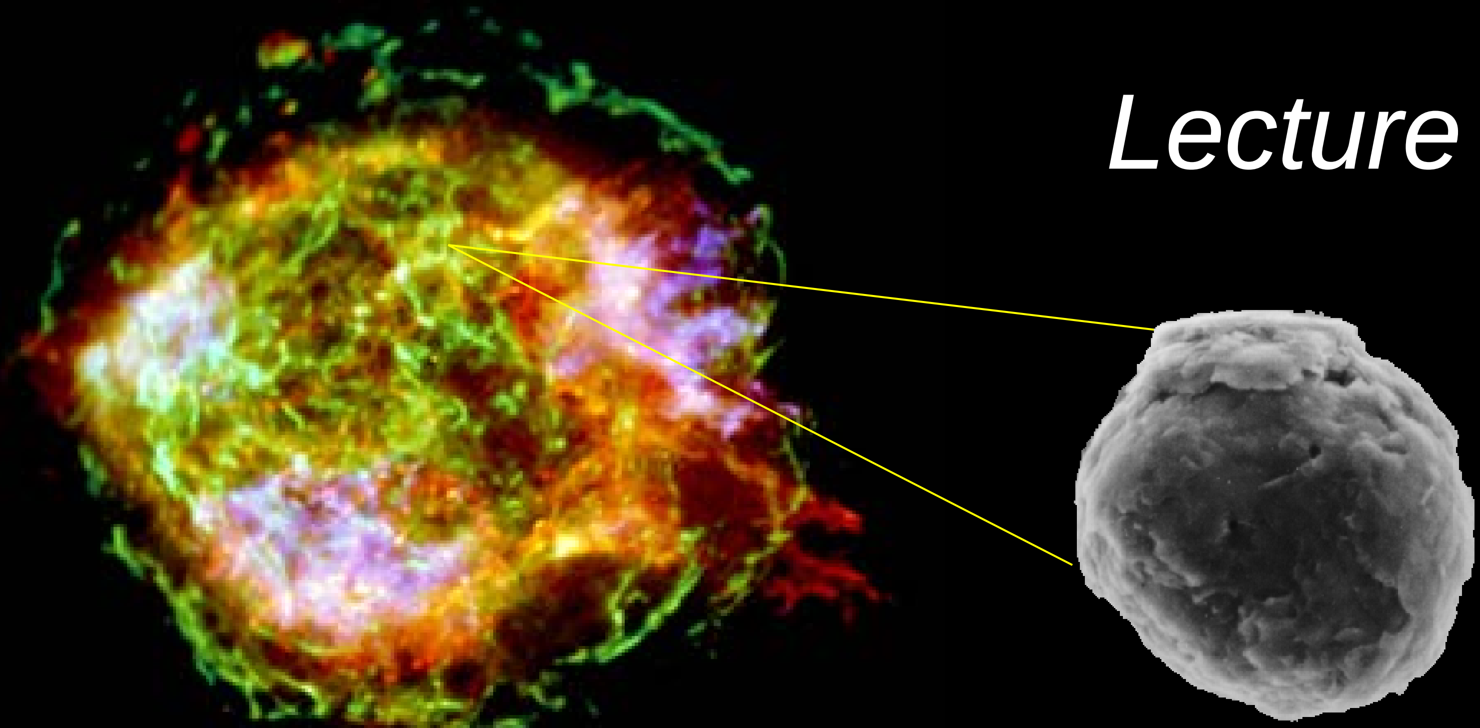
Presolar Stardust in the Solar System



Lecture II

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Carnegie Institution of Washington

Les Houches Winter School, February 2017

Outline

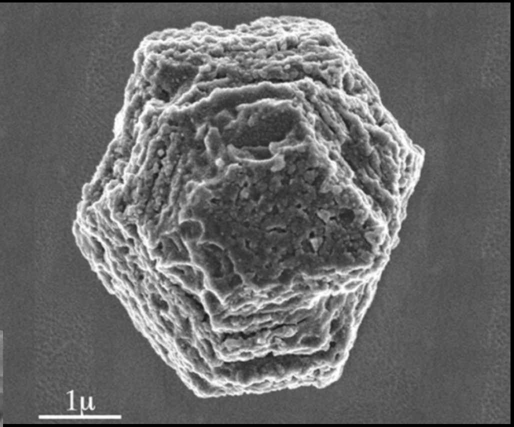
- Presolar Grain Implications for stellar evolution, nucleosynthesis, and Galactic Chemical Evolution

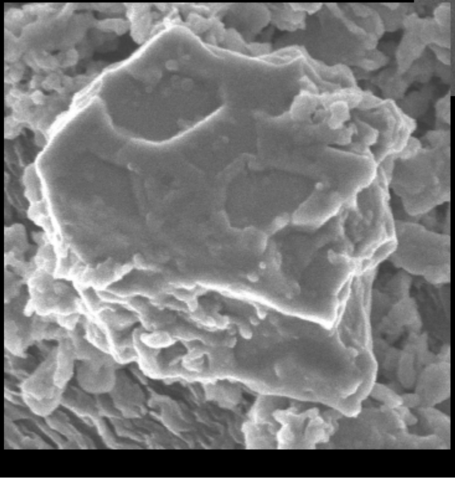
- Mineralogy of Presolar Grains

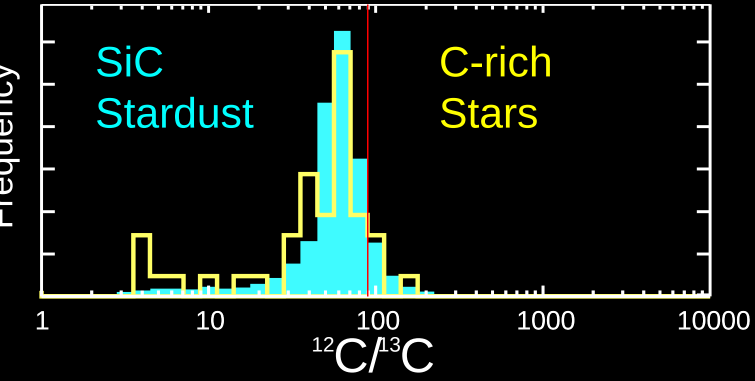
- Presolar Grains and the early Solar System

C-rich AGB Stardust

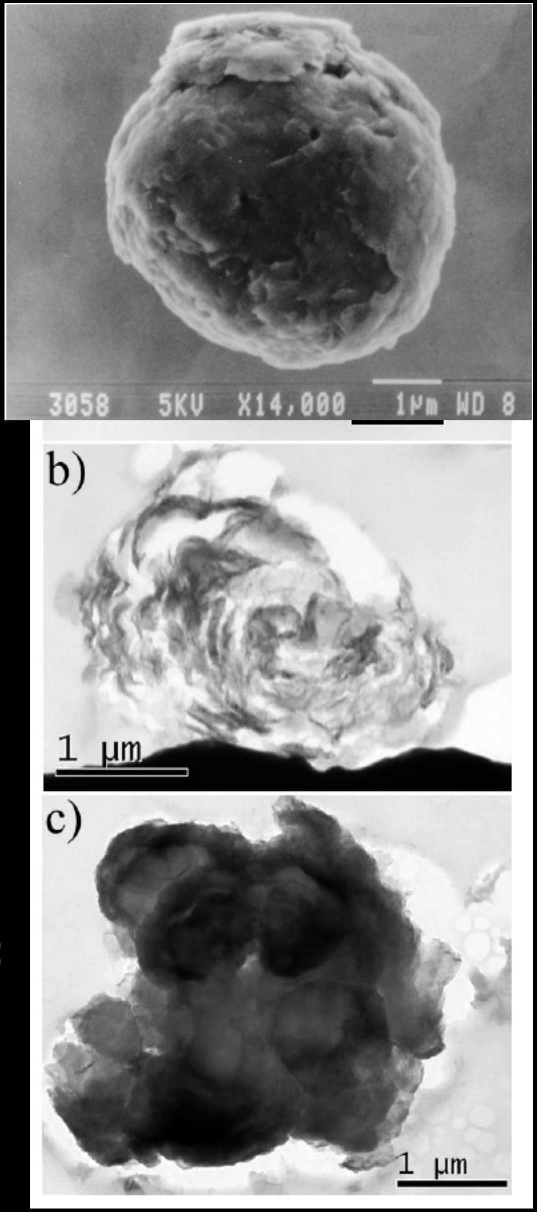
- >90% of SiC grains





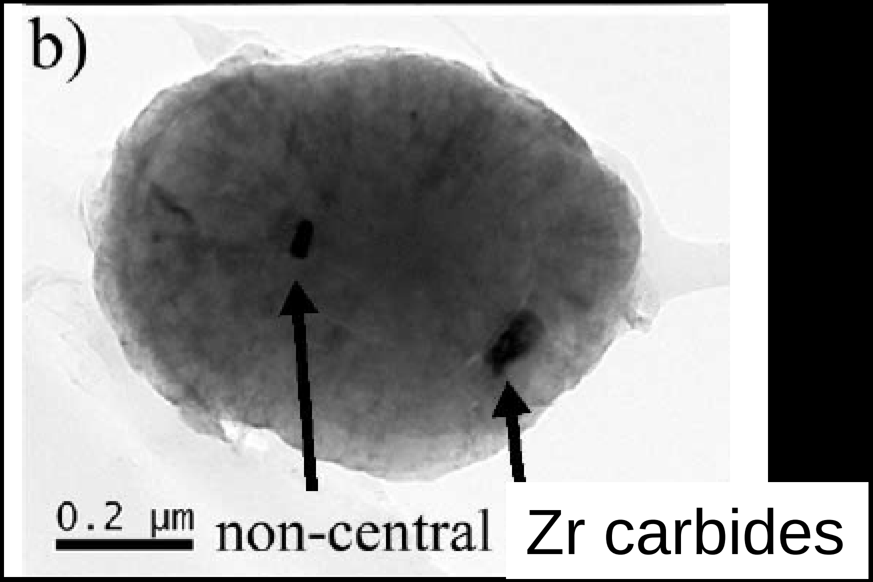


- ~50% of “graphite” grains (which show range of morphology/ crystallinity)

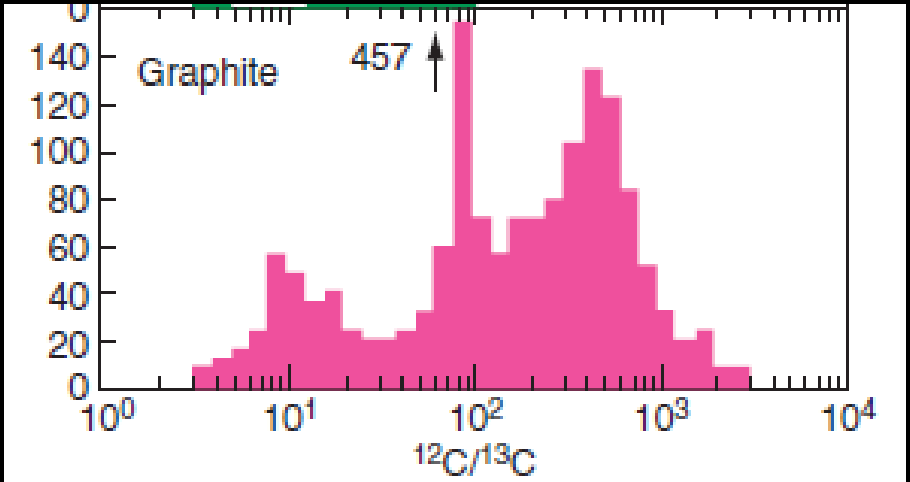


AGB origin of ~50% of presolar graphite

- Enriched in ^{12}C and *s*-process elements (*e.g.*, sub-grains of ZrC, MoC, etc)
- Data imply origin in low-metallicity AGB stars
    - Higher ^{12}C/^{13}C than SiC

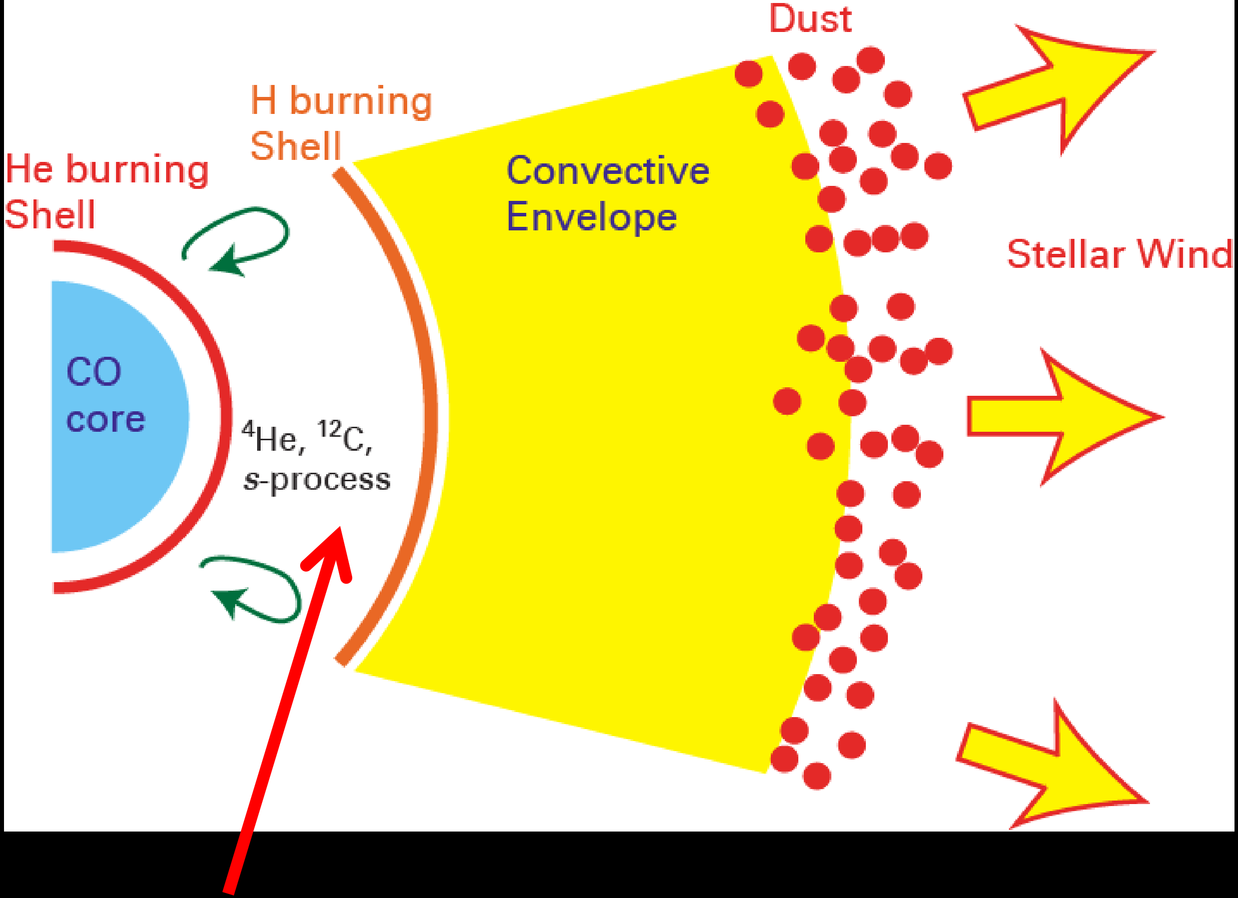


non-central Zr carbides



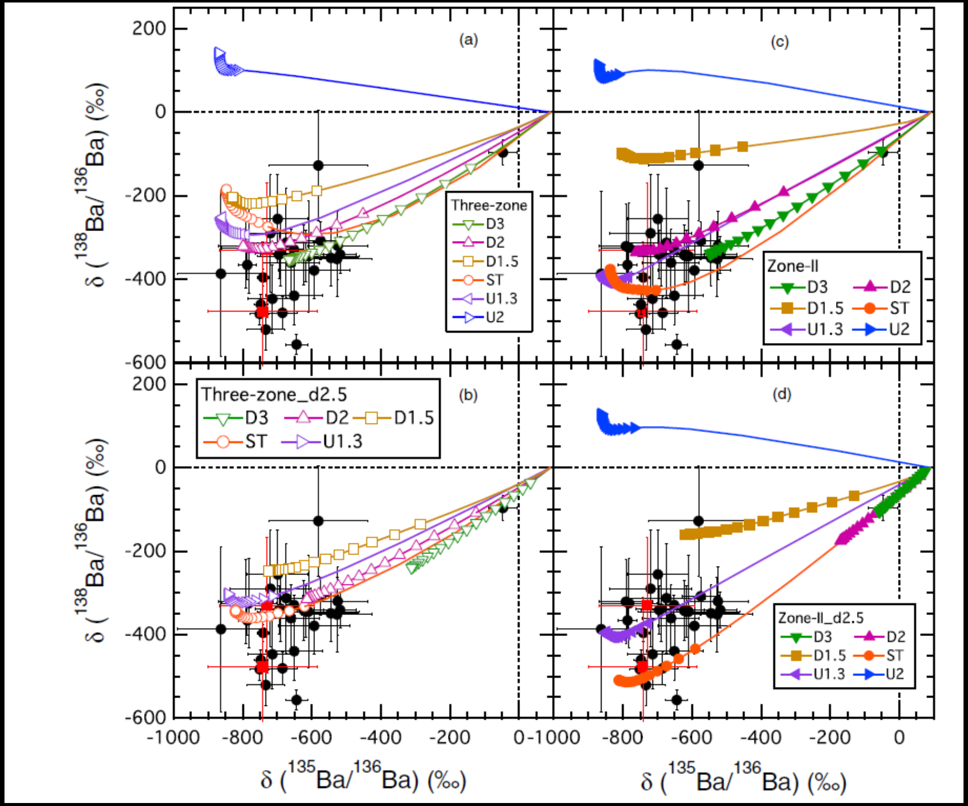
Croat et al (2005); Zinner et al. (2006)

AGB *s*-process nucleosynthesis



- Neutrons mainly from $^{13}C(\alpha,n)^{16}O$; some from $^{22}Ne(\alpha,n)^{25}Mg$
- Origin of ^{13}C thought to be from p mixed below H shell, but poorly constrained

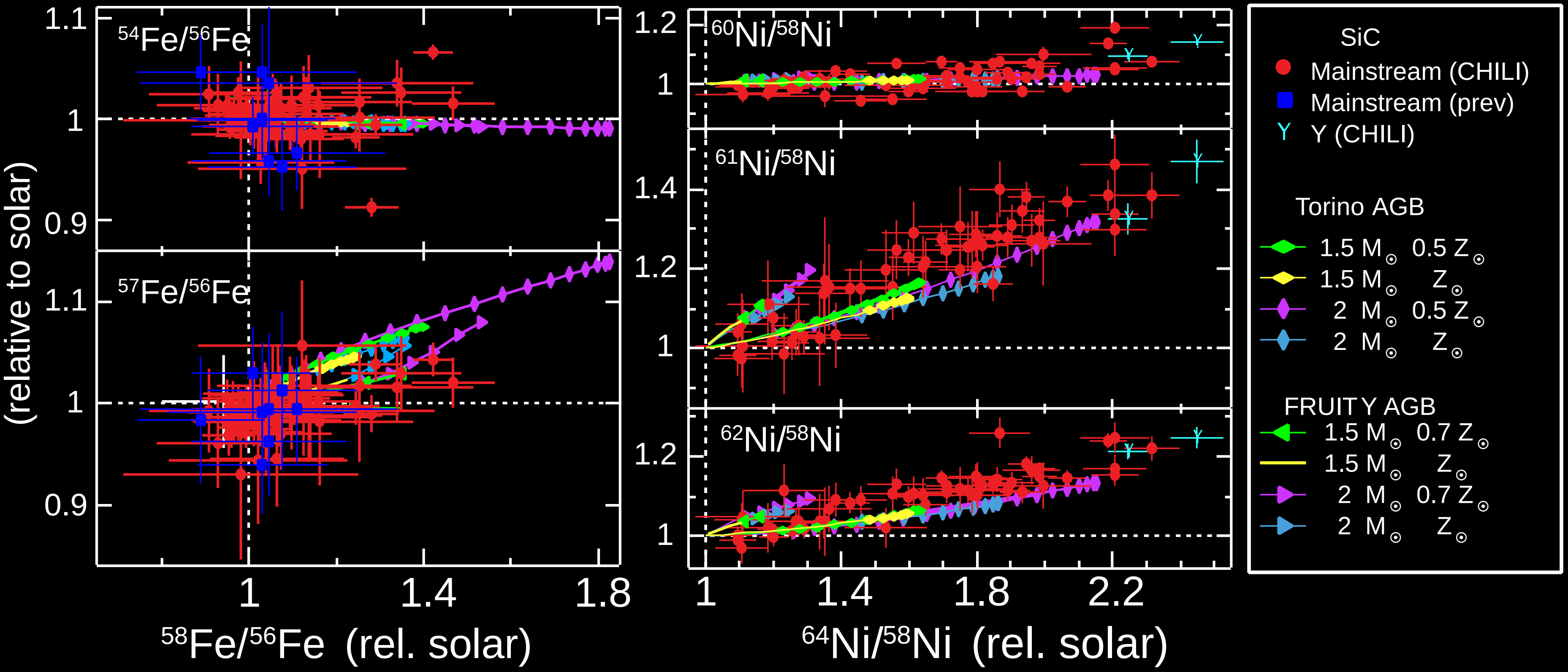
AGB *s*-process nucleosynthesis



- *s*-process not that well-understood; precise results depend on many parameters (stellar mass, metallicity, poorly understood mixing processes)
- Grains can constrain model parameters, improve understanding of how s-process works in stars

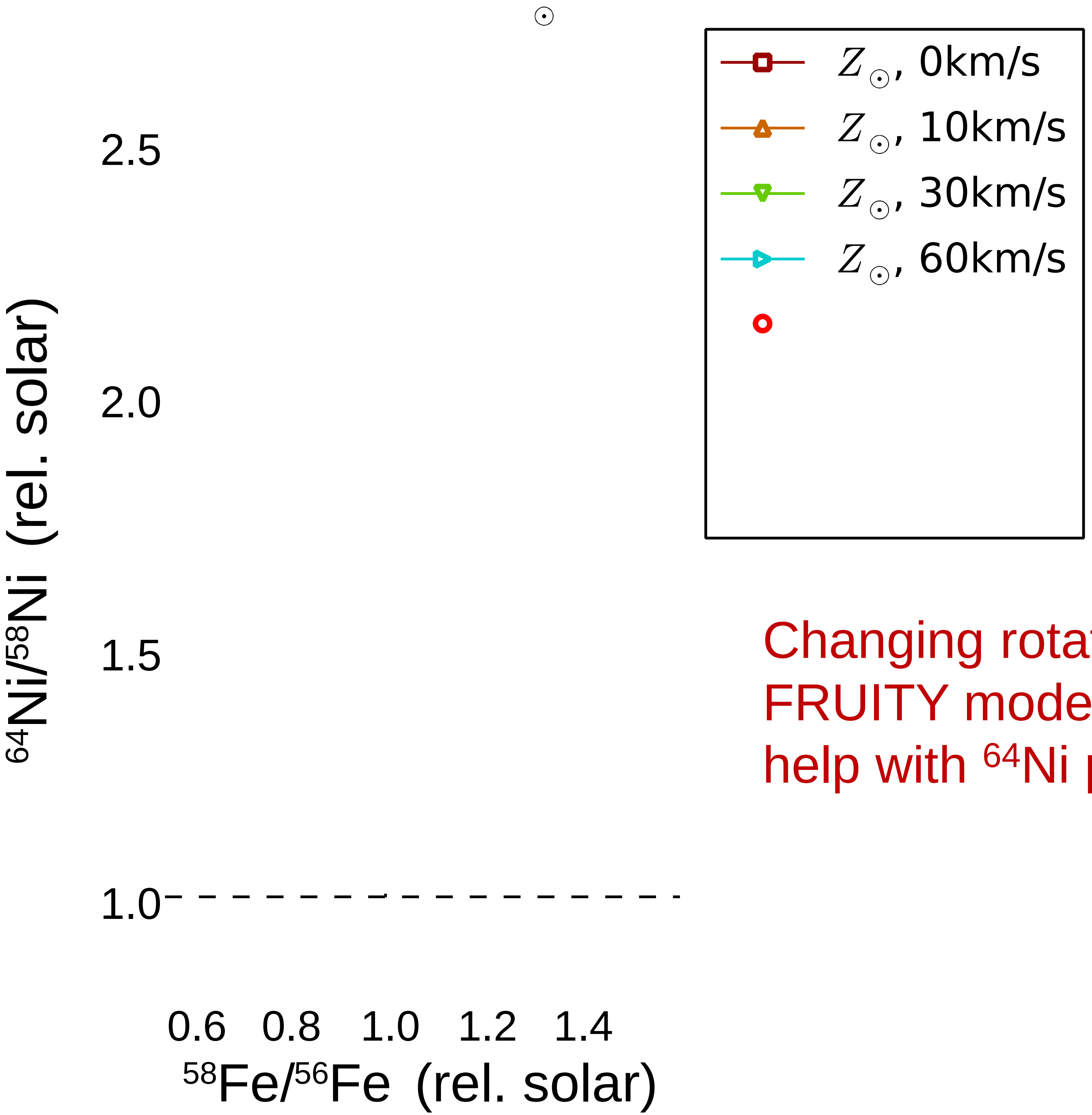
Liu et al., ApJ 2014

CHILI Fe,Ni data in AGB SiC



- AGB models broadly agree with trends, but important differences in detail
  - FRUITY underpredict ^{64}Ni

Davis, Treppitsch, Stephan+

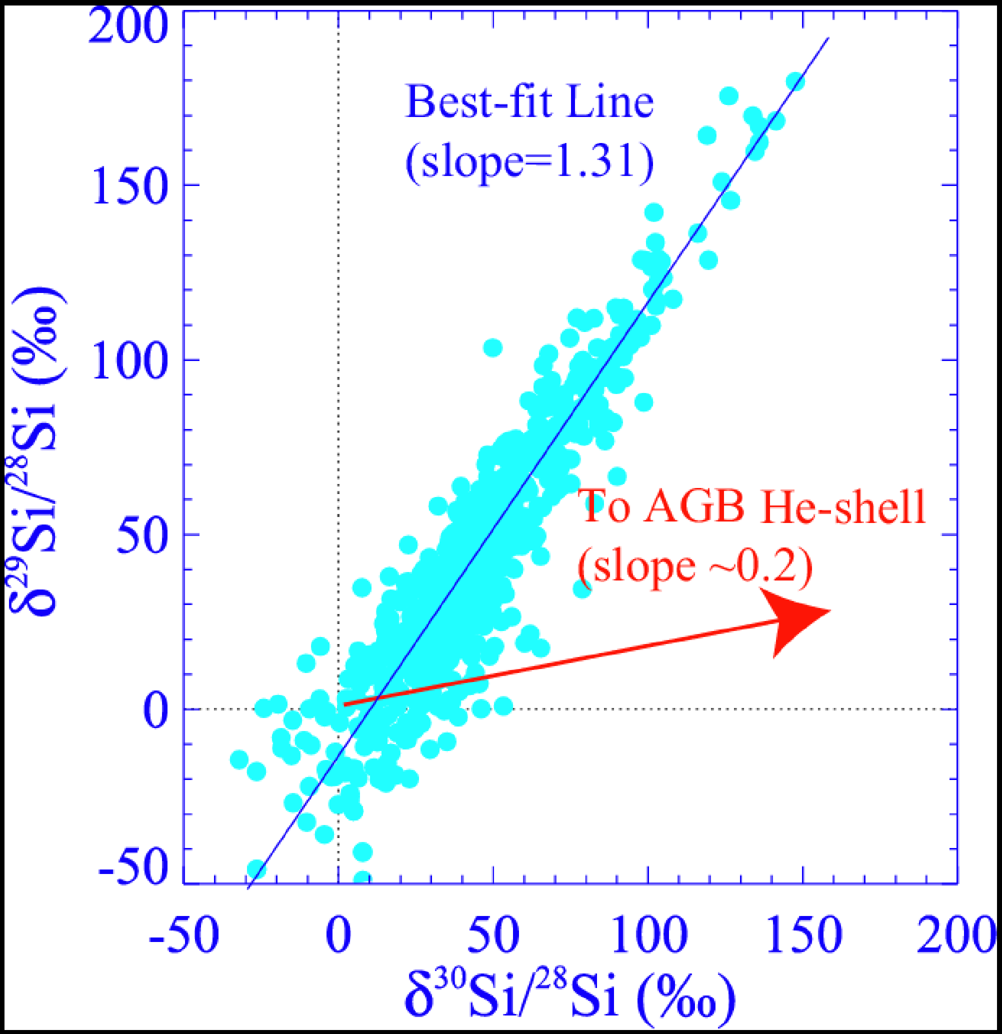


Changing rotation rate in FRUITY models doesn’t help with ^{64}Ni problem

courtesy A . Davis

Silicon in Presolar SiC

- Si isotopes do not match AGB models
- Data form linear array, but slope steeper than predicted for nuclear processes in AGB stars
  - Also true of Ti



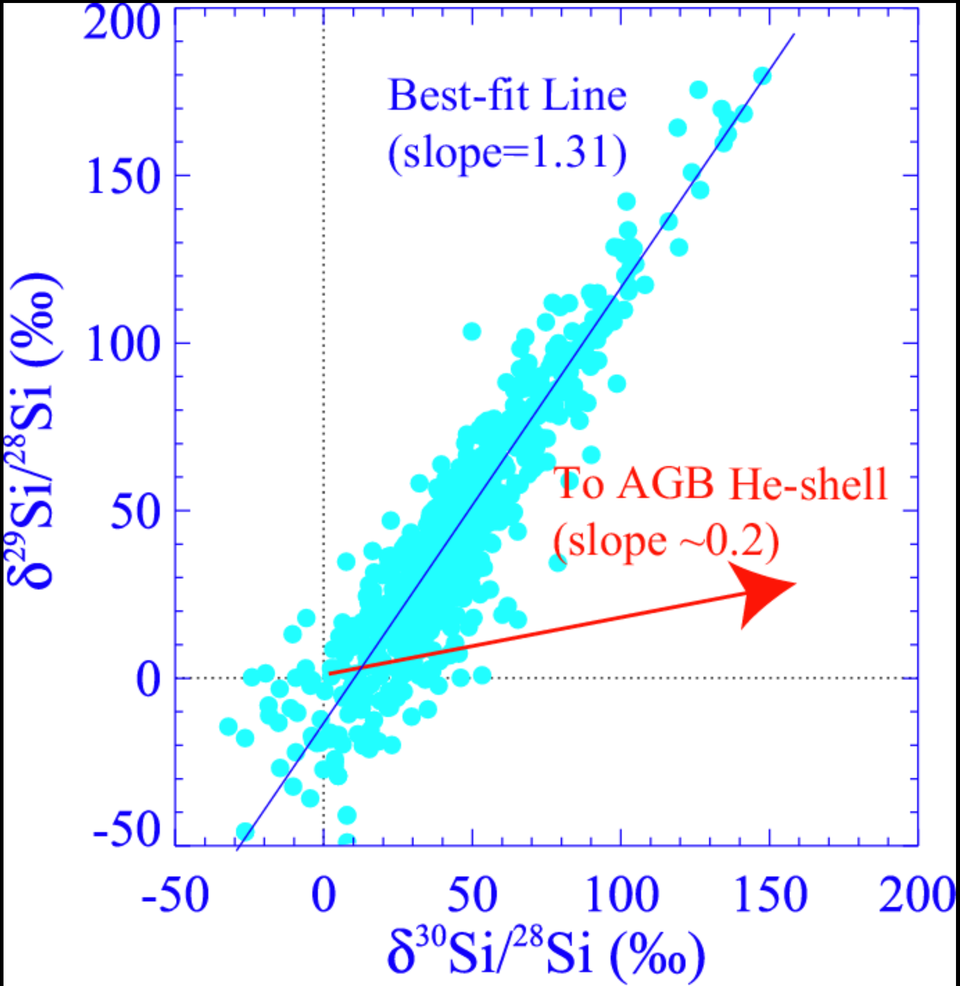
$\delta R=(R_m/R_\odot-1)\times1000$

$^{29}Si/^{28}Si$ (solar) = 0.051

$^{29}Si/^{28}Si$ (solar) = 0.033

Silicon in Presolar SiC

- Si isotopes do not match AGB models
- Data form linear array, but slope steeper than predicted for nuclear processes in AGB stars
  - Also true of Ti



