Rare Supernova Products as a Tracer of Dust Mixing in the Early Solar System

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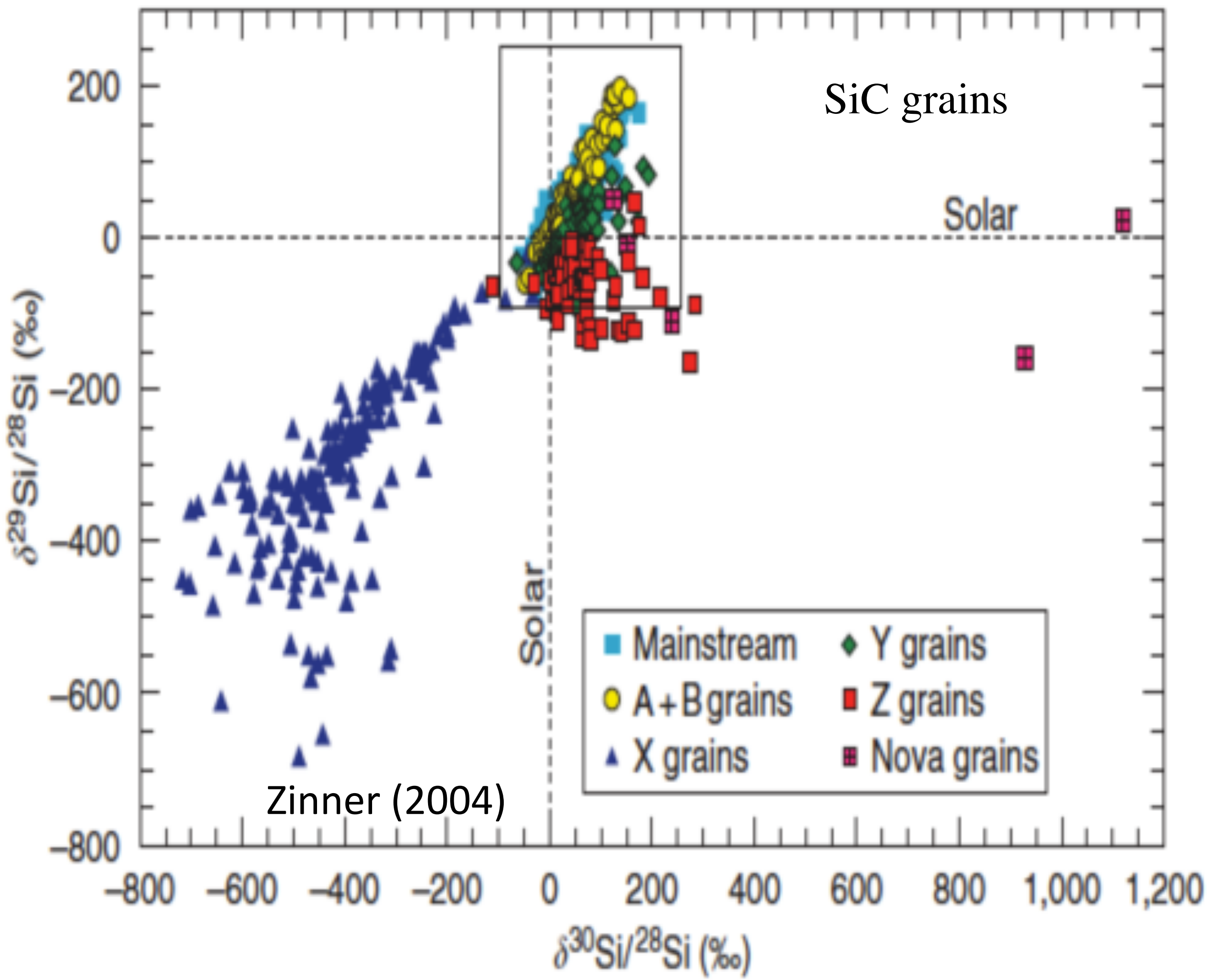
Isotopic compositions are ***normal*** in the solar system



Astronomy

Circumstellar Ejecta

Pre-solar Grains

Anomalies

Mixing & Homogenization Processes

Uniform

Solar Grains (micro-)
Earth, Moon (macro-)
Meteorites,Comets

Cosmochemistry

Isotopic Homogeneous Solar System

Davis (2007)

Parent	Mean Life	Daughter	Initial Abundance	Nucleosynthesis	Sites
^{7}Be	76.6d	^{7}Li	^{7}Be/^{9}Be~10^{-3}		
^{41}Ca	147Kyr	^{41}K	^{41}Ca/^{40}Ca~10^{-8}	s process; O burning	Massive star; AGB
^{36}Cl	434Kyr	^{36}S, ^{36}Ar	^{36}Cl/^{35}Cl~$4x10^{-6}$		
^{26}Al	1.03Myr	^{26}Mg	^{26}Al/^{27}Al~$5x10^{-5}$	H or C burning	Massive star; RGB; AGB
^{60}Fe	2.16Myr	^{60}Ni	^{60}Fe/^{56}Fe~5-$10x10^{-7}$	C burning; n burst; s process; nNSE	Massive star; AGB; SNIa
^{10}Be	2.18Myr	^{10}B	^{10}Be/^{9}Be~10^{-3}		
^{53}Mn	5.4Myr	^{53}Cr	^{53}Mn/^{55}Mn~$1x10^{-5}$	Si burning; NSE	Massive star; SNIa
^{107}Pd	9.4Myr	^{107}Pd	^{107}Pd/^{108}Pd~$5x10^{-5}$	r or s process	Massive star; AGB; neutron star
^{182}Hf	12.8Myr	^{182}W	^{182}Hf/^{180}Hf~$1.1x10^{-4}$	r process; n burst	Massive star; neutron star
^{129}I	22.7Myr	^{129}Xe	^{129}I/^{127}I~10^{-4}		
^{205}Pb	25Myr	^{205}Tl	^{205}Pb/^{204}Pb~1-$2x10^{-4}$		
^{92}Nb	50Myr	^{92}Zr	^{92}Nb/^{93}Nb~10^{-4}		
^{244}Pu	115Myr	F-Products	^{244}Pu/^{238}U~$7x10^{-3}$		
^{146}Sm	149Myr	^{142}Nd	^{146}Sm/^{147}Sm~$9x10^{-4}$		

