The Formation of Pluto's Small Satellites

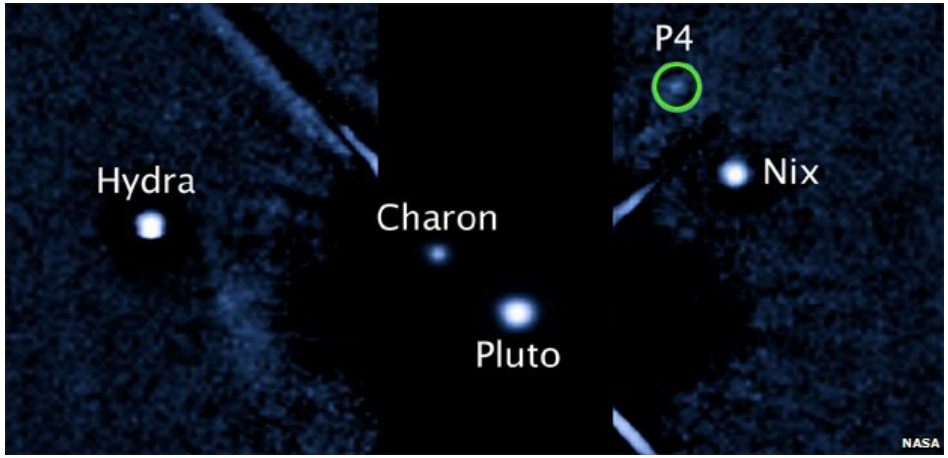
(Proof of the Existence of God?)

Hal Levison
Southwest Research Institute
Boulder, CO
USA

With help from:
Kevin Walsh, Robin Canup, Bill Ward, and Dave Kaufmann

An Apple- and Microsoft-Free Presentation

Overview of System



Name	Semi-major Axis	Period	Eccentricity	Inclination	Mass
Charon	17	1	$<8\times10^{-5}$	0.001°	0.117
Nix	43	3.99	0.001	0.2°	$\lesssim4\times10^{-6}$
P4	51	5.03	<0.02	?	TINY
Hydra	57	6.06	0.001	0.2°	$\lesssim7\times10^{-6}$

Tholen et al. (2008); Weaver et al. (2006); Showalter et al. (2011); Youdin et al. (2012); Buie et al.(2012)

Things to note:

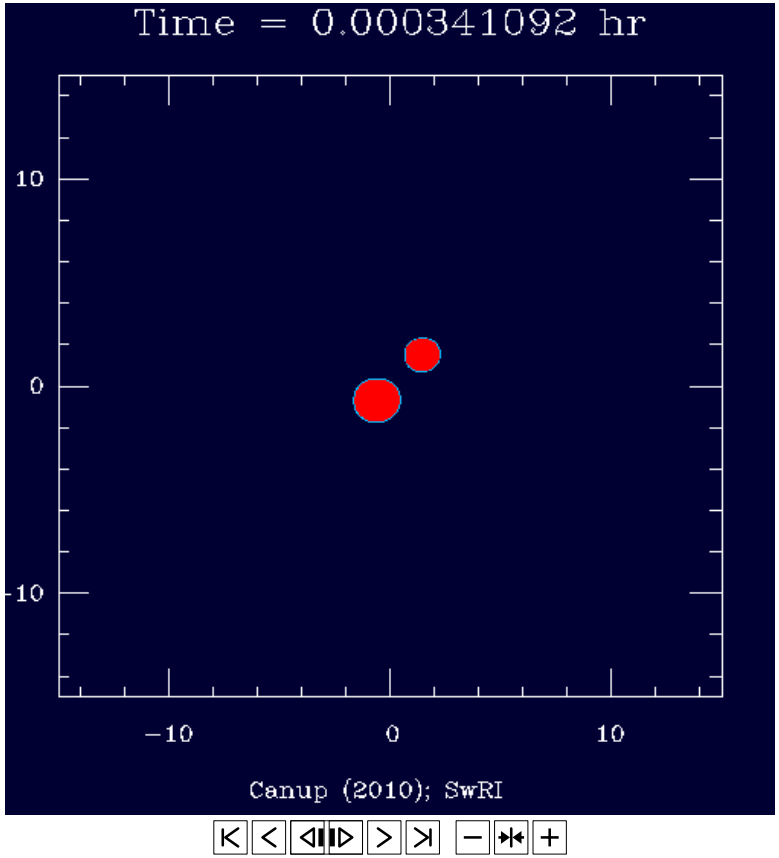
- Nearly-circular, co-planar, prograde orbits $\Rightarrow$ formed out of a disk(?)
- All three small guys are near resonances. (4:1, 5:1, 6:1)
- They are really, really tiny (So why does anyone care?)
- They are really far from Pluto.
- New HST data show no other satellites and no rings. *(Buie)*

The Story People Want to Tell

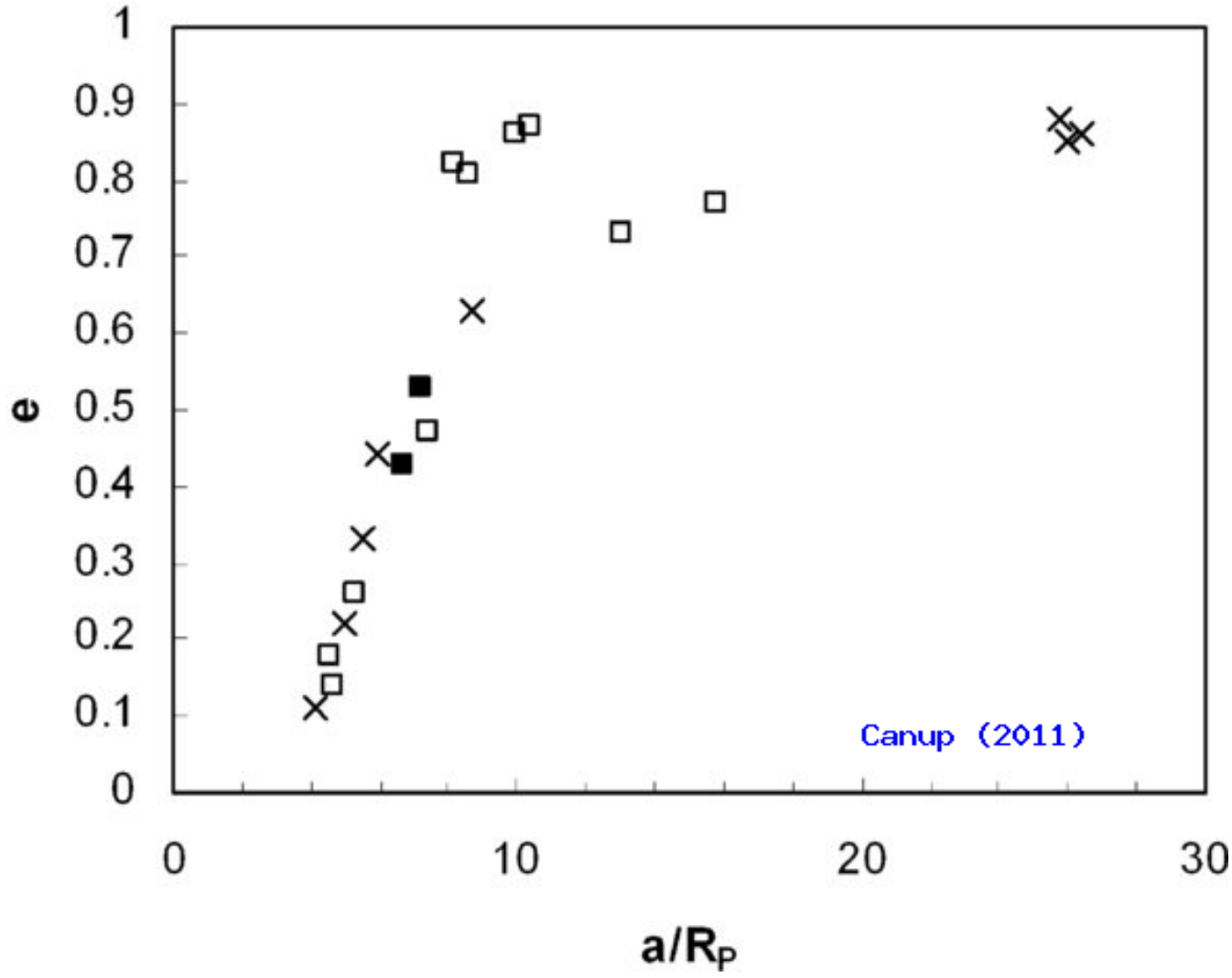
- Charon forms in a collision with a massive KBO. *(Mckinnon; Canup)*

