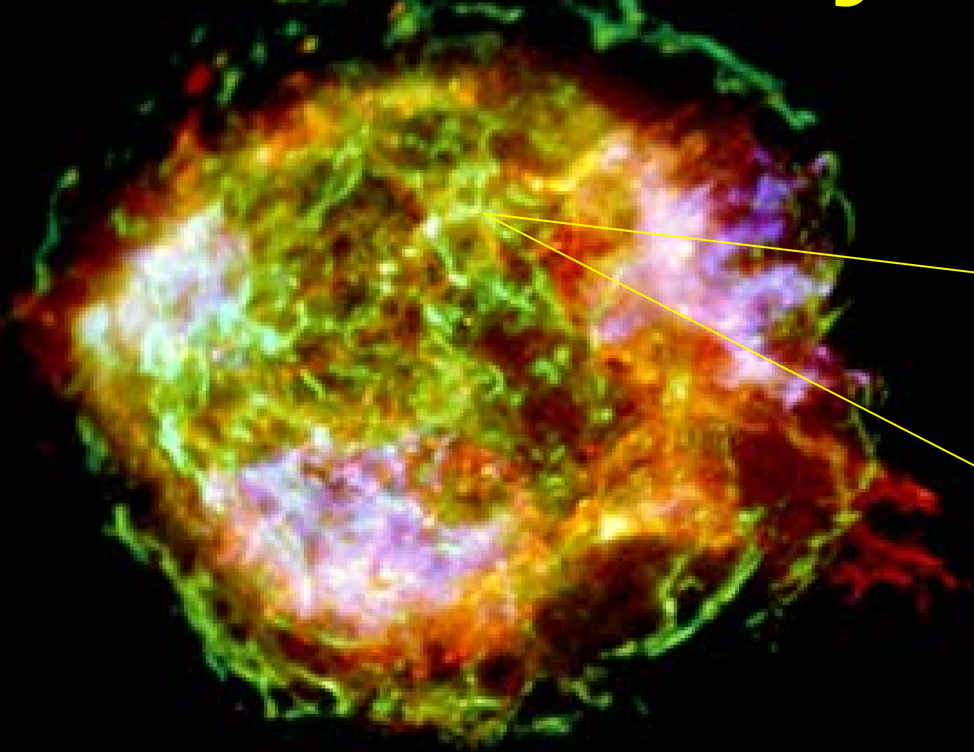
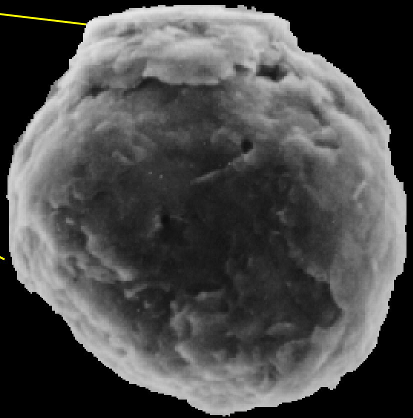
Supernova Dust in the Solar System



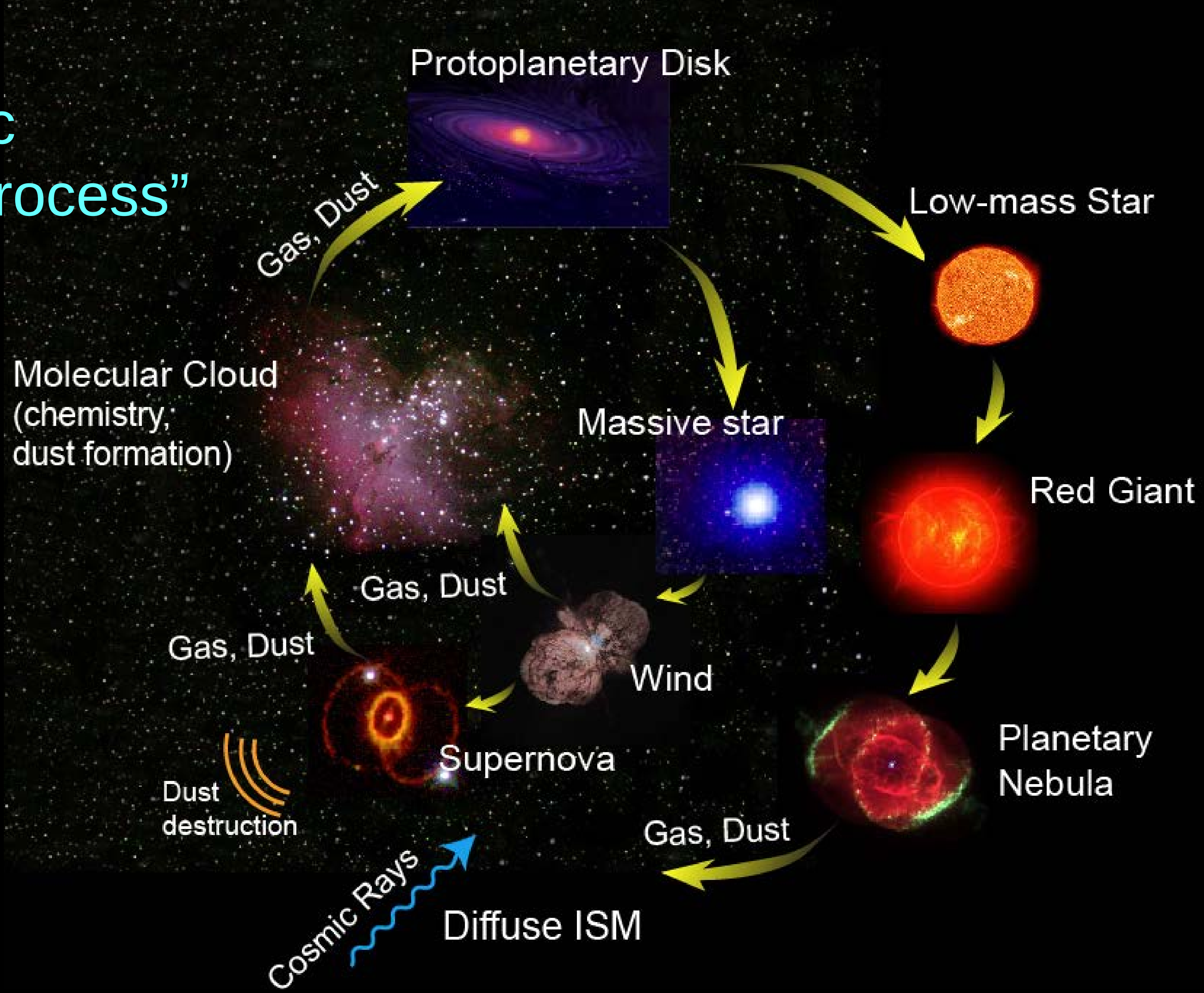


Larry R. Nittler
Earth and Planets Laboratory
Carnegie Institution of Washington

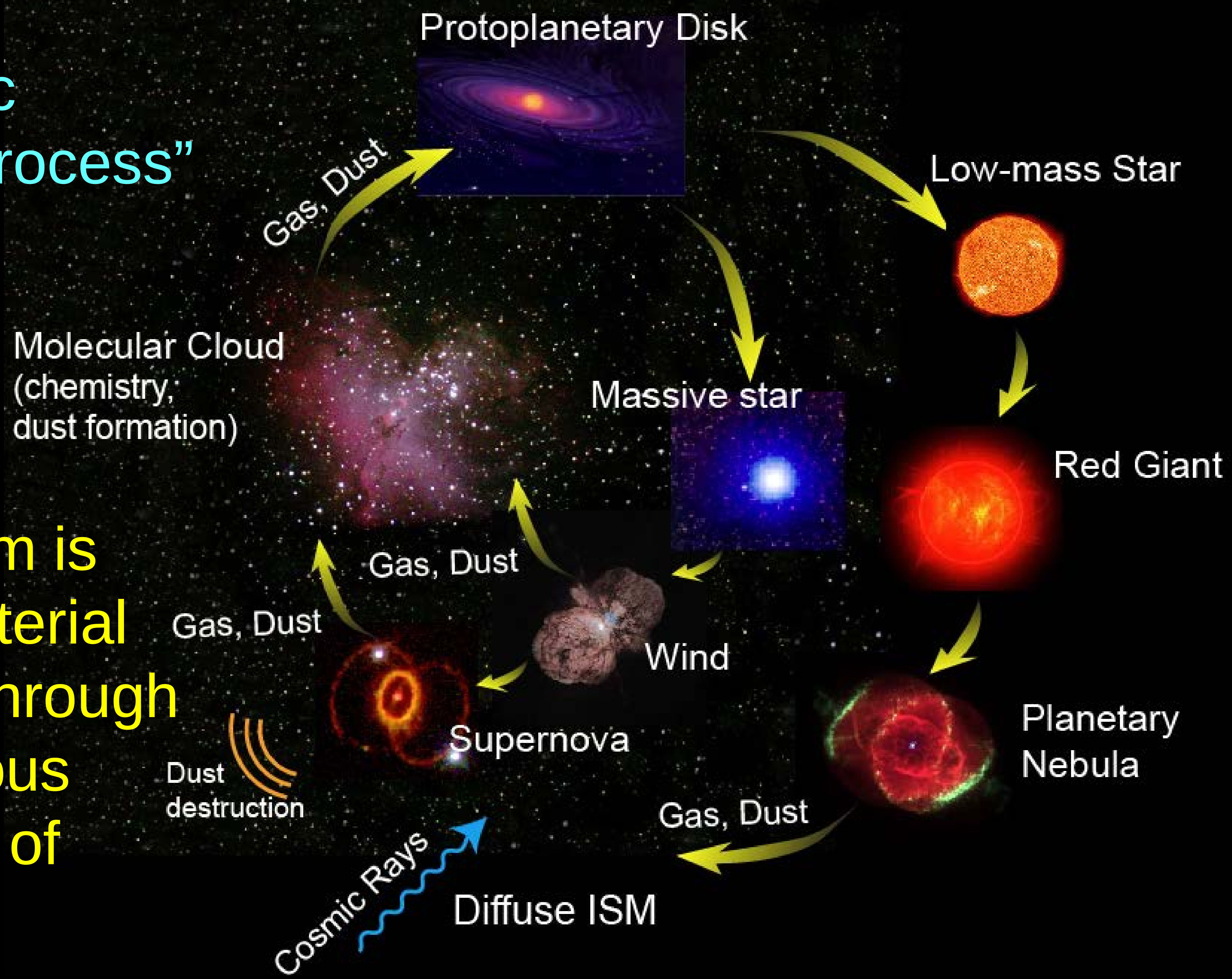
@LarryNittler

APS Mid-Atlantic Senior Physicists Group March 24, 2021

“The Cosmic Recycling Process”



“The Cosmic Recycling Process”



Solar System is made of material processed through many previous generations of stars

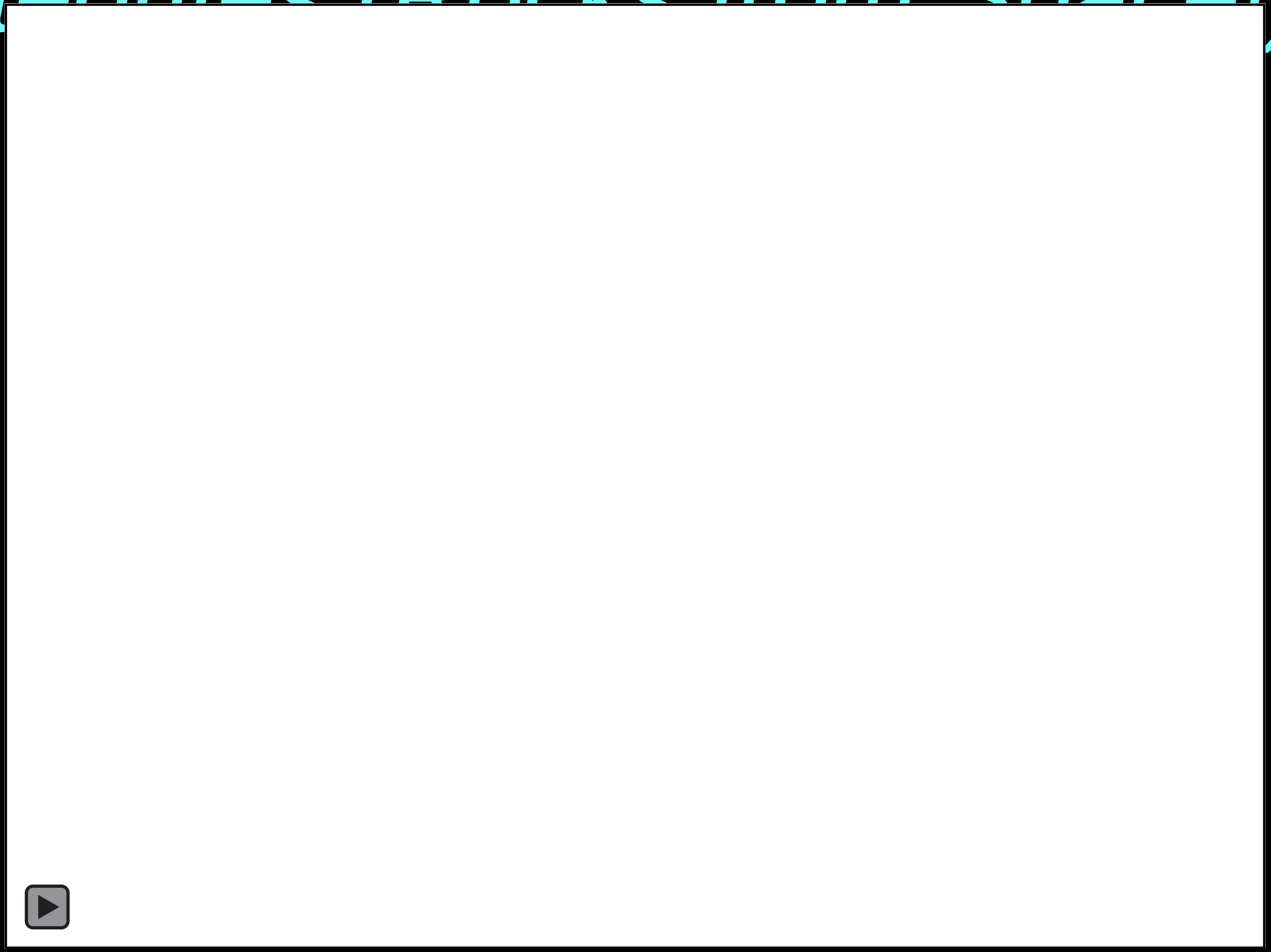
The Solar System 4.6 billion years ago

Most original materials processed in disk

Asteroids and comets are leftovers from planet formation; preserve record of earliest materials and conditions

We get samples of asteroids via meteorite falls!

Meteorites (Rocks from Space!)

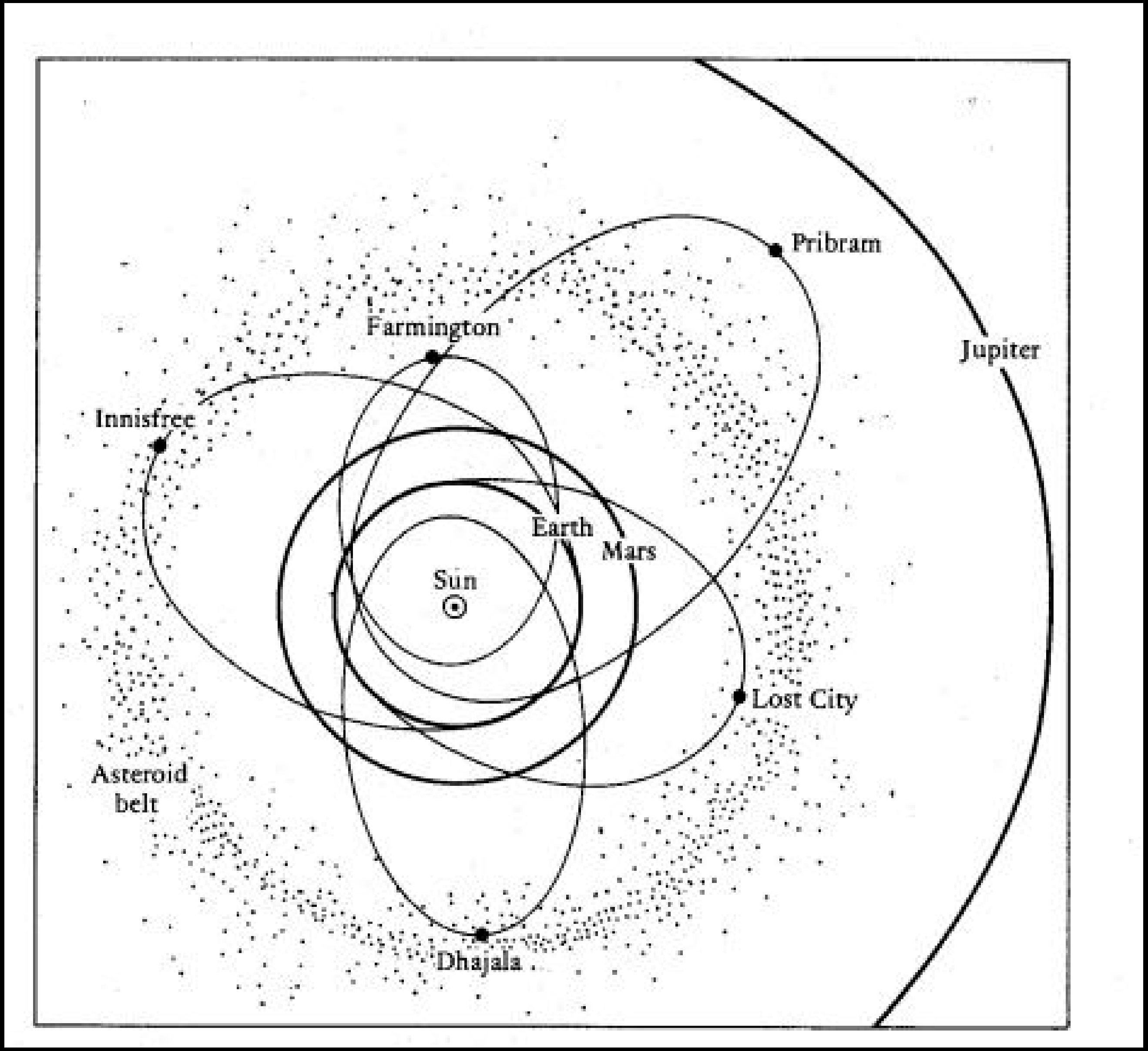


Peekskill, New York, October 9, 1992

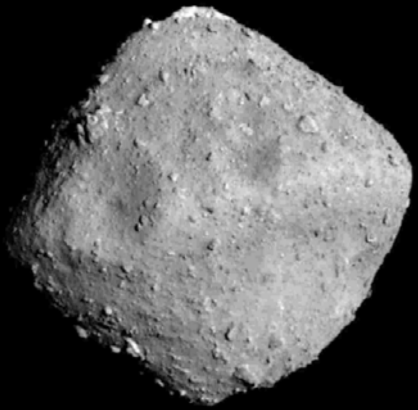
Where are they found?

- All over the Earth, but deserts best due to long lifetimes against weathering

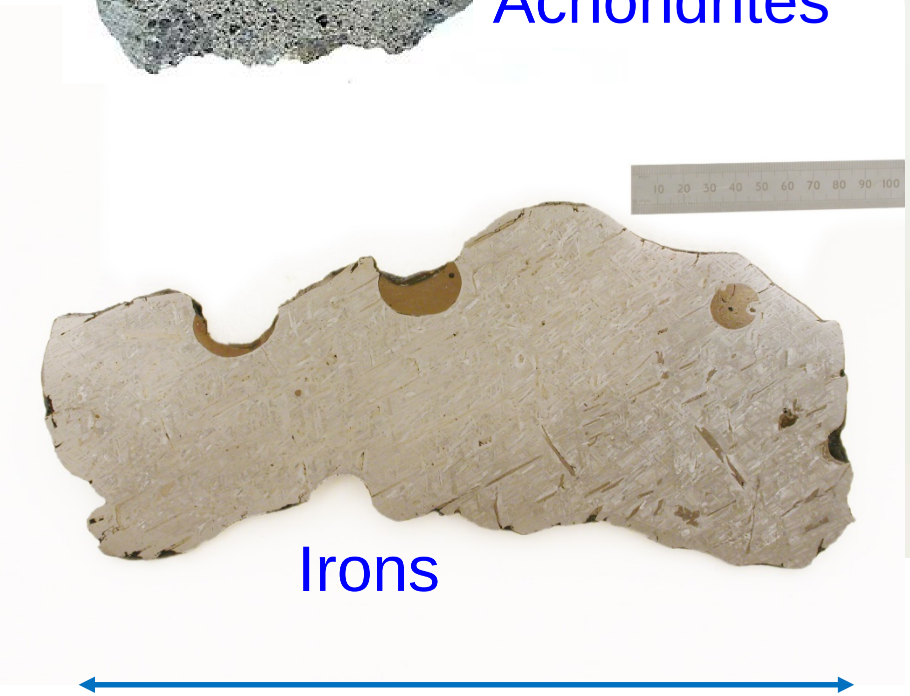
Where are they from?

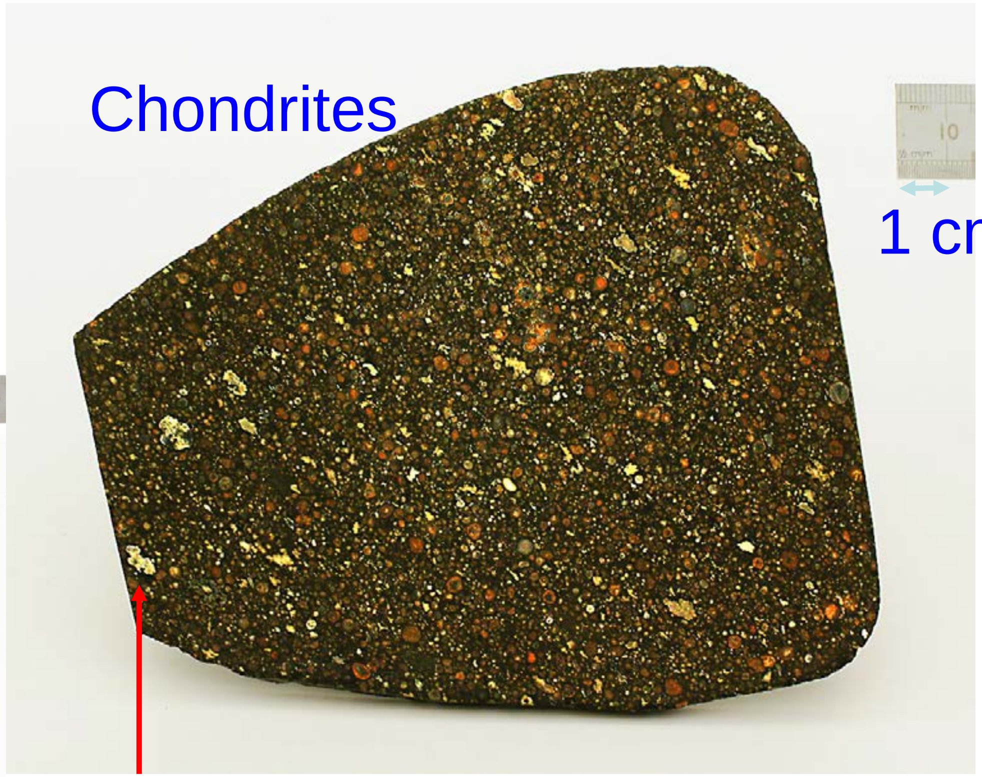


Asteroids!



Recorders of first few million years (Ma)



