Ultima Thule: Formation via the streaming instability and binary hardening with gas drag

Wladimir Lyra

California State University

Jet Propulsion Laboratory

Funding

Exploplanet Research Program XRP - 2018

ngvla Next Generation Very Large Array

NRAO 2017

XRP - 2016

SPACE TELESCOPE SCIENCE INSTITUTE Operated for NASA by AURA

HST Cycle 24, 2016

NExScI

Sagan Program, 2012

NSF

NSF AST 2010

Computational Facilities

NSF XSEDE

Victoria, May 15th, 2019

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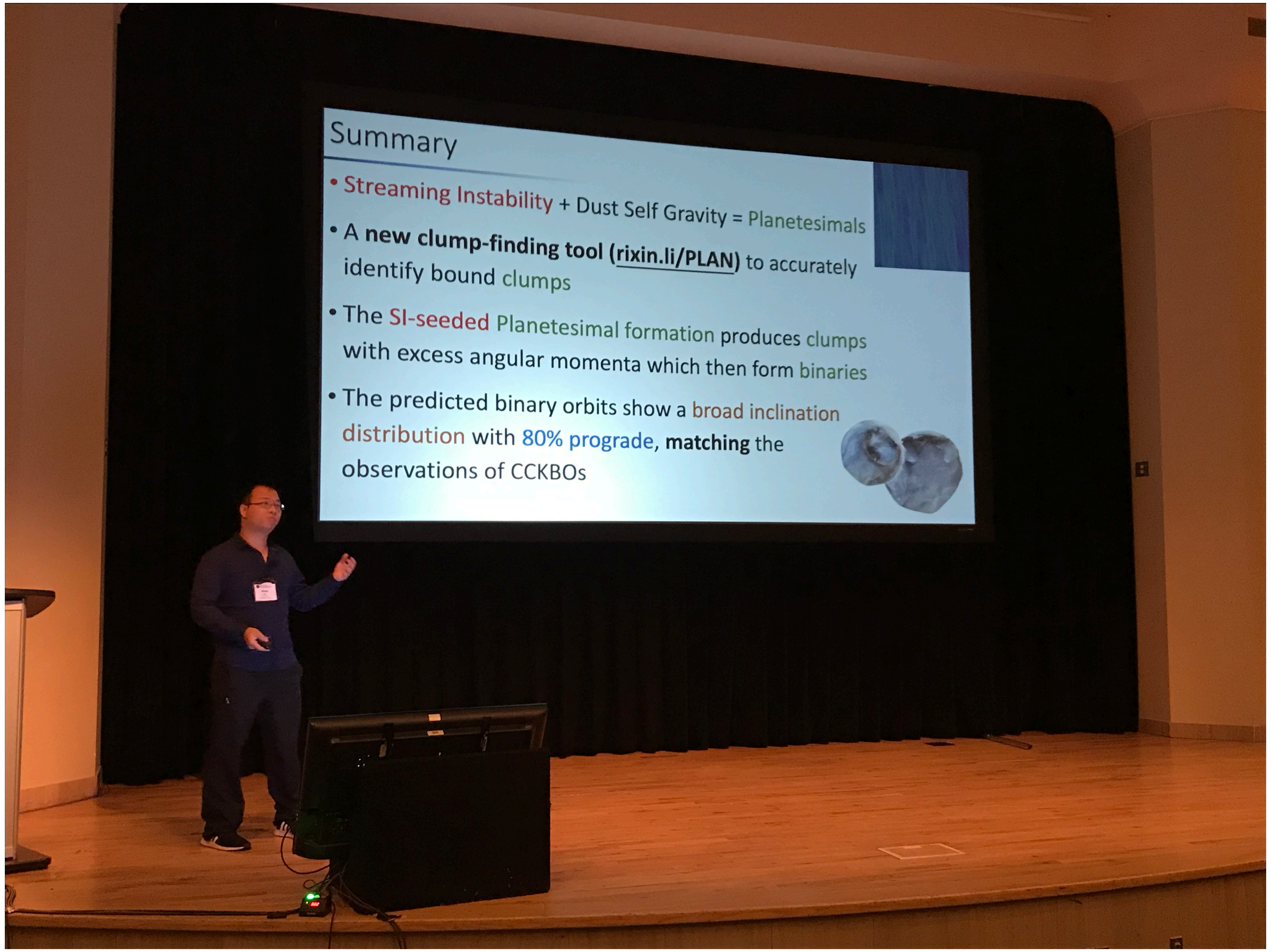
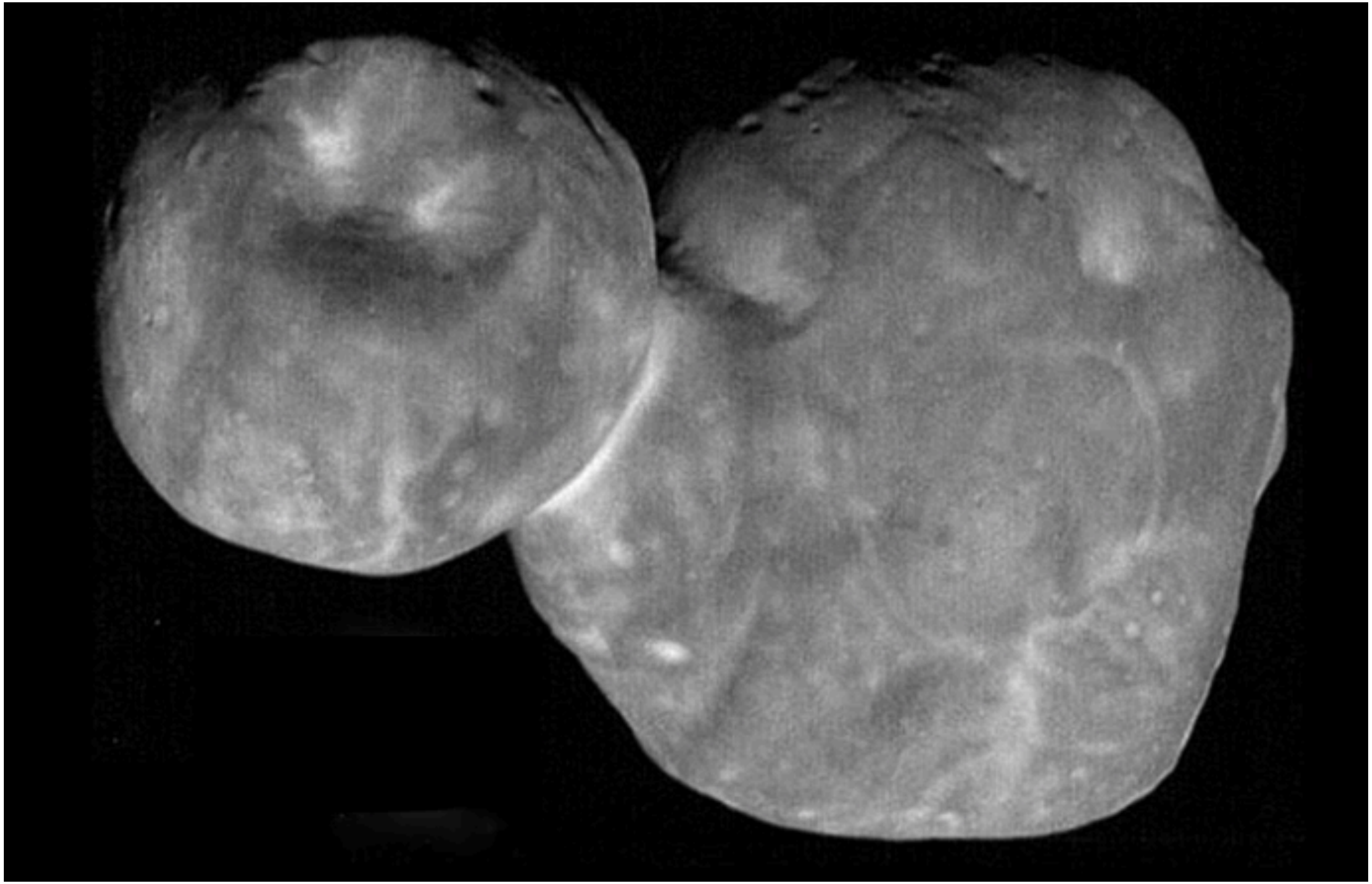
Ultima Thule: ~~Formation via the streaming instability~~ and binary hardening with gas drag

Rixin Li gave half
of my talk already,
Here's the summary
for that half



Rixin Li's talk

Ultima Thule

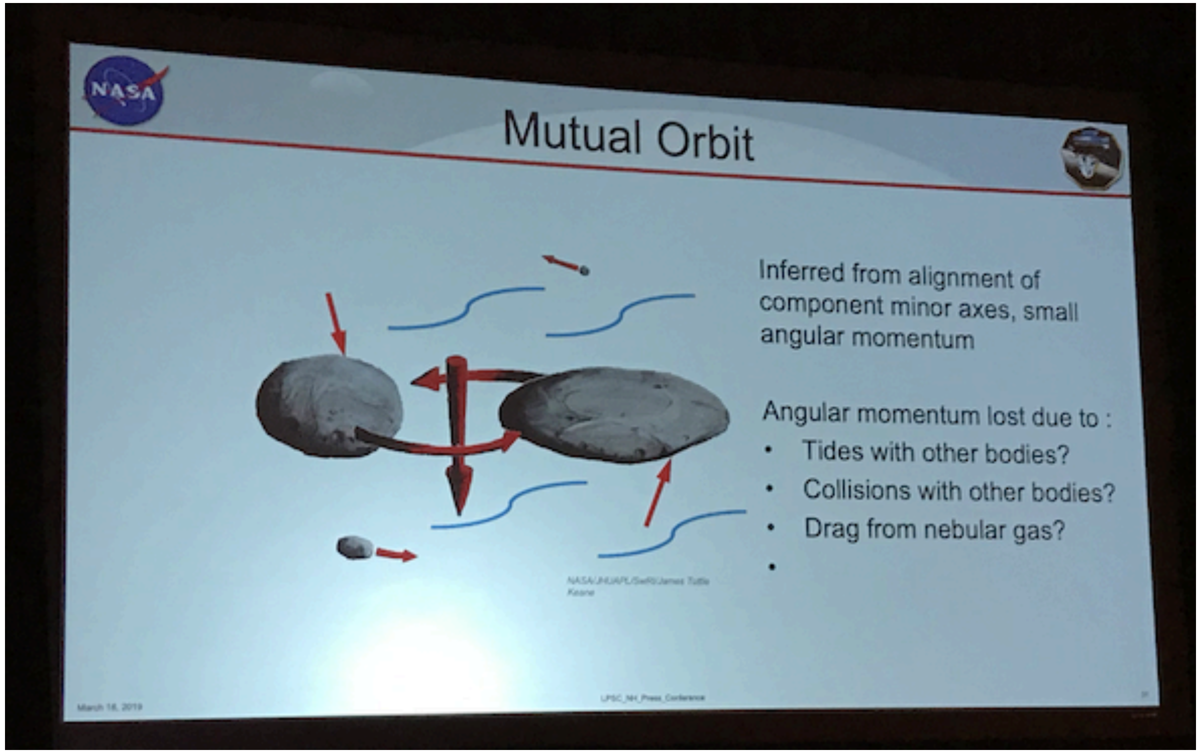


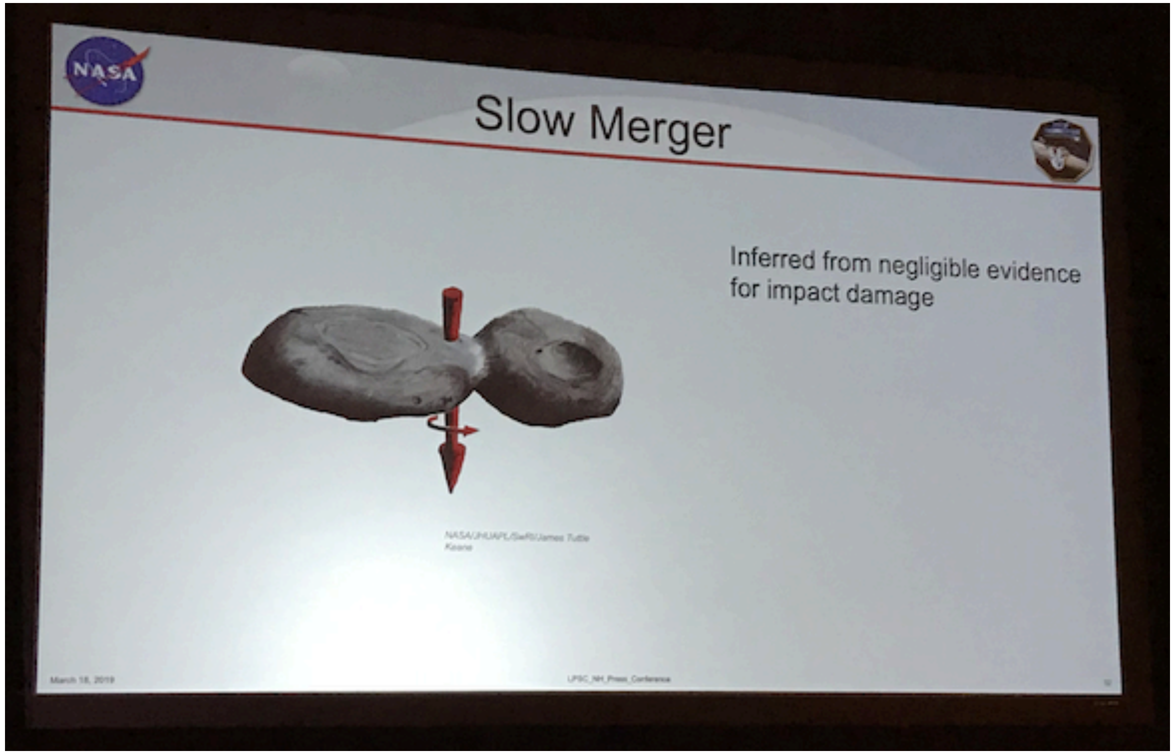
New Horizons Flyby, Jan 2019

W. Lyra

How was angular momentum lost?

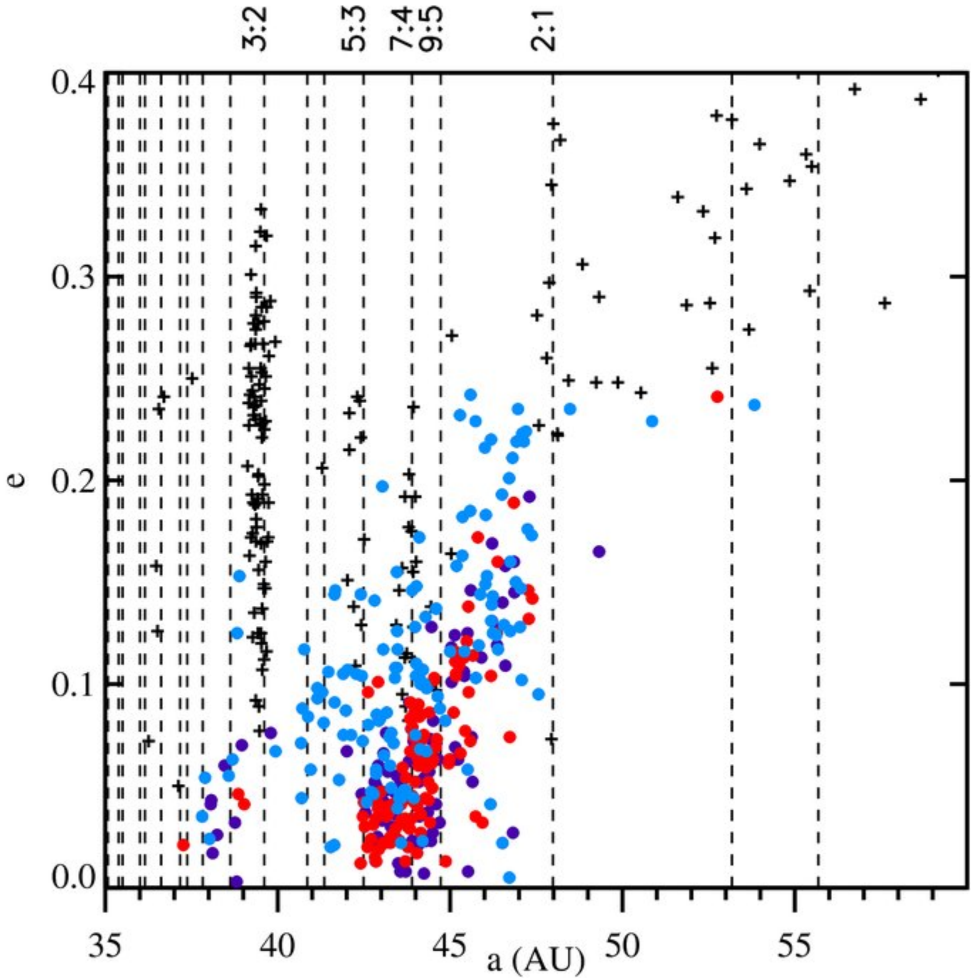
Constraint: Slow merger (~2 m/s: human walking speed)