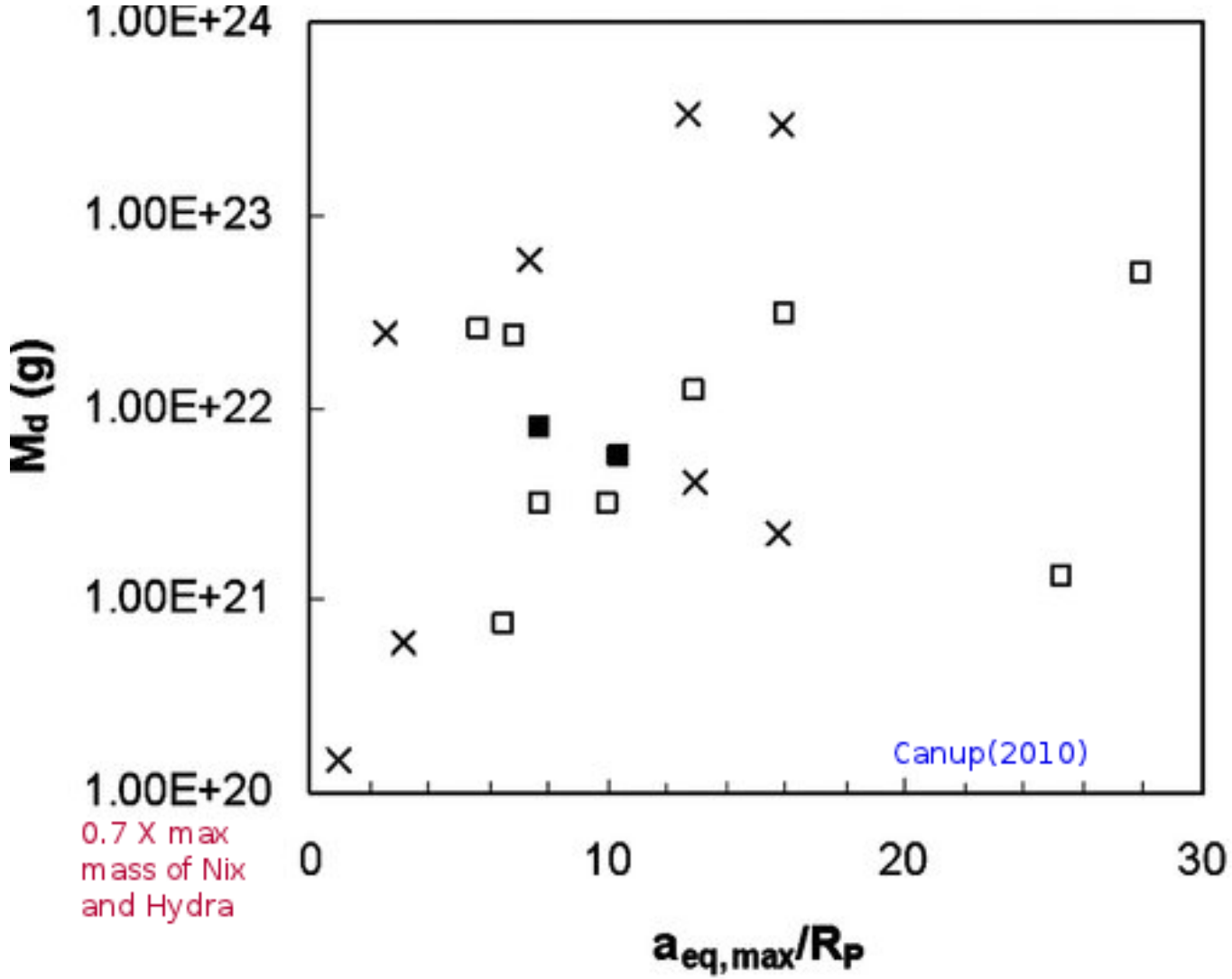
  Canup (2011):

  - Need objects involved in collision to be partially differentiated.
  - Produces a Charon on an eccentric orbit with $a \lesssim 10\,R_P$.
  - Also, an ice rich debris disk, but inside of $\sim 20\,R_P$.
    - Recall that Hydra is at $\sim 60\,R_P$.
    - We need something to move the satellites out.

