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Isotopic anomalies of trans-iron elements observed in meteorites: Constraints for nucleosynthesis

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Introduction: Nucleosynthesis of trans-iron elements

Neutron capture processes

s (slow) - process

AGB stars

NASA

r (rapid) - process

Supernovae

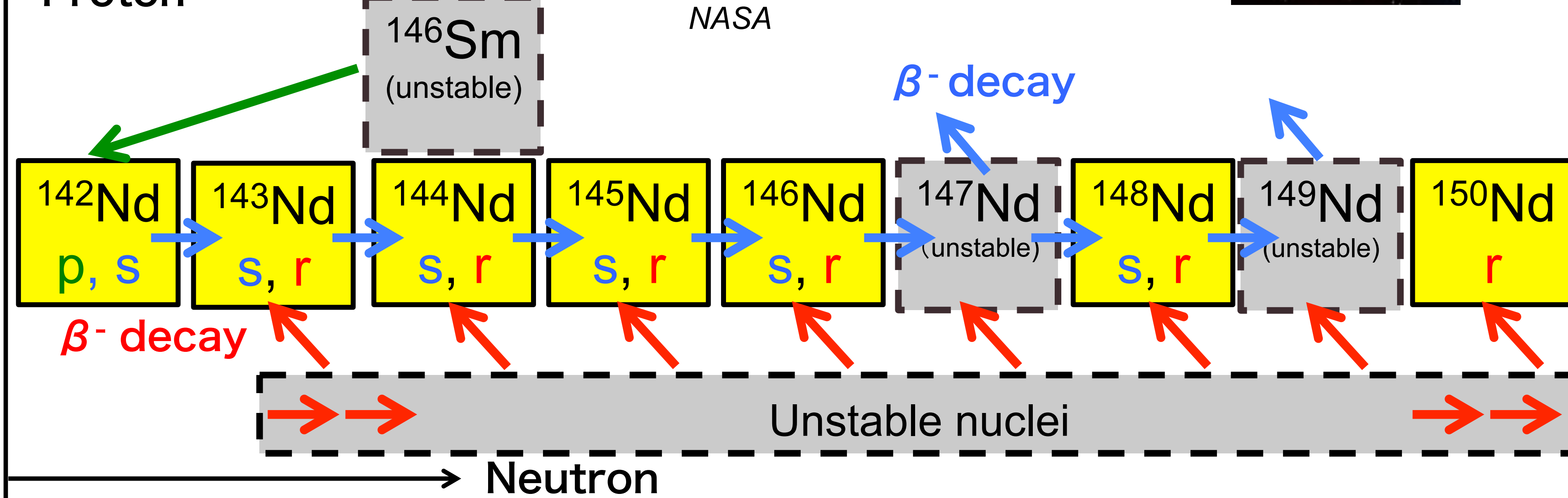
NASA

Neutron star mergers

Caltech

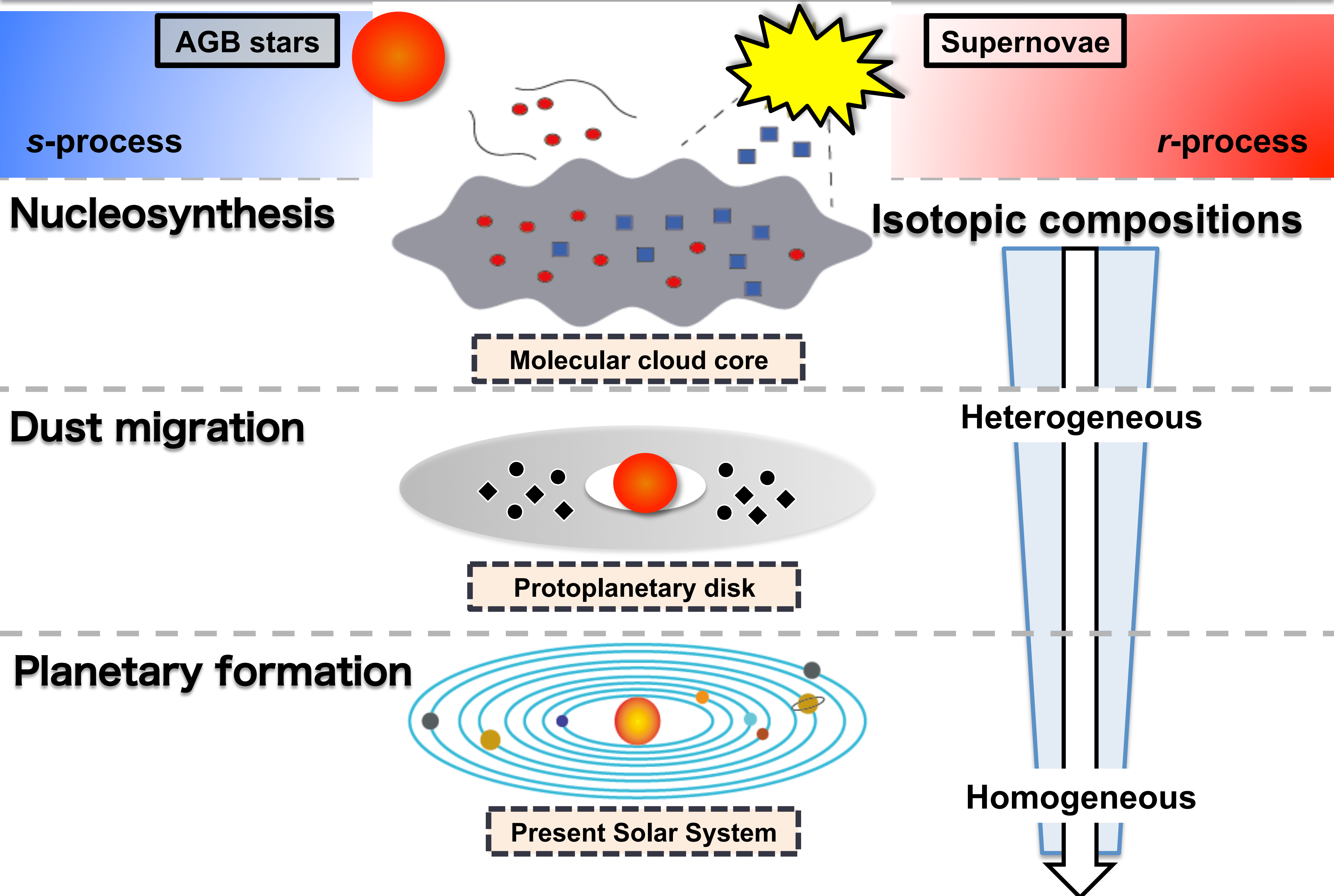
p (photodissociation) -process

Supernovae



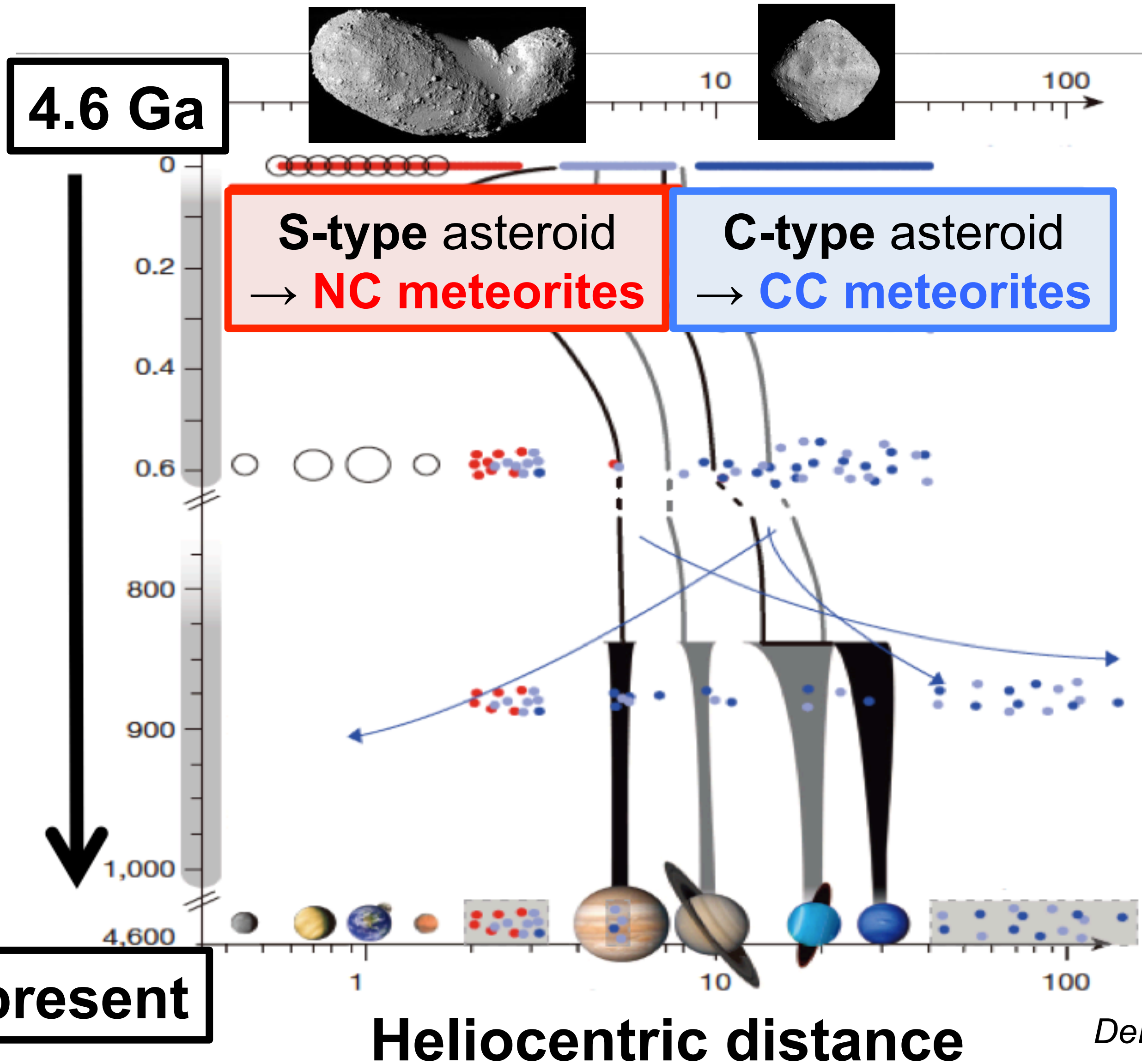
Elemental abundances of Solar System reflect the nucleosynthesis in the stellar environments

