Isotopes in Stardust: presolar silicon carbide grains

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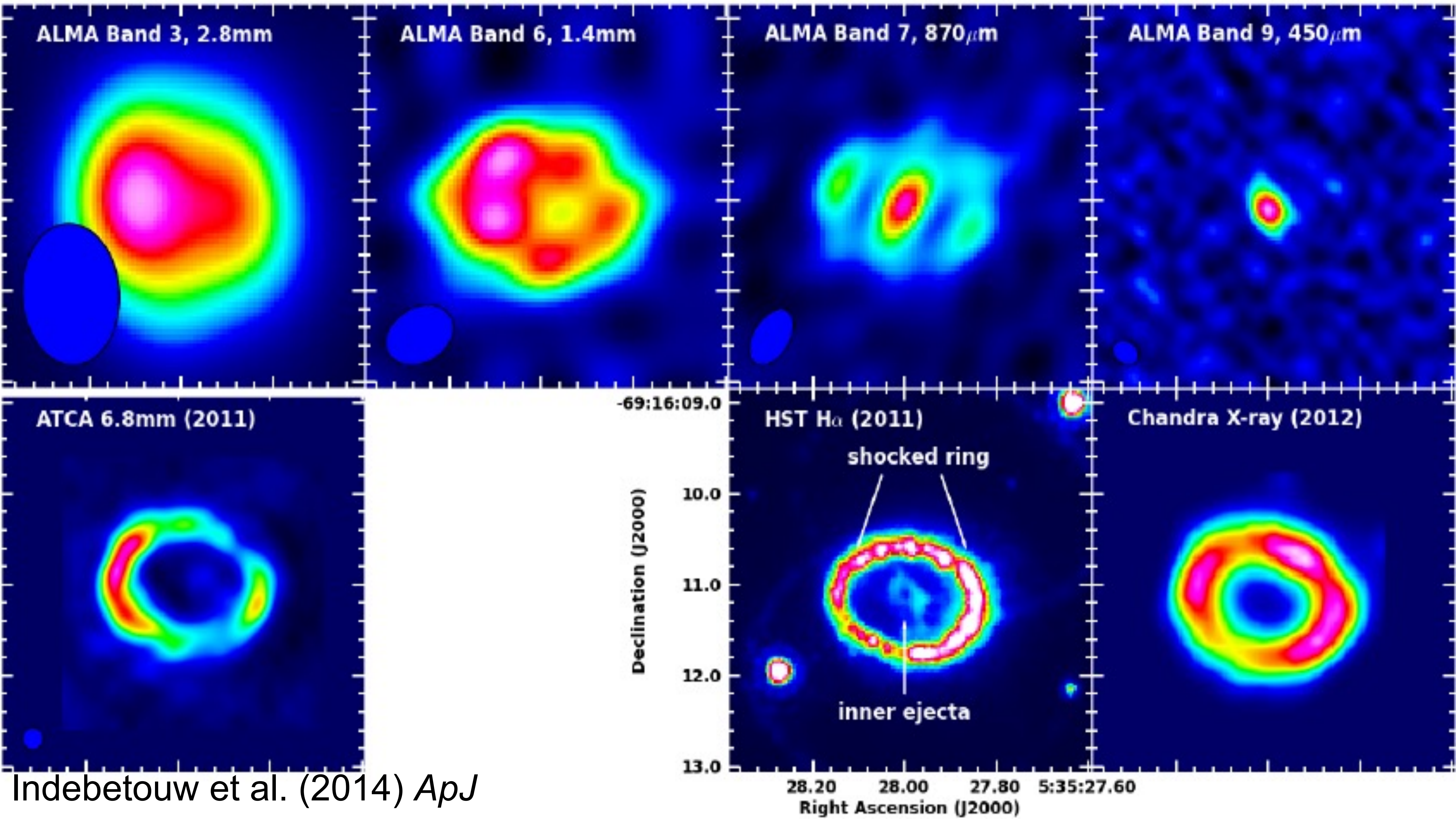
“The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. **We are made of star stuff**.*”*

— Carl Sagan, Cosmos



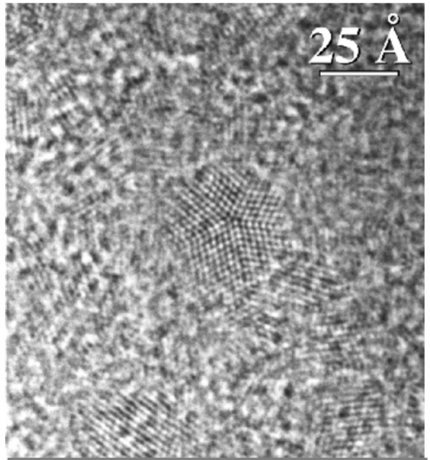
Indebetouw et al. (2014) *ApJ*


Where the telescope ends,
the microscope begins.

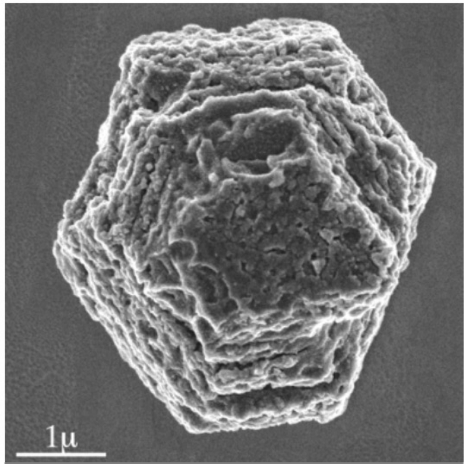
Types of Presolar Grains

See Ann Nguyen's lecture that introduces presolar grains, solar system, and meteorites

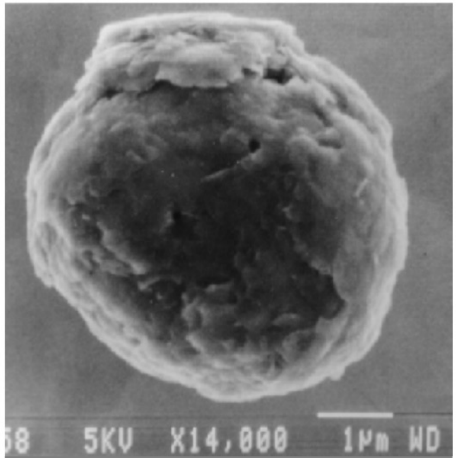
- First presolar grains (diamond, SiC, graphite) discovered by exotic noble gas signatures in 1987 (Lewis et al. 1987, Bernatowicz et al. 1987, Amari et al. 1990)
- More detailed isotopic studies and identification of additional presolar phases and subtypes made possible by Secondary Ion Mass Spectrometry (SIMS)



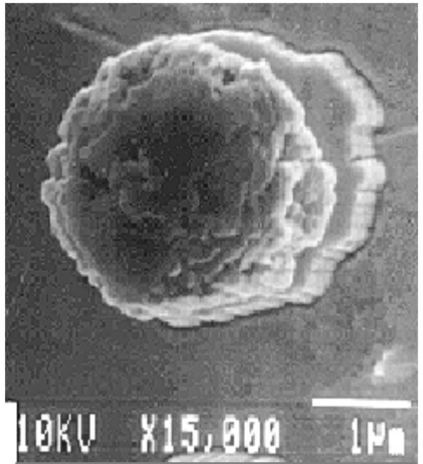
Nanodiamond
2 nm
~1400 ppm



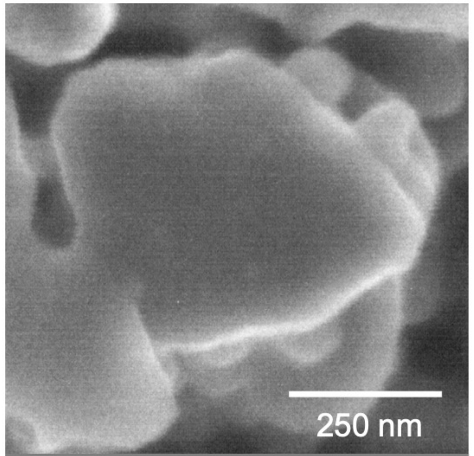
SiC
0.3 – 20 μm
~20 ppm



Graphite
1 – 20 μm
~5 ppm

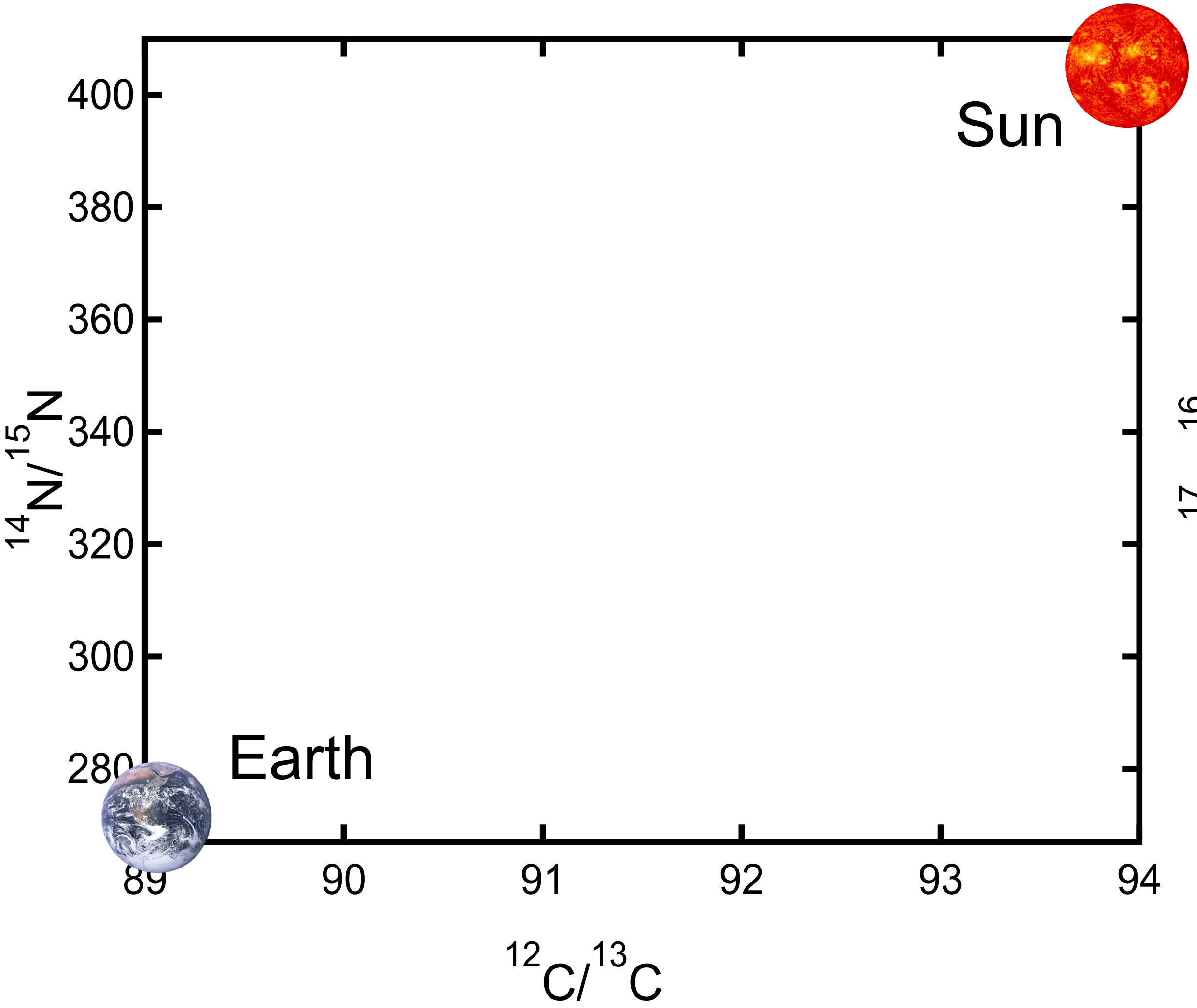


Oxides
0.05 – 5 μm
< 100 ppm

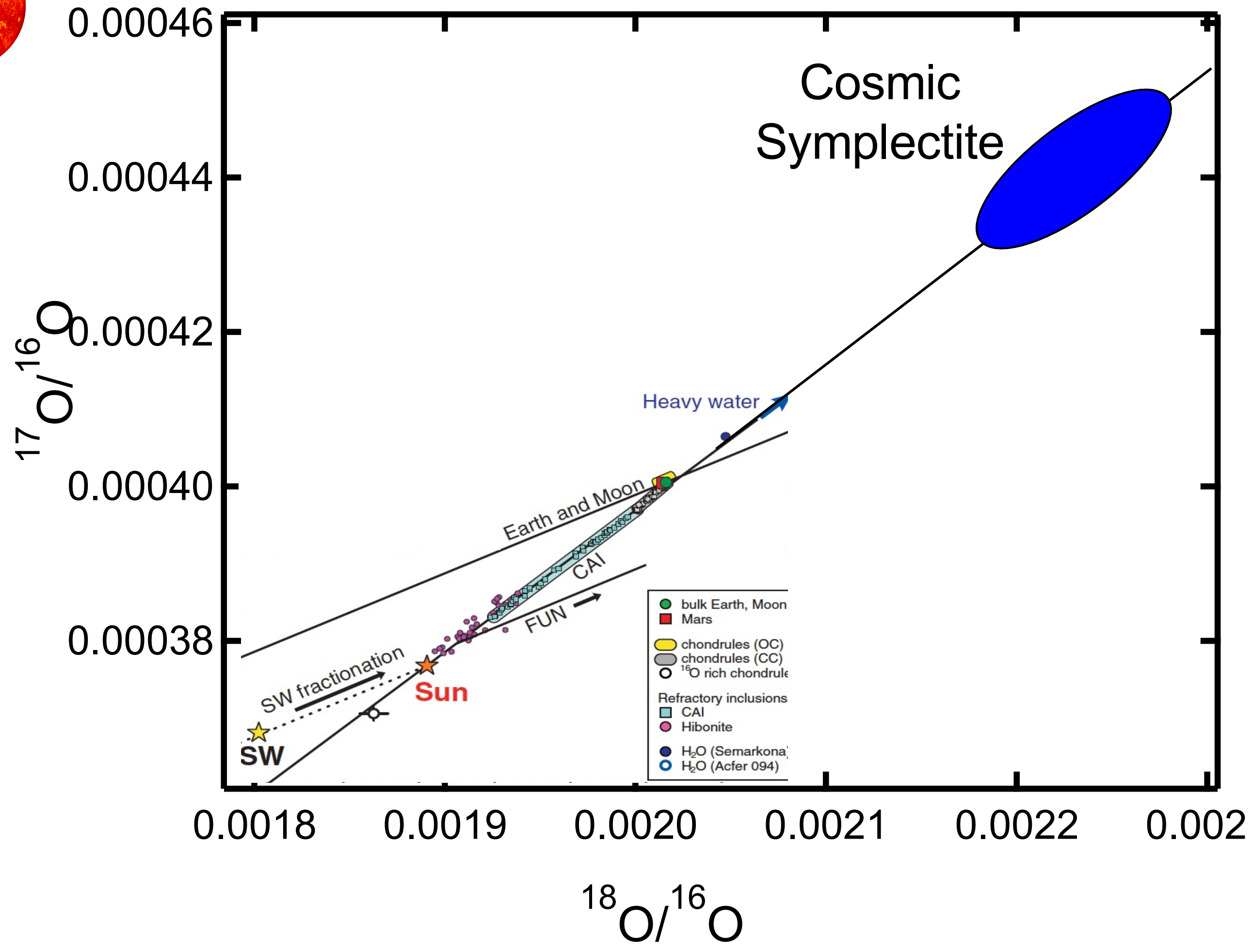


Silicates
0.05 – 2 μm
< 15,000 ppm

Solar System Composition

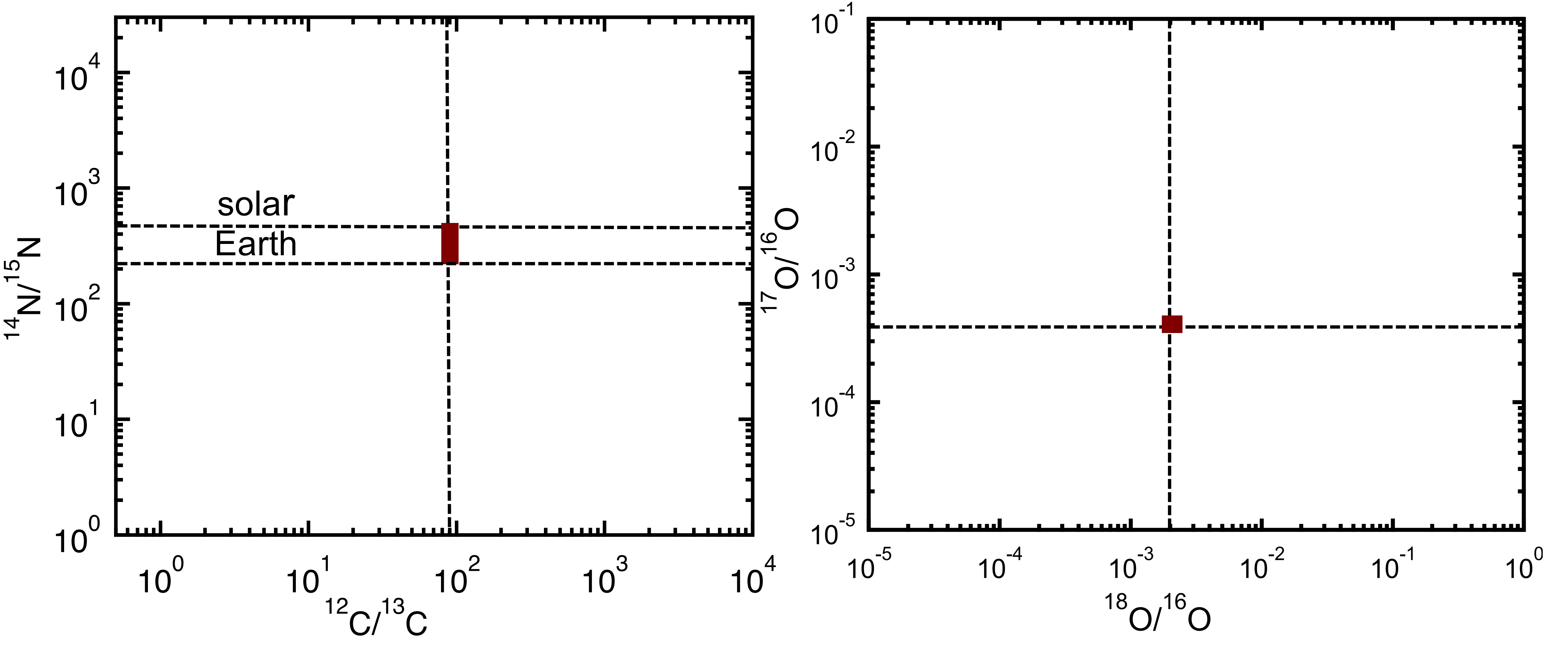


Marty et al. (2011), Lyons et al. (2016)

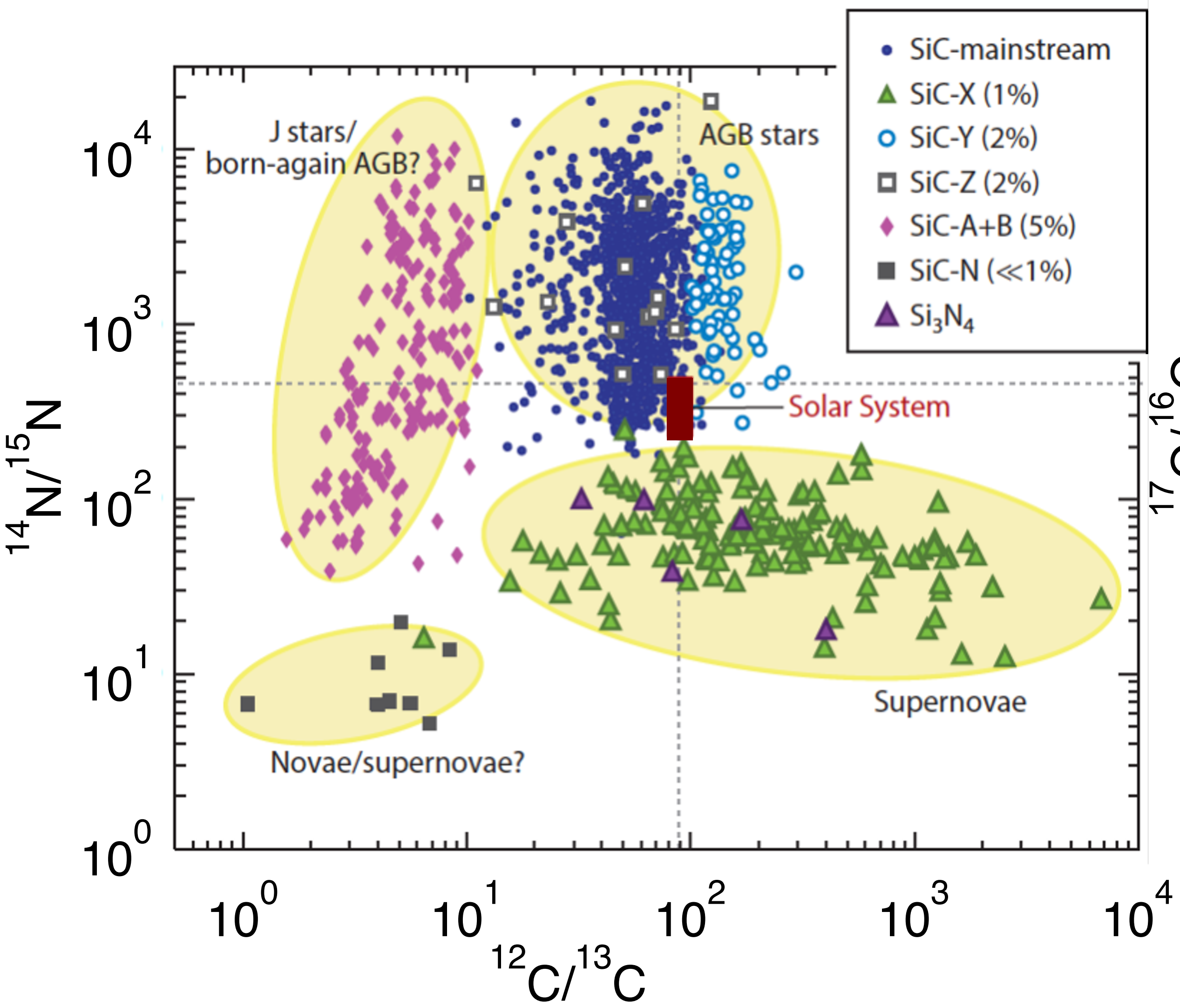


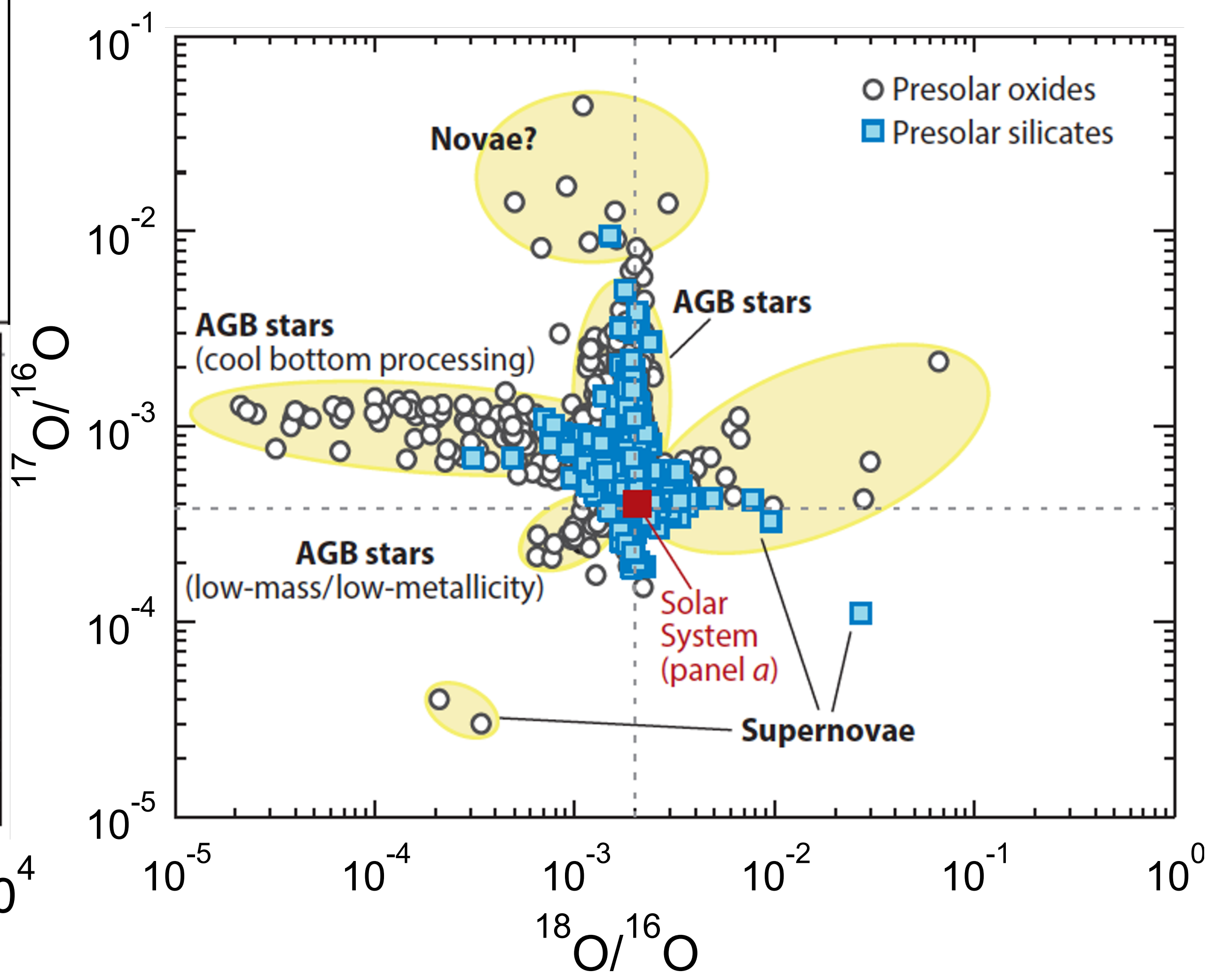
Mckeegan et al. (2011)

Why are They Presolar Grains?

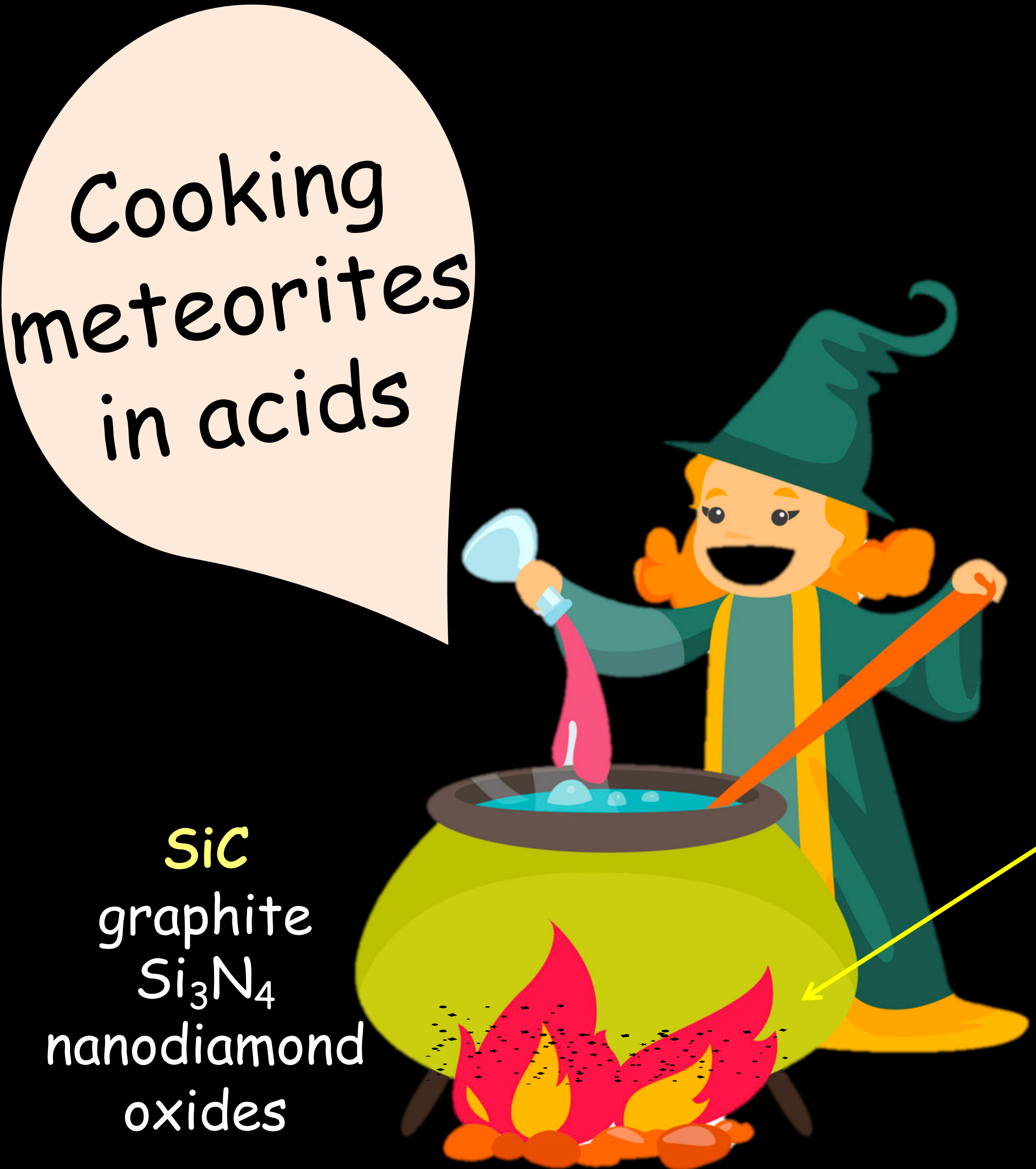


Huge Isotopic Anomalies!

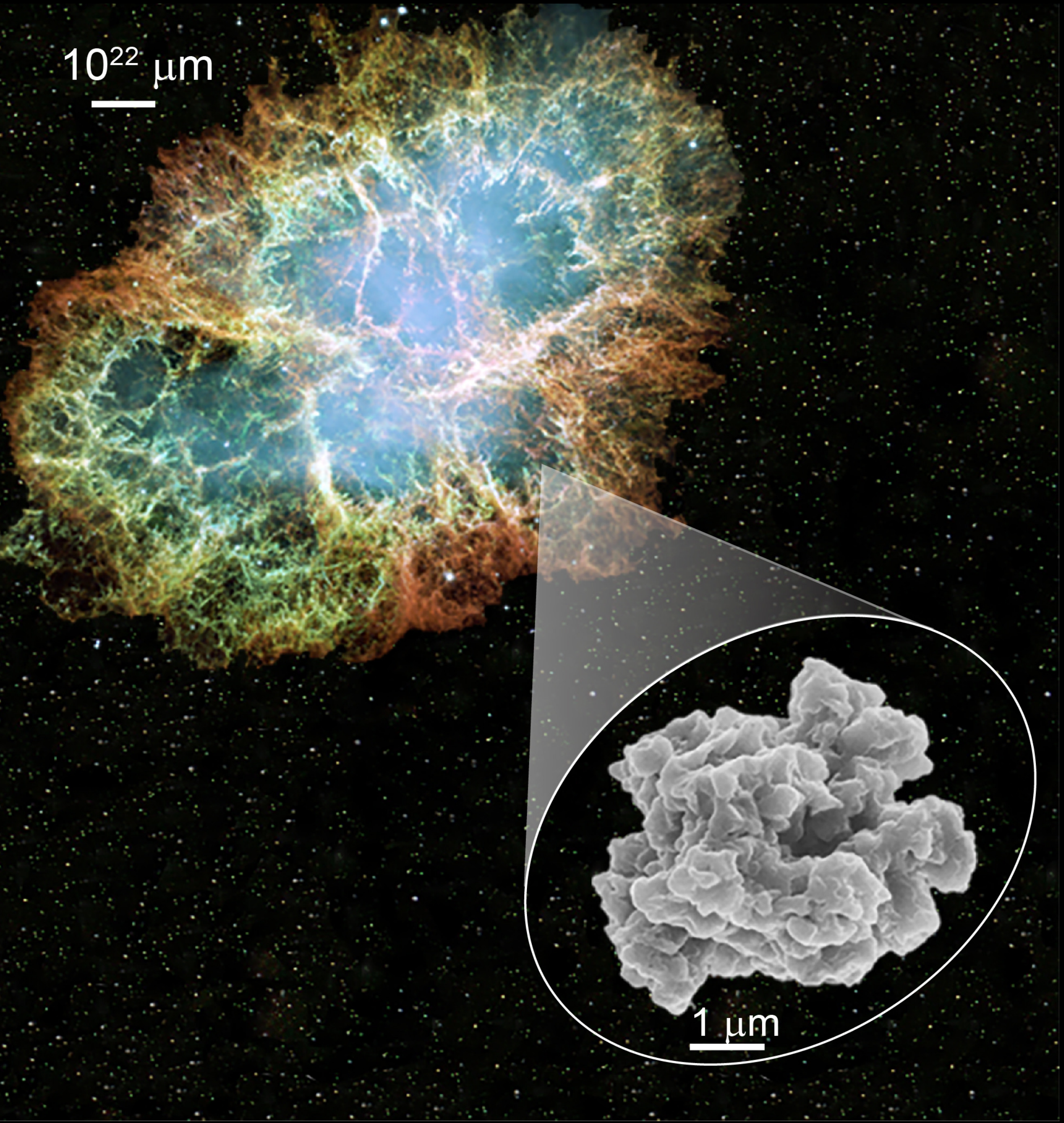




How can we find presolar grains in pristine meteorites?



Burn down the haystack to find the needle!



Outline

1. Analytical Techniques

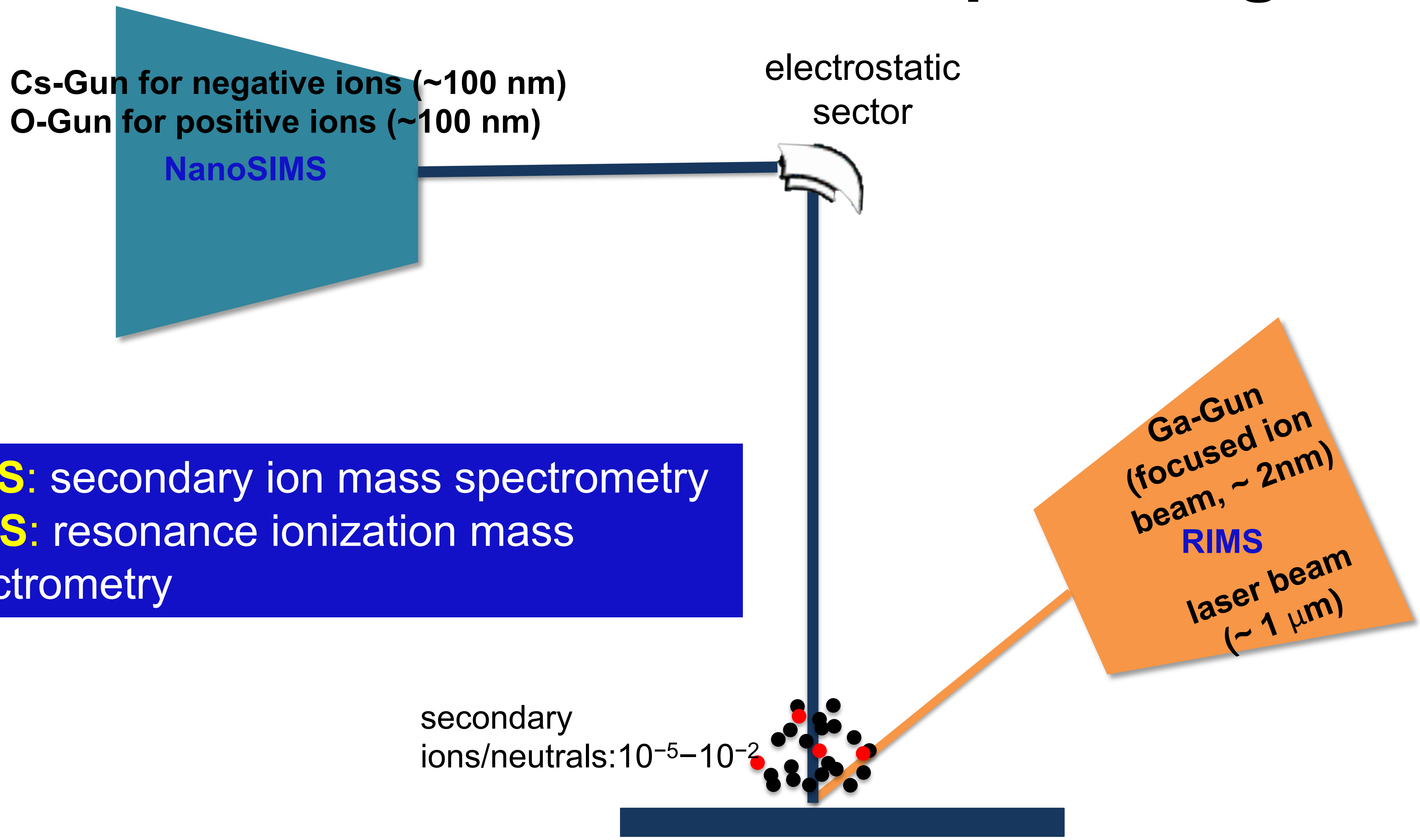
2. Different Types of Grains and Their Stellar Origins

