Meteorites, linkage to asteroids, and the Early Solar System

Meteorite terminology

Meteoroid: a small rock in space

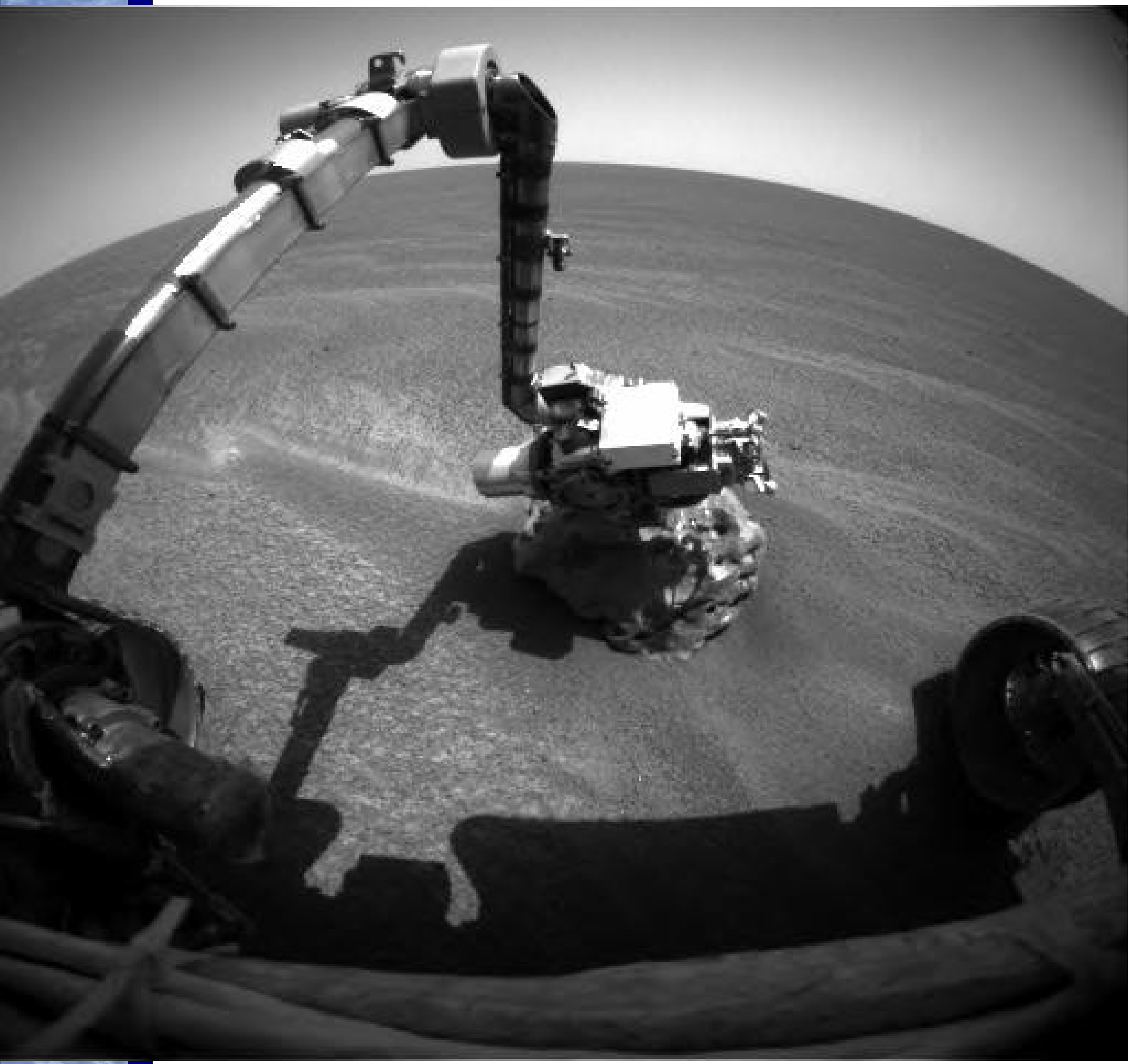
Meteorite: The fragments (if any) that reach the ground once a meteoroid has passed through the Earth's atmosphere.

Meteor: (="a shooting star"). Visible light emitted when meteoroid passes through the Earth's atmosphere. Big ones are called 'bolides'

The meteor phenomena

- Meteoroid enters top of atmosphere (~100 km up) at 15-40 km/s (typical)
- Friction with atmosphere produces light (the meteor) and then slows particle to sub-sonic speed
  - The meteoroid catastrophically fragments.
- IF any surviving fragments fall to Earth, they become *meteorites*
  - If retrieved quickly, a 'fall'
  - If not, they are 'finds'

Not just Earth



An iron meteorite has been found on Mars

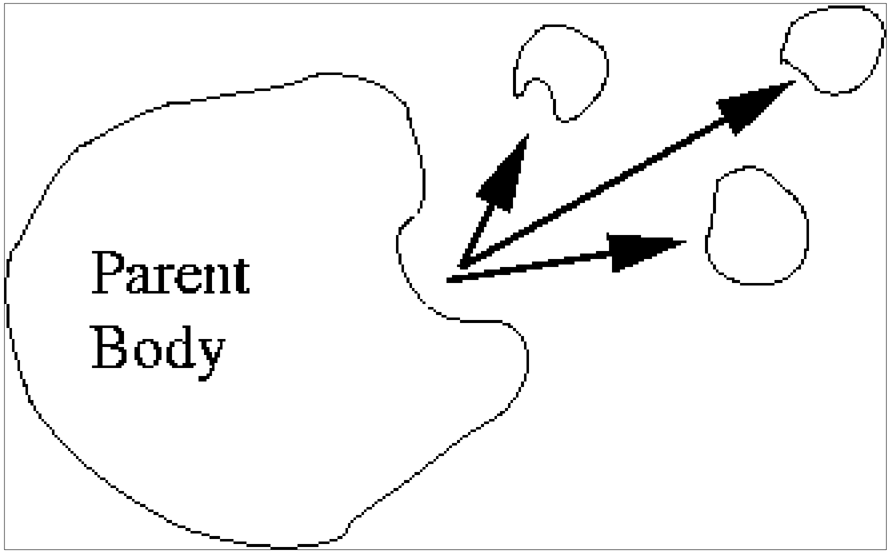
Found by martian rovers
- About 30 cm across

Not a surprise...but cool!

`Parent bodies'

Meteorites are small pieces from some 'parent body'

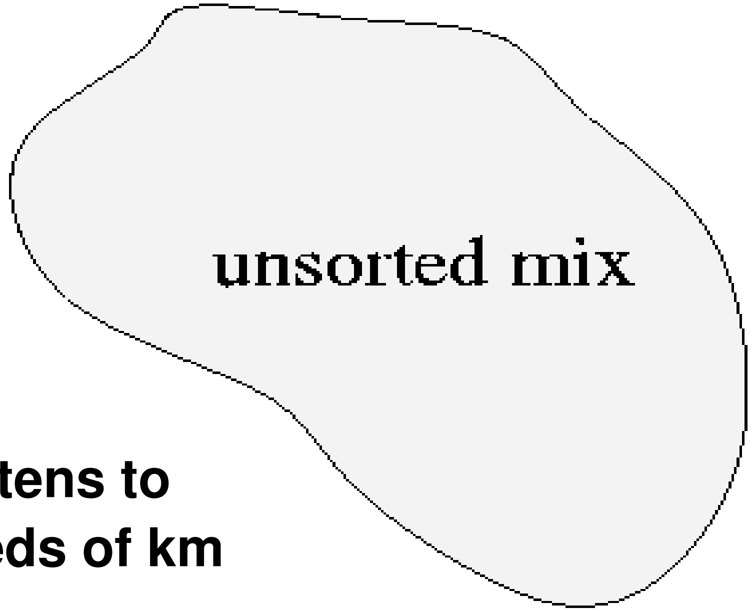
- nearly all are asteroidal



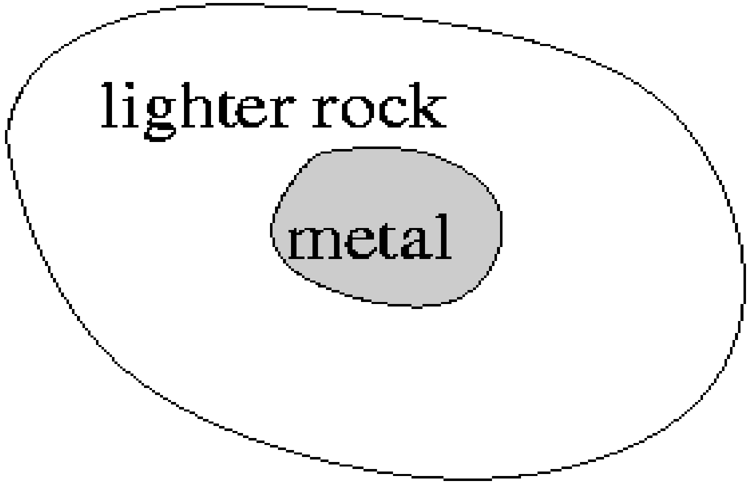
Meteoroid lived most of Solar System history in this bigger body until collision released millions of meteoroids.

