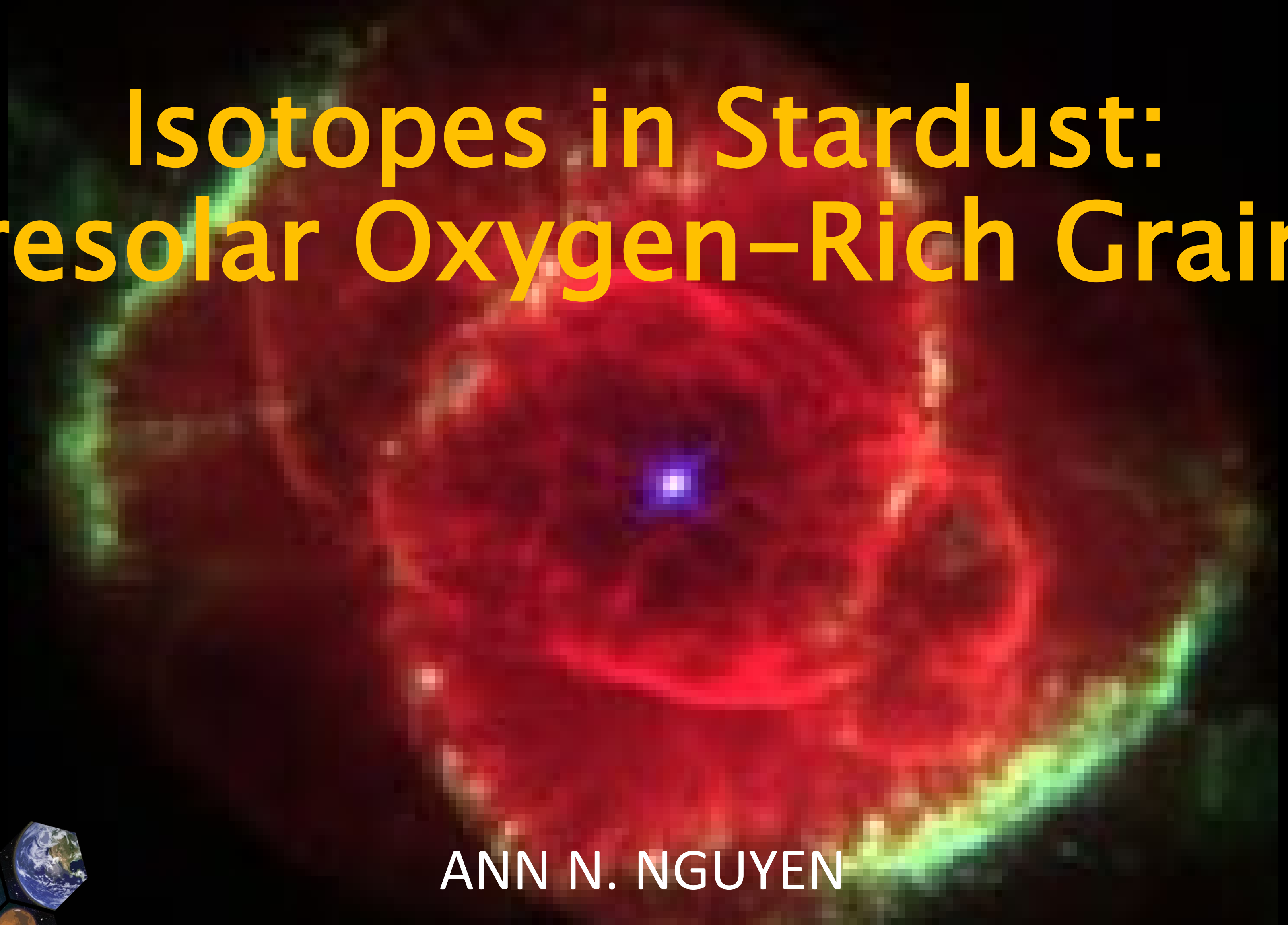
Isotopes in Stardust: Presolar Oxygen-Rich Grains

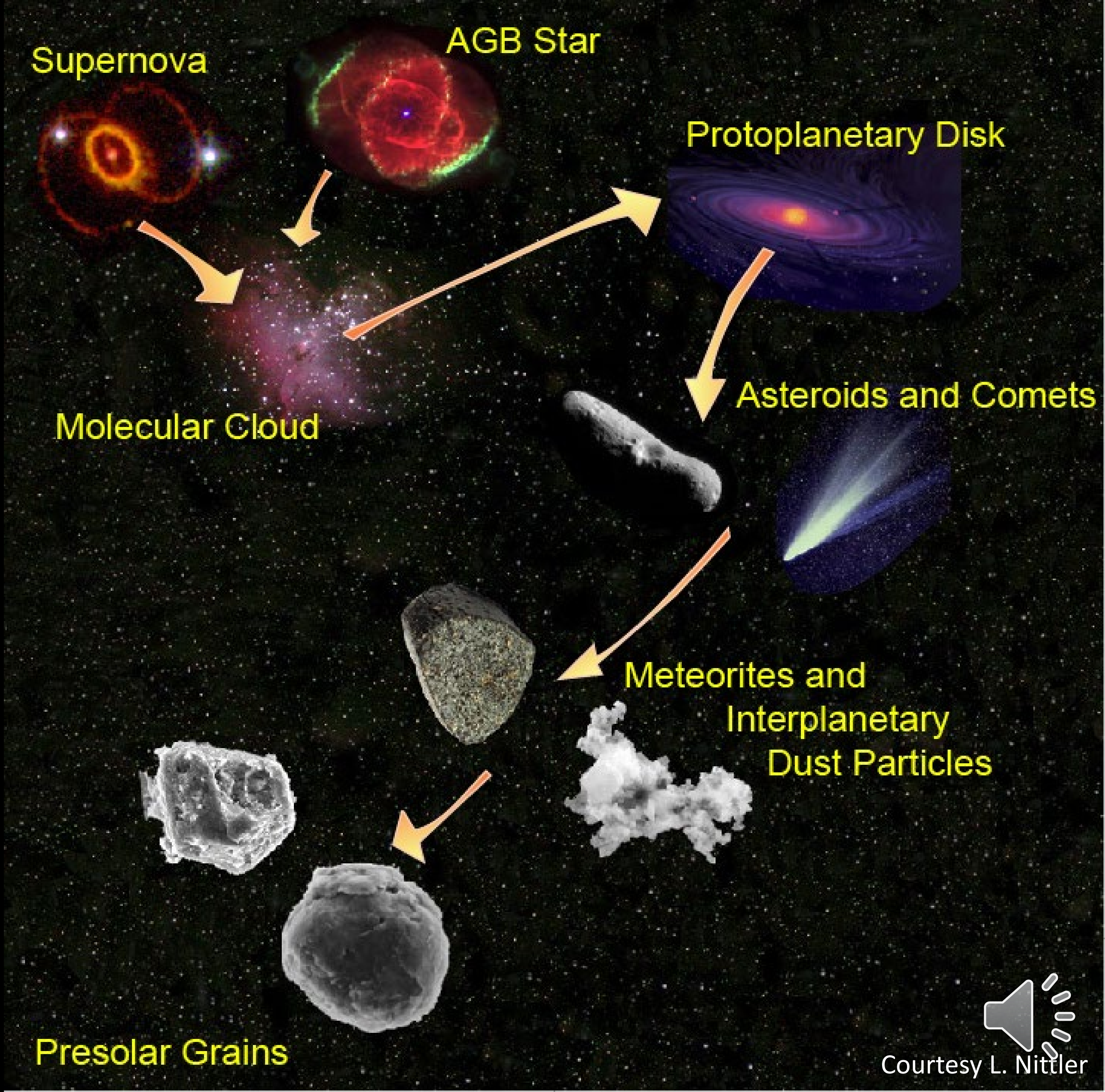


ANN N. NGUYEN

NASA Johnson Space Center, Houston TX

Presolar Stardust

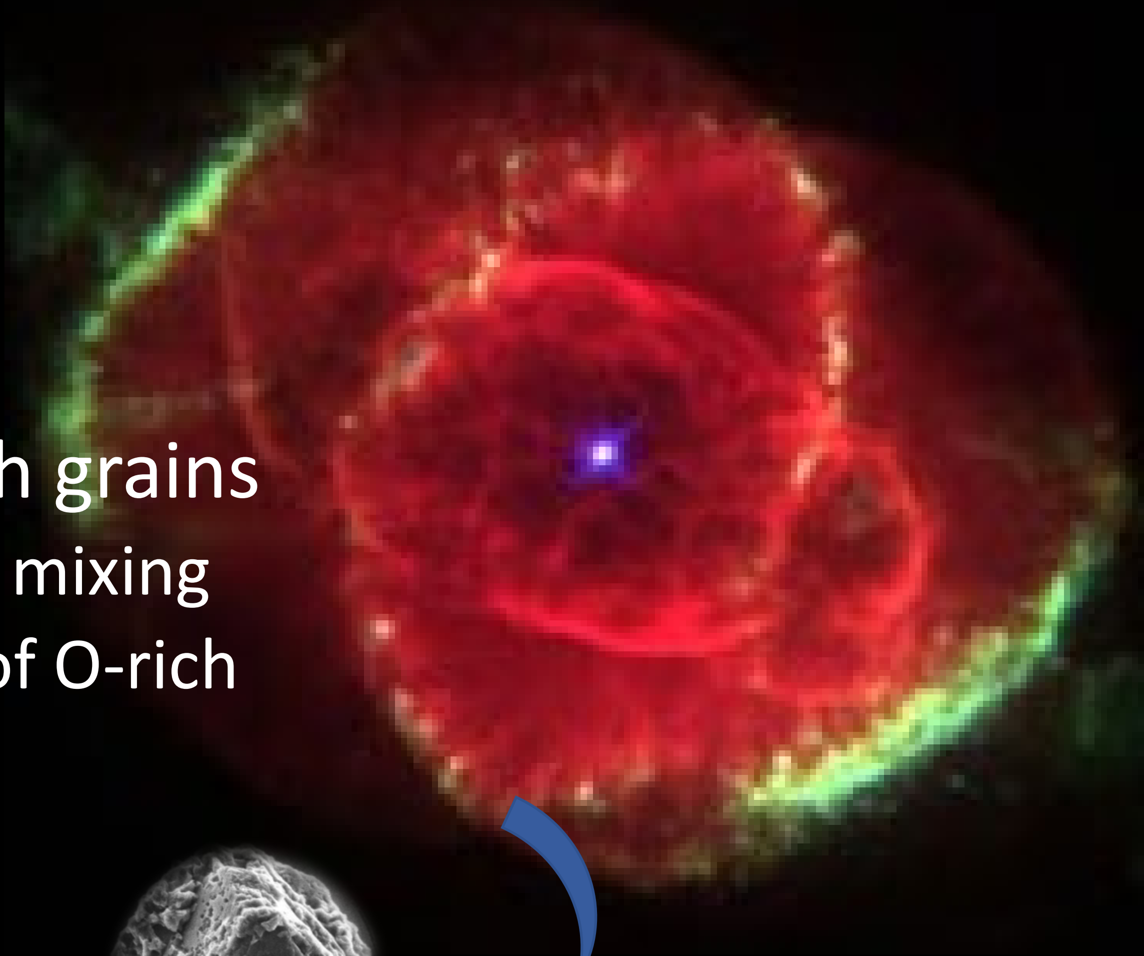
- Grains condense around mass-losing evolved stars
- Survive processing in space and during formation of the solar system
- Incorporated into asteroids and comets
  - Find surviving stardust grains in meteorites, interplanetary dust particles, and cometary samples
- Presolar grains preserve isotopic compositions of parent stellar sources

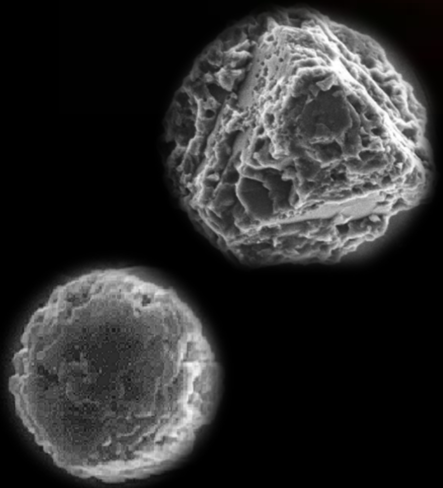


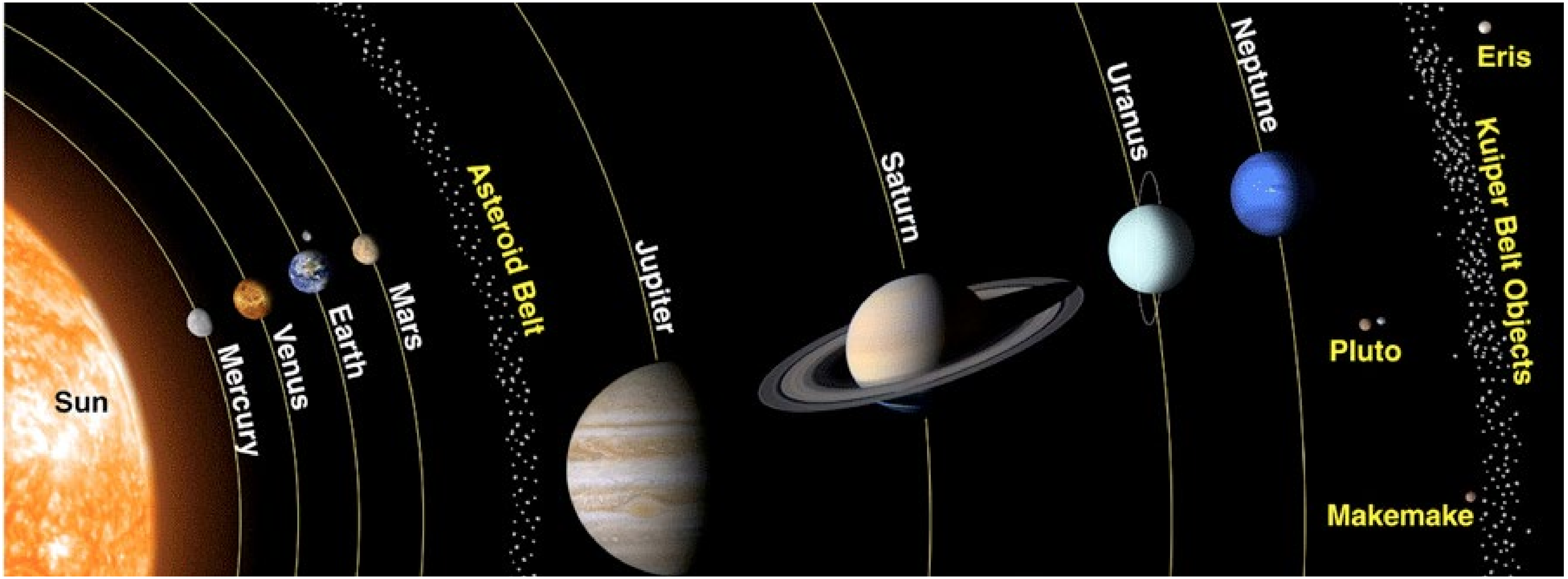
Courtesy L. Nittler

Outline

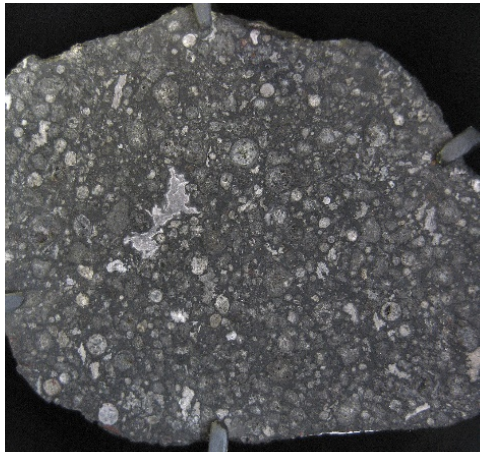
1. Presolar grain identification
2. Analytical techniques in the lab
3. Isotopic studies of presolar O-rich grains
    a. Stellar evolution, nucleosynthesis, mixing
    b. Stellar origins of different groups of O-rich presolar grains
        i. AGB grains
        ii. SN grains
        iii. Nova grains



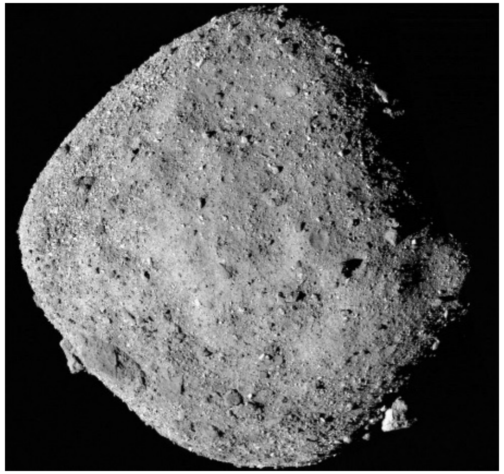




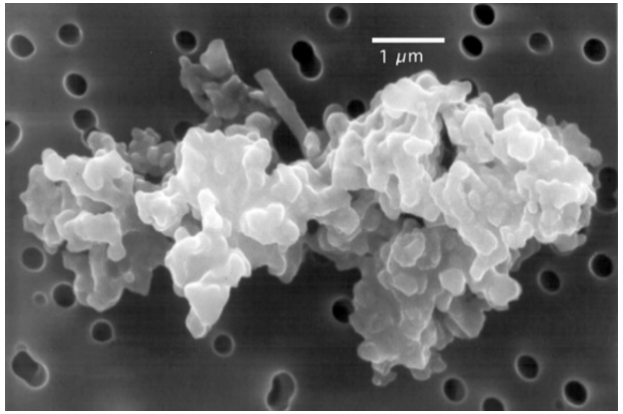
Primitive Chondrites



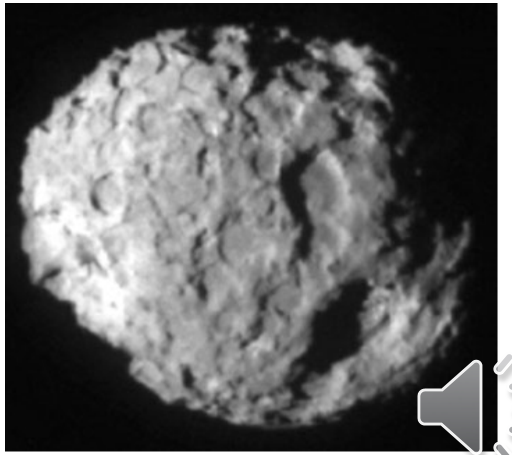
Asteroid Return Samples



Interplanetary Dust Particles



Comet Return Samples



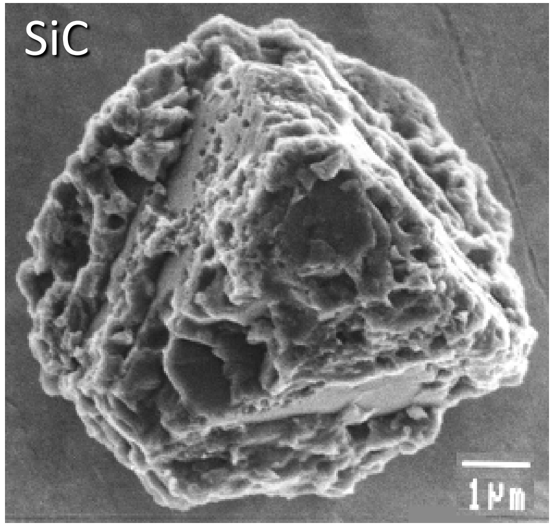
How are presolar grains isolated?

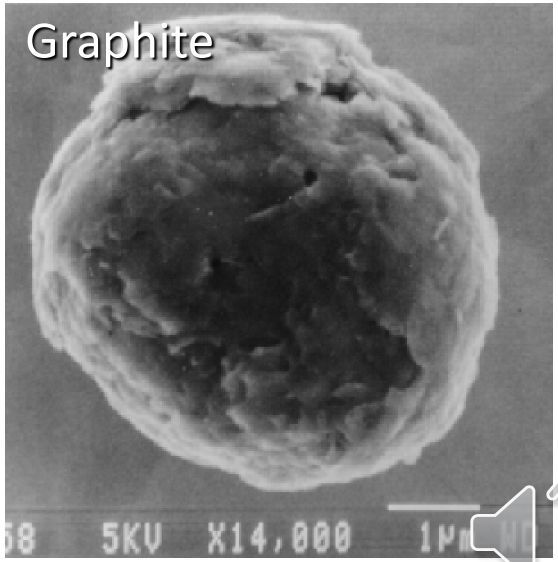
"burning down the haystack to find the needle"...

