Origin of the solar system – insights from meteoritic components

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Danish National Research Foundation

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STARPLAN

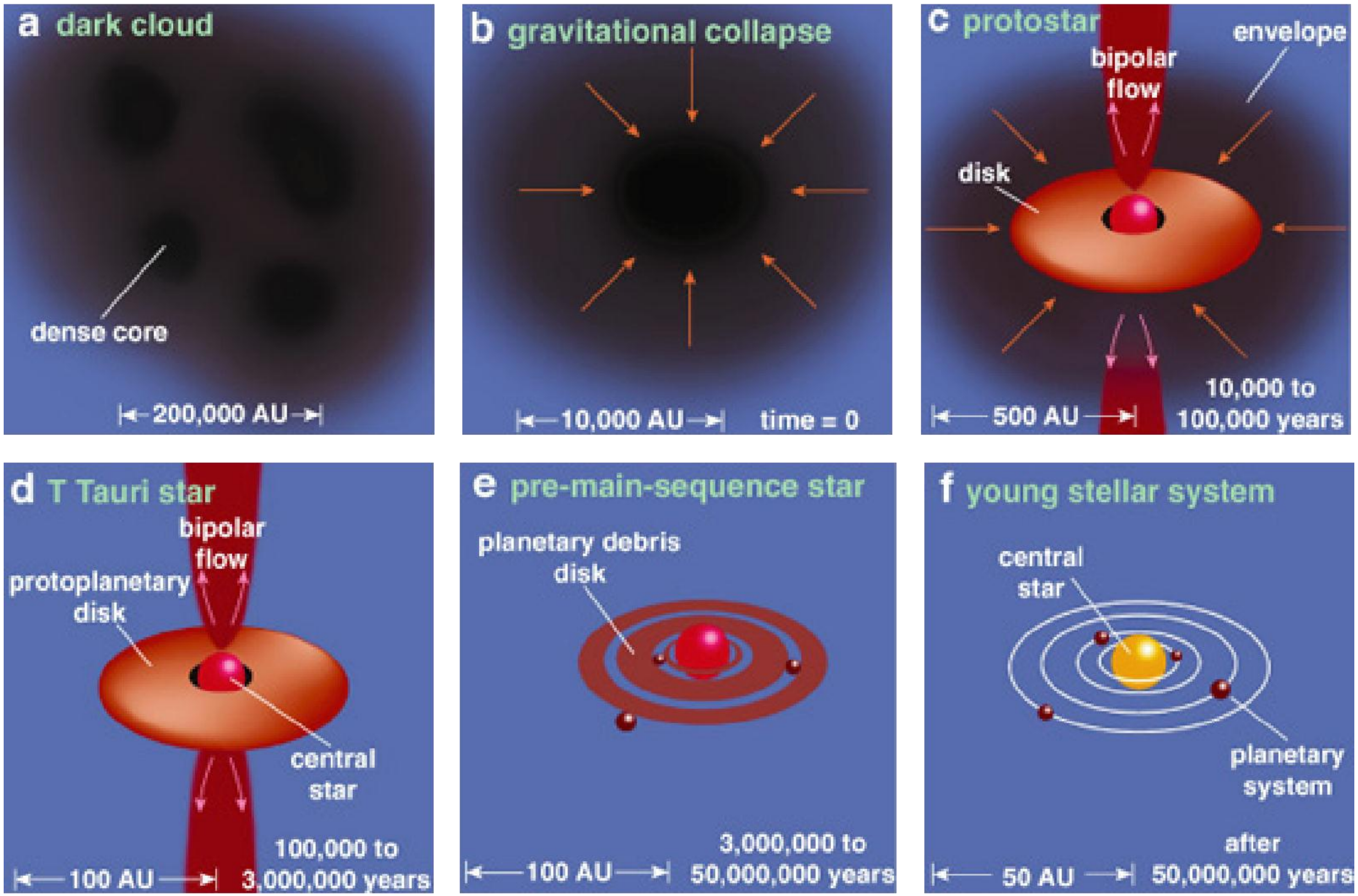
CENTRE FOR STAR AND PLANET FORMATION

A research centre for cosmochemistry, astrophysics and astronomy

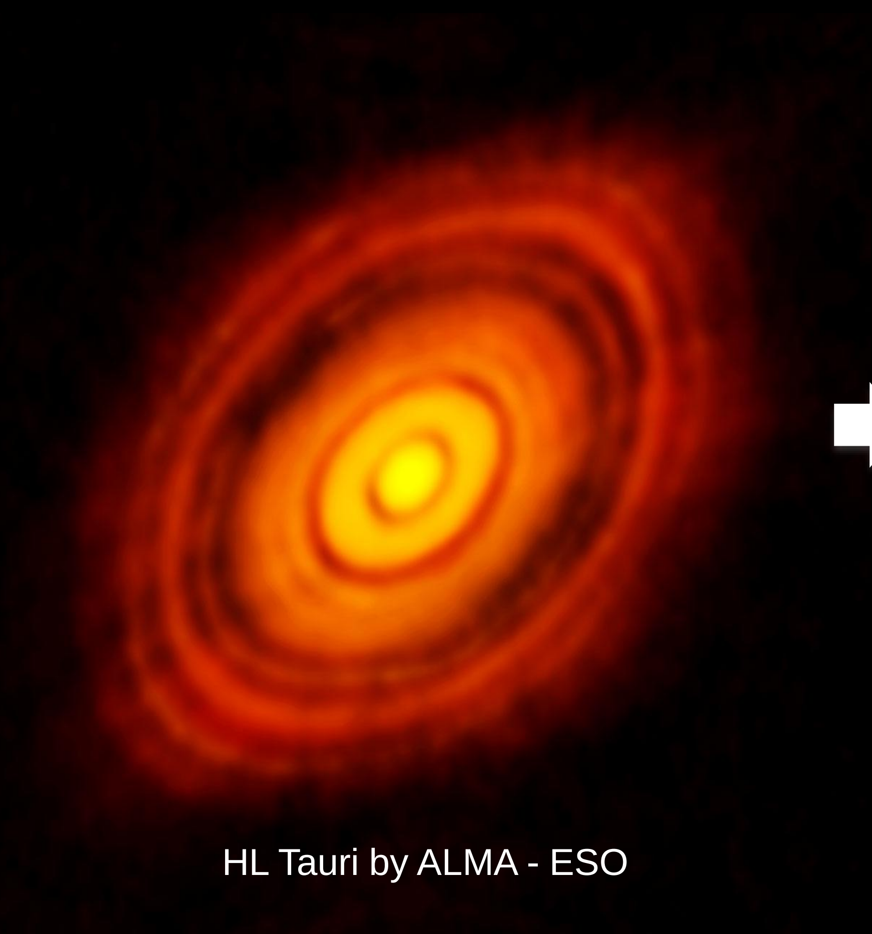
Funded by the Danish National Research Foundation

Solar system formation and cosmochemistry

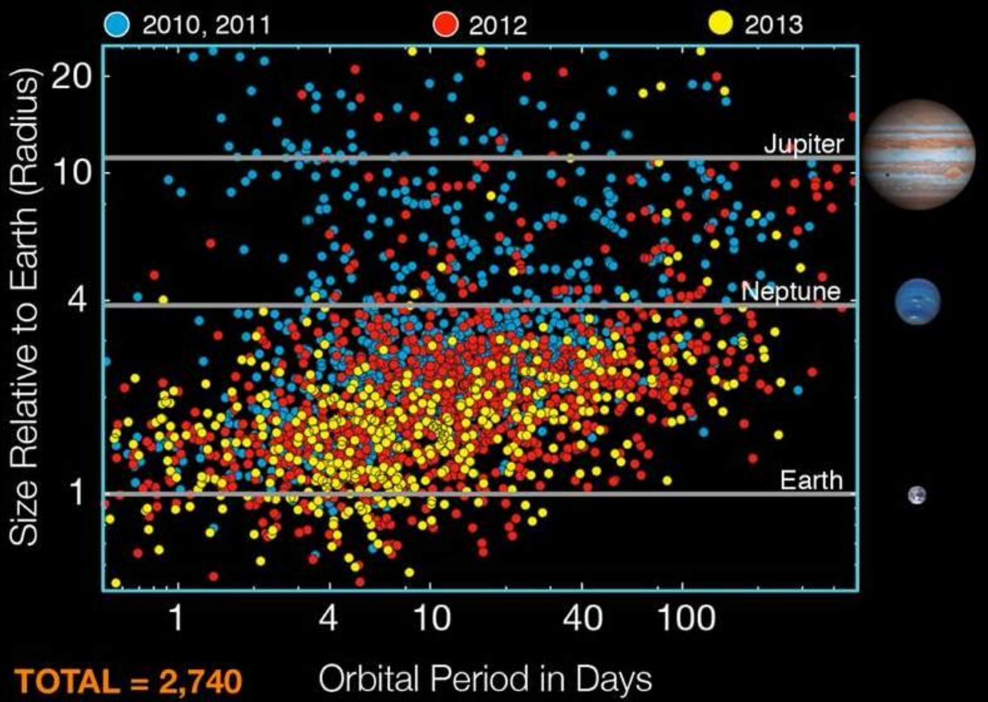
Understanding the formation of planetary systems: from collapse of protosellar cores to the formation of solids and their assembly into asteroids and planets



A new era in astrophysics: ***diversity of planets***

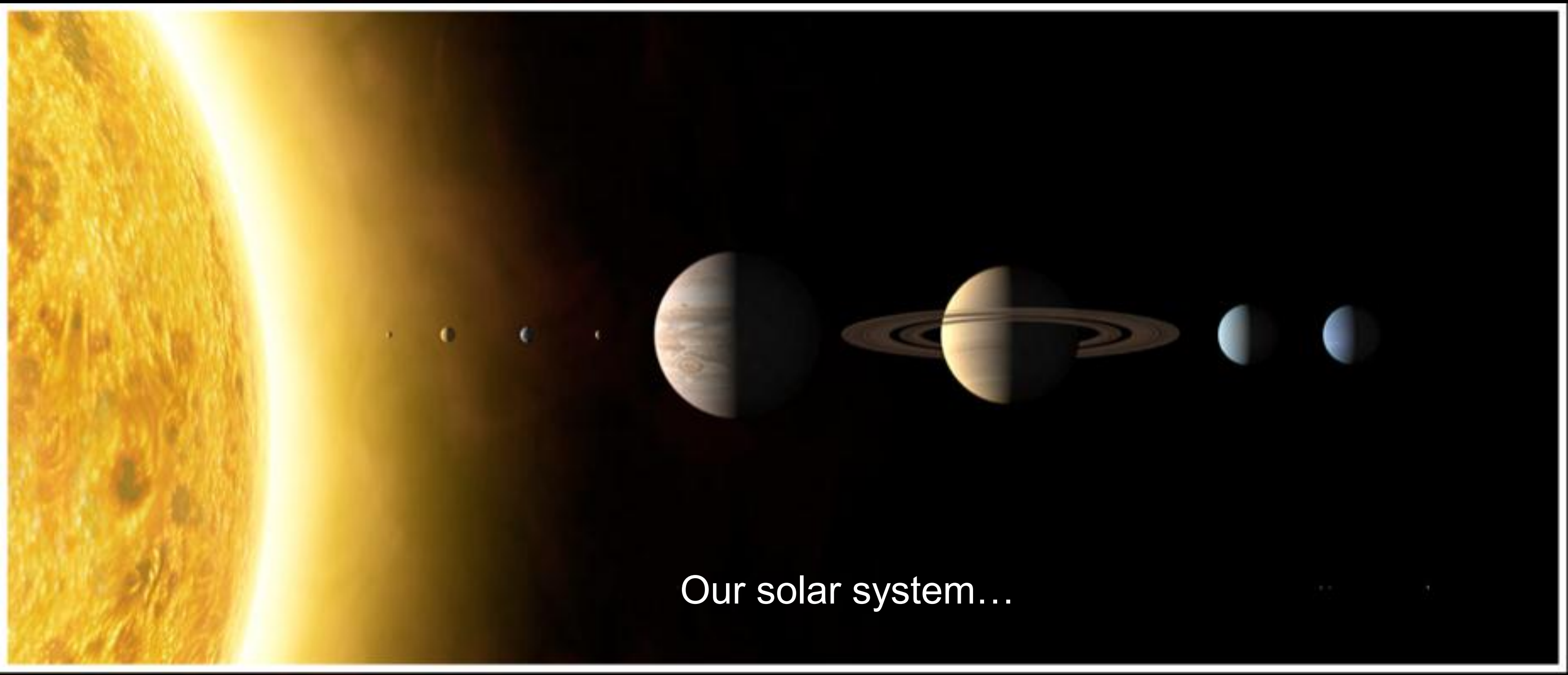


HL Tauri by ALMA - ESO



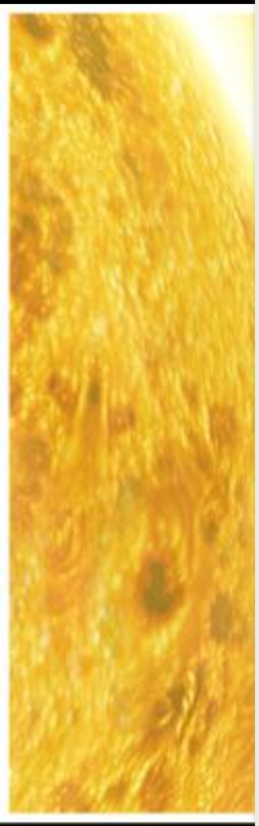
How does nature do it?

A new era in astrophysics: ***diversity of planets***



How does nature do it?

A new era in astrophysics: ***diversity of planets***



Key topics addressable with meteorite data:

1. Solid formation and disk dynamics

2. Chemical and thermal evolution of the PPD

3. Mass transport regimes in the PPD

4. Mass transport and planet formation

Initial conditions for terrestrial planet formation

A new era in astrophysics: ***diversity of planets***

Key topics addressable with meteorite data:

1. Solid formation and disk dynamics
2. Chemical and thermal evolution of the PPD
3. Mass transport regimes in the PPD
4. Mass transport and planet formation

Initial conditions for terrestrial planet formation

→ **Ability to analyze smaller samples**

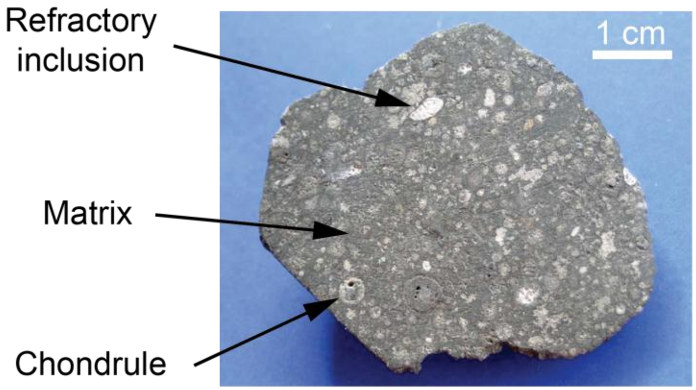
→ **Multiple datasets on individual sample**

→ **Improve resolution by factor of 10 to 100**

A time-window into solar system processes

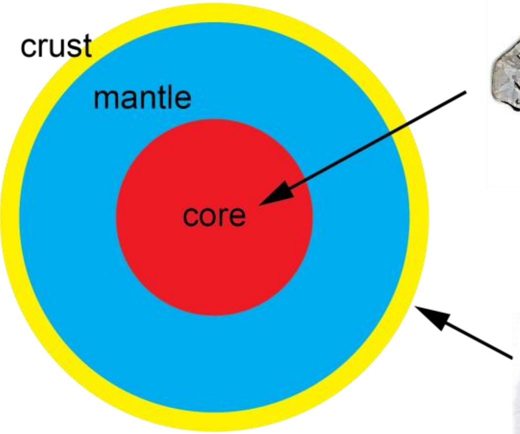
Meteorites and their components provide the ONLY means to probe the earliest formative stages of the Sun and its protoplanetary disk

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

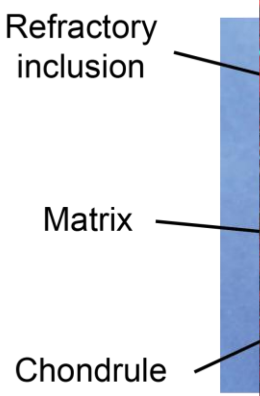
- Asteroid accretion efficiency
- Timing of accretion and differentation
- Mechanism(s) of planetary differentaition