Some fraction escape the asteroid belt and a tiny fraction of those end up hitting the top of Earth's atmosphere

Parent body types



Scale: tens to hundreds of km



'Primitive' or 'Undifferentiated'

Most chondrites come from this type

'Processed' or 'differentiated'

Achondrites, stony-irons, irons (going deeper into body)

Meteorite types

92.8%	**Stones:**	
---	***Chondrites***	85.7%
---	***Achondrites***	7.1%
1.5%	**Stony-Irons**	
5.7%	**Irons**	

100.0%	***Of falls***	

Stony meteorites

Two types:

ACHONDRITES

Rare

From differentiated parent bodies

CHONDRITES

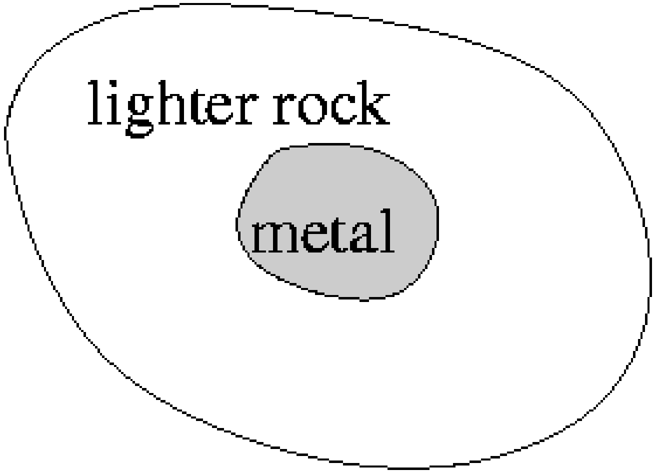
Most common

Primitive parent body

Stony-Irons

Interface between metal core and rocky crust of a differentiated parent body

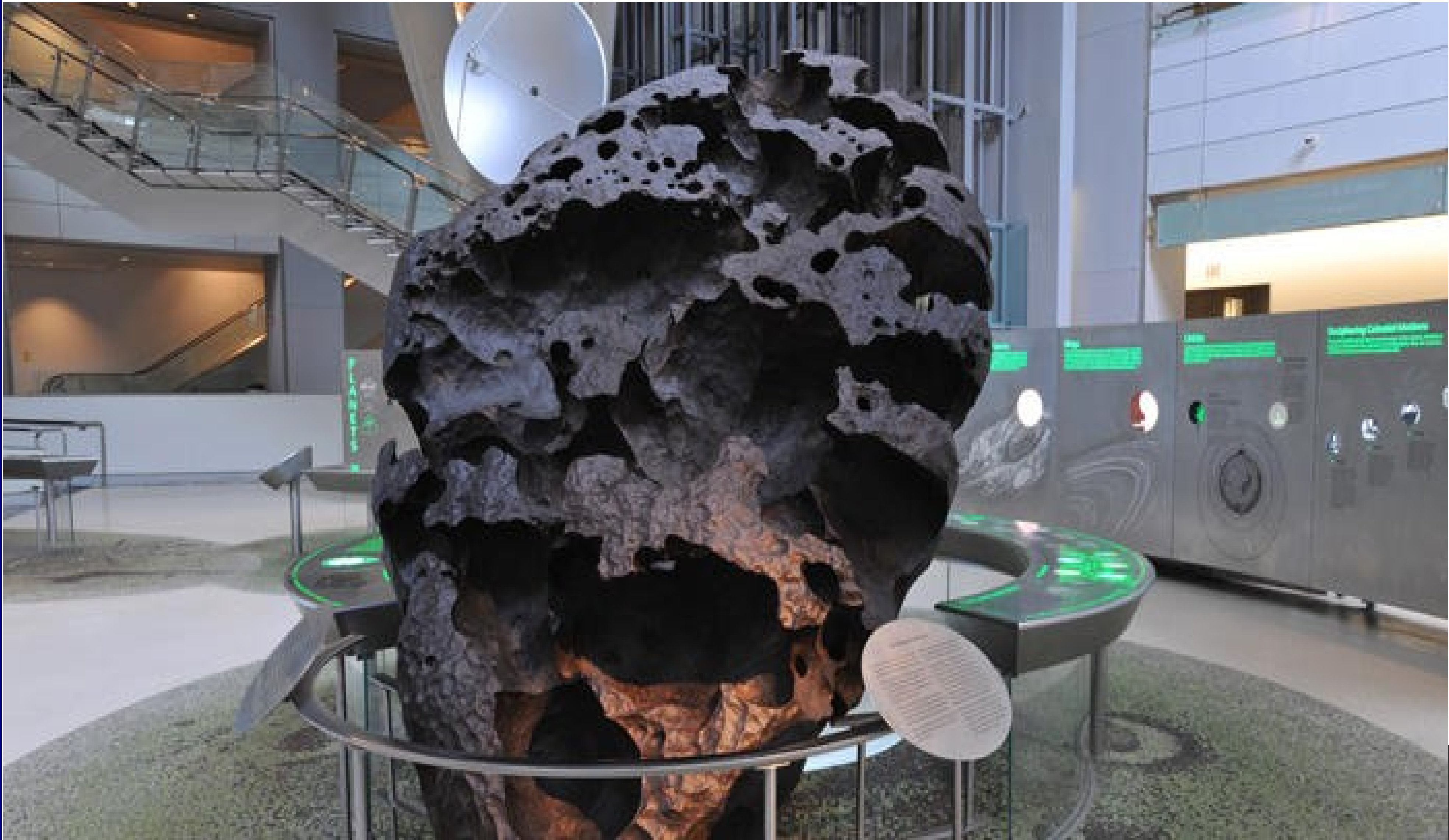
Nickel-iron metal embedded in silicate



Irons

Cores of differentiated parent bodies

Some very large iron meteorites have been found and preserved



Most common falls are Chondrites

There are many classes
H, L, LL, E, C
With lots of sub-types
(all this detail beyond A200)

