An introduction to

Solar System Dating

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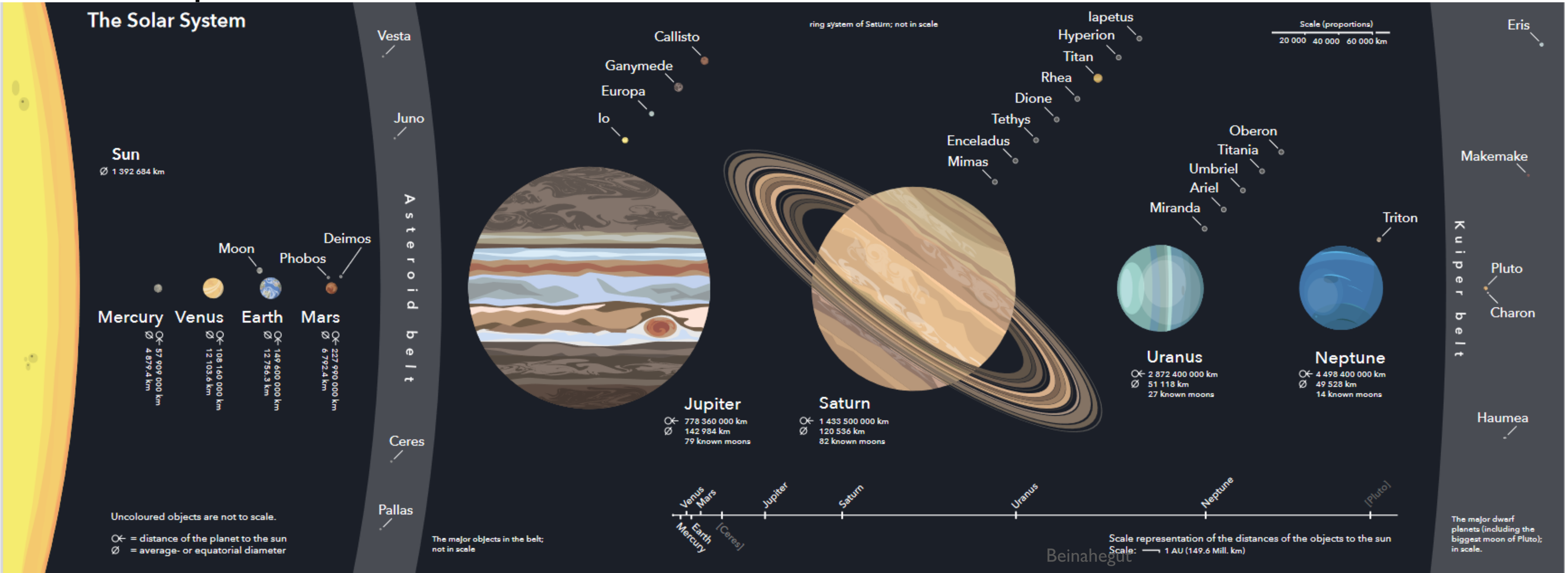
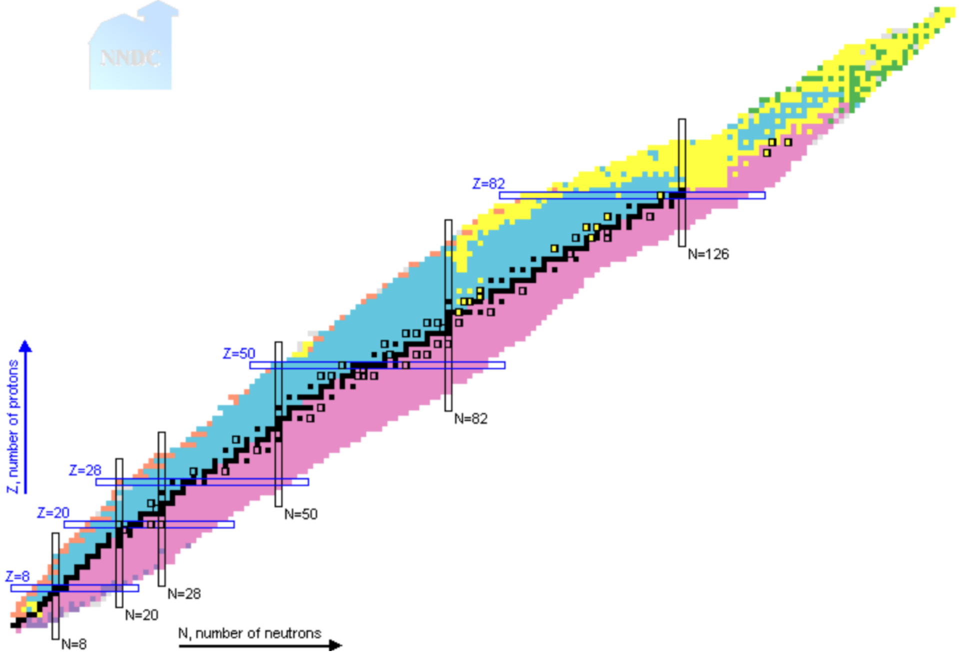
"The solar system is 4.6 billion years old" …how do we know that?