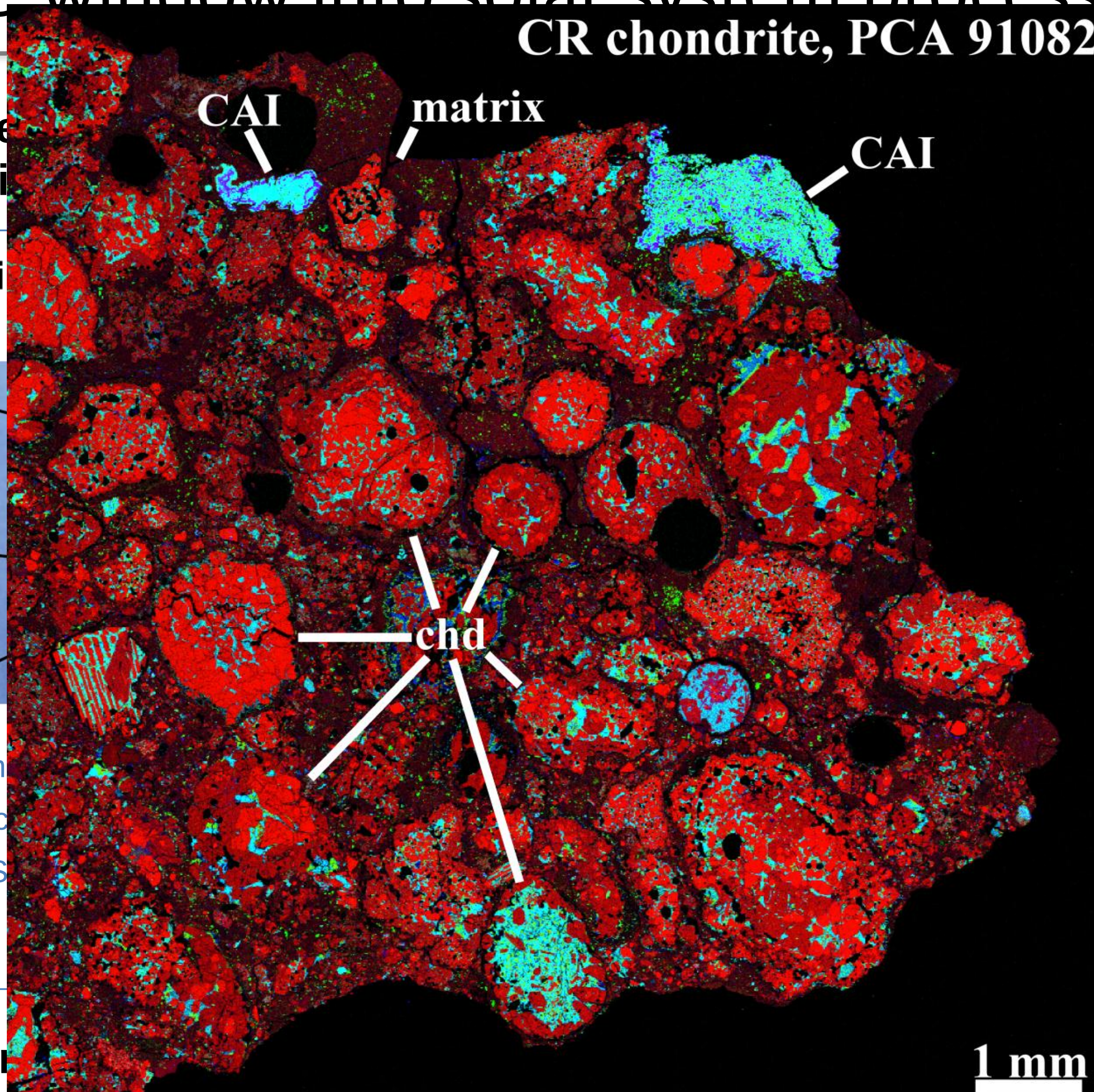
Huge potential – but need to interpret the meteorite record in the context of a collapsing MC evolving into a young star and its protoplanetary disk

A time-window into solar system processes

Mete... s to probe the earli... y disk

Pri...





iron meteorites

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Nucleosynthetic m...

Timescale of MC c...

Formation of the S...

Thermal evolution ...

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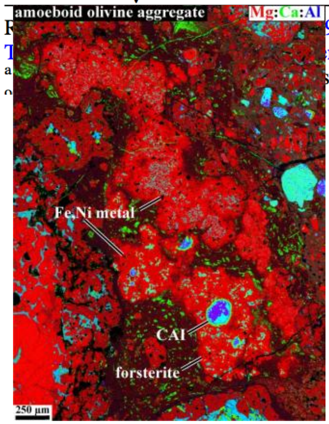
Huge poter... e context of a collapsing MC evolving into a young star and its protoplanetary disk

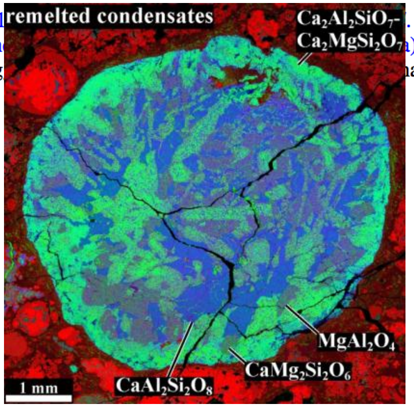
Short-lived radionuclides

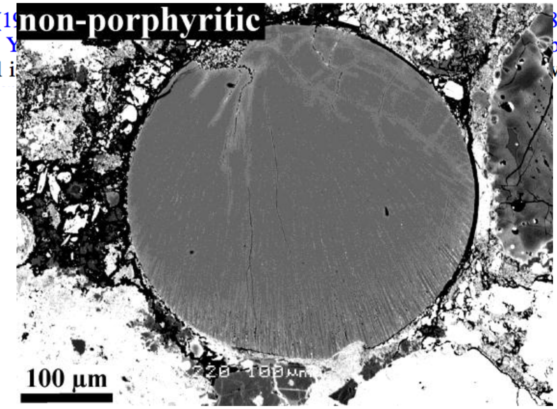
Former presence of now-extinct radionuclides in meteorites provides insights into the astrophysical environment of solar system formation, chronology of solid formation and thermal history of asteroidal bodies.

Table 1 Short-lived radioactive nuclides once existing in solar system objects.[a]

Fractionation[b]	*Parent nuclide*	*Half-life* (Myr)	*Daughter nuclide*	*Estimated initial solar system abundance*	*Objects found in*
Nebular	^{41}Ca	0.1	^{41}K	$10^{-8} \times {}^{40}$Ca	CAIs
	^{26}Al	0.7	^{26}Mg	$(4.5 \times 10^{-5}) \times {}^{27}$Al	CAIs, chondrules, achondrite
	^{10}Be	1.5	^{10}B	$(\sim 6 \times 10^{-4}) \times {}^{9}$Be	CAIs
Planetary	^{53}Mn	3.7	^{53}Cr	$(\sim 2\text{-}4 \times 10^{-5}) \times {}^{55}$Mn	CAIs, chondrules, carbonates, achondrites
	^{60}Fe	1.5	^{60}Ni	$(\sim 3 \times 10^{-7}) \times {}^{56}$Fe	achondrites, chondrites
	^{107}Pd	6.5	^{107}Ag	$(\sim 5 \times 10^{-5}) \times {}^{108}$Pd	iron meteorites, pallasites
	^{182}Hf	9	^{182}W	$10^{-4} \times {}^{180}$Hf	planetary differentiates
	^{129}I	15.7	^{129}Xe	$10^{-4} \times {}^{127}$I	chondrules, secondary minerals
	^{92}Nb	36	^{92}Zr	$10^{-4} \times {}^{93}$Nb	chondrites, mesosiderites
	^{244}Pu	82	Fission products	$(7 \times 10^{-3}) \times {}^{238}$U	CAIs, chondrites
	^{146}Sm	103	^{142}Nd	$(9 \times 10^{-4}) \times {}^{147}$Sm	chondrites







The ^{26}Al-to-^{26}Mg decay system ($T_{1/2}$~ 0.7 Myr)

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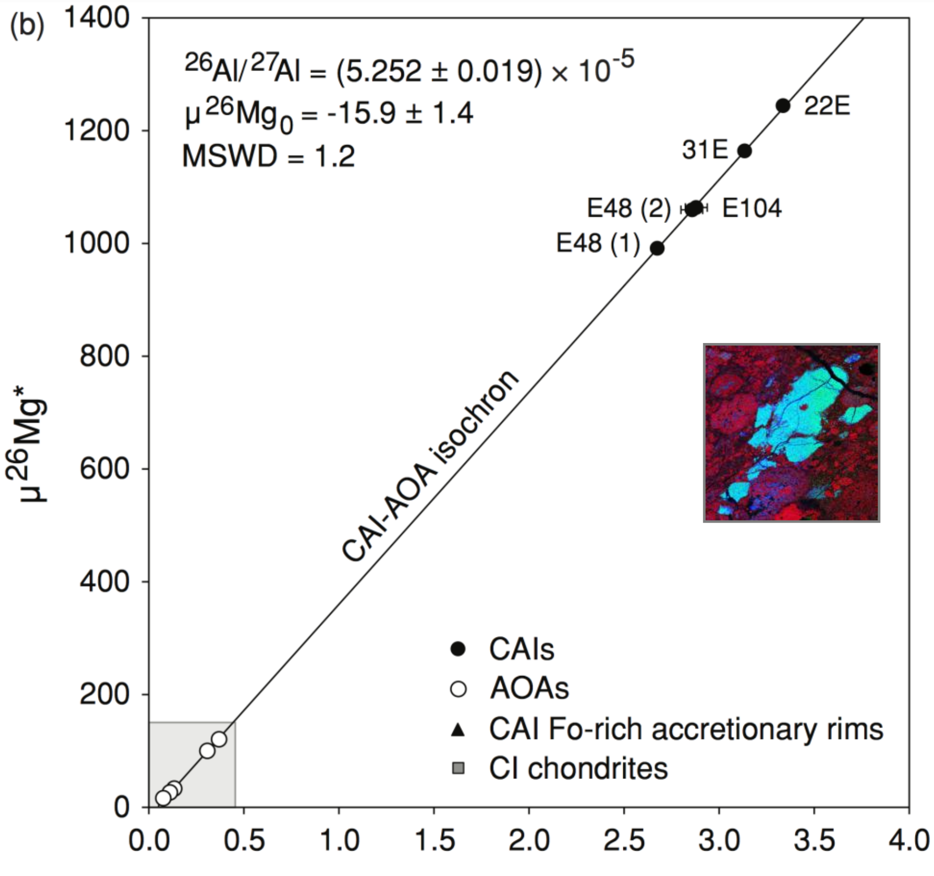

Larsen*et al*. 2011, *ApJ* **324**, 374

- Formation interval of 2,500 years
- ^{26}Al/^{27}Al of ~5 × 10^{-5}
- ^{26}Al potent heat source
- ^{26}Al/^{27}Al much higher than predicted by GCE

Late-stage contamination of nascent SS by massive star?

Peculiar formation history?

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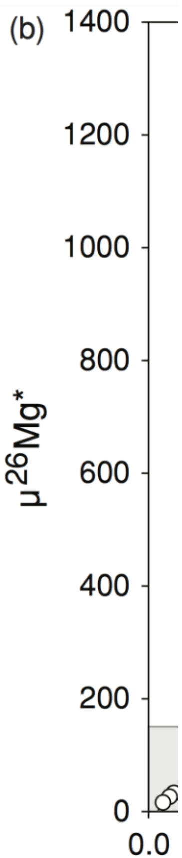

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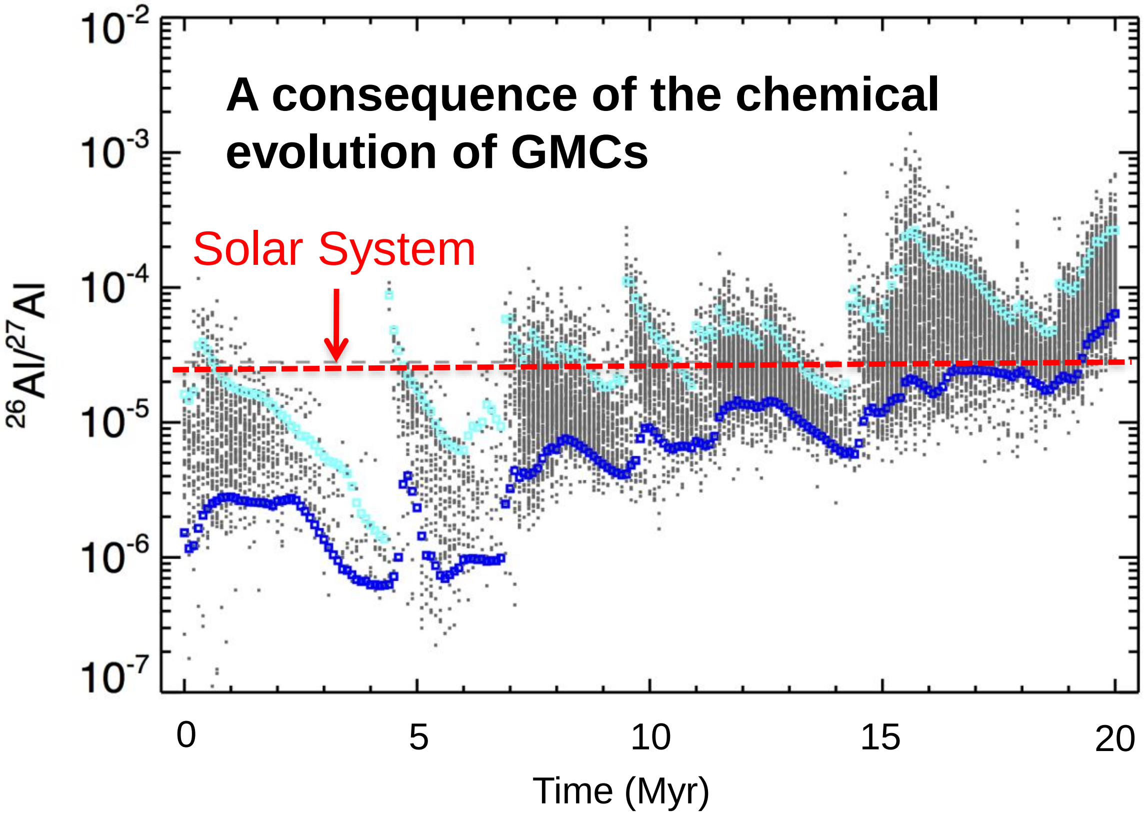
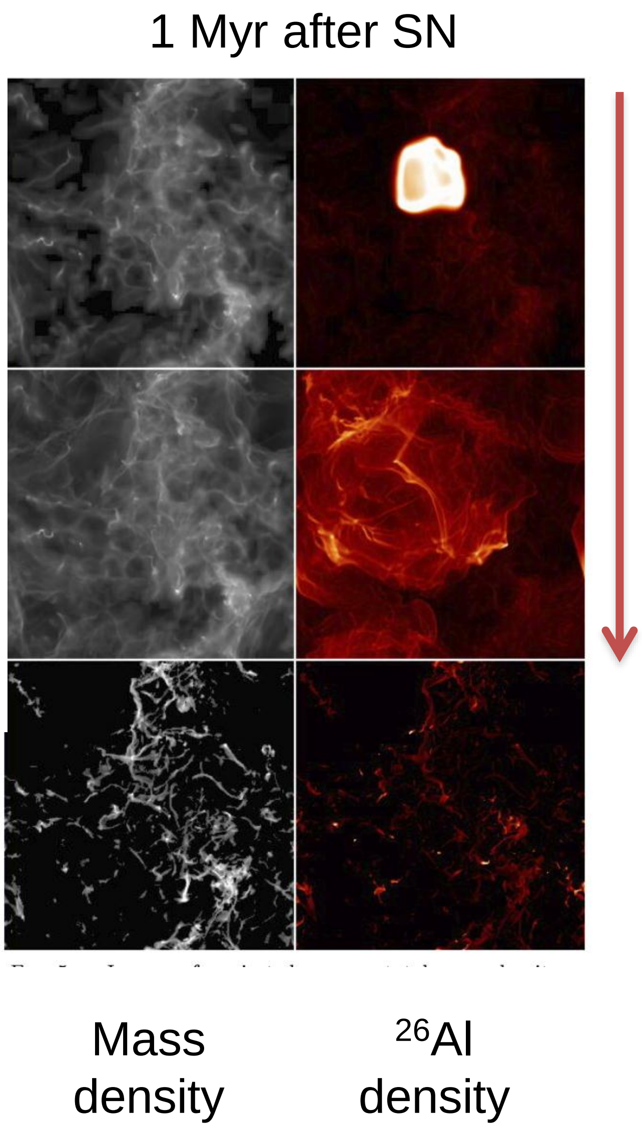
Realistic simulations of evolving GMCs



