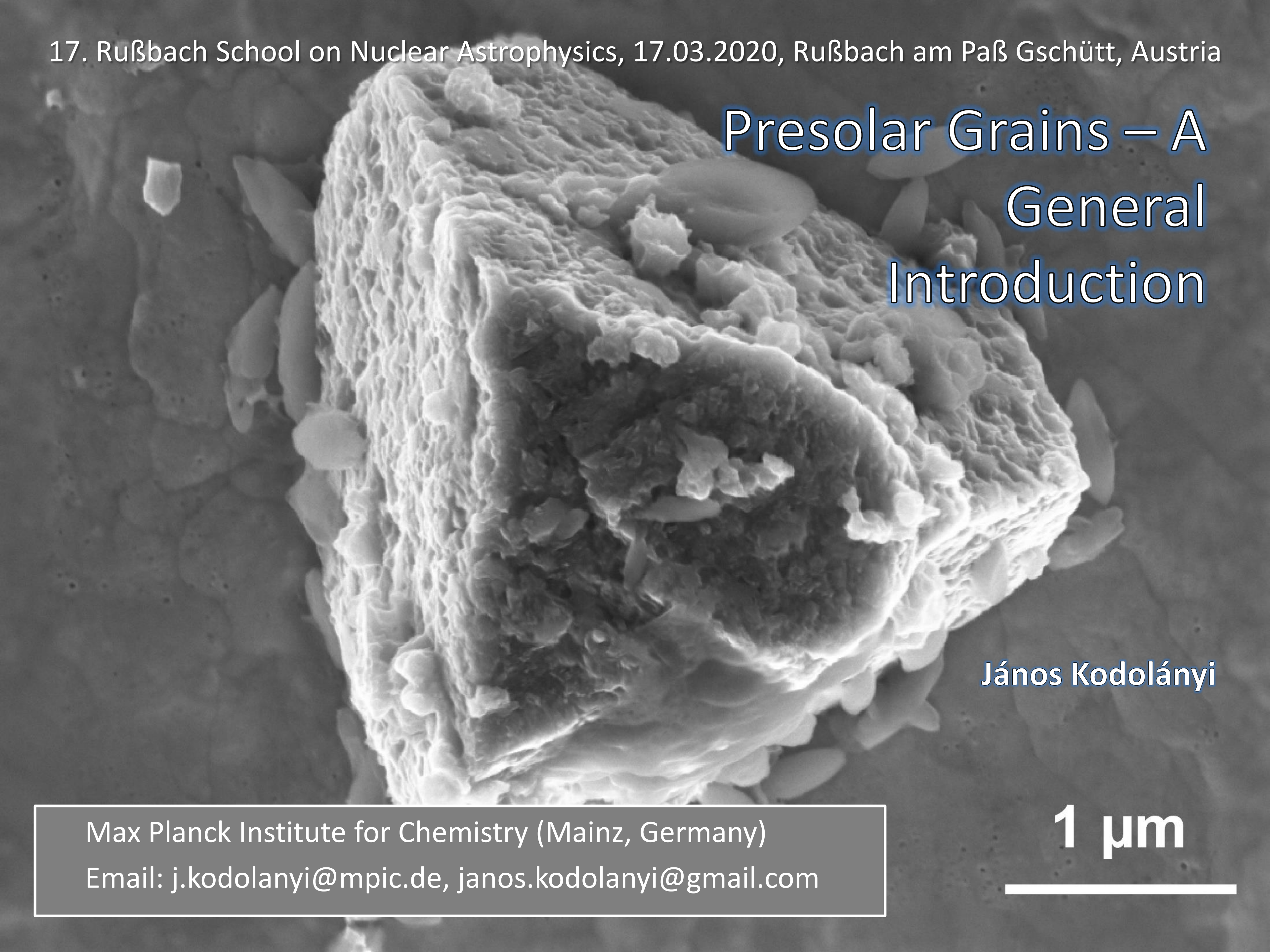
17. Rußbach School on Nuclear Astrophysics, 17.03.2020, Rußbach am Paß Gschütt, Austria

Presolar Grains – A General Introduction

János Kodolányi

Max Planck Institute for Chemistry (Mainz, Germany)

Email: j.kodolanyi@mpic.de, janos.kodolanyi@gmail.com

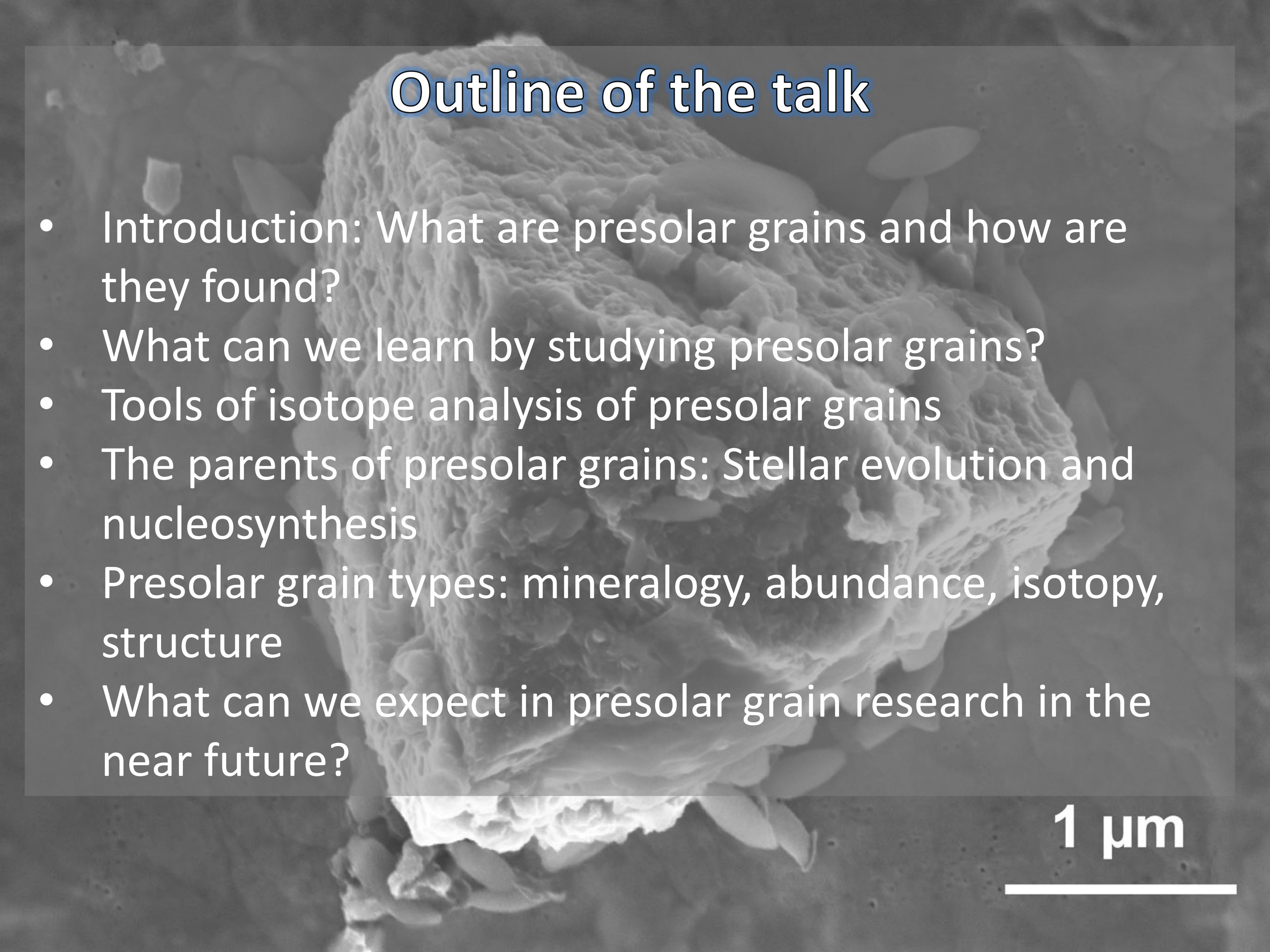


Collaborators (past and present)

- Peter Hoppe, Jan Leitner – Max Planck Institute for Chemistry (Mainz, Germany)
- Christian Vollmer – Westfälische Wilhelms-Universität Münster (Münster, Germany)
- Maren Müller – Max Planck Institute for Polymer Research (Mainz, Germany)
- Thomas Stephan – The University of Chicago (U.S.A.)
- Reto Trappitsch – Lawrence Livermore National Laboratory (Livermore, U.S.A.)
- Marco Pignatari – University of Hull (U.K.)
- Wataru Fujiya – Ibaraki University (Mito, Japan)

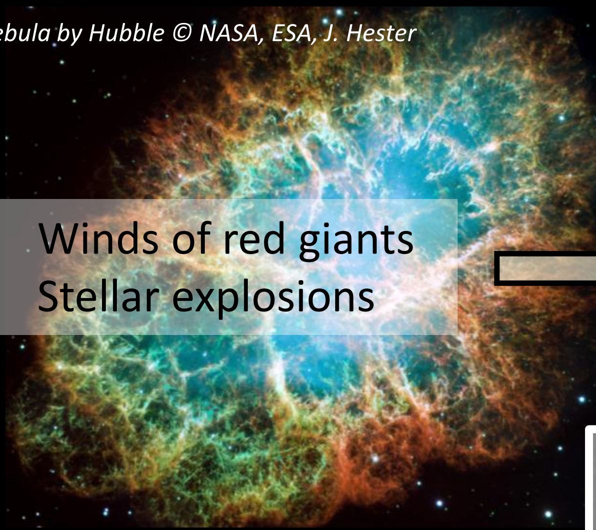
Outline of the talk

- Introduction: What are presolar grains and how are they found?
- What can we learn by studying presolar grains?
- Tools of isotope analysis of presolar grains
- The parents of presolar grains: Stellar evolution and nucleosynthesis
- Presolar grain types: mineralogy, abundance, isotopy, structure
- What can we expect in presolar grain research in the near future?



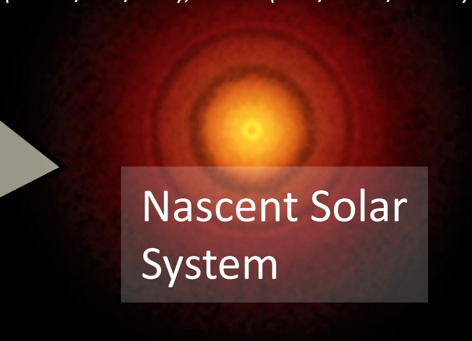
Introduction

Crab Nebula by Hubble © NASA, ESA, J. Hester

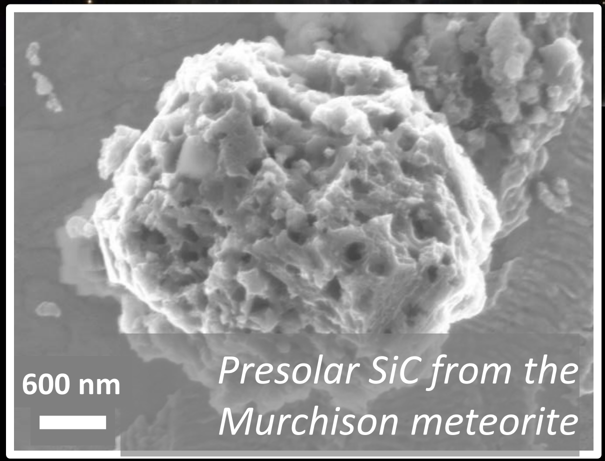


IRAS 05437+2502 by Hubble © ESA/Hubble, R. Sahai and NASA

TW Hydrae and associated disc by ALMA © S. Andrews (Harvard-Smithsonian CfA); B. Saxton (NRAO/AUI/NSF); ALMA (ESO/NAOJ/NRAO)

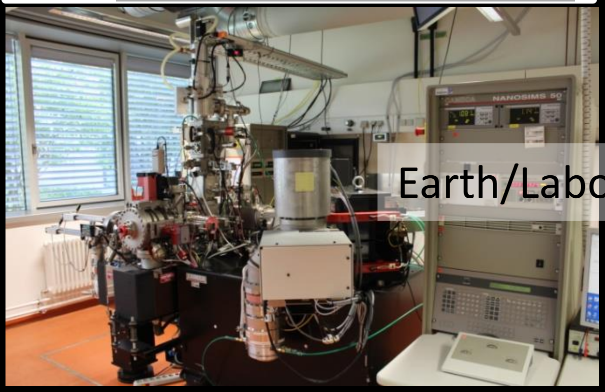


- Few nm to several µm diameter stellar dust grains that **pre**-date the **Solar** System, and partially or completely survived early Solar System processing: *fossil, extra-Solar System stellar dust for direct study in the lab*



Presolar SiC from the Murchison meteorite

A piece of the Murchison meteorite (Field Museum, Chicago, U.S.A.)



NanoSIMS at the Max Planck Institute for Chemistry (Mainz, Germany)

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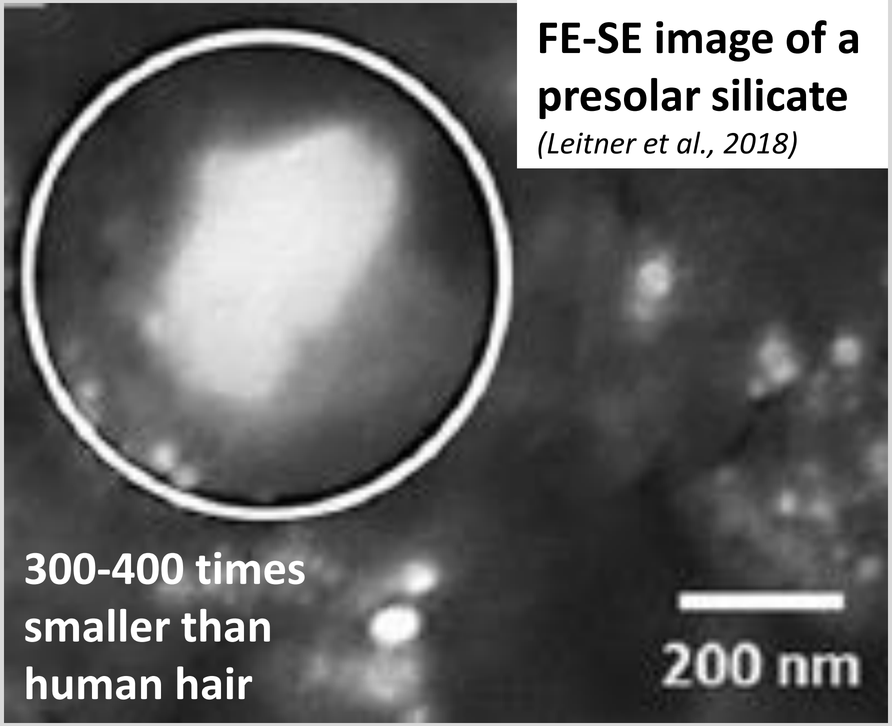
Introduction

- Most grains are small (diameter <250 nm)
- Silicates, oxides, graphite, SiC, etc.
- Found in meteorite matrices, interplanetary dust particles (IDPs) and cometary dust, based on *anomalous isotope composition* (i.e., composition outside the range of Solar System isotope variations) – sampling bias?
- First presolar isotope anomalies detected in bulk samples (H, O, *Ne, Xe*)
- First presolar grains detected in chemically separated aliquots of primitive meteorites



FE-SE image of a presolar silicate
(Leitner et al., 2018)

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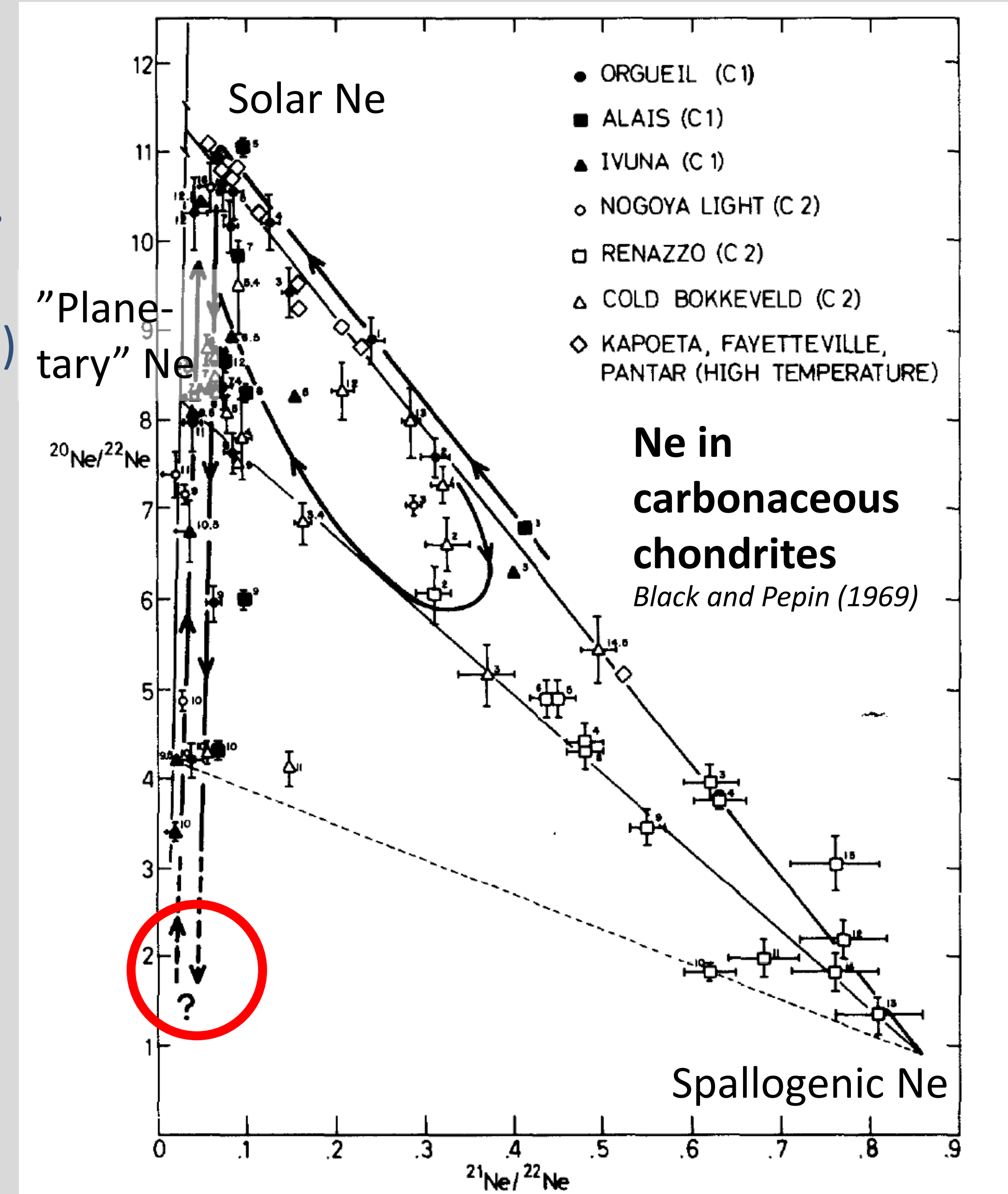

Introduction

$$\delta^{x}Si = 1000 \times \left[\frac{\left(\frac{^{x}Si}{^{28}Si}\right)_{Grain}}{\left(\frac{^{x}Si}{^{28}Si}\right)_{Solar}} - 1\right]$$

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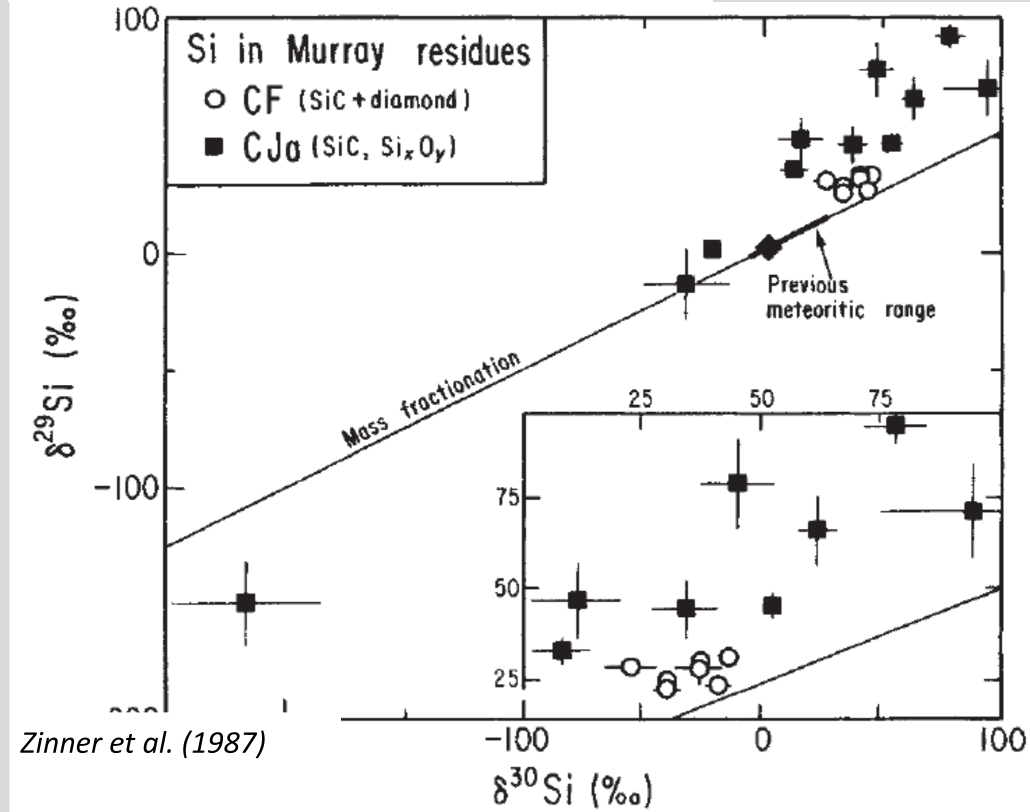

Zinner et al. (1987)

730 LETTERS TO NATURE NATURE VOL. 330 24/31 DECEMBER 1987

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

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

Why presolar grains?

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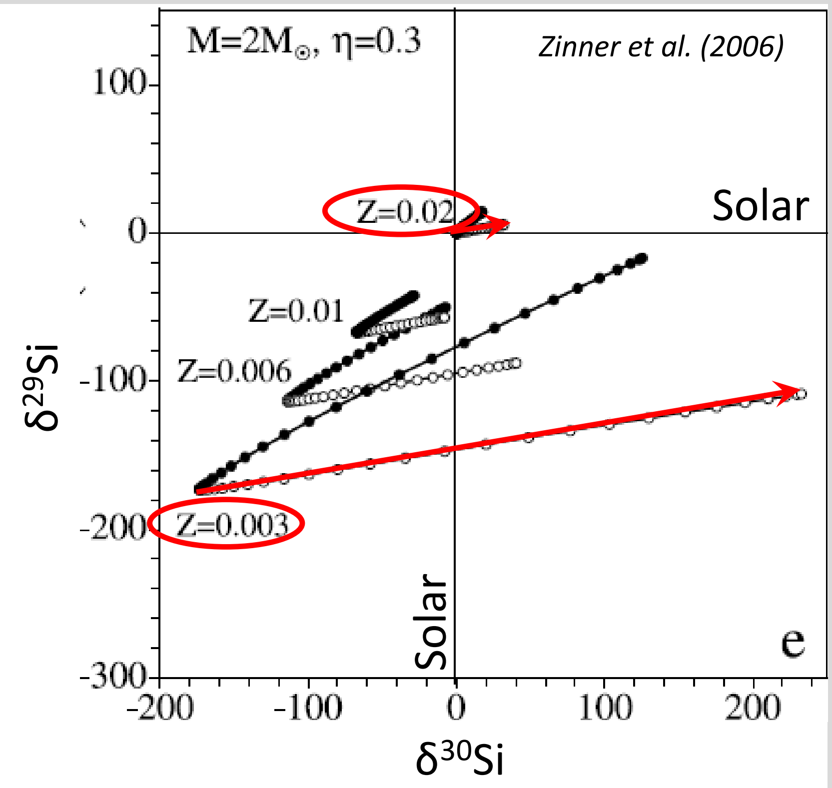
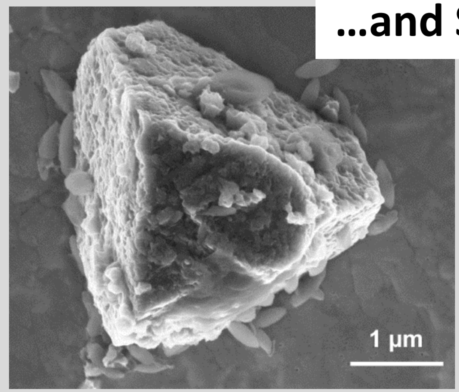
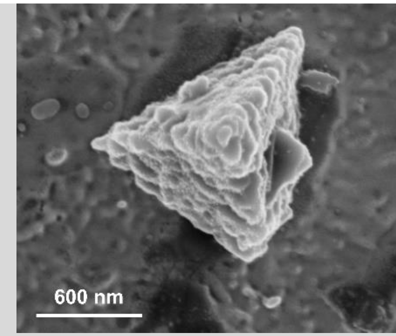
They document stellar evolution and Galactic Chemical Evolution

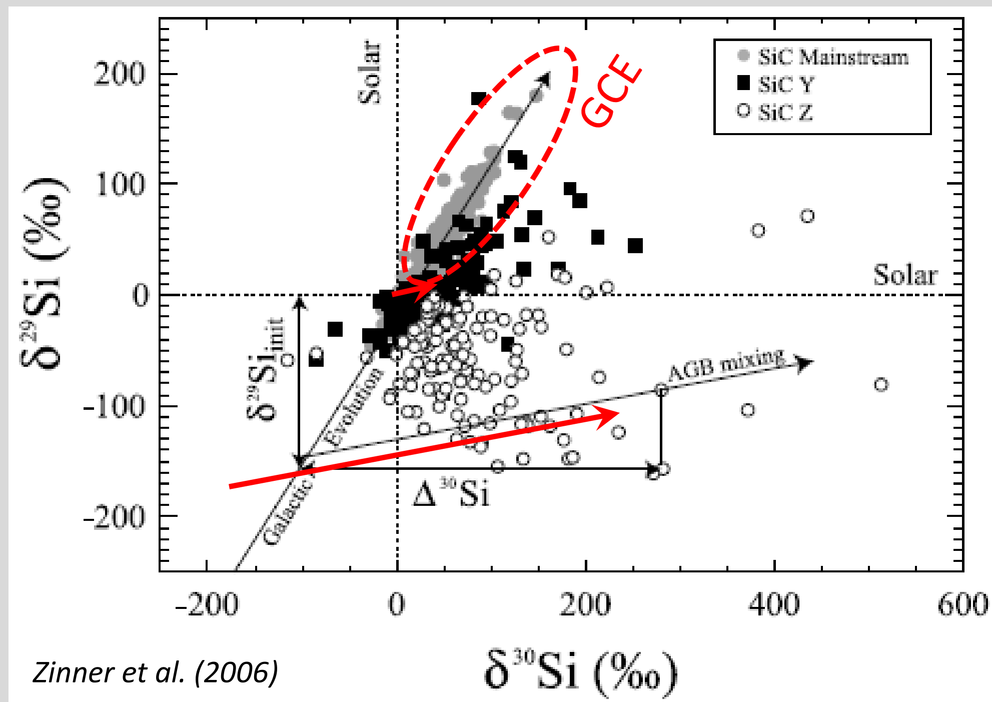
E.g., Si isotope model predictions for AGB stars…



…and SiC grains from AGB stars







Why presolar grains?