John Spencer's talk

Cold Classical Kuiper Belt Object



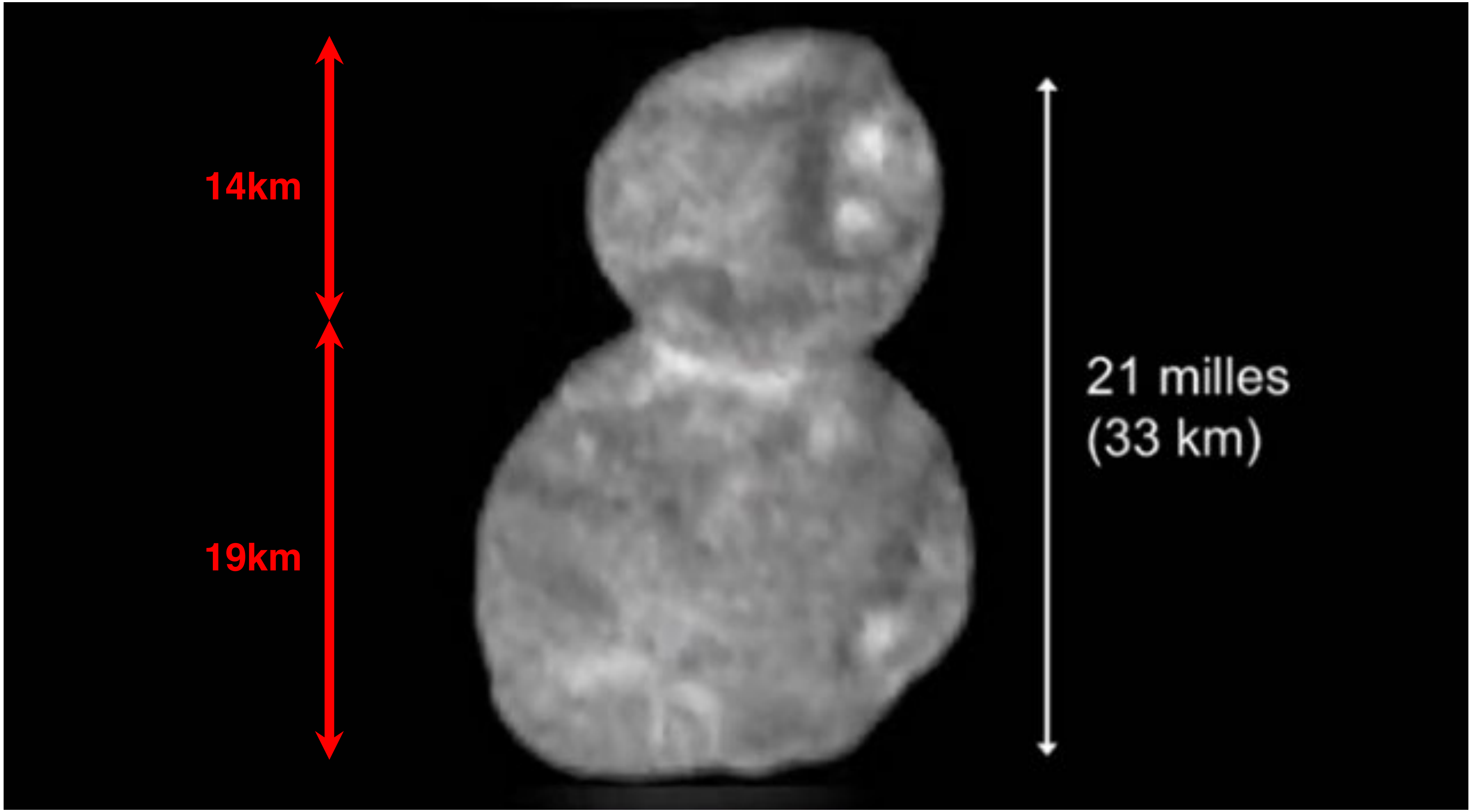
+ Resonant and Scattered
Cold Classical *i*<2°
"Ambiguous" 2°<*i*<6°
Hot Classicals i>6°

Presumably pristine planetesimals

W. Lyra

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

Ultima Thule: Dimensions



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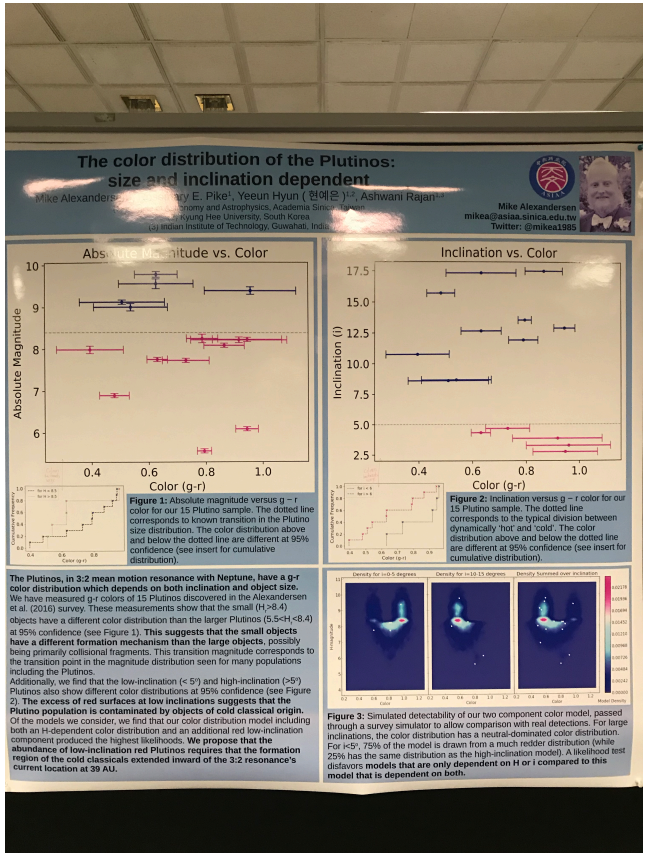
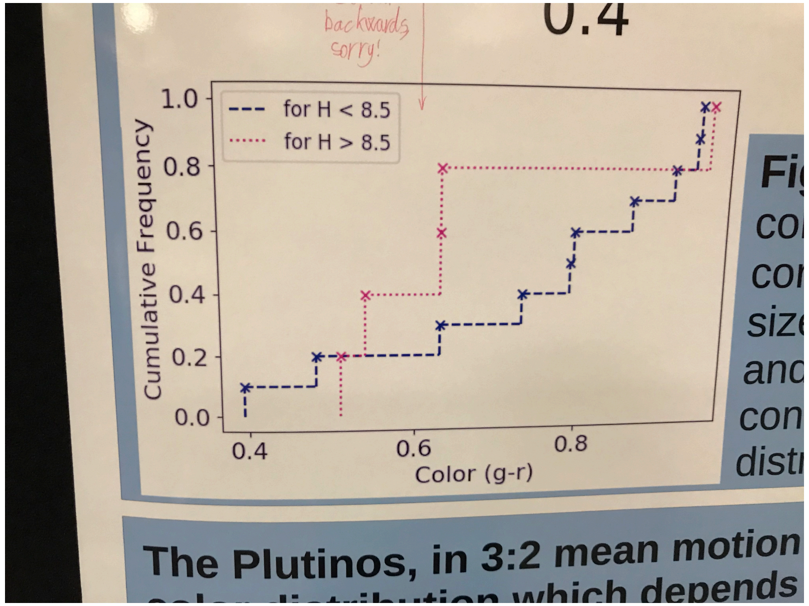
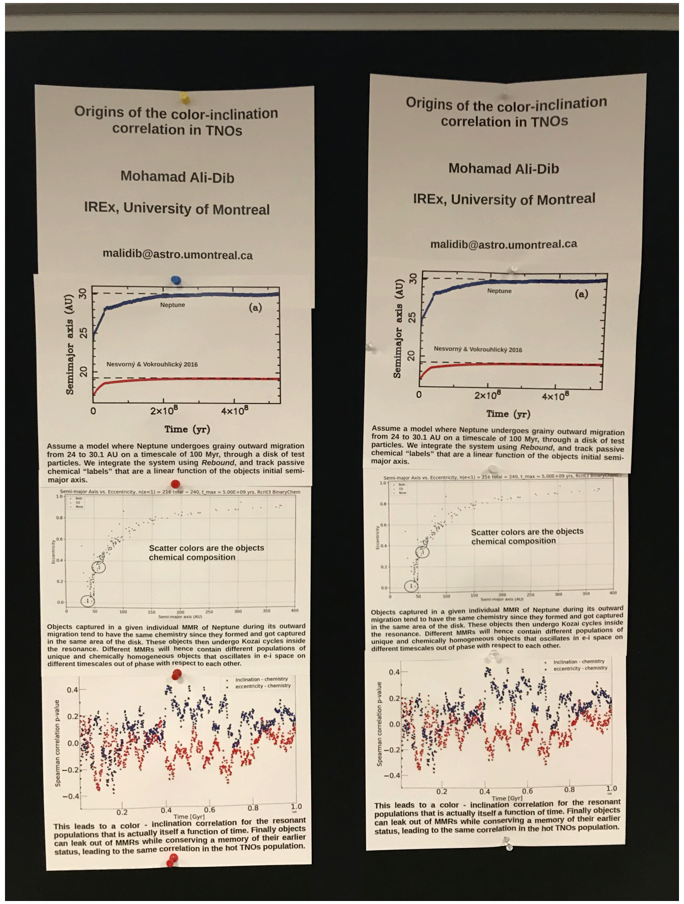
Large and Small TNOs fundamentally different

Difference in color points to difference in formation (check these posters outside)

Correlation mass-color and color-inclination (thus mass-inclination)

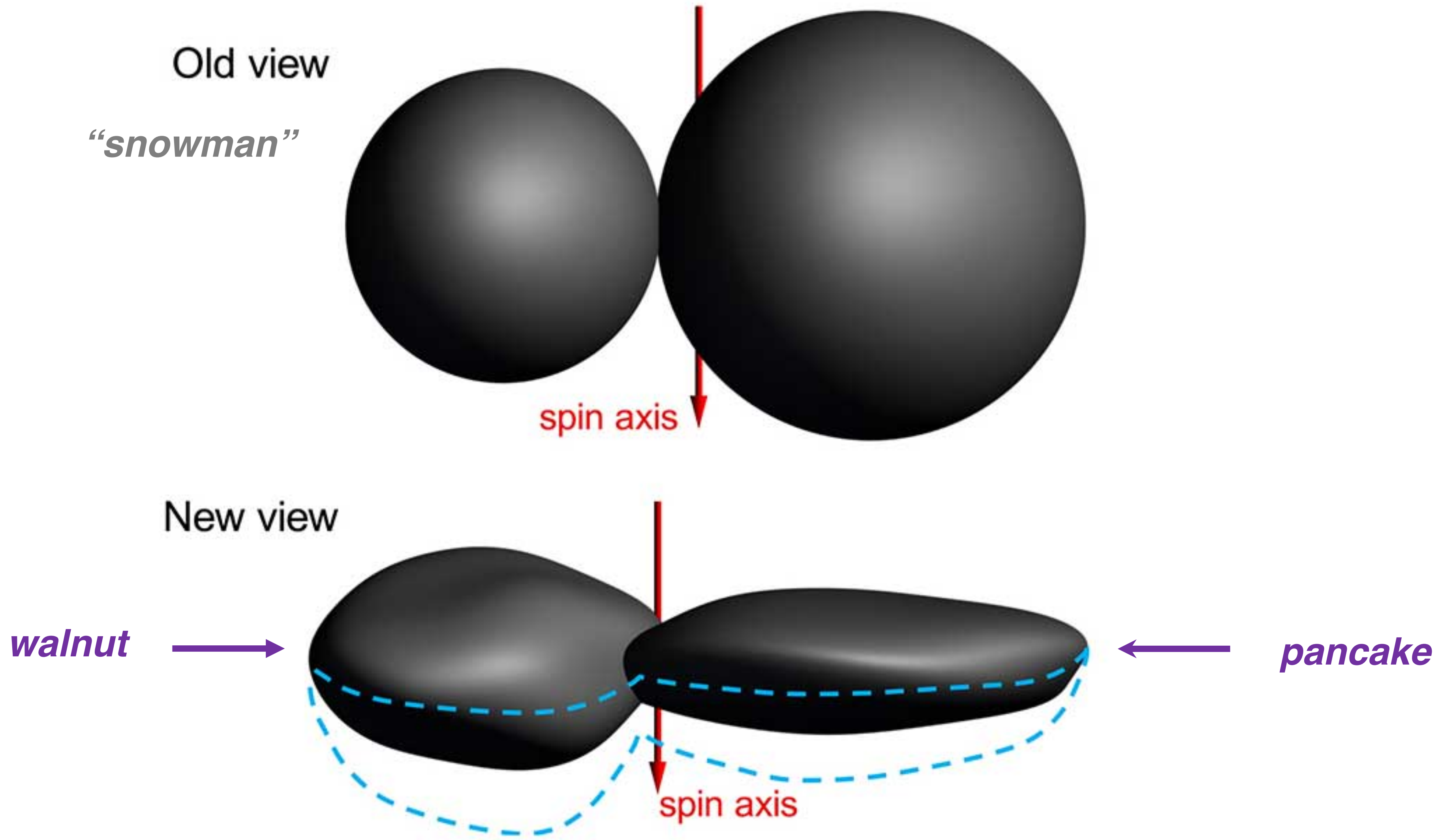






See also Fraser+'14 and Spencer's talk

Ultima Thule: Shape



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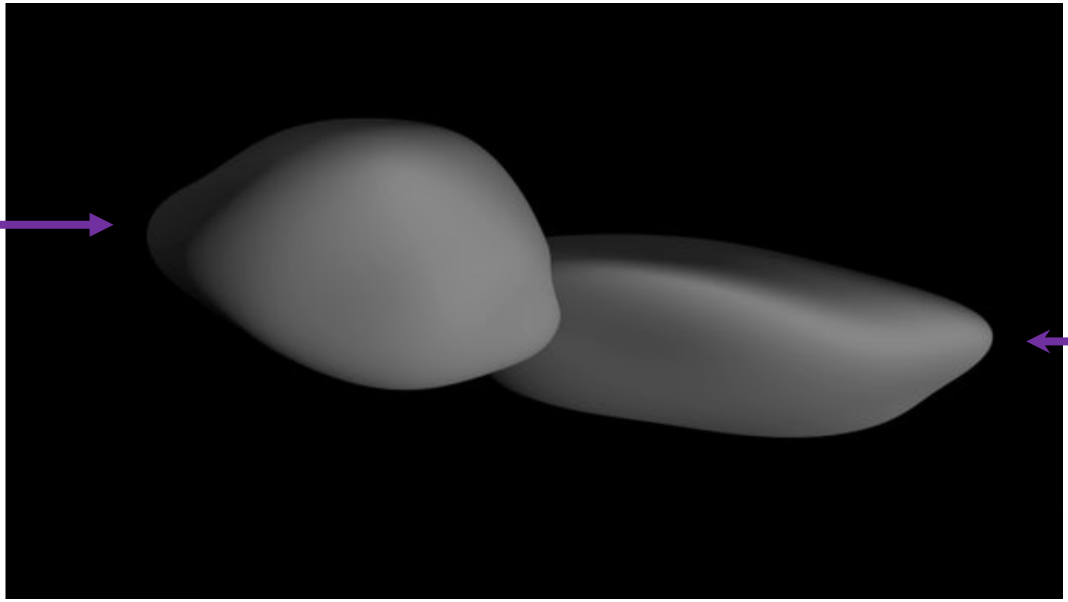
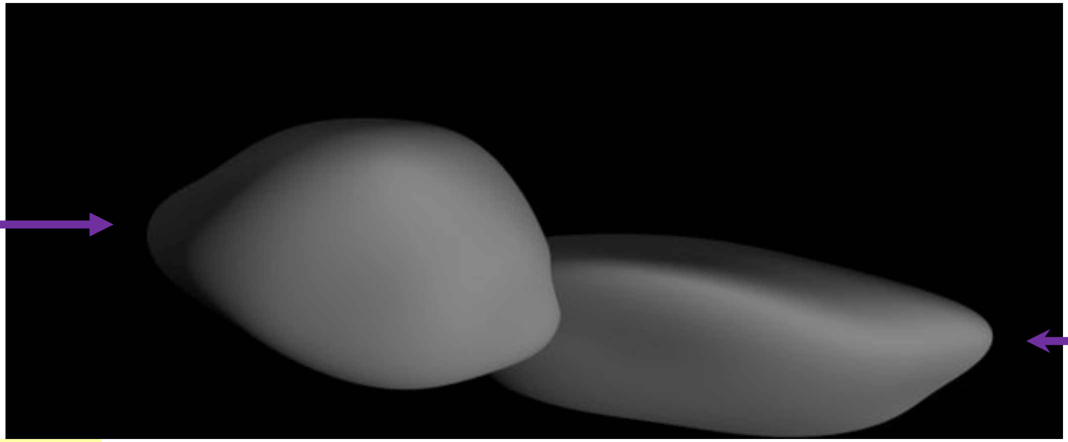
walnut



