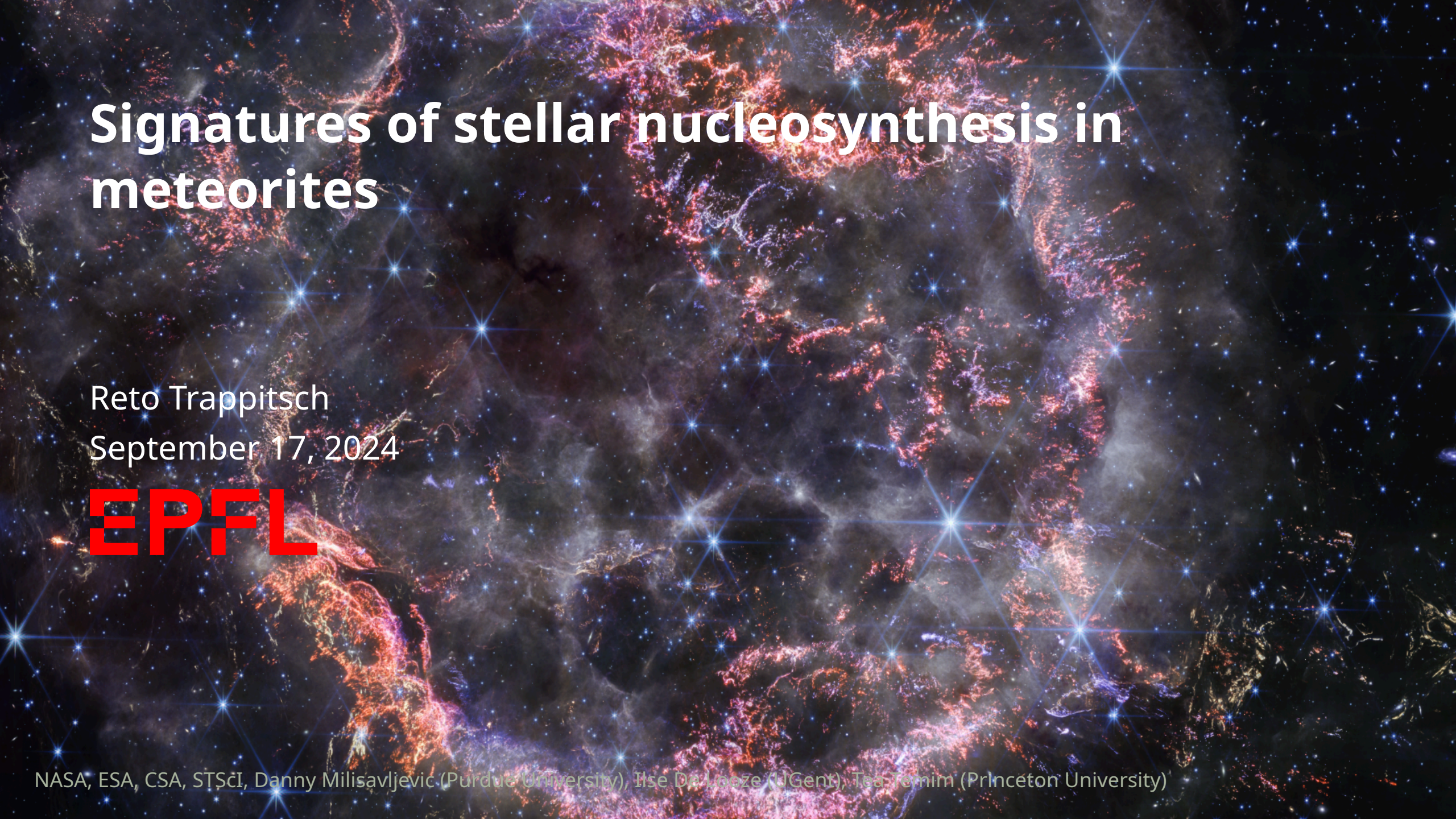
Signatures of stellar nucleosynthesis in meteorites

Reto Trappitsch

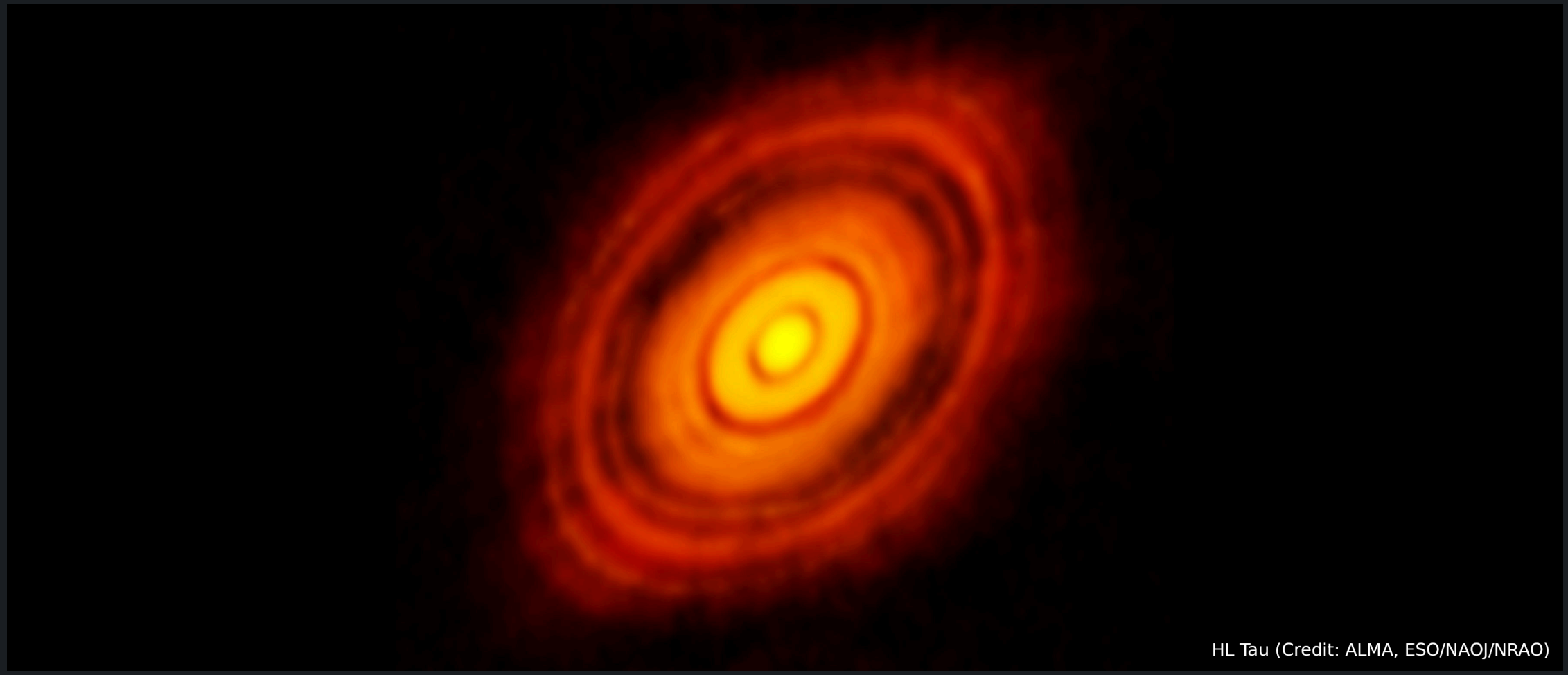
September 17, 2024

EPFL



NASA, ESA, CSA, STScI, Danny Milisavljevic (Purdue University), Ilse De Looze (UGent), Tea Temim (Princeton University)

The solar nebula – a turbulent environment



HL Tau (Credit: ALMA, ESO/NAOJ/NRAO)

Meteorites – the poor researcher's space probe

- Falls and finds
- Generally found in hot and cold deserts

Meteorites come in various shapes and densities

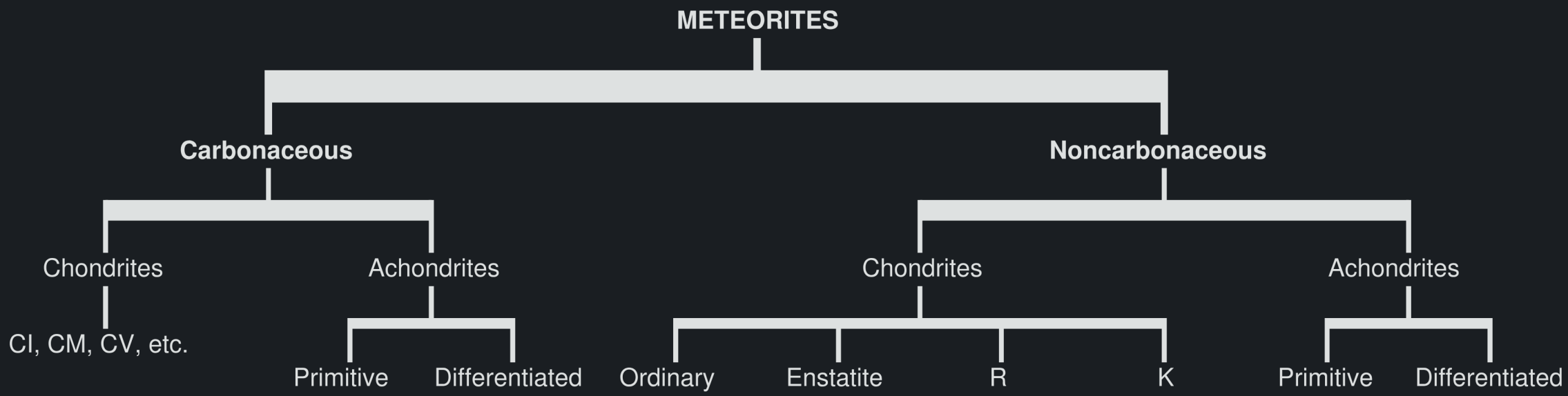
Differentiated

- Got hot and (partially) melted
- Highly altered due to the heat

Undifferentiated

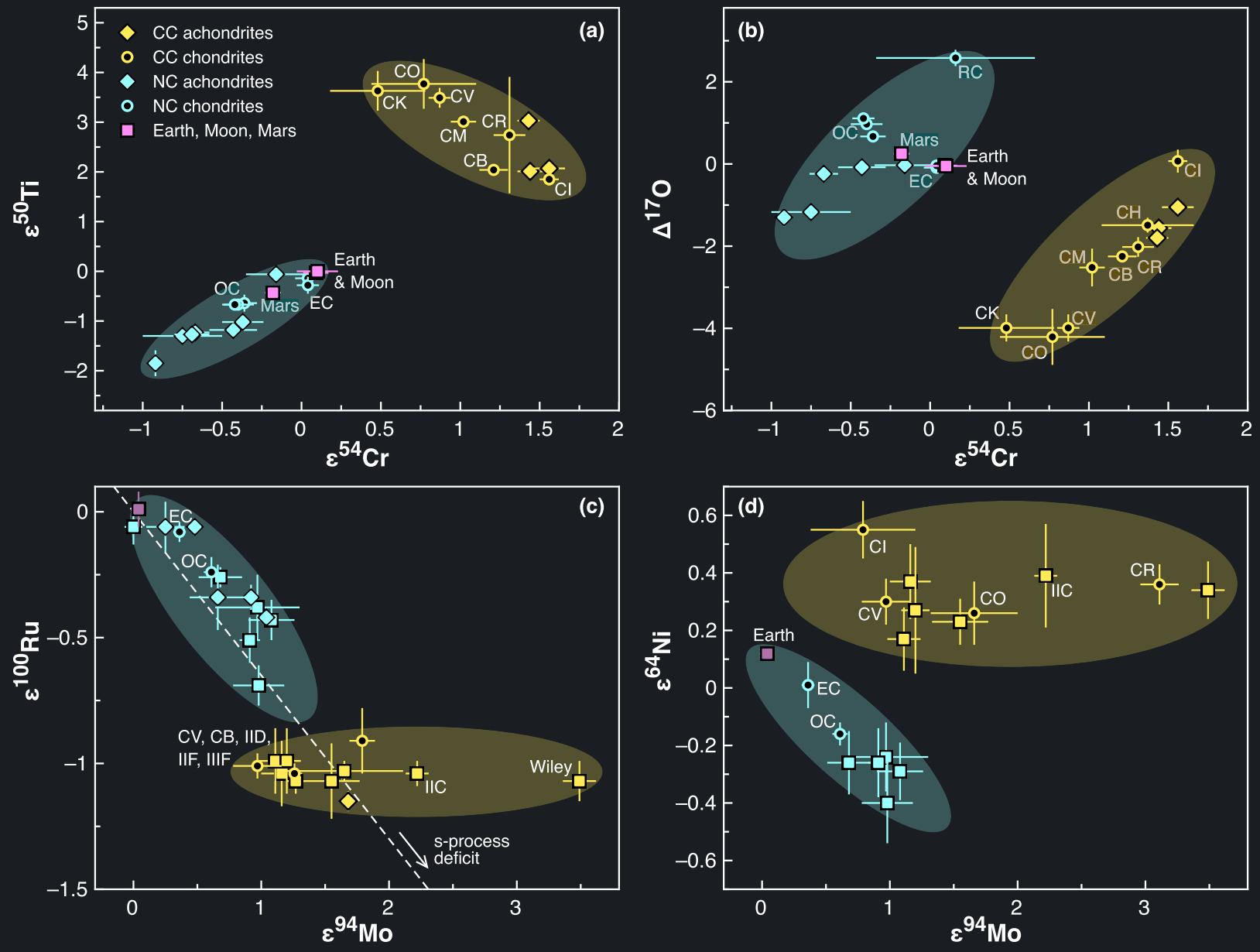
- Silicates and metals still mixed
- Most primitive meteorites