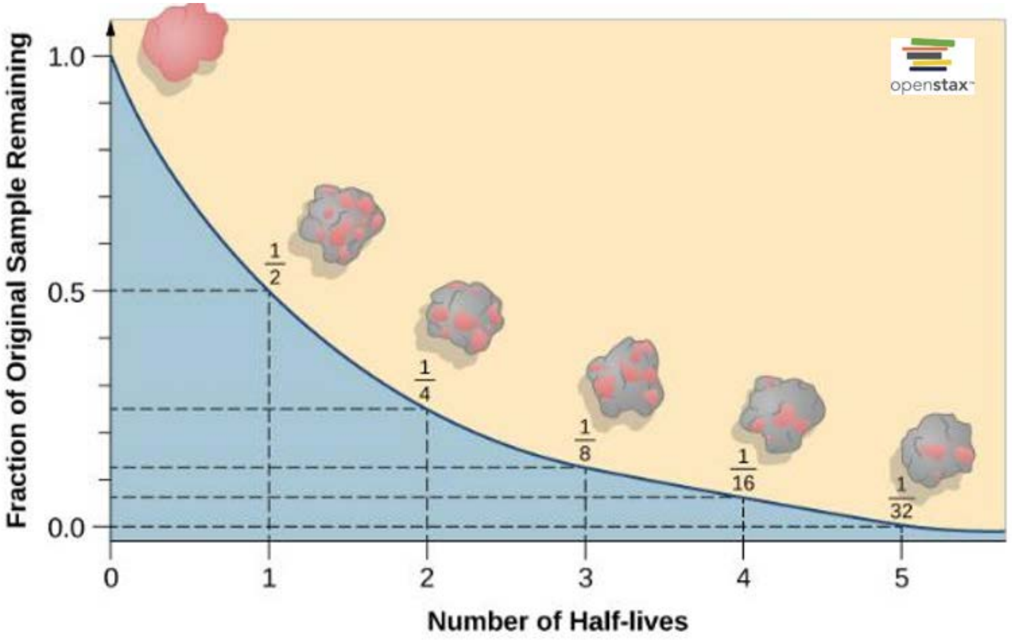
- Age determination in the solar system primarily consists of
  - Radioactive dating
  - Crater counting
  - Comparing to other systems
  - Computer models



Radioactive Decay

- Most nuclei undergo radioactive decay, which is a spontaneous transmutation into different isotope
- Each nucleus has a particular decay probability, which is constant, that determines the overall rate of decay for an ensemble of that nucleus. However, the decay of a single nucleus is random.
- This leads to the "universal decay law", whereby the abundance of an isolated sample of a radioactive nucleus will decay exponentially
  - $N(t) = N(0)e^{-\lambda t}$
  - λ is the decay constant, which is related to the (more familiar) half-life via: $\lambda = \frac{\ln(2)}{t_{½}}$
  - The half-life, $t_{½}$, is the time it takes for half of the sample to decay