- Both Si, Ti isotopes believed to reflect *initial compositions* of parent stars: **Galactic Chemical Evolution**

Galactic Chemical Evolution

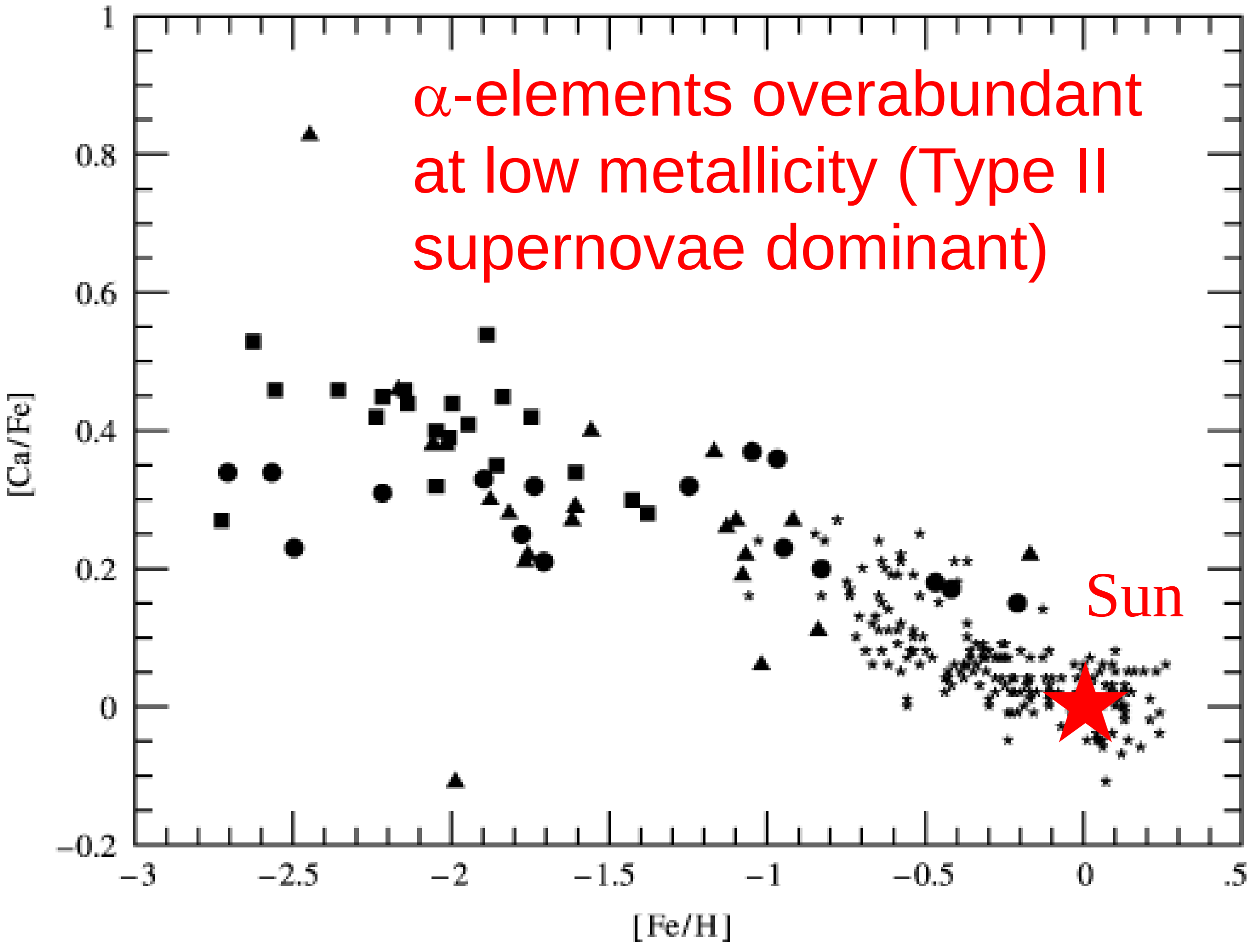
- Elemental/isotopic ratios change with time because:
  - – Different timescales for different nucleosynthesis sites
    - SNII: Evolve quickly, enrich early Galaxy with r-process, “α-elements”
    - Low-mass stars evolve more slowly, s-process from AGB stars and Fe from SN-Ia delayed

  - – Key Parameter: *Metallicity*:
    - Mass fraction of elements heavier than He
    - Z_{sun}~1.4%
    - $[Fe/H] = \log(Fe/H) – \log(Fe/H)_{Sun}$

Galactic Chemical Evolution

- Different nucleosynthetic character:
  - “Primary” isotopes: synthesis independent of metallicity
    - ^{12}C, ^{16}O, α-elements, Fe
  - “Secondary”: synthesis depends on prior presence of metals
    - ^{13}C, ^{17}O, ^{18}O, s-process, etc.
  - Secondary/Primary ~ Z

Galactic Chemical Evolution

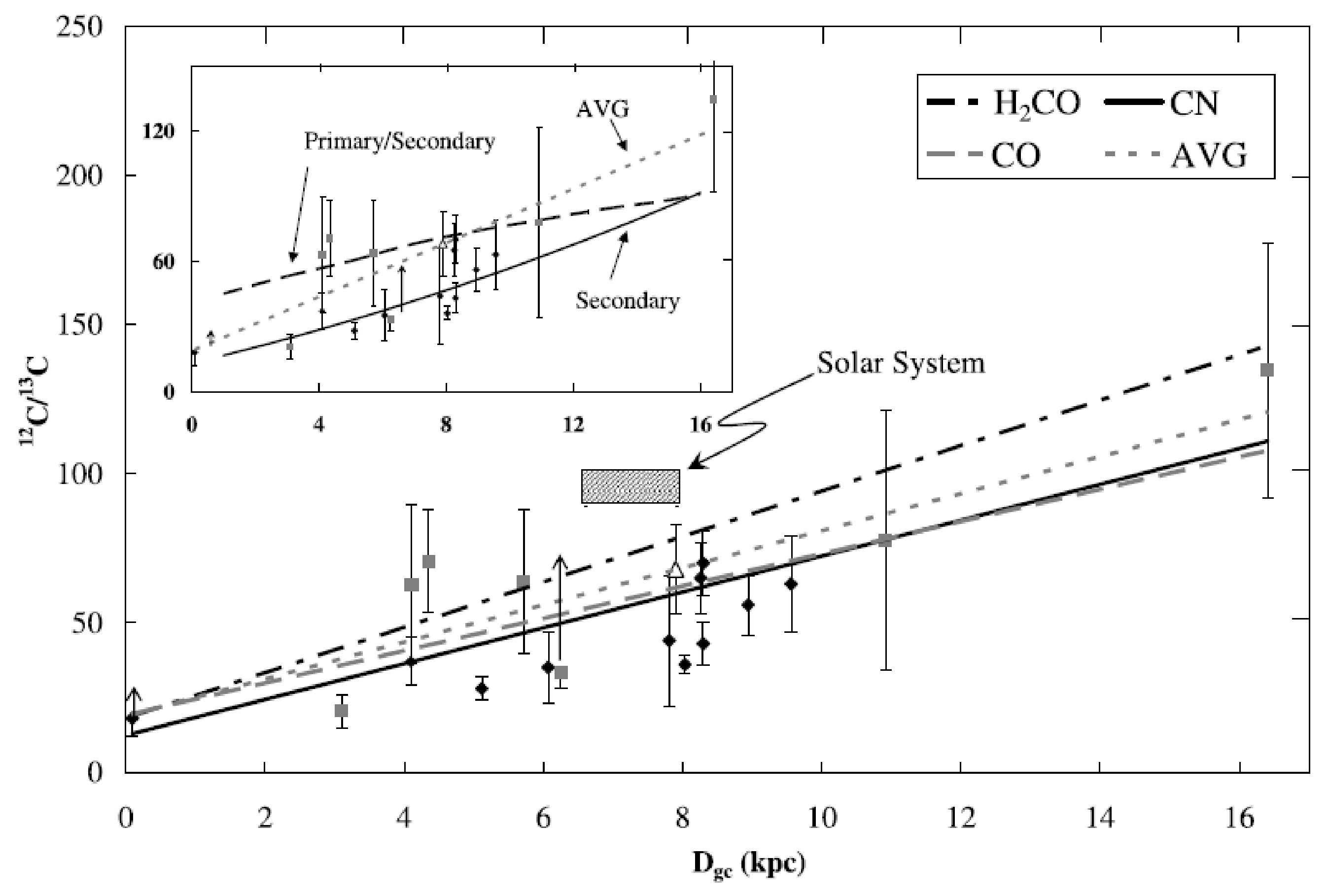


α-elements overabundant at low metallicity (Type II supernovae dominant)

Sun

Figure 7 Observed evolution of the calcium to iron abundance ratio with metallicity (▲: Hartmann and Gehren (1998); ■: Zhao and Magain (1990); ●: Gratton and Sneden (1991); ★: Edvardsson *et al.*, (1993)).

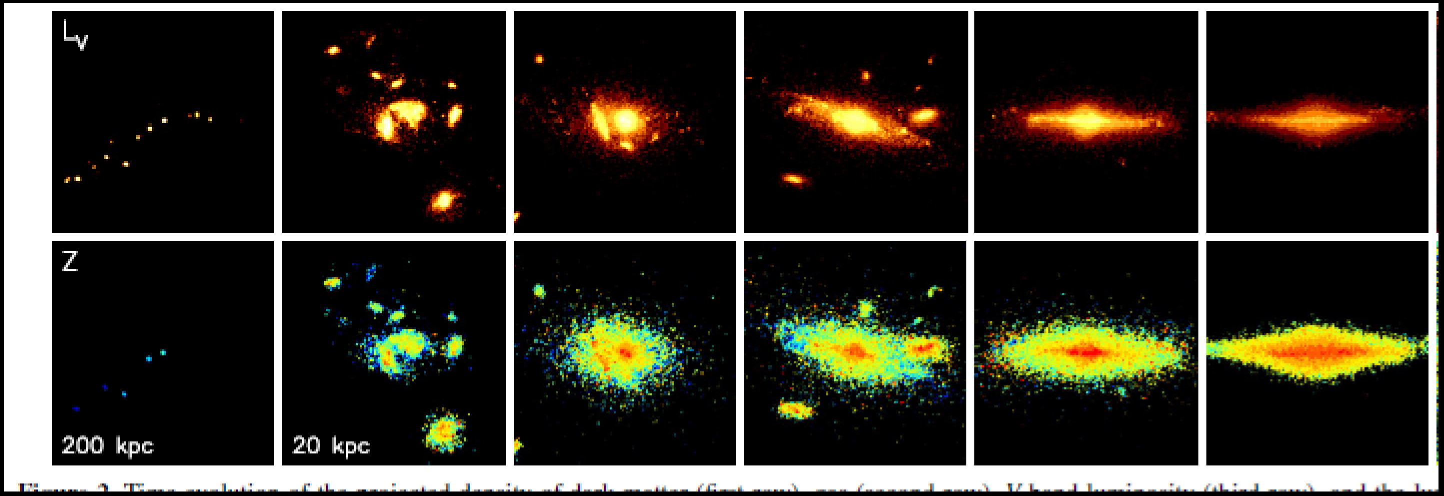
Galactic Chemical Evolution



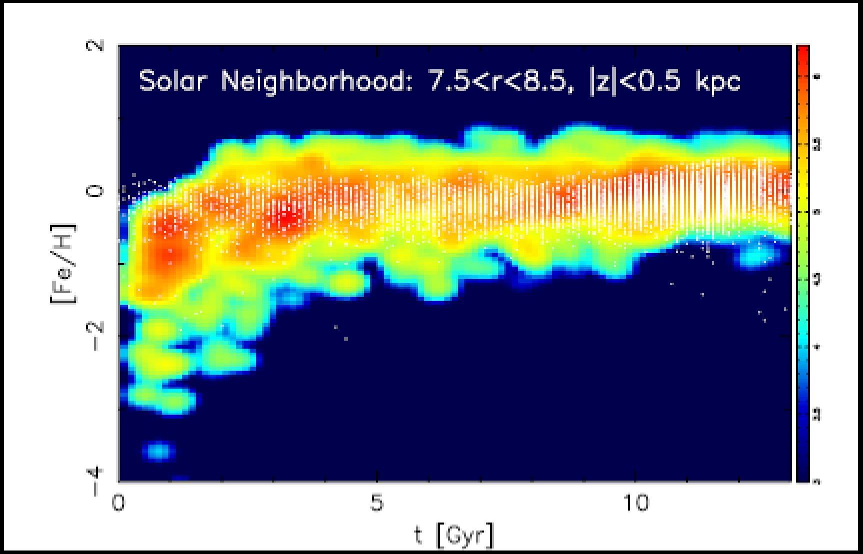
- Isotopic gradients seem to confirm GCE idea

Milam et al (2005)

Galactic Chemical Evolution



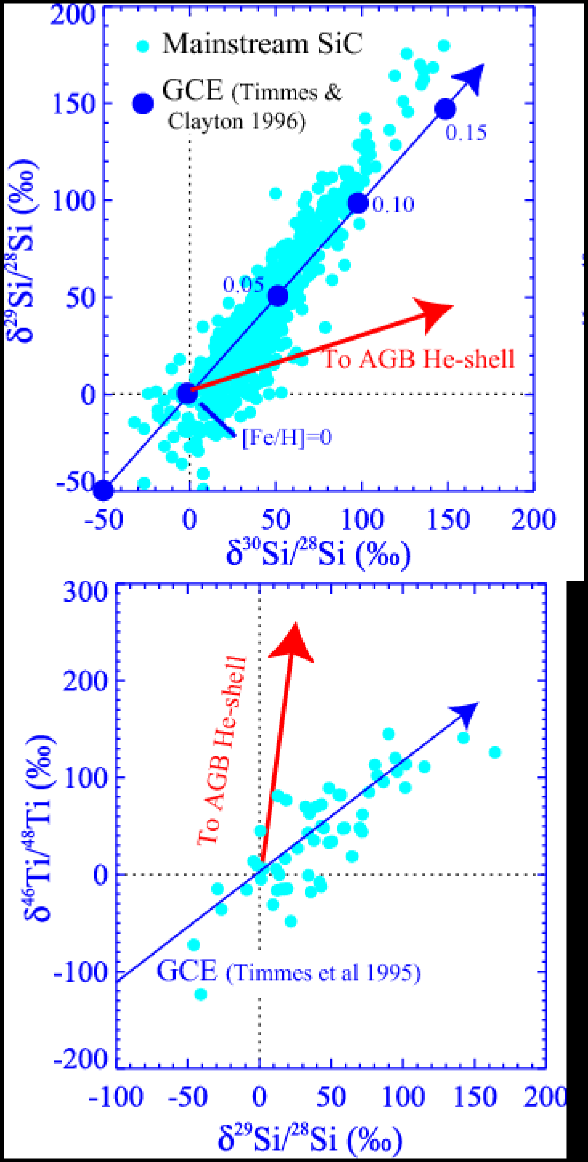
Time



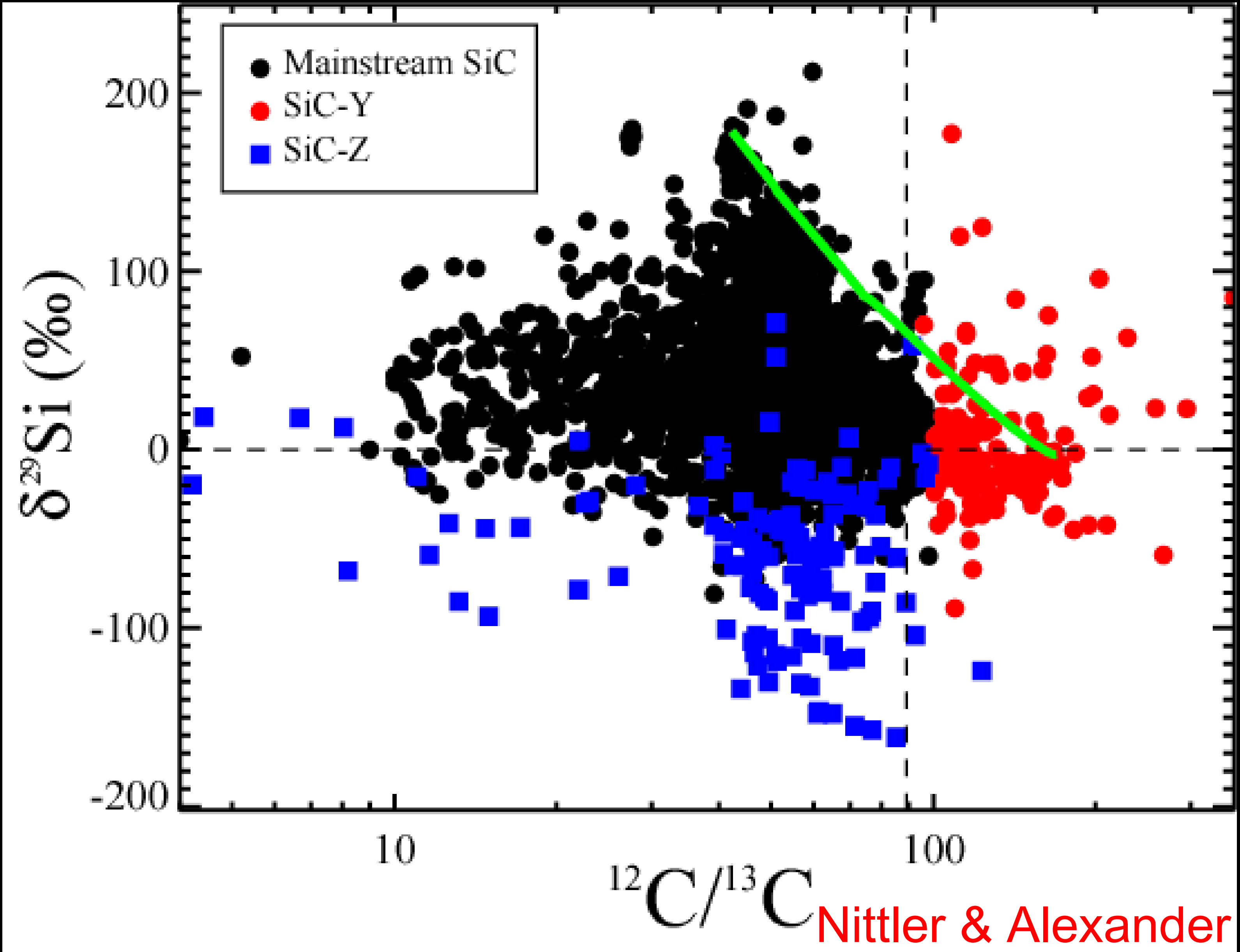
Kobayashi & Nakasato, 2011

Galactic Chemical Evolution

- Some AGB stardust isotopes reflect starting compositions of parent stars: GCE
- Parent stars of mass ~1.2$M_\odot$ to ~4$M_\odot$ and thus formed from 4.6 to ~12 Gyr ago *(Nittler+ 1997)*
  - Complementary sample to stellar compositions for GCE studies – snapshot of solar neighborhood 4.6 Gyr ago

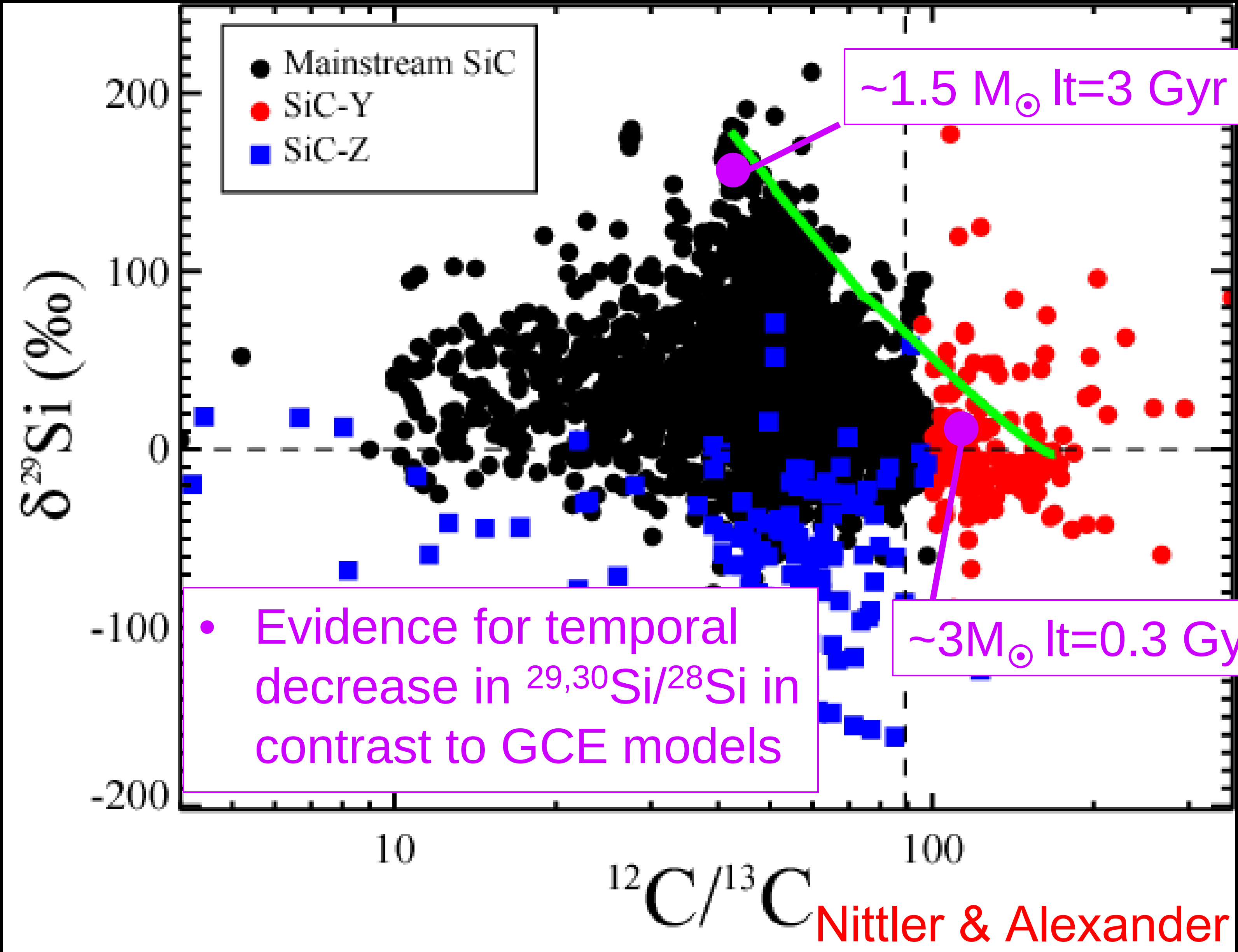


GCE and Presolar SiC



Nittler & Alexander 2003

GCE and Presolar SiC



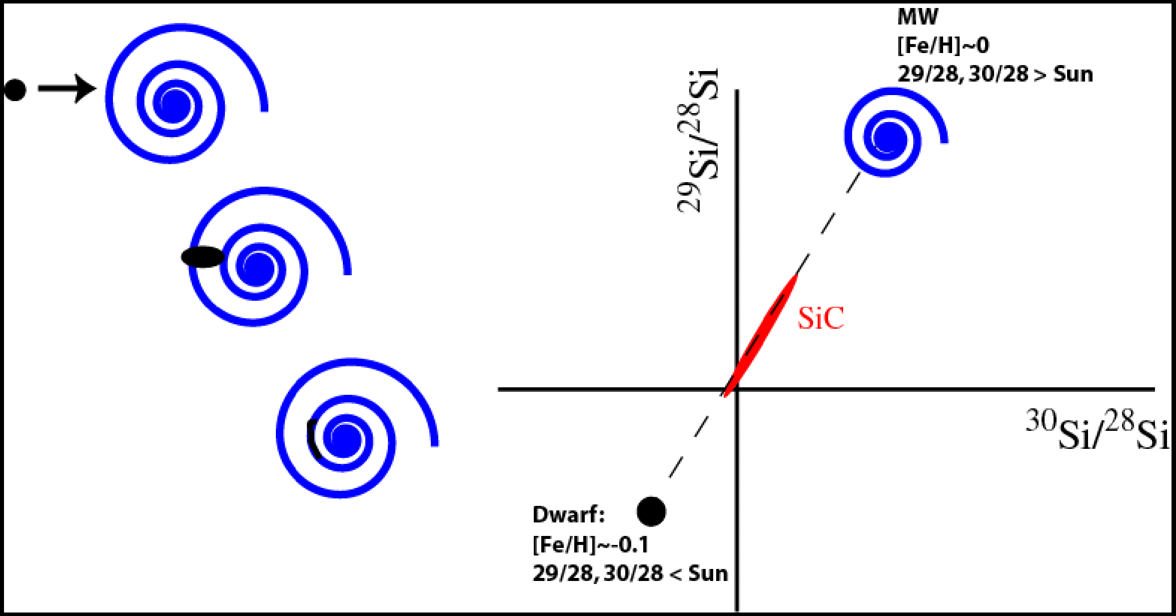
~1.5 $M_{\odot}$ lt=3 Gyr

~3$M_{\odot}$ lt=0.3 Gyr

- Evidence for temporal decrease in $^{29,30}Si/^{28}Si$ in contrast to GCE models

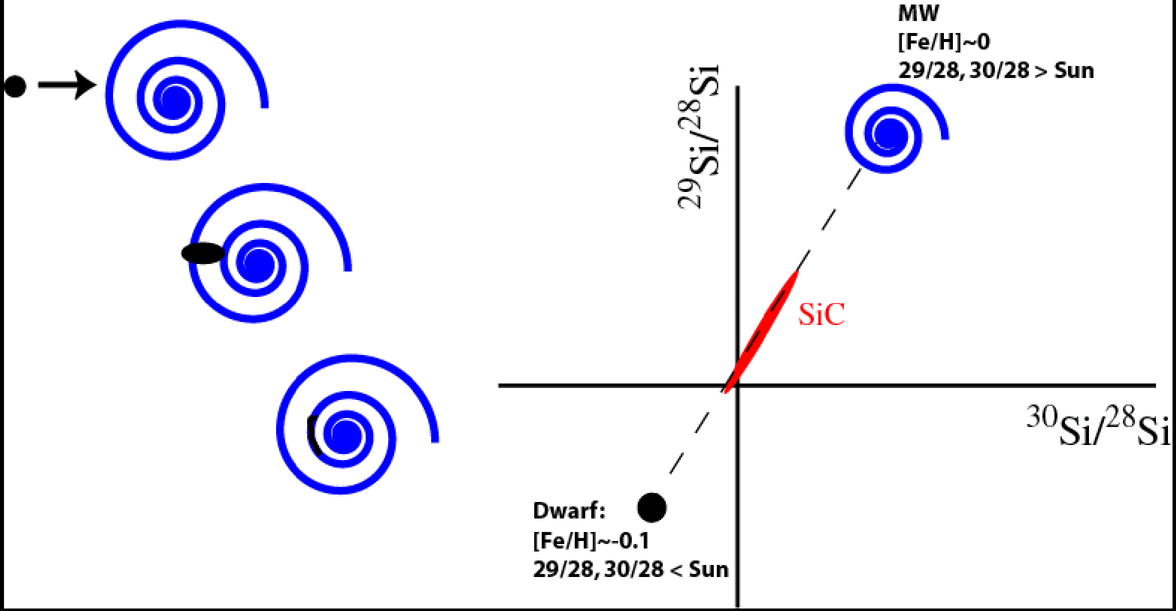
Nittler & Alexander 2003

Presolar Galactic Merger (D. D. Clayton 2003)



- Explains SiC Si and Ti isotopic correlation lines (DDC 2003)
- Slope on Si plot can be explained (Hoppe et al. 2010)

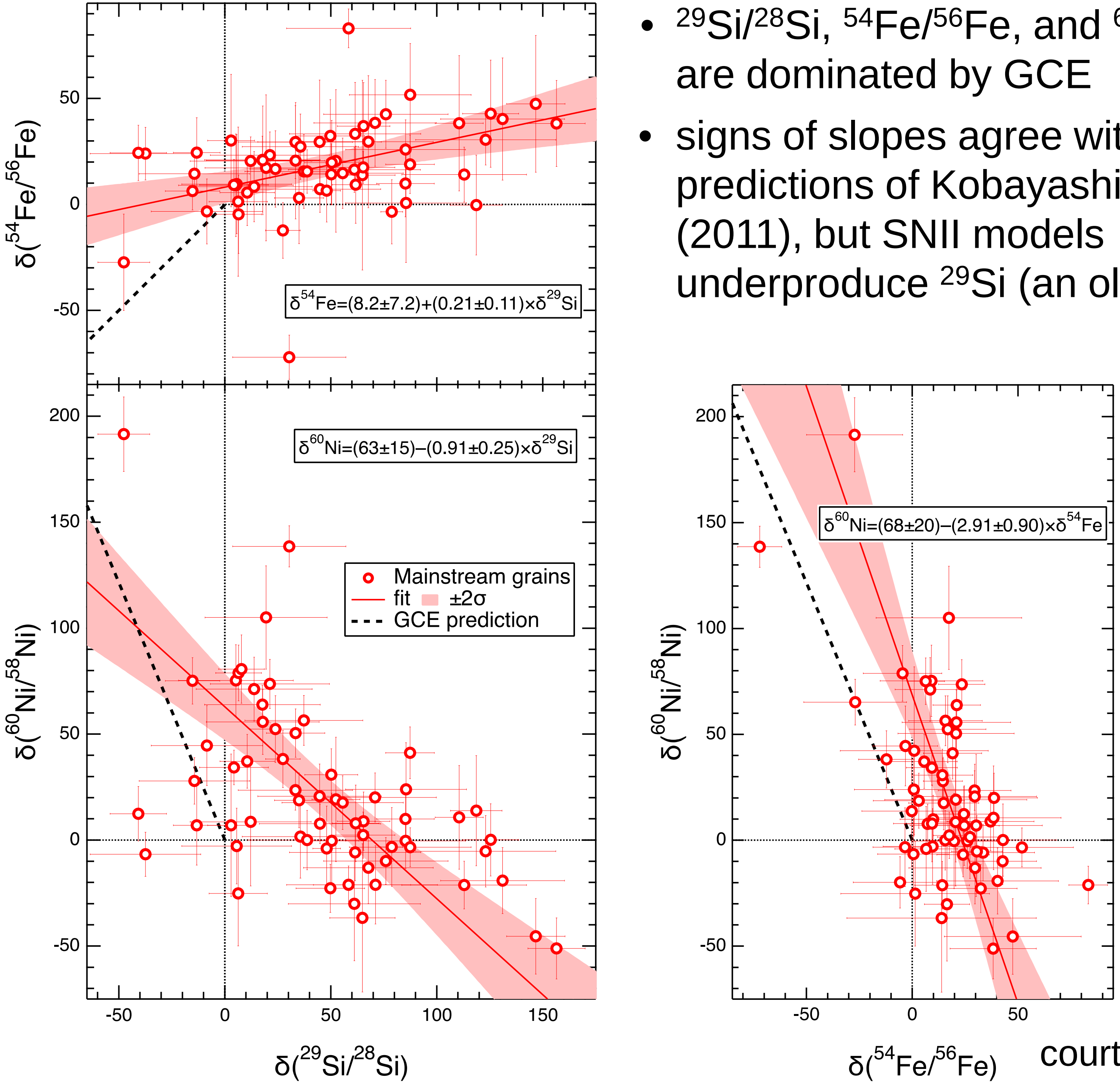
Presolar Galactic Merger (D. D. Clayton 2003)



- Explains SiC Si and Ti isotopic correlation lines (DDC 2003)
- Slope on Si plot can be explained (Hoppe et al. 2010)

- Induced starburst qualitatively can explain “inverse” GCE and dominance of low-mass AGBs among SiC parents (Nittler 2013)

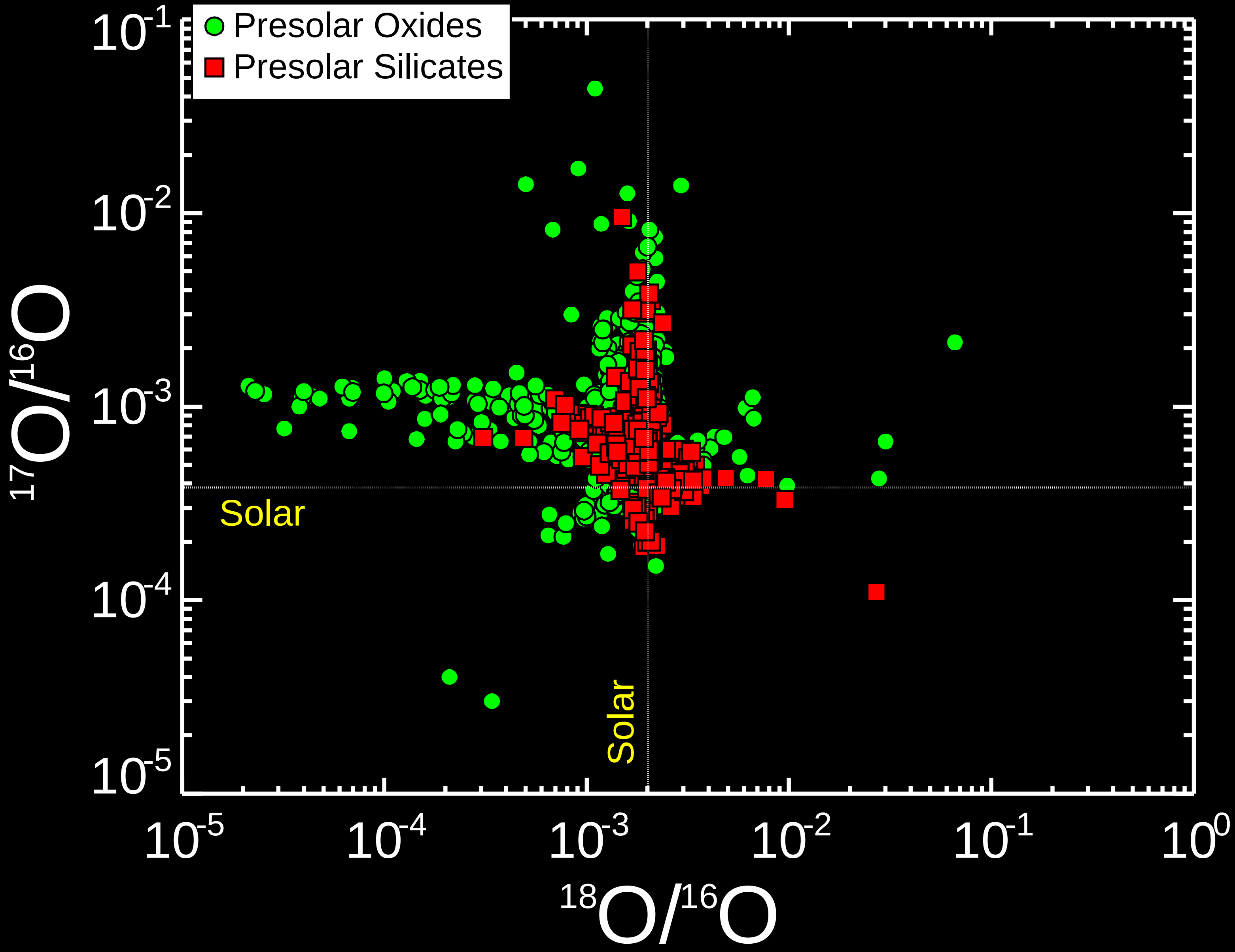
Potential to probe Galactic processes ~5-6 Gyr ago!



