Origin of Rare Isotopes in Presolar Grains as a Probe of Neutrino Mass Hierarchy and Supernova Nucleosynthesis

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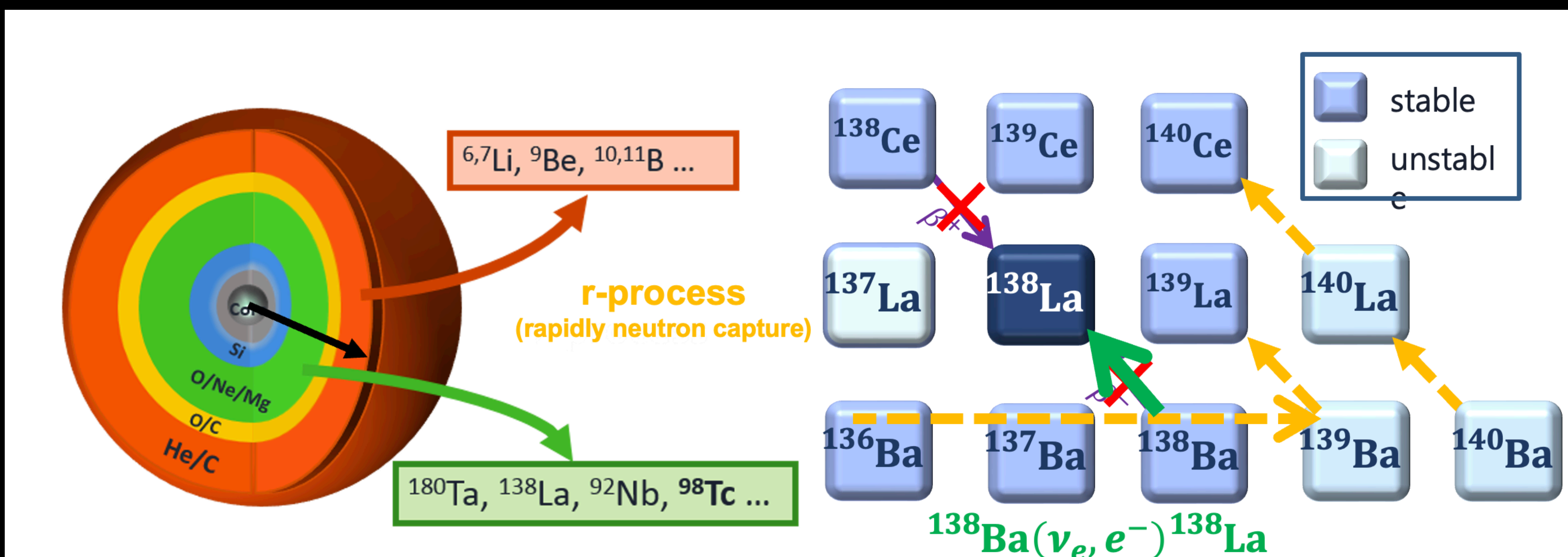
Neutrino-process

Neutrino Flux $$\frac{d\phi_{\nu_e}}{dE_{\nu_e}} = \frac{L_{\nu_e}}{8\pi^2 R_\nu^2} \frac{E_{\nu_e}^2}{exp(E_{\nu_e}/T_{\nu_e}) + 1}$$



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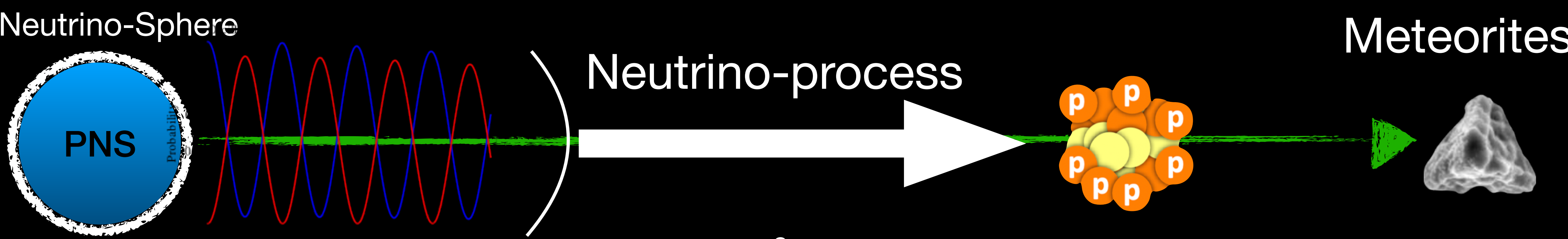

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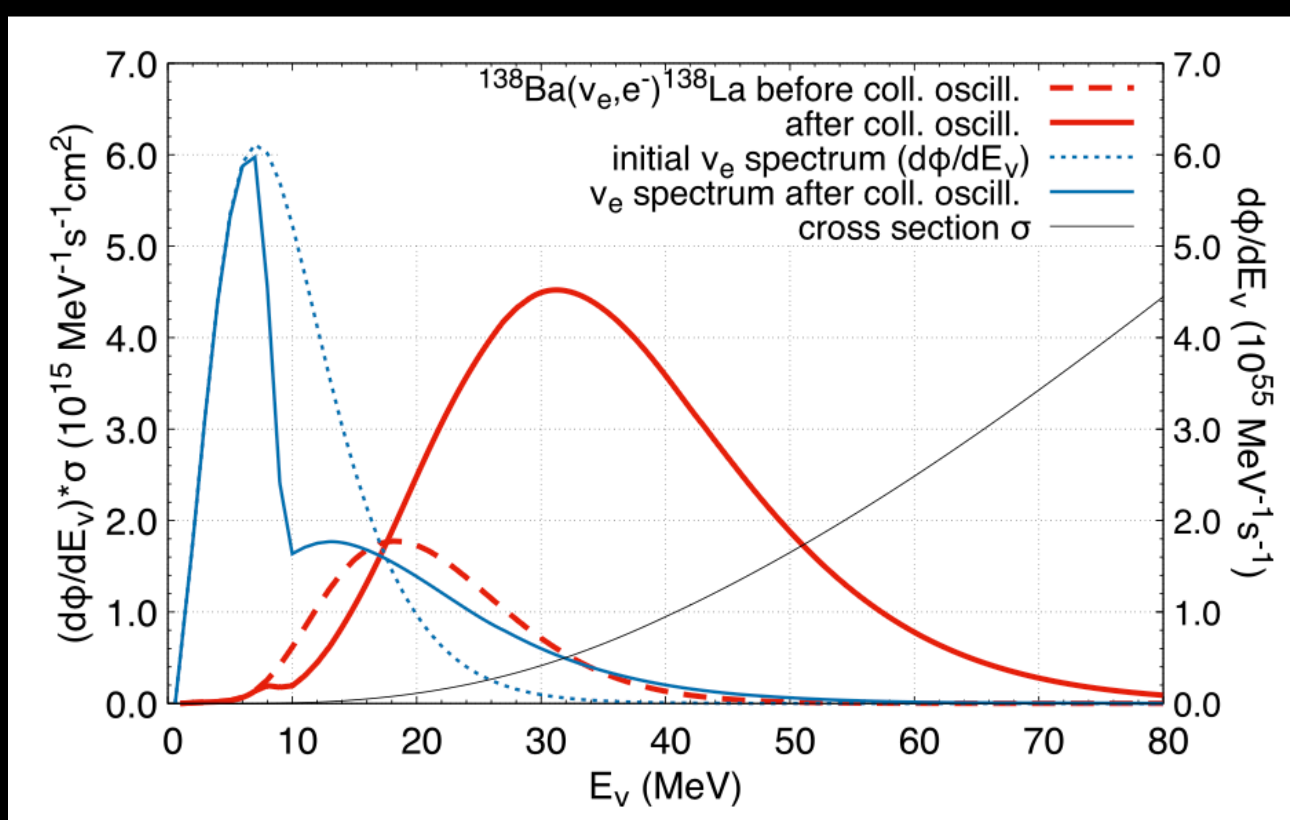

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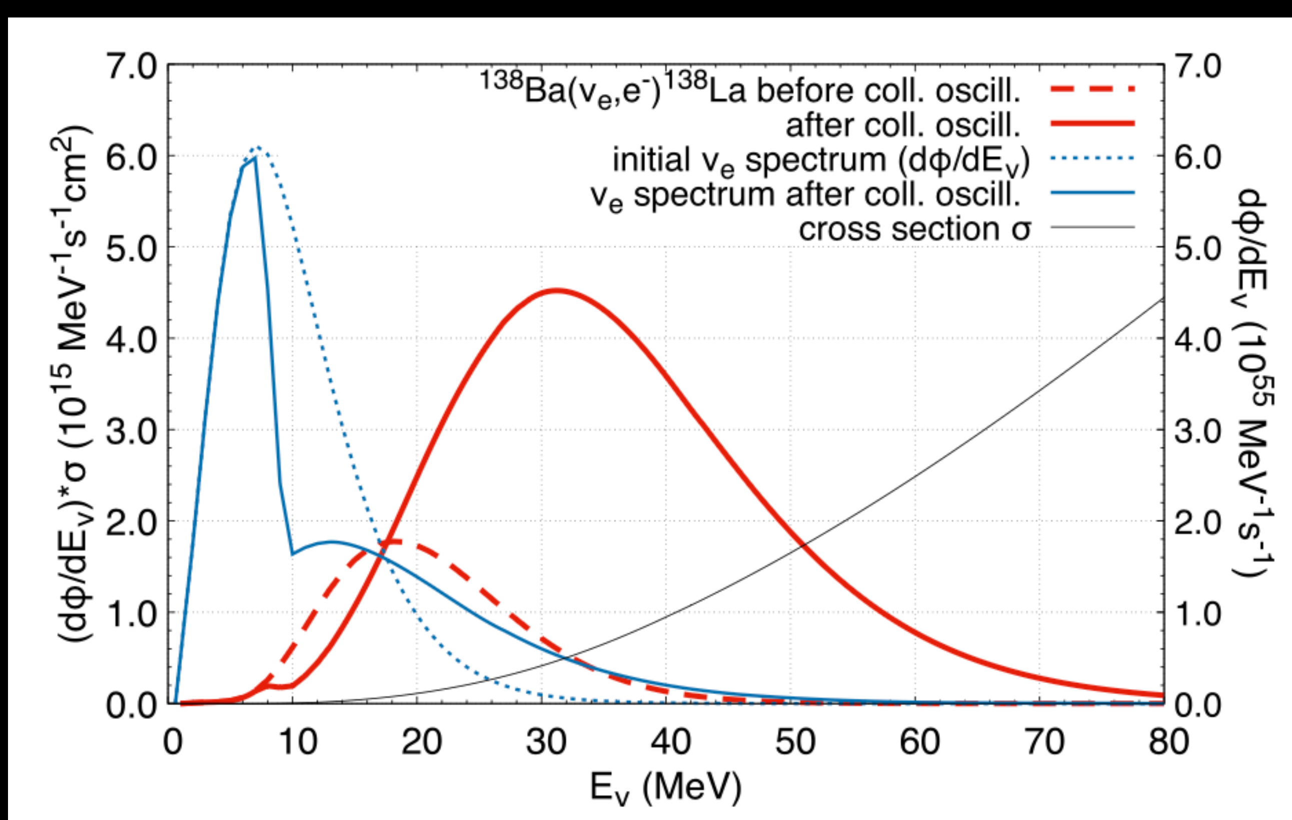

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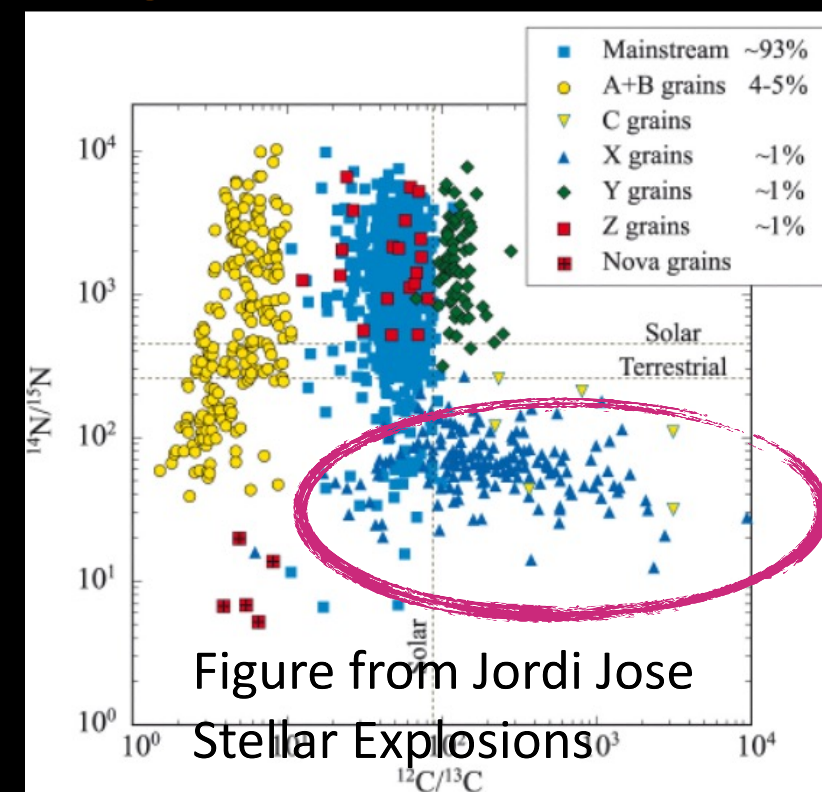

Characteristics of SiC X-Grains SN grain

- Enhanced ^{12}C (^{12}C/^{13}C > Solar)
- Enhanced ^{28}Si (^{28}Si/^{29,30}Si> Solar)
- Decay of 26Al (t1/2=7E5yr), 44Ti (t1/2=60yr)
- Deficient ^{14}N (^{14}N/^{15}N < Solar)

Our Model

•Initial mass: **20** M$_\odot$ evolves to a **helium core of 6**M$_\odot$before collapse, **SN1987A** (*Kikuchi et al., 2015 from Hashimoto PTP, 94,663 (1995)*)

•Hydrodynamics model (*blcode*)
(Mezzacappa et al. 1993)

•post-process Nucleosynthesis model

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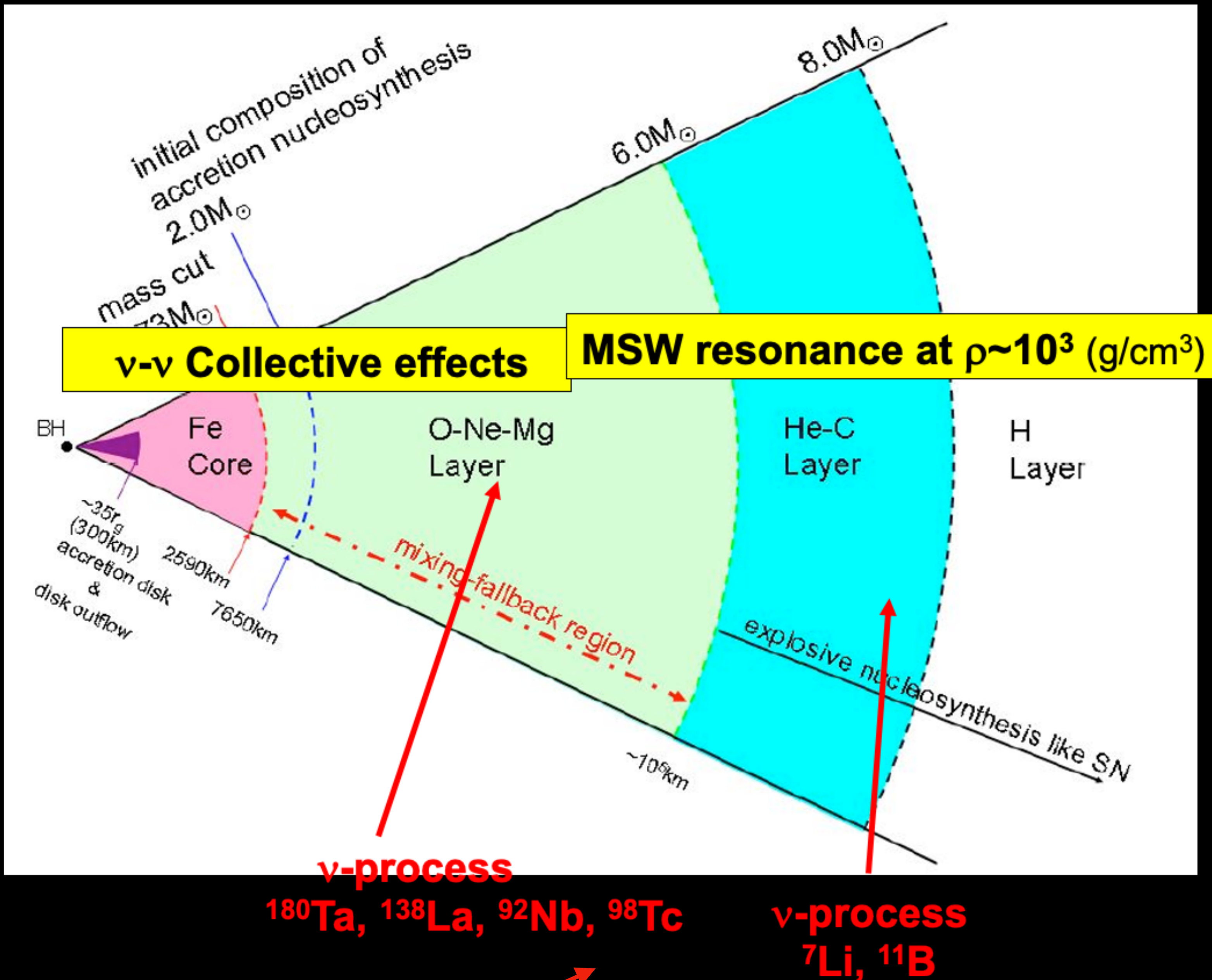


