Stellar grains in the laboratory: Messengers from the Sky

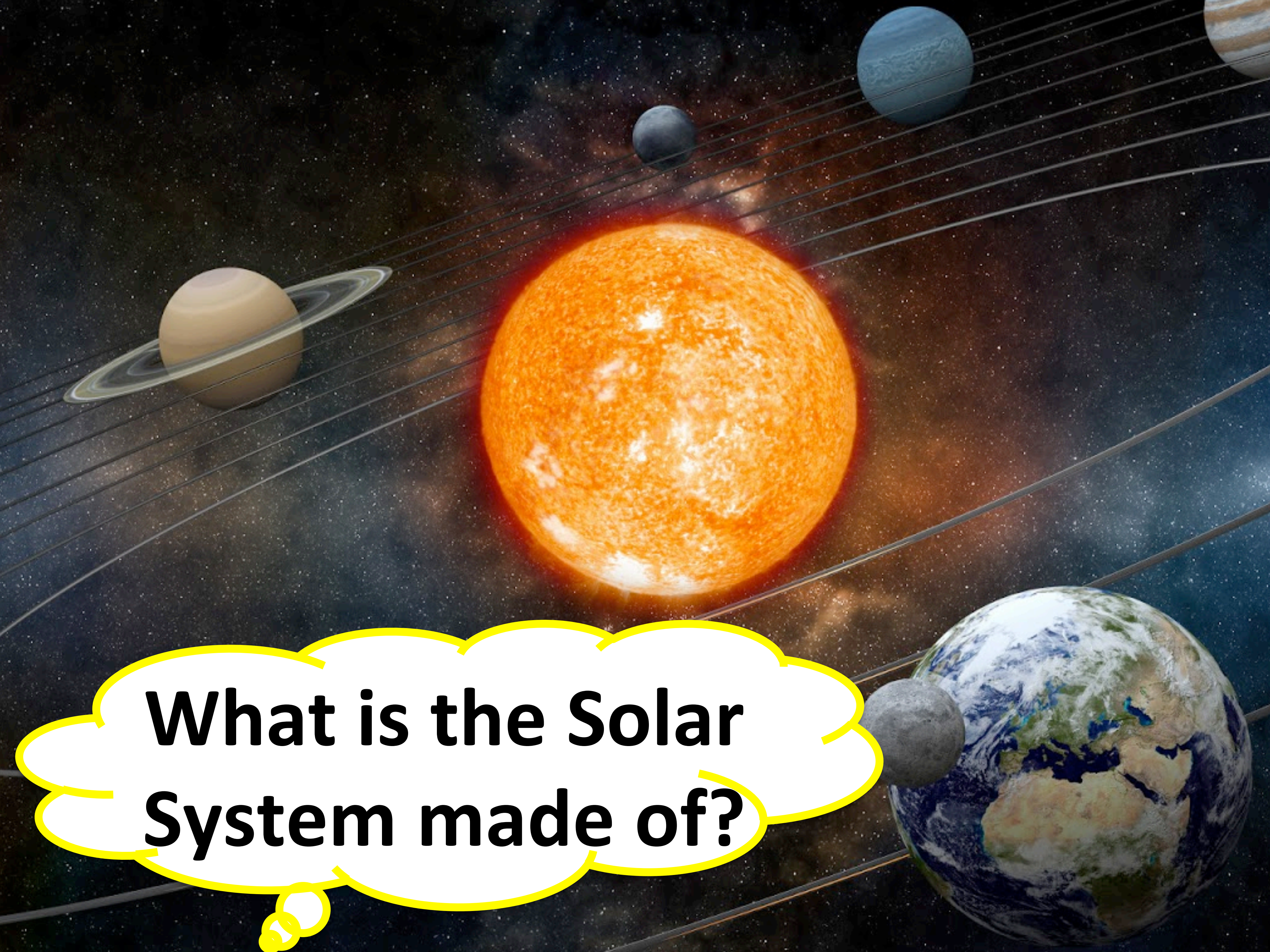
The stardust revolution led by Ernst Zinner

Maria Lugaro

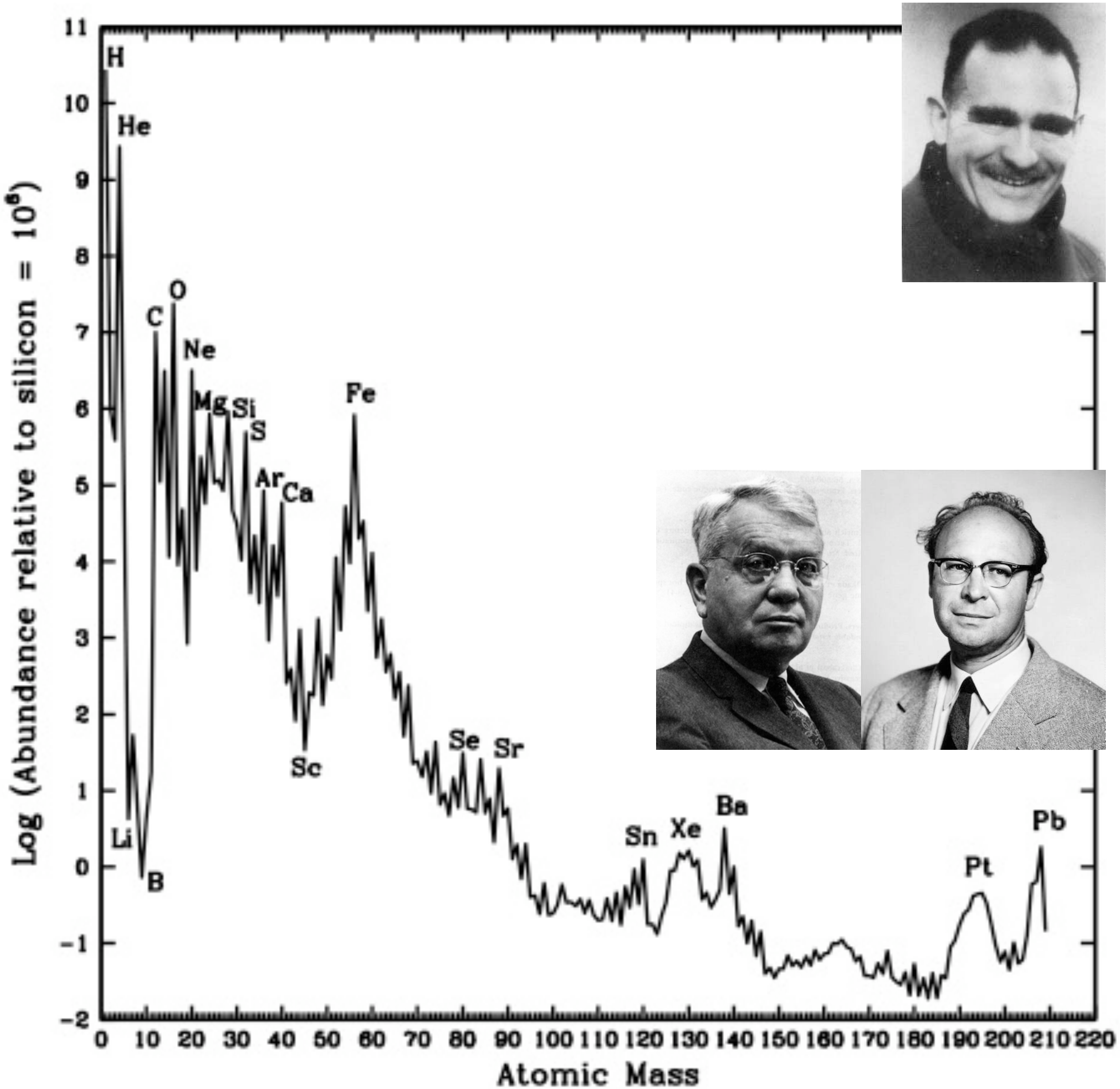
Konkoly Observatory, Hungarian Academy of Sciences

Monash Centre for Astrophysics, Monash University, Australia


What are stars made of?
NGC 6397
Hubble Space Telescope Image


What is the Solar System made of?

Solar System abundances: *from meteorites*

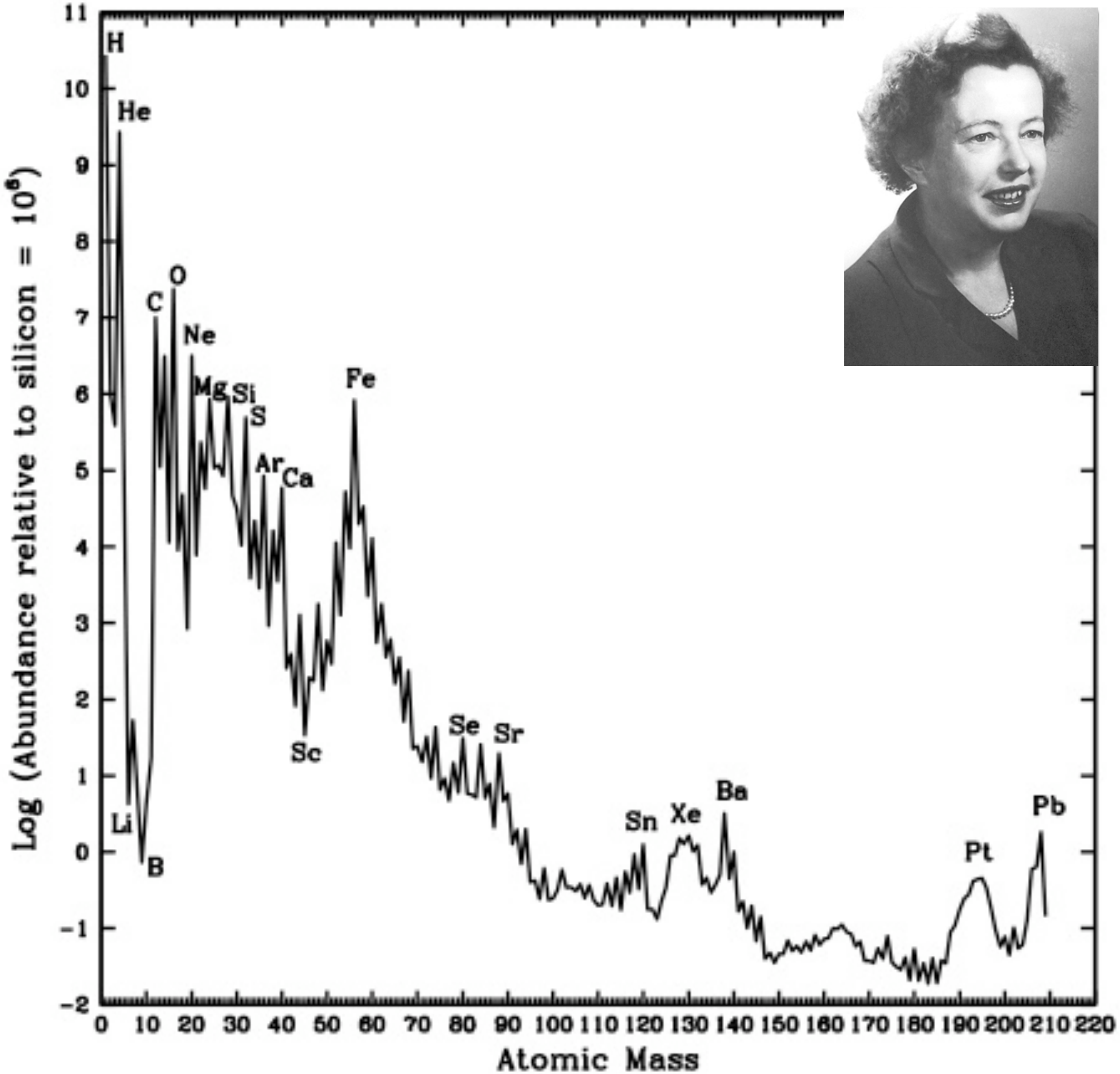


In **1938, Victor Goldschmidt** compiles the first list of *cosmic* abundances

In **1956, Harold Urey** and **Hans Suess**, publish the first table of isotopic cosmic abundances

