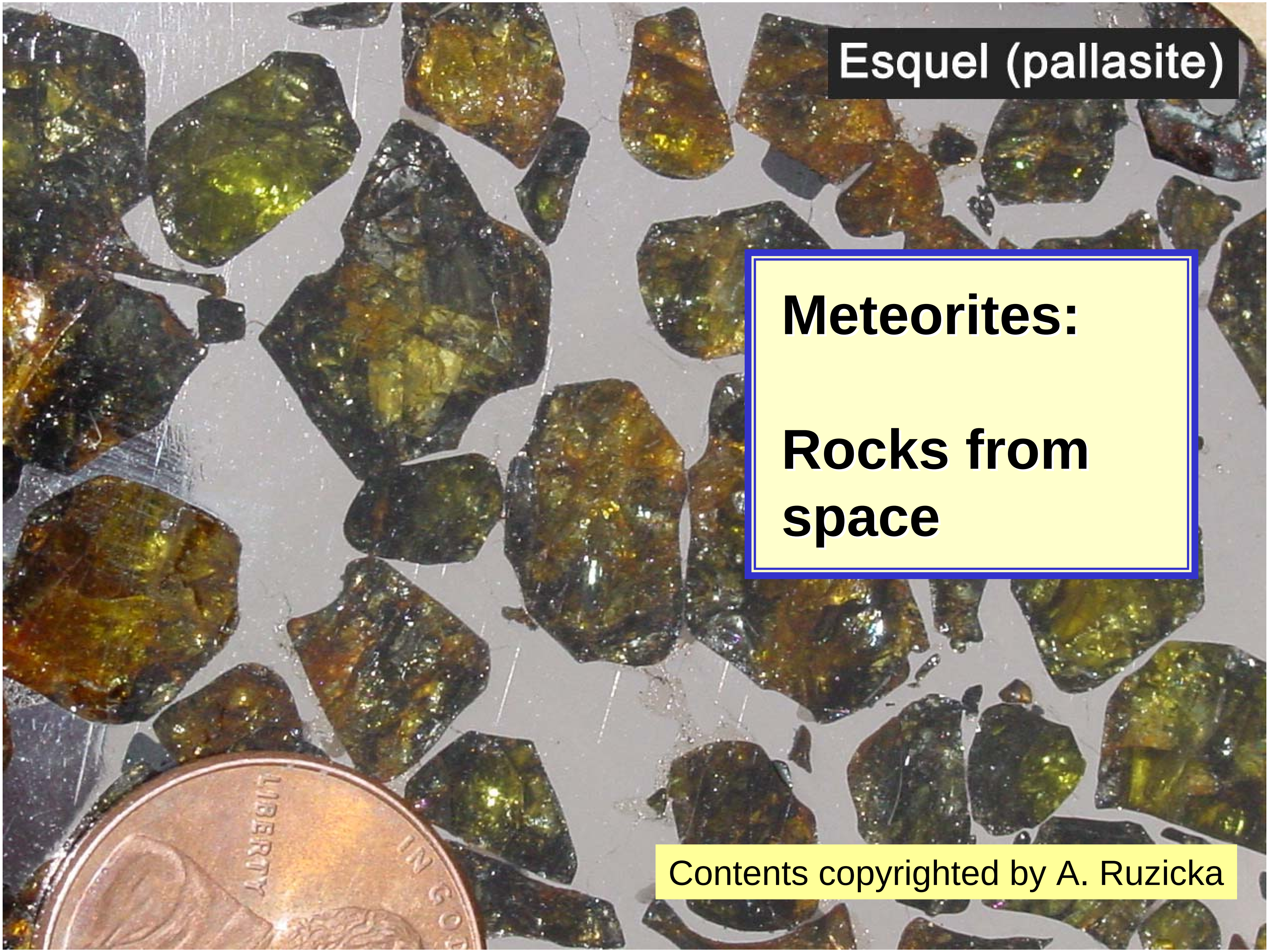
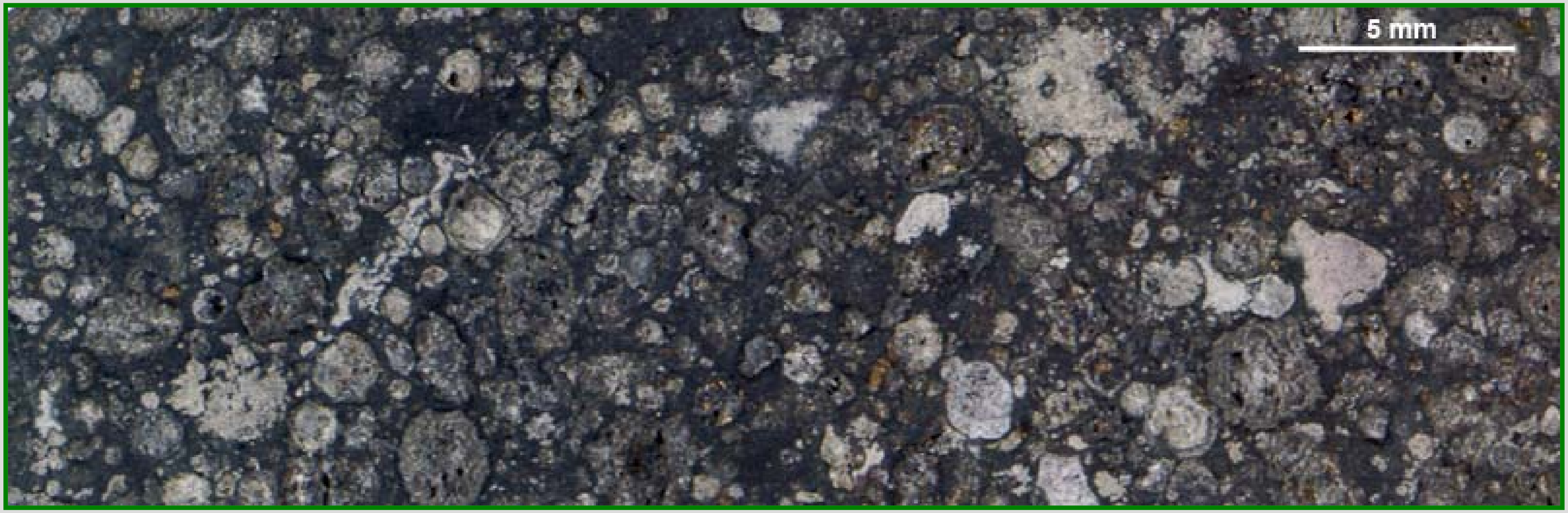


Meteorites:

Rocks from space

meteorites are mainly derived from small interplanetary bodies that escaped significant LATE endogenic activity

they provide our best rock record of early solar system processes



^^ Vigarano (CV3 carbonaceous chondrite)

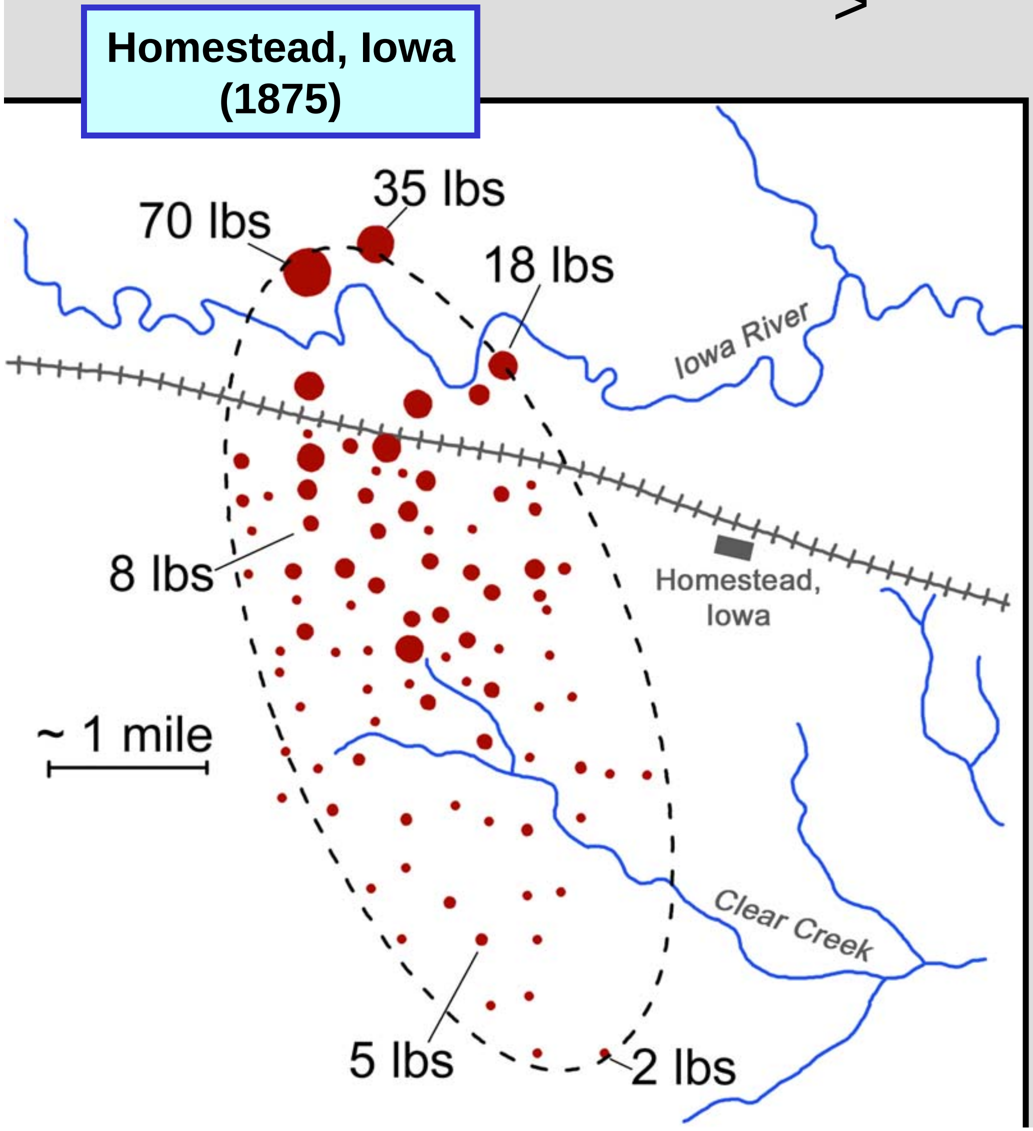
A. Meteoroids, meteors, and meteorites
B. Sources of meteorites
C. Meteorite types
D. Differentiated meteorites
E. Chondrites
F. Important results

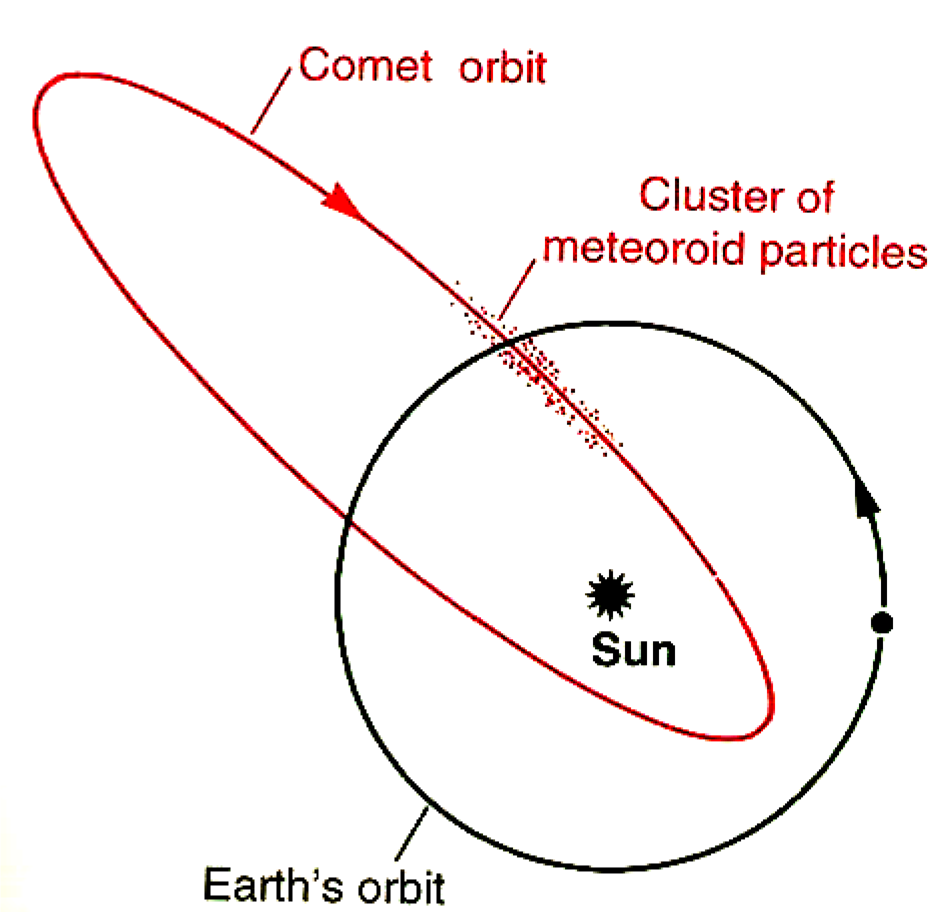
A. Meteoroids, meteors, and meteorites

Meteoroid	Object in space, smaller than asteroid
↓	
Meteor (Fireball)	Object burning up (ablating) in atmosphere
↓	
Meteorite	Object found on ground, originated on different planetary body

Fireball
break-up
>

<
Meteorite
strewn field





Meteoroid particles clustered along a comet's orbit can produce meteor storms if Earth encounters them.

