

Solar system chronology

WE Heraeus Winterschool “The early phase of planet formation”
Bad Honnef 18.2.2008

Articles for this lecture:

Trieloff M. and Palme H. (2006) The origin of solids in the early solar system. In: Planet Formation – Theory, Observations, and Experiments (Eds. H. Klahr & W. Brandner), pp.64-89, Cambridge: Cambridge University Press
(basic principles of cosmochemistry and chronology for astrophysicists)

Trieloff M., Jessberger E.K., Herrwerth I., Hopp J., Fiéni C., Ghéllis M., Bourot-Denise M. and Pellas P. (2003). Structure and thermal history of the H-chondrite parent asteroid revealed by thermochronometry. *Nature* 422, 502-506.

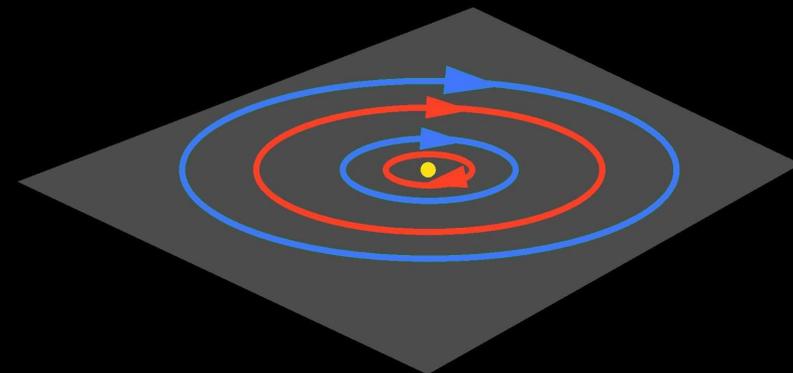
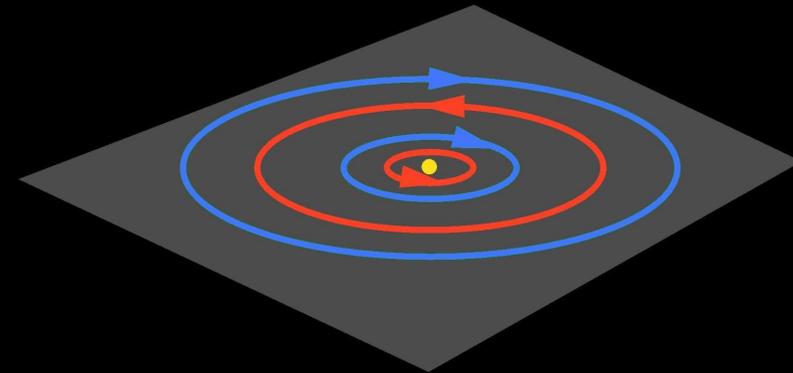
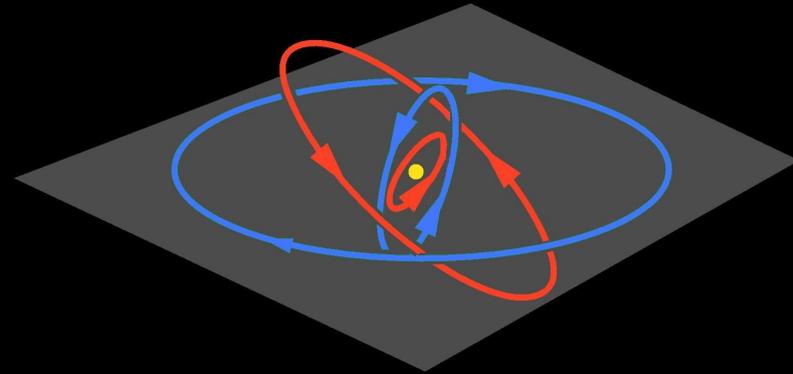
Trieloff M., Kunz J., Clague D.A., Harrison D. and Allègre C.J. (2000) The nature of pristine noble gases in mantle plumes. *Science* 288, 1036-1038.

Request offprints from: trieloff@min.uni-heidelberg.de



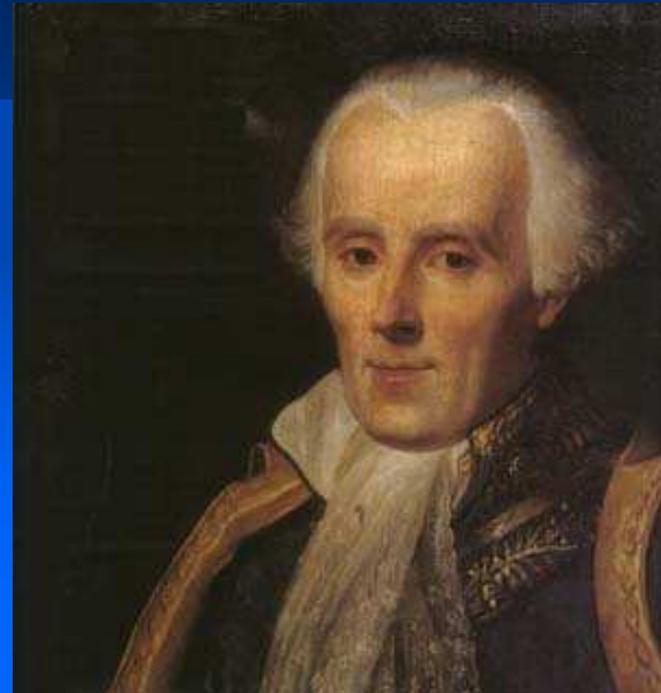
M. Trieloff

University of Heidelberg, Institute of Mineralogy,
Heidelberg, Germany





Immanuel Kant
(1724-1804)



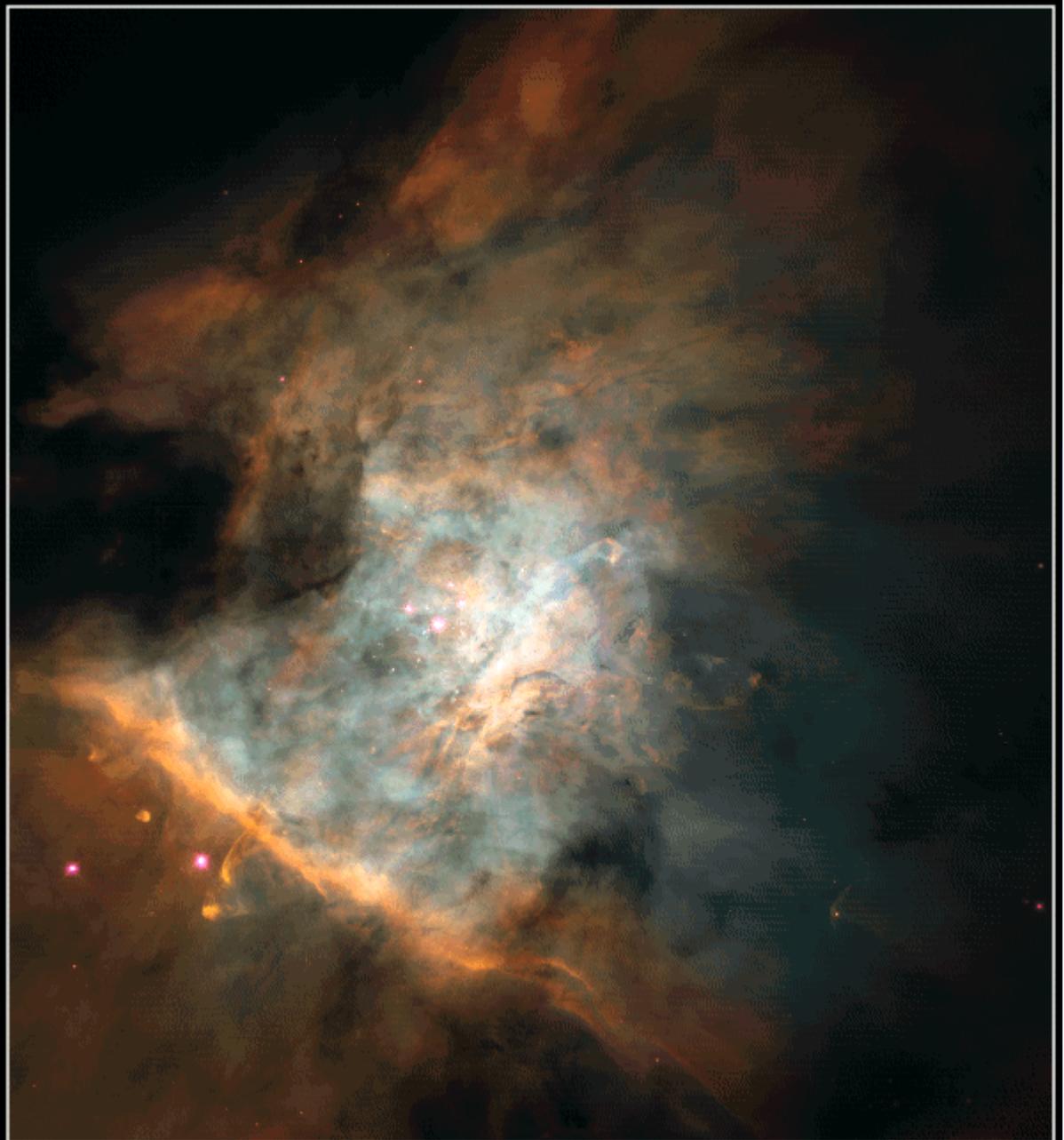
Pierre Simon Laplace
(1749-1827)

Origin of the solar system:

**→ collapse of an interstellar cloud (gas + dust),
planet formation in a rotating accretion disc**

**→ nearly circular orbits in the ecliptic plane, low
inclinations**

**Star formation in
the Orion nebula:**

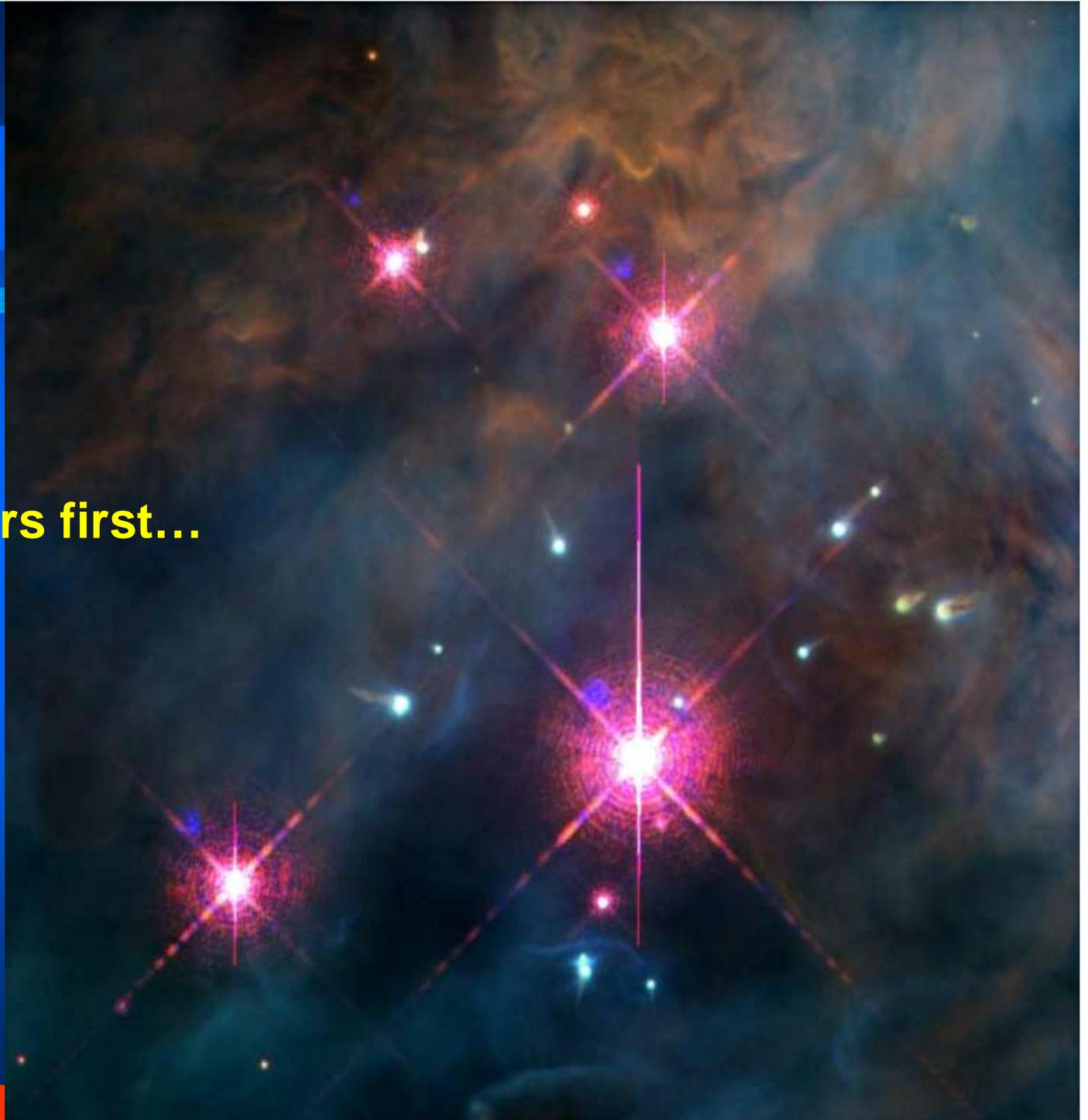


Orion Nebula Mosaic

HST · WFPC2

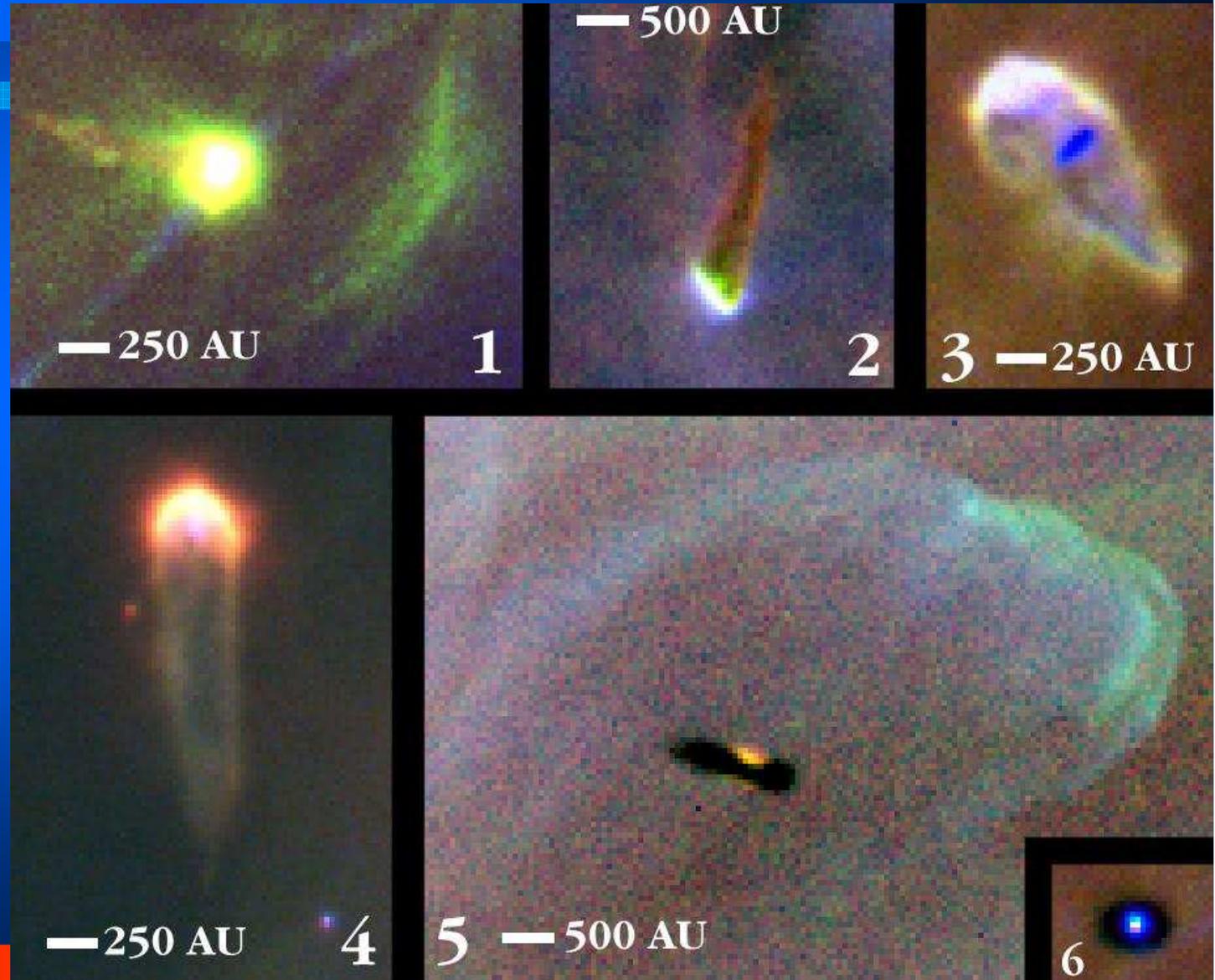
PRC95-45a · ST ScI OPO · November 20, 1995
C. R. O'Dell and S. K. Wong (Rice University), NASA

Mass rich stars first...



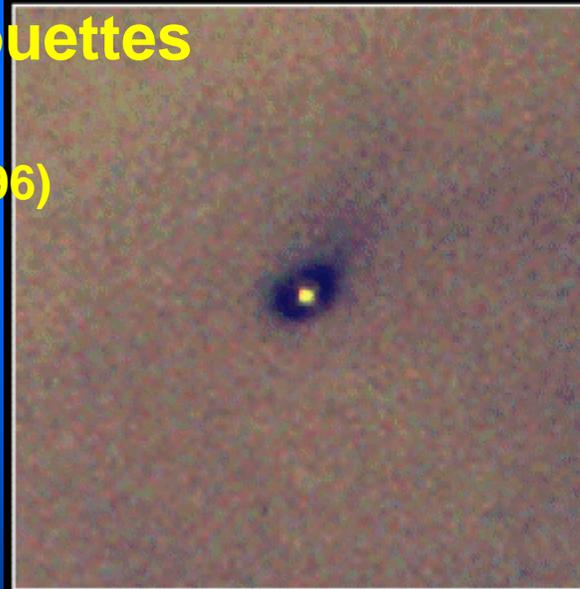
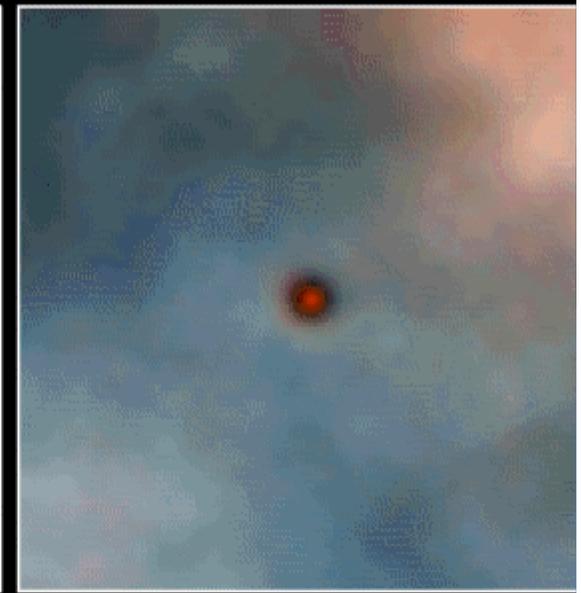
Protoplanetary discs in the Orion nebula

Solar mass stars still infant ...



**Undisturbed discs
photographed as silhouettes**

(McCaughrean and O'Dell, 1996)



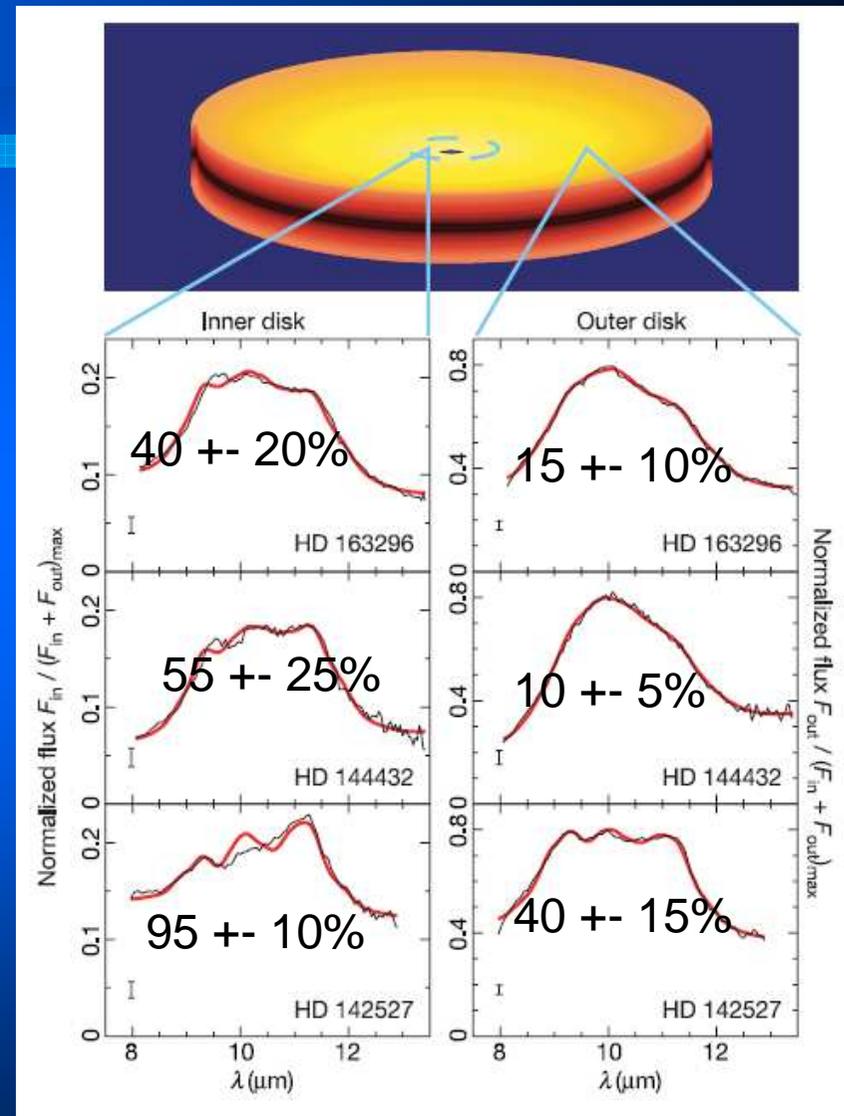
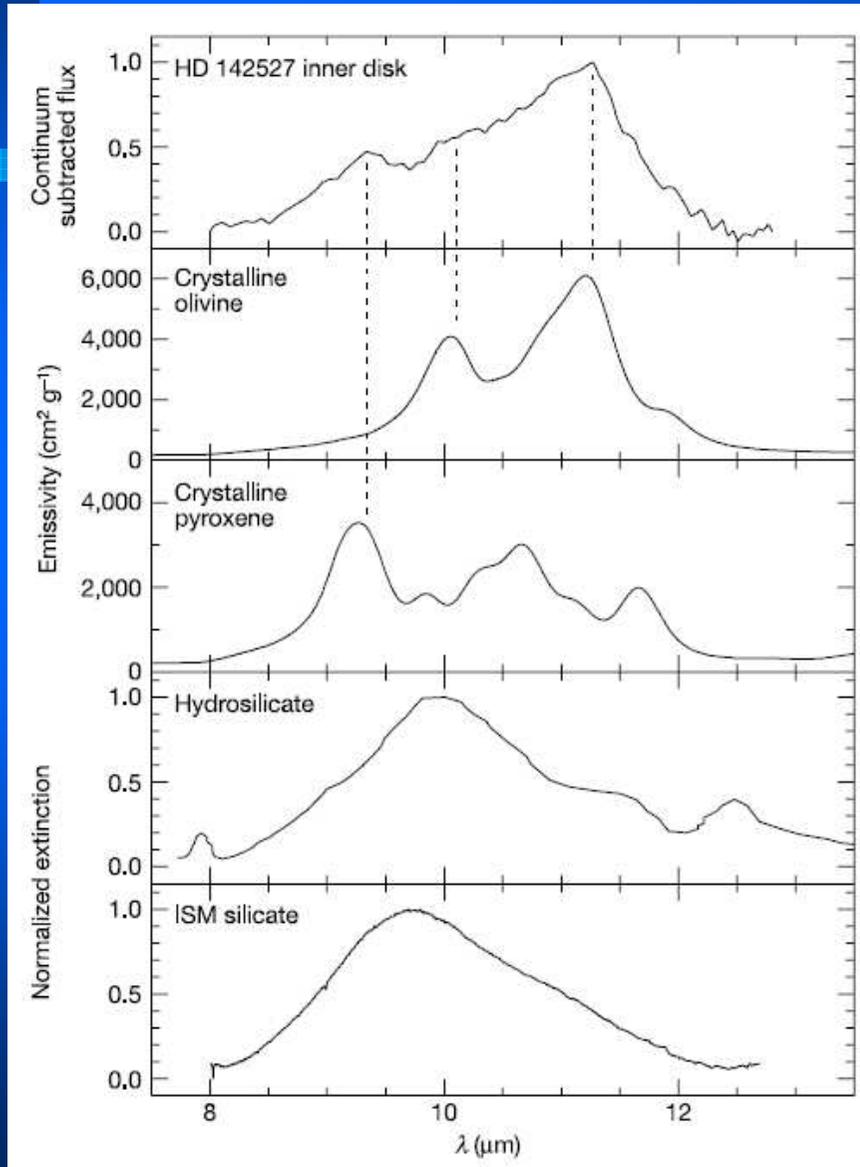
**Protoplanetary Disks
Orion Nebula**

