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

KONKOLY

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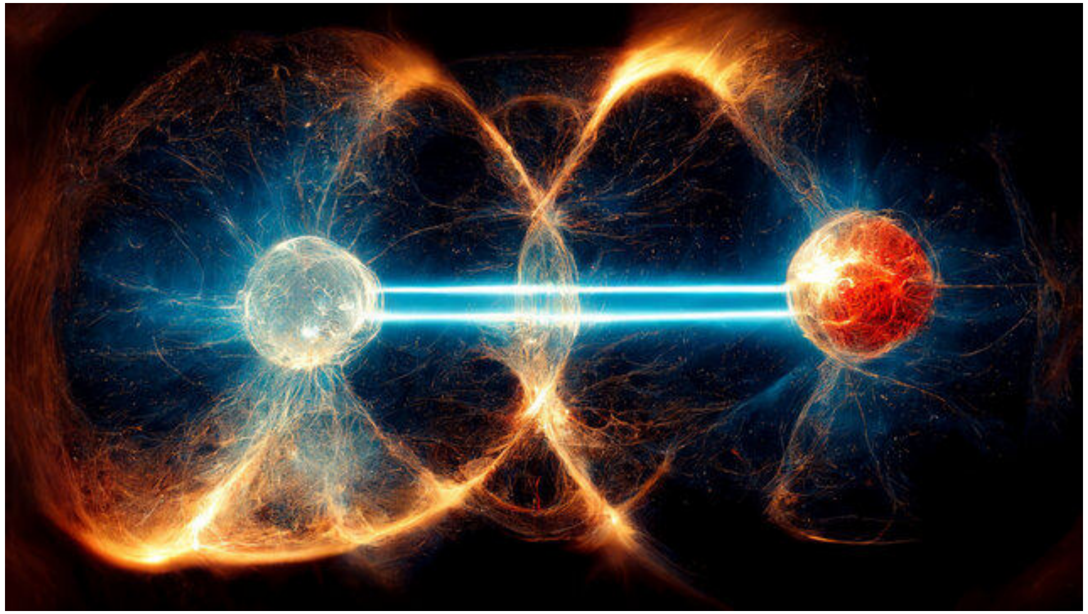
RESEARCH, DEVELOPMENT
AND INNOVATION OFFICE

RADIOSTAR erc

ChETEC INFRA

Lendület/Momentum
Program of the *Hungarian
Academy of Sciences*

Nuclear burning



Length scale ~ 10^{-14} m

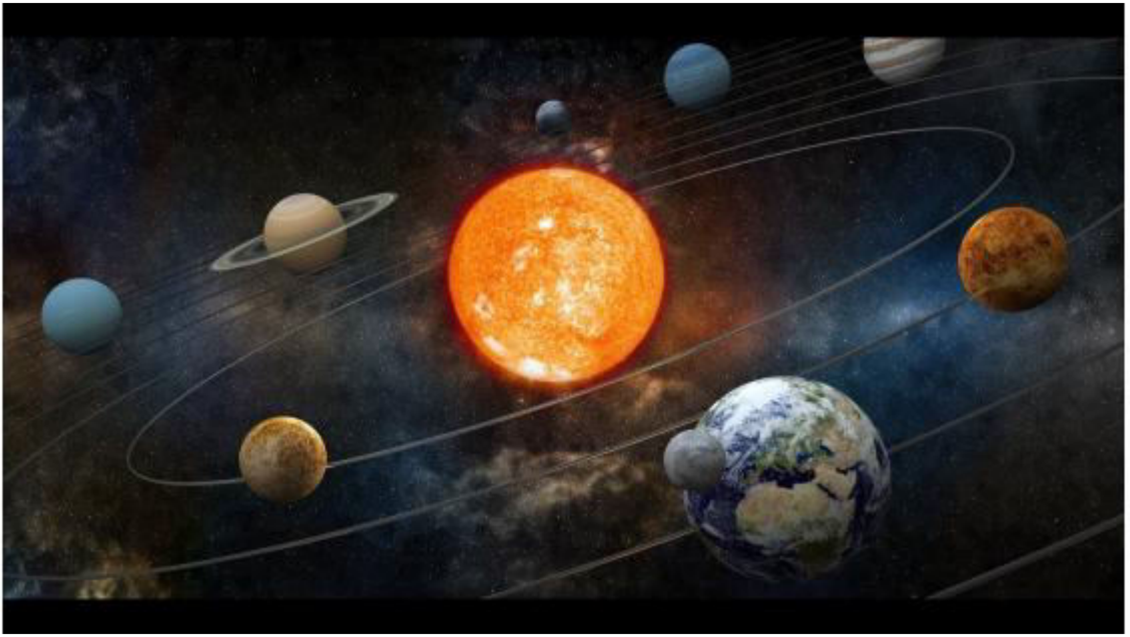
Temperature > 10^{7} K

inside stars

?

