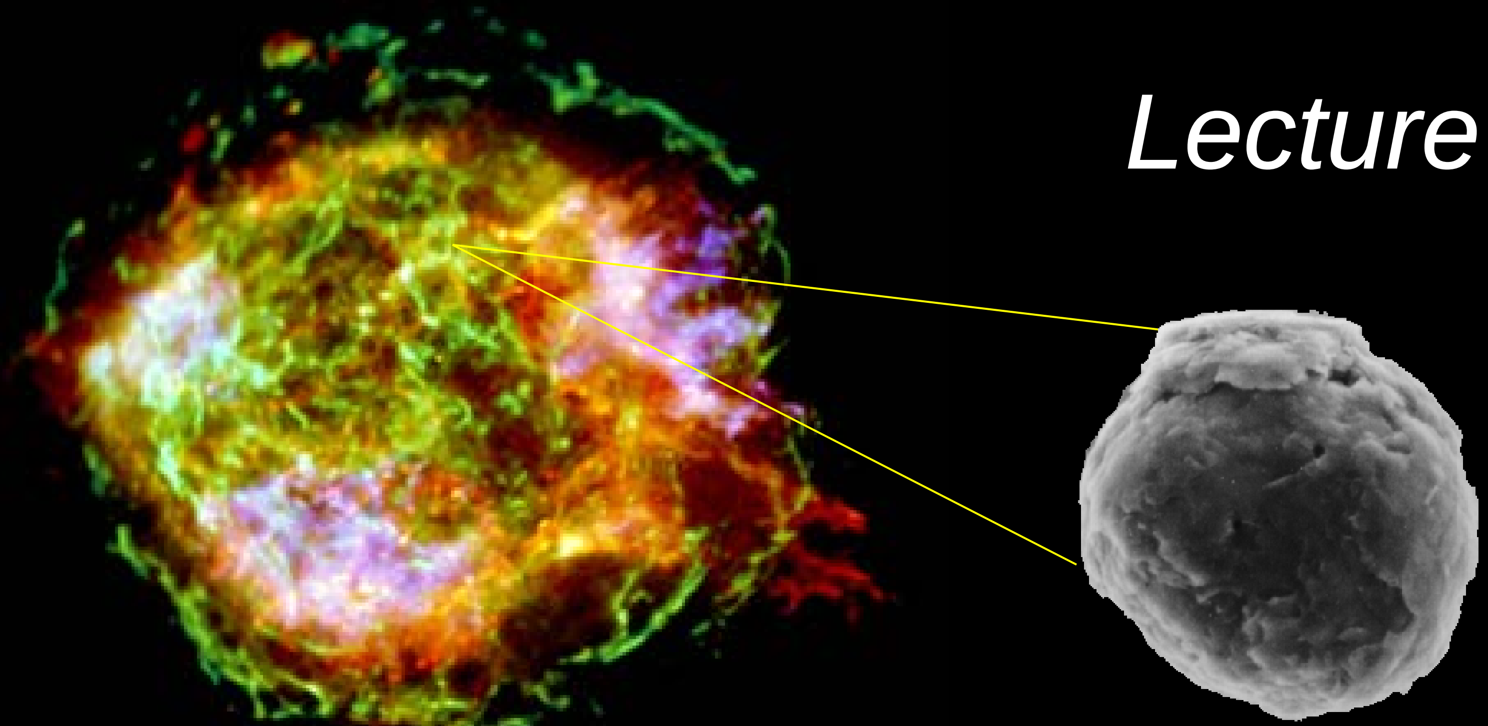
Presolar Stardust in the Solar System

Lecture I



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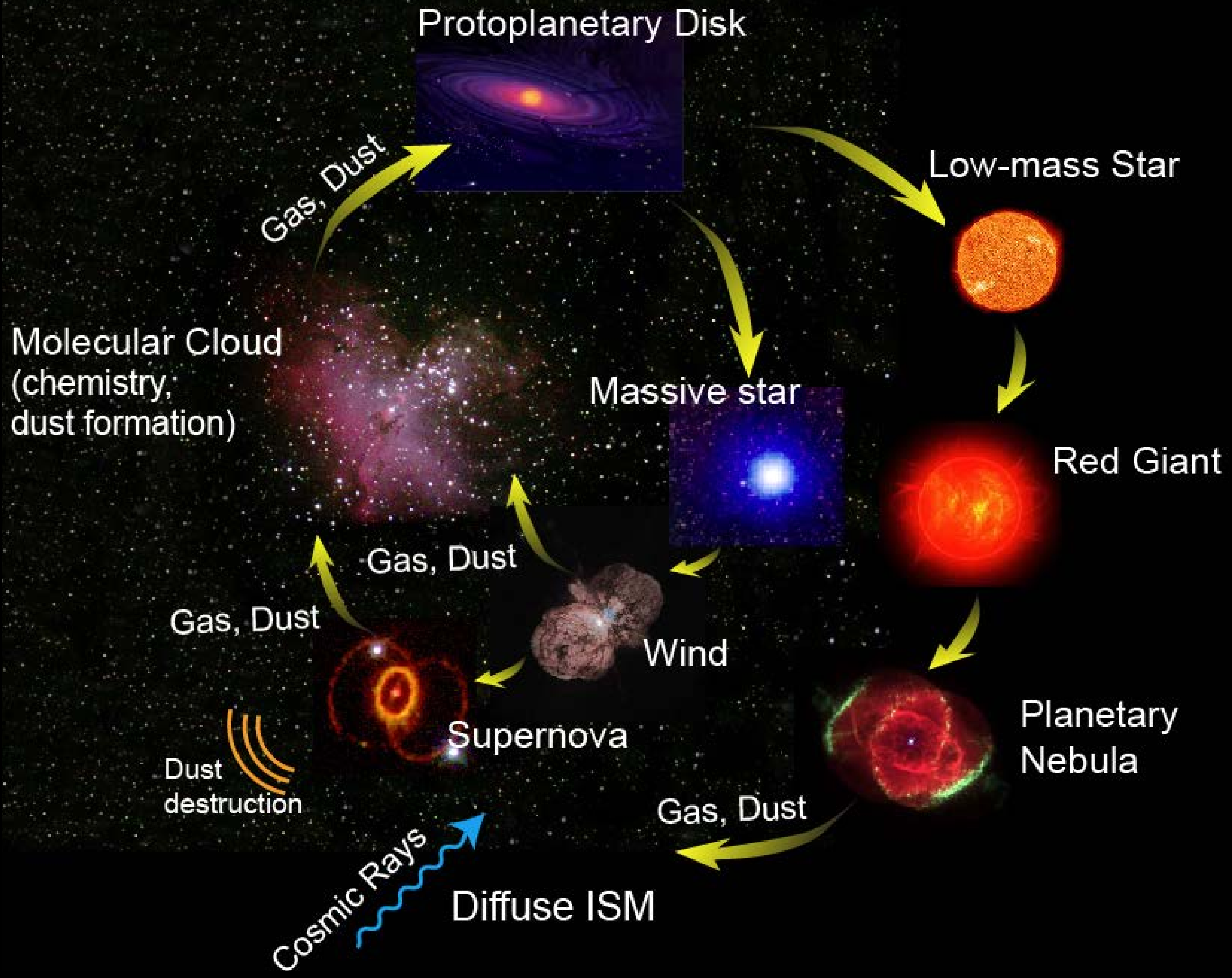
Department of Terrestrial Magnetism
Carnegie Institution of Washington

Les Houches Winter School, February 2017

Outline

- Introduction to primitive extraterrestrial materials and presolar grains
- Tools of presolar grain research
- Overview of stellar evolution and nucleosynthesis



Protoplanetary Disk

Low-mass Star

Red Giant

Planetary Nebula

Gas, Dust

Diffuse ISM

Cosmic Rays

Supernova

Dust destruction

Gas, Dust

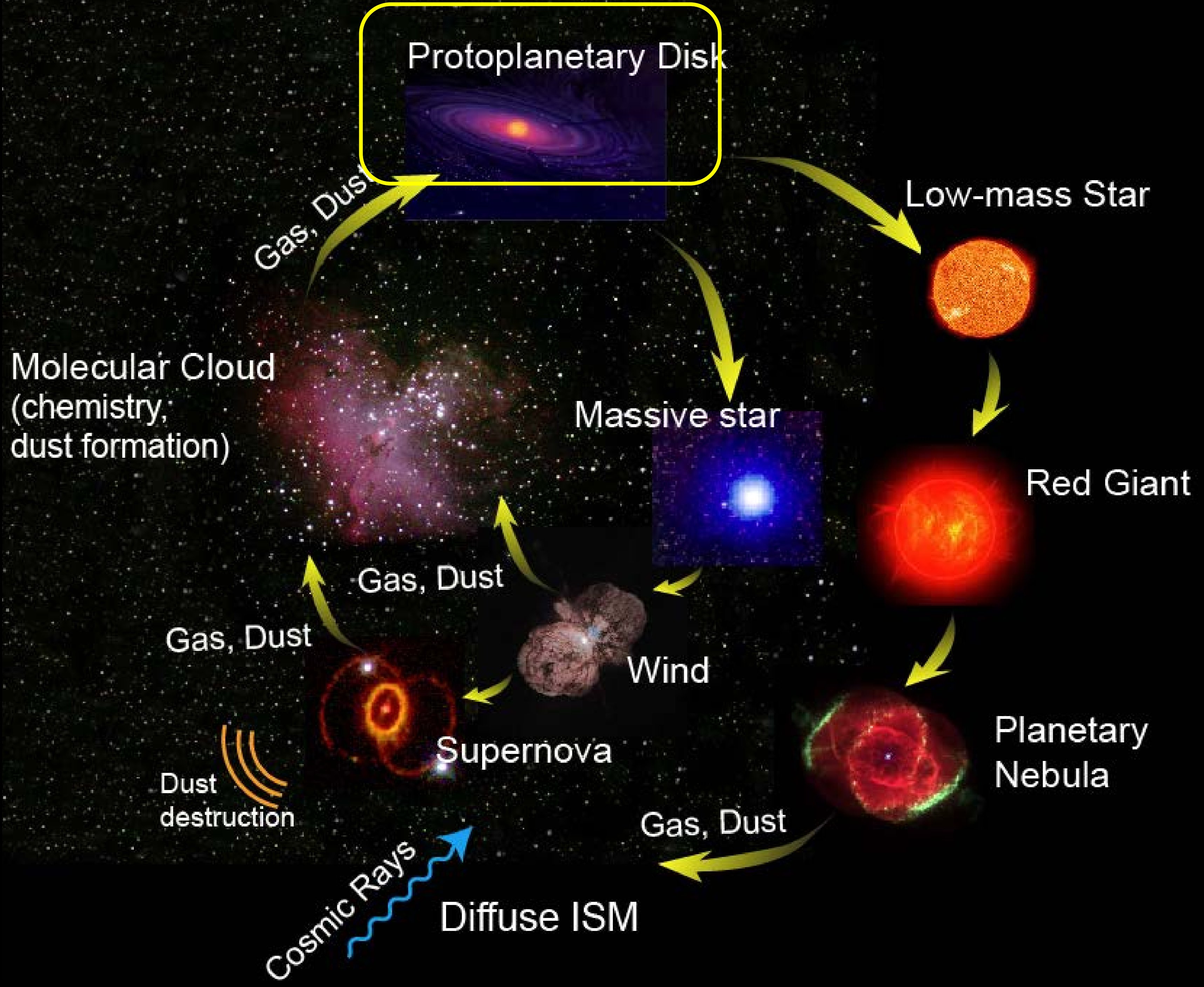
Molecular Cloud
(chemistry,
dust formation)

Gas, Dust

Massive star

Wind

Gas, Dust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Low-mass Star
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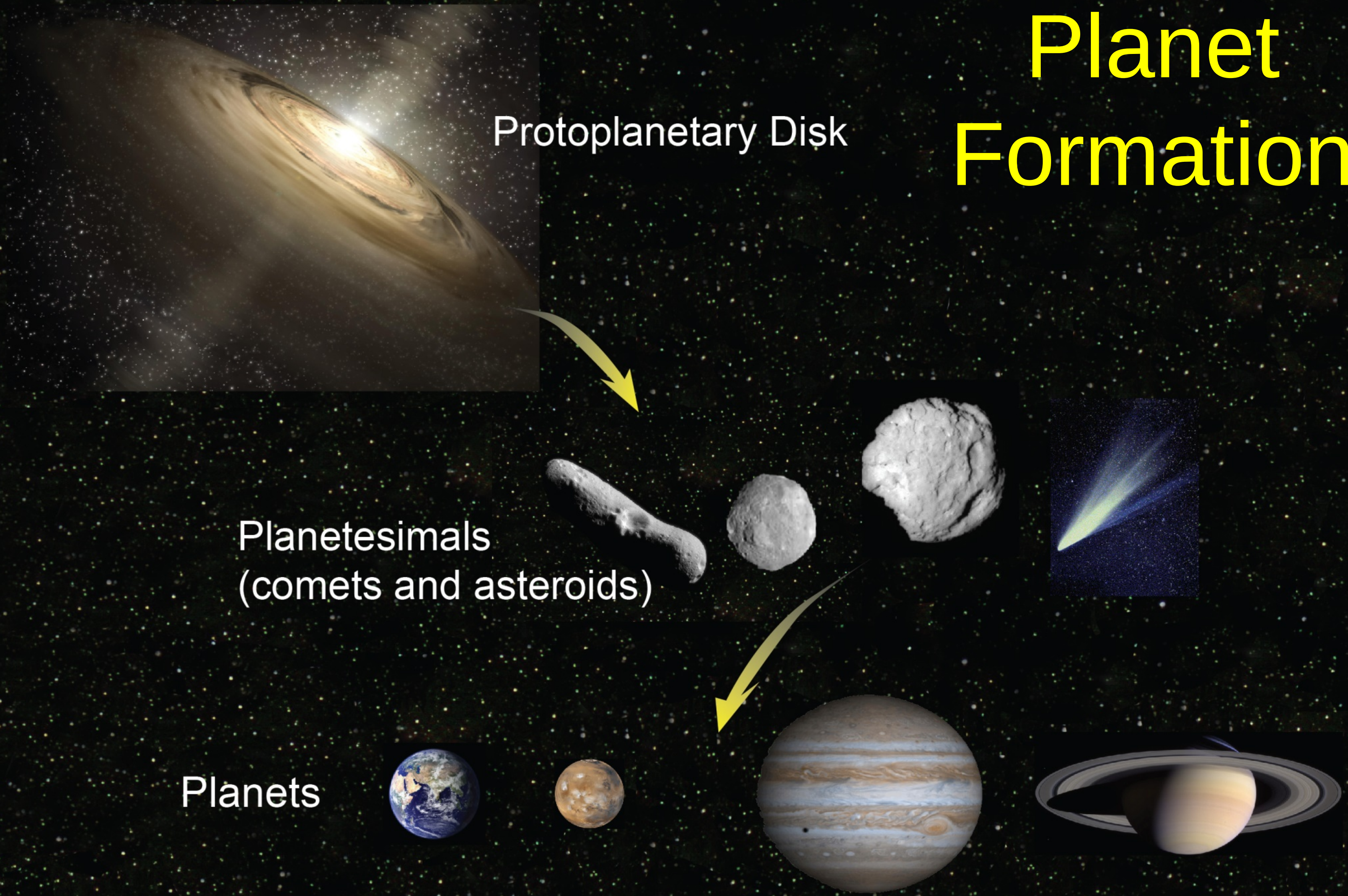
Planet Formation

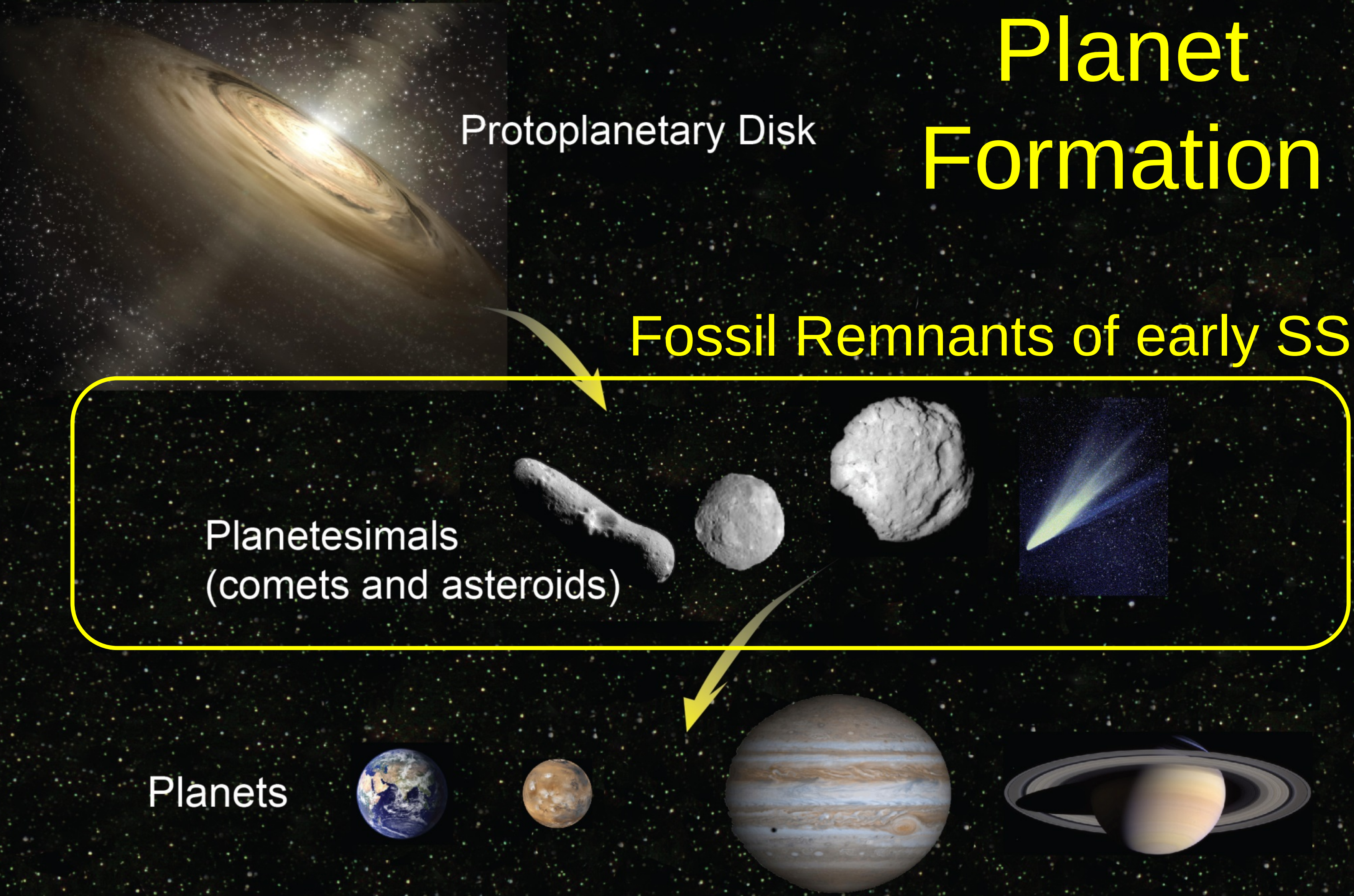


Protoplanetary Disk

Planetesimals
(comets and asteroids)

Planets

Planet Formation



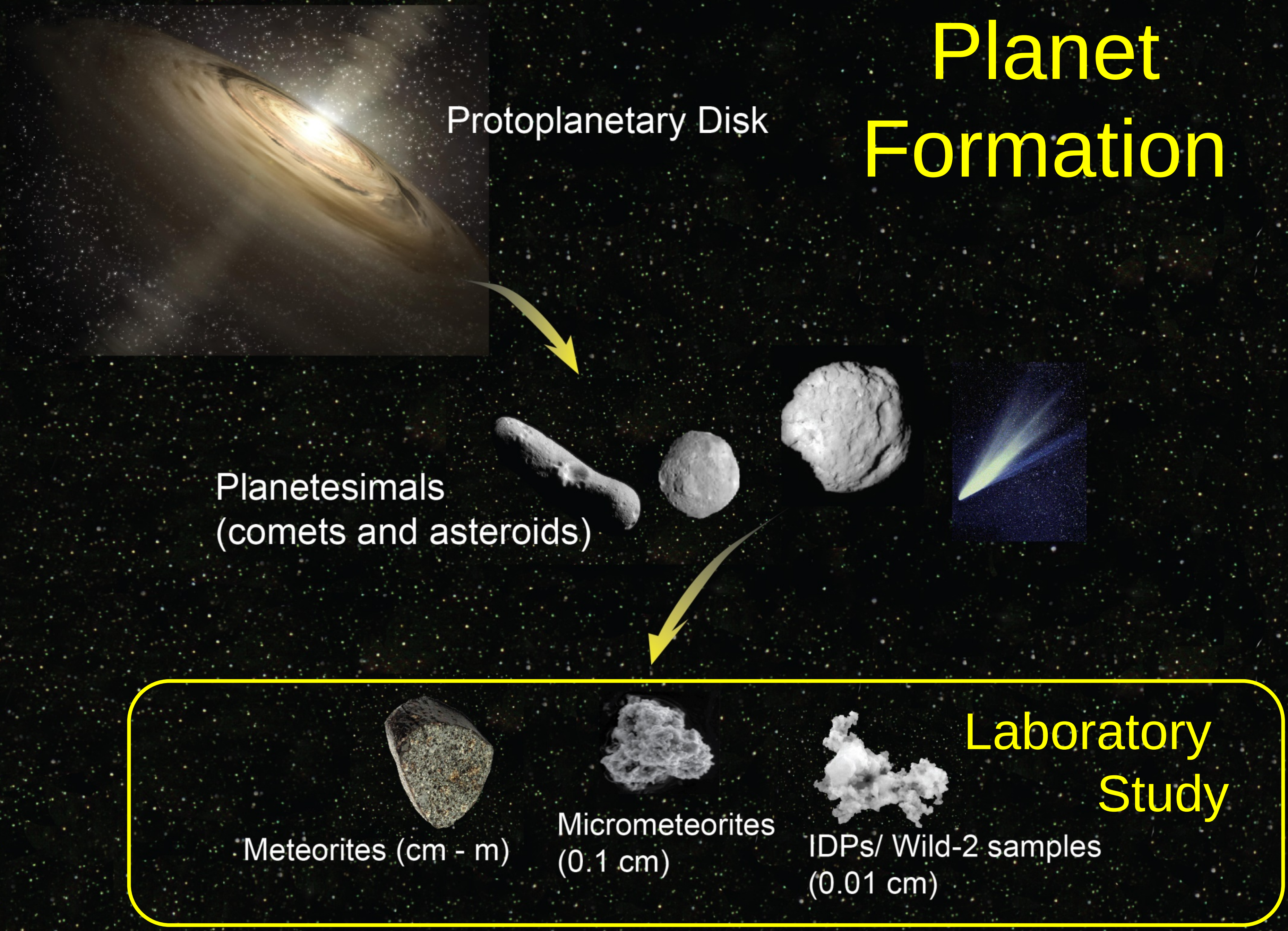
Protoplanetary Disk

Fossil Remnants of early SS

Planetesimals
(comets and asteroids)

Planets

Planet Formation



Protoplanetary Disk

Planetesimals
(comets and asteroids)

Laboratory Study

Meteorites (cm - m)

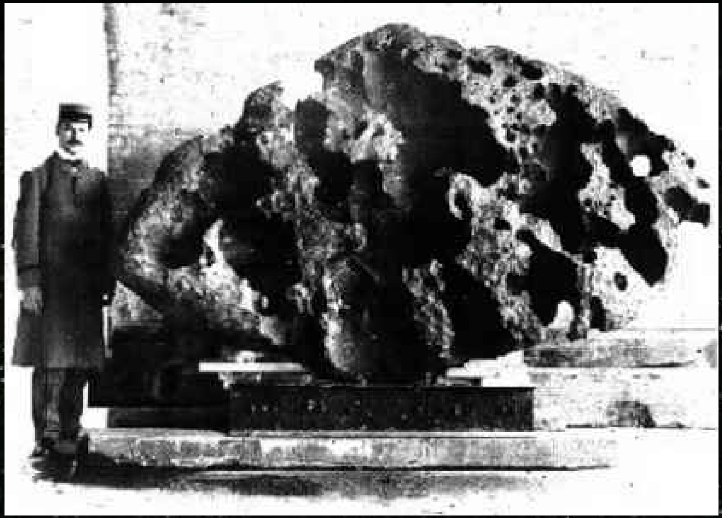
Micrometeorites
(0.1 cm)

IDPs/ Wild-2 samples
(0.01 cm)