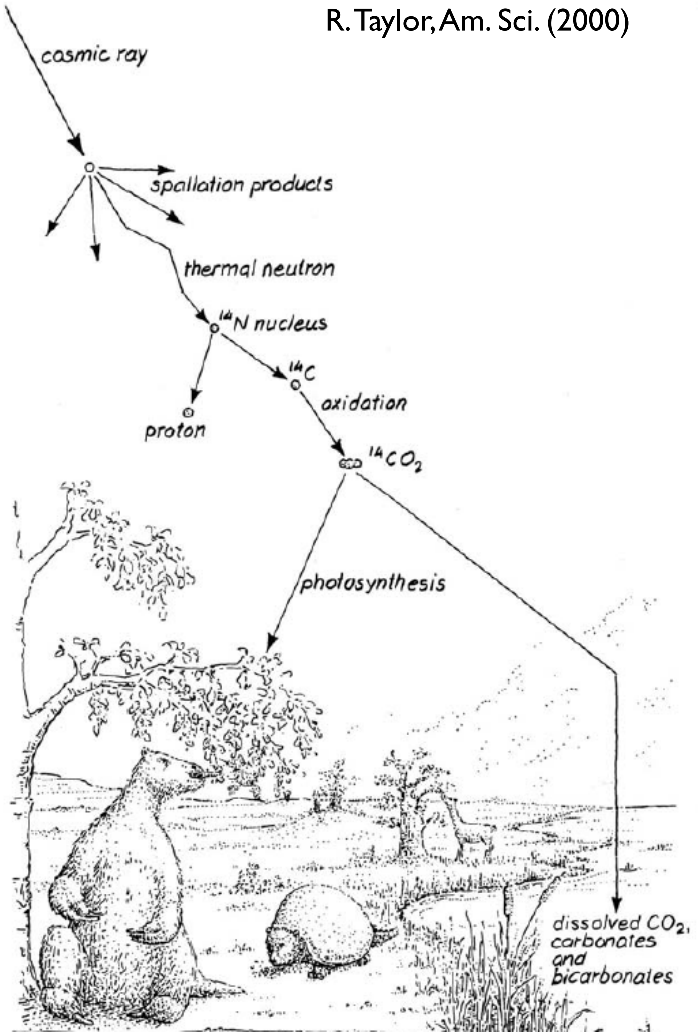




Radiometric dating: *basic concept*

R. Taylor, Am. Sci. (2000)

- If I knew how much of a particular isotope was originally in a sample, then the current abundance could be used to determine the sample age
- Example: Carbon-dating
  - ^{14}C ($t_{½} \approx 5700$ yr) is constantly replenished on Earth's surface by cosmic ray spallation
  - Living organisms have a constant intake of carbon, so the $^{14}C/^{12}C$ ratio is ~constant.
    [Nuclear incidents and varying cosmic ray flux complicate this]
  - Once the organism dies, there is no longer carbon uptake, so the ^{14}C decays away steadily
  - 5700 years after an organism has died, the $^{14}C/^{12}C$ ratio is half of the original constant value. In general, time since death is:
    - $\frac{^{14}C}{^{12}C}(t) = \frac{^{14}C}{^{12}C}(0)e^{-\ln(2)t/(5700\,yr)}$
    - $t = -\frac{5700}{\ln(2)}\ln\left[\frac{^{14}C}{^{12}C}(t)/\frac{^{14}C}{^{12}C}(0)\right]$ years
  - After ~10 half-lives, the ratio (1/1024) is difficult to measure, so other nuclear chronometers are needed



