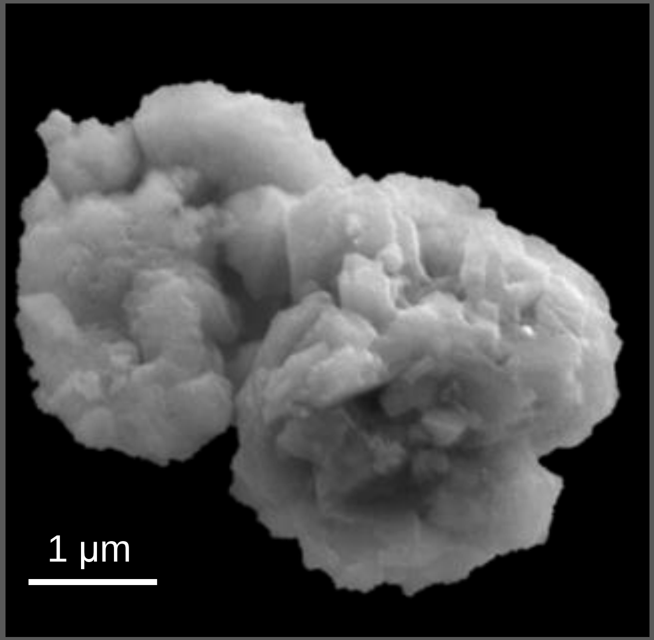
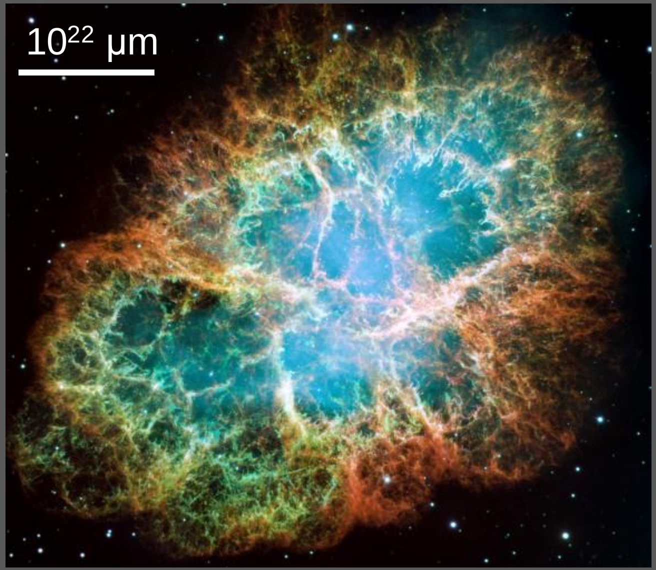
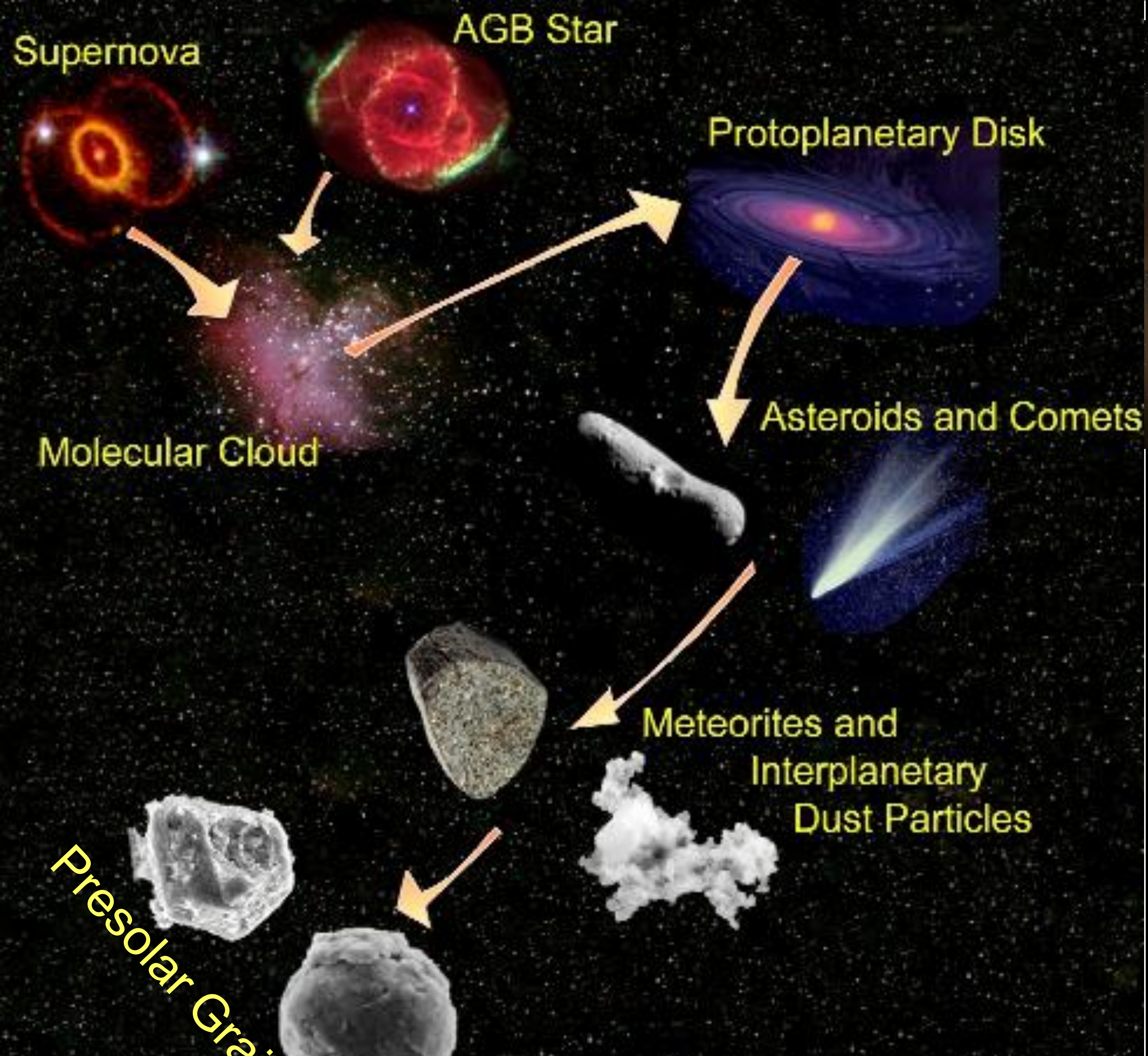


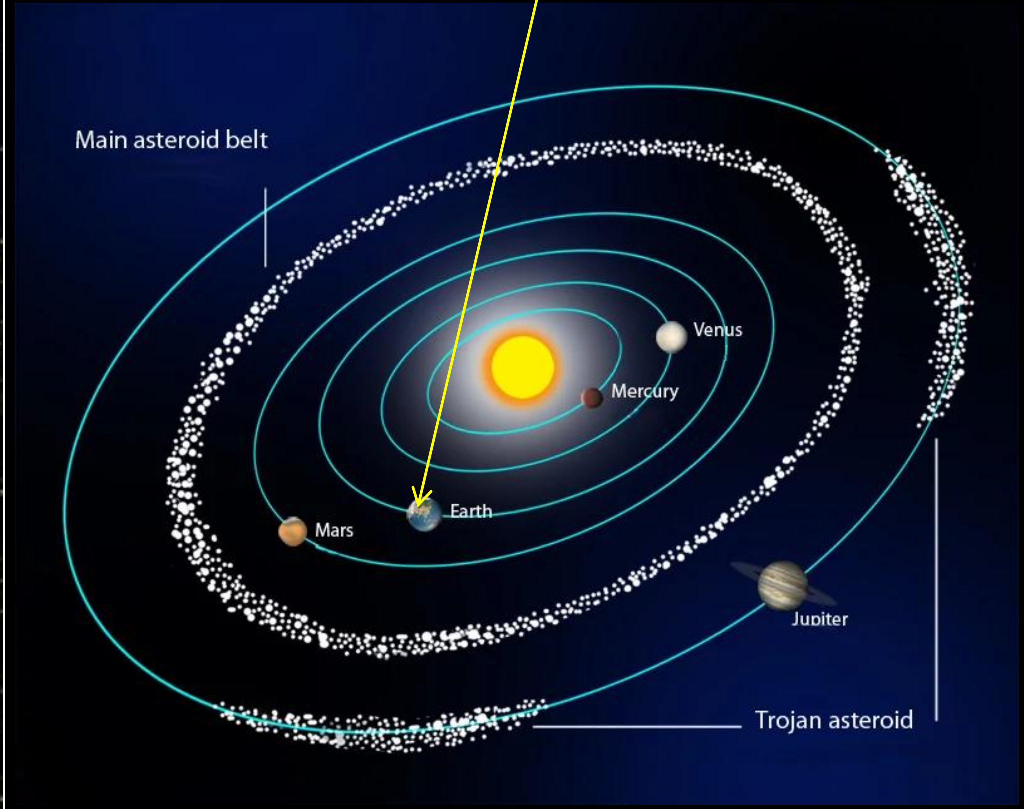


Explosive Nucleosynthesis in Core-collapse Type II Supernovae: Constraints from Presolar Grains

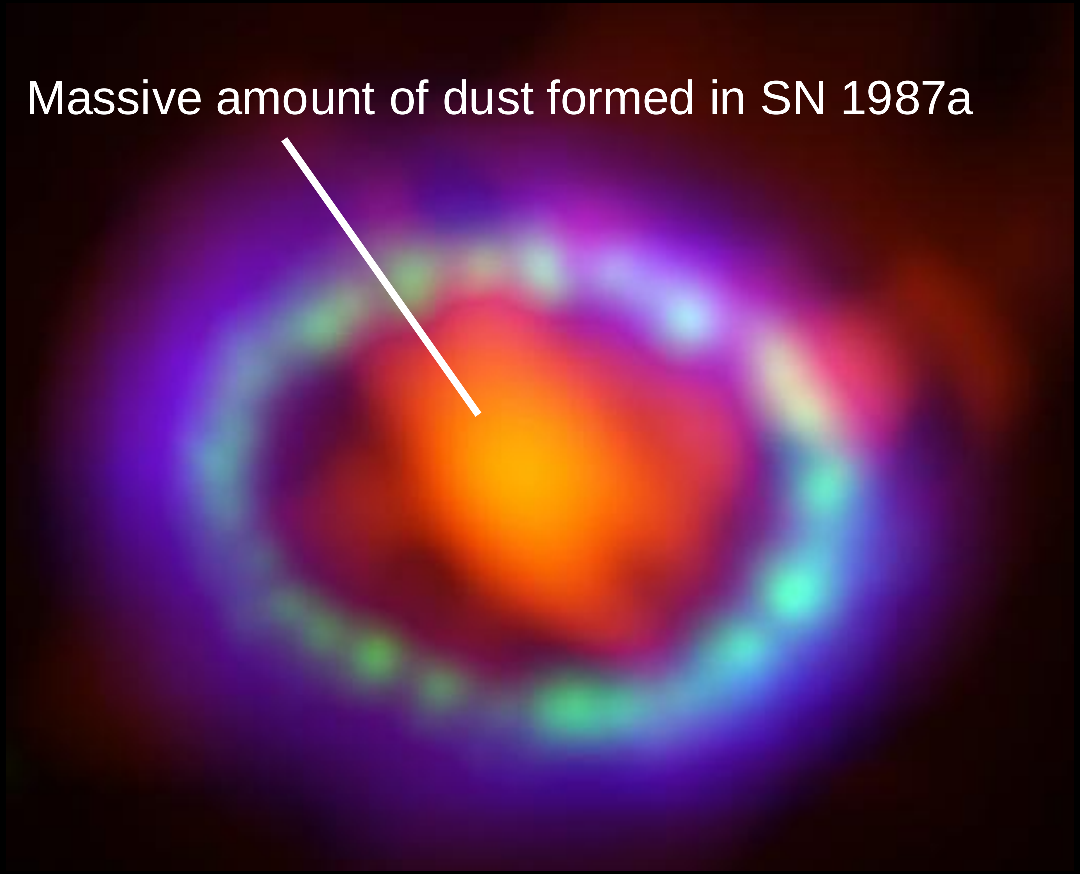
Nan Liu, Boston University
Conel Alexander, Carnegie Institution
Jianhua Wang, Carnegie Institution
Bradley Meyer, Clemson University
Larry Nittler, Arizona State University
Lucas Walls, Clemson University
Ananya Jain, Boston University

