Mass transport regimes in the solar protoplanetary disk – evidence from meteoritic components

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CENTRE FOR STAR AND PLANET FORMATION

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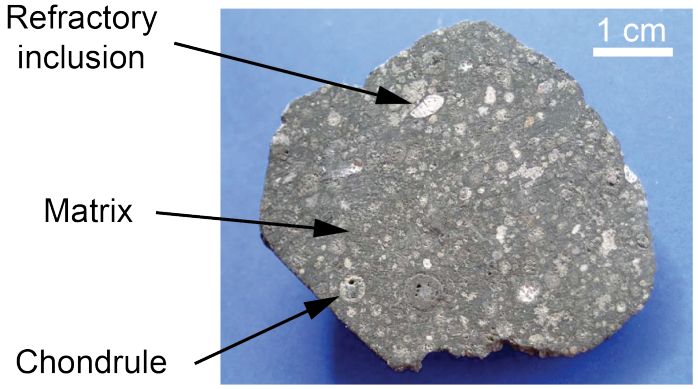
A time-window into solar system processes

Meteorites and their components provide the ONLY means to probe the earliest formative stages of the Sun and its protoplanetary disk

Primitive meteorites



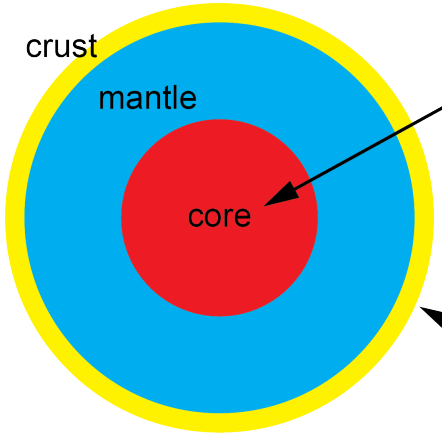
Nucleosynthetic make-up of molecular cloud (MC)

Timescale of MC collapse

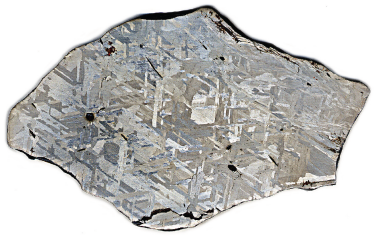
Formation of the Sun and protoplanetary disk

Thermal evolution of protoplanetary disk

Differentiated asteroids



iron meteorites



basaltic meteorites

Asteroid accretion efficiency

Timing of accretion and differentation

Mechanism(s) of planetary differentaition

Huge potential – but need to interpret the meteorite record in the context of a collapsing MC evolving into a young star and its protoplanetary disk

A time-window into solar system processes

Mete… …s to probe the
earli… …y disk

Pri…

Refractory inclusion

Matrix

Chondrule

Nucleosynthetic m…

Timescale of MC c…

Formation of the S…

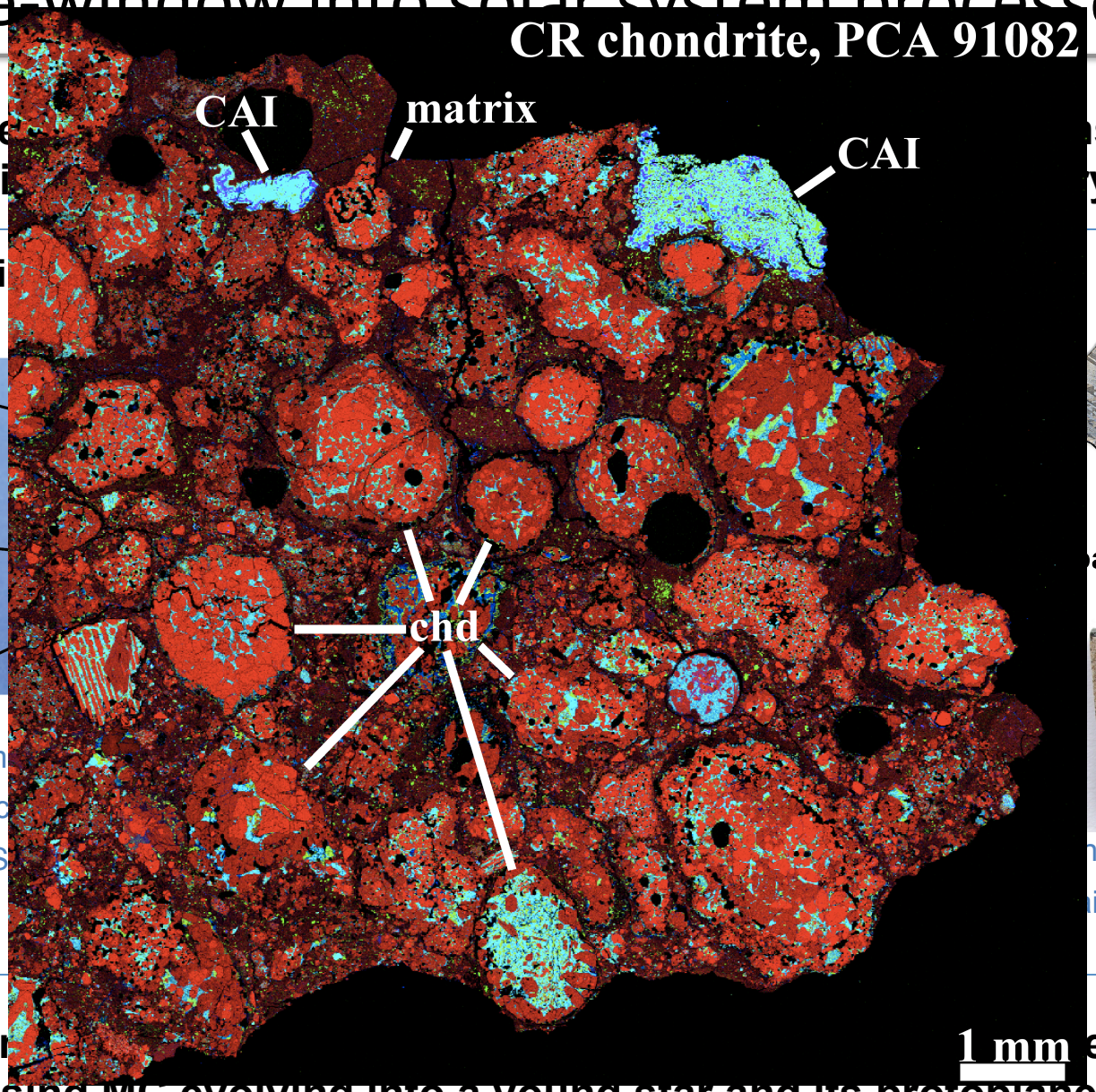
Thermal evolution …

iron meteorites

…asaltic meteorites

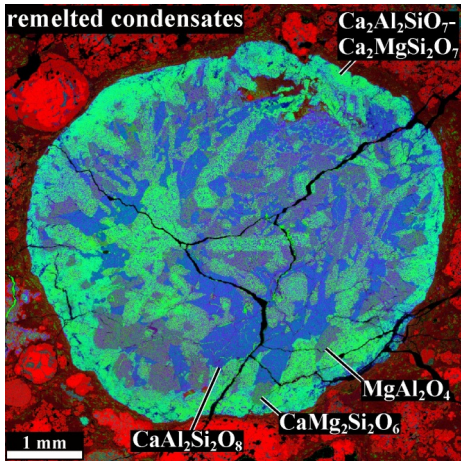
…n

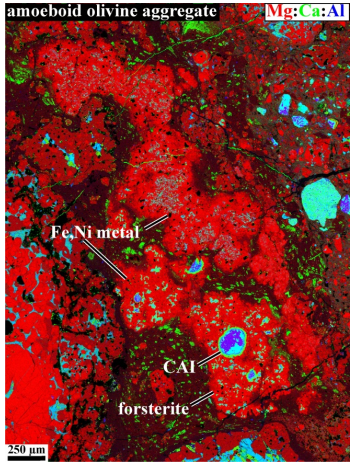
…ition



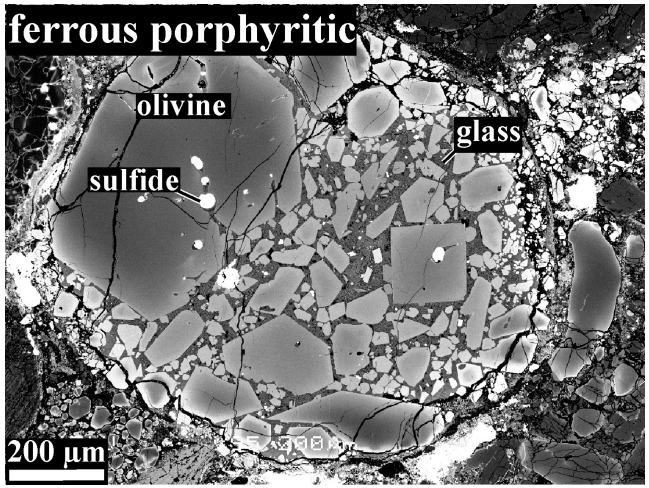
Huge poter… …e context of
a collapsing MC evolving into a young star and its protoplanetary disk

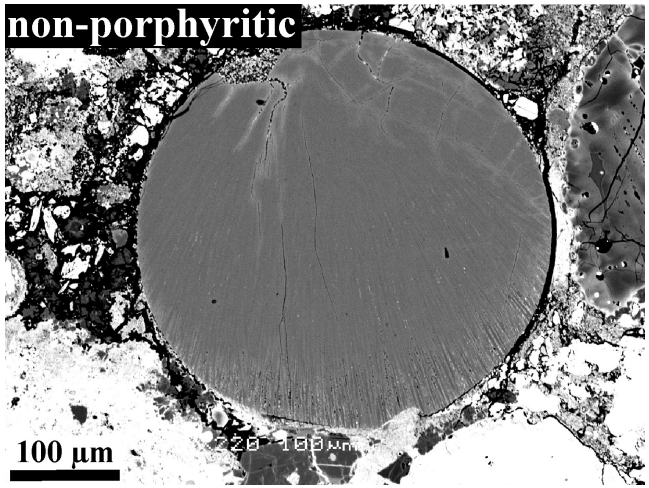
Chondrite components – CAIs & chondrules





