Nuclear burning recorded in meteorites as a tracer of the birth of the Sun and its planets

KONKOLY

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NATIONAL RESEARCH, DEVELOPMENT AND INNOVATION OFFICE

2018-2020 and 2022-2026

RADIOSTAR erc

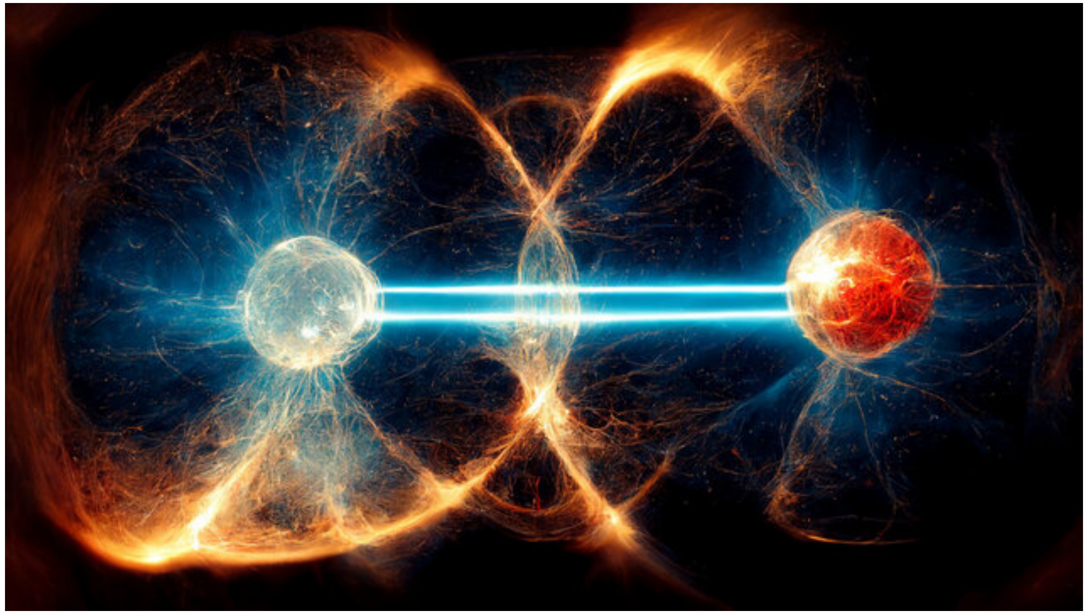
2017-2023

ChETEC INFRA

2019-2025

mta.hu

Nuclear burning



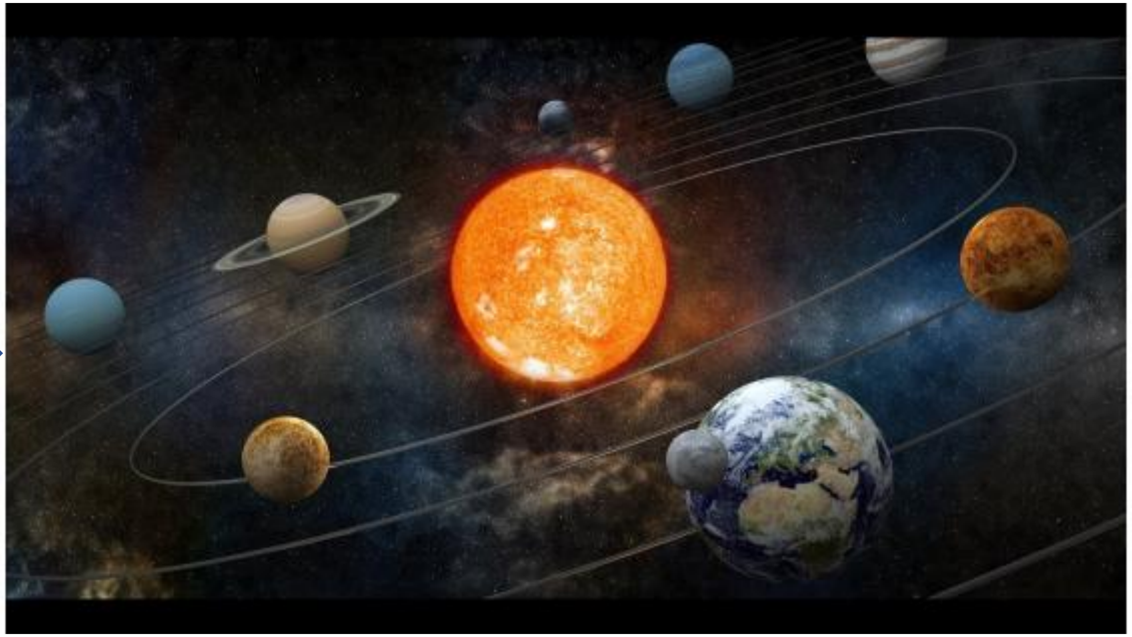
Length scale ~ 10^{-14} m

Temperature > 10^{7} K

inside stars

?

The birth of the Sun and its planets

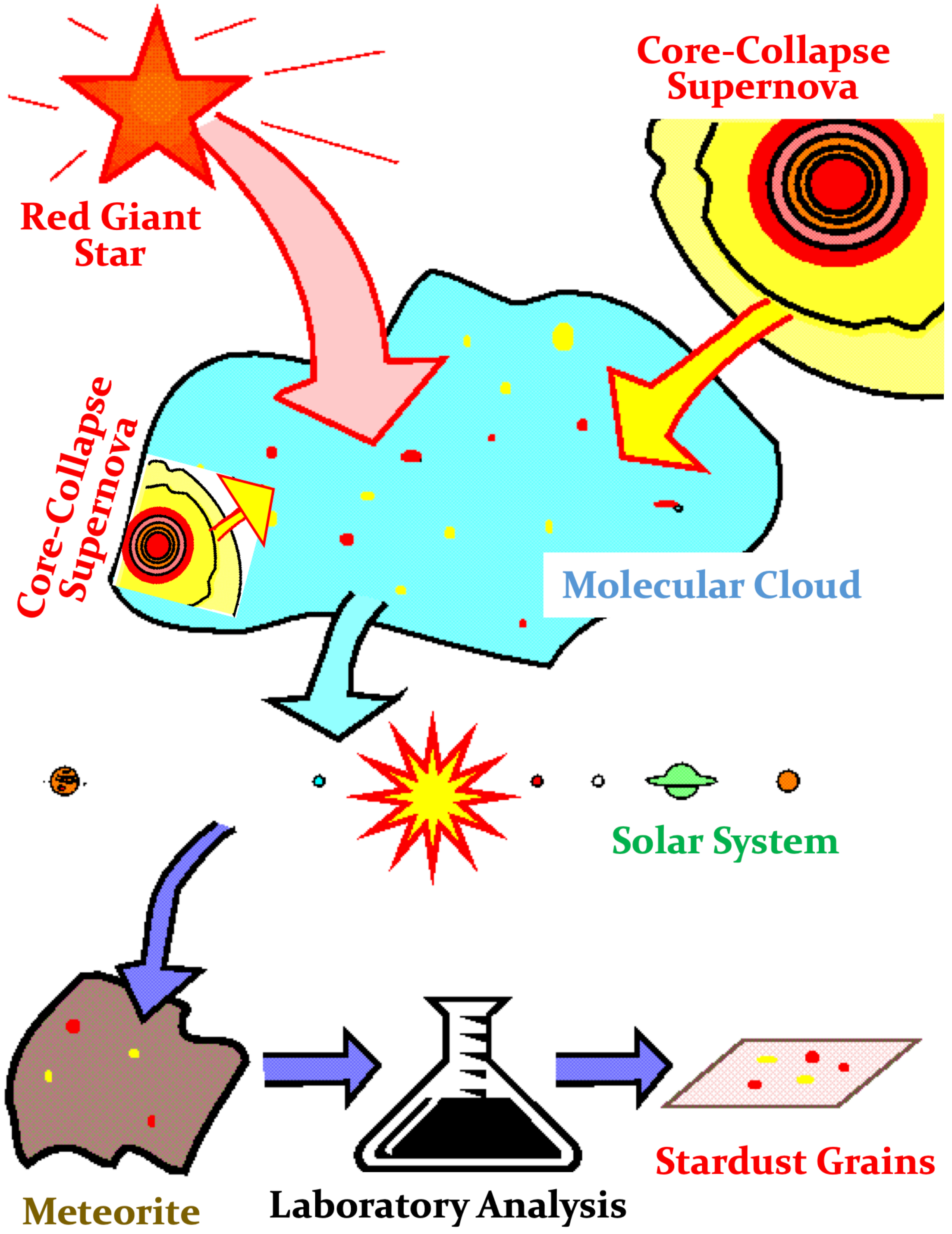


Length scale ~ 10^{16} m

Temperature < 10^{3} K

inside a molecular cloud

STAR-DUST

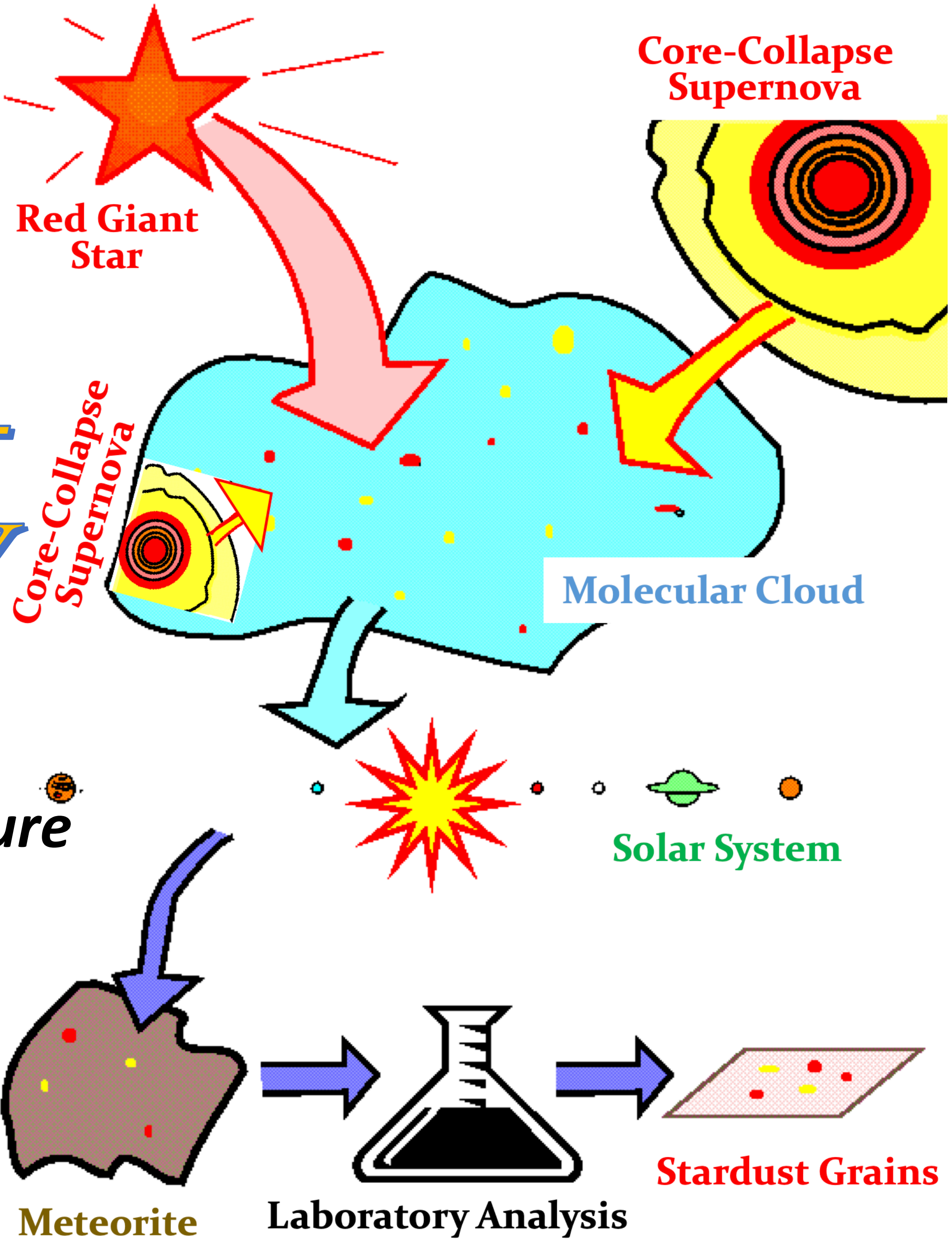


carried the signatures of nuclear processes from stars into meteorites

Figure from Larry Nittler

1. STAR-DUST

2. RADIO-ACTIVITY



carried the signatures of nuclear processes from stars into meteorites

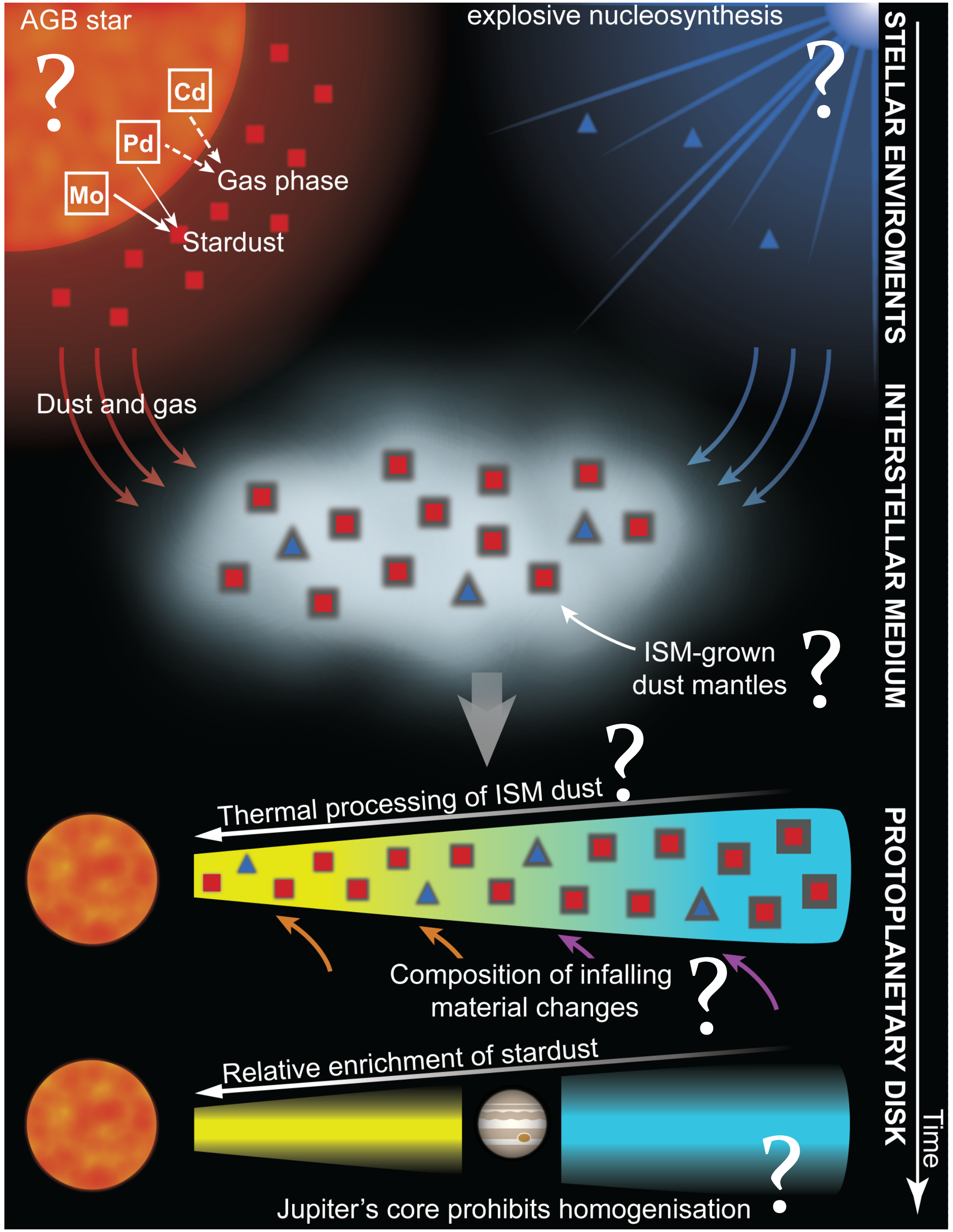
If stardust was destroyed the signature still survived in:

3. BULK-ROCKS

Figure from Larry Nittler

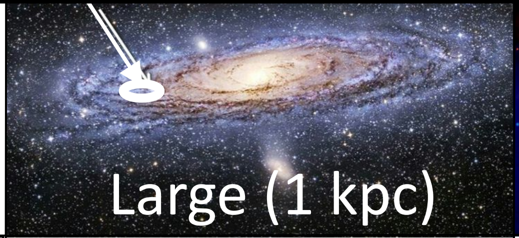
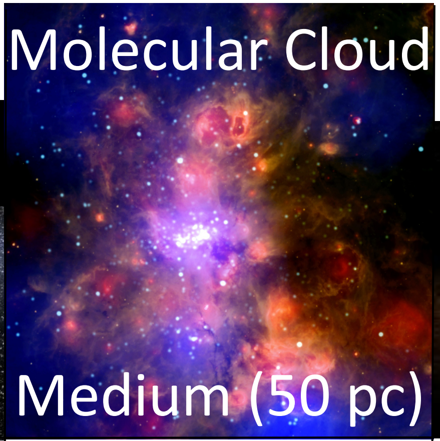
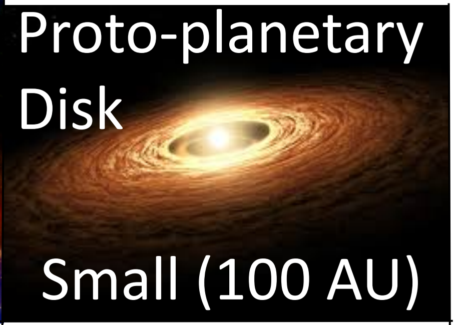
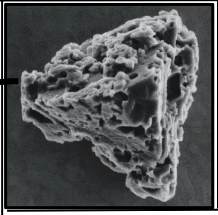
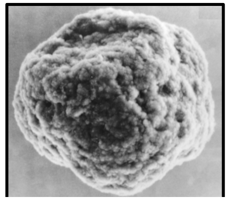
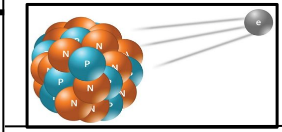
Which *stars were present in the Galaxy* at the time of the formation of the Sun?

How did material distributed *inside the protoplanetary disk*?



In which *environment* did the Sun formed, and what kind of *material it accreted* from its molecular cloud?

Figure from Mattias Ek

Type ↓ / Scale →		Solar Neighbourhood  Large (1 kpc)	Molecular Cloud  Medium (50 pc)	Proto-planetary Disk  Small (100 AU)
STAR-DUST 1.	 ≈ 90% from asymptotic giant branch (AGB) stars	✓		
	≈ 10% from core-collapse supernovae 	✓	✓	
RADIO-ACTIVITY 2.	0.1 < half life < 100 Myr  *short-lived*	✓	✓	
BULK-ROCKS 3.	Meteoritic rocks and inclusions 		✓	✓

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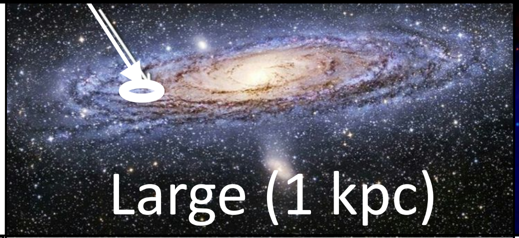
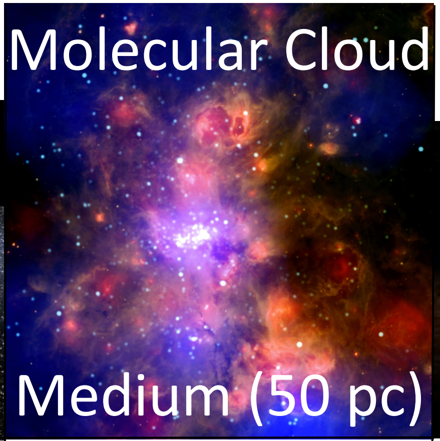
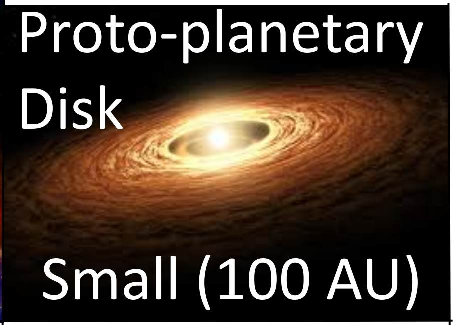
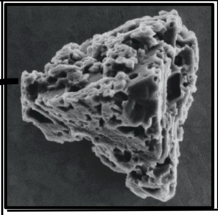
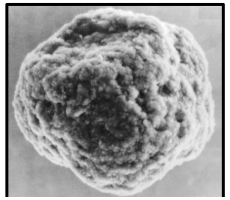
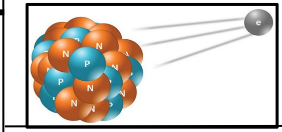
Type ↓	Scale →	Solar Neighbourhood  Large (1 kpc)	Molecular Cloud  Medium (50 pc)	Proto-planetary Disk  Small (100 AU)
STAR-DUST 1.	 ≈ 90% from asymptotic giant branch (AGB) stars	✓		
	≈ 10% from core-collapse supernovae 	✓	✓	
RADIO-ACTIVITY 2.	0.1 < half life < 100 Myr  *short-lived*	✓	✓	
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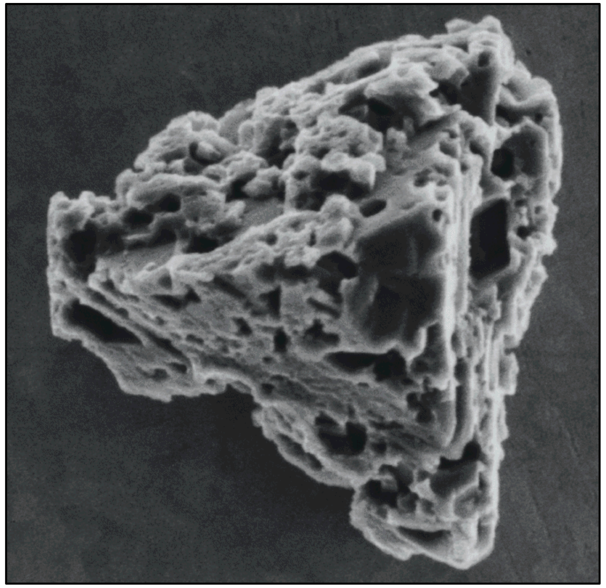
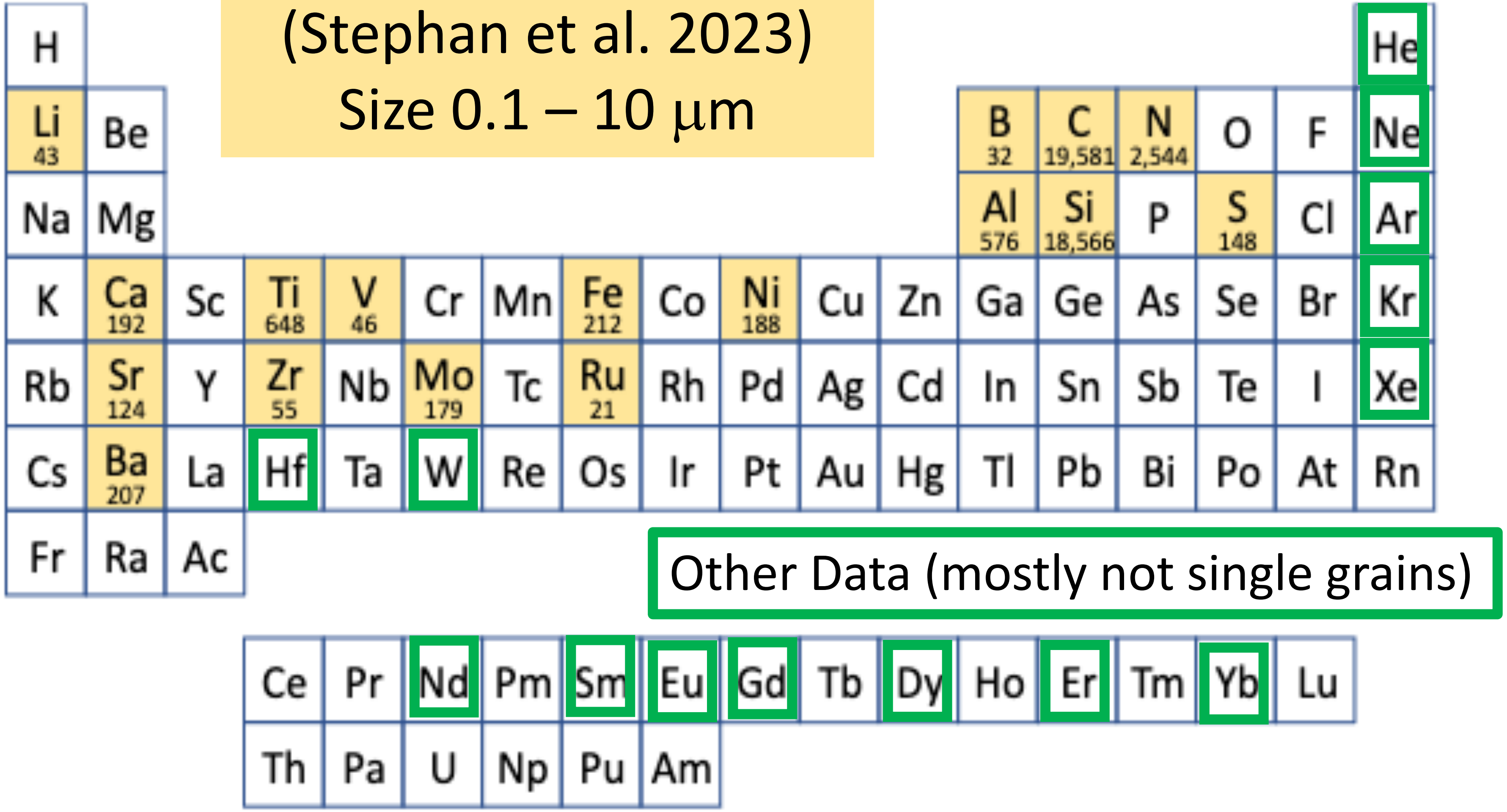


Presolar Grain Database
of single grains
(Stephan et al. 2023)
Size 0.1 – 10 μm



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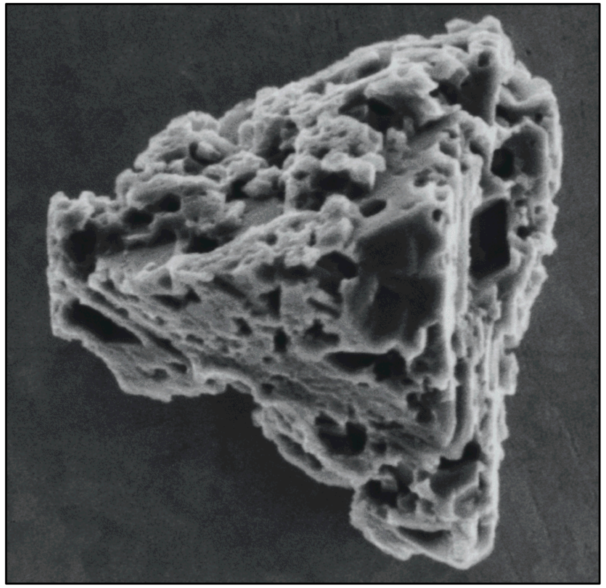