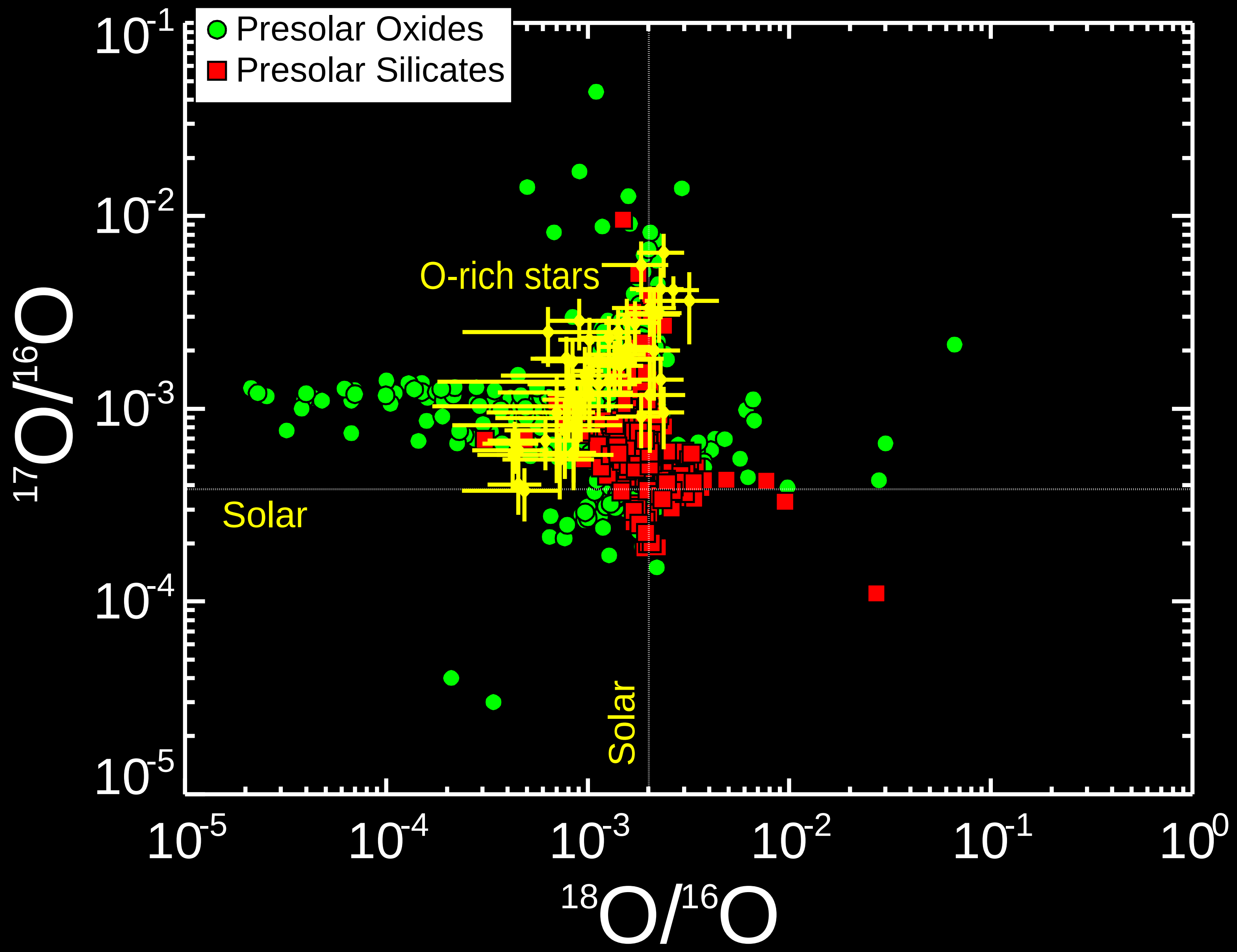
- ^{29}Si/^{28}Si, ^{54}Fe/^{56}Fe, and ^{60}Ni/^{56}Ni are dominated by GCE
- signs of slopes agree with predictions of Kobayashi et al. (2011), but SNII models underproduce ^{29}Si (an old problem)

courtesy A . Davis

O-rich stardust



O-rich stardust



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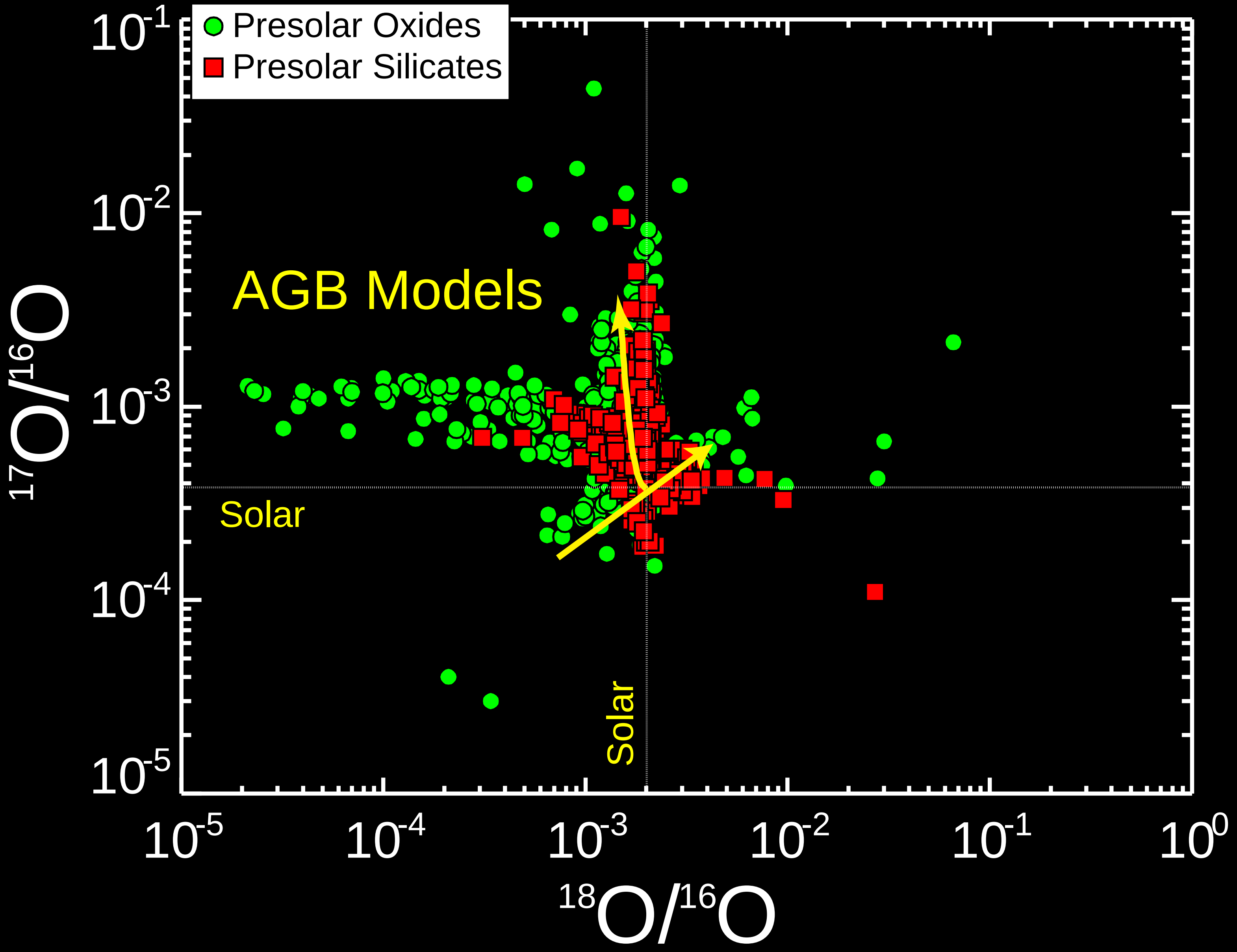
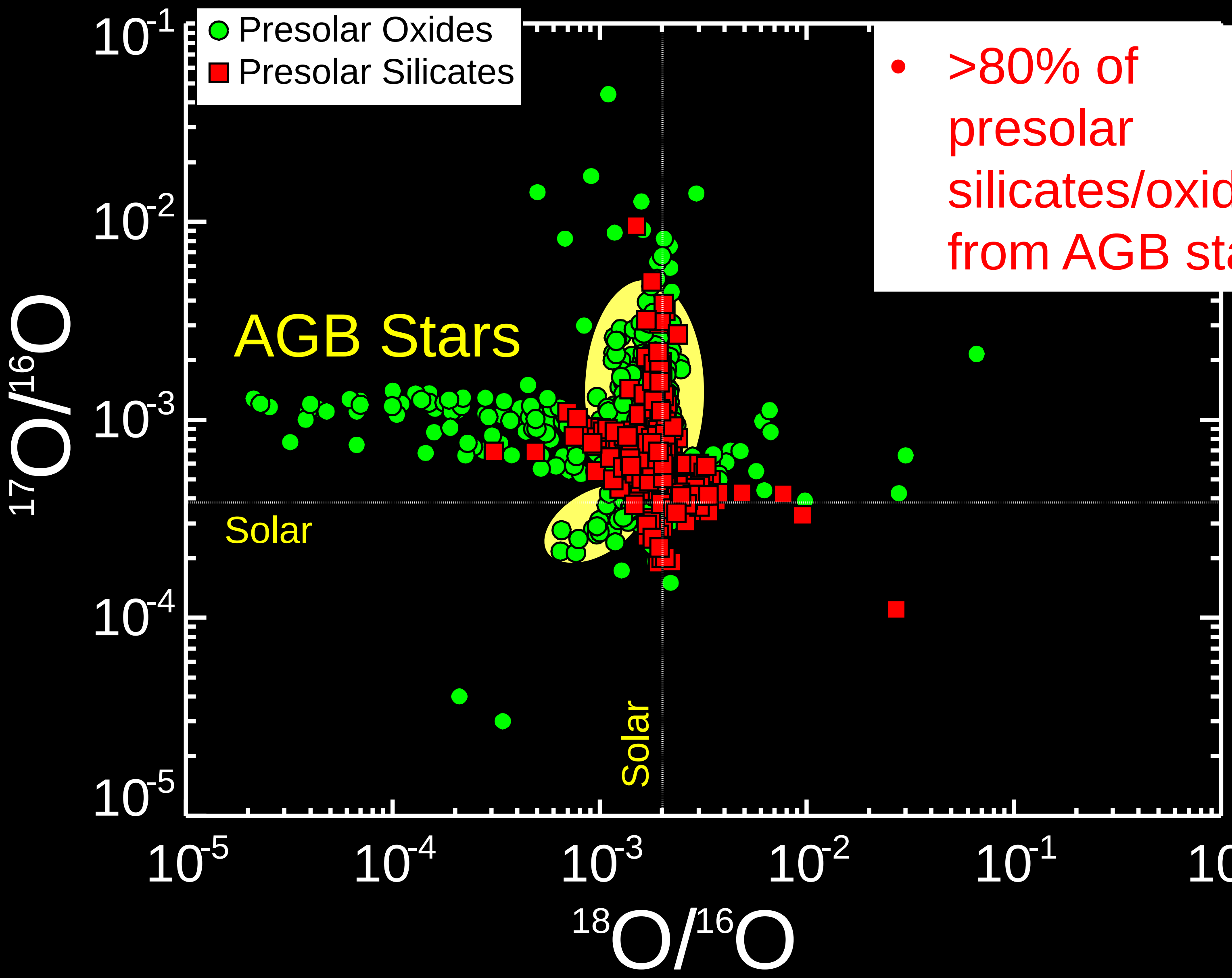
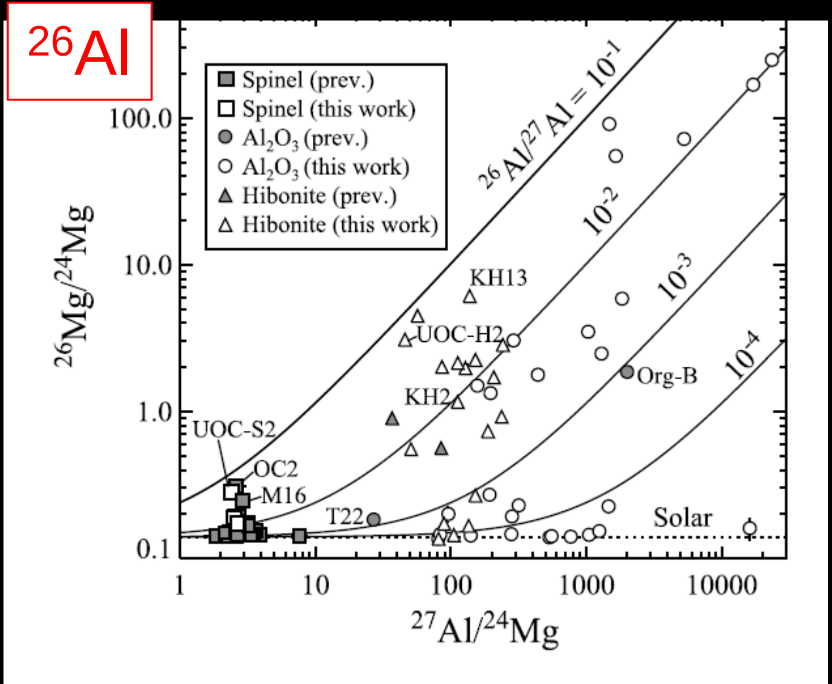


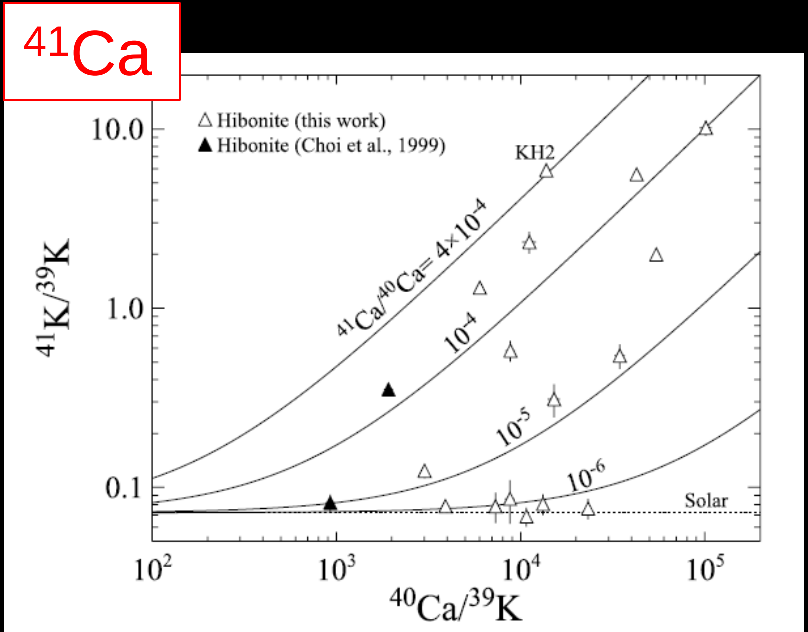
O-rich AGB stardust



- >80% of presolar silicates/oxides from AGB stars

Extinct radioactivities

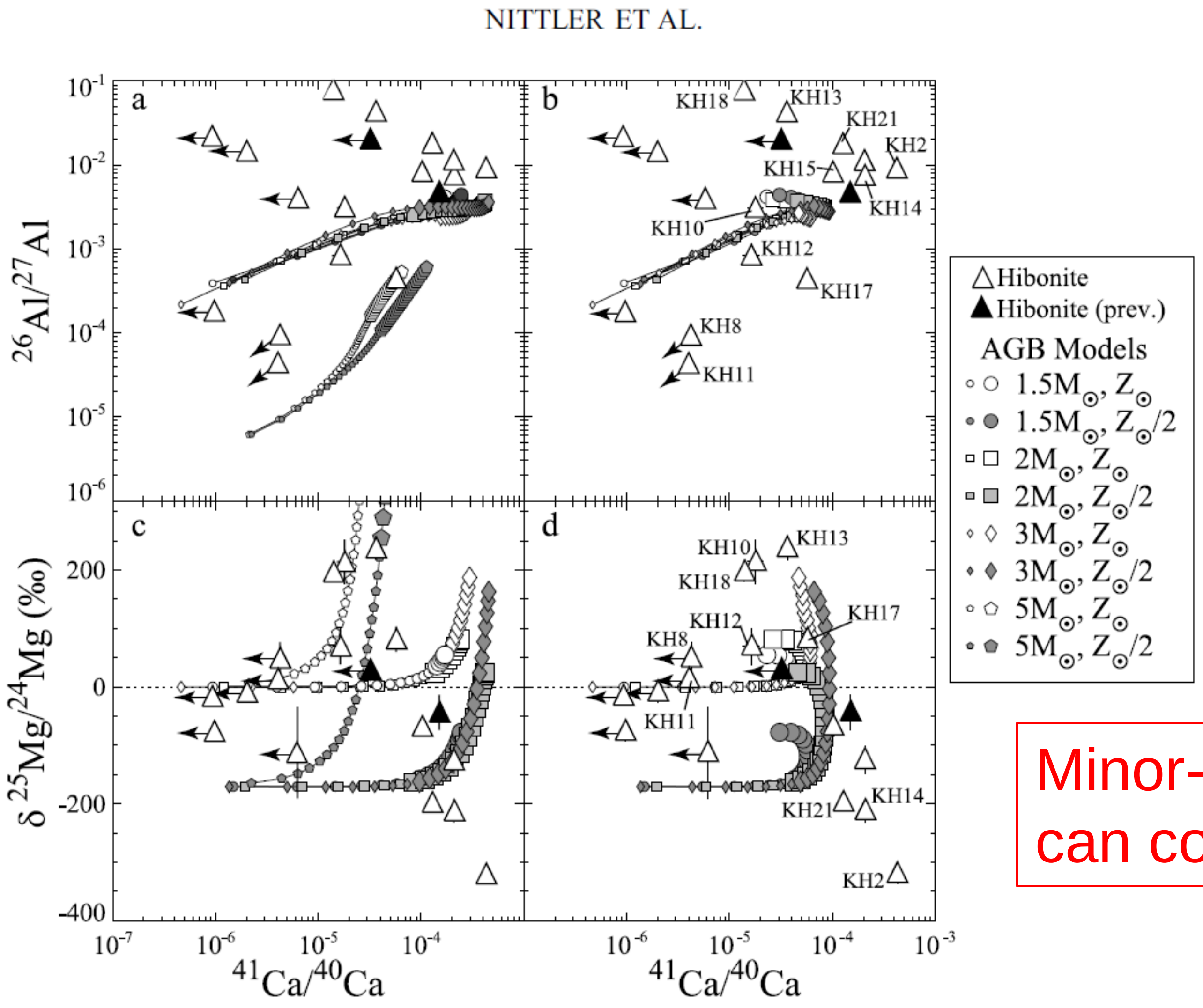




Nittler *et al.* ApJ 2008

- Can detect extinct radioactive isotopes by excesses of daughter isotopes. In some grains Mg is monoisotopic ^{26}Mg

O-rich AGB presolar stardust



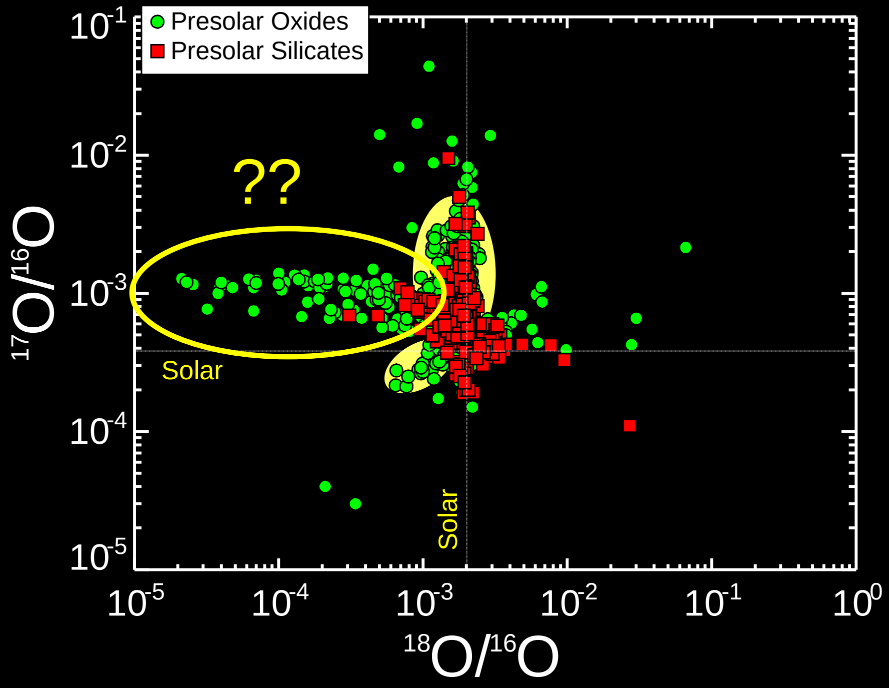
Minor-element data can constrain models

Nittler *et al.* ApJ 2008

^{18}O-poor grains

- Large ^{18}O depletions indicate CNO-cycle H burning in envelope
  - Hot-bottom burning? >4 $M_\odot$ AGB stars
  - Cool-bottom processing (“extra mixing”)?

  <2 $M_\odot$ AGB stars



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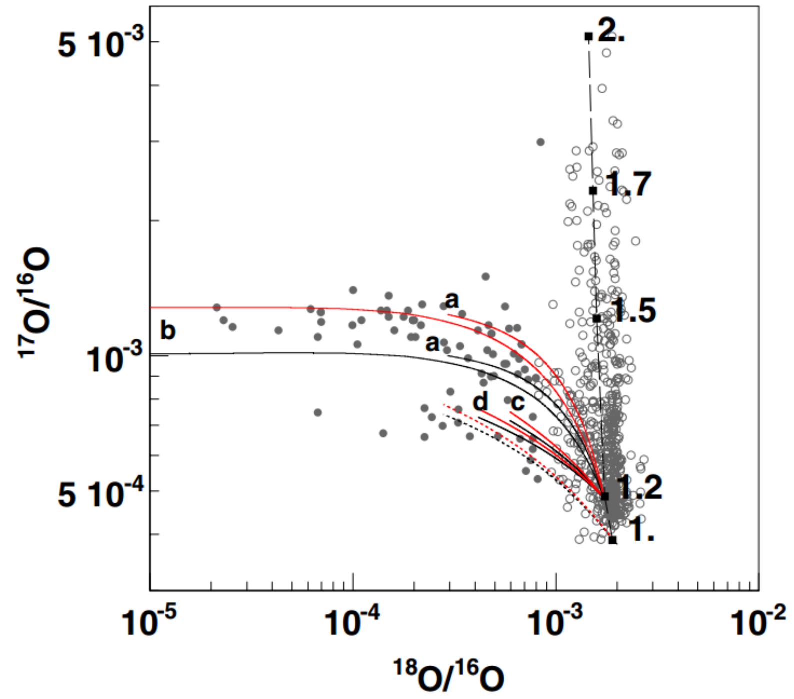
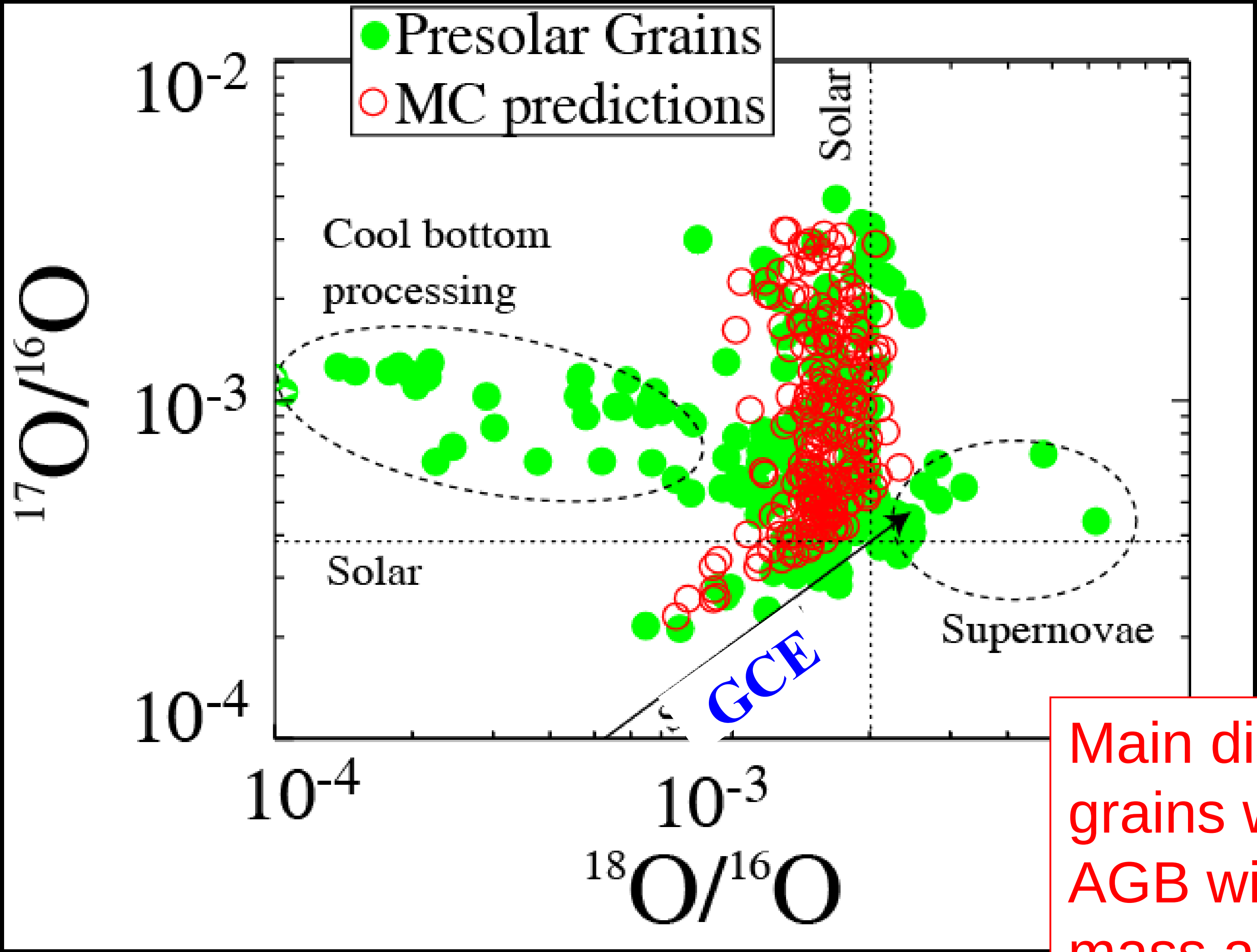