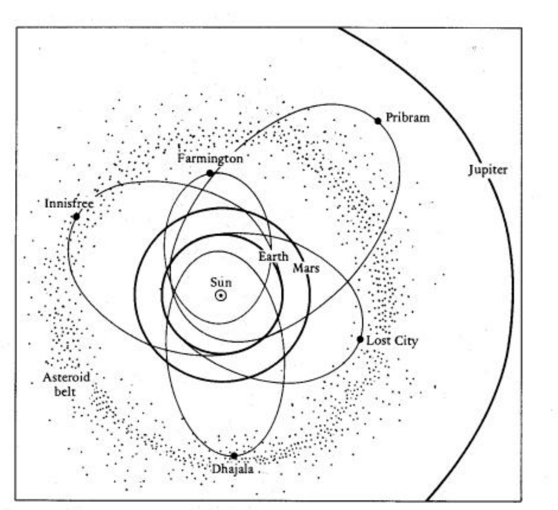
Meteorites

Fireball over Yellow Springs, Ohio
Credit: John Chumack

Meteorite on Antarctic ice (L. Nittler)



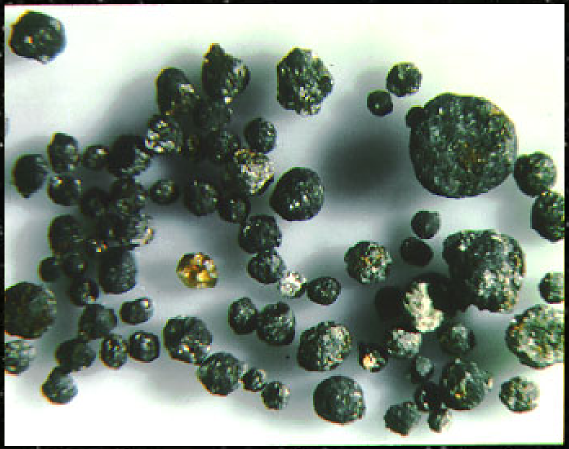
Willamette iron meteorite



Orbit trajectories indicate origin in asteroid belt

Chondrites

- Meteorites from undifferentiated planetesimals – primitive ‘cosmic sediments’ of protoplanetary disk



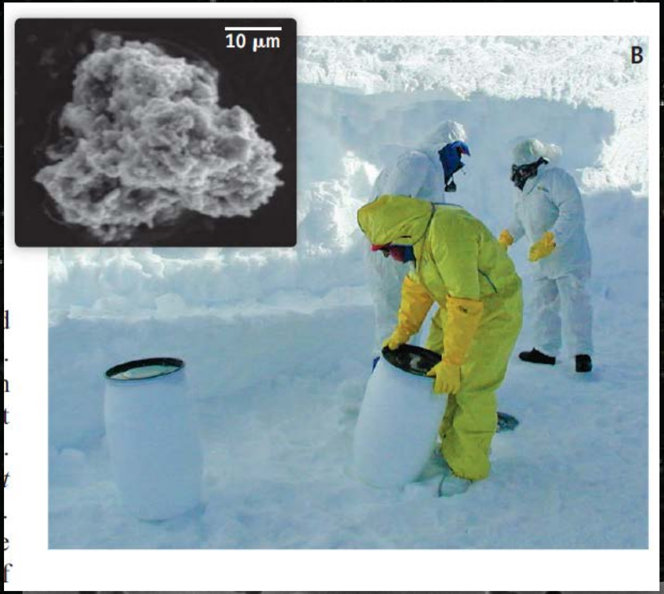
Full of “Chondrules” <mm-sized silicate spheres

Chondrules

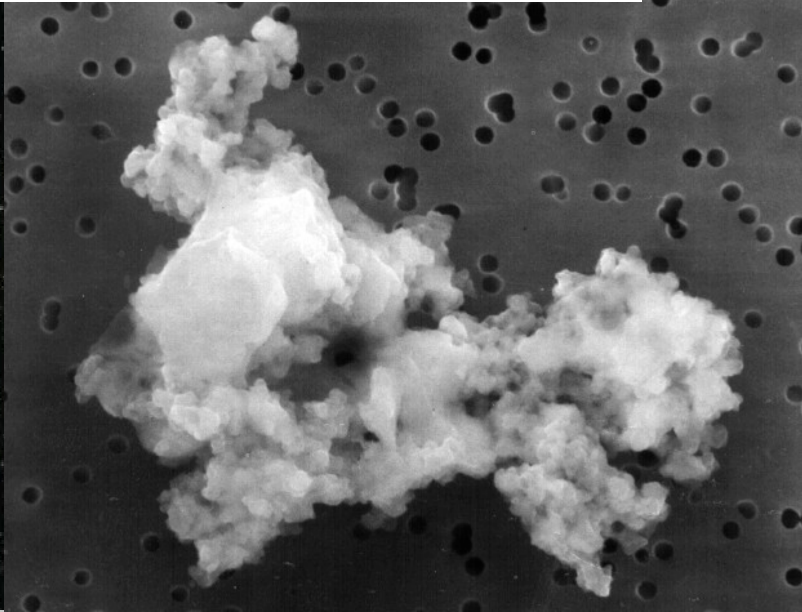
Calcium, Aluminum-rich Inclusions,CAIs (First Solids in Solar System;4.567 Gyr)

In between is “matrix” (sub-micron dust)

Interplanetary Dust Particles (IDPs) and Antarctic Micrometeorites

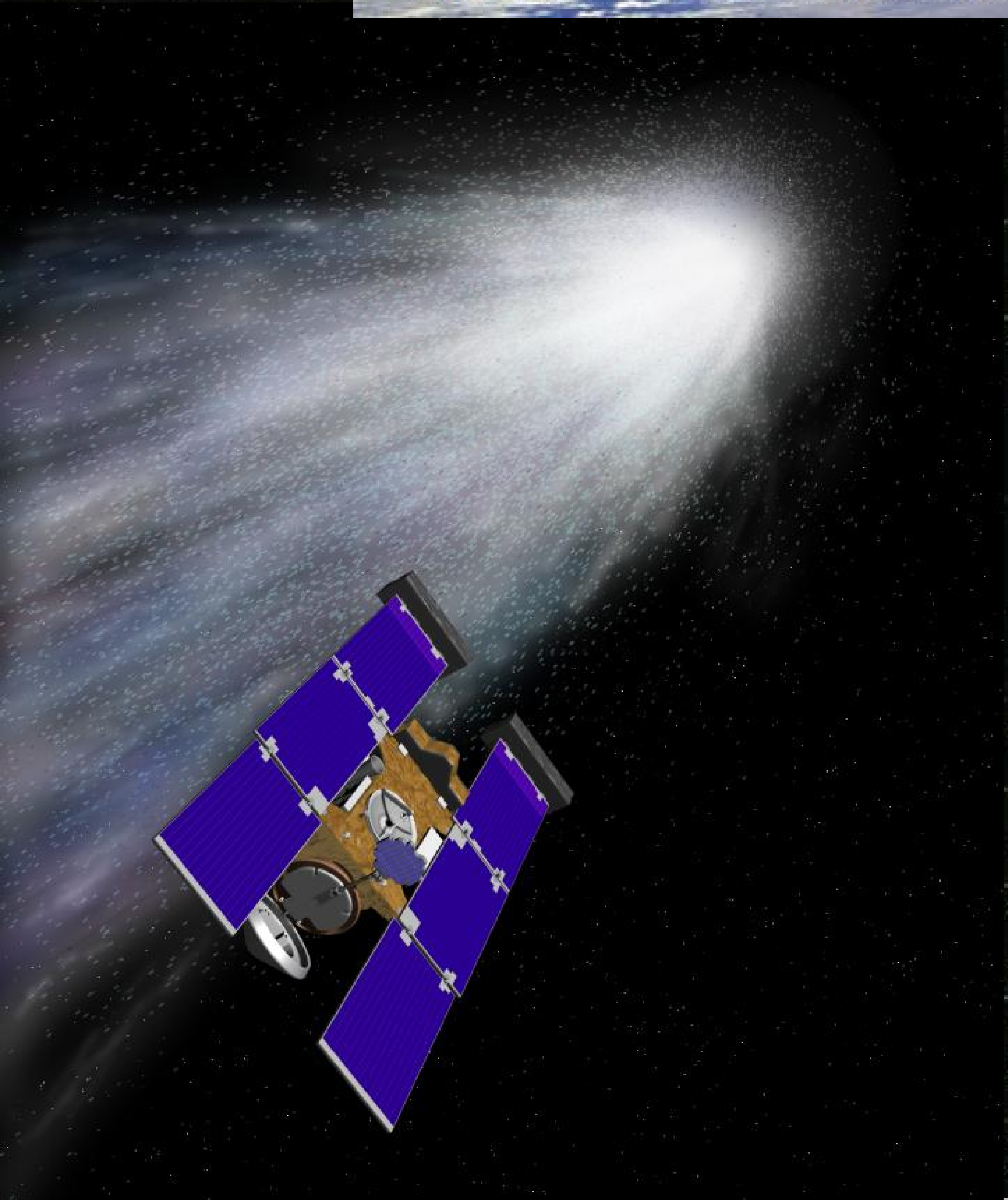


- Collected in stratosphere by modified U2 spy planes and in Antarctica by melting/filtering snow
- Originate in comets and asteroids



STARDUST

NASA's COMET SAMPLE RETURN MISSION



- NASA mission, flew through tail of comet Wild-2, collected dust particles and returned them to Earth (Jan 2006)
- Dust collected at 6.1 km/s in “aerogel” and as impact residues in Al foils

Primitive ET samples

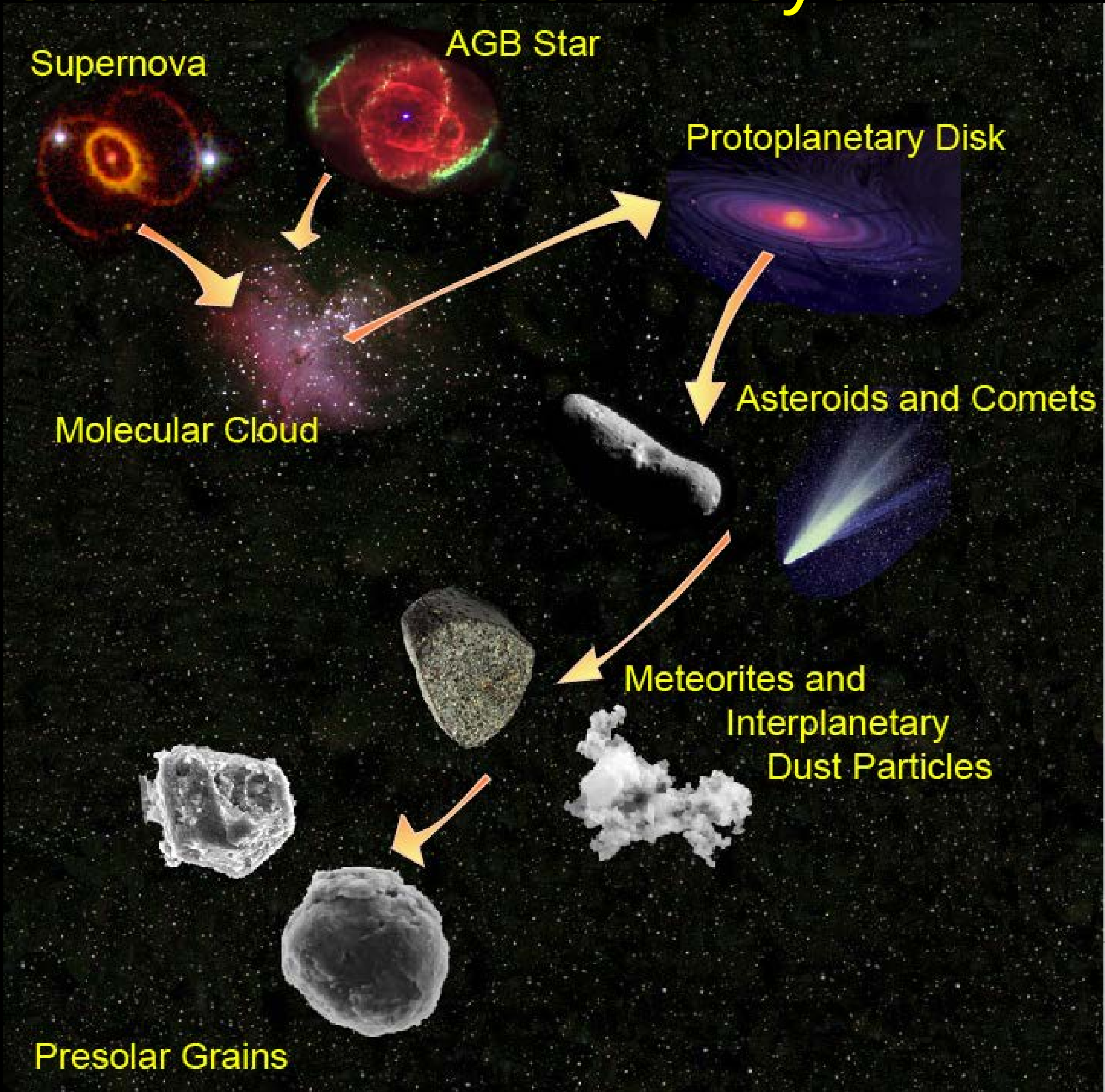
- Non-biological “fossils,” containing a record of:
  - Starting materials of the Solar System
  - What the Solar System was like at beginning
  - Earliest stages of planetary processes
  - Timescales for early processes

- Focus here on one rare component

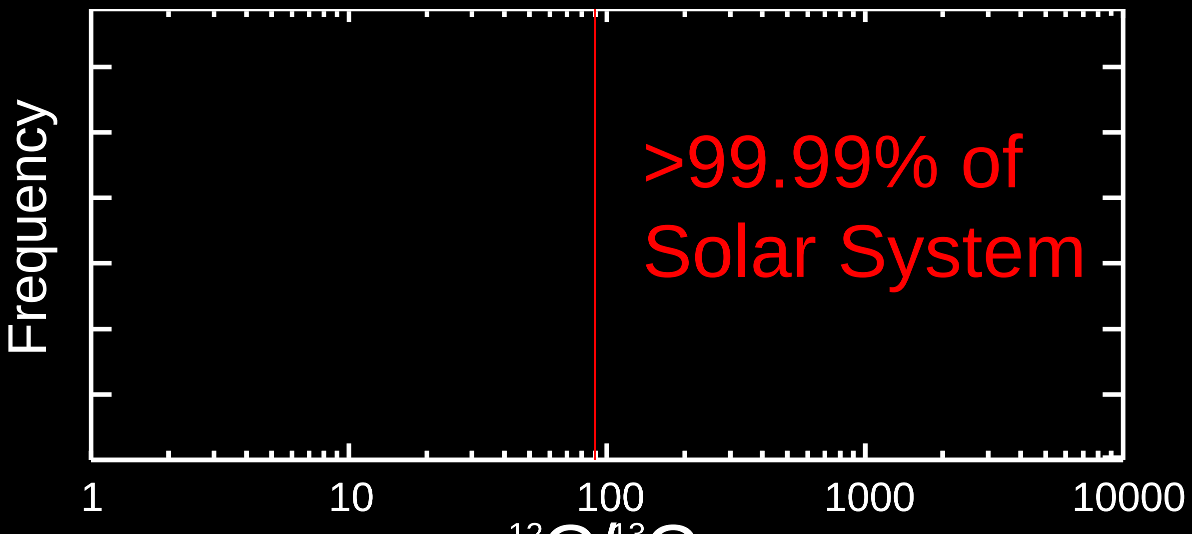
PRESOLAR STARDUST

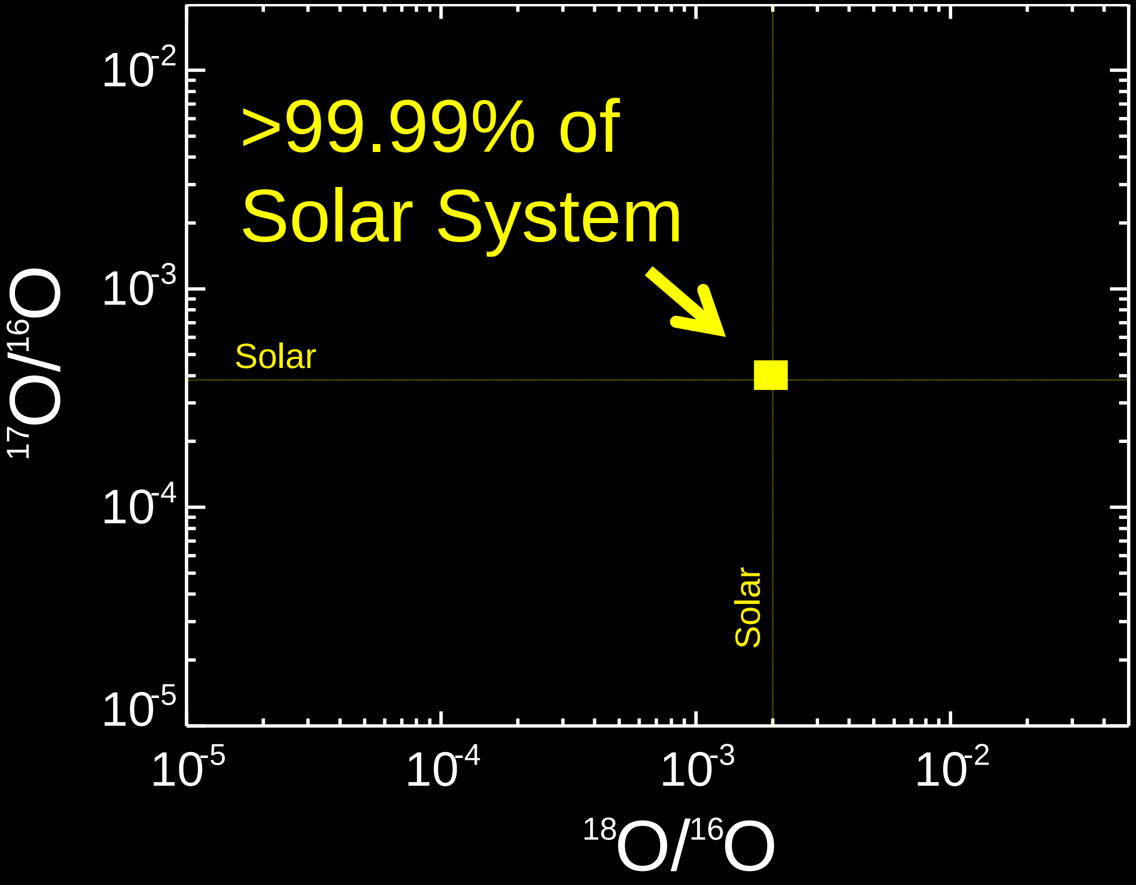
Presolar Stardust in the Solar System

- Bona-fide stardust from ancient dead stars
- Survived interstellar processes and solar system formation
- Found today surviving in meteorites and interplanetary dust particles
  - <~100 ppm



How do we know?





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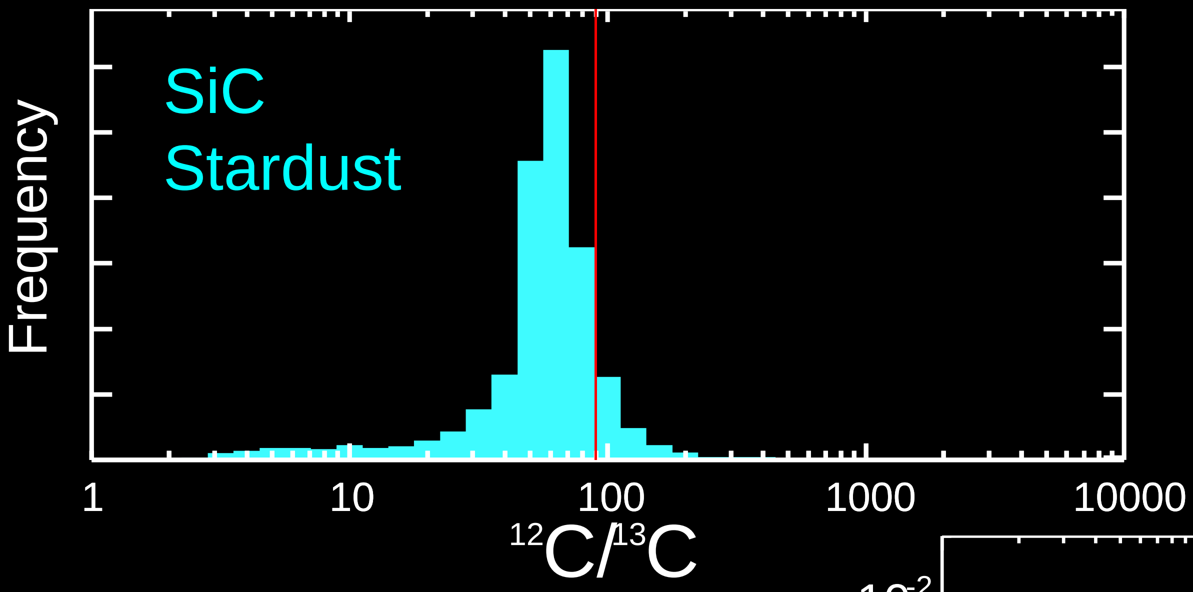
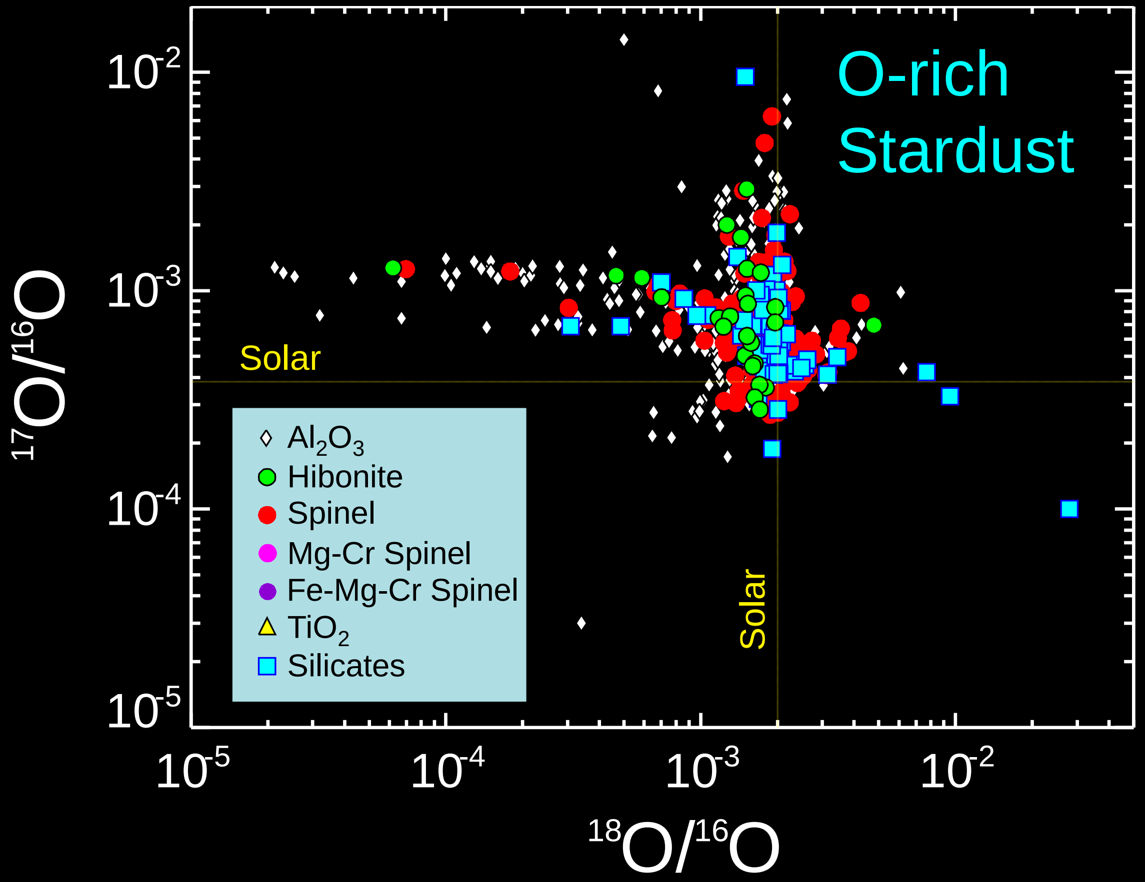
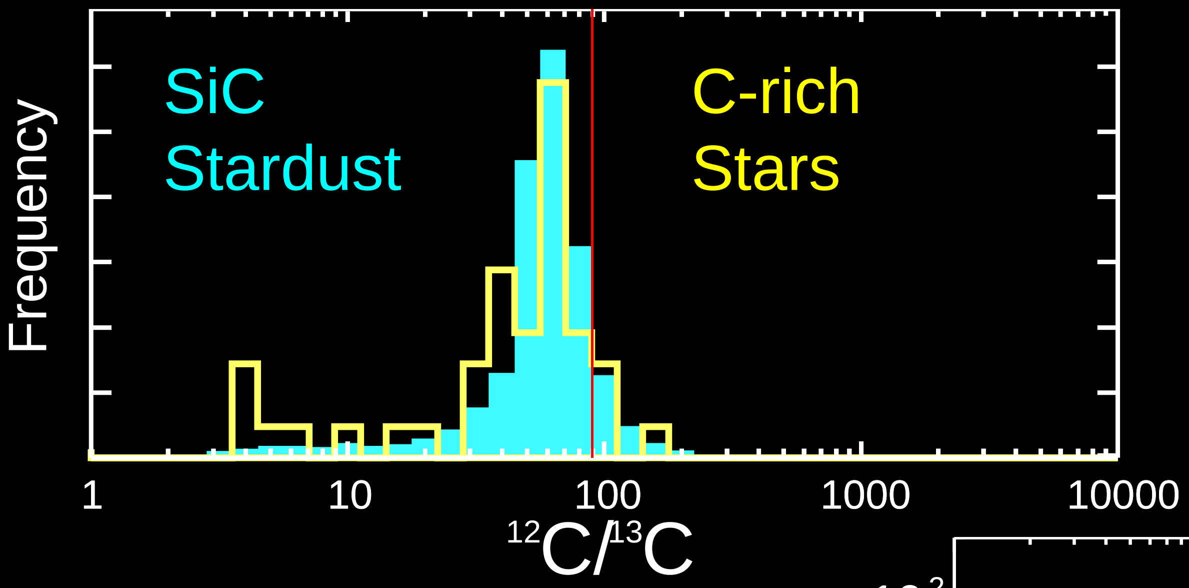