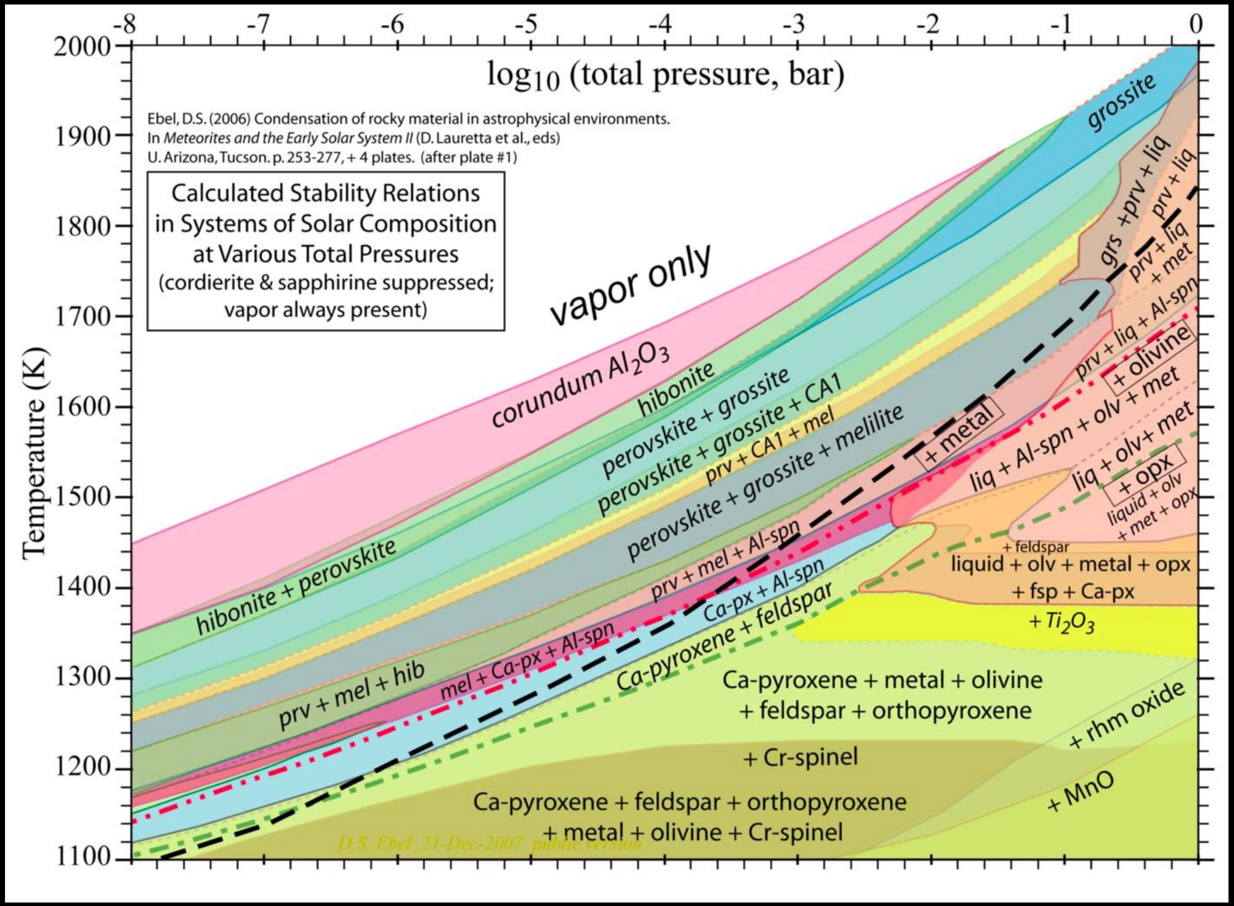


by Larry Nittler, not to scale



Dust Formation After Supernova Explosion

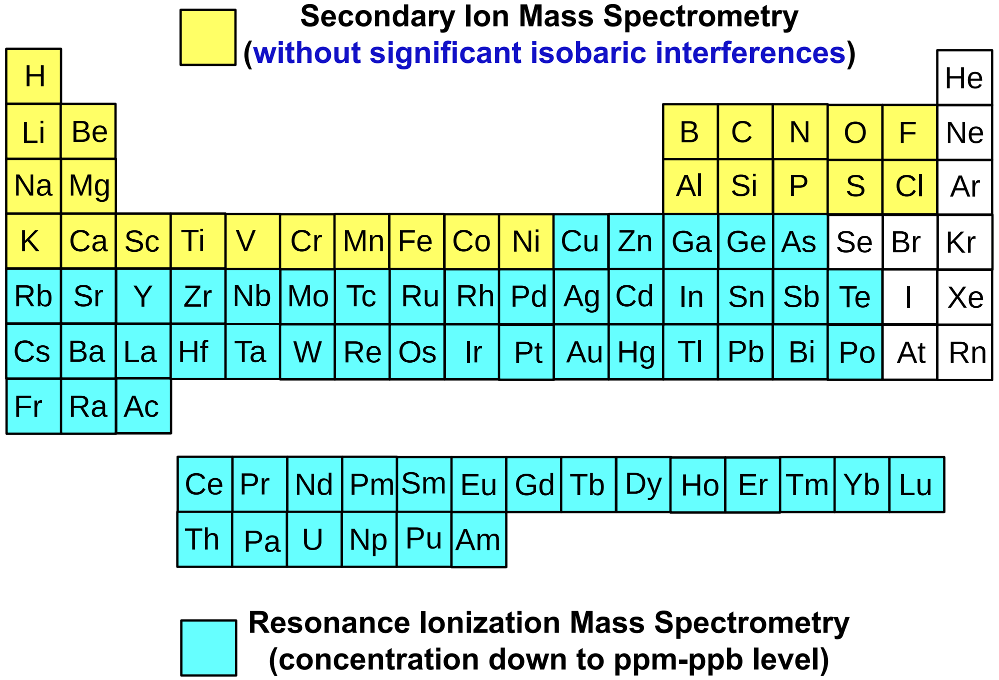


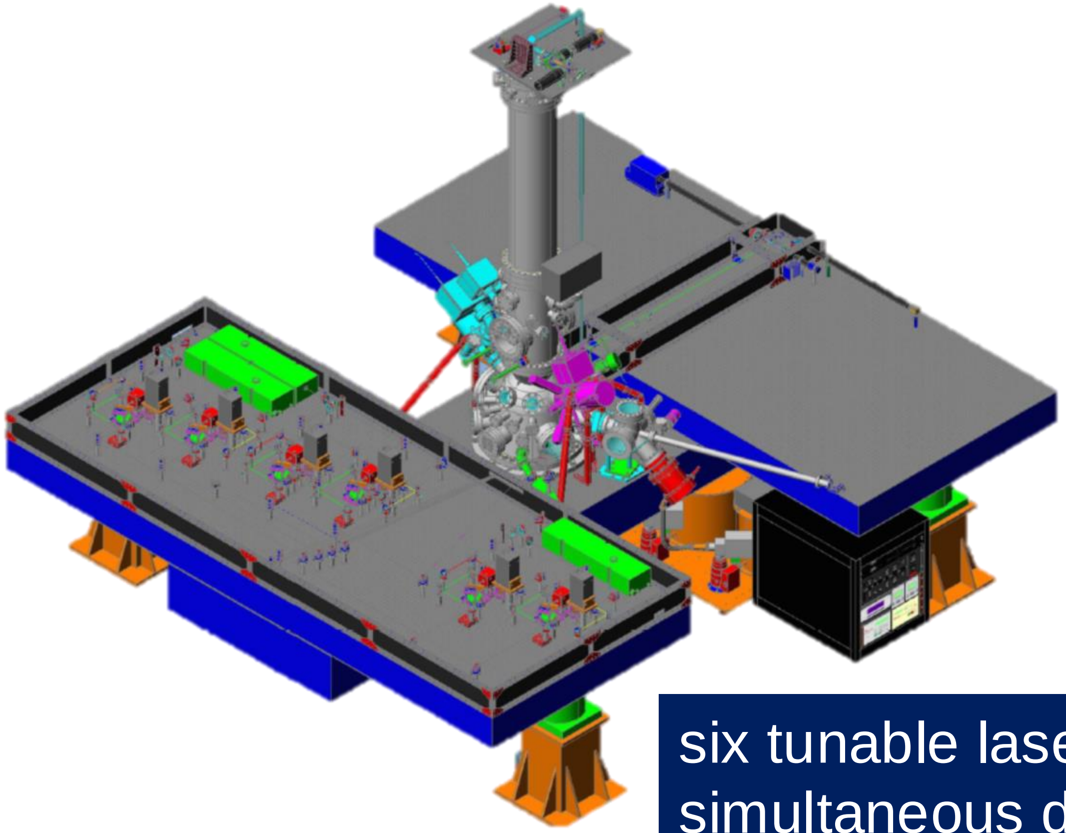


- The elemental composition of a grain is determined by both the gas composition and condensation condition (P/T)
- The isotopic composition of a gran is determined by that of the ejecta from which the grain condensed

Presolar Grain Analysis in Laboratory

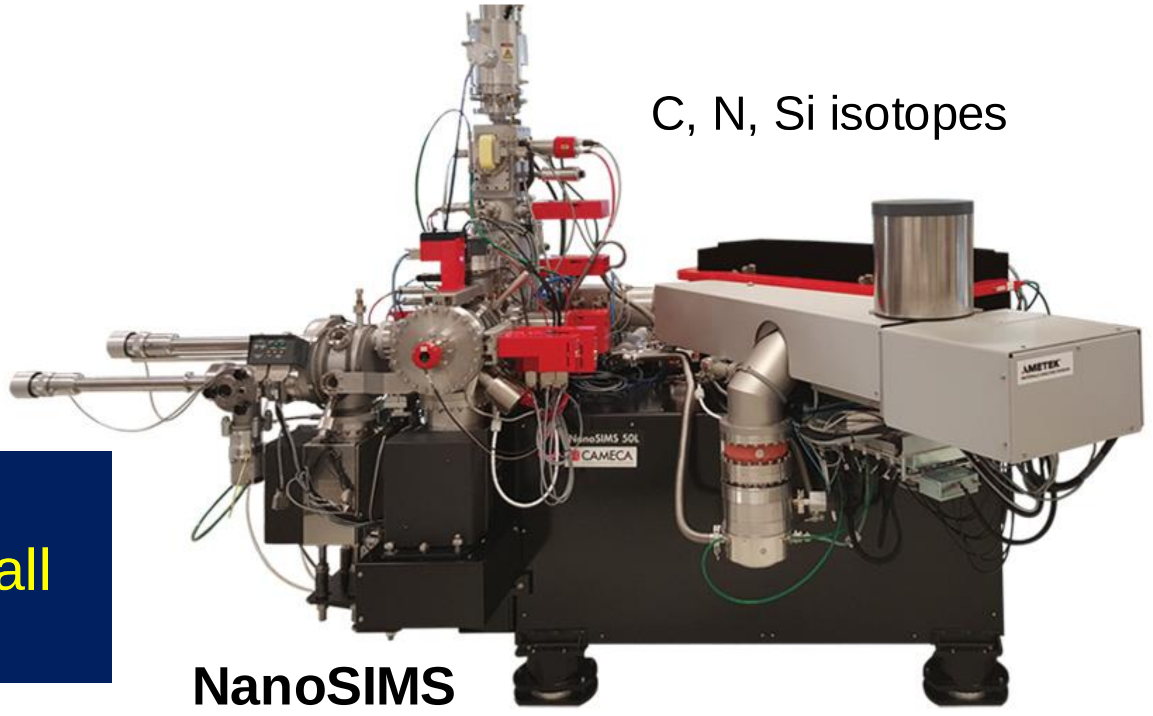
CHILI
(Chicago Instrument for Laser Ionization)



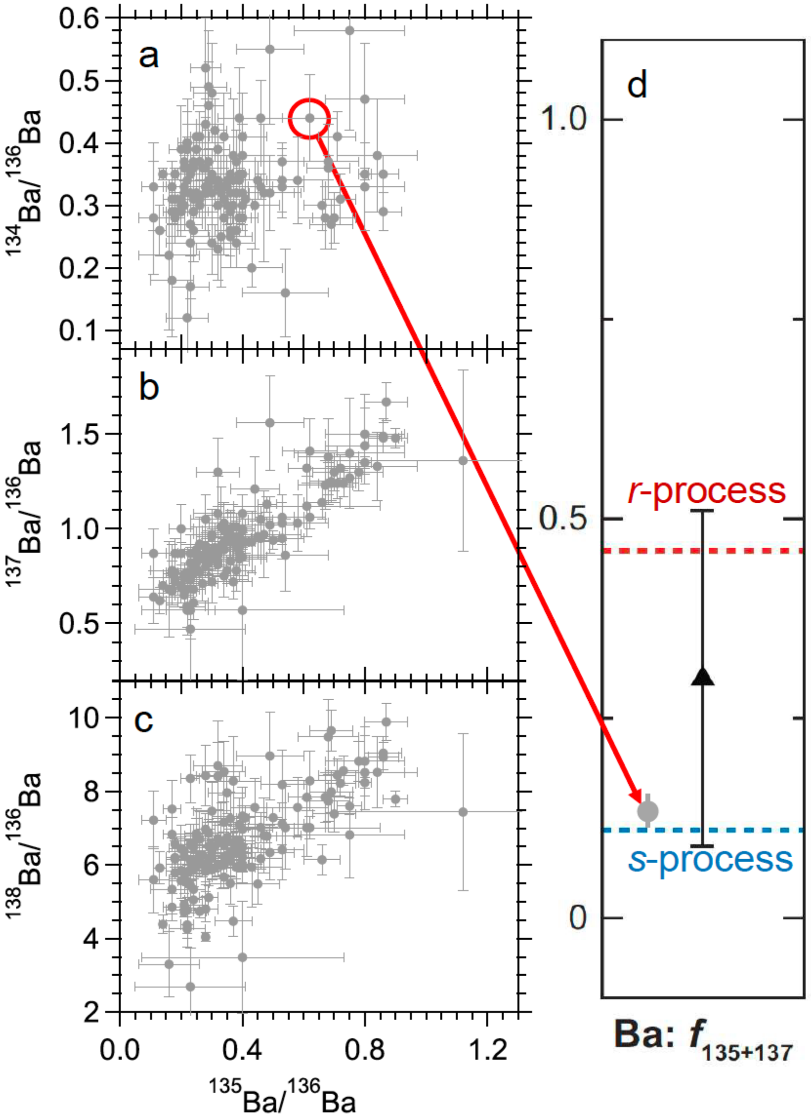


six tunable lasers allow simultaneous detection of all isotopes of three elements