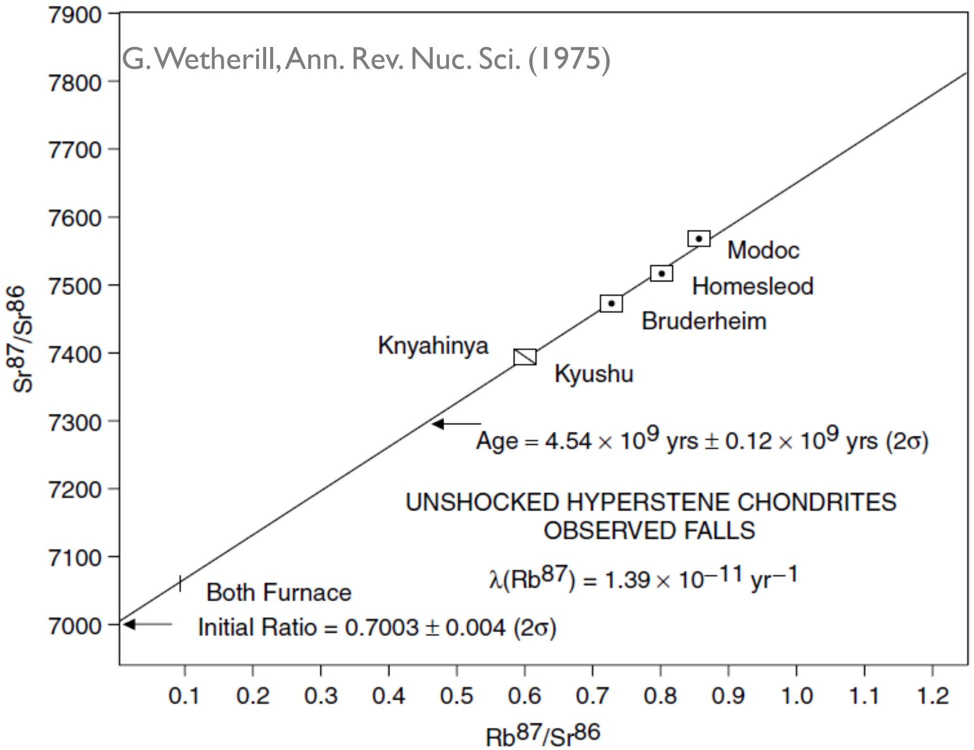
This is how we know the Shroud of Turin is only from ~1300AD
(P.E.Damon et al. Nature 1989)

Radiometric dating: *getting more advanced*

- Often life is more complicated:
  We may not know the initial abundance of an isotope in a sample and chemical effects may have changed the abundance (e.g. a gas escaping a rock)
- Instead focus on isotopic ratios, choosing a different isotope of the same element as a reference, where the reference is stable and not fed by a long-lived decay
- Know that the sum of abundance along a decay chain (e.g. ^{87}Rb→^{87}Sr) is constant over time:

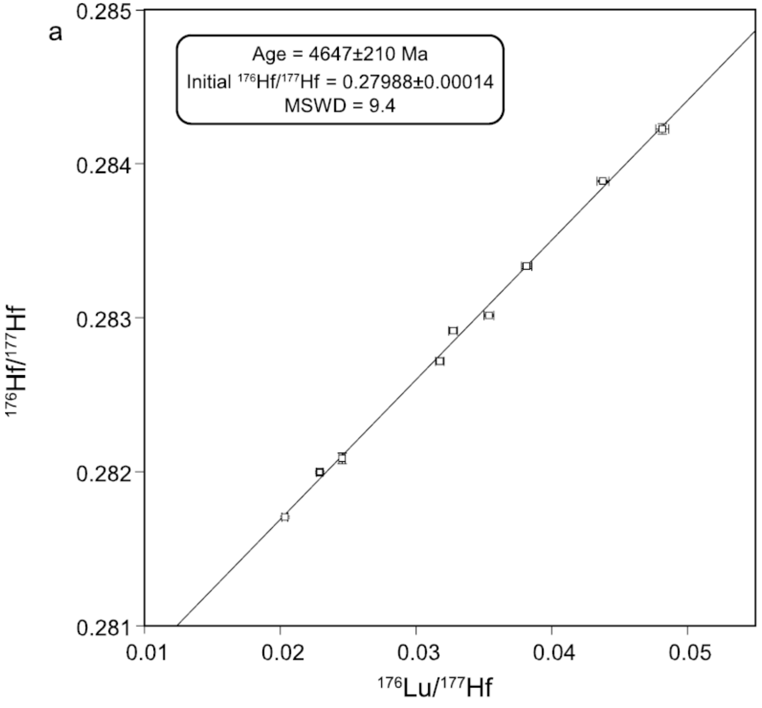
$$\frac{N_1(t)+N_2(t)}{N_s} = \frac{N_1(0)+N_2(0)}{N_s}$$

