CATASTROPHIC METEORITE IMPACTS ON EARTH

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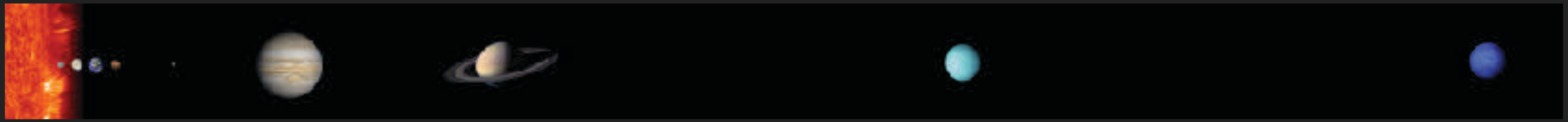


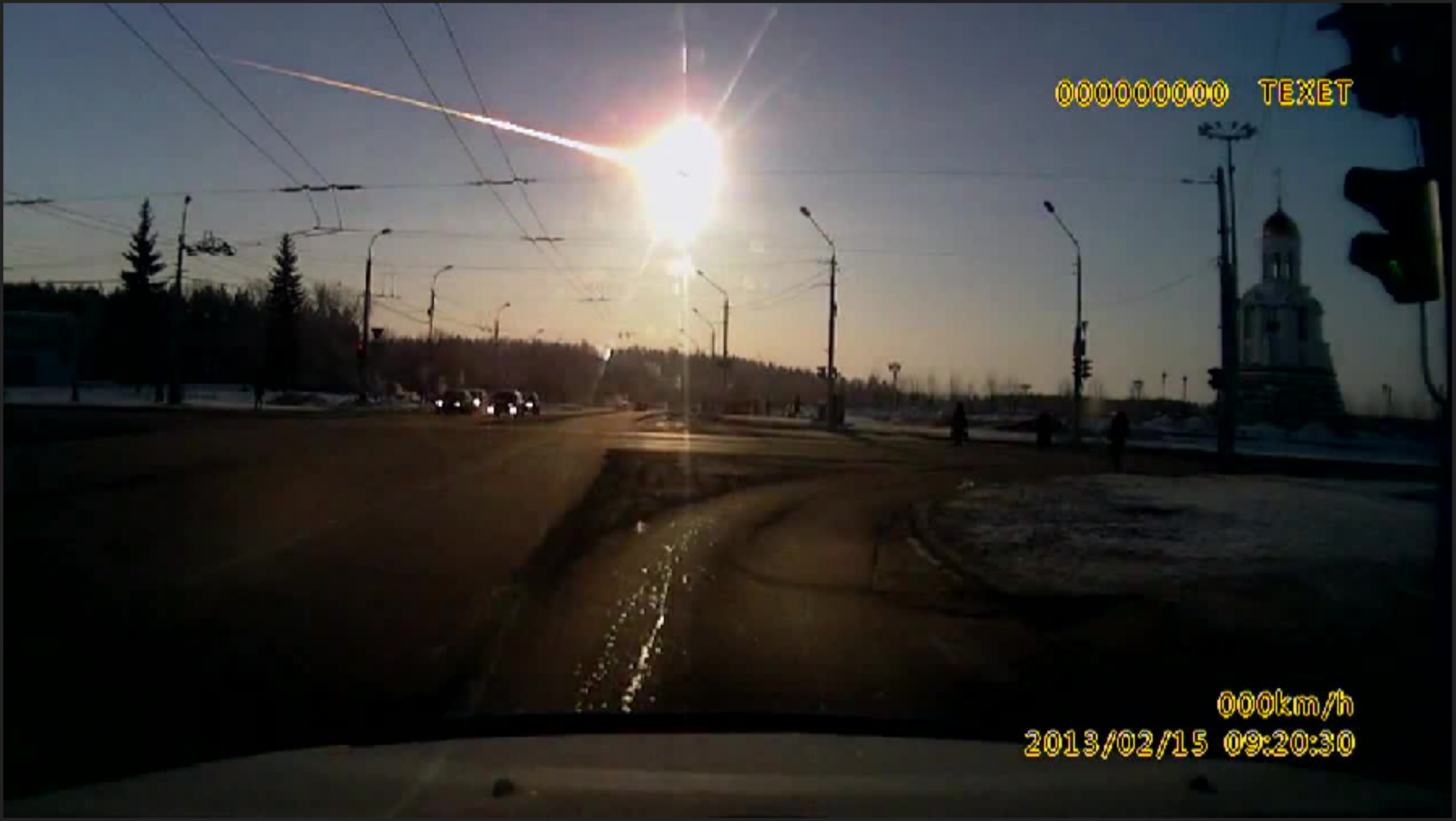
Solar system with different scales for distance and for size: presents role of giant planets

THE ULTIMATE IN COLD CASE INVESTIGATIONS

- The history of life on Earth punctuated by extinction events
- What are probable causes and how can we identify the correct one? Are we at risk?
- What does this have to do with computers? And how is this connected to the Earth's origin and evolution?
- Computer application of laws of physics to identify *what* happens
- Advanced physics-theory to explain *why/how often* it happens

MAJOR IMPACT EVENTS HELPED DEFINE EARTH HISTORY

CHELYABINSK METEOR 20 METER DIAMETER 20 KM/S (40,000 MPH)