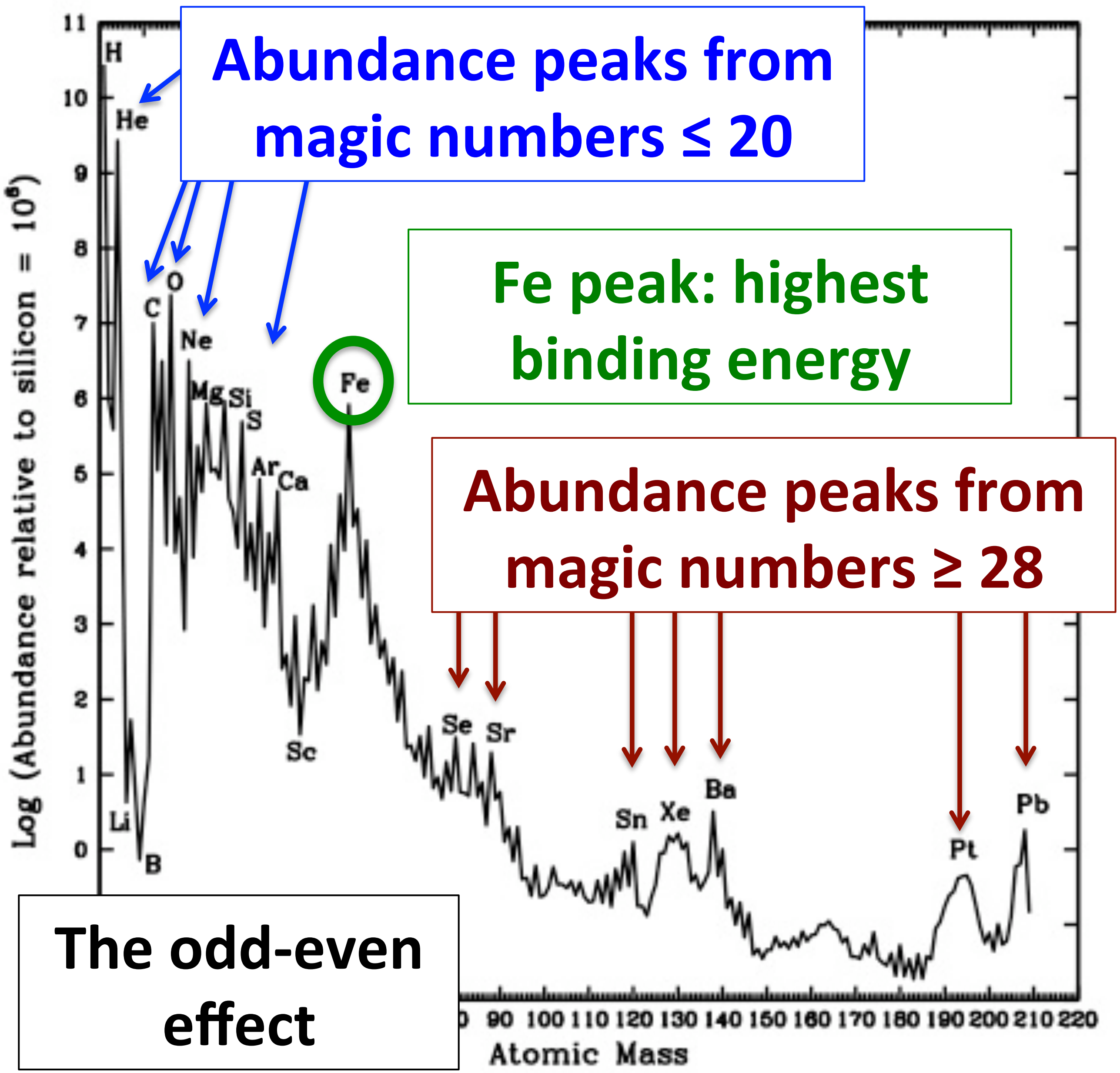
Anders, Grevesse, Palme, Lodders +

Solar System abundances: ***nuclear physics***



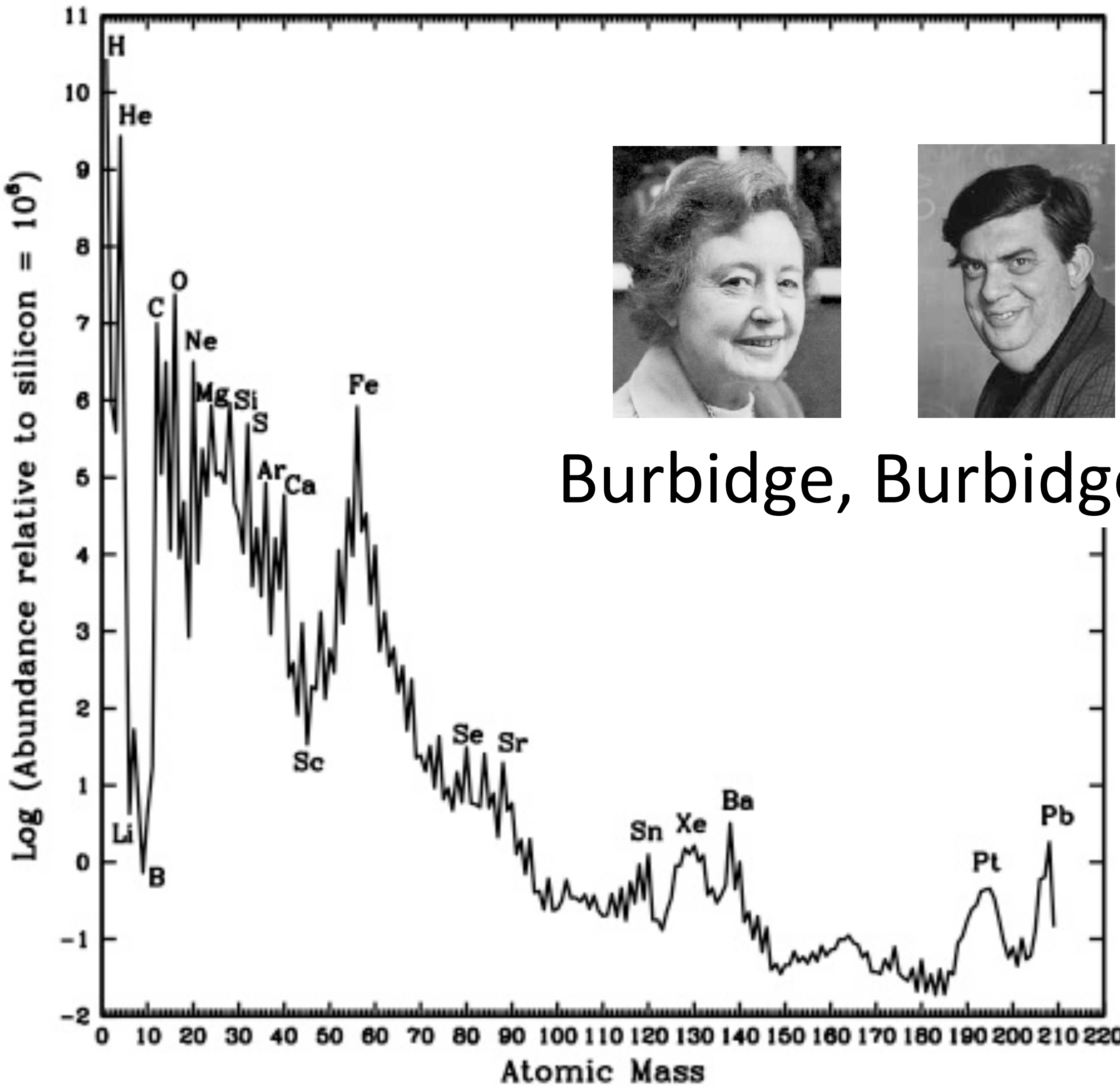
In 1950, **Maria Goeppert Mayer**'s model for the atomic nucleus explains why **magic numbers** of nucleons result in more stable configurations: 2, 8, 20, 28, 50, 82, and 126.

Solar System abundances: ***nuclear physics***

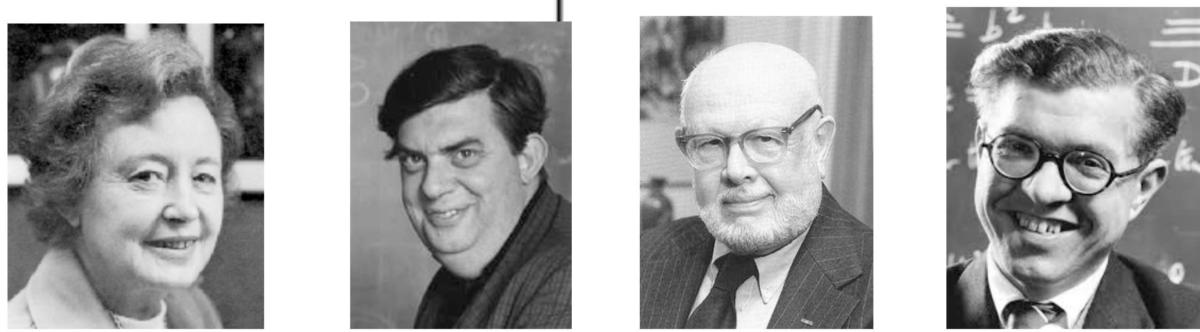


In 1950, **Maria Goeppert Mayer**'s model for the atomic nucleus explains why **magic numbers** of nucleons result in more stable configurations: 2, 8, 20, 28, 50, 82, and 126.

Solar System abundances: ***nucleosynthesis***



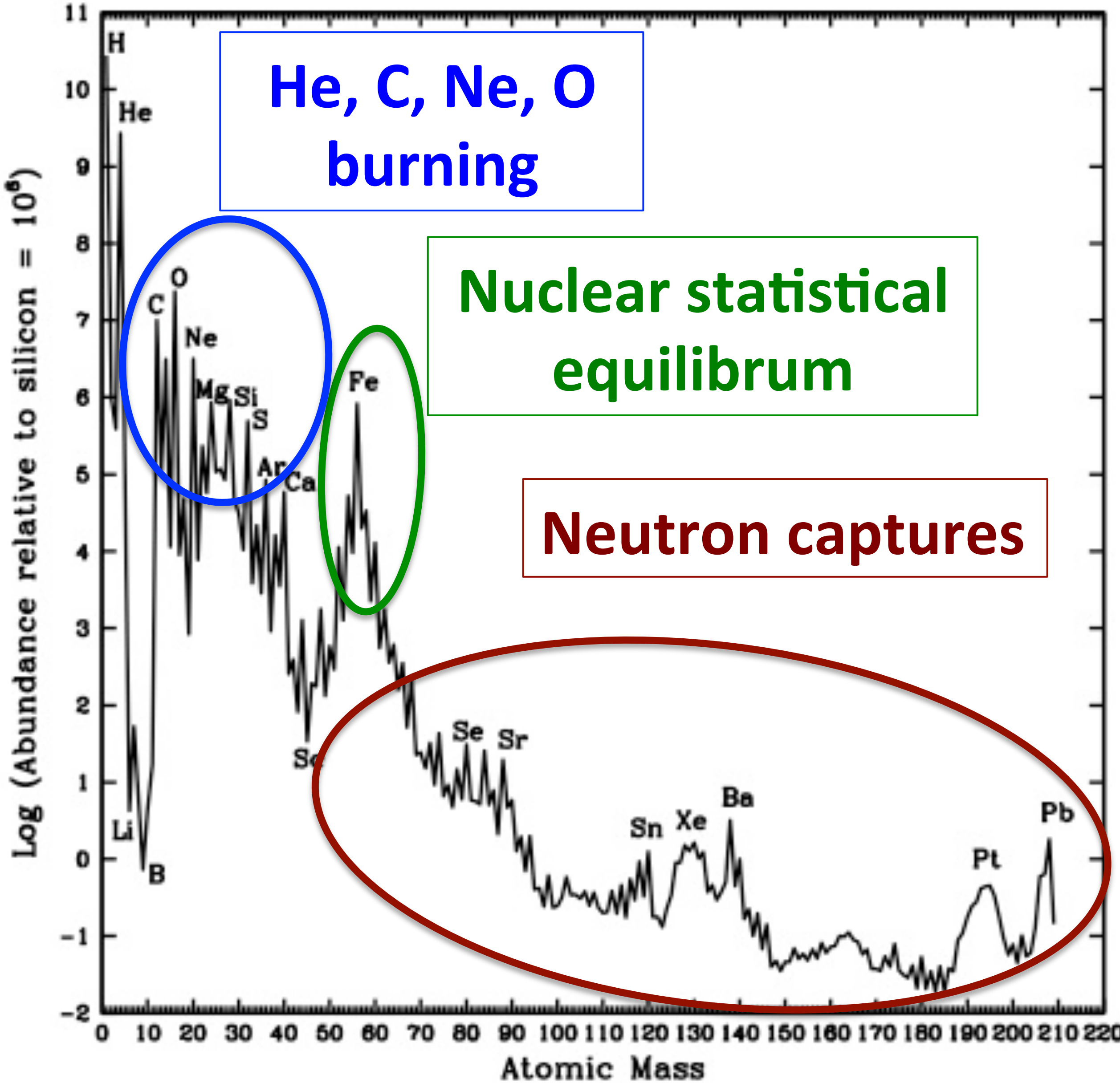
In **1957**, **B^{2}FH**



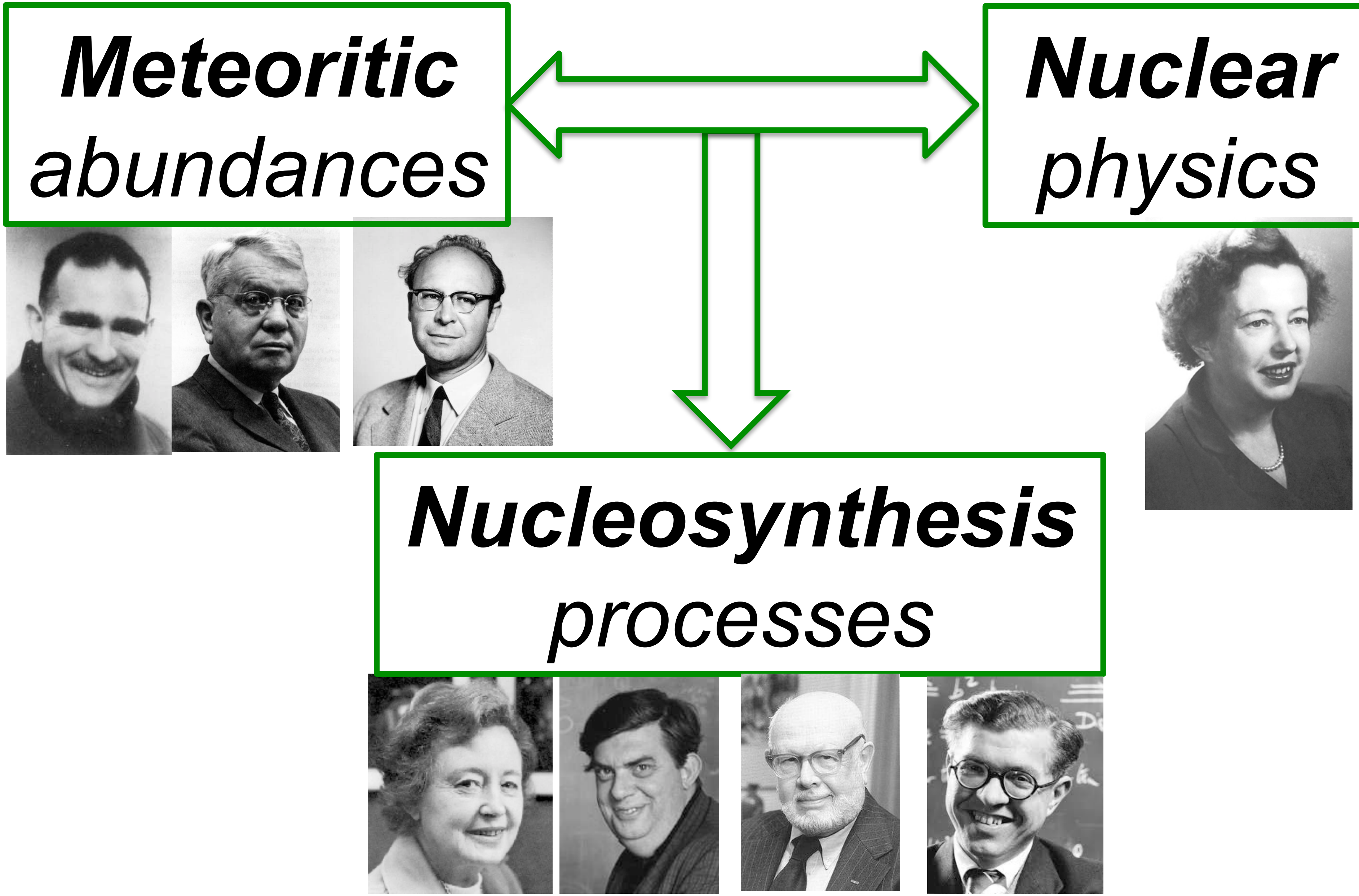
Burbidge, Burbidge, Fowler & Hoyle

publish the first classification of nucleosynthesis processes

Solar System abundances: ***nucleosynthesis***



In **1957**, **Margaret Burbidge et al. (B^2FH)** publish the first classification of nucleosynthesis processes


Meteoritic abundances
Nuclear physics
Nucleosynthesis processes

The cosmic abundances revolution!