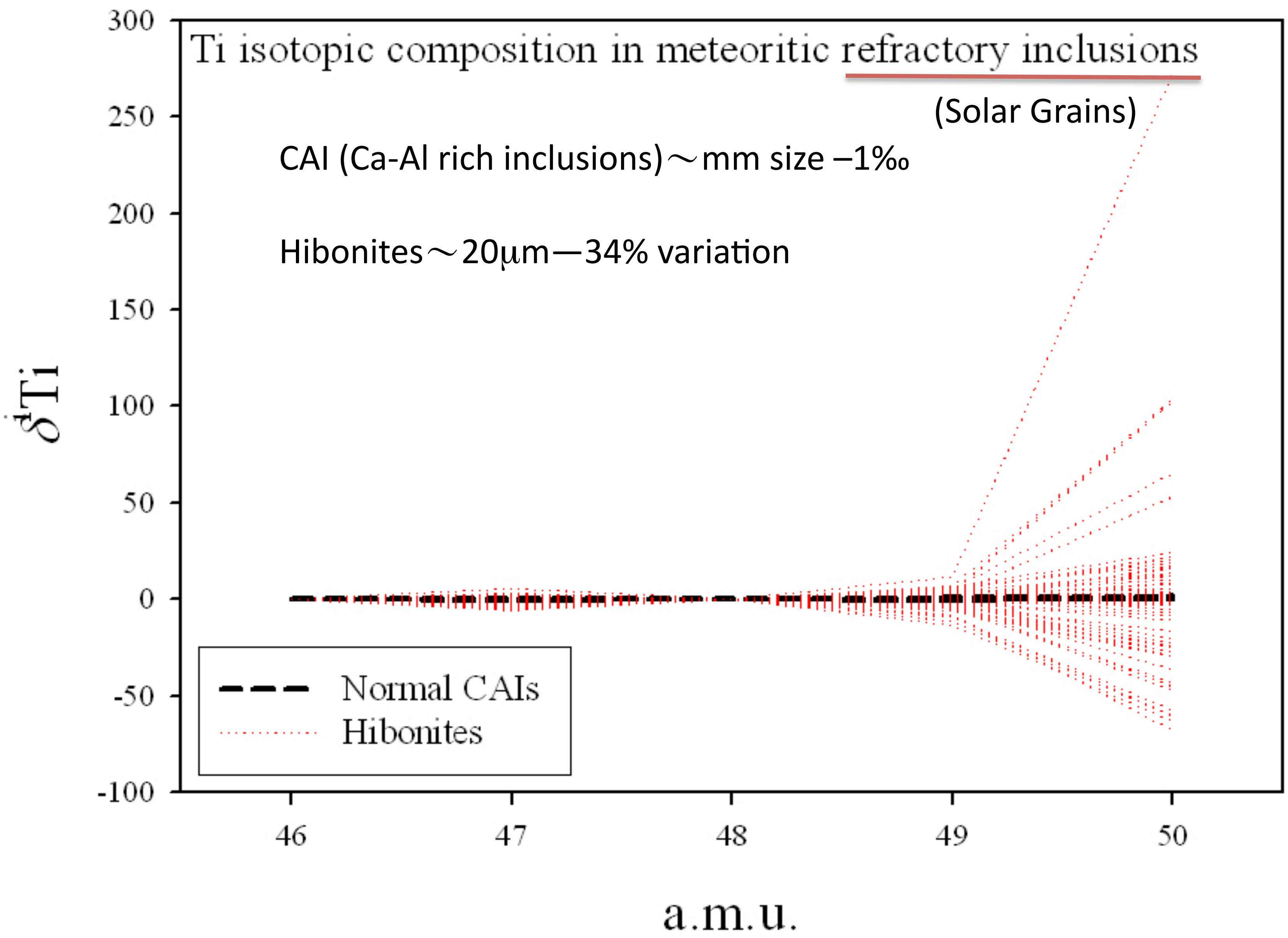
Irradiation

Irradiation/Stellar Products

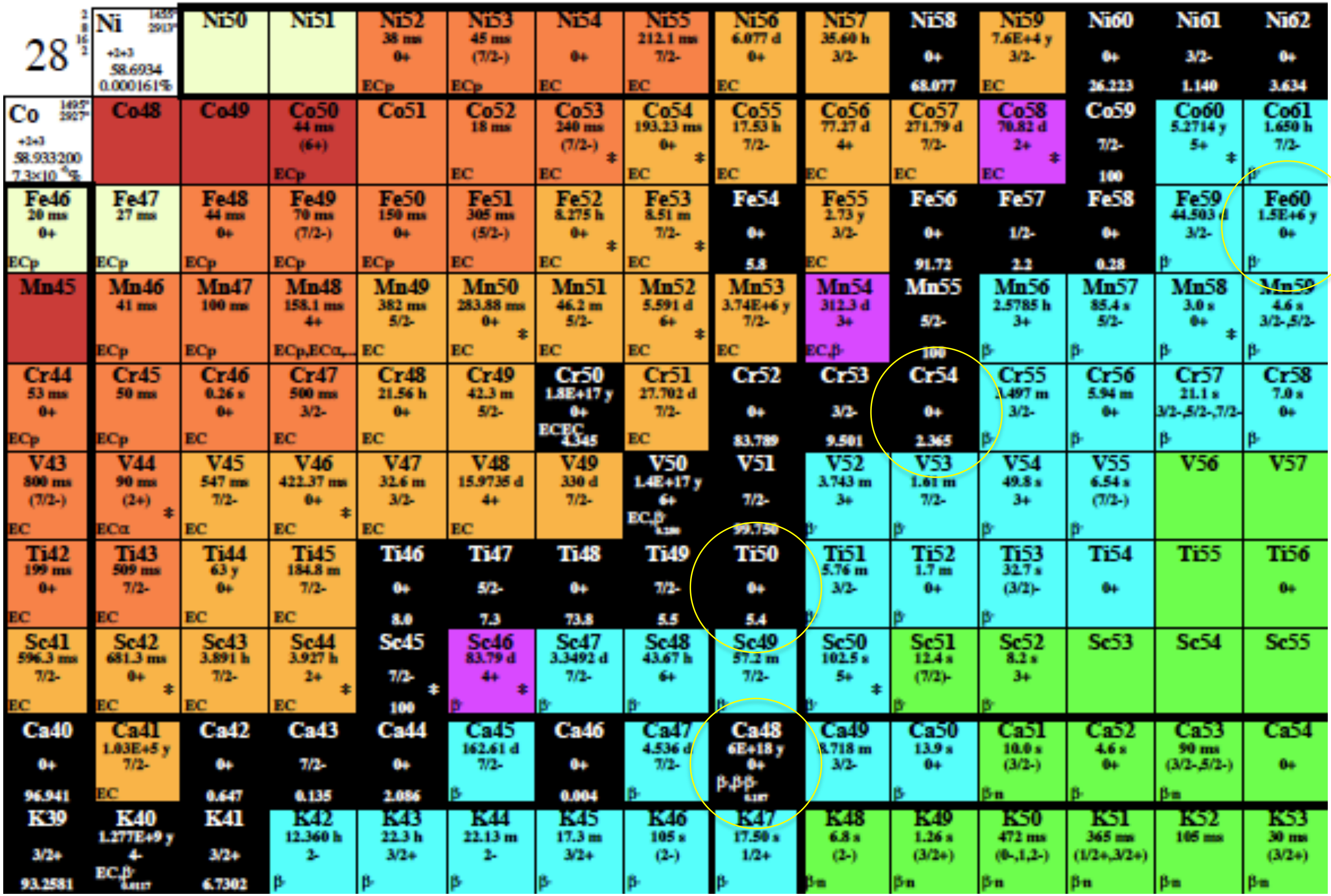
Stellar Products

Lived ^{60}Fe in the early solar system—A nearby event?

Heterogeneity in Small Phase!