Allende carbonaceous chondrite

Acid dissolution - dissolve meteorites in acids and analyze residue

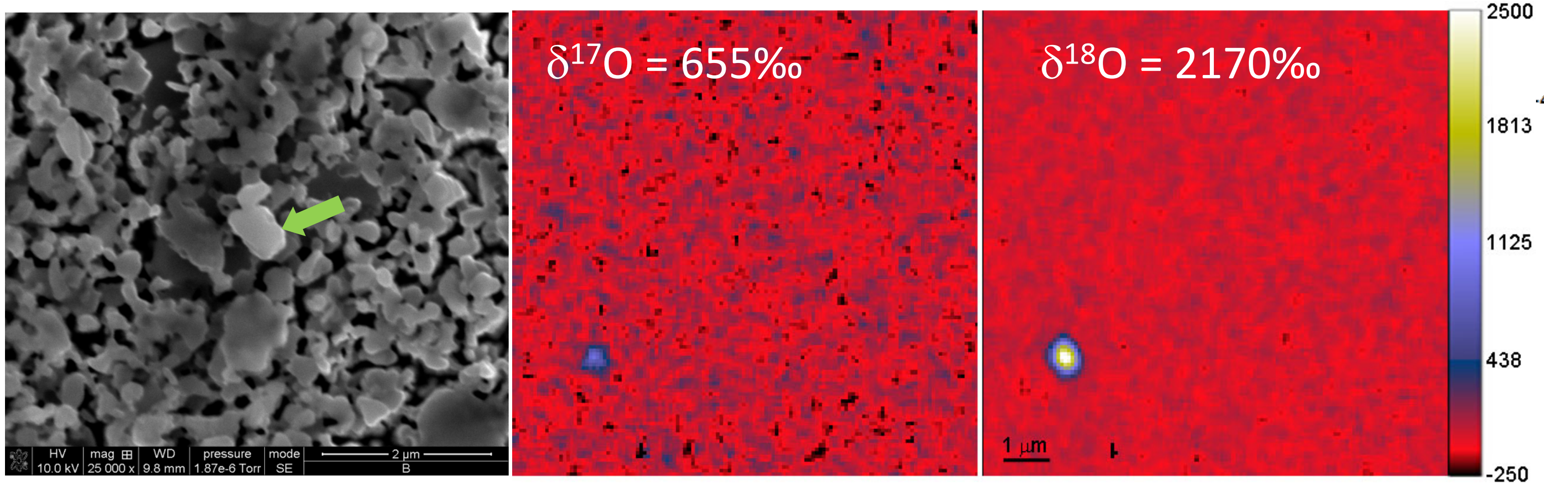
In situ analyses

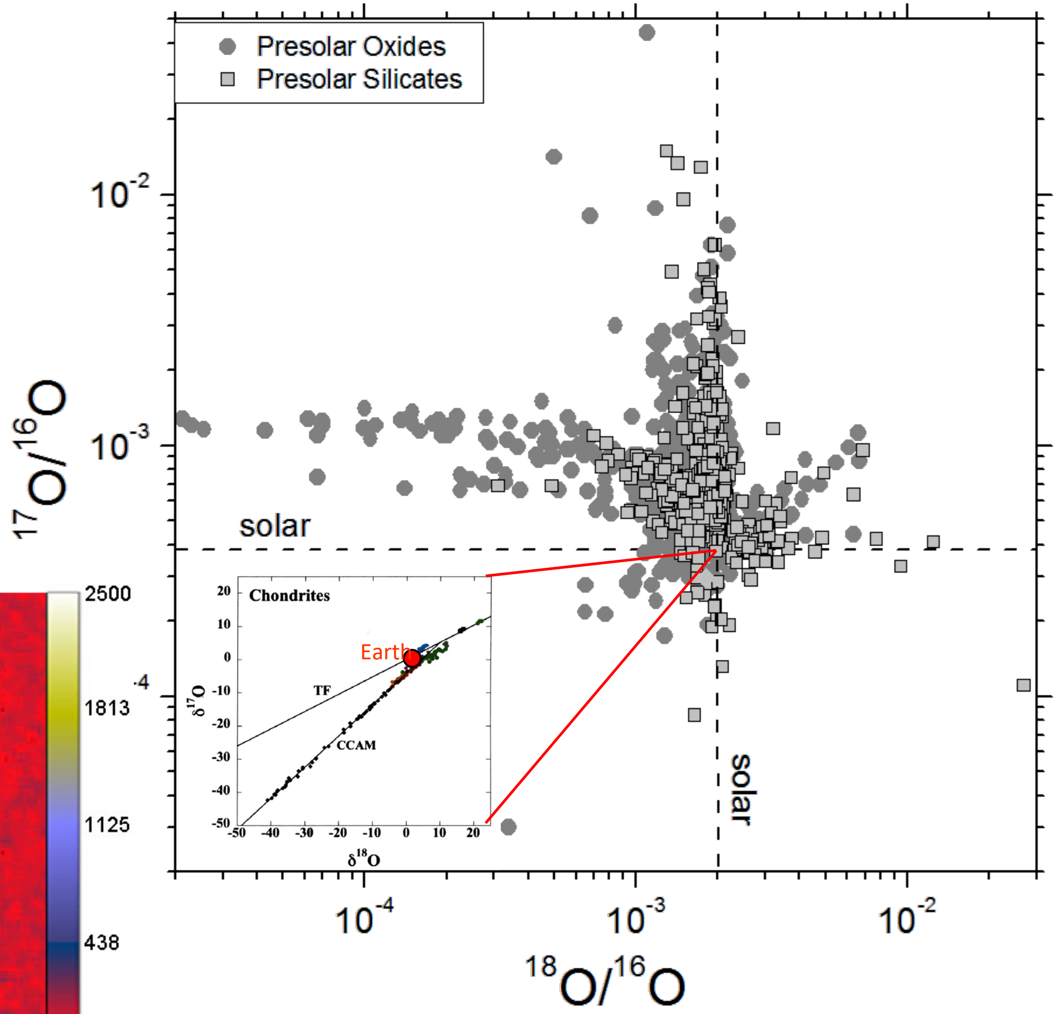




How are presolar grains identified?

- Isotopic compositions of many elements are vastly different from any Solar System material
- Compositions cannot be produced by chemical reactions and require ***nuclear processes in stars***

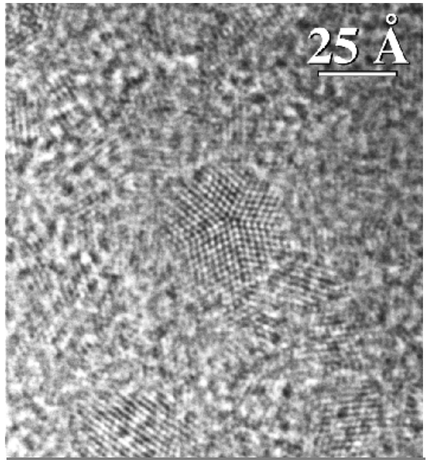




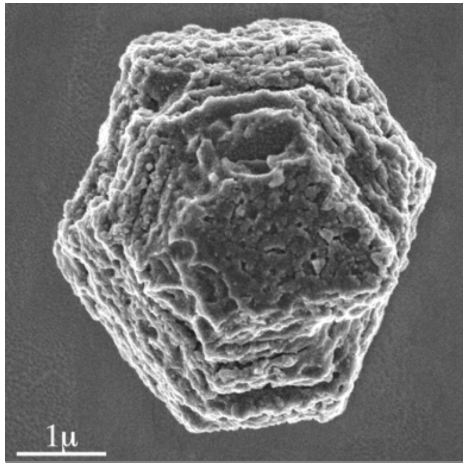
Large ^{17}O and ^{18}O enrichments produced in supernovae via H and He burning

Types of Presolar Grains

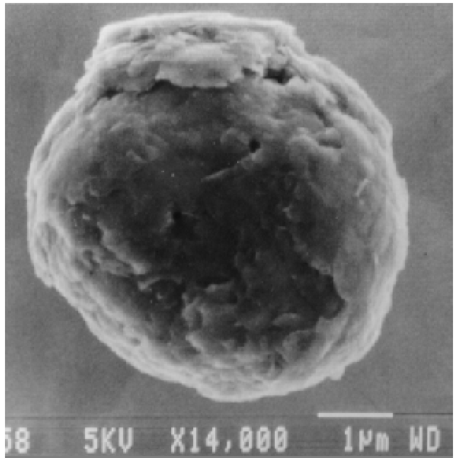
- First presolar grains (diamond, SiC, graphite) discovered by exotic noble gas signatures in 1987 (Lewis et al. 1987, Bernatowicz et al. 1987, Amari et al. 1990)
- More detailed isotopic studies and identification of additional presolar phases and subtypes made possible by Secondary Ion Mass Spectrometry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



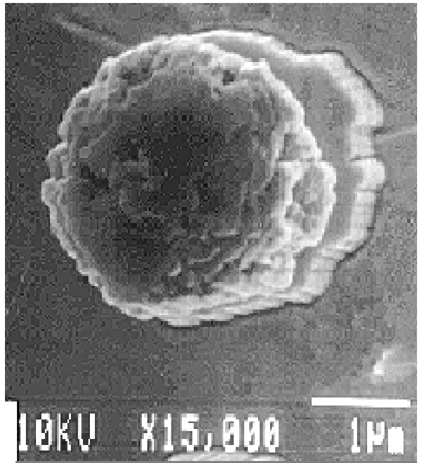
Nanodiamond
2 nm
~1400 ppm



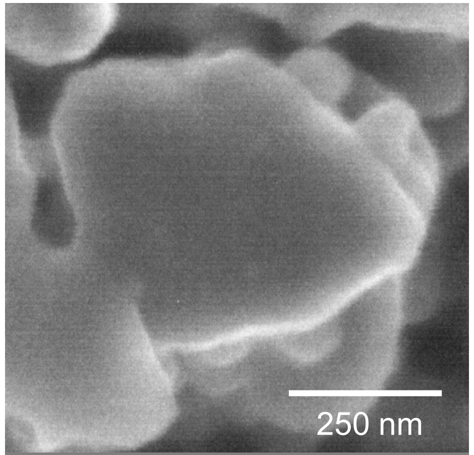
SiC
0.3 – 20 μm
~20 ppm



Graphite
1 – 20 μm
~5 ppm



Oxides
0.05 – 5 μm
< 100 ppm



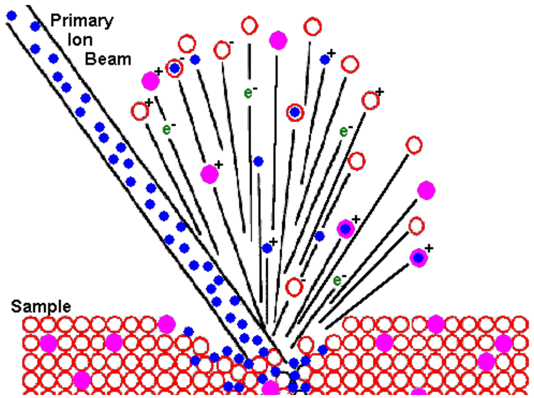
Silicates
0.05 – 2 μm
< 15,000 ppm

What can we learn from presolar grains?

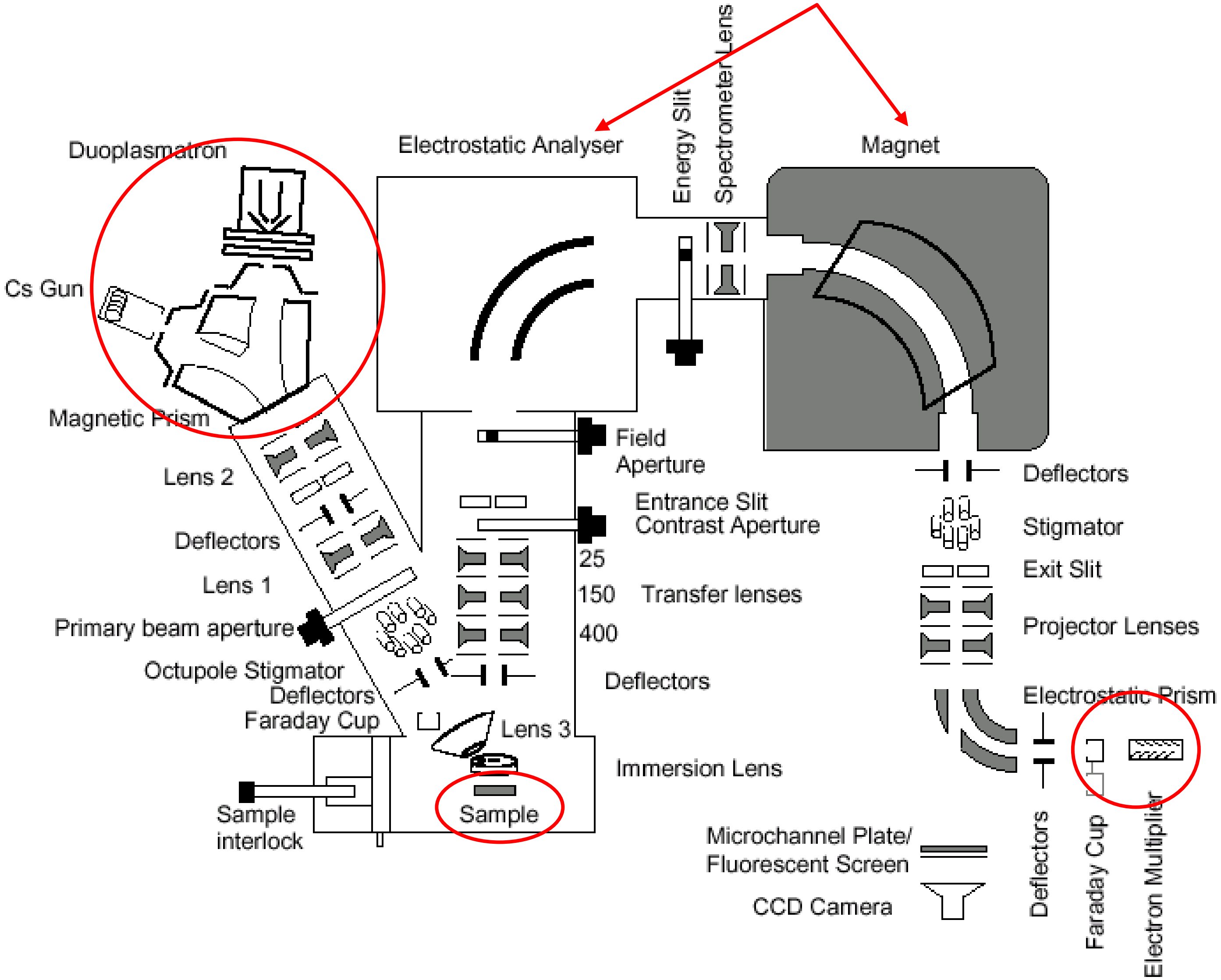
- Stellar nucleosynthesis
- Stellar evolution and mixing processes
- Galactic chemical evolution
- Major stellar sources of dust
- Dust condensation conditions in circumstellar environments
- Dust processing in the interstellar medium
- Processing in the early solar system
- Processing on the asteroid or comet parent body

Presolar silicate grains are unique probes of these processes

Techniques: Secondary Ion Mass Spectrometry (SIMS)

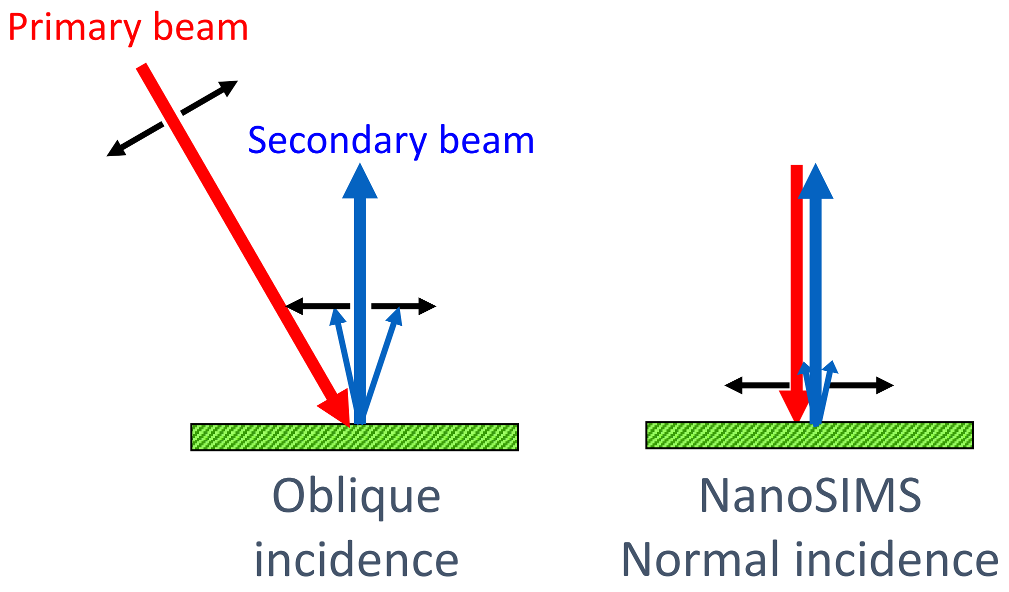


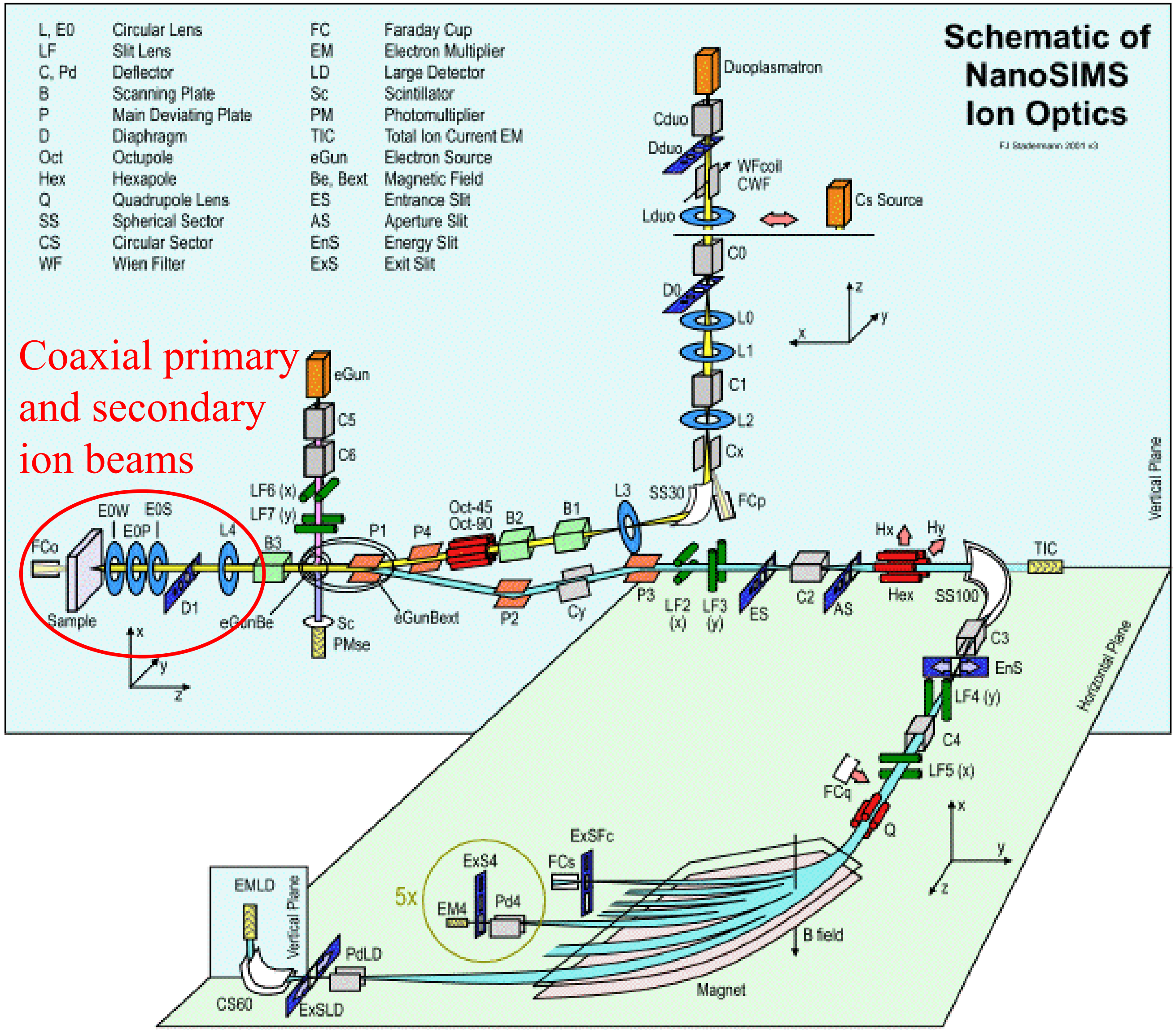
Primary beam sputters sample surface and isotopes ejected as secondary ions



- Spatial resolution > 1 micron
- Measure one mass at a time
- Allow for *in situ* analyses

Techniques: Secondary Ion Mass Spectrometry (SIMS)

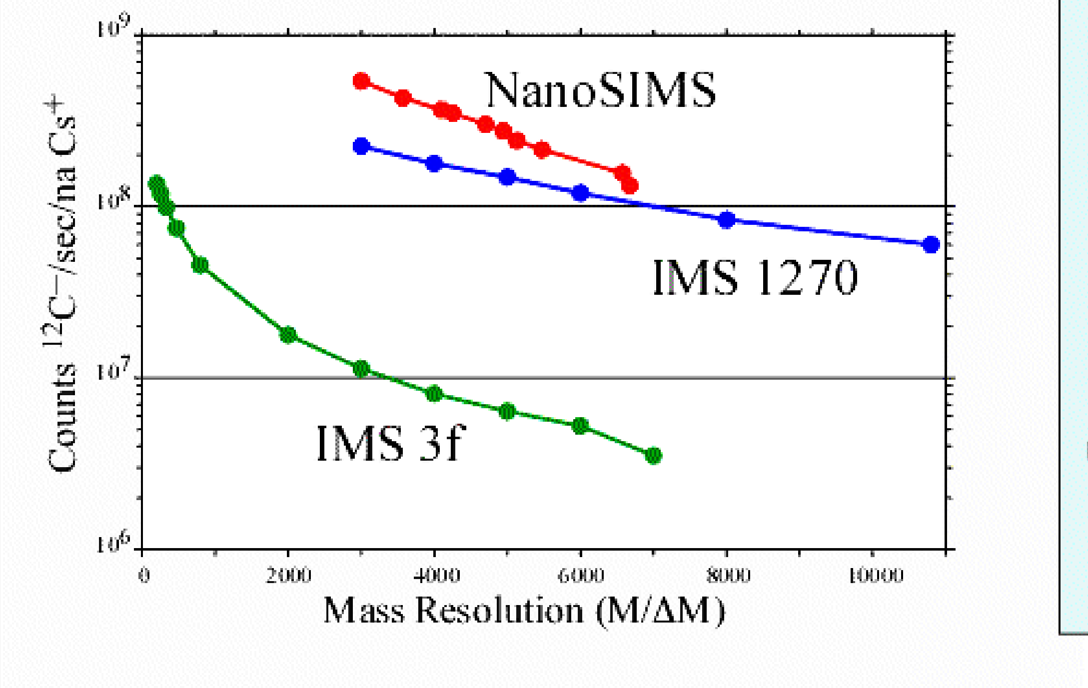


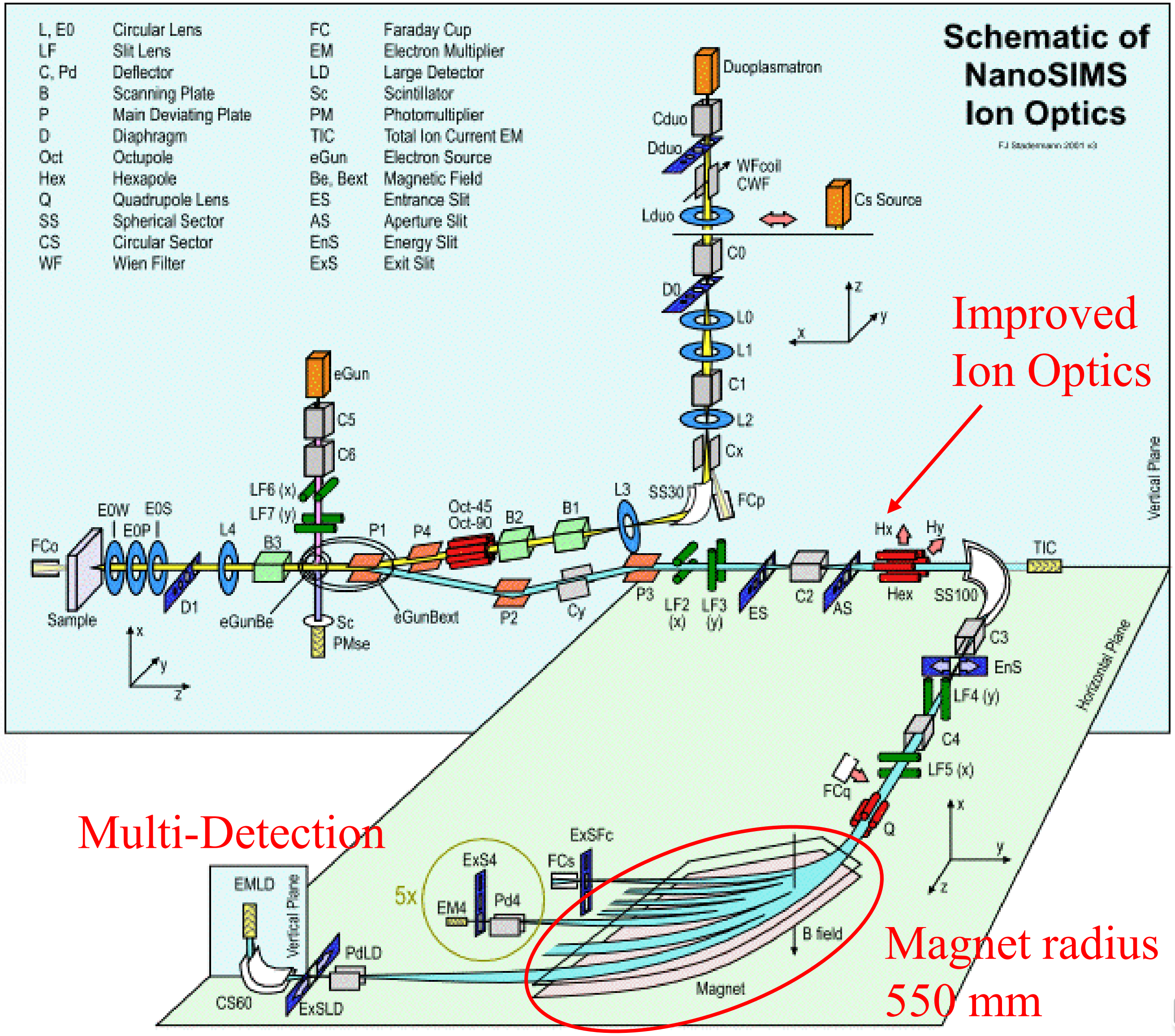


- Small working distance of the primary focusing lens and normal incidence
  - ➢ Smaller primary ion beam spot
- Earlier secondary ion beam focusing
  - ➢ Reduce aberration of system
  - ➢ High secondary ion collection efficiency