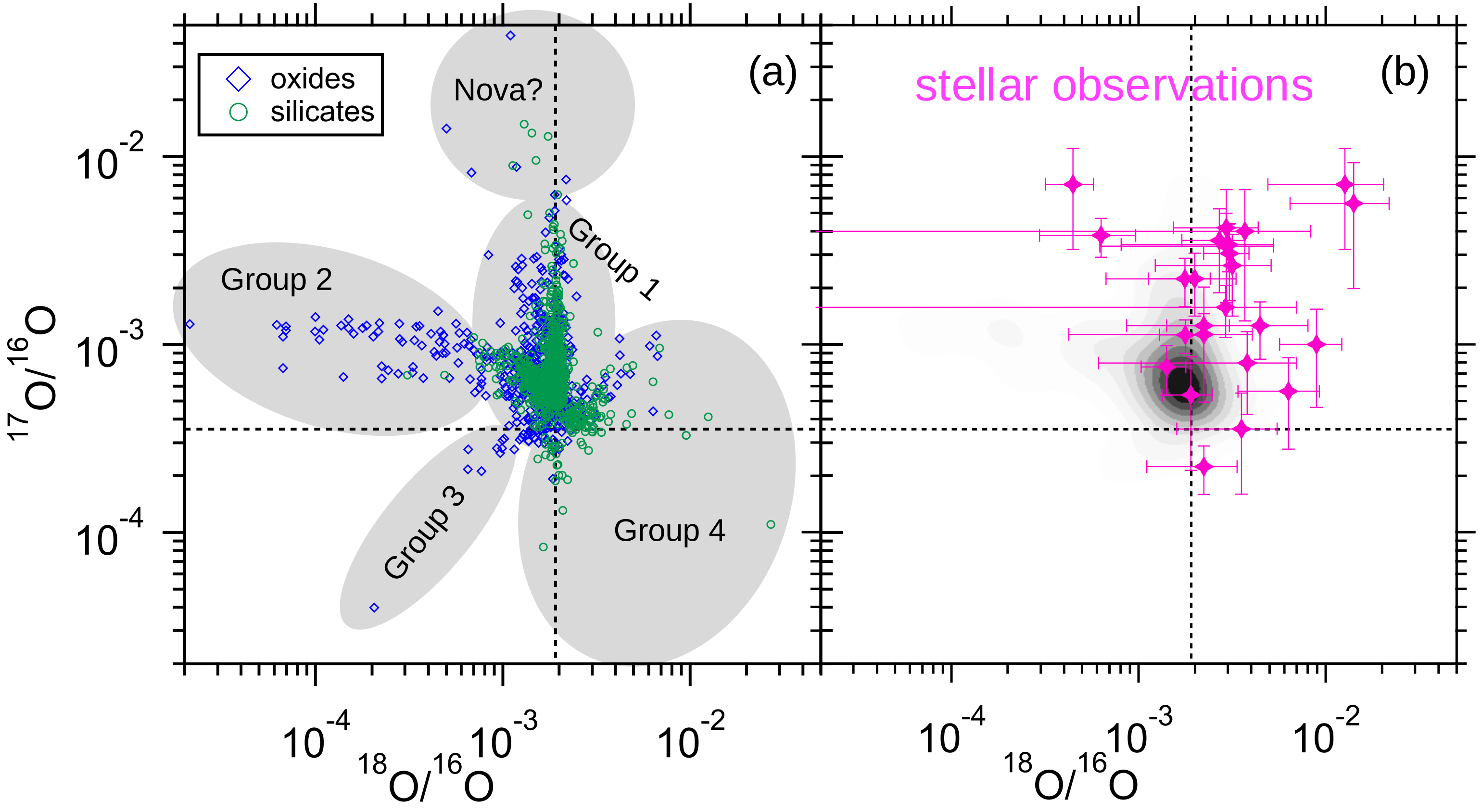
Stephan et al. (2016) *IJMS*



Microscope vs Telescope Isotope Analysis

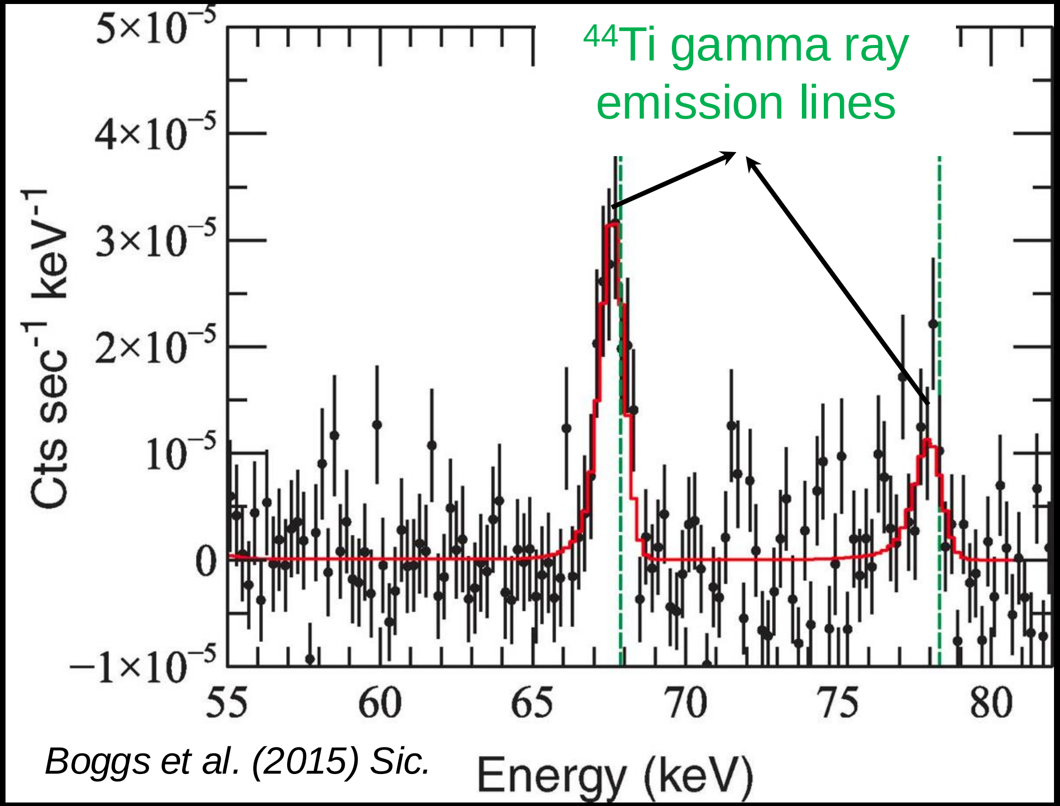


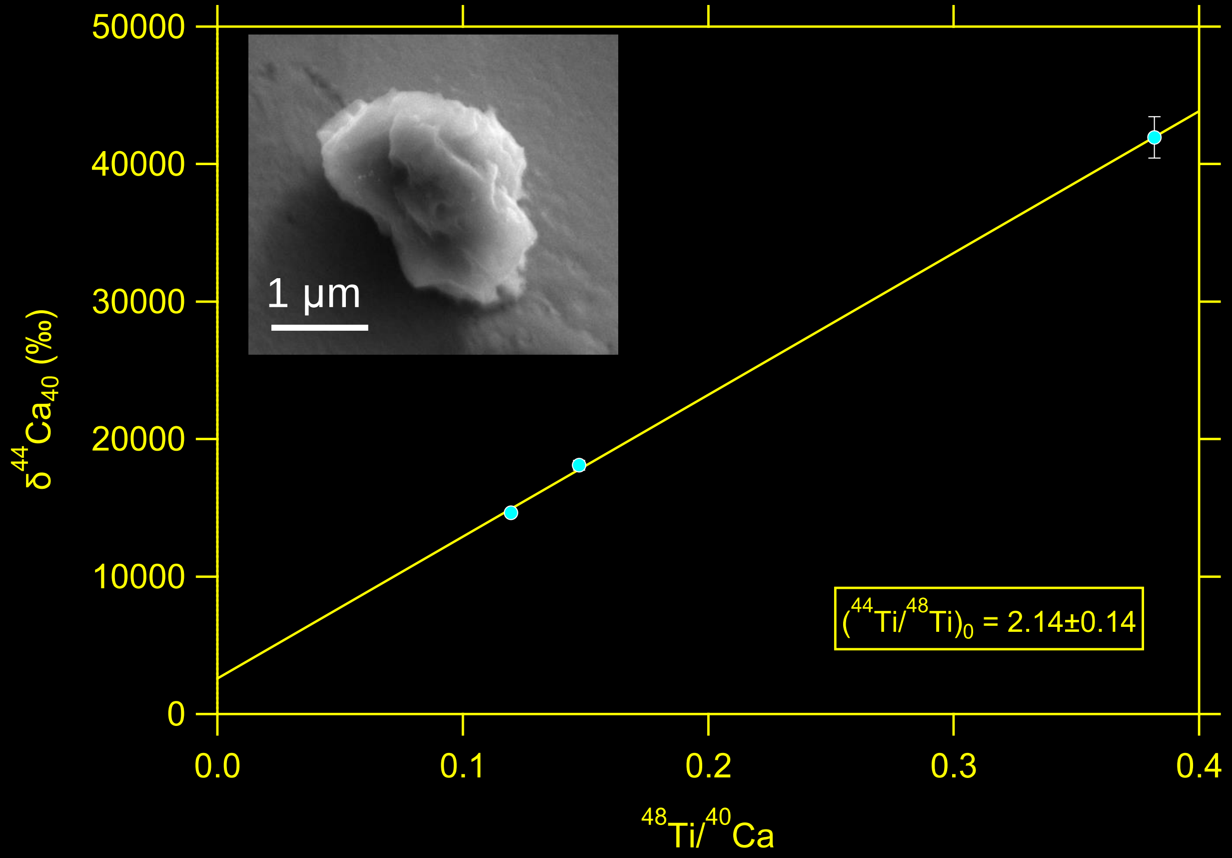
from Liu et al. (2022) Universe



Plots above based on data from presolar grain database (Hynes and Gyngard 2009) and stellar observations from Lebzelter et al. (2015) and Hinkle et al. (2016)

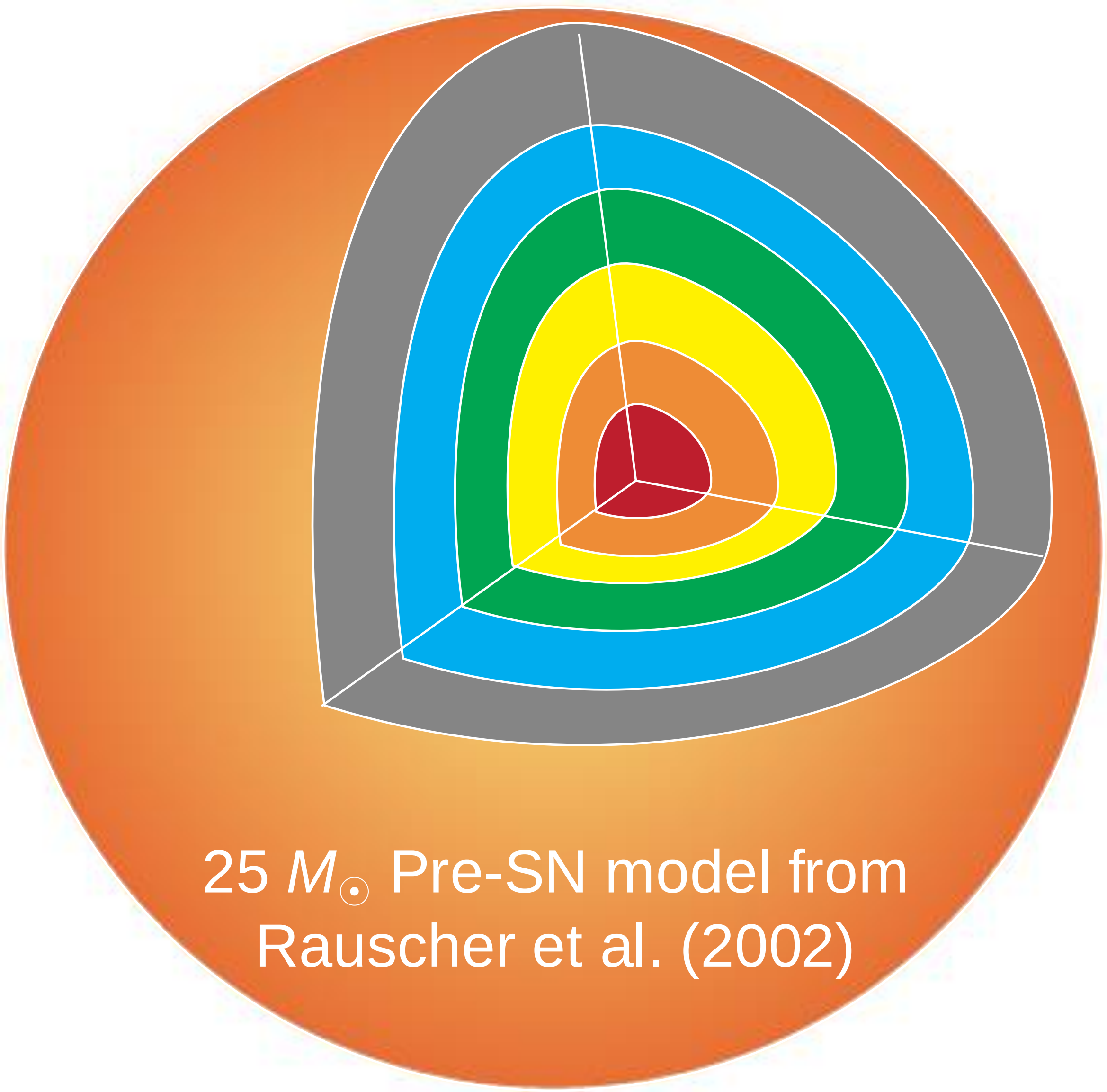
Titanium-44: Smoking Gun of Supernova Nucleosynthesis



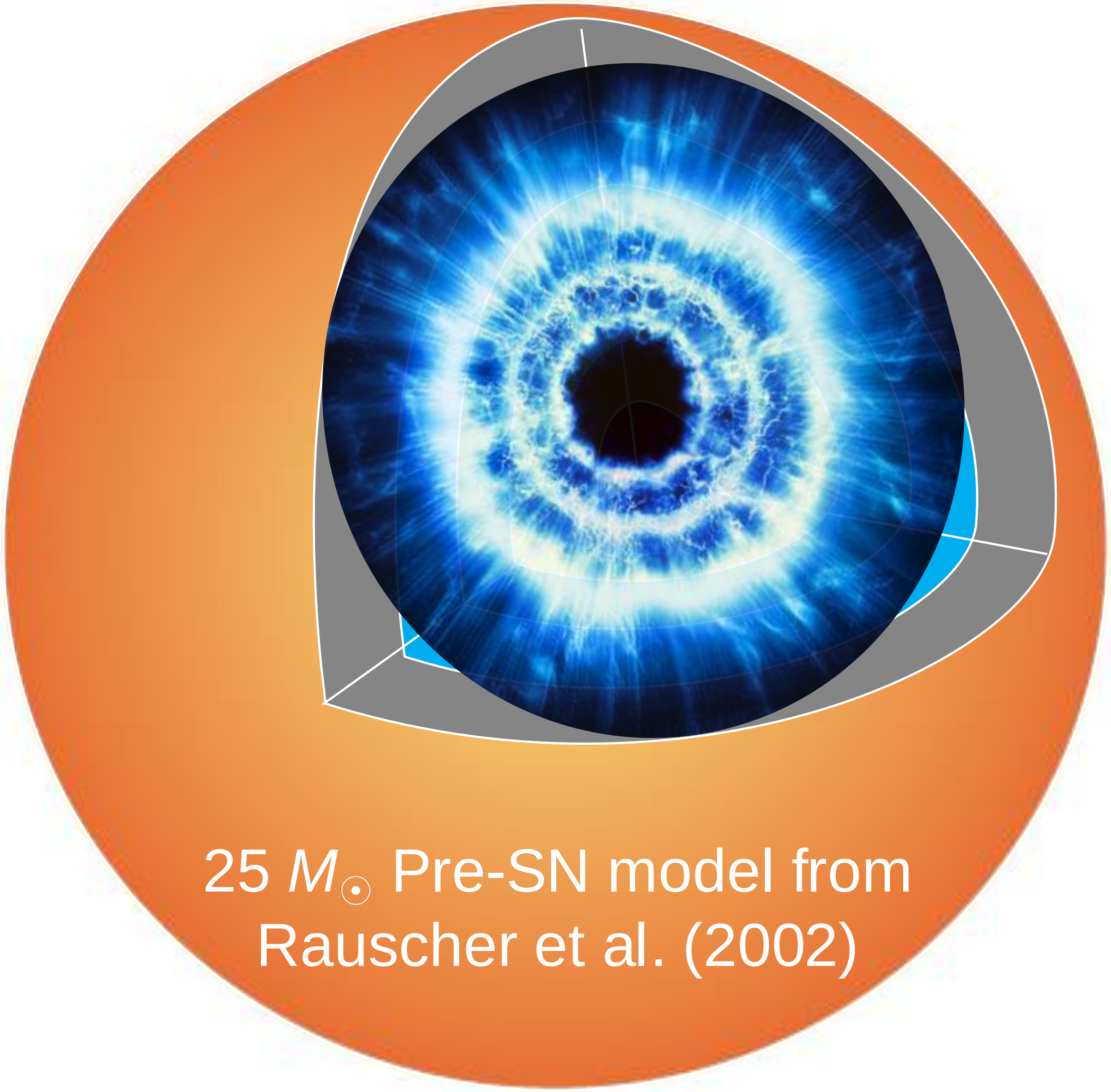


^{44}Ti ($t_{1/2}$ = 60 years): Inferred initial presence in many presolar grains (SiC, Si_3N_4, graphite), pointing to their Type II core-collapse supernova (CCSN) origin.