2.1 AGB Dust

2.2 Type II Supernova Dust

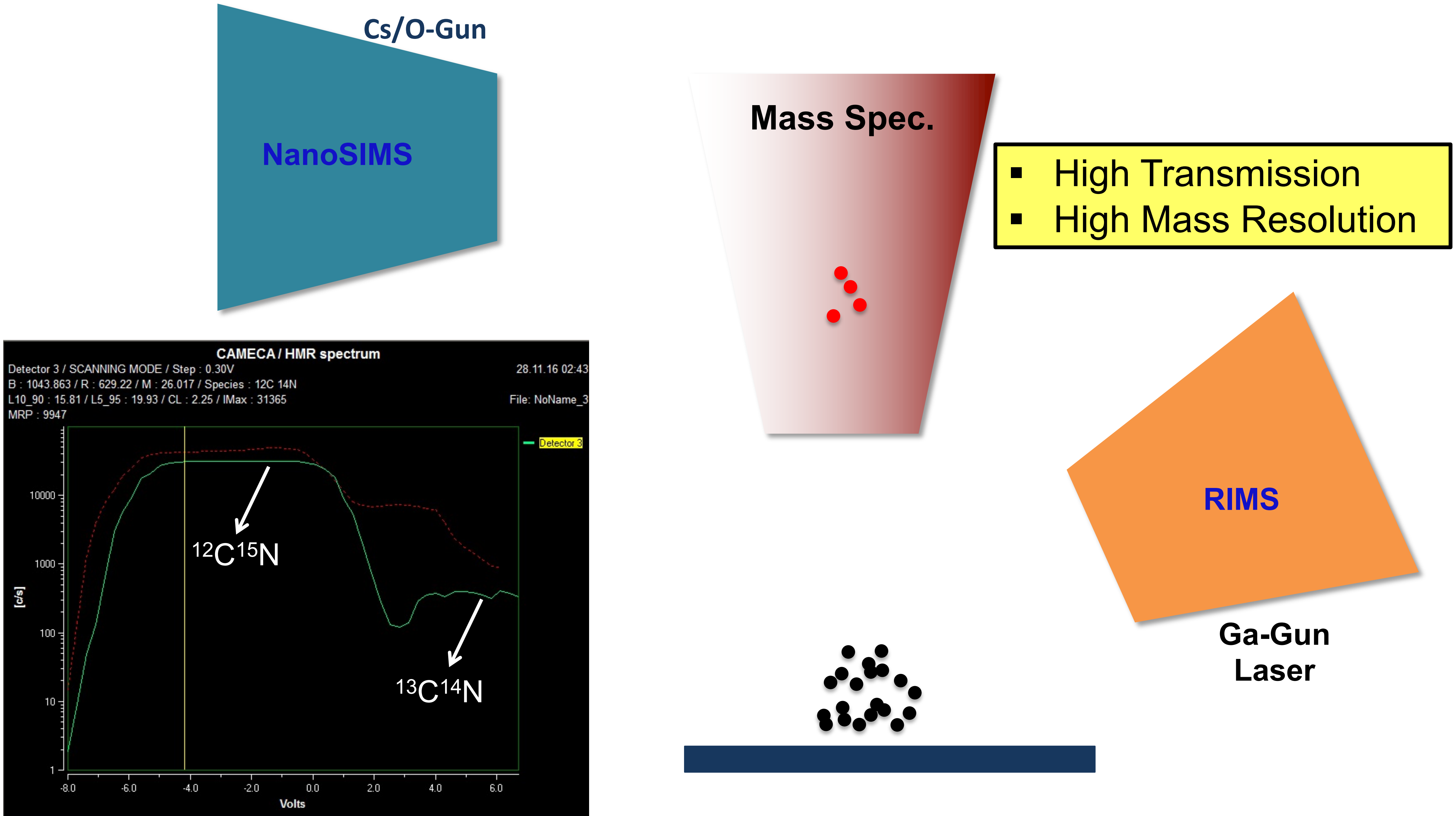
2.3 Mysterious ^{13}C-rich SiC Dust

SIMS versus RIMS: Sputtering



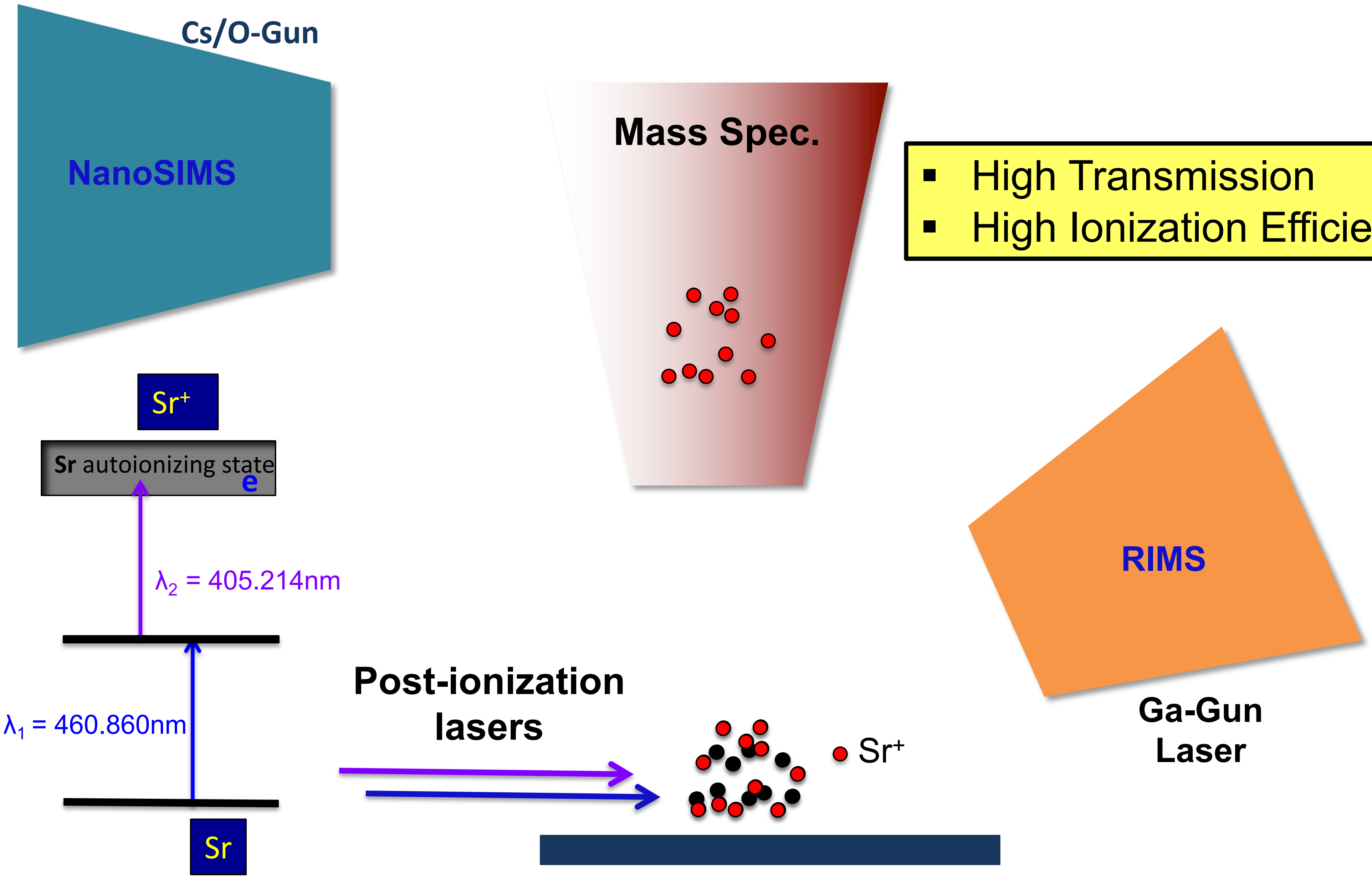
SIMS: secondary ion mass spectrometry
RIMS: resonance ionization mass spectrometry

SIMS Ionization

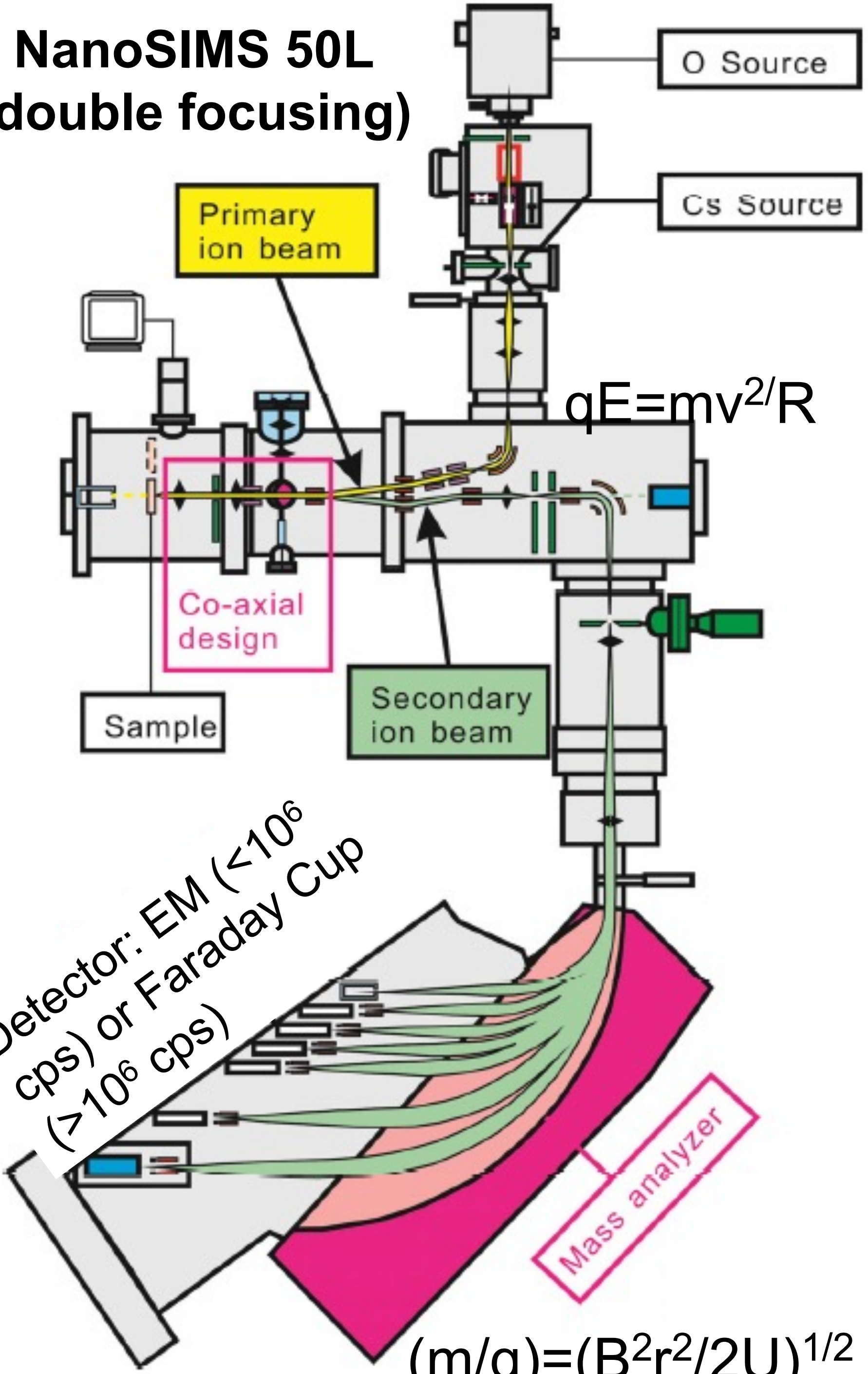


RIMS Ionization

- High Transmission
- High Ionization Efficiency



NanoSIMS 50L (double focusing)

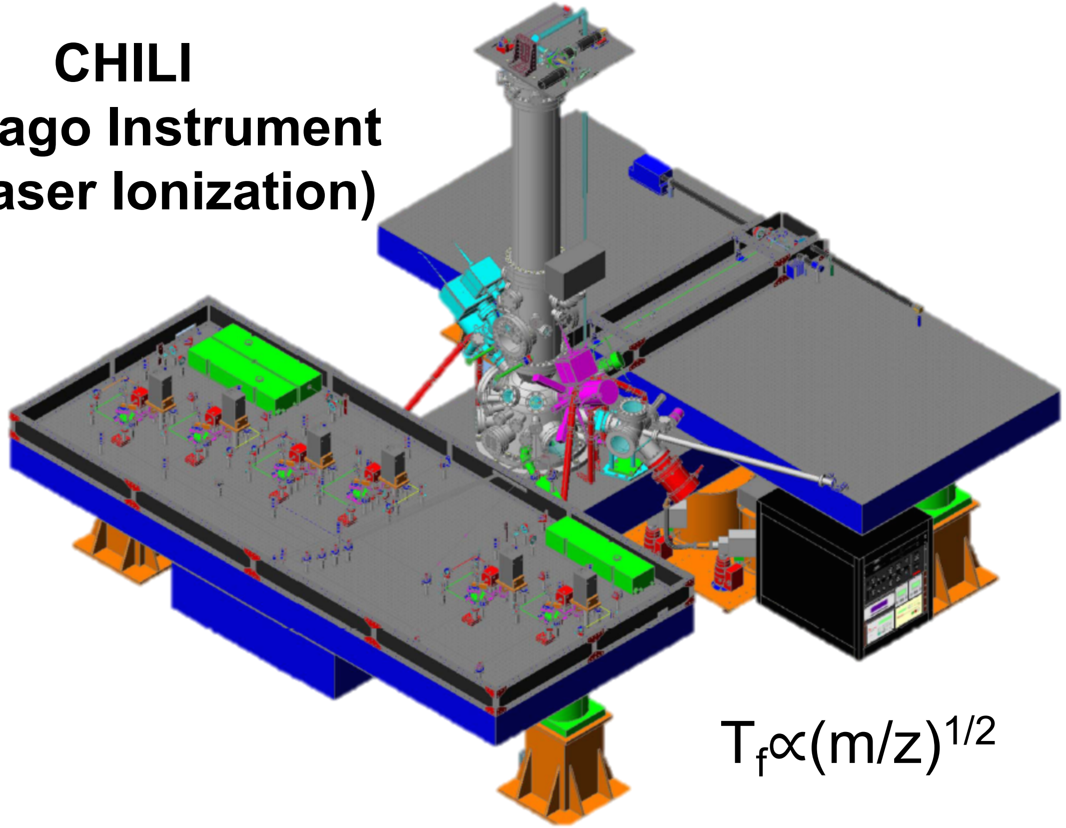


$$qE=mv^2/R$$

$$(m/q)=(B^2r^2/2U)^{1/2}$$

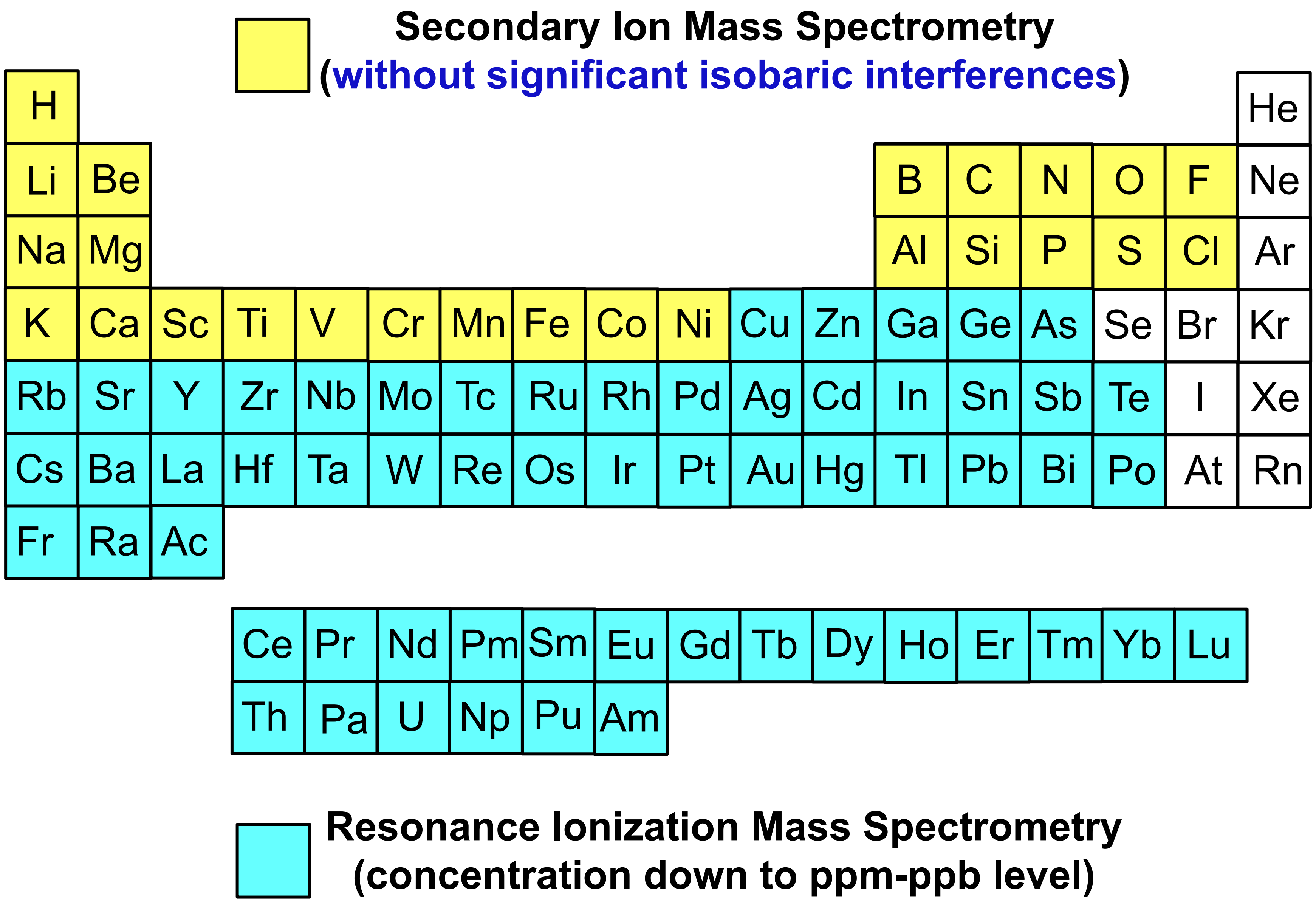
	NanoSIMS 50L	CHILI
Ionization	secondary ions	neutrals+post-ionization
Selectivity	Low	High
Mass Res.	High	Low
Mass Spec.	magnetic sector	time of flight

CHILI (Chicago Instrument for Laser Ionization)



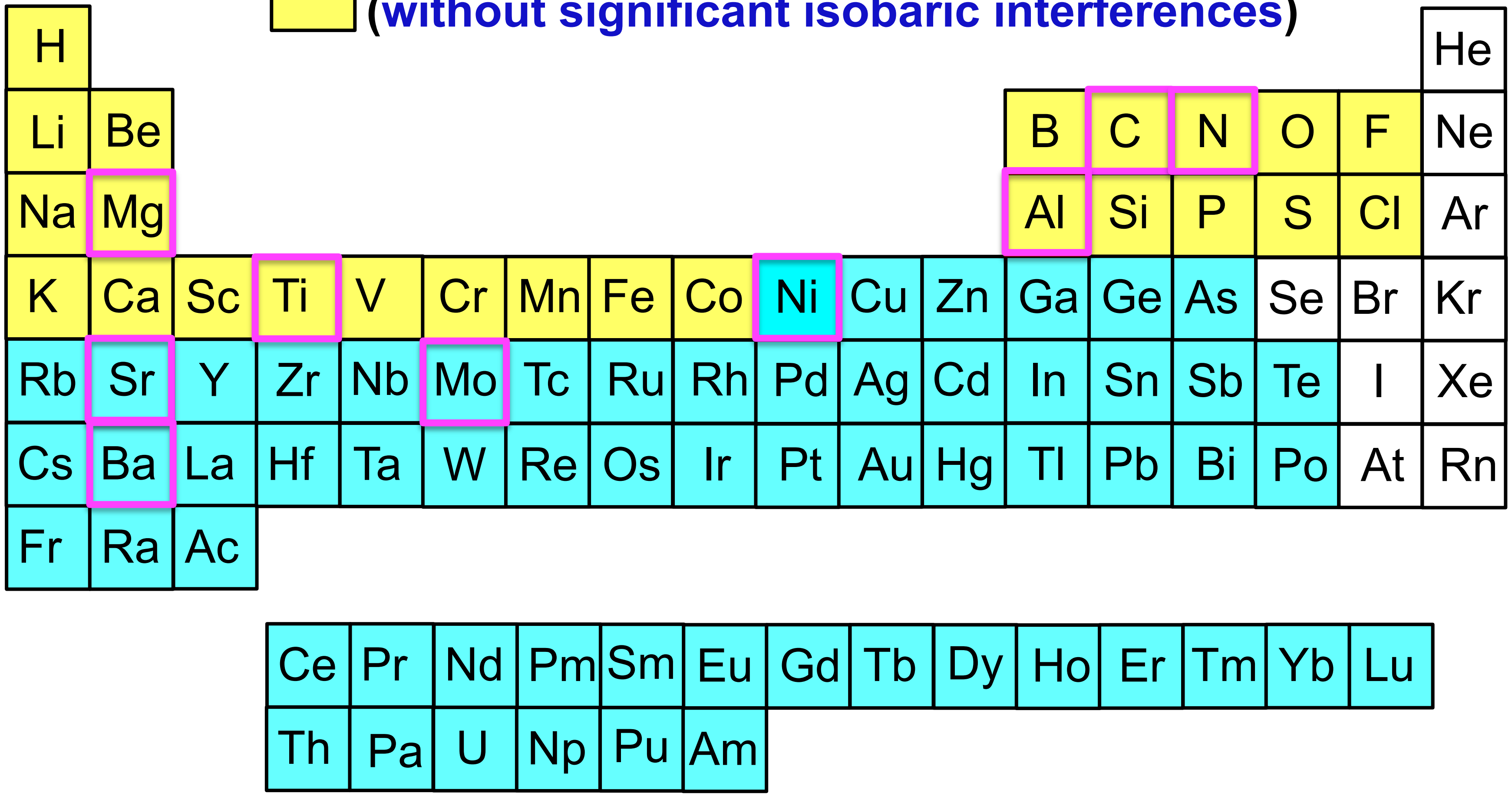
$$T_f \propto (m/z)^{1/2}$$

Elements Accessible to SIMS and RIMS

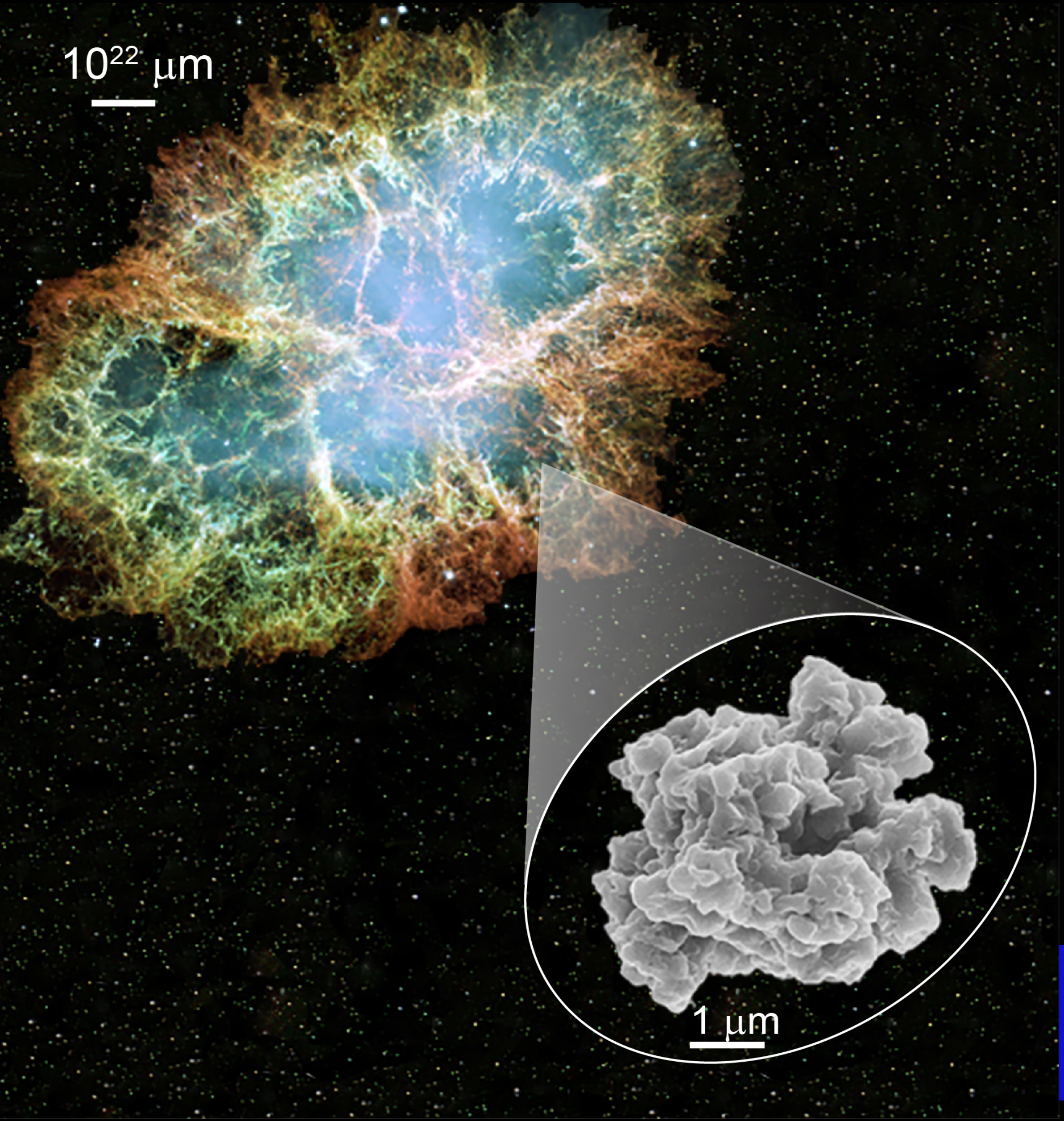


Elements Accessible to SIMS and RIMS

Secondary Ion Mass Spectrometry
(without significant isobaric interferences)



Resonance Ionization Mass Spectrometry
(concentration down to ppm-ppb level)



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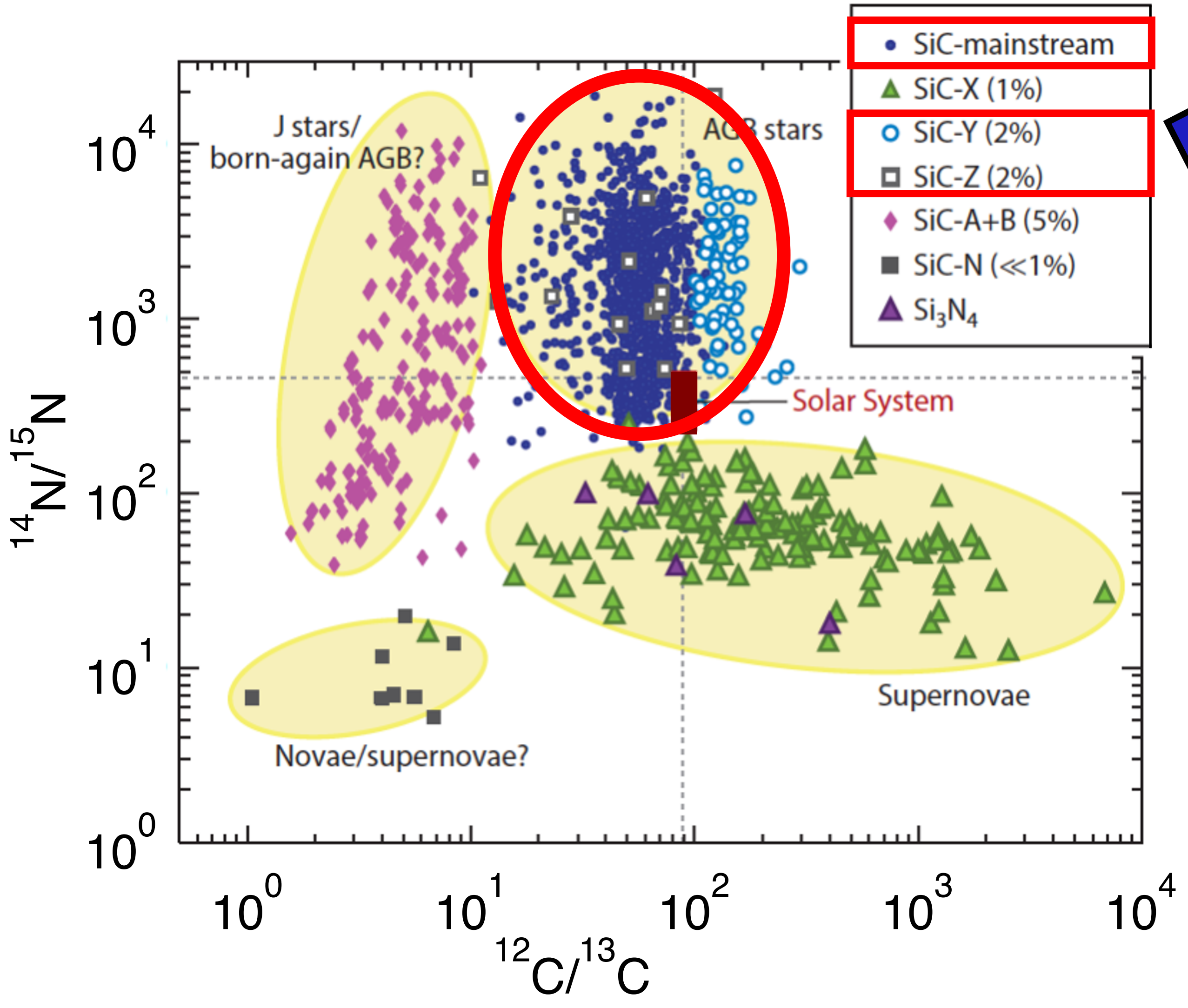
See Amanda Karakas's lecture on *s*-process and AGB stars

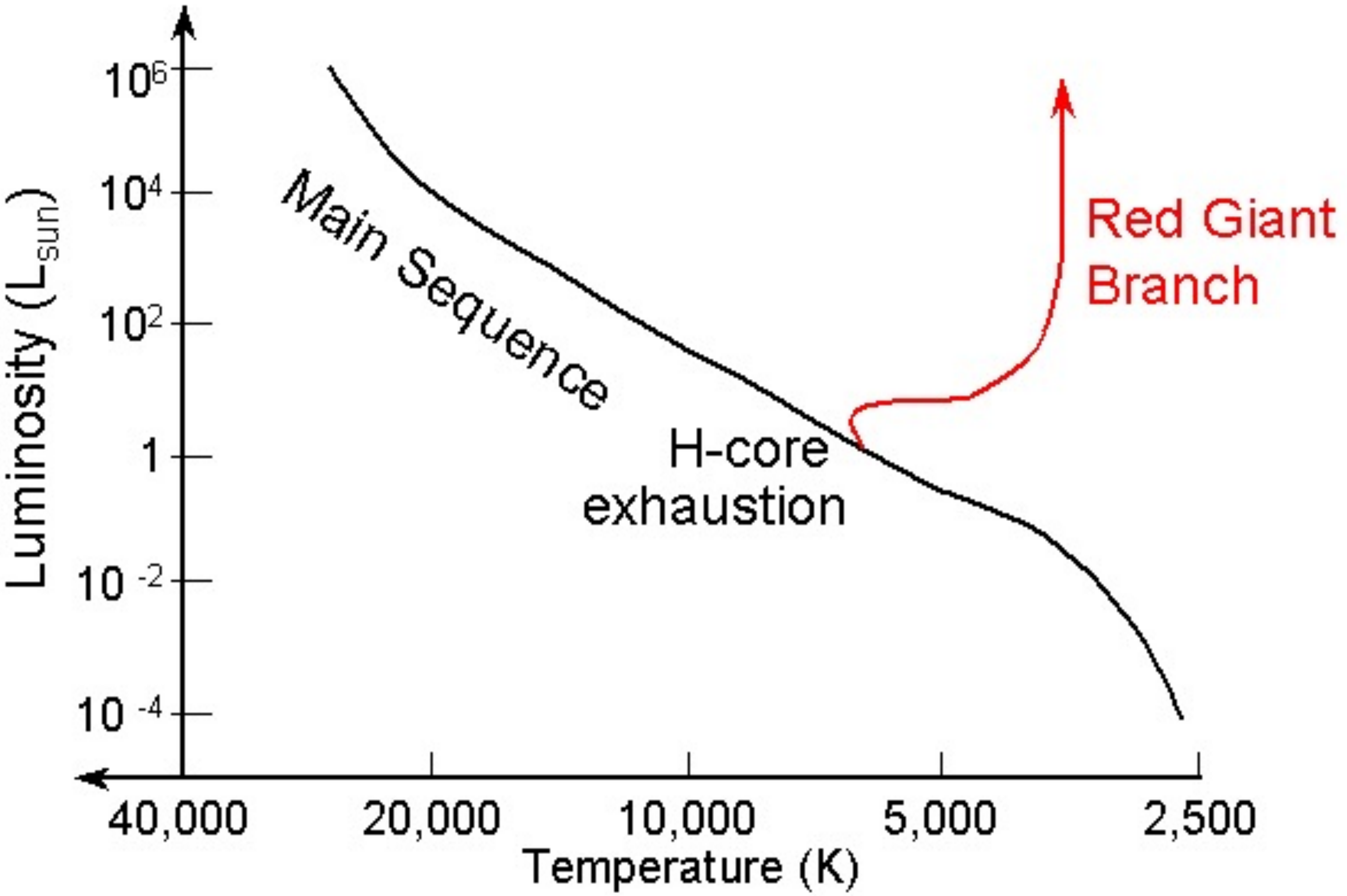
Stellar Origins of Presolar SiC

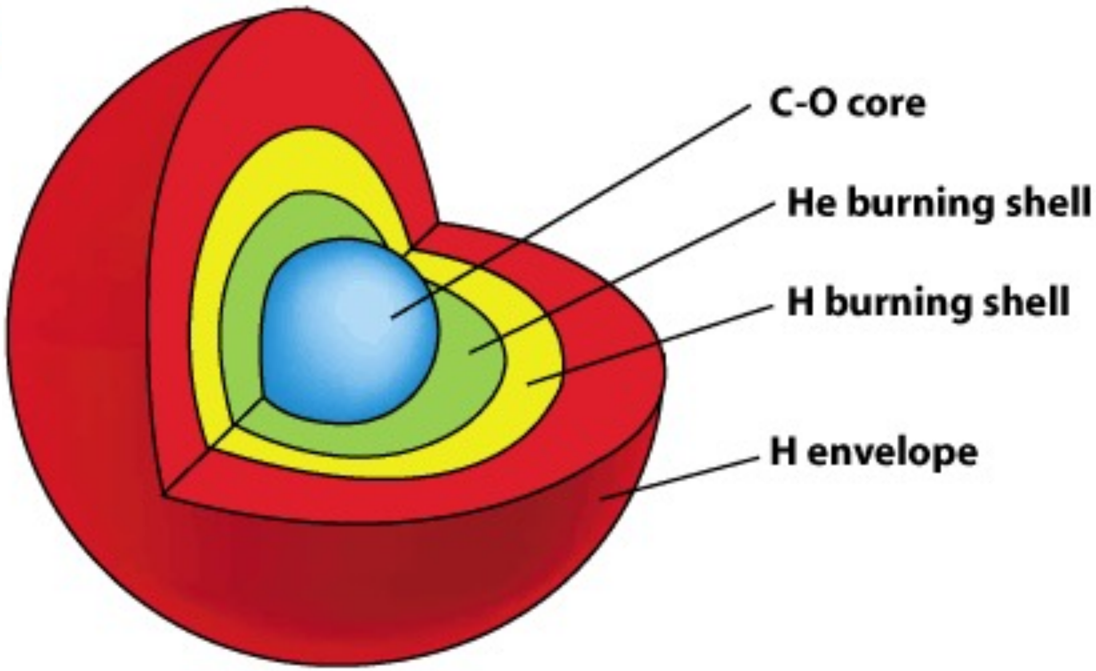


Nittler & Ciesla (2016) *ARA&A*

formed in C-rich envelope of low-mass asymptotic giant branch stars

AGB Phase: An Advanced Evolutionary Stage

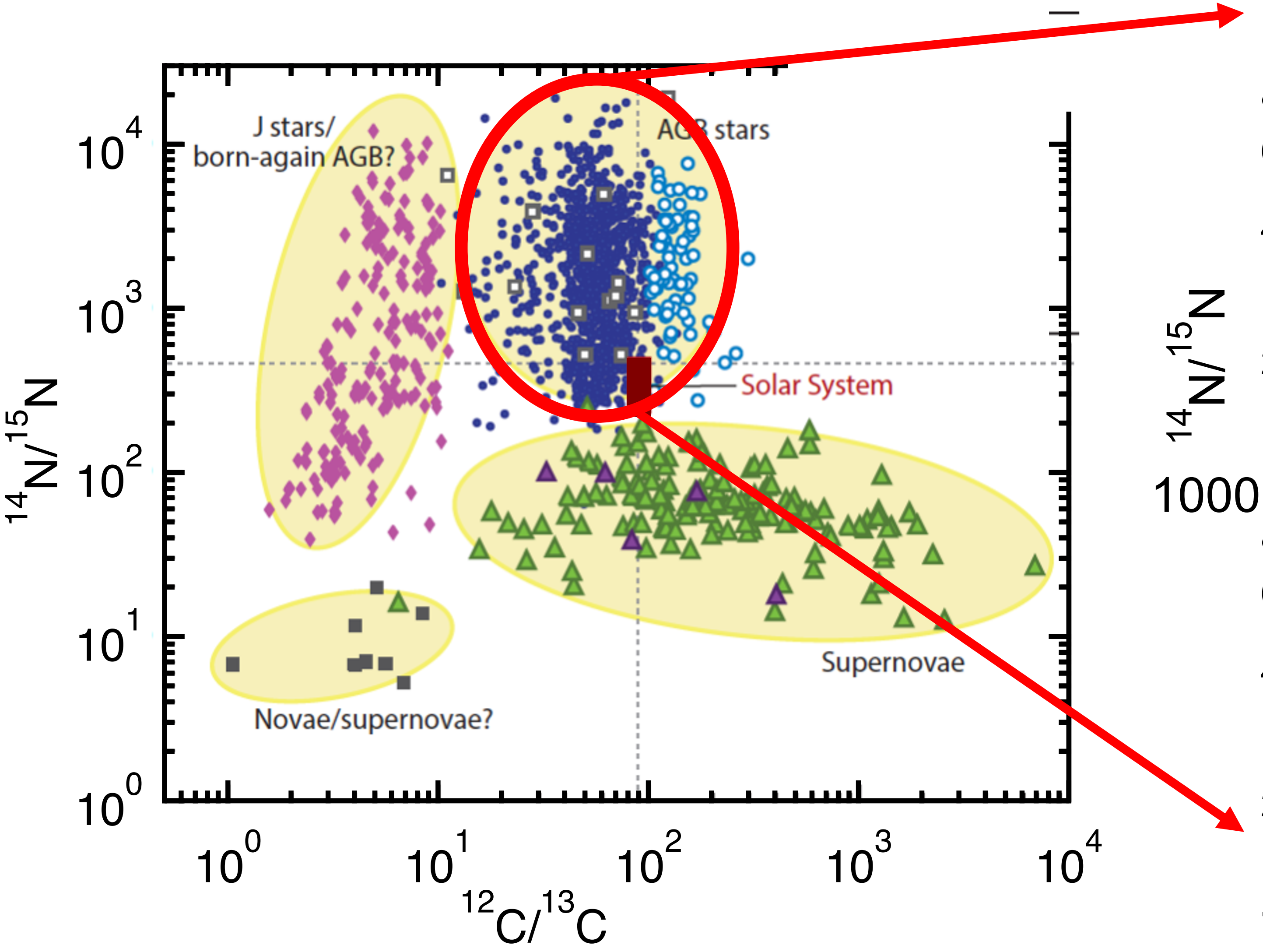


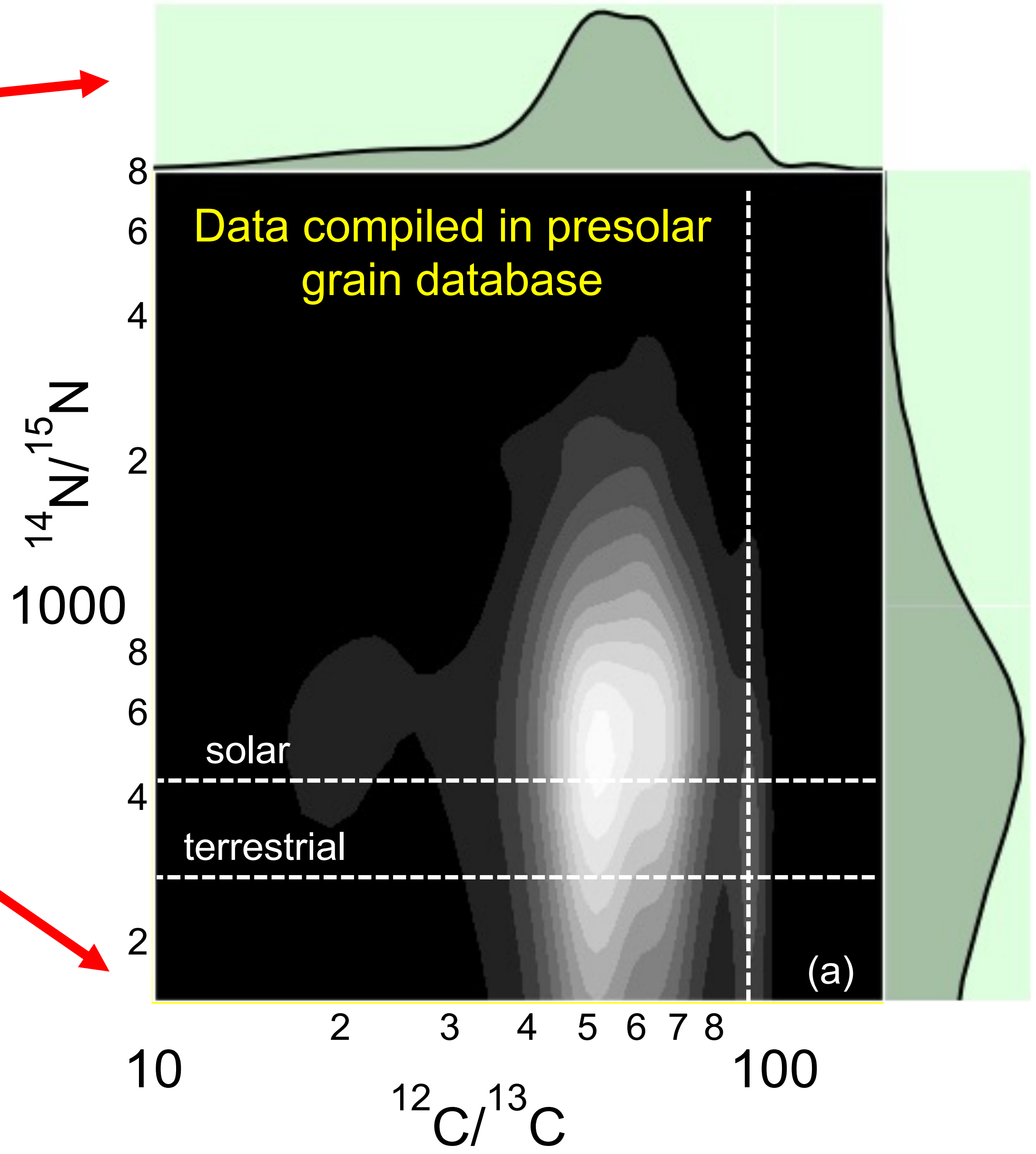


AGB: Asymptotic Giant Branch, an advanced evolutionary stage of stars with masses below ~8 $M_{\odot}$.

