COSMOCHEMSTRY OF PRESOLAR GRAINS

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Content.

1. **Presolar samples in the S.S.**
3. **Discvovery of anomalous compositions in meteorites.**
4. **Measurements in grains: from noble gases to main species**
5. **The stellar origin of many presolar grains**
6. **Grain anomalies & AGB stars: noble gases, s-elements, CNO**
7. **Constraints to stellar models: mixing & reaction rates**
8. **Radioactive Nuclei: any meaningful explanation?**
9. **X grains, selection effects & many things we don’t know.**

Workshop in Nuclear Astrophysics - Russbah, March 10,2014

THE COMPOSITION OF THE SUN AND ITS CARRIERS

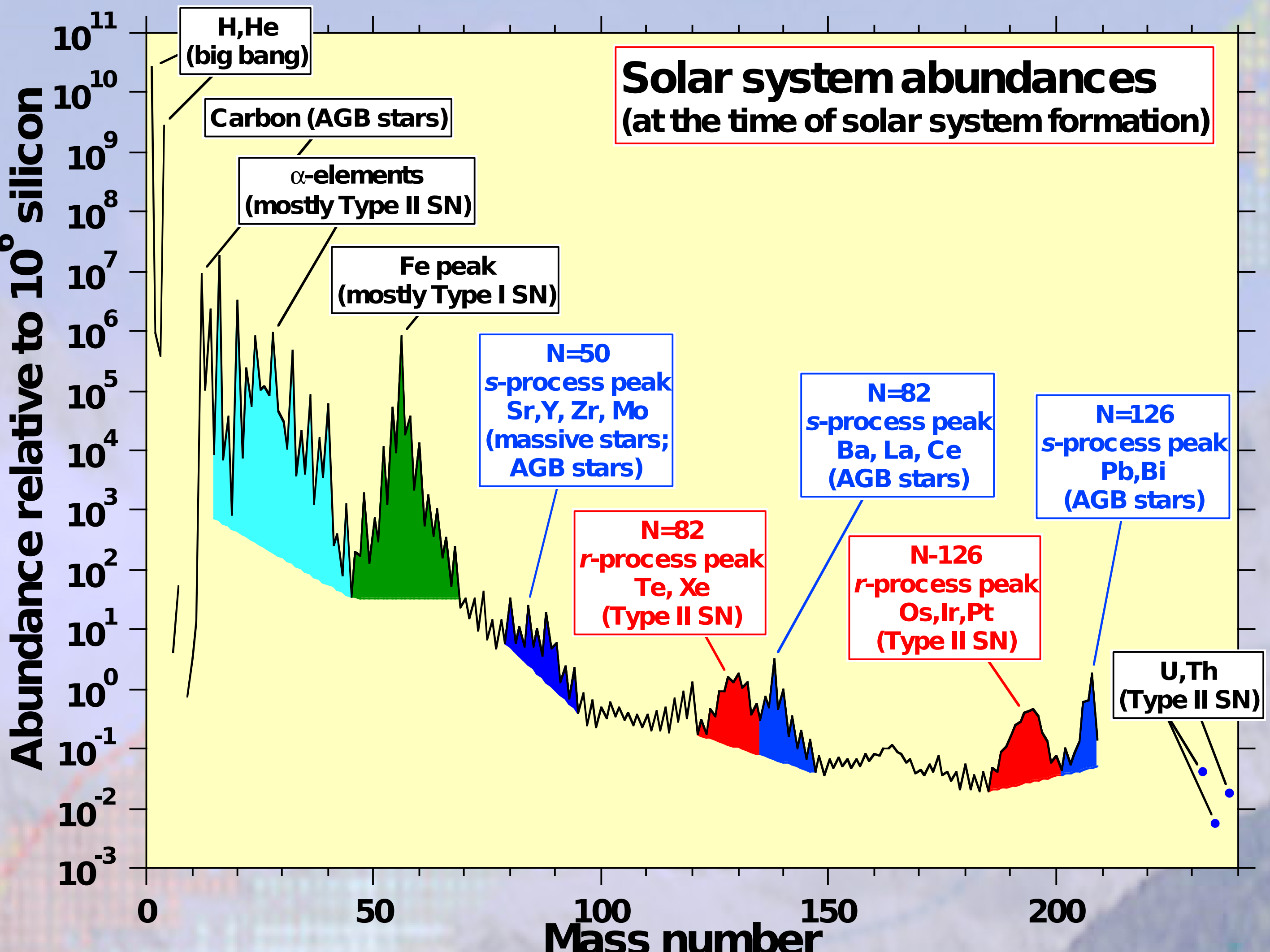
Solar Elemental Abundances

Element	Number %	Mass %
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.8
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

In 40 years, not much change!

The Sun inherited its composition from the Interstellar Medium (ISM); not NECESSARILY from its gas phase!
Refractory elements were strongly segregated in solids, as in the ISM today.
Identifying the carriers and finding reservoirs that remained unmixed/unmelted means separating the ingredients from which the cake was made!

THE ISOTOPIC SOLAR COMPOSITION



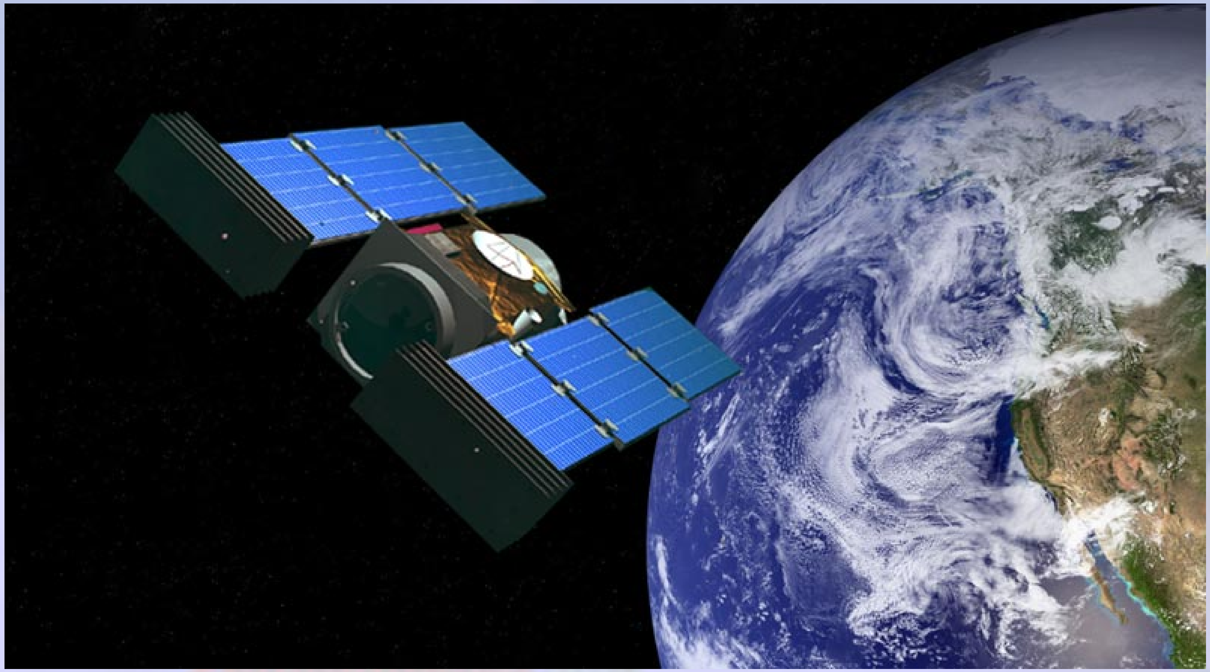
As you may hear in these days, even from the *average* composition of the Sun we infer many properties of nucleosynthesis processes. Separating the carriers would permit to study them with exceptional accuracy.

ANCIENT METEORITES GENTLY PROVIDED TO US

Allende (Mexico, 1969)

Murchison (Australia, 1969)

THE SAMPLES



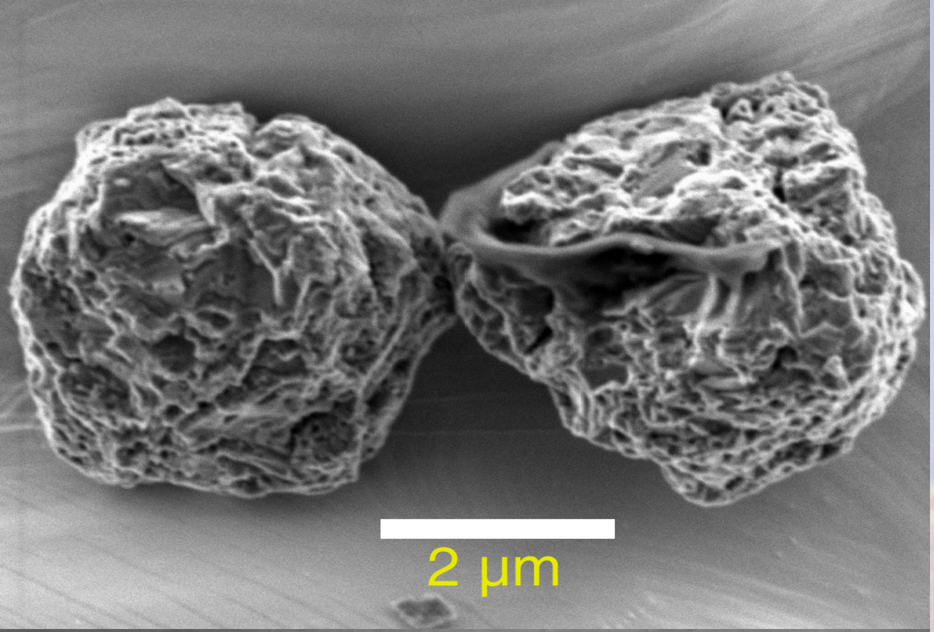
Material with unaltered composition, hence relatively rich in the original solid constituents from which the average solar abundances derive is found in comets, ancient meteorites and small solids of non-planetary origin.

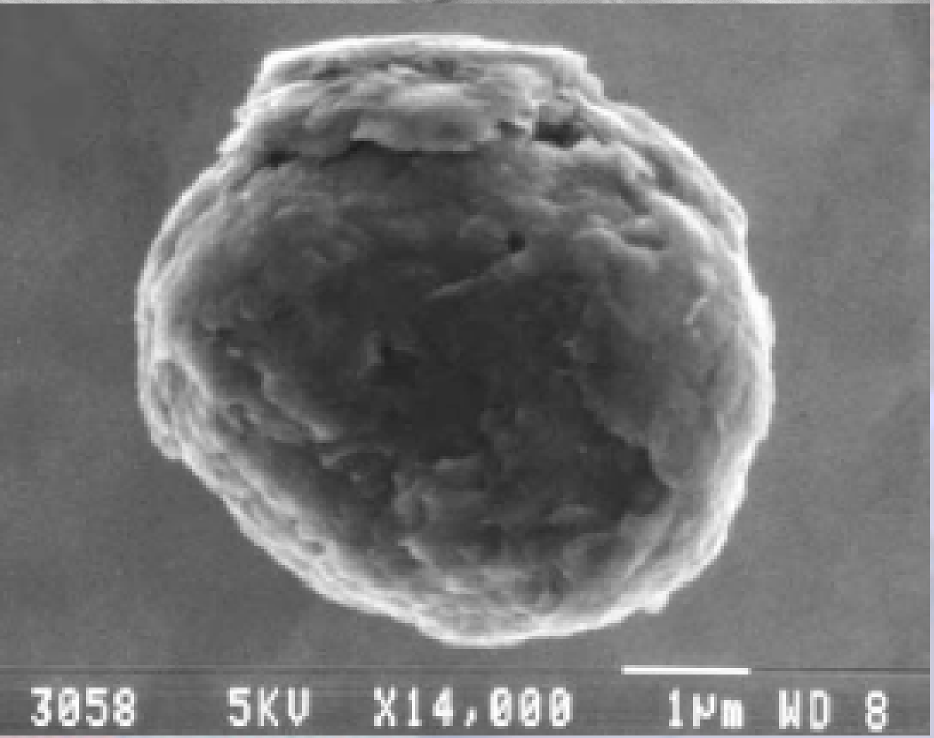
In the period 1999-2011 the STARDUST mission sampled the comet WILD-2 and sent to the Earth a collection of tiny particles trapped by a special “basket” of AEROGEL

ANOMALIES FOUND IN METEORITES

Reynolds (1960) early recognized that pristine meteorites had sub-systems showing excesses of ^{129}Xe from radioactive ^{129}I (Ryenolds, 1960) Subsequently Reynolds & Turner (1964) characterized another Xe anomaly, called Xe-HL, with excesses of light and heavy Xe isotopes with respect to ^{130}Xe. They guessed this was the relics of fission.