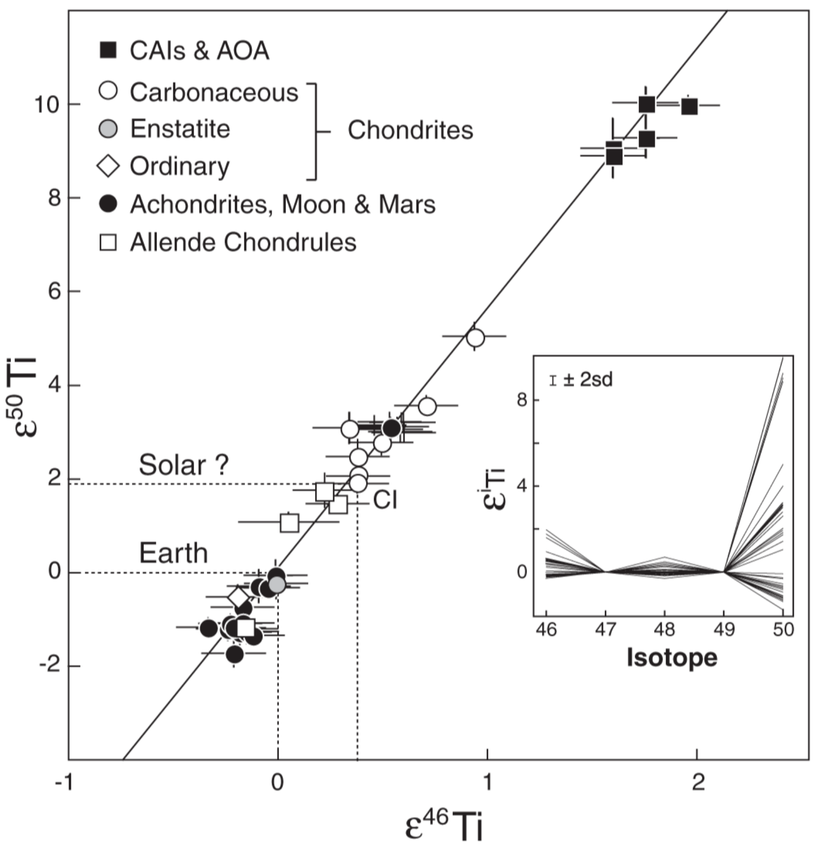


Solar system $^{26}Al/^{27}Al$ level is easily reproduced in star-forming gas during the evolution of the GMC

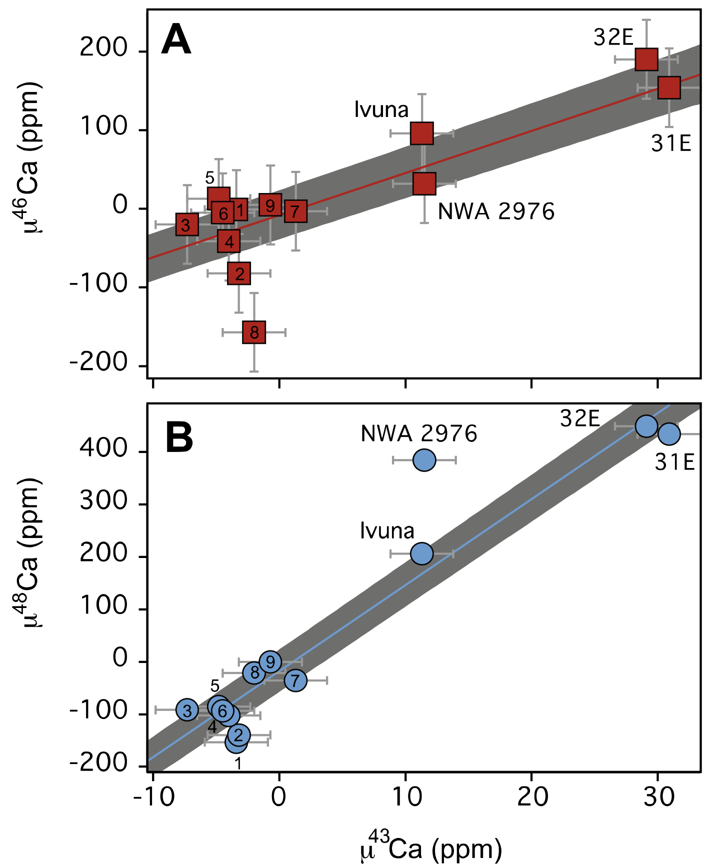
Still some problems with ^{60}Fe…

Binary (un)mixing of dust components?

The correlated isotope anomalies may represent binary un-mixing of physically well-homogenized dust components: a new supernova dust component (multiple SNe) and an older galactic background component



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



Schiller *et al*. 2015, *GCA* **149**, 88

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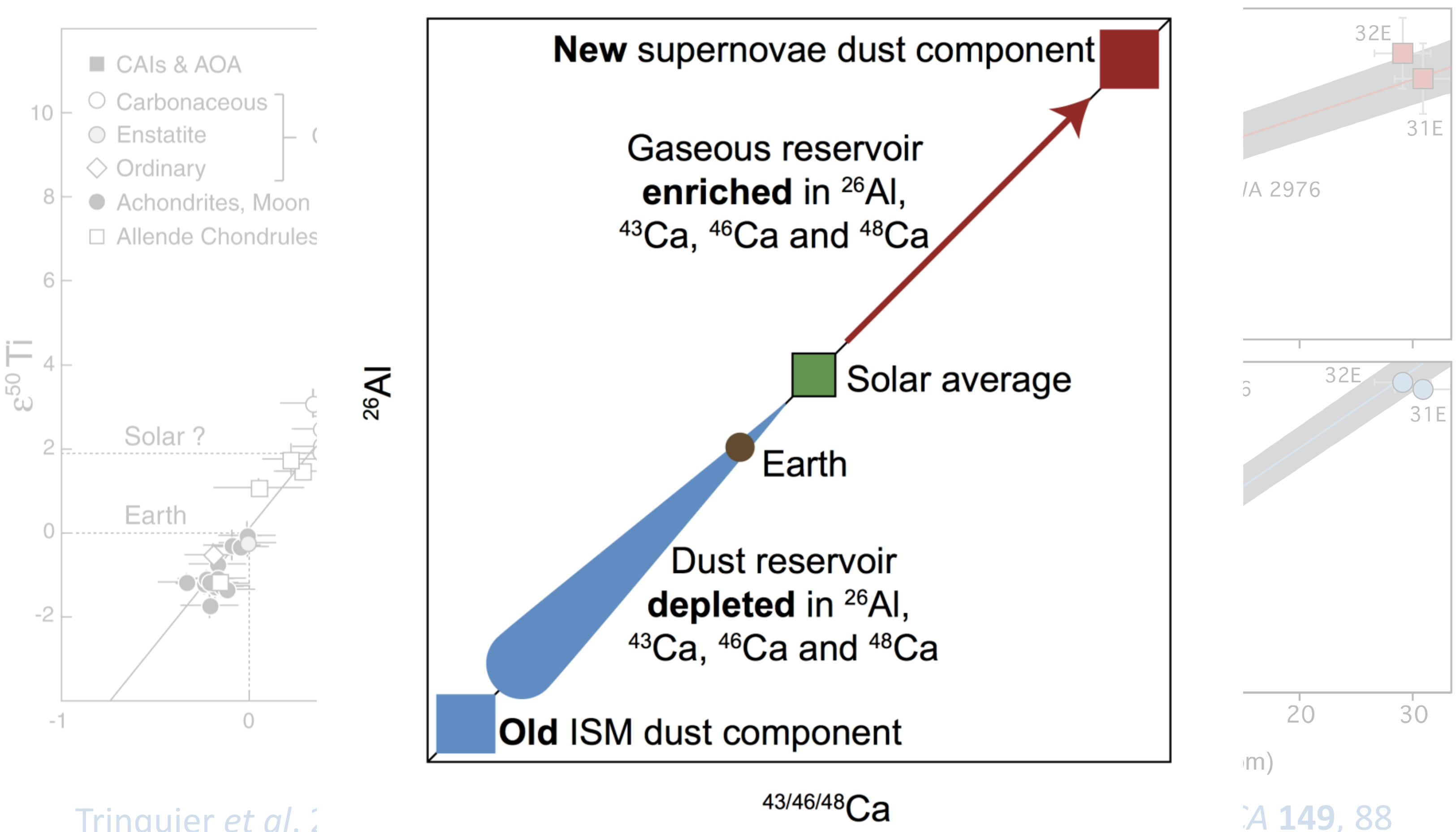
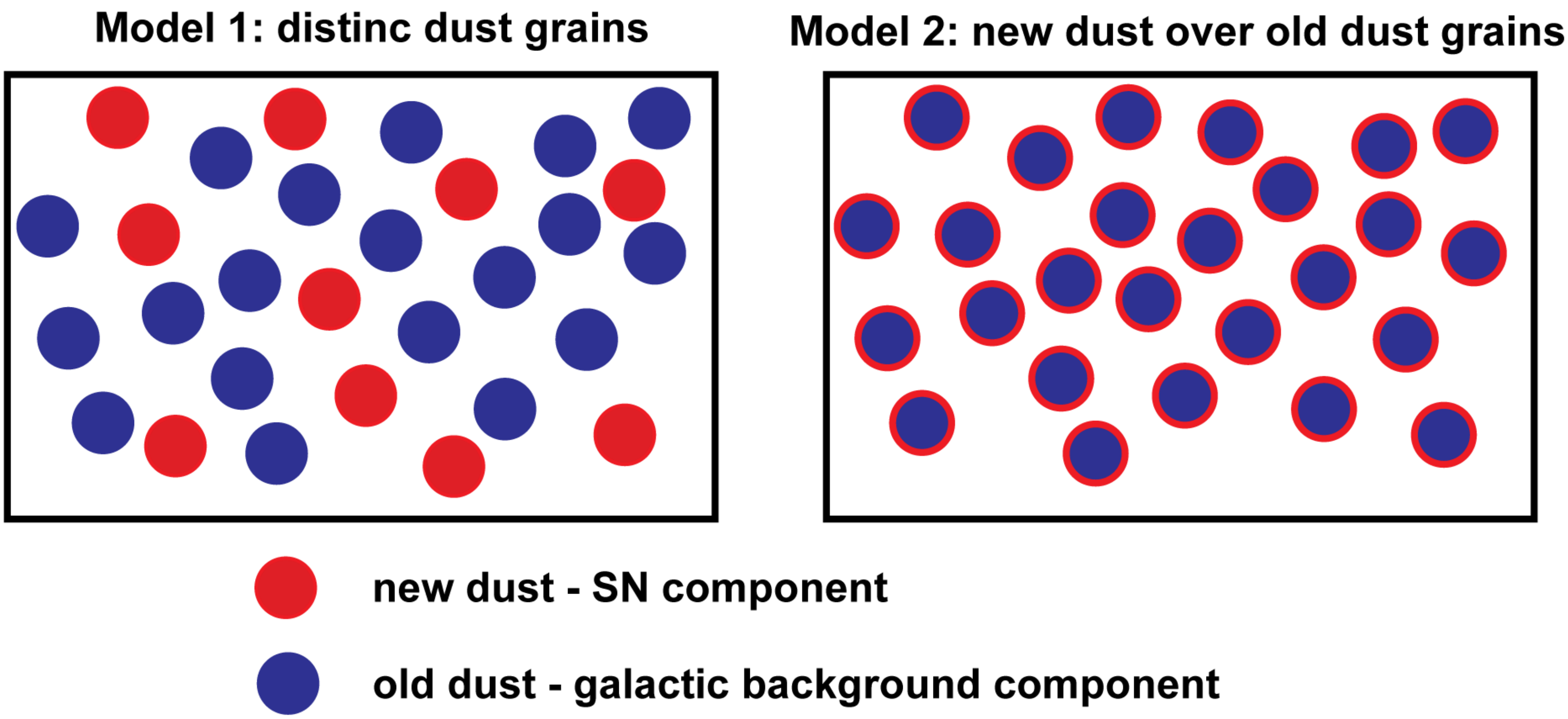
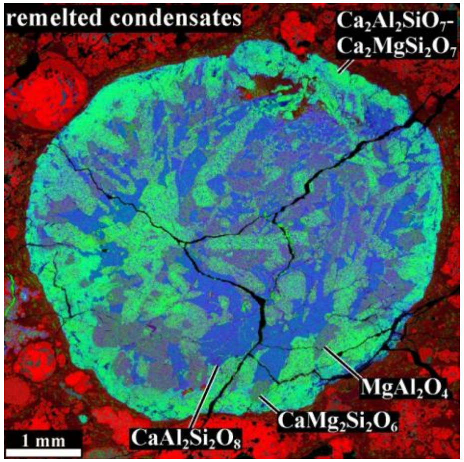


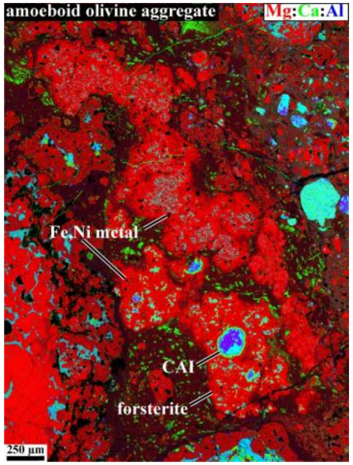
Dust dichotomy: old *vs* new

Model requires two generation of dust with different thermal properties. New (freshly synthesized) SN dust is thermally unstable and can be affected by thermal processing. Old dust processed in ISM (warm ISM?) and is more refractory.

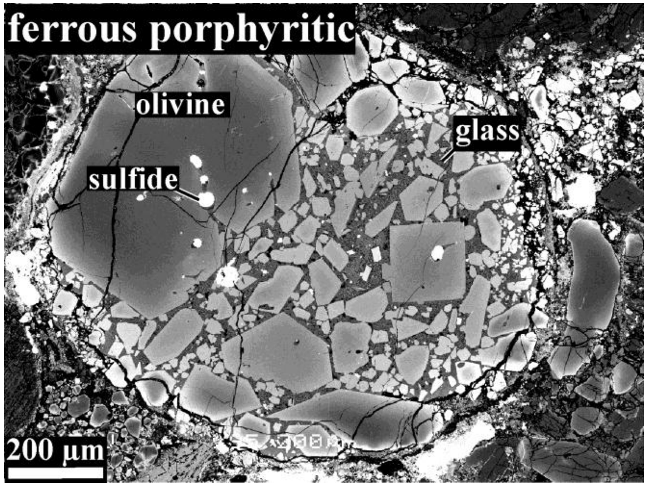


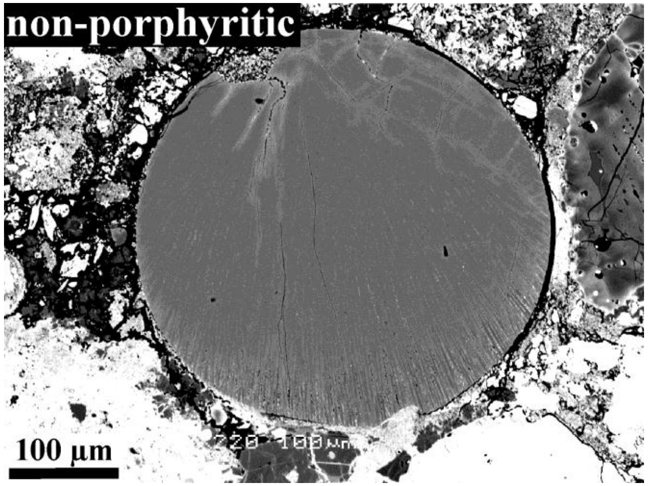
Chondrite components – CAIs & chondrules





Early-formed gas condensates
^{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

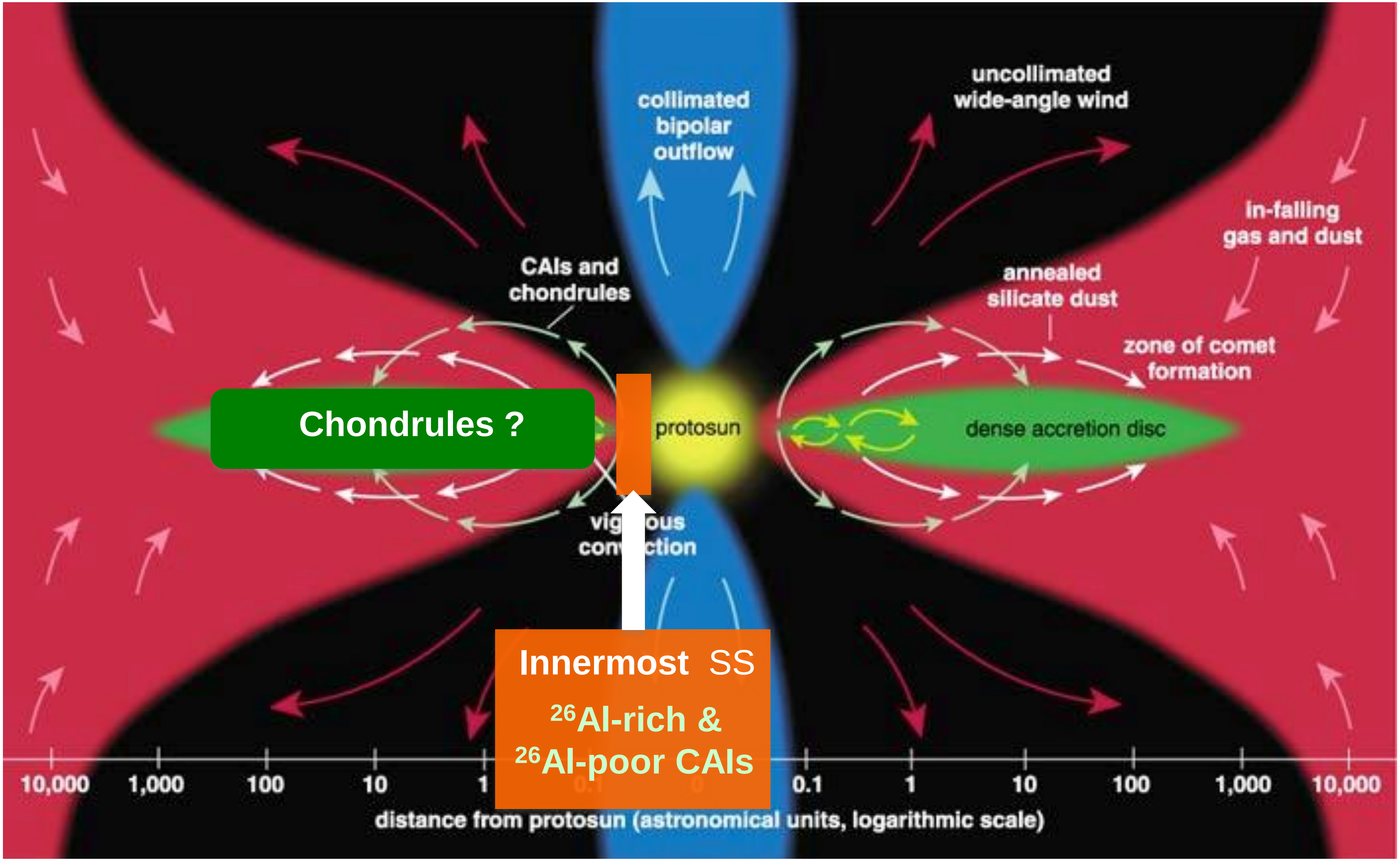




Molten dust balls
In all chondrites
Low $[^{26}Al/^{27}Al]_0$
Variable Pb-Pb ages
Disk lifetime