^{26}Al-rich CAIs (canonical)
^{26}Al-poor CAIs (FUNs)
Perhaps formed within 2,500 years
Evidence for ^{10}Be – innermost PPD
Present in carbonaceous chondrites
Nearly absent in other chondrites

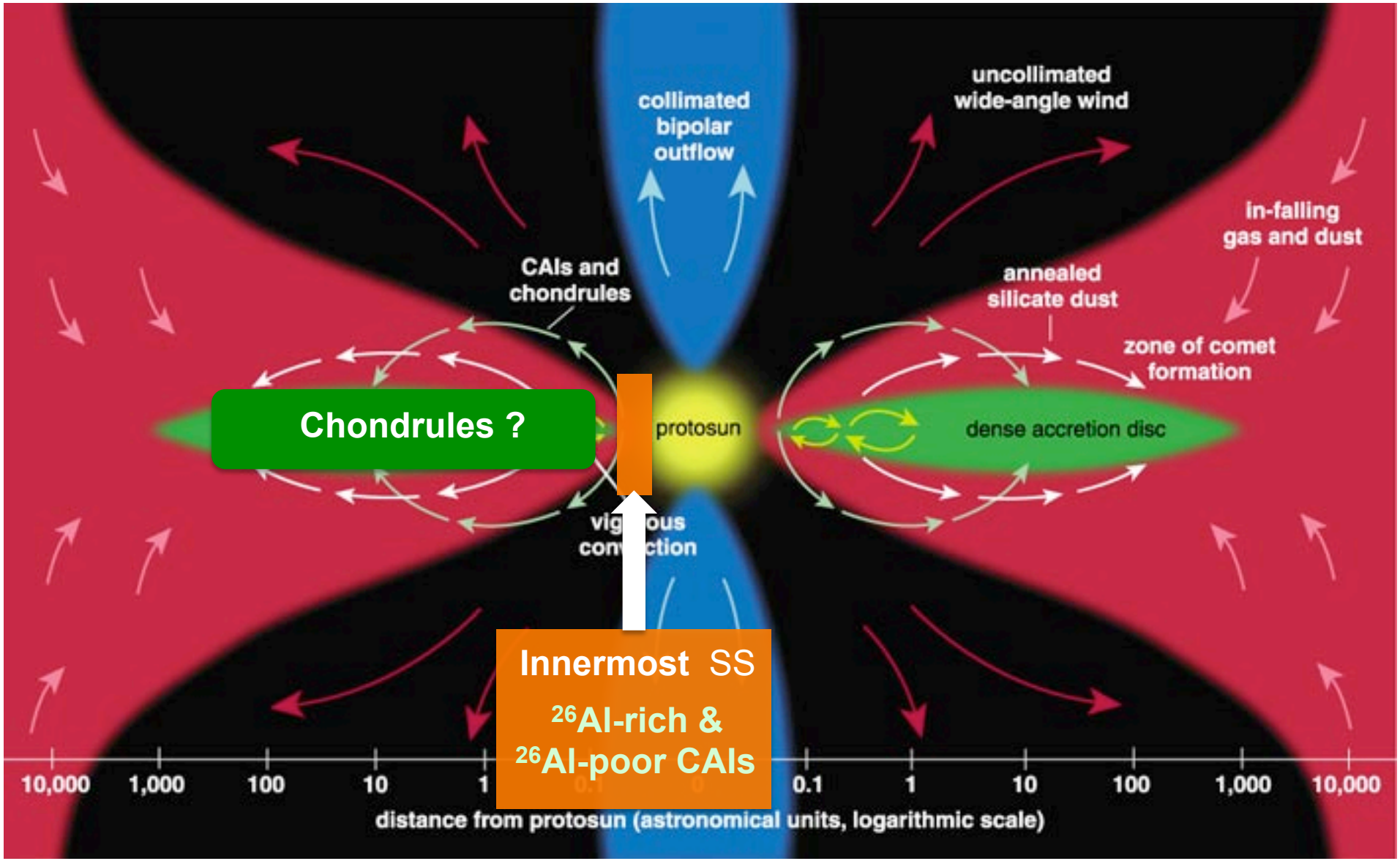




In all chondrites
Low $[^{26}Al/^{27}Al]_0$
Variable Pb-Pb ages
Disk lifetime

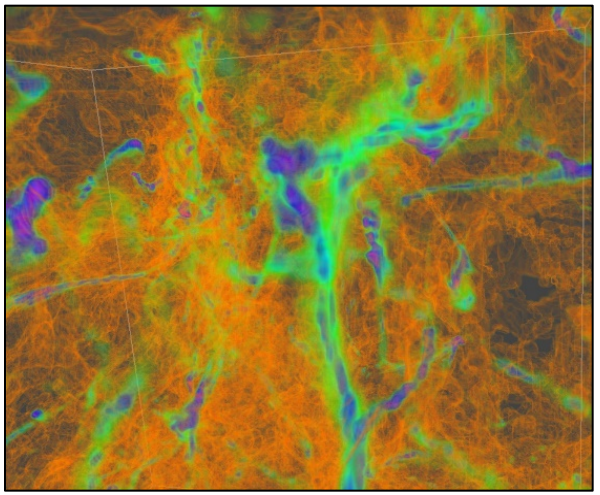
Let's not worry about the matrix for now… mixture of components

Dynamical evolution of the protoplanetary disk



Supercomputer simulations: clouds to disks

- *ab initio* simulations of formation of circumstellar disks (a first!)
  - Using Adaptive Mesh Refinement (modified version of RAMSES)
- Outer scale 40 pc, inner scale 0.01 AU
  - Ratio 1 : 2^{30} ≈ 1 : 1 billion
  - Zoom over 7 orders of magnitude

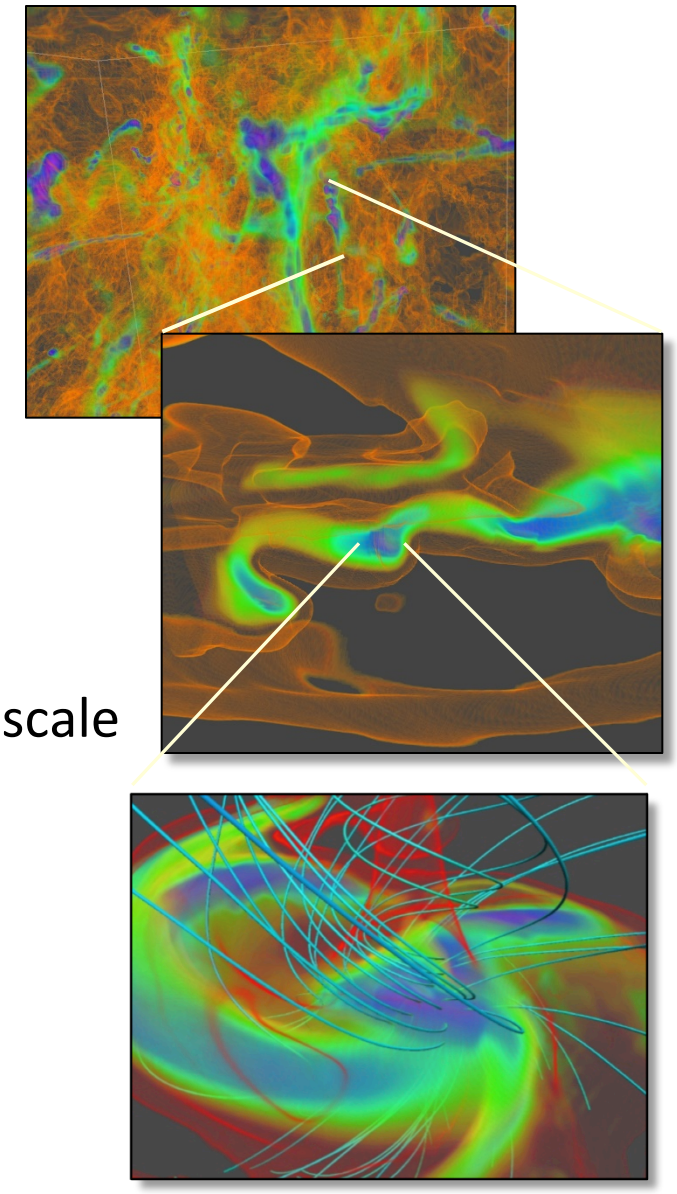


- A few stars
  - All ≈ solar-mass star
  - Plan: Get a statistically significant sample of solar mass stars
- The initial and boundary conditions follow from the statistical properties of the interstellar medium