The cosmic abundances revolution!

- ***Do all stars share the "cosmic" abundances of the Solar System?***
- ***Where do nucleosynthetic processes happen?***

The cosmic abundances revolution!

- ***Do all stars share the "cosmic" abundances of the Solar System?***
- ***Where do nucleosynthetic processes happen?***

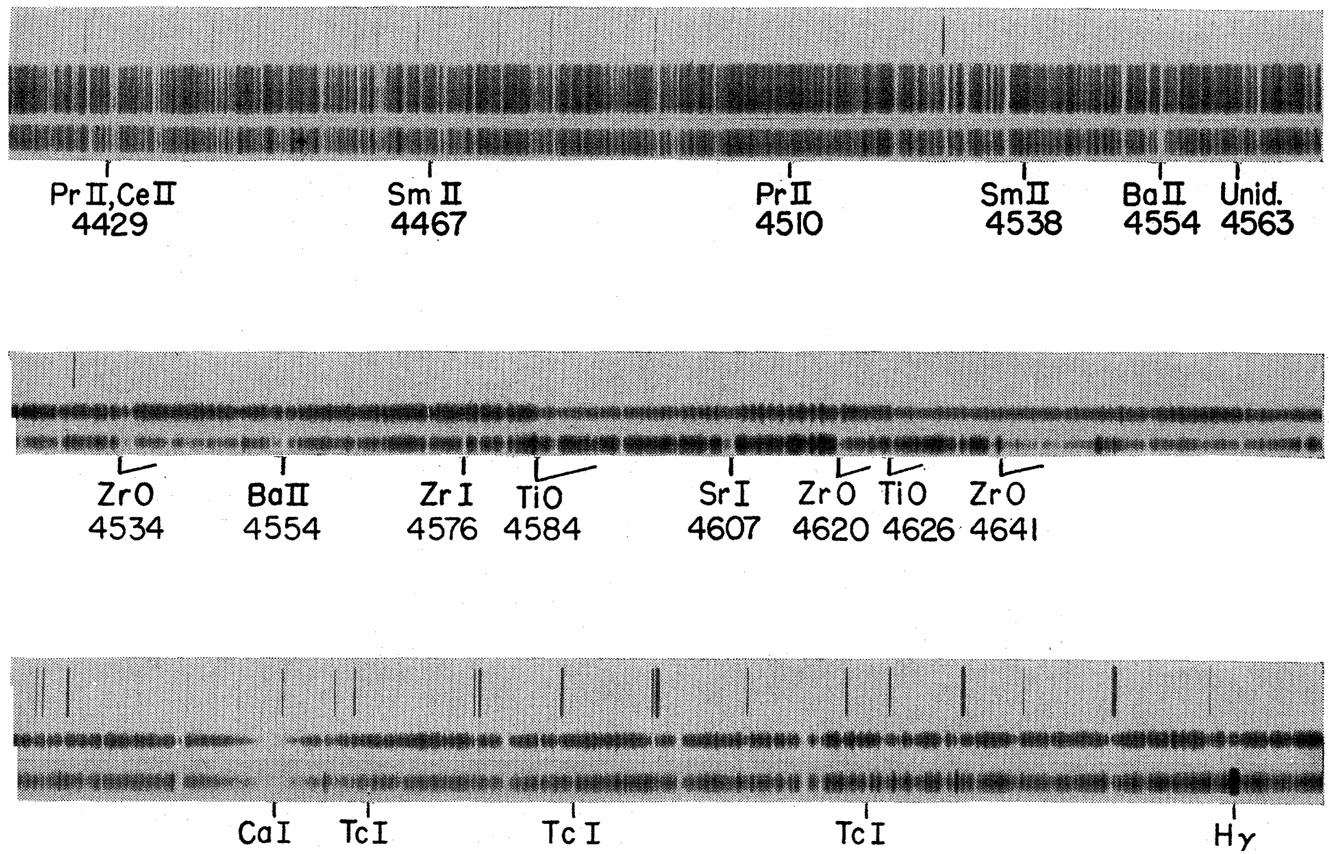
What are stars made of?

Spectroscopy in the 1950s…

normal star
peculiar star

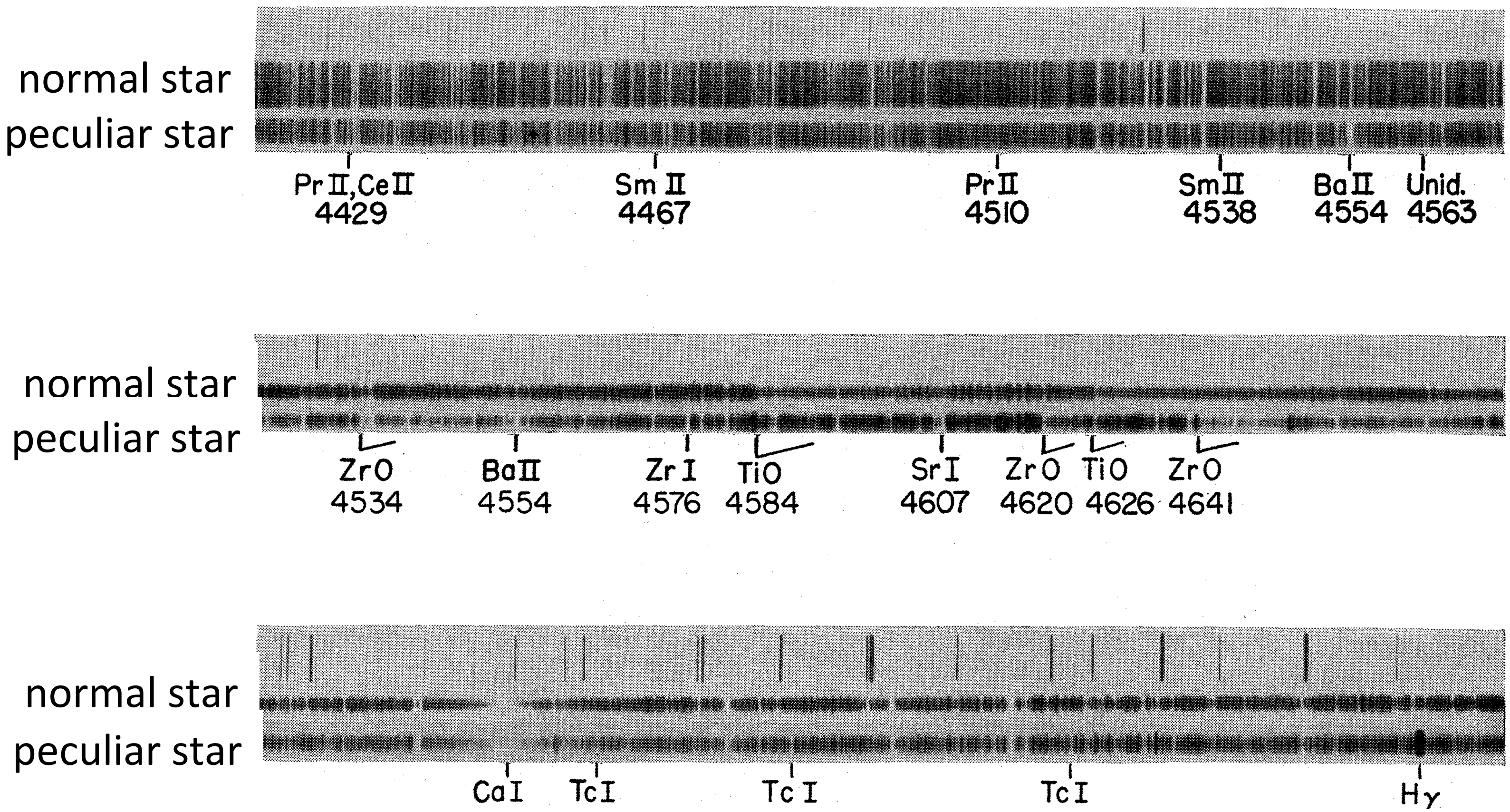
normal star
peculiar star

normal star
peculiar star



Merrill 1952, Burbidge et al. 1957

Spectroscopy in the 1950s…



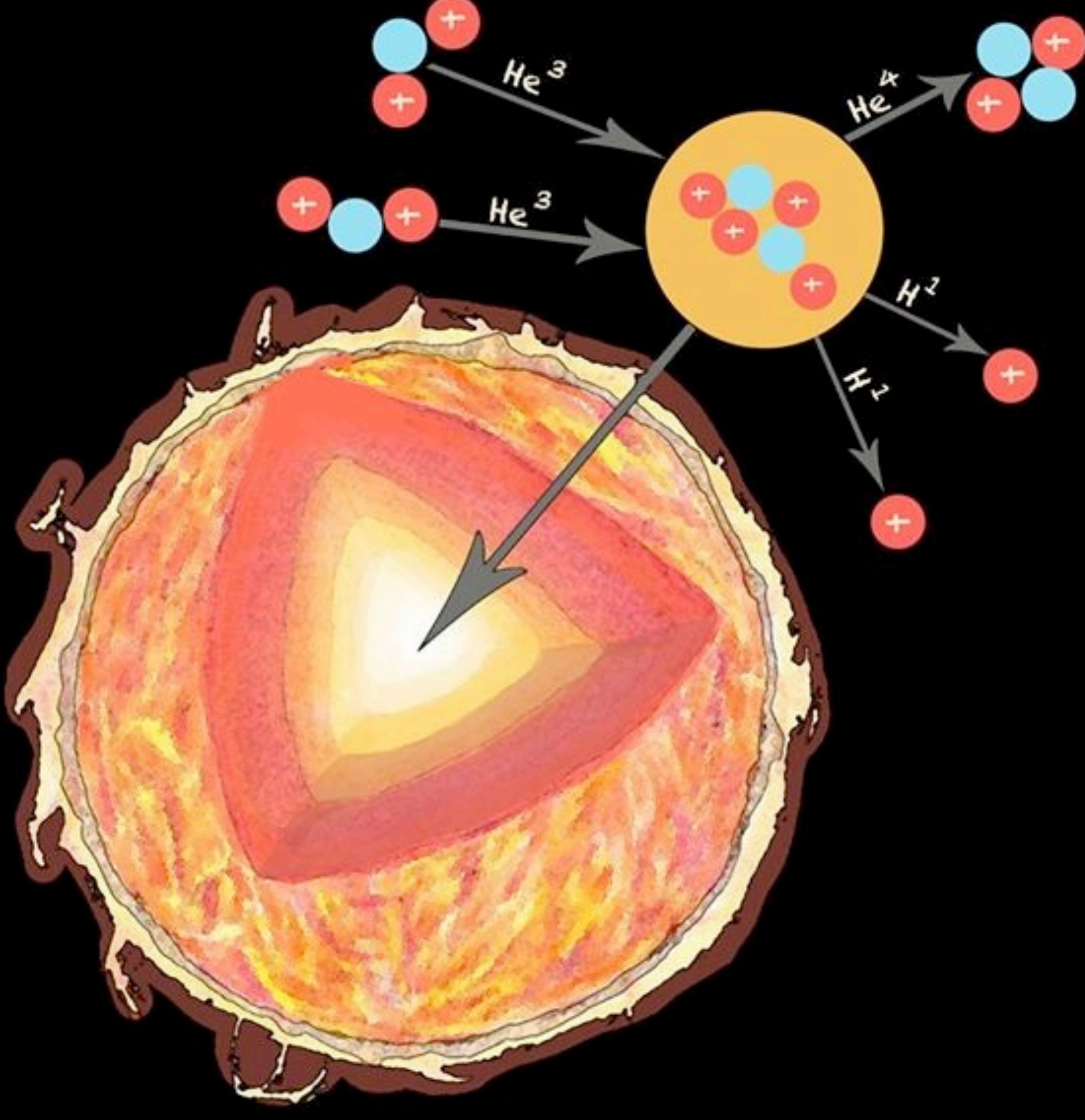
Merrill 1952, Burbidge et al. 1957

Not all stars are made of the same stuff!

The cosmic abundances revolution!

- ***Do all stars share the "cosmic" abundances of the Solar System?*** **NO!**
- ***Where do nucleosynthetic processes happen?*** **Inside stars!**

What are stars made of?



Nuclear reactions in stars produce all the elements in the Universe from C to U

Can we derive stellar abundances with meteorites?

Can we derive stellar abundances with meteorites?

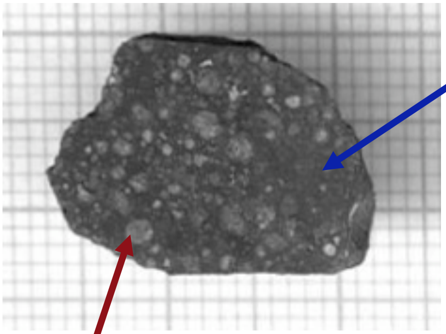
Remarkably YES!

Thanks to the work of Ernst Zinner

Can we derive stellar abundances with meteorites?

