Planet migration in the Solar system

Renu Malhotra
Lunar and Planetary Laboratory
The University of Arizona

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  @ 4.5 Gyr ago: orbits more compact + a lot more debris (asteroids, comets)

  @ 3.9 Gyr ago: debris cleared up (mostly), planets settled into their present orbits

A little bit about me …

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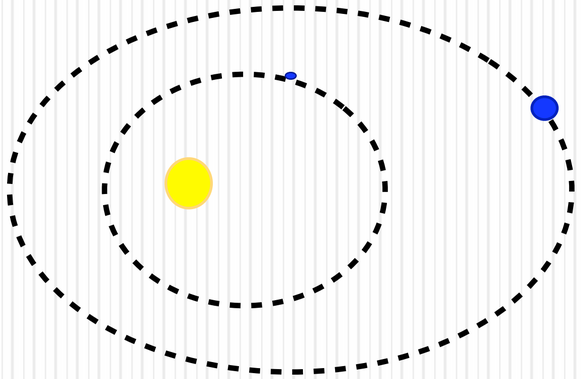

I am interested in the “architecture” of planetary systems
- how planetary masses and orbits are arranged
- how they form and change over time

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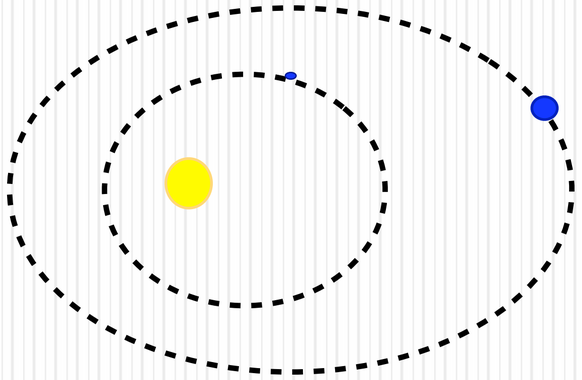

I am interested in the "architecture" of planetary systems
- how planetary masses and orbits are arranged
- how they form and change over time

physics + astronomy + mathematics

my own peregrinations…

my own peregrinations…

New Delhi
+various
1961-1968

Hyderabad
1968-1978

New Delhi
1978-1983

St. Ann's School, Secunderabad, India

all-girls school

St. Ann's School, Secunderabad, India

all-girls school

Indian Institute of Technology, Delhi

~3% !

St. Ann's School, Secunderabad, India

all-girls school

Indian Institute of Technology, Delhi

~3% !


World map
Arctic OCEAN
Arctic OCEAN
N
Arctic OCEAN
GREENLAND (DENMARK)
ALASKA (USA)
CANADA
RUSSIA
North Pacific OCEAN
UNITED STATES OF AMERICA
North Atlantic OCEAN
North Pacific OCEAN
KAZAKHSTAN
MONGOLIA
CHINA
INDIA
MEXICO
BRAZIL
INDIAN OCEAN
AUSTRALIA
South Pacific OCEAN
South Atlantic OCEAN
Antarctica
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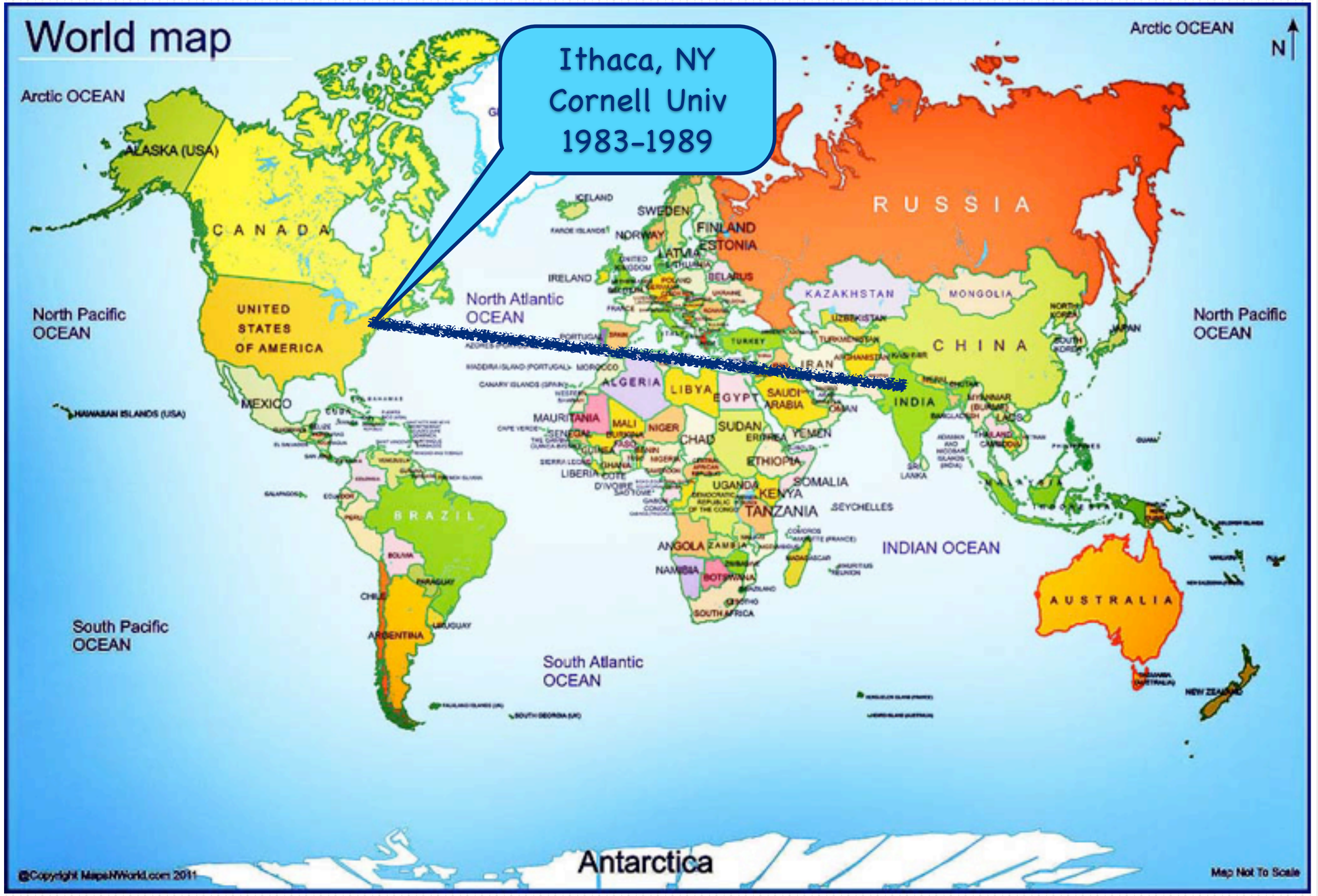
Map Not To Scale


World map
Ithaca, NY
Cornell Univ
1983-1989
Arctic OCEAN
N
Arctic OCEAN
ALASKA (USA)
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UNITED STATES OF AMERICA
North Pacific OCEAN
North Atlantic OCEAN
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ICELAND
SWEDEN
FINLAND
NORWAY
ESTONIA
LATVIA
IRELAND
BELARUS
KAZAKHSTAN
MONGOLIA
CHINA
North Pacific OCEAN
TURKEY
IRAN
ALGERIA
LIBYA
EGYPT
SAUDI ARABIA
INDIA
MEXICO
MAURITANIA
MALI
NIGER
CHAD
SUDAN
ERITREA
YEMEN
ETHIOPIA
SOMALIA
KENYA
UGANDA
TANZANIA
SEYCHELLES
BRAZIL
ANGOLA
ZAMBIA
NAMIBIA
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ARGENTINA
South Atlantic OCEAN
Antarctica
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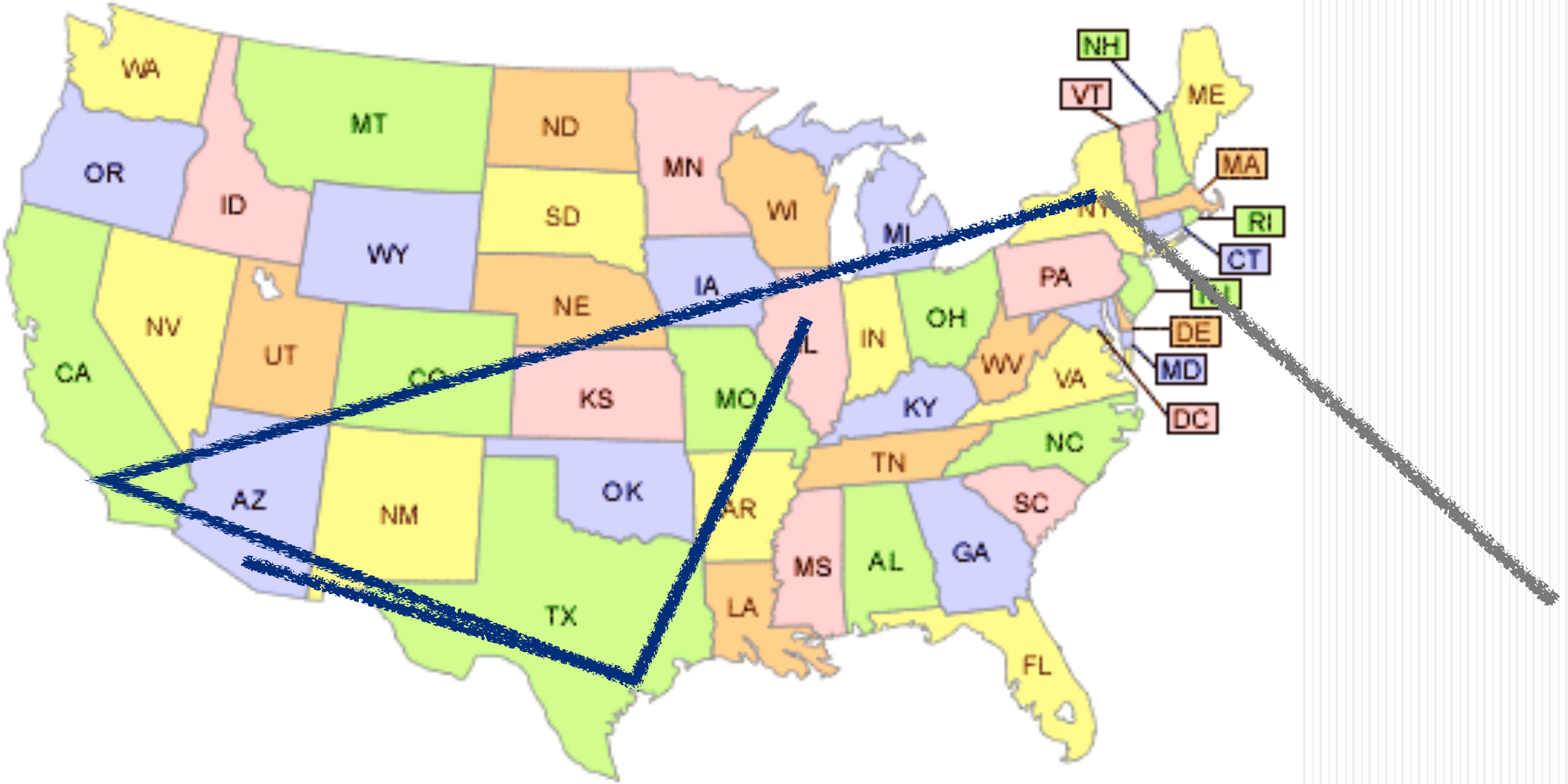
Map Not To Scale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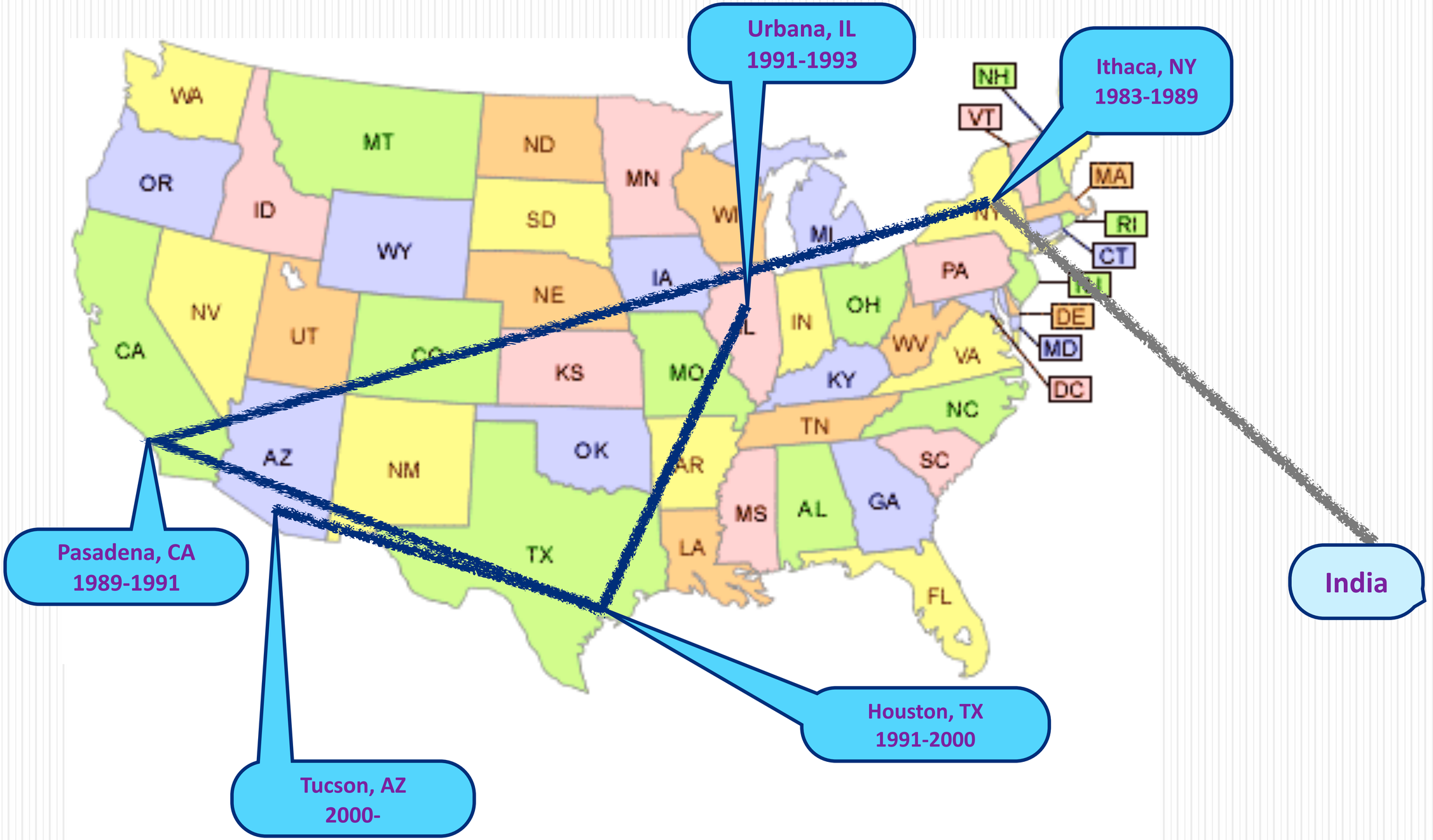
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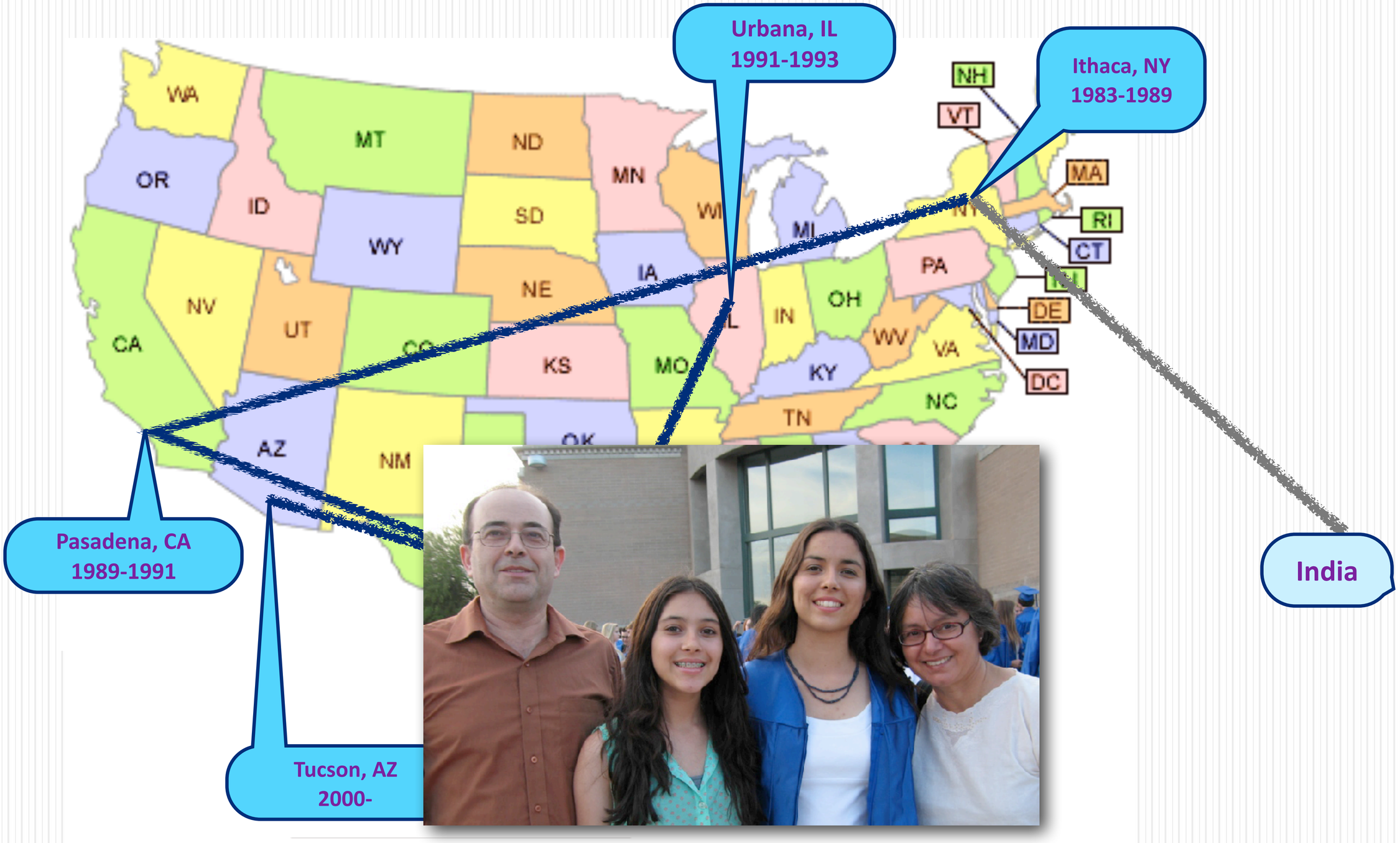
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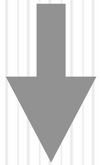
MD
DC