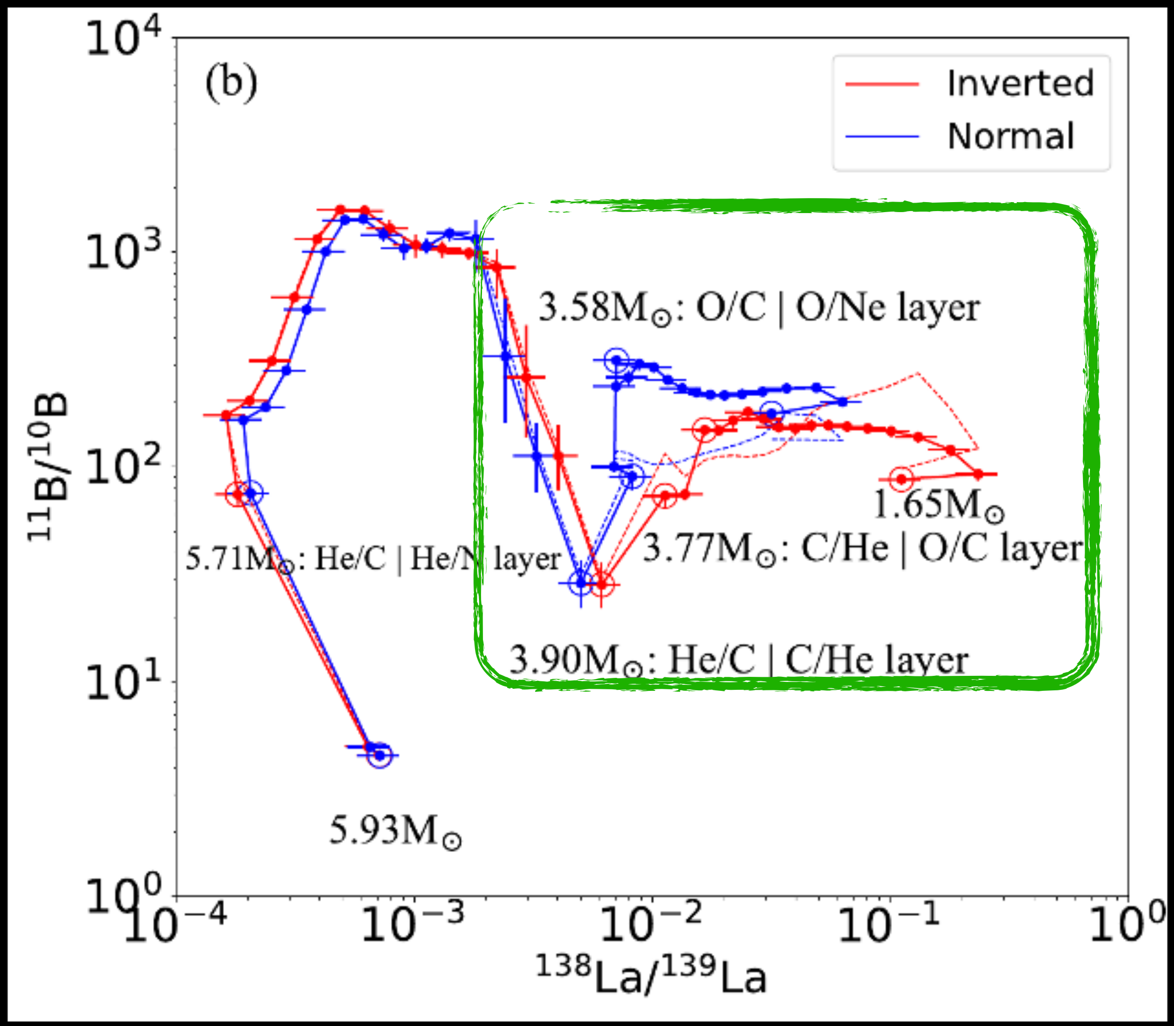
Neutrino Oscillations

- MSW effect:
Neutrino flavor change at high density material.

- Collective effect:
Self-interaction in neutrino sphere.

Change the neutrino flavor and affect the *ν*-induced reaction

Compare with grains forming region



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Clear difference: 3.58-3.90 $M_\odot$

X grain measurement: $^{11}B/^{10}B$=4.68±0.31 (Fujiya et al 2011 ApJ)

→ Admixture of GCR contribution exists.

Combining Lanthanum and Lithium, the Boron isotopic ratio

✓ν-mass hierarchy dependence → Prof. Kajinio's talk

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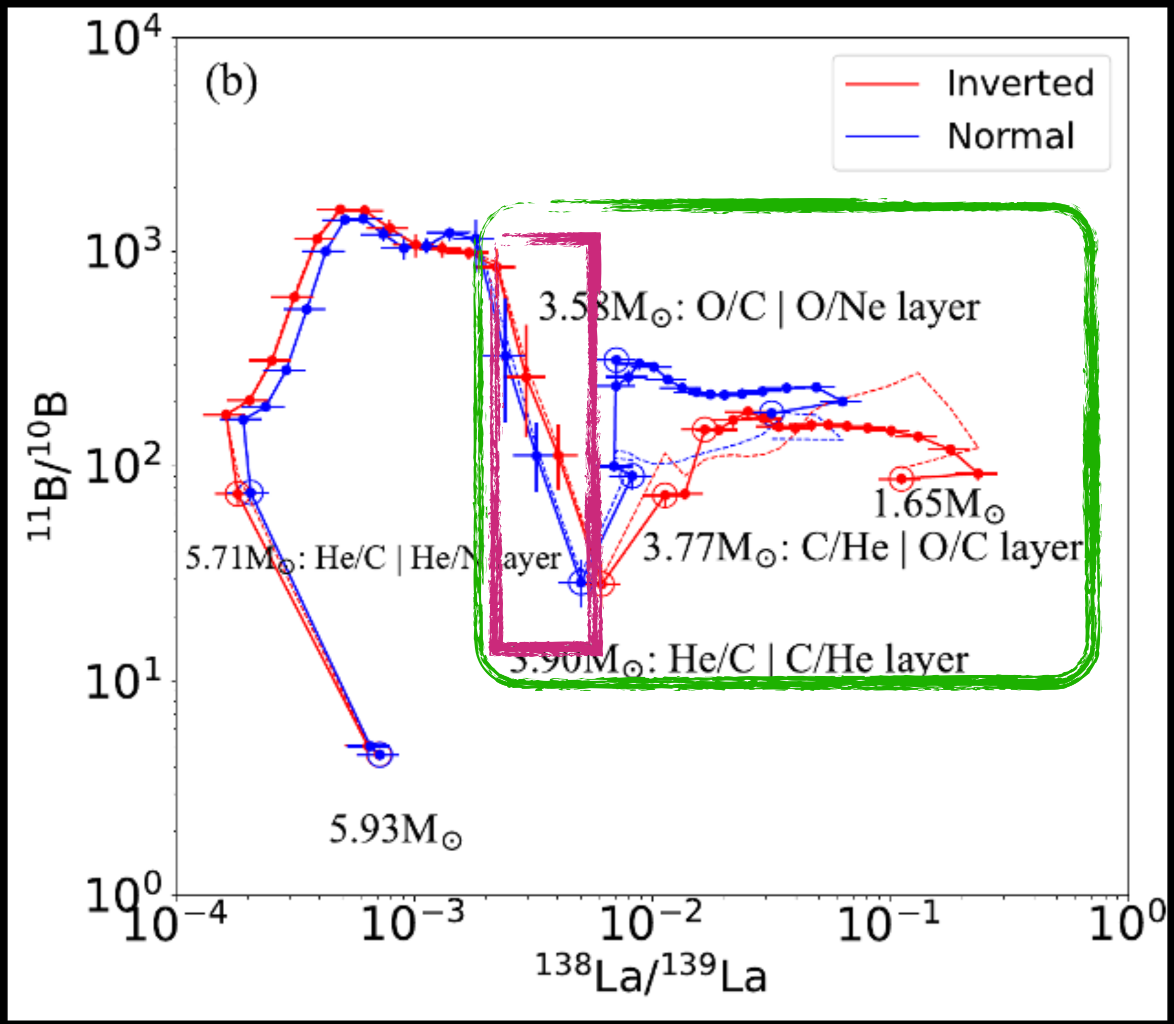

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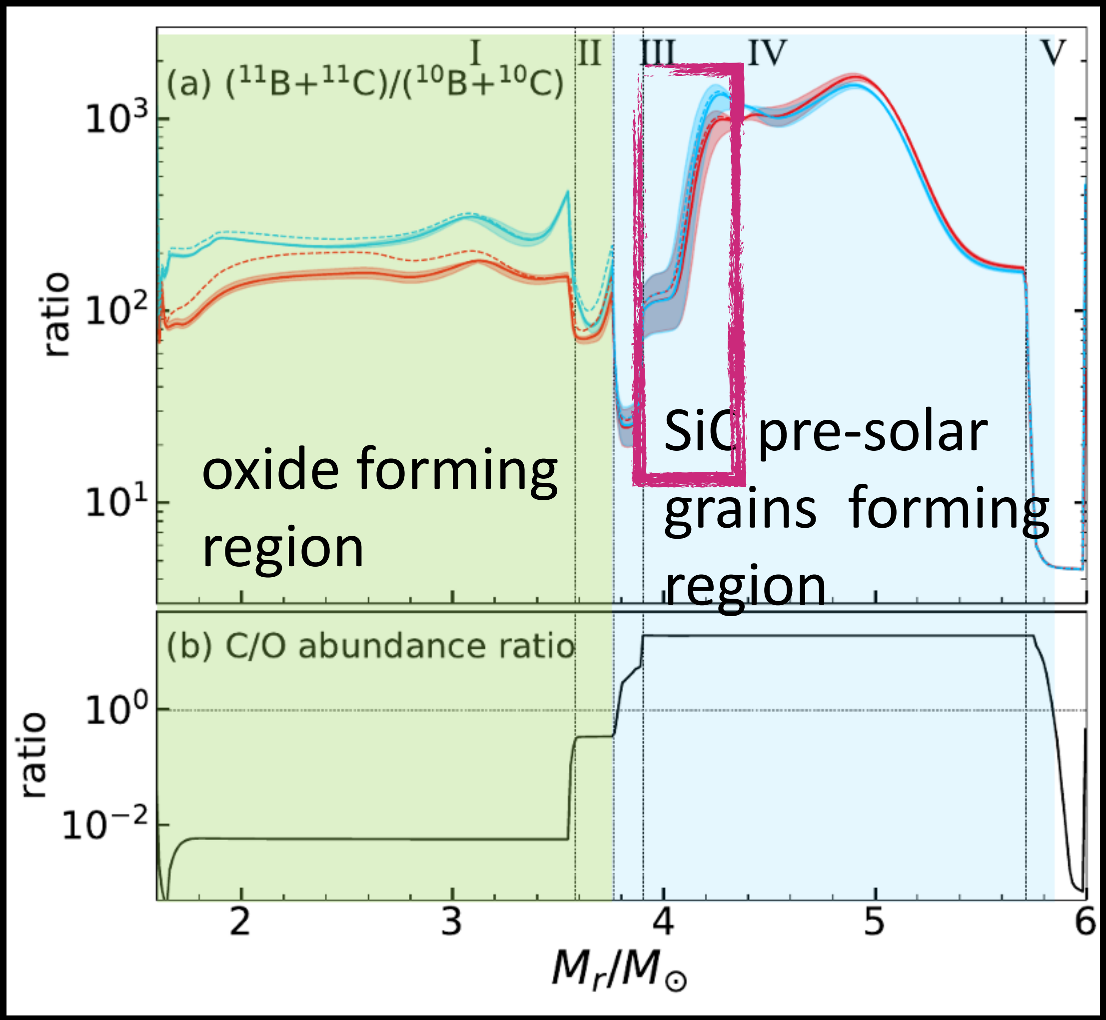

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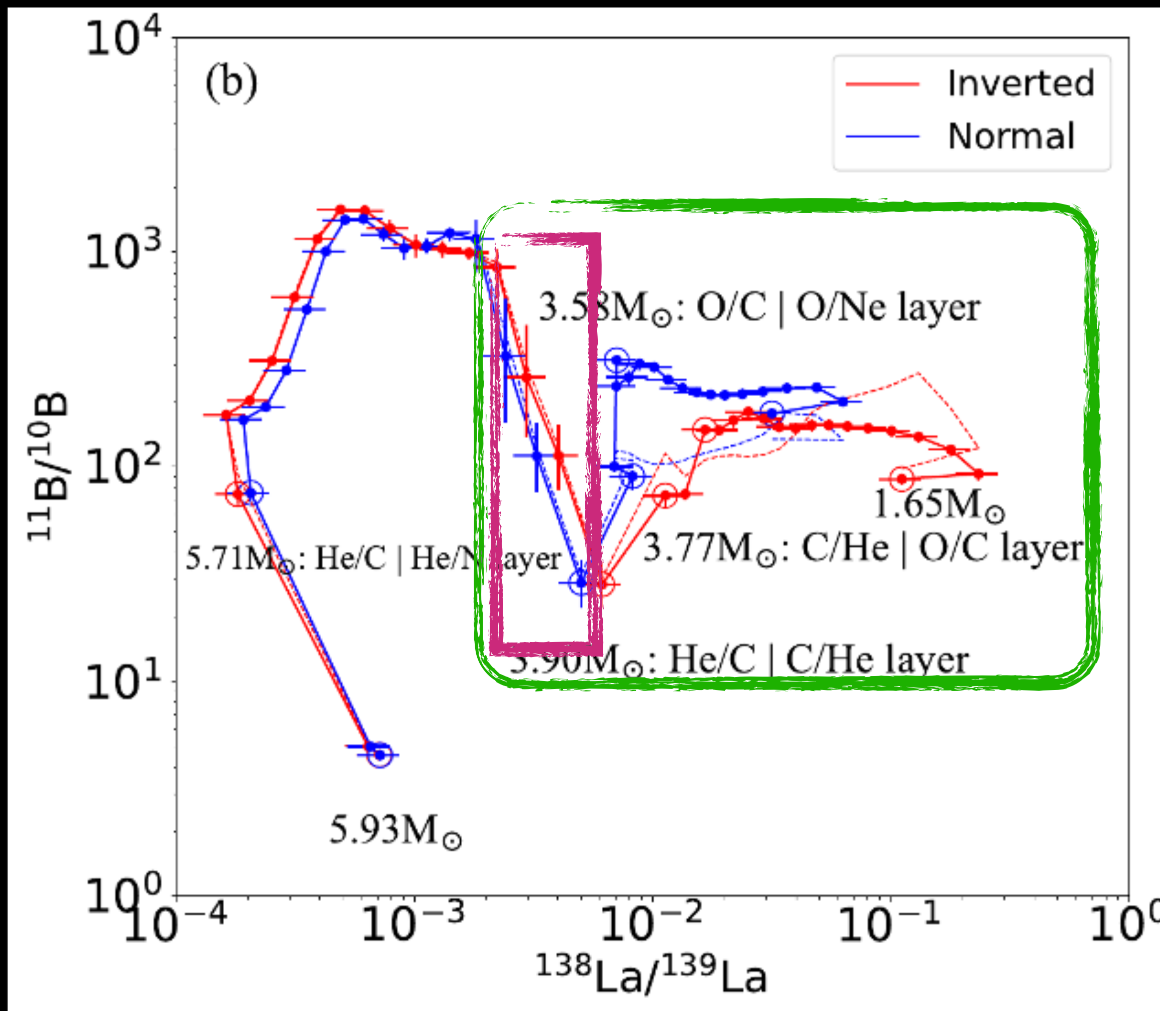