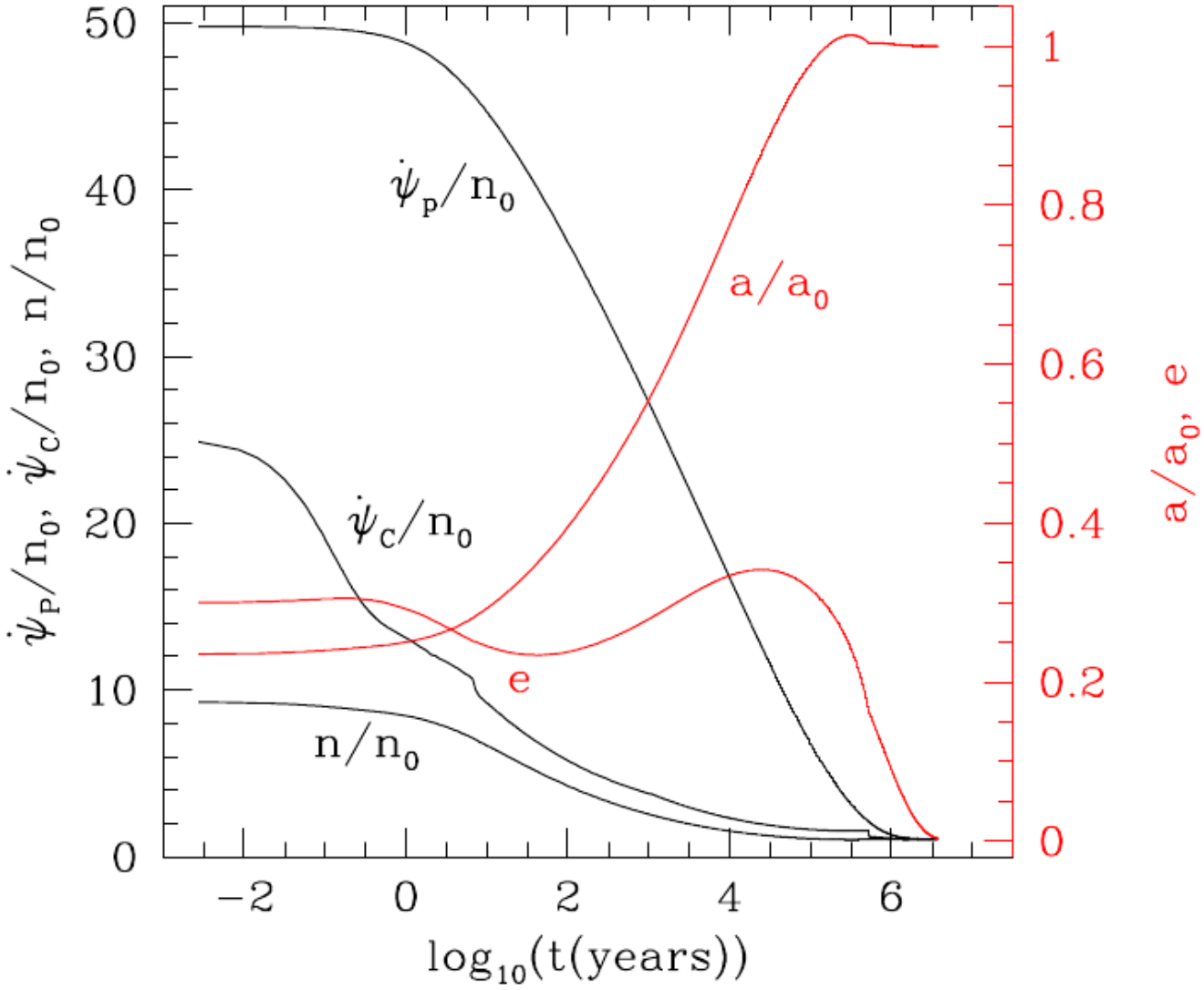


- Charon tidally evolves outward.
- The small satellites get trapped in resonances as Charon moves out.
  - Like the Kuiper belt.
  - Unfortunately, it is not so easy.


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
e
0
10
20
30
a/R_P
Canup (2011)

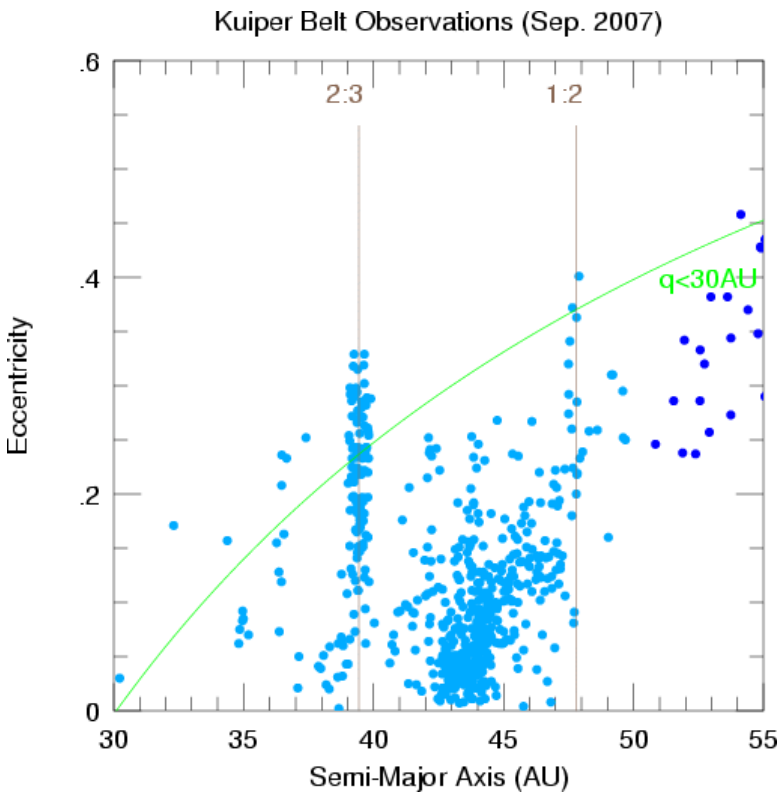

1.00E+24
1.00E+23
1.00E+22
1.00E+21
1.00E+20
M_d (g)
0
10
20
30
$a_{eq,max}/R_P$
Canup(2010)
0.7 X max mass of Nix and Hydra

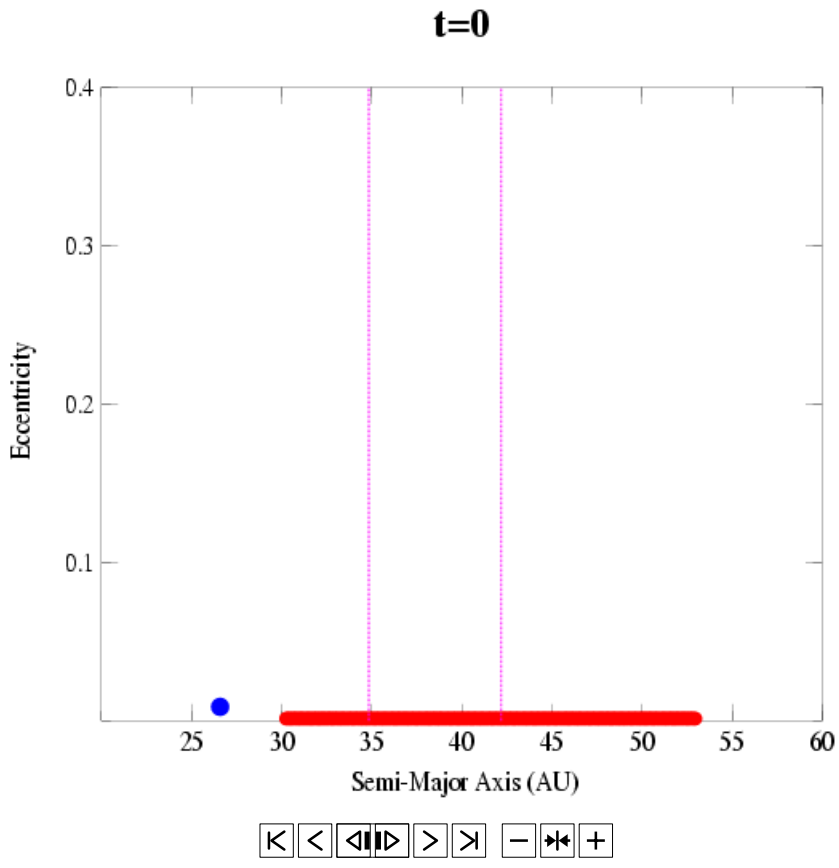
Peale et al. (2011)



Basics of Resonance Trapping

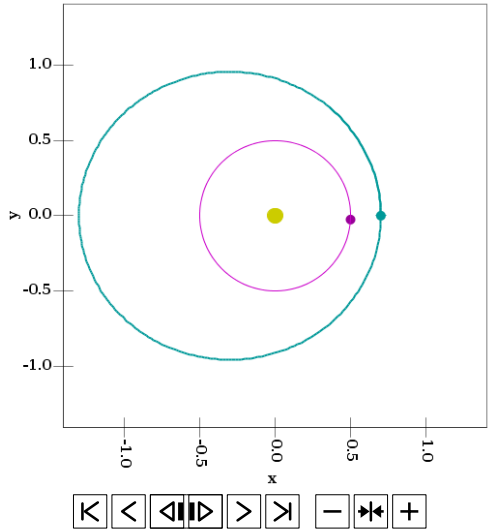
- *'Normal'* MMRs excite eccentricities during outward migration.
  - This has been used to explain the structure of the Kuiper belt.
  - This is a problem because Charon has to move so far that small guys become unstable.
- But, there are really 2 basic types of mean motion resonances.
  1. *Lindblad Resonances* (LRs):
     - Resonance between radial period of small guy and synodic period.
     - Strength is a function of eccentricity of small guy.
     - These are the 'normal' resonances.
  2. *Corotation Resonances* (CRs):
     - Resonance between the orbital periods of small and big guys.
     - Strength is a function of eccentricity of big guy.
     - Don't see them in Solar System because 'big guys' are nearly-circular.
- Ward & Canup (2006) showed that CRs might be able to do it.
  - Recall that Charon is eccentric so these resonance exist.
  - And, corotation resonances do **not** excite eccentricities.
- However, there is a current debate about whether this can work.
  - The latest analytic work suggests that Nix and Hydra can be captured if $e_C < 0.0528$. No one has done P4. *(Ward & Canup)*
  - Careful numerical work has not been able to reproduce this *(Peale et al. 2011)*
- Probably need to find another mechanism.