Nucleosynthesis of N-Rich Fe-Peak Nuclides



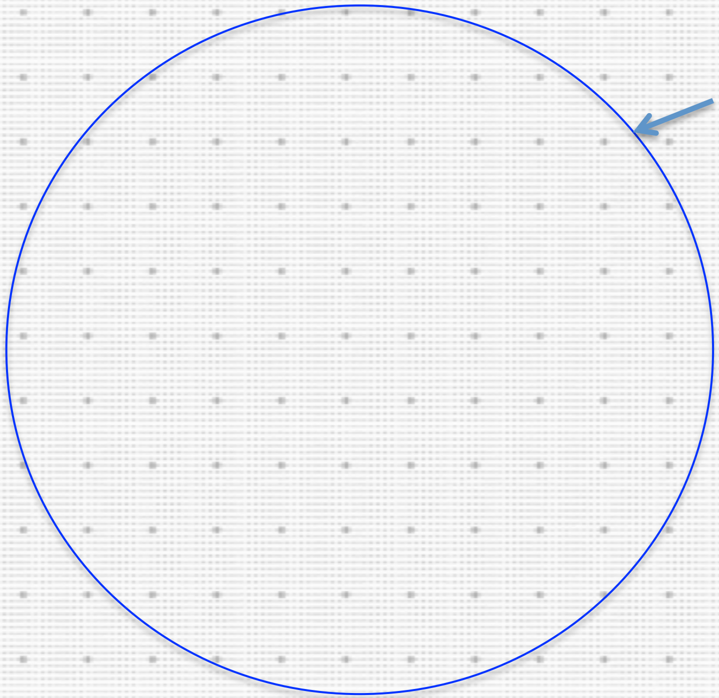
Fluctuation Idea: Rare $^{48}Ca\underline{^{50}Ti}^{16}O_3$ grains follow Poisson distribution in homogeneous Solar Nebula

D～20μm=>3x10-^{12}g ^{50}Ti (hibonites)