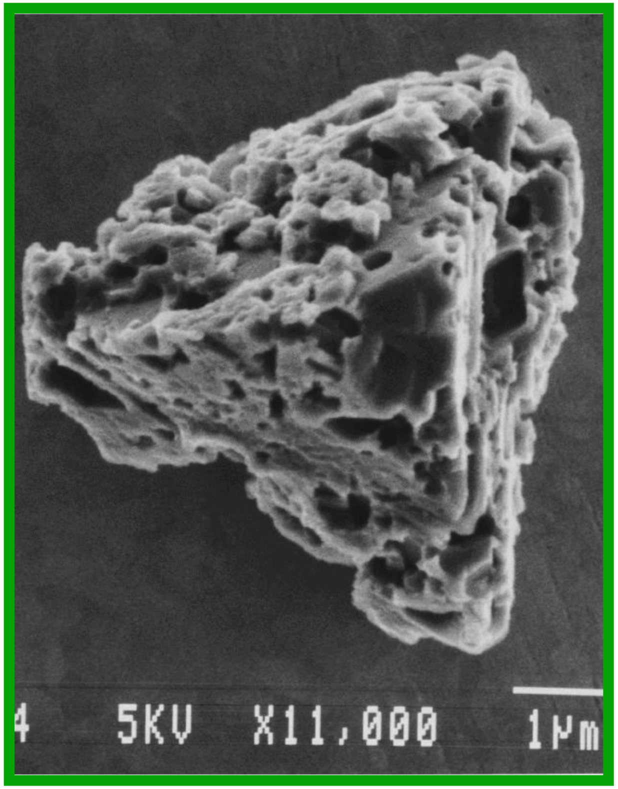
Microscopic ***stardust*** is found inside meteorites

Allende meteorite
(Mexico, 1969)
Carbonaceous
chondrite



Matrix:
amalgam of
amorphous
material and
crystals of
very small
dimensions
size ~ 1 μm

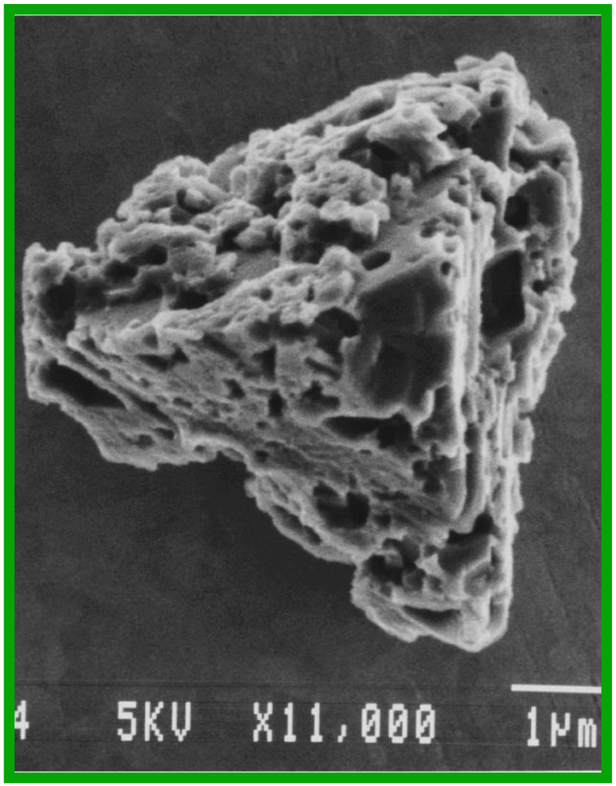
Chondrules
size ~ 1 mm



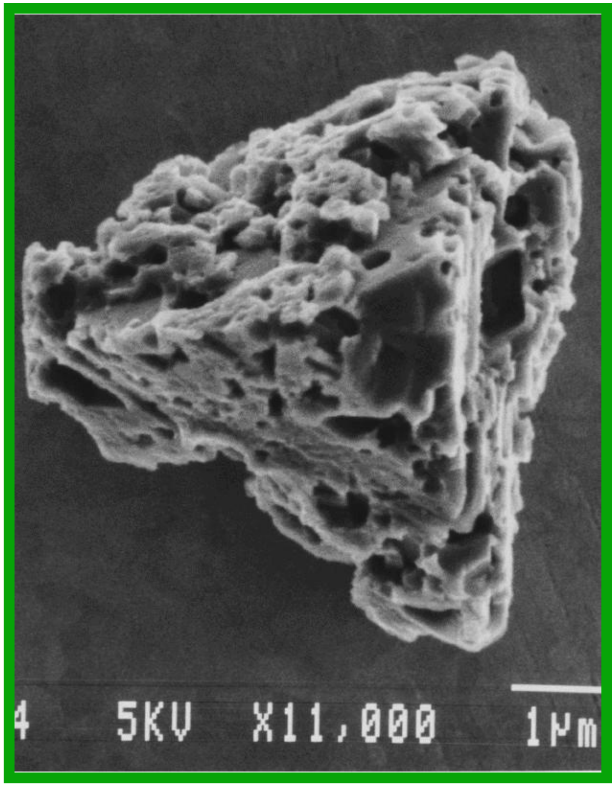
Courtesy of Sachiko Amari

Stardust grains

How do we know that this grain came from a star?

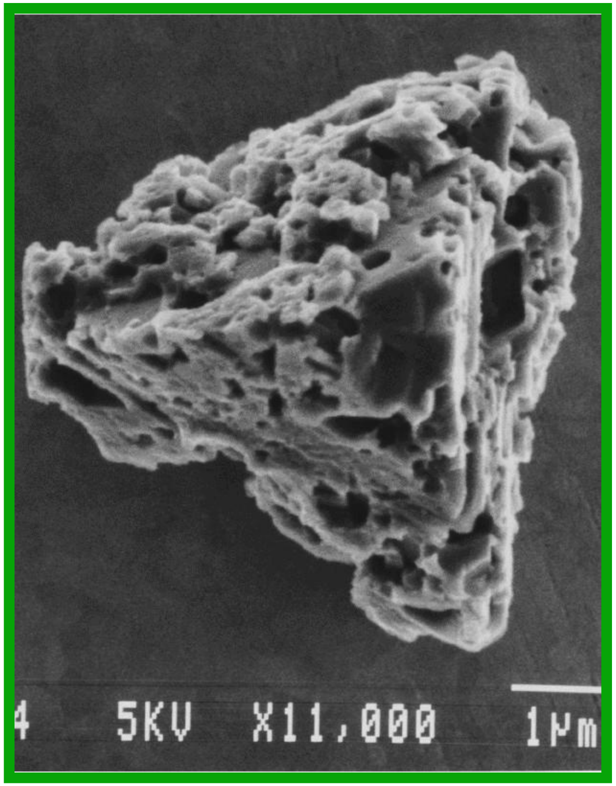


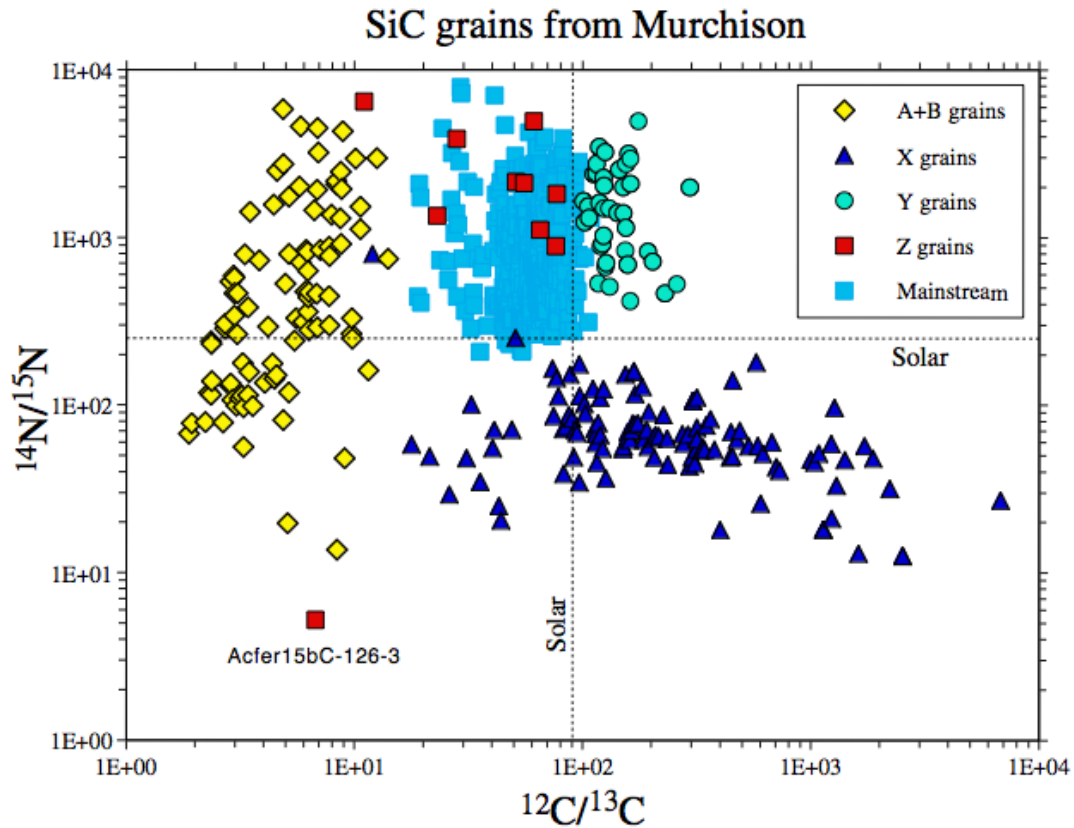
How do we know that this grain came from a star?



- In the Solar System $^{12}C/^{13}C=89$
- In this grain $^{12}C/^{13}C=50$

How do we know that this grain came from a star?



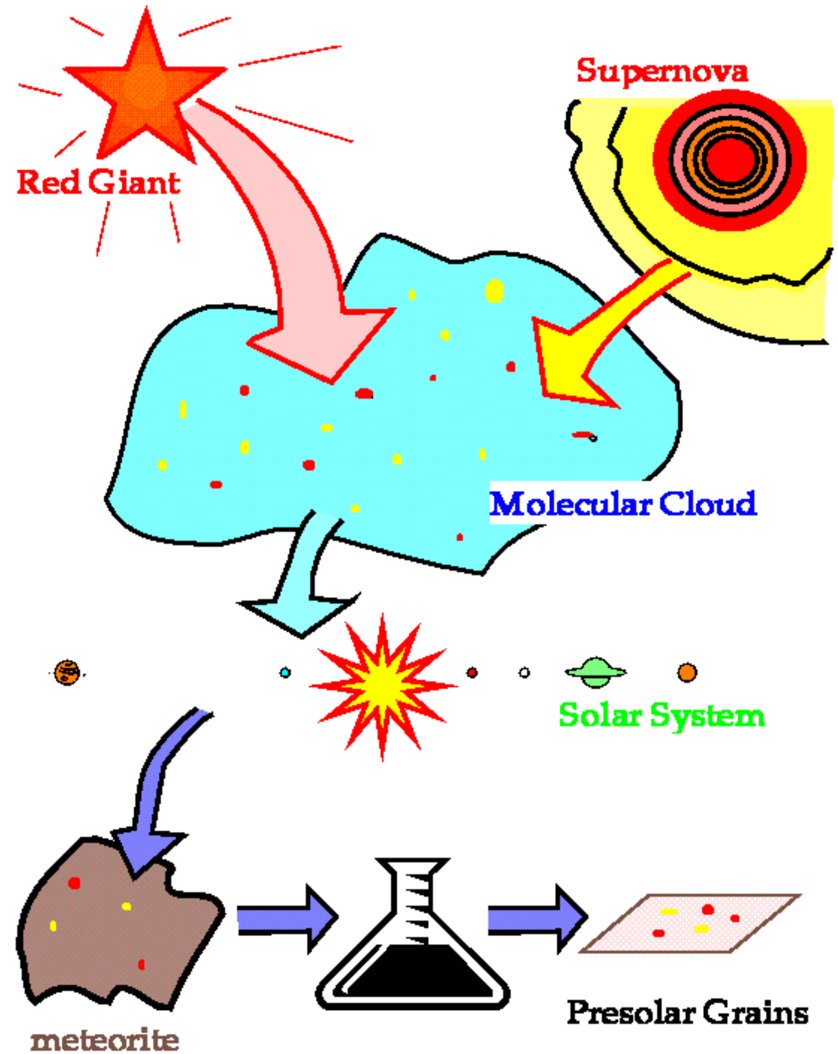


- In the Solar System $^{12}C/^{13}C=89$
- In this grain $^{12}C/^{13}C=50$

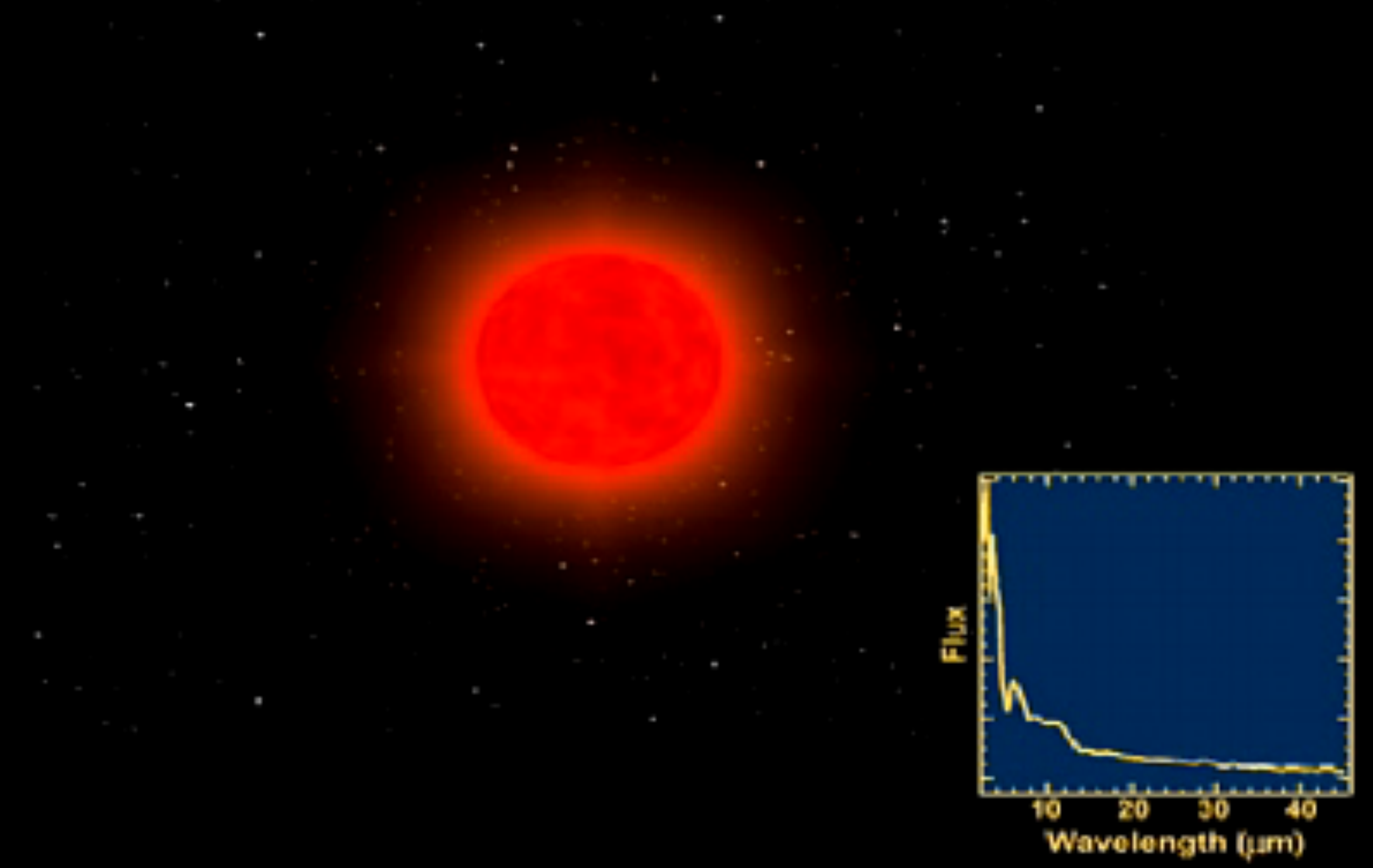
How did stardust travel to us?

