The first million years of the Solar system: from dust to planets

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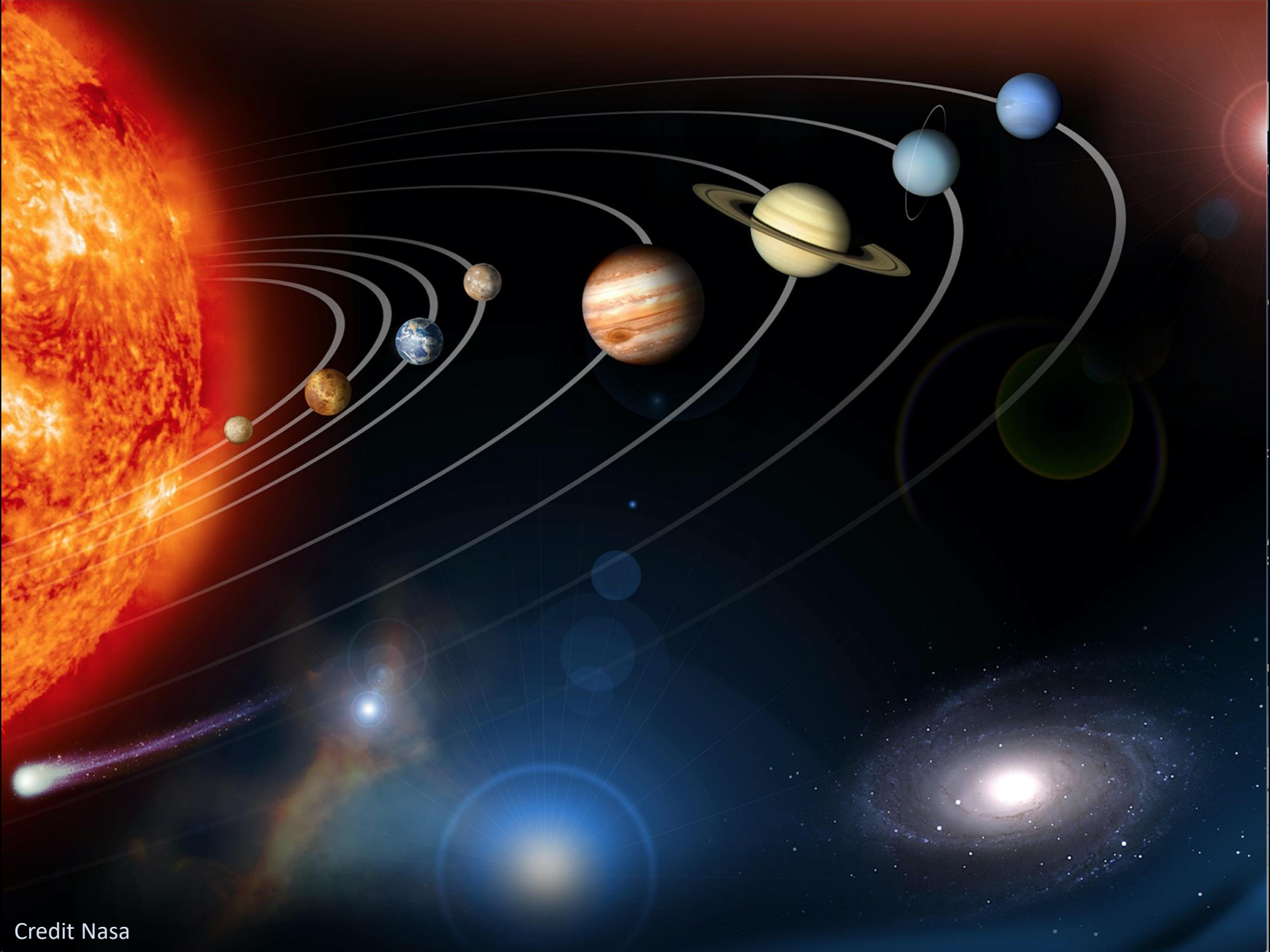


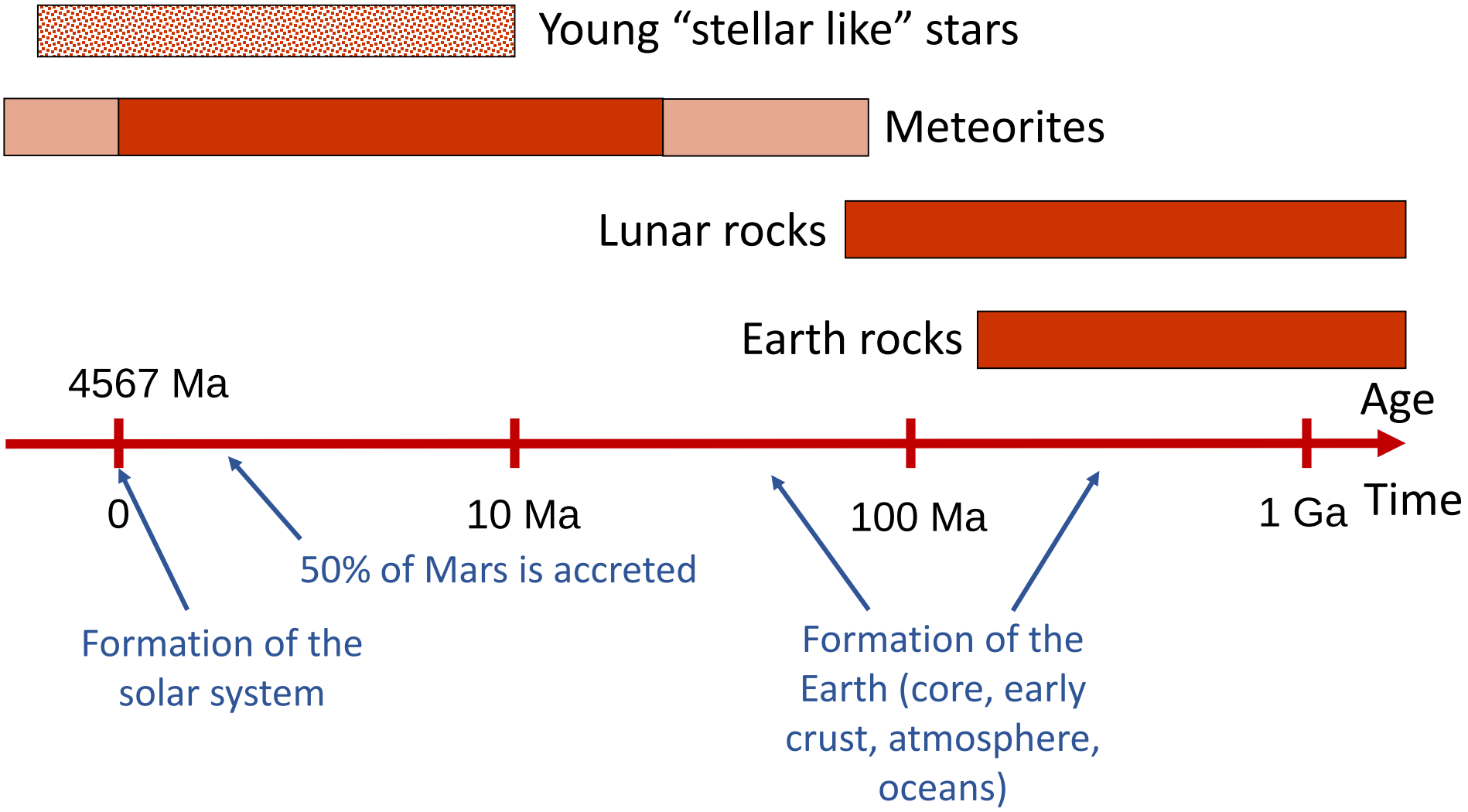
Credit Nasa

Three different types of information to reconstruct the origin of the Earth

- Astrophysical observations of young stellar systems analogous to our early Solar system

- Cosmochemical studies of meteorites (fossils of the epoch of the disk before the formation of the Earth)

- Geological and geochemical studies of Hadean and archean rocks



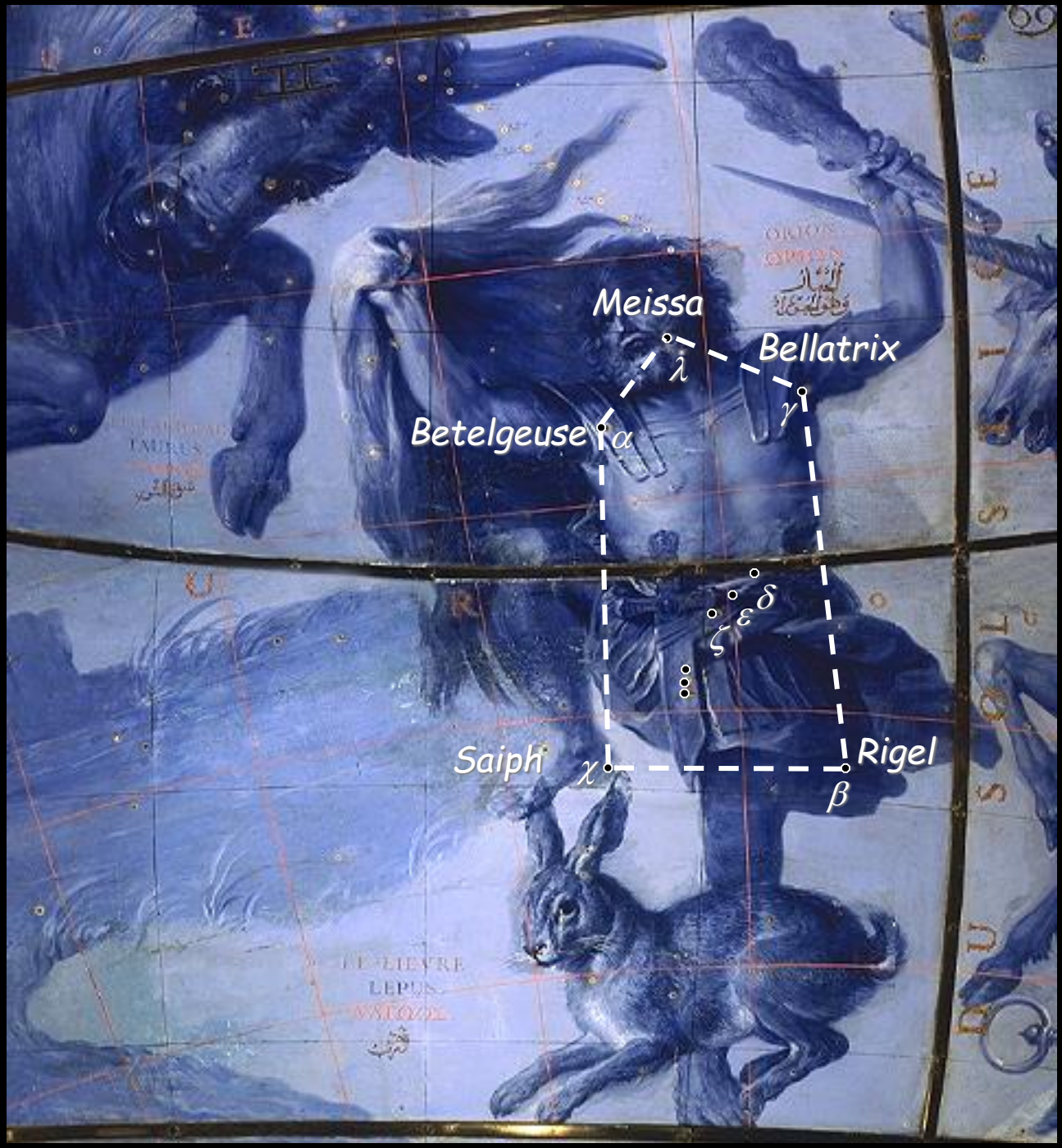
Two kinds of samples : light from stars or solid samples from meteorites (including Mars), the Earth, and the Moon