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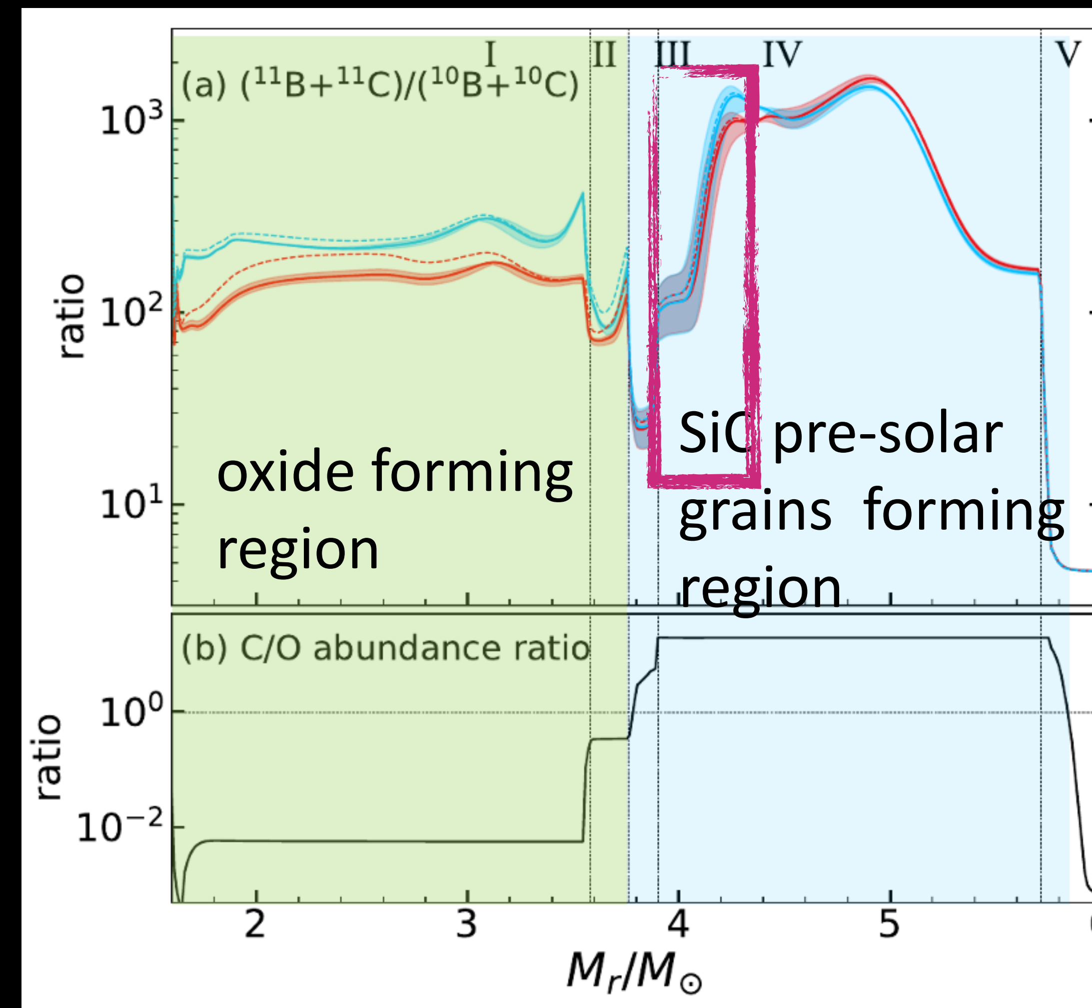

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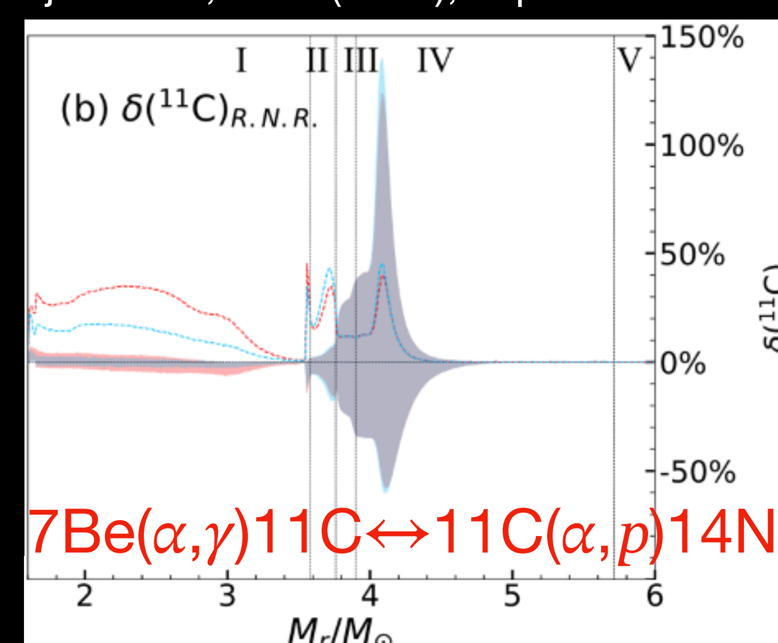

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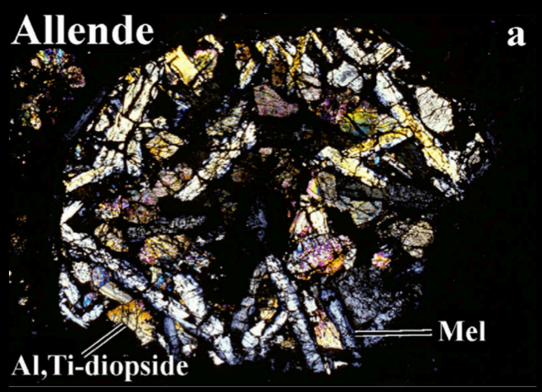
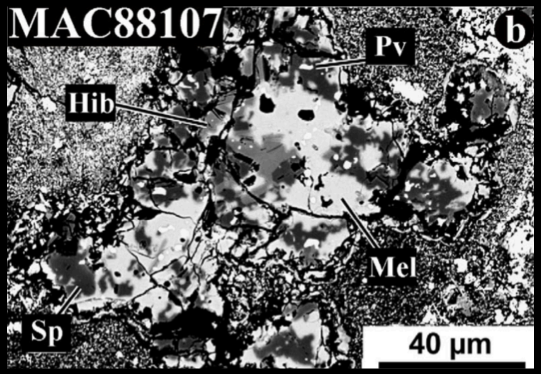
Uncertainty mainly due to 11C(α,p)14N

Compare with Calcium-aluminum-rich inclusions

- Oldest solar system solids

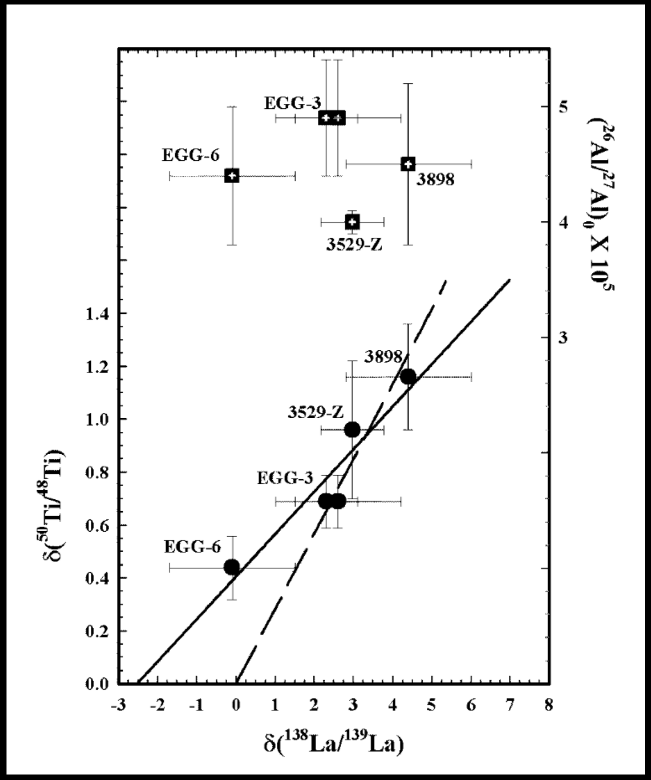




MacPherson et al 2005

Yesterday's talk

- Correlation in CAIs



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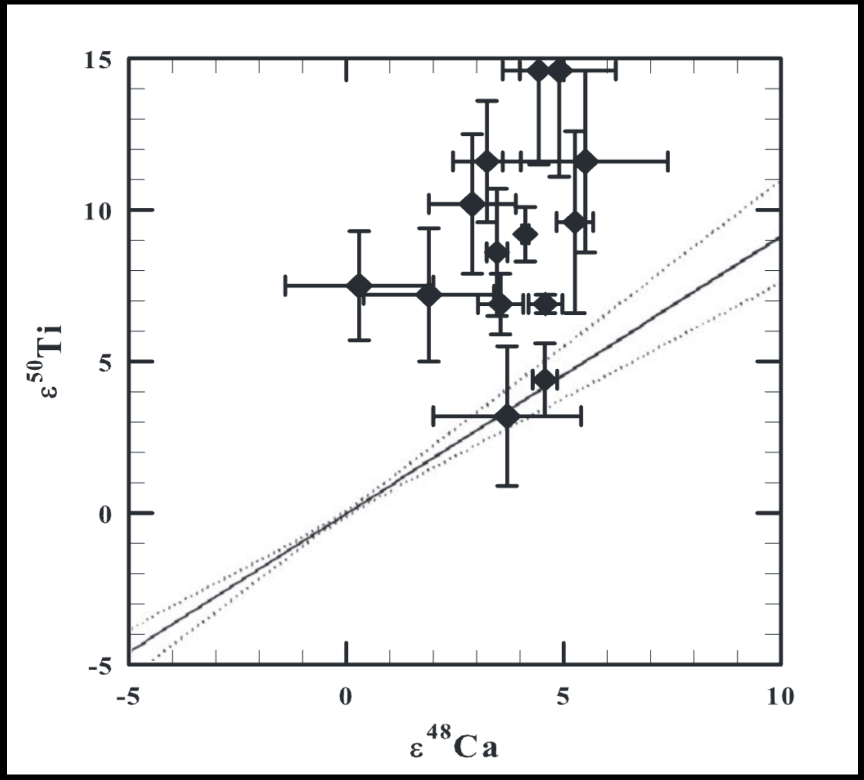

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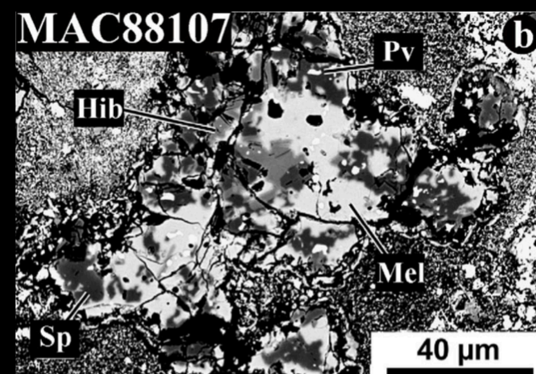

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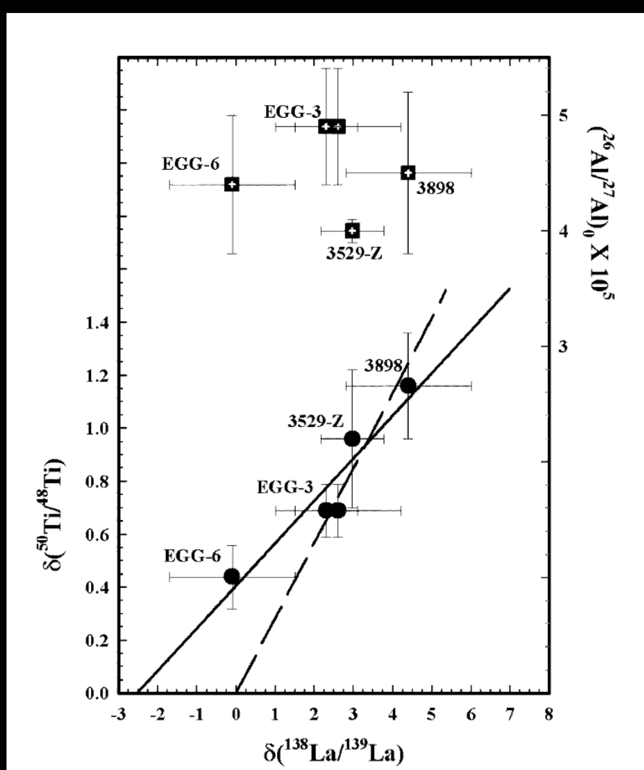

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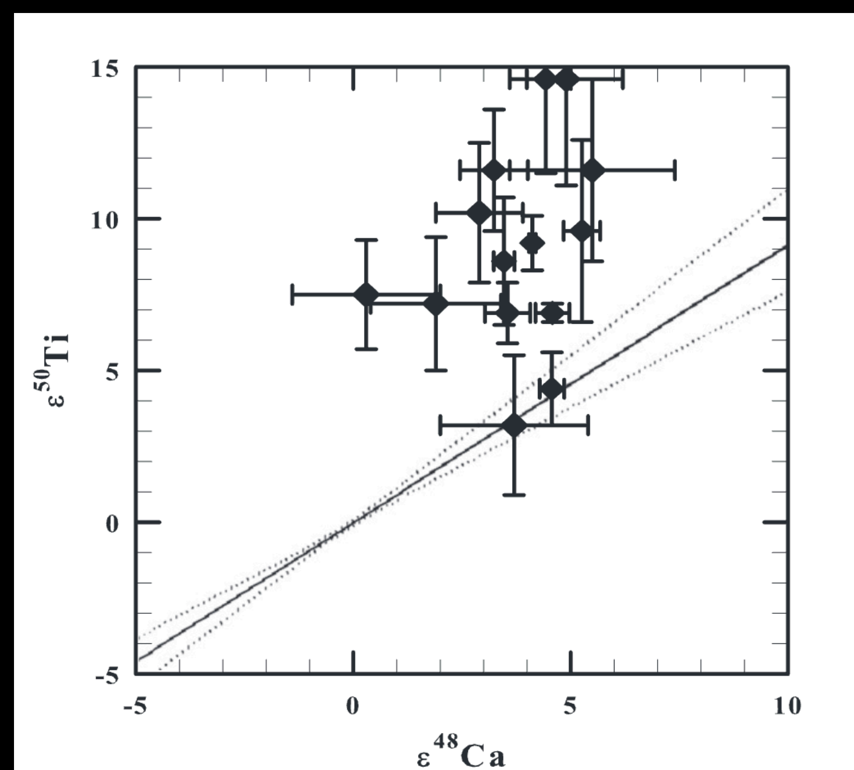

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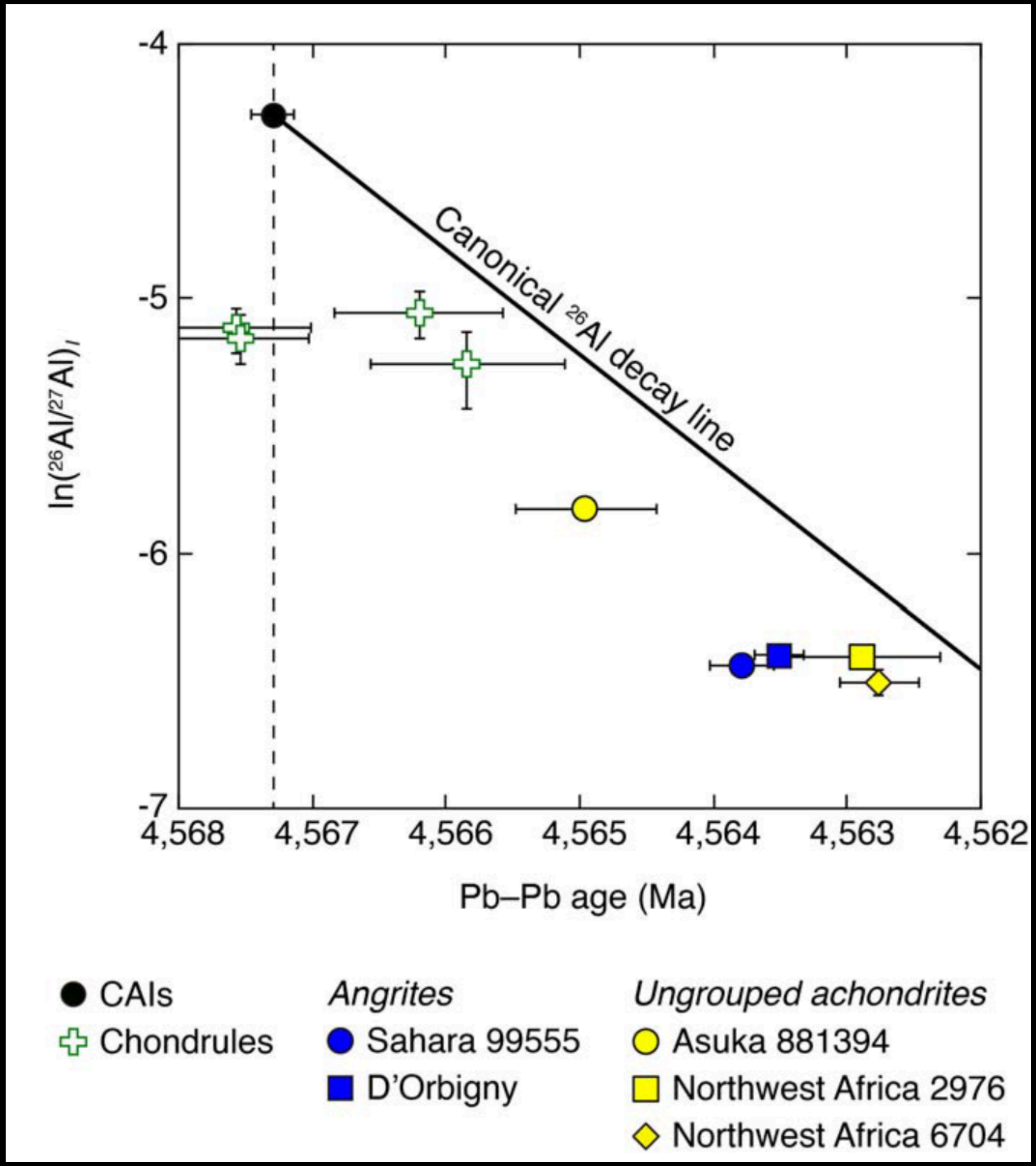
Origin of the anomaly?