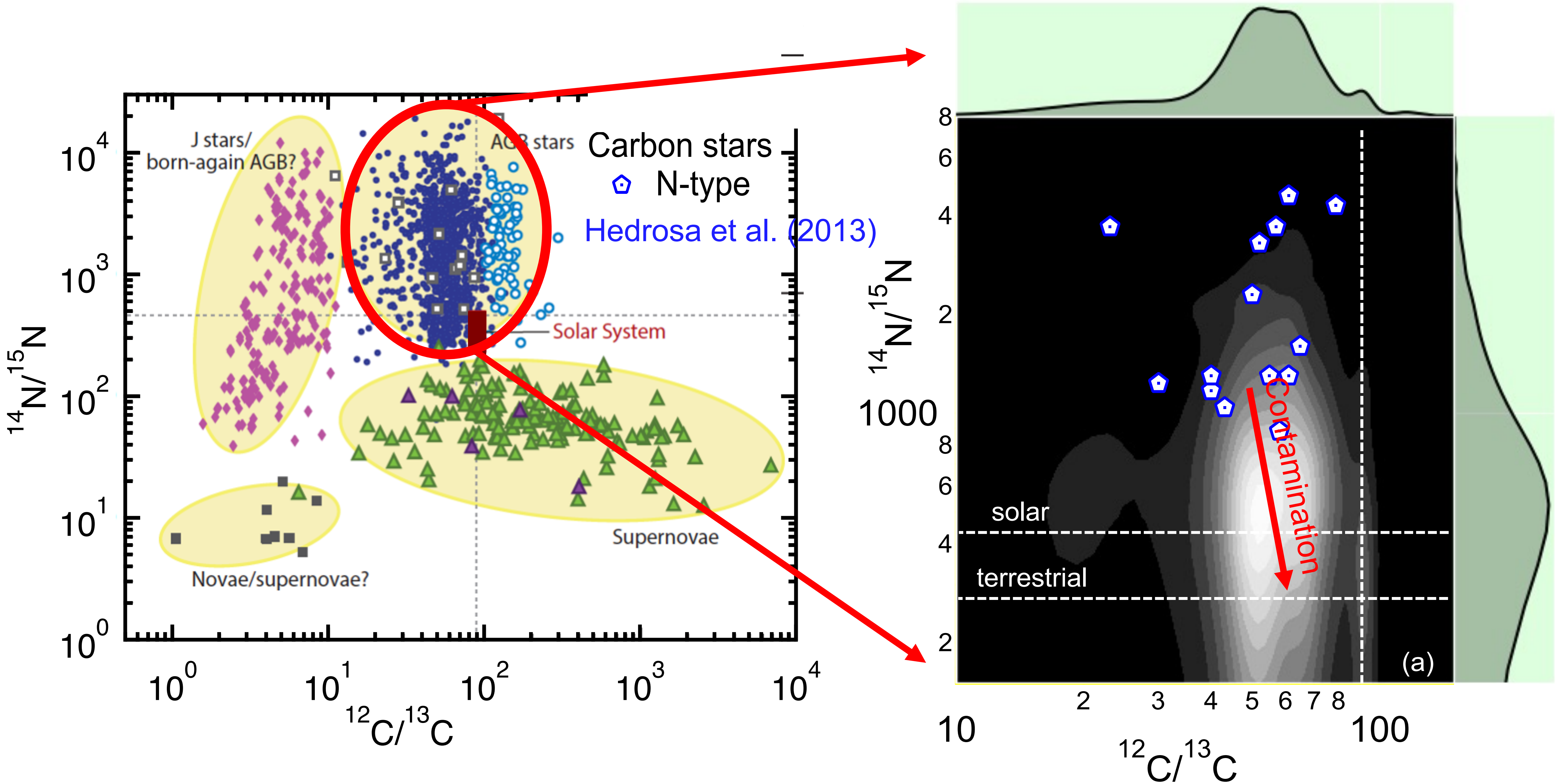
C-rich AGB: Parent stars of C-rich presolar grains, ~1.5–3 $M_{\odot}$.

Stellar Origins of SiC from AGB Stars

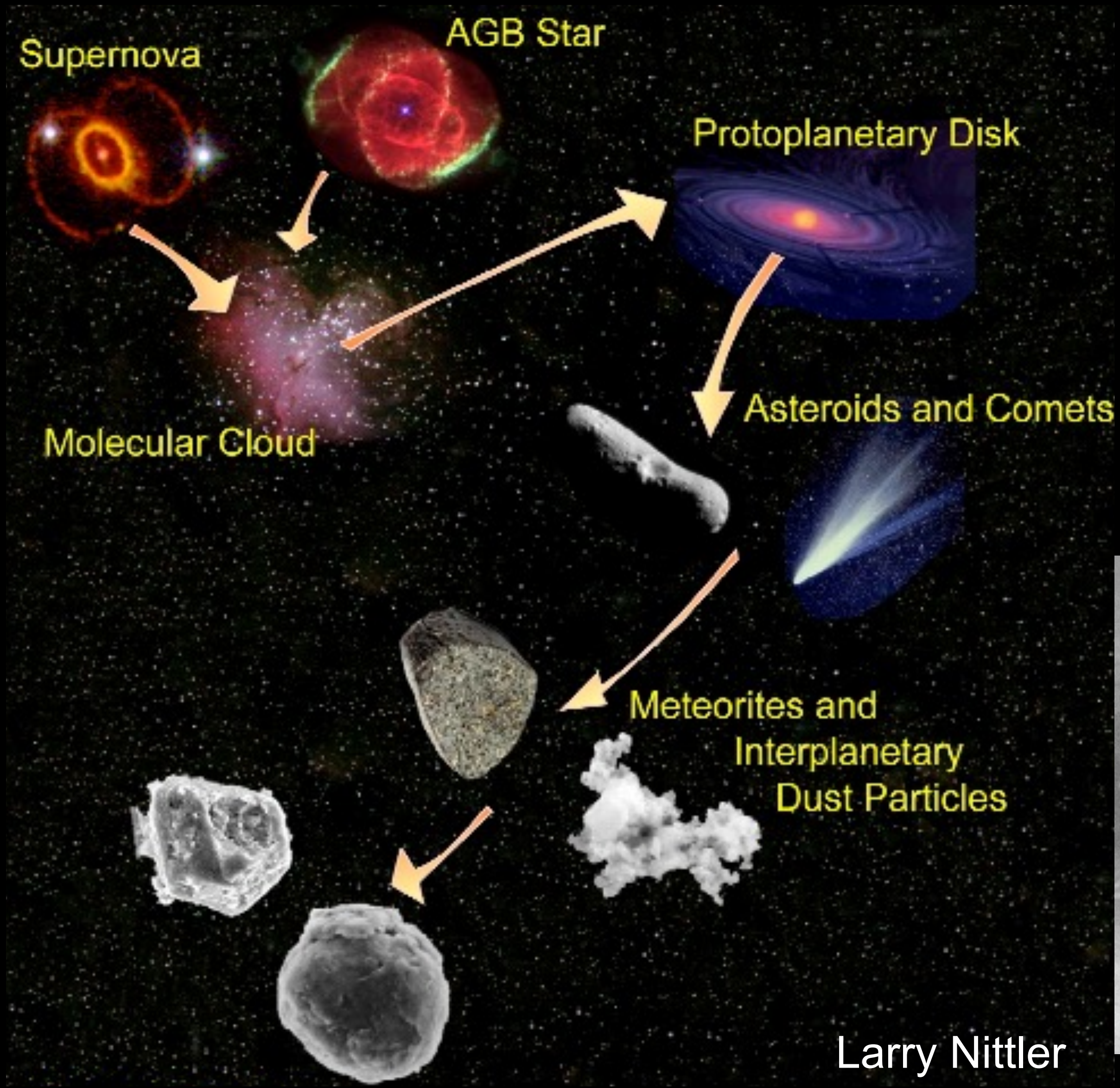


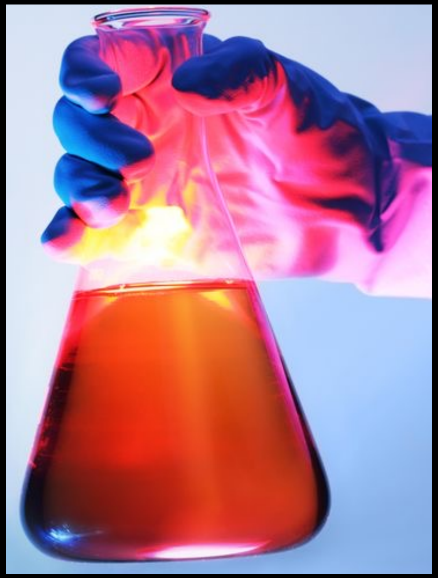


Grain-Observation Discrepancy

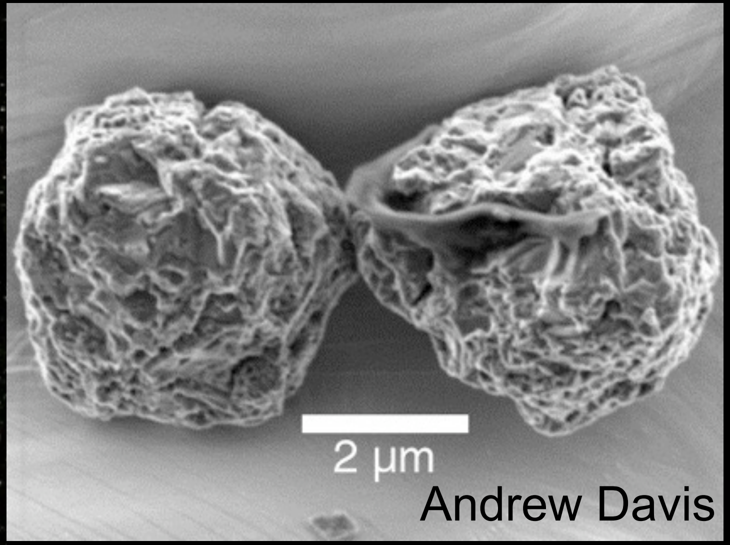


Asteroidal and Terrestrial Contamination





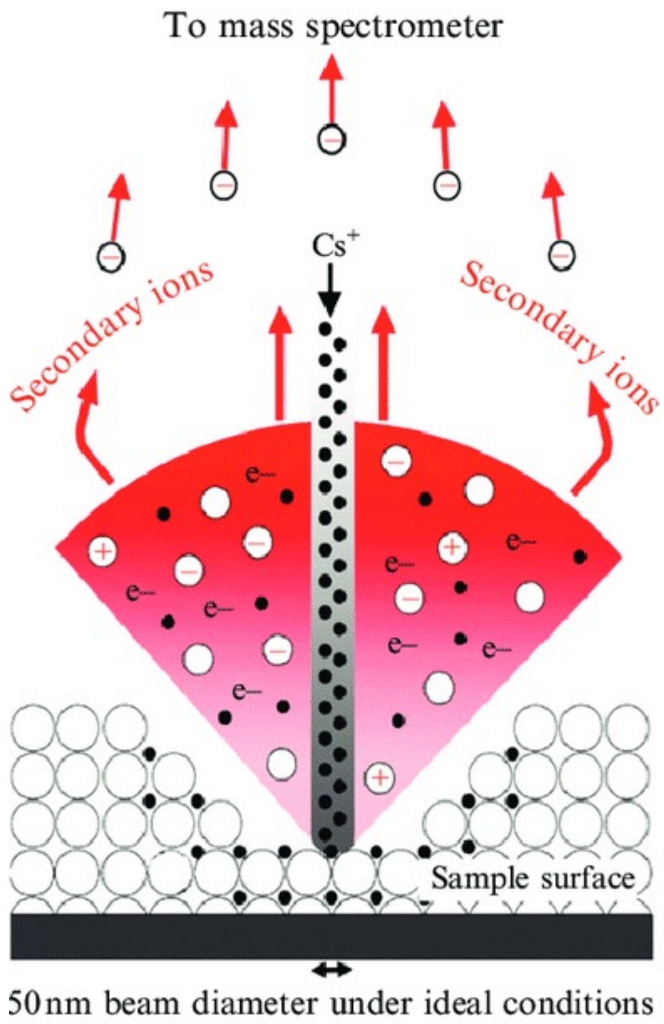
Additional terrestrial contamination caused by e.g., acid dissolution and laboratory analysis.

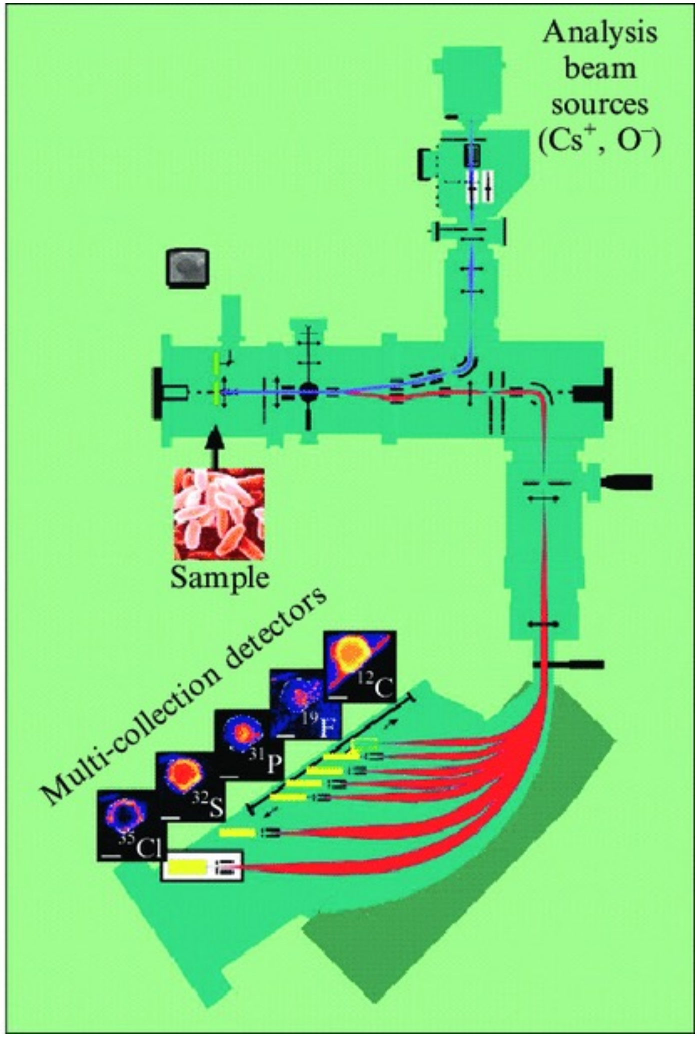


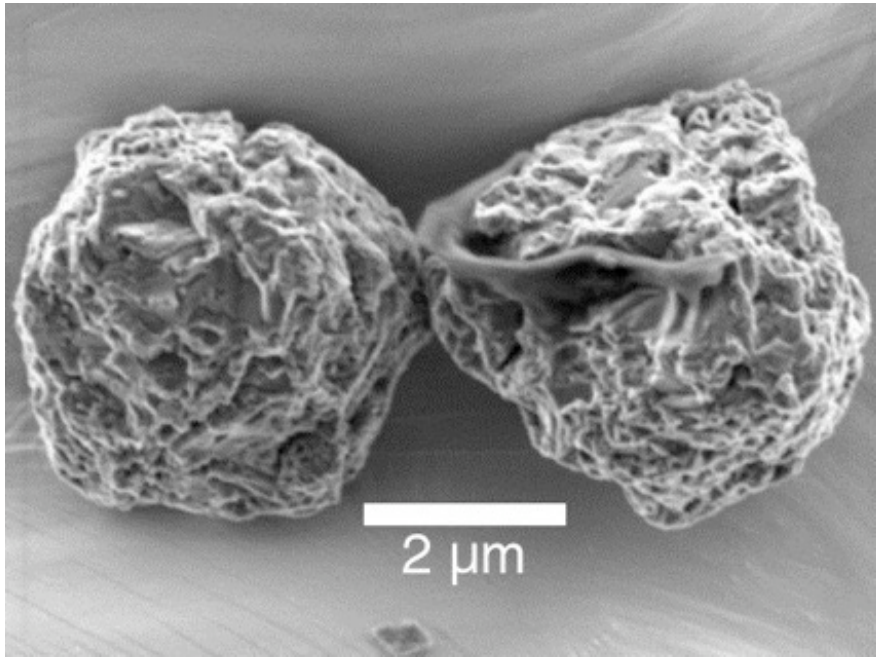
A mainstream SiC coated by organic gunk.

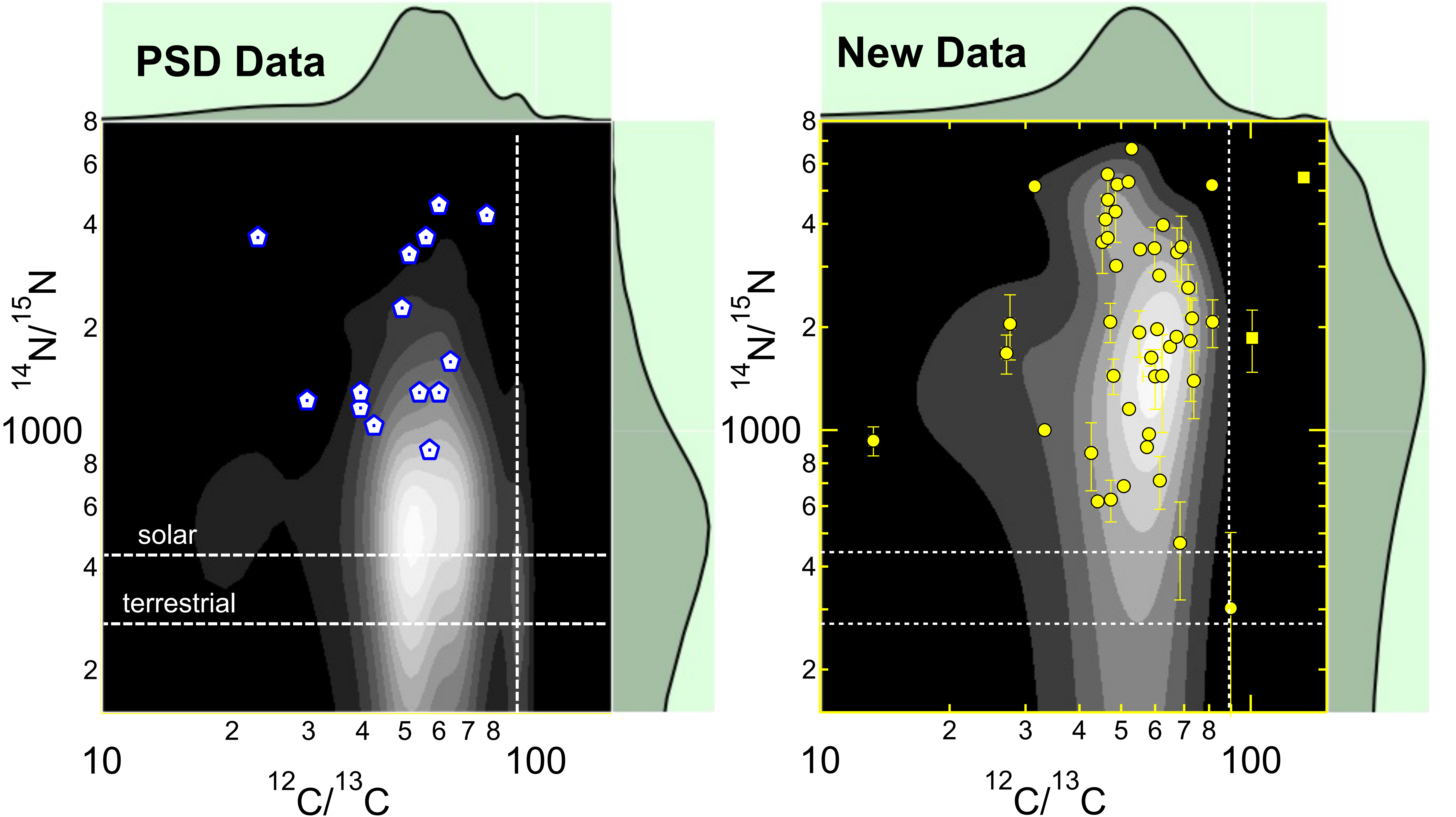
Approach to Suppress Contamination

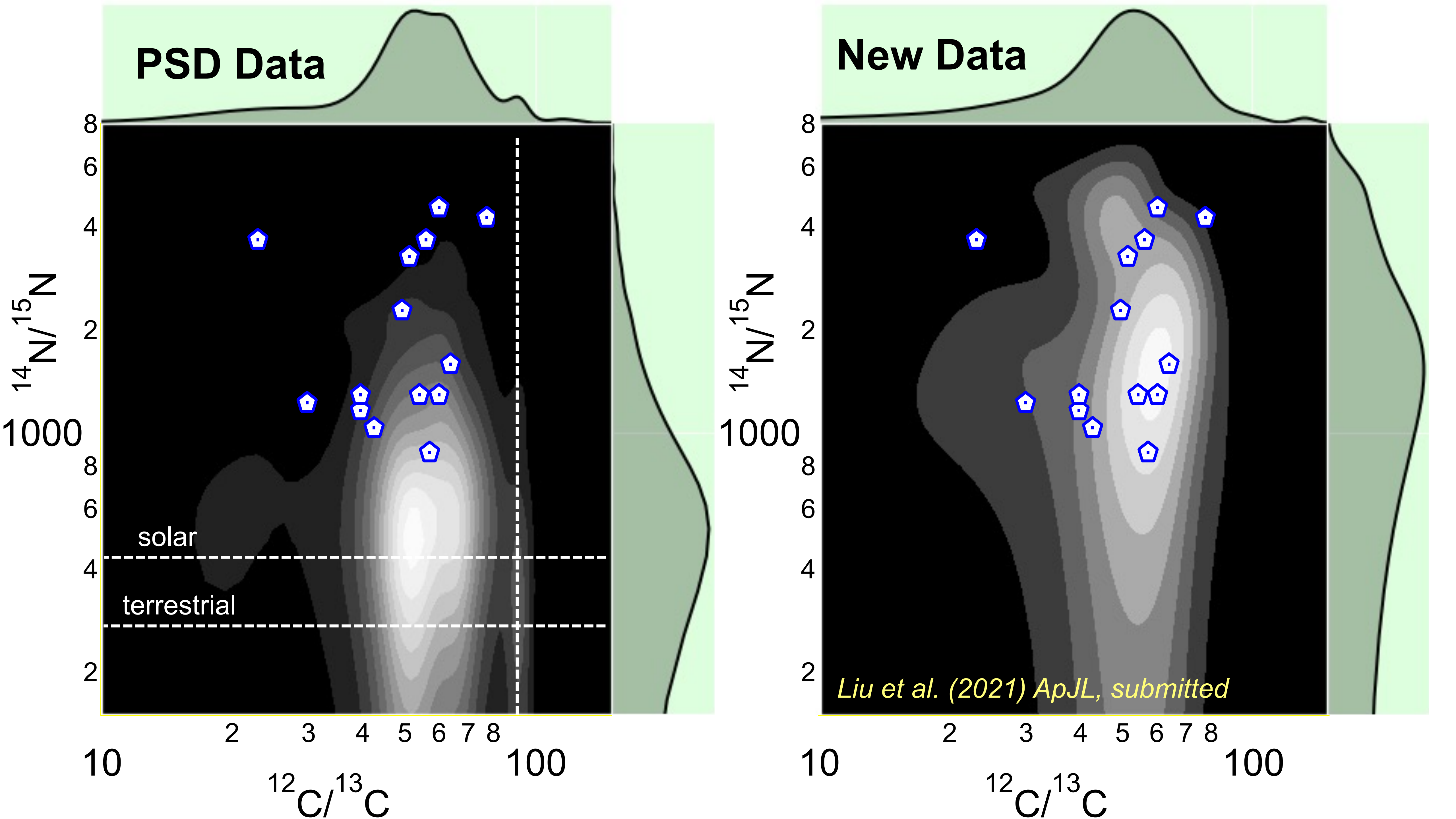
Extensive Sputtering

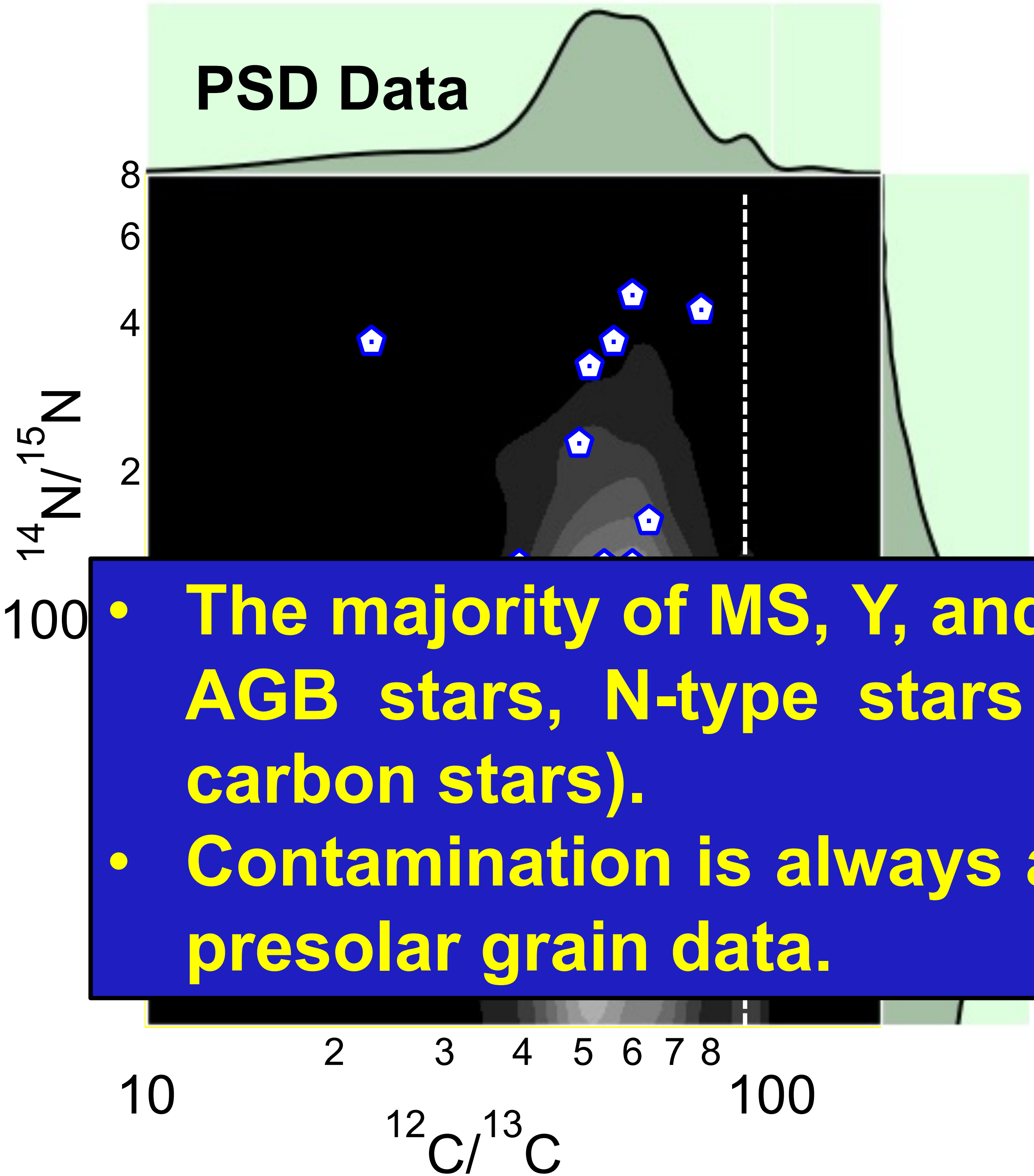


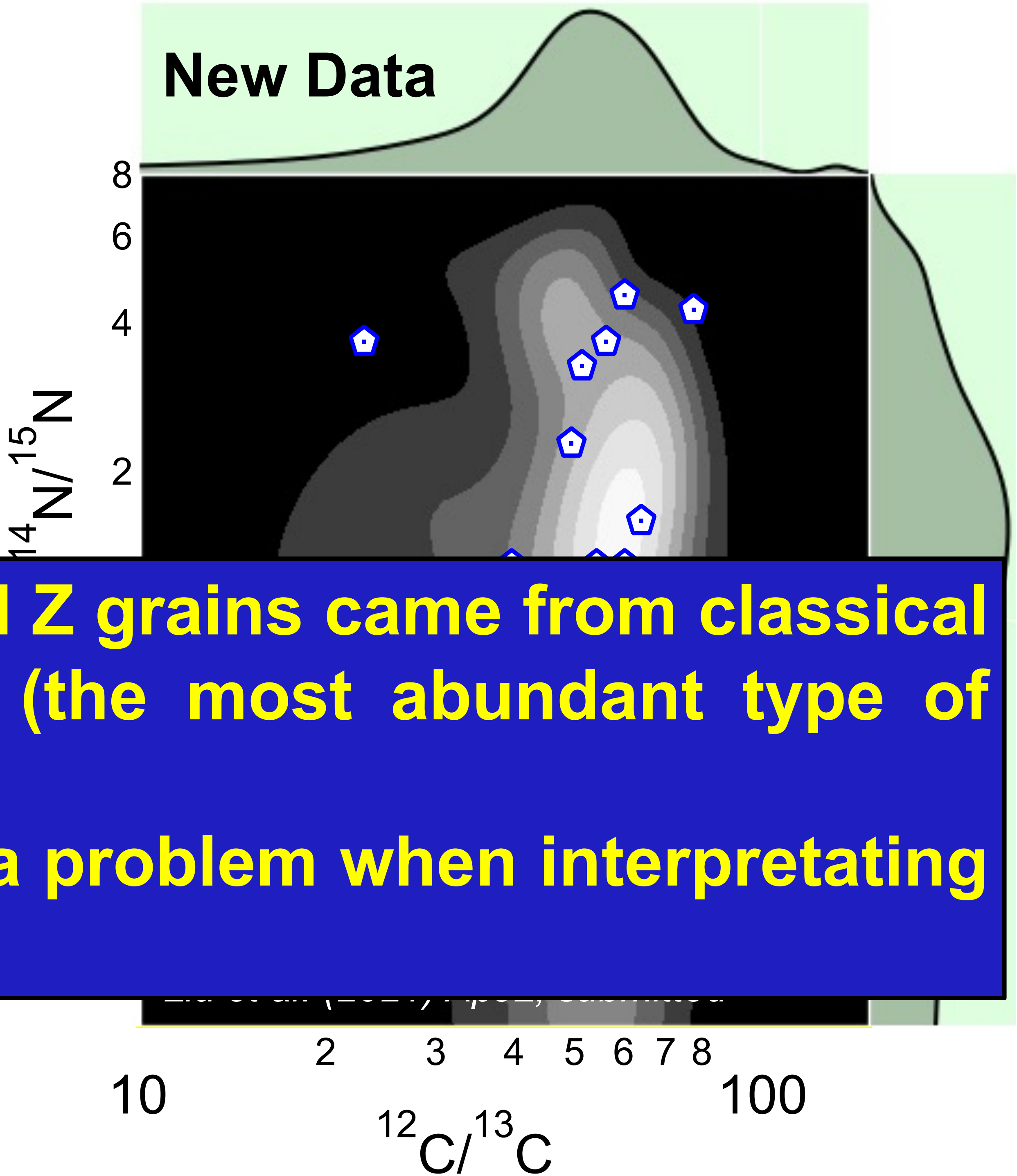





PSD Data
New Data
solar
terrestrial
$^{14}N/^{15}N$
$^{12}C/^{13}C$
1000
10
100
2
3
4
5
6
7
8


PSD Data
New Data
solar
terrestrial
Liu et al. (2021) ApJL, submitted
$^{14}N/^{15}N$
$^{12}C/^{13}C$
10
100
1000





- The majority of MS, Y, and Z grains came from classical AGB stars, N-type stars (the most abundant type of carbon stars).
- Contamination is always a problem when interpretating presolar grain data.

AGB Stars: main stellar site for *s*-process

SPECTROSCOPIC OBSERVATIONS OF STARS OF CLASS S

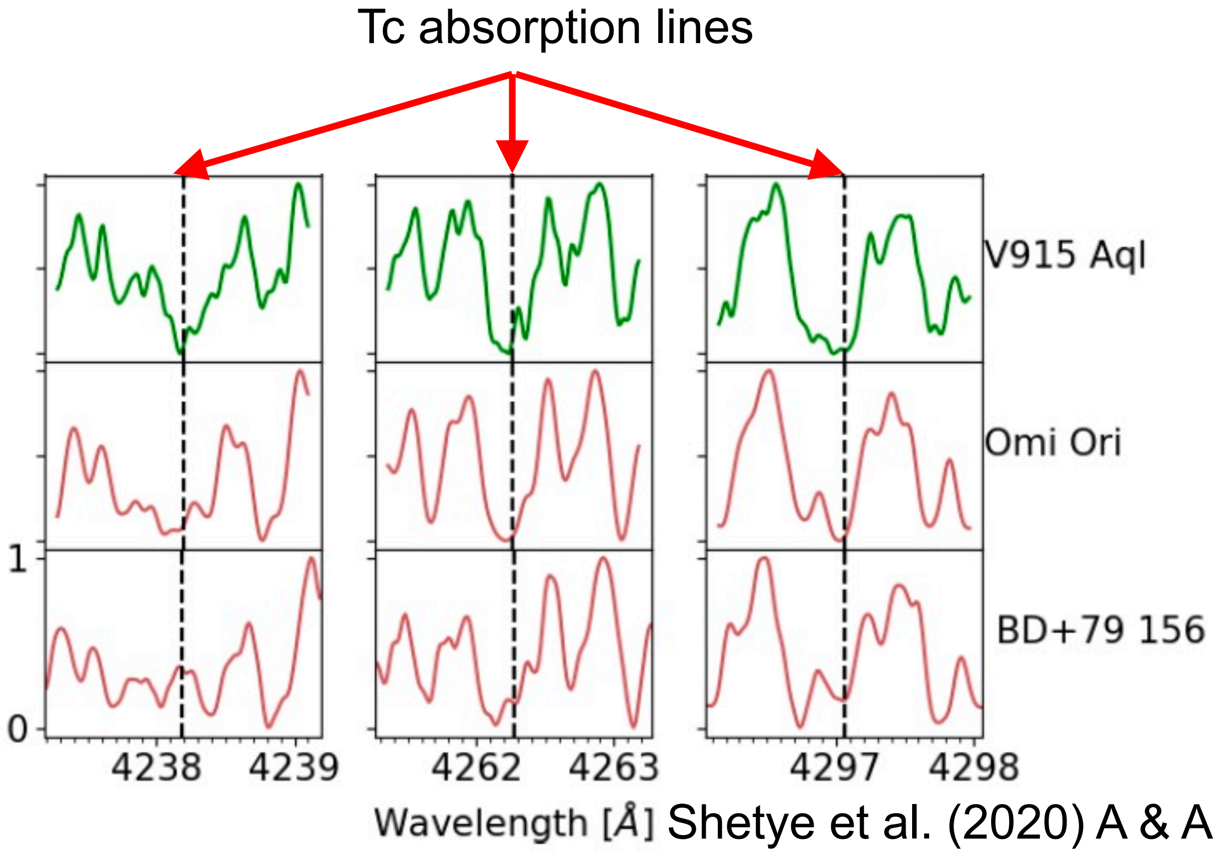
PAUL W. MERRILL
MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Received February 27, 1952

ABSTRACT

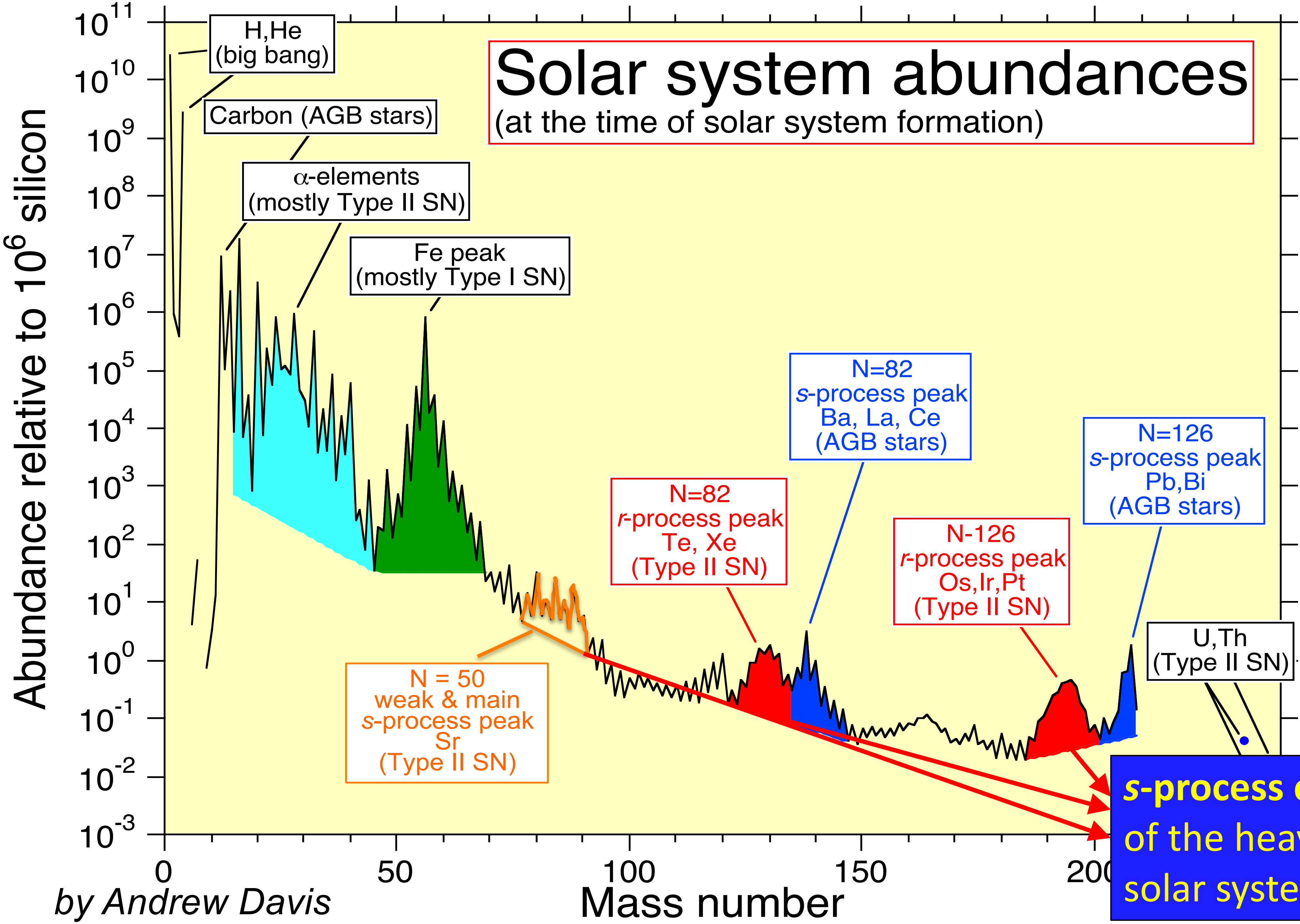
This paper presents a brief survey of S-type spectra based largely on spectrograms with dispersion 9 A/mm of eight stars obtained by I. S. Bowen with the 200-inch telescope. The intensities of several groups of absorption lines and bands and of the more important emission lines are compared in various stars. Radial velocities from both bright and dark lines and a supplementary list of absorption lines identified in the green region are included. The remarkable behavior of certain bright lines of *V* I and of *Cr* in the spectrum of R Cygni is described.

Ru98 0+ 1.88	Ru99 5/2+ 12.7	Ru100 0+ 12.6	Ru101 5/2+ 17.0	Ru102 0+ 31.6
Tc97 2.6E6 y 9/2+ * EC	Tc98 4.2E+6 y (6)+ β-	Tc99 2.111E+5 y 9/2+ * β-	Tc100 15.8 s 1+ β-	Tc101 14.22 m (9/2)+ β-
Mo96 0+ 16.68	Mo97 5/2+ 9.55	Mo98 0+ 24.13	Mo99 65.94 h 1/2+ β-	Mo100 1.2E19 y 0+ β-β- 9.63

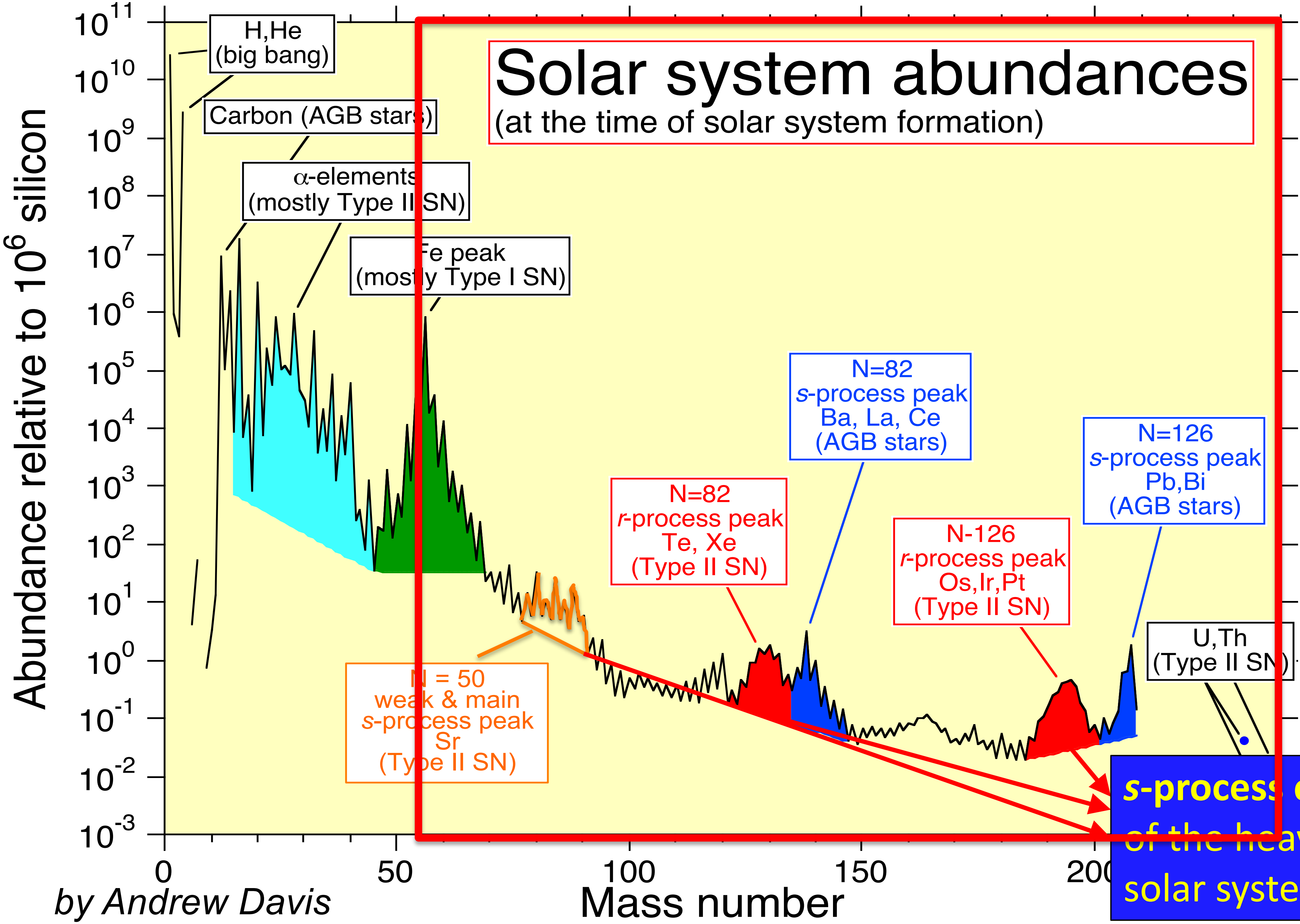


Shetye et al. (2020) A & A

In situ production of Tc inside AGB stars!