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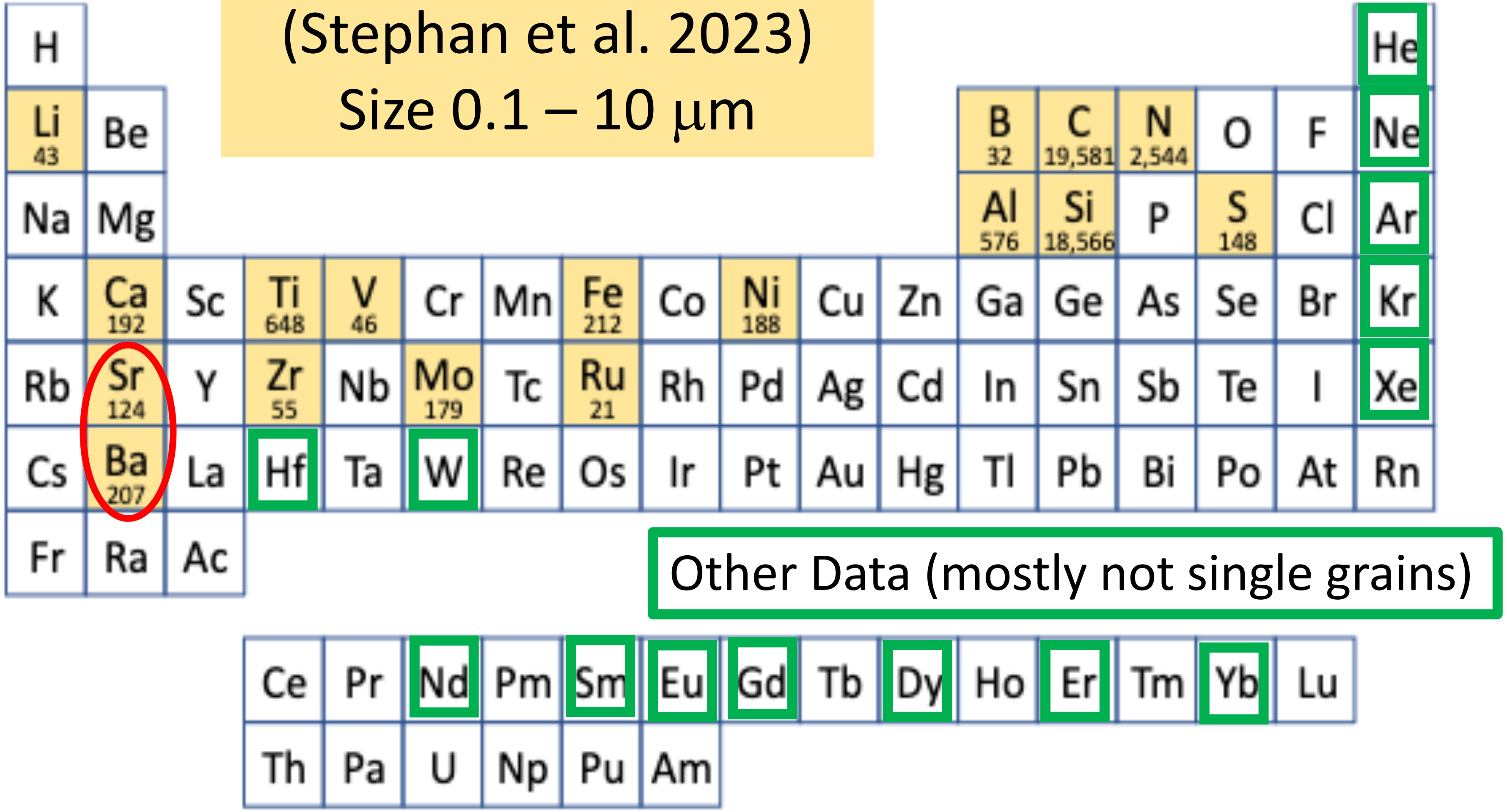

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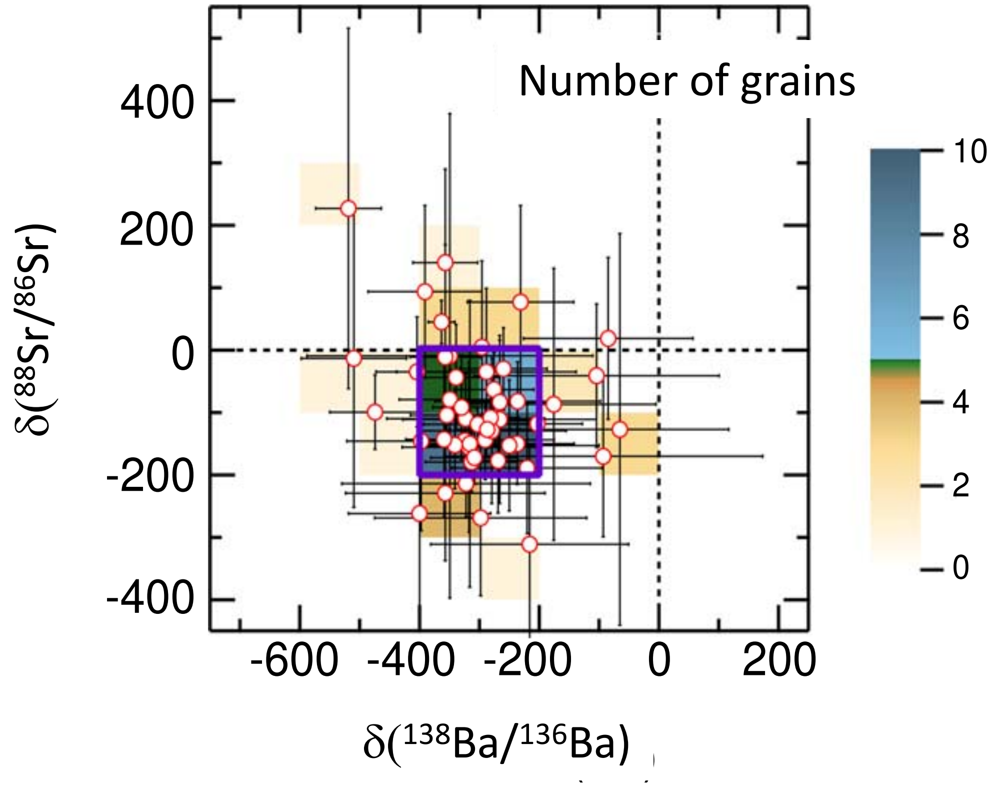
SiC grains from AGB stars show the *slow* neutron-capture signature:

e.g., the large (≈ μm) grains



Profile of the ^{13}C neutron source?
(Liu et al. 2018)

Metallicity?
(Lugaro, Karakas et al. 2018)

Treatment of mixing?
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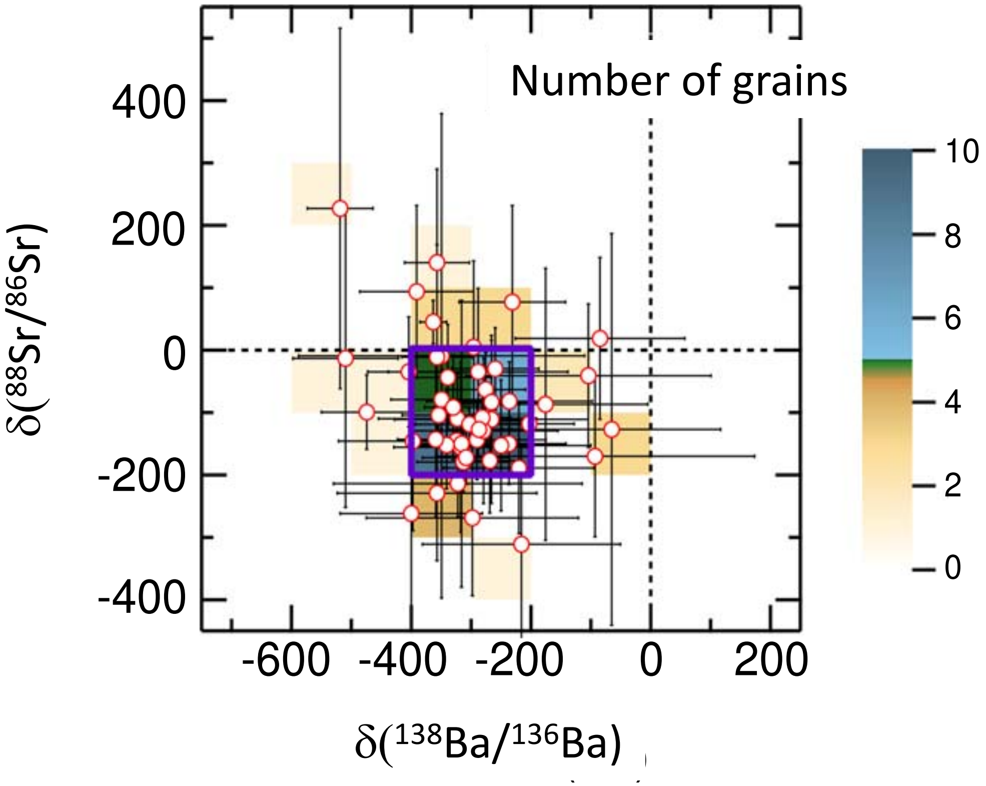

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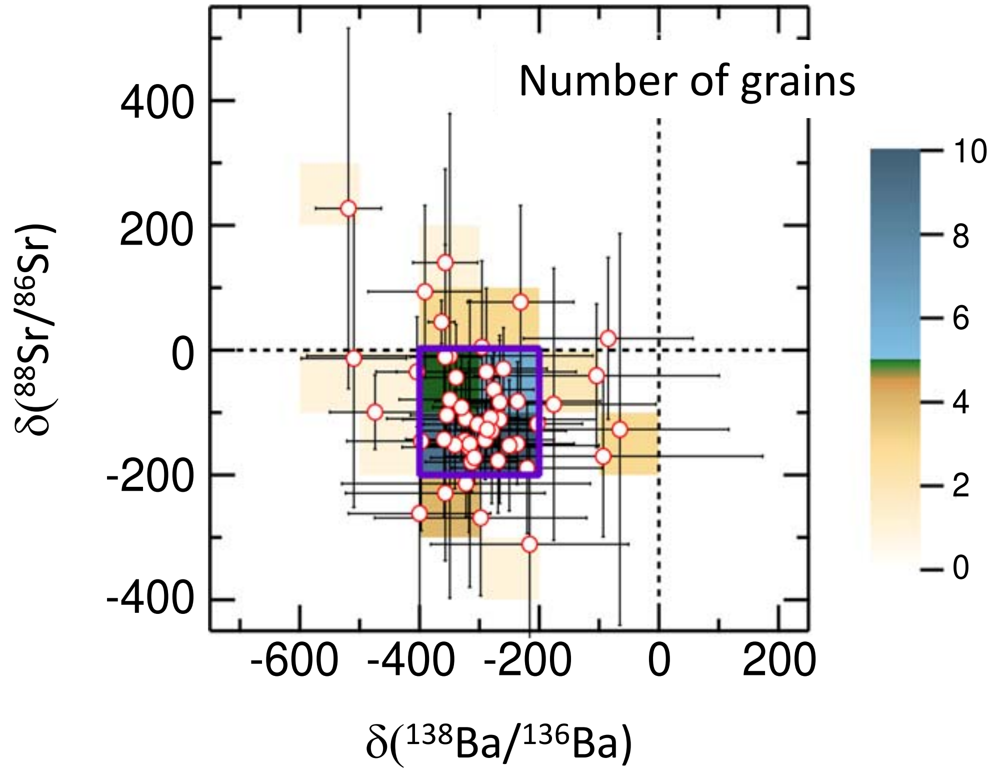

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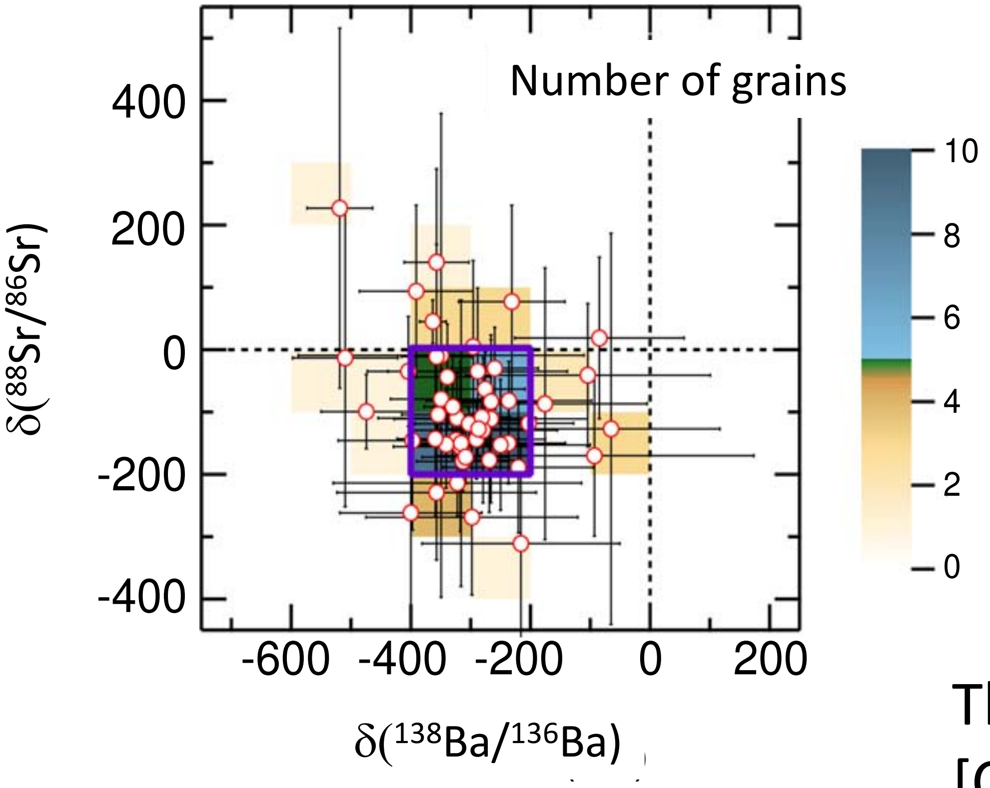