Introduction: Evolution of Solar System



Introduction: Carrier grains of trans-iron elements

NC: **N**on-**C**arbonaceous meteorites **CC**: **C**arbonaceous **C**hondrites



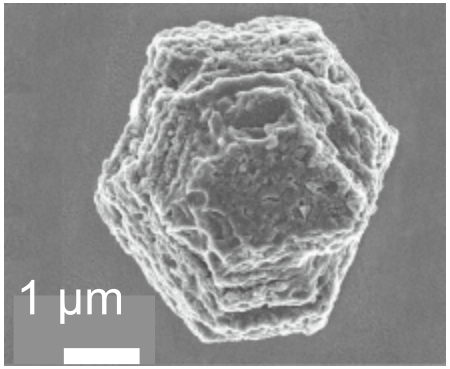
DeMeo and Carry (2014)

Introduction: Carrier grains of trans-iron elements

★ Presolar grains in meteorites

<u>carrier grains for *s*-nuclides</u>

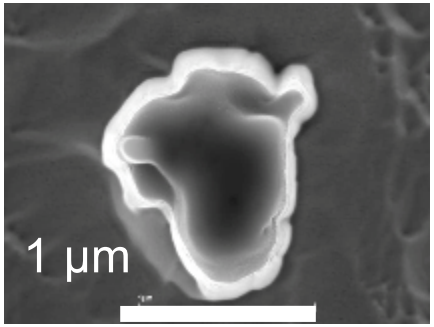
- **Mainstream SiC** etc.
  - *s*-enriched isotopic compositions *(e.g., Yin et al. 2006)*



Mainstream SiC
Zinner (2014)

<u>(possible) carrier grains for *r*- and *p*- nuclides：</u>

- **X-type SiC** etc.
  - Si isotopic compositions likely from supernovae



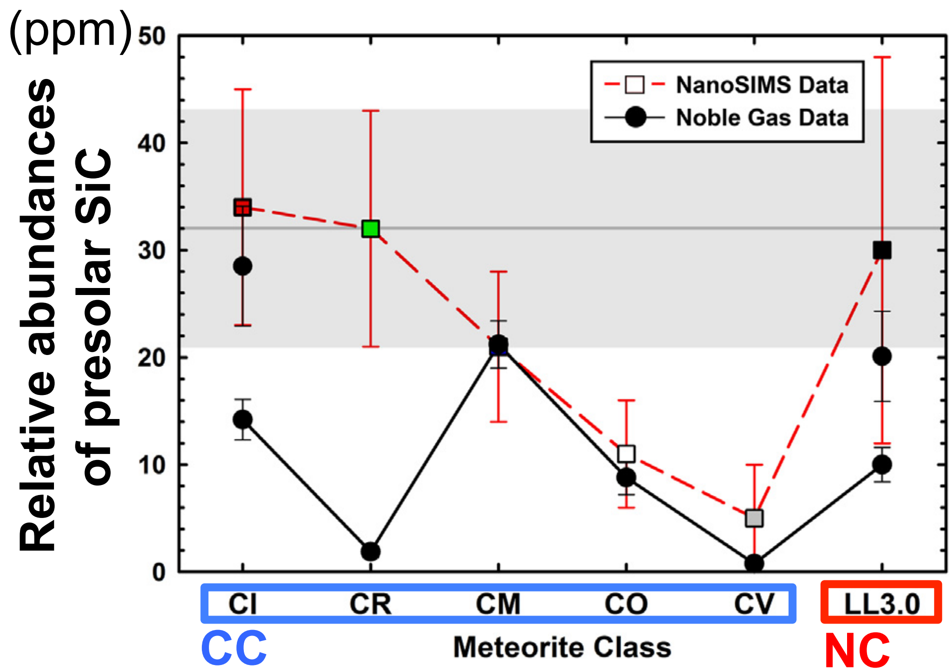
X-type SiC *Max-Plank HP*

Presolar grains carried trans-iron elements into the early Solar System

Introduction: Distribution of presolar grains

How these presolar grains were distributed in the early Solar System?

① Relative abundances of presolar grains in meteorites



Davidson et al. (2014)

× alteration in meteorite parent bodies destroyed the grains

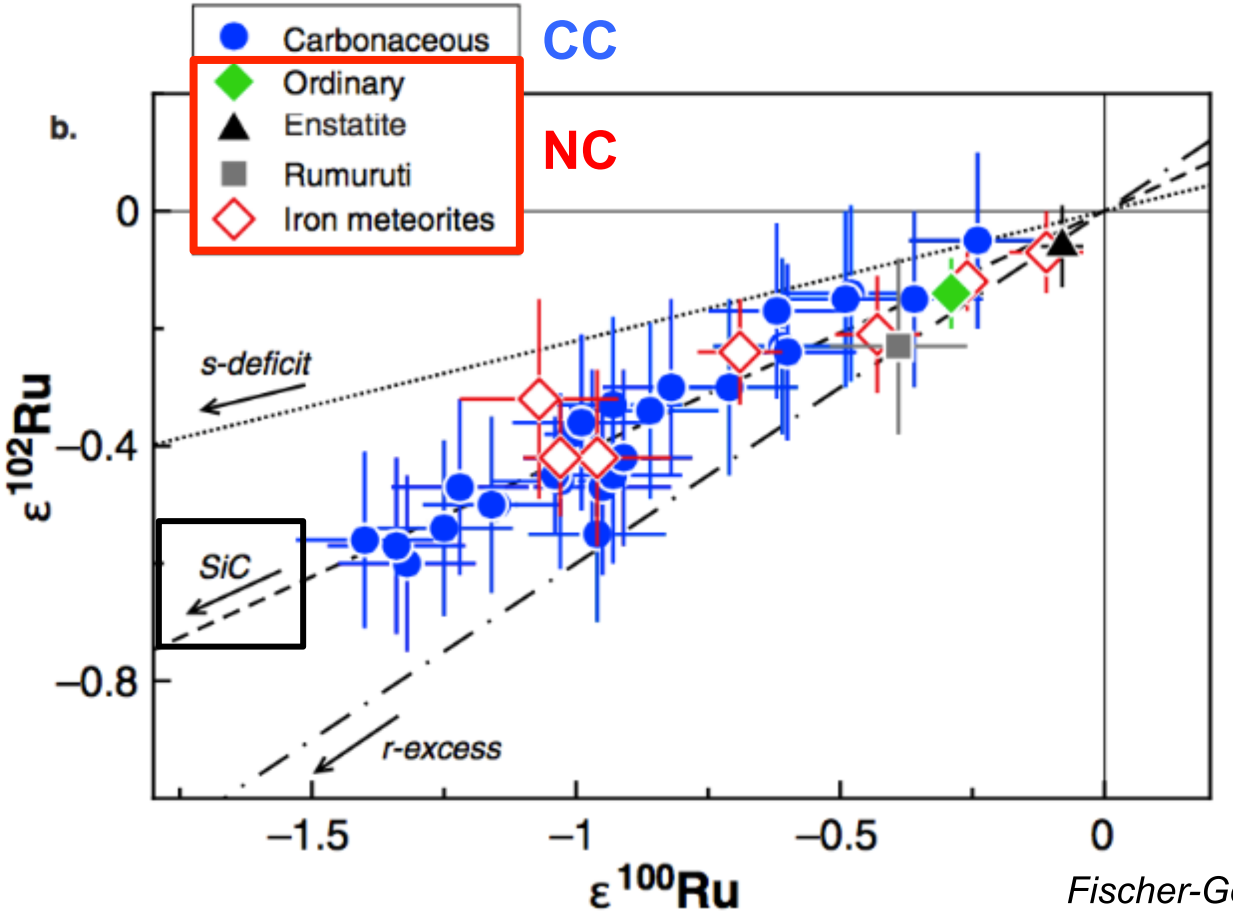
② Isotopic compositions in bulk meteorites

○ initial isotopic compositions including presolar grains

Introduction: Nucleosynthetic isotopic anomalies

The **mass-independent** isotopic differences (**heterogeneities**) between meteorite and terrestrial rocks.

$$\varepsilon^{100}\mathrm{Ru} = ((^{100}\mathrm{Ru}/^{101}\mathrm{Ru})_{\mathrm{meteorites}} / (^{100}\mathrm{Ru}/^{101}\mathrm{Ru})_{\mathrm{terrestrial}} - 1) \times 10^4$$