10 carrier grains to form a small size inclusion=>

$$1/\sqrt{10} \equiv 32\%(\text{variation})$$

Grain size～1μm=> 3x10^{-12}g ^{50}Ti=>

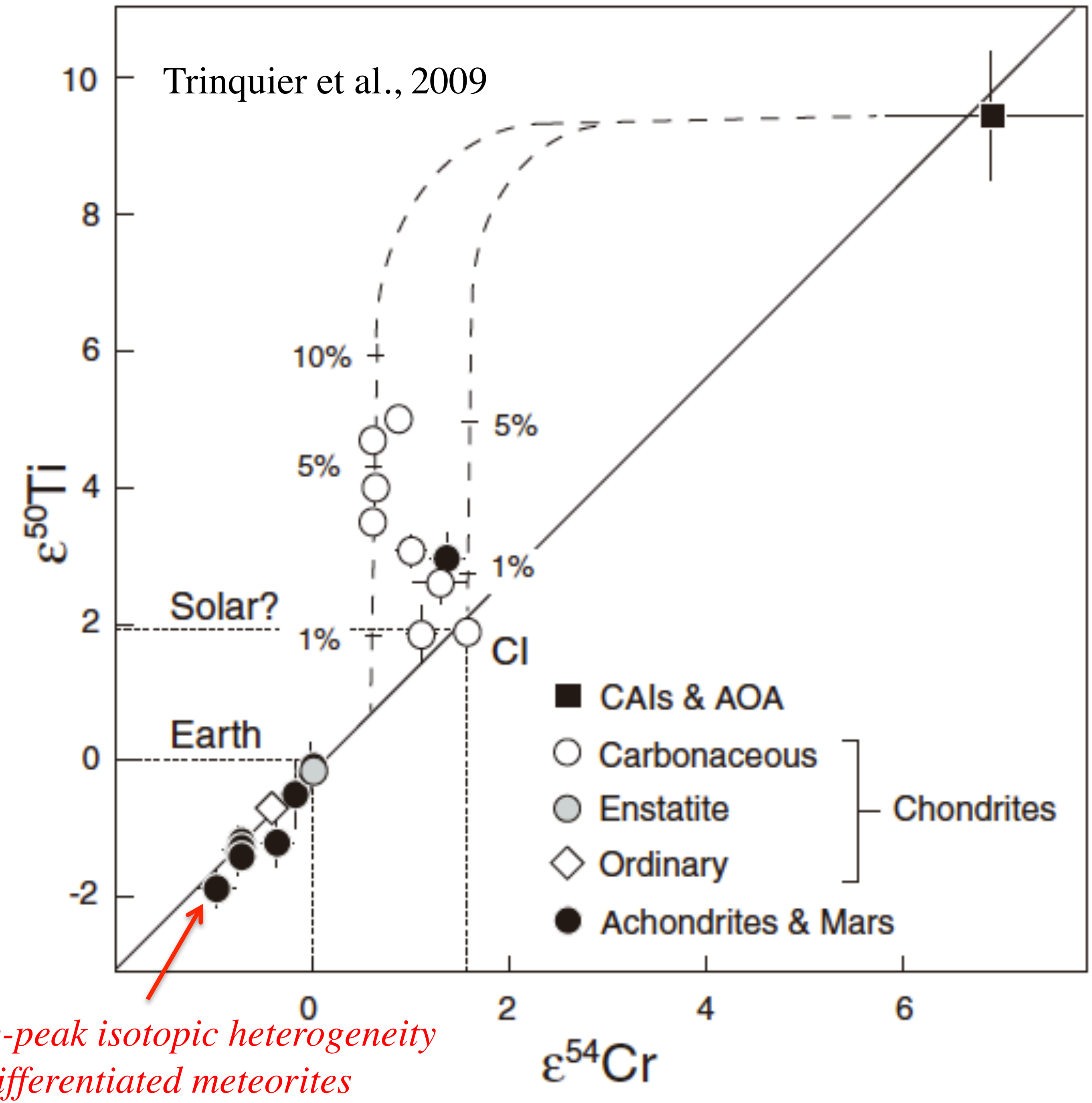


D～1mm (CAIs)