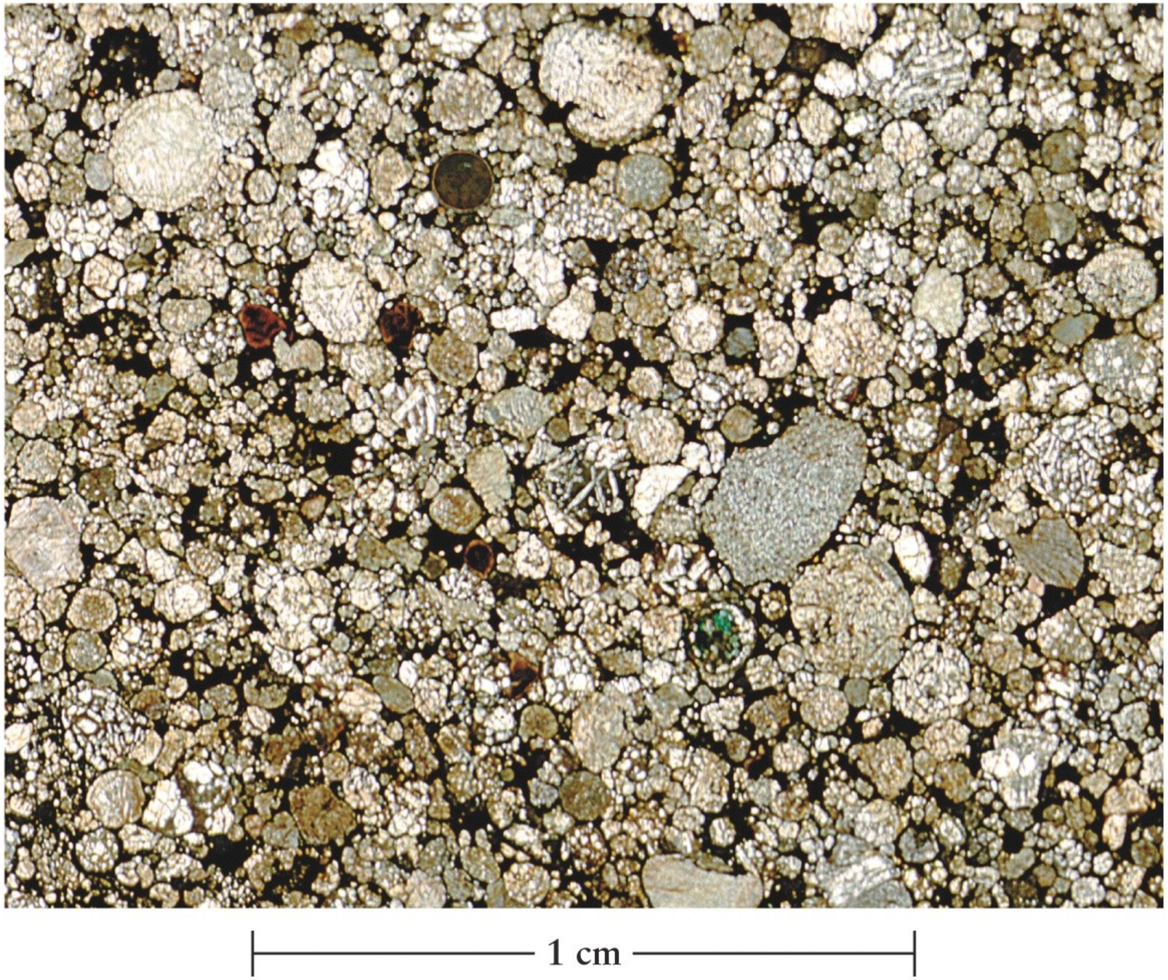
Chondrites contain **chondrules**

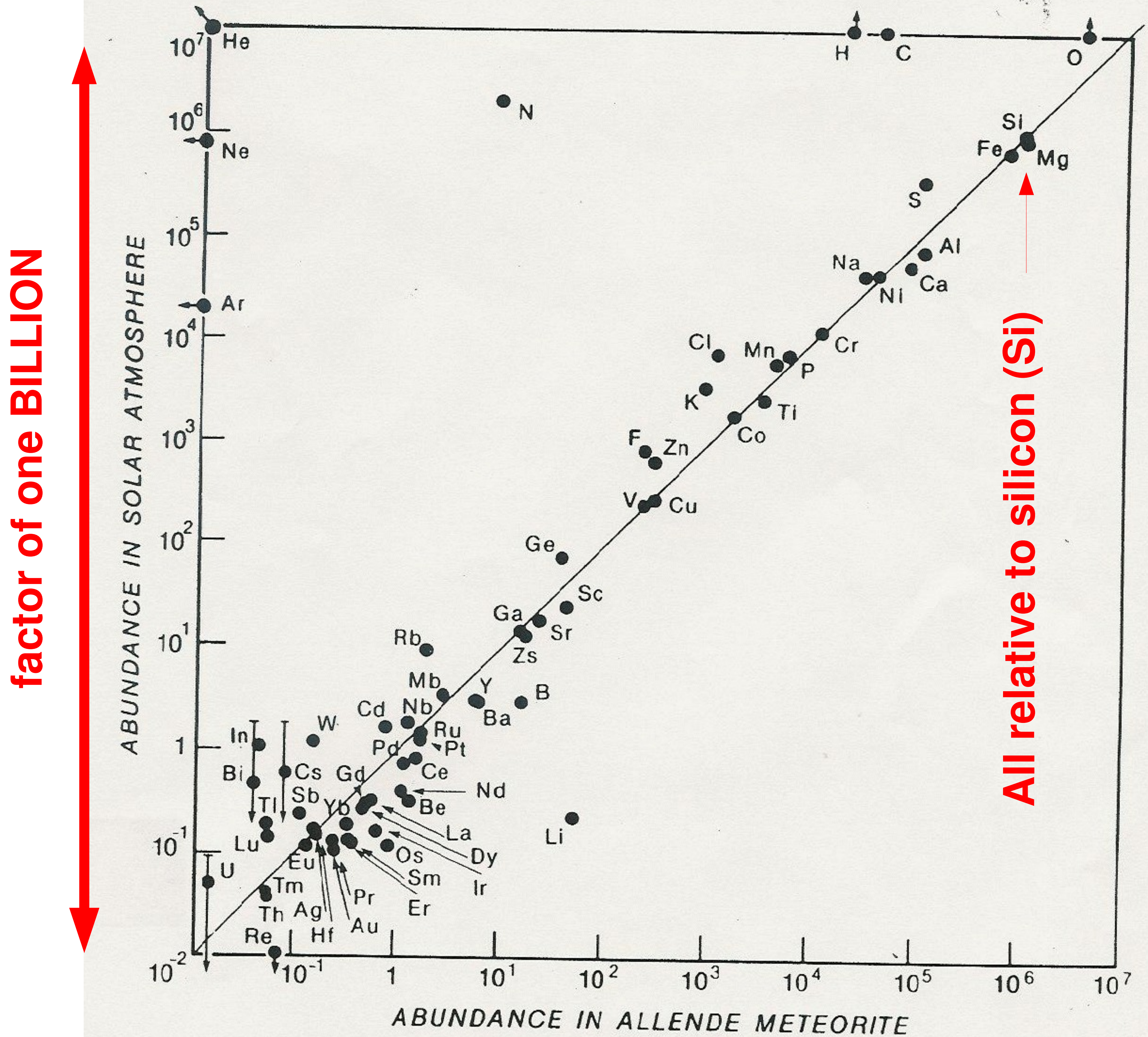
- Chondrules:
  mm-sized spheres of silicate

  Heated/cooled very fast! (~1000 K) ('frozen' droplets of melt).

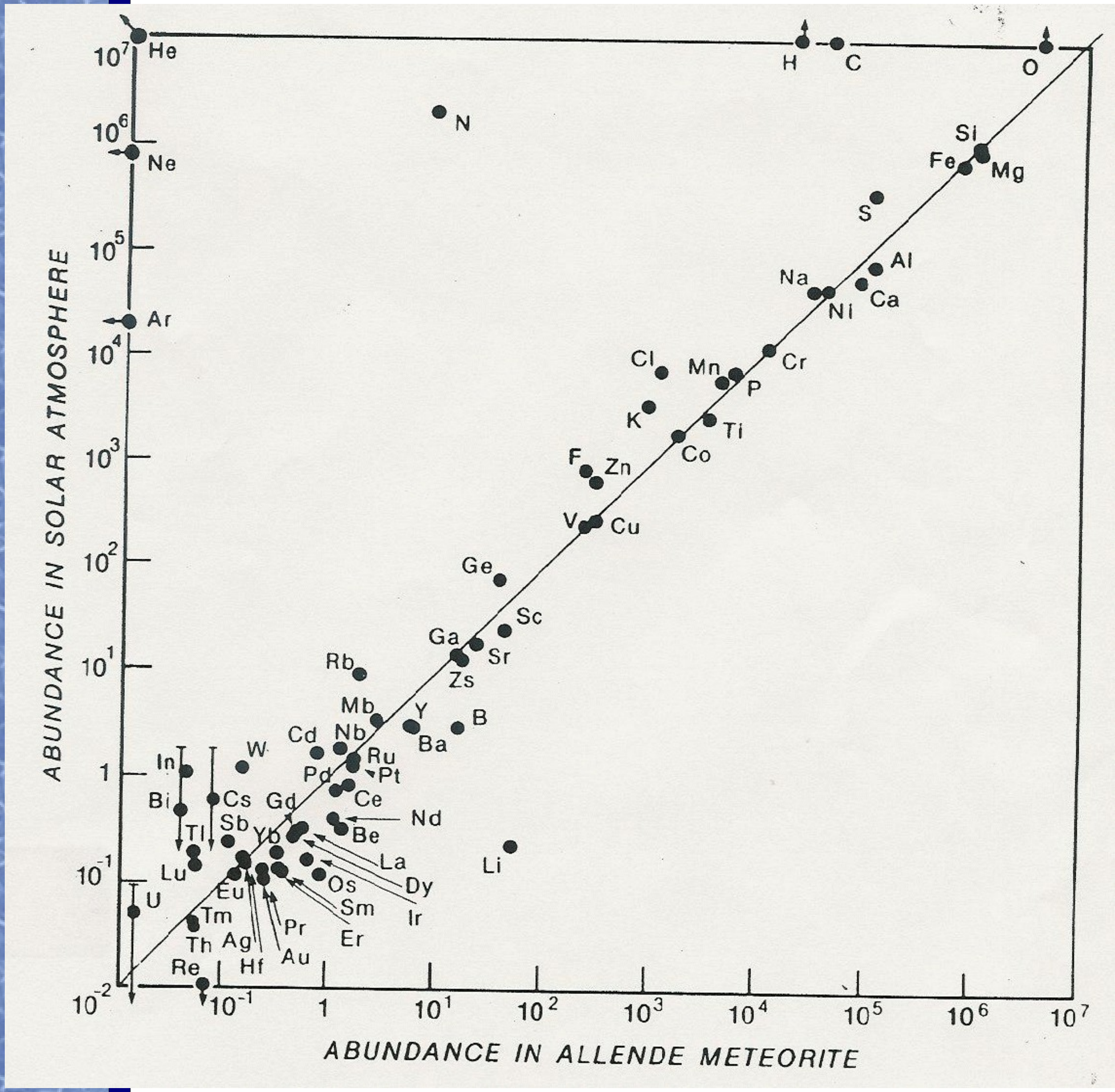
-NOT found in Earth or Moon rocks

DIRECT PROBE of the protosolar nebula!




factor of one BILLION
All relative to silicon (Si)
ABUNDANCE IN SOLAR ATMOSPHERE
ABUNDANCE IN ALLENDE METEORITE
10^7
10^6
10^5
10^4
10^3
10^2
10^1
1
10^-1
10^-2
He H C O N Ne Si Fe Mg S Al Na Ni Ca Ar Cl Mn Cr P K Ti Co F Zn V Cu Ge Sc Ga Sr Zs Rb Mb Y Ba B Cd Nb W Ru Pt Pd Ce In Bi Cs Gd Nd Sb Yb Be Tl La Dy Lu Os Ir Li U Eu Sm Tm Pr Er Th Ag Au Re Hf

Except for some elements, chondrites have an isotopic pattern **identical to the Sun's atmosphere!**



Solar abundances are known by measurements of the *absorption spectrum* of the Sun

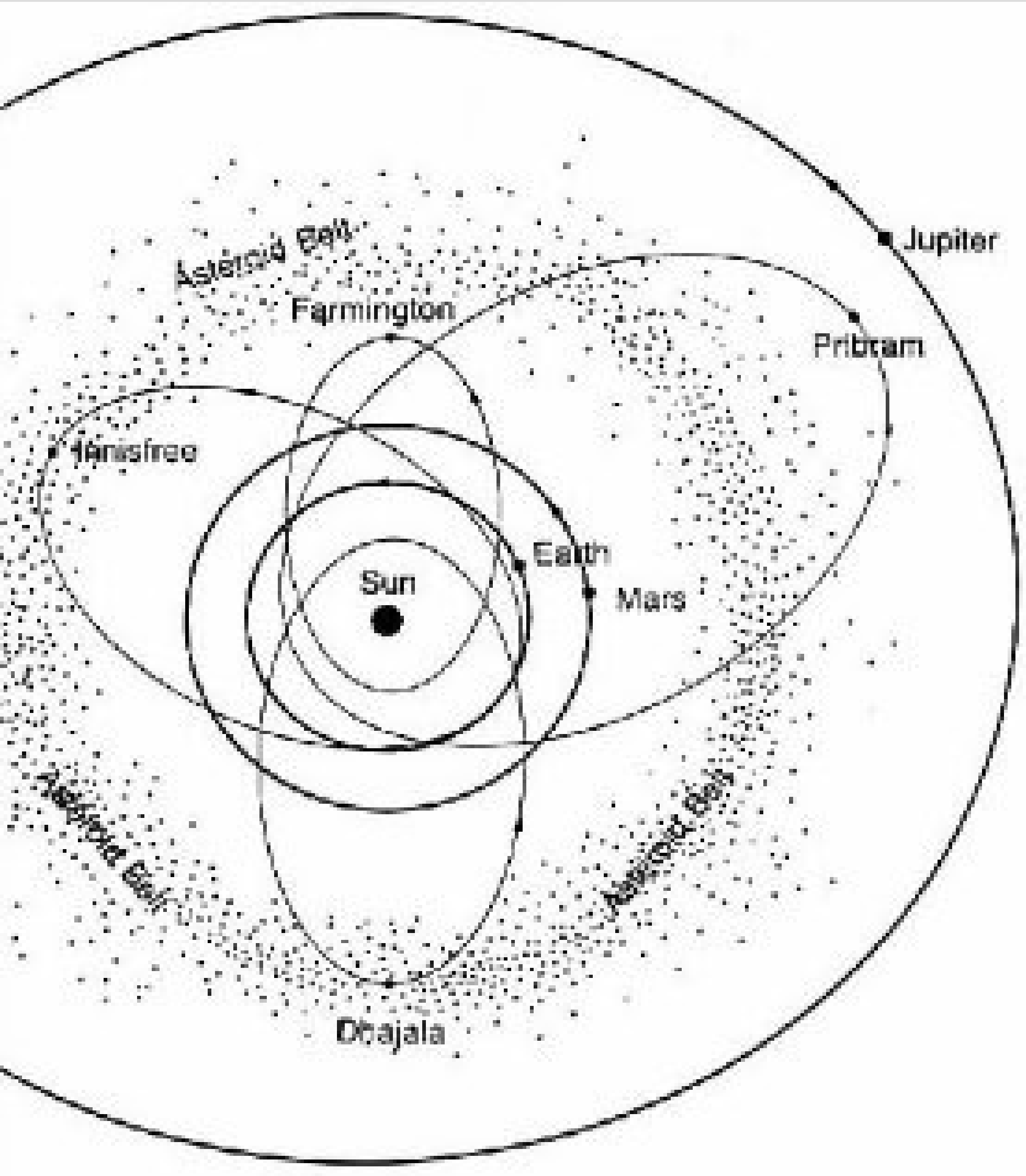
Chemical processes explain the outliers. Example: Noble gases (upper left of diagram) NEVER condense into solids in the protosolar nebula, so can be found in Sun but not in meteorites)

Why do we think we know where meteorites come from?