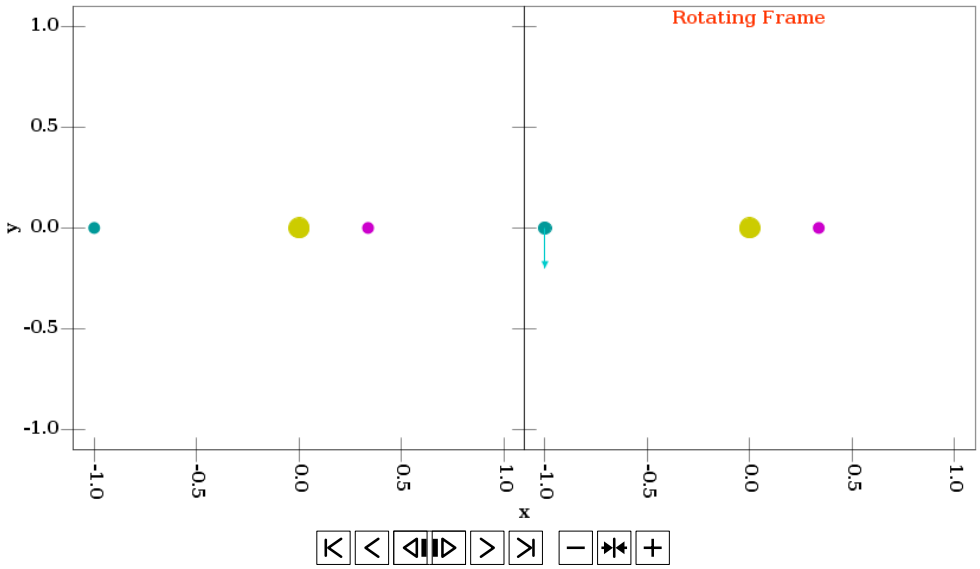

Kuiper Belt Observations (Sep. 2007)
2:3
1:2
q<30AU
Eccentricity
Semi-Major Axis (AU)
0
.2
.4
.6
30
35
40
45
50
55


t=0
Eccentricity
Semi-Major Axis (AU)
0.1
0.2
0.3
0.4
25
30
35
40
45
50
55
60

- An unperturbed orbit: distance has the same period as mean motion.
- If you add a massive body the 2 periods are different.
- Thus, there are 2 different resonances at 2 slightly different locations.

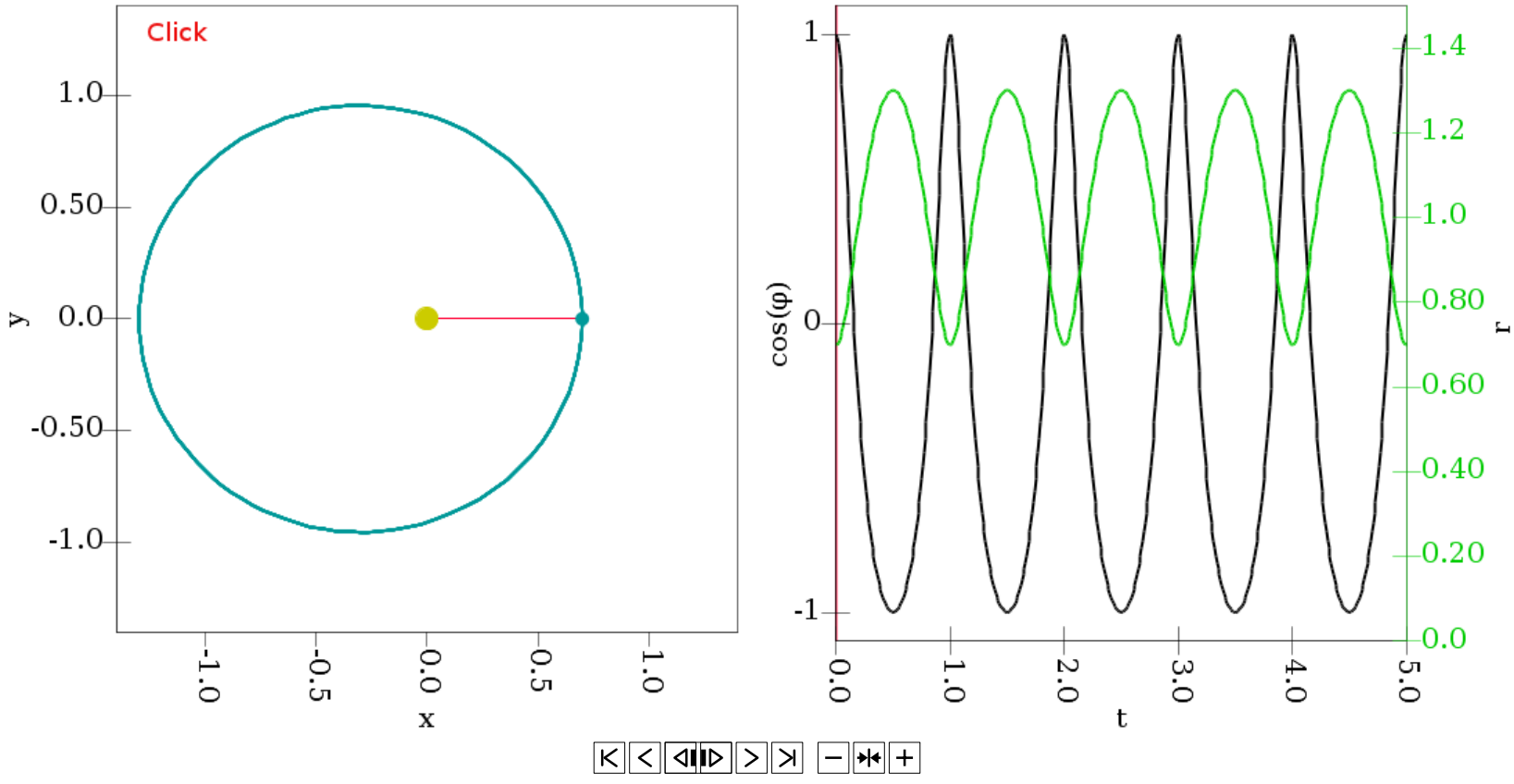
- *Lindblad Resonances* (LRs):
  - Resonance between the radial period of small guy and synoptic period.
  - So, small guy is at same place in orbit at conjunction $\Longrightarrow$ large changes in e.





Corotation Resonances (CRs):

- Resonance between orbital periods.
- Geometry at conjunction changes $\Longrightarrow$ weak.
- Unless e of big guy is large.