CBP favored because HBB predicts too high ^{17}O/^{16}O

Wasserburg +1995; Nittler+1997; Nollett+ 2003; Lugaro+ 2007; Palmerini+ 2011

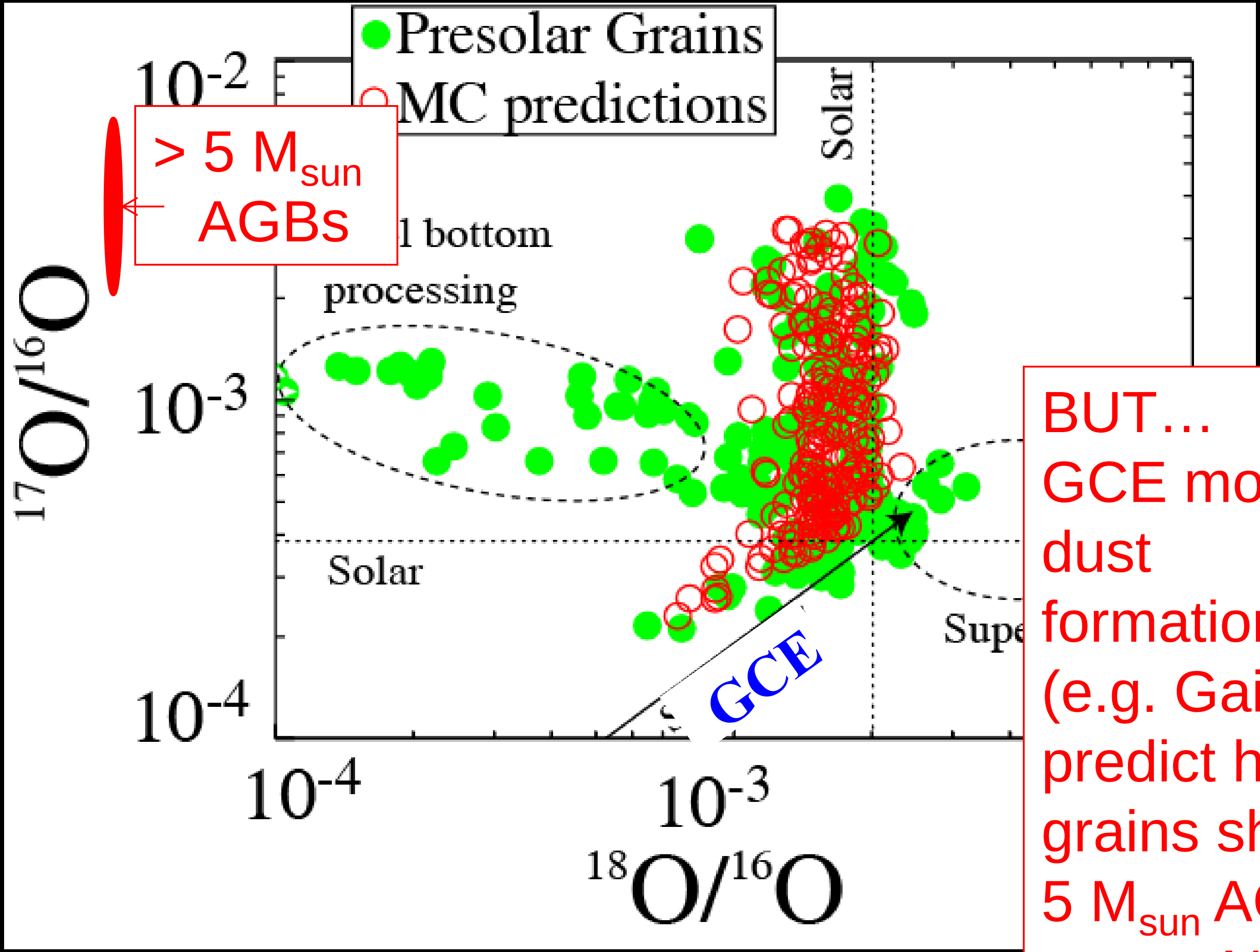
Presolar O-rich Stardust Grains



Main distribution of grains well explained by AGB with range of mass and metallicity (simple GCE)
~10% from supernovae

Nittler, *PASA*, 2009

Presolar O-rich Stardust Grains



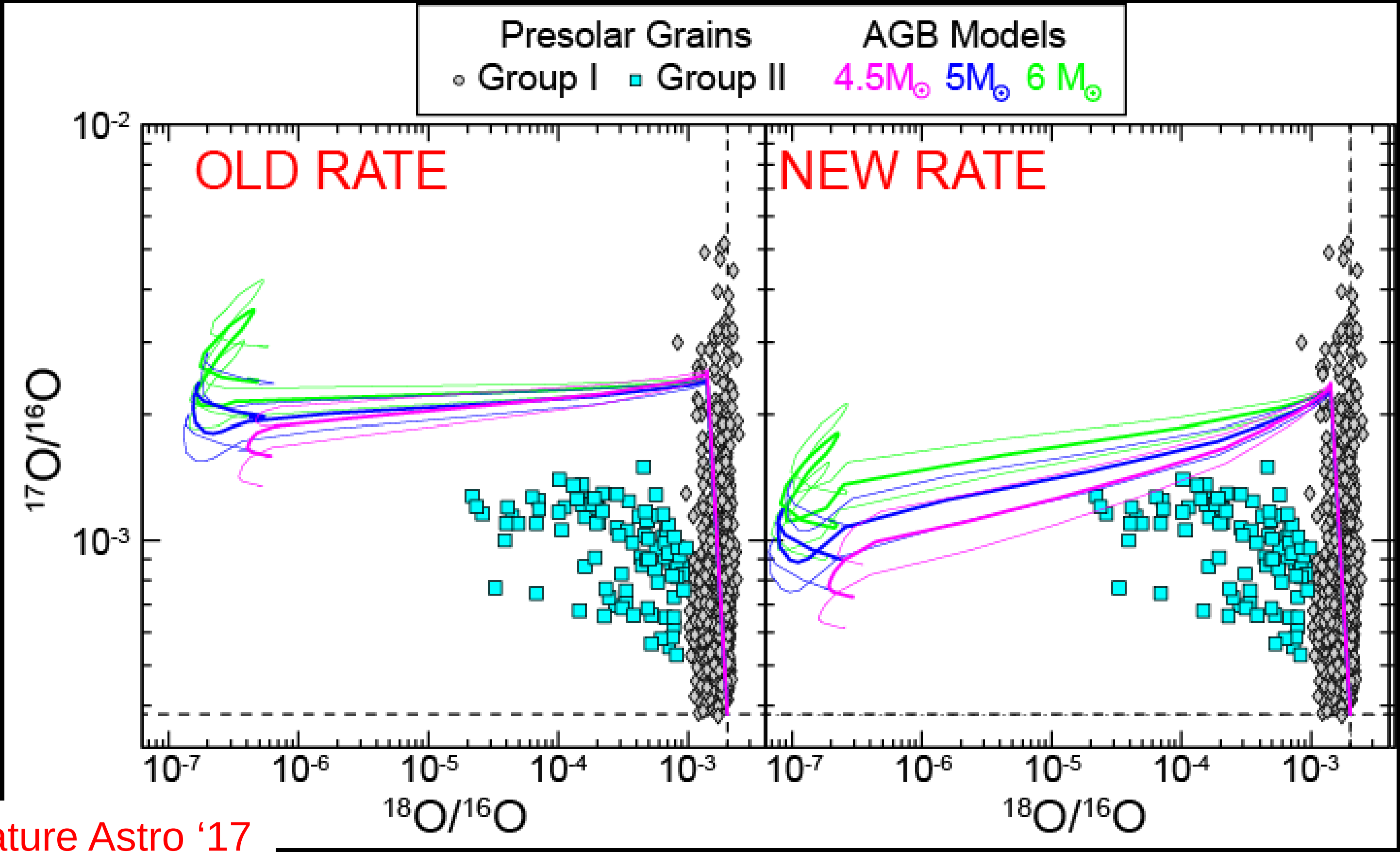
$> 5\ M_{sun}$
AGBs

BUT…
GCE models including dust formation/destruction (e.g. Gail+ 2009) predict half of presolar grains should be from $> 5\ M_{sun}$ AGB stars (HBB)
NOT SEEN

Nittler, *PASA*, 2009

HBB re-visited

- New underground measurement of $^{17}O(p,\alpha)^{14}N$ rate 2x higher than previous accepted value (Brune+, *PRL* 2017)
  - Predicts lower $^{17}O/^{16}O$ in HBB



Lugaro+ Nature Astro '17

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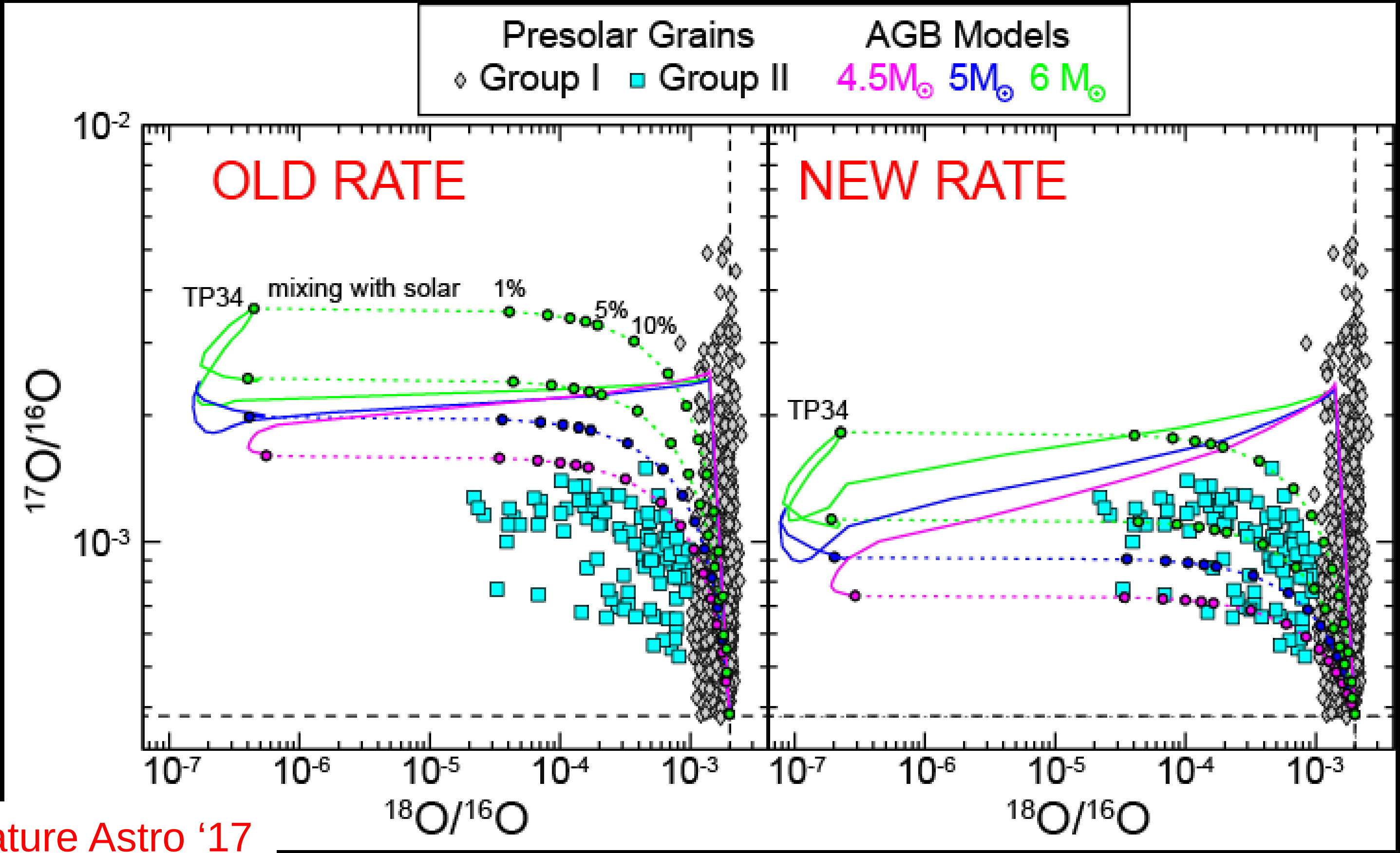

Lugaro+ Nature Astro '17

HBB re-visited

- New reaction rate implies larger fraction of presolar grains from massive AGB stars than previously thought
  - Requires mixing of HBB signature with more normal material: binary interactions?
  - More consistent with galactic evolution/ dust processing models that predict large fraction of presolar grains should be from massive AGBs (Gail+ 2009)

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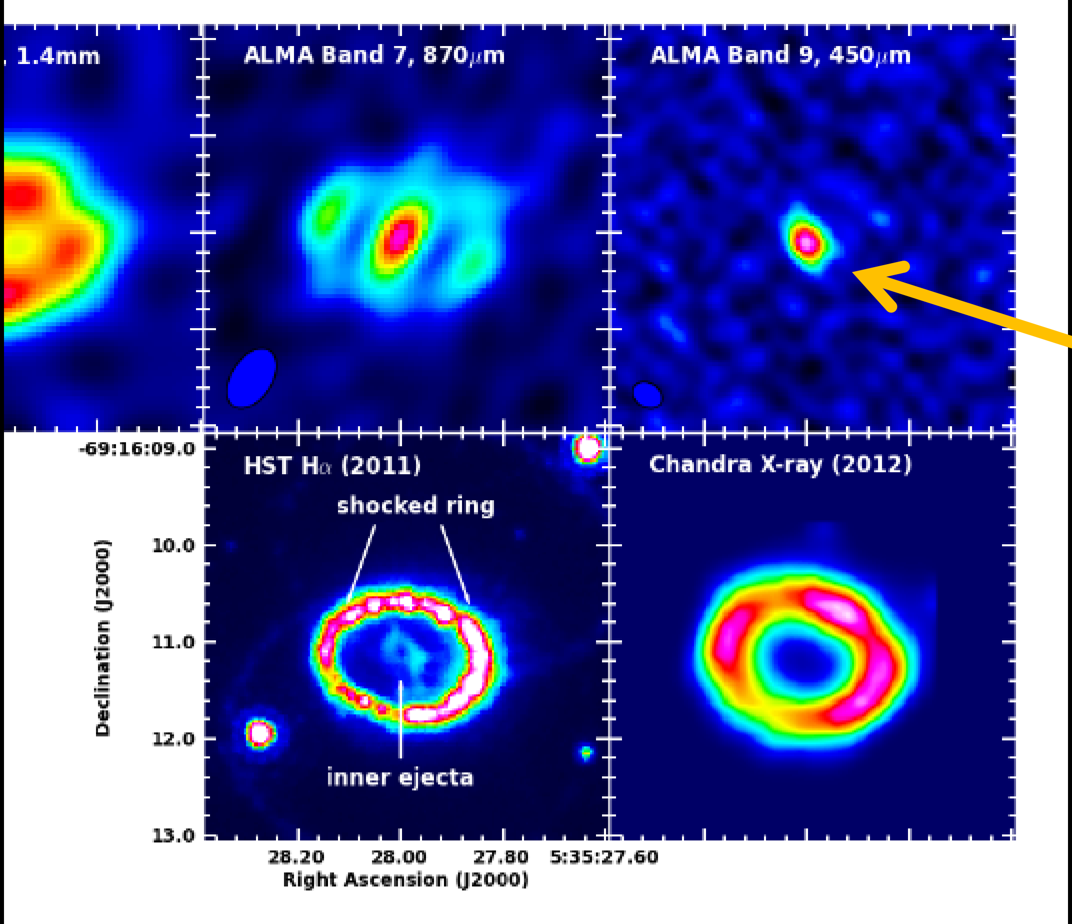
  - Requires mixing of HBB signature with more normal material: binary interactions?
  - More consistent with galactic evolution/ dust processing models that predict large fraction of presolar grains should be from massive AGBs (Gail+ 2009)
- *Highlights interface of nuclear physics, astrophysics and laboratory cosmochemistry for presolar grains*

Supernova Dust

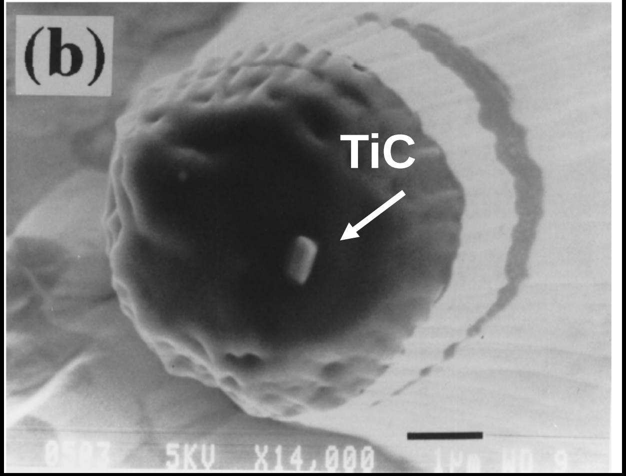
- How much dust and what types produced by SNe hotly debated in astronomical community



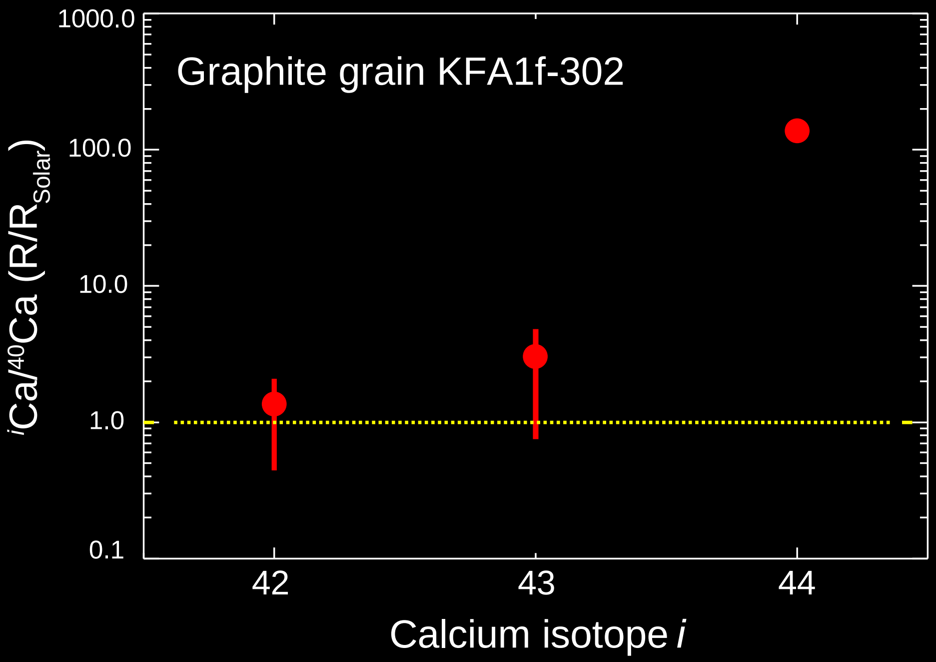
ALMA detection of cold dust in SN 1987A (Indebetouw et al. 2014)

Supernova presolar grains

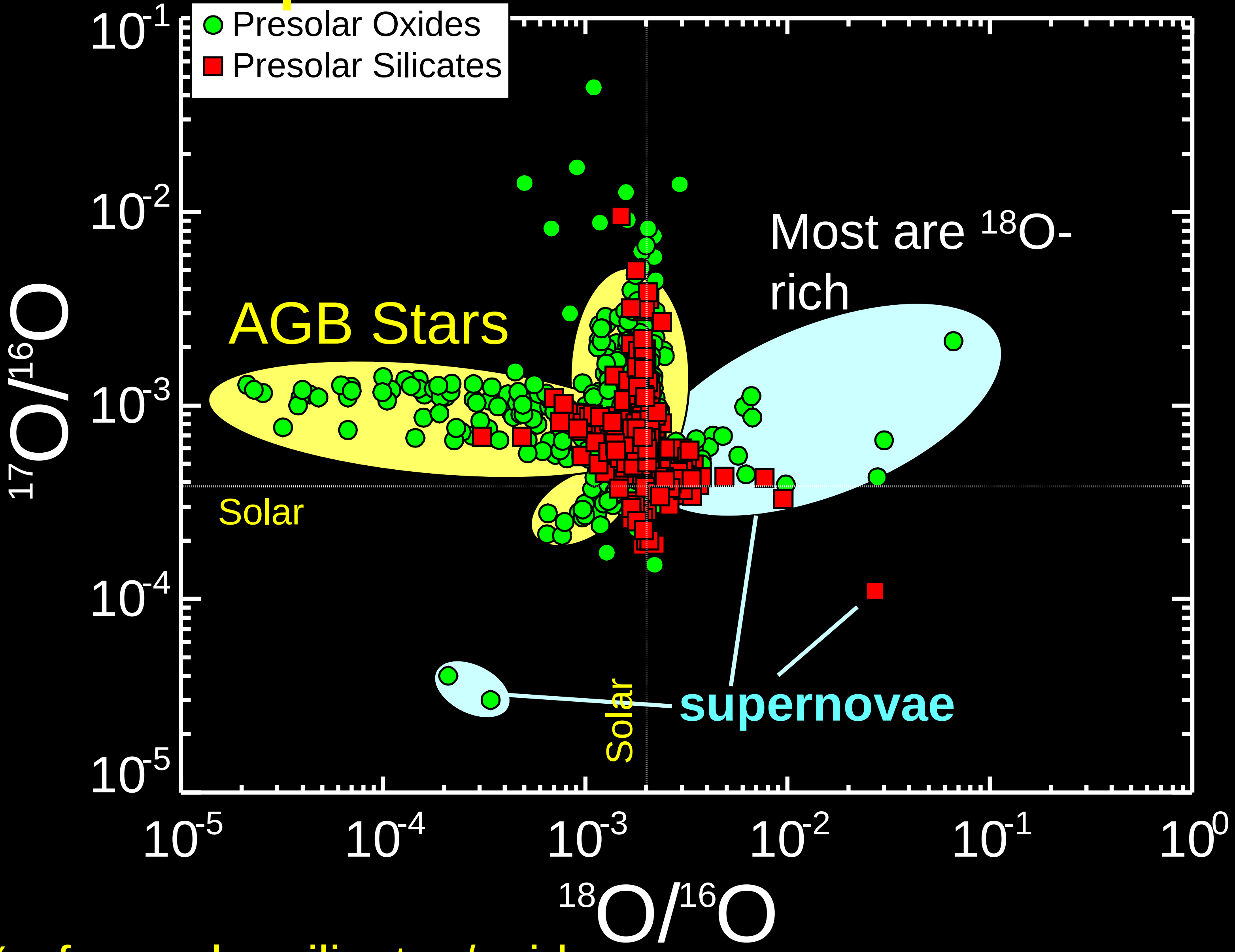
- ~2% of SiC, <50% of graphite, ~10% of oxides/silicates originated in Type II supernovae
- “Smoking gun” is extinct ^{44}Ti
  - – 60y half-life; SN product



Nittler et al. 1996, Amari & Zinner 1997

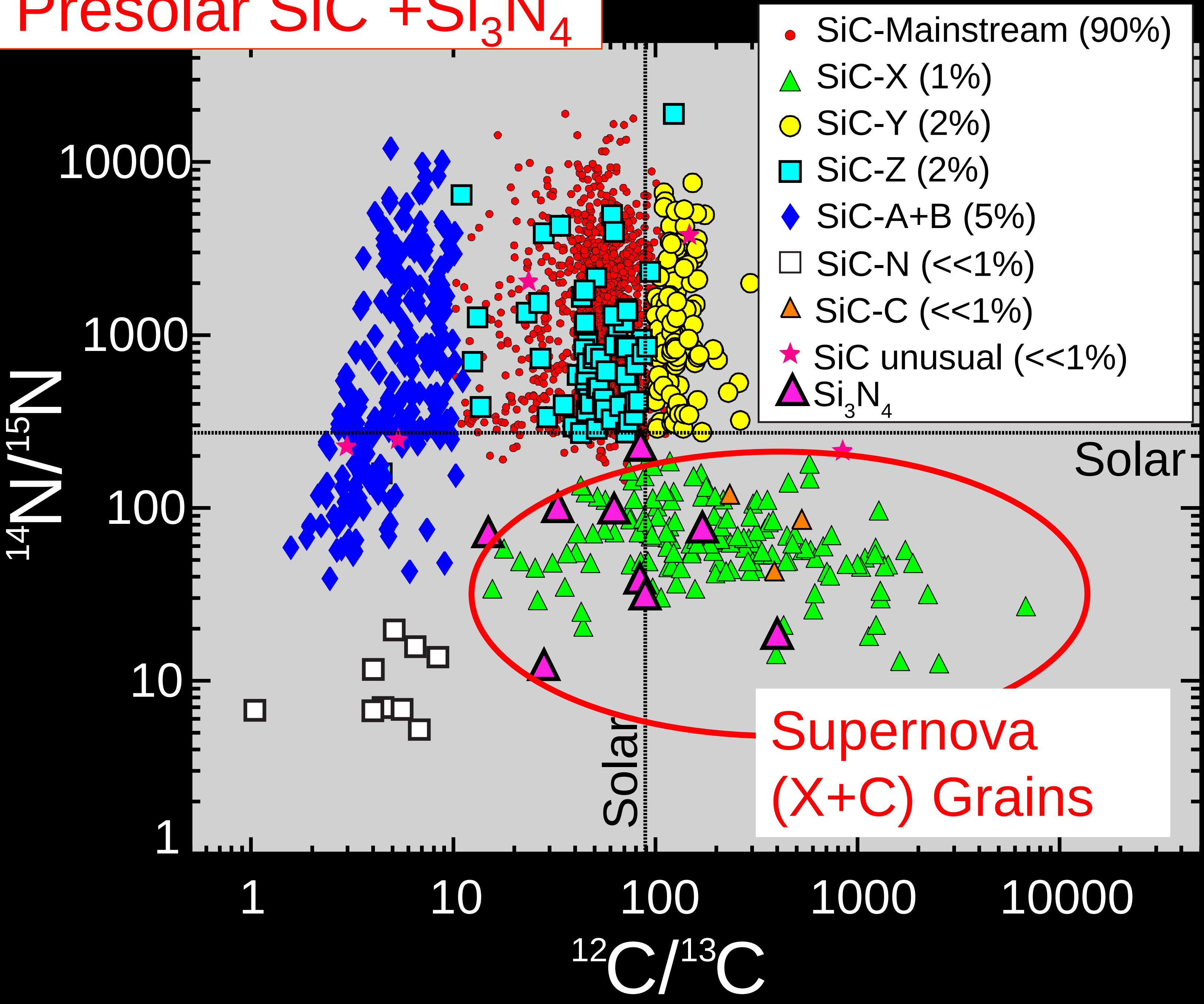


Supernova O-rich dust



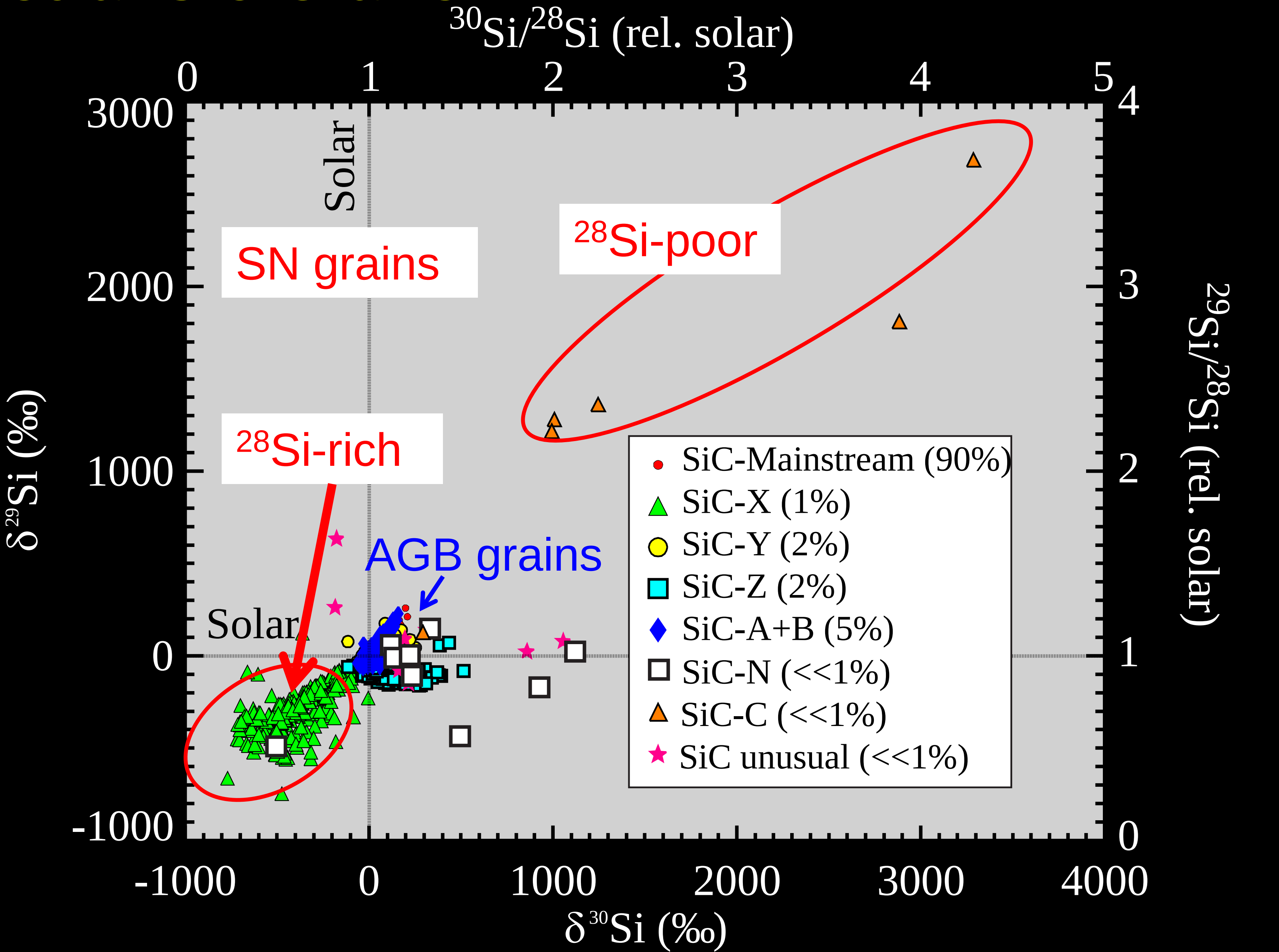
~10% of presolar silicates/oxides

Presolar SiC +Si_3N_4

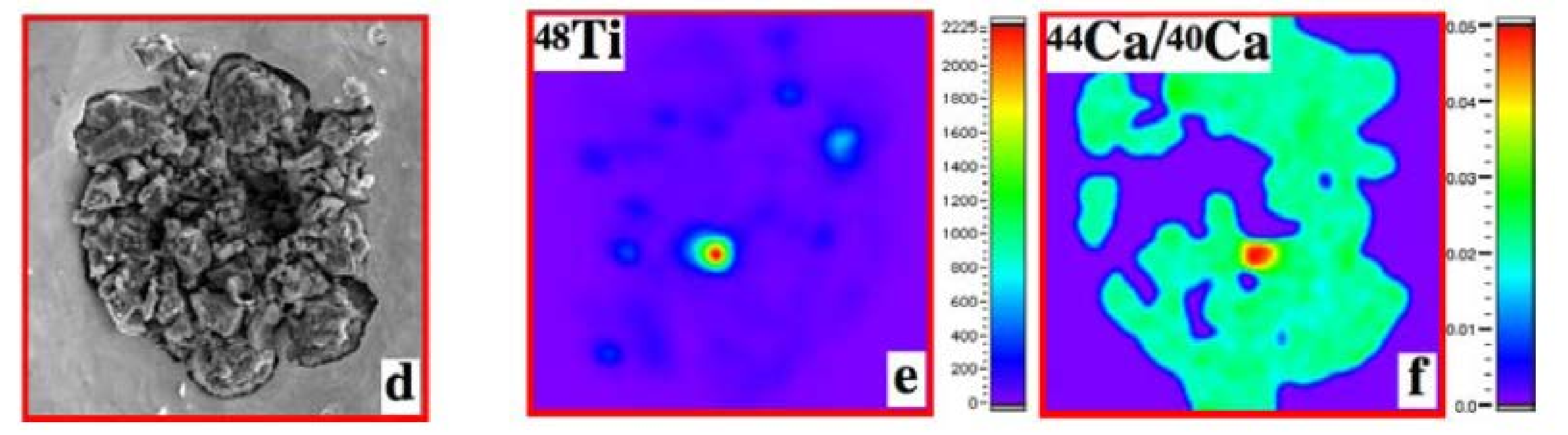


Supernova
(X+C) Grains

Presolar SiC Grains



“Bonanza”