- Almost all meteorites are fragments of main-belt asteroids
- This result was clear before we ever went and got pieces of asteroids
- How can we know?

The Asteroid-Meteorite Connection

The most important link for understanding planet formation



In order to link meteoritic samples to Solar System formation models, we must understand the origin of meteorites and their relation to the protosolar nebula.

Links :
- meteoritics
- planetary astronomy
- petrology

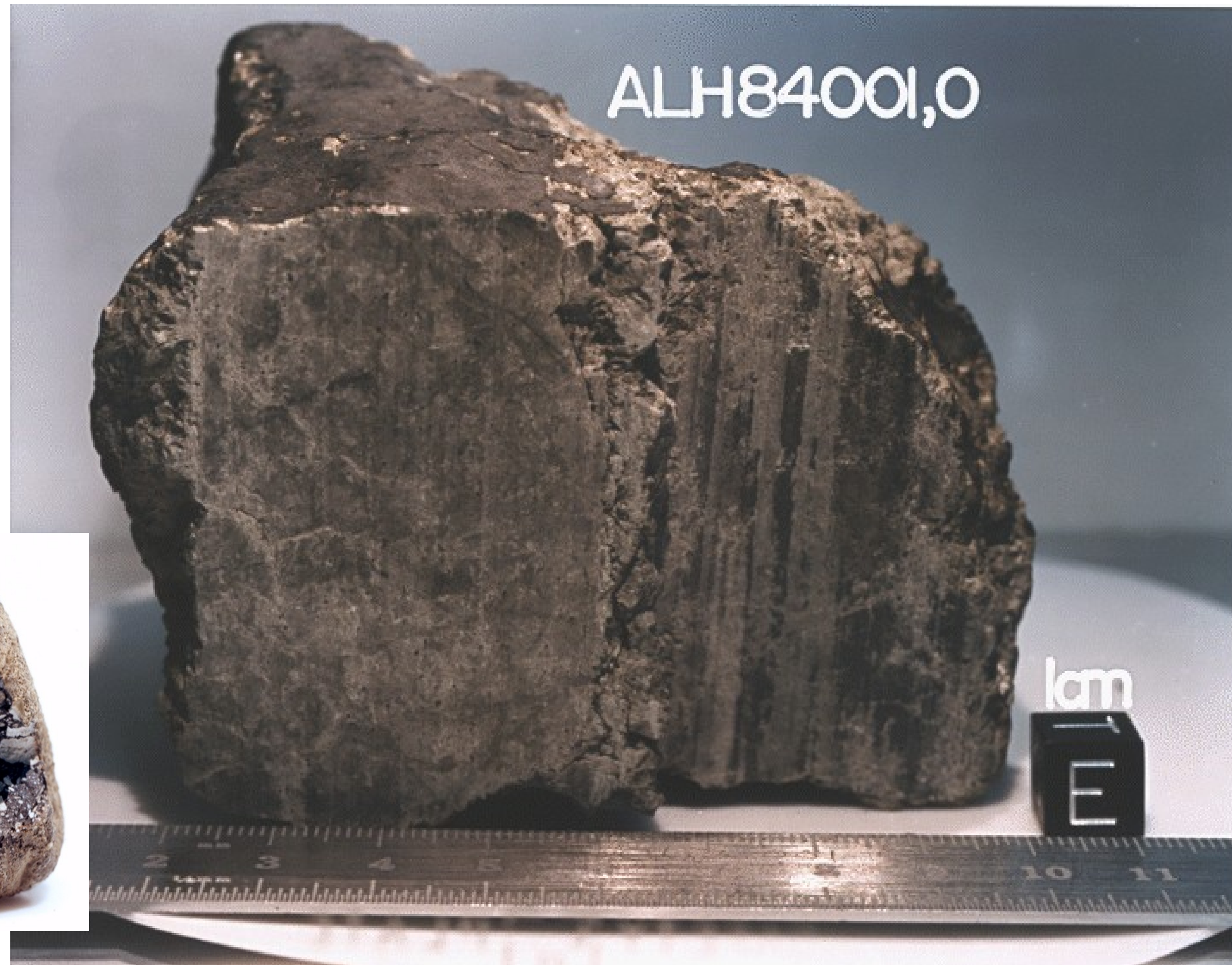
Where do meteorites come from?
Facts

1) Most meteorites *are* from the asteroid belt.
2) ~0.1% certainly from the Moon (anorthosites, impact breccias)
3) ~0.1% are from a large object with a Mars-like atmosphere (=> Mars)
4) Some *could* be from comets

Not ALL meteorites come from asteroids (but >99% are).

A few dozen are fragments blasted off the Moon and Mars in asteroid impacts.