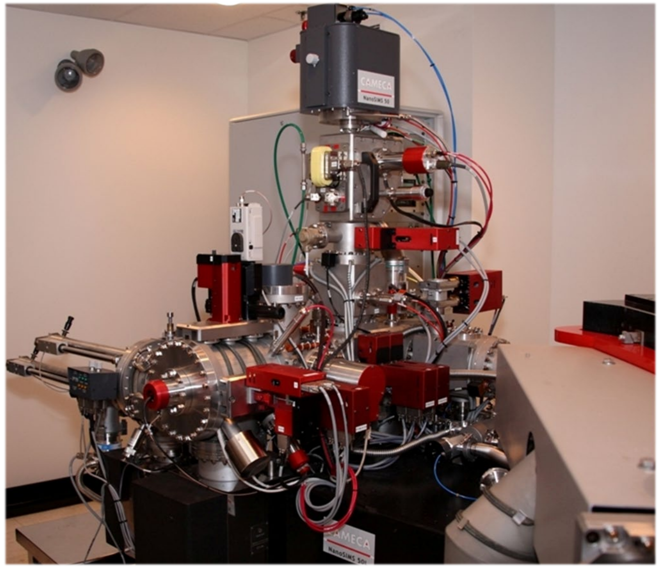
Techniques: Secondary Ion Mass Spectrometry (SIMS)

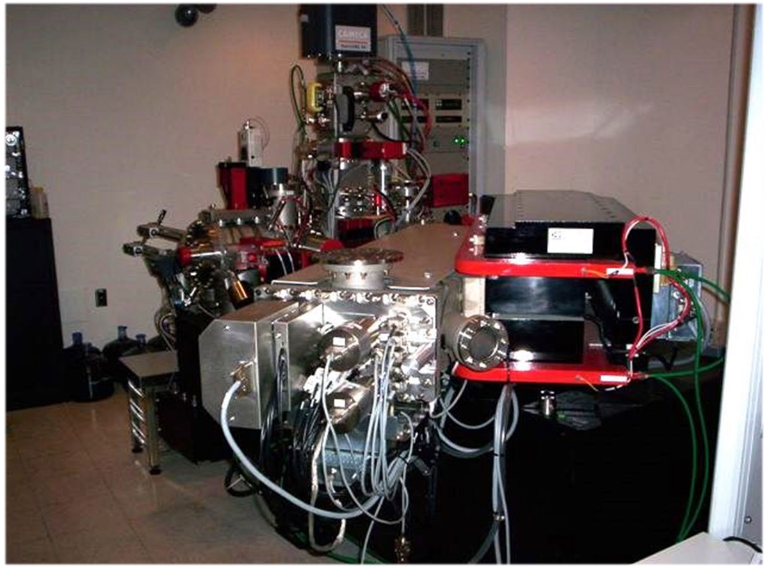
High Sensitivity at HMR



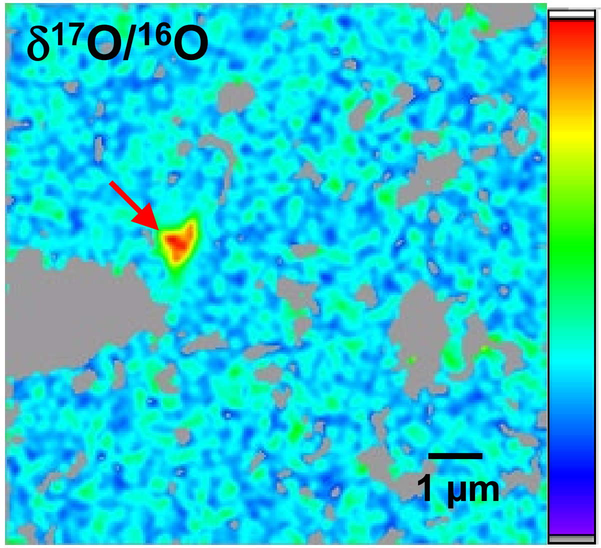


Techniques: Secondary Ion Mass Spectrometry (SIMS)





NanoSIMS ion probe @ NASA JSC

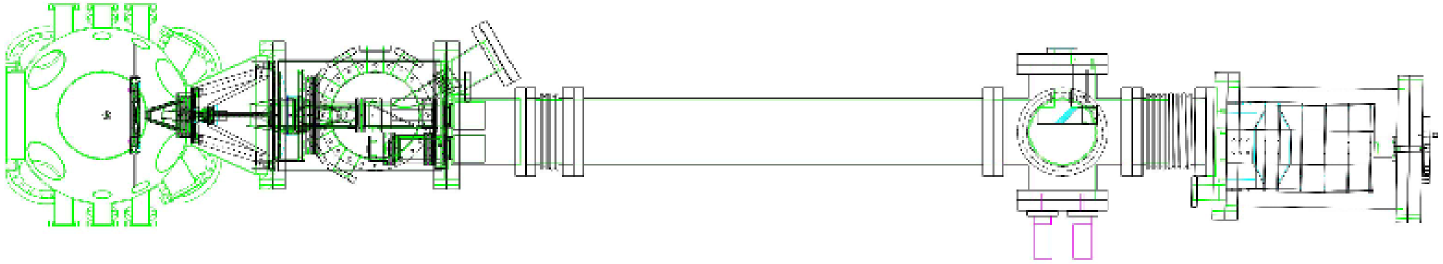


- High spatial resolution (~100 nm)
- High transmission at high mass resolution
- Multiple masses and isotopic systems measured simultaneously
- Raster ion imaging capability
- ***Major and minor element isotopic measurement of single sub-µm grains***

Techniques: Resonance Ionization Mass Spectrometry (RIMS)

- Lasers used to selectively ionize specific elements
- ***Heavy trace element isotopic analysis of single grains > 1 μm***

→ *Nan Liu's talk*

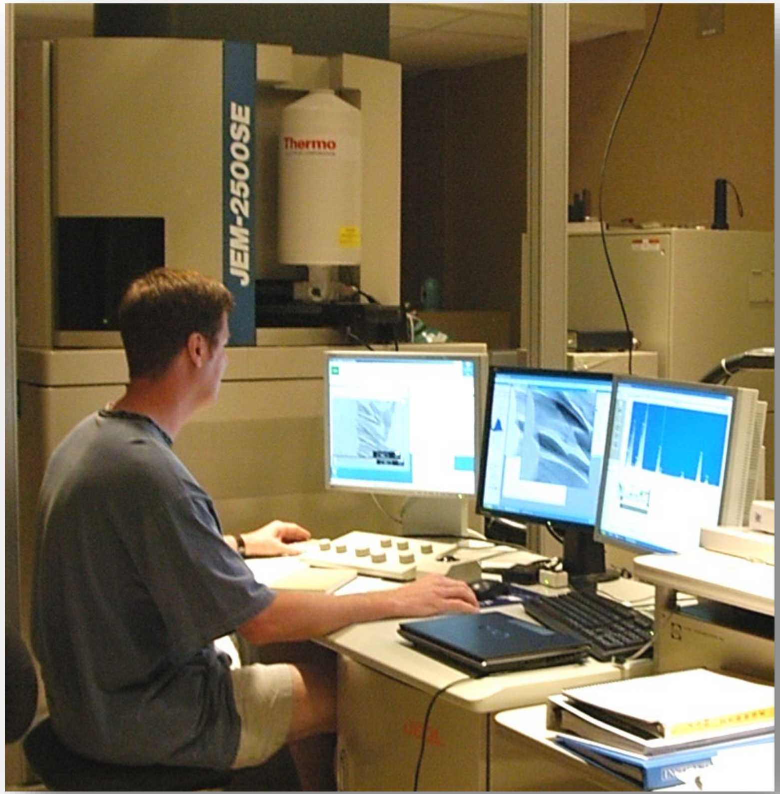


"CHARISMA" Argonne National Lab

Techniques: Transmission Electron Microscopy (TEM)

Determine mineralogy, structure and chemical compositions on nm-scale

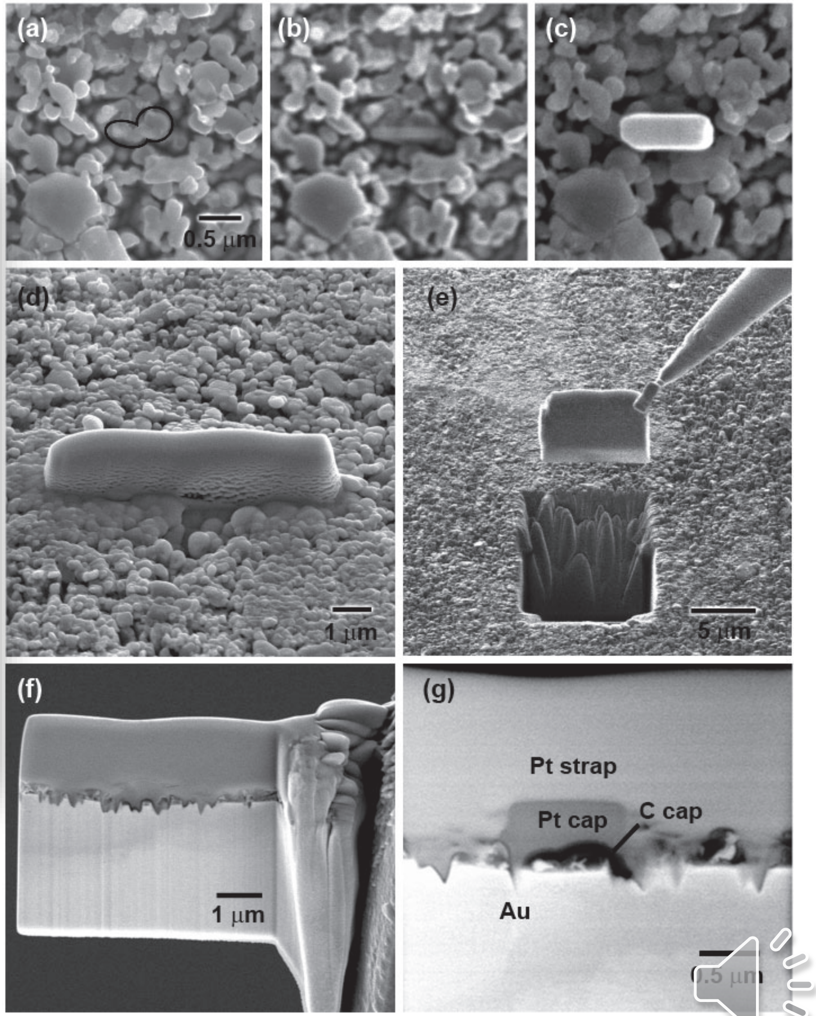
JEOL 2500 FE-TEM @ NASA JSC



- ✓ Quantitative, nm-scale chemical mapping
- ✓ Atomic scale imaging and mineral analysis
- ✓ Oxidation state determination by EELS

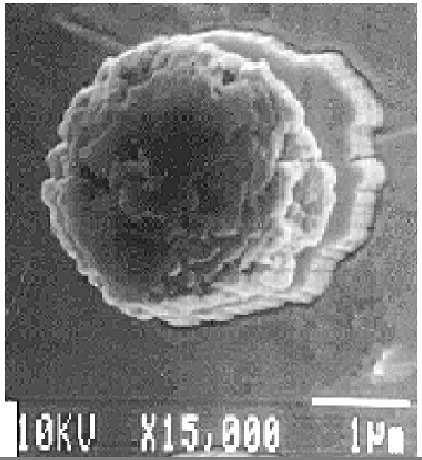
FEI Quanta 3D 600 FIB @ NASA JSC

- ✓ Used to prepare samples for TEM and NanoSIMS analyses

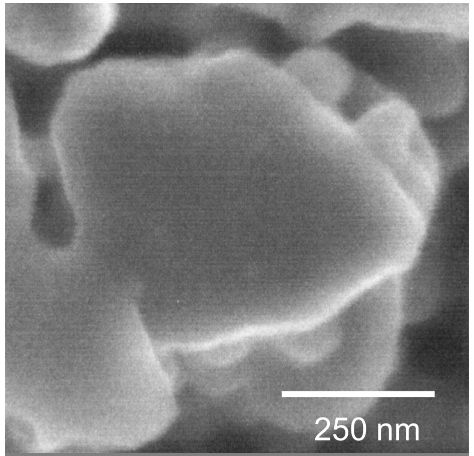


Isotopic Studies of Presolar O-rich Grains

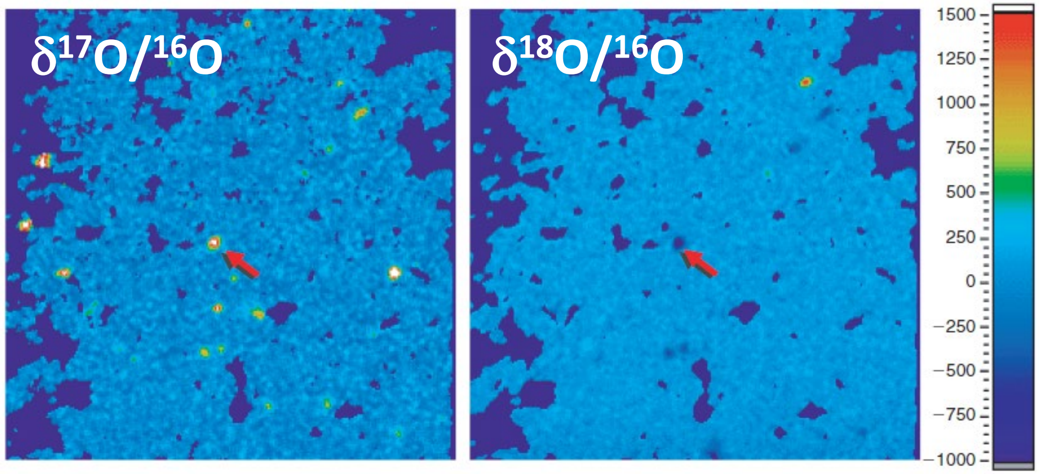
- Nearly all SiC grains are presolar and can be identified by X-ray mapping or isolated by acid dissolution
- Solar System formed under oxidizing conditions producing a majority of O-rich dust
- Higher background of O-rich grains having “normal” isotopic composition
- ***Isotopic compositions of O-rich grains must be determined to establish their presolar nature → SIMS studies (isotopic imaging)***



Oxides:
corundum, spinel, hibonite, TiO_2, chromite

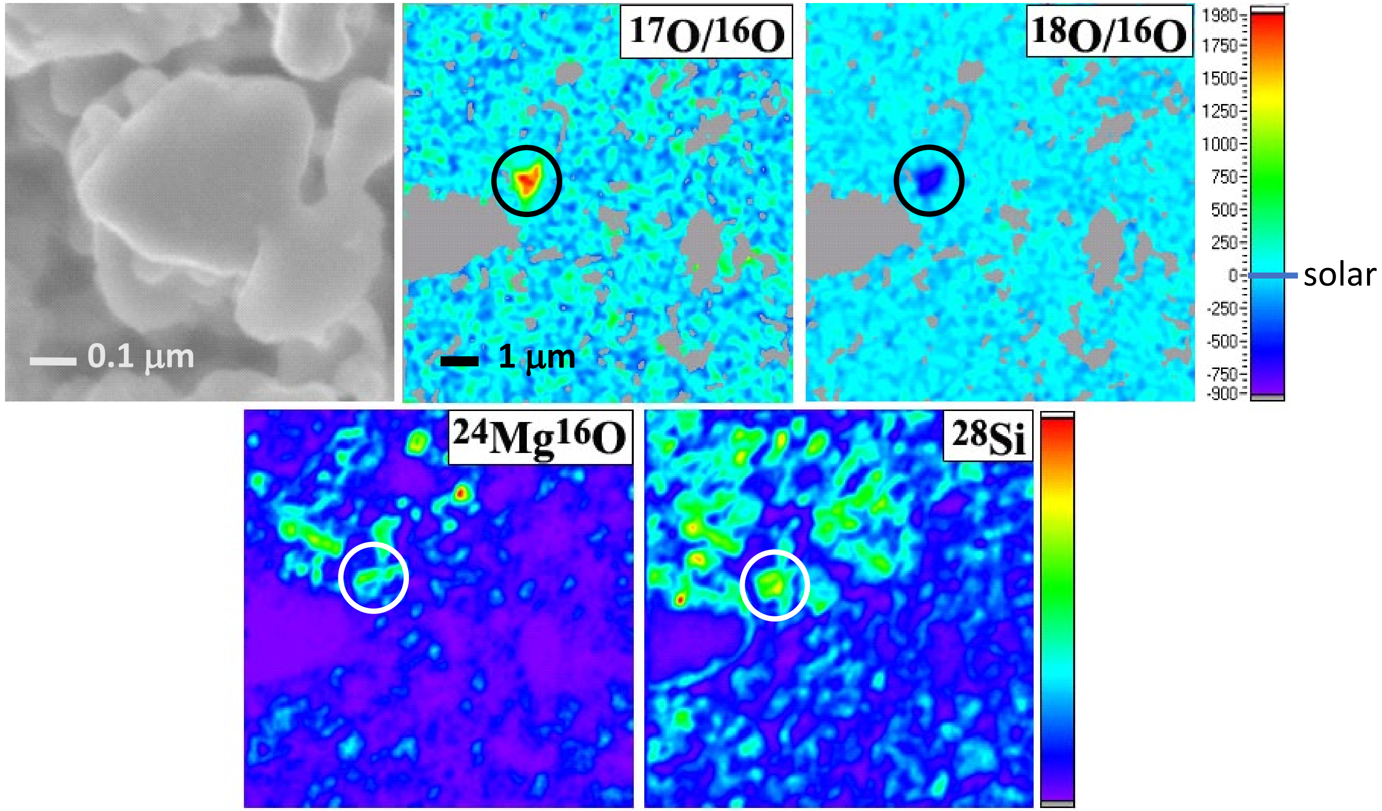


Silicates
non-stoichiometric, olivine, pyroxene



Isotopic Studies of Presolar O-rich Grains

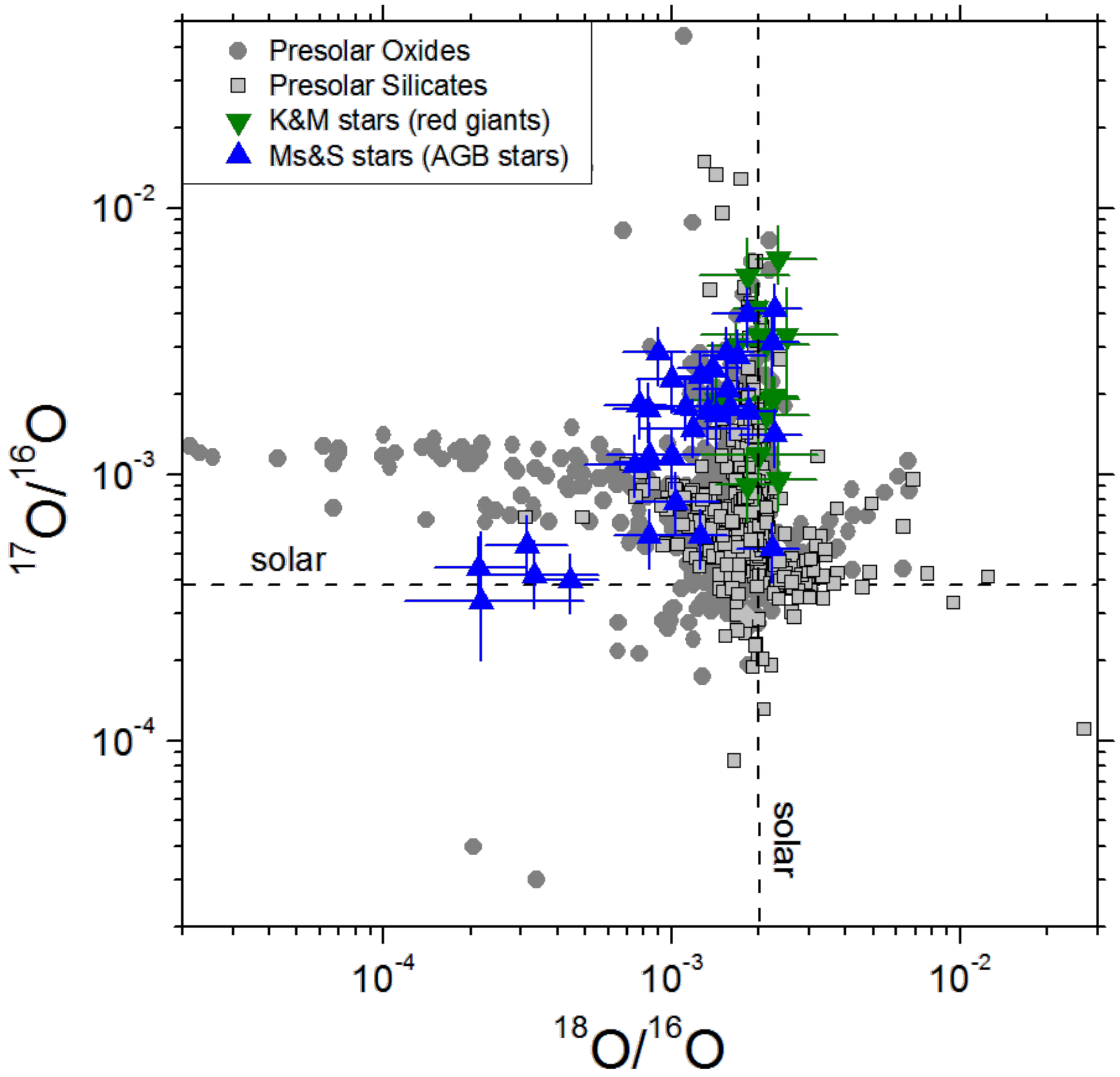
- Silicate grains susceptible to destruction by alteration on asteroid or comet parent body and by laboratory treatment
    - Only preserved in very primitive samples (little aqueous alteration)
    - Cannot be chemically isolated like SiC and oxide grains
- Silicate grains have small sizes (average 250 nm)
    - Requires high spatial resolution → NanoSIMS