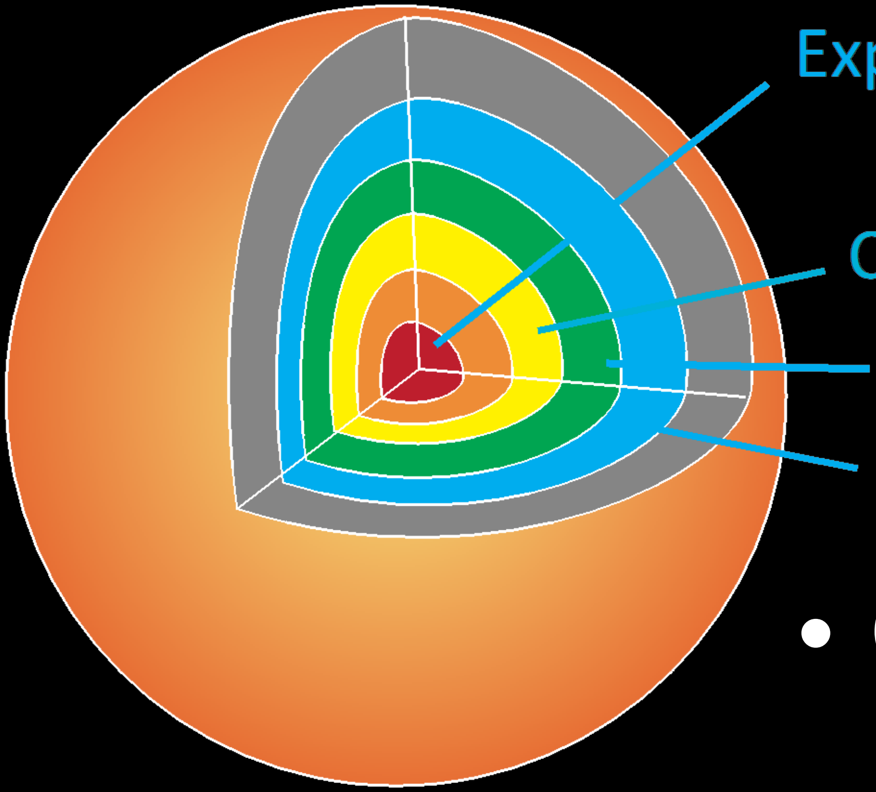


- 30 micron SiC X-grain!
- Giant aggregate, isotopically homogeneous in Si, C, N

Supernova dust can be BIG

Zinner + 2011; Gyngard+ submitted

Presolar Supernova Stardust



Explosive burning: ^{28}Si, ^{44}Ti

C burning: ^{16}O, ^{24}Mg

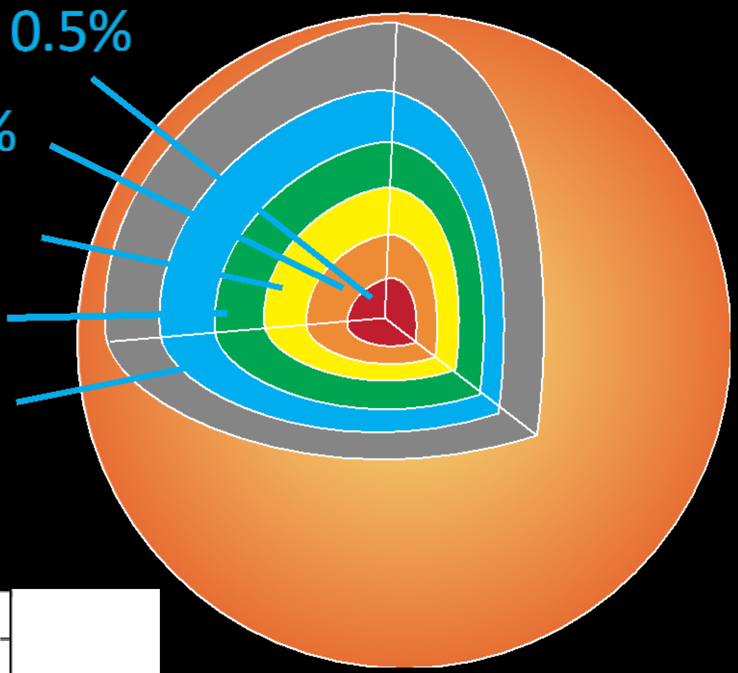
He burning: ^{12}C, ^{15}N, ^{18}O

H burning: ^{13}C, ^{14}N, ^{17}O, ^{26}Al

- Grain compositions point to contributions from different shells
    - Mixing!

Supernova Mixing

Mixing in grain parents dominated by outer envelope and H-burning zone



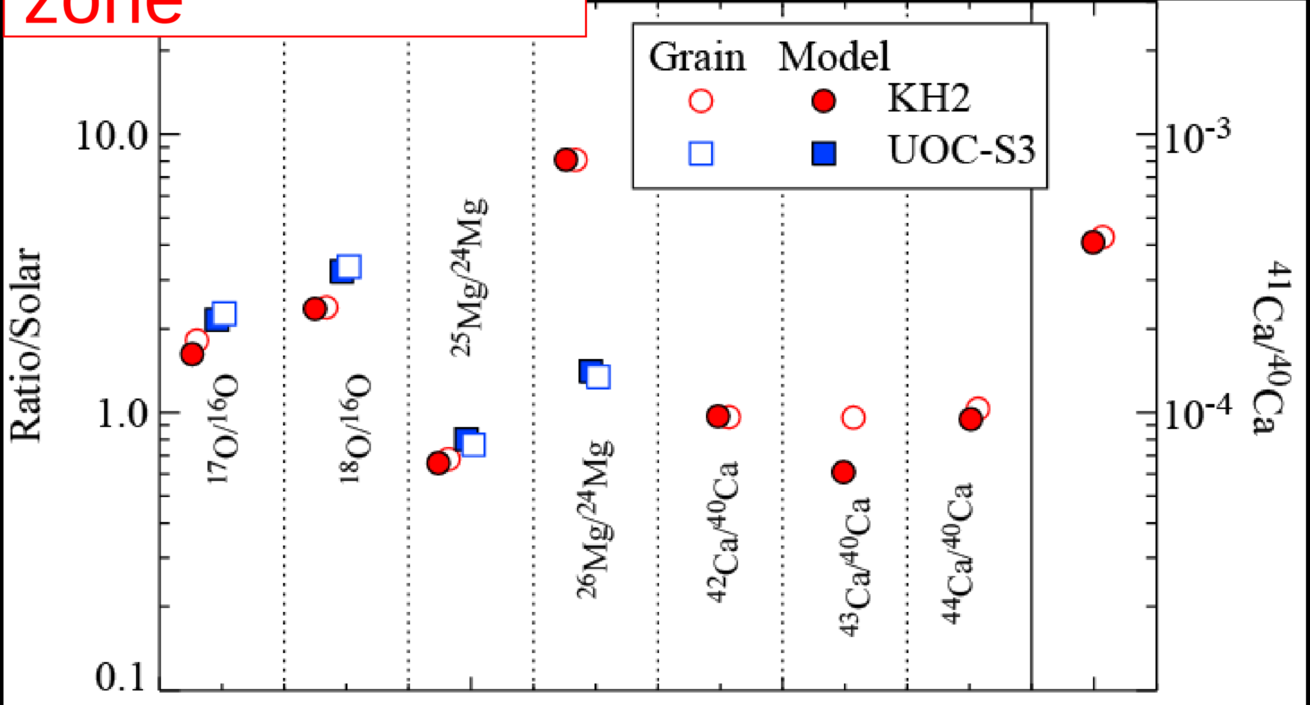
Explosive burning: 0.5%

O, Ne burning: 0.4%

C burning: 0.1%

He burning: 1%

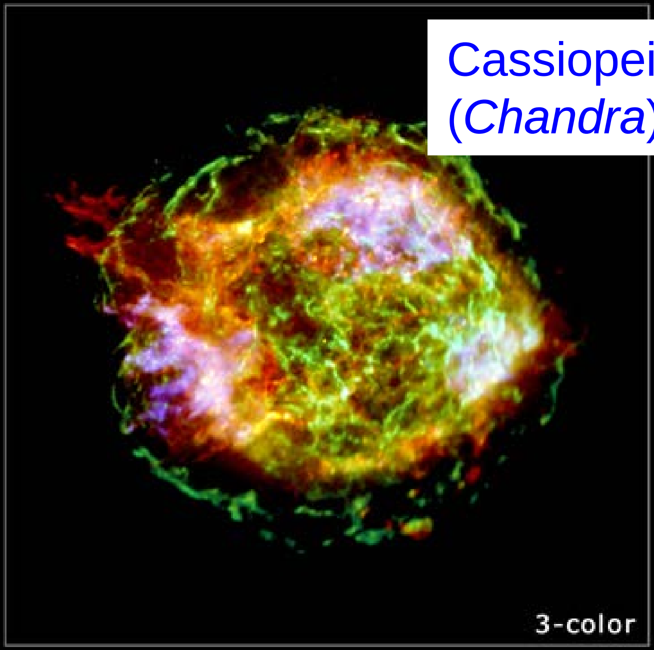
H burning: 98%



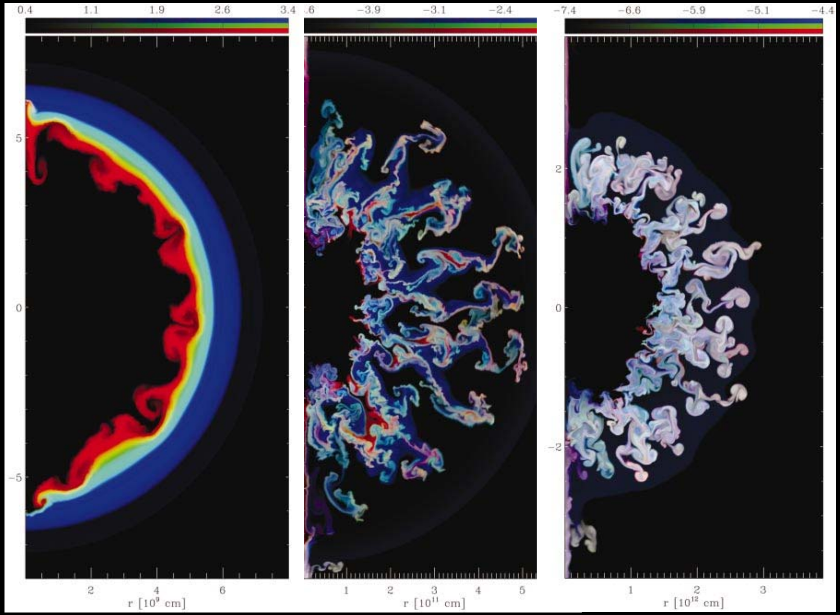
Nittler *et al.* ApJ 2008

Supernova Mixing

- Observations and theory both indicate extensive mixing of SN ejecta, due to hydrodynamic instabilities



Cassiopeia-A
(*Chandra*)

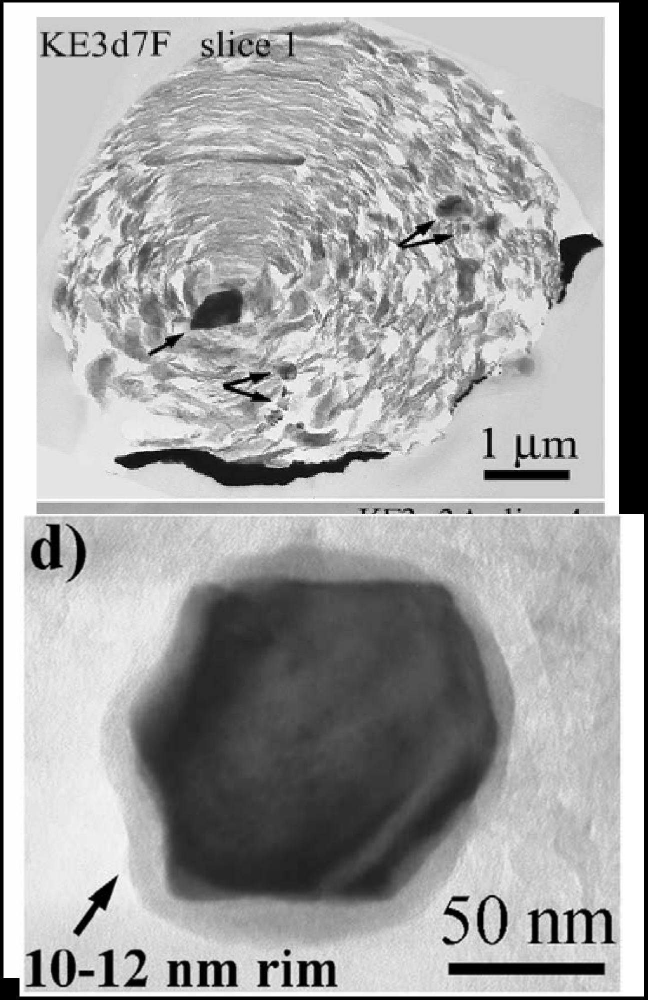


- But neither can yet probe microscopic scales required to explain grains

2-d hydrodynamic simulation by Kifonidis et al. (A&A 2003)

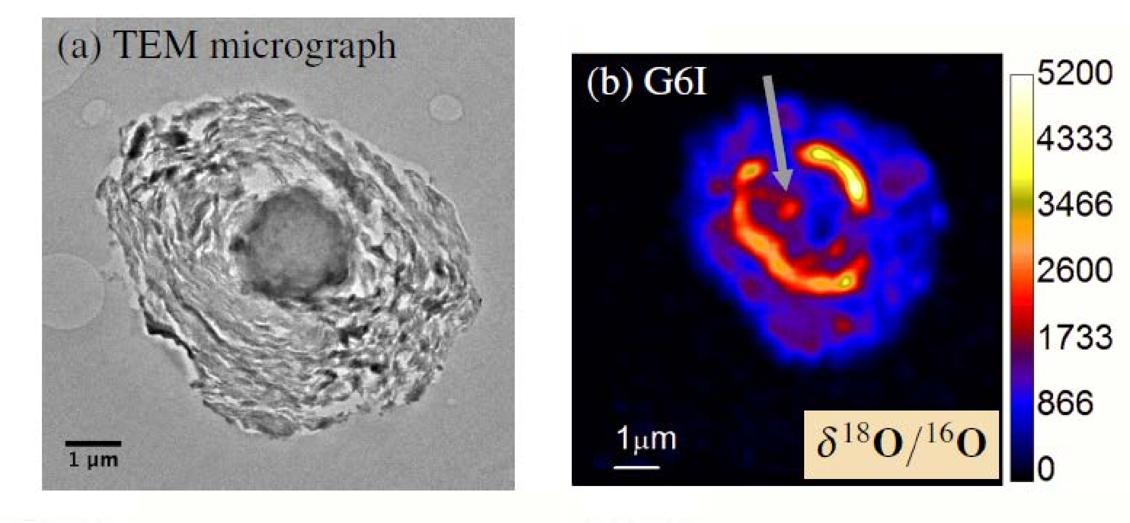
Supernova Graphite

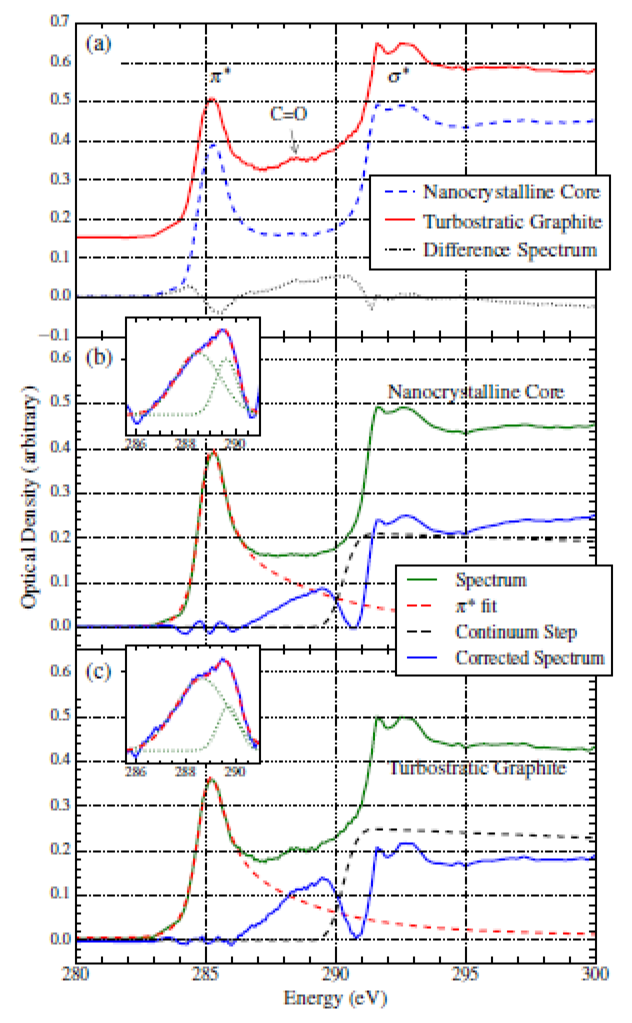
- SN graphites lower density, incorporate more trace elements (O, Si …) than AGB grains
- Like AGB grains, can reach >10 µm in size
- Abundant TiC and Fe-Ni metal sub-grains
  - sputtered rims
  - wide range of O isotopic compositions and Ti/V ratios



Croat *et al.* 2003

Supernova Graphite



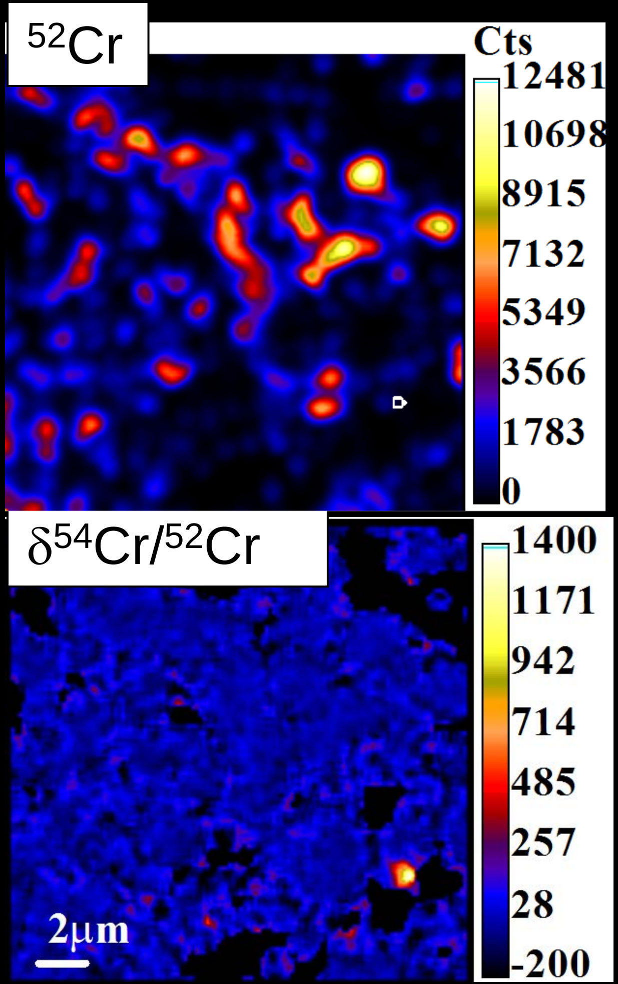


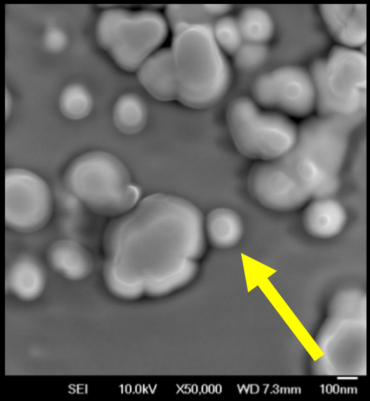
- One SN graphite with nanocrystalline core, mantled by graphite shells (Groopman+2014)
  - Structure/chemistry indicates changing chemical/physical conditions during grain growth

C-edge X-ray Absorption Spectra

^{54}Cr-rich grains

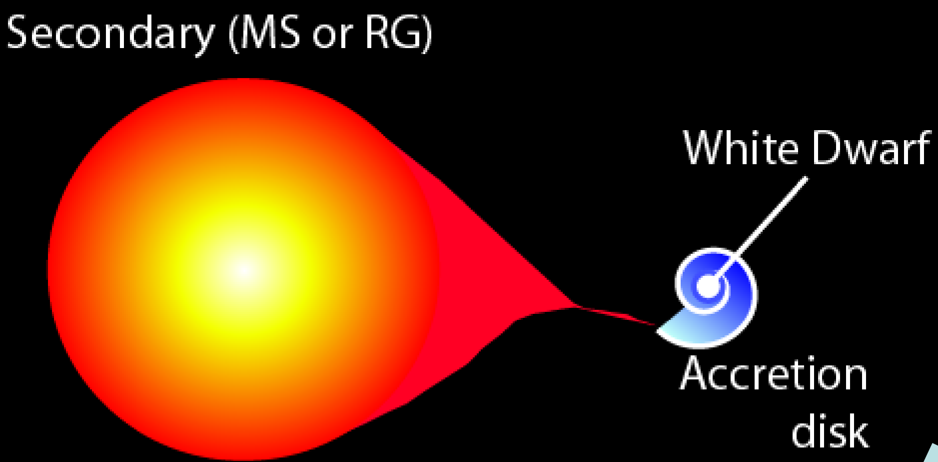
- Extreme ^{54}Cr-rich sub-μm oxides in Orgueil meteorite (Dauphas *et al.*, 2010; Qin et al. 2011)
  - <100 nm
  - Inferred ^{54}Cr/^{52}Cr may be >20 times solar, but measurements not resolved
  - Most likely formed in ^{16}O-rich C-burning shells of Type II Supernovae

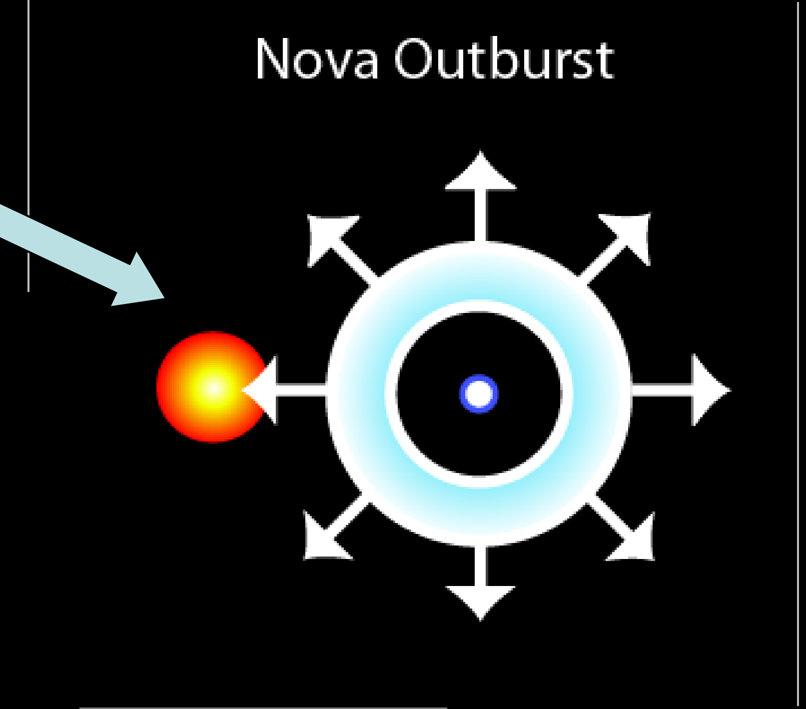


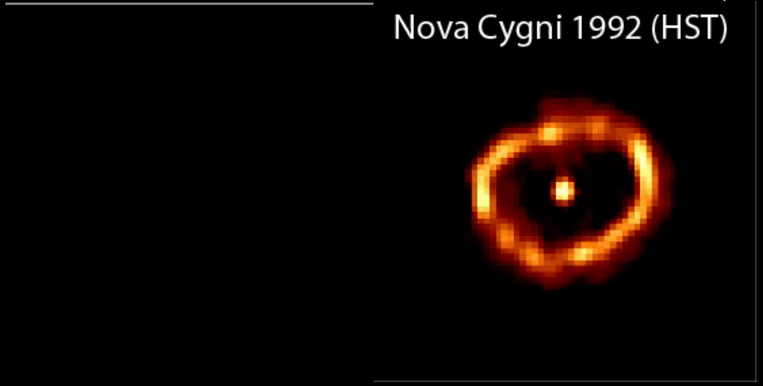


Supernova dust can be SMALL!

Nova Stardust?

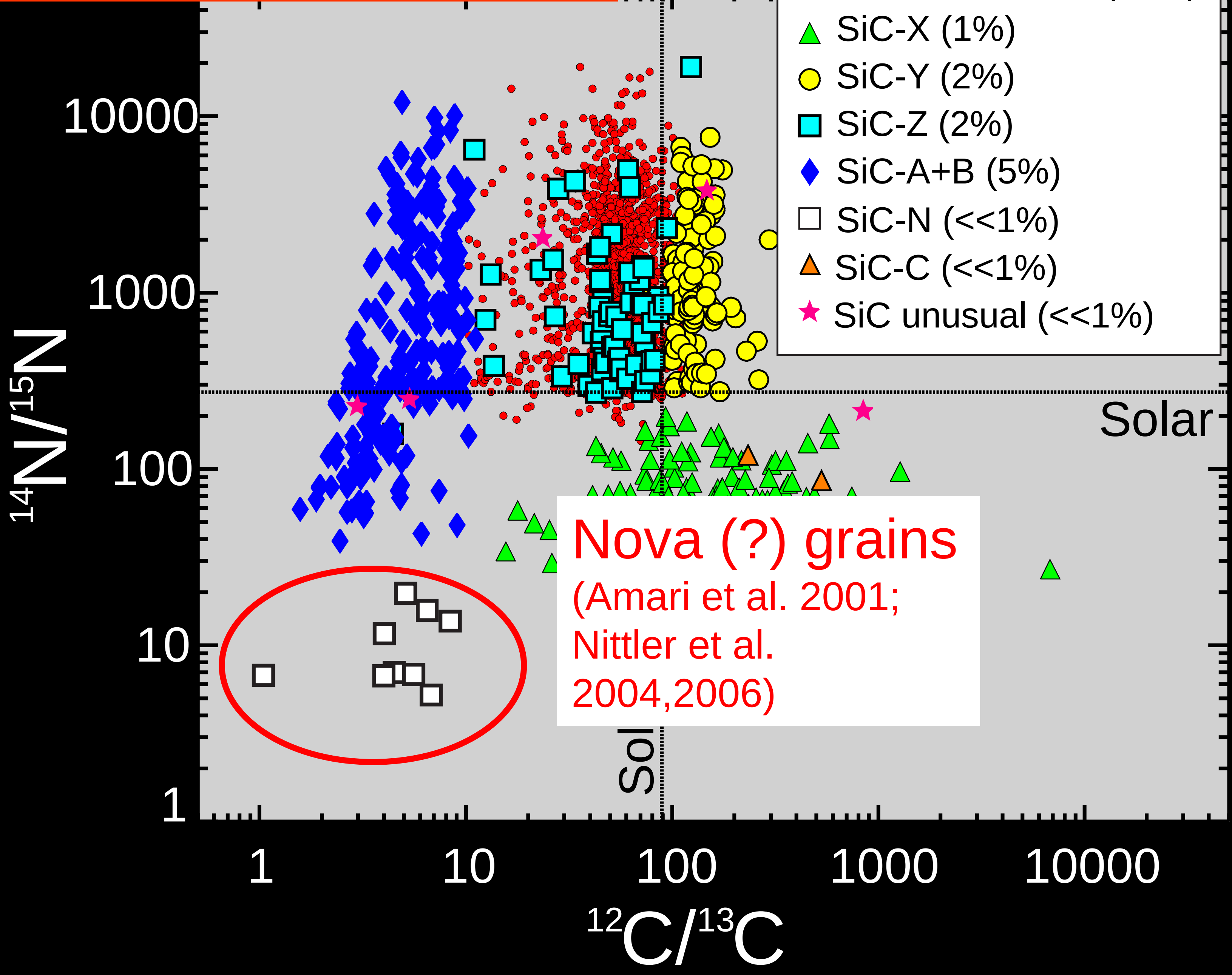






- High-temperature H-burning (e.g., Gehrz et al. 1998)
  - Low $^{12}C/^{13}C$, $^{16}O/^{17}O$, $^{16}O/^{18}O$
  - Production of ^{22}Ne , ^{26}Al
  - Modification of isotopes of other light elements (up to S, possibly higher, Jose et al. 2007)

Presolar SiC Grains

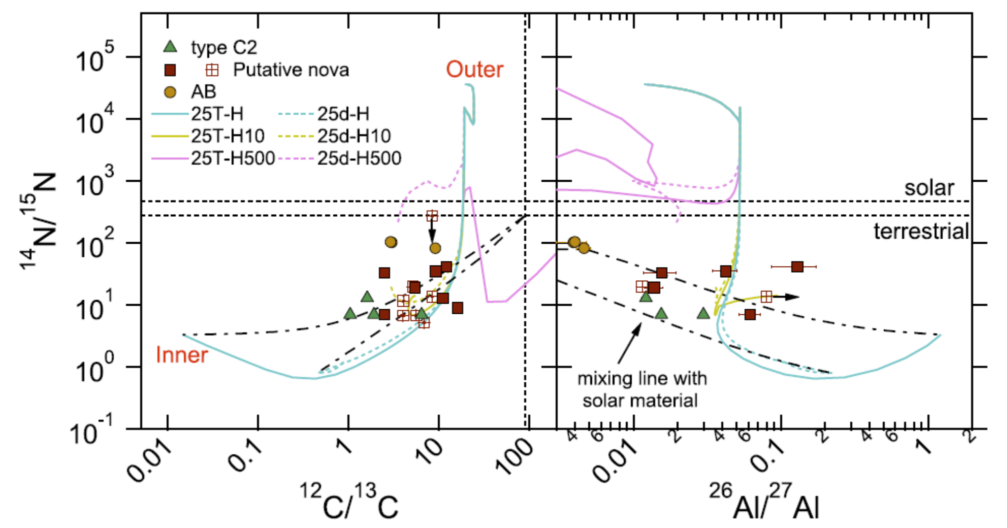


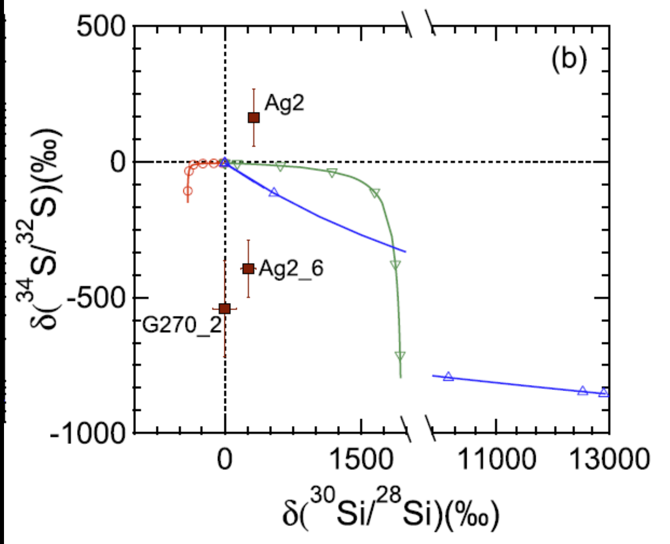
Nova (?) grains

(Amari et al. 2001; Nittler et al. 2004,2006)

Nova SiC Grains?