HST · WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995

M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

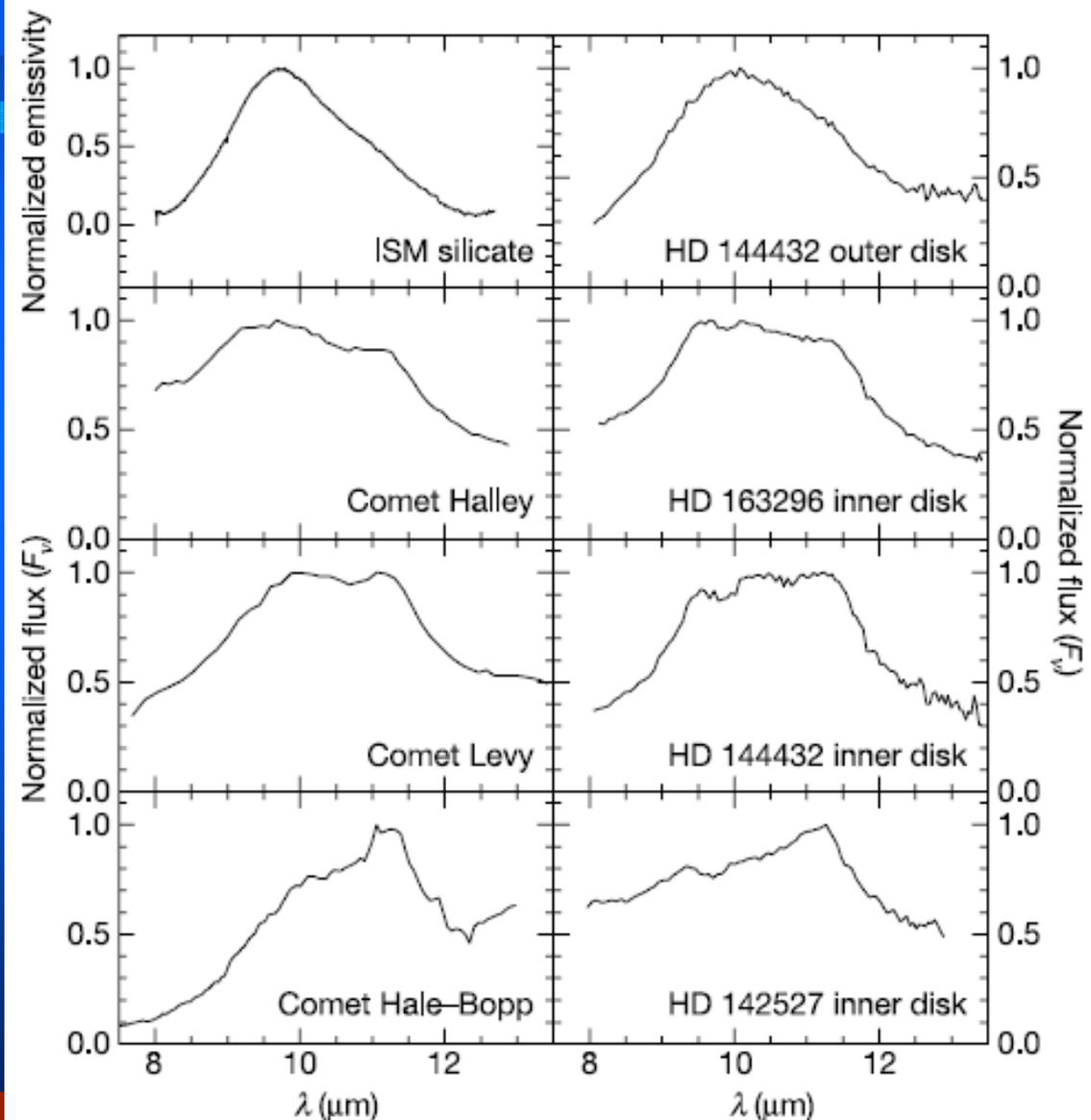
IR spectroscopy of protoplanetary disks: Mg silicates olivine+pyroxene – crystalline fraction higher in inner disks (van Boekel et al. 2004)



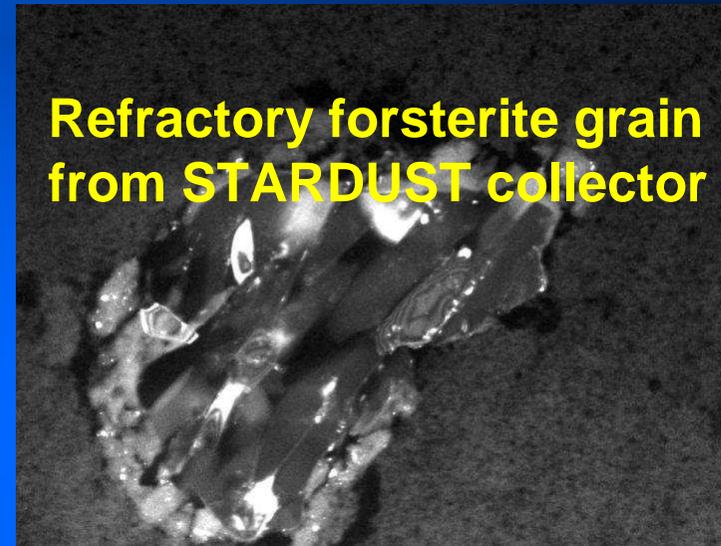
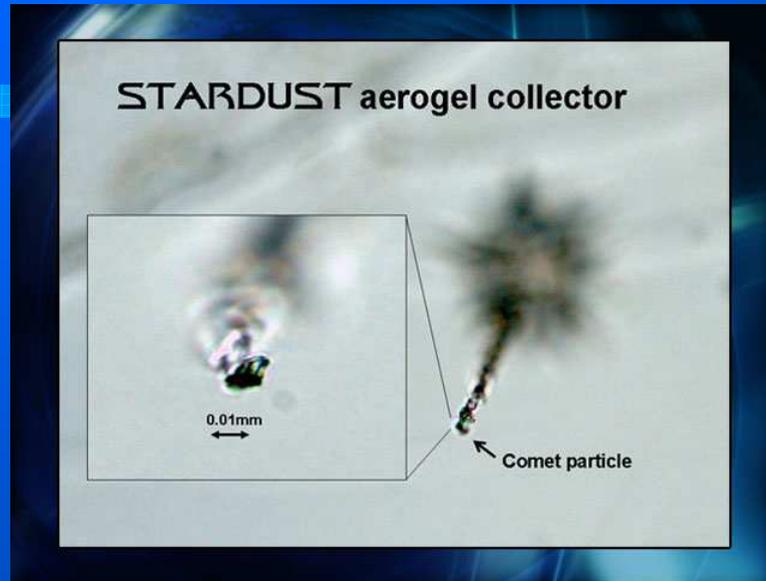
IR spectroscopy of protoplanetary disks: Mg silicates olivine+pyroxene – crystalline fraction higher in inner disks (van Boekel et al. 2004)

Crystalline fractions in some outer disks considerable, similar to solar system comets (Wooden et al., 2000)

→ Dust processing in disks and radial mixing into outer disks

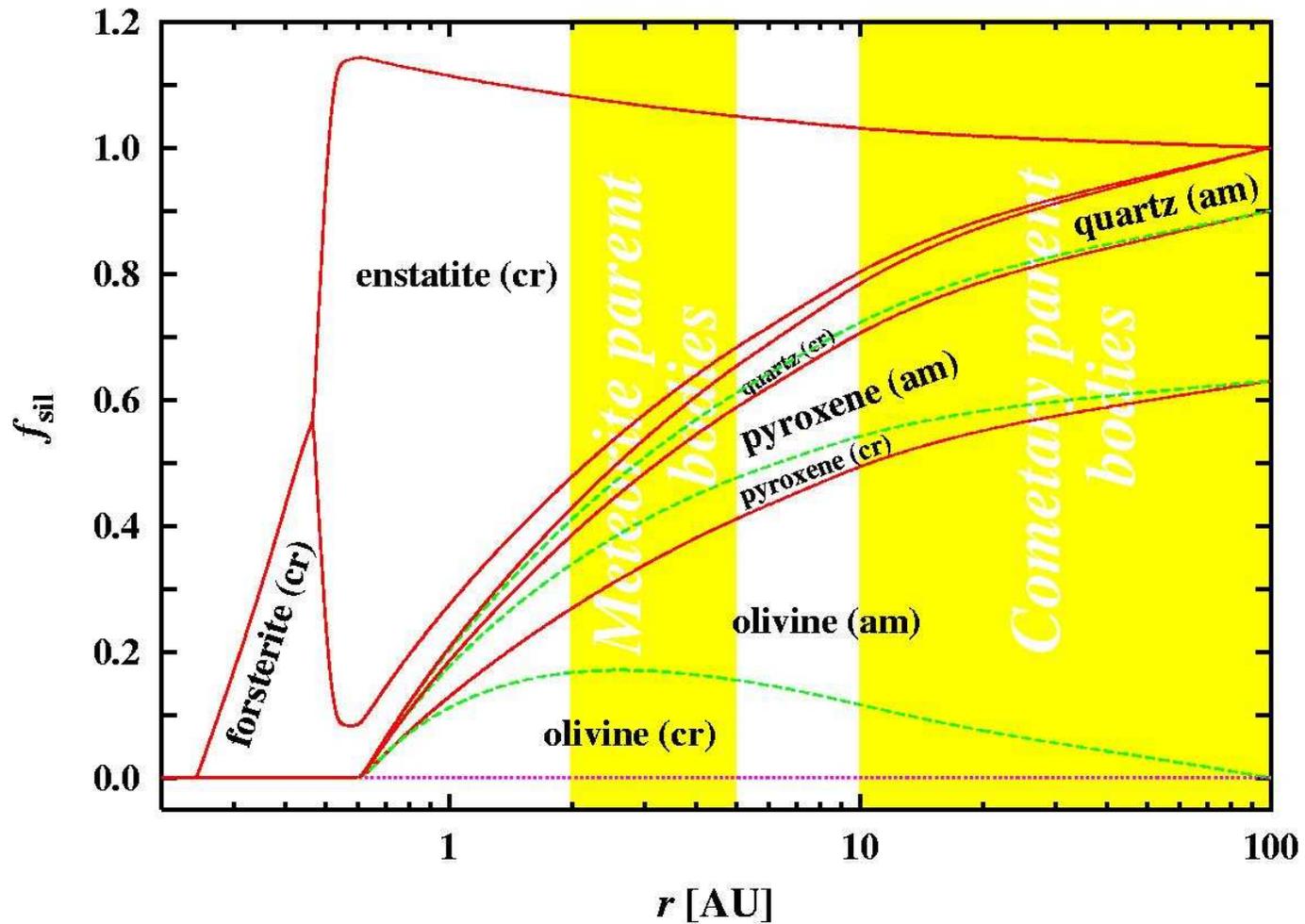


Cometary grains from comet Wild-2 returned by the STARDUST mission



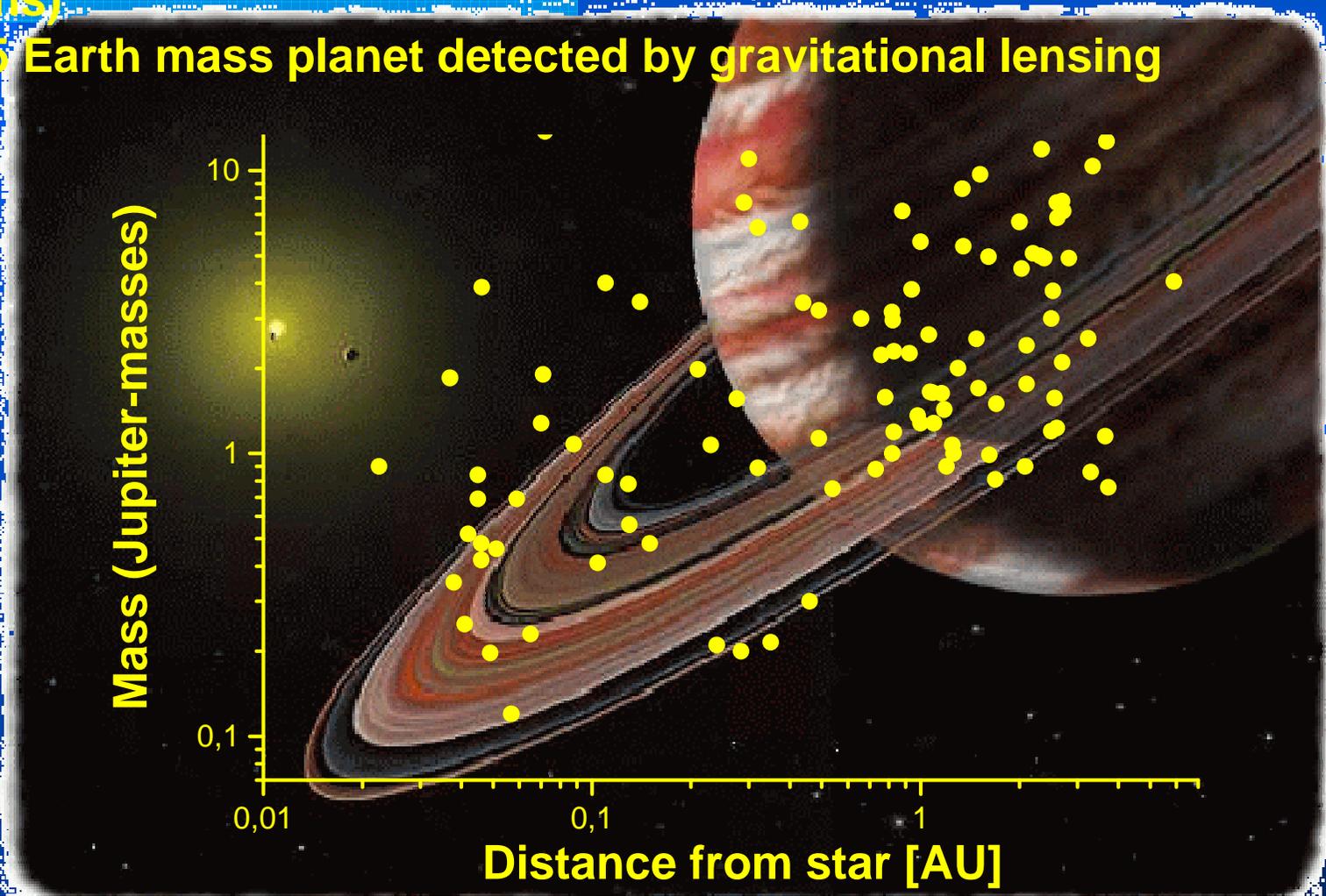
First results: Silicates (Olv, Px, Fs), glass, Fe-Ni sulfides, refractory grains (An,Di,Sp) no phyllosilicates and carbonates in Wild-2 grains

Models taking into account annealing, evaporation, and condensation of Mg silicates reproduce radial mixing of crystalline species into outer disk / comet forming regions (Gail 2003)



Planets in extrasolar systems: exotic (observationally biased), but they exist:

- 1995-2007: ~250 exoplanets found (radial velocity variations, transits)
- 2006: 5.5 Earth mass planet detected by gravitational lensing



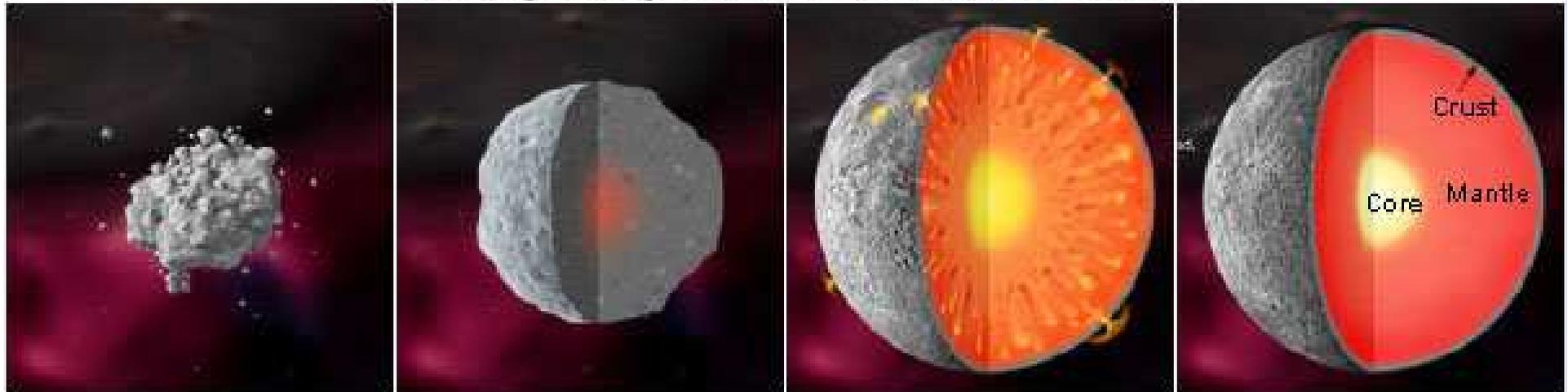
Formation of planets in our solar system 4.5 Ga ago?

Geoscientists need rocks ! → Eyewitnesses of planet formation

Problems:

- Earth rocks: available, but young
- tectonically active, suffered large scale differentiation processes
- Other planetary rocks: no sample return (except for Moon)

A Rocky Body Forms and Differentiates



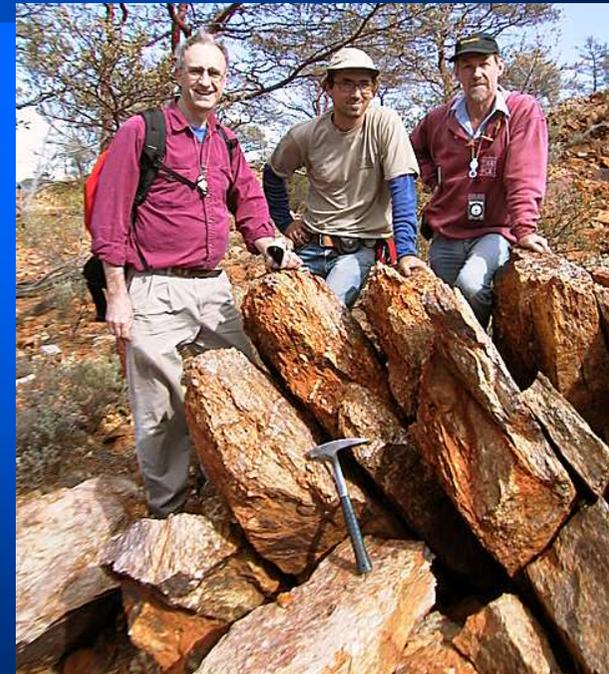
(From Smithsonian National Museum of Natural History - http://www.mnh.si.edu/earth/text/5_1_4_0.html)

Oldest rocks:
→ Isua, Greenland (3.8-3.9 Ga)

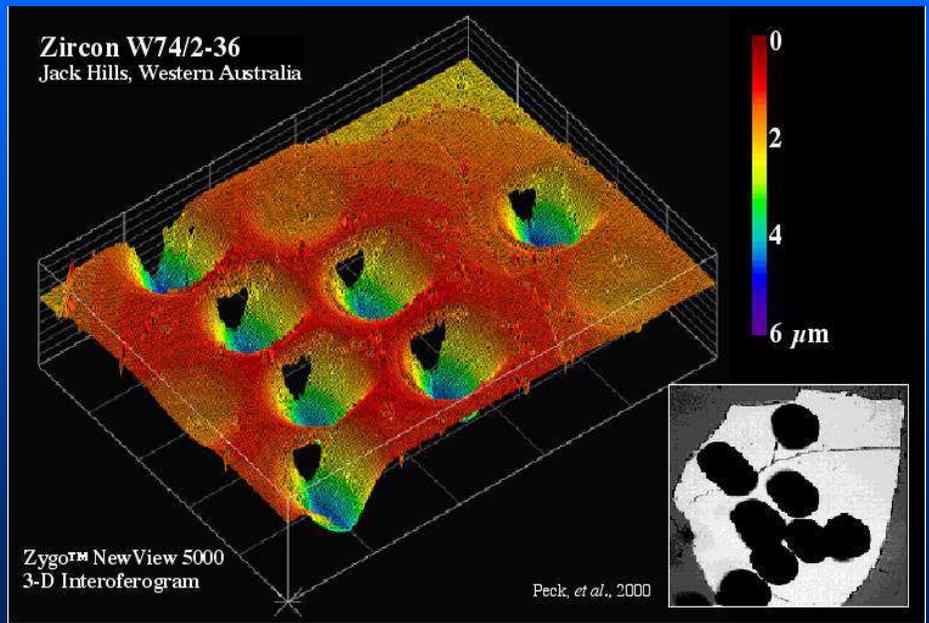
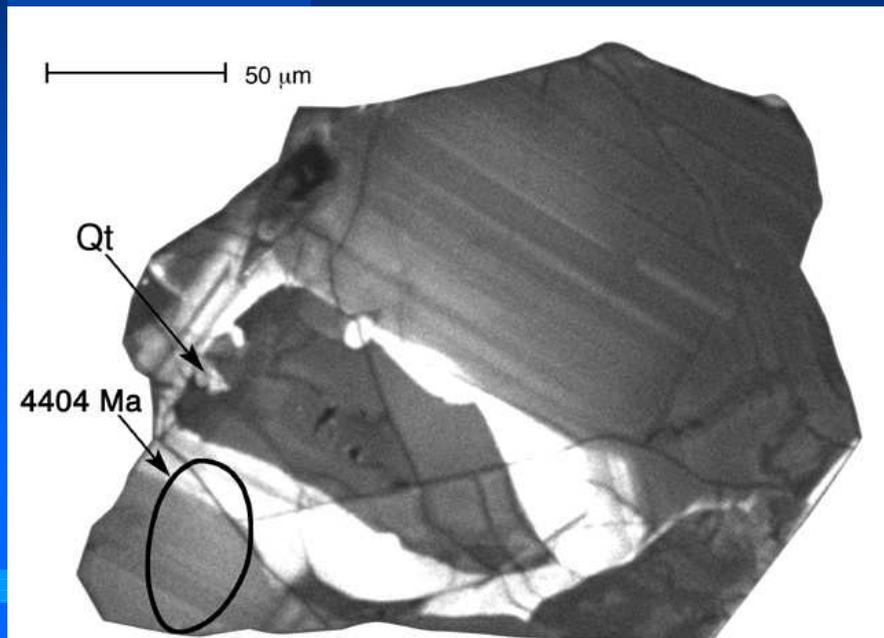




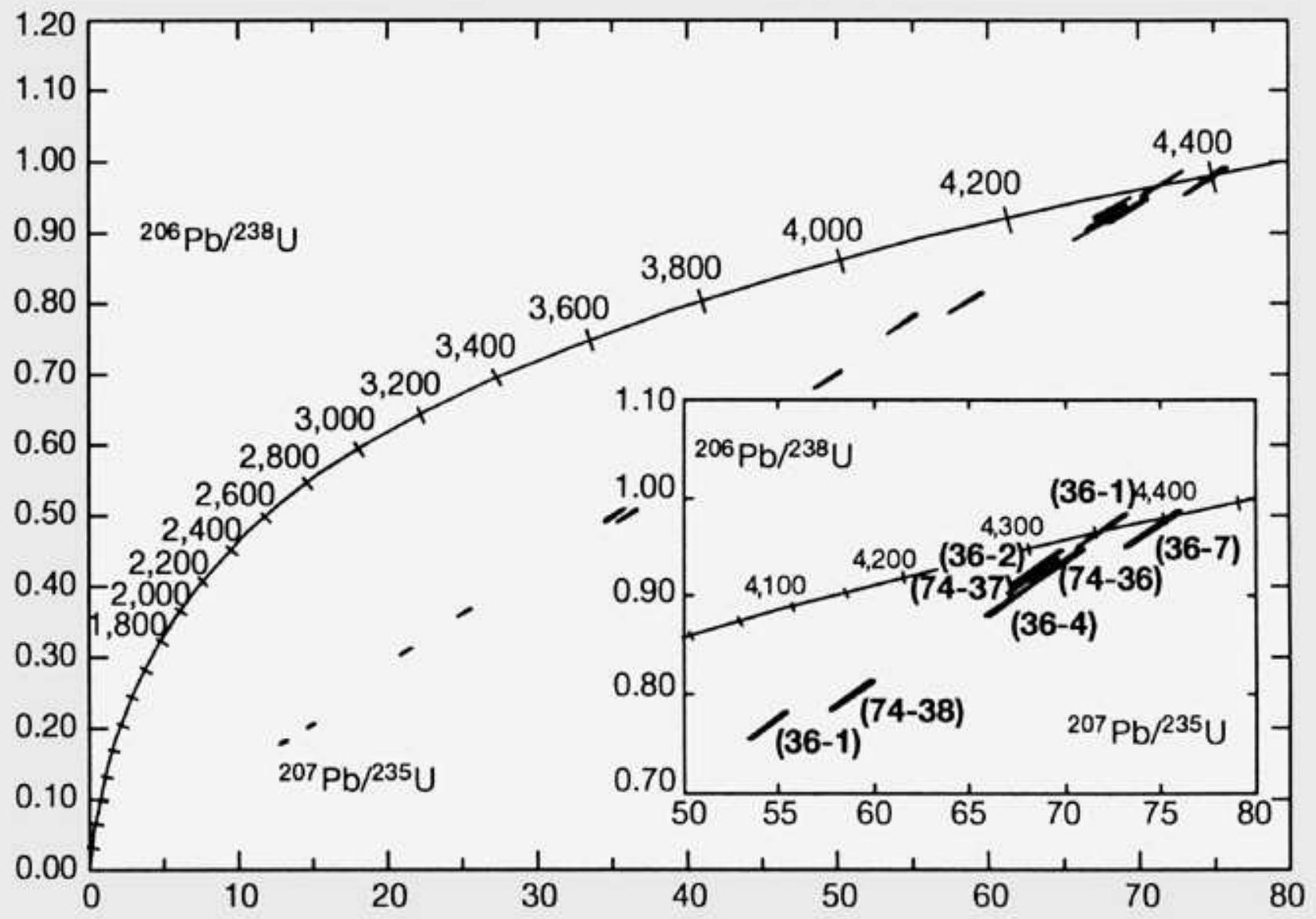
Oldest minerals:
→ Zirkons
→ Jack Hills, West Australia



U-Pb-Pb age of zircons, Jack Hills, Australia: 4404 ± 4 Ma (Peck et al., 2001; Wilde et al., 2001)



U-Pb-Pb age of zircons, Jack Hills, Australia: 4404 ± 4 Ma (Peck et al., 2001; Wilde et al., 2001)



Formation of planets in our solar system 4.5 Ga ago?