⇔

The birth of the Sun and its planets

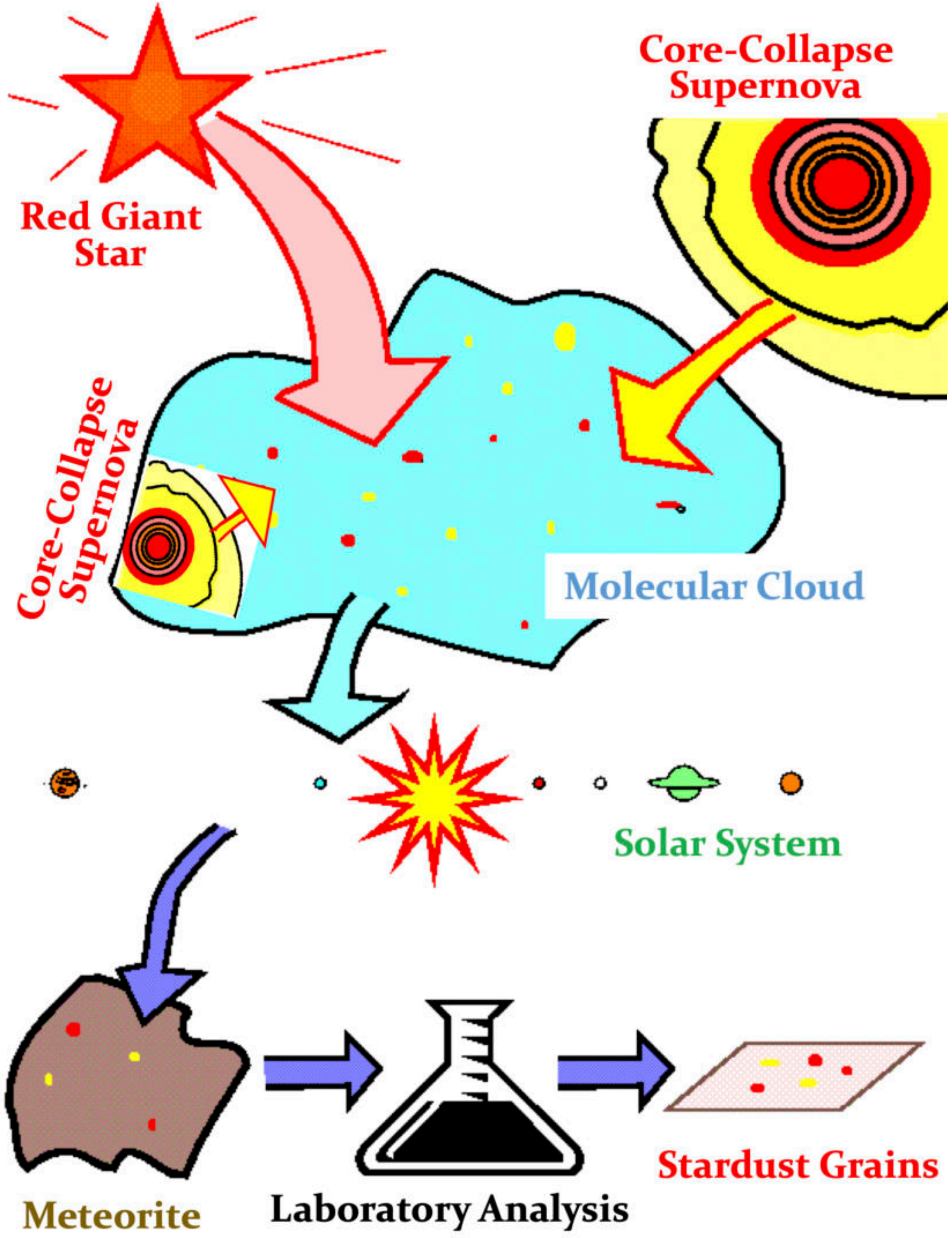


Length scale ~ 10^{16} m

Temperature < 10^{3} K

inside a molecular cloud

STAR-DUST

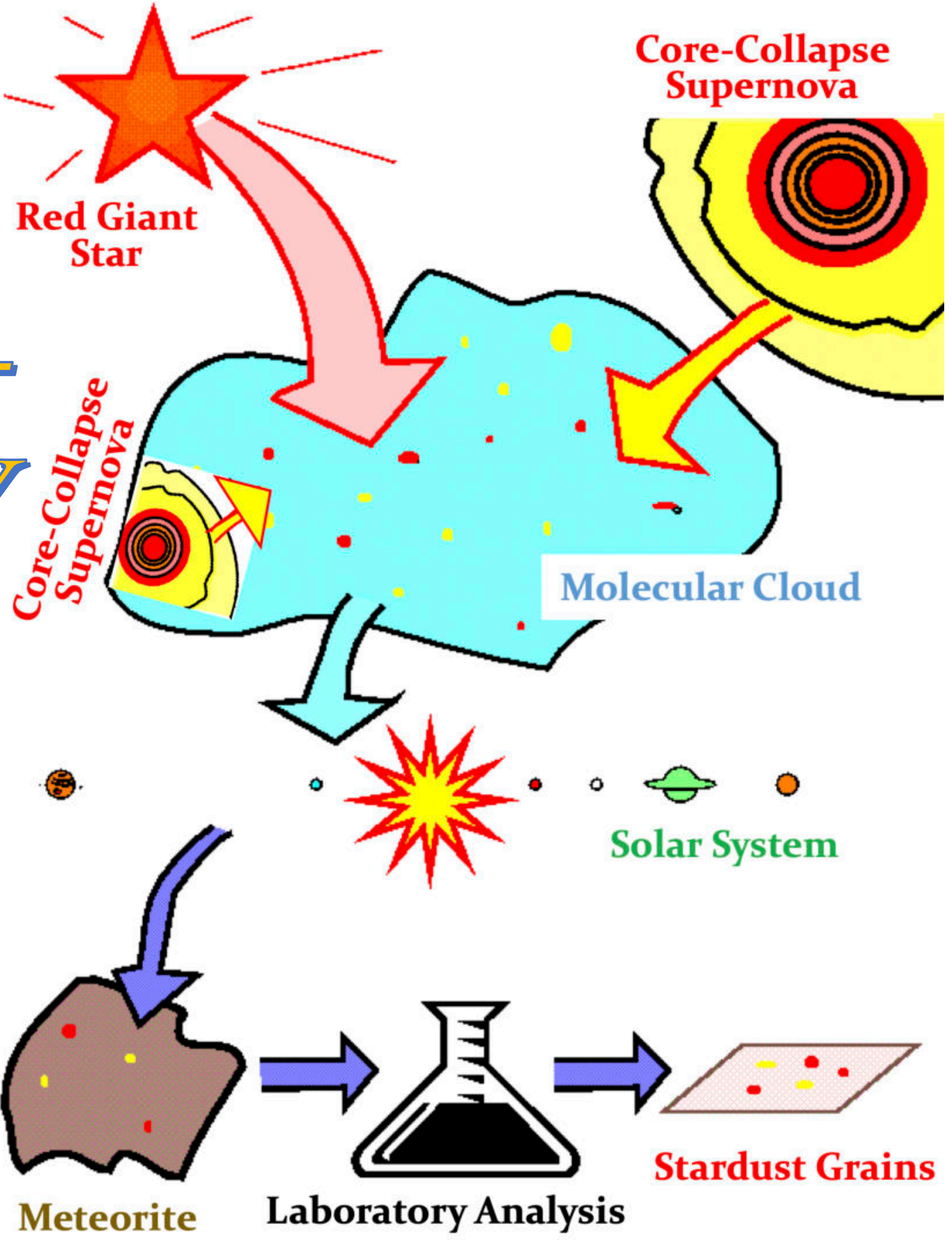


carried the signatures of nuclear processes from stars into meteorites

Figure from Larry Nittler

1. STAR-DUST

2. RADIO-ACTIVITY



carried the signatures of nuclear processes from stars into meteorites

Figure from Larry Nittler

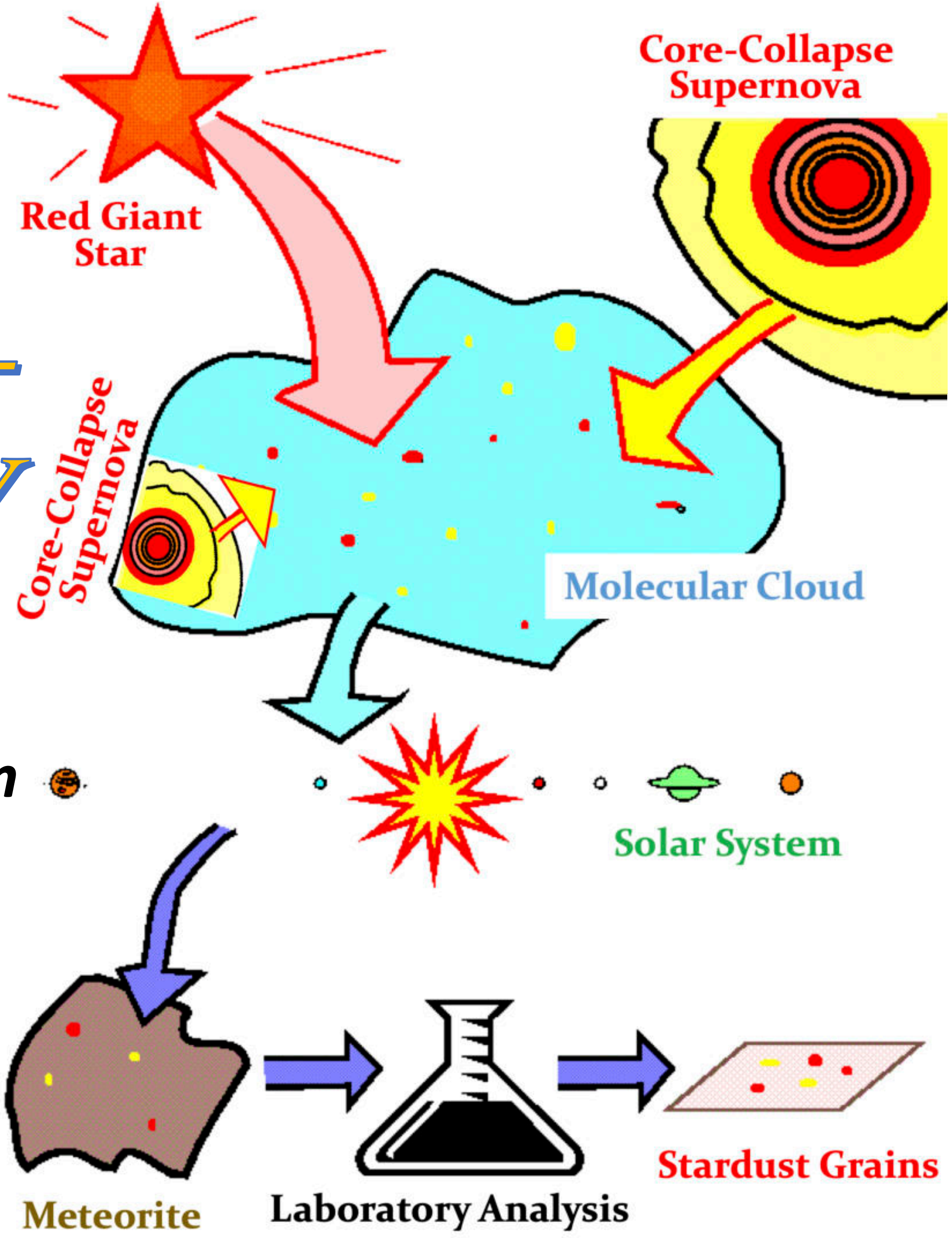
1. STARDUST

2. RADIOACTIVITY

Even if stardust was destroyed, some signatures survived in

3. BULK-ROCKS

See lectures by Christoph Burkhardt

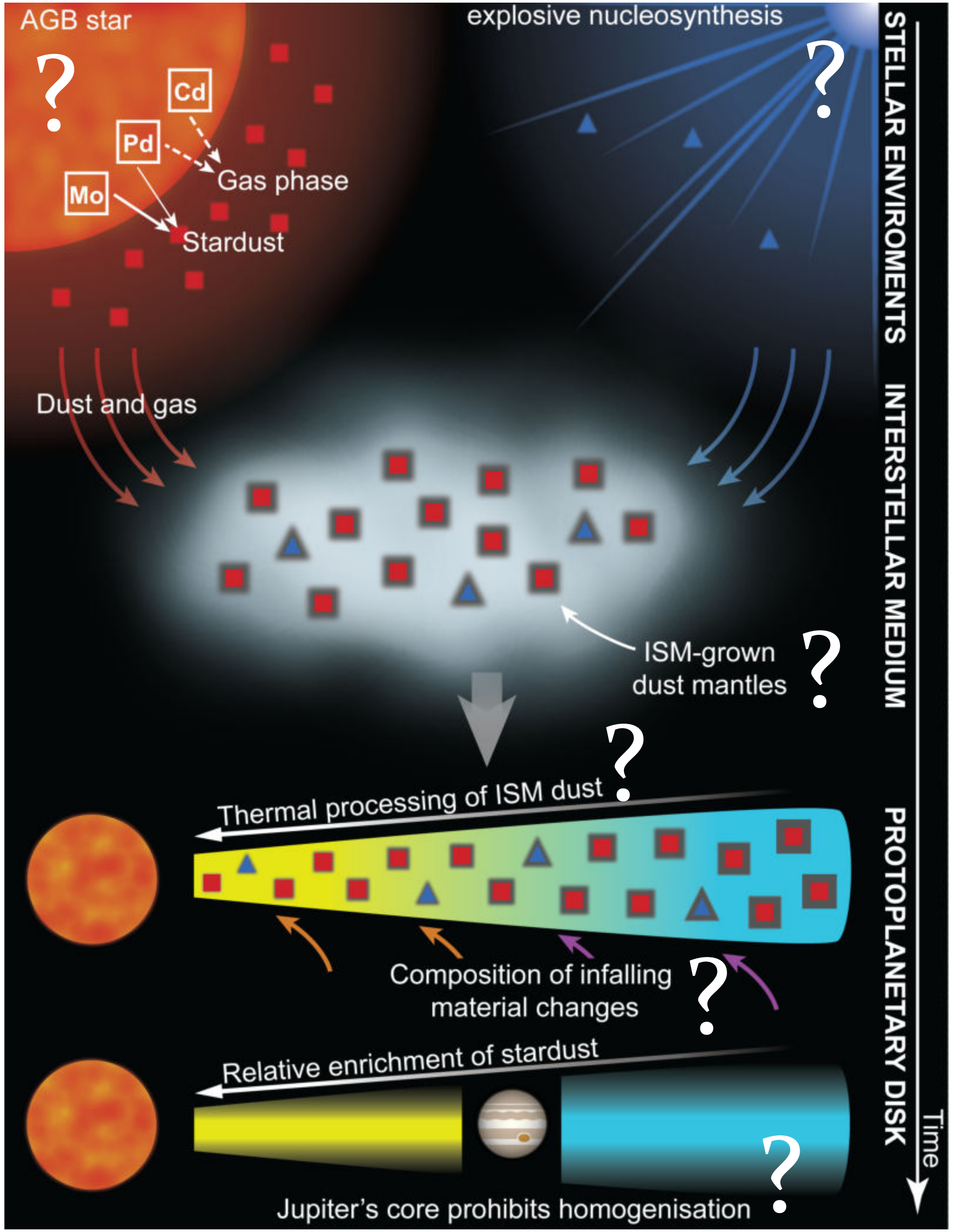


carried the signatures of nuclear processes from stars into meteorites

Figure from Larry Nittler

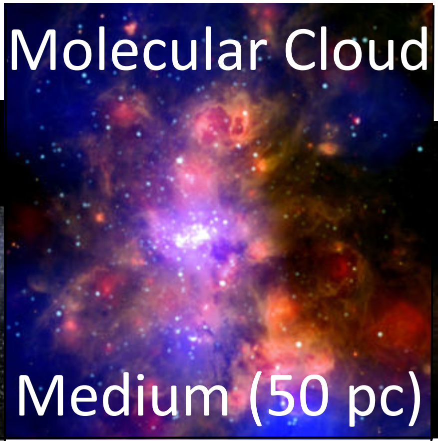
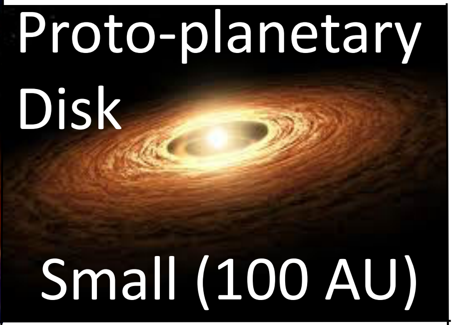
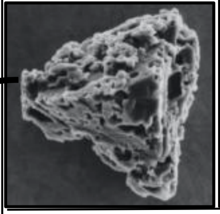
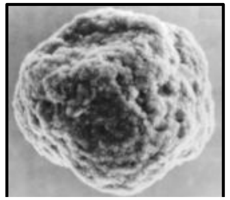
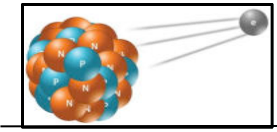
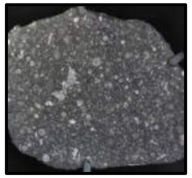
Which *stars were present in the Galaxy* at the time of the formation of the Sun?

How did material distributed *inside the protoplanetary disk?*

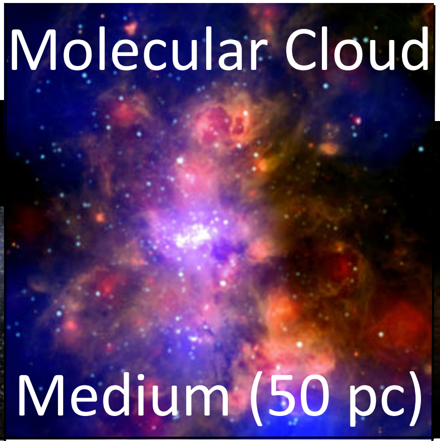
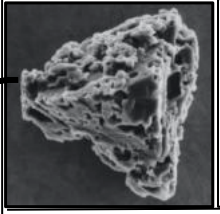
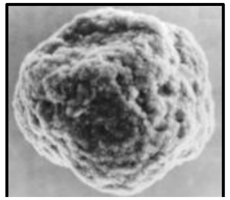
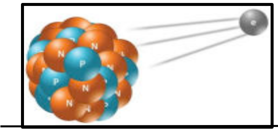
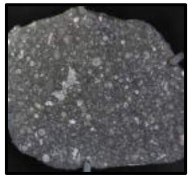


In which *environment* did the Sun formed, and what kind of *material it accreted* from its molecular cloud?

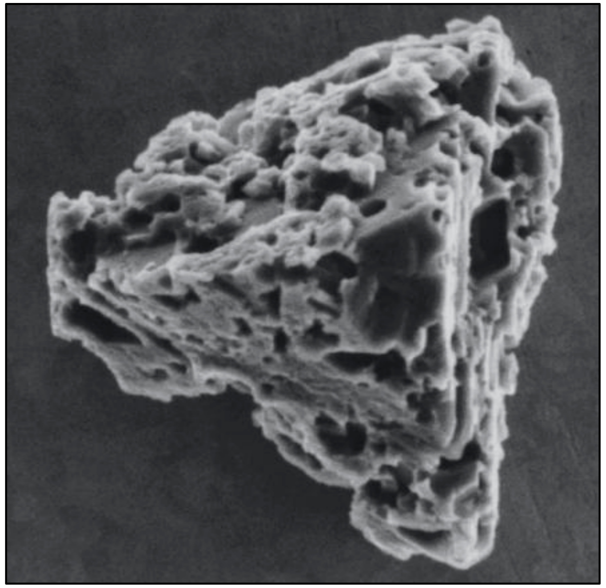
Figure from Mattias Ek

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 		✓	✓

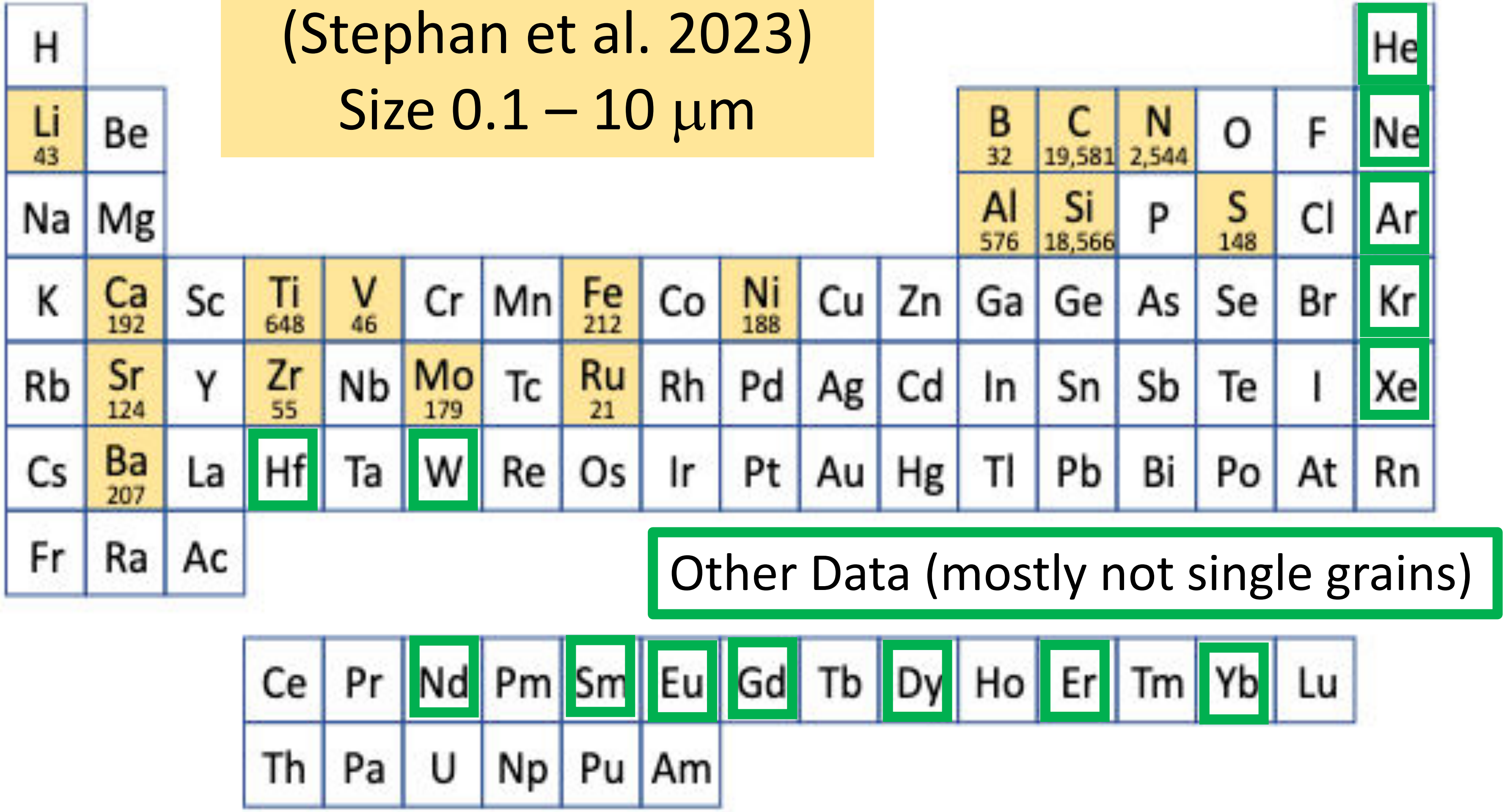
Example cases

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	✓		
	≈ 10% from core-collapse supernovae 	✓	✓	
RADIO-ACTIVITY 2.	0.1 < half life < 100 Myr  *short-lived*	✓	✓	
BULK-ROCKS 3.	Meteoritic rocks and inclusions 		✓	✓

Silicon Carbide (SiC) grains



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



H																	🟩 He
Li 43	Be											B 32	C 19,581	N 2,544	O	F	🟩 Ne
Na	Mg											Al 576	Si 18,566	P	S 148	Cl	🟩 Ar
K	Ca 192	Sc	Ti 648	V 46	Cr	Mn	Fe 212	Co	Ni 188	Cu	Zn	Ga	Ge	As	Se	Br	🟩 Kr
Rb	Sr 124	Y	Zr 55	Nb	Mo 179	Tc	Ru 21	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	🟩 Xe
Cs	Ba 207	La	🟩 Hf	Ta	🟩 W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															
			Ce	Pr	🟩 Nd	Pm	🟩 Sm	🟩 Eu	🟩 Gd	Tb	🟩 Dy	Ho	🟩 Er	Tm	🟩 Yb	Lu	
			Th	Pa	U	Np	Pu	Am									

🟩 Other Data (mostly not single grains)

There are also graphite grains, oxide grains (aluminium oxides, spinel, hibonite), silicate grains, nano diamonds and other less abundant types

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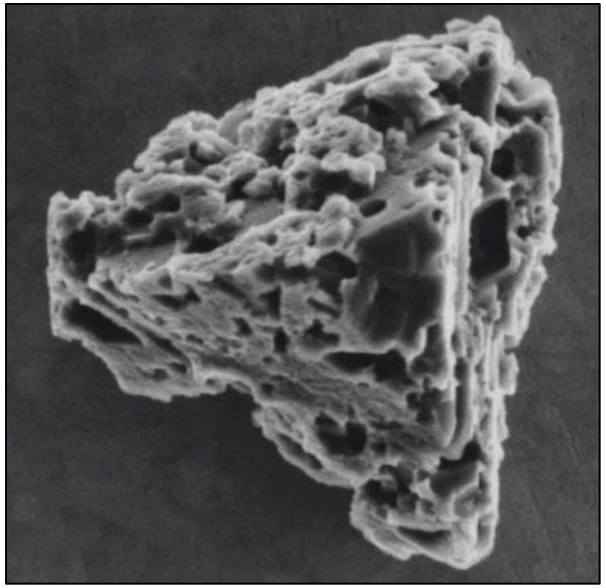