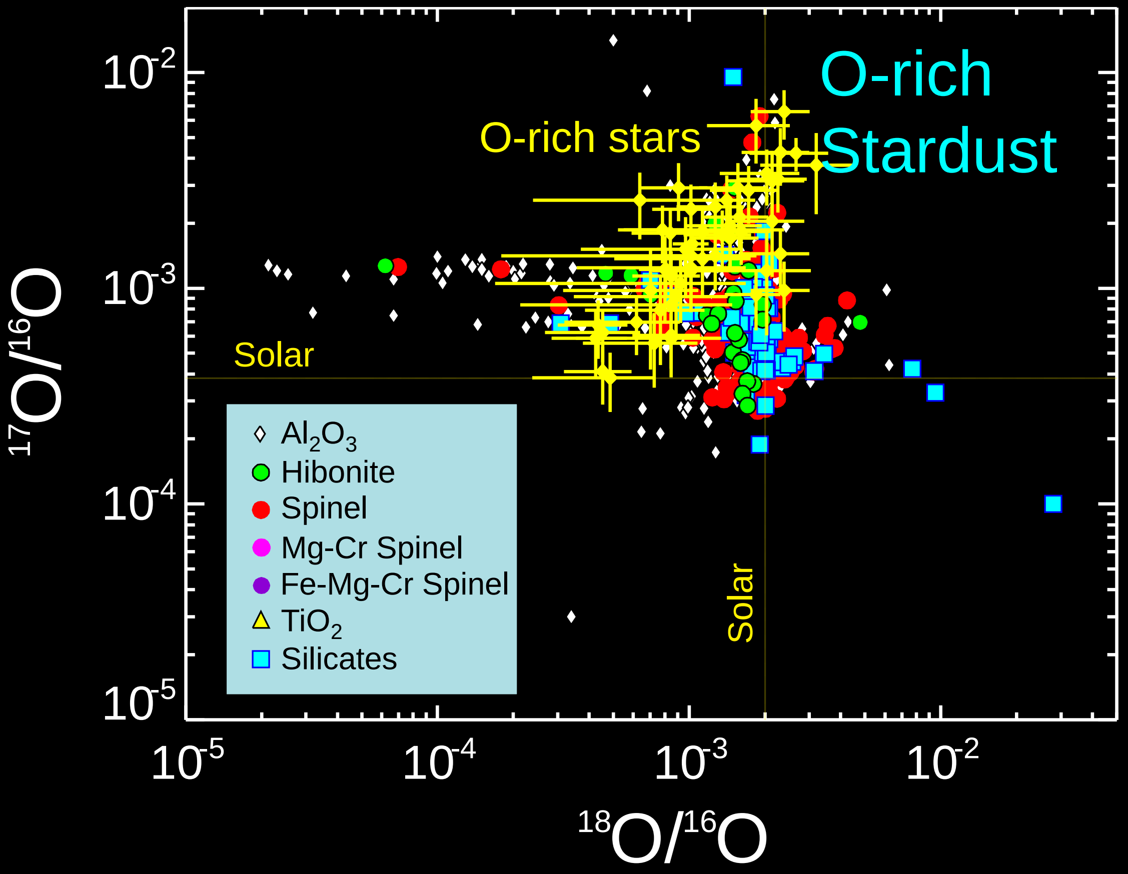


- Isotopic ratios in grains extremely unusual and distinct from ranges found in solar system material
- Too large to explain by physical/chemical processes

How do we know?



- Isotopic variations require *nuclear* processes.
- Origin in STARS



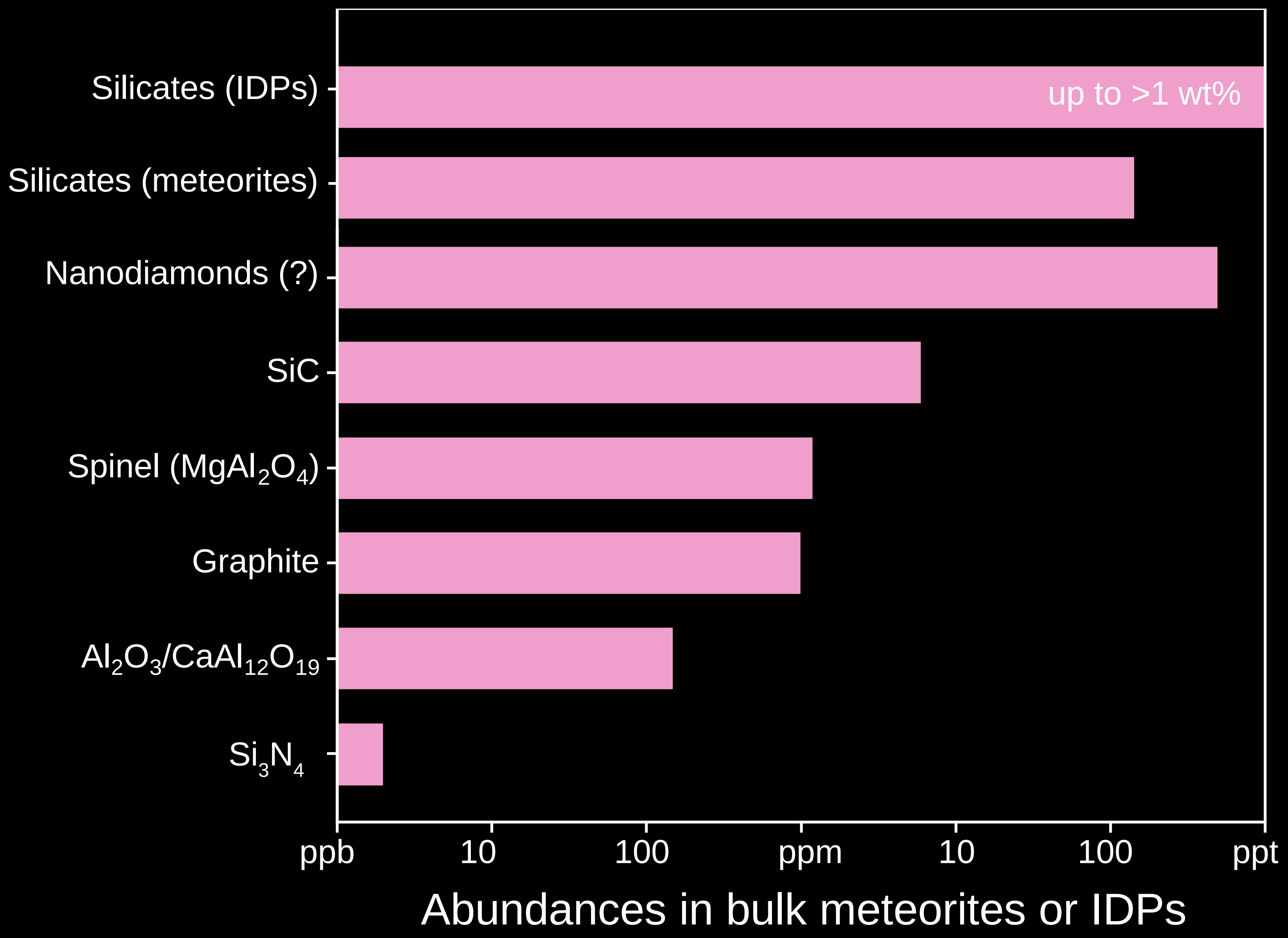
Presolar Stardust

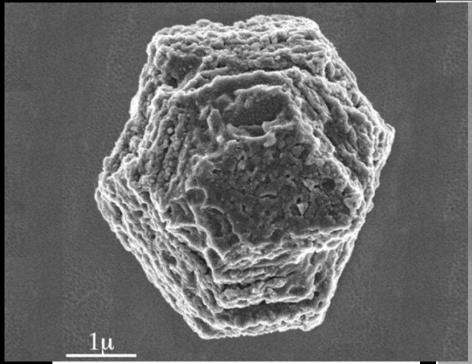
- Each presolar grain is a solid piece of a *single* star at a *given* time in its evolution
  - Isotopic/elemental composition is fossil record of *nucleosynthesis* (process by which elements are made)

- Each presolar grain survived processing in interstellar medium, early solar system and meteorite/comet parent body
  - Abundances, chemical/structural data can constrain such processes

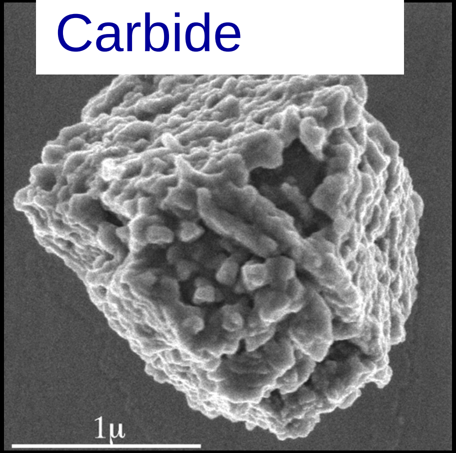
- Laboratory measurements of grains provide detailed information about stellar/interstellar/ early solar system processes
  - Such analyses possible by modern techniques despite small sizes of grains (<1μm)

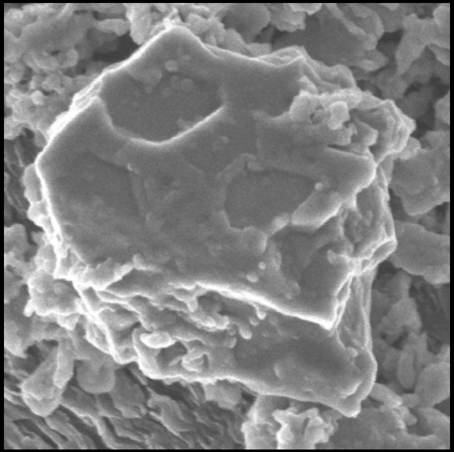
Presolar Grain Types

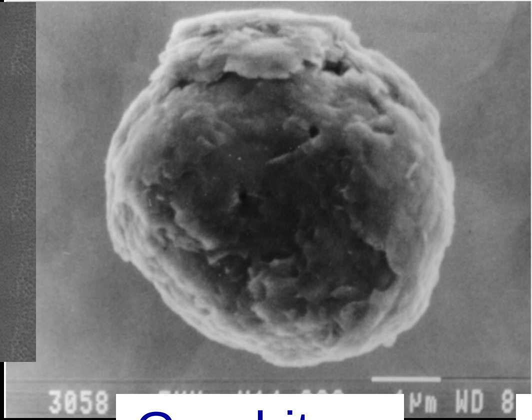




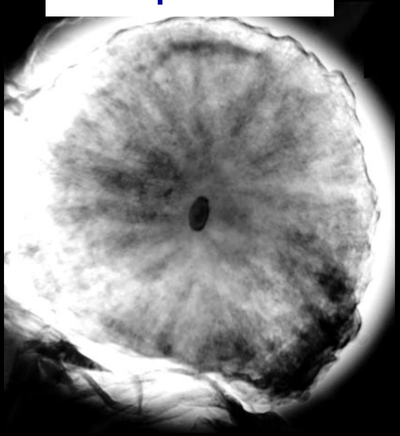
Silicon
Carbide

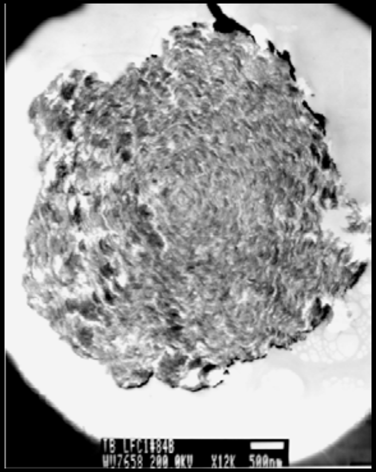


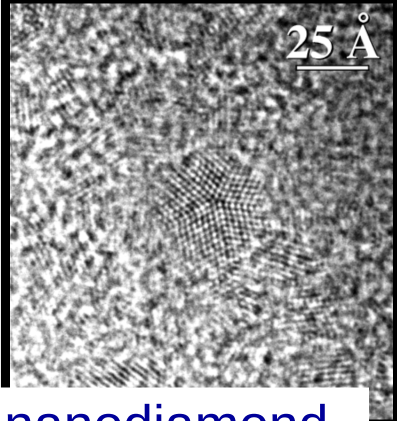




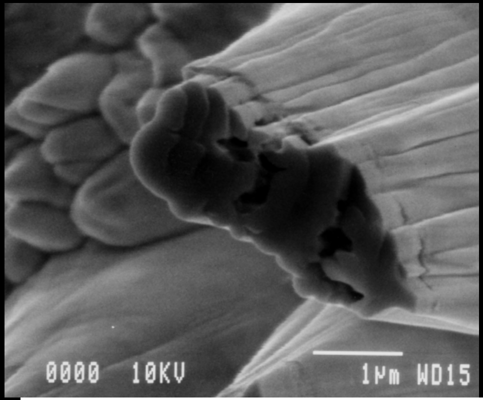
Graphite



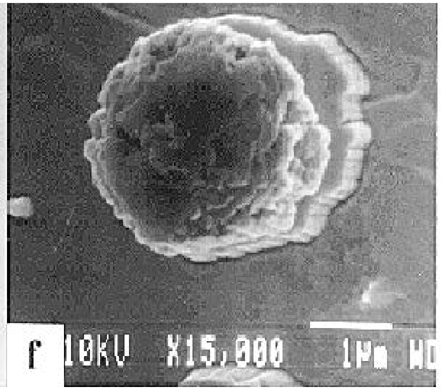


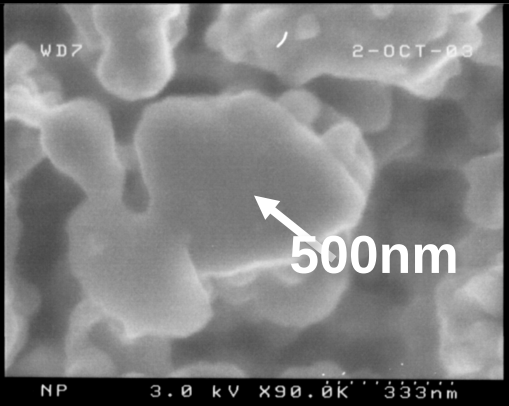


nanodiamond

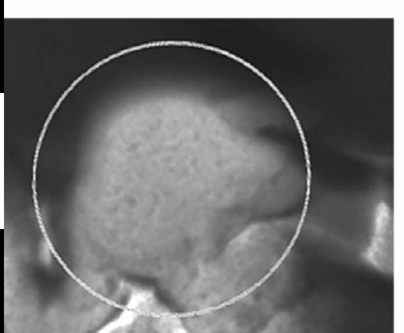


Oxides(Al_2O_3,
$MgAl_2O_4$, TiO_2 …)





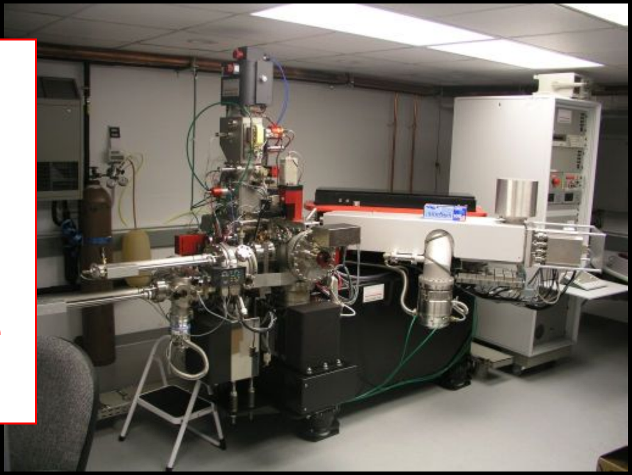
Silicates (Glass,
$MgSiO_4$ …)



Stardust tools ("telescopes")

Secondary Ion Mass Spectrometry (SIMS)

- Major/minor element isotope ratios (>100nm)



Carnegie Inst. NanoSIMS

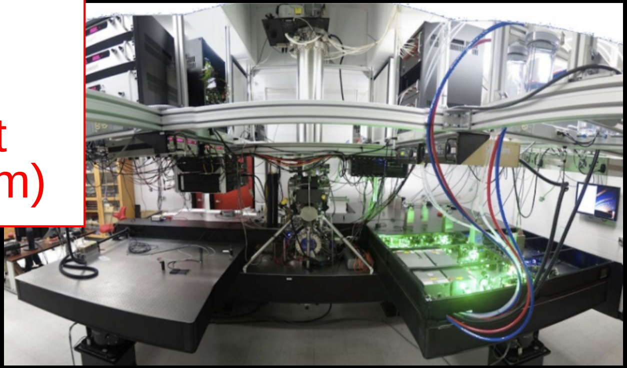
Electron Microscopy

- Morphology/ mineralogy/ microstructure (>1nm)

NION Ultra-STEM
Scanning Transmission Electron Microscope
Naval Research Lab

Resonance Ionization Mass Spectrometry (RIMS)

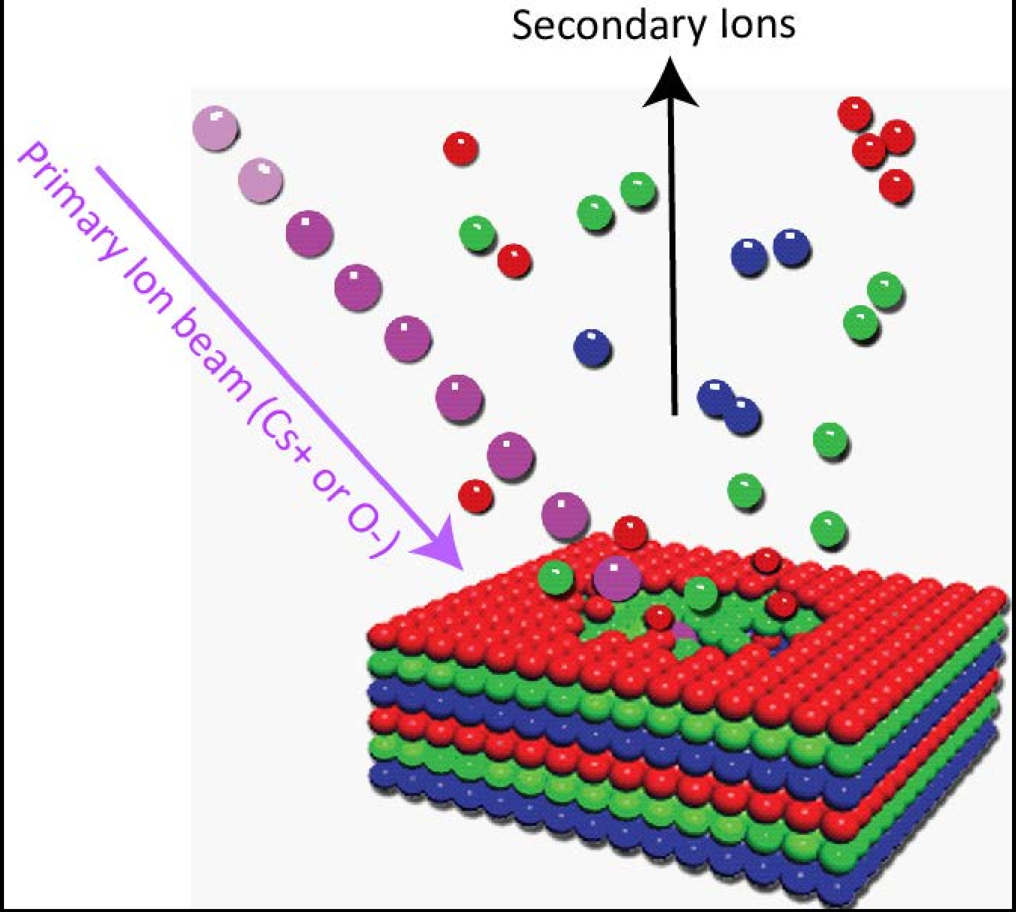
- Trace-element isotopes (>1μm)



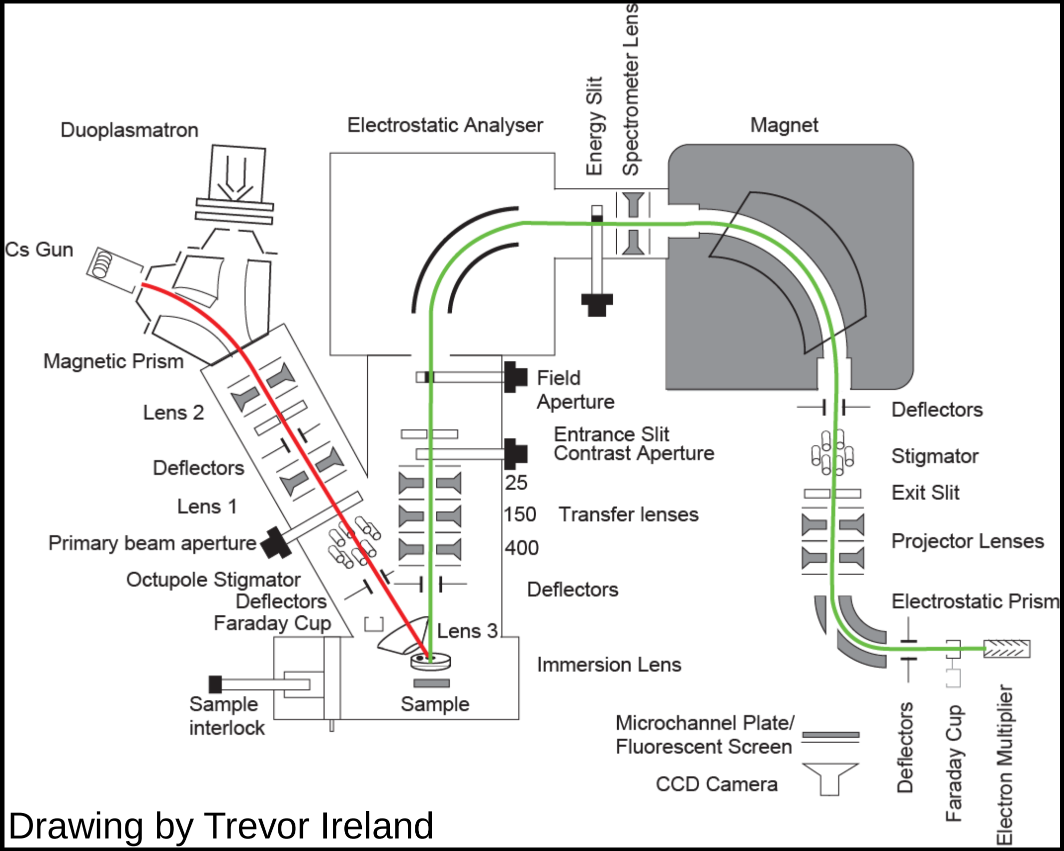
"CHILI" U Chicago

Secondary Ion Mass Spectrometry (SIMS)

- Use ion sputtering to determine major/minor element isotope ratios
- Beam can be focused to small spot for spatially-resolved measurements
- Highly sensitive