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

Dynamical evolution of the protoplanetary disk



The U-Pb system: absolute assumption-free ages

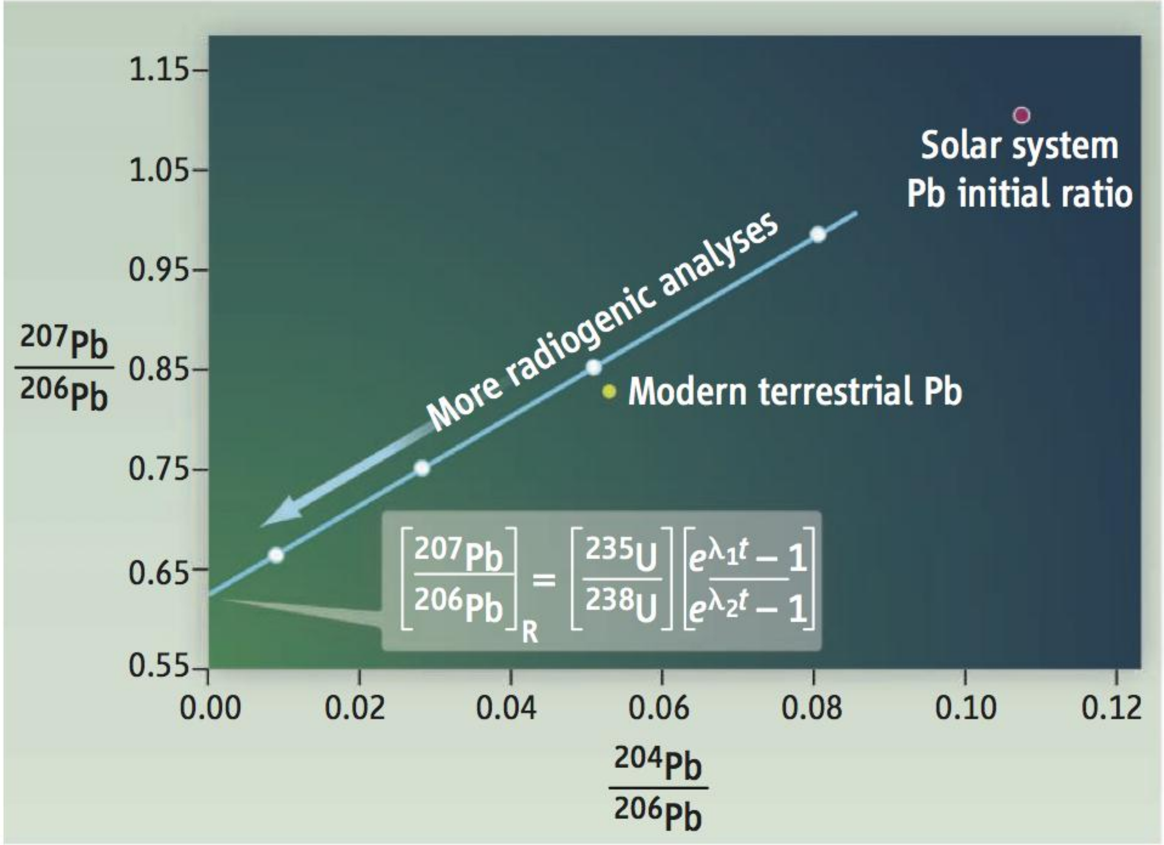
- The U-Pb decay system is the only assumption-free chronometer that provide absolute ages with a resolution of ~200,000 years

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

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

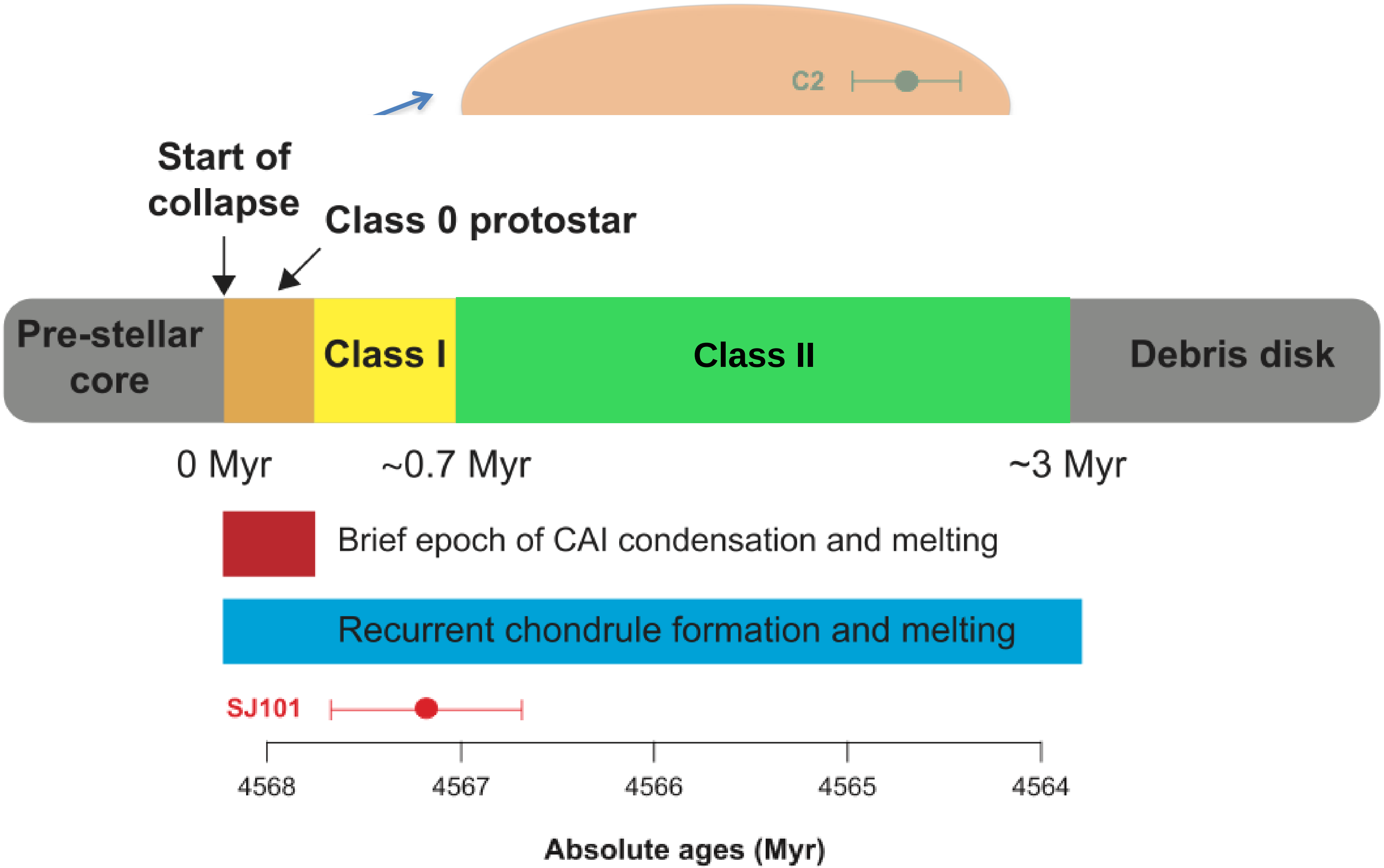
$^{235}\mathbf{U} \rightarrow {}^{207}\mathbf{Pb}$

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



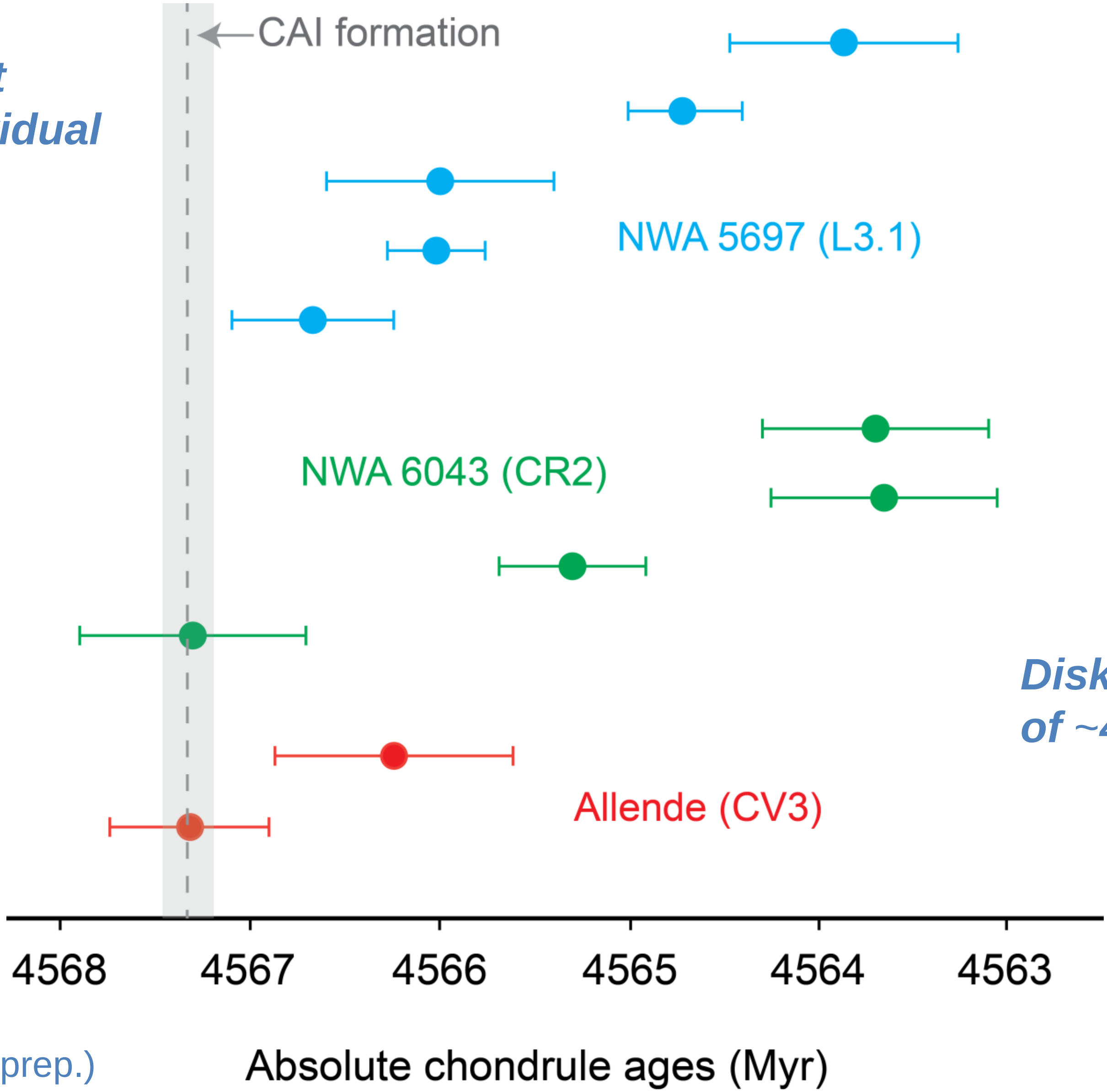
Absolute chronology of CAIs and chondrules

Chondrule formation started contemporaenously with CAIs and lasted about 3 Myr



Absolute chronology of chondrules – new data

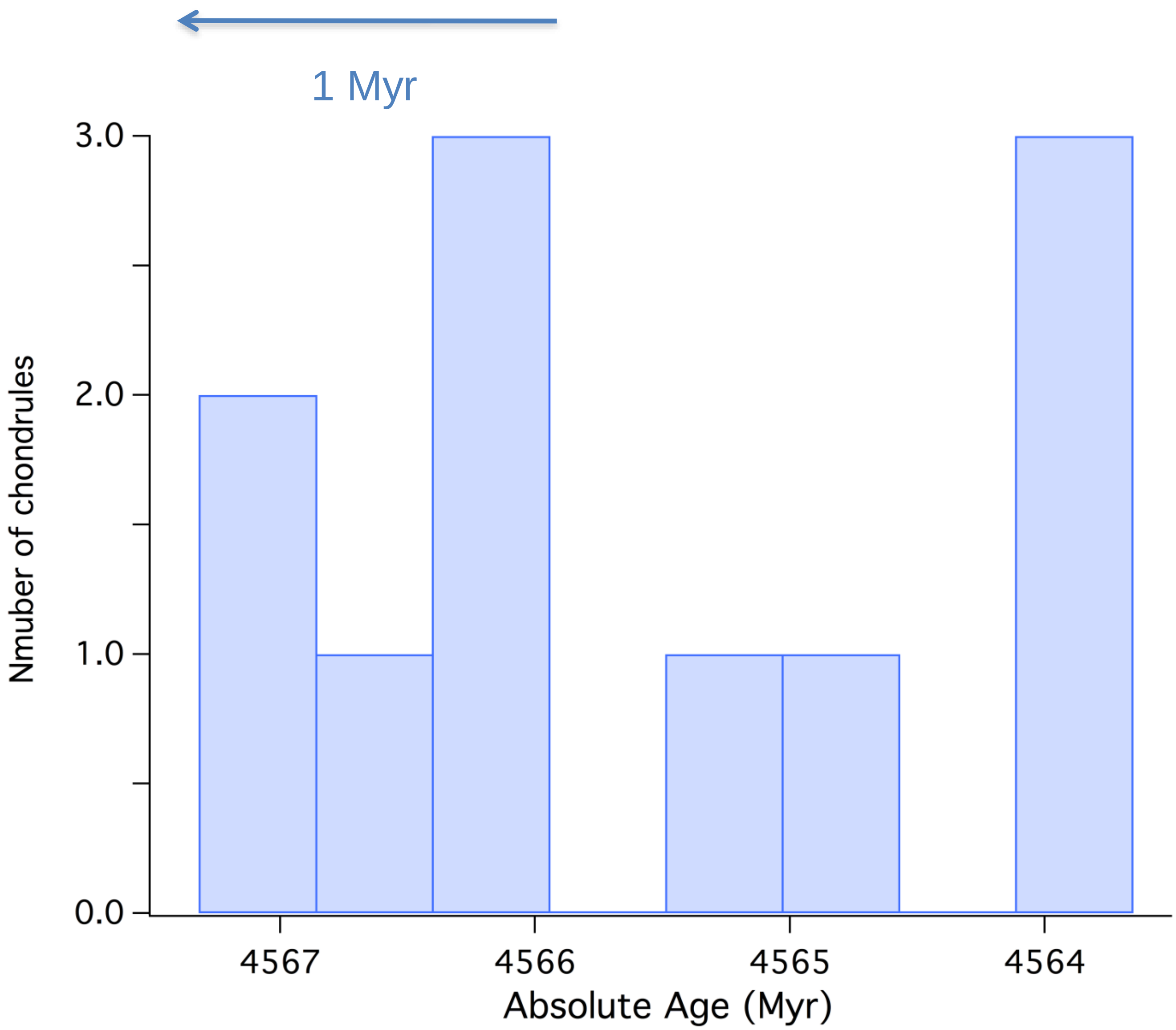
Only data that exist for individual chondrules!



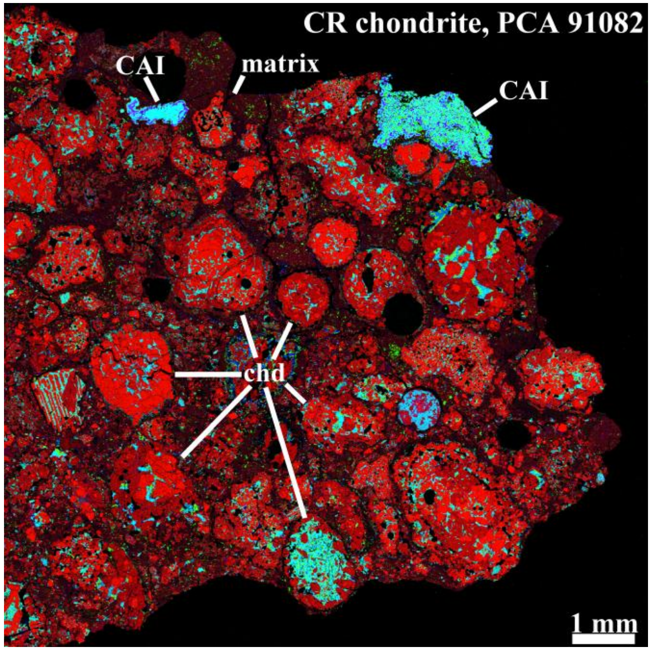
Disk lifetime of ~4 Myr?

