

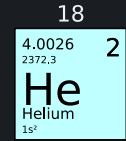
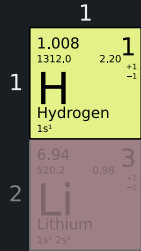
Studying the galactic chemical evolution of isotopes by analyzing presolar grains

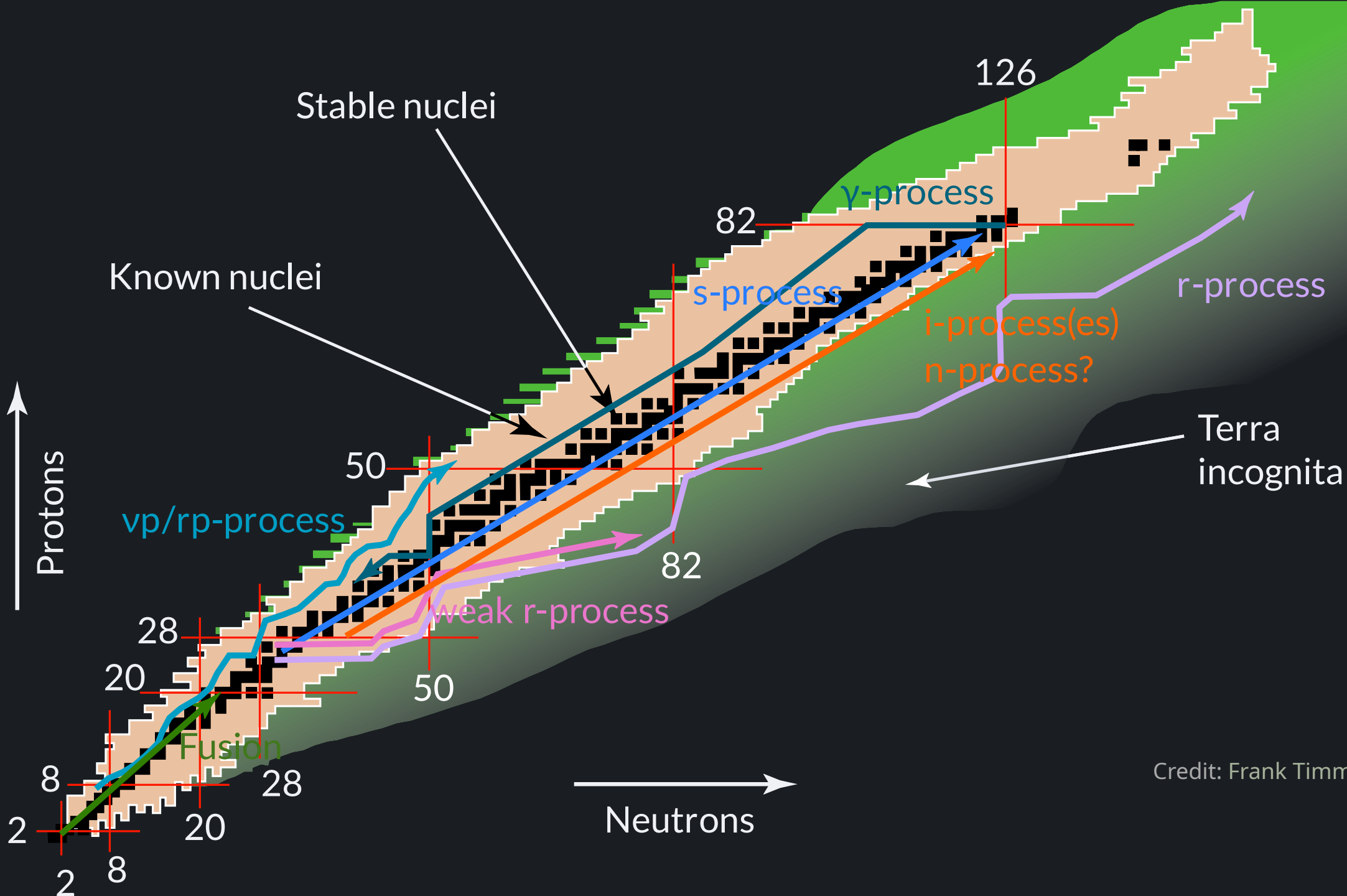
Reto Trappitsch

April 11, 2025

EPFL

The Big Bang made mainly hydrogen and helium





Credit: Frank Timmes

Observations allow us to decipher the details

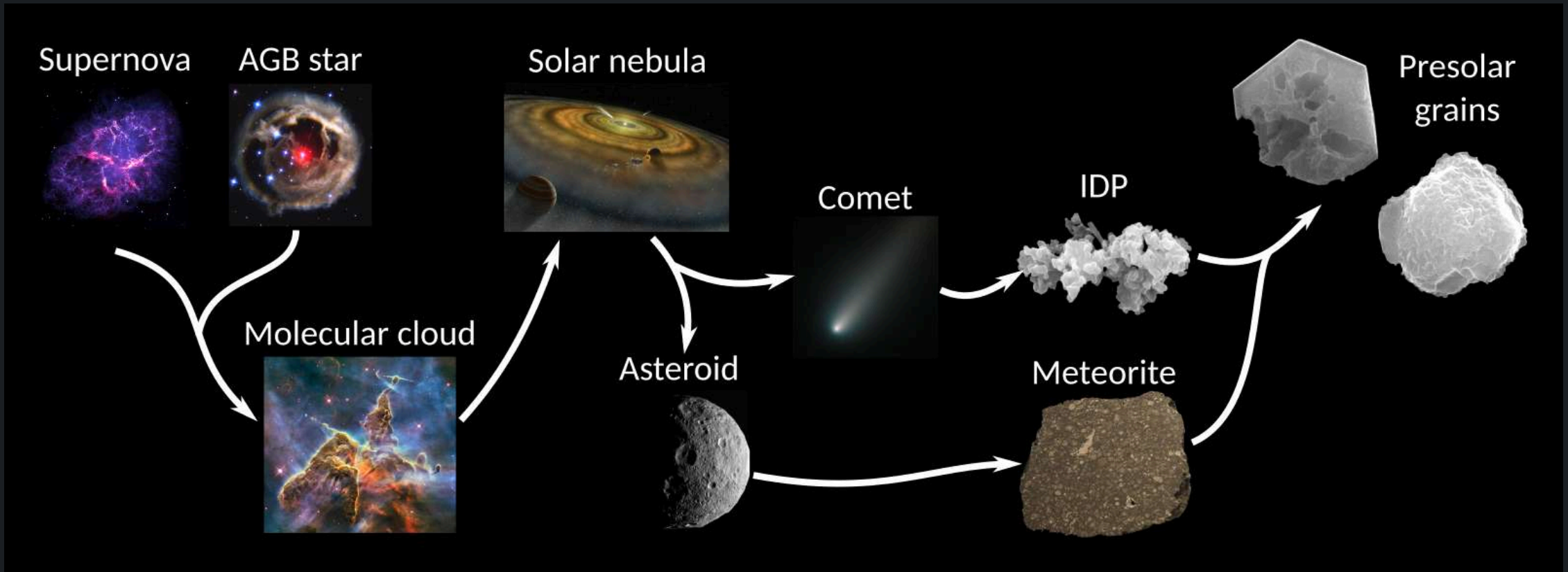
- Spectroscopy to determine elemental abundances
- Relate to nucleosynthesis
 - E.g., Observation of live Tc in AGB stars (Merrill, 1952)
 - Origin of s-process
- Study galactic chemical evolution by observing metal-poor stars

We also have stellar messengers in the solar system!



VLT, Credit: ESO/José Francisco Salgado (josefrancisco.org)

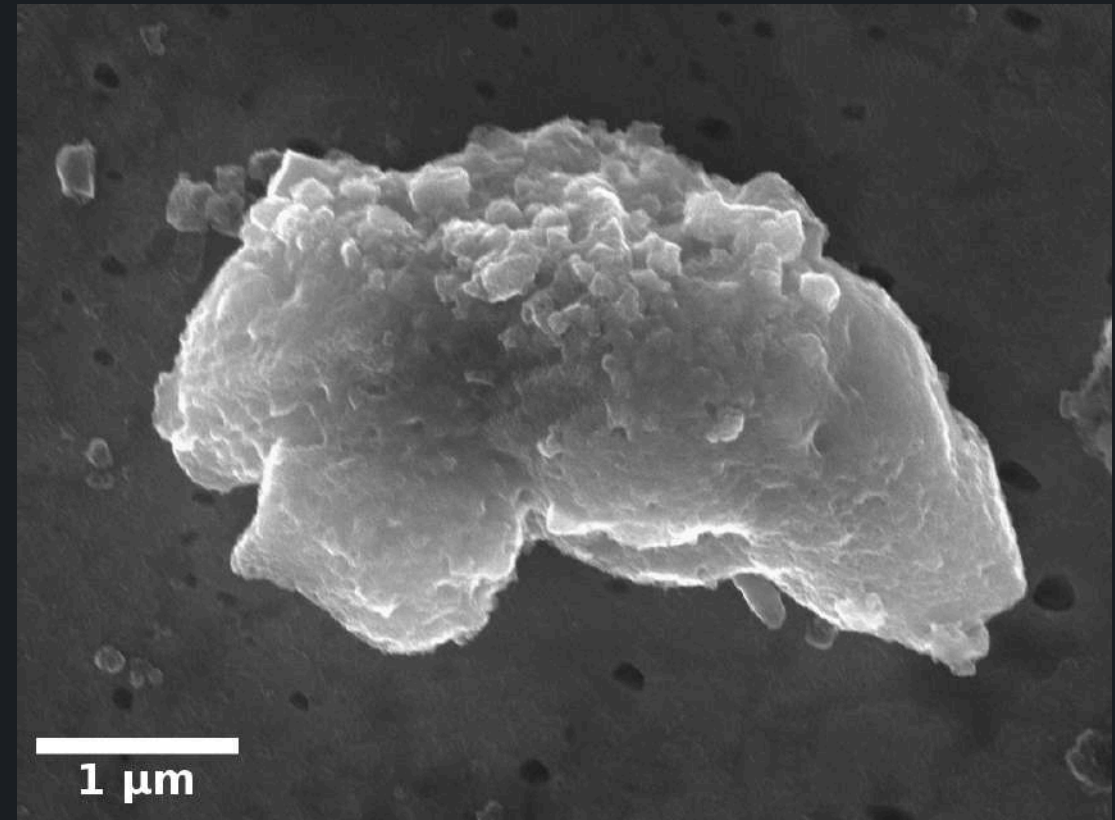
Stellar messengers in our solar system



A zoo of presolar grains

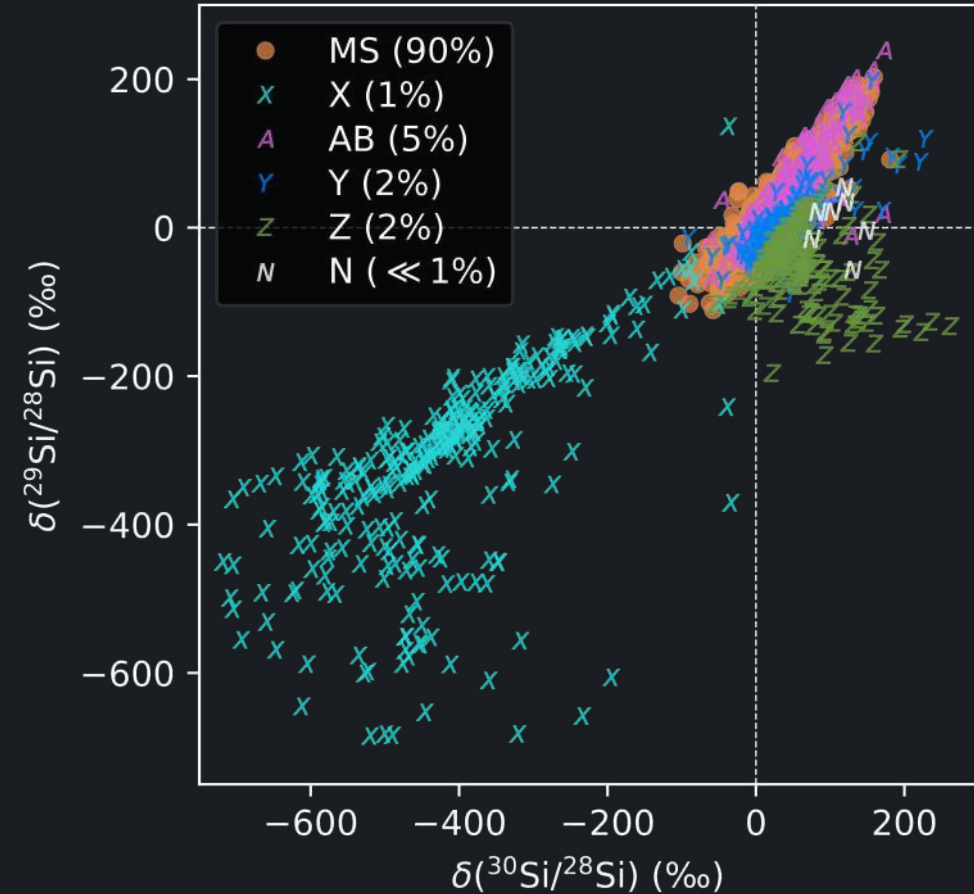
- Nanodiamonds: $\sim 10^3 - 10^4$ atoms
- Silicon carbide: The hardy ones
- Graphites: Large but fragile
- Silicates & Oxides: Small and fragile