With a lot of measurements come a lot of different groups



Warren et al. (2011)

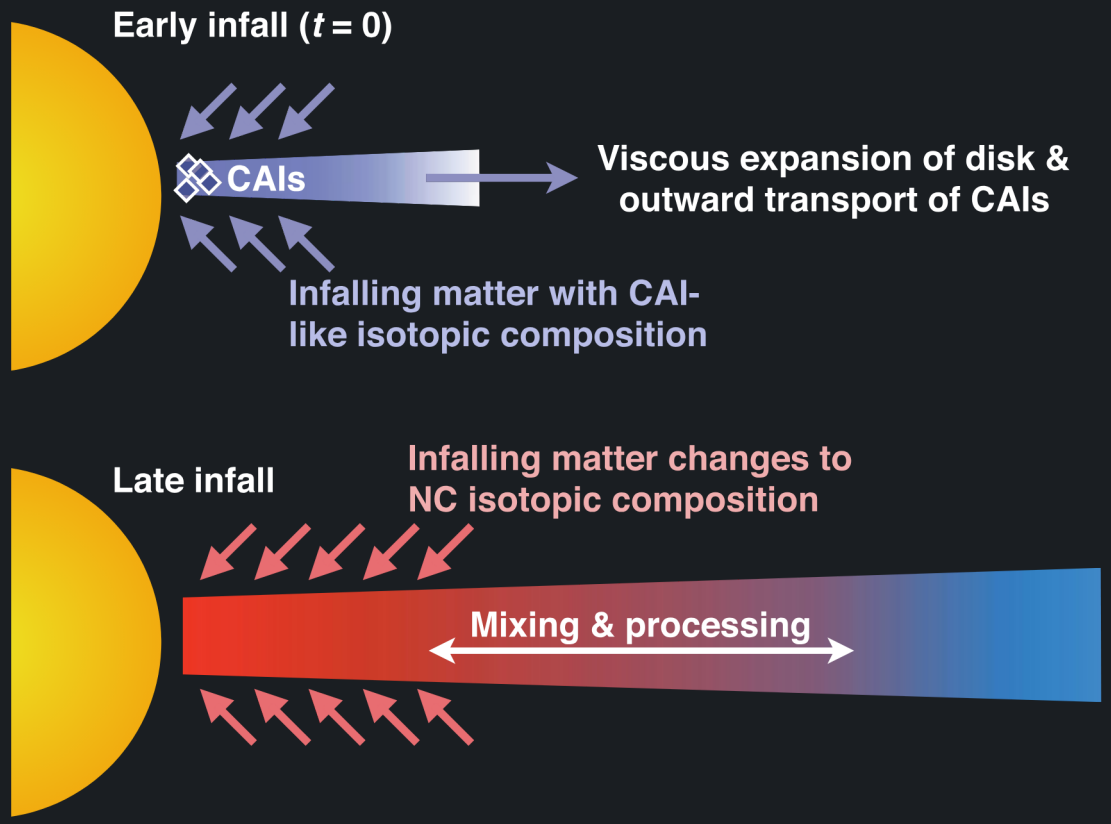
Precision measurements of meteorites indicate grouping



after Kleine et al. (2020)

Jupiter – separator of reservoirs in the solar system

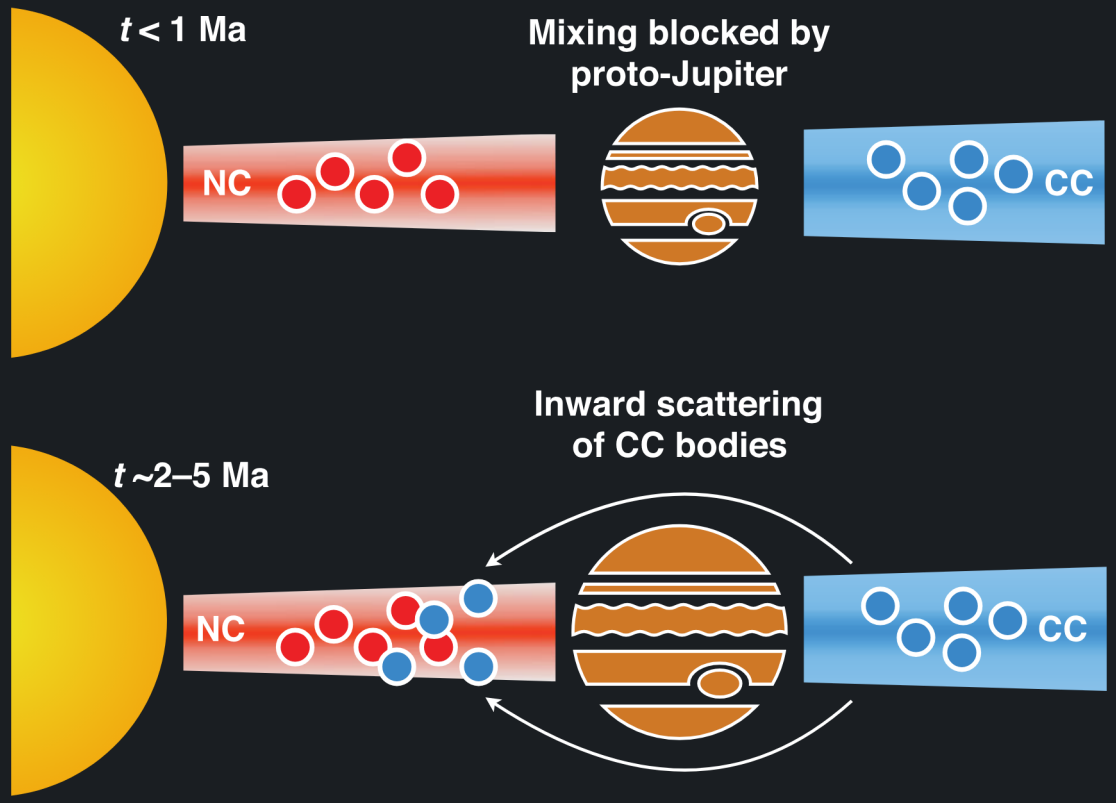
- Early infall of material: forms the first material (CAIs)
- Late infall: separation of NC & CC
- Jupiter core formation: Separates the two reservoirs
- After asteroids formed:
  - Migration of Jupiter and Saturn
  - Mixes material in solar system (grand tack model)



after Kleine et al. (2020)

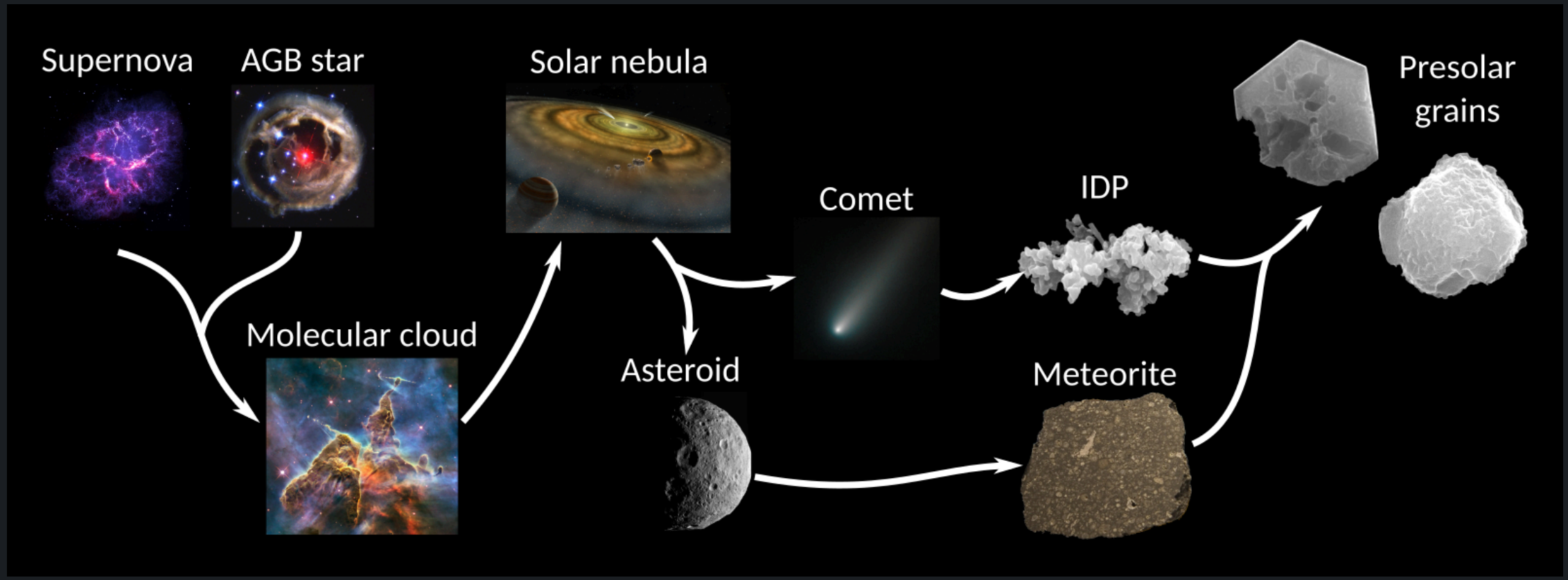
Jupiter – separator of reservoirs in the solar system

- Early infall of material: forms the first material (CAIs)
- Late infall: separation of NC & CC
- Jupiter core formation: Separates the two reservoirs
- After asteroids formed:
  - Migration of Jupiter and Saturn
  - Mixes material in solar system (grand tack model)



after Kleine et al. (2020)