Credit: Dan Duriscoe US National Park Service

Orion the Hunter

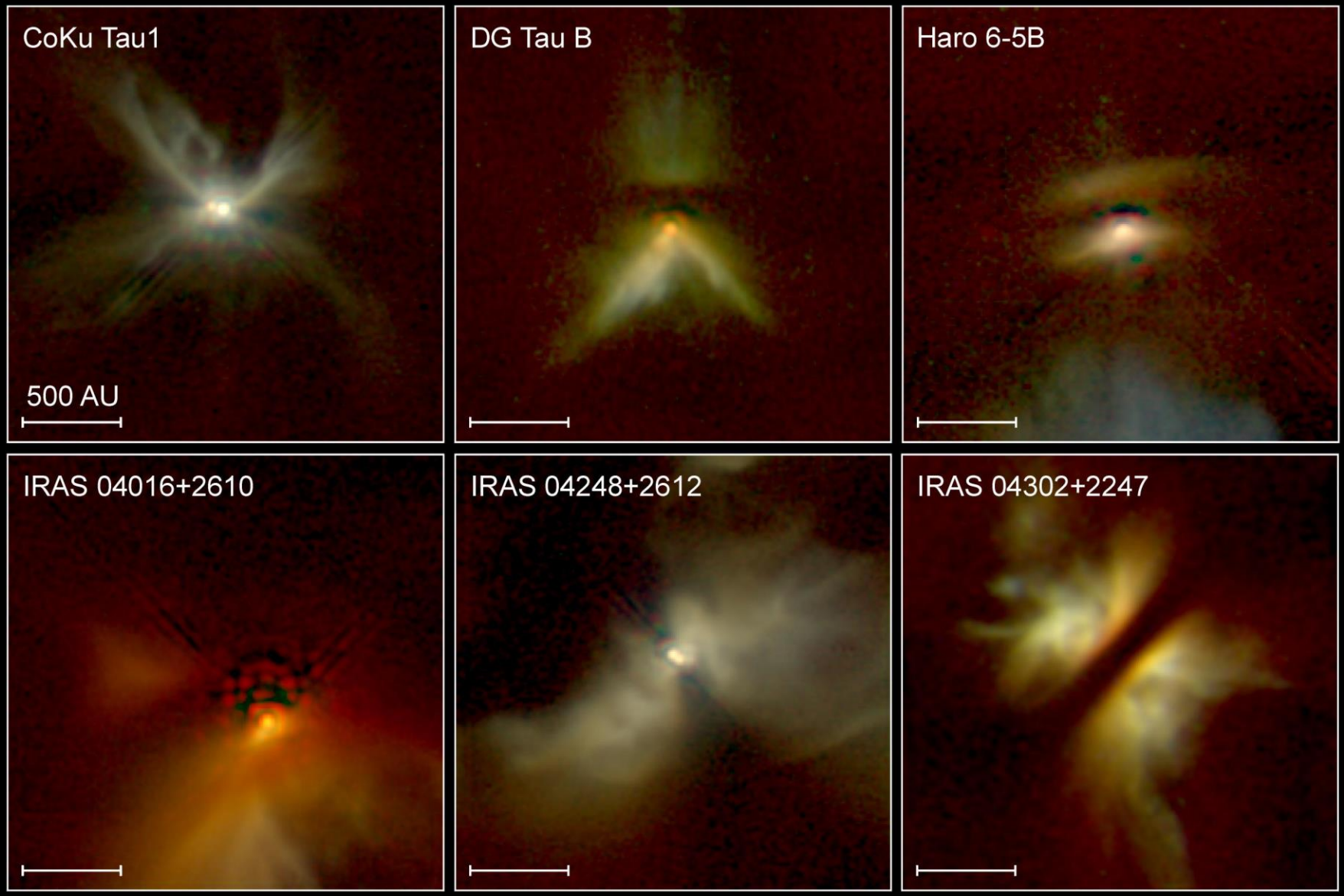
(Globe by Coronelli for the king of France Louis XIV in 1682)

The Orion constellation



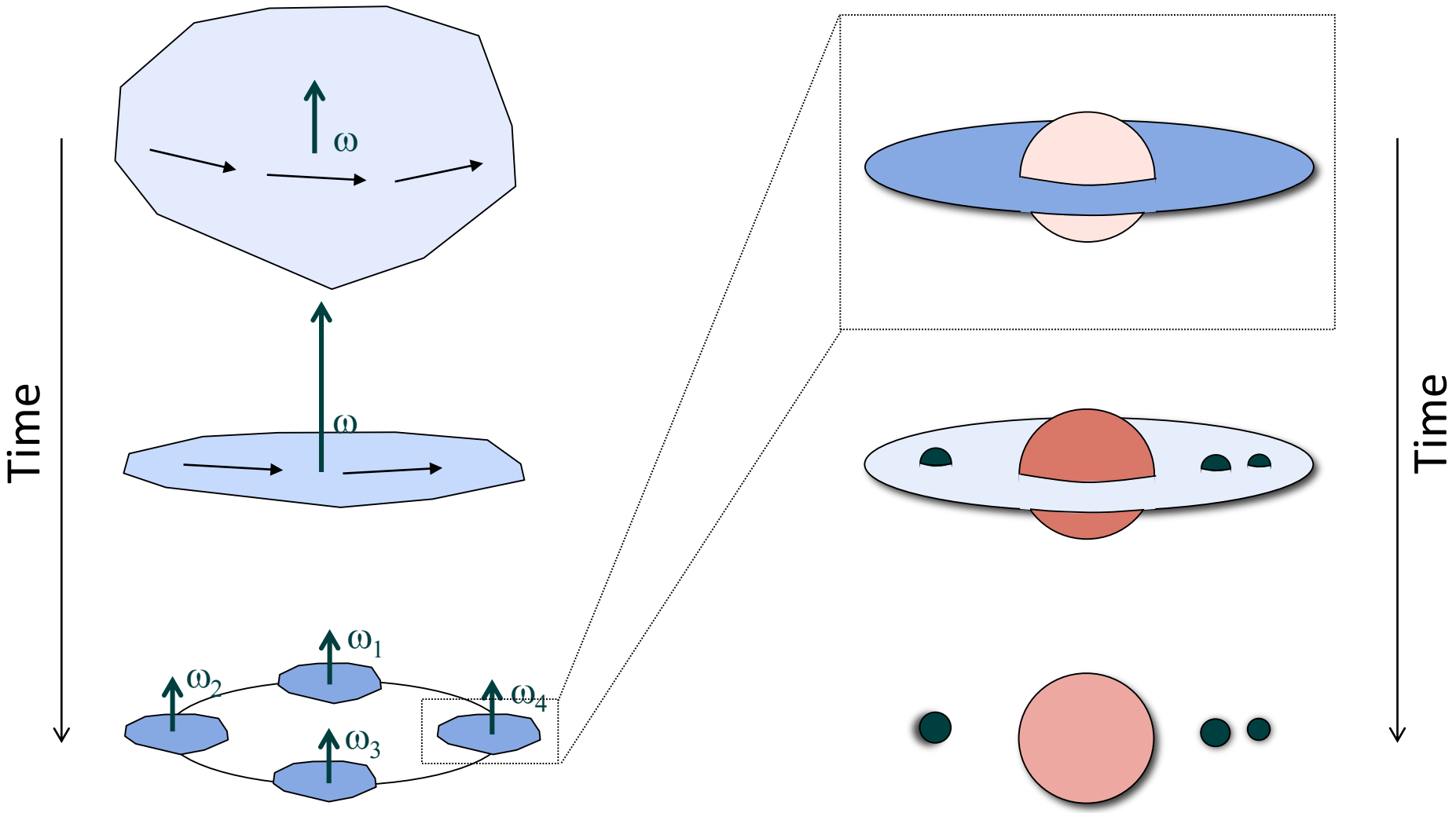
The Orion nebula (M42)
Distance: 1344 ly
Size: 24 ly

Chandra Orion Ultradeep Project
Courtesy Eric Feigelson (COUP/NASA)

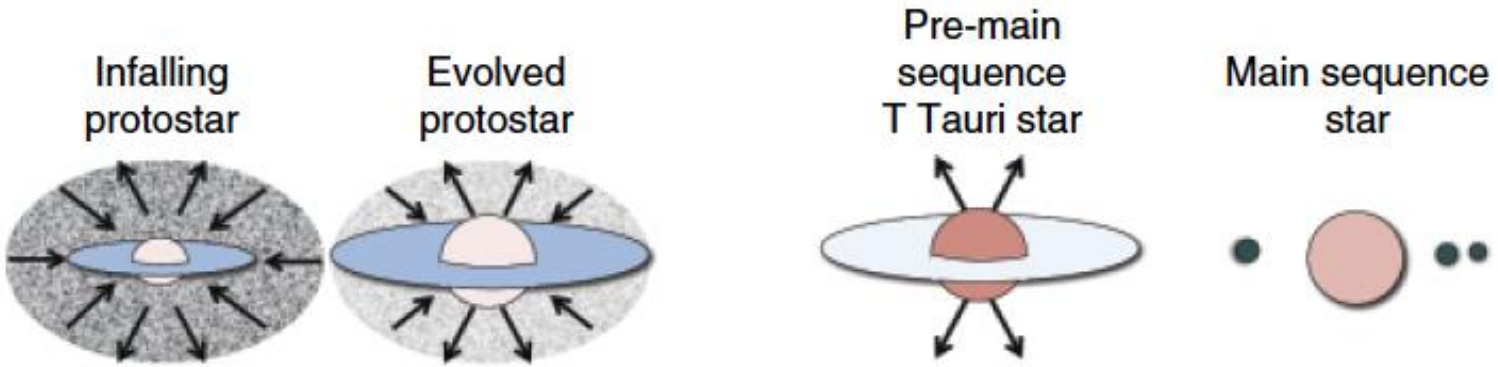


HST images, Taurus-Auriga molecular cloud (Padget et al., 1999)