- Ti48, Ca48, Cr54: mainly synthesized via the neutron-rich nuclear statistical equilibrium near the core, where $T_9 \sim 5-6$
- Ca48 may fall back to the PNS in CCSN (Nomoto et al. 2006), so a rare neutron rich SNe Ia (nSNe Ia) can make contributions

→ Hard to explain the La138 anomaly

- Mixtures between grains condensed from ejecta of neutron-rich accretion-induced SNe Ia and the O/Ne–O/C zone of core-collapse SNe II?

Compare with CAIs (Preliminary)



Iizuka et al, ApJL (2025)

- Some achondrites and chondrules in chondrites have distinctly lower 26Al/27Al at the time of the formation of the meteorites.

→ non-uniform distribution of 26Al in the protosolar disk

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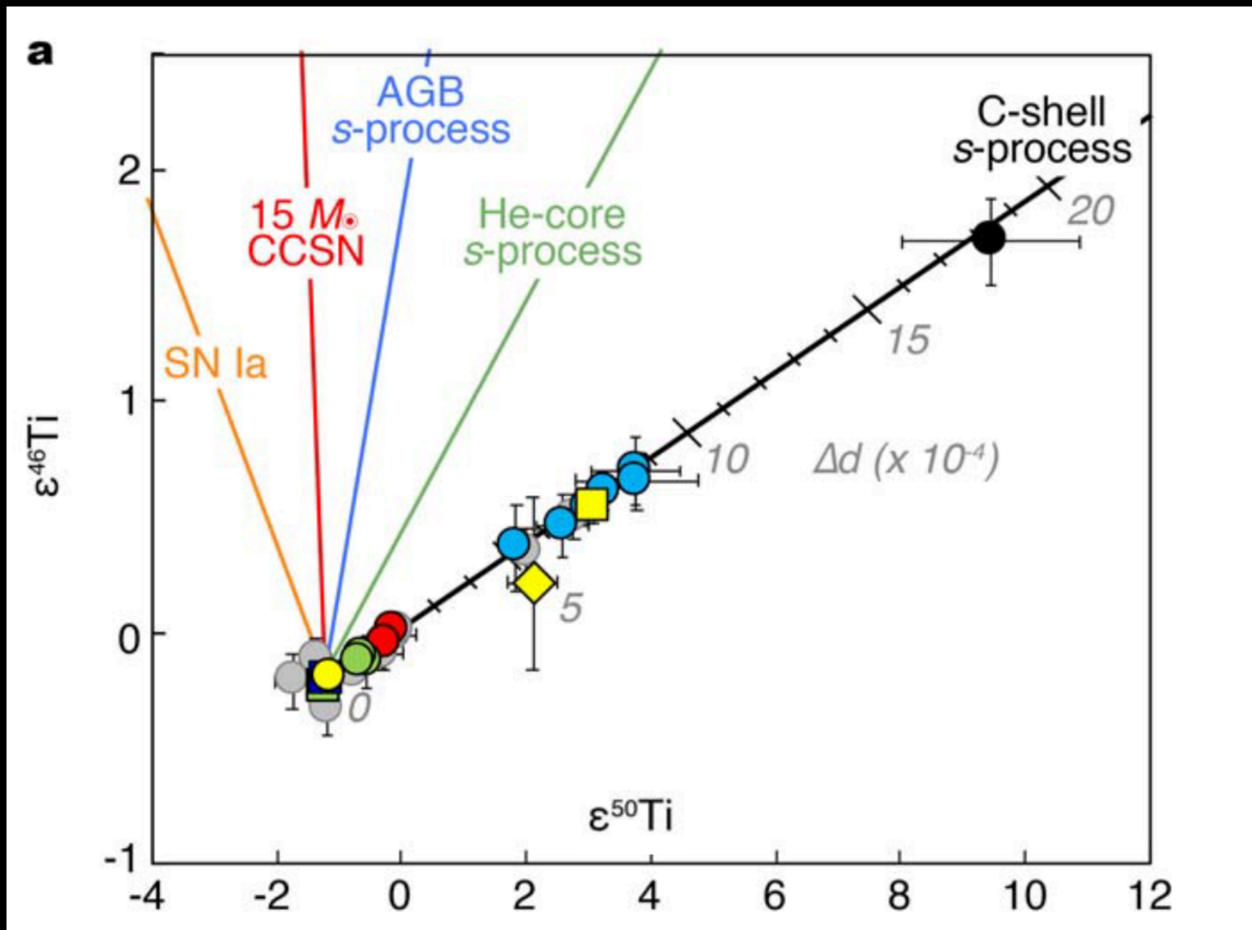

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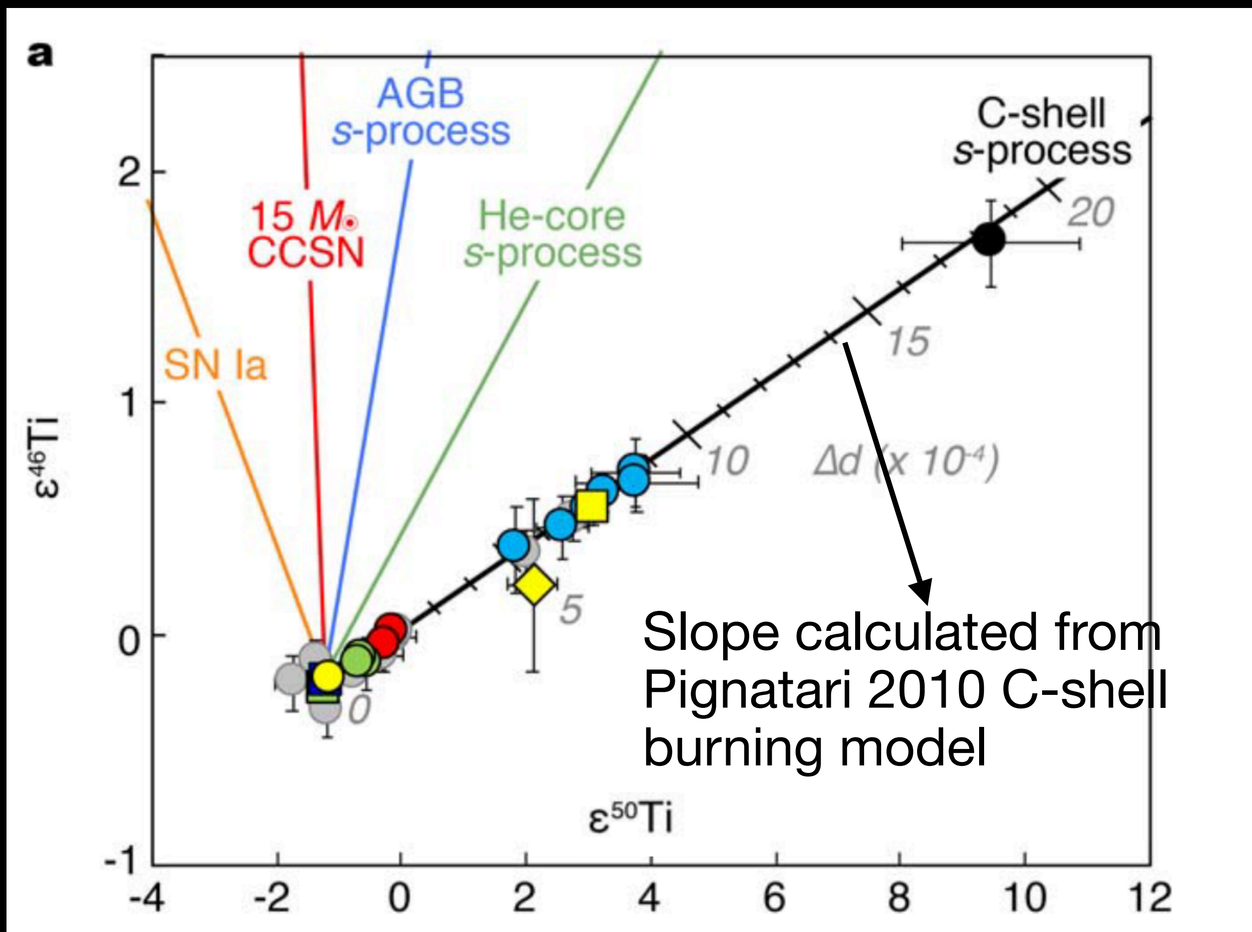

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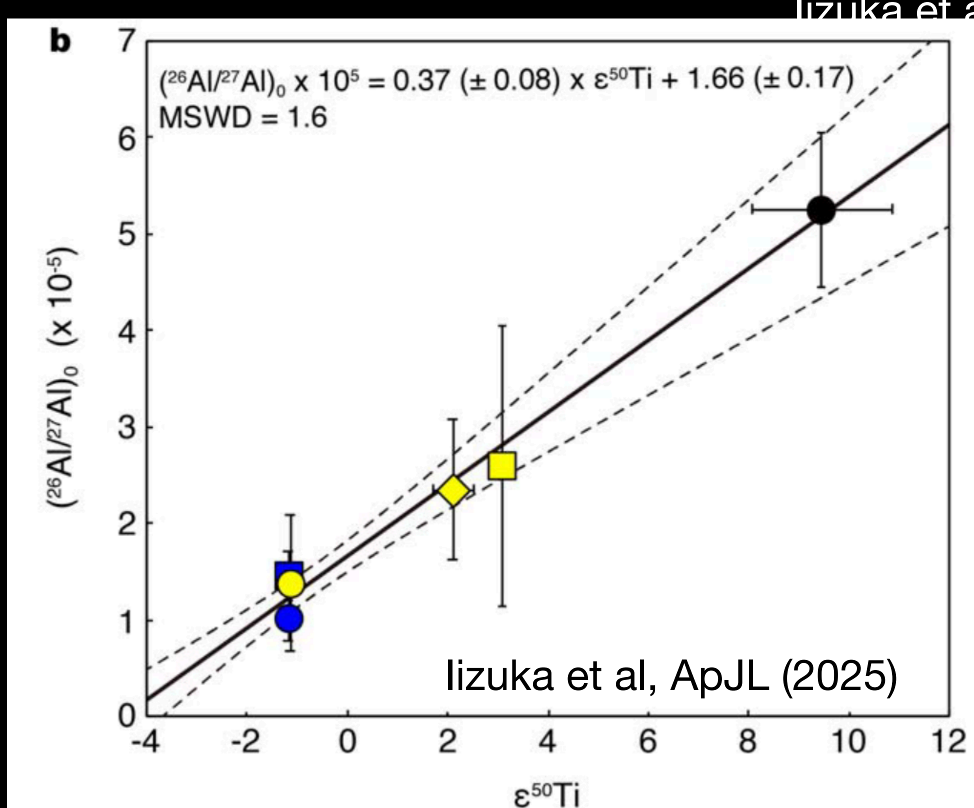

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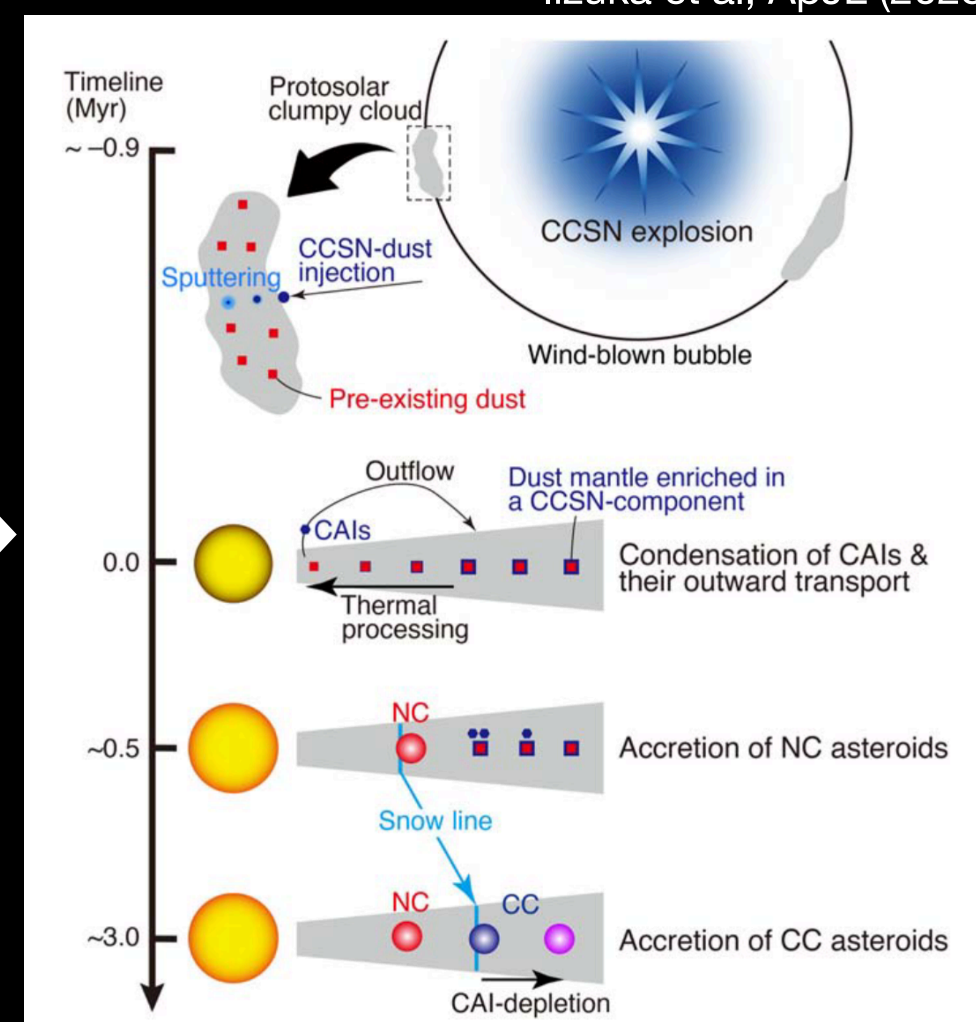

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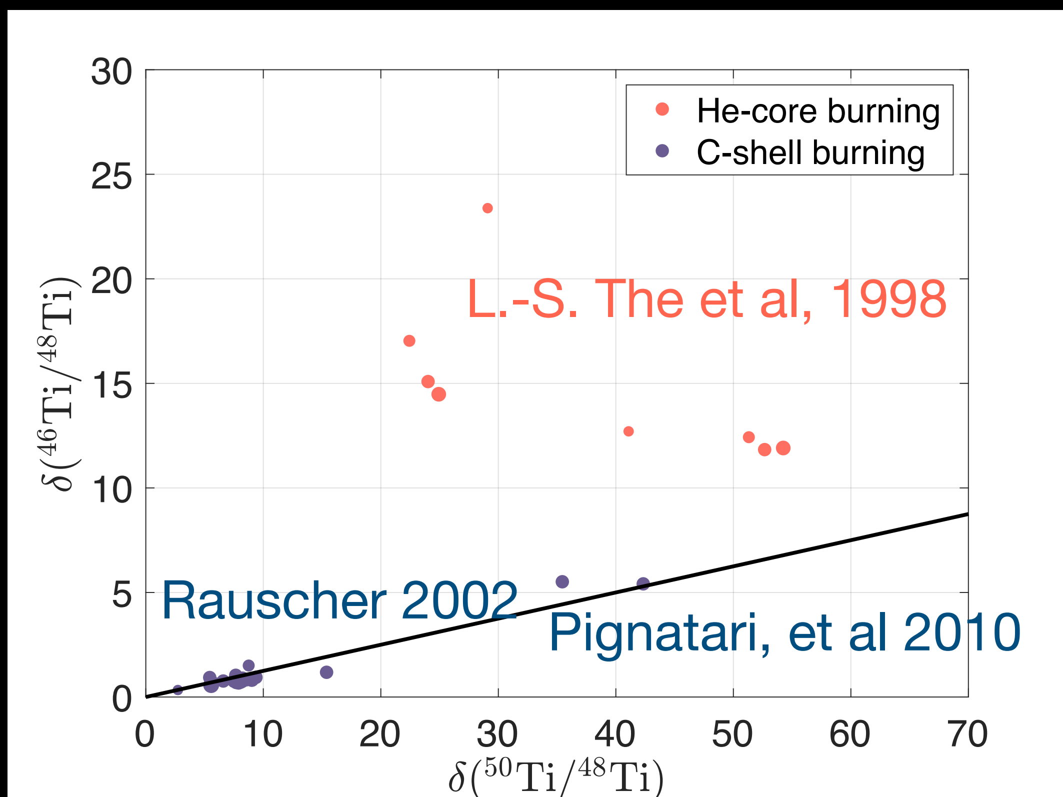
- We further investigate more s-process data, find the correlation remains with C-shell buring