Stellar messengers in our solar system

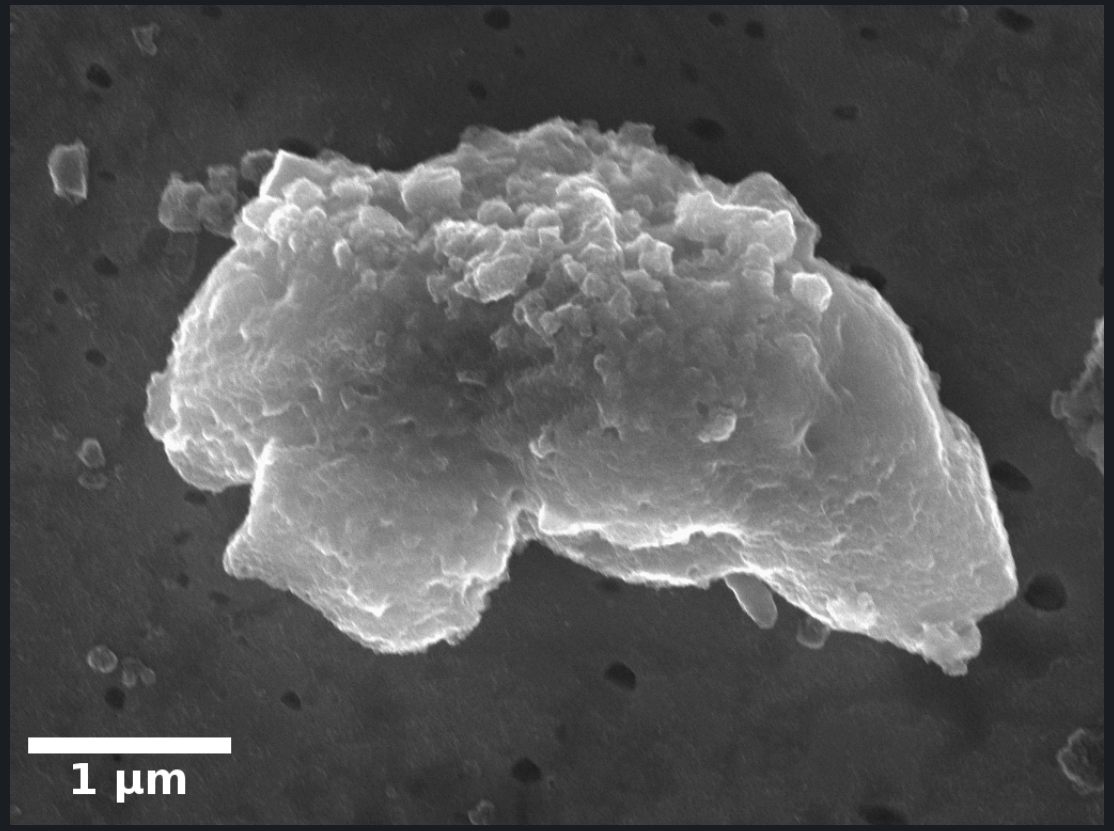


*For current-day messengers see **talk by Dominik Koll**, Wednesday morning*

A zoo of presolar grains

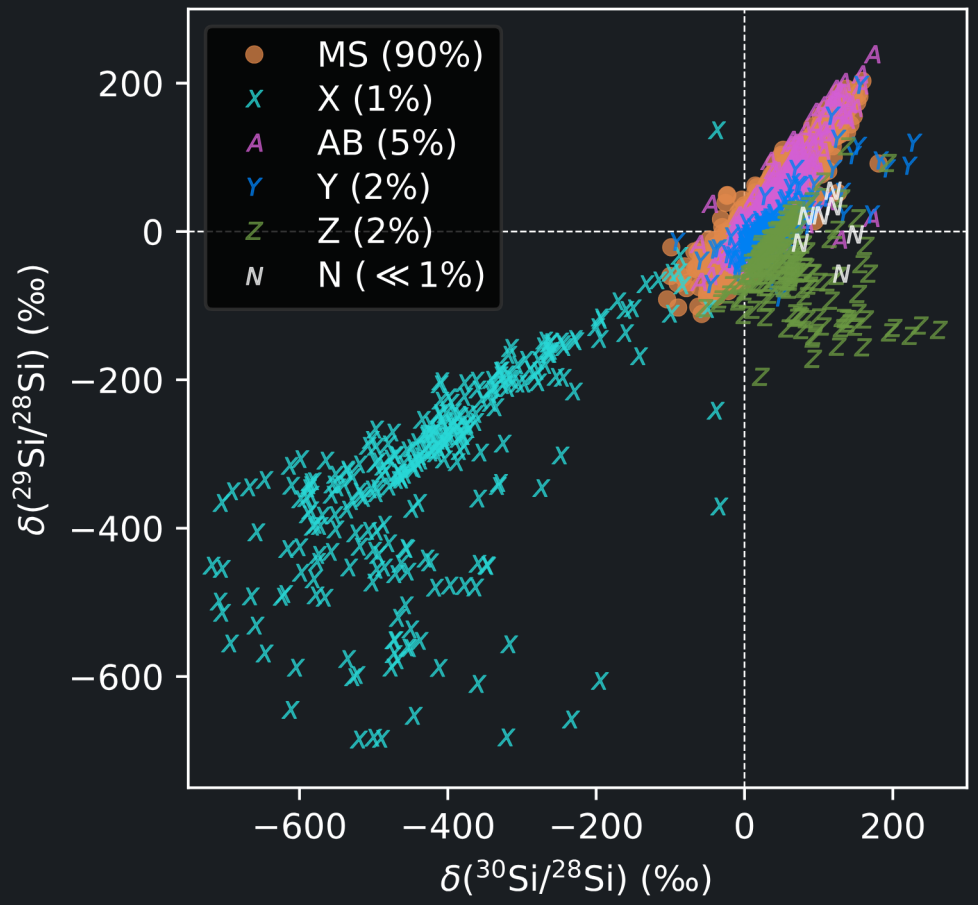
- Nanodiamonds: ~10^6 atoms
- Silicon carbide: The hardy ones
- Graphites: Large but fragile
- Silicates: Small and fragile
- …

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



Silicon carbide grains: Are they presolar?

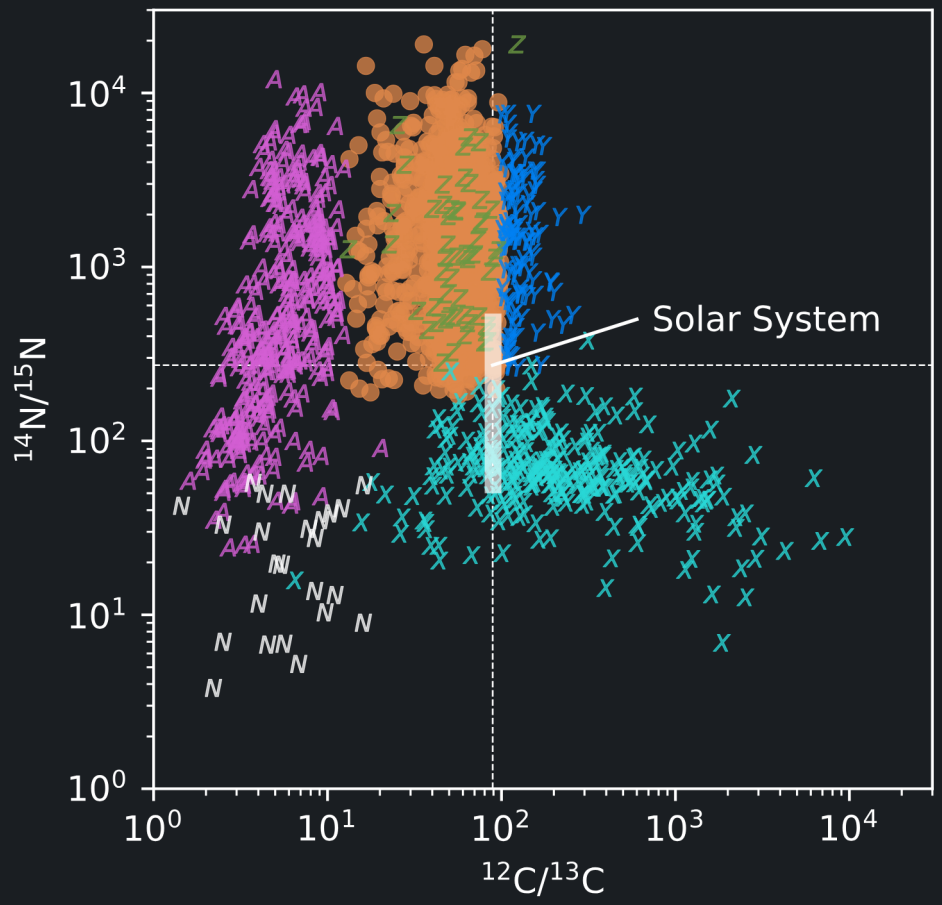
- δ-units: Deviation from solar in ‰
- Extreme isotope compositions
- Determine provenance by analyzing Si, C, & N isotopes
- Hands-on astrophysical samples
  - Stellar nucleosynthesis
  - Galactic chemical evolution



Each grain contains its parent star's nucleosynthetic signature

Silicon carbide grains: Are they presolar?

- δ-units: Deviation from solar in ‰
- Extreme isotope compositions
- Determine provenance by analyzing Si, C, & N isotopes
- Hands-on astrophysical samples
  - Stellar nucleosynthesis
  - Galactic chemical evolution