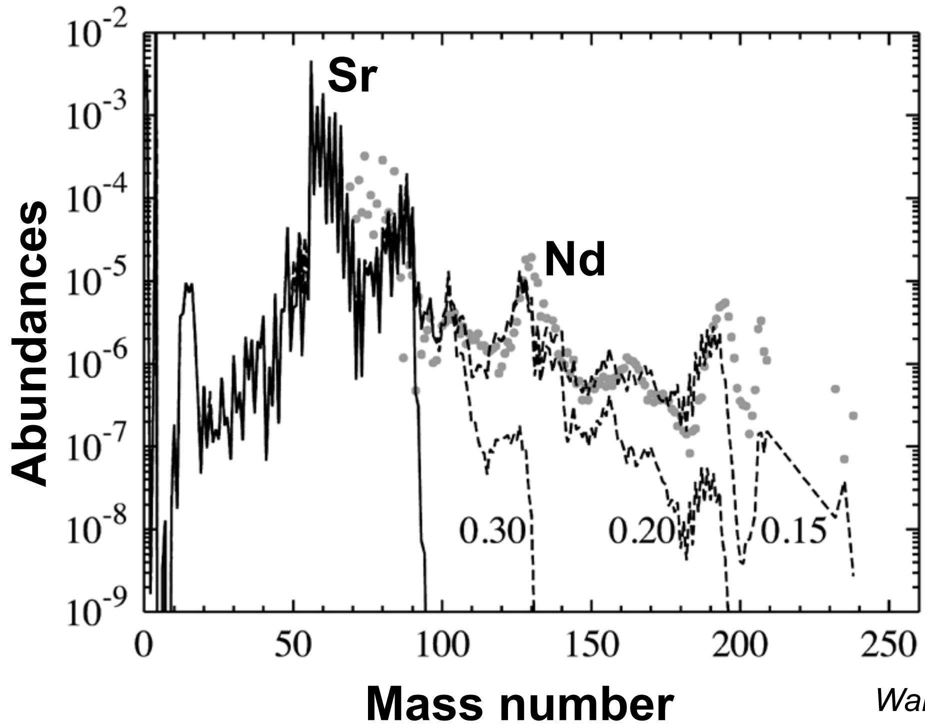


Fischer-Gödde and Kleine (2017)

Bulk meteorite reflects the heterogeneous distribution of presolar grains

Introduction: Sr isotope anomalies in meteorites

- ✓ **Unknown:**
  The cause of the heterogeneous distribution of presolar grains in the early Solar System.
- ✓ We focus on **Sr** and **Nd** isotopes.
  - ✓ Affinity to **silicate minerals** (main components of the early Solar System)
  - ✓ Possibly decoupled ***r*-process source**



Wanajo (2014)

Objective of this study

To reveal the origin of heterogeneous distribution of presolar dusts in the early Solar System

Methods

High-precision Sr and Nd isotope analyses of bulk chondrites

Samples

All samples were powdered

- Carbonaceous chondrites × 6
- Non-carbonaceous (enstatite and ordinary) meteorites ×7

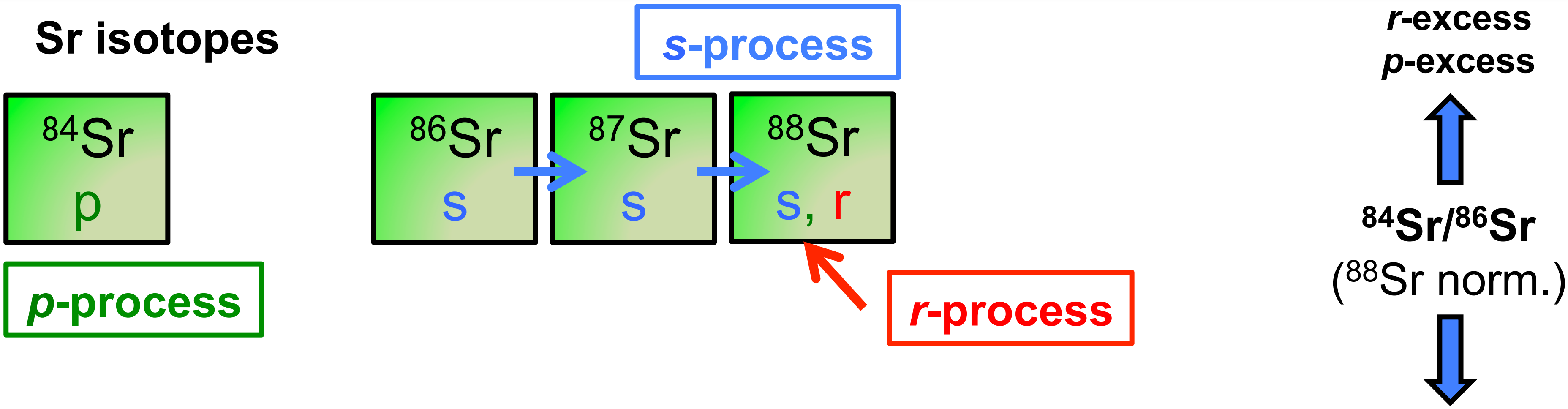
Mass spectrometry

Thermal **I**onization **M**ass **S**pectrometry (TIMS)

Precision: **^{84}Sr/^{86}Sr**: ±20 ppm, **^{150}Nd/^{144}Nd**: ±8.8 ppm (2 SD)

Background: Sr and Nd isotopes

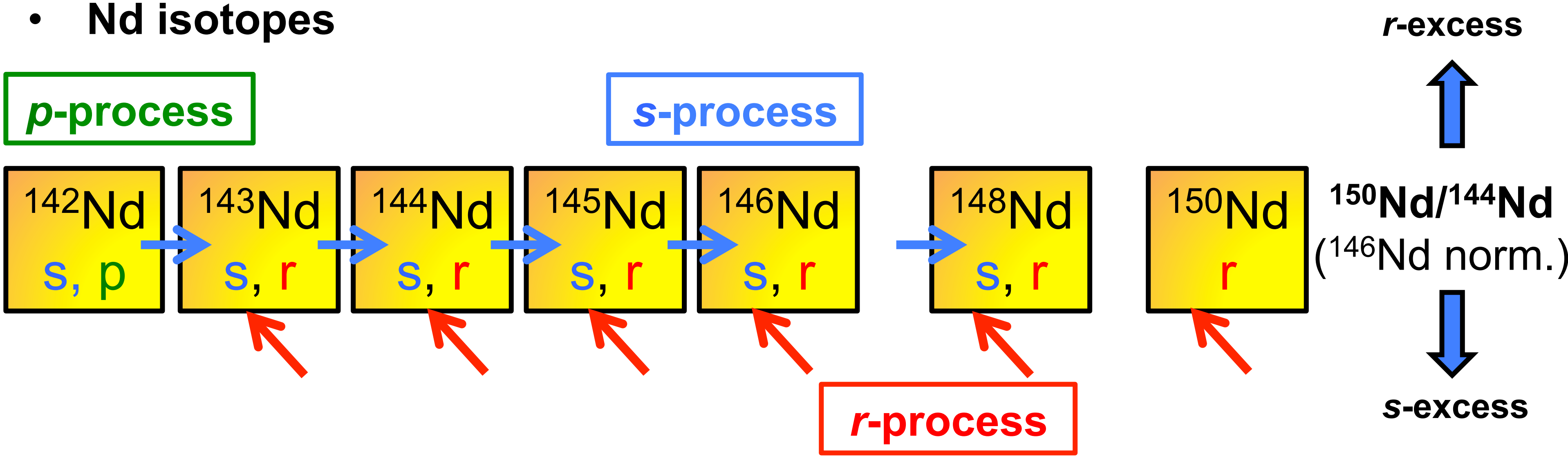
- **Sr isotopes**



✓ ^{88}Sr is used for the mass-dependent isotopic fractionation.

✓ ^{84}Sr/^{86}Sr ratios reflect the contribution from *s*-, *r*-, and *p*-nuclides.