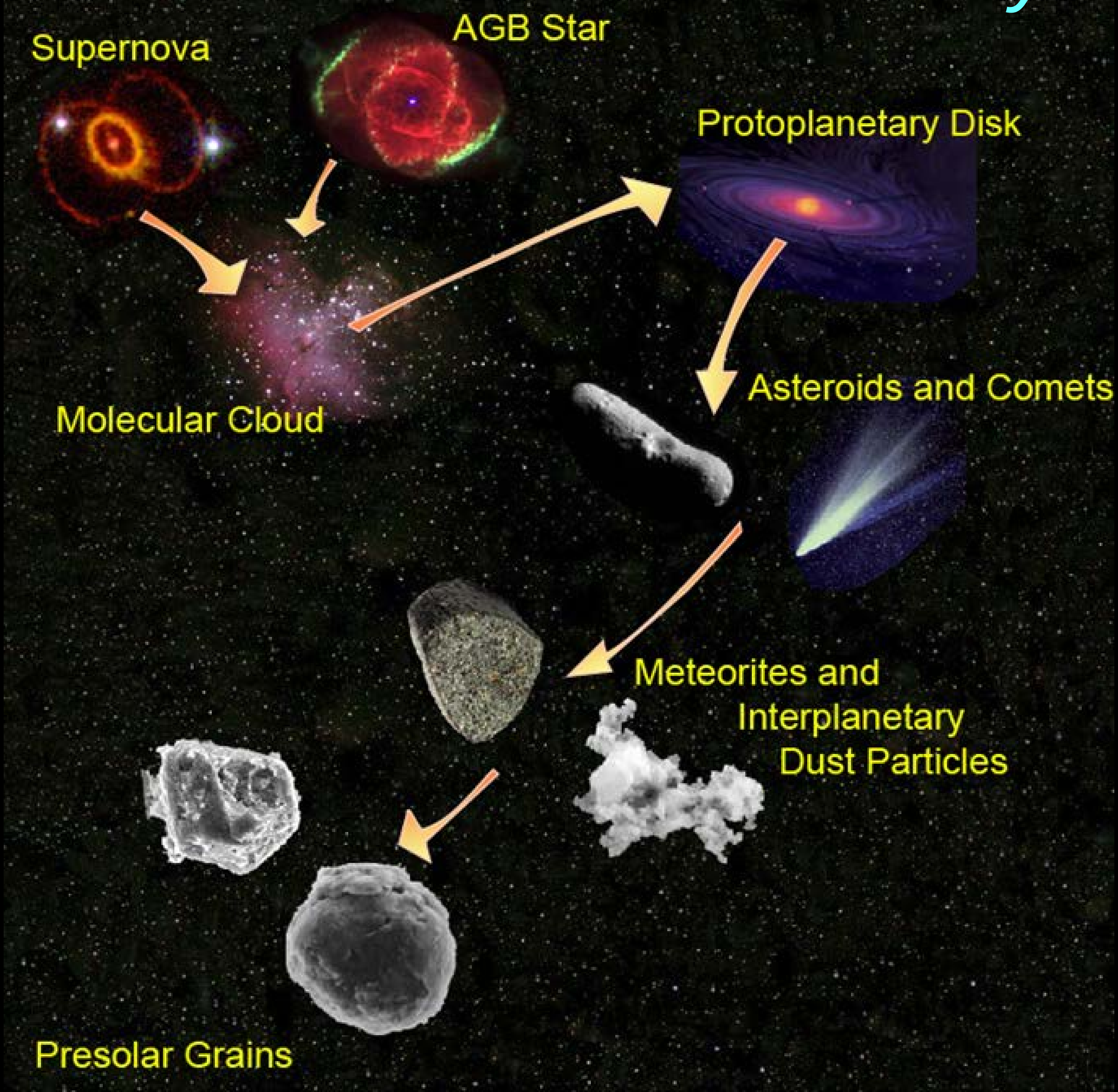


4,567.3±0.2 million years old

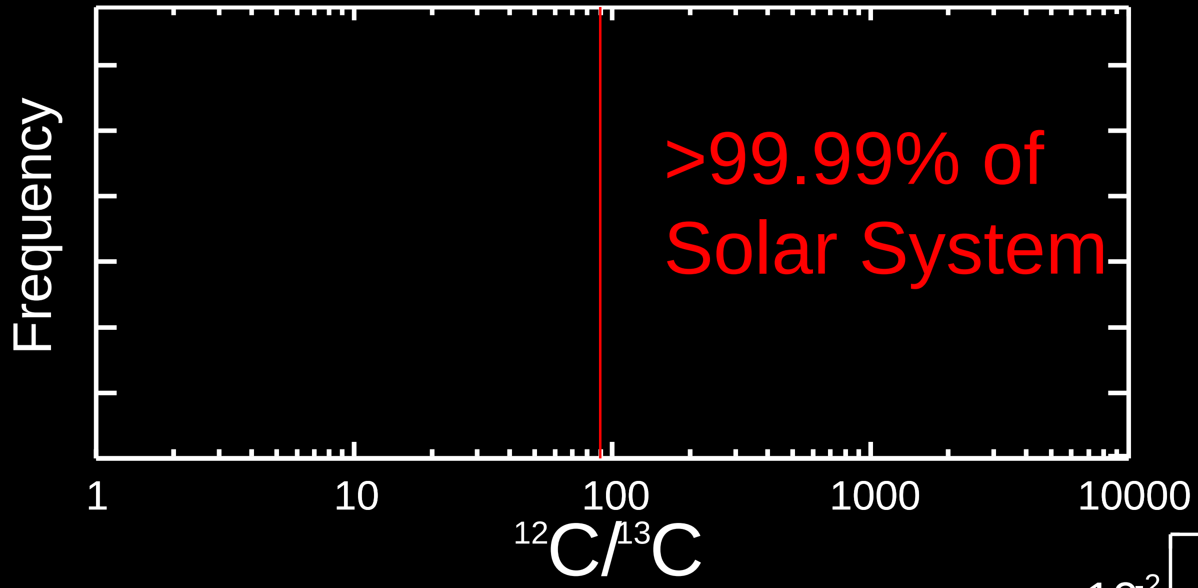
Formed in <2 Ma

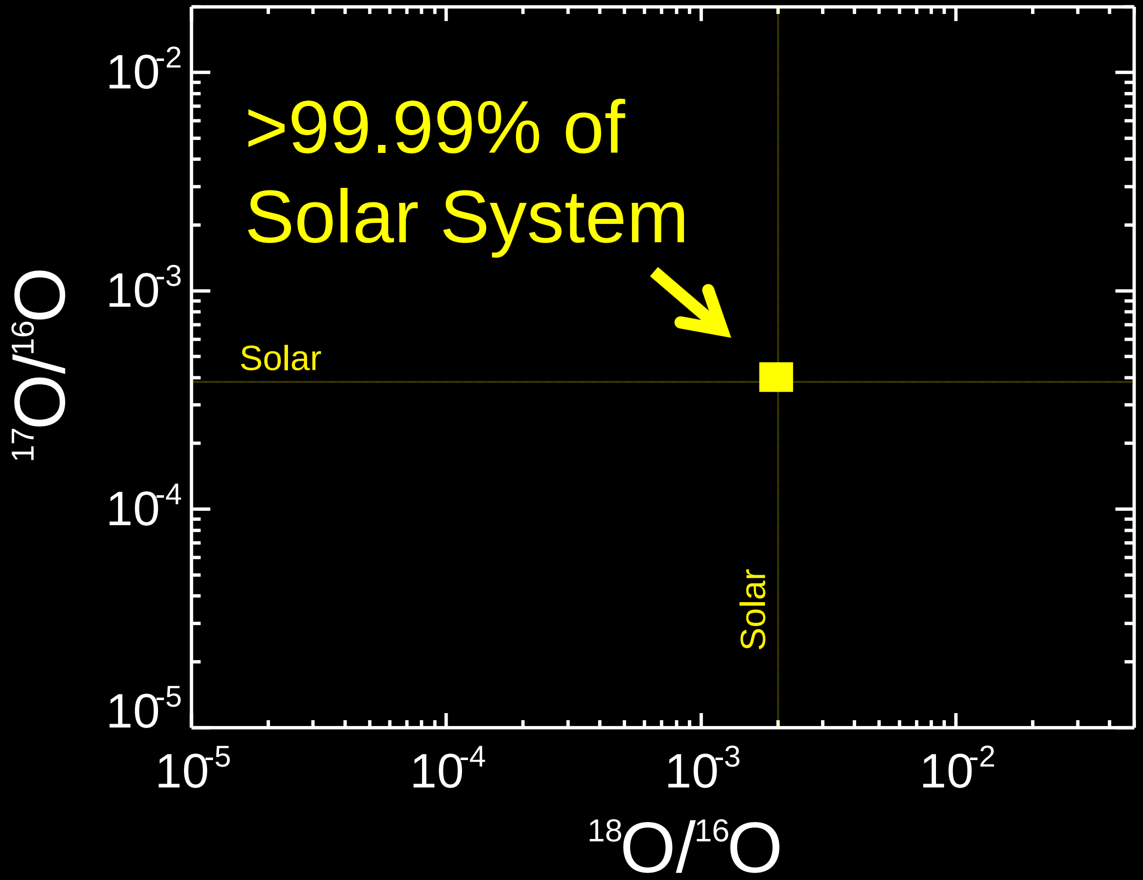
Formed in ~2-4 Ma

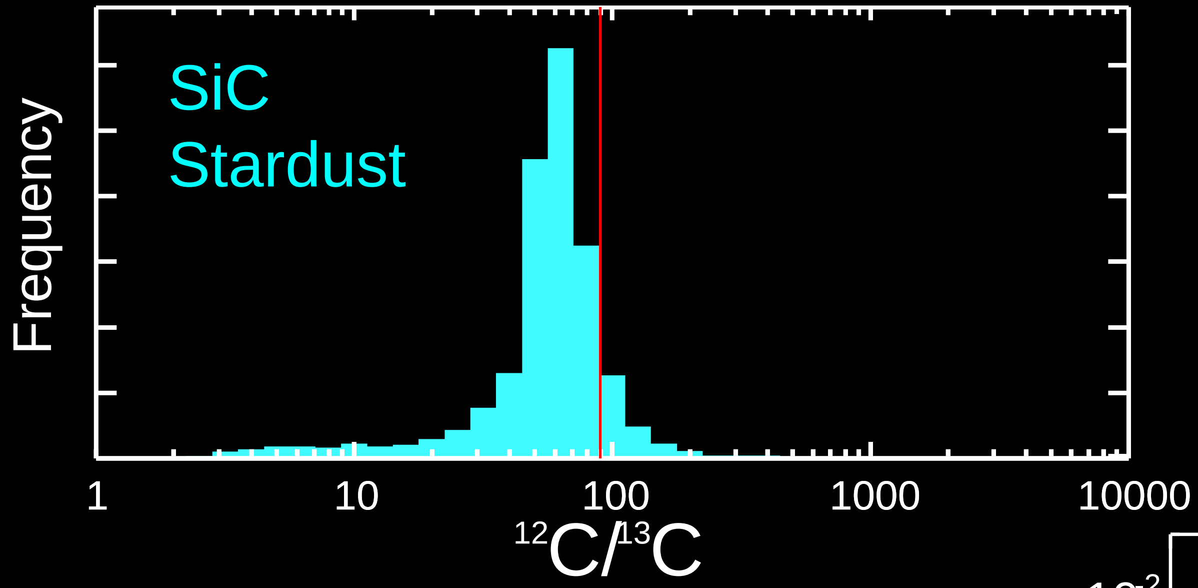
Presolar Stardust in the Solar System



How do we identify presolar grains?







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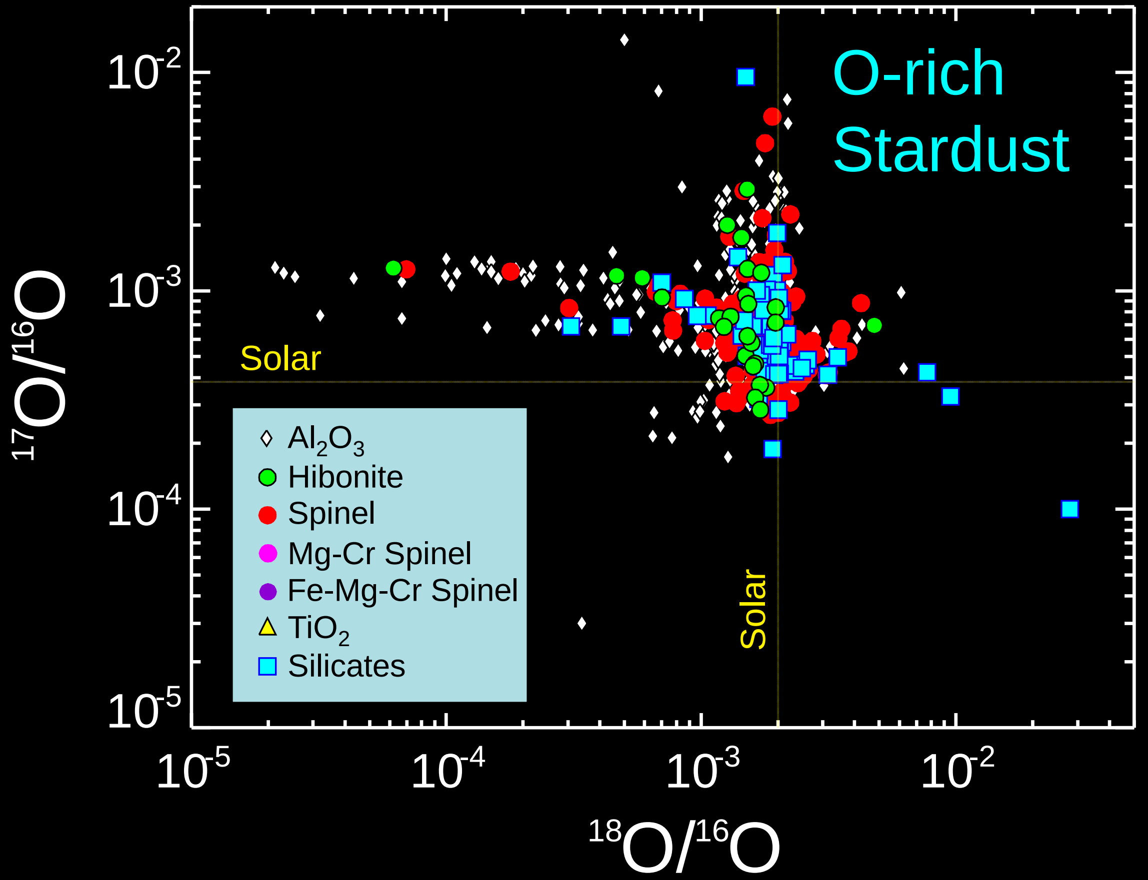
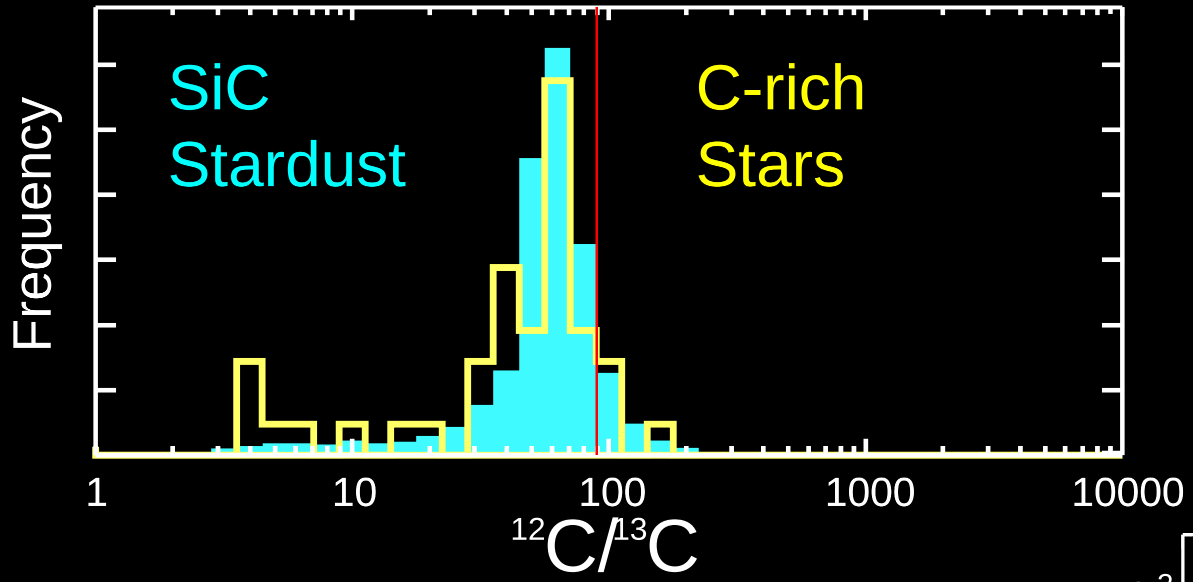
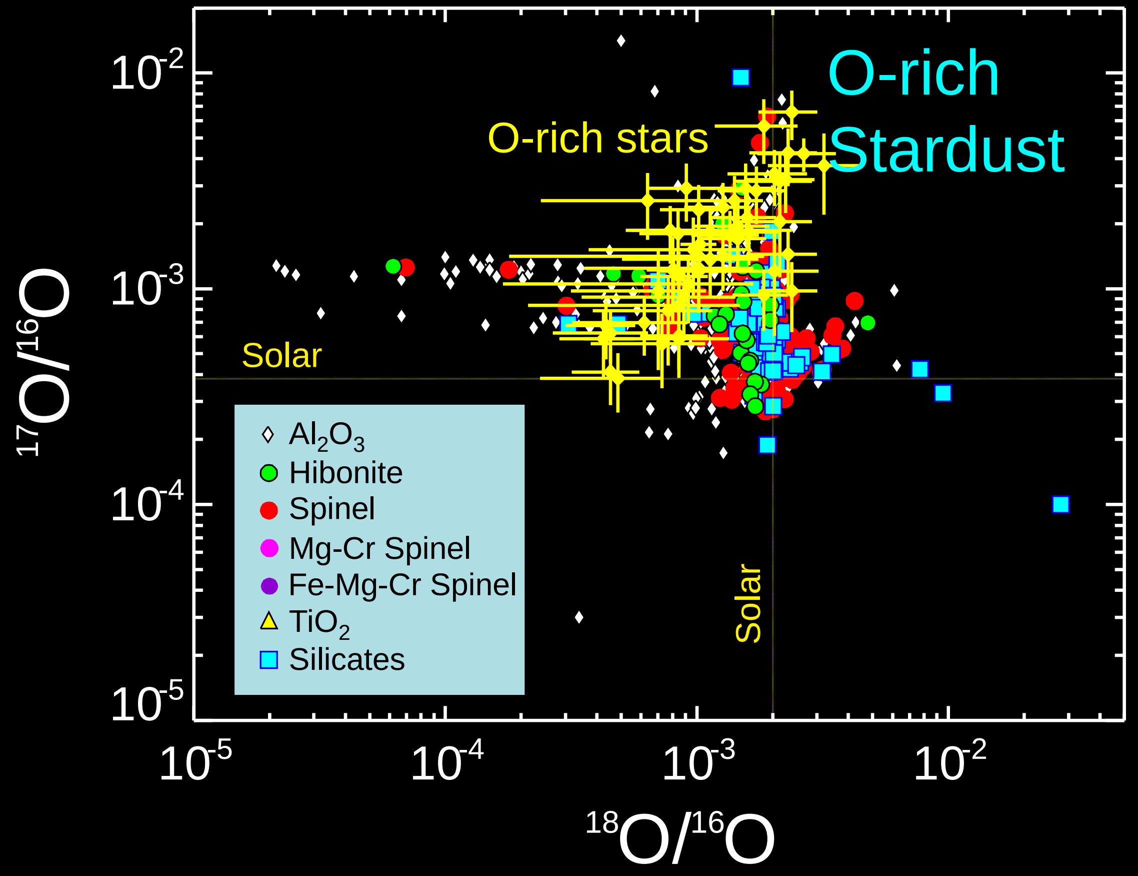


- Isotopic ratios in grains extremely unusual and distinct from solar system ranges
- Too large to explain by physical/chemical processes

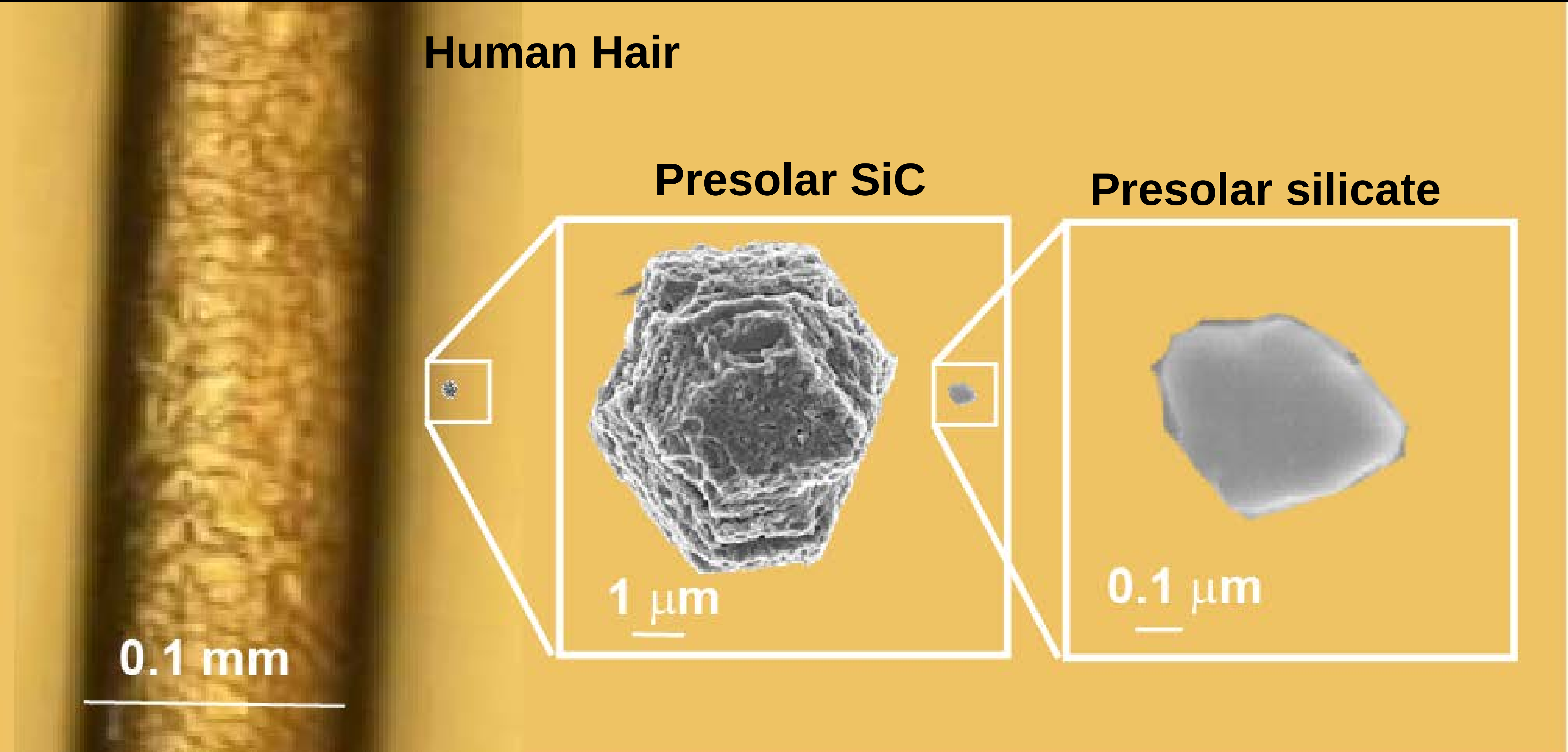
How do we identify presolar grains?



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

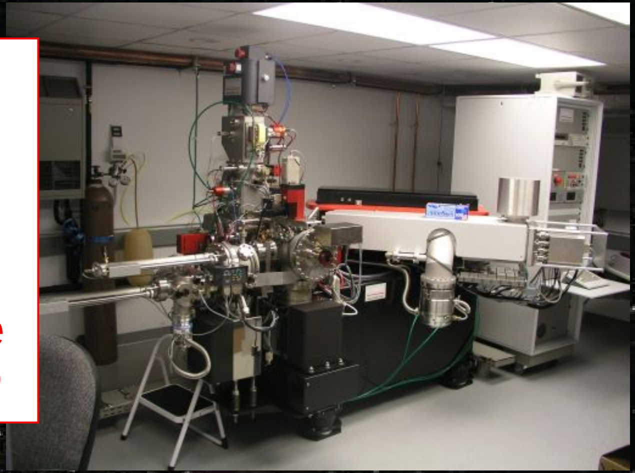


Presolar grains are small



Stardust "telescopes"

Secondary Ion Mass Spectrometry (SIMS)
- Major/minor element isotope ratios (>100nm)

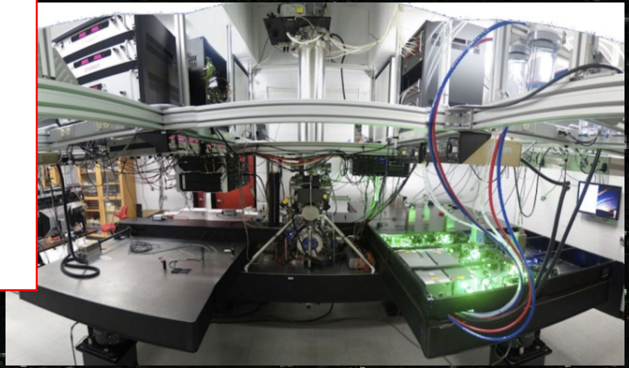


Carnegie Inst. NanoSIMS

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

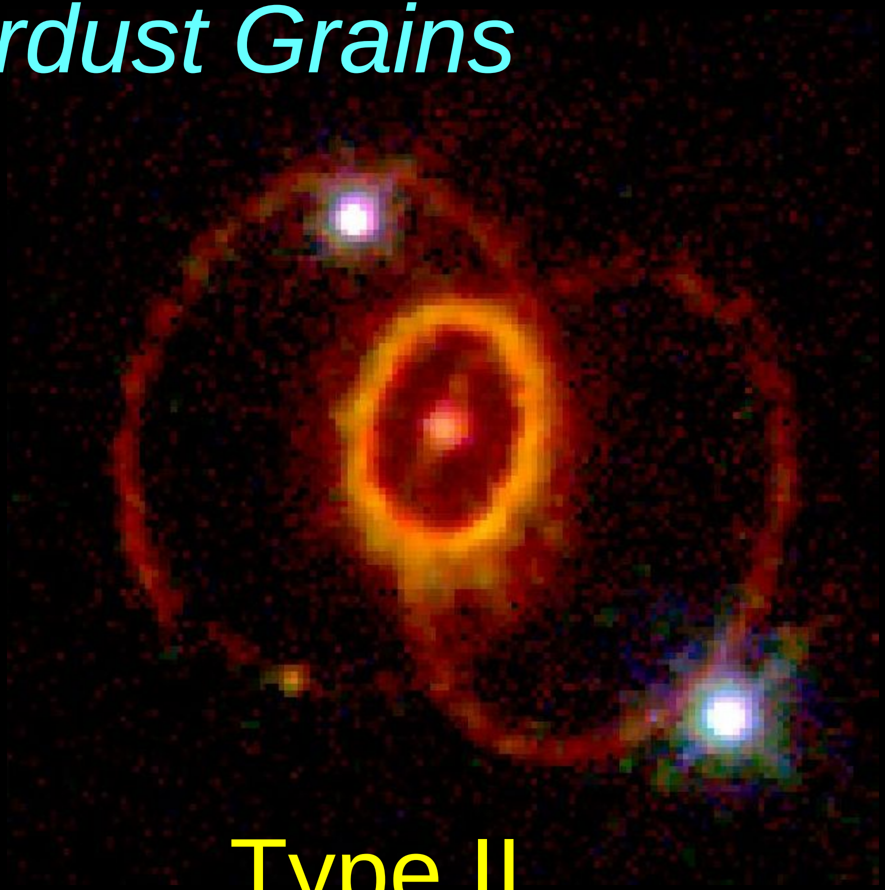
Pristine nature of presolar grains makes them useful probes of:

- 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

Sources of Presolar Stardust Grains

AGB Stars

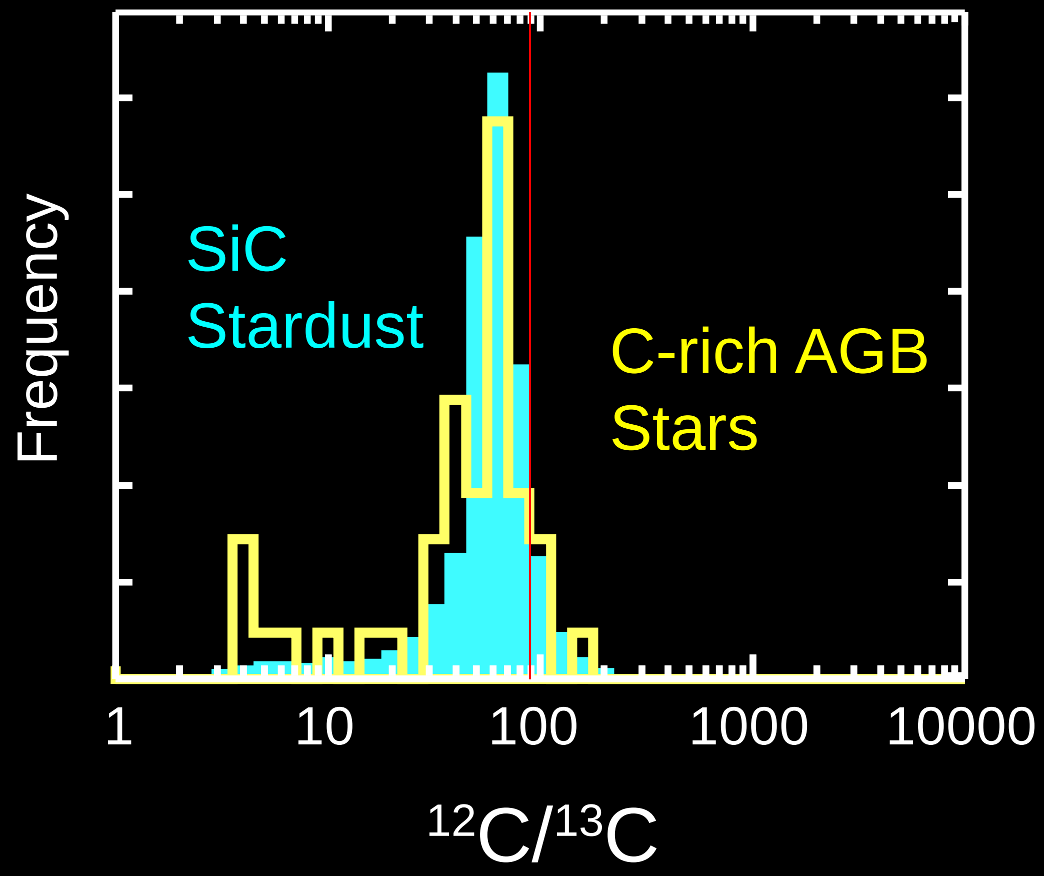
(evolved Sun-like stars)

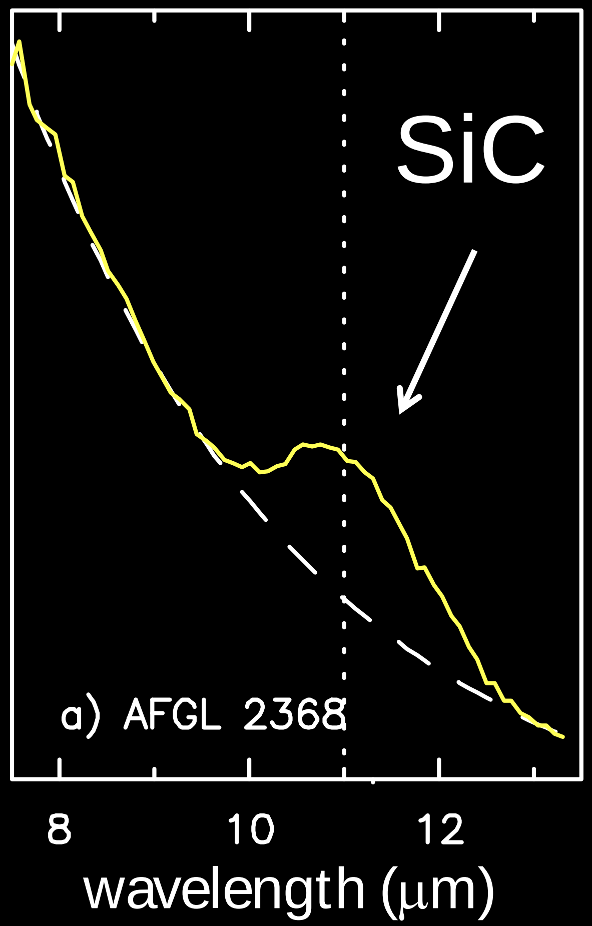


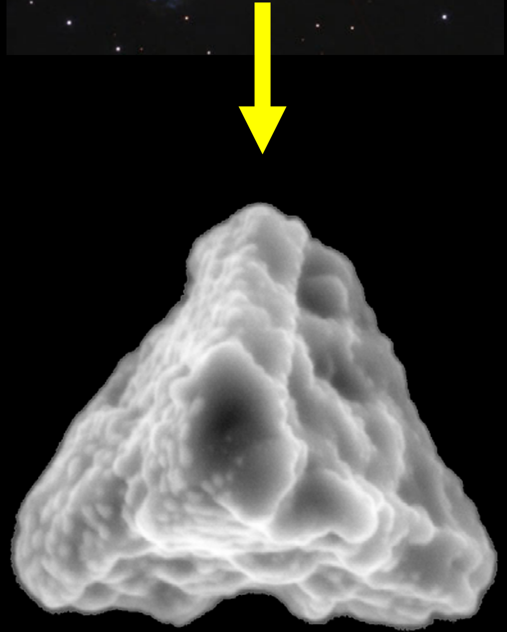
Type II Supernovae

(explosions of massive stars)