Lunar meteorite



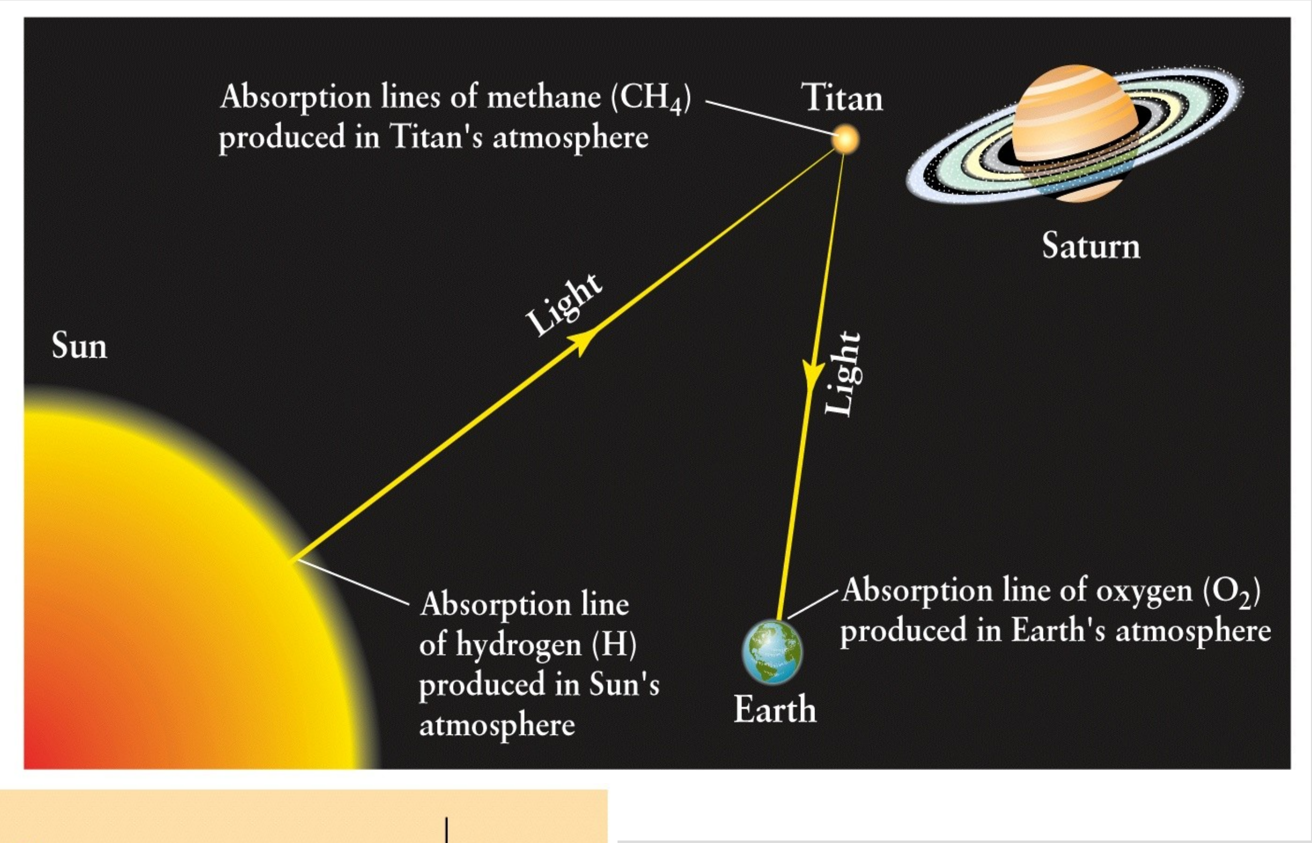
Martian meteorite

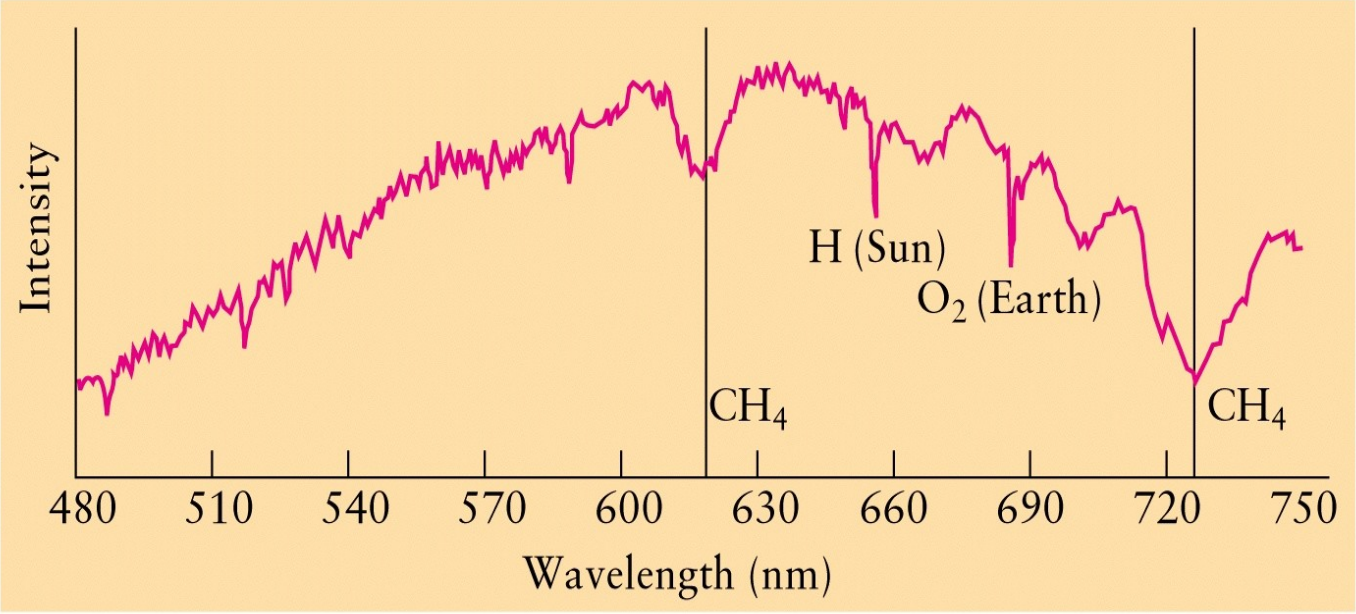
Evidence for asteroidal origin

1) *Reflectance spectra* of many meteorites (taken in lab) resemble those of some asteroids. (next slides)

Reflectance Spectra

- We observe many objects in the solar system in *reflected* light; just modify the Sun's spectrum and reflect it back to us.





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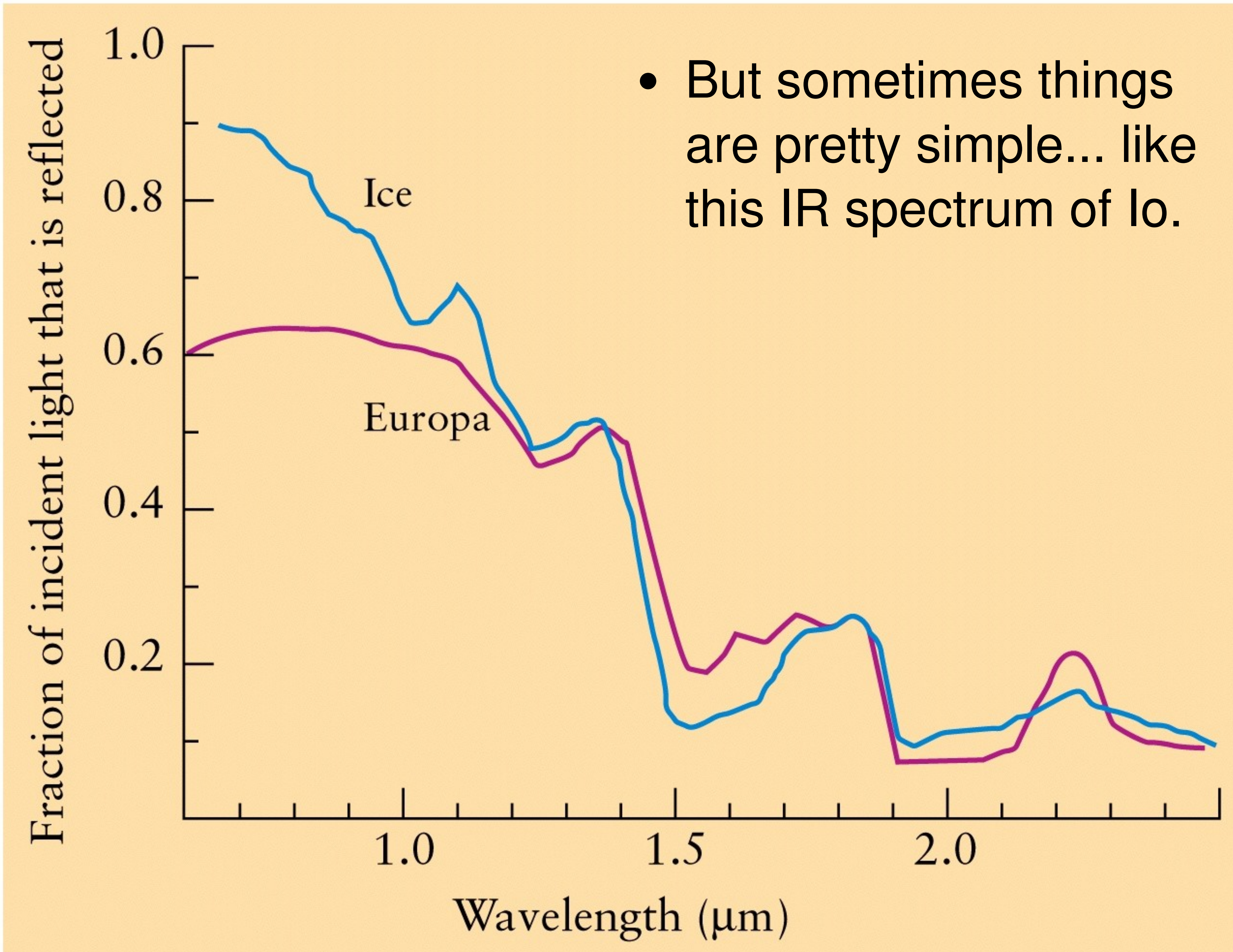
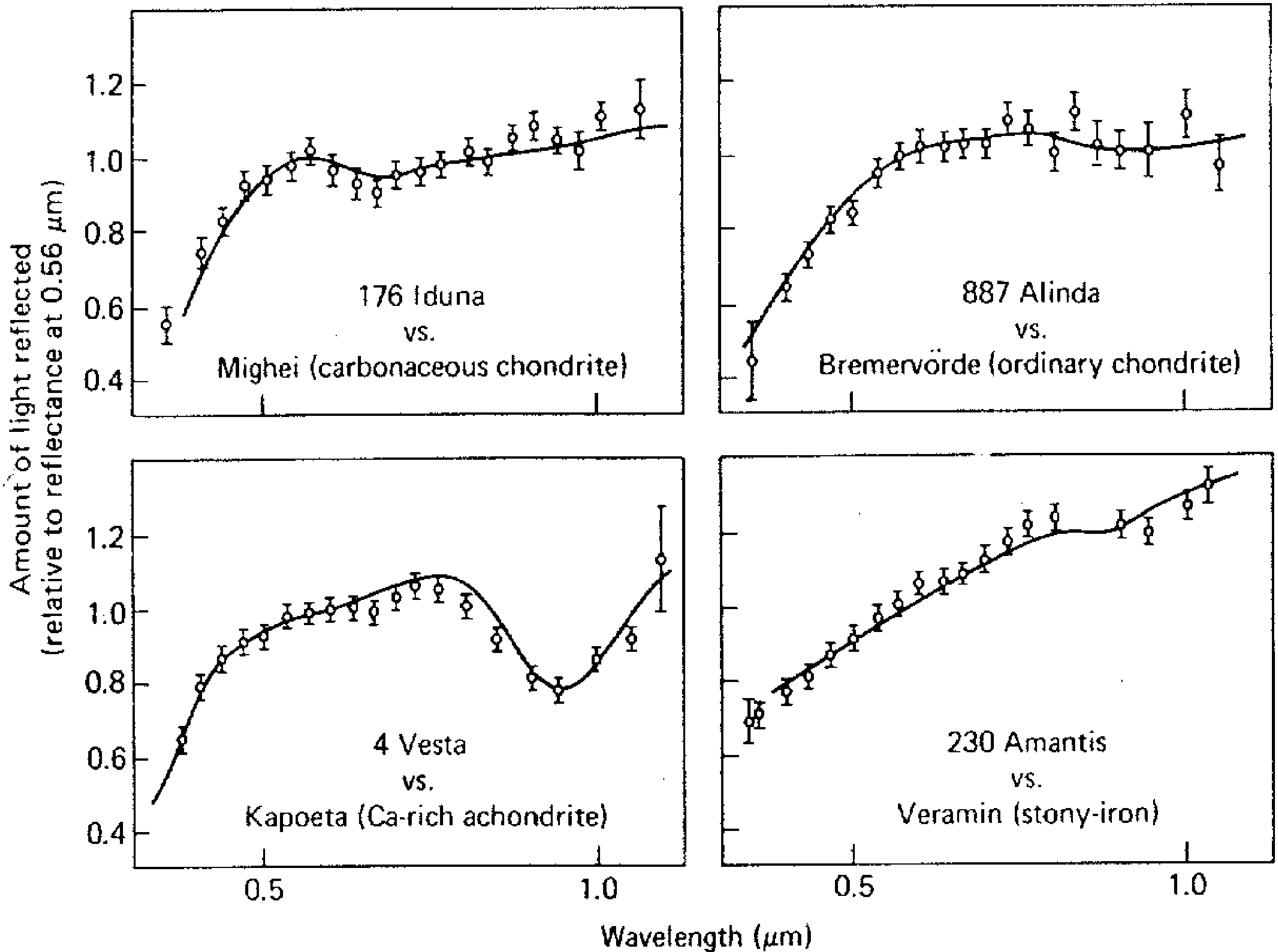
- The origin of a particular feature may not be obvious!