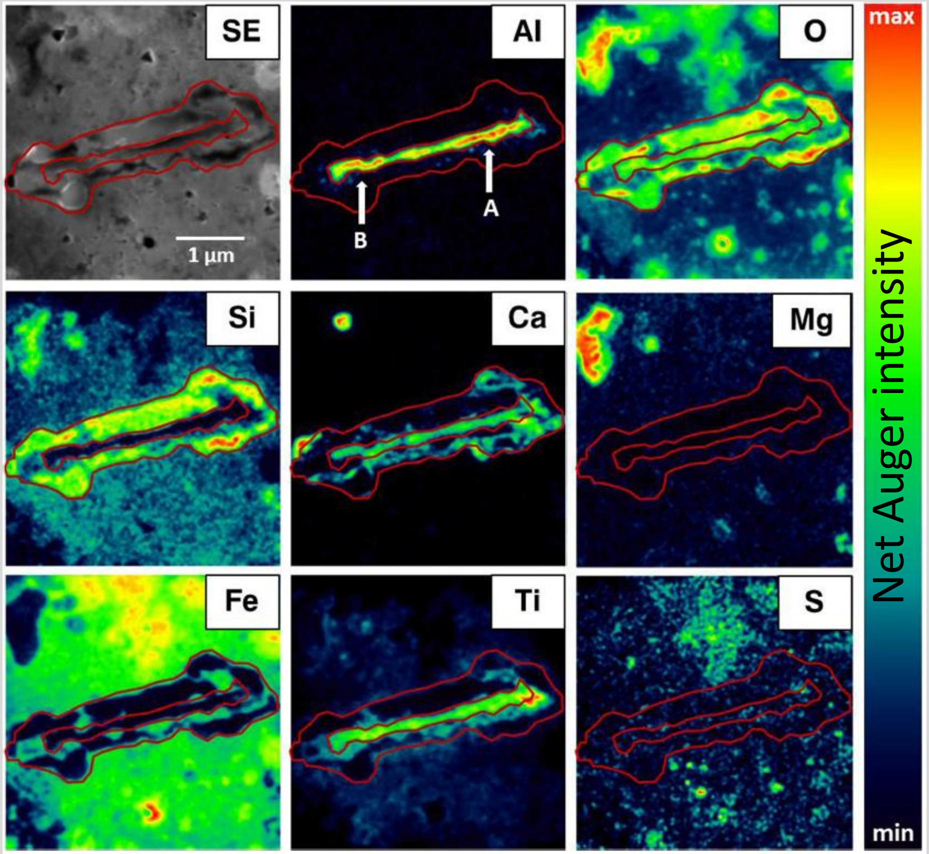
They tell about dust formation in stellar environments…

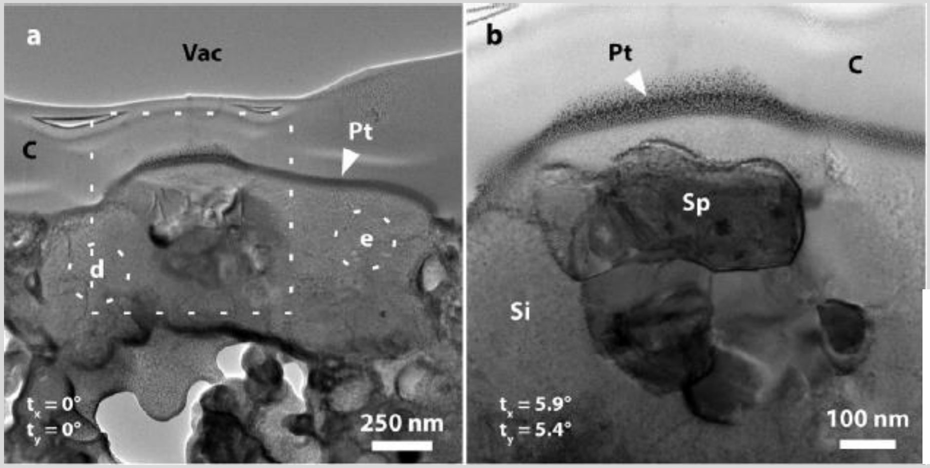
- Pressure and T of condensing gas
- Condensation sequence(s)
- Kinetics of condensation

…and about ISM/early Solar System processes:

- Condensation of additional material
- Grain alteration/destruction

Polymineralic AGB condensate *(Leitner et al., 2018)*





AGB spinel aggregate with silicate mantle that formed in the ISM or the Solar System *(Zega et al., 2020)*

Why presolar grains?

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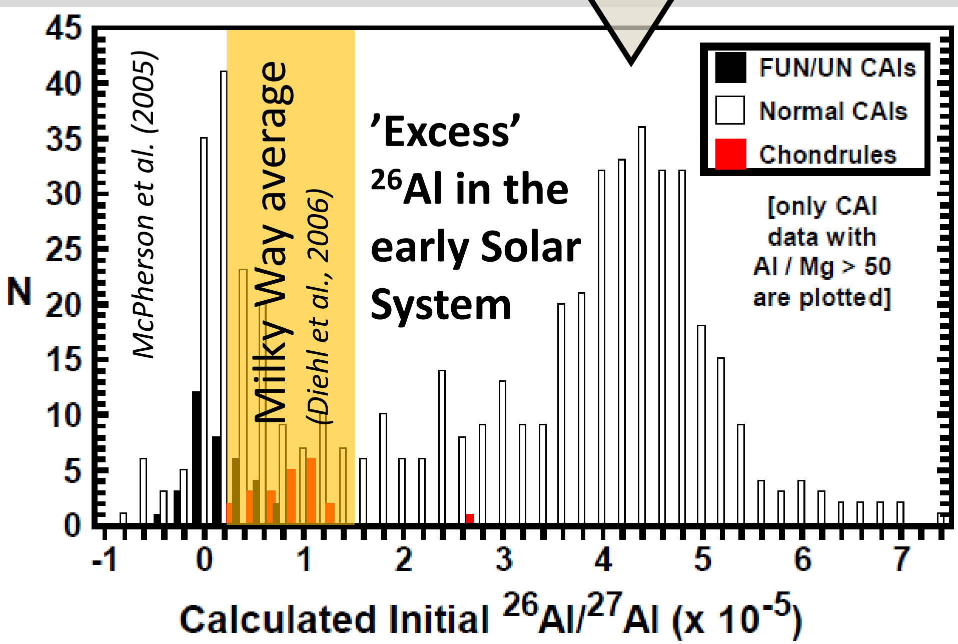
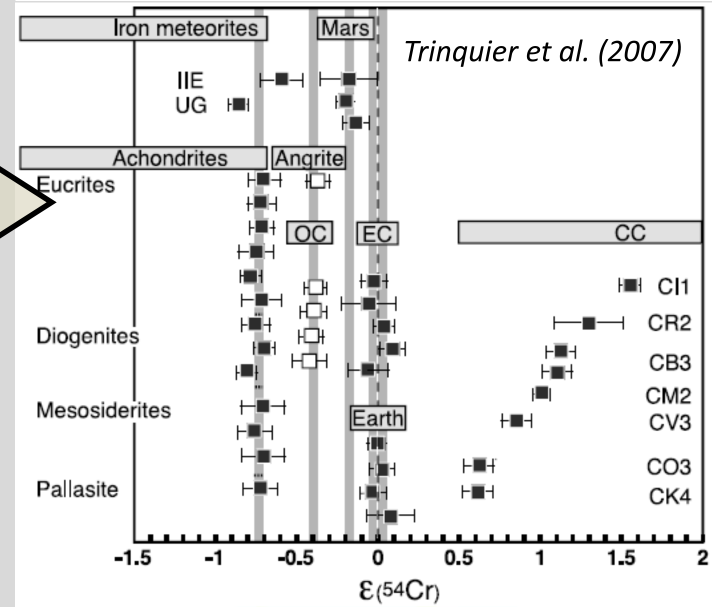
They provide information about the Galactic environment at Solar System birth:

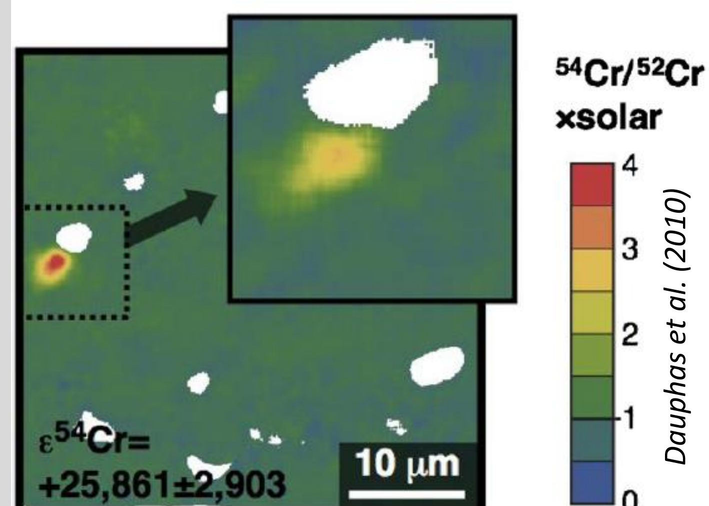
- Some isotope anomalies observed in bulk meteorites can be attributed to presolar dust
- ^{26}Al present at Solar System birth was probably delivered by presolar dust from massive star(s) *(e.g., Gaidos et al., 2009)*



CAIs: Ca-, Al-rich inclusions (oldest dated Solar System objects)

^{54}Cr-enriched spinel grains





What kind of data?

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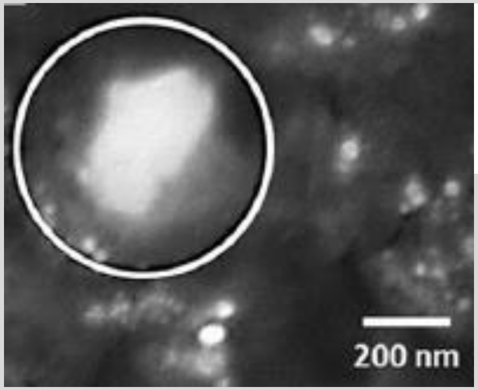

FE-SE image of a presolar silicate
(Leitner et al., 2018)

- Isotope composition
- Chemical composition
- Structural data
- Relative abundance
- Isotope/chemical/structural analysis of individual presolar grains requires *nano-analytical techniques:*

- Isotope compositions usually measured by nanoscale secondary ion mass spectrometry (the instrument is abbreviated NanoSIMS) and by resonance ionization mass spectrometry (RIMS; instruments: CHILI, LION, CHARISMA)
- Chemical composition determined by Auger spectroscopy and energy dispersive X-rax spectroscopy (EDX)
- Structural data obtained using transmission electron microscopy (TEM)

Isotope analysis

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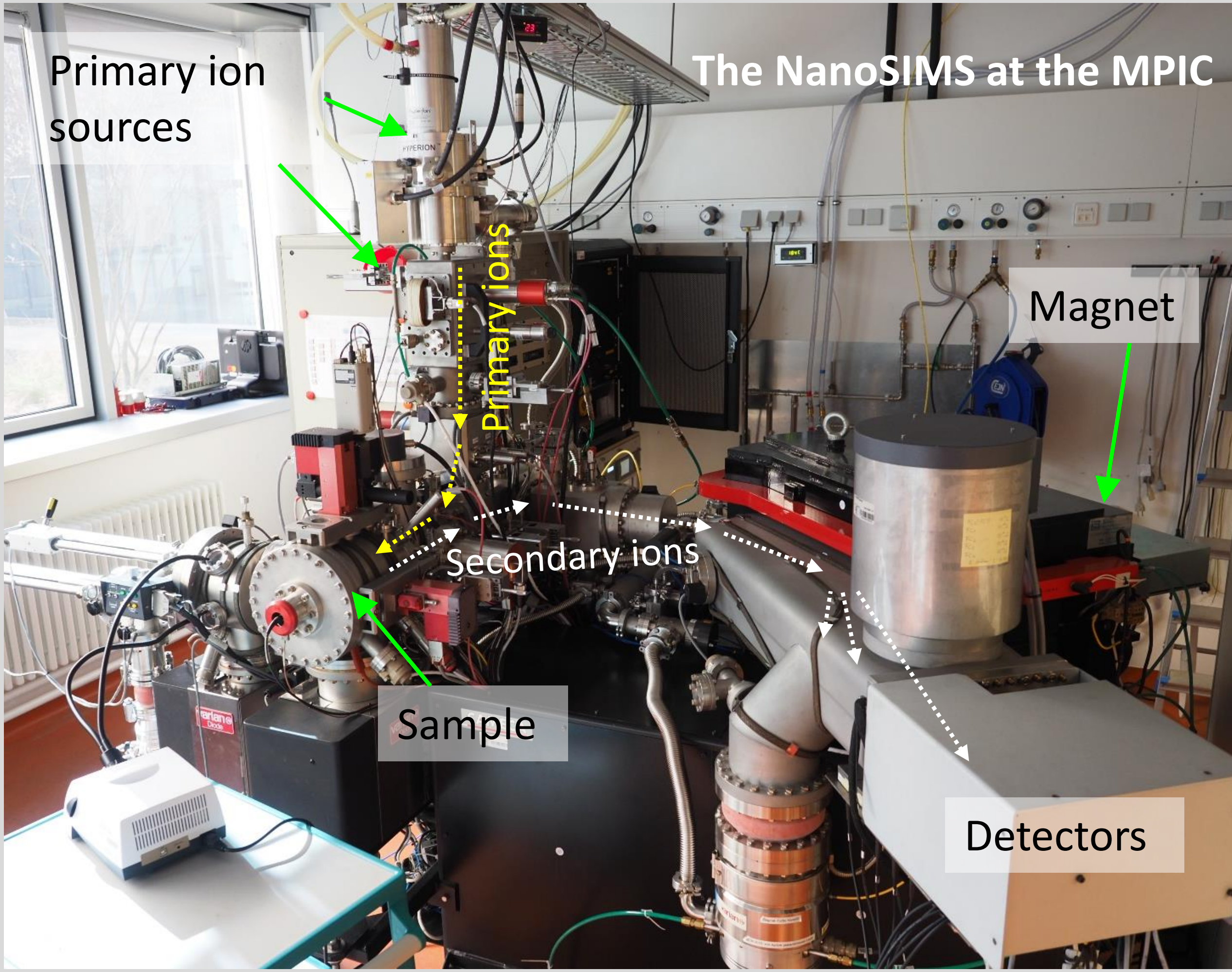
I. NanoSIMS:

- Secondary ion mass spectrometer
- Two primary ion sources (Cs^+, Hyperion: O^+ or O^-)
- Spatial resolution down to 80 nm
- 5 masses analysed simultaneously
- Mass resolving power (MRP): several thousand (hydride interferences of major elements are easily resolved)
- Precision (isotope ratios of major elements in presolar grains): % level



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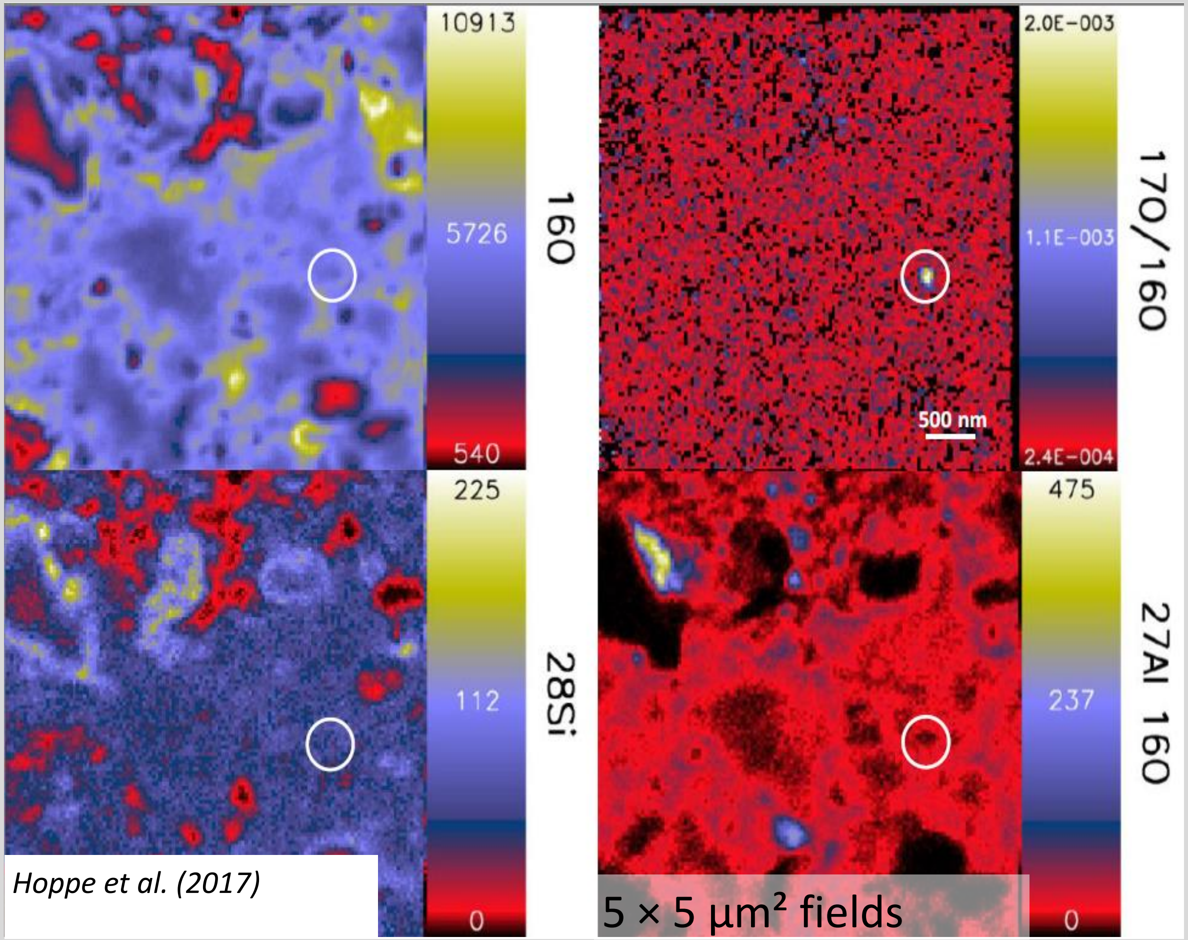

Hoppe et al. (2017)

5 × 5 µm² fields

○ = Presolar grain with isotope anomaly

Isotope analysis

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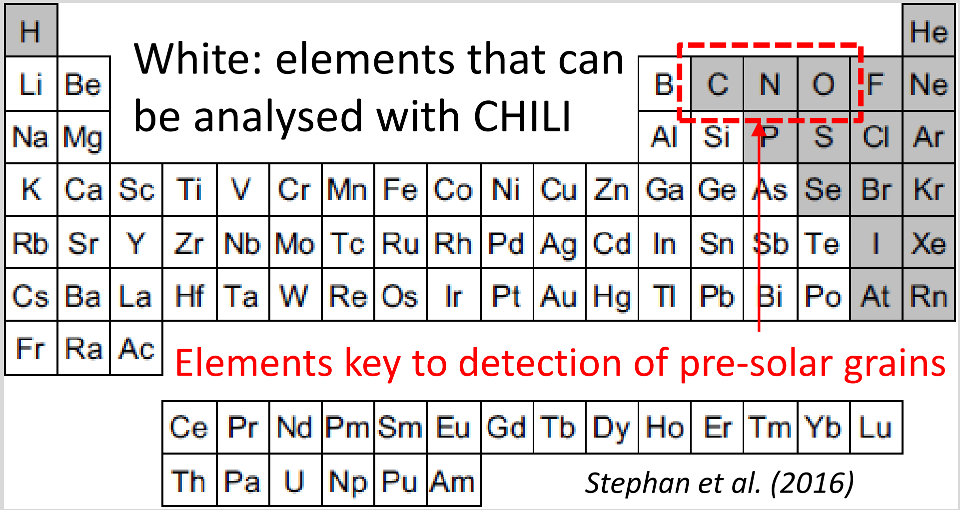
II. RIMS:

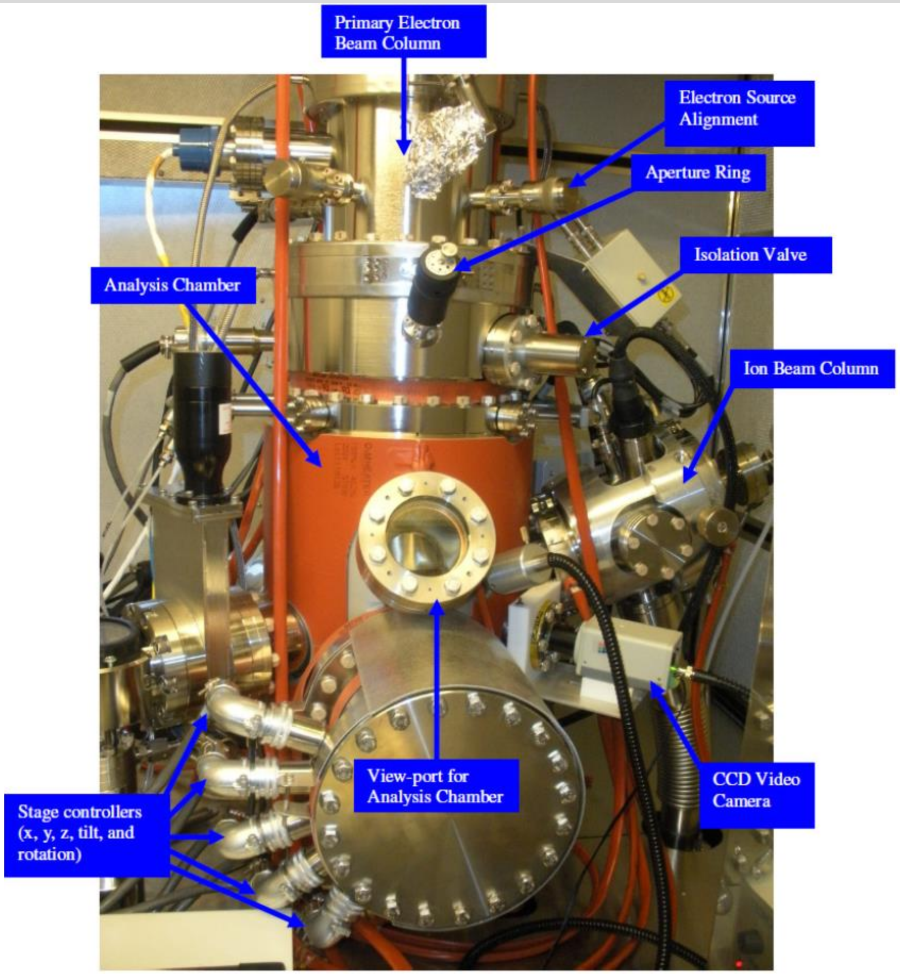
- Ionization of selected elements
- Ion or laser beam used to sample analyte
- Currently ~1 µm spatial resolution
- Low mass resolution (MRP <~1500), high useful yield (up to ~10 %)
- Some isotope systems are not accessible due to insufficient ionisation
- Isobaric interference problems circumvented
- Precision (isotope ratios of major elements in presolar grains): % level or better

CHILI, The University of Chicago

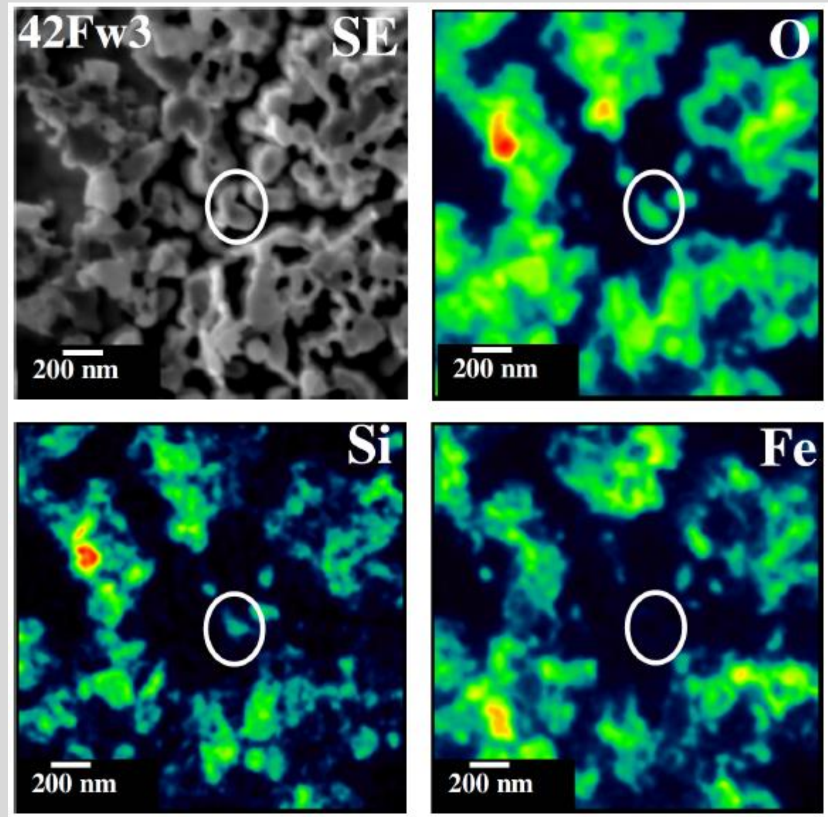


Chemical analysis

- SEM-EDX (Scanning Electron Microscope-Energy Dispersive X-ray Spectroscopy)
- TEM-EDX (Transmission Electron Microscope-EDX)
- Auger spectroscopy