>>

Leonid shower

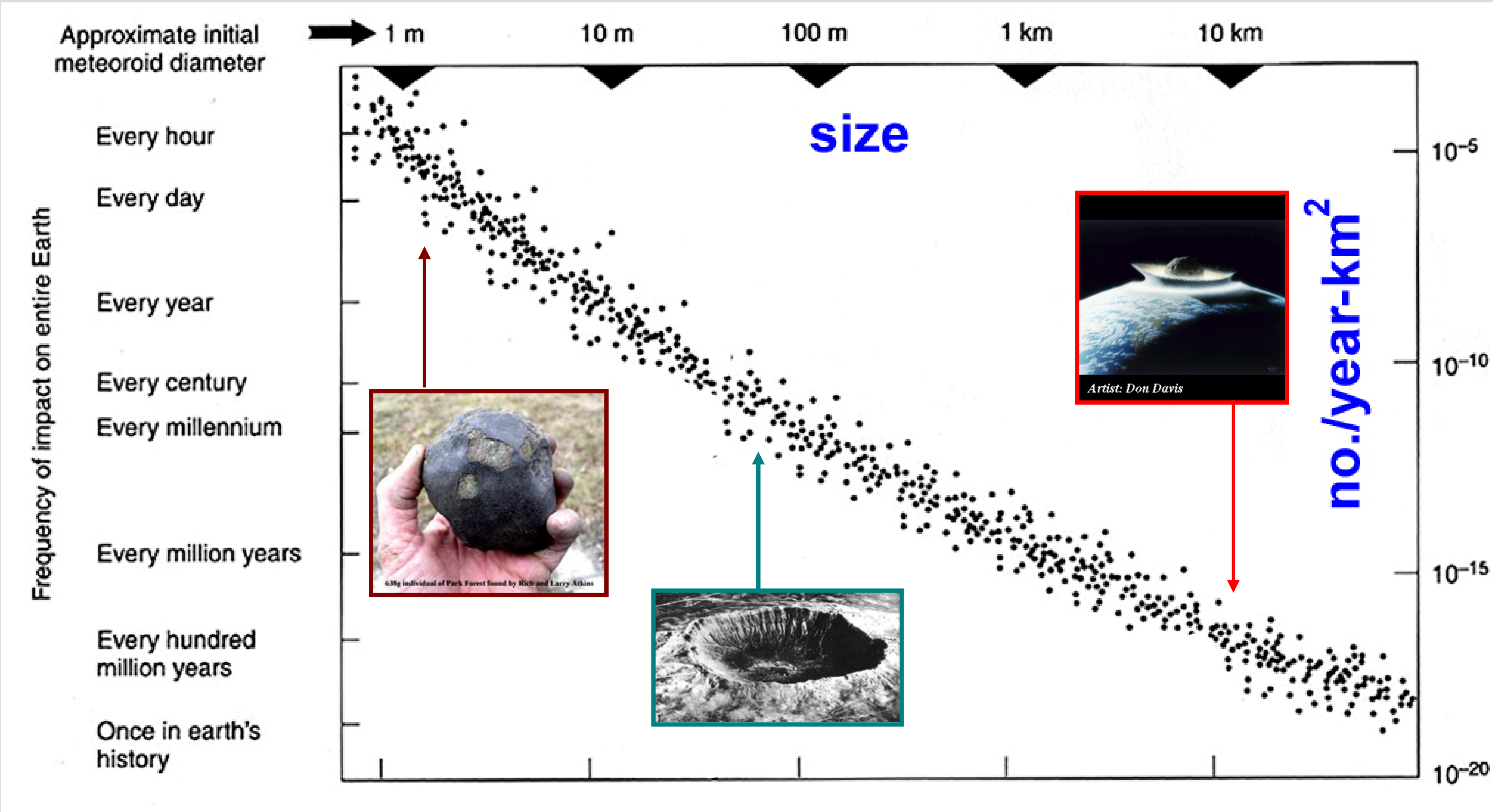
72 min composite,
8 exposures (F. Espenak)

1992 Peekskill fireball video clips

(How to turn a $300 car into one worth $10,000.)

Results of ablation: fusion crust, thumbprints, fragmentation

Size-frequency diagram for meteoroids hitting Earth



meteorites are mainly derived from meter-sized meteoroids

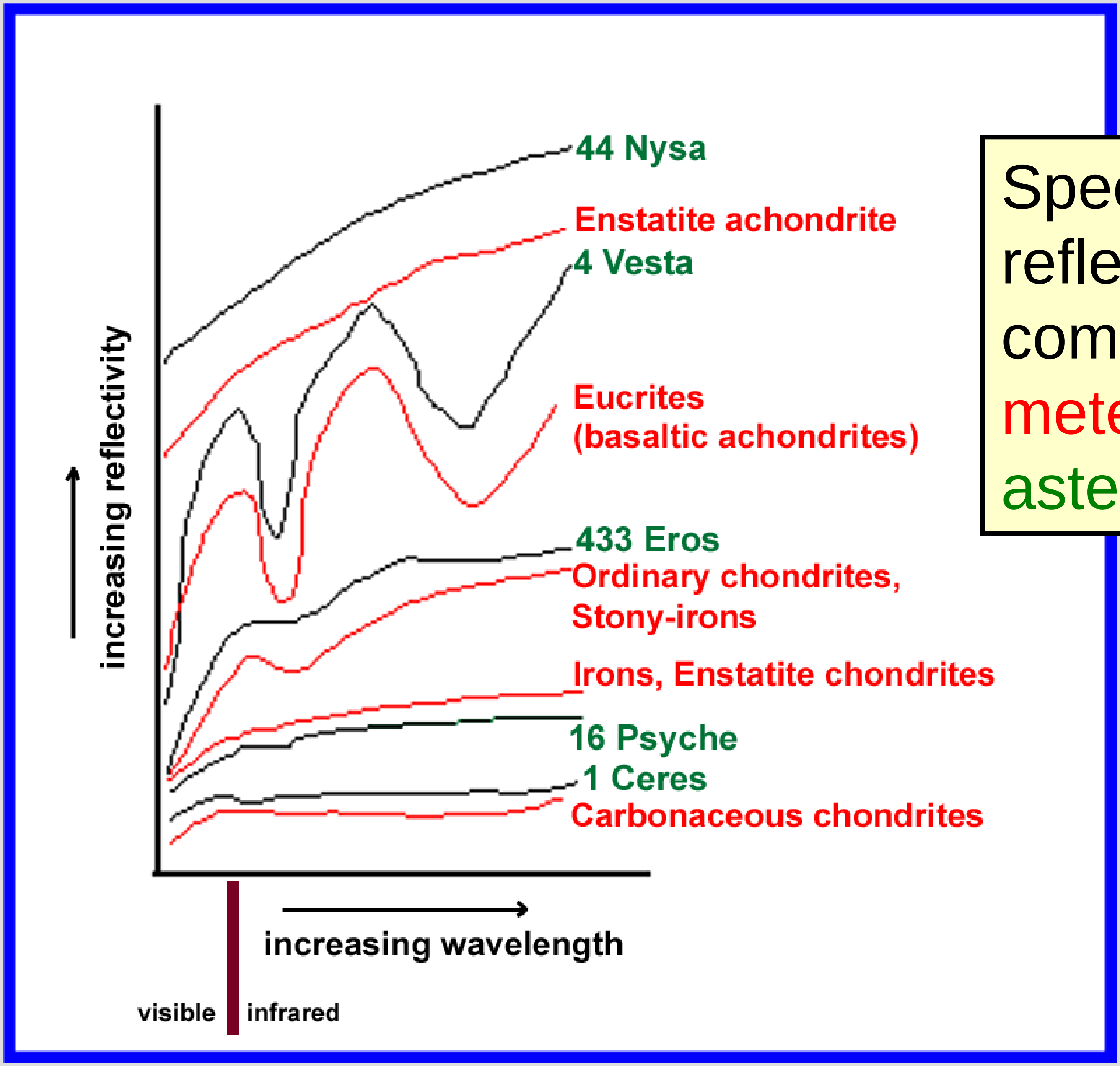
B. Sources of meteorites

sources:

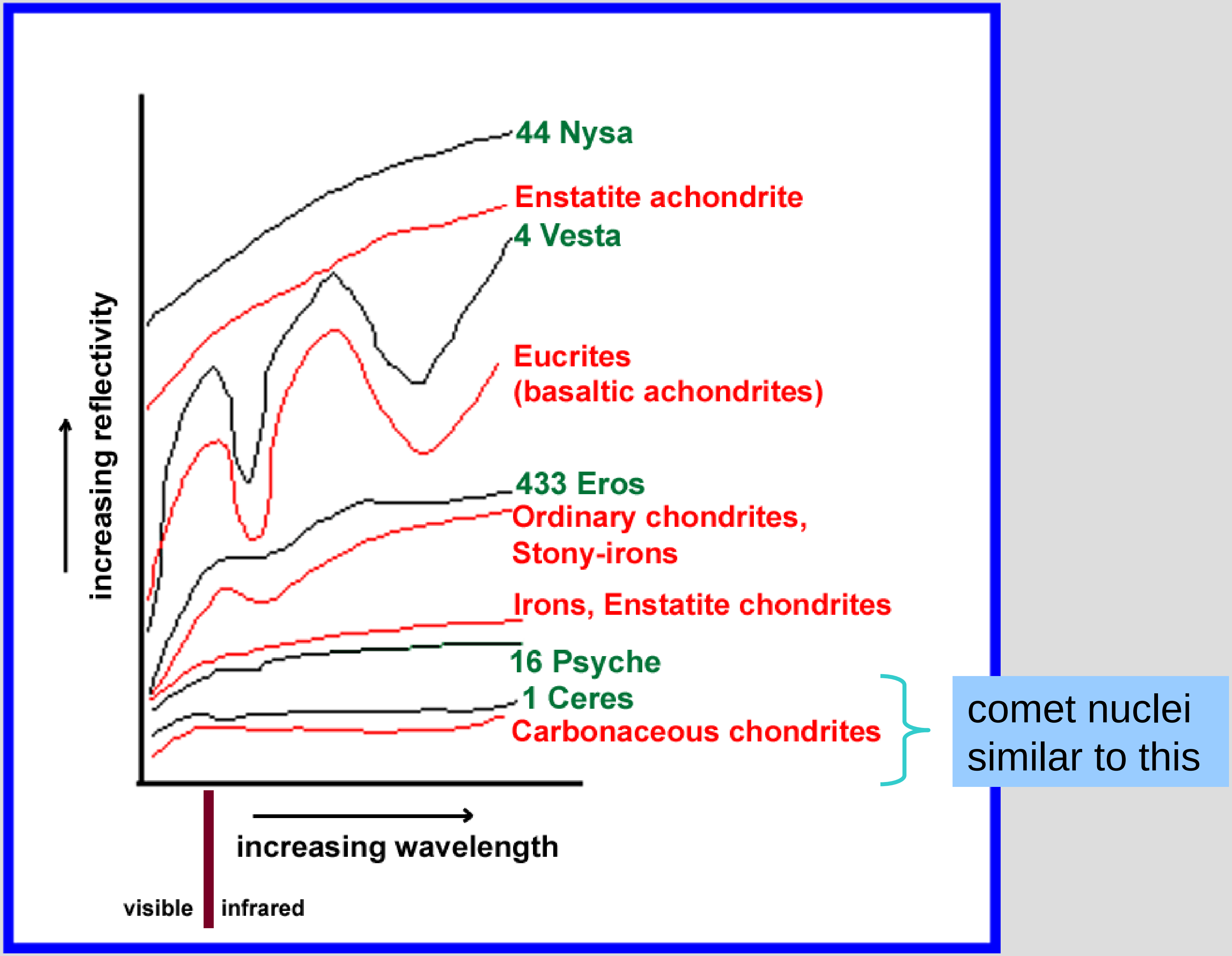
-- interplanetary bodies (mostly asteroids, but some comet-like)

-- Moon

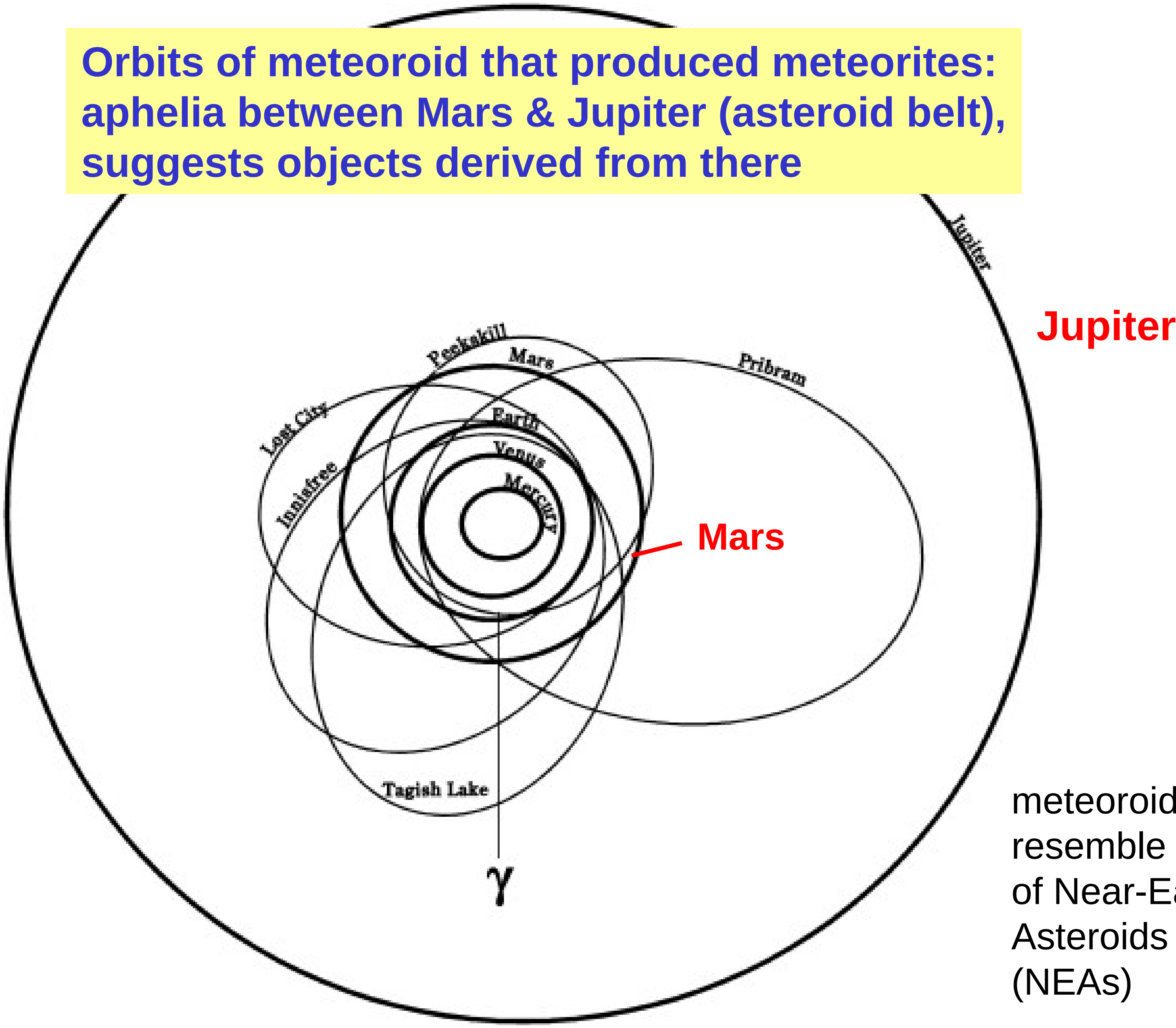
-- Mars



Spectral reflectance comparison: meteorites & asteroids


44 Nysa
Enstatite achondrite
4 Vesta
Eucrites
(basaltic achondrites)
433 Eros
Ordinary chondrites,
Stony-irons
Irons, Enstatite chondrites
16 Psyche
1 Ceres
Carbonaceous chondrites
comet nuclei
similar to this
increasing reflectivity
increasing wavelength
visible
infrared