Nguyen & Zinner Science 2004

O Isotopic Compositions of Presolar O-rich Grains

- Isotopic compositions of red giants similar to those of presolar O-rich grains
- Ratios from SIMS measurements of presolar grains have much higher precision than spectroscopic observations
- ***Isotopic compositions reflect distinct stellar sources and nucleosynthetic processes***

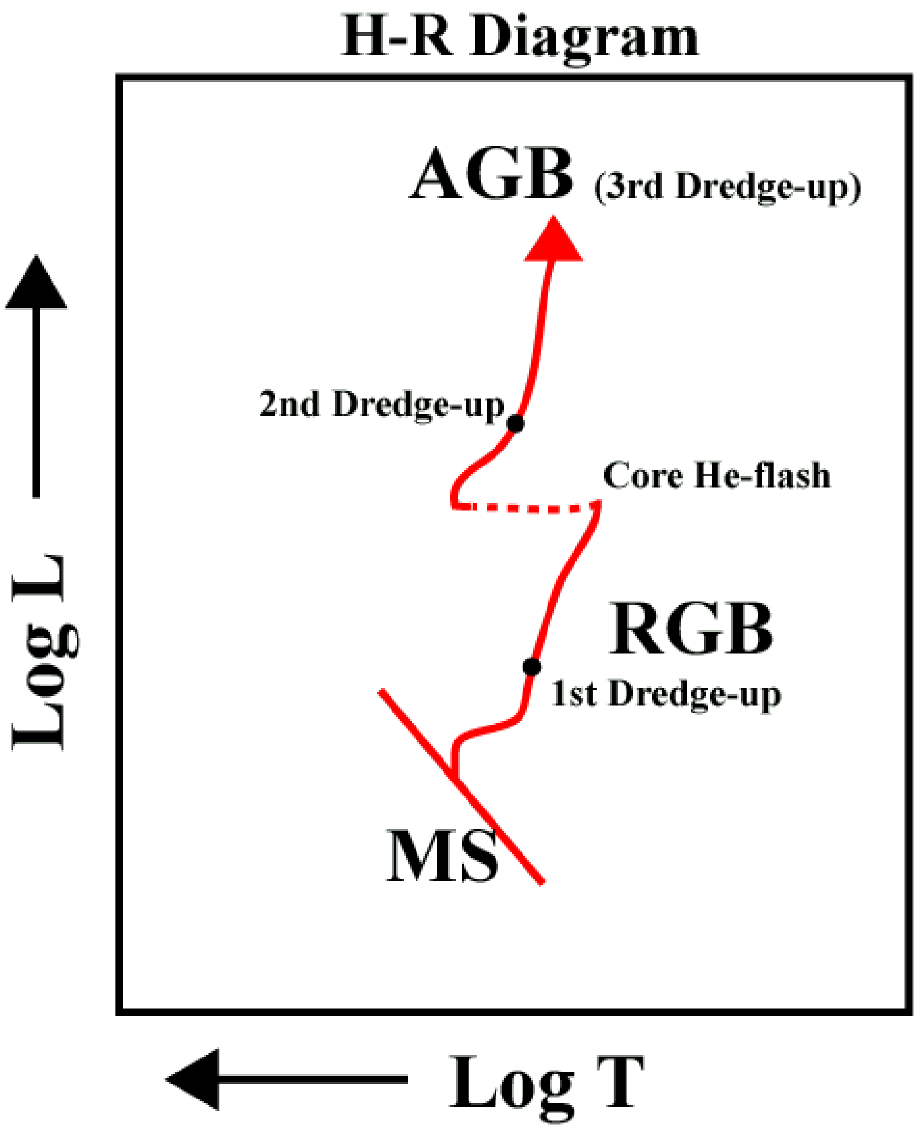


Evolution of 1–8 $M_\odot$ Stars

- 1^{st} Dredge-up:
  - Mix MS (core) H-burning products into envelope
  - ➢ Enrich ^{17}O, deplete ^{18}O

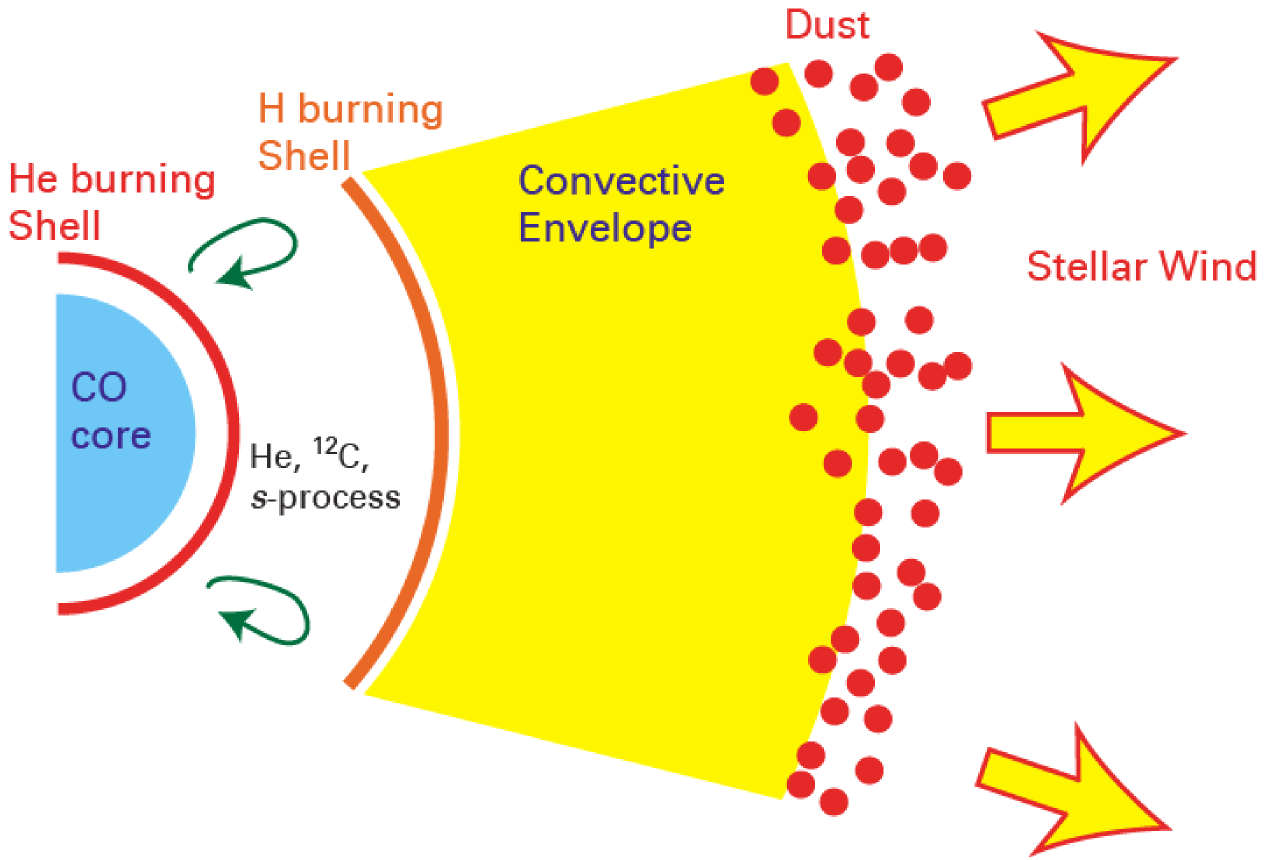
- 2^{nd} Dredge-up (>3 $M_\odot$):
  - Further mixing of H-burning products

- 3^{rd} Dredge-up:
  - Mix H-, He-burning shell material
  - ^{12}C, *s*-process elements
  - C > O with repeated 3^{rd} dredge-up
    - Carbonaceous phases condense



Evolution of 1–8 $M_\odot$ Stars

- 1^{st} Dredge-up:
  - Mix MS (core) H-burning products into envelope
  - ➢ Enrich ^{17}O, deplete ^{18}O
- 2^{nd} Dredge-up (>3 $M_\odot$):
  - Further mixing of H-burning products
- 3^{rd} Dredge-up:
  - Mix H-, He-burning shell material
  - ^{12}C, *s*-process elements
  - C > O with repeated 3^{rd} dredge-up
    - Carbonaceous phases condense



Processes affecting O, Mg, and Si Isotopes: Galactic Chemical Evolution

- Chemical composition of the Galaxy evolves with time as generations of stars are born and die – products of nucleosynthesis ejected into ISM

- Metallicity (Z) increases with time
  - Z = mass fraction elements heavier than He

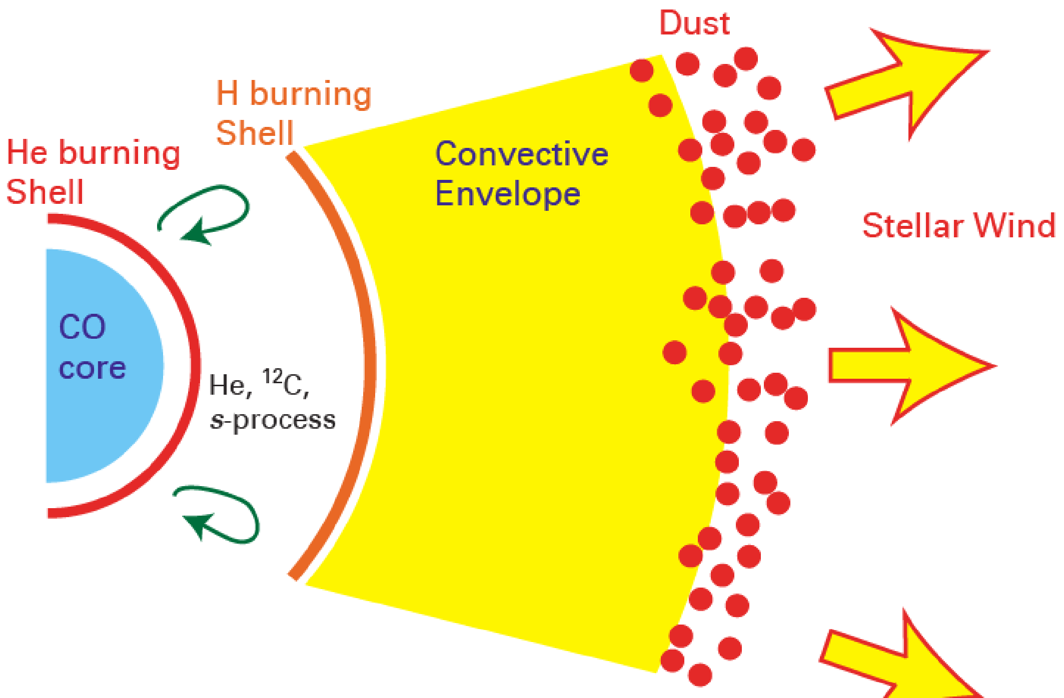
- Isotopic ratios change over time
  - Primary (major) isotopes (e.g., ^{16}O, ^{24}Mg, ^{28}Si) can be produced from H, He
  - Secondary (minor) isotopes (e.g., ^{17}O, ^{18}O, ^{25}Mg, ^{26}Mg, ^{29}Si, ^{30}Si) require pre-existing CNO
  - Secondary isotopes enhanced relative to primary isotopes with time
  - (Secondary isotope)/(primary isotope) ratios increase with time (e.g., $^{18}O/^{16}O$, $^{25}Mg/^{24}Mg$, $^{30}Si/^{28}Si$)

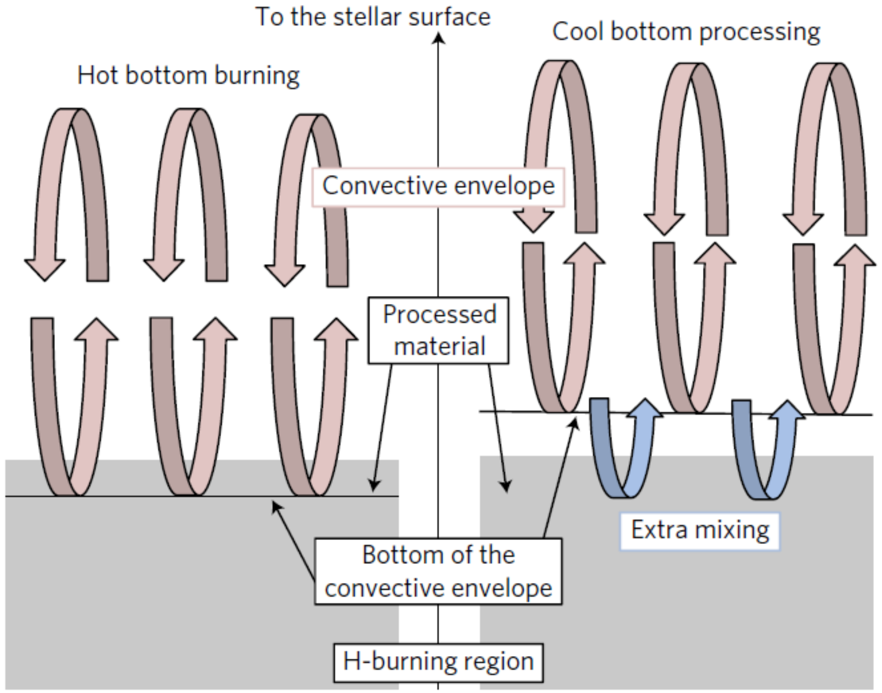
Nuclear Reactions Affecting O, Mg, and Si Isotopes

REACTION	O ISOTOPES	MG ISOTOPES	SI ISOTOPES
p-capture	$^{16}O \rightarrow {}^{17}O$ $^{17}O \rightarrow {}^{18}O$ $^{18}O \rightarrow {}^{15}N$	$^{25}Mg \rightarrow {}^{26}Al \dashrightarrow {}^{26}Mg$	
n-capture		$^{26}Al \rightarrow {}^{26}Mg$	$^{28}Si \rightarrow {}^{29}Si$ $^{29}Si \rightarrow {}^{30}Si$
α-capture	$^{12}C \rightarrow {}^{16}O$ $^{13}C \rightarrow {}^{16}O$	$^{22}Ne \rightarrow {}^{25}Mg$ and ^{26}Mg	

- AGB stars: reactions occur in H- and He-burning shells; products brought to the surface by 3rd dredge-up
- SN: reactions occur in multiple zones

Extra Mixing Processes AGB Stars



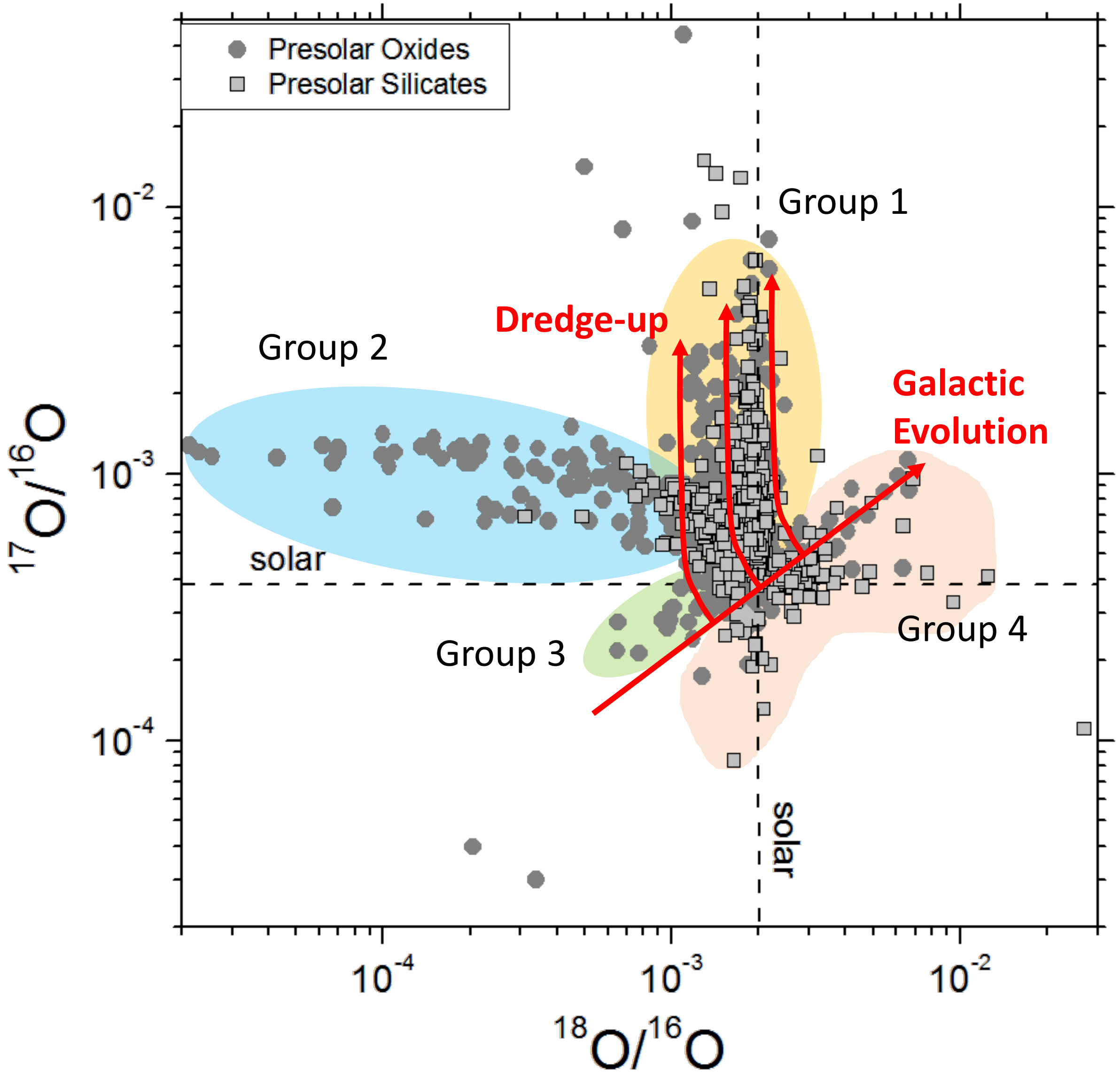


From Lugaro et al. 2017

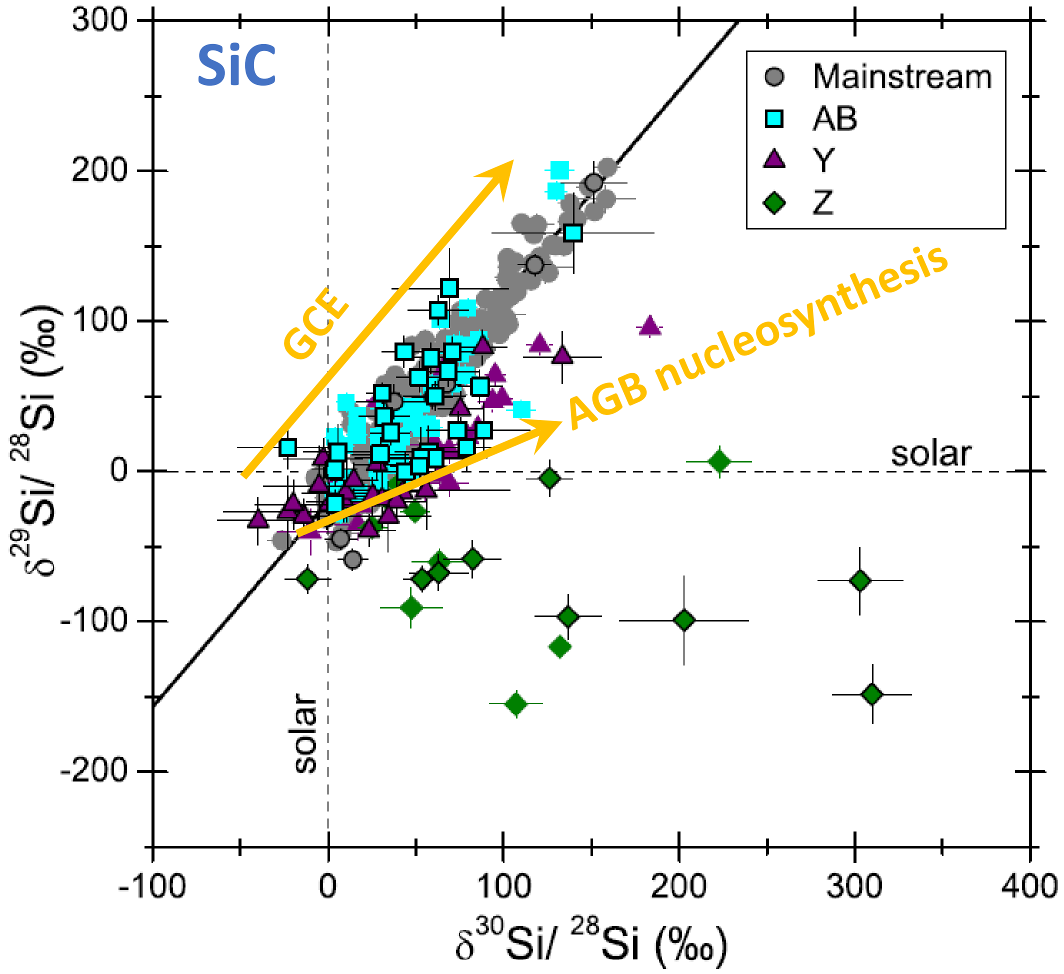
- Material processed in H-burning region cycled into the envelope (enhances ^{26}Al, destroys ^{18}O)
- Cool Bottom Processing (CBP) in low mass stars – envelope gets close to H-burning region and radiative extra mixing brings processed material into envelope (Wasserburg et al 1995, Nollett et al 2003)
- Hot Bottom Burning (HBB) in intermediate mass stars – material at base of envelope gets hot enough to undergo H-burning, and mixing occurs via convection (Boothroyd et al 1995, Lugaro et al 2007)