Bollard *et al.* (in prep.)

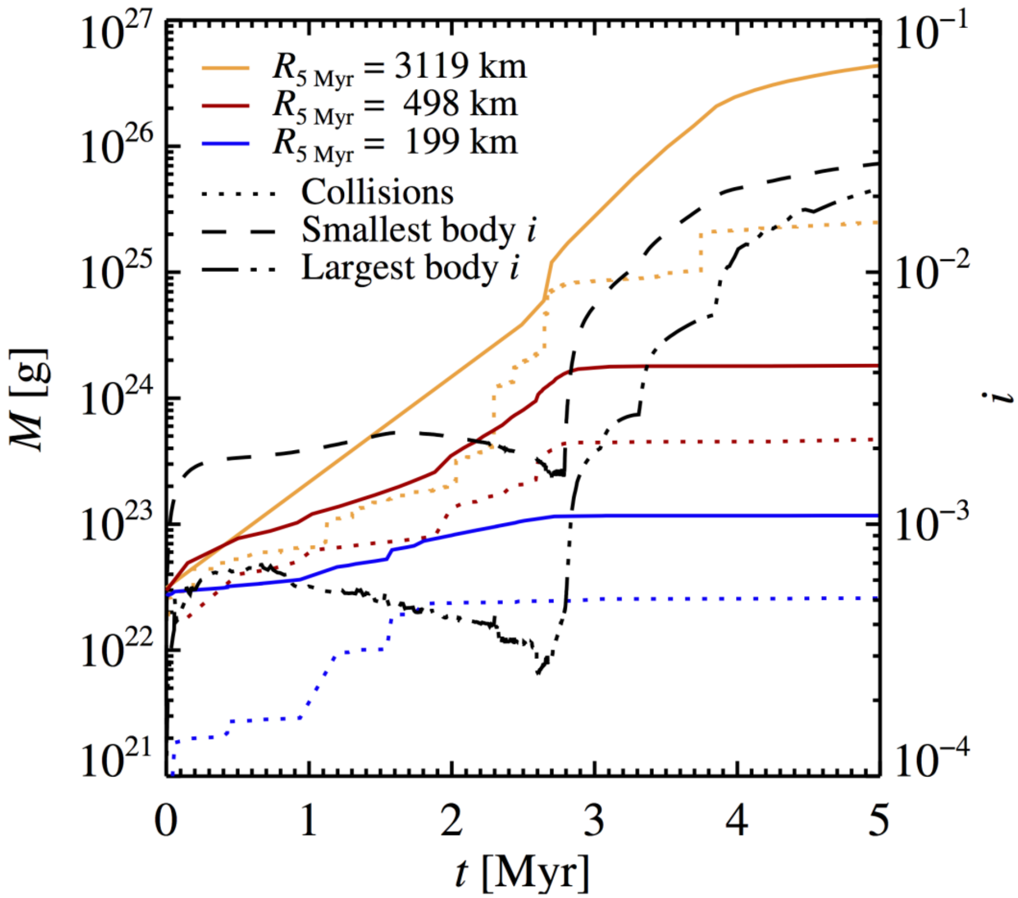
Age distribution of chondrules (N = 11... soon 50!)



Chondrules as building blocks of planets?

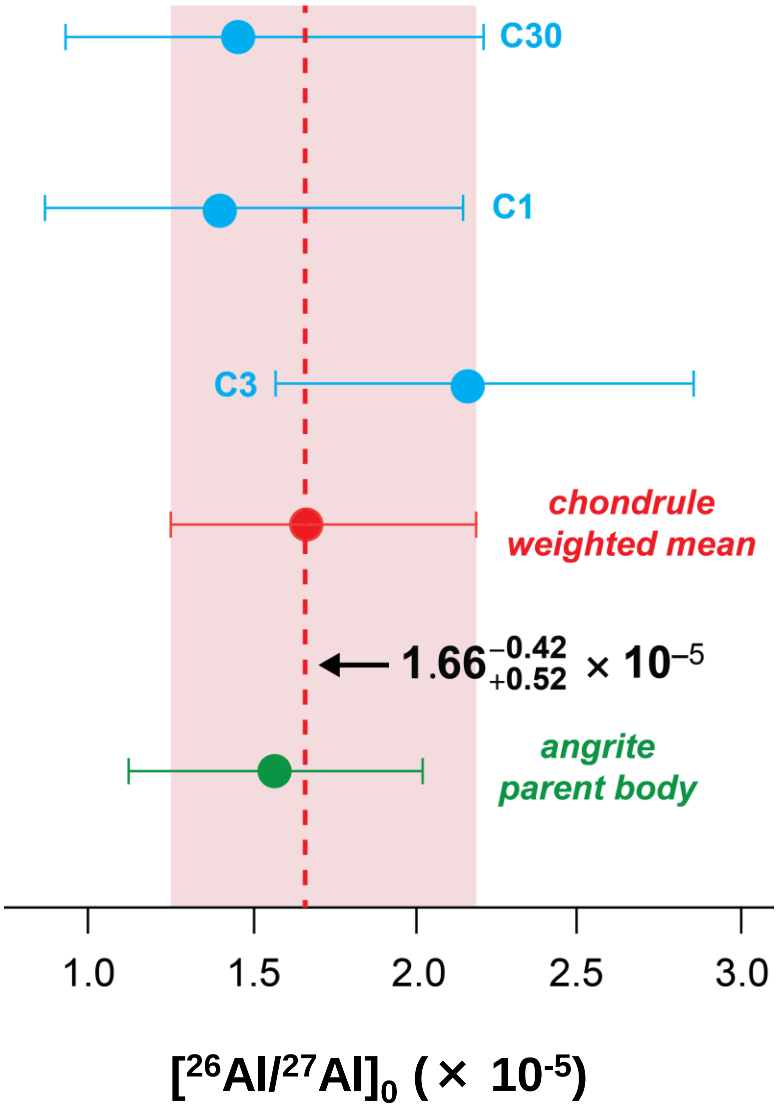


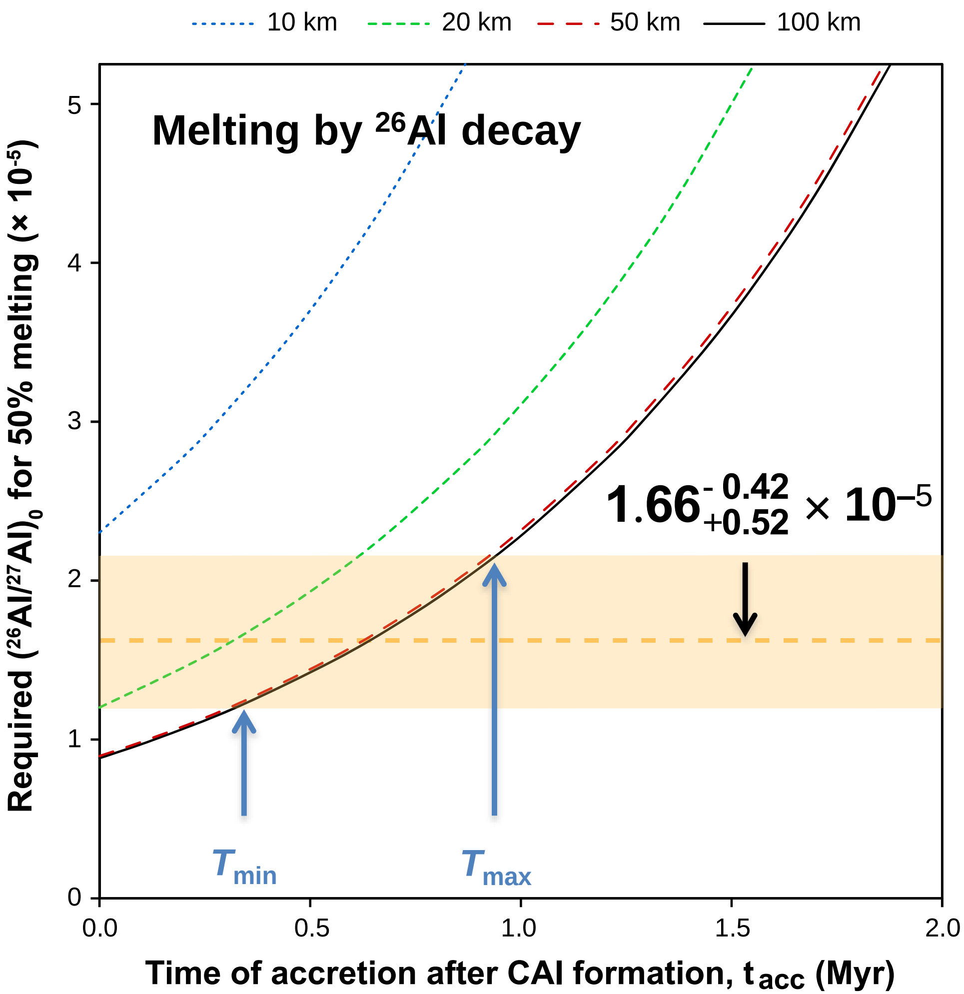
Johansen *et al.* (2015), submitted



Growth of asteroidal bodies and planetary embryos by chondrules accretion!

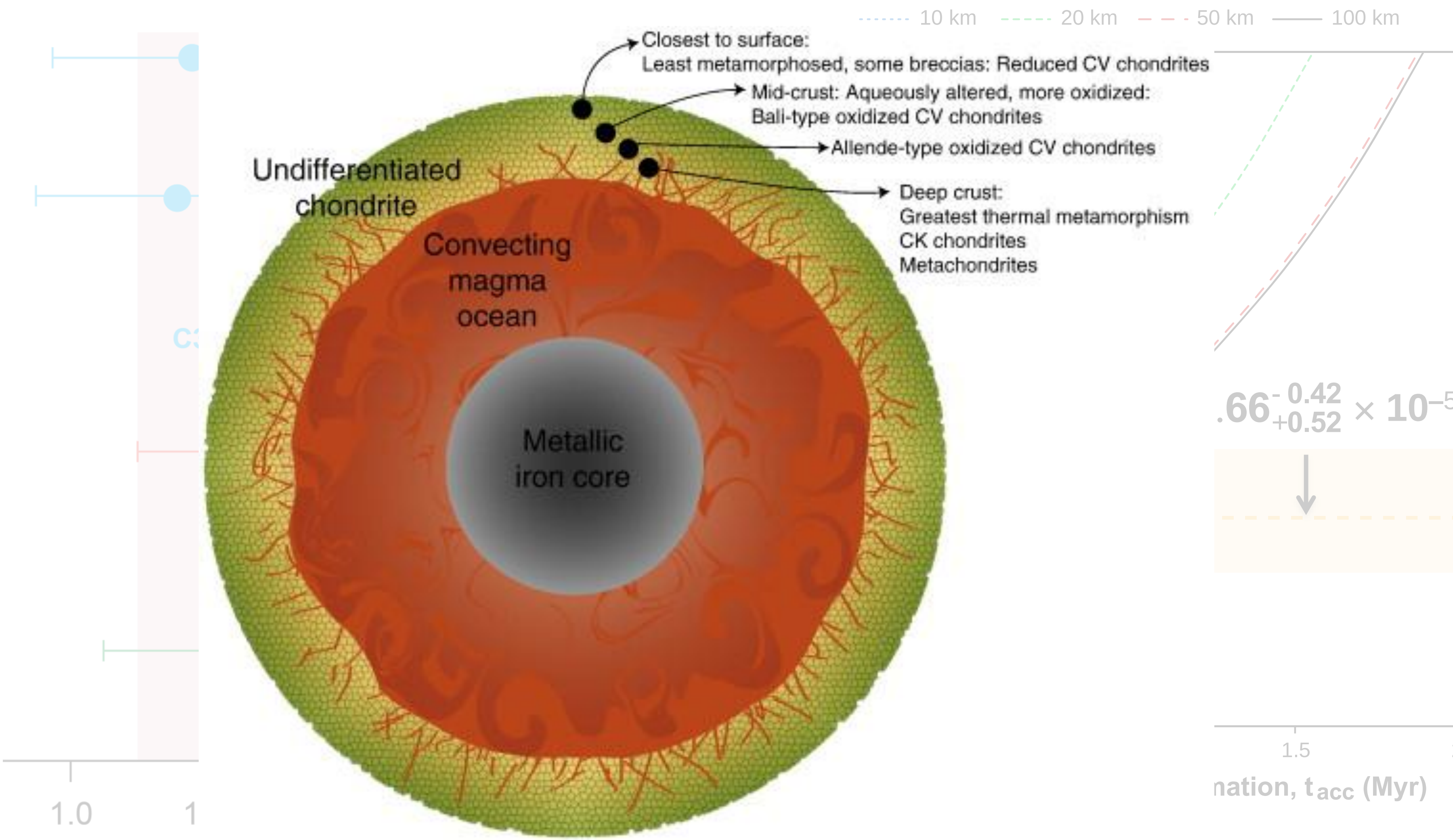
Reduced $[^{26}Al/^{27}Al]_0$ level in planet-forming region





Olsen *et al.* (submitted)

Reduced $[^{26}Al/^{27}Al]_0$ level in planet-forming region

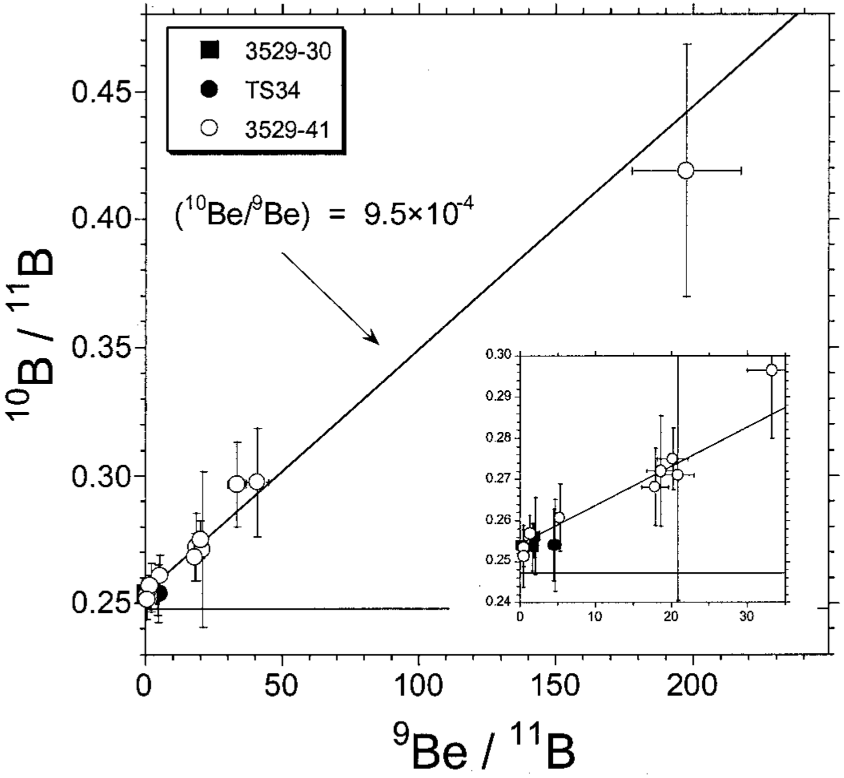


$[^{26}Al/^{27}Al]_0$ ($\times$ 10^{-5})

Elkins-Tanton *et al.* (2011), *EPSL* **305**, 1 Olsen *et al.* (submitted)