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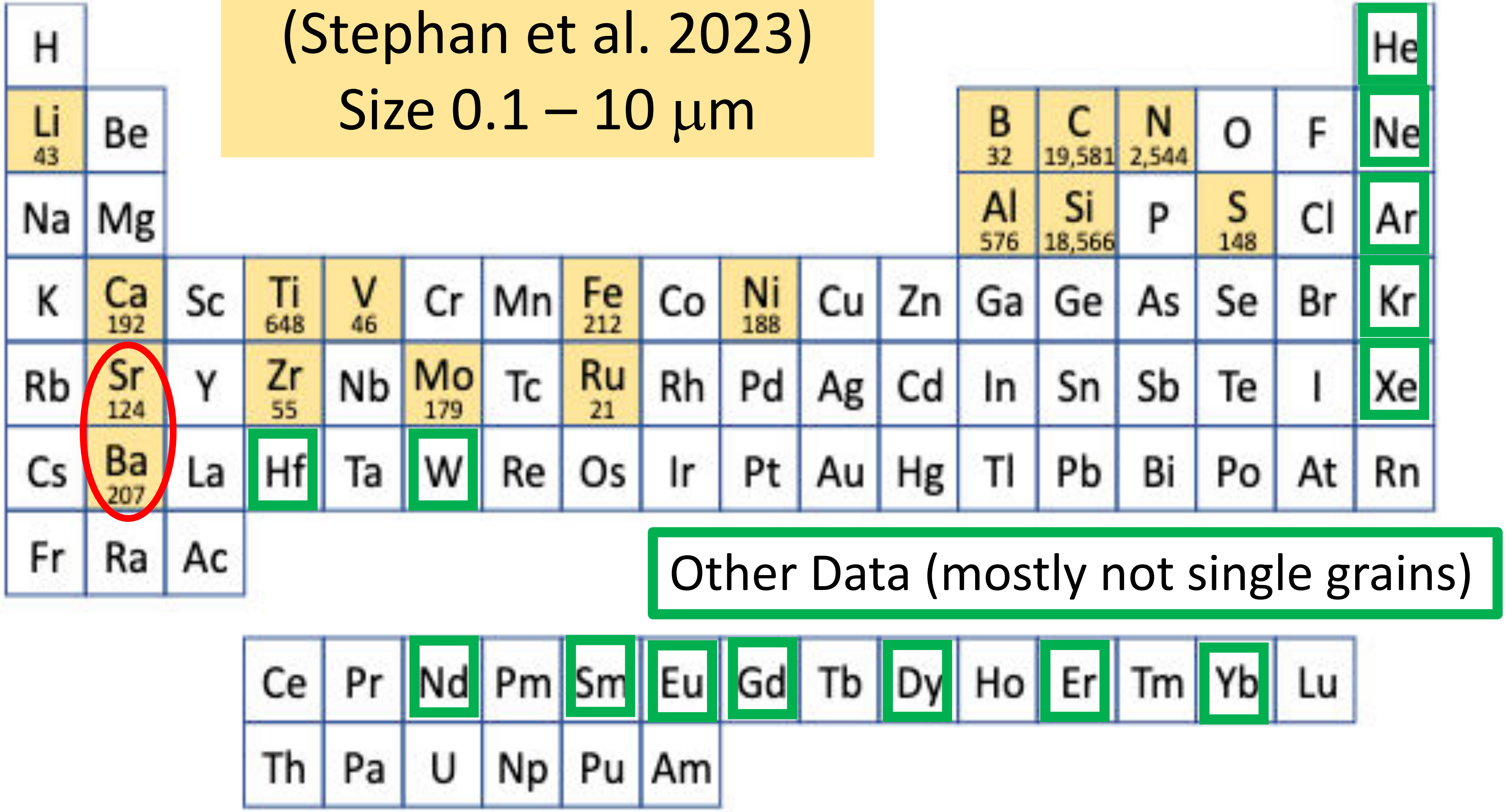

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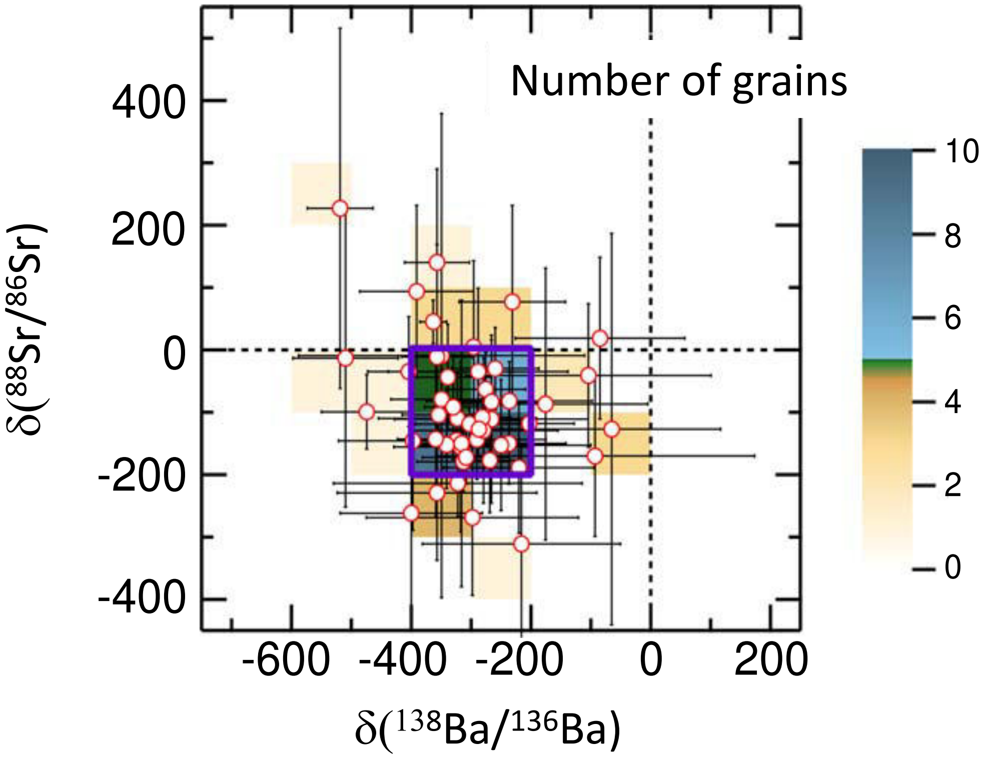
SiC grains from AGB stars show the *slow* neutron-capture signature: e.g., the large (≈ μm) grains



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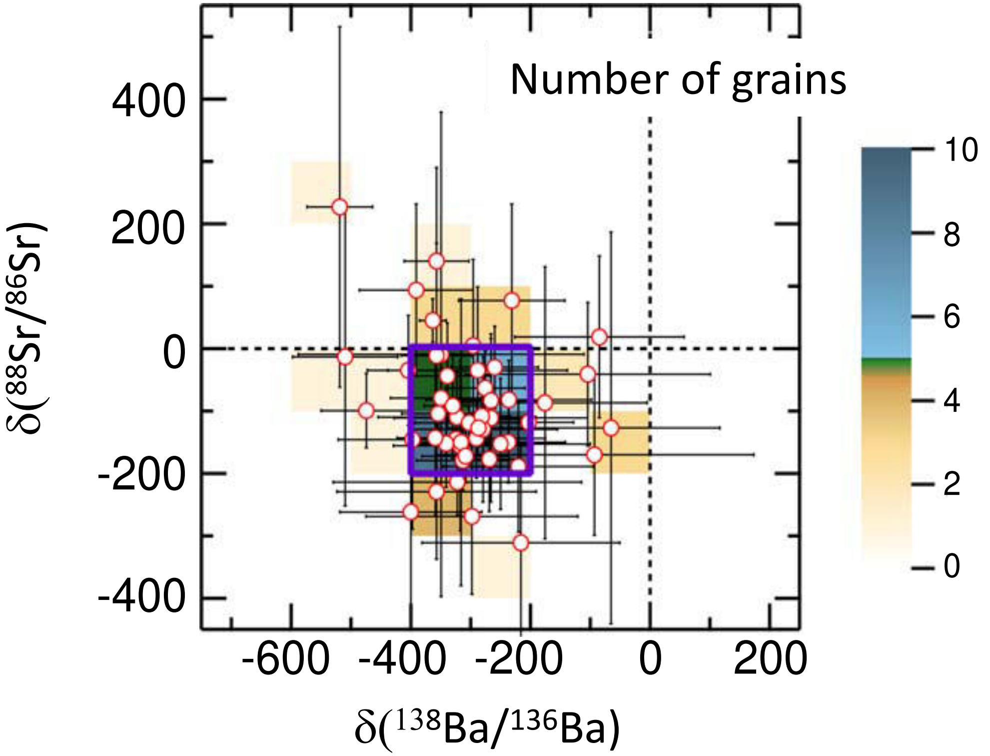
Profile of the ^{13}C neutron source?
(Liu et al. 2018)

Metallicity?
(Lugaro et al. 2018)

Treatment of mixing?
(Battino et al. 2019)



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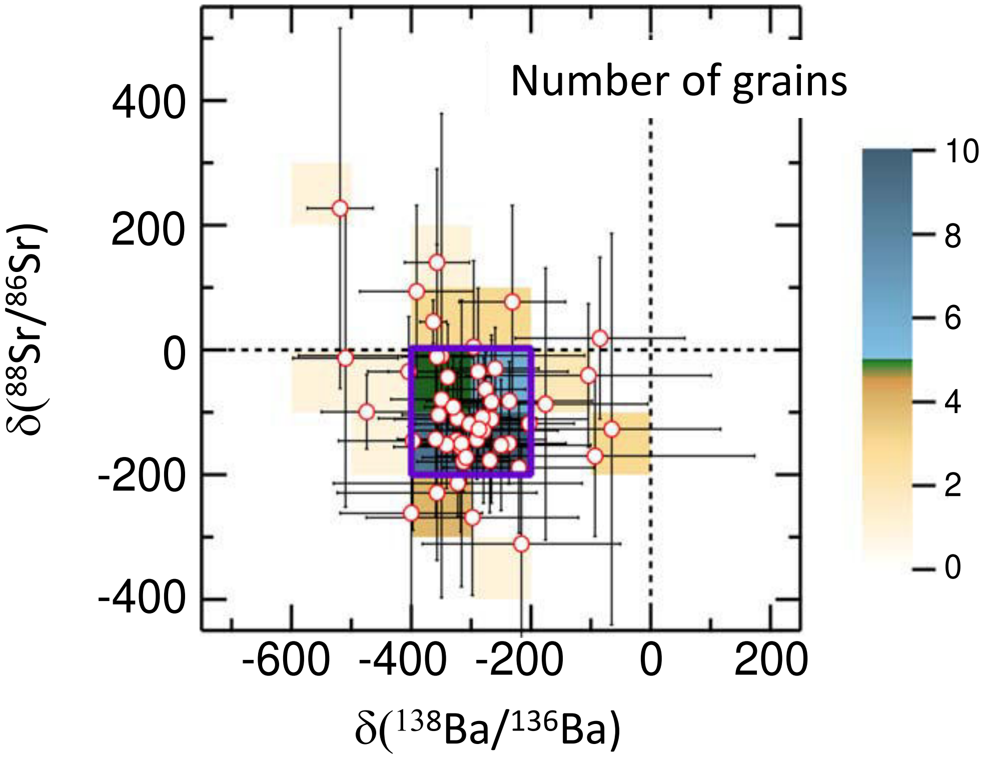

Neutron captures produce negative δ(^{88}Sr/^{86}Sr) only when [Ce/Y] is also negative!
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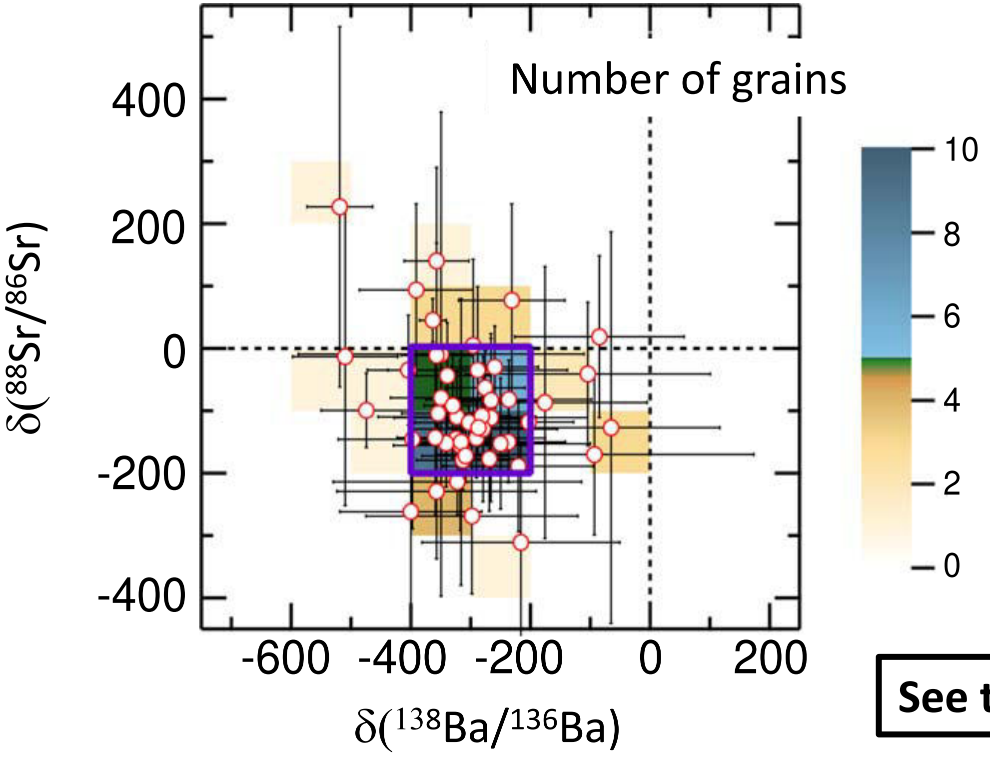

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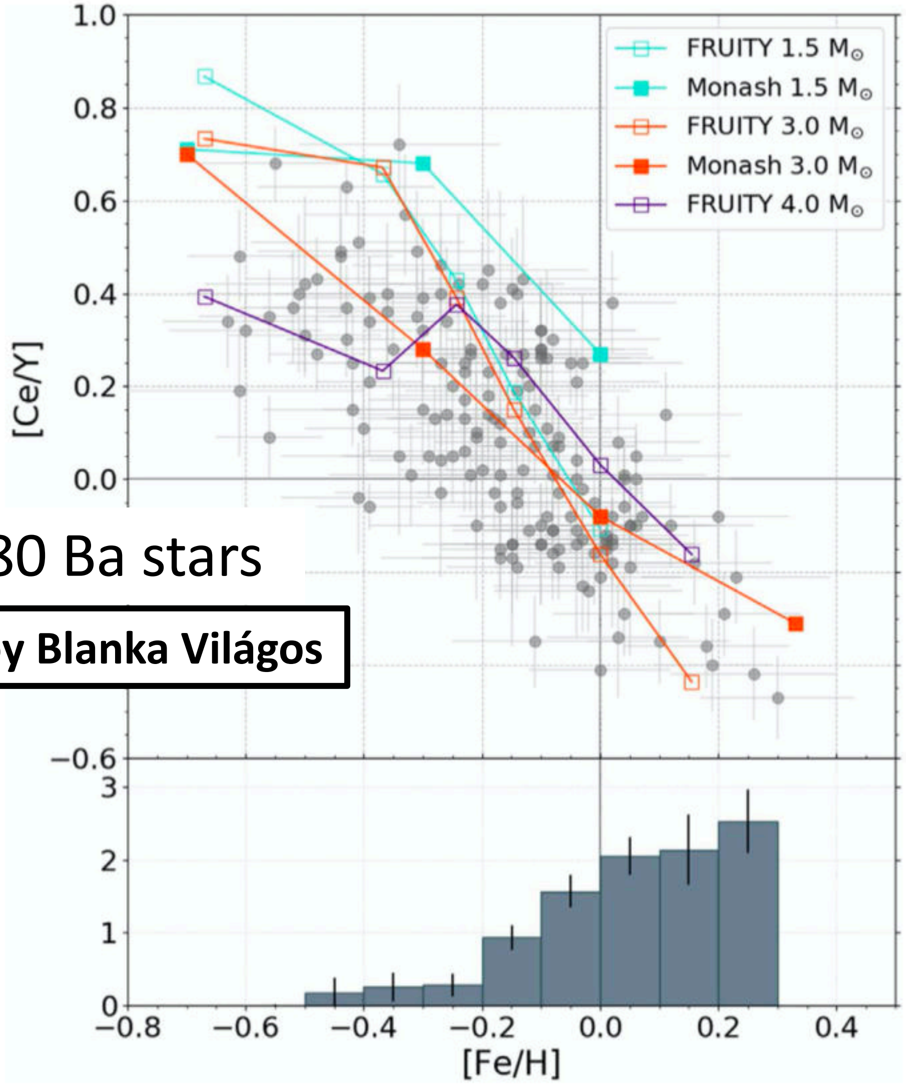