- Since $N_1(0) = N_1(t)e^{\lambda_1 t}$, $\frac{N_2(t)}{N_s} = \frac{N_2(0)+N_1(t)(1+e^{\lambda_1 t})}{N_s}$
- This is an equation for a line, $y = mx + b$, where the slope $m = (1 + e^{\lambda_1 t})$ and the y-intercept $b = \frac{N_2(0)}{N_s}$
- Since we know the decay constant of ^{87}Rb λ_1, the slope of these ratios for many meteoritic samples gives the age, t

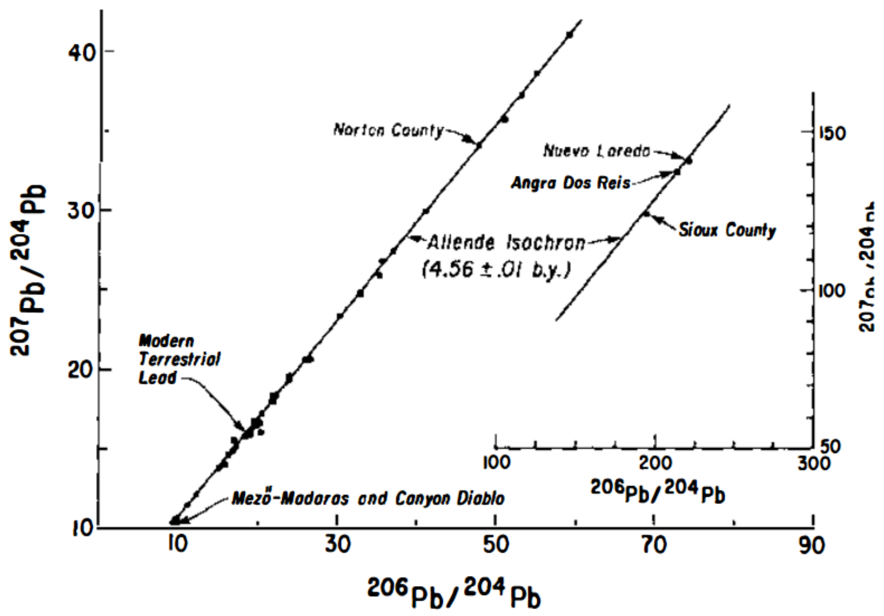


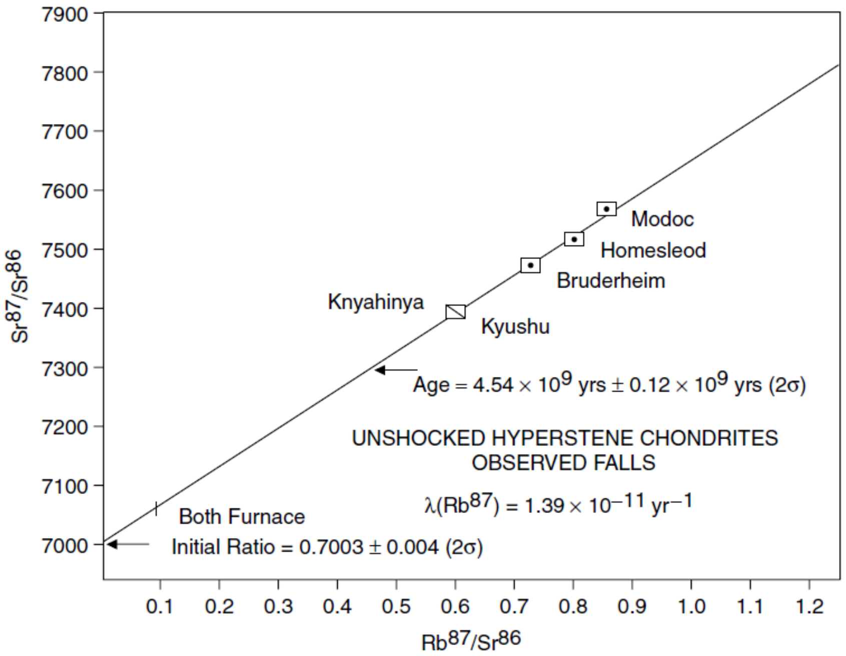
Radiometric dating from meteorites give a consistent picture, the solar system is 4.56 Gyr old