In the next years noble gases in early meteorites were studied franctically. The fall of Allende (1969) offered new sources for analysis. In 1977 Lee et al. discovered ^{26}Al (through its decay product ^{26}Mg) Lewis, Gross & Anders (1975) showed that anomalies affected other noble gases. ^{22}Ne/^{20}Ne larger than the average S.S. ratio was foun (Ne-H).

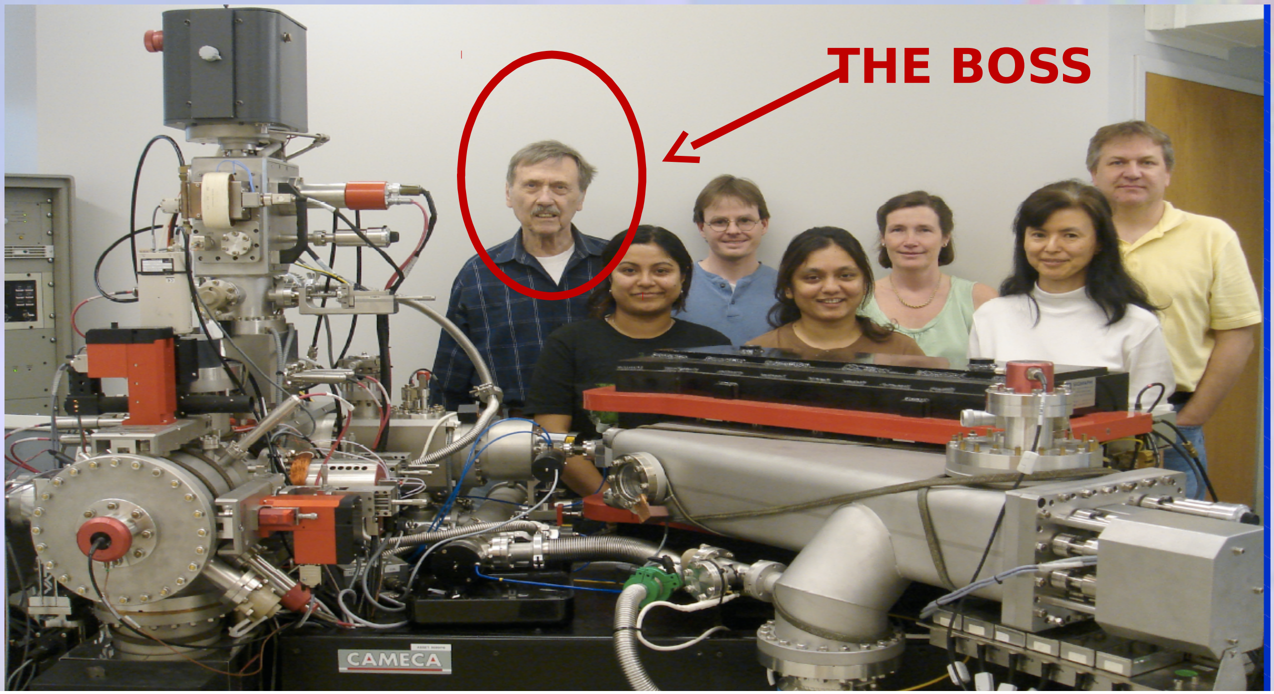




From bulk to grains.

Samples examined by Reynolds & Turner (1964) were large (from mm to cm size).
After the Moon landing mass spectroscopy and chemical separation techniques made enormous jumps.
In St. Louis Zinner & co. started selecting (through acids) resistent SiC grains

The Saint Louis Group



How can you find a needle in a haystak?

Simple: you burn the haystak and what remains is the needle!

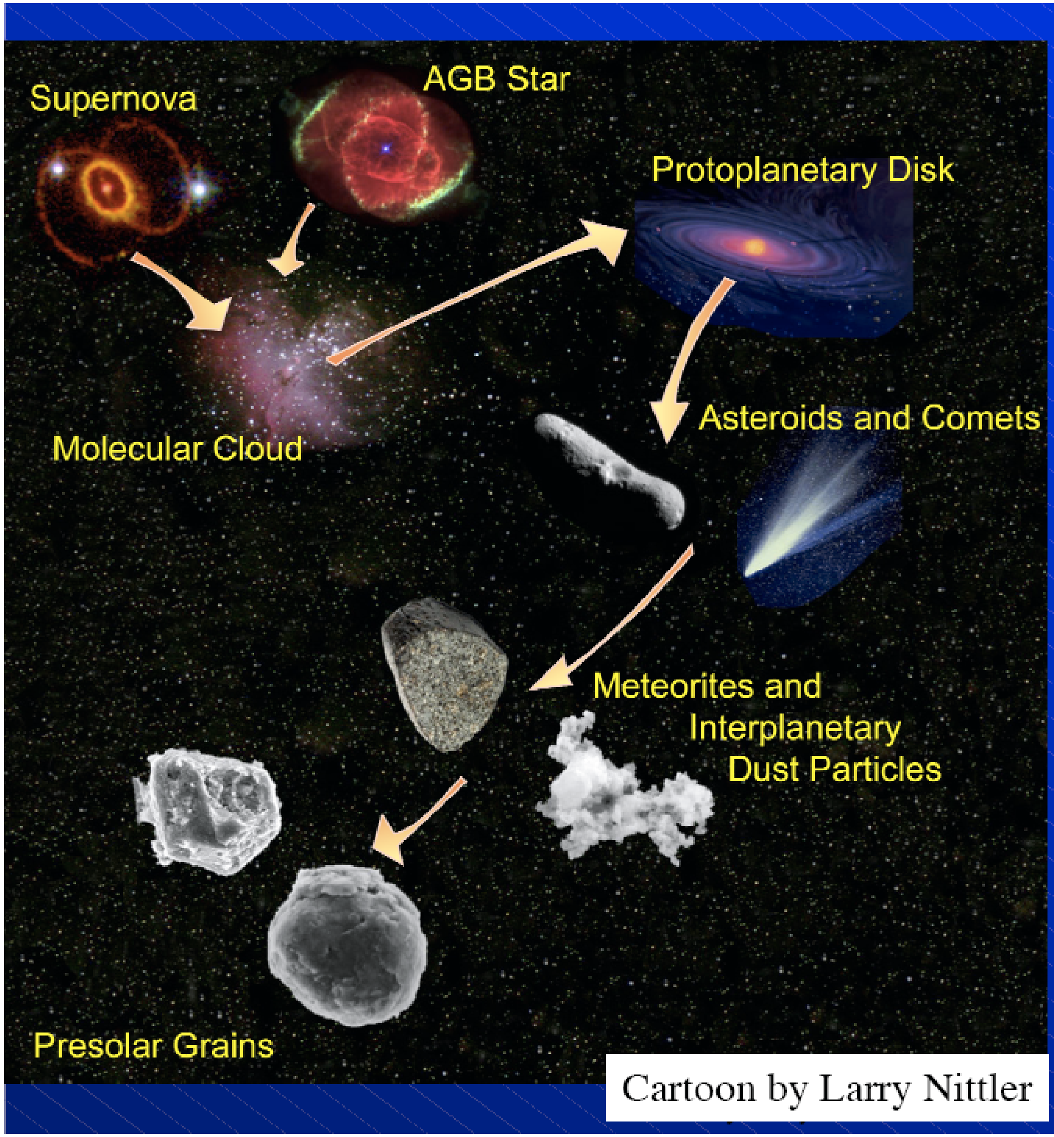
In those years and until now, crucial role played by the Max Planck Institute for Chemistry (Mainz).

Experimentalists: Uli Ott, Peter Hoppe,...

Theory group headed by Karl-Ludwig Kratz

Strange enough, the Max Planck Institute shows apparently no interest in continuing the tradition!

PRESOLAR GRAINS



In the last 25 years a new source of information on isotopic abundances in stars has become available in the form of stardust preserved in primitive meteorites.

Grains from Red Giants and supernovae were included into the molecular cloud that collapsed into our Solar System.

Some of these grains are preserved in primitive meteorites, from which they can be extracted and studied in detail in the laboratory.

THE INTERPRETATION

Meteoritic silicon carbide: pristine material from carbon stars

Roy S. Lewis, Sachiko Amari & Edward Anders*

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2. †Present address: McDonnell Center for Space Sciences, Washington University, St Louis, Missouri 63130-4899, USA.

All five noble gases in interstellar silicon carbide grains have grossly non-solar isotopic and elemental abundances that vary with grain size but are strikingly similar to calculated values for the helium-burning shell of low-mass carbon stars. Apparently these grains formed in carbon-star envelopes, and were impregnated with noble gas ions from a stellar wind. Meteoritic SiC provides a detailed record of nuclear and chemical processes in carbon stars.

Nature 348, 293 (1990)

On the astrophysical interpretation of isotope anomalies in meteoritic SiC grains

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3. ‡International School for Advanced Studies, Via Beirut 4, 34014 Trieste, Italy

Meteoritic silicon carbide grains, formed in the winds from carbon stars, contain noble gases and other species whose elemental and isotopic abundances are a probe of stellar nucleosynthesis. Theoretical models of carbon stars can explain a variety of measured abundances, in particular the range of krypton isotope ratios and the excess ^{22}Ne found in the grains.

Nature 348, 298 (1990)

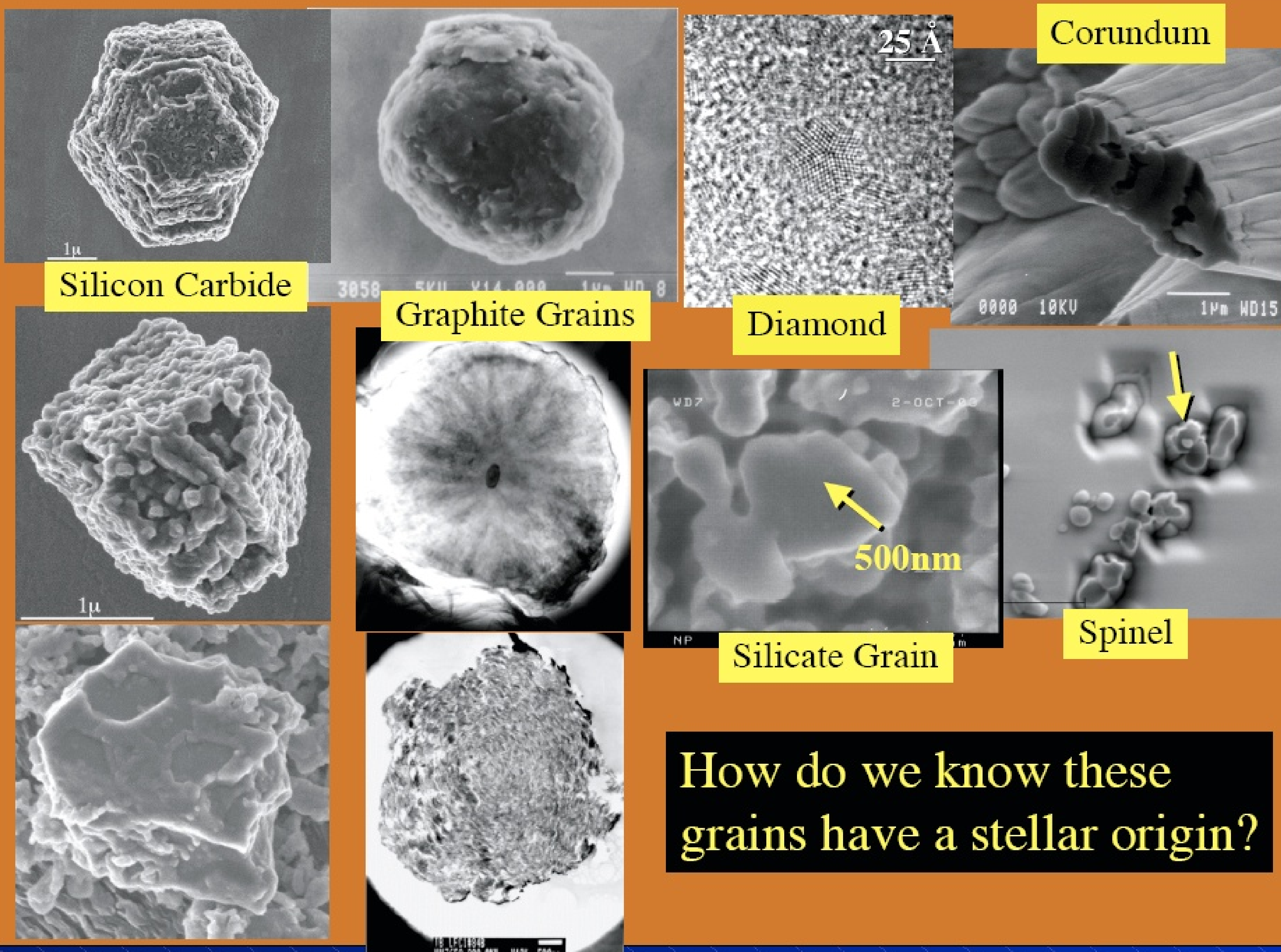
AGB STARS ENTER THE PICTURE !