Cameca ims-3f/6f ion probe



Drawing by Trevor Ireland

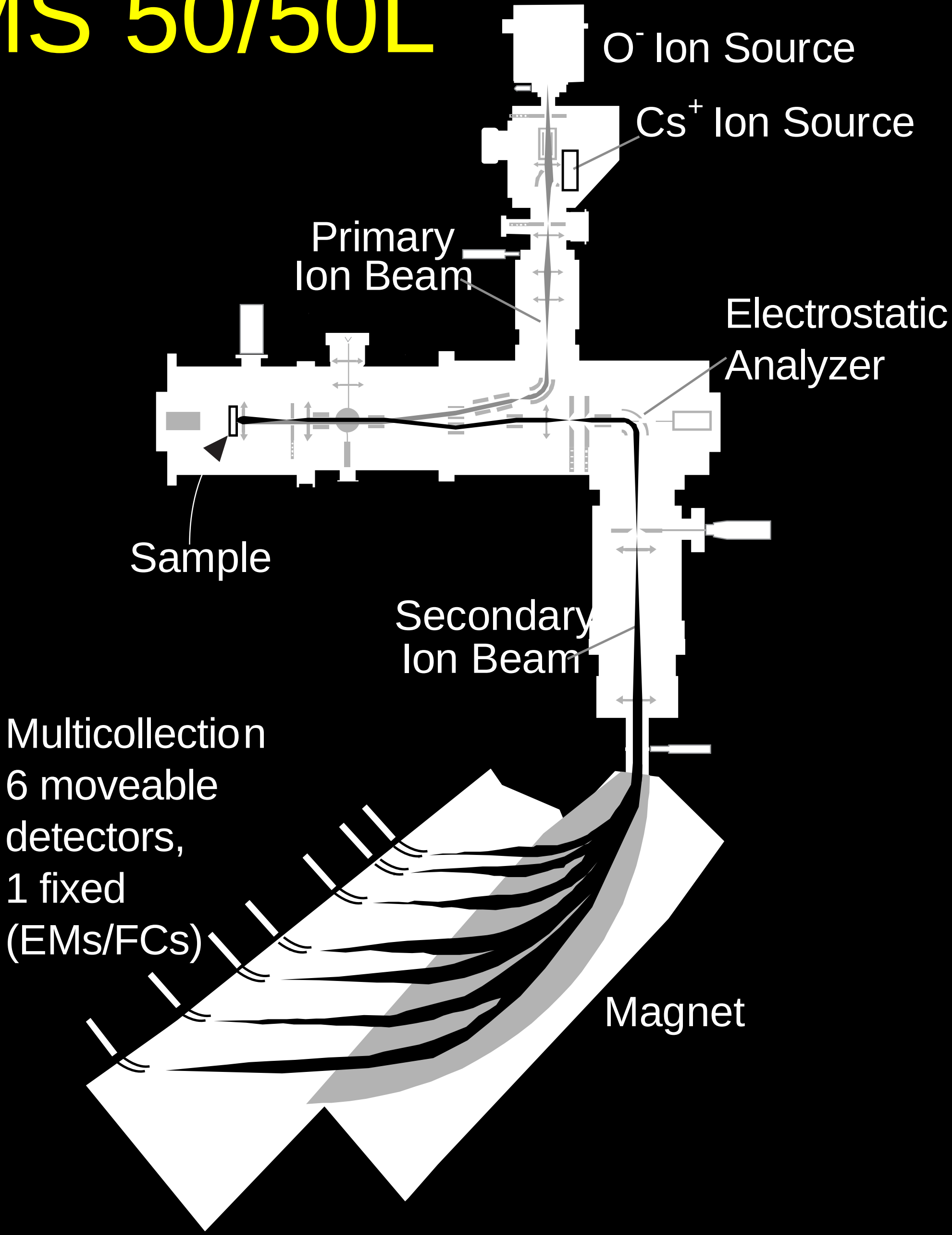
Carnegie ims-6f

- Used for majority of presolar grain data 1987-2003
- 1970’s design
- 1μm spatial resolution, high sensitivity

Cameca NanoSIMS 50/50L

- Since ~2000
- <100nm spatial resolution, very high sensitivity
- Simultaneous collection of multiple masses
- Allows measurements of *more* elements in *smaller* samples; huge advantages for presolar grains

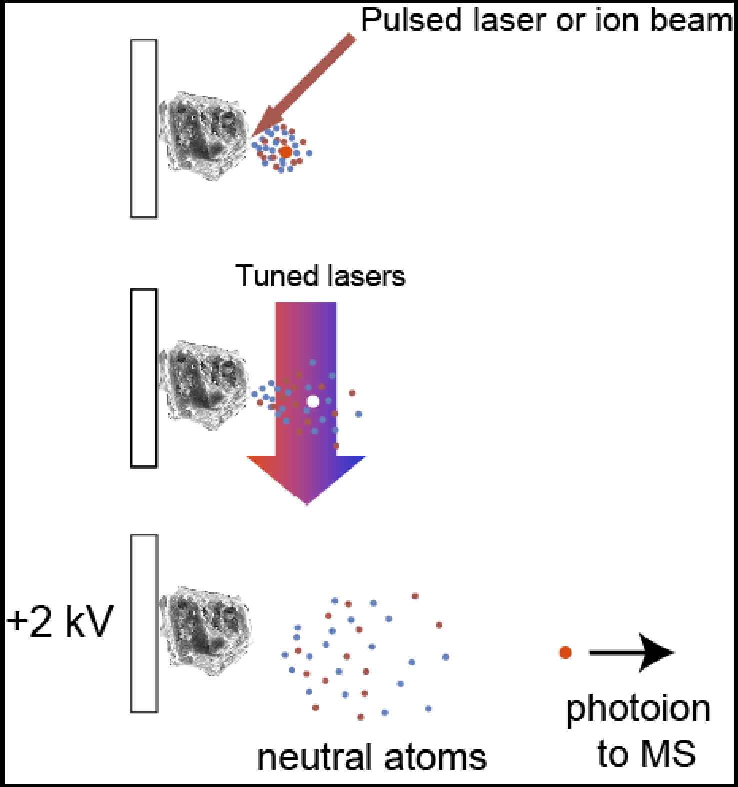
Carnegie NanoSIMS

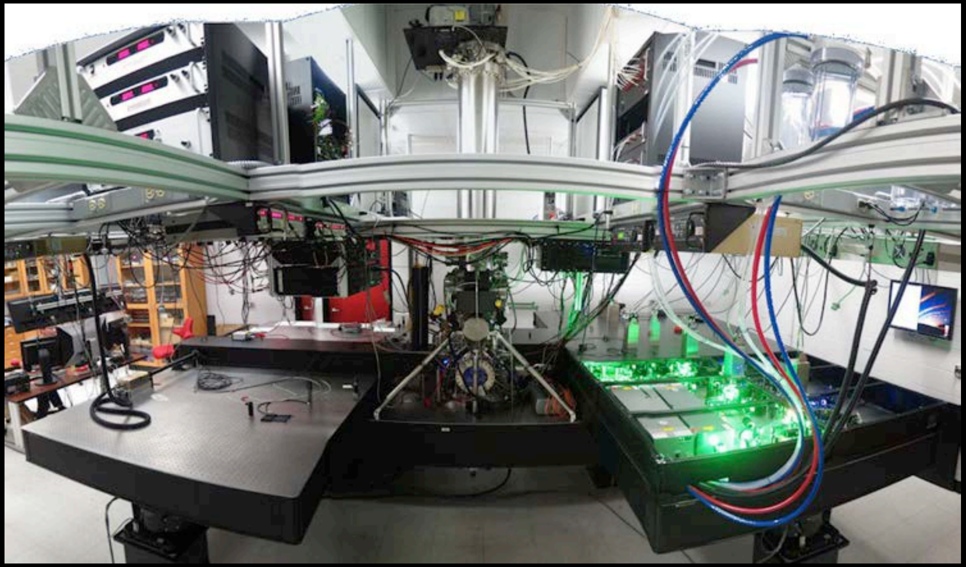


SIMS limitations

- Destructive technique
- Even with high sensitivity, limited by # atoms in small samples; Poisson uncertainty on N counts= sqrt(N)
- Example:
  - A 1-micron SiC grain contains ~5×10^{10} atoms
  - Typical presolar SiC has ~0.1% Al
  - Al efficiency by SIMS is <~10^{-2}
  - Typical inferred ^{26}Al/^{27}Al for presolar SiC is 10^{-3}
  - Gives 500 measureable radiogenic ^{26}Mg atoms in whole grain (4% uncertainty)
- Some isobaric interferences unresolvable
  - Can correct some (e.g. ^{50}Cr on ^{50}Ti), but not others (e.g. Zr/Mo)

Resonance Ionization Mass Spectrometry (RIMS)

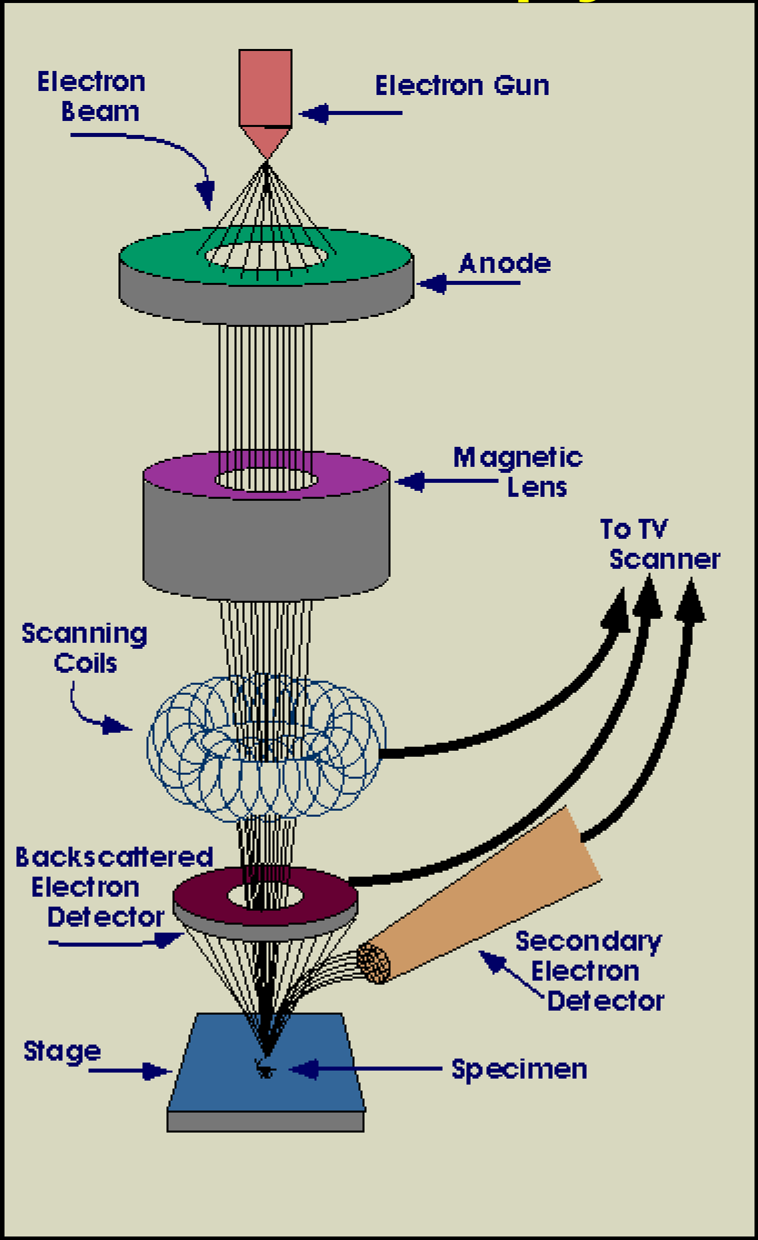


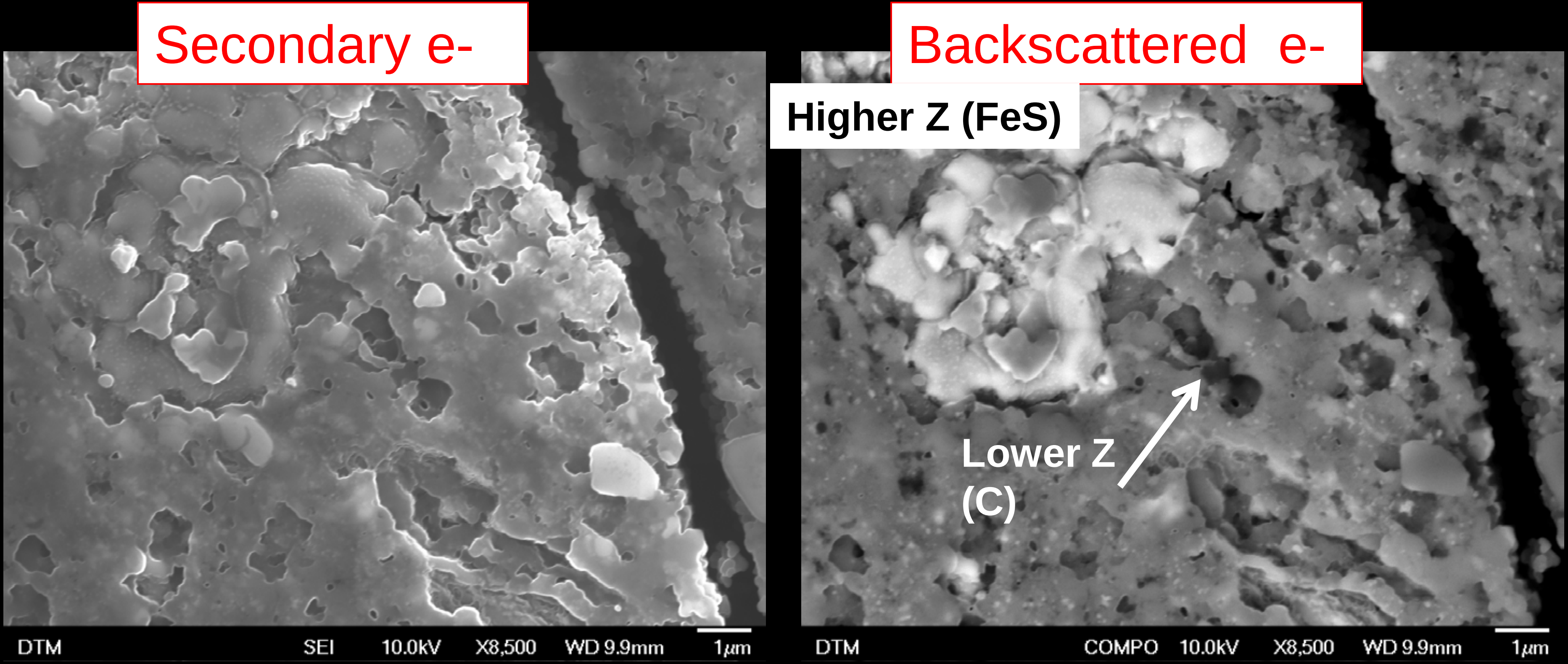


- Extreme sensitivity to select elements (can fully exclude isobaric in interferences)
- *CHILI* – unprecedented flexibility and sensitivity (Ga$^+$ ion beam + 6 lasers)

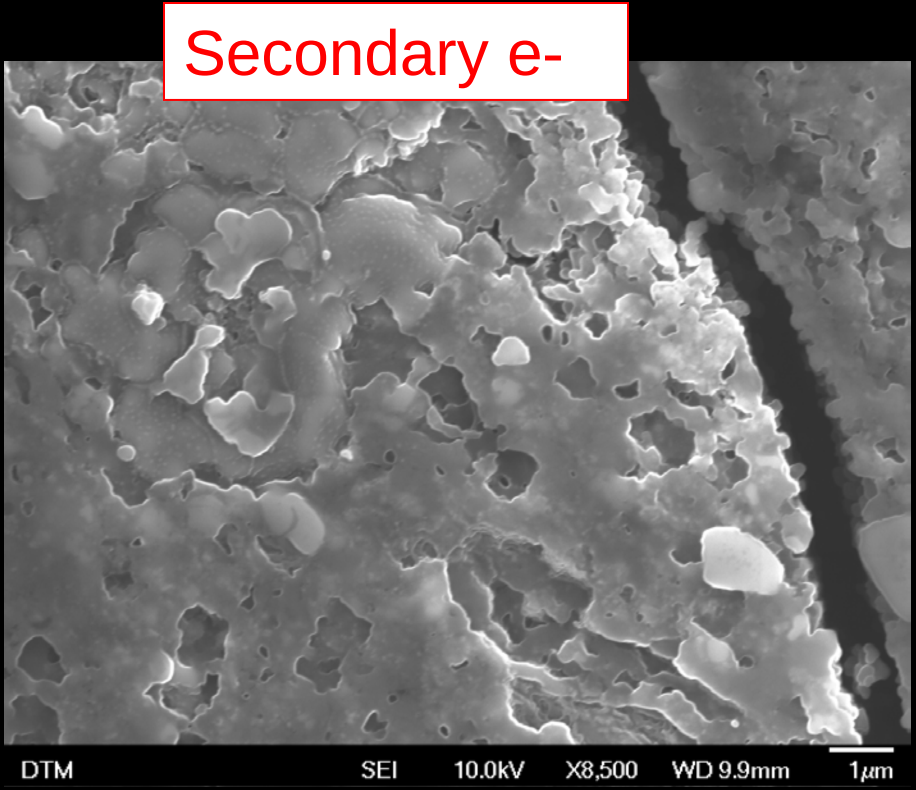
Scanning Electron Microscopy

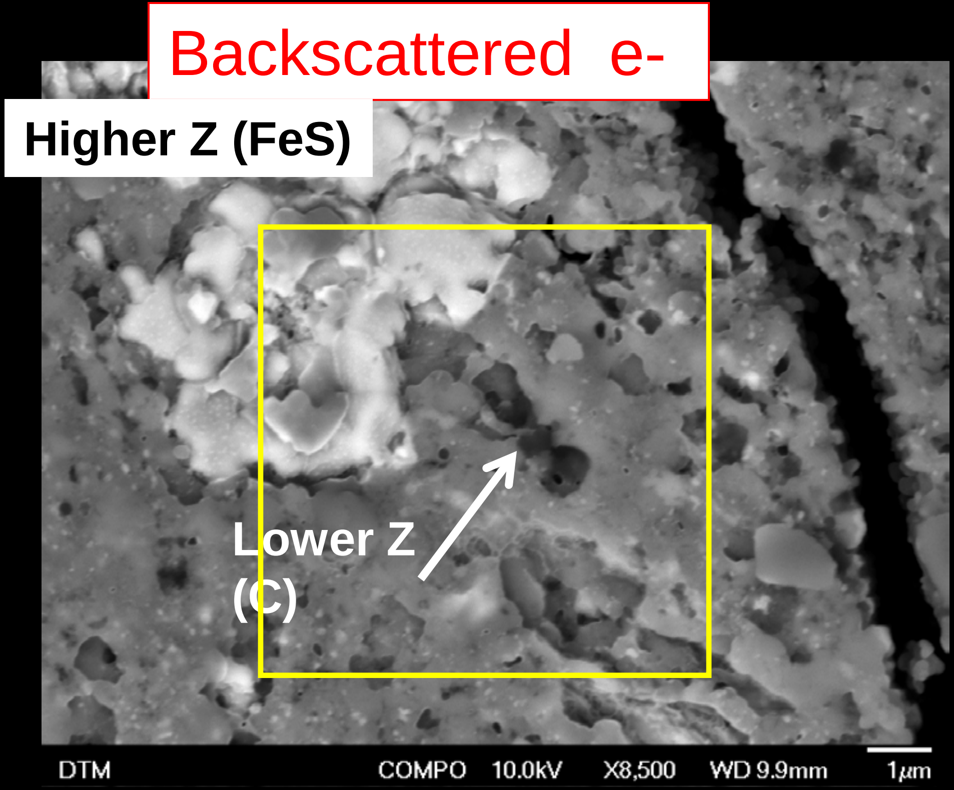
- Focus beam of (3-20 keV) electrons on sample
  - – few nm resolution imaging
- Detect:
  - – secondary e- (topography)
  - – backscatter e- (composition/ topography)
  - – X-rays (compositional info)



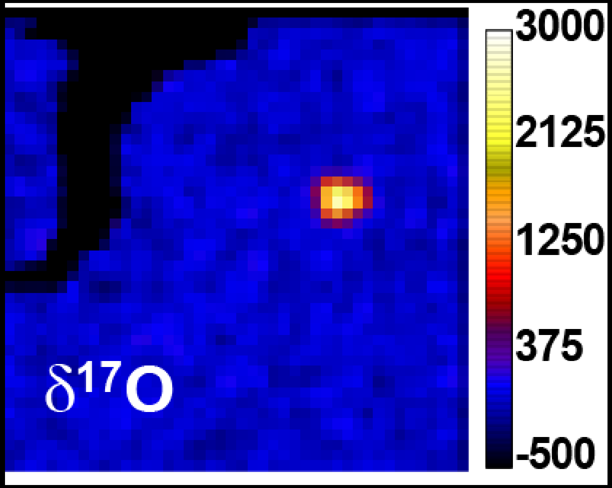


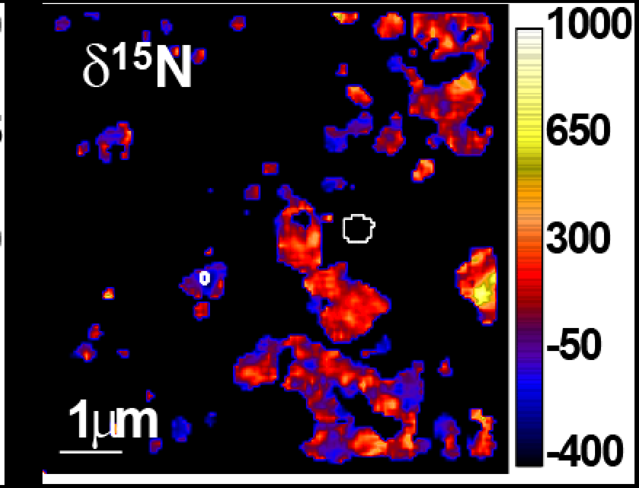
CR3 meteorite QUE 99177 (Nguyen et al 2008)





- Can also correlate with NanoSIMS images

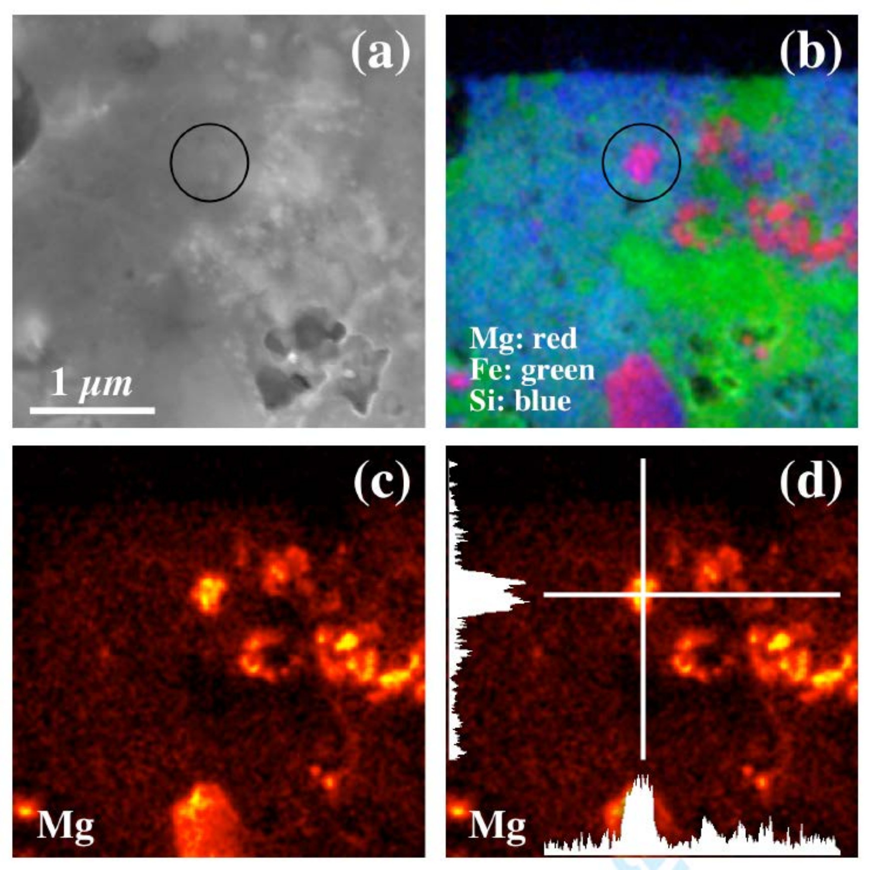




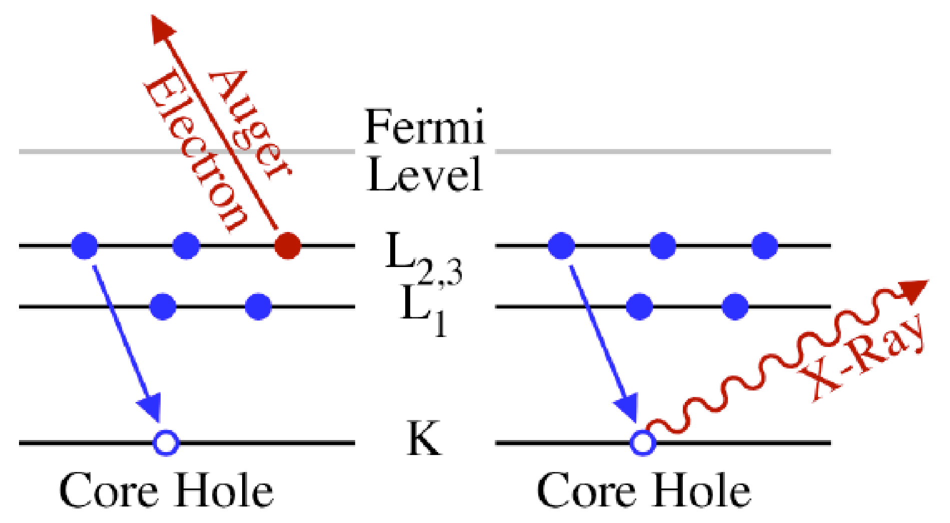
CR3 meteorite QUE 99177 (Nguyen et al 2008)