Debaille et al. Earth Plan. Sci Lett. 2017



G. Wetherill, Ann. Rev. Nuc. Sci. (1975)



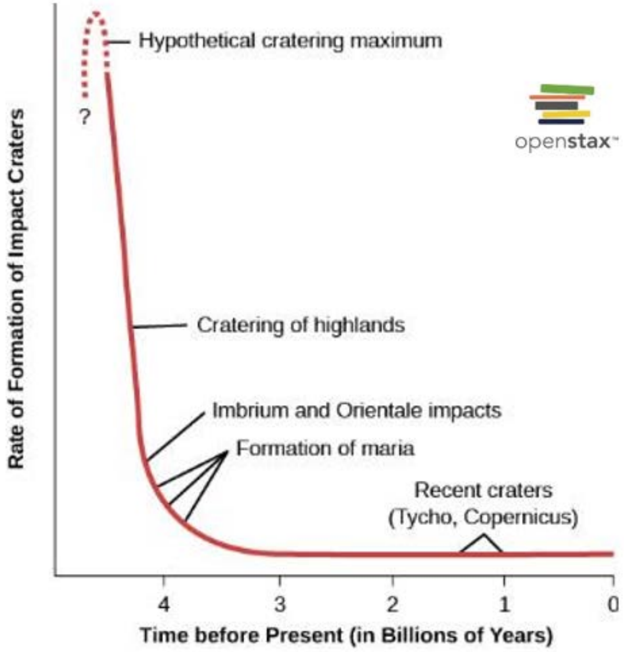


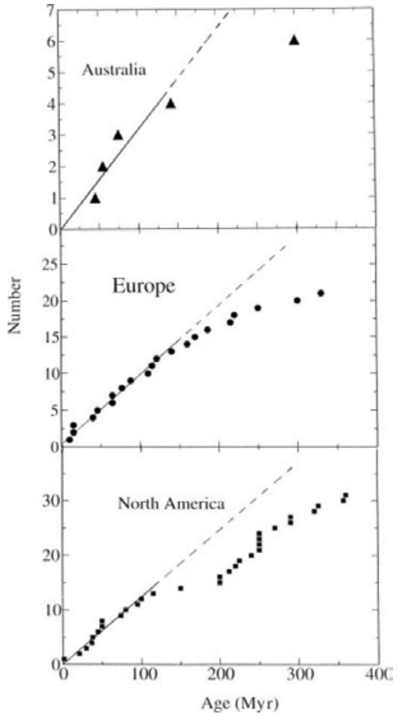
Why meteorites? No geology. On Earth, you have to be sure you're getting the oldest rock and not just the oldest rock you can find

Crater counting, for relative ages

- Assuming a constant rate of impacts on a planet or moon, the number of craters within an area should be directly related to the surface age
- For instance, an area with fewer craters may have had more recent volcanic activity, resulting in a fresher surface
- However, the rate of bombardment isn't necessarily constant.
- Radiometric dating has helped make crater counting an absolute measurement of ages
- Crater-counting still has the issue of secondary craters resulting in double-counting, so craters need to be carefully examined.
- Crater erosion is an issue on objects with weather

Fortezzo, Spudis & Harrel (USGS)