180 Ba stars

See talk by Blanka Világos

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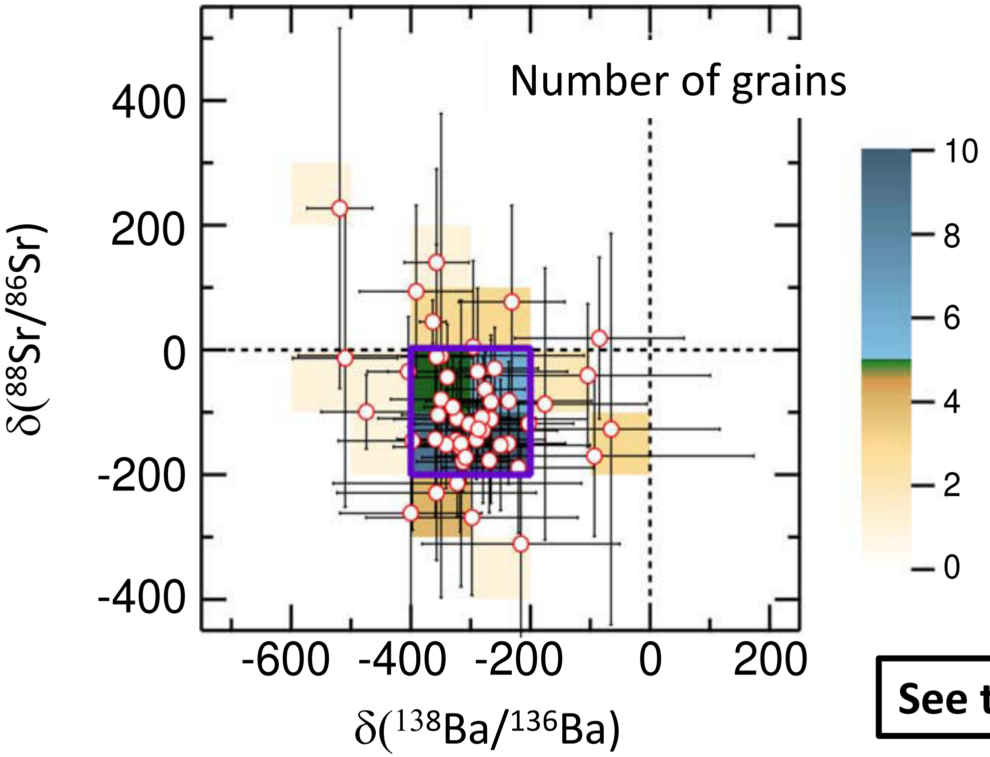

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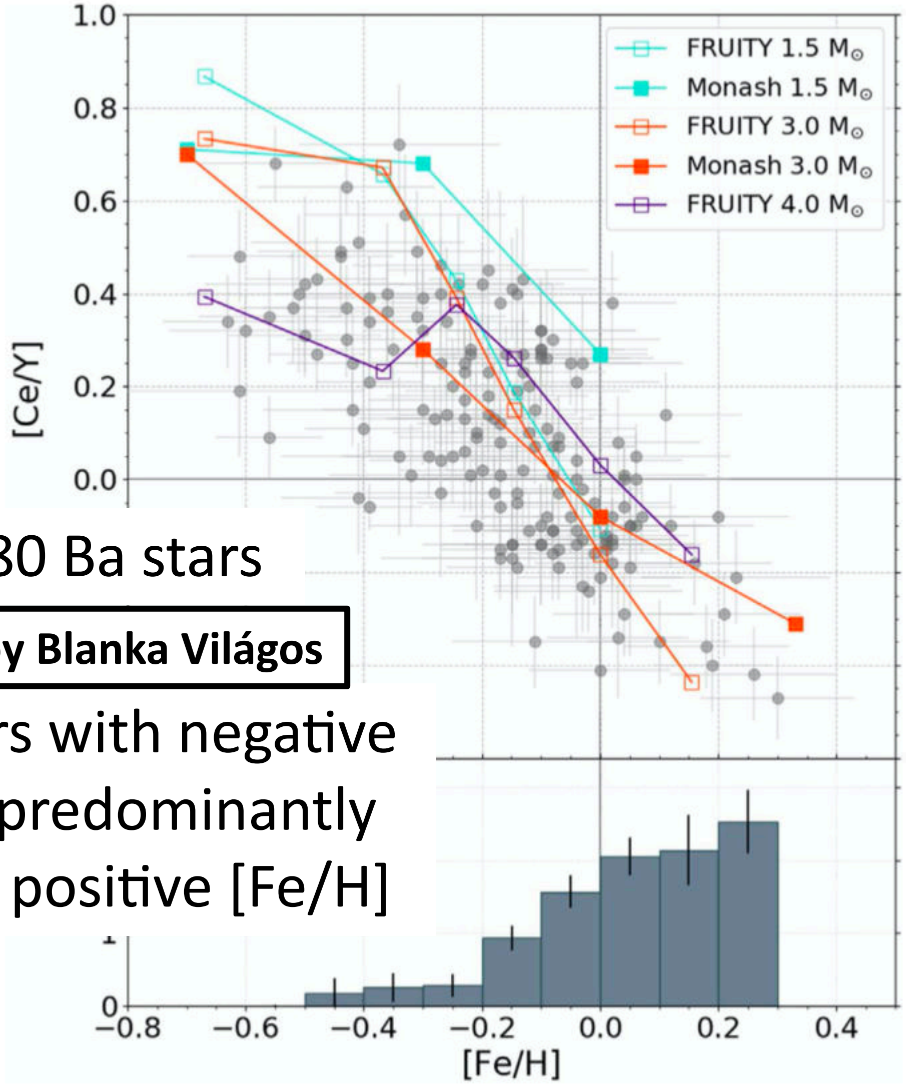

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The Ba stars with negative [Ce/Y] are predominantly those with positive [Fe/H]

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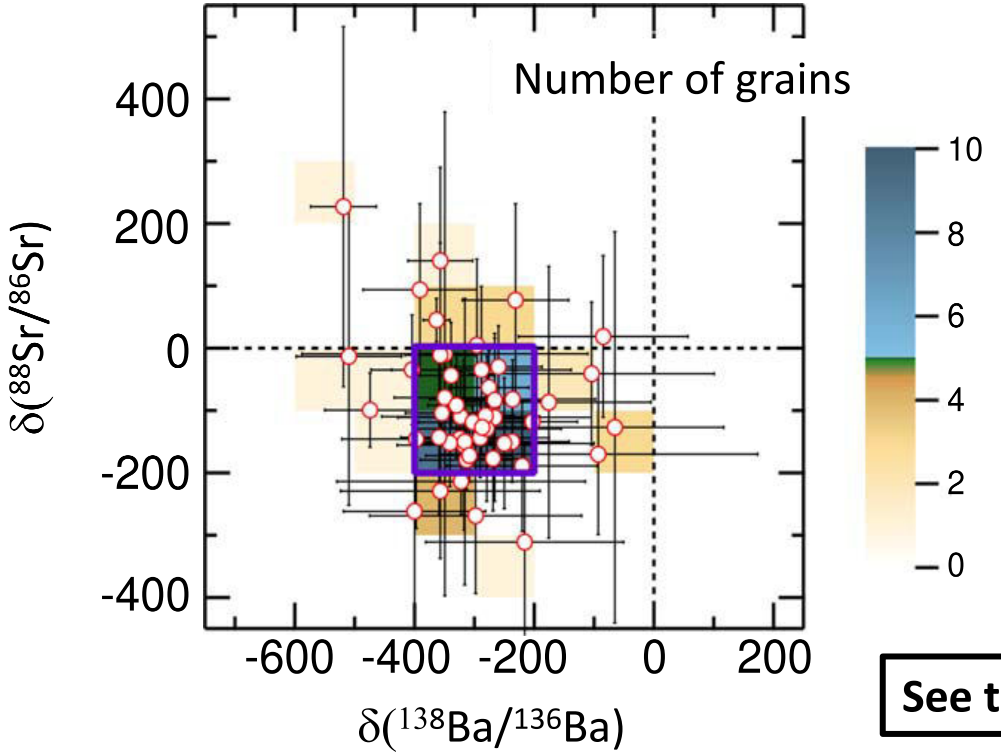

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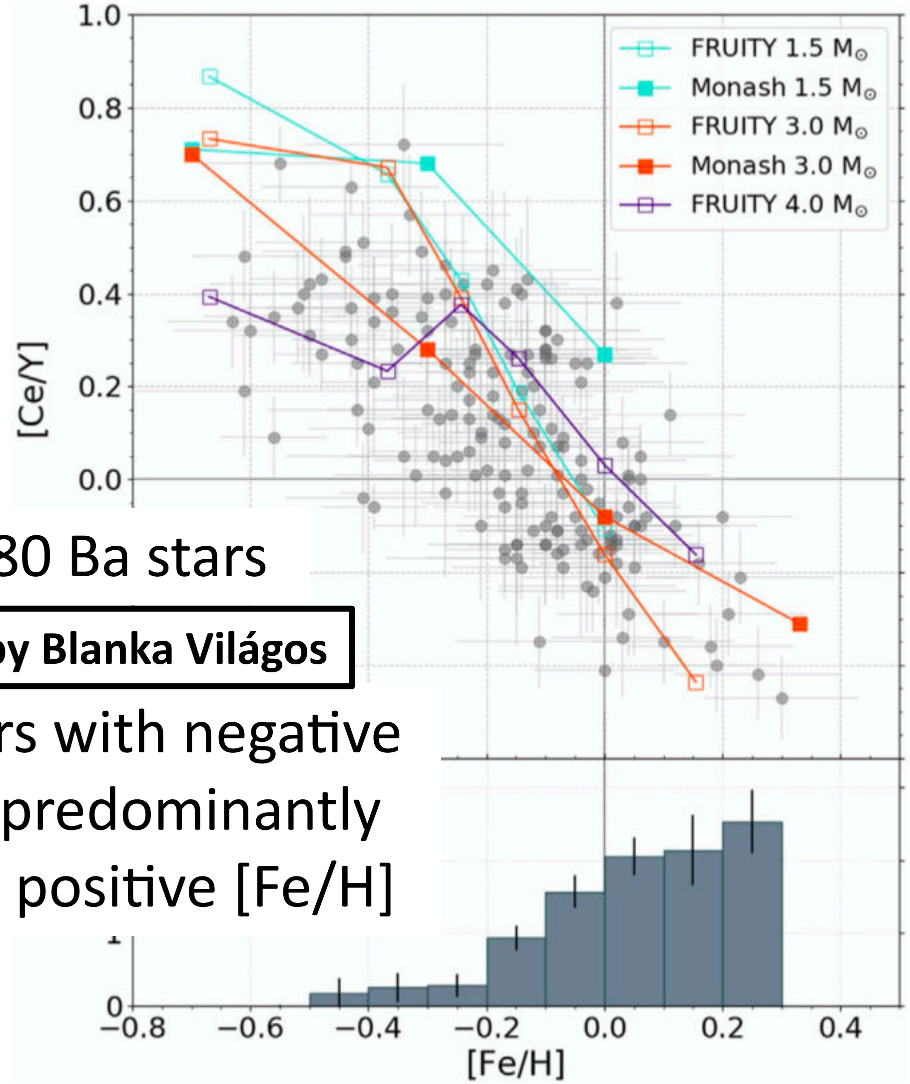


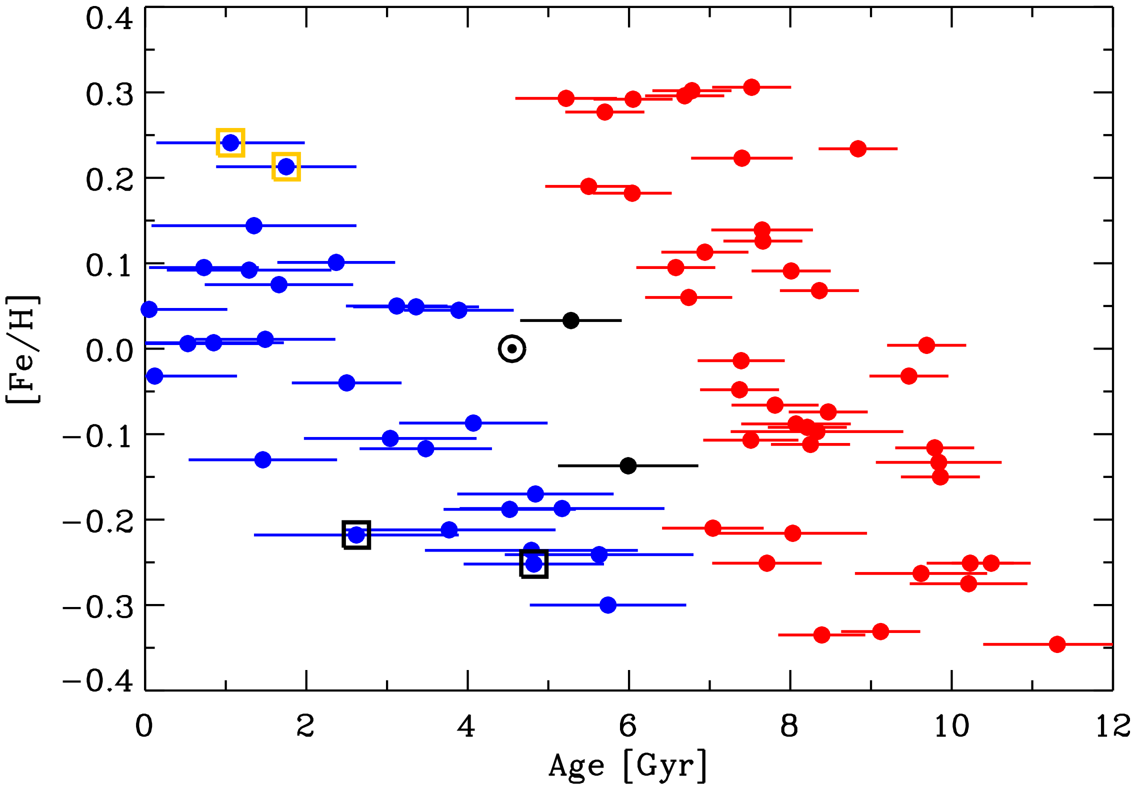
180 Ba stars

See talk by Blanka Világos

The Ba stars with negative [Ce/Y] are predominantly those with positive [Fe/H]

The **large** SiC grains must have originated from AGB stars with positive [Fe/H]