GEOLOGIC TIME SCALE PUNCTUATED BY MASS EXTINCTIONS

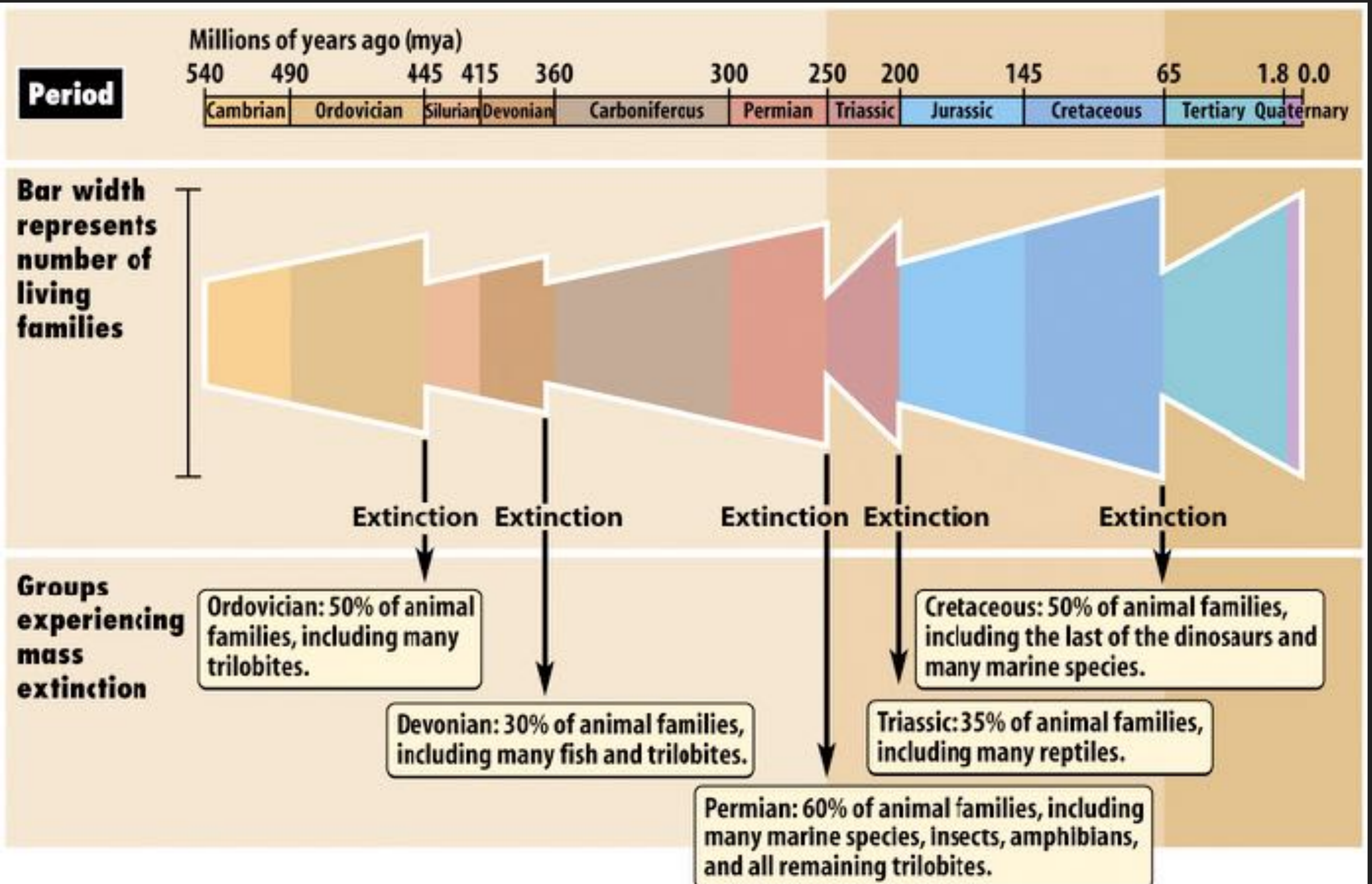
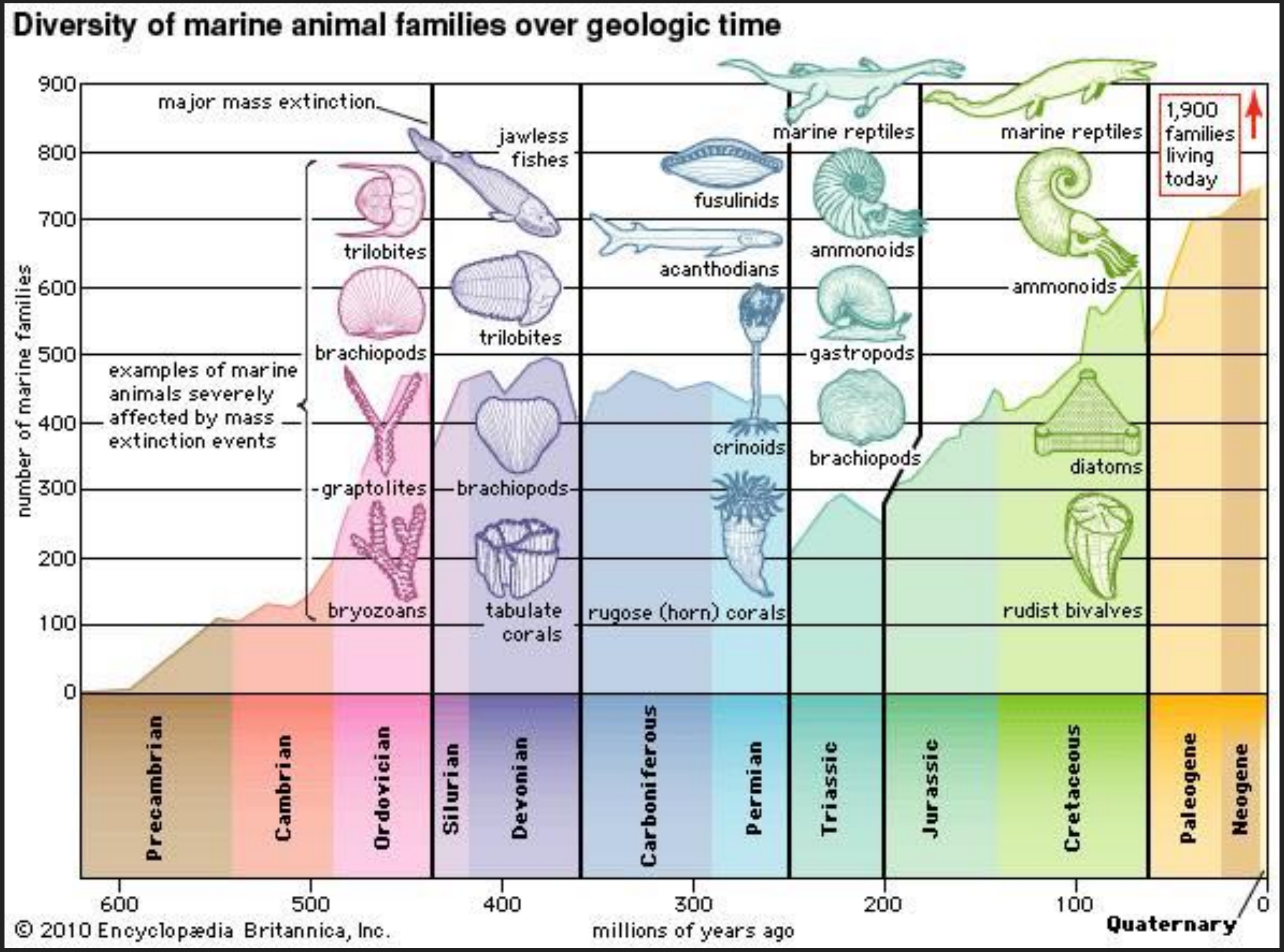


Figure 19-8 Discover Biology 3/e

GEOLOGIC TIME SCALE PUNCTUATED BY MASS EXTINCTIONS



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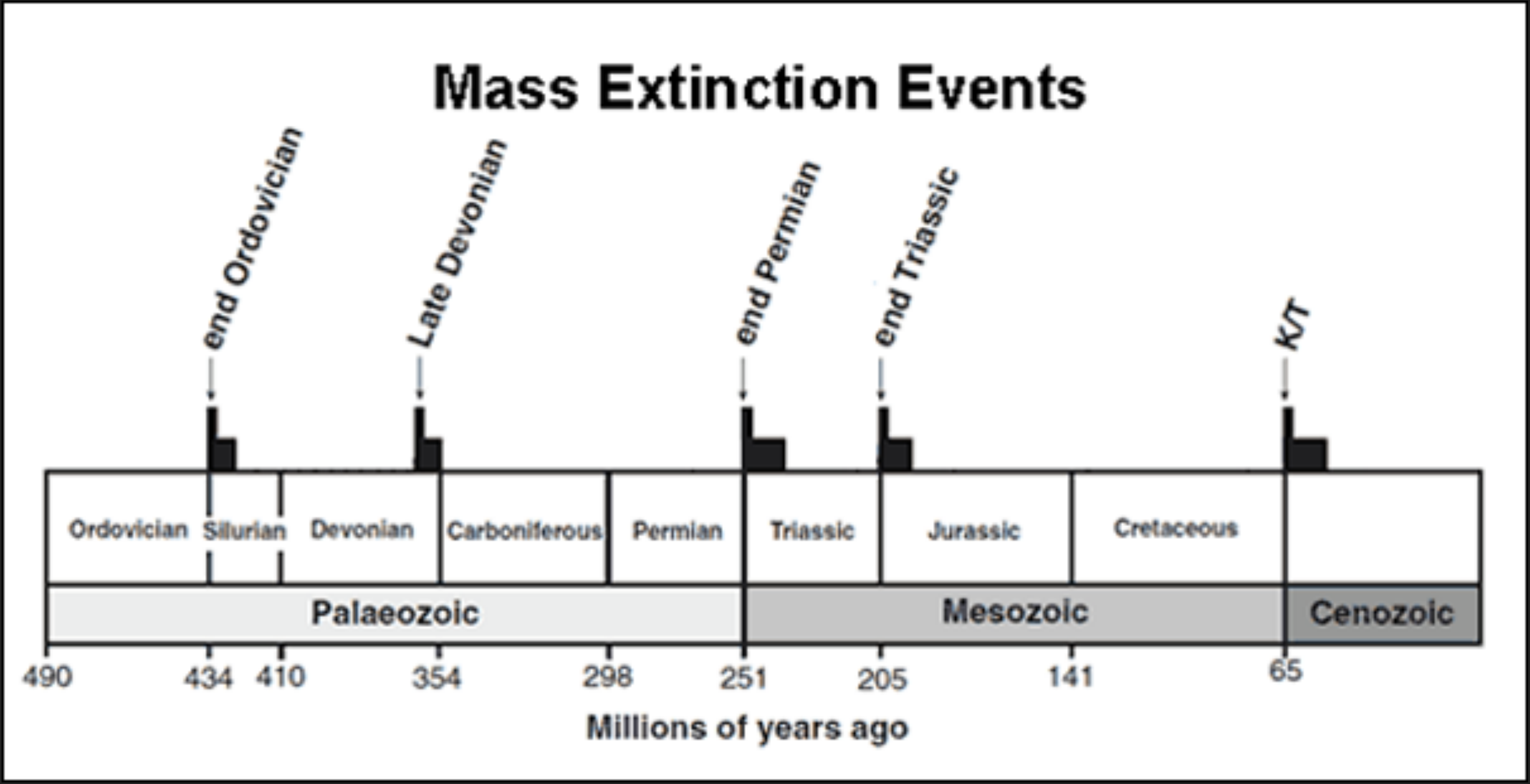


POSSIBLE EXPLANATIONS FOR EXTINCTIONS

- Explanations must explain event occurring *everywhere* on Earth (and in oceans, lakes) during a relatively well-defined time, and have a viable causal agent
- Rules out viral mechanisms (different species, etc.), volcanism (requires trigger over many continents), …
- Massive meteoritic impact events… We have found evidence (Chixulub crater off Yucatan peninsula), Iridium deposits at 65 Ma (million year) level + fossil record age

GIANT PLANET SHIELDING: MYTH OR FACT

- Astronomical folklore: Jovian planets, by virtue of their size and gravitational attraction, shield the inner solar system from collisions with outer solar system material (planetesimals)
- Wetherill (1994) developed a computer method to study the interaction of planetesimals with the Jovian planets exploiting a clever approximate description
- Öpik developed an approximation to describe gravitational interaction subject to a special condition