Evidence for large scale outward transport

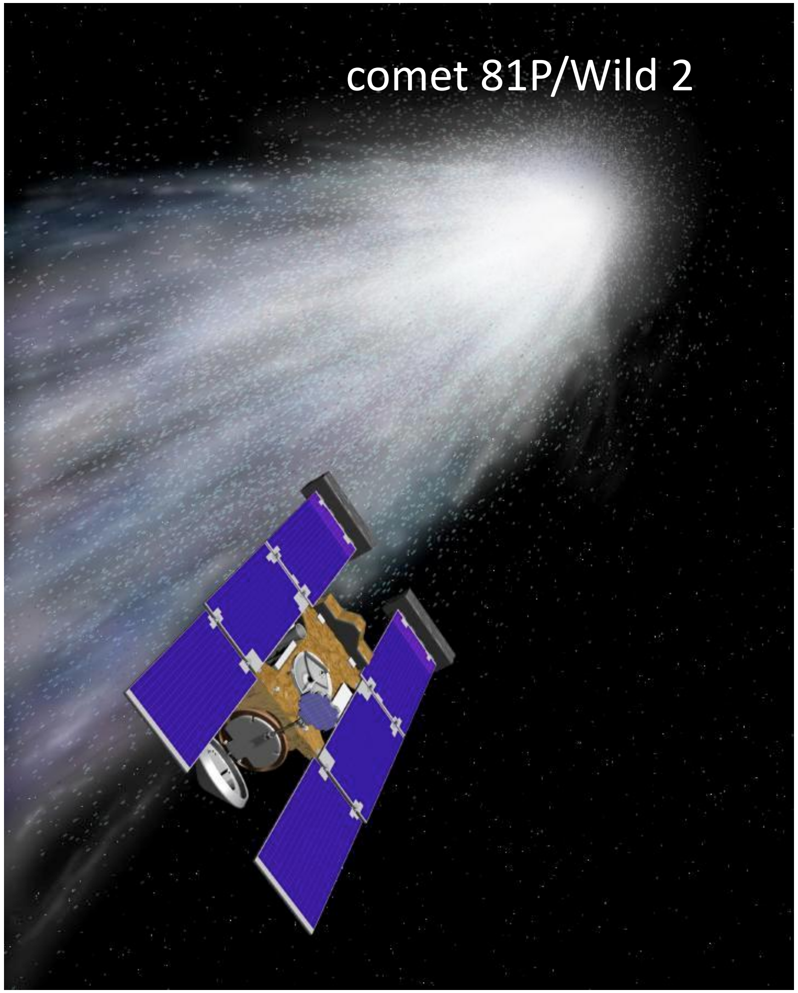
Presence of refractory high-temperature components in the accretion regions of carbonaceous chondrites (formed beyond snow line) requires efficient outward transport

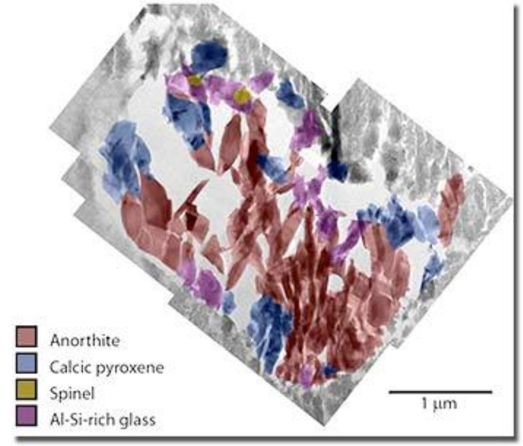


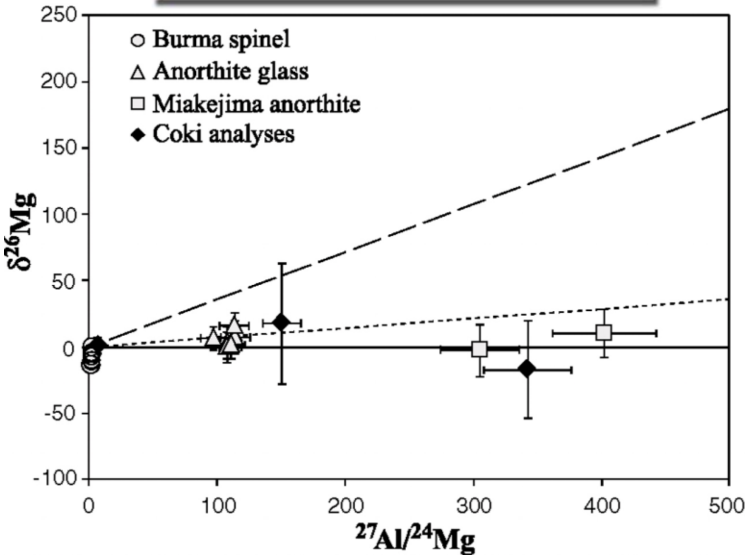
McKeegan *et al.* (2000) *Science* **289**, 1334

^{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



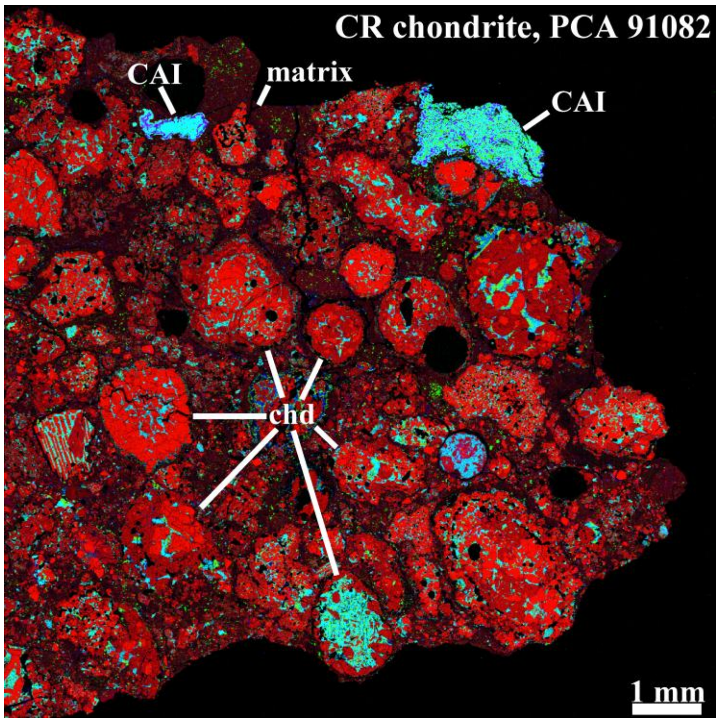




Matzel *et al.* (2010) *Science* ***328***, *483*

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 form? Locally? Various distances?

Isotope fingerprinting - using ^{54}Cr as DNA

Chondrites formed in the INNER SS:

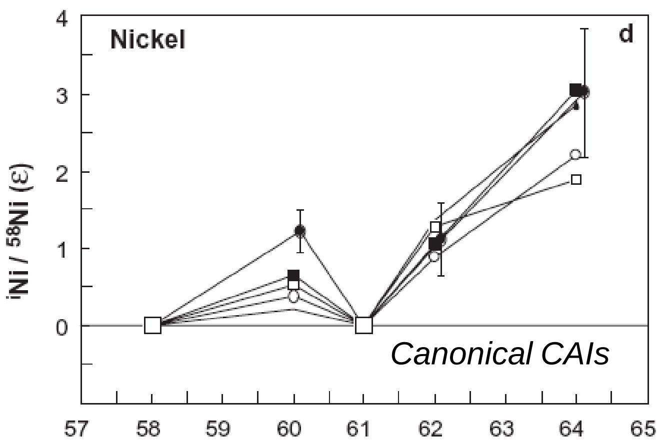
➔ *Enstatite and ordinary chondrites*

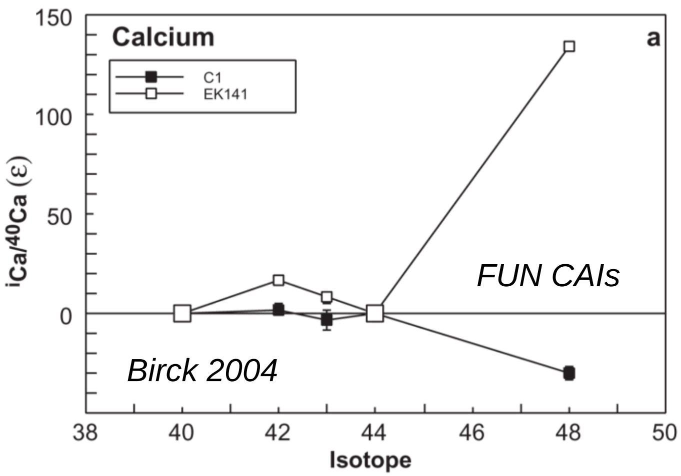
Chondrites formed in the OUTER SS:

➔ *CV and CR carbonaceous chondrites*

Evidence for widespread isotope heterogeneity

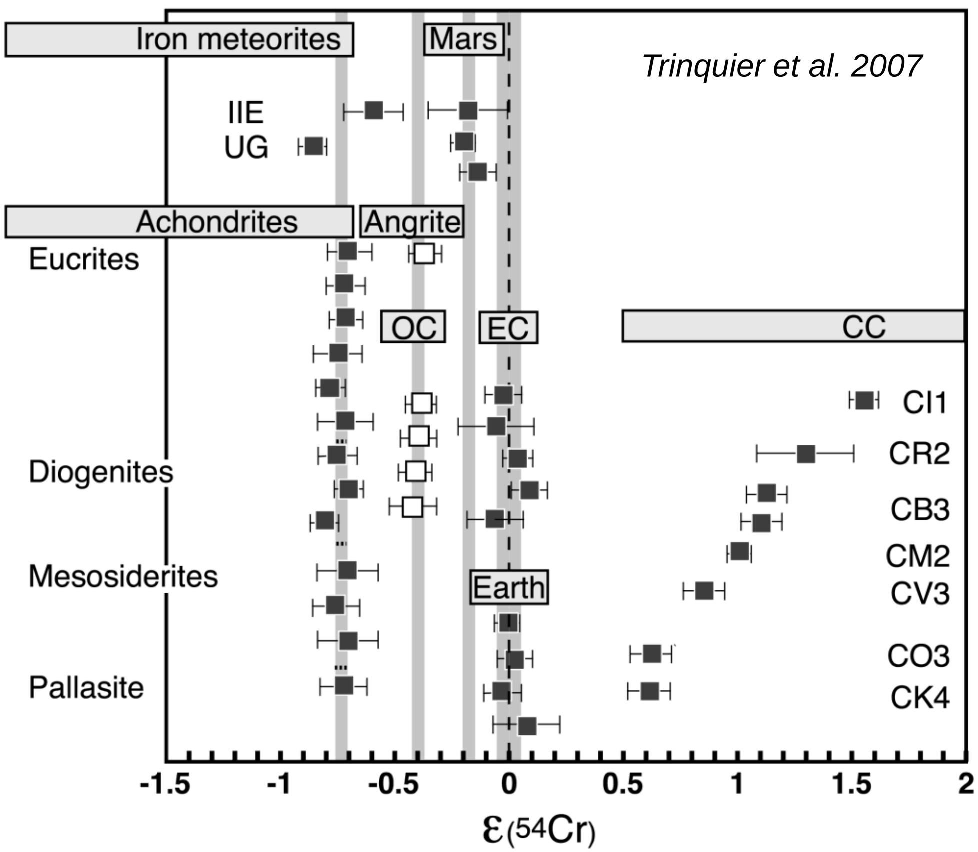
The discovery more than 30 years ago of isotopic anomalies in meteorites and their components indicates inefficient mixing of presolar components in the protoplanetary disk.