Click
1.0
0.50
0.0
-0.50
-1.0
y
-1.0
-0.5
0.0
0.5
1.0
x
1
0
-1
cos(φ)
0.0
1.0
2.0
3.0
4.0
5.0
t
1.4
1.2
1.0
0.80
0.60
0.40
0.20
0.0
r

The Role of Collisional Damping

With Kevin Walsh

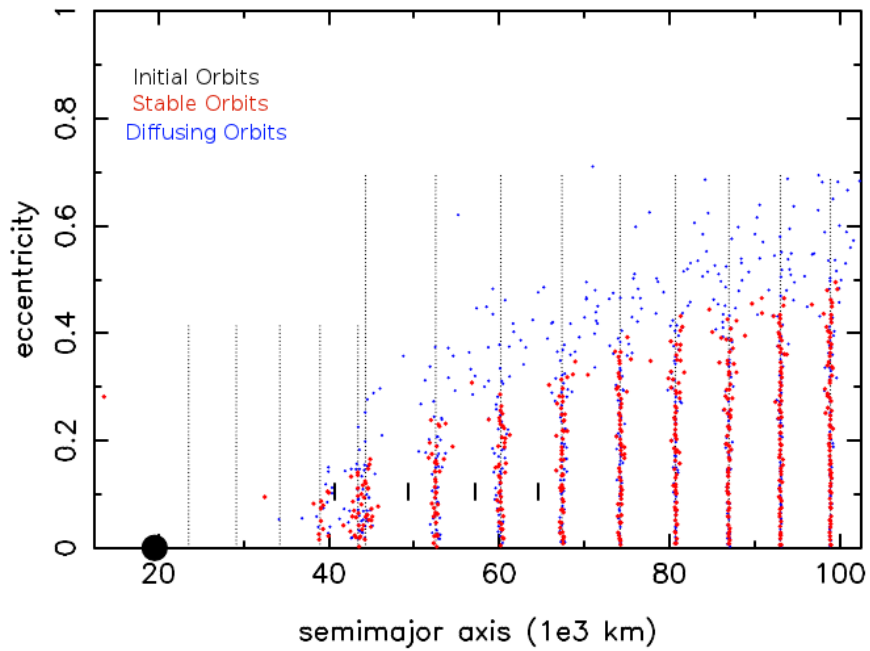
- Previous work has ignored the effects of collisions.
  - These can affect orbits because energy is not conserved.
    - It decreases energy $\Longrightarrow$ circular orbits.
    - Recall that Nix, Hydra, and P4 are on low-eccentricity orbits.
  - In unperturbed systems angular momentum **is** conserved $\Longrightarrow$ can't move things out very far.
    - At most a factor of 2, which is not enough.
- However, the gravitational perturbations of Charon can pump angular momentum into the system.

  Comes in two forms:

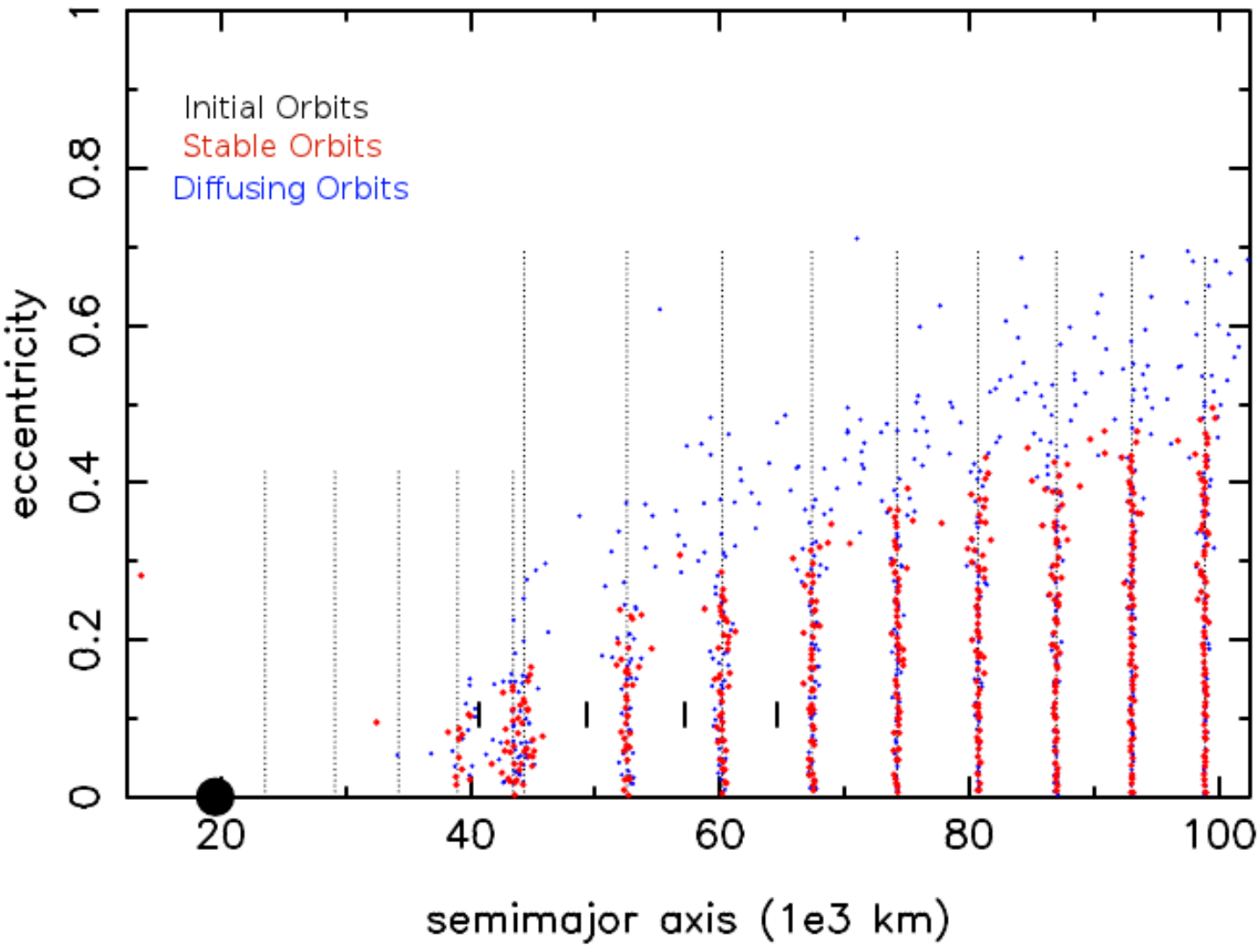
  1. Distant scatterings.
  2. Mean motion resonances.
- We address each separately.