Silicon Carbide (SiC) are the best studied phase due to their size and hardness



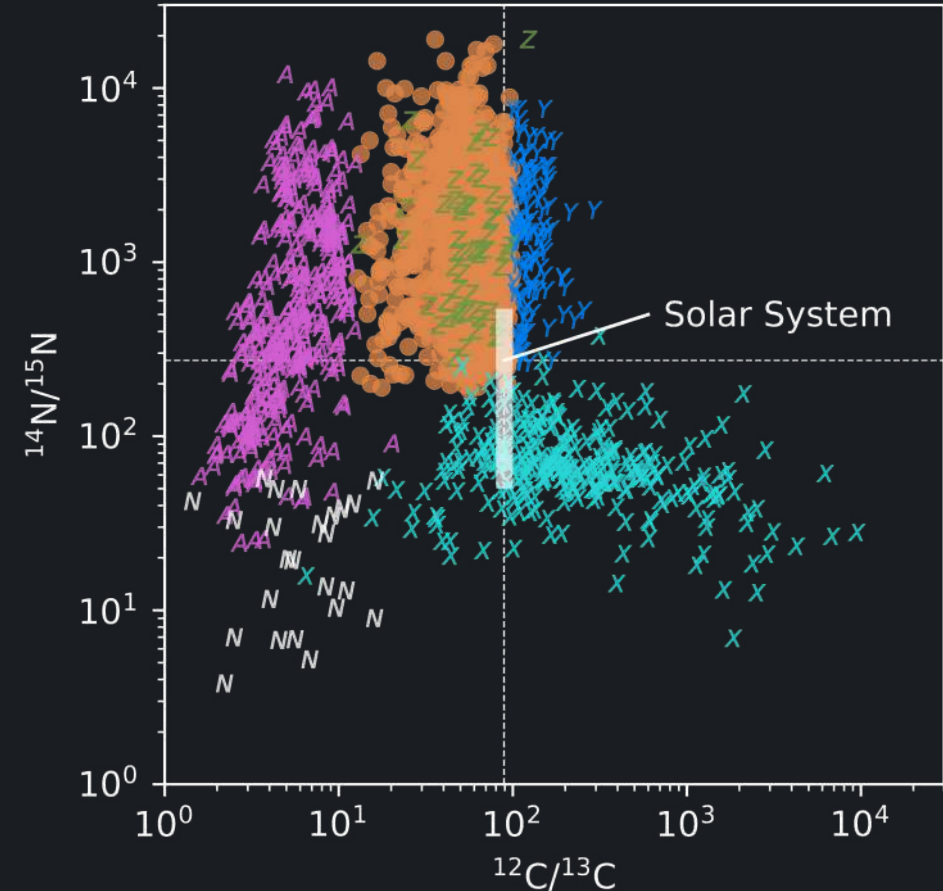
Silicon Carbide grains: Are they presolar?

- δ -units: Deviation from solar in ‰
- Presolar grains have extreme isotope compositions
- Classified by analyzing Si, C, & N isotopes
- Fingerprint of the parent star's composition
- Hands-on astrophysical samples
 - Galactic chemical evolution
 - Stellar nucleosynthesis

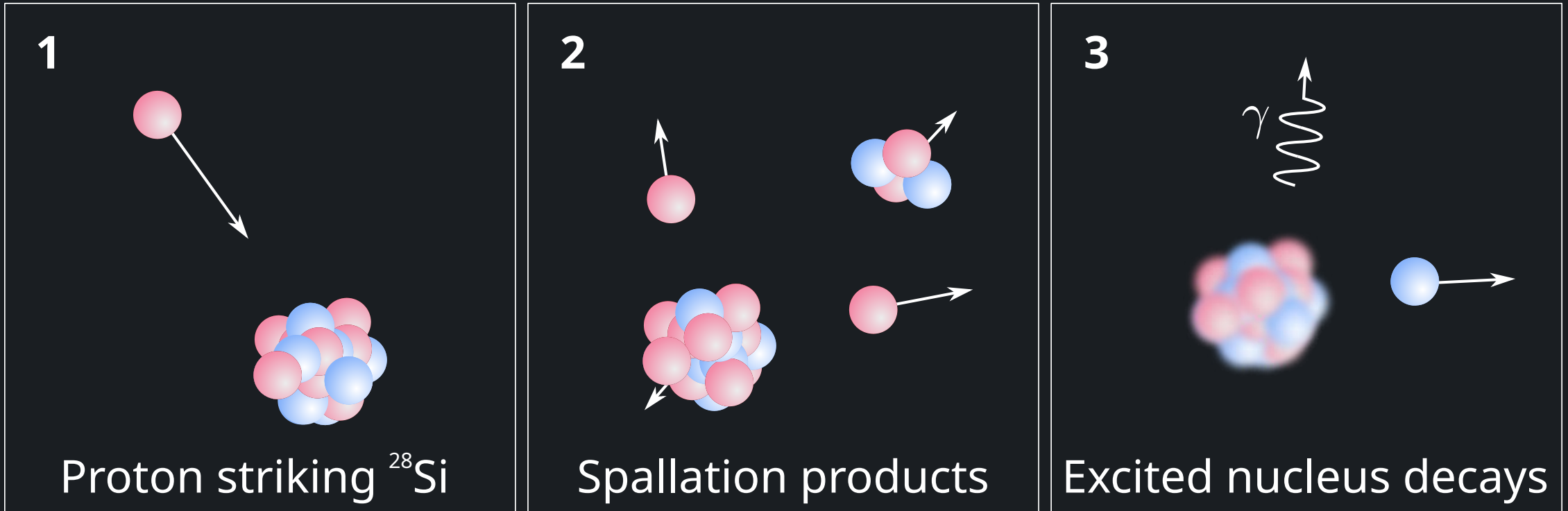


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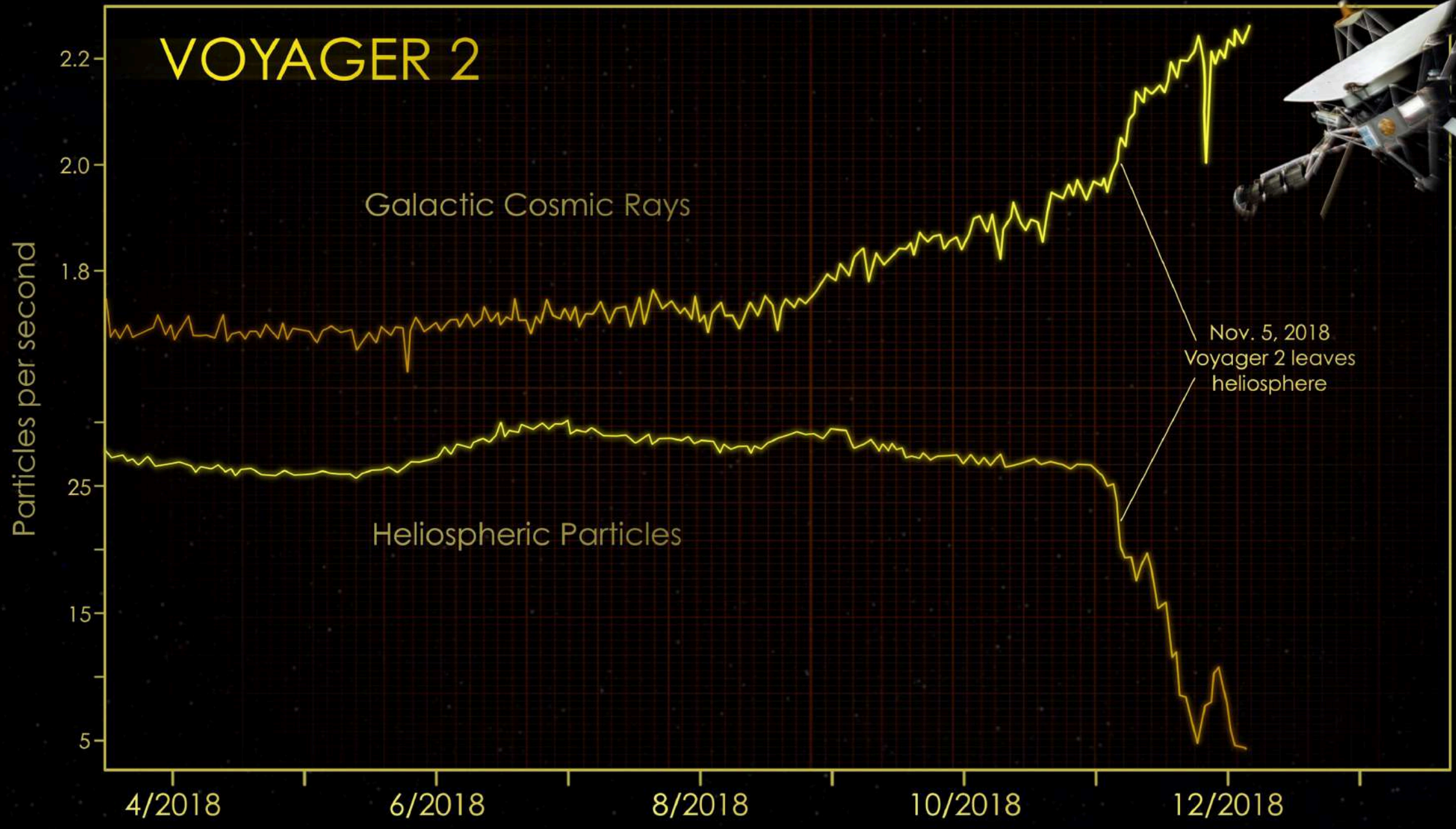
Cosmic-ray induced spallation in the interstellar medium



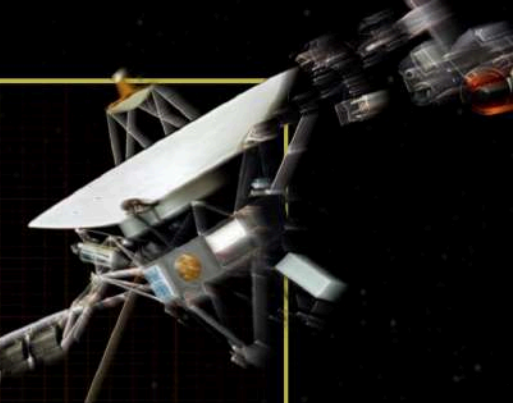
Production rates can be modeled with cosmic-ray spectrum in interstellar medium

Trappitsch and Leya (2016)

VOYAGER 2

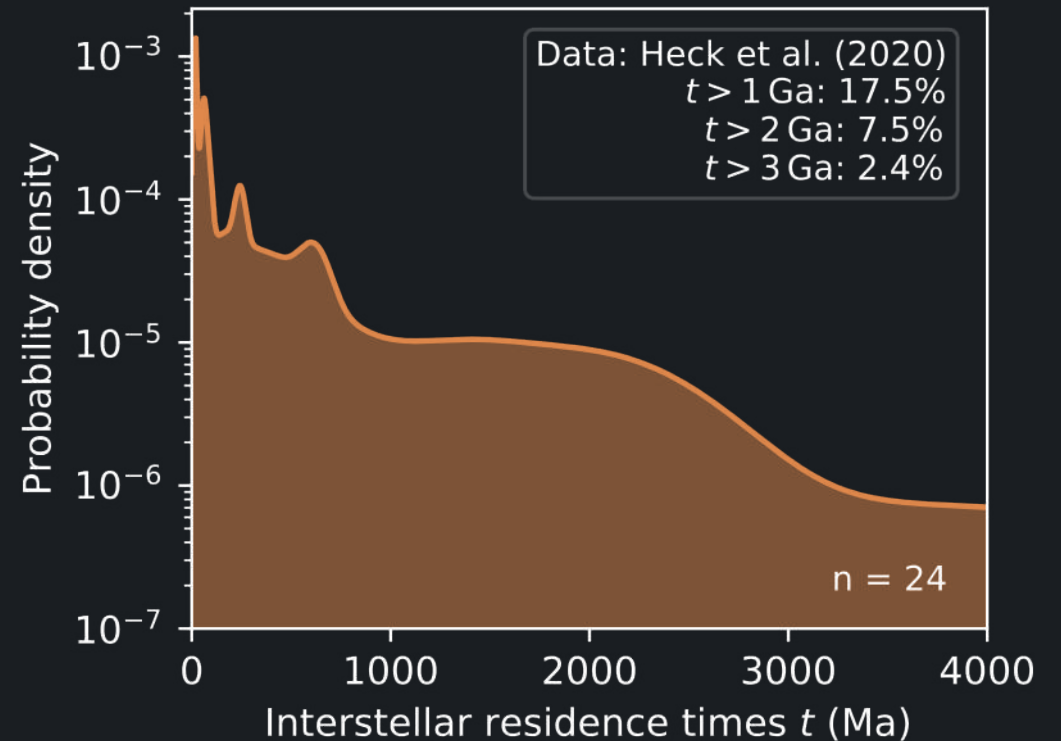


Nov. 5, 2018
Voyager 2 leaves
heliosphere



How old are presolar grains? At least 4.5 billion years!

- Cosmic-rays induce production of nuclides
- Ideal proxy for exposure age: ^{21}Ne concentration
 - Does not condense into grain
 - Produced from Si
- Most grains formed <1 Ga prior to solar system
- Some grains are several billion years old!