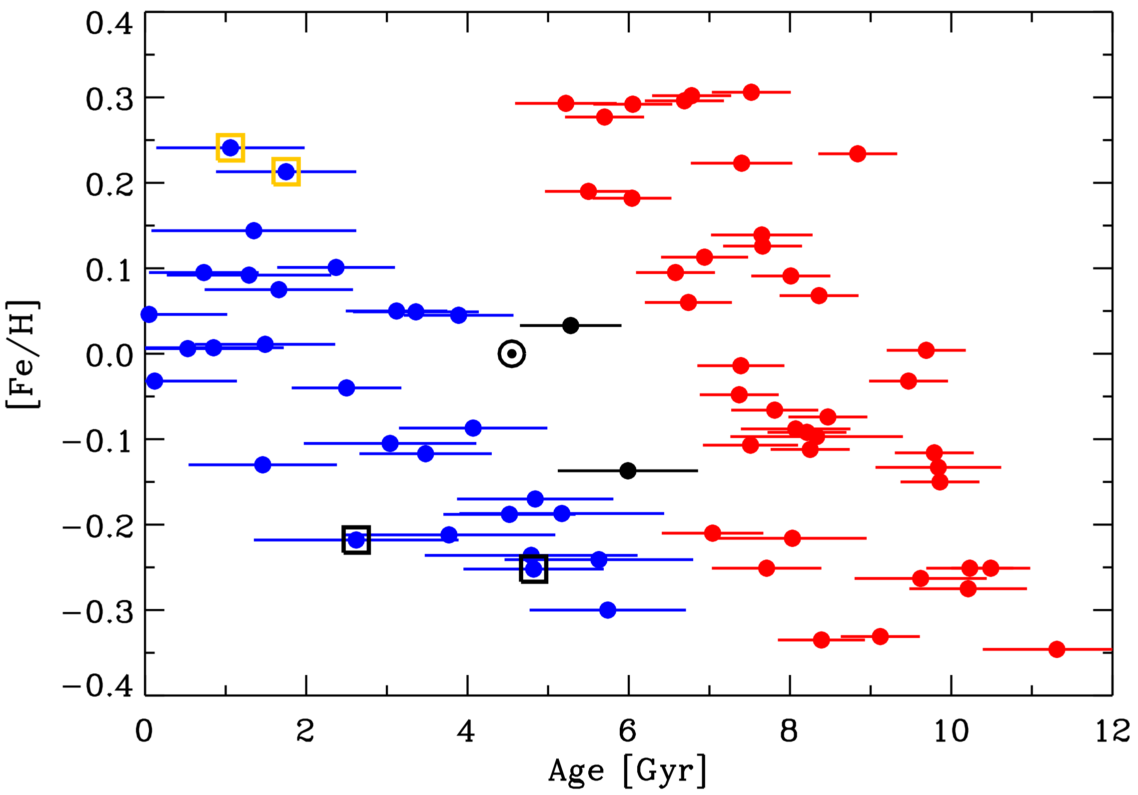
Age-metallicity relationship in the solar neighborhood

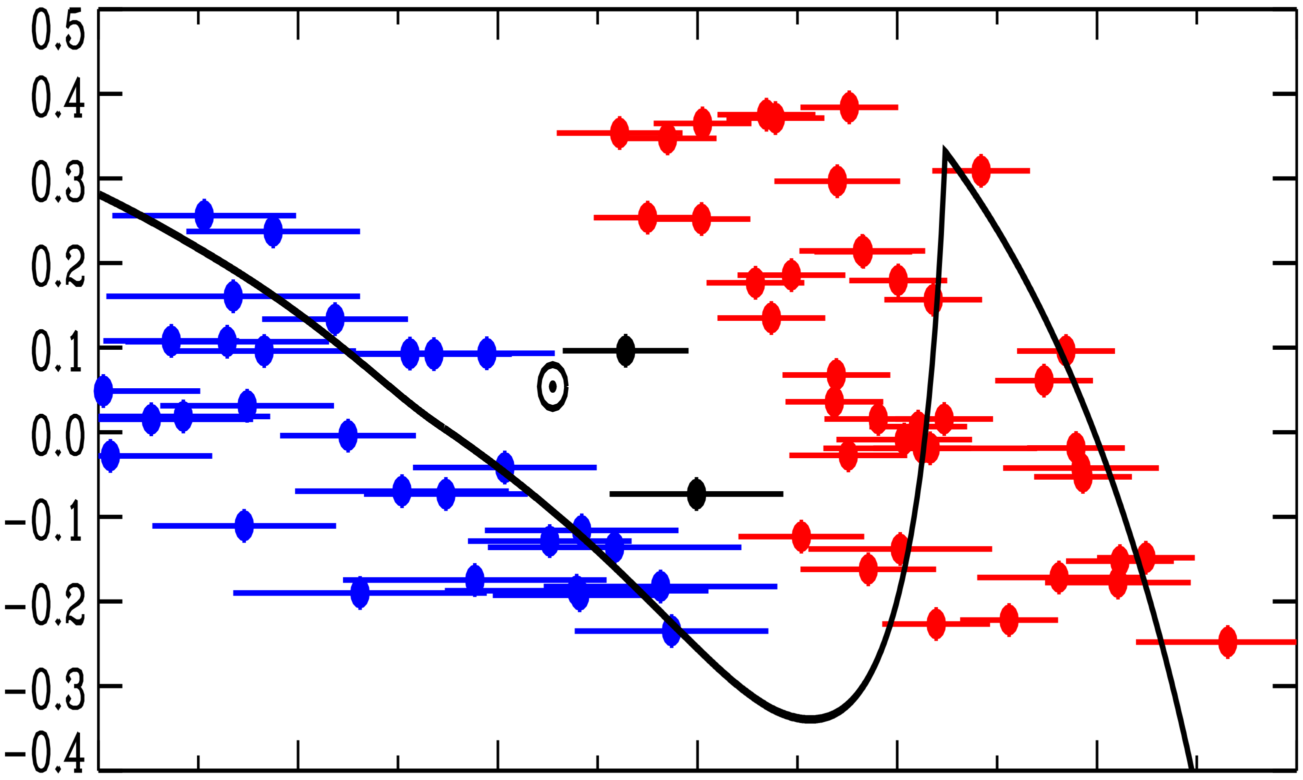


Nissen et al. (2020): 72 nearby solar-type stars with very well determined ages show two distinct sequences. The old but high metallicity stars:

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

Age-metallicity relationship in the solar neighborhood





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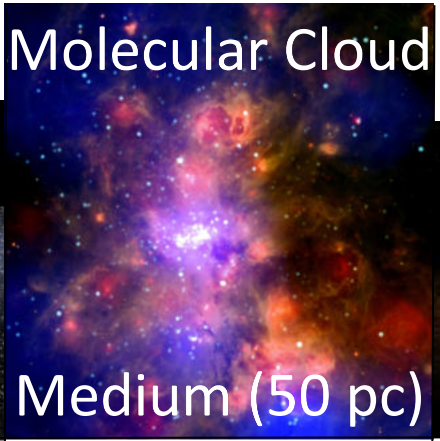
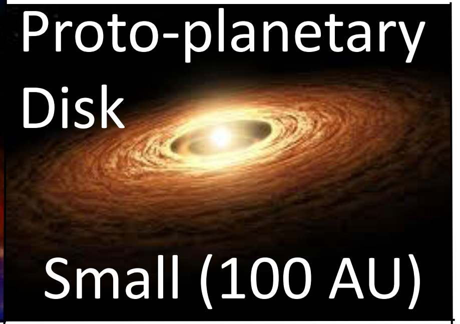
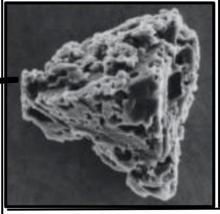
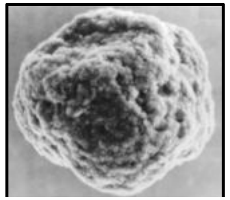
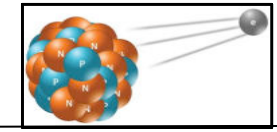
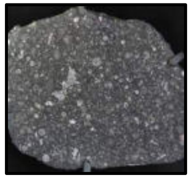
The large SiC grains support Scenario 1.

For example, the **black line**: 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	✓		
	≈ 10% from core-collapse supernovae 	✓	✓	
RADIO-ACTIVITY 2.	0.1 < half life < 100 Myr  *short-lived*	✓	✓	
BULK-ROCKS 3.	Meteoritic rocks and inclusions 		✓	✓

Chemical Evolution of the Milky Way

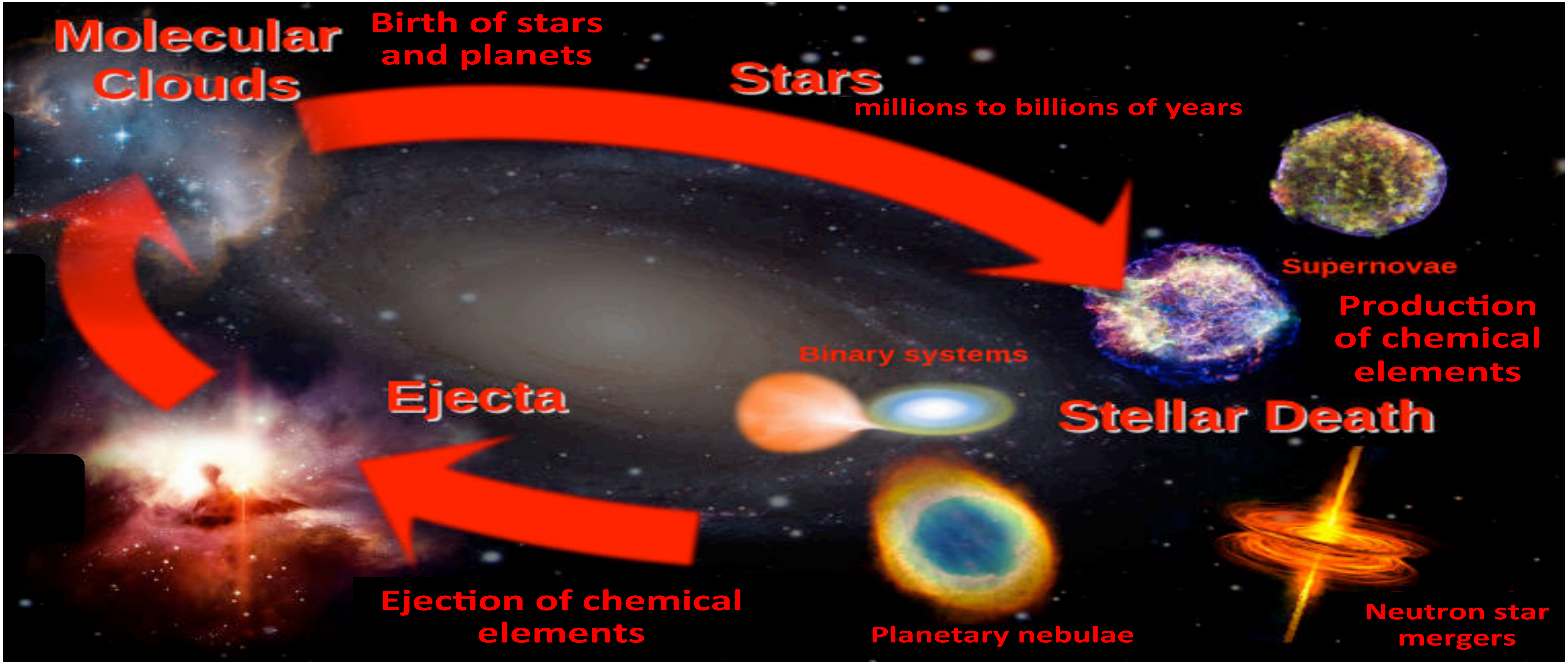
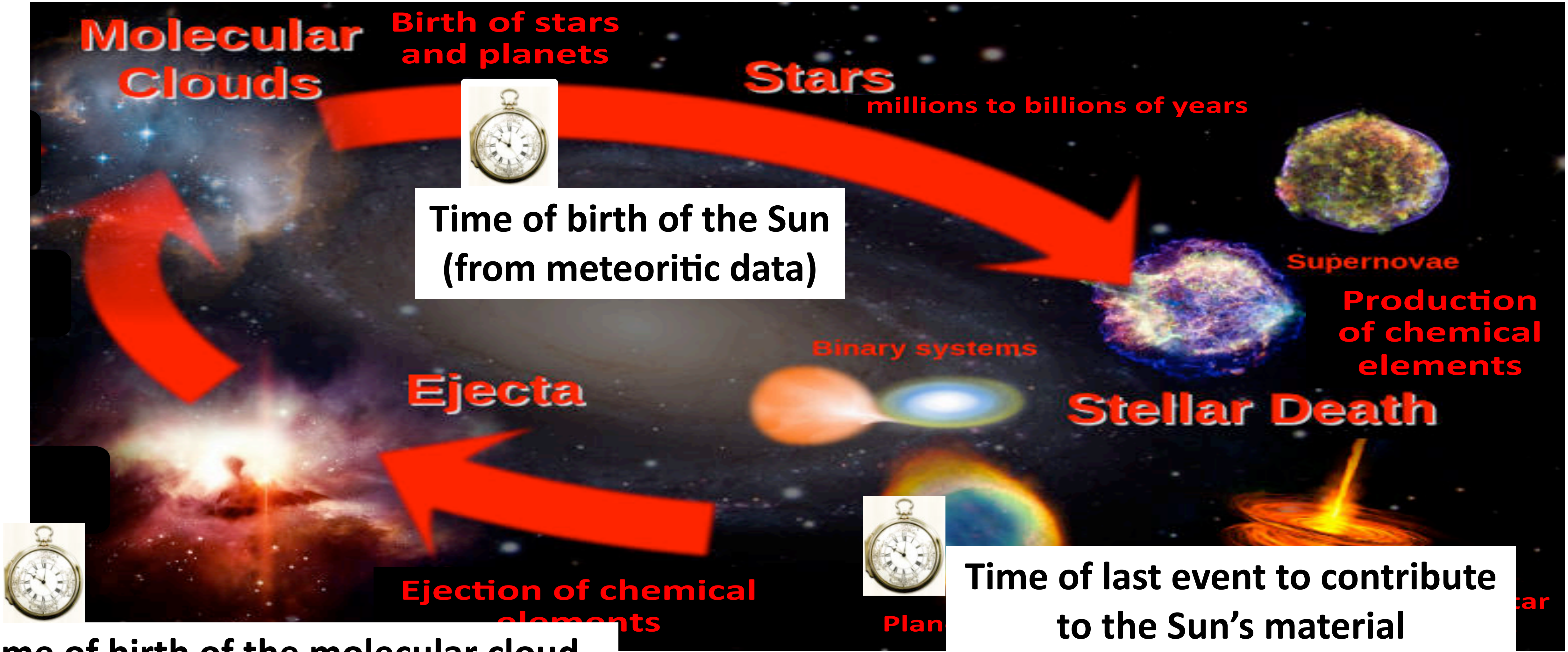