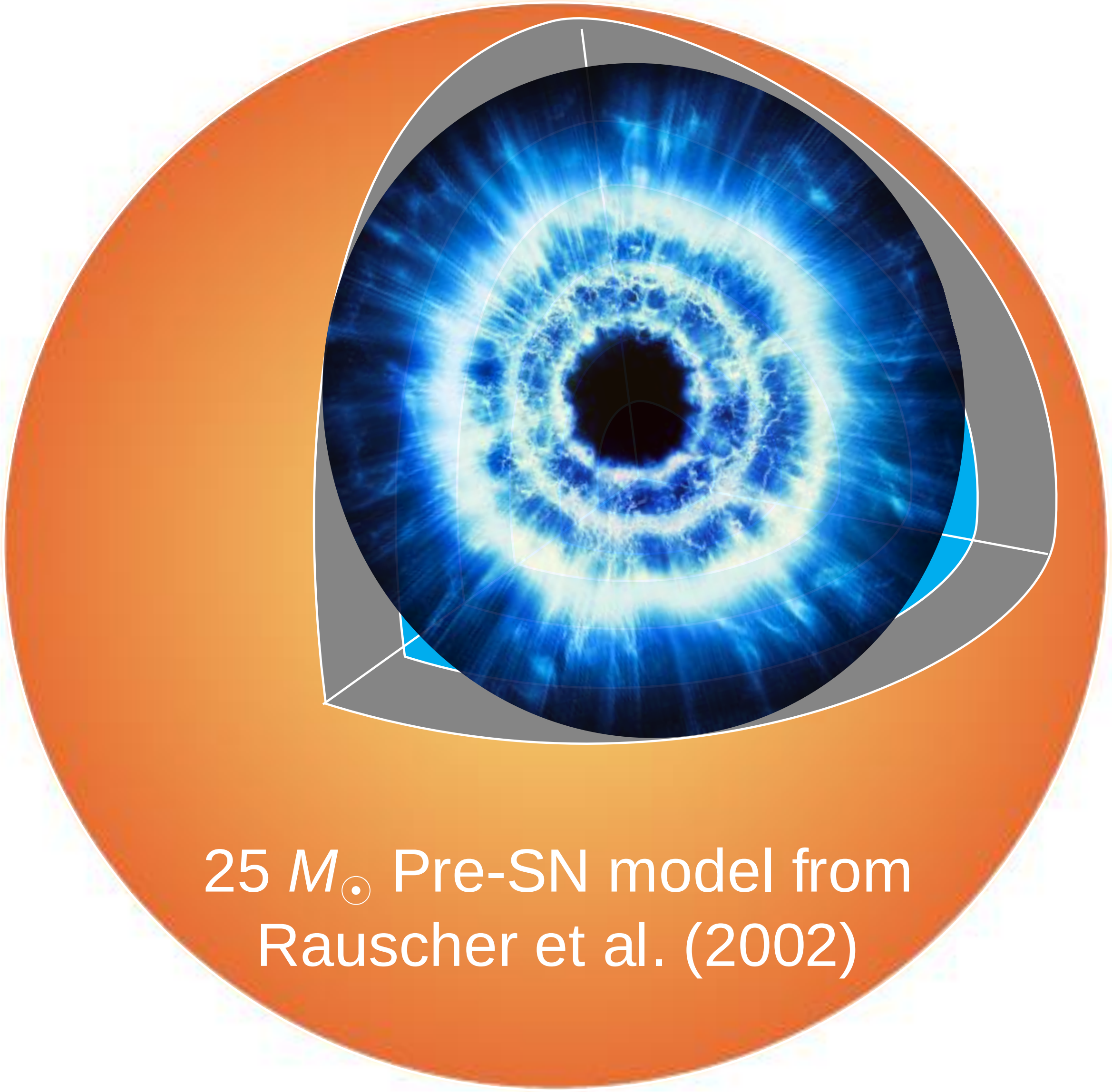
1D CCSN Nucleosynthesis Models

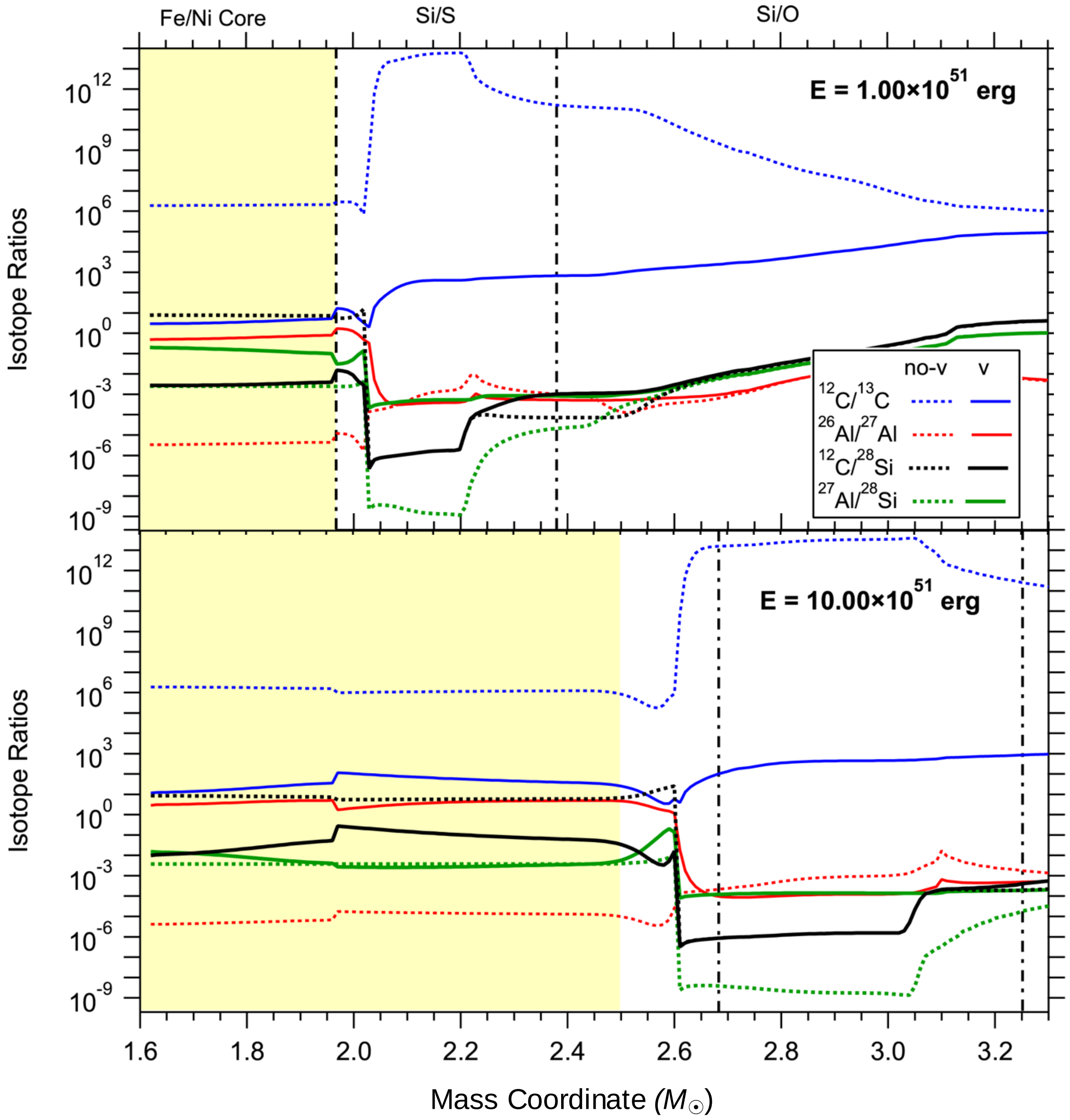


1D CCSN Nucleosynthesis Models

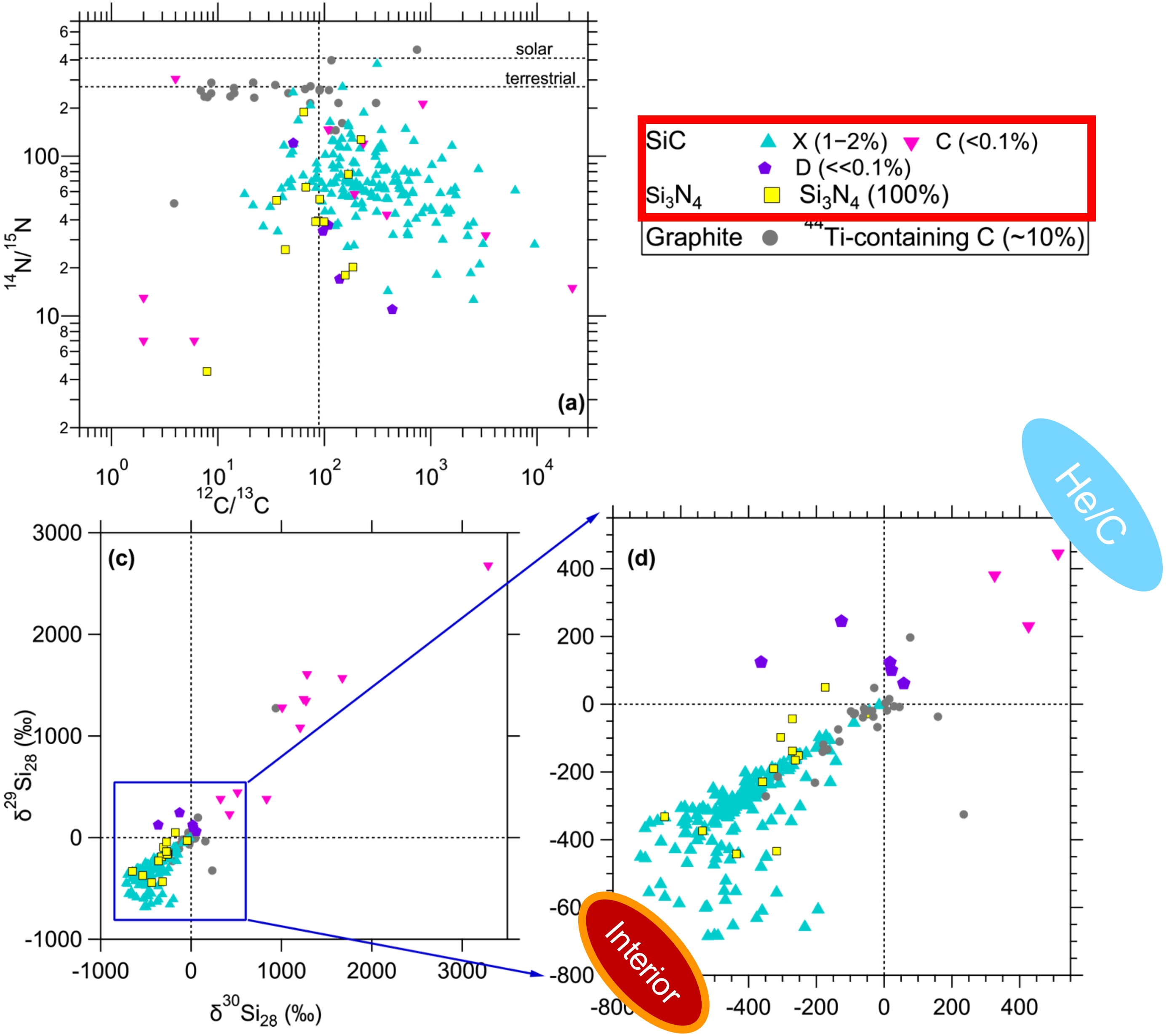


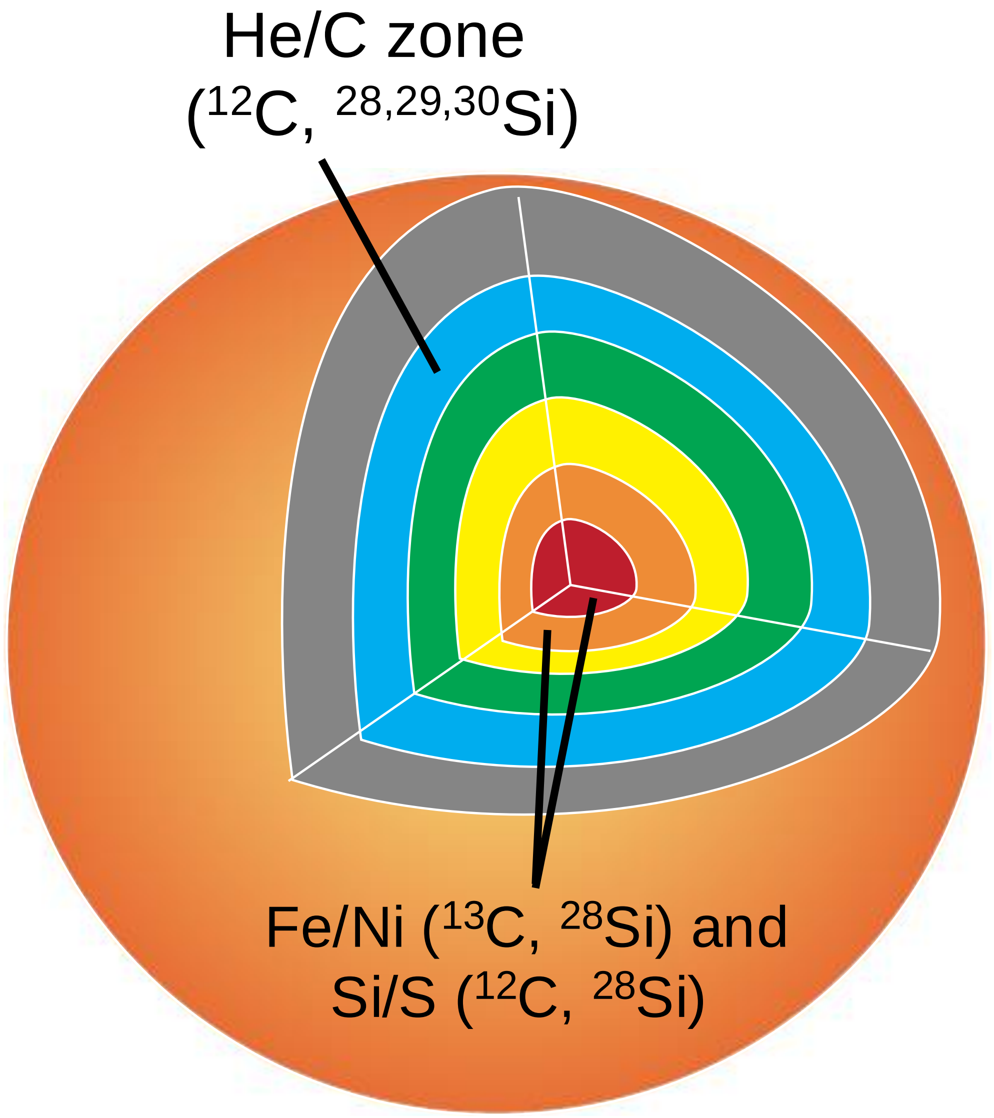
1D CCSN Nucleosynthesis Models



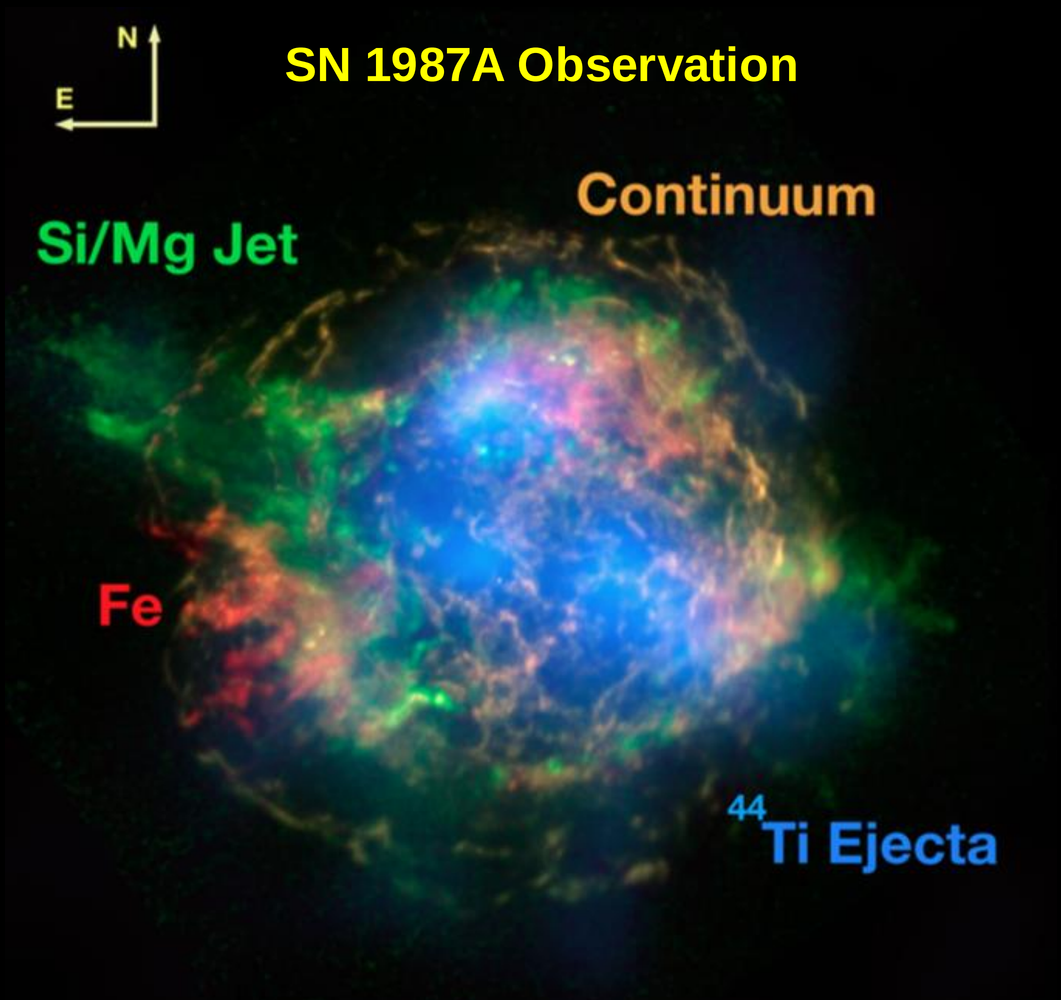


Diverse Isotopic Signatures of CCSN Grains



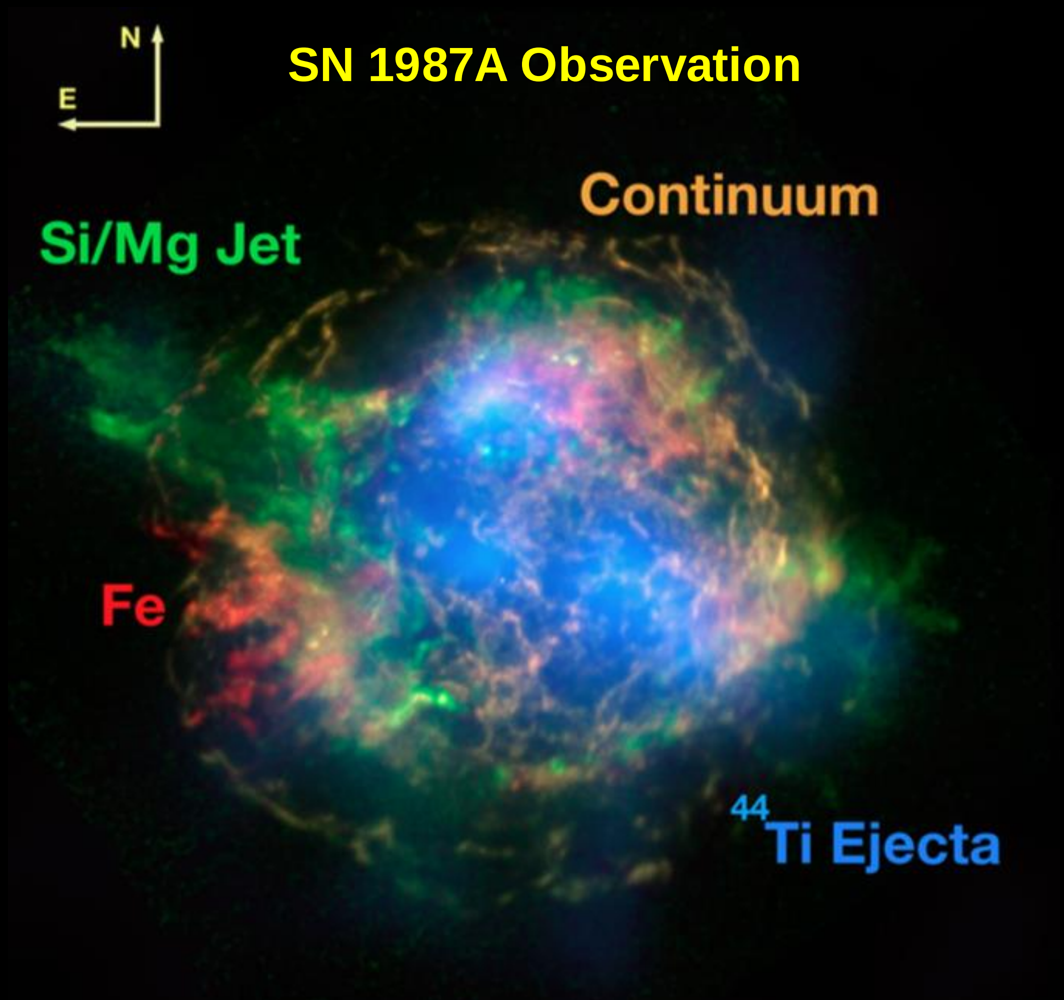


Supernova Explosion and Supernova Dust

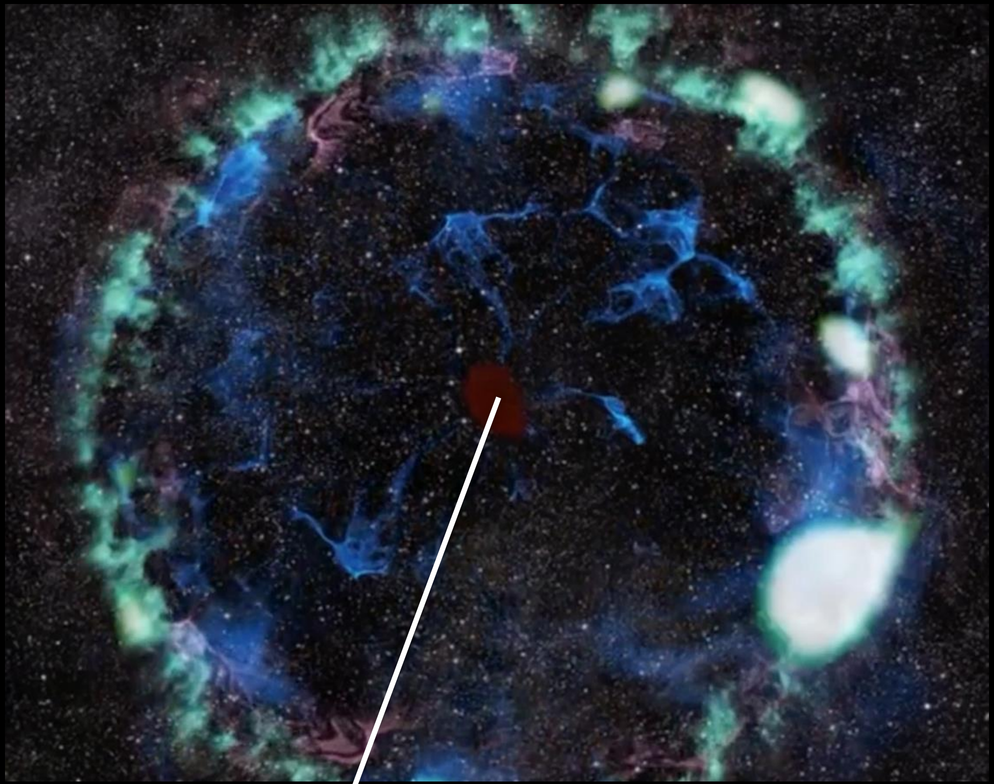


Grefenstette et al. (2016) *ApJ*

Supernova Explosion and Supernova Dust

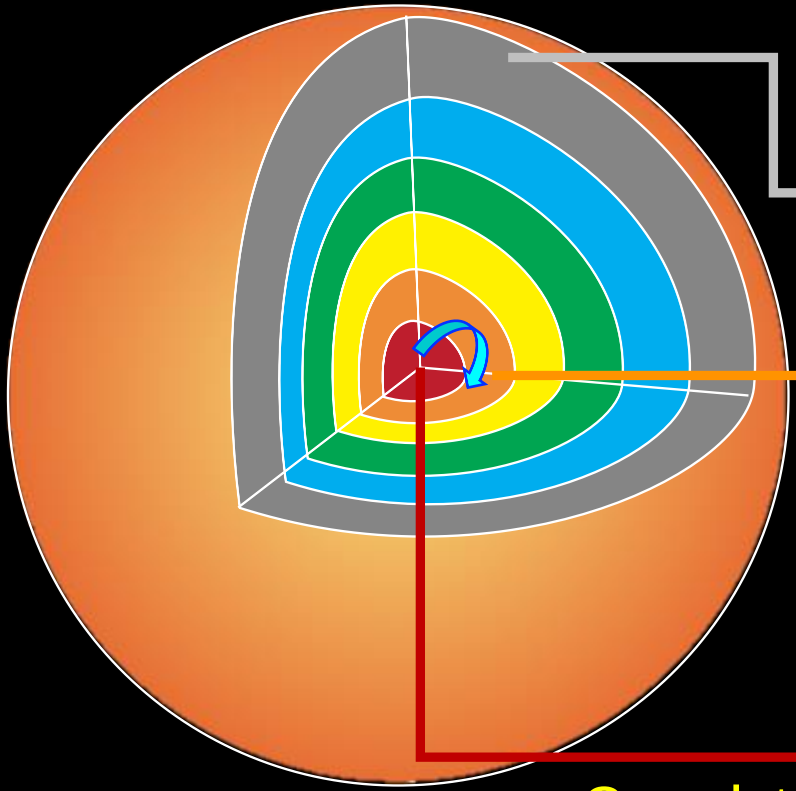


Grefenstette et al. (2016) *ApJ*



Depending predominantly on explosive supernova nucleosynthesis and mixing

CCSN SiC Grains — Products of Large-scale Mixing