Undergraduate: Physics

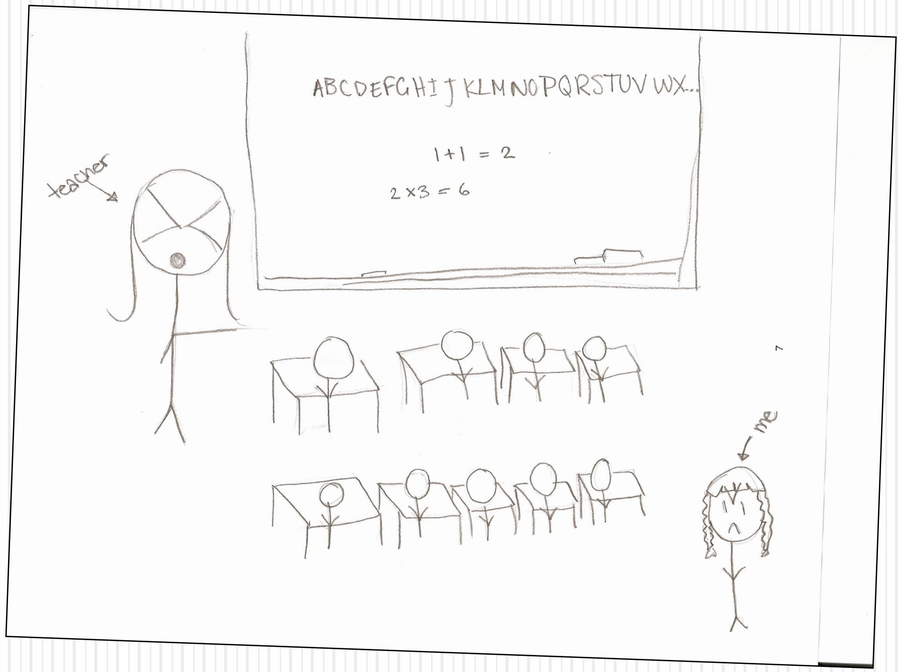
Graduate studies: Physics



Dynamical systems - chaos theory

Planetary dynamics/planetary science

factors that have been important in my life and career



- adversity
& serendipity

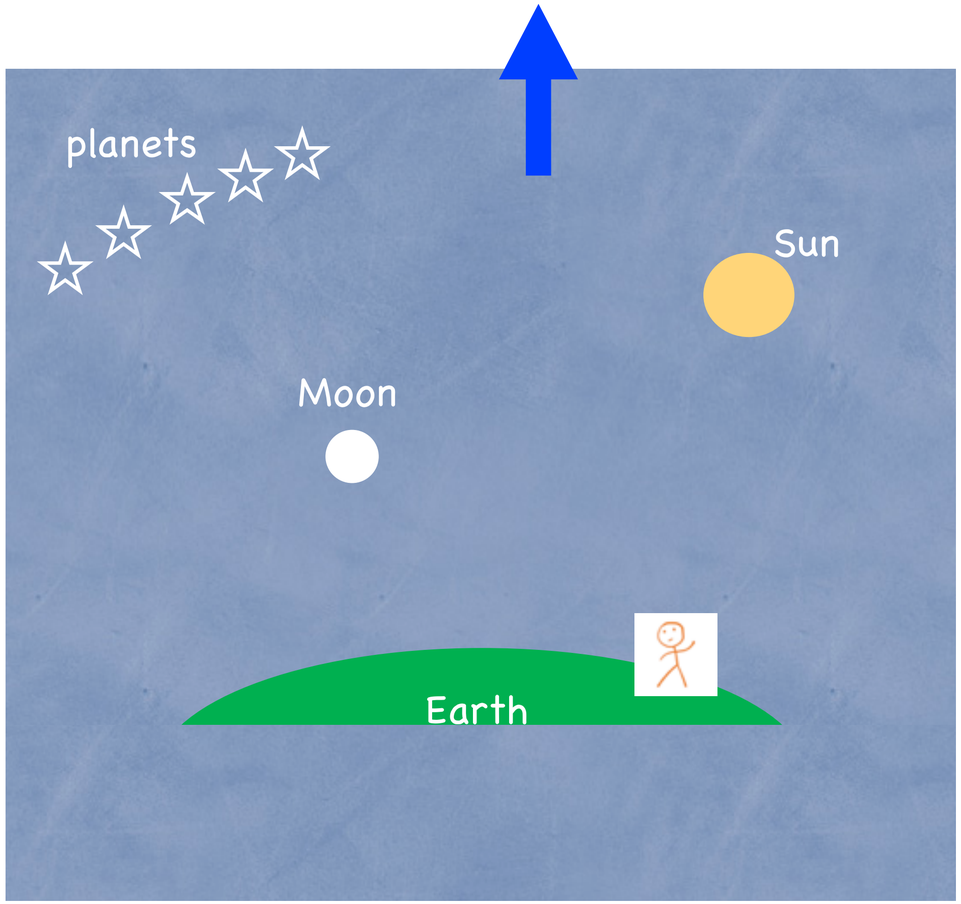
- curiosity
- ignoring distractions
- perseverance
- perfectionism

- broad-minded parents
- teachers & mentors
- partner
- USA ... country & society