Auger Nanoprobe at the WUSTL
Image credit: Maitrayee Bose

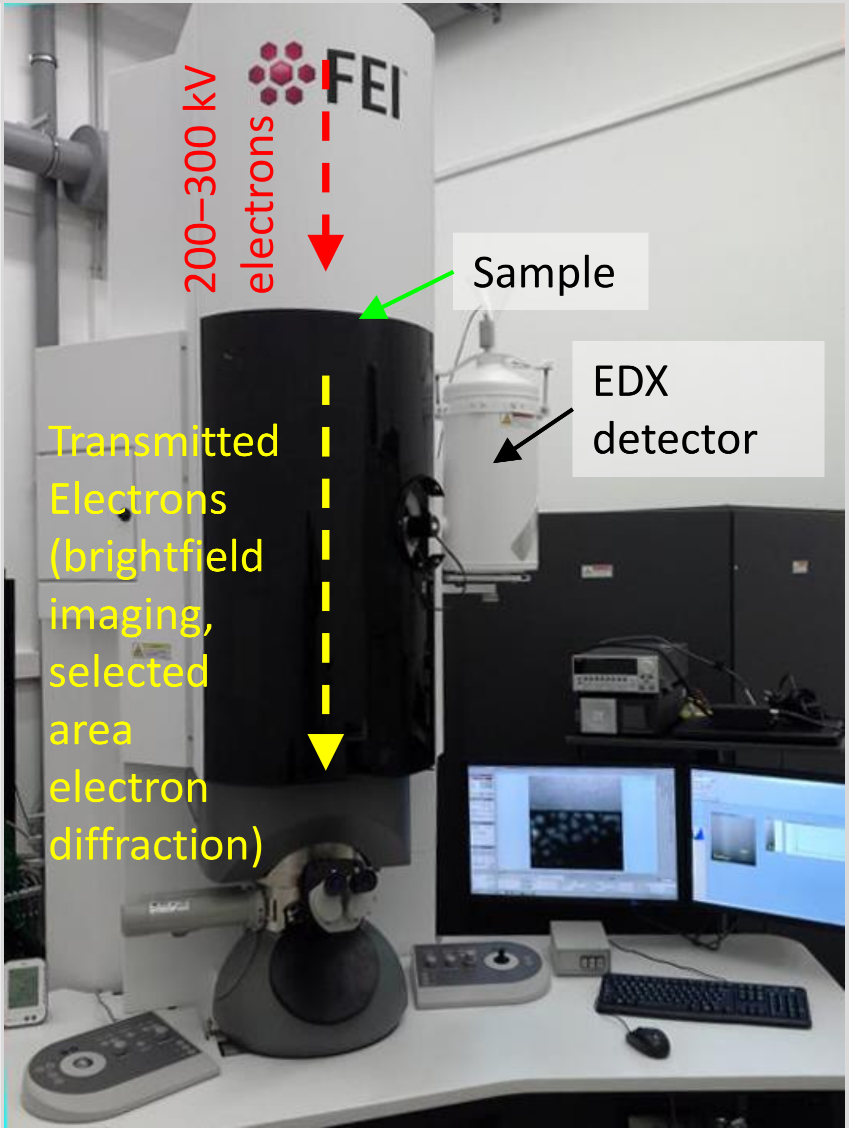


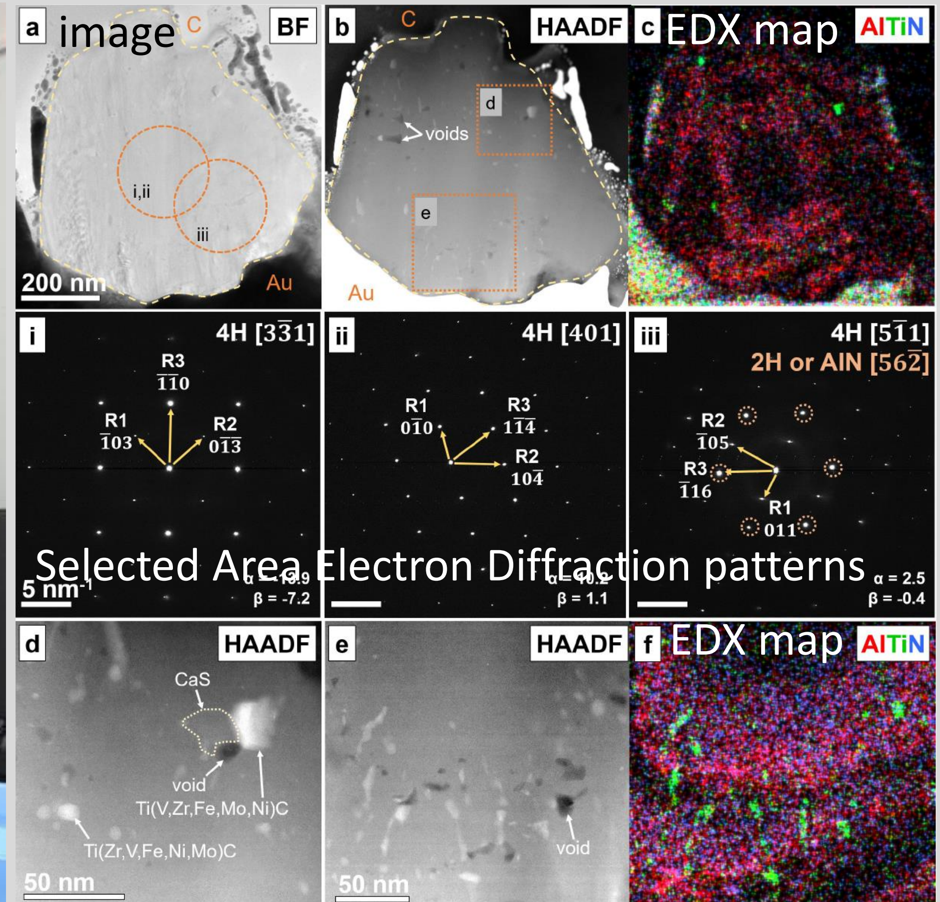
Auger element maps of presolar silicate grain (circled) from the Acfer 094 carbonaceous chondrite

Structural analysis

- TEM

FEI Themis TEM at the University of Münster
Image credit: WWU





Mainstream SiC grain *(Singerling et al., 2021)*

Stellar evolution and nucleosynthesis

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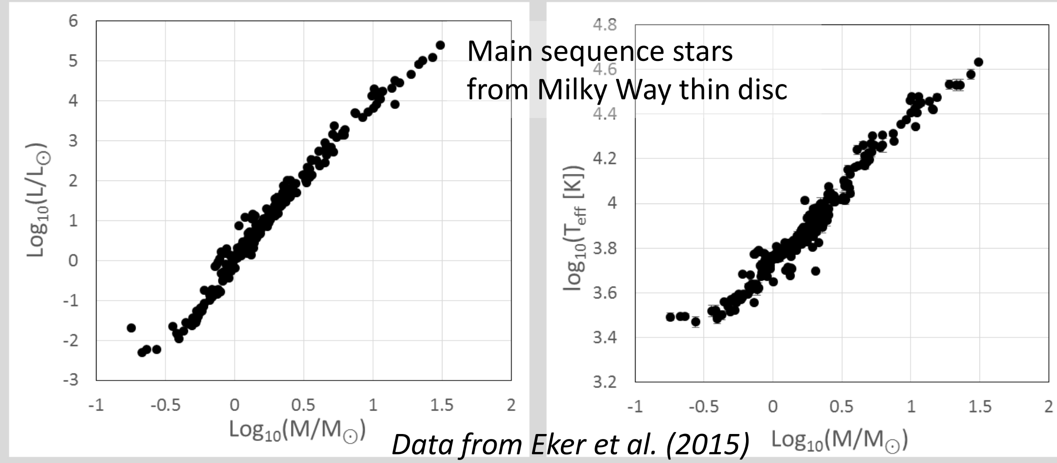
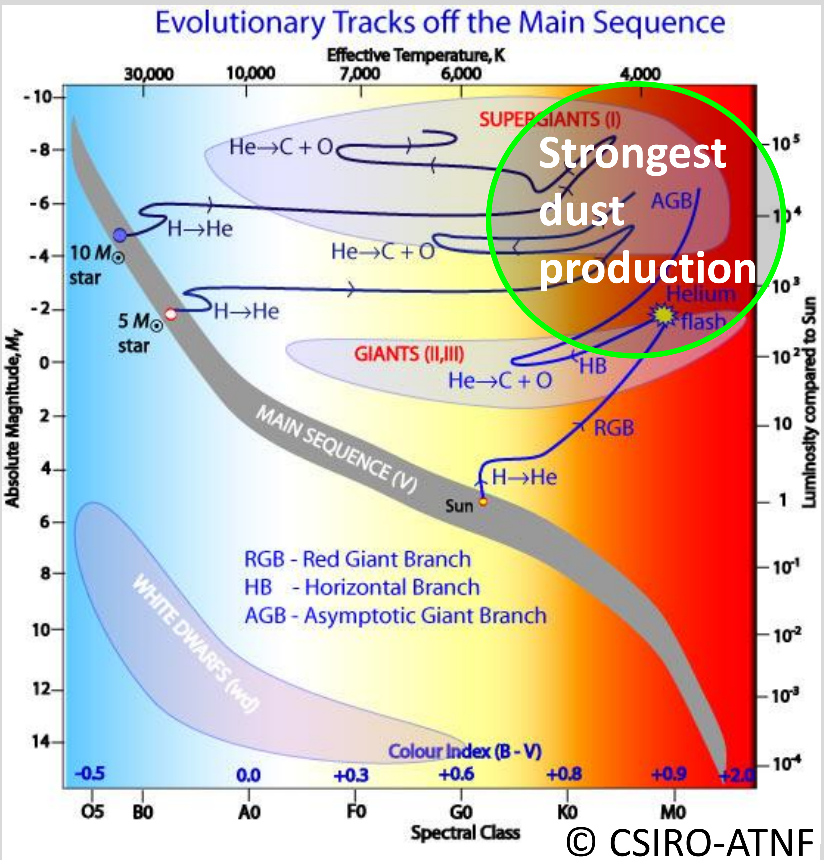
$$E_{nuc} + E_{gr} = E_{int} + E_{rad}$$



Data from Eker et al. (2015)



- Stellar evolution and nucleosynthesis depend primarily on stellar mass and metallicity (other factors: mass loss, presence of companion)
- More massive stars on main sequence are more luminous, hotter, and they ’age’ faster
- Nucleosynthesis occurs in stellar interiors, nucleosynthesis products are brought to stellar surface (source of matter that condenses into dust) by convection

Stellar evolution and nucleosynthesis

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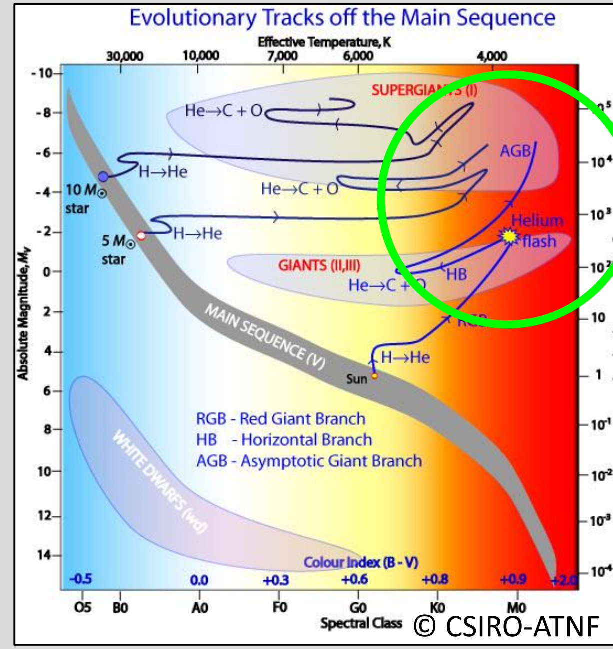
Low- and intermediate mass stars ($M_{Init} < 8–10 \times M_\odot$)

- Main sequence: core H burning (p-p chain, producing ^{4}He, at higher masses the CNO cycle, producing ^{13}C, ^{14}N, and ^{17}O)
- RGB: shell H burning (CNO cycle, NeNa cycle; main products: ^{4}He, ^{13}C, ^{14}N, ^{17}O, ^{26}Al)
- AGB: shell H burning (CNO, NeNa, MgAl cycles) and He burning (α-captures, *s*-process; main products: ^{4}He, ^{12}C, ^{16}O, ^{22}Ne, n-rich isotopes, isotopes around N = 50 and 82 abundance peaks); C/O of star's envelope increases, changing the minerals condensing in the stellar winds



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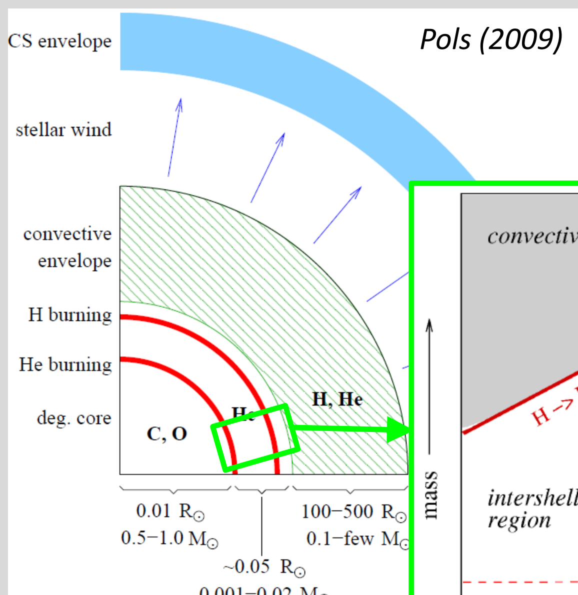
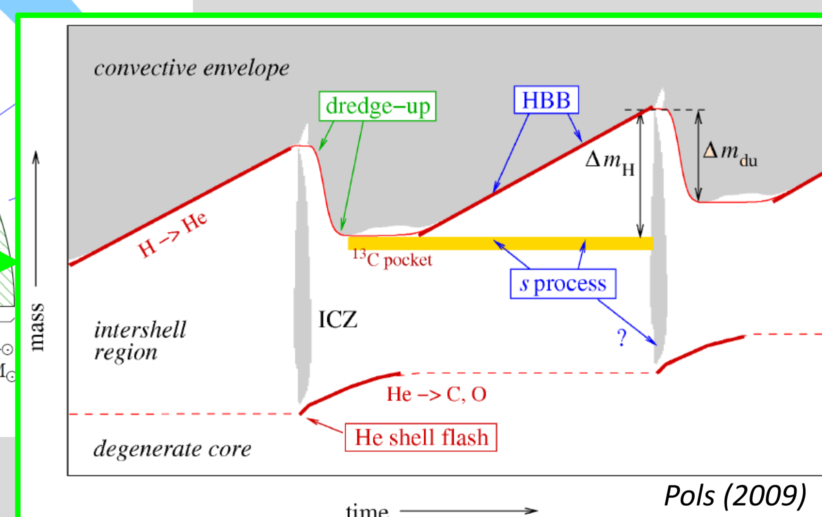


Pols (2009)



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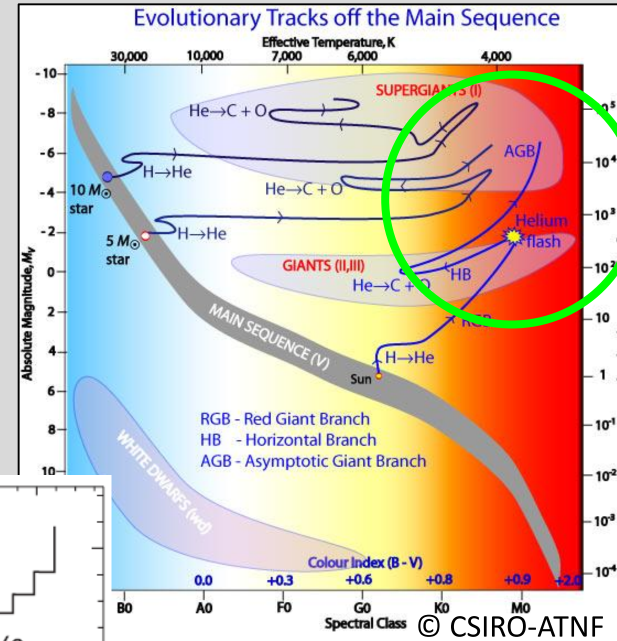

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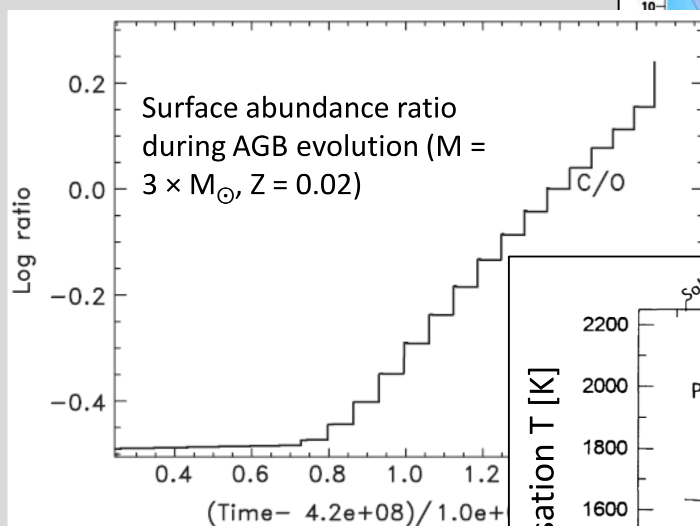
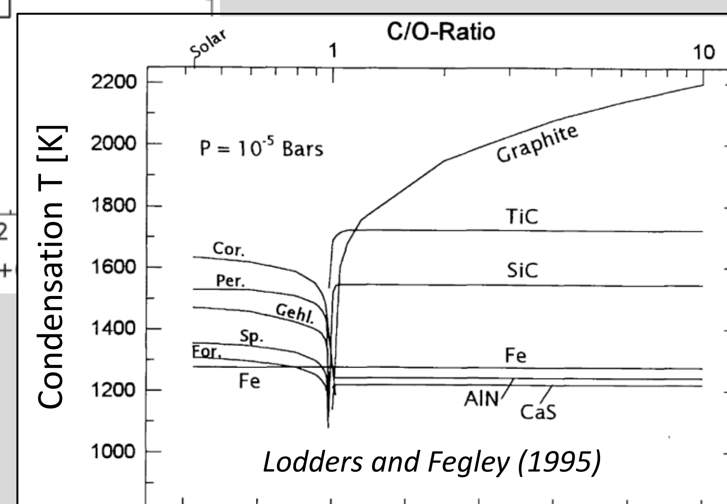


Karakas and Lattanzio (2007)



Lodders and Fegley (1995)

Stellar evolution and nucleosynthesis

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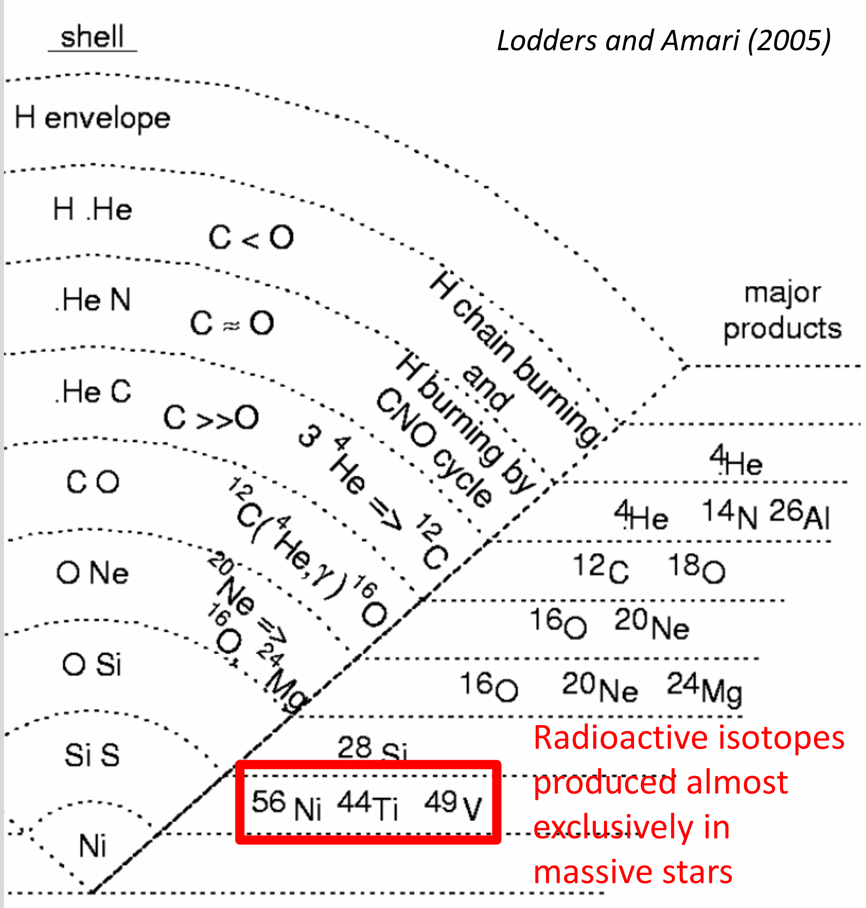
Massive stars ($M_{Init} > 8–10 \times M_{\odot}$)

- More nuclear burning stages, than in low and intermediate mass stars, because core can heat up sufficiently enough to ignite fusion reactions of successively heavier elements (i.e., C and heavier)
- After core collapse, a large fraction of the matter overlying the core is ejected and partially and temporarily compressed/heated
- Hydrostatic and explosive burning
- Proton-, α- and n-captures, similar to what happens in low and intermediate mass stars, but at higher T and density
- Rapid n-capture = *r*-process, during explosion; main products are very n-rich isotopes
- *p*-process



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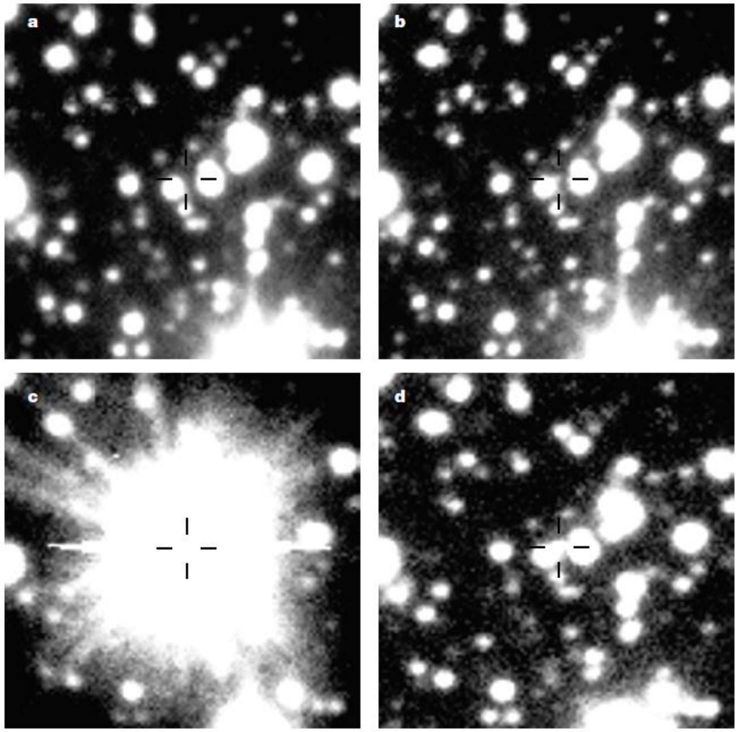
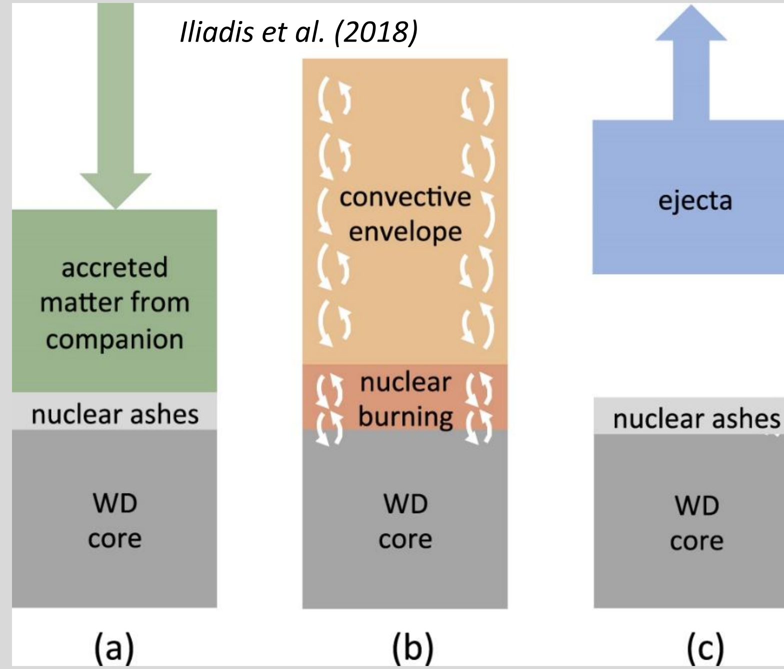


V1213 Cen *Mróz et al. (2016)*



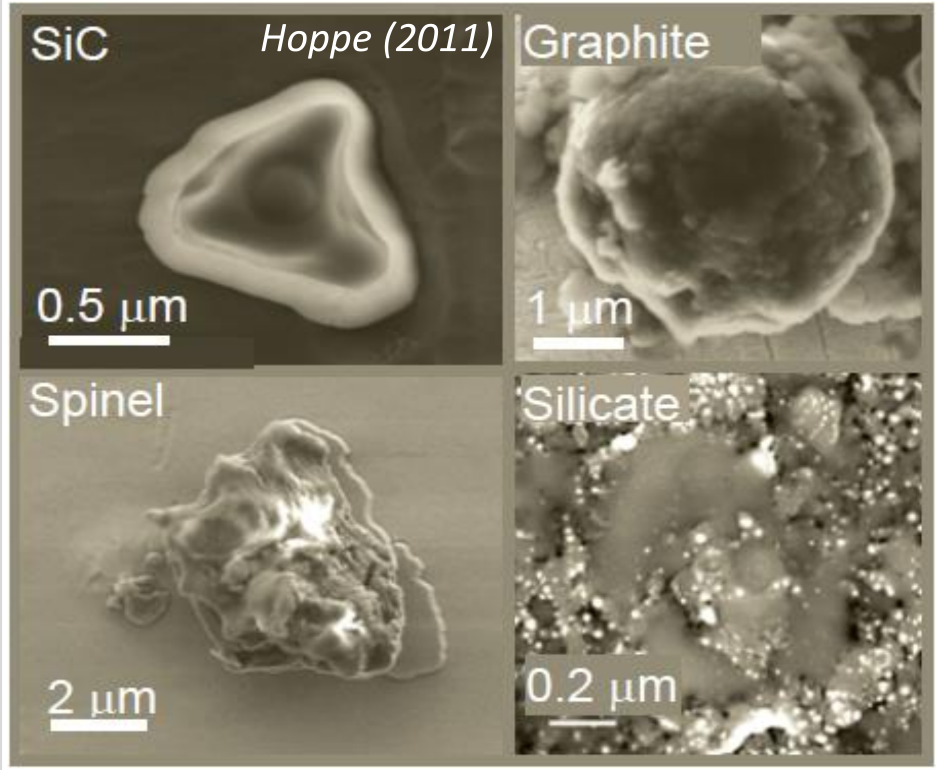
Novae

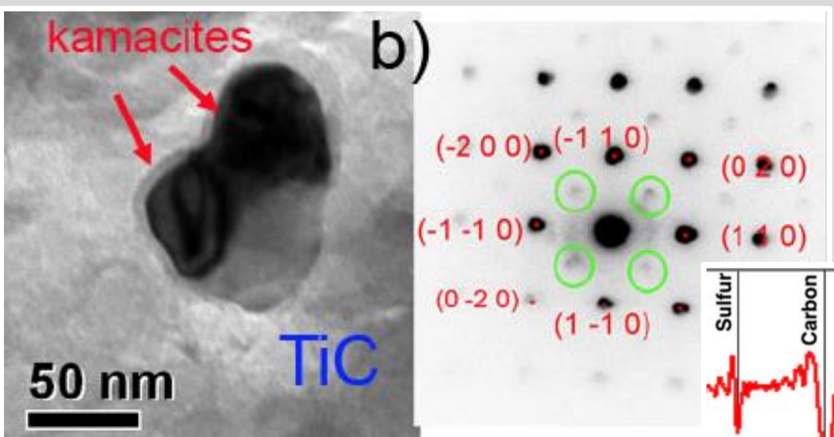
- Thermonuclear runaway on a CO or a ONe white dwarf due to accumulation of H-rich matter from nearby companion (binary system)

- Explosive H burning (hot CNO cycle; main products: ^{13}C, ^{15}N, ^{17}O, ^{22}Ne, ^{26}Al)
- Heavy element isotope abundances unaffected

Presolar grain types

- O-rich grains: **silicates** (olivine, enstatite, non-stoichiometric compounds), **spinel**, **corundum** (and amorphous Al_2O_3), hibonite, chromite, FeO, MgO, SiO_2
- C-rich grains: **SiC**, **graphite**, TiC (and other refractory carbides), diamond
- Other: Si_3N_4, kamacite, Fe-Ni silicides, oldhamite, iron sulphide (troilite?)