***s*-process contribution**: half of the heavy elements in the solar system.



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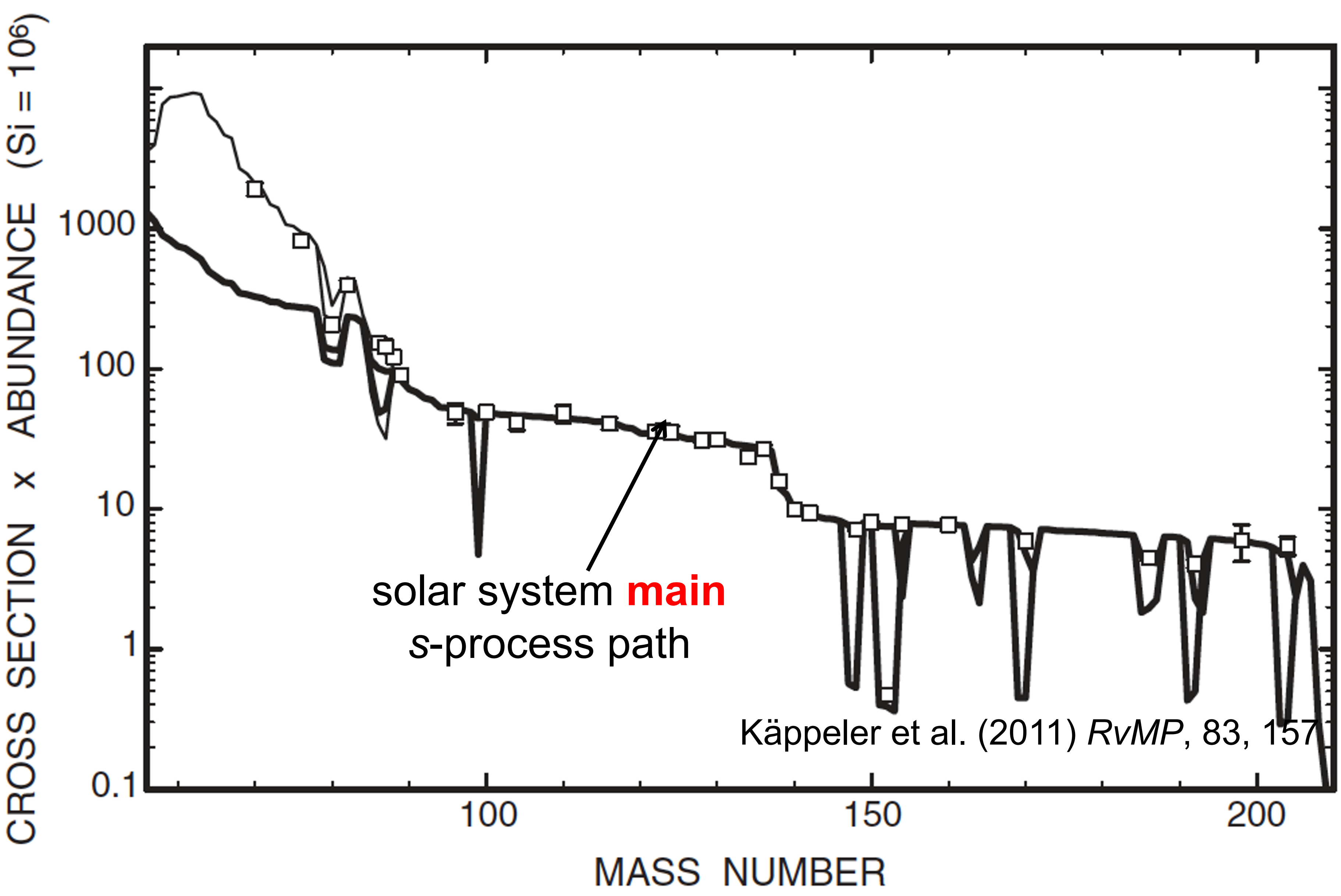
s-Process: slow neutron-capture process



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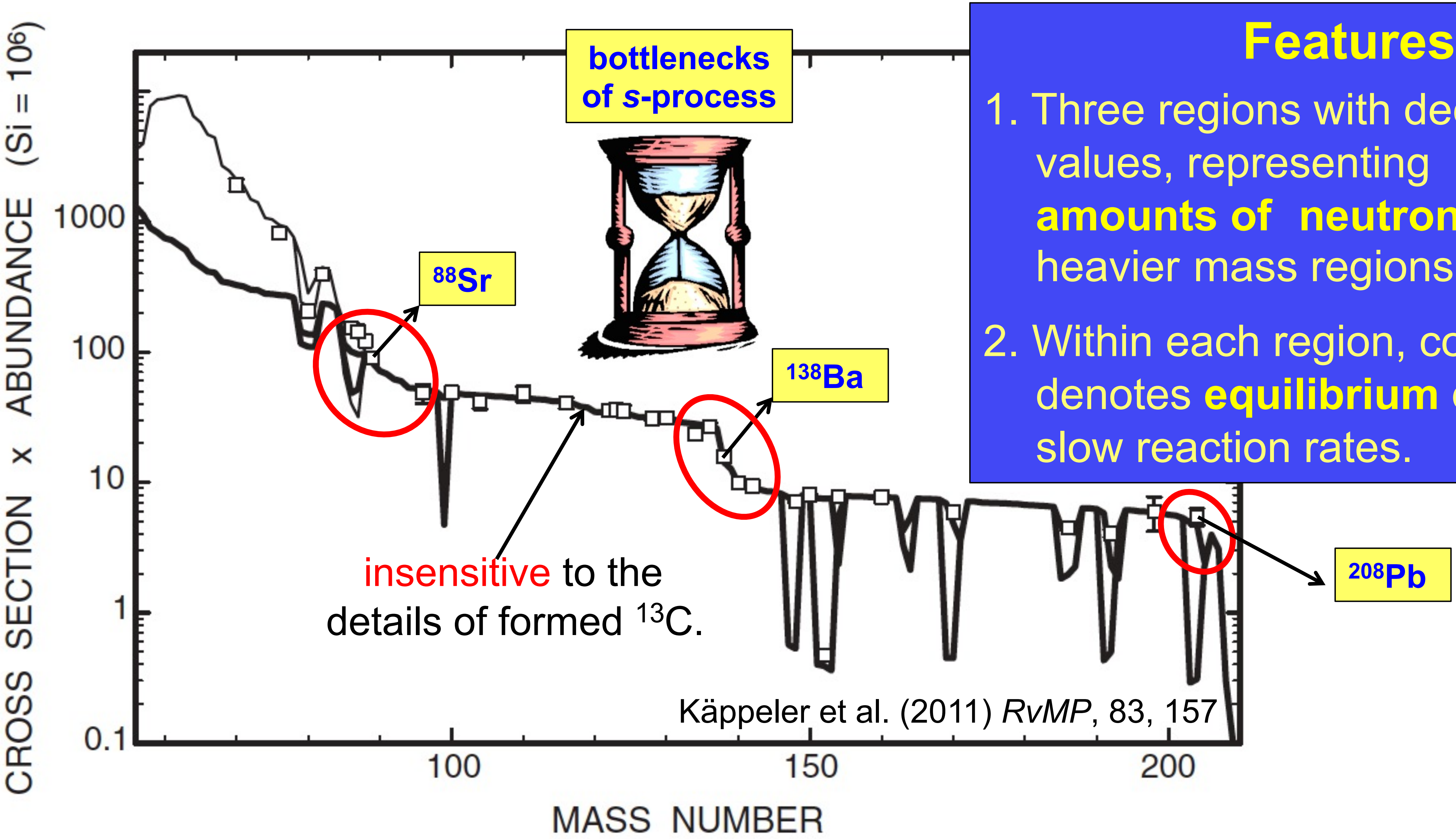
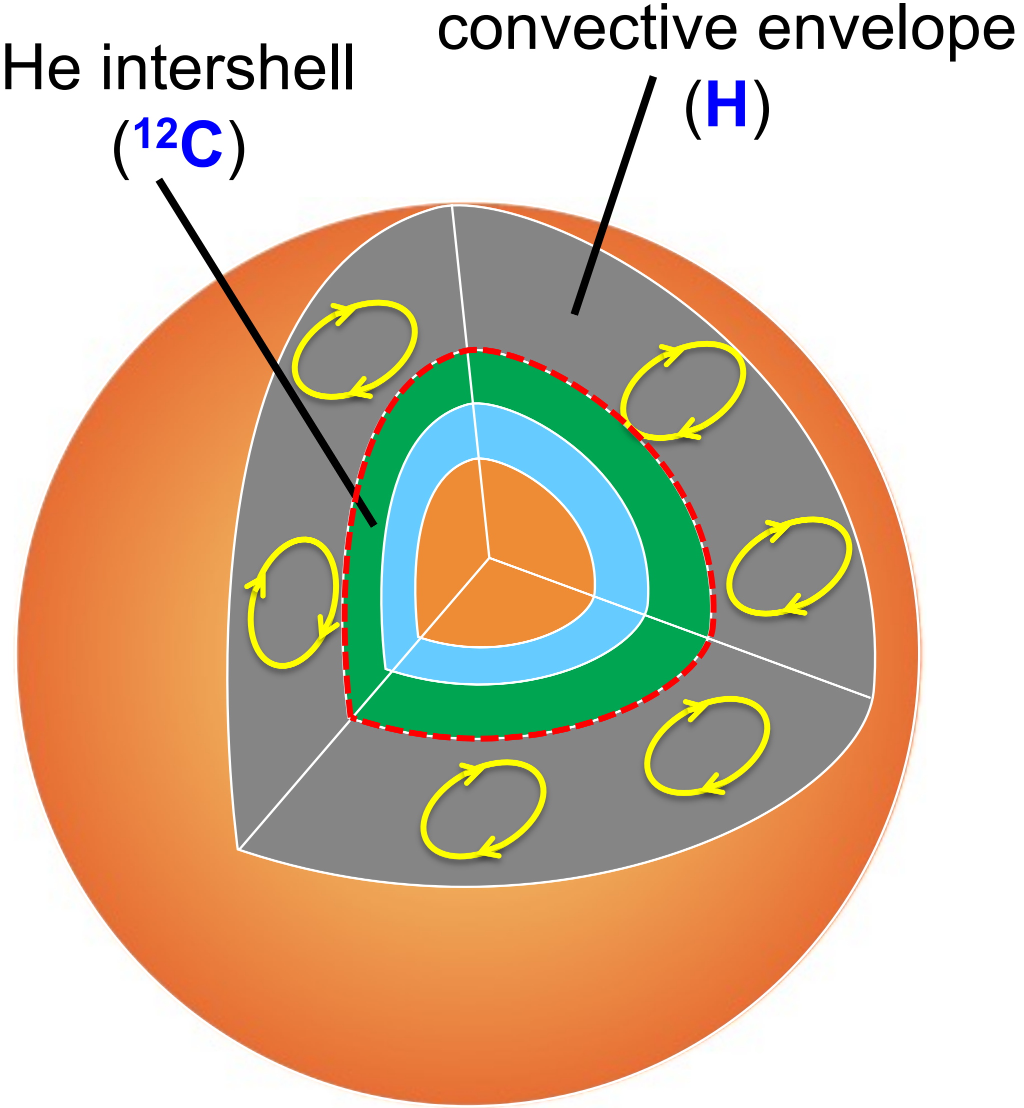


Features

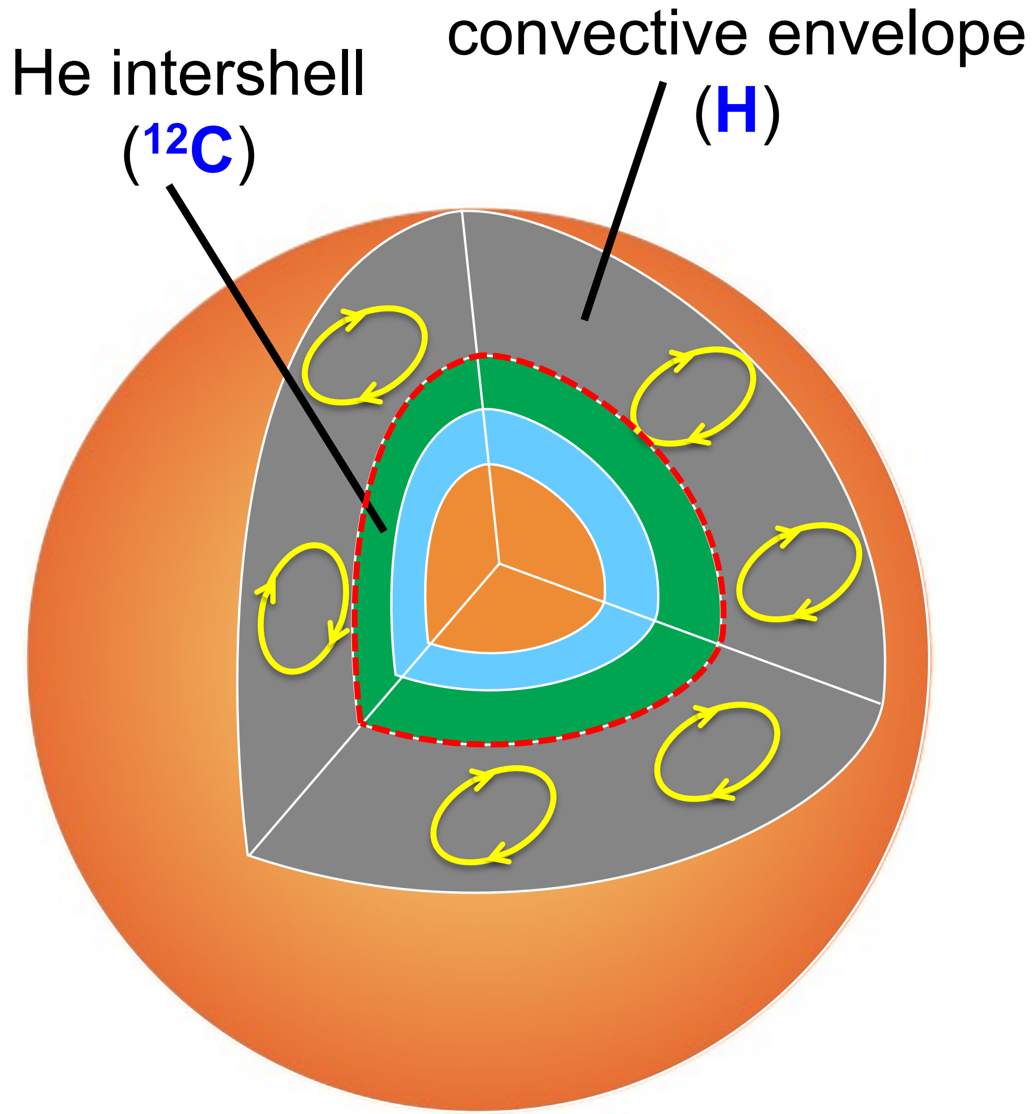
1. Three regions with decreasing y values, representing **decreasing amounts of neutrons** reaching heavier mass regions.
2. Within each region, constant y denotes **equilibrium** due to the slow reaction rates.

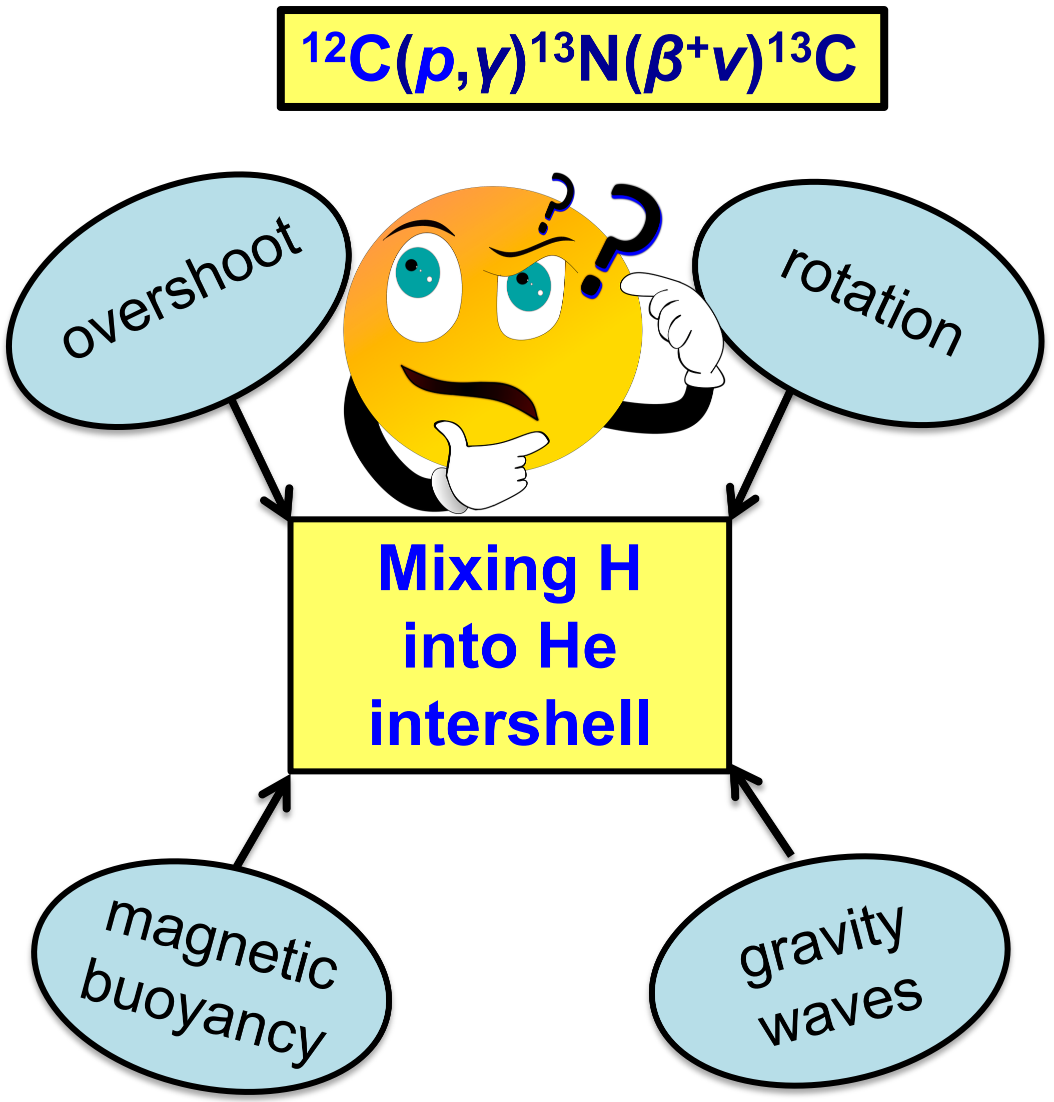
Major Neutron Source for *s*-Process: $^{13}C(\alpha,n)^{16}O$



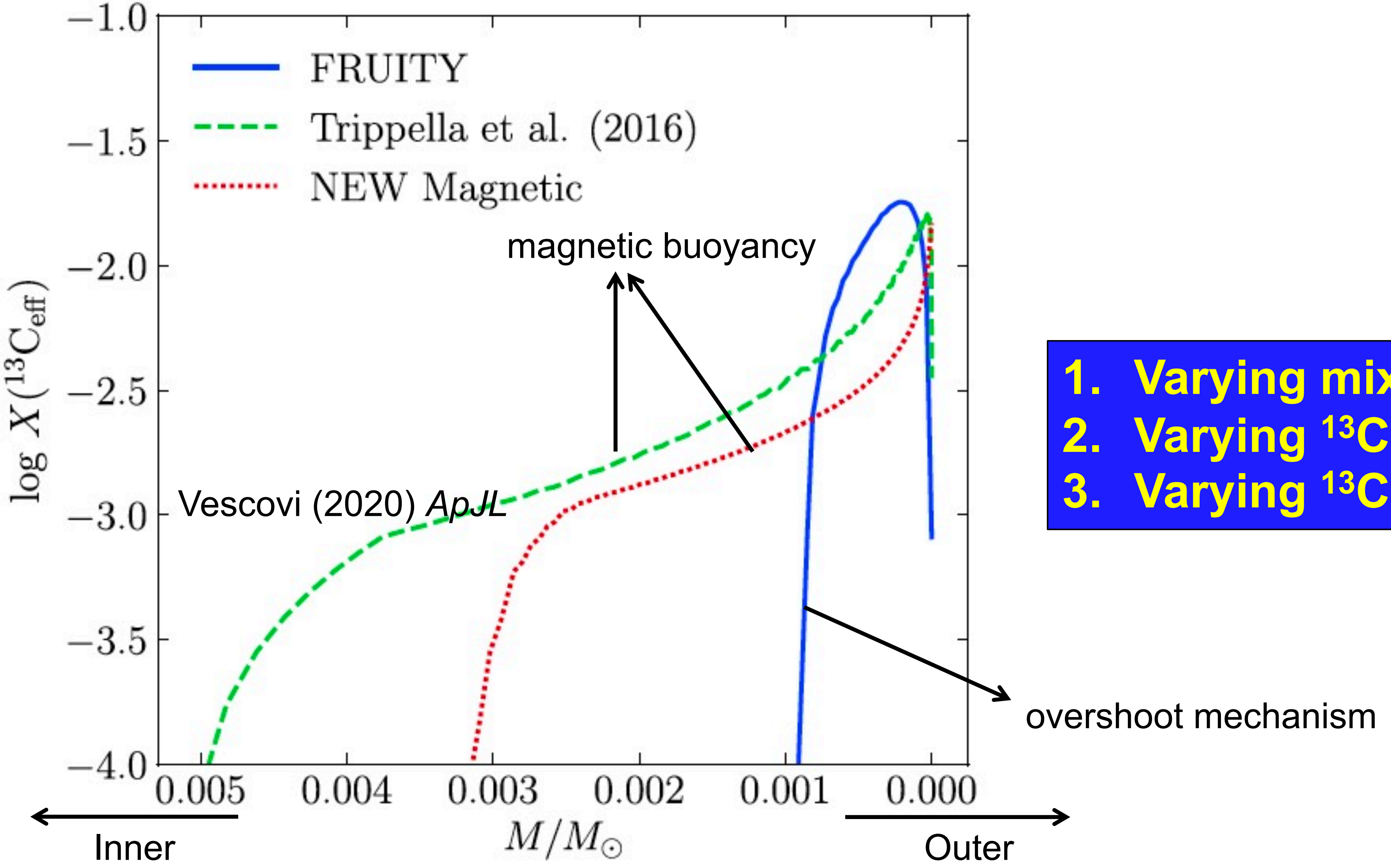
$^{13}C(\alpha,n)^{16}O$: providing neutrons with a density of **10^7 to 10^8 cm^{-3}**, in agreement with solar system *s*-process distribution and astronomical observations of *s*-process elements.

Problem for AGB Stellar Modelers: local mixing of H into He-intershell



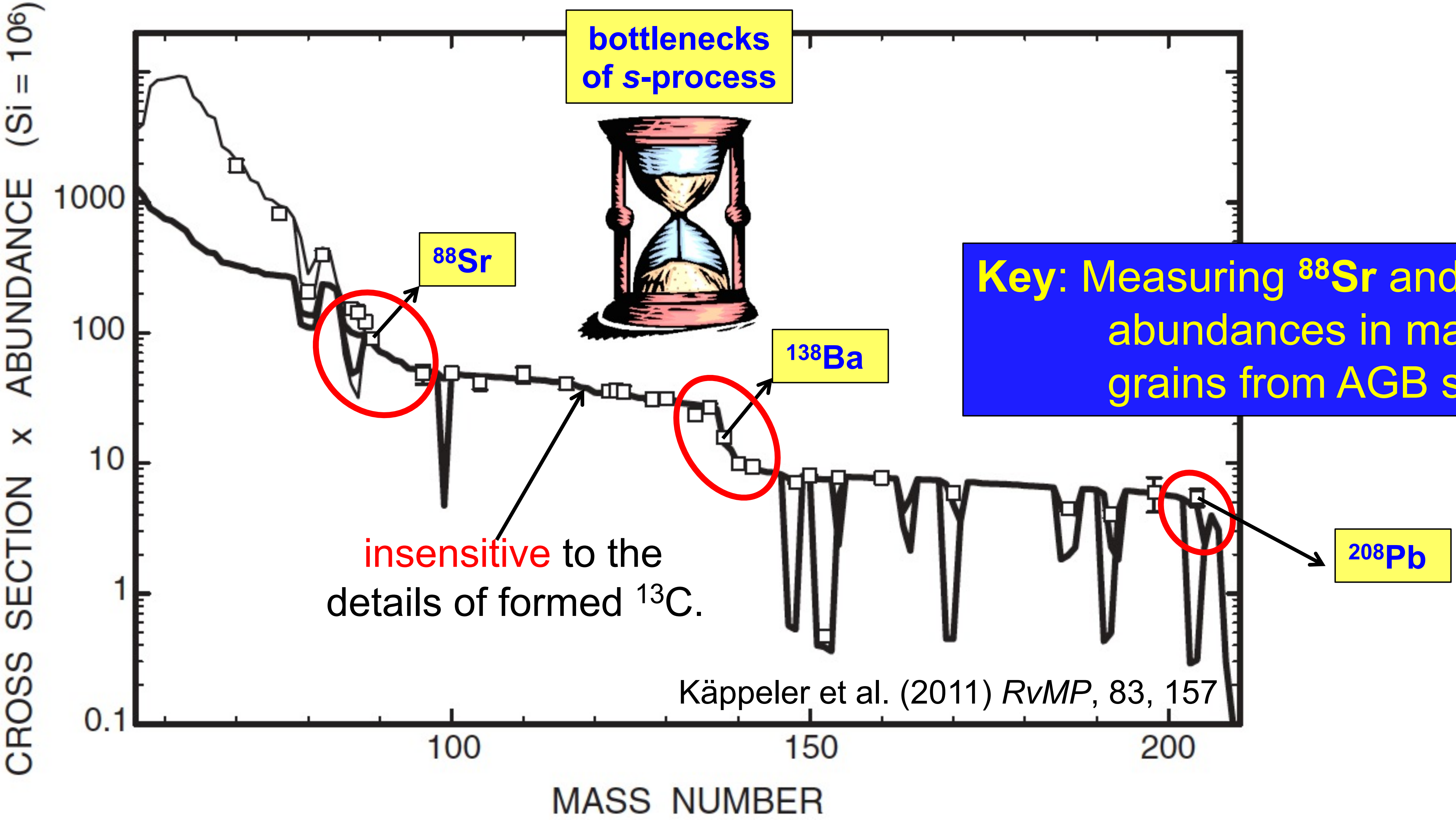


Discrepant Modeling Results for Mixing



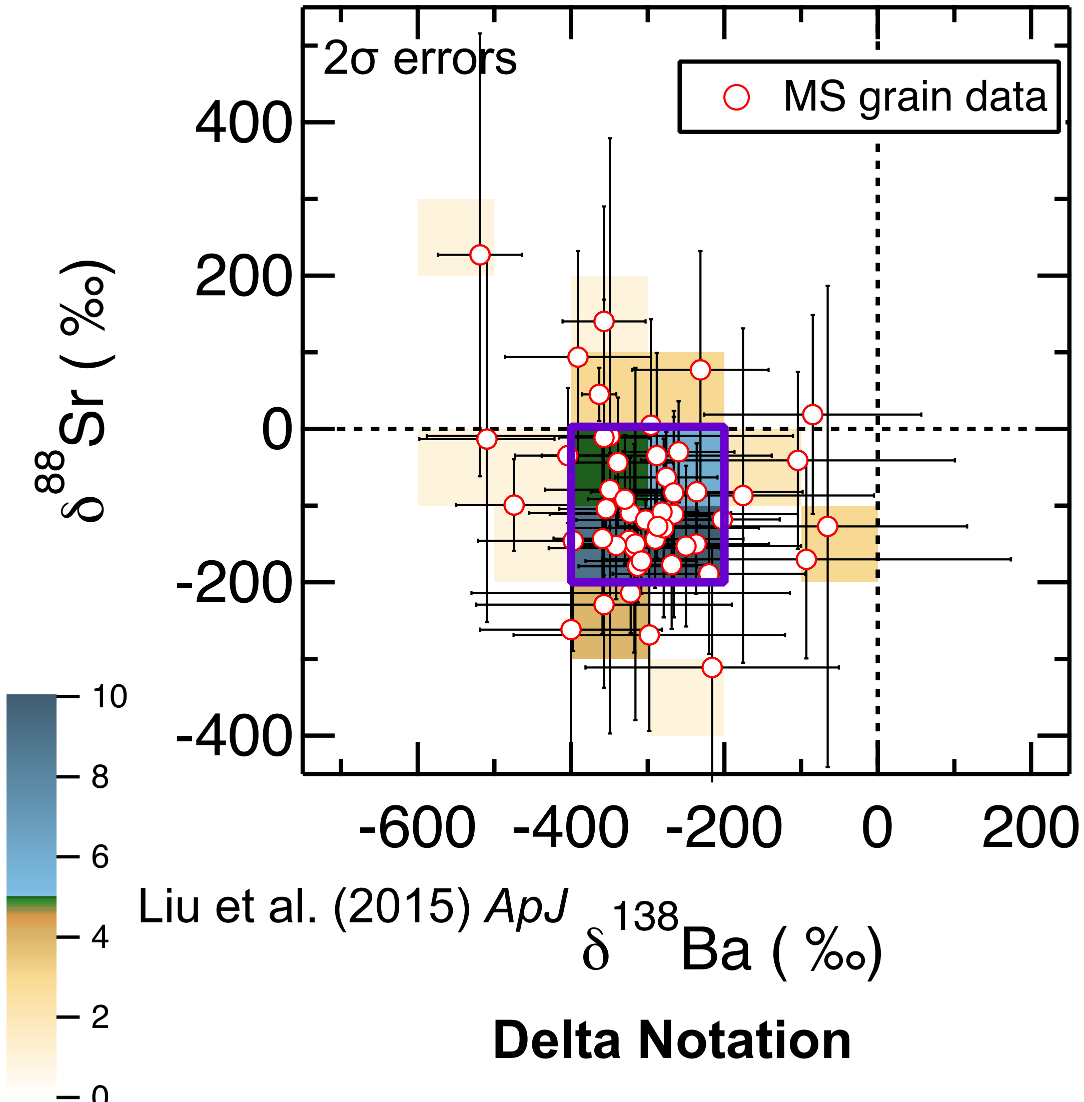
1. Varying mixing depths.
2. Varying ^{13}C mixing profiles.
3. Varying ^{13}C concentrations.

Smoking Guns for Constraining ^{13}C Formation



Key: Measuring ^{88}**Sr** and ^{138}**Ba** abundances in mainstream SiC grains from AGB stars.

MS SiC Isotopic Data of Sr, Ba

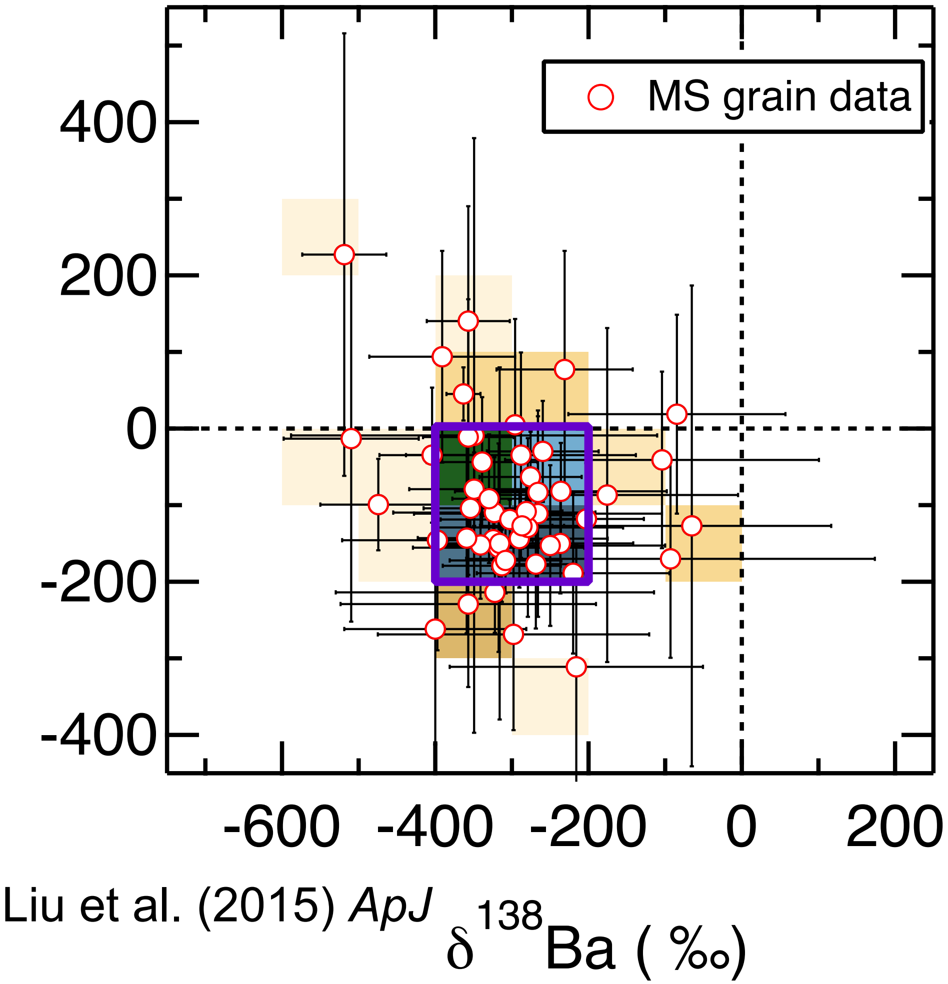


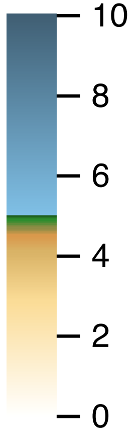
Liu et al. (2015) *ApJ*

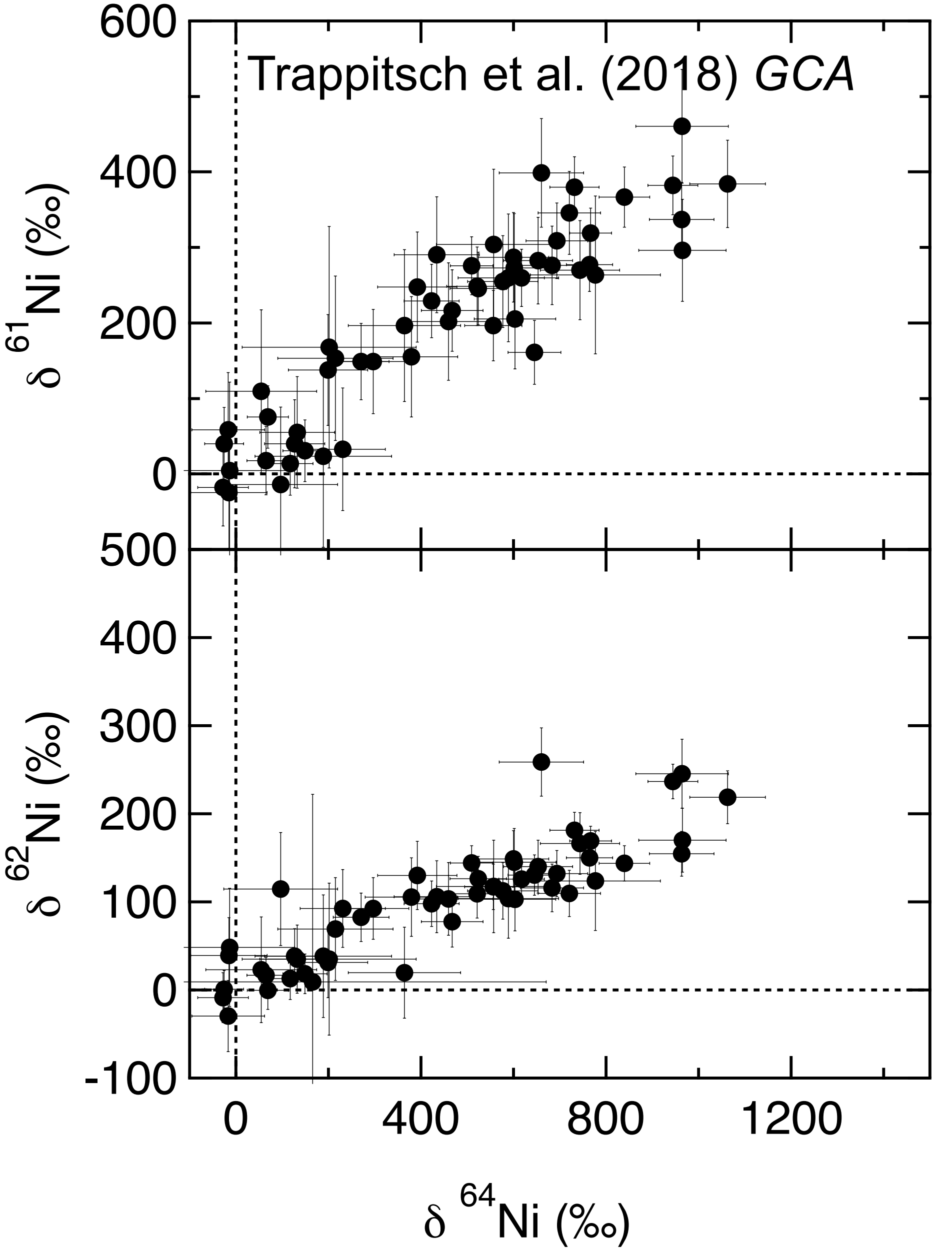
Delta Notation

$\delta^{88}Sr = [(^{88}Sr/^{86}Sr)_{SiC}/(^{88}Sr/^{86}Sr)_{std} - 1] \times 1000$

MS SiC Isotopic Data of Sr, Ba and Ni







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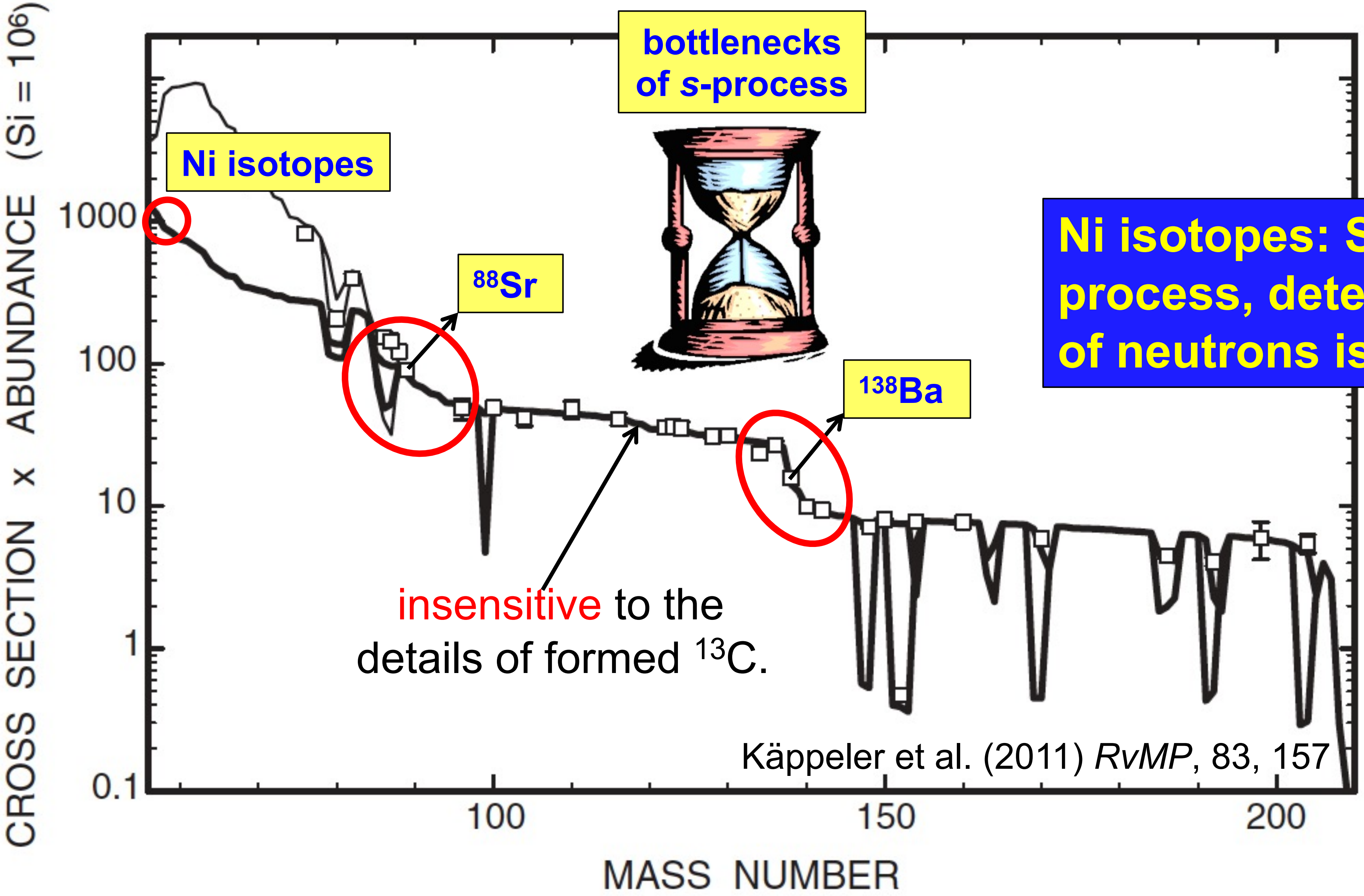
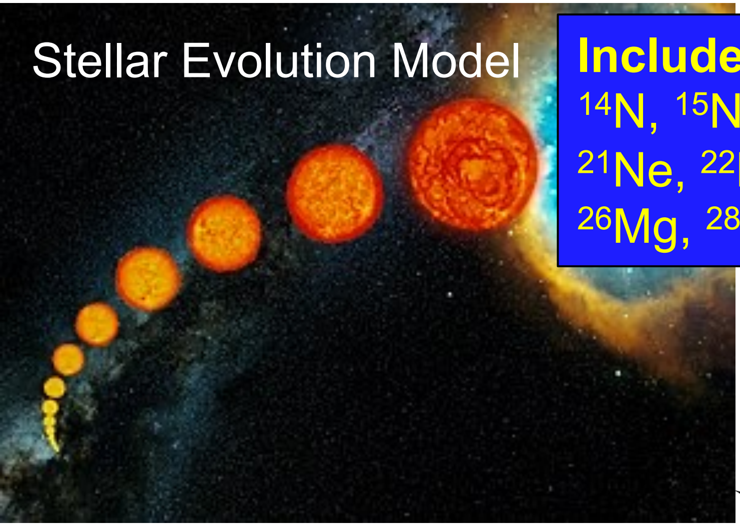


Ni isotopes: Starting point of the *s*-process, determining what fraction of neutrons is trapped here.