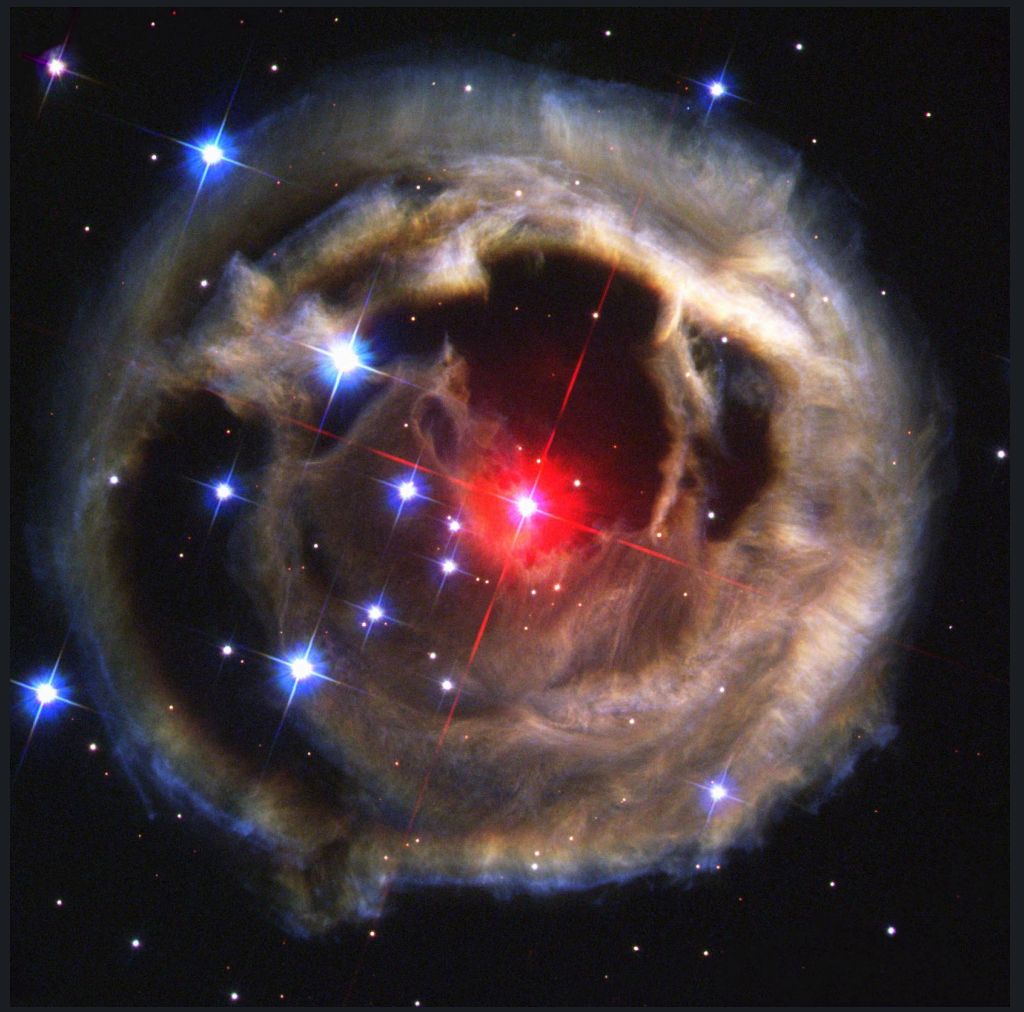


Each grain contains its parent star's nucleosynthetic signature

Asymptotic giant branch (AGB) stars

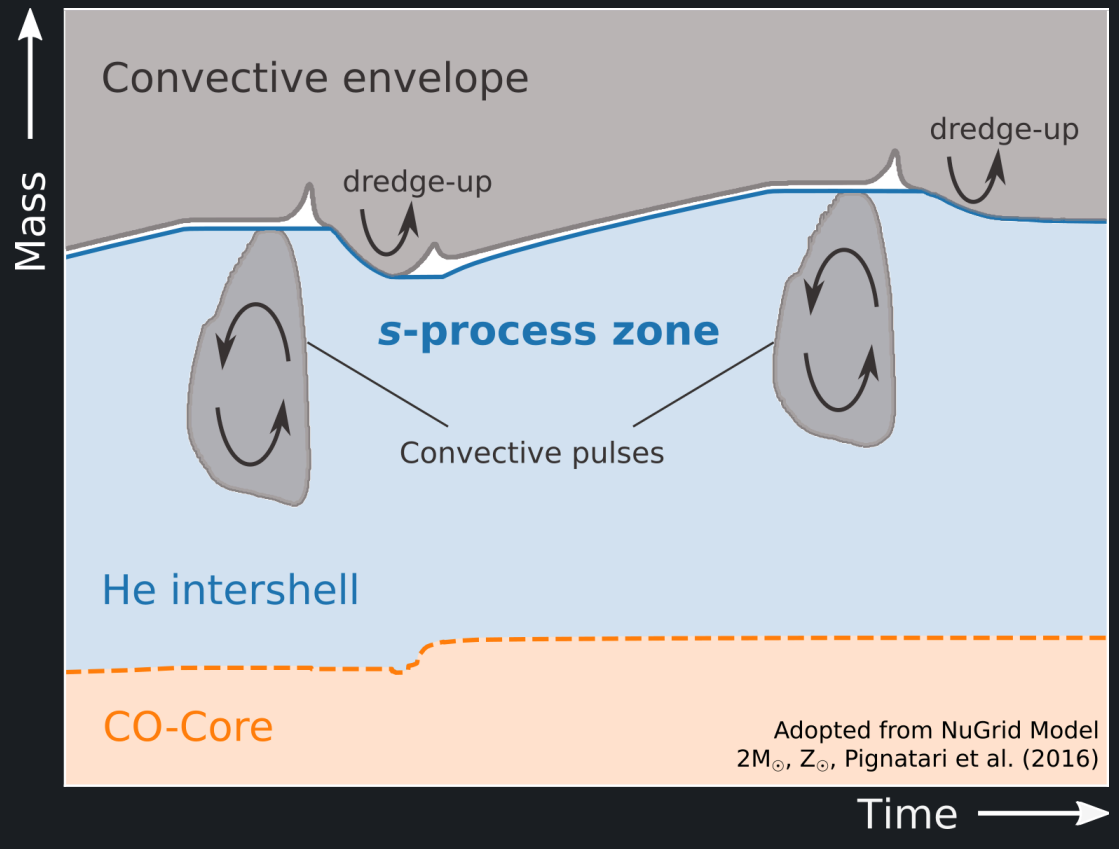
- **Copious** dust producers
- Host of the *s*-process
- Two important neutron sources
  - $^{13}C(\alpha,n)^{16}O$
  - $^{22}Ne(\alpha,n)^{25}Mg$
- Envelope well mixed
- Form SiC grains

Presolar SiC grains: directly probe the stellar envelope!



V838 Monocerotis (Credit: ESA/Hubble)

The two neutron sources at work



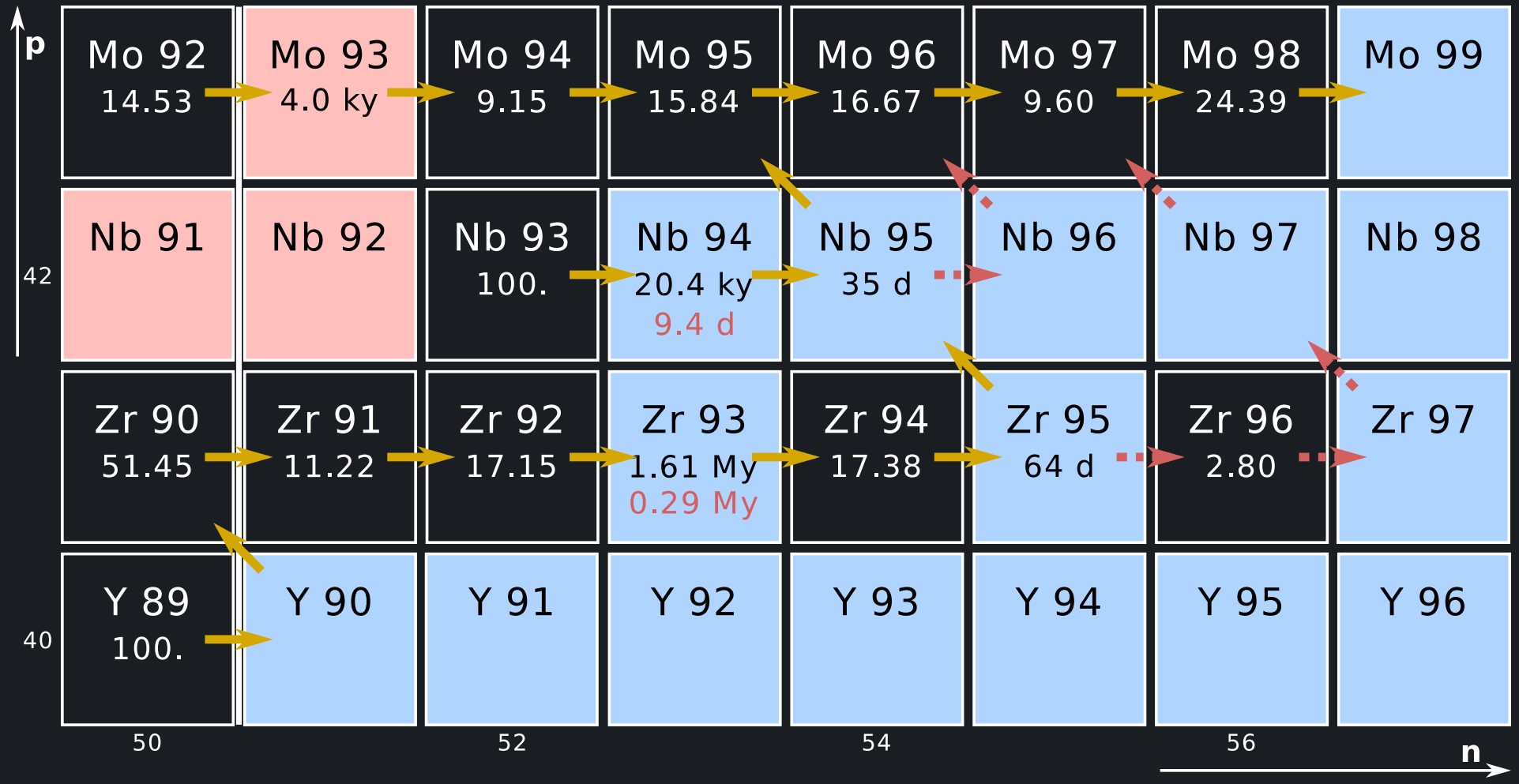
$^{13}C(\alpha,n)^{16}O$

- Main *s*-process neutron source
- Neutron density: $< 10^7$ cm^{-3}
- Thousands of years

$^{22}Ne(\alpha,n)^{25}Mg$

- Bottom of He intershell
- Max. neutron density ~10^9 cm^{-3}
- A few years

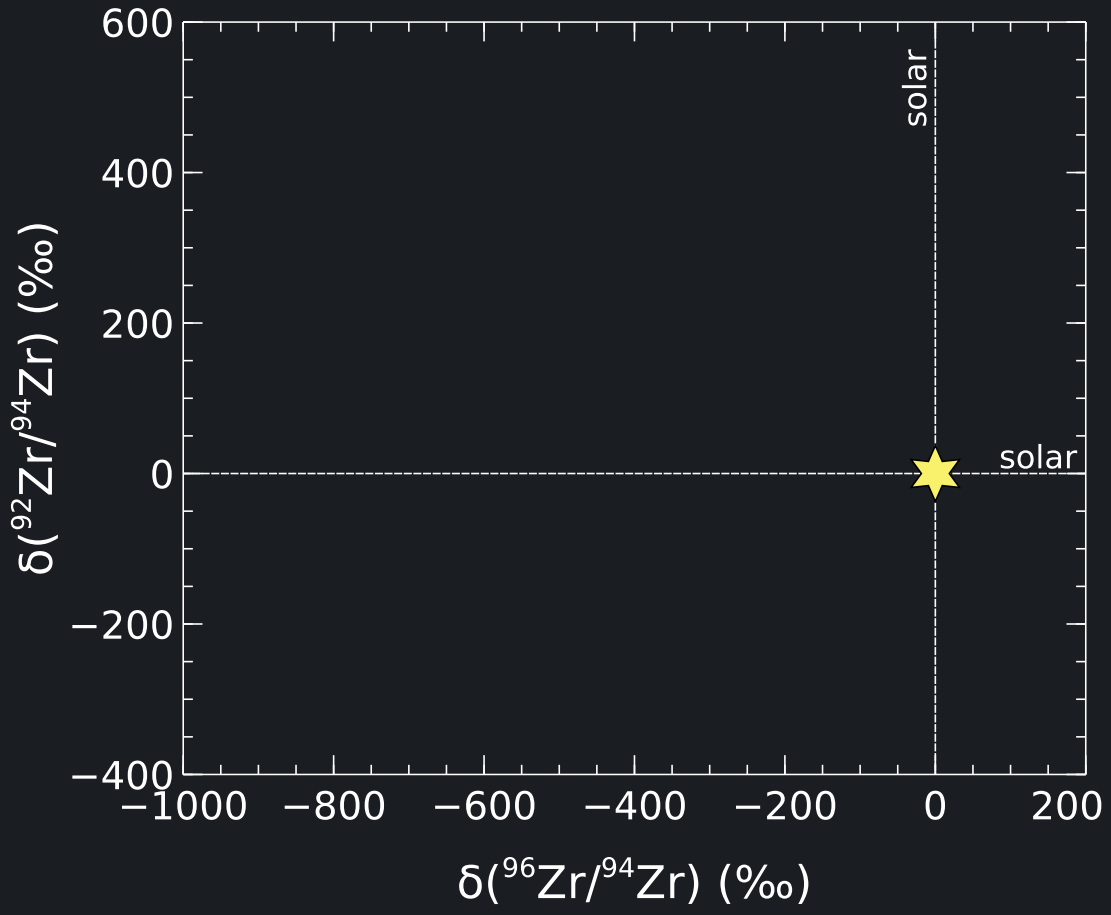
We can see these signatures in presolar grains!