Nordlund *et al.* (2013) astro-ph/1309.2278

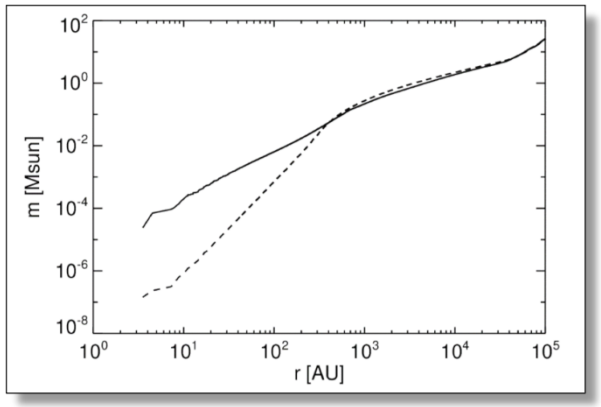
Zooming in on the formation of PPD

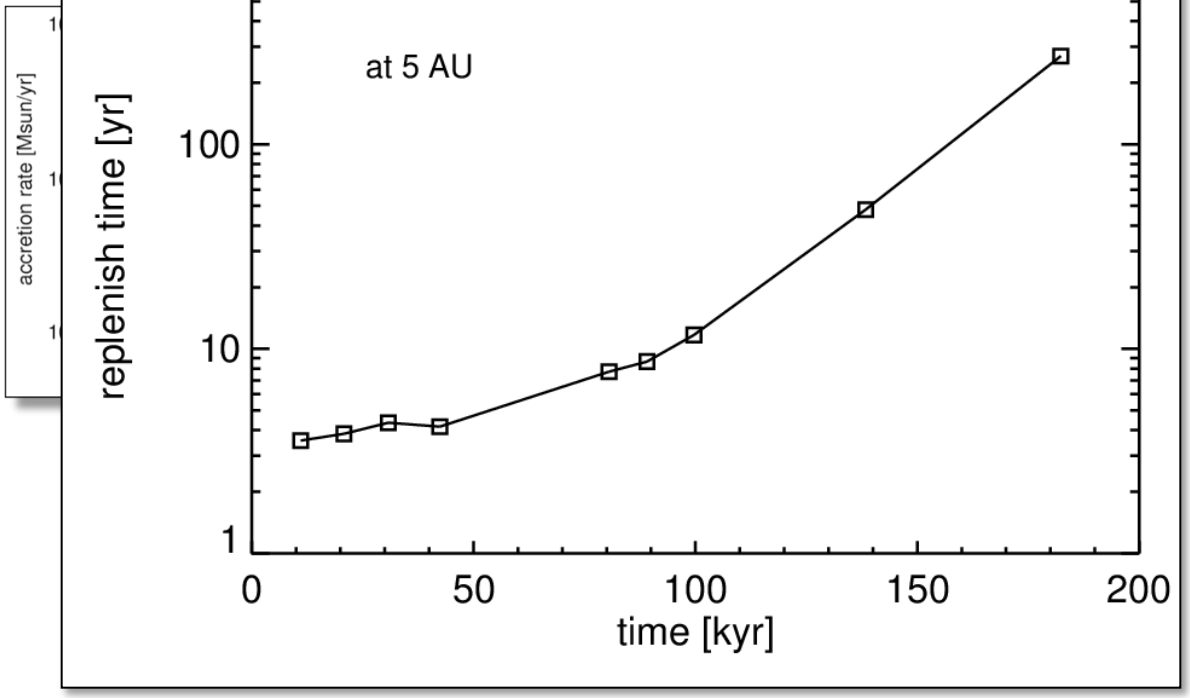
- ***Giant Molecular Cloud scales***
  - Size: 40pc
  - Refinement: $2^{16} \Rightarrow$ cell size 125 AU
  - Time duration: ≈ 10 Myr
- ***Stellar accretion scales***
  - Dynamic scale: ≈ 0.5 pc = 10.000 AU
  - Refinement: $2^{22} \Rightarrow$ cell size 2 AU
  - Time duration: ≈ 100 kyr ≈ accretion time scale
- ***Accretion disk scales***
  - Dynamic scale: ≈ 5 AU
  - Refinement: 2^{29} => cell size 0.015 AU (!)
  - Time duration: ≈ 1000 yrs



Disk replenishment time scales

(disk mass) / (accretion rate) = time scale

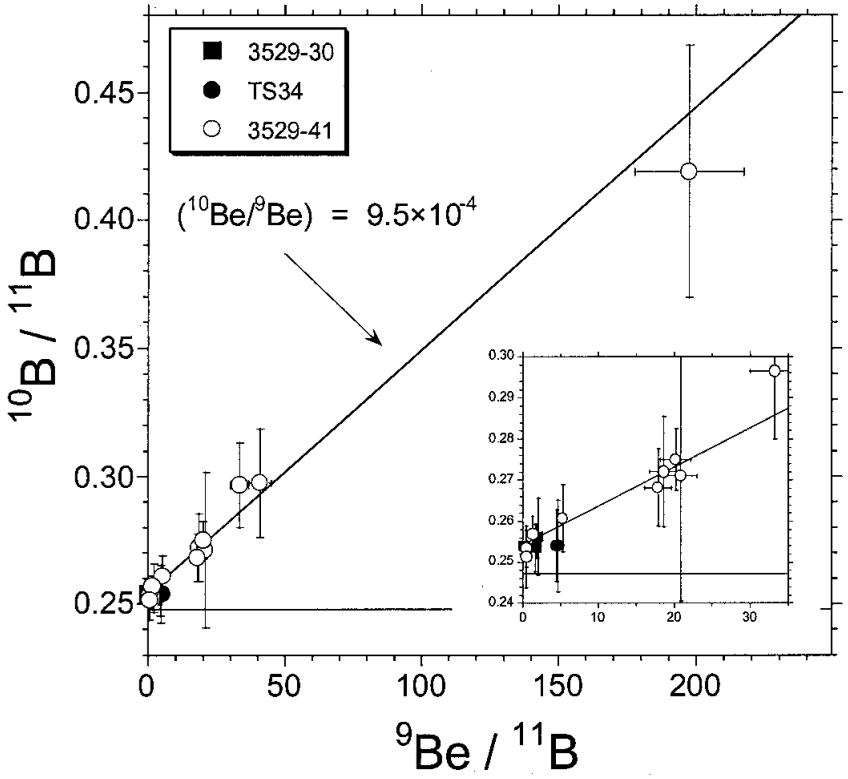




Extremely brief residence time of material in the protoplanetary disk

Evidence for large scale outward transport

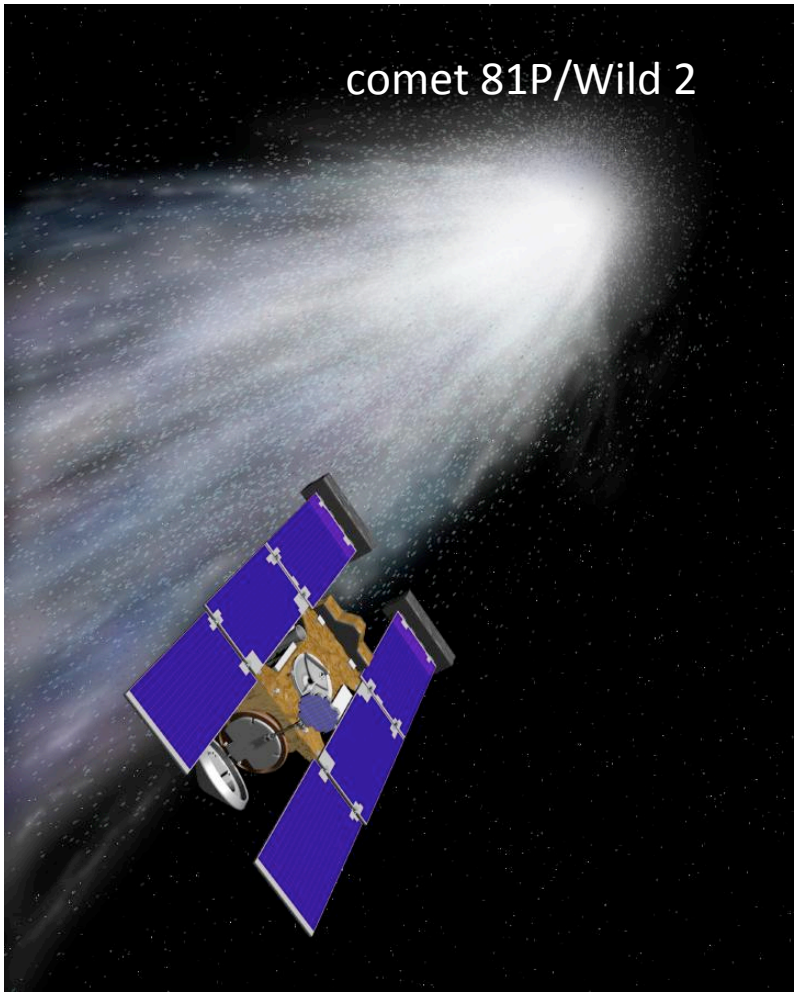
Presence of refractory high-temperature components in the accretion regions of carbonaceous chondrites (formed beyond snow line) requires efficient outward transport

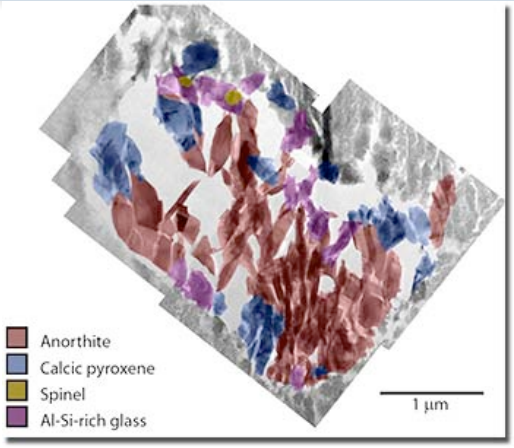


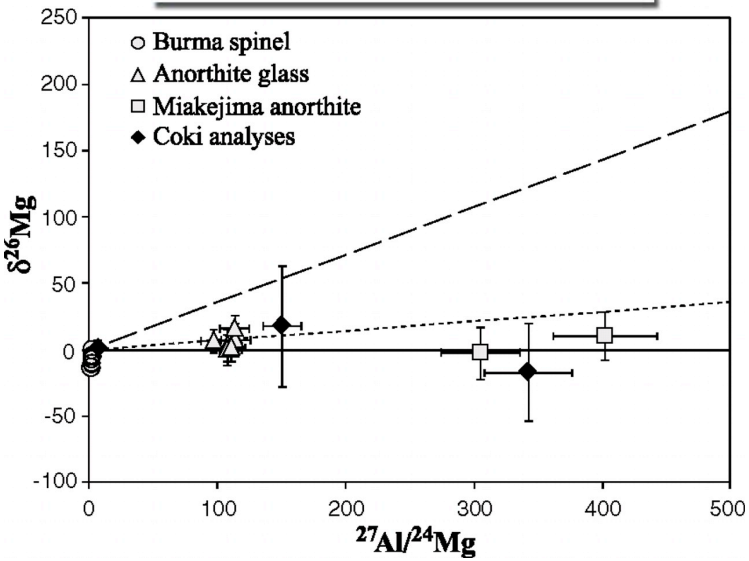
McKeegan *et al.* (2000) *Science* **289**, 1334

^{26}Al-free CAI-like object in comet 81P/Wild 2?