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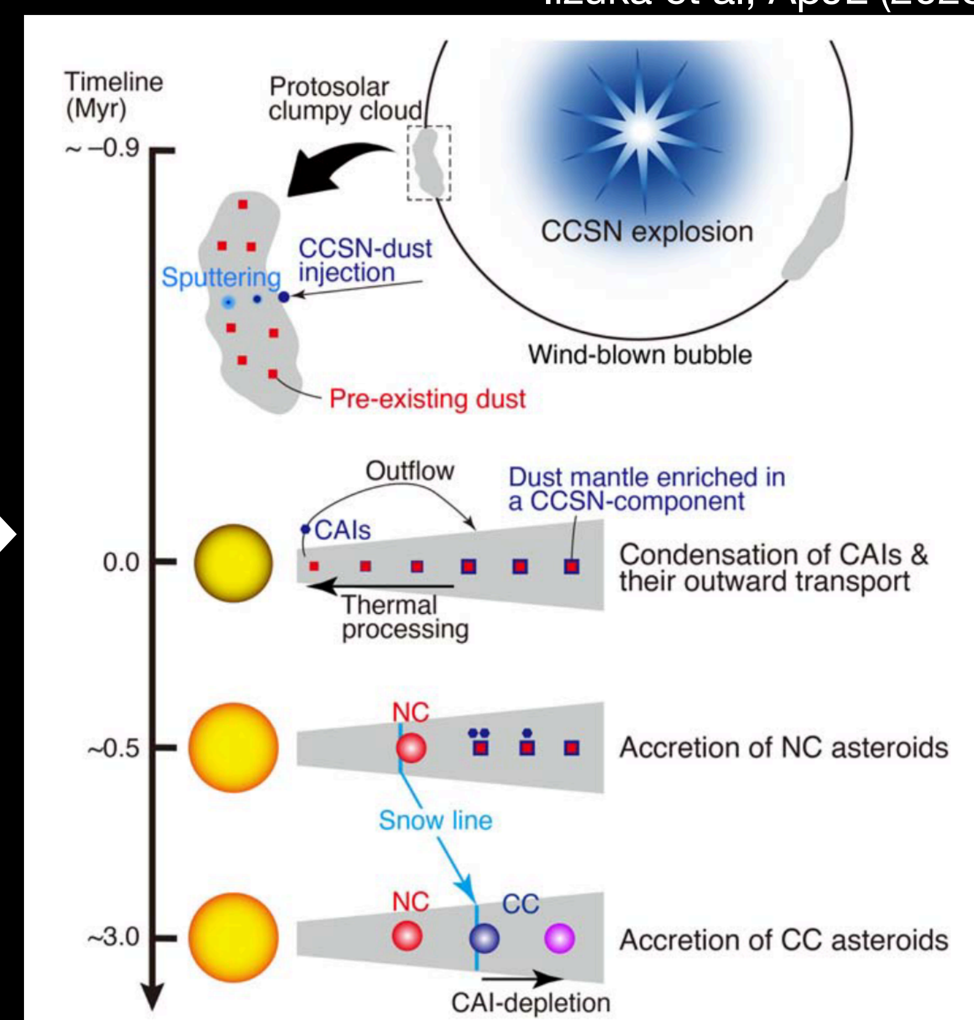

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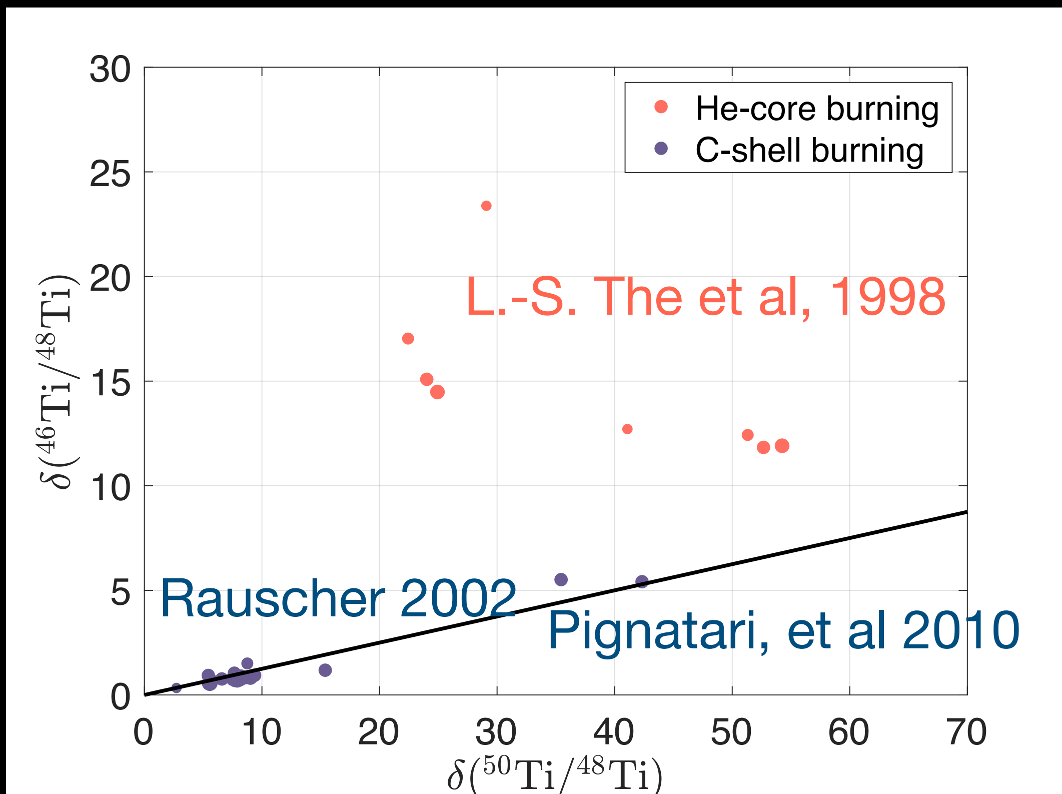

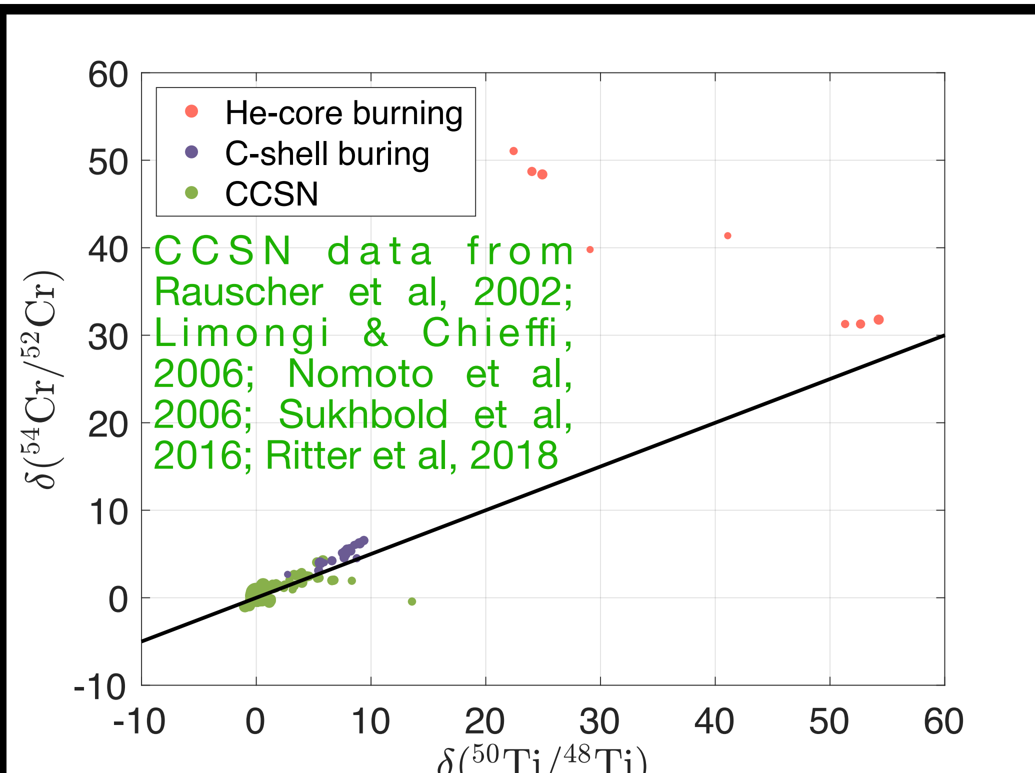

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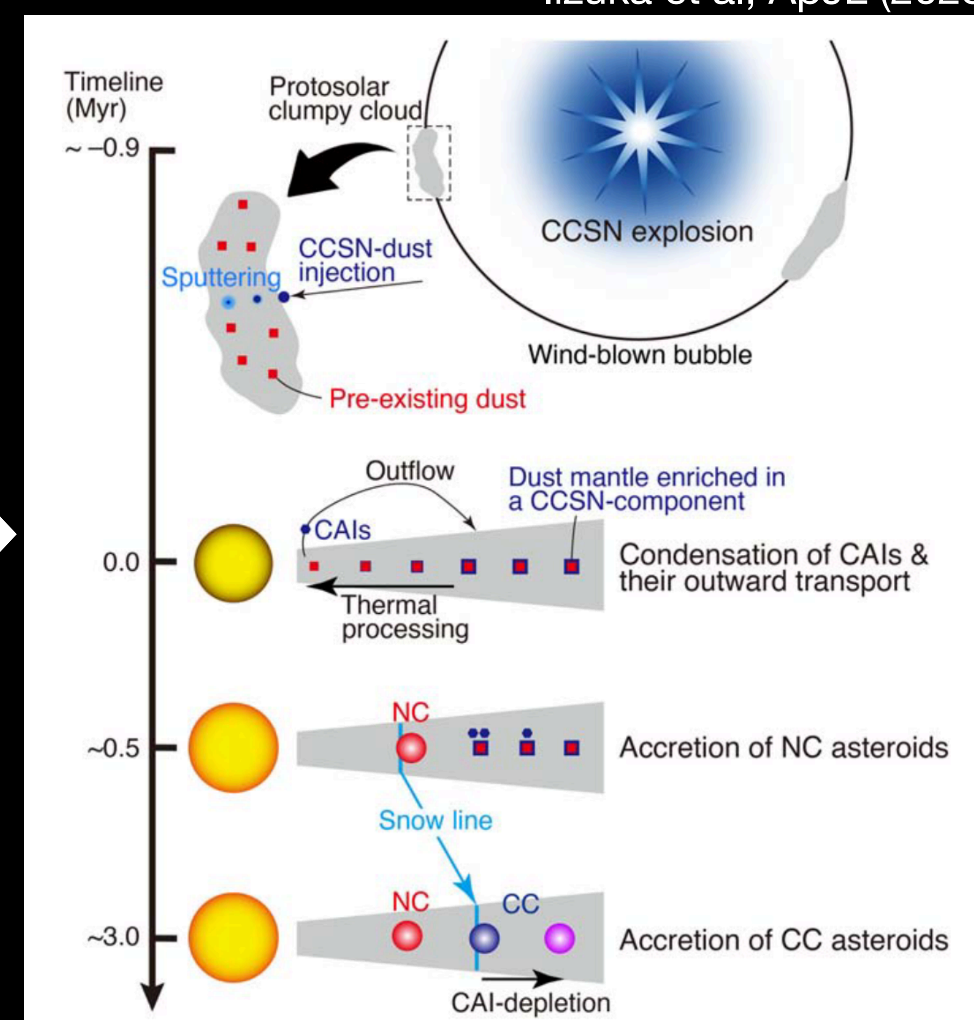

Compare with CAIs (Preliminary)

- La138 anomaly vs Ti50 anomaly

CAI Allende	$\delta(^{138}La/^{139}La)$* (per mil)	$\delta(^{50}Ti/^{48}Ti)$ (per mil)
Sample 1	6.0 ± 1.6	...
Sample 2	−0.8 ± 1.6	...
	0.4 ± 1.6	...
Sample 3	3.1 ± 1.6	...
	3.2 ± 1.6	...
USMN 3898	4.4 ± 1.6	1.16 ± 0.20 (5)
3529-Z	3.0 ± 0.8	0.96 ± 0.26 (6)
EGG-3	2.6 ± 1.6	0.69 ± 0.10 (5)
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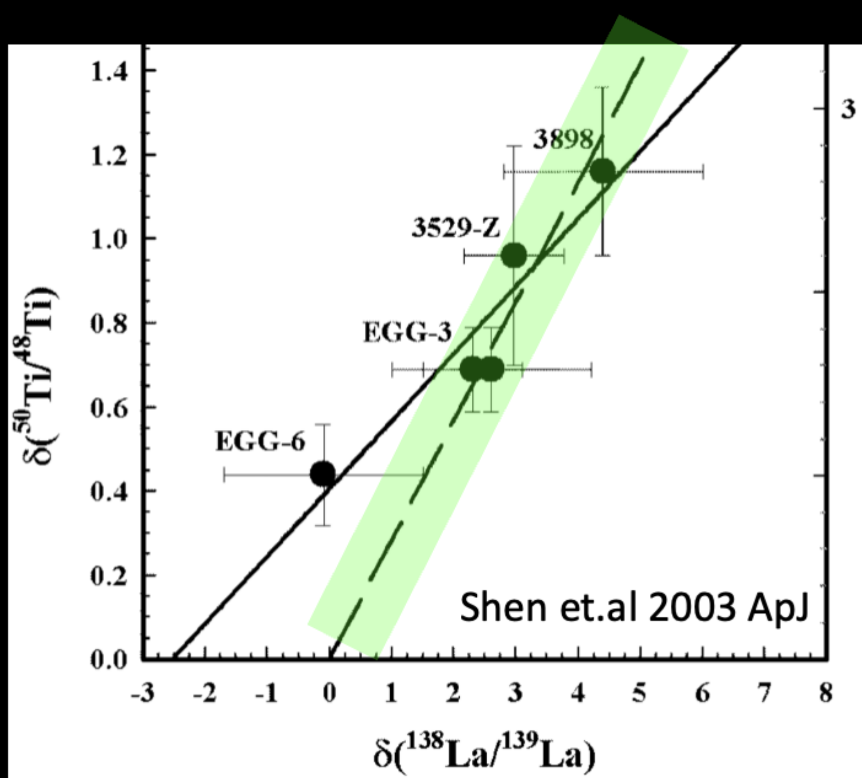
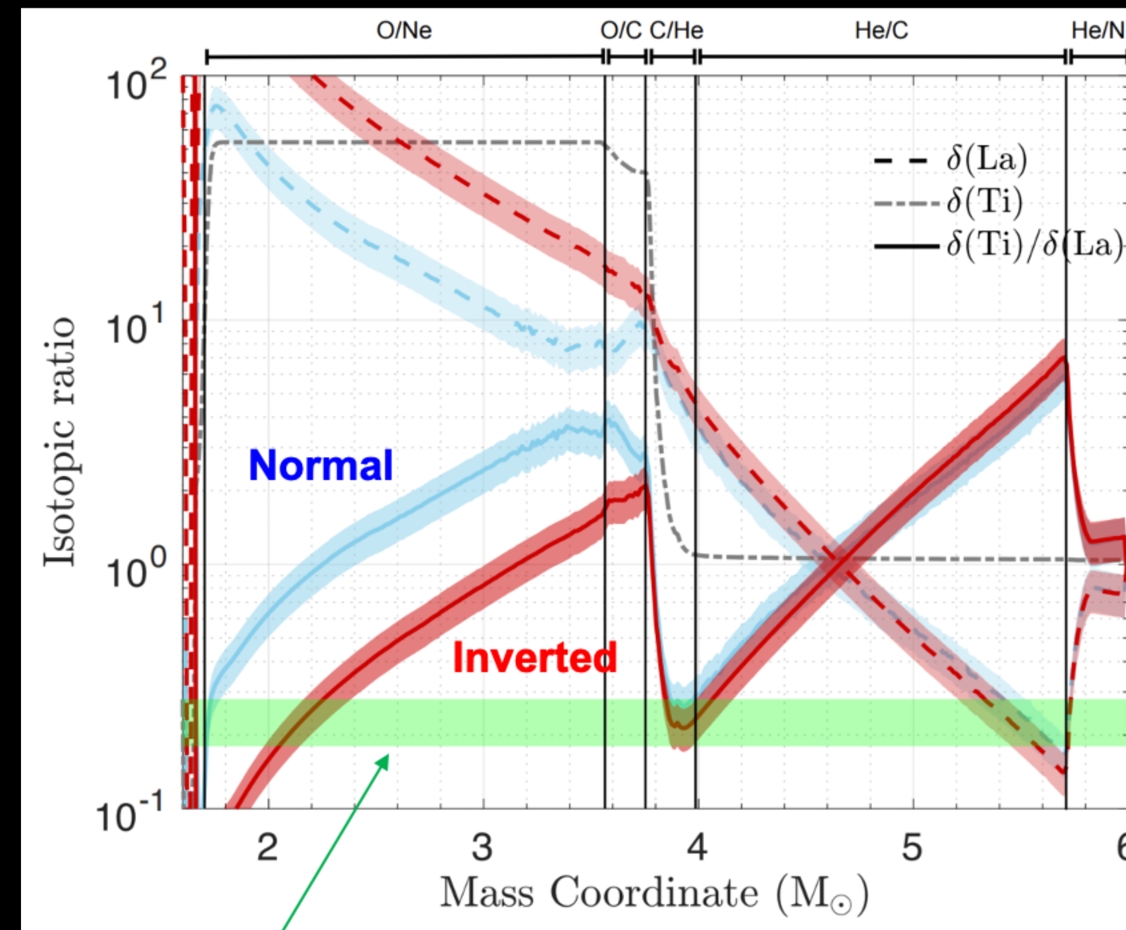