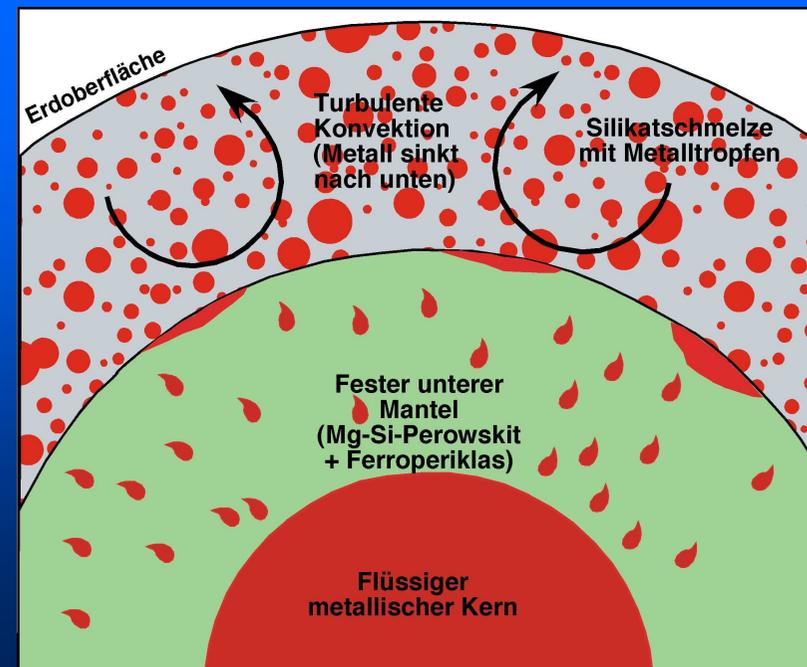
Geoscientists need rocks ! → Eyewitnesses of planet formation

Problems:

- Earth rocks: available, but young (generally < 3.8 Ga, zircons up to 4.4 Ga)
- Planetary rocks: no sample return (except for Moon)
- Even if rocks from other terrestrial planets are available, most probably they are not remnants of early stages of protoplanet formation, as these did not survive early energetic large scale planetary differentiation processes (core formation, mantle-crust differentiation)

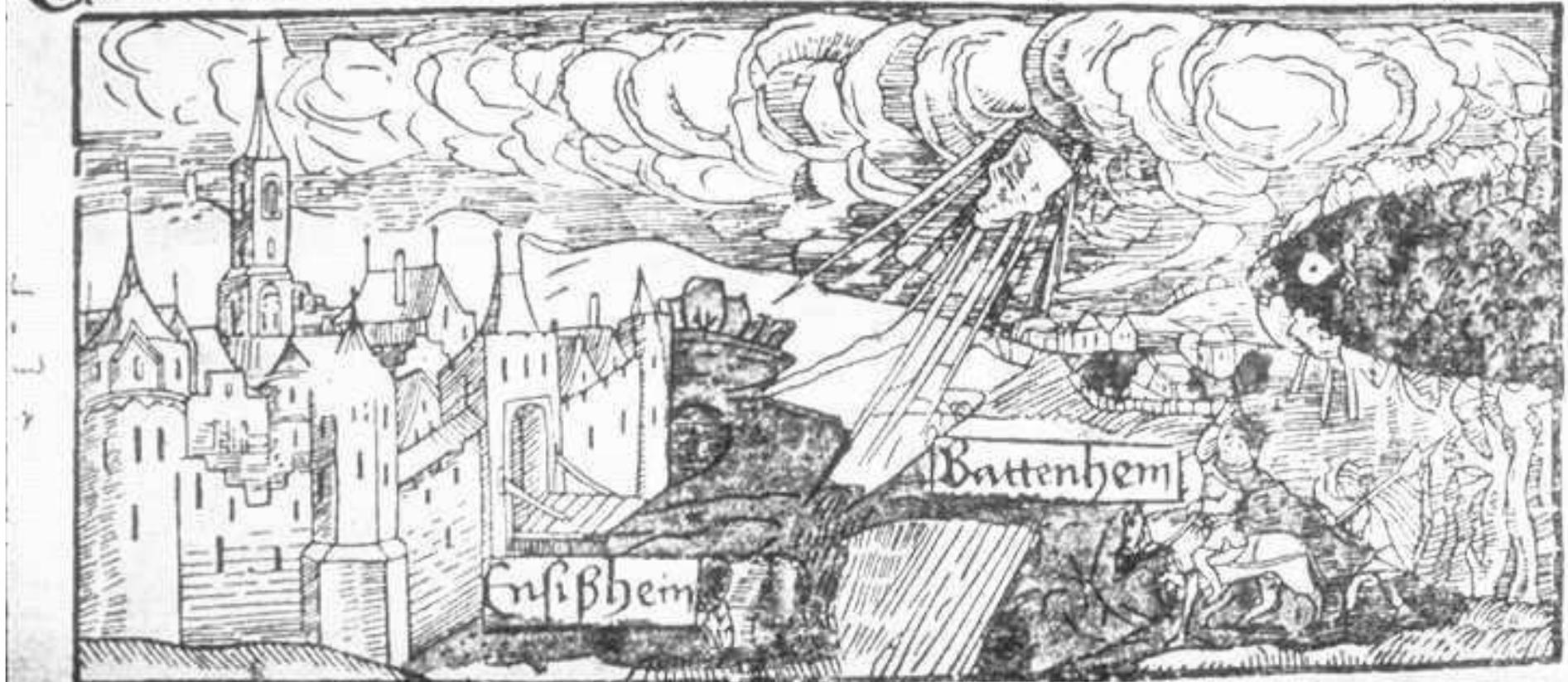
Solution: *Meteorites*

- samples from small planetesimals that escaped energetic planetary formation / differentiation processes



1492: Stony meteorite Ensisheim

Von dem donnerstein gefallē im ¹⁴92^{er} jar: vor Ensisheim



1492: Stony meteorite Ensisheim



1492: Stony meteorite Ensisheim



**Hans Baldung Grien:
The conversion of Saulus
(1505)**



Location:

Pittsburgh, PA

©Tom Reinheimer,

247 Hallock St.,

Pittsburgh, PA

USA

15211

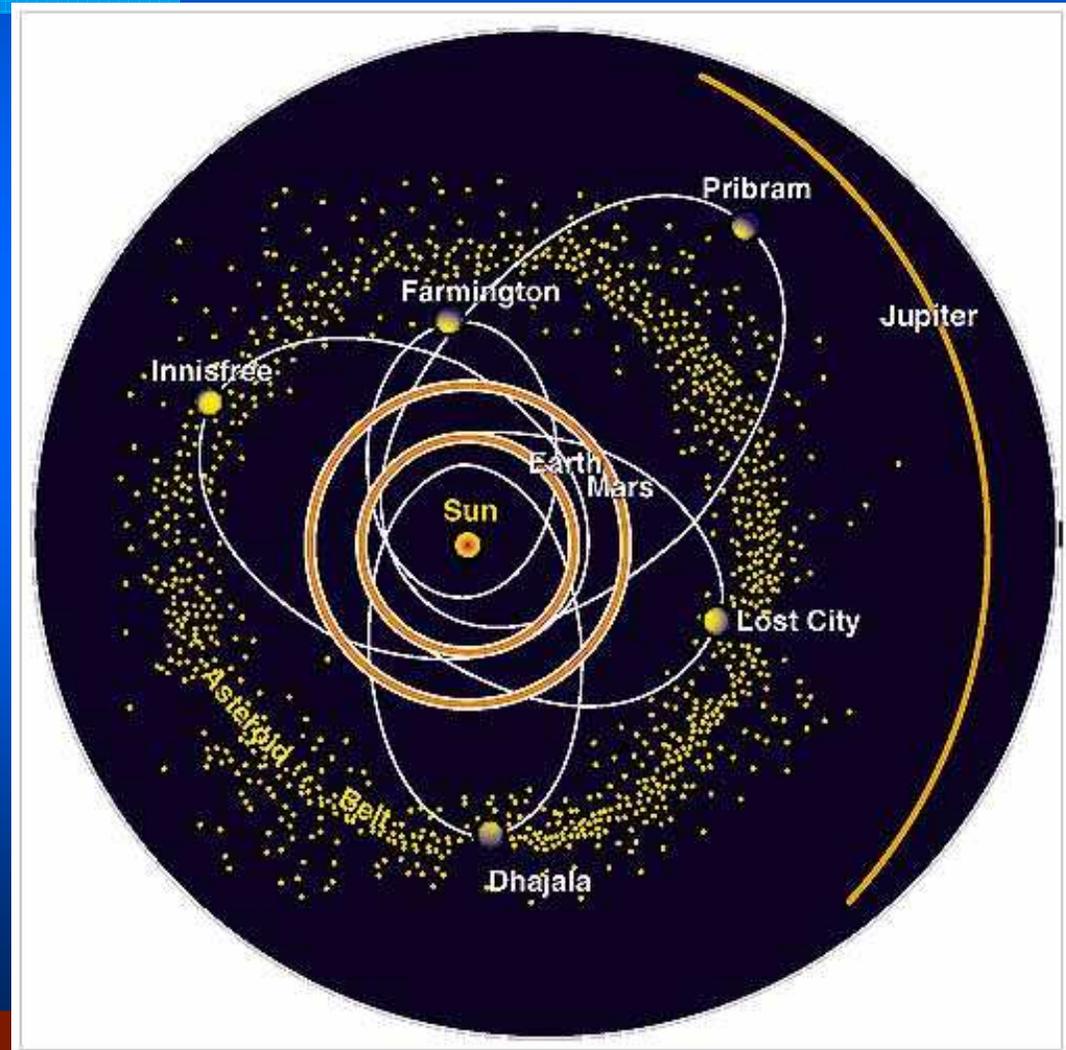
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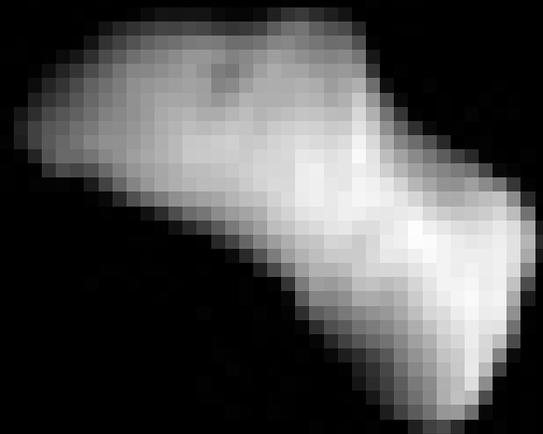




Meteorites: Fragments of small bodies in the solar system, the asteroids between Mars and Jupiter

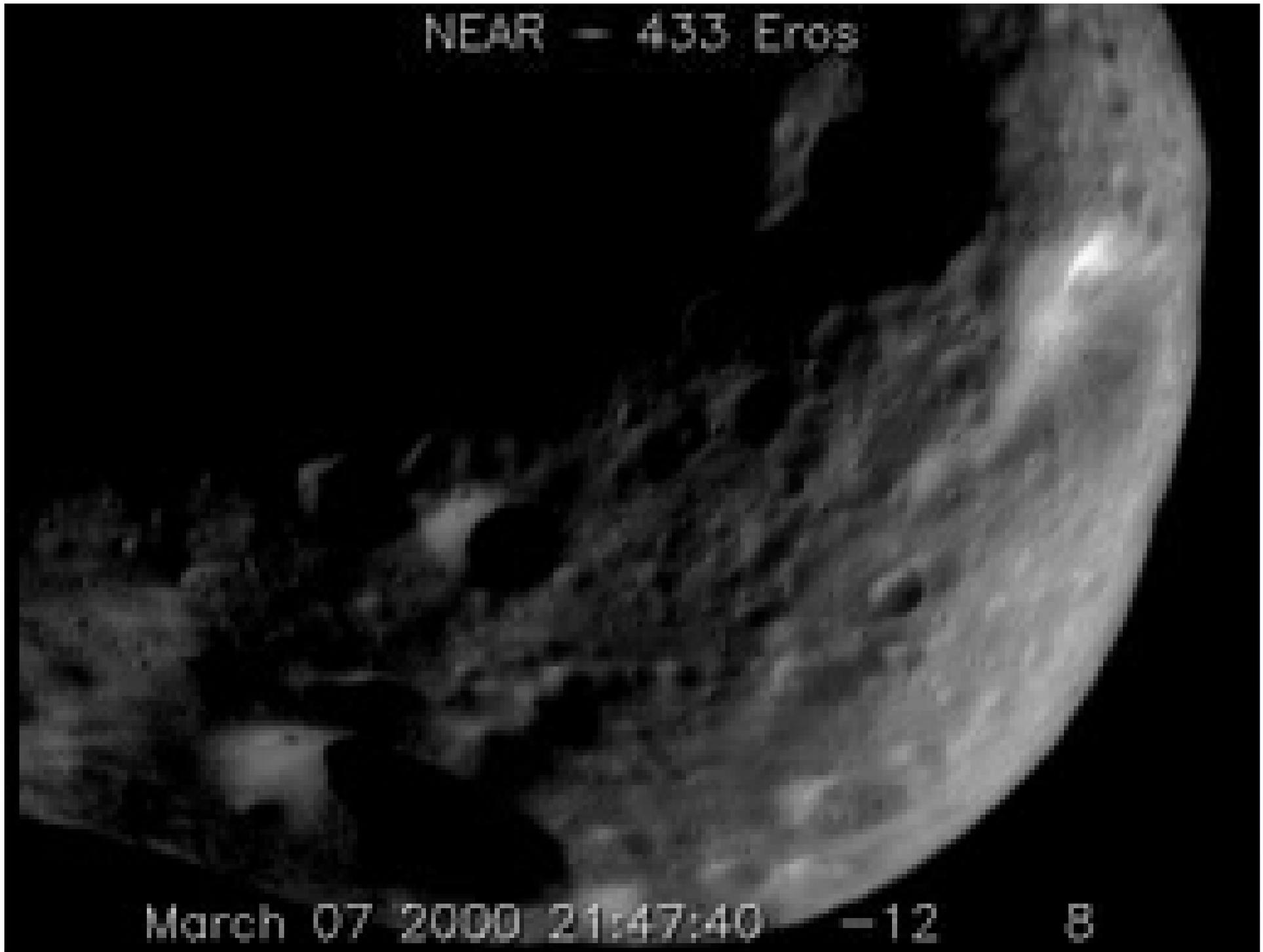
Inferred number of parent bodies is >100 (accretion to full-sized planet inhibited by early Jupiter?!)





Feb 6 2000 02:00:00

NEAR - 433 Eros

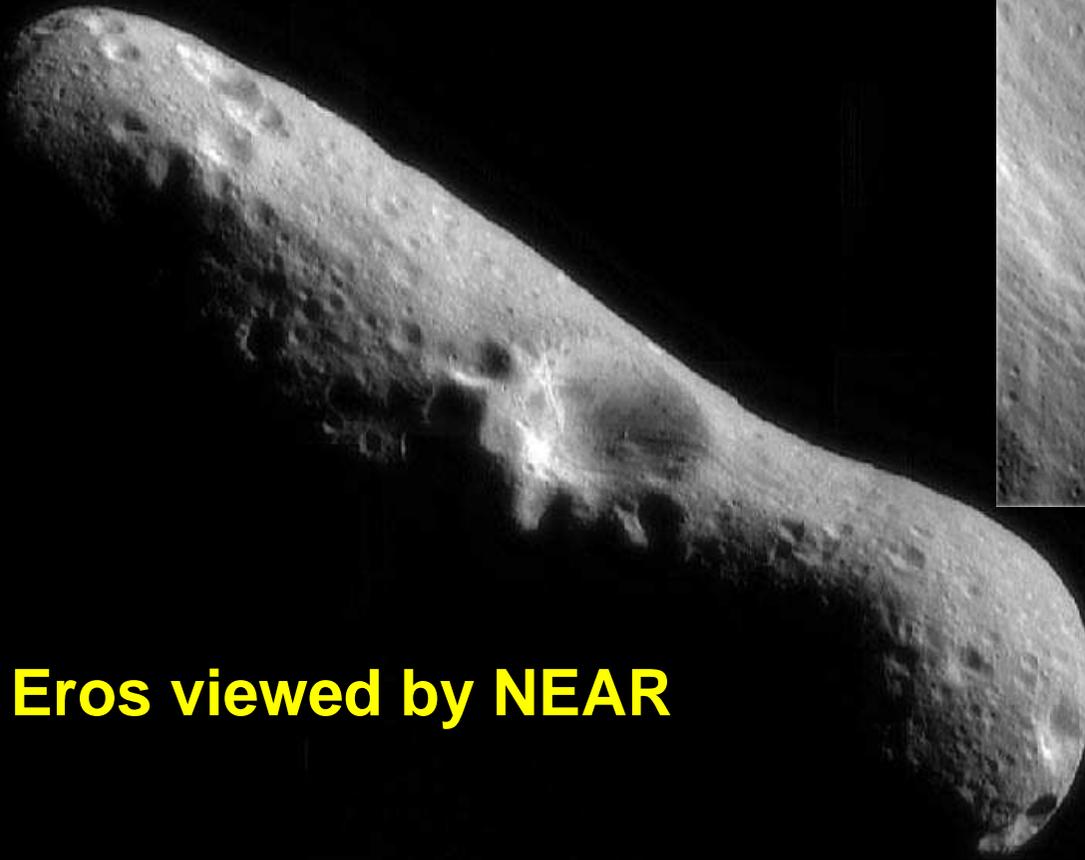


March 07 2000 21:47:40 -12 8

Problem: recognition of early processes through secondary effects of collisions and impact cratering (shock metamorphism, reheating, disturbance of radiometric clocks, etc.)



Eros viewed by NEAR

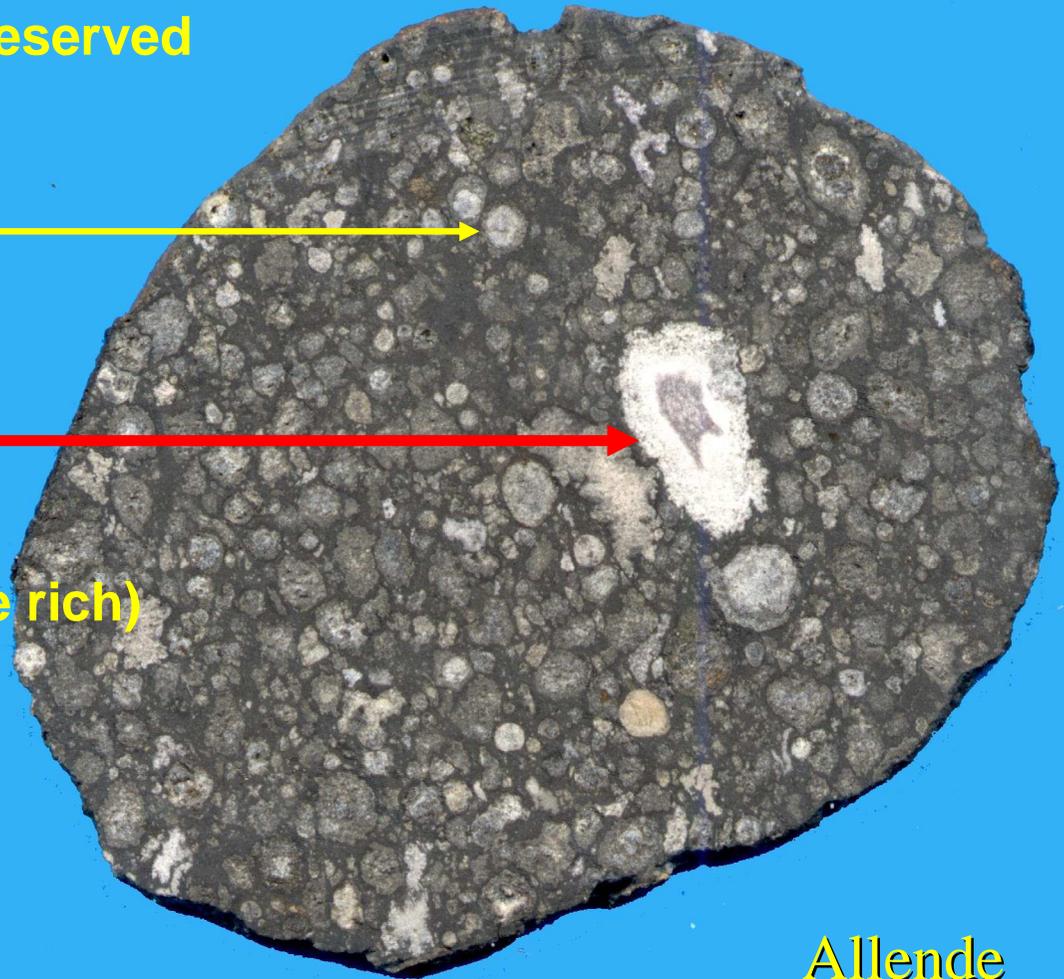


Carbonaceous chondrites (CI, CM, CV, CO, ...): (mild thermal/aqueous metamorphism)

→ undifferentiated, e.g.
preaccretional structures preserved

- Chondrules
- Ca,Al-rich inclusions
- Fine grained matrix (volatile rich)

→ undifferentiated, e.g.
'cosmic' Fe,Ni abundance



Allende

Variation of oxidation state and metal abundance demonstrates compositional variety of undifferentiated planetary bodies

Ordinary chondrites:

H: high Fe

L: Low Fe

LL: Low total, low metallic Fe

Enstatite chondrites

Carbonaceous chondrites:
named after main member

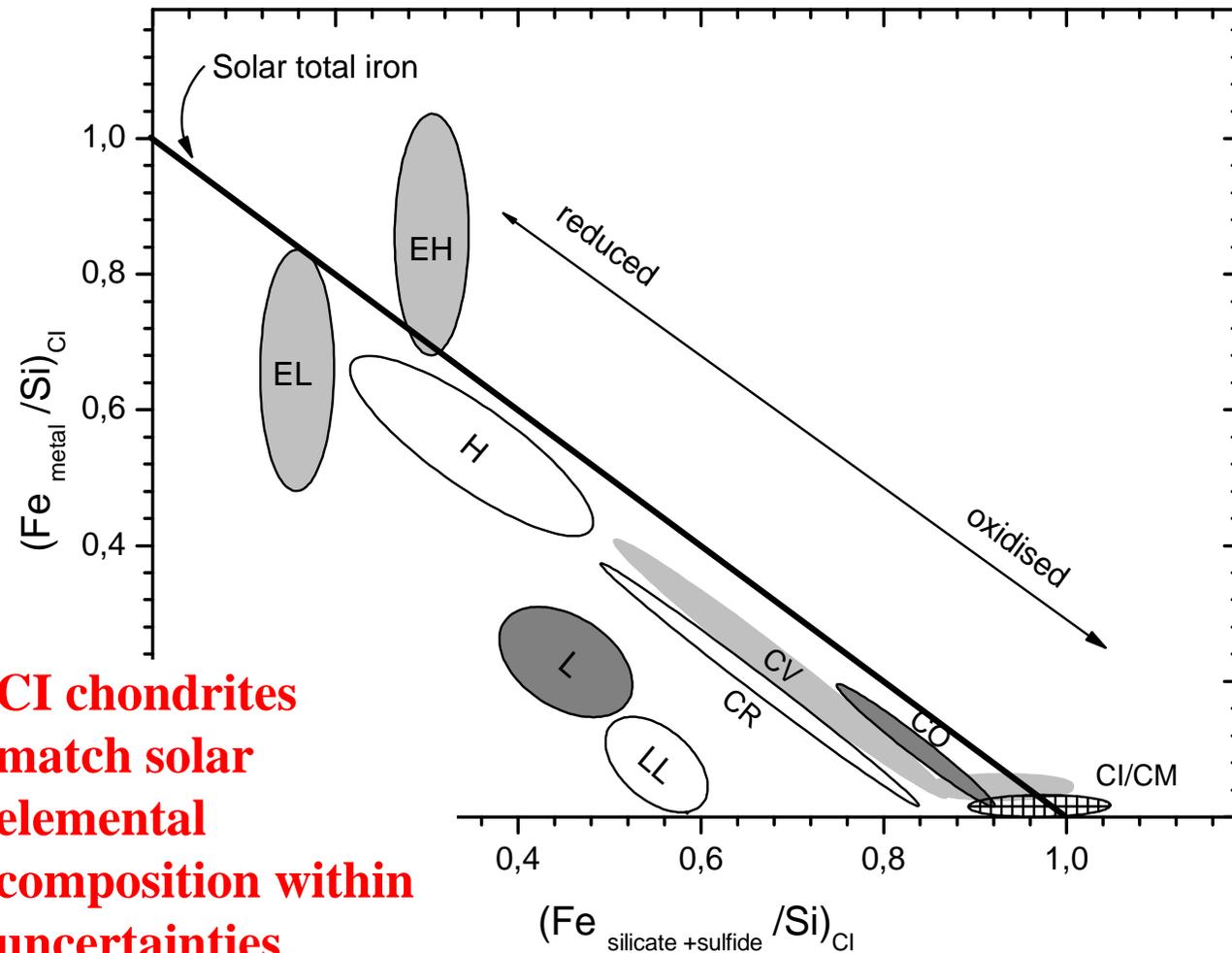
CI (Ivuna) →

CM (Mighei)