Figure from Richard Longland

Radioactive Chemical Evolution of the Milky Way

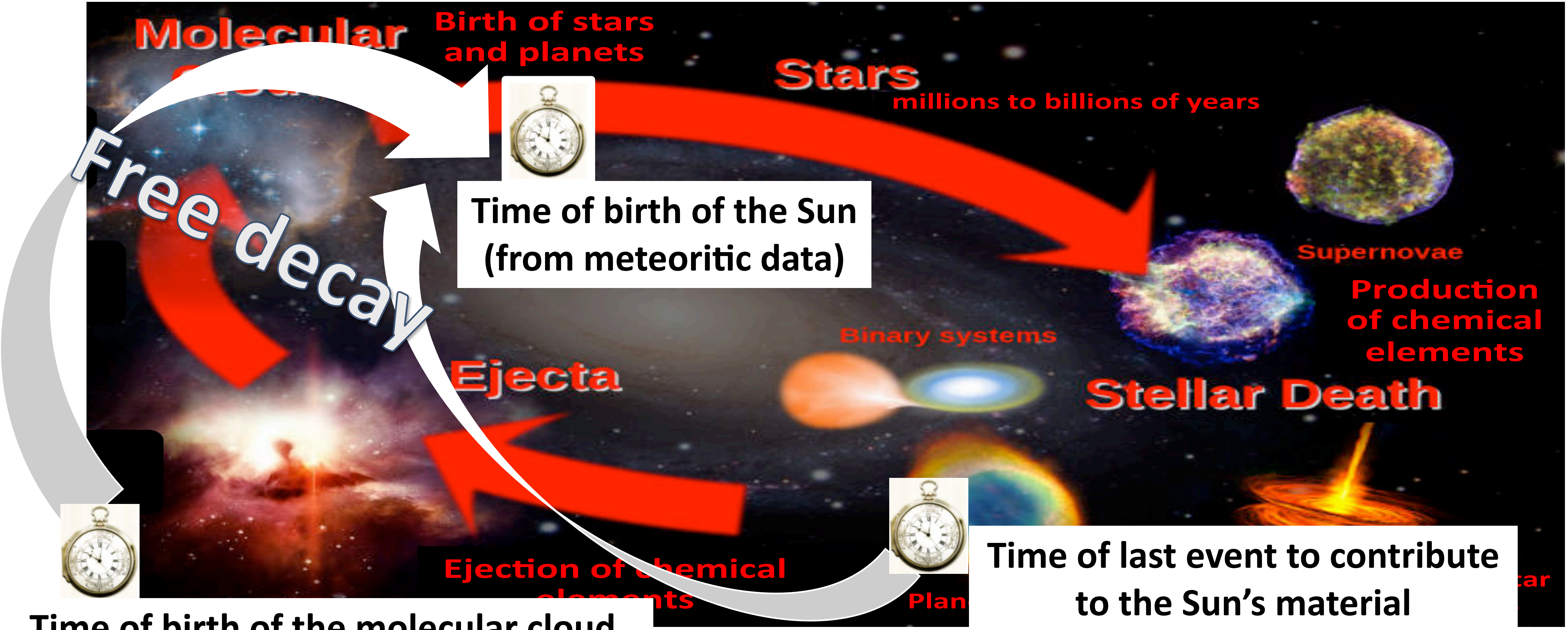


Time of birth of the Sun
(from meteoritic data)

Time of last event to contribute to the Sun’s material
(from stellar nucleosynthesis models)

Time of birth of the molecular cloud
(from stellar nucleosynthesis and galactic evolution models)

Radioactive Chemical Evolution of the Milky Way



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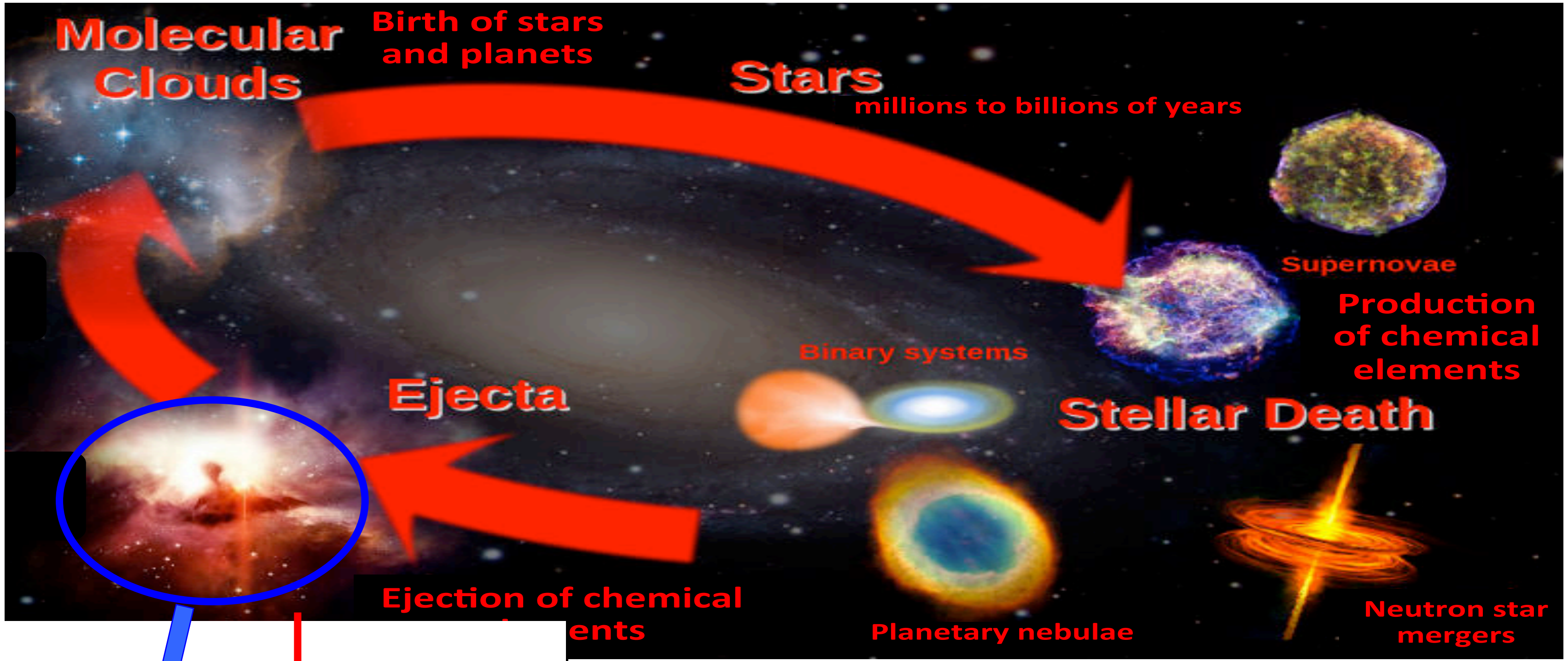
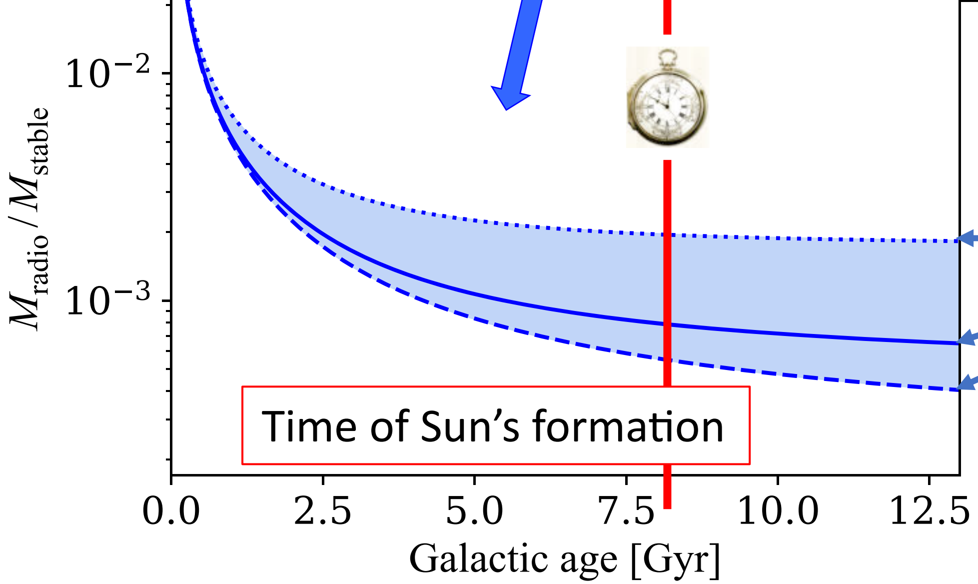
Radioactive Chemical Evolution of the Milky Way

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

Radioactive Chemical Evolution of the Milky Way

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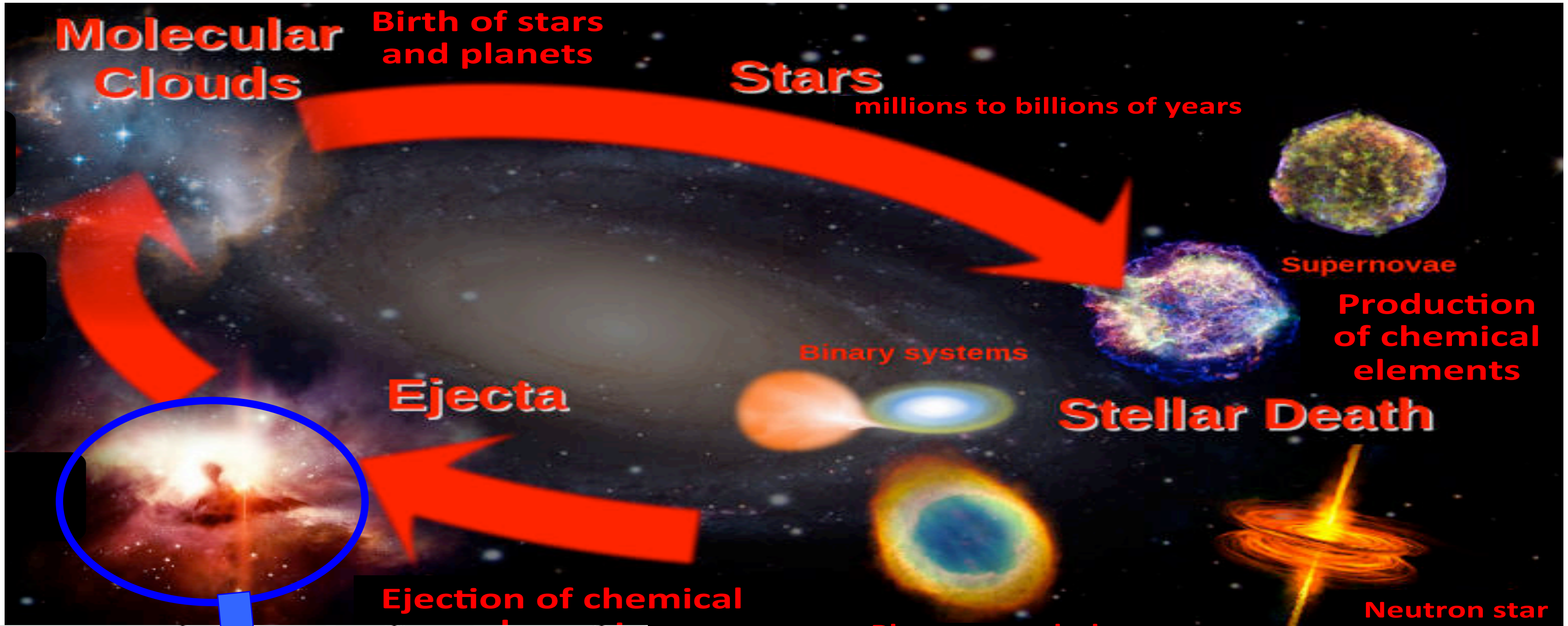
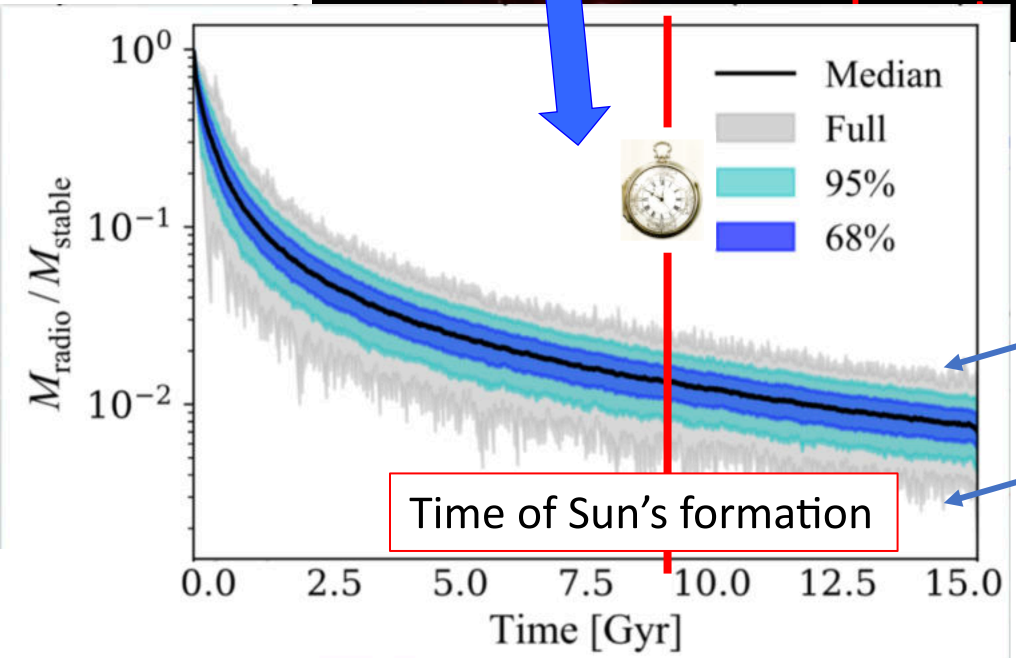


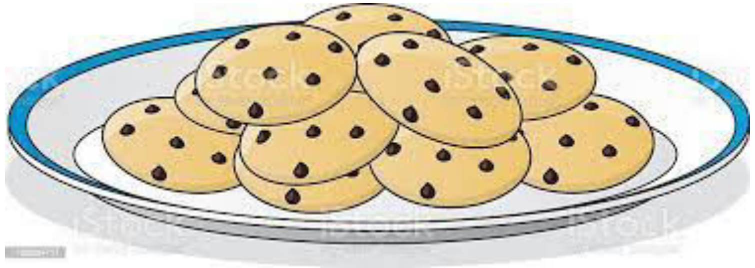


Time of Sun's formation

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

Evolution of the number of biscuits in a plate



Every time interval τ someone eats half of the biscuits from the plate

Every time interval δ someone adds biscuits to the plate

How many biscuits are on the plate?