He/C and He/N Material

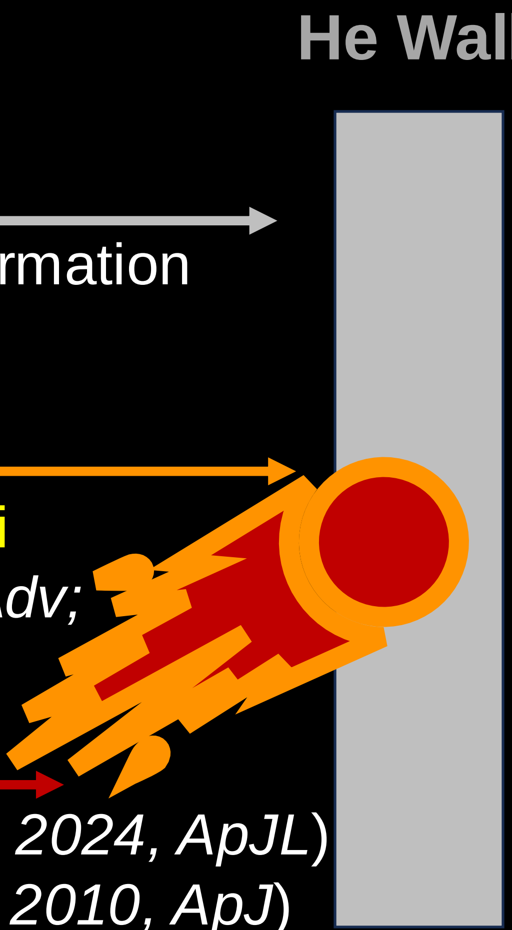
- C, N-rich condensation for dust formation
- Neutron-burst isotopic signatures

Inner Si/S Material

- Correlated radiogenic ^{49}Ti and ^{28}Si enrichments (*Liu et al. 2018, Sci Adv; Liu et al. 2023 LPSC*)

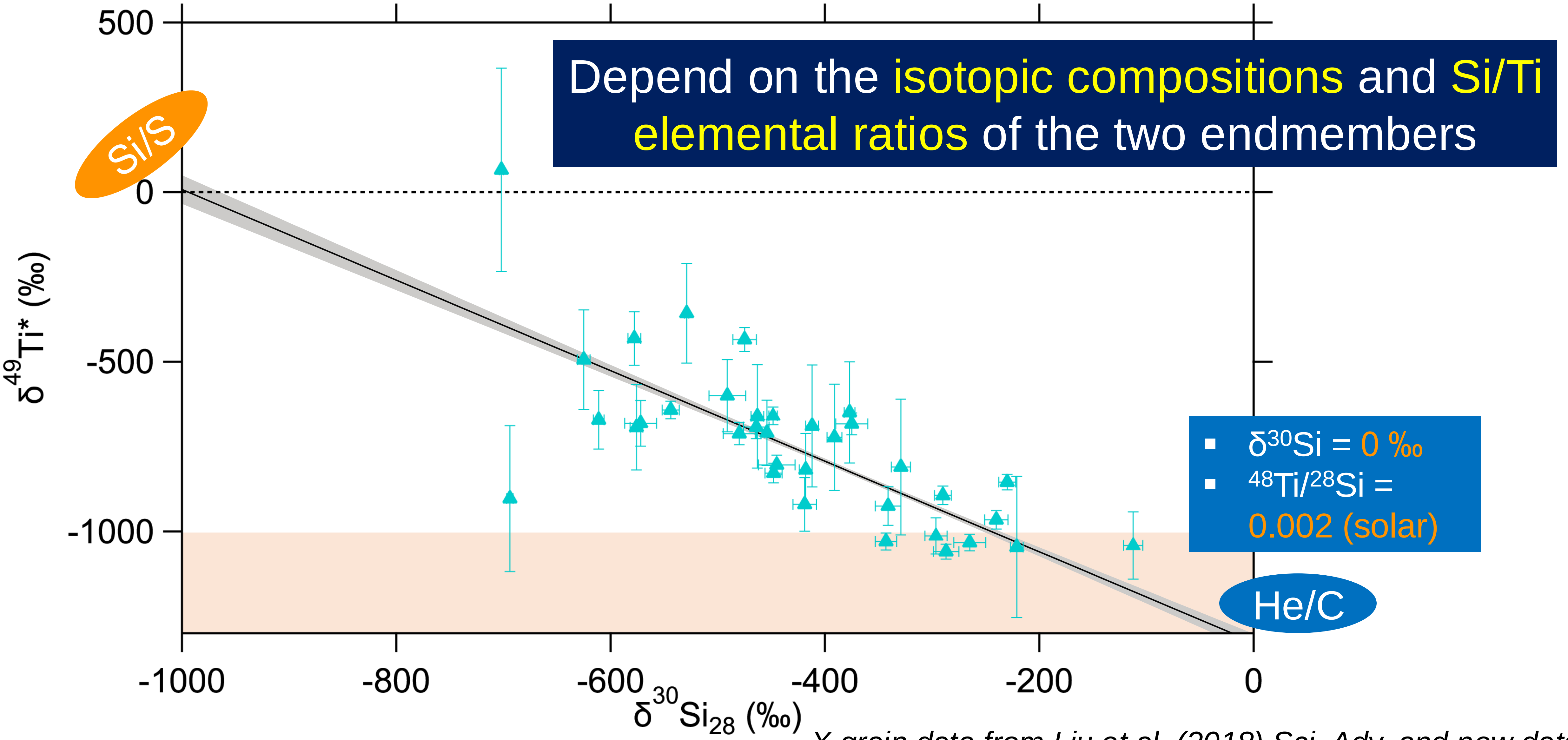
Fe/Ni Material

- Correlated ^{26}Al and ^{28}Si enrichments (*Liu et al. 2024, ApJL*)
- Correlated ^{44}Ti and ^{28}Si enrichments (*Lin et al. 2010, ApJ*)



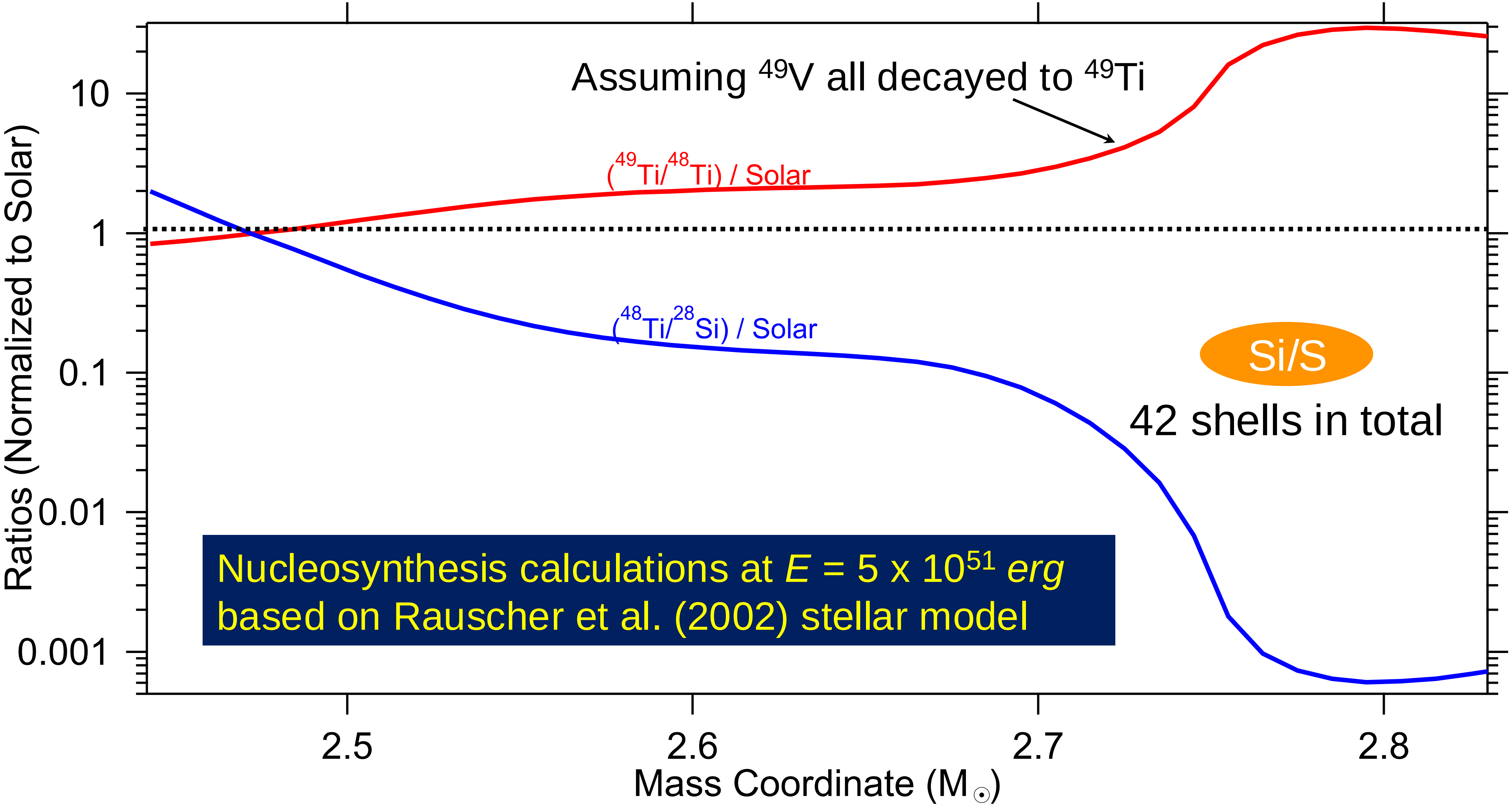
3D hydrodynamic simulations of supernova explosions predict pile up of core material in the He shell due to shock deacceleration (*e.g., Wongwathanarat et al. 2017*)

How Could X Grains Form Such A Tight Correlation?