THE ADVENT OF NANO-SIMS

The nano-SIMS (nano-Secondary Ion Mass Spectrometry) technique allowed studies of presolar grains to make a large forward jump.

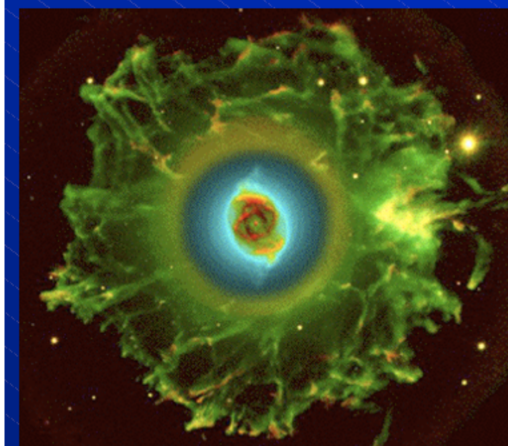
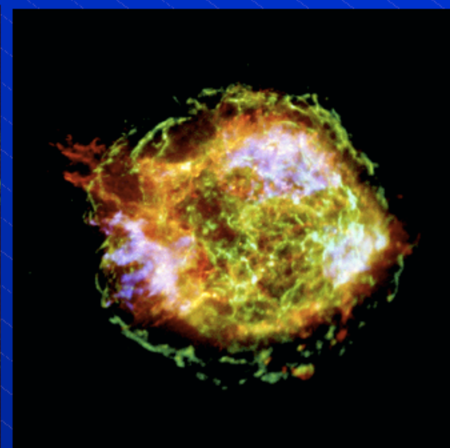
Nano-SIMS perform mass-spectrometry on secondary ions, sputtered from a solid target (the grain) by the impact of a primary beam of charged particles. High-accuracy experiments now allow measuring single grains for the isotopes of major species.

More recently, laser sputtering techniques (Andy Davis, Chicago) permitted to select individual nuclei of trace species and to analyze *single* grains for trace element isotopes.

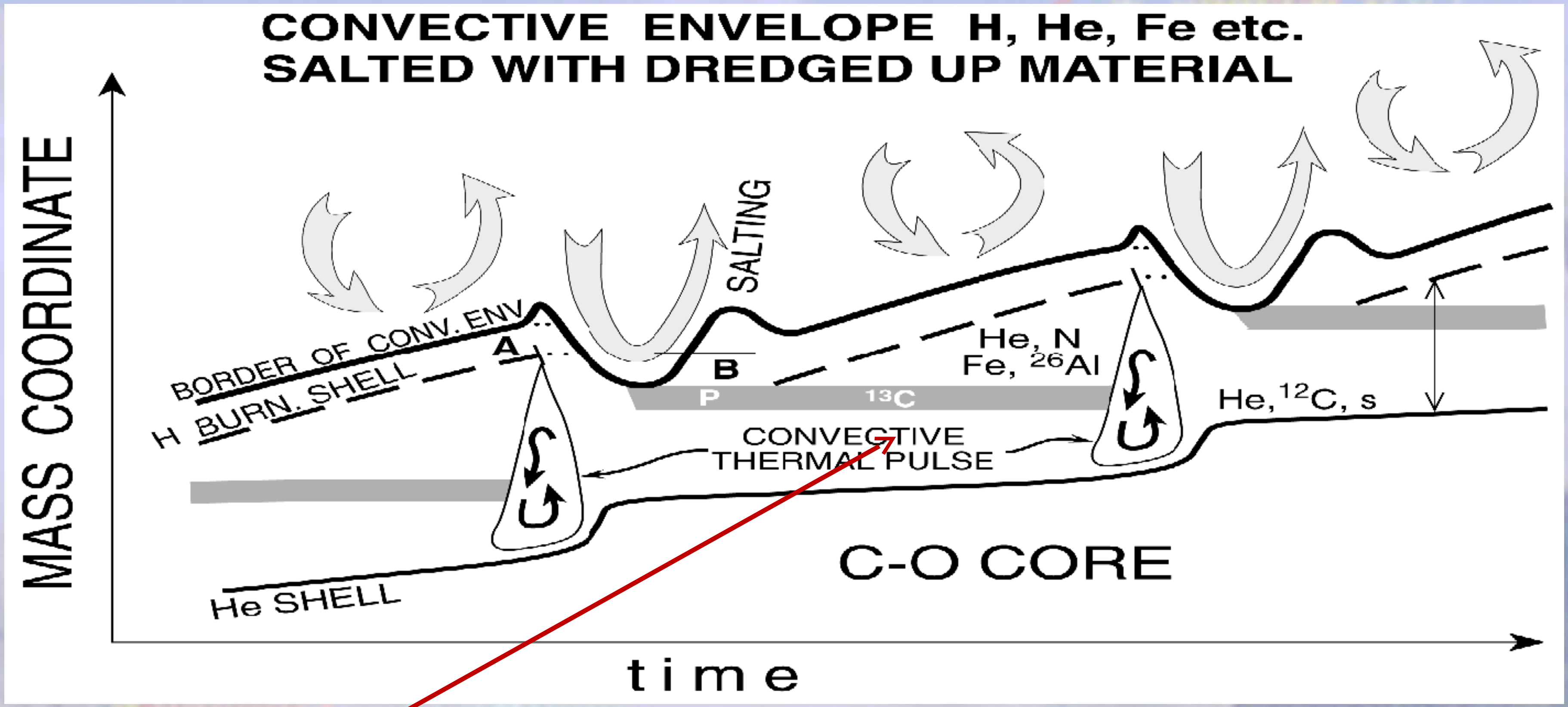


How do we know these grains have a stellar origin?

Stellar Sources of Presolar Grains

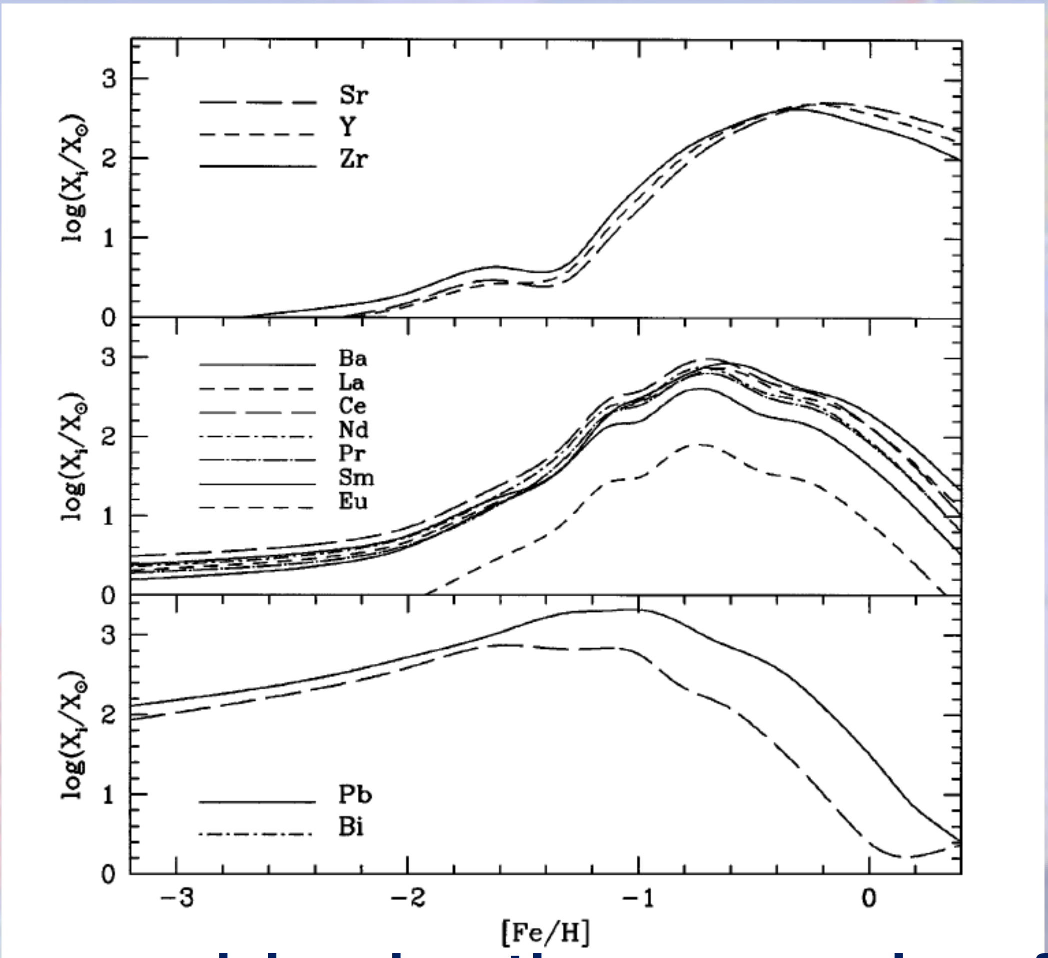
AGB Stars	Supernovae	Novae
		
Cat Eye Nebula	Cassiopeia A	Nova Cygni 1992
>90% of SiC, Silicates, Oxides; ~50% of Graphite	<5% of SiC, Silicates, Oxides; ~50% of Graphite, 100% Si_3N_4	<1% of SiC, Silicates, Oxides, Graphite

The thermal pulses and the third dredge-up



13C(α,n)16 O recently from the ASFIN COLLAB

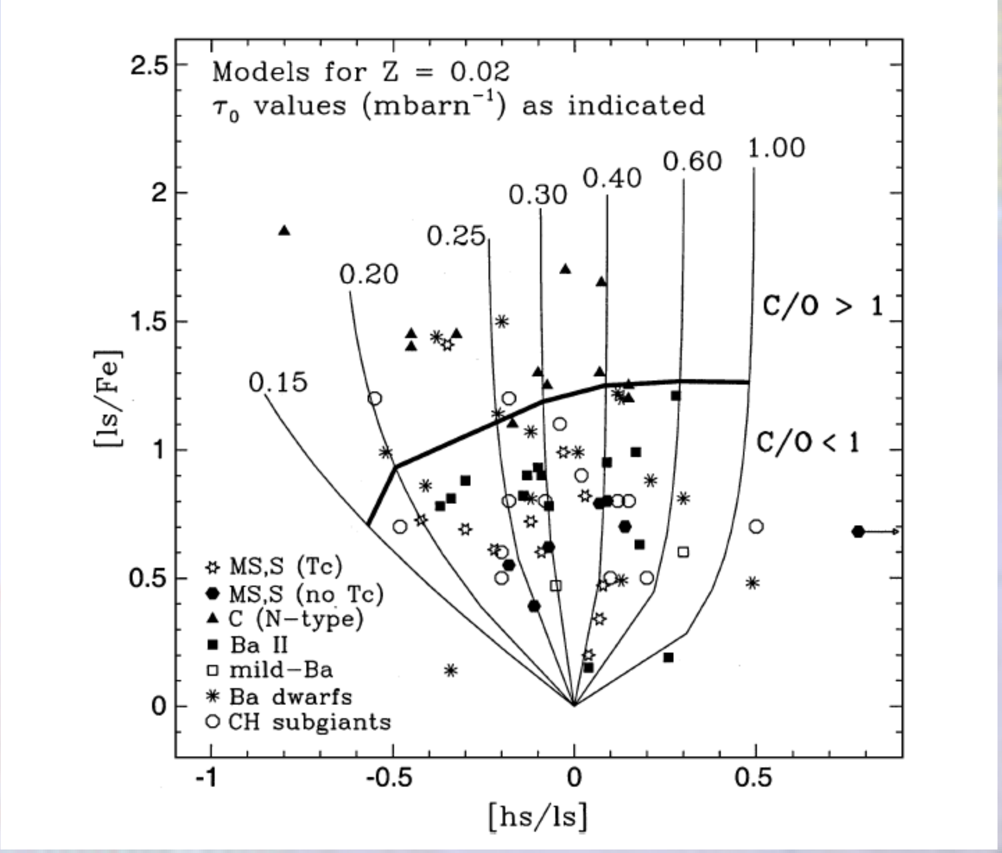
S-PROCESS PREDICTIONS VARY WITH METALLICITY