pancake

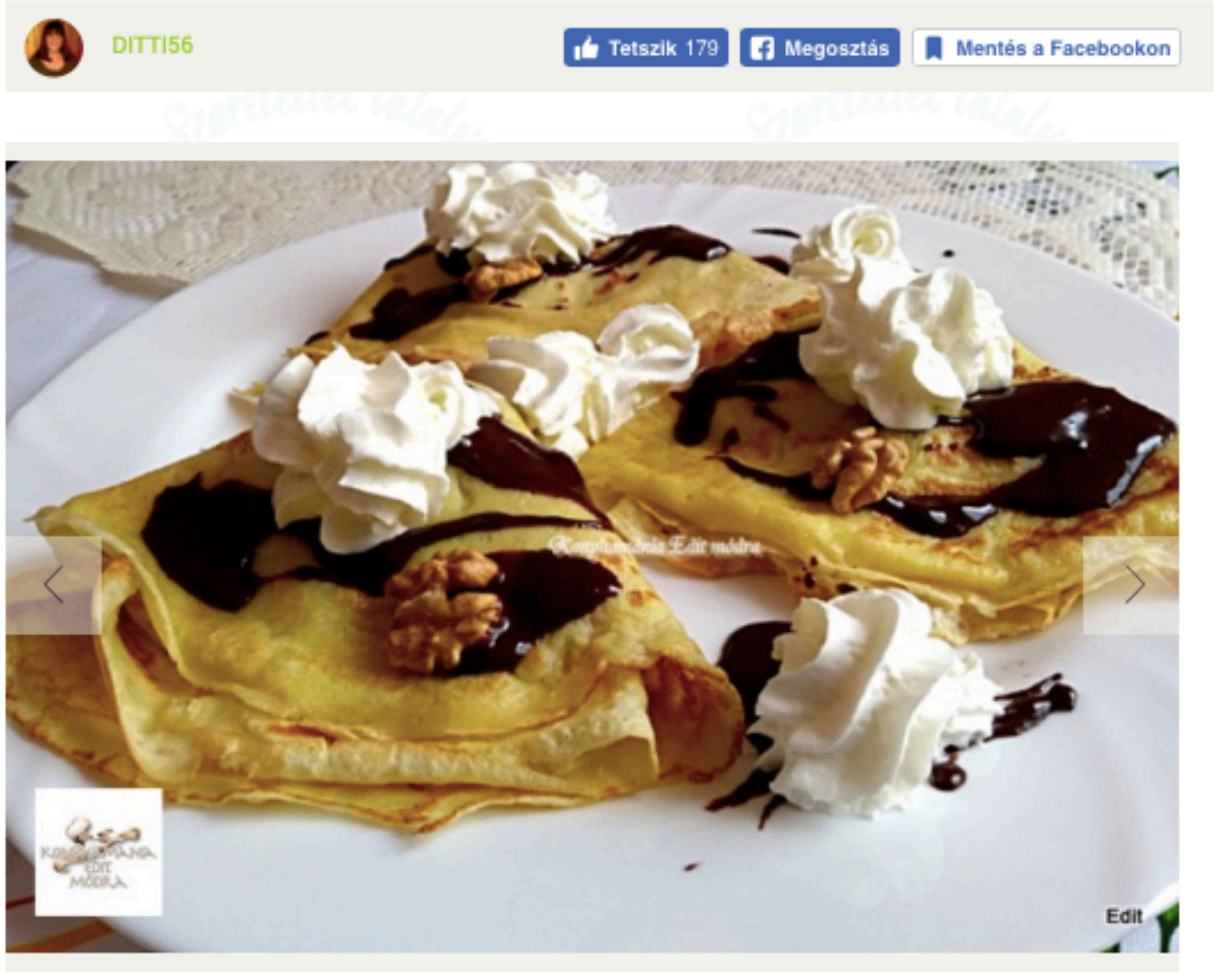
walnut



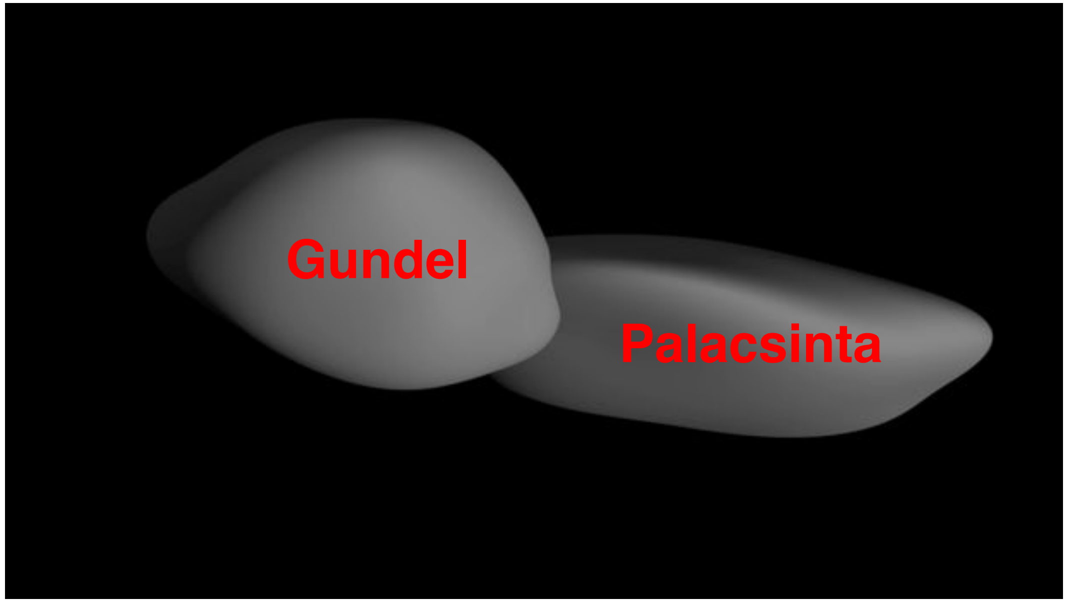
pancake

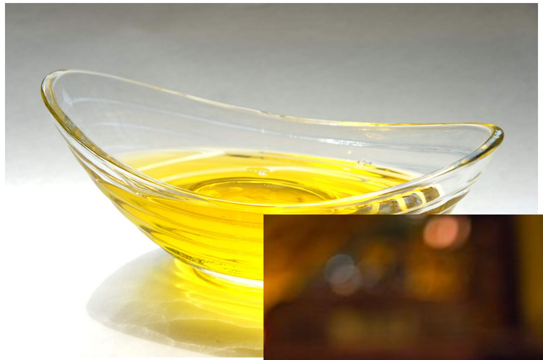
An official name for the object, consistent with the naming guidelines of the International Astronomical Union, will be proposed by the *New Horizons* team after the spacecraft's flyby, when the properties of (486958) 2014 MU_{69} are known well enough to choose a suitable name.[30][23]

GUNDEL PALACSINTA



Naming suggestion:
a walnut pancake Hungarian dessert









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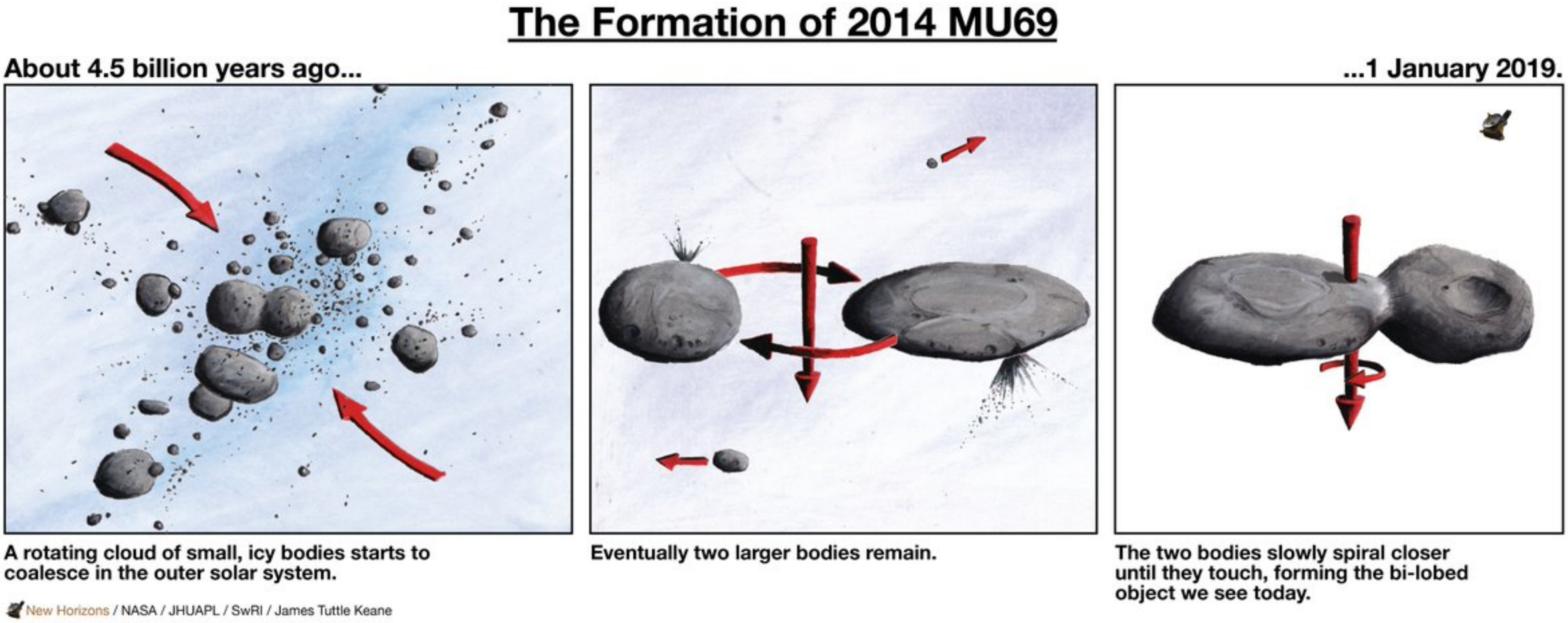
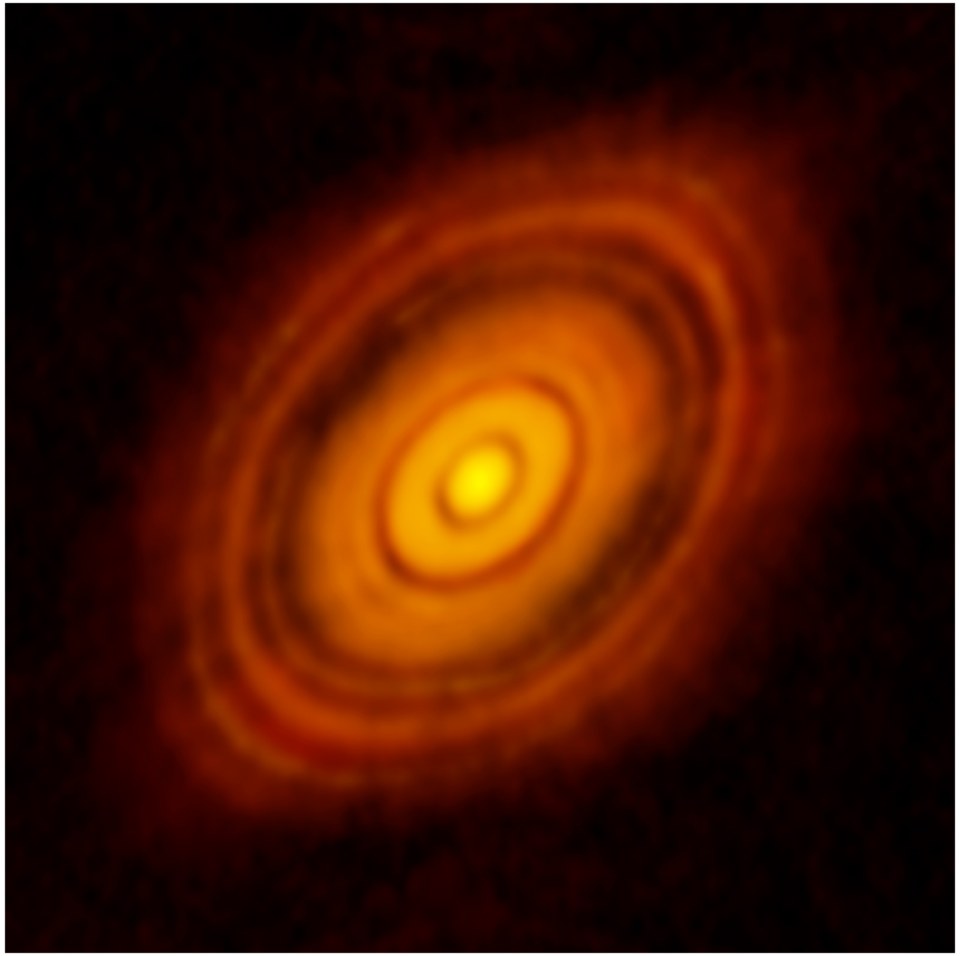
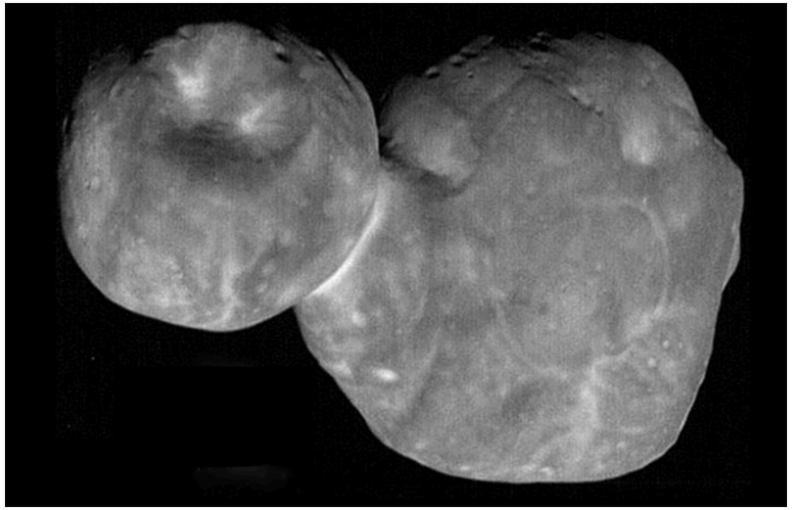
The Cartoon Image



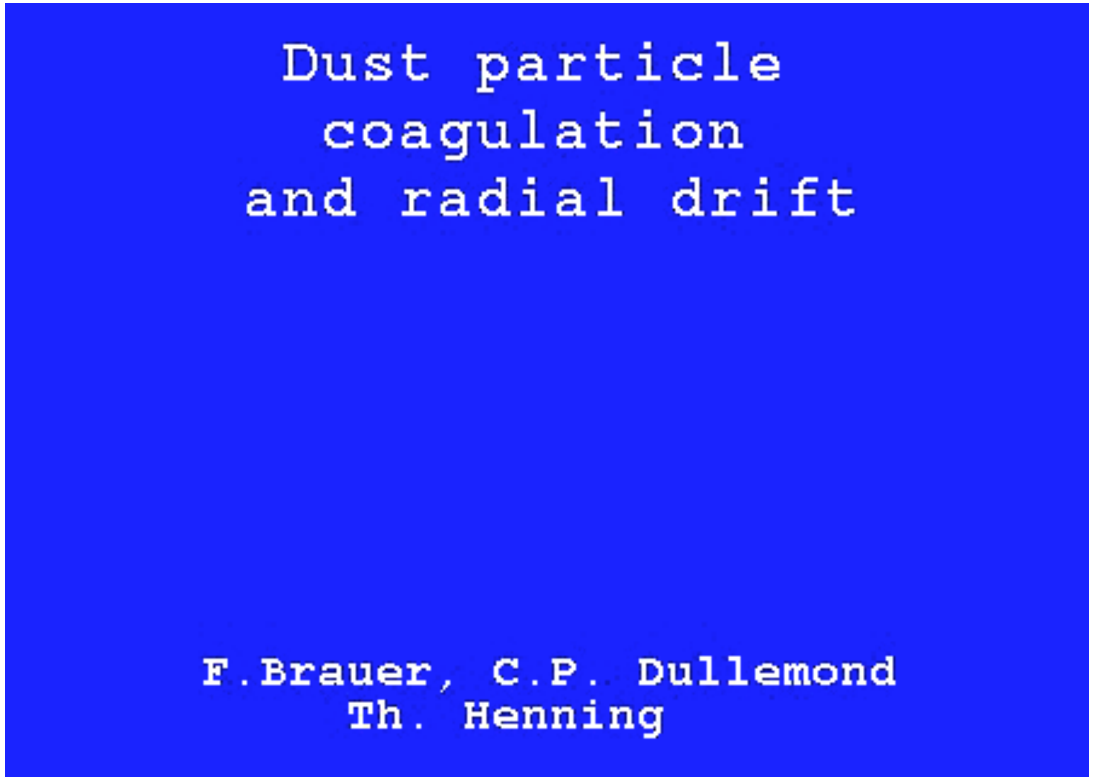
Beyond the cartoon image



How?