A LITTLE HISTORY

- Primitive computer method seemed to show that astronomical intuition was right…
- Less than 1% of outer solar system objects hurled into inner solar system crossing Earth's orbit
- But more accurate investigations (7 digit accuracy) proved otherwise? Around 15% of "planetesimals" made it….
- And we're still here attending this meeting
- *What's going on?*

SIMULATION RESULTS

- Wetherill showed that the current Jovian planet configuration prevents 99 - 99.9% of planetesimals from entering the inner solar system and crossing terrestrial planet orbits using Öpik approximation without checking validity
- Horner & Jones (2008) employed more accurate simulations in related problems; found potential for terrestrial planet collisions
- Newman, Sharp, & Grazier (2014) showed that 60% of Wetherill's planetesimal orbits are invalid; 15% of planetesimals enter inner solar system, confirmed by Grazier (2015)

Author(s)	Wetherill	NBS	Grazier	NBS	Grazier	NBS	HJ	HJ
Year	1994	2016	2015	2016	2015	2016	2008	2008
Region	Cometary	Cometary	Jup-Sat	Jup-Sat	Sat-Ura	Sat-Ura	Ast. Belt	Ast. Belt
N	8,000	100,000	10,000	500,000	10,000	100,000	100,000	100,000
Duration	4.5×10^9	2×10^8	10^8	10^8	10^8	10^8	10^7	10^7
Earth crossers	n/g	9.5%	12.1%	16.1%	7.8%	13.0%	n/g	n/g
Mars crossers	n/g	17.1%	27.9%	34.0%	18.3%	26.6%	n/g	n/g
Earth hits	-	0	-	5	-	0	10,233	$\approx$ 2
Mars hits	-	0	-	1	-	0	$\approx$ 100	$\approx$ 100

UNCOVERING THE MYSTERY…

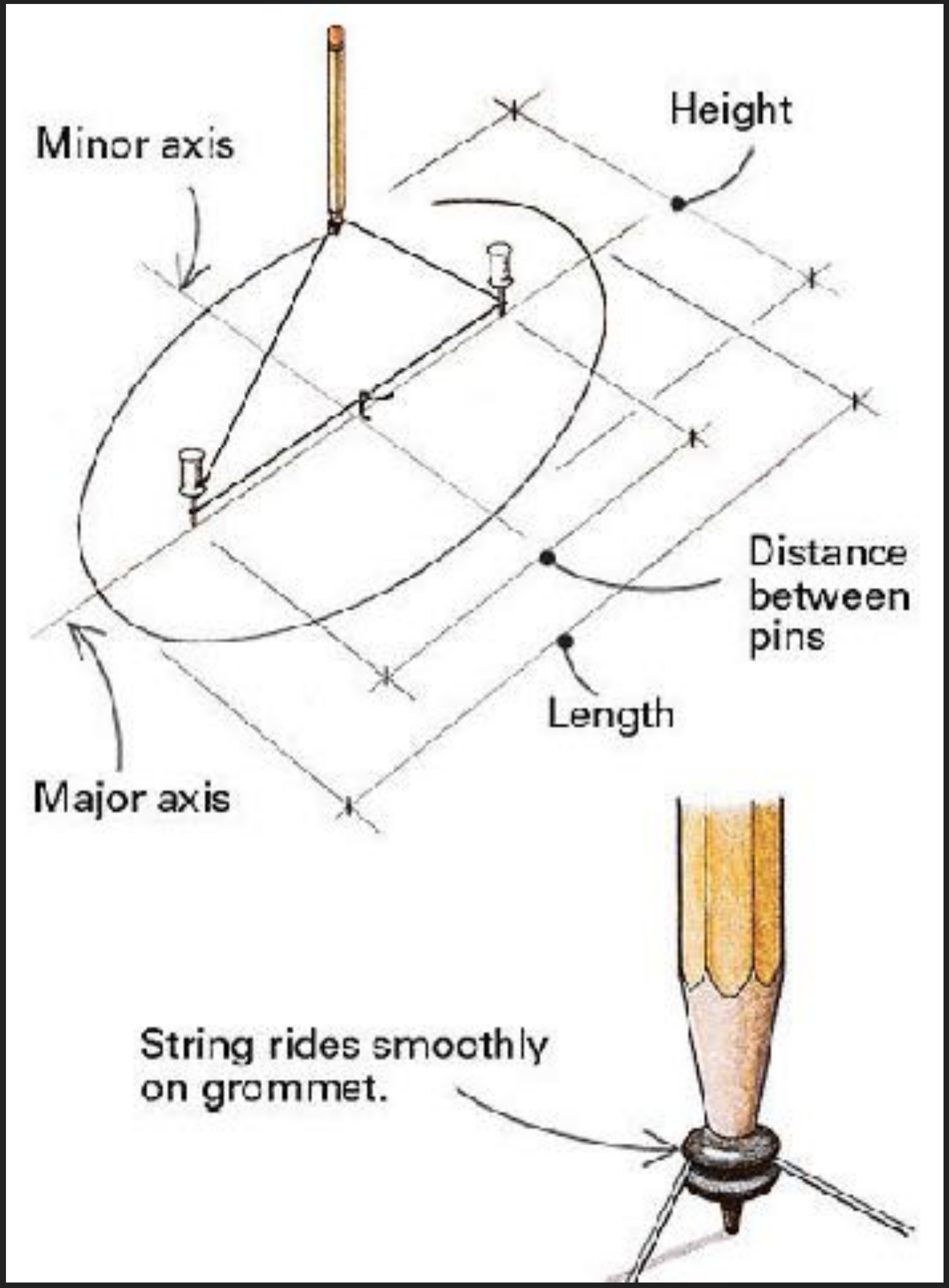
- Make computer algorithms much more accurate and include gravitational influence of Earth and Mars
- Look for actual impacts, not just planetesimals crossing our orbit; misses, fortunately, do not count
- Requires we understand a little bit about the orbits of comets and asteroids, as well as how they are affected by the Gas Giants or Jovian planets

JOVIAN PLANETS, MARS, EARTH, PLUS 500,000 PLANETESIMALS

- We add two terrestrial planets into orbit computation for giant planets with much more accurate algorithm (11 digit accuracy)
- We confirmed our earlier finding that approximately 15% of planetesimals originating in the outer solar system are deflected into the inner solar system
- However, we discovered that only 1 in 10^5 planetesimals will collide with Earth or Mars over 10^8 years (loosely conforms with related calculations by Horner & Jones)
- Fundamental question is *why* so few collisions? Was Wetherill right for unexpected reasons?

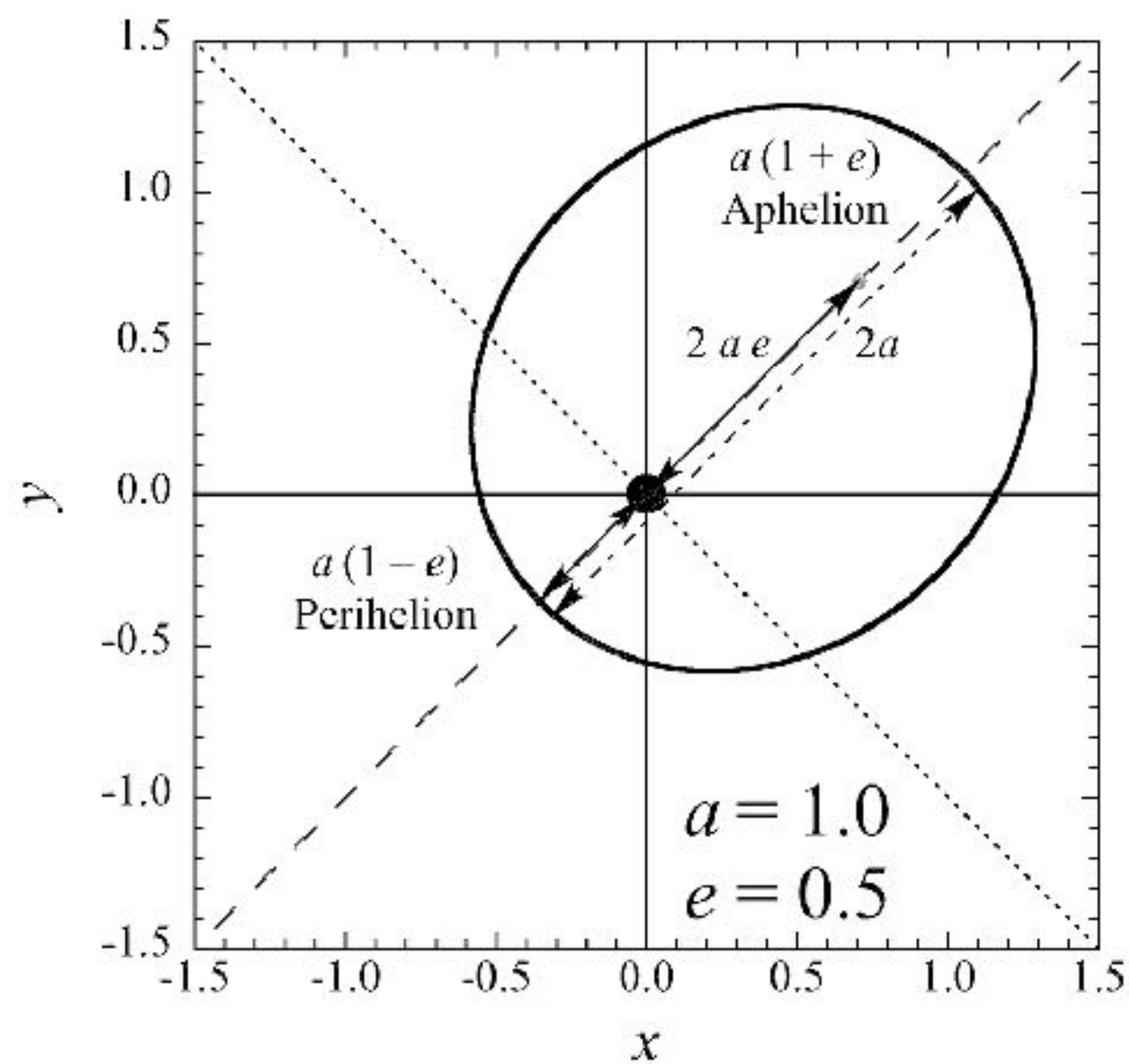
KEPLER MYSTICALLY (CONICS) SUGGESTED ELLIPTICAL ORBIT