CV (Vigarano)

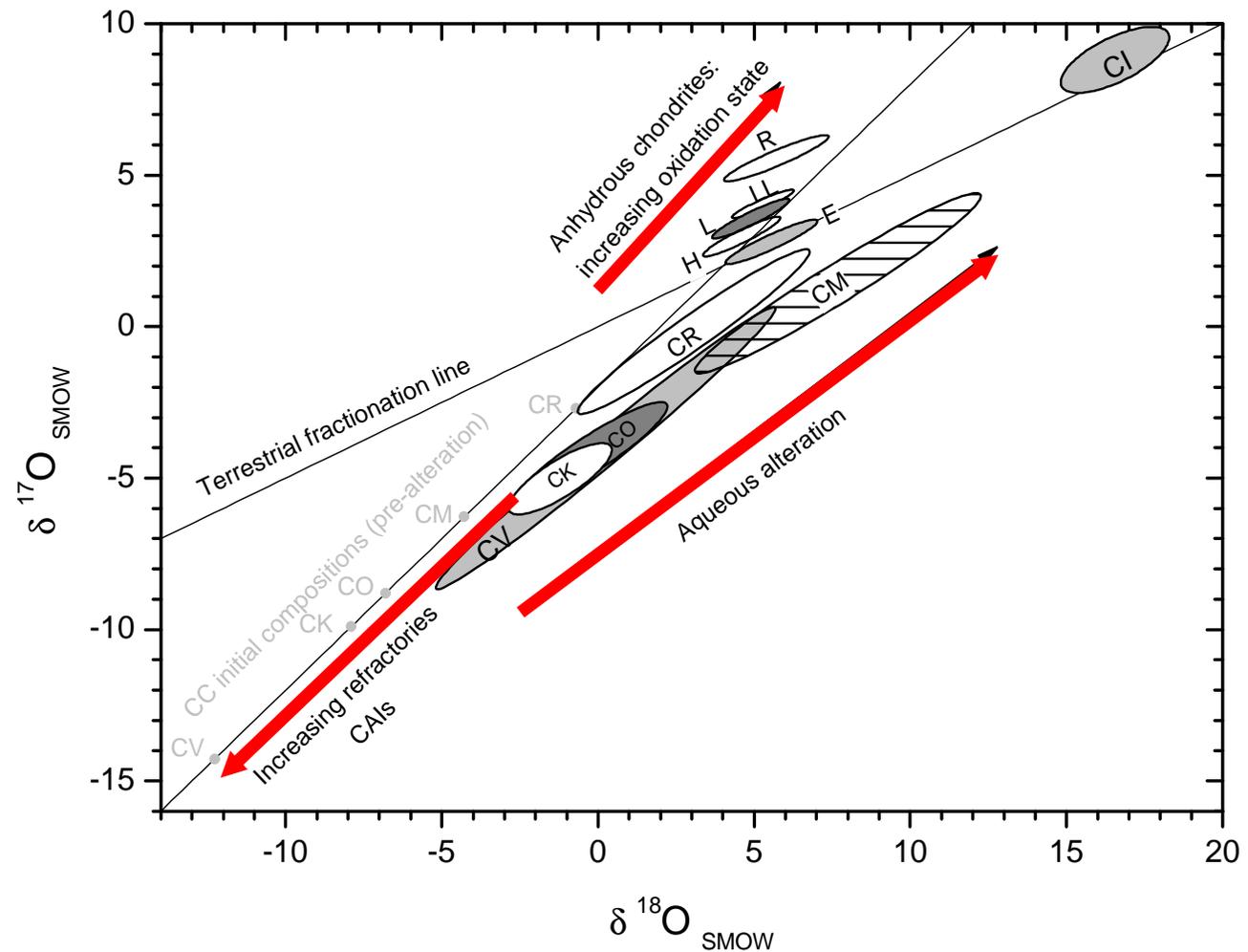
CO (Ornans)

CI chondrites match solar elemental composition within uncertainties



Variation of oxygen isotopic composition demonstrates variety of undifferentiated planetary bodies

Reason of ^{16}O enrichment in carbonaceous chondrite anhydrous minerals: Disk chemistry or presolar oxides?



**Carbonaceous chondrites (CI, CM, CV, CO, ...):
(mild thermal/aqueous metamorphism) → preaccretional structures
preserved**

4564.7 ± 0.6 Ma

(CR Acfer059;
Amelin et al., 2002)

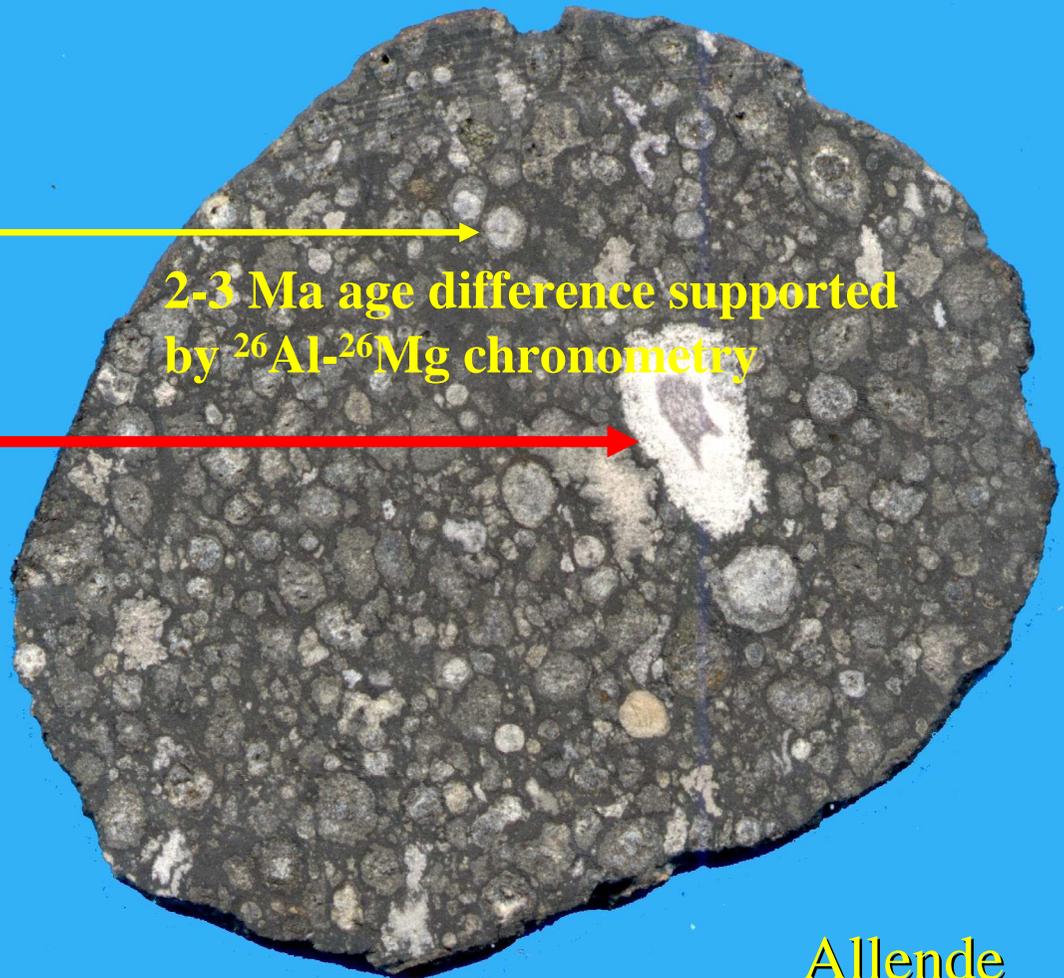
- **Chondrules**

2-3 Ma age difference supported
by ^{26}Al - ^{26}Mg chronometry

- **Ca,Al-rich inclusions**

4567.2 ± 0.6 Ma

(U-Pb-Pb, CV Efremovka;
Amelin et al., 2002)



Allende

**Carbonaceous chondrites (CI, CM, CV, CO, ...):
(mild thermal/aqueous metamorphism) → preaccretional structures
preserved**

4564.7 ± 0.6 Ma

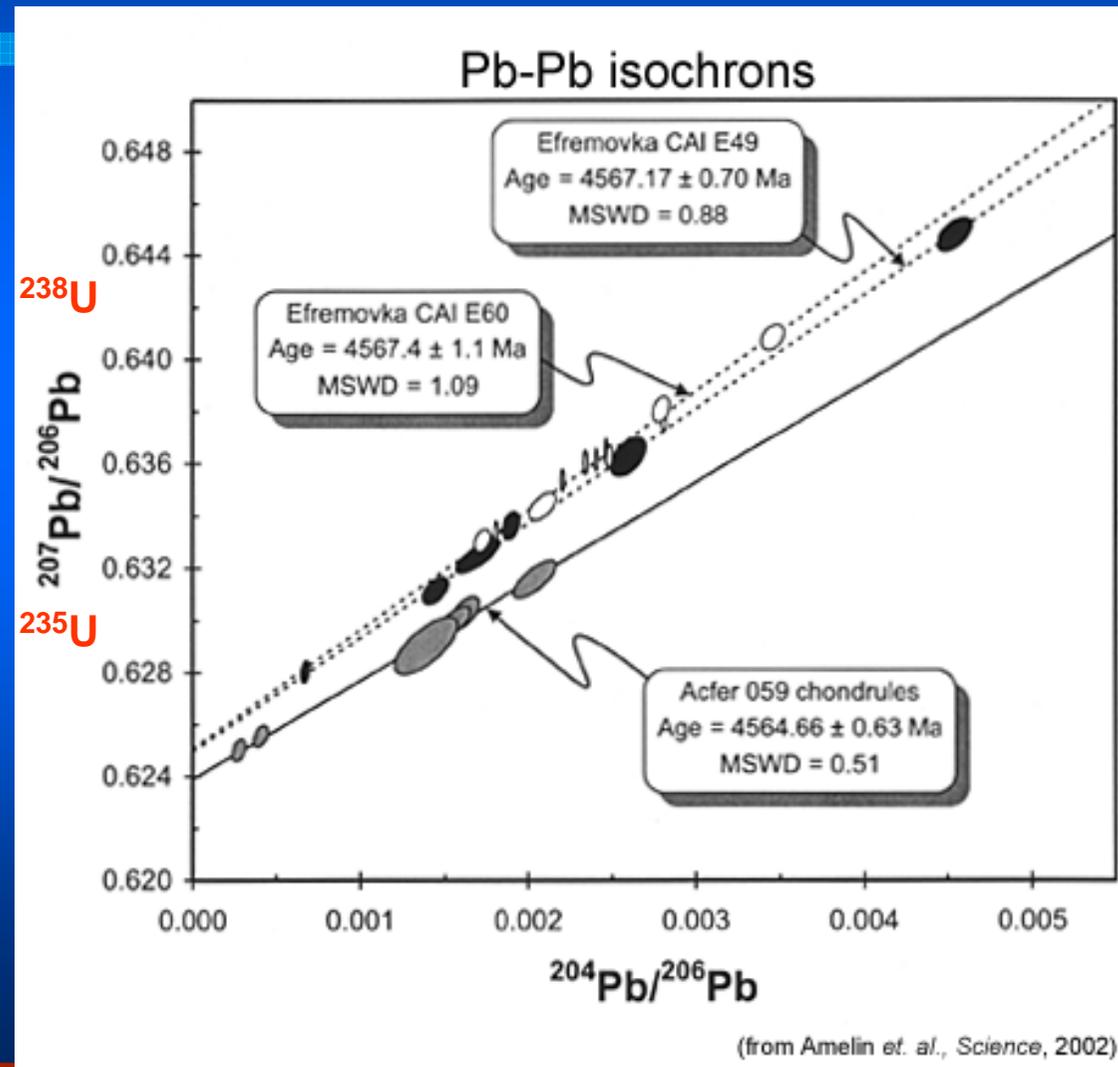
**(CR Acfer059;
Amelin et al., 2002)**

• **Chondrules**

• **Ca,Al-rich inclusions**

4567.2 ± 0.6 Ma

**(U-Pb-Pb, CV Efremovka;
Amelin et al., 2002)**



Zoned type B1 CAI from
Leoville (CV)

Fassaite (Ti-rich diopside)

Melilite

Anorthite

Melilite

Fassaite

Anorthite

200µm

MAG = 78 X

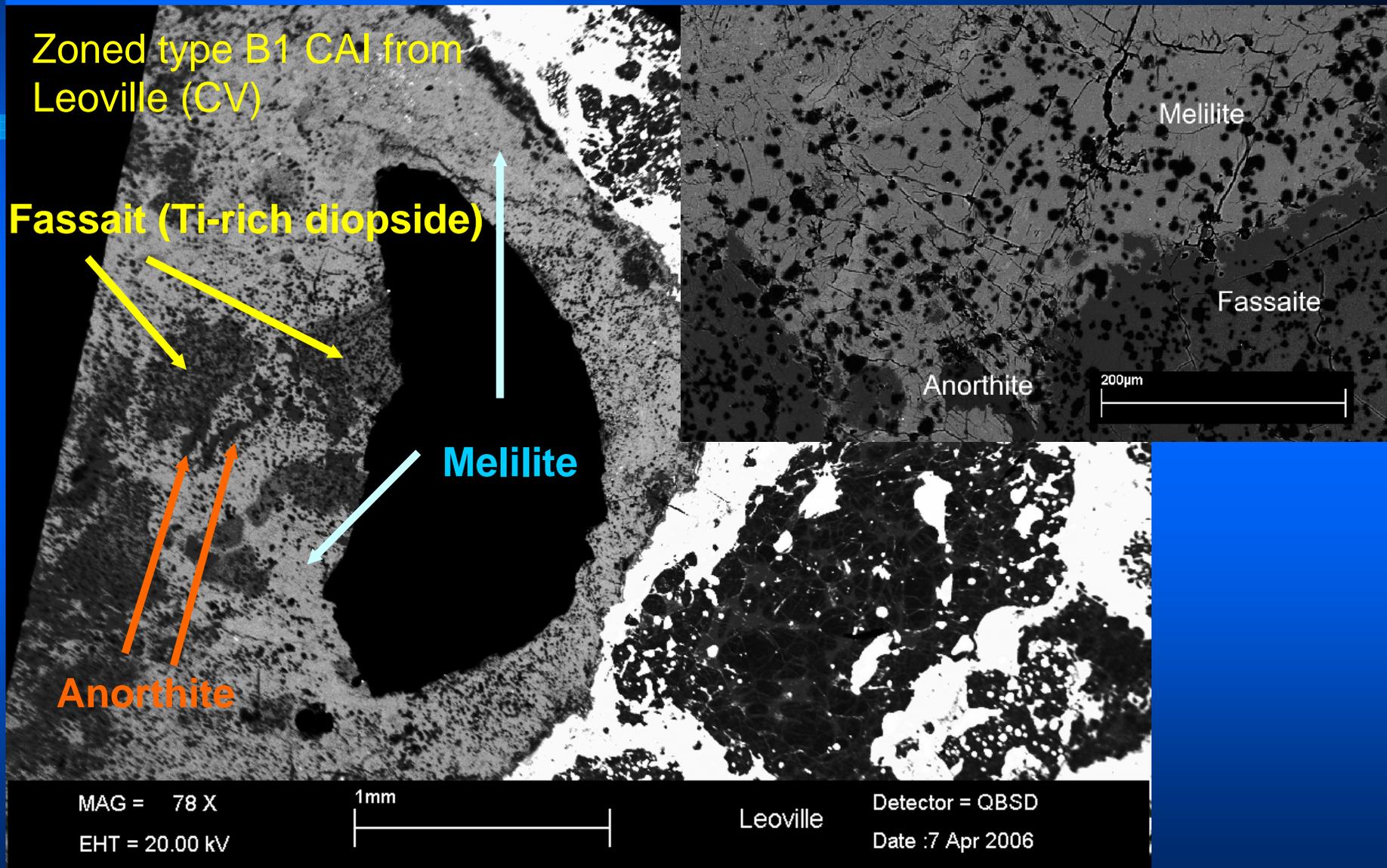
EHT = 20.00 kV

1mm

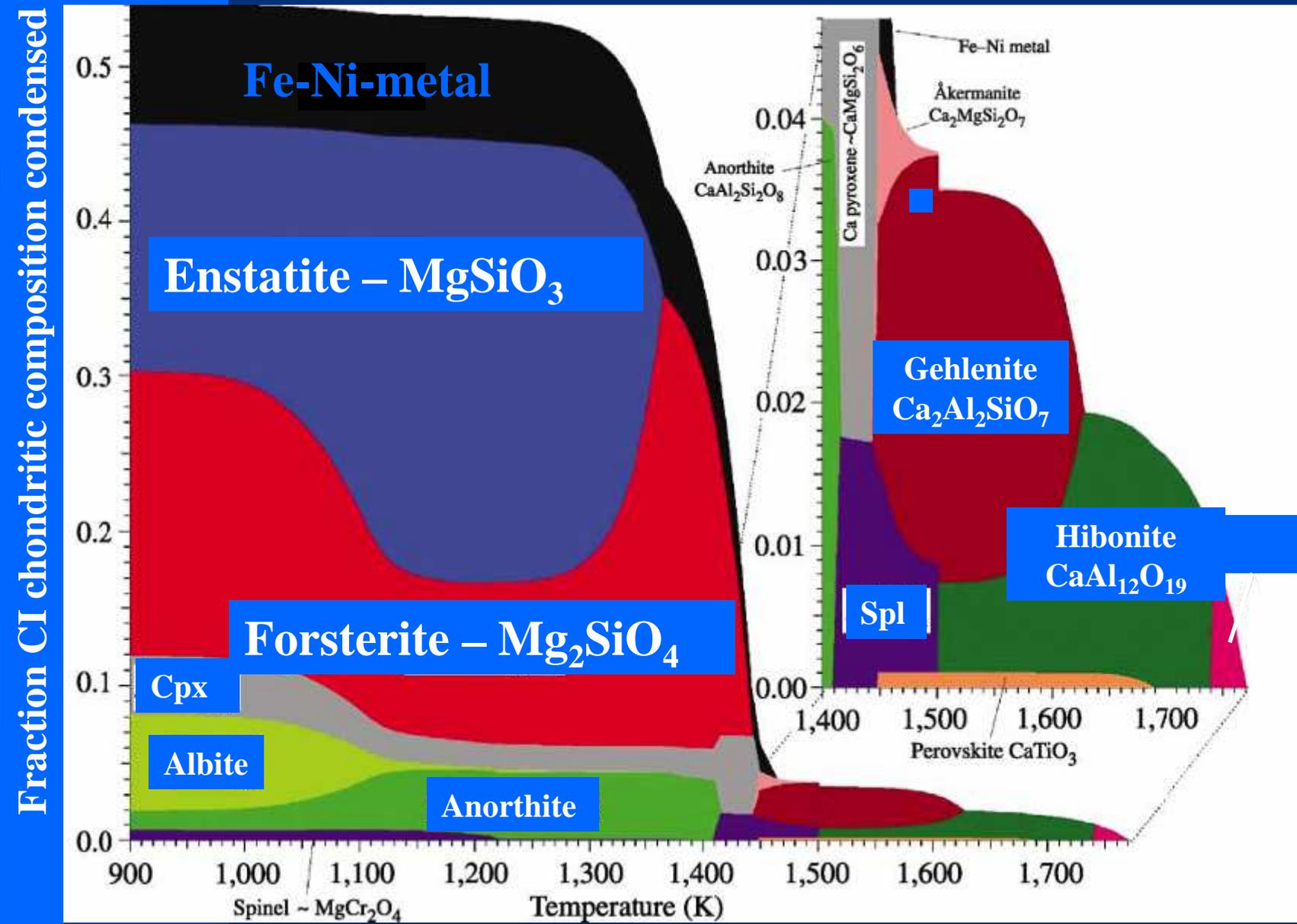
Leoville

Detector = QBSD

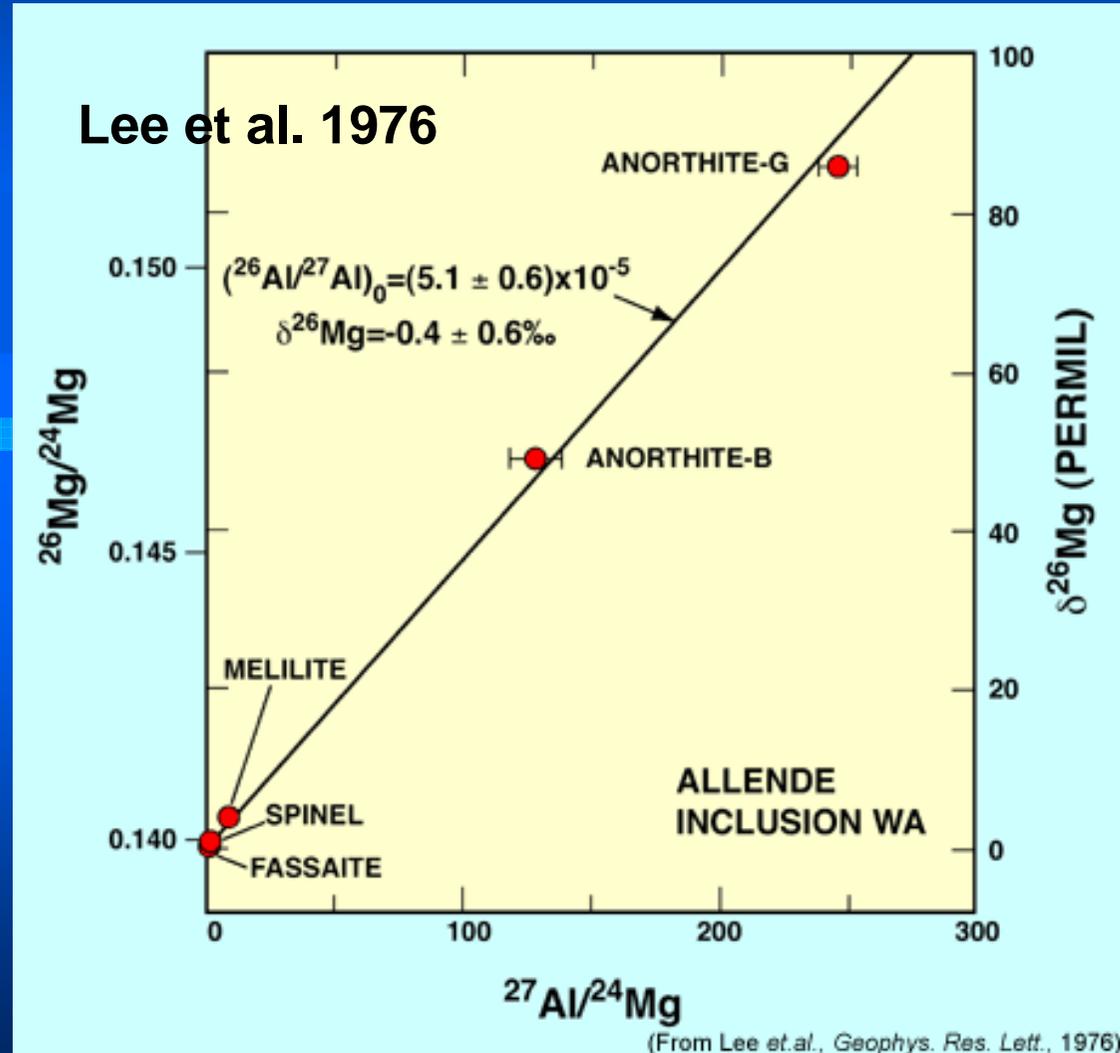
Date : 7 Apr 2006



Condensation sequence of minerals in a cooling solar nebula:
 Ca,Al minerals important high temperature condensates