Orbits of meteoroid that produced meteorites: aphelia between Mars & Jupiter (asteroid belt), suggests objects derived from there



meteoroid orbits resemble those of Near-Earth Asteroids (NEAs)

Example of meteorite derived from water-rich (comet-like) body, outer part of asteroid belt

Tagish Lake (C2 ungrouped carbonaceous chondrite)

5.8% C
density = 1.67 g/cm^3
spectra similar to D-type asteroids & comet nuclei
rich in phyllosilicate (saponite & serpentine), carbonate (siderite)
contains forsterite, sulfide, magnetite, spinel, low-Ca pyroxene, FeNi-metal, pre-solar grains, PAHs, chondrules, CAIs

Comparison of mineral assemblages in Tagish Lake & comets

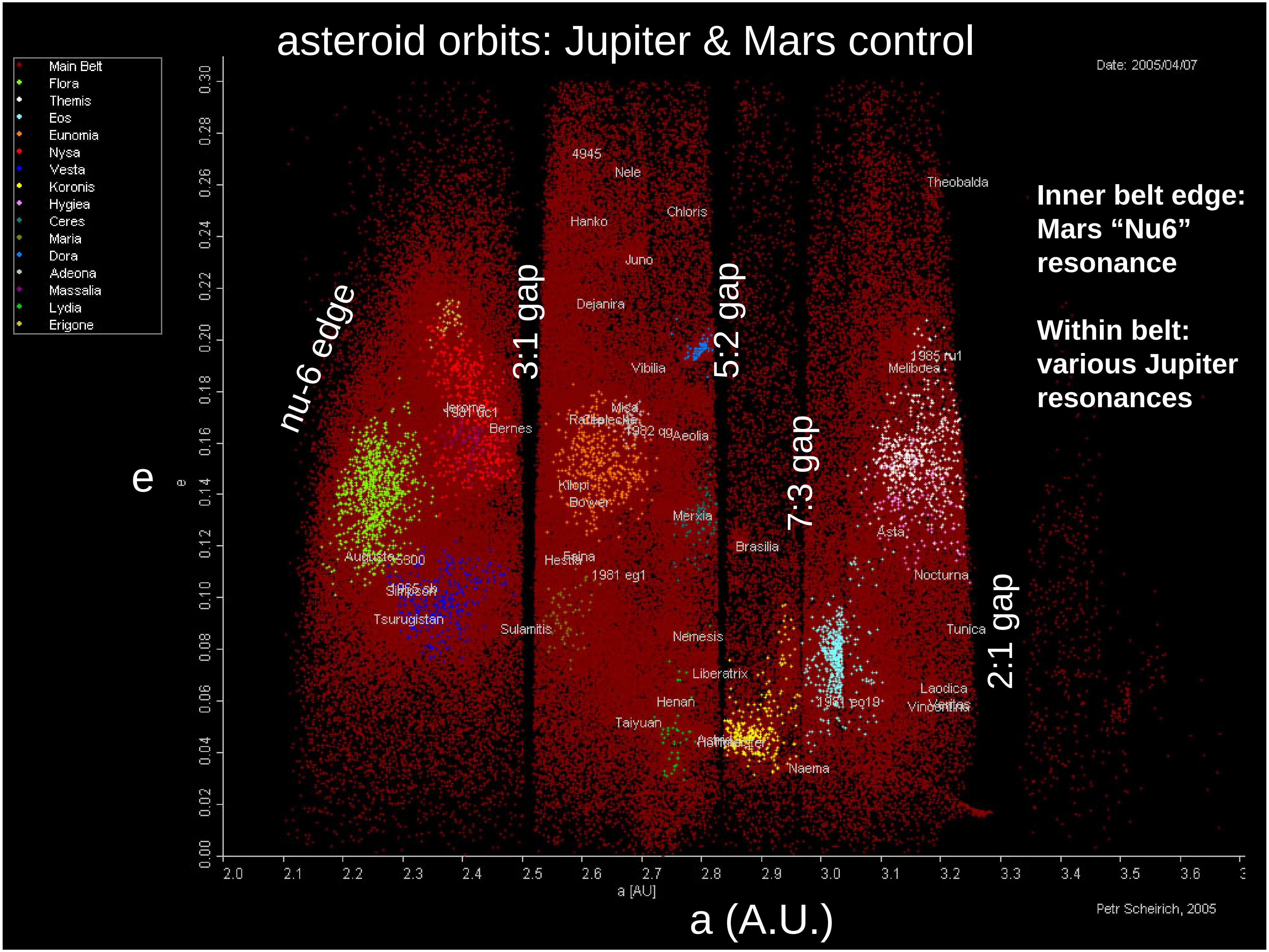
Tagish Lake meteorite	P/Wild-2 comet dust	P/Tempel-1 comet
phyllosilicate	--	phyllosilicate
carbonate	--	carbonate
organics (PAHs)	organics	organics (PAHs)
olivine	olivine	olivine
sulfide	FeNi-sulfide	sulfide
magnetite	--	--
spinel	--	spinel
low-Ca pyroxene	low-Ca pyroxene	pyroxene
FeNi-metal	--	Fe-metal
pre-solar grains	pre-solar grains	--
chondrules	--	--
CAIs	one CAI	--
--	--	H_2O + CO_2 + CO ice

Meteorite Express: How to get from the asteroid belt to the Earth

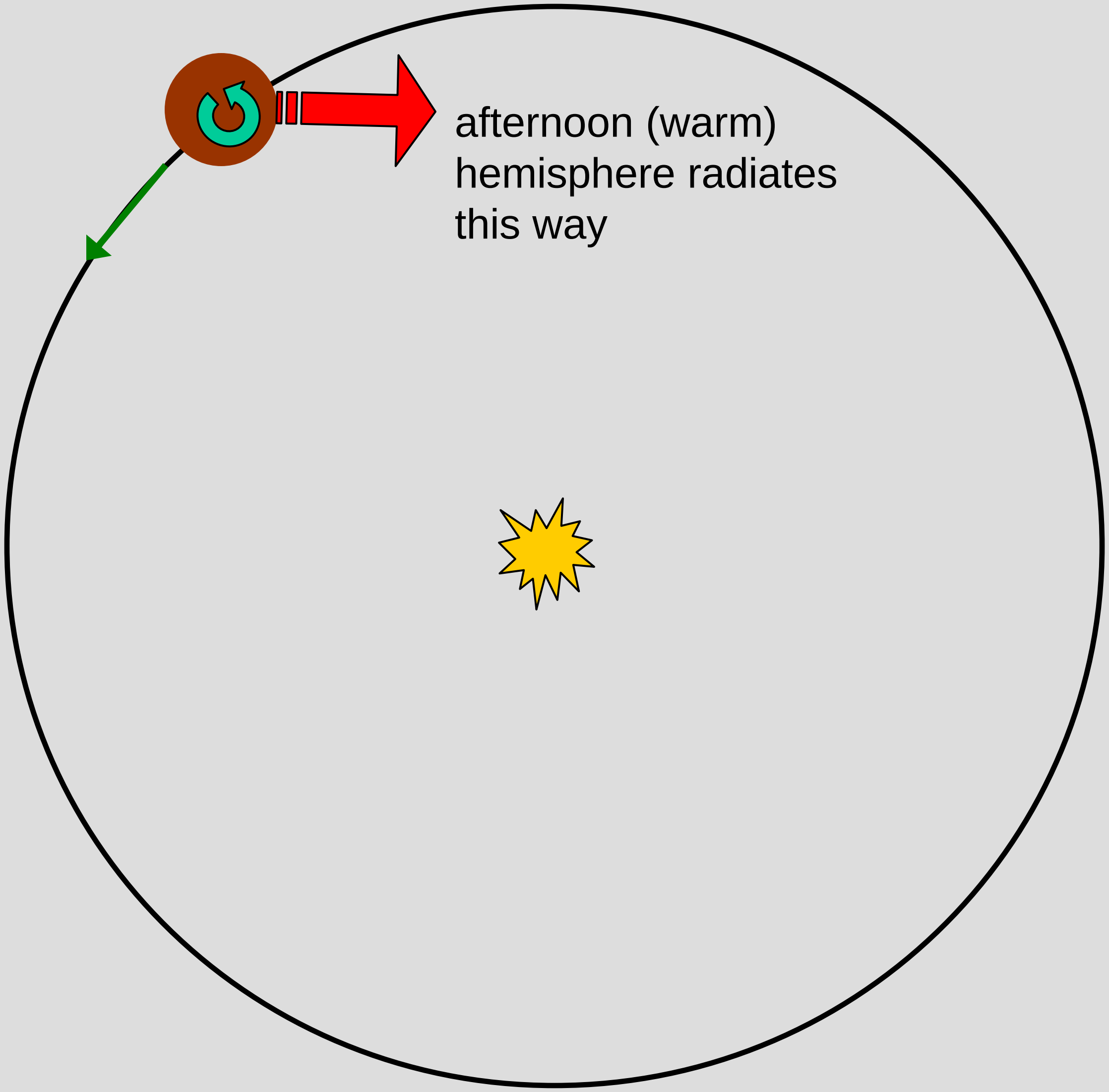
(1) Perturbations by Jupiter…
can put asteroidal material into Earth-crossing orbits (Kirkwood gap clearing). Gravity of Mars also important.

(2) Collisions occur…
among asteroids, producing meteoroids

(3) The Yarkovsky Effect…
can cause rotating m-sized objects to spiral inwards to (or outwards from) the sun.


asteroid orbits: Jupiter & Mars control
Main Belt
Flora
Themis
Eos
Eunomia
Nysa
Vesta
Koronis
Hygiea
Ceres
Maria
Dora
Adeona
Massalia
Lydia
Erigone
Date: 2005/04/07
nu-6 edge
3:1 gap
5:2 gap
7:3 gap
2:1 gap
4945
Nele
Theobalda
Hanko
Chloris
Juno
Dejanira
Vibilia
1985 ru1
Melibdea
Jerome
1981 uc1
Bernes
Misa
1992 qq
Aeolia
Kilopi
Bower
Merxia
Asta
Brasilia
Augusta
5300
Hestia
Eeina
1981 eg1
Nocturna
Simpson
Tsurugistan
Sulamitis
Nemesis
Tunica
Liberatrix
Laodica
Henan
1981 eo18
Taiyuan
Naema
e
a [AU]
a (A.U.)
Petr Scheirich, 2005
Inner belt edge: Mars "Nu6" resonance
Within belt: various Jupiter resonances