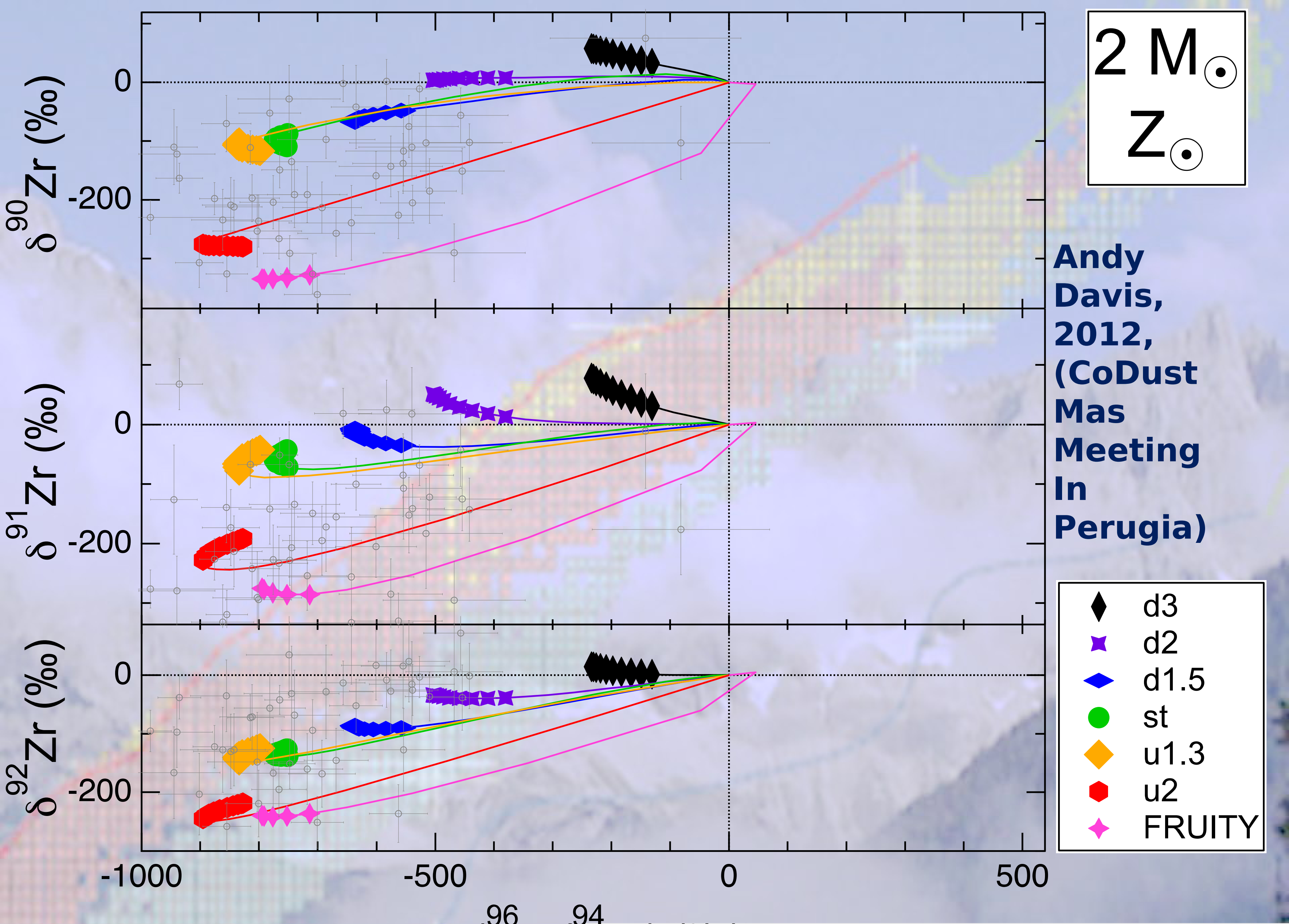
Busso et al 1999
ARAA 37

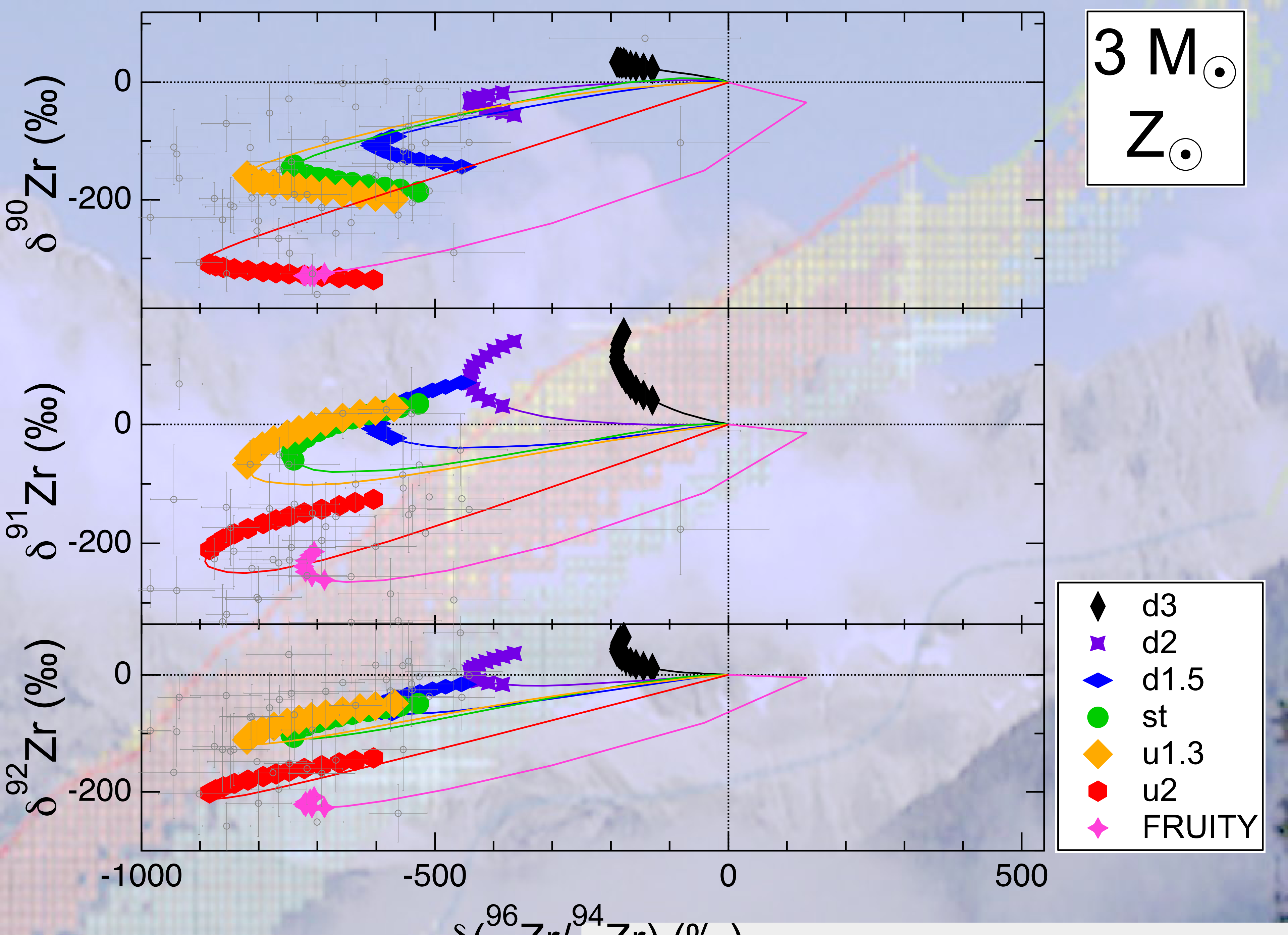
s-Process models using the same number of neutrons per heavy seed produce different s-element abundances for variable metallicity.

DIFFERENT s-PROCESS COMPOSITION IN AGB STARS

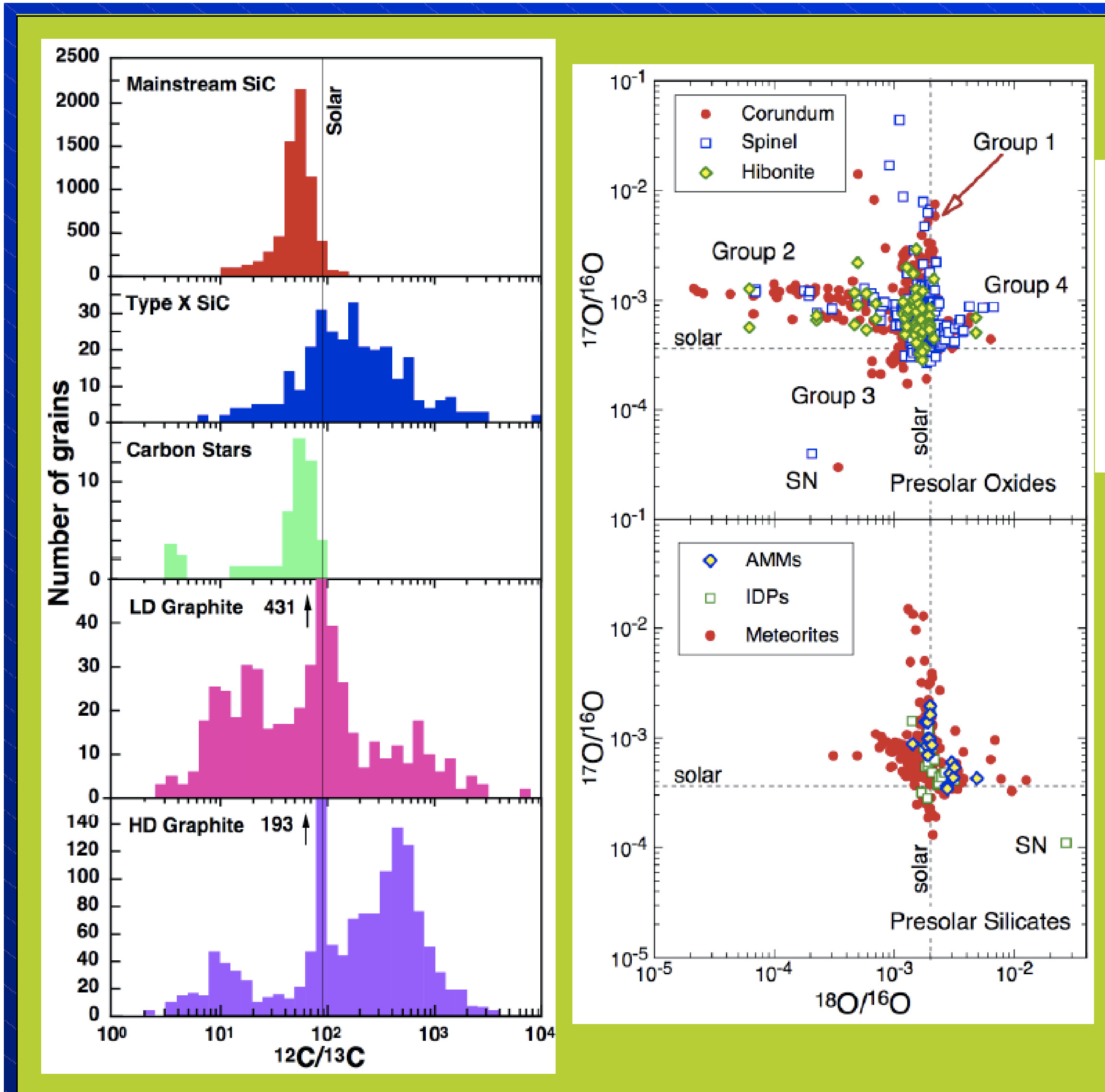


Different s-process compositions exist in stars with same metallicity (different amounts of neutrons released, different number of nucleosynthesis cycles). Similar spread found in grains, since the first discoveries on noble gases.