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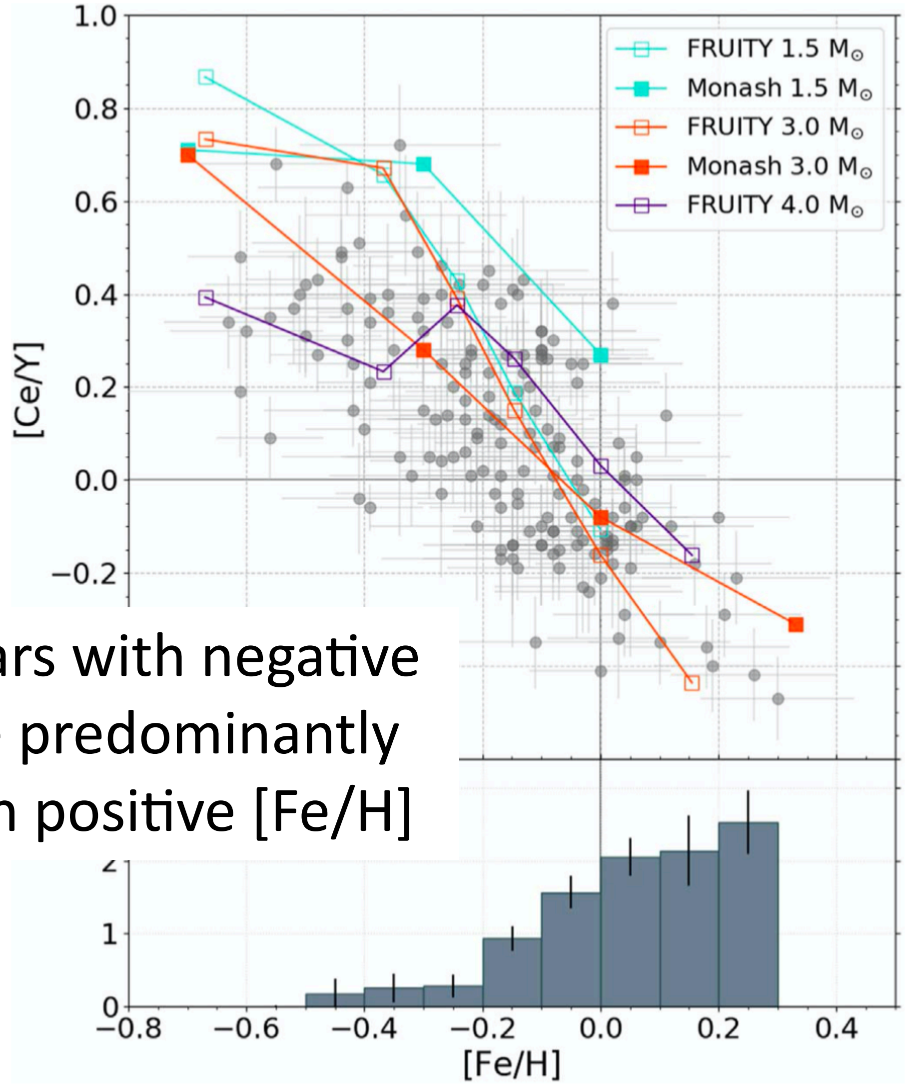

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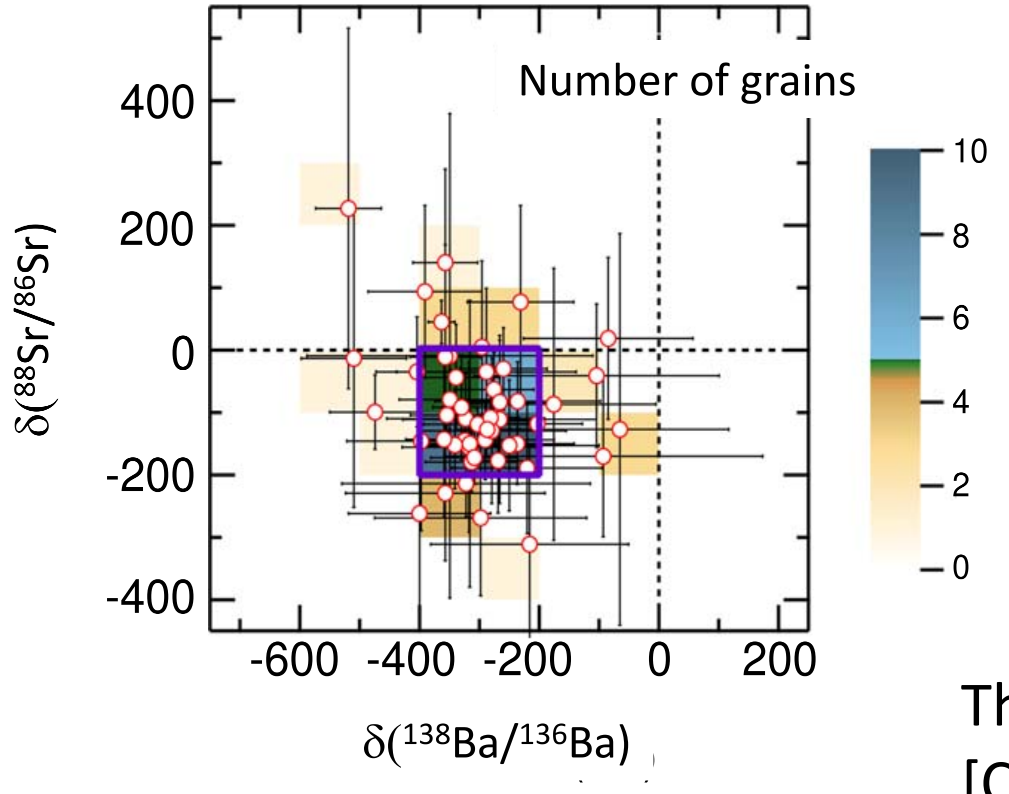

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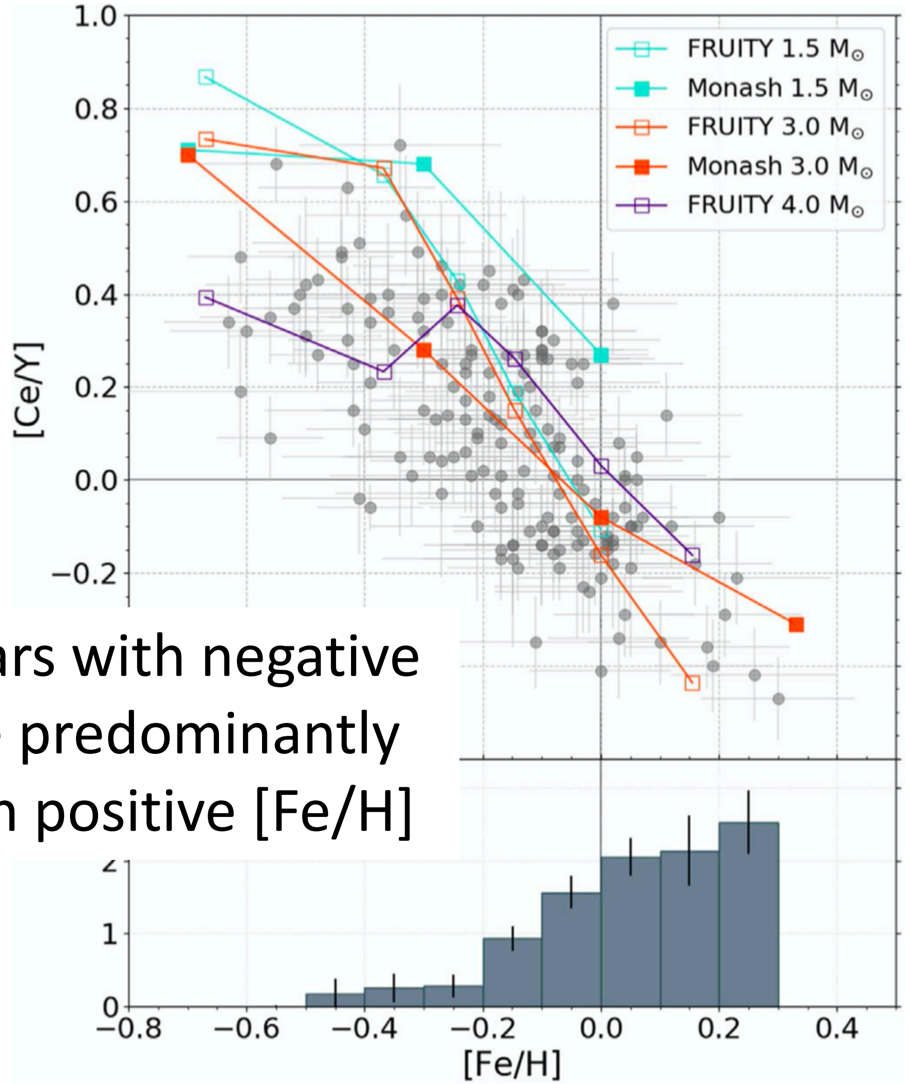

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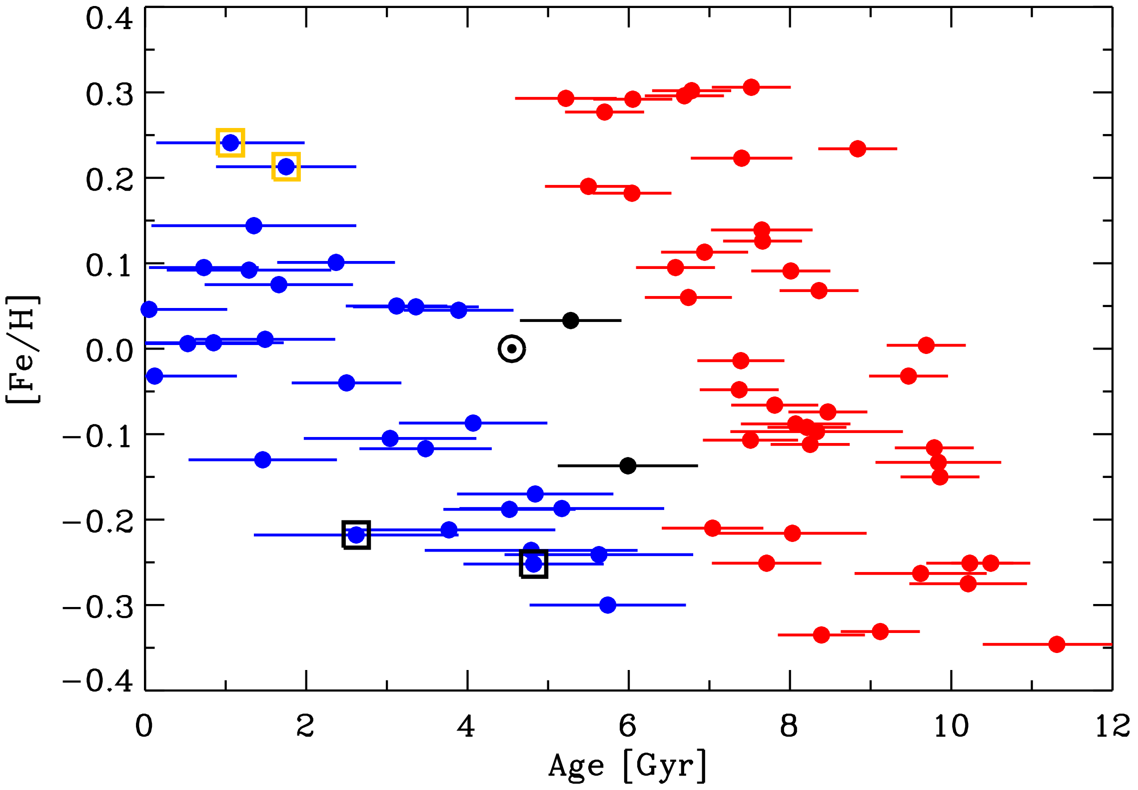
Astrochemistry: The large (≈ μm) SiC grains must have formed in AGB stars with metallicity higher than solar

Age-metallicity relationship in the solar neighborhood



Nissen et al. 2020: 72 nearby solar-type stars with very well determined ages show two distinct sequences. The high metallicity stars

1. *Were there at the time of the formation of the Sun?*
2. *Did they migrate there later*?

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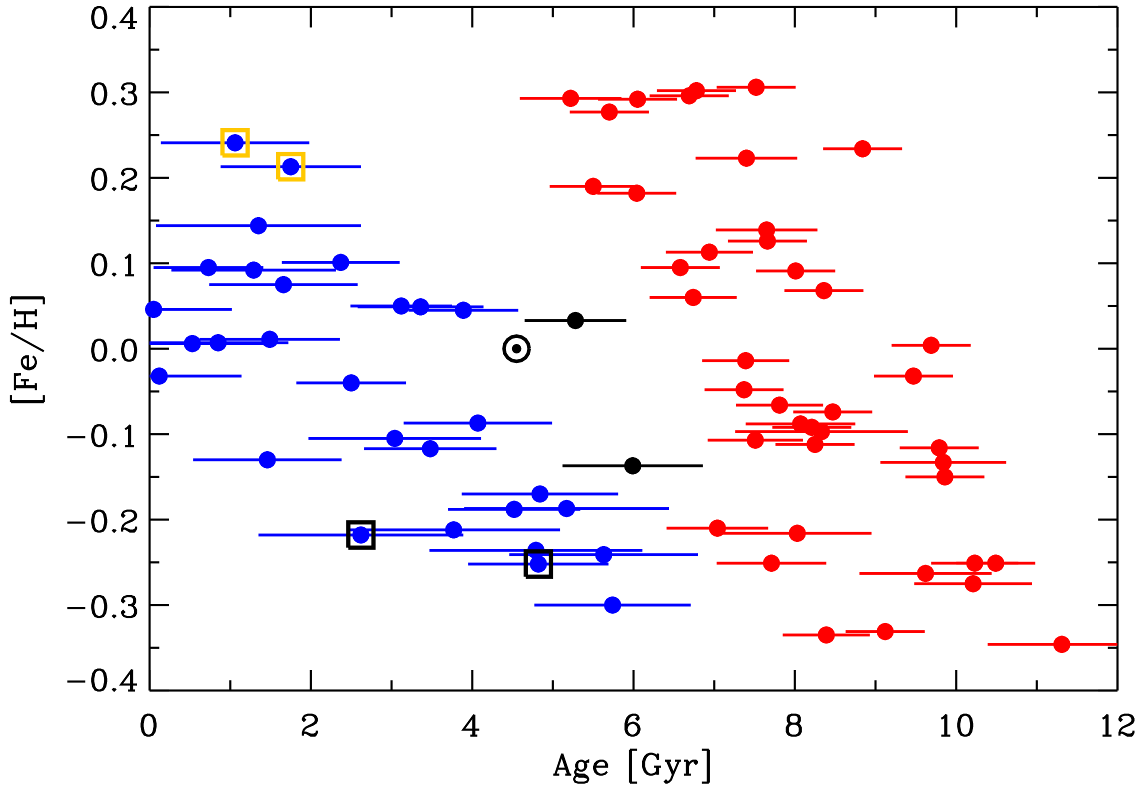