Auger Spectroscopy

- Auger electrons also produced upon electron-irradiation of samples
  - Allows chemical analysis with better spatial resolution than SEM X-ray analysis, but less sensitive

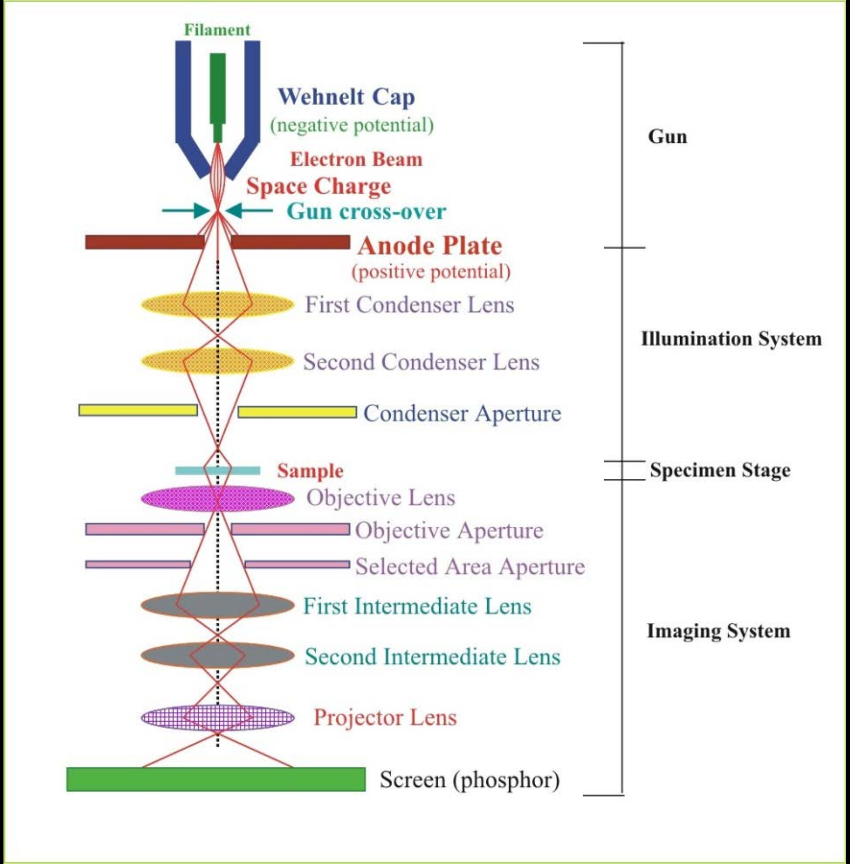


Stadermann et al (2008)

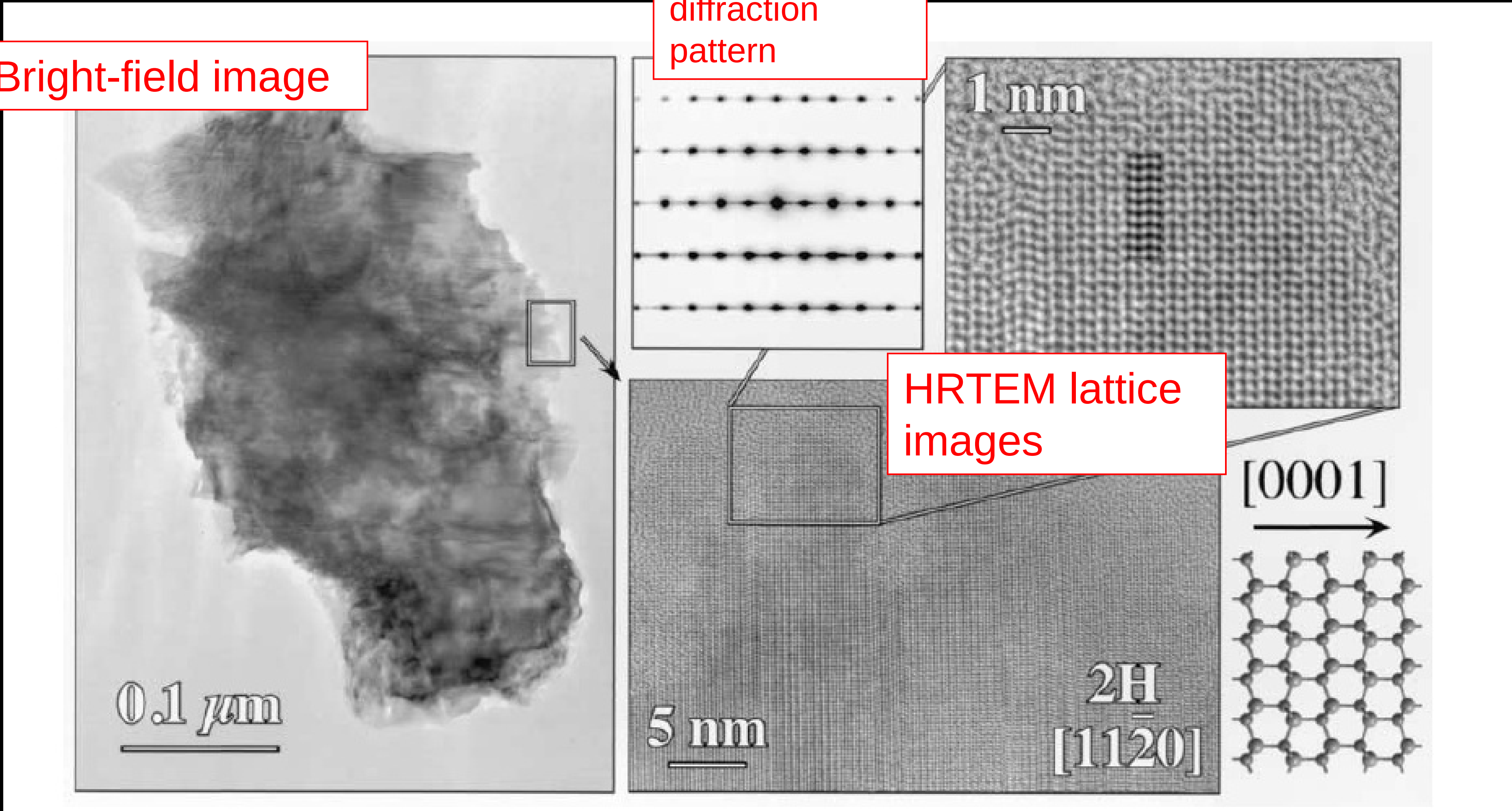


Transmission Electron Microscopy

- Focus beam of 60-300 keV electrons through thin (<100 nm) sample
- High-magnification (atomic-resolution) imaging/ X-ray chemical mapping
- Electron diffraction (structural information)
- Electron energy-loss spectroscopy (EELS, provides compositional and chemical bonding information)



TEM of presolar SiC grain

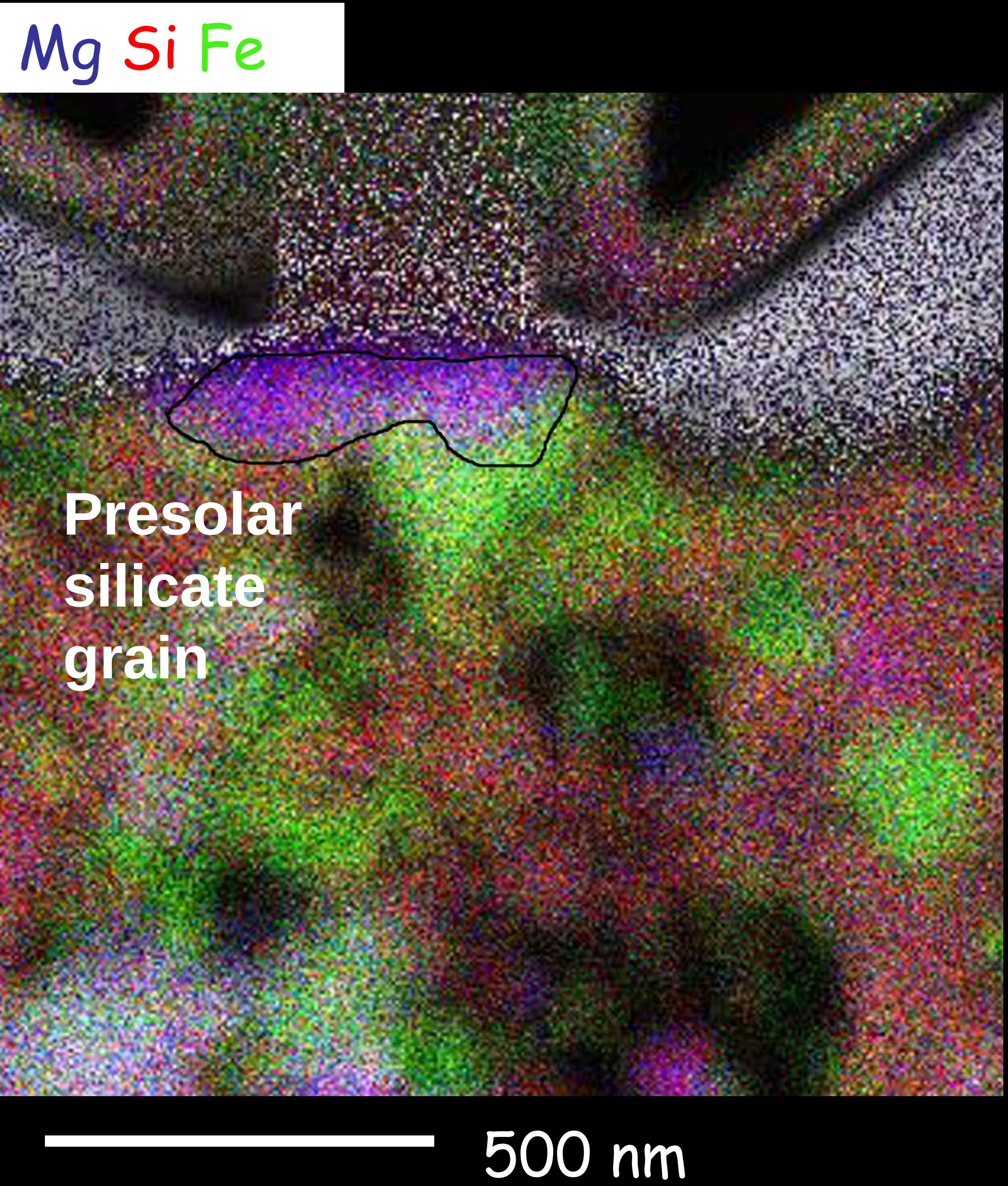


Bright-field image

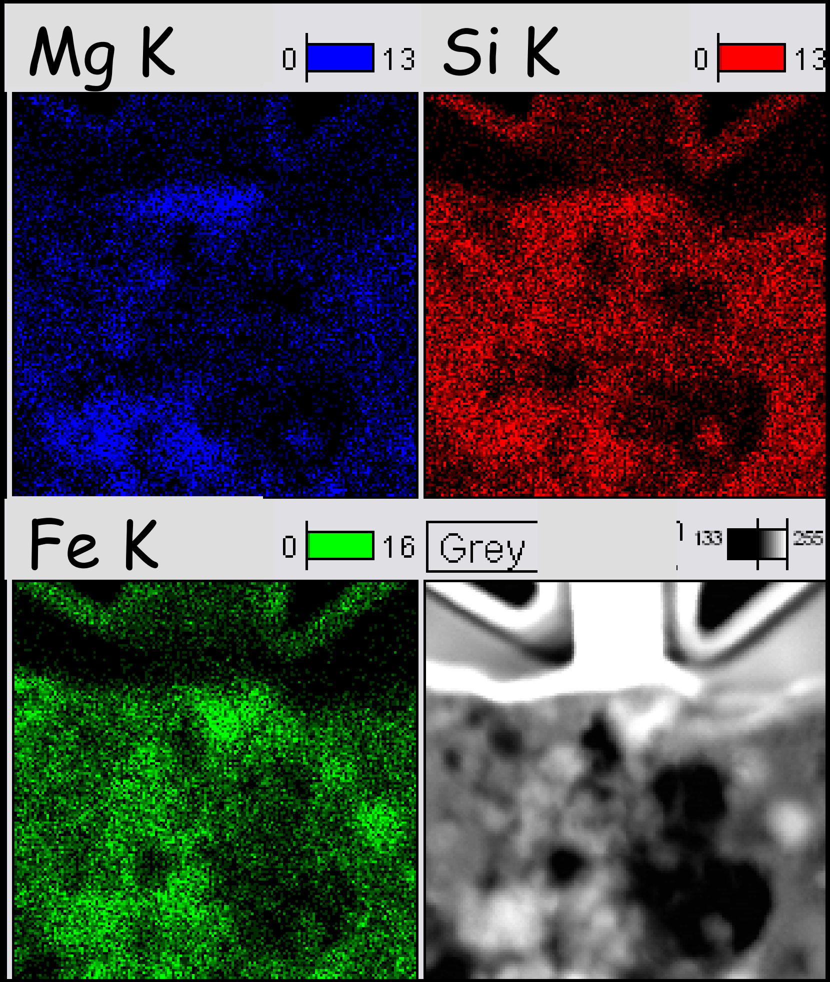
Electron diffraction pattern

HRTEM lattice images

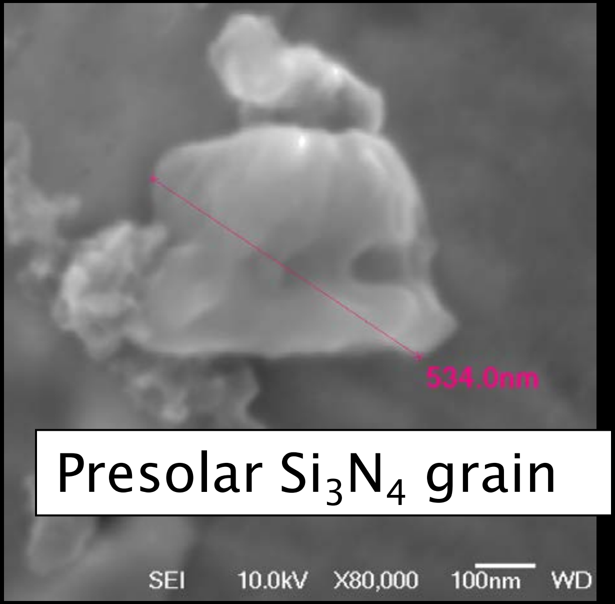
STEM EDS Mapping



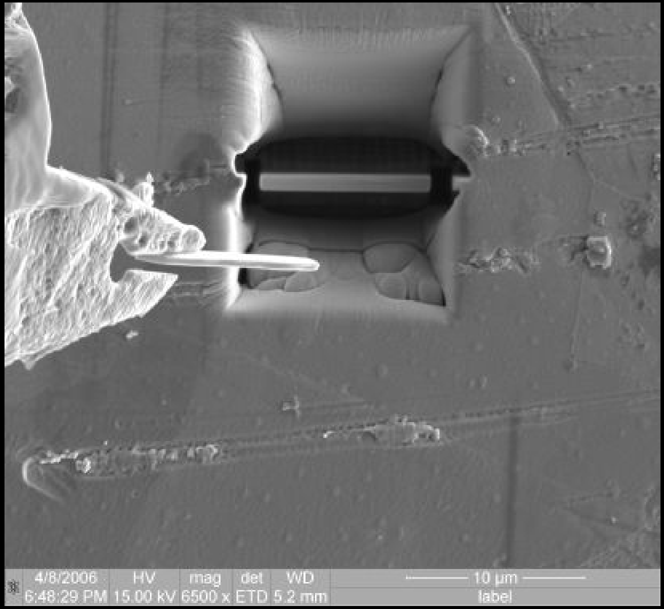
Presolar silicate grain



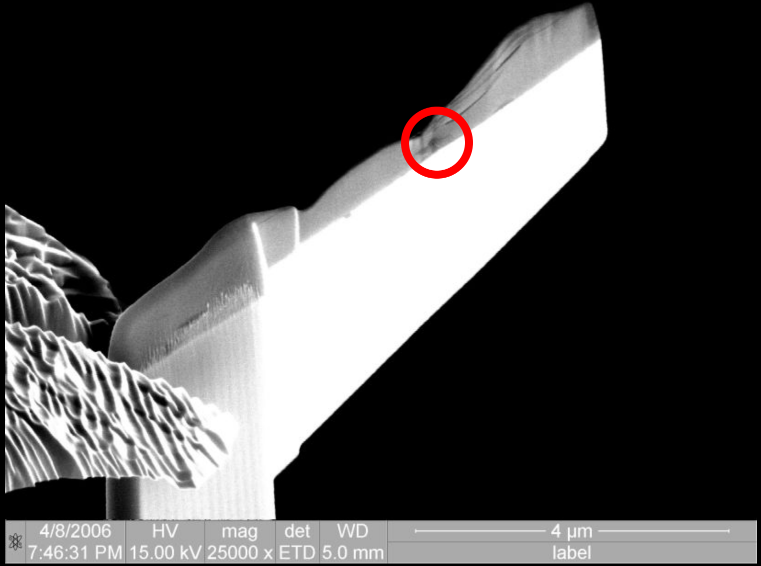
Focused Ion Beam (FIB)



Presolar Si_3N_4 grain

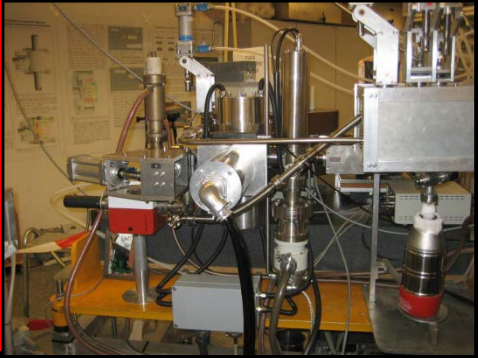


- SEM with ion gun
  - Technology developed for semiconductor industry
- Use <50 nm Ga^+ beam to cut slices of samples
- Lift-out using *in situ* micromanipulator

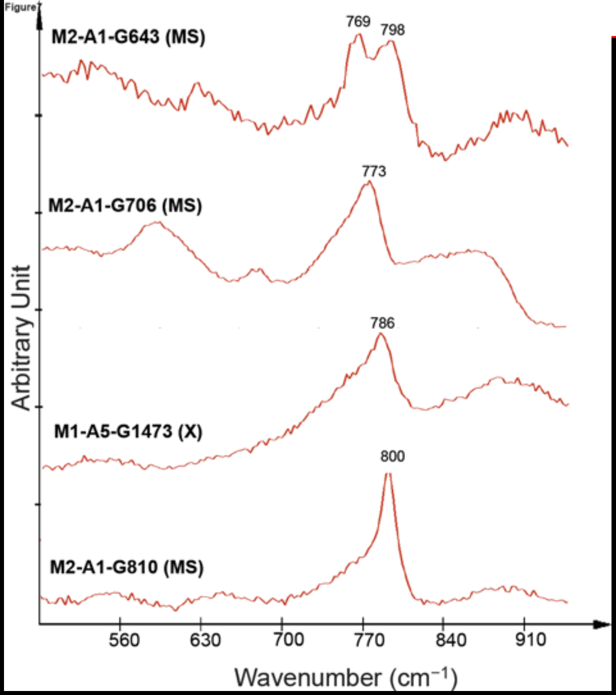


Other techniques

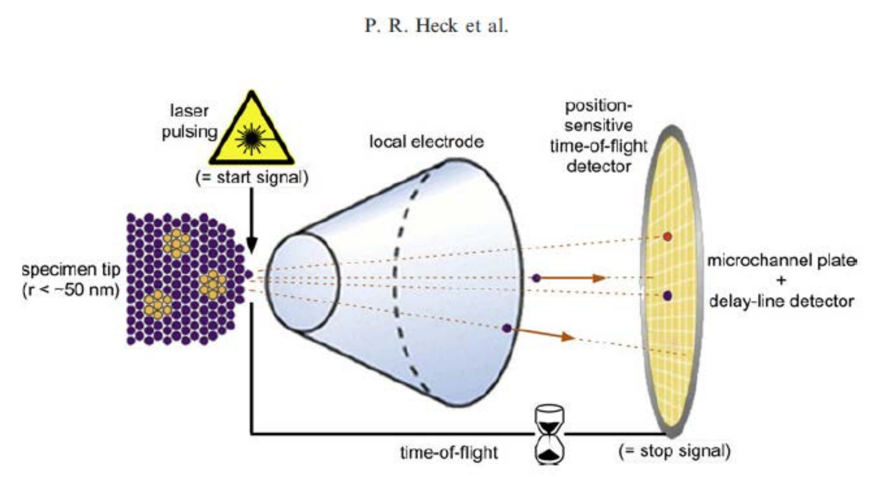
- Noble gas mass spectroscopy
  - Laser-heating of grains, purification and MS of gases



- Raman spectroscopy
  - Inelastic scatter of laser light by lattice vibrations



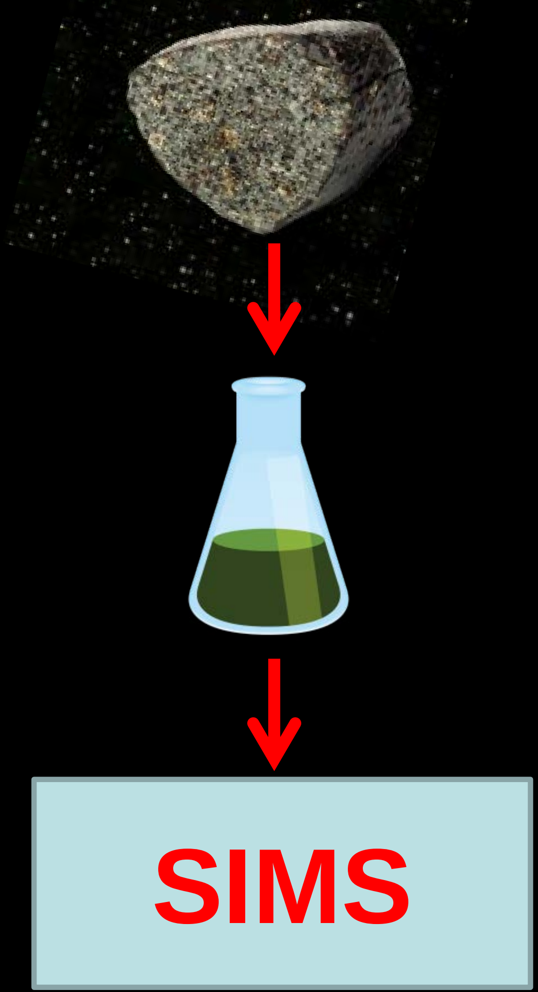
- Atom-probe tomography
  - atom-by-atom 3d reconstructions