2 M☉
Z☉
Andy Davis, 2012, (CoDust Mas Meeting In Perugia)
d3
d2
d1.5
st
u1.3
u2
FRUITY
δ90Zr (‰)
δ91Zr (‰)
δ92Zr (‰)
δ(96Zr/94Zr) (‰)
0
-200
-1000
-500
500

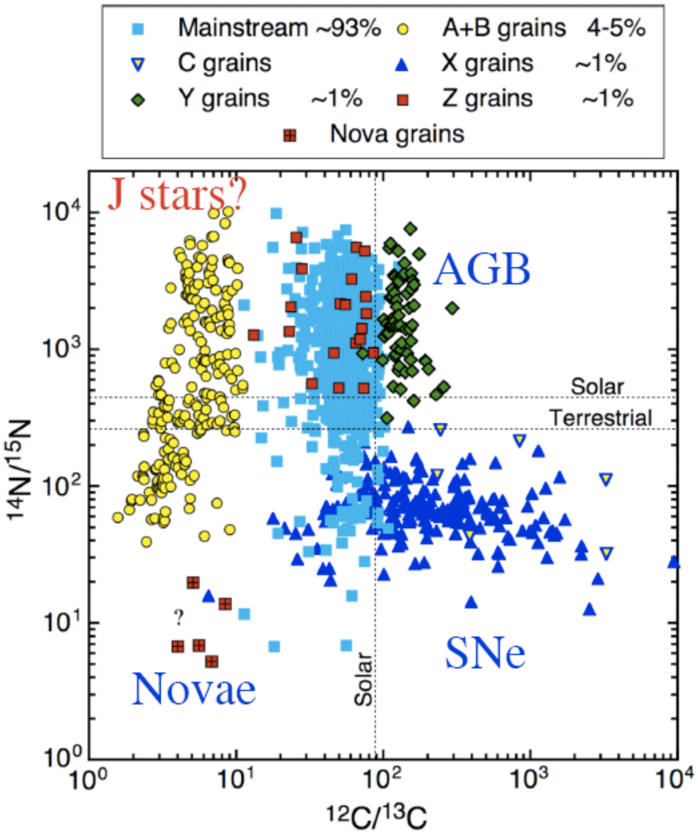

3 M☉
Z☉
δ90Zr (‰)
δ91Zr (‰)
δ92Zr (‰)
δ(96Zr/94Zr) (‰)
0
-200
-1000
-500
0
500
d3
d2
d1.5
st
u1.3
u2
FRUITY

ISOTOPIC ABUNDANCES IN SiC GRAINS



Isotopic Abundances In C-rich (SiC) and O-rich (Al2O3) Presolar Grains

PUZZLING CLASSES OF GRAINS DISCOVERED



SiC AB grains

We infer stellar sources from isotopic ratios

>10,000 SiC grains have been analyzed

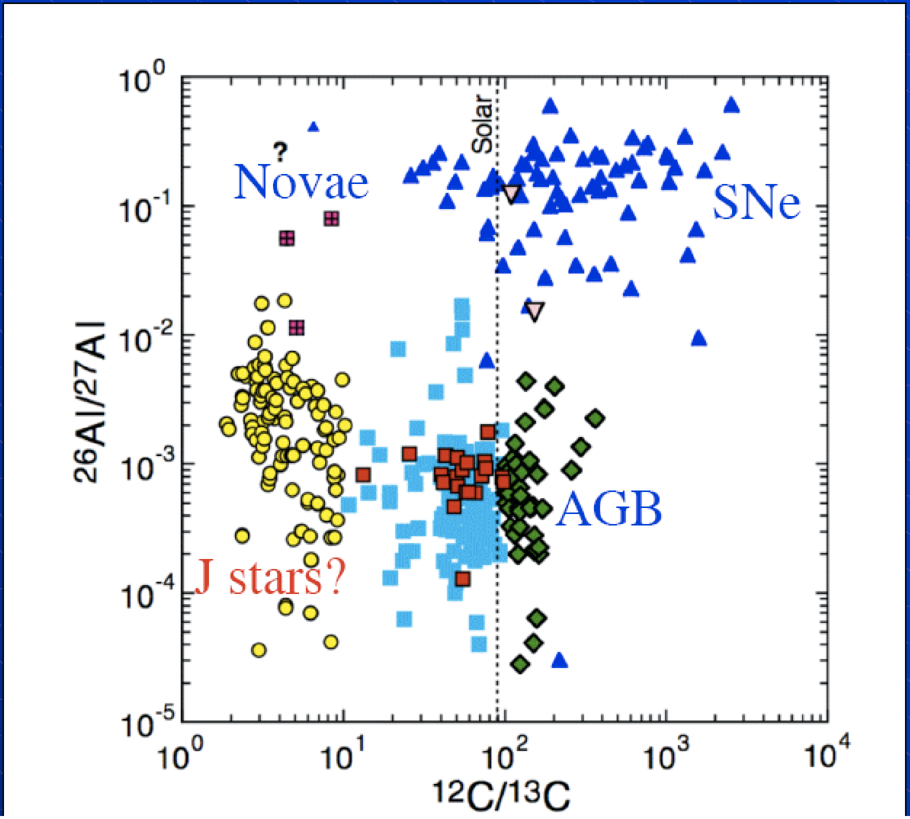
AGB Mainstr., Y, Z

SNe C, X

J stars? AB

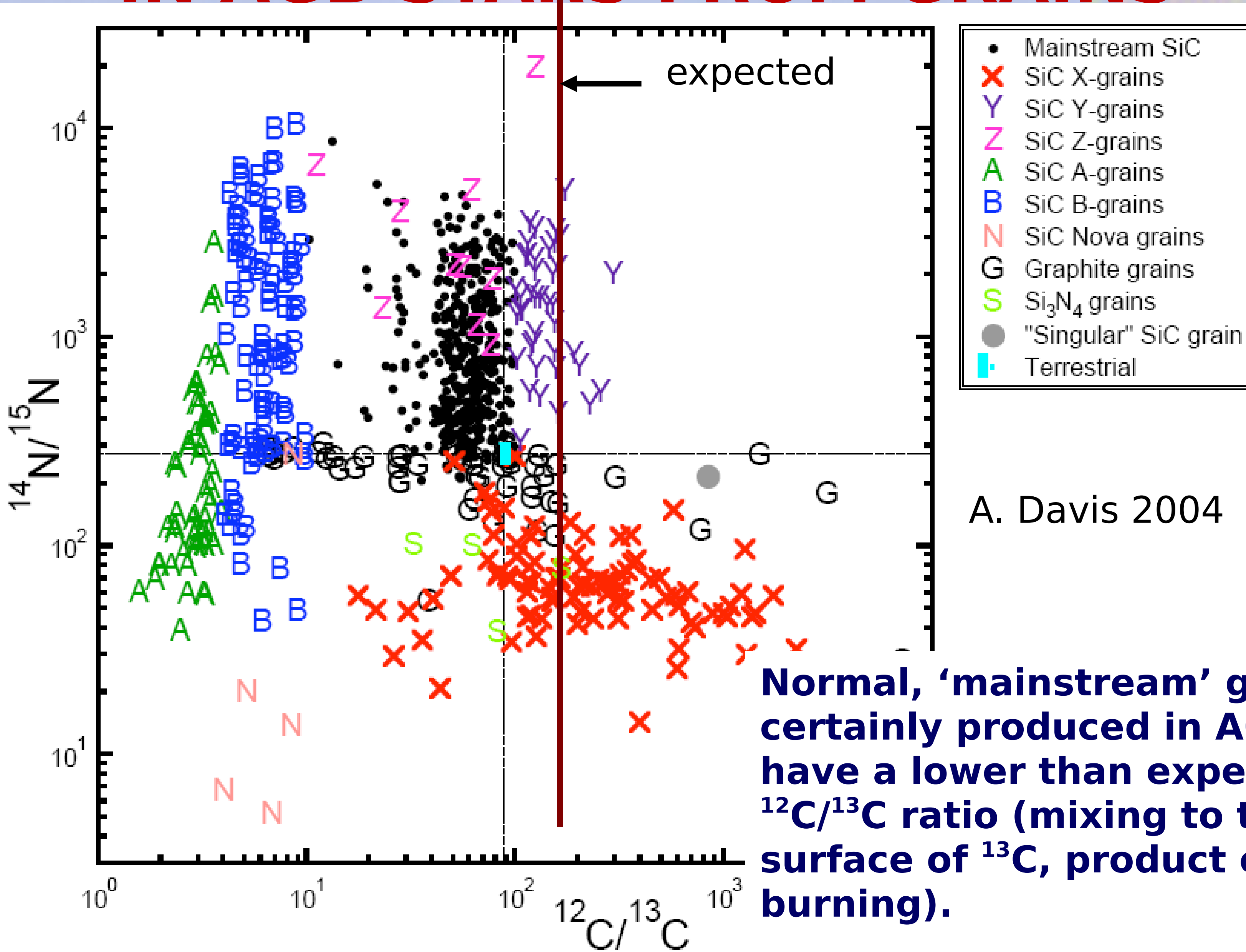
Novae

SiC GRAINS CONTAINING ^{26}Mg (^{26}Al DECAY)



^{26}Al abundances dispersed. Correlation with ^{13}C unclear.

CONSTRAINTS ON R. RATES & MIXING IN AGB STARS FROM GRAINS



Normal, 'mainstream' grains certainly produced in AGBs have a lower than expected $^{12}C/^{13}C$ ratio (mixing to the surface of ^{13}C, product of H burning).

The problem: a reminder
(The $^{12}C/^{13}C$ ratio on the RGB)

Standard models → distinction between:

Radiative layers
$$\left.\frac{\mathrm{d}T}{\mathrm{d}r}\right|_{rad} = -\frac{3}{16\sigma}\cdot\frac{k_R\rho}{T^3}\cdot\frac{L(r)}{4\pi r^2} \rightarrow \left.\frac{\mathrm{dlog}T}{\mathrm{dlog}p}\right|_{rad} = \nabla_{rad} = \frac{\Re}{4\pi \mathrm{G}}\cdot\frac{1}{k_R\mu}\frac{L(r)}{M_r}$$
if $\nabla_{rad} < \nabla_{ad}$

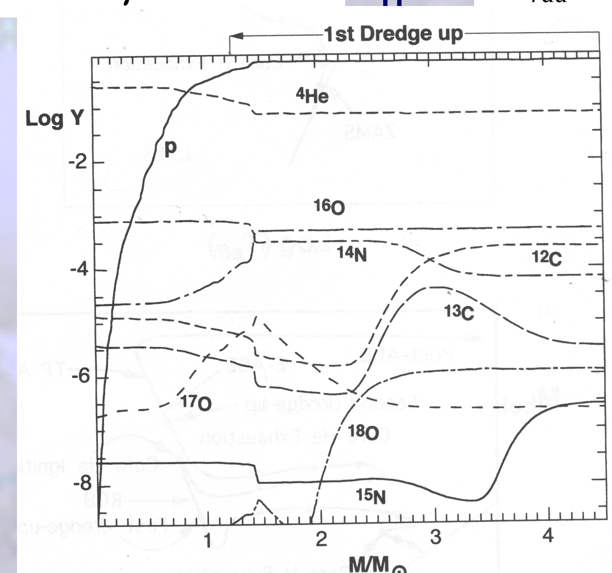
Convective layers
$$\left.\frac{\mathrm{d}T}{\mathrm{d}r}\right|_{ad} = -\left(1-\frac{1}{\gamma}\right)\frac{T}{p}\mathrm{G}\frac{\rho M_r}{r^2} \rightarrow \left.\frac{\mathrm{dlog}T}{\mathrm{dlog}p}\right|_{ad} = \nabla_{ad} = \frac{\gamma-1}{\gamma} \leq 0.4$$
if $\nabla_{rad} > \nabla_{ad}$

More convection?