AGB origin of most presolar SiC grains







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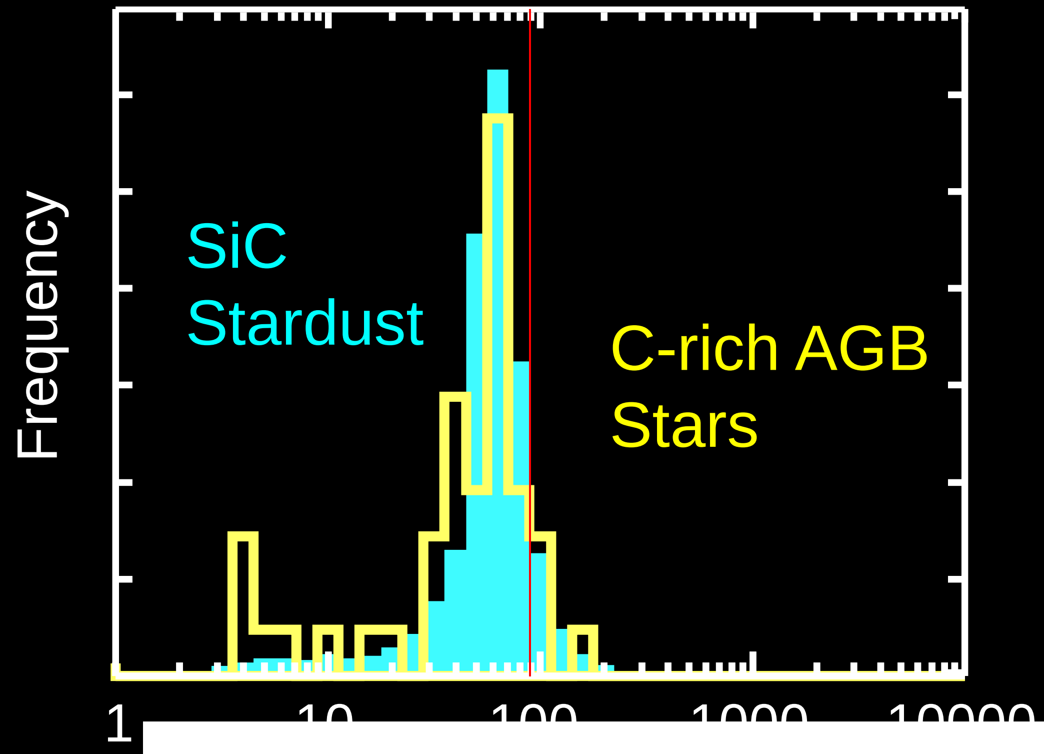
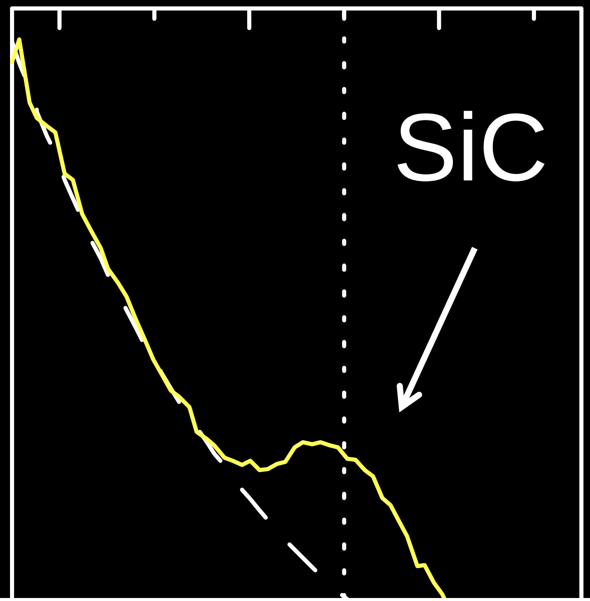
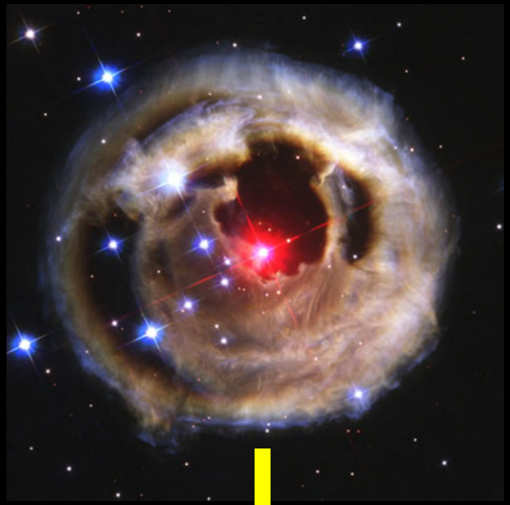
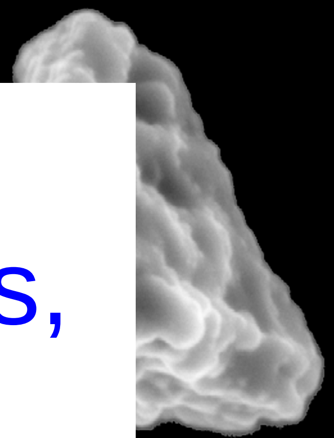




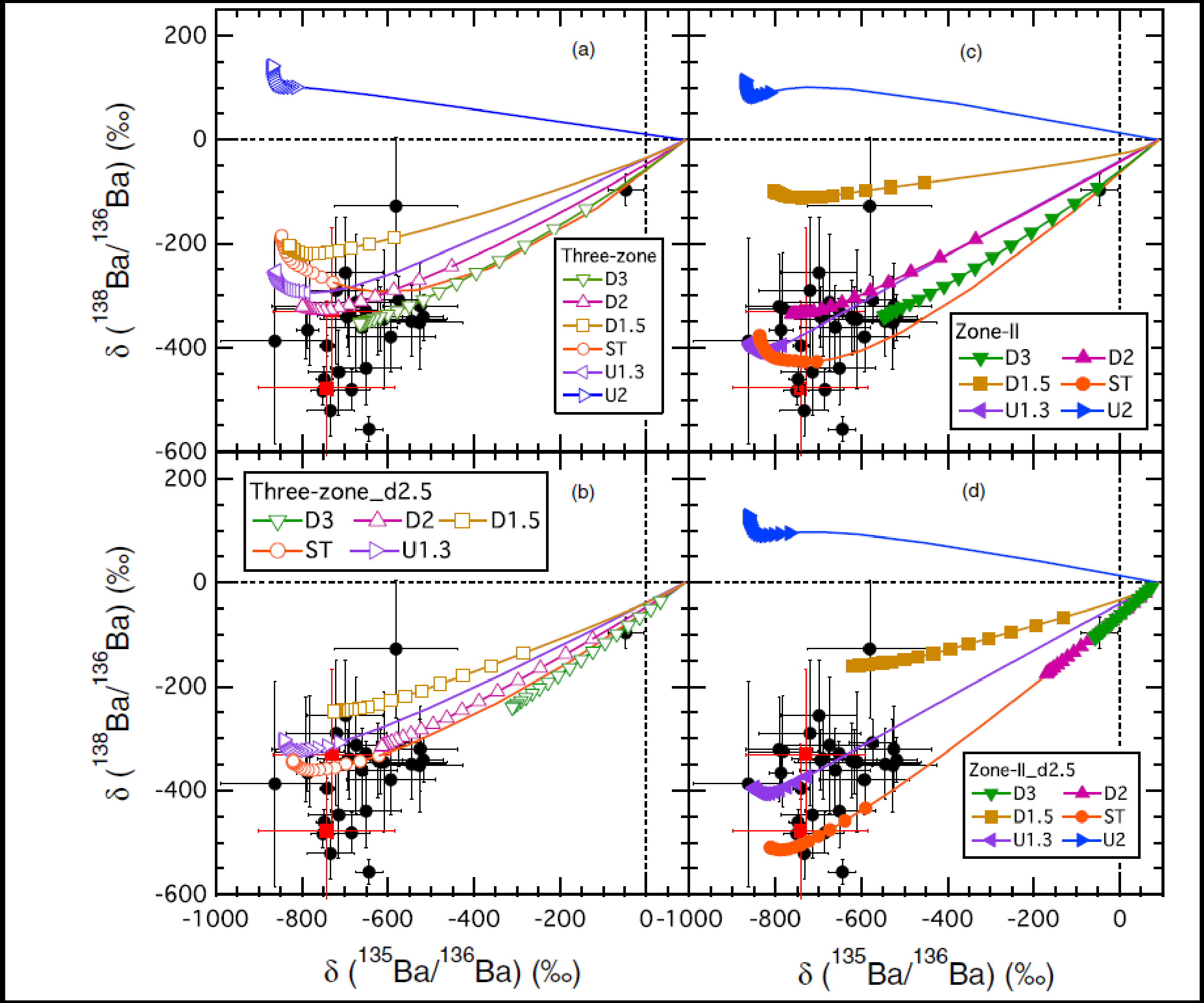




Comparison with astronomical observations indicates AGB star origins, but grains can tell us much more

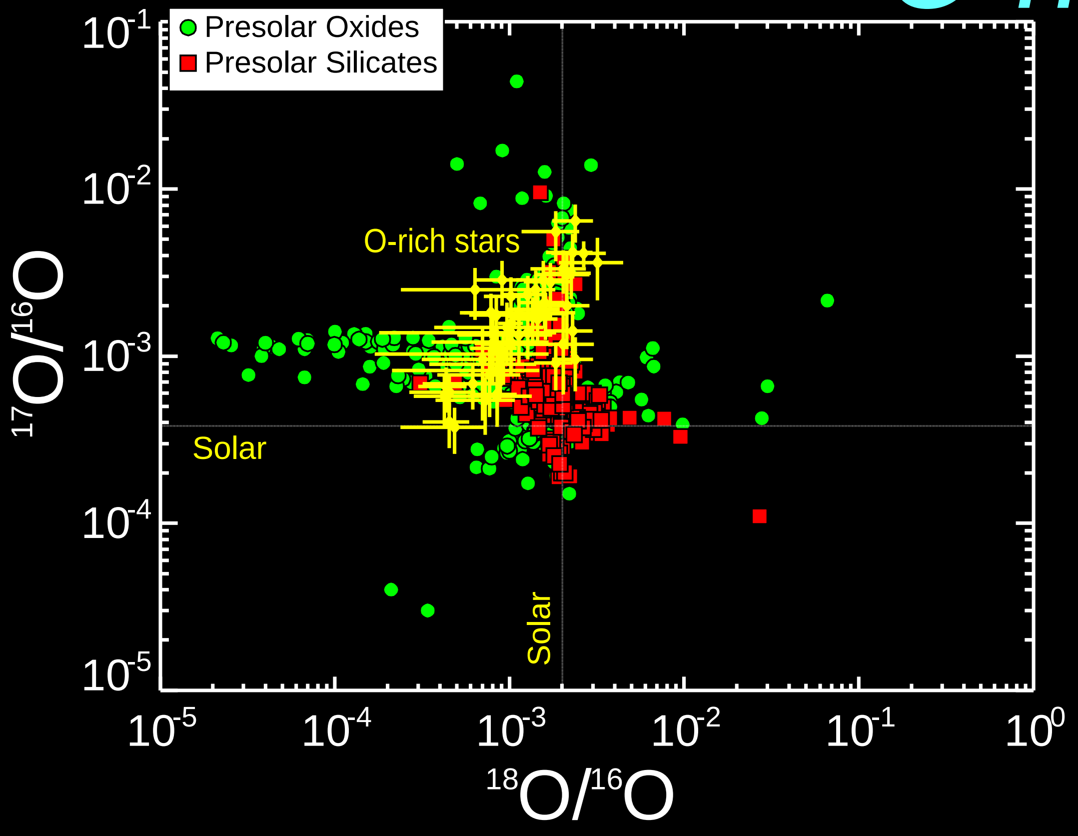
Heavy element nucleosynthesis

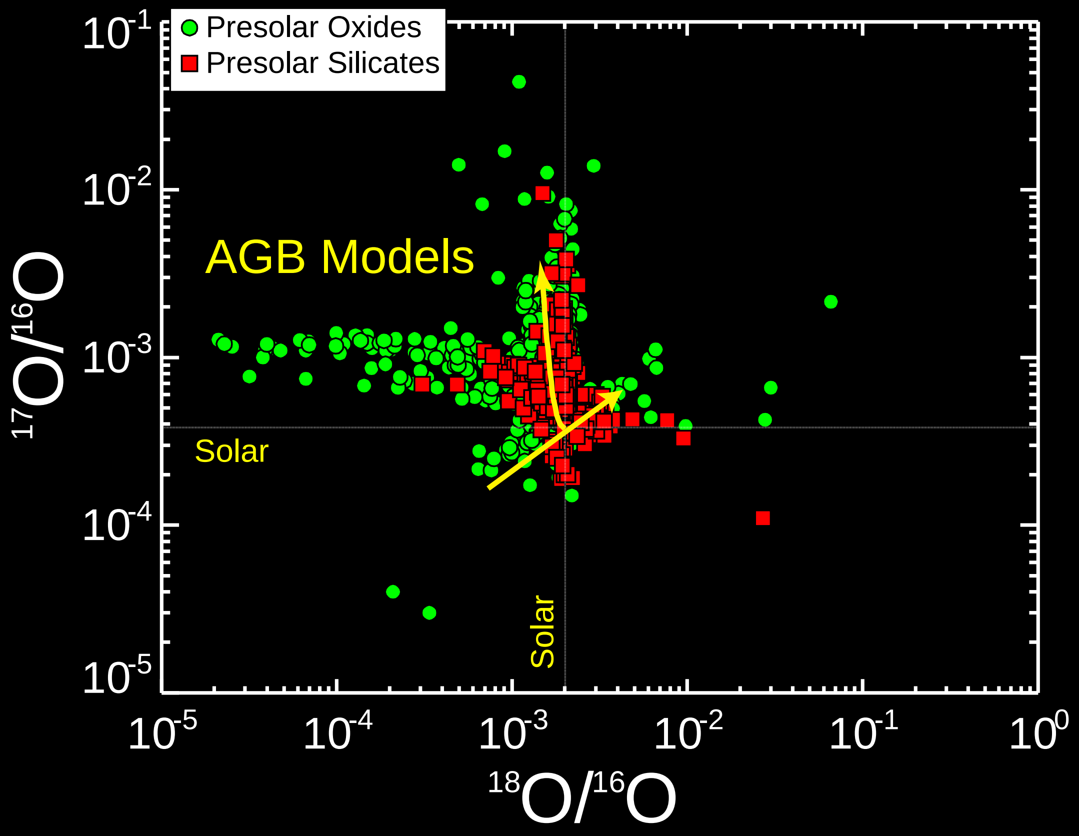
- Use RIMS to measure heavy trace element isotopes which are not possible astronomically (Ba, Mo, Zr, Sr, …)
- Can test theory with very high precision



Liu et al., ApJ 2014

O-rich stardust





- Comparison with both observations and models indicate vast majority of grains formed in AGB stars
  - But what about supernovae?

Supernovae

Enormous explosions of stars!

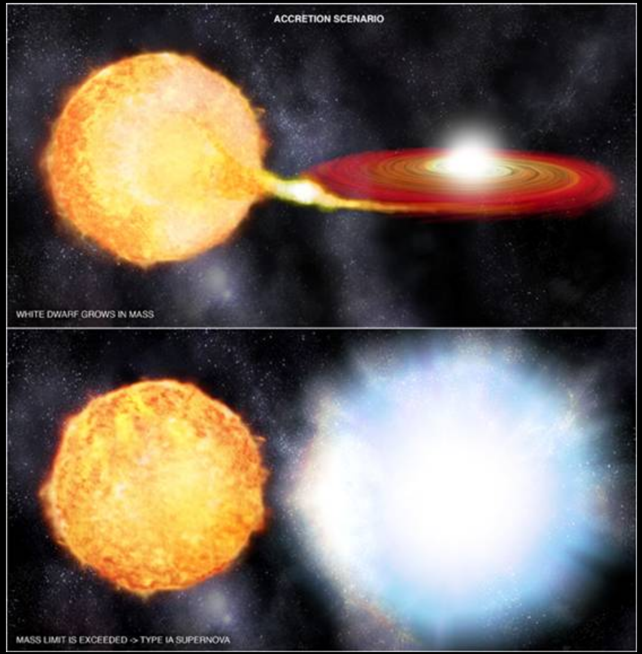
Release ~10^{46} joules energy

Type II

SN 1987A before and after

Explosion of massive (>$10M_{sun}$) stars – produce most elements from O – Fe

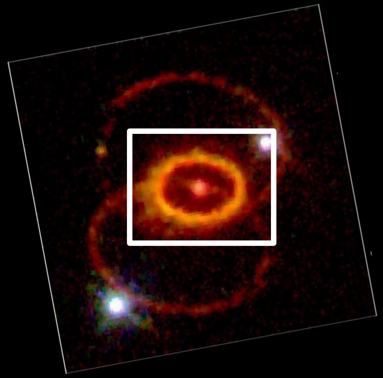
Type Ia

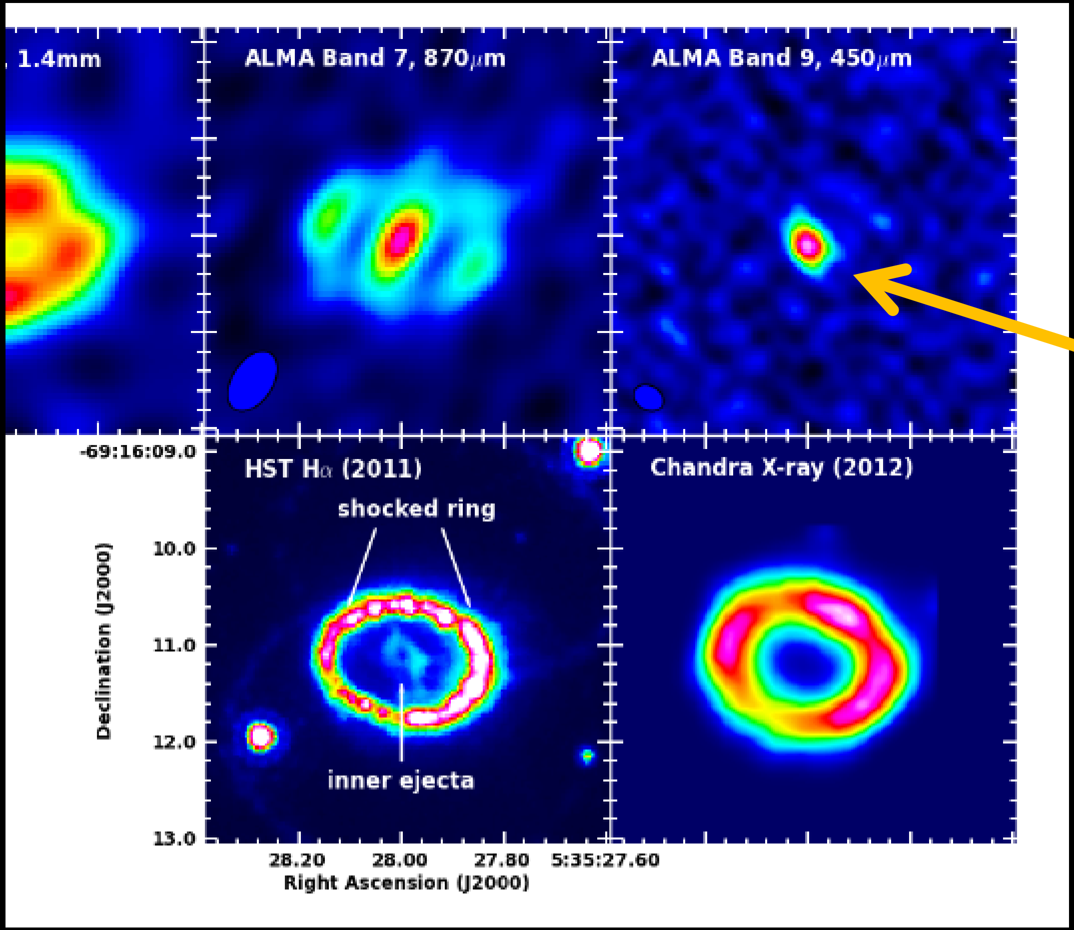


Explosion of white dwarf (probably) - produce Fe-peak elements

Supernova Dust

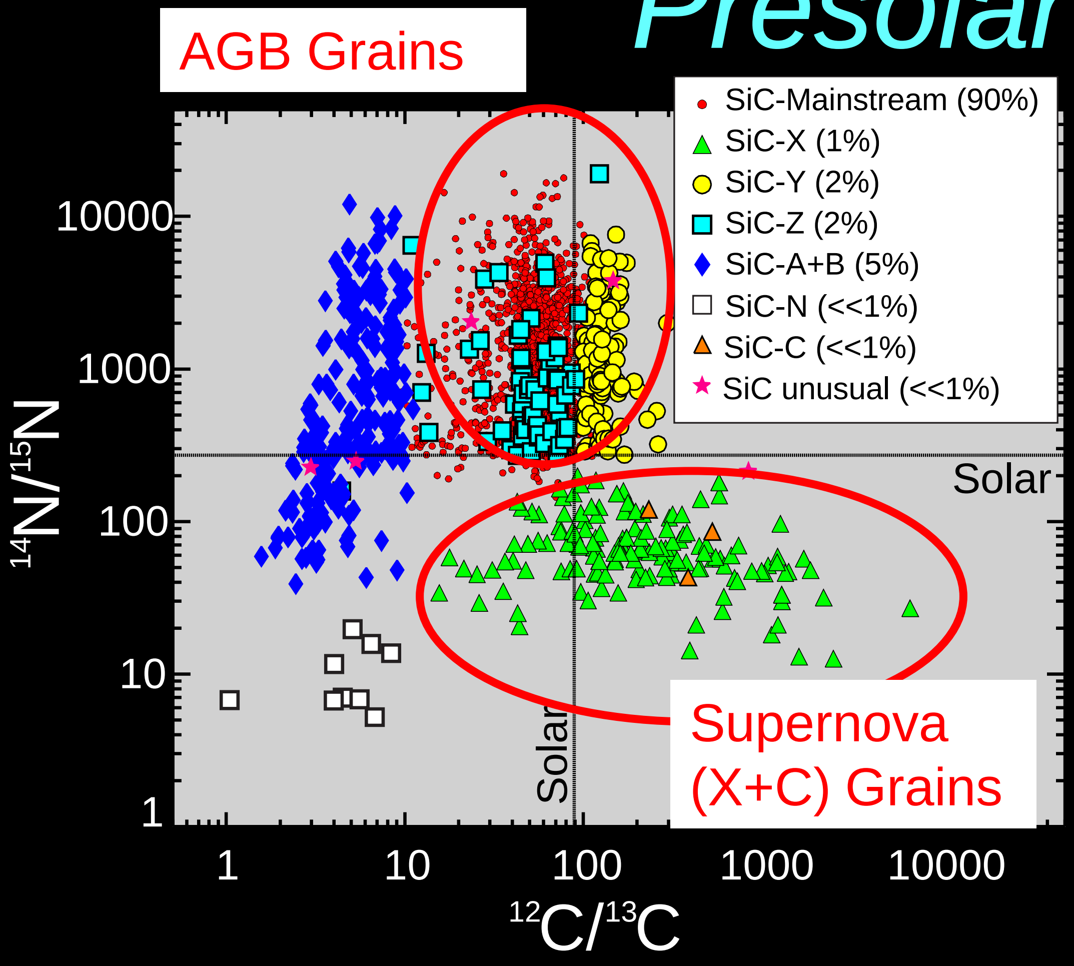
- How much dust and what types produced by in supernovae hotly debated in astronomical community

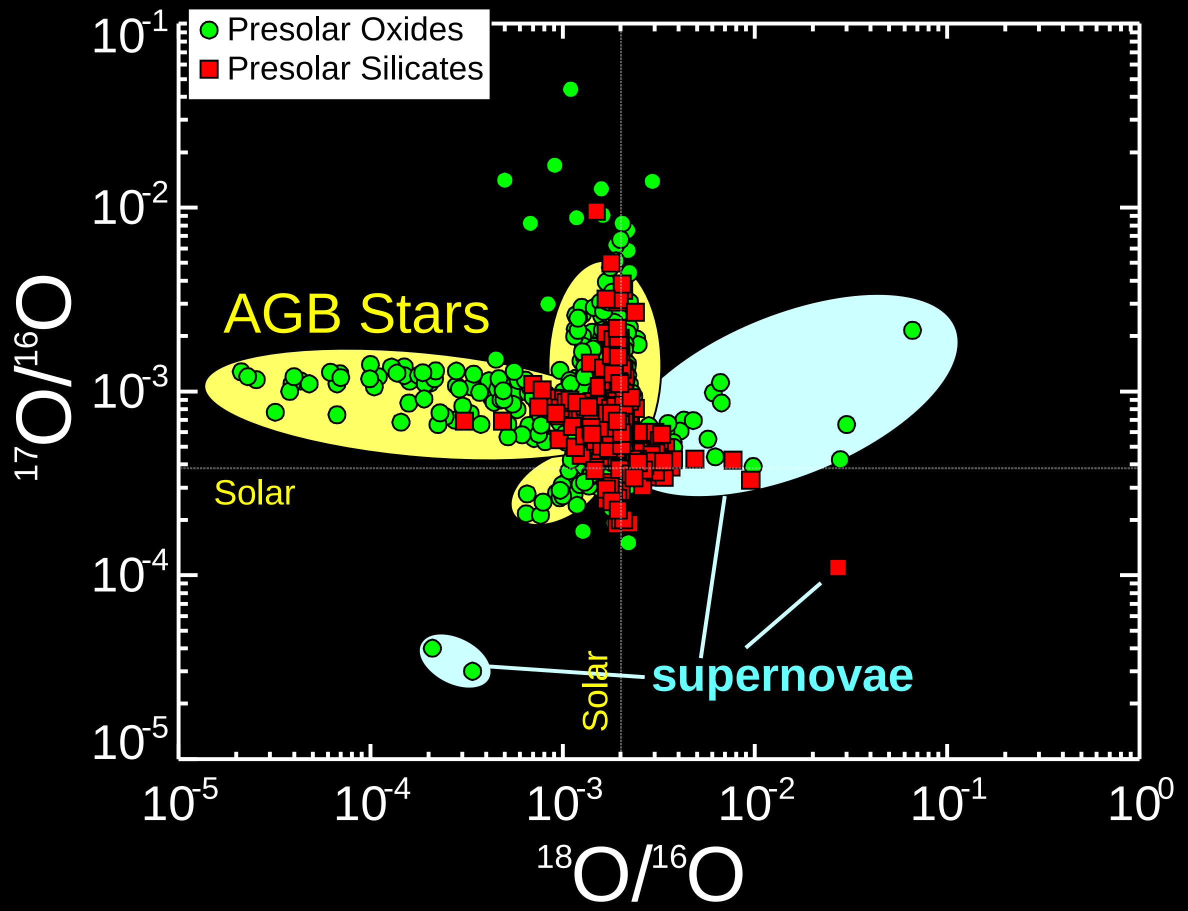




ALMA detection of cold dust in SN 1987A (Indebetouw et al. 2014)