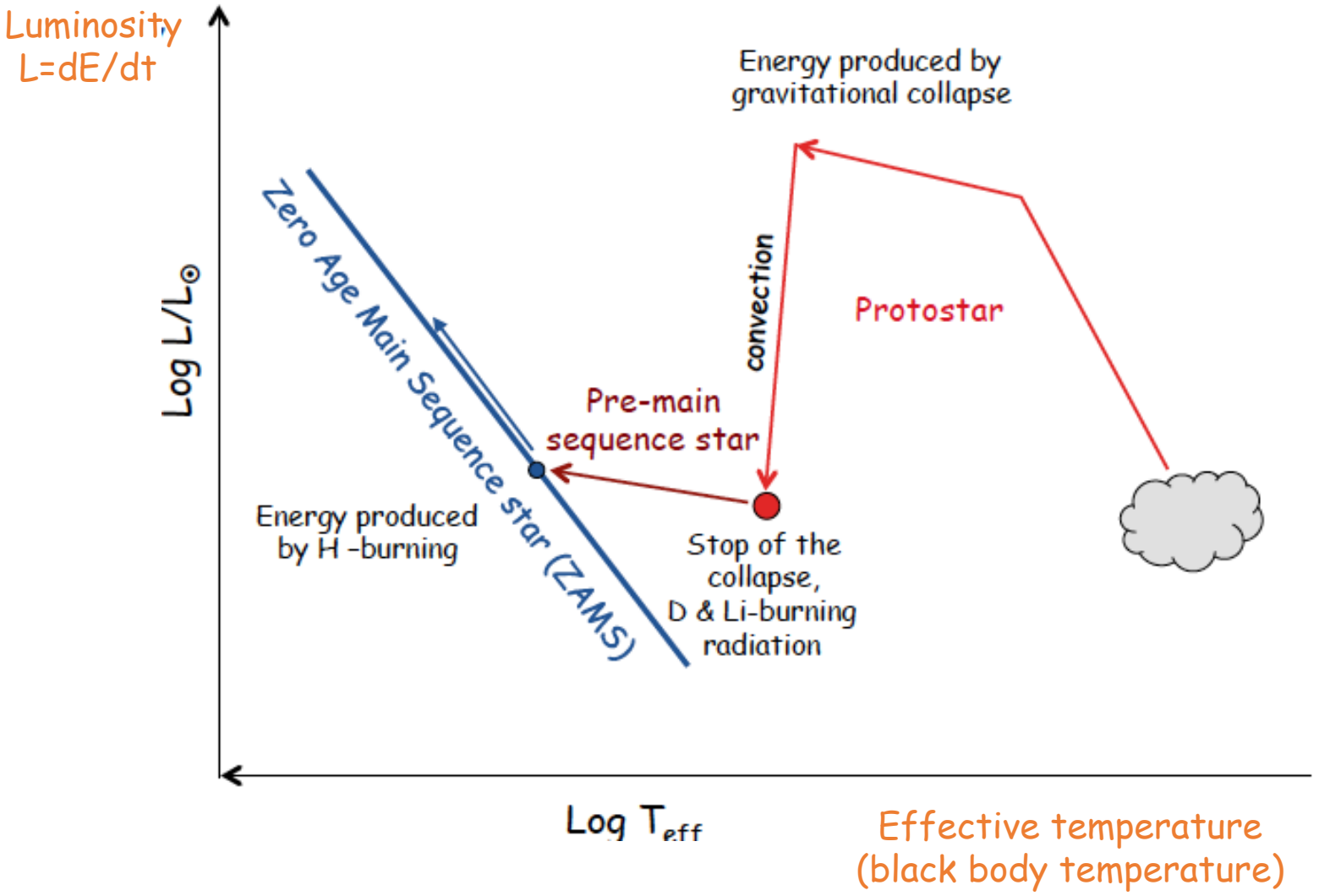
From a cloud of interstellar gas and dust to the Solar system



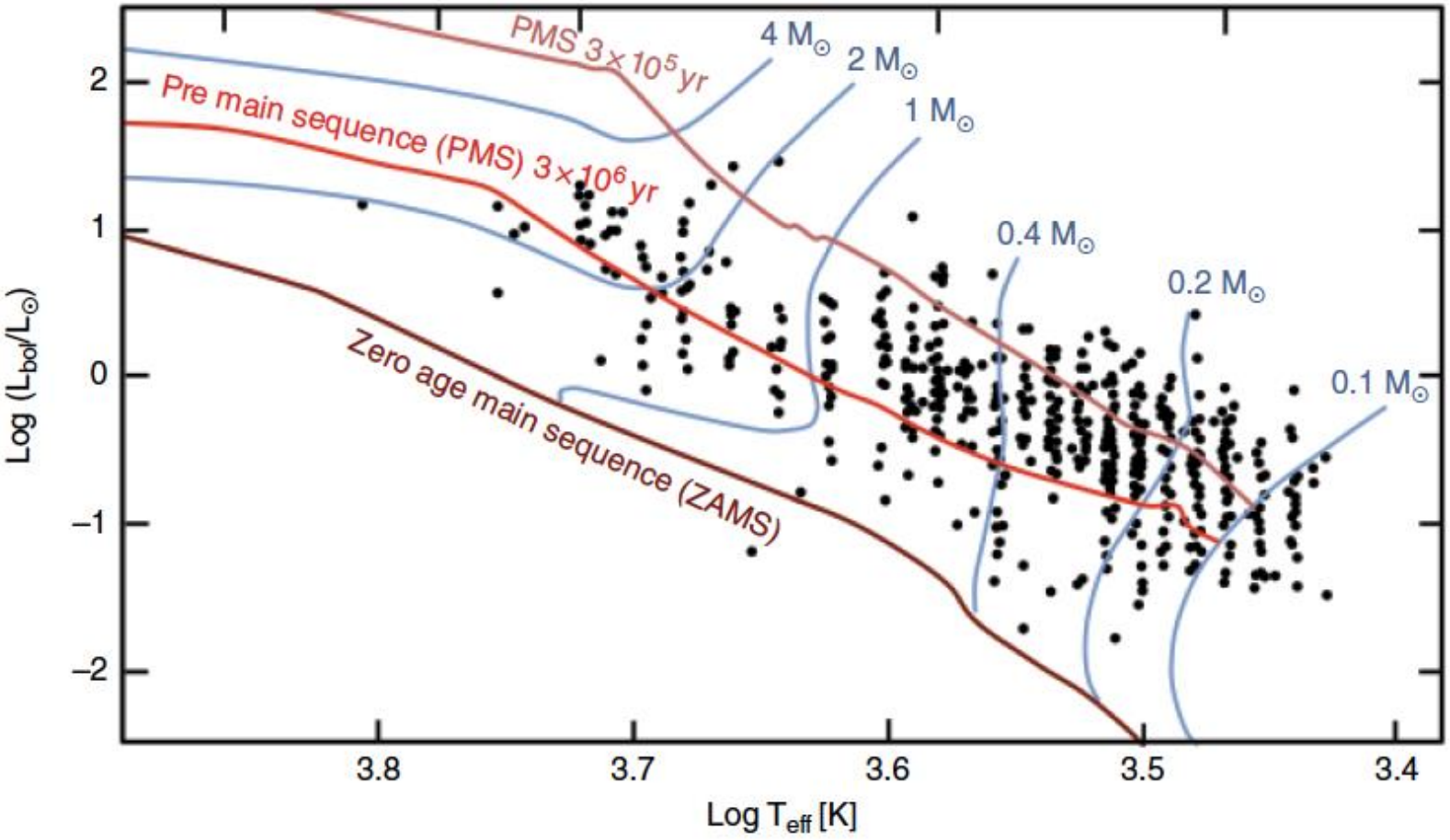
Classification of young stars from André & Montmerle (1994), Feigelson & Montmerle (1999)



Theoretical evolution of a forming star (Hertzsprung-Russel diagram)

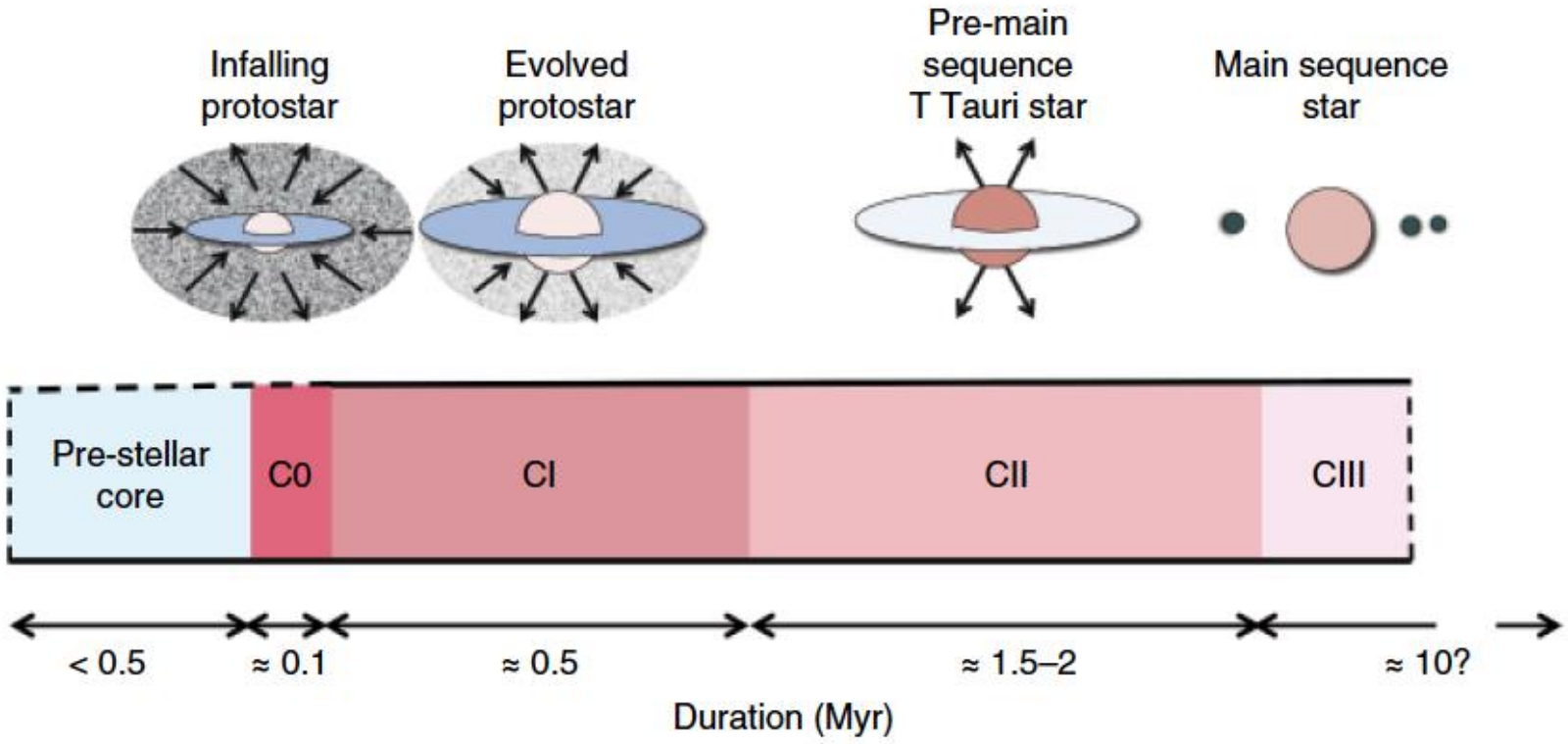


Observed evolution of a forming stars



Credit Preibisch et al. (2005), Siess et al. (2000)

Classification of young stars from André & Montmerle (1994), Feigelson & Montmerle (1999)



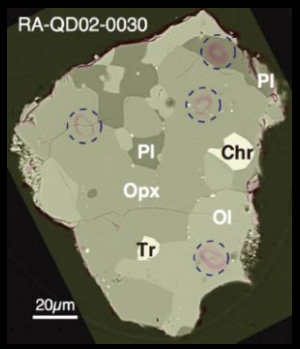
Average duration of each class from Evans et al. 2009

HL Tauri in Taurus constellation (d= 450 light year, age 100 000 years)