Deciphering the stellar conditions

- SiC condenses only if C/O > 1
- Heavier stars get hotter
  - Stronger $^{22}Ne(\alpha,n)^{25}Mg$
  - Produce more ^{96}Zr
- Nuclear physics complicates picture further
- Presolar grains allow deciphering stellar conditions

see, e.g., Liu et al. (20xx), Stephan et al. (2019)

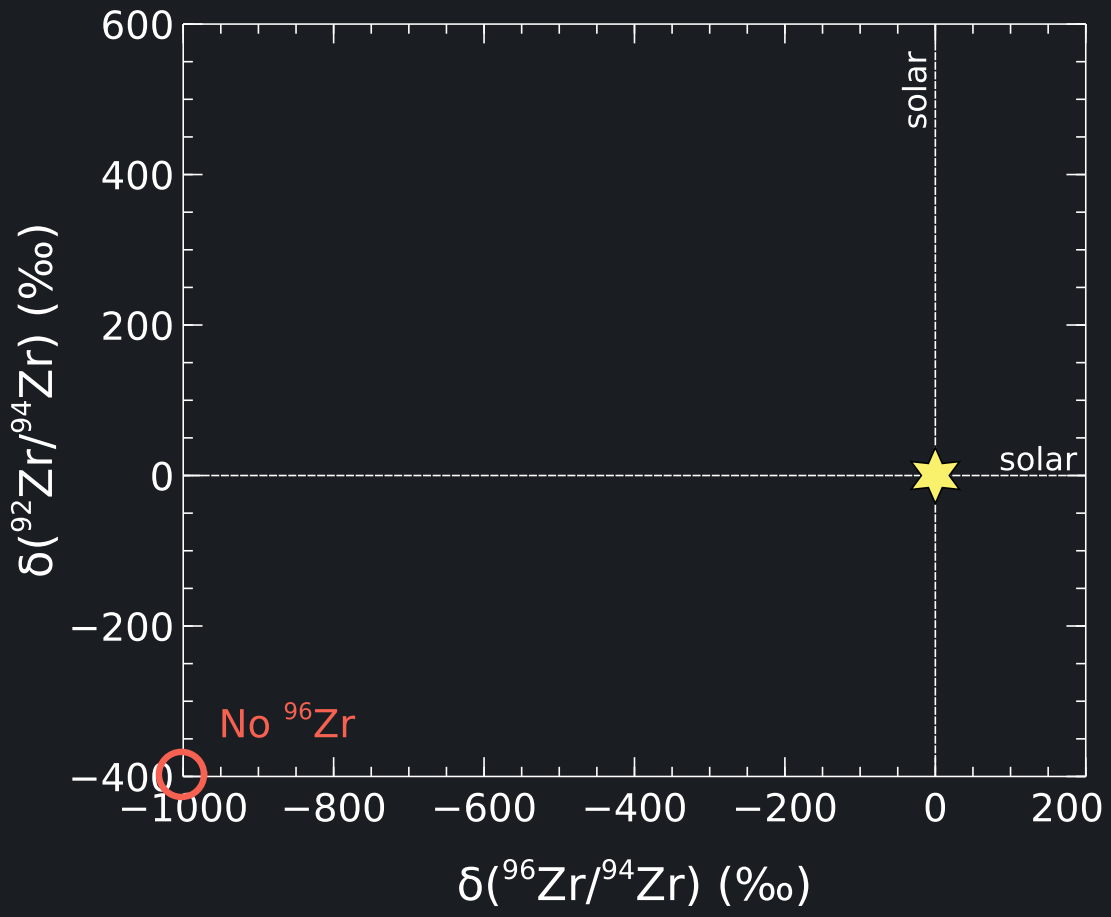


AGB models: Lugaro et al. (2018)

Deciphering the stellar conditions

- SiC condenses only if C/O > 1
- Heavier stars get hotter
  - Stronger $^{22}Ne(\alpha,n)^{25}Mg$
  - Produce more ^{96}Zr
- Nuclear physics complicates picture further
- Presolar grains allow deciphering stellar conditions

see, e.g., Liu et al. (20xx), Stephan et al. (2019)

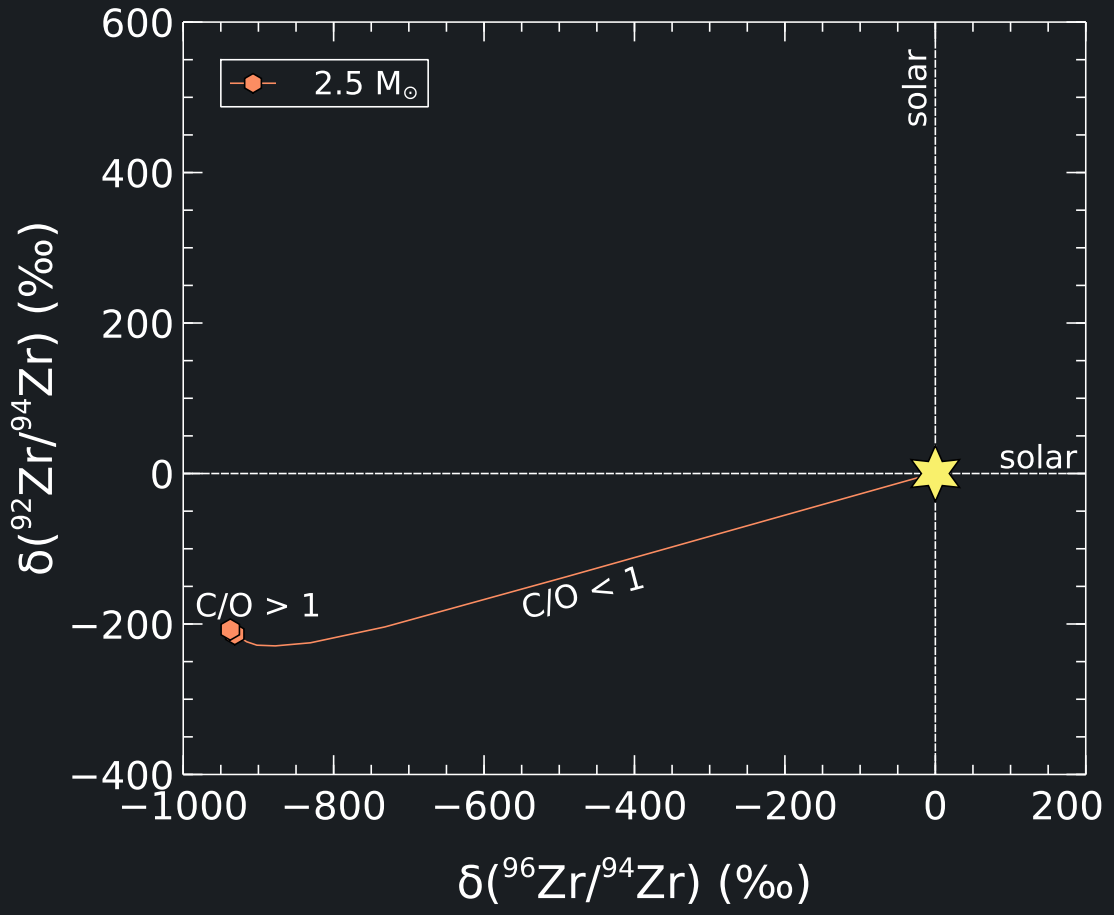


AGB models: Lugaro et al. (2018)

Deciphering the stellar conditions

- SiC condenses only if C/O > 1
- Heavier stars get hotter
  - Stronger $^{22}Ne(\alpha,n)^{25}Mg$
  - Produce more ^{96}Zr
- Nuclear physics complicates picture further
- Presolar grains allow deciphering stellar conditions

see, e.g., Liu et al. (20xx), Stephan et al. (2019)

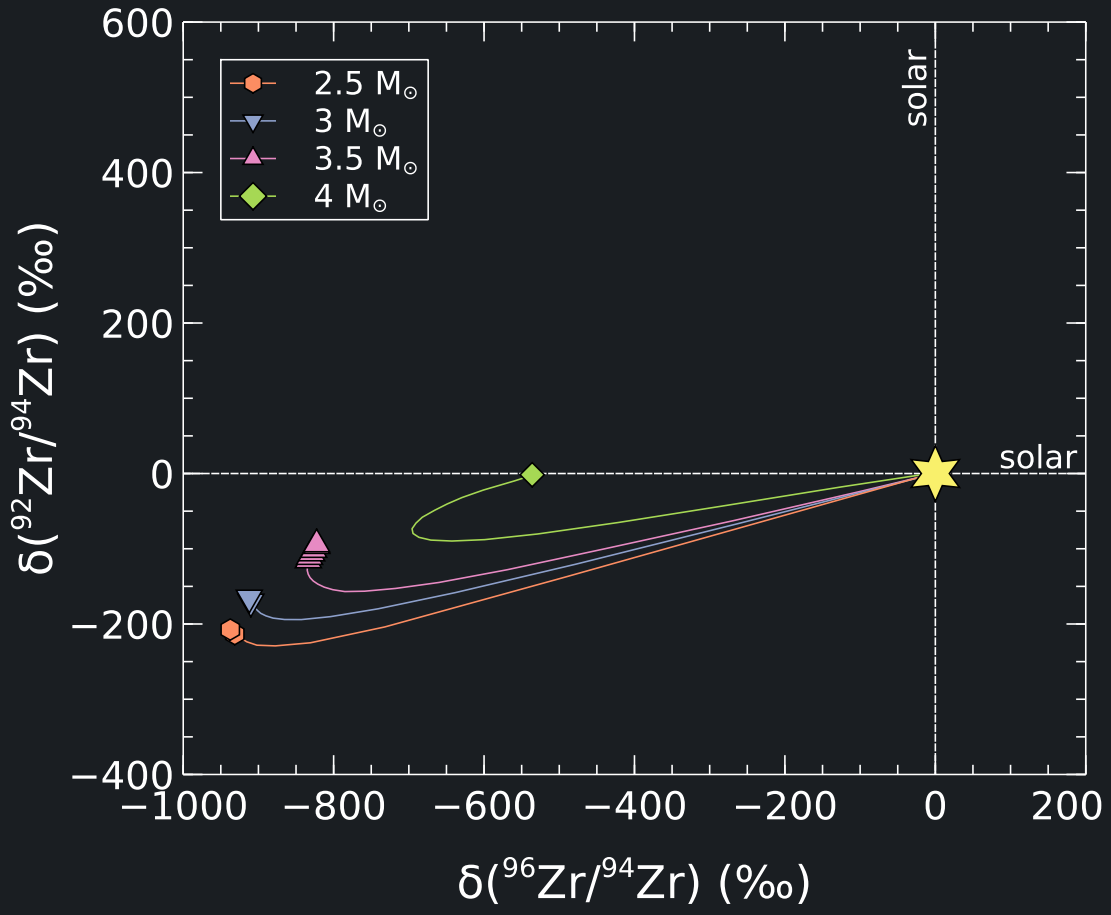


AGB models: Lugaro et al. (2018)

Deciphering the stellar conditions

- SiC condenses only if C/O > 1
- Heavier stars get hotter
  - Stronger $^{22}Ne(\alpha,n)^{25}Mg$
  - Produce more ^{96}Zr
- Nuclear physics complicates picture further
- Presolar grains allow deciphering stellar conditions

see, e.g., Liu et al. (20xx), Stephan et al. (2019)

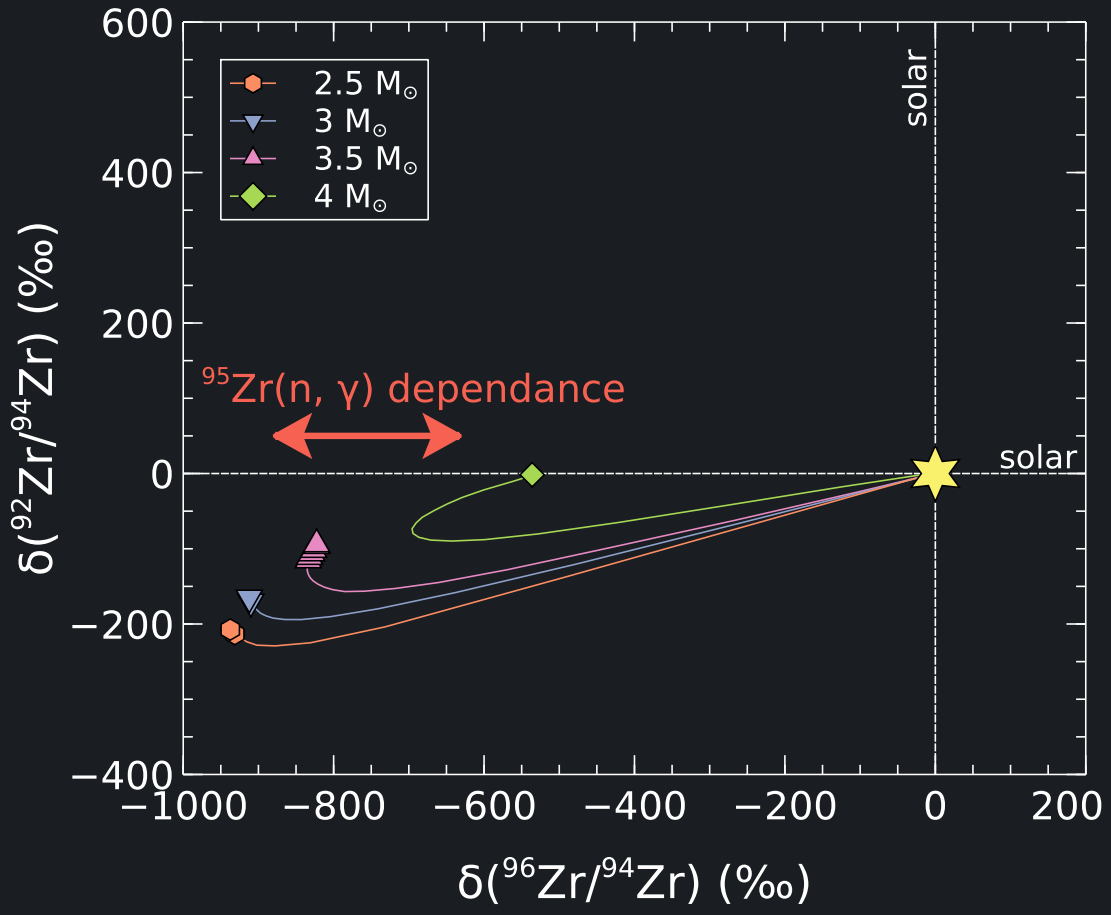


AGB models: Lugaro et al. (2018)