The Yarkovsky Effect



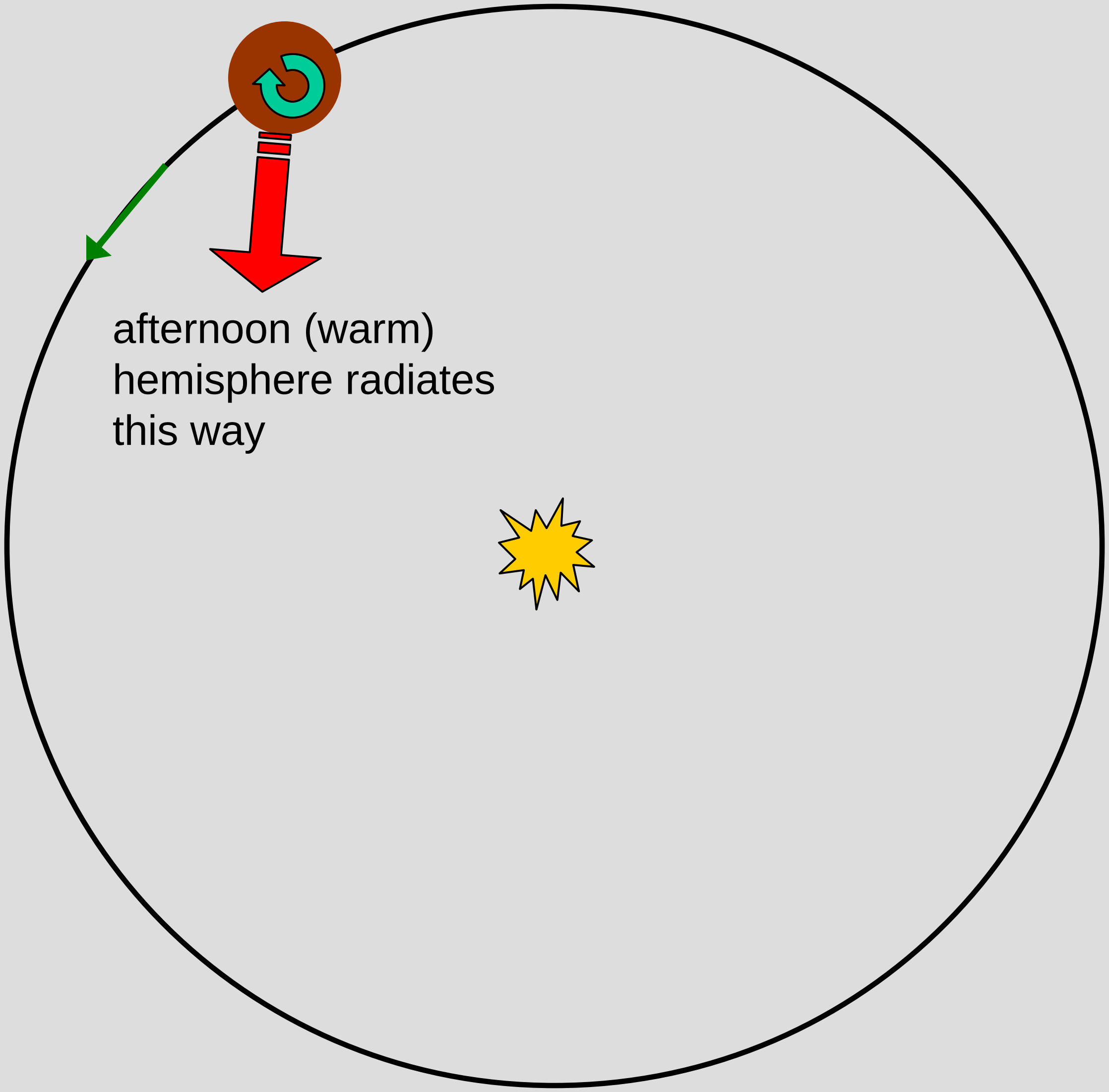
Prograde revolution + prograde rotation

---

1. IR thrust pushes object forward, like extra booster

2. Object gradually moves away from sun (orbit expands)

The Yarkovsky Effect



Prograde revolution + retrograde rotation

---

1. IR thrust acts like break

2. Object gradually falls towards sun (orbit shrinks)

The Yarkovsky Effect is most effective for m-sized bodies

Bodies << 1 m across (e.g., dust)

-- more affected by photons from sun

e.g., light pressure
causes micron-sized particles to spiral away from sun

e.g., Poynting-Robertson Effect
causes cm-sized particles to spiral in towards sun

Bodies >> 1 m across (e.g., asteroids)

-- more affected by gravity

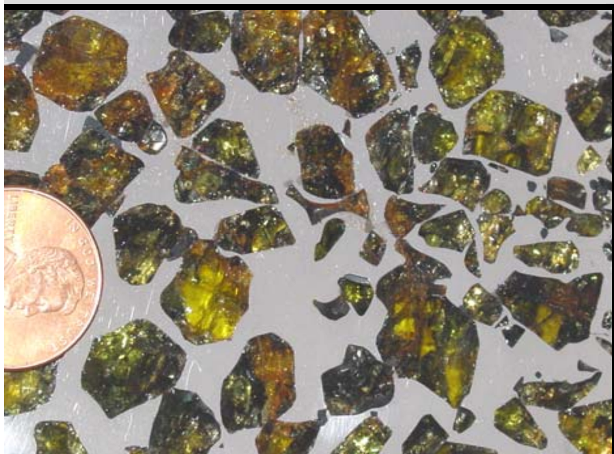
C. Meteorite types

Types of meteorites… a simple classification

Designation	Proportion of metal & silicate
Iron	*>> 50% metal alloy*
Stony-iron	*~ 50% metal, ~ 50% silicate*
Stony	*>> 50 % silicate*

Kinds of meteorites

Iron >



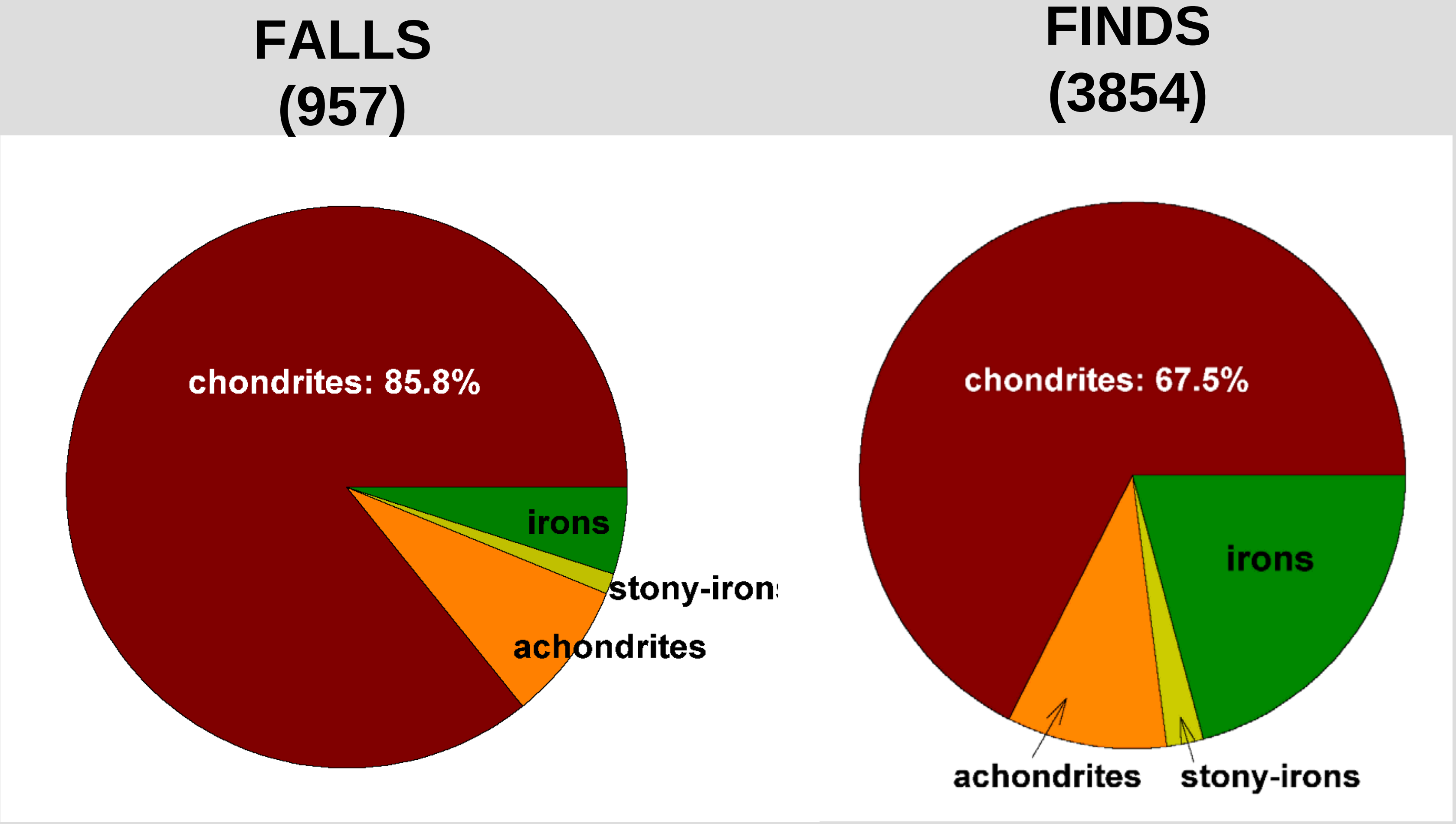
< Stony-iron

pallasite (L), mesosiderite (R)

Stony >

chondrite (L)
achondrite (R)

Meteorite statistics (as of year 2000)



Probably now have >20,000 meteorites, thanks to recovery from Antarctica & the Sahara. New find statistics resemble the fall statistics.

Classes, rock types, and parent bodies

Designation	Class & rock types	# parent bodies*
Stony	chondrites: agglomerate	> 13
Stony	achondrites: igneous, often breccia	> 8
Stony-iron	pallasite: igneous	> 3
Stony-iron	mesosiderite: igneous, meta-breccia	1 (2)
Iron	many groups: igneous	50-80?

* as inferred from chemical & isotopic studies

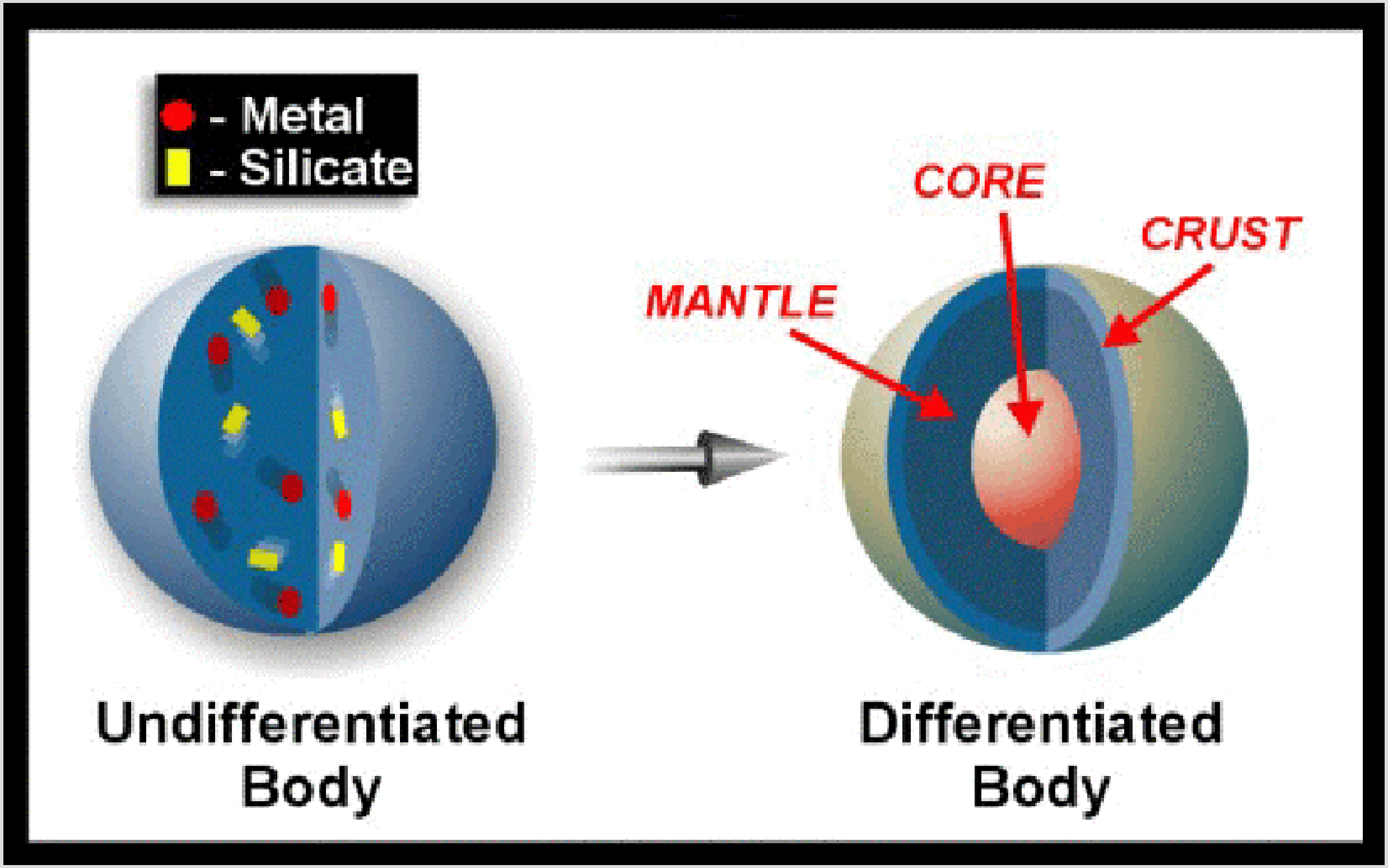
Types of meteorites… a fundamental classification

Designation	Rock type
Chondrite ***(stony)***	***agglomerate-- never melted***
All else ***(stony, stony-iron, iron)***	***igneous; impact breccias-- melted at least once***