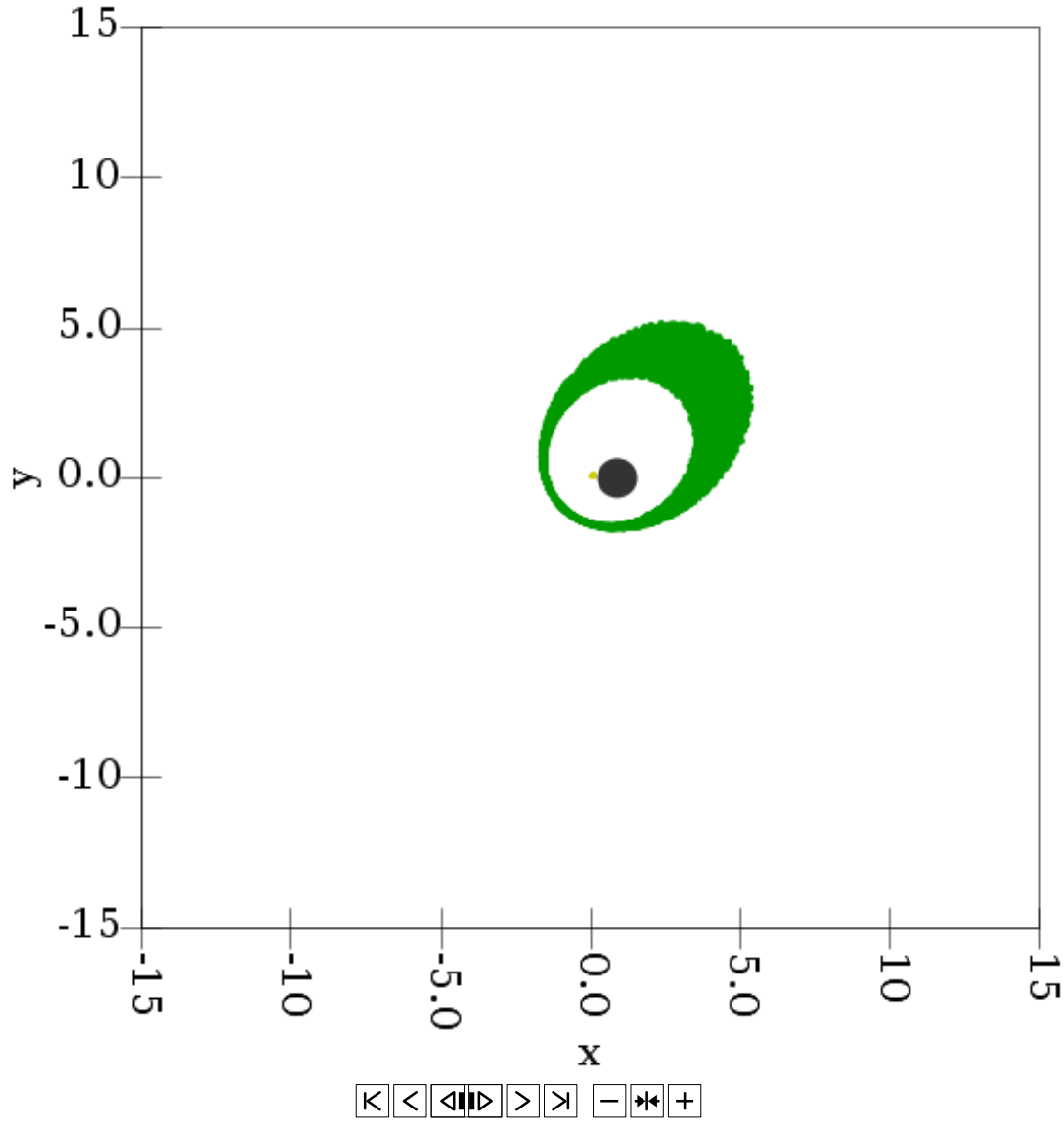
Distant Scatterings

- Charon is very massive and thus can push particles around.
- There is a huge region beyond Charon that is not stable.



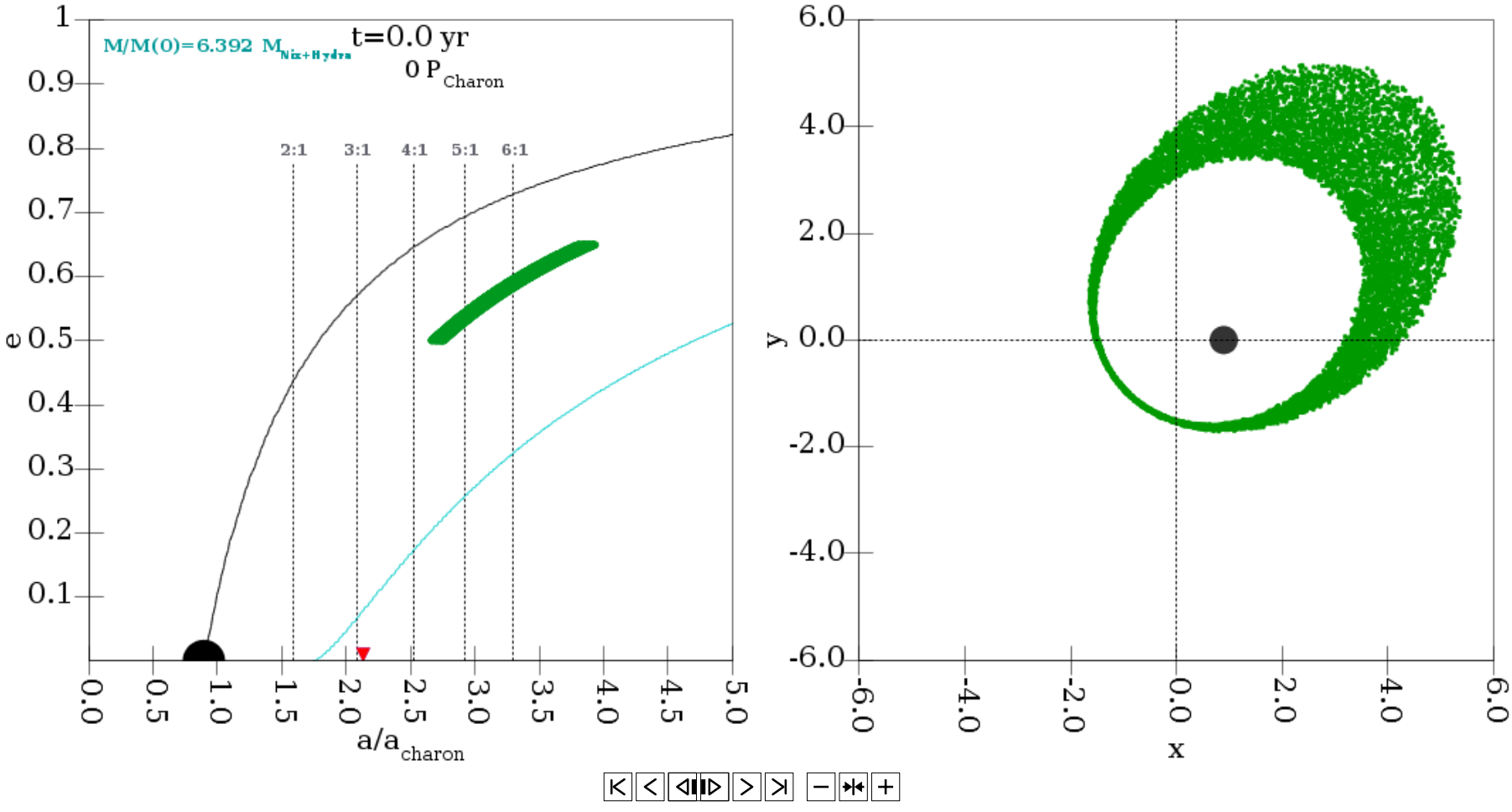
- In just an orbit or two, it can push objects outward.
  - I.e. increase angular momentum.
- If we include collisional evolution, we can get mass at large distances.
  - This can now be done with a new code called *LIPAD*.
  - Need a high collisional depth $\Longrightarrow$ small objects.
  - But, initially velocities are high enough to fragment bodies.
    - So, grinding will aid the process


Initial Orbits
Stable Orbits
Diffusing Orbits
eccentricity
0
0.2
0.4
0.6
0.8
1
20
40
60
80
100
semimajor axis (1e3 km)