Analysis of samples returned from STARDUST mission suggest the presence of early-formed ^{26}Al-free CAI material in the accretion region of Jupiter-family comets



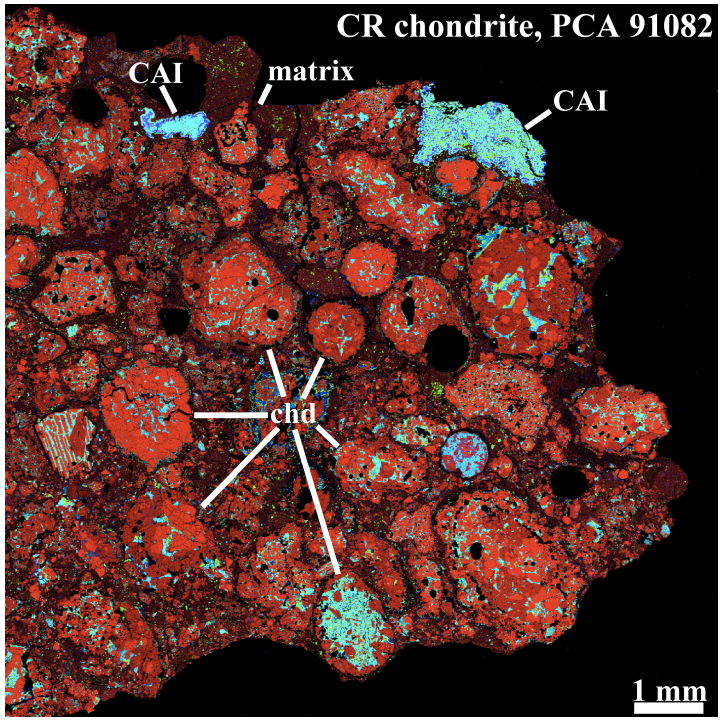




Matzel *et al.* (2010) *Science* ***328****, 483*

This study: using chondrules to track transport

Chondrule are the dominant chondrite constituent and must reflect one of the most energetic process that operated in the early solar system: **precursor material to planets.**



Are there age variations amongst chondrules from individual chondrite groups? Storage?

U-corrected Pb-Pb dating

Where did chondrules from individual chondrite groups formed? Locally? Various distances?

Isotope fingerprinting - using ^{54}Cr as DNA

Chondrites formed in the INNER SS:

➔ *Enstatite and ordinary chondrites*

Chondrites formed in the OUTER SS:

➔ *CV and CR carbonaceous chondrites*

The U-Pb system: absolute assumption-free ages

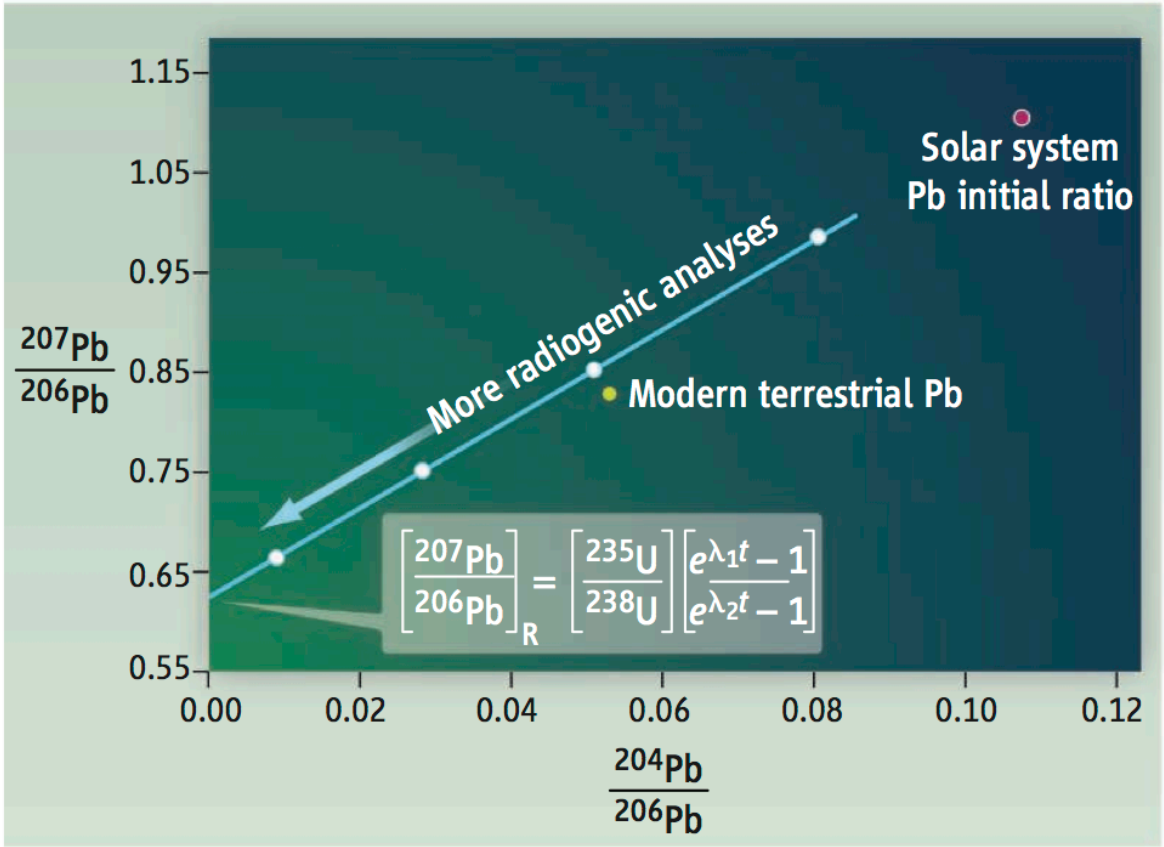
- The U-Pb decay system is the only assumption-free chronometer that provide absolute ages with a resolution of ~200,000 years