- Kepler (1609) made claim (First Law), but he verified (before Galileo and telescopes!)
- Elliptical shape requires calculus, but an elementary school student can do it with tacks and string
- Major and minor axis of lengths *a (1+e)* and *a (1-e)*: simple algebra, **not** rocket science!



PLANETESIMAL ORBITS IN THE SOLAR SYSTEM

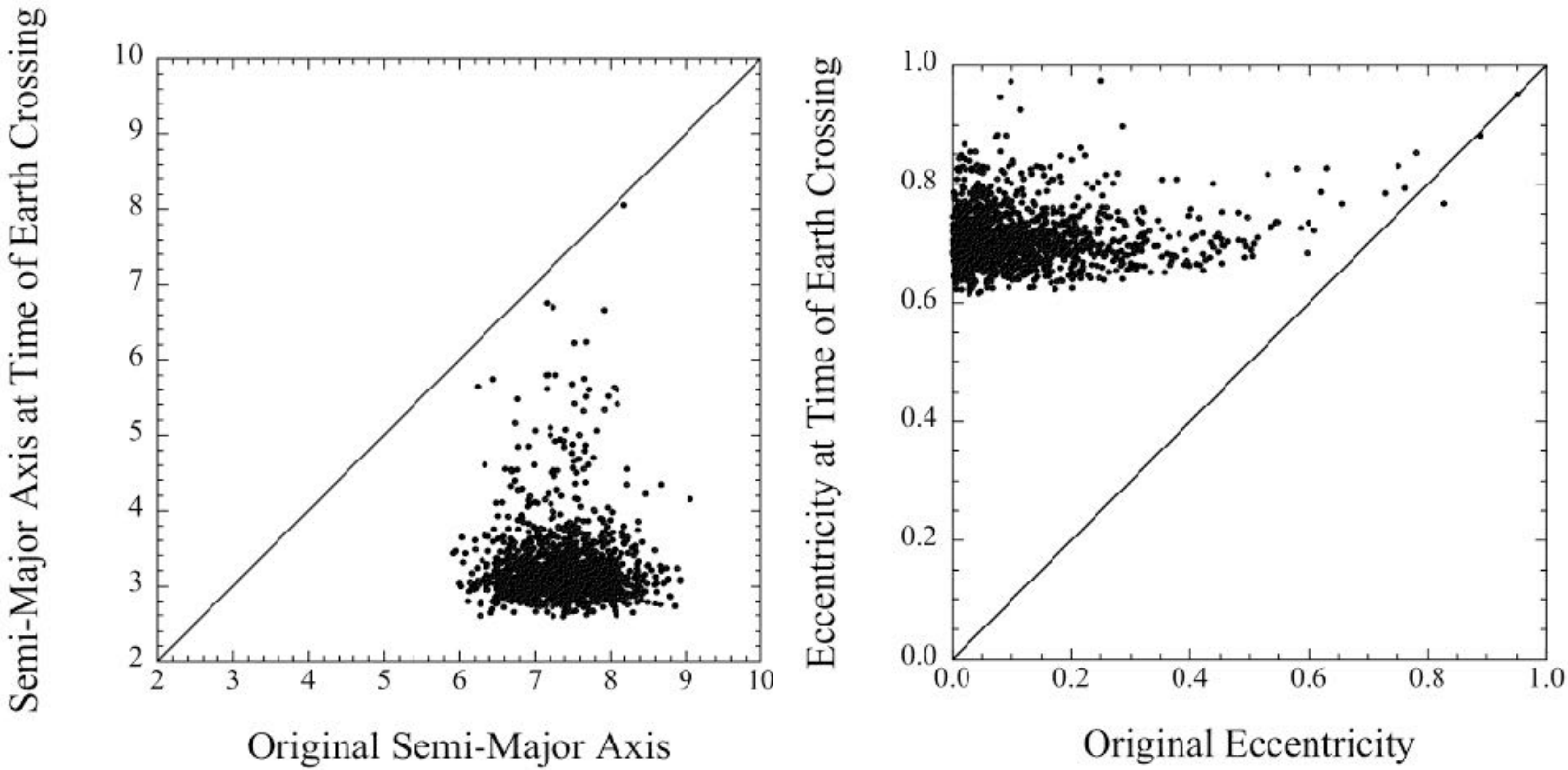
- Simplest description: planetesimal follows Kepler's laws relative to the sun; first law with ellipse/focus
- Semi-major axis *a* and eccentricity *e* with primary focus at sun; inclination *i* of orbital plane relative, e.g., to Sun-Jupiter orbital plane; *a*, e, and *i* remain constant



A QUANTITATIVE DETECTIVE STORY

- Employ “data mining” on orbit calculations performed when a planetesimal crosses Earth’s orbit
- Look for unexpected patterns and found two
  - Semi-major axis *a* (related to energy of orbiting particle) substantially reduced
  - Eccentricity *e* of orbit substantially increased, guarantying (skipping details) that planetesimal will spend most of its time in outer solar system