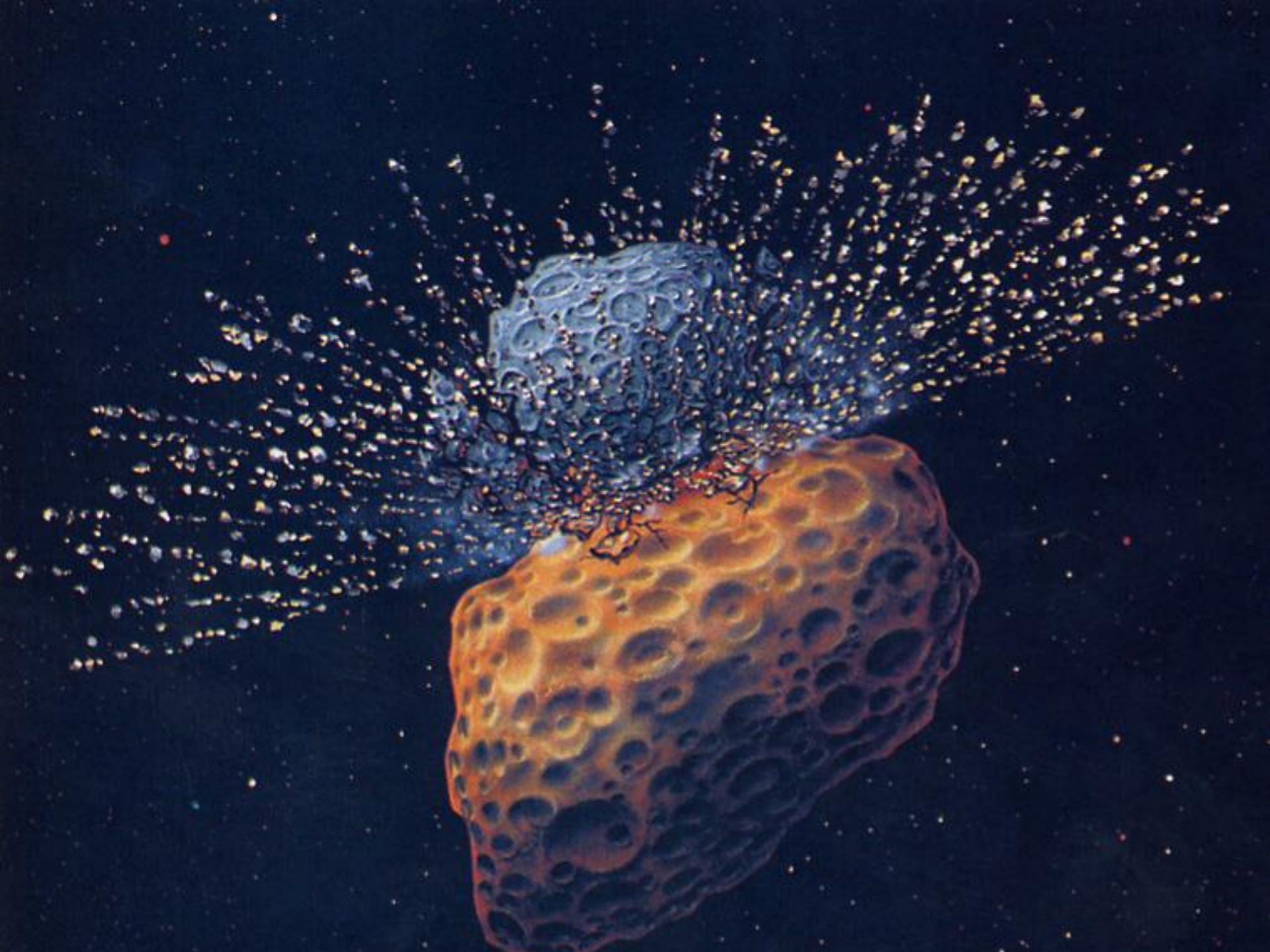
Credit ALMA (ESO/NAOJ/NRAO)

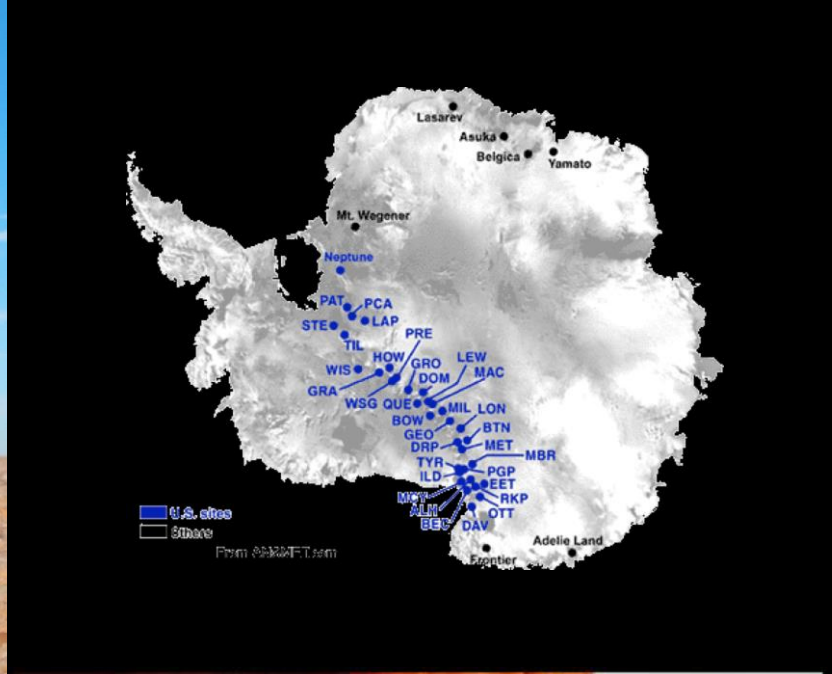
Credit Nasa

More than 1 million asteroids >1km
≈ 200 astreoids > 100 km
Biggest one: Ceres 933 km



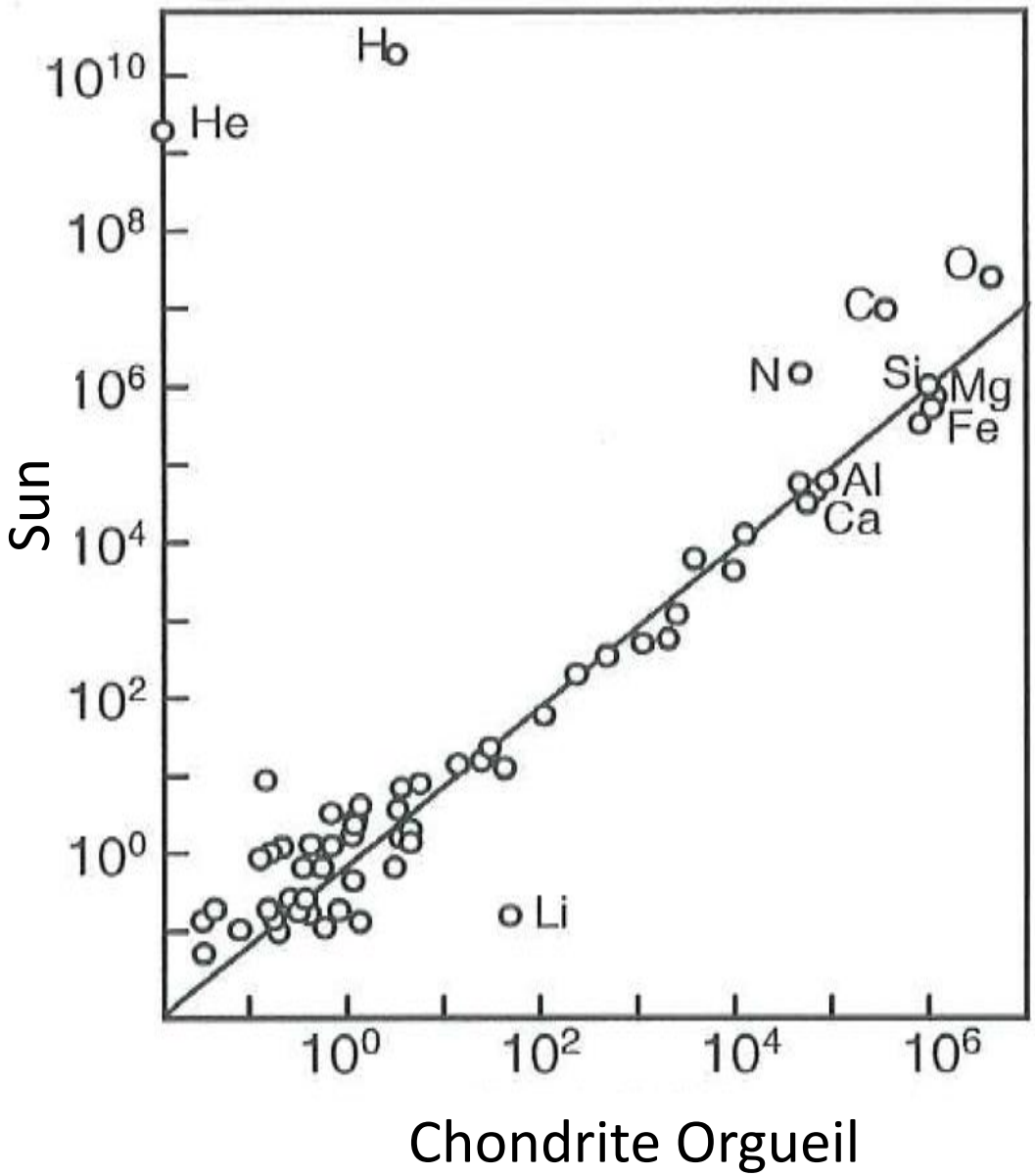
Mission JAXA Hayabusa
Asteroïd Itokawa = chondrite LL
(Yurimoto et al., 2011)

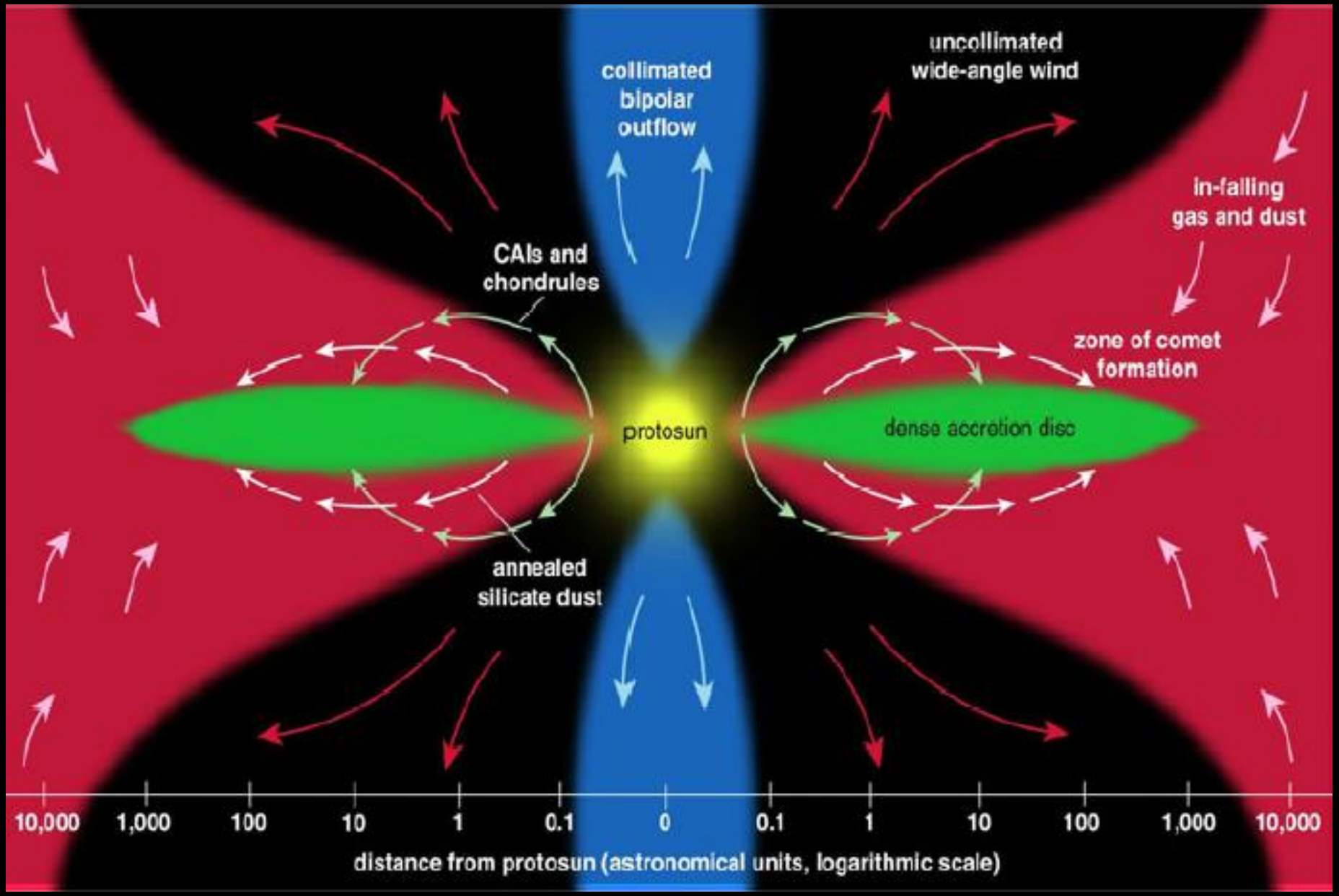



Lasarev
Asuka
Belgica
Yamato
Mt. Wegener
Neptune
PAT
PCA
LAP
STE
TIL
PRE
HOW
WIS
GRO
LEW
DOM
MAC
GRA
WSG
QUE
MIL
LON
BOW
BTN
GEO
DRP
MET
MBR
TYR
PGP
ILD
EET
RKP
OTT
DAV
Adelie Land
Frontier
U.S. sites
Others