Deciphering the stellar conditions

- SiC condenses only if C/O > 1
- Heavier stars get hotter
  - Stronger $^{22}Ne(\alpha,n)^{25}Mg$
  - Produce more ^{96}Zr
- Nuclear physics complicates picture further
- Presolar grains allow deciphering stellar conditions

see, e.g., Liu et al. (20xx), Stephan et al. (2019)

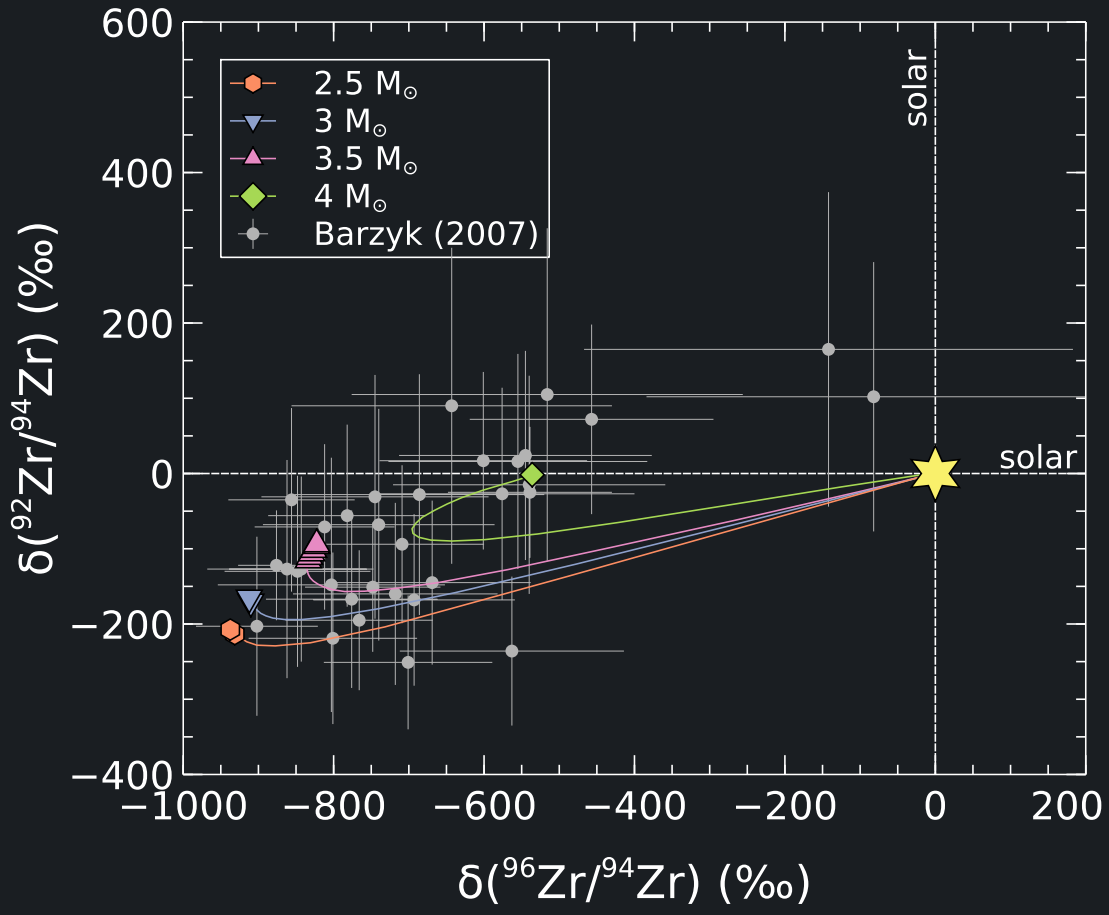


AGB models: Lugaro et al. (2018)

Deciphering the stellar conditions

- SiC condenses only if C/O > 1
- Heavier stars get hotter
  - Stronger $^{22}Ne(\alpha,n)^{25}Mg$
  - Produce more ^{96}Zr
- Nuclear physics complicates picture further
- Presolar grains allow deciphering stellar conditions

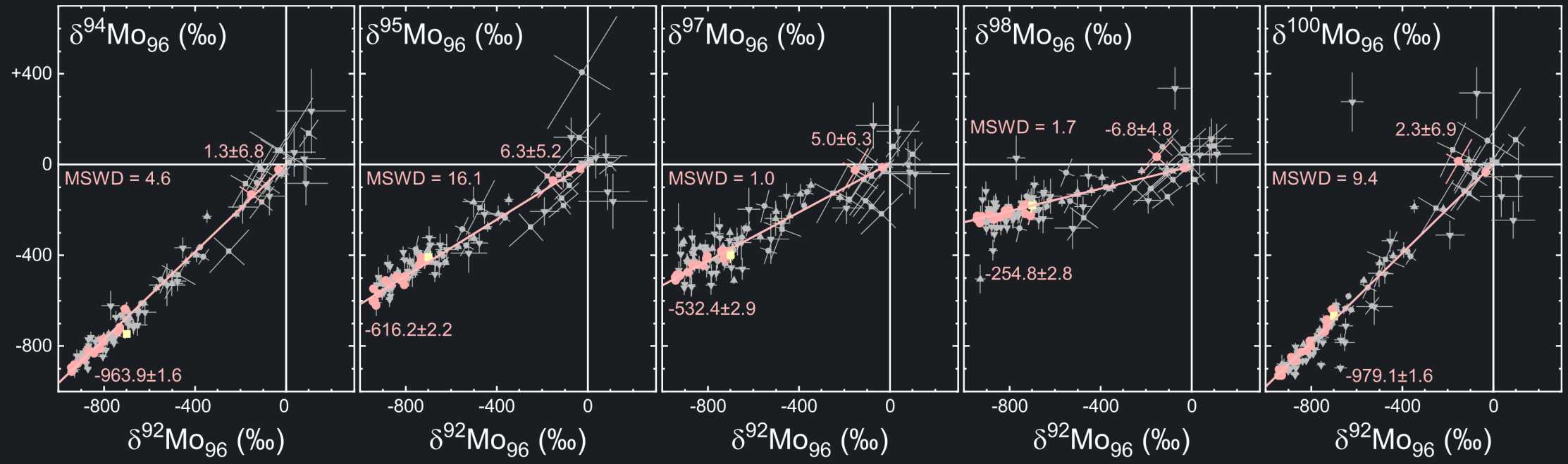
see, e.g., Liu et al. (20xx), Stephan et al. (2019)



AGB models: Lugaro et al. (2018)

Molybdenum is especially interesting

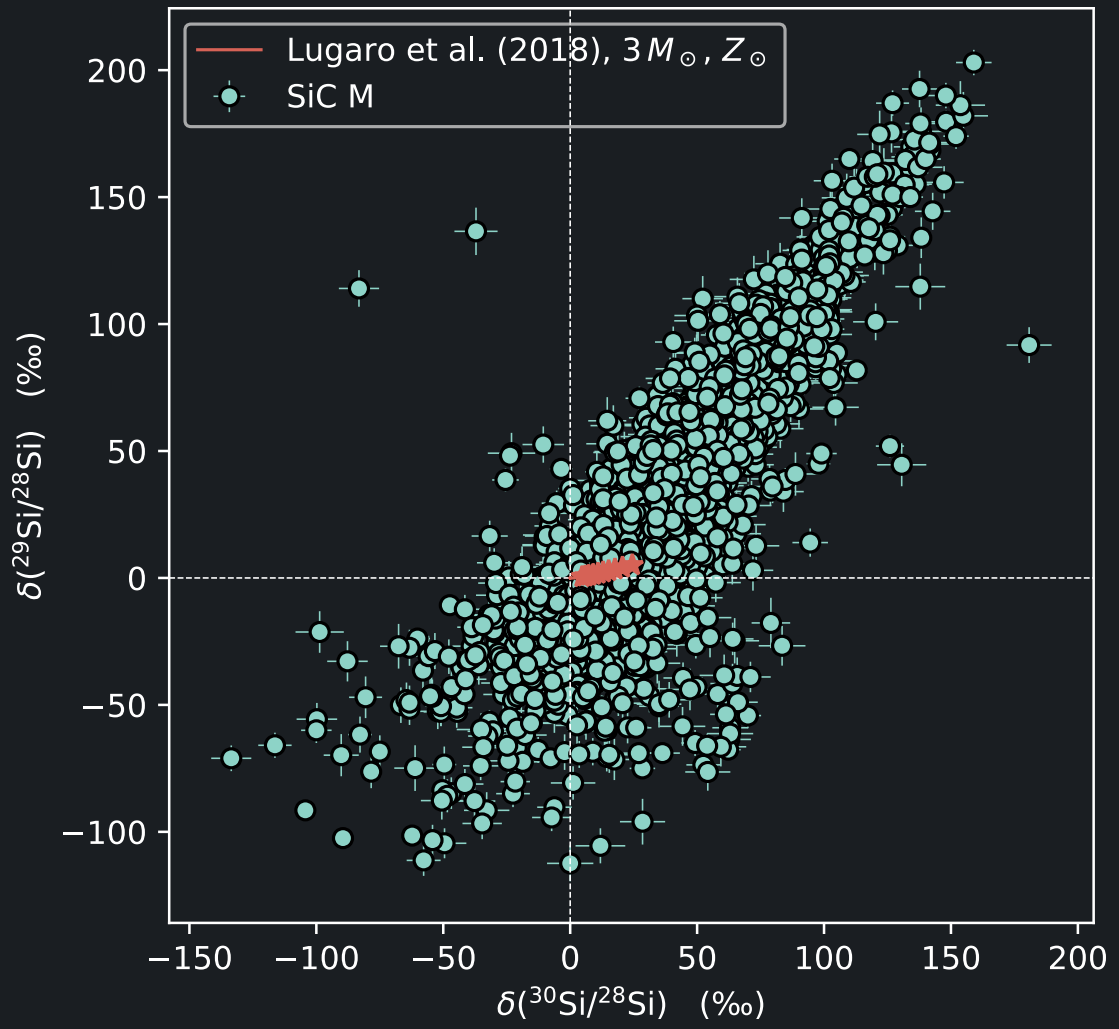
Measurements indicate constant *r*/*p* isotope production



Stephan et al. (2019)

- ^{92}Mo not made in s-process but destroyed
- Extrapolation towards no-^{92}Mo yield pure *s*-process composition
- This would be possible for other elements, e.g., Ru, Sm, and (maybe) Pt