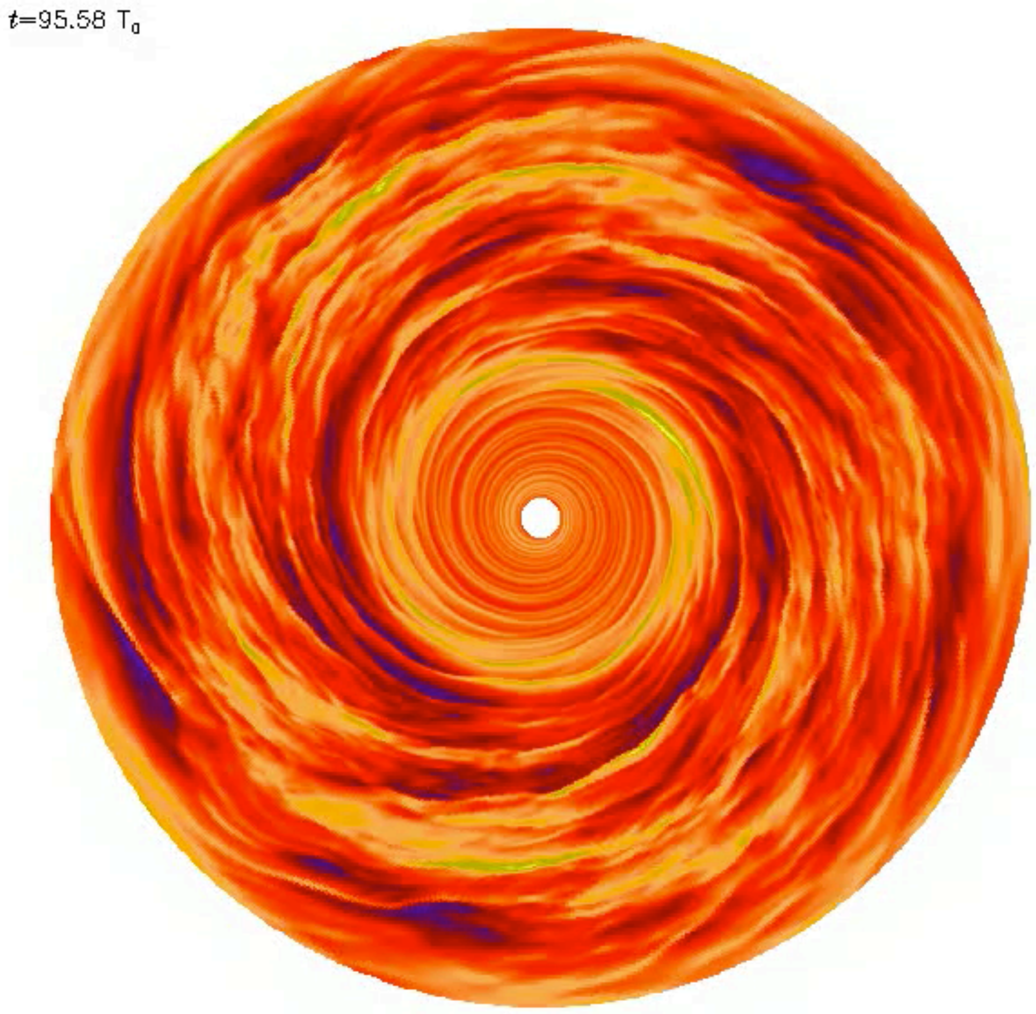


Dust coagulation and drift



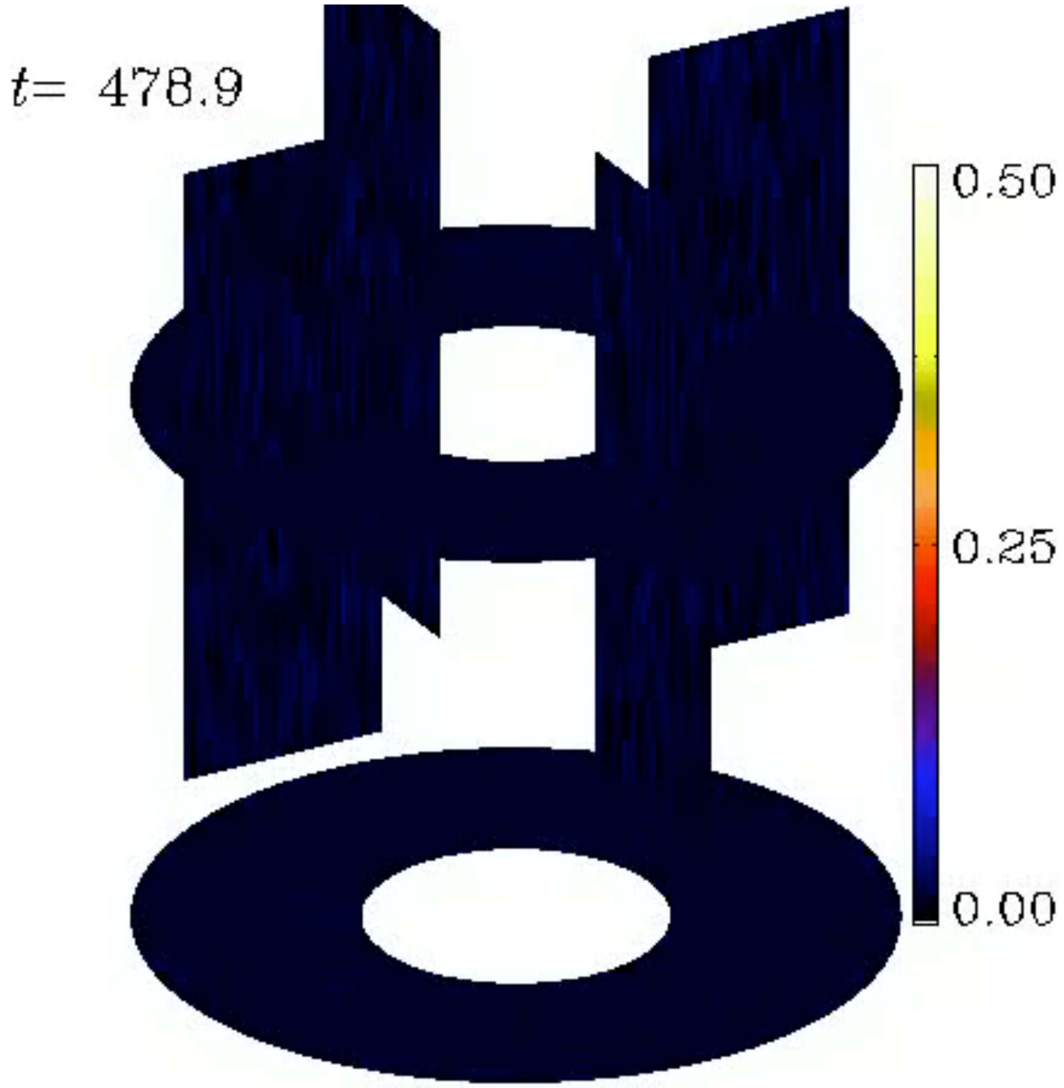
Brauer et al. (2008)

Dust retention: Disk structure



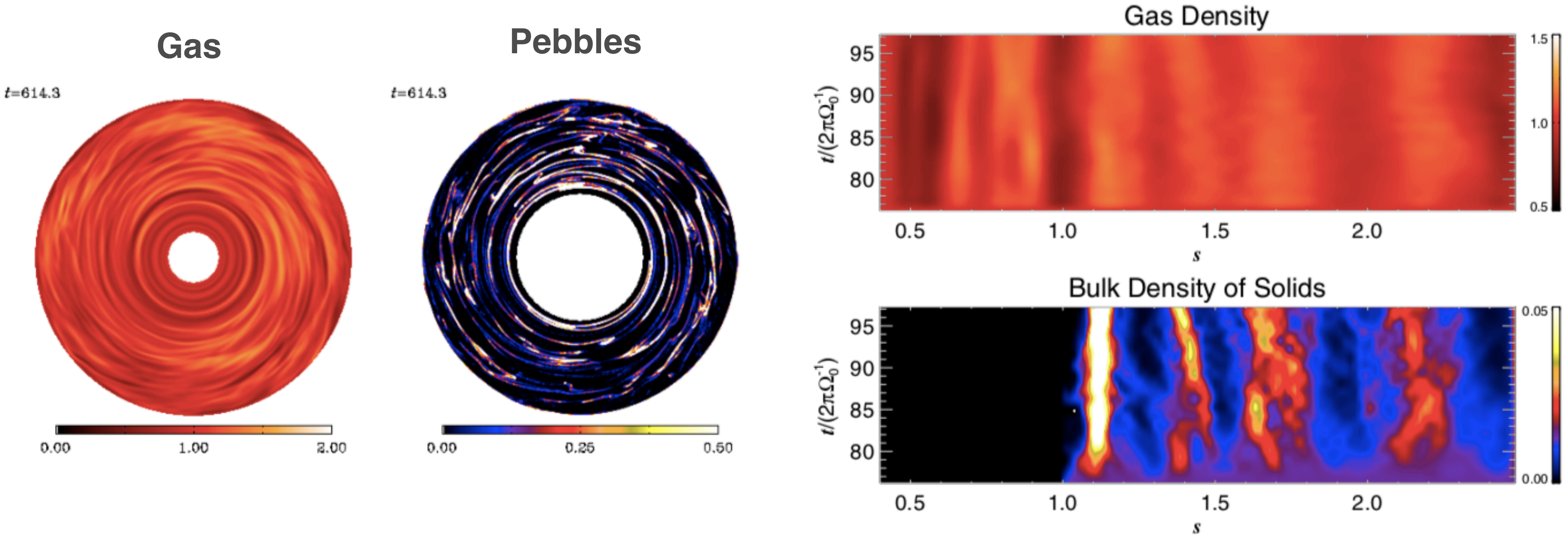
Lyra+ ‘15

Turbulence concentrates solids mechanically in pressure maxima



Lyra et al. (2008a)

Dust retention: Disk structure



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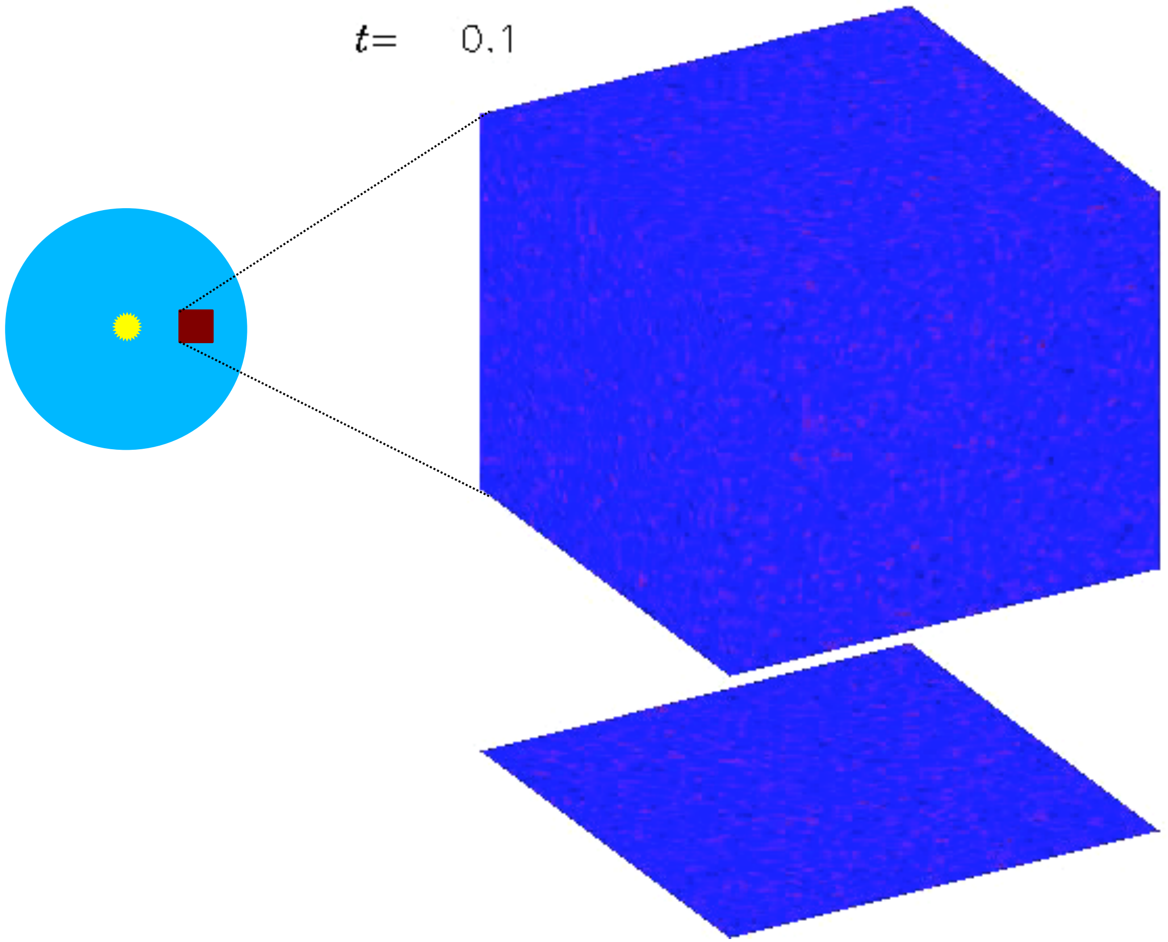
Lyra+ 08a

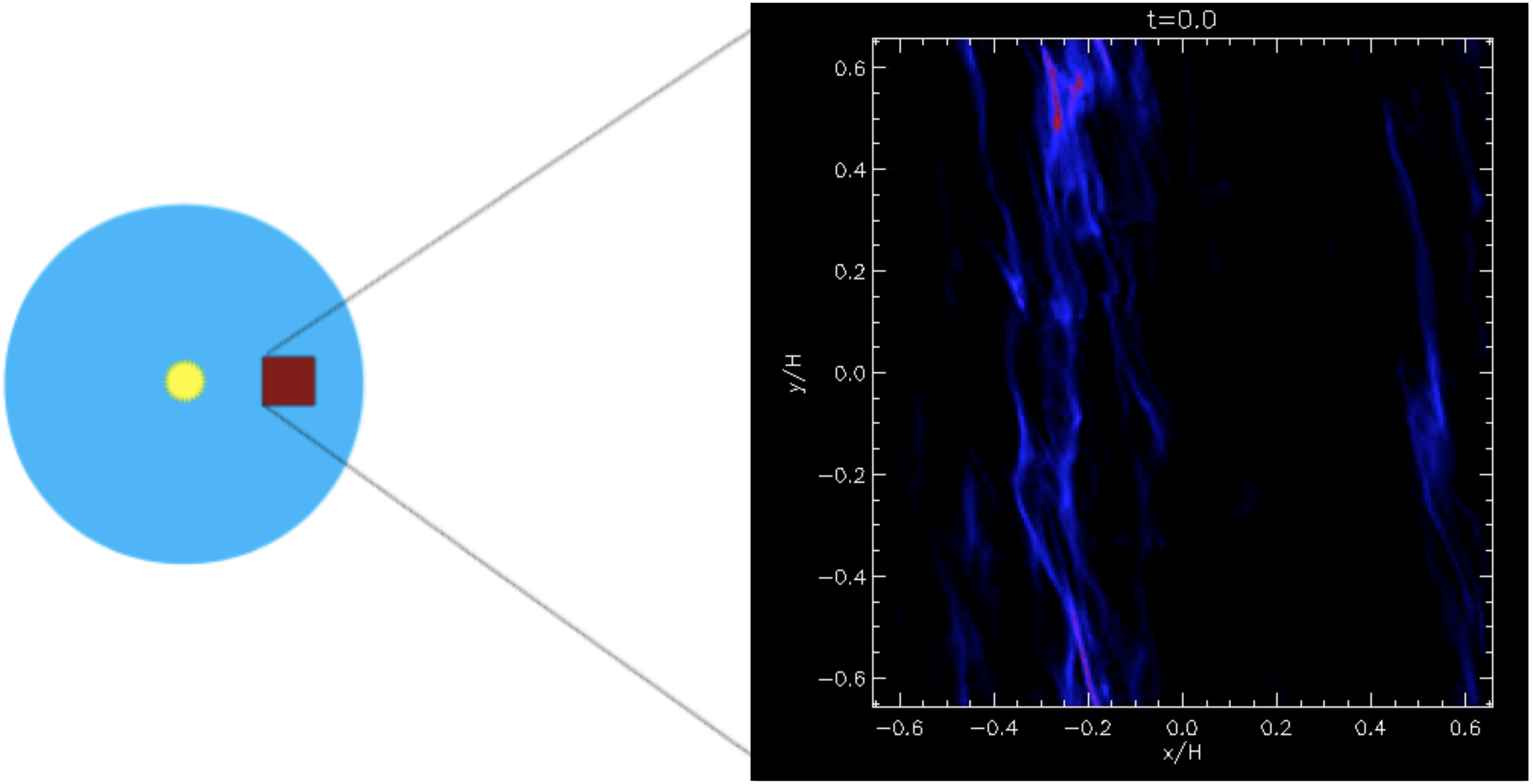
Streaming Instability

The dust drift is hydrodynamically unstable



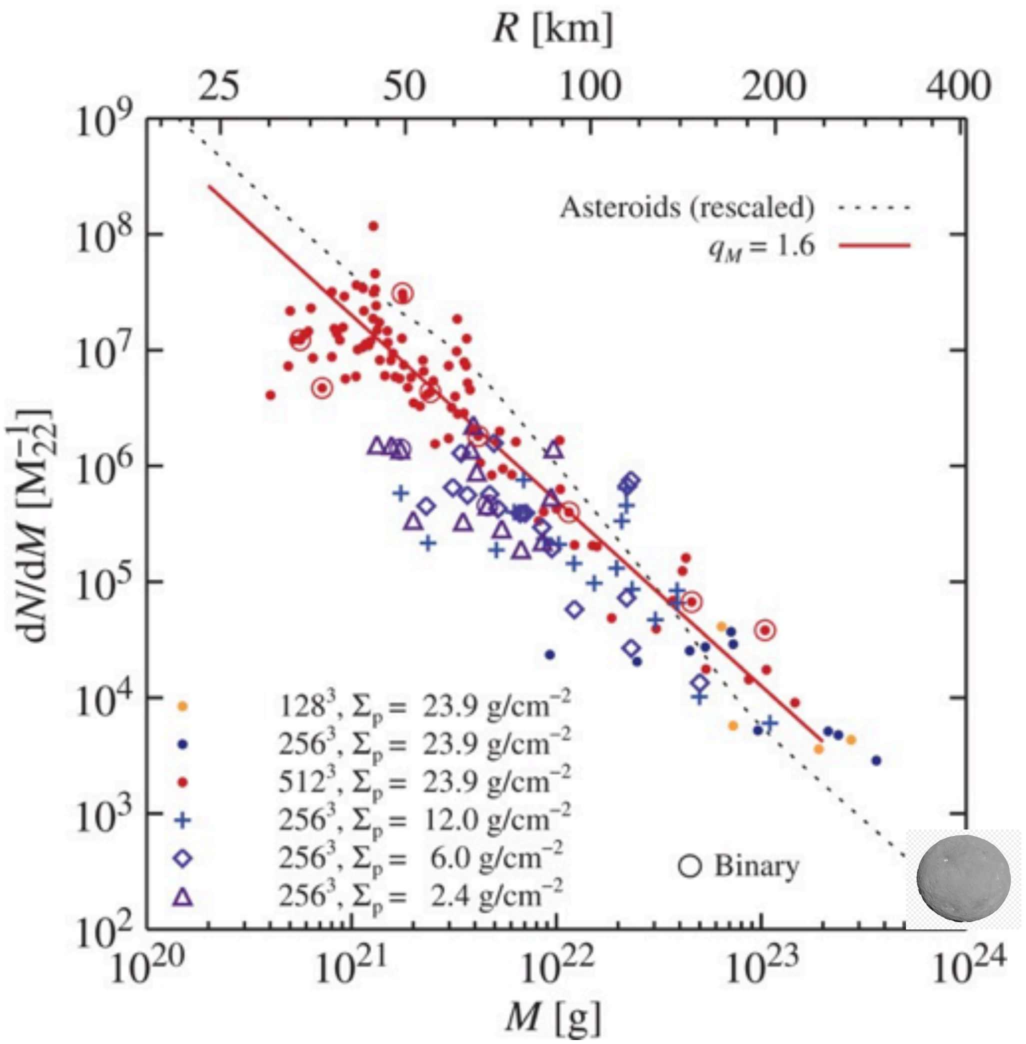
Youdin & Goodman (2005), Johansen & Youdin (2007), Youdin & Johansen (2007)

Gravitational collapse into planetesimals



Johansen et al. (2007)

Planetesimals’ Initial Mass Function



Convergence with resolution; slope 1.6

Johansen et al. (2015)