Stellar grains were

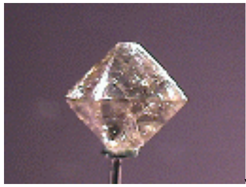
- ✓ born in circumstellar regions around ancient stars,
- ✓ ejected into the interstellar medium,
- ✓ preserved during the formation of the solar system, and
- ✓ trapped inside primitive meteorites from where they are now extracted and analysed.

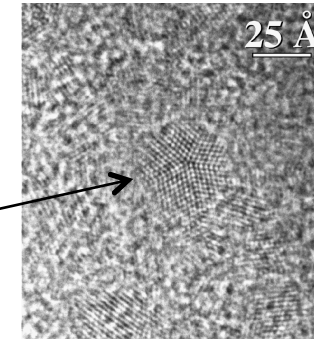


Courtesy of Larry Nittler

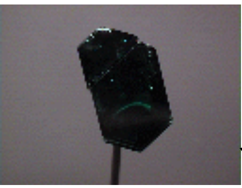


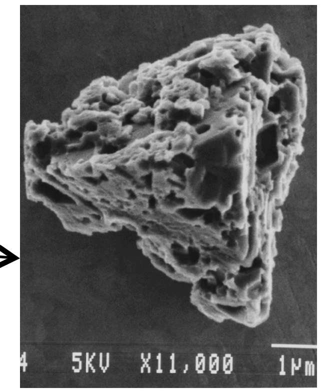
Artist impression.
Courtesy of Pedro Garcia-Lario, ESA and Anibal García-Hernandez, IAC

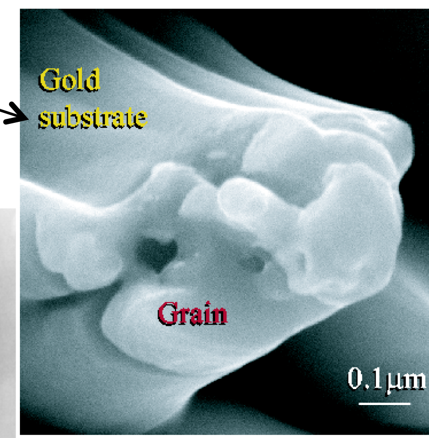


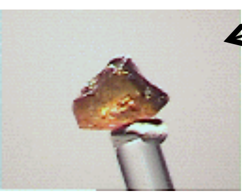


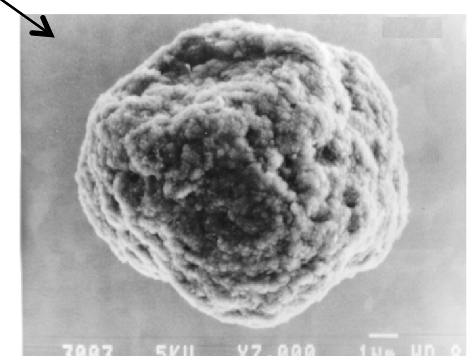
TYPE	ABUNDANCE ppm	SIZE μm
diamond	>750	0.002
silicates	50	0.1 – 0.5
silicon carbide (SiC)	9	0.1 – 20
spinel ($MgAl_2O_4$)	1	0.5
graphite	>2	0.8 – 28
corundum (Al_2O_3)	0.005	0.5 – 4
silicon nitride (Si_3N_4)	>0.002	$\sim$ 1







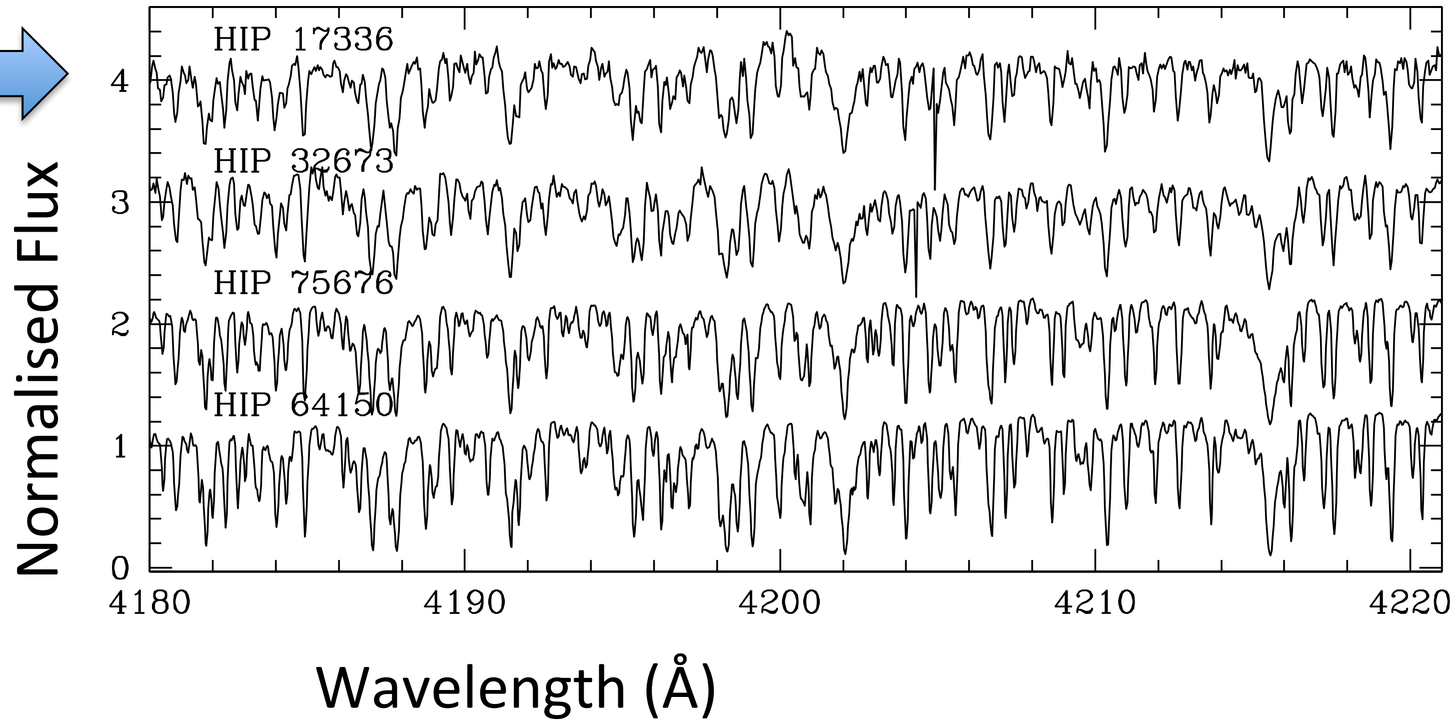




Telescopes *versus* Stardust

Telescopes *versus* Stardust: *the uncertainties*

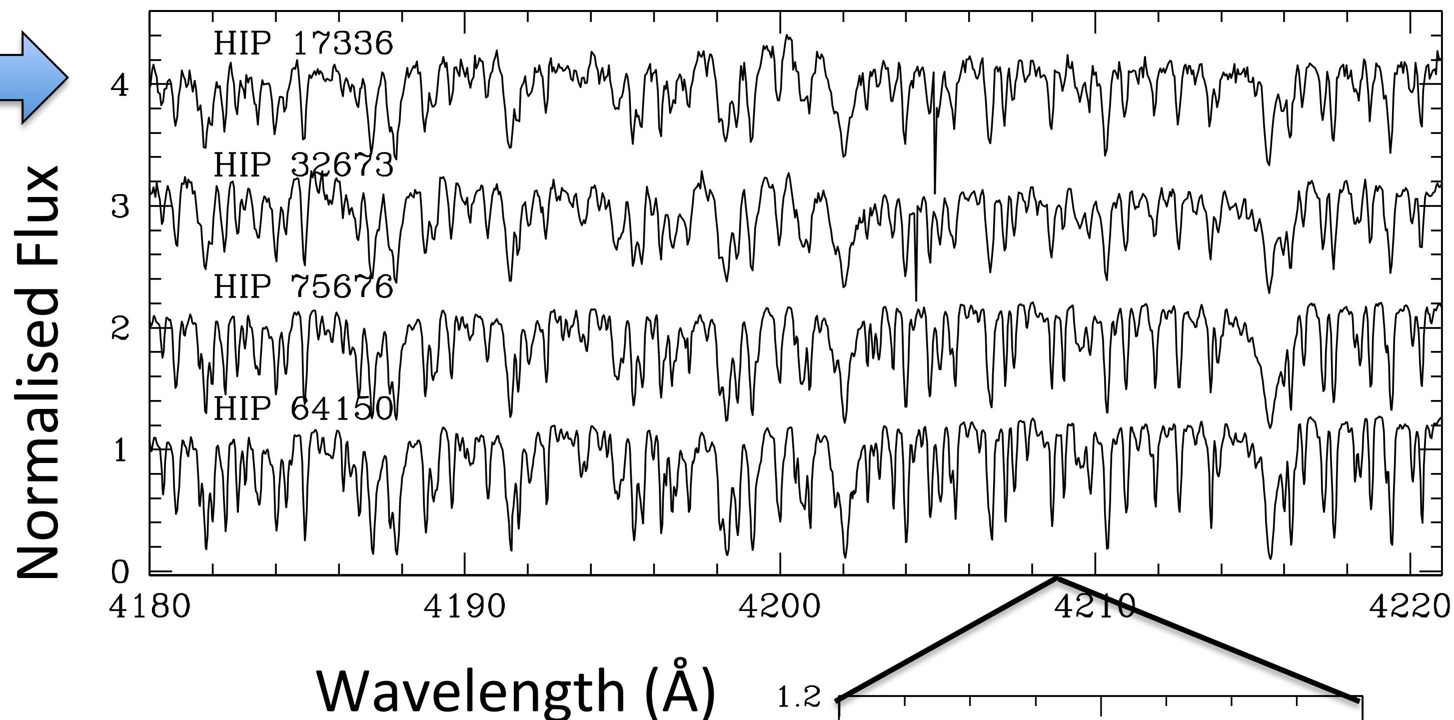
Stellar spectra



Courtesy of Valentina D'Orazi

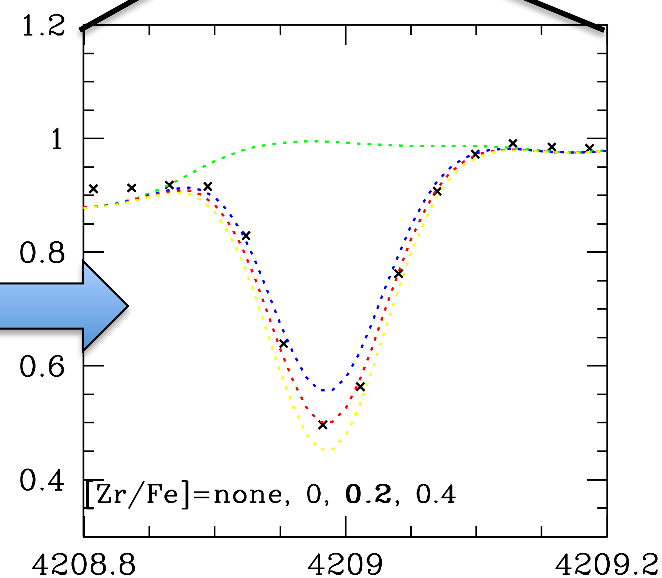
Telescopes *versus* Stardust: *the uncertainties*