Evolution of the number of biscuits in a plate

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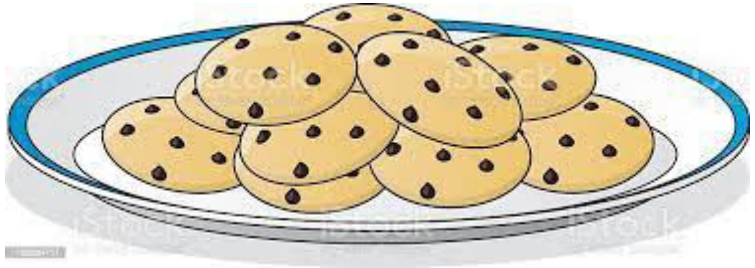


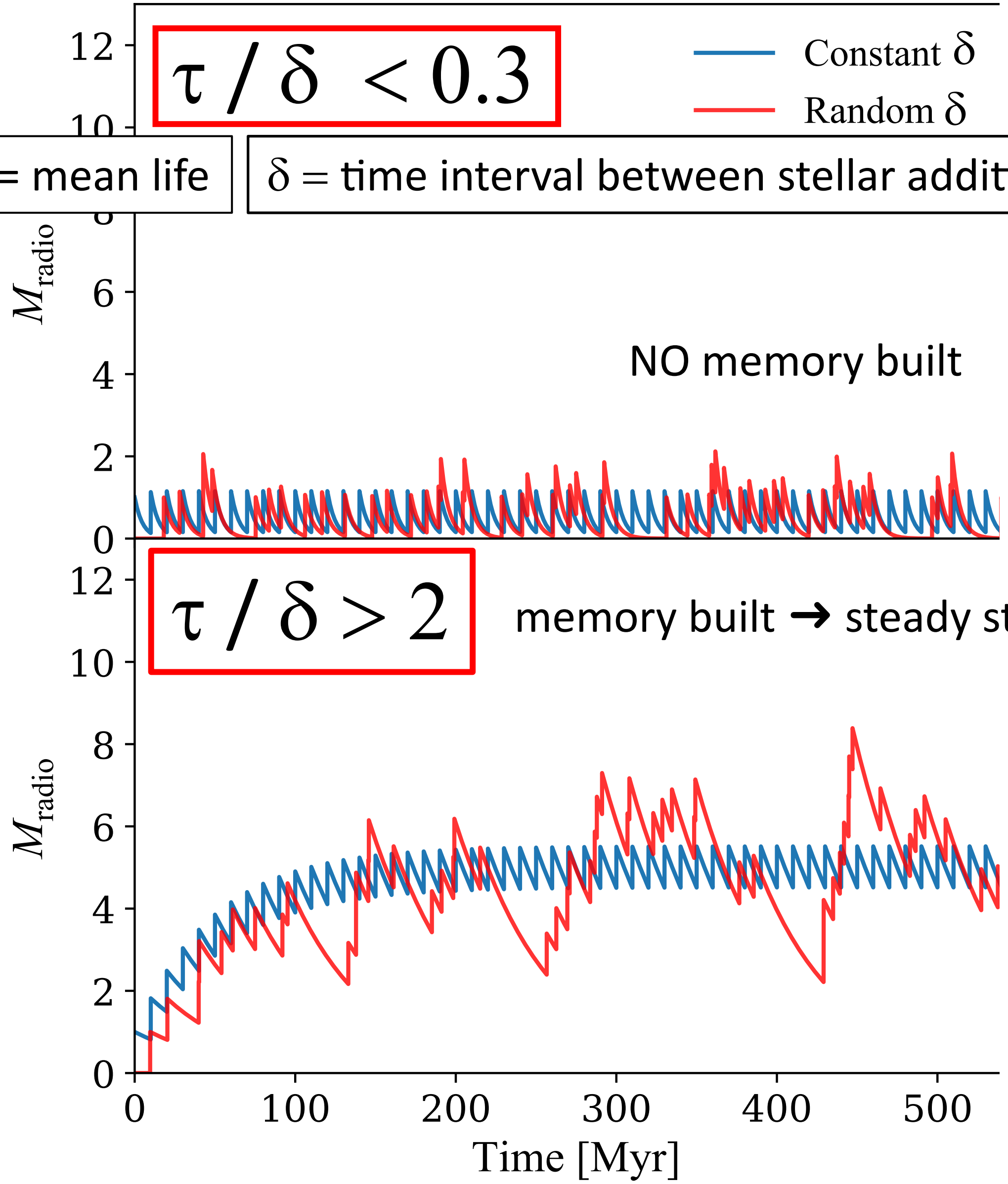
Every time interval δ someone adds biscuits to the plate

How many biscuits are on the plate?

If τ/δ is small, then there are typically no biscuits, unless they were just added

If τ/δ is large, then the number of biscuits can build up!

Radioactive Chemical Evolution of the Milky Way



$\tau / \delta < 0.3$

τ = mean life

δ = time interval between stellar additions

NO memory built

$\tau / \delta > 2$

memory built → steady state

Radioactive Chemical Evolution of the Milky Way

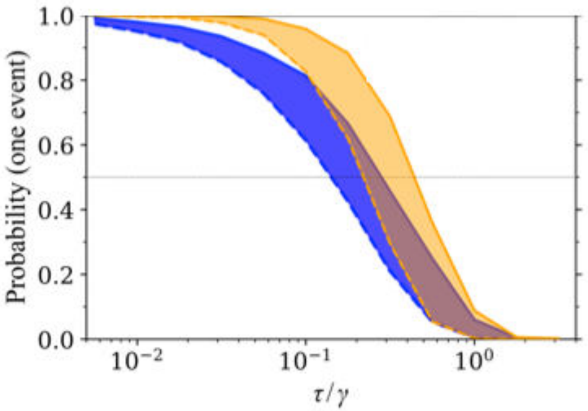
***Rapid* neutron-capture process nuclei**:

^{129}I and ^{247}Cm

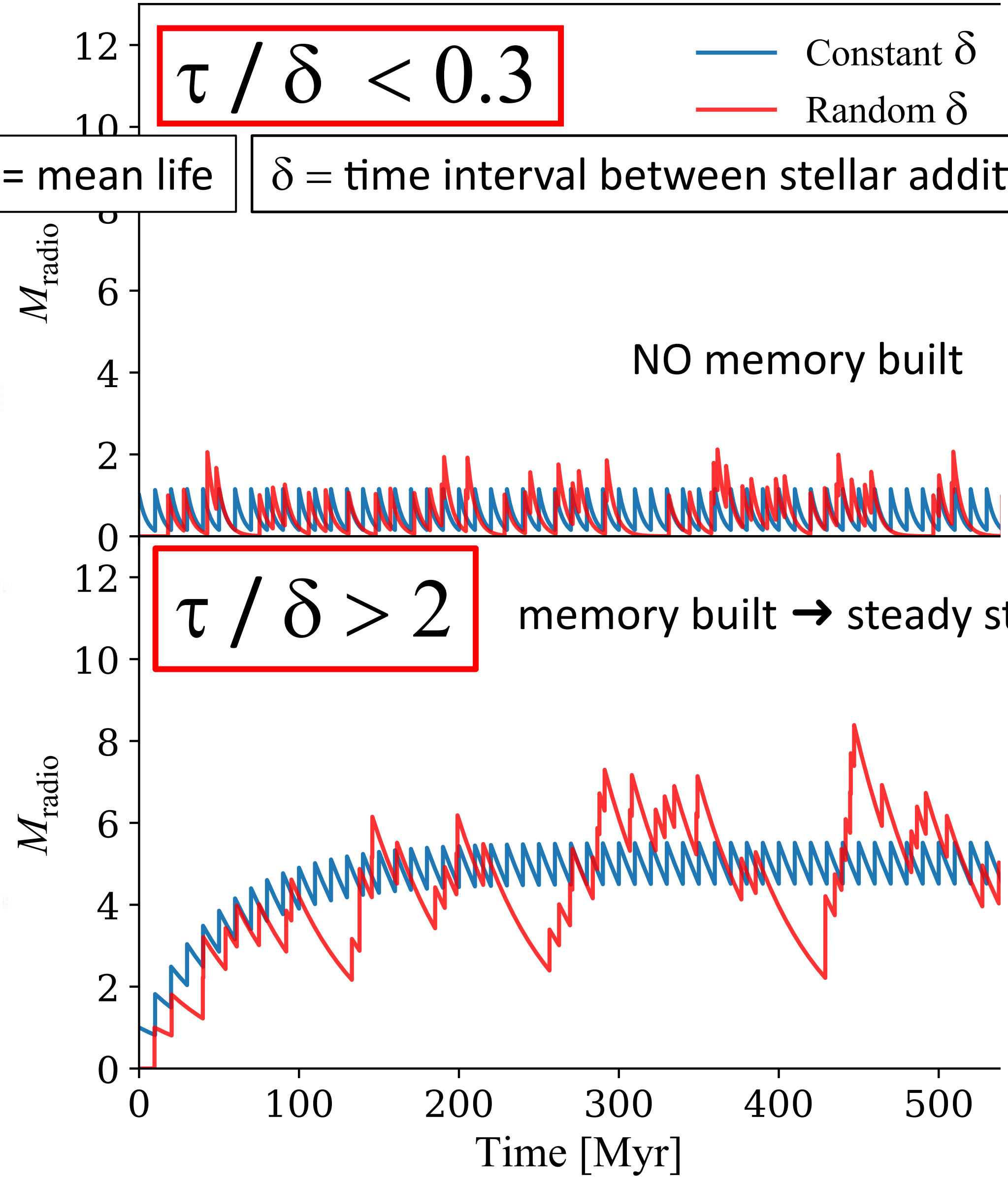
τ ~ 22 Myr

δ ~ 100-500 Myr

Rare sources



We find the probability that the isotope carries the memory of one event only



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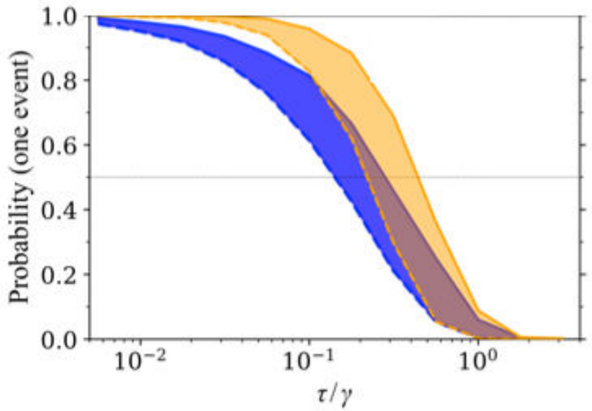


We find the probability that the isotope carries the memory of one event only

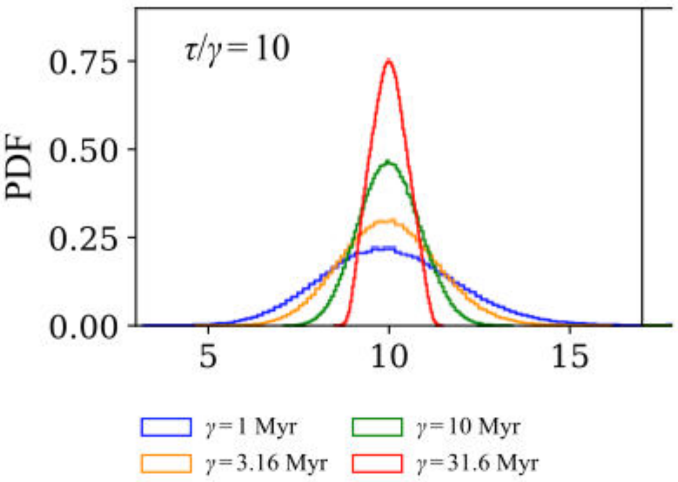
Slow **neutron-capture process nuclei**:

^{107}Pd and ^{182}Hf

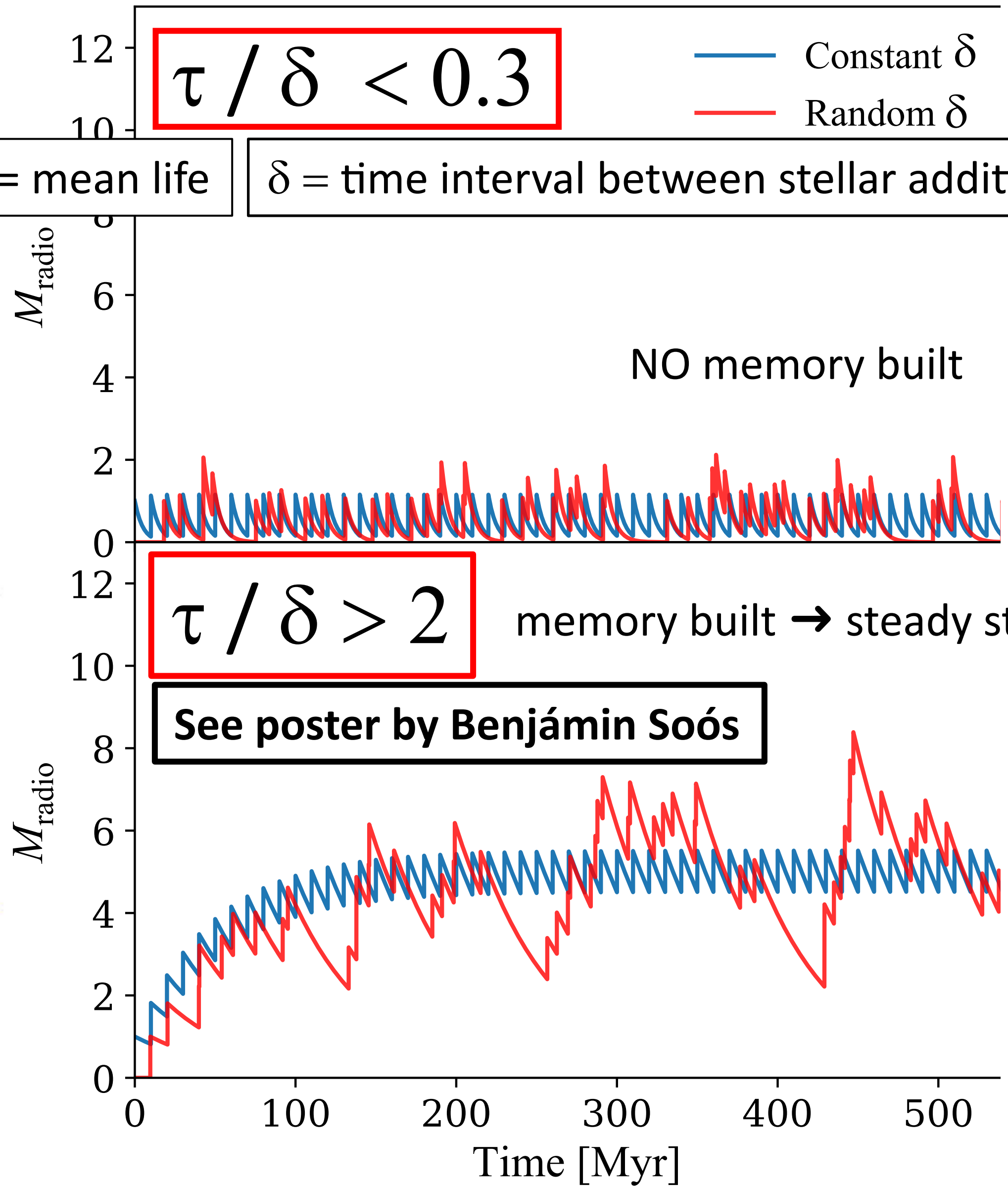
τ ~ 10 Myr

δ ~ 5 Myr

Common sources



We define a distribution, simmetric or not



$\tau / \delta < 0.3$

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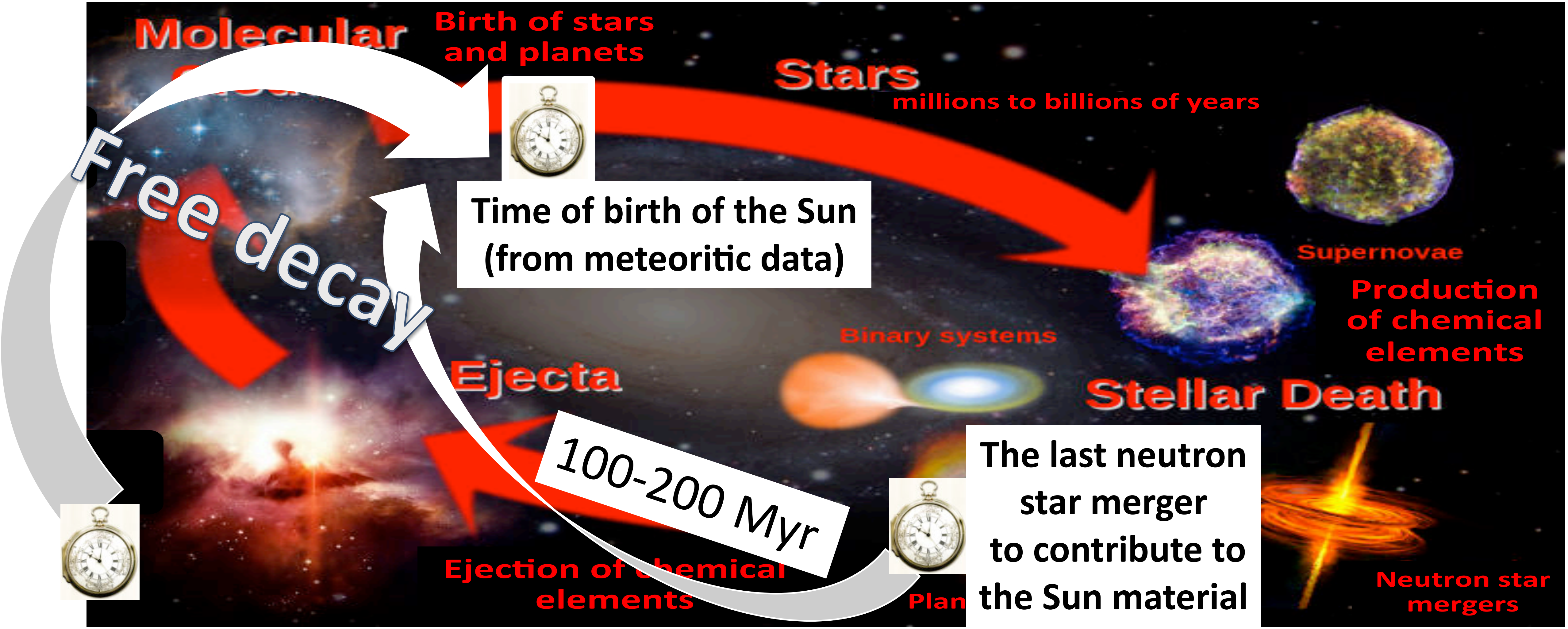
memory built → steady state