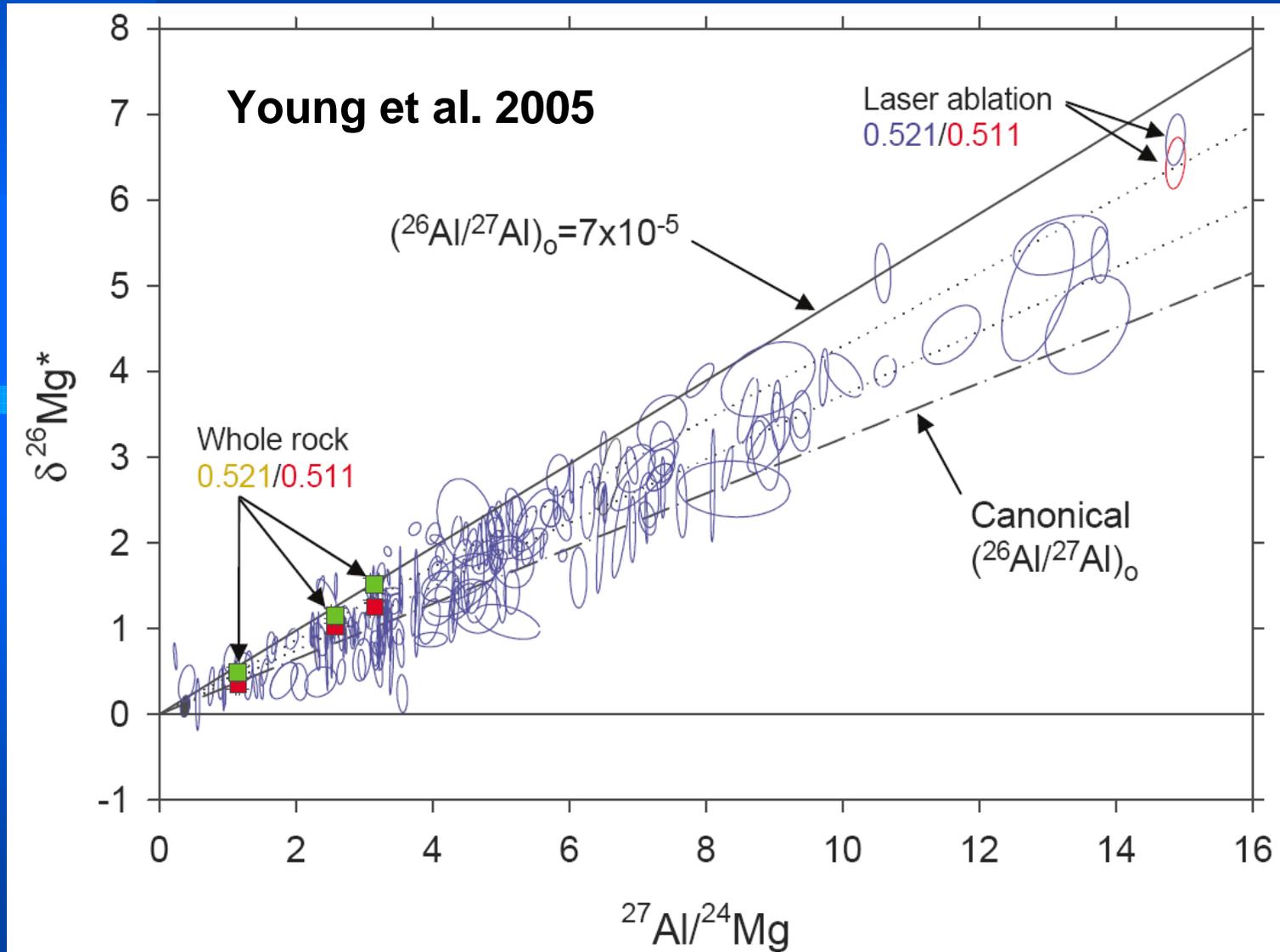


**Ca,Al-rich Inclusions: refractory mineral assemblages, oldest solar system objects $\rightarrow 4567.2 \pm 0.6$ Ma (Amelin et al., 2002)
 \rightarrow contain excess ^{26}Mg from decay of short-lived ^{26}Al**



Ca,Al-rich Inclusions: refractory mineral assemblages, oldest solar system objects → 4567.2± 0.6 Ma (Amelin et al., 2002)

^{26}Al - ^{26}Mg systematics: Processing within few 0.1 Ma



Trapezium (Orion nebula)

Short-lived nuclides in the early solar system and their half-lives:

$^{26}\text{Al} \rightarrow ^{26}\text{Mg}$ (0.72 Ma)

$^{129}\text{I} \rightarrow ^{129}\text{Xe}$ (16 Ma)

$^{182}\text{Hf} \rightarrow ^{182}\text{W}$ (9 Ma)

$^{53}\text{Mn} \rightarrow ^{53}\text{Cr}$ (3.7 Ma)

$^{244}\text{Pu} \rightarrow \text{fission}$ (80 Ma)

$^{10}\text{Be} \rightarrow ^{10}\text{B}$ (1.5 Ma)

$^{41}\text{Ca} \rightarrow ^{41}\text{K}$ (0.1 Ma)

$^{60}\text{Fe} \rightarrow ^{60}\text{Ni}$ (1.5 Ma)

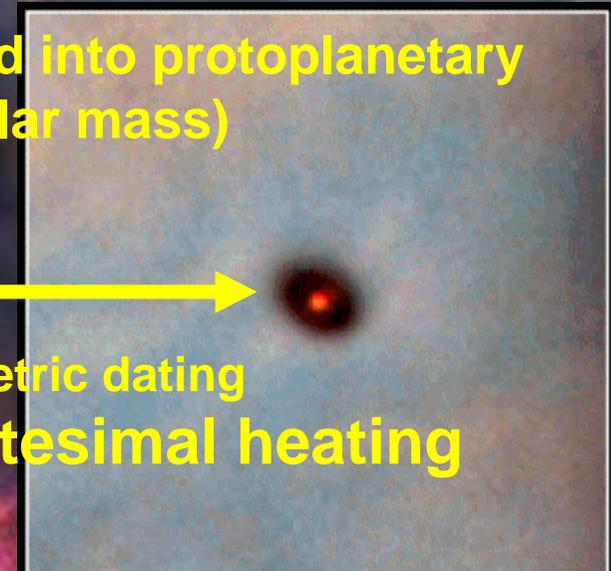
... injected into protoplanetary disks (solar mass)

→ Radiometric dating

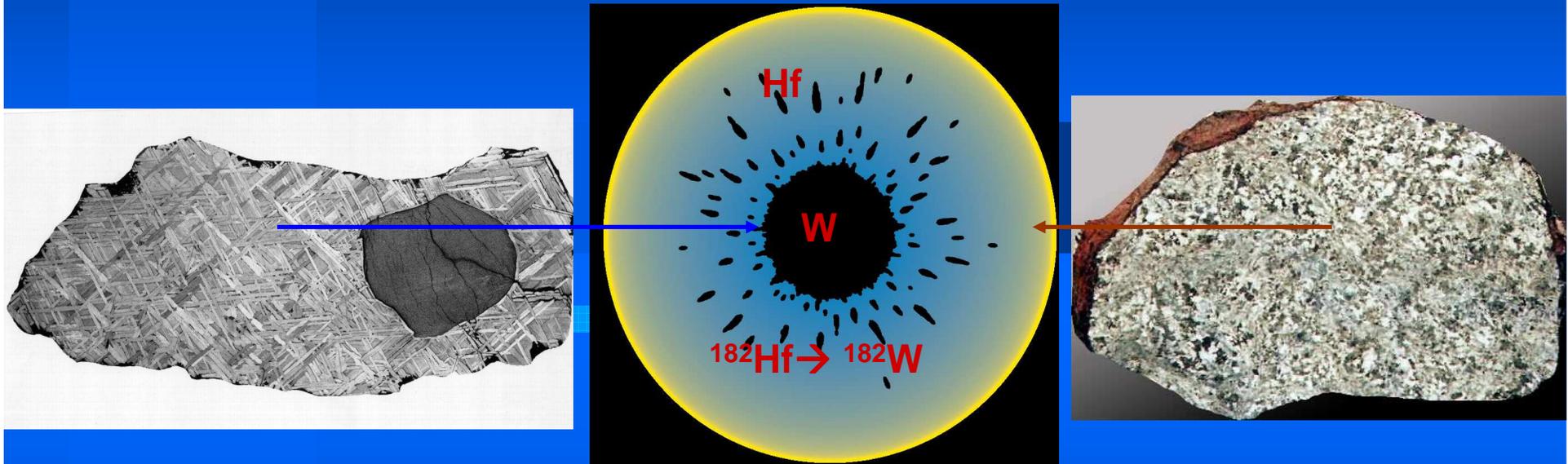
→ Planetesimal heating

... nucleosynthesis in mass-rich stars

... or nuclear reactions due to solar irradiation (^{10}Be)



Early formed asteroids: high abundance of ^{26}Al , strongest heating effects → Differentiated meteorites: from metallic cores and silicate mantles and crusts of differentiated asteroids

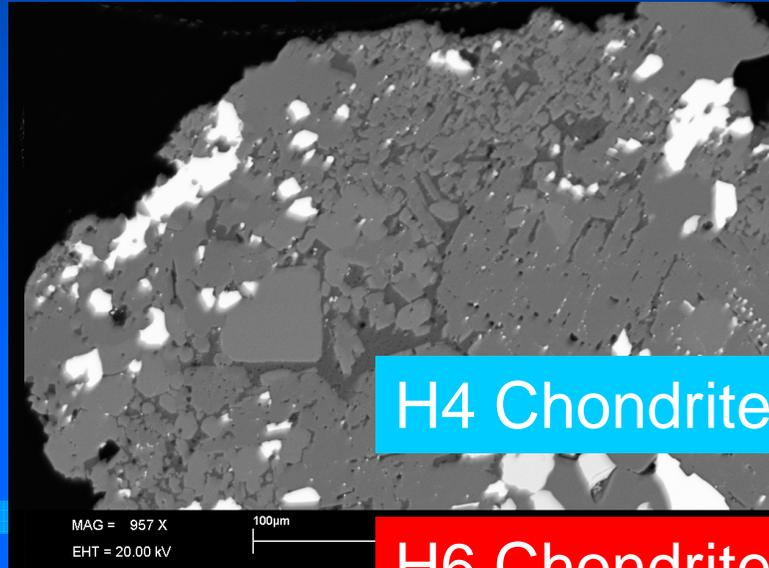


Fast accretion and differentiation

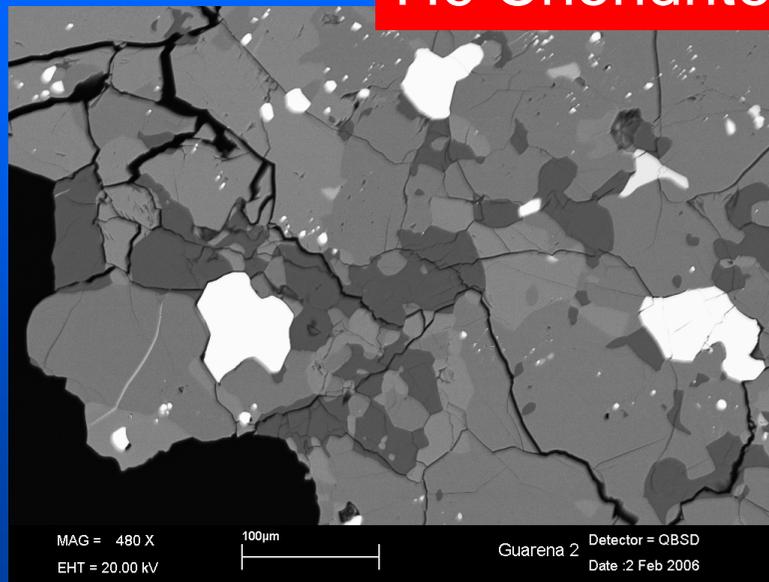
→ formation of metallic cores contemporaneously with CAIs (^{182}Hf - ^{182}W ; Kleine et al., 2004; Schersten et al. 2004)

→ formation and cooling of basaltic crust within few Ma (Eucrites, Angrites: Pb-Pb-dating; e.g. Lugmair and Galer, 1992; Baker et al., 2005)

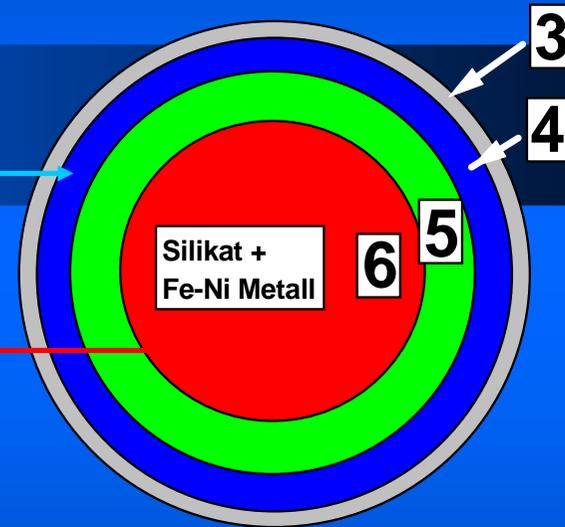
Ordinary chondrites (H, L, LL): significant thermal metamorphism by ^{26}Al decay heat

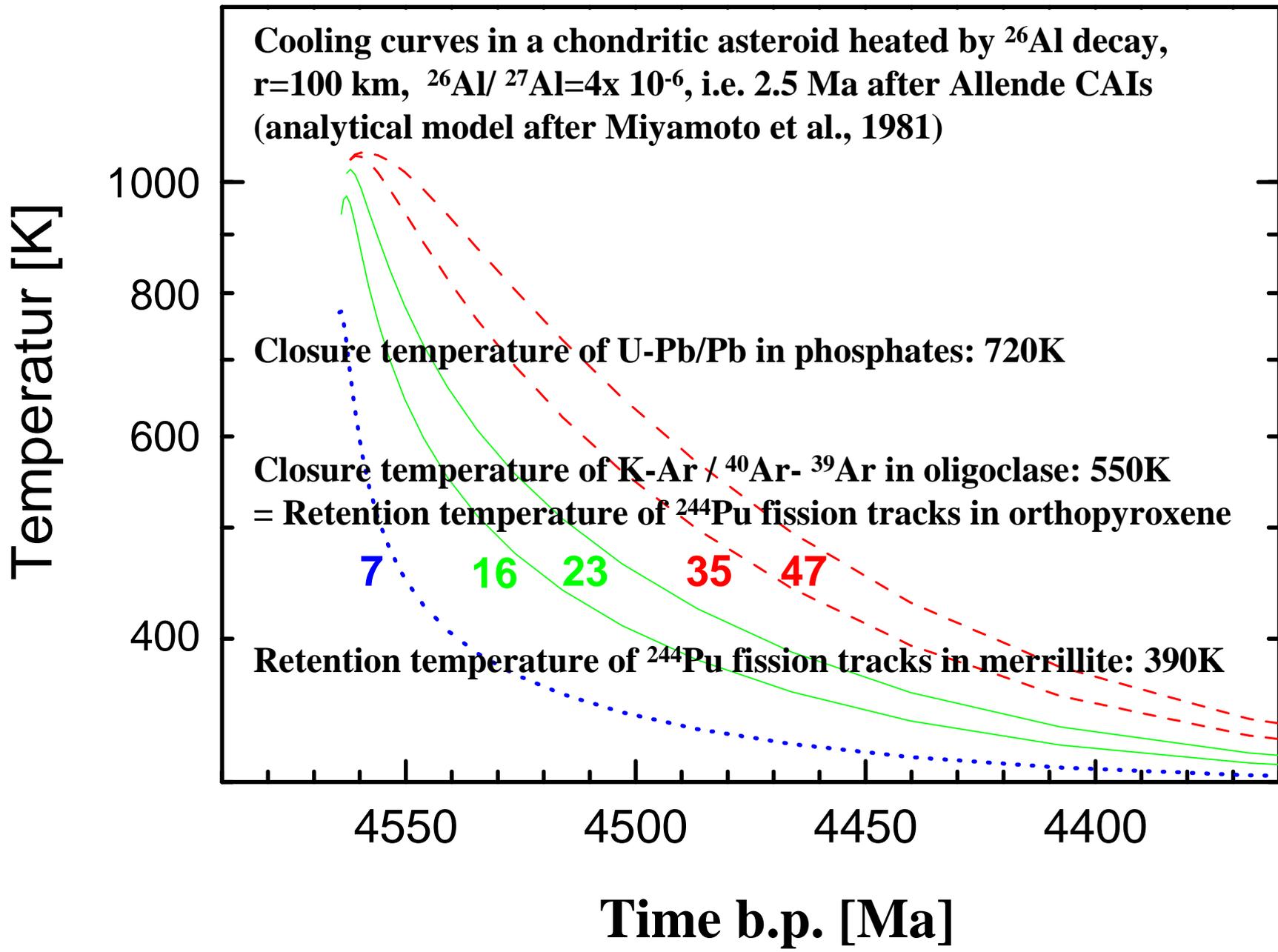


H4 Chondrite (~650°C)



H6 Chondrite (~850°C)

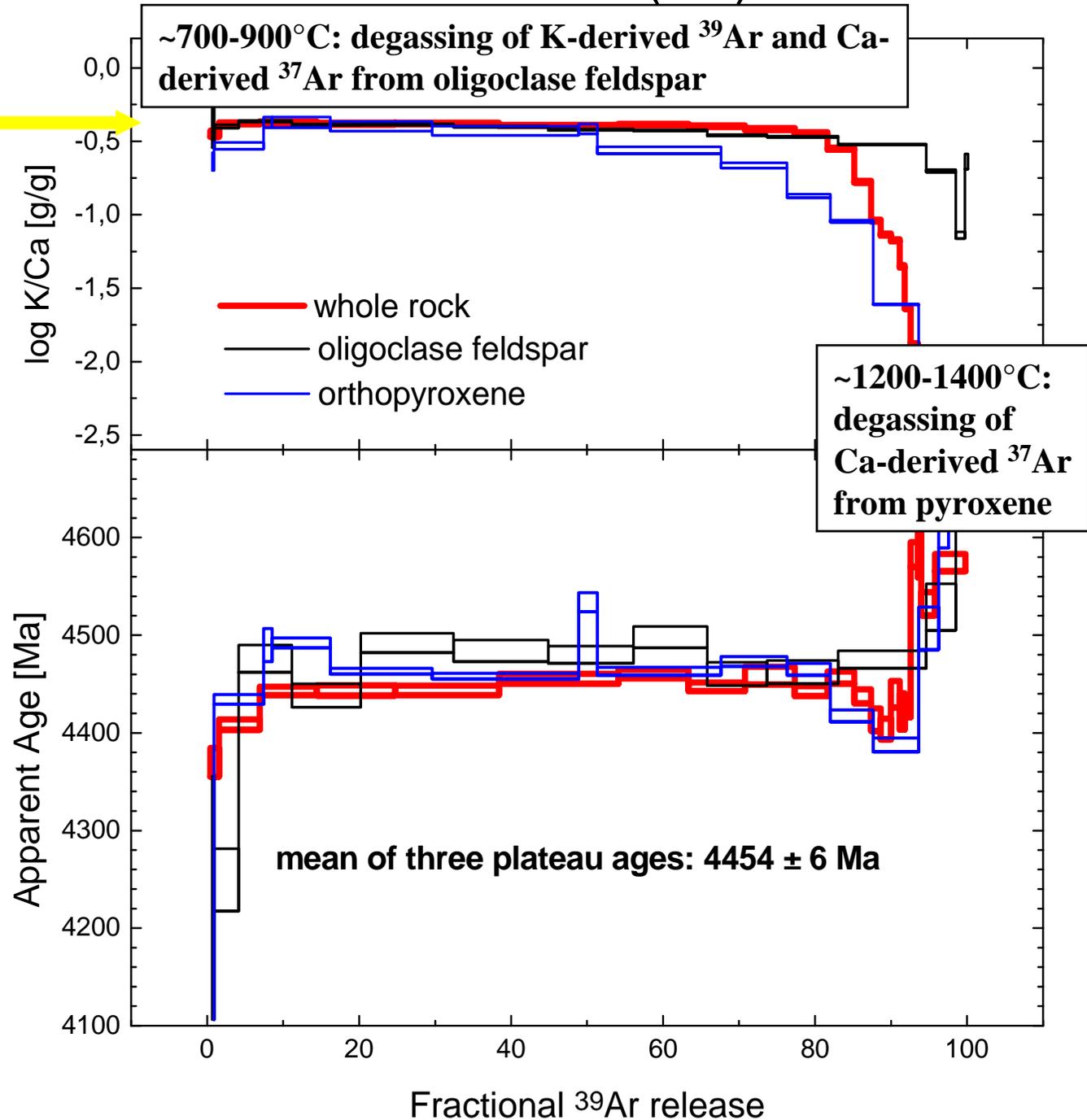




Oligoclase feldspar composition (EMPA)

K-⁴⁰Ar budgets of whole rock sample, feldspar separate and also pyroxene separate are all dominated by oligoclase feldspar
→ No difference in closure temperature
→ No significant age differences
→ mean age represents cooling through oligoclase closure temperature of 550 K

Guarena (H6)



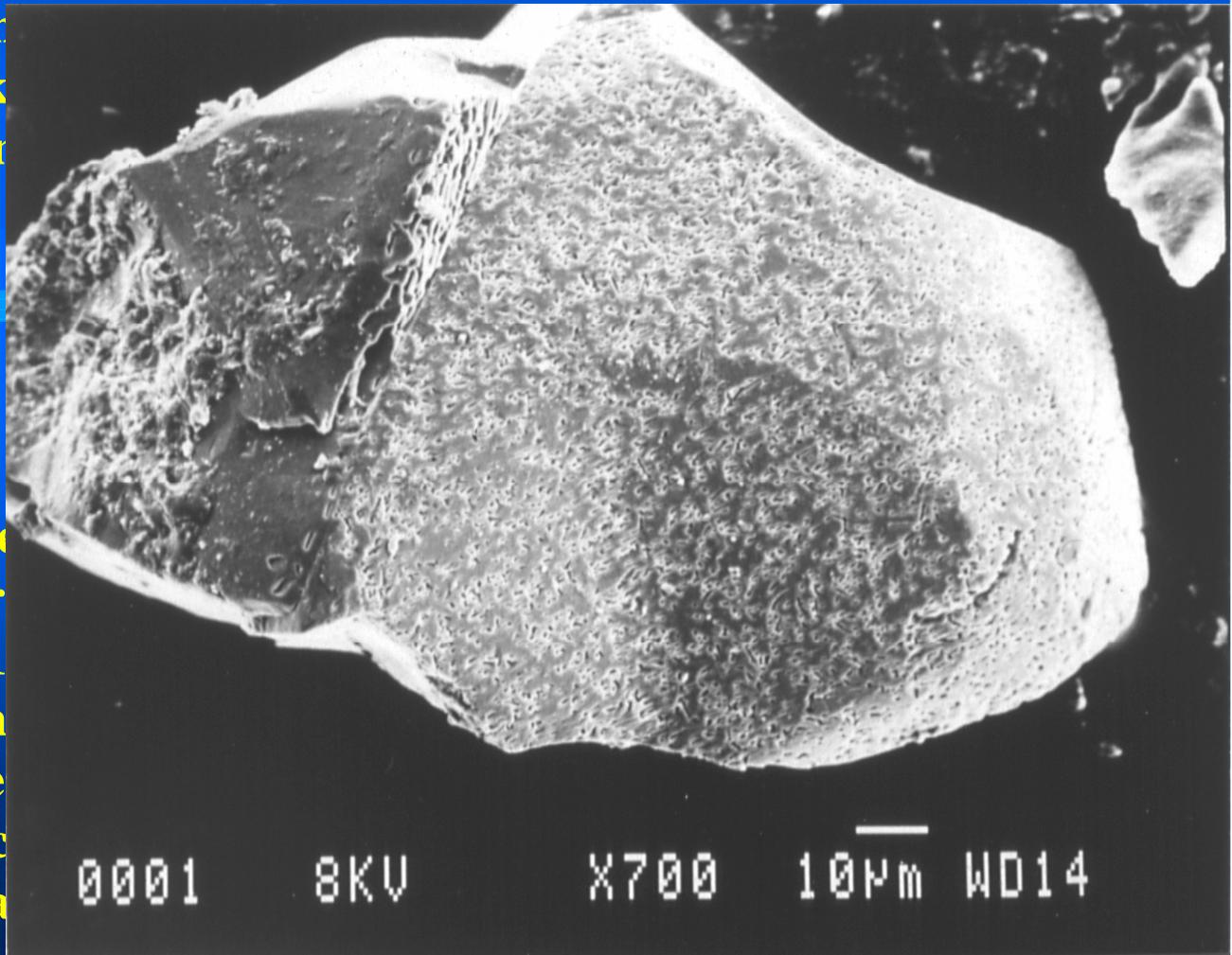
^{244}Pu – fission track chronometry

(Laboratoire de Minéralogie du Muséum d'Histoire Naturelle de Paris)

- Activity of short lived ^{244}Pu ($\tau_{1/2} = 80 \text{ Ma}$) in the early solar system produces radiation damage (fission tracks) in phosphates (e.g. merrillite) and adjacent silicates (e.g. orthopyroxene)
- Different retention temperatures lead to different fission track densities
- Typical corrections (involving track annealing) are small (tracks $< 1\%$)