Reflectance Spectra



- But sometimes things are pretty simple... like this IR spectrum of Io.

Reflectance spectra of asteroids match reflectance spectra of meteorite surfaces



Evidence for asteroidal origin

1) *Reflectance spectra* of many meteorites (taken in lab) resemble those of some asteroids.

2) Orbits of several recovered meteorites have been measured:

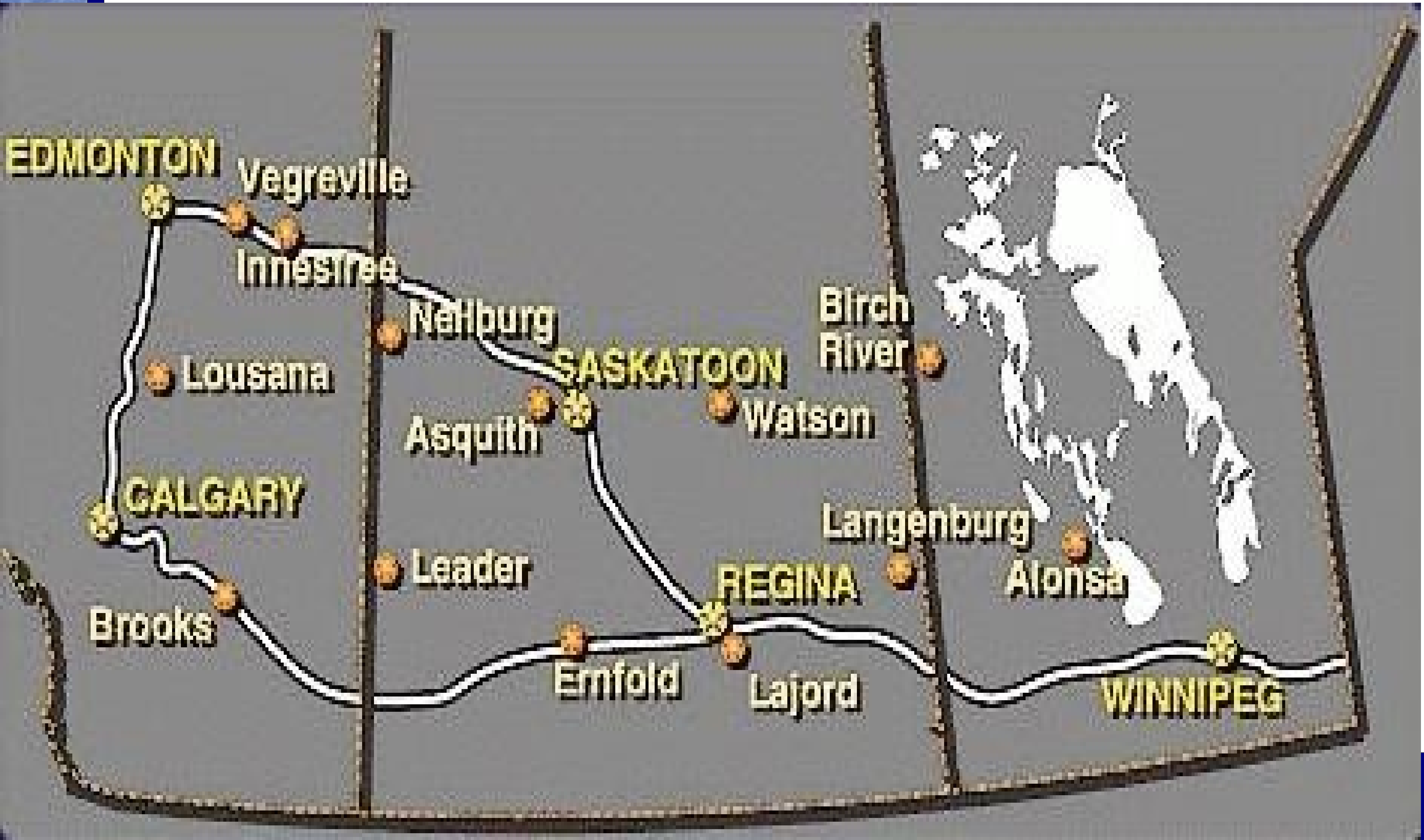
   - egs., Pribram, Lost City, Innisfree
   - All had perihelion <1 AU, aphelion in the asteroid belt.

Canadian MORP project

- (M)eteorite (O)bservation and (R)ecovery (P)roject
- Monitored skies of central prairies for about a decade

Canadian MORP project

- Monitored millions of square kilometers



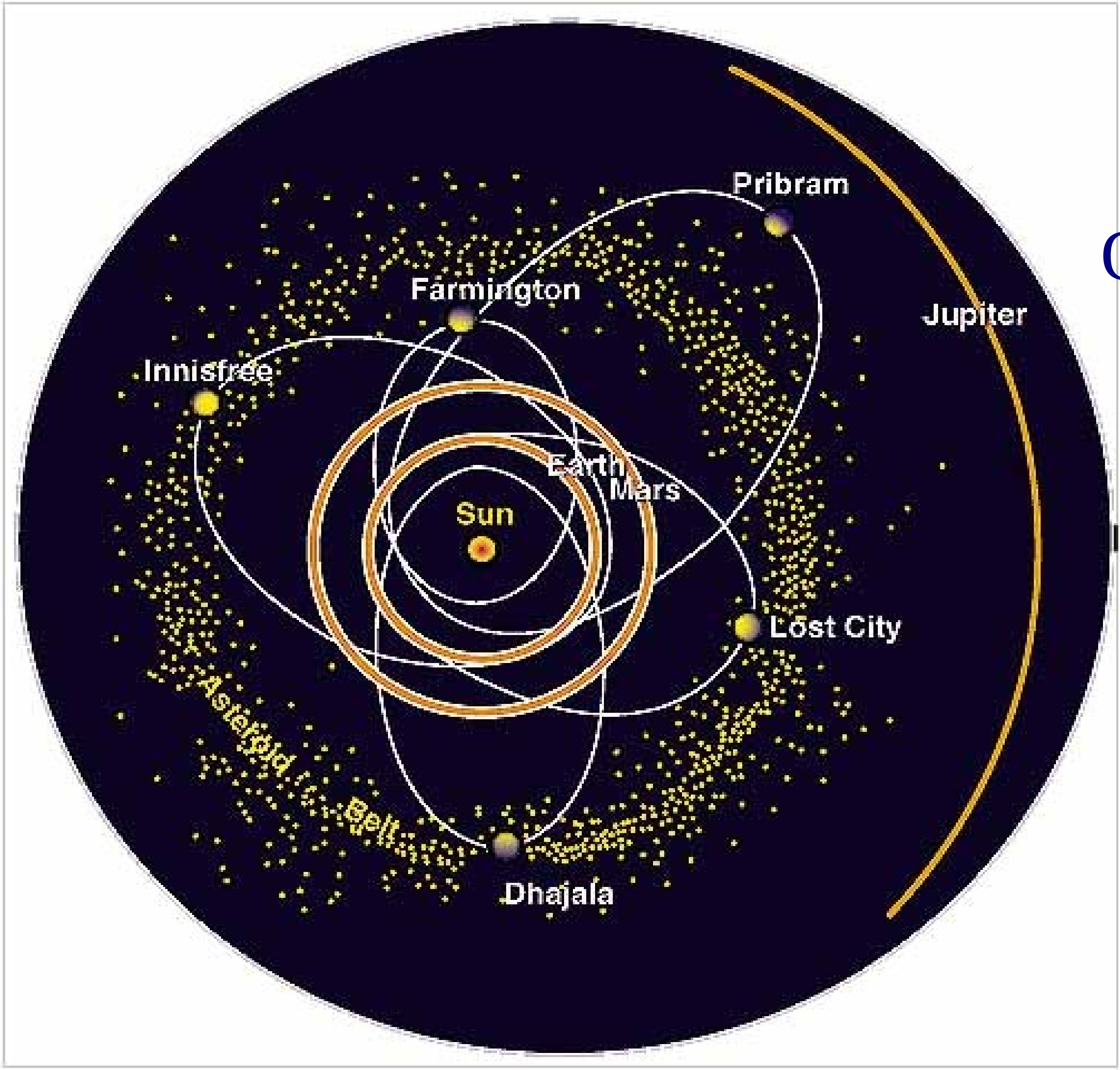
Canadian MORP project

Triangulation allows orbit computation

Meteorite orbit determination

- If meteor is well-observed, a recovered fall can give the orbit of the meteoroid.
- Note the black 'fusion crust'

<-- Innisfree



Orbits of three well-known falls

Meteorites solidified long long ago....

Meteorites are the oldest 'thing' you can touch.

They (almost) all date back to the very formation of the Solar System when the first solid particles were sedimenting out of the protosolar nebula to start forming planets

How do we know???

How does radioactive dating work?

- There are are multiple methods.
- When it works, the simplest method is illustrated by the Rubidium-Strontium method:
- The decay is :

$$^{87}_{37}Rb \rightarrow \, ^{87}_{38}Sr + \, ^{0}_{-1}\beta$$

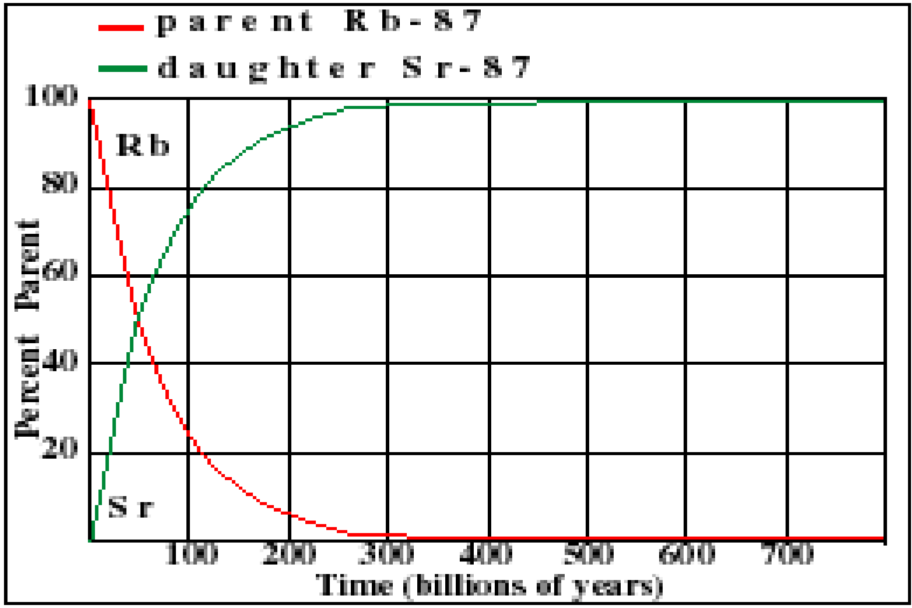
Half-life : 48.8 Gyr

Rb-85 (37 protons, 48 neutrons) is stable.