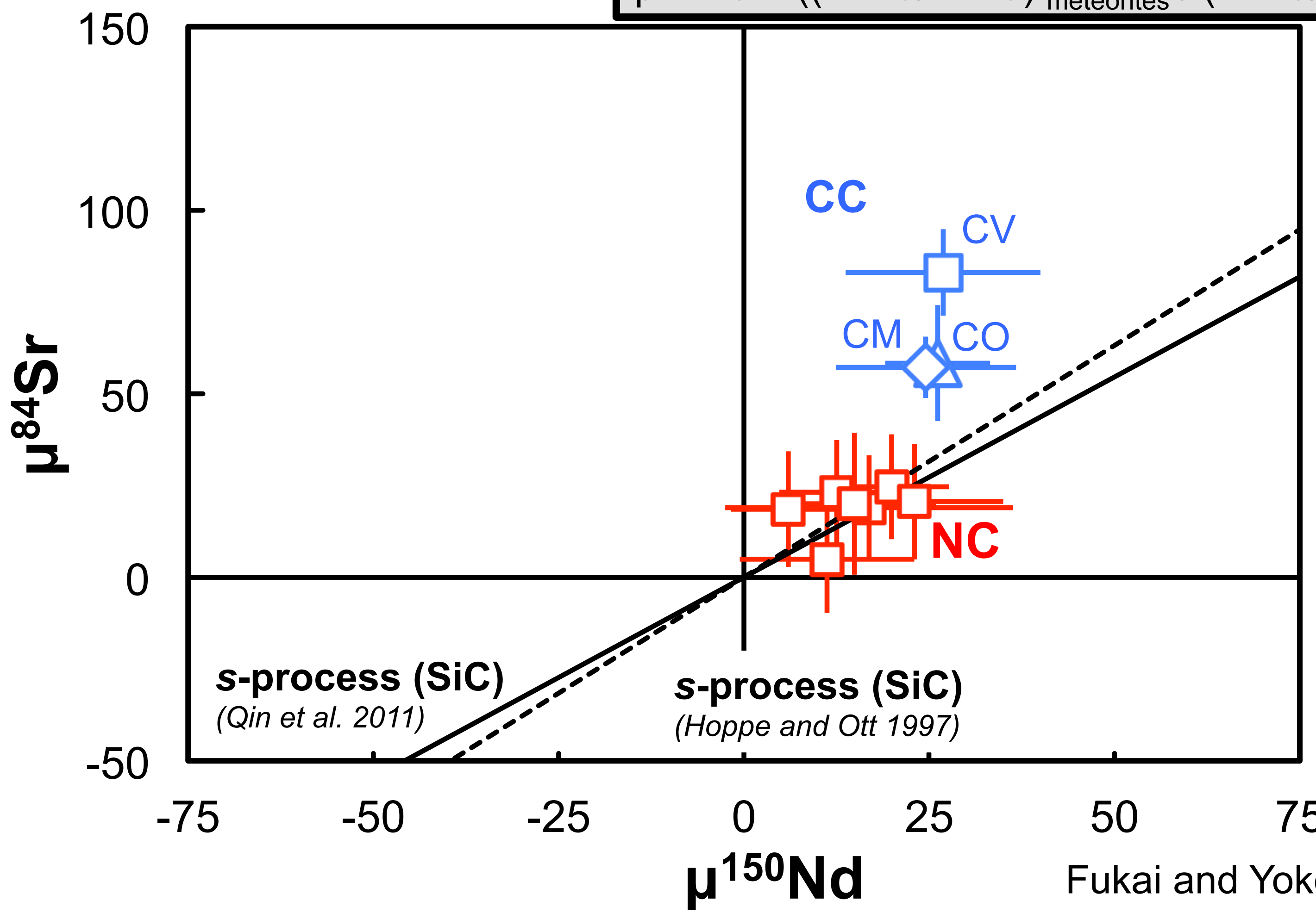
- **Nd isotopes**



Results: Nucleosynthetic Sr and Nd isotopic anomalies

$\mu^{84}Sr = ((^{84}Sr/^{86}Sr)_{meteorites} / (^{84}Sr/^{86}Sr)_{Earth} - 1) \times 10^6$

$\mu^{150}Nd = ((^{150}Nd/^{144}Nd)_{meteorites} / (^{150}Nd/^{144}Nd)_{Earth} - 1) \times 10^6$



(Error bars: 2 SE)

normalized to **terrestrial basalts**

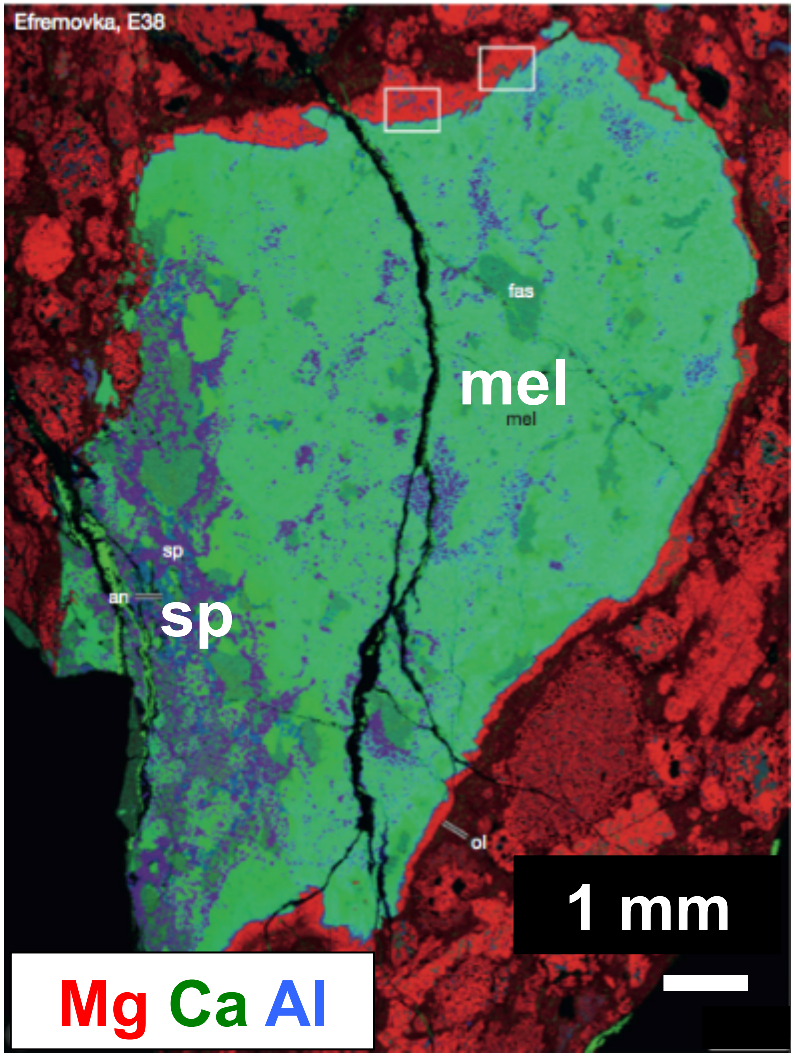
Fukai and Yokoyama (2019) *ApJ*

- ✓ **NC** and **CCs** show the Sr and Nd isotopic heterogeneities.
- ✓ **CCs** were deviated from the mixing line of **presolar SiC**.

Discussion: CAI

→ The isotopic anomalous components in CC...

CAI (Calcium and Aluminum rich Inclusion)



- Condensed in the early Solar System
  - not "**presolar**" grain
  - The oldest component in the Solar System
- Condensed at high temperature
  - they formed close to the Sun?
    (1400–1800 K)

CAI abundances in chondrites (vol. %)

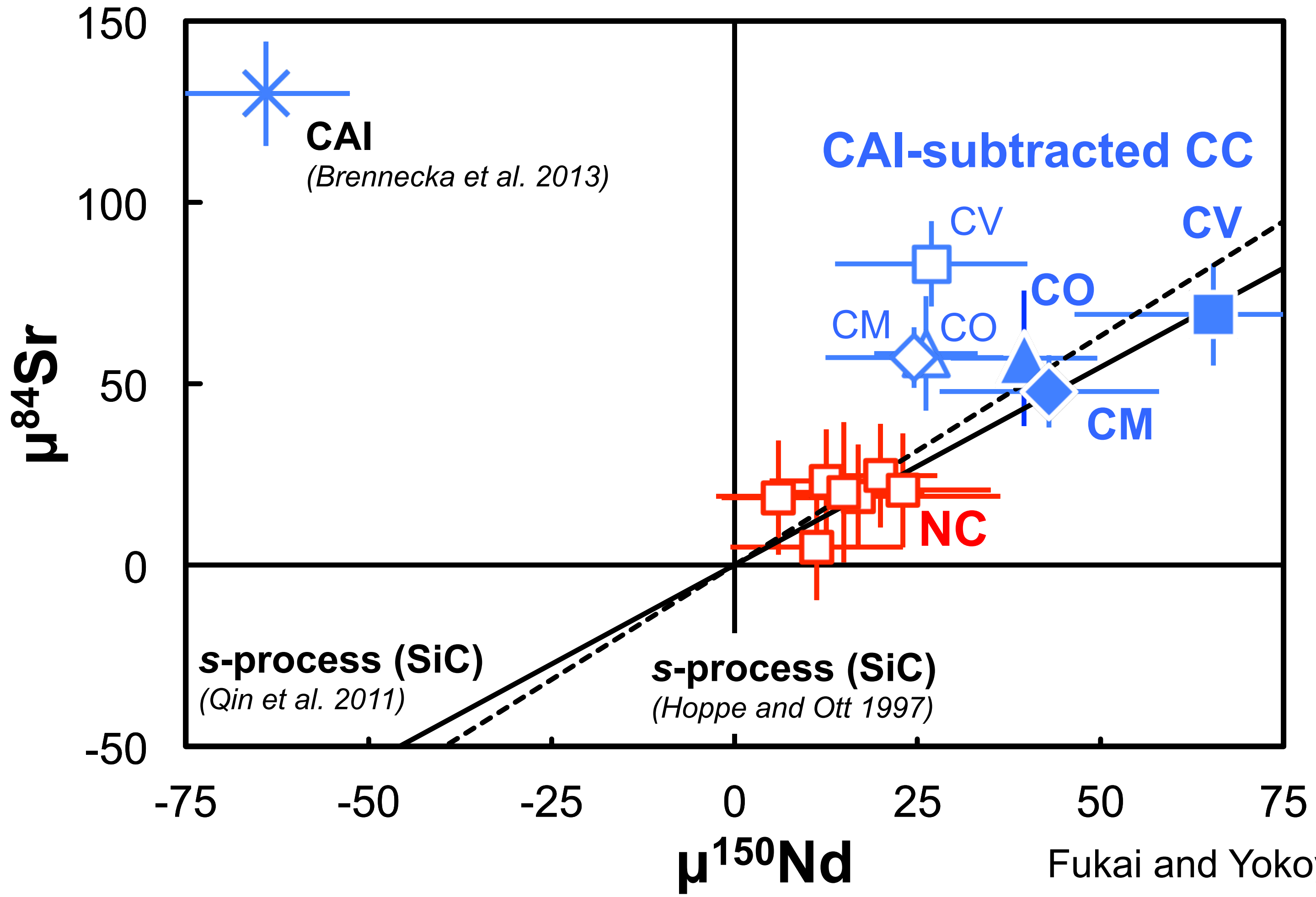
(Hezel et al. 2008)

CV: 3.0 % CM: 1.2 % CO: 1.0 % CR: 0.1 %

OC, EC (NCs): < 0.1 %

Scott and Krot (2014)