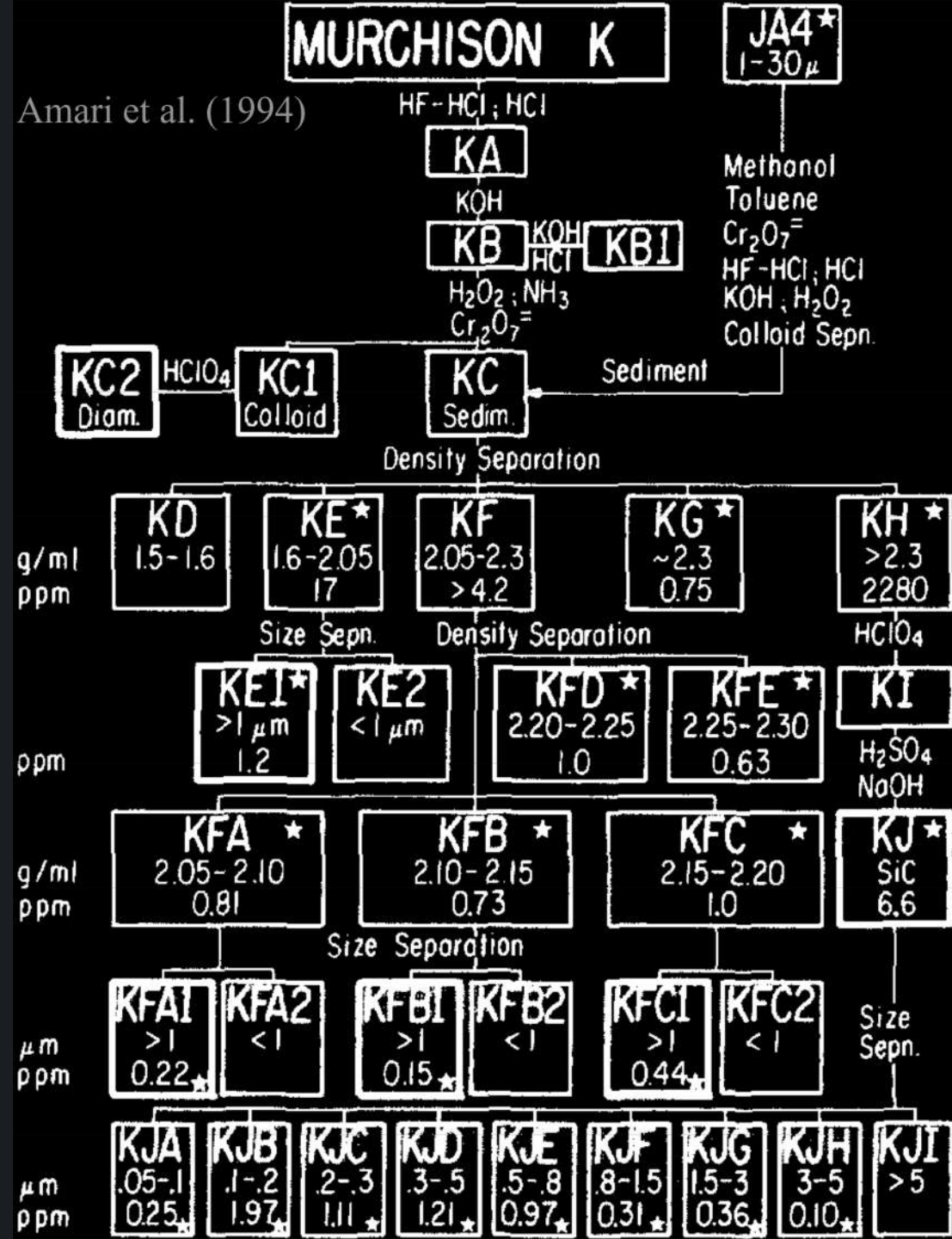


Sample preparation

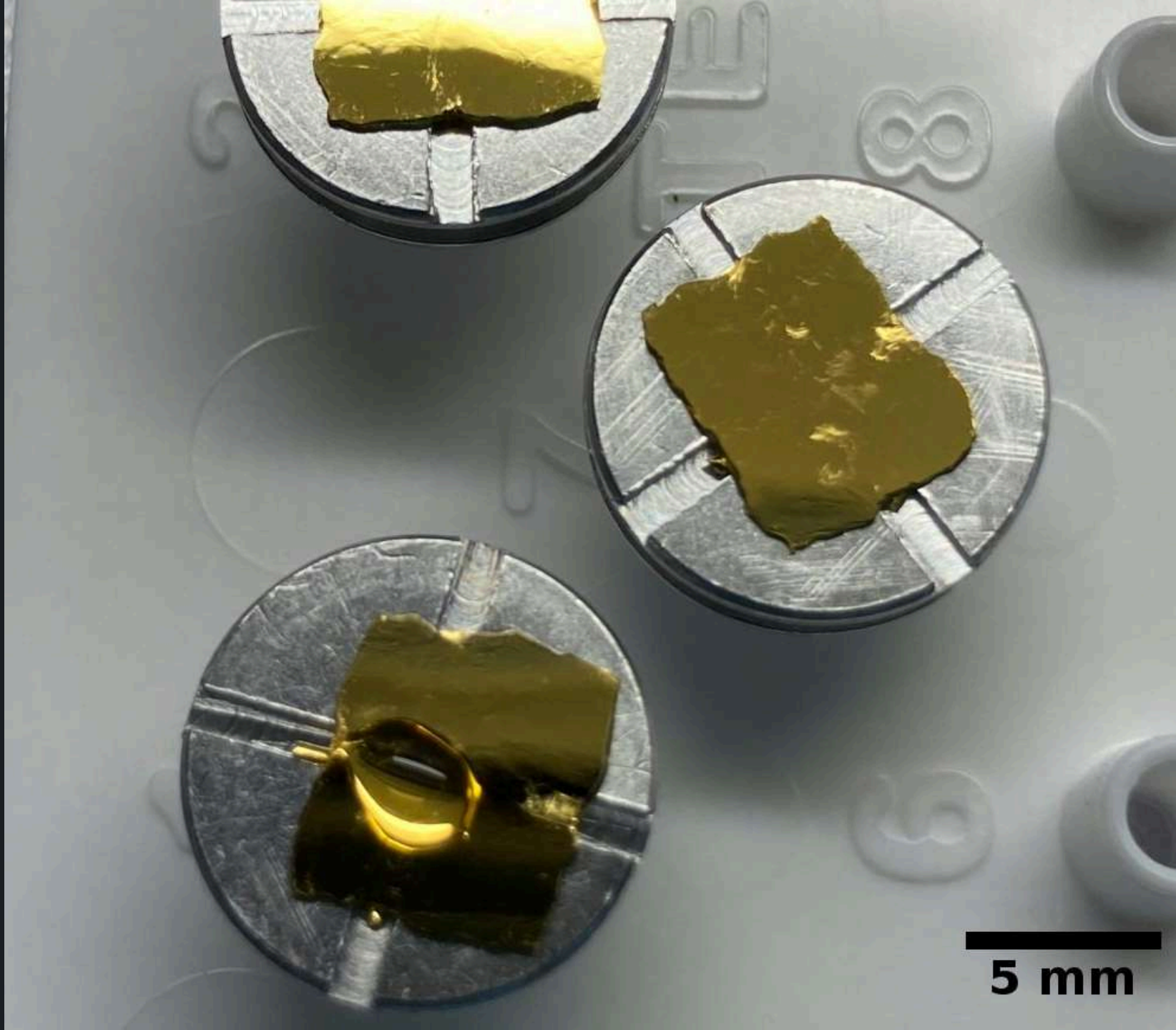
Chemical separation

- Dissolve meteorite with acids
- Heavy liquid separation

Finding the needle in the haystack by burning down the hay



**Sample deposition
on ultra-clean gold
foil**



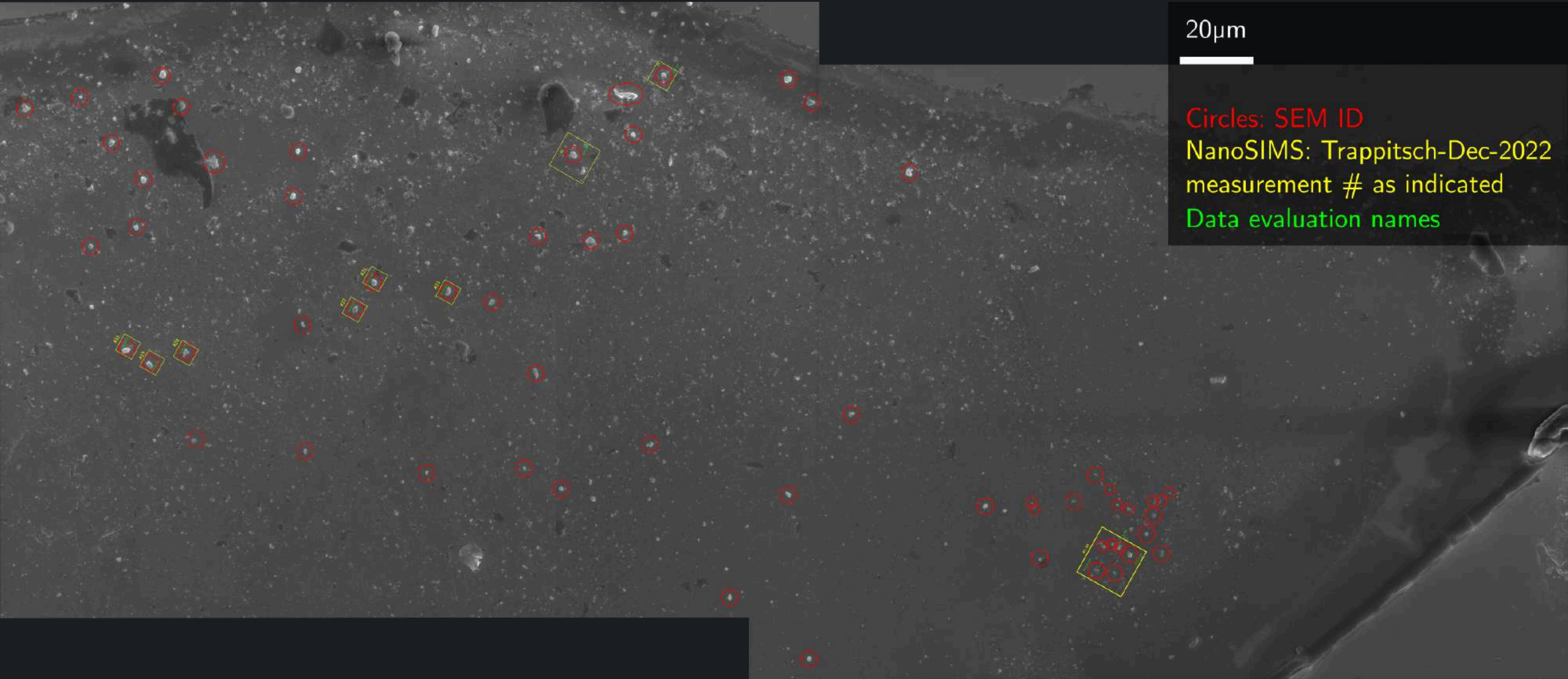
5 mm

Sample imaging

- Mapping sample mount with secondary electron microscope
- Identify presolar grains by energy dispersive X-Ray spectroscopy

Maps aid in navigating the sample mount





20µm

Circles: SEM ID
NanoSIMS: Trappitsch-Dec-2022
measurement # as indicated
Data evaluation names

Sample classification

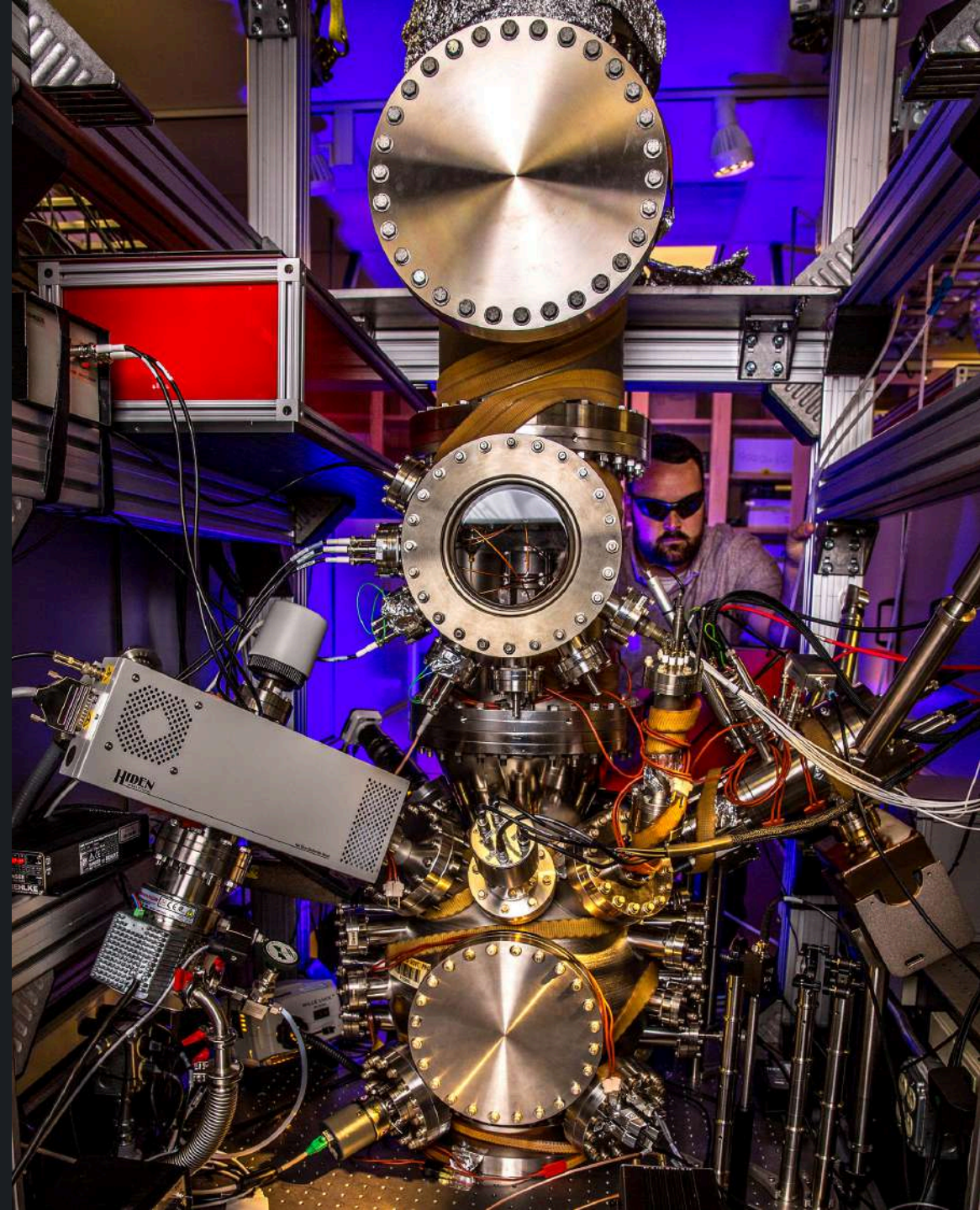
- Analyze C, N, and Si isotopes
- Nanoscale secondary ion imaging
- Ideal instrument to measure major element isotopes