Stellar Sources "Group 1" Grains

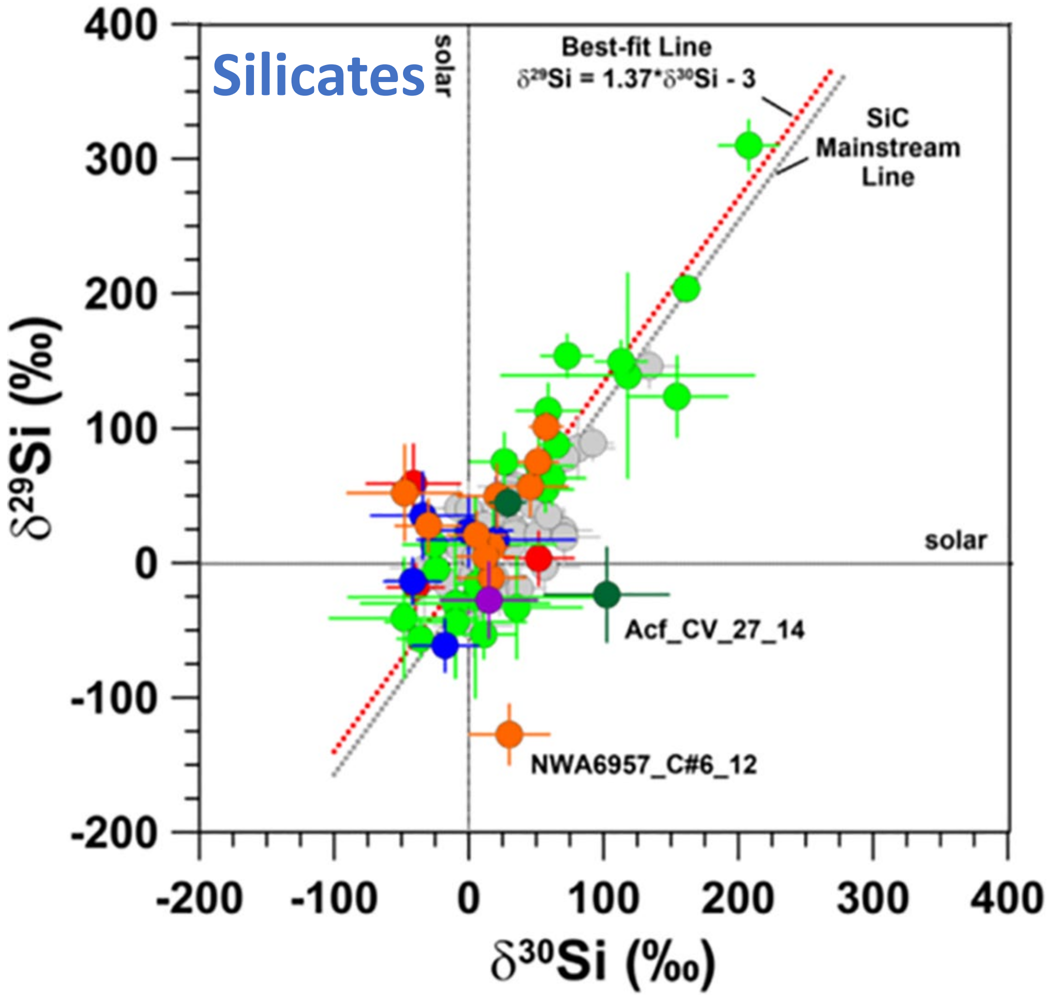
- Ratios of *most* Group 1 grains explained well by formation around low mass (< 3 M $_\odot$) RG and AGB stars
- Dredge-up brings products of H-burning to stellar envelope
- Stellar mass inferred from $^{17}O/^{16}O$ (dredge-up depth increases with mass)
- Stellar metallicity (Z) inferred from $^{18}O/^{16}O$
  - Range of metallicities agree well with GCE model predictions



Si Isotopic Ratios AGB Grains



Nguyen et al. 2017

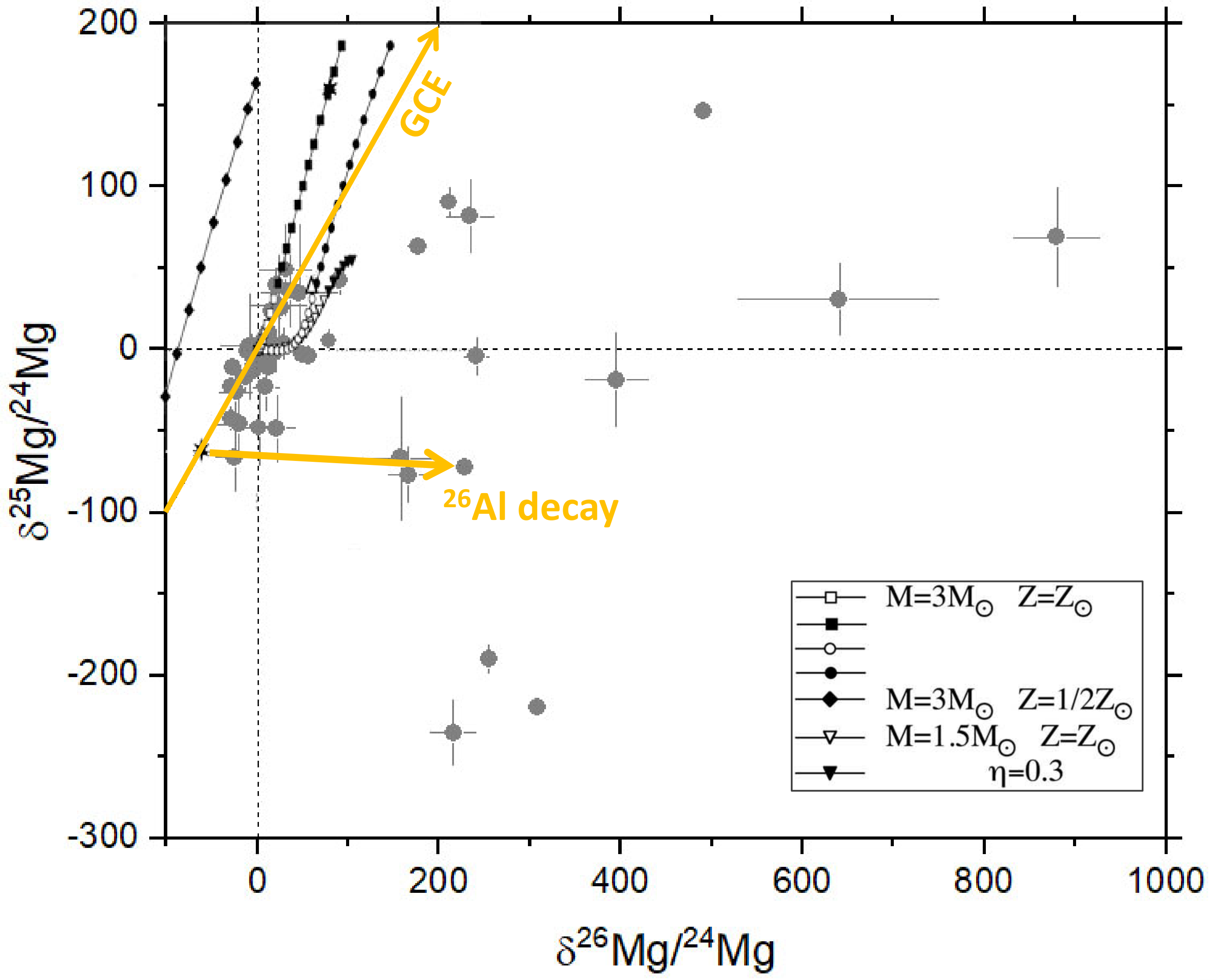


Adapted from Hoppe et al. 2021

Si isotopic ratios of AGB SiC and silicates largely governed by GCE, but silicate grains have less contribution from AGB nucleosynthesis

Mg Isotopic Ratios "Group 1" Oxides

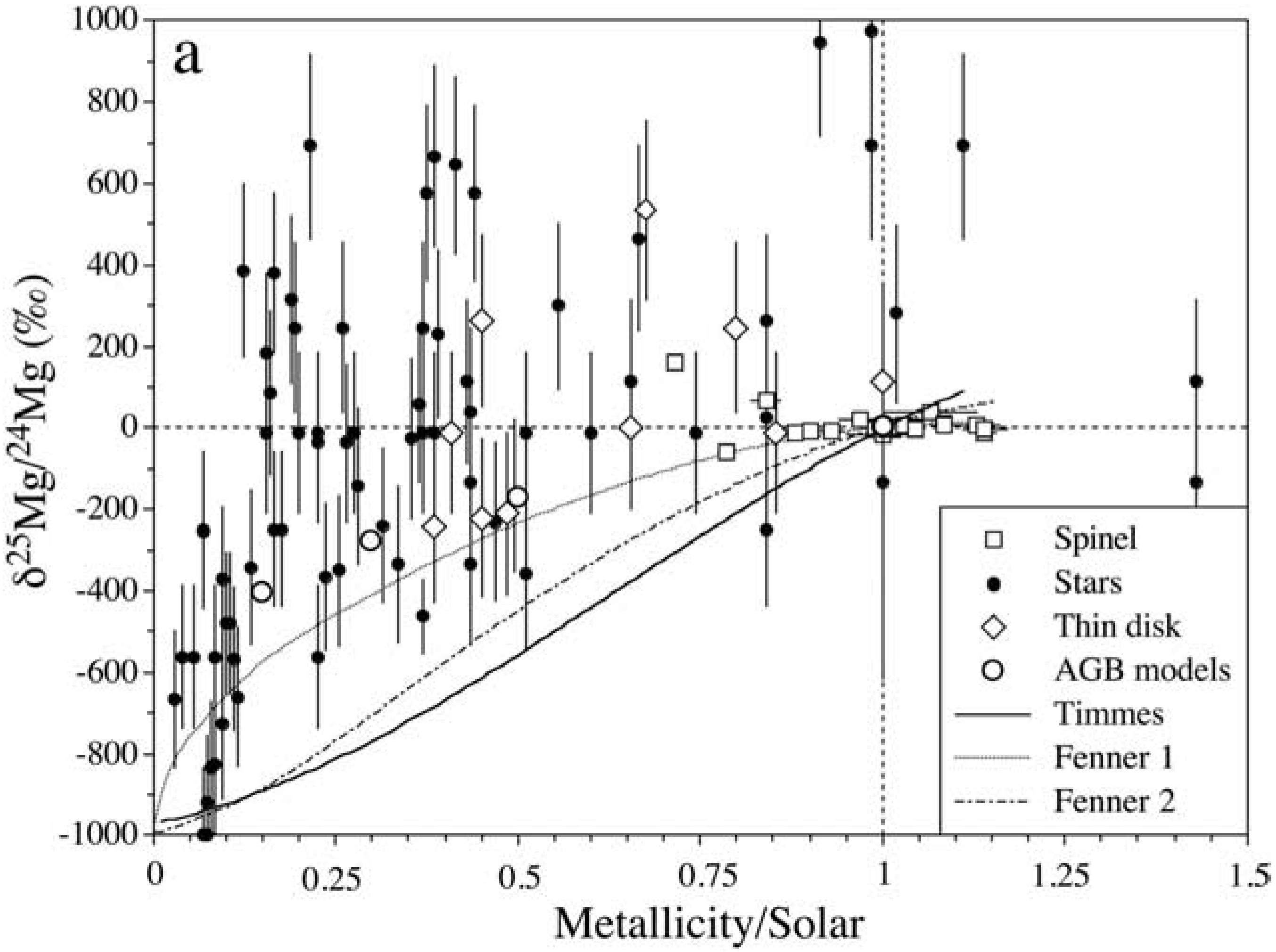
- Many grains agree with GCE and AGB models
  - Parent stars have a range of mass and Z
- Some grains have larger ^{26}Mg excesses from ^{26}Al decay than models predict
  - Extra mixing processes?
  - SN Sources?
- ^{25}Mg excesses of some grains exceed model predictions for O-rich stars
  - GCE origin
  - Origin in massive star experiencing HBB



Data presolar grain database: Hynes & Gyngard 2009
Stellar models: Zinner et al. 2005

Mg Isotopic Ratios “Group 1” Oxides: GCE

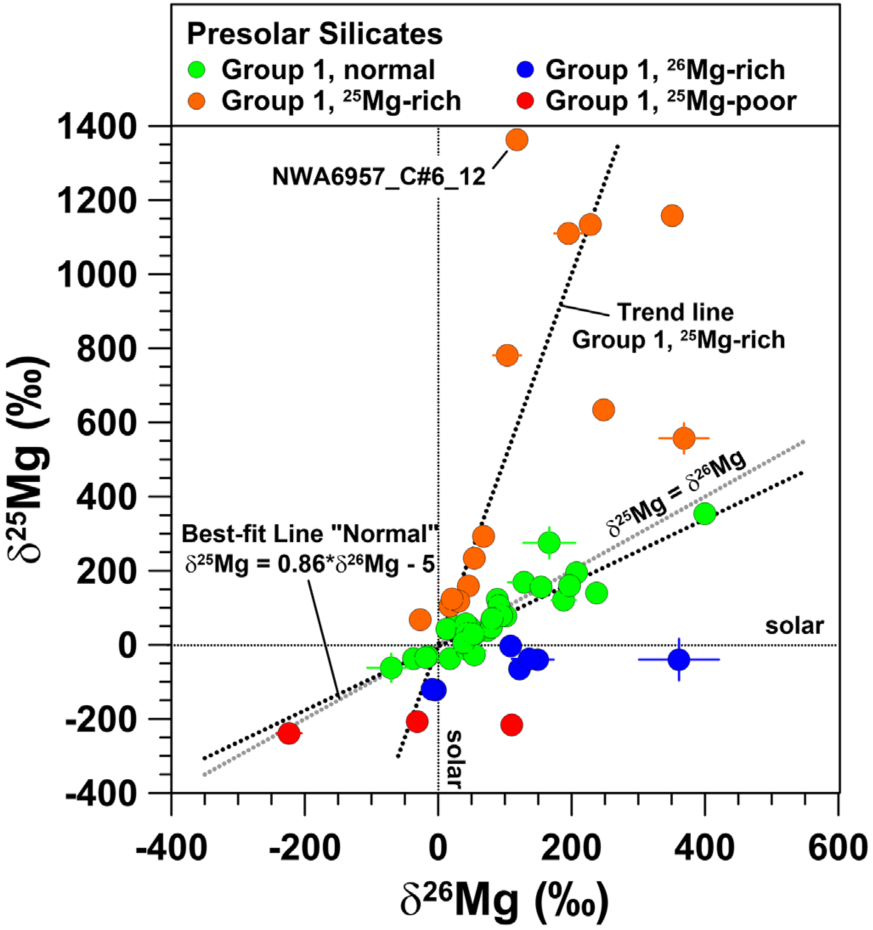
- Grain data fit best by “Fenner 1” model of GCE that includes nucleosynthetic contributions from AGB stars

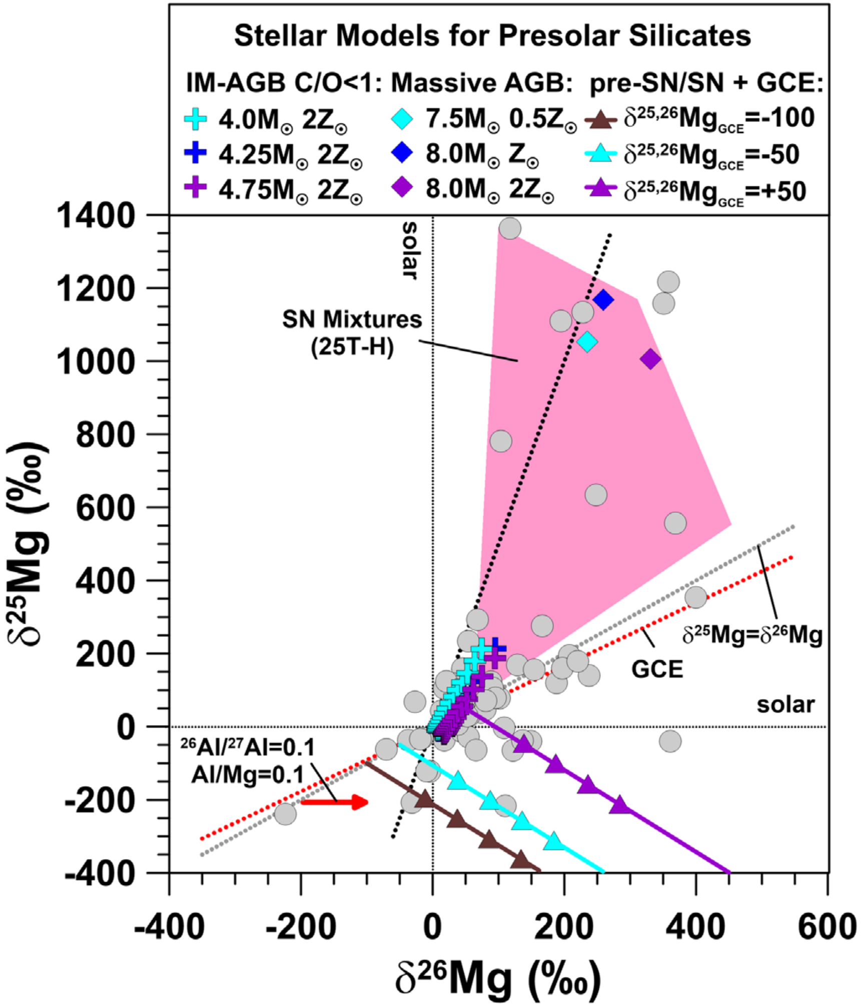


From Zinner et al. 2005

Mg Isotopic Ratios “Group 1” Silicates

- Recent Mg isotopic analyses of Group 1 silicates revealed subgroups
- Compositions of “normal” grains follow GCE → low-mass AGB stars
- ^{26}Mg-rich and ^{25}Mg-poor grains from supergiants (pre-SN stars) or SN
- ^{25}Mg-rich grains could have SN (Leitner et al. 2019; Hoppe et al 2021) or super-AGB (Verdier-Paoletti et al. 2019) sources.
- Grains with smaller ^{25}Mg enrichments could derive from intermediate-mass, high Z AGB stars (Hoppe et al 2021)

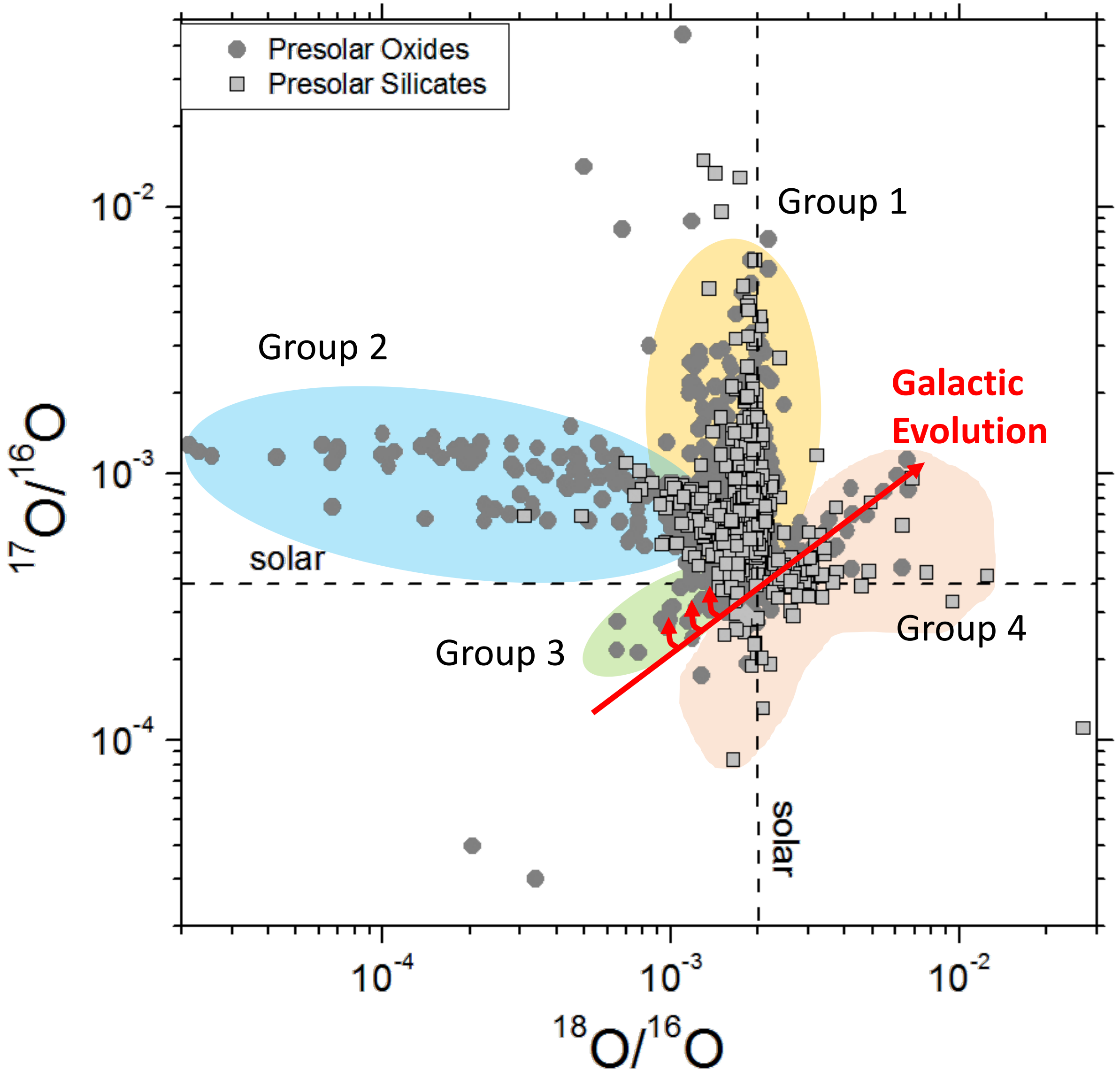




From Hoppe et al. 2021

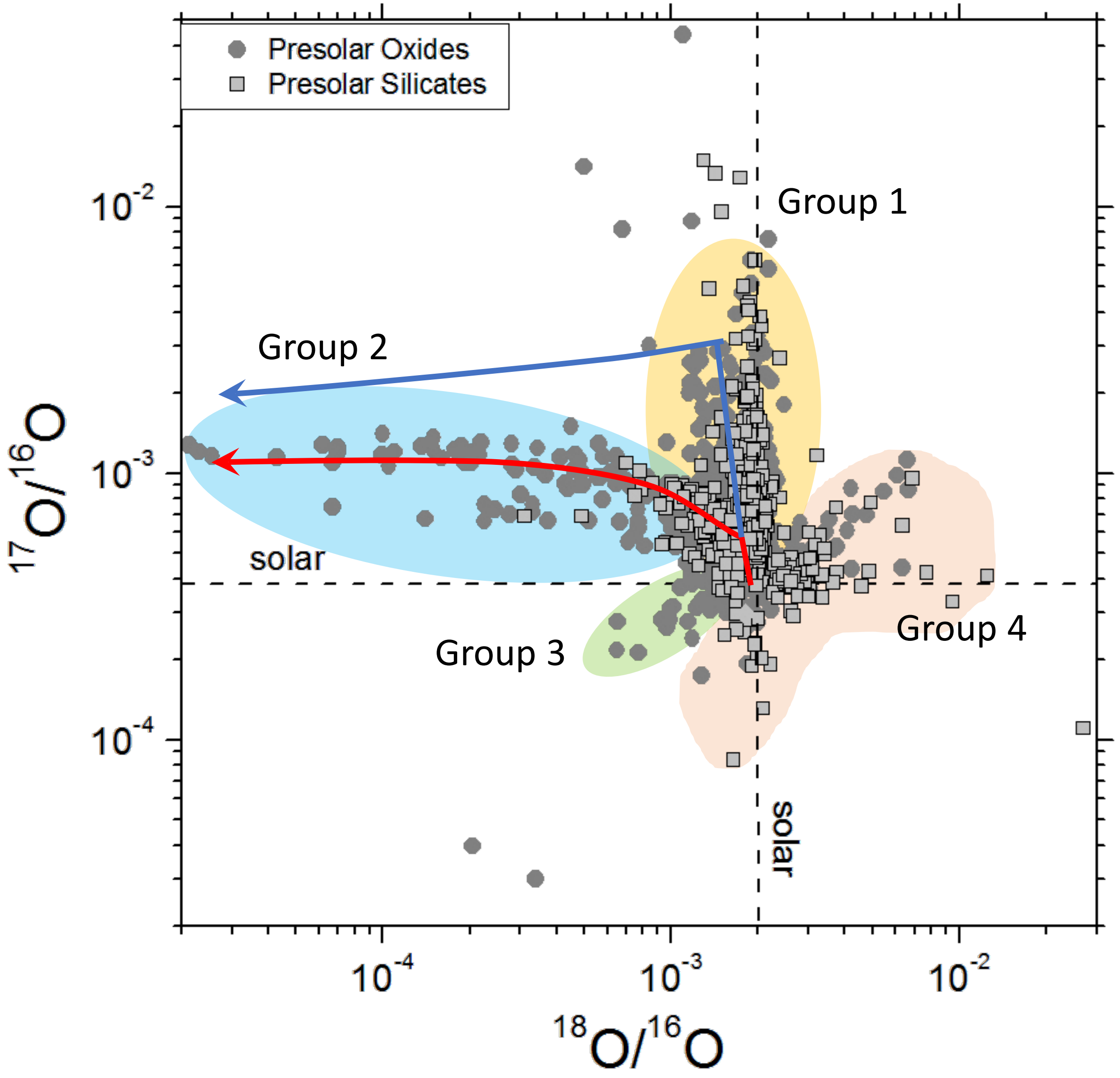
Stellar Source "Group 3" Grains

- From low mass, low metallicity RG and AGB stars
- Low $^{17}O/^{16}O$ and $^{18}O/^{16}O$ ratios reflect GCE
- Parent stars formed early in the Galaxy