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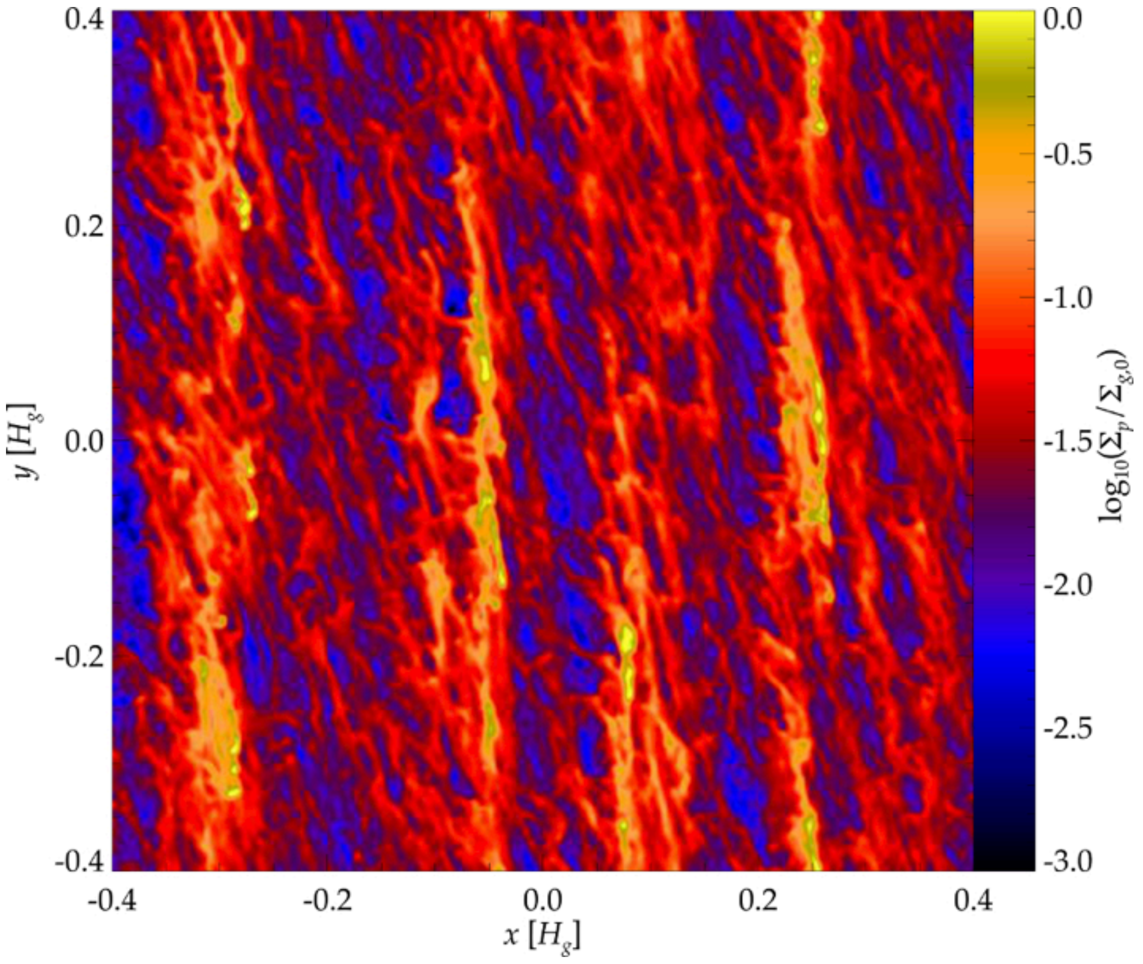
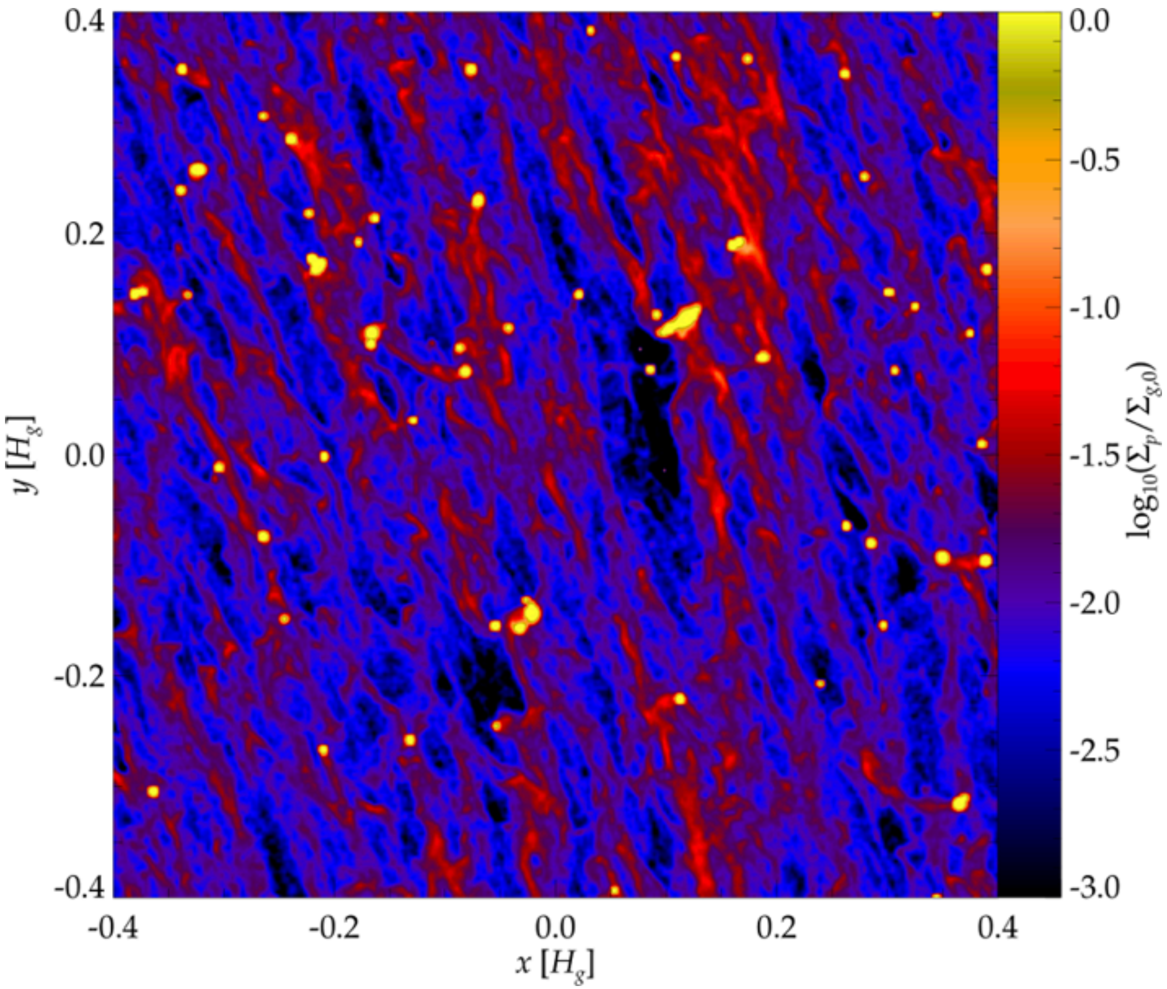
Adapted from slide by Chao-Chin Yang

Large box simulations





Emergence of axisymmetric structure

Larger planetesimals: planetary embryos formed

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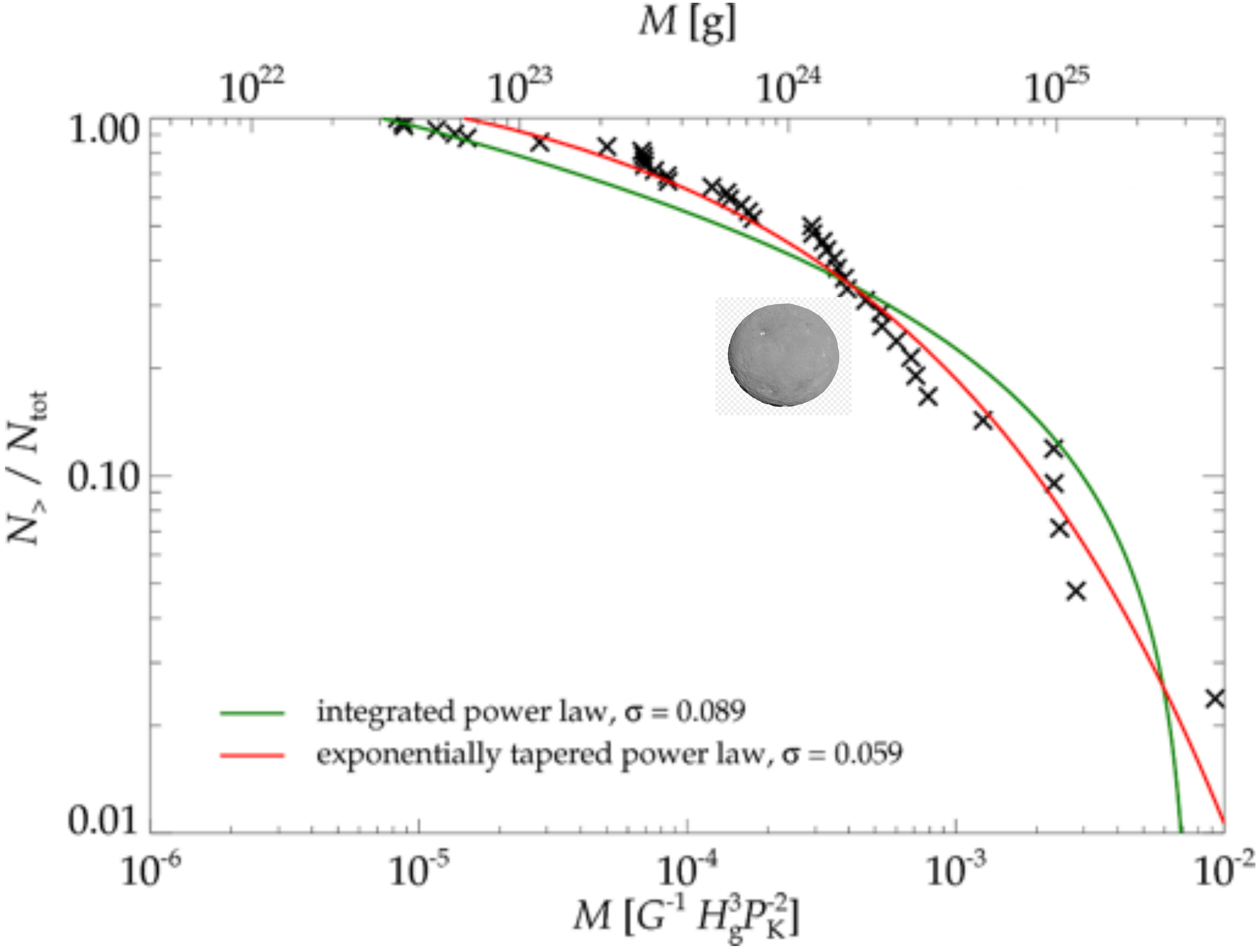
Yang & Johansen (2014); Schäfer, Yang, & Johansen (2017)

Adapted from slide by Chao-Chin Yang

Planets' Initial Mass Function



(Shallow) exponential cut-off

Cut-off mass depends on ring separation (toward oligarchic phase)

Schäfer, Yang, & Johansen (2017)

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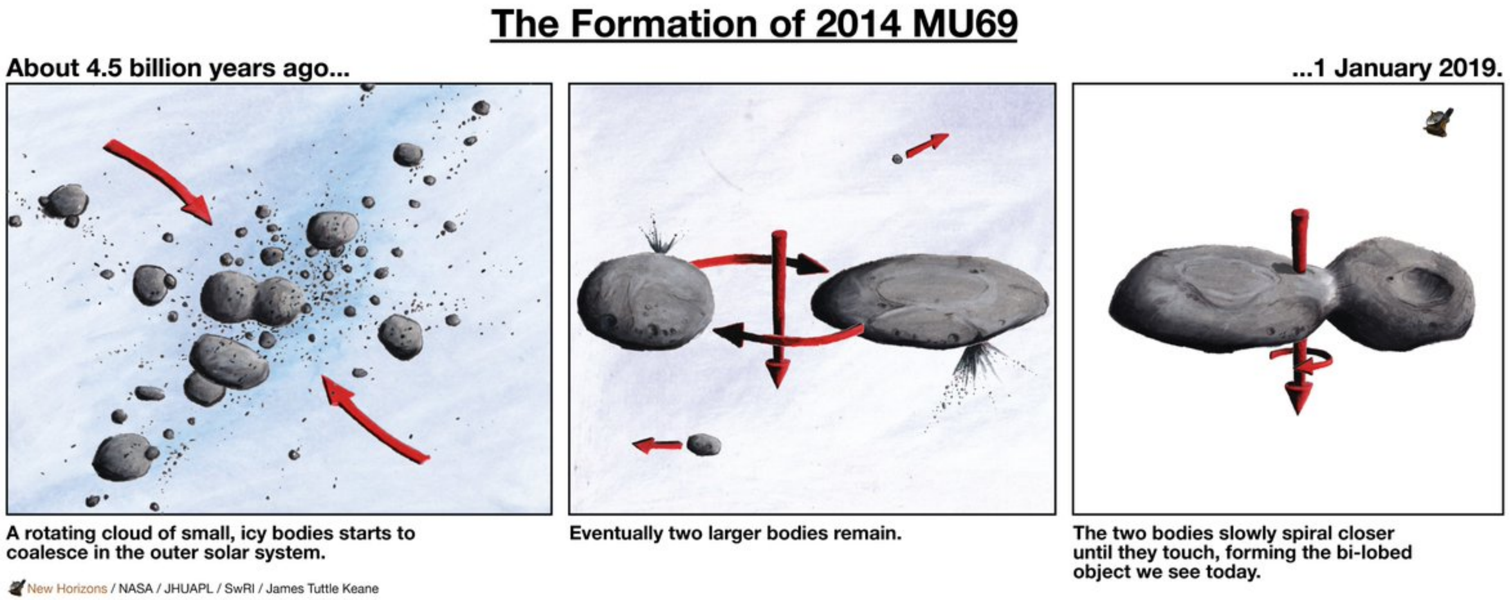
Adapted from slide by Chao-Chin Yang

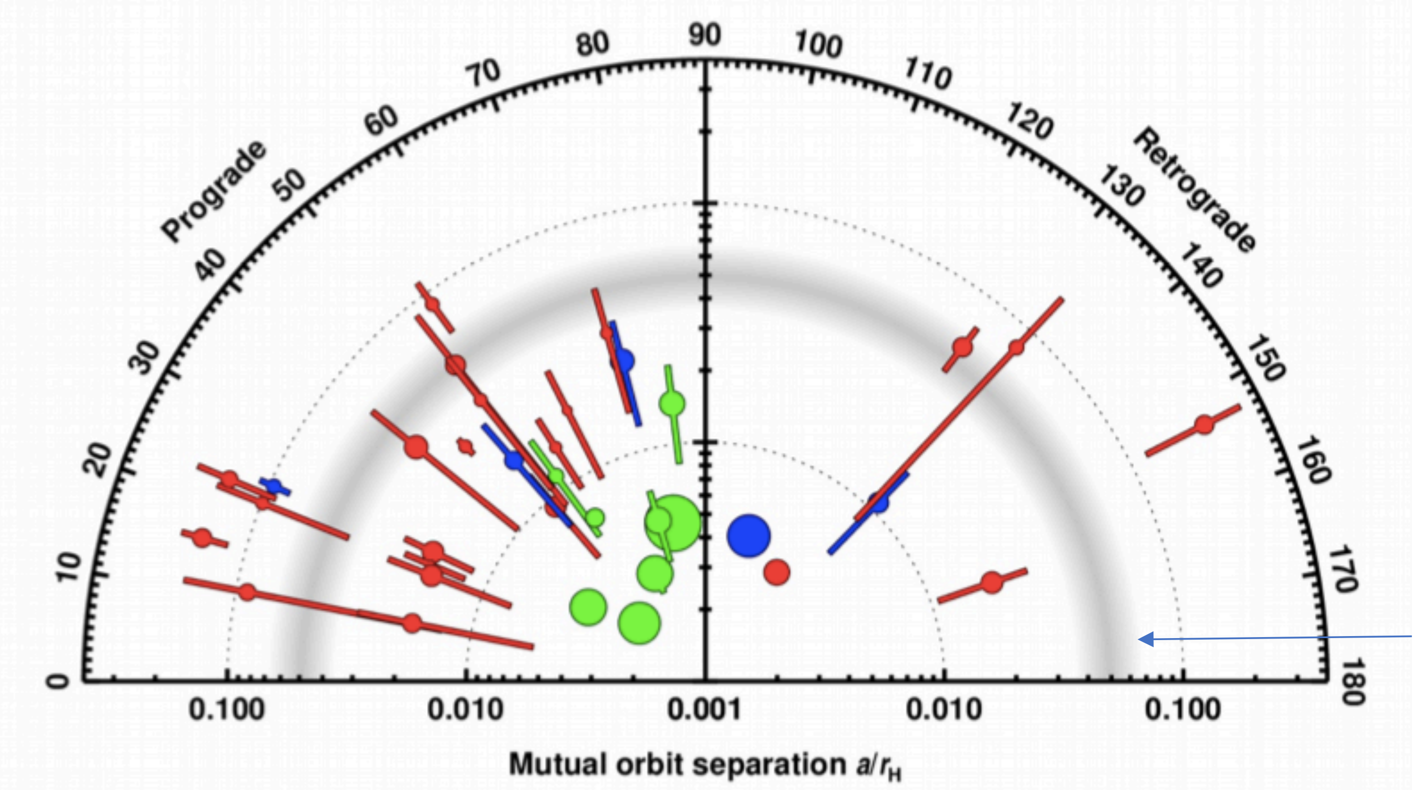
Ultima Thule is retrograde

Obliquity is ~100^{o}



Angular Momentum: Prograde vs Retrograde

Protractor Plot



Cold TNOs

Resonant

Centaurs / Scattered

0.05 a/r_H transition tight-wide binaries

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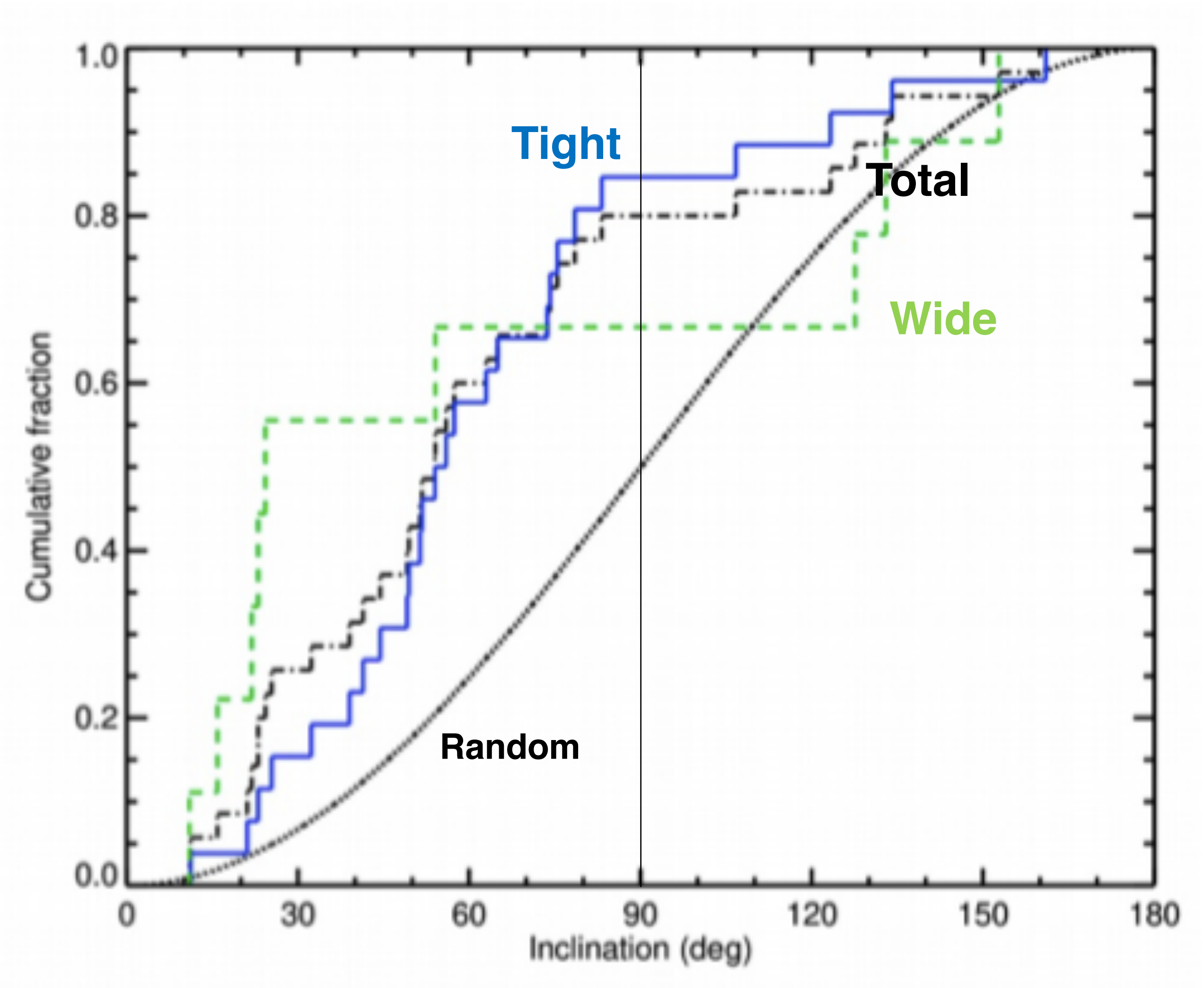
Noll+08, Grundy+19, Emmanuel Lellouch's talk, Rixin Li's talk