Types of meteorites… a fundamental classification

Designation	Rock type
Chondrite *(stony)*	*agglomerate-- never melted*

unique (yet common) rock type in solar system;
formed in early solar system only



Chondrites | **All other rocks**

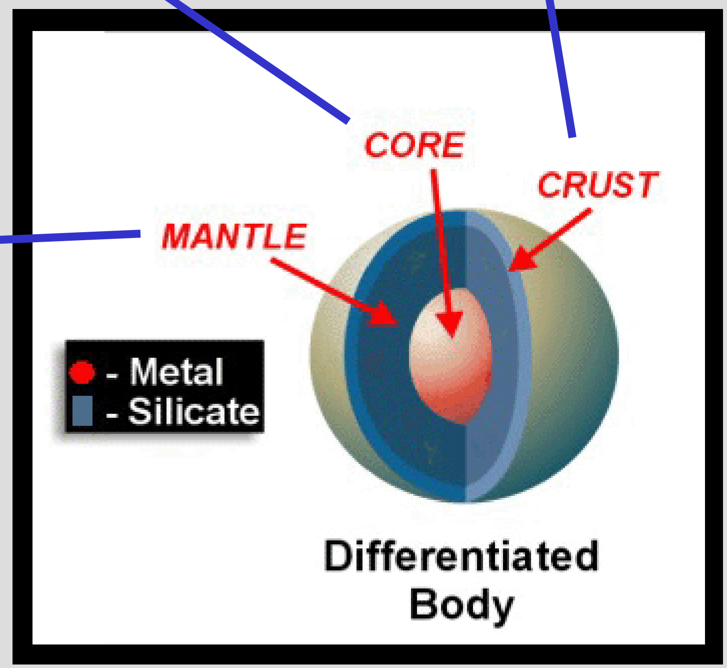
D. Differentiated meteorites

- achondrites
- irons
- stony irons

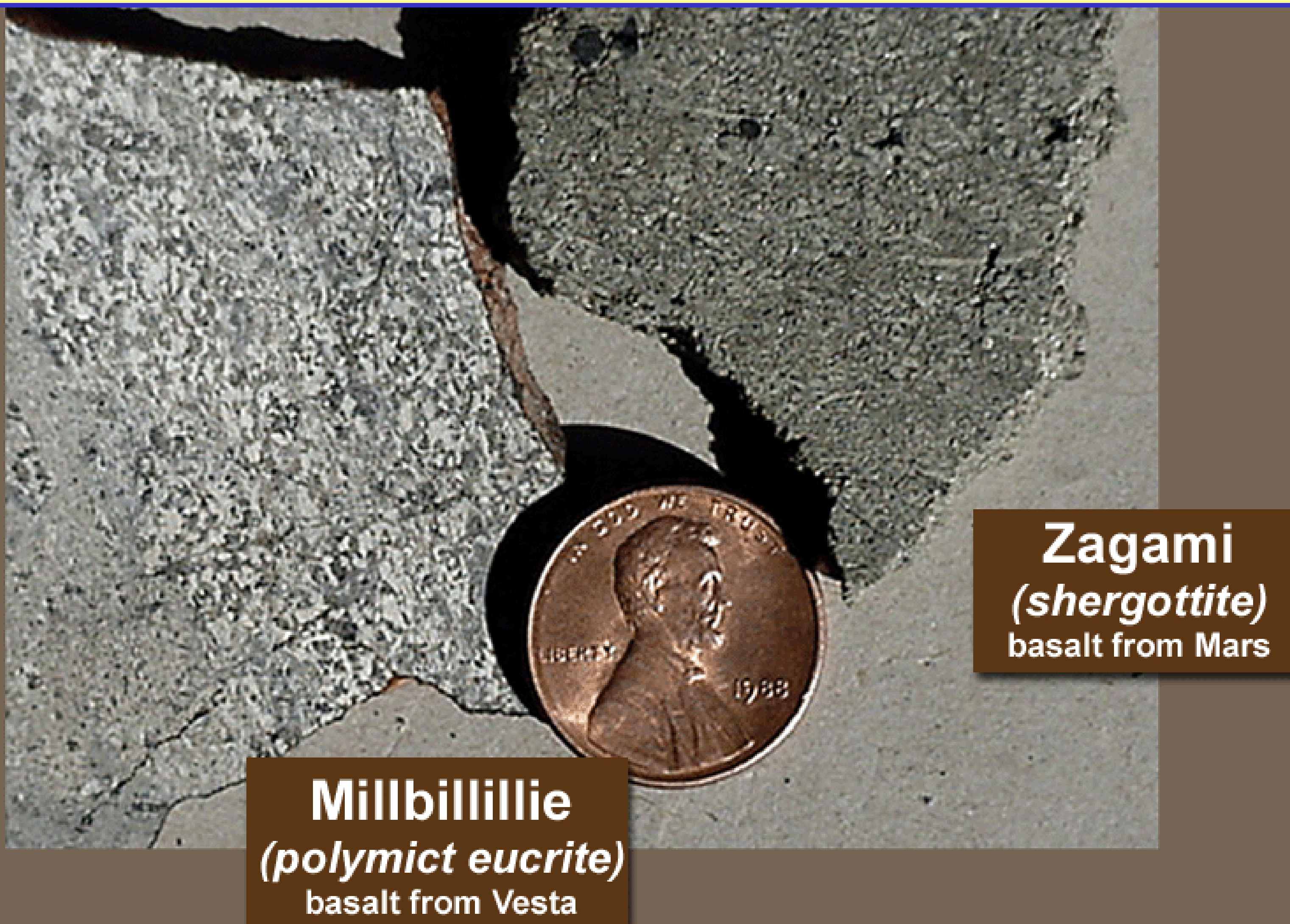
Gibeon (IVA iron)

Millbillillie (eucrite)

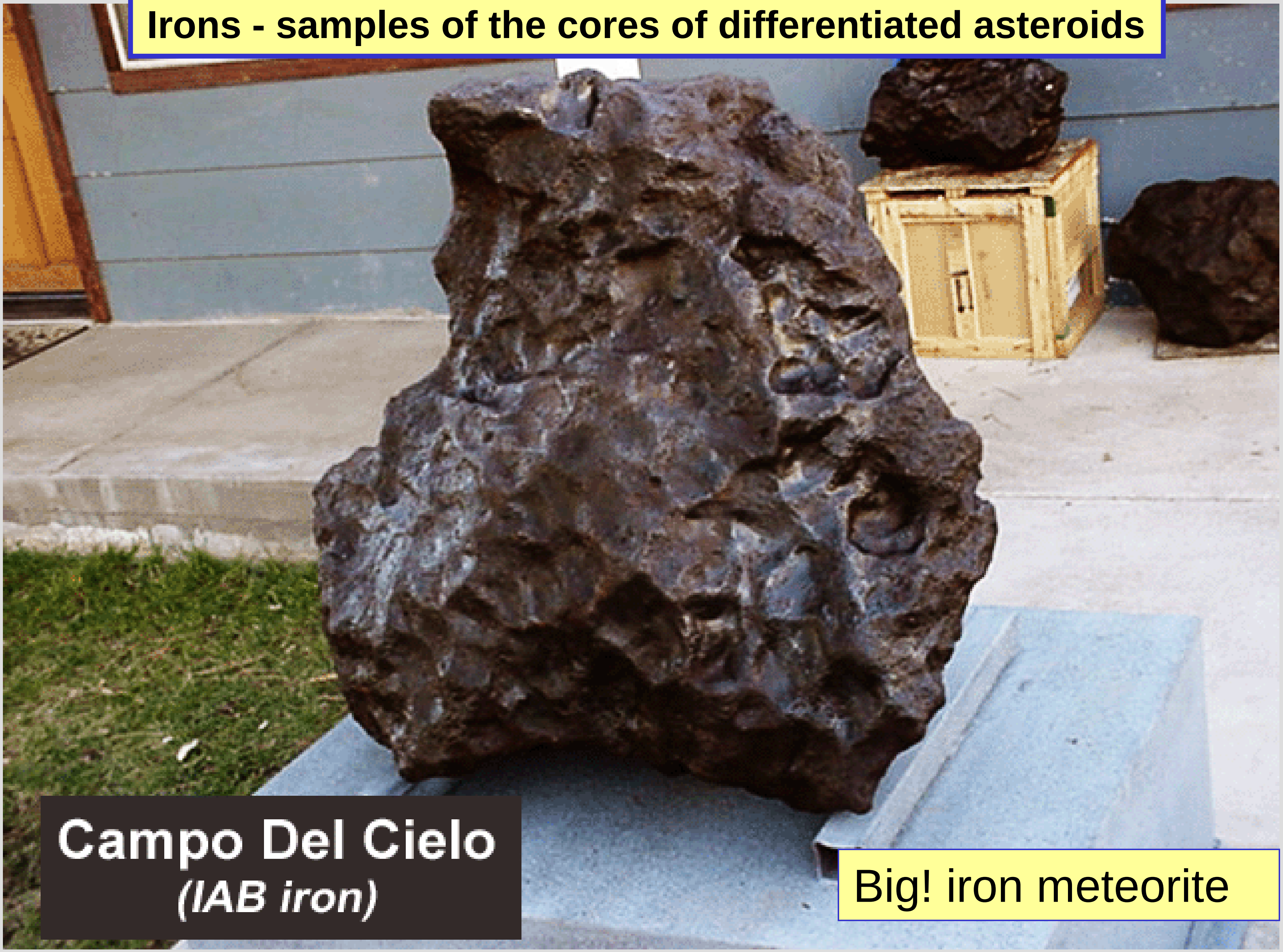
NWA 1464 (urelilite)



Achondrite - any stony meteorite NOT a chondrite - samples of crusts and mantles of differentiated asteroids, the Moon, and Mars



Irons - samples of the cores of differentiated asteroids



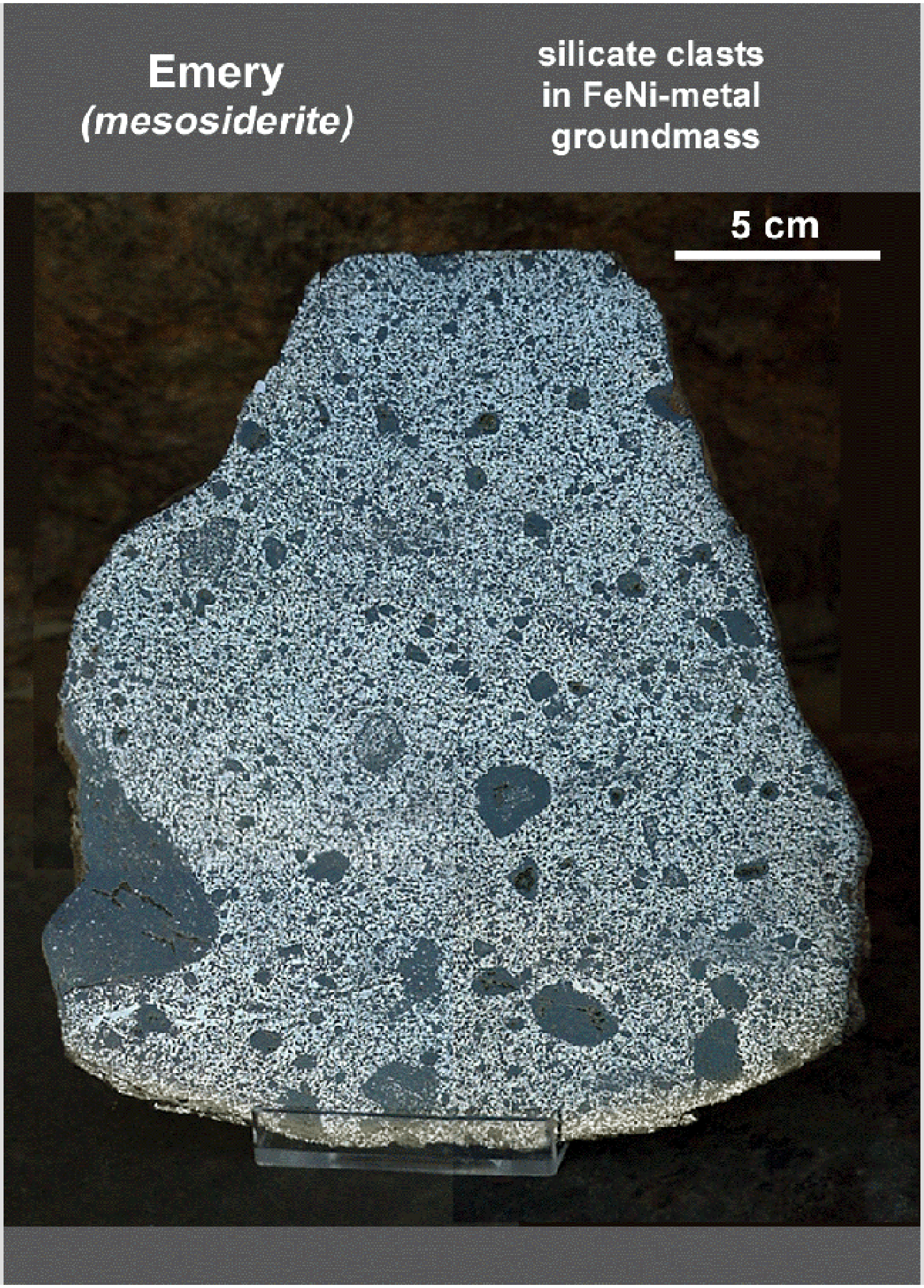
Iron meteorite: slow-cooling in a metallic core

Ahumada

(pallasite)

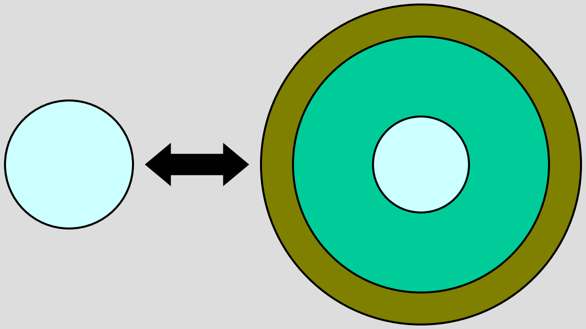
origin:
olivine crystals floating in a pool of metallic liquid (core-mantle boundary)

olivine (mantle)
olivine + metal
metal (core)



Mesosiderite

collision of two differentiated asteroids?



collisionally-stripped metal core

target body

E. Chondrites

Agglomerates of materials with diverse histories

Solar-like bulk composition (planetary building blocks)