INITIAL AND FINAL (AT CROSSING) ORBITAL PARAMETERS



INITIAL AND FINAL (AT CROSSING) ORBITAL PARAMETERS

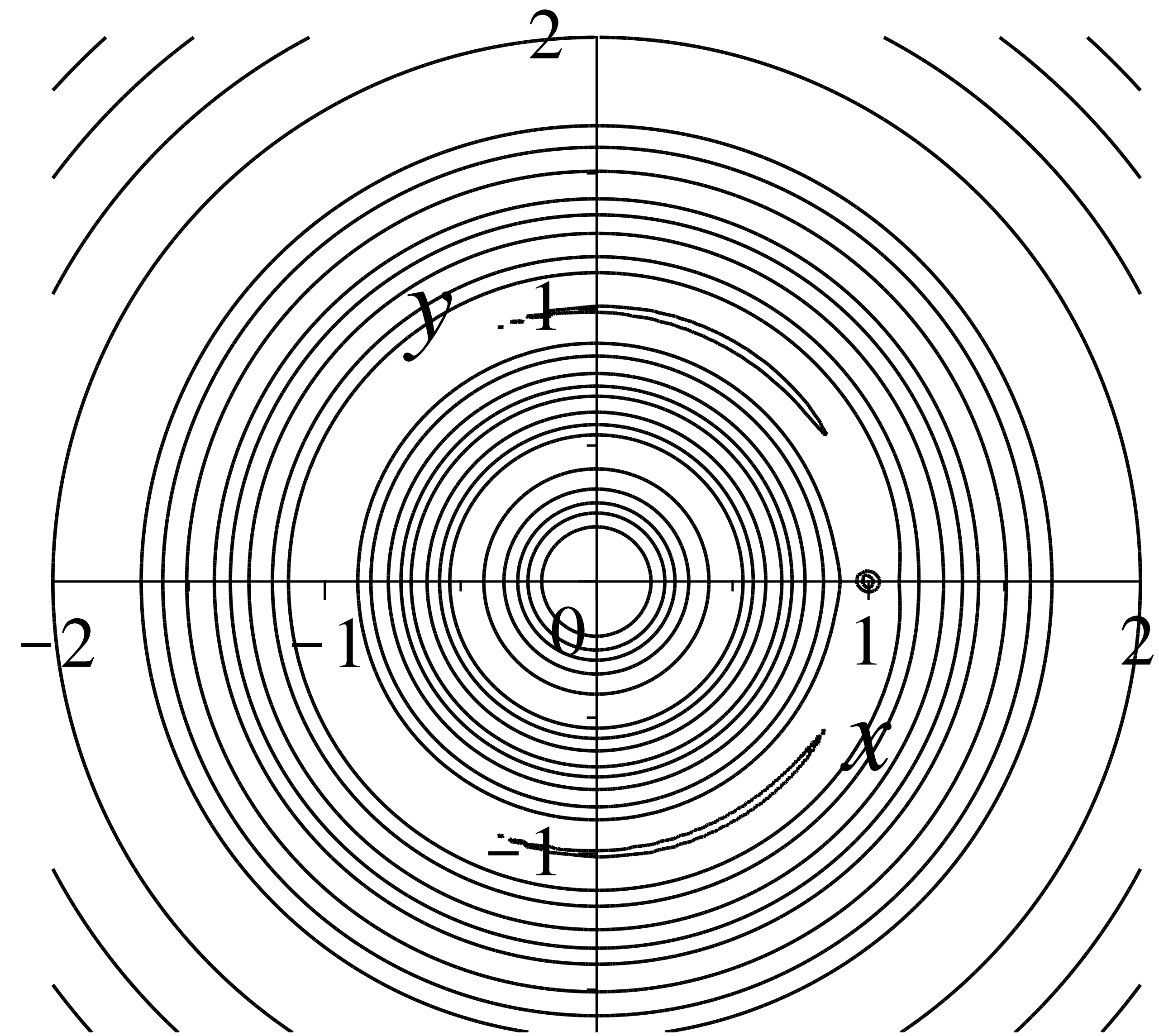
- With 1,546 planetesimals out of 10,000 crossing the Earth's orbit (15%), we observe that *all* of them have their semi-major axes reduced and almost *all* of them have their eccentricities increased; other simulations with 5 x 10^5 planetesimals
- All perihelia $a\,(1 - e) < R_E$ (Earth orbit crossers) but aphelia $a\,(1 + e)$ are in Jovian planet zones; Kepler's 2nd law (equal areas in equal times) guarantees these planetesimals spend most of their time in the outer solar system subject to ejection by giant planets
- *Why*, though, do we have systematic drops in a and jumps in e?

JUPITER CONTROLS OUTER SOLAR SYSTEM

- Kepler’s picture based on object orbiting the sun with no external influence
- Jupiter has 0.1% mass of the sun but has strong influence; “3-body” problem of Sun-Jupiter-comet addressed over a century by Hamilton, Jacobi, Tisserand, and Poincaré
- Hill’s curves (in Sun-Jupiter rotating frame) shows how particles can be trapped (Lagrange points)
- Tisserand showed that *a* and *e* no longer independent, due to Jupiter, but connected via a formula he developed

HILL'S CURVES: TRANSITIONING FROM 2 TO 3 BODIES

- Sun at the origin, Jupiter is at 1 (R_J); planetesimal orbits near sun ***bounded*** by circles and are individually Keplerian
- Coordinates rotate over 11.82 yr; M_{Sun} = 1,048 M_J, M_J = 318 M_E
- Further out, Jupiter's gravity alters picture; Lagrange points, periJovian orbits, etc., with complex trajectories
- Still further out, orbits resume Keplerian flavor bounded by circles



F.F. TISSERAND'S CRITERION

- When mass of planet relative to sun is small, Jacobi constant *J* can be accurately approximated by

$$J = \frac{R}{a} + 2\sqrt{\frac{a}{R}\left(1-e^2\right)}\cos\left(i\right)$$

a = semi-major axis
e = eccentricity
i = inclination (near 0°)
R = radial distance to planet;
a and *e* can vary, but *J* preserved for 3-body

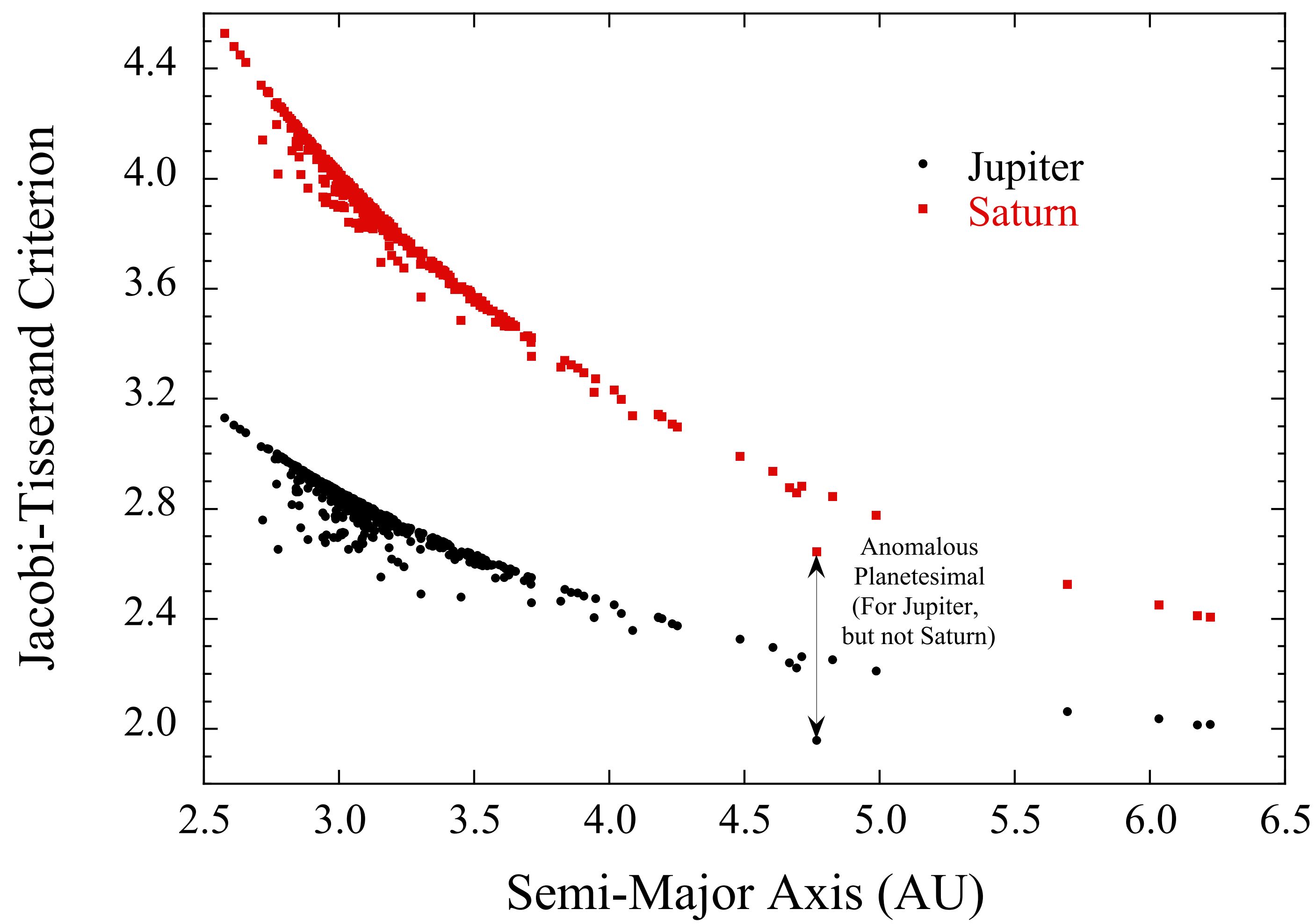
TISSERAND'S DATA FOR JUPITER-RELATED COMETS

- From vol. IV, page 205 of Tisserand's *Traité de Mécanique Céleste*
- Formula major tool in 3-body problem dynamics for comets
- Apply to simulation

		a.	i.	$\varpi - \Omega$.	l.	$a(1+e)$.	$a(1-e)$.	α.	$\varpi_1 - l$.
Encke..........	1795	2,21	14°	182°	335°	4,09	0,33	0,580	+ 2°
Blanpain* (1)....	1819	2,85	9	350	247	4,82	0,88	0,555	0
Helfenzrieder*...	1766	2,93	8	177	80	5,45	0,41	0,487	− 9
Tempel.........	1873	3,00	13	185	125	4,65	1,35	0,571	+ 1
Barnard*	1884	3,08	5	301	126	4,84	1,32	0,567	0
De Vico	1844	3,10	3	279	162	5,02	1,18	0,556	+ 1
Tempel-Swift...	1869	3,11	5	106	223	5,16	1,06	0,544	0
Brorsen	1846	3,14	31	13	283	5,62	0,66	0,475	+13
Winnecke	1858	3,14	11	162	113	5,50	0,79	0,512	−17
Lexell*.........	1770	3,16	2	224	184	5,66	0,66	0,500	− 8
Tempel.........	1867	3,19	6	125	60	4,82	1,56	0,570	− 4
Pigott*.........	1783	3,26	45	354	233	5,05	1,47	0,487	− 3
Barnard*	1892	3,41	31	170	»	5,40	1,43	»	»
Brooks*........	1886	3,41	13	177	53	5,49	1,33	0,533	− 3
Spitaler*........	1890	3,44	13	13	228	5,06	1,82	»	»
D'Arrest........	1851	3,44	14	175	153	5,71	1,17	0,519	−10
Tuttle*.........	1858	3,52	20	26	0	5,88	1,16	0,505	+21
Finlay..........	1886	3,54	3	316	205	6,09	0,99	0,502	−17
Wolf......... ..	1884	3,58	25	173	210	5,58	1,58	0,518	−11
Biéla...........	1772	3,58	17	213	268	6,16	1,00	0,491	+22
Holmes*........	1892	3,62	21	12	»	5,11	2,14	»	»
Brooks*........	1889	3,67	6	344	185	5,39	1,95	0,556	− 3
Faye...........	1843	3,81	11	201	209	5,94	1,68	0,529	+21

TISSERAND CRITERION: JUPITER OR SATURN?