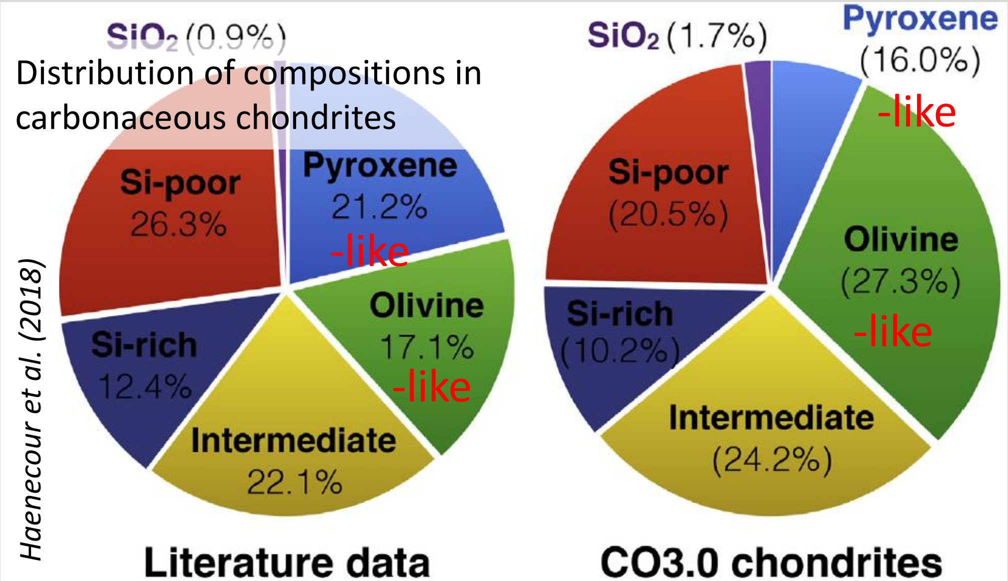


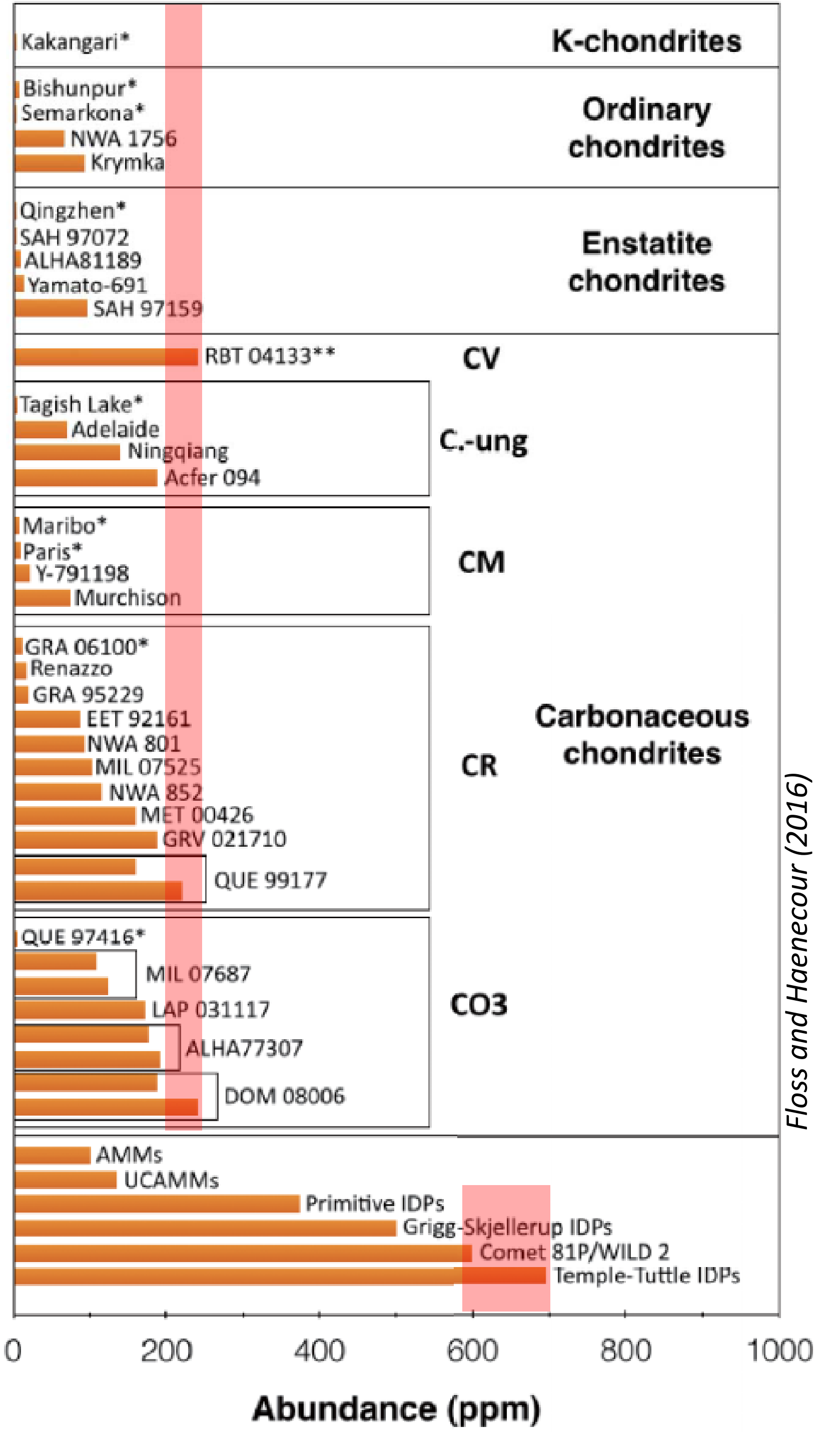
TiC and kamacite inclusions in graphite *(Croat et al., 2011)*

Graphite with iron sulphide inclusion

Presolar silicates

- In situ detection (chemical grain separation impossible)
- Abundance maximum at 200–250 ppm (by volume) in primitive meteorites and 600–700 ppm in IDPs
- Longest dimension usually 200–300 nm
- Vast majority is ferromagnesian silicates with olivine-like, enstatite-like and non-stoichiometric compositions
- Al-rich silicates, Ca-Mg-rich silicates rare





Presolar silicates

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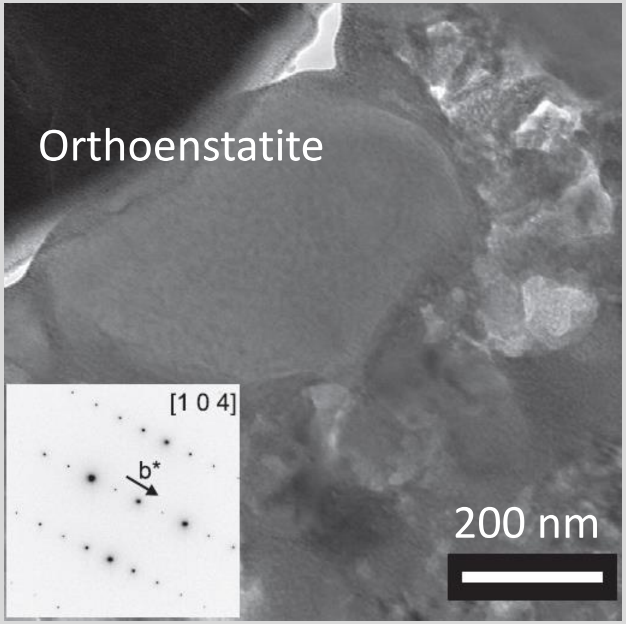
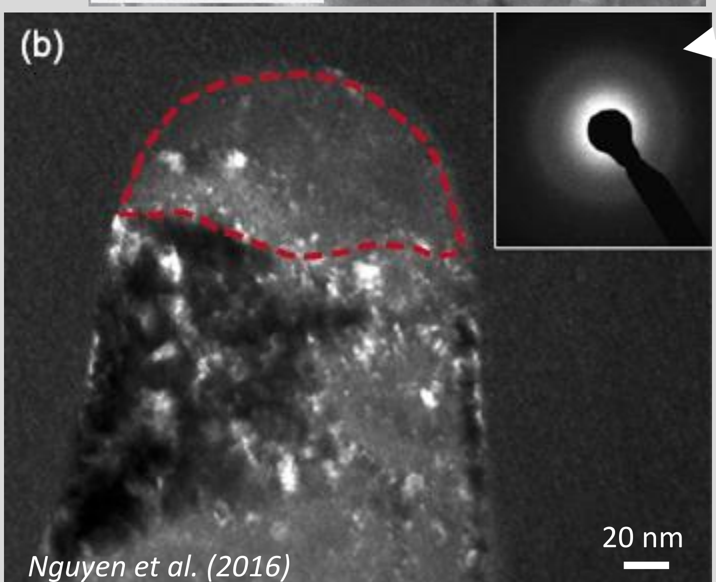
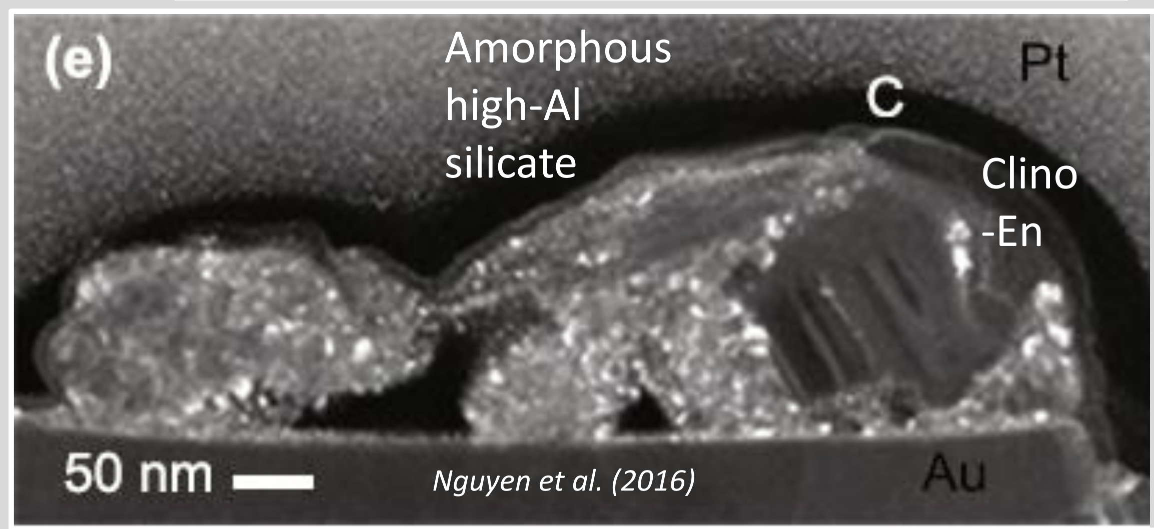


Vollmer et al. (2013)

- Glass (also for grains that have stoichiometric olivine or enstatite composition), single crystals of olivine and enstatite as well as polycrystalline aggregates
- Glass grains are most abundant, but sampling may be biased (e.g., grain size matters when grains are chosen for FIB lift-out and structural analysis with TEM)

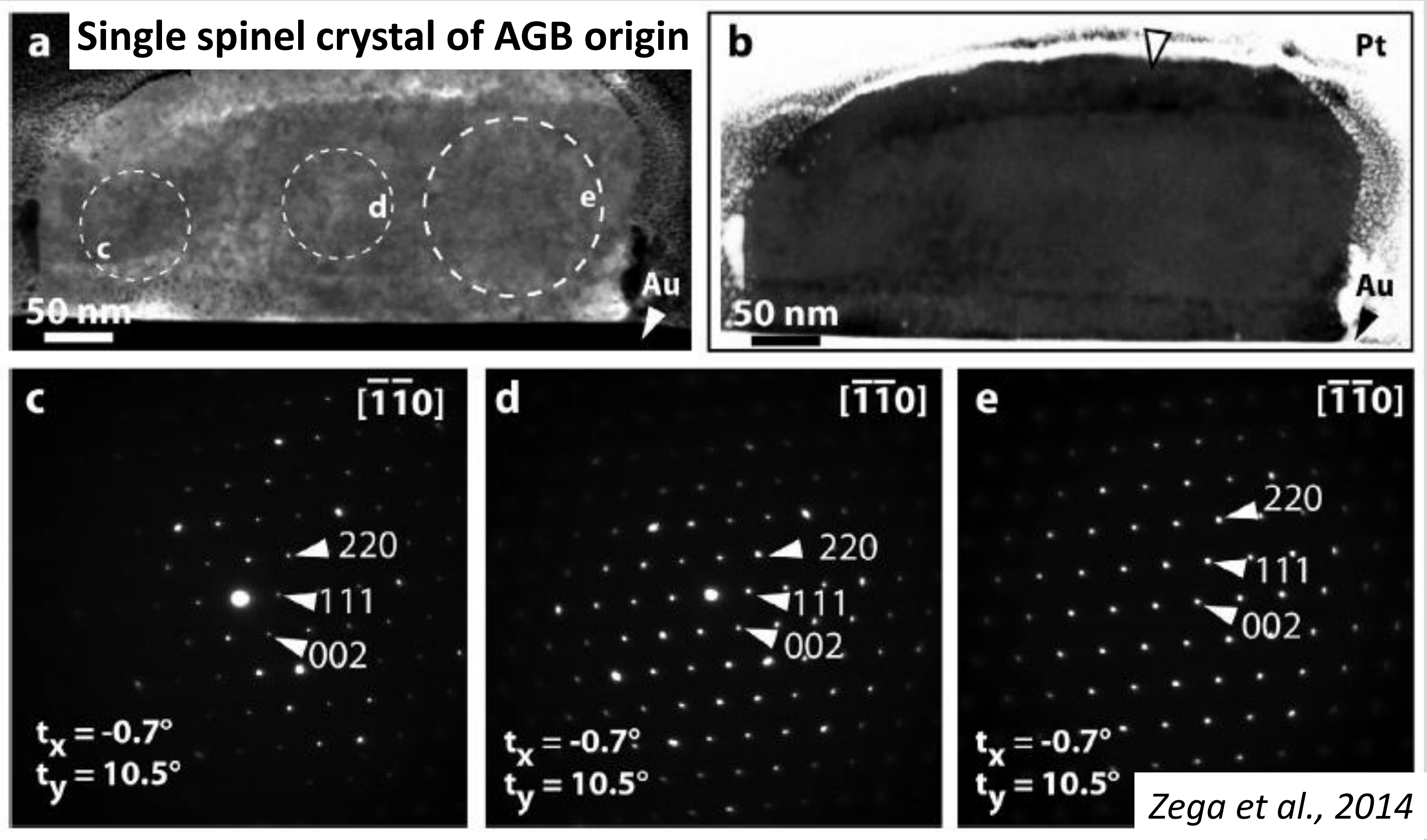


Typical selected area electron diffraction (SAED) pattern of amorphous material



Presolar oxides

- Can be separated from meteorite matrices (but together with Solar System oxides)
- Abundance about 10–12 ppm in primitive meteorites
- Spinel, hibonite, MgO, FeO, TiO_2, corundum and amorphous Al_2O_3
- Single crystals and crystal aggregates



Zega et al., 2014

Presolar silicates and oxides: isotopy

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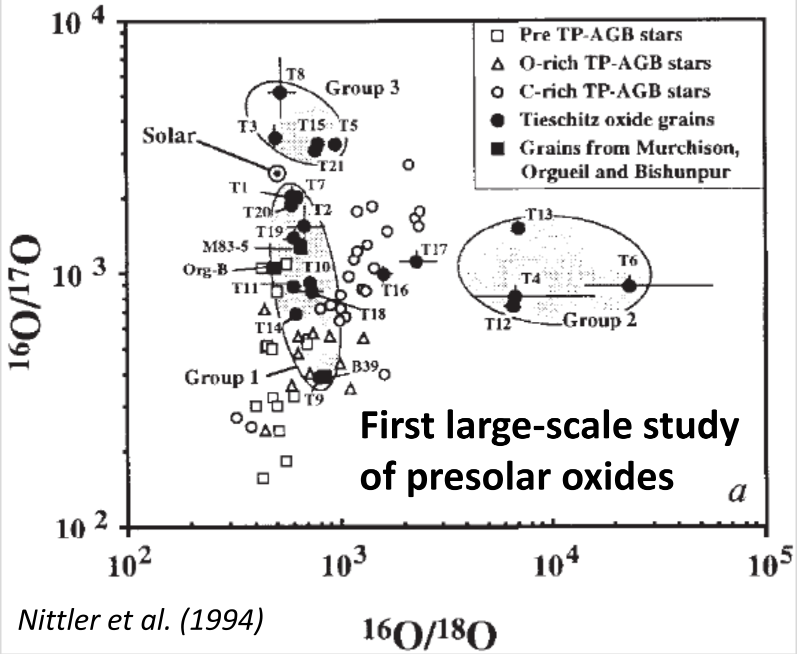
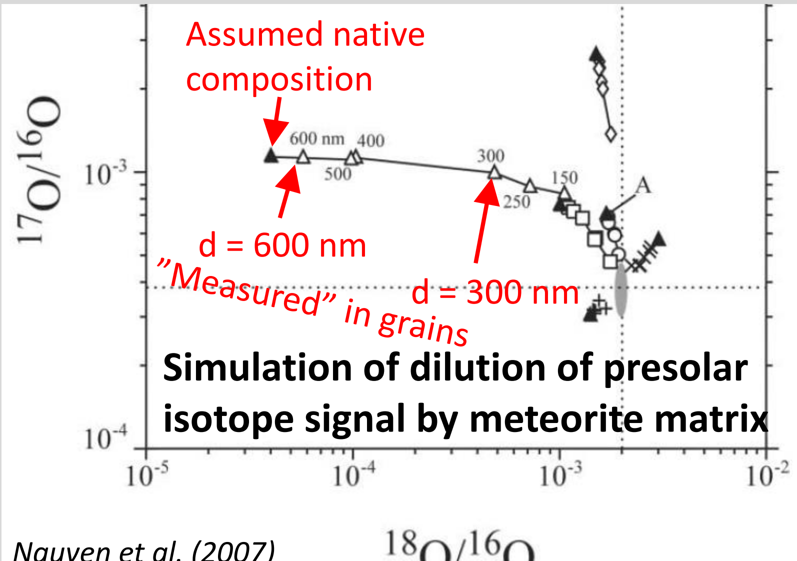
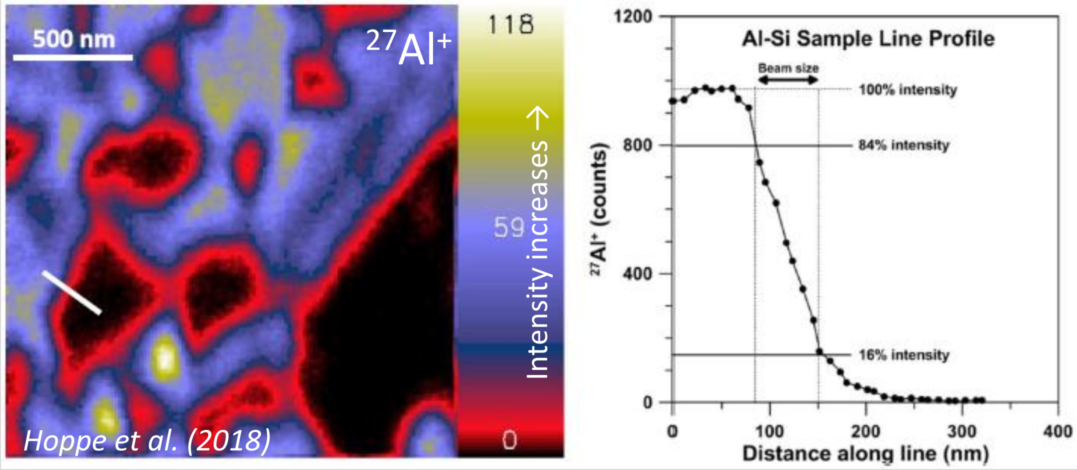


Nittler et al. (1994)



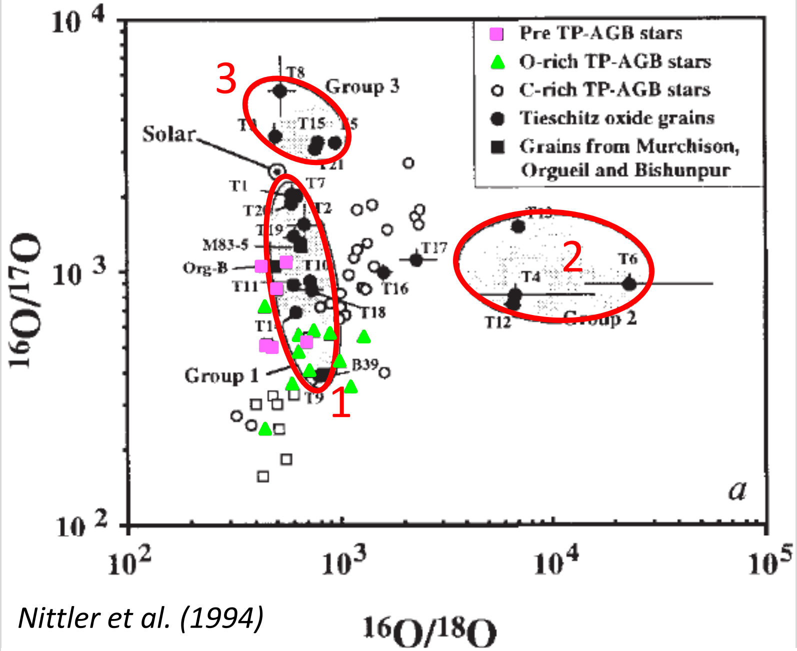
Nguyen et al. (2007)

- Plenty of data: <u>O</u>, Mg, Si (silicates)
- Limited/sporadic data: Ca, Ti, Cr, Fe, Ni
- Consequences of the fact that oxides can be chemically separated:
  - Oxide data are less affected by contamination than silicate data
  - Oxides have been studied for longer than silicates
- Isotope measurements of elements with low electronegativity benefited greatly from improvement of O primary ion source of NanoSIMS a few years ago (so far, silicate isotope record is most affected)

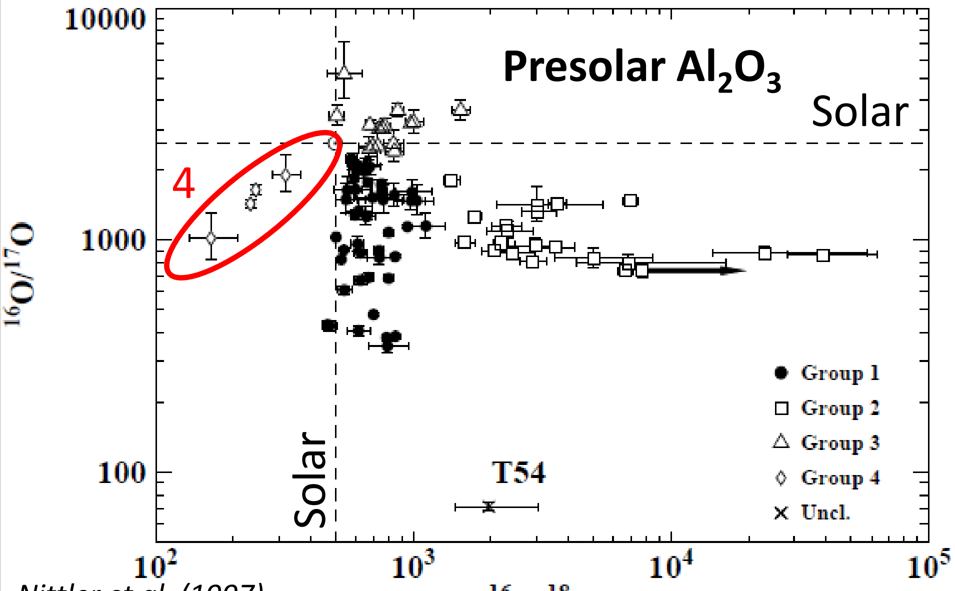


Hoppe et al. (2018)