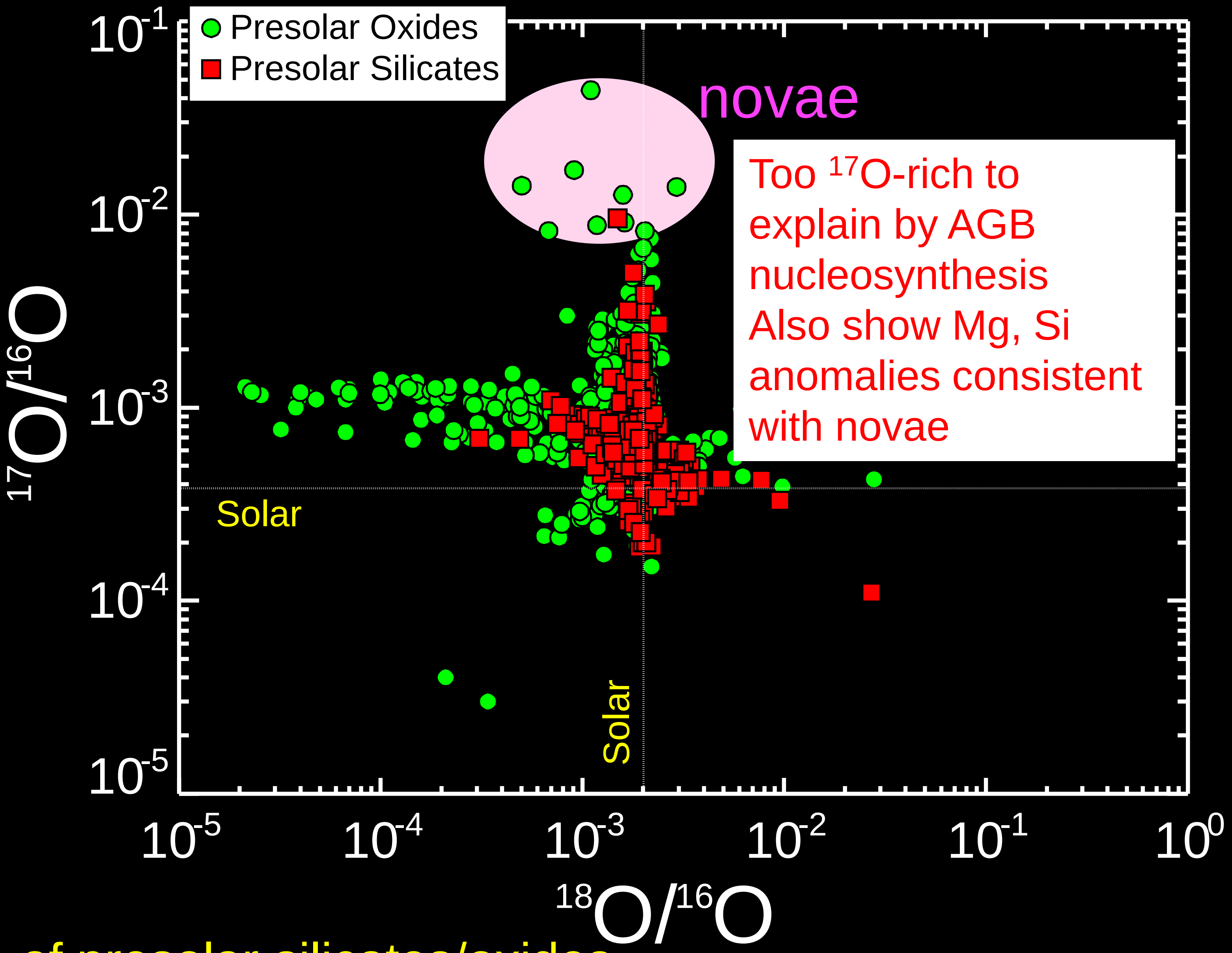
- Measured 14 new “nova” grains Minor-element isotopes point to supernovae (!) for several grains
  - Requires H ingestion into He-burning shell during explosion – explosive H-burning (Pignatari *et al.* 2015)
  - Nova origin compatible with some grains but not required (SN may be preferred)





Liu et al. 2016

Nova O-rich dust



Too ^{17}O-rich to explain by AGB nucleosynthesis

Also show Mg, Si anomalies consistent with novae

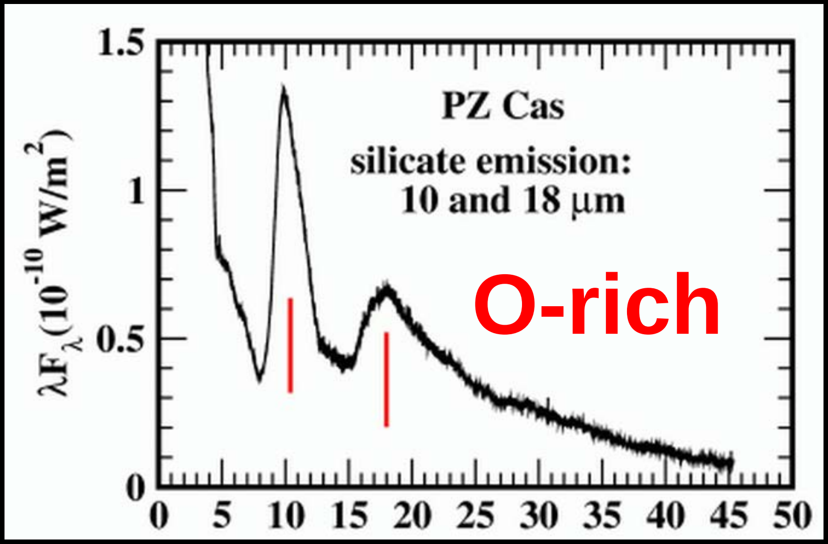
~1% of presolar silicates/oxides

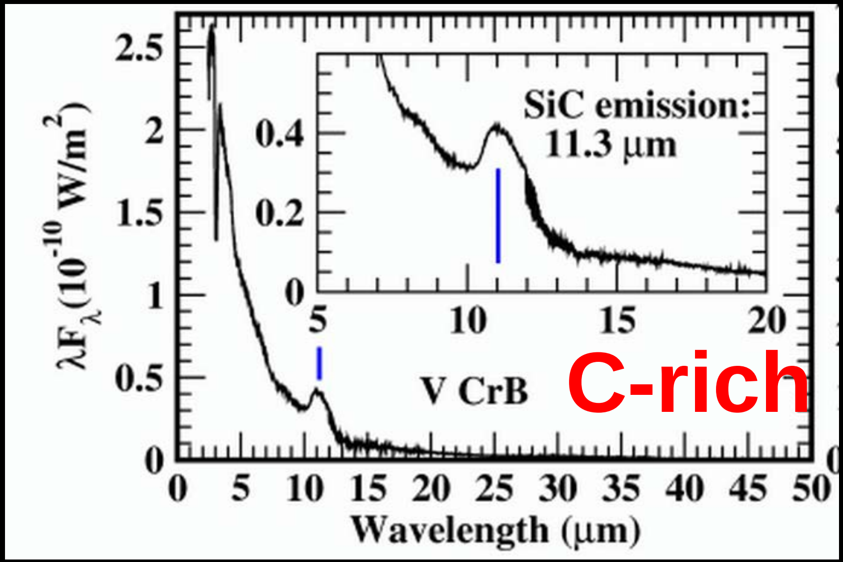
Presolar Grain Mineralogy

- Presolar grains condensed in stellar environments, were subjected to processes in the ISM (collisions, radiation …) and in the early SS (heating, water ,…)
- Structures and compositions can provide info on all stages of grain histories

AGB star chemistry/mineralogy

- Mixing ("dredge-up") of ^{12}C from He-shell gradually increases C/O ratio; when >1 chemistry drastically changes
  - C/O<1 : silicates/oxides condense
  - C/O>1: SiC, C condense



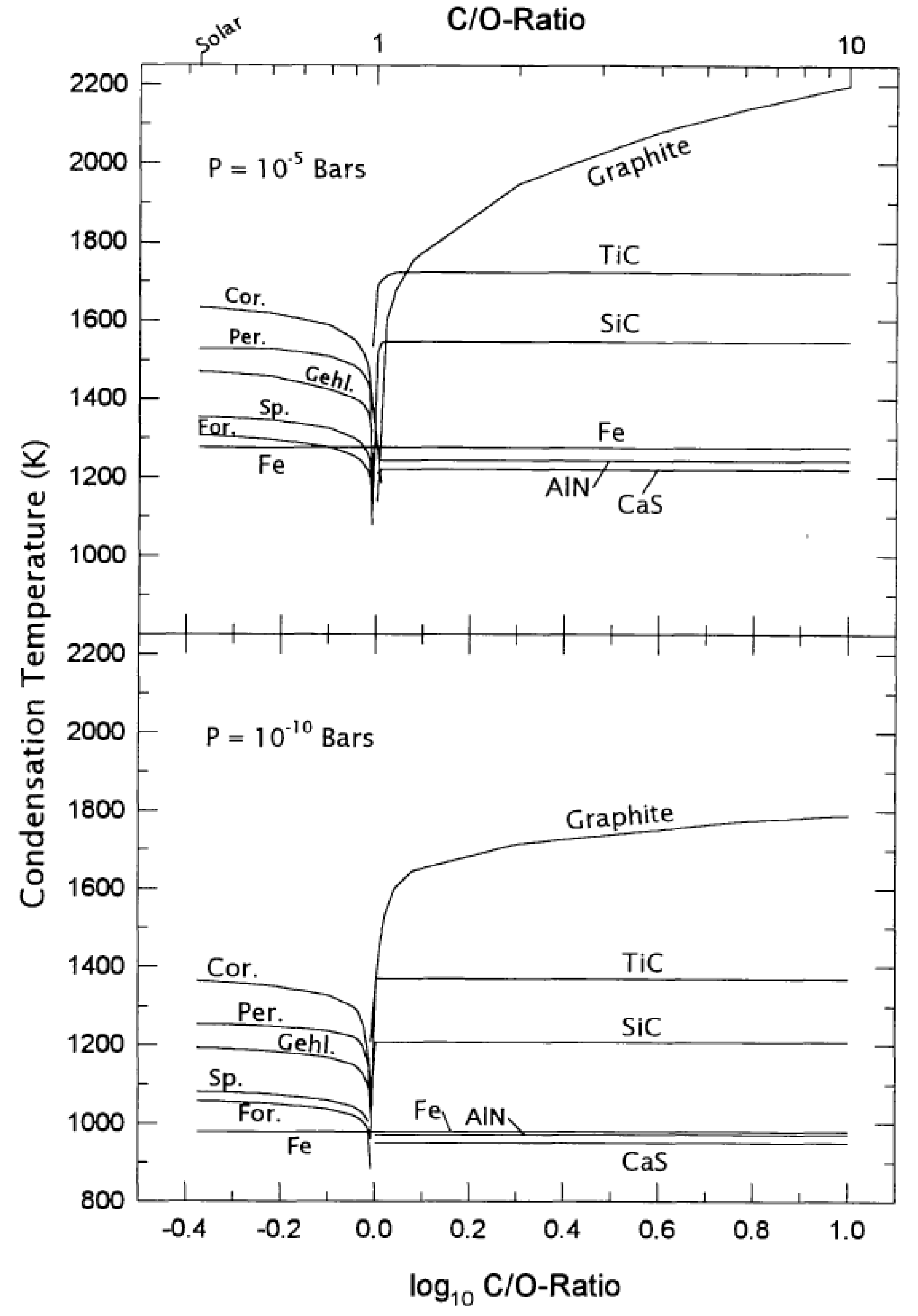


http://www.stsci.edu/~volk/

Equilibrium Condensation

- As hot gas in stellar outflow cools, molecules and then dust condense.
- With laboratory thermodynamic data, can compute condensation sequences of what minerals should form in equilibrium under given gas composition, pressure, etc

Equilibrium Condensation



What about Grains?

Lodders & Fegley (1995)

Presolar Grains and Equilibrium Condensation?

- Identified high-T phases from AGB stars are predicted
  - O-rich: Al_2O_3, $CaAl_{12}O_{19}$, $MgAl_2O_4$, TiO_2, Mg_2SiO_4…
  - C-rich: Graphite, SiC, TiC

Presolar Grains and Equilibrium Condensation?

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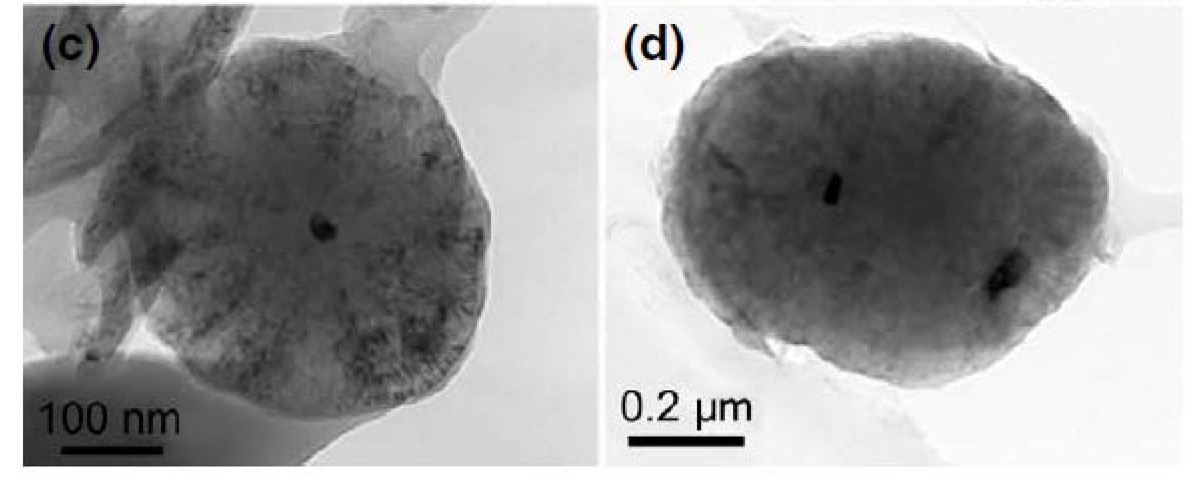
- Internal carbides in graphite imply sequential formation (Bernatowicz *et al.* 1996)



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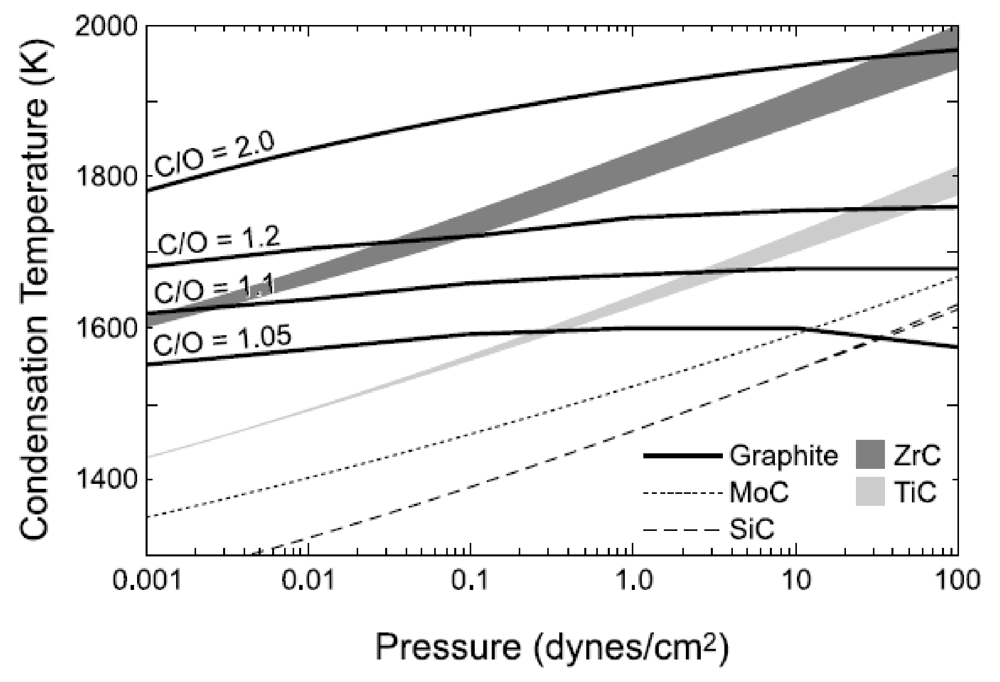
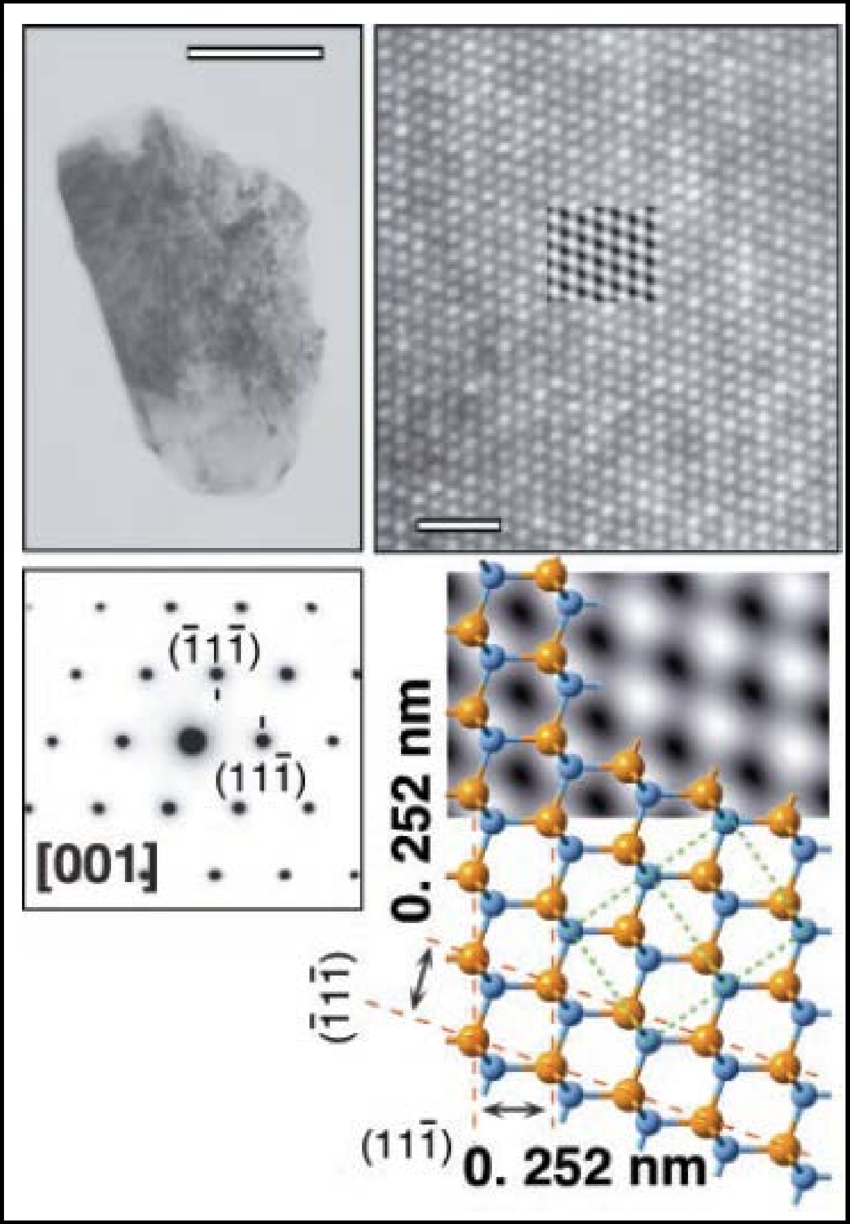


- TiC before graphite requires relatively high pressures, low C/O ratio
- (Bernatowicz *et al.* 1996)

SiC microstructures

- In laboratory, SiC forms in >100 distinct structures (polytypes)
- >500 SiC grains previously studied by TEM (Daulton et al, 2002, 2004)
  - Isotopes not known, but most grains from AGB stars
  - Most grains either cubic (3C) or hexagonal (2H); generally single crystals with many defects
  - Two lowest-T polytypes
  - A few grains with more unusual structures found (Li, Stroud+ submitted)



Mineralogy of O-rich AGB Stardust

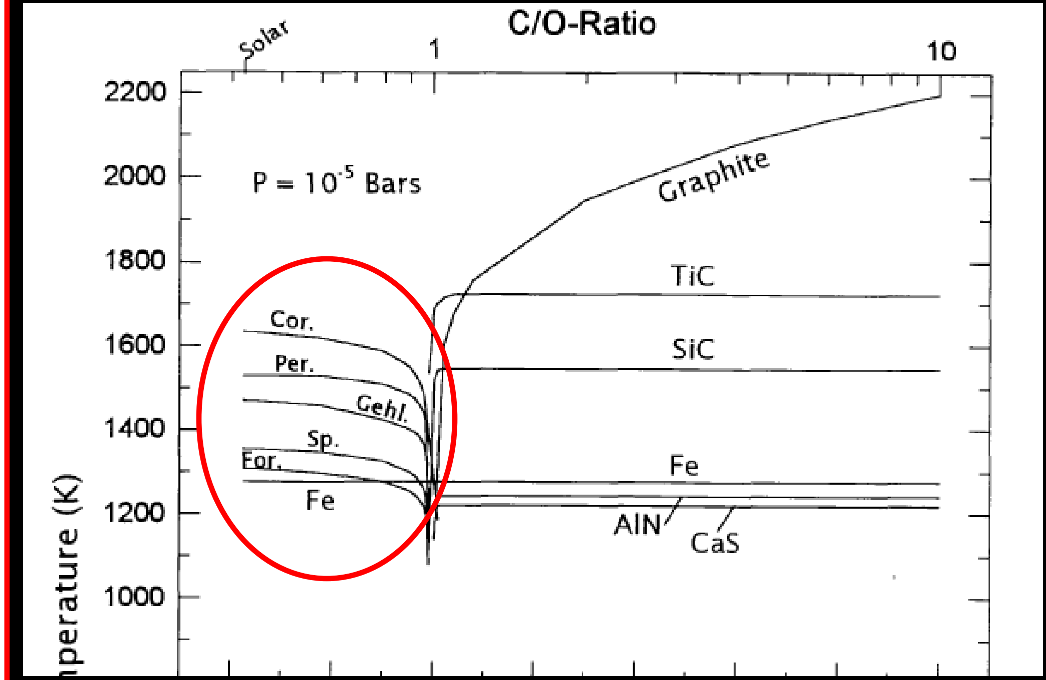
- Equilibrium condensation:

C/O=0.5

$P_{Total} = 1 \times 10^{-5}$

Corundum (Al_2O_3)	**1633 K**
Hibonite ($CaAl_{12}O_{19}$)	**1562 K**
Perovskite ($CaTiO_3$)	**1537 K**
Melilite (Ca Al sil.)	**1472 K**
Spinel ($MgAl_2O_4$)	**1351K**
Plagioclase (Ca Al sil.)	**1320 K**
Forsterite (Mg_2SiO_4)	**1305 K**
Fe Metal	**1287 K**
Ti_4O_7	**1252 K**
Enstatite ($MgSiO_3$)	**1246 K**

Yoneda and Grossman (1995) GCA

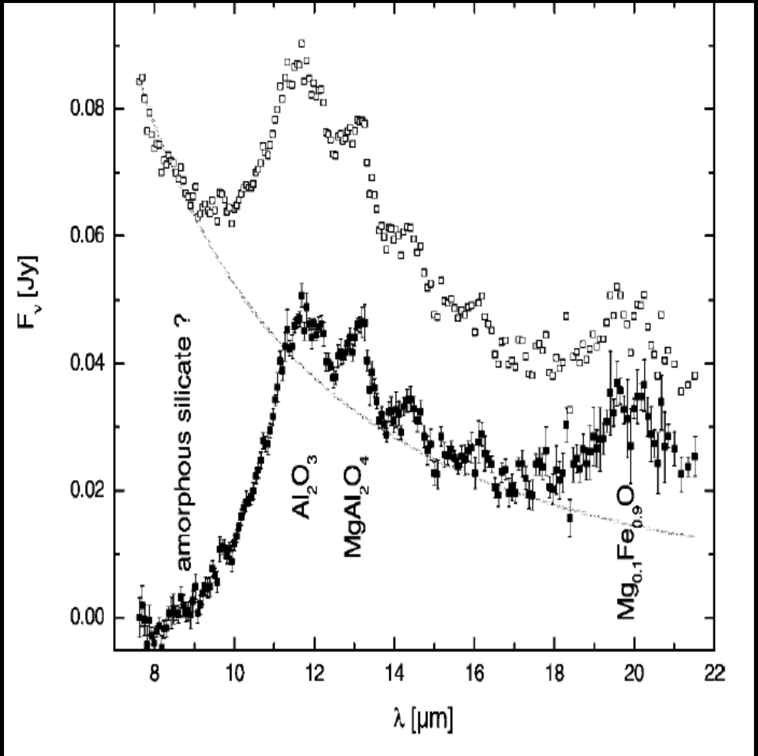


Lodders & Fegley (1995)

Identified Presolar Stardust Phases

Mineralogy of O-rich AGB Stardust

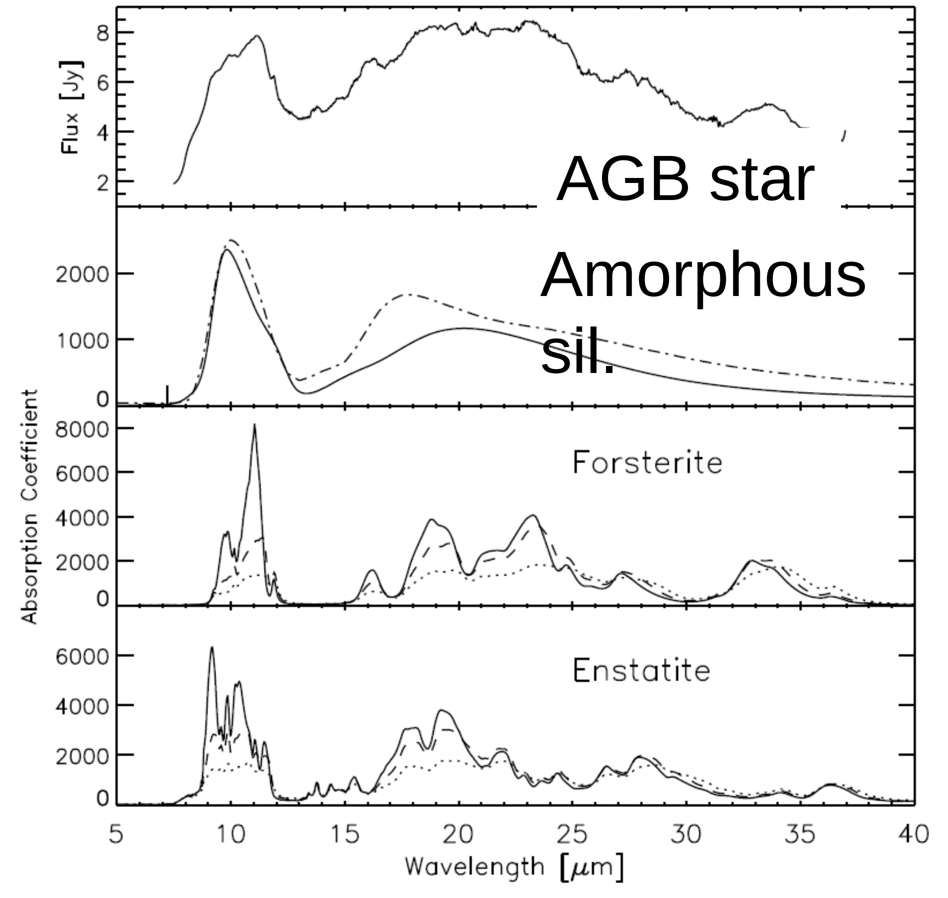
- Oxides:
- Many O-rich AGB stars have broad 11μm feature attrib. to amorphous Al_2O_3, 13μm feature attrib. crystalline Al_2O_3 and/or $MgAl_2O_4$, 20μm feature from Mg,Fe oxides.



Lebzelter, et al. (2006)

Mineralogy of O-rich AGB Stardust

- Silicates:
- Amorphous
  - broad features, attrib. to olivine [$(Mg,Fe)_2SiO_4$] stoichiometry
- Crystalline
  - Sharp features
  - Mg-rich olivine/pyroxene

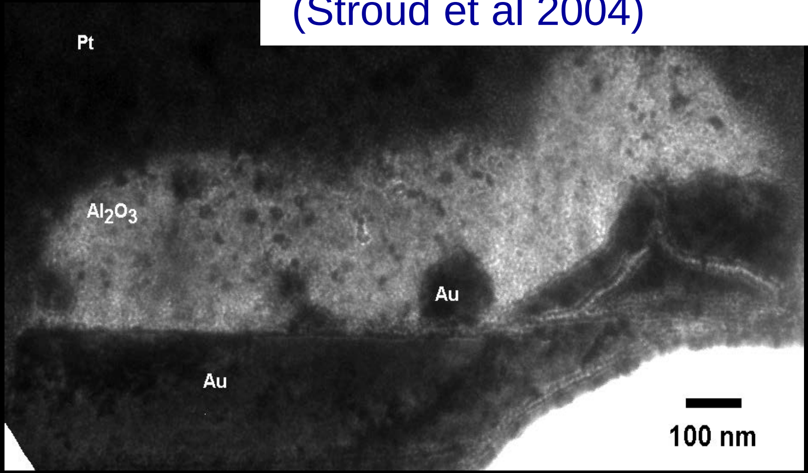


Gielen et al. (2008)

Difficulty: spectral features for phases depends on chemistry, grain size, shape, temperature, crystal structure, etc. highly non-unique problem!