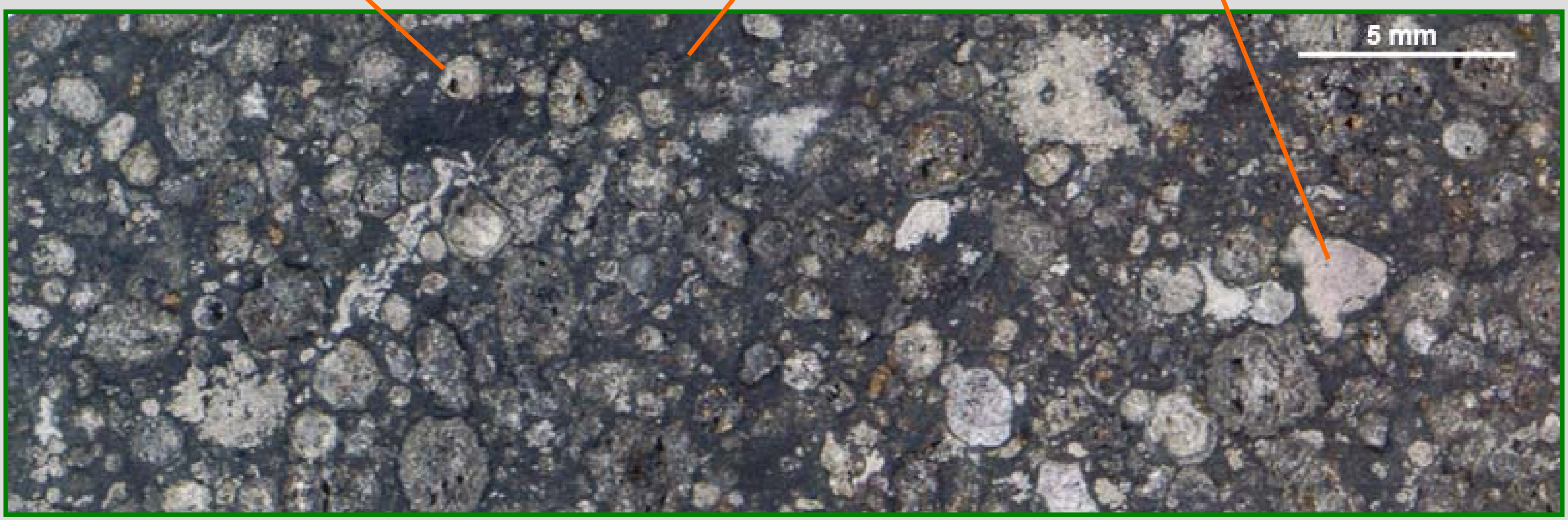
Formed in protoplanetary disk (solar nebula)

Chondrites-- agglomerates of materials with diverse histories

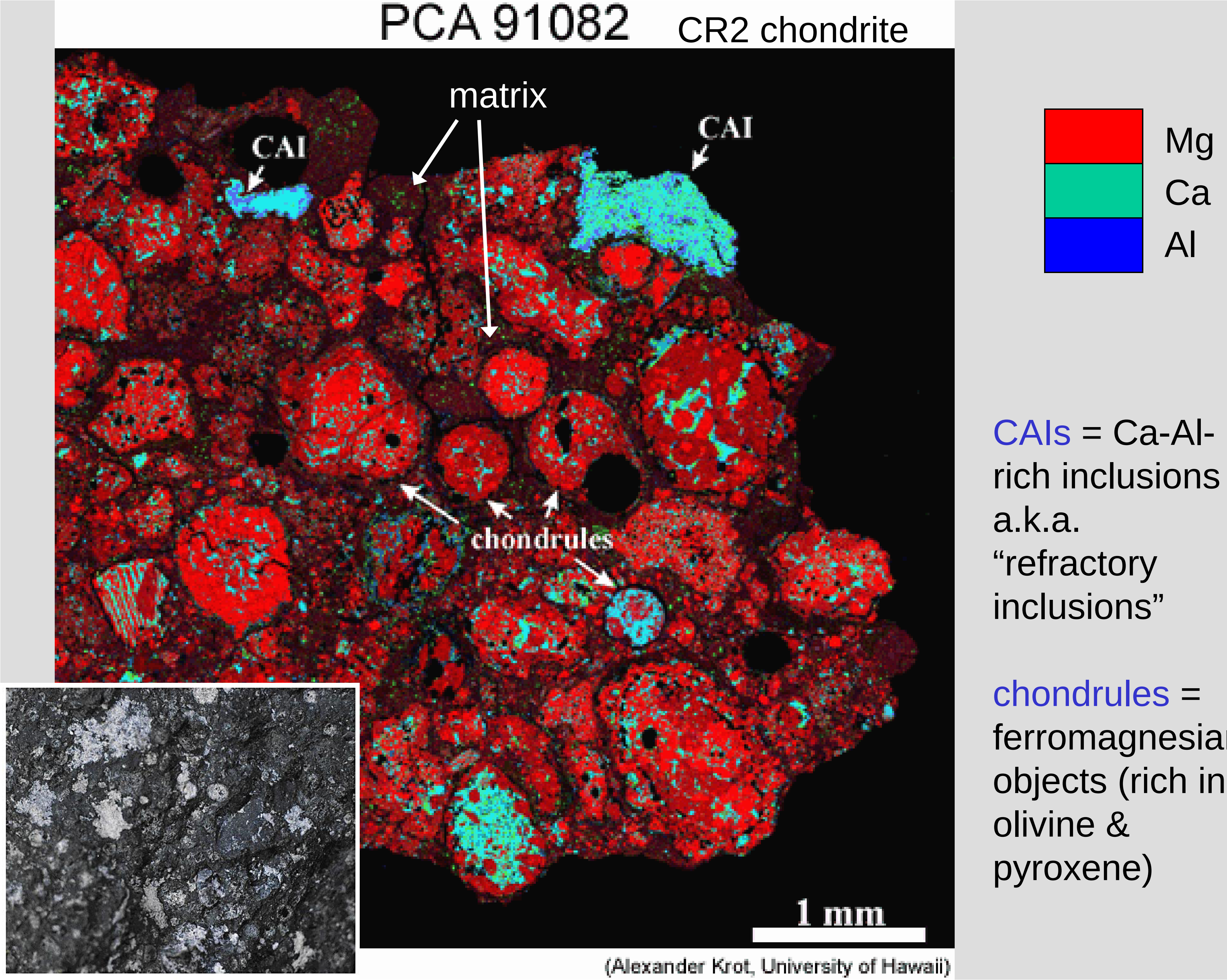
CAIs – high-T condensates & vaporization residues

matrix, includes pre-solar grains & low-T organic matter

chondrules – remelted objects

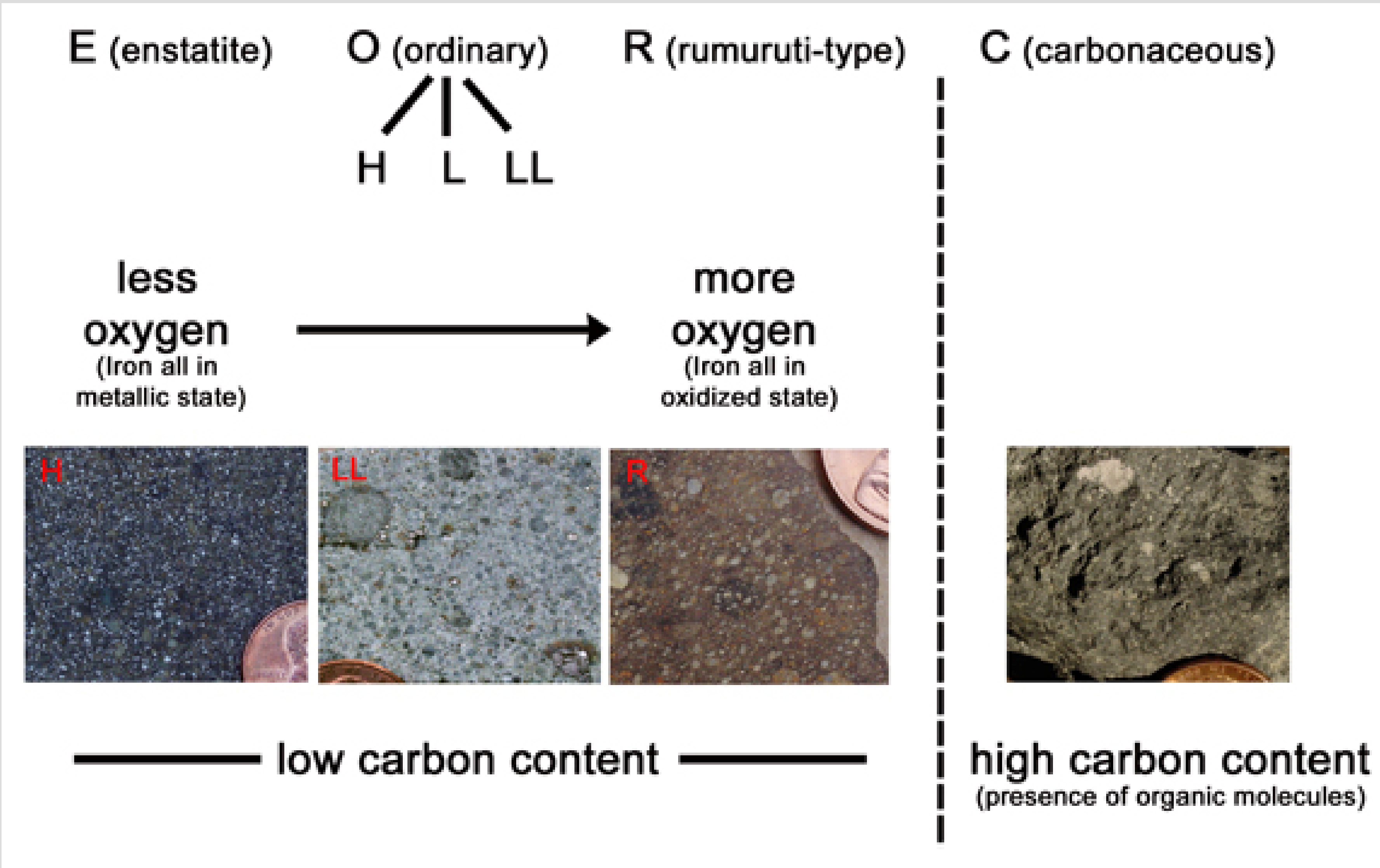


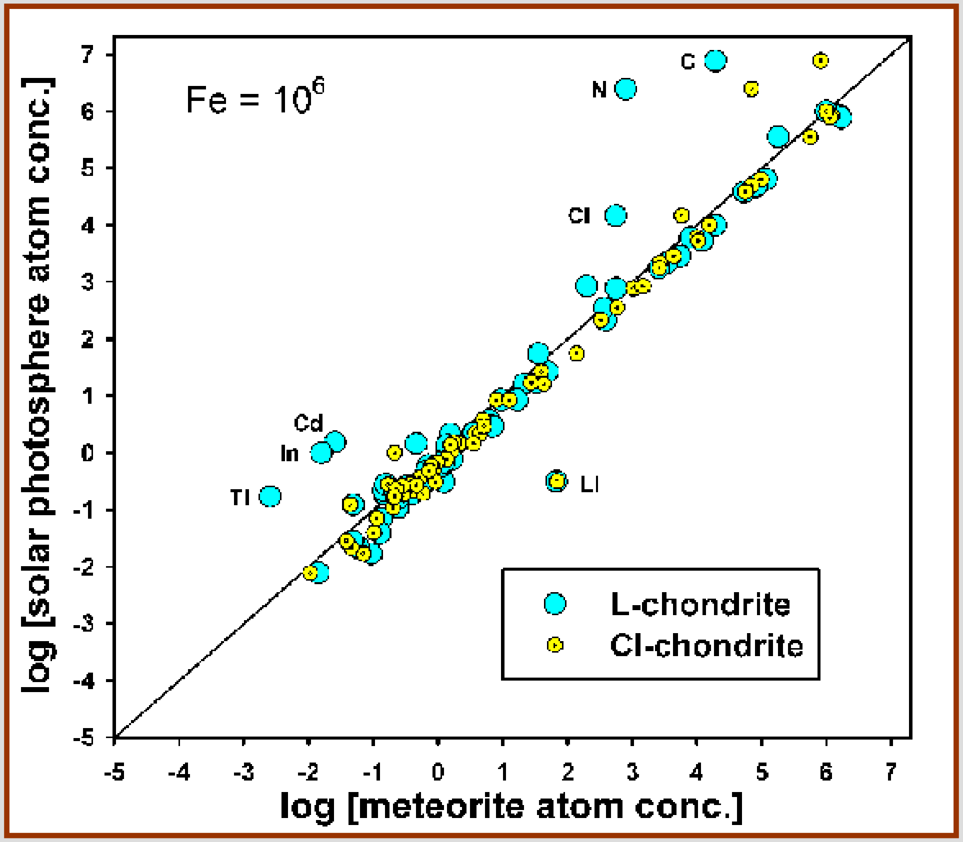
Vigarano (CV3 chondrite)



CAIs = Ca-Al-rich inclusions a.k.a. “refractory inclusions”

chondrules = ferromagnesian objects (rich in olivine & pyroxene) chondrites– different types, vary in proportion of carbon & oxygen