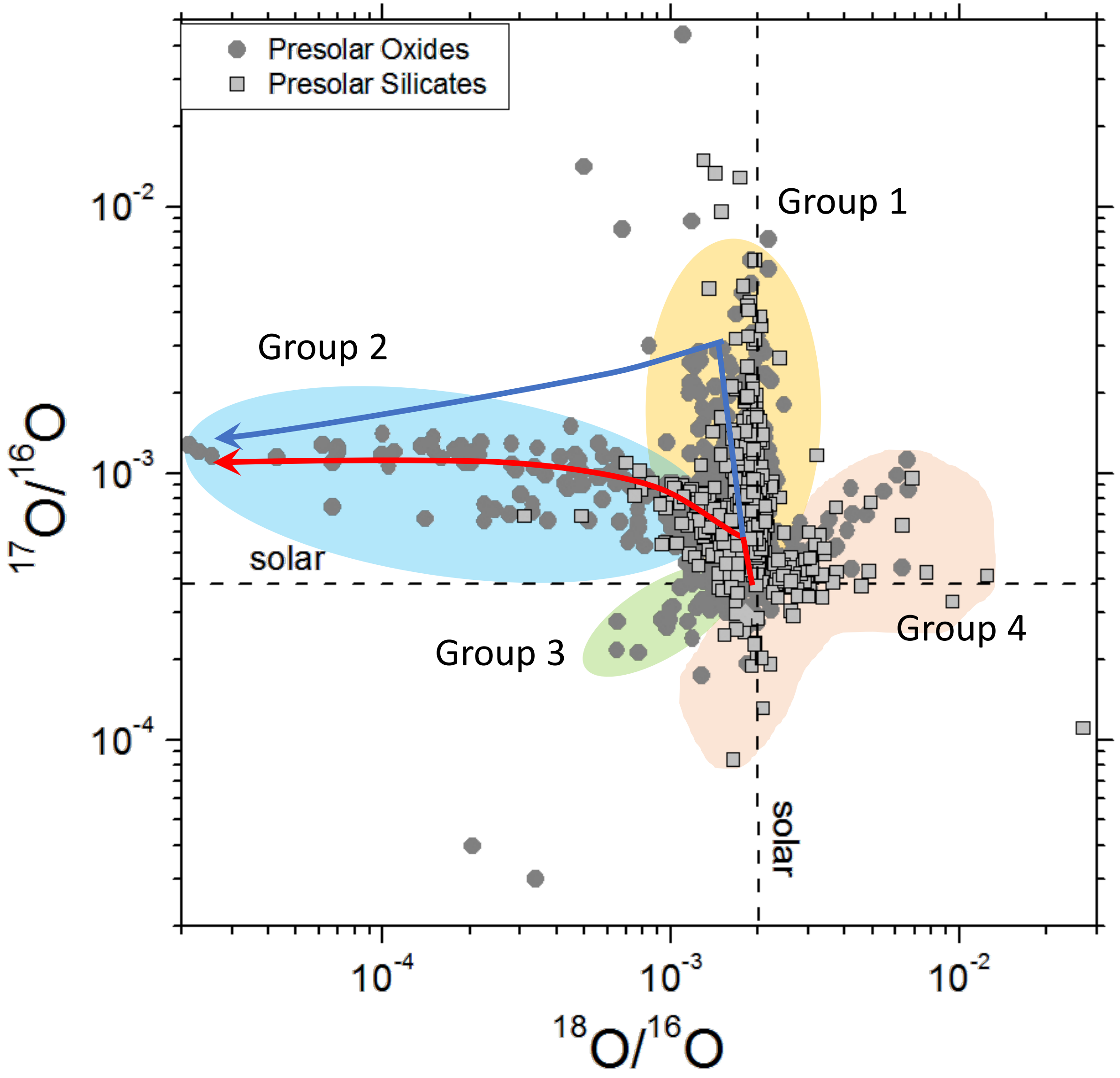
Stellar Source “Group 2” Grains

- ^{18}O depletions require extra mixing processes
- CBP in low-mass AGB stars? (Wasserburg et al 1995, Nollett et al 2003)
- HBB in intermediate mass (>4 $M_{\odot}$) AGB stars? (Boothroyd et al 1995, Lugaro et al 2007)



Stellar Sources "Group 2" Grains

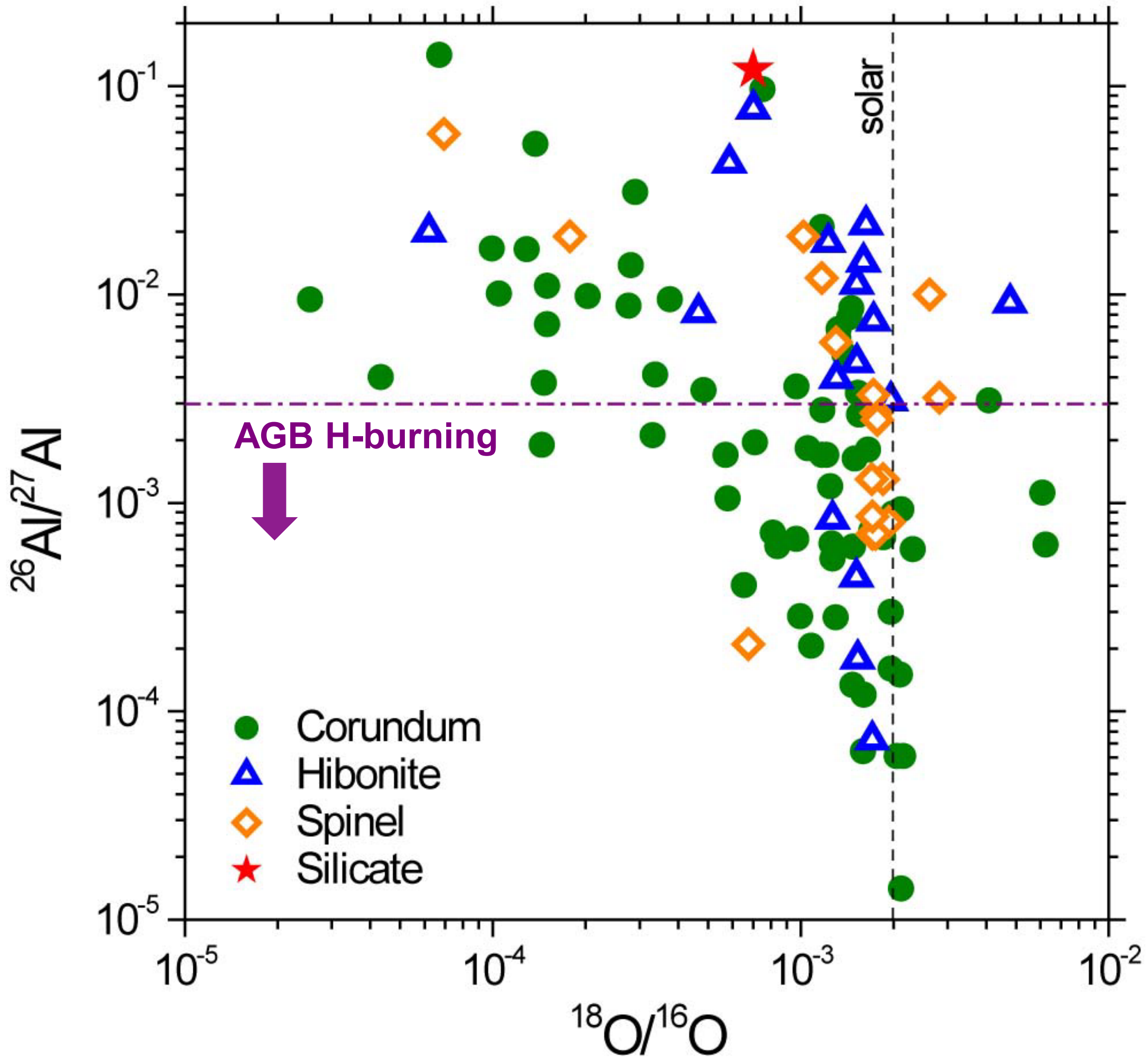
- ^{18}O depletions require extra mixing processes
- CBP in low-mass AGB stars? (Wasserburg et al 1995, Nollett et al 2003)
- HBB in intermediate mass (>4 $M_{\odot}$) AGB stars? (Boothroyd et al 1995, Lugaro et al 2007)
- New experimentally determined $^{17}O(p,\alpha)^{14}N$ reaction rate supports HBB (Lugaro et al. 2016)



AGB Mixing Processes

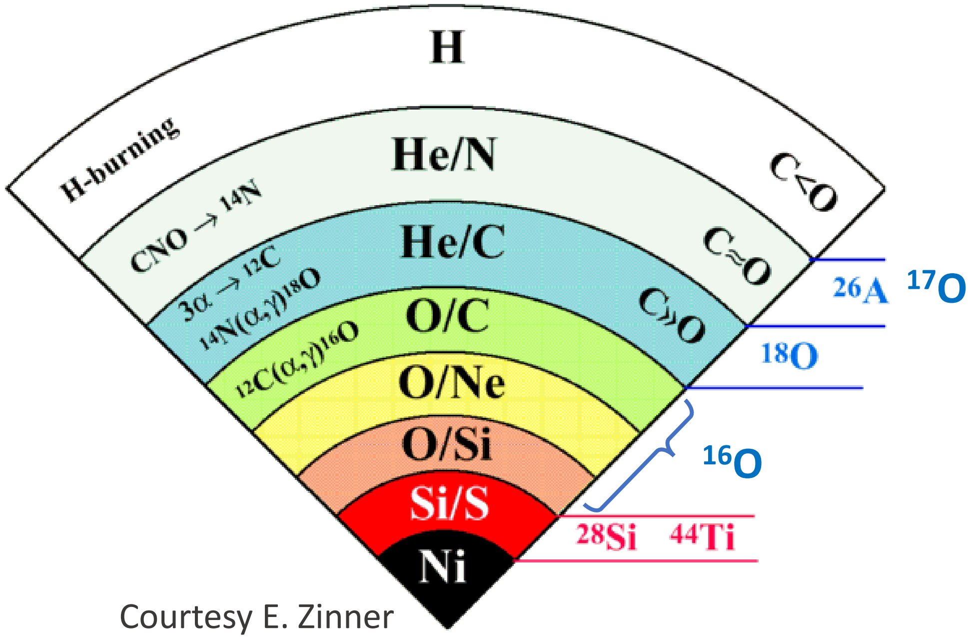
- Grains with large ^{26}Mg excess from in situ decay of ^{26}Al
- $^{26}Al/^{27}Al$ ratios exceed values from shell H-burning and 3rd dredge-up in AGB stars (Karakas & Lattanzio, 2003)

- During CBP, ^{18}O destruction depends on rate of mass circulation
- ^{26}Al production depends on temperature (depth) reached by material

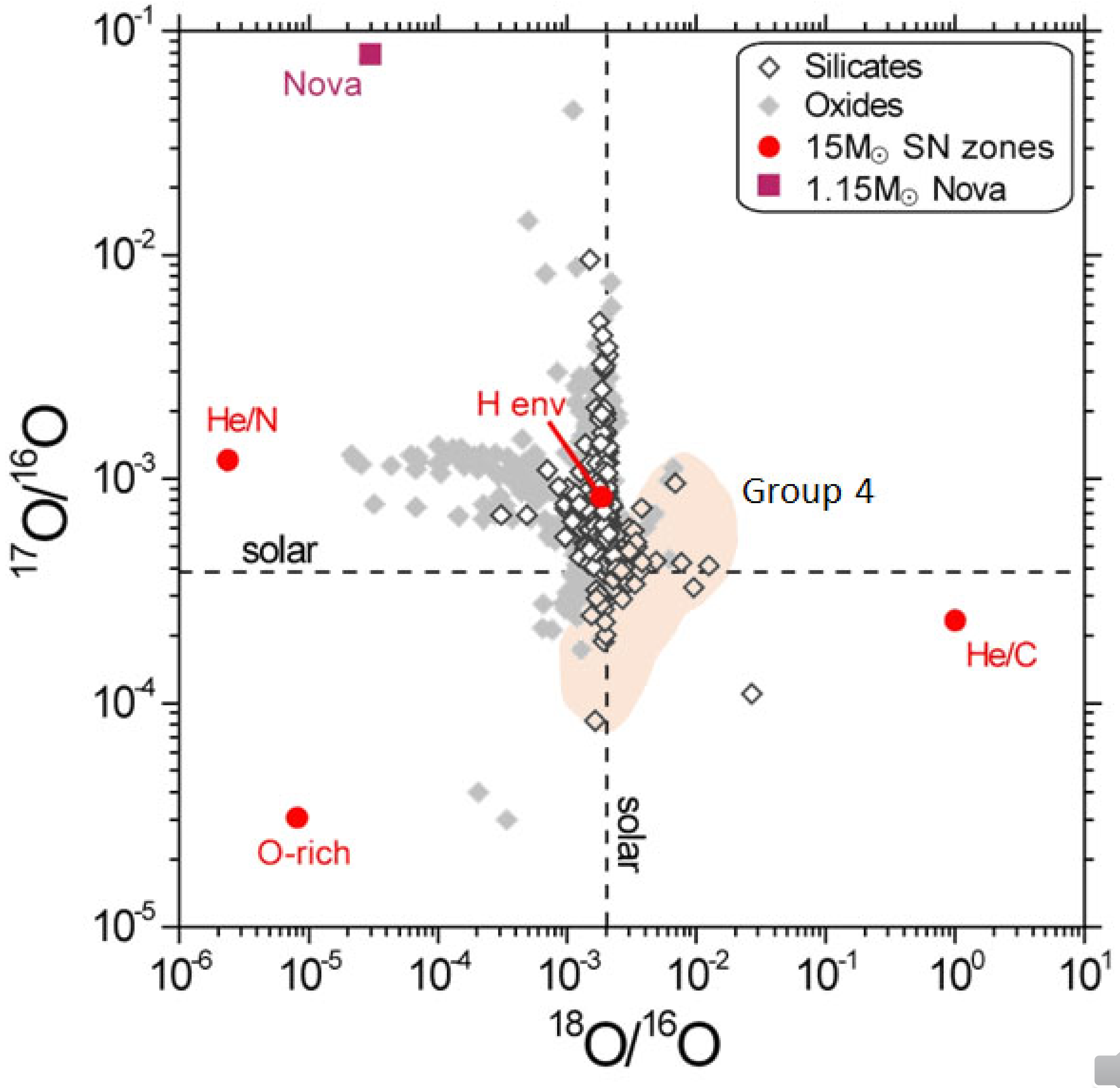


Stellar Source “Group 4” Grains

- Mixing of material from various supernova zones can reproduce O isotopic compositions
- SN sources strengthened by observed isotopic anomalies in other elements

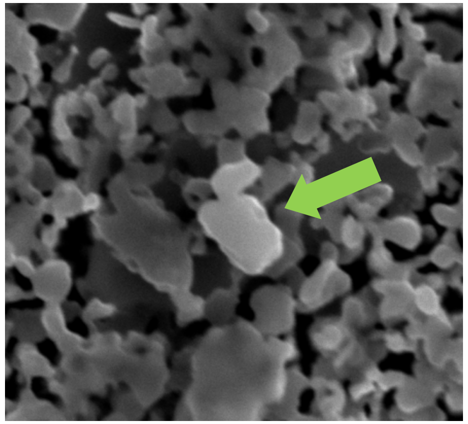


Courtesy E. Zinner

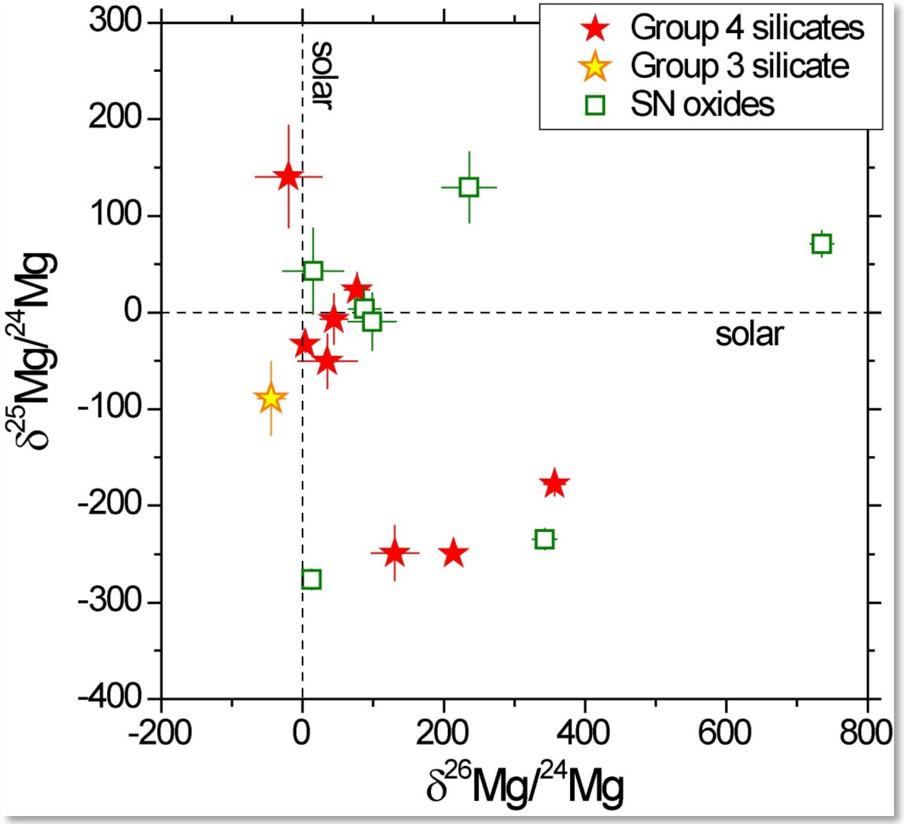


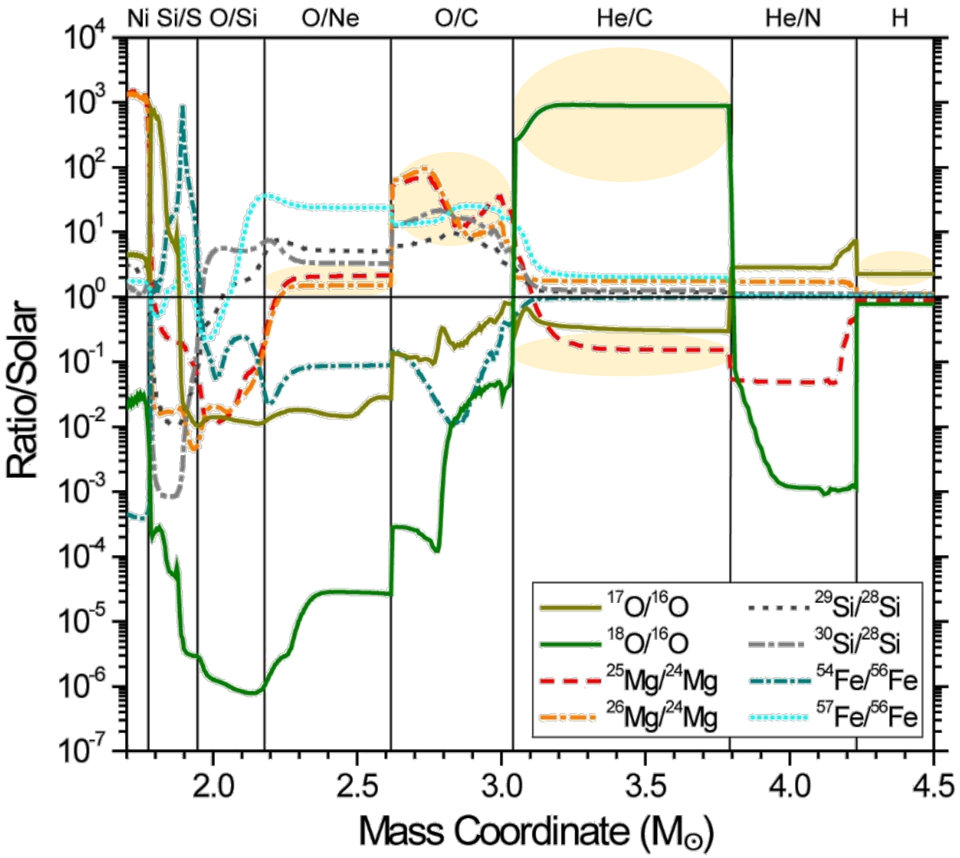
SN model: Rauscher et al. 2002

Mg Isotopic Compositions Group 4 Grains



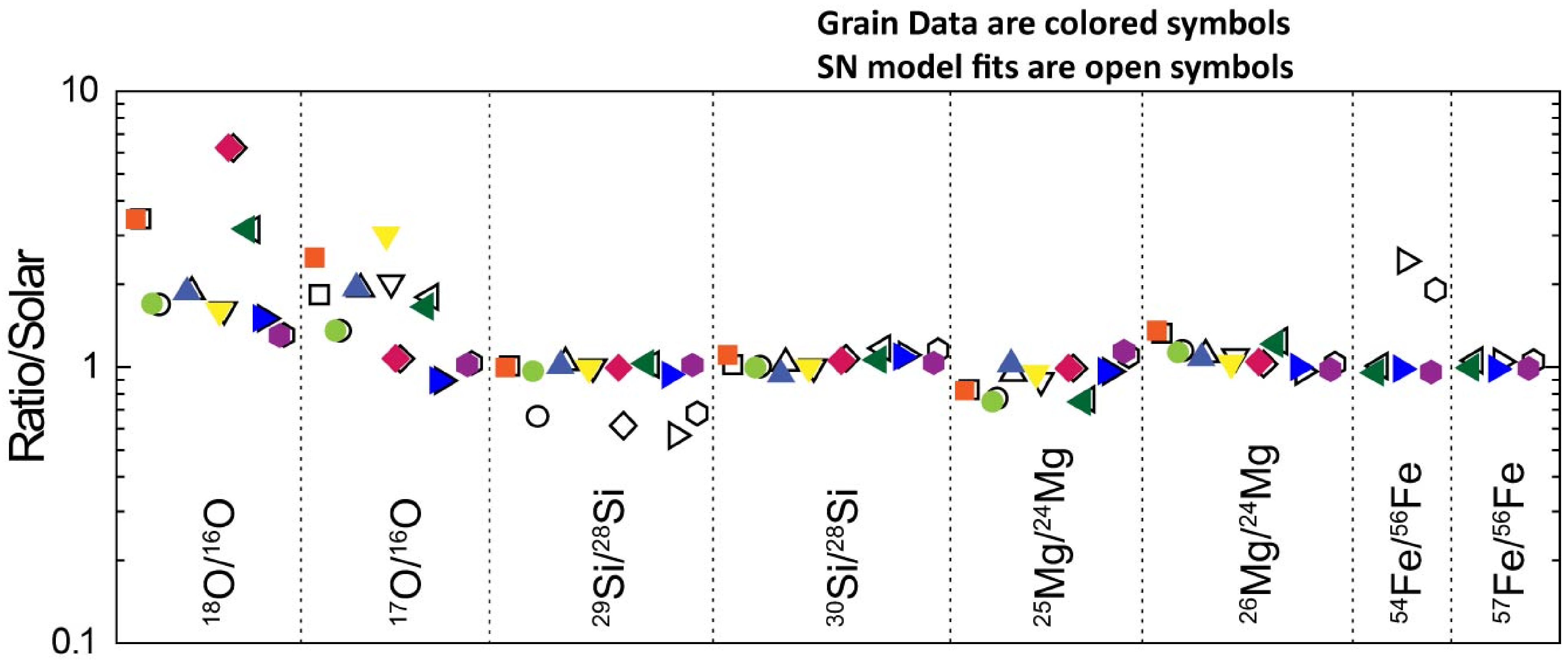
Adapted from
Nguyen & Messenger, ApJ 2014