No! We need a process slow enough to let ^{13}C reform

At right: First dredge-up in a 5 Mo star according to Dearborn.

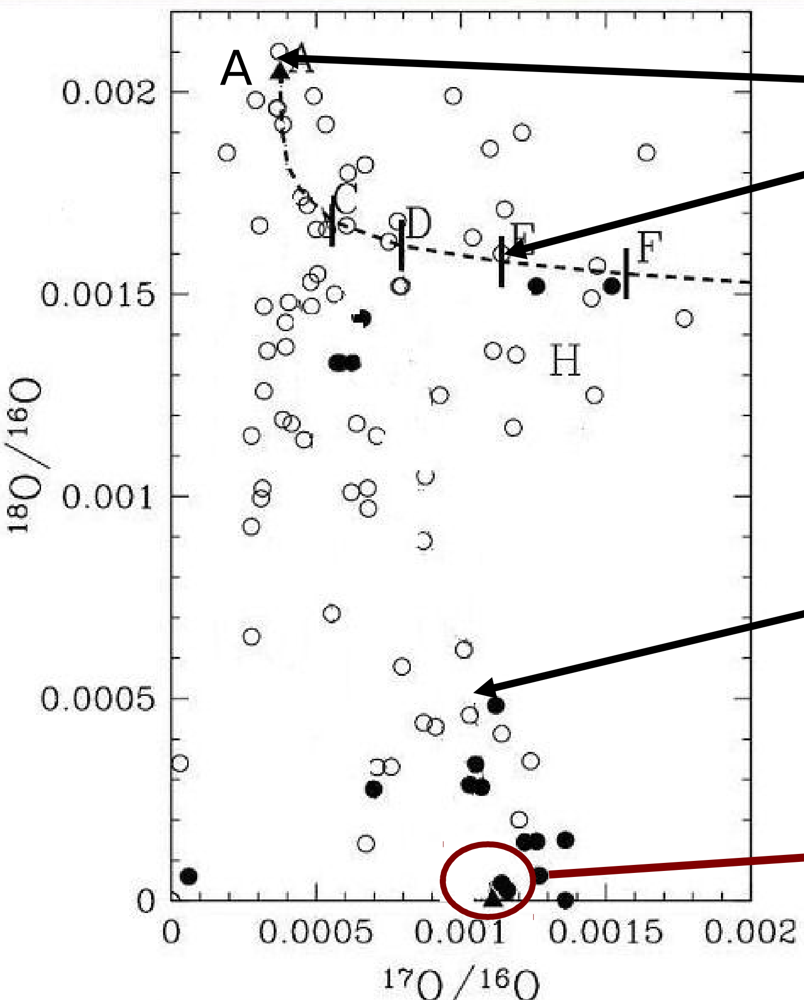
All ^{13}C is taken to the surface, but the 12/13 ratio does not decline below about 20.



After the 1°DU $^{12}C/^{13}C$ drops from 89-90 (solar) to 20-30. But we have stars with values 4-20.

Presolar Al_2O_3 grains

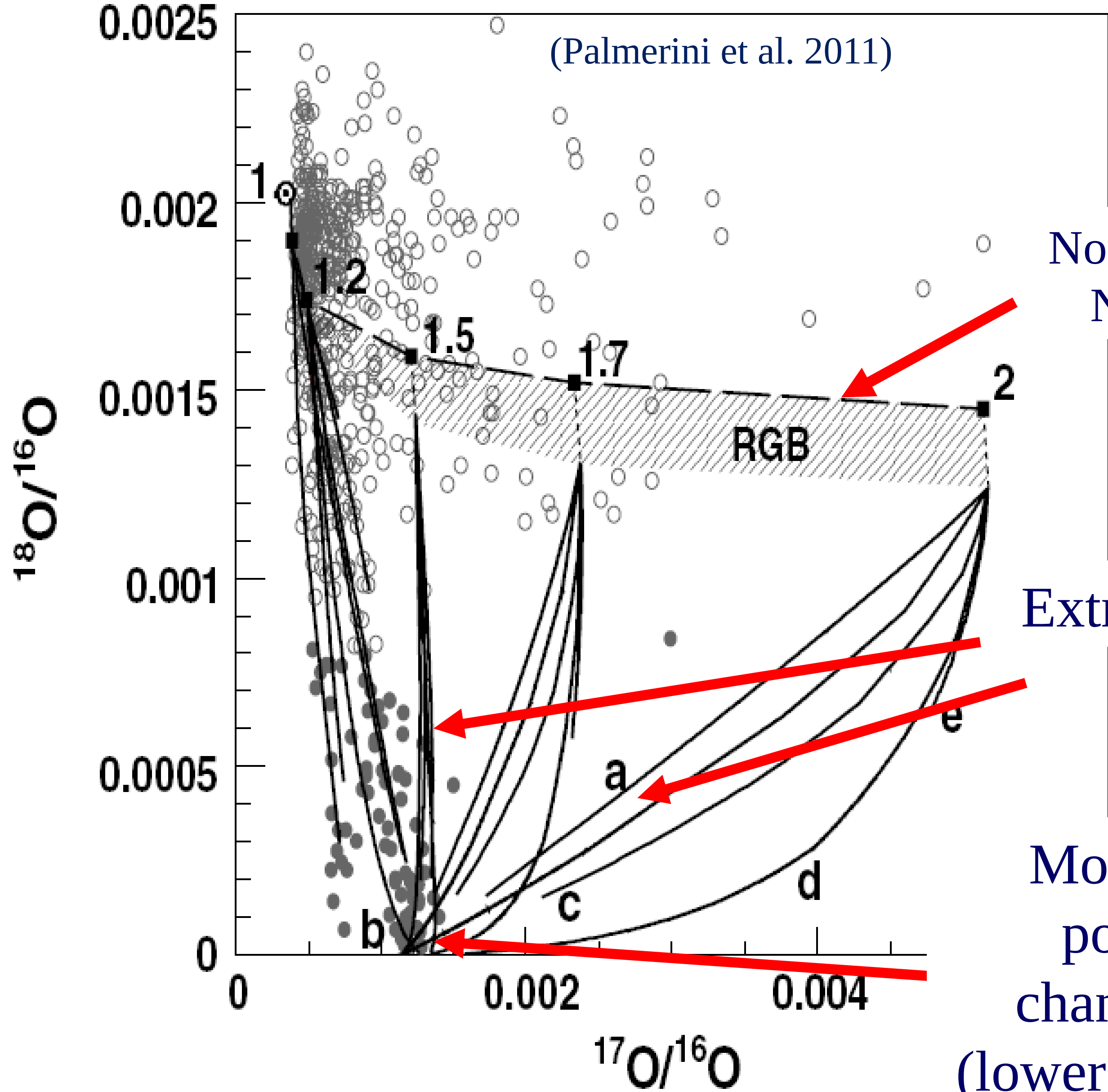
Presolar Grains: Nittler et al. 1997



Solar ratios □ point A; ratios after first dredge-up for masses 1.1 – 2.0 M8 : C-F

Dots: oxide grains of group 2, due to further mixing occurring in AGB stars.

CNO equilibrium (dependency on T!!)

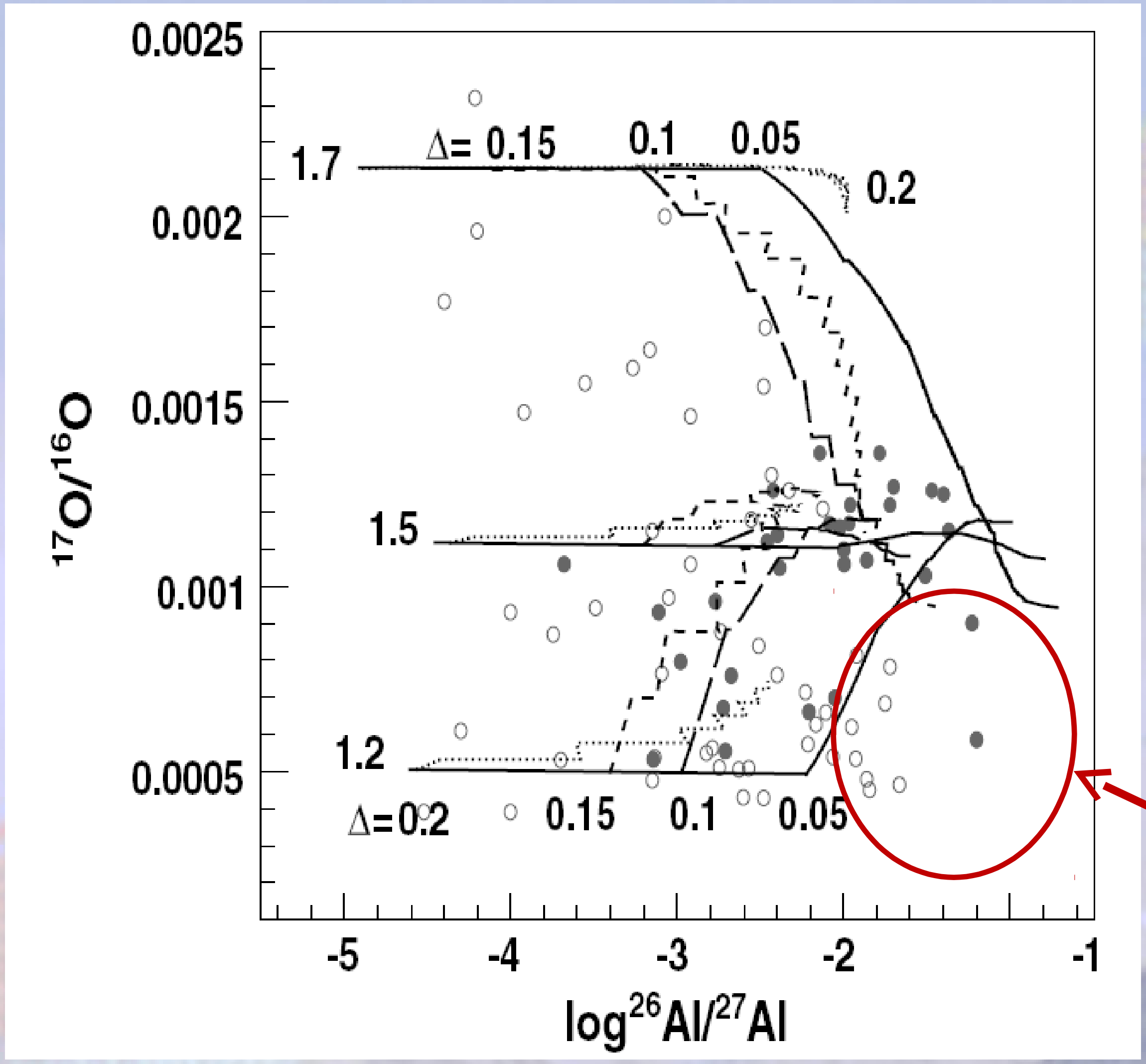


Normal Evolution
NACRE rates

Extramixing (cbp)

Moving the end-point requires changing the rate (lower ^{17}O destruction)