Presolar Supernova Dust



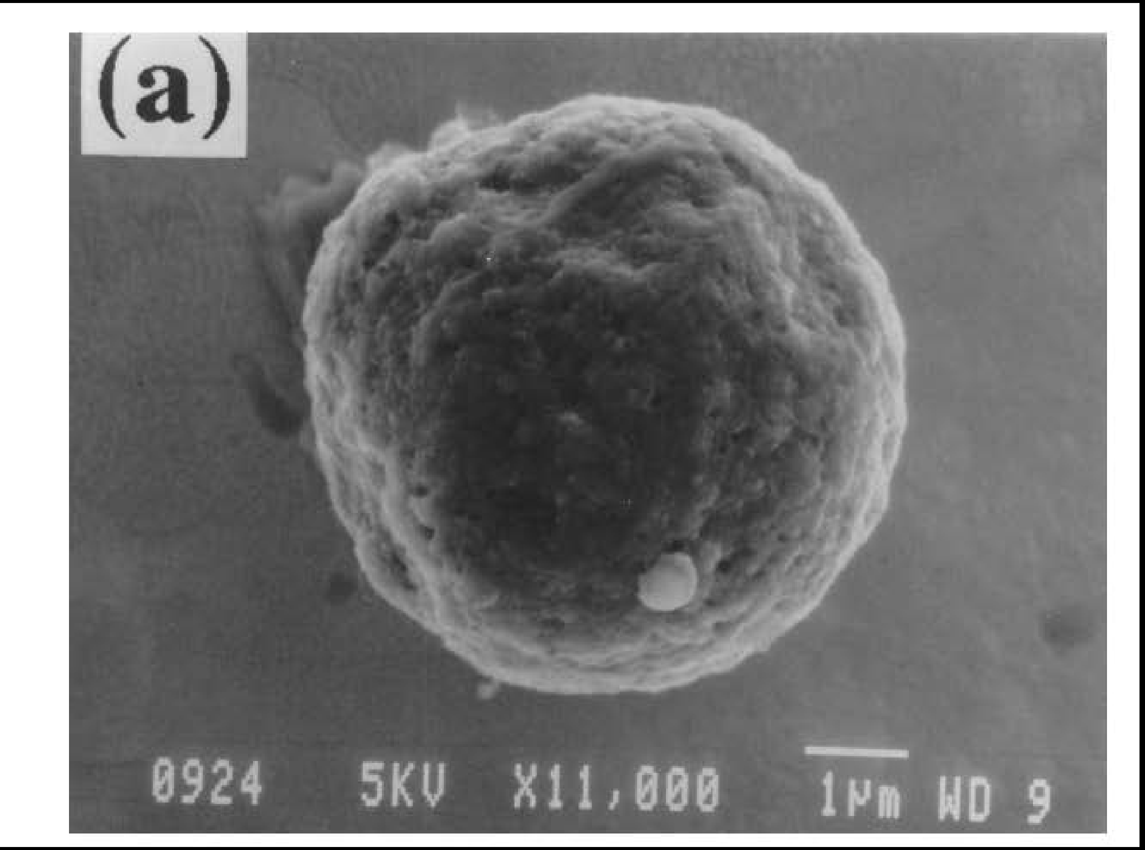


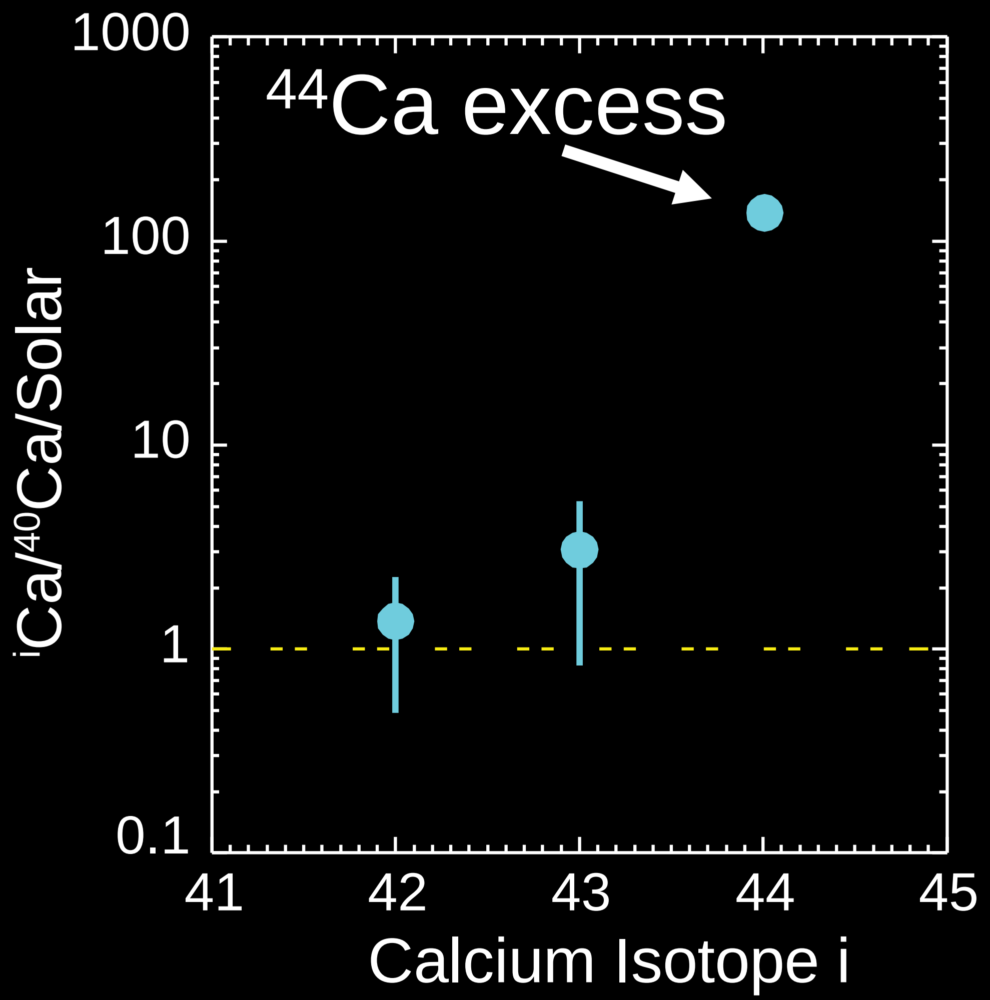
1-20% of presolar oxide, silicate, SiC, graphite stardust is from Type II supernovae!

How do we know?

Presolar Supernova Dust

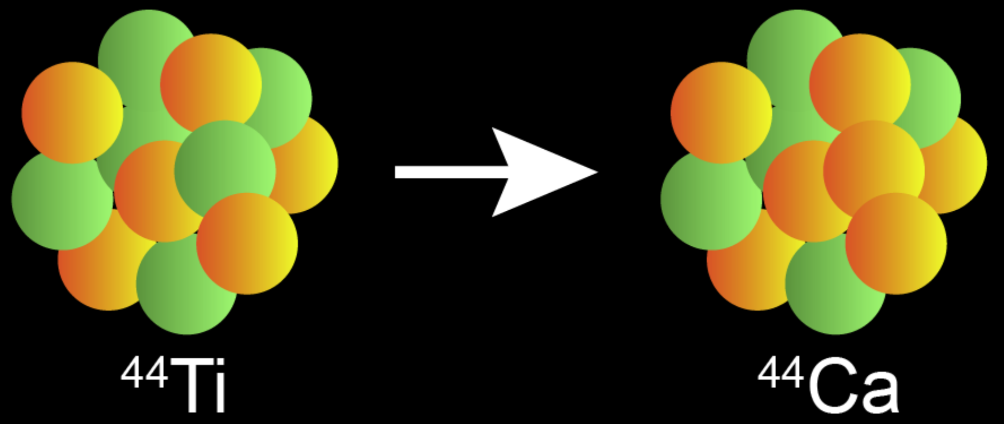
Nittler et al. 1996





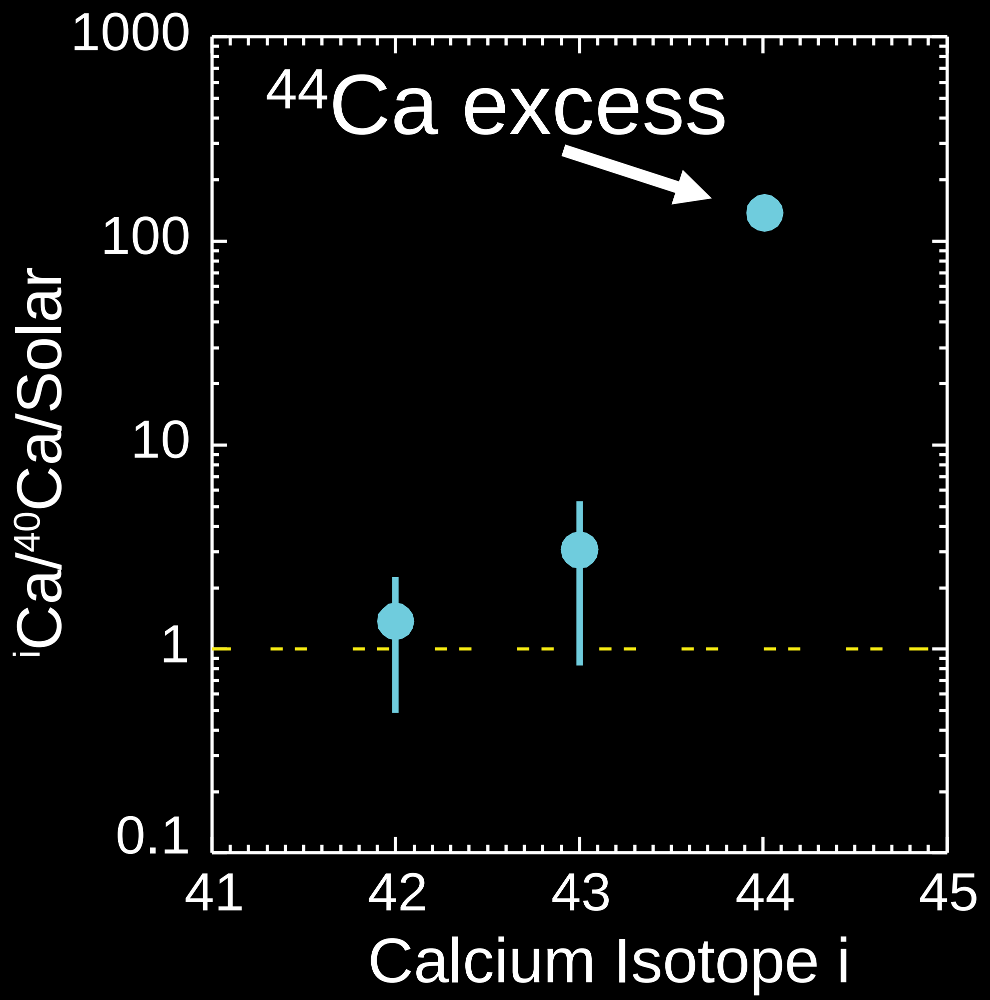
Presolar Supernova Dust

Nittler et al. 1996



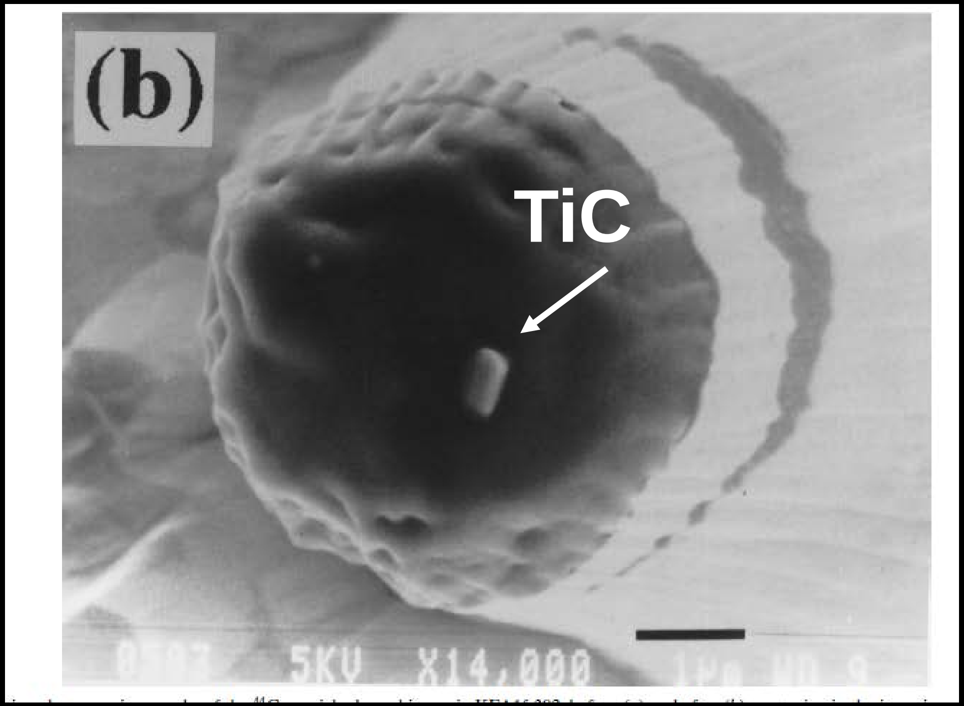
59 year $t_{1/2}$; made in Supernovae

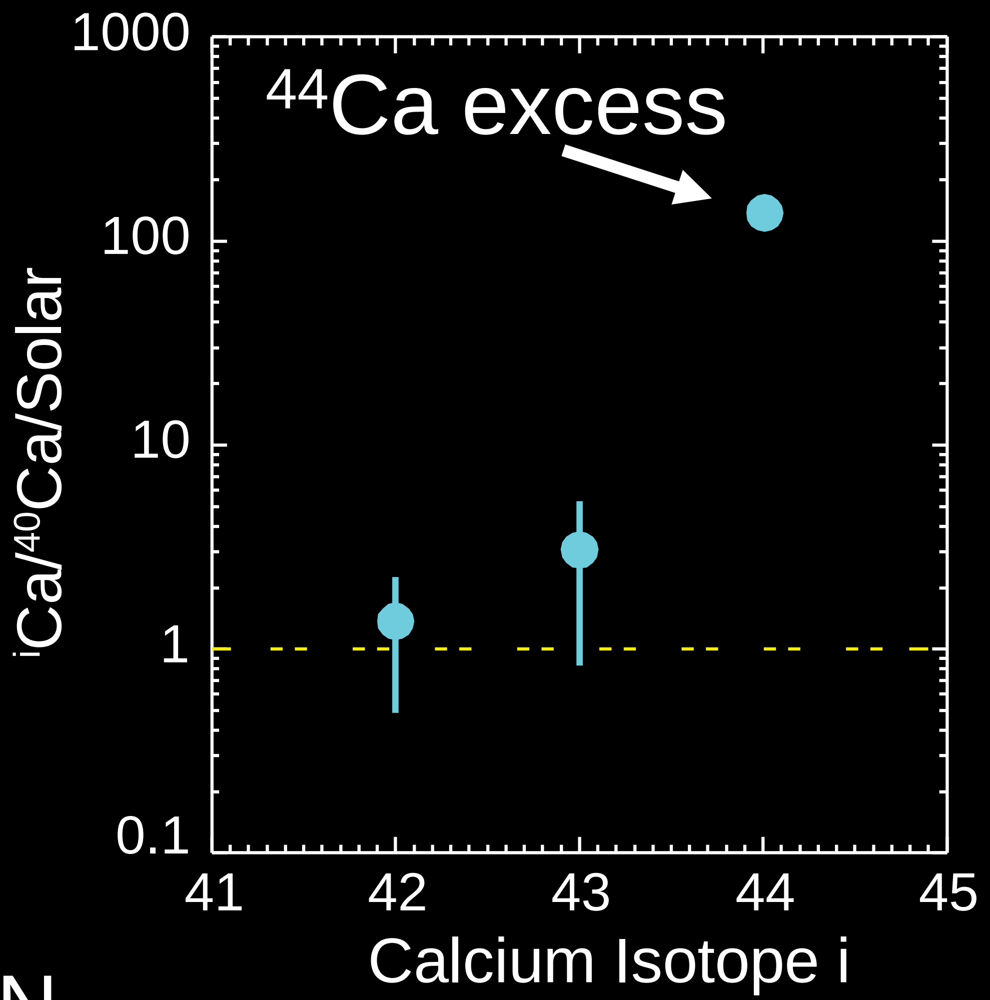
Grain formed with live ^{44}Ti
in a SUPERNOVA!



Presolar Supernova Dust

Nittler et al. 1996

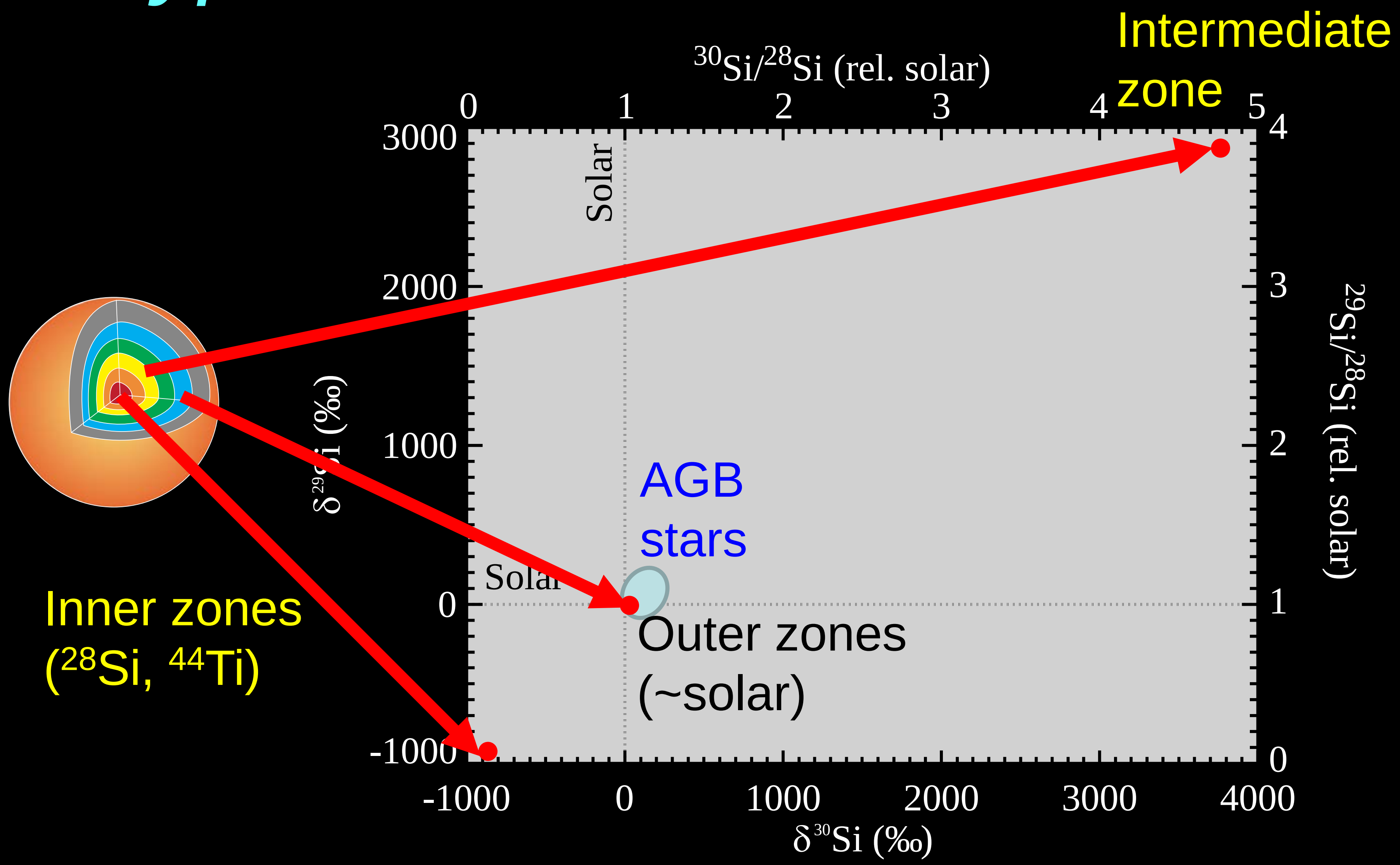




- Grain formed with live ^{44}Ti
  in a SUPERNOVA!
- Other isotopes also point to SN

Type II SN zones

- Before explosion, massive star is “onion”-like



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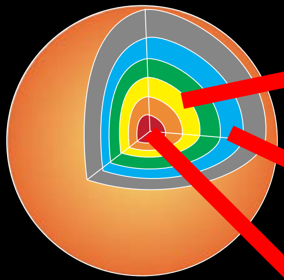
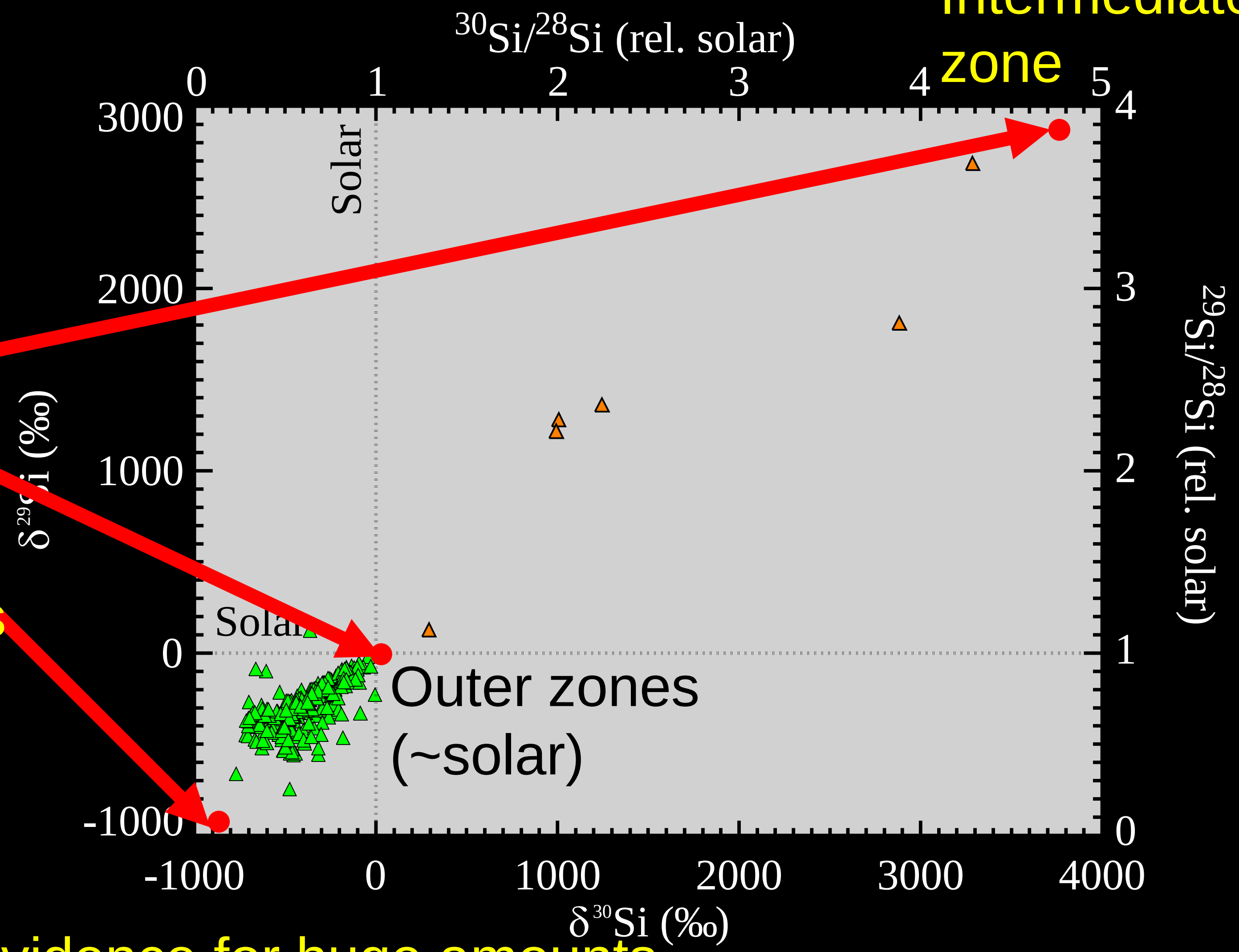
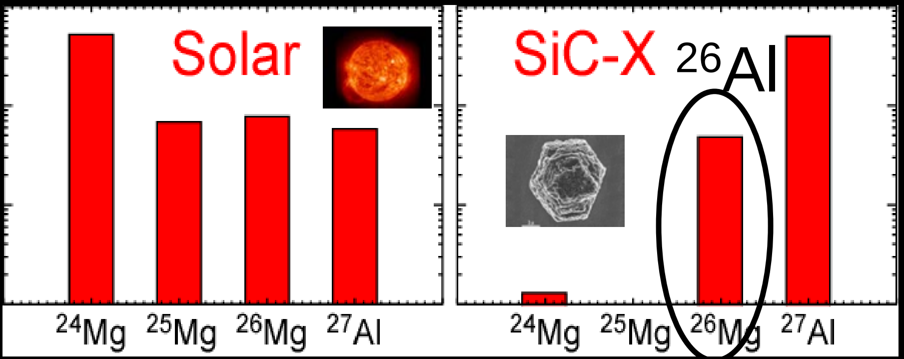




Inner zones (^{28}Si, ^{44}Ti)



Also evidence for huge amounts of ^{26}Al ($t_{1/2}=7 \times 10^5$ yr) from intermediate layers

Type II SN zones

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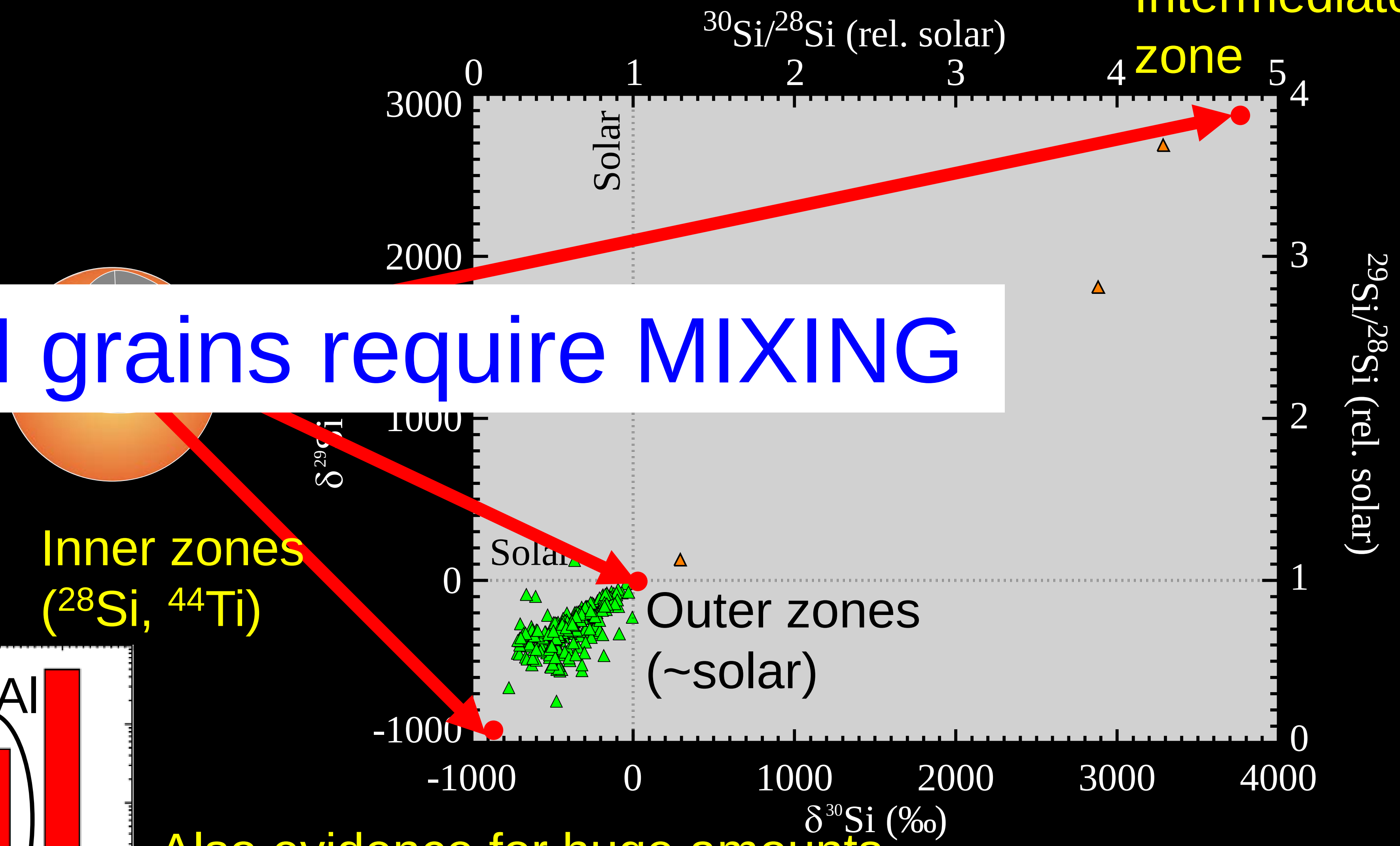
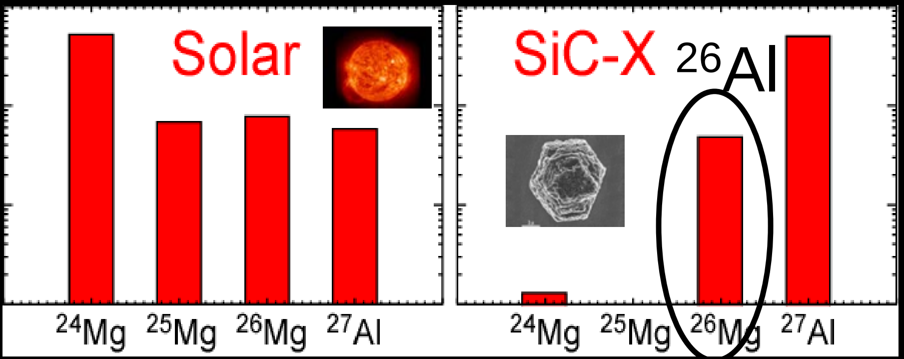
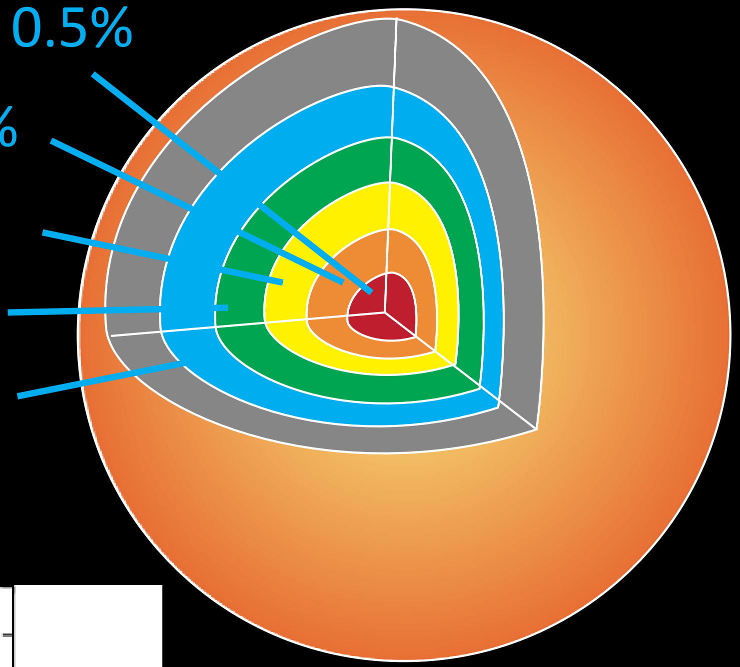