Determine the type of parent star for each grain



Trace element isotopes

- Need for a high-sensitivity technique
- Resonance Ionization Mass Spectrometry (RIMS)
 - Useful yield up to 40%
 - No isobaric interferences
- Currently only two instruments world-wide
- RIMS allows measuring most of the periodic table



RIMS Periodic Table

accessible by RIMS

published RIMS studies

published RIMS isotopic measurements

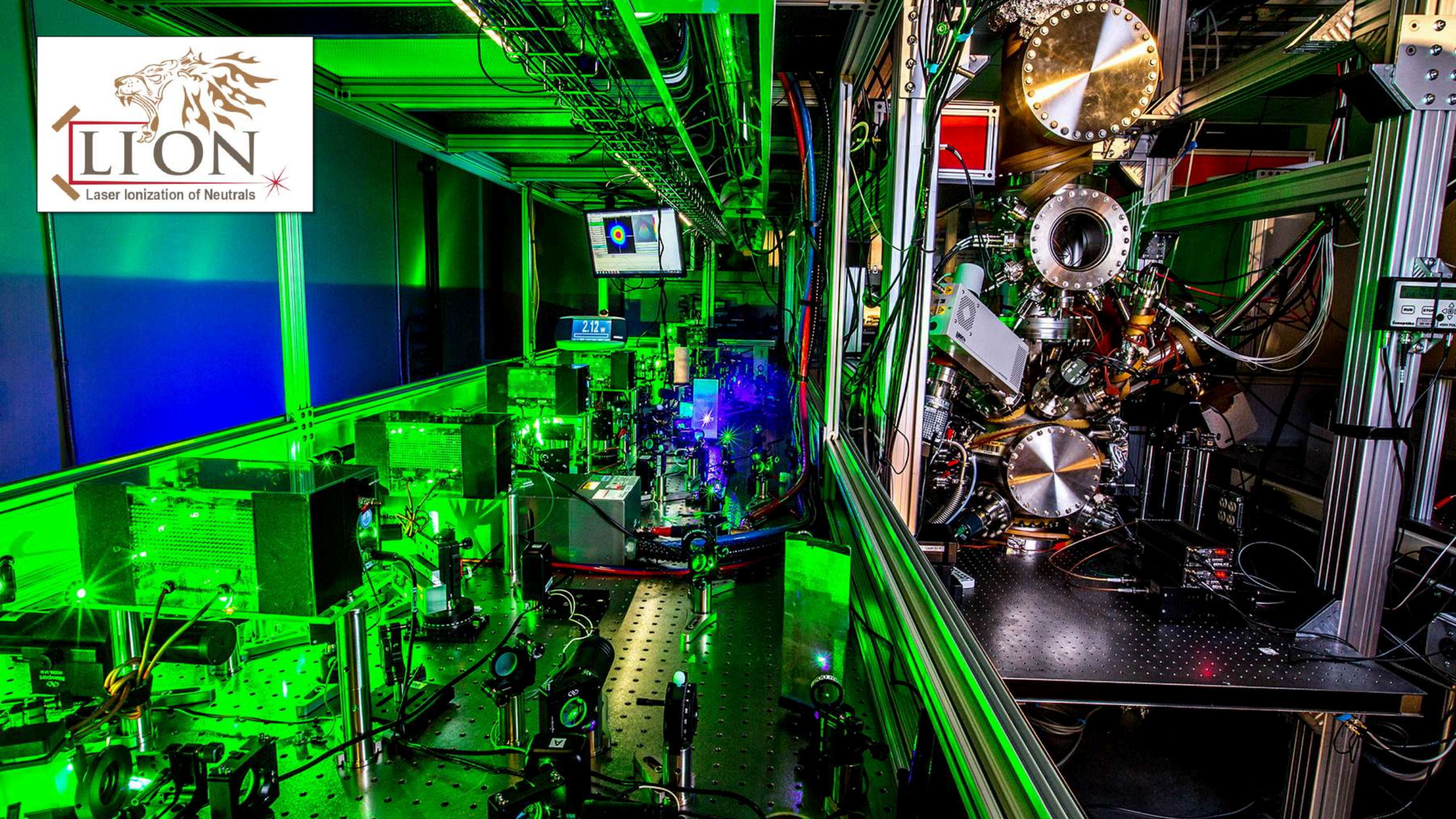
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|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| H | | | | | | | | | | | | | | | | | He |
| Li | Be | | | | | | | | | | | B | C | N | O | F | Ne |
| Na | Mg | | | | | | | | | | | Al | Si | P | S | Cl | Ar |
| K | Ca | Sc | Ti | V | Cr | Mn | Fe | Co | Ni | Cu | Zn | Ga | Ge | As | Se | Br | Kr |
| Rb | Sr | Y | Zr | Nb | Mo | Tc | Ru | Rh | Pd | Ag | Cd | In | Sn | Sb | Te | I | Xe |
| Cs | Ba | * | Hf | Ta | W | Re | Os | Ir | Pt | Au | Hg | Tl | Pb | Bi | Po | At | Rn |
| Fr | Ra | ** | | | | | | | | | | | | | | | |

*

| | | | | | | | | | | | | | | |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| La | Ce | Pr | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er | Tm | Yb | Lu |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|

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| | | | | | | | | | | | | | | |
|----|----|----|---|----|----|----|----|----|----|----|----|----|----|----|
| Ac | Th | Pa | U | Np | Pu | Am | Cm | Bk | Cf | Es | Fm | Md | No | Lr |
|----|----|----|---|----|----|----|----|----|----|----|----|----|----|----|



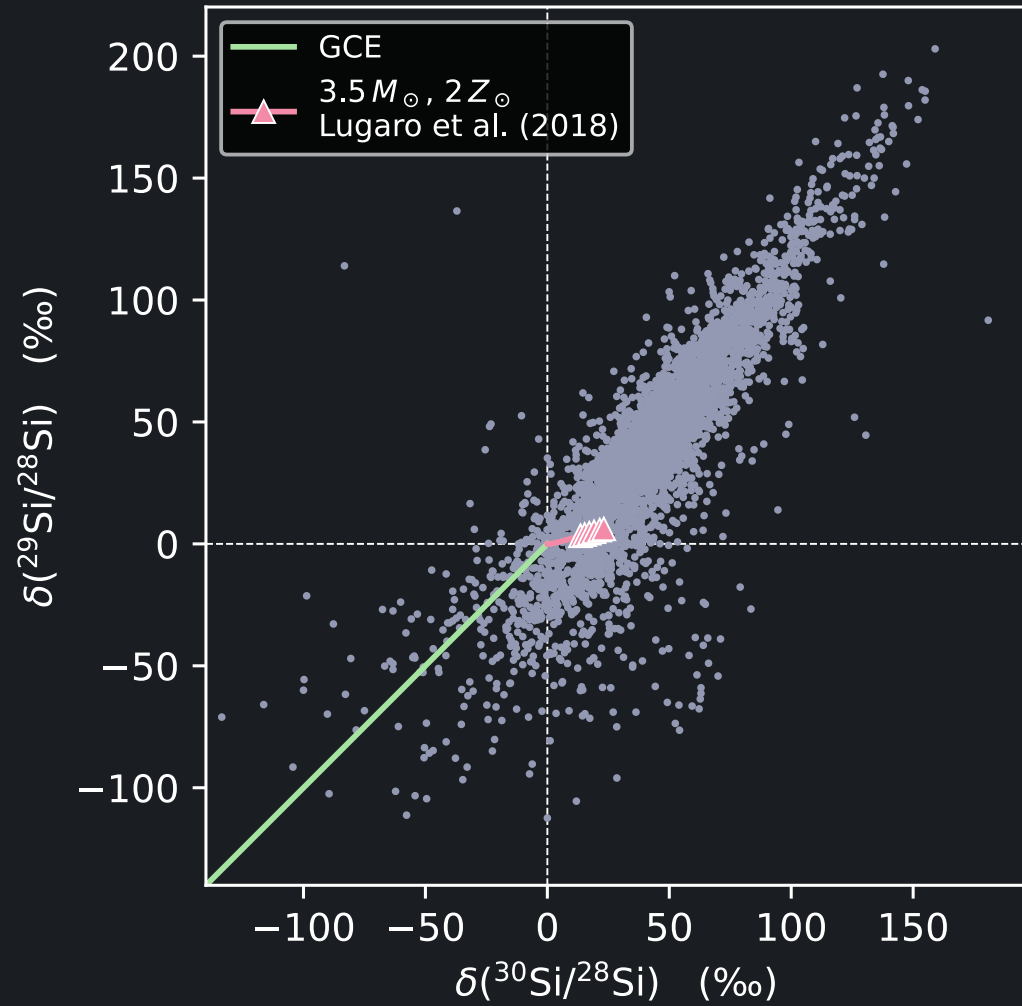
Asymptotic giant branch (AGB) stars

- Expand rapidly and cool
- Cycles between H and He burning
- **Copious** dust producers
- Host of the s-process

V838 Monocerotis (Credit: ESA/Hubble)



The galactic chemical evolution (GCE) puzzle



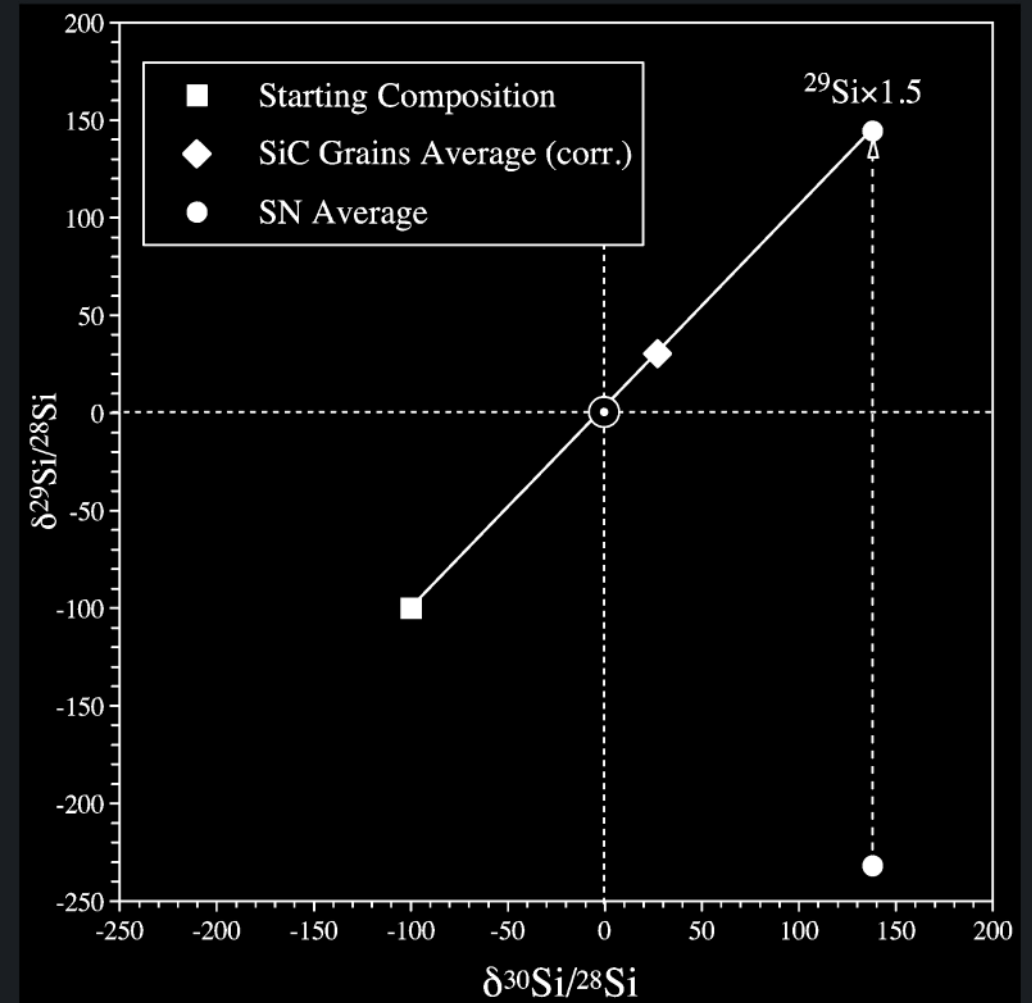
- Presolar grains are older than the solar system
- However, many of them are enriched in ^{29}Si and ^{30}Si compared to the sun
- Heterogeneous GCE
- Models predict a slope ~ 1 line for correlation
- Actual measurements show slope 1.34 (Stephan et al., 2024)