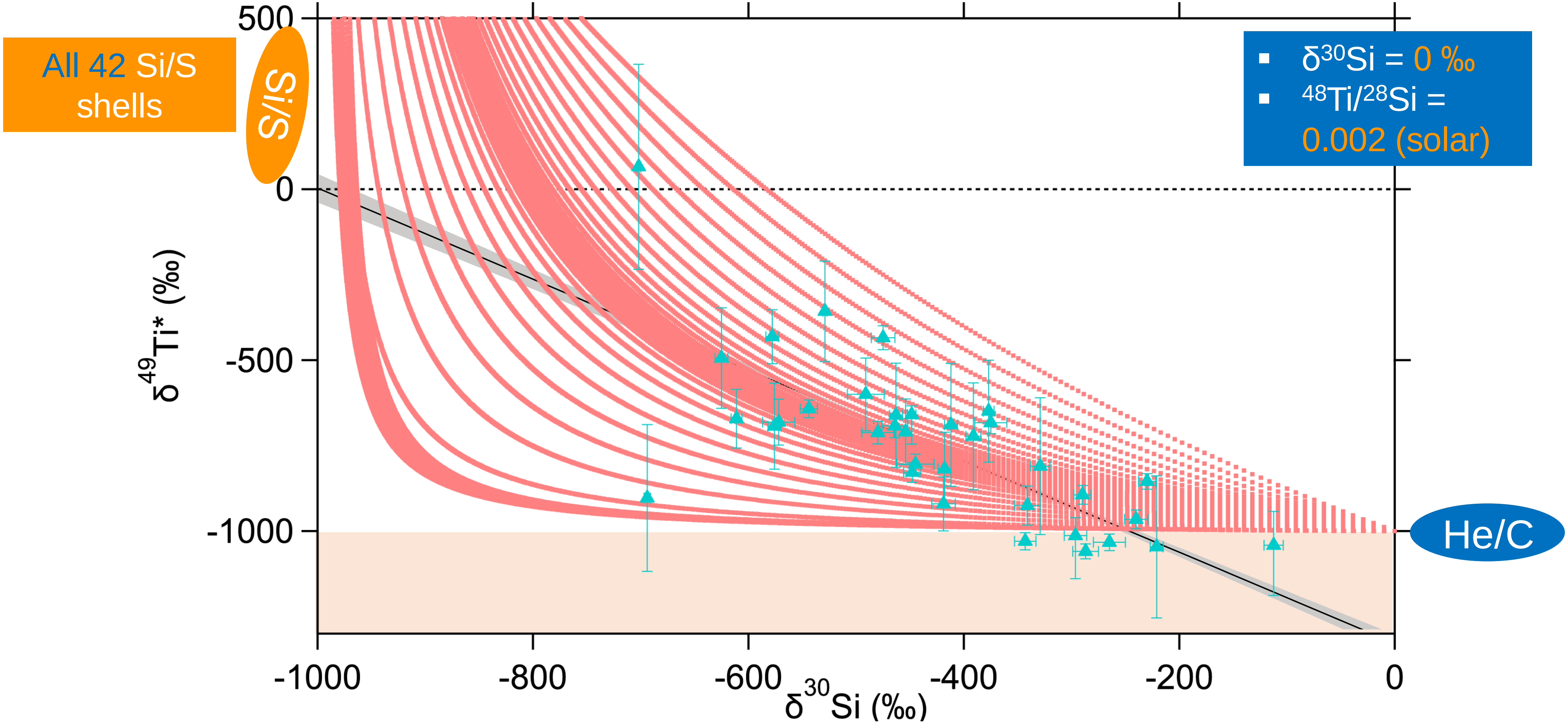


X grain data from Liu et al. (2018) Sci. Adv. and new data

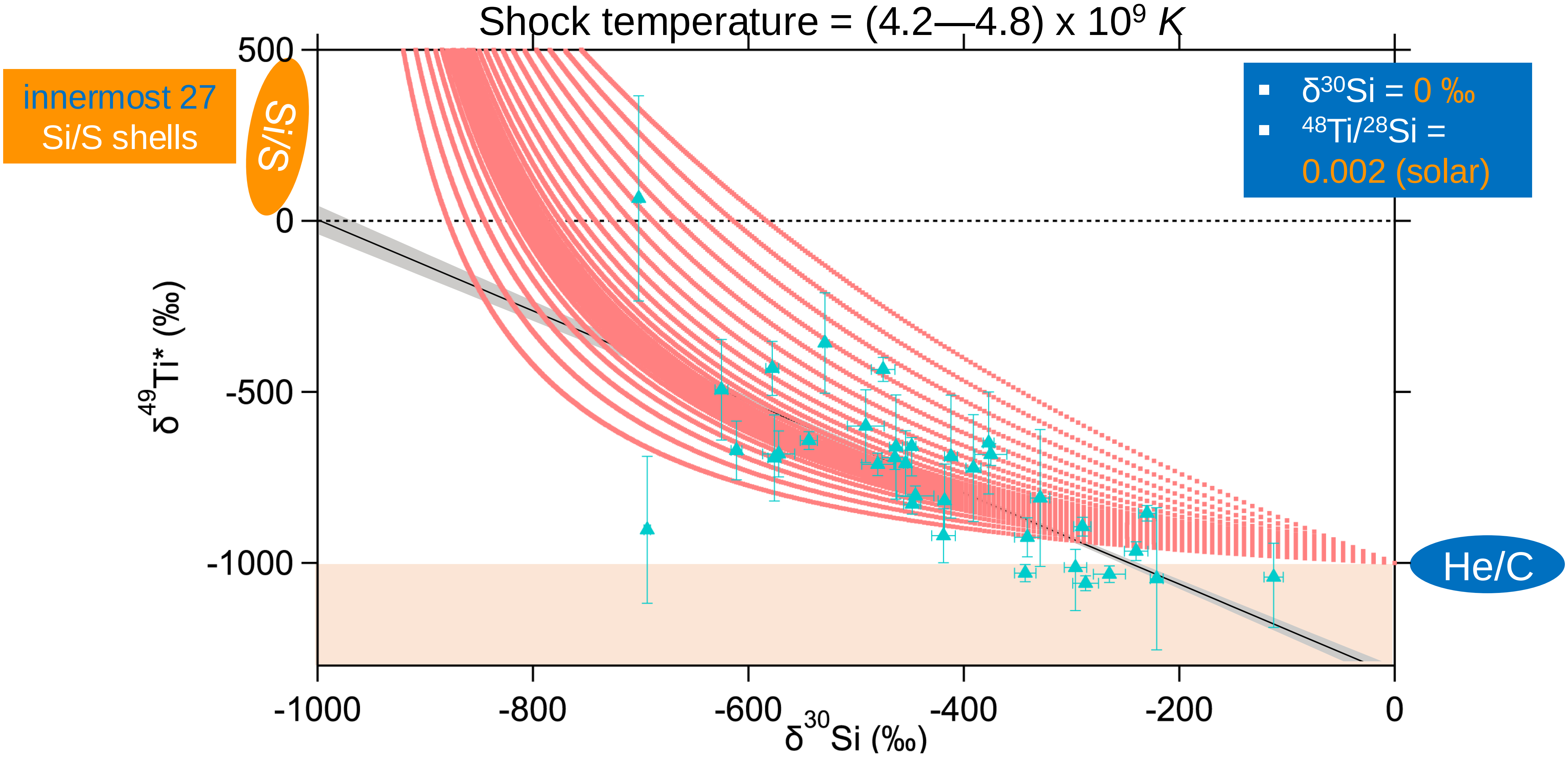
25 $M_\odot$ Model Calculations for Si/S Zone



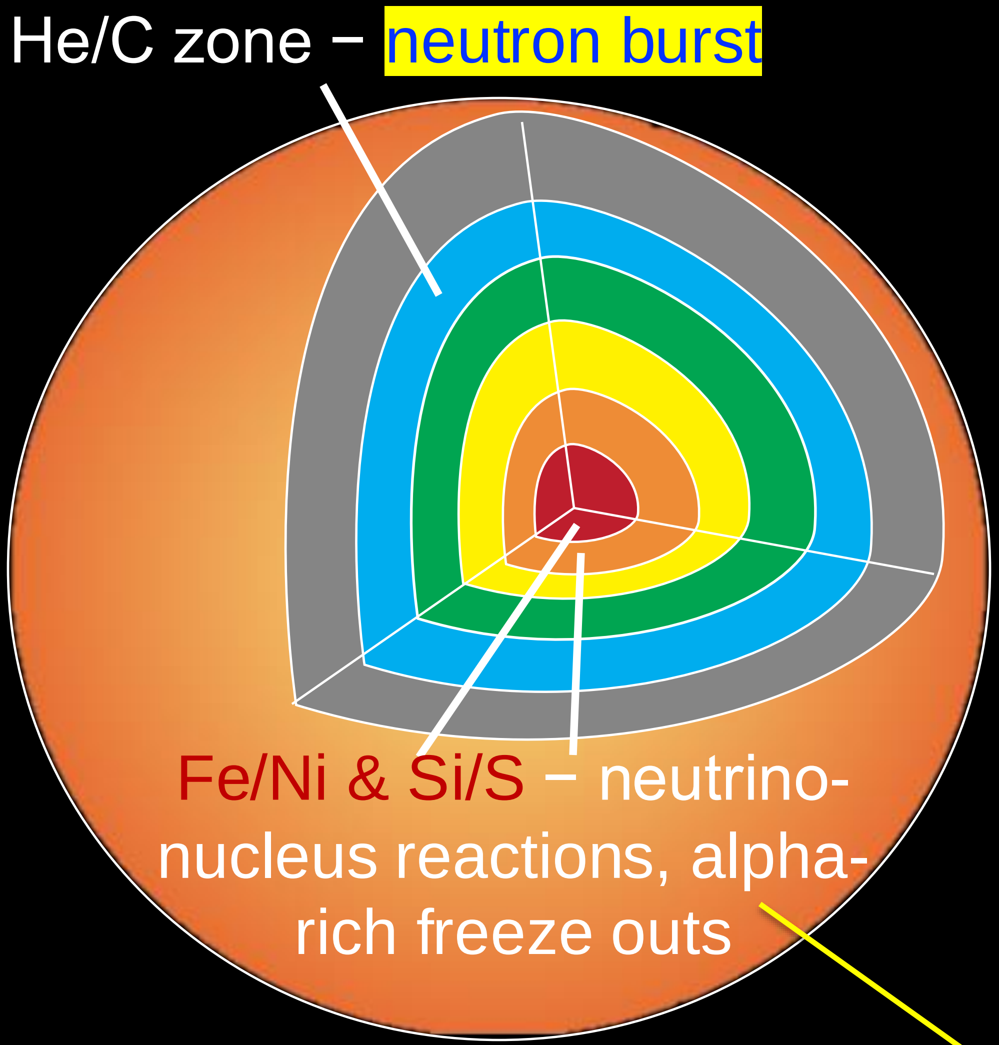
Mixing Si/S with Outer C-rich Materials



Inner Si/S Shells Best Explain Grain Data



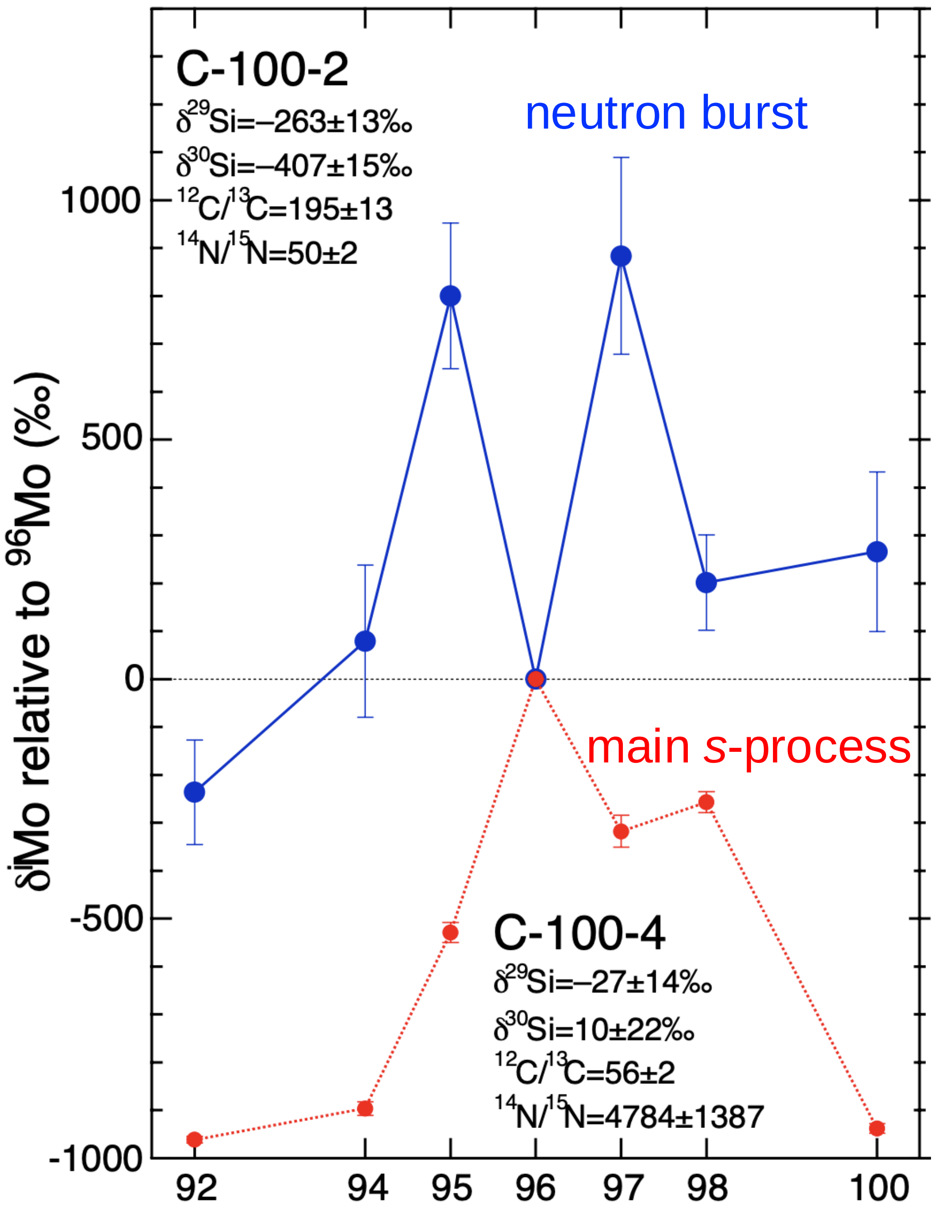
Quick Summary



Presolar X SiC and Si_3N_4 grains sampled materials from Fe/Ni, Si/S, and He/C zones (and shells above)

Discussed in Liu et al. (2024) ApJL

Heavy-element Isotopic Compositions of X Grains

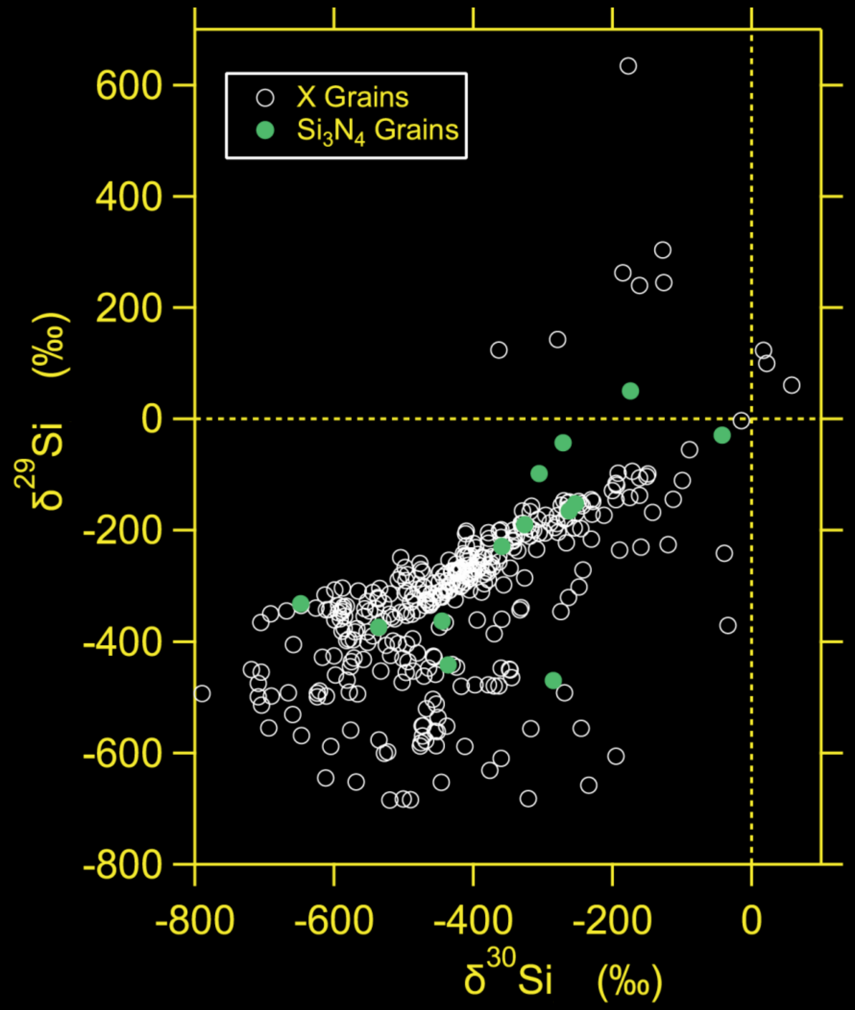


Pellin et al. (1999)

Neutron Bursts

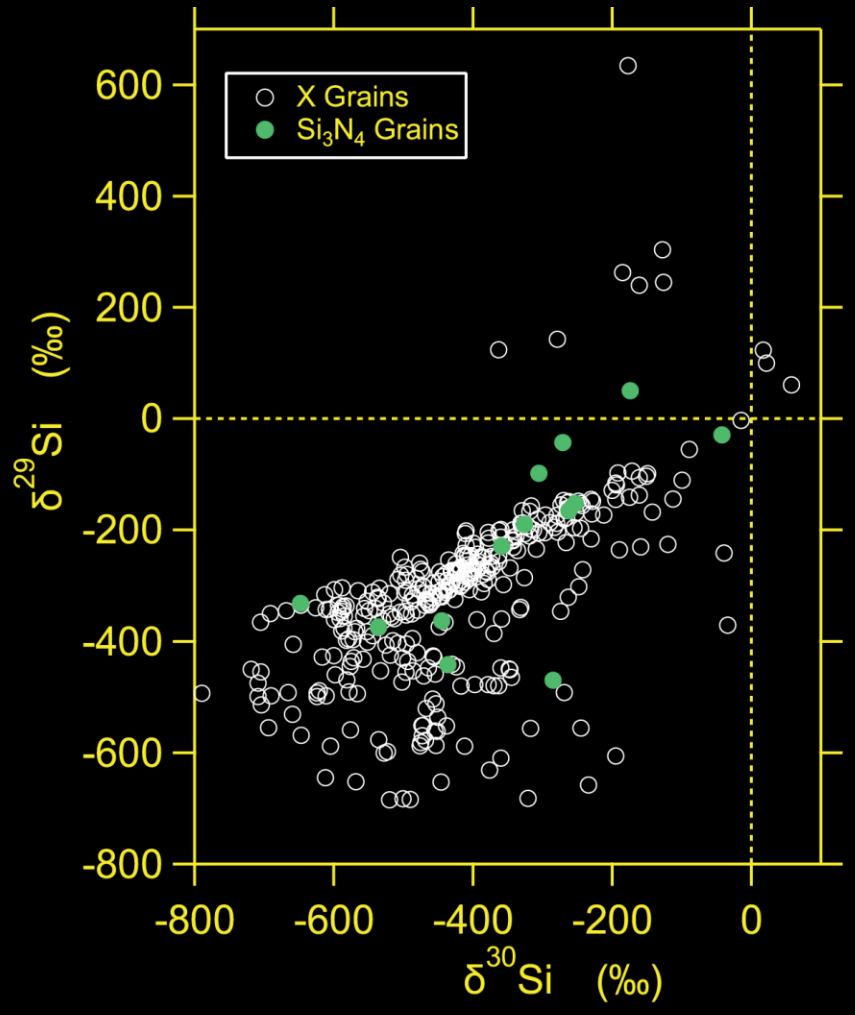
- Powered by $^{22}Ne(\alpha,n)^{25}Mg$
- Neutron density of 10^{17} n/cm^3 at T ~ 10^9 K (Meyer et al. 2000)
- Could occur in He/C zone during explosion (e.g., Liu et al. 2018)