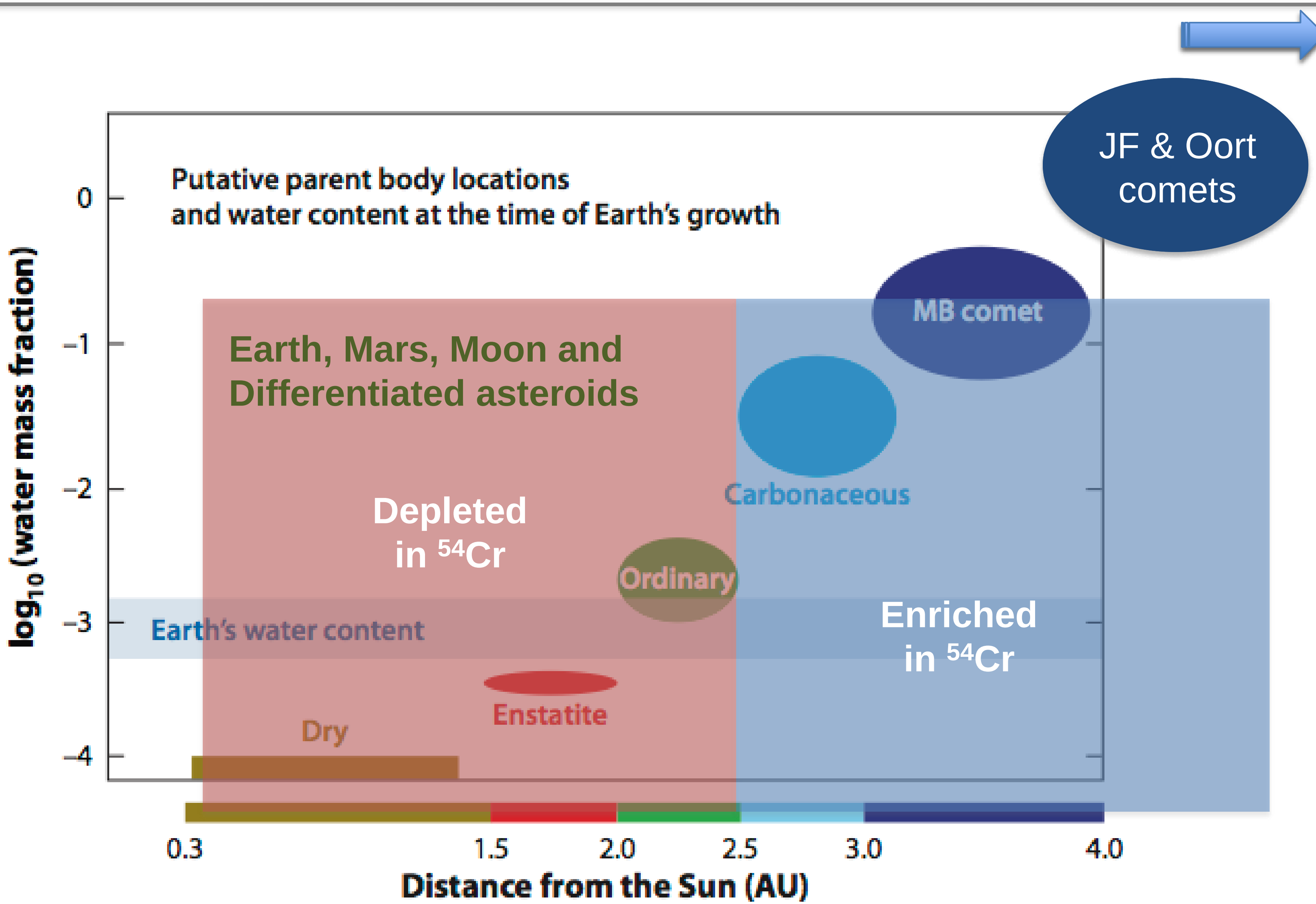


Early solar system solids

Bulk planetary materials

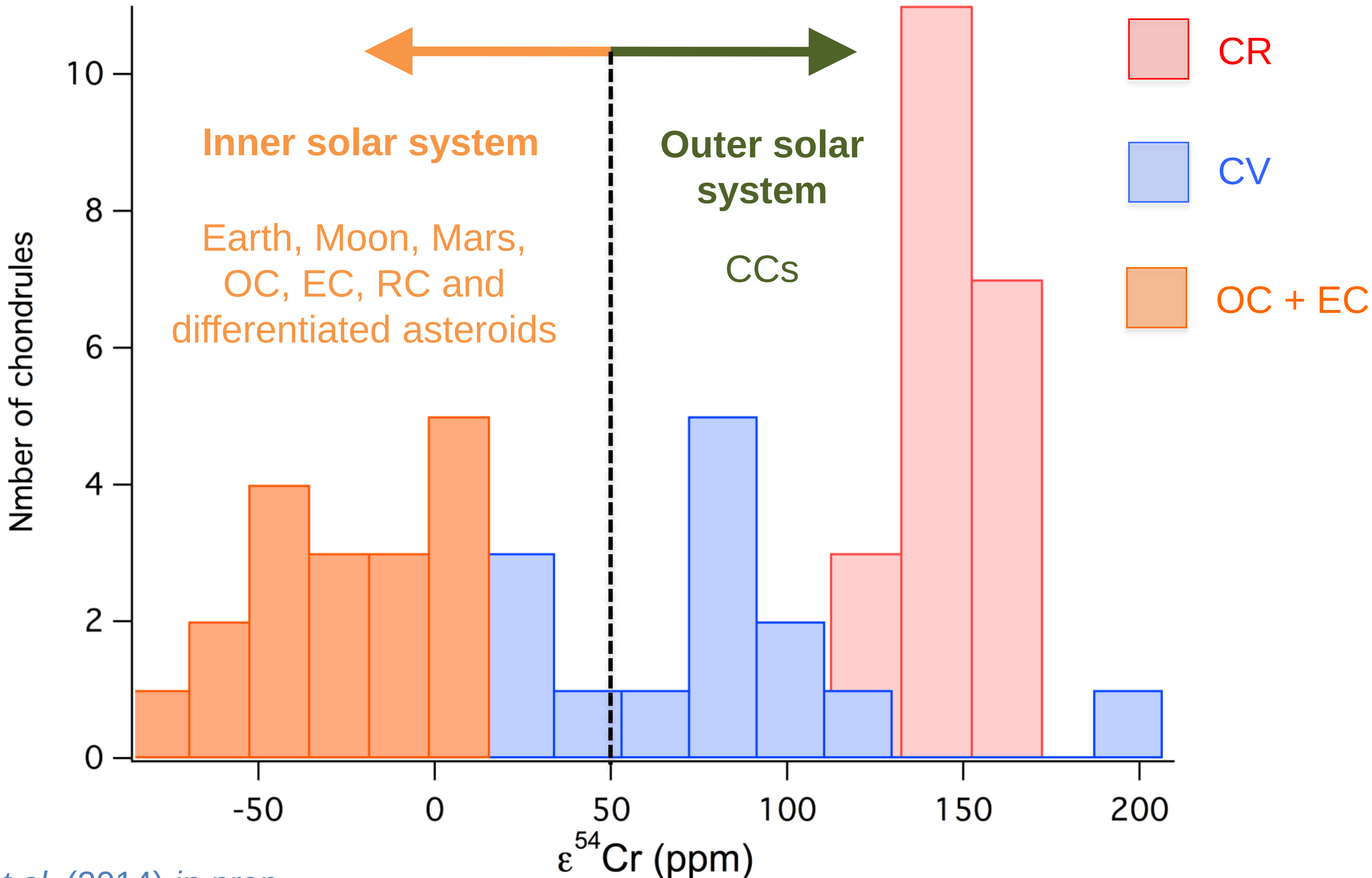


Accretion regions of chondrite classes



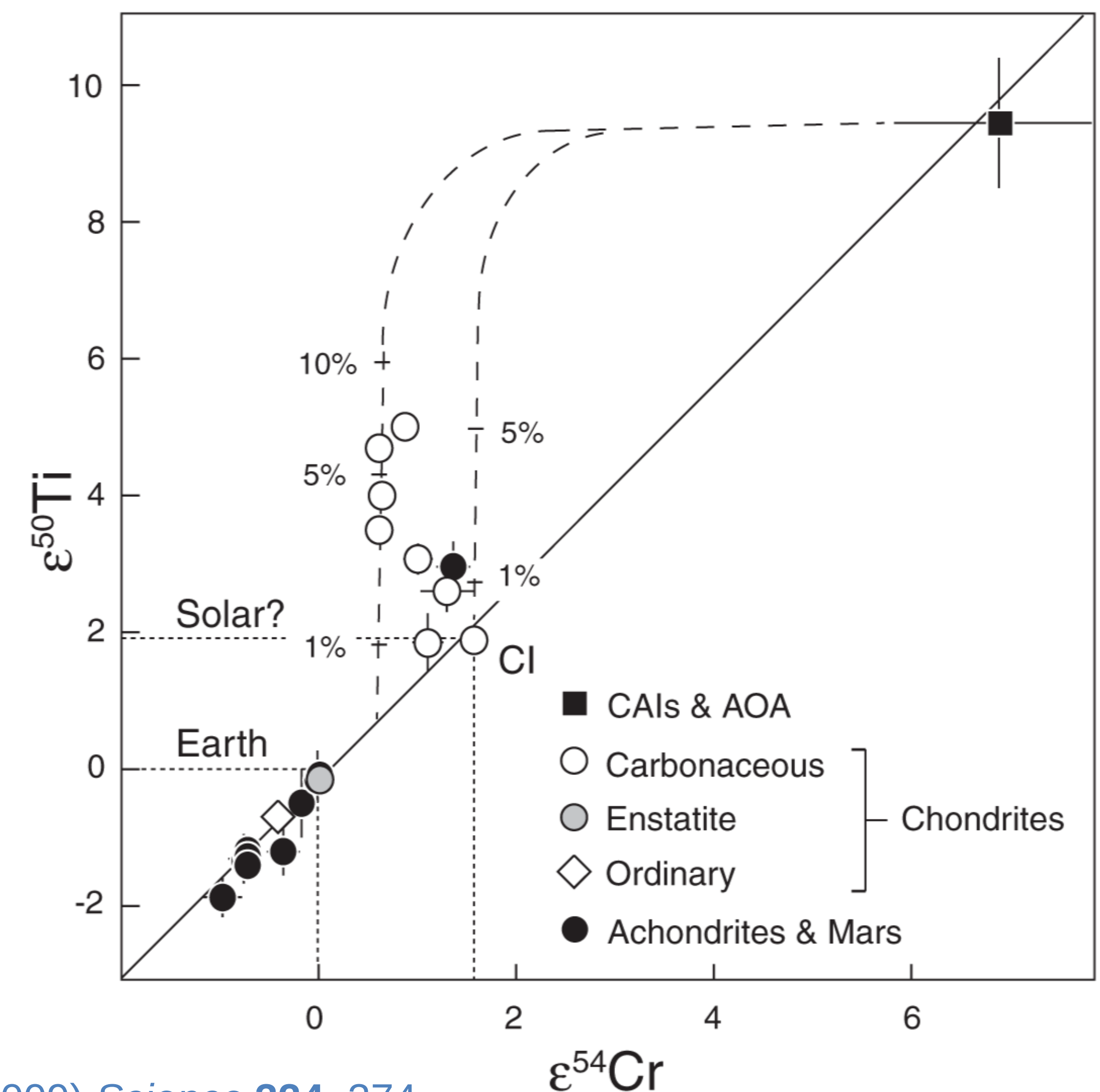
Morbidelli *et al.* (2012)

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



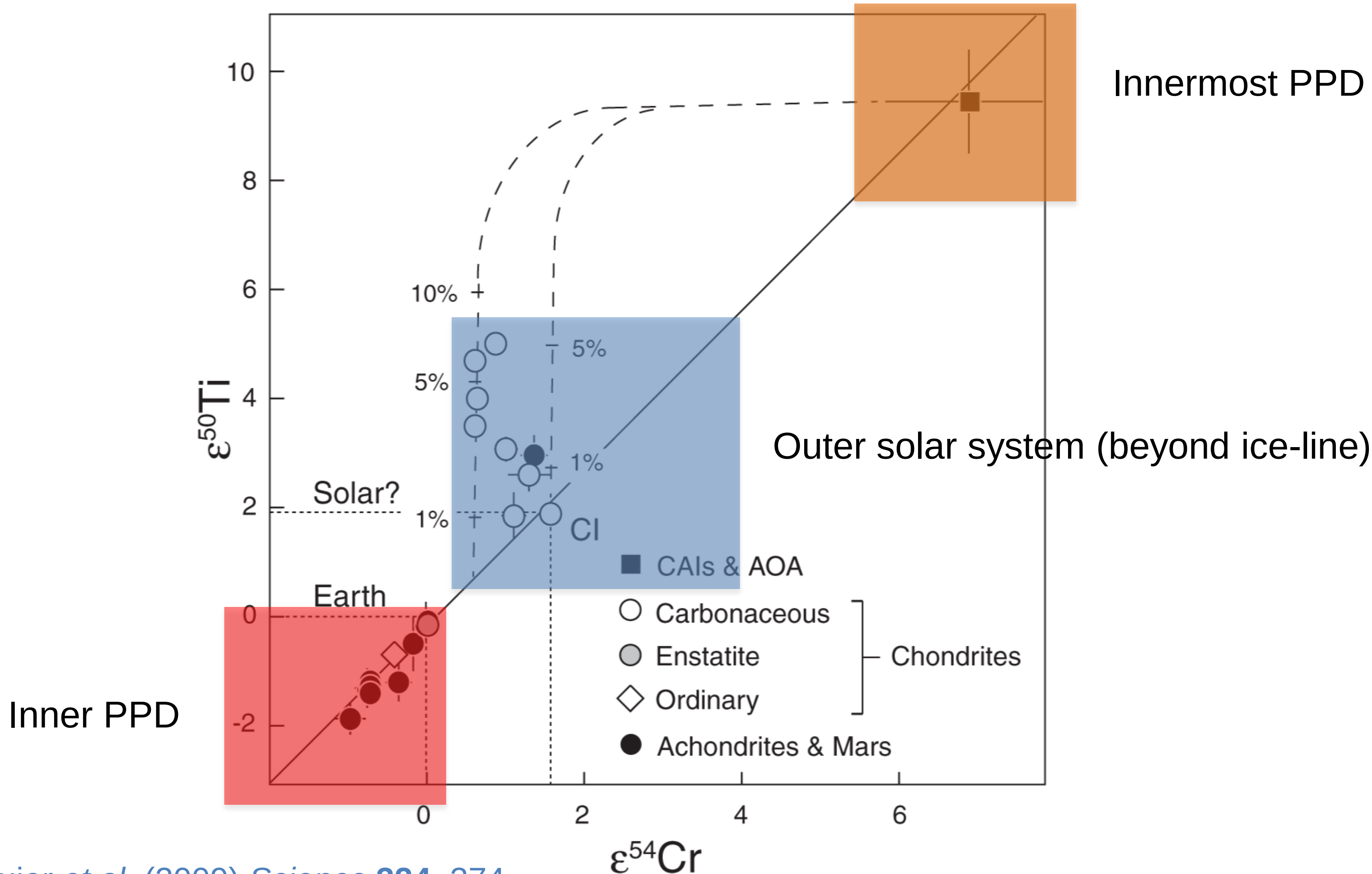
Olsen *et al.* (2014) *in prep.*

No (almost) CAI material in inner solar system?



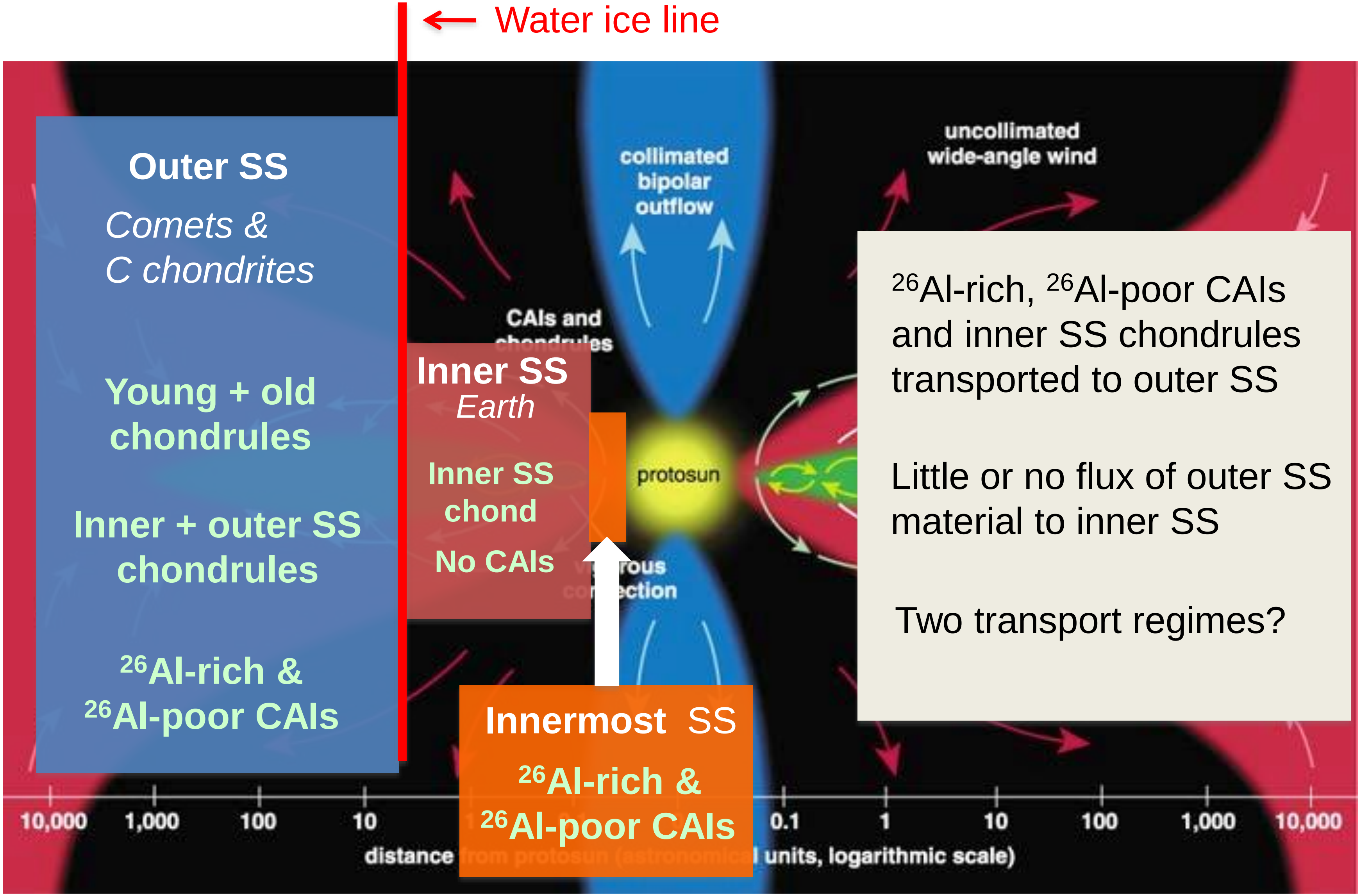
Trinquier *et al.* (2009) *Science* **324**, 374

No (almost) CAI material in inner solar system?

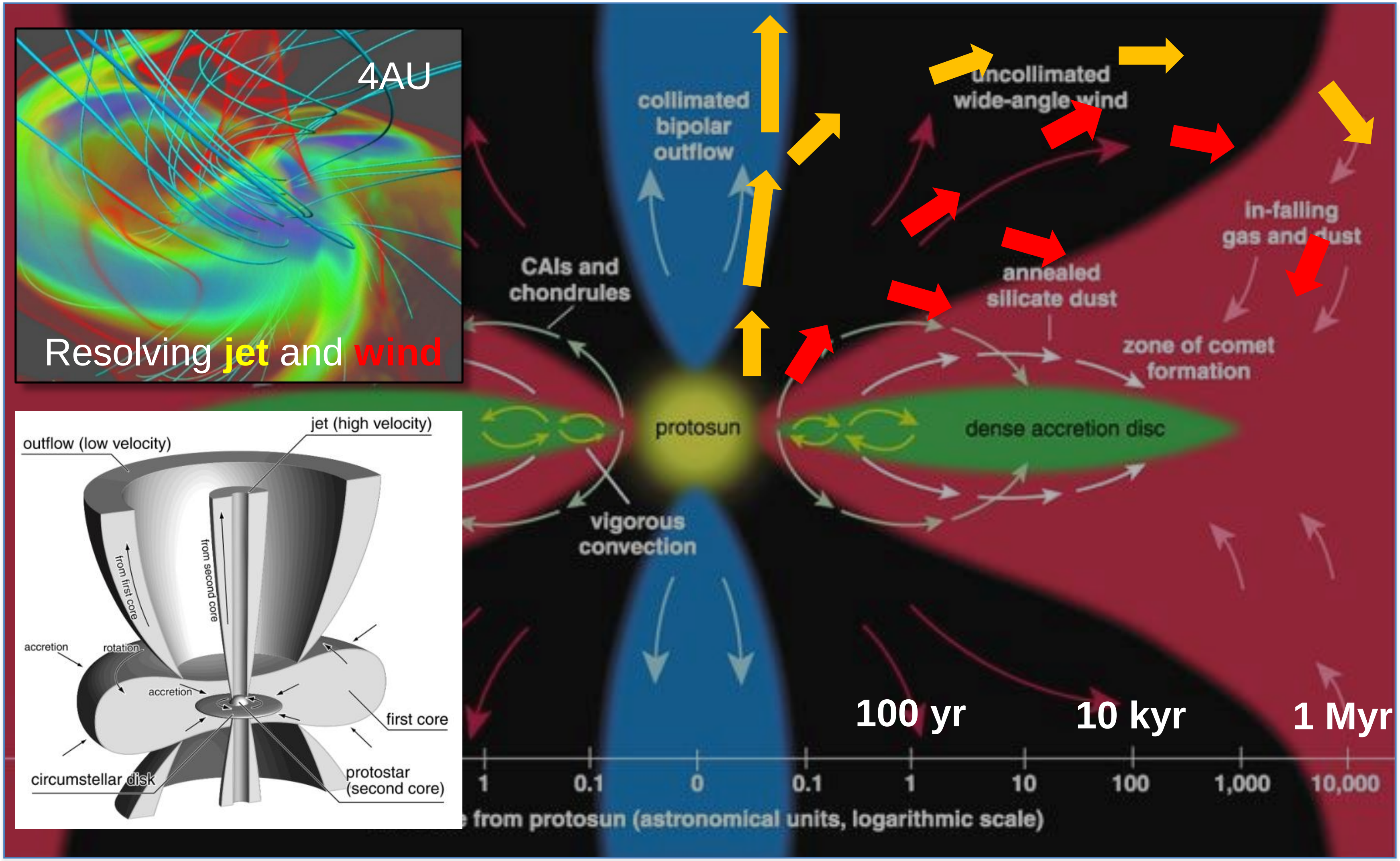


Trinquier *et al.* (2009) *Science* **324**, 374

Protoplanetary disk reservoirs



The conveyor belt paradigm

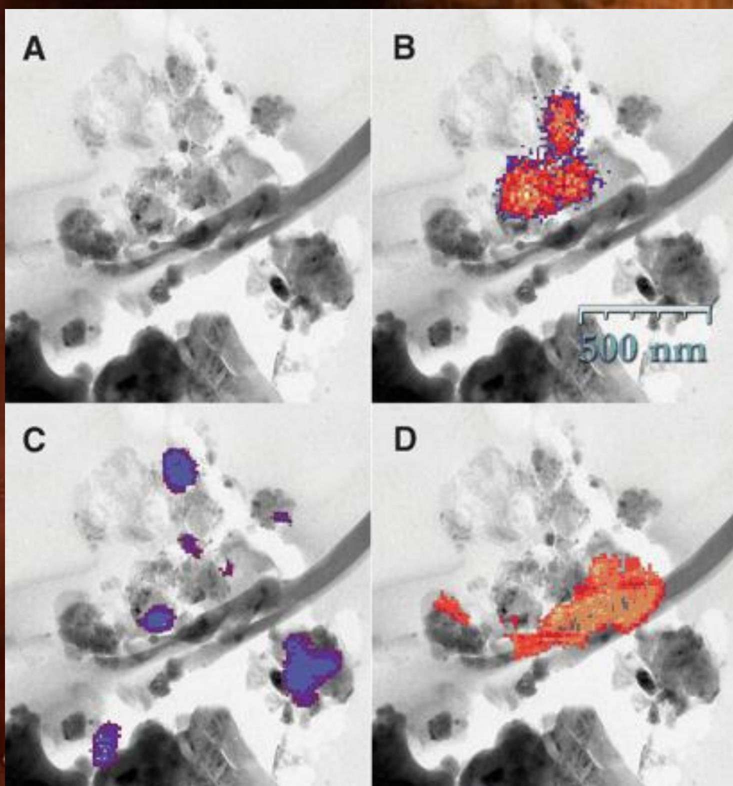


Key observations and questions

- *Sun born in cluster – GMC has input from multiple SN sources*
- *Thermal processing of dust results in isotope heterogeneity in disk solids*
- *Chondrule formation during lifetime of disk (both inner and outer SS)*
- *Chondrule production promotes the rapid assembly of planetary embryos*
- *Chondrule forming process(es) operating in inner and outer SS*
- *Two transport regimes? Large scale (jet) and small scale (wind)?*
- *Limited inward transport of outer SS material in inner SS?*
- *Giant planet formation creating disk gaps and limiting inward mass transport?*

Comets contain the start-up material?