Some early ideas to solve this puzzle

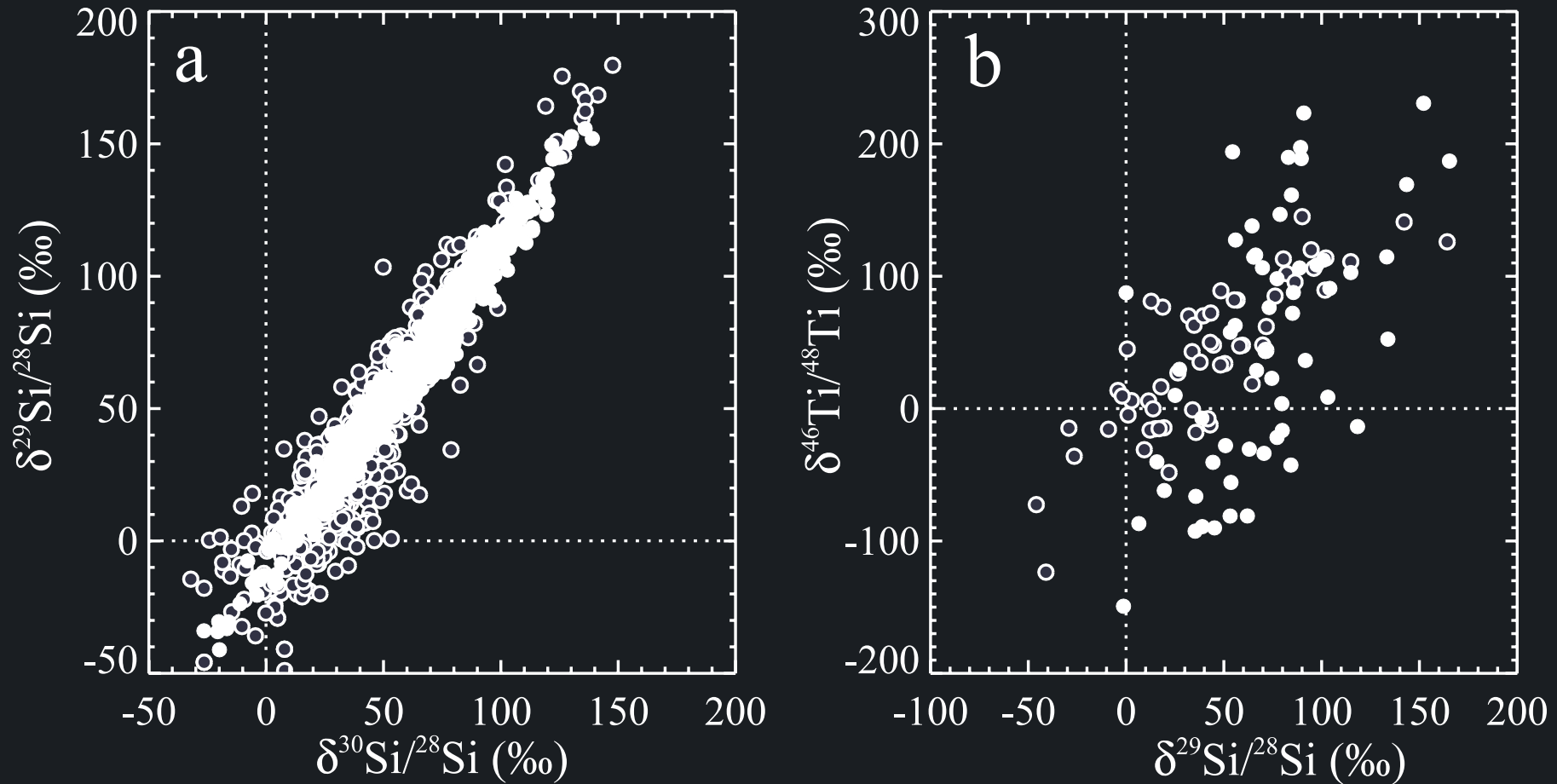
- GCE models do not reproduce the solar silicon abundances.
Recommendation: Renormalize! (Timmes and Clayton, 1996)
- Combination of AGB stars and supernovae yields (Timmes and Clayton, 1996)
- Nuclear uncertainties might play a crucial role (Timmes and Clayton, 1996)
- Different migration histories for stars vs. dust (Clayton, 1997)
- Presolar galactic merger induced starburst (Clayton, 2003)

Heterogeneous GCE of Si - Lugaro et al. (1999)

- Start with defined initial composition
- Add randomly a few supernovae to create a new composition
- Record the Si isotopic composition and repeat
- Supernovae produce too little $^{29}\text{Si}^*$
- Overall, this model can explain the Si isotopic composition, but...



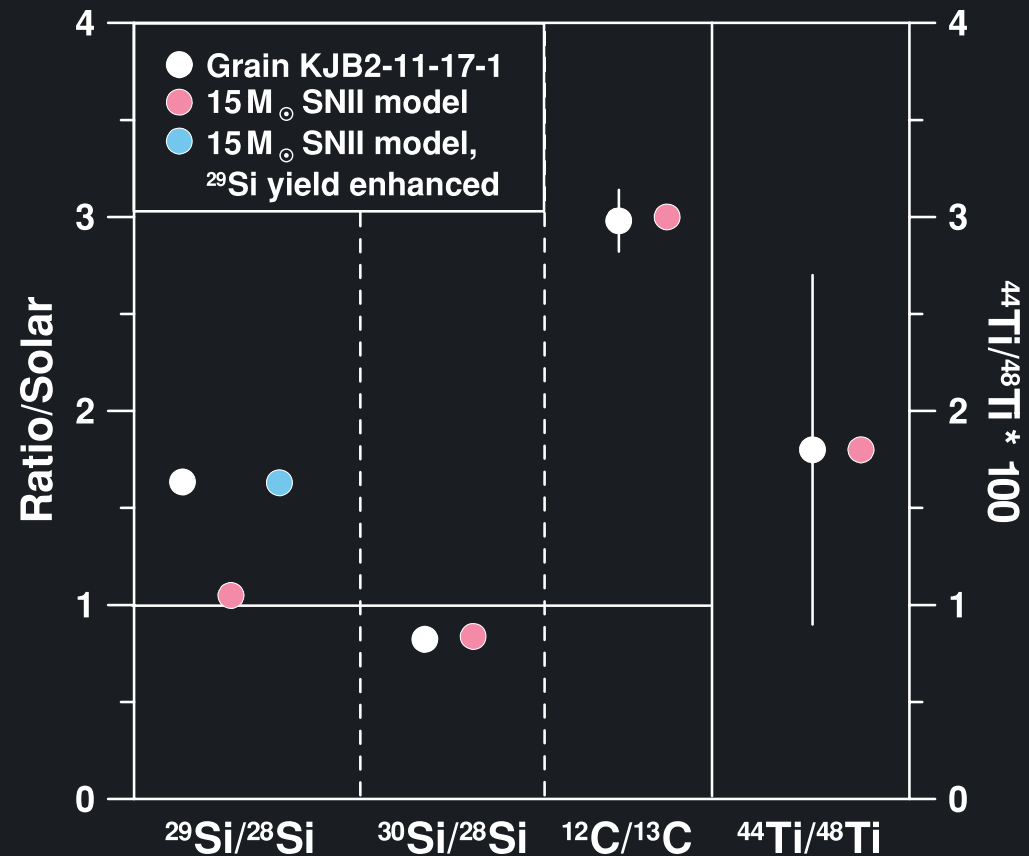
Heterogeneous GCE of Si and Ti - Nittler (2005)



More problems with ^{29}Si - Hoppe et al. (2009)

- Analyzed SiC X grains from supernovae
- **Does not trace GCE, but supernova nucleosynthesis**
- Too little ^{29}Si when all other isotope ratios matched
- Proposed to enhance $^{26}\text{Mg}(\alpha, n)^{29}\text{Si}$

Clearly, nuclear reaction rates and their uncertainties play a key role!



Supersolar Si isotopes: A selection effect?