- Comparison with our model



Constraint from measured CAIs

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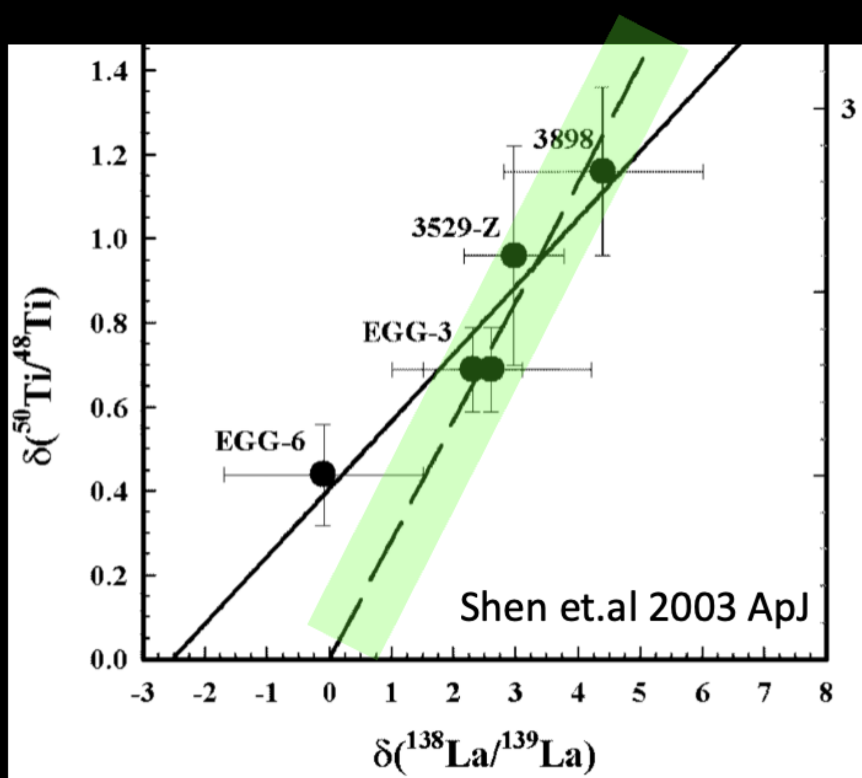

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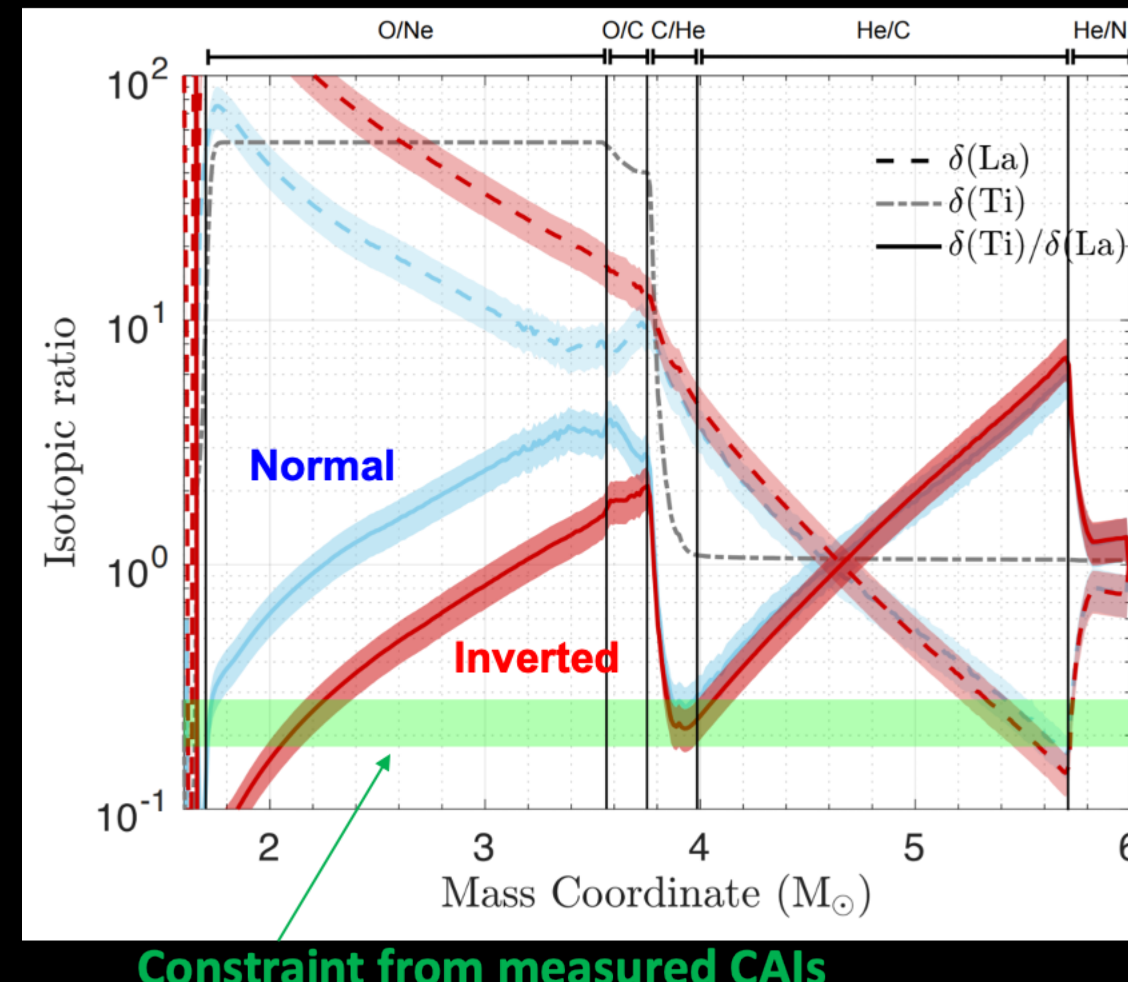

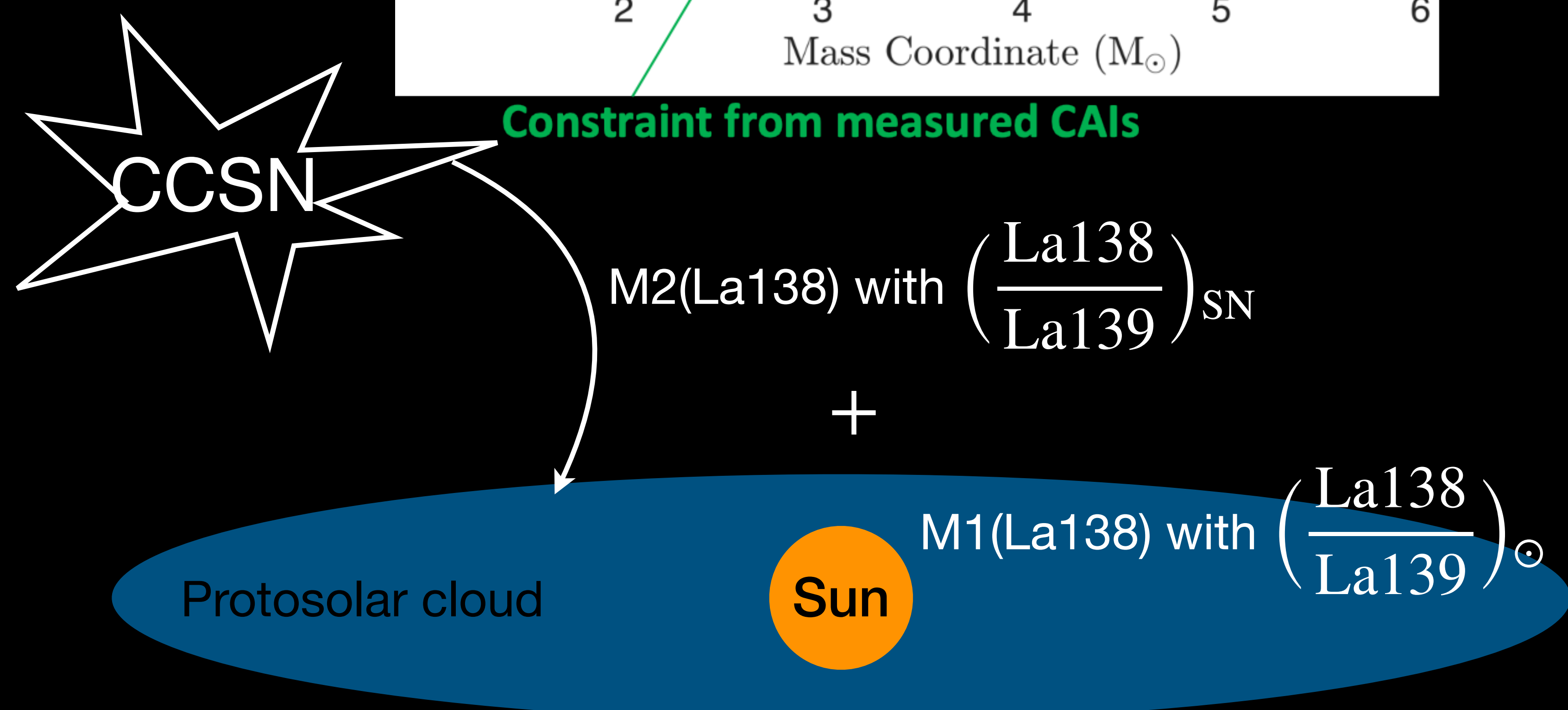

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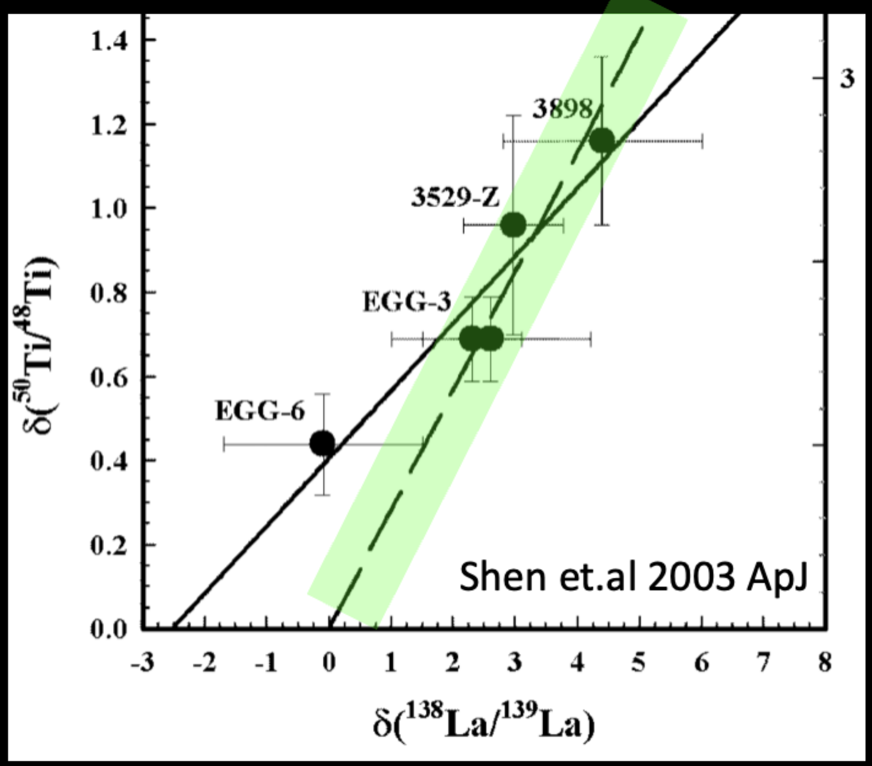

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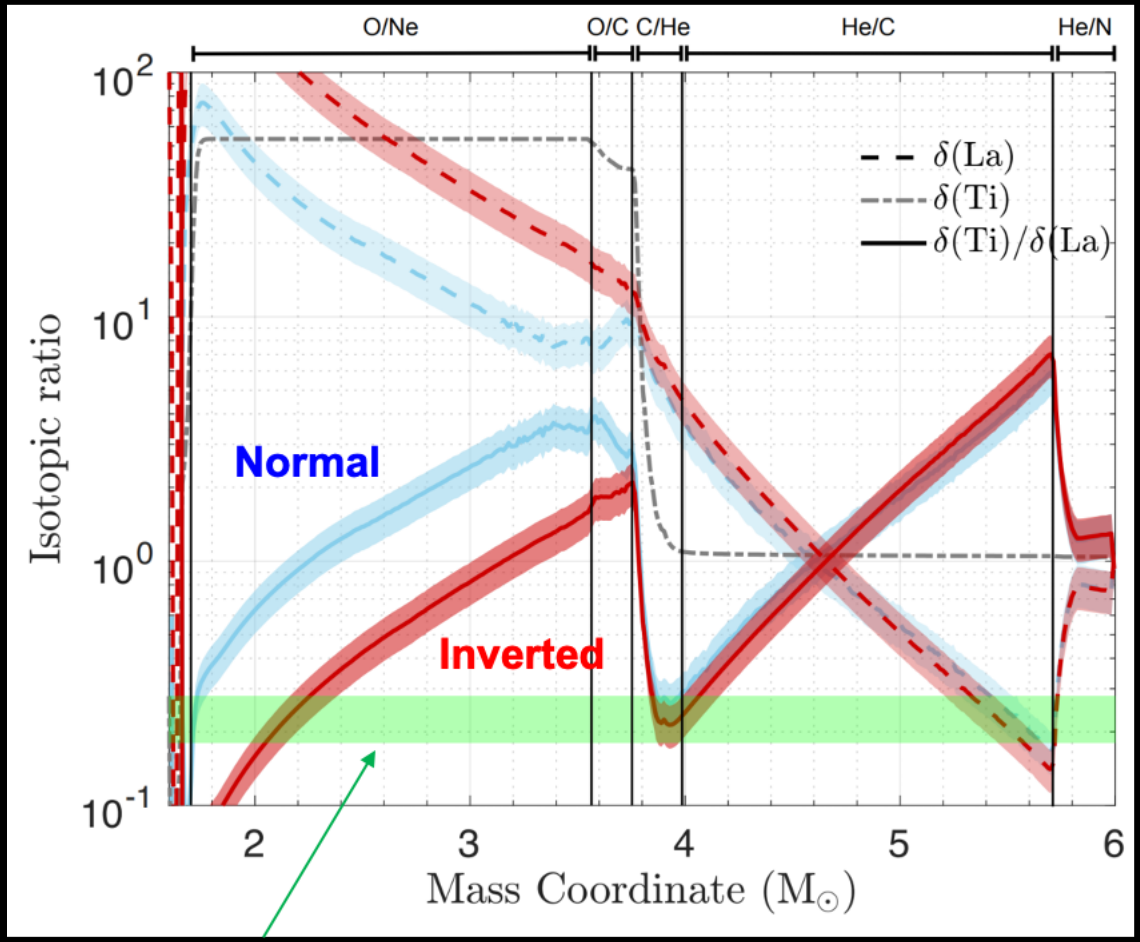


Constraint from measured CAIs

- Time interval $\Delta t = 0.75\mathrm{Myr}$, consistent with $0.94 + 0.25/-0.21\mathrm{Myr}$ in Iizuka et al, 2025