Stellar spectra



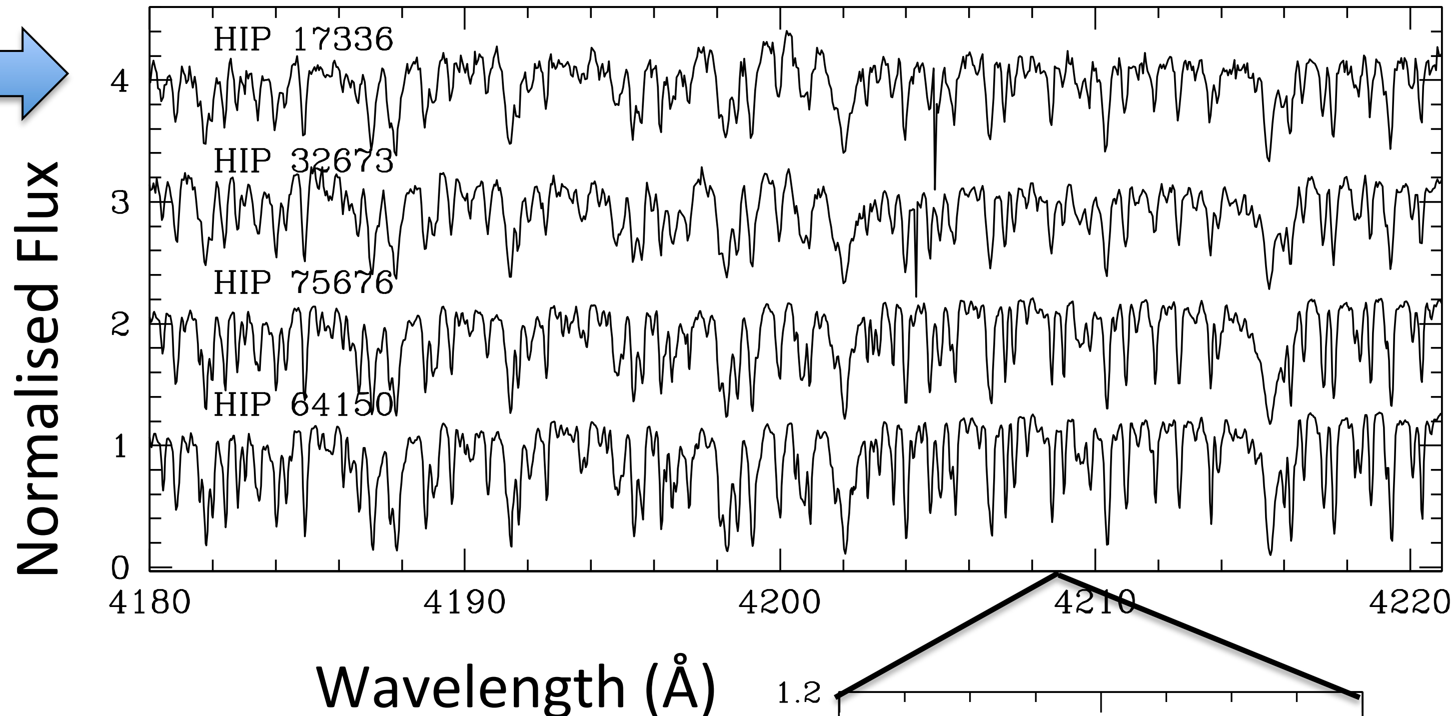
Courtesy of Valentina D'Orazi

Need a model



Telescopes *versus* Stardust: *the uncertainties*

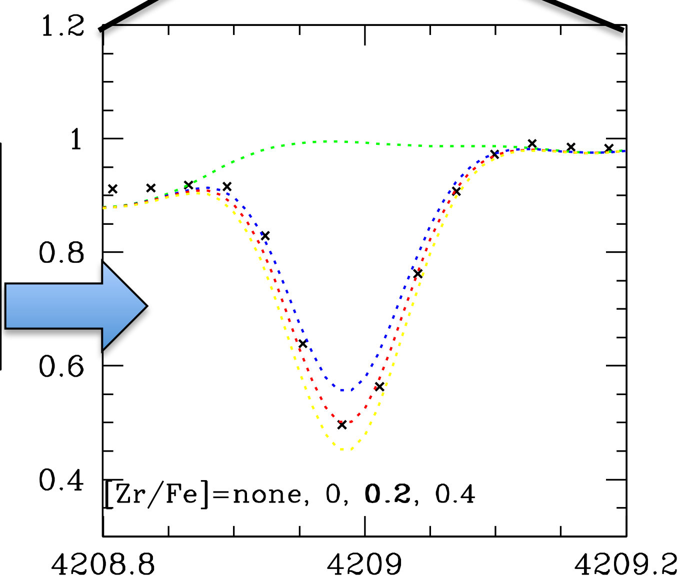
Stellar spectra



Courtesy of Valentina D'Orazi

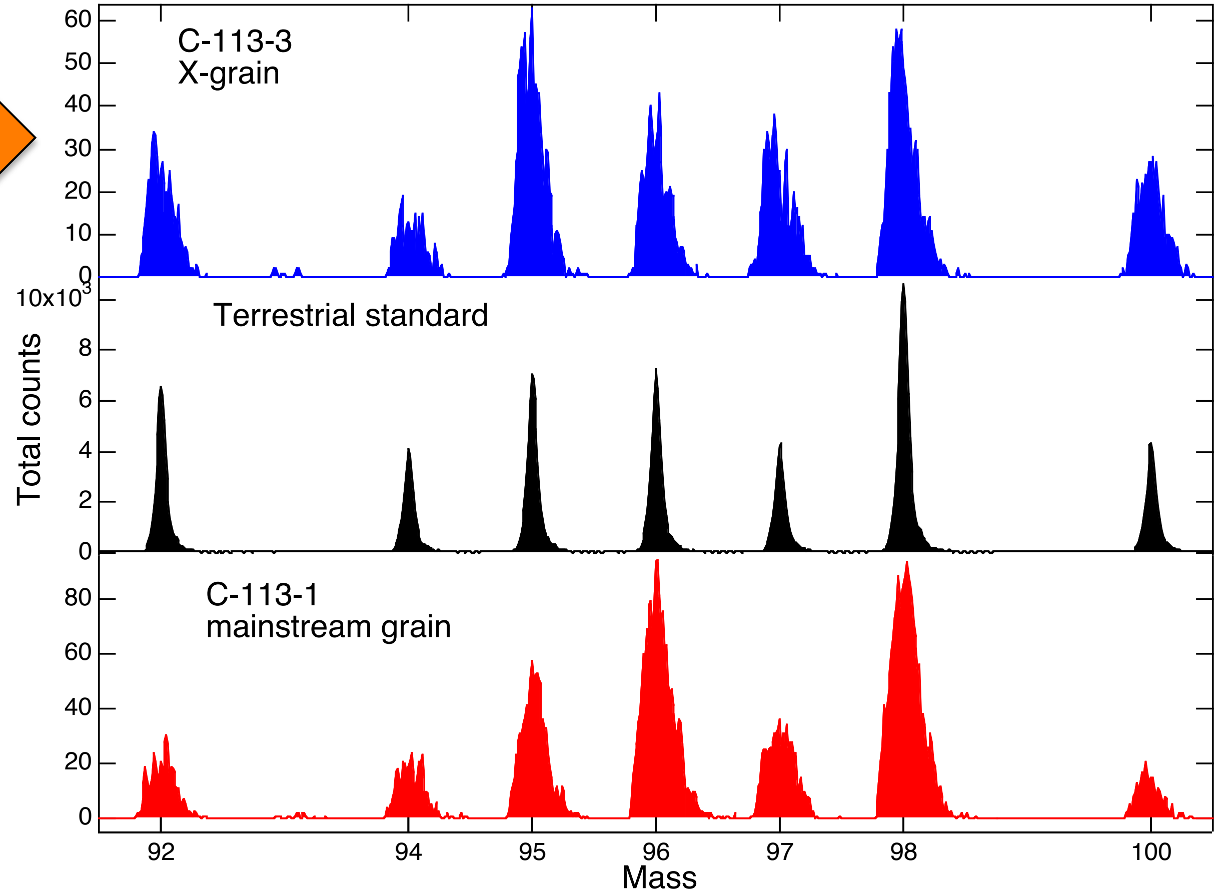
Large uncertainties! typically 100%

Need a model



Telescopes *versus* **Stardust**: *the uncertainties*

Mass Spectrometry, no need of models



Courtesy of Andrew Davis

Small uncertainties! typically 10%

Telescopes *versus* **Stardust**: *the isotopes*

Isotopic abundances are impossible or difficult to derive: 

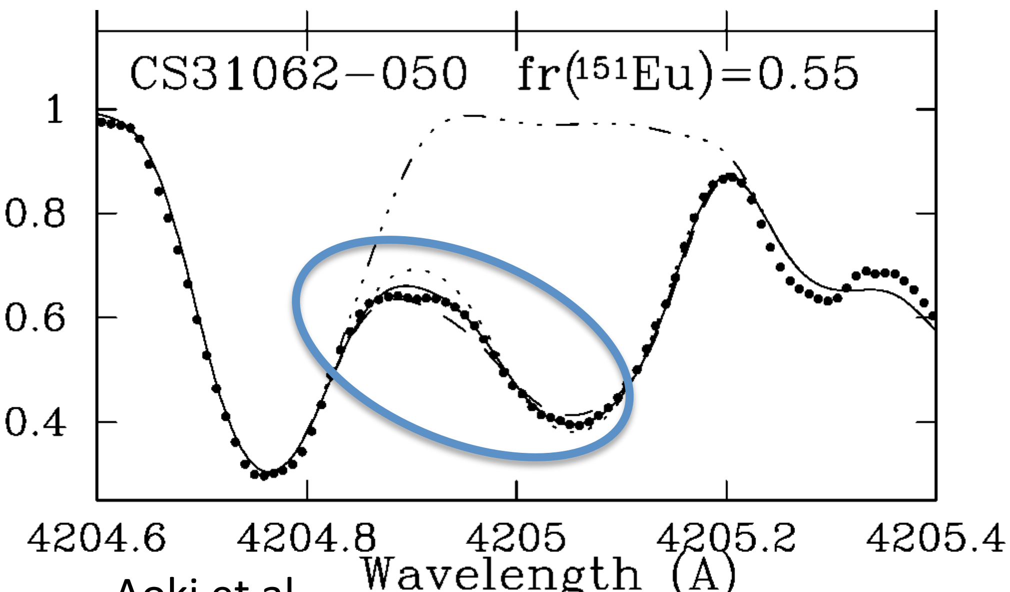
Isotopic abundances are the standard output: 

Telescopes *versus* **Stardust**: *the isotopes*

Isotopic abundances are impossible or difficult to derive:

Isotopic abundances are the standard output:

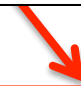
$fr(^{151}Eu) = ^{151}Eu/Eu$



Aoki et al. (2003)

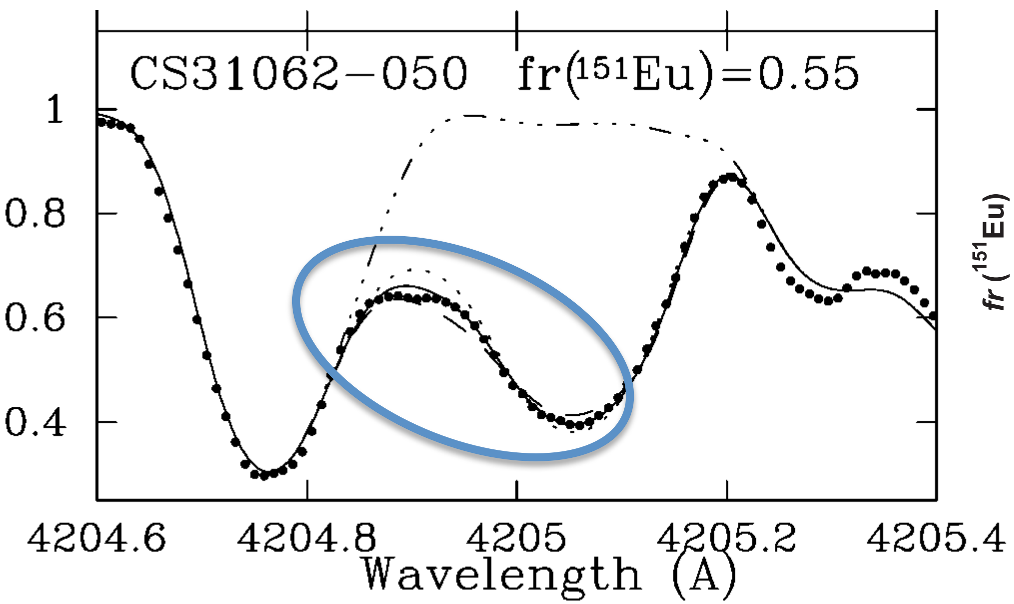
Telescopes *versus* Stardust: *the isotopes*

Isotopic abundances are impossible or difficult to derive:

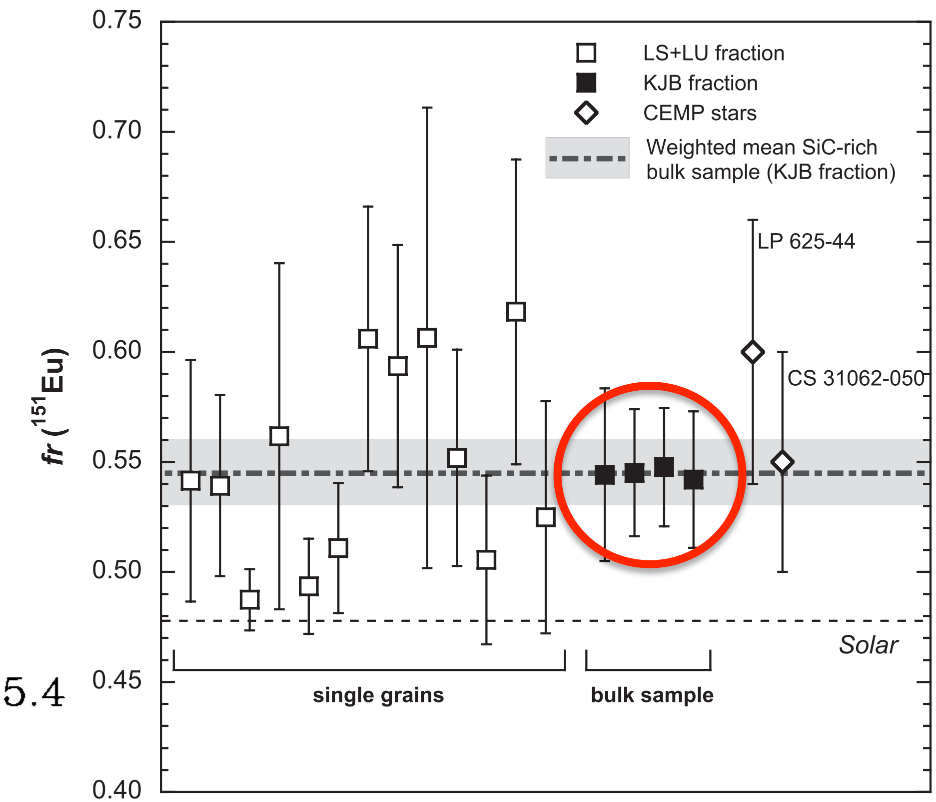


Isotopic abundances are the standard output:

$fr(^{151}Eu)={}^{151}Eu/Eu$



Aoki et al. (2003)



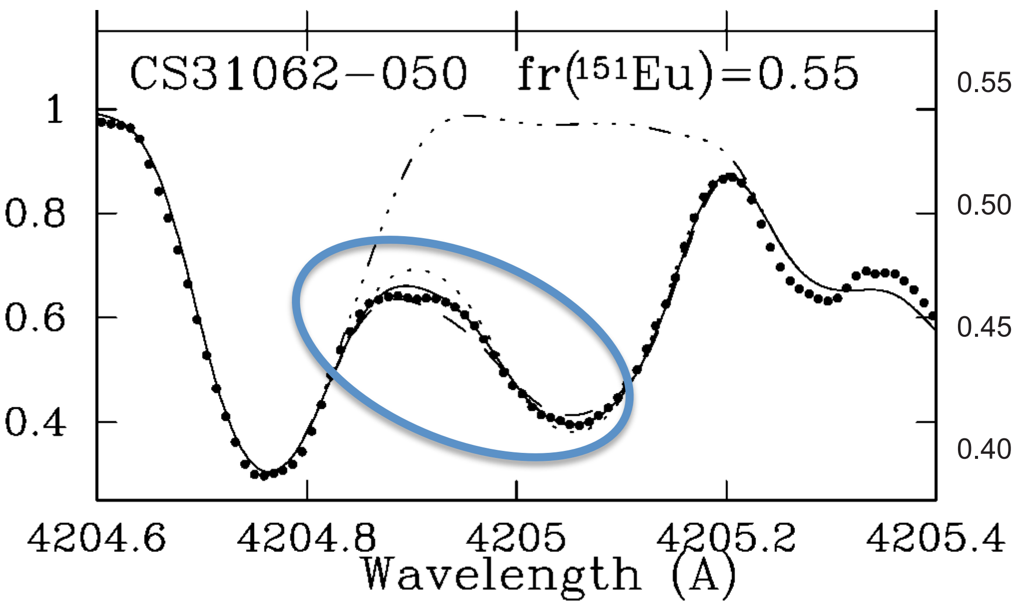
Avila et al. (2013)