Angular Momentum: Prograde vs Retrograde

~80% of TNO binaries are prograde



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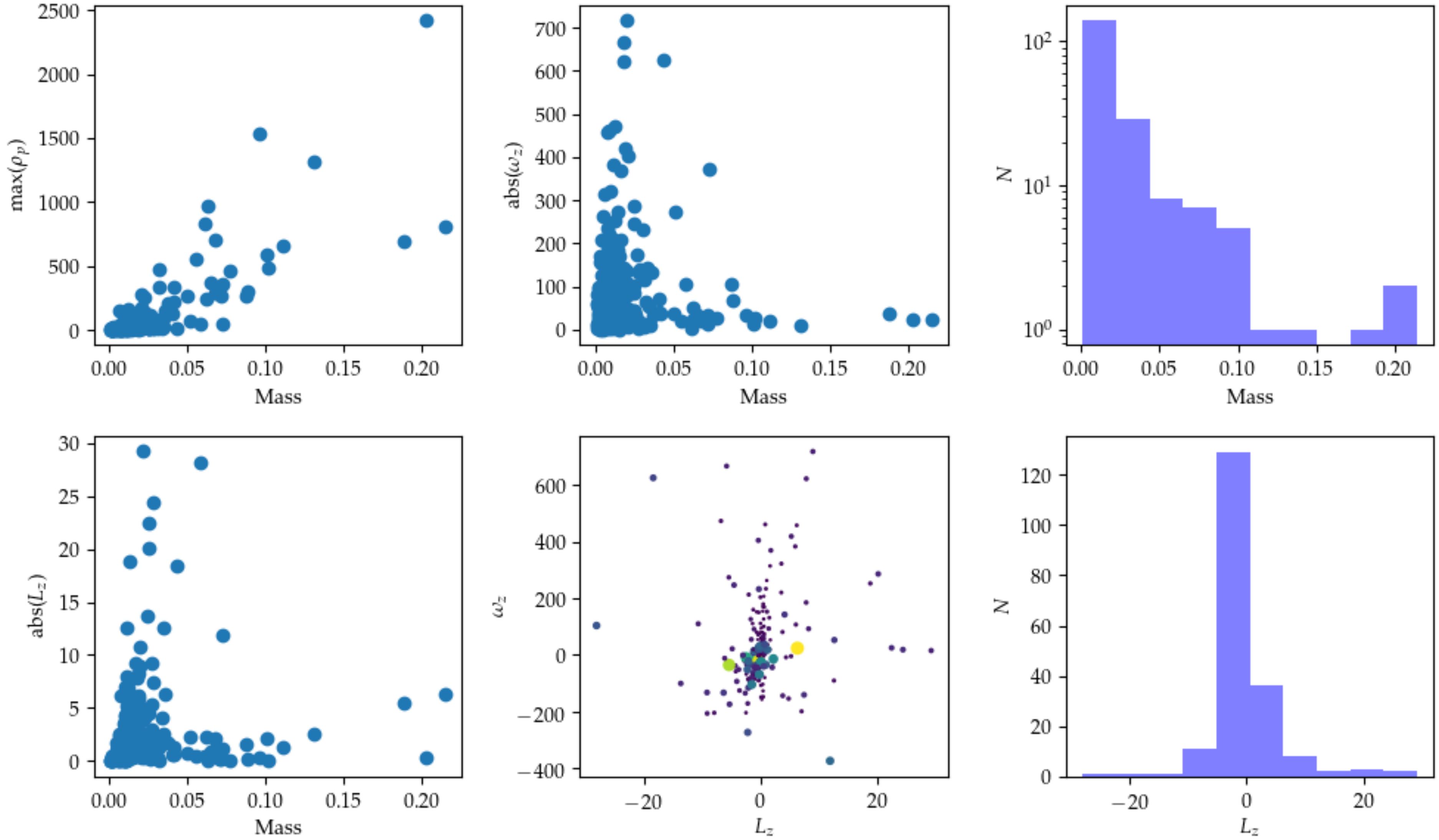
Grundy+19, Rixin Li's talk

Simulation results from YJ14



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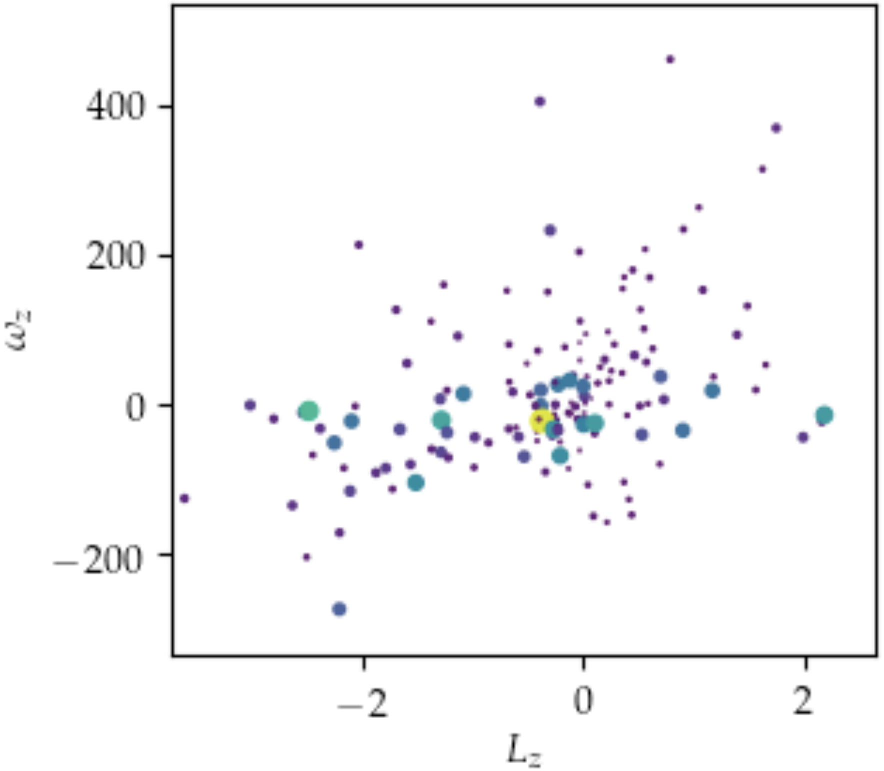
Data from Yang & Johansen (2014)

Gas vorticity and clump angular momentum



No strong correlation
No preference for prograde or retrograde

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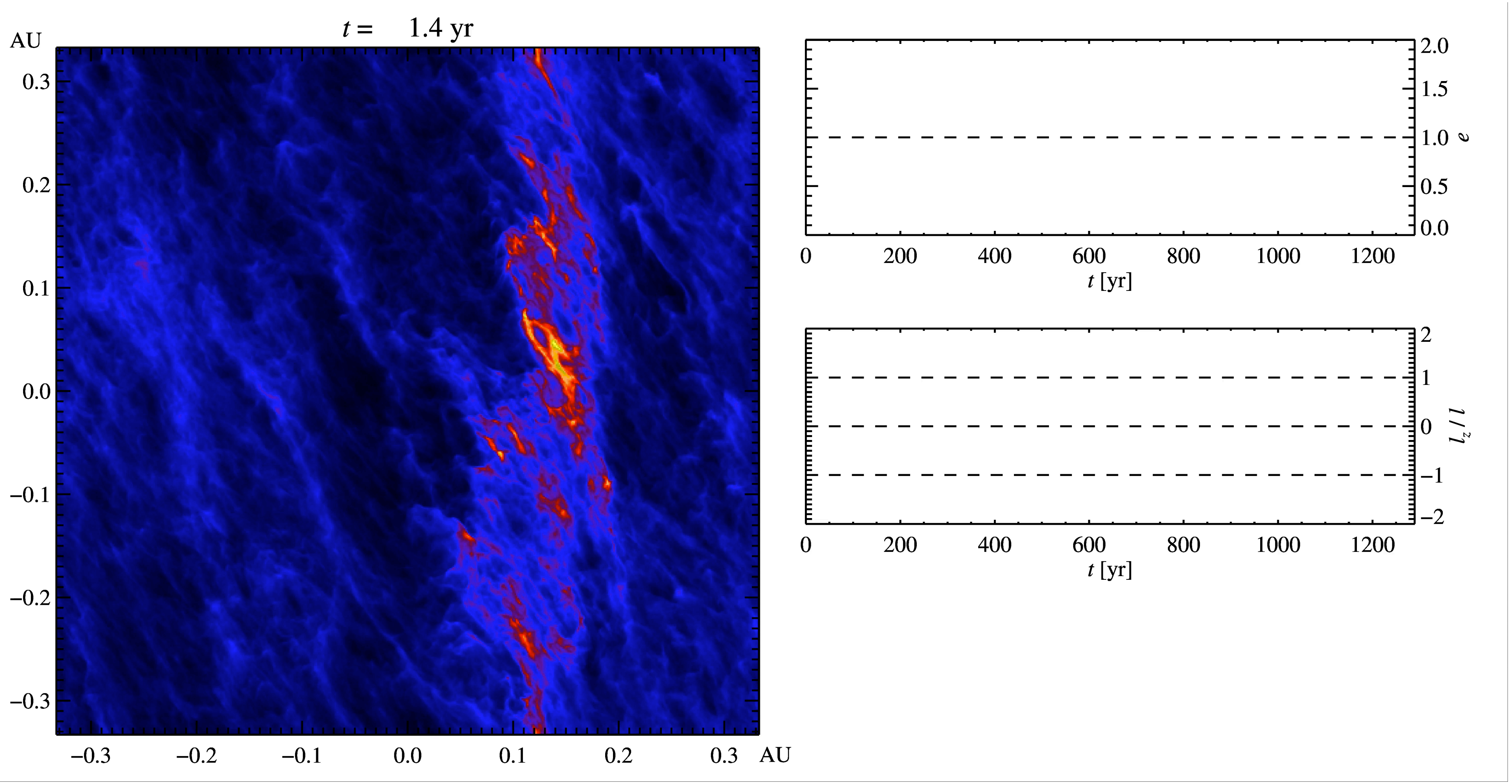
Data from Yang & Johansen (2014)

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



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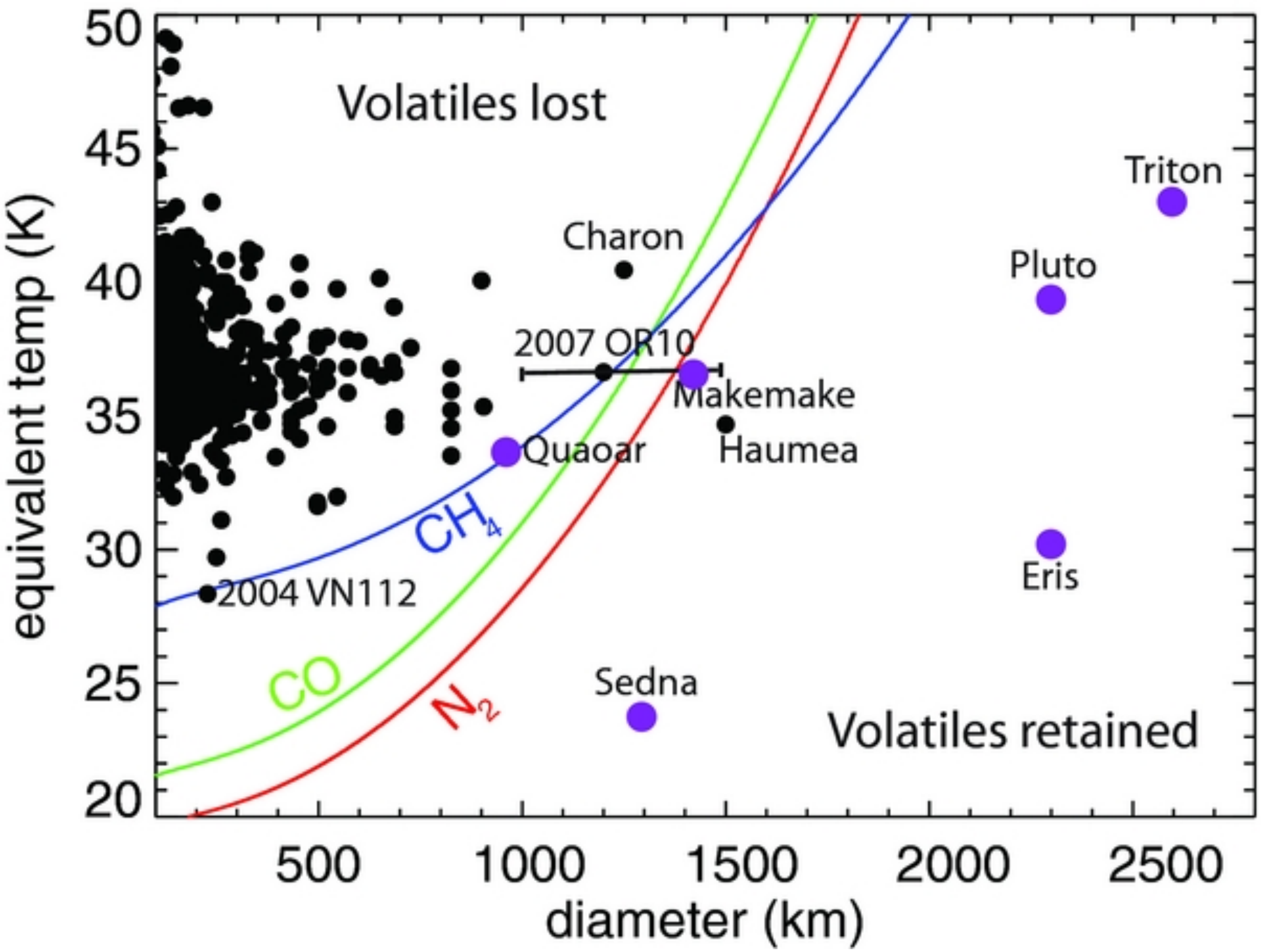
Data from A. Johansen (private communication), Rixin Li's talk

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

(Casey Lisse's talk!)

Needs shielding from starlight!!

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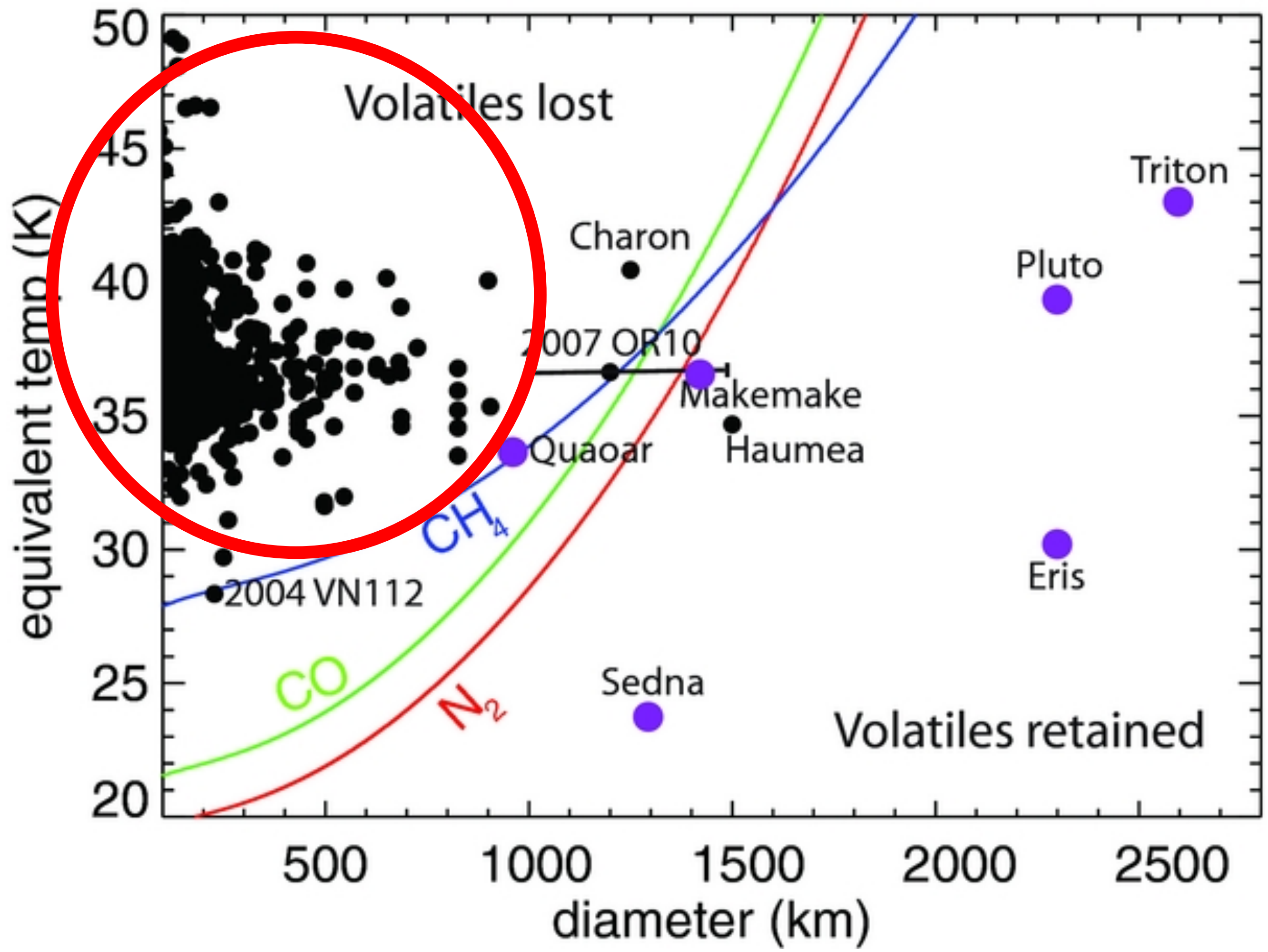
Brown, Burgasser, & Fraser (2011); also Casey Lisse's talk

Retention of volatiles

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



Losing the rum….