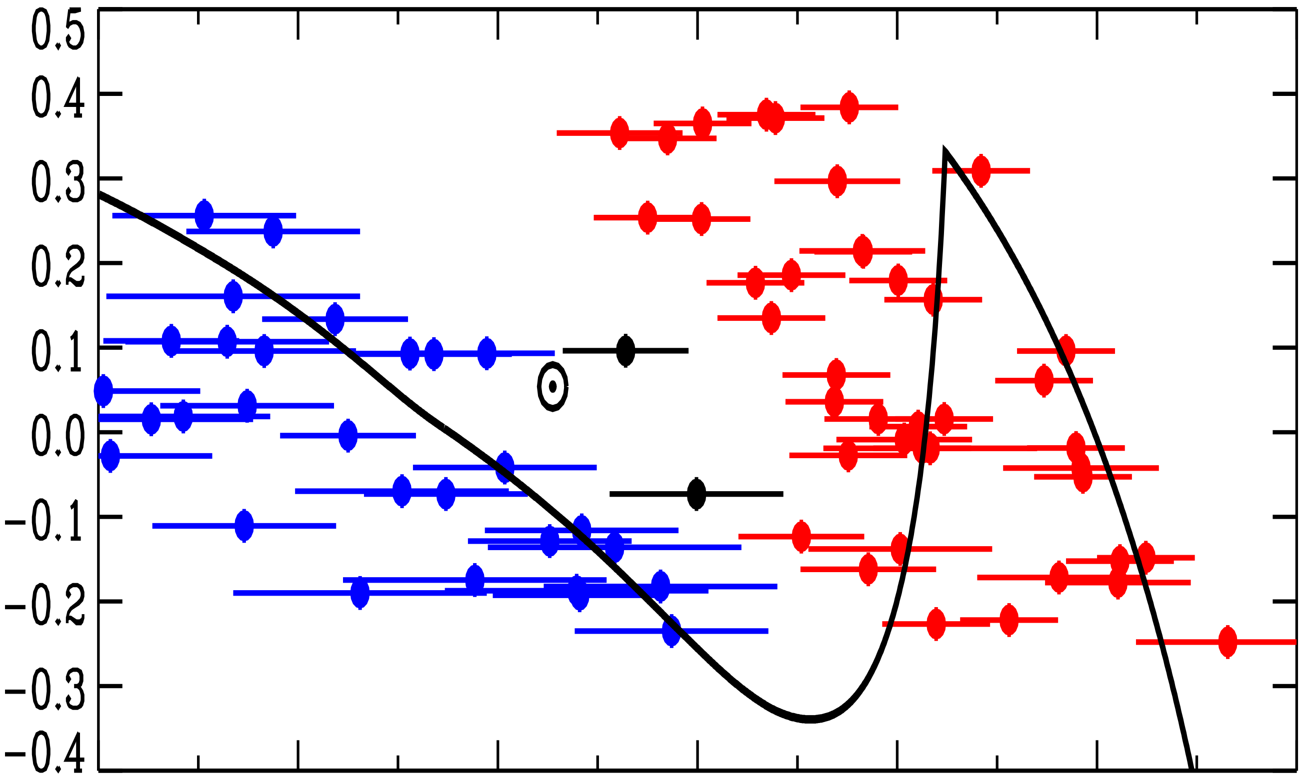

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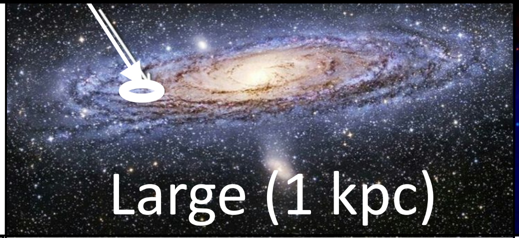
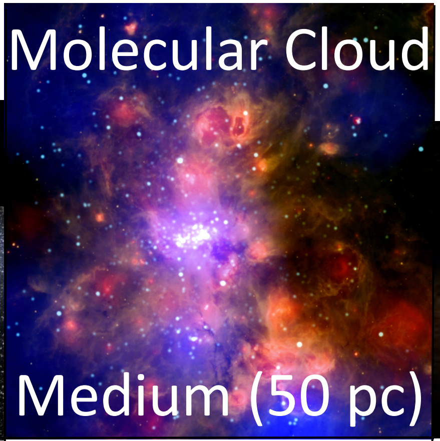
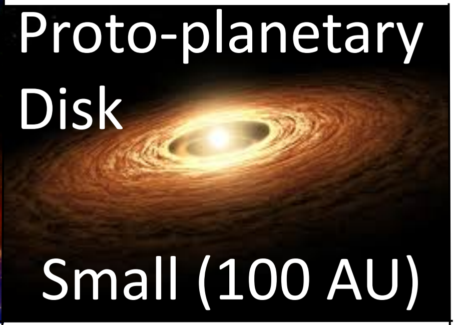
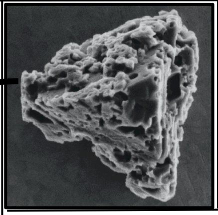
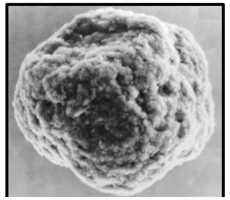
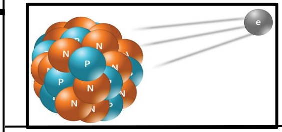
The SiC grains support Scenario 1.

For example, **black line**: the two-infall galactic chemical evolution (GCE) model of Spitoni et al. (2019).

Example cases

Type ↓ / Scale →		Solar Neighbourhood  Large (1 kpc)	Molecular Cloud  Medium (50 pc)	Proto-planetary Disk  Small (100 AU)
STAR-DUST 1.	 ≈ 90% from asymptotic giant branch (AGB) stars	✓ (circled)		
	≈ 10% from core-collapse supernovae 	✓	✓	
RADIO-ACTIVITY 2.	0.1 < half life < 100 Myr  *short-lived*	✓	✓ (circled)	
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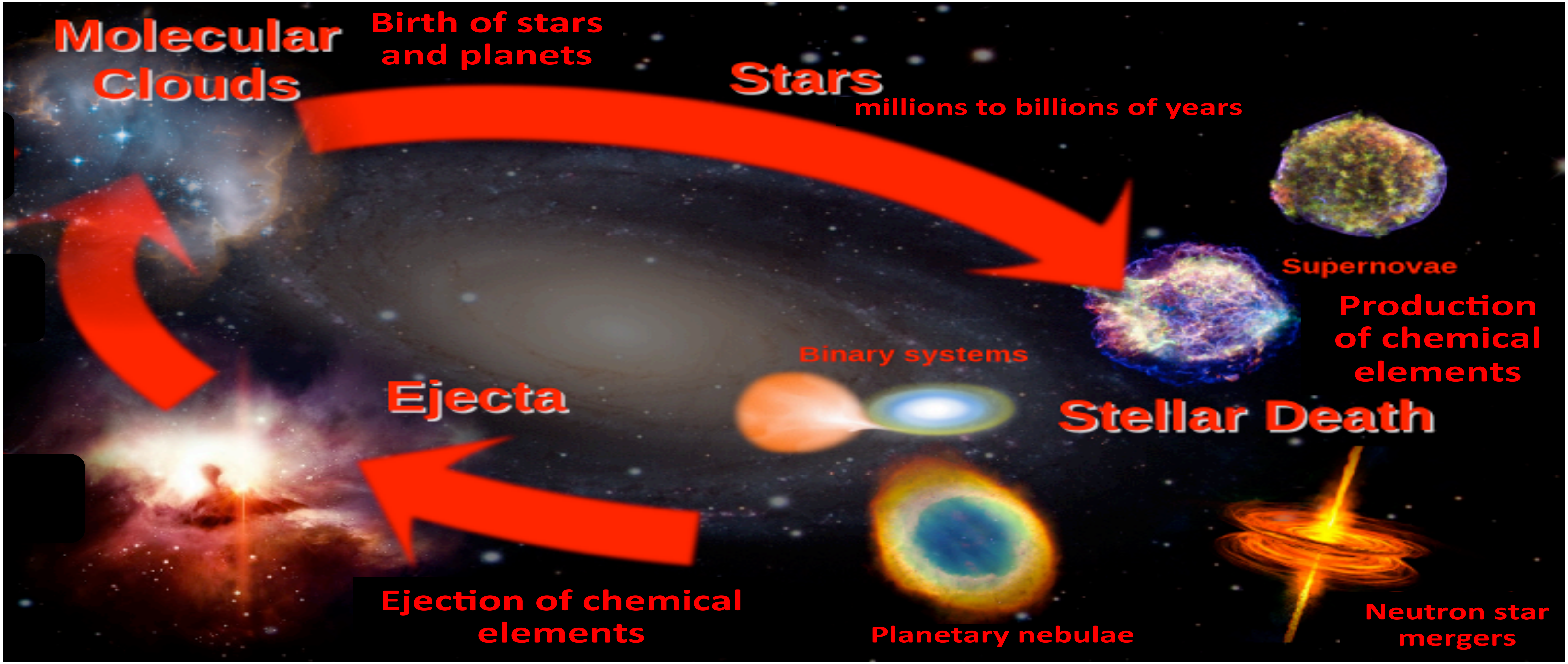
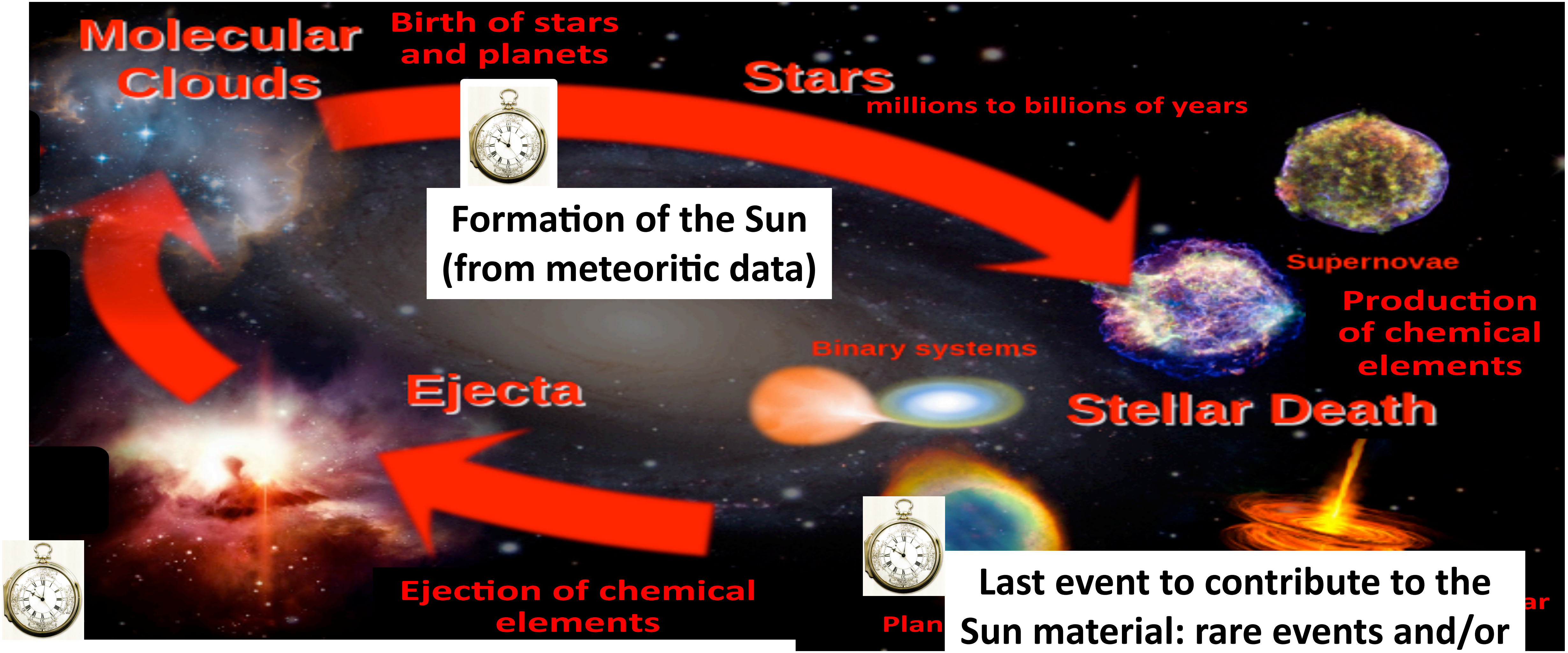
Chemical Evolution of the Milky Way



Radioactive Chemical Evolution of the Milky Way



Formation of the Sun (from meteoritic data)

Last event to contribute to the Sun material: rare events and/or short half lives (from stellar nucleosynthesis models)

Formation of the molecular cloud: common events and/or long half lives (from stellar nucleosynthesis and galactic evolution models)

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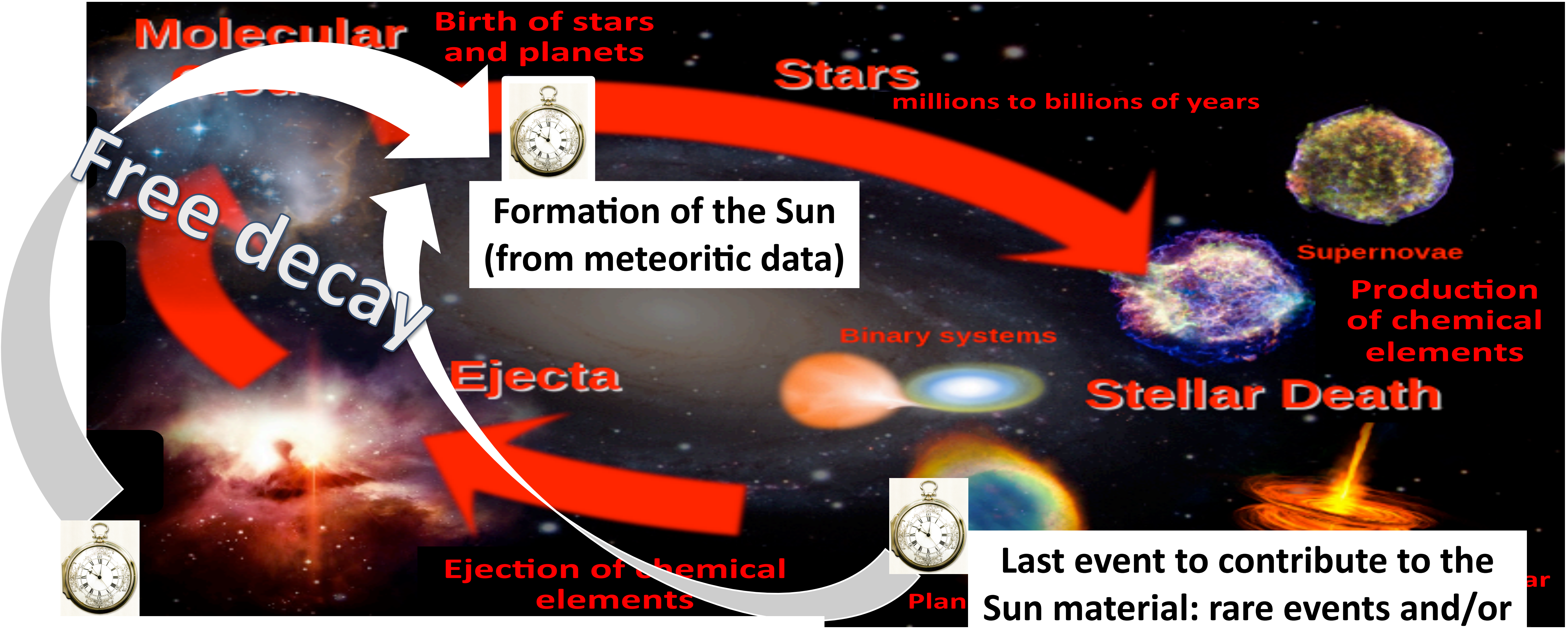