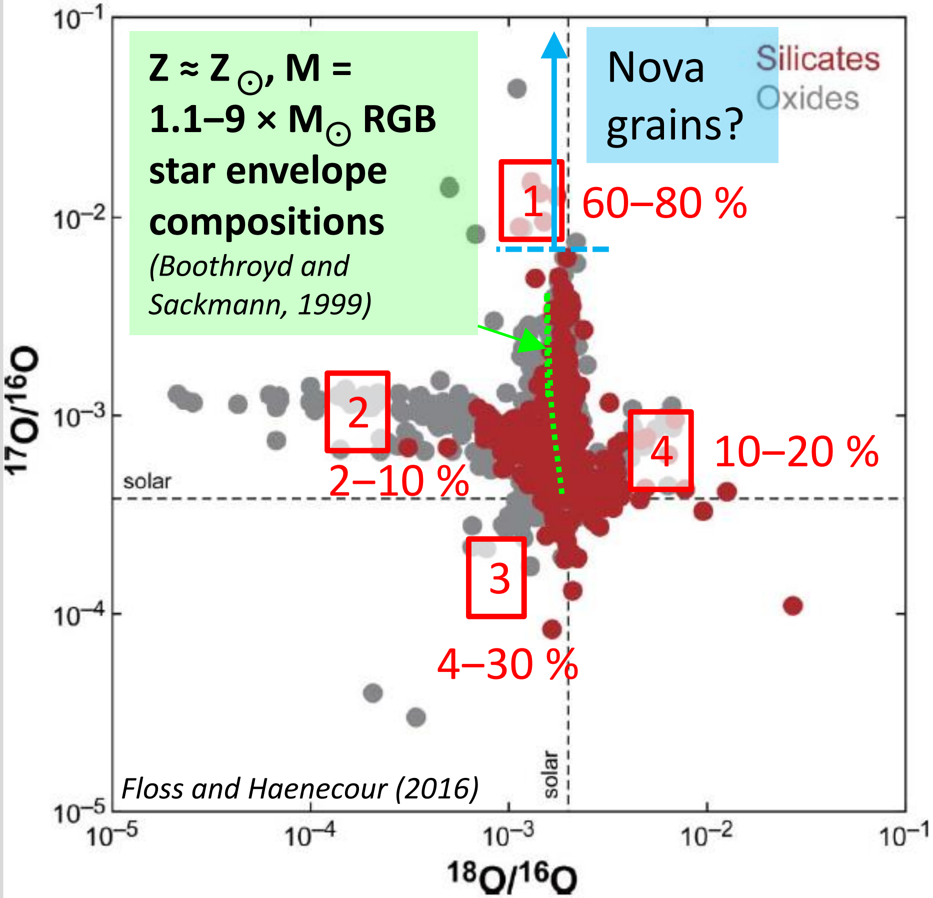
Presolar silicates and oxides: isotopy



Nittler et al. (1994)

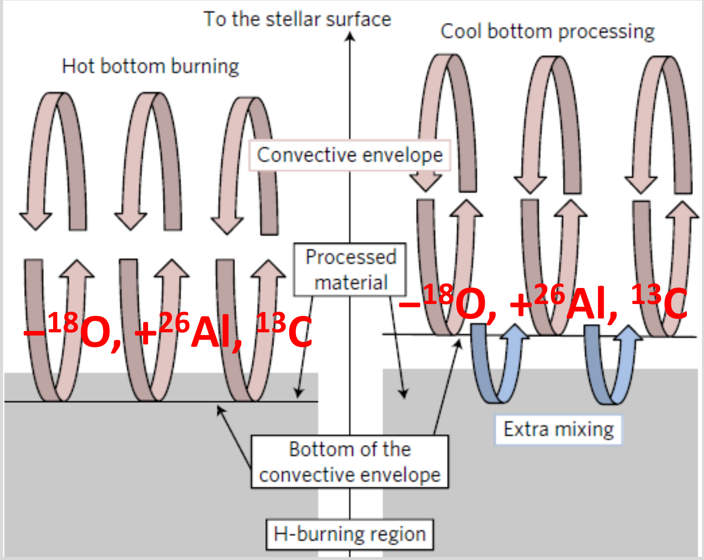


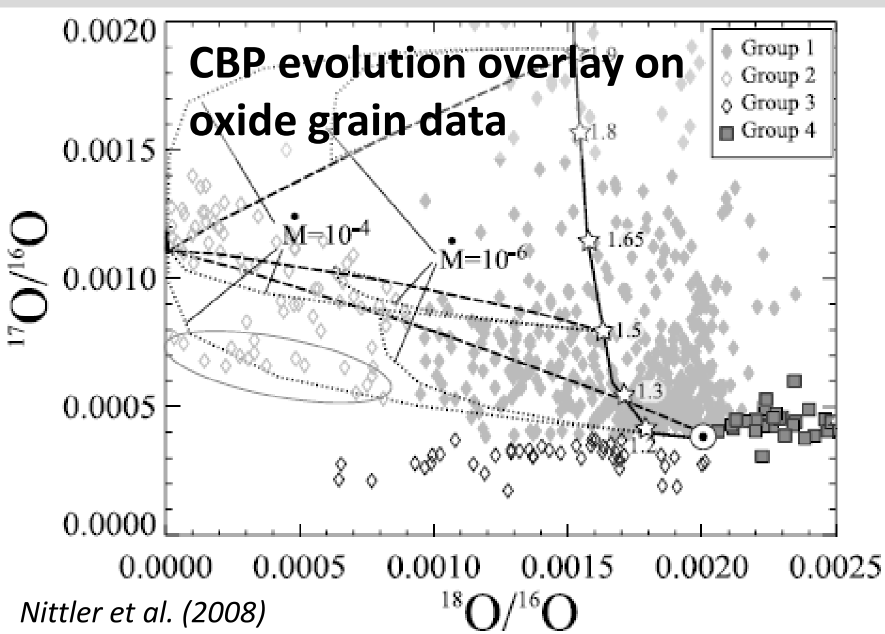
Nittler et al. (1997)

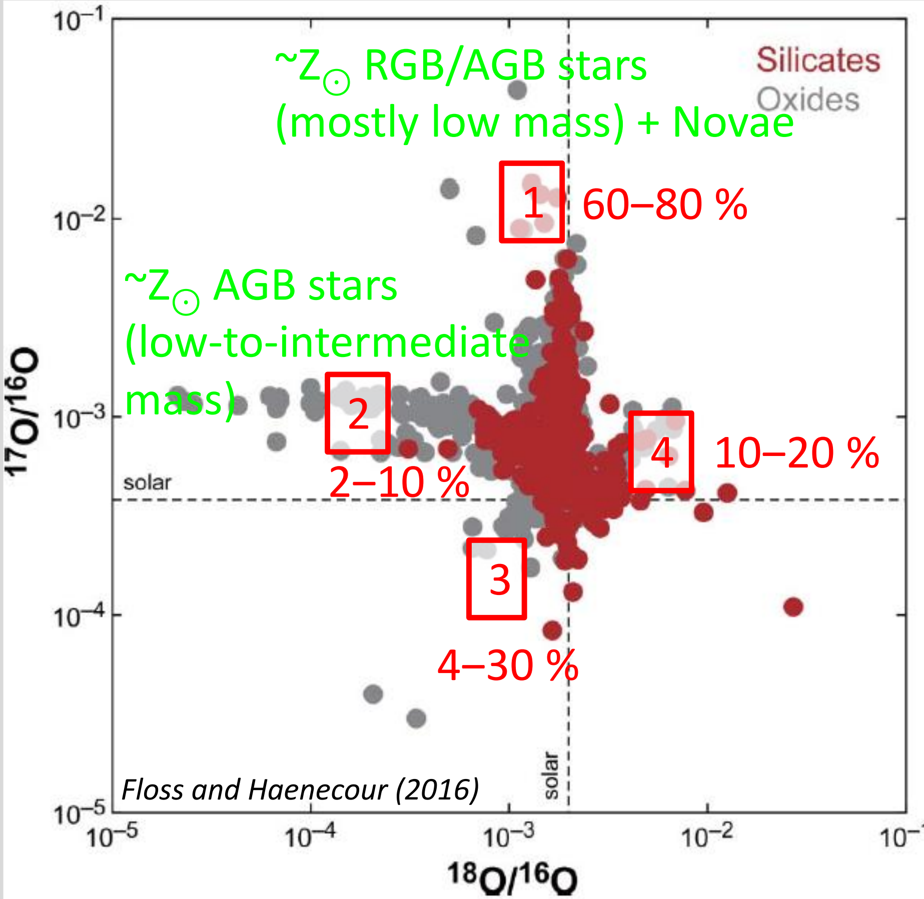


- Four distinct groups based on oxygen isotopes
- Most abundant grains' oxygen isotope composition consistent with RGB or low-mass AGB star origin

Presolar silicates and oxides: isotopy

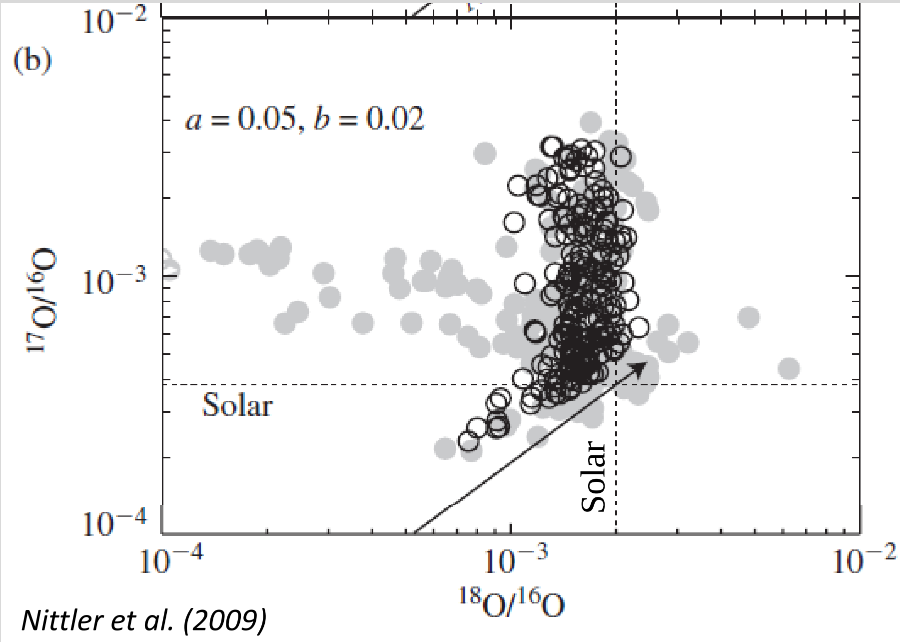


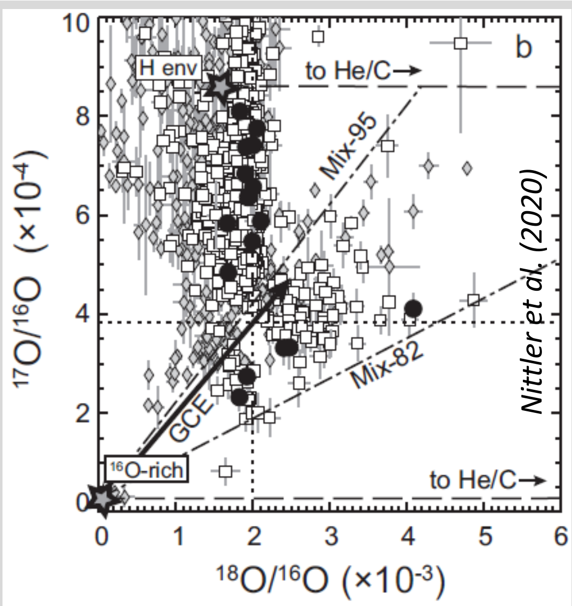


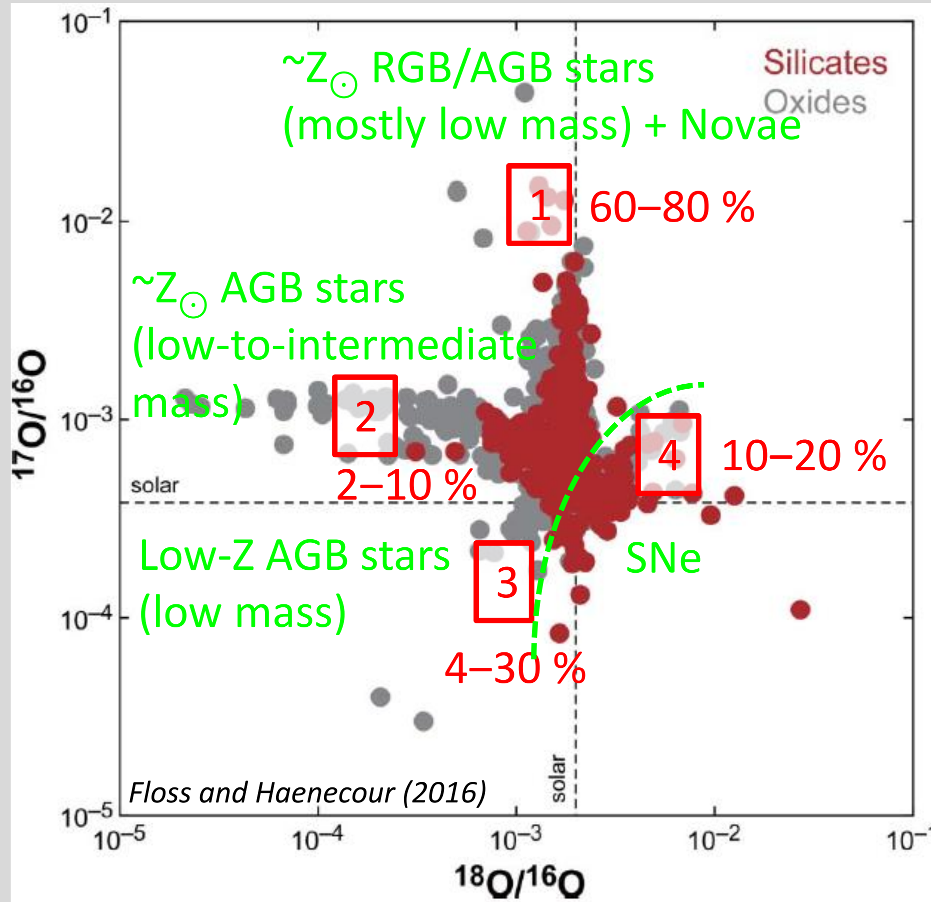


- H burning at high T (> 40 MK) depletes ^{18}O, but requires extra mixing (low mass stars) or hot stellar envelope (intermediate mass stars)

Presolar silicates and oxides: isotopy







- Group 3 grains with low $^{17}O/^{18}O$ originated in low mass stars with sub-solar Z
- ^{18}O-enrichment in some Group 3 and all Group 4 grains is best explained by nucleosynthesis in SNe

Presolar silicates and oxides: isotopy

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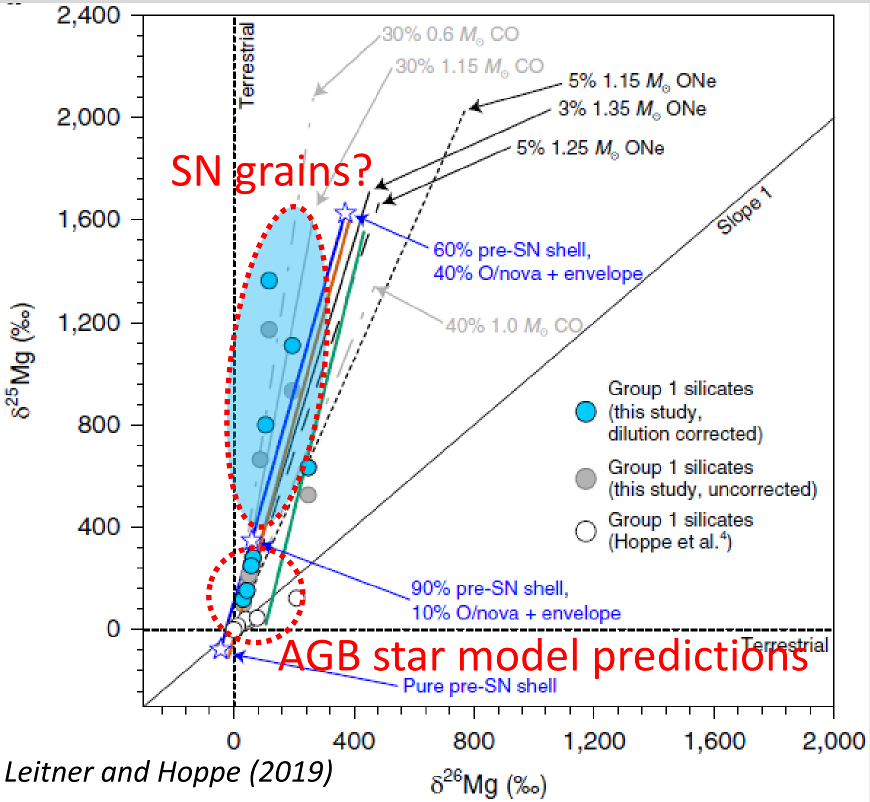
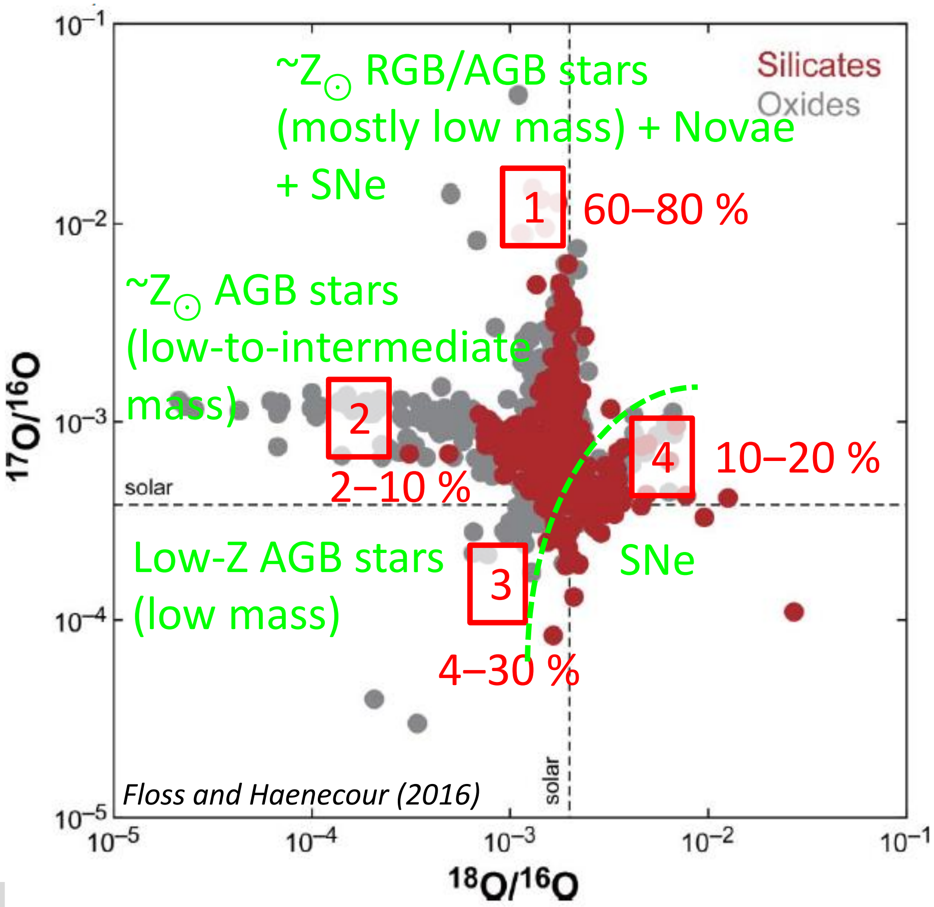
- Mg isotope data reveal more
- 3–12 % of Group 1 silicate grains have large enrichments in ^{25}Mg and small enrichments in ^{26}Mg, which is more consistent with an SN origin (nova origin unlikely for the lack of collateral shifts in O and Si isotope compositions)

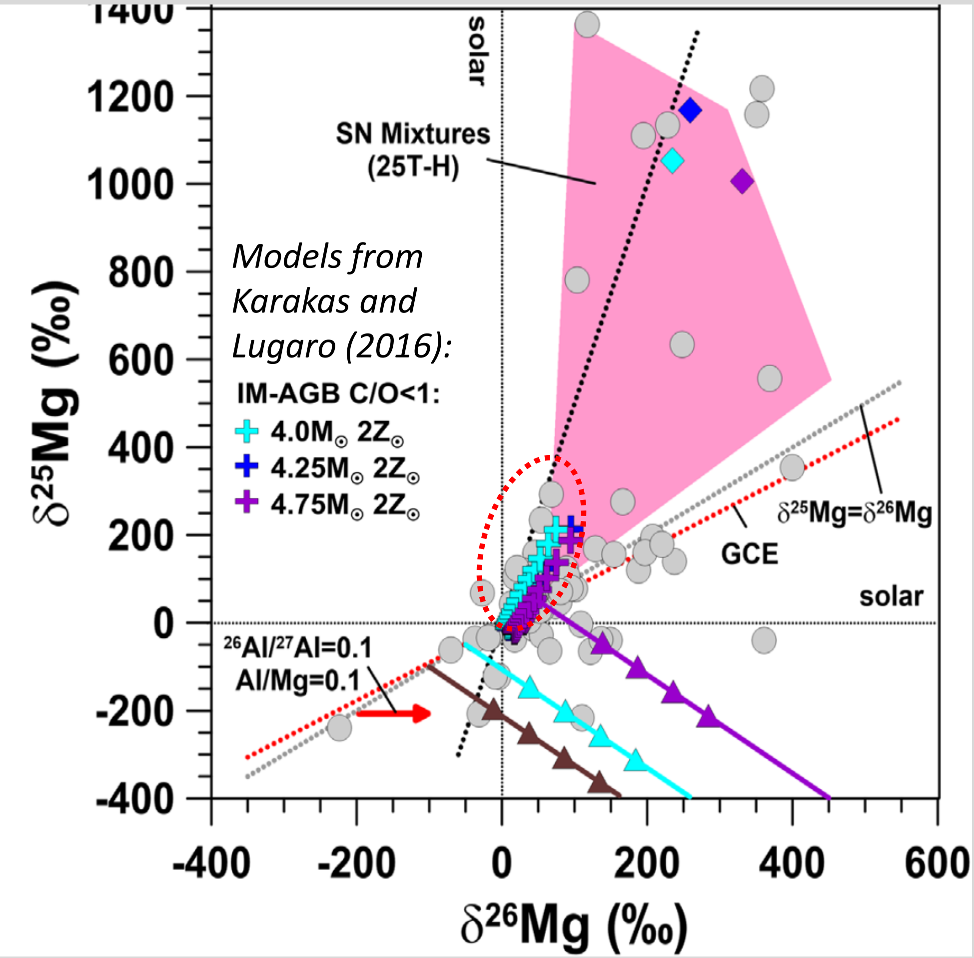


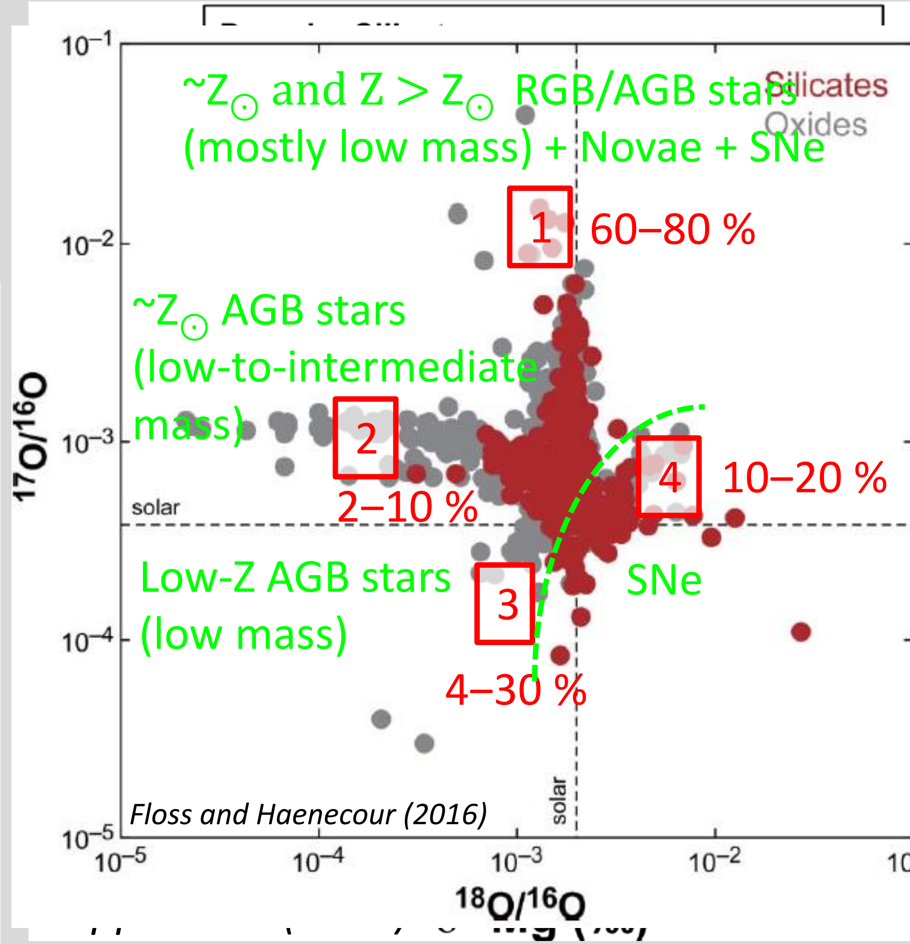


- This 'SN subgroup' within Group 1 grains have so far been not recognised among oxides!