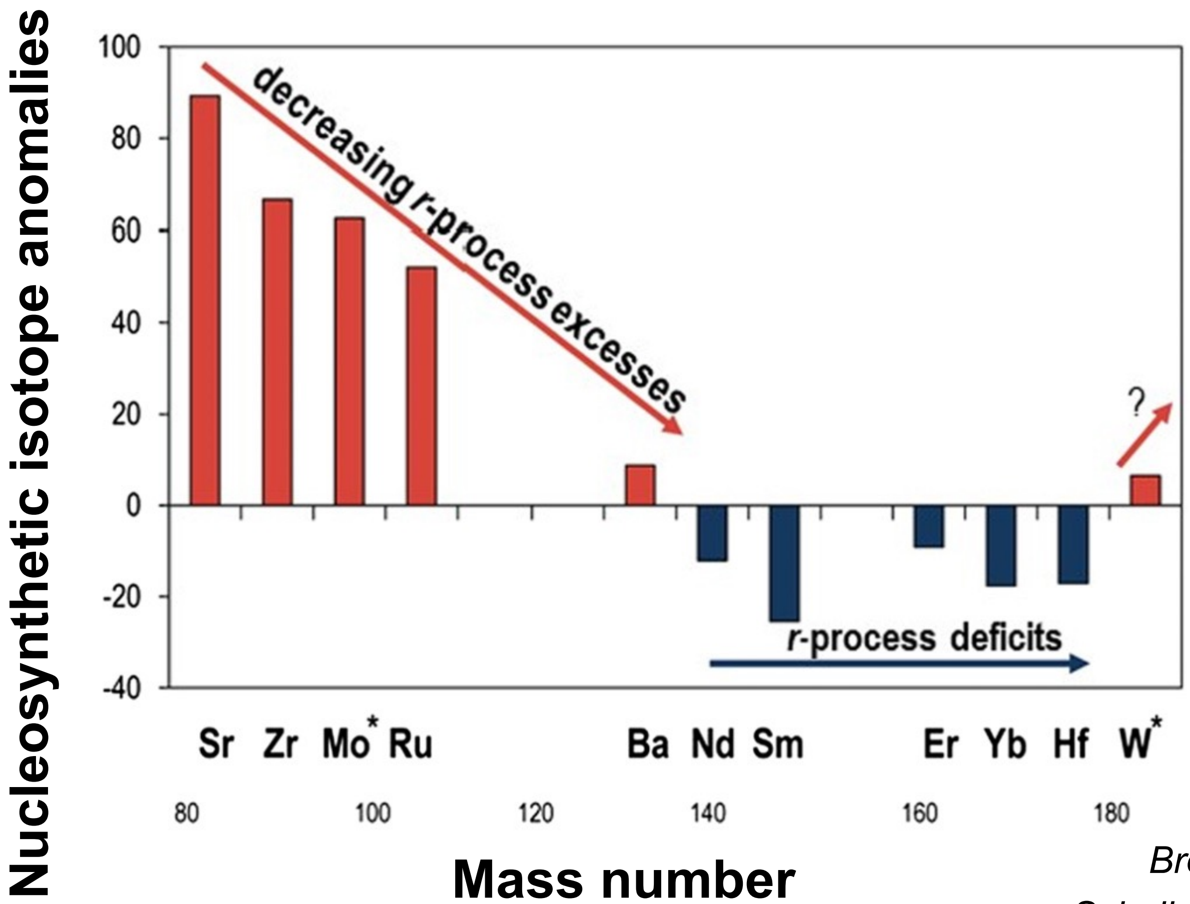
Discussion: Nucleosynthetic Sr–Nd correlation



Fukai and Yokoyama (2019) *ApJ*

- ✓ **NC** and **CAI-subtracted CC** reflect the heterogeneous distribution of presolar SiC in the early Solar System.

Discussion: Isotopic anomalies on CAI



Brennecka et al. (2013)
Schollenberger et al. (2018)

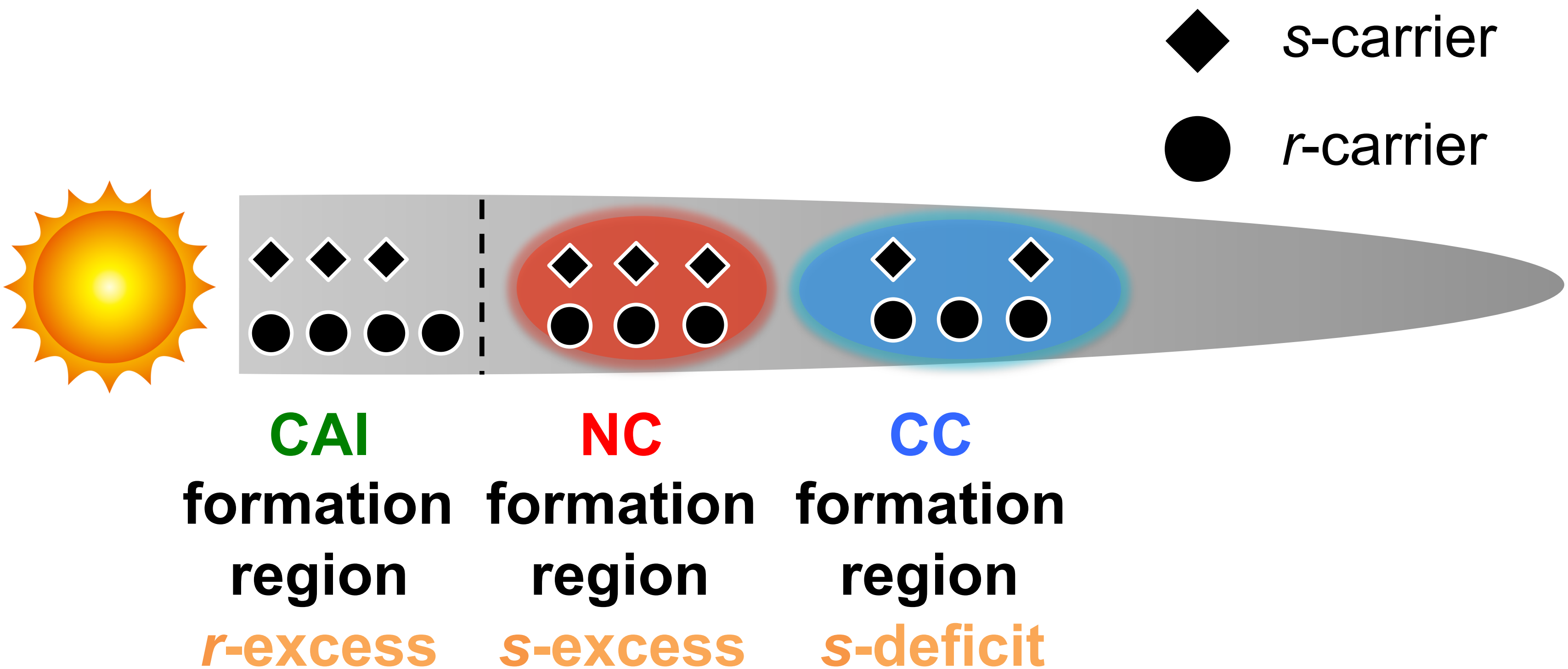
✓ Author concluded ***r*-nuclides** attributed isotopic anomalies on CAI.

✓ The observed anomalies decrease with **mass number**.

→ Suggesting the presence of ***r*-process carrier from Type II Supernova**?

Summary

Presolar grains distribution in the early Solar System



Presolar SiC (*s*-process carrier):

heterogeneously distributed in **NC** and **CC** formation region

Supernova grains? (*r*-process carrier):

heterogeneously distributed in **CAI** formation region

Conclusion

- **NC** and **CAI-subtracted CC** reflect the heterogeneous distribution of *s*-process carriers (presolar SiC) in the early Solar System.

- **CAI in CC** reflects the heterogeneous distribution of *r*-process carriers (supernova grains?) in the early Solar System.

- **Need to measure the trans-iron elements isotopic compositions of supernova grains**

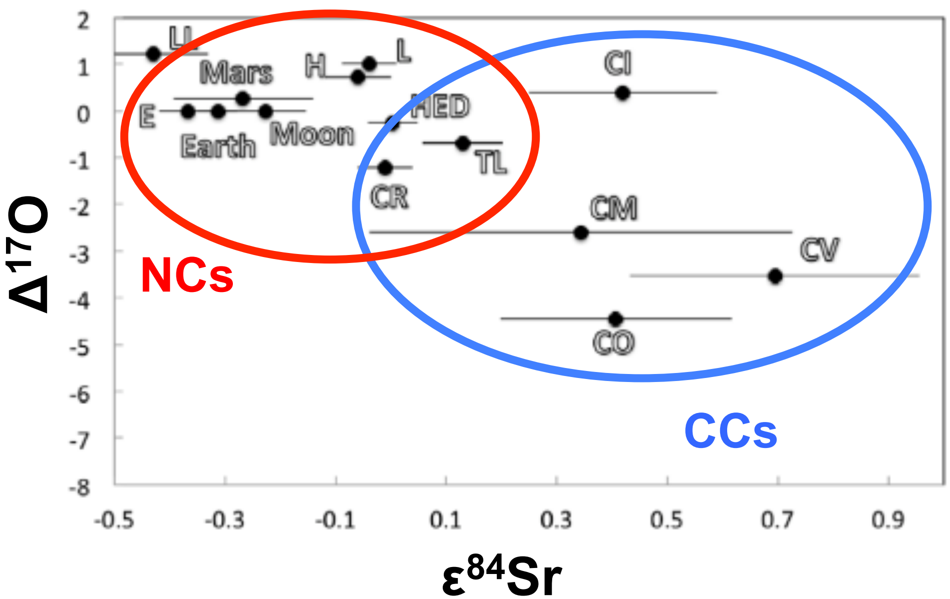
For questions

Introduction: Previous studies

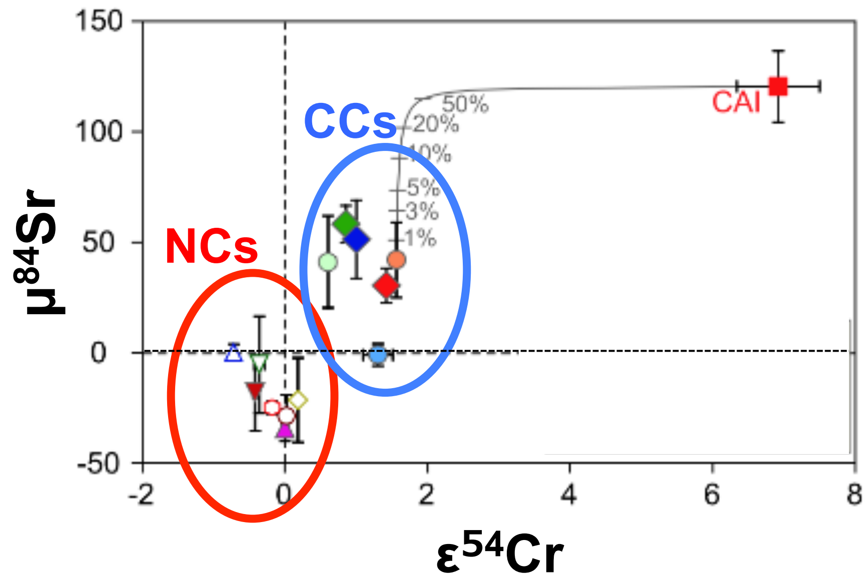
✓ Sr has only three unradiogenic isotopes (^{84}Sr, ^{86}Sr, and ^{88}Sr).