$^{238}U \rightarrow {}^{206}Pb$

$T_{1/2} \sim 4.5$ Gyr

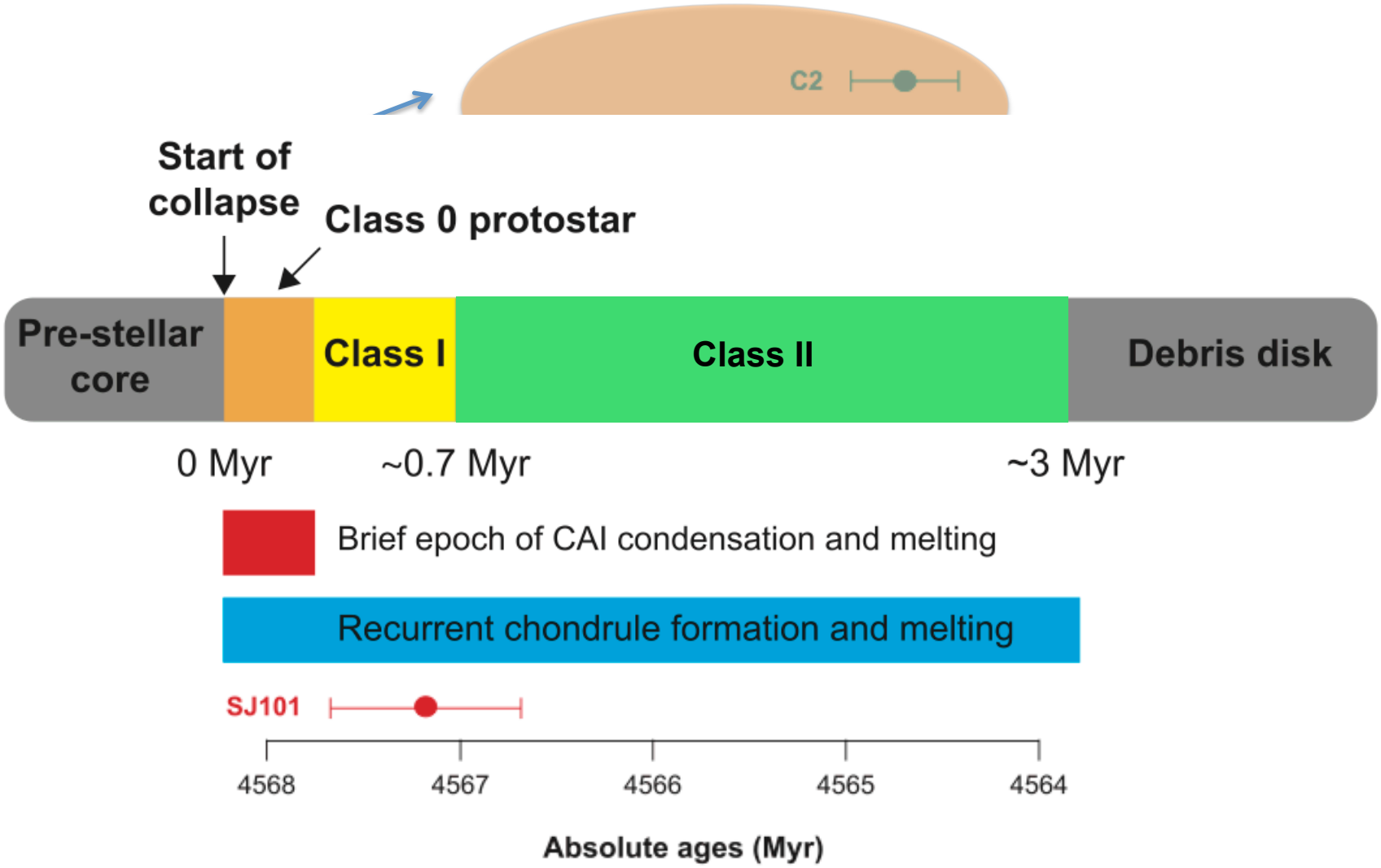
$^{235}U \rightarrow {}^{207}Pb$

$T_{1/2} \sim 0.7$ Gyr

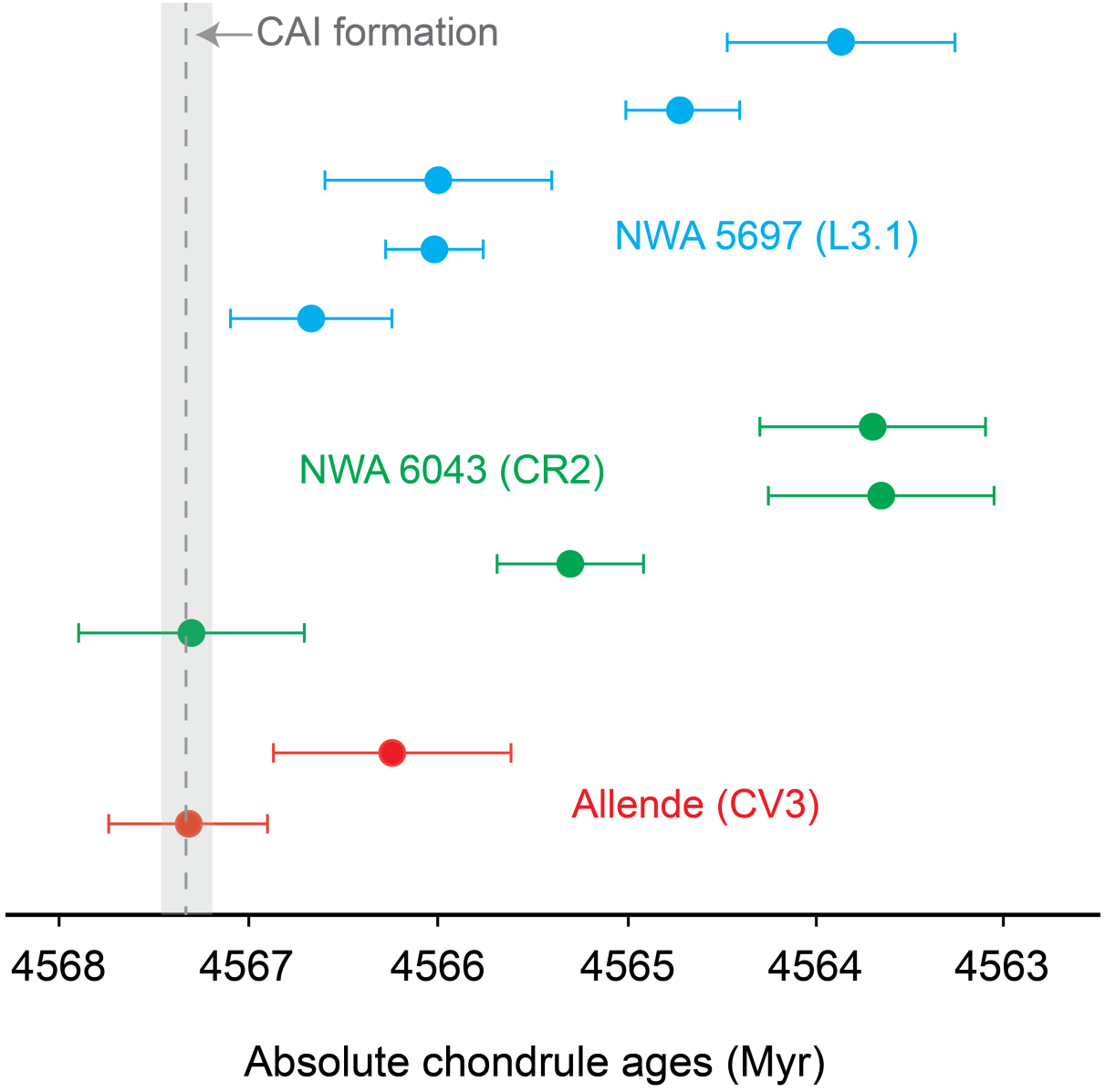


Absolute chronology of CAIs and chondrules

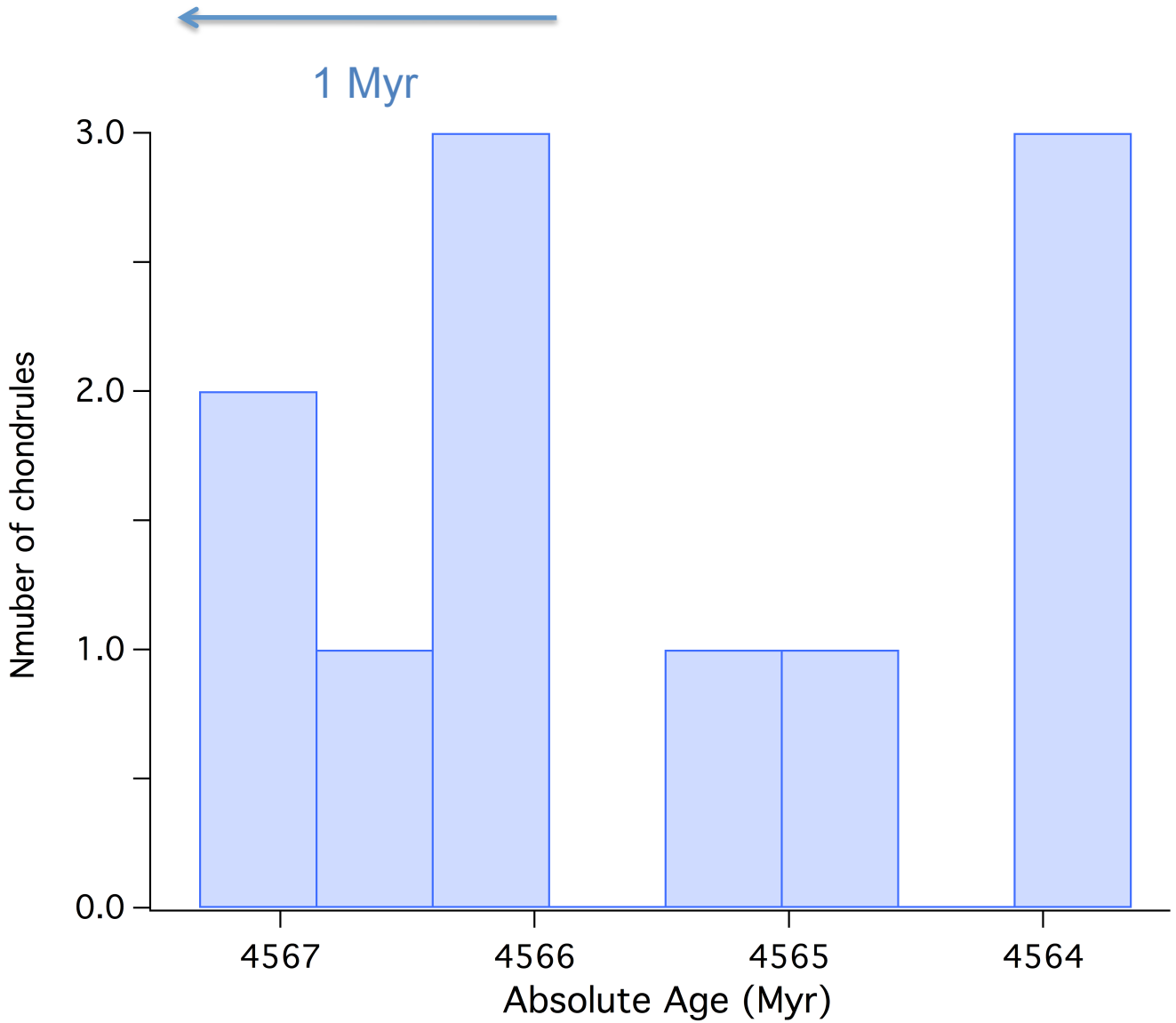
Chondrule formation started contemporaenously with CAIs and lasted about 3 Myr



Absolute chronology of chondrules – new data

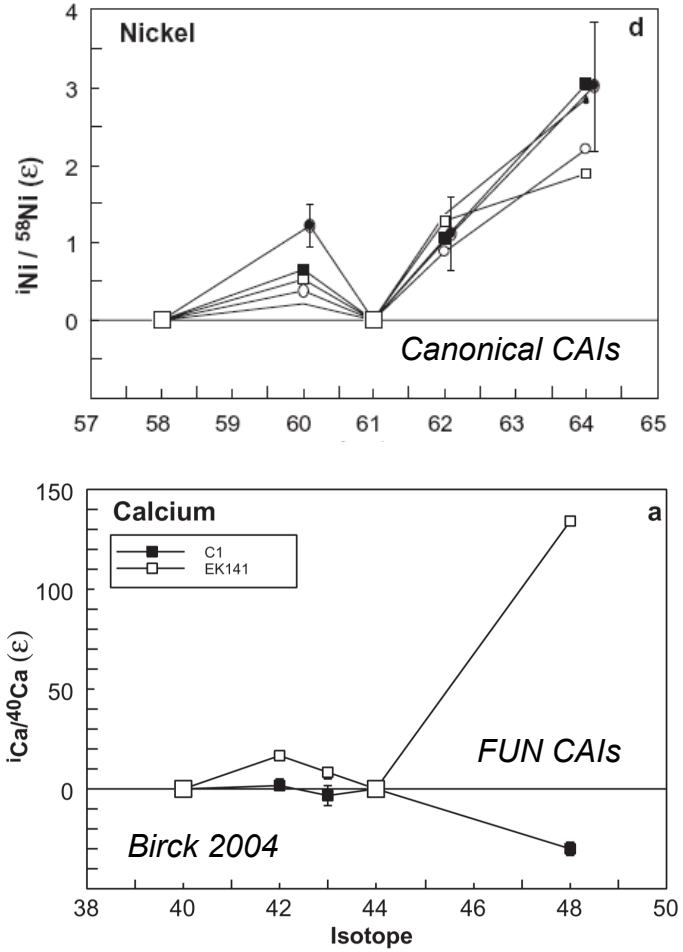


Age distribution of chondrules (N = 11… soon 50!)