Presolar silicates and oxides: isotopy

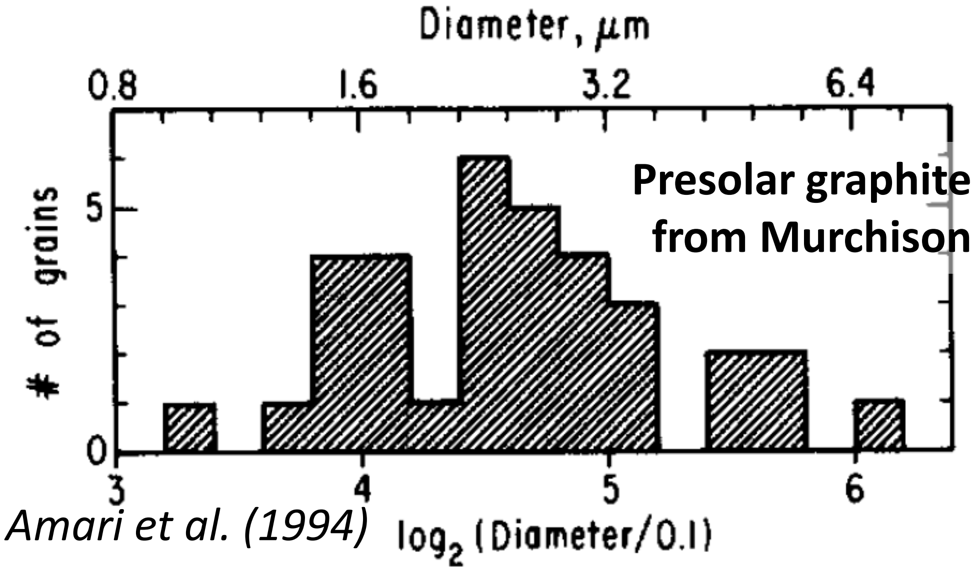
- Mg isotope data reveal more



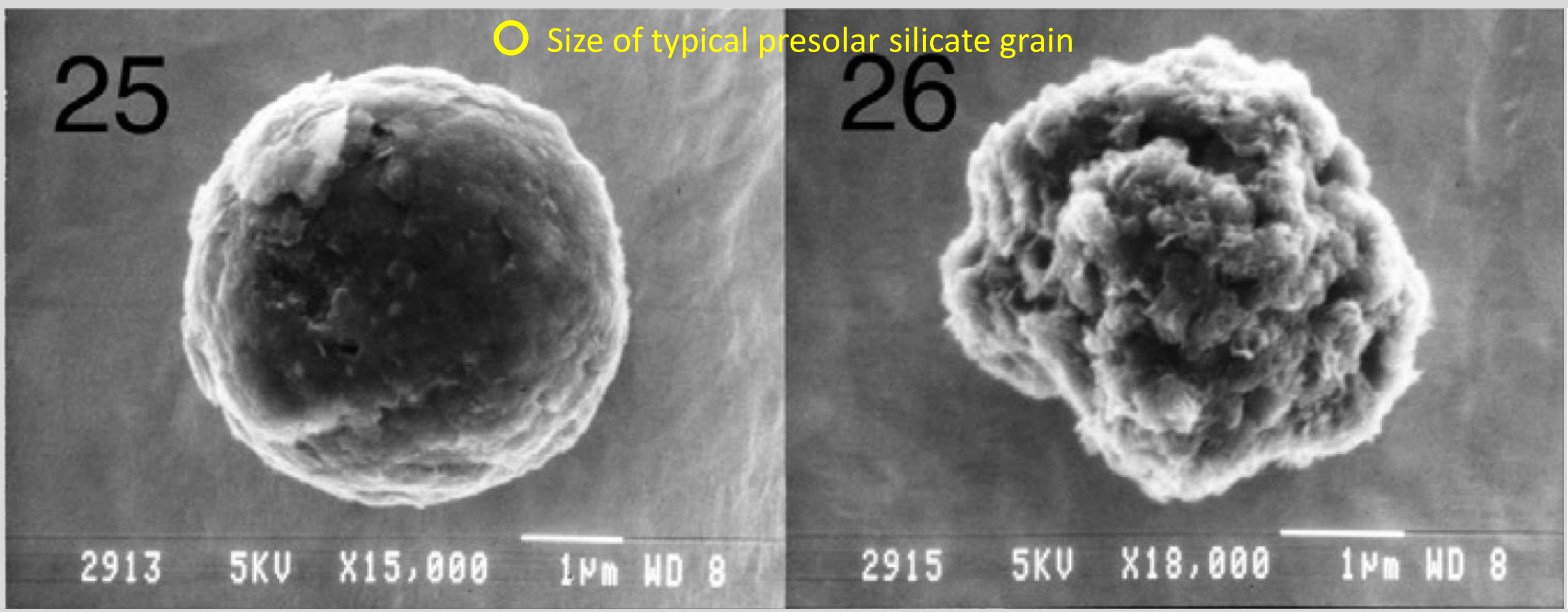


Presolar graphite

- Separation possible, but difficult
- <10 ppm in carbonaceous chondrites
- Up to several µm in diameter
- ’Onions’ and ’cauliflowers’



Amari et al. (1994)



Presolar graphite grains with ’onion’ and ’cauliflower’ morphologies from the Murchison meteorite

Amari et al. (2014)

Presolar graphite

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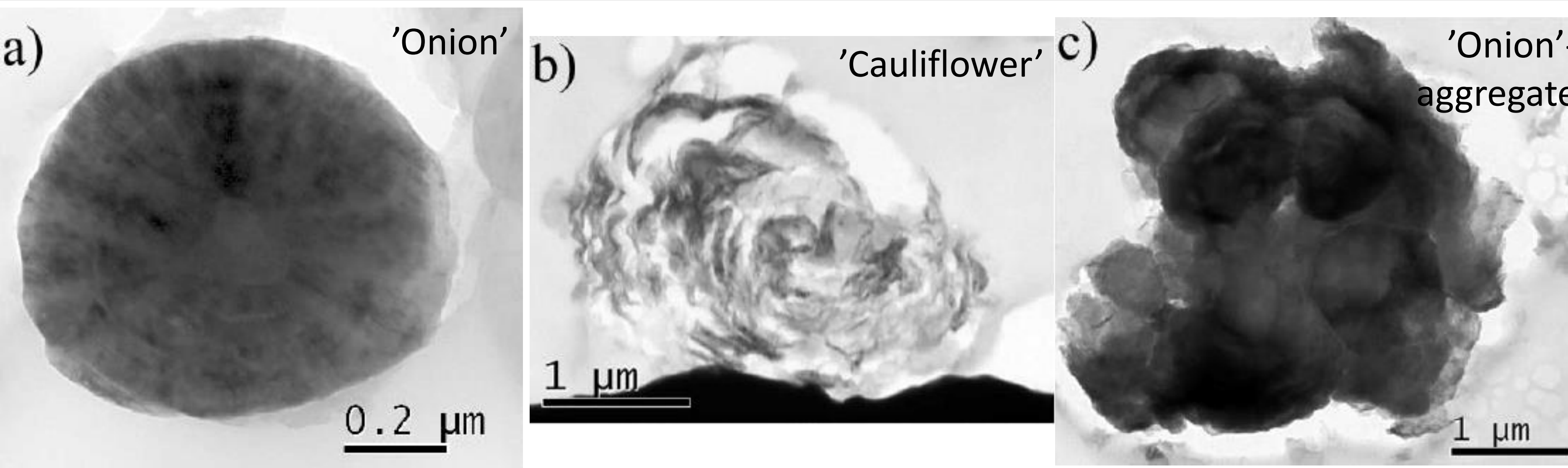
- ’Onion’
  - More abundant among high density (HD) graphite fractions
  - Concentraic layers of well-graphitised carbon
  - Hardly ordered assemblage of nanometre graphene sheets in core

- Cauliflower
  - More abundant in low density graphite (LD) fractions
  - Concentric but contorted/curved layers of graphite with no long range continuity, or
  - Aggregate of ’onions’

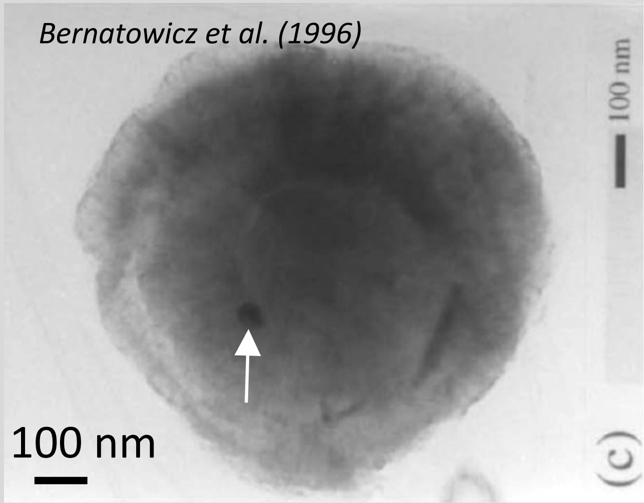


TEM images of slices of ’onion’ and ’cauliflower’ presolar graphite grains from the Murchison meteorite

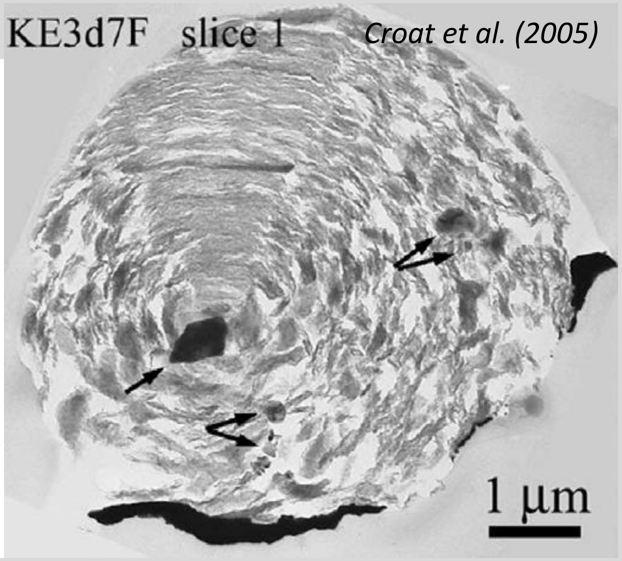
Croat et al. (2005)

Presolar graphite

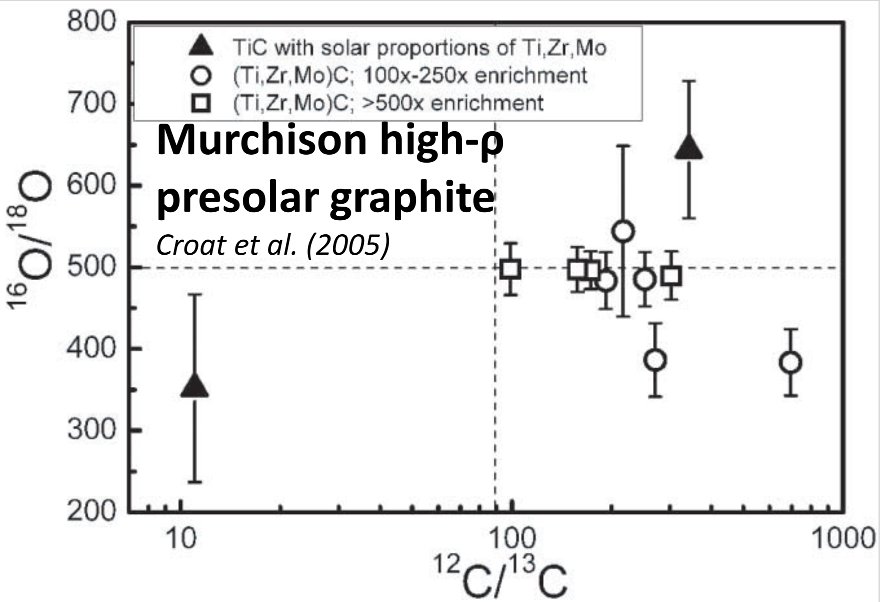
- ’Onion’
  - More abundant among HD graphite fractions
  - Concentraic layers of well-graphitised carbon
  - Hardly ordered assemblage of few-nm graphene sheets or TiC grain in core
  - TiC inclusions enriched in Zr and Mo (refractory elements whose abundance is enhanced by the *s*-process)
- ’Cauliflower’
  - More abundant in LD graphite fractions
  - Concentric but contorted/curved layers of graphite with no long range continuity, or
  - Aggregate of ’onions’
  - TiC inclusions with Zr and Mo below detection limit, but a lot of V

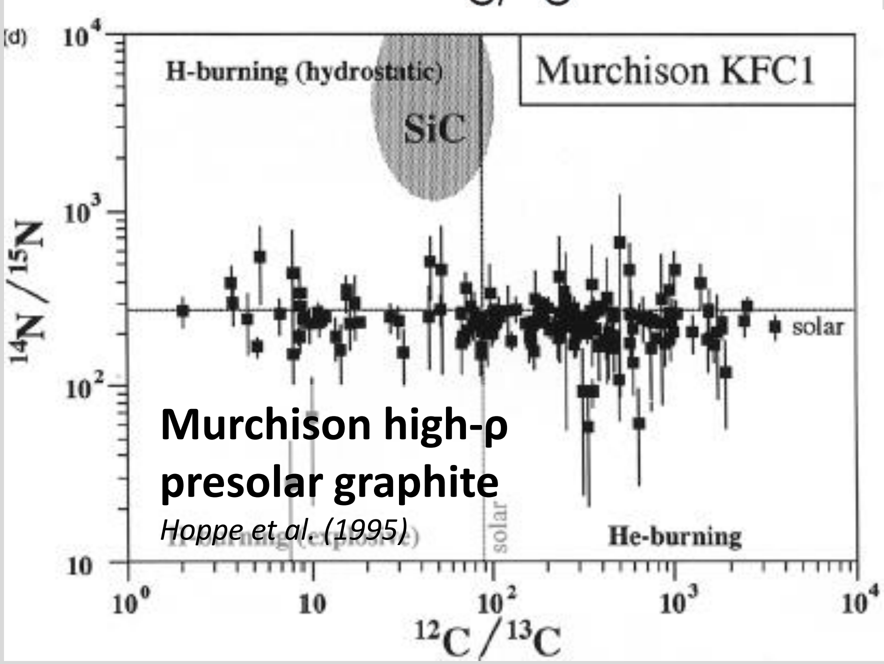


TEM images of presolar graphites from the Murchison meteorite; arrows indicate TiC inclusions



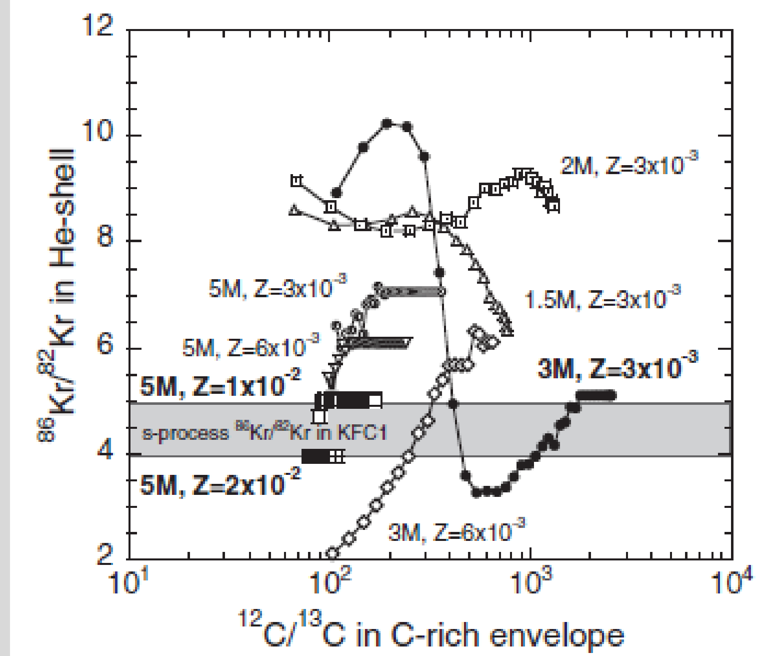
Presolar graphite





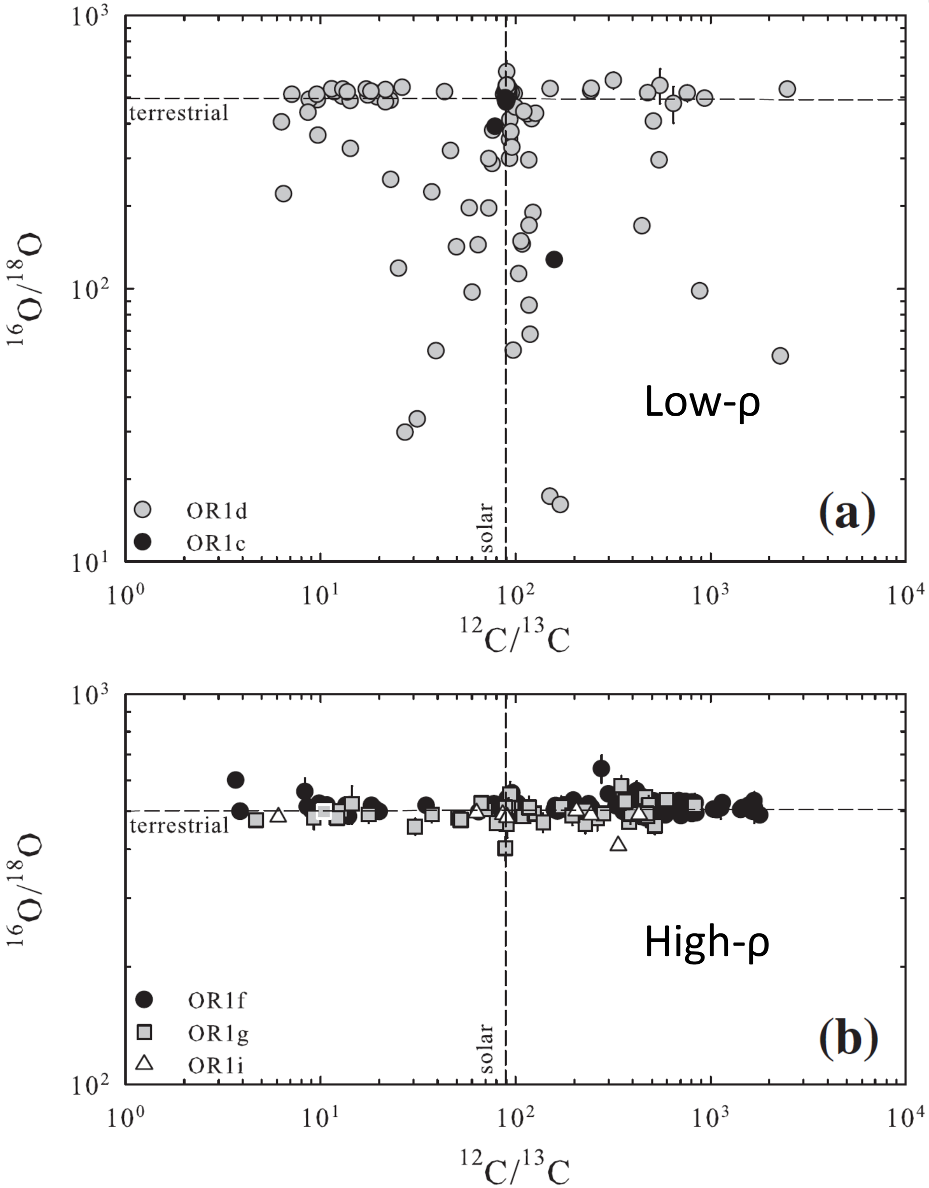
- Graphite grains + Zr- and Mo-rich TiC, several times solar $^{12}C/^{13}C$, and *s*-process dominated noble gas isotope ratios probably originated in the winds of low-Z and low-mass AGB stars
- More abundant in HD graphite fractions

AGB models and high-ρ graphite data *Amari et al. (2014)*

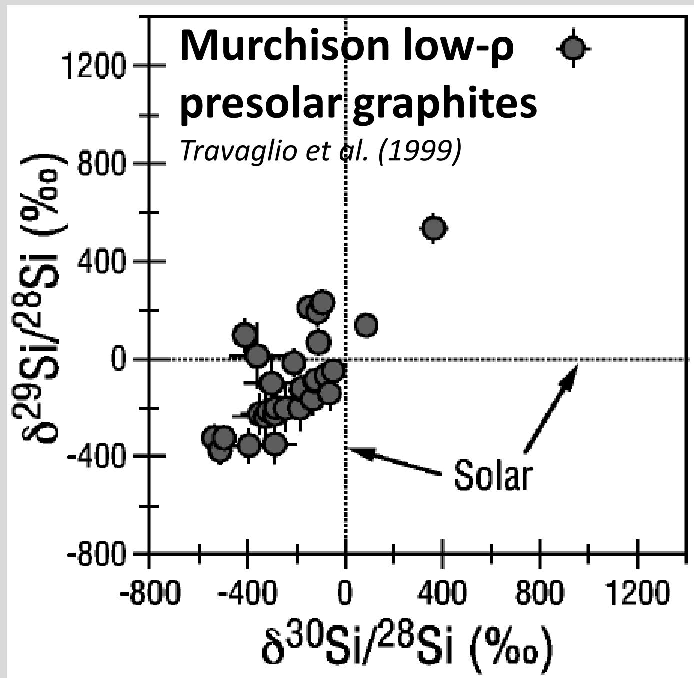


Presolar graphite

Presolar graphite from Orgueil *Jadhav et al. (2013)*



- Graphite grains with ^{28}Si and/or ^{18}O enriched isotope composition probably condensed in SN ejecta
- Graphite grains with evidence for the former presence of ^{44}Ti or large amounts of ^{26}Al condensed in SN ejecta
- Such grains are more common in the LD graphite fractions



Presolar graphite

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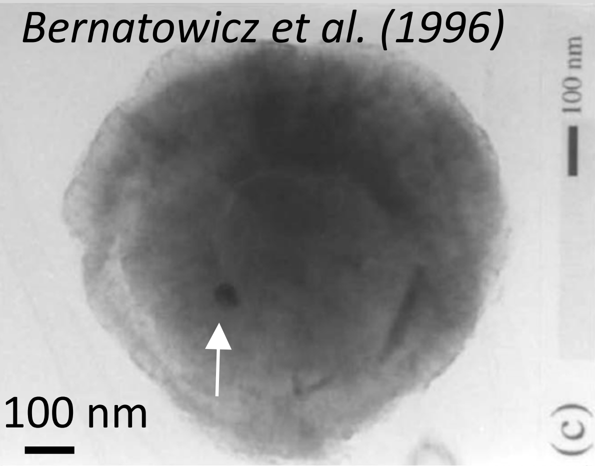
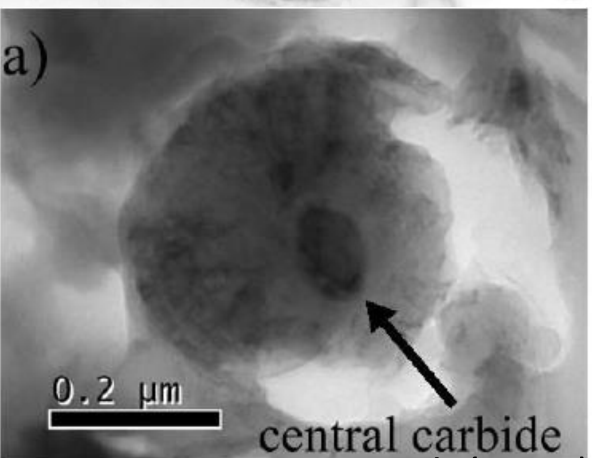
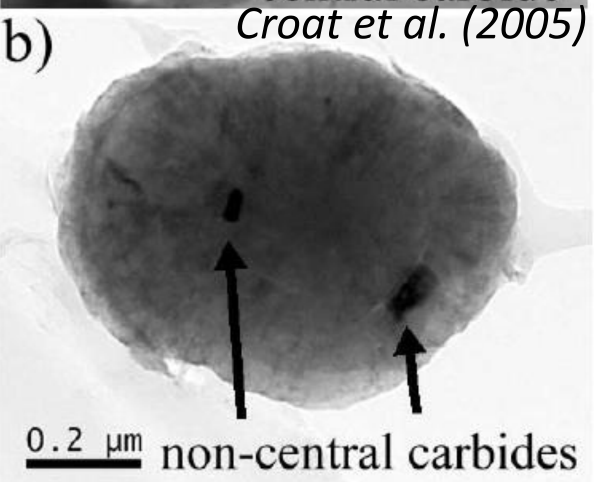
- Graphite grains provide unique insight into grain condensation around evolved stars

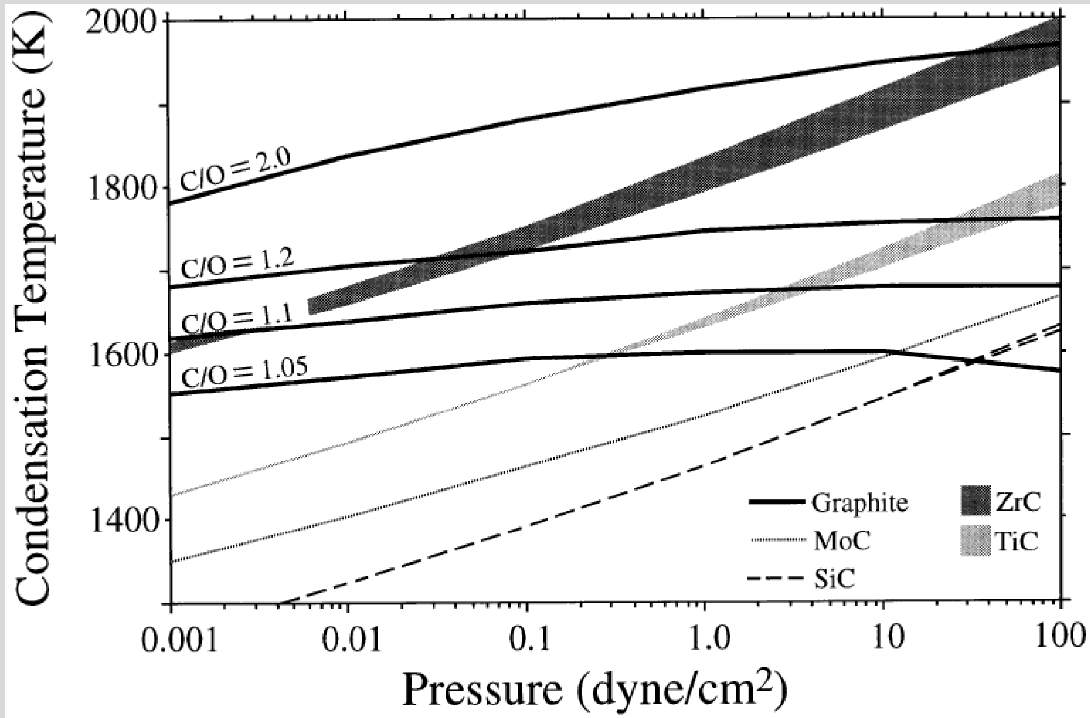
Bernatowicz et al. (1996)





Croat et al. (2005)





Bernatowicz et al. (1996, based on Lodders & Fegley, 1995)