→ **$\varepsilon^{84}Sr$** data must be compared with other isotopic systems.

✓ Correlations with the other isotopic systems (**$\Delta^{17}O$**, **$\varepsilon^{54}Cr$**) were suggested.



Moynier et al. (2012)



Yokoyama et al. (2015)

Analytical problems of previous studies

1. incomplete acid digestion of bulk chondrites containing presolar grains
2. use of different sample aliquots for different isotope systems

Experimental procedures

Terrestrial rocks
- Basalt (GSJ standard)

Chondrites (petrologic grade>4)
- Y-980223 (EH6)
- A-882039 (EL6)
- Forest City (H5)
- Saratov (L4)
- Modoc (L6)
- Tuxtuac (1905) (LL5)
- Saint-Severin (LL6)

Chondrites (petrologic grade<4)
- Y-691 (EH3)
- Y-980115 (CI)
- Orgueil (CI)
- Murchison (CM2)
- Kainsaz (CO3)
- Allende (CV3)

High temperature digestion
$HF - HNO_3 - HClO_4$

High-pressure digestion
$HF - HNO_3 - \mathbf{H_2SO_4}$

DAB-2 (BERGHOF)

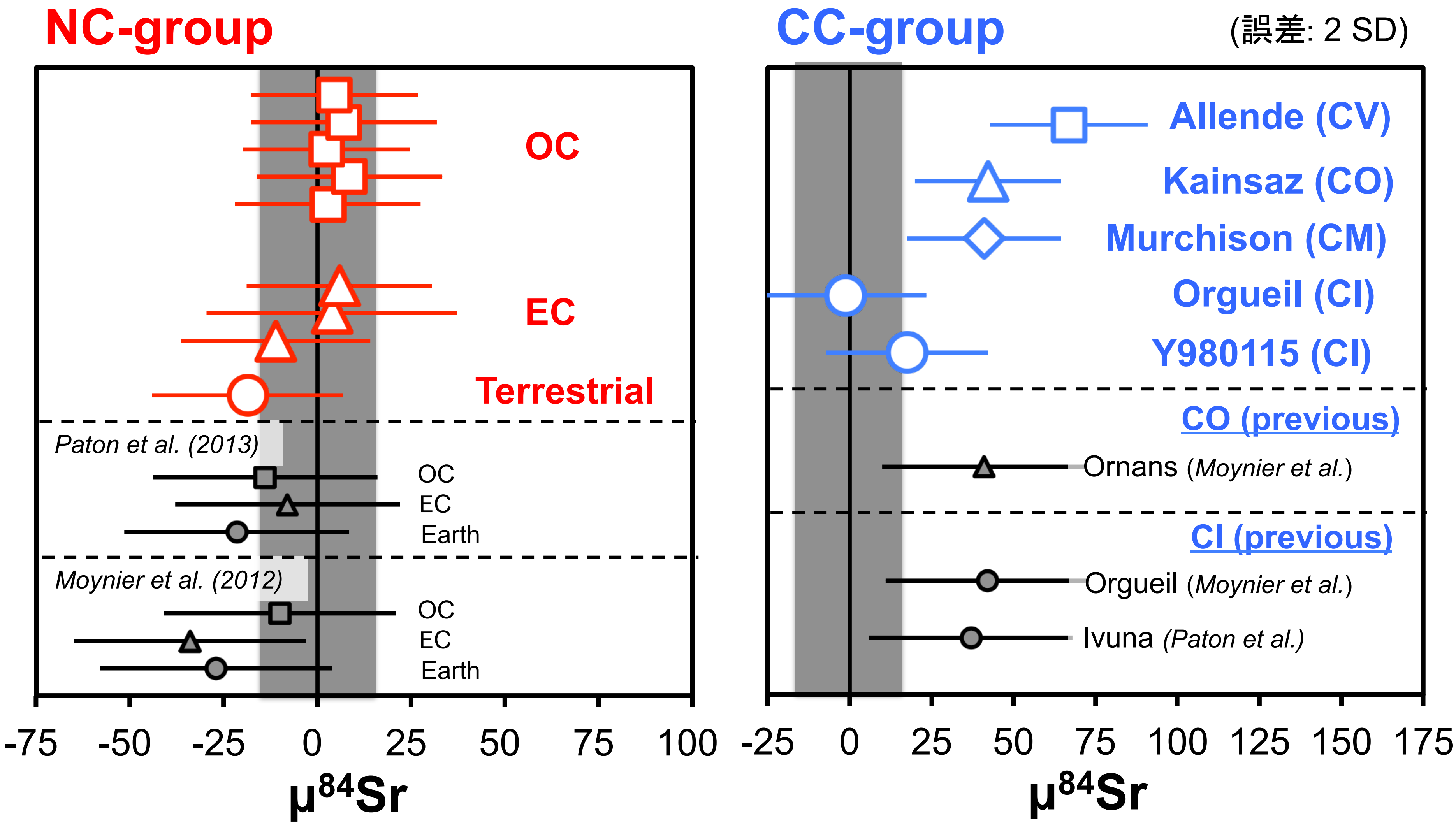
Chemical separation

Triton Plus @ Tokyo Tech

Sr and Nd isotopic analyses
with the dynamic-multicollection method using TIMS
$\mathbf{^{84}Sr/^{86}Sr}$: ±20 ppm / $\mathbf{^{148}Nd/^{144}Nd}$: ±6.2 ppm / $\mathbf{^{150}Nd/^{144}Nd}$: ±8.8 ppm (2 SDs)

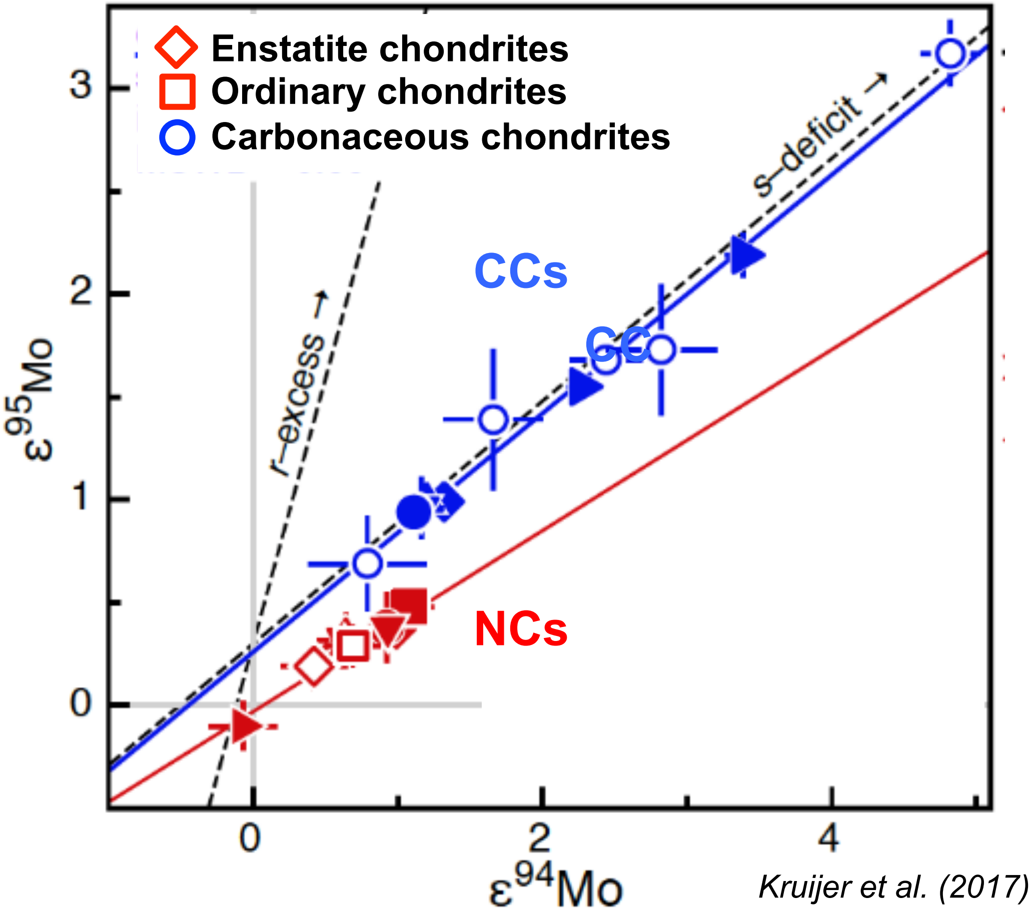
Fukai et al. (2017) IJMS

Results: Sr isotopic analysis



- ✓ NC: homogeneous CC: heterogeneous
- ✓ Previous CI data reflect the incomplete digestion