Telescopes *versus* **Stardust**: *the isotopes*

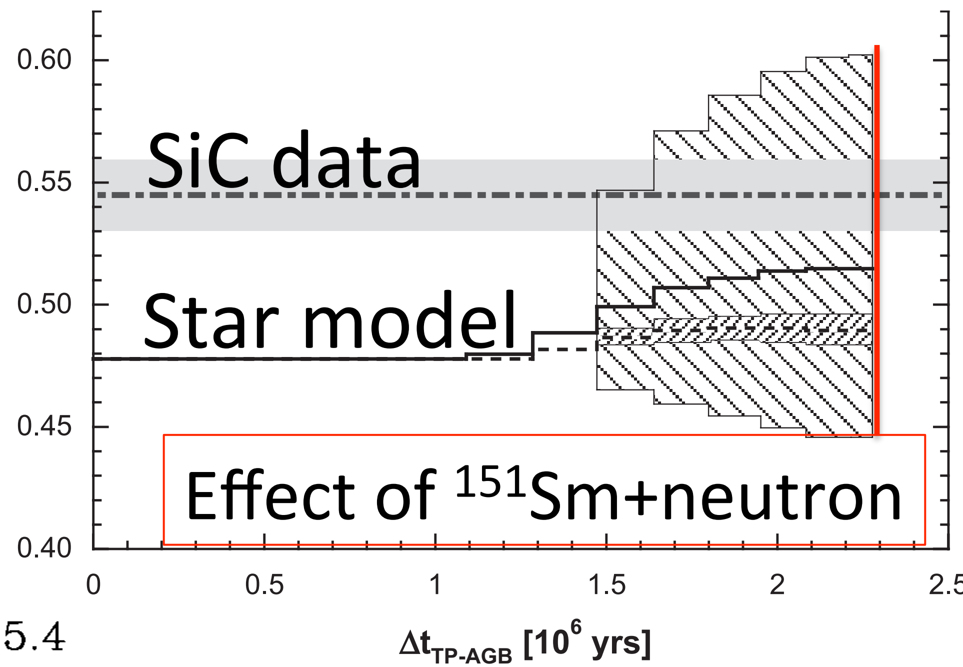
Isotopic abundances are impossible or difficult to derive:

Isotopic abundances are the standard output:

$fr(^{151}Eu) = {}^{151}Eu/Eu$



(2003)



Avila et al. (2013)

Telescopes *versus* **Stardust:** *the challenge*

We know which star we are looking at…

We need to guess which was the parent star

In most cases we can make an initial qualitative guess, but it is only via continuous effort in the modelling of stellar nucleosynthesis that we can truly interpret and exploit the stardust data!

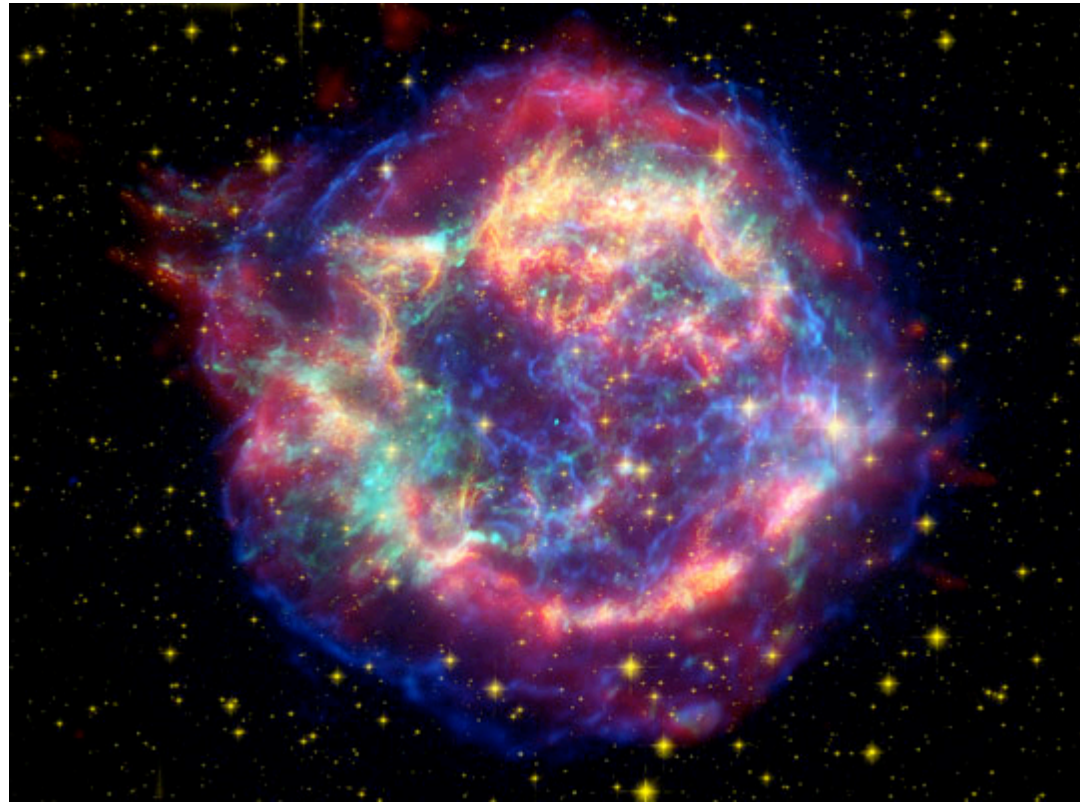
The stardust revolution!

Some examples of the application of stardust:

- Supernova and nova explosions
- Structural and evolutionary properties of single and binary stars
- The origin of the elements heavier than iron
- The chemical and dynamical evolution of the Milky Way Galaxy
- Dust formation around stars and (super)novae
- The nucleosynthetic components in the solar protoplanetary disk, the presolar dust inventory and its distribution

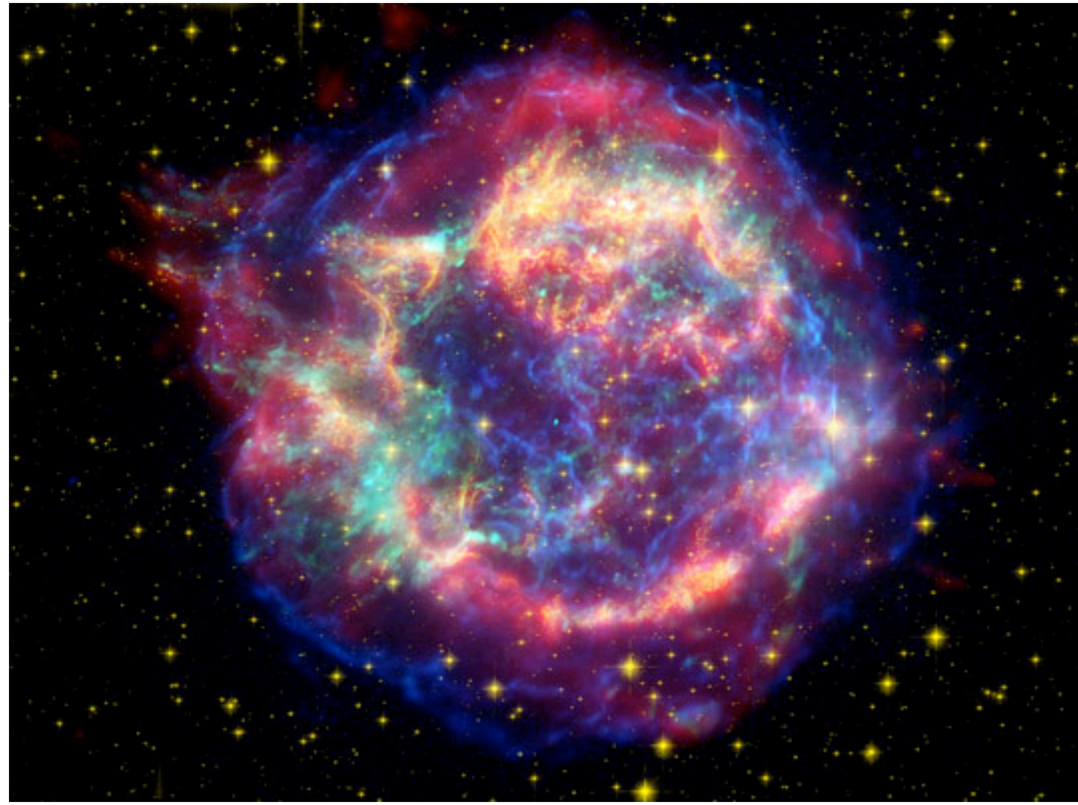
Core-collapse supernovae

- The final fate of massive stars
- Some of the most mysterious astrophysical objects
- No agreement yet on the explosion mechanism
- Abundance determinations are rare…

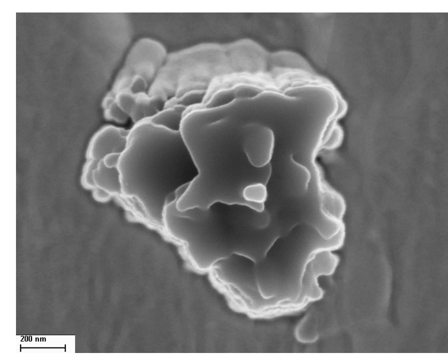


Core-collapse supernovae

- The final fate of massive stars
- Some of the most mysterious astrophysical objects.
- No agreement yet on the explosion mechanism
- Abundance determinations are rare…



…but we have stardust that formed in these objects!

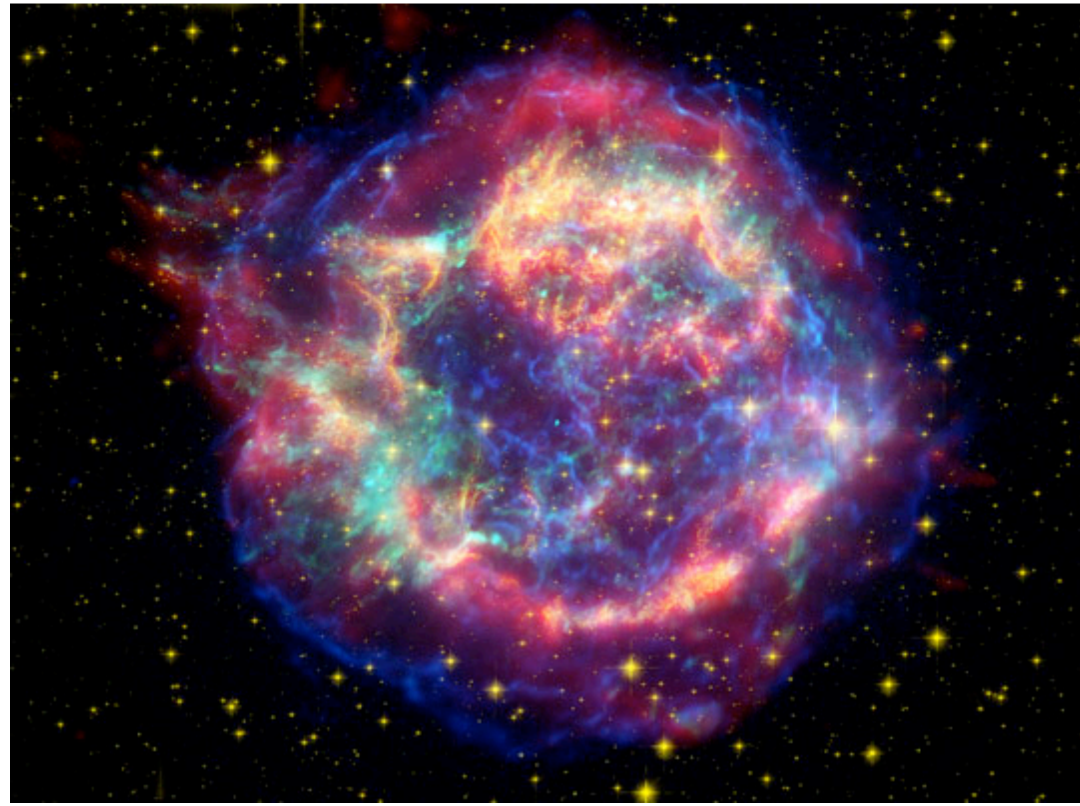


Courtesy of Peter Hoppe

Core-collapse supernovae

Pignatari et al. 2013; Pignatari, Zinner, et al 2013; Pignatari, Zinner, et al. 2015

Most of the grains can be explained by **explosive He burning** in supernovae with **high shock velocities and temperatures**:

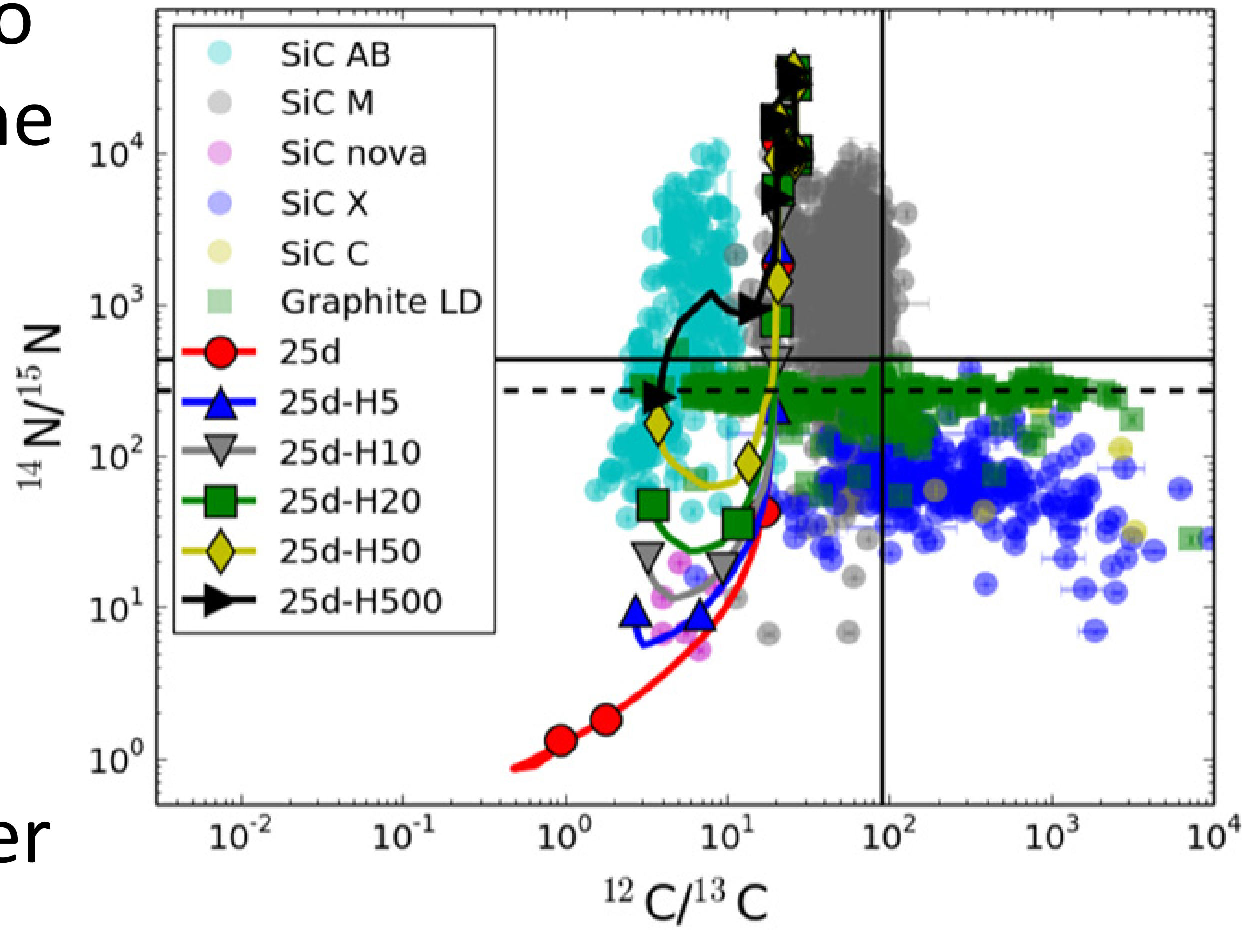


possibly the high-temperature tail of a distribution of conditions in ***asymmetric*** supernovae.

Core-collapse supernovae

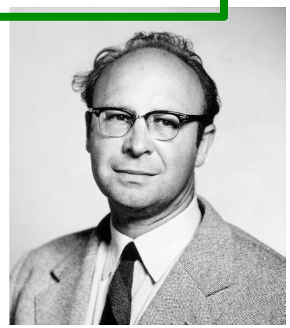
Pignatari et al. 2013; Pignatari, Zinner, et al 2013; Pignatari, Zinner, et al. 2015

If **H is ingested** into the He shell and the supernova shock hits the shell with some H, the models reproduce grains with $^{12}C/^{13}C$ and $^{14}N/^{15}N$ ratios lower than solar.



Meteoritic
abundances



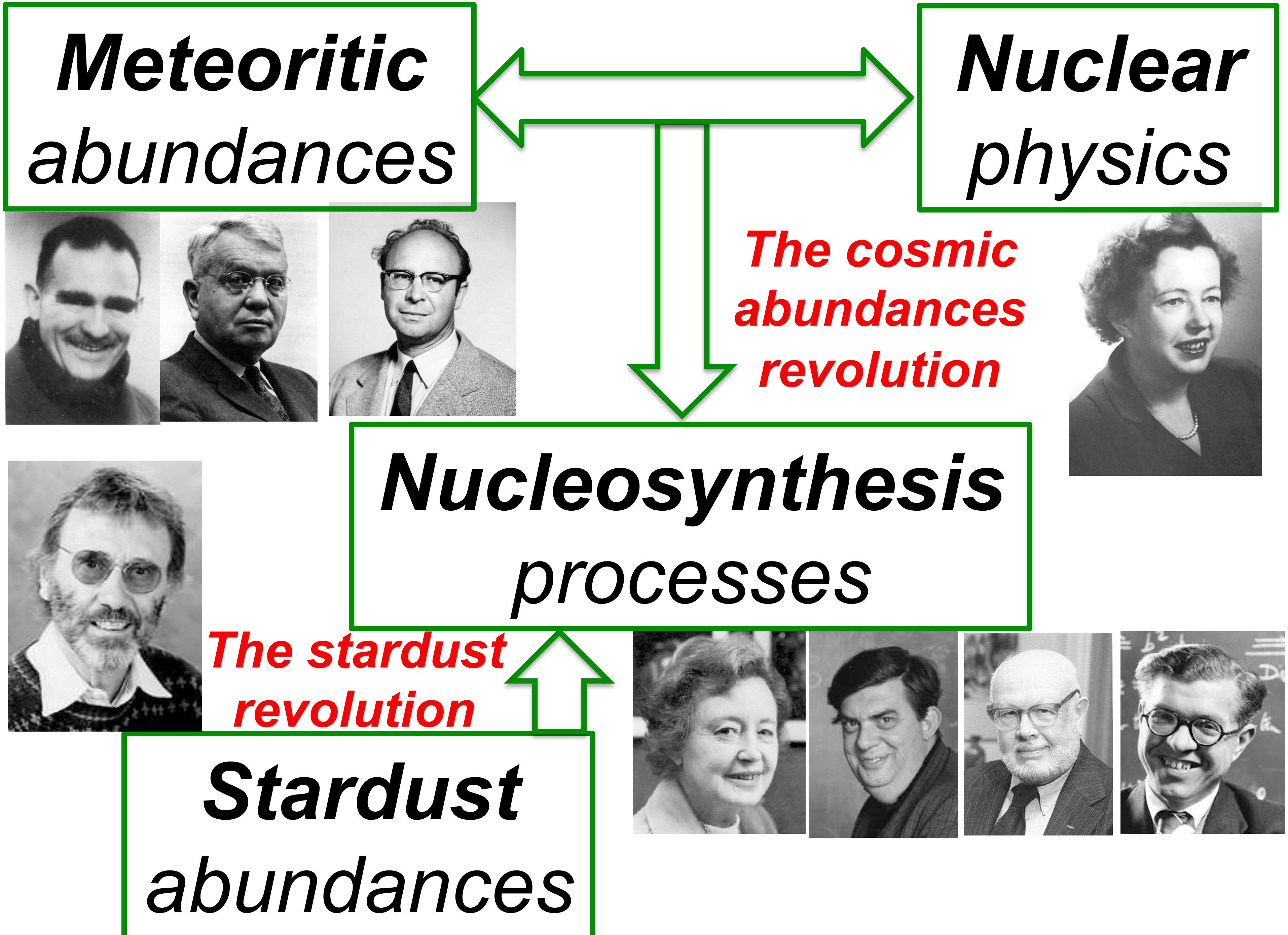


Nuclear
physics

The cosmic abundances revolution!

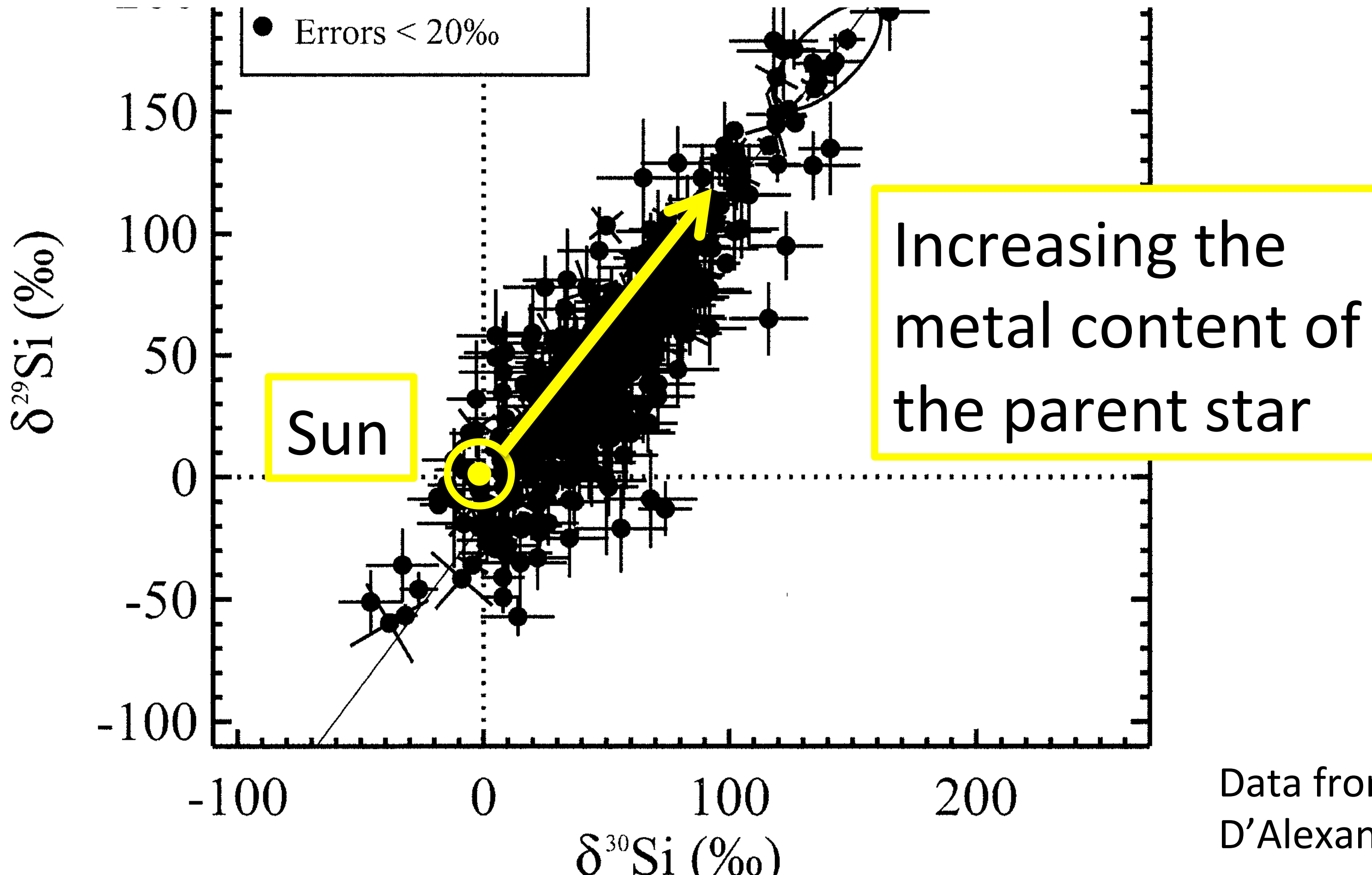
Nucleosynthesis
processes





Meteoritic abundances
Nuclear physics
The cosmic abundances revolution
Nucleosynthesis processes
The stardust revolution
Stardust abundances

On Galactic stellar migration and dust production

Most stardust SiC grains originated in giant stars. They show evidence of parent stars with more metals than the Sun!



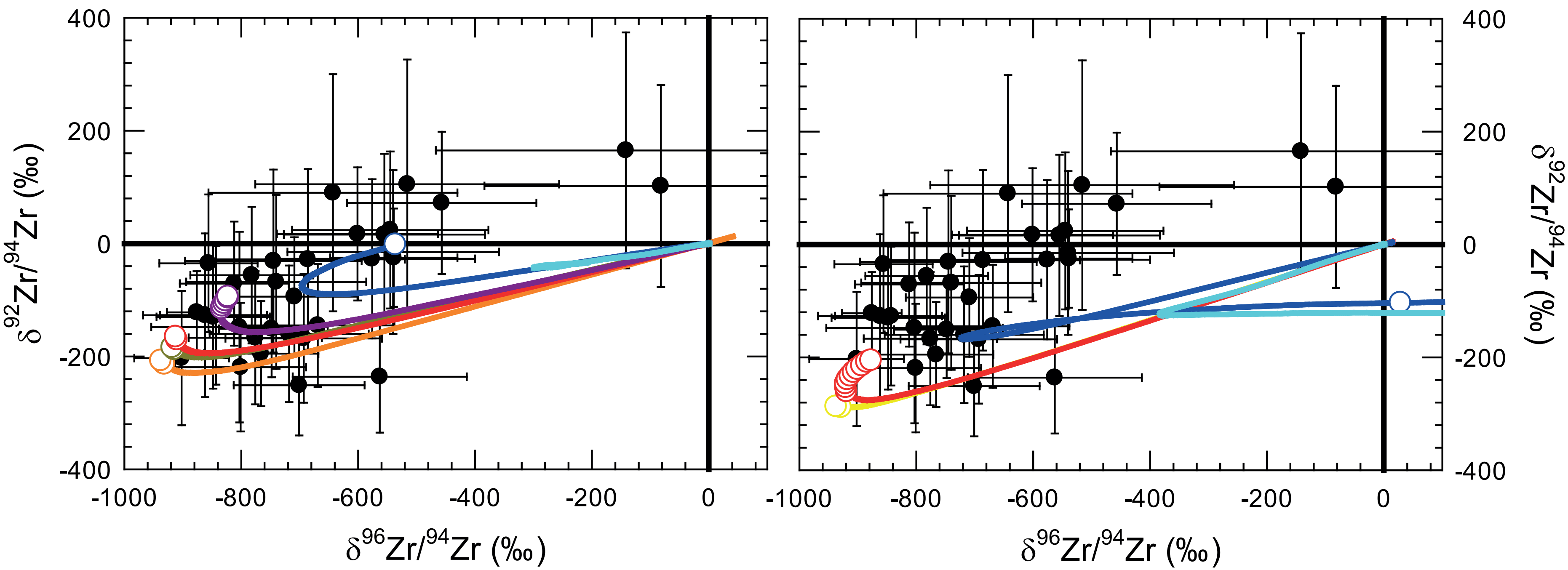
Data from Nittler & D'Alexander (2003)

On Galactic stellar migration and dust production

Most stardust SiC grains originated in giant stars. They show evidence of parent stars with more metals than the Sun!

Models of solar metal content

Models of 2 x solar metal content



Stars with initial mass from 2 to 4.5 solar masses, Lugaro et al. in prep

On Galactic stellar migration and dust production

Stars with different metal content (depending on where they are born) migrate through the Galaxy -> *stardust are Galactic* … (Don Clayton)

This migration effect is also observed from large stellar surveys,
stardust represent an independent constraint but shows a more pronounced effect
Selection effect due to more efficient dust formation as the metal content increases?