Orgueil (MNHN)

The chondrite Orgueil has the chemical composition of the Sun: it shows that presolar dust and gas transformed into planetesimals





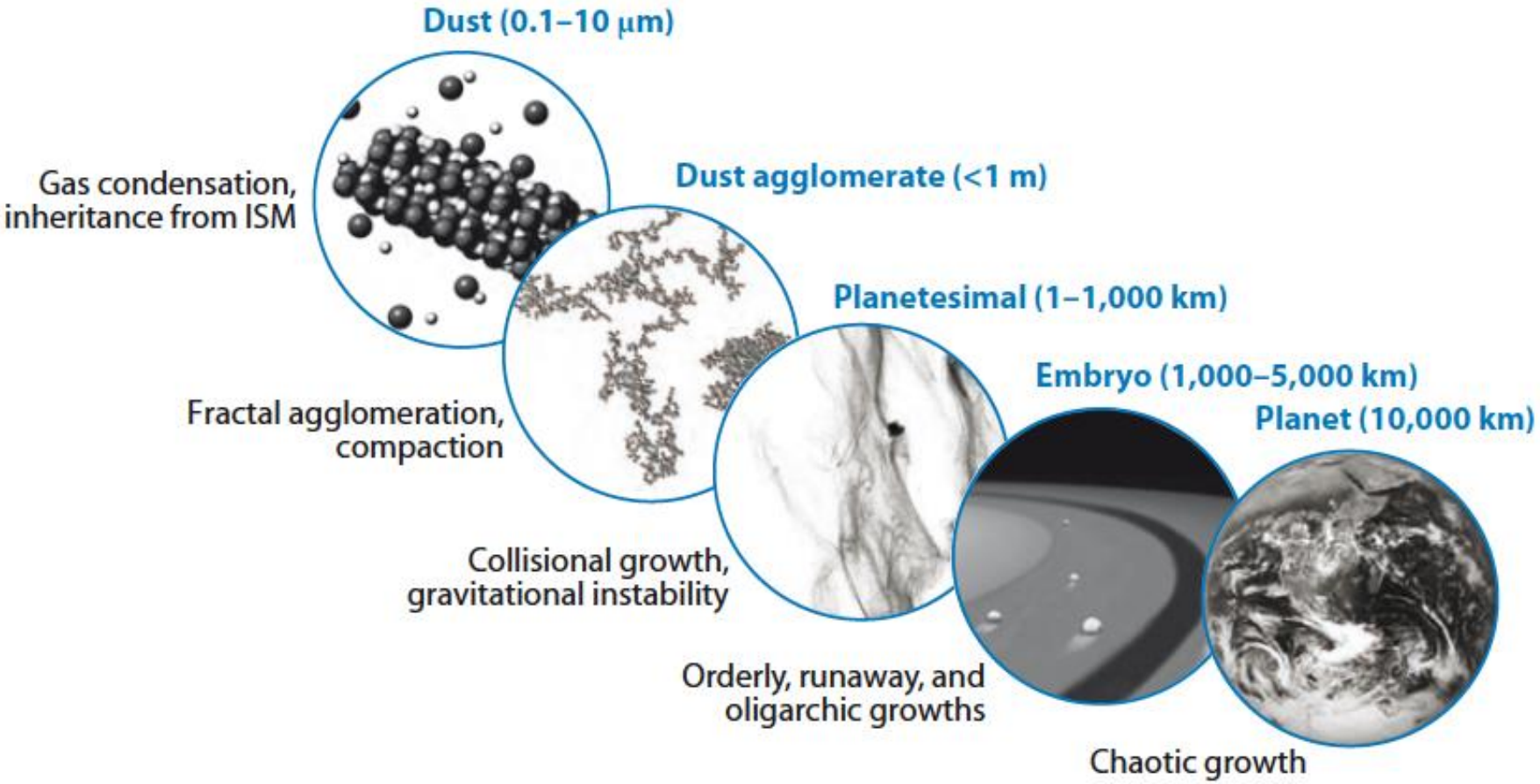
Credit www.psrd.hawaii.edu

Chondrites are “sediments” formed in the accretion disk

They are fragments of planetesimals (100 -1000 km size) that populated the Solar accretion disk a few Myrs after the start of the Solar system (much before the formation of the Earth but much after time zero)

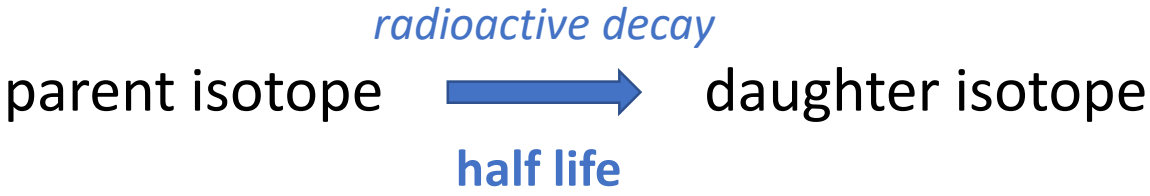
Chondrites are made of:

- chondrules (10 µm-mm) and their fragments: silicate spherules melted at high temperature in the disk from pre-existing solids
- Ca-, Al-rich inclusions (CAIs) made in the disk from condensation products from the gas
- matrix made from a variety of minerals (low T phases, presolar phases, …)



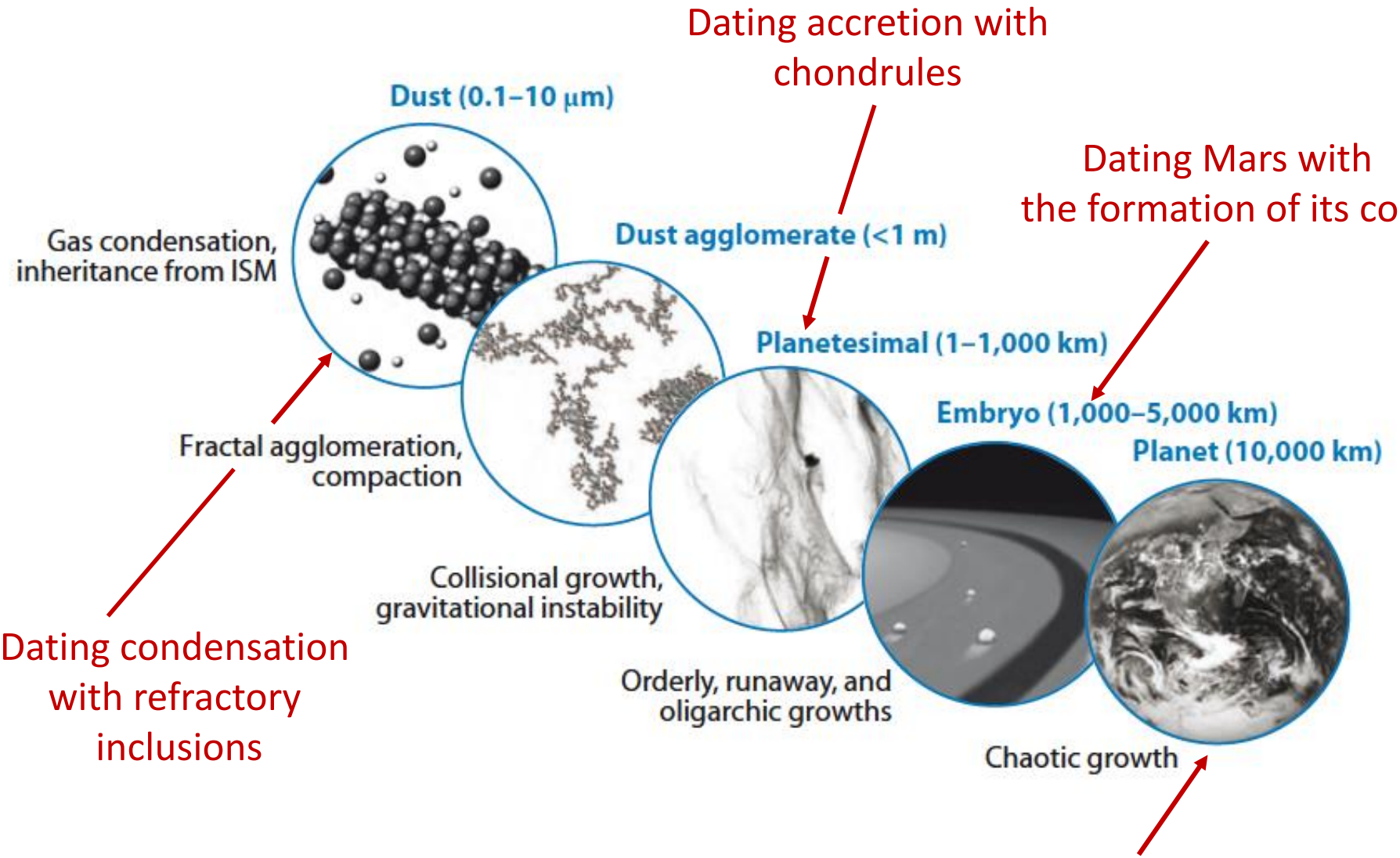
Dauphas & Chaussidon (2011)