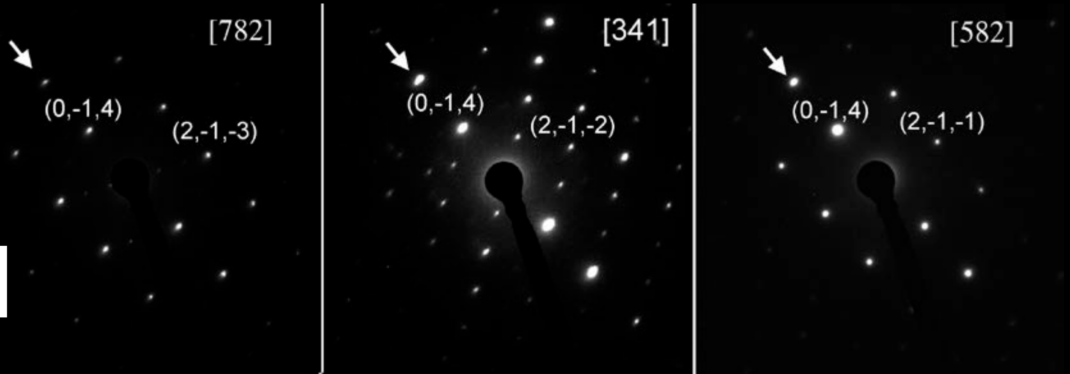
Mineralogy of Presolar AGB oxides

- ~30 presolar oxides (Al_2O_3, $MgAl_2O_4$, $CaAl_{12}O_{19}$) analyzed by TEM (Stroud+ 2004; Zega+ 2011,2014, Takigawa+ 2014
  - – Most crystalline
  - – One amorphous Al_2O_3



Amorphous AGB Al_2O_3 grain (Stroud et al 2004)

- Confirms astronomical result that both amorphous and crystalline Al_2O_3 forms



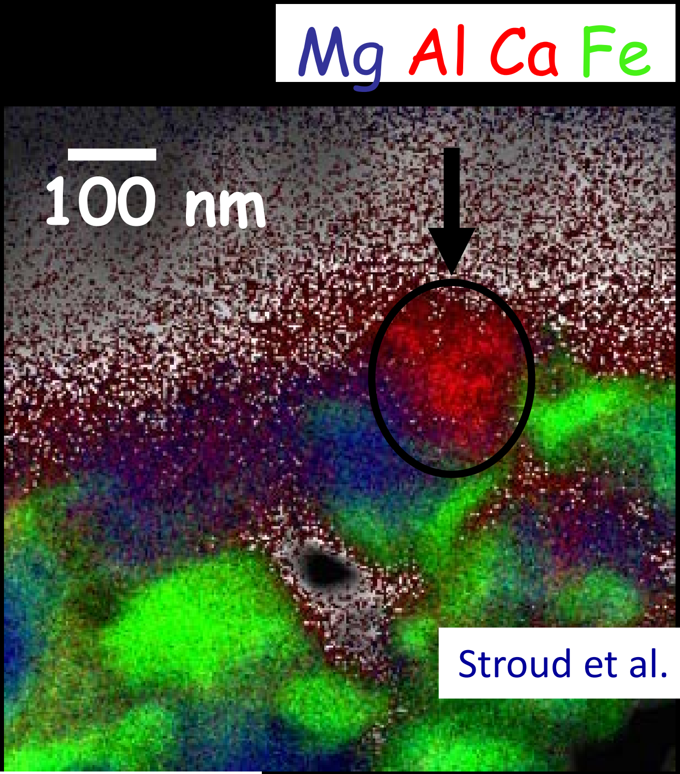
Electron diffraction pattern of Al_2O_3 grain

Mineralogy of Presolar AGB silicates

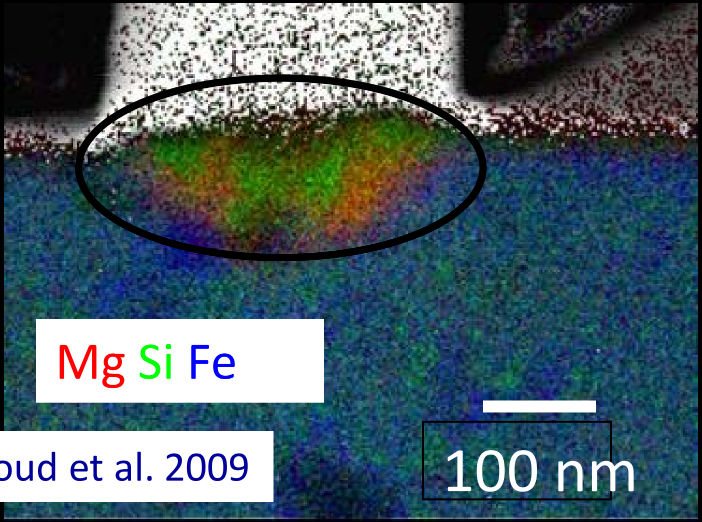
- Large number of silicate grains now identified, but small sizes (<500 nm) make mineralogical determination difficult
- Auger e- spectroscopy reveals diversity of chemical compositions
  - Wide range of Fe/Mg, Ca and/or Al-rich phases, pure SiO_2
- TEM data available for ~54 presolar silicates (Messenger, Stroud, Nguyen, Vollmer, etc)

Mineralogy of O-rich AGB Stardust

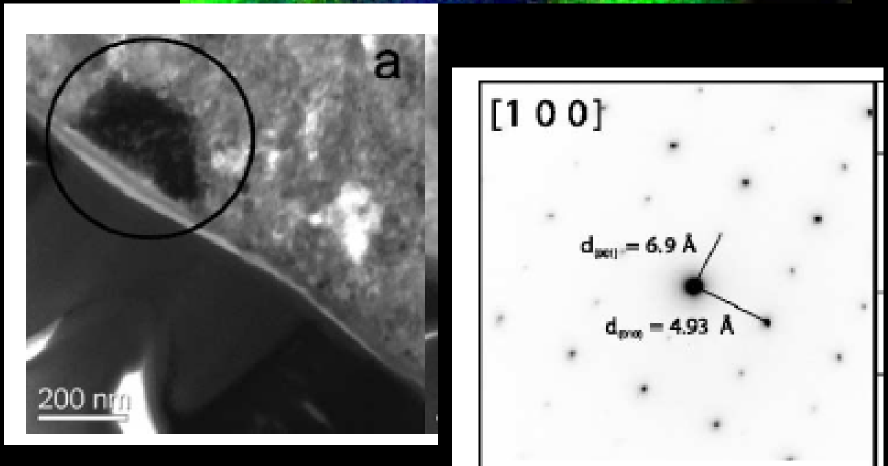
- ~2/3 are amorphous or finely nanocrystalline, non-stoichiometric and chemically heterogeneous on <50nm scale
- Need IR measurements!!
- 1/3 crystalline grains, many are Mg_2SiO_4 but others present



Stroud et al. 2008



Stroud et al. 2009



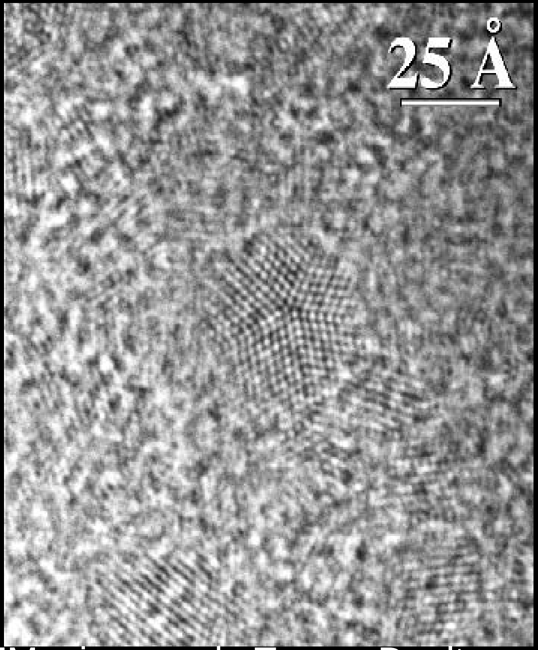
Vollmer et al. 2007

Mineralogy of O-rich AGB Stardust

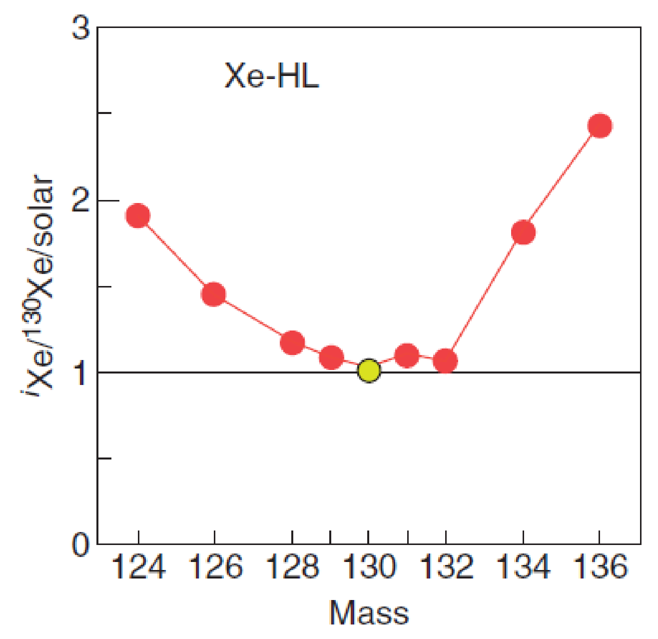
- Highest-T phases:
  - Include single crystals, phases predicted by equilibrium (Al_2O_3, Mg_2SiO_4, …)
- Lower-T phases
  - Include non-stoichiometric amorphous silicates, unusual Cr-oxides
- Implications:
  - Many silicate grains form in AGB stars under highly dynamic, probably non-equilibrium conditions
  - Huge diversity in compositions, many non-stoichiometric (makes life harder for IR spectroscopists)

Presolar (?) Nanodiamonds

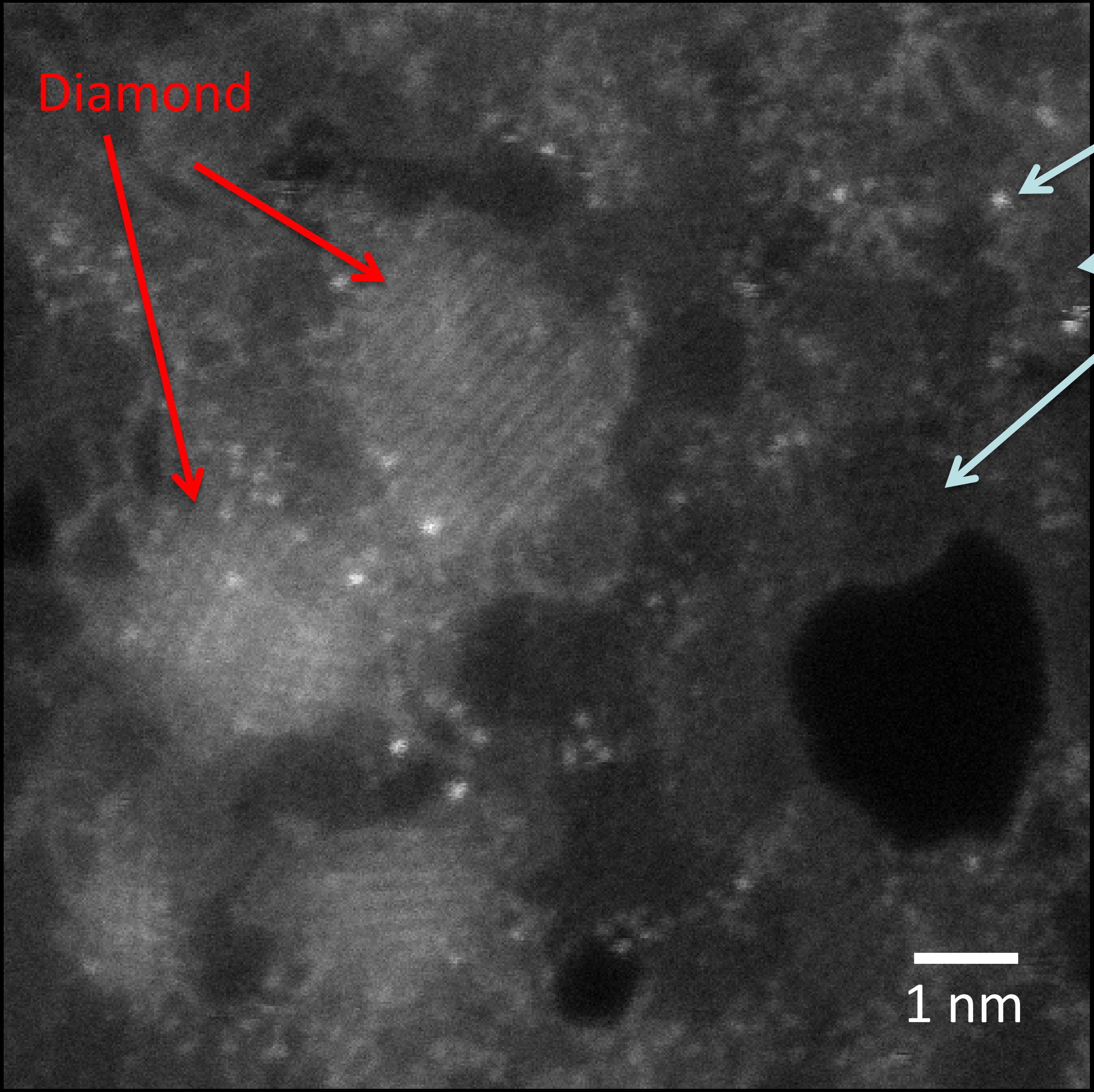
- Tiny (2nm), abundant (500 ppm)
- Isotopically anomalous in N, Xe, and Te, but C normal.
  - Measurements only possible in bulk (millions of grains at a time)
  - Xe, Te point to supernova source, but only tiny fraction of grains contain these (1in 10^6 has a Xe atom!)
  - N isotopes match composition of Sun (based on Jupiter, lunar soils, Genesis samples)
- Possible that vast majority formed in Solar System (Dai et al., *Nature*, 2002)
  - Possibly observed in protoplanetary disks (Van Kerckhoven et al. 2002)



TEM micrograph: Tyrone Daulton



Aberration corrected STEM of nanodiamond residue

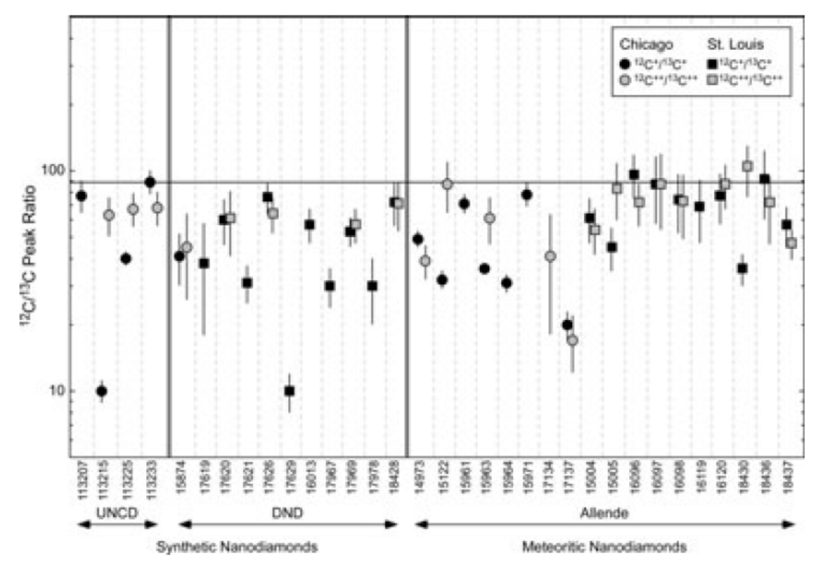


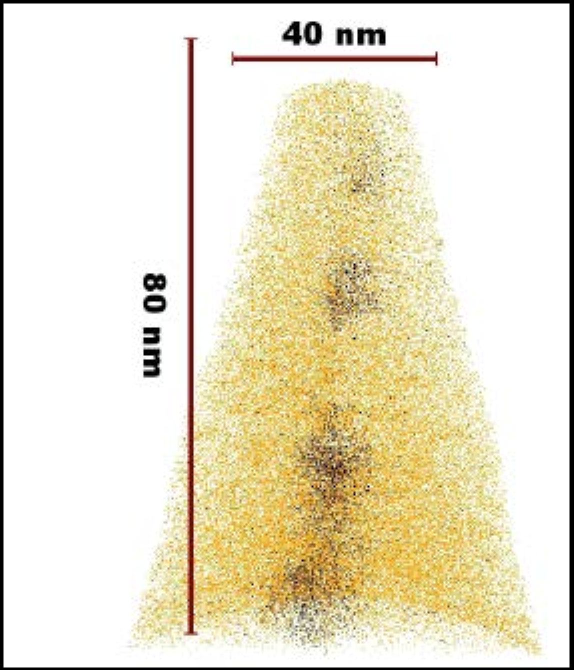
Stroud *et al.*, ApJ 2011

- Second phase (disordered “glassy C”)
- Formation by SN shock in ISM?
- New technology may allow single-atom Xe detection!

Atom-probe analysis of single nanodiamonds

- Towards single-grain isotope analysis
  - (Heck et al.,2012, 2014; Lewis et al. 2012)



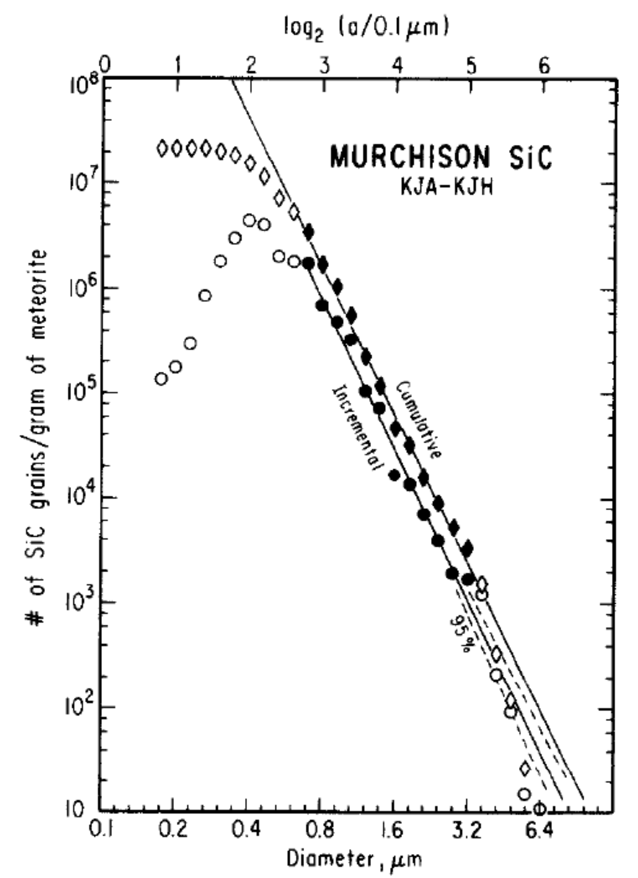


Presolar grains and interstellar dust

- All presolar grains were once (>4.6 Gyr ago) interstellar grains (e.g., Dartois+Leroux lectures)
- What can they tell us about ISD?
  - Grain sizes?
  - Lifetimes?
  - Processing?
  - Crystallinity?

Presolar Grain size

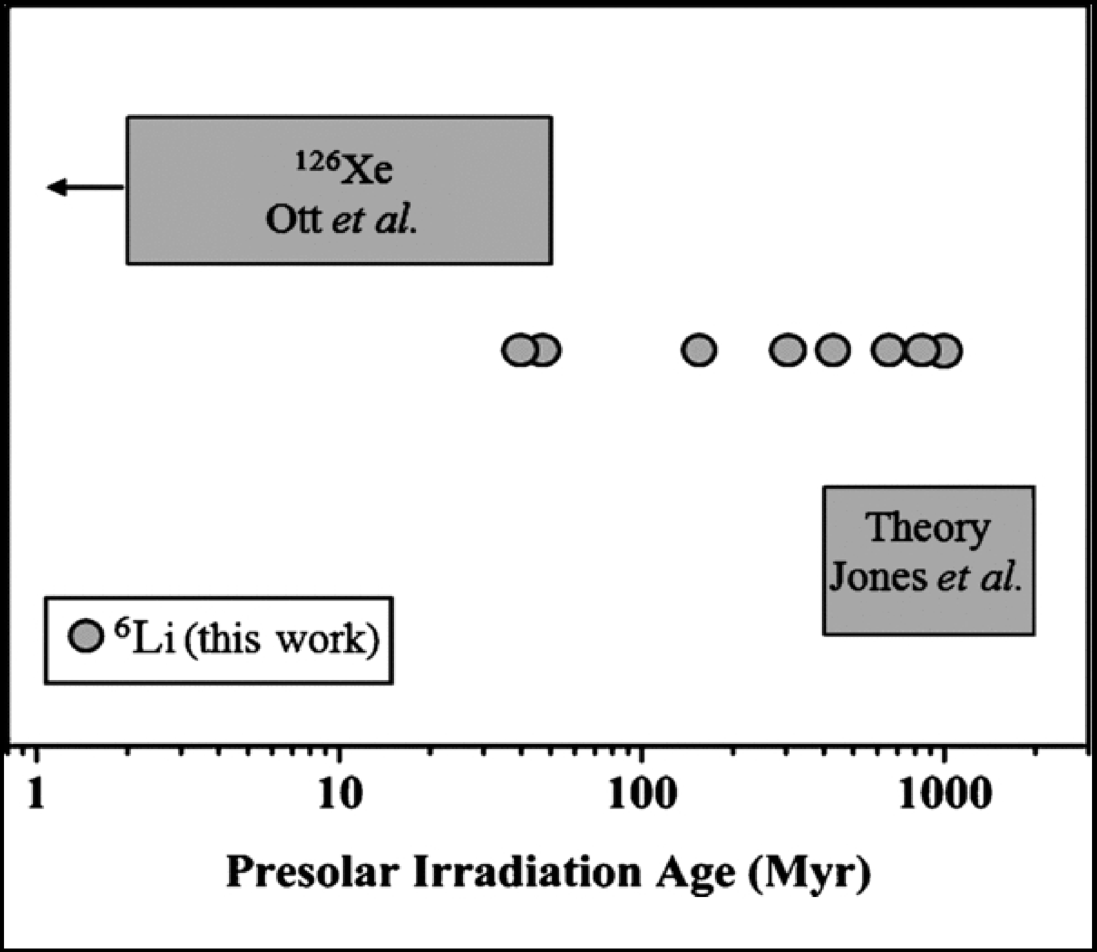
- SiC:
  - power-law dist (<100-nm to >20 μm)
- Silicates:
  - <1 μm; typical size ~300-nm
  - But high-res imaging indicates 2x as many at small sizes (Hoppe+ 2015)
  - Similar to ISD



Amari et al 1994

Lifetimes of IS Dust

- Not yet possible to directly age-date presolar grains (e.g., U)
- SiC ages estimated from cosmogenic Ne, Xe, Li isotopes
  - Large grains, large uncertainties
  - Unrepresentative?

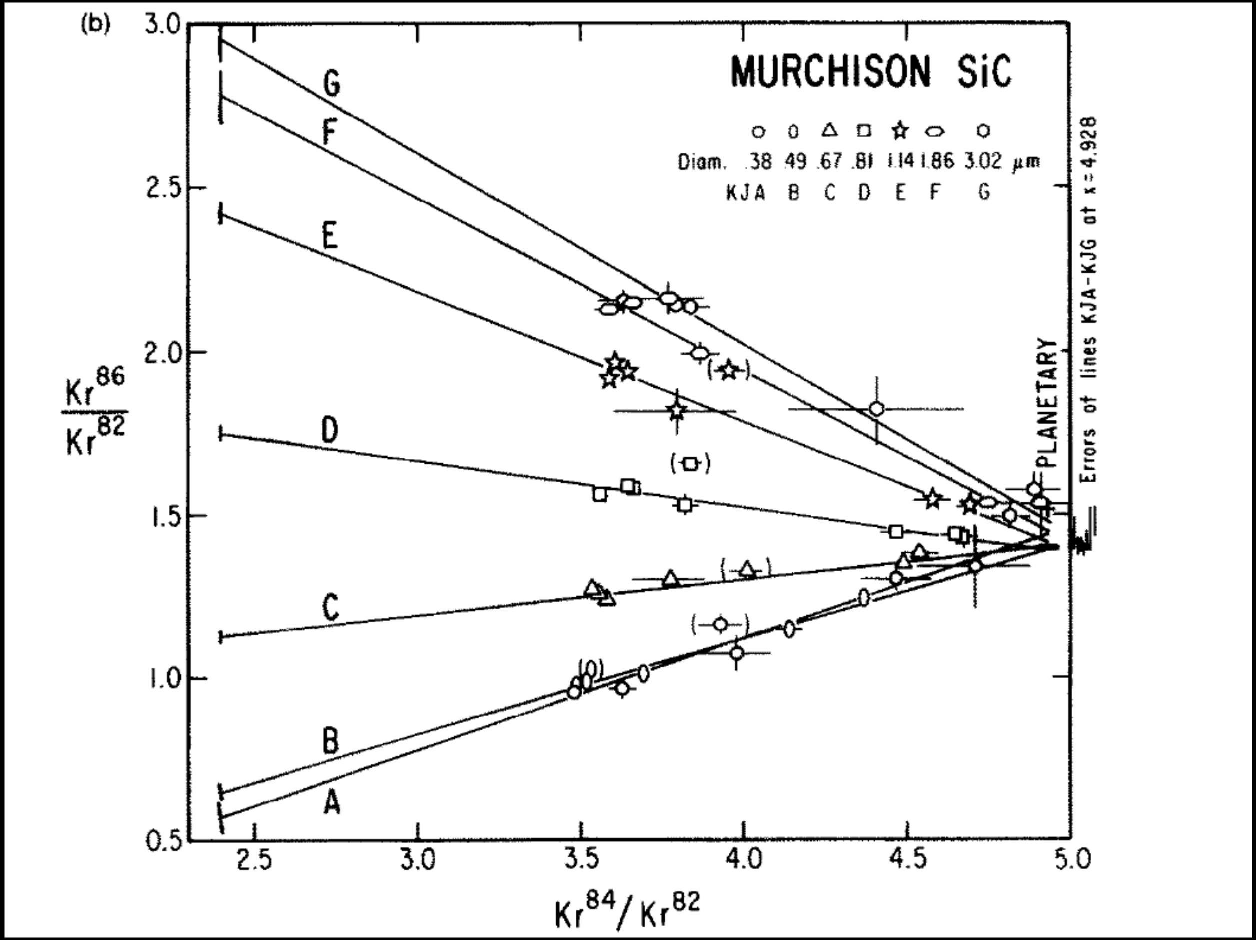


Gyngard et al. (2009)

IS grain destruction?

- Grains destroyed by SN shock waves (grain-grain, grain-gas collisions, e.g., A. Jones)
  - Evidence in presolar grain data?

IS grain destruction?

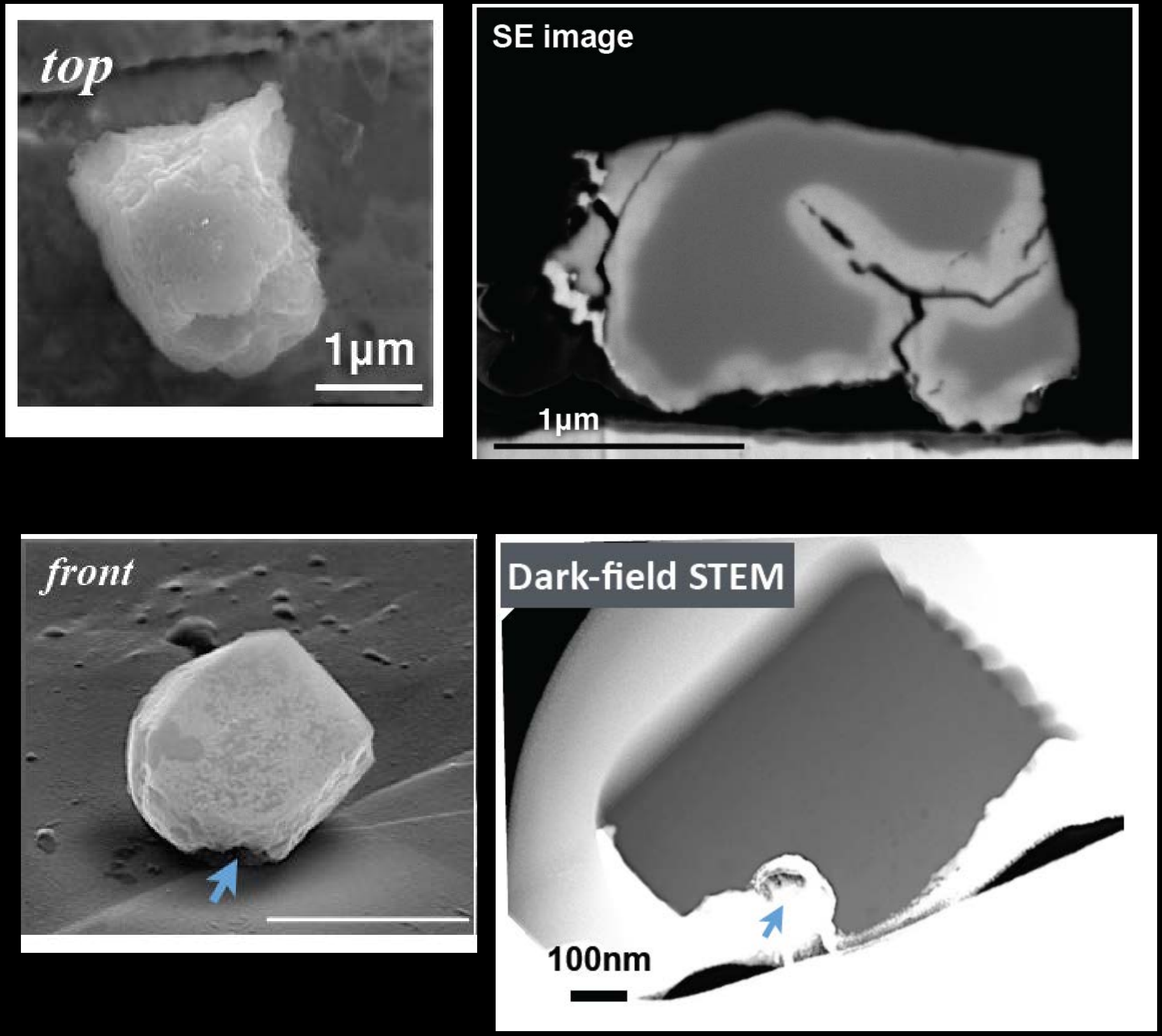


Lewis et al. (1994)

- SiC grains of different sizes show distinct nucleosynthetic signatures
  - – No evidence of fragmentation

IS grain destruction?