But Rb-87 (37 protons, 50 neutrons) is unstable and decays to Sr-87 (38 p, 49 n) by having a neutron turn to a proton (and emit a beta particle, which is just an electron.

Exponential radioactive decay

- There are a huge number N_o of radioactive atoms, which each have a tiny probability of decaying (with probability λ per atom per unit time). The number of decays is thus
  - $dN = -\lambda N_o dt$ with solution: $$N = N_0 e^{-\lambda t}$$
- So the parent nucleus (Rb-87) decays away:
- The 'daughter' nucleus (Sr-87) rises in response:



$Sr\text{-}87_{now} = Sr\text{-}87_o + \boxed{Sr\text{-}87_{rad}}$

$= Rb\text{-}87_o - Rb\text{-}87_{now} = Rb\text{-}87_{now} \, (e^{\lambda t} - 1)$

But how can you measure the number of atoms? You can't.

- But you can measure RATIOS of the quantities of atoms, in a mass spectrometer
- So need a stable comparison. Here use Sr-86 and divide previous equation by it, giving:

$$\frac{^{87}Sr_{now}}{^{86}Sr_{now}} = \frac{^{87}Sr_{initial}}{^{86}Sr_{initial}} + \frac{^{87}Rb_{now}}{^{86}Sr_{now}} (e^{\lambda t} - 1)$$

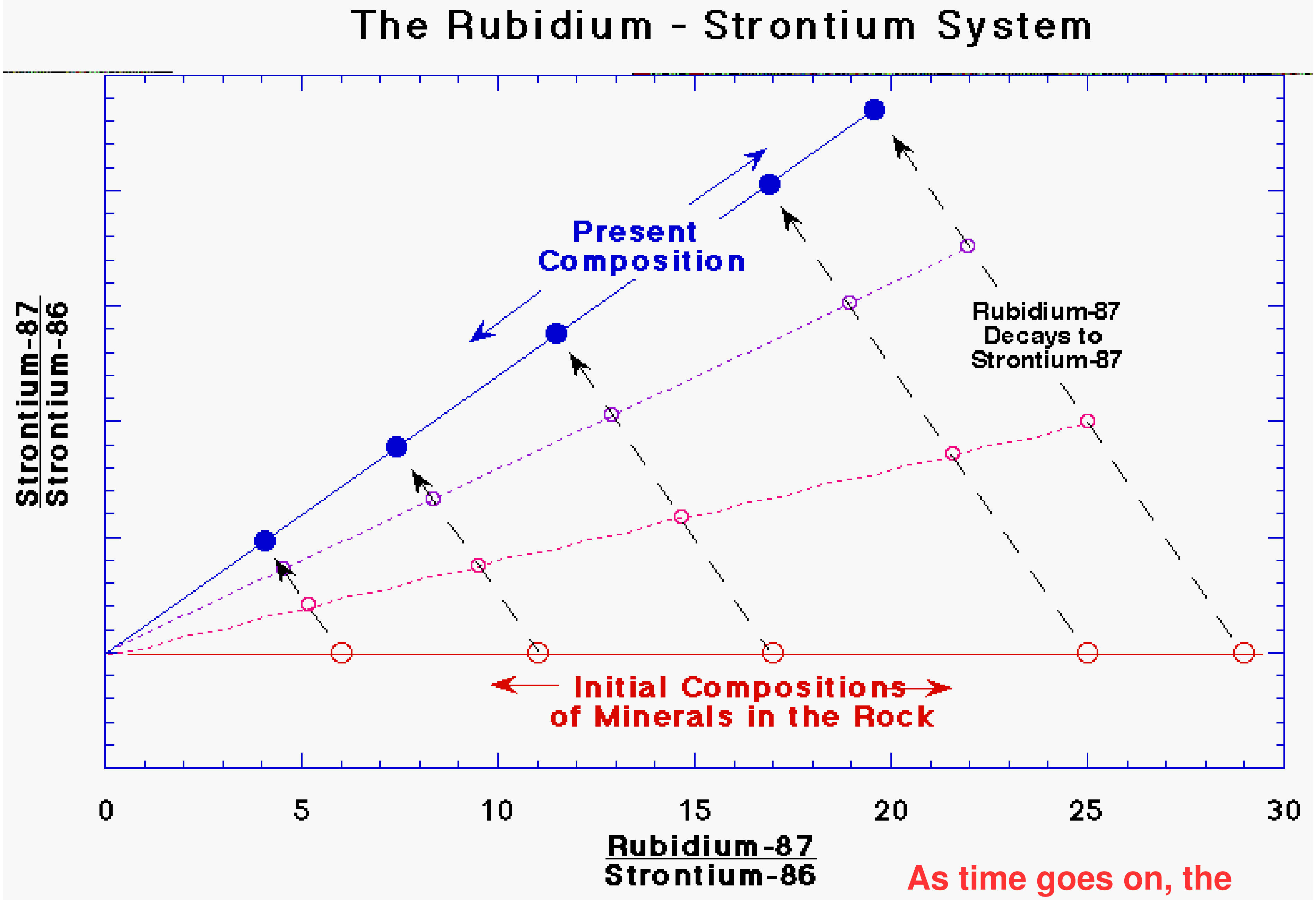
$$y = b + x \; m$$

Aside: For small t, could invert from any given single point, but don't know the initial value!

$$t = \frac{(Sr^{87}/Sr^{86})_{measured} - (Sr^{87}/Sr^{86})_{initial}}{(\lambda)\ (Rb^{87}/Sr^{86})_{measured}},$$

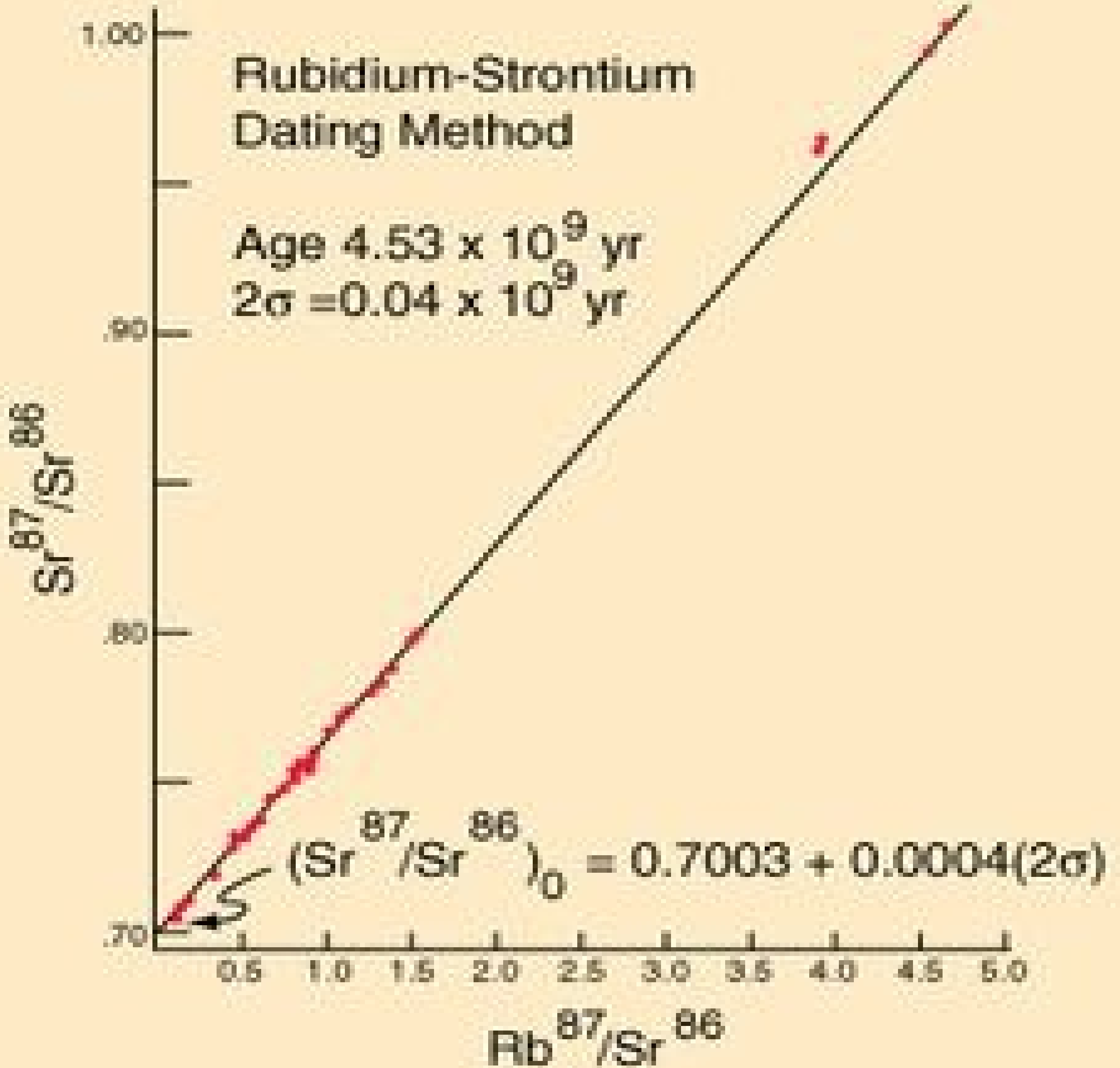
Don't use this equation!