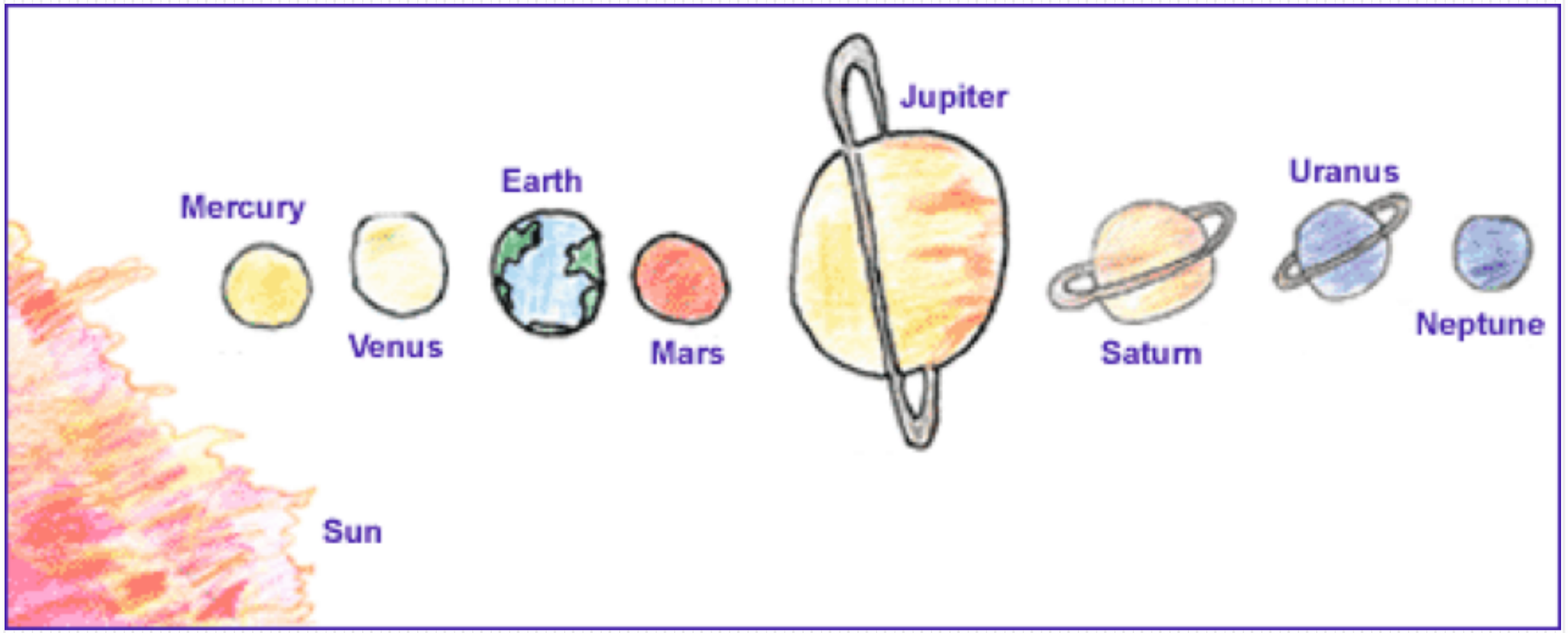
On to planets…

Ancient concept of cosmos

eternal,
unchanging

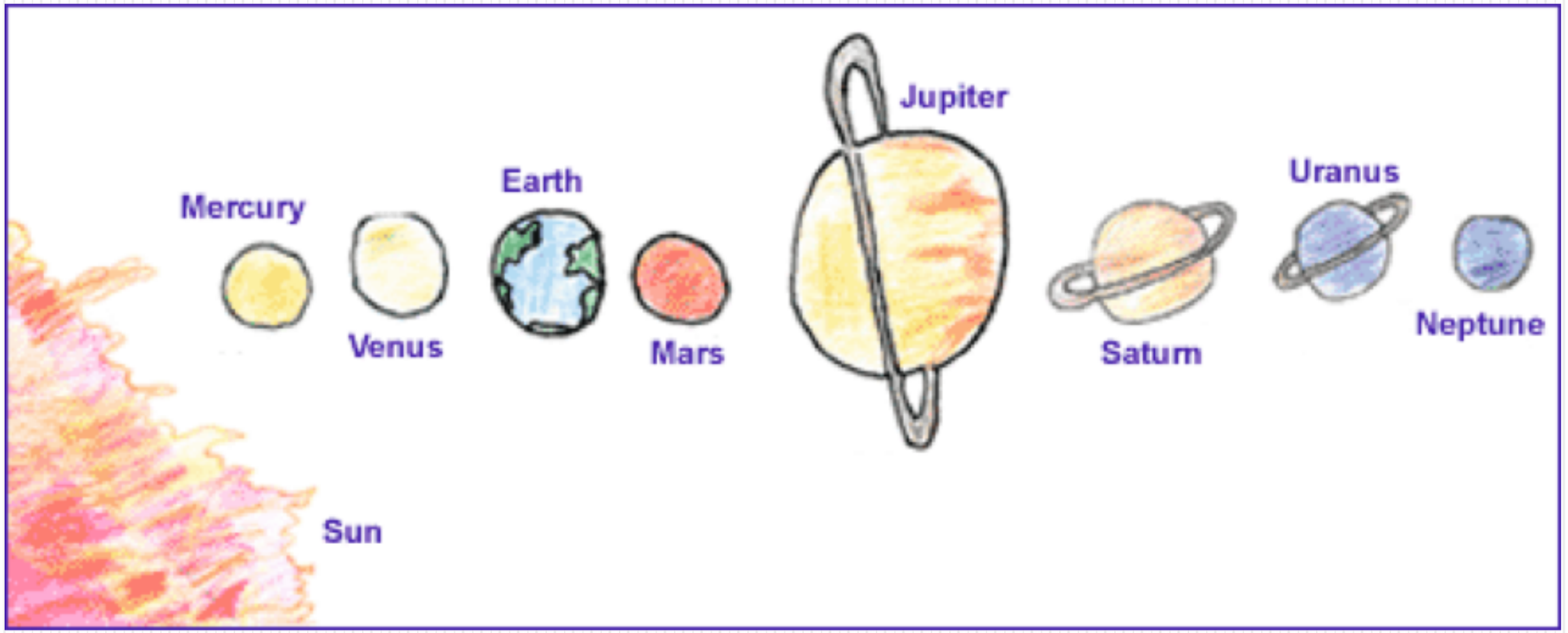


Modern concept of the cosmos



Earth is a planet in the solar system …
in the Milky Way Galaxy … in the Local Cluster of galaxies … in the Universe

Modern concept of the cosmos

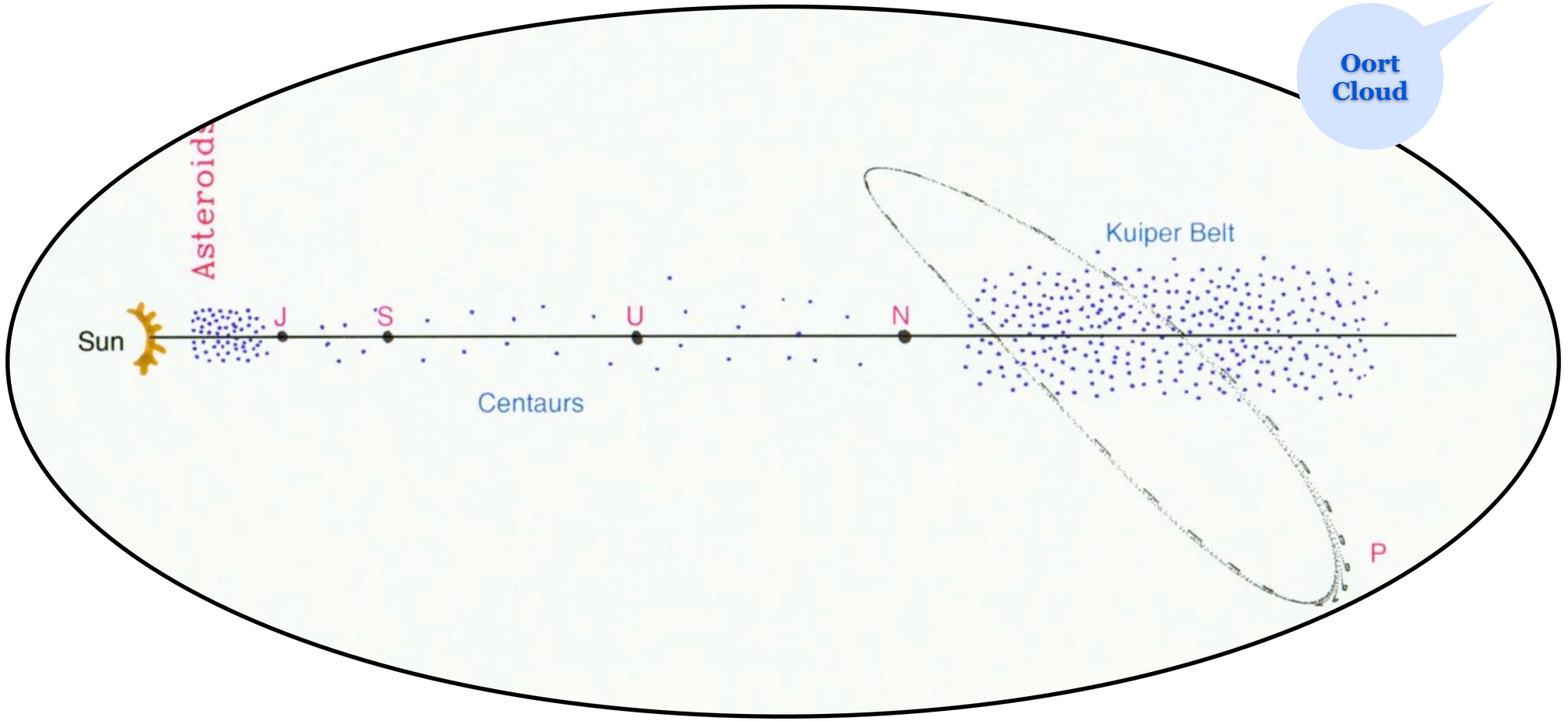


Earth is a planet in the solar system …
in the Milky Way Galaxy … in the Local Cluster of galaxies … in the Universe

evolves on many timescales

Four or Five distinct neighborhoods in the Solar system

also some stragglers in-between (NEOs, Centaurs)