We can date very precisely all these processes using natural radioactivity

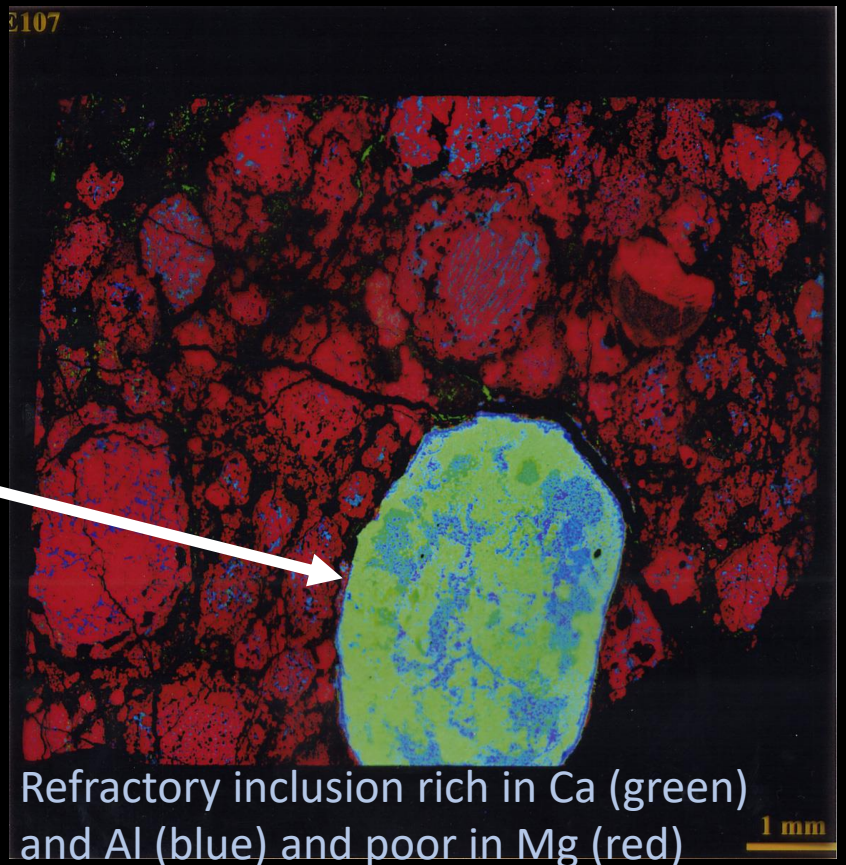


Meteorites are the oldest rocks we know: they have accumumated the products of the radioactive decay of several parent isotopes (e. g. isotopes of uranium decay to isotopes of lead)

High precision analyses of the concentration of the parent and daughter isotopes allow to reach a precision of ± 0.2 million years on an age of 4.5 billion years


Dating accretion with chondrules
Dating Mars with the formation of its core
Dust (0.1–10 μm)
Gas condensation, inheritance from ISM
Dust agglomerate (<1 m)
Planetesimal (1–1,000 km)
Embryo (1,000–5,000 km)
Planet (10,000 km)
Fractal agglomeration, compaction
Collisional growth, gravitational instability
Orderly, runaway, and oligarchic growths
Chaotic growth
Dating condensation with refractory inclusions
Dating the accretion of the Earth with the formation of the Moon and the formation of the Earth core

Allende chondrite

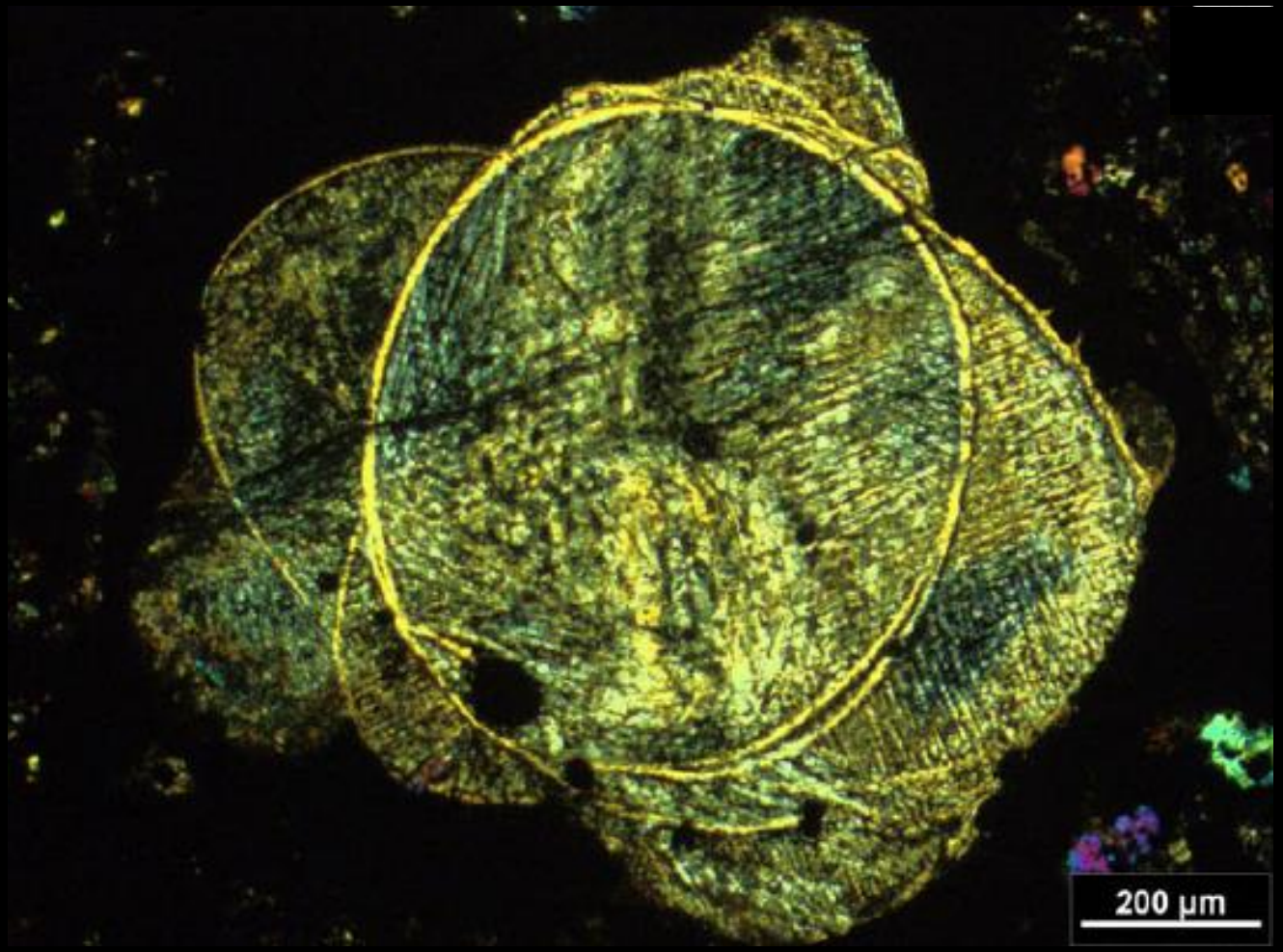


Refractory inclusion rich in Ca (green) and Al (blue) and poor in Mg (red)

The refractory inclusions are the oldest components of meteorites, the oldest minerals of the solar system

Age = 4567.3 ± 0.2 million years (Connelly et al., 2012)

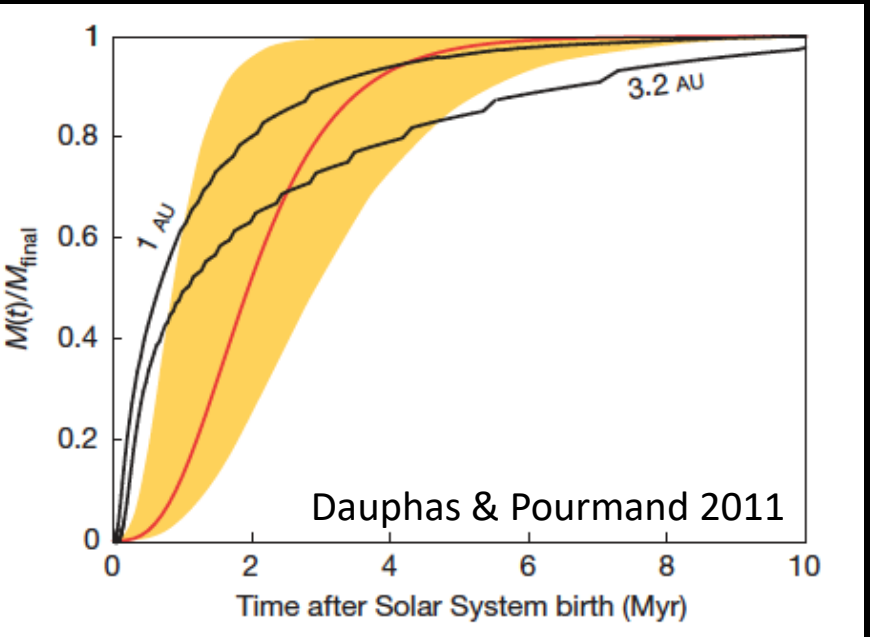
“Exceptional” example of a compound chondrule from Allende made of 16 individual chondrules accreted together (Bischoff et al., 2017)



Minimum age of chondrules = age of accretion of chondrites
≈ 4563 million years

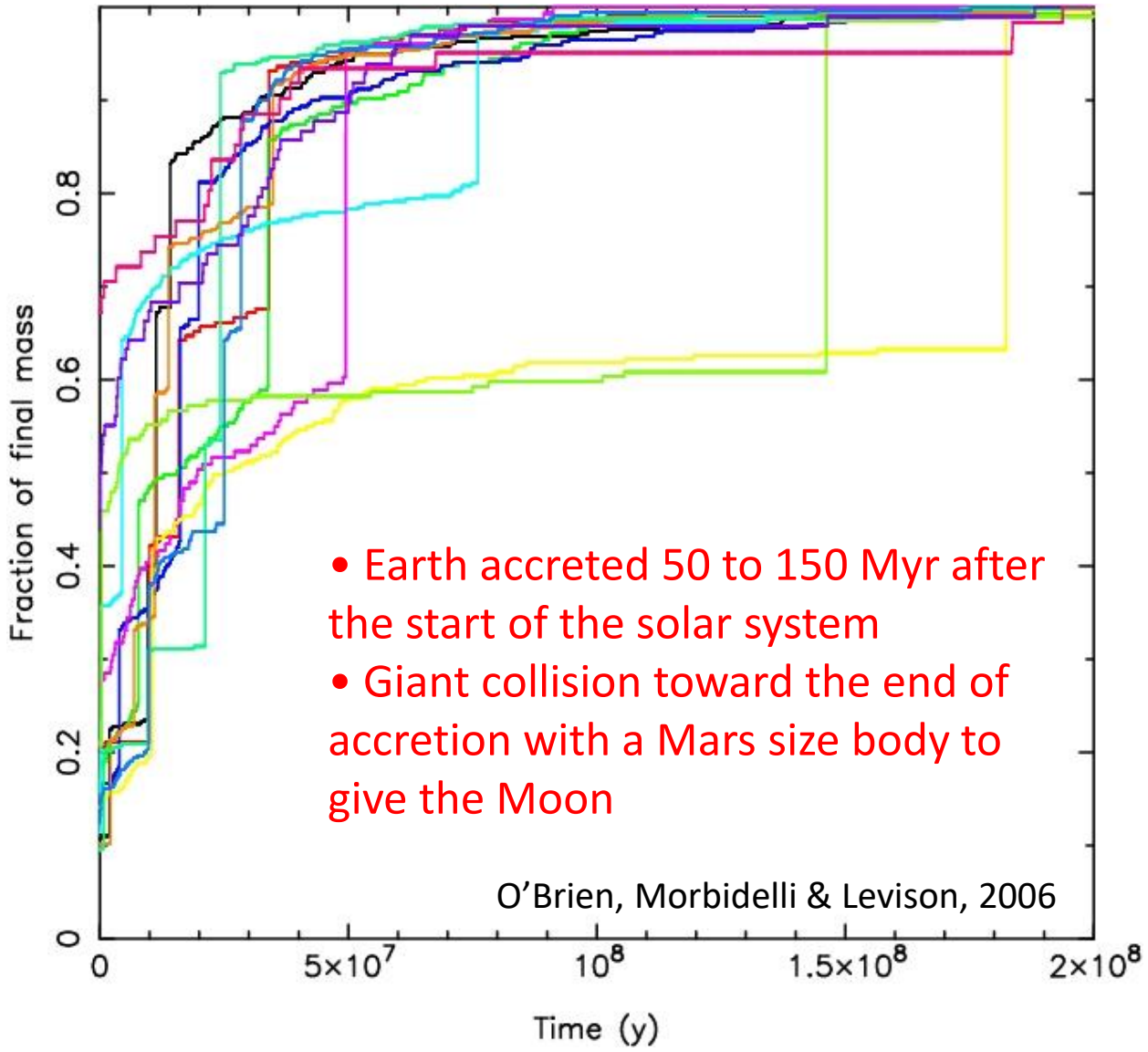
Martian meteorite fell in 1815 in France in the village of Chassigny