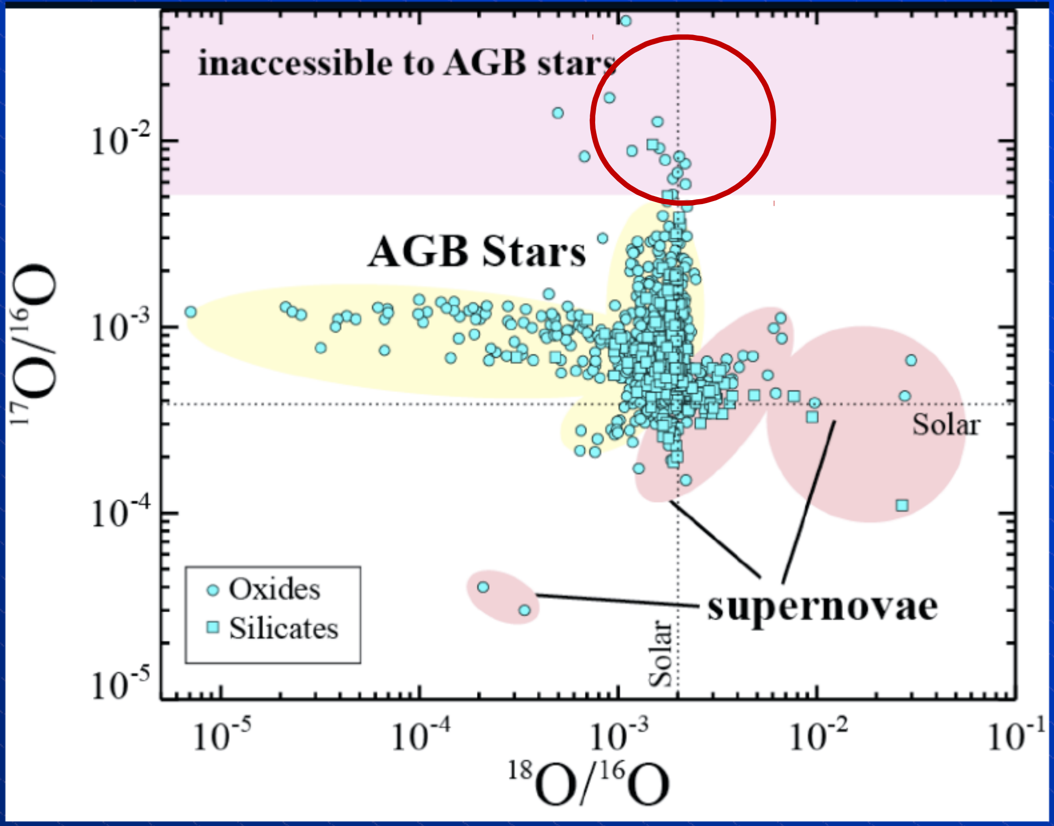
OXIDE GRAINS vs PARAMETERIZED MIXING



Palmerini et al. 2014 (in preparation)

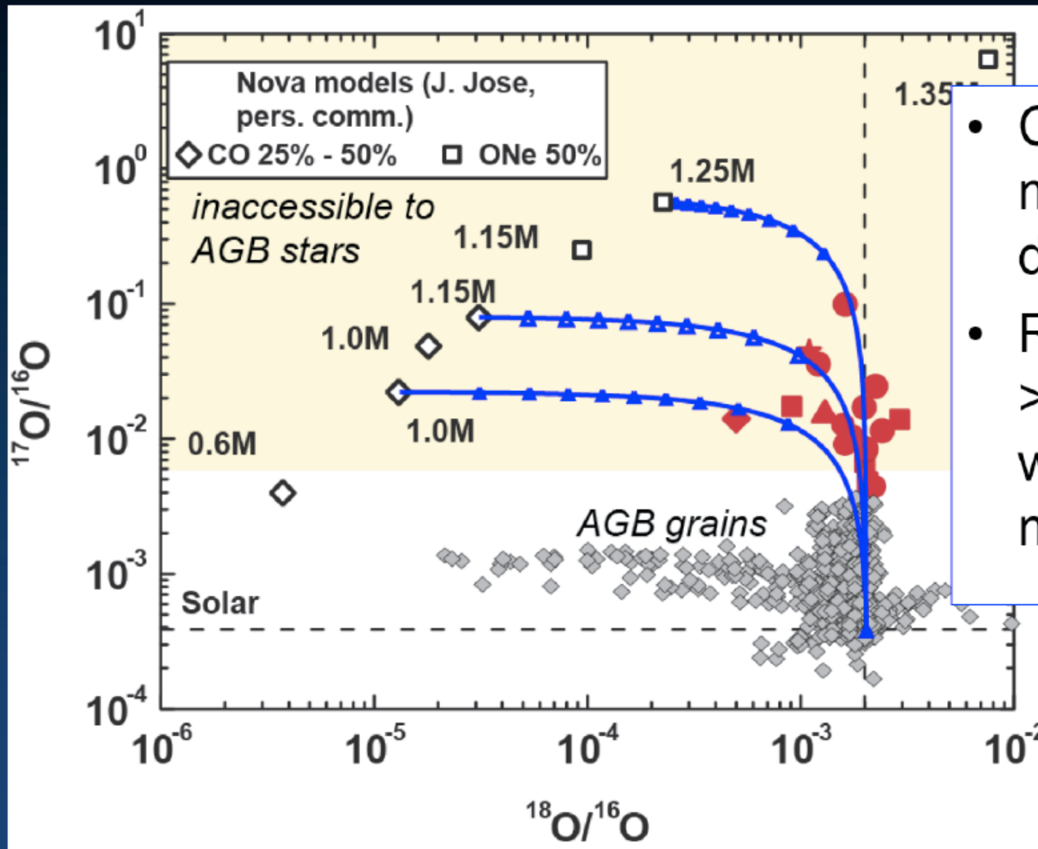
Explained by intermittent magnetic buoyancy or other forced mechanisms

O-rich grains from novae



Borrowed from Gyngard and Nittler

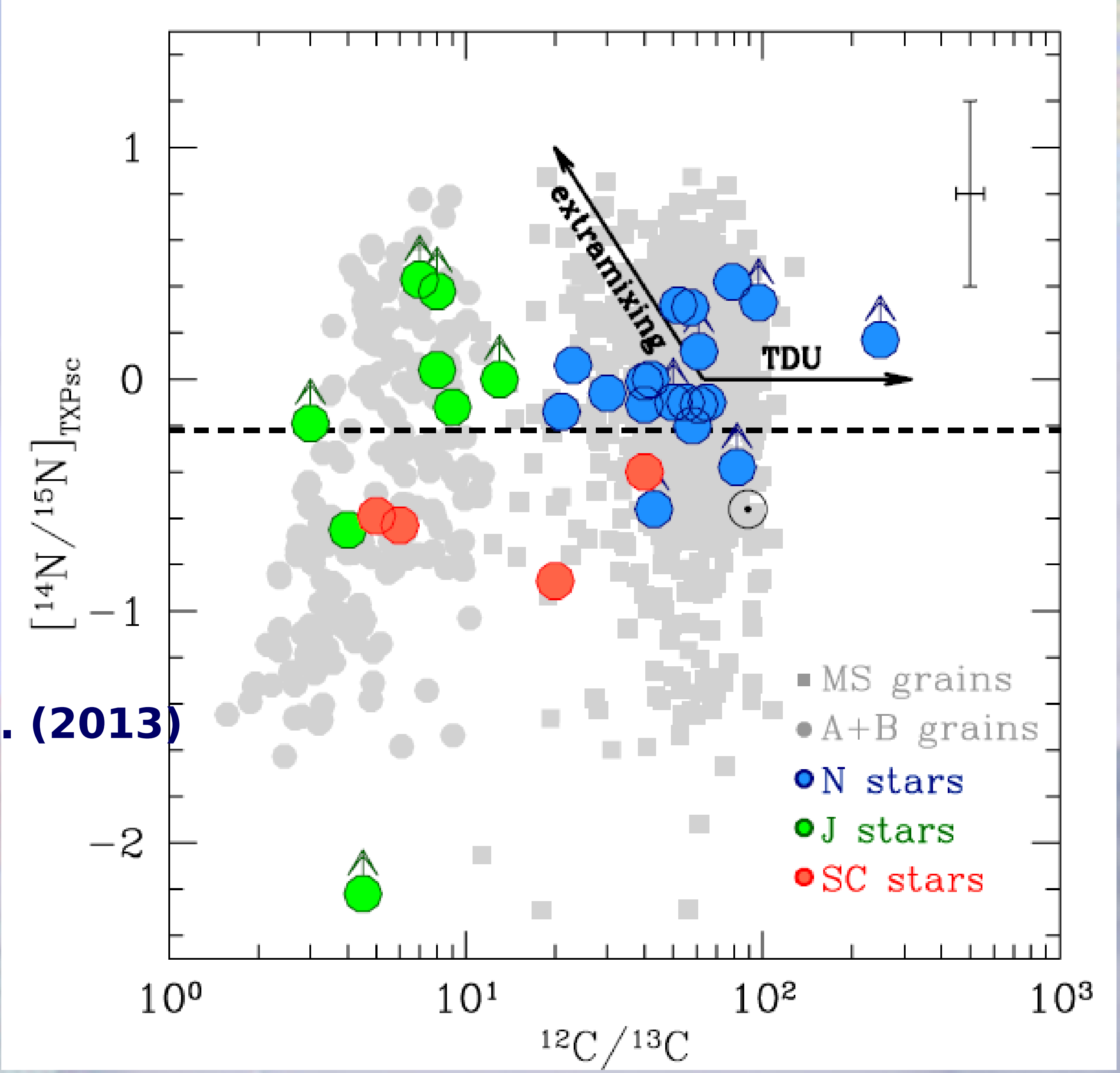
Even peculiar cases, in which ^{17}O and ^{18}O are both enhanced (at odds with H-burning composition) exist.



- Current nova models miss data
- Requires >90% mixing with normal material

17O-rich grains from Nittler et al. 1997, 2008, 2012; Gyngard et al. 2010; Leitner et al. 2012

FROM GRAINS TO STARS. PECULIAR ISOTOPIC RATIOS



Hedrosa et al. (2013)

Types, abundances, sizes and sources of stardust.

Mineral Type	Abund (ppm)	Size (μm)	Stellar source	Relative contribution
Diamond	1400	0.002	SNII; solar system?	
SiC	30	0.3–50		
Mainstream			AGB (1.5–3 $M_\odot$)	90%
X			SNII	1.5%
Y			~1/2 solar metallicity AGB	few %
Z			~1/4 solar metallicity AGB	few %
AB			J-stars; born-again AGB	<5%
C			SNII	0.1%
Nova			Novae	0.1%
Graphite	10	1–20		
			SNII	60%
			AGB (1.5–3$M_\odot$)	30%
			J-stars; born-again AGB	<10%
			Novae	<10%
Si_3N_4	0.002	≤1	SNII	100%
Oxides	50	0.1–2		
Silicates	200	≤1		
1			AGB (1–2.2 $M_\odot$)	70%
2			AGB (<1.8 $M_\odot$; CBP)	15%
3			AGB (low mass & metallicity); SNII	5%
4			SNII	10%
N			Novae	<1%

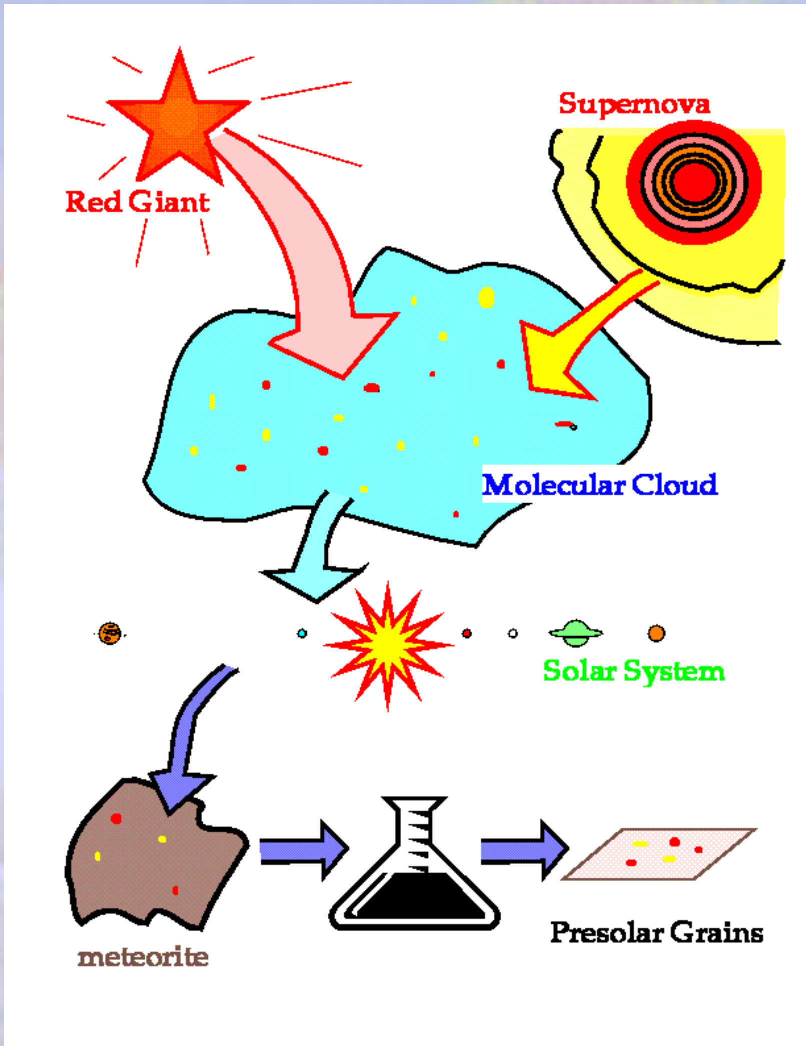
- AGB stars produce most extrasolar grains recovered in meteorites. They force us to reconsider C-star nucleosynthesis.