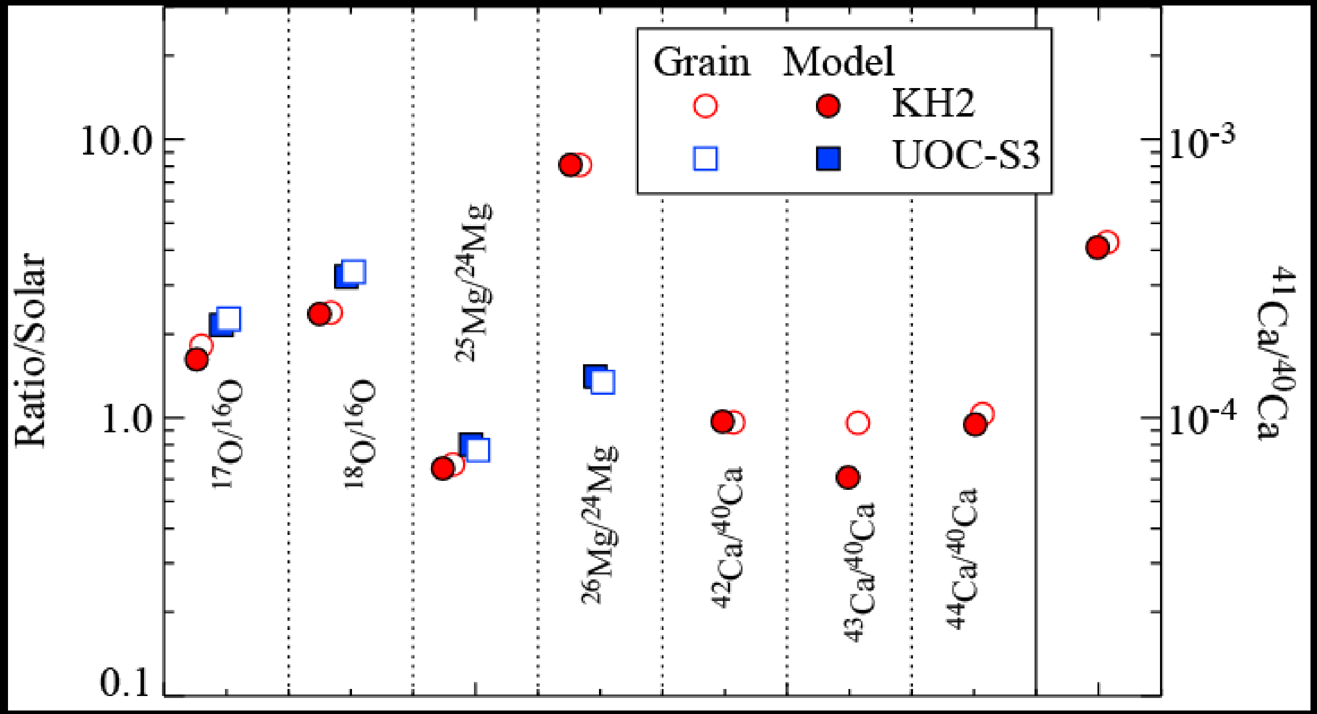


Also evidence for huge amounts of ^{26}Al ($t_{1/2}$=7 x 10^5 yr) from intermediate layers

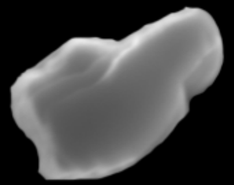
Supernova Mixing

Can reproduce grain compositions by mixing zones from nucleosynthesis calculations





Hibonite ($CaAl_{12}O_{19}$) and Spinel ($MgAl_2O_4$)

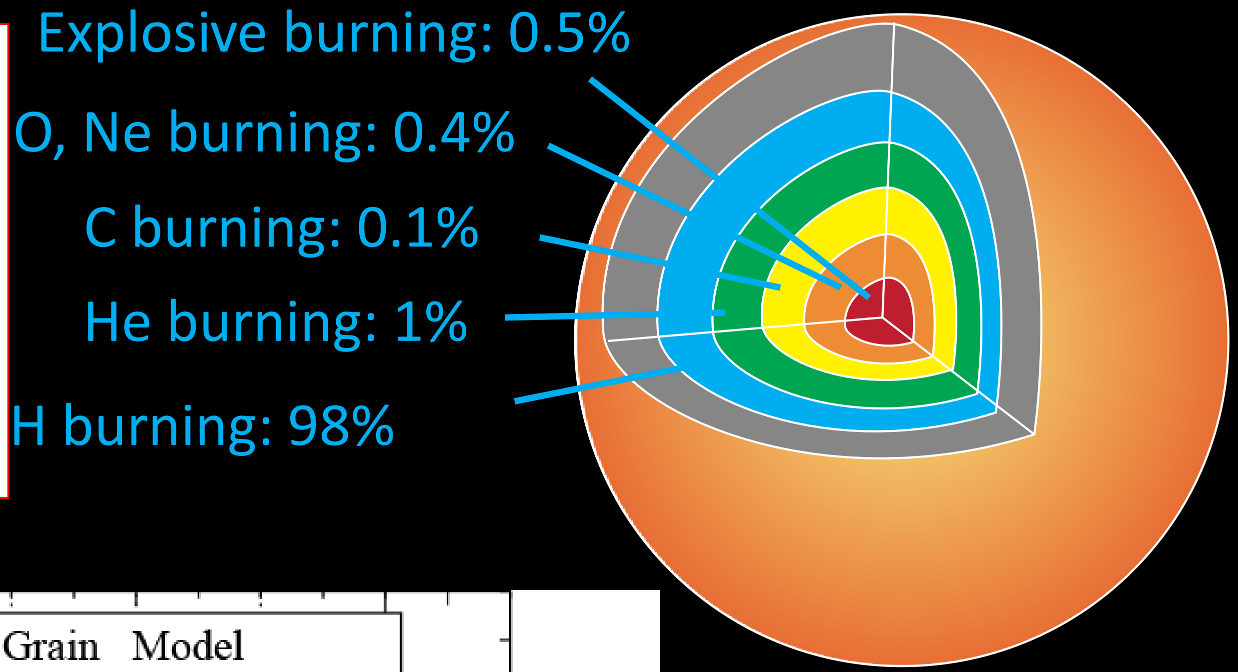


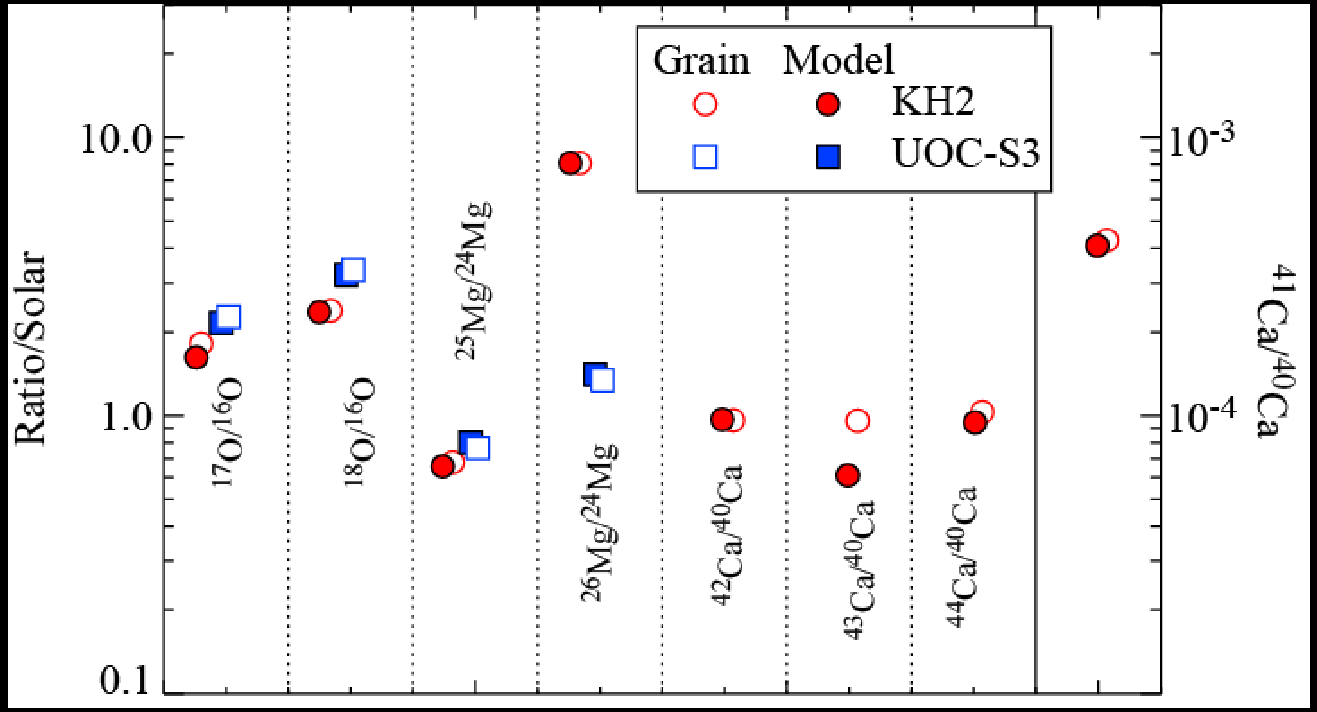
Nittler *et al.* ApJ 2008

Supernova Mixing

Can reproduce grain compositions by mixing zones from nucleosynthesis calculations

But is SN mixing reasonable?





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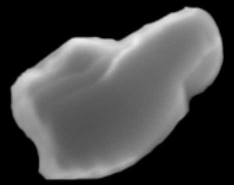
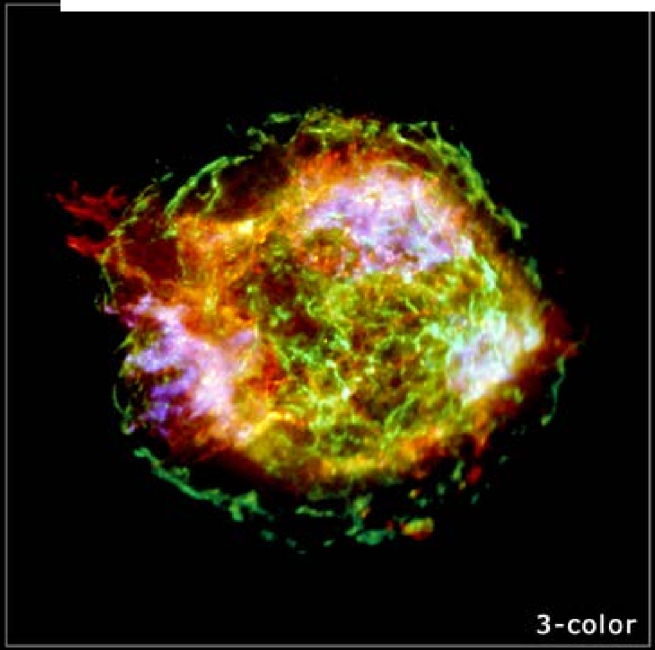
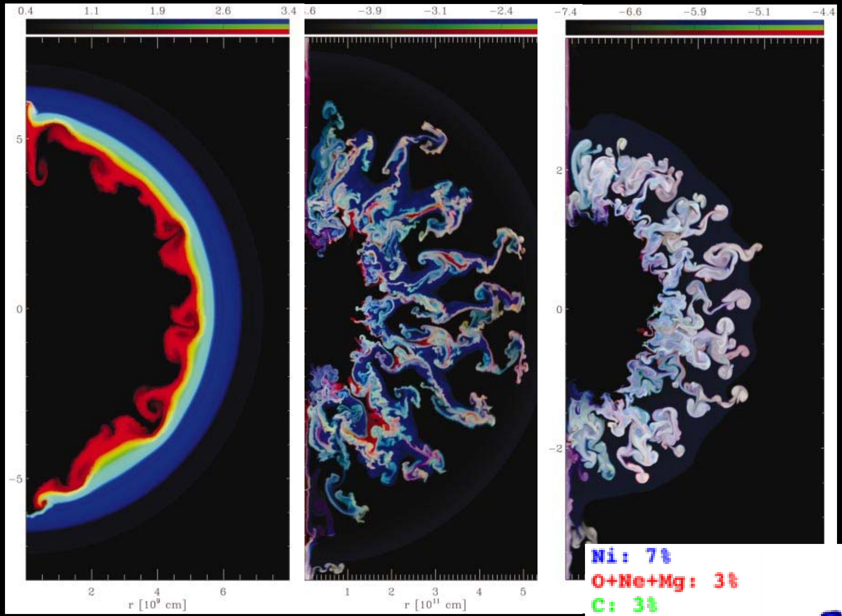


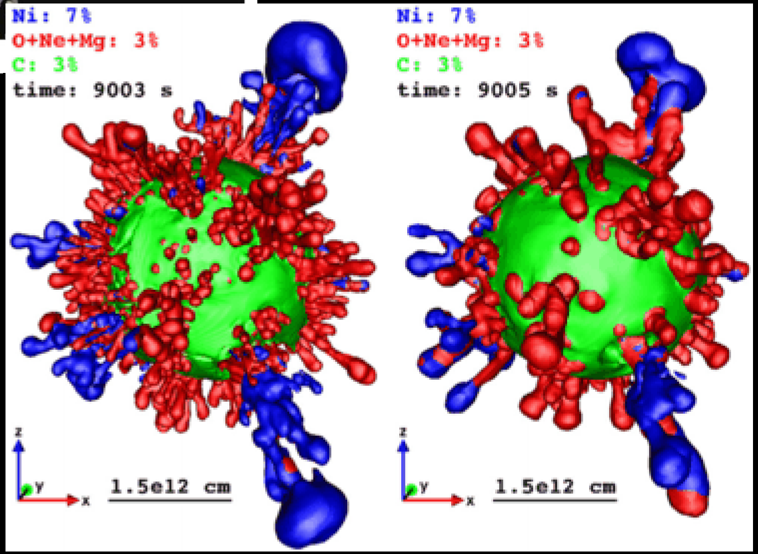
Nittler *et al.* ApJ 2008

Supernova Mixing

X-ray observations of Cassiopeia-A SN remnant



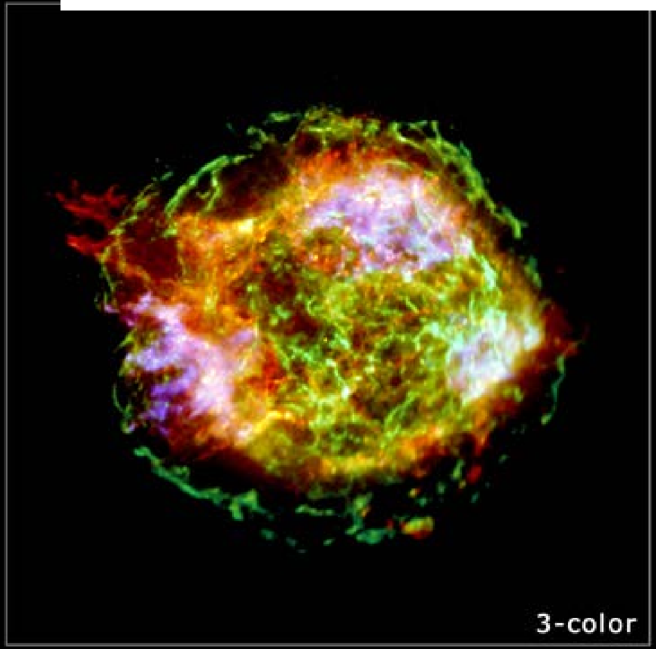


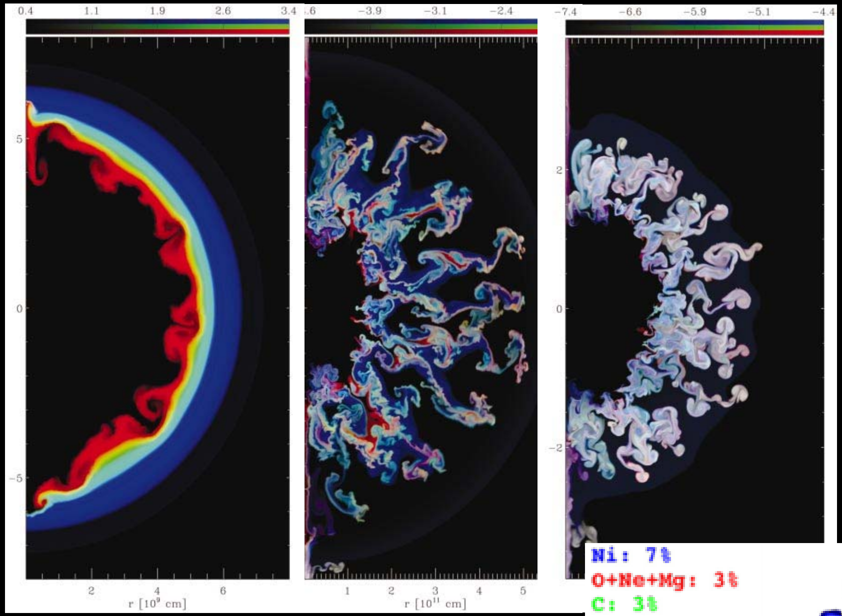


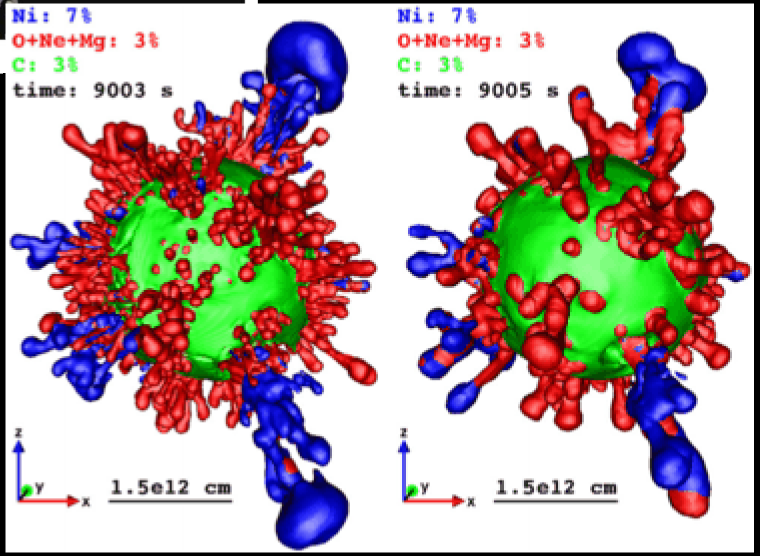
Computer simulations of SN mixing

Supernova Mixing

X-ray observations of Cassiopeia-A SN remnant





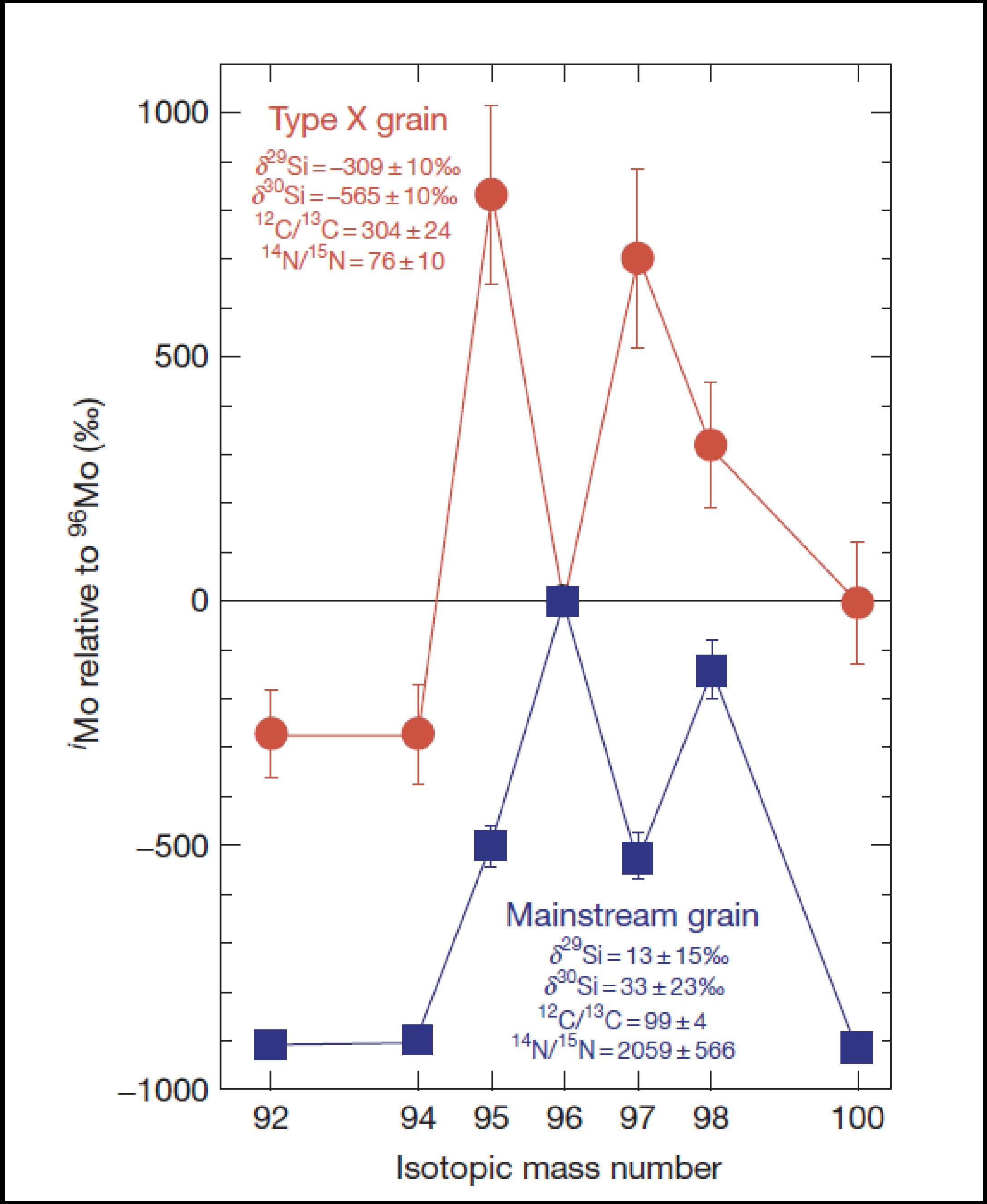


Computer simulations of SN mixing

Observations and theory can't (yet) probe same spatial scale as grains

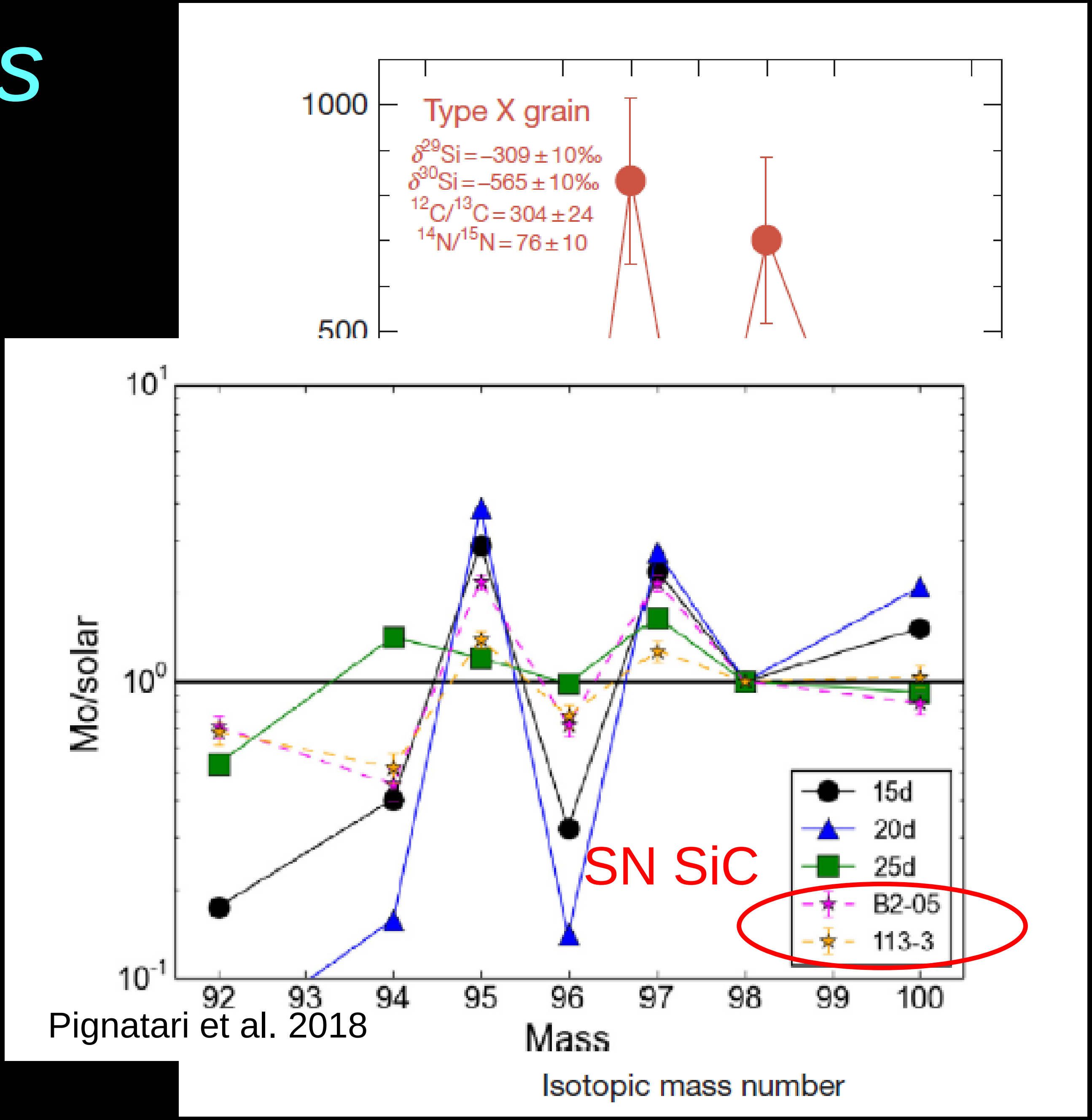
SN nucleosynthesis

- SN and AGB SiC have distinct trace-element isotopes (measured by RIMS)
  - AGB (Mainstream) *s*-process
  - SN: “neutron-burst”