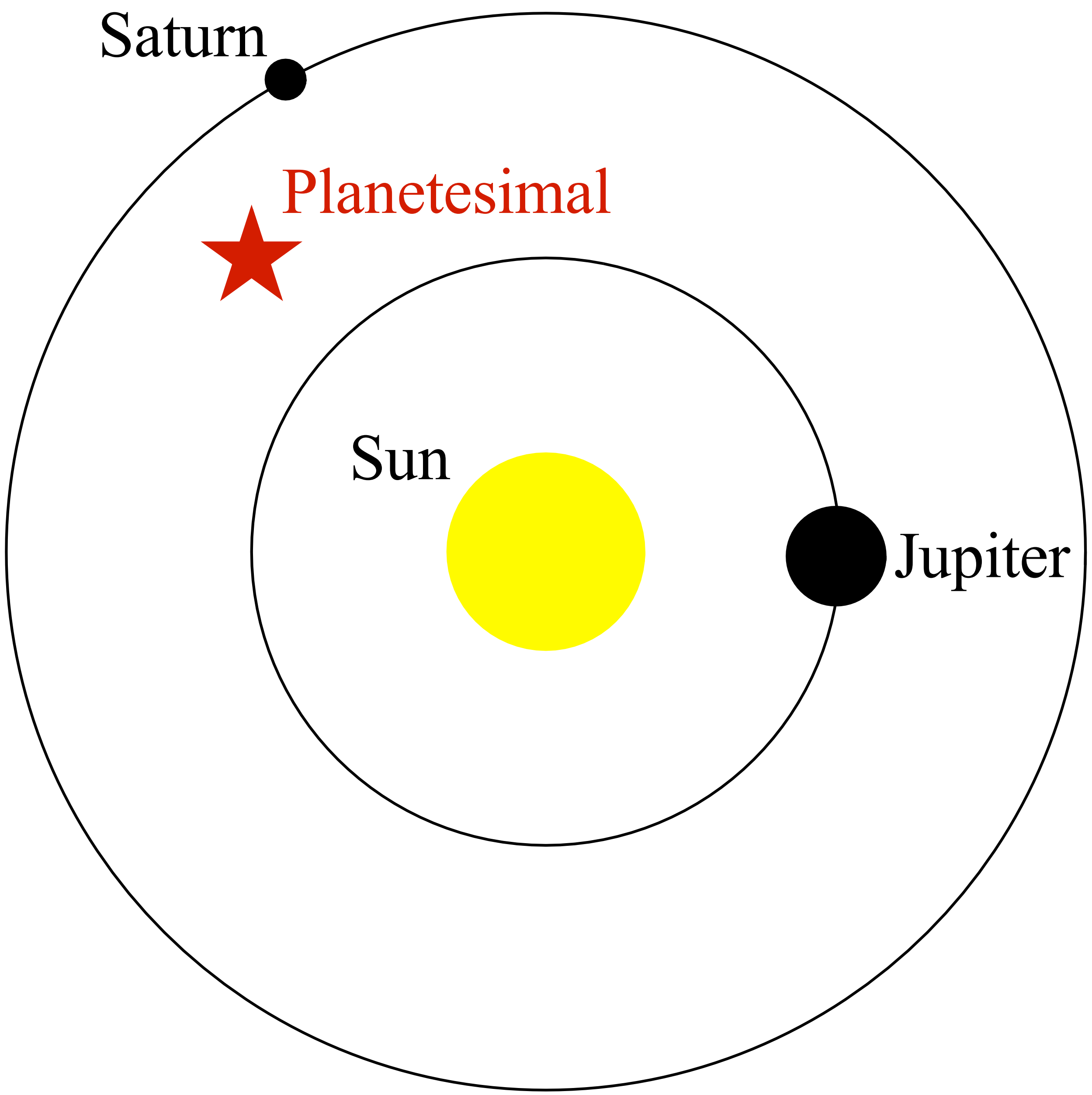
- Calculate Tisserand parameter *J* for simulation results at time of Earth orbit crossing
- Should be around 3 for planet associated with "three body" problem
- Almost all planetesimals controlled by Jupiter at that instant



JUPITER GOVERNS, BUT SATURN PERTURBS

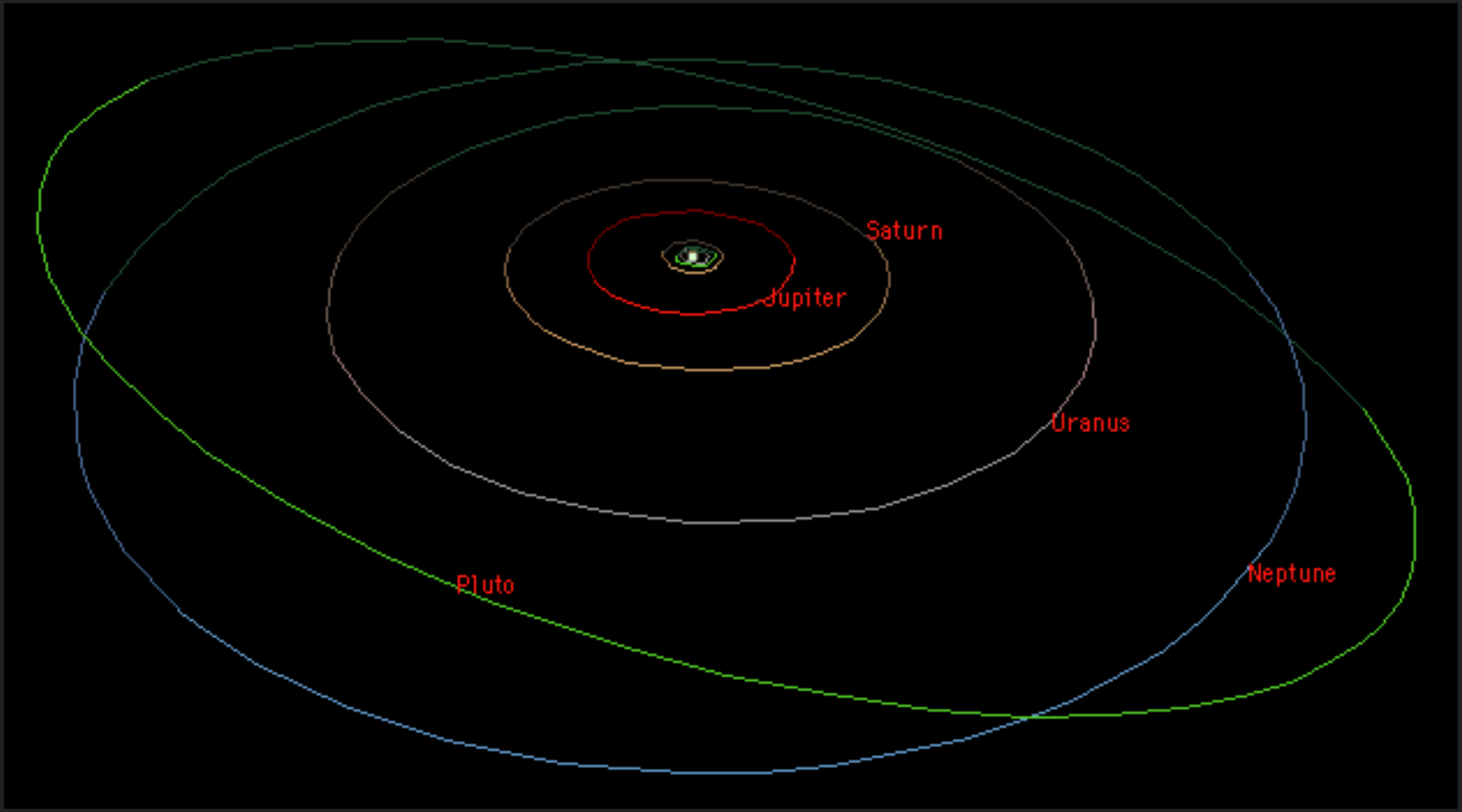
- Saturn behaves as though it is an external "shepherd," concept familiar to us from planetary ring dynamics
- Planetesimals interior to Saturn's orbit can lose energy to Saturn, when closer to it than Jupiter, and become more tightly bound; perturbation also influences J
- Repeated interactions with Saturn will steadily reduce a planetesimal's semi-major axis