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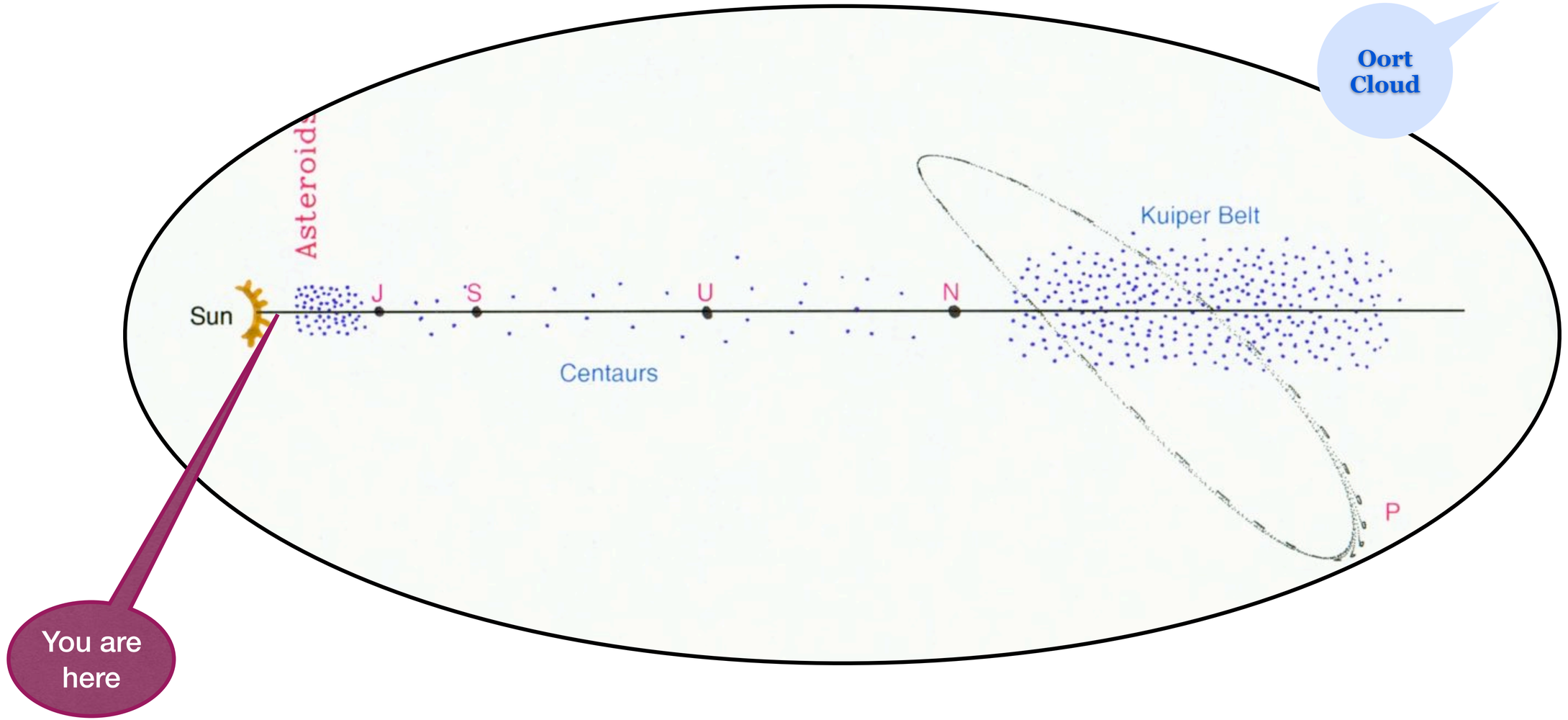
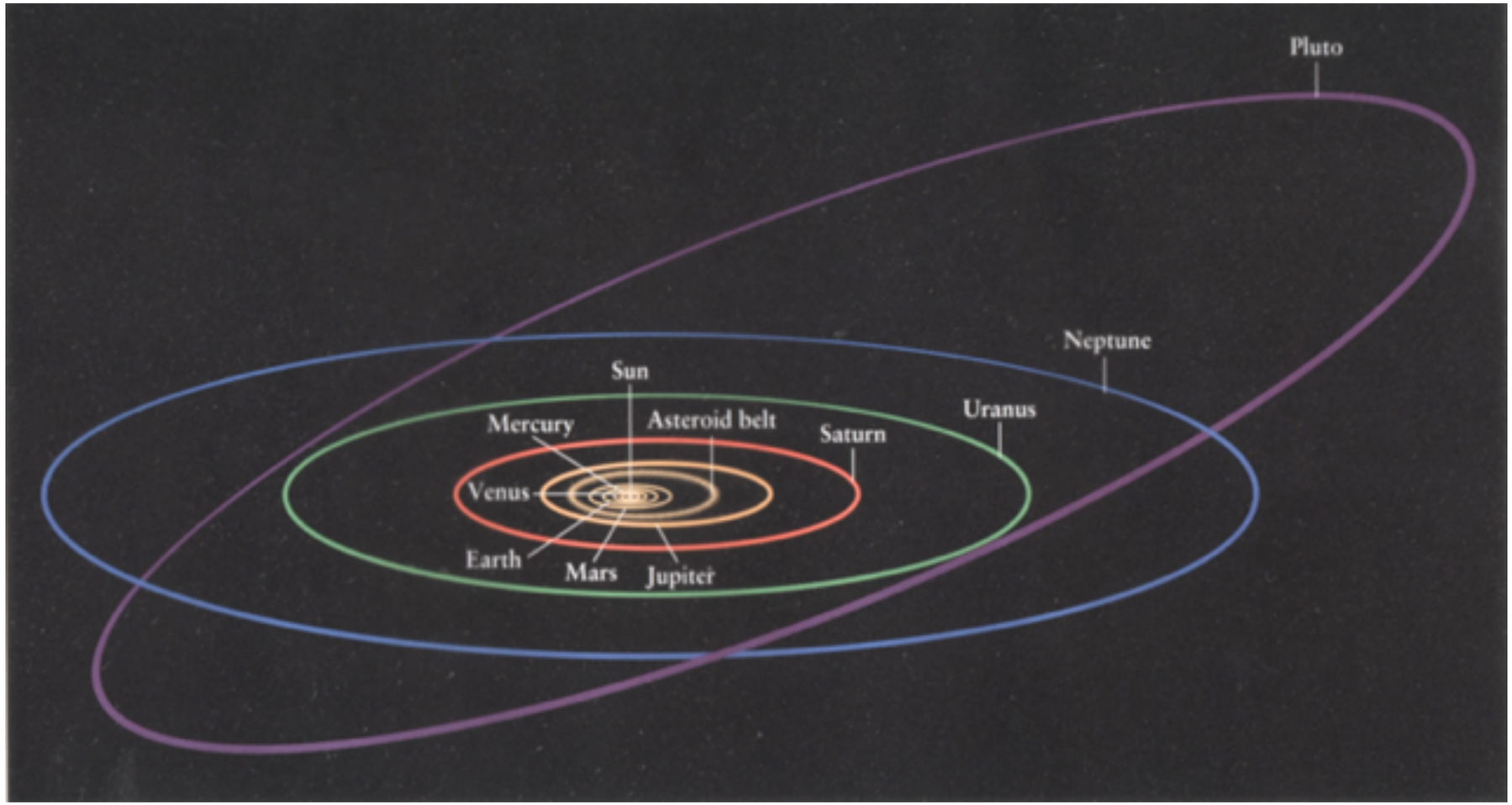
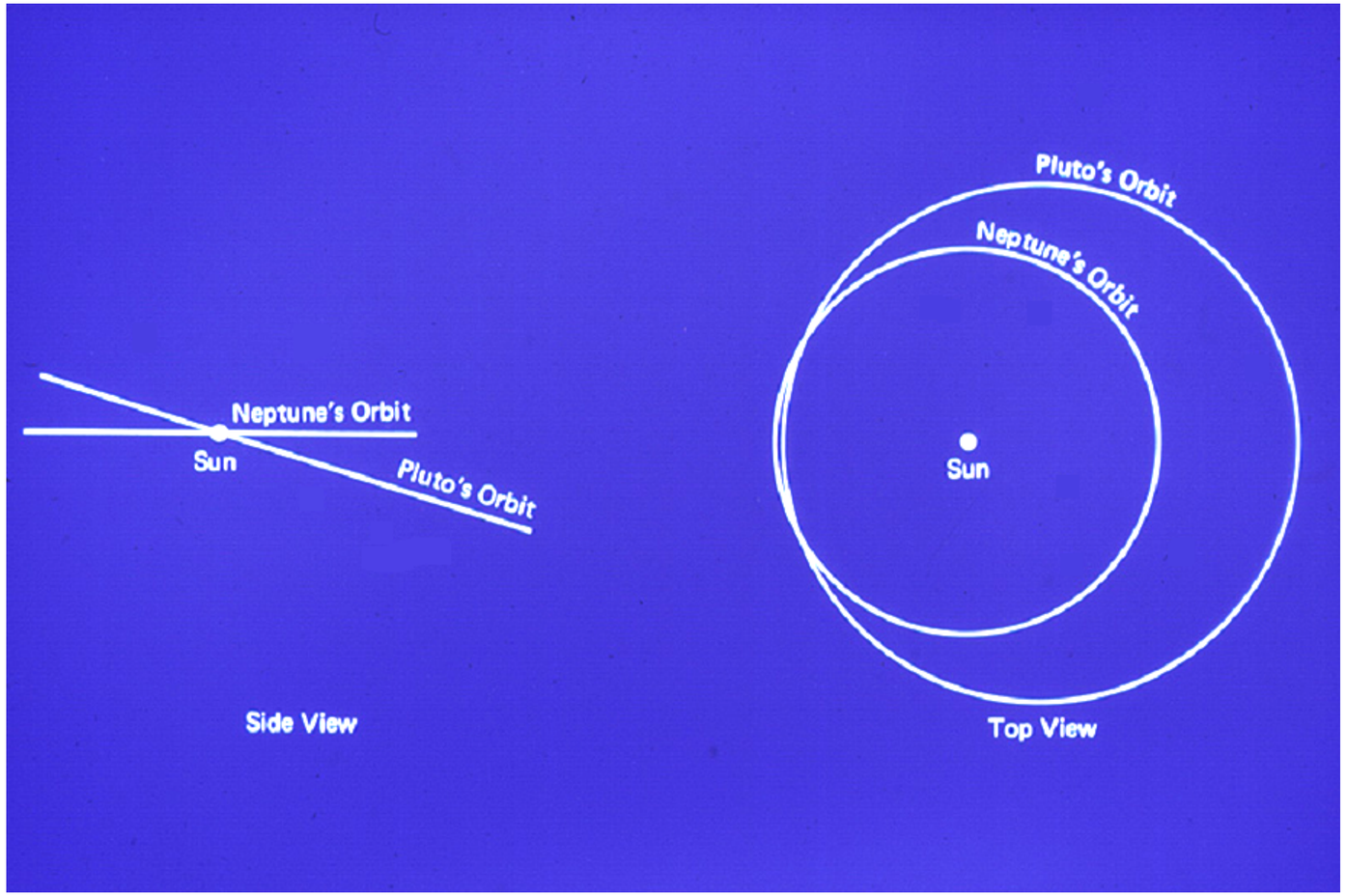


circa ~1990 … Nine planets in the solar system



Pluto is eccentric
its orbital path overlaps that of Neptune
but it is in no danger of colliding with Neptune



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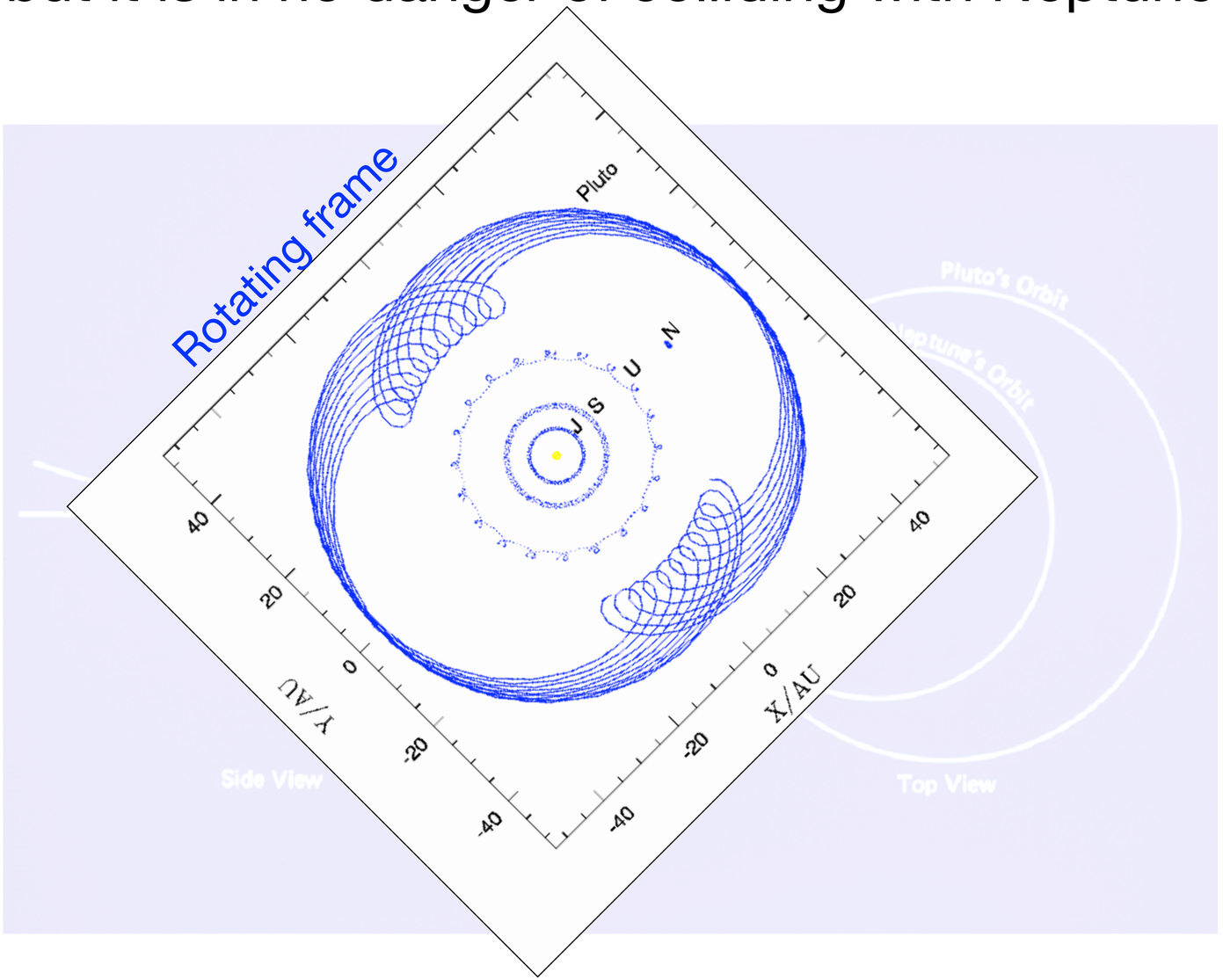