P. R. Heck et al.

Finding presolar grains

- Acid dissolution

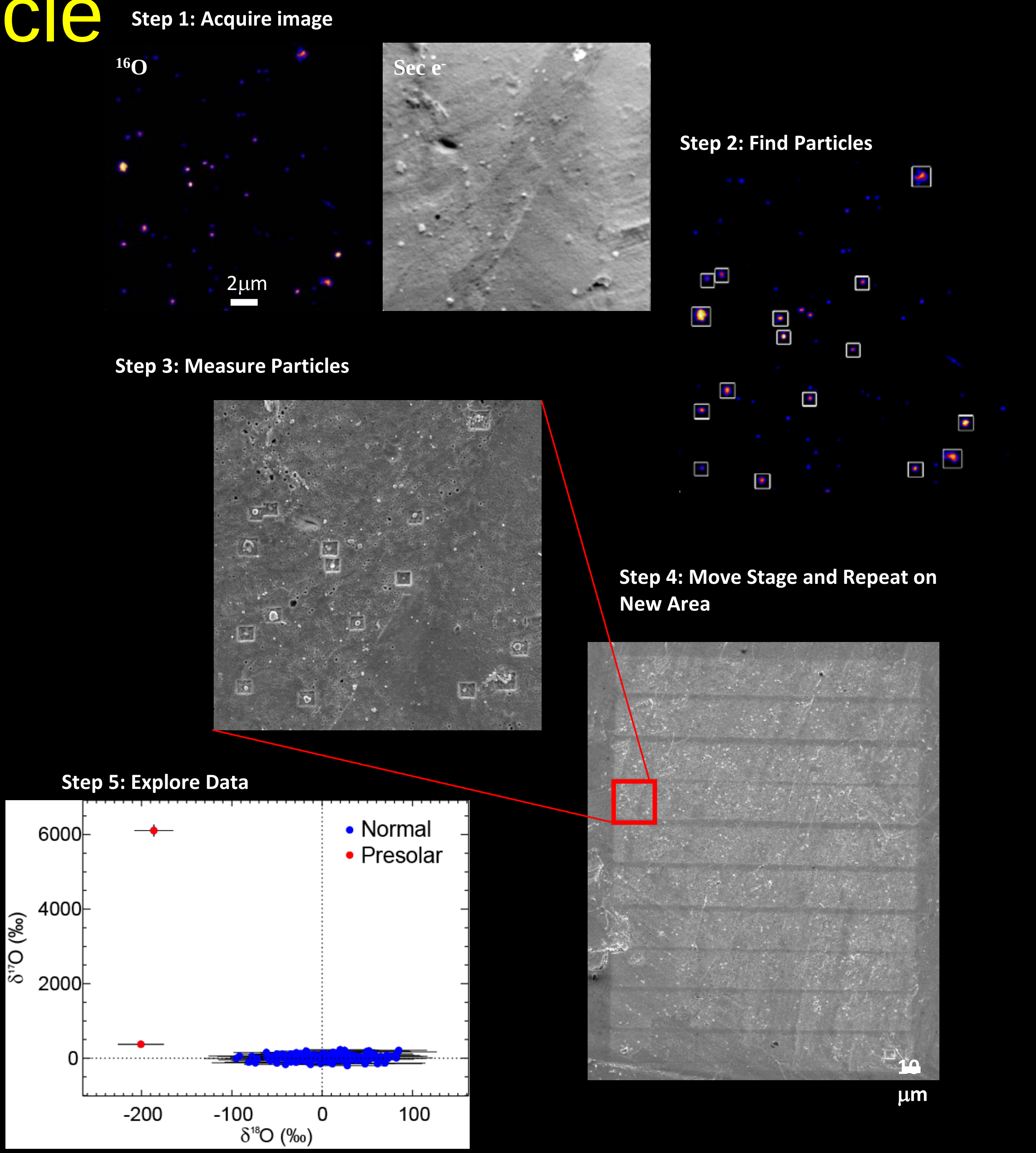
“burning down the haystack”



SIMS

Automatic particle analysis

- Fully automated NanoSIMS isotopic measurements of particles
- Can scan 100s particles per day
- Used successfully for presolar oxides and SiC (Nittler et al. 2003, 2008; Gyngard et al., 2010; Hoppe et al. 2010)



Step 1: Acquire image

Step 2: Find Particles

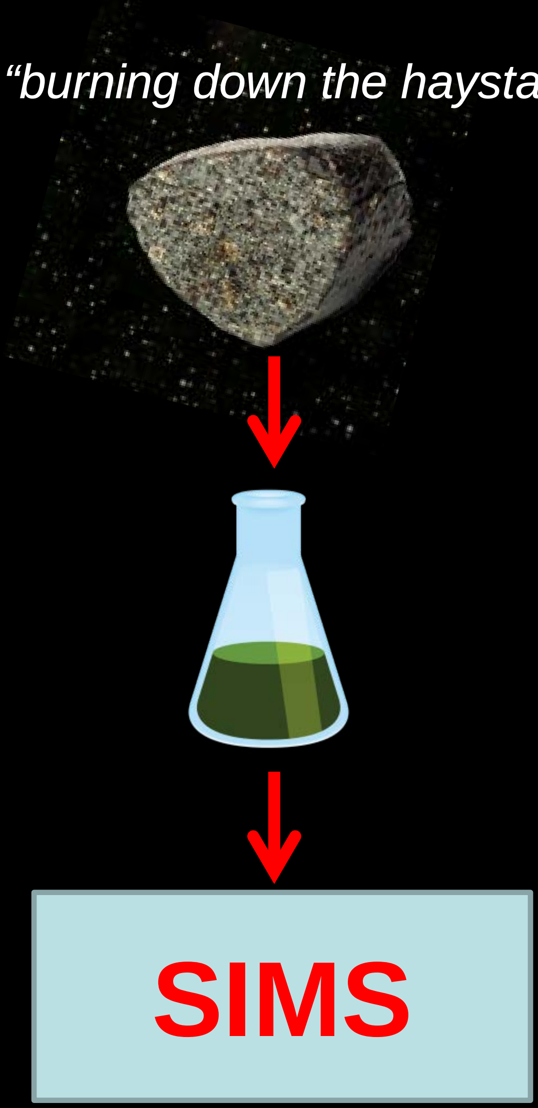
Step 3: Measure Particles

Step 4: Move Stage and Repeat on New Area

Step 5: Explore Data

Finding presolar grains

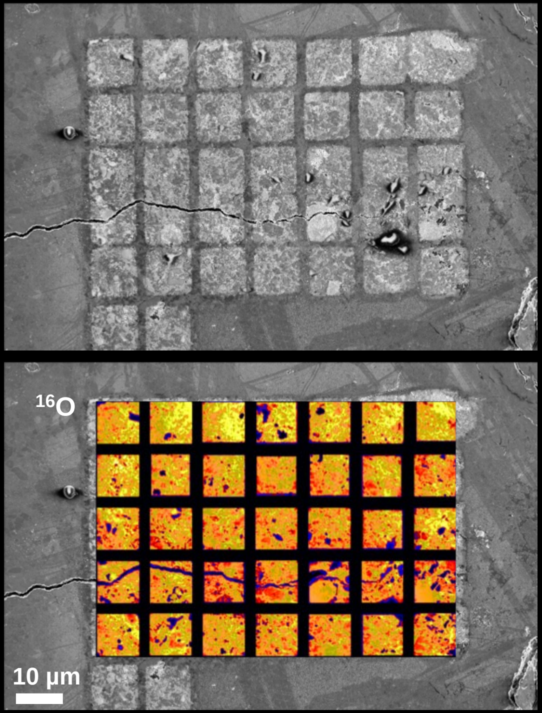
- Acid dissolution



“burning down the haystack”

SIMS

- *In situ* mapping

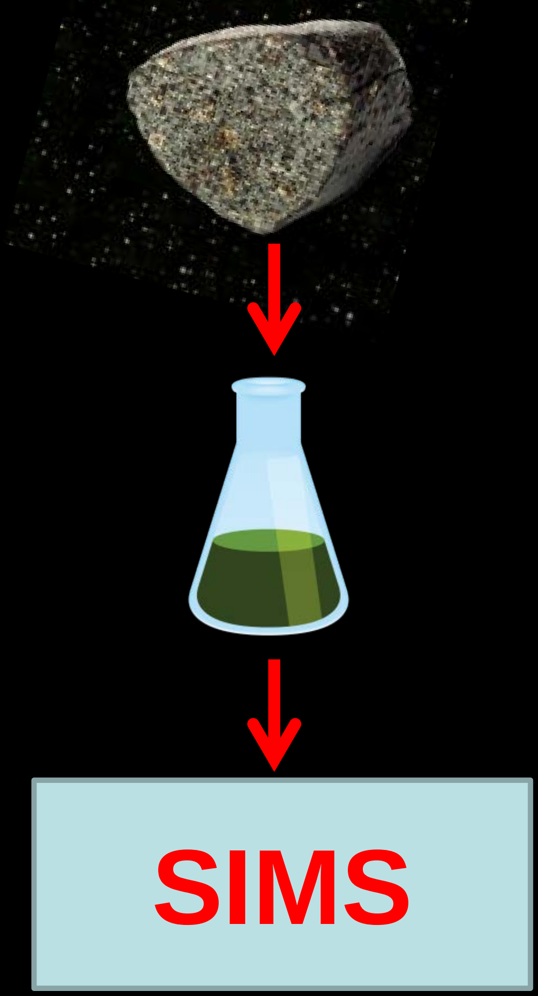


MIL 07687 CR chondrite- J. Davidson

Finding presolar grains

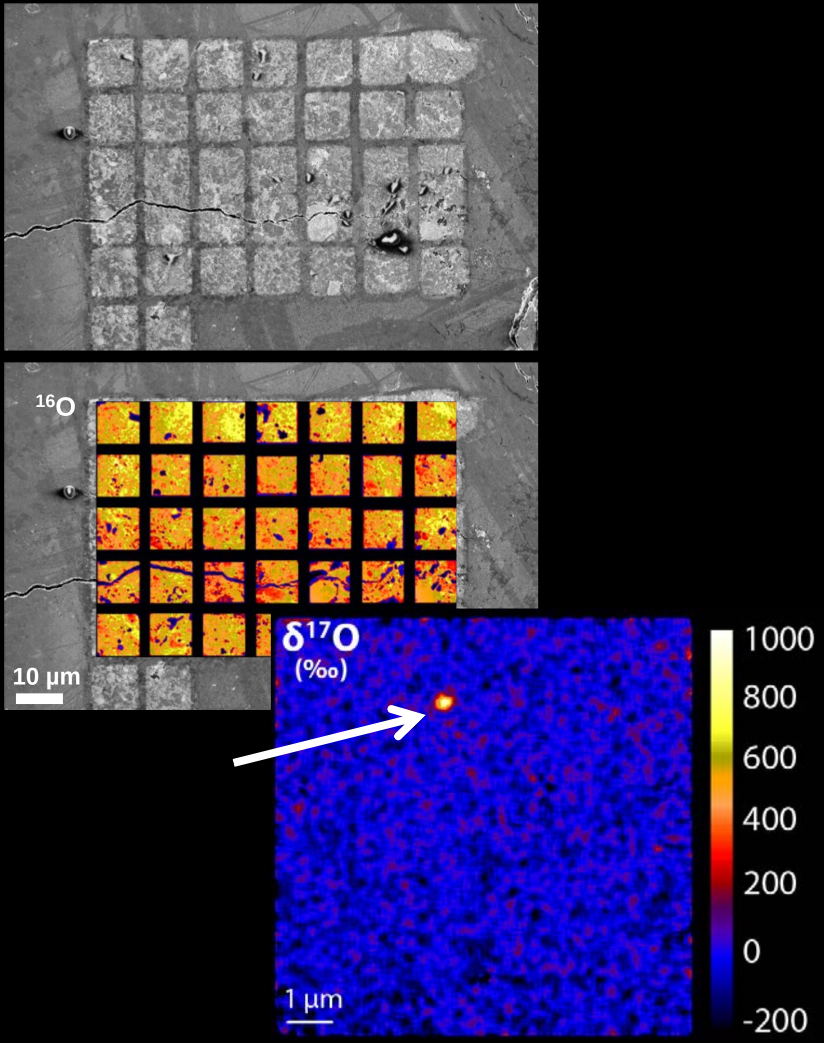
- Acid dissolution

“burning down the haystack”



SIMS

- *In situ* mapping

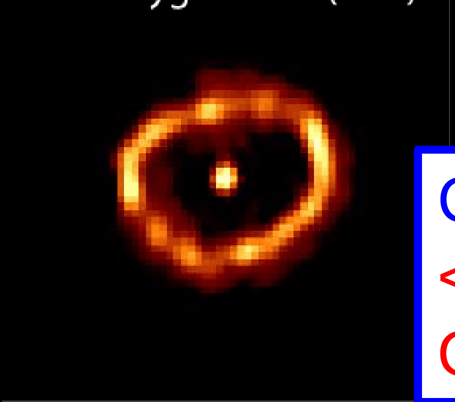


MIL 07687 CR chondrite- J. Davidson

Sources of Presolar Stardust Grains

Asymptotic Giant Branch (AGB) stars:
>90% of SiC, Silicates, Oxides

Type II Supernovae
<10% of SiC, Silicates, Oxides, <50% Graphite, 100% Si_3N_4



Nova Cygni 1992 (HST)

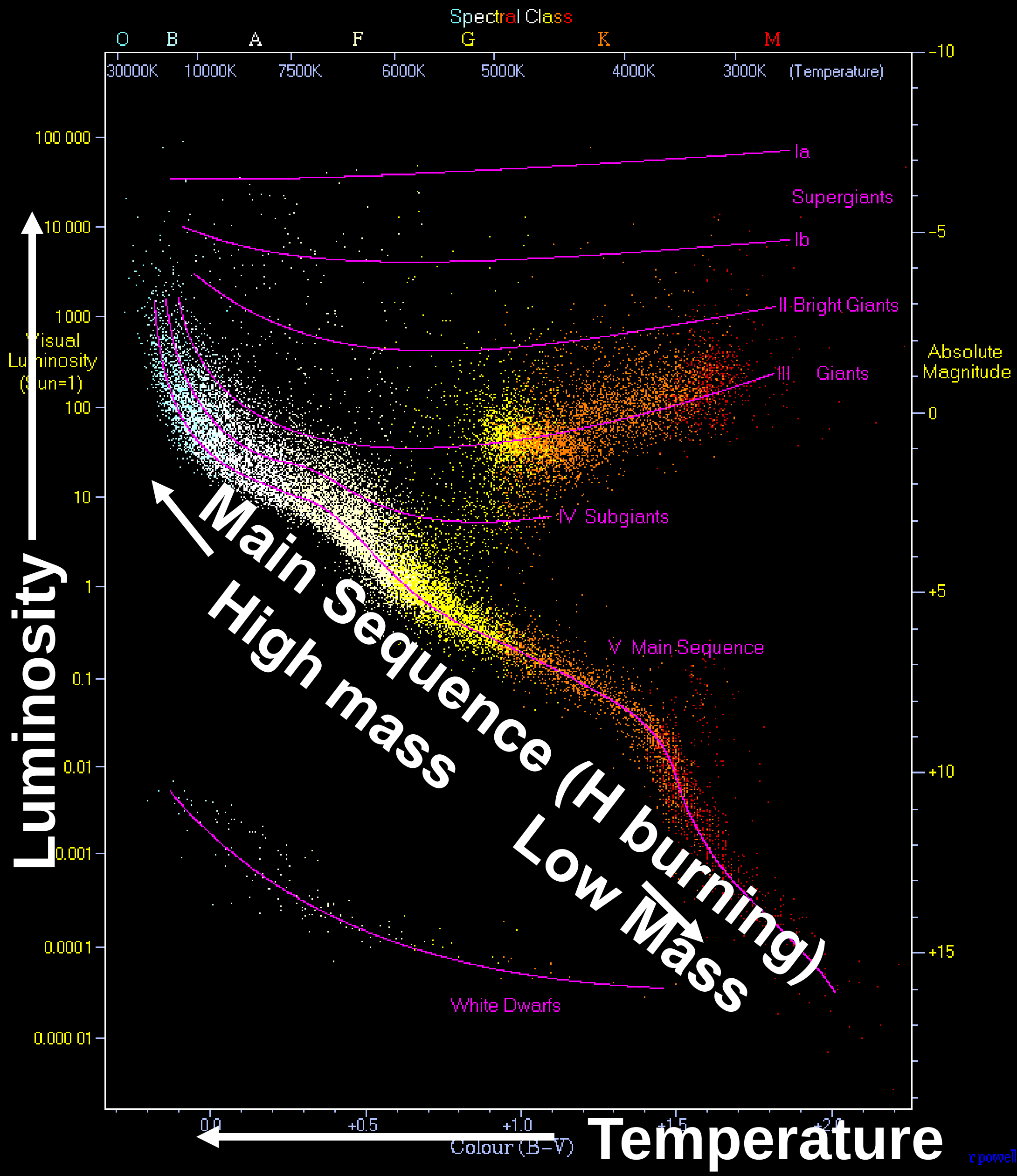
Classical Novae (?)
<1% SiC, Silicates, Oxides, Graphite

Stellar Evolution

- Stars are powered by exothermic nuclear fusion reactions. Gravitational collapse occurs until hot enough for nuclear fuel to burn
  - e.g., 4 ^{1}H -> ^{4}He + 27 MeV
- Energy release from reactions stabilizes star against collapse until fuel exhausted
- Further collapse until heavier fuel ignites
- Repeats until “degeneracy pressure” supports core or no more exothermic reactions possible.

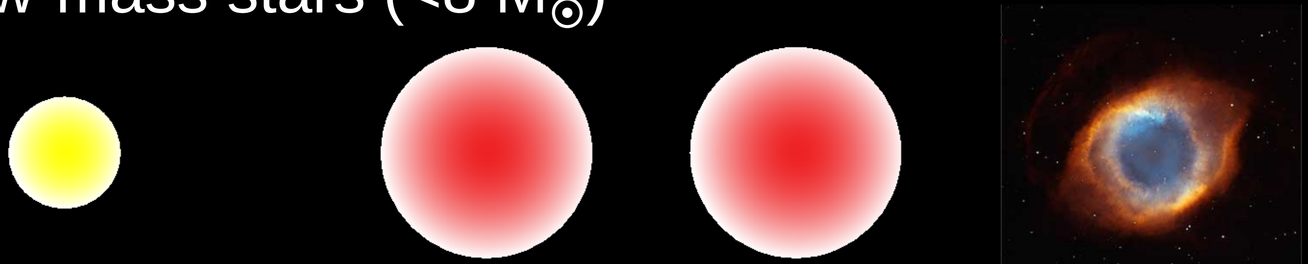
Stellar Evolution

- Stars lie in restricted ranges on Hertzprung-Russell Diagram
  - Diagram reflects mass and evolutionary history of stars
  - Most stars on main sequence (powered by H-burning)
  - $\sim 10^{10} M^{-3}$ yr



Stellar Evolution

Low-mass stars (<8 $M_\odot$)



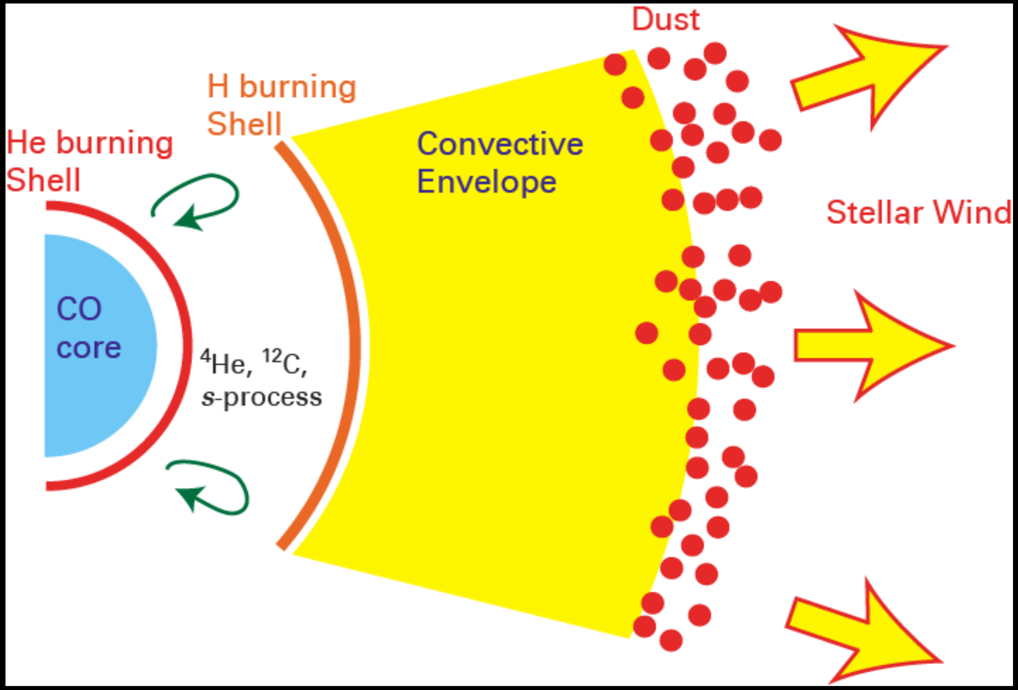
“Main Sequence”
H → He

Red Giant
He → C

AGB Star
He → C

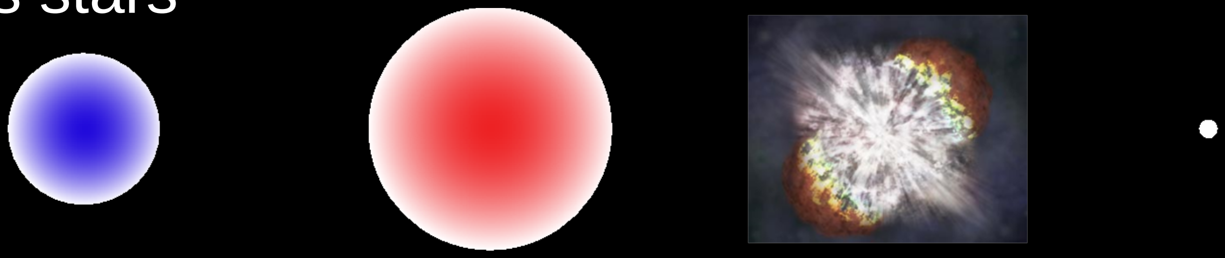
Planetary Nebula

Schematic Structure of an AGB star



Stellar Evolution

Massive stars (>10 $M_\odot$) burn hotter and faster then lower mass stars



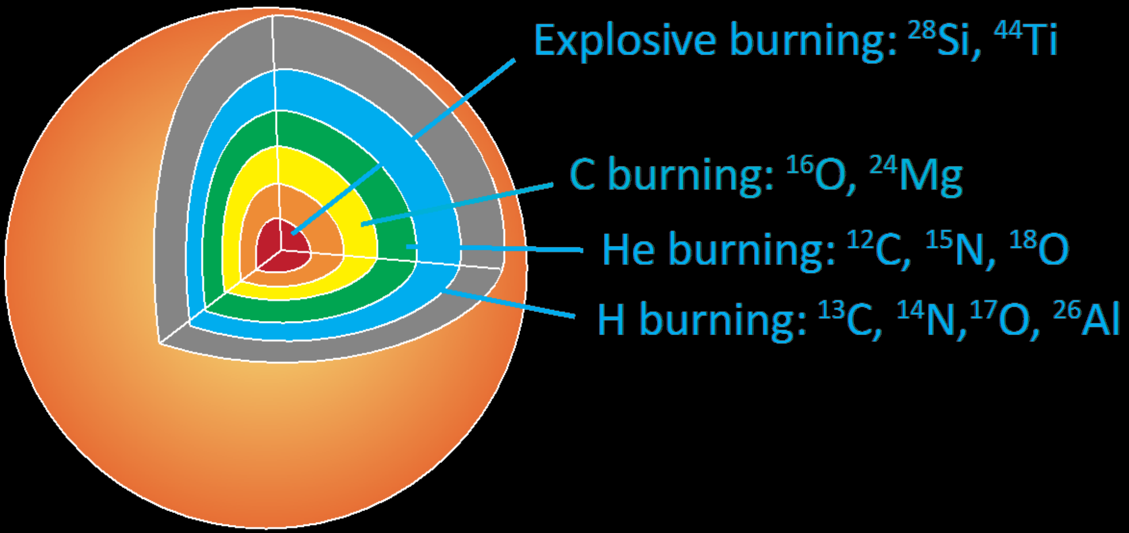
“Main Sequence”
$H \rightarrow He$

Red Supergiant
$He \rightarrow C \rightarrow O \rightarrow Mg \rightarrow Si \rightarrow Fe$

Supernova

Neutron Star
or Black Hole

Schematic structure of a pre-supernova massive star

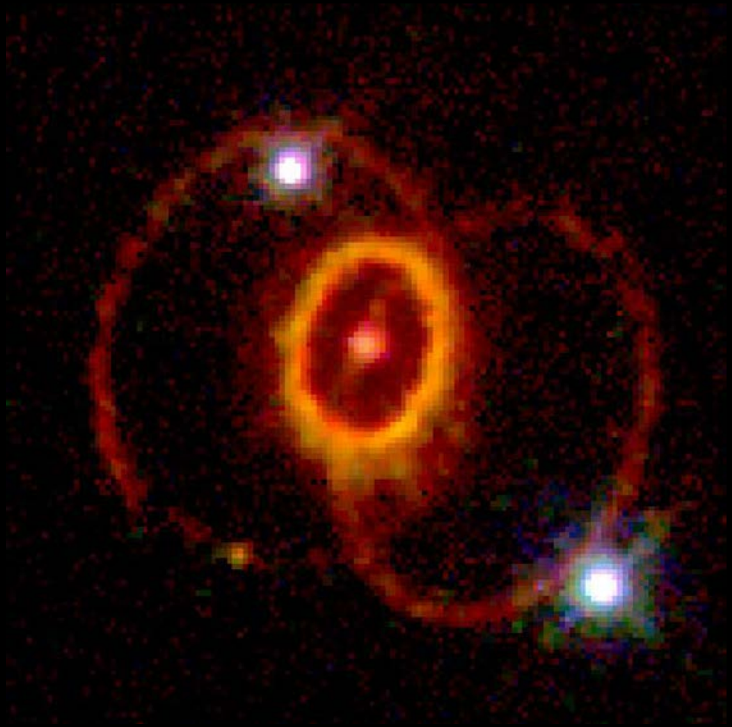


Type II Supernovae

SN 1987A before
and after

- Enormous explosions of stars (~10^{46} J)