HD graphite grains with refractory carbide inclusions

Presolar SiC

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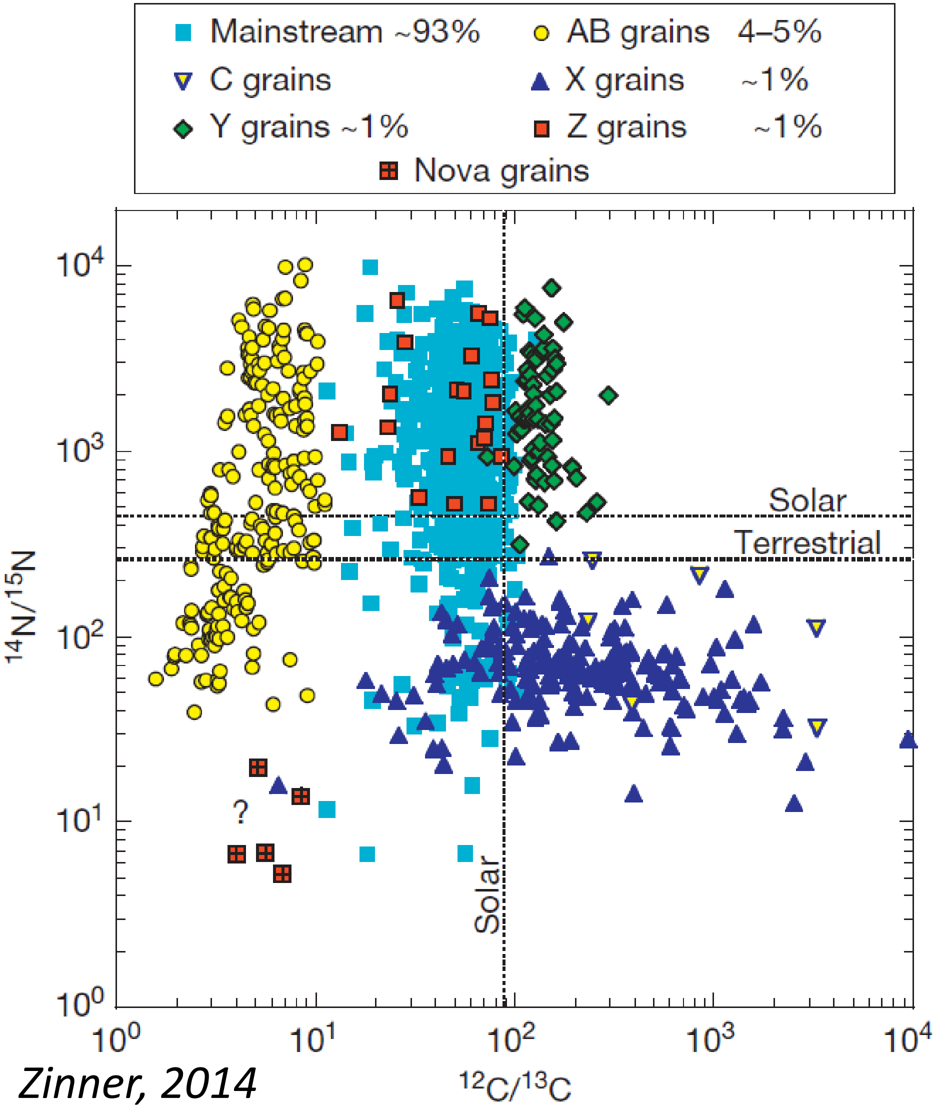
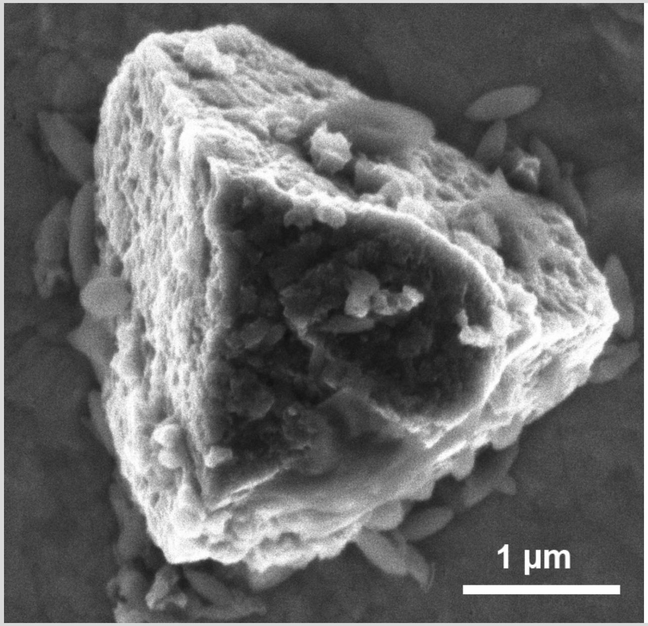


Zinner, 2014



SE image of a giant SiC from the Murchison meteorite

- Best studied presolar grain type
- Isotope data: $\boxed{\text{Si, C, N,}}$ Ne, Mg, S, Ca, Ti, Fe, Ni, Sr, Zr, Mo, Ru, Ba
- Abundance: 30–60 ppm in the matrices of primitive meteorites
- Normally sub-µm size
- Mainstream (MS), AB (1&2), Y, Z, X, and C grains

Presolar SiC

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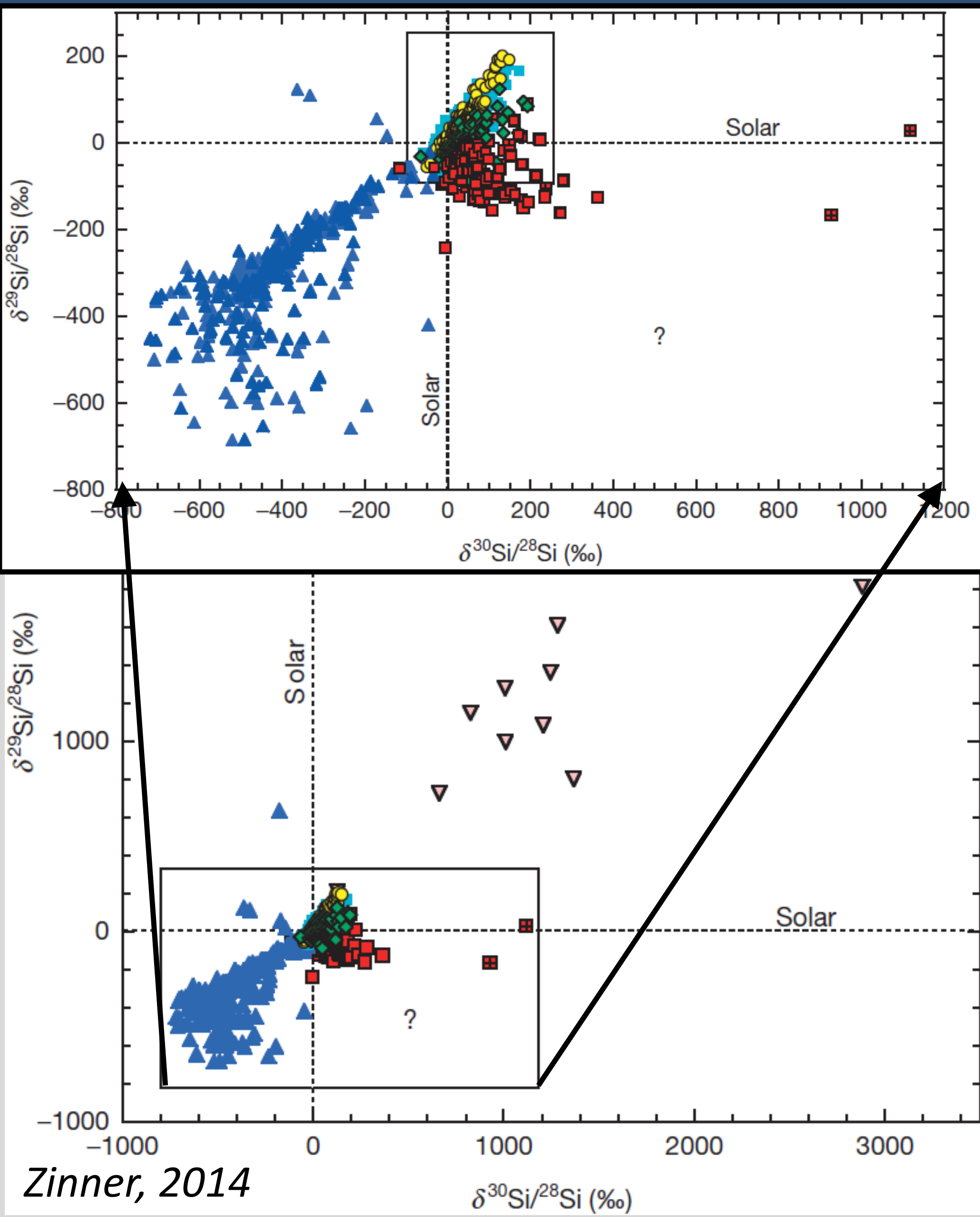
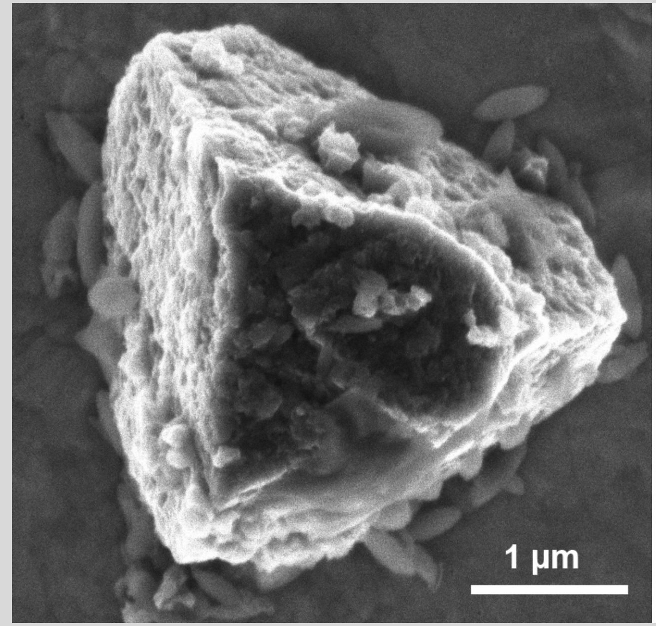


Zinner, 2014



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Presolar SiC

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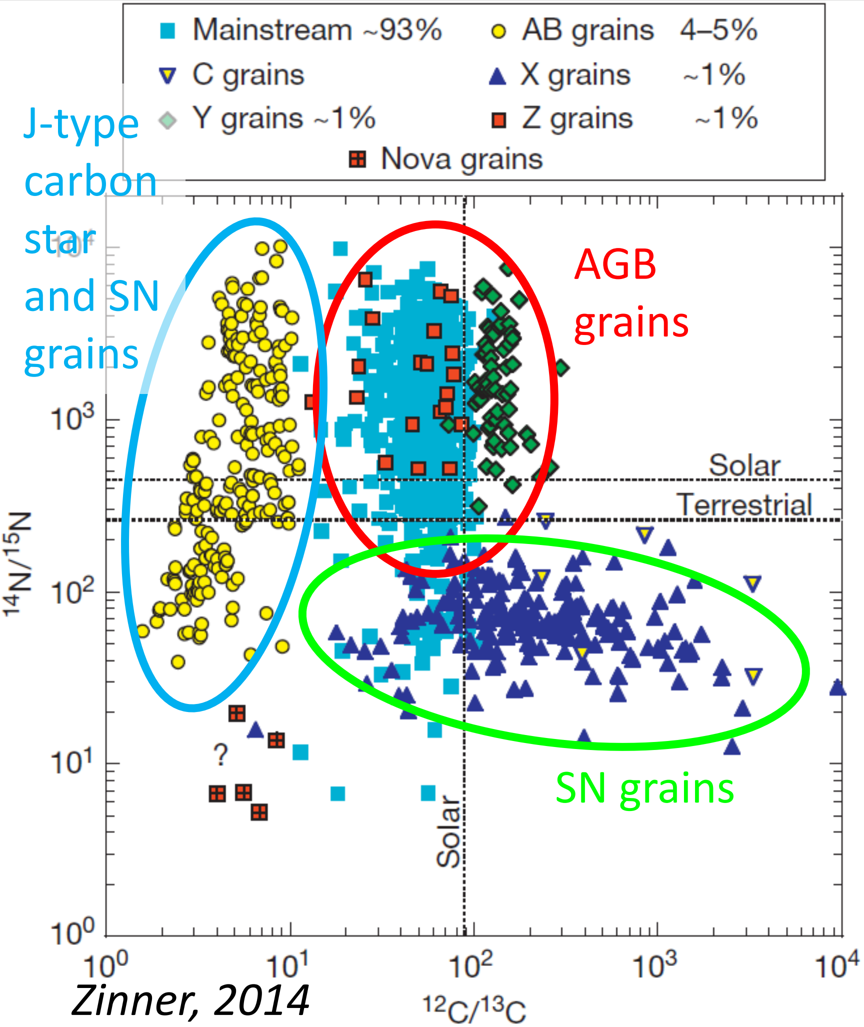
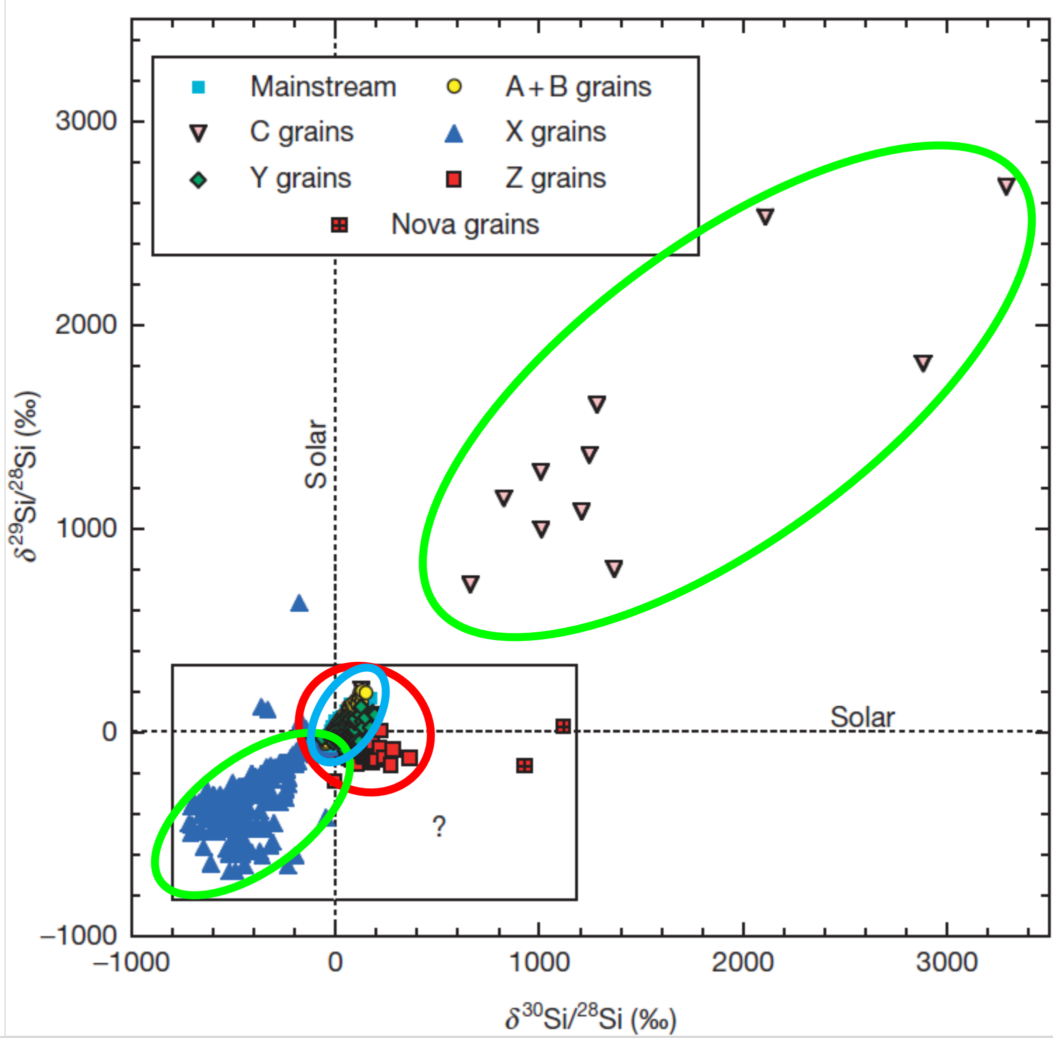
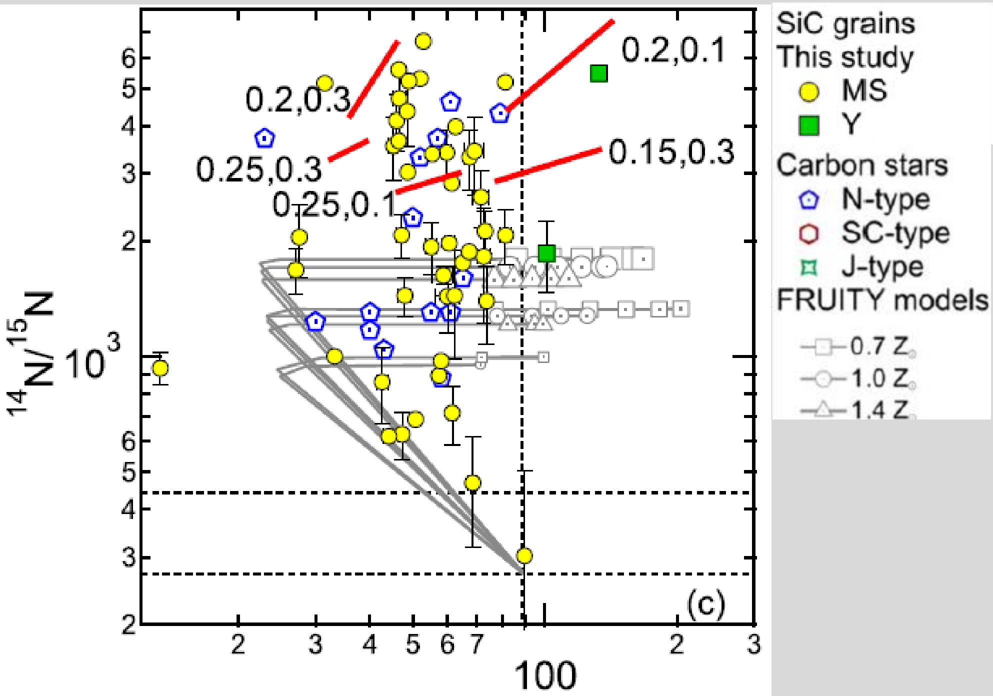


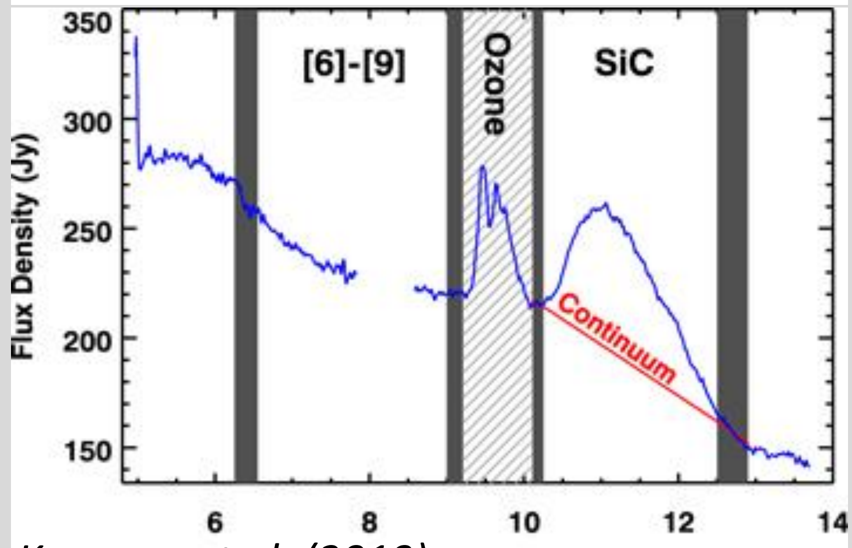


Presolar SiC

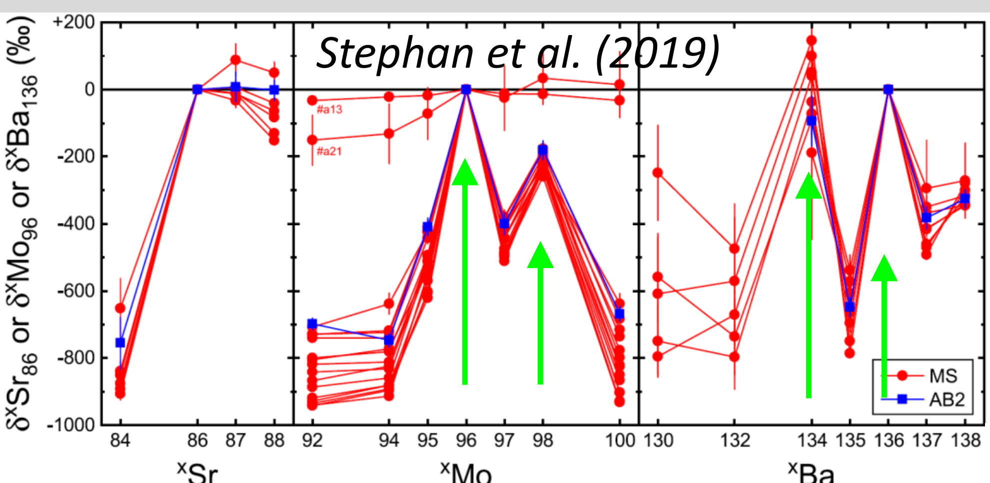


Liu et al. (2021)

V1132 Cen (carbon star) IR spectrum with 11µm SiC feature



Kraemer et al. (2019)



- MS grains originate in M < 3 × M$_\odot$, Z$_\odot$ AGB stars
- Excellent natural probes of *s*-process nucleosynthesis

Green: s-process only, or s-process dominated isotopes

Presolar SiC

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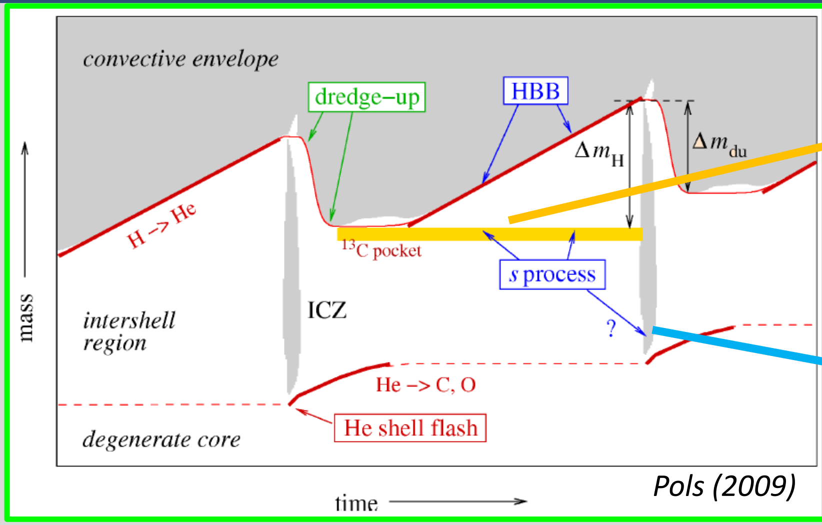
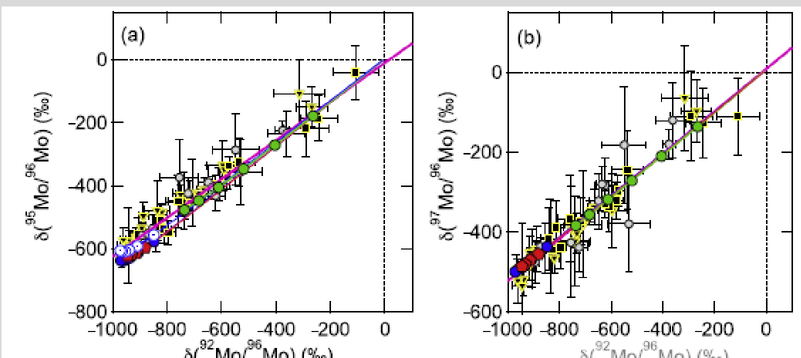
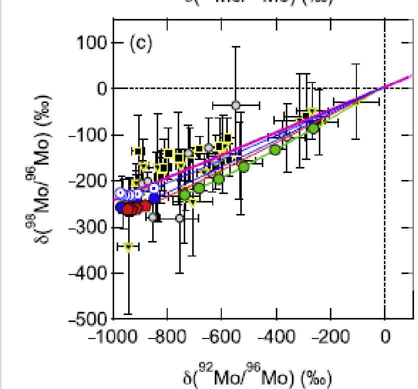


Pols (2009)

$^{13}C(\alpha,n)^{16}O$ long-lasting (millenia), low n-flux ($<10^8$ ncm^{-3}), operates at lower T (100–150MK)

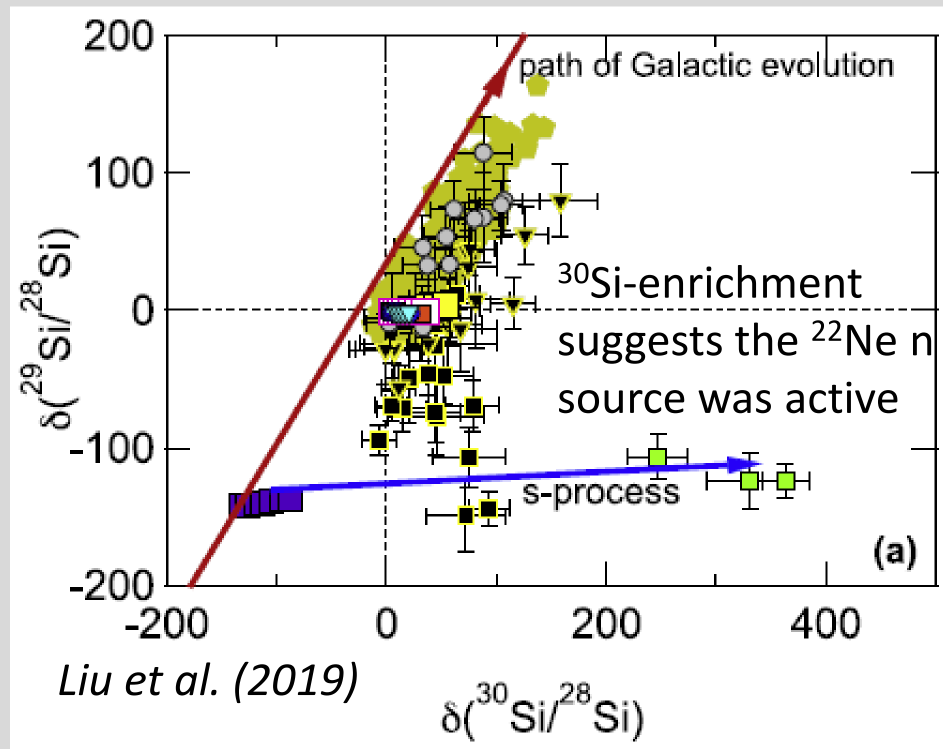
$^{22}Ne(\alpha,n)^{25}Mg$ short (decades at most), high n-flux (10^{10}–10^{11} ncm^{-3}), operates at higher T (>300MK) only marginally activated in AGB SiC grains' parents – or is it?