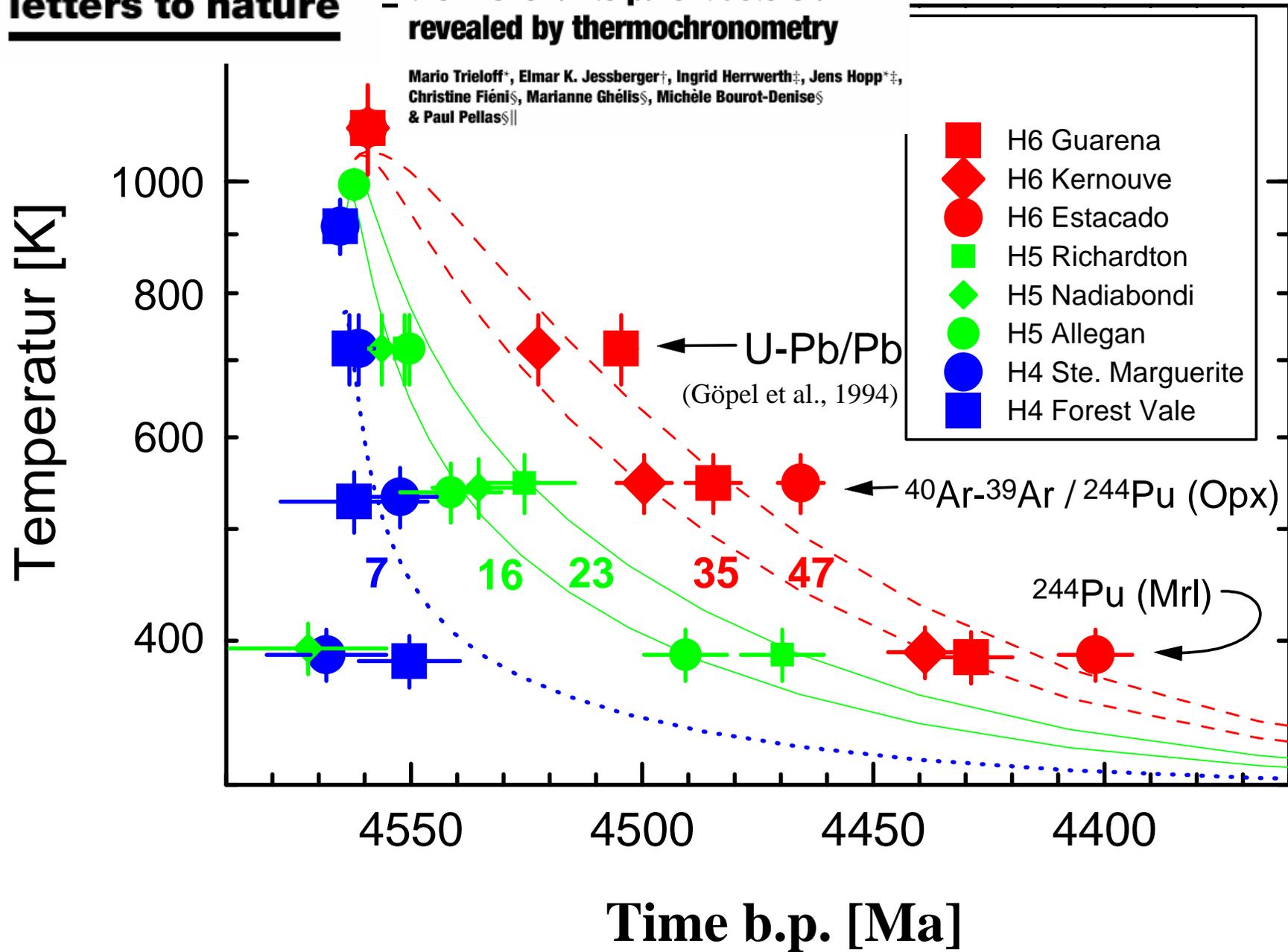
Methodological improvements

- Annealing of cosmic-ray tracks by tempering at 290°C (1 hour)
- Evaluation of OPX and merrillite fission track densities
- Integration of relative fission track densities
- Counting of up to 70 tracks per grain
- Correction for mineralogy



Structure and thermal history of the H-chondrite parent asteroid revealed by thermochronometry

Mario Trieloff[†], Elmar K. Jessberger[†], Ingrid Herrwerth[‡], Jens Hopp^{*‡},
Christine Fiéni[§], Marianne Ghélias[§], Michèle Bourot-Denise[§]
& Paul Pellas^{§||}



Chronology of the Early solar system:

Calibration of short-lived nuclide chronometers relative to U-Pb-Pb:

$^{26}\text{Al} \rightarrow ^{26}\text{Mg}$ (0.72 Ma)

$^{129}\text{I} \rightarrow ^{129}\text{Xe}$ (16 Ma)

$^{53}\text{Mn} \rightarrow ^{53}\text{Cr}$ (3.7 Ma)

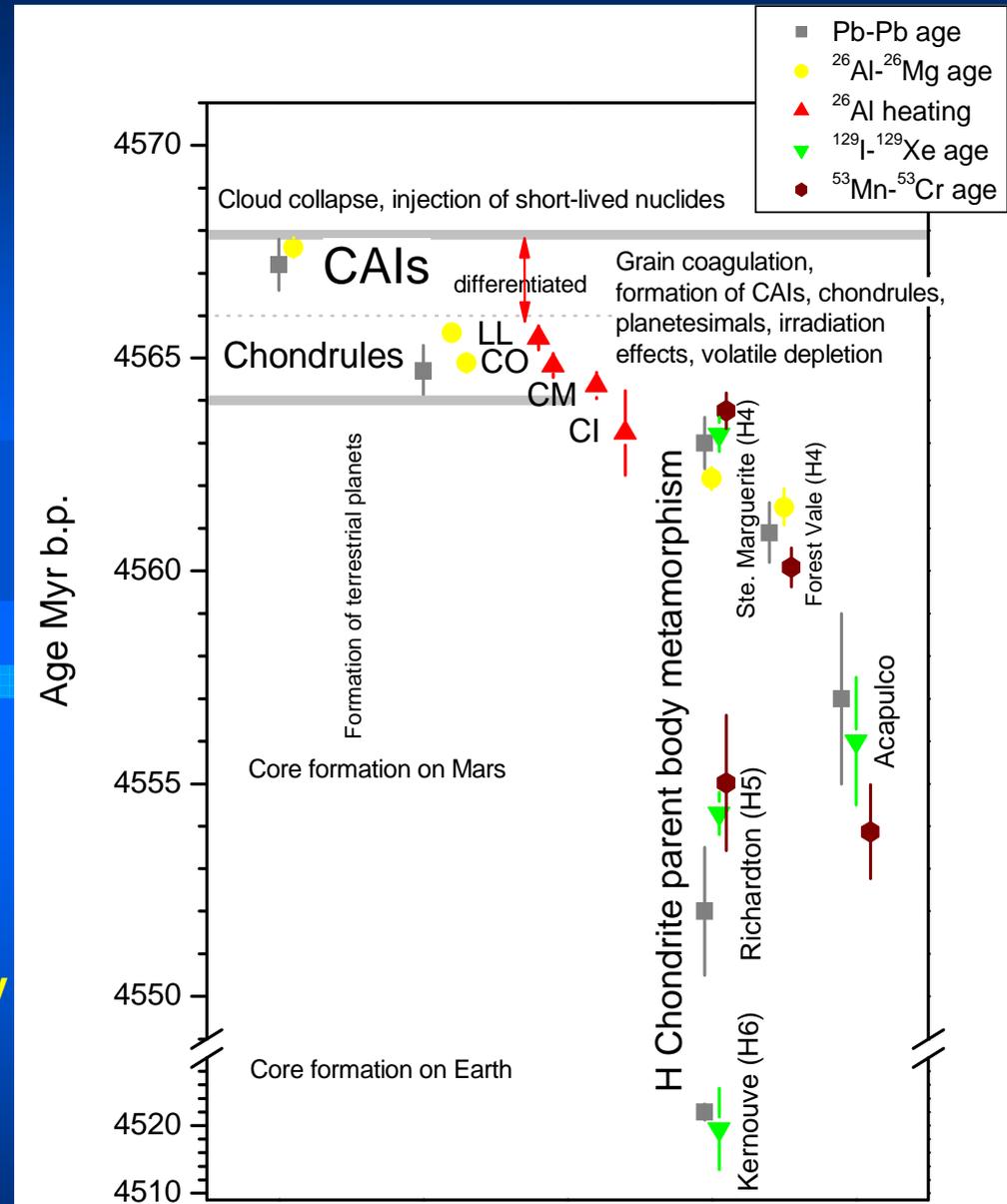
using rapidly cooled rocks !

^{26}Al heating model ages

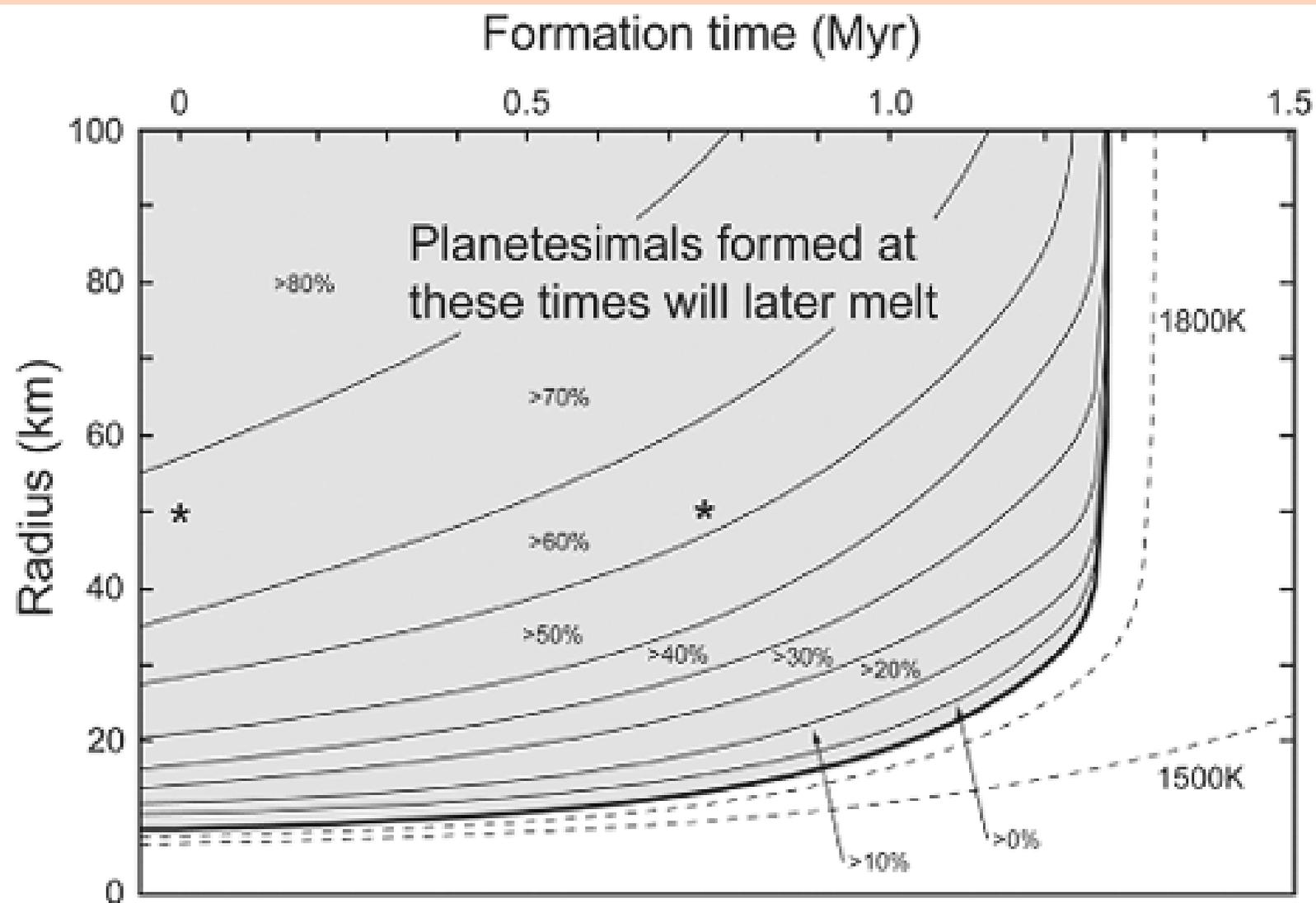
→ Earlier parent body formation

→ Higher heating by ^{26}Al decay energy

(Tieloff & Palme, 2006)



Asteroid Melting Calculations



(from Hevey and Sanders, 2006, *Meteoritics & Planetary Science*, v. 41, p. 95-106.)

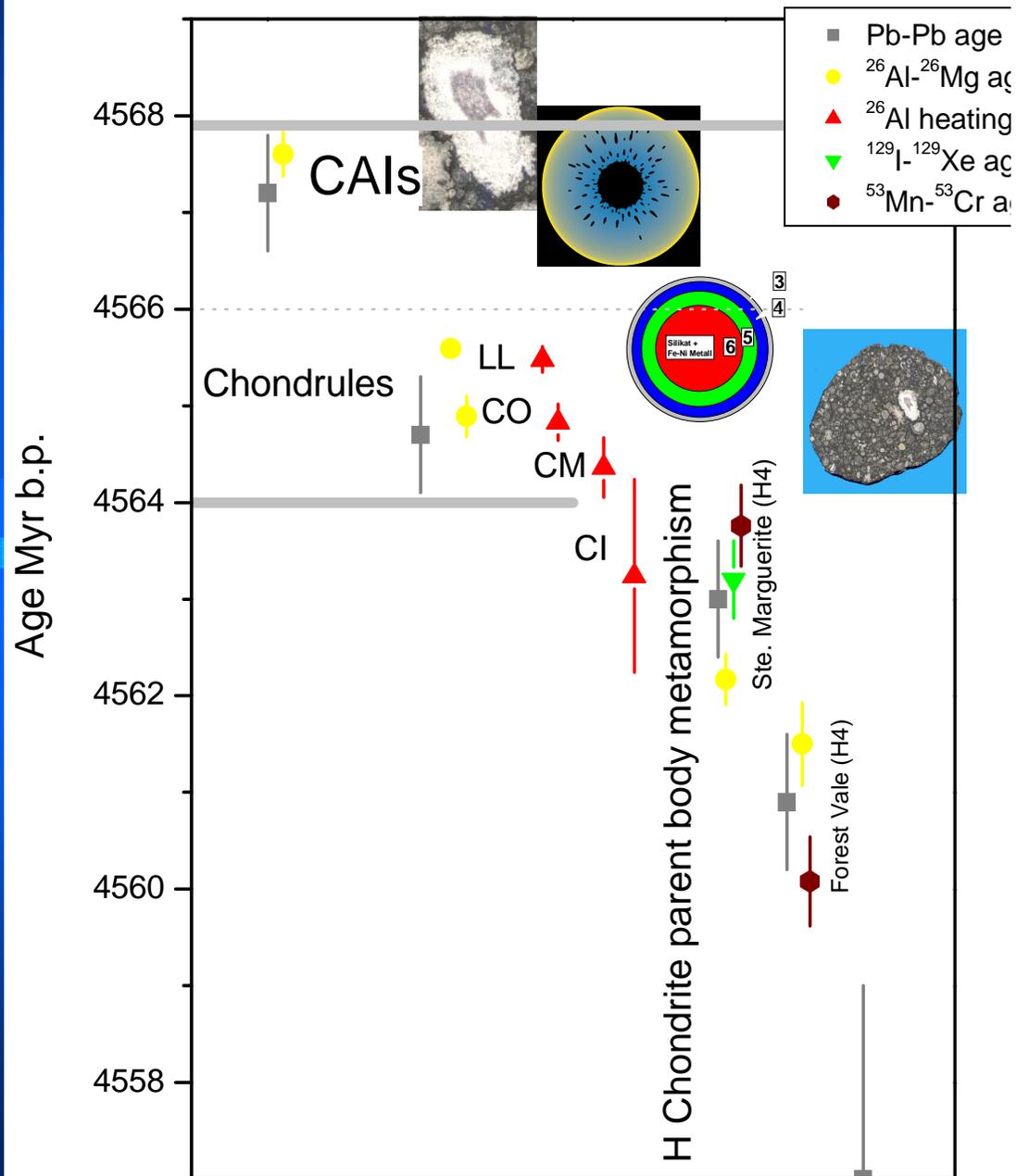
Collaps of protosolar nebula, injection of short-lived nuclides, dust grain growth by coagulation (hit and stick collisions up to km-sized bodies)

4567,2 Ma: CAIs, chondrules, planetesimals (heating, differentiation)

+2 bis +4 Ma: Chondrules, “late” planetesimals, moderate heating, no differentiation

→ ^{26}Al - ^{26}Mg ages of latest/most LL chondrules agree with ^{26}Al abundance necessary to heat LL parent body to maximum metamorphic T of $\sim 900^\circ\text{C}$

→ ^{26}Al - ^{26}Mg ages of latest/most CO chondrules agree with ^{26}Al abundance necessary to heat CO parent body to maximum metamorphic T of $\sim 600^\circ\text{C}$

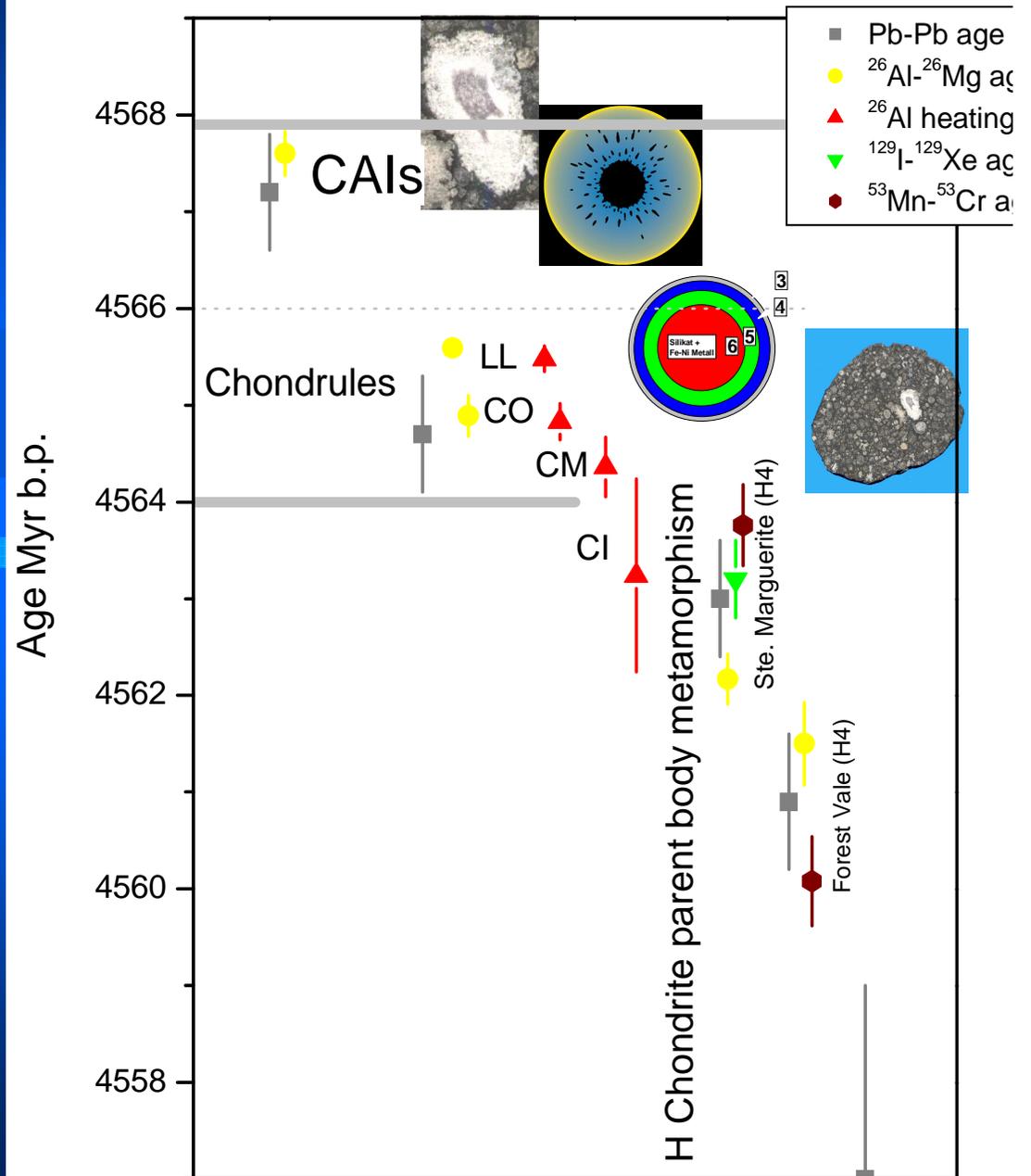


Collaps of protosolar nebula, injection of short-lived nuclides, dust grain growth by coagulation (hit and stick collisions up to km-sized bodies)

4567,2 Ma: CAIs, chondrules, planetesimals (heating, differentiation)

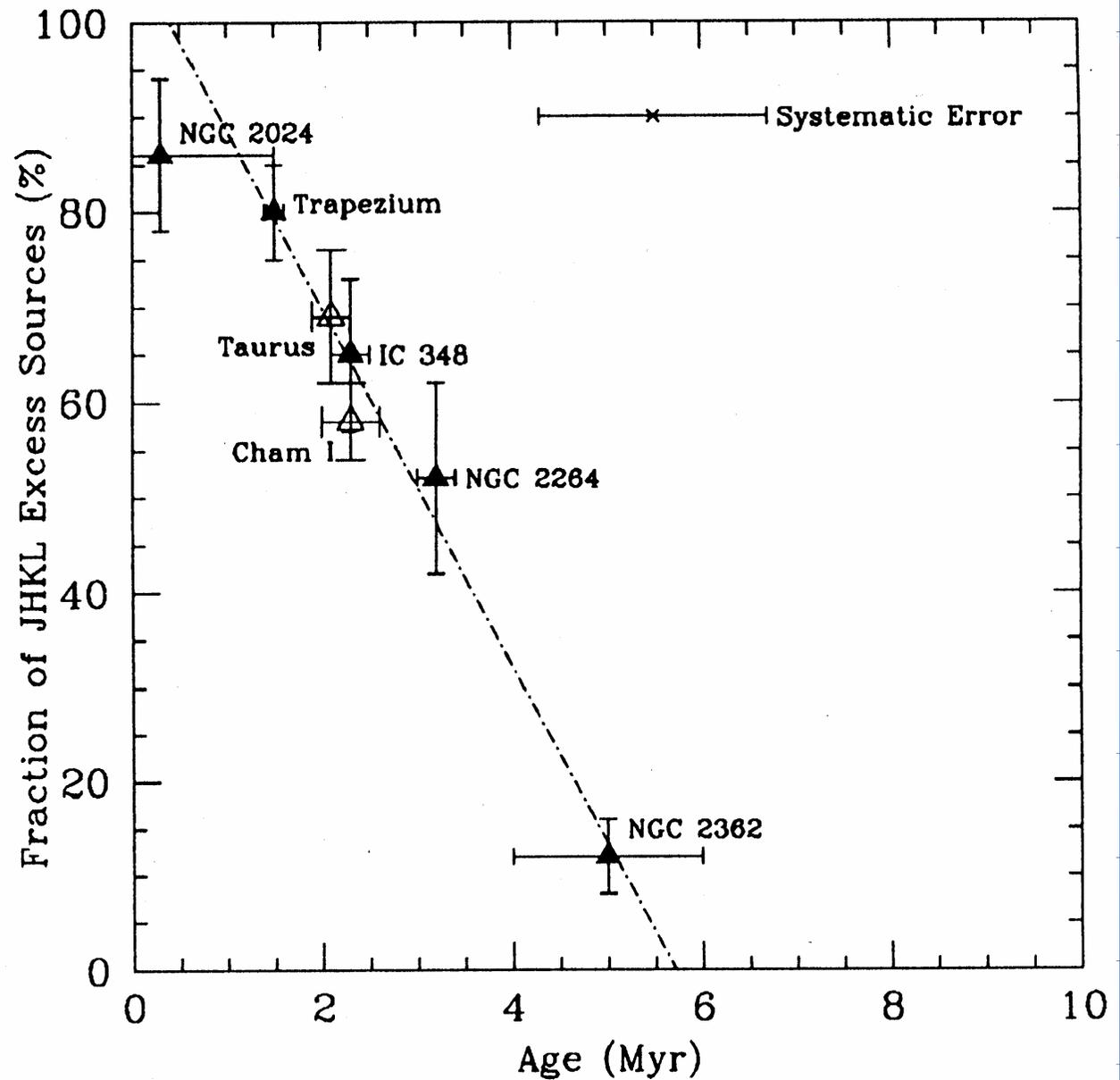
+2 bis +4 Ma: Chondrules, "late" planetesimals, moderate heating, no differentiation

Fast parent body formation after chondrule formation
 → consistent with chemical complementarity of chondrules and matrix (Palme, Hezel, Klerner)



**Disappearance
of dust disk:
<6 Ma**

(Haisch et al. 2001)