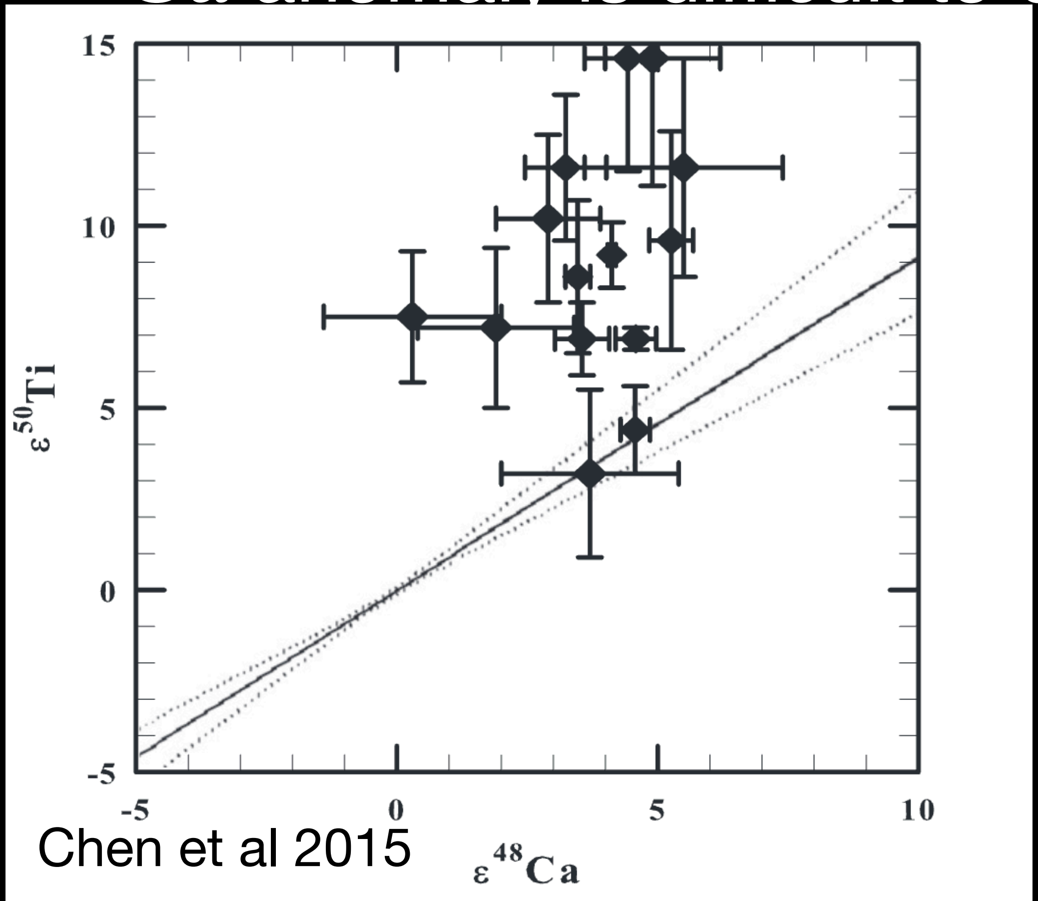
$$\Delta\left(\frac{^{26}Al}{^{27}Al}\right)_{0,CAI-angrite} = \Delta d_{0,CAI-angrite} \times \frac{A^{Al27}X^{Al26}_{ejecta}}{A^{Al26}X^{Al26}_{solar}} e^{-\Delta t/\tau}$$

$$X(^{26}\mathrm{Al})_{\mathrm{ejecta}} = 3.37 \times 10^{-6}$$

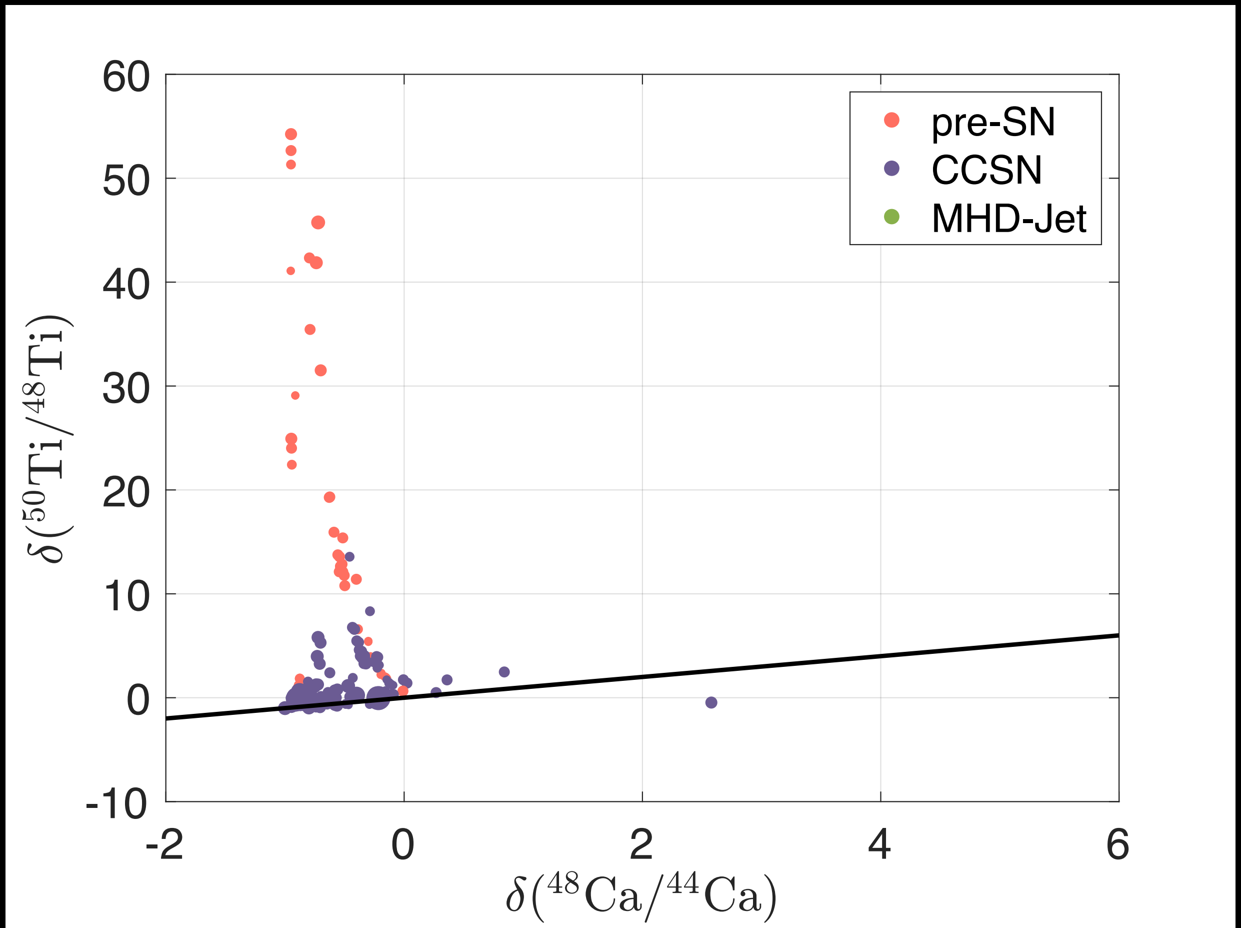
$$\tau = 1.05\mathrm{Myr};\ \Delta \mathrm{d} = 1.77 \times 10^{-3}$$

Compare with CAIs (Preliminary)

- ^{48}Ca anomaly is difficult to explain



Chen et al 2015



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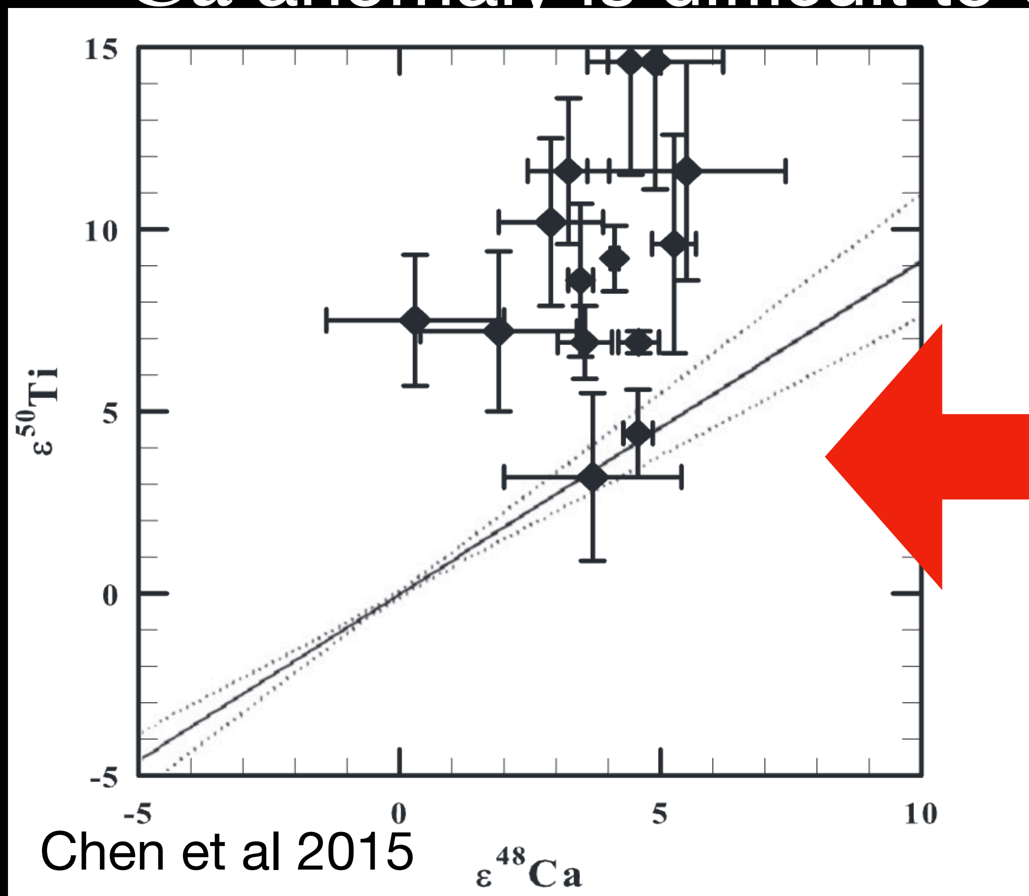

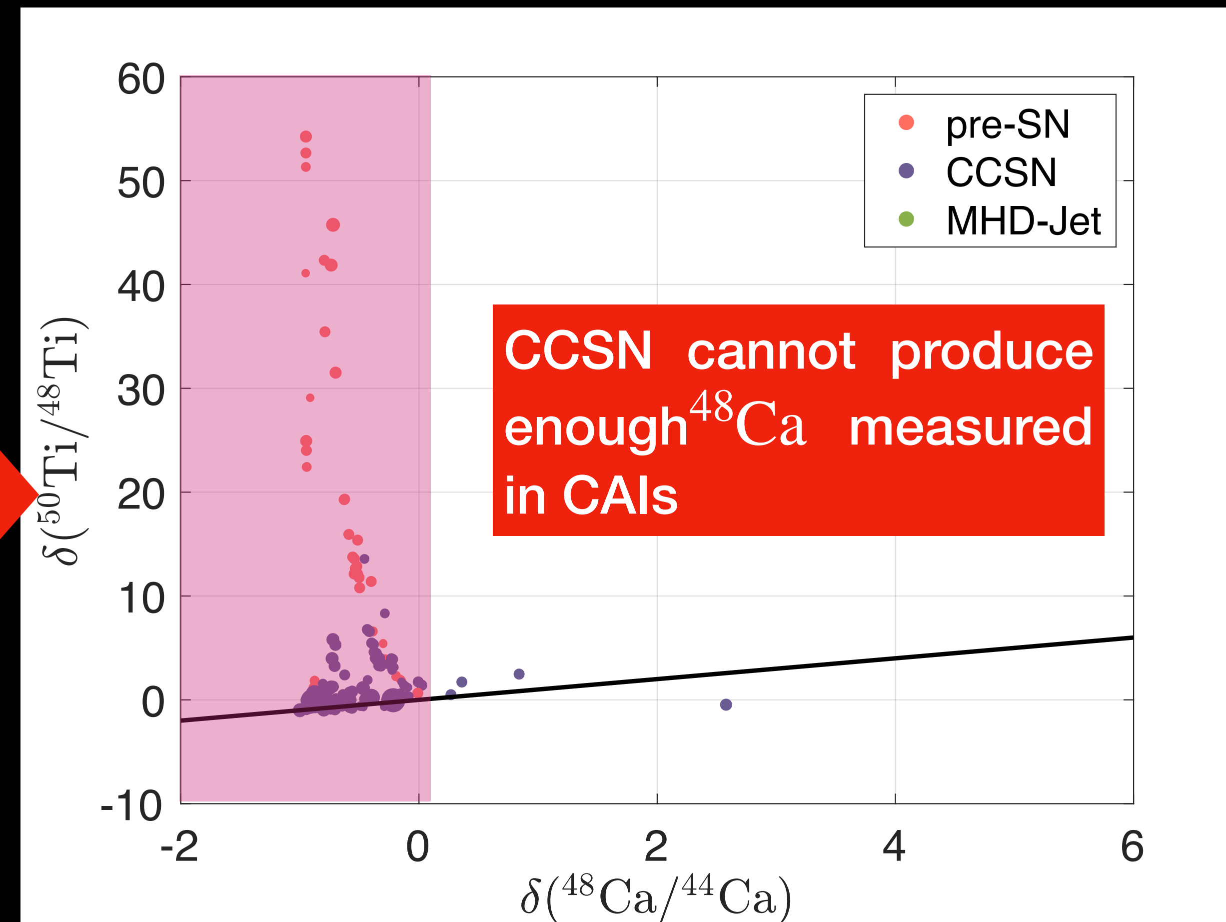

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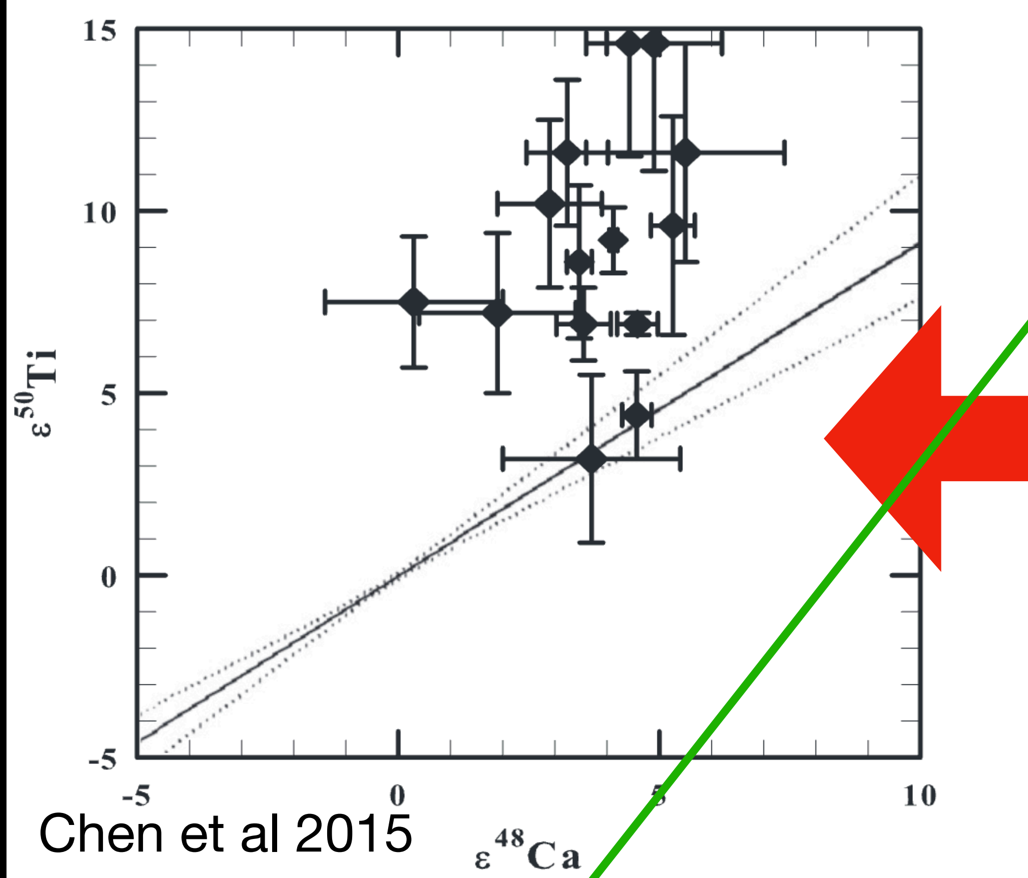