Type II Supernovae

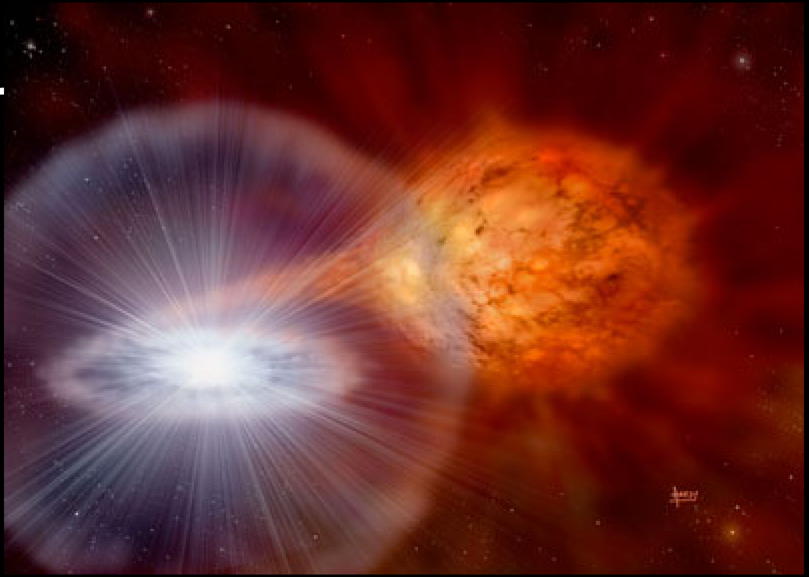


SN 1987A in 1994

- Enormous explosions of stars
- Nuclear factories (main sources of many elements)

Stellar Evolution – close binaries

- More massive star evolves to WD; accretes matter from companion



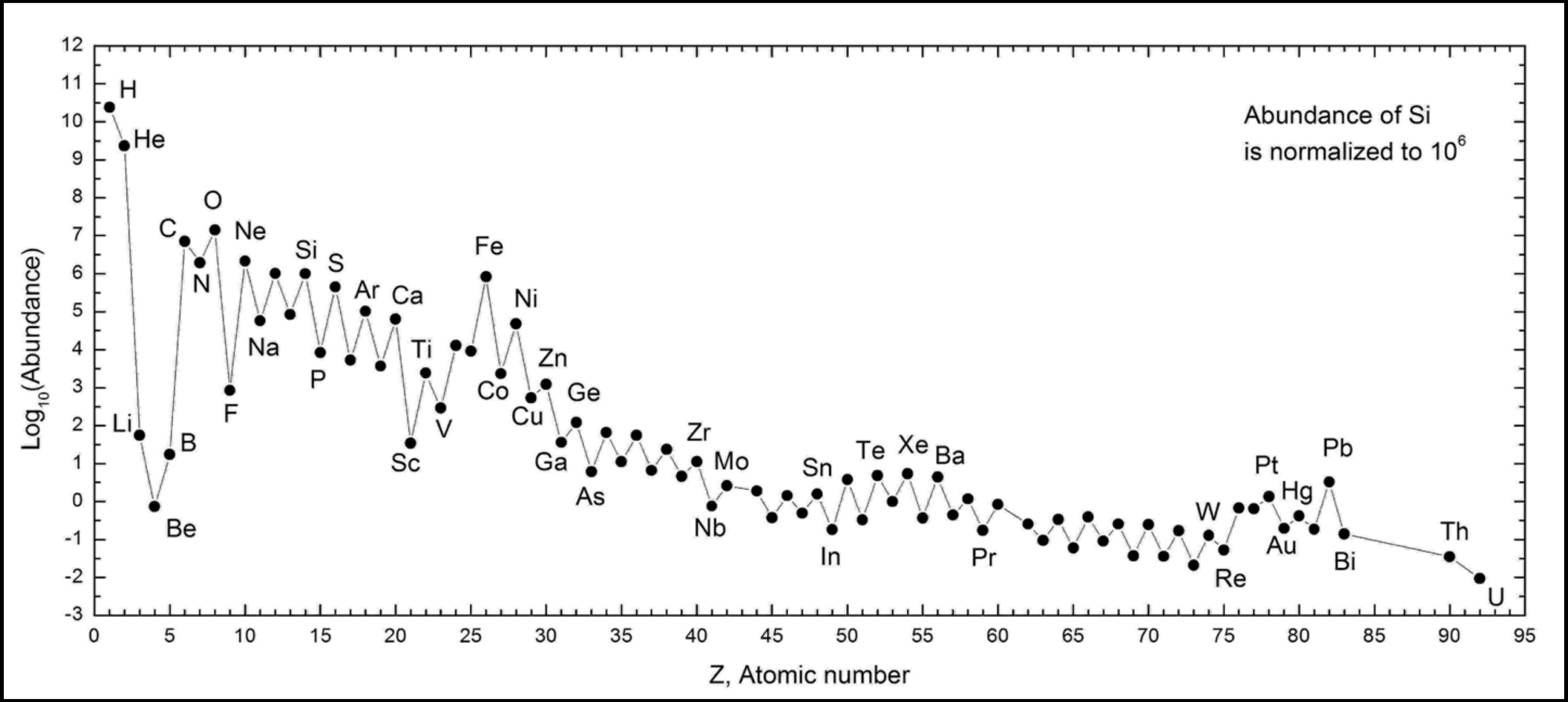
Type Ia SN

- WD explodes, leaving neutron star
  - ~10^{44} J
- Produce mostly Fe

Classical Nova

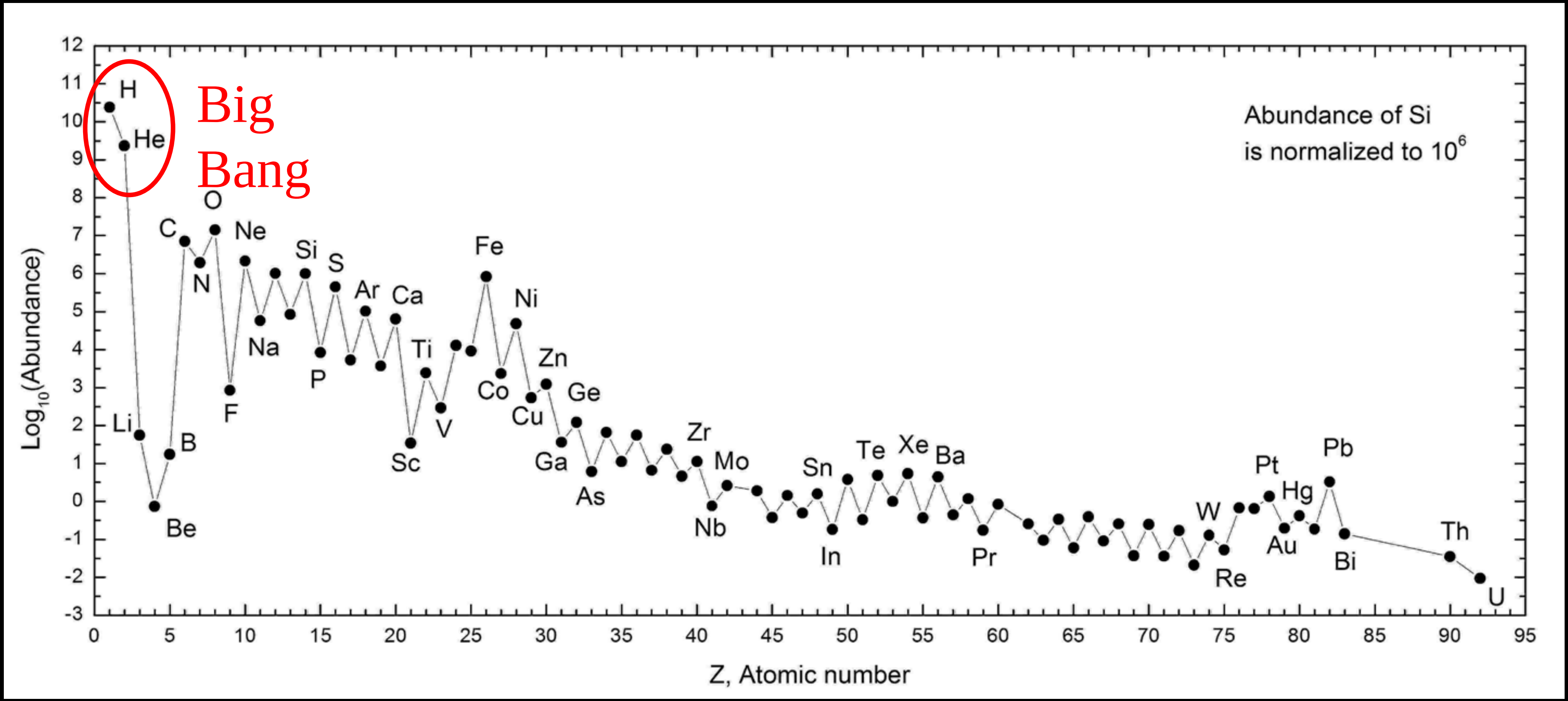
- Accreted H explodes
  - ~10^{37} J
- Recurrent explosions

Nucleosynthesis



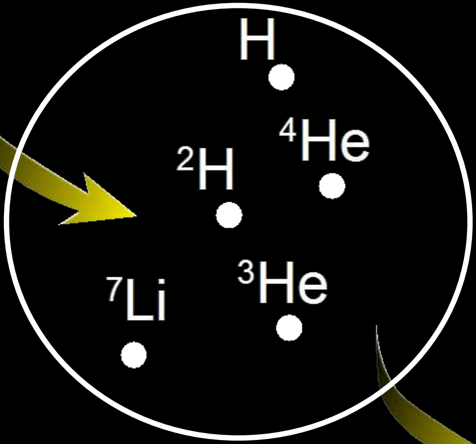
- Solar abundance pattern:
  - Regularities reflect nuclear properties
  - Several different processes
  - Mixture of material from many, many stars

Nucleosynthesis

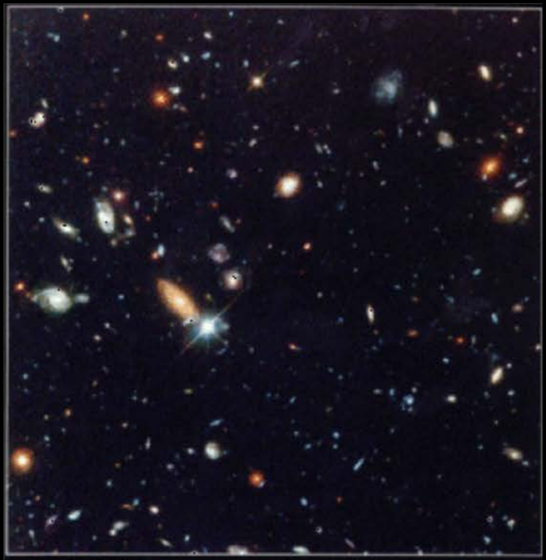


Big Bang

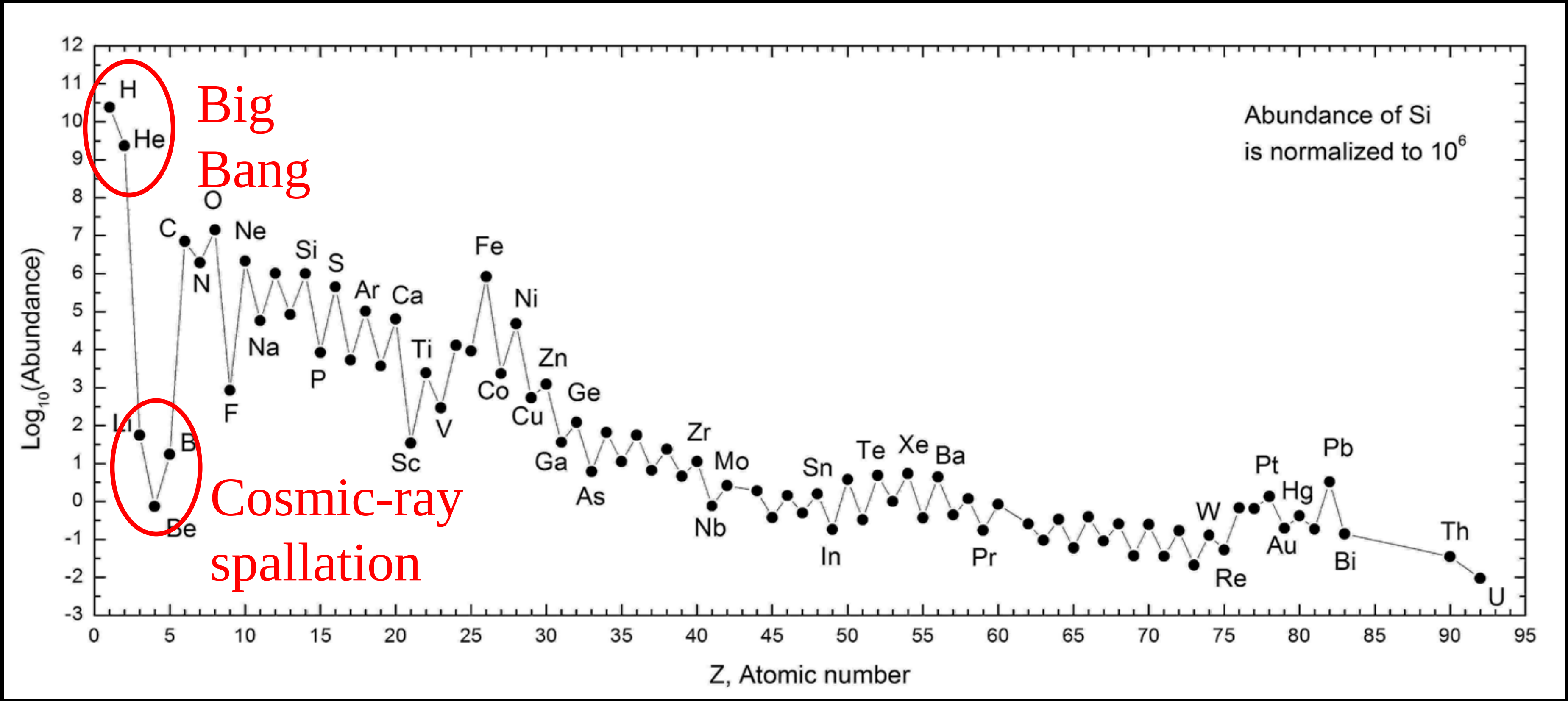
BBN (~5 min.)



Stars/Galaxies
(>~400 Myr)



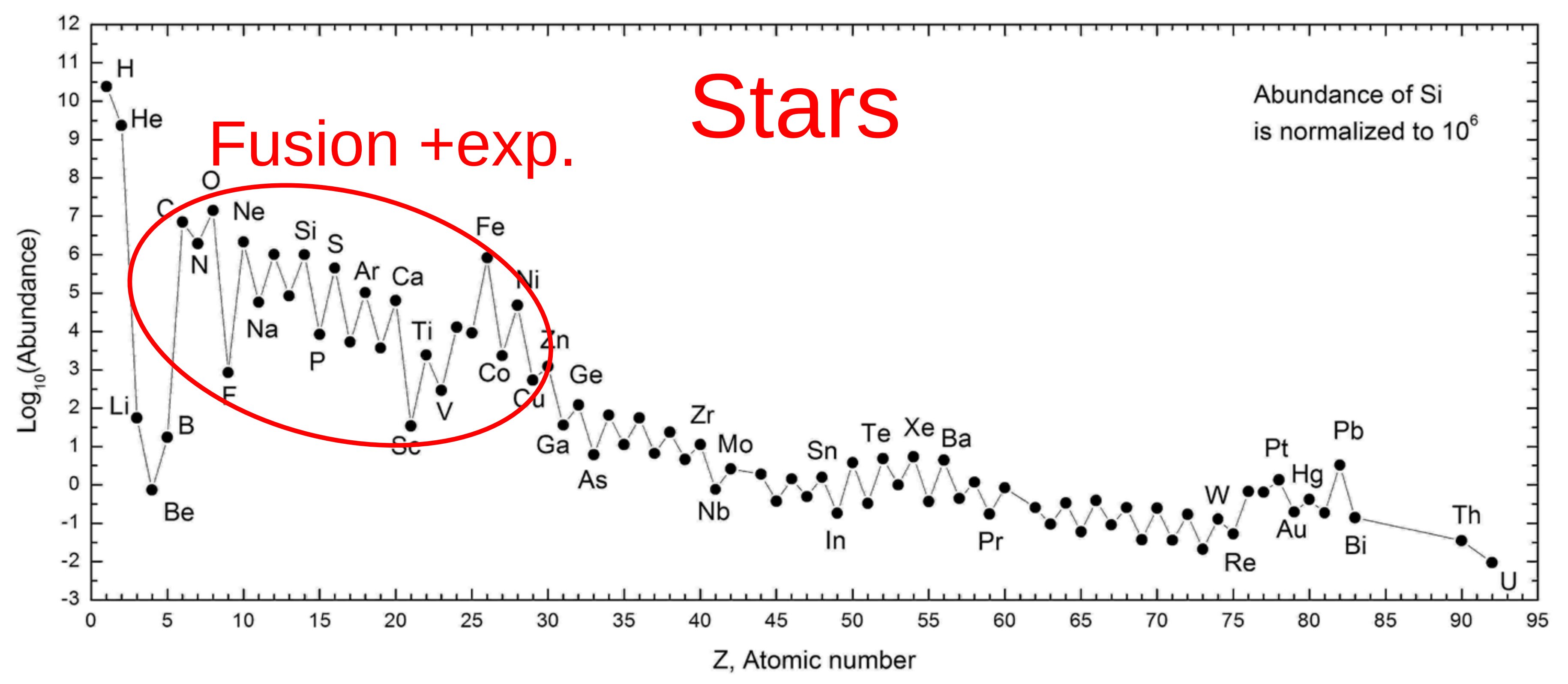
Nucleosynthesis



Big Bang

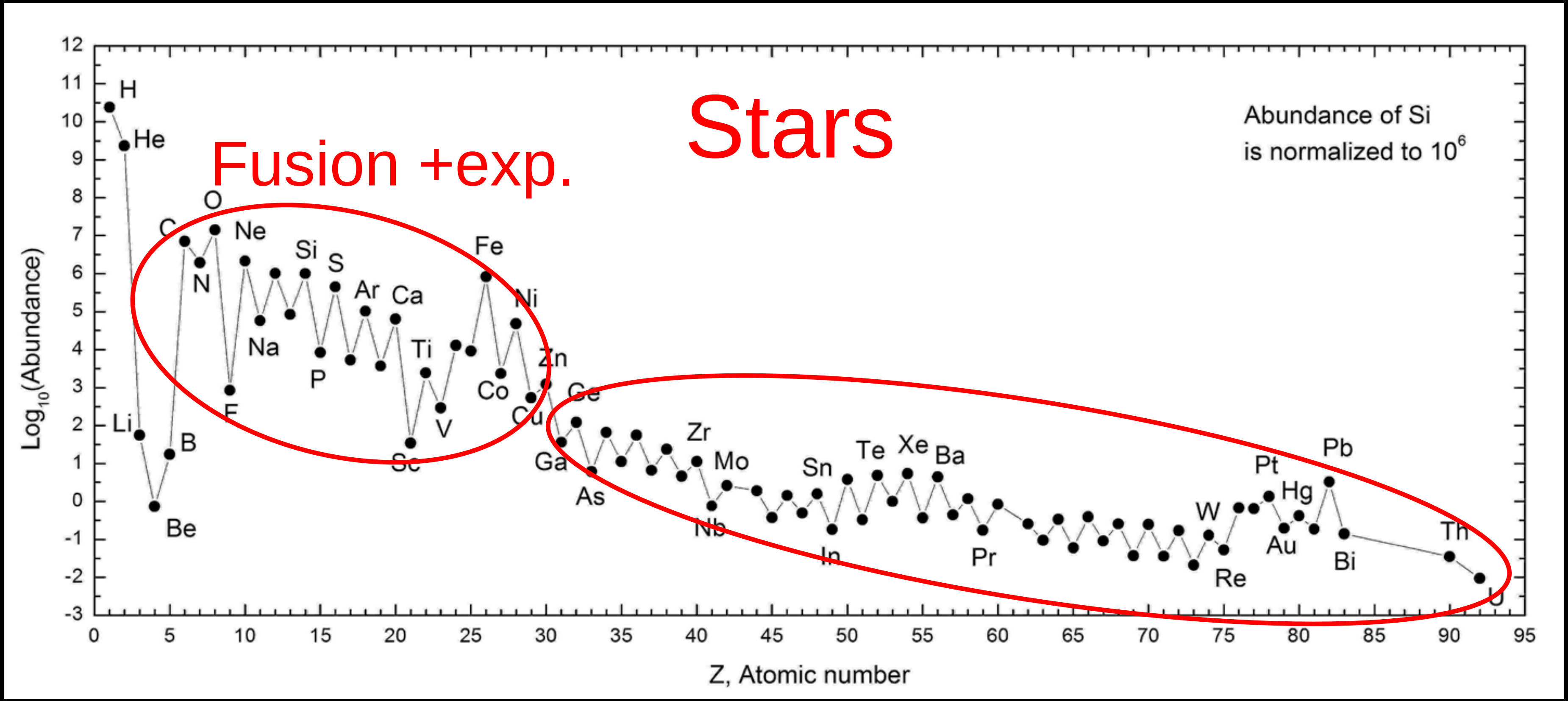
Cosmic-ray spallation

Nucleosynthesis



- Above Fe, cannot produce energy by fusion

Nucleosynthesis



Stars

Fusion +exp.