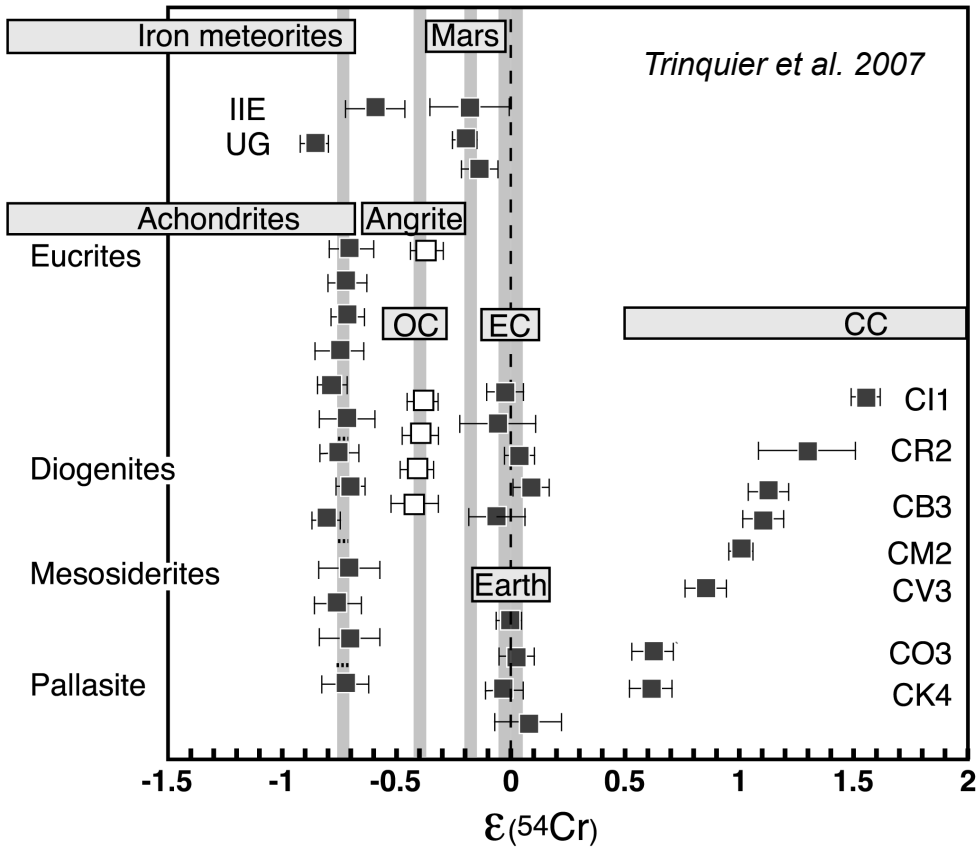
Evidence for widespread isotope heterogeneity

The discovery more than 30 years ago of isotopic anomalies in meteorites and their components indicates inefficient mixing of presolar components in the protoplanetary disk.