Y and Z grains' Mo isotope compositions can be modelled without the ^{22}Ne n source

Liu et al. (2019)

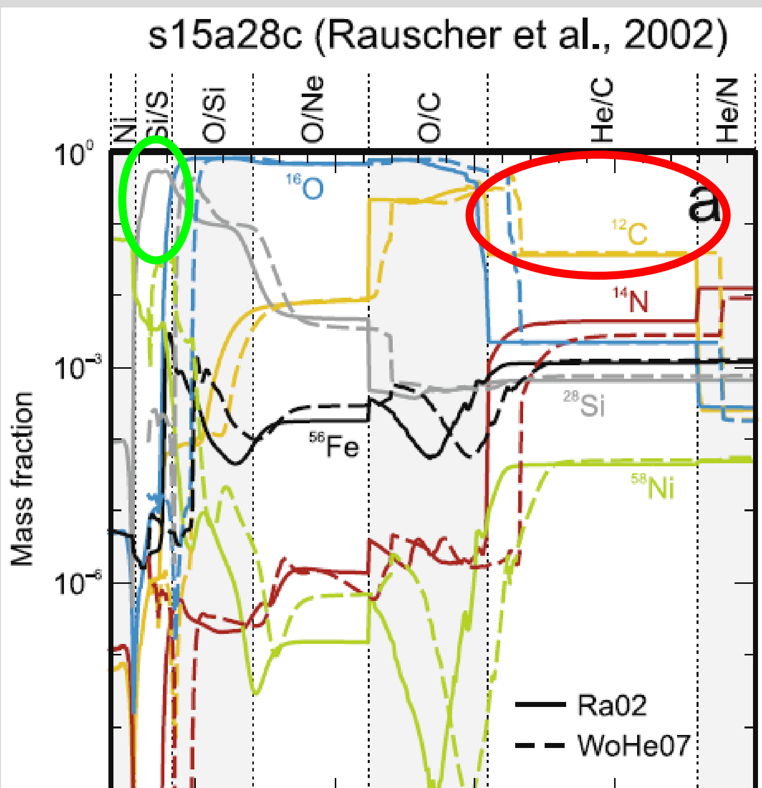


^{30}Si-enrichment suggests the ^{22}Ne n source was active

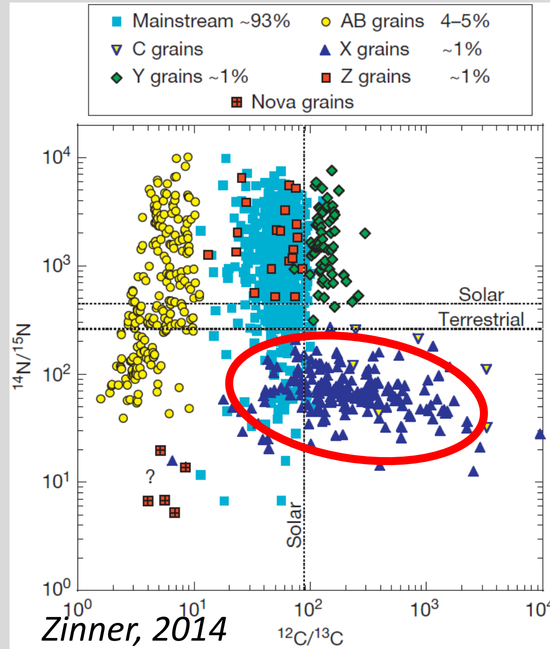
Liu et al. (2019)

Presolar SiC

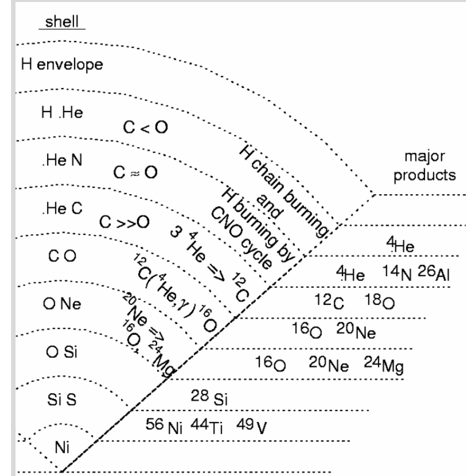
- X and C grains have peculiar isotope compositions
- SN origin likely because of C-N-Si isotope compositions, and the former presence of diagnostic short-lived radioactive isotopes (e.g., ^{44}Ti)



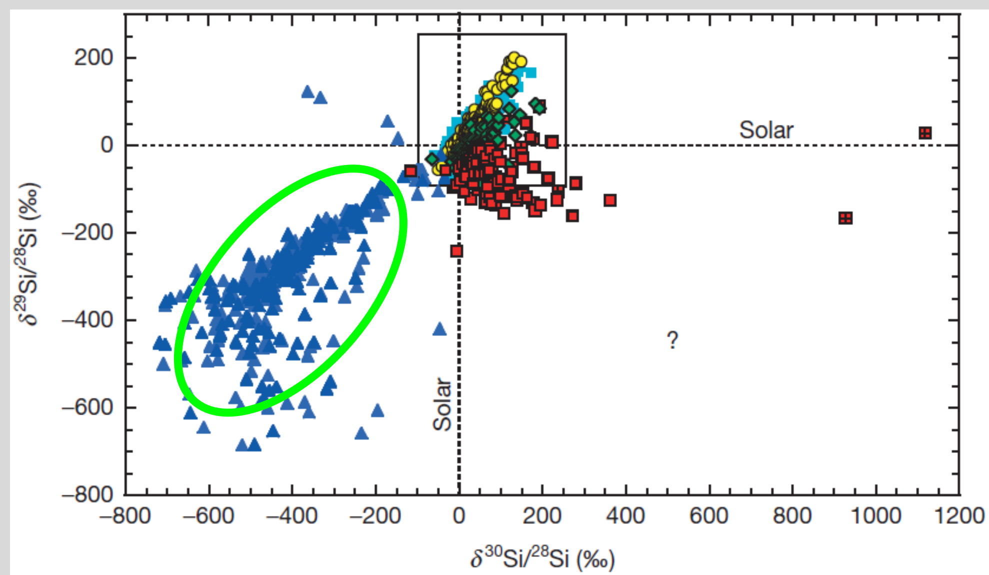
Kodolányi et al. (2018a)



Zinner, 2014



Lodders and Amari (2005)



Presolar SiC

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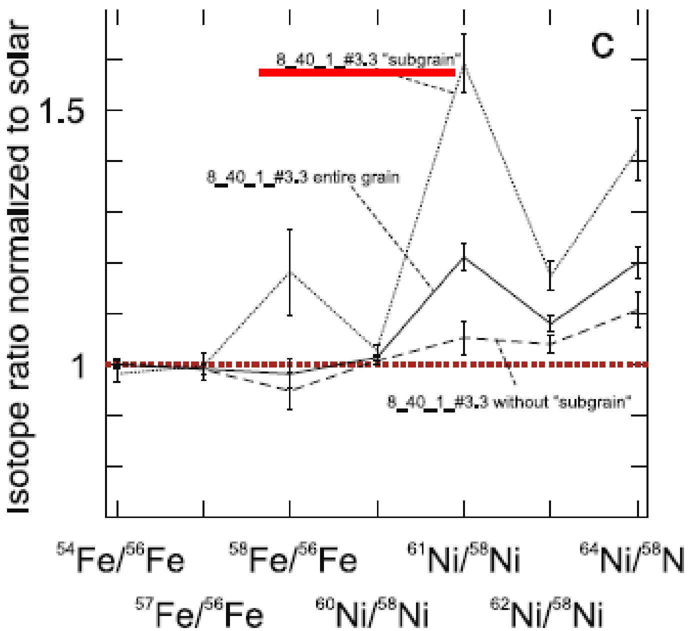
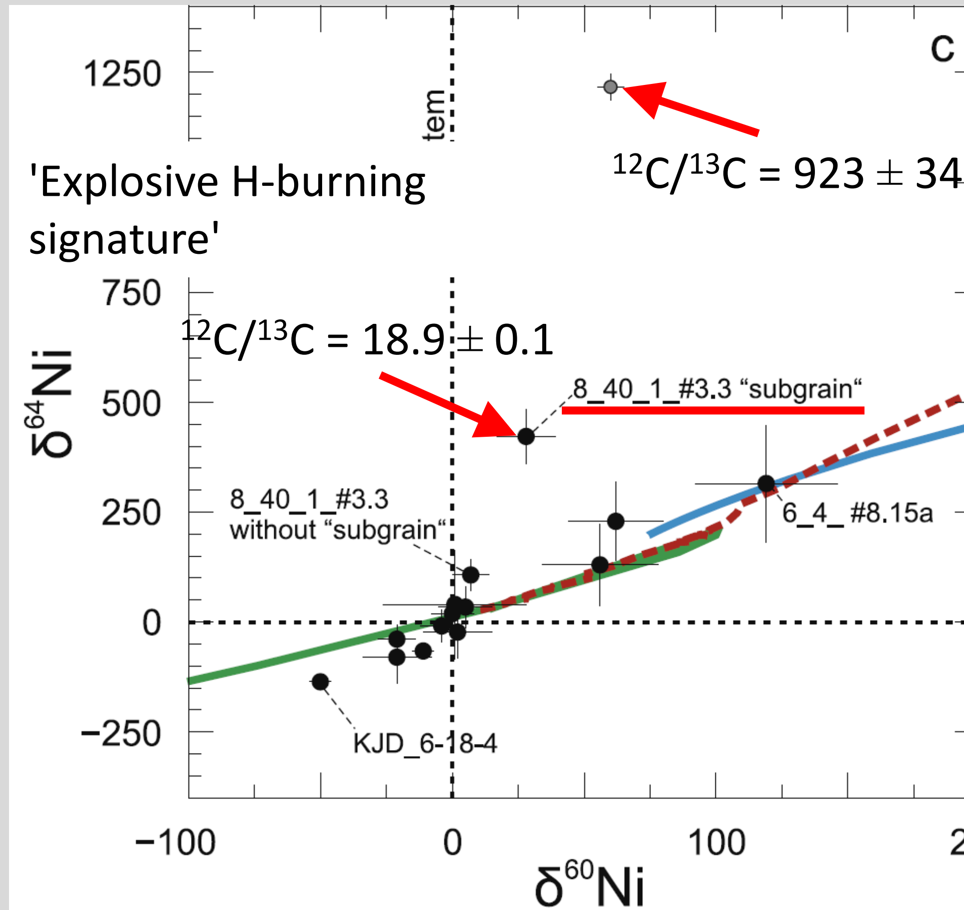
- X and C grains have peculiar isotope compositions
- Mixing and chemical fractionation?
- Comparison with 1D models not satisfactory

Pre-SN hydrostatic shell burning
'*s*-process signature'



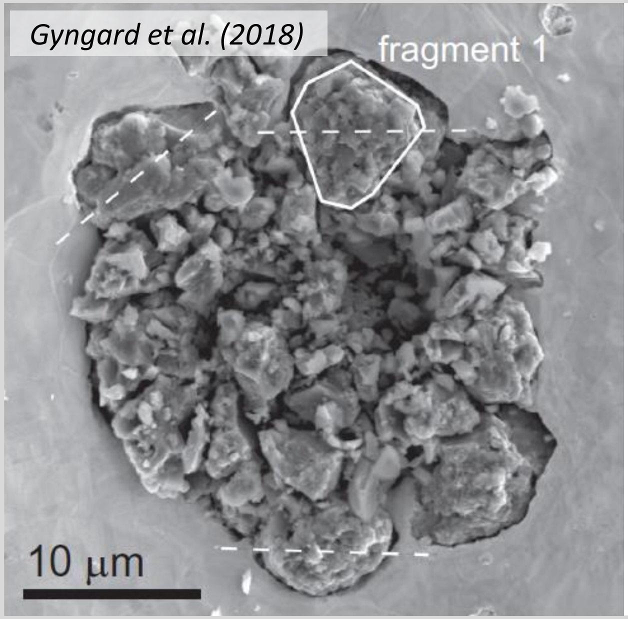
Kodolányi et al. (2018a)



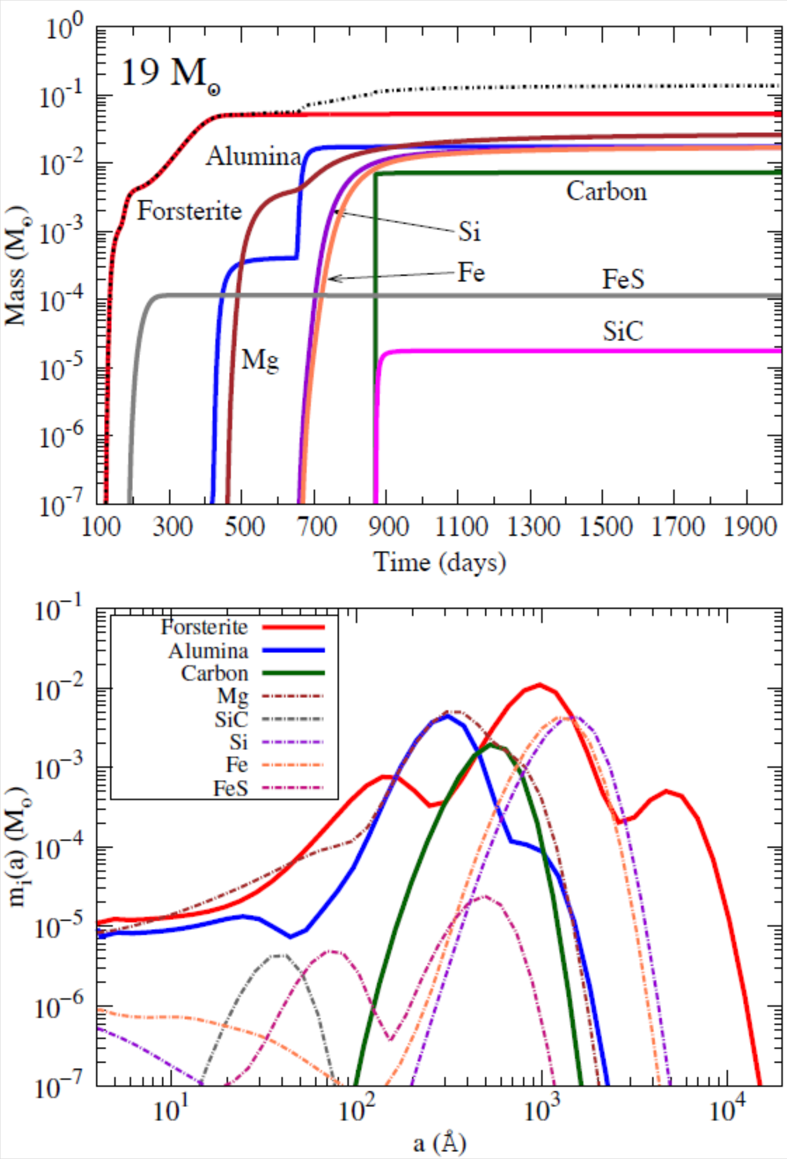
Presolar SiC

- *Kinetic condensation models:*
  - Molecule formation, molecular clusters, grains
  - Condensation T few 100 K
  - C/O > 1
  - Carbon dust precedes or accompanies formation of SiC in He/C zone matter

Gyngard et al. (2018)



The giant SiC X grain 'Bonanza'



Sarangi and Cherchneff (2015)

Presolar SiC

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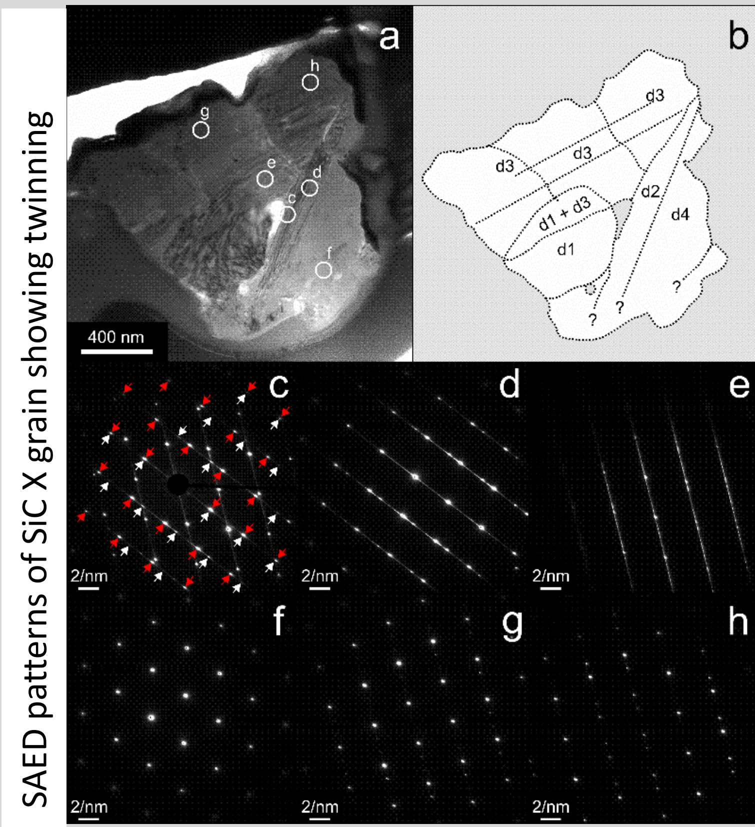
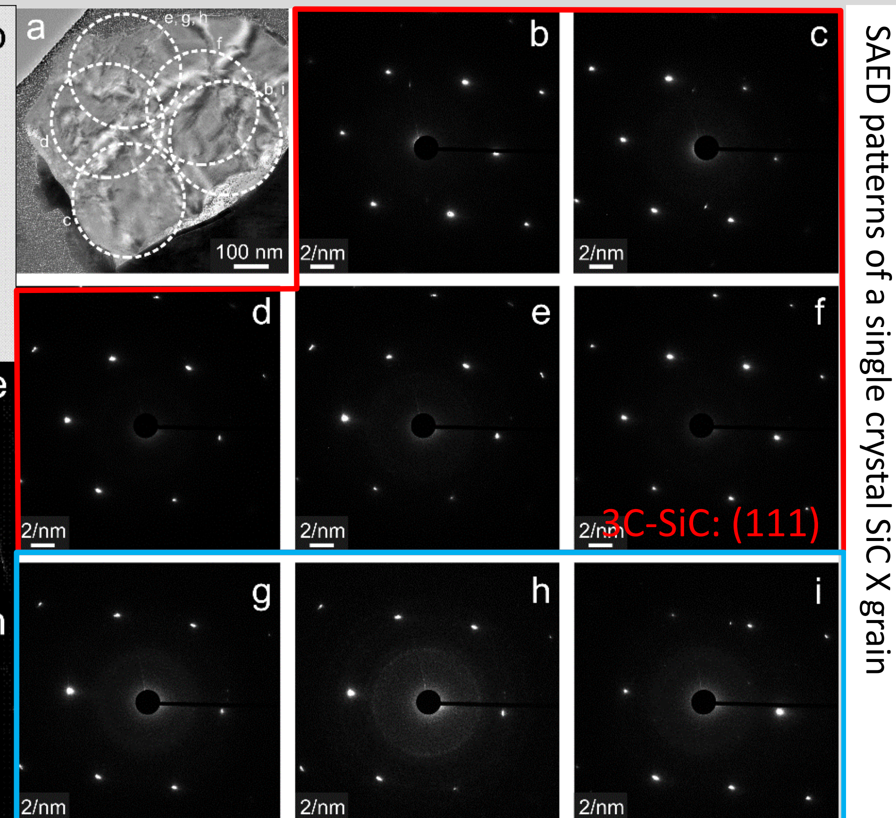
- *Presolar grain record:*
- Single crystals: up to >1 µm diameter
- Polycrystalline grains: epitaxial crystal domains, twinning
- *Formation of large grains not by coagulation of smaller grains (but there are exceptions)*





Kodolányi et al. (2018b)

(b–f)^(g–i) = 35.5°

3C-SiC: (114)

Presolar SiC

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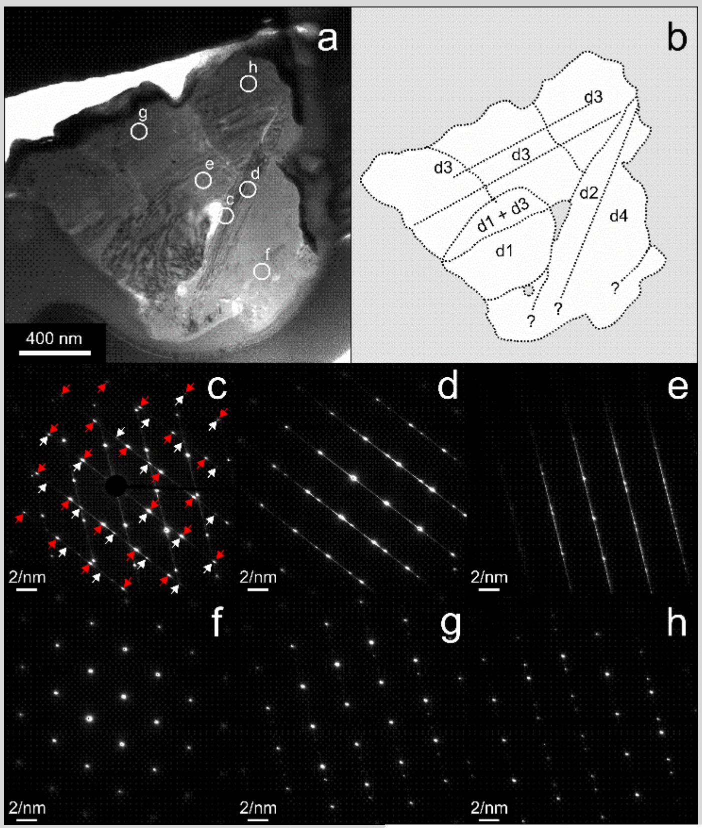
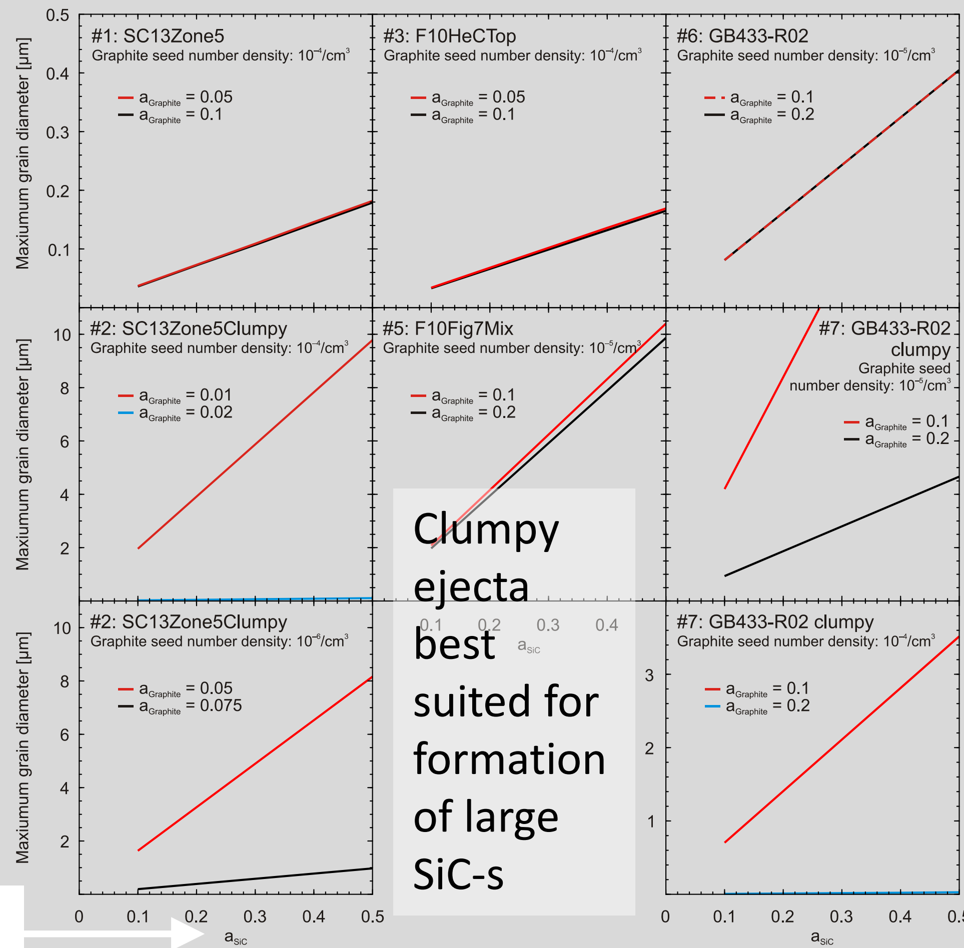


a = Sticking coefficient

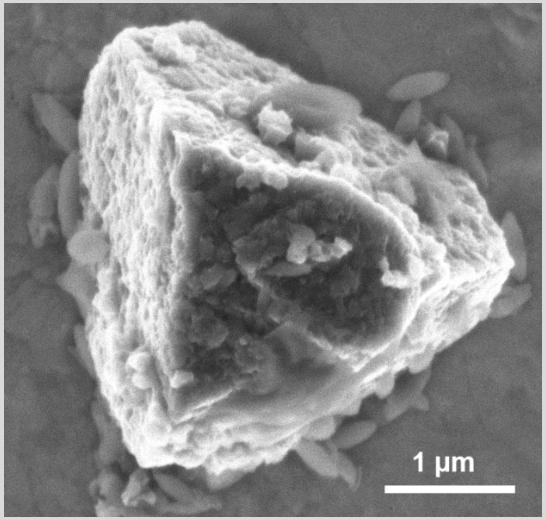


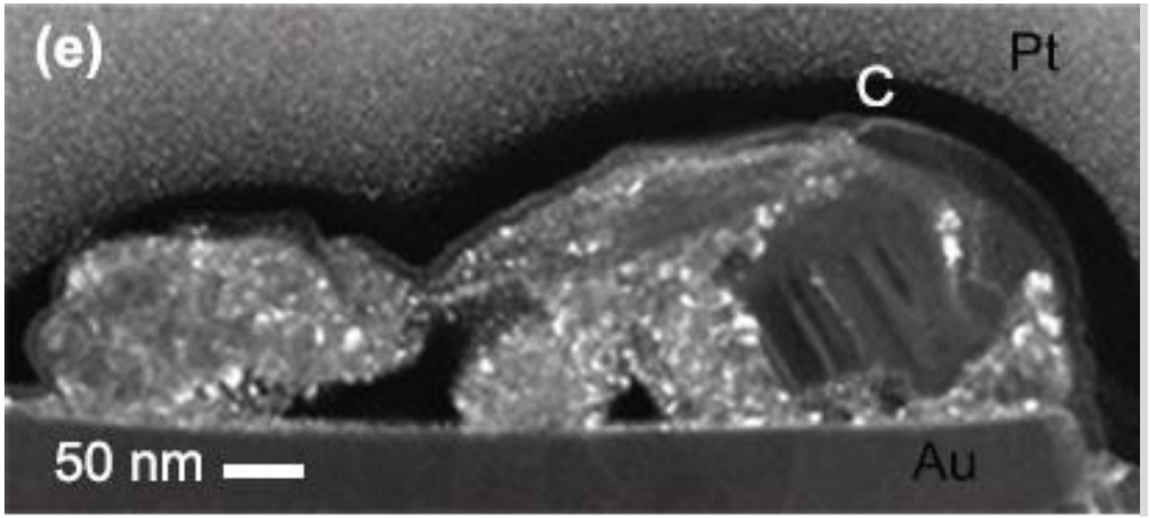
Clumpy ejecta best suited for formation of large SiC-s

Kodolányi et al. (2018b)

What comes next?

- Hyperion O ion source allows alkaline and transition metals to be measured in silicates (but isobaric interferences are an obstacle): Ca, Ti
- More, spatially better resolved data from CHILI (e.g., Mo isotopes in SiC X grains
- 3D SN nucleosynthesis models (there are some already, e.g., *Schulte et al., 2021*)
- Condensation will be better understood with a number of new TEM studies, especially the condensation of silicates





Summary

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- Presolar grains are usually small (d < 250 nm) stellar dust grains of extra Solar System origin, that are found in the matrices of primitive meteorites and in cometary dust
- Silicates, oxides, SiC, graphite are the most important
- Presolar grains carry important messages about stellar nucleosynthesis, Galactic Chemical Evolution, and grain condensation
- Most abundant presolar grain types condensed in the winds of low-mass AGB stars of about solar metallicity
- Some presolar grains come from core collapse SNe