SN nucleosynthesis

- SN and AGB SiC have distinct trace-element isotopes (measured by RIMS)
  - AGB (Mainstream) *s*-process
  - SN: “neutron-burst”
  - Can match to SN models



SN nucleosynthesis: ^{15}N-problem

- SN-SiC grains rich in ^{15}N (low $^{14}N/^{15}N$); not easily reproduced by SN nucleosynthesis calculations

SN nucleosynthesis: ^{15}N-problem

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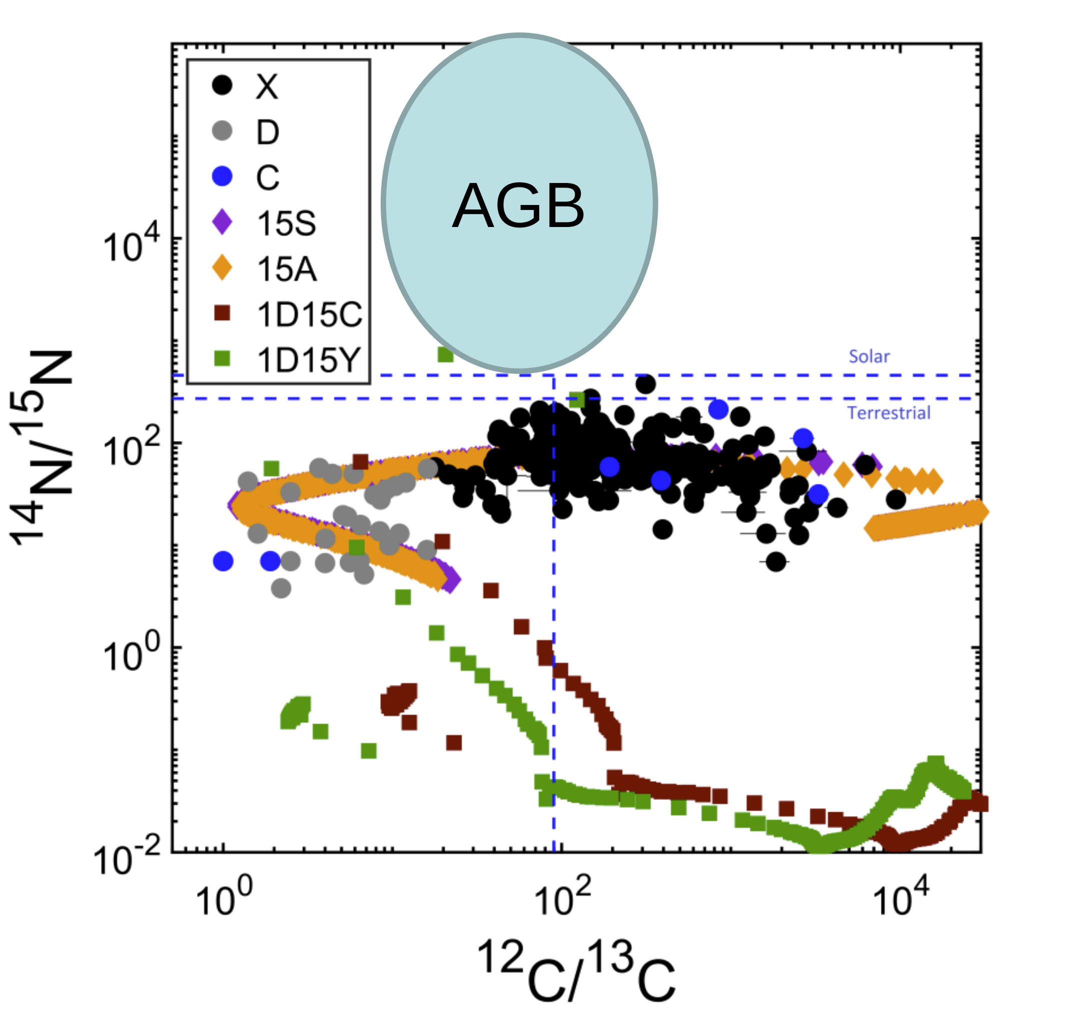
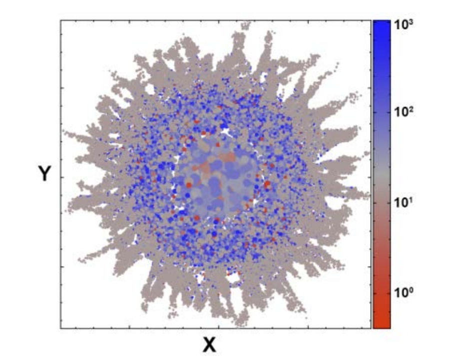
- Solved with 3-D models? (Schulte et al., 2021)

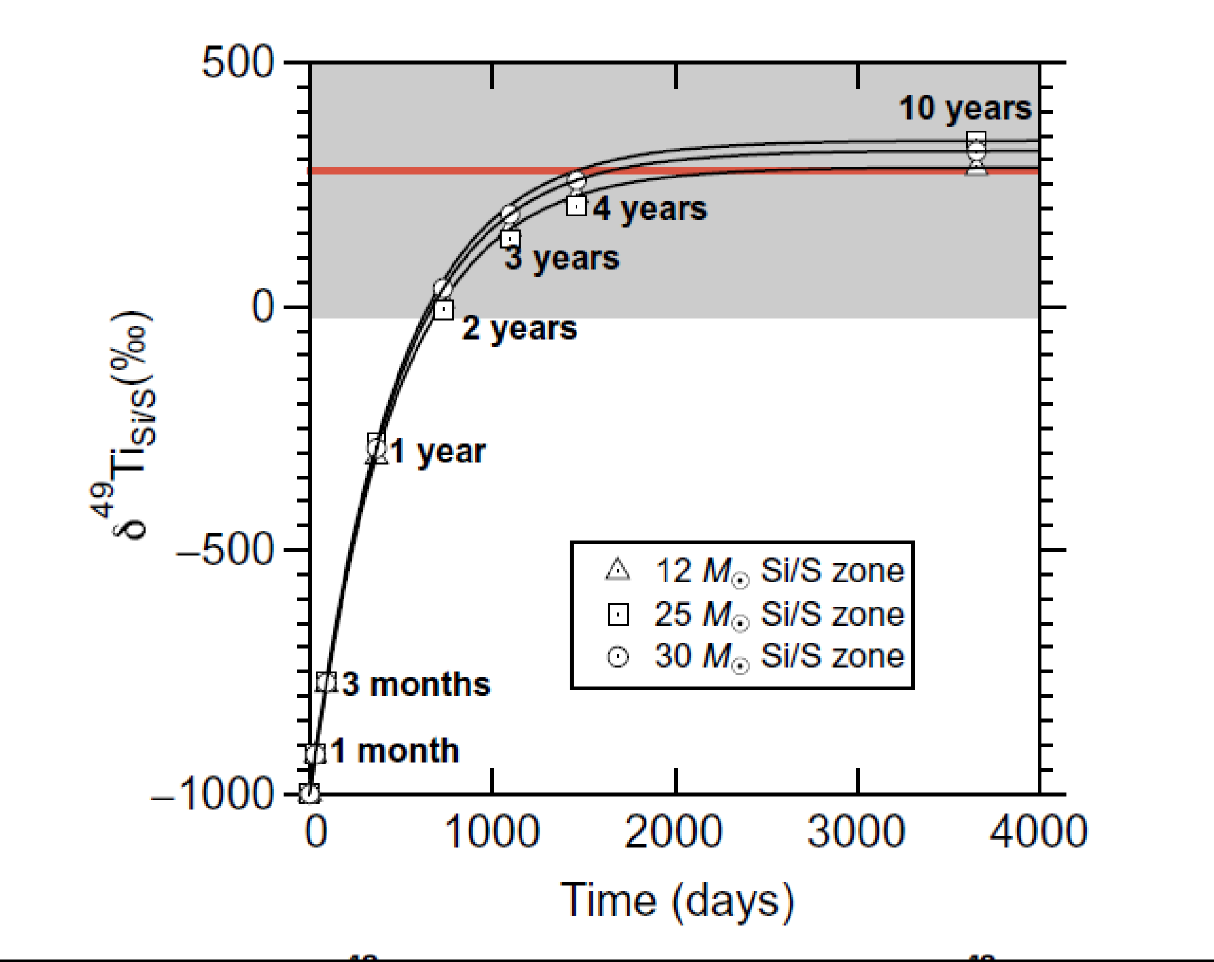




(b) 15S $^{14}N/^{15}N$ in X-Y plane

Timing of SN grain formation?

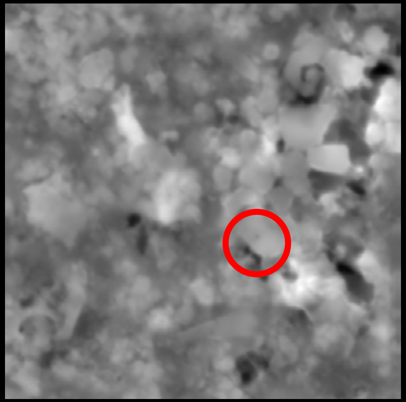
- SN SiC grains have ^{49}Ti enrichments from 2 places:
  - Inner zone where synthesized as ^{49}V (half-life=330 days)
  - He-burning zone (made by n capture); also source of C in grains
- ^{49}Ti-^{28}Si correlation indicates grain formation after ^{49}V decay
  - Indicates SiC grains formed >2 yr after explosion



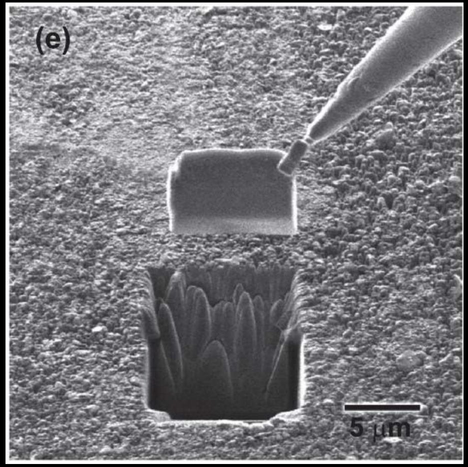
Liu et al., Science Advances, 2018

Presolar grain microstructures

- Transmission electron microscopy can reveal nm-scale crystal structures/compositions
  - Reflect physical/conditions of grain formation in stellar environments
  - Requires state-of-the-art focused ion beam methods to extract sections for TEM

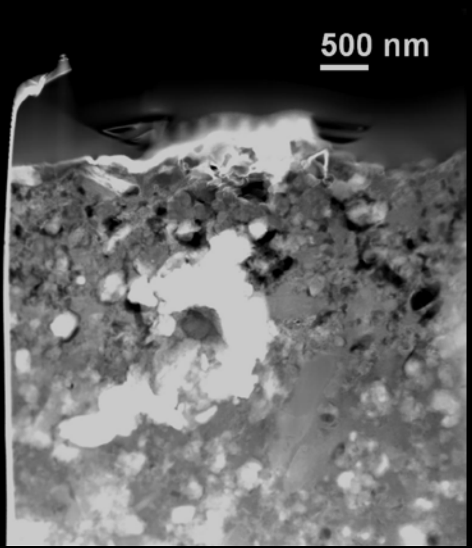


SEM

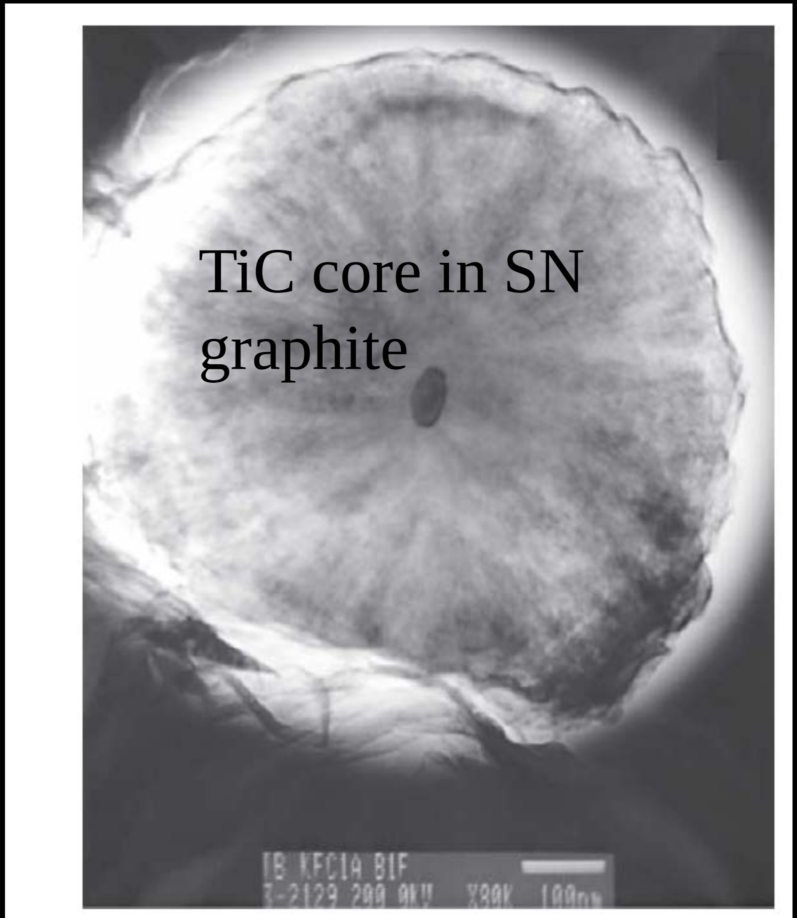


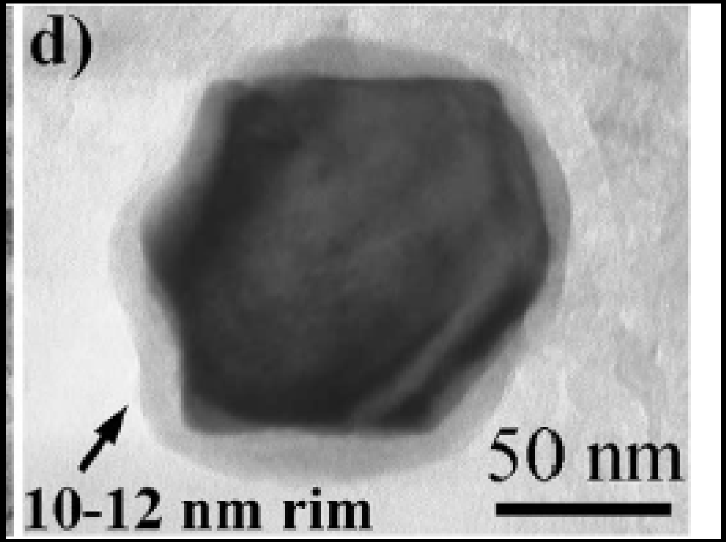
FIB

TEM



Supernova Grain Formation

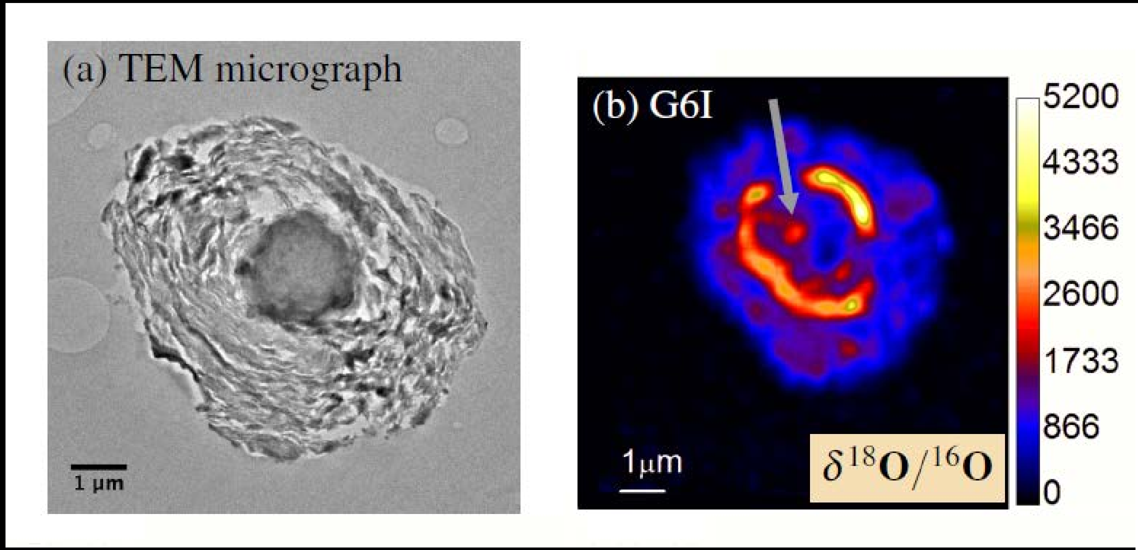


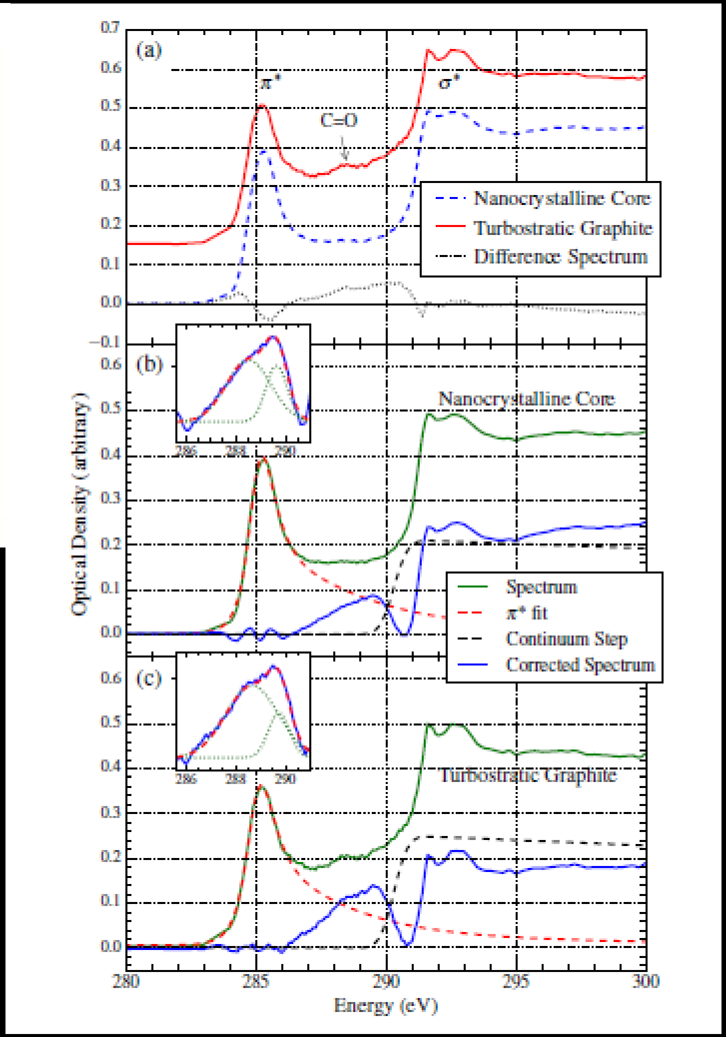


Radiation damaged rim on TiC sub-grain – condensed 1st

- Grains record very complicated growth history
- Changing chemical and physical conditions (temperature, density, composition)

Supernova Grain Formation

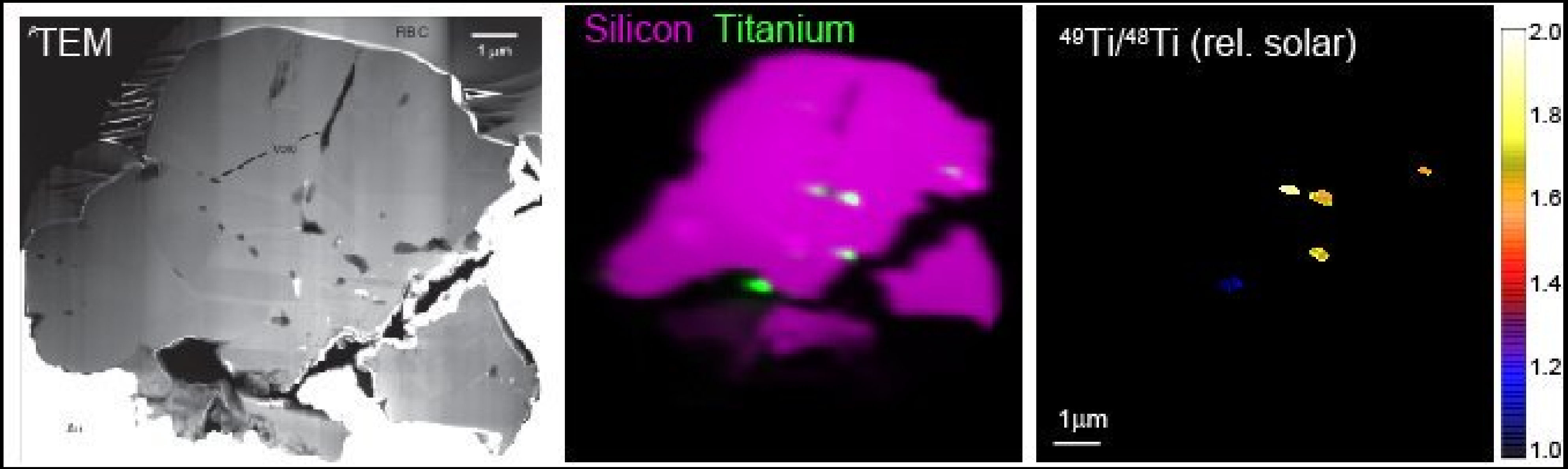




C-edge X-ray Absorption Spectra

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

Supernova Grain Formation



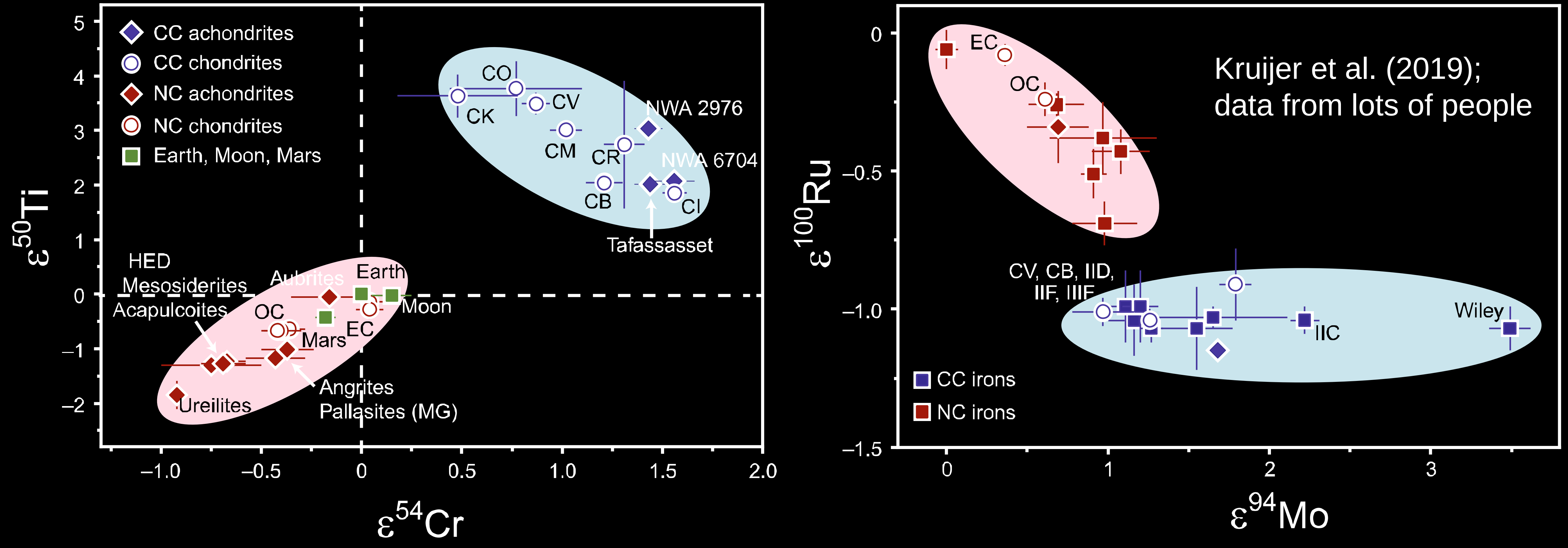
- Grains record very complicated growth history
- Changing chemical and physical conditions (temperature, density, composition)

Isotope measurements of sub-grains now possible (Verdier et al. 2019)

Other types of SNe?

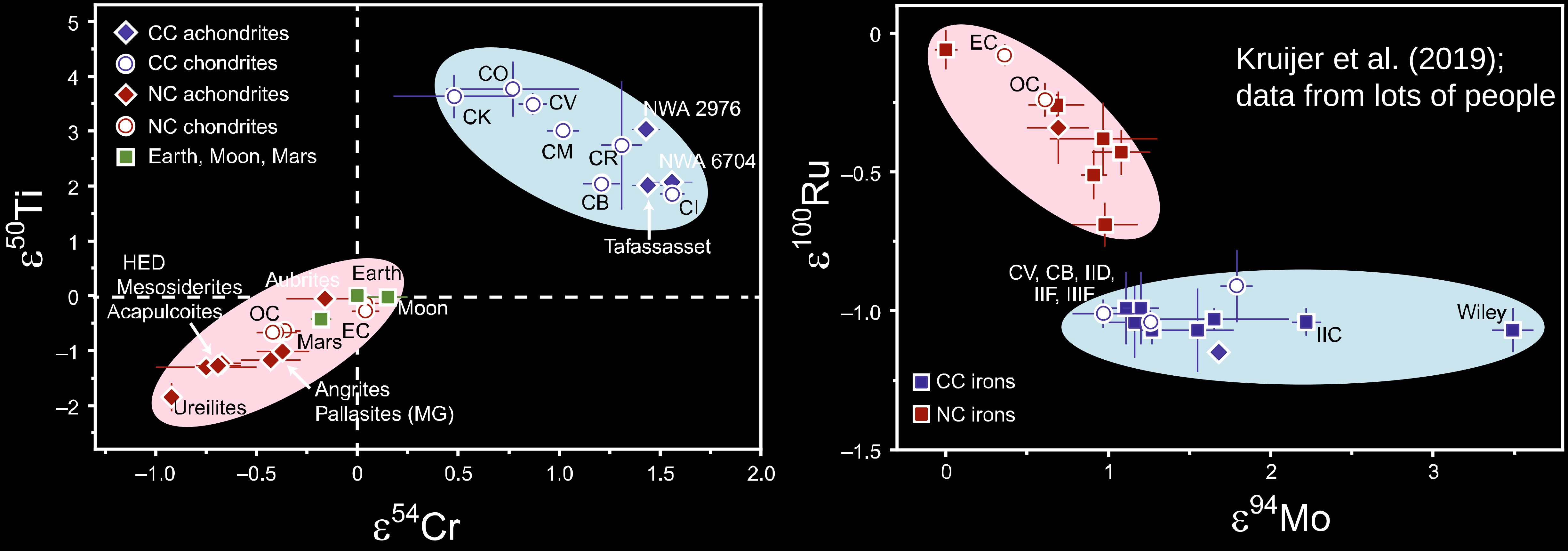
- Do we have presolar grains from supernovae besides Type II?
  – Let’s take a side trip to bulk meteorites ….