See poster by Benjámin Soós

Radioactive Chemical Evolution of the Milky Way



Free decay

Time of birth of the Sun (from meteoritic data)

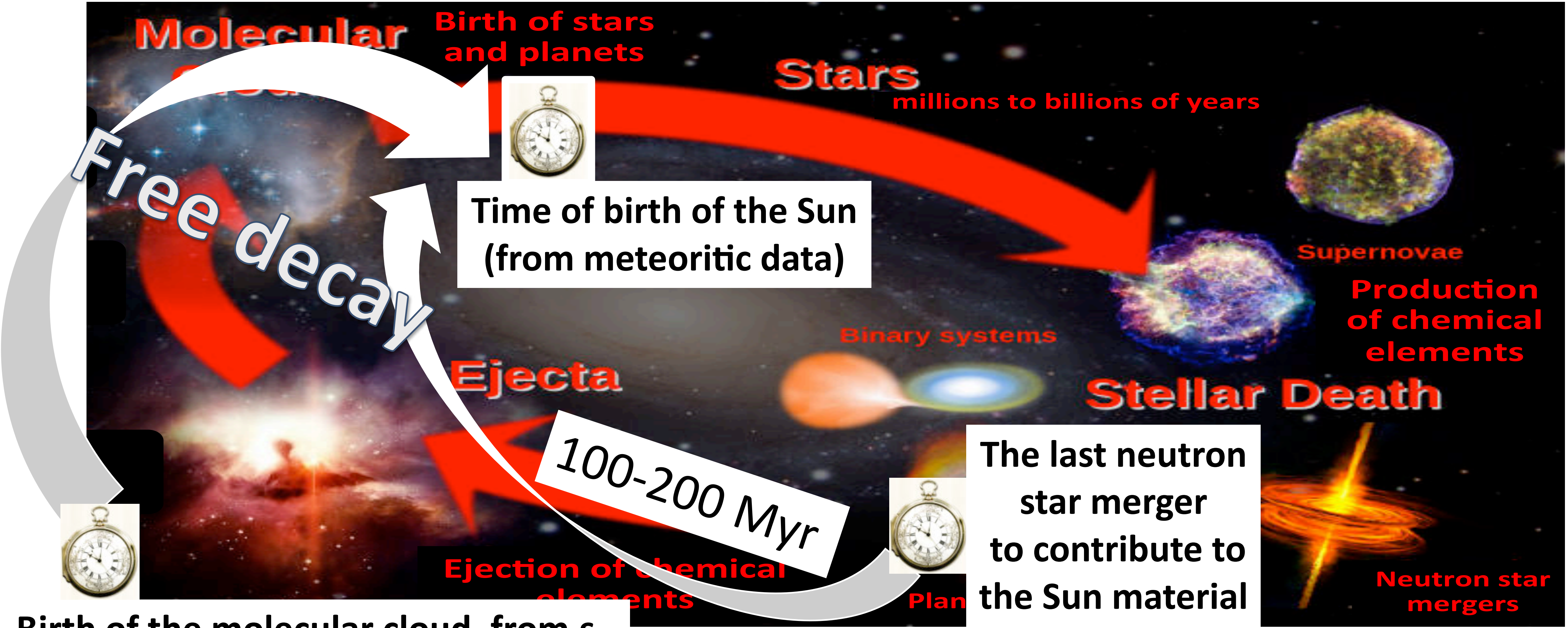
100-200 Myr

The last neutron star merger to contribute to the Sun material

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

Côté et al. 2021, Science

Radioactive Chemical Evolution of the Milky Way



Free decay

Time of birth of the Sun (from meteoritic data)

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The last neutron star merger to contribute to the Sun material

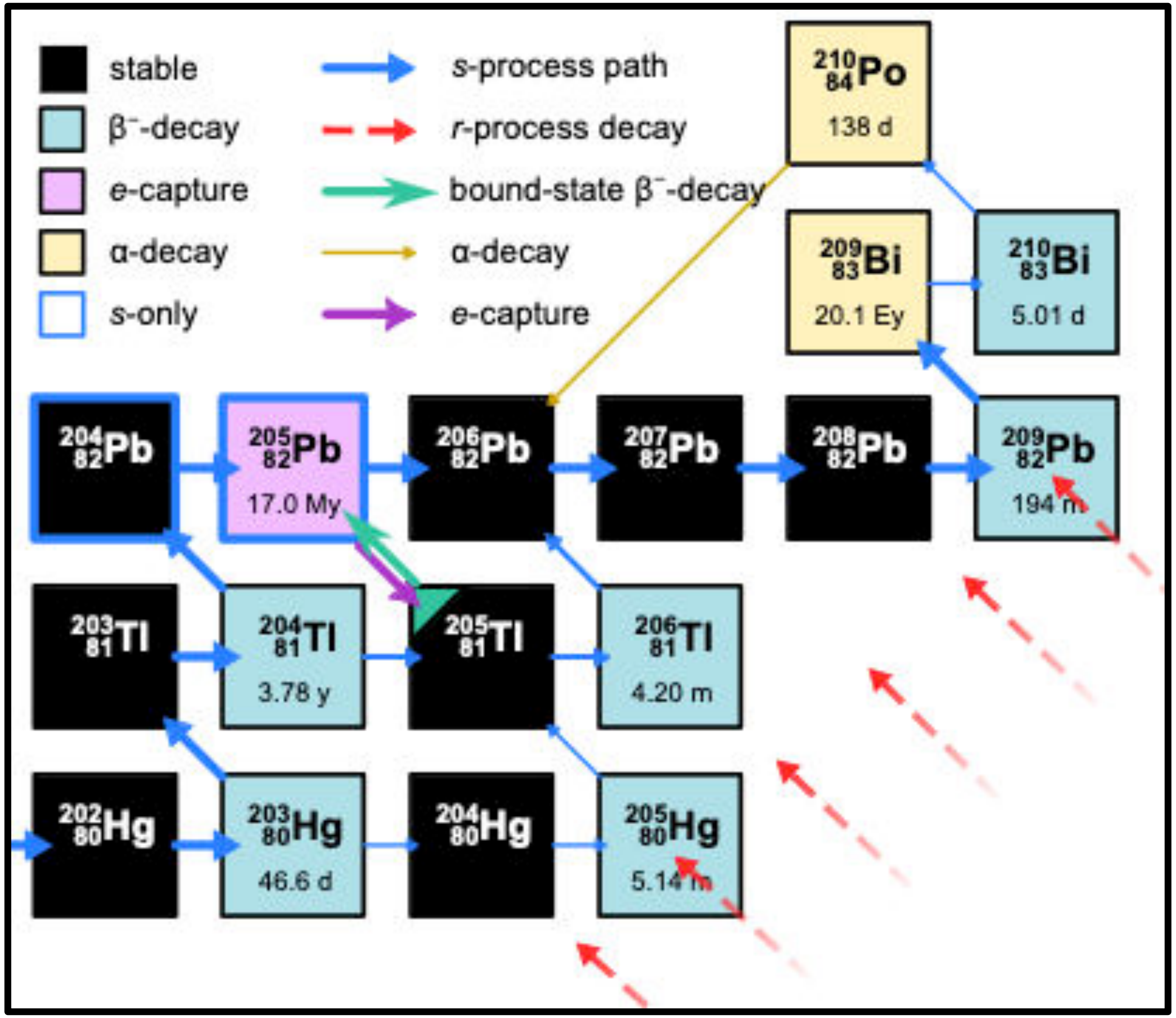
from r-process ^{129}I and ^{247}Cm

Côté et al. 2021, Science

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

Trueman et al. 2022, ApJ

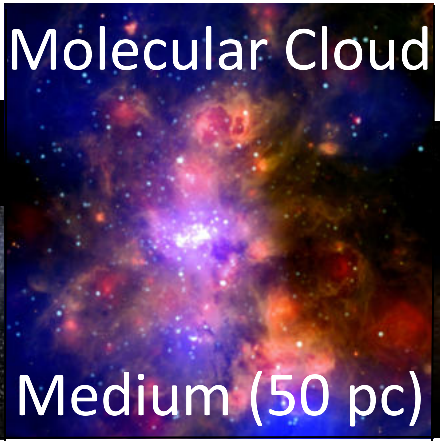
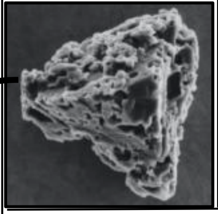
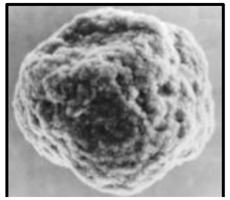
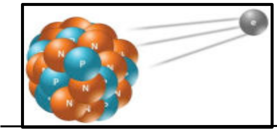
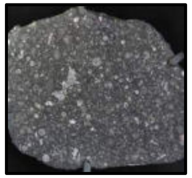
With ^{107}Pd, ^{135}Cs, and ^{182}Hf, ^{205}Pb is also produced by the *s* process in AGB stars



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

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	✓		
	≈ 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.

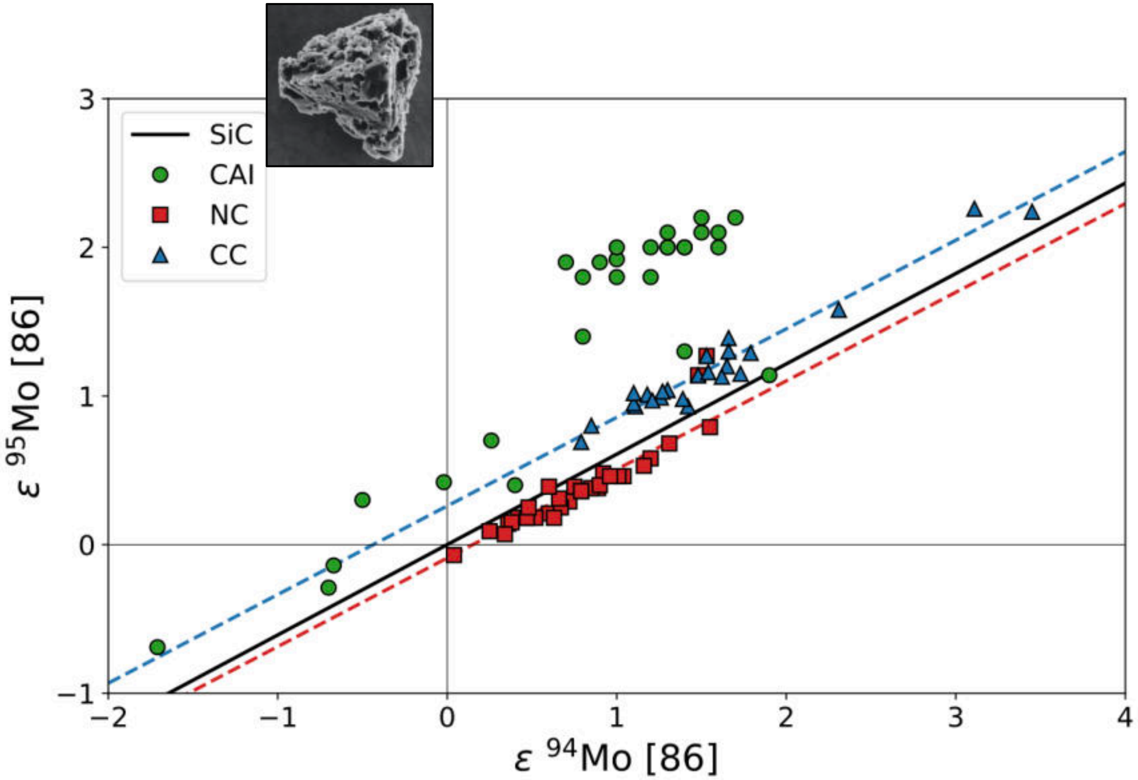
See lectures by Christoph Burkhardt

1. Anomalies probably 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

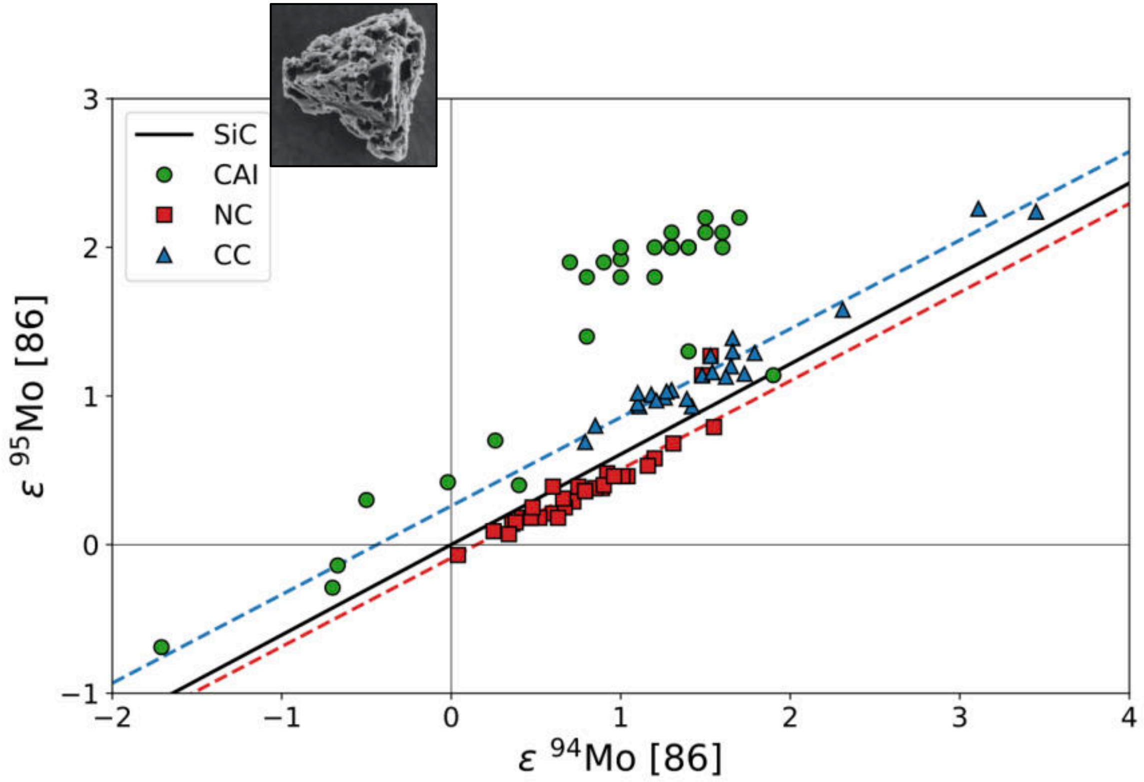
Example: Molybdenum variations in bulk meteorites