Neutron capture (s-, r-processes)

"p-process"

Neutron capture

s-process

- n-captures “slow” relative to β-decay
- Mostly from AGB stars, some from SNe

r-process

- Many n-captures between β-decays
- Astrophysical site(s) unknown but colliding neutron stars is current favorite

p-process

- Proton-rich nuclei of heavy elements originally thought to be made by proton capture, now believed to be both γ-process (photodisintegration of heavy elements) and ν-process (neutrino inetractions)

r/s deconvolution

- Many isotopes are made by both *r* and *s* processes
- Solar abundances deconvolved into *r* and *s* patterns based on theoretical understanding of *s*-process (starting in 1950s)
- For decades, s- and *r*-process patterns were purely mathematical constructs

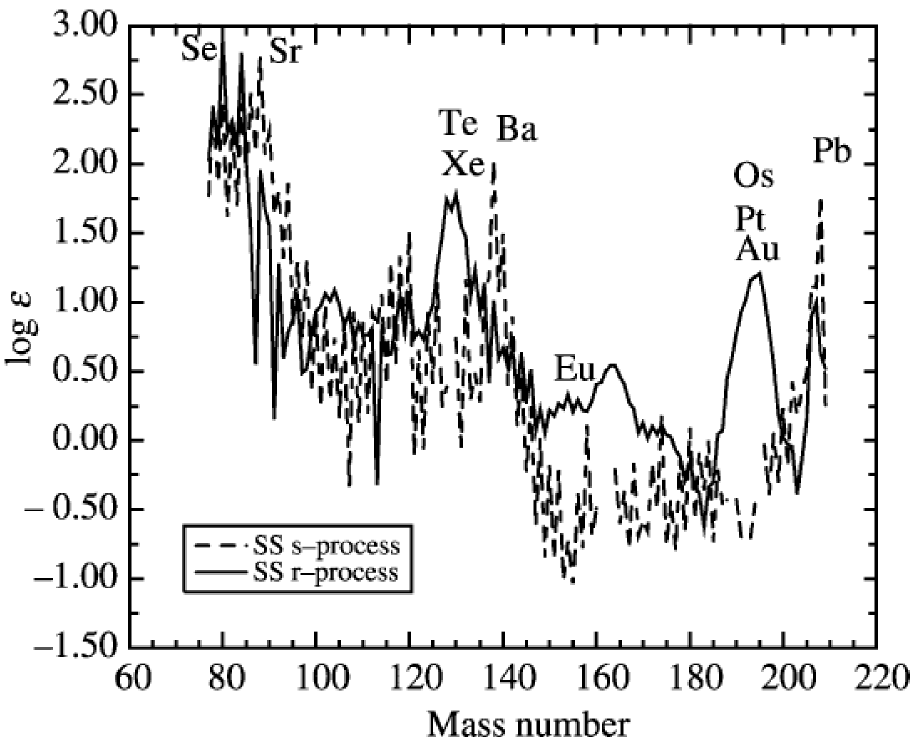
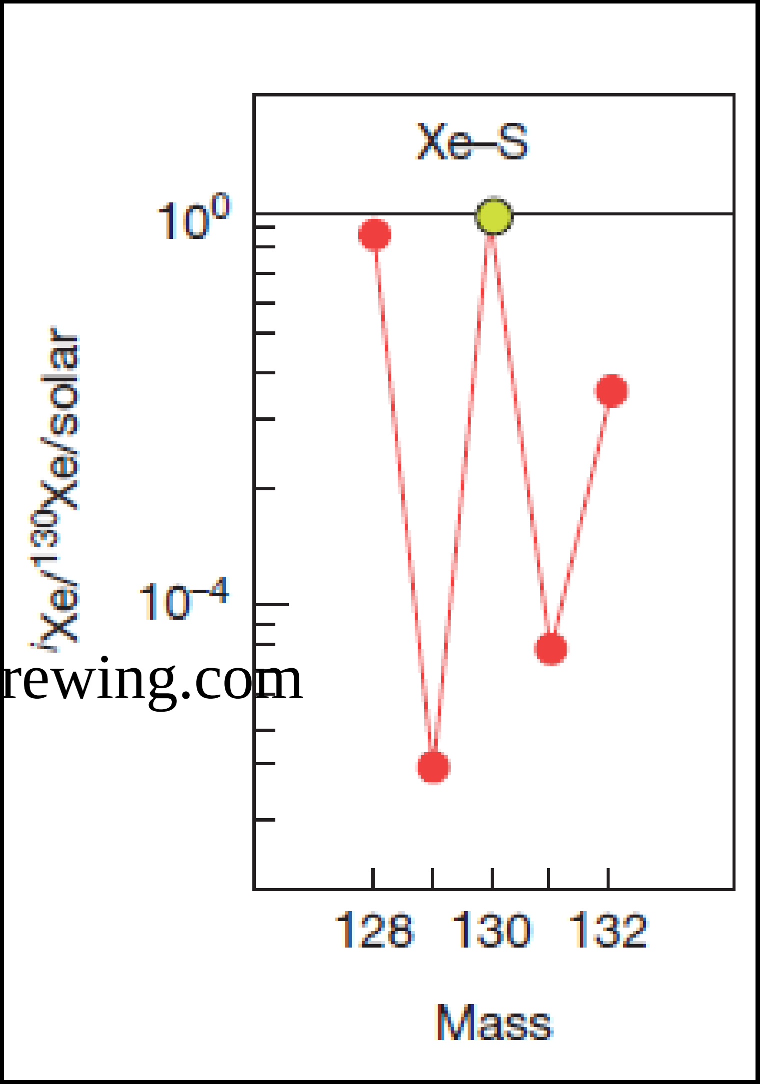


Figure 2 The s-process and r-process abundances in solar system matter (based upon the work by Käppeler *et al*., 1989). Note the distinctive s-process signature at

r/s deconvolution

- Many isotopes are made by both *r* and *s* processes
- Solar abundances deconvolved into *r* and *s* patterns based on theoretical understanding of *s*-process (starting in 1950s)
- For decades, s- and *r*-process patterns were purely mathematical constructs

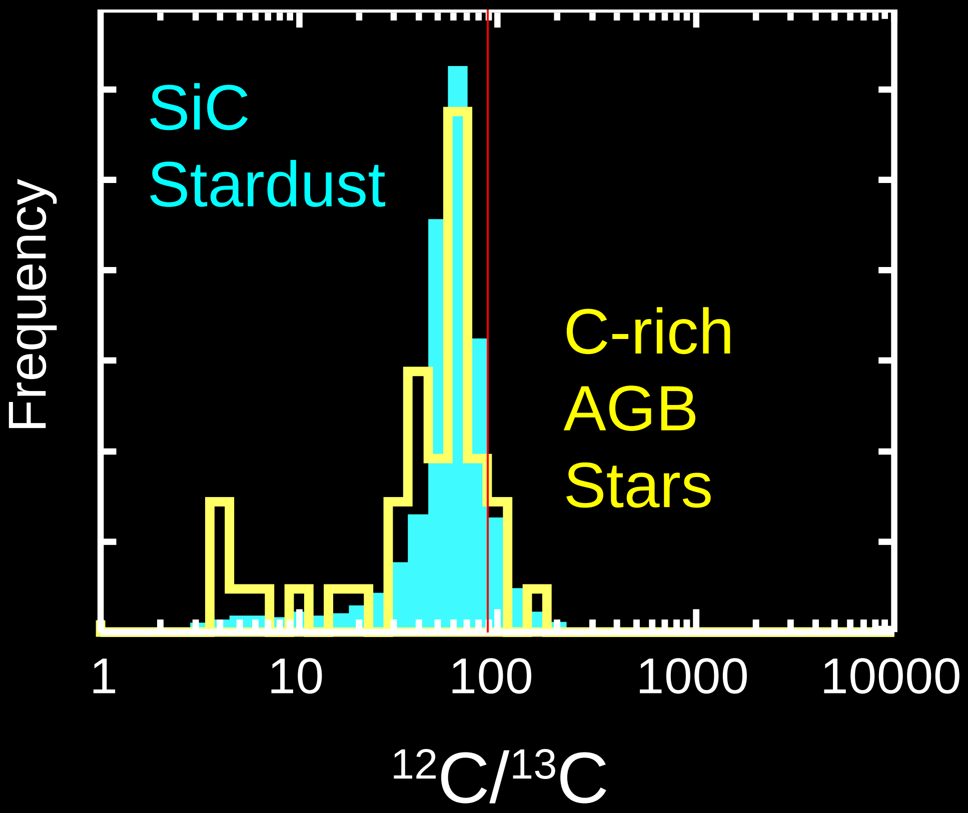


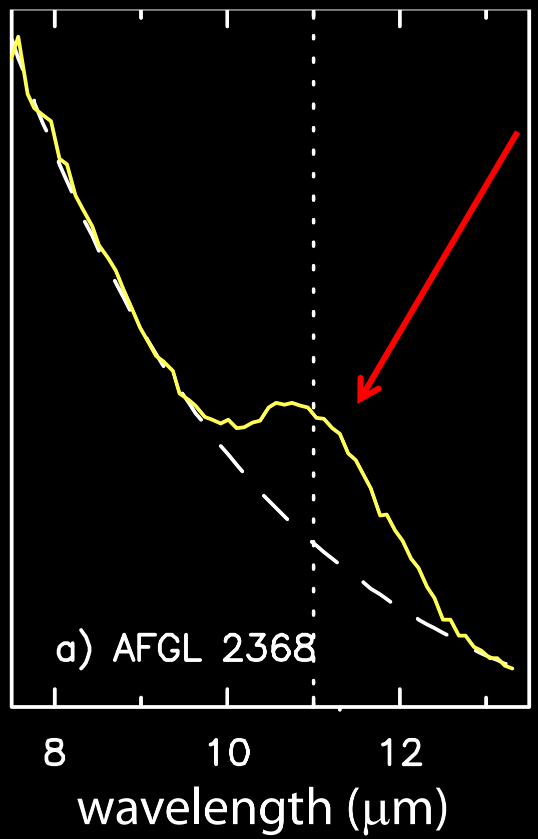
Pure s-process Xe in presolar SiC!

Origins of Presolar Grains

- Iterative approach:
  - Compare compositions with astronomical data, theory to try to identify stellar source type (e.g. AGB vs supernova)
  - Once source is identified, take advantage of unique information obtained from lab measurements to test models, etc.
- Example: Silicon Carbide (SiC)

AGB star origin of most presolar SiC

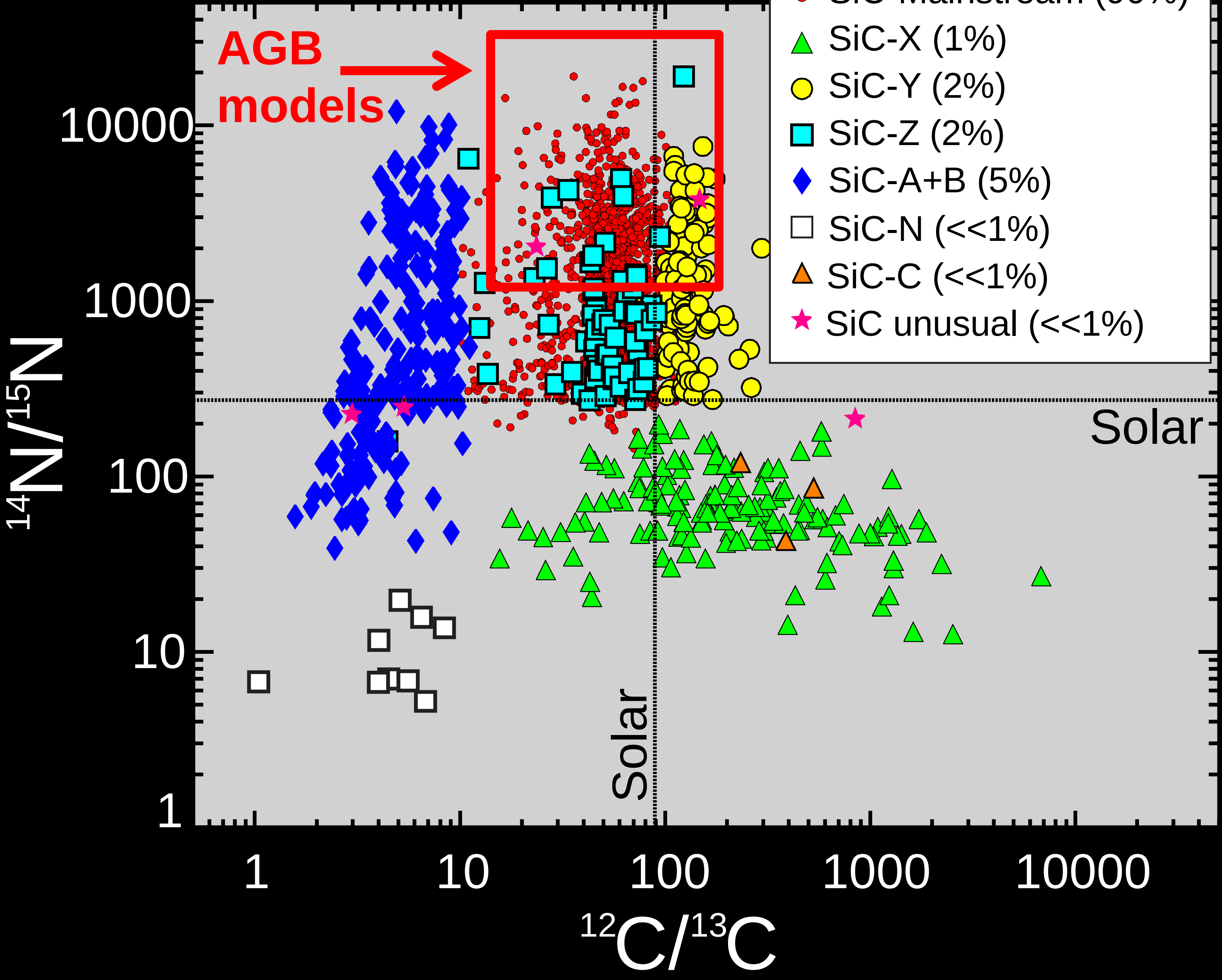




Carbon isotopes match AGB stars, ^{13}C rich and ^{15}N-poor from mixing of H-burnt ashes into envelope

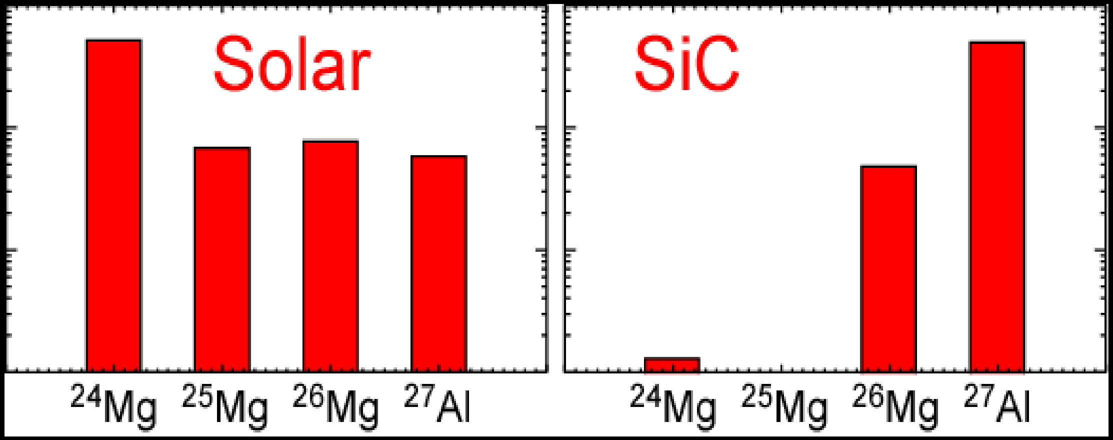
Infrared emission feature from SiC in AGB star (Speck et al., 2005)

SiC Grains

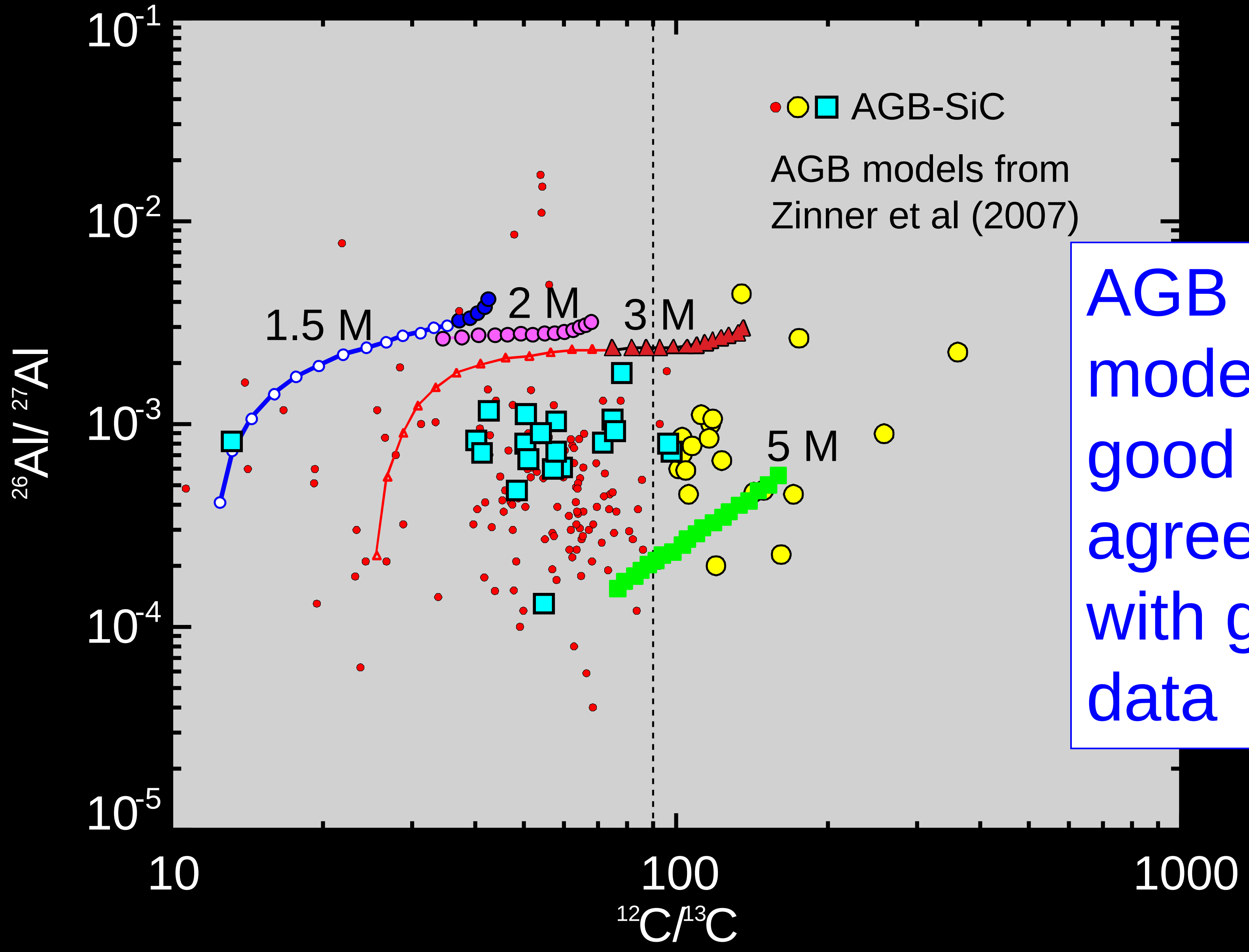

AGB models
SiC-Mainstream (90%)
SiC-X (1%)
SiC-Y (2%)
SiC-Z (2%)
SiC-A+B (5%)
SiC-N (<<1%)
SiC-C (<<1%)
SiC unusual (<<1%)
Solar
Solar
$^{14}N/^{15}N$
10000
1000
100
10
1
$^{12}C/^{13}C$
1
10
100
1000
10000

Extinct Radioactivities

- Recognized by excesses in daughter products
  - Crucial for Early SS chronology (Gounelle lecture)
- E.g., ^{26}Al:
  - half-life = 720,000 years
  - Produced in variety of stars (including AGB)
  - Observed in Galaxy by γ-ray emission
  - Observed as nuclear “fossil” in meteorites and presolar grains (^{26}Mg excess)



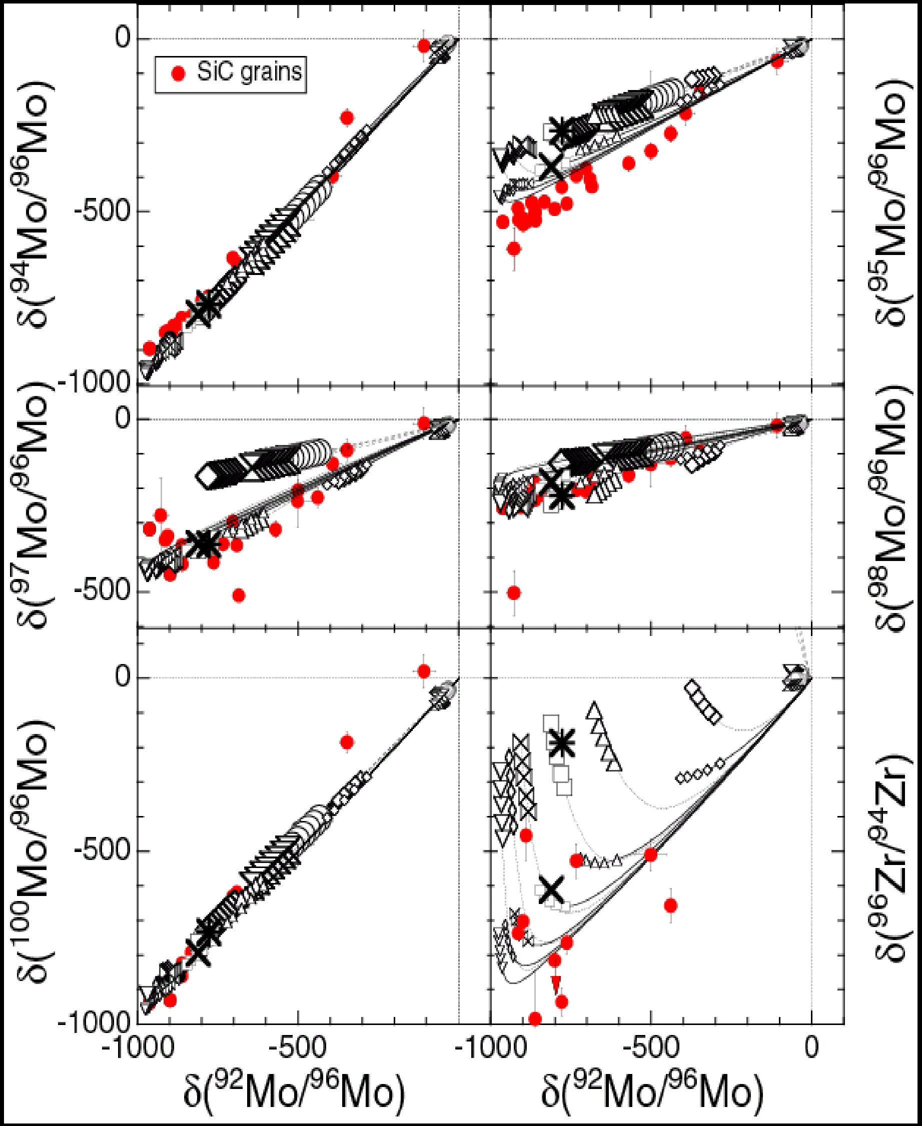
^{26}Al in presolar SiC



AGB models in good agreement with grain data

AGB presolar SiC

- Heavy elements in SiC stardust reflect *s*-process
  - *Confirm* AGB source
  - *Confirm* existence of *s*-process
  - *Constrain* models
  - *Suggest* errors in nuclear data



Data from Argonne/Chicago group, Models from Torino group

AGB origin of most presolar SiC

- Heavy elements in SiC stardust reflect *s*-process
  - *Confirm* AGB source
  - *Confirm* existence of *s*-process
  - *Constrain* models
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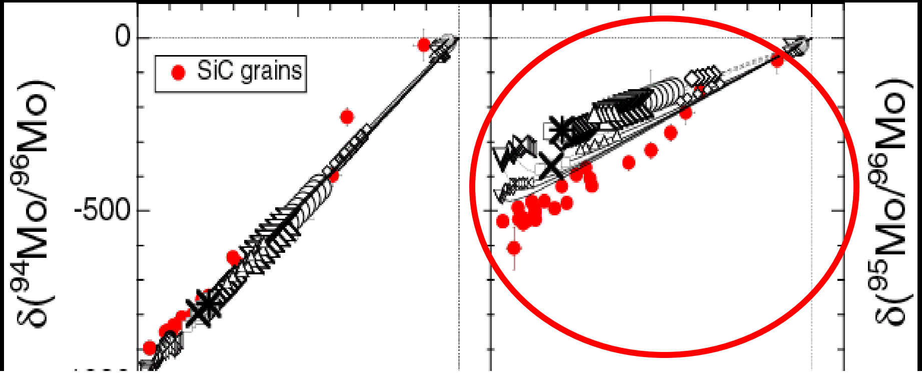

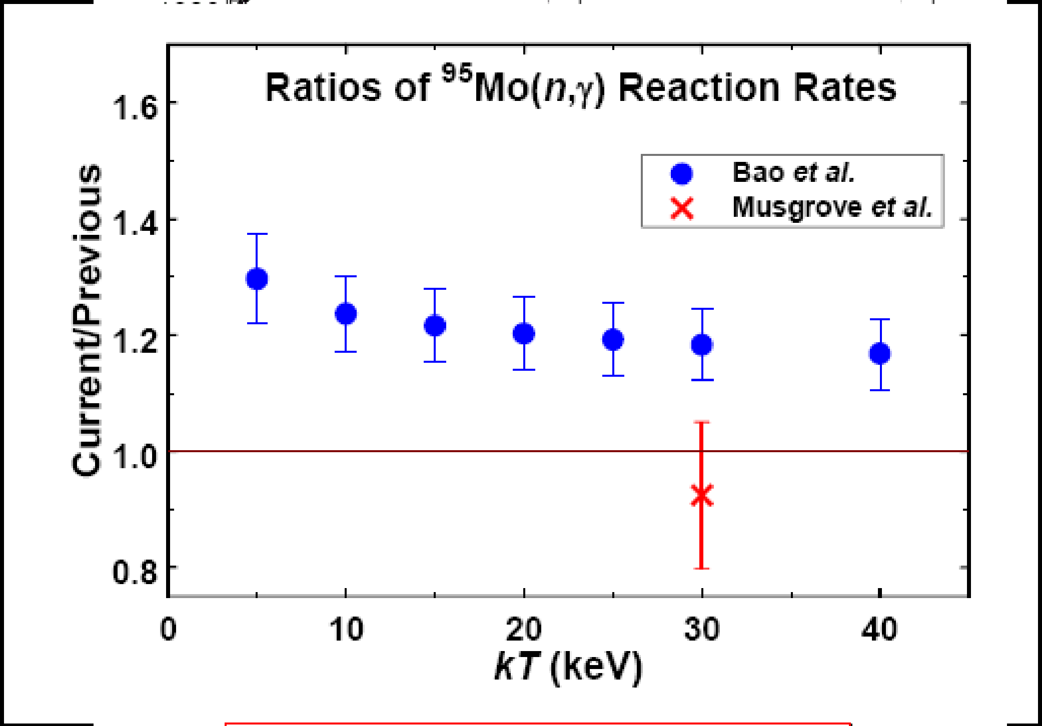

Koehler et al. (2008)

up,

Models from Torino group

Pristine nature of presolar grains makes them useful probes of:

- Cosmology
- Stellar nucleosynthesis
- Stellar evolution and mixing
- Galactic chemical evolution
- Dust formation in stellar environments
- Dust processing in the interstellar medium
- Sources of material for Solar System
- Early Solar System processes