- AGB stars produce ^{26}Al, and its abundance (even when high!) can be explained by nucleosynthesis & mixing models. ^{26}Al in the Early Solar System was essential in melting large bodies.

- Can an AGB star have ‘salted the soup’ of the Early Solar System with ^{26}Al and other short-lived nuclei?: (^{26}Al, ^{41}Ca, ^{60}Fe, and ^{107}Pd : Busso et al. 2003; Lugaro et al 2008)

- Most people don’t believe that, as the probability of an encounter with the forming Sun is VERY small.

- However we now know that dust is the carrier of many isotopic peculiarities and AGB stars are the main dust producers in the Universe.



		3.0 $M_\odot$, $Z = Z_\odot/3$ $f_0 = 4.0 \times 10^{-3}$	**(W+06)**	**6.7 $M_\odot$, $Z = Z_\odot$,** $f_0 = 3.3 \times 10^{-3}$	**(TR+09)**	**Measured or extrapolated**
Parent P	**Index** I	$(N_P/N_I)_{\Delta_1}$ Δ_1 **= 0.53 Myr**	$(N_P/N_I)_{\Delta_2}$ Δ_2 **= 6.5 Myr**	$(N_P/N_I)_{\Delta_1}$ Δ_1 **= 0.53 Myr**	$(N_P/N_I)_{\Delta_2}$ (Δ_2) **= 6.0 Myr**	**at** $t = \Delta_i$
^{26}**Al**	^{27}**Al**	$5.0 \cdot 10^{-5}$	$8.5 \cdot 10^{-8}$	$3.2 \cdot 10^{-5}$	$9.8 \cdot 10^{-8}$	$5.0 \cdot 10^{-5}$ (Δ_1)
^{41}**Ca**	^{40}**Ca**	$1.5 \cdot 10^{-8}$	–	$1.5 \cdot 10^{-8}$	–	$\geq 1.5 \cdot 10^{-8}$ (Δ_1)
^{60}**Fe**	^{56}**Fe**	$2.1 \cdot 10^{-6}$	$1.0 \cdot 10^{-7}$	$2.6 \cdot 10^{-6}$	$1.7 \cdot 10^{-7}$	$0.5 - 1 \cdot 10^{-6}$ (Δ_1)
^{107}**Pd**	^{108}**Pd**	$3.8 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	$3.8 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$ (Δ_2)
^{93}**Zr**	^{92}**Zr**	$2.5 \cdot 10^{-4}$	$1.2 \cdot 10^{-5}$	$1.6 \cdot 10^{-4}$	$8.6 \cdot 10^{-6}$	**(?)**
^{99}**Tc**	^{100}**Ru**	$1.9 \cdot 10^{-5}$	–	$1.4 \cdot 10^{-5}$	–	**(?)**
^{135}**Cs**	^{133}**Cs**	$3.6 \cdot 10^{-5}$	$3.5 \cdot 10^{-6}$	**n.a.**	**n.a.**	1.6×10^{-4} **(?)**
^{205}**Pb**	^{204}**Pb**	$\leq 3.4 \cdot 10^{-4}$	$\leq 2.5 \cdot 10^{-4}$	**n.a.**	**n.a.**	$1 - 2 \times 10^{-4}$ (?)

Busso (2011), Lecture Notes in Physics

DO WE BELIEVE IN THIS MODEL?

Most people don't

I am curious and I don't exclude anything

SNe or other nucleosynthesis sources are equally unlikely (because of little dust) and don't offer the same "god compromize" for various short lived nuclei.

Before coming back to this issue we need to know better the variation of the lifetime with T,ρ. Recent work shows that stellar weak interactions are essentially NOT known sufficiently well (SEE NEXT).

We'll see. Maybe some of the young researchers present will see, one day.

The Astrophysical Journal, 764:118 (12pp), 2013 February 20 doi:10.1088/0004-637X/764/2/118

THEORETICAL ESTIMATES OF STELLAR e^- CAPTURES. I. THE HALF-LIFE OF ^{7}Be IN EVOLVED STARS

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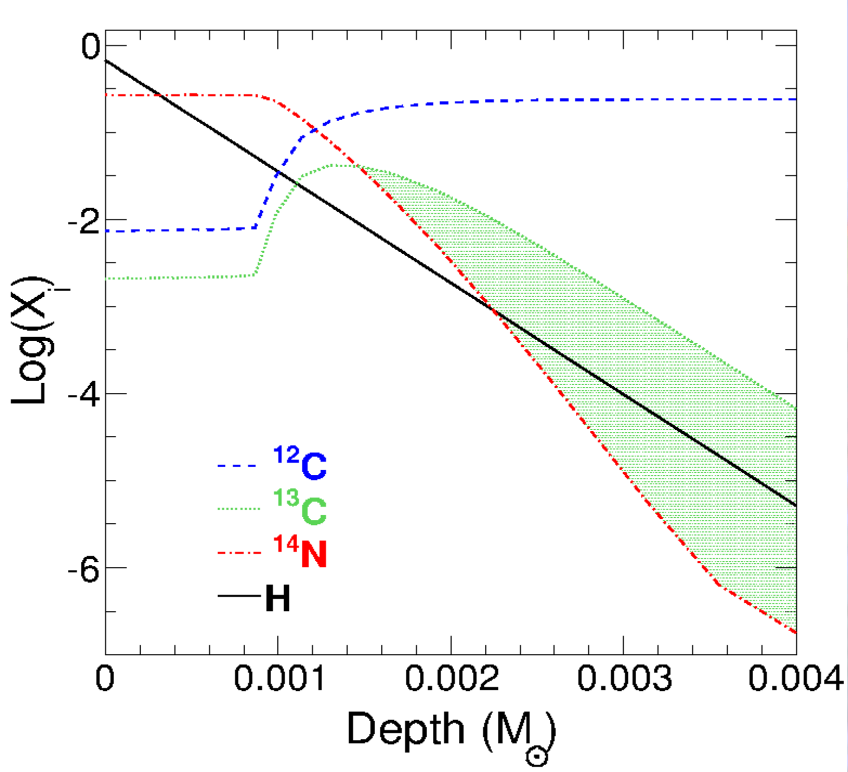
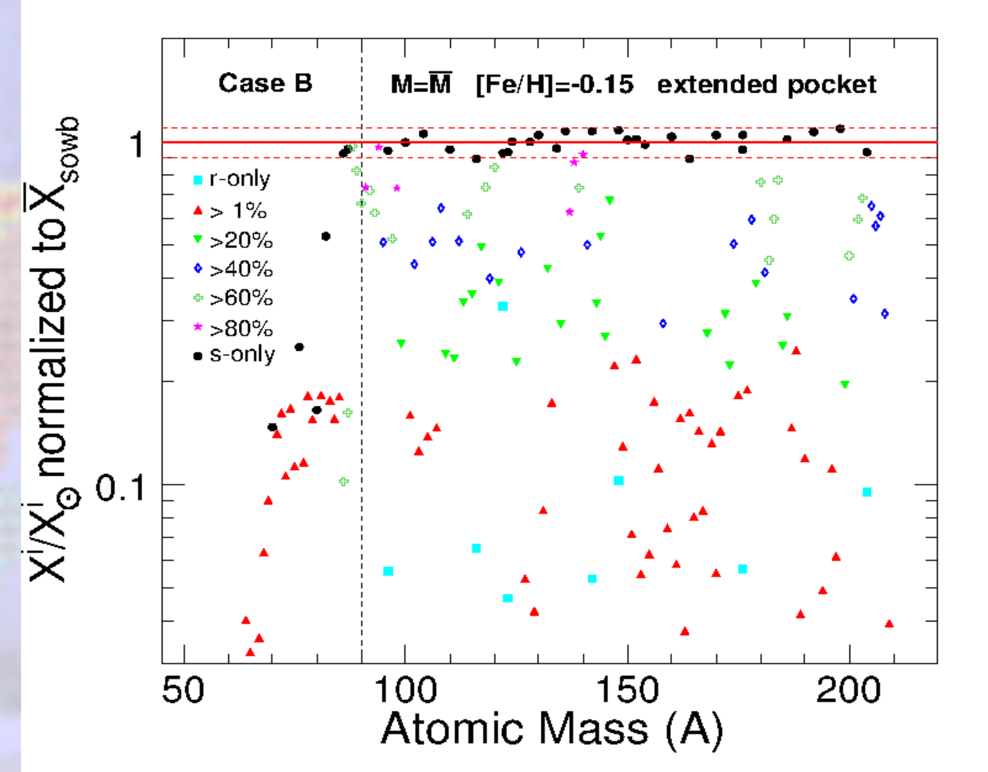
ABSTRACT

The enrichment of Li in the universe is still unexplained, presenting various puzzles to astrophysics. One open issue is that of obtaining reliable estimates for the rate of e^- captures on ^{7}Be for T and ρ conditions that are different from the solar ones. This is of crucial importance for modeling the Galactic nucleosynthesis of Li. In this framework, we present here a new theoretical method for calculating the e^- capture rate in typical conditions for evolved stars. Furthermore, we show how our approach compares with state-of-the-art techniques for solar conditions, where various estimates are available. Our computations include (1) "traditional" calculations of the electronic density at the nucleus, to which the e^- capture rate for ^{7}Be is proportional, for different theoretical approaches including the Thomas–Fermi, Poisson–Boltzmann, and Debye–Hückel (DH) models of screening; and (2) a new computation, based on a formalism that goes beyond the previous ones, adopting a mean-field "adiabatic" approximation to the scattering process. The results obtained with the new approach as well as with traditional ones and their differences are discussed in some detail, starting from solar conditions, where our approach and the DH model essentially converge to the same solution. We then analyze the applicability of both our method and the DH model to a rather broad range of T and ρ values, embracing those typical of red giant stars, where both bound and continuum states contribute to the capture. We find that over a wide region of the parameter space explored, the DH approximation does not really stand, so that the more general method we suggest should be preferred. As a first application, we briefly reanalyze the ^{7}Li abundances in red giant branch and asymptotic giant branch stars of the Galactic disk in light of a revision in the Be decay only; however, we emphasize that the changes we find in the electron density at the nucleus would also induce effects on the electron screening (for p-captures on Li itself, as well as for other nuclei) so that our new approach might have rather wide astrophysical consequences.

Key words: nuclear reactions, nucleosynthesis, abundances – plasmas – stars: AGB and post-AGB –

Another role for AGB stars?





From models with extended neutron reservoirs (Maiorca et al. 2012), recent efforts suggest (Trippella et al.) that s- and r-processing are the only ingredients needed to explain heavy neutron-rich nuclei, without any LEPP contrinution.
If this idea is OK → constraints to massive star nucleosynthesis & reaction rates!

CONCLUSIONS

THE RECOVERY OF SOME OF THE SOLID INGREDIENTS THAT CONTRIBUTED TO THE FORMATION OF THE SOLAR ABUNDANCES CHANGED NUCLEAR ASTROPHYSICS

GRAINS RECOVERED AND MEASURED ARE THE OBJECT OF STRONG SELECTION EFFECTS RELATED TO THEIR REFRACTORY NATURE AND RESISTENCE TO STRESSES.

SN UNDERSAMPLED; AGB STARS OVERSAMPLED.

THEY ARE IDENTIFIED BY PRESENCE OF S-ELEMENTS, THE Ne-(H) ANOMALY, THE RUN OF C AND O ISOTOPES, DEEP MIXING SIGNATURES

EXPLAINING THEM IN DETAIL FORCED THE MODELS TO CHANGE: EXTRAMIIXNG INTRODUCED, ITS PROPERTIES STUDIED, REACTION RATES DETERMINED.

UNDERSTANDING WHICH KIND OF STARS WERE AT THE ORIGIN OF THE SHORT LIVED NUCLEI IN THE EARLY SOLAR NEBULA, REQUIRES ANOTHER CHANGE; A NEW APPROACH TO WEAK INTERACTIONS IN STARS (ALREADY STARTED).