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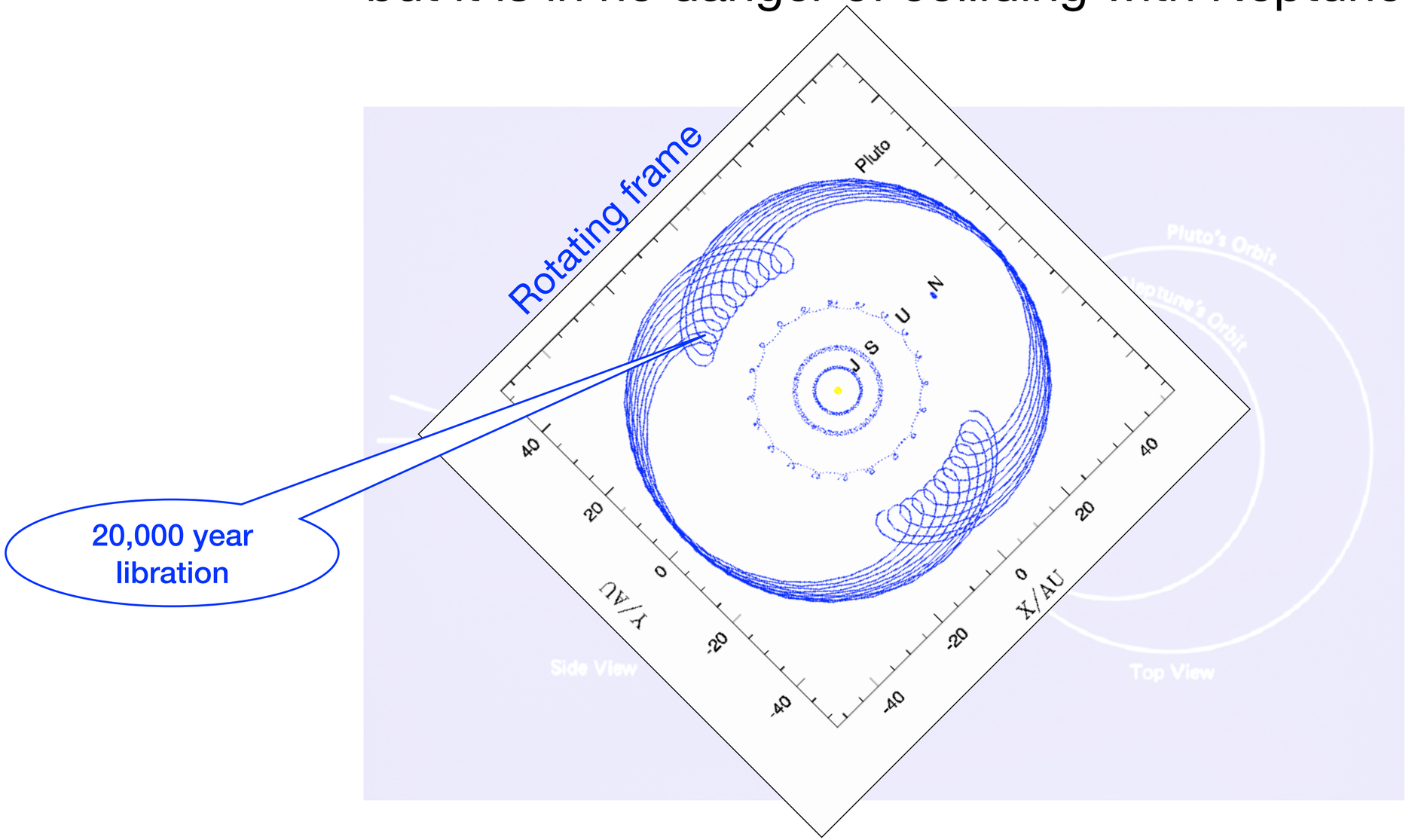
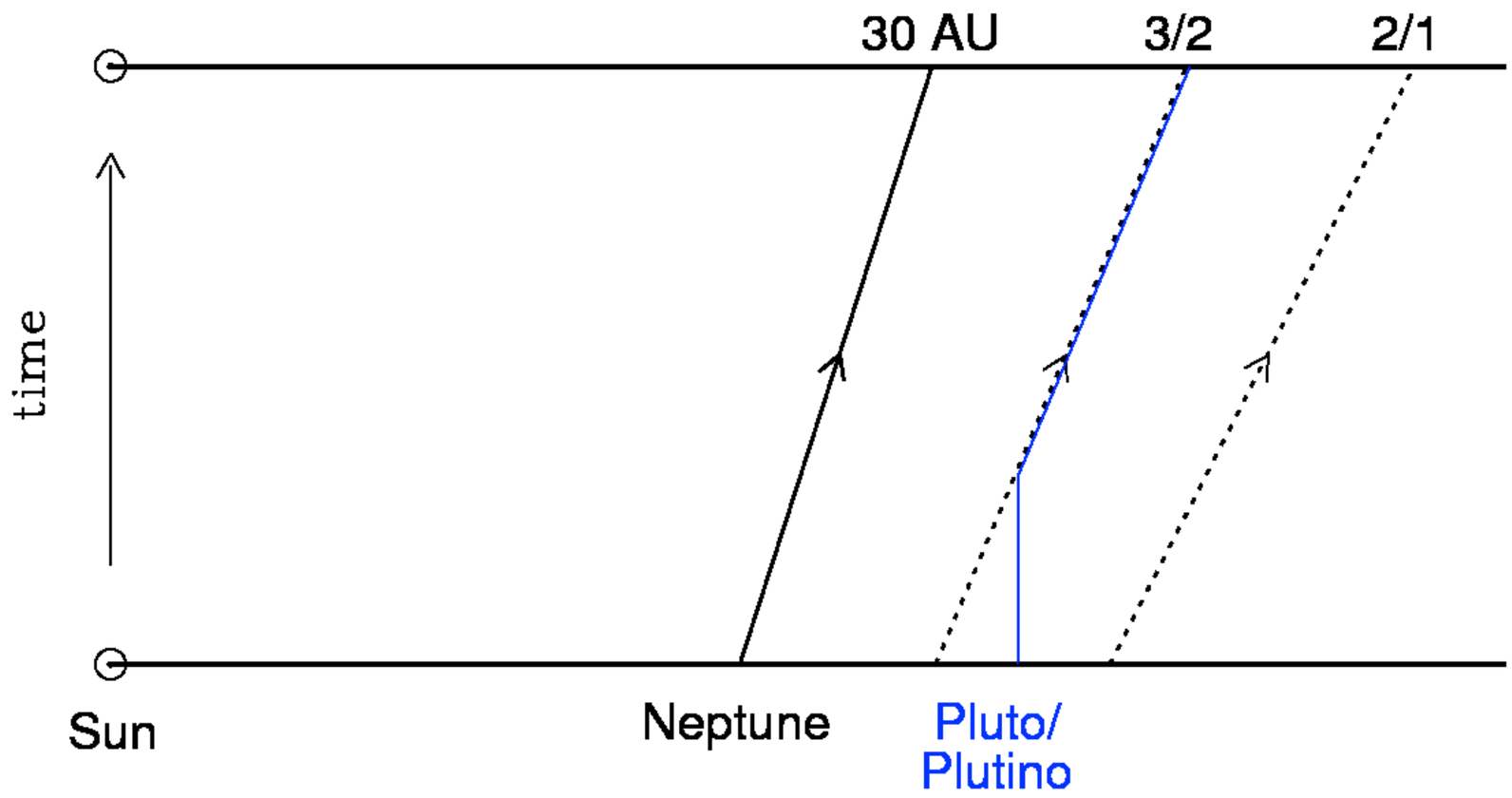


Neptune's migration and Resonance sweeping



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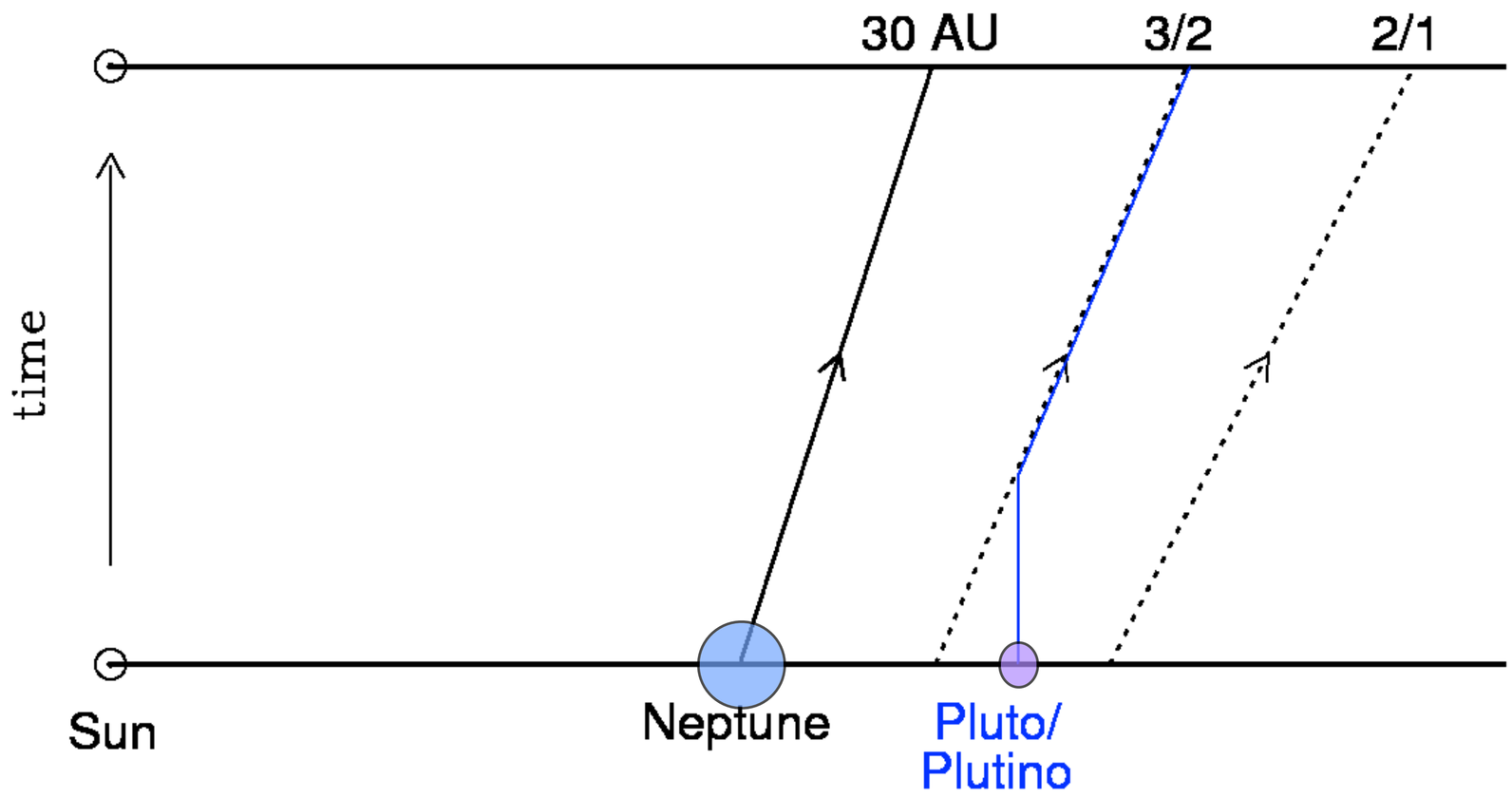