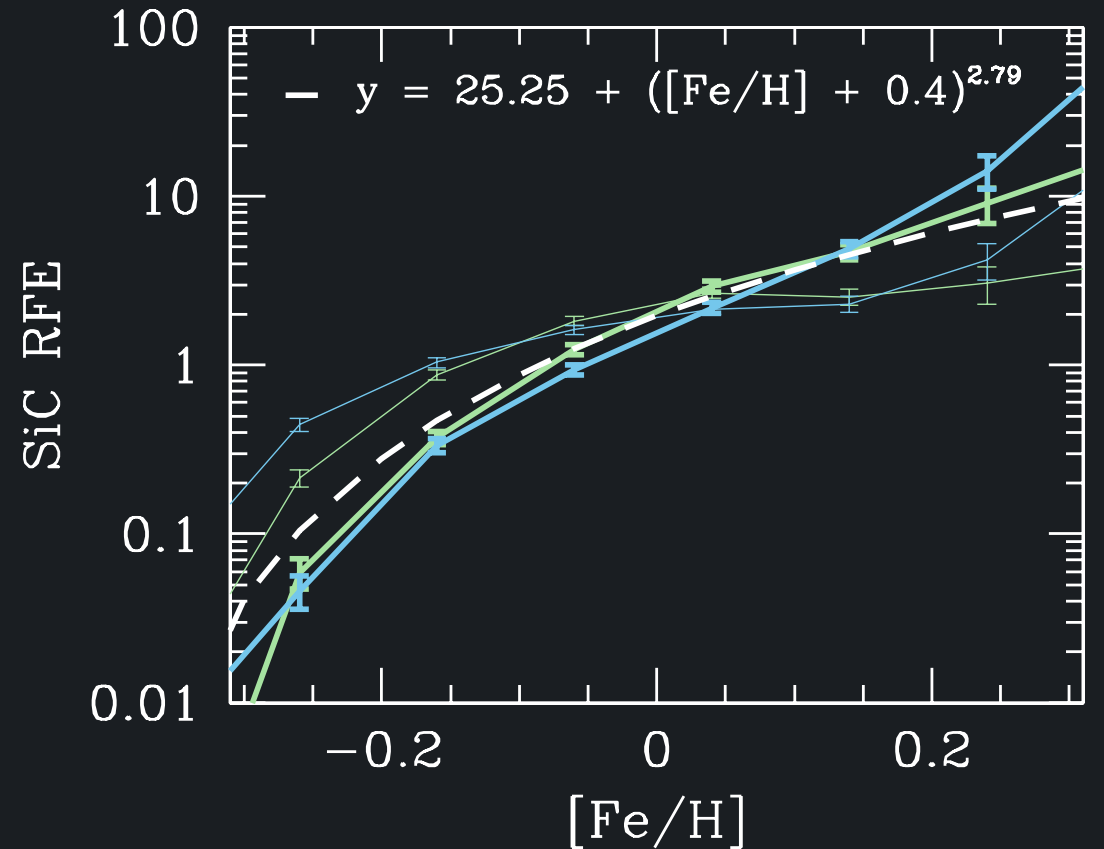
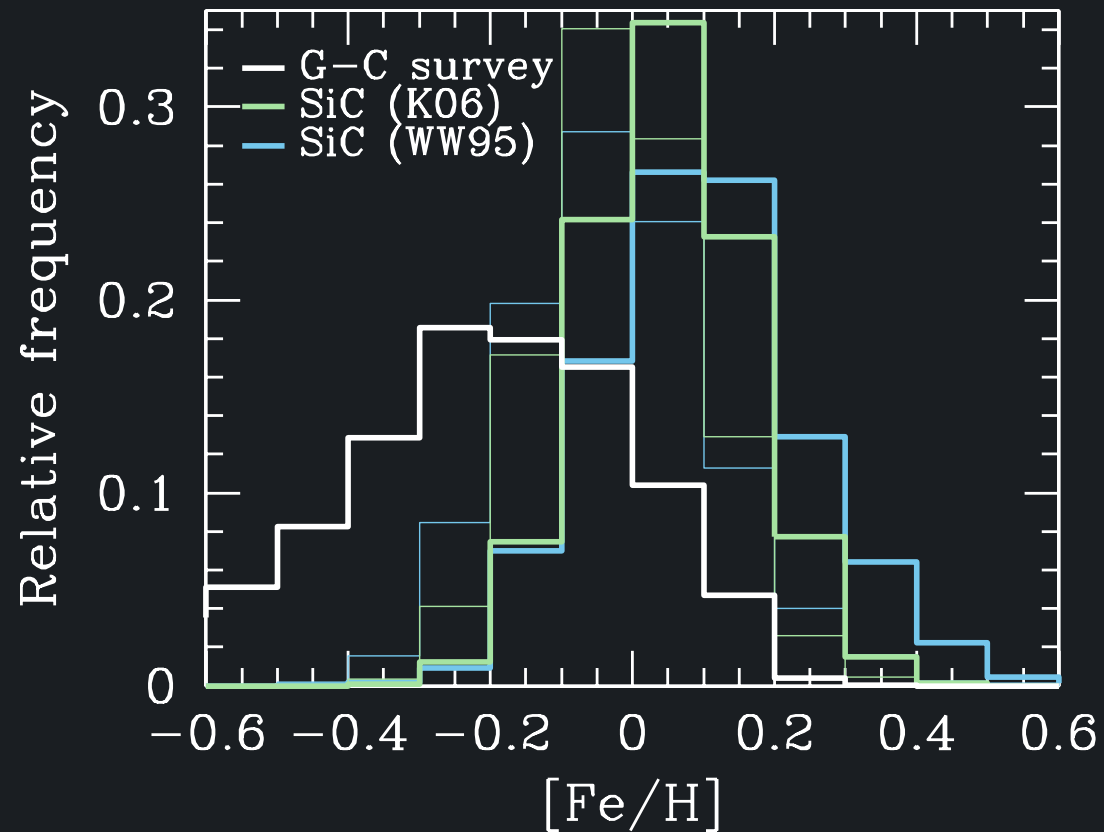
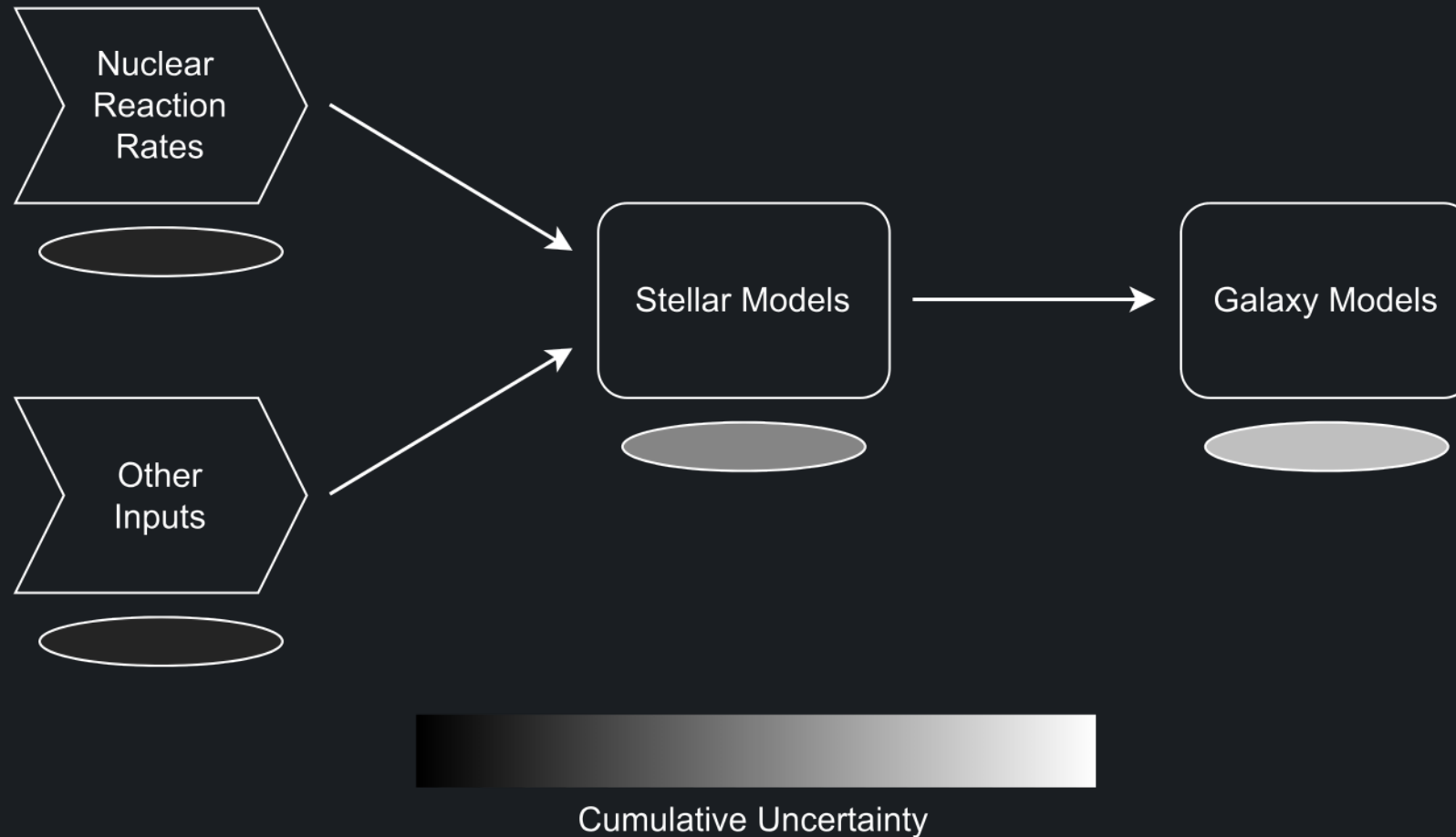
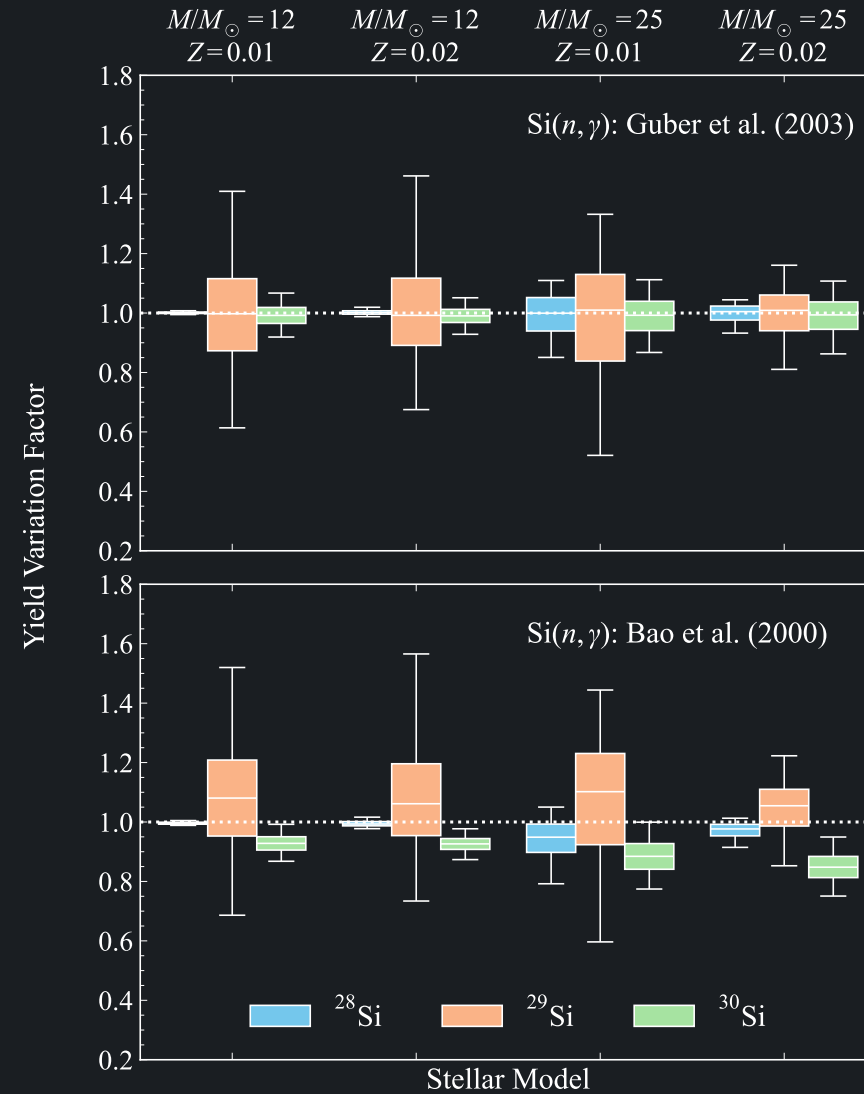
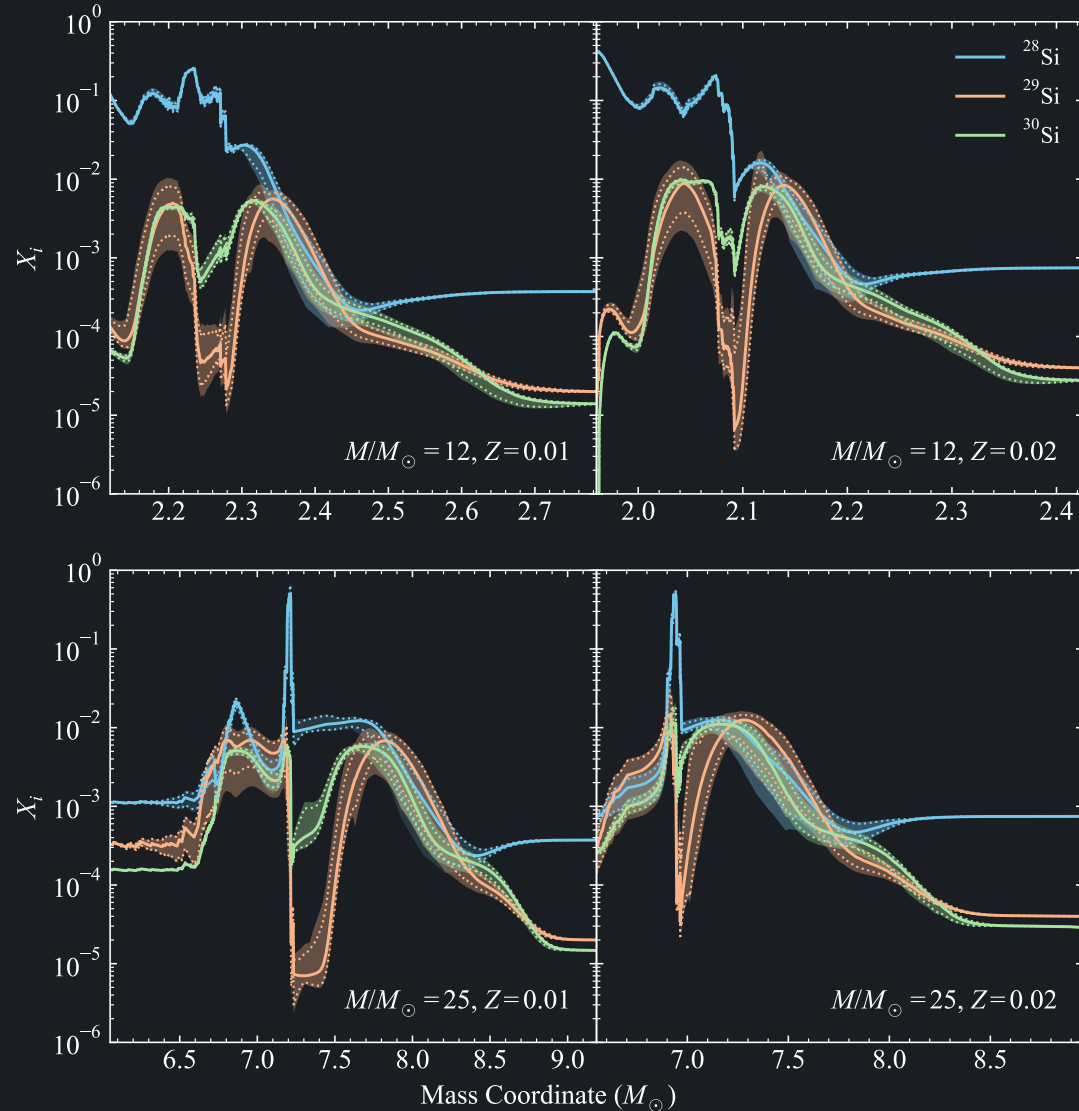


Figure from Lewis et al., 2013, but see also Lugaro et al. (2020)

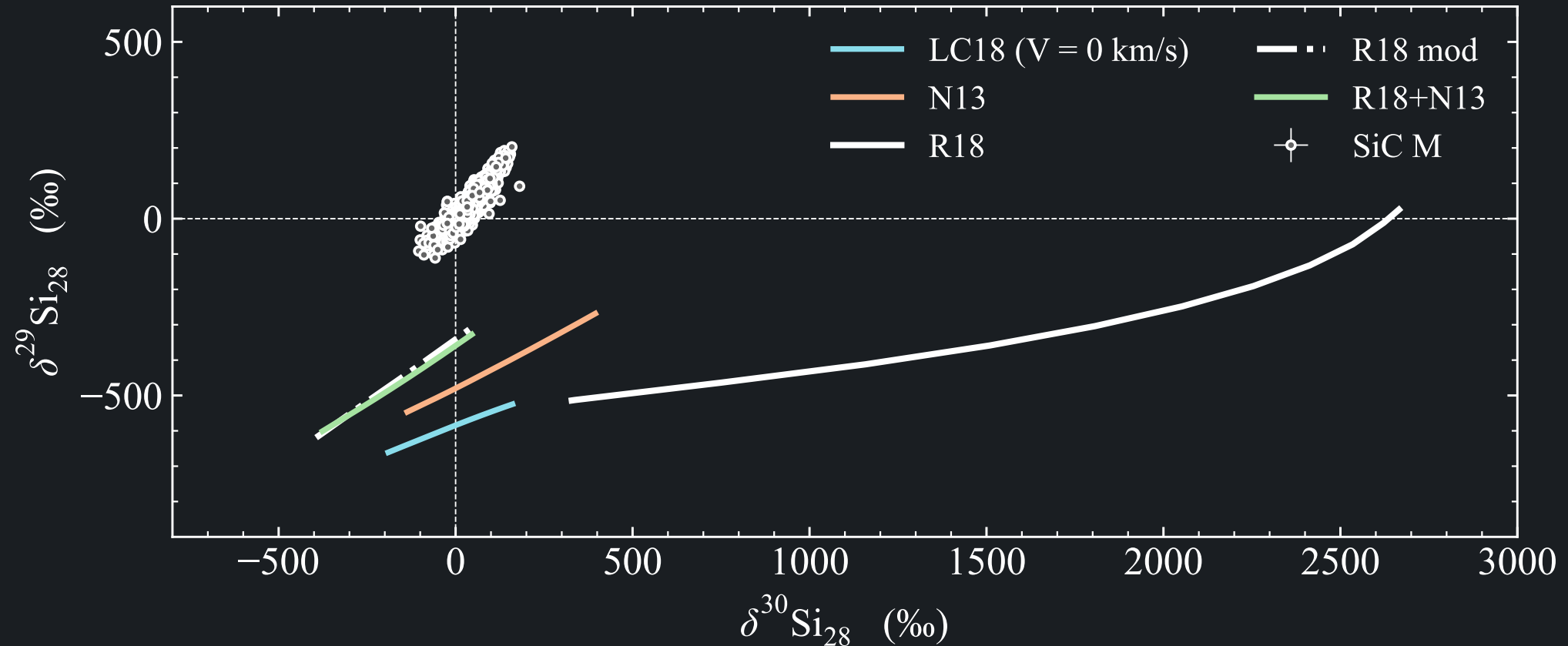
Re-visiting nuclear reaction rate uncertainties and their influence on the slope of the mainstream line