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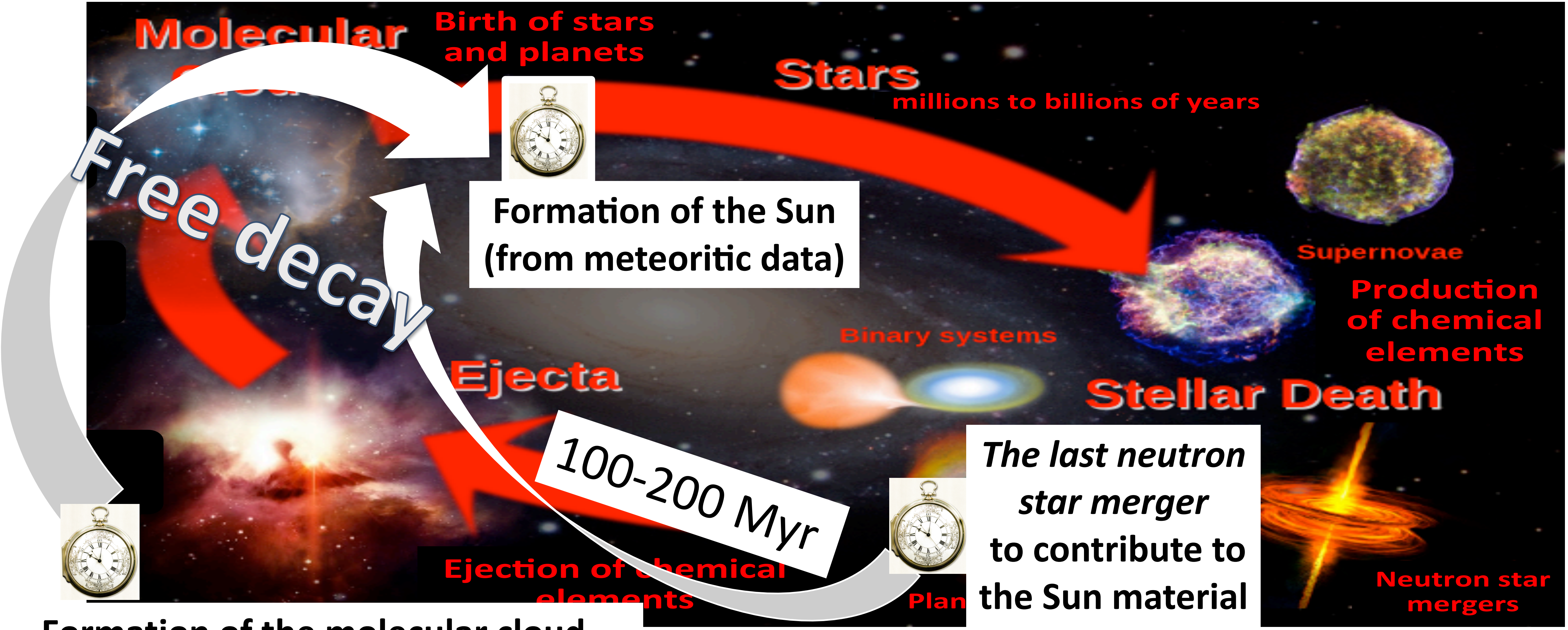


Formation of the molecular cloud, from *s*-process ^{107}Pd ^{135}Cs, and ^{182}Hf

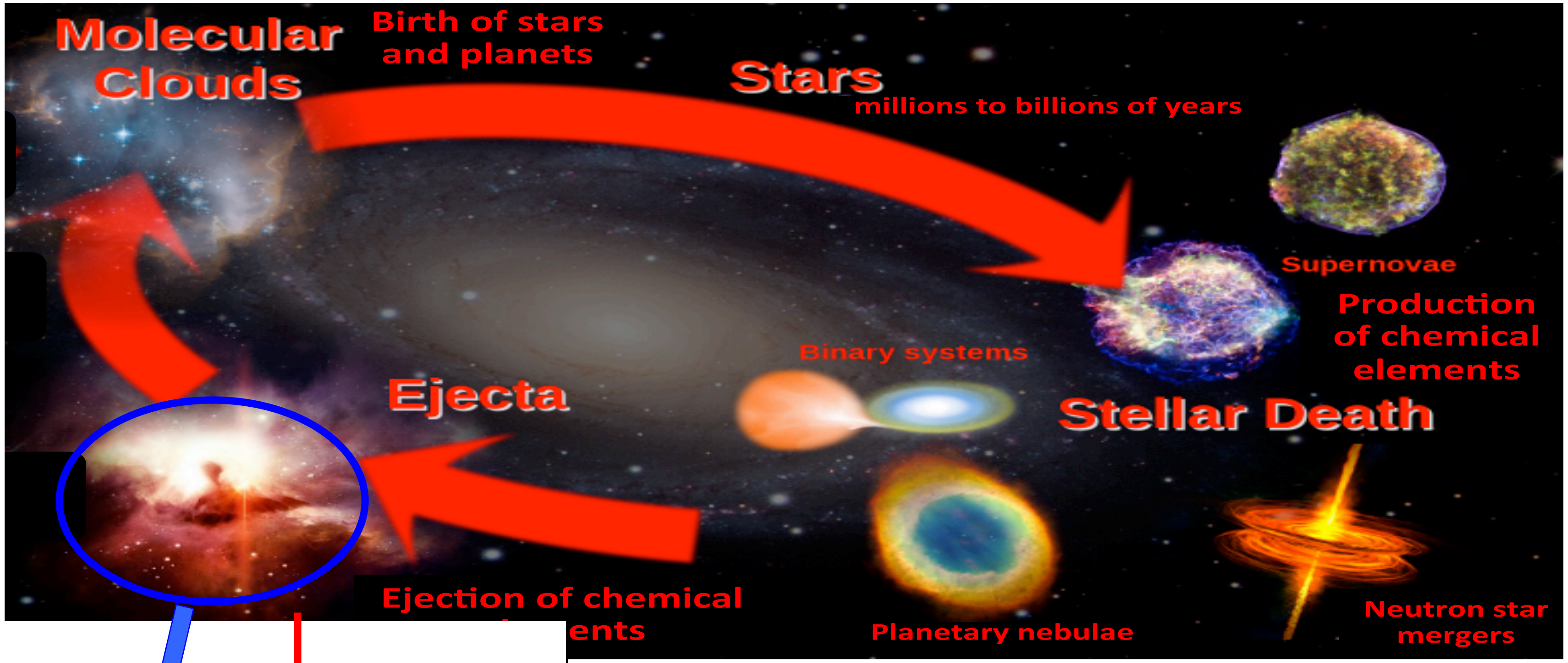
Trueman et al. 2022, ApJ

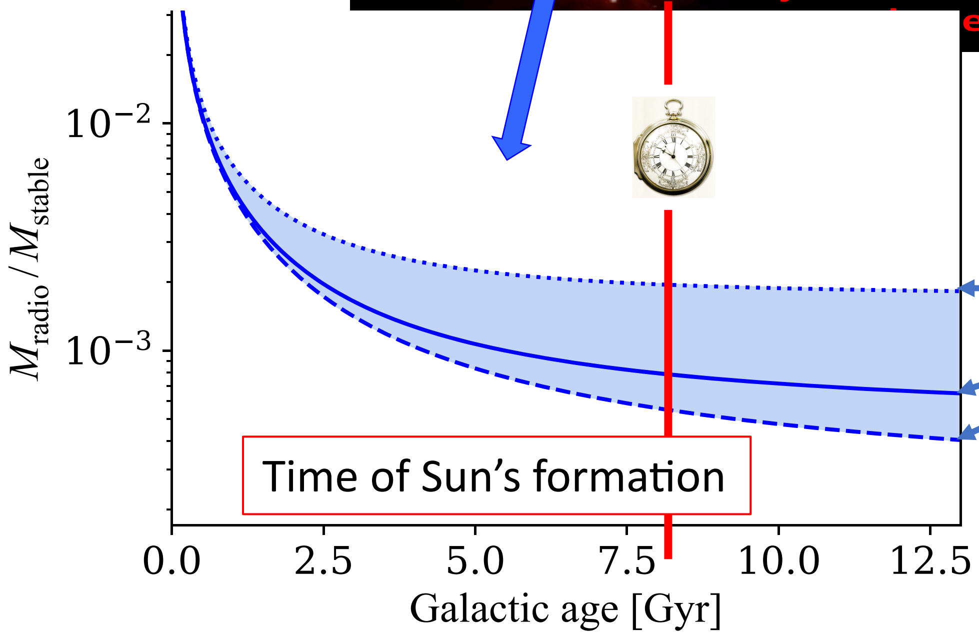
from r-process ^{129}I and ^{247}Cm

Côté et al. 2021, Science

Radioactive Chemical Evolution of the Milky Way

Evolution of the mass ratio of a radioactive to stable nucleus





Uncertainties from, e.g., mass of gas, star formation rate etc.: **three** different independent realizations of the Milky Way

Côté et al. 2019a, ApJ

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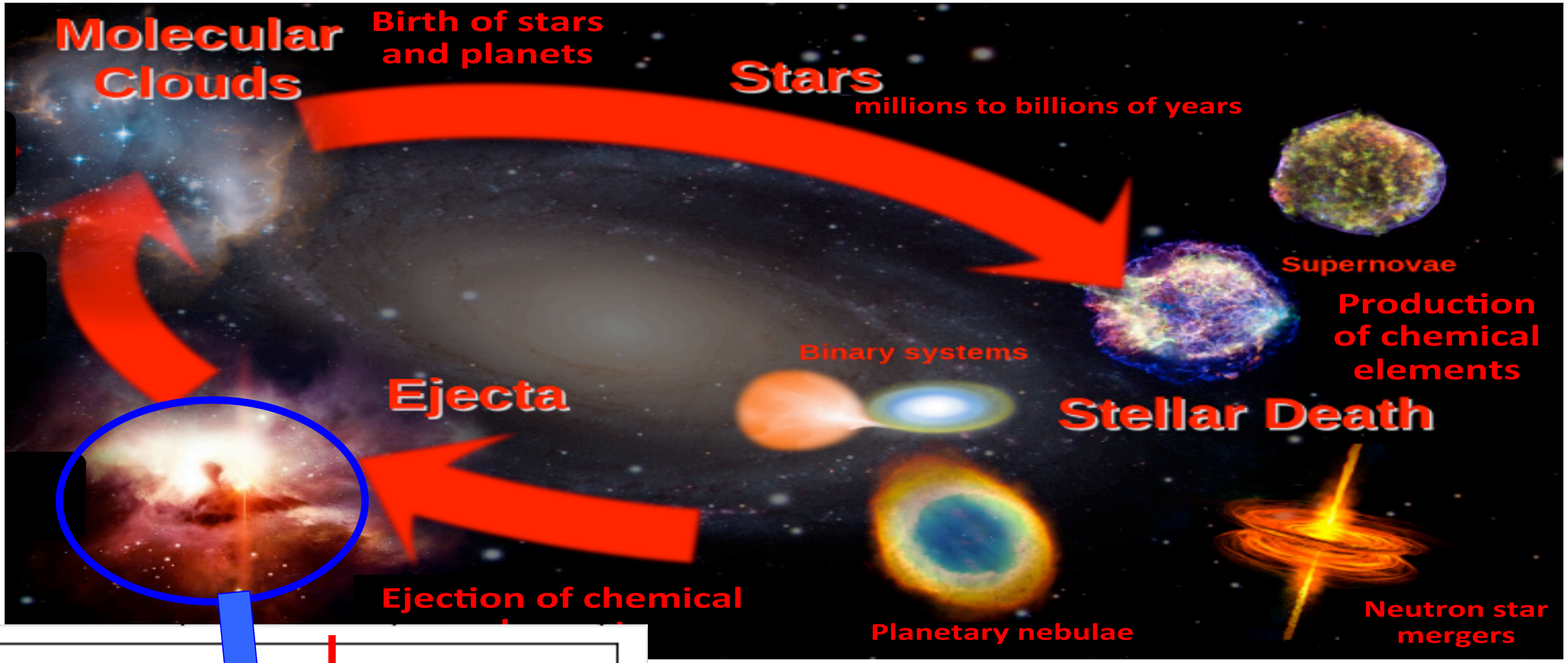
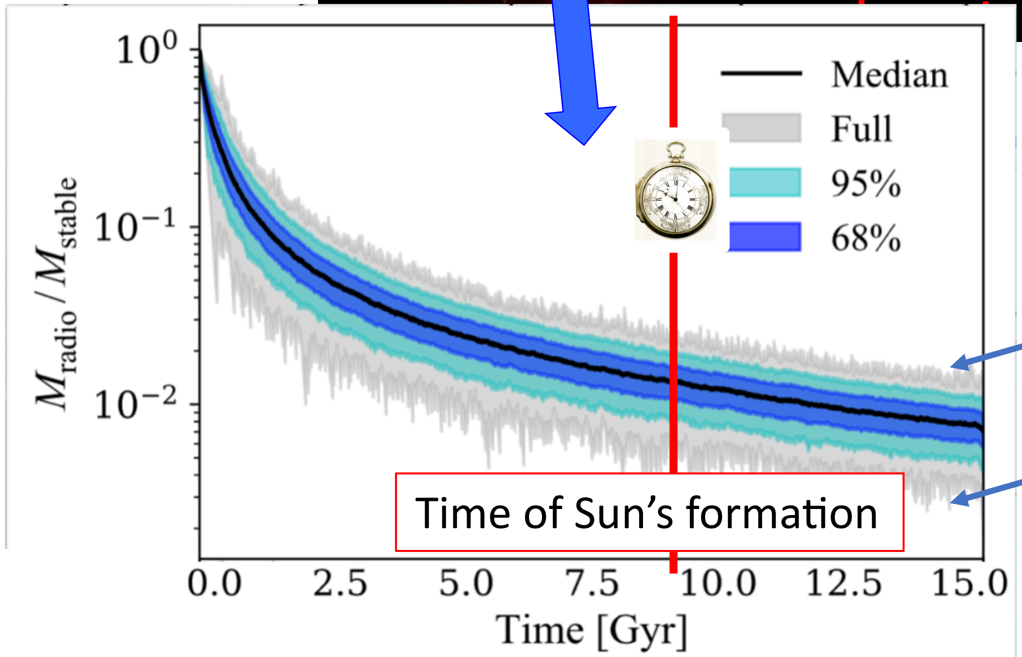