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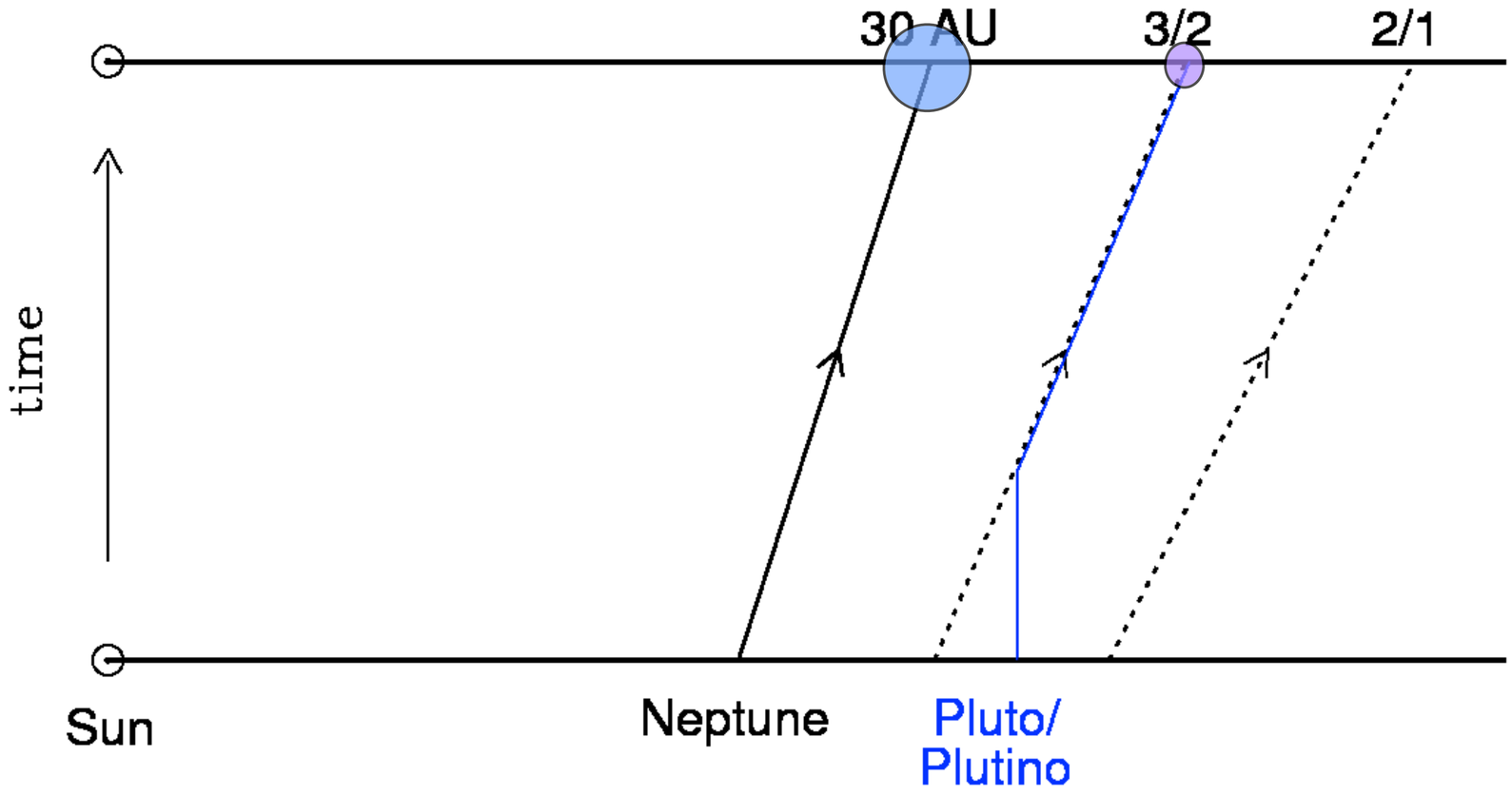
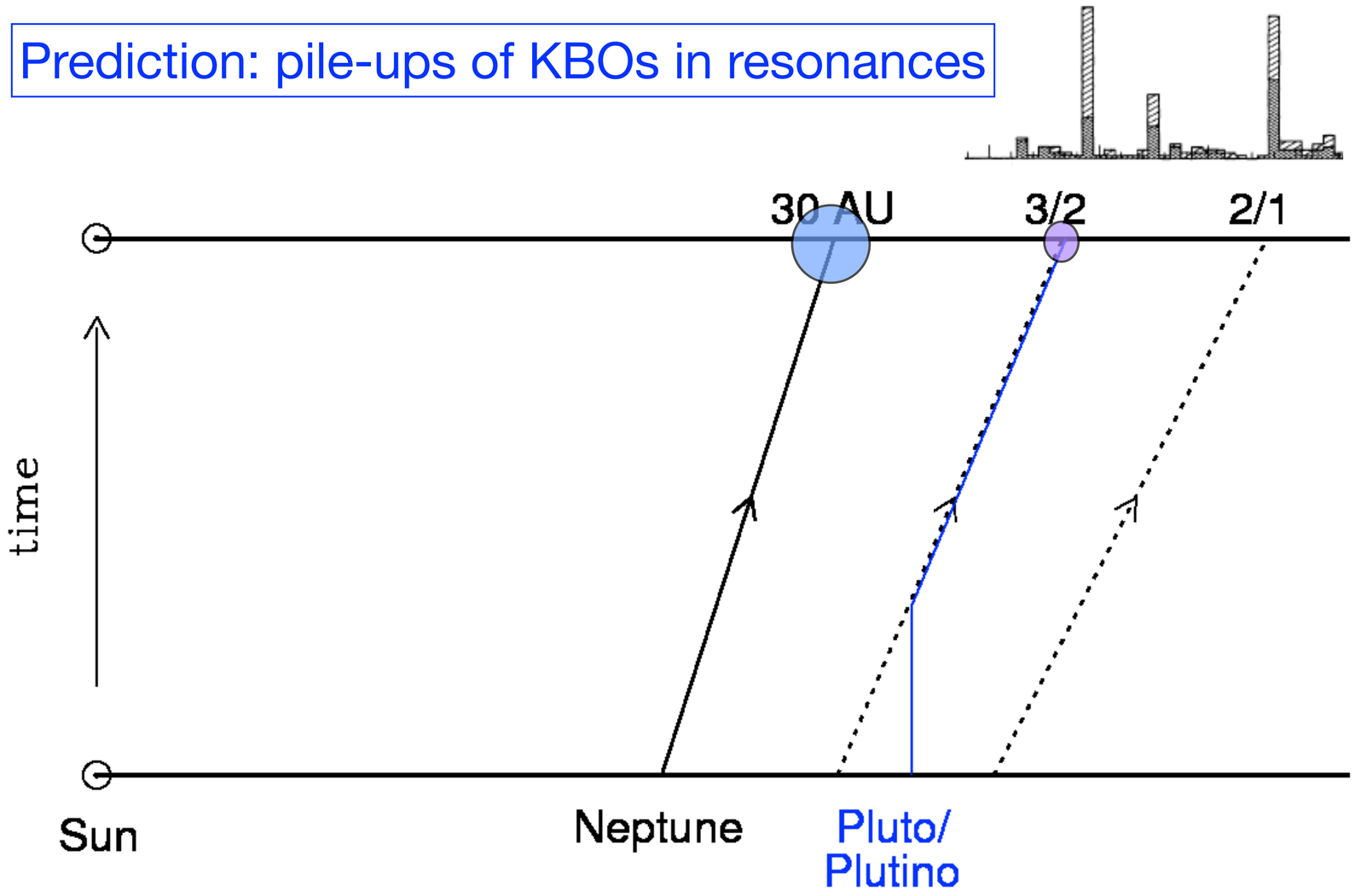
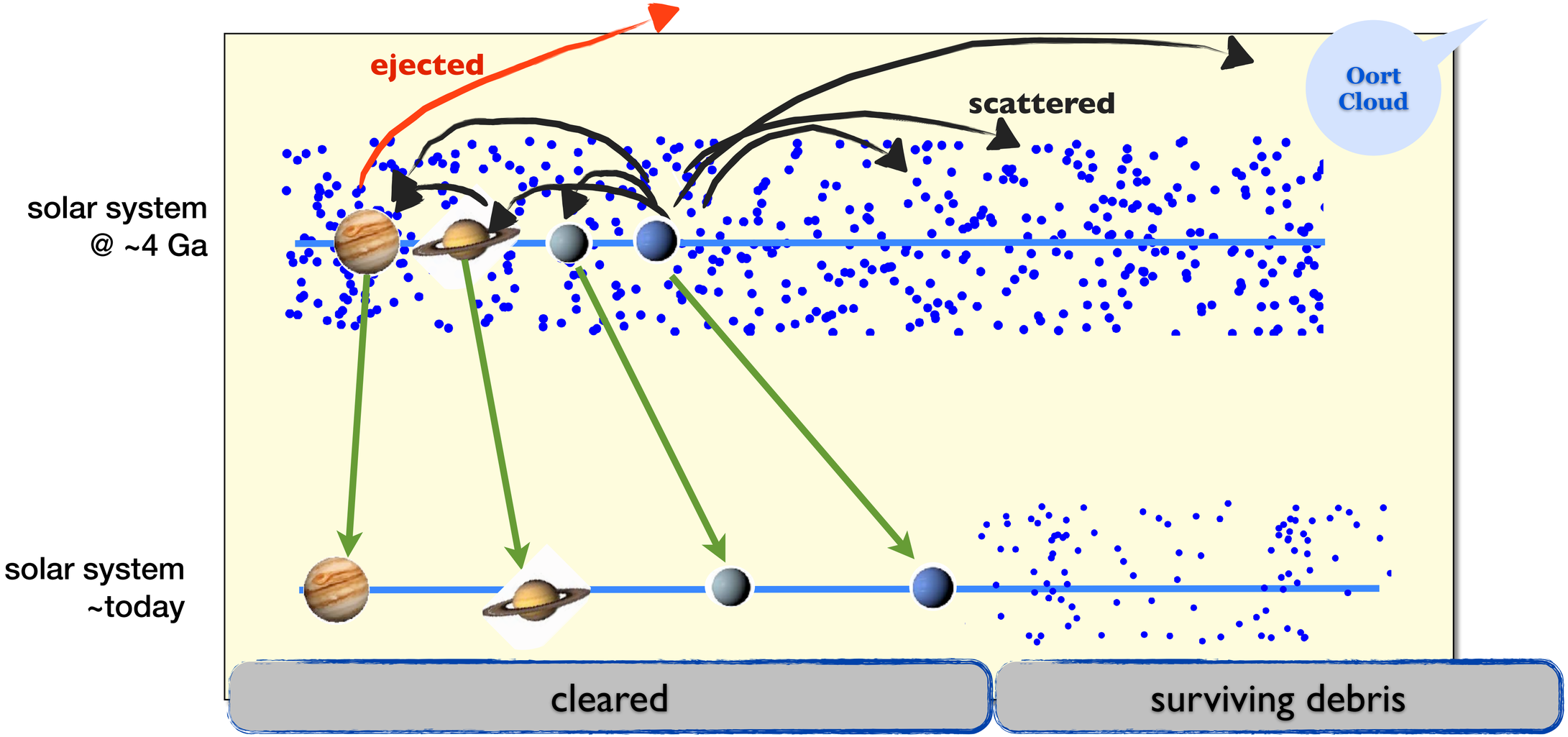


Neptune's migration and Resonance sweeping

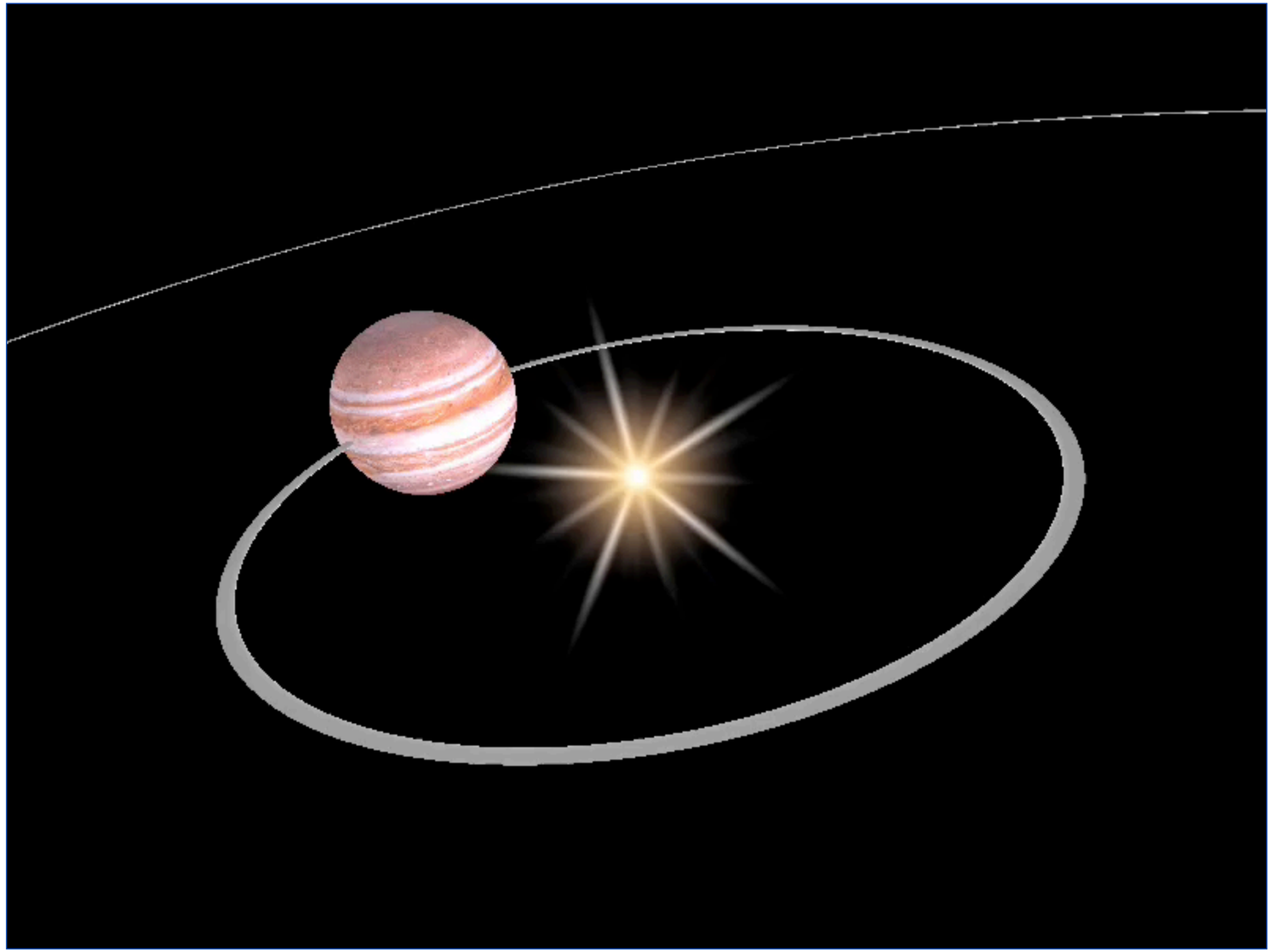
Prediction: pile-ups of KBOs in resonances



Giant planet migration fueled by leftover planetesimals



Planetesimal clearing ➡ back-reaction on the planets



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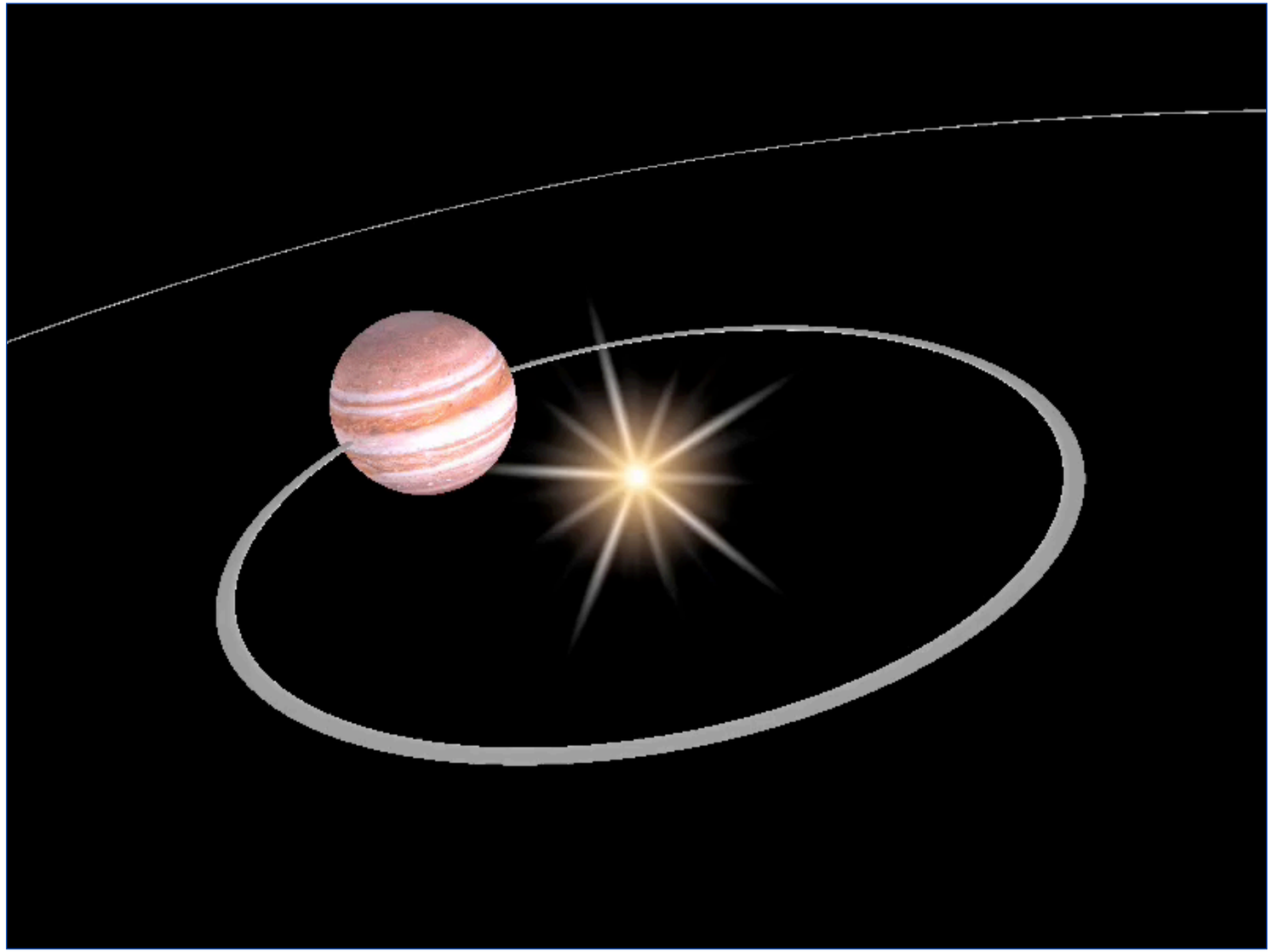