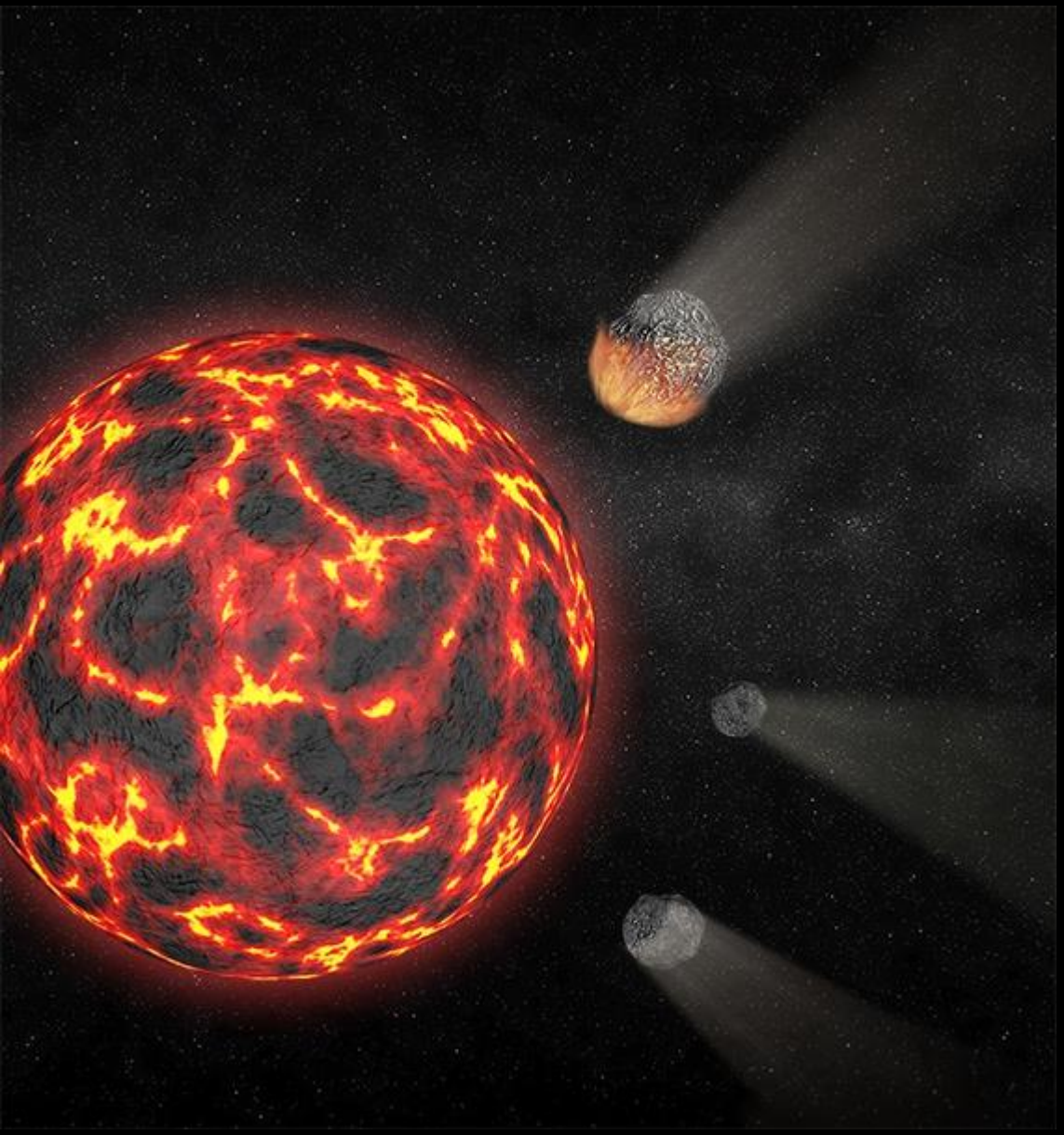
Credit MNHN Paris



Dating of martian meteorites tell that Mars has reached 50% of its size 1.8 Myr after the start of the solar system

Example of numerical simulations showing the accretion of the Earth from planetesimals and embryos

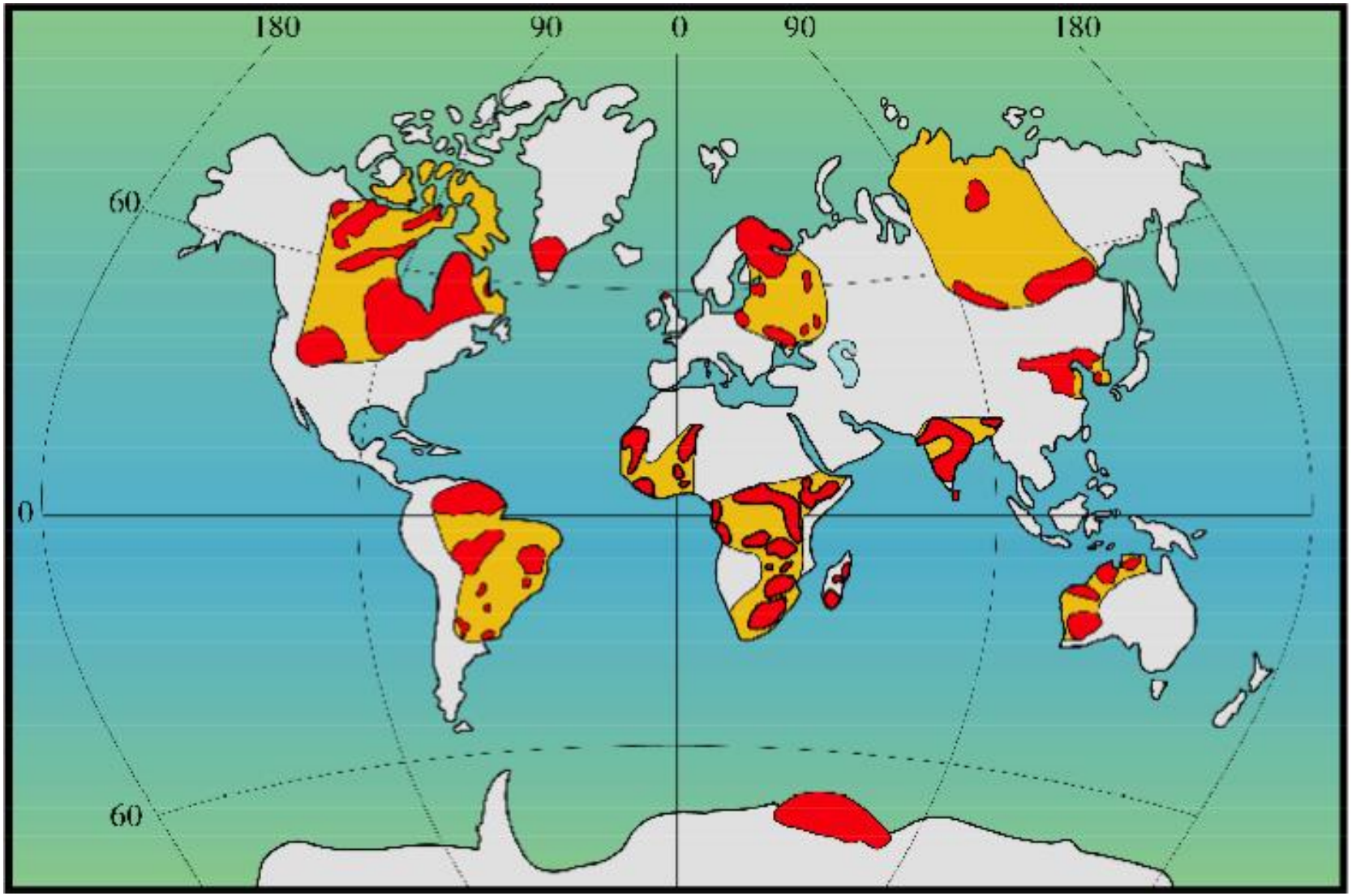




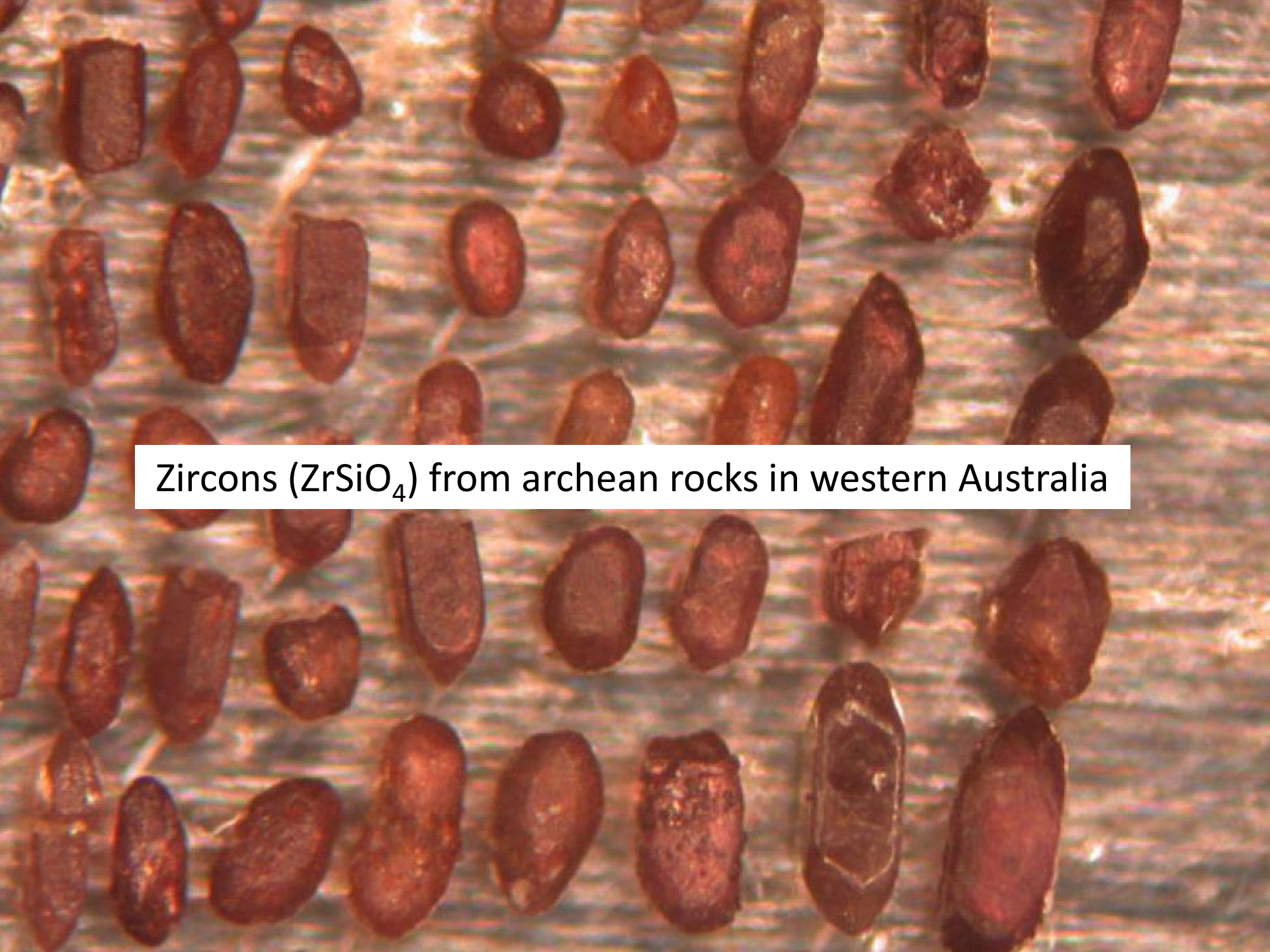
The Earth covered with a magma ocean ≈4.5 Gyrs ago