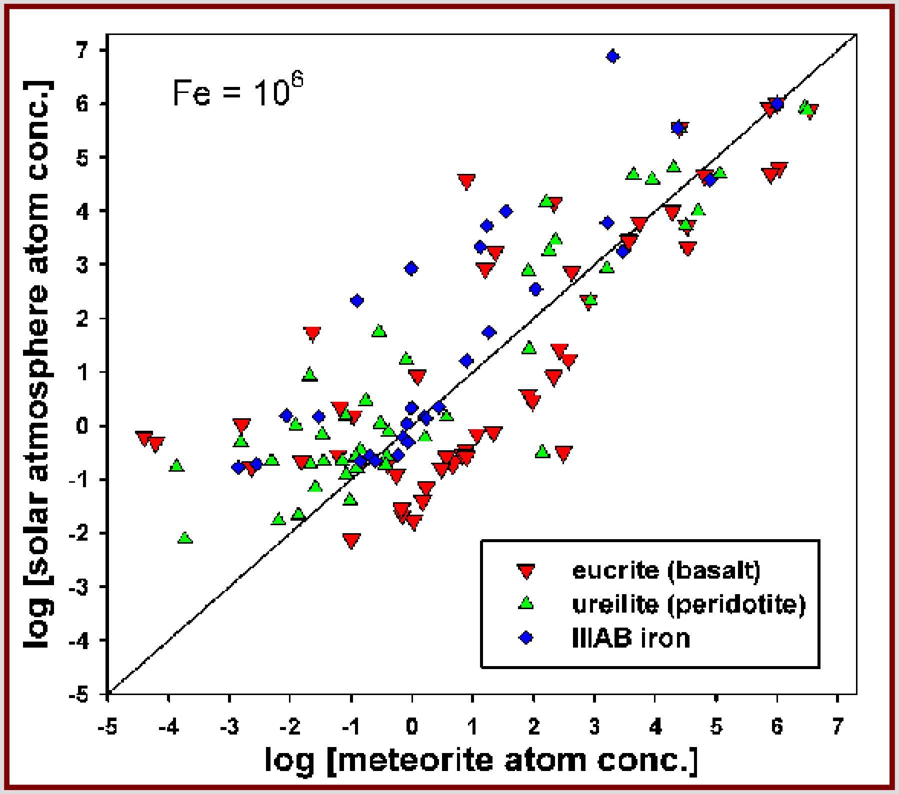




Chondrites uniquely have quasi-solar composition

^^ chondrites vs. sun

differentiated meteorites vs. sun >>



protoplanetary disks (proplyds)

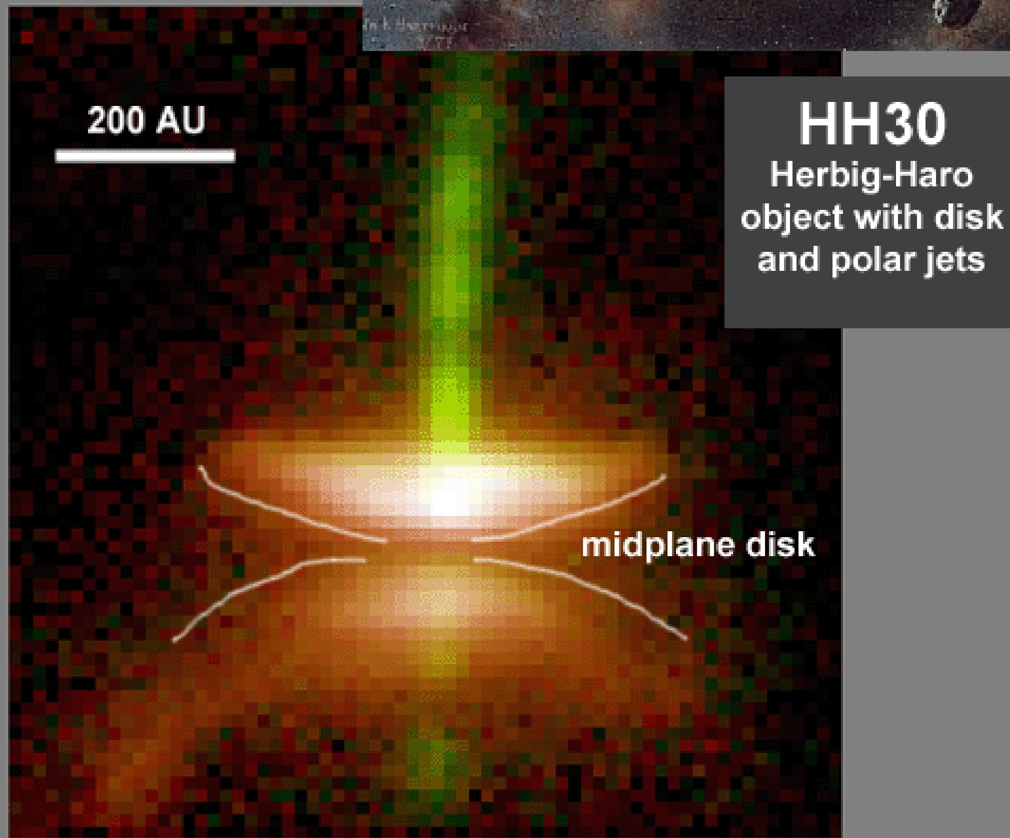


image: *Hubble Space Telescope*

F. Important results

1. Planetary rock-swapping has occurred throughout solar system history.

- ~30 martian meteorites, ~40 lunar meteorites recognized on Earth; younger than 4.56 b.y.
- Impact-blasted off surfaces; brought to Earth in last ~0.1-10 m.y. probably many more at earlier times
- Now finding meteorites on the Moon and Mars

<< Meridiani Planum iron meteorite (IAB) (MER Opportunity image, sol 339)

Important results

2. The decay of short-lived radioactive nuclides was an important heat source in the early solar system.

- Evidence for many short-lived nuclides found in various meteorites, can be used as relative chronometers
- Many meteorite parent bodies melted & differentiated. Short-lived radioactive decay most promising heat source

Important results

3. The solar system formed in a short period.

- Dating by short-lived chronometers & precise Pb-Pb system
- Time to make & melt meteorite parent bodies ~2-5 Ma

time ~ 0.1-5 Ma ↓

molecular cloud (cold gas + dust)
proplyd (warmer gas + dust)
proplyd (warmer gas + dust + planetesimals)

Important results

4. Pre-solar grains were incorporated & preserved in chondritic meteorites

<< contains microscopic pre-solar grains, found by acid dissolution, gas extraction, or isotope mapping

Pre-solar grains:

- **SiC**
- **nanodiamond**
- **graphite**
- **corundum**
- **Si_3N_4**
- **organic matter**

Formed around multiple types of stars (red giants, supervovae)

Important results

5. Pre-biotic organic synthesis occurred in solar system building blocks

- Organic compounds found in interstellar medium (ISM)--molecular clouds
- Solar system formed by collapse of molecular cloud; chondrites formed in the early solar system and contain similar organic compounds

Rich in pre-biotic organic material (incl. amino acids)

Many organic compounds in carbonaceous chondrites

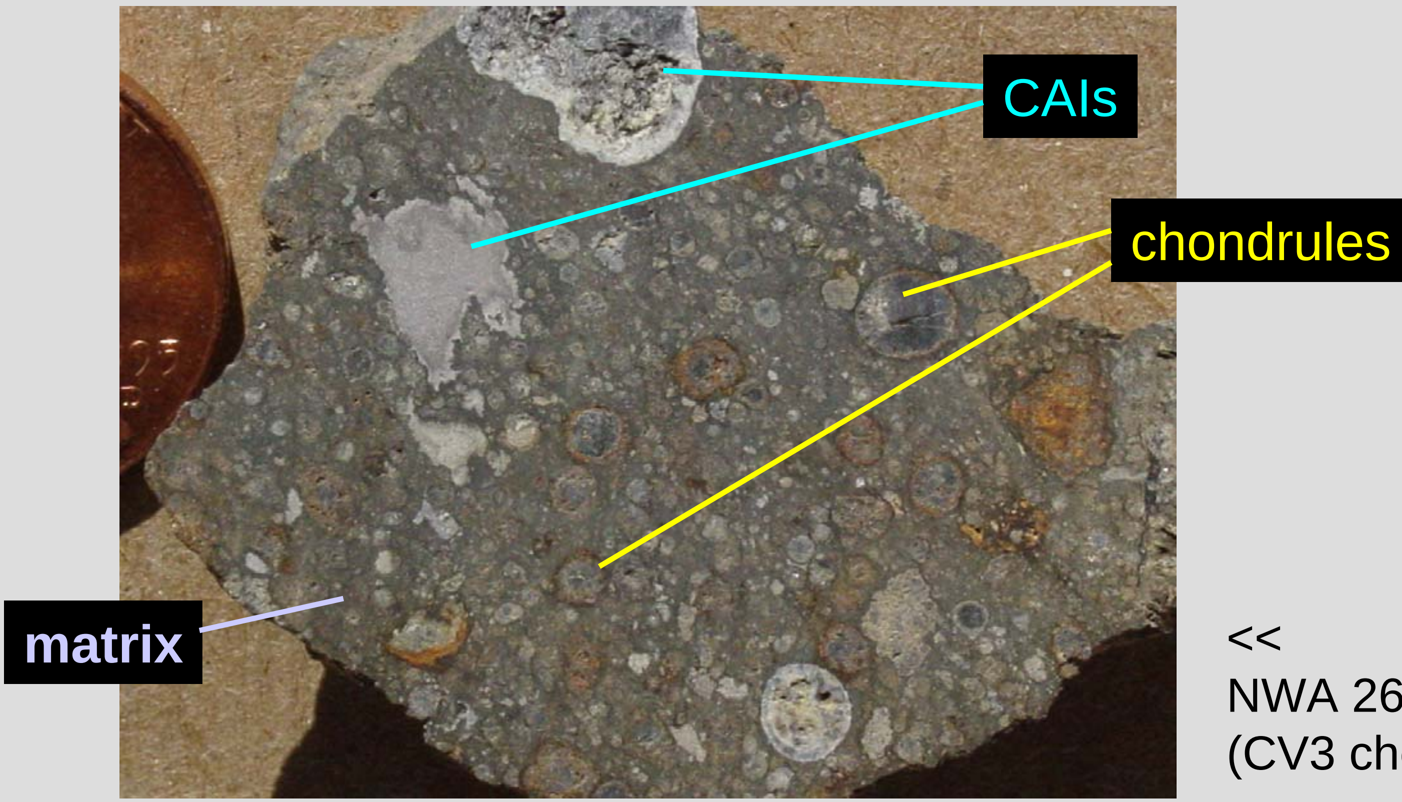
Include: macromolecular (kerogen-like) carbon, carboxylic acids, dicarboxylic acids, amino acids, lower alkanes, higher alkanes, aromatic hydrocarbons, N-compounds

Pre-terrestrial origin:

- no terrestrial source for some compounds
- compounds destroyed by terrestrial exposure & weathering
- racemic mixtures
- often isotopically anomalous (e.g., high D/H ~ 10x seawater)

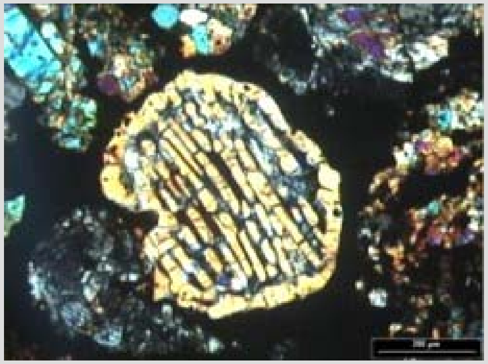
Important results

6. A substantial amount of dust in the early solar system was processed by intense heating events to make chondrules & CAIs (Ca-Al-rich inclusions).

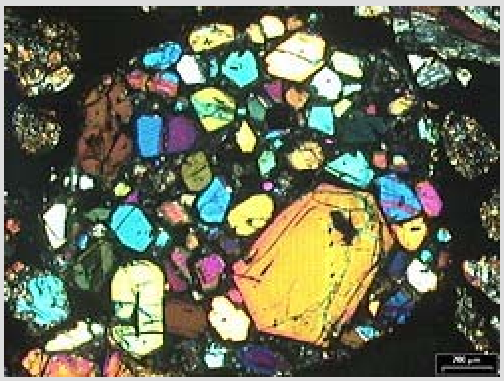


<<
NWA 2697
(CV3 chondrite)