Needs shielding from the starlight flambé.

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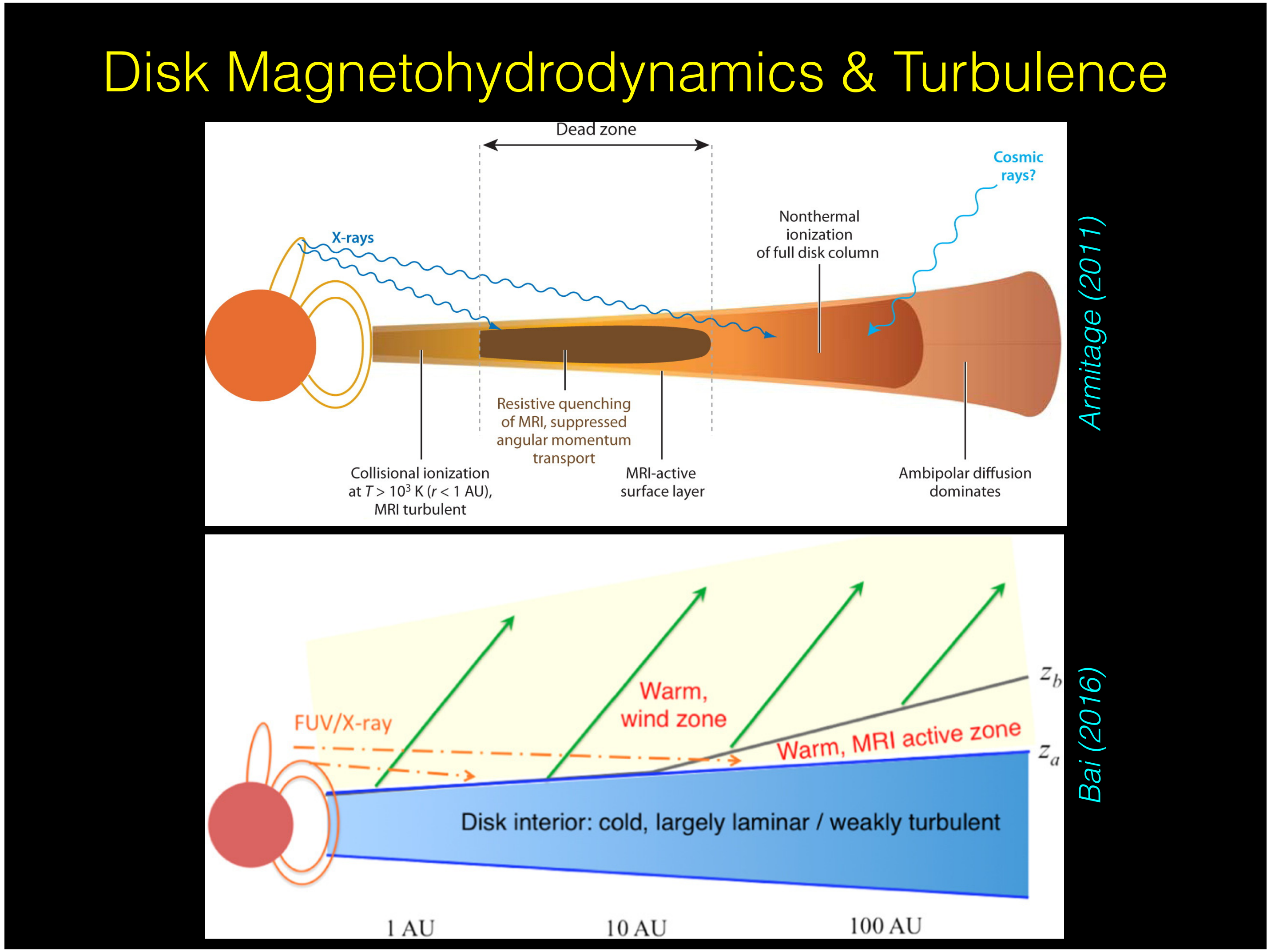
Brown, Burgasser, & Fraser (2011); also Casey Lisse's talk

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

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

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

For equal mass:

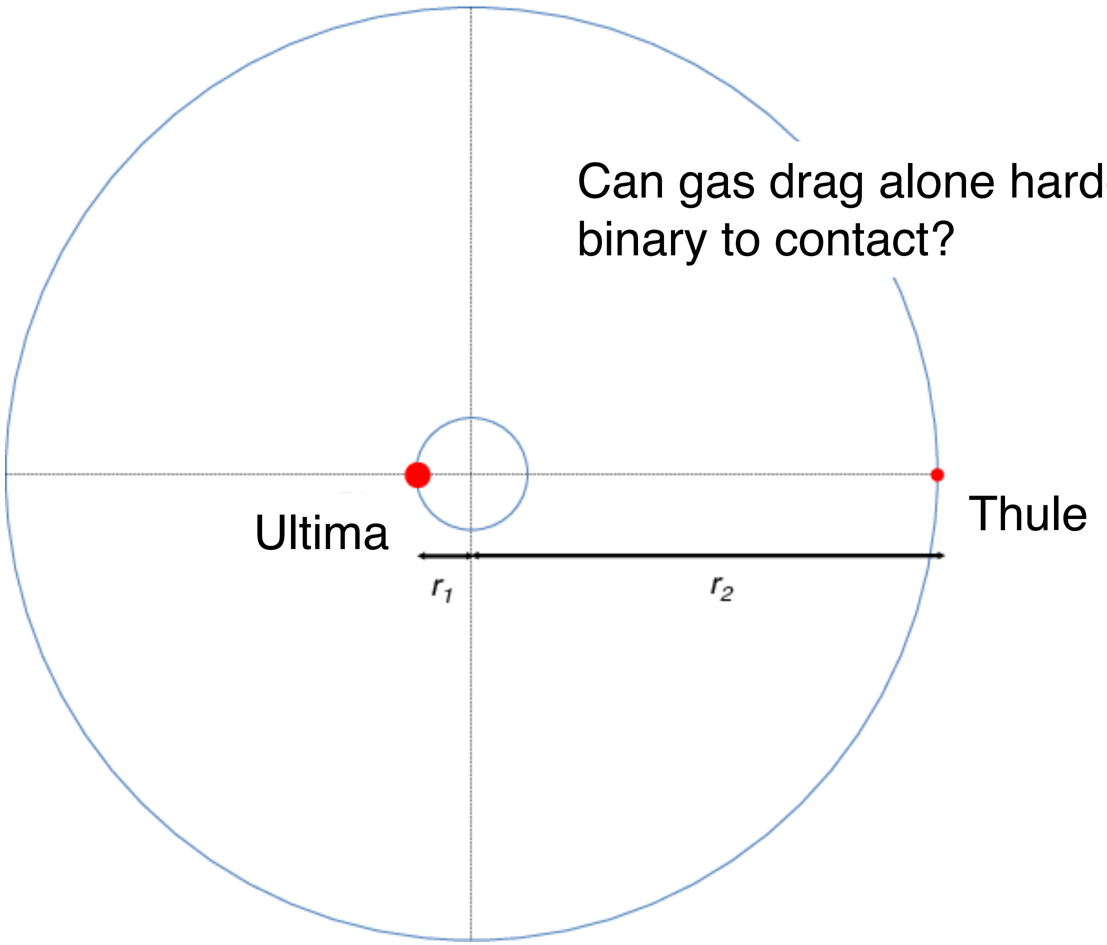
$$r\ddot{\phi} + 2\dot{r}\dot{\phi} = -\frac{r\dot{\phi}}{\tau}$$

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

Exponential decay of angular momentum !

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

Can gas drag alone harden the binary to contact?



Lyra+ in prep

Angular momentum loss via nebular drag

gravity

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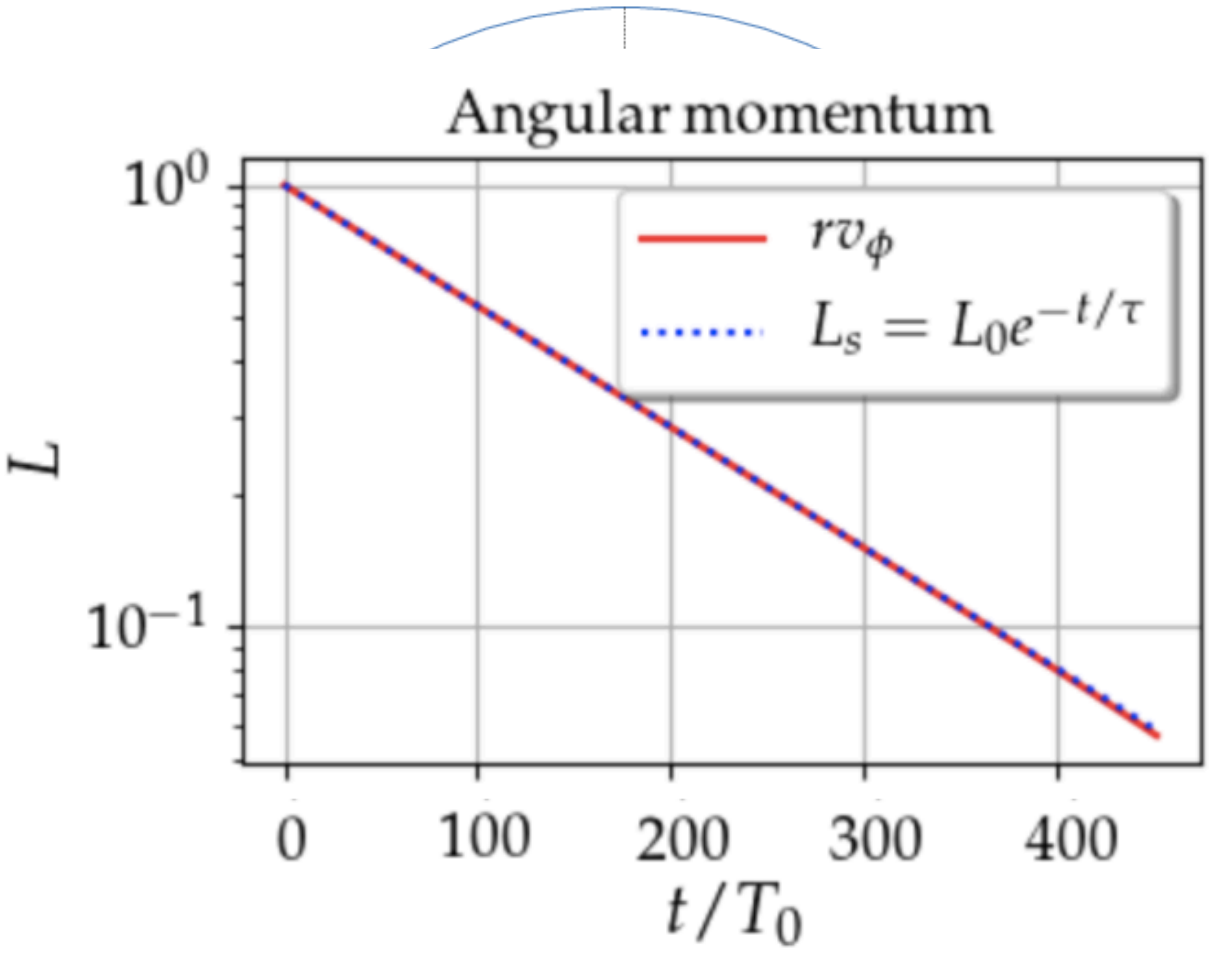

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Lyra+ in prep

Hardening during disk lifetime

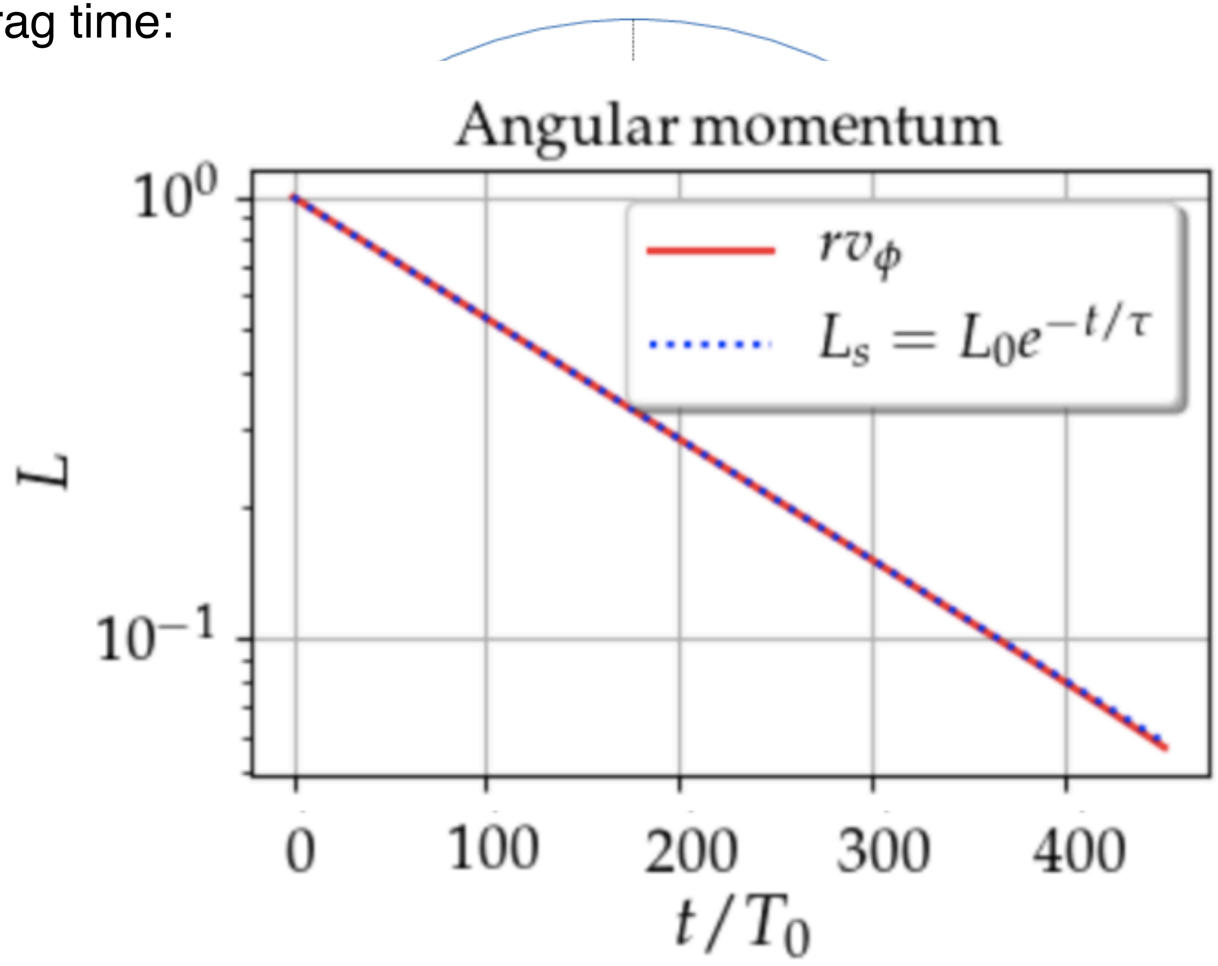
For unequal mass the physics is similar, the
drag time is just replaced by an effective drag time:

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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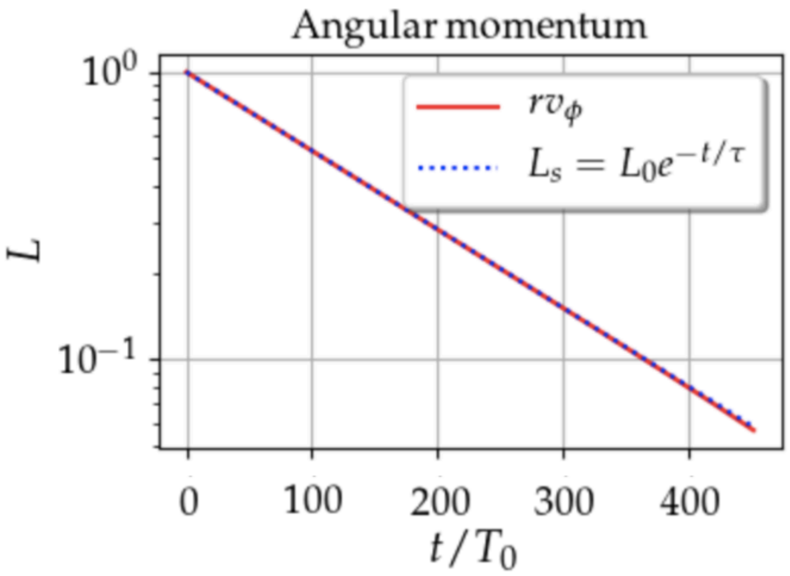
Lyra+ in prep