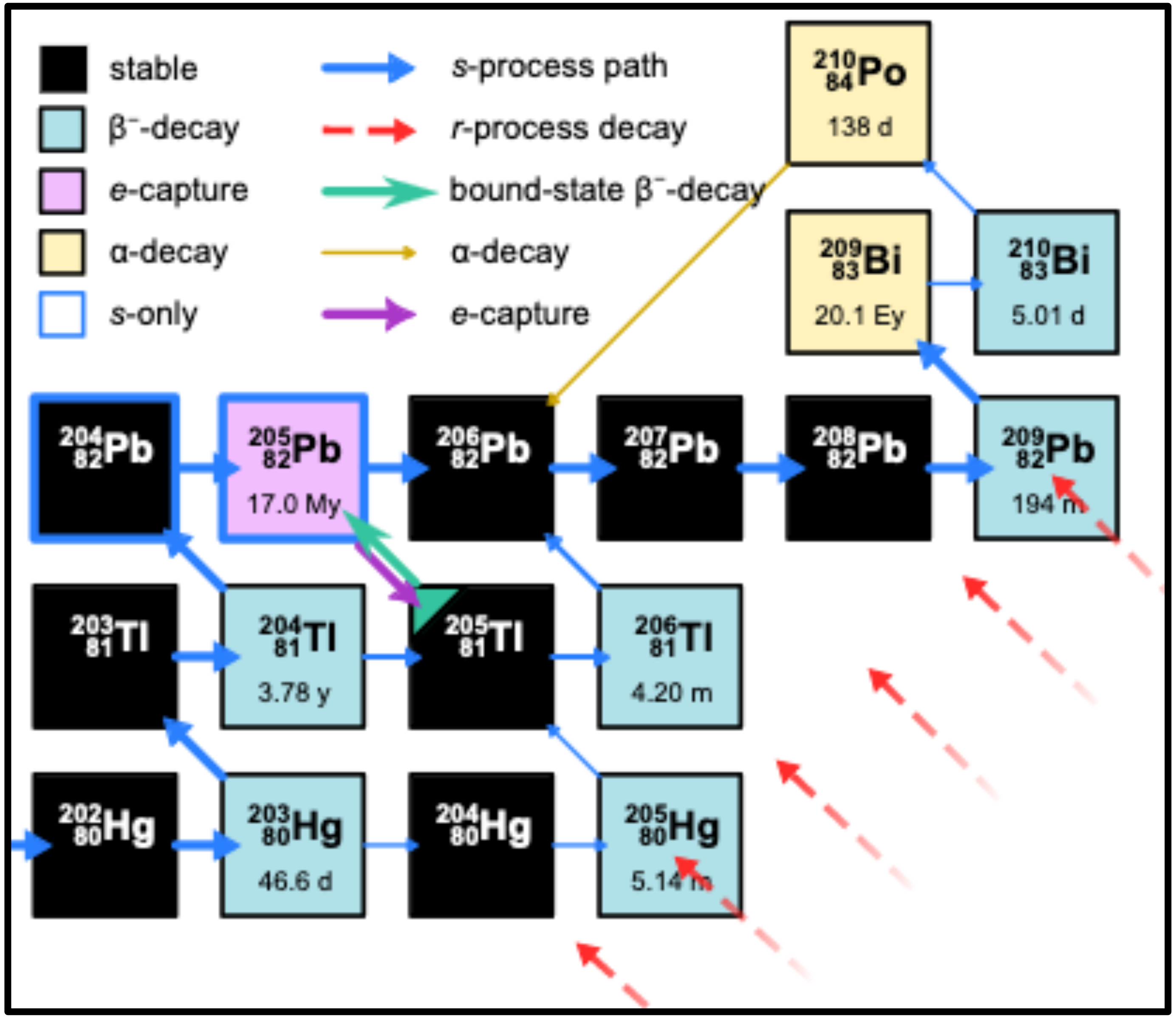
Talk by Benjamin Wehmeyer



But stellar ejecta are **discrete in time:** using a Monte Carlo method we need to add a further **statistical uncertainty** (**median**, **1σ**, **2σ**, **full**) to each of the three Galaxies.

Côté et al. 2019b, ApJ; Yagüe López et al. 2021, ApJ

With ^{107}Pd, ^{135}Cs, and ^{182}Hf, ^{205}Pb is also produced by the *s* process in AGB stars



Nuclear Physics:

1. First experimentally derived decay rates for ^{205}Tl
2. First Accurate ^{205}Pb and ^{205}Tl decay rates as function of stellar temperature and density!

Leckenby et al., in preparation

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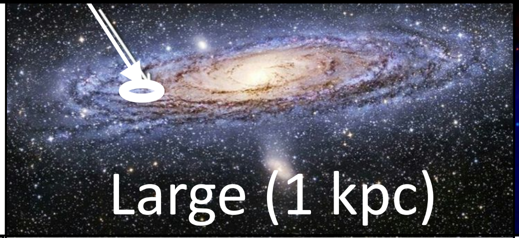
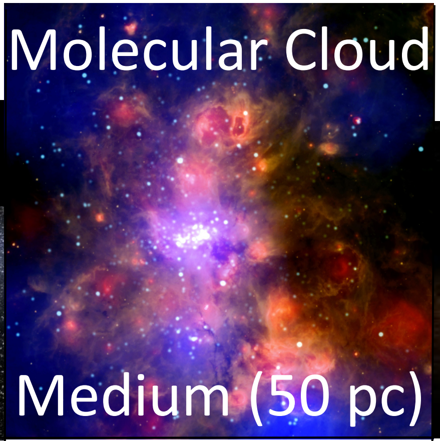
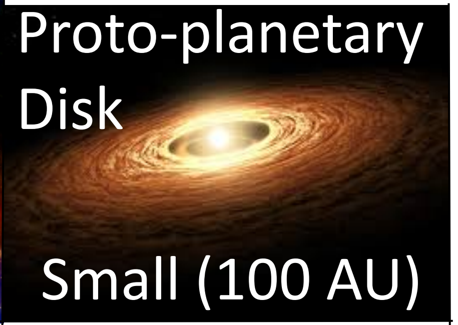
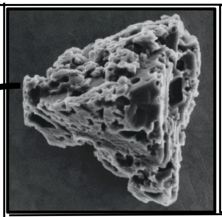
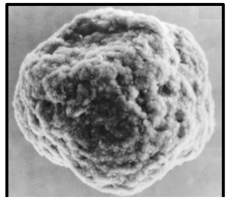
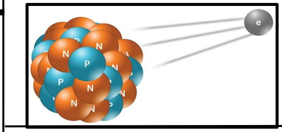
Type ↓ / Scale →	Solar Neighbourhood  Large (1 kpc)	Molecular Cloud  Medium (50 pc)	Proto-planetary Disk  Small (100 AU)
STAR-DUST 1.  ≈ 90% from asymptotic giant branch (AGB) stars	(✓)		
≈ 10% from core-collapse supernovae 	✓	✓	
RADIO-ACTIVITY 2. 0.1 < half life < 100 Myr  *short-lived*	✓	(✓)	
BULK-ROCKS 3. Meteoritic rocks and inclusions 		✓	(✓)

Analysis of bulk meteoritic rocks has revealed ***small but widespread variations*** in stable isotope abundances.

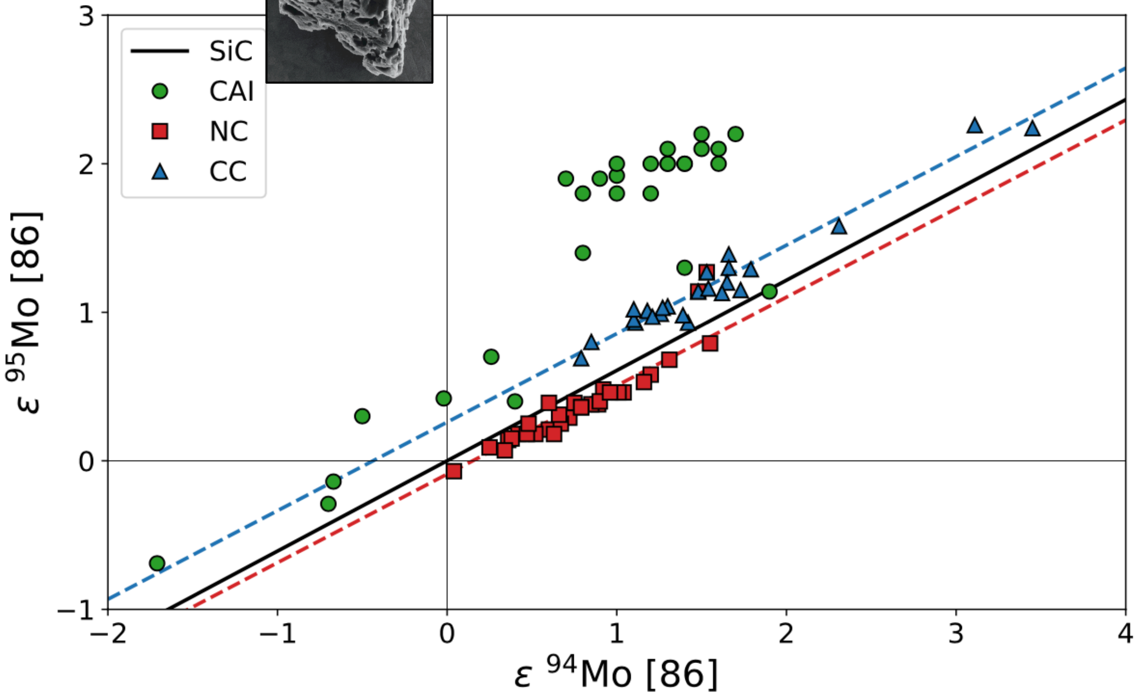
Talk by Mattias Ek

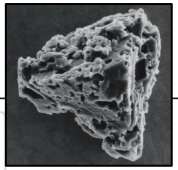
1. Anomalies were carried into the Solar System by a "**carrier**", a "**physical trap**", probably **stardust**

2. The **stardust** was destroyed, and the nuclear signature diluted. Very small variations ~ $\mathbf{10^{-4} - 10^{-5}}$, error bars ~ $\mathbf{10^{-6}}$

3. How did the **stardust** distribute these anomalies is not fully known, many scenarios are proposed

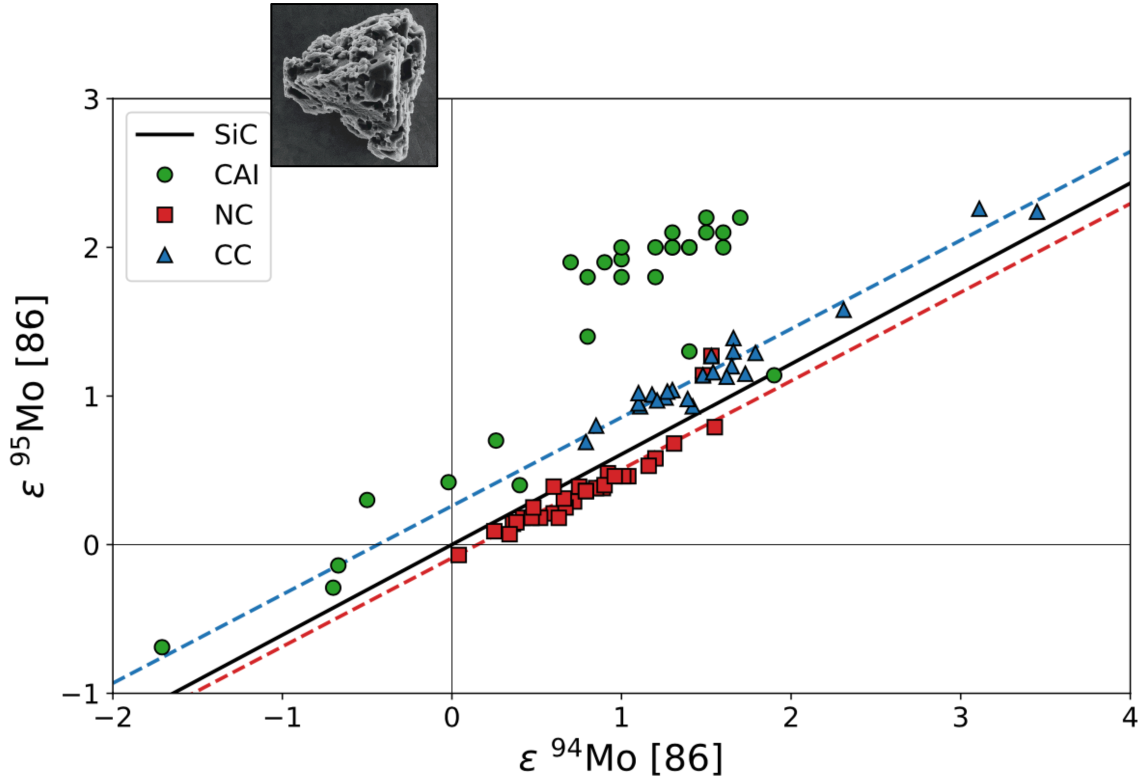
Example: Molybdenum variations in bulk meteorites





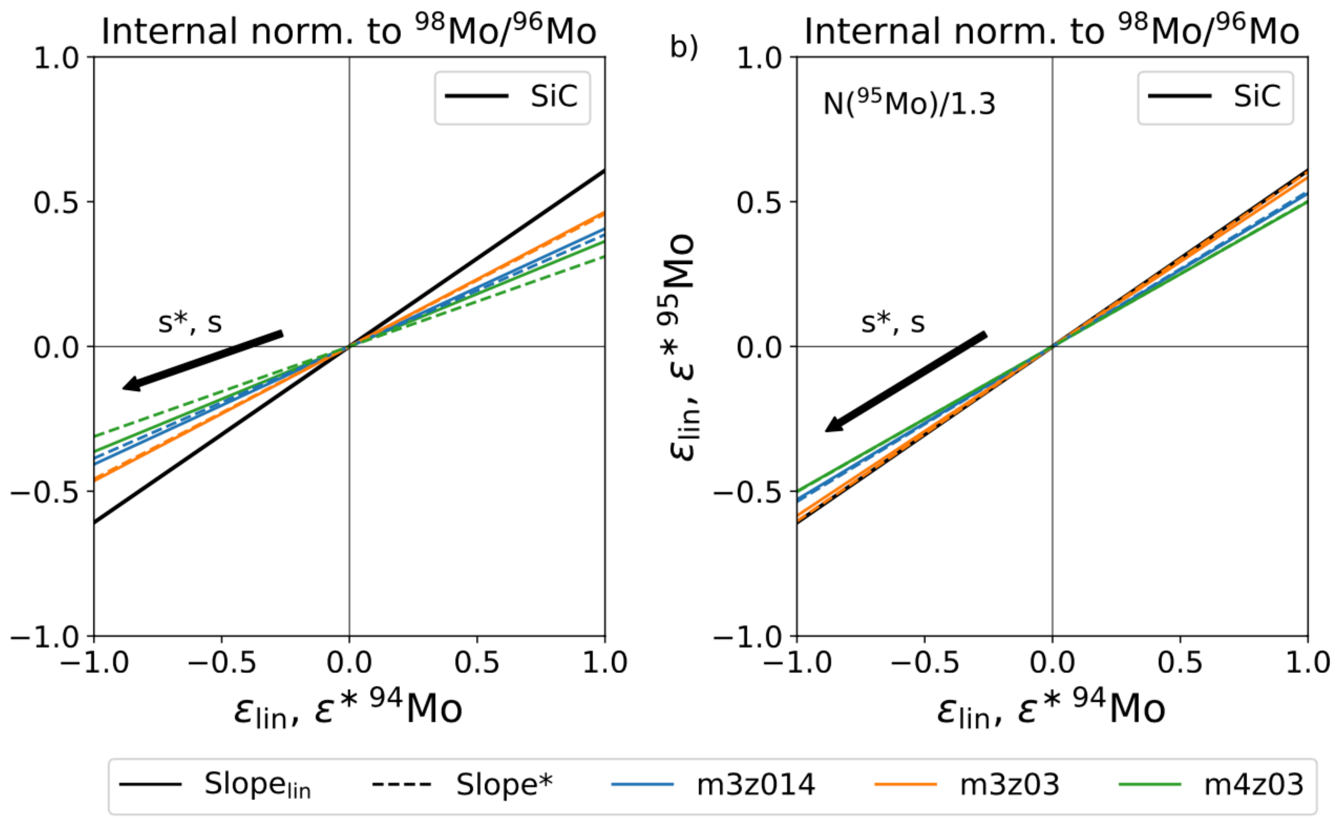
Nuclear Physics: neutron-capture cross sections needed!