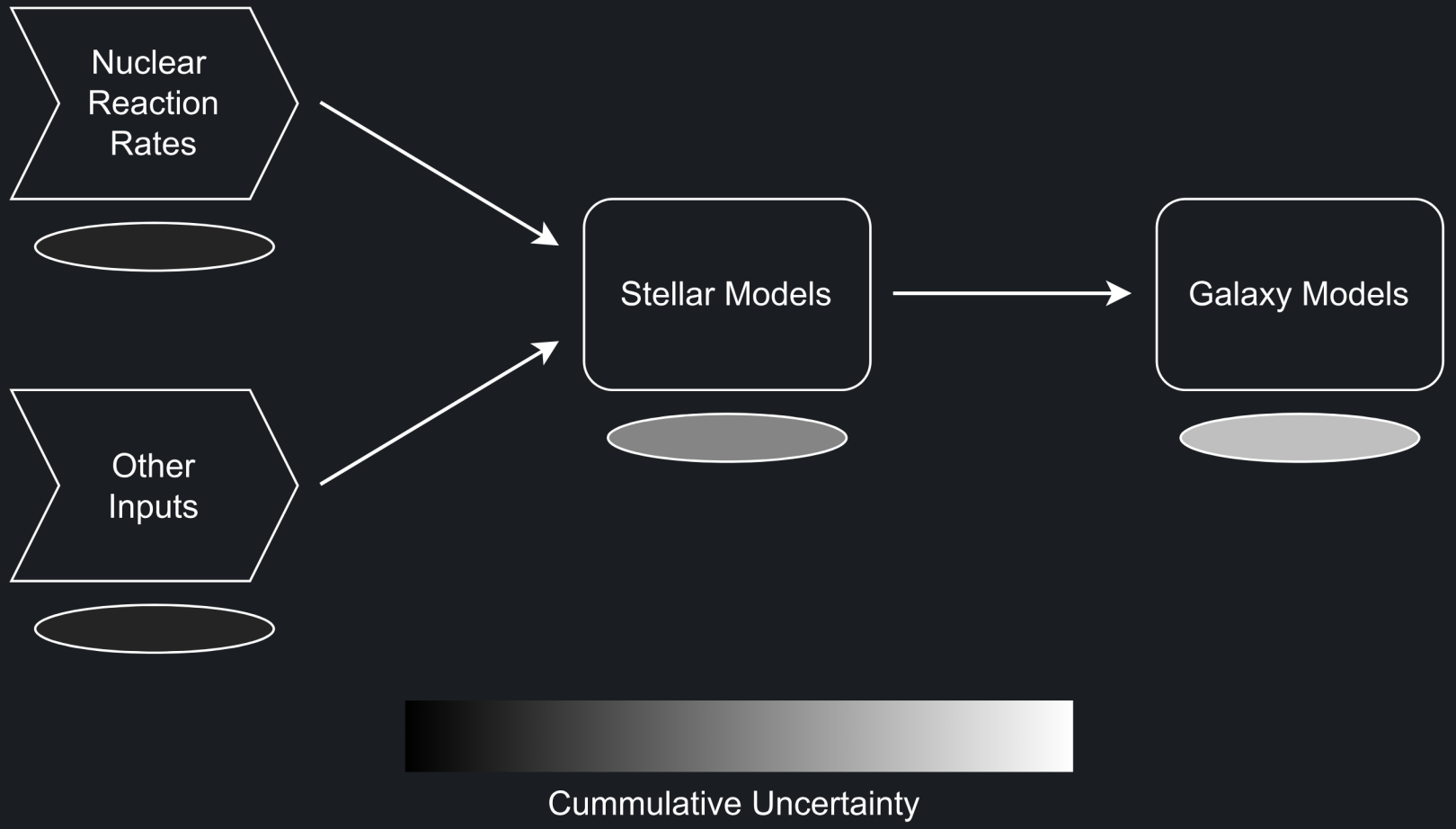
The galactic chemical evolution (GCE) puzzle



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

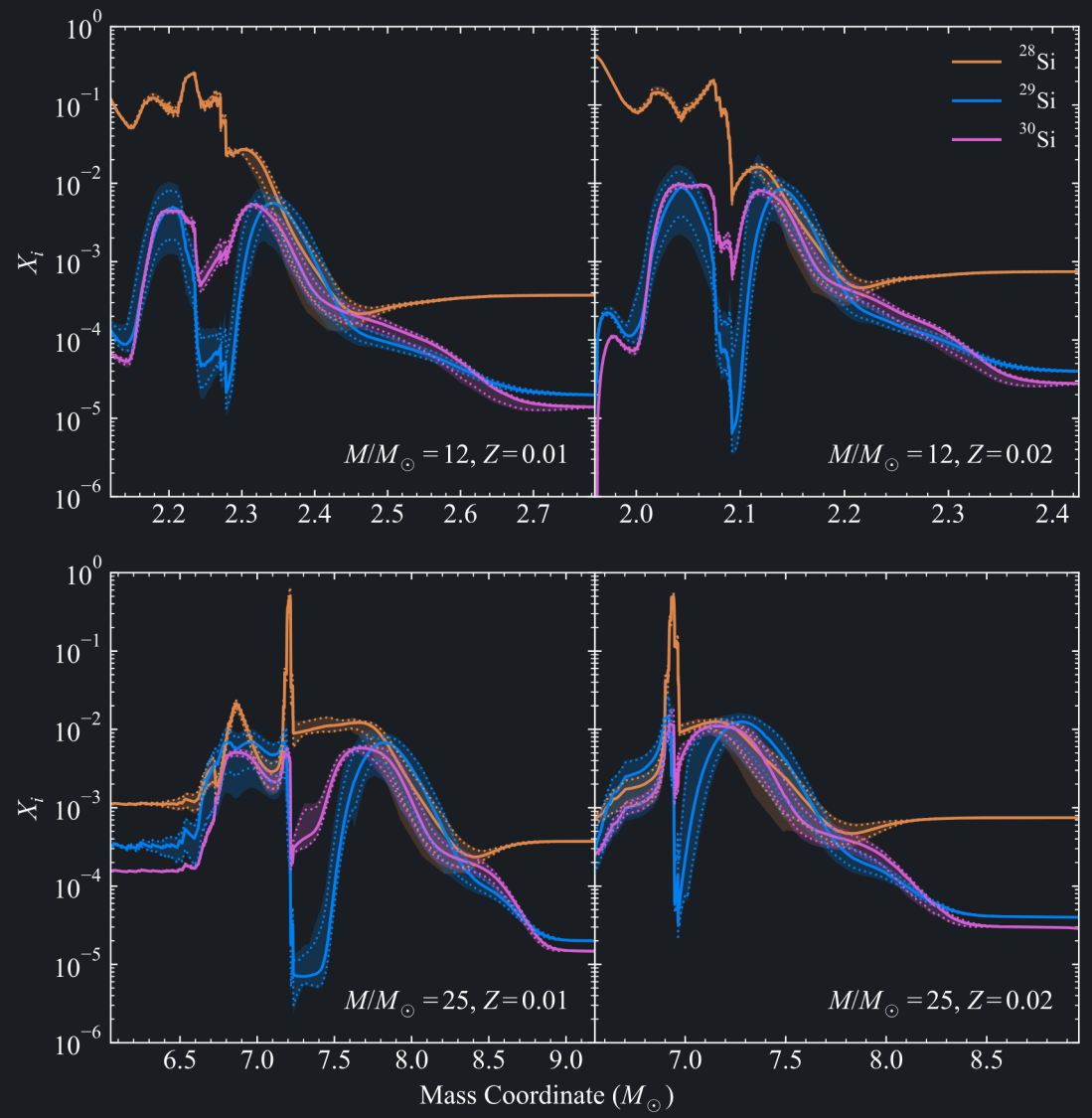
What is going on?

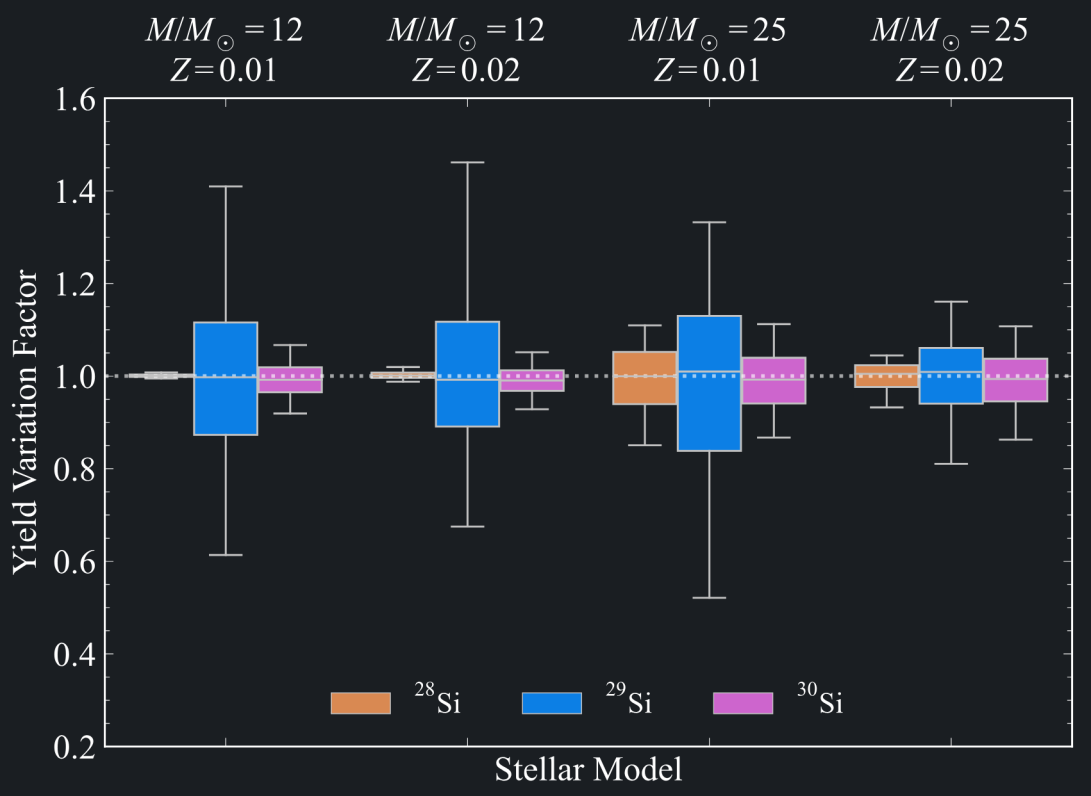
The influence of nuclear reaction rates on the slope



Fok et al. (in review)

Stellar nucleosynthesis effects

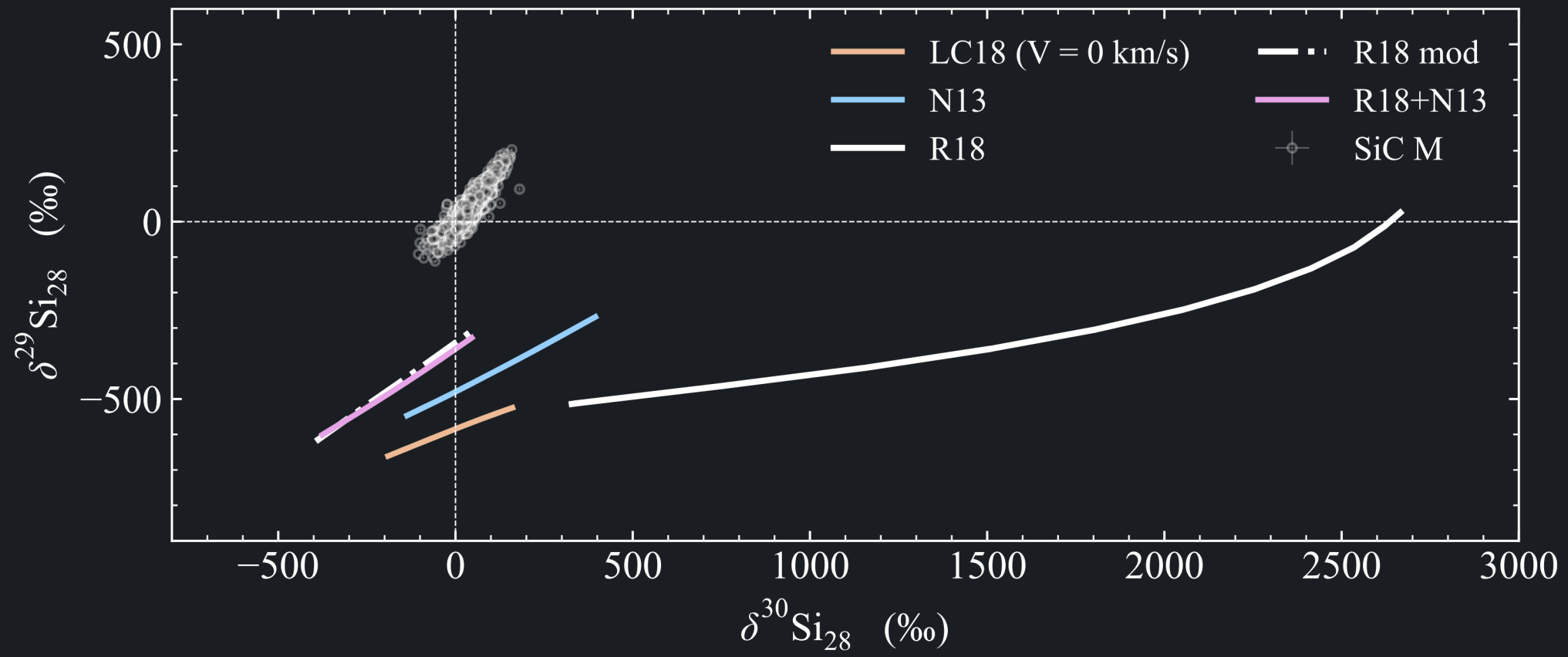




Nuclear reaction rate uncertainties have a large influence, especially on ^{29}Si