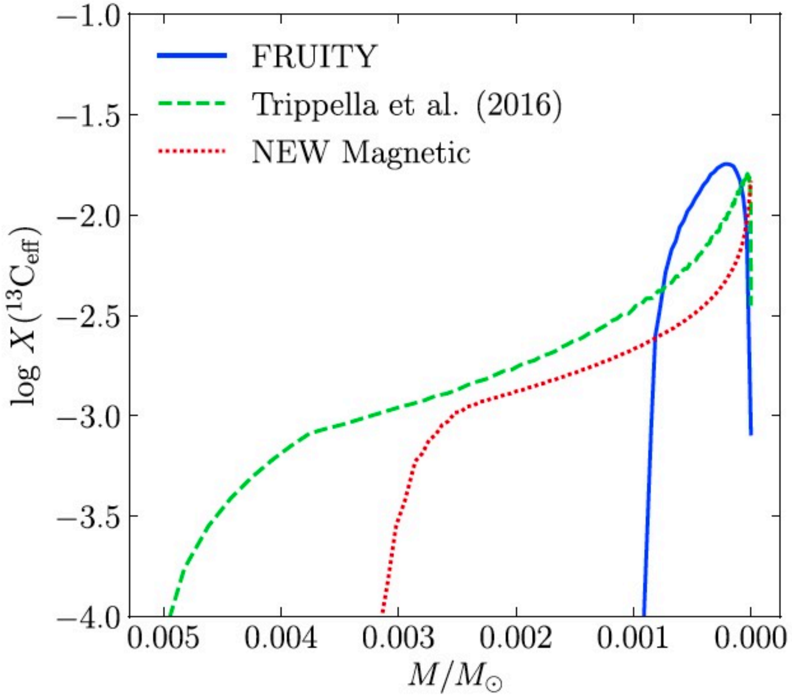
Post-process Nucleosynthesis Calculations

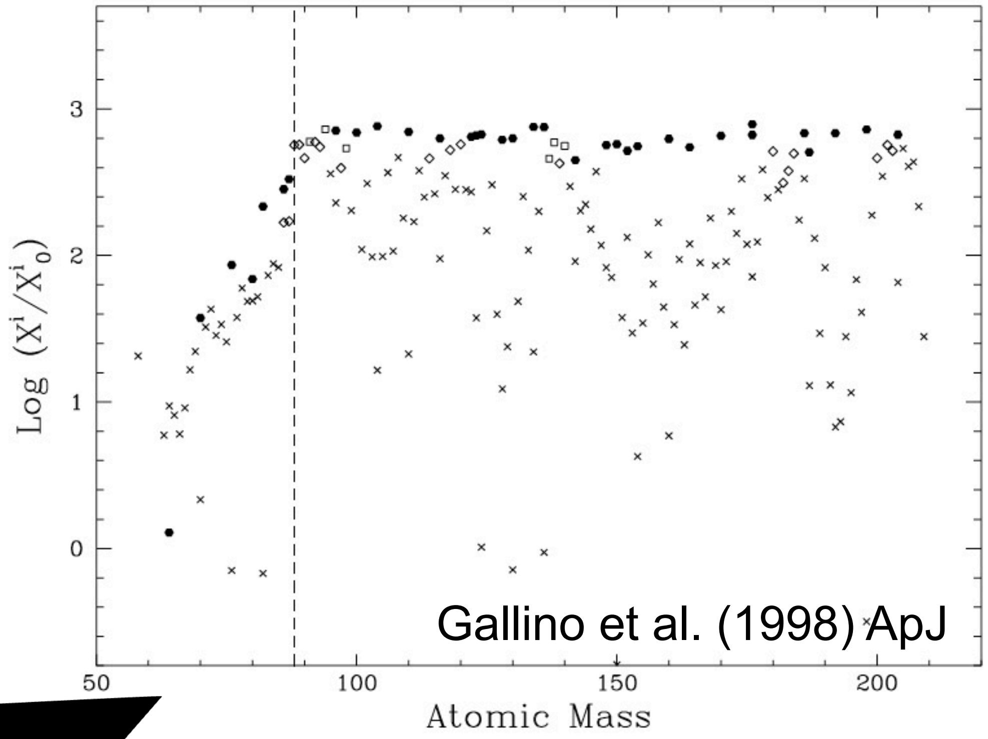


Included : ^{1}H, ^{3}He, ^{4}He, ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{18}O, ^{19}F, ^{20}Ne, ^{21}Ne, ^{22}Ne, ^{23}Na, ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{28}Si, **energy-providers!**

Post-process nucleosynthesis model: the whole nucleosynthesis network is included!

(P, T) conditions with time

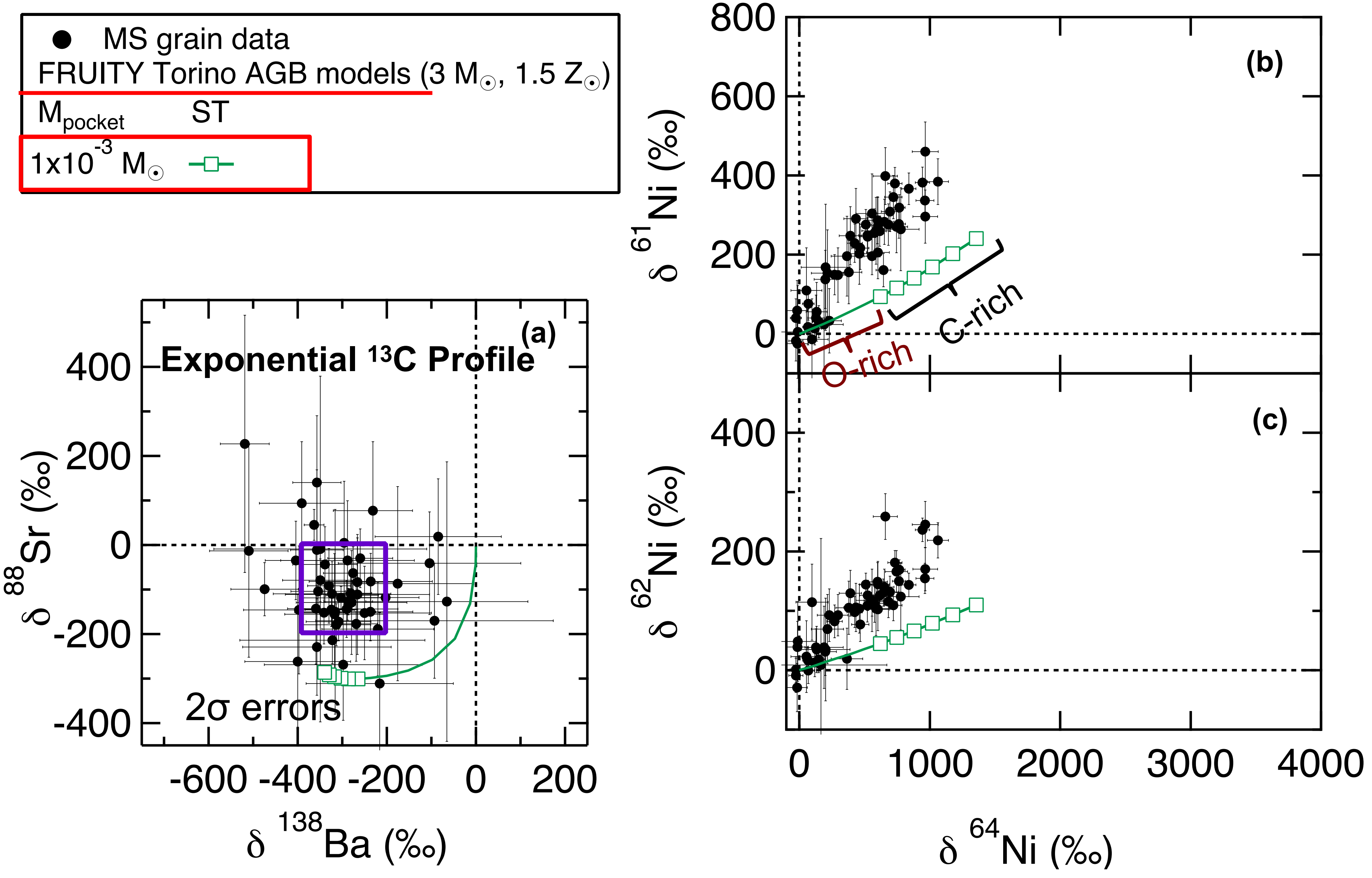




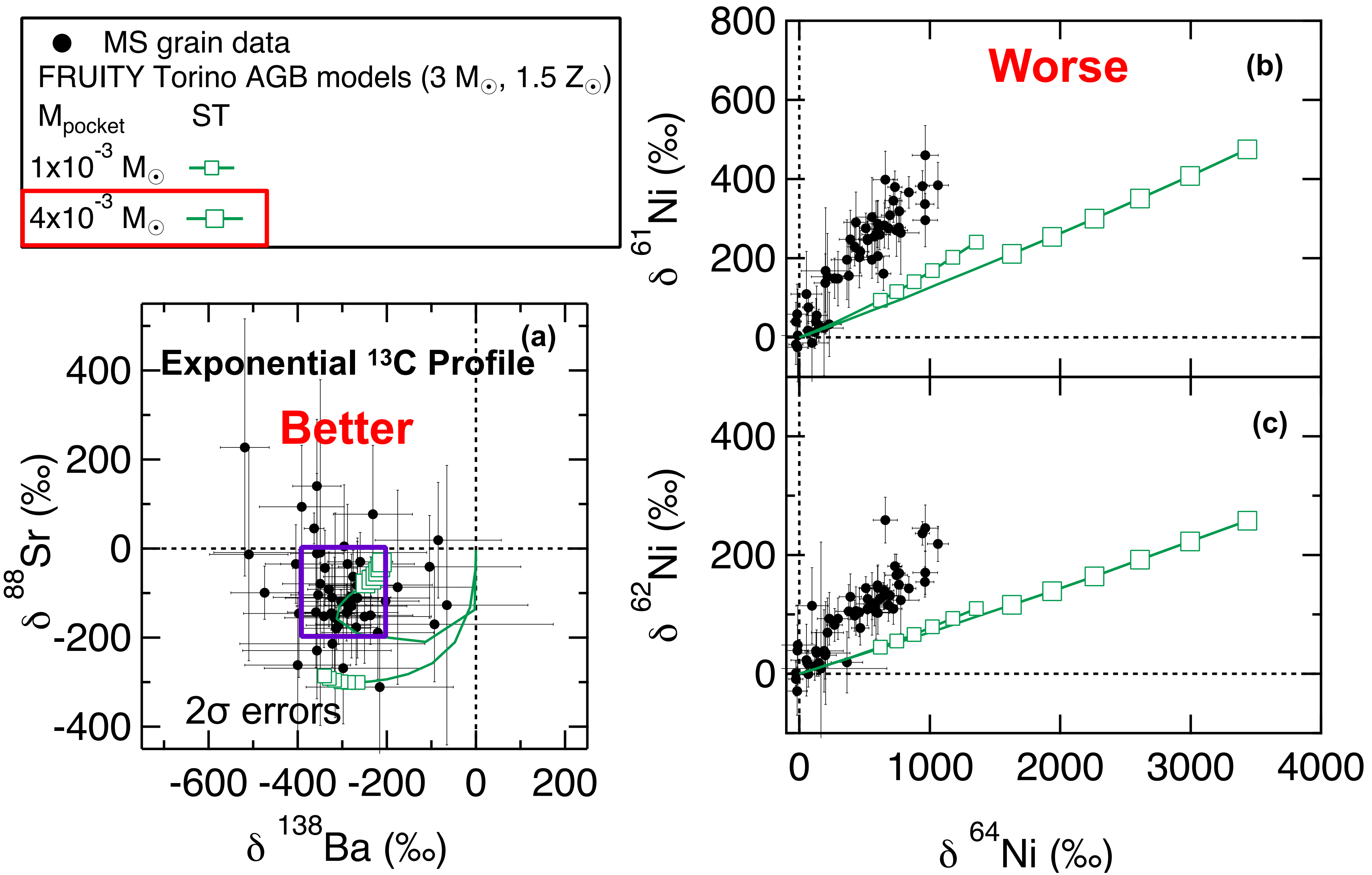
H mixing profile

Advantage: easy test of various stellar parameters.

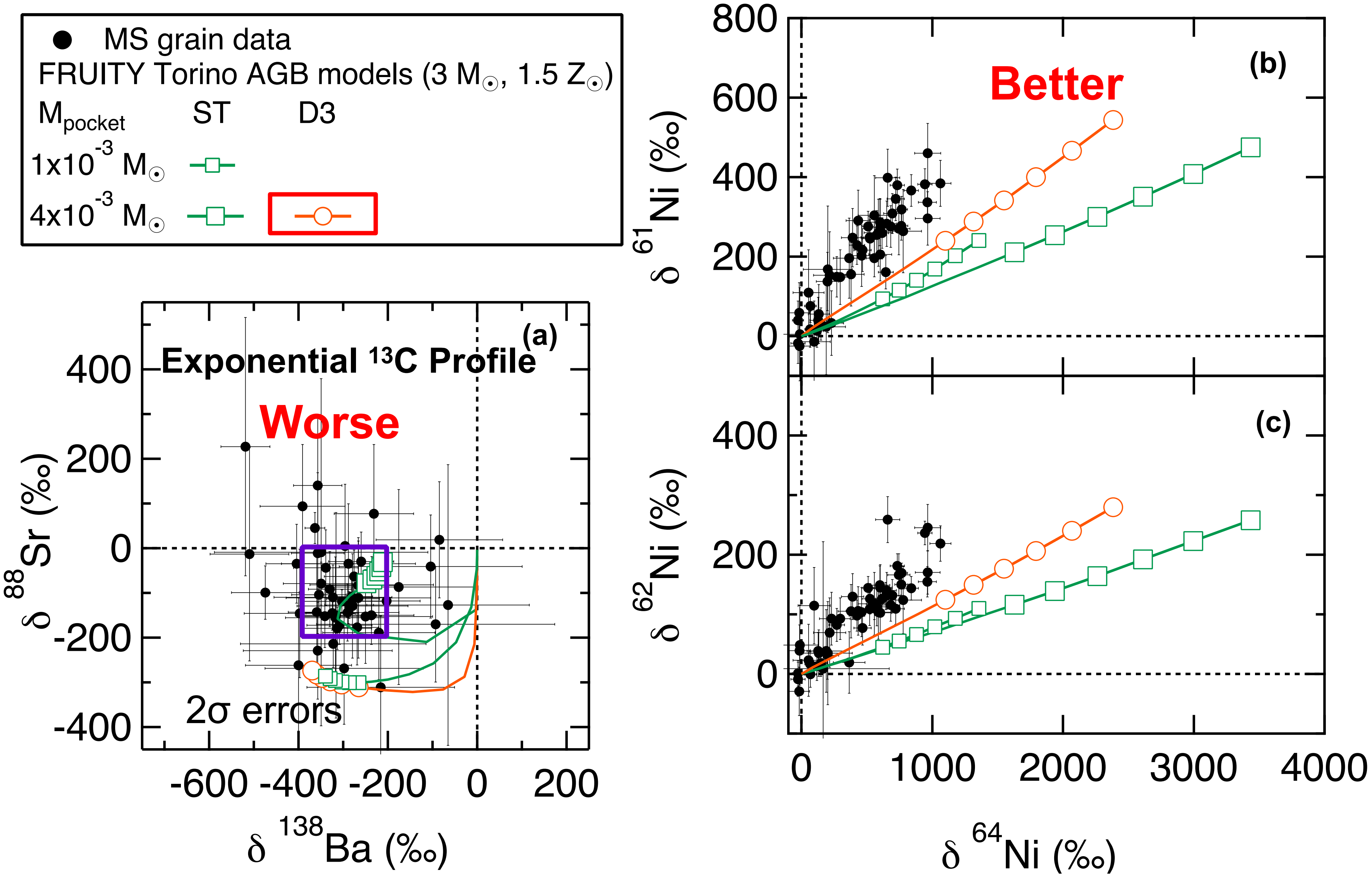
Standard Exponential ^{13}C-Pocket



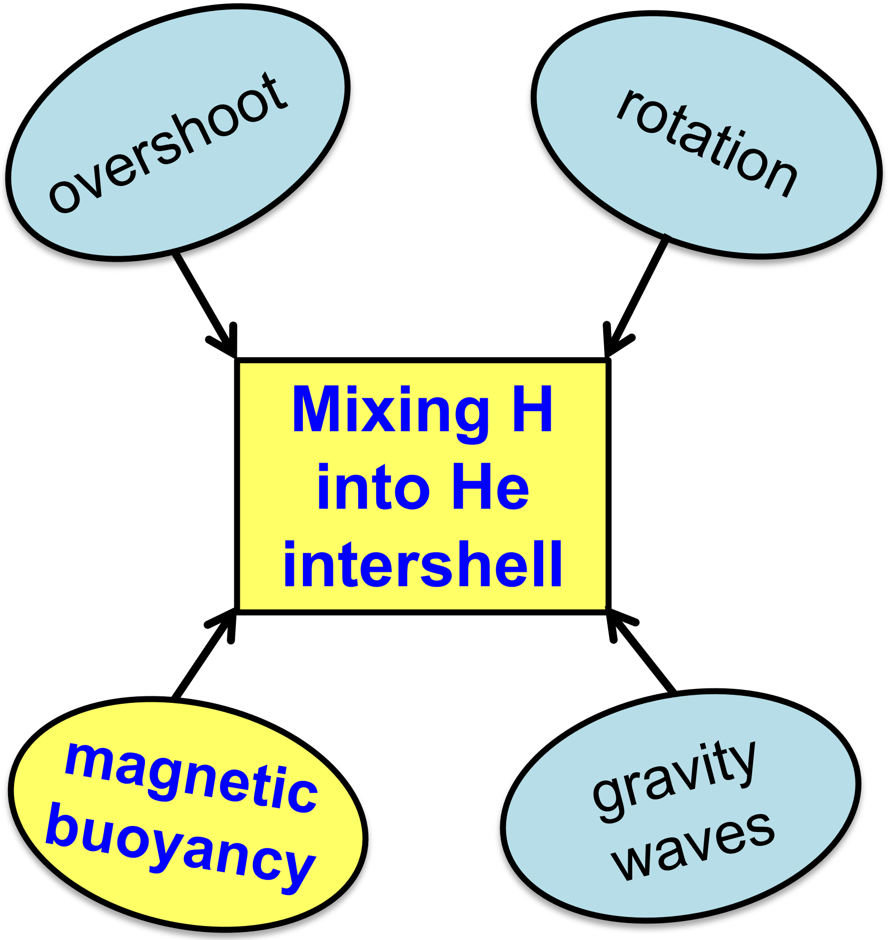
Standard Exponential ^{13}C-Pocket

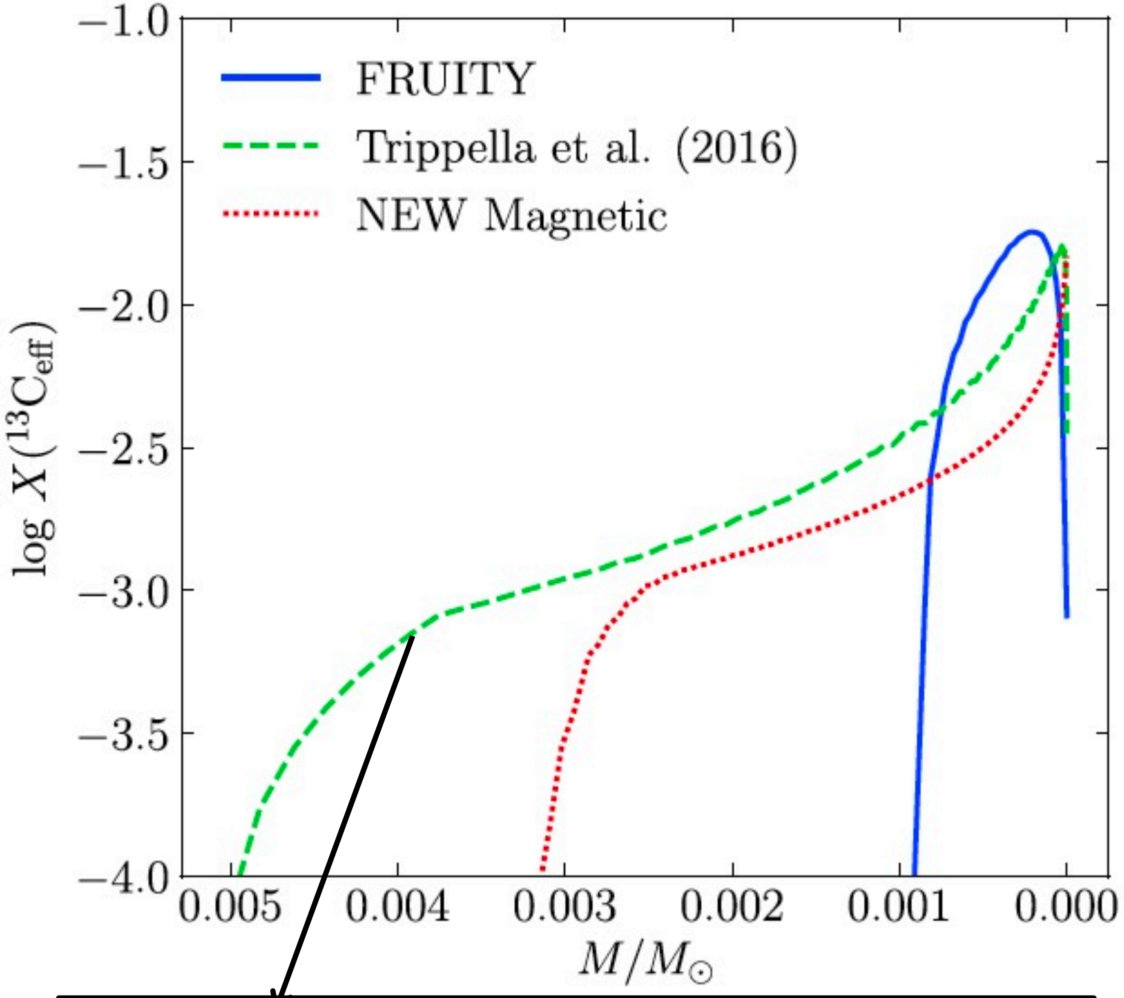


Standard Exponential ^{13}C-Pocket



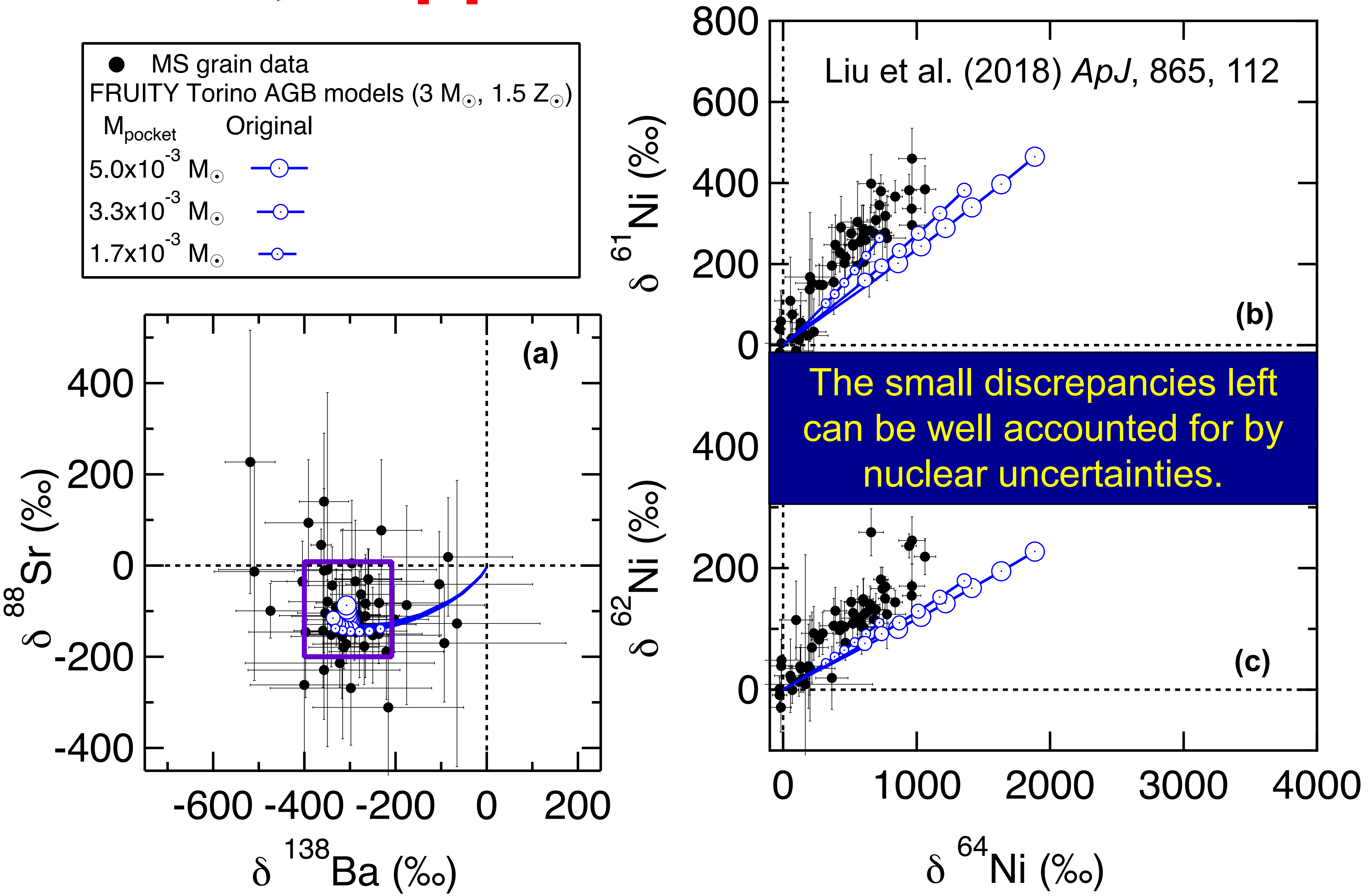
Mixing of H by Magnetic Buoyancy



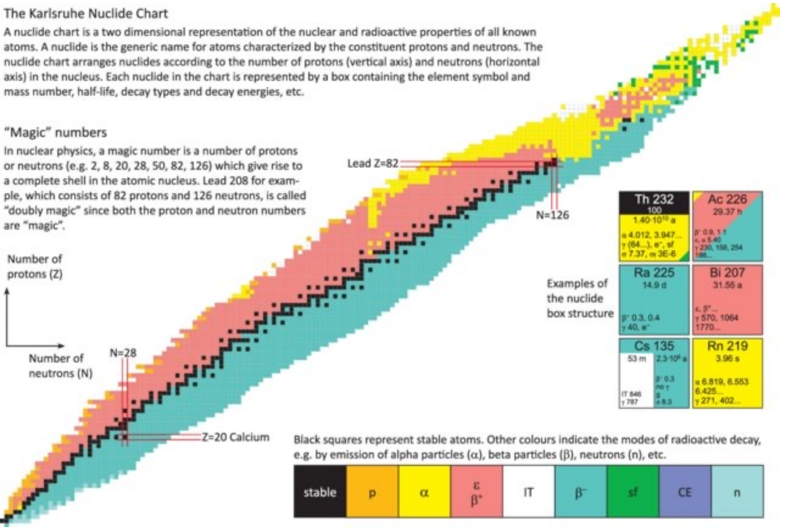


1. deeper mixing
2. lower ^{13}C density on average
3. relatively more flattened

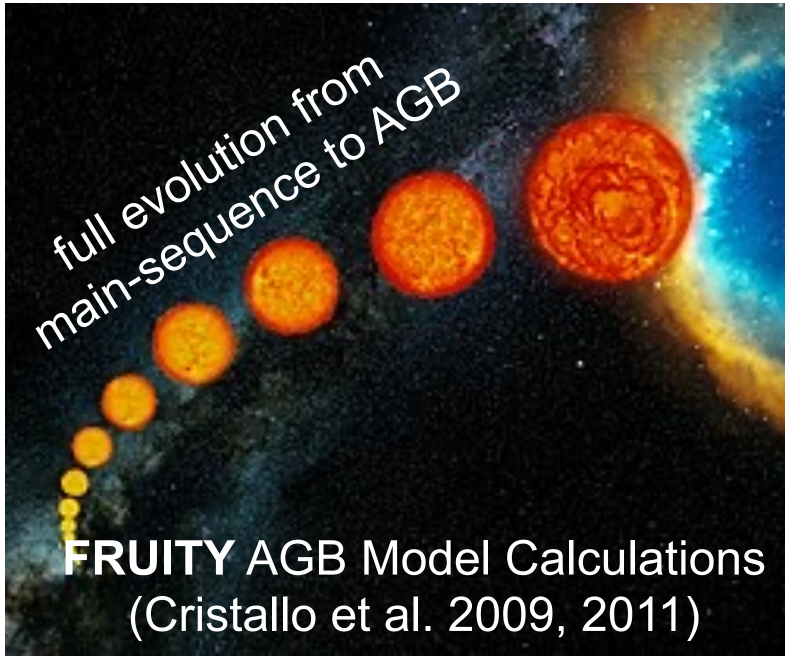
Yes, Trippella Pocket works!



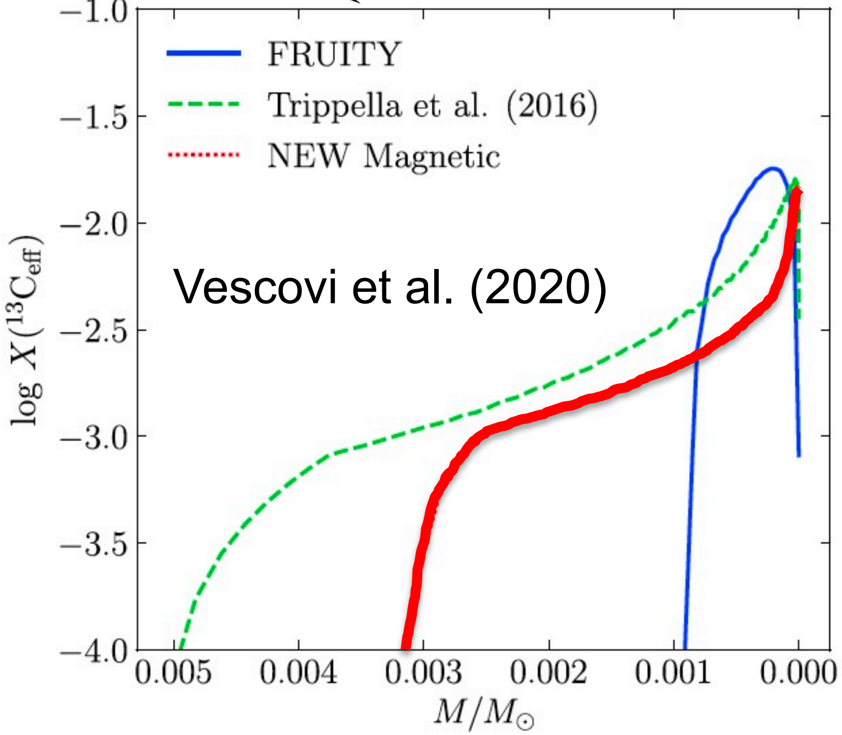
Fully Coupled Stellar and Nucleosynthesis Calculations



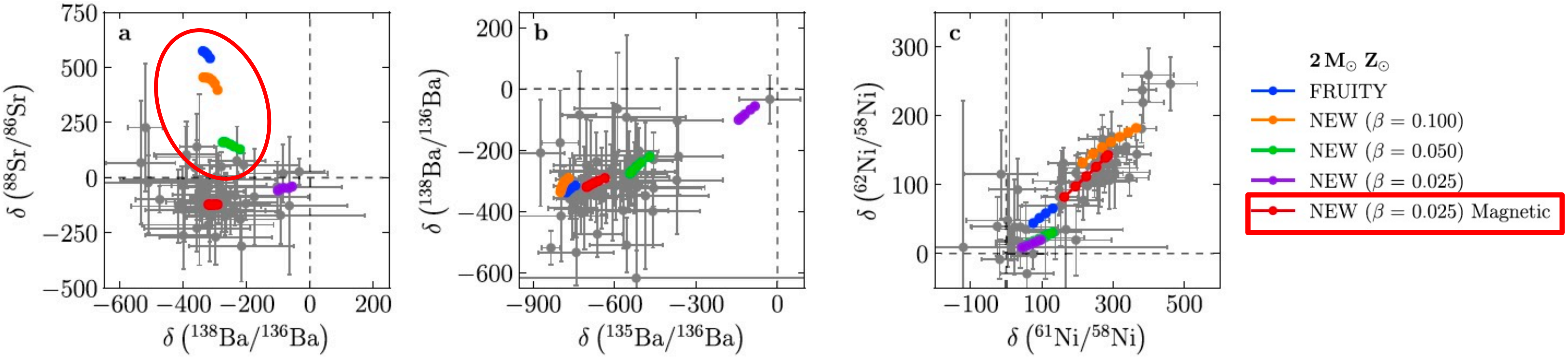
full nucleosynthesis network



Follow ^{13}C formation by magnetic buoyancy



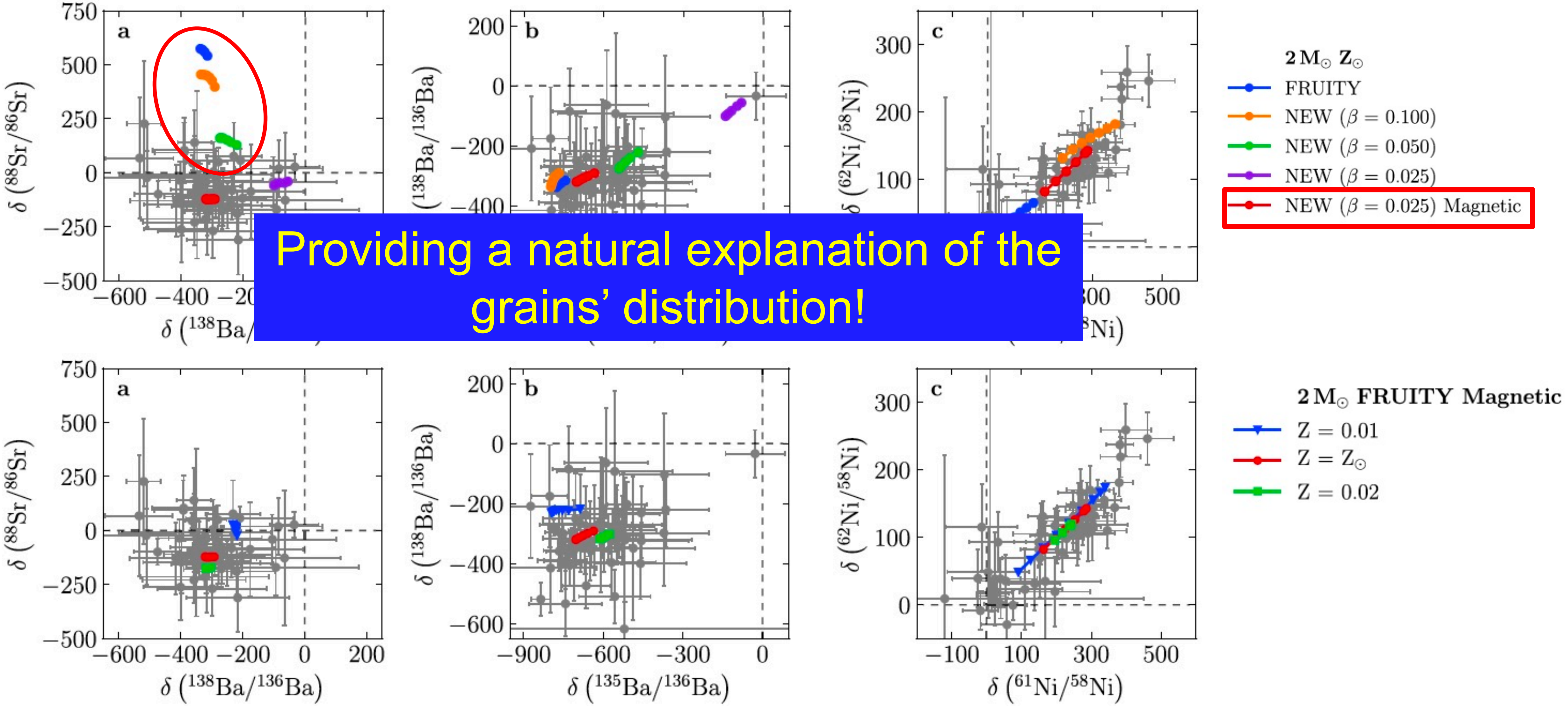
The Crucial Role of Magnetic Buoyancy is Further Supported!