S_3N_4 and X SiC – Isotopic Twins



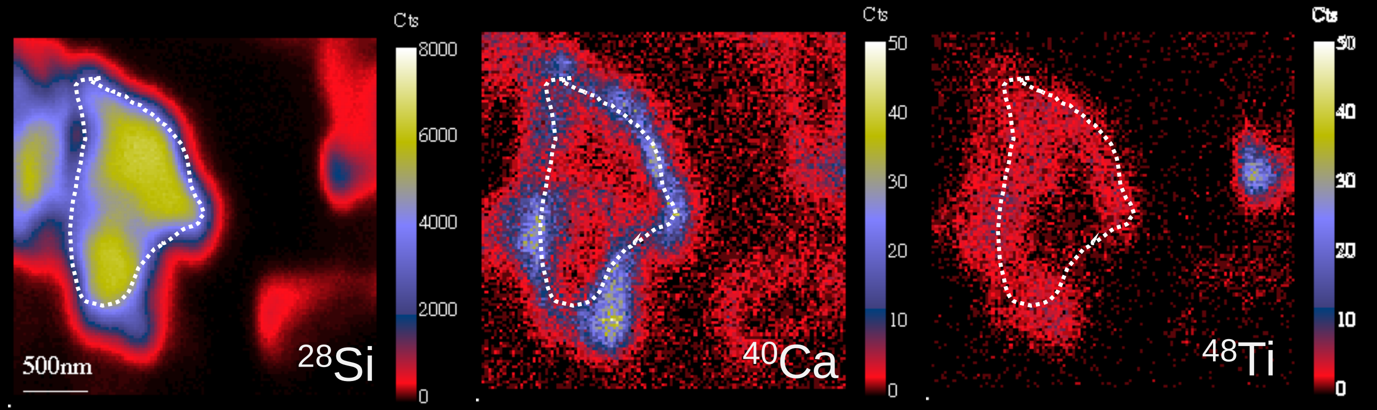
Presolar Grain Database (Stephan et al. 2014, ApJS), Nittler et al. 1995, Lin et al. 2010, and this study

S_3N_4 and X SiC – Isotopic Twins

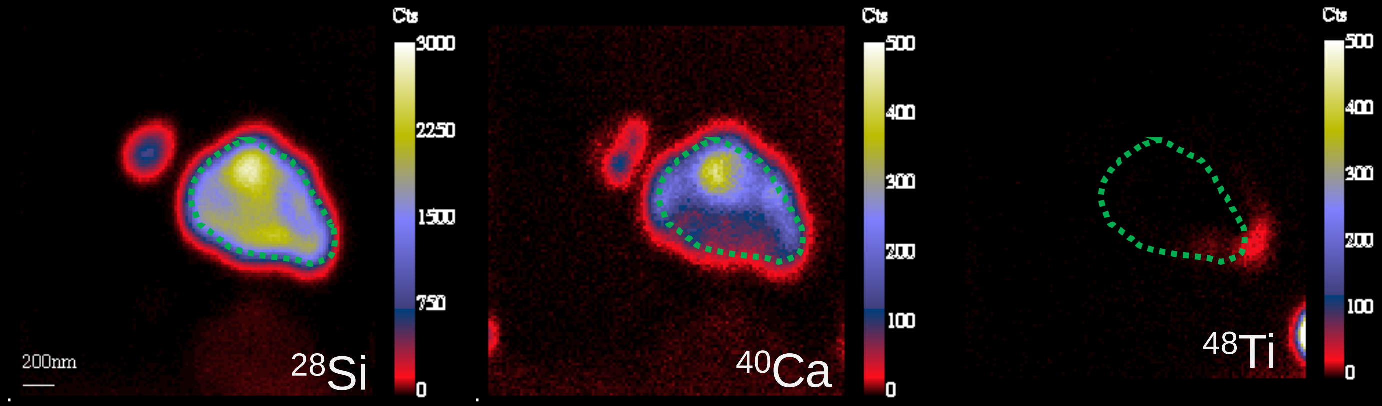


Presolar Grain Database (Stephan et al. 2014, ApJS), Nittler et al. 1995, Lin et al. 2010, and this study

Type X SiC – Intrinsic Ti with extrinsic Ca



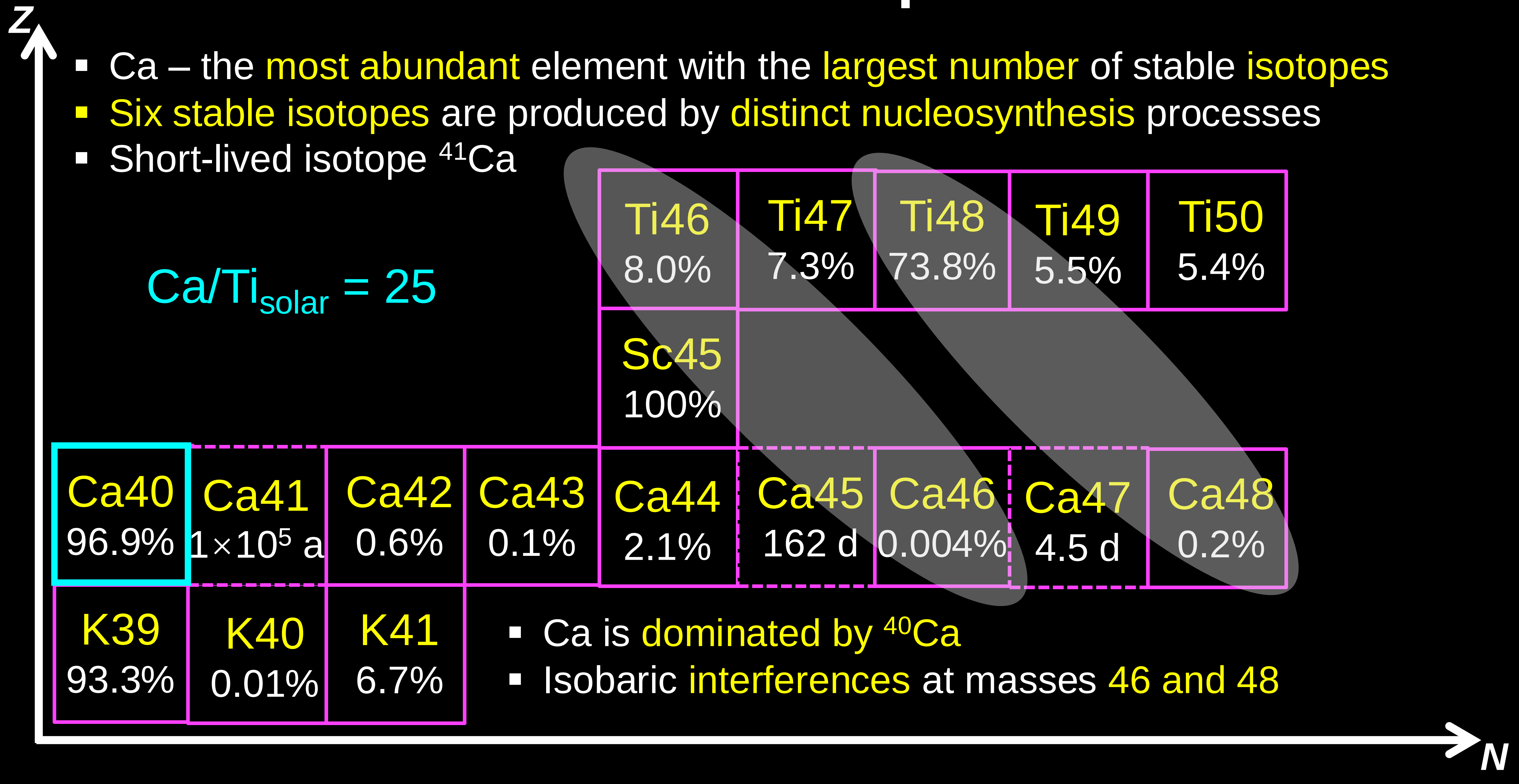
Si_3N_4 – Intrinsic Ca with little Ti



Si_3N_4 and X grain data can be combined to reliably reduce $^{46}Ca/^{40}Ca$ and $^{48}Ca/^{40}Ca$ ratios

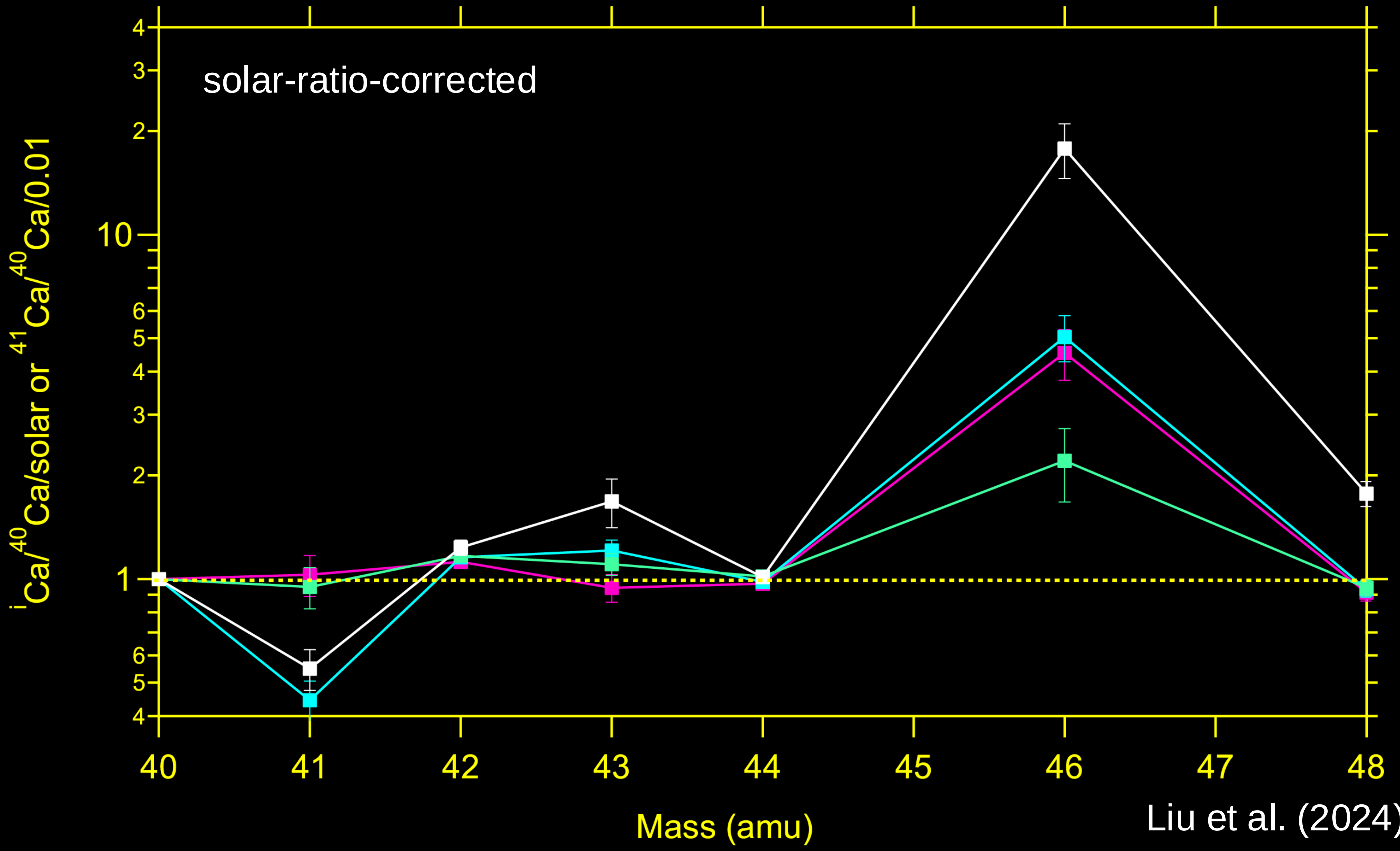
Calcium Isotopes

- Ca – the most abundant element with the largest number of stable isotopes
- Six stable isotopes are produced by distinct nucleosynthesis processes
- Short-lived isotope ^{41}Ca



- Ca is dominated by ^{40}Ca
- Isobaric interferences at masses 46 and 48

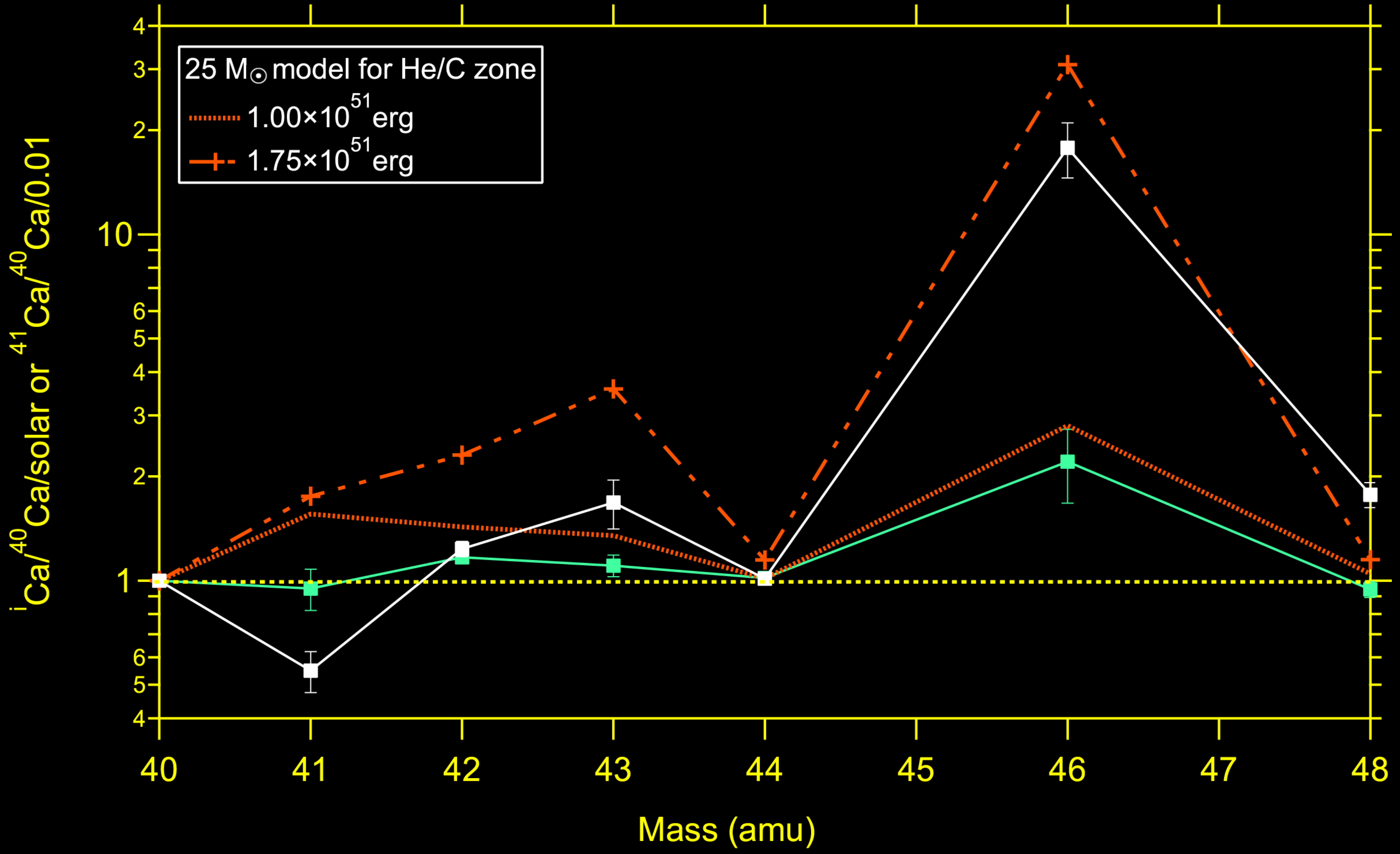
Si_3N_4 Calcium Isotopic Patterns



Liu et al. (2024) in prep.