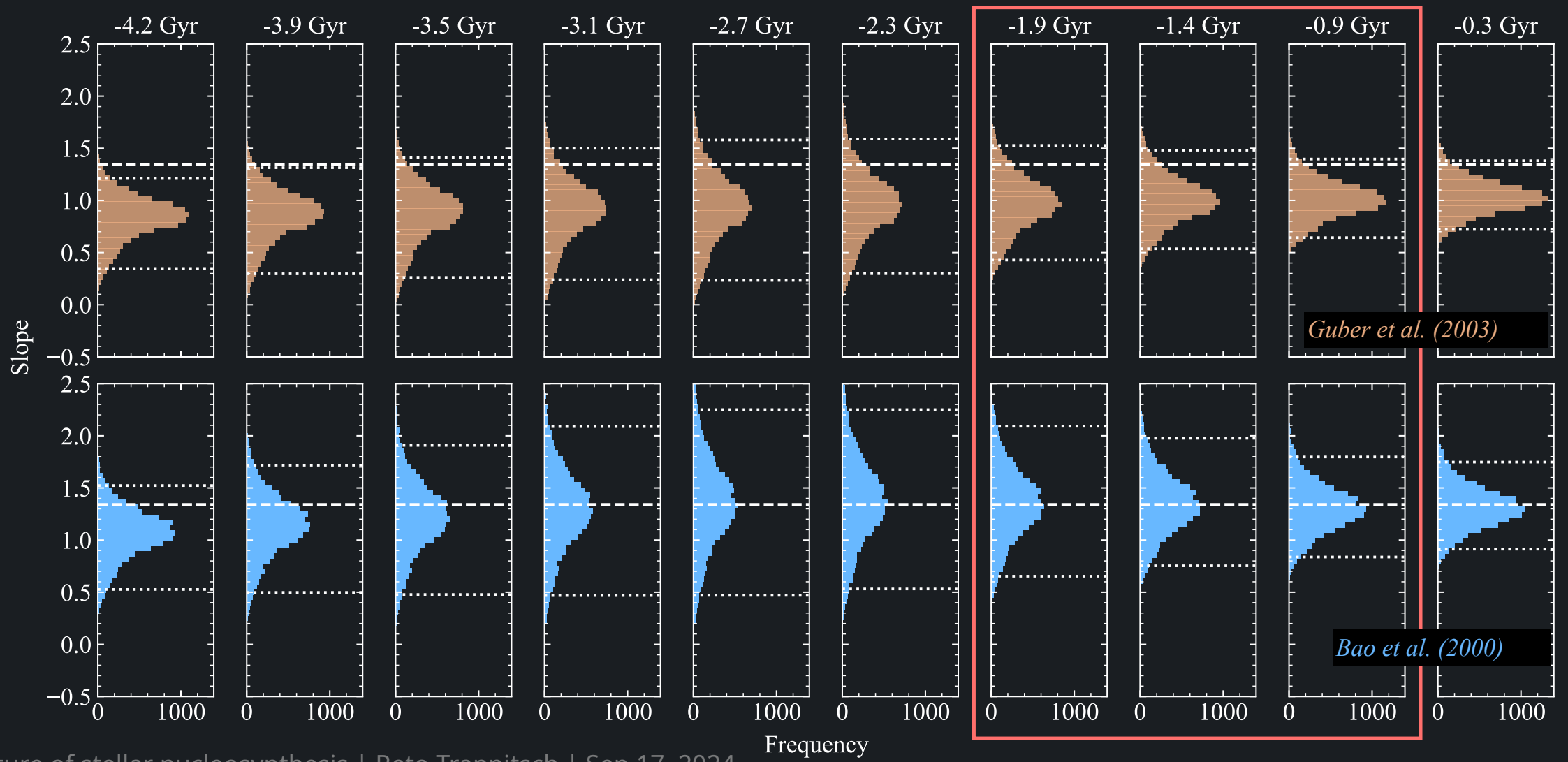
Fok et al. (in review)

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!

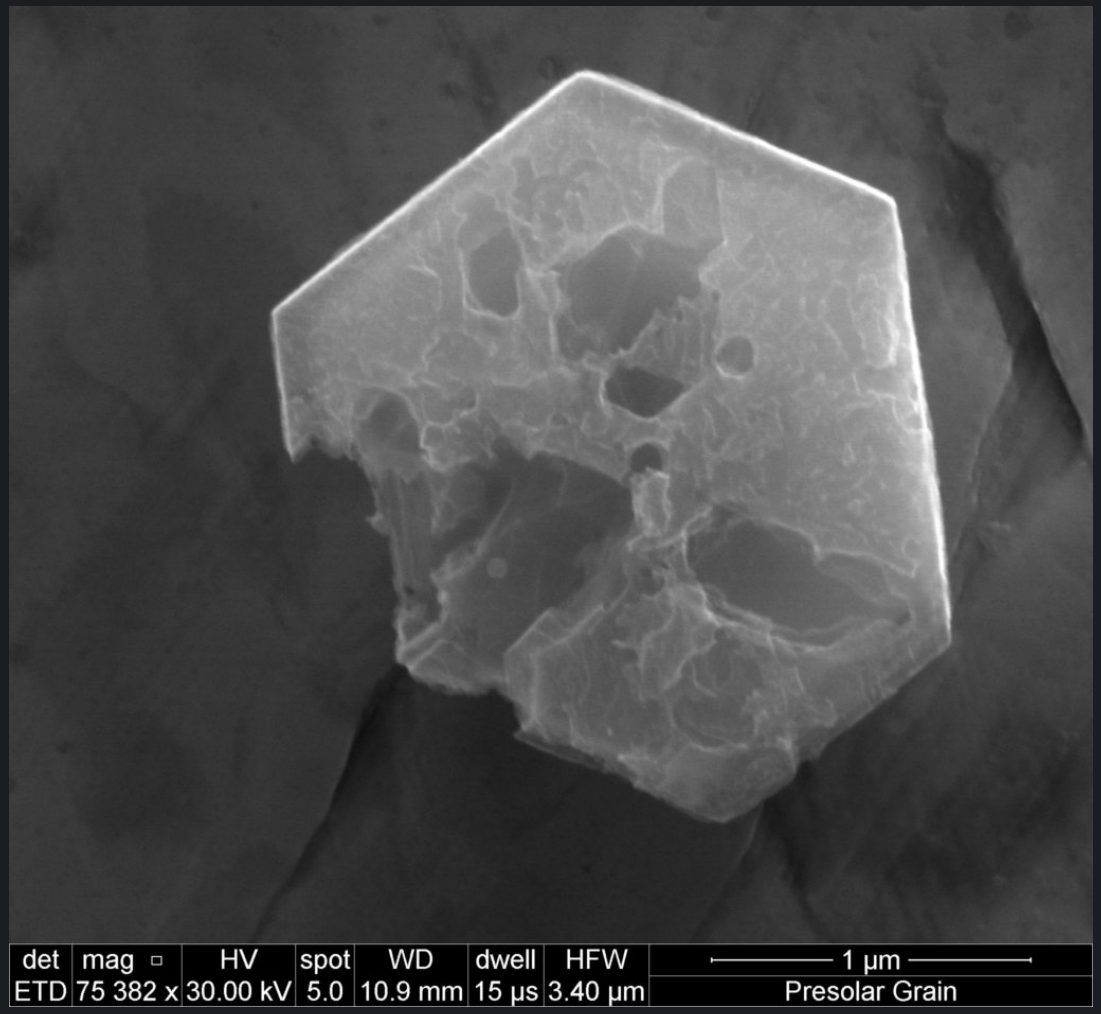
Nuclear reaction rate uncertainties could explain the model-data discrepancy



Presolar grain analysis: Hands-on astrophysics…

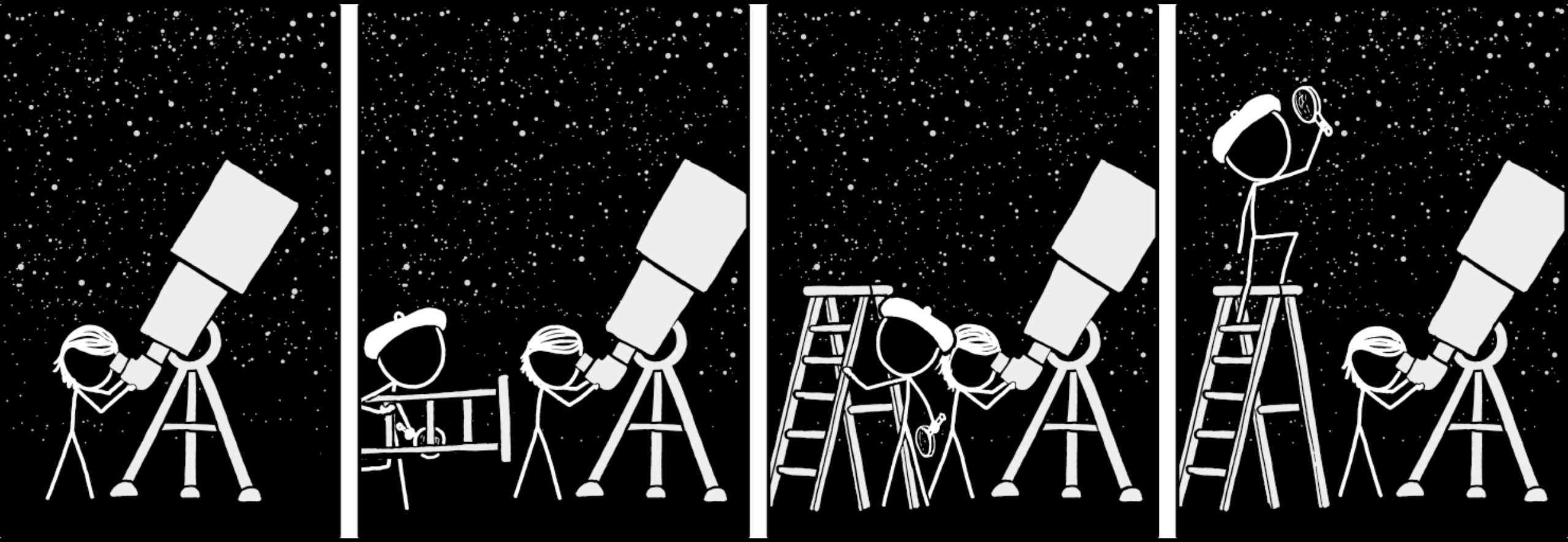
- Isotopic messenger
- Fine probes for many processes
  - *s*-process nucleosynthesis
  - Rare nucleosynthesis processes
  - GCE
  - …
- Recent advances in measurement techniques

Stay tuned!



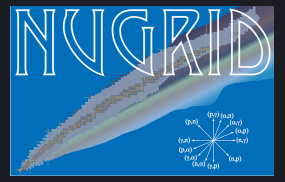
SiC grain imaged in the secondary electron microscope

… or astronomy with a microscope



xkcd.com

Acknowledgement

Brandeis University	Hung Kwan Fok*
Lawrence Livermore National Laboratory	Jutta Escher, Jason Harke, Richard Hughes, Brett Isselhardt, Wei Jia Ong, Mike Savina, Ziva Shulaker, Barbara Wang
The University of Chicago	Andy Davis, Mike Pellin, Philipp Heck, Thomas Stephan
Konkoly	Benoit Côté*, Marco Pignatari*, Maria Lugaro
	NuGrid collaboration*