Overshoot: no consistent match
Magnetic: consistent match

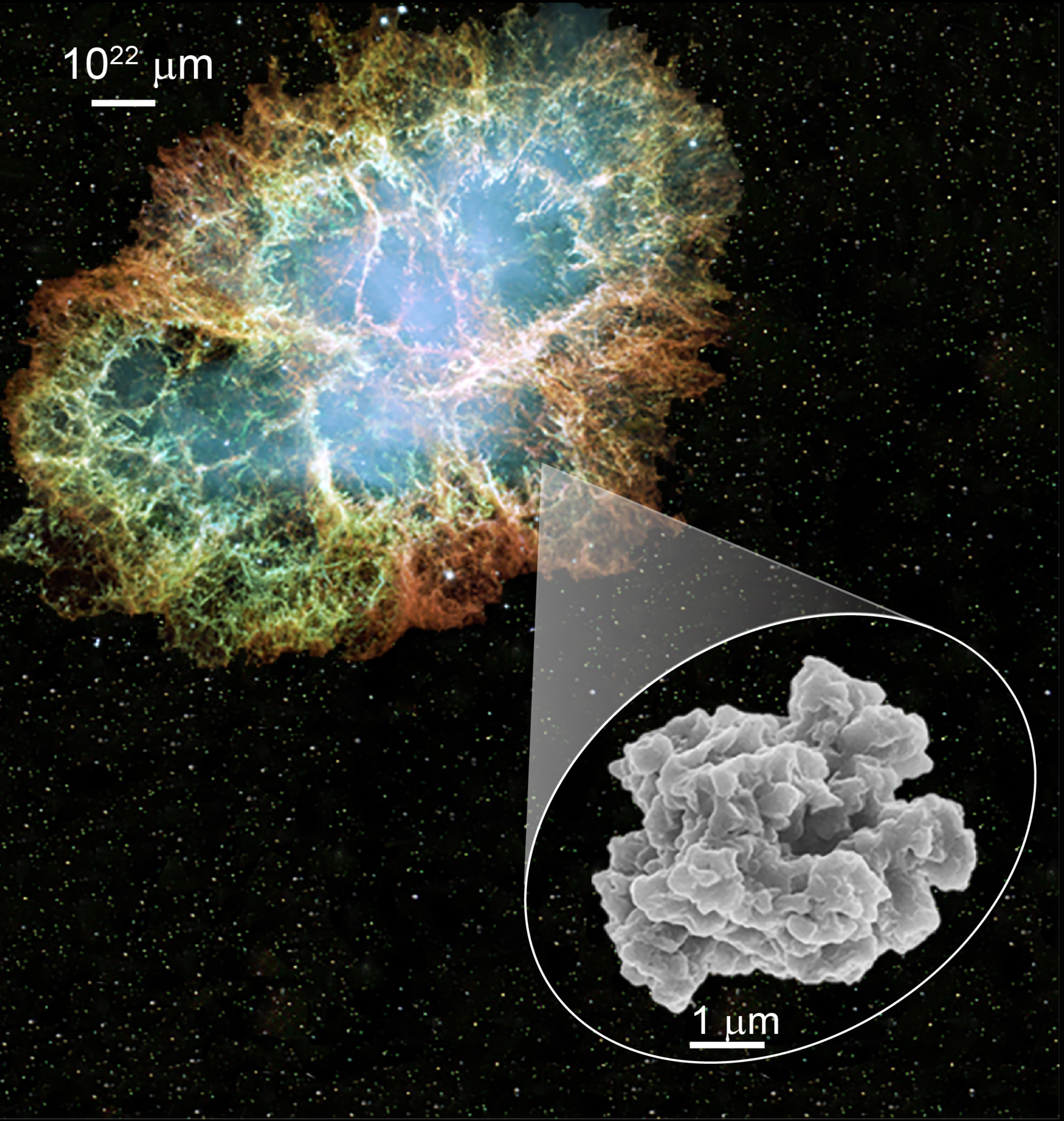
Vescovi et al. (2020) *ApJL*

The Crucial Role of Magnetic Buoyancy is Further Supported!



Providing a natural explanation of the grains' distribution!

Vescovi et al. (2020) *ApJL*



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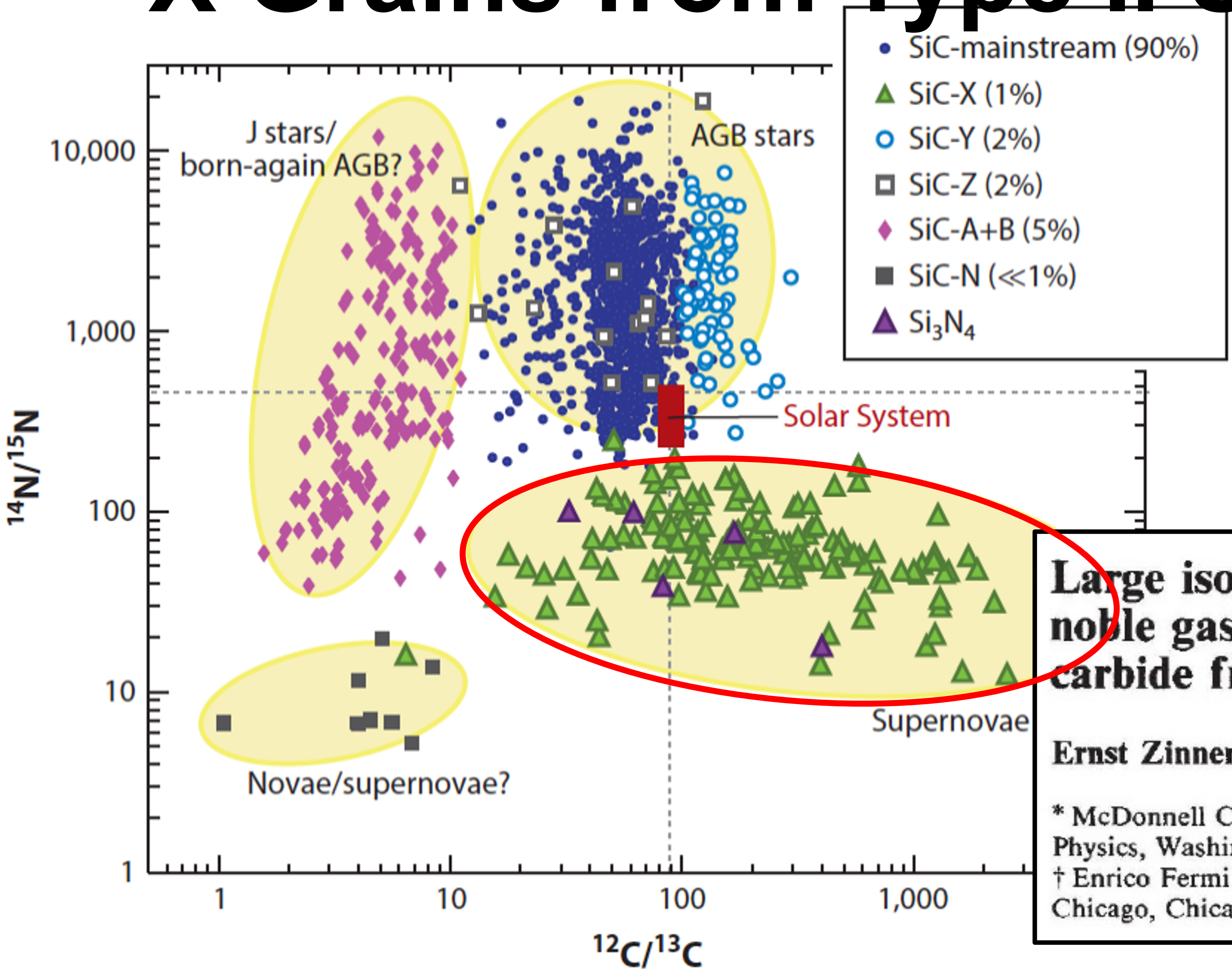
X Grains from Type II Supernovae



Fun Facts

1969: Murchison fall v.s.
Lunar sample return

1987: SN 1987A explosion
v.s. discovery of
presolar SiC

Large isotopic anomalies of Si, C, N and noble gases in interstellar silicon carbide from the Murray meteorite

Nature (1987)

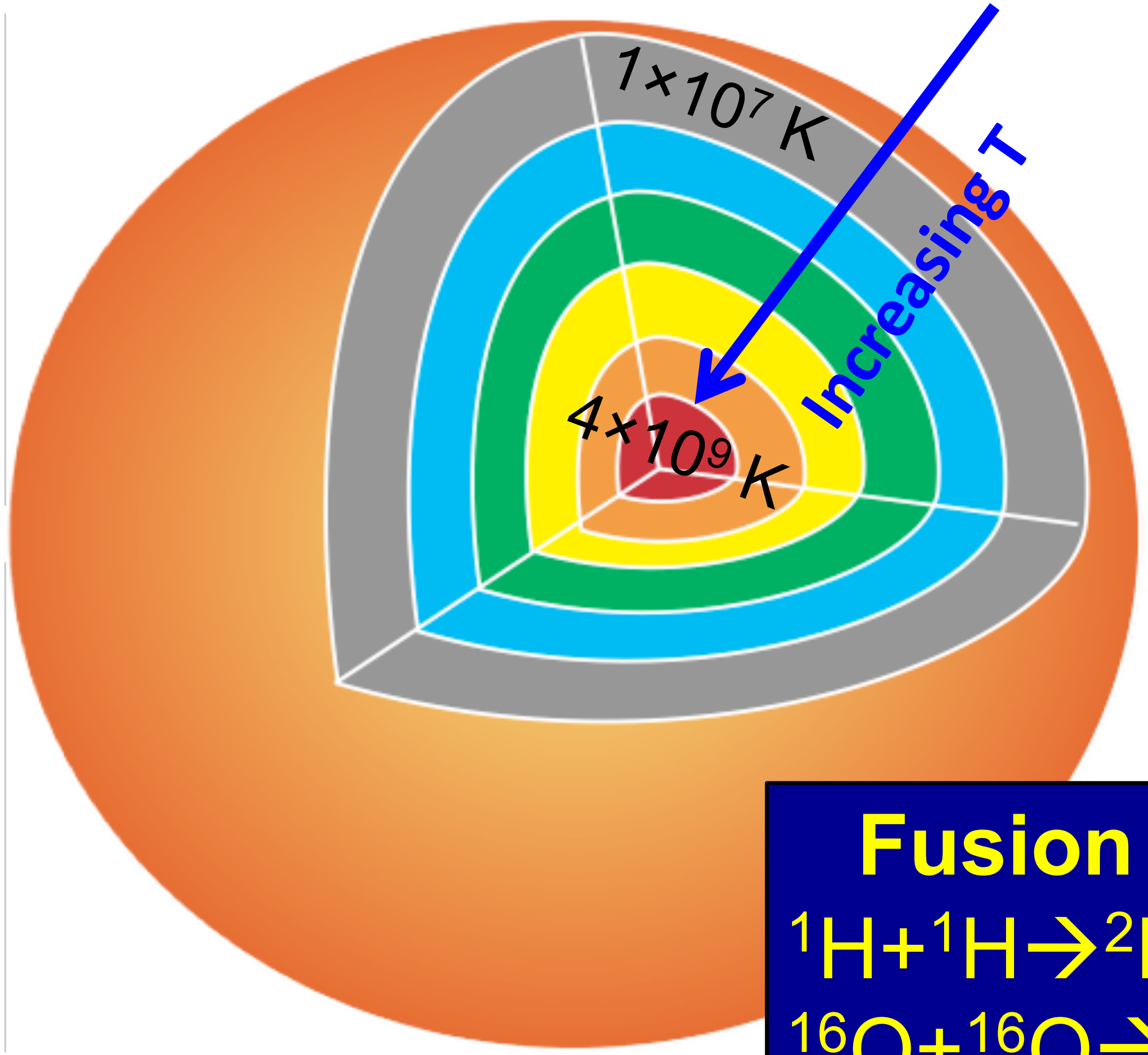
Ernst Zinner*, Tang Ming† & Edward Anders†‡

* McDonnell Center for the Space Sciences and Department of Physics, Washington University, St Louis, Missouri 63130, USA
† Enrico Fermi Institute and Department of Chemistry, University of Chicago, Chicago, Illinois 60637, USA

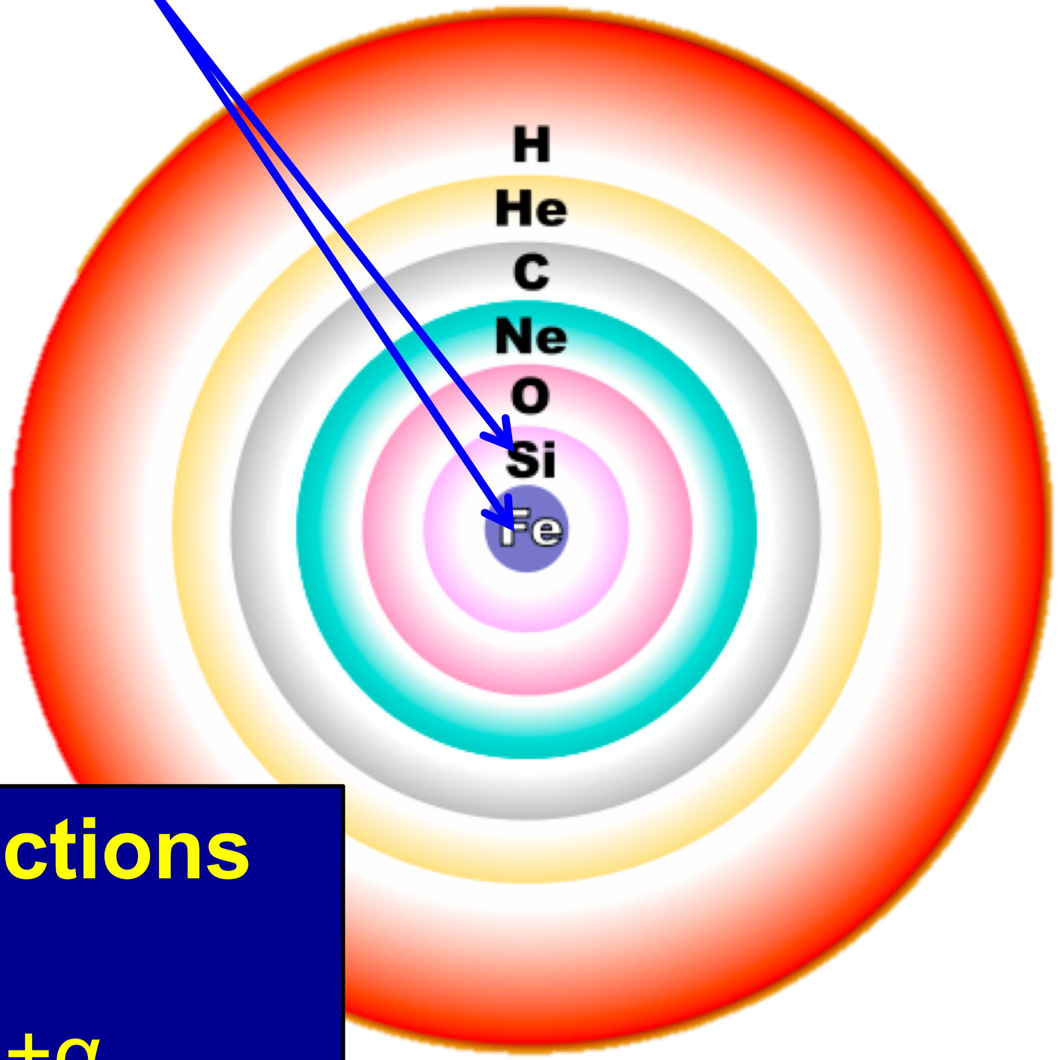
Supernova Explosion & Dust Formation

Scientific visualization of supernova evolution (A. Angelich)

Supernova Nucleosynthesis



^{44}Ti (formed during α-rich freeze-out)

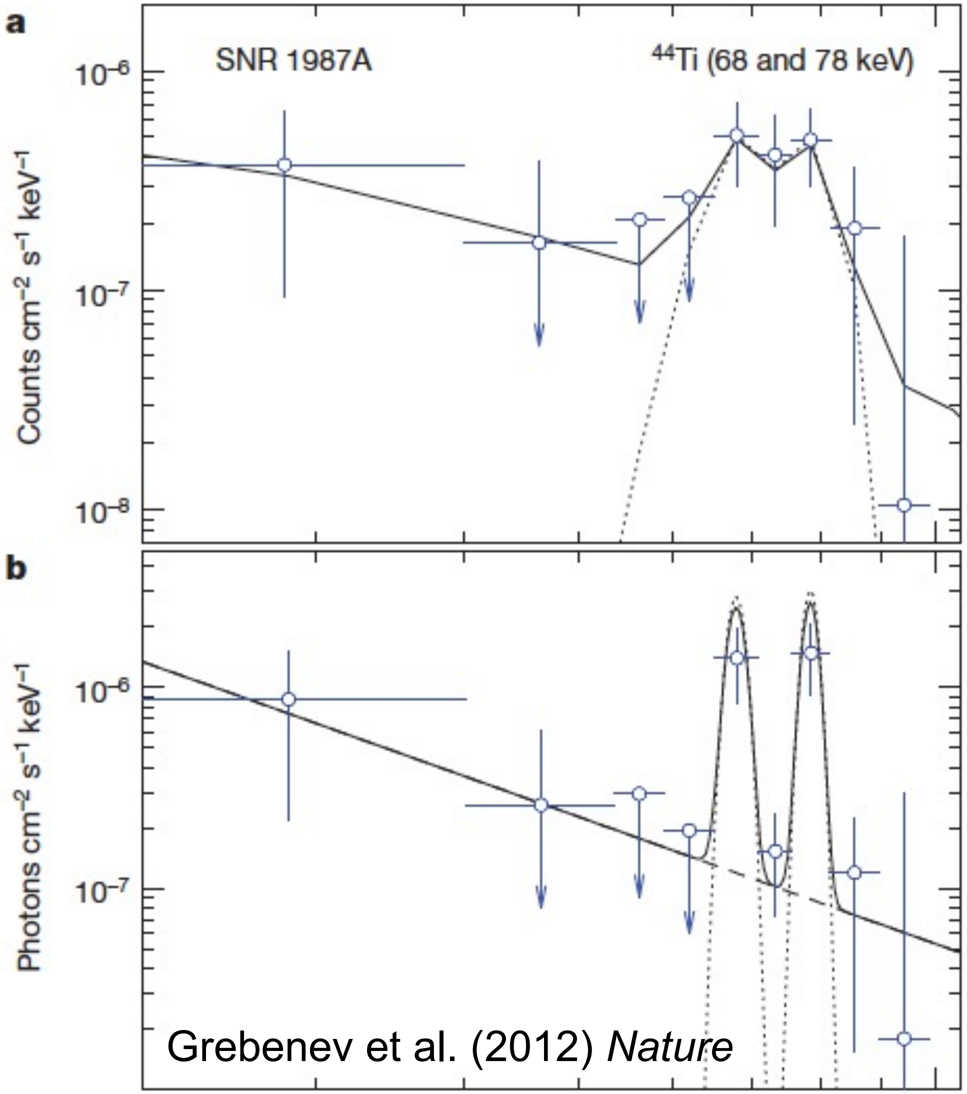


Fusion Reactions

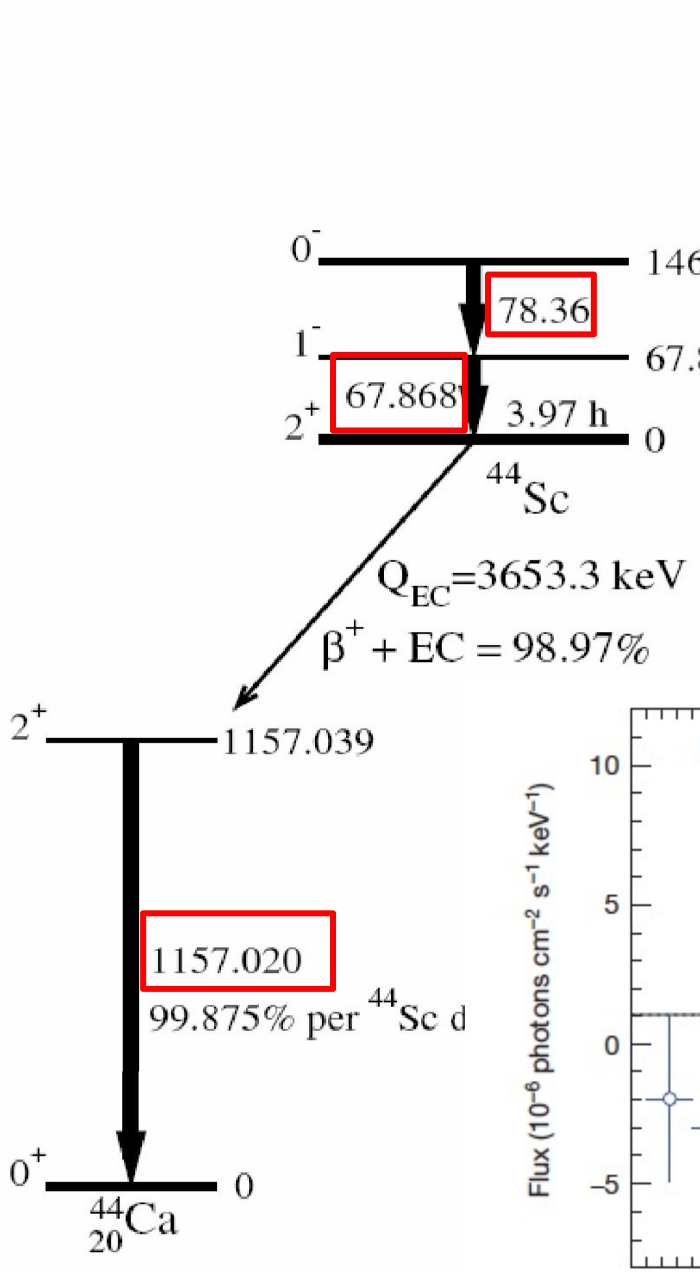
$^{1}H+^{1}H \rightarrow ^{2}He$

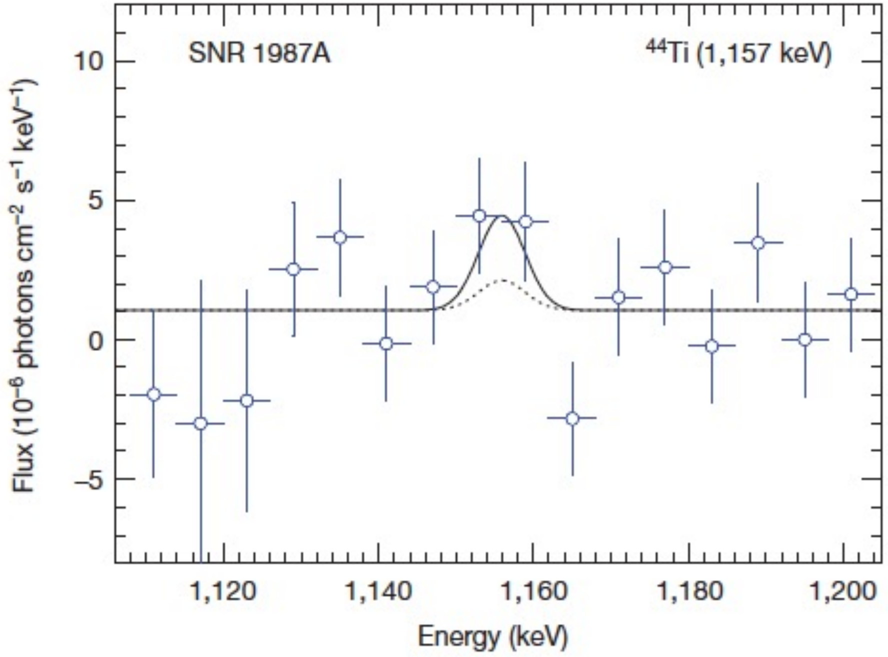
$^{16}O+^{16}O \rightarrow ^{28}Si+\alpha$

44Ti



Grebenev et al. (2012) *Nature*

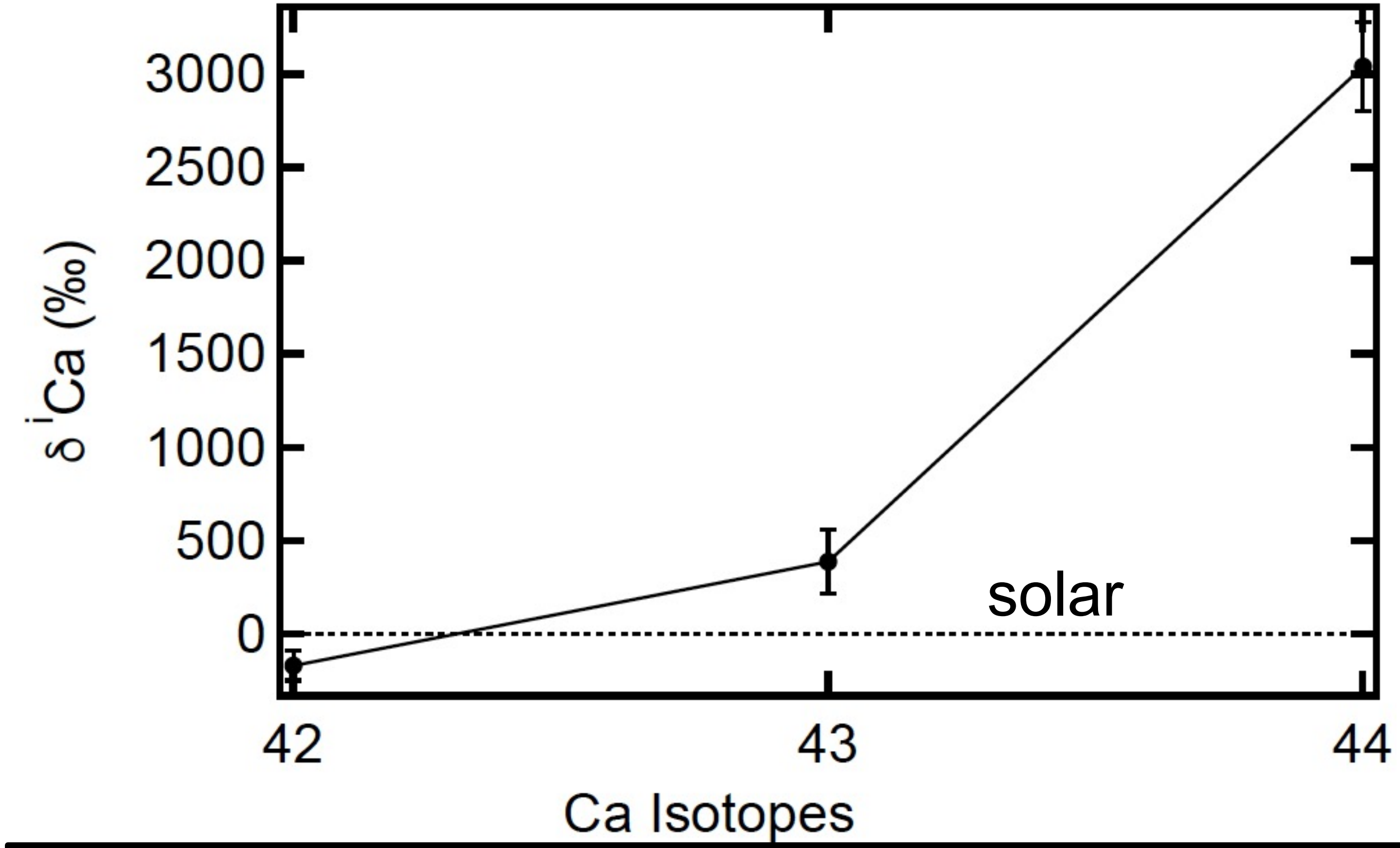


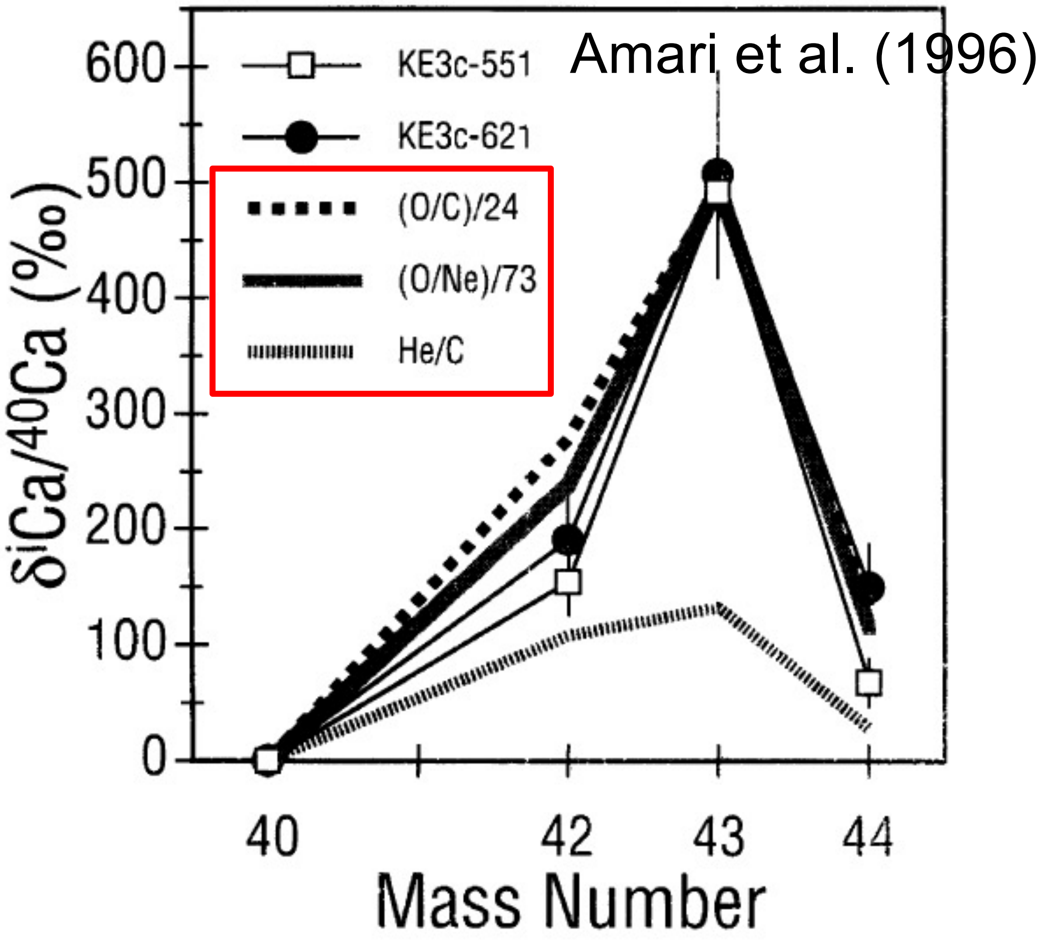


Also observed for Cas A (Grefenstette et al. 2014)

Extinct ^{44}Ti in X Grains

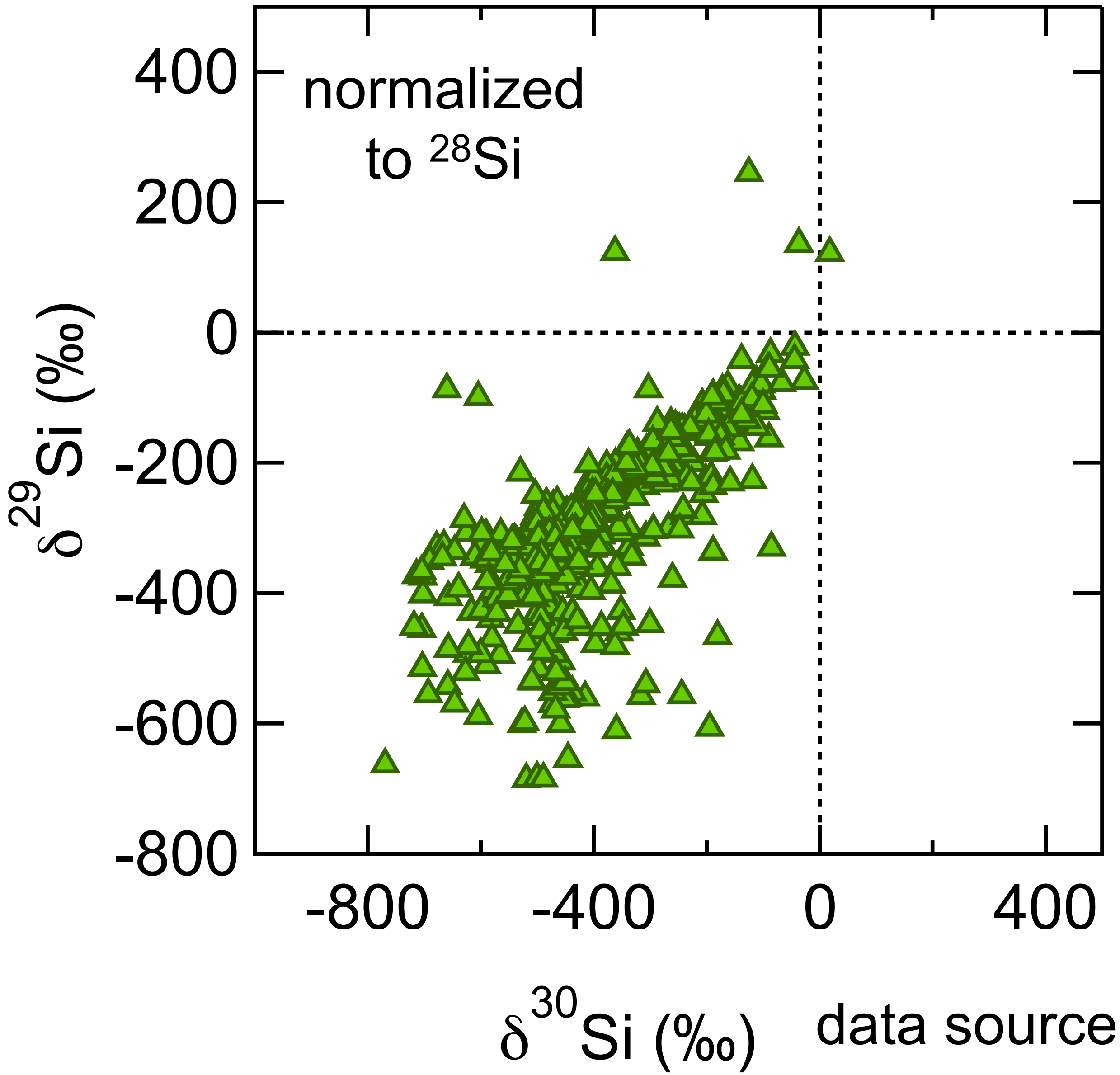
$\delta^{i}Ca = [(^{i}Ca/^{40}Ca)_{grain}/(^{i}Ca/^{40}Ca)_{std} - 1] \times 1000$

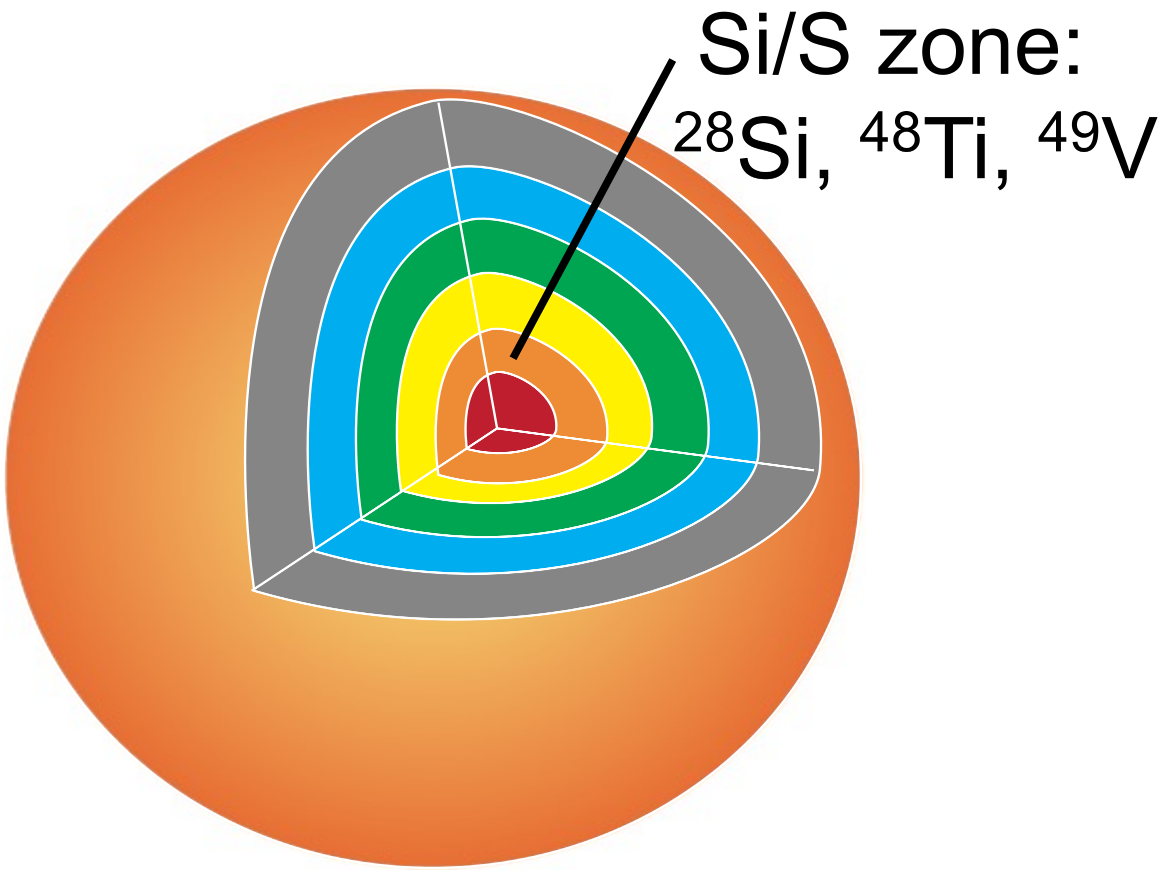




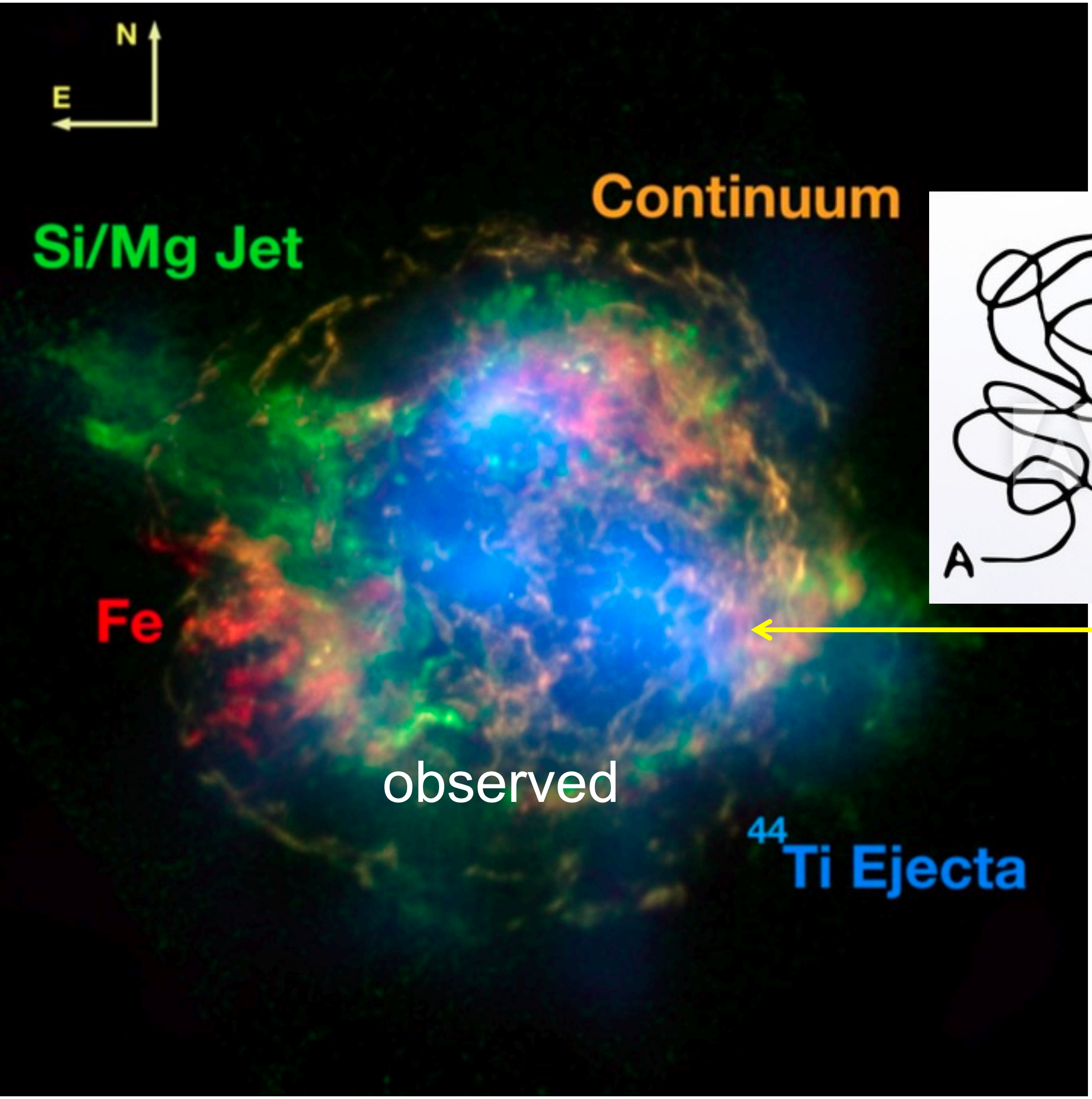
SN models predict large excesses in ^{43}Ca compared to ^{44}Ca. The observed ^{44}Ca excesses therefore point to the decay of ^{44}Ti.