Analytical solution

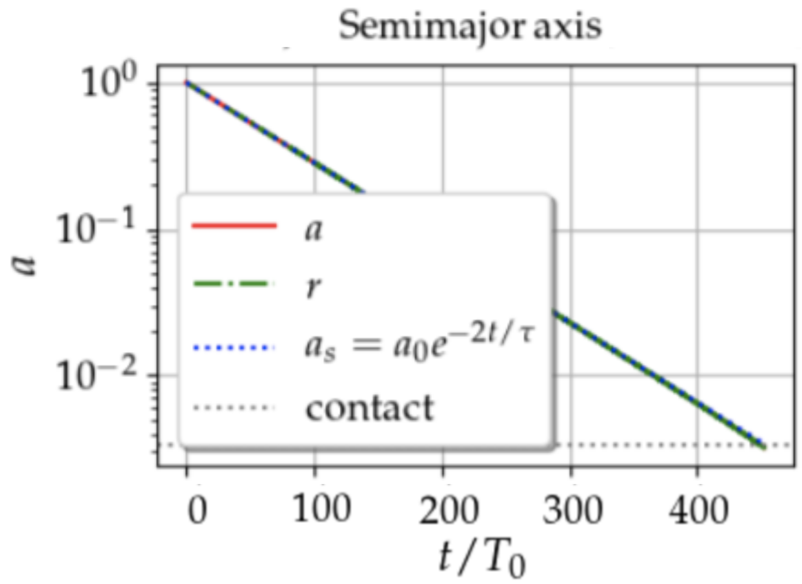
Exponential decay of angular momentum

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



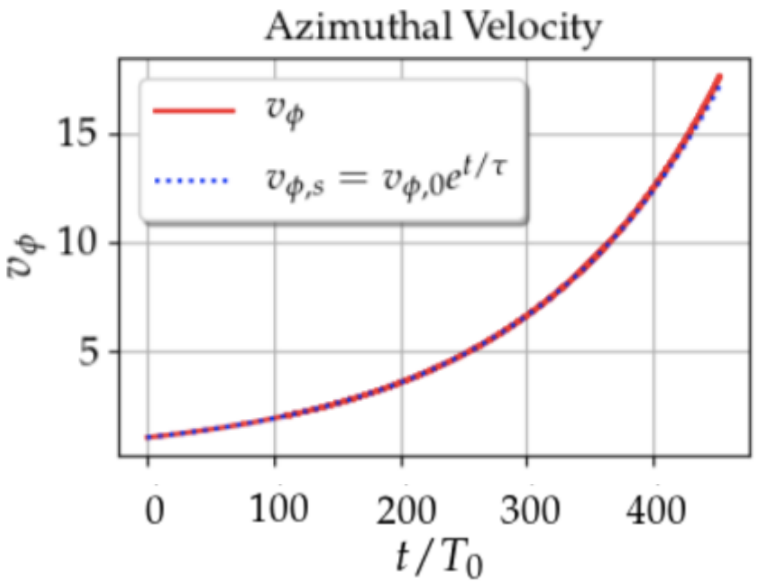
Exponential decay of semimajor axis

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



Exponential increase of orbital velocity

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



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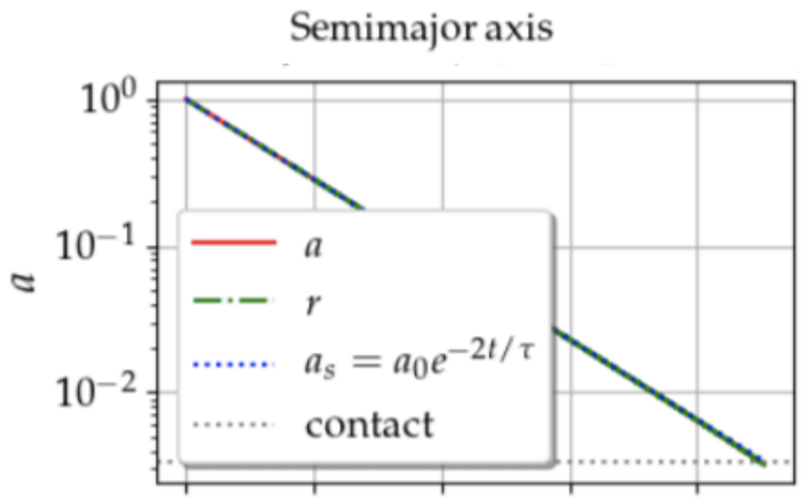
Analytical solution



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

Lyra+ in prep

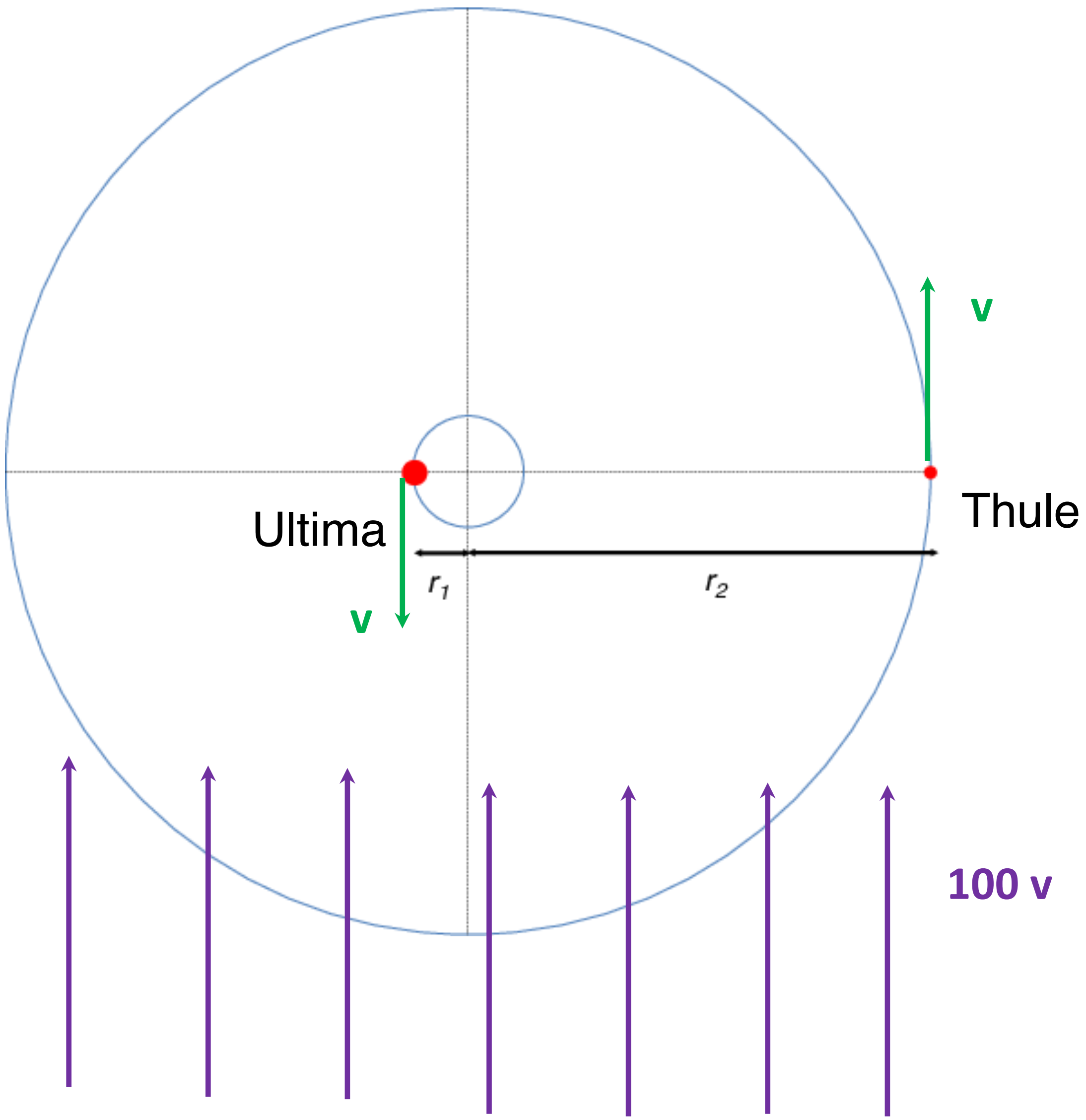
Wind

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

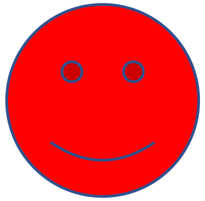


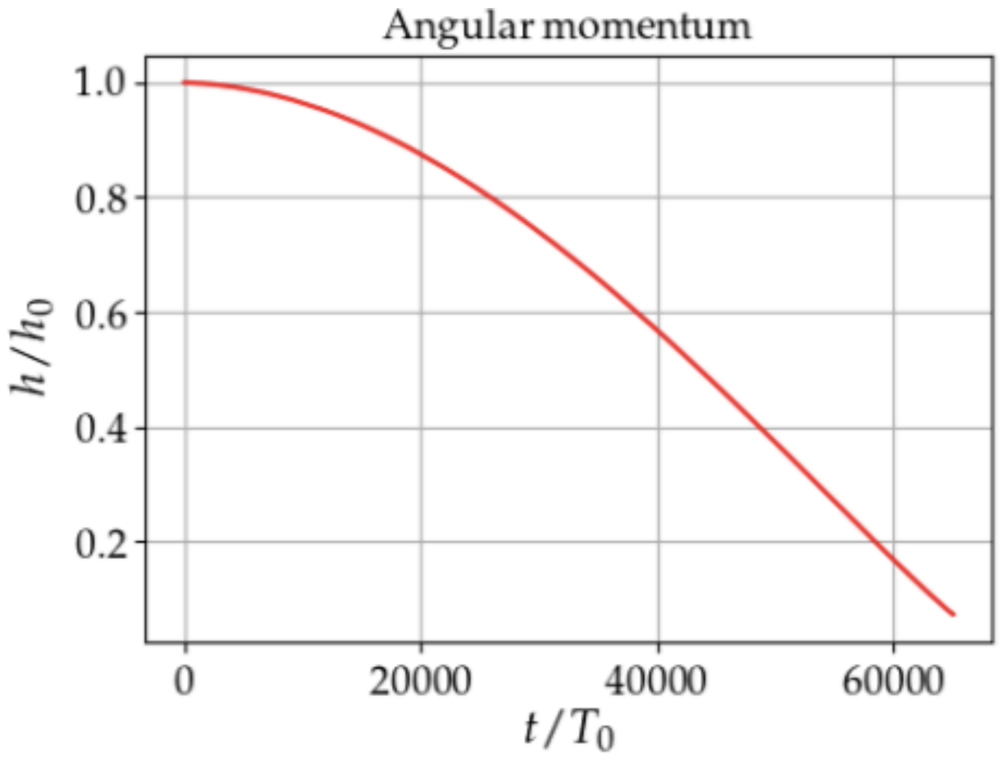
Lyra+ in prep

Sub-Keplerian wind-driven hardening

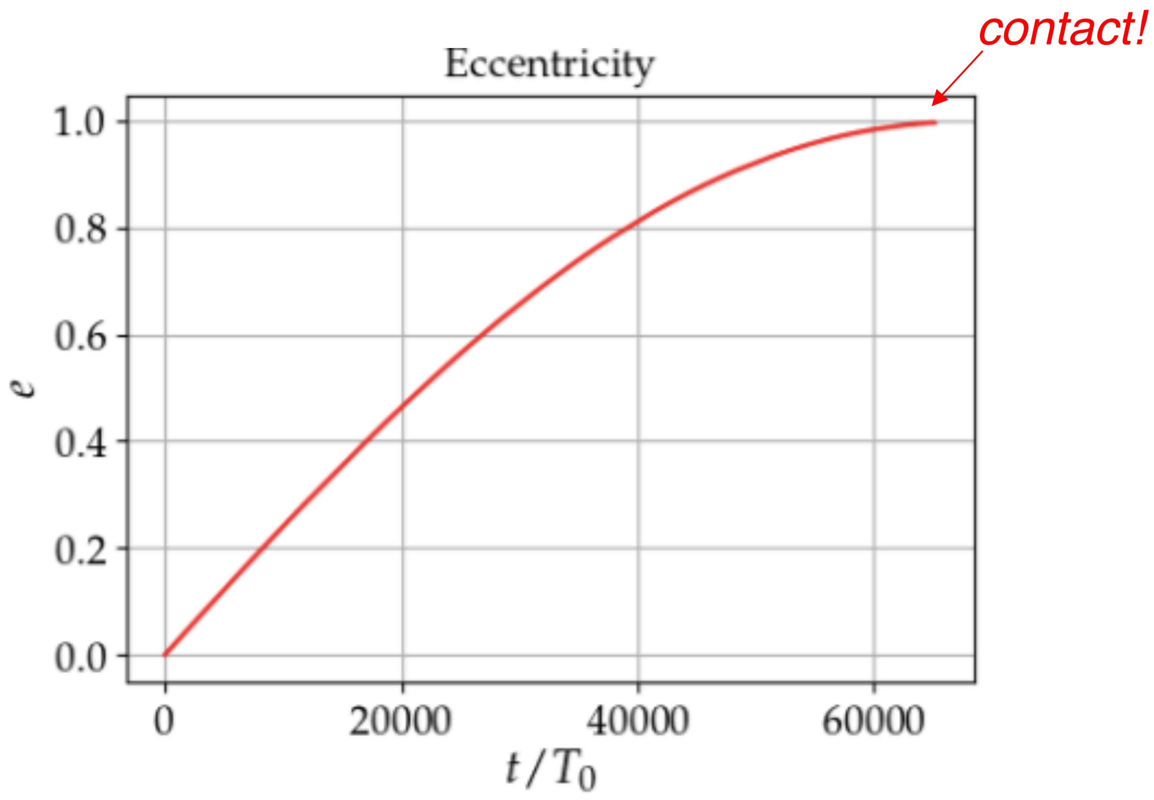
$\tau\Omega$ = 10^7

$t_{contact}$ ~ 10 Myr





Orbital drag makes it lose angular momentum



Wind increases eccentricity

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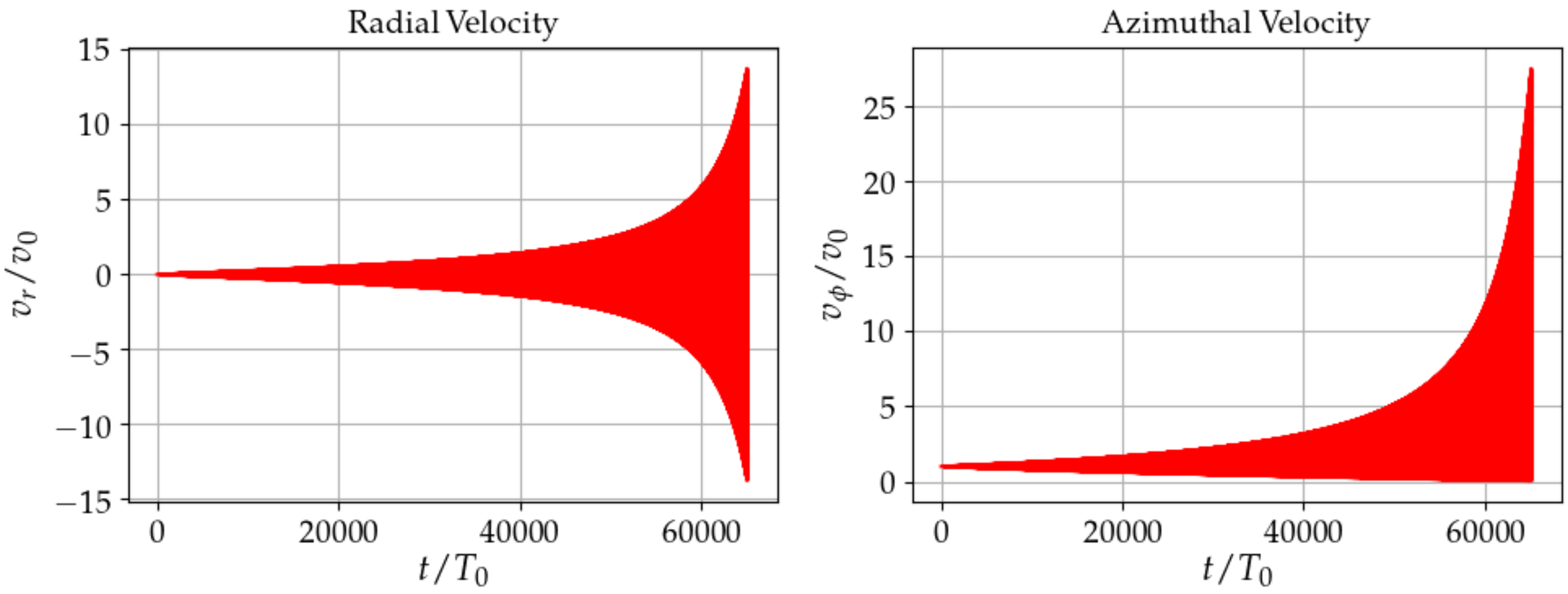
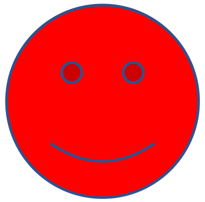
Sub-Keplerian wind-driven hardening



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



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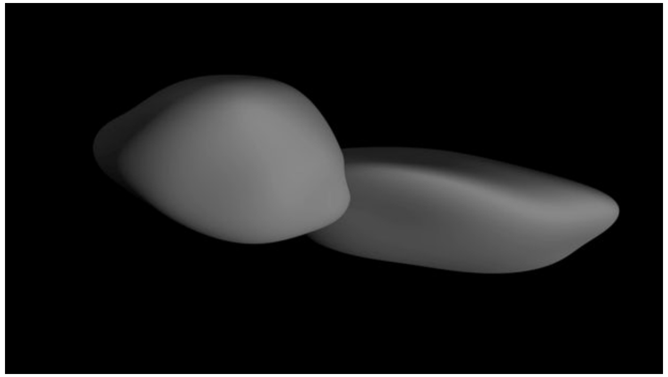
Lyra+ in prep

Conclusions
(or: walnut pancake recipe)

Ingredients

- One disk with little turbulence.
- Pebbles plentiful.
- A large scale pressure gradient.



Directions

Toss the pebbles in the disk and let it stream. Set the turbulence dial to “low” to keep viscous heating from sublimating the N_2 (you will need it for frosting). Set your kitchen timer to a few kyr. By that time you should have plenty of mid-separation binaries. Set aside and let it cool in the draft of the pressure gradient. Set the timer for 10 Myr or until disk dissipates. Flame it with galactic radiation. Serve with a side of red tholin.

Manuscript in preparation, if I can get a quiet week or two.