Bulk isotope anomalies in Solar System



- ε is 10^{-4} deviation from standard
  - e.g., ε^{54}Cr=1 means 1 parts in 10,000 more ^{54}Cr than Earth (relative to other Cr isotopes)

Bulk isotope anomalies in Solar System

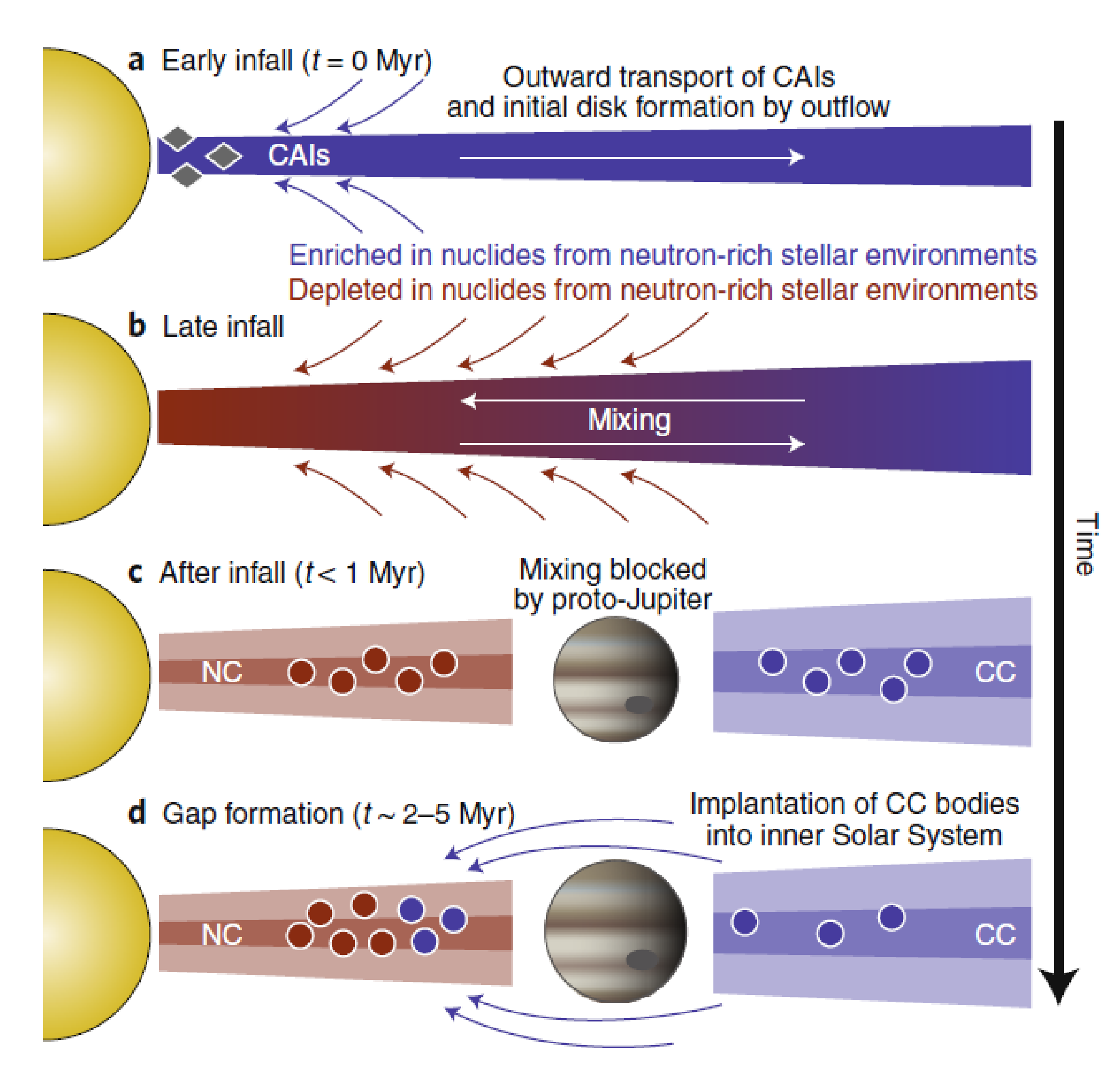


- Two Solar System reservoirs: CC (outer) and NC (inner) with different mix of nucleosynthetic precursors

Bulk isotope anomalies in Solar System

- Lots of models
- Most involve spatio-temporal changes in distribution of presolar stardust grains from distinct stellar sources

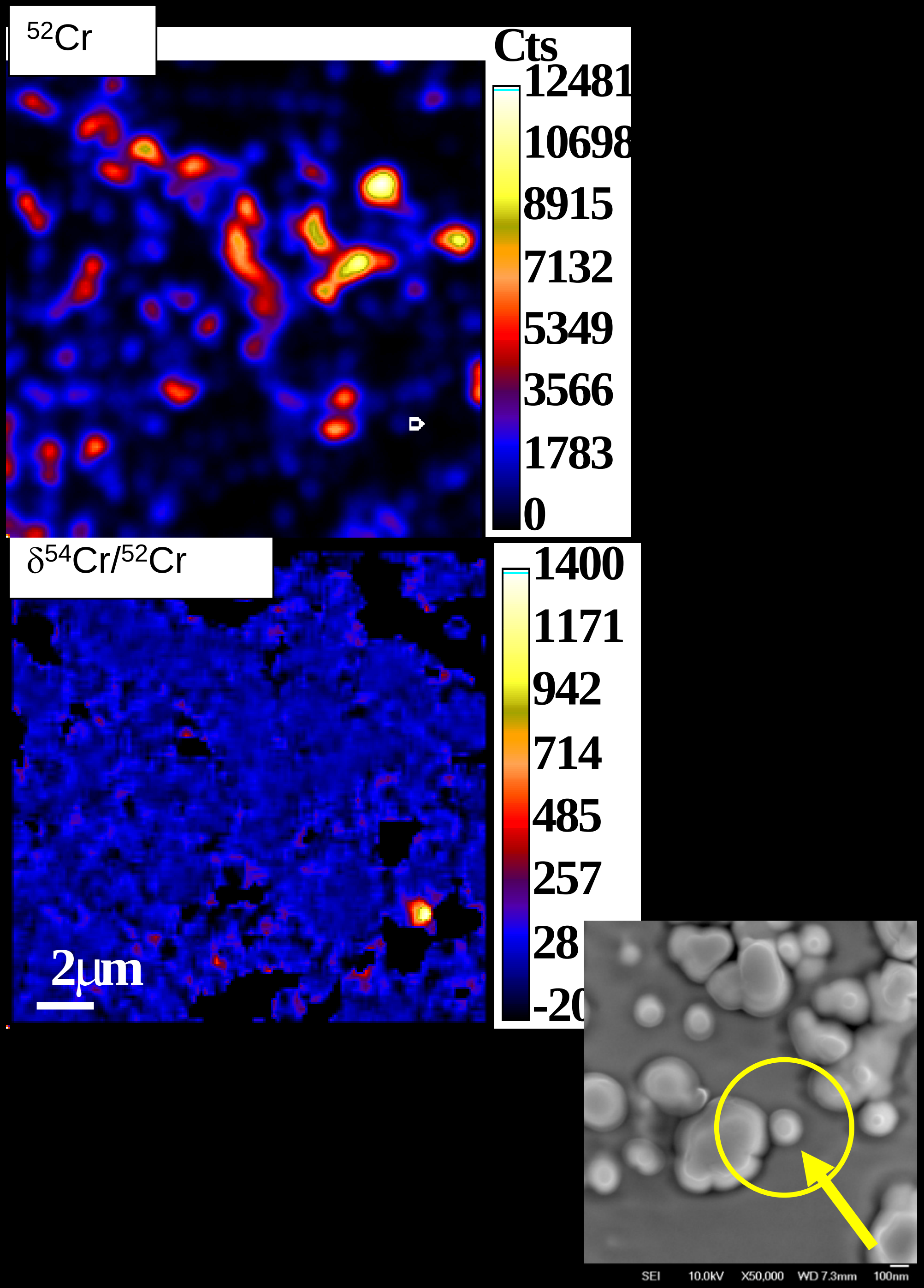
- Can we find presolar grain carriers of bulk anomalies?



Kruijer et al.

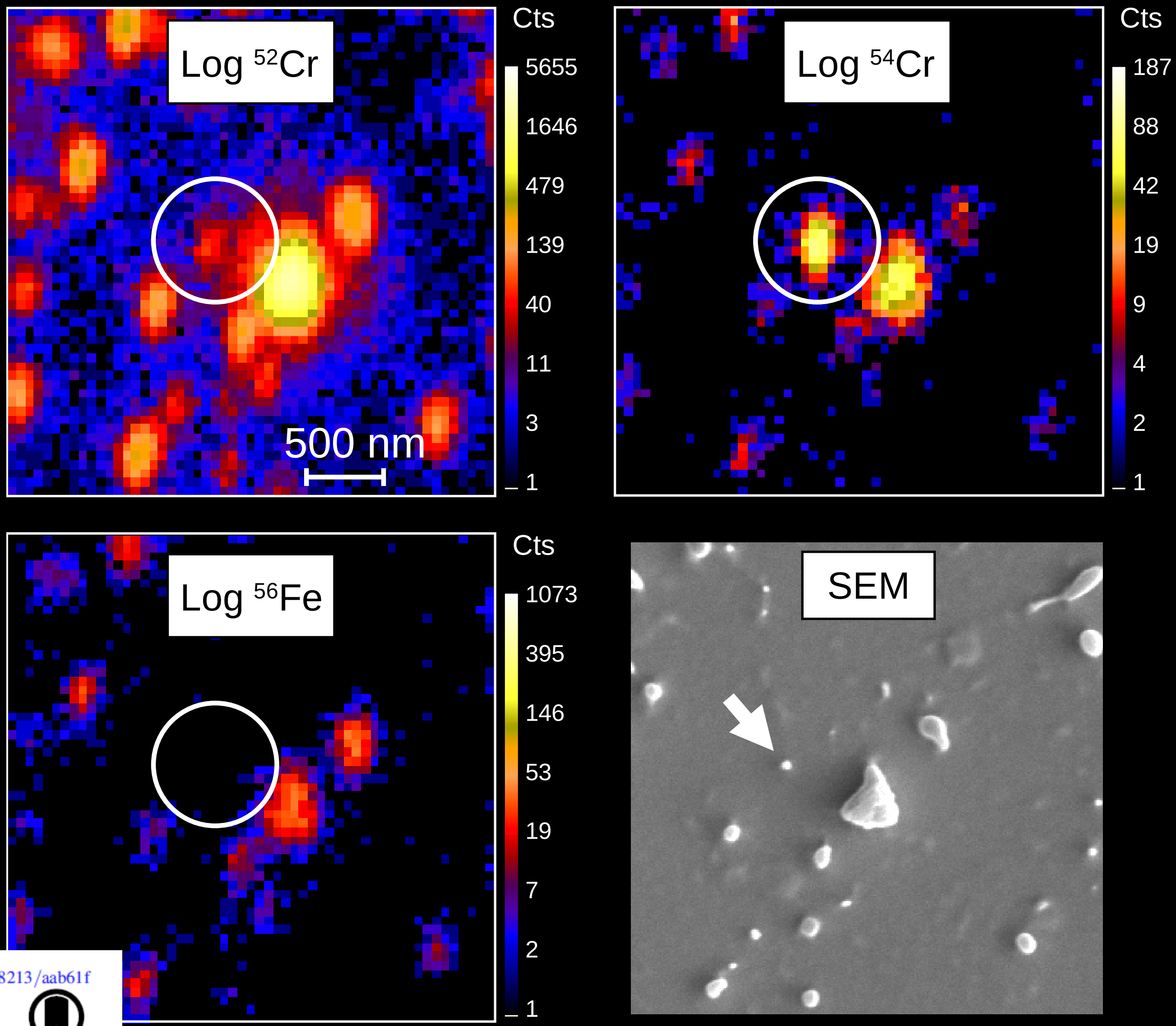
^{54}Cr Carrier

- YES!
  - Dauphas et al. (2010) and Qin et al. (2011) found highly ^{54}Cr-rich sub-μm oxide grains in acid-resistant residues of Orgueil CI chondrite
  - $^{54}Cr/^{52}Cr$ up to 3.5 x Solar
  - But, ion probe beam size much larger than grains –isotope dilution makes measured ratios lower limits
    - Makes stellar origin ambiguous



^{54}Cr-rich grains

- 2017: obtained new high-resolution ion source, revisited ^{54}Cr problem
- Identified additional ^{54}Cr-rich grains, without dilution problems!



THE ASTROPHYSICAL JOURNAL LETTERS, 856:L24 (7pp), 2018 April 1
https://doi.org/10.3847/2041-8213/aab61f

CrossMark

Extremely ^{54}Cr- and ^{50}Ti-rich Presolar Oxide Grains in a Primitive Meteorite: Formation in Rare Types of Supernovae and Implications for the Astrophysical Context of Solar System Birth

Larry R. Nittler, Conel M. O'D. Alexander, Nan Liu[1], and Jianhua Wang
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Received 2018 February 24; accepted 2018 March 11; published 2018 March 27

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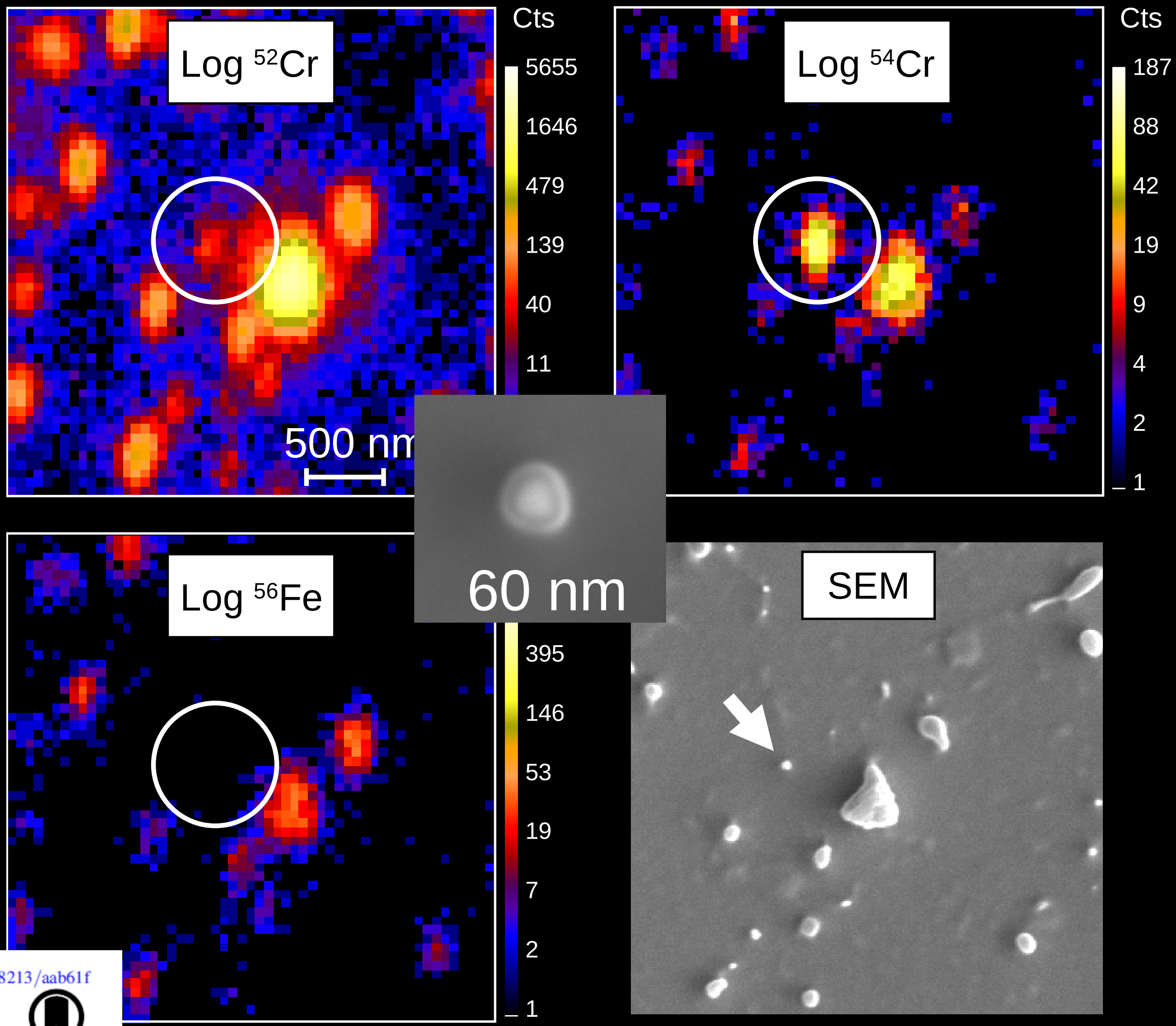

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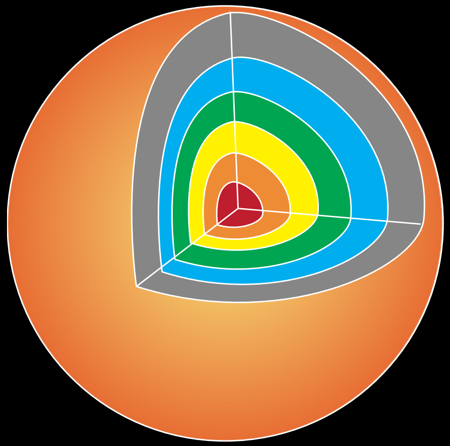
Origin(s) of ^{54}Cr-rich Grains?

- Extreme ^{54}Cr enrichment requires *supernova* source

- Type II SN?
  - Make ^{54}Cr, ^{50}Ti by neutron capture during core and shell He- and C-burning
  - Ruled out by poor match to data!



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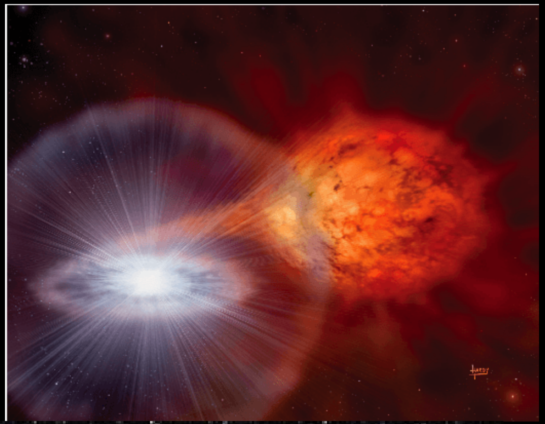
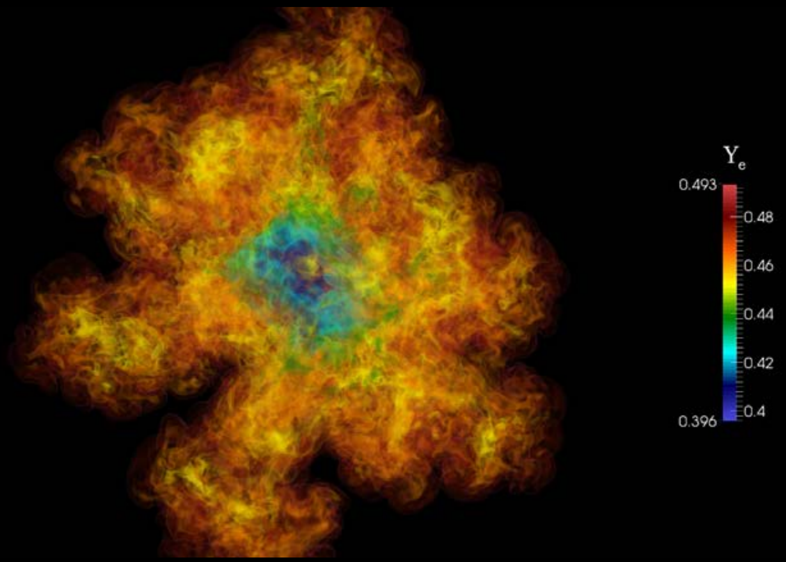


- High-density Type Ia?
- If WD material at particularly high density, low-entropy conditions lead to very n-rich nucleosynthesis, possible source of rare nuclei like ^{48}Ca, ^{50}Ti, ^{54}Cr (e.g., Meyer et al. 1996; Woosley 1997; Yu & Meyer 2013)
- Not known if exist!

Origin(s) of ^{54}Cr-rich Grains?

- Extreme ^{54}Cr enrichment requires *supernova* source

- Electron-capture supernova?
  - Possible end-stage of life of stars of ~7-10 solar masses (following "Super-AGB" phase, which may produce lots of *s*-process, short-lived radioactivities [Trigo-Rodriguez + 2009])
  - Not known if exist!



Electron Capture Supernovae (ECSN)

- If ONeMg core of super-AGB star reaches Chandrasekhar mass, electron captures on ^{20}Ne *may* lead to thermonuclear runaway and stellar explosion. Ejecta characterized by very neutron-rich material.

Two proposed types

c-ECSN

- Core collapses to form neutron star, shock wave ejects newly formed material
  - Nomoto et al. (1984), Doherty et al (2017)

t-ECSN

- Thermonuclear runaway leads to explosion before core can collapse
  - Jones et al. (2016, 2018)

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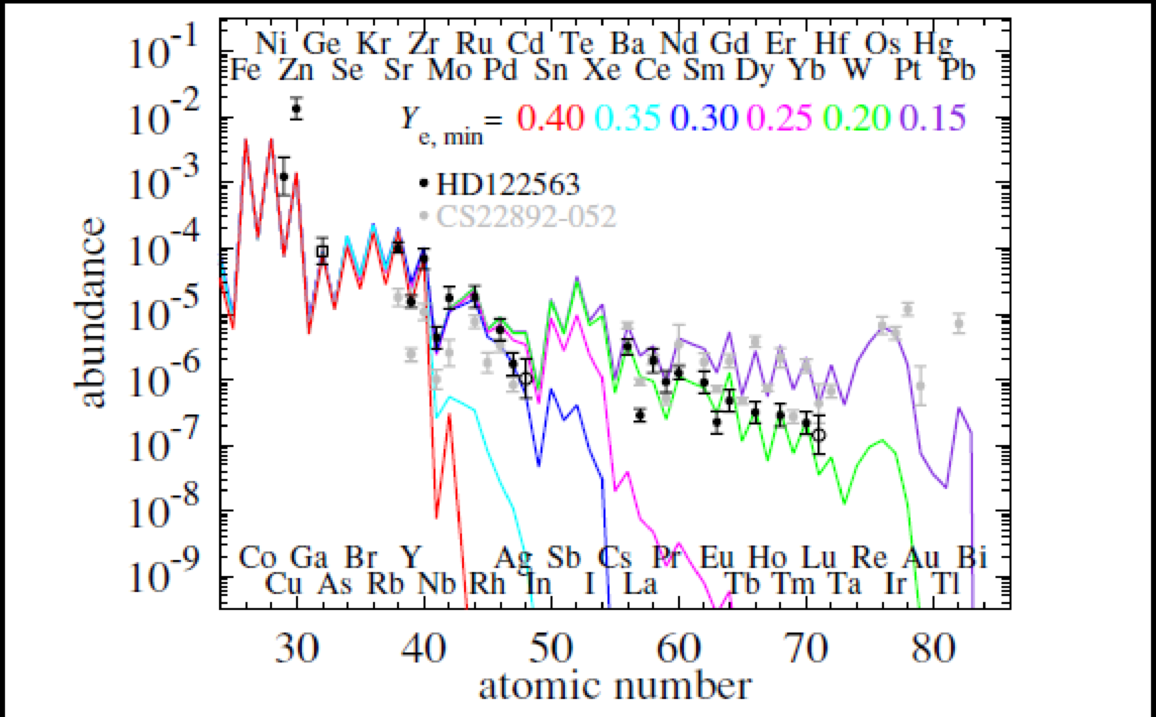
- Thermonuclear runaway leads to explosion before core can collapse
  - Jones et al. (2016, 2018)

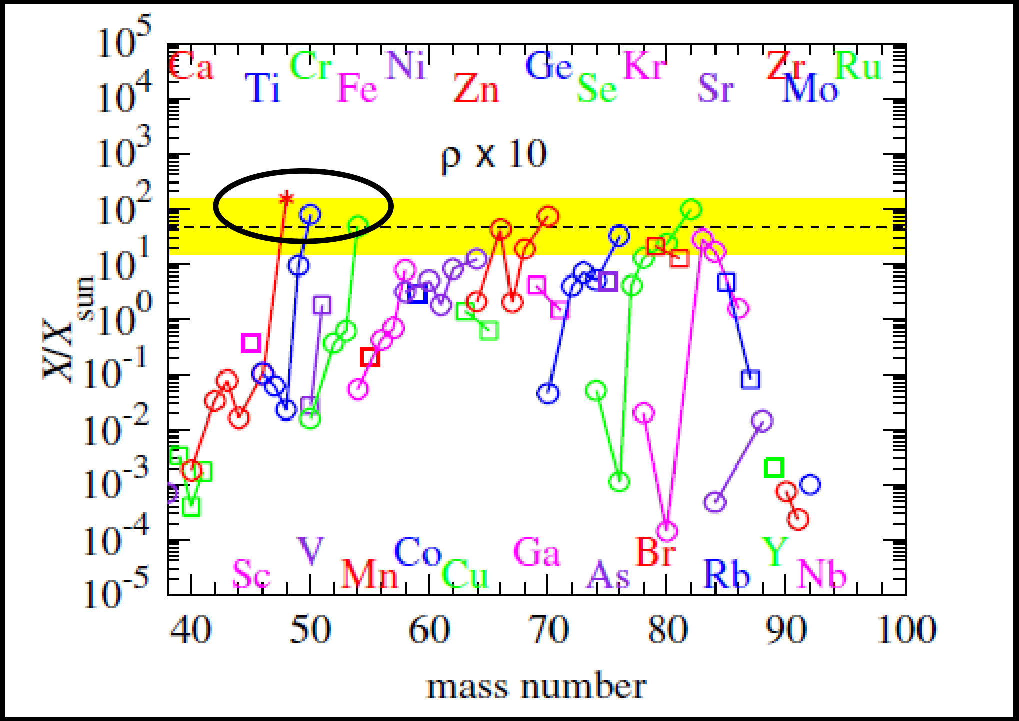
Caveat: unknown if ECSN actually occur!

c-ECSN nucleosynthesis

- Eject ~10^{-2} $M_\odot$ material, very n-rich ejecta

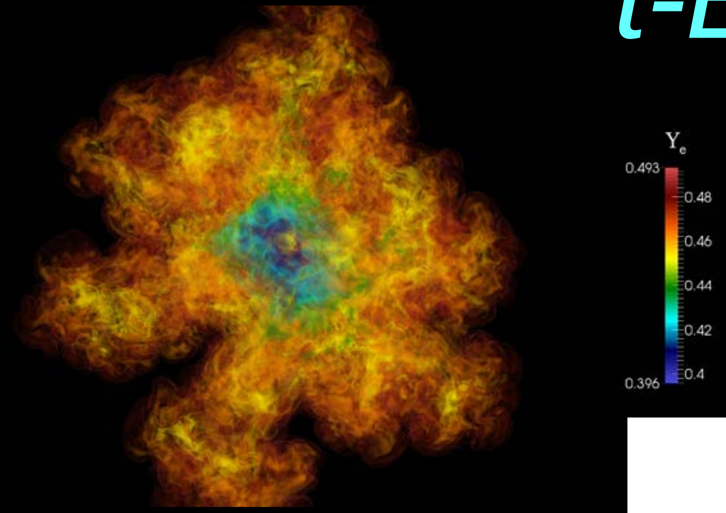


Light *r*-process peak production in c-ECSN
(Wanajo et al 2011)