Stellar nucleosynthesis effects

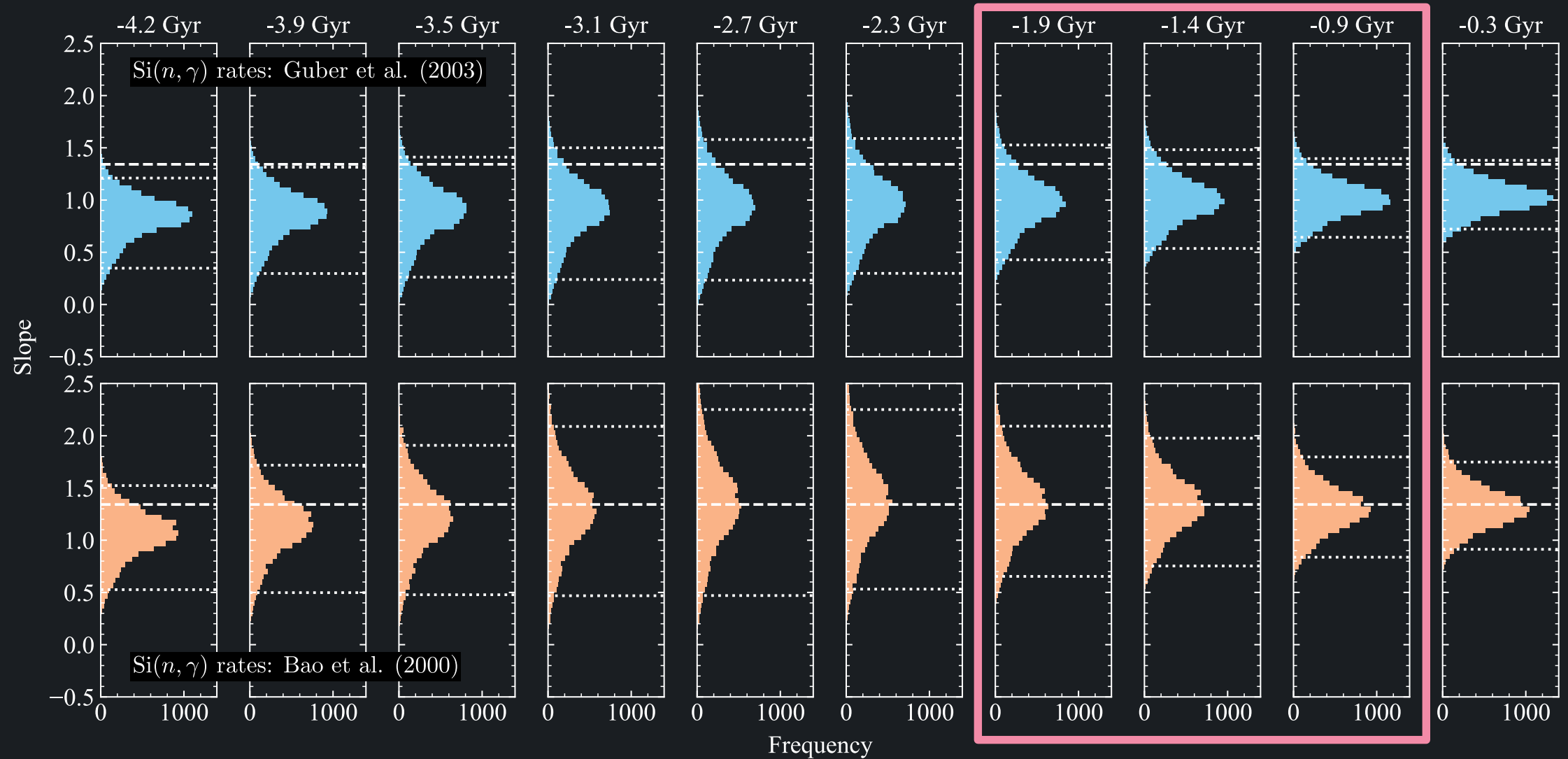


C-O shell mergers complicate the picture further

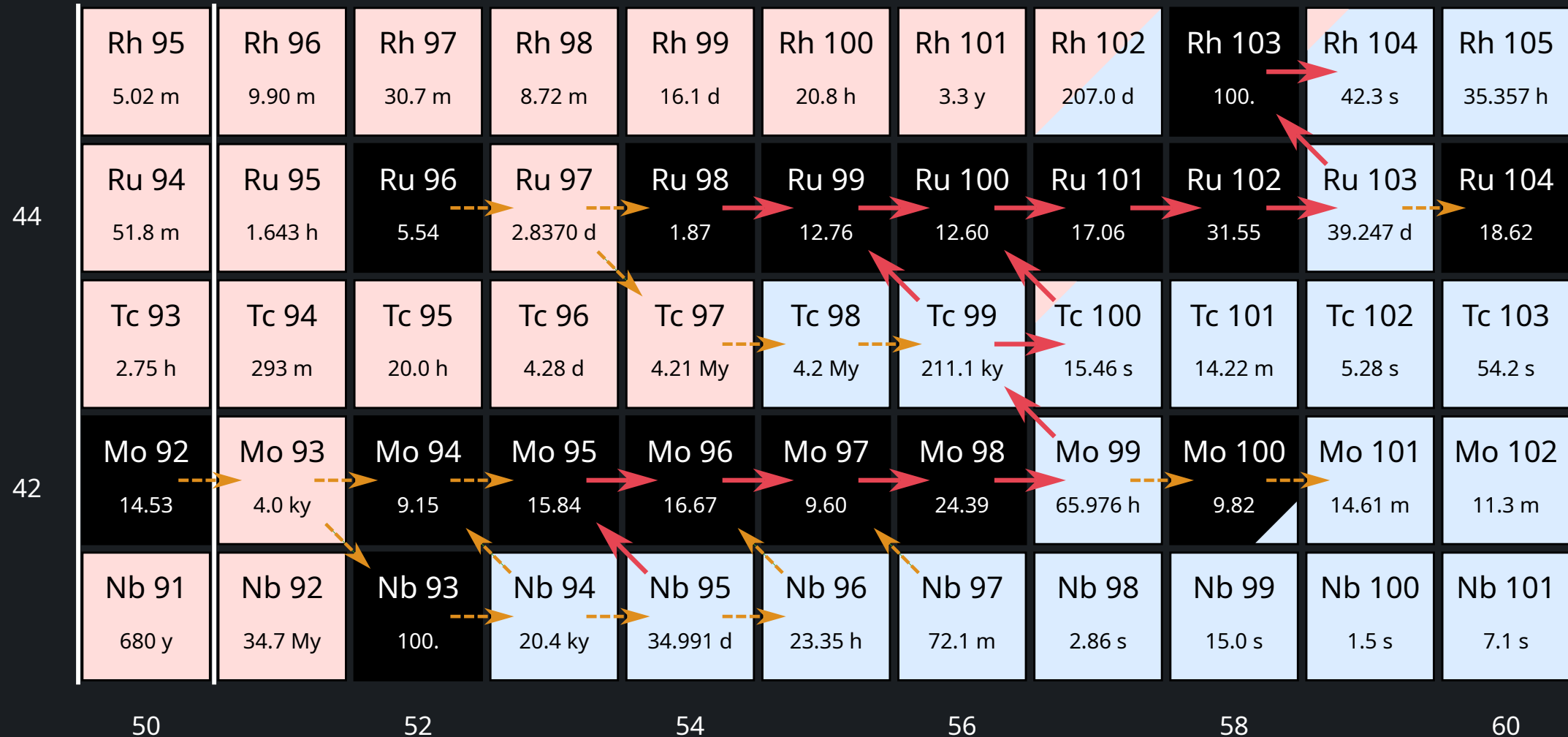


- Ritter et al. (2017) proposed shell mergers solve abundance of odd-Z elements
- Isotopes do not agree and are a much finer probe!

Nuclear reaction rate uncertainties are important!

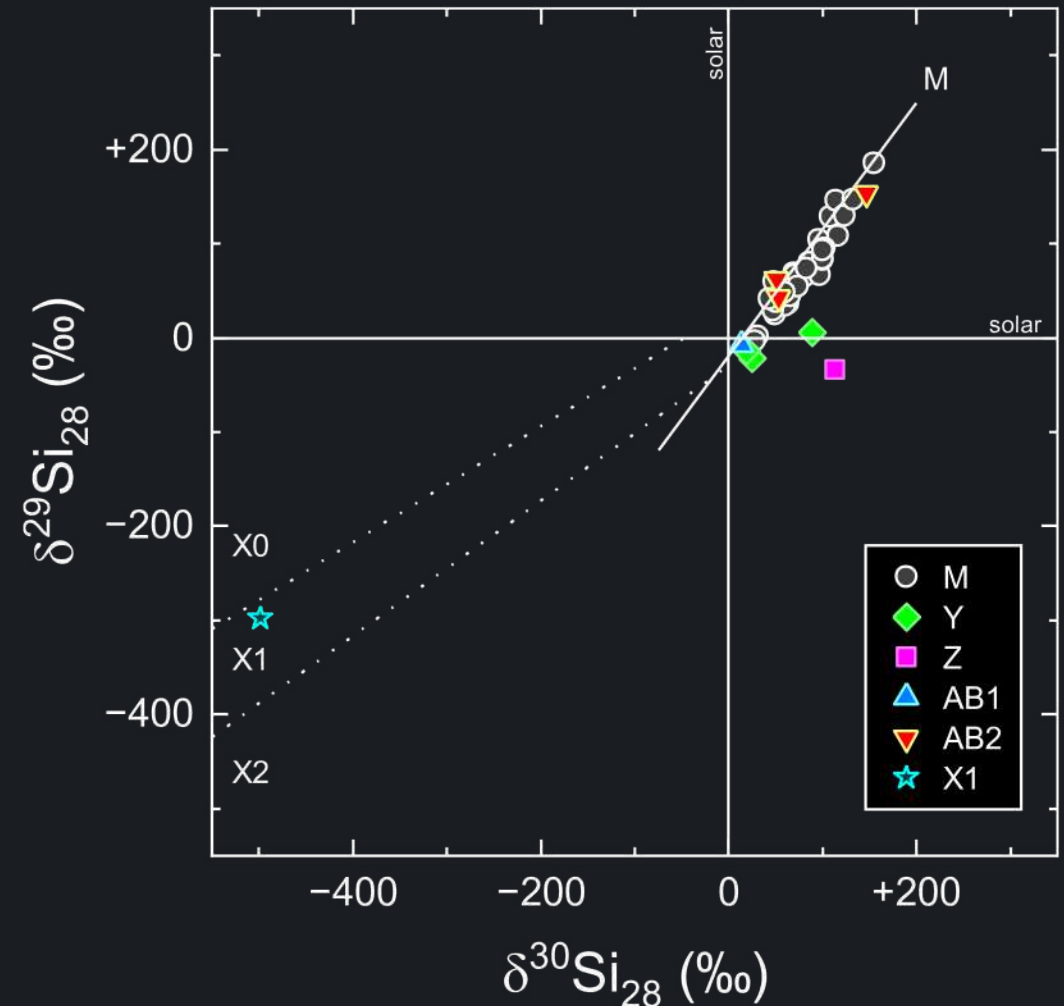


GCE of rare isotopes - *r/p*-ratio for Mo and Ru



r and *p*-nuclei in the solar neighborhood were well mixed

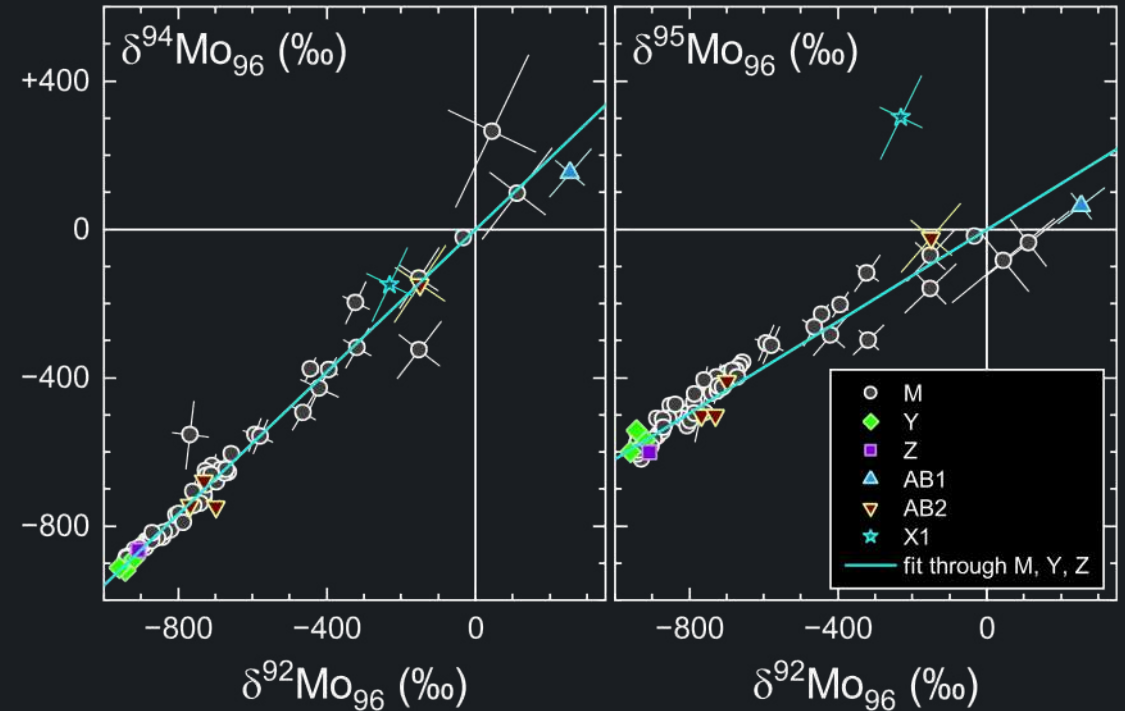
- 55 presolar SiC grains measured for Mo, Ru, and Ba isotopes
Stephan et al. (2025)
- Grains from AGB stars allow deciphering the *s*-process in the parent star
- *r*- and *p*-composition can be determined as the 1–*s* component



Mo, Ru, Ba correlations

- p -nuclei destroyed in s -process
- Example Molybdenum
 - ^{96}Mo : Pure s -process nuclei
 - $\delta^{92}\text{Mo}_{96}$ in s -process: -1000‰
- High precision presolar grain data