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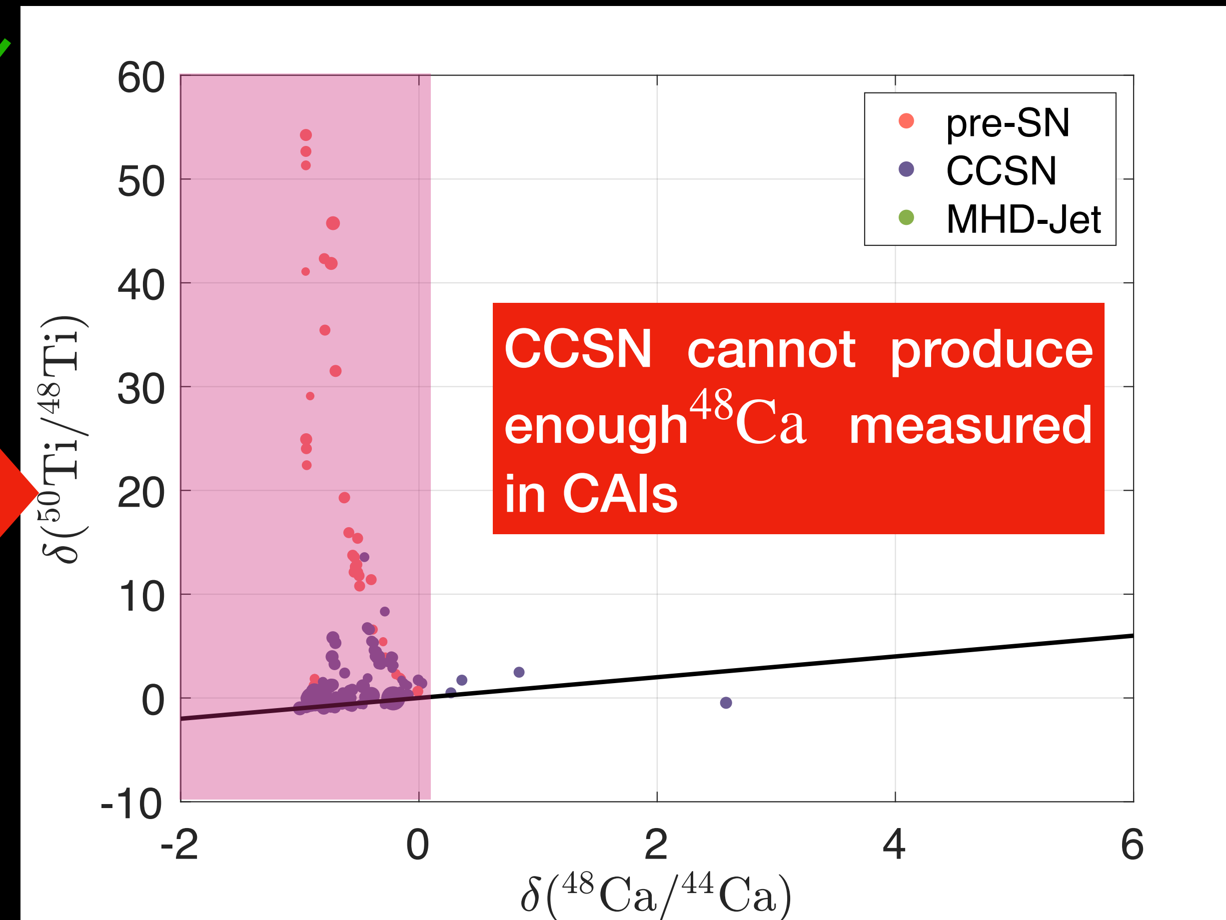

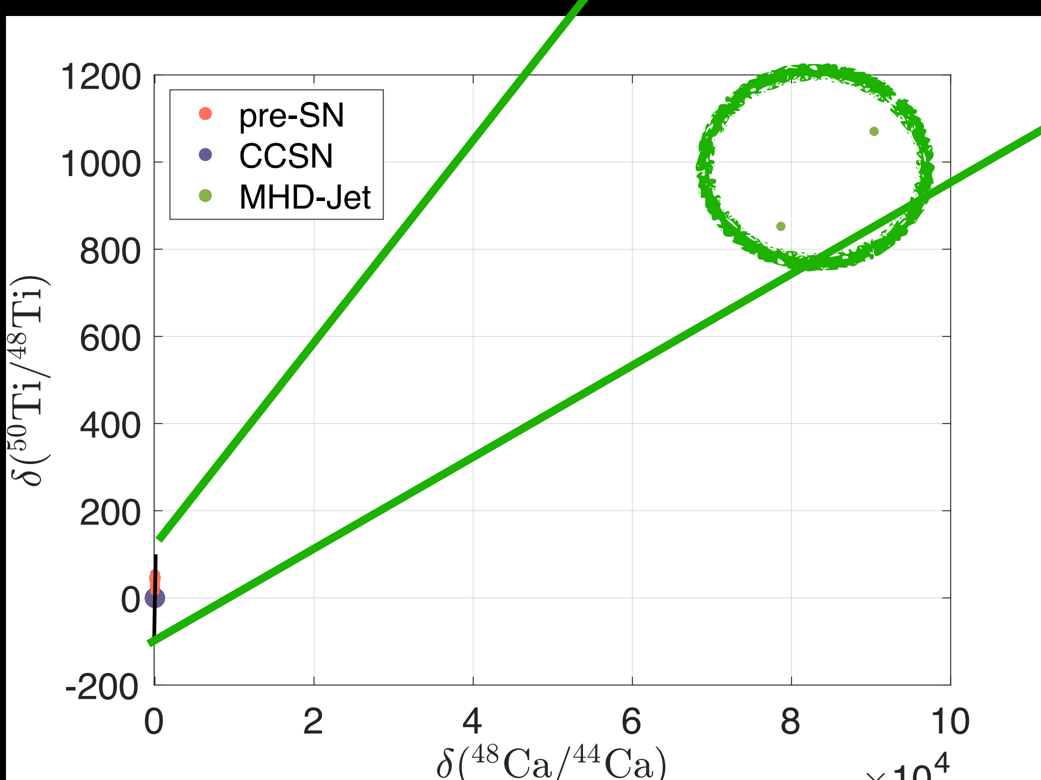

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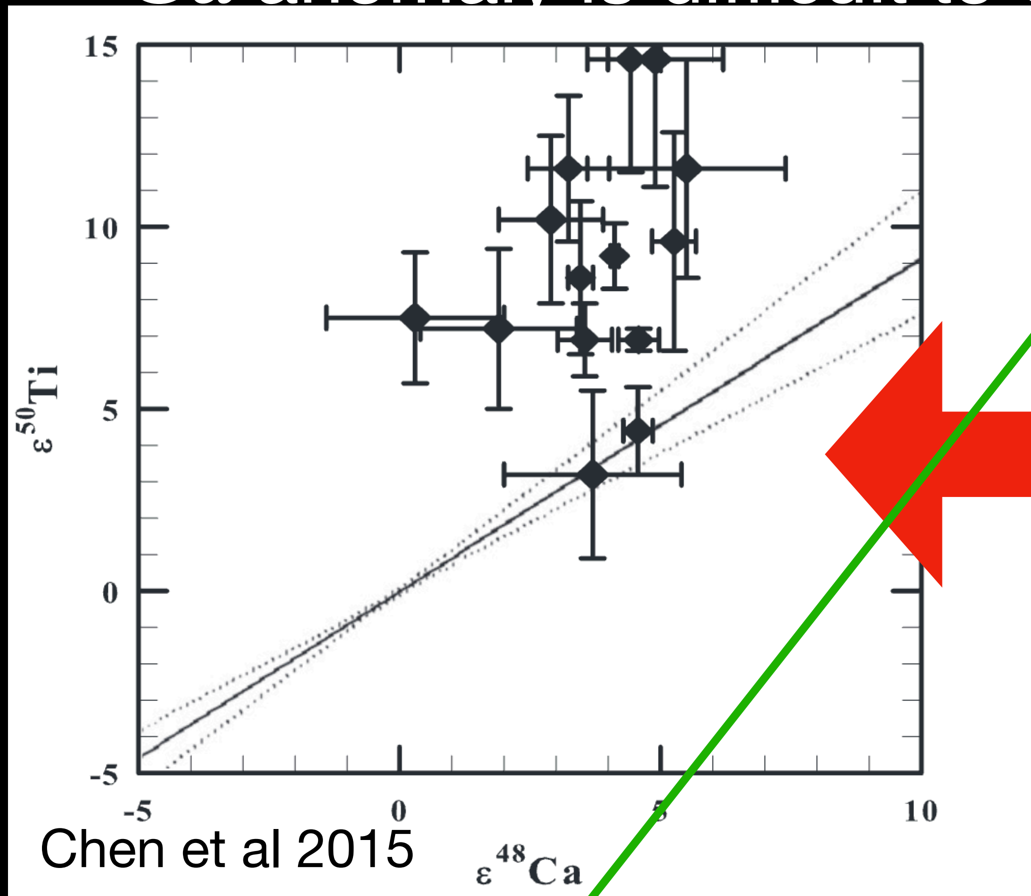
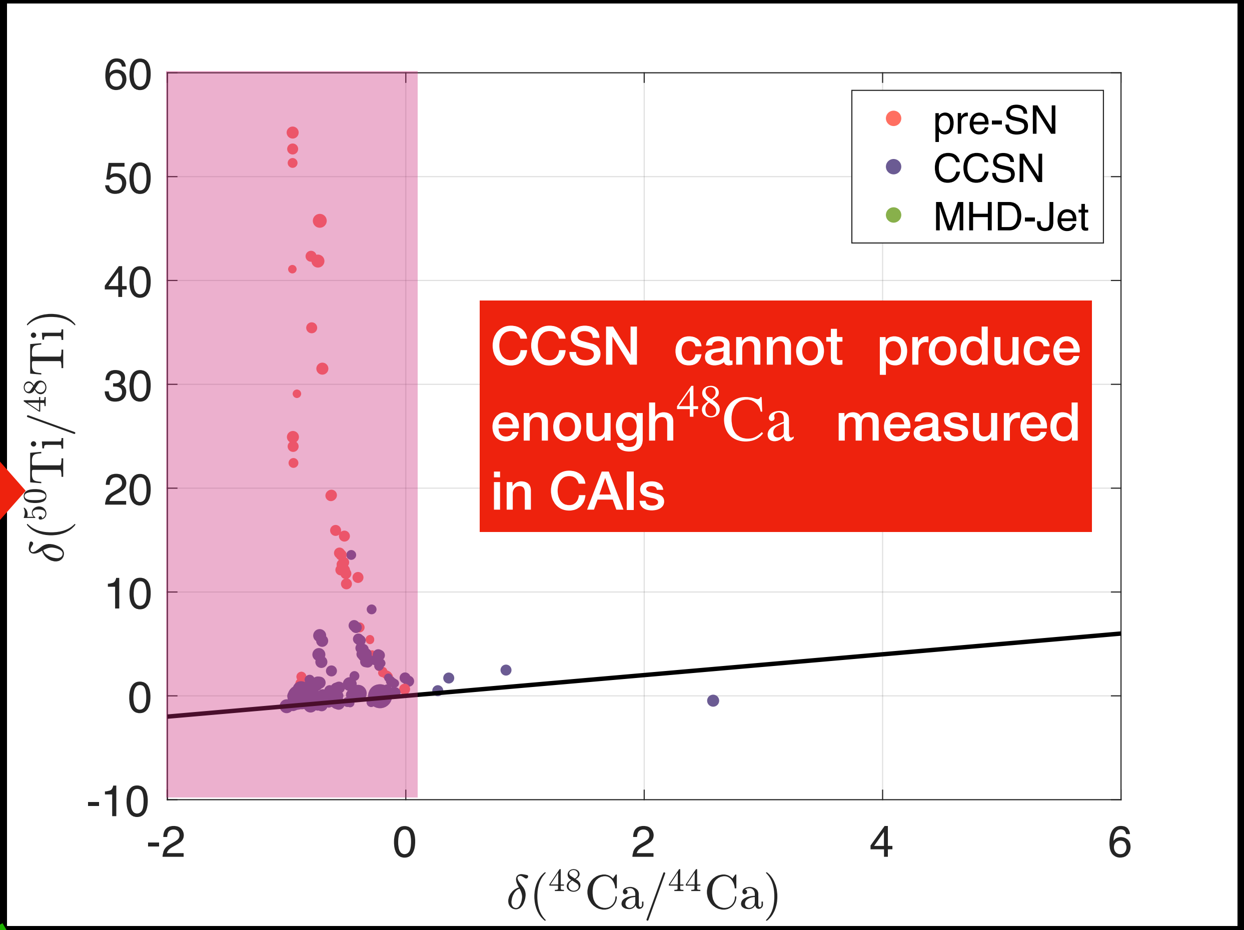
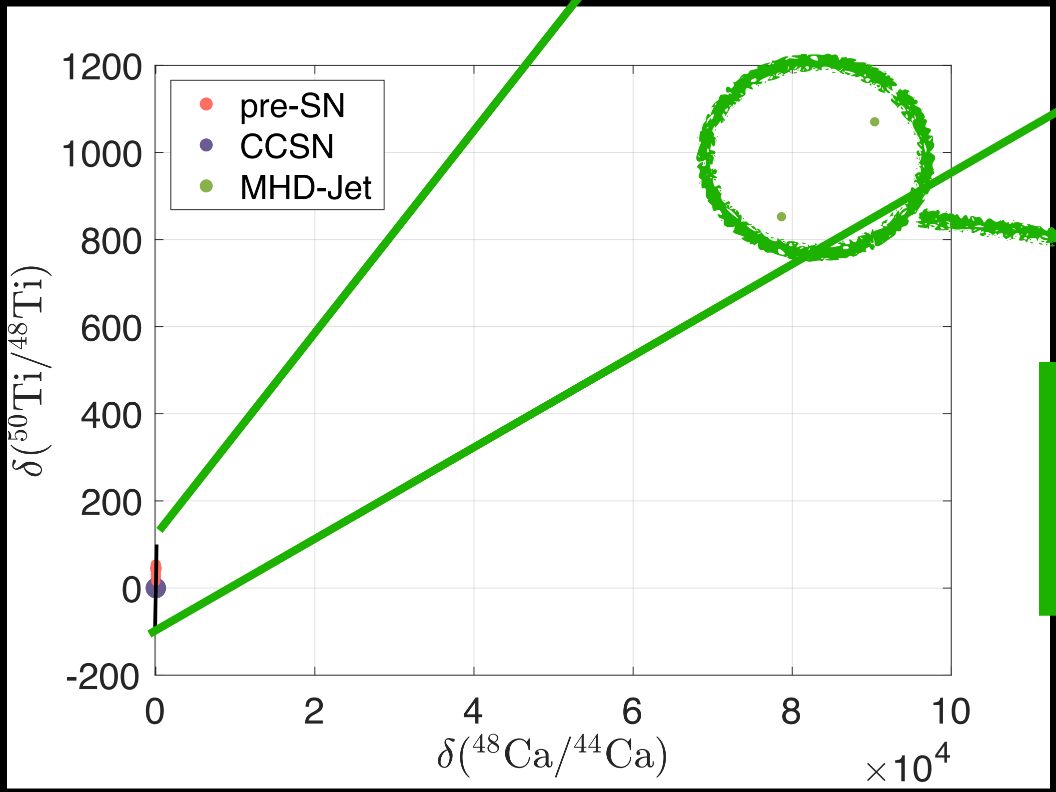
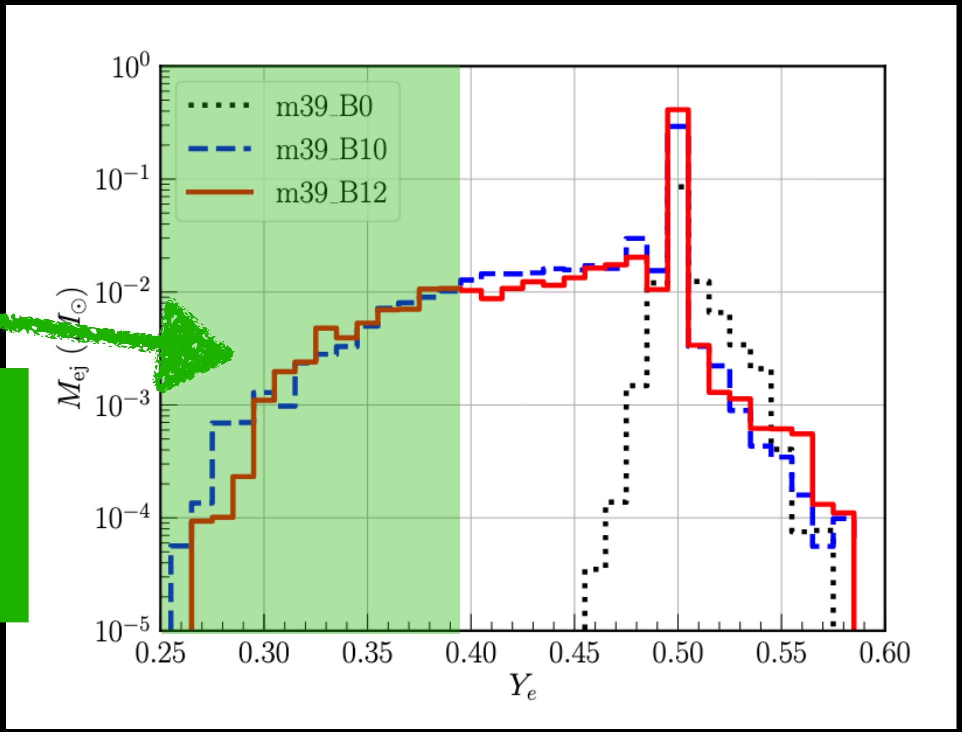






Low Y_e from MHD-Jet SNe could be the solution!



Zha et al, ApJ (2024)

Conclusion

1. $^{138}La/^{138}La$ & $^{11}B/^{10}B$ isotopic ratio in X grain → Hierarchy difference (a factor of 2~3 difference)
   → A Novel Astrophysical probe to constrain the mass hierarchy.

2. Most uncertainty comes from C11(α,p)N14
   → new motivation for the nuclear experiment.

3. δ(Ti)/δ(La) in CAIs → CCSN origin
   → new evidence for La origin in SN.

4. Ca48 anomaly in CAIs →possibly from low Y_e ejecta of MHD-Jet SNe?
   → Single event to explain the anomaly in CAIs.