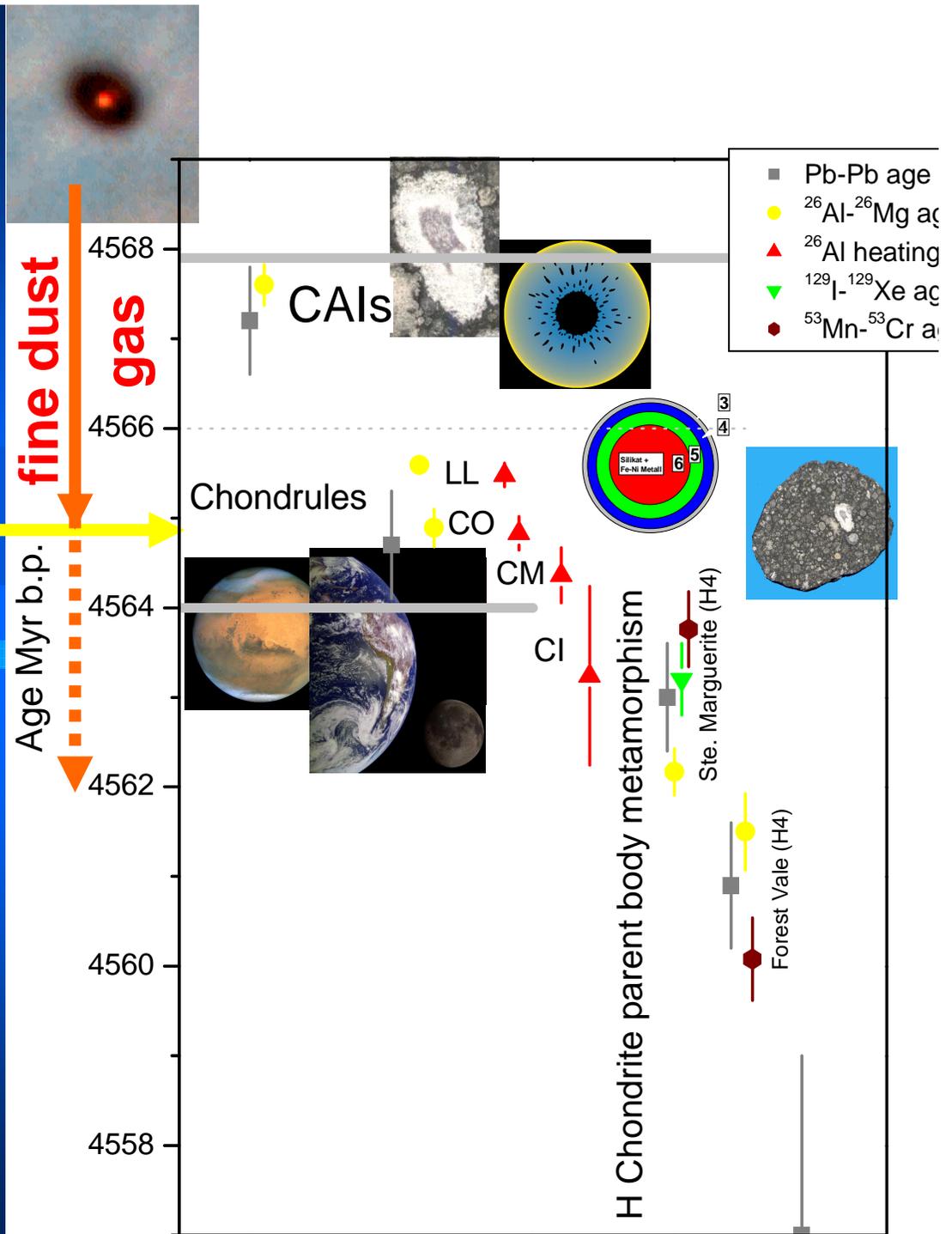


Collaps of protosolar nebula, injection of short-lived nuclides, dust grain growth by coagulation (hit and stick collisions up to km-sized bodies)

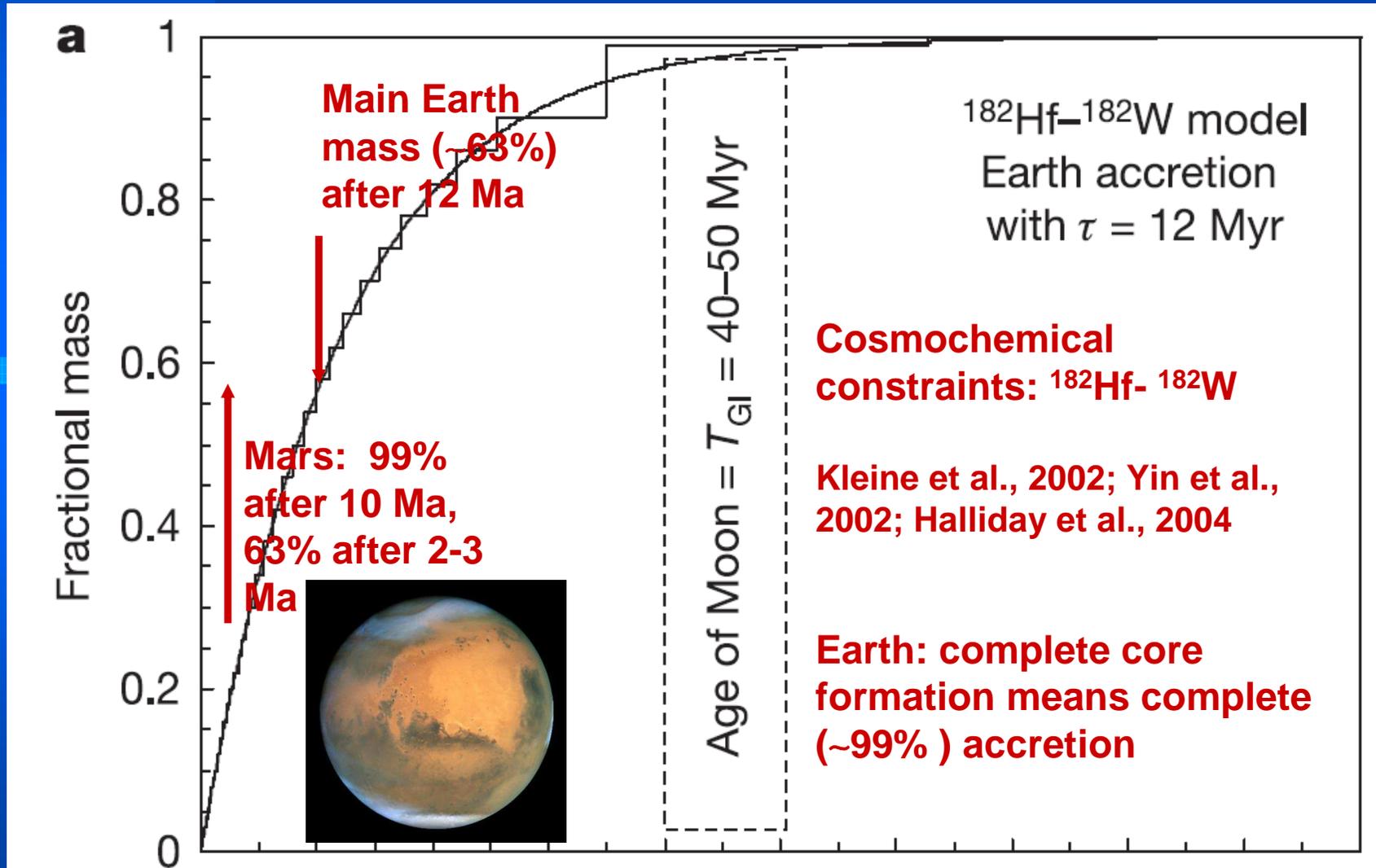
4567,2 Ma: CAIs, chondrules, planetesimals (heating, differentiation)

+2 bis +4 Ma: Chondrules, "late" planetesimals, moderate heating, no differentiation

Dust and gas loss after 2-4 Ma
 → Jupiter present (acquired gas from solar nebula gas)
 → Jupiter prevented formation of planet in asteroid belt
 → terrestrial planets present as early as outer planets ???



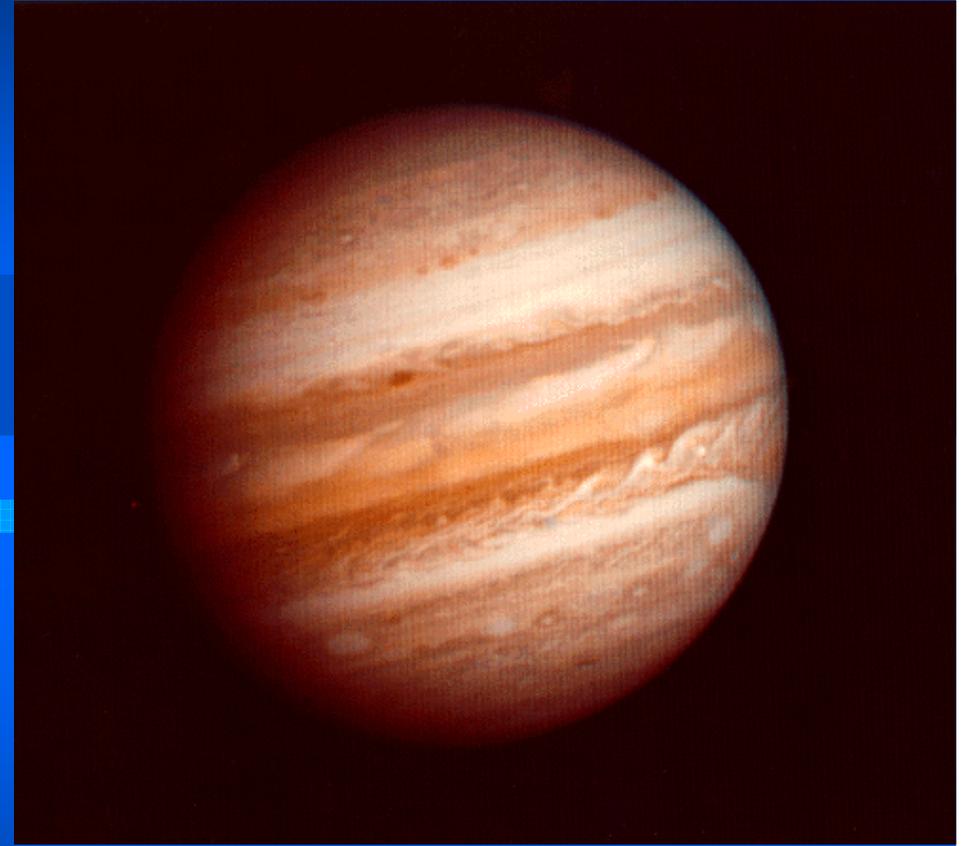
**Km to 100km sized planetesimals can rapidly grow to nearly Mars-sized protoplanets by gravitational interaction (<few Ma),
final growth to terrestrial planets needs tens of Ma via dynamical excitation**



Standard model for Jupiter formation: “bottom up” (core-accretion)



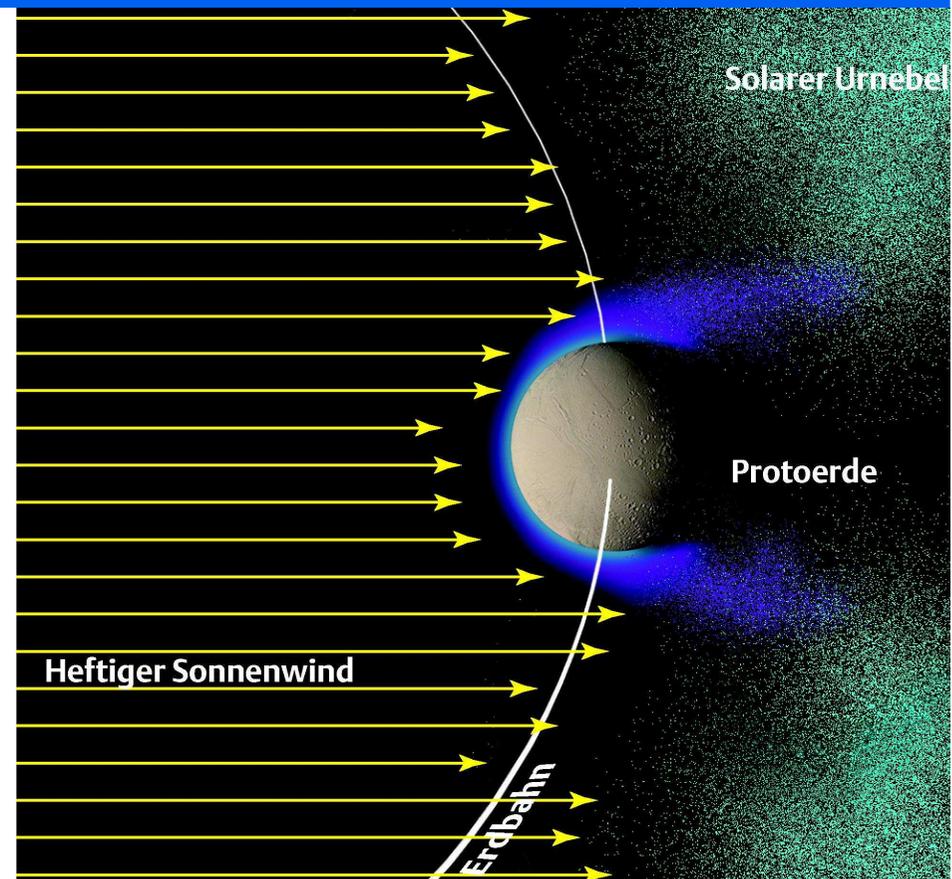
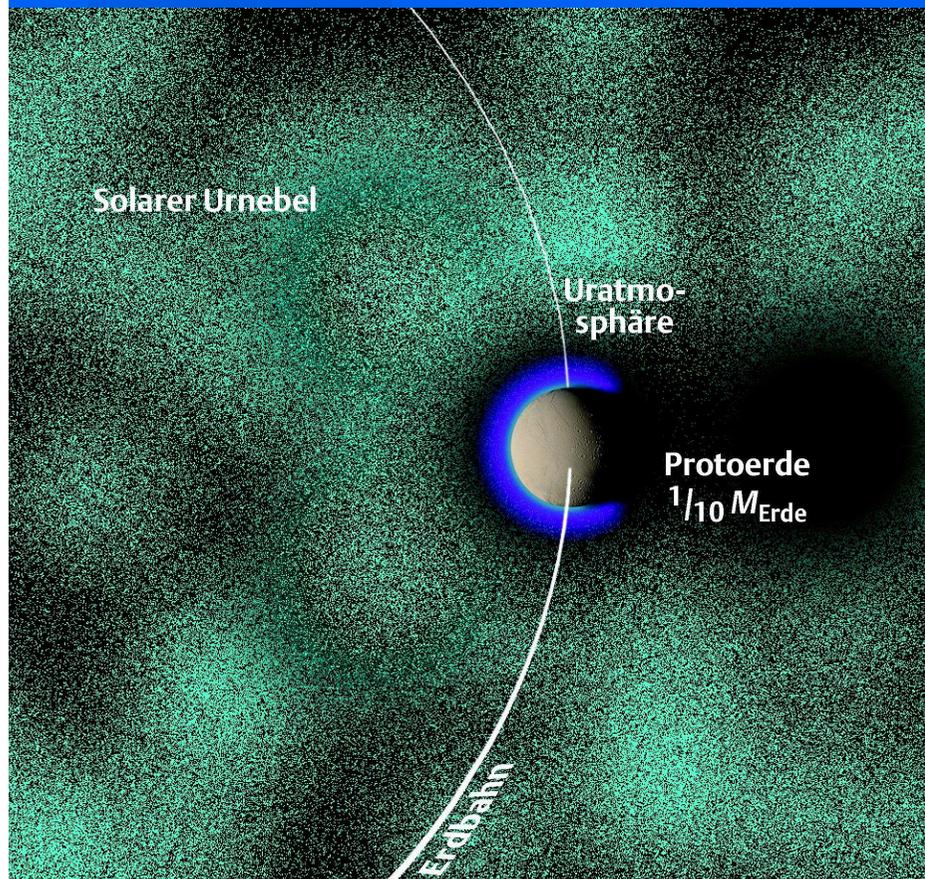
1) Accretion of a core (10 x Earth mass) of icy rocky planetesimals



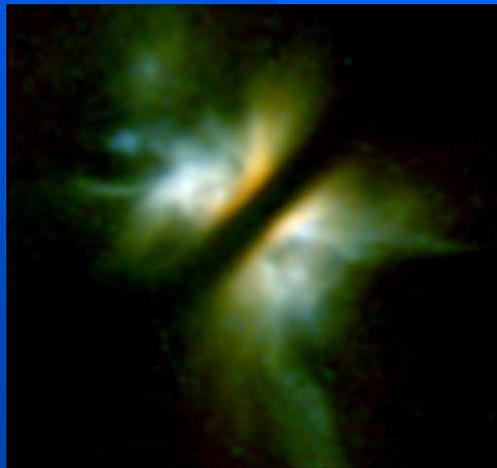
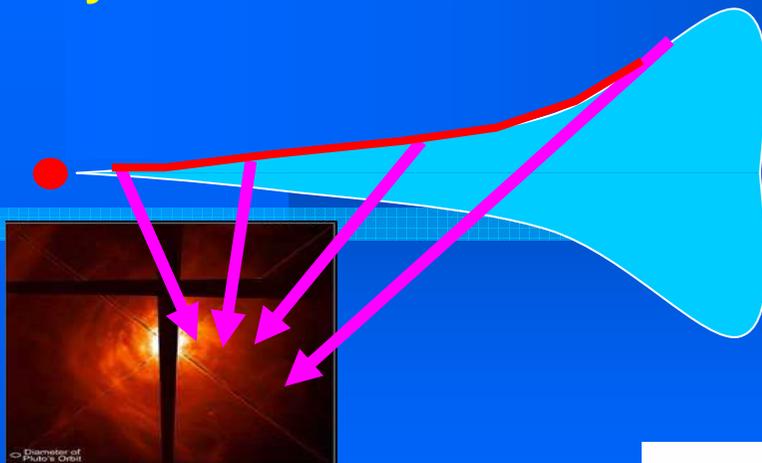
2) Subsequent acquisition of solar gas (within 2-4 Ma)

Bottom-up / Jupiter-like model for terrestrial planets?

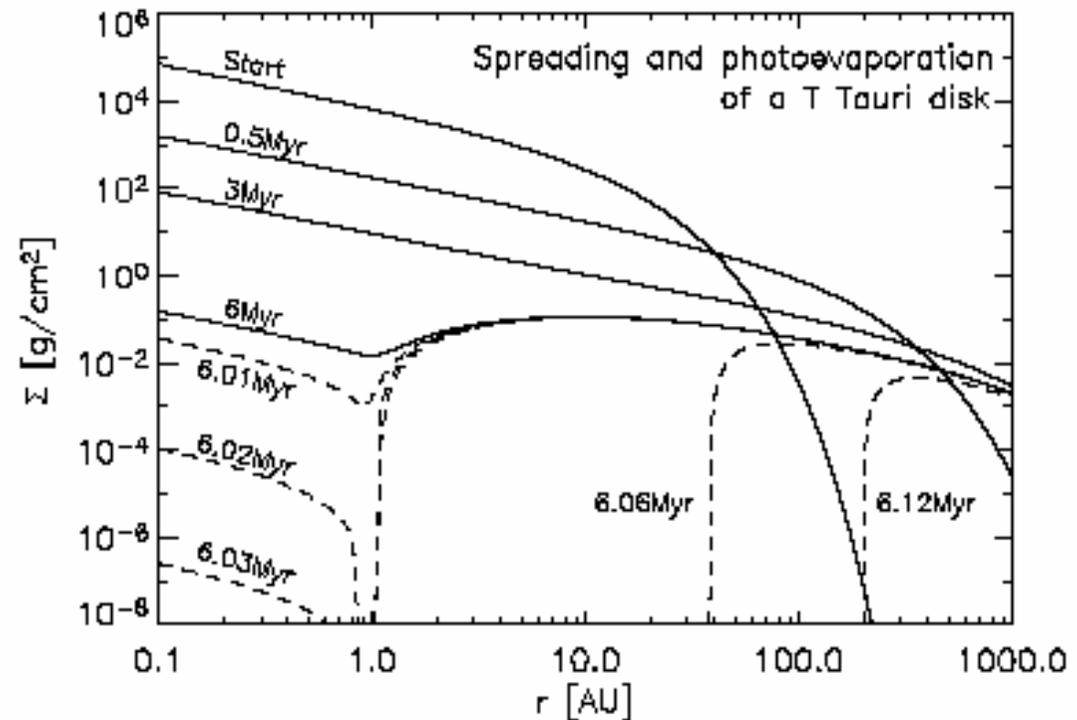
- fast accretion of the nearly full-sized proto Earth before dissipation of solar nebula gas
- gravitative acquisition of solar type protoatmosphere of ~100 bar
- magma ocean due to insulating effect
- dissolution of solar gas neon ($^{20}\text{Ne}/^{22}\text{Ne}=13.8$) and helium
(Hayashi et al., 1979; Harper and Jacobsen, 1996; Porcelli et al., 2001)



- Likely mechanism for disk loss: 1) Accretion onto the protostar**
2) Photoevaporation of flared / irradiated disks (Alexander et al. 2006)



- Afterwards: Irradiation of solid bodies, implantation of solar wind ions
 → Tracer of body size: only small bodies acquire significant solar He,Ne ions



Solar He and Ne in Earth's mantle
(pre 2000 interpretation):

→ evidence for solar gas neon from
“Jupiter-like” atmosphere (Earth full
sized before disk dissipation after 2-4
Ma)

SCIENCE

REPORTS

The Nature of Pristine Noble Gases in Mantle Plumes

Mario Trieloff,^{1*}† Joachim Kunz,¹ David A. Clague,²
Darrell Harrison,³ Claude J. Allègre¹

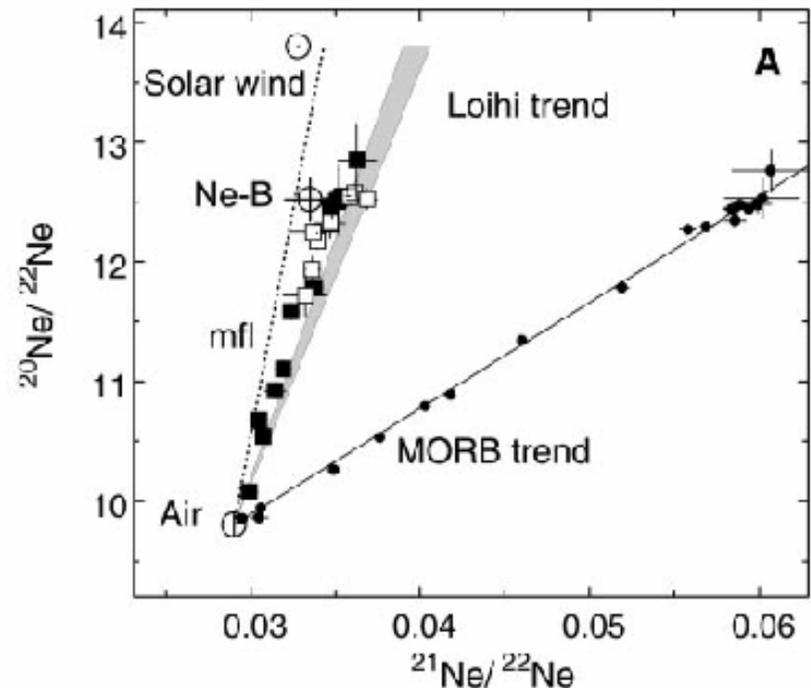
Solar wind implanted neon in Earth's
mantle:

$^{20}\text{Ne} / ^{22}\text{Ne} = 12.49 \pm 0.06$

→ indistinguishable from meteoritic

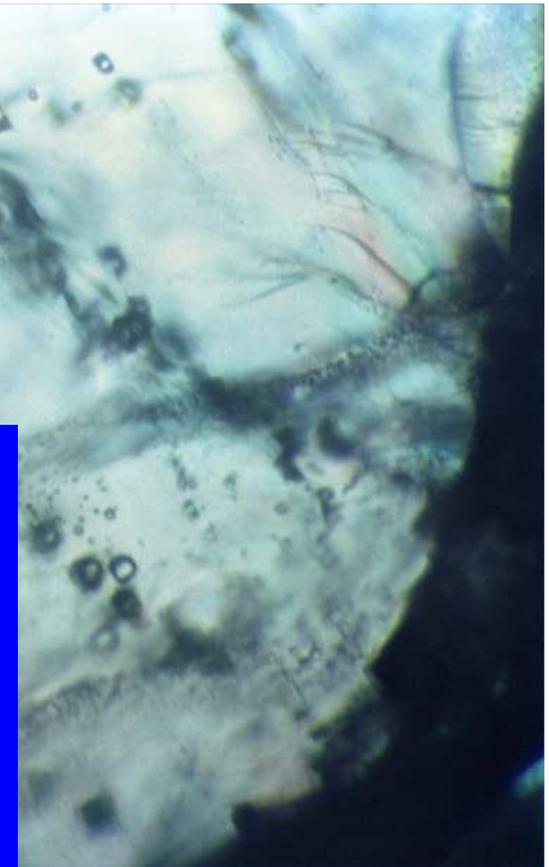
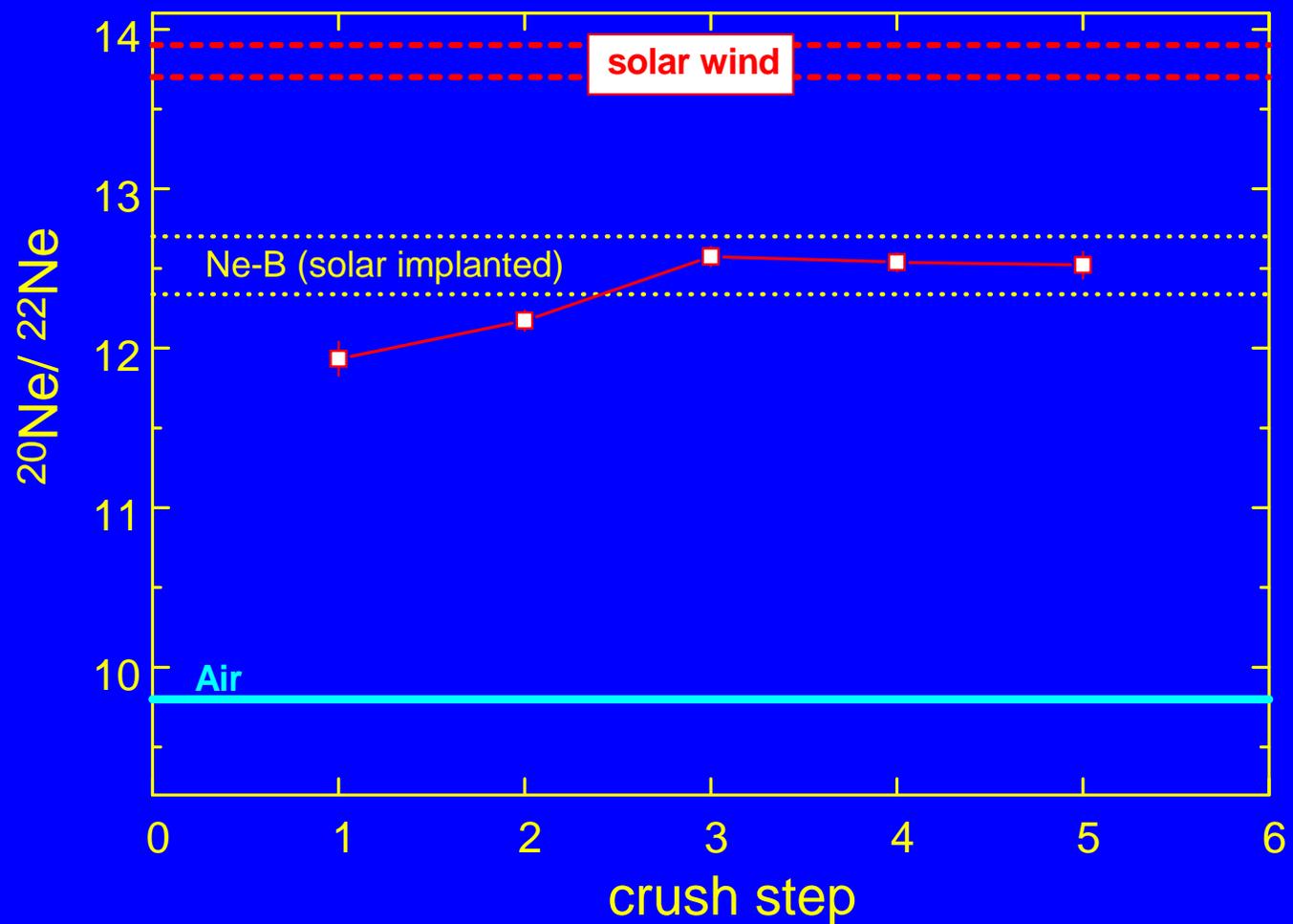
Ne-B: $^{20}\text{Ne} / ^{22}\text{Ne} = 12.52 \pm 0.18$