15
10
5.0
y 0.0
-5.0
-10
-15
-15
-10
-5.0
0.0
5.0
10
15
x

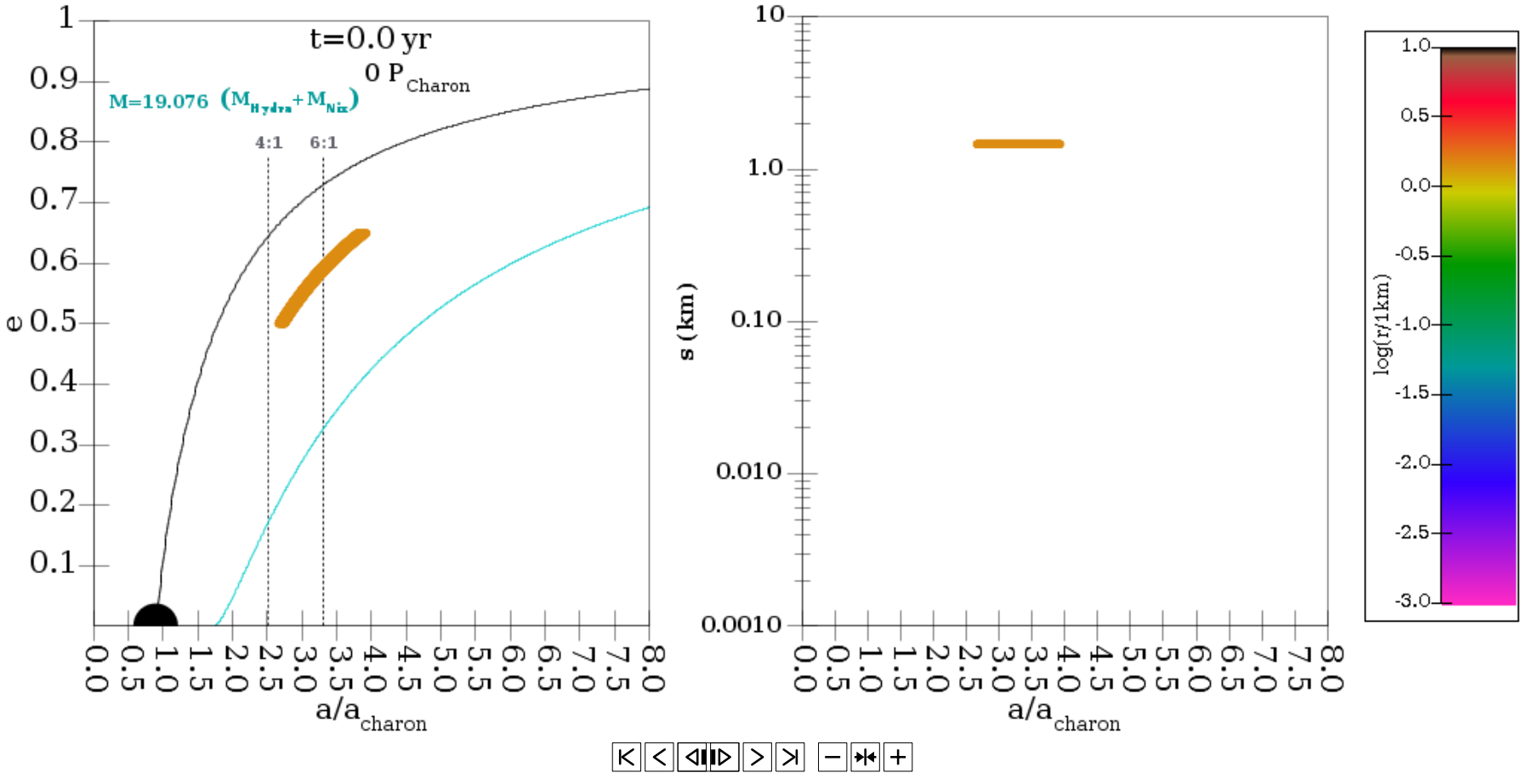
Example with no growth/fragmentation:

50 m objects: total mass of $7\times10^{-5}\ M_{\rm pluto} = 6\times(M_{\rm Nix}+M_{\rm Hydra})$



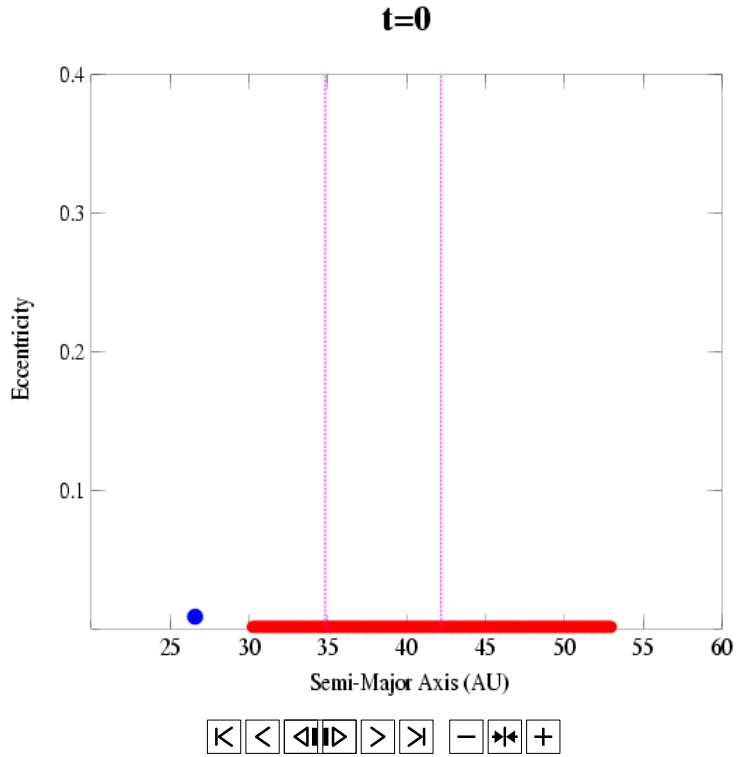
Example with growth/fragmentation: $1.5\,\mathrm{km}$ objects:

total mass $= 2\times10^{-4}\,M_{\mathrm{pluto}} = 19\times(M_{\mathrm{Nix}}+M_{\mathrm{Hydra}})$



Collisional Damping Near Mean Motion Resonances

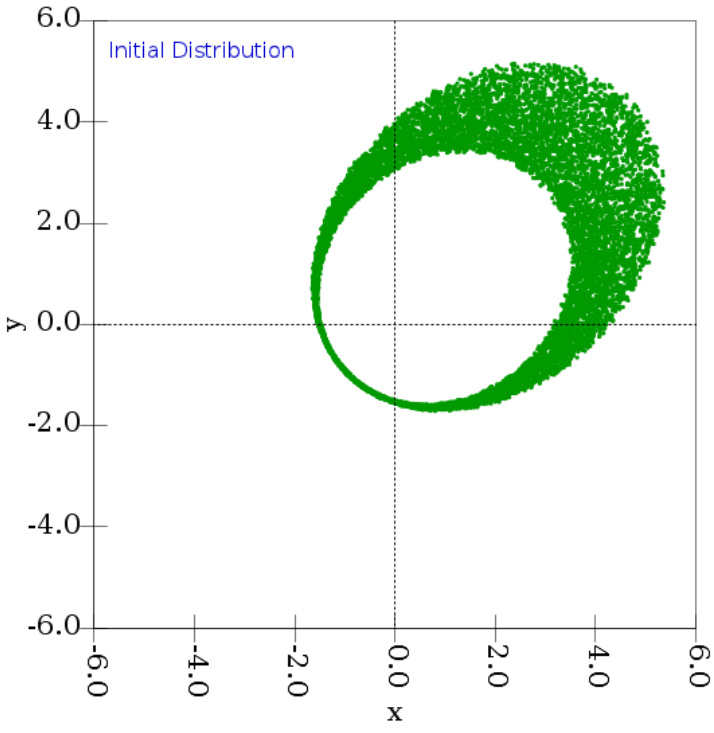
- Recall that the outward migration of big guy can trap small guys in LRs.
- This also happens if drag is bringing the little guys in.
- Indeed, all you need is converging orbits.
- This increases angular momentum of particles.