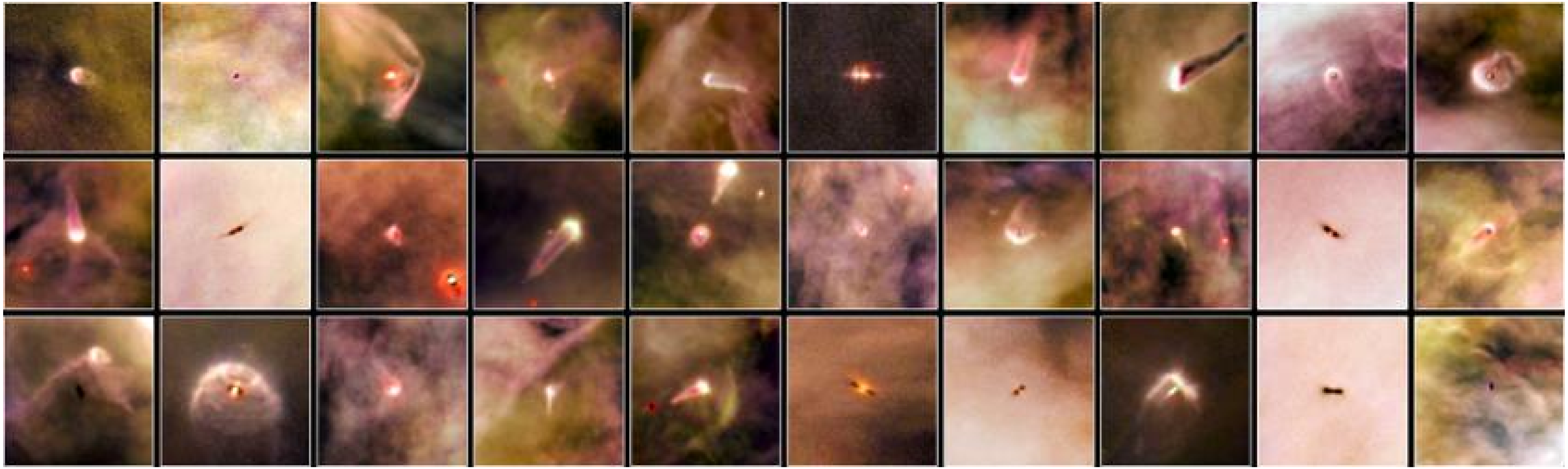




D. Hughes MNRAS 2000

Comparison to other systems, for early history

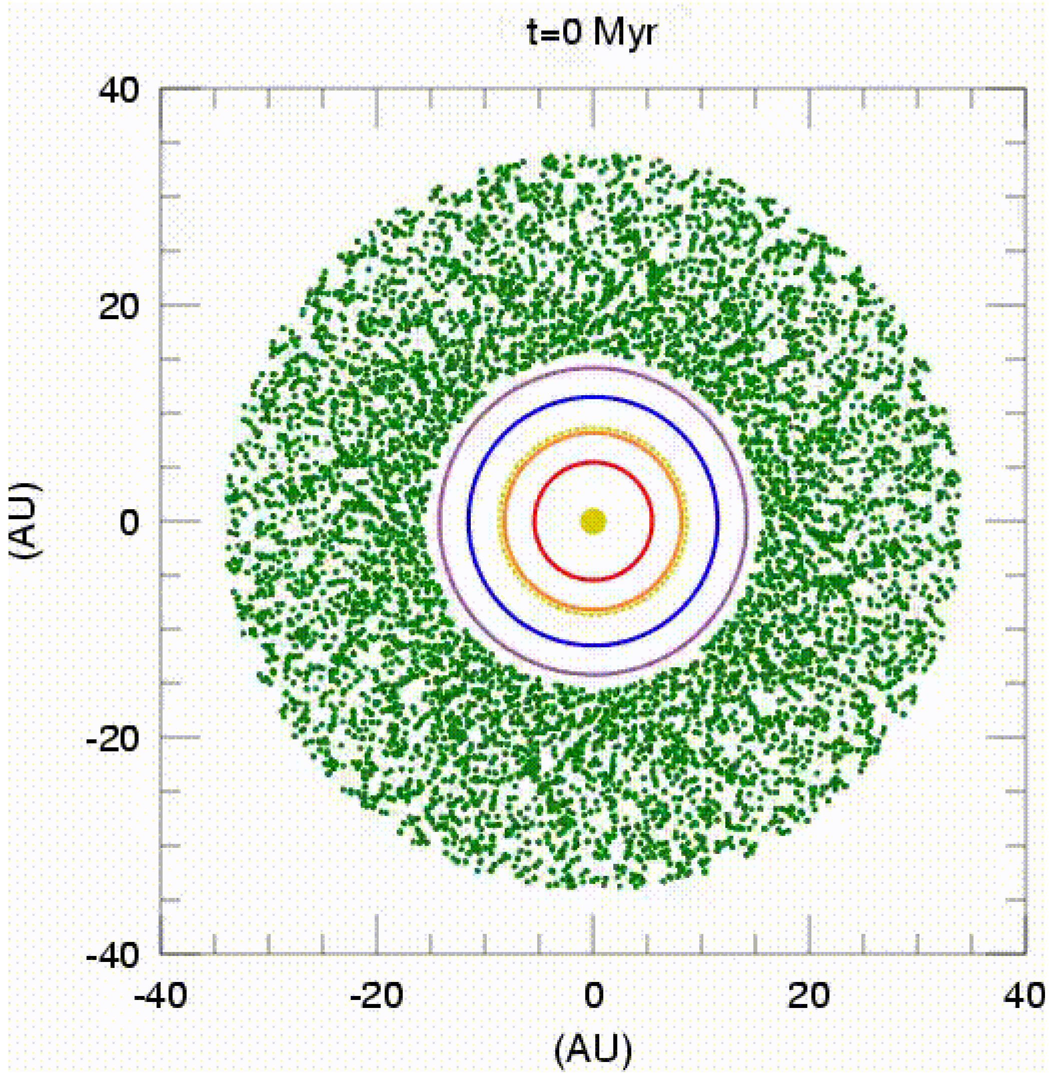
For young stellar systems, we can use a star's position on the HR-diagram for the age, and use this to determine the timescale for planet formation (See Intro to Planet Formation)