→ evidence for small Earth precursor
planetesimals, irradiated after disk
dissipation at 2-4 Ma

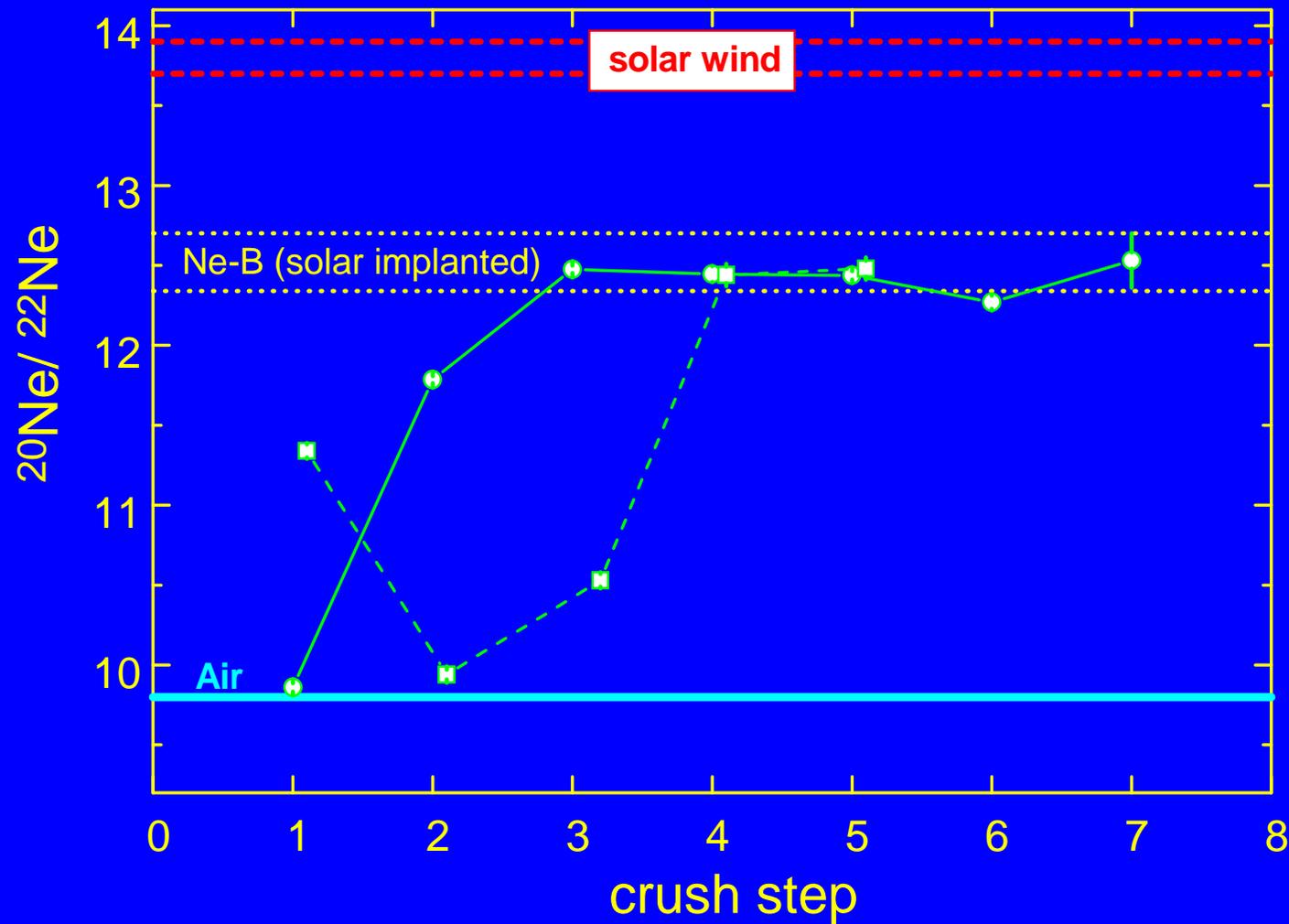
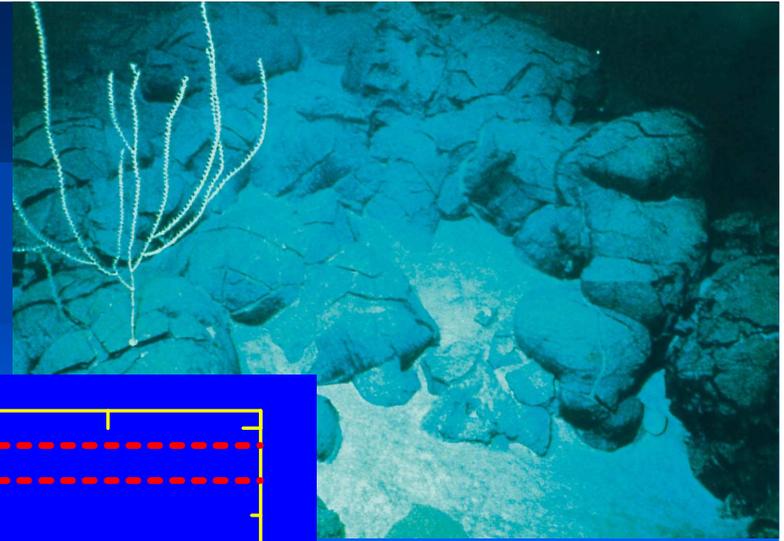


Loihi dunite KK27-9, Icelandic glasses Dice 10 and 11, and mid-Atlantic popping rock 2πD43 yield indistinguishable maximum $^{20}\text{Ne}/^{22}\text{Ne}$ ratios with a mean of 12.49 ± 0.06 in the advanced crushing steps (Table 1) (8, 18), indicating that this value represents the original endmember of the mantle source preserved in the most retentive vesicles of the rocks. This ratio is different from the solar ratio of 13.80 ± 0.10 represented by present-day solar wind (19) but indistinguishable from the meteoritic occurrence of solar neon (Ne-B) $^{20}\text{Ne}/^{22}\text{Ne} = 12.52 \pm 0.18$ (20, 21). The reproducibility of

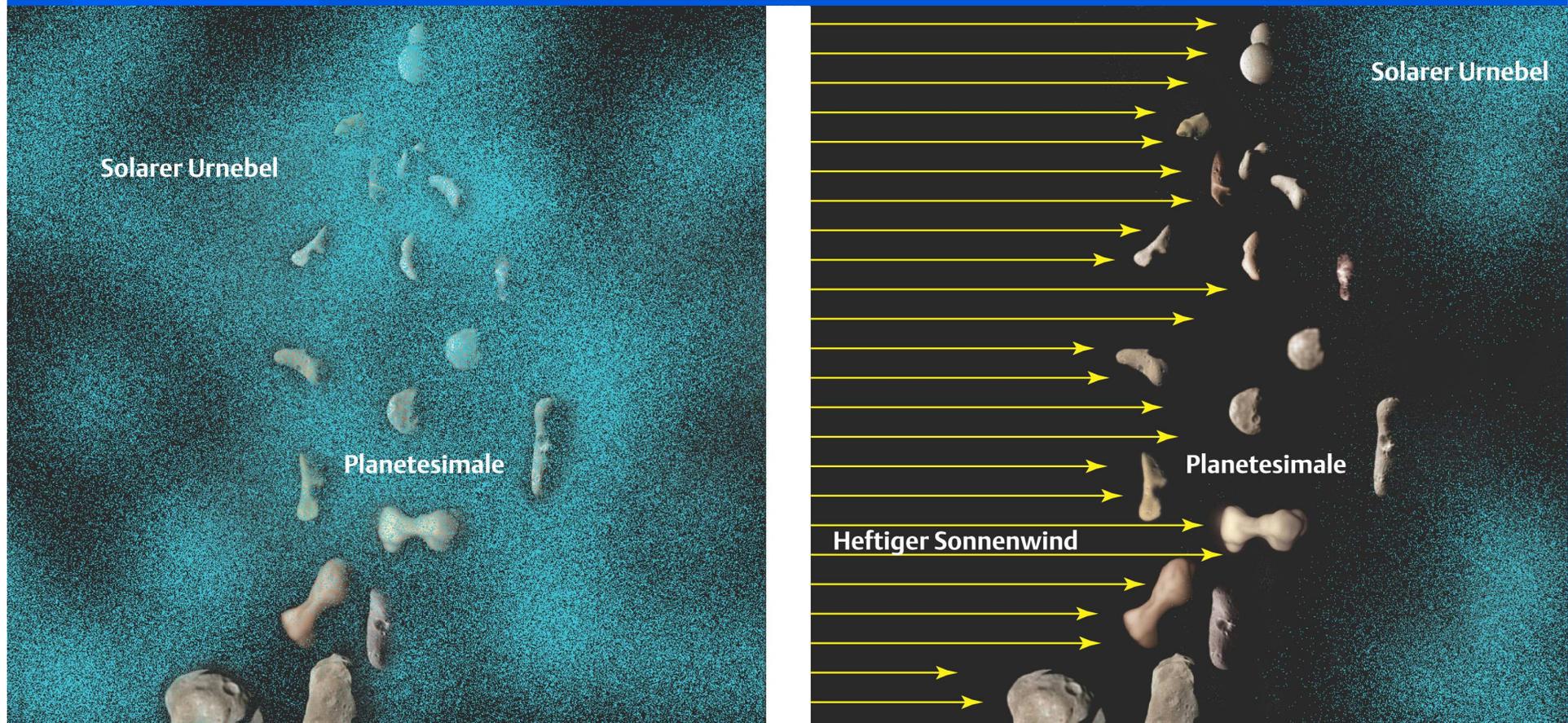
Lower mantle neon from the Hawaiian mantle plume source in Loihi dunite KK27-9



Upper mantle neon from the highly vesicular mid atlantic ridge glass 2IID43



- Accretion of km-sized planetesimals (high surface to volume ratio!)
- Implantation of solar wind neon (“Ne-B”; $^{20}\text{Ne}/^{22}\text{Ne}=12.5$) after dissipation of solar nebula gas (Tieloff et al., 2000, 2002; Wetherill, 1981)
- final Earth accretion
- protracted accretion supported by core formation age: 33 ± 2 Ma after Allende (W isotopes; Kleine et al., 2002) and standard accretion models (e.g. Wetherill, 1990)



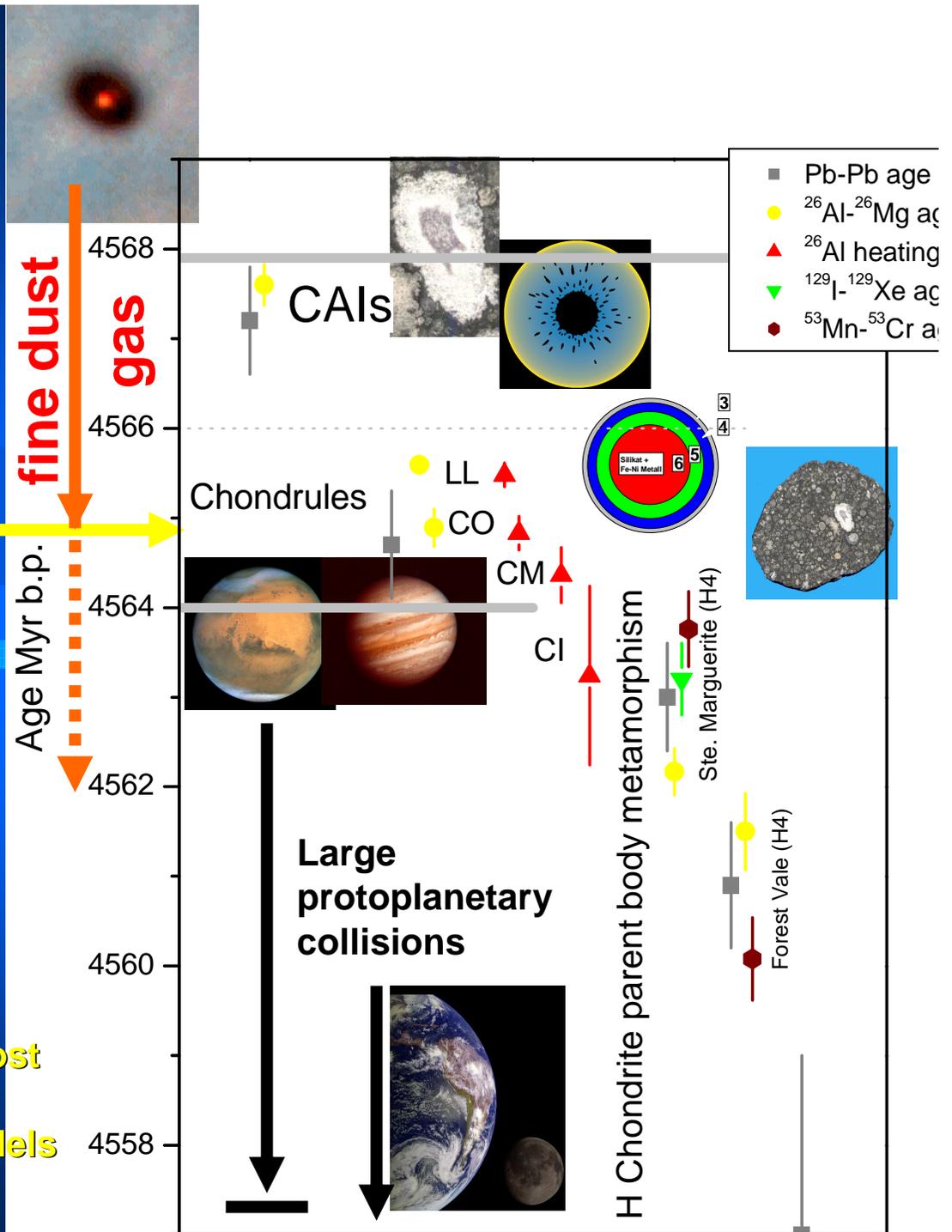
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Dust and gas loss after 2-4 Ma
 → Jupiter present (acquired gas from solar nebula gas)
 → Jupiter prevented formation of planet in asteroid belt
 → terrestrial planets present as early as outer planets ???
No !

Solar wind irradiation requires planetesimal size when solar gas was lost (Tieloff et al. 2000)
 → Supported by theoretical growth models and Hf-W dating (Kleine et al. 2002)



Collaps of protosolar nebula, injection of short-lived nuclides, dust grain growth by coagulation (hit and stick collisions up to km-sized bodies)

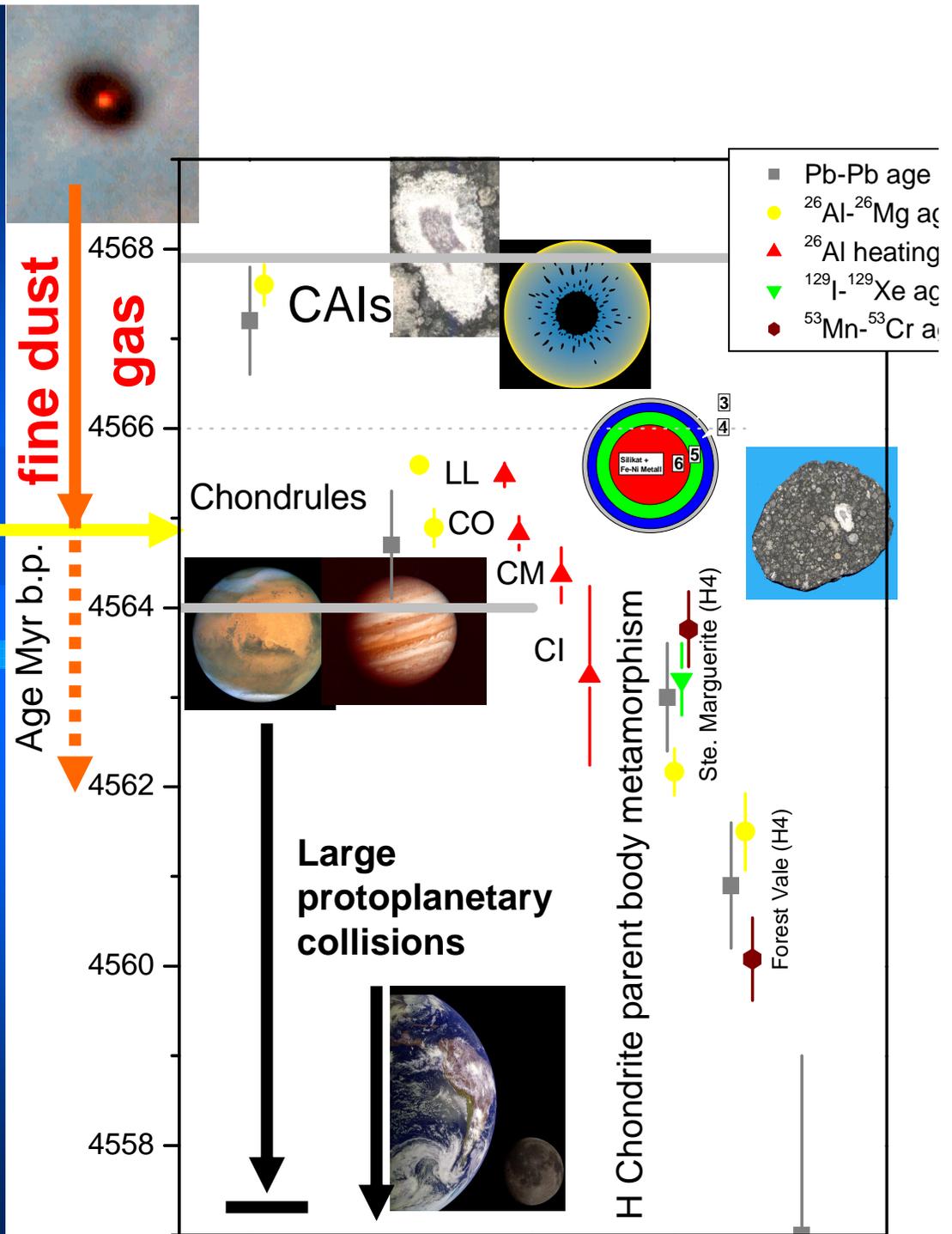
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Problem:

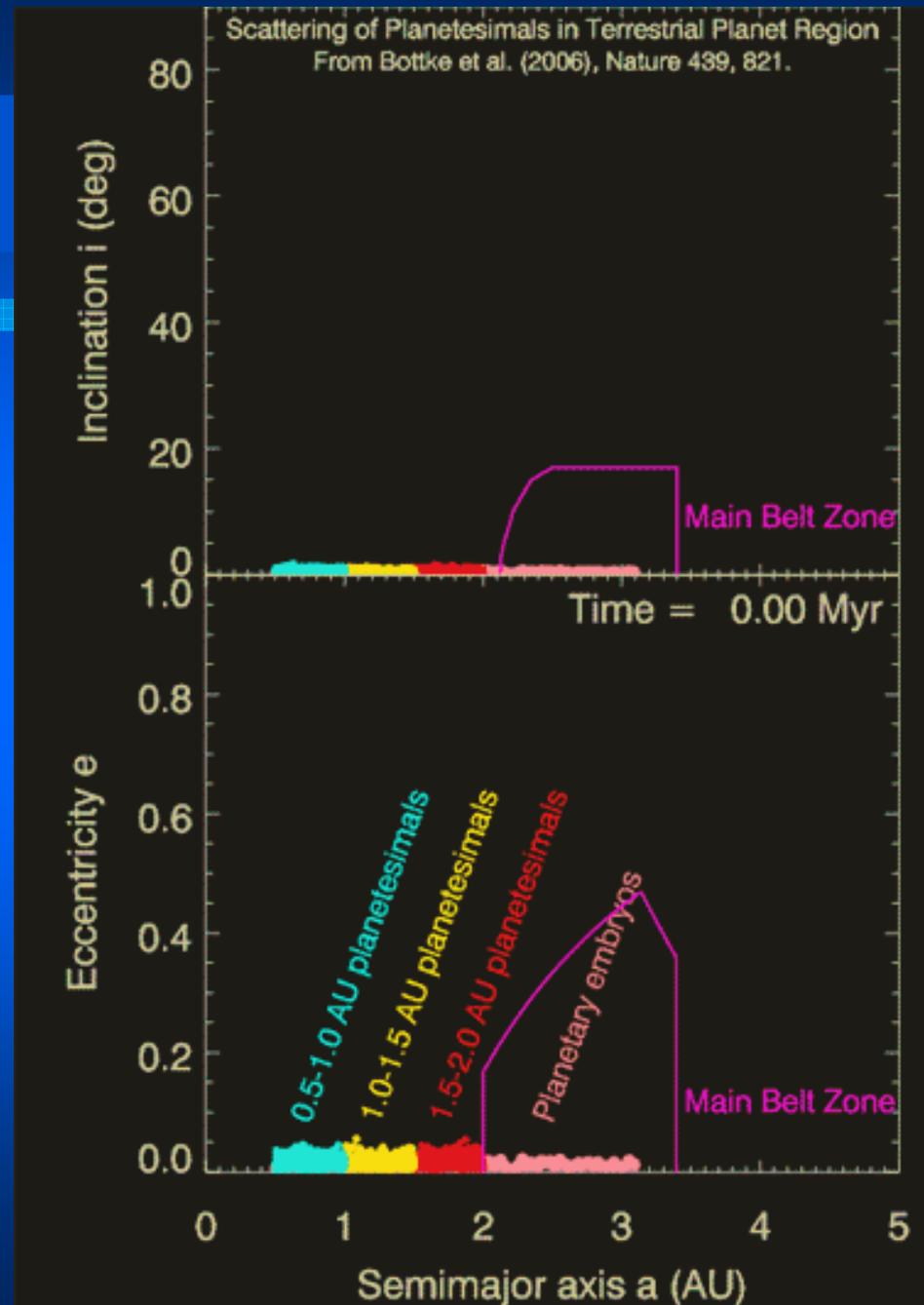
Asteroid sized planetesimals fast, but why over time interval of 3-4 Ma?

Faster formation close to the sun?



What determines speed of planetesimal formation via coagulation?

- Critical sizes / relative velocities (“m-size barrier” → experiments)
- Effect of mass density
 - 1) Solar system gradient: higher mass density in inner solar system, i.e. faster formation of inner solar system planetesimals
- Bottke et al. 2006 : iron meteorites are from planetesimals scattered from the inner solar system into the asteroid belt



Conclusions:

Early solar system chronology

- Meteorites trace the origin of the Earth and early solar system processes (growth from dust to planetesimals, planetary differentiation, processing of minerals, etc.)
- Well developed framework of early solar system chronology based on radioisotope chronometry applied to meteorites
- Formation of small planetesimals in the inner solar system within few 3-4 Ma (within disk lifetime), early differentiation triggered by heat from short-lived radionuclides
- Terrestrial planets acquired major mass after the giant planets (e.g. Jupiter) - Mars: 10 Ma, Earth: 30 Ma
- Earth precursor planetesimals were irradiated by solar particles