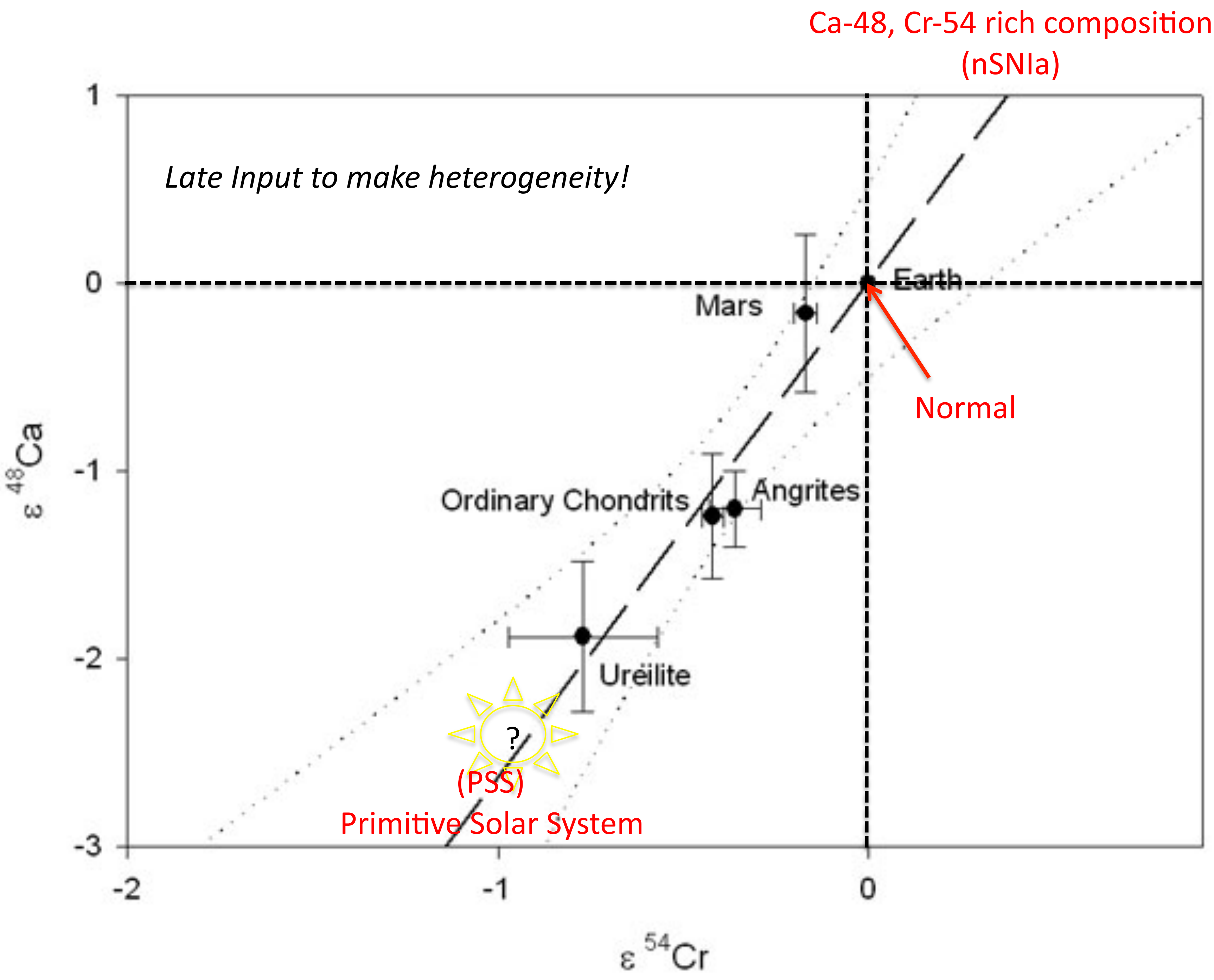
10^6 carrier grains to form a larger size inclusion=>

$$1/\sqrt{10^6} \equiv 1‰$$

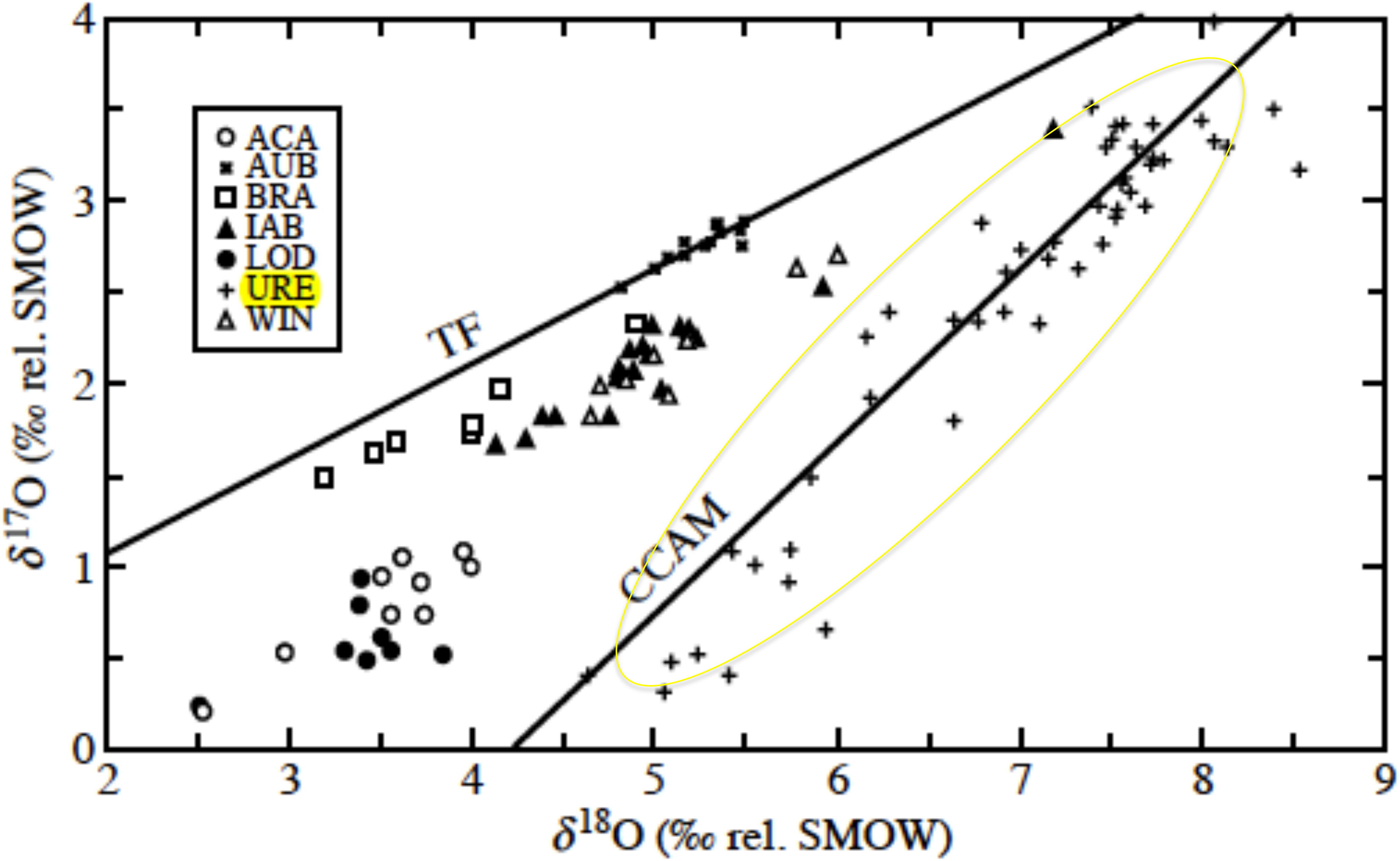
=> Solar System is homogeneous distribution including of short-lived radioisotopes