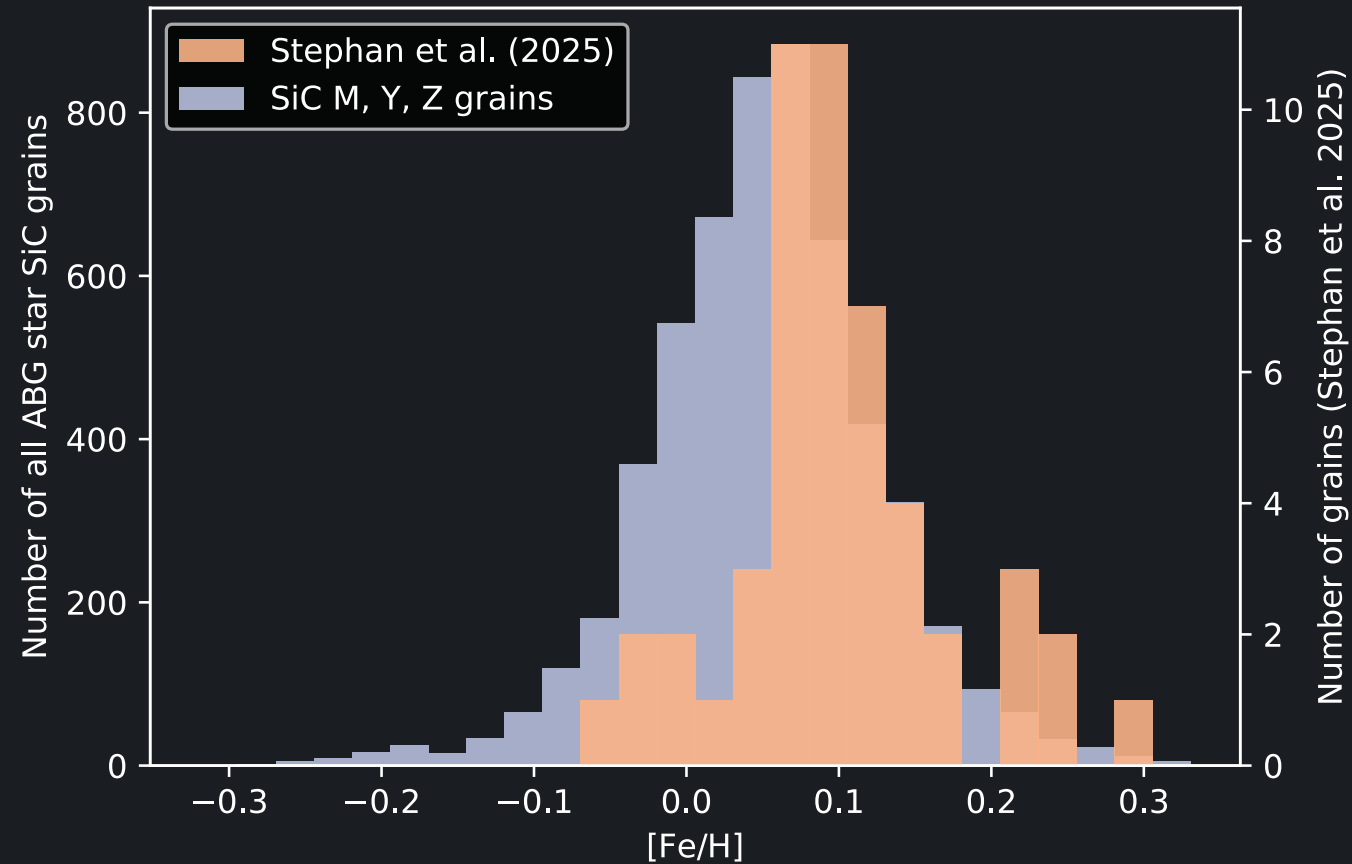
The r - and p -processes contributed at fixed rates to the various parent star's initial composition as well as to the solar composition



Stephan et al. (2025)

What metallicities are we actually sampling?

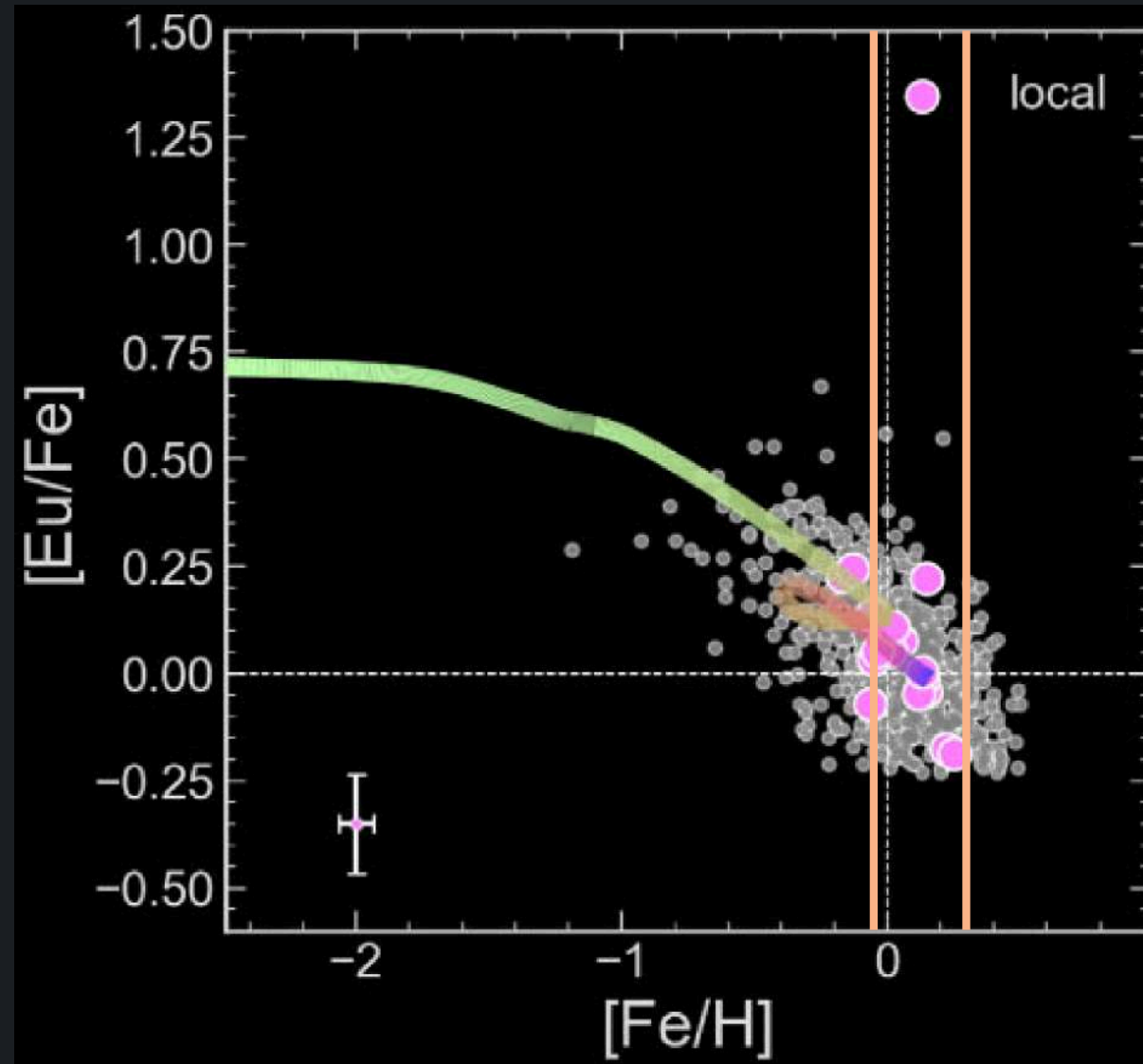
- Compare $\delta^{29}\text{Si}_{28}$ with GCE
(Kobayashi et al. (2011))
- Determine $[\text{Fe}/\text{H}]$ of a grain's parent star
- Details in Lewis et al. (2013)
- Distribution as expected slightly supersolar



Compare with observations

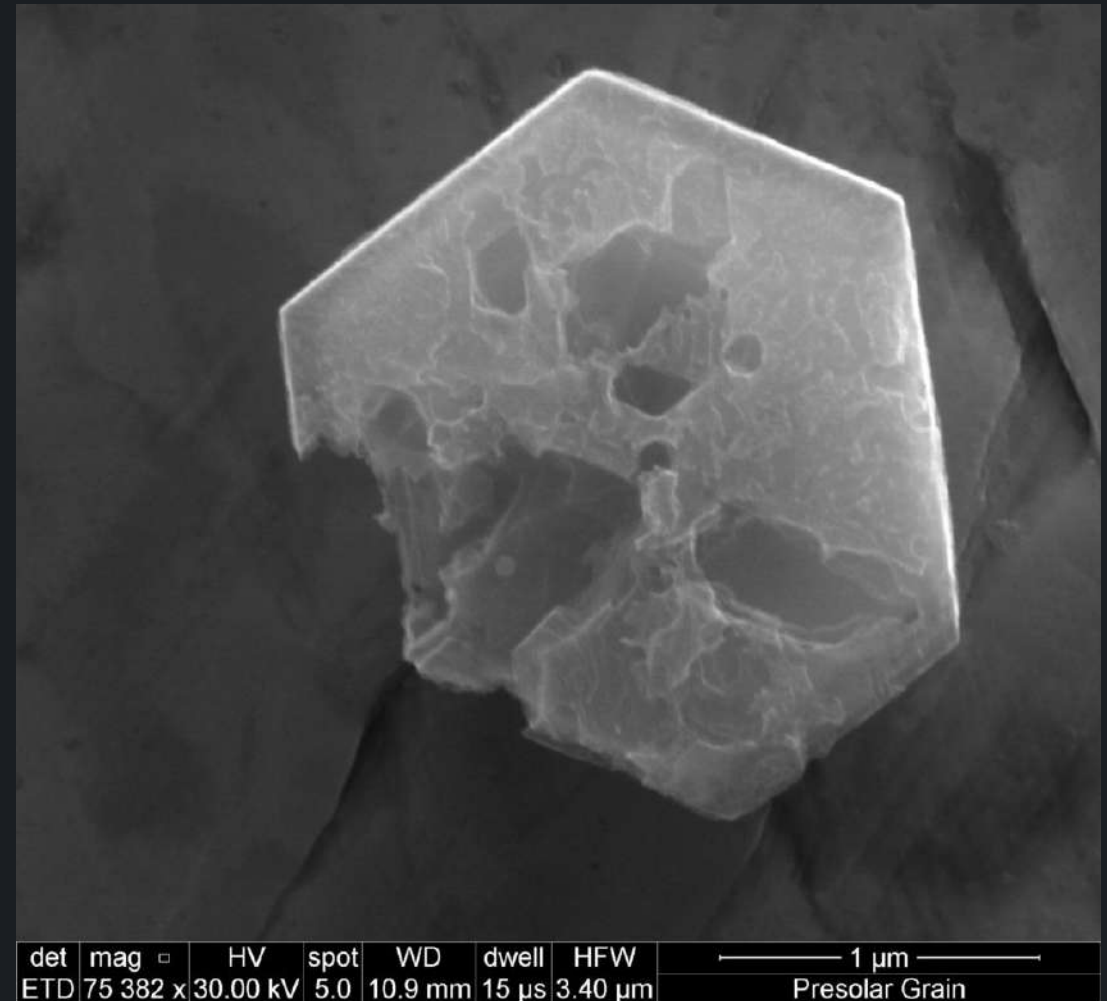
- [Eu/Fe]: r -process tracer
- Figure after Molero et al. (2023)
- Metallicity spread from Stephan et al. (2025): orange bars
- Observations show spread, but what about r/p -ratio?

Need isotopic GCE models with adequate astrophysical r - and p -isotope production sites



Presolar grain analysis: Hands-on astrophysics...

- Presolar grains from AGB stars: valuable proxies for GCE
- Isotopes are a very fine probe!
- The Si isotope chondrium
 - ^{29}Si underproduced in models
 - Grain formation bias
 - Nuclear reaction rate uncertainties play a major role
- Mo, Ru, Ba: Tracing the r/p -ratio through (recent) GCE



SiC grain imaged in the secondary electron microscope

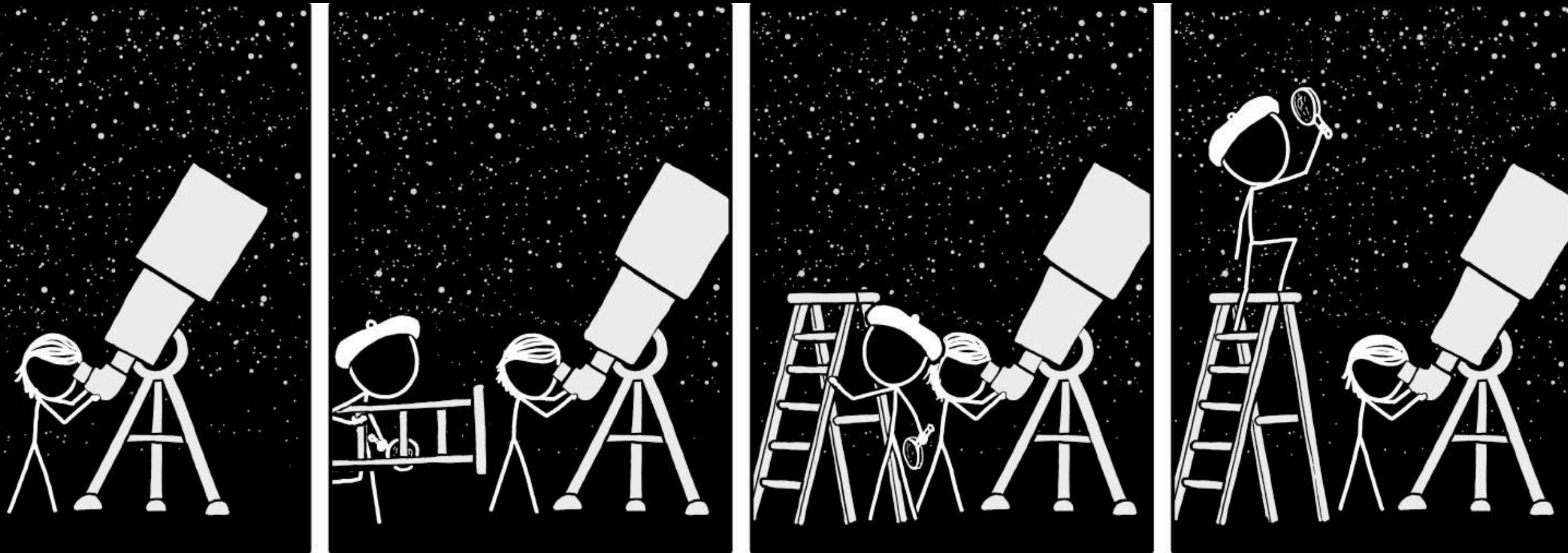
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NASA, ESA, NRAO/AUI/NSF and G. Dubner (Univ. of Buenos Aires)

... or astronomy with a microscope



xkcd.com