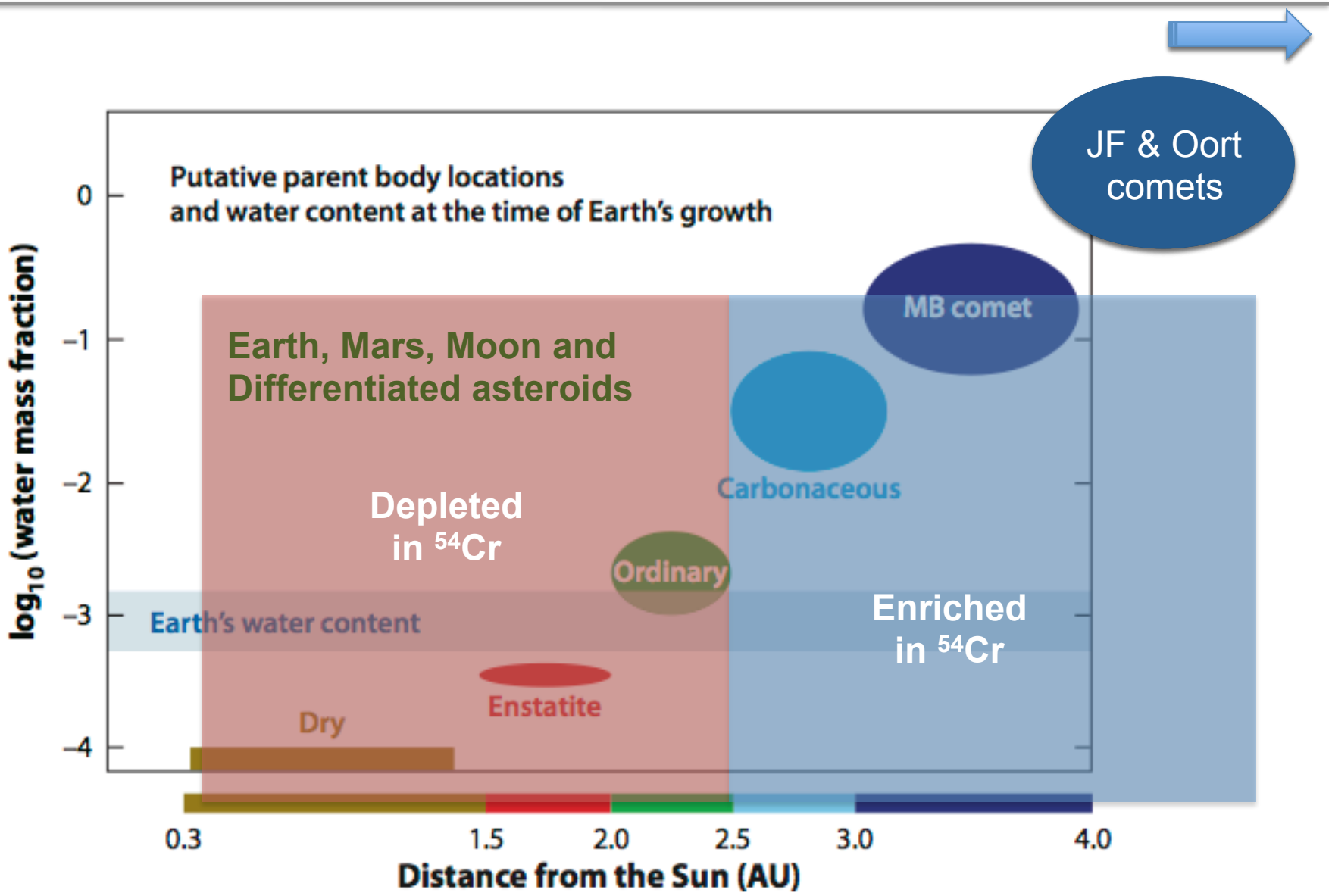


Early solar system solids

Bulk planetary materials

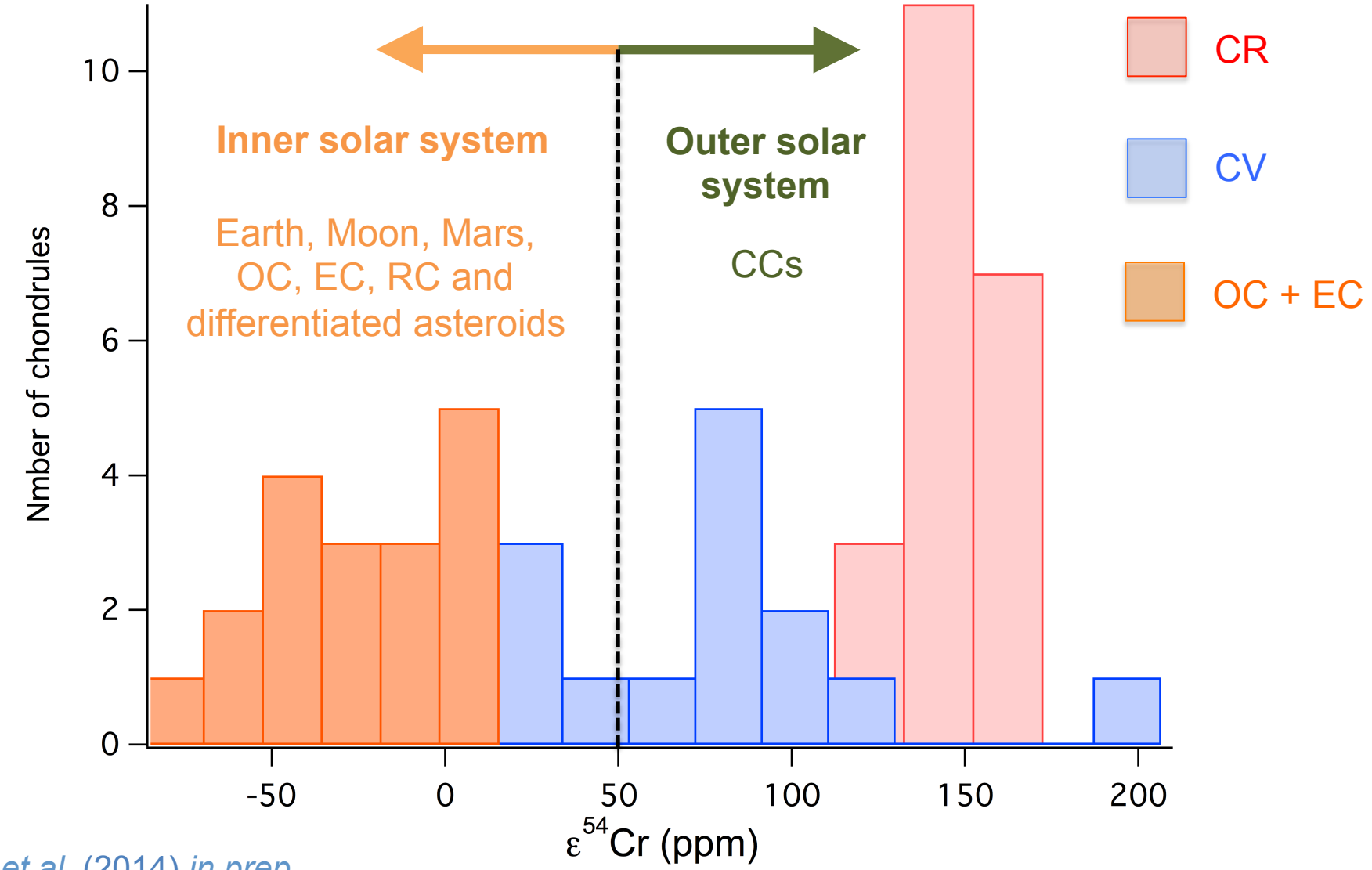


Accretion regions of chondrite classes



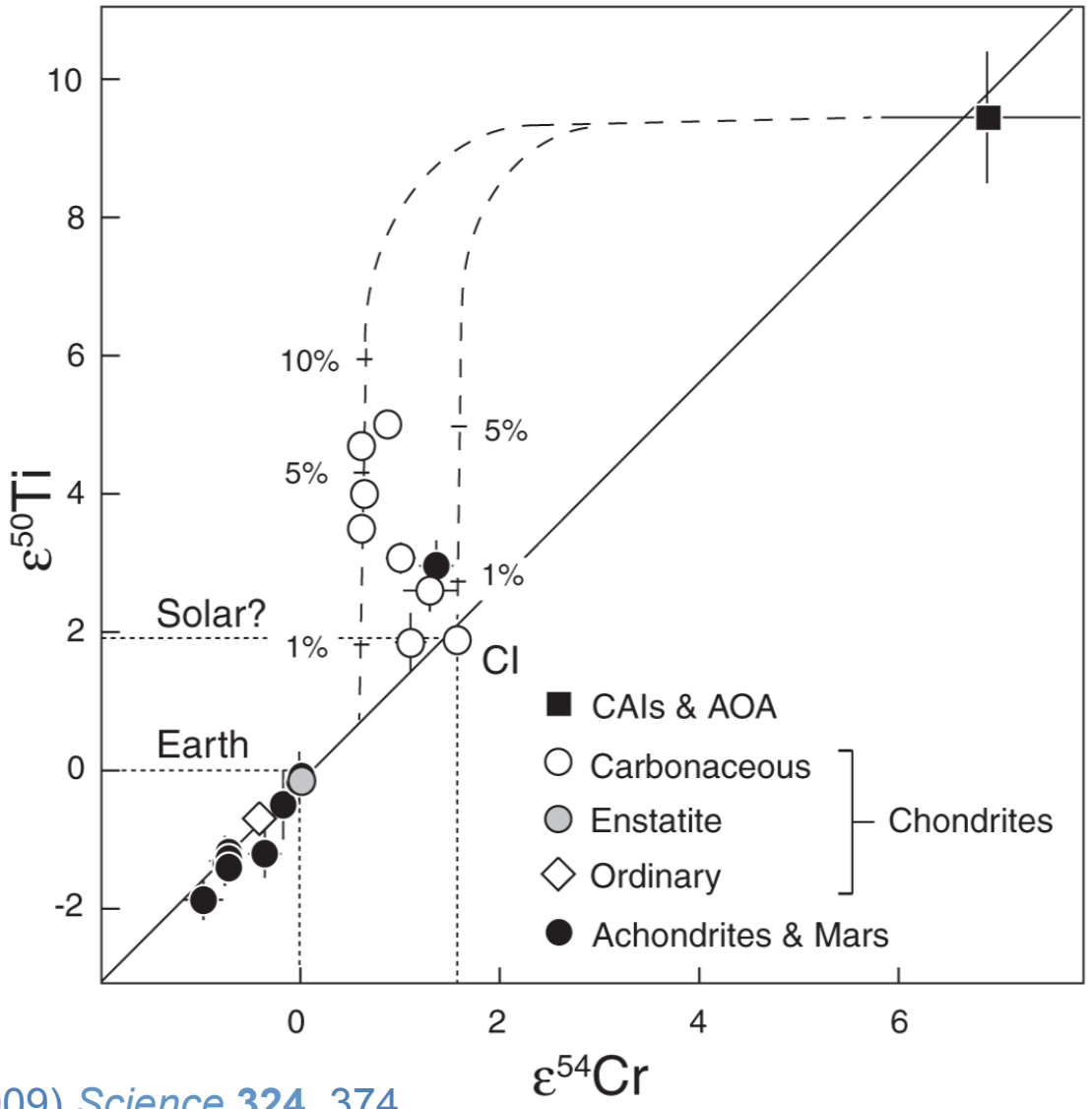
Morbidelli *et al.* (2012)

^{54}Cr results: CV, CR, EC + OC chondrules (N=61)



Olsen *et al.* (2014) *in prep.*

No (almost) CAI material in inner solar system?



Trinquier *et al.* (2009) *Science* **324**, 374

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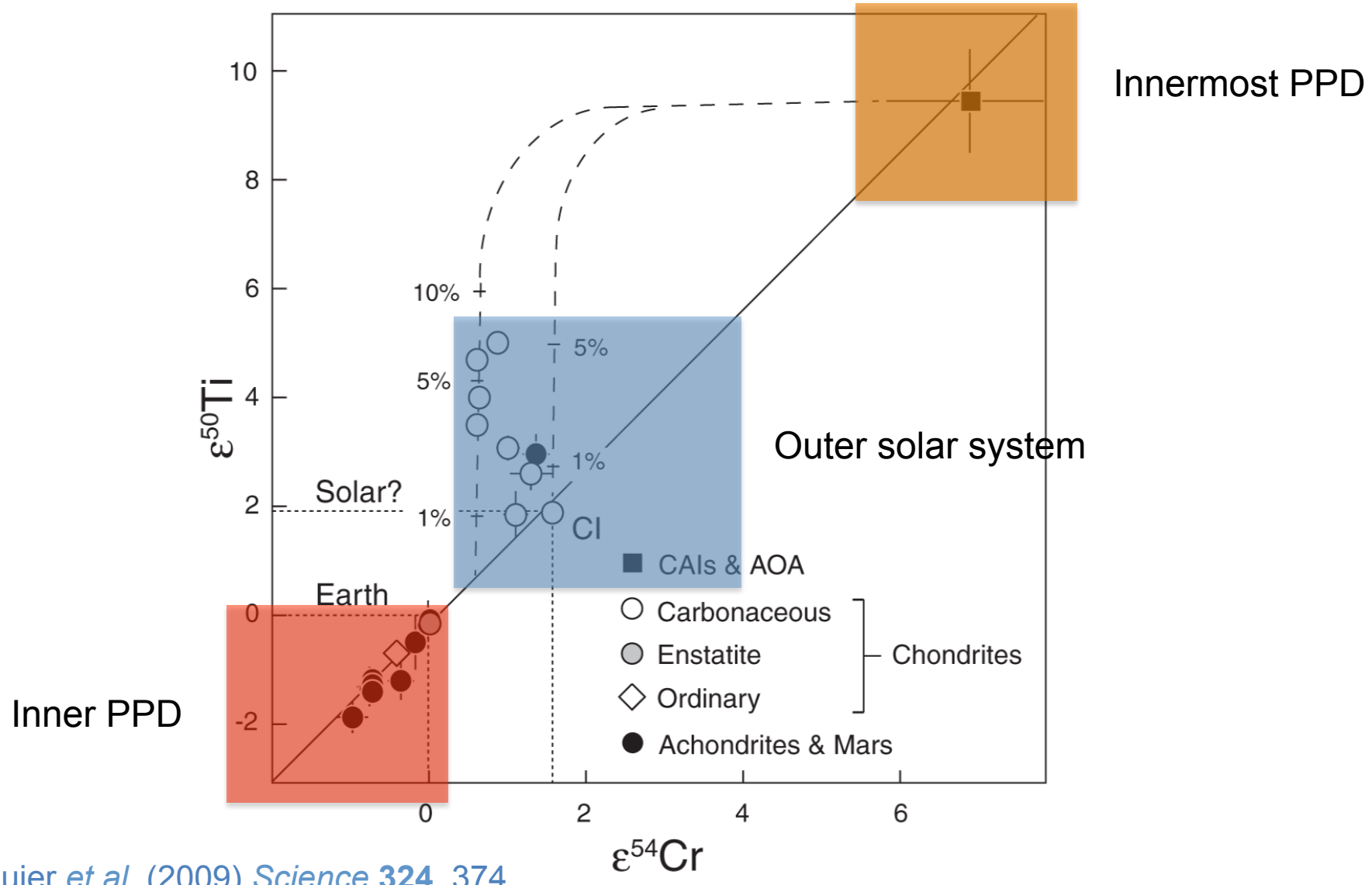
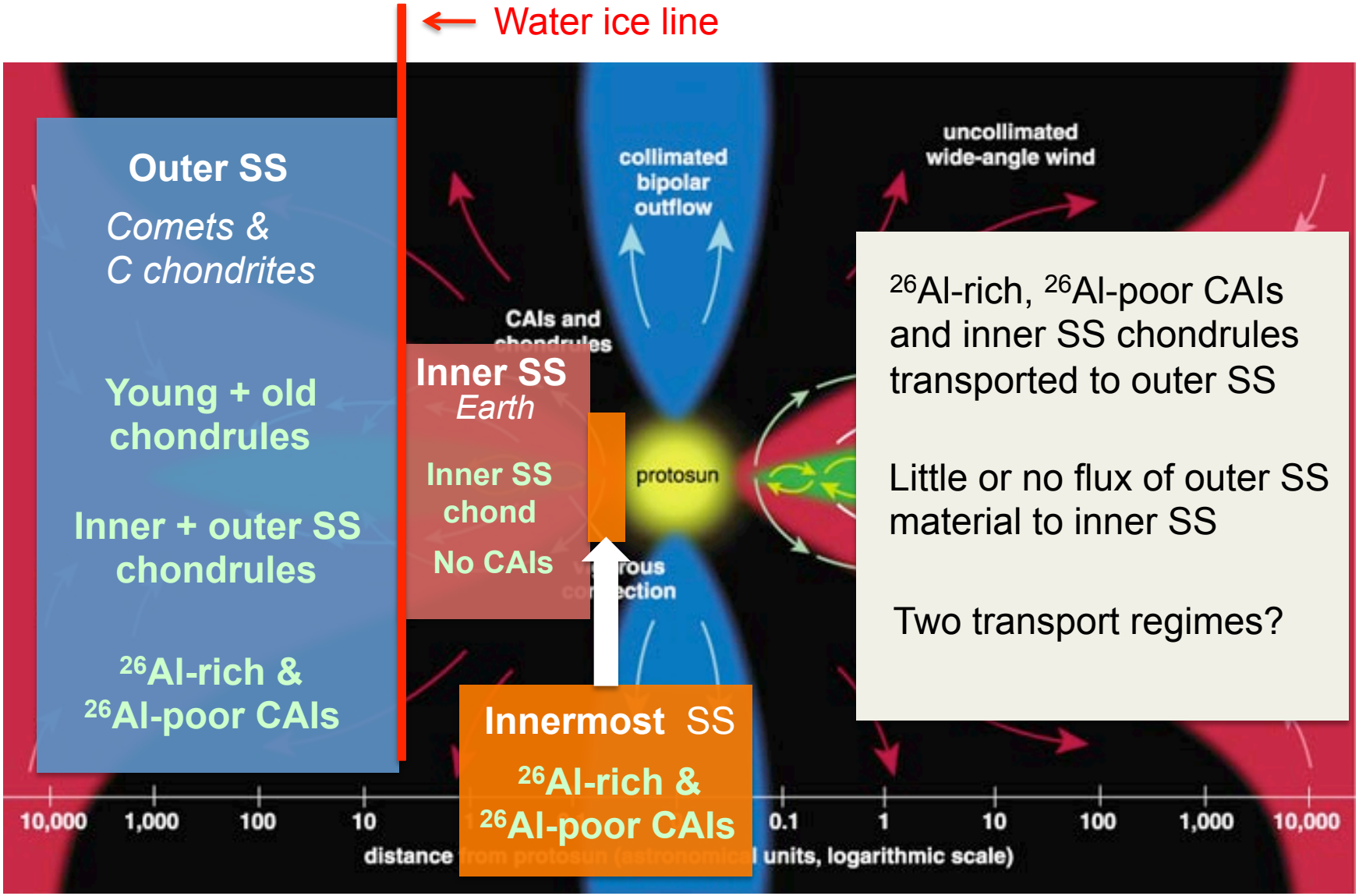