N-rich Fe-peak isotopic heterogeneity in differentiated meteorites



Ca-48, Cr-54 rich composition
(nSNIa)
Late Input to make heterogeneity!
1
0
-1
-2
-3
-2
-1
0
ε ⁴⁸Ca
ε ⁵⁴Cr
Earth
Mars
Normal
Ordinary Chondrits
Angrites
Ureilite
?
(PSS)
Primitive Solar System



Solar Nebula still existed!

HETOROGENEITY ON PLANETARY SCALE

- Most likely a late input event makes the solar system incomplete mixing during homogenization, and ^{48}Ca strongly supports scenario of a n-rich SNIa event.
- Why isotopic deficit of n-rich Fe-peak nuclides was occurred in asteroid?

EJECTED MASSES[a] FOR SLOW DEFLAGRATIONS (Woosley 1997)

^{40}Ca	3.71E−03	4.30E−03	3.77E−03	3.22E−03	3.23E−03
^{44}Ca	6.53E−06	7.84E−06	7.76E−06	7.38E−06	7.78E−06
^{46}Ca	3.50E−10	1.99E−08	5.77E−08	6.36E−07	4.91E−06
^{48}Ca	1.19E−09	3.07E−04	4.57E−03	1.80E−02	2.56E−02
^{47}Ti	4.38E−09	3.08E−08	1.29E−07	1.70E−06	7.51E−06
^{48}Ti	1.14E−04	1.07E−04	1.09E−04	1.09E−04	1.01E−04
^{49}Ti	5.14E−07	6.15E−05	3.92E−04	9.46E−04	1.35E−03
^{50}Ti	4.14E−05	2.28E−03	6.81E−03	1.10E−02	1.43E−02
^{51}V	1.66E−05	1.29E−04	3.40E−04	5.81E−04	7.40E−04
^{50}Cr	3.97E−05	5.32E−05	6.15E−05	6.54E−05	6.77E−05
^{52}Cr	3.42E−03	5.54E−03	7.87E−03	9.48E−03	1.01E−02
^{53}Cr	2.96E−04	6.15E−04	9.82E−04	1.24E−03	1.36E−03
^{54}Cr	4.00E−04	6.28E−03	1.36E−02	1.78E−02	1.98E−02
^{55}Mn	3.85E−03	5.89E−03	7.38E−03	8.33E−03	8.78E−03
^{54}Fe	4.81E−02	6.12E−02	6.96E−02	7.53E−02	7.79E−02
^{56}Fe	3.81E−01	4.30E−01	4.59E−01	4.73E−01	4.79E−01
^{57}Fe	1.13E−02	1.34E−02	1.50E−02	1.60E−02	1.64E−02
^{58}Fe	1.36E−03	1.06E−02	1.93E−02	2.33E−02	2.53E−02
^{59}Co	5.68E−04	1.03E−03	1.39E−03	1.63E−03	1.74E−03
^{58}Ni	5.84E−02	7.22E−02	8.13E−02	8.81E−02	9.15E−02
^{60}Ni	9.07E−03	1.55E−02	2.18E−02	2.64E−02	2.86E−02
^{61}Ni	1.50E−04	2.71E−04	3.84E−04	4.53E−04	4.84E−04
^{62}Ni	1.03E−03	4.06E−03	7.07E−03	8.81E−03	9.64E−03
^{64}Ni	8.94E−06	1.42E−03	3.65E−03	5.13E−03	5.79E−03
^{63}Cu	1.21E−06	2.20E−05	8.61E−05	1.39E−04	1.64E−04
^{65}Cu	3.96E−07	7.55E−06	3.15E−05	5.30E−05	6.33E−05
^{64}Zn	4.55E−05	5.34E−05	5.68E−05	5.90E−05	5.74E−05
^{66}Zn	2.78E−06	9.14E−04	5.92E−03	1.01E−02	1.21E−02
^{67}Zn	2.31E−09	3.70E−06	2.32E−05	5.25E−05	7.13E−05
^{68}Zn	1.52E−07	7.72E−06	7.39E−04	2.28E−03	3.05E−03
^{70}Zn	5.83E−11	6.79E−07	7.89E−06	9.01E−04	1.84E−03
^{69}Ga	6.45E−10	3.29E−07	1.09E−05	2.93E−05	3.89E−05
^{71}Ga	9.90E−12	2.18E−09	1.71E−06	1.70E−05	2.59E−05
^{72}Ge	1.39E−09	3.35E−07	1.19E−05	2.86E−05	5.87E−05
^{73}Ge	1.37E−11	3.04E−09	5.37E−08	2.07E−05	4.60E−05
^{74}Ge	5.38E−12	1.31E−08	1.89E−05	1.16E−04	1.62E−04
^{76}Ge	3.86E−13	1.45E−07	1.12E−06	3.51E−04	8.63E−04
^{75}As	4.88E−14	8.28E−09	3.00E−07	8.15E−07	1.11E−06
^{77}Se	7.45E−14	1.73E−09	7.37E−07	7.29E−06	1.23E−05
^{78}Se	1.07E−13	1.24E−07	1.85E−05	2.86E−05	3.74E−05
^{80}Se	2.38E−13	3.35E−09	4.22E−05	2.28E−04	3.35E−04
^{82}Se	2.25E−14	9.14E−09	1.76E−07	1.08E−04	2.90E−04
^{79}Br	2.72E−15	1.73E−10	1.25E−07	2.16E−05	5.37E−05
^{81}Br	2.24E−15	4.52E−10	2.93E−07	1.26E−06	2.01E−06
^{83}Kr	7.03E−15	9.51E−11	3.92E−07	9.34E−06	2.08E−05
^{84}Kr	7.30E−14	4.76E−09	1.11E−05	9.50E−05	1.58E−04
^{85}Rb	2.88E−15	1.41E−09	3.11E−07	9.15E−07	1.34E−06
^{53}Mn[b]	1.14E−04	2.01E−04	2.52E−04	2.85E−04	3.04E−04
^{60}Fe[b]	4.95E−07	1.22E−03	4.43E−03	6.94E−03	8.04E−03
^{59}Ni[b]	4.26E−04	6.70E−04	8.19E−04	9.36E−04	9.90E−04