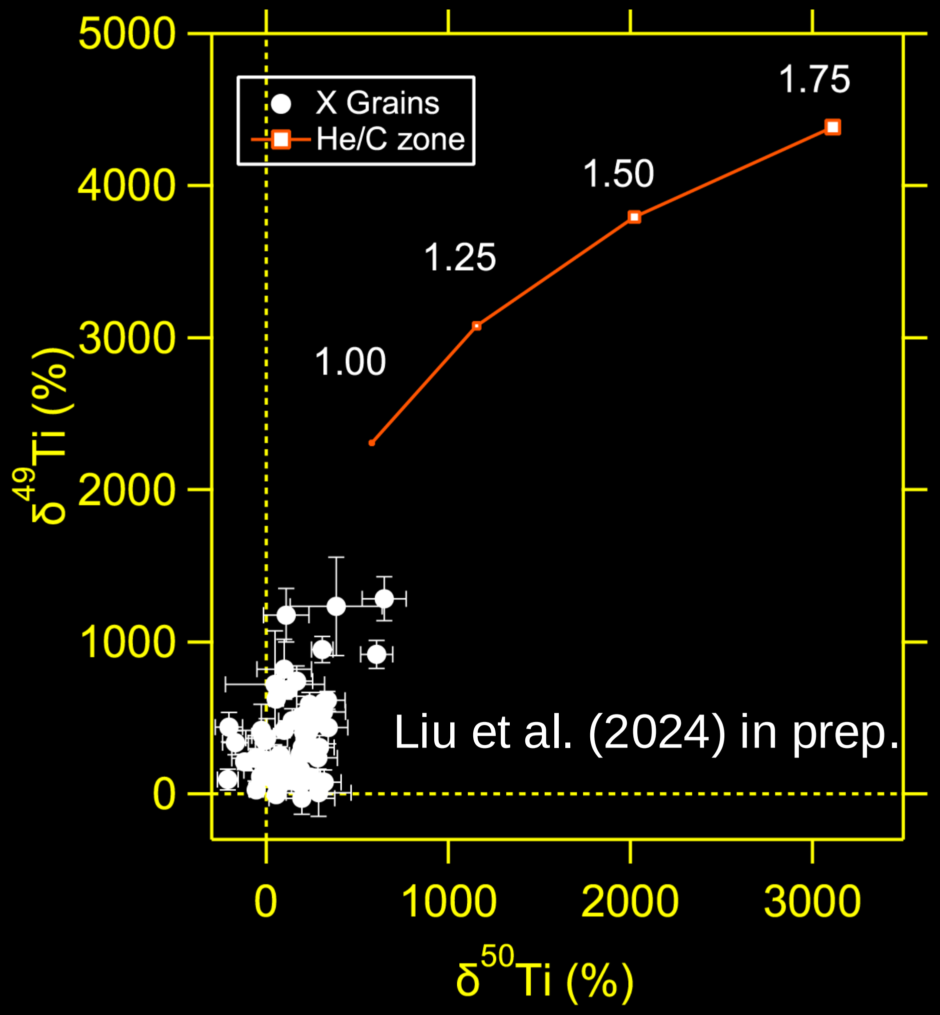
- Si_3N_4 grains show the largest enrichments in ^{46}Ca
- Neutron-burst signature, powered by $^{22}Ne(\alpha,n)^{25}Mg$ that provides ~10^{17} neutrons/cm^3

Neutron-burst in the He/C Zone

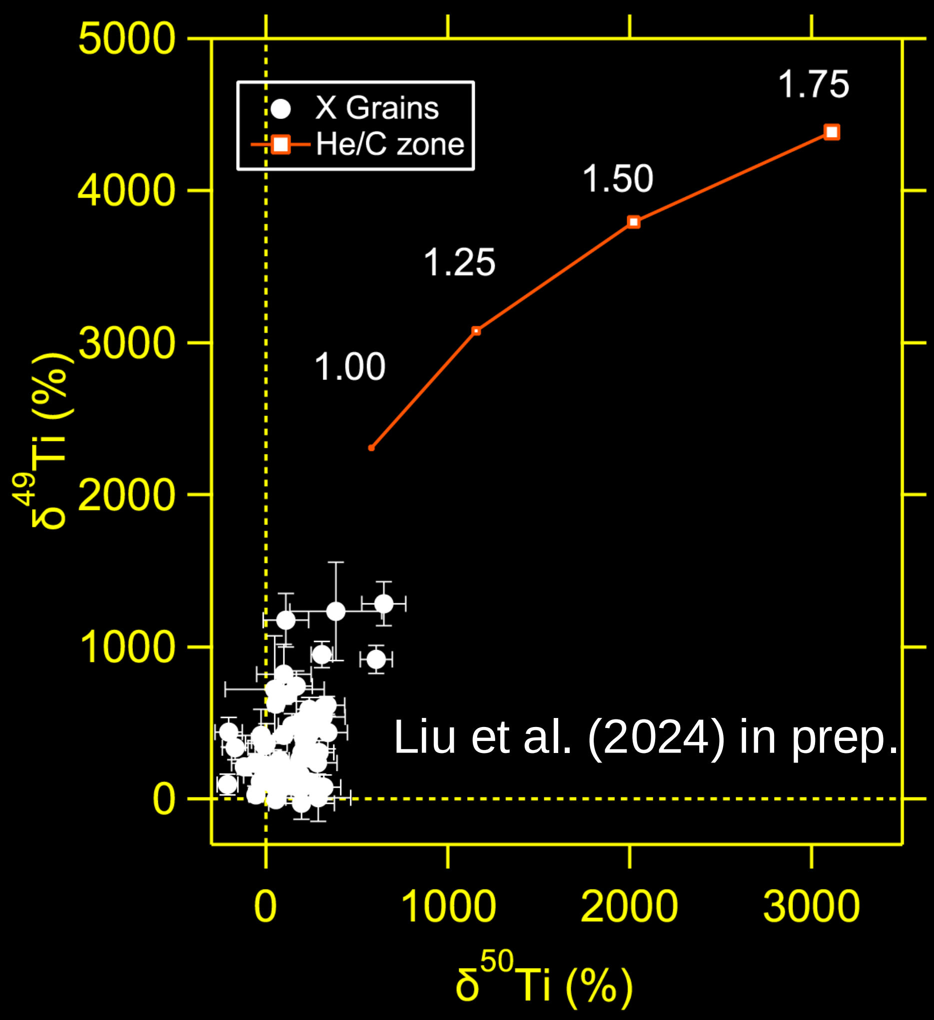


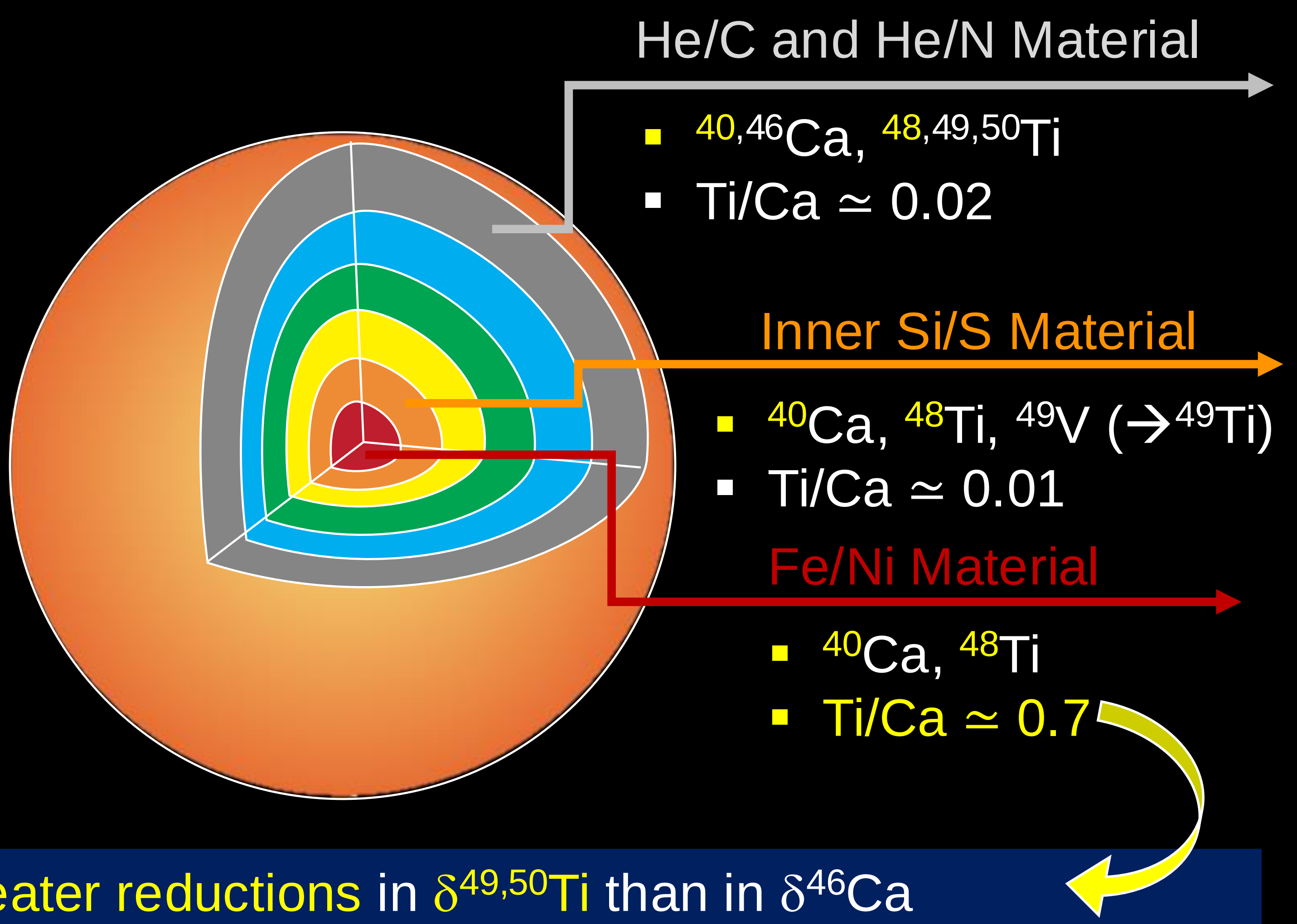
- Grain data overall agree with predicted H/C zone's compositions at (1.00-1.75) x 10^{51} erg
- Small discrepancies may reflect nuclear uncertainties, GCE effects, etc.

Contribution of Fe/Ni Material



Contribution of Fe/Ni Material





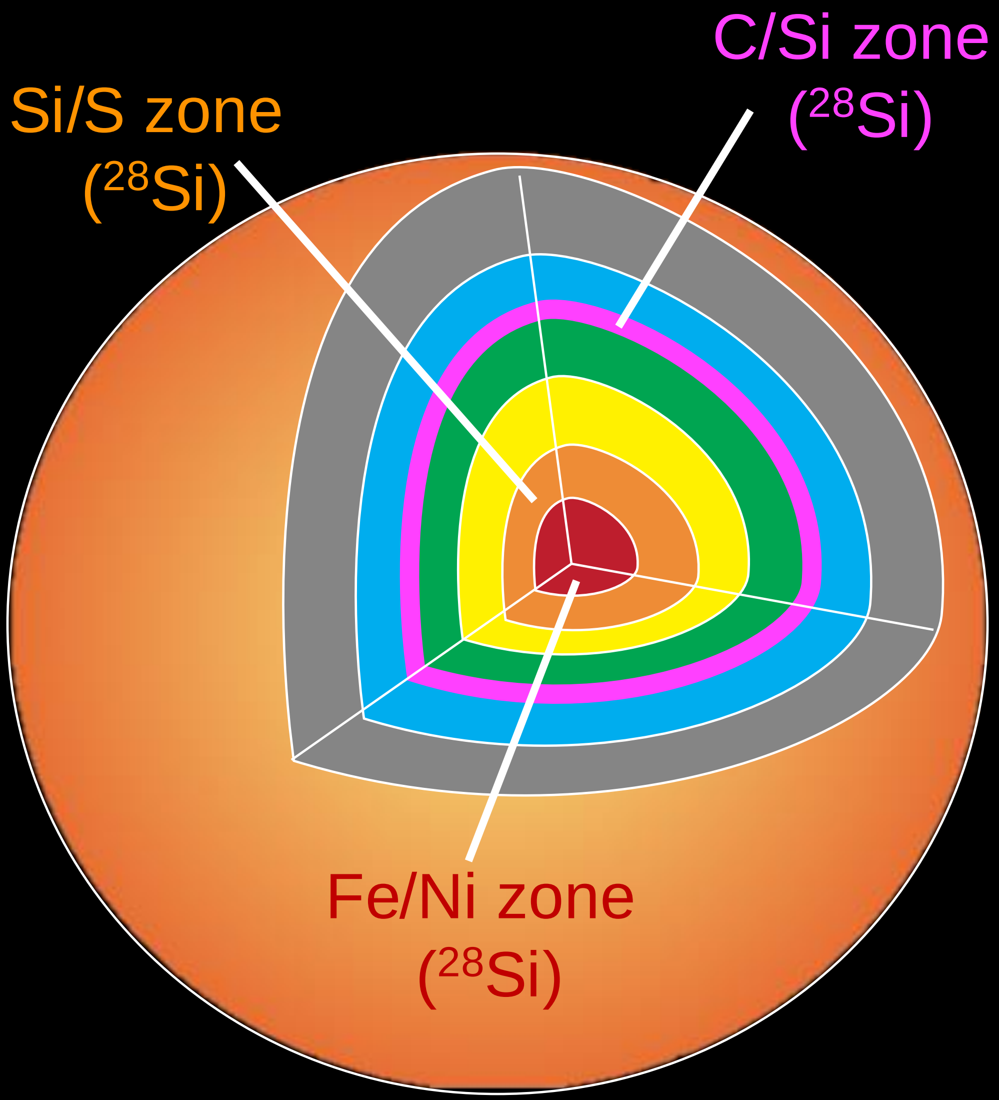
- Mixing with core material leads to greater reductions in $\delta^{49,50}$Ti than in δ^{46}Ca
- He/C to core mixing ratio ≃ 97:3, but more Si_3N_4 data are needed to improve the statistics

Conclusions and Outlook

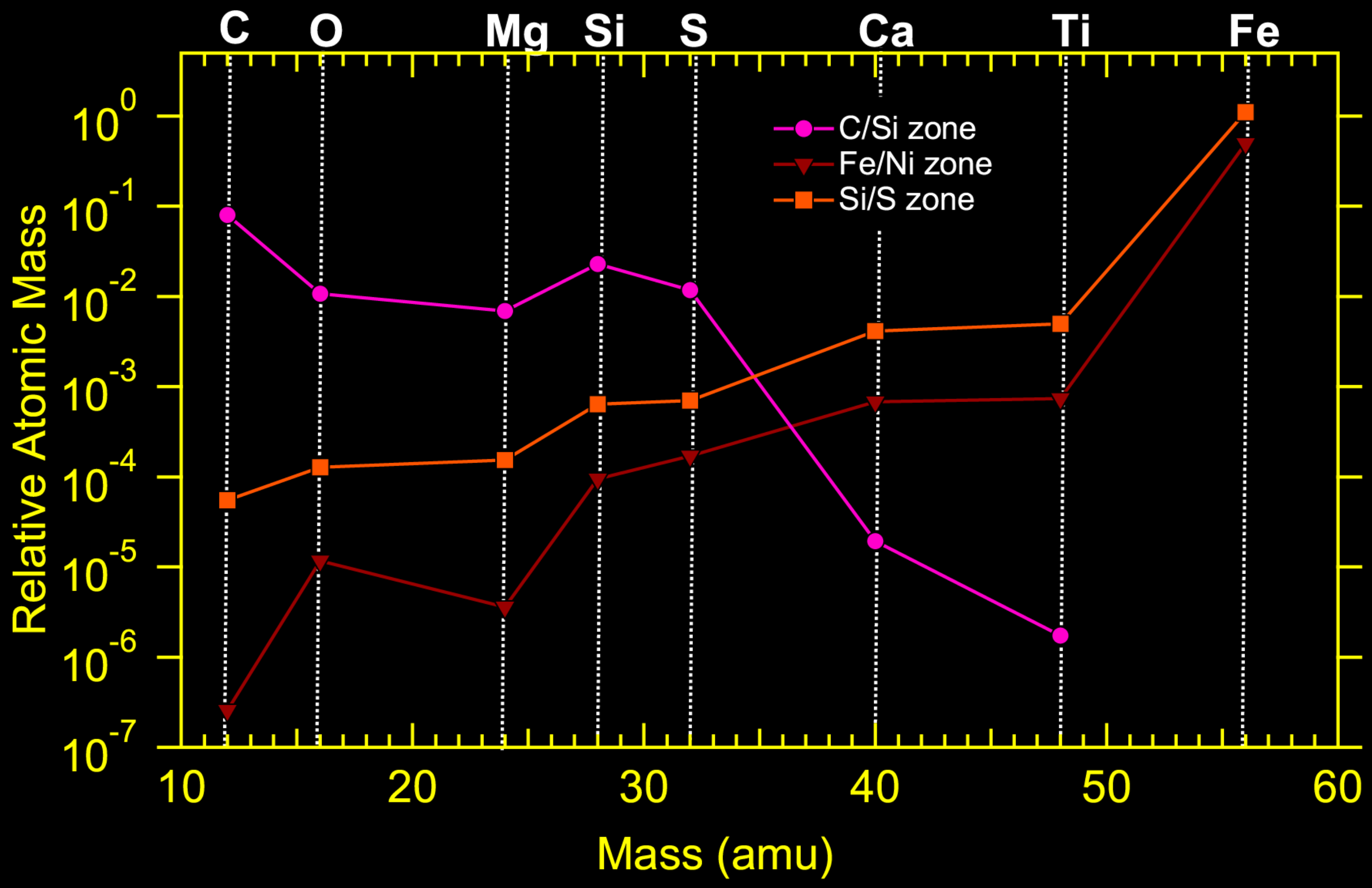
- Presolar grains from CCSN include SiC, Si_3N_4, and graphite with diverse isotopic compositions, recording the signatures of a variety of nucleosynthesis processes occurring in their parent CCSNe
- Their heavy-element isotopic signatures are controlled by neutro-bursts in the He/C zone and light-element isotopic signatures by both the neutron bursts and alpha-rich freezeouts in deep interior, thus enabling constraining the relative mixing ratios across CCSNe
- Nuclear uncertainties are needed to be investigated to assess uncertainties in our derived constraints

Extra Slides

Could Local, Small-scale Mixing Work?



The C/Si zone was proposed by Pignatari et al. (2013) ApJL



These alpha-processes produce significantly different elemental patterns