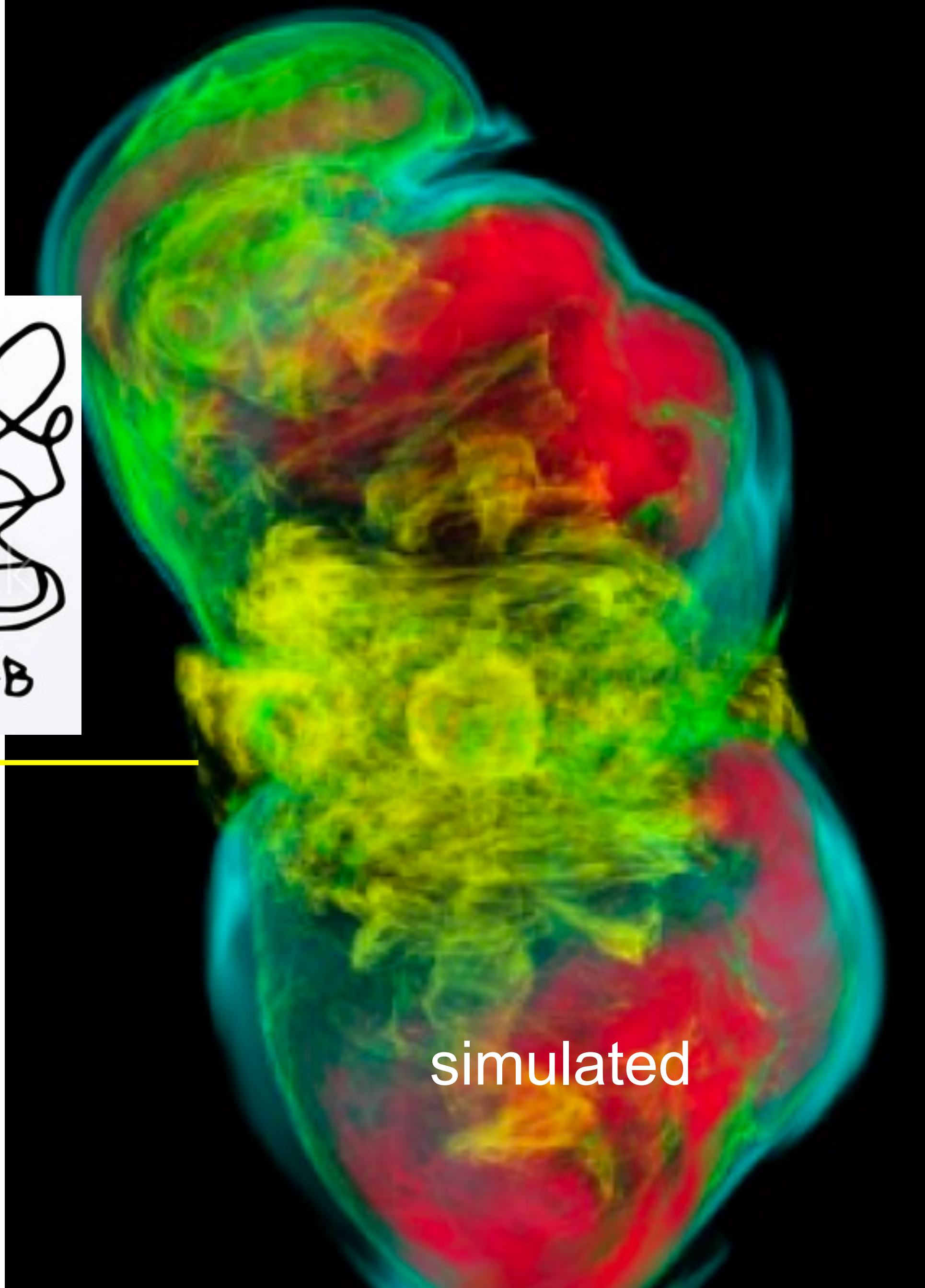
^{28}Si Excesses in Si/S Zone





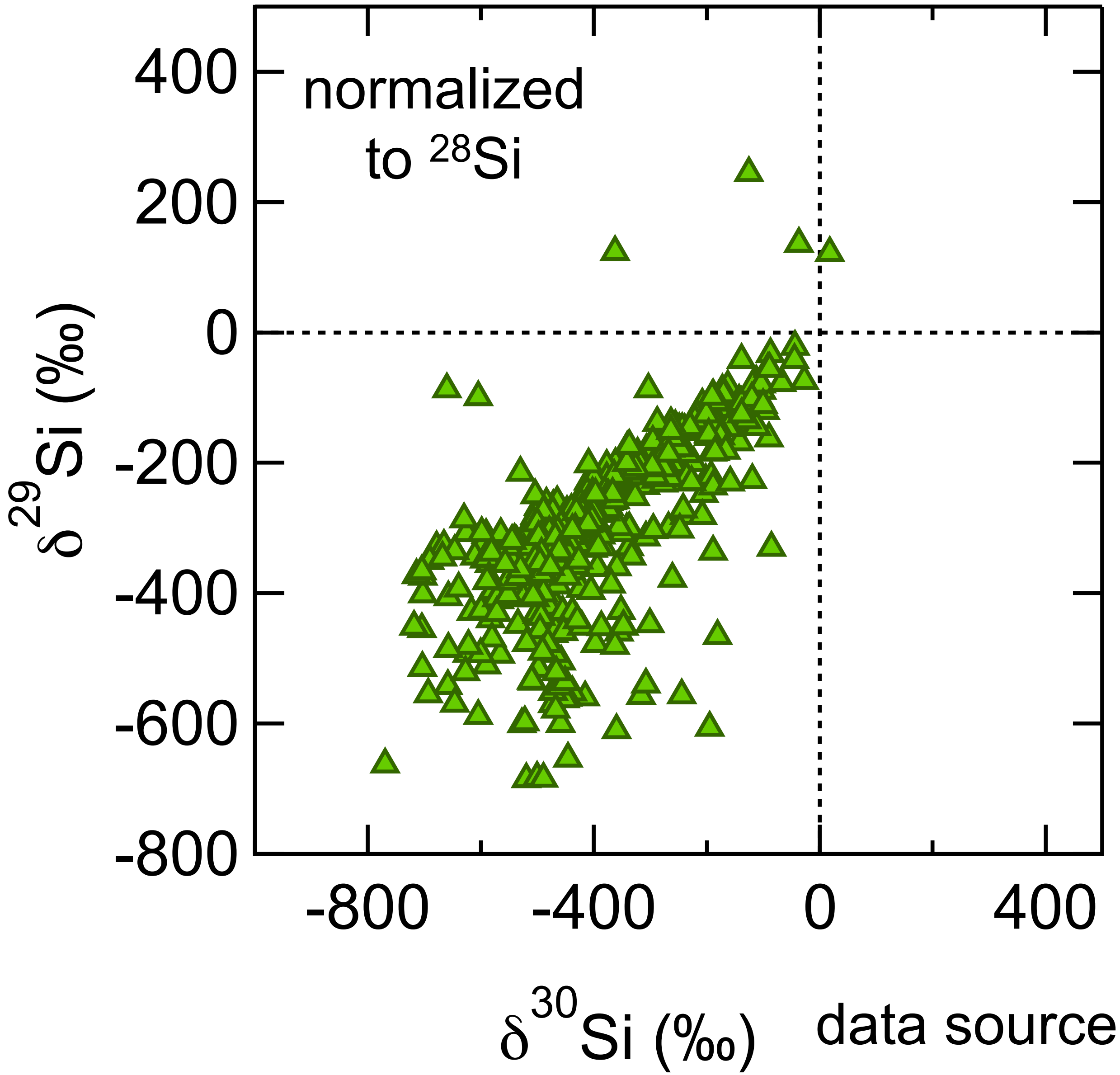
data source: Presolar grain database

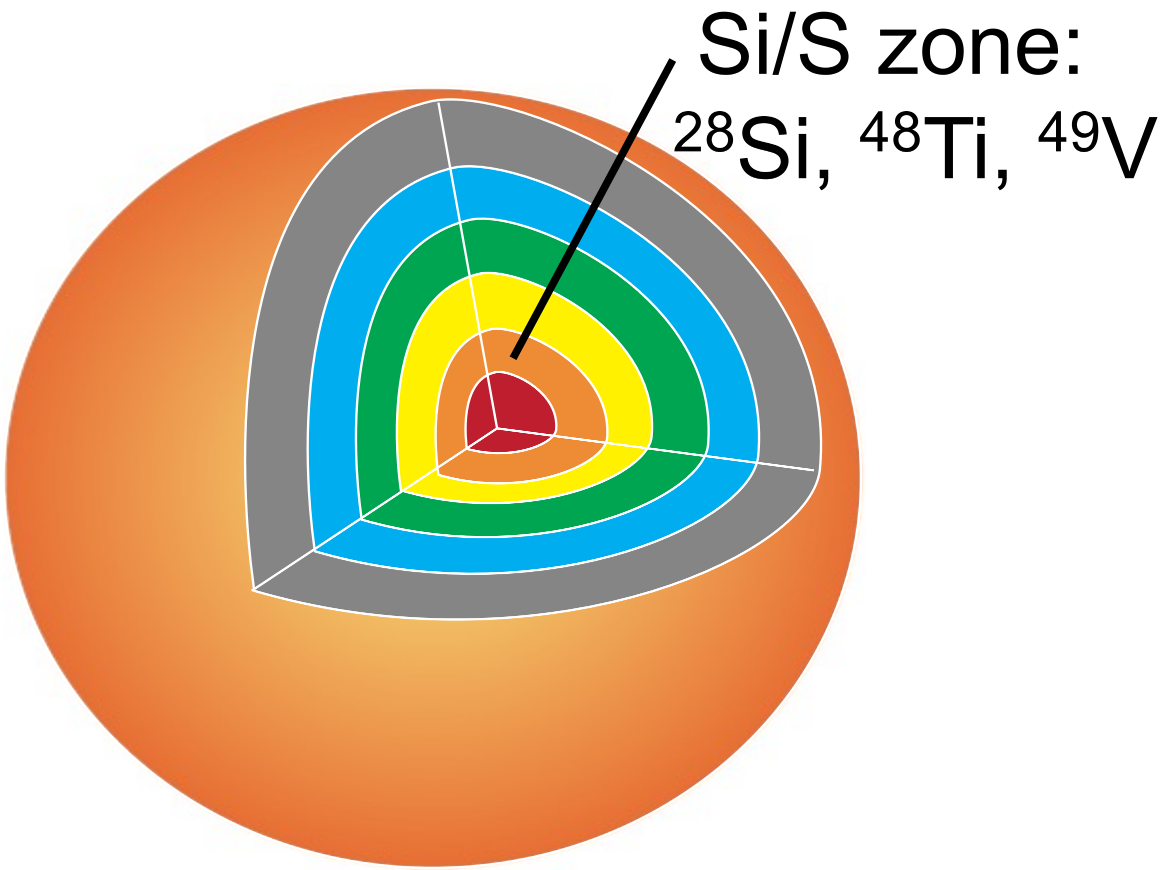




Mösta et al. (2014) *ApJL*

^{28}Si Excesses in Si/S Zone

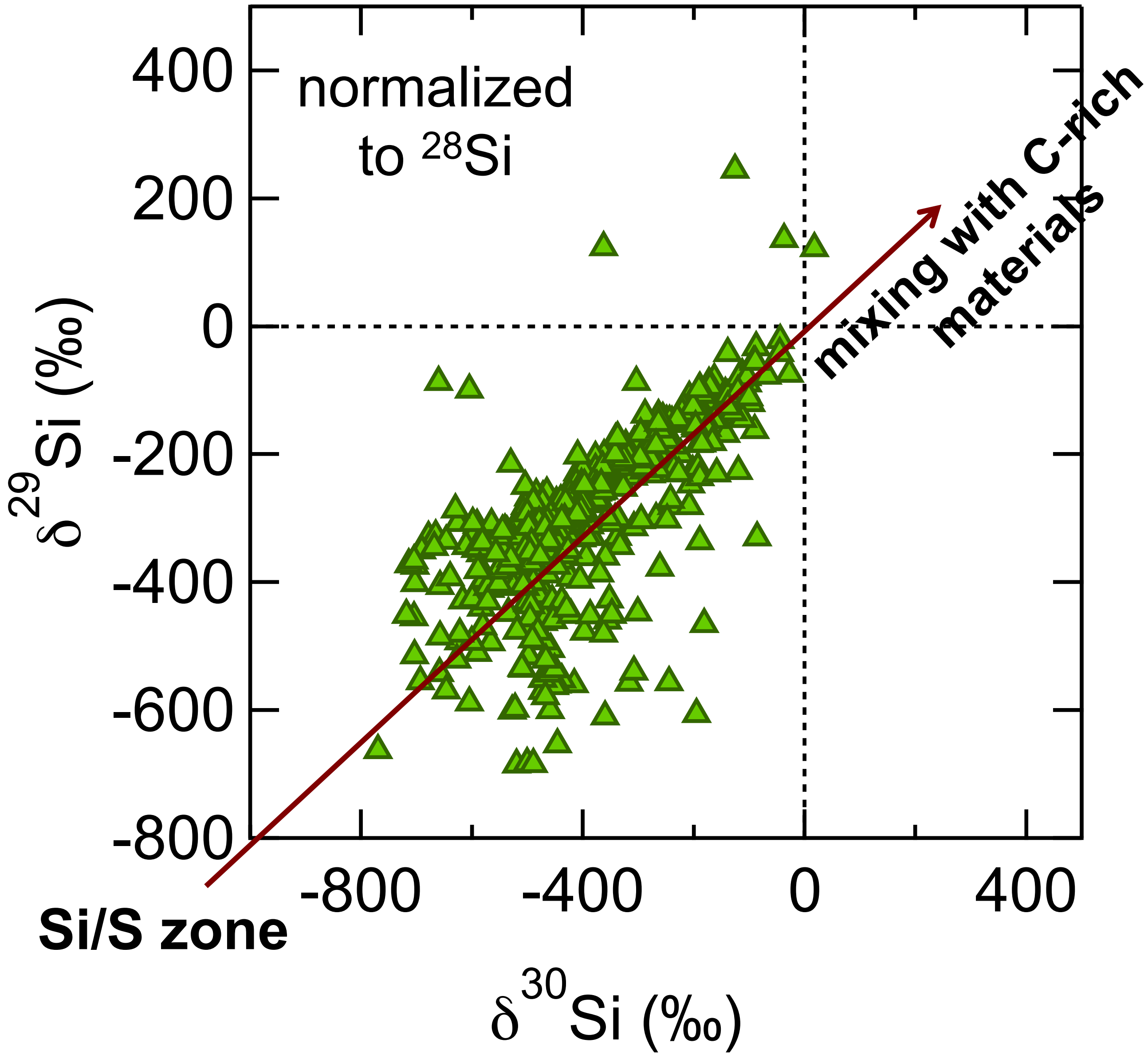


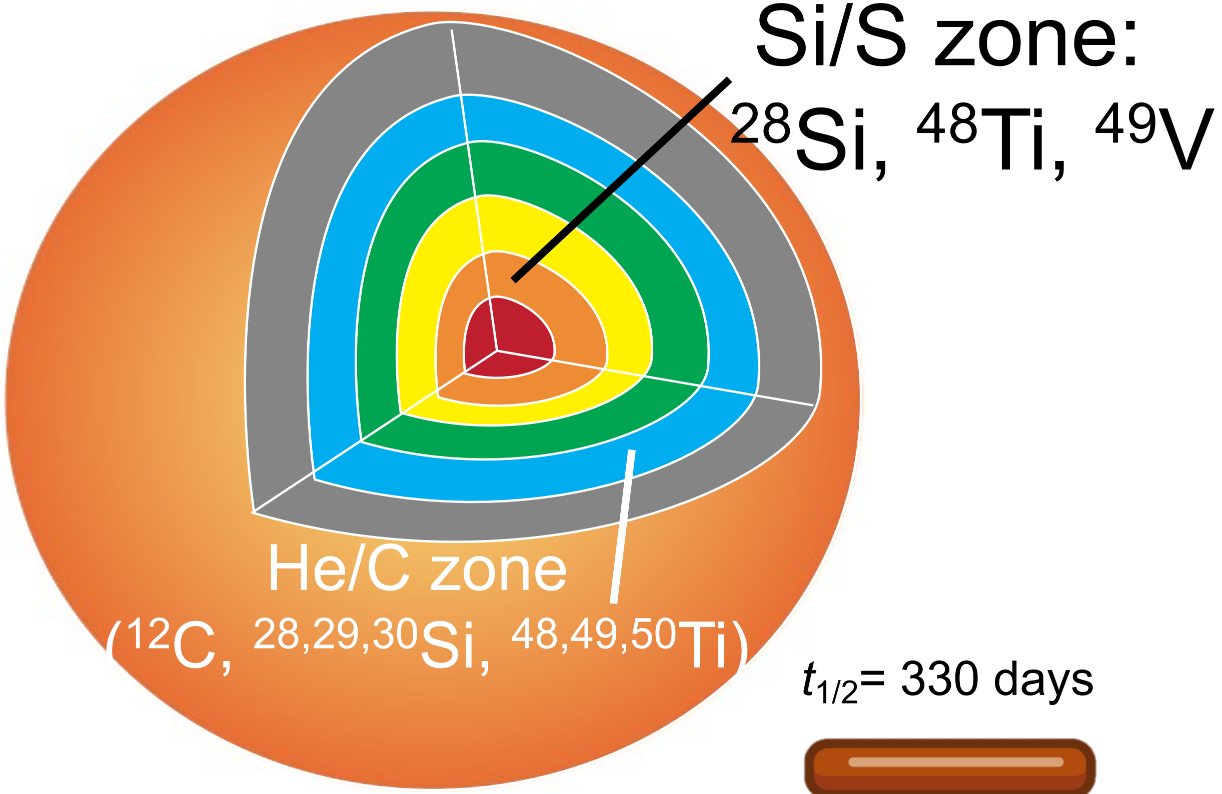


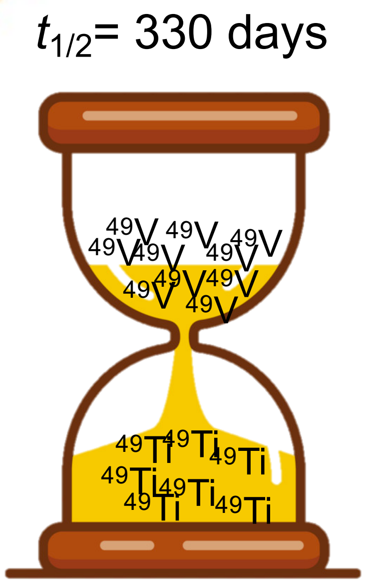
$^{49}V \rightarrow ^{49}Ti$ ($t_{1/2}$= 330 days)

data source: Presolar grain database

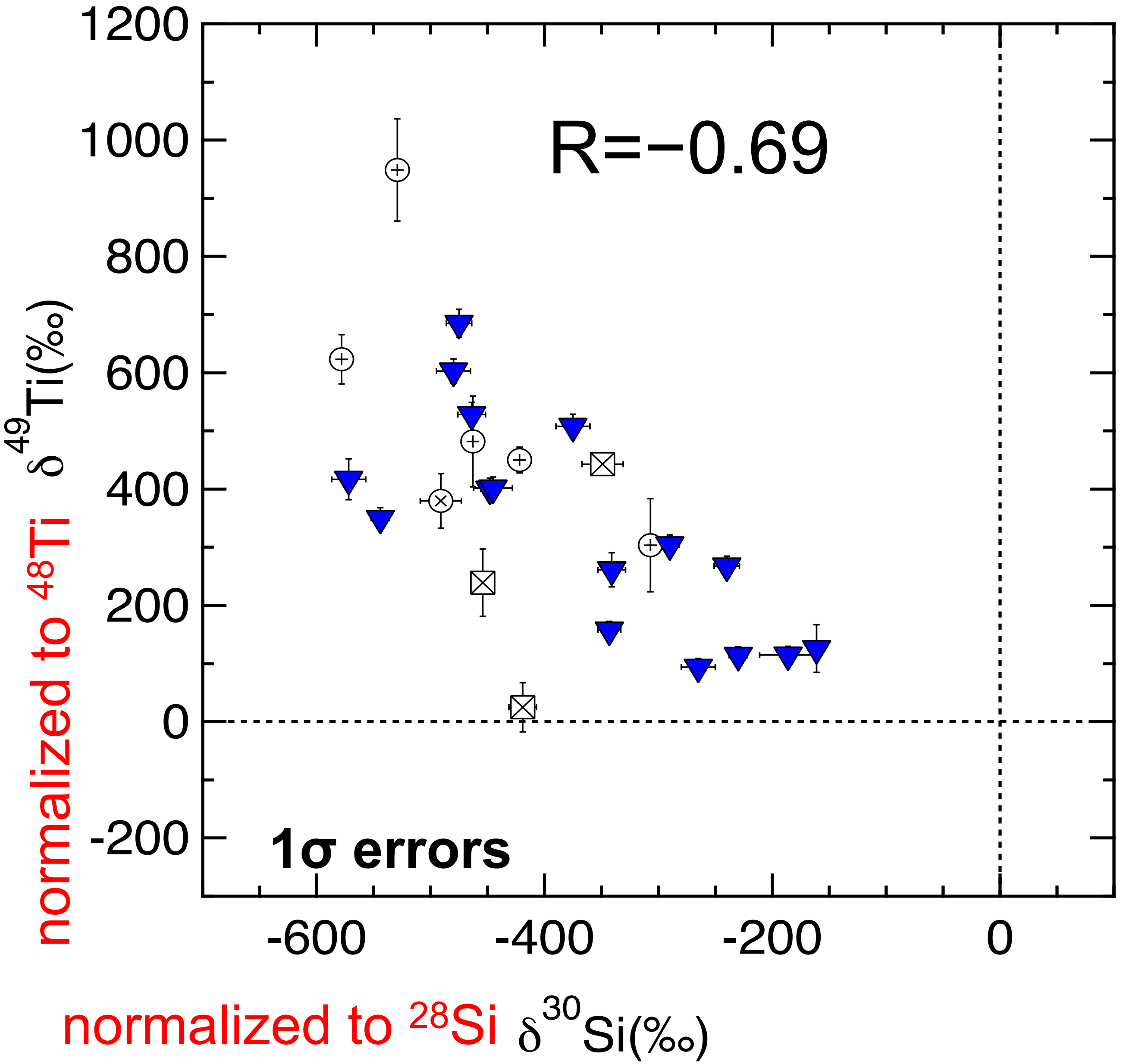
Origin of ^{49}Ti in X Grains

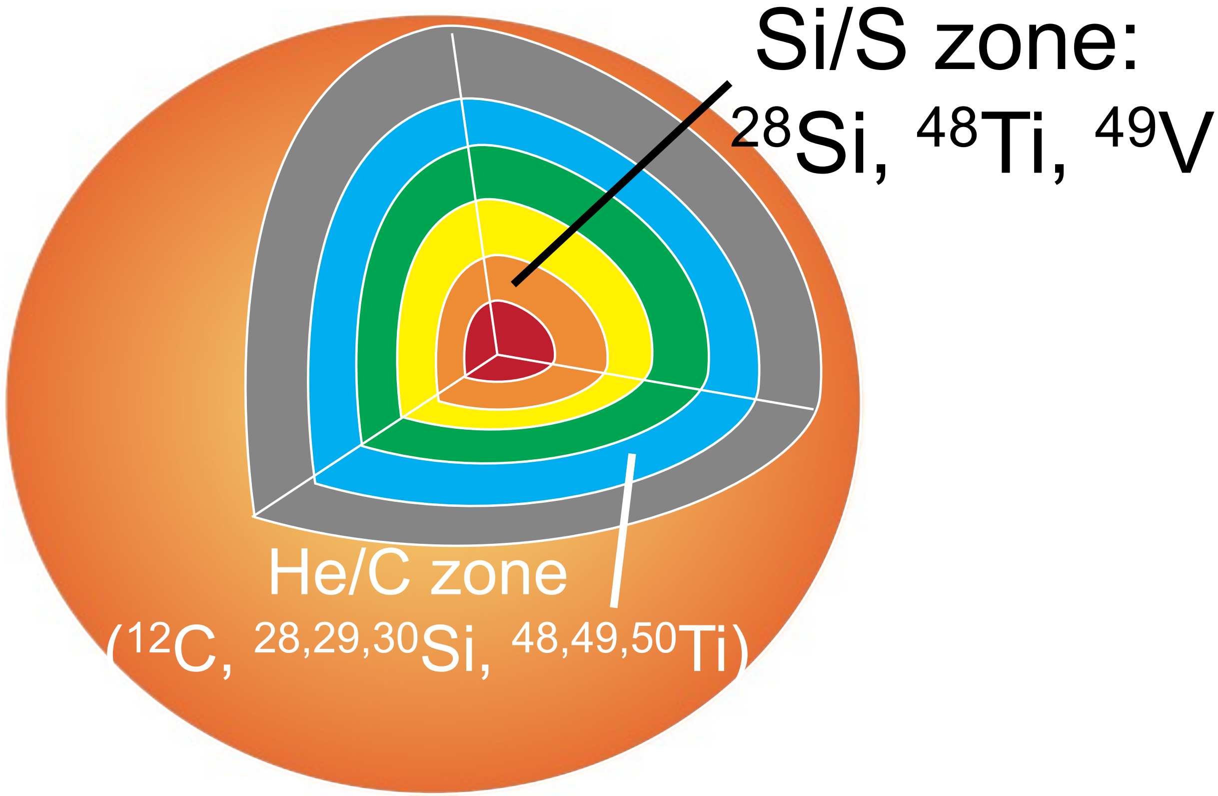






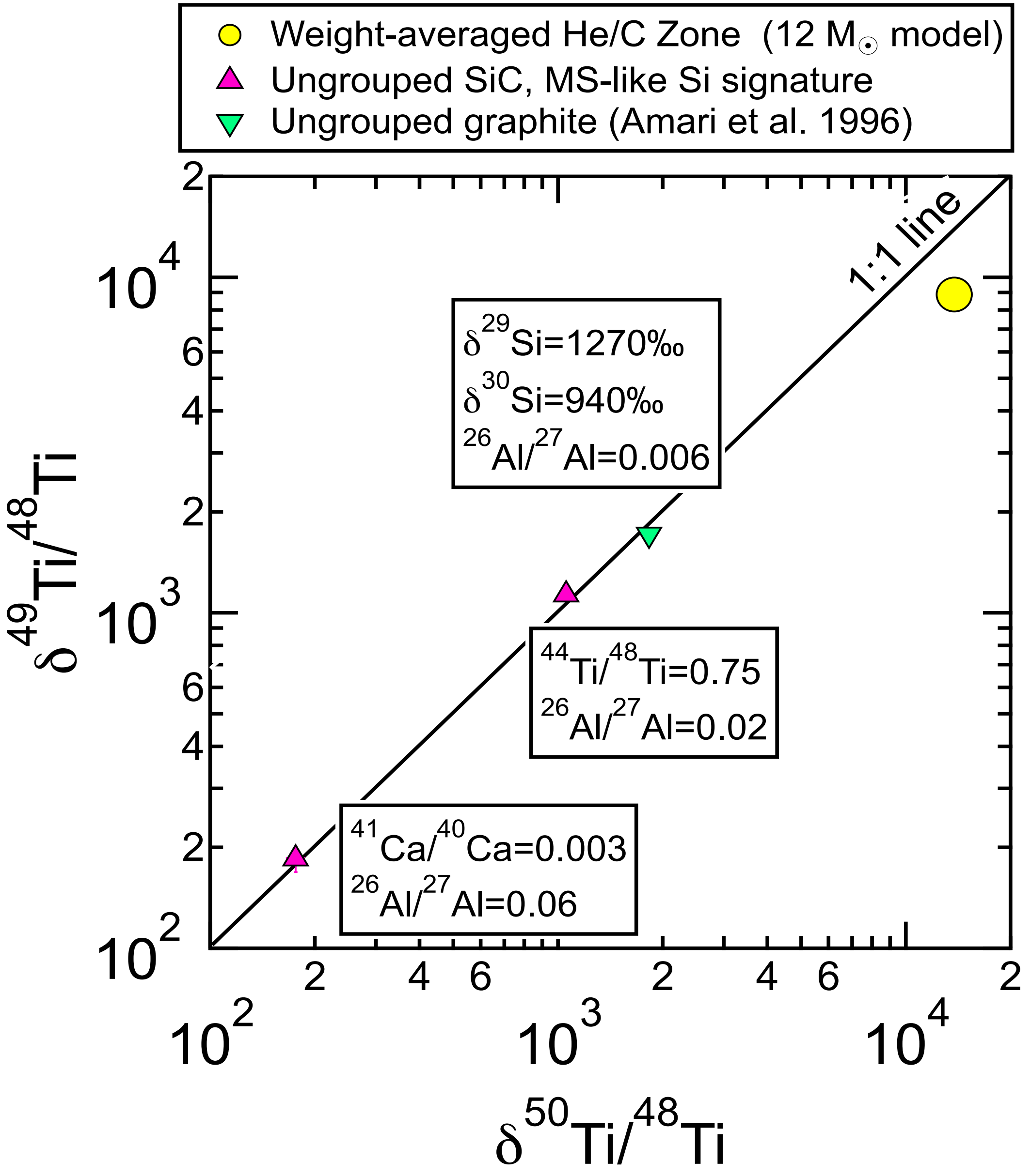
^{49}Ti Correlates with ^{28}Si Excesses

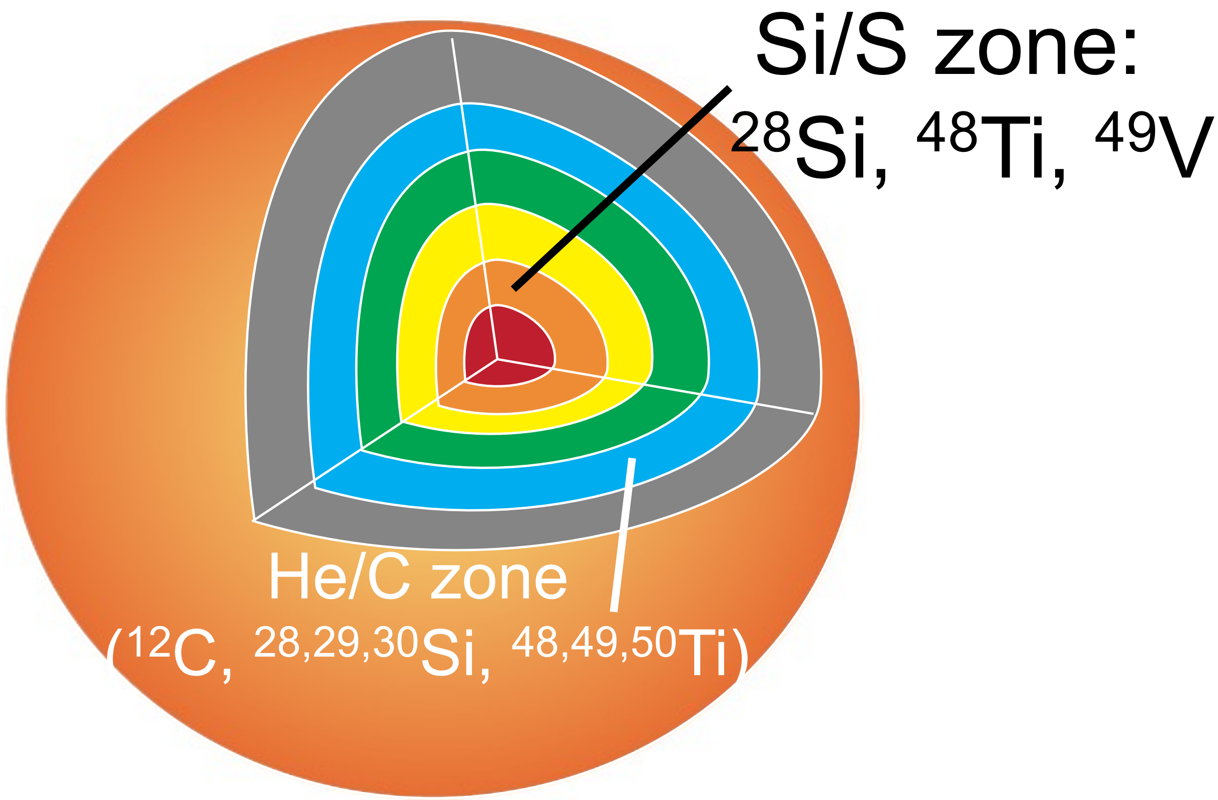




Constraints: small contribution from He/C zone.

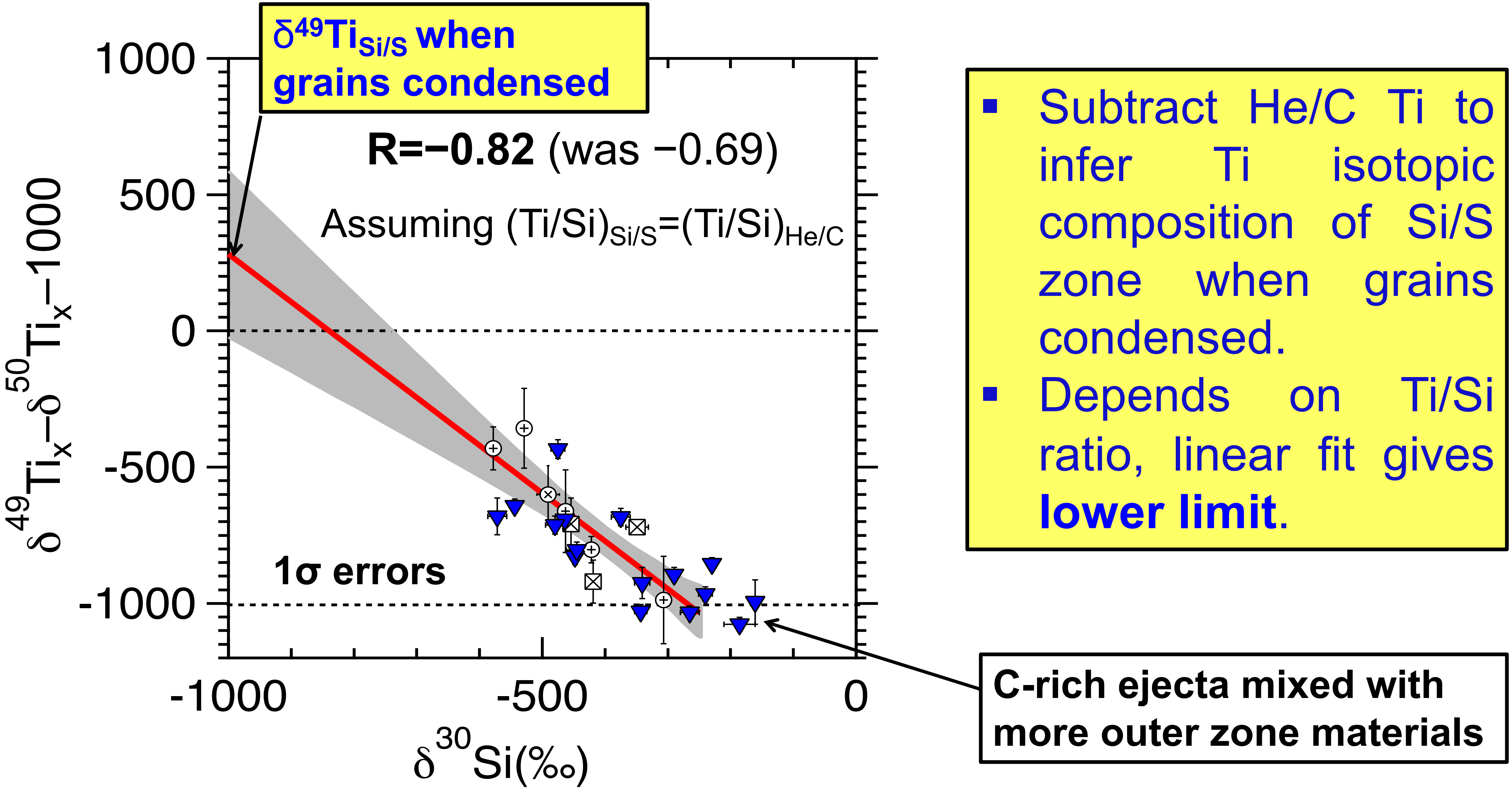
^{49}Ti Correlates with ^{28}Si Excesses





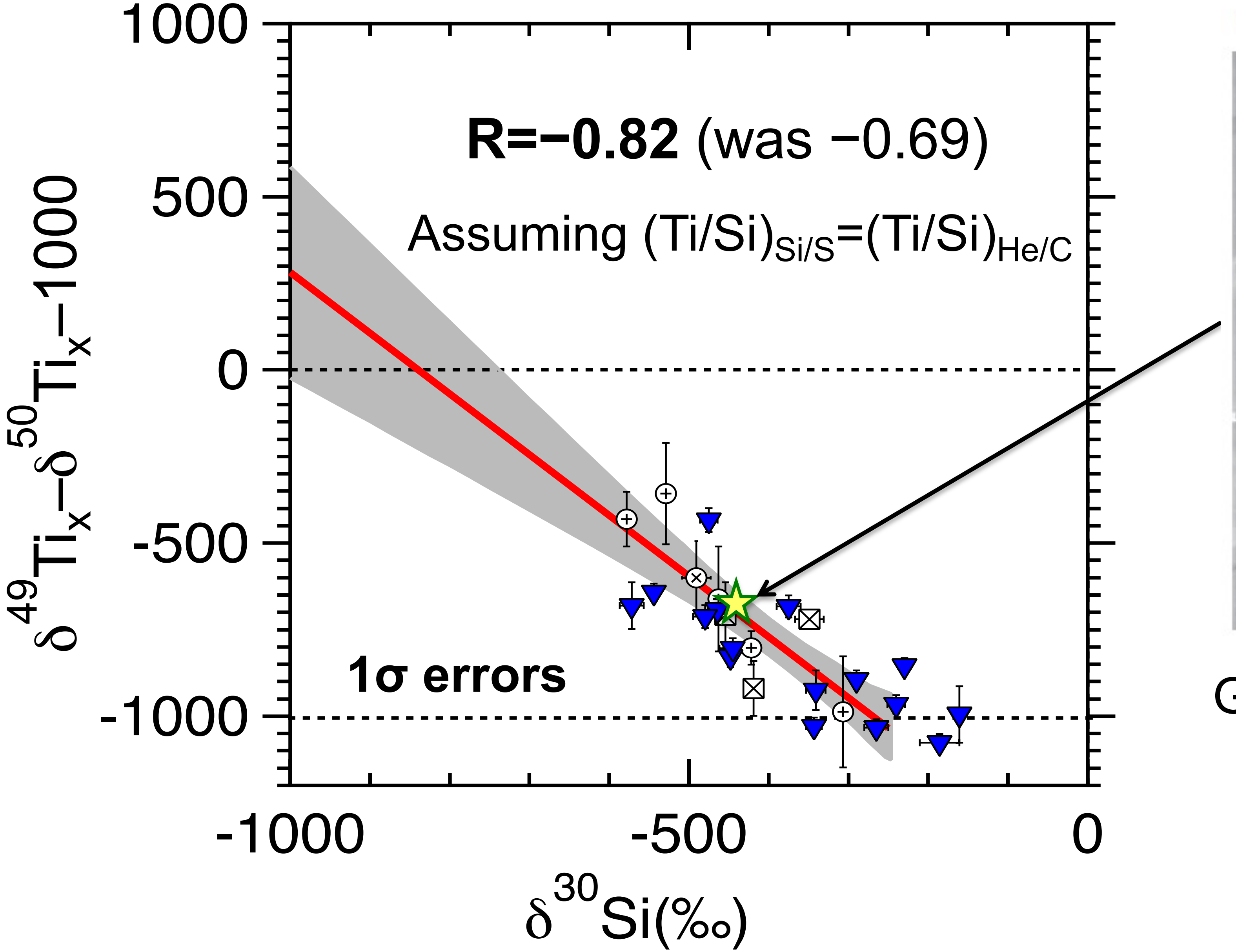
Supernova grain data indicate that in He/C zone, ^{49}Ti ≈ ^{50}Ti.

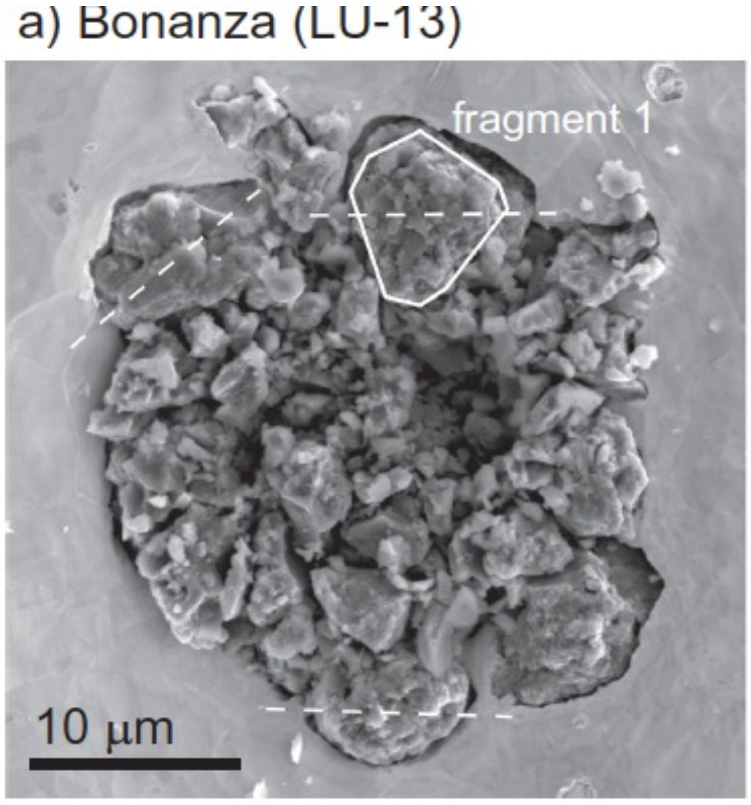
Calculation of δ^{49}Ti in the Si/S Zone



- Subtract He/C Ti to infer Ti isotopic composition of Si/S zone when grains condensed.
- Depends on Ti/Si ratio, linear fit gives **lower limit**.