Trinquier *et al.* (2009) *Science* **324**, 374

Protoplanetary disk reservoirs

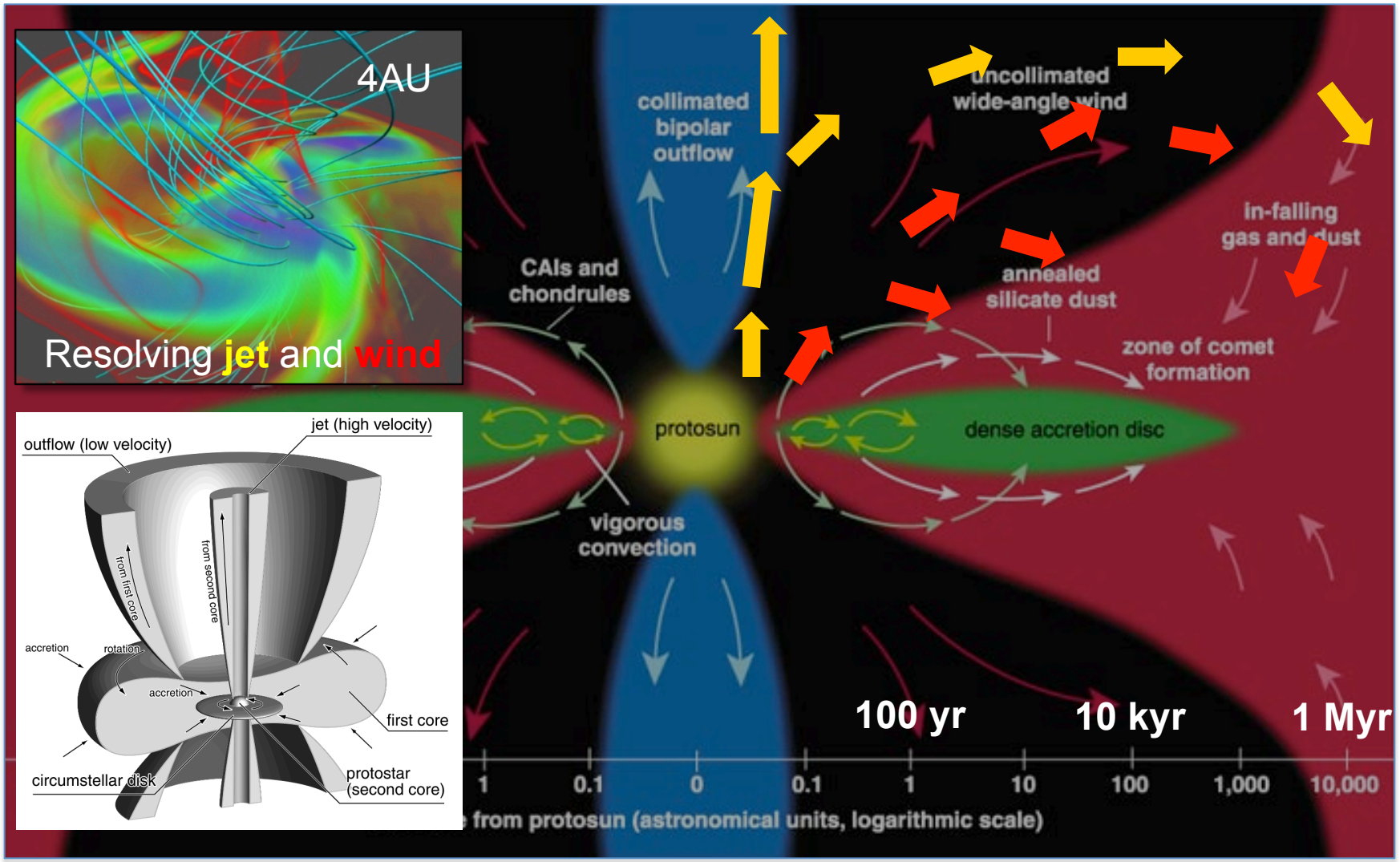


^{26}Al-rich, ^{26}Al-poor CAIs and inner SS chondrules transported to outer SS

Little or no flux of outer SS material to inner SS

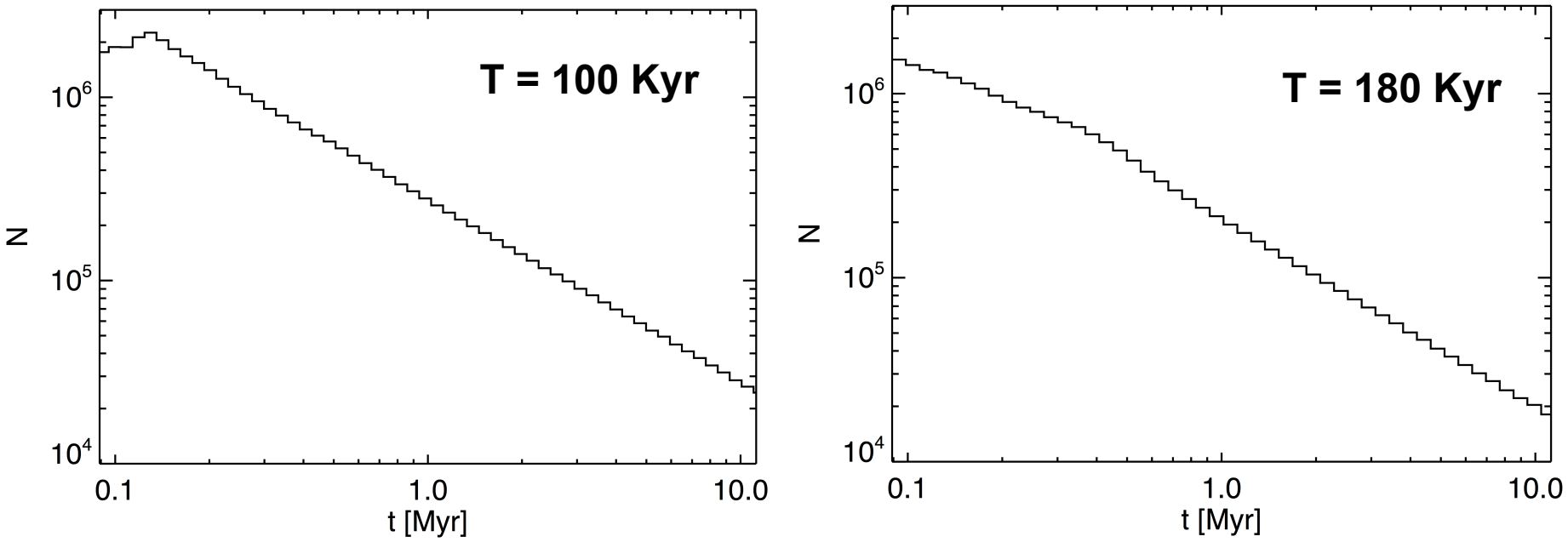
Two transport regimes?

The conveyor belt paradigm



Return timescales to inner solar system

From simulations of a solar mass protostar: distribution of number of voxels from 1,200 to 40,000 AU in 3-D space as a a function of return timescales to inner solar system



Presence of voxels at any one time with long return timescales

Observations and questions

What do we think we know

- *Chondrites and their components sample the composition of the disk at different times and in different regions – chondrules are good messengers*
- *Fundamental isotopic (^{54}Cr…) difference between inner and outer SS*
- *Plenty of early formed refractory material (^{26}Al-rich and ^{26}Al-poor) in the outer SS but **not** in the inner SS – large scale outward transport*
- *Evidence for local recycling in the inner SS – local outward transport*
- *Chondrule forming process operating in inner and outer SS*

Remaining important questions

Observations and questions

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Remaining important questions

- *How do we prevent outer SS stuff to drift in for 5 Myr? Jupiter?*
- *Two transport regimes? Large scale (jet) and small scale (wind)?*