SOLAR MASS FRACTIONS (ANDERS & GREVESSE 1989)

Mass Fraction	Isotope	Mass Fraction	Isotope	Mass Fraction
7.06(-1)	^{30}Si	2.35(-5)	^{51}V	3.77(-7)
4.80(-5)	^{31}P	8.16(-6)	^{50}Cr	7.42(-7)
2.93(-5)	^{32}S	3.96(-4)	^{52}Cr	1.49(-5)
2.75(-1)	^{33}S	3.22(-6)	^{53}Cr	1.72(-6)
6.50(-10)	^{34}S	1.87(-5)	^{54}Cr	4.36(-7)
9.35(-9)	^{36}S	9.38(-8)	^{55}Mn	1.33(-5)
1.66(-10)	^{35}Cl	2.53(-6)	^{54}Fe	7.13(-5)
1.07(-9)	^{37}Cl	8.55(-7)	^{56}Fe	1.17(-3)
4.73(-9)	^{36}Ar	7.74(-5)	^{57}Fe	2.86(-5)
3.03(-3)	^{38}Ar	1.54(-5)	^{58}Fe	3.70(-6)
3.65(-5)	^{40}Ar	2.53(-8)	^{59}Co	3.36(-6)
1.11(-3)	^{39}K	3.47(-6)	^{58}Ni	4.94(-5)
4.36(-6)	^{40}K	5.54(-9)	^{60}Ni	1.96(-5)
9.59(-3)	^{41}K	2.63(-7)	^{61}Ni	8.60(-7)
3.89(-6)	^{40}Ca	5.99(-5)	^{62}Ni	2.78(-6)
2.17(-5)	^{42}Ca	4.20(-7)	^{64}Ni	7.27(-7)
4.05(-7)	^{43}Ca	8.97(-8)	^{63}Cu	5.75(-7)
1.62(-3)	^{44}Ca	1.43(-6)	^{65}Cu	2.65(-7)
4.13(-6)	^{46}Ca	2.79(-9)	^{64}Zn	9.92(-7)
1.30(-4)	^{48}Ca	1.38(-7)	^{66}Zn	5.88(-7)
3.34(-5)	^{45}Sc	3.89(-8)	^{67}Zn	8.76(-8)
5.15(-4)	^{46}Ti	2.23(-7)	^{68}Zn	4.06(-7)
6.77(-5)	^{47}Ti	2.08(-7)	^{70}Zn	1.38(-8)
7.76(-5)	^{48}Ti	2.15(-6)	^{69}Ga	3.96(-8)
5.81(-5)	^{49}Ti	1.64(-7)	^{71}Ga	2.71(-8)
6.53(-4)	^{50}Ti	1.64(-7)	^{70}Ge	4.32(-8)
3.43(-5)	^{50}V	9.26(-10)		

Unit: Solar Mass

$$\left(\frac{^{48}Ca}{^{44}Ca}\right)_{Normal} \equiv \frac{\left(^{48}Ca_{PSS}\right) + x\left(^{48}Ca_{SN}\right)}{\left(^{44}Ca_{PSS}\right) + x\left(^{44}Ca_{SN}\right)} \qquad x : SN-fraction$$

$$\left(\frac{^{48}Ca}{^{44}Ca}\right)_{Normal} \approx \left(\frac{^{48}Ca}{^{44}Ca}\right)_{PSS} + x\left(\frac{^{48}Ca}{^{44}Ca}\right)_{SN} \times \left(\frac{^{44}Ca_{SN}}{^{44}Ca_{Normal}}\right)$$