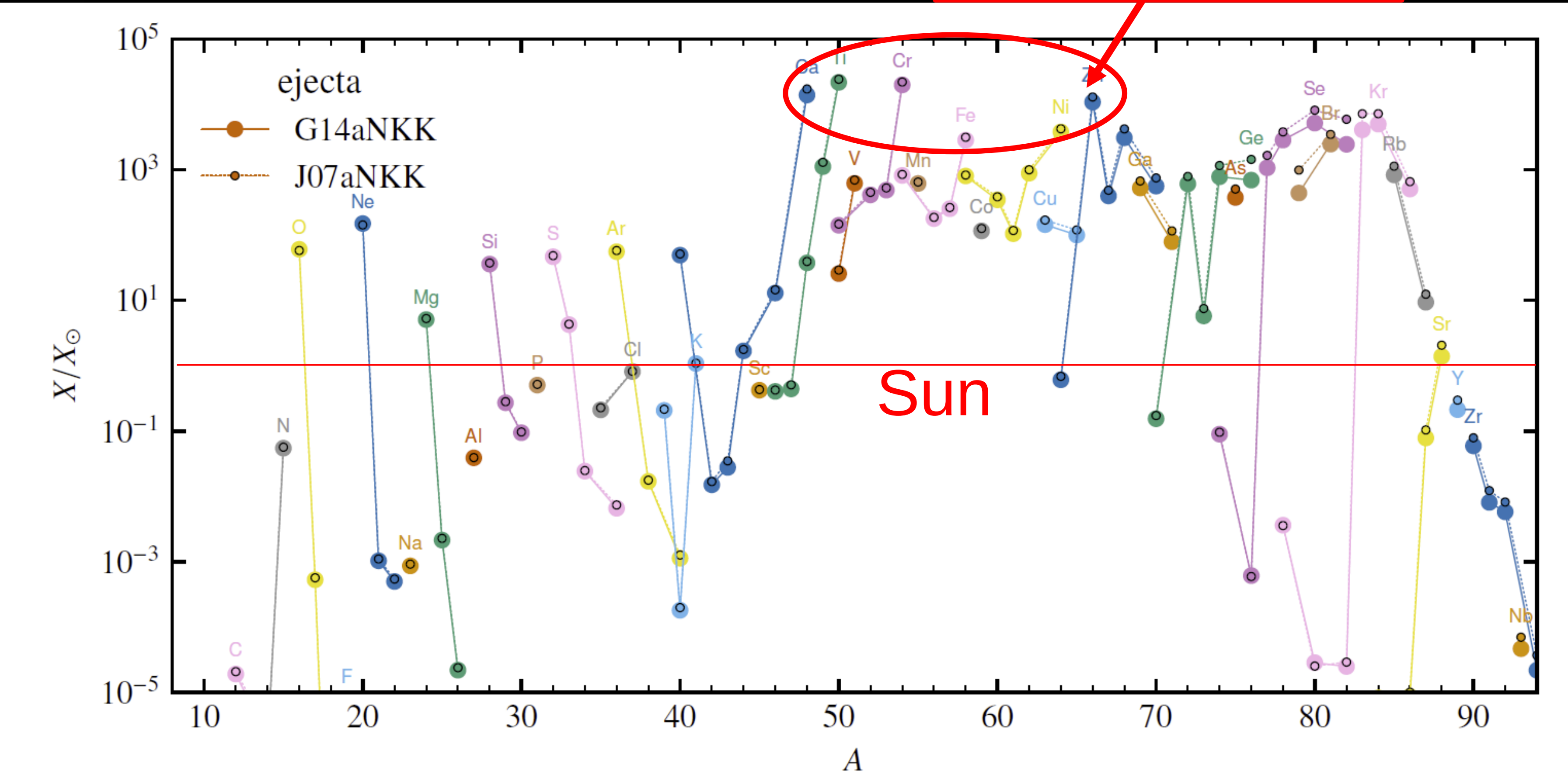
^{48}Ca, ^{50}Ti, ^{54}Cr production in c-ECSN
(Wanajo et al 2013)

t-ECSN nucleosynthesis



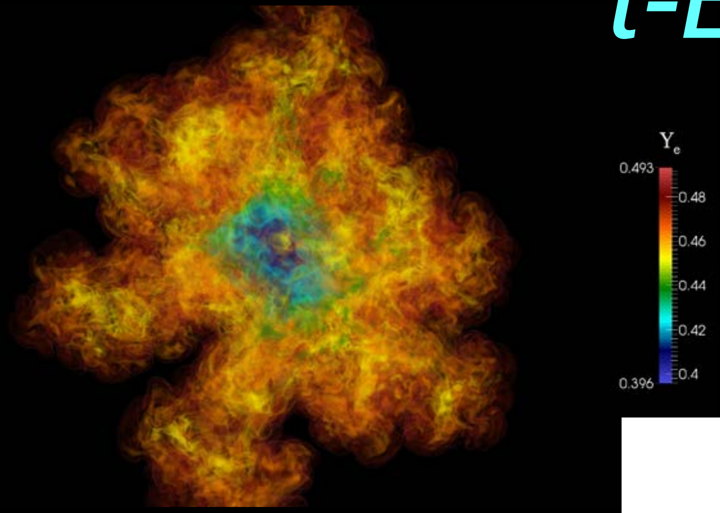
- Eject 0.1-1 $M_\odot$ material, very n-rich ejecta

^{48}Ca, ^{50}Ti, ^{54}Cr, ^{60}Fe
^{64}Ni, ^{66}Zn



(Jones et al., A&A 2019)

t-ECSN nucleosynthesis



- Eject 0.1-1 $M_\odot$ material, very n-rich ejecta,
- Also O, Mg, Si

^{48}Ca, ^{50}Ti, ^{54}Cr, ^{60}Fe
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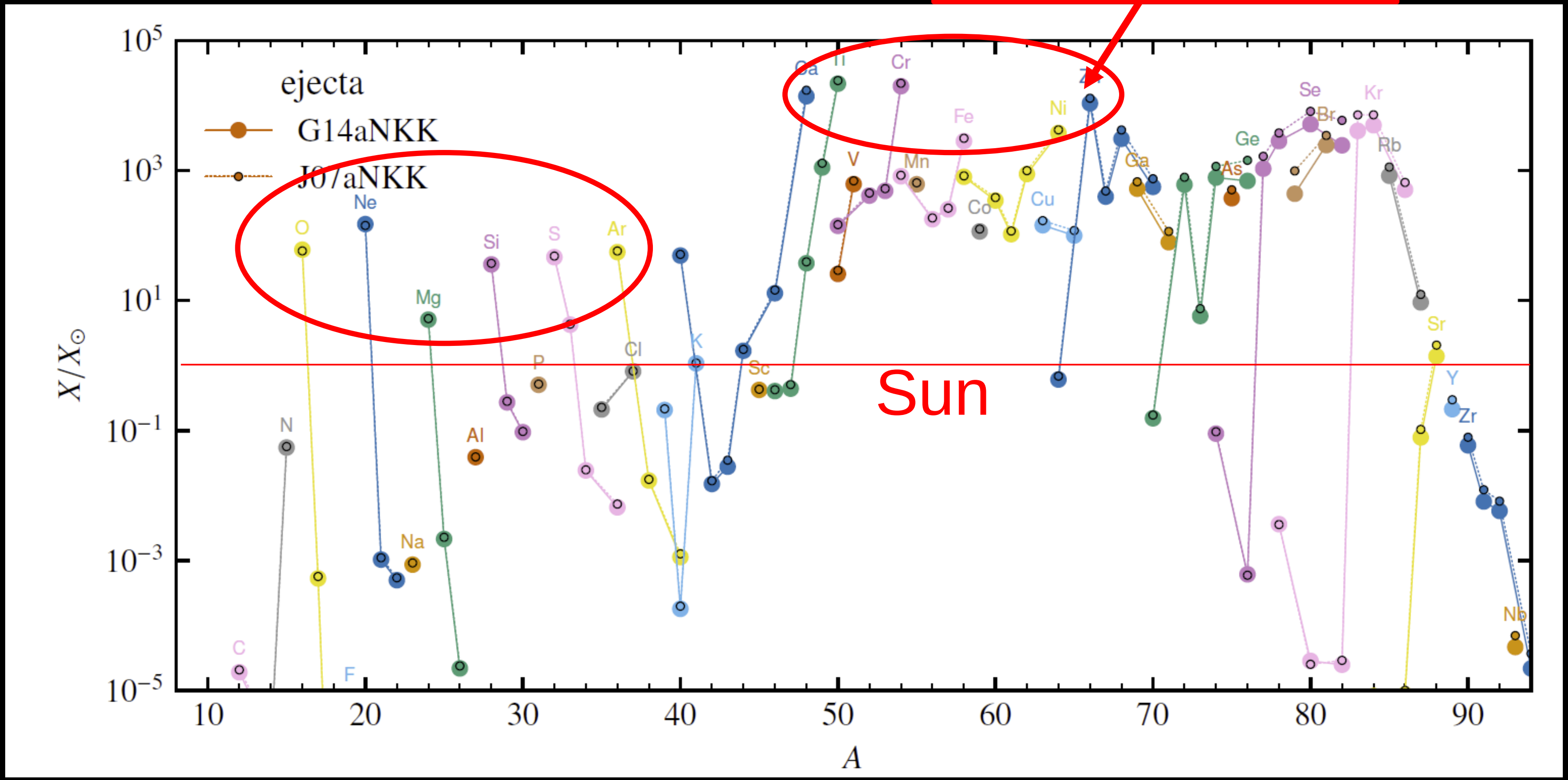
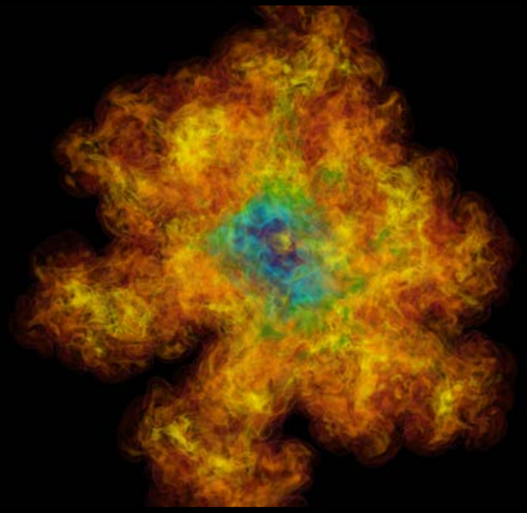
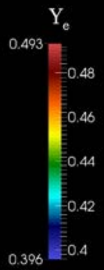


(Jones et al., A&A 2019)

t-ECSN nucleosynthesis





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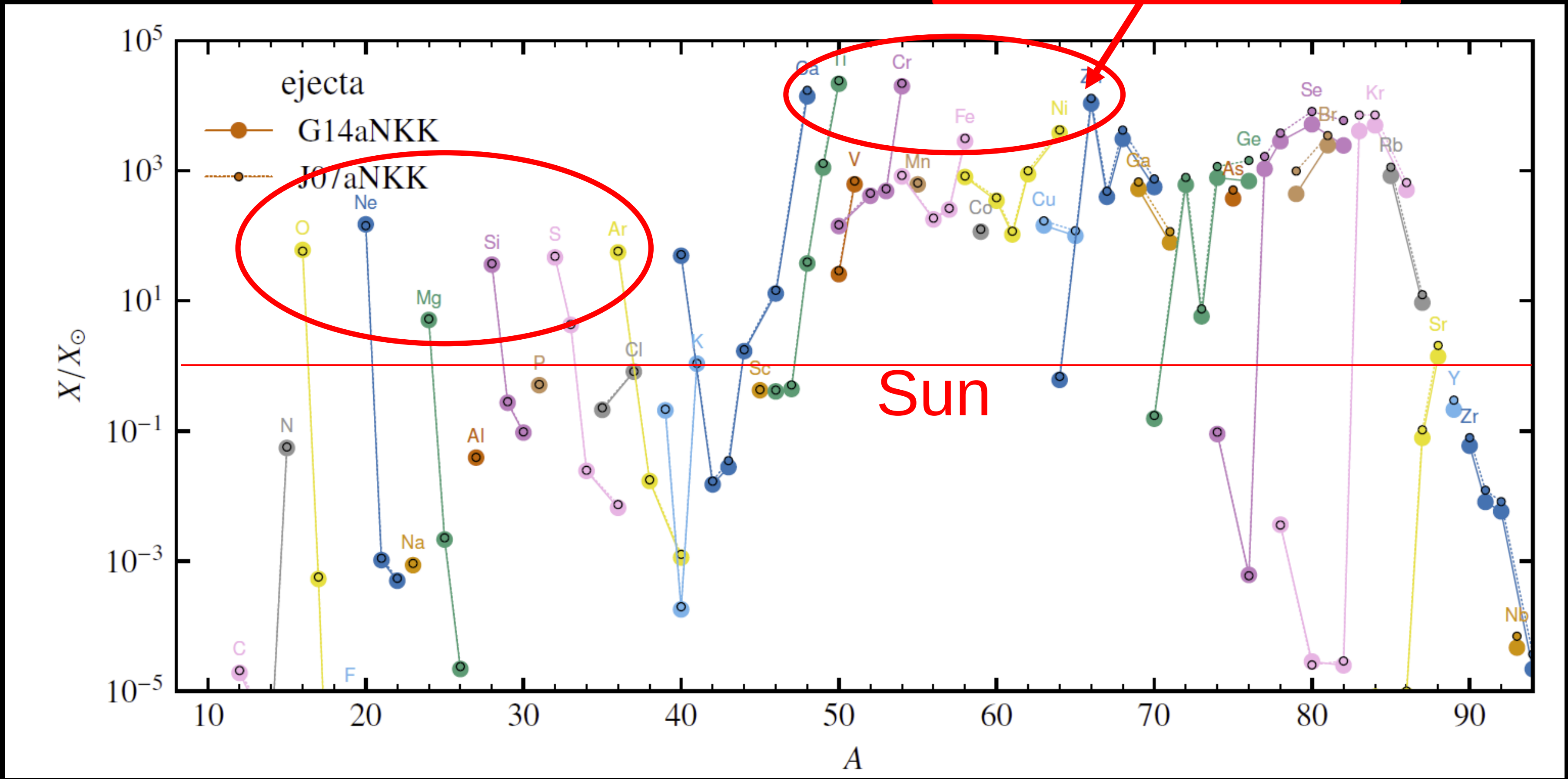
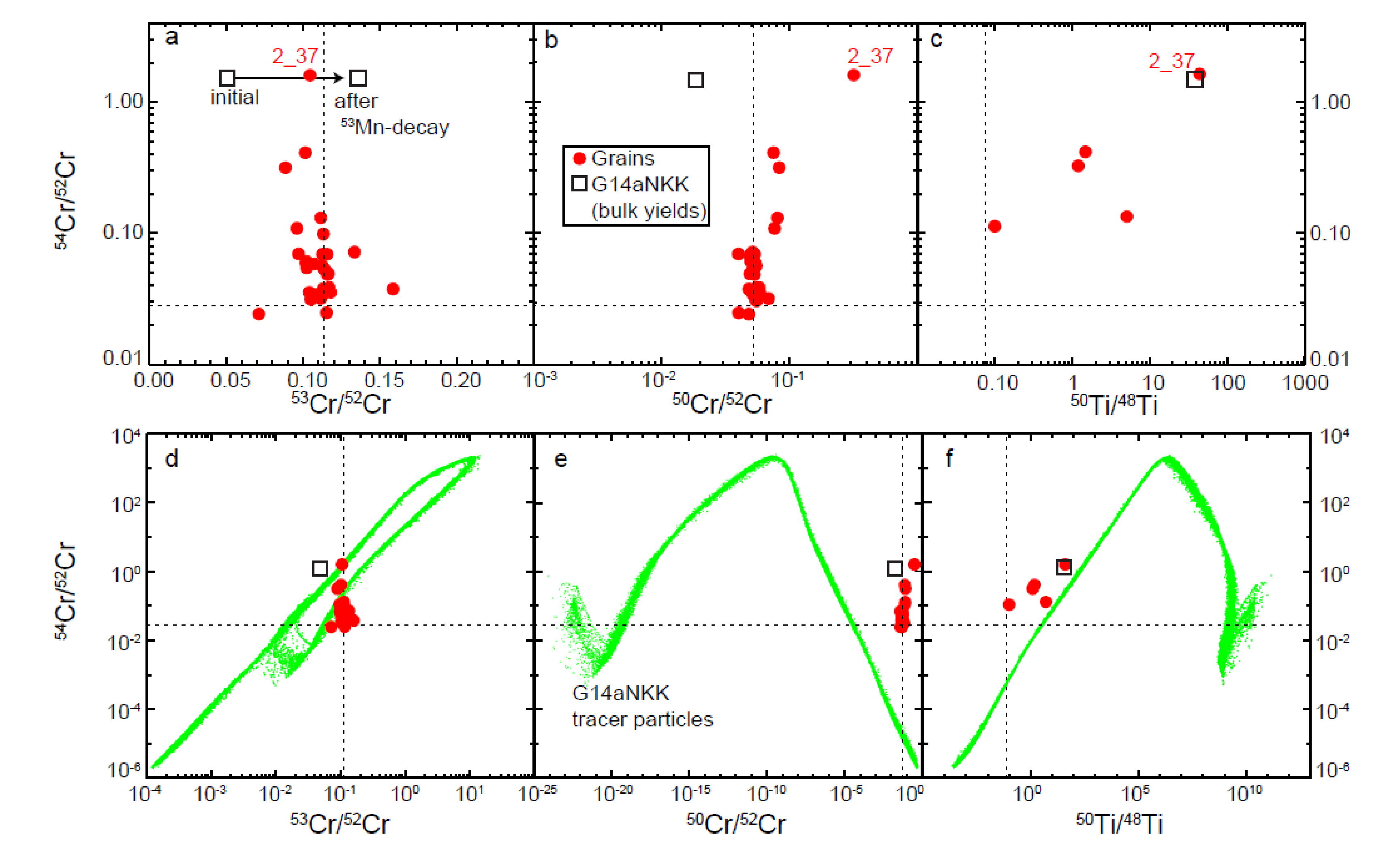


t-ECSN = "high-density SNIa "? (Meyer 1996; Woosley & Weaver 1995)

(Jones et al., A&A 2019)

t-ECSN nucleosynthesis

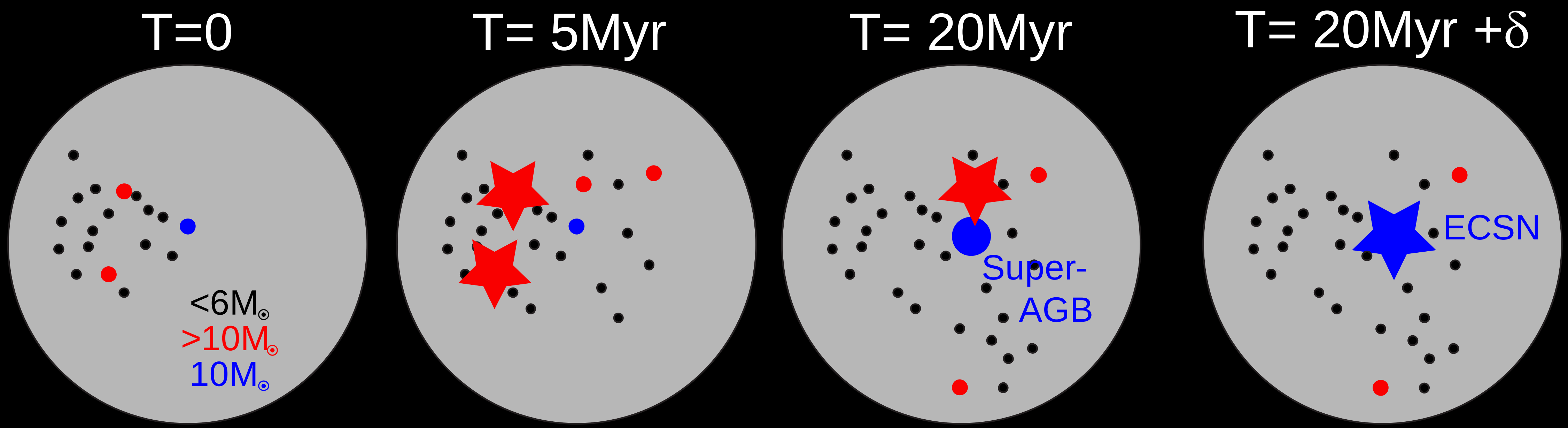
- Excellent match of composition to most extreme ^{54}Cr- and ^{50}Ti-rich presolar grain (Nittler et al. 2018; Jones et al. 2019)



ECSN and the Solar System?

- Neutron-rich nucleosynthesis may explain bulk isotope anomalies

- Lifetime of S-AGB stars range from ~20-50 MY
  - Overlaps with star-forming region lifetimes
  - Plausible interaction with nascent Solar System (much less likely for lower-mass AGB, SNIa, neutron star mergers etc)
  - Self-pollution of Sun's parental cloud?

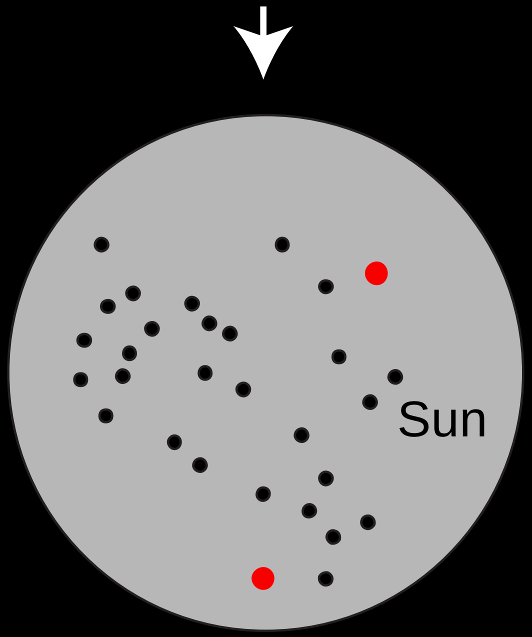


- Advantage:

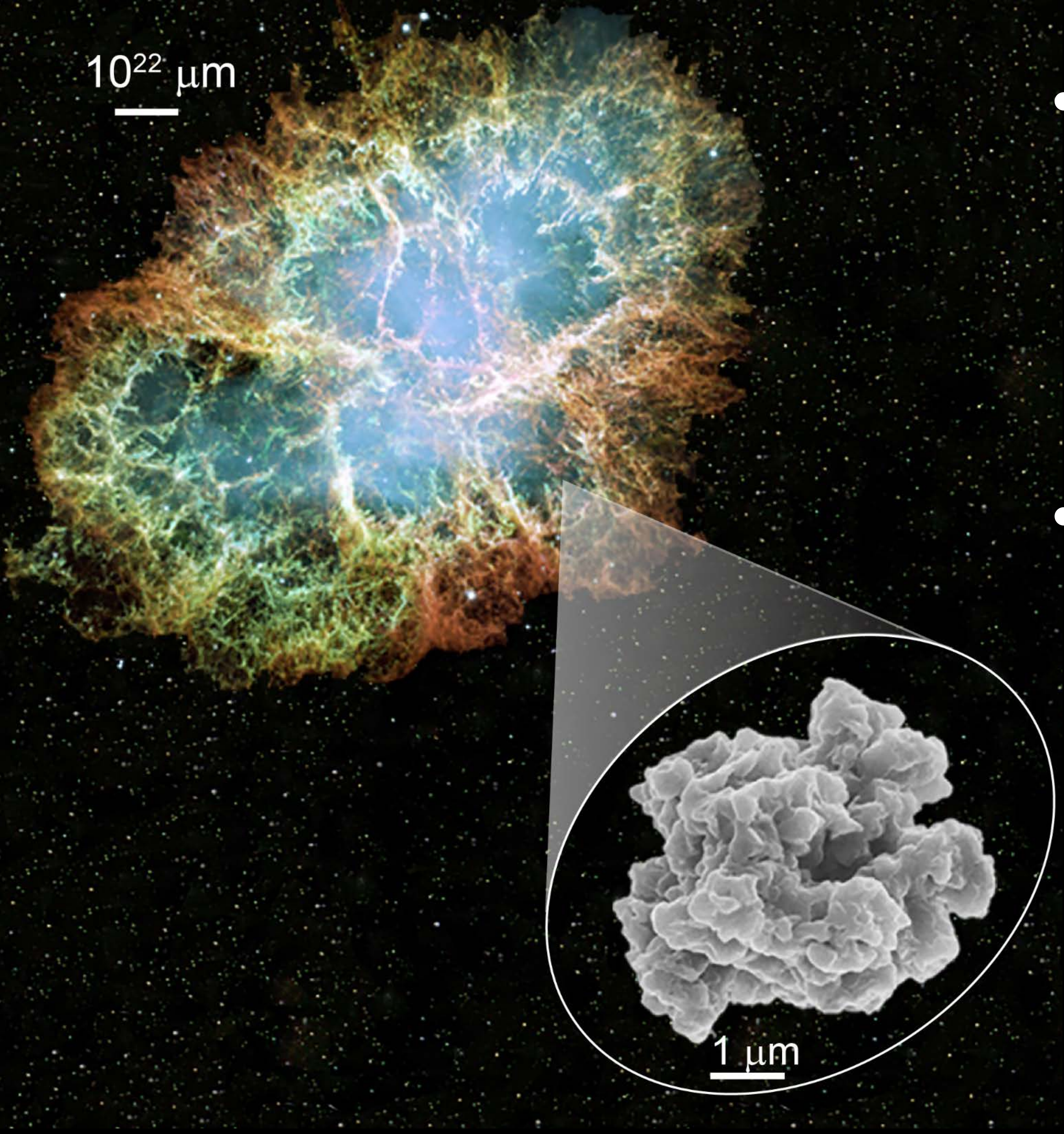
  Nucleosynthetic site that best explains correlations of light n-rich and r-process Mo, timescale ~works

- Disadvantages:

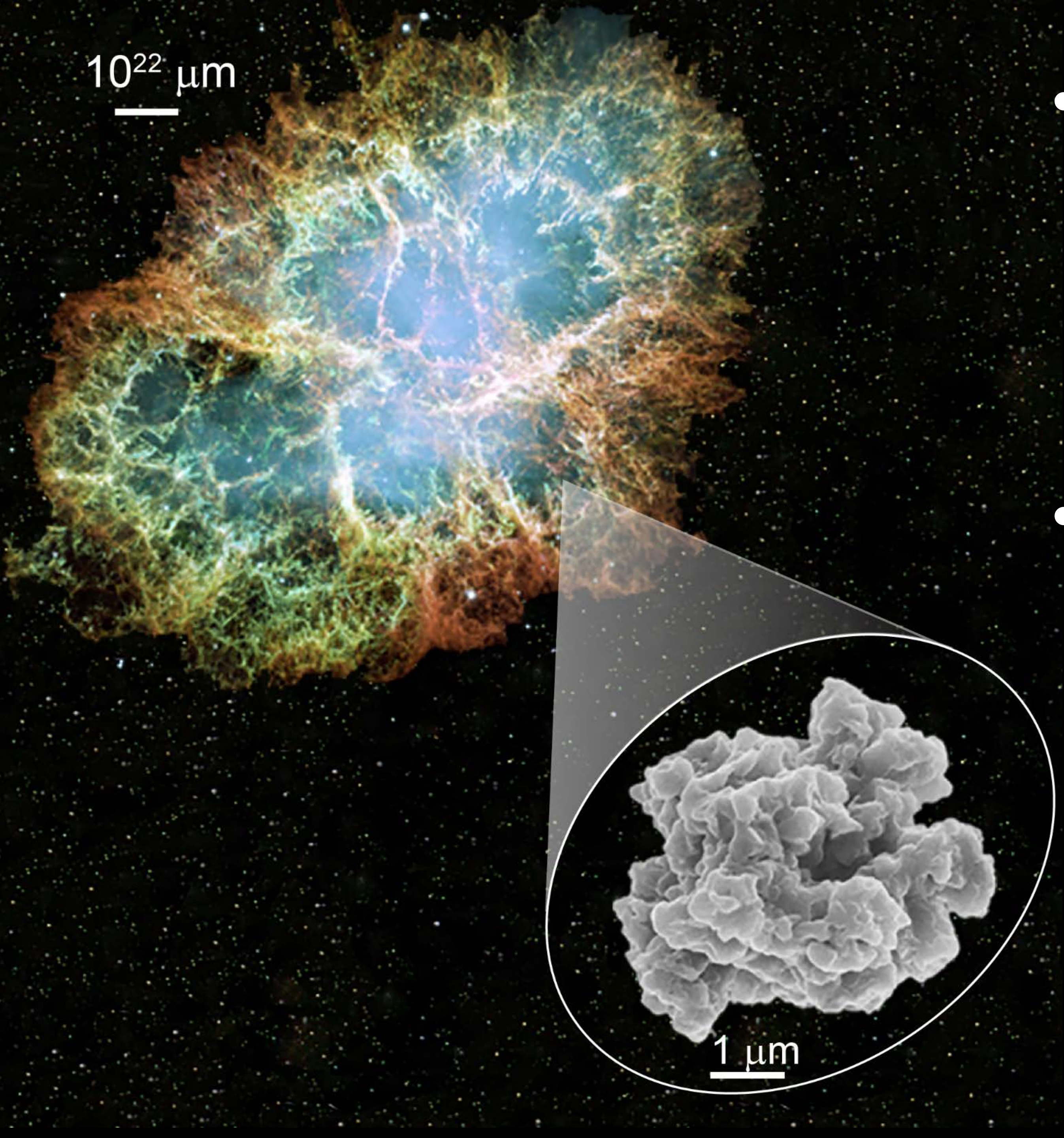
  Don’t know if ECSN exist, modeling very uncertain, need to find more presolar carriers



Inspired by SPACE model of M. Gounelle et al.



- Presolar stardust in meteorites allows us to probe stars in the laboratory!
  - Take advantage of advanced microanalytical technologies
- Presolar supernova grains provide important astrophysical information unobtainable any other way
  - Nucleosynthesis, grain formation, timescales …



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THANK YOU!