NASA/ESA, L. Ricci (ESO))

Comparison to models

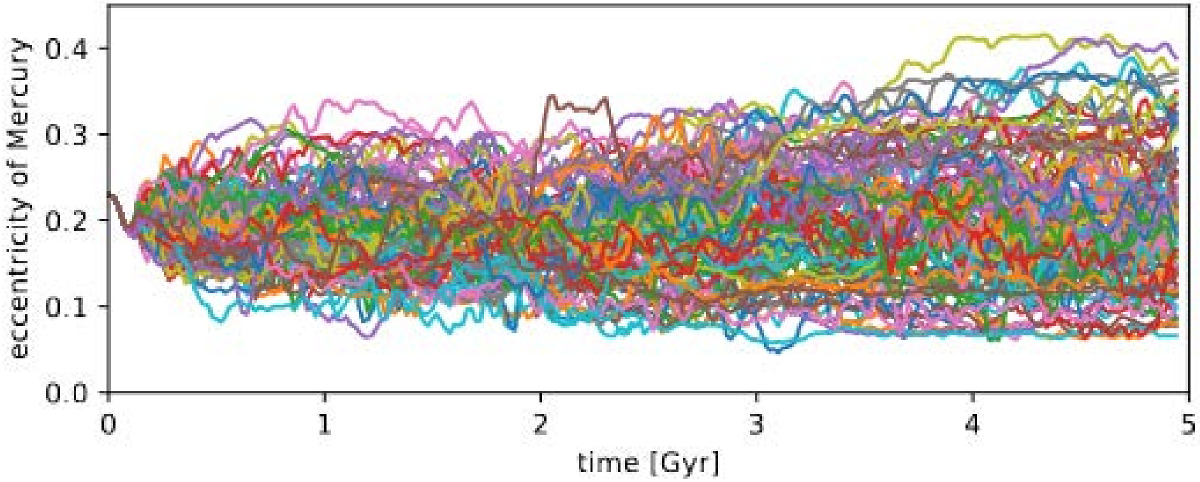
Simulations can offer possible explanations for how the solar system got to be how it is



Hal Levison (SwRI)

…but one issue is that the solar system is "chaotic".

- E.g. perturbing Mercury's initial position by ~1mm results I largely different eccentricity.



- The "solution" is that lots of model calculations need to be run in order to develop a probabilistic picture of the solar system