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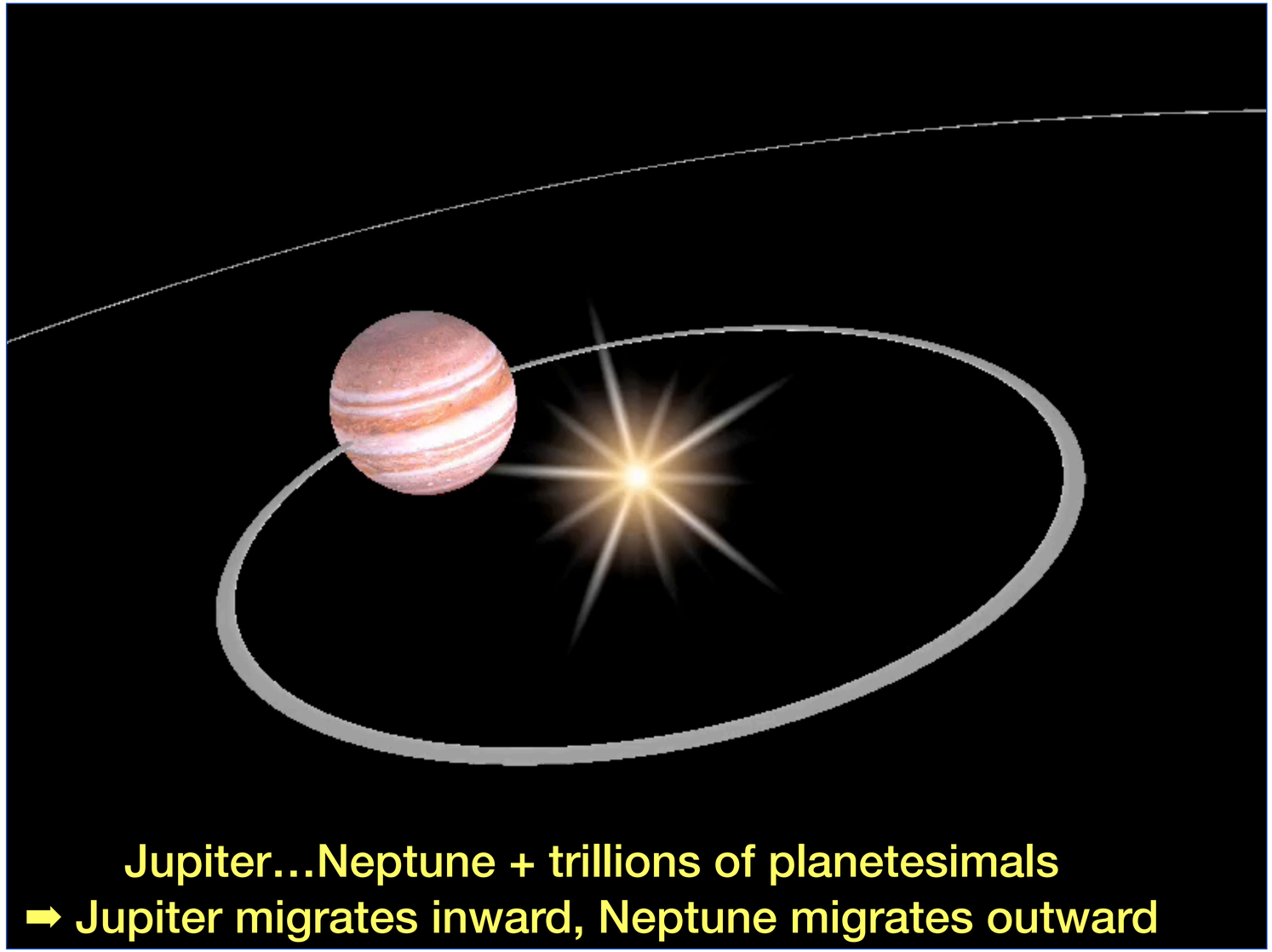


NATURE · VOL 365 · 28 OCTOBER 1993

The origin of Pluto's peculiar orbit

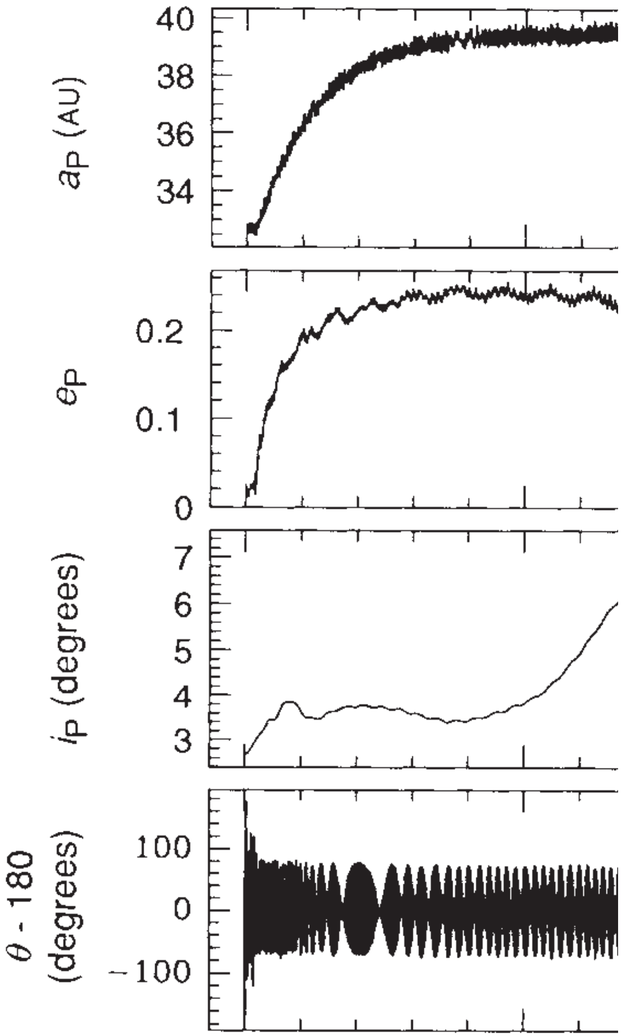
Renu Malhotra

$$e^2_{\mathrm{P,final}} - e^2_{\mathrm{P,initial}} \approx \frac{1}{j+1} \ln\left(\frac{a_{\mathrm{N,final}}}{a_{\mathrm{N,initial}}}\right)$$

Pluto's resonance and eccentricity

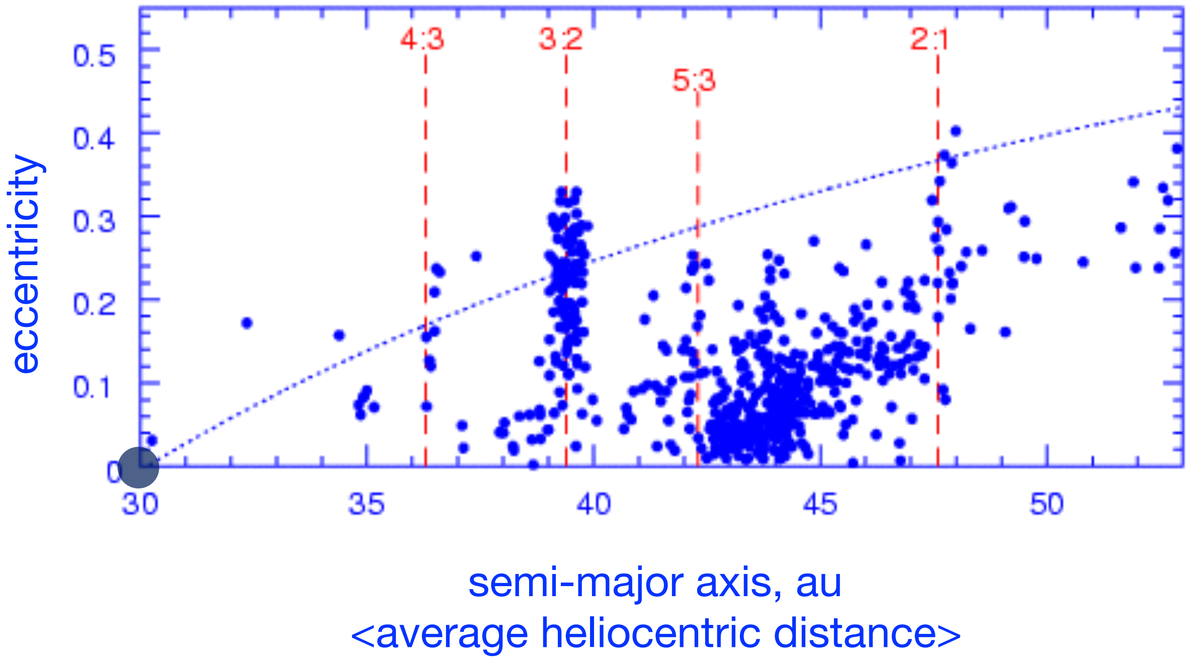
Neptune's migration

$e_P = 0.25 \quad \Rightarrow \quad \Delta a_N \approx 5$ au

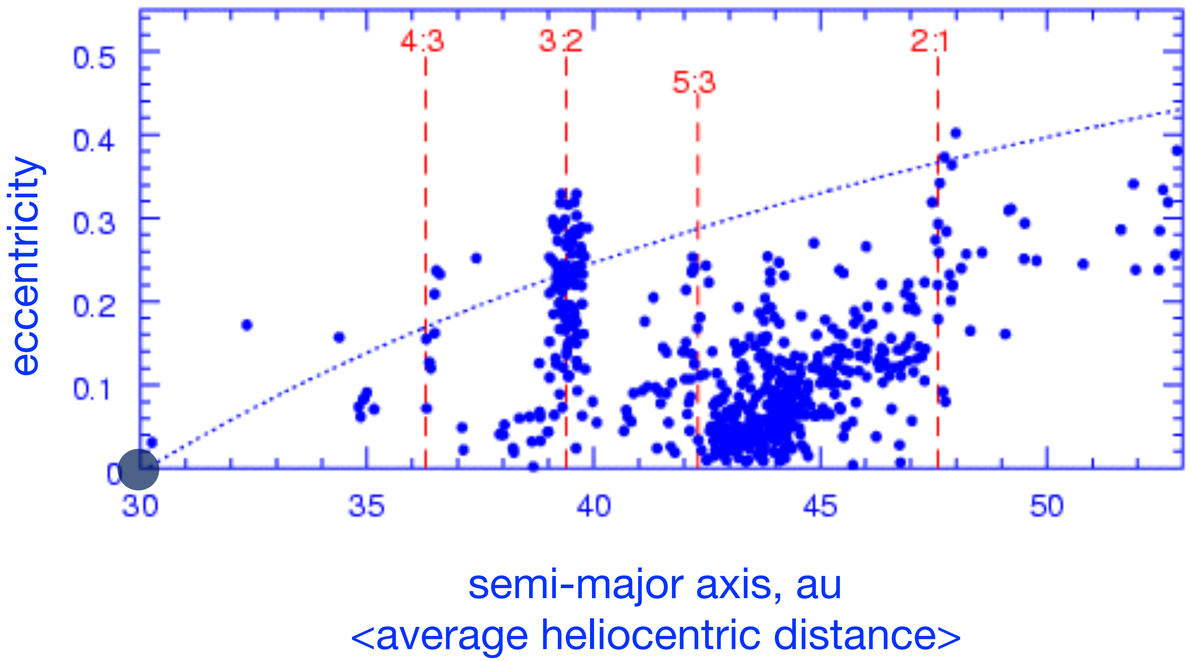


Confirmed with computer simulations

Kuiper Belt observations



Kuiper Belt observations



resonances, eccentricities, inclinations
➡ **Neptune migrated out ≈10AU**

Other observational tests?