CARTOON DEPICTING ROLE OF SATURN V. JUPITER



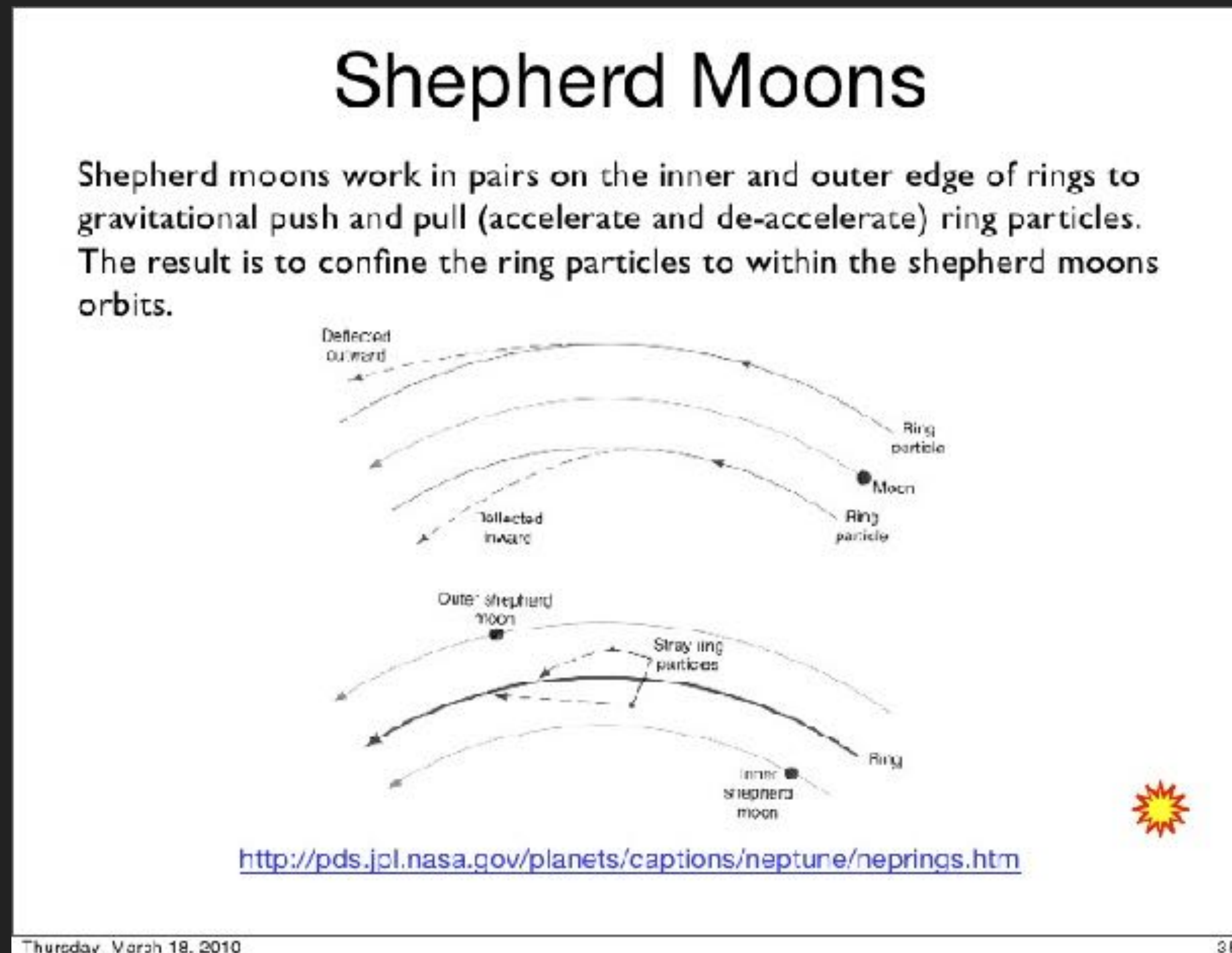
When a planetesimal is closer to Saturn than to Jupiter, Saturn will serve as a "shepherd" for the planetesimal's orbit driving it inward.

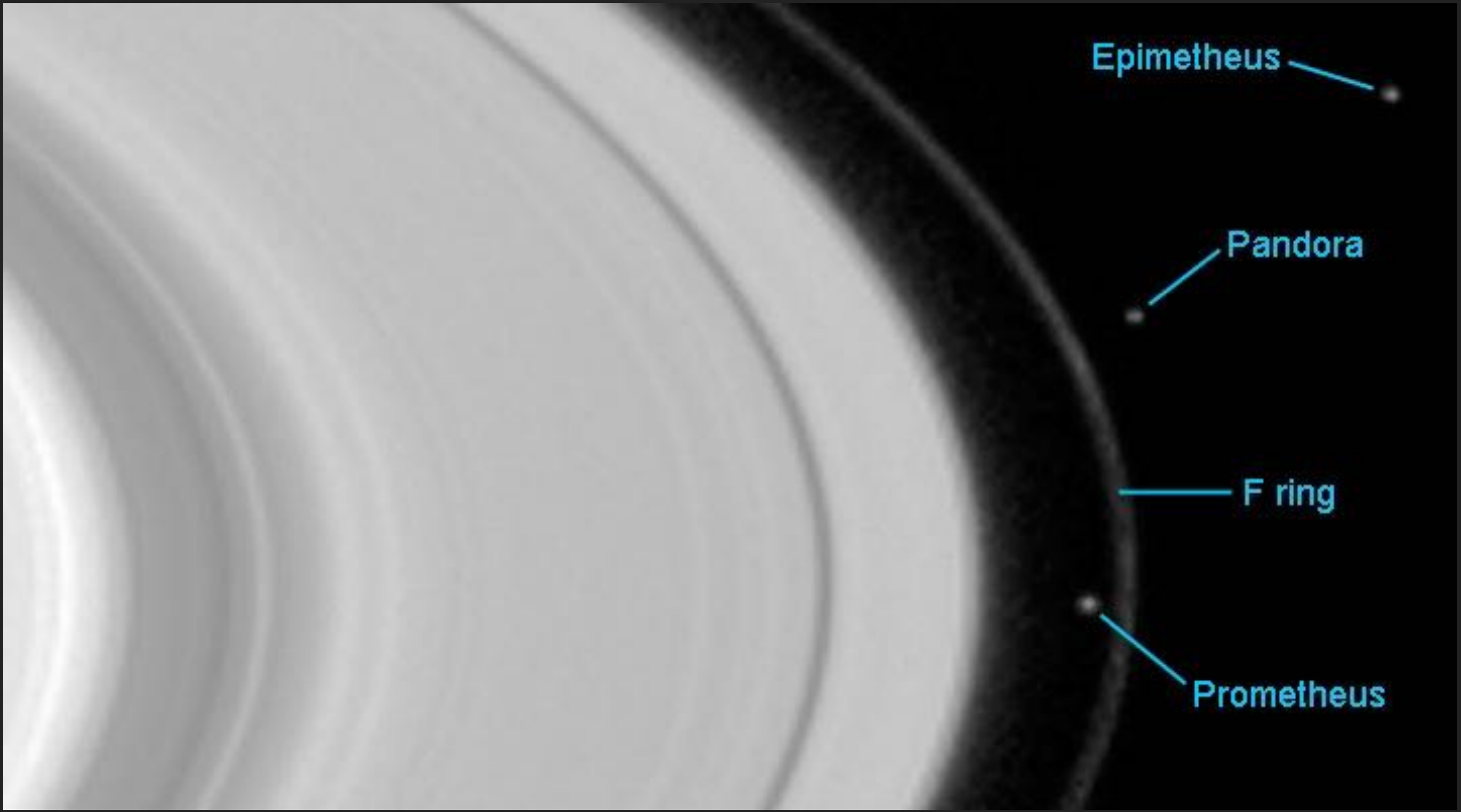
JUPITER 317.8, SATURN 95.2, URANUS 14.6, NEPTUNE 17.2 (M_{EARTH})