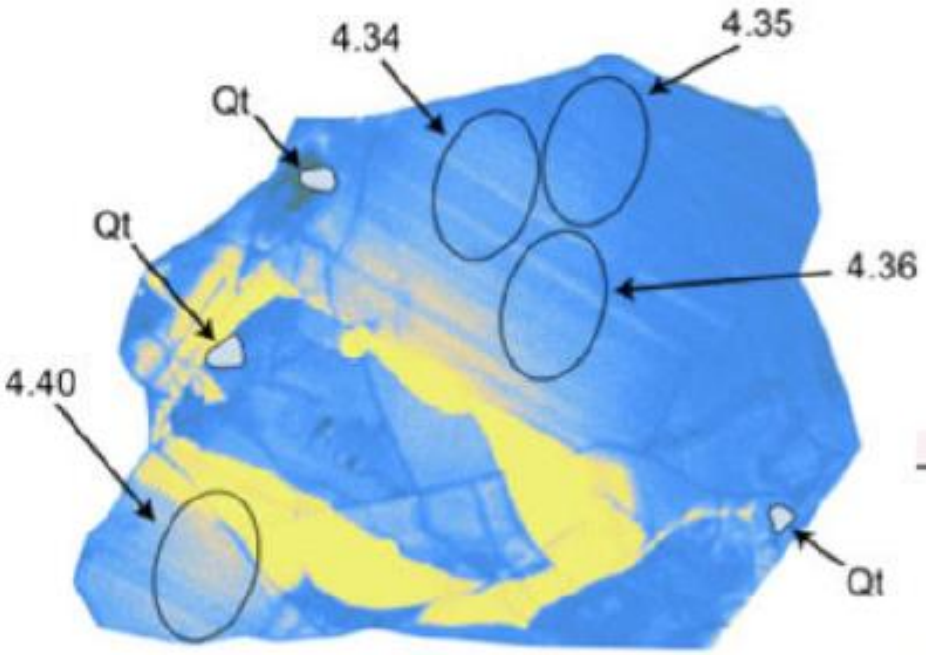
the Earth ≈ 4.4 G yrs ago

No rock from this early period (Hadean) has been preserved

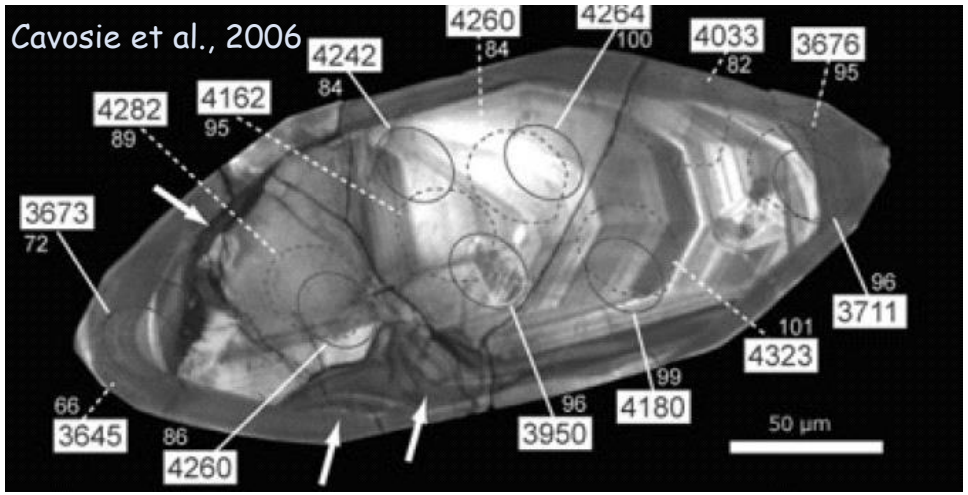


Red = rocks older than 2.5 Gyr at the surface of the Earth
(yellow rocks older than 2.5 Gyr below the surface)


Zircons ($ZrSiO_4$) from archean rocks in western Australia

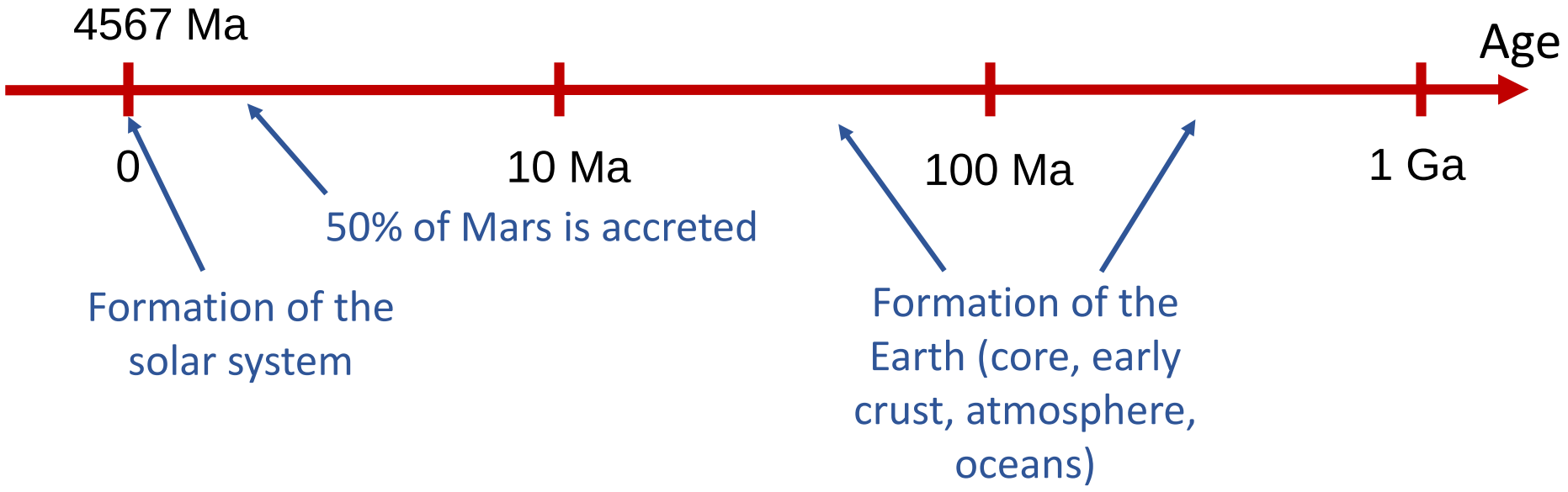


Wilde et al. 2001

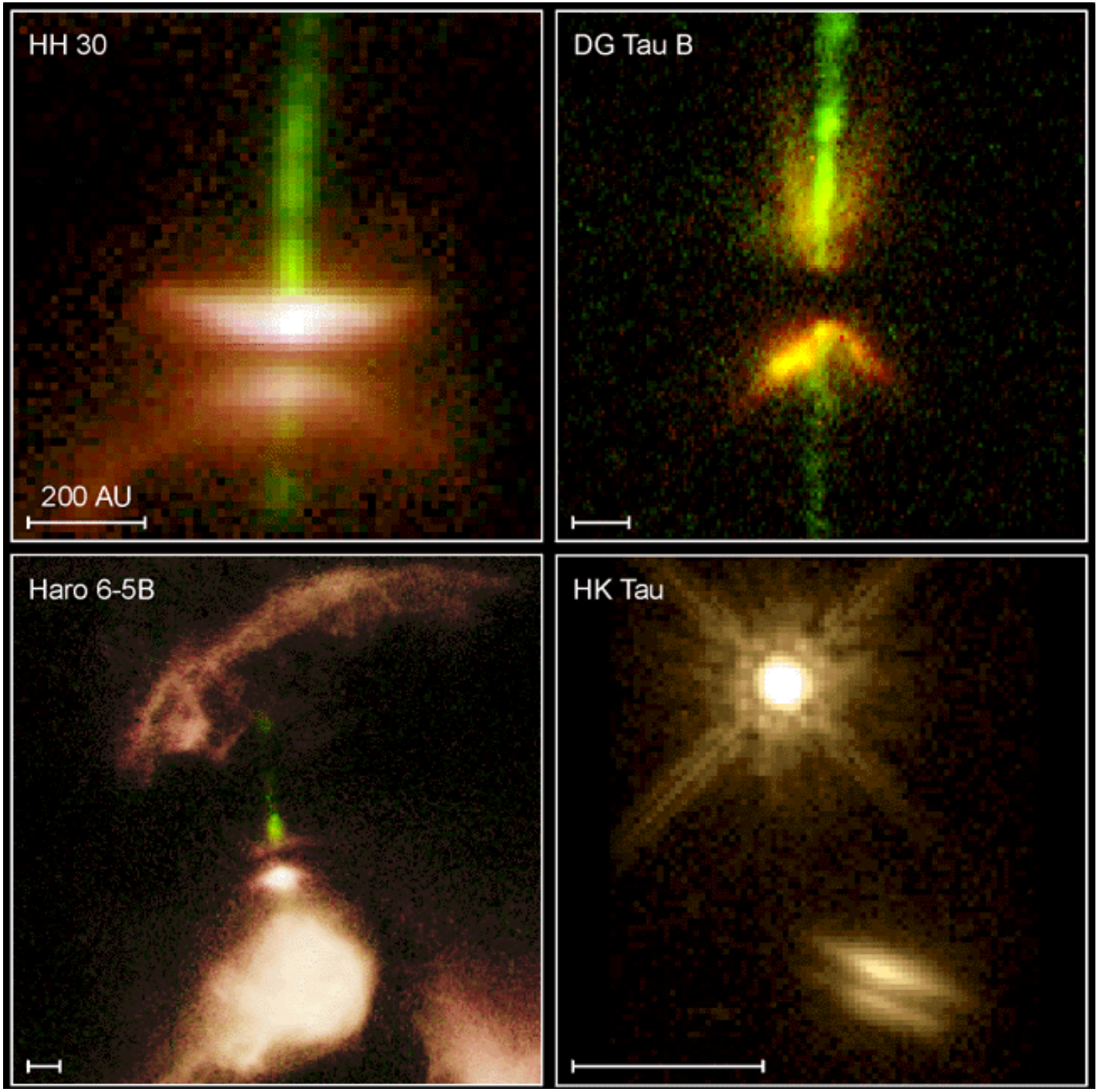


Zircons as old as 4.37 Gyr show that a crust was existing at that time on Earth


Credit NASA


4567 Ma
Age
0
10 Ma
100 Ma
1 Ga
50% of Mars is accreted
Formation of the solar system
Formation of the Earth (core, early crust, atmosphere, oceans)

Chandra observation (7 days long, 50 X-rays images)
Courtesy Eric Feigelson (COUP/NASA)


HH 30
200 AU
DG Tau B
Haro 6-5B
HK Tau