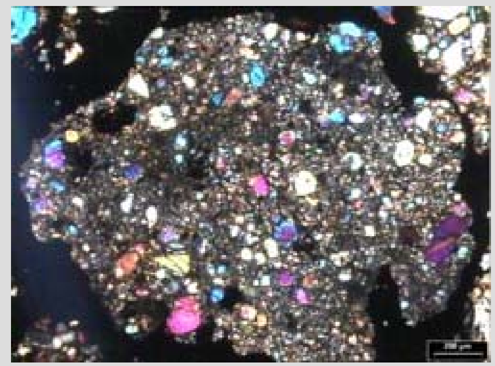
Chondrule textures in thin-section



<< barred olivine, almost completely remelted

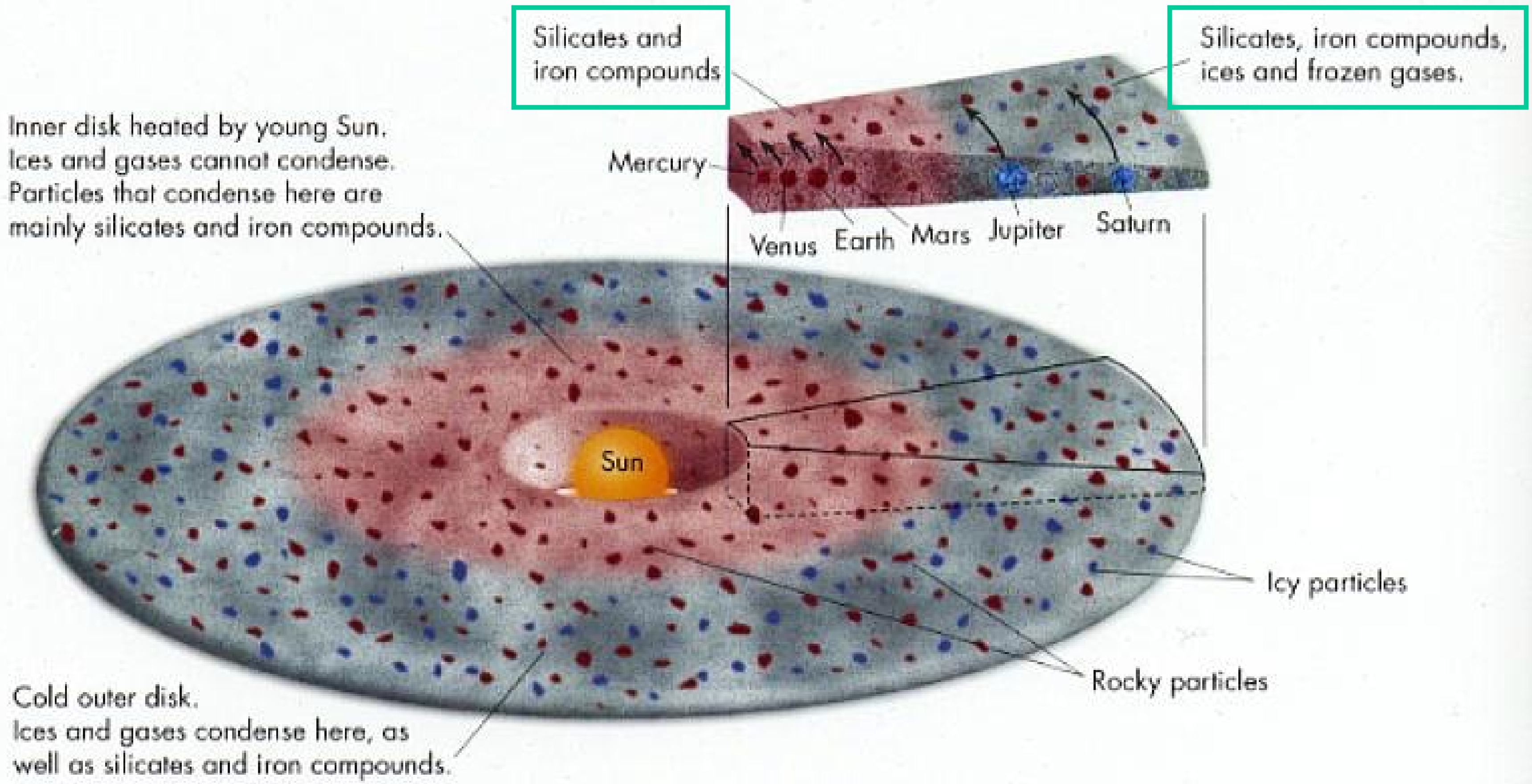


<< microporphyritic olivine >>
mostly remelted

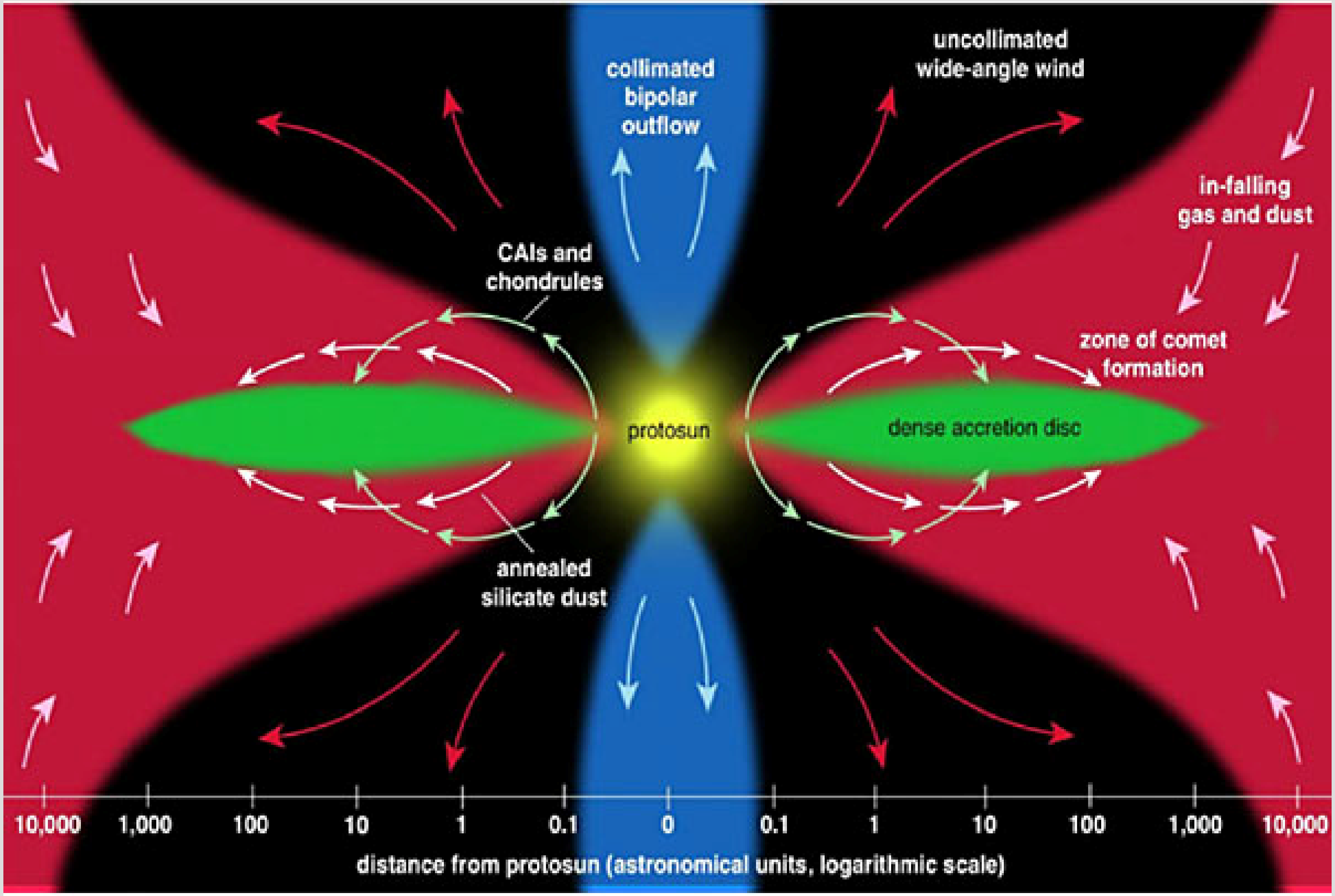


radial pyroxene & microporphyritic pyroxene , completely or partly remelted >>

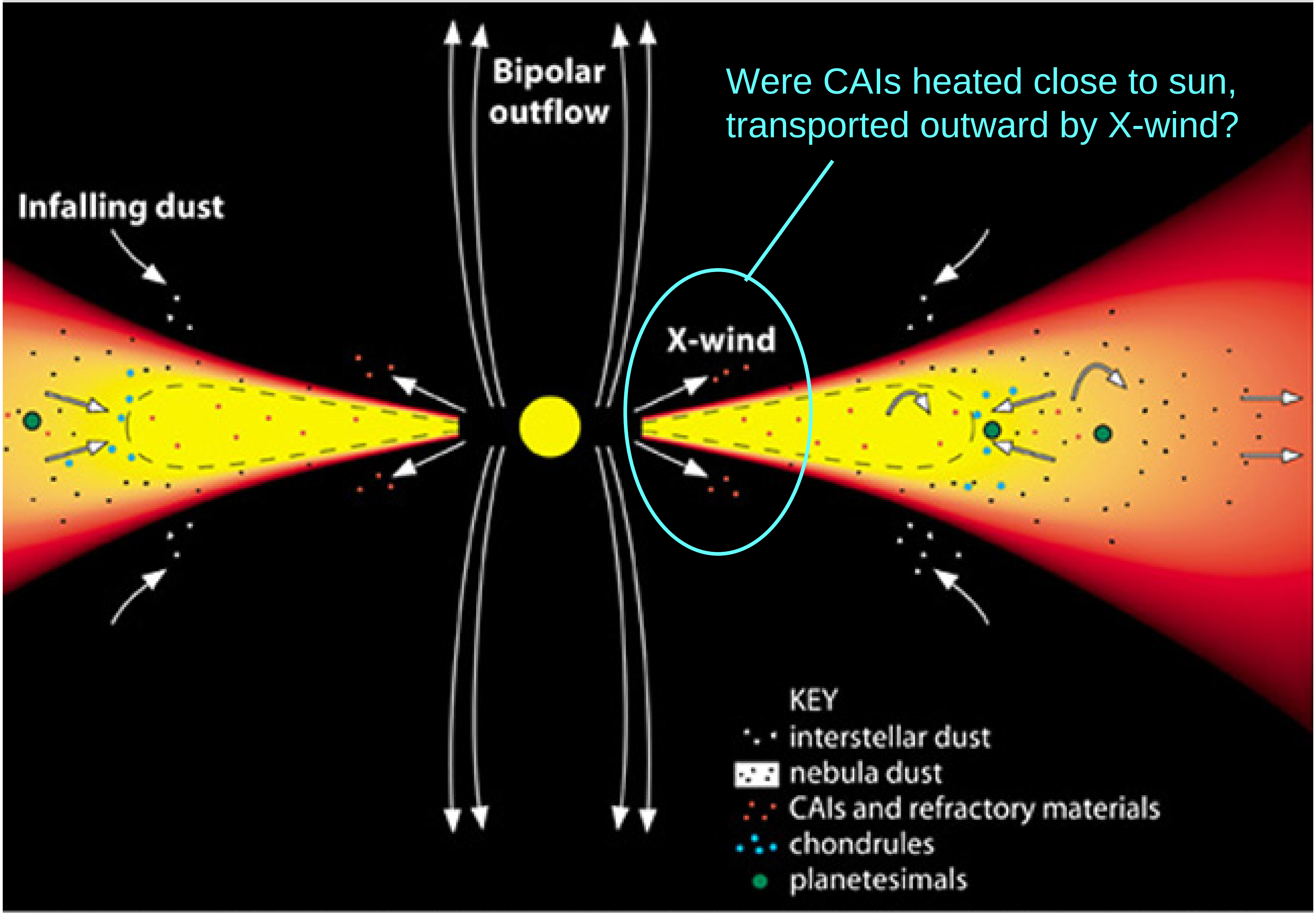
General picture of solar nebula: hotter closer to sun…
so dust composition must vary with distance from sun



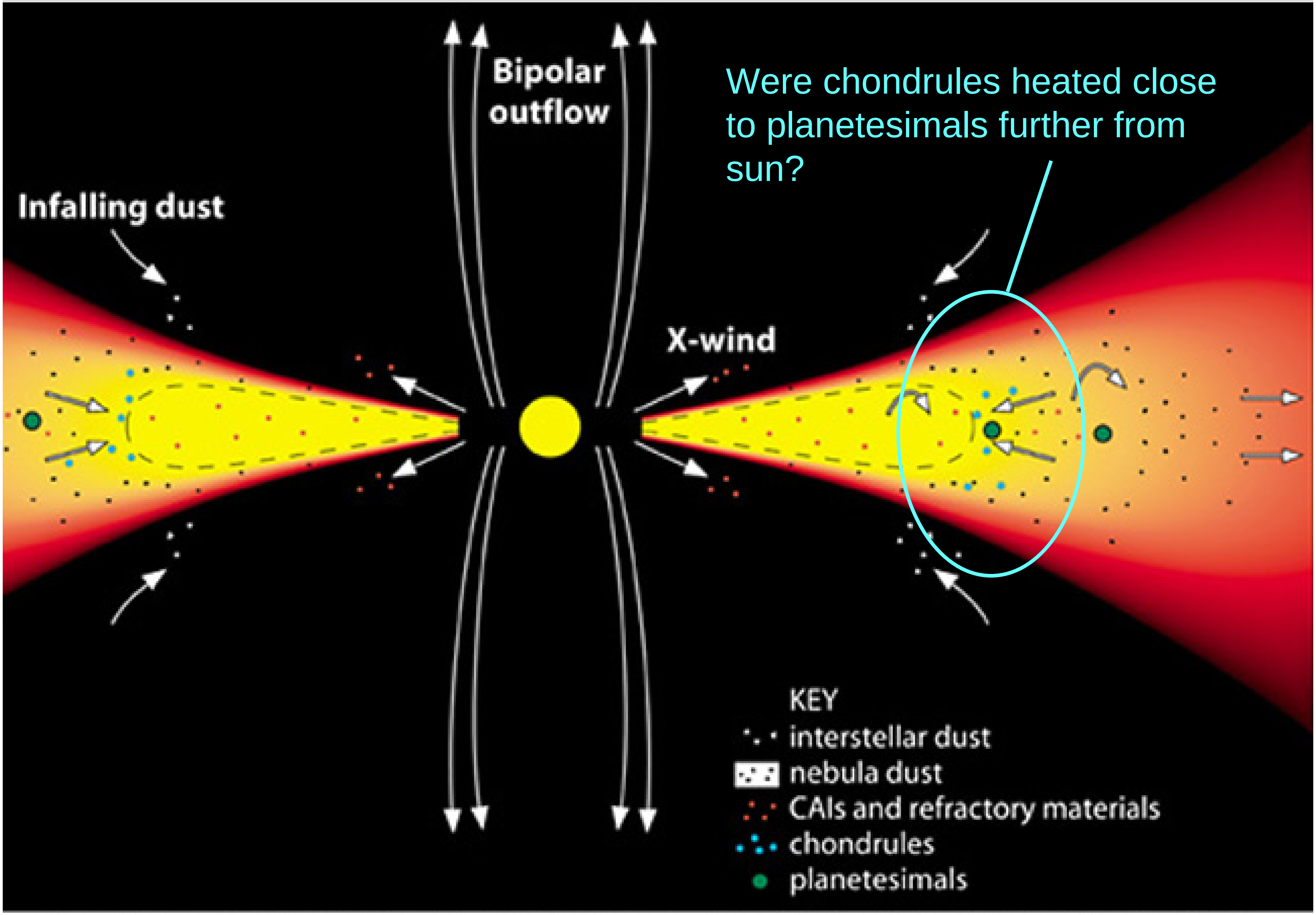
But chondrules & CAIs indicate we have also localized intense heating. Heated particles must become mixed with cooler dust to form chondritic material (unmelted asteroids & comets).



(from Nuth, J. A., 2001, *American Scientist*, v. 89, p.230.)



(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)



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