Introduction: Isotopic heterogeneity in meteorites

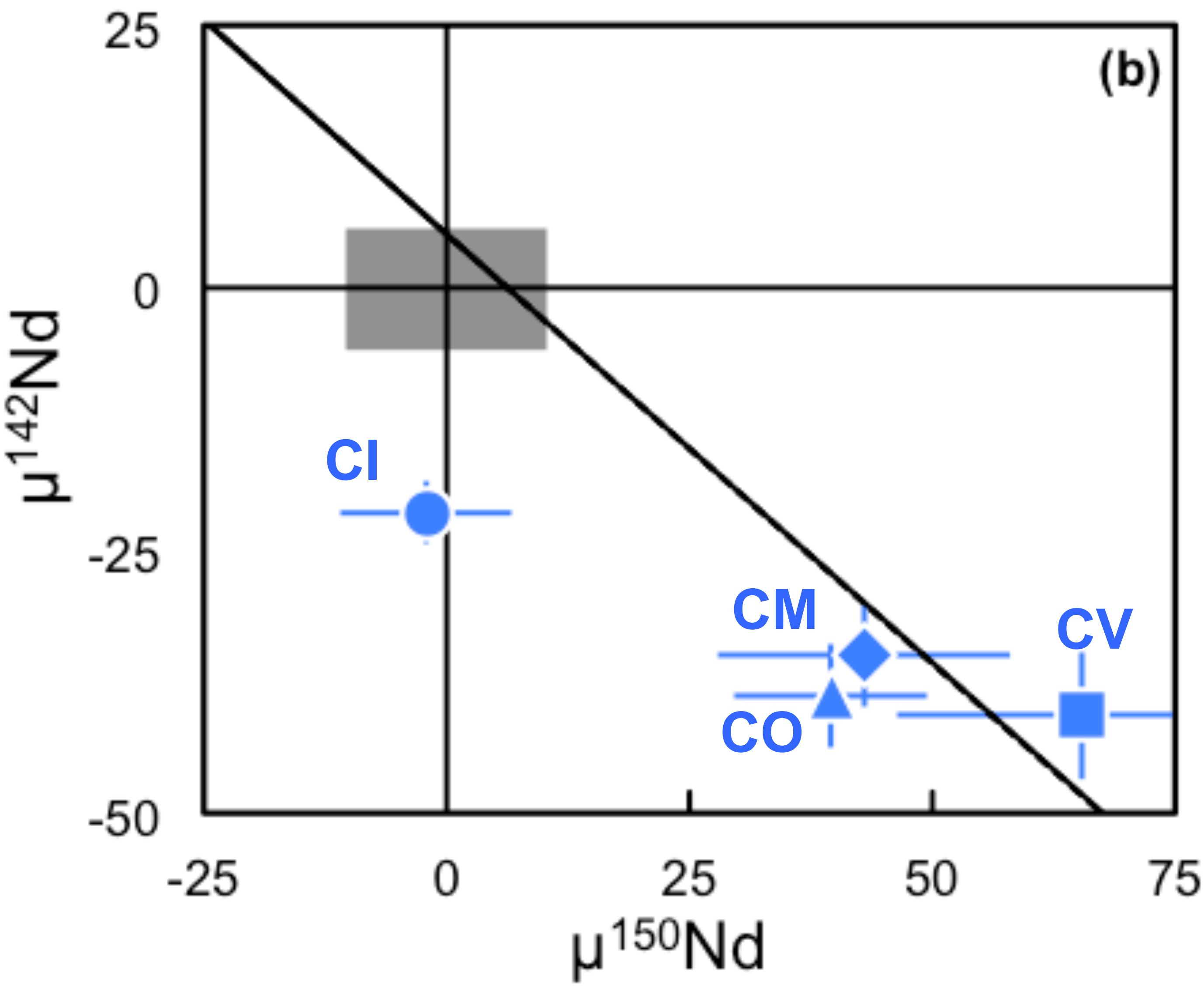


Kruijer et al. (2017)

CC: **C**arbonaceous **C**hondrites **NC**: **N**on-**C**arbonaceous meteorites

✓ The observed dichotomy reflects Solar System evolution.

Results: 142Nd



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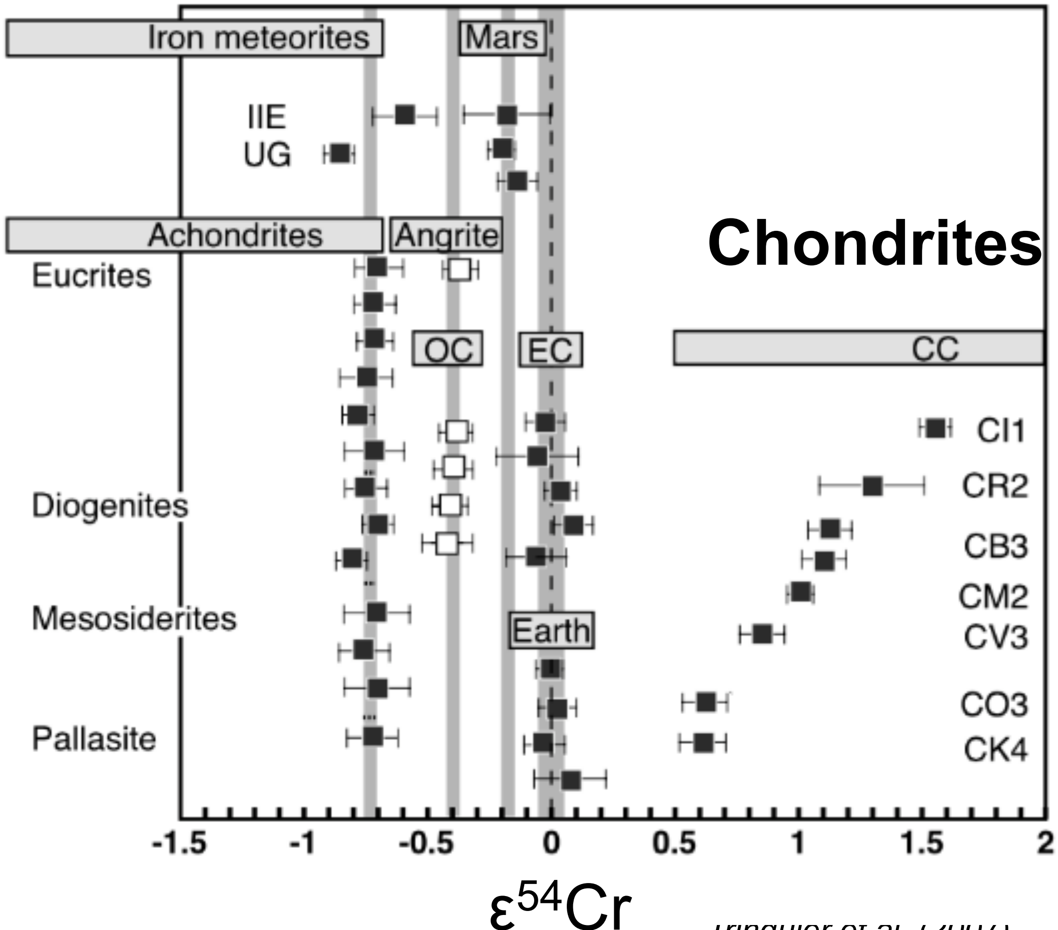
$$\varepsilon^{54}Cr = ((^{54}Cr/^{52}Cr)_{meteorites} / (^{54}Cr/^{52}Cr)_{terrestrial} - 1) \times 10^4$$



Trinquier et al. (2007)

Discussion: Disk evolutionary model

Carrier grains of Sr and Nd isotope anomalies in chondrites

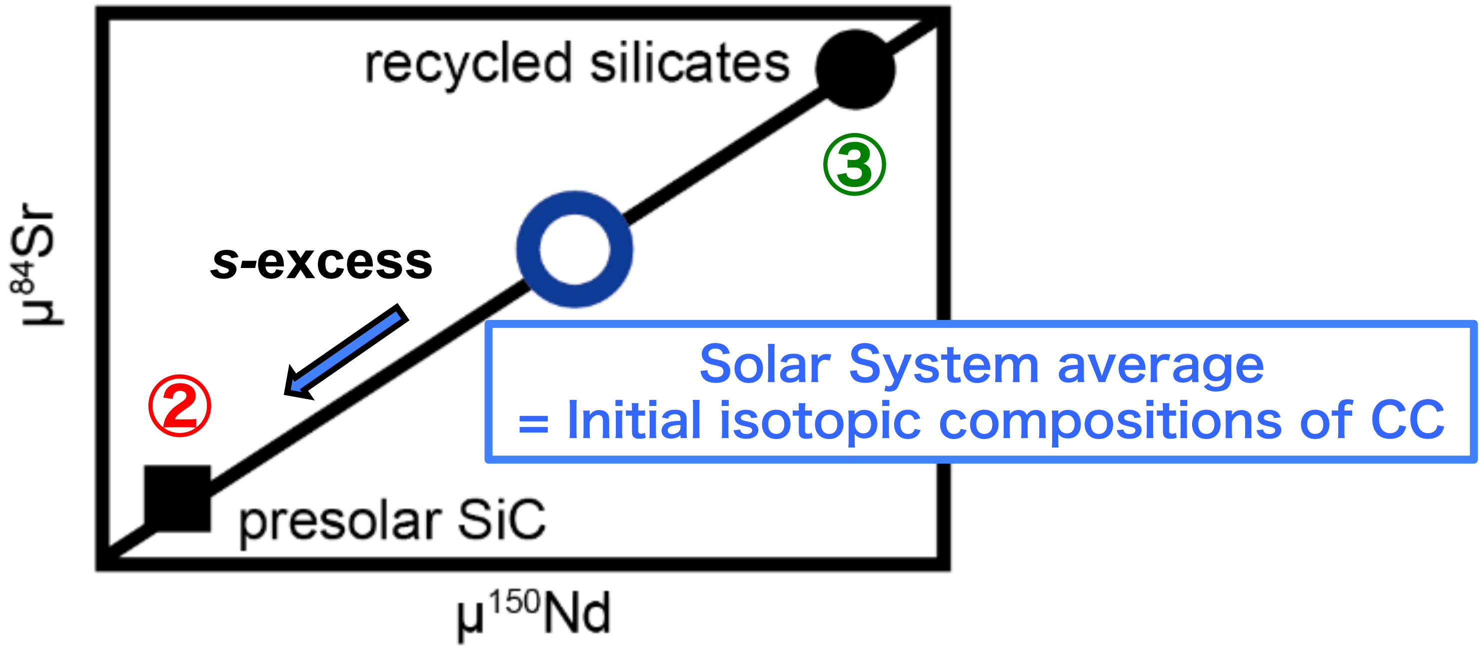
① **CAI** (subtracted by mass-balance calculation)