Example: Molybdenum variations in bulk meteorites



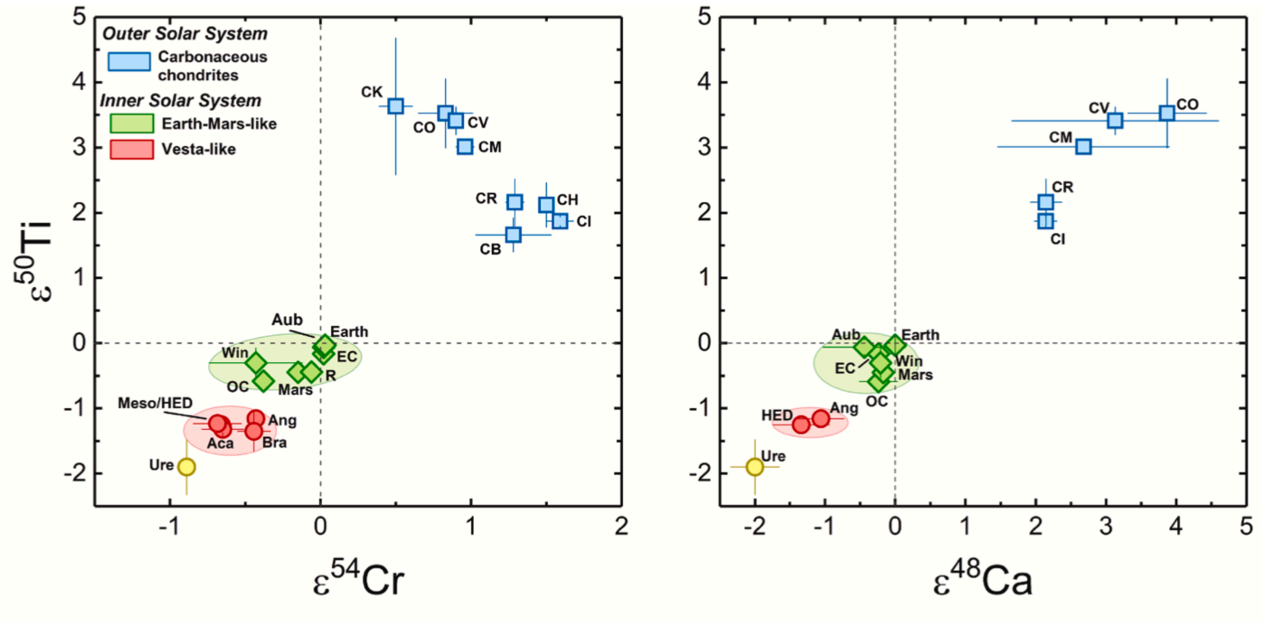
Nuclear Physics: neutron-capture cross sections needed!

Nuclear Physics: Koehler (2022, PRC) measured a ^{95}Mo neutron-capture cross section 30% higher than the standard by Winters and Macklin (1987, ApJ)



Lugaro, Ek et al. (2023, EPJA)

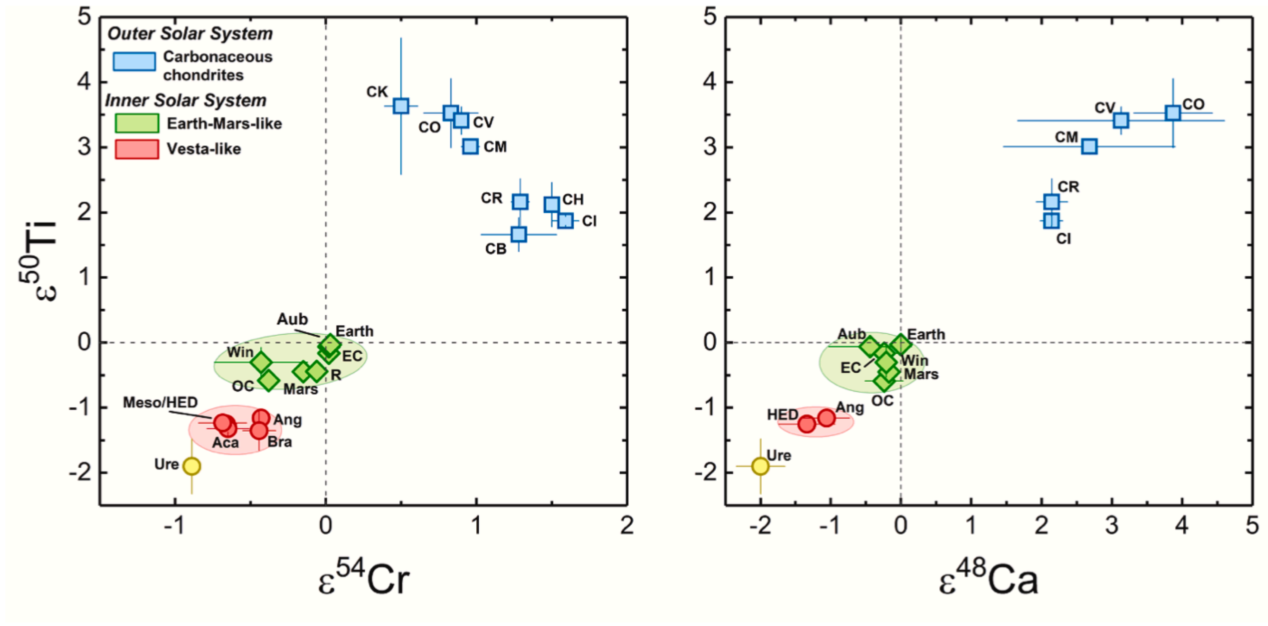
Example: Ca, Ti, Cr variations in bulk meteorites



Nuclear Physics: neutron-capture cross sections and decay rates needed!

Figure from Rüfenacht et al. (2023, GCA)

Example: Ca, Ti, Cr variations in bulk meteorites



Nuclear Physics: neutron-capture cross sections and decay rates needed!

Figure from Rüfenacht et al. (2023, GCA)

^{40}Ca: Dillman et al. Phys. Rev. C (2009)

^{42}Ca, ^{43}Ca, ^{44}Ca: Musgrove *et al.*, Nucl. Phys. (**1977**)

^{46}Ca: Mohr *et al.*, Phys. Rev. C (1999).

^{48}Ca: Mohr *et al.*, Phys. Rev. C (1997).

^{46}Ti, ^{47}Ti, ^{48}Ti, ^{49}Ti, ^{50}Ti: Allen et al. Technical report AAEC/E402, Australian Atomic Energy Commission (**1977**).

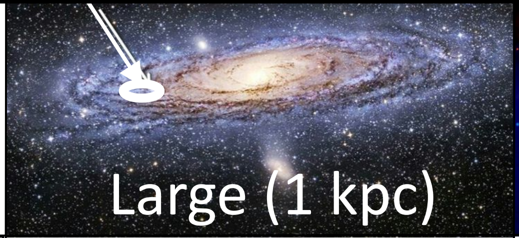
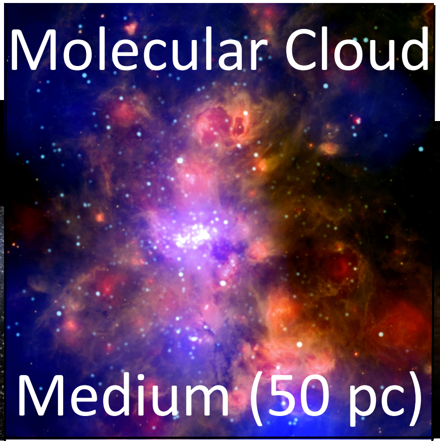
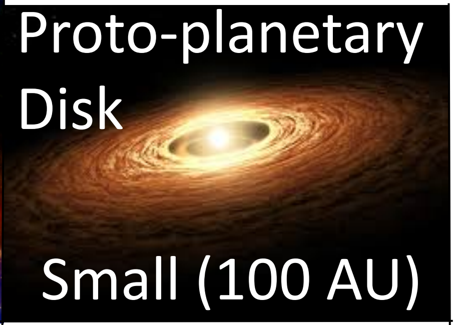
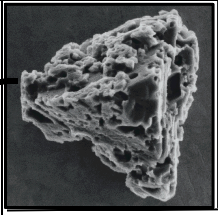
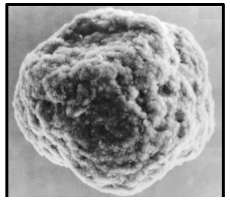
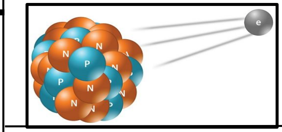
^{50}Ti: Sedyshev *et al.*, Phys. Rev. C (1999).

^{50}Cr, ^{53}Cr, ^{54}Cr: M. Kenny *et al.*, Technical report AAEC/E400, Australian Atomic Energy Commission (**1977**).

^{52}Cr: Rohr *et al.*, Phys. Rev. C (1989)

^{41}Ca, ^{45}C, ^{51}Cr : only theoretical (n,γ); latest decay rates from Fuller et al. **1987**

Summary of example cases

Type ↓ / Scale →		Solar Neighbourhood  Large (1 kpc)	Molecular Cloud  Medium (50 pc)	Proto-planetary Disk  Small (100 AU)
STAR-DUST 1.	 ≈ 90% from asymptotic giant branch (AGB) stars	Age-metallicity relationship		
	≈ 10% from core-collapse supernovae 	✓	✓	
RADIO-ACTIVITY 2.	0.1 < half life < 100 Myr  *short-lived*	✓	Last neutron star merger and time between birth of molecular cloud and birth of the Sun	
BULK-ROCKS 3.	Meteoritic rocks and inclusions 		✓	Mo variations from AGB SiC

Open-source tools for Nuclear Astro/Cosmochemistry

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **524,** 6295–6330 (2023) https://doi.org/10.1093/mnras/stad2167
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The chemical evolution of the solar neighbourhood for planet-hosting stars

Marco Pignatari,[1,2,3,4,5★] Thomas C. L. Trueman,[1,3,4] Kate A. Womack,[3] Brad K. Gibson,[3,5] Benoit Côté,[1,4,5,6] Diego Turrini,[7,8,9] Christopher Sneden,[10] Stephen J. Mojzsis,[1,2,11] Richard J. Stancliffe,[4,12] Paul Fong,[3,4] Thomas V. Lawson,[3,4,13] James D. Keegans,[4,14] Kate Pilkington,[15] Jean-Claude Passy,[16] Timothy C. Beers[5,17] and Maria Lugaro[1,2,18,19]

OMEGA+ One-zone Model for the Evolution of GAlaxies (Côté et al. 2017)
nugrid.github.io/NuPyCEE/

DRAFT VERSION FEBRUARY 27, 2024
Typeset using LaTeX **twocolumn** style in AASTeX631

Stellar Interpretation of Meteoritic Data and Plotting (SIMPLE): Isotope Mixing Lines for Seven Sets of Core-Collapse Supernova Models

MARCO PIGNATARI,[1,2,3] GEORGY V. MAKHATADZE,[4,1,2] GÁBOR G. BALÁZS,[1,2,5] MATTIAS EK,[6] ALESSANDRO CHIEFFI,[7] CARLA FROLICH,[7] CHRIS FRYER,[7] FALK HERWIG,[7] THOMAS LAWSON,[3] MARCO LIMONGI,[7] THOMAS RAUSCHER,[7] LORENZO ROBERTI,[1,2] MARIA SCHÖNBÄCHLER,[6] ANDRE SIEVERDING,[7] RETO TRAPPITSCH,[7] AND MARIA LUGARO[1,2,5,8]

SIMPLE Stellar Interpretation of Meteoritic data and Plotting (Pignatari et al., in preparation)
astrohub.uvic.ca/chetec/

developed/supported by ChETEC-INFRA

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Lugaro, Maria; **Pignatari**, Marco; **Côté**, Benoit; **Yagüe López**, Andrés; **Brinkman**, Hannah; **Cseh**, Borbála; **Den Hartogh**, Jacqueline; **Doherty**, Carolyn; **Lawson**, Thomas; **Pető**, Mária; **Soós**, Benjámin; **Trueman**, Thomas; **Világos**, Blanka; **Molnar** Laszlo, **Plachy** Emese; **Szányi** Balász; Bányai, Evelin; **Balázs**, Gábor; **Karakas**, Amanda (Monash, Australia); **Kobayashi**, Chiaki (Hertfordshire, UK); **Schoenbachler** Maria and **Ek** Mattias (ETH Zurich), **Makhatadze** Georgy (IPGP, Paris)