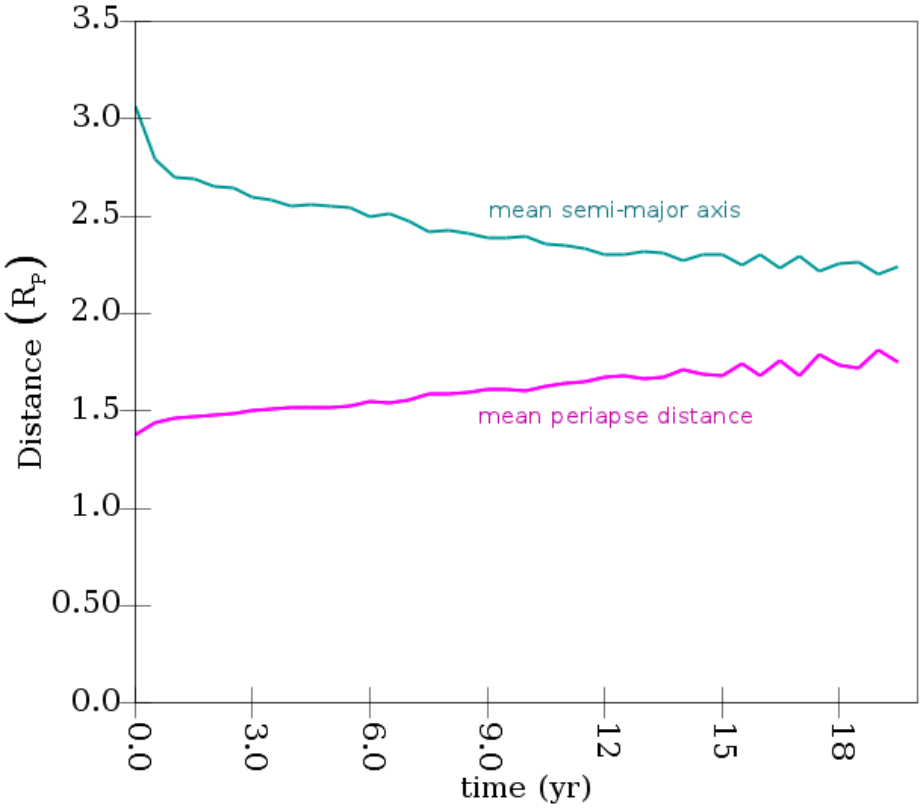


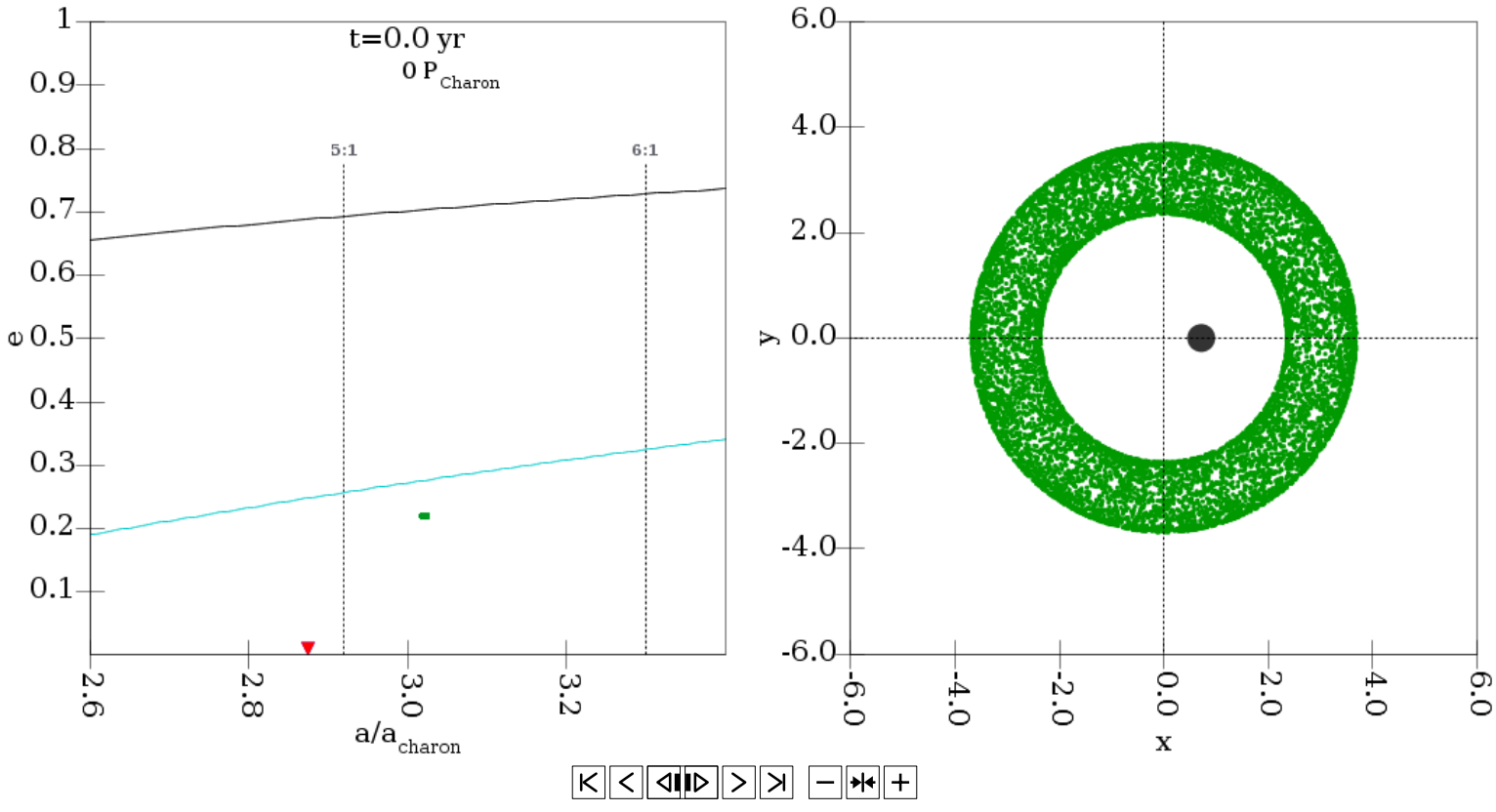
- An unperturbed collisionally damped ring has a slow decrease in semi-major axis.
- This, however, can lead to resonance crossing, which can dump in angular momemtum.
  - It is subtle and works best when Charon is eccentric.
  - Perhaps this can explain why the satellites are near resonances.

So, we should be happy, right?

No Charon:


Initial Distribution
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
y
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
x


3.5
3.0
2.5
2.0
1.5
1.0
0.50
0.0
Distance (R_P)
mean semi-major axis
mean periapse distance
0.0
3.0
6.0
9.0
12
15
18
time (yr)


t=0.0 yr
0 P Charon
5:1
6:1
e
a/a charon
y
x

So, why is this guy frowning?

- After all, we have mechanisms that:
  1. deliver material beyond the 6:1 mean motion resonance.
  2. put material preferentially near the resonances.

- Unfortunately, we have yet to be able to turn this into a model that works.
  - We first thought we could use ejecta from cratering events on Charon. But,
    - It crosses Charon's orbit too deeply $\Longrightarrow$ very short lifetime.
    - It was too dynamically excited, including stuff of retrograde orbits.
    - It fine tuning to get the ejection velocities right.

- Fortunately, there are other ideas that we can try:
  1. Satellite(s) were carried outward by the LRs and collided and ground when their orbits crossed.
     - Probably means multiple generations of satellites.
  2. Satellite(s) that were broken up by external KBOs.
     - Recall, the system was in an environment where Pluto got hit by something big.
     - So, the lifetime of Nix and Hydra must be short.
  3. Two external KBOs collide close to Pluto leaving a debris disk.
     - Can you get the prograde orbits at the end?

Conclusions

- Forming Nix, P4, and Hydra has turned out to be a pain.
  1. They are far from Pluto
  2. They are in low-eccentricity, low-inclination orbits.
  3. They are near mean motion resonances with Charon.
- Standard tidal migration of Charon does not work.
  1. 'Normal' LRs will excite the eccentricities toooooo much.
  2. CRs will not excite eccentricities, but it is not clear that we can get capture.
- We have shown that collisional damping with perturbations of Charon can:
  - deliver a lot of material beyond the 6:1 MMR.
  - put material preferentially near the resonances.
  - However, we have not been able to put these ideas into a model.

This talk can be found at www.boulder.swri.edu/∼hal/talks.html.

We thank NASA's OPR program for support.

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3. The Story People Want to Tell
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5. Resonances
6. The Role of Collisional Damping
7. Distant Scatterings
8. Collisional Damping Near Mean Motion Resonances
9. So, why is this guy frowning?
10. Conclusions