② **presolar SiC**: ***s*-excess** (Qin et al. 2011, Paton et al. 2013, Yokoyama et al. 2015)

→ Condensation at AGB stars

③ **recycled silicates**: ***s*-deficit**

→ Condensation at solar nebula and / or molecular cloud



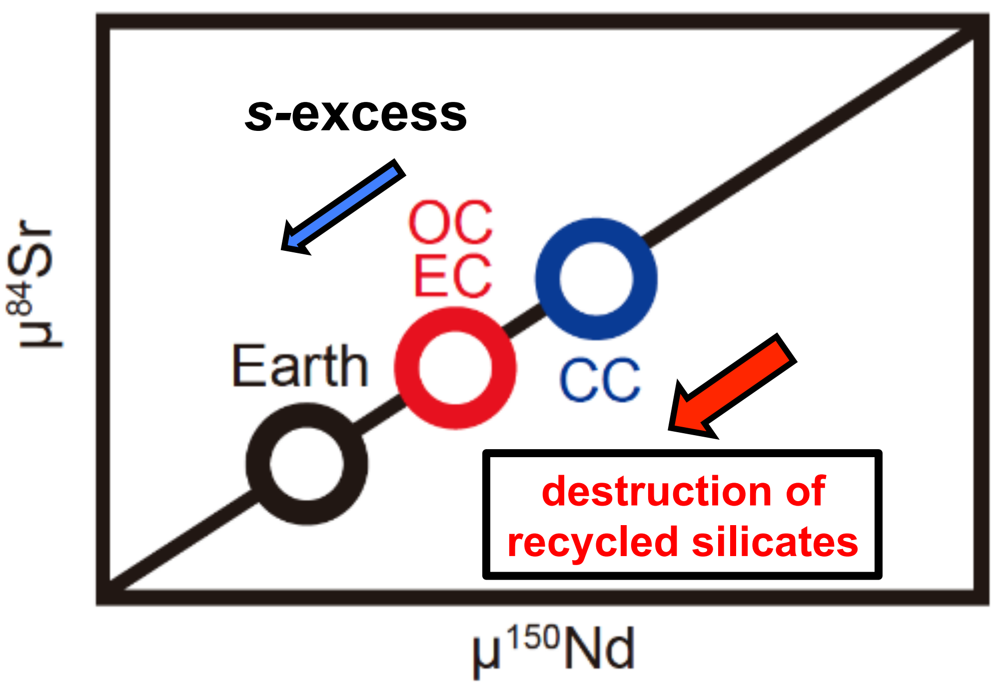
Discussion: Disk evolutionary model

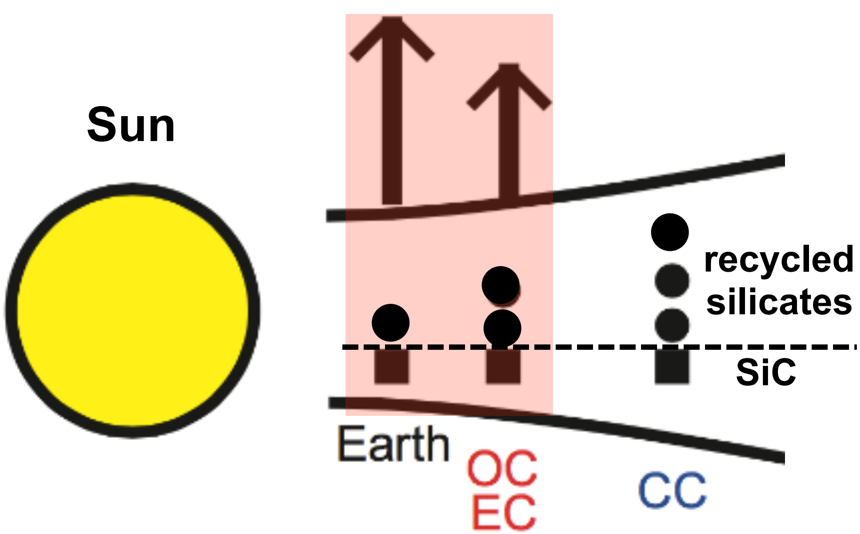
1st step: Selective dust destruction in NC formation region

1. Preferential destruction of recycled silicates by nebular thermal processing in NC formation region

*__presolar SiC__: thermally strong (condensed at 1600 K)

recycled silicates: thermally weak (condensed at 1400 K)





Fukai and Yokoyama **in press** *ApJ*

Discussion：Disk evolutionary model

2nd step: dust transportation to CC formation region

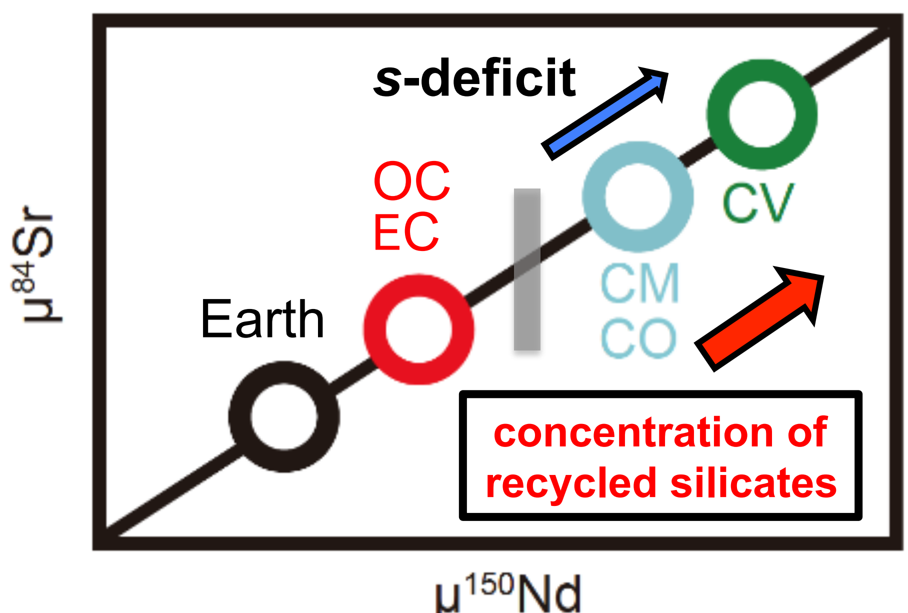
1. Decreasing of disk temperature

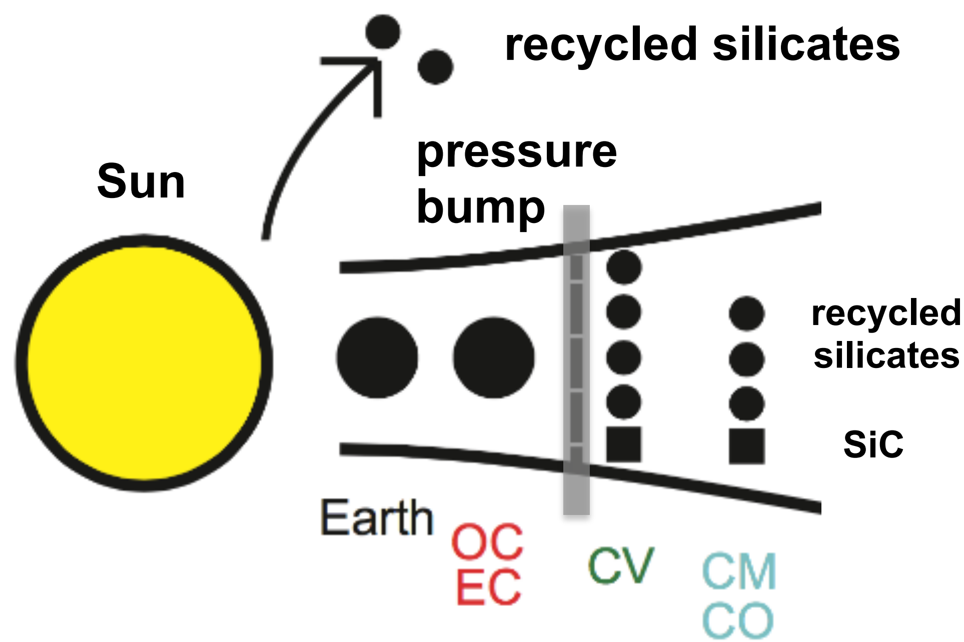
↓

2. Jupiter formation between NC and CC formation region

↓

3. concentration of recycled silicates in pressure bump





Fukai and Yokoyama **in press** *ApJ*