Asteroid belt

Impact craters on planetary surfaces

Asteroid belt - Kirkwood gaps

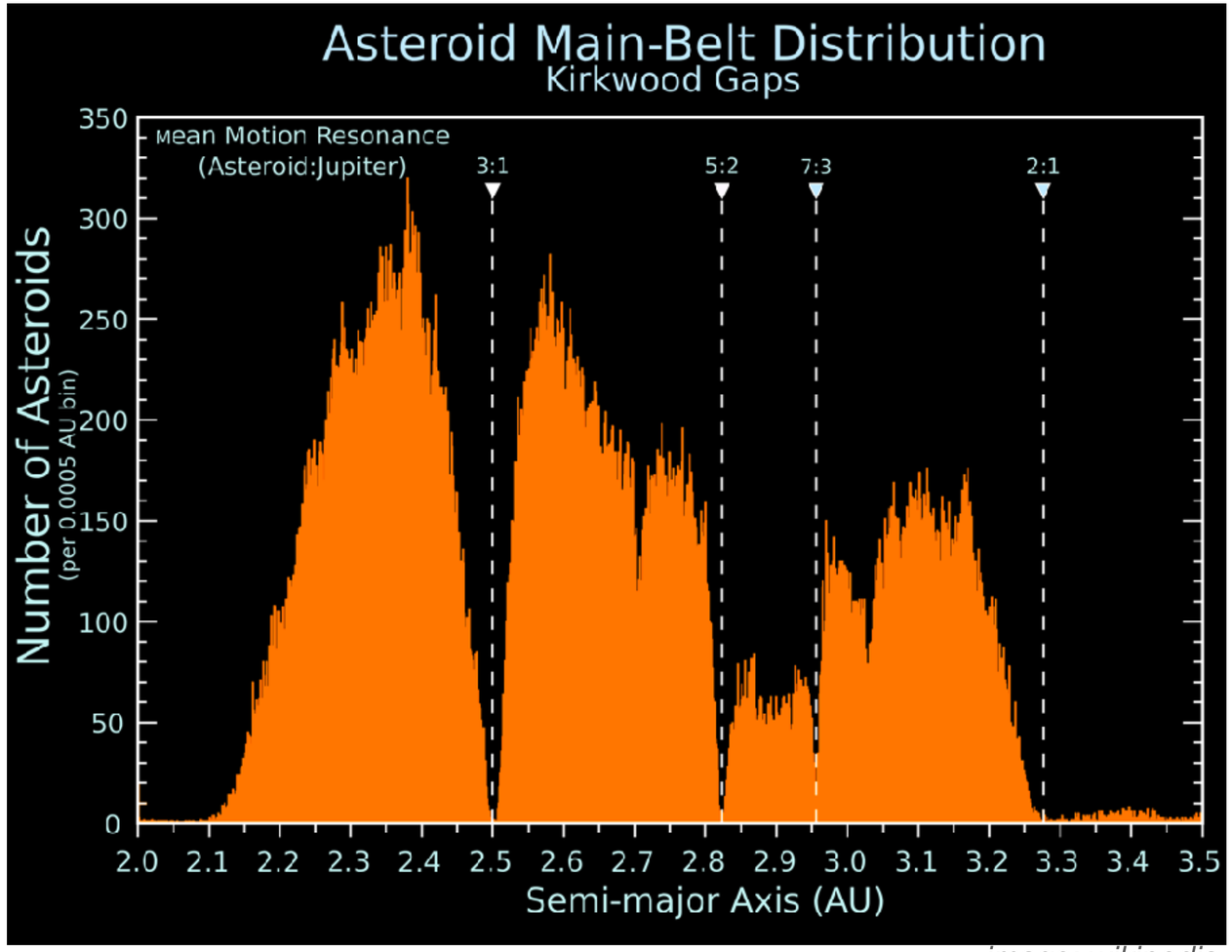


image: wikipedia

Asteroid belt - Kirkwood gaps

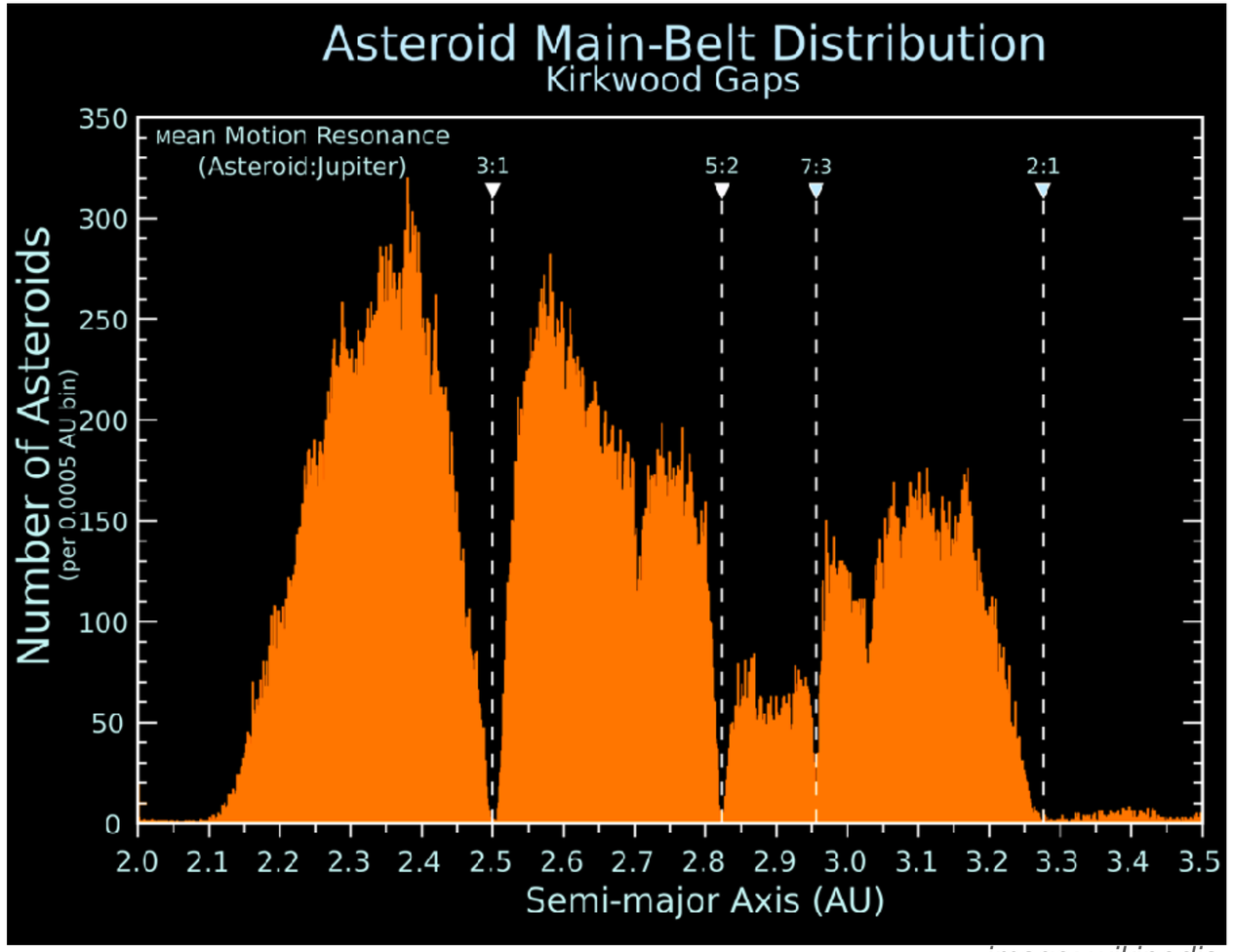


image: wikipedia

Discovered by Daniel Kirkwood

in 1857, when less than 100 asteroids were known

Kirkwood related the locations of the gaps to mean motion resonances w/Jupiter

Asteroid belt - Kirkwood gaps

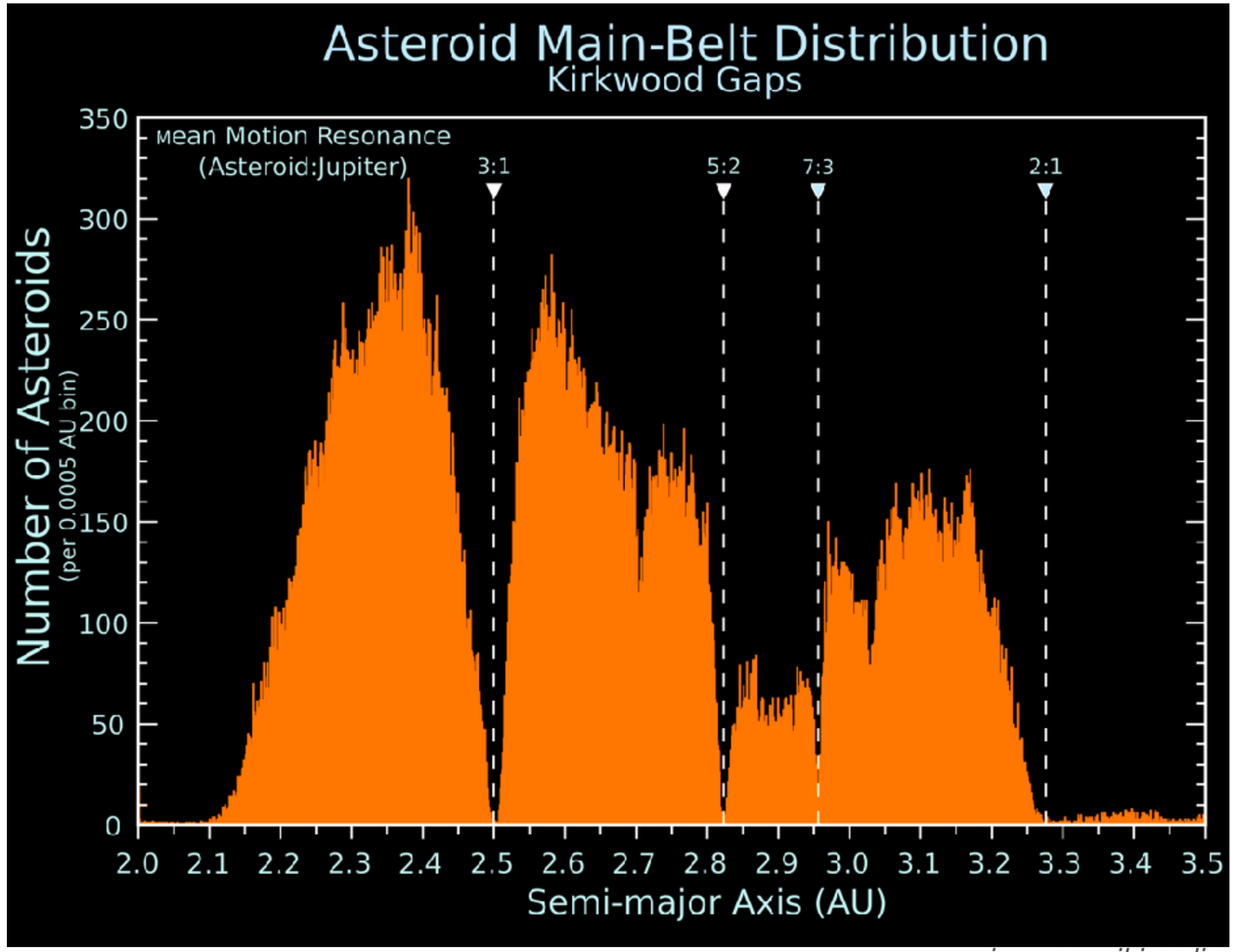


image: wikipedia

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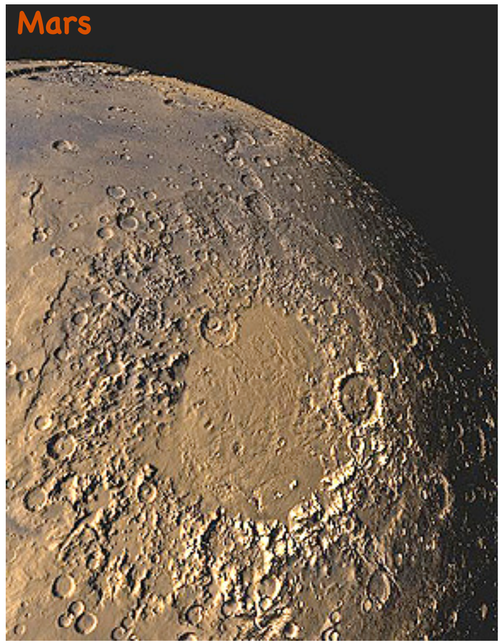
Kirkwood related the locations of the gaps to mean motion resonances w/Jupiter

The gaps sizes are best explained if Jupiter migrated inward from a slightly larger orbit

Moon

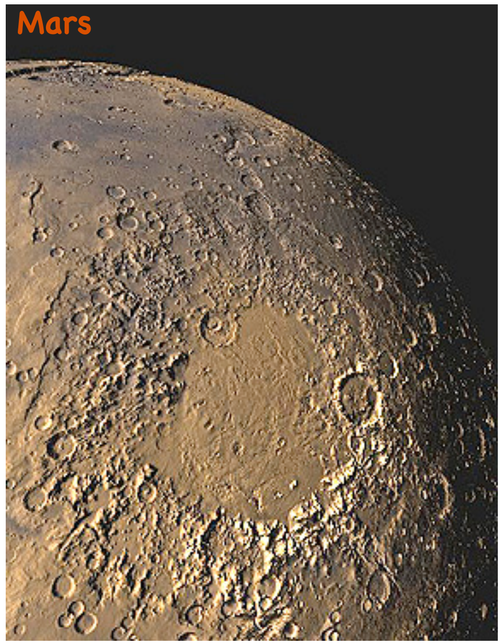


Mercury

Moon

Venus

Mars



Summary

- The solar system has not always looked like it does now (@ age of 4.567 Gy)

  @ 4.5 Gyr ago: orbits more compact + a lot more debris (asteroids, comets)
  @ ~4 Gyr ago: debris cleared up (mostly), planets settled into their present orbits

- That early dynamic period had major consequences
  - ✦ planetary re-arrangements ⇒ (more) stable orbits
  - ✦ heavy meteoroidal bombardment
  - ✦ very little asteroidal/cometary debris left, hence low bombardment rate on Earth

- Details under active study and debate