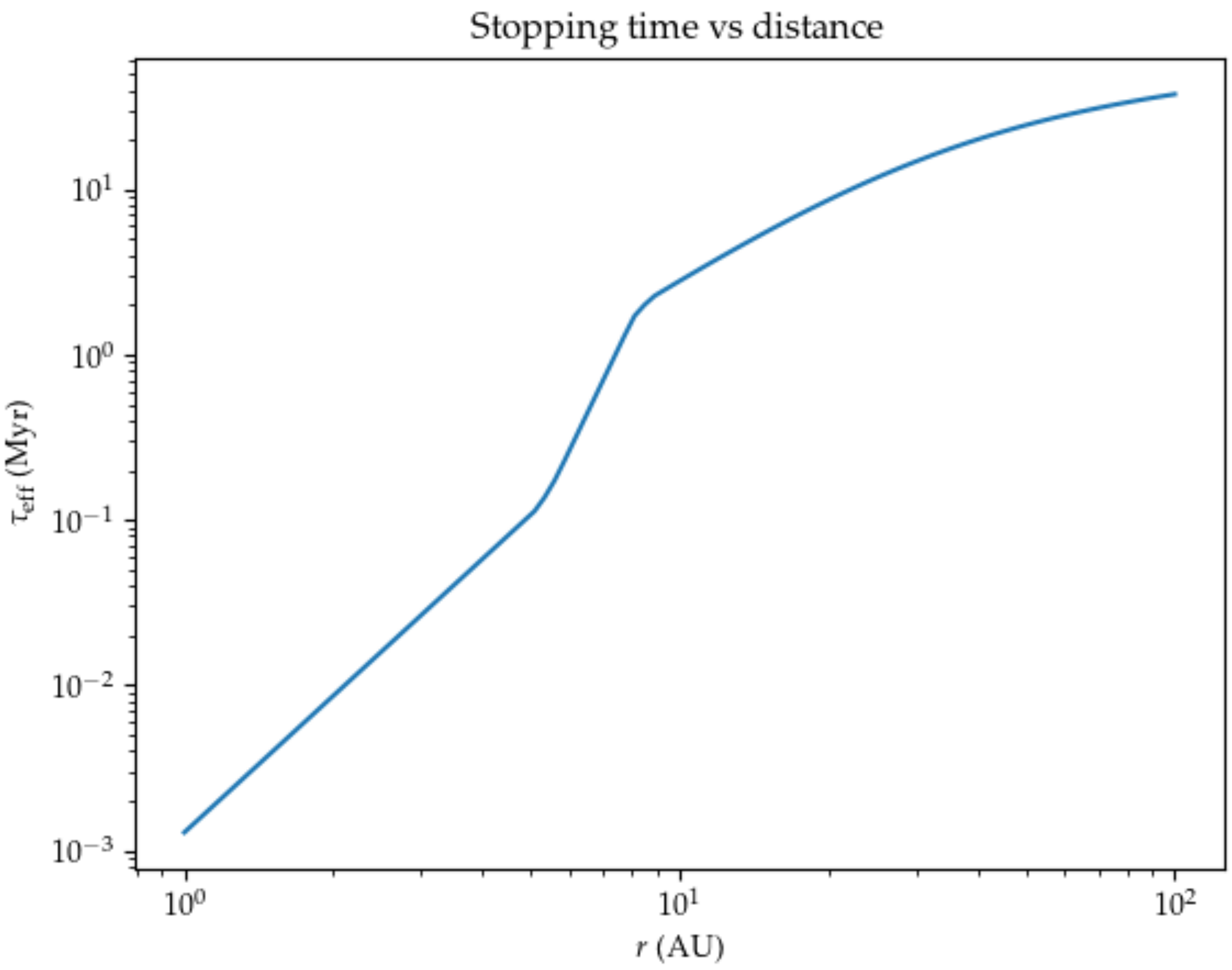


$V_{contact} \sim 3$ m/s

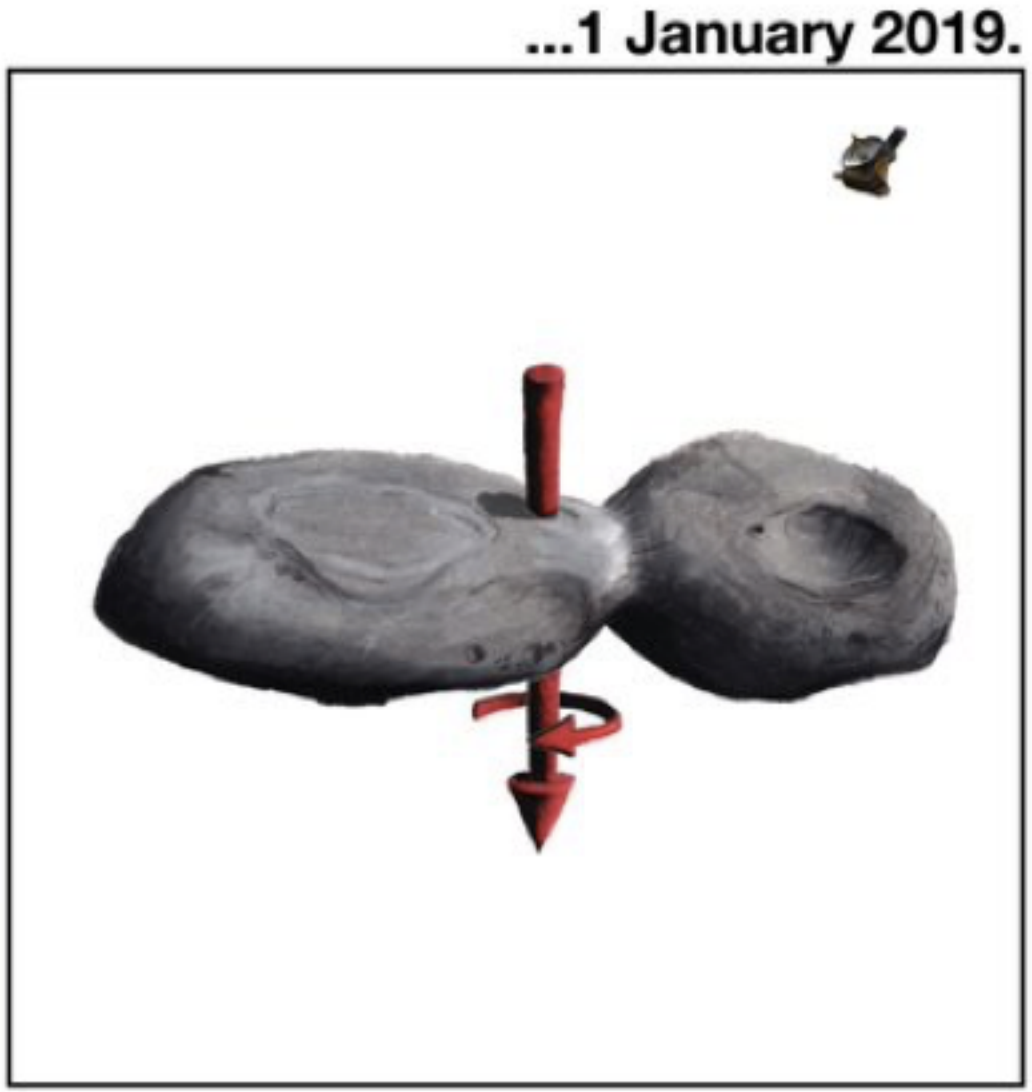


Lyra+ in prep

Asteroid belt vs Kuiper belt



Conclusions



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