- SO, in general one plots a group of measures and determines slope *m* and intercept *b* graphically



$$\frac{^{87}Sr_{now}}{^{86}Sr_{now}} = \frac{^{87}Sr_{initial}}{^{86}Sr_{initial}} + \frac{^{87}Rb_{now}}{^{86}Sr_{now}}\left(e^{\lambda t} - 1\right)$$

As time goes on, the measured points remain in a straight line



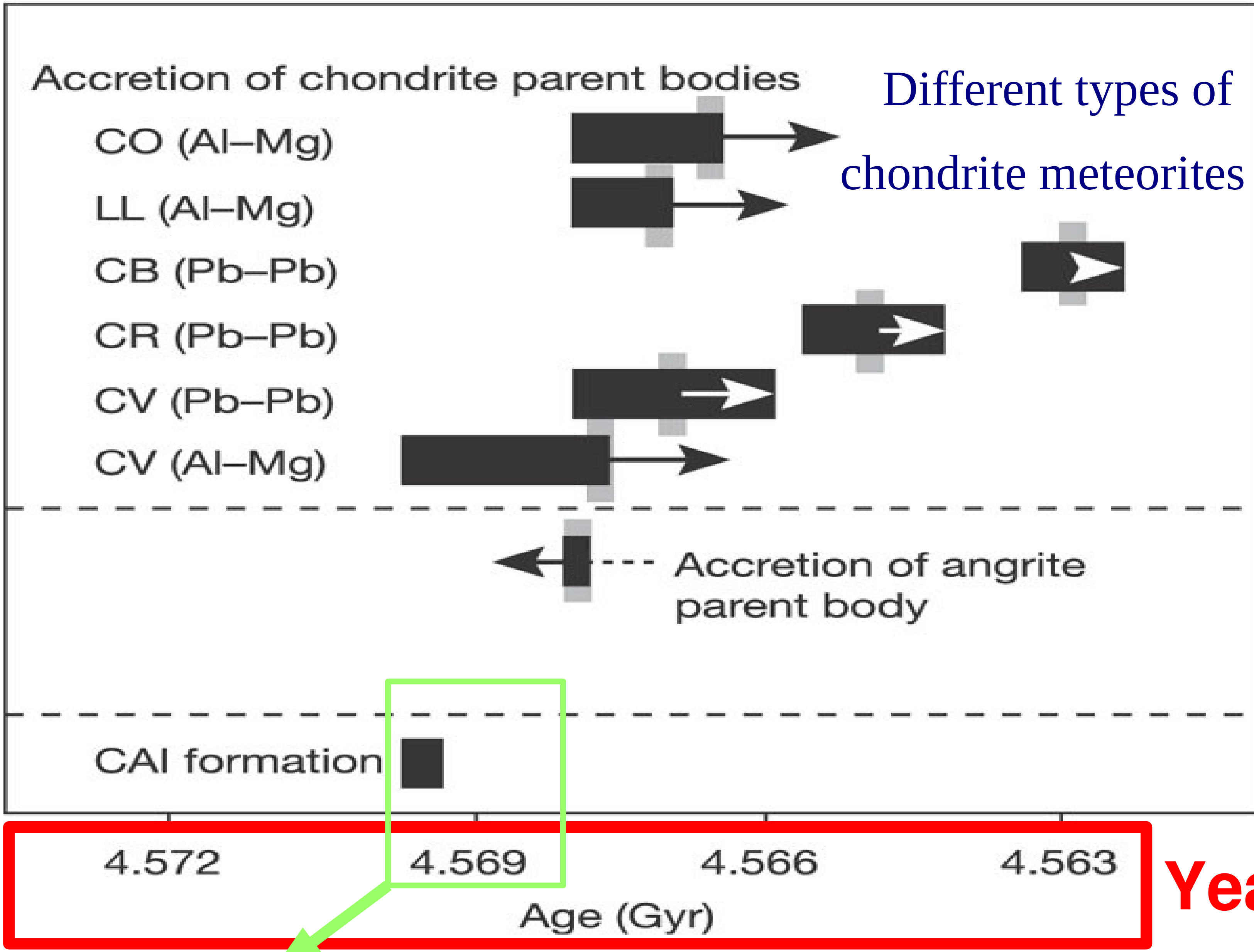
G. W. Wetherill, Ann. Rev. Nucl. Sci. 25, 283 (1975)

The slope and intercept both give interesting information

- **Slope** **gives time *since sample solidified.***

- **Intercept** **gives the initial ratio of Sr isotopes when the rock solidified**

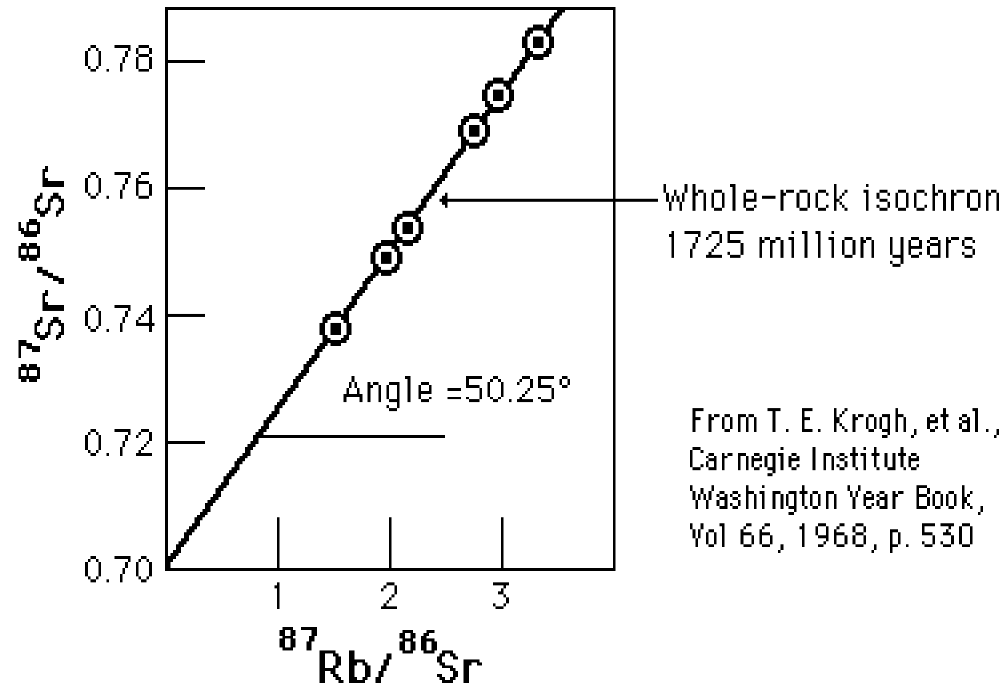
Radioactive dating



Years ago

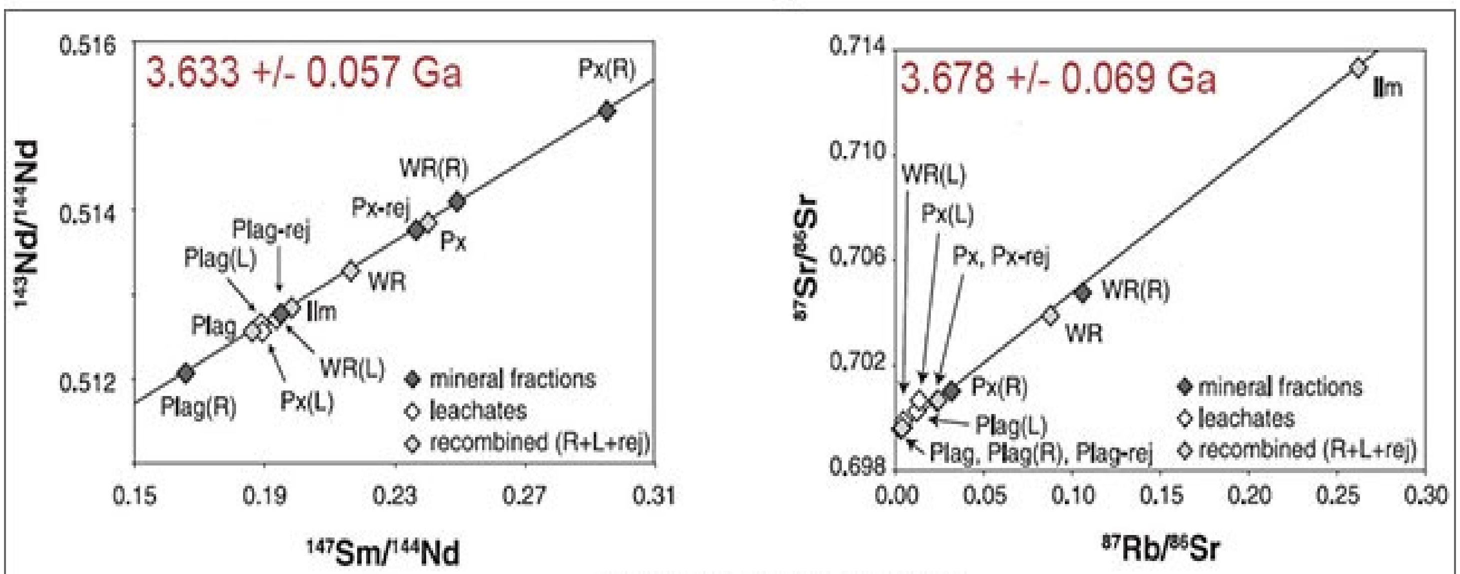
Condensation ages of the oldest known solids
= 'the age of the Solar System'

Meteorites are all ancient, but other places in the Solar System are younger



Whole-rock rubidium-strontium isochron for a set of samples of a Precambrian granite body exposed near Sudbury, Ontario.

Mare Basalt -- Apollo 10017



Differentiated asteroids cooled slowly

- The Ni-Fe in iron meteorites is very pure : settled to core
- Because they cooled slowly can see growth of iron grains: Widmanstätten Pattern
- Bigger bodies cool slower. Measurements of metalographic cooling rates imply: PB~100-200 km