Pristine, unmodified molecular cloud matter formed in the cold outermost solar system



Comet 67P/Churyumov-Gerasimenko

Comets contain the start-up material?

Pristine, unmodified molecular cloud matter formed in the cold outermost solar system

Asteroids sample return missions:

JAXA Hayabusa 2: C-type (2019)

NASA OSIRIS-REx: C-type (2023)

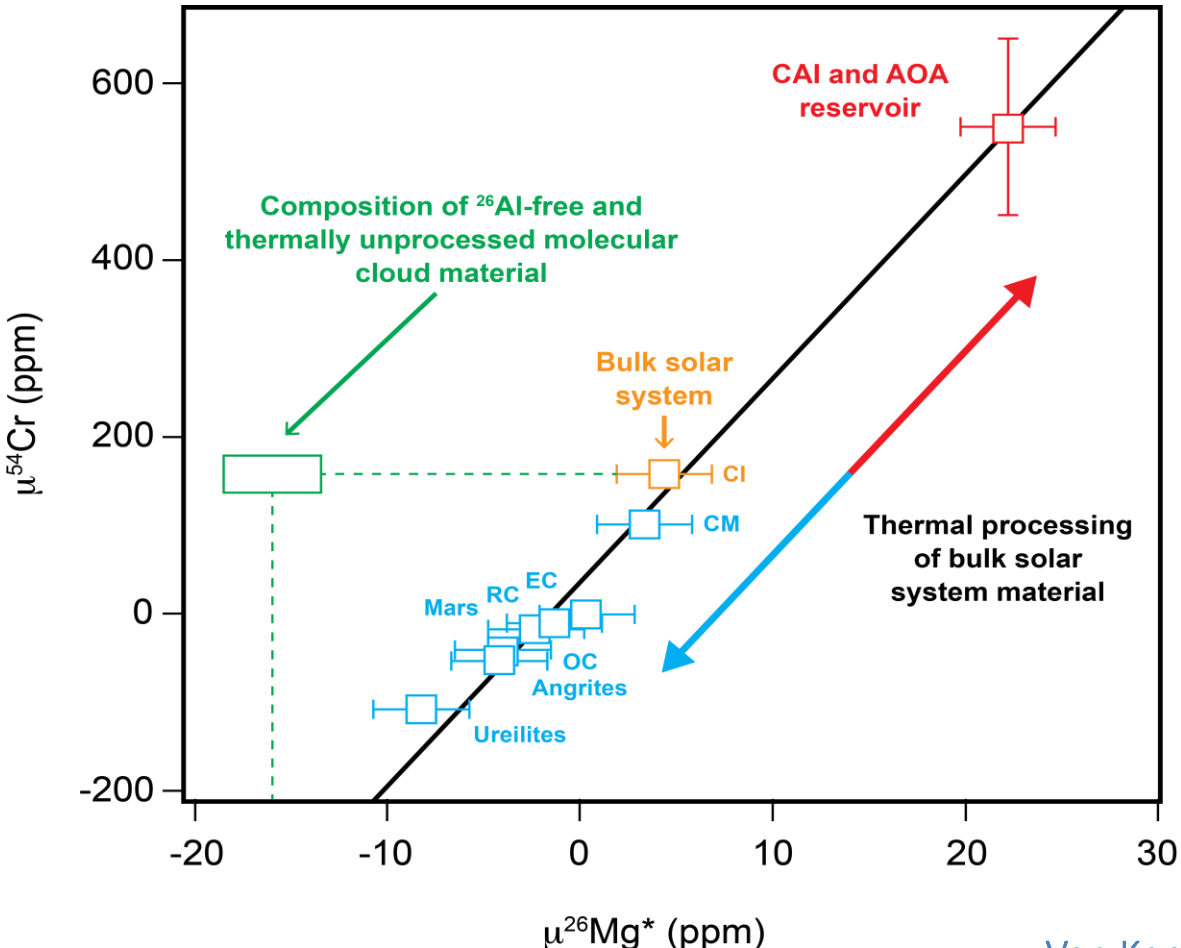
Under evaluation:

Marco-Polo 2D: D-type (2031)

Comet 67P/Churyumov-Gerasimenko

Search of the holy grail – primordial GMC matter?

What is the expected composition of primordial thermally unprocessed GMC matter? The make-up of the GMC prior to its pollution by stellar-derived ^{26}Al.

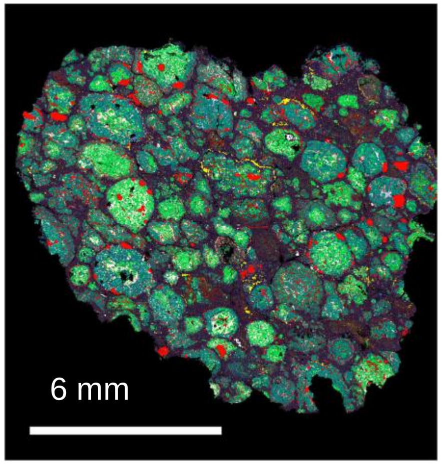


Some unprocessed GMC material is expected to survive in the outer solar system

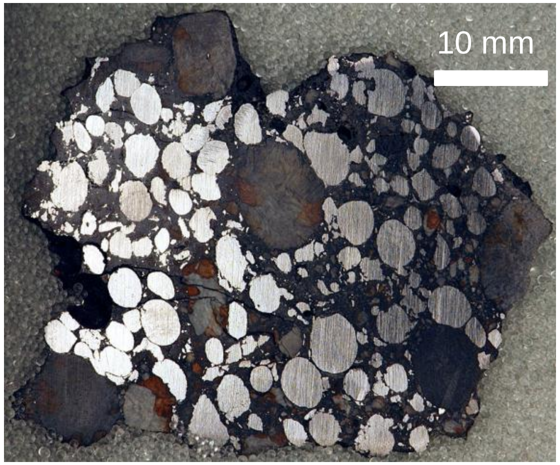
Accretion regions of cometary obejcts?

Van Kooten *et al*. (2015) *Science,* submitted

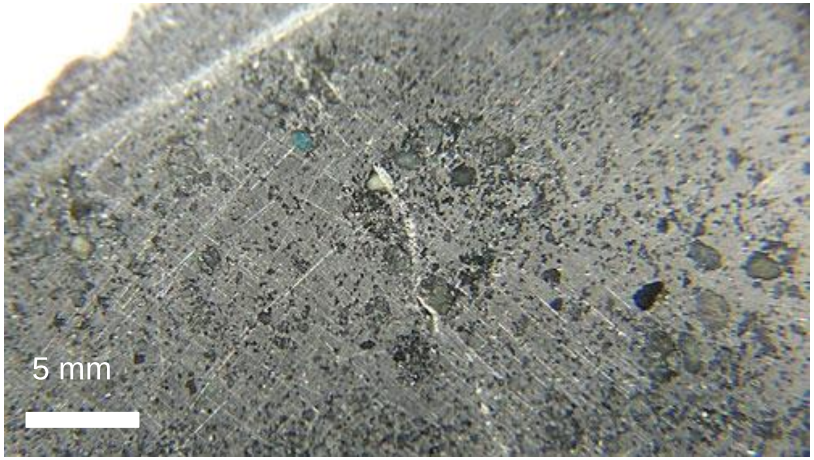
Metal-rich chondrites: samples of the outer SS?



CR chondrites



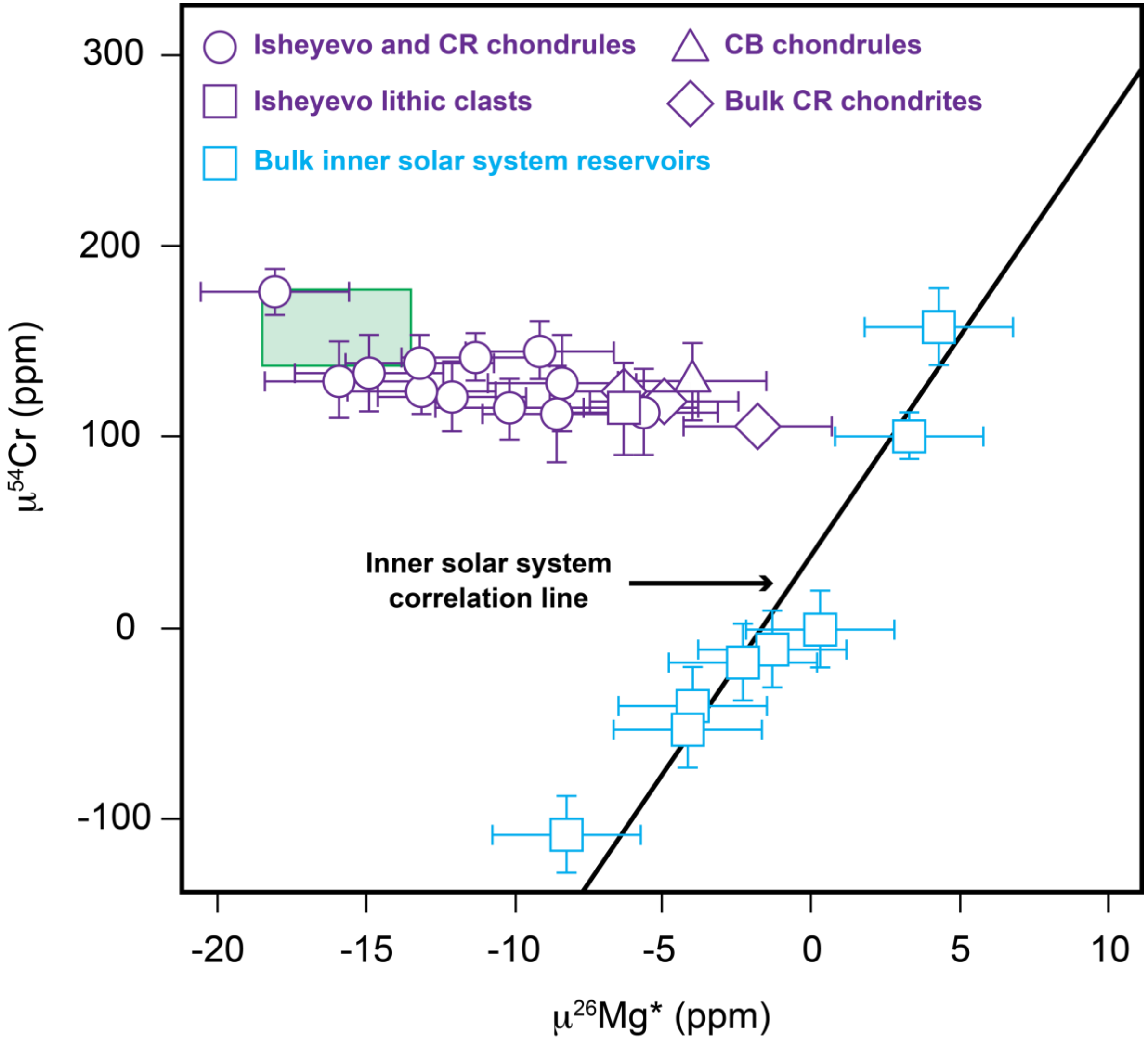
CB chondrites



CB/CH chondrites

- Bulk CR, CB and CH have large ^{15}N enrichments (200 to 1500‰)
- CH chondrites contain lithic clast with extreme ^{15}N enrichments (5000‰)
- CR chondrites contain the highest abundance of presolar grains
- CB and CH chondrites parent bodies accrete >5 Myr after T_0

The isotope signature of primordial GMC?



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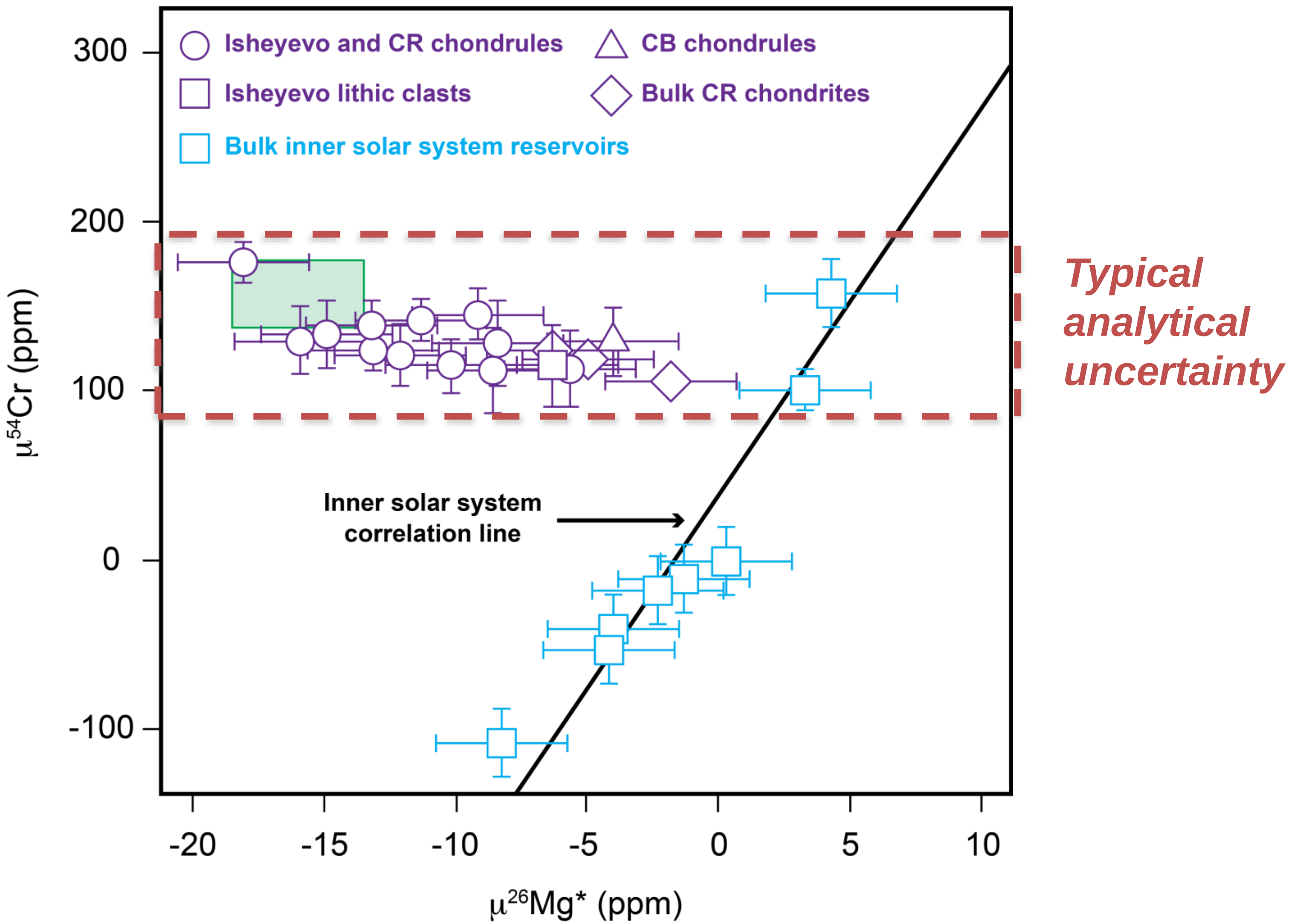
The isotope signature of primordial GMC?



Van Kooten *et al*. (2015) *Science,* submitted