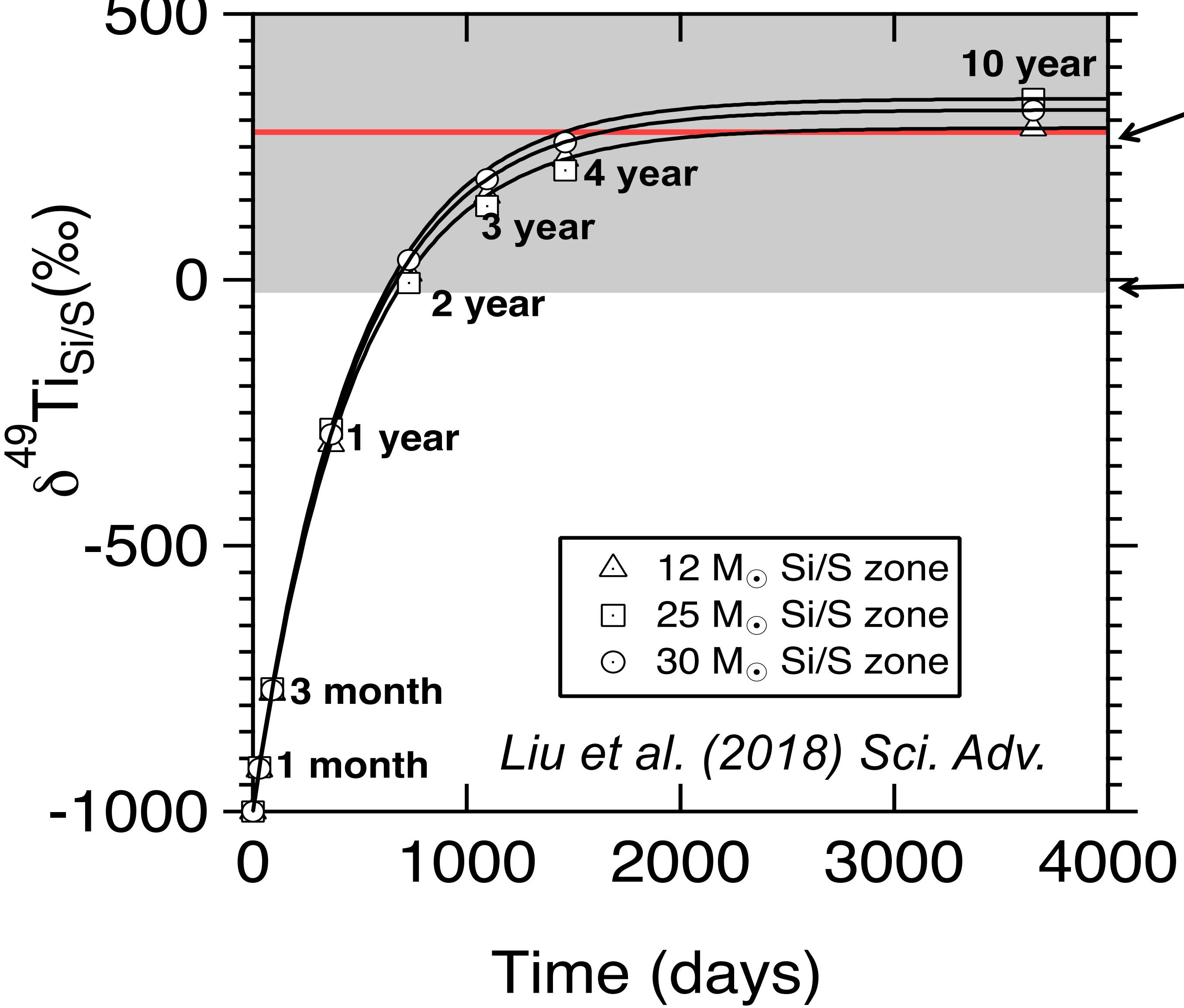
Calculation of δ^{49}Ti in the Si/S Zone





Gyngard et al. (2018) *GCA*

$\delta^{49}Ti_{Si/S}$ Constrains Timing of SiC Formation in Supernovae

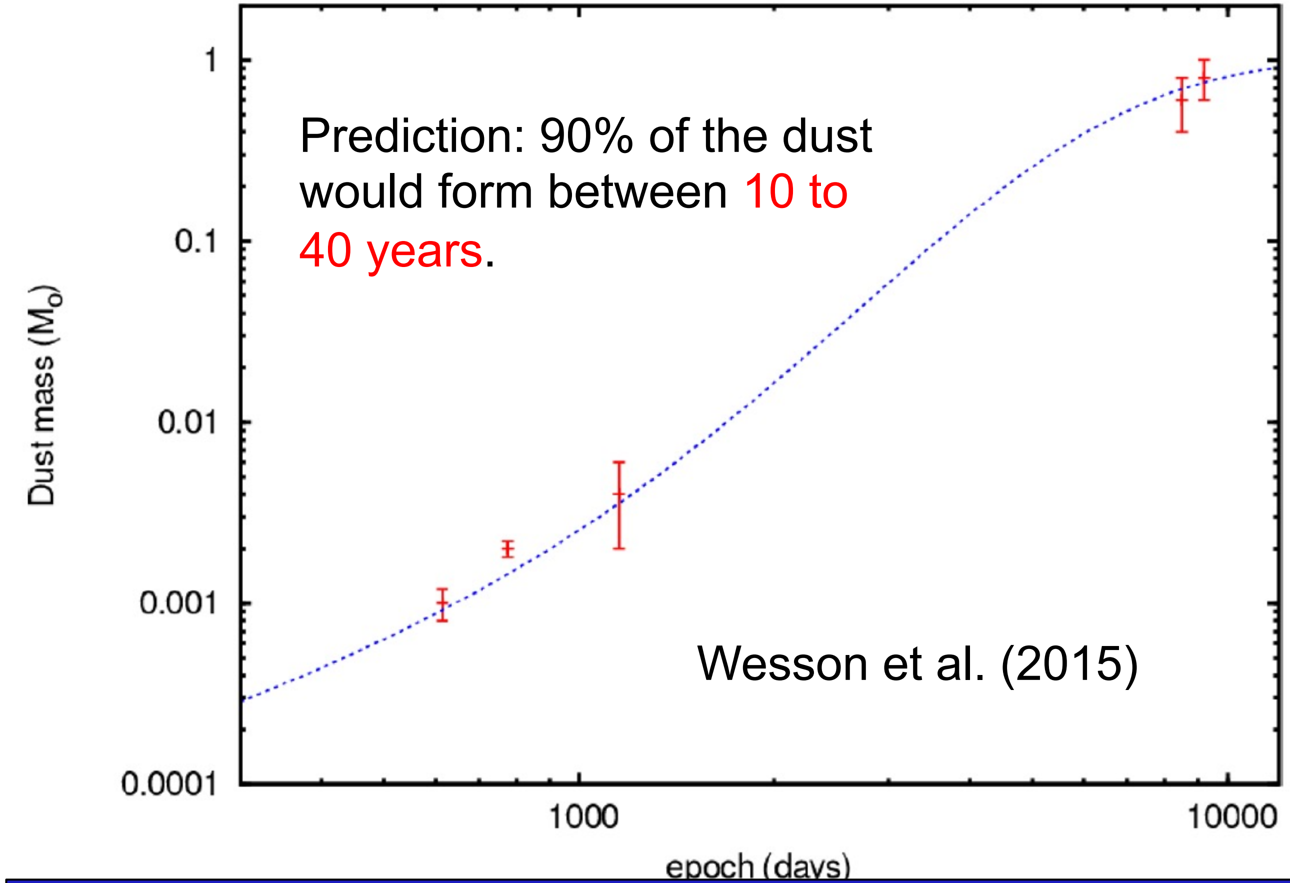


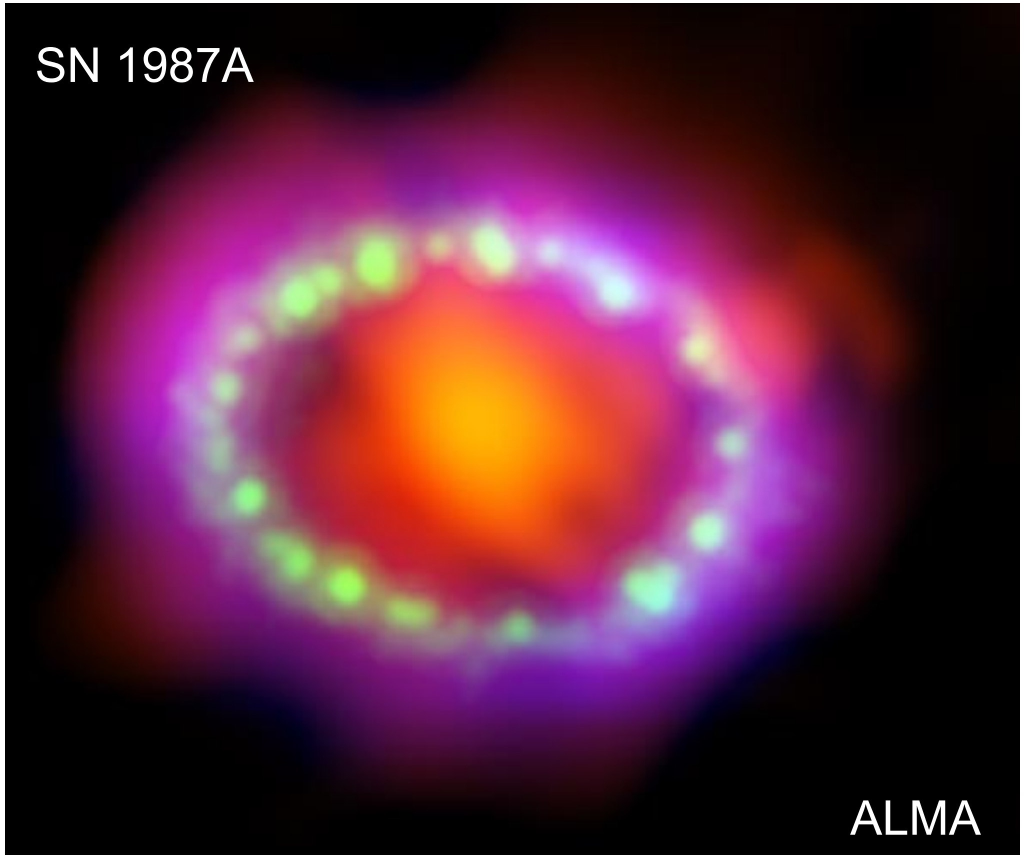
Derived by the linear fit, LOWER LIMIT.

lower 95% confidence band of the linear fit.

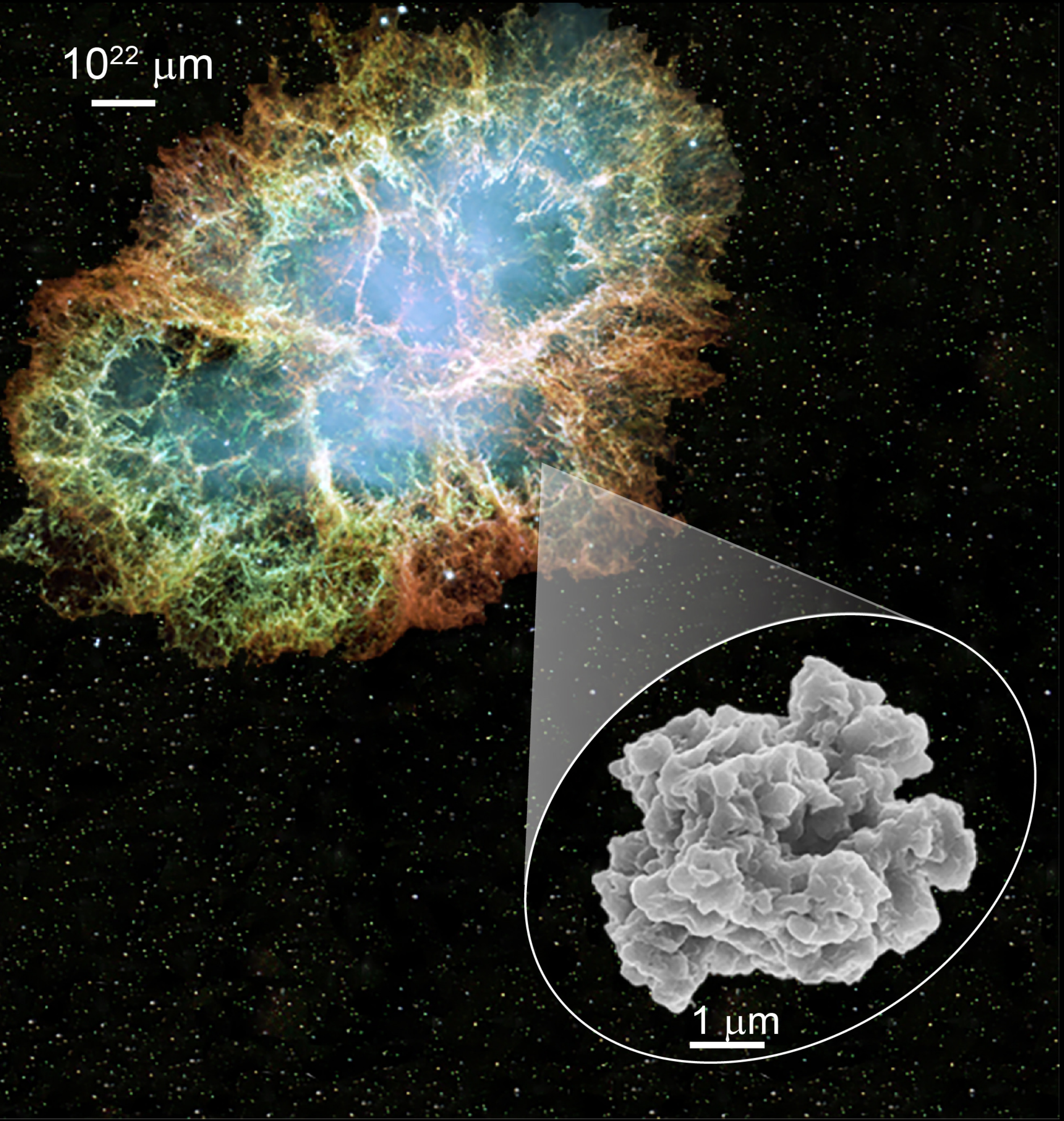
The **95% lower limit** of $\delta^{49}Ti_{Si/S}$ derived by the linear fit constrains condensation to occur at least 2 yrs after SN explosions, consistent with astronomical observations.

Dust Production in SN 1987A Over 30 Years





- ❑ Dust formation can occur as early as a few months after SN explosions (e.g., Andrews et al. 2016).
- ❑ But VERY FEW SNe have been observed to quantify dust production later than 1000 days.
- ❑ The inferred timescale for grain formation in SN 1987A is CONSISTENT with the grain data, >2 yrs.



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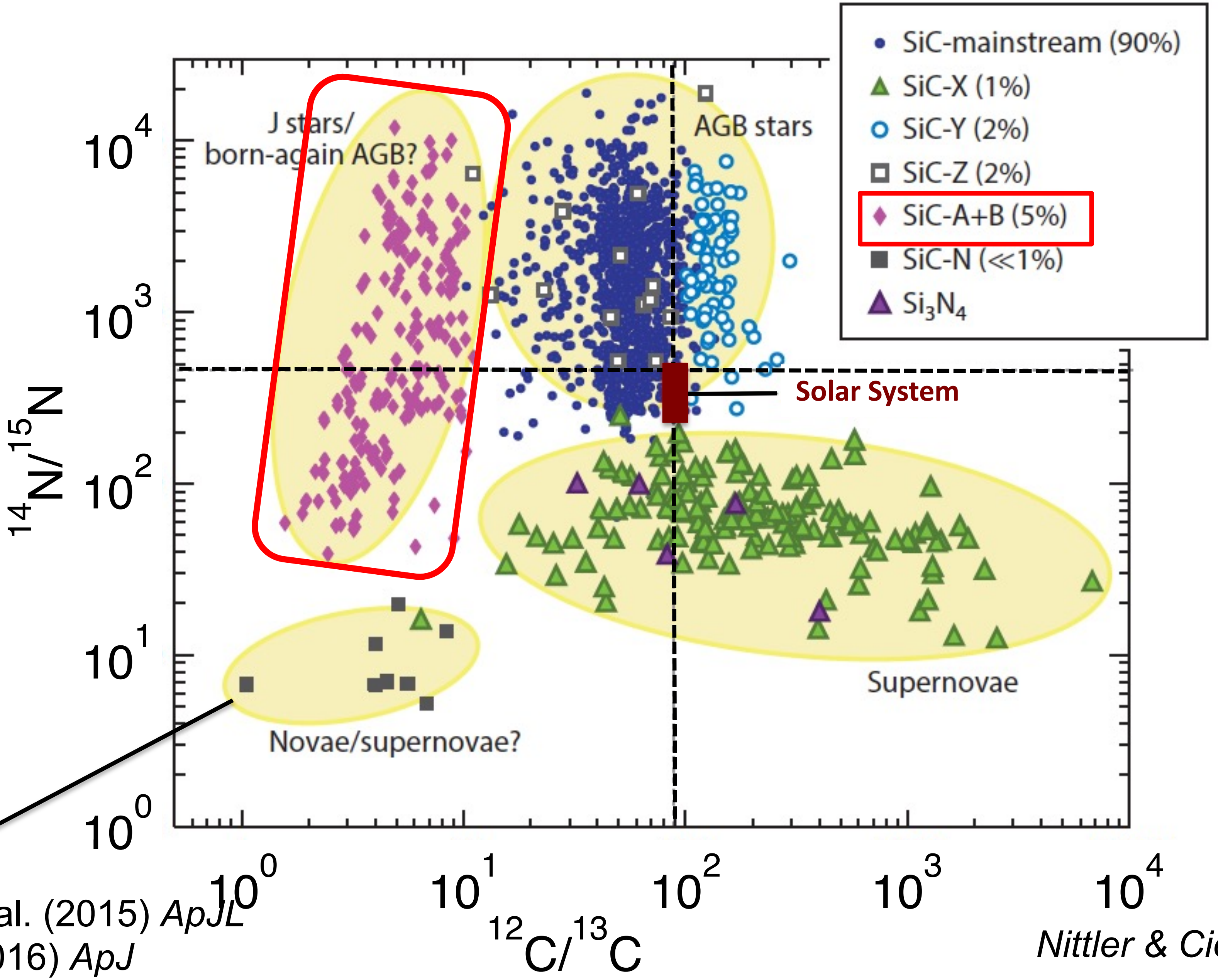
^{13}C-rich Grains: What are Their Stellar Sources?

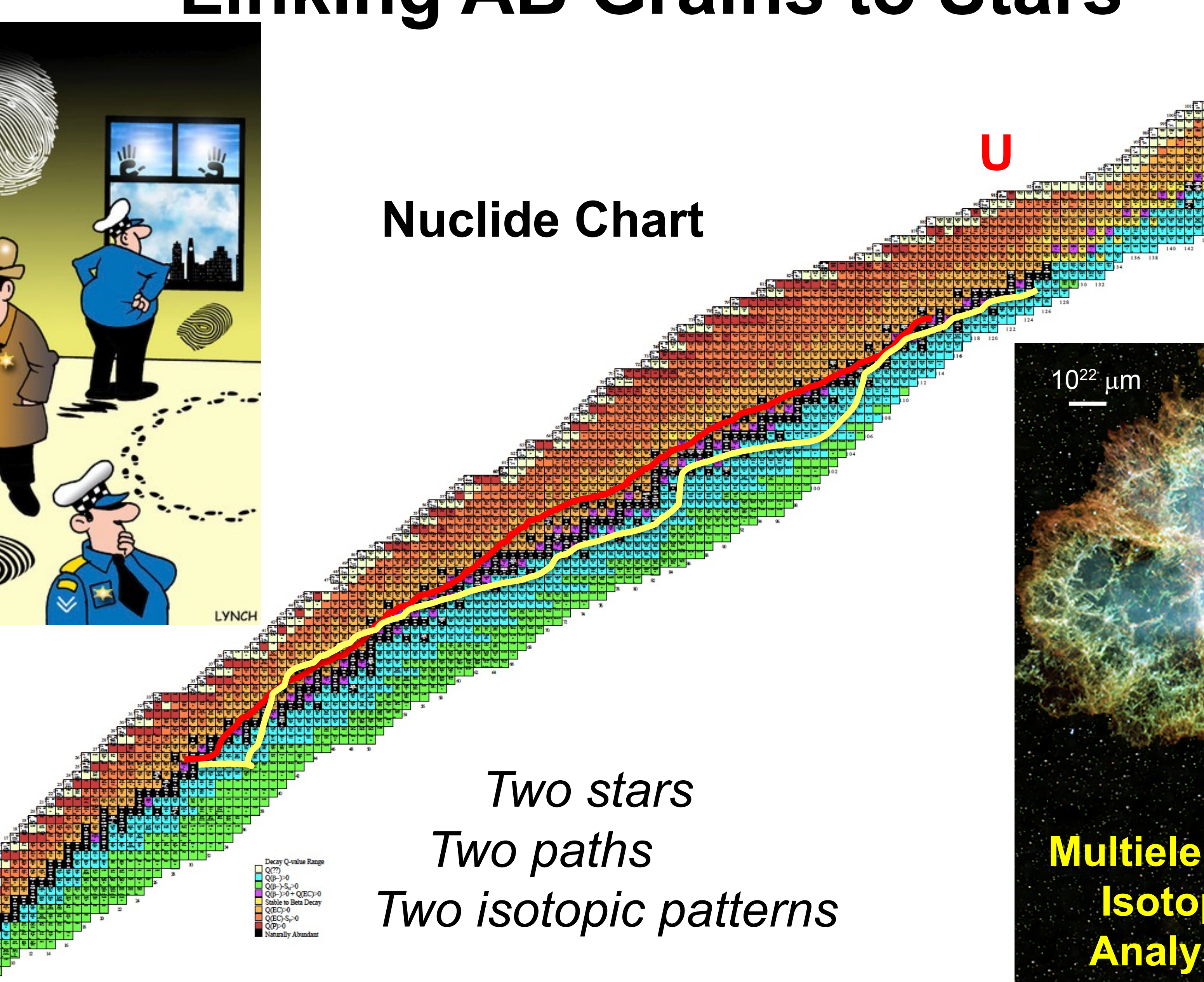


See Pignatari et al. (2015) *ApJL*
Liu et al. (2016) *ApJ*

Nittler & Ciesla (2016) ARA&A, 54,53

Linking AB Grains to Stars

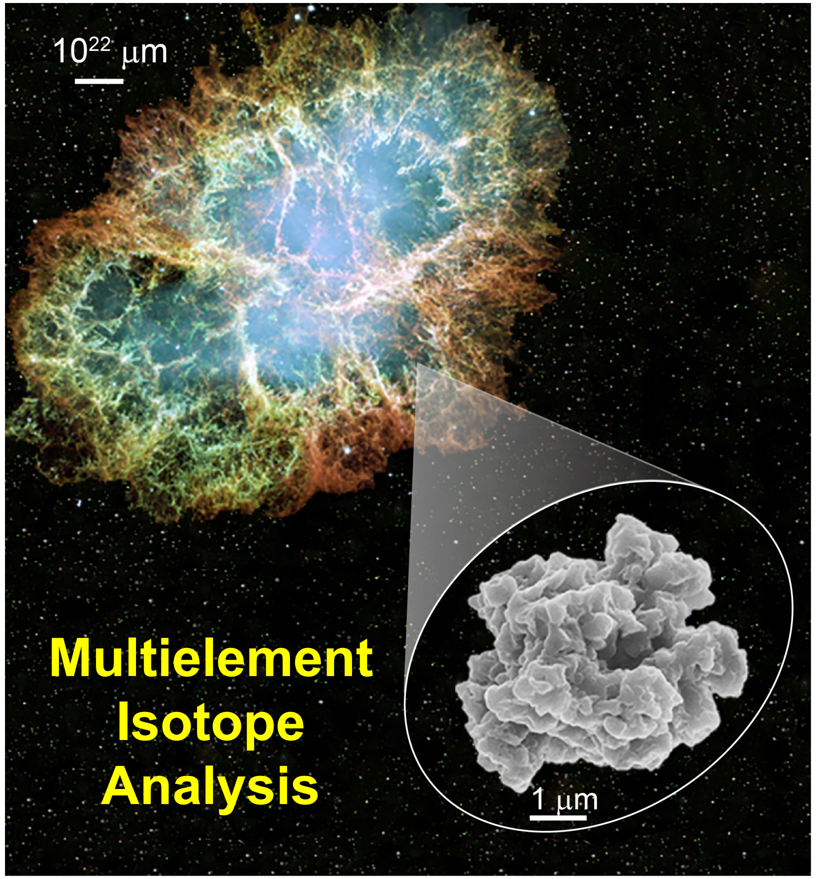
Nuclide Chart



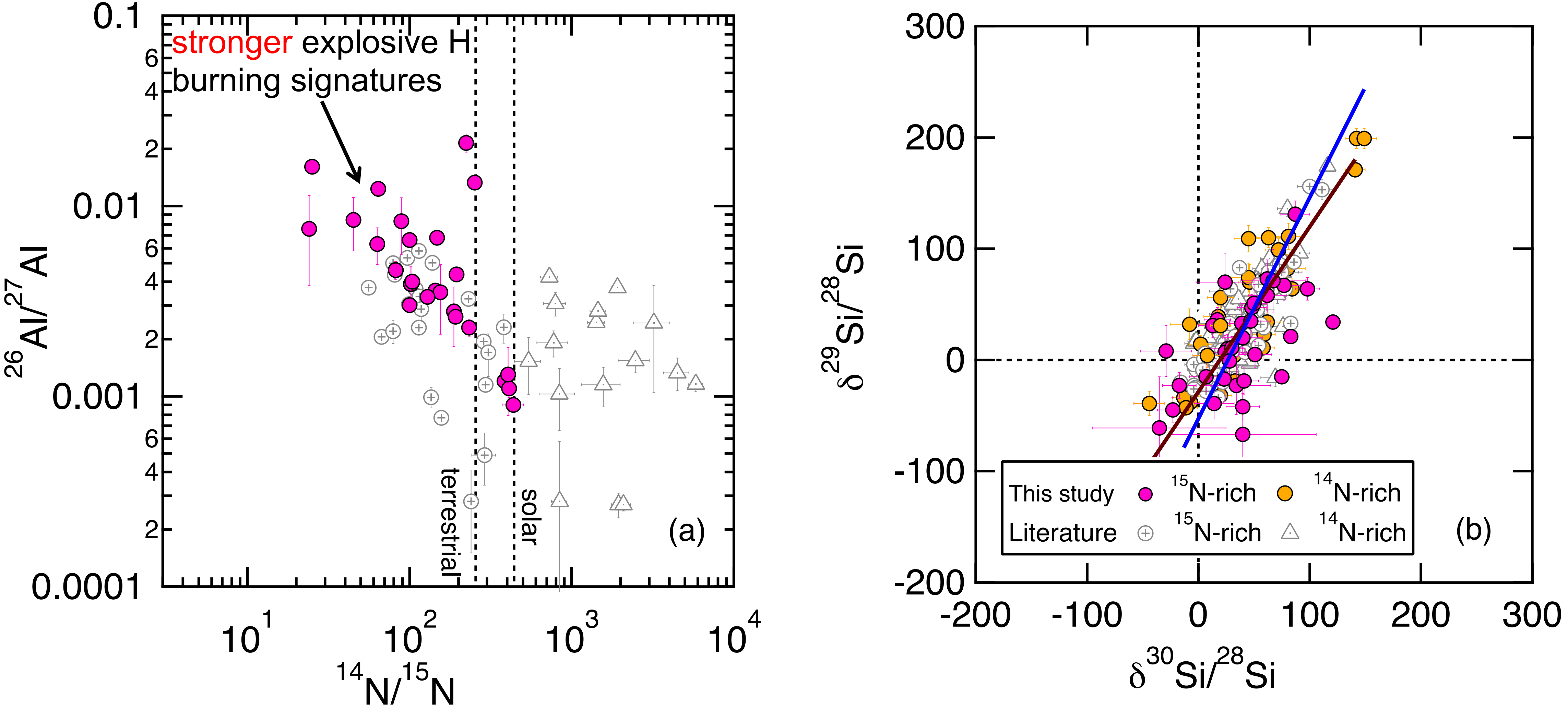
Two stars

Two paths

Two isotopic patterns



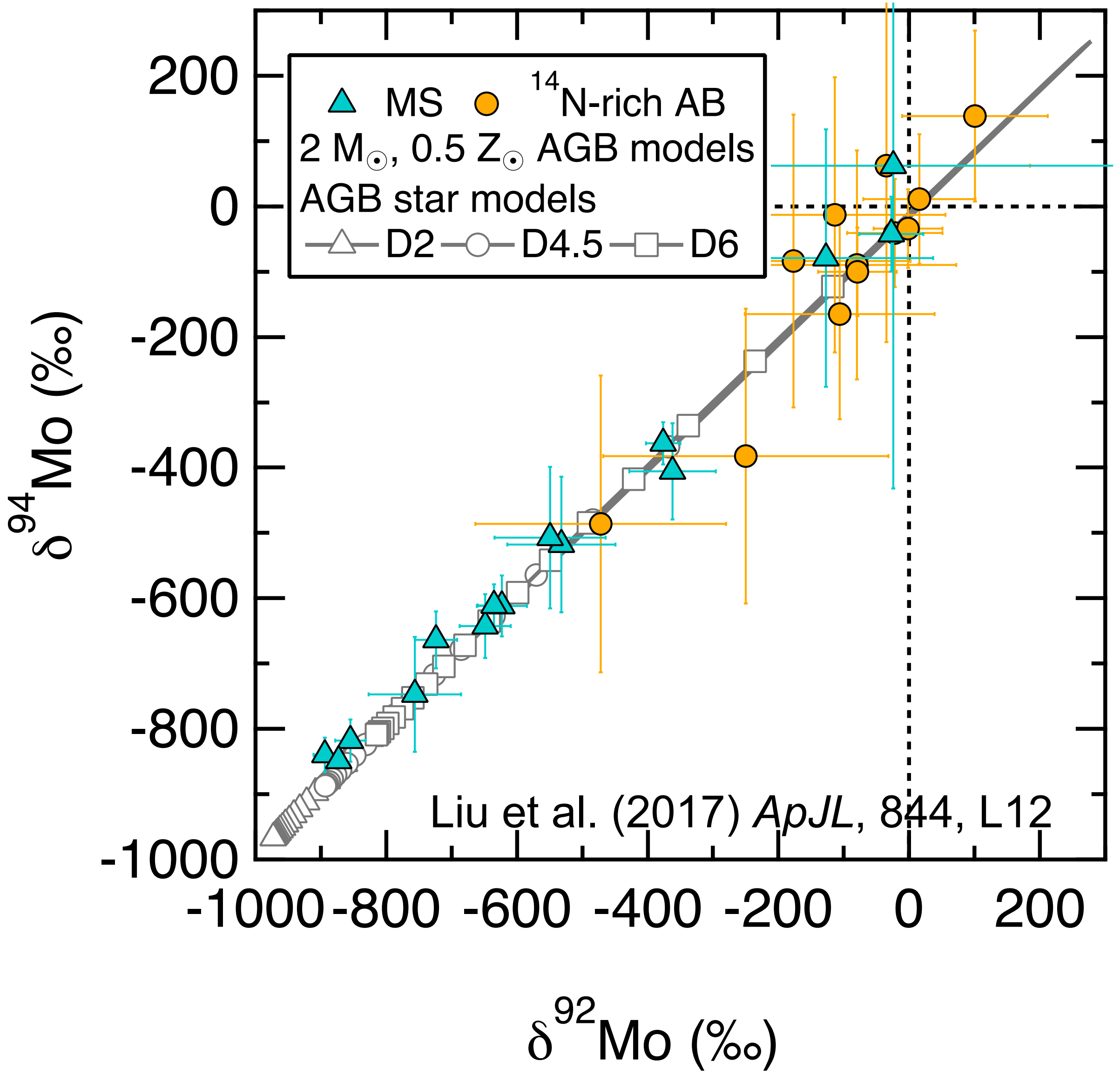
Two Groups of AB Grains



Consistent differences in N, Al, and Si isotope ratios

Liu et al. (2016) *ApJ*, 820, 140; Liu et al. (2017) *ApJL*, 844, L12; Liu et al. (2017) *ApJL*, 842, L1

^{14}N-rich AB : Mainly J-type Stars

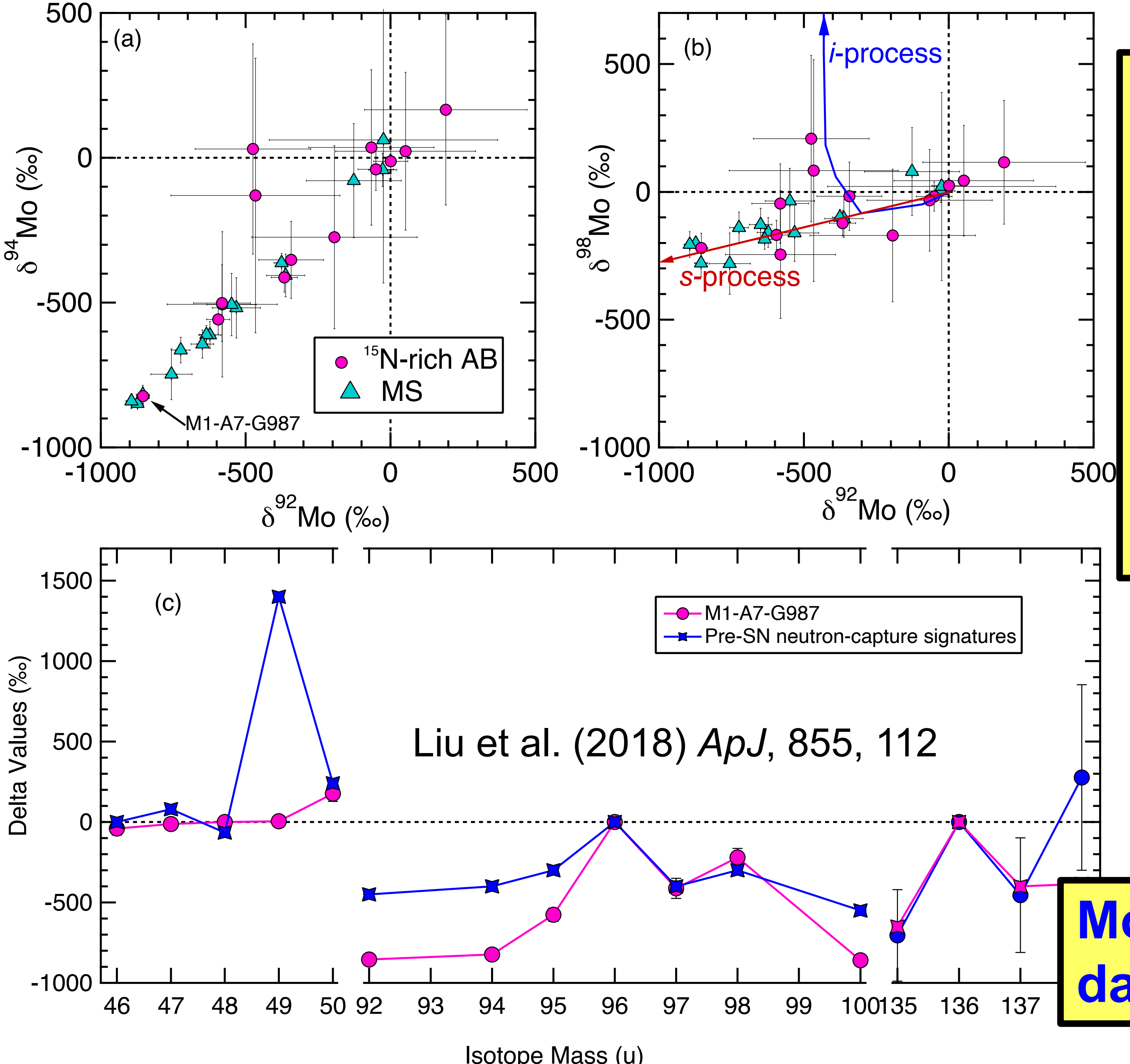


Similarities between ^{14}N-rich AB grains and J-type stars

- near-solar metallicities.
- similar C and N isotope ratios.
- close-to-solar heavy-element isotopic compositions.
- Both are relatively abundant.

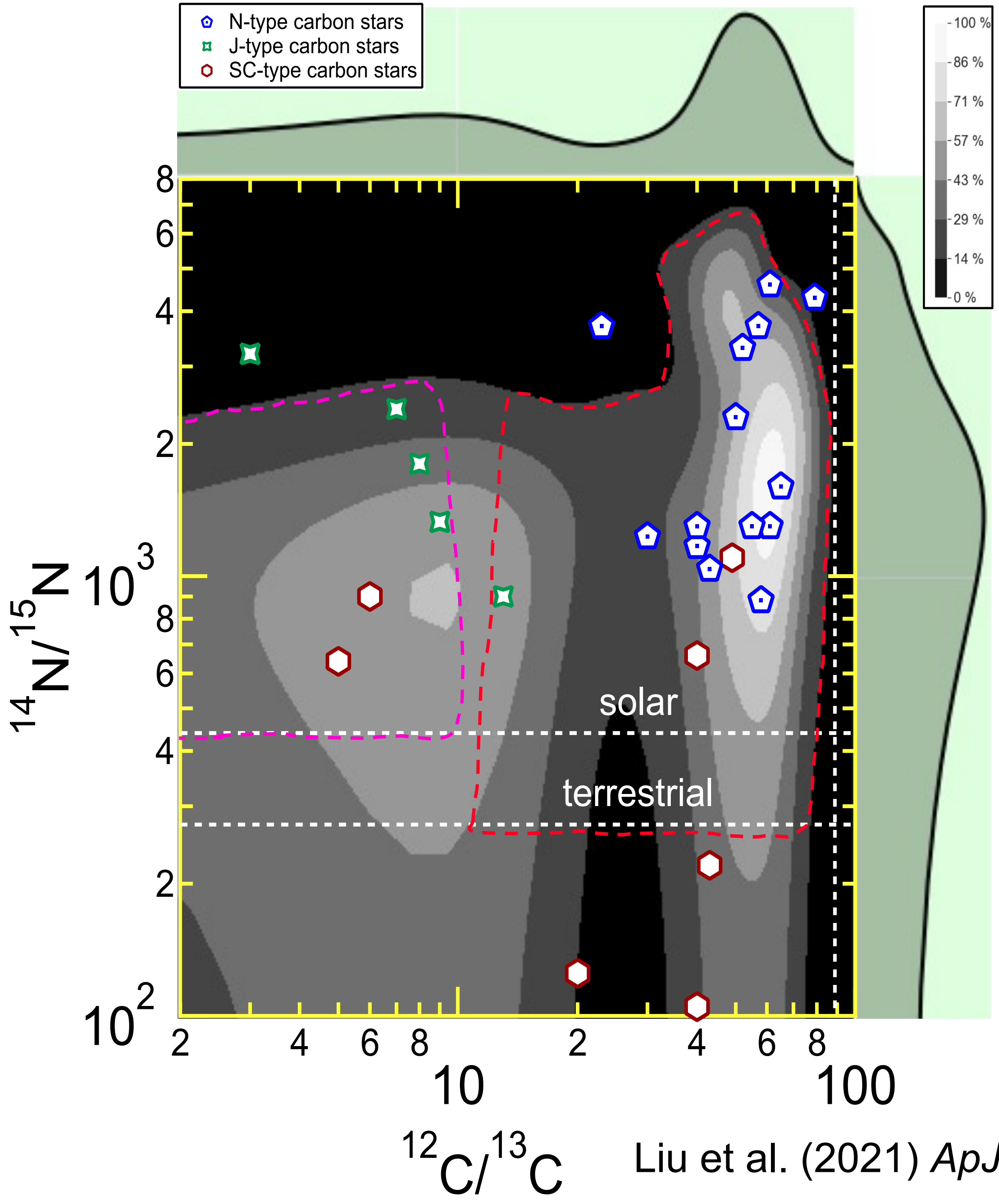
J-type star observations: Abia & Isern (2000) *ApJ*, 536, 438

^{15}N-rich AB Grains : *Supernovae?*



The coexistence of ^{13}C, ^{15}N, ^{26}Al, and *s*-process enrichments together point to **supernovae** as their progenitor stars.

More observational data are NEEDED!



Liu et al. (2021) *ApJL*, submitted

- **^{14}N-rich AB** grains overlap with **J-type carbon stars** and a few **^{13}C-rich SC-type carbon stars** in their C and N isotopic composition.
- No carbon stars lie in the region where **^{15}N-rich AB grains** are located, pointing out that these grains were likely sourced from **the ejecta of explosive events**, *e.g.*, supernovae.

Conclusions