- Transmission Electron Microscopy of presolar Al_2O_3
- Possible evidence of interstellar shock processing (cracks, micro-craters)



Takigawa+ 2014, in preparation

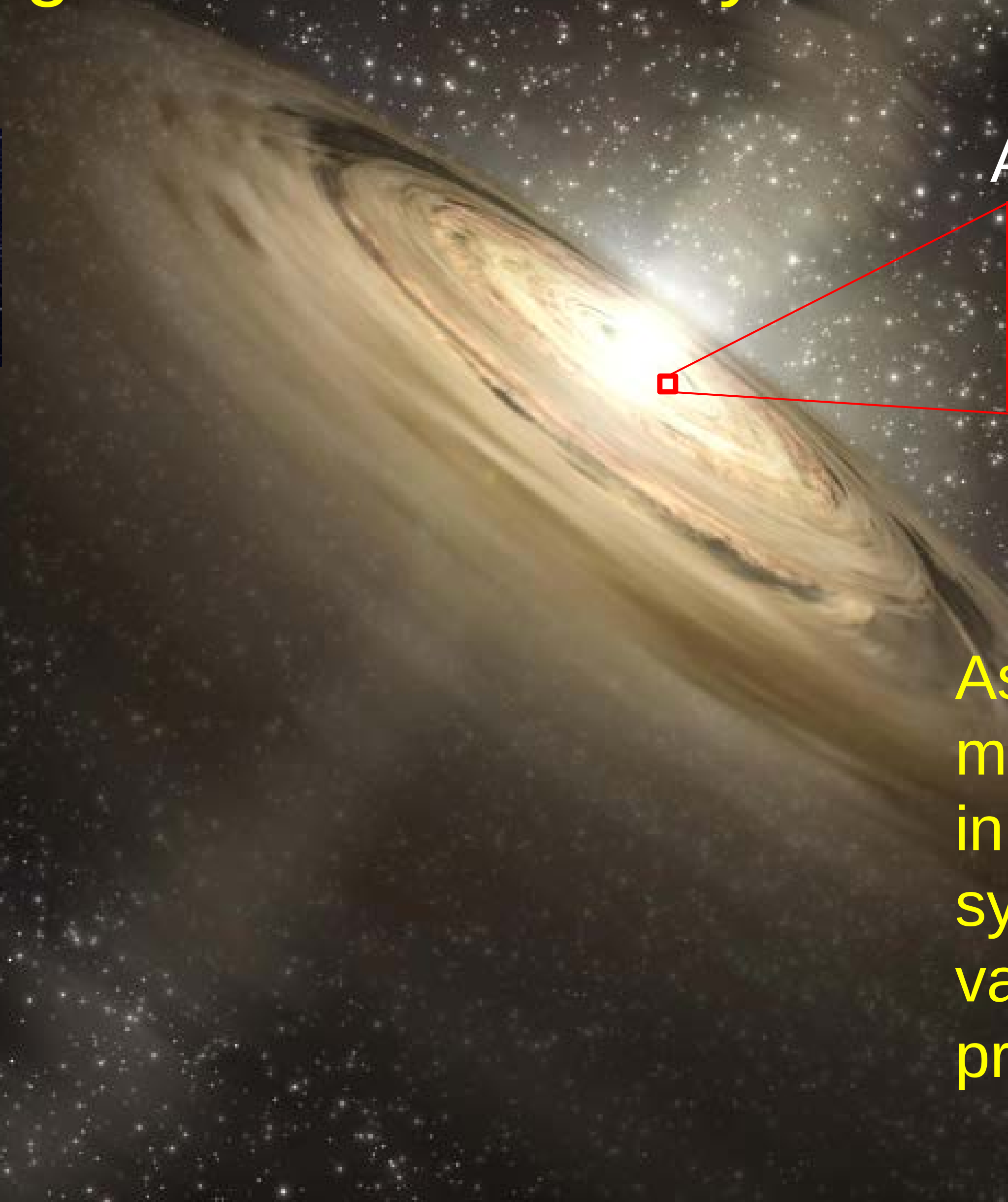
Crystallinity of circumstellar/interstellar dust

- IR observations indicate (Kemper+ 2004):
  - AGB star silicates: ~10-20% crystalline
  - Interstellar silicates: <2% crystalline
- Presolar grains: ~1/3 crystalline
  - ~similar to circumstellar
- Either:
  - 1) Low-crystallinity of ISD reflects amorphization and amorph. grains selectively destroyed in early SS (crys. fraction coincident)
  - 2) Most amorphous silciates in ISM formed there

Interstellar origin of IS dust

- Long argued on the basis of production/destruction timescales
  - And consistent with presolar grain crystallinity
- Destruction by SN shocks observed
- Support from gas-phase depletions in diffuse ISM:
  - Most Fe produced in Type IA supernovae that do not produce dust (i.e. injected as atoms)
  - Fe is 99% depleted onto dust in ISM
  - Fe thus somehow condenses onto/into dust in the ISM
- But, mechanism not known

Presolar grains and the early Solar System



COMETS

Cometary IDPs: outer solar system, highly primitive, little processing

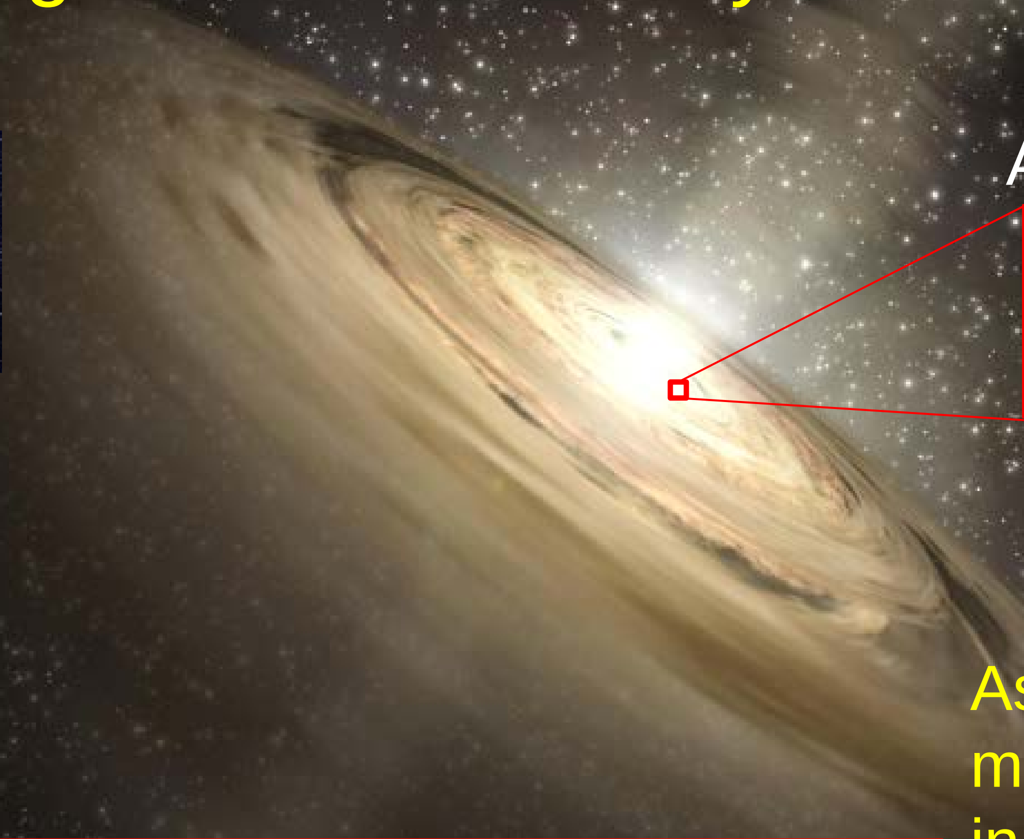
ASTEROIDS

Asteroidal meteorites: inner solar system, variable processing

Presolar grains and the early Solar System

COMETS

Cometary IDPs: outer solar system, highly primitive, little processing



Use presolar grain abundances as tracers of early SS (disk/planetary) processing

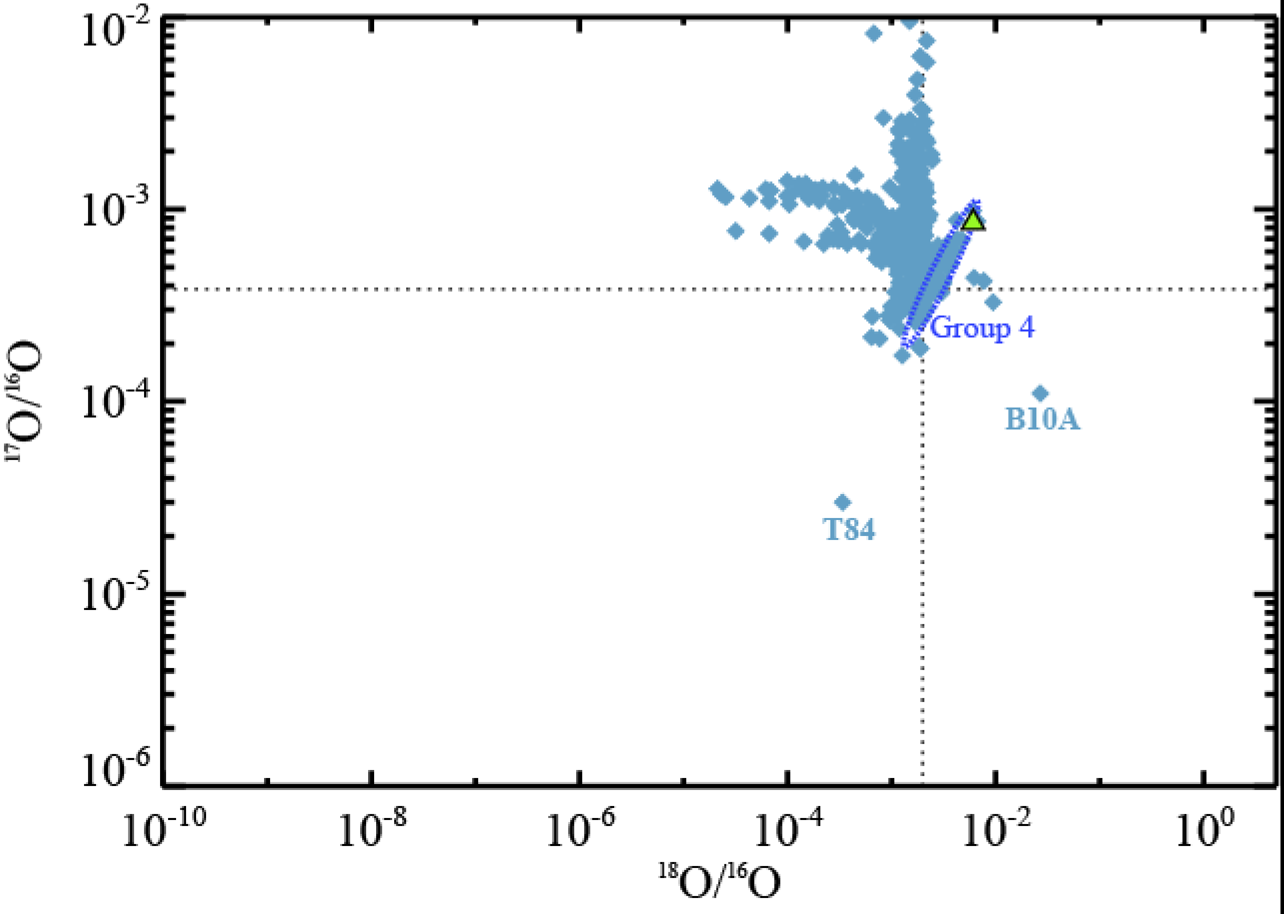
ASTEROIDS

Asteroidal meteorites: inner solar system, variable processing

Evidence for SN injection?

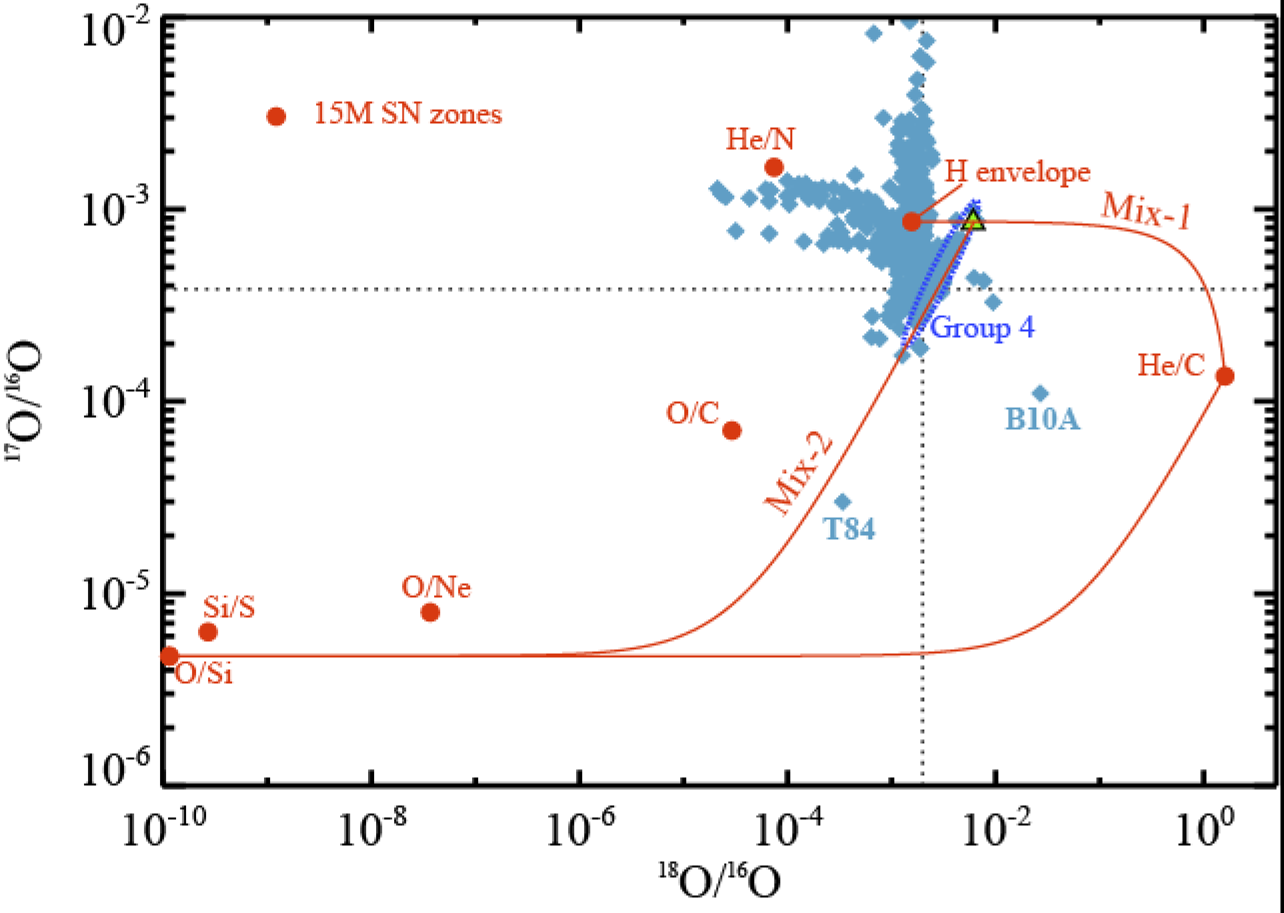
- Many ideas for SS formation involve interaction with one or more supernovae (Cameron, Boss, Gounelle, …)
  - e.g., triggered core collapse+ injection of short-lived radioactivities; sequential enrichment of molecular cloud; …
- Evidence in presolar grain record?
  - Most grains from large number of AGB stars
  - 10% of silicates, 2% SiC, 50% graphite from SNe – evidence for few sources?

Supernova oxides/silicates



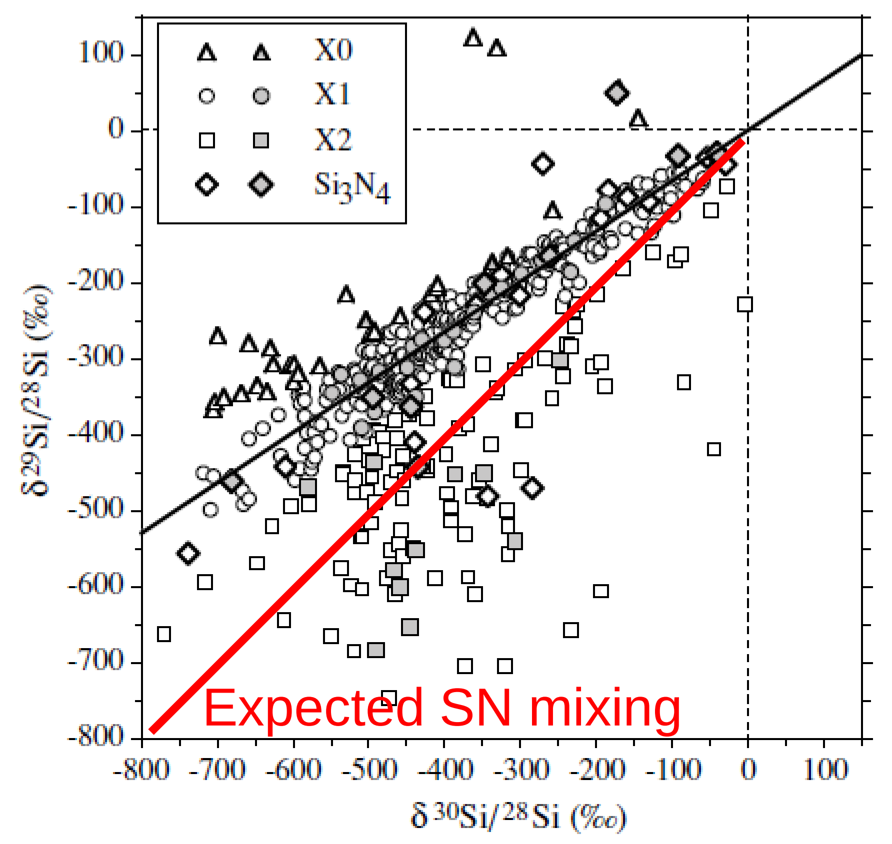
- ‘Group 4’ (^{18}O-rich) grains from SNe (Nittler+ 2008)

Supernova oxides/silicates



- O isotopes of many lie on arbitrary mixing line -> evidence for single source??

Supernova SiC/Si_3N_4



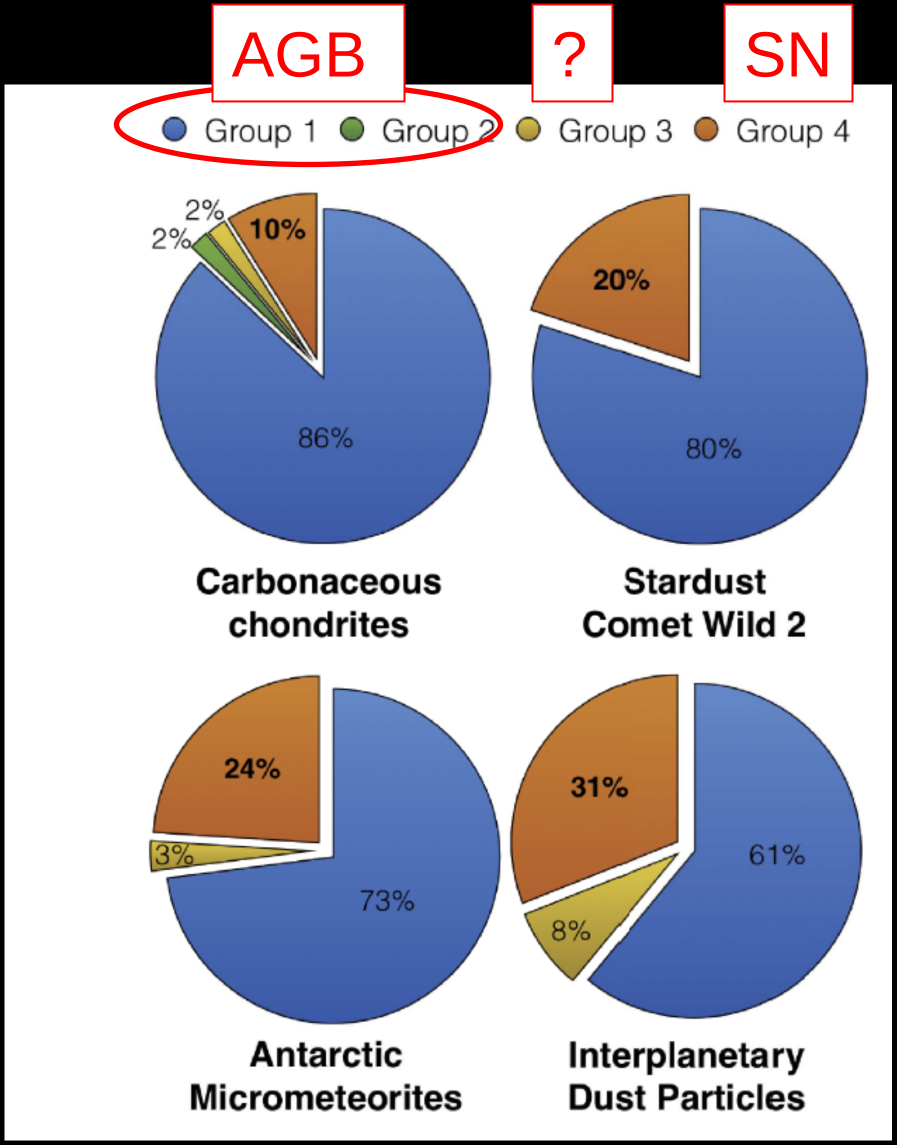
Lin et al. ApJ 2010

- Si isotopes of many fall on single (mixing) line on Si 3-isotope plot
- If SN models correct, ^{28}Si-rich end-member requires special mixing
  - Again: evidence for single source?
  - Not good correlation with other isotopes

Supernova/AGB silicate ratio

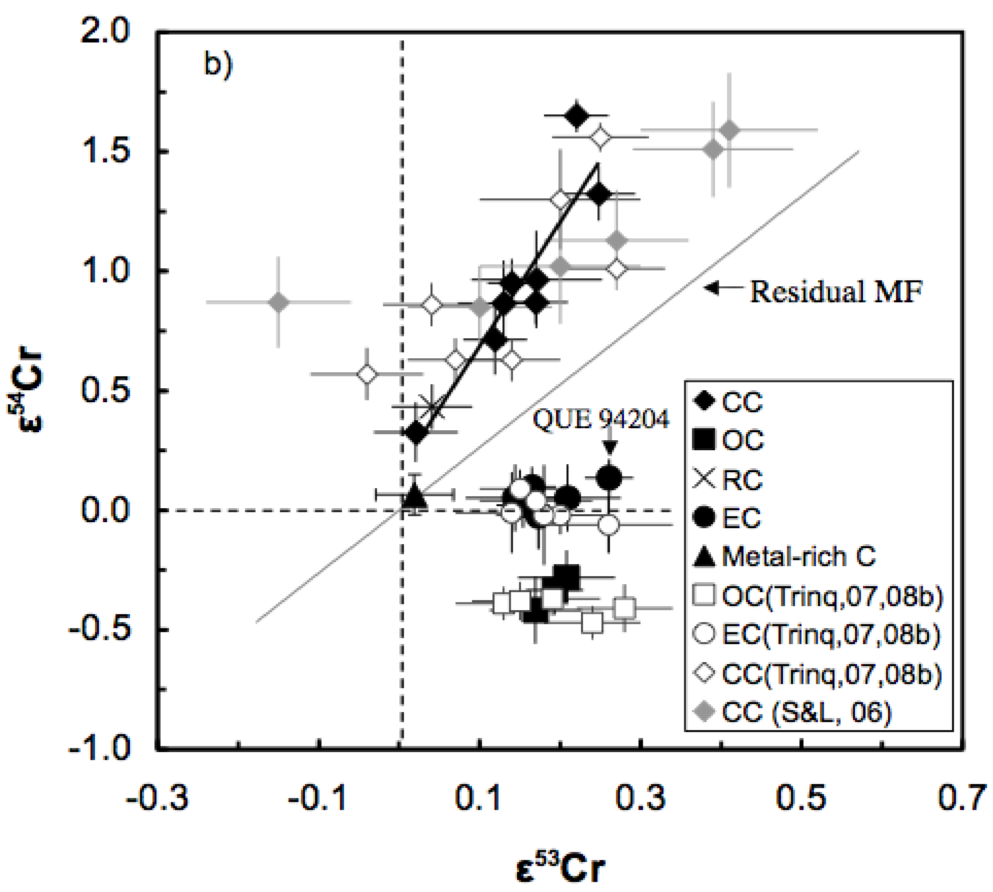
- Presolar silicates found in meteorites, interplanetary dust particles, Antarctic micrometeorites, and comet Wild-2 samples.
  - Last three argued to come form comets, sample outer disk, whereas meteorites sample inner disk
  - Same mix of supernova and AGB presolar grains throughout SS?

- No! Evidence that SN grains are more abundant in cometary samples (Qin+ 2011; Floss+Haenencour 2016)

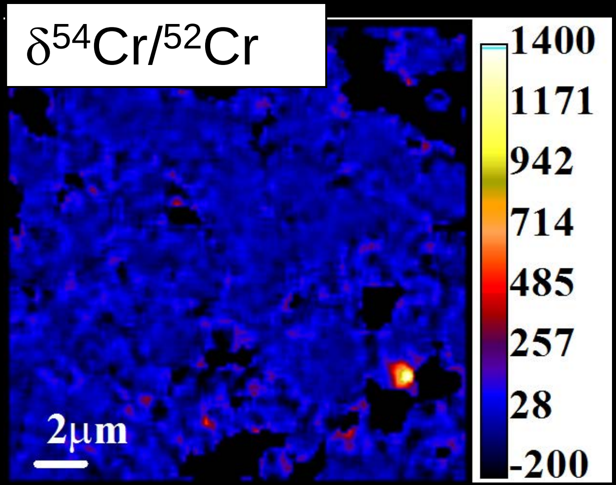


Floss+Haenencour 2016

^{54}Cr anomalies



Bulk Chondrites (Qin+2010; see Burkardt talk)

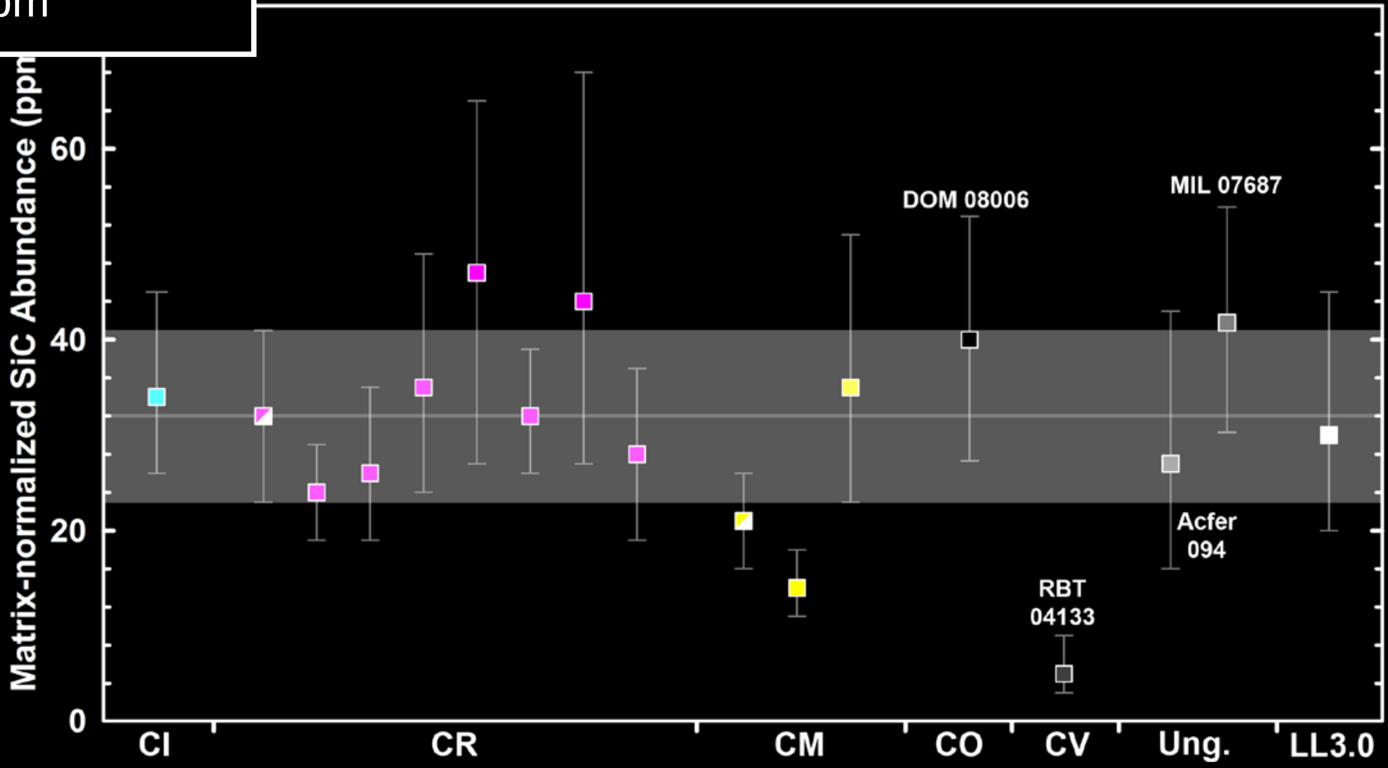


- Heterogeneous distribution of 54Cr carriers among planetary bodies/meteorite parent bodies?

- Both presolar silicate and ^{54}Cr data suggest heterogeneous distribution of supernova grains in protosolar disk. If real, what does it mean?
  - Direct SN injection into an already-formed disk (Ouelette+2010)?
  - Variable processing of SN versus AGB grains throughout disk?
    - Unlikely explanation: no difference in mineralogy between SN/AGB silicates
  - Size-sorting?
    - Might work for tiny ^{54}Cr-rich grains, but same size range for AGB/SN silicates

Presolar Grain Abundances

Pristine chondrites:
~30 ± 10 ppm



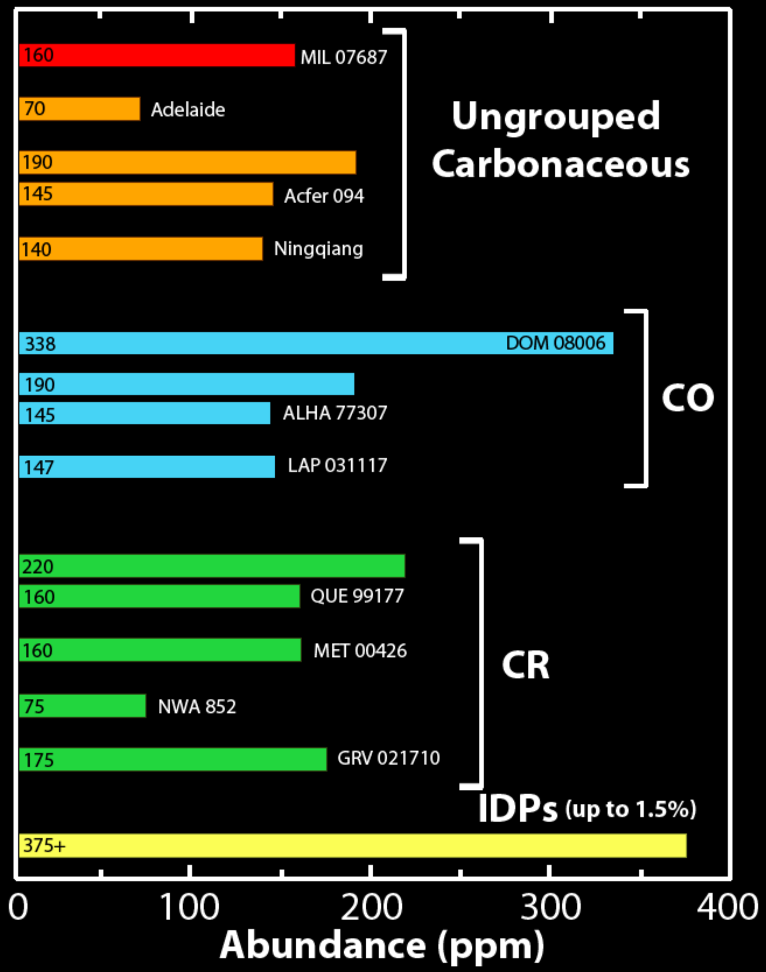
Modified from: Davidson *et al.*, *GCA* (2014)

Matrix-forming region of ESS was well-mixed (in terms of presolar grains)
Variations seen in heated meteorites (Gary Huss et al.), but SiC not strongly affected by aqueous processing

Presolar Grain Abundances

O-anomalous grains
(silicates + oxides):

- Sensitive tracers of disk and parent body processes (e.g., hydrothermal)
- Highest in cometary IDPs – IDPs more primitive than even most primitive meteorites
  - But still tiny fraction of bulk comet



Davidson *et al.*, *LPSC* (2014). Previous data: Nguyen & Zinner (2004), Floss et al. (2006), Floss & Stadermann (2009, 2012), Nguyen et al. (2010), Zhao et al. (2011, 2013), Leitner et al. (2012), Nittler et al. (2013).

Conclusions

- Presolar grains of stardust are preserved in primitive meteorites and cometary dust
- As direct condensates from stellar outflows and explosions, presolar grains are unique tools to probe wide variety of stellar/interstellar/protosolar processes
  - Confirm AGB stars as sources of s-process heavy elements and improve understanding of nuclear processes
  - Indicate extensive and heterogeneous mixing in supernova ejecta
  - Indicate Milky Way dust dominated by AGB stardust
  - Probe small degrees of parent-body processing in asteroids early in solar system history

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