- ^{18}O from He/C zone, ^{17}O from H envelope
- ^{26}Mg from O/Ne, O/C zones, ^{25}Mg depletion from He/C zone
- Must mix various proportions of different SN zones to produce isotopic ratios

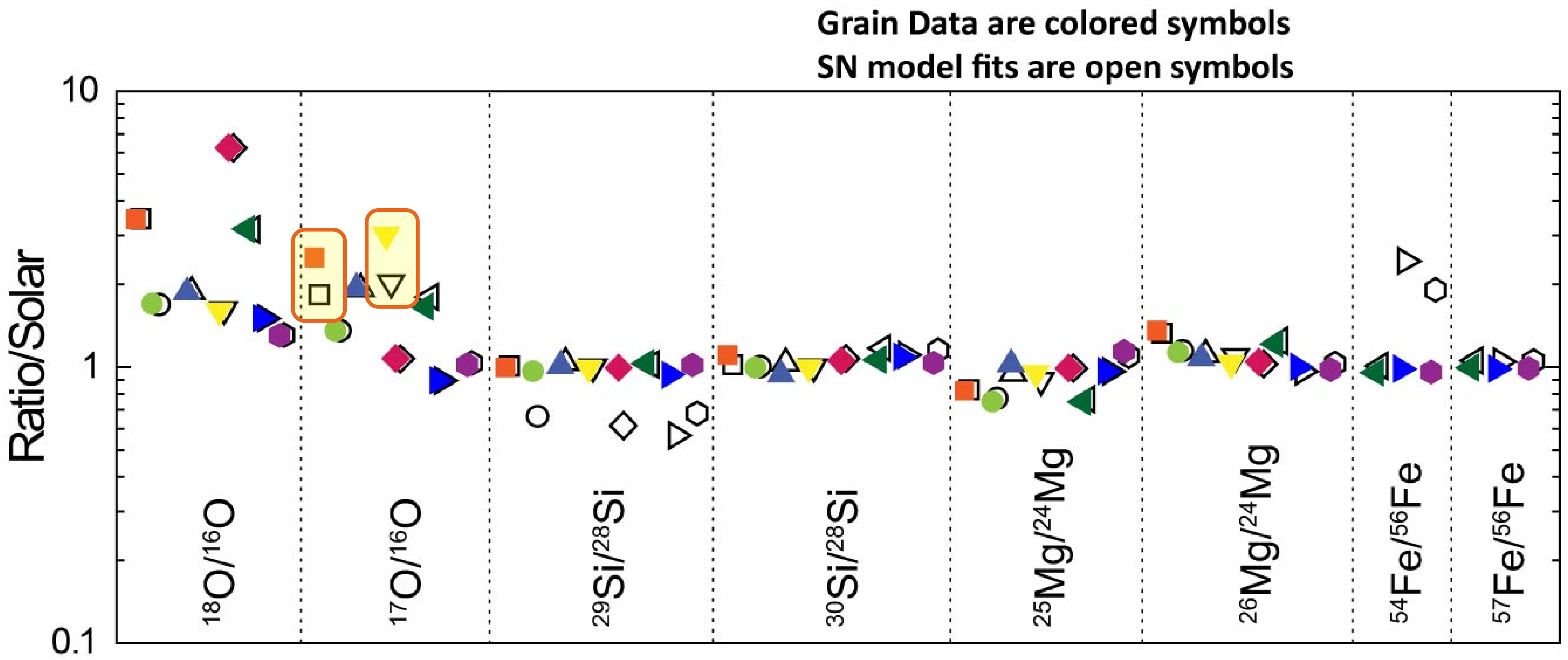
15 M$_\odot$ SN Model Fits to Grain Data



Nguyen & Messenger, ApJ 2014

- Perform mixing calculations to fit grain data using one 15M$_\odot$ SN type II model
- Mixing < 2% inner zone material with outer zones produces good fits to the grain data with a few discrepancies

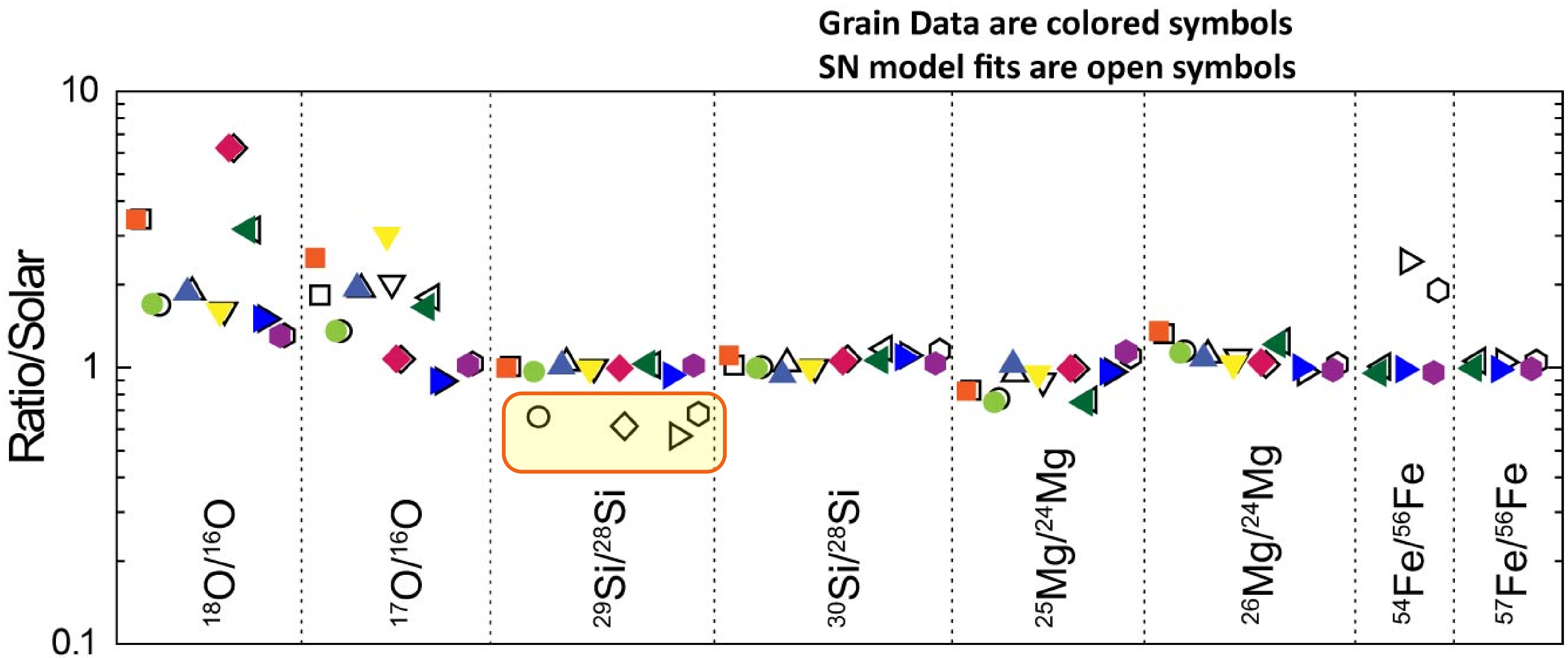
15 M$_\odot$ SN Model Fits to Grain Data



Nguyen & Messenger, ApJ 2014

- Model underproduces ^{17}O in two grains
- Better fits are obtained with SN models of lower mass

15 $M_\odot$ SN Model Fits to Grain Data

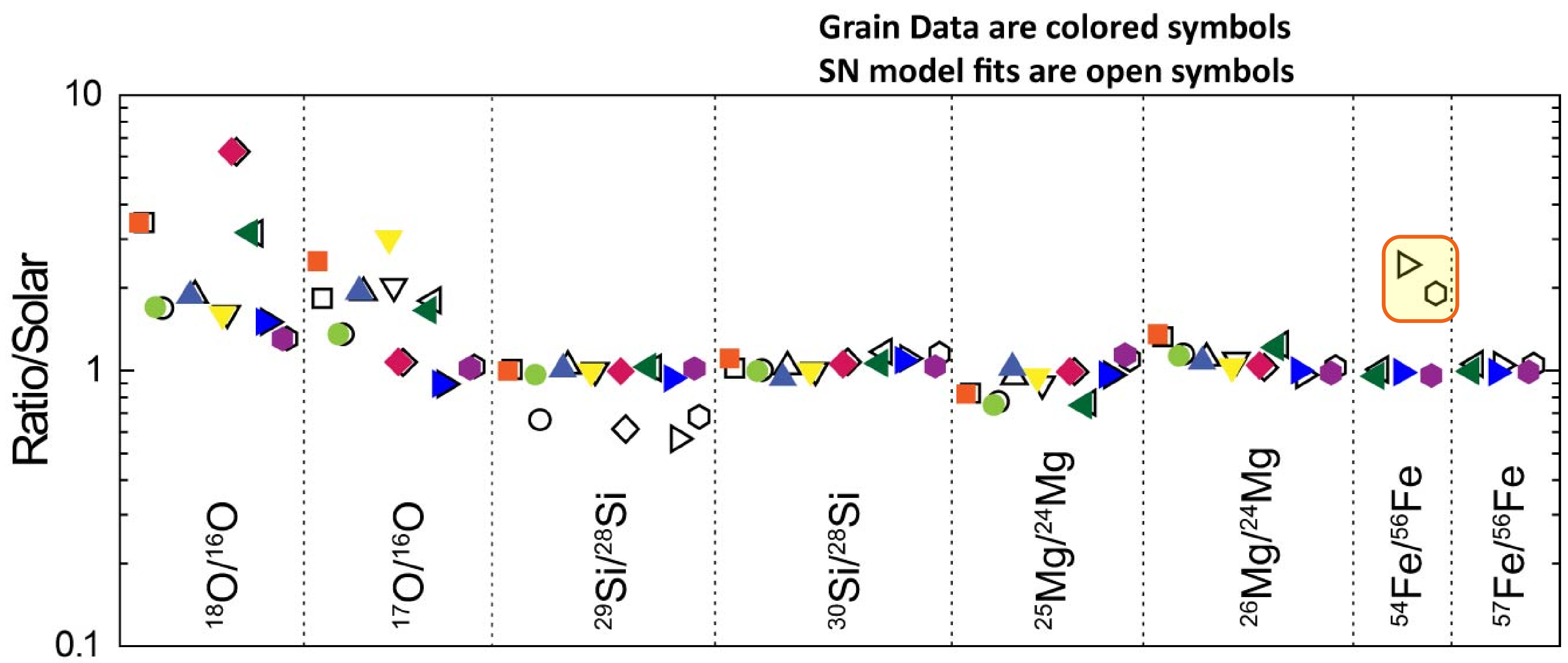


Nguyen & Messenger, ApJ 2014

- Model underproduces ^{29}Si
- Travaglio et al. (1998) suggested 2x increase in ^{29}Si production in O/Ne and O/Si zones
  - Modification invoked to explain unusually ^{29}Si-rich supernova SiC (Hoppe et al. 2009)

➢ Doubling ^{29}Si yield in O/Ne and O/Si zones reproduces $^{29}Si/^{28}Si$ of the grains

15 $M_\odot$ SN Model Fits to Grain Data

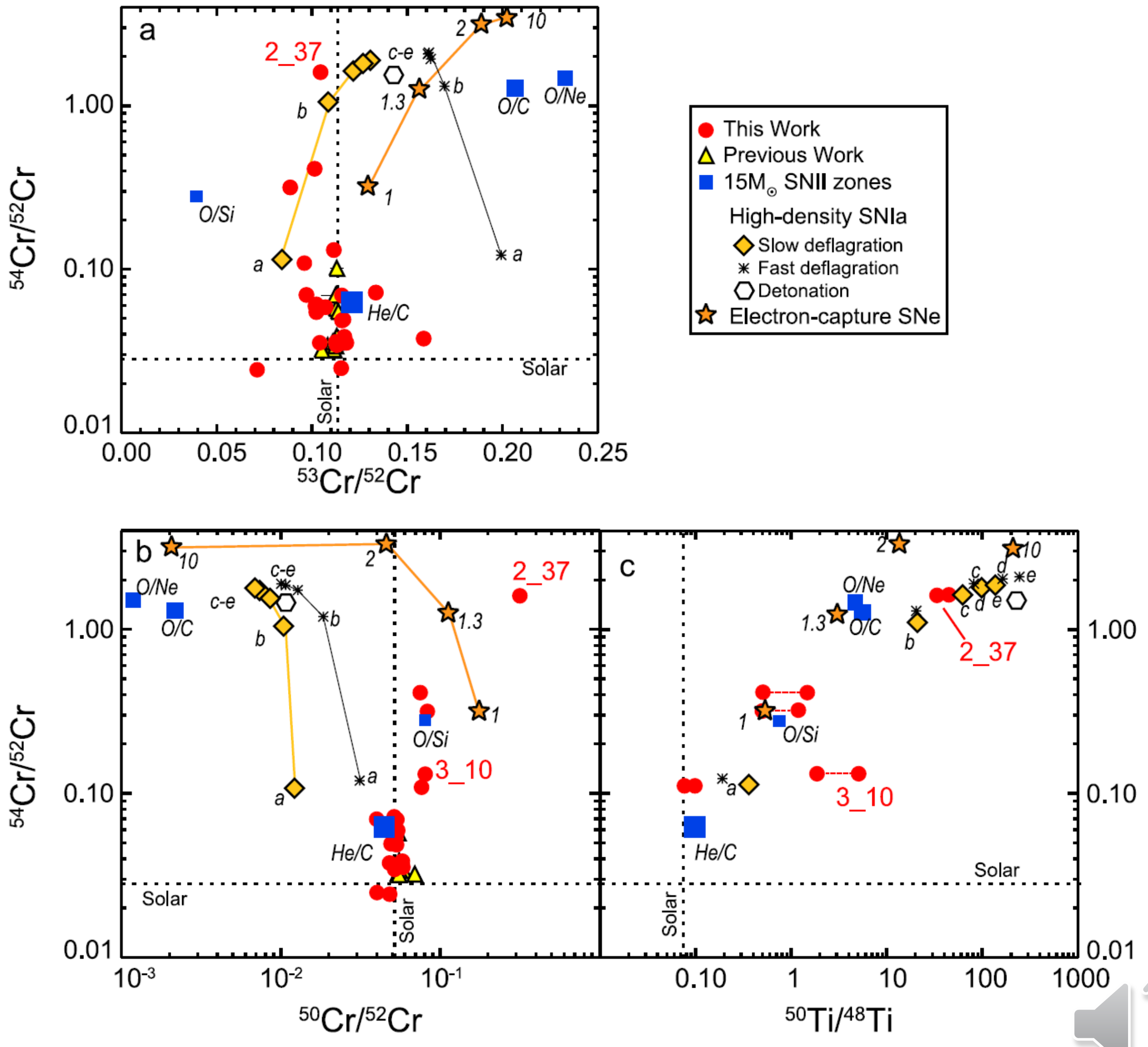


Nguyen & Messenger, ApJ 2014

- Predicted ^{54}Fe excesses are not observed in these silicate grains nor SiC X grains
- Possible elemental fractionation in the Si/S zone

Presolar Chromite: Electron-Capture SN Sources

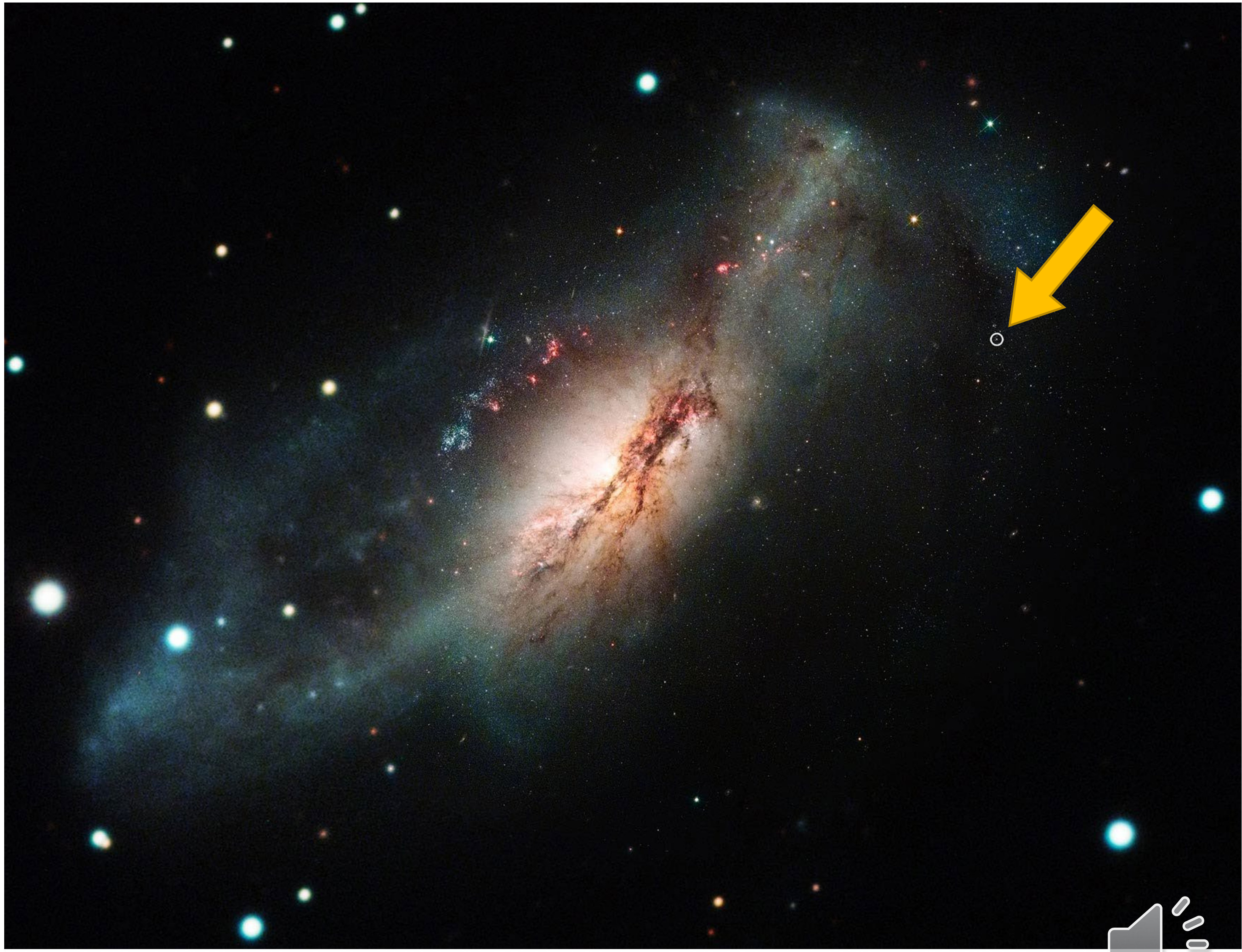
- ^{54}Cr enrichments in small oxide grains (Nittler et al. 2018, Dauphas et al. 2010, Qin et al. 2011)
    - 40 – 300 nm
    - Anomalies increase with decreasing grain size
    - Carriers of bulk Cr variations in solar system materials
- Mass-50 enrichments may be ^{50}Ti rather than ^{50}Cr
- High-density Type Ia supernovae (SN Ia)?
- Electron-capture supernovae (ECSN) from core collapse of super-AGB stars (8-10 $M_{\odot}$)?