$(^{48}Ca/^{50}Ti)_{ss} \sim (^{48}Ca/^{50}Ti)_{nSNIa}$

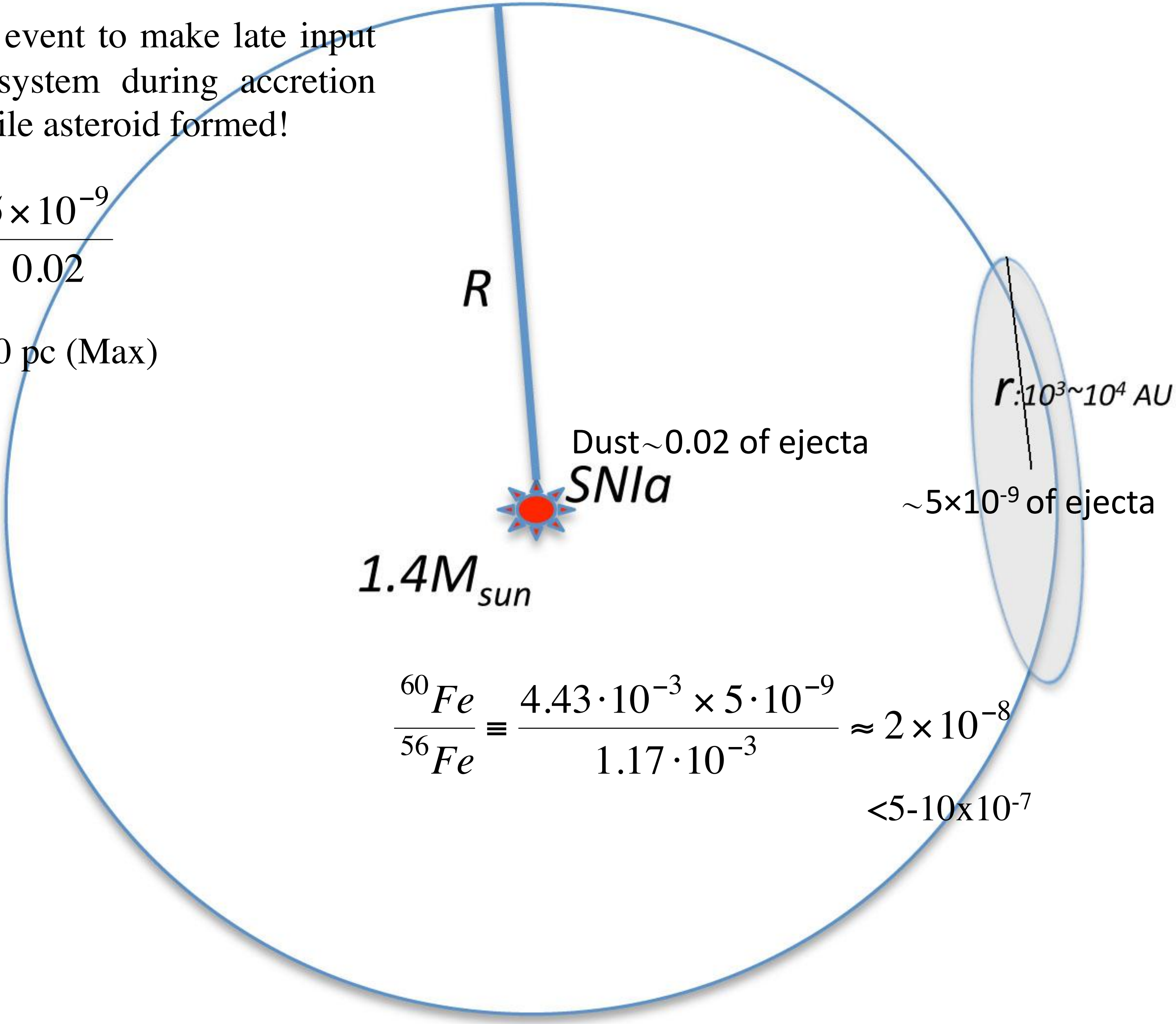
nSNIa Model	NCD2A	NCD4A	NCD6A	NCD7A	NCD8A
SN Fraction by Ca	2.00E-02	7.77E-08	5.22E-09	1.32E-09	9.31E-10
SN Fraction by Ti	3.80E-07	6.90E-9	2.31E-09	1.43E-09	1.10E-09
SN Fraction by Cr	2.40E-09	1.53E-10	7.05E-11?	5.39E-11?	4.85E-11?

Fractionation?/^{52}Cr overabundance?

A nearby event to make late input to solar system during accretion epoch while asteroid formed!

$$\frac{\pi r^2}{4\pi R^2} \equiv \frac{5\times 10^{-9}}{0.02}$$

R=10~100 pc (Max)



$$\frac{^{60}Fe}{^{56}Fe} \equiv \frac{4.43\cdot 10^{-3}\times 5\cdot 10^{-9}}{1.17\cdot 10^{-3}} \approx 2\times 10^{-8}$$

$<5\text{-}10\times 10^{-7}$

Factors to R

- Size of solar system in late accretion epoch: ≤100AU => Factor: 0.1~0.01?
- Angle between solar disk and ejecta path => Factor: 0.4?
- Solar Magnetism => 0.5?

=> Distance of a Nearby nSNIa: R=0.2 pc

(Agreed with Adams (2010):0.1~0.3pc)

Summary

- $^{48}Ca/^{44}Ca$ heterogeneity in differentiated meteorites imply late input nSNe Ia dust during solar system formation.
- Overproduced nSNe Ia Cr suggests either interstellar fractionation or ^{52}Cr effects.
- nSNe Ia nuclides deficit in asteroids may be due to neighboring Jupiter effect to cease late accumulation!?