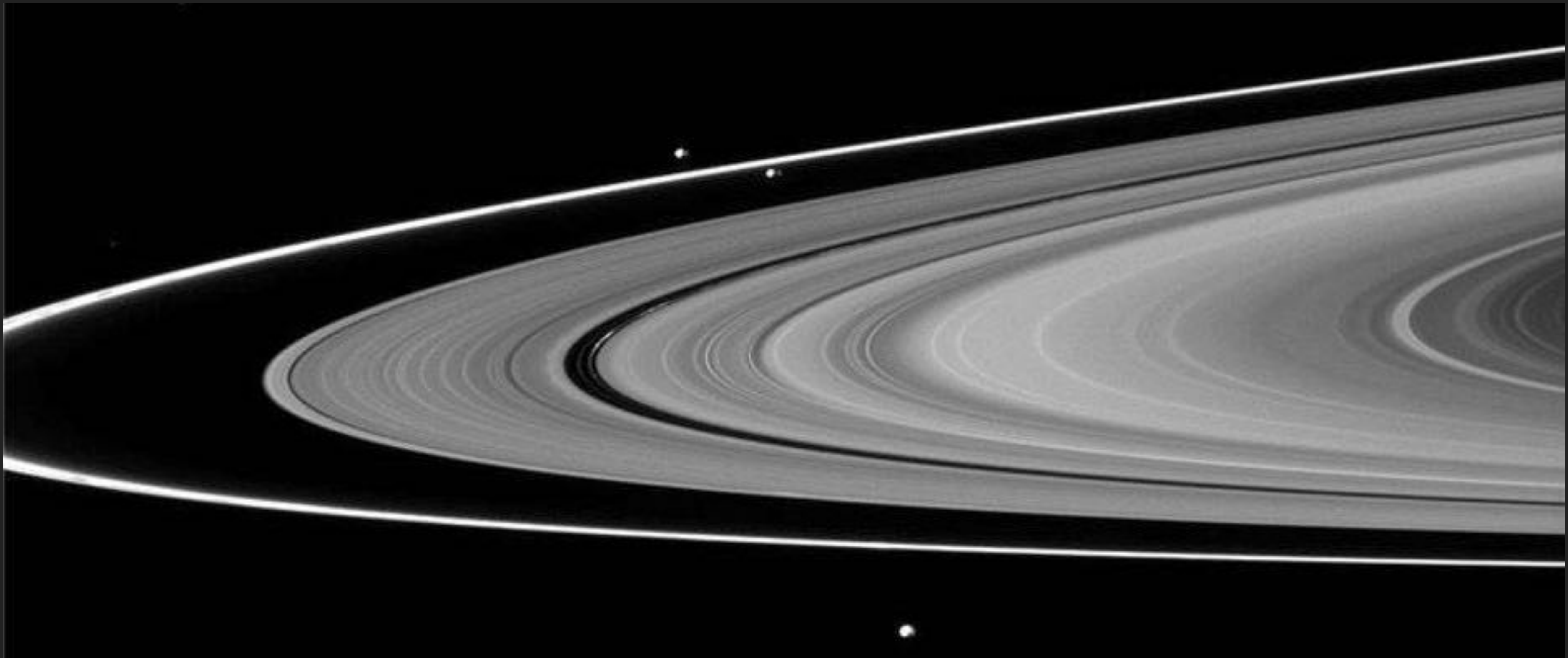
TINY OBJECTS INTERACTING WITH PLANETARY SATELLITES

- If inside satellite's orbit, object moves faster and loses energy ("dynamical friction") and becomes more tightly bound (pulled in)
- If outside satellite's orbit, get pushed out



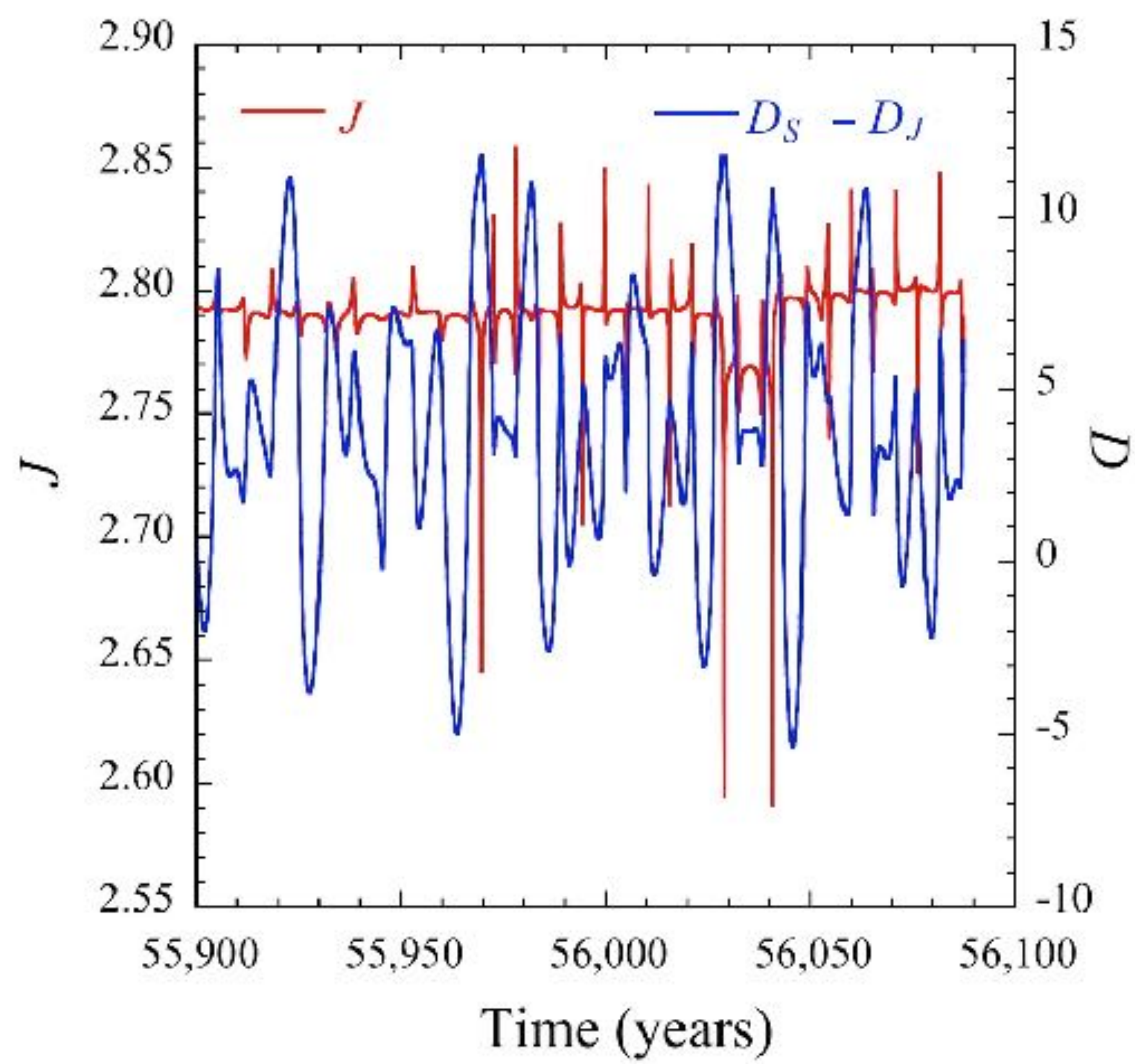

Epimetheus
Pandora
F ring
Prometheus

CREATES GAPS BETWEEN SATURNIAN RINGS; RELATED RESONANCE EFFECTS PRODUCE KIRKWOOD GAPS IN ASTEROID BELT



JUPITER GOVERNS BUT SATURN PERTURBS

- Since Jupiter's mass is 3.34 that of Saturn, expect that gravitational perturbation will only occur when planetesimal is much closer to Saturn than to Jupiter or $D_S < D_J$
- Demonstrated in figure; showing J for Jupiter and D_S - D_J after 10^6 years



JUPITER GOVERNS BUT SATURN PERTURBS

- Three body description with Jupiter and constant Tisserand parameter J obeyed most of the time
- Relatively close approach by planetesimal to Saturn results in more tightly bound orbit, so semi-major axis a drops
- When a drops, eccentricity e increases; well-known result due to Dermott & Murray (1981) for shepherding
- Exchanging roles of Jupiter and Saturn in this "four body scenario" provides analytic basis for simulation results

DISCUSSION AND CONCLUSIONS

- Wetherill (1994) employed Öpik approximation to show that 99 - 99.9% of outer solar system planetesimals would be prevented from entering inner solar system
- Recent studies showed that around 15% of planetesimals are injected into the inner solar system
- We have shown that they develop smaller semi-major axes but higher eccentricities leading to continued long residence times in the outer solar system and ejection

DISCUSSION AND CONCLUSIONS (CONT.)

- We find that only 1 planetesimal in 10^5 will collide with Earth; important in understanding our impact (including extinction) history as well as delivery of volatiles from outer solar system
- Arguably, similar mechanisms applied in the early solar system inasmuch as Jupiter and Saturn were likely present due to instabilities resulting in their formation
- This helps explain the non-existence (Boehnke et al., 2016) of a *Late Heavy Bombardment*; injected planetesimals were not sufficiently long-lived in the inner solar system to have much of an impact