From Nittler et al. 2018

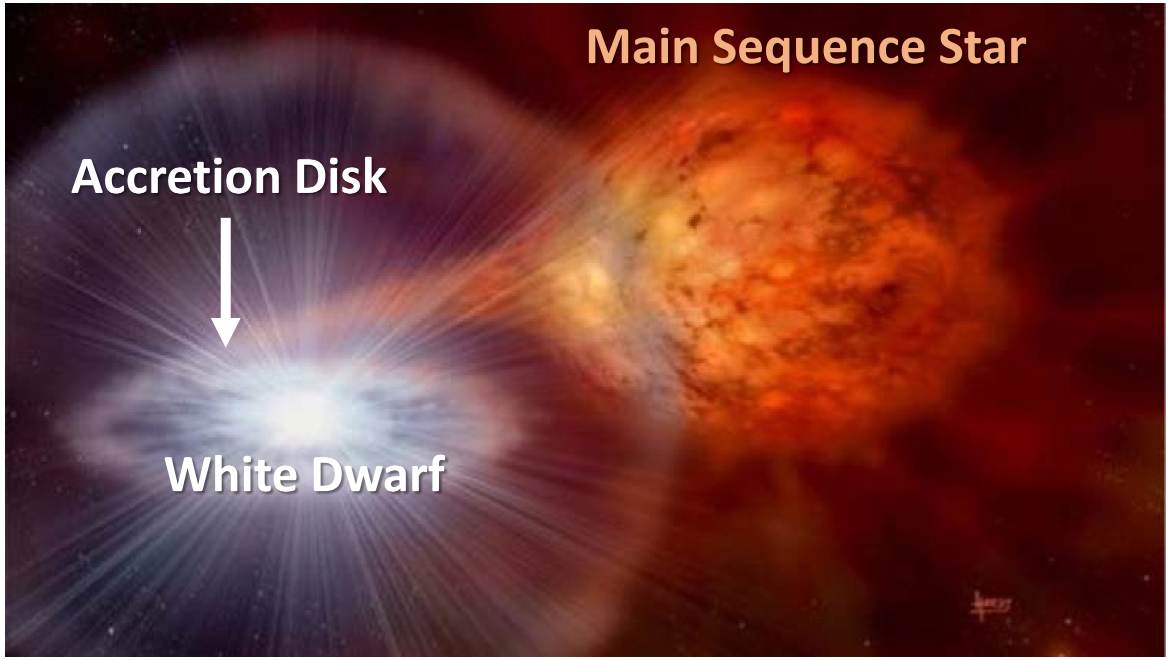
Presolar Chromite: Electron-Capture SN Sources

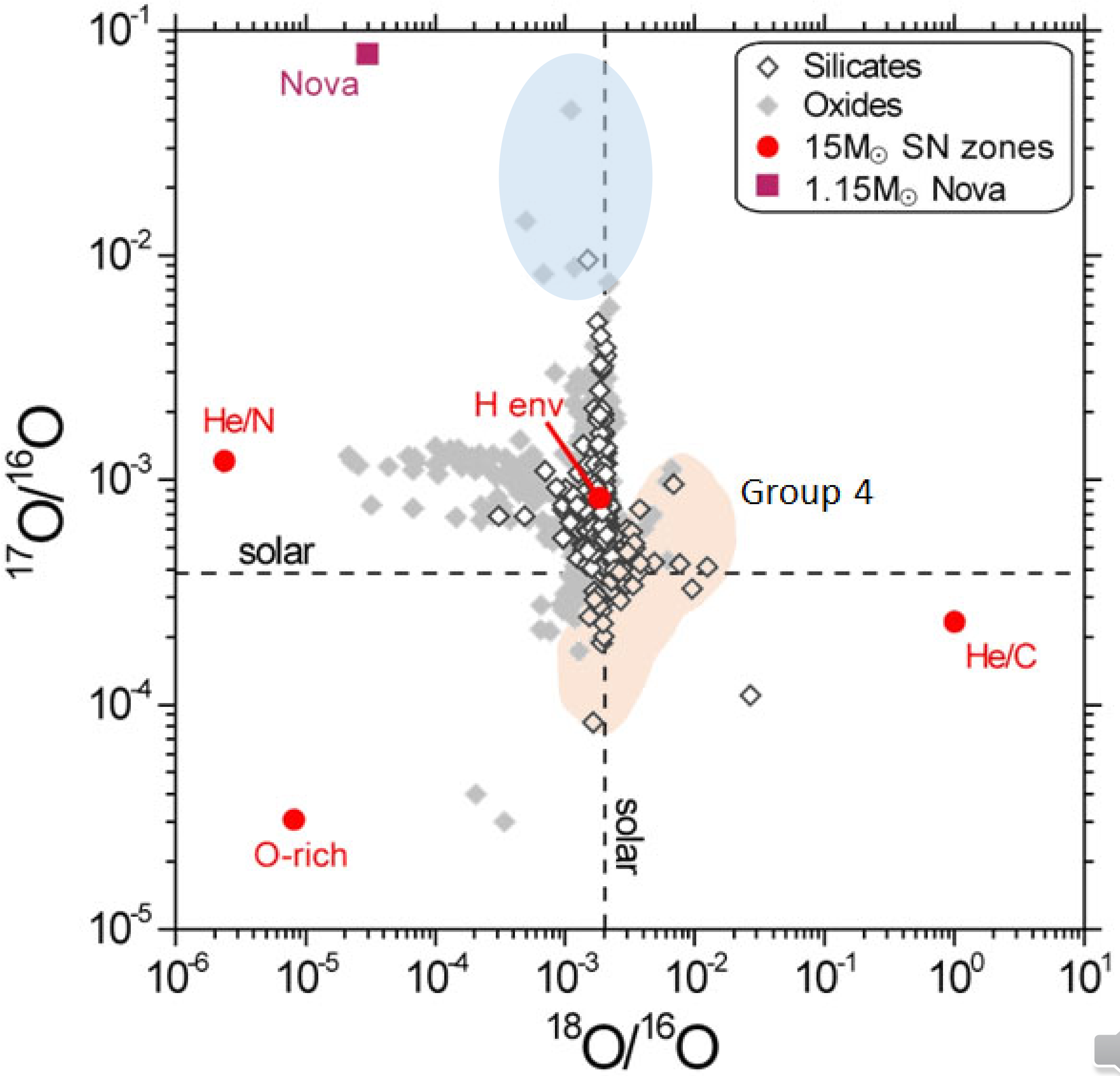
- Existence of ECSN theorized 40 years ago
- Recent evidence for ECSN!! (Hiramatsu et al. 2021 Nature Astronomy)



Stellar Source "Extreme ^{17}O-rich" Grains

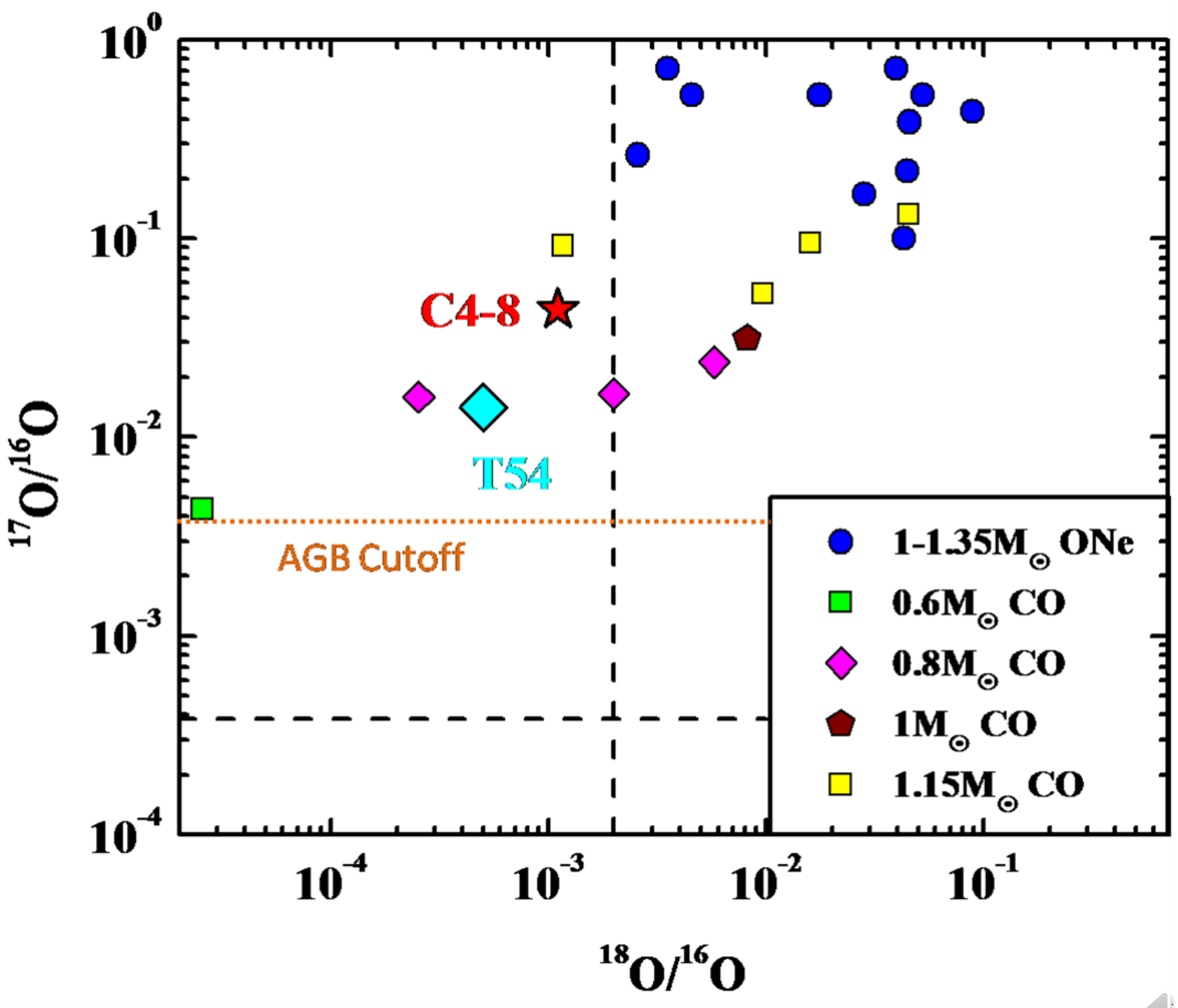
- Extreme ^{17}O enrichments cannot be produced by AGB nucleosynthesis
- Novae produce abundant ^{17}O through explosive H-burning
  - Accretion H-rich material onto white dwarf





Nova Model Comparisons

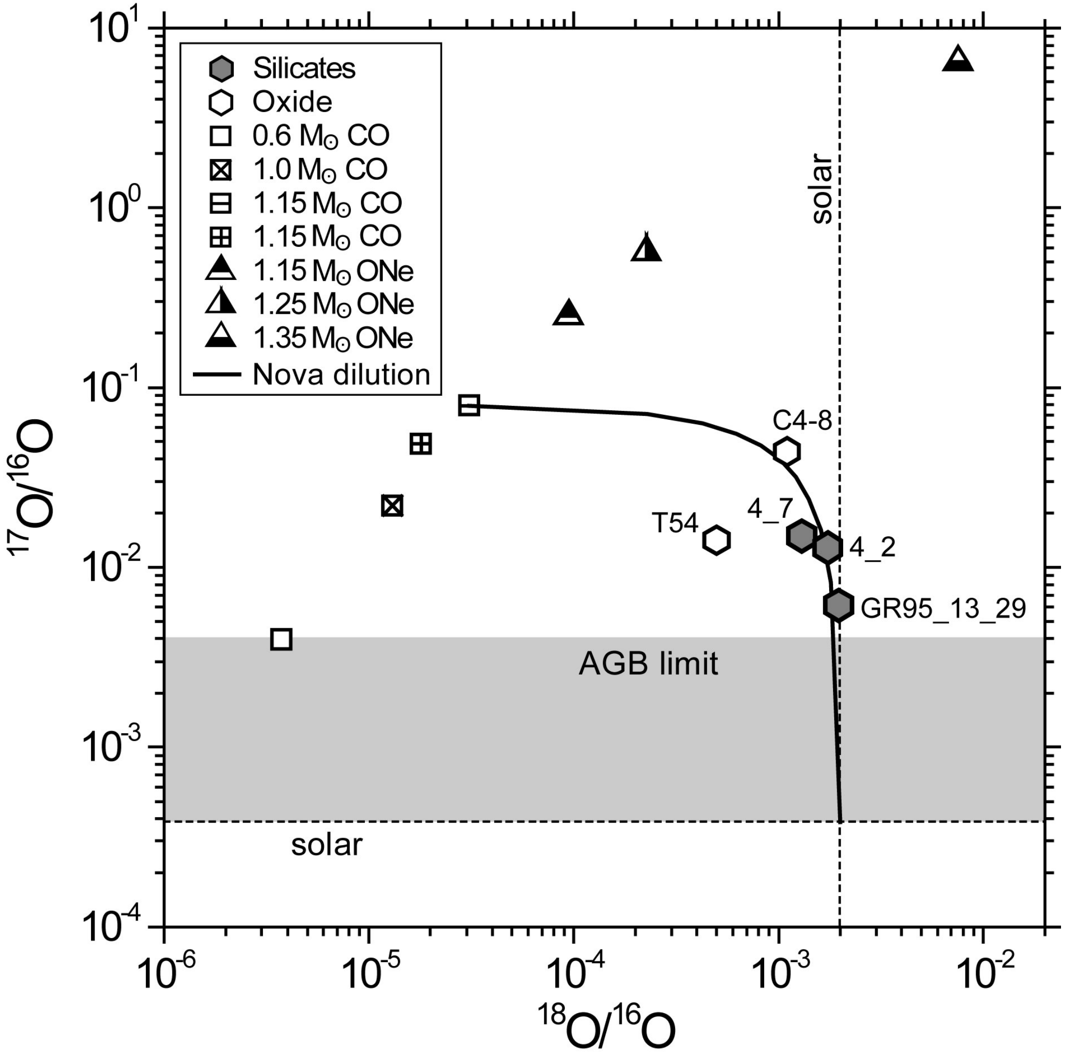
- Previous nova models produced large amounts of ^{17}O and ^{18}O (José et al. 2004)
- Models did not fit presolar grain data
- Updated reaction rates for $^{17}O(p,\gamma)^{18}F$ and $^{18}F(p,\gamma)^{19}Ne$ → lower predicted ^{18}O abundances



Courtesy F. Gyngard

Nova Model Comparisons

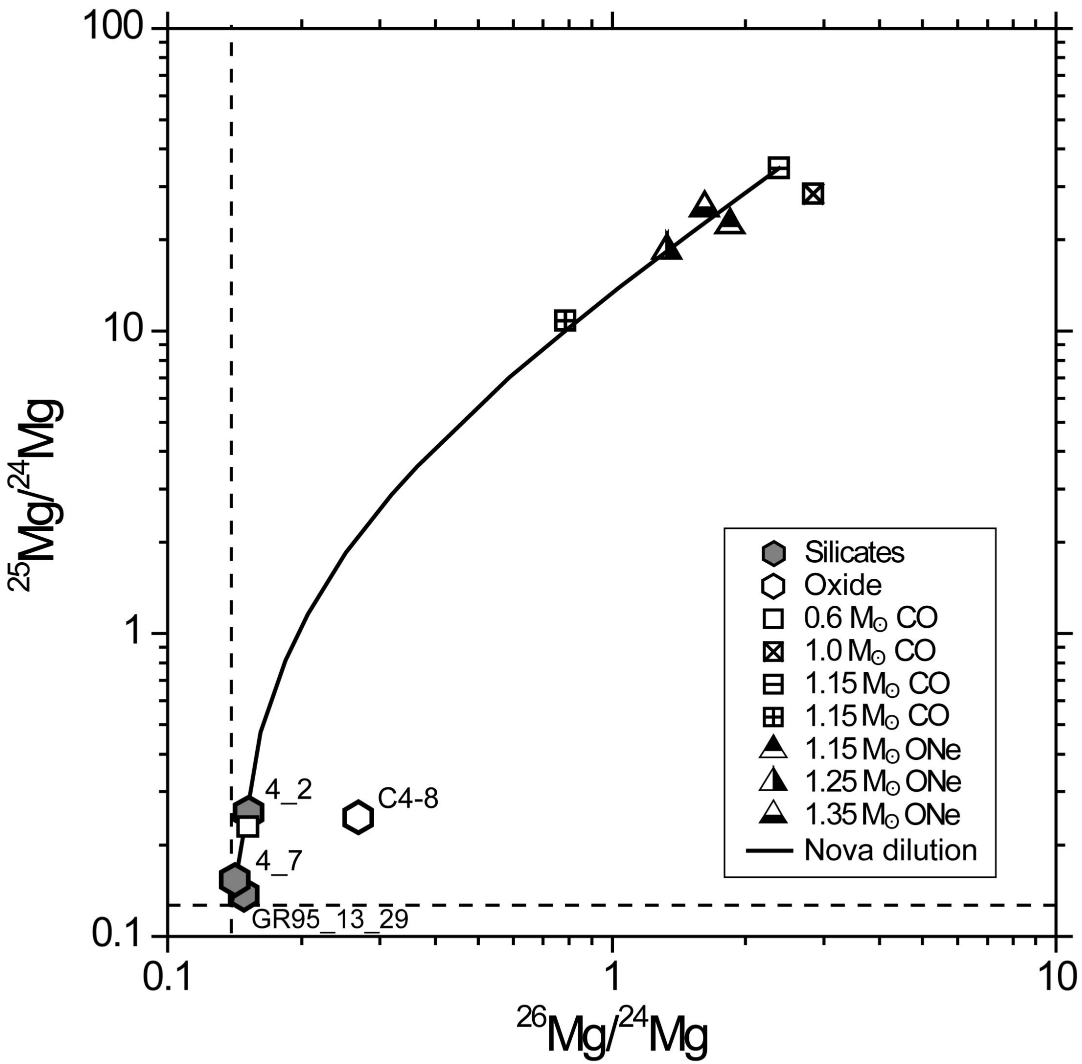
- O composition of most presolar silicates and oxides best matched by strong dilution of 1.15 $M_\odot$ CO nova (~2%) with isotopically close-to-solar material (companion star?)



From Nguyen & Messenger 2014

Nova Model Comparisons

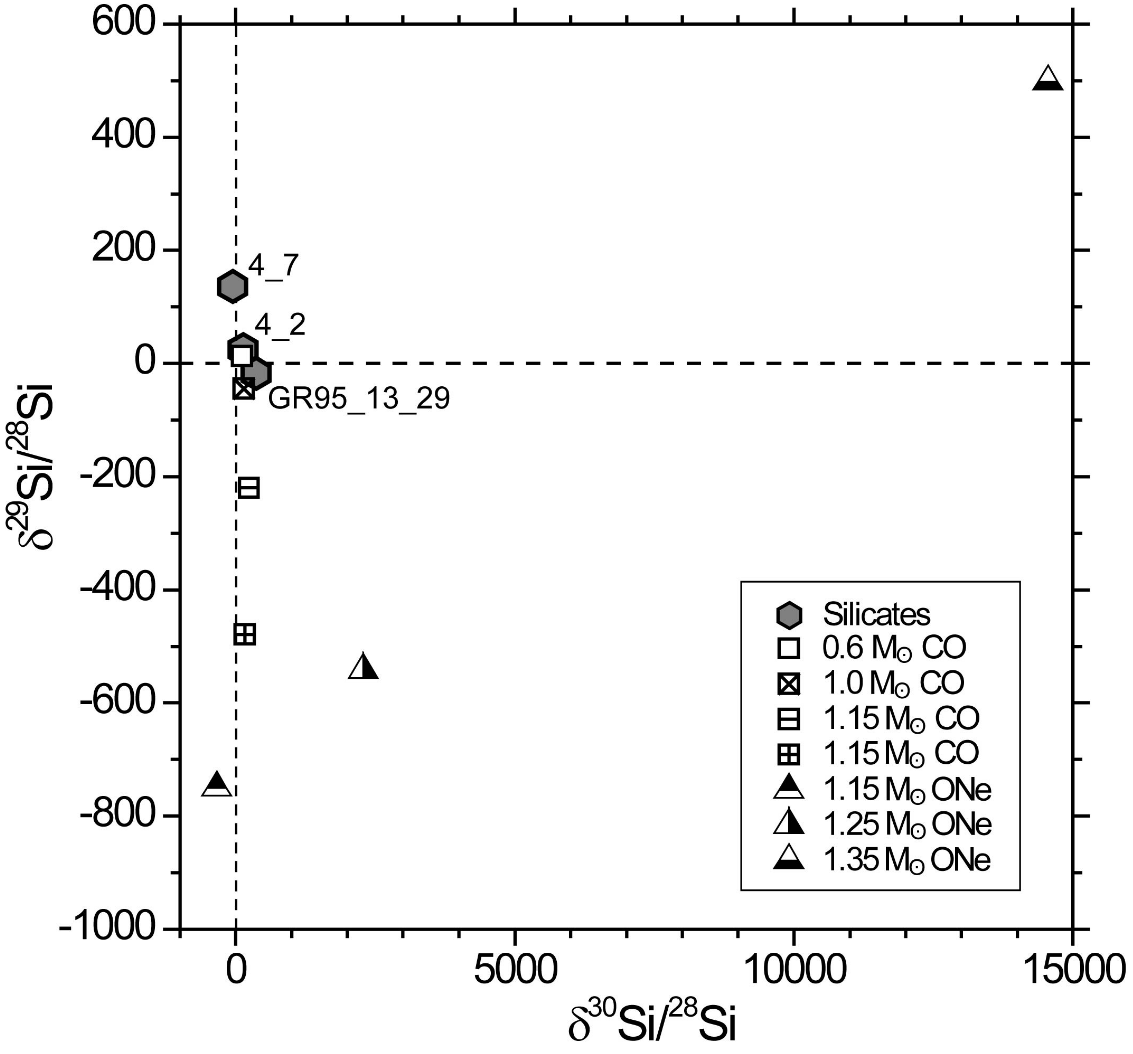
- Nova models generally predict much more extreme ^{25}Mg and ^{26}Mg enrichments than observed in stardust grains
- Mg compositions of most presolar grains consistent with 0.6 $M_\odot$ CO nova, but also strong dilution of nova models



From Nguyen & Messenger 2014

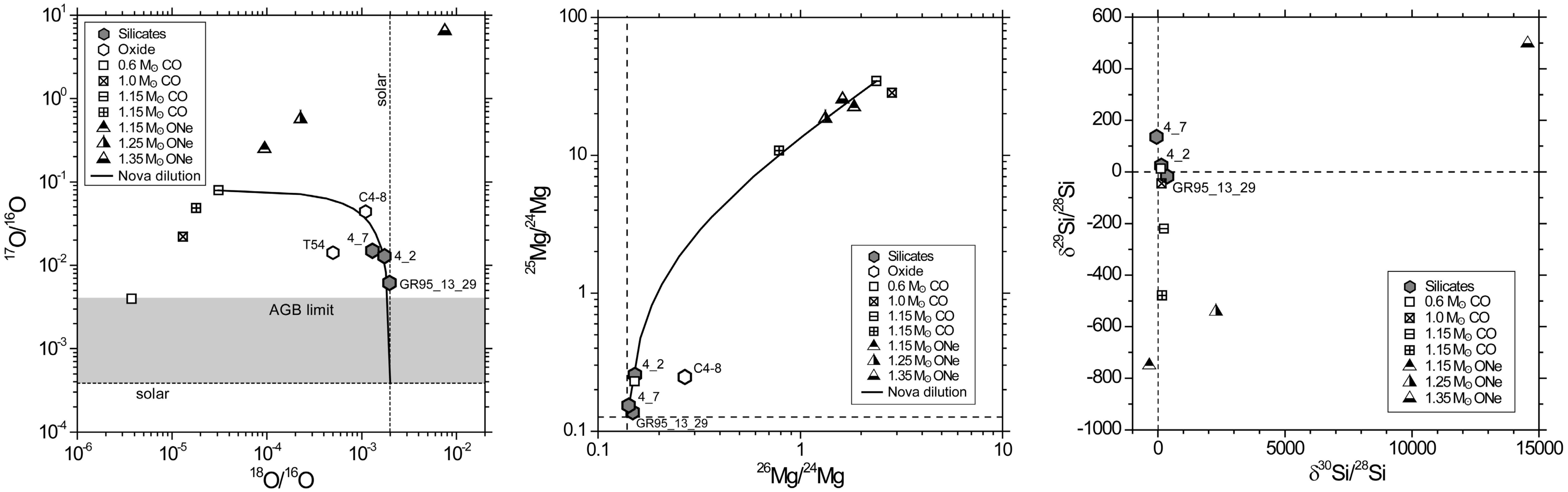
Nova Model Comparisons

- Most nova models produce large ^{29}Si depletions
- One model produces large ^{29}Si and ^{30}Si enrichments
- Si isotopic ratios of two presolar silicates matched by 0.6 $M_{\odot}$ CO nova, but also strong dilution of nova models
- ^{29}Si enrichment of silicate grain 4_7 matched by strong dilution of 1.35 $M_{\odot}$ ONe nova



From Nguyen & Messenger 2014

Nova Model Comparisons



From Nguyen & Messenger 2014

- New CO nova model simulations match compositions of some grains (mainly SiC) *without dilution* (Iliadis et al. 2018)
- Some "nova" SiC grains now likely SN (Liu et al. ApJ 2016)

Summary

- Isotopic analysis of presolar stardust grains in the lab is a powerful method for conducting astronomy with high precision
- Allow for tight constraints to be placed on astrophysical models of stellar evolution, nucleosynthesis, GCE
- Especially important is obtaining the isotopic compositions for multiple elements within single grains!
- Have identified presolar O-rich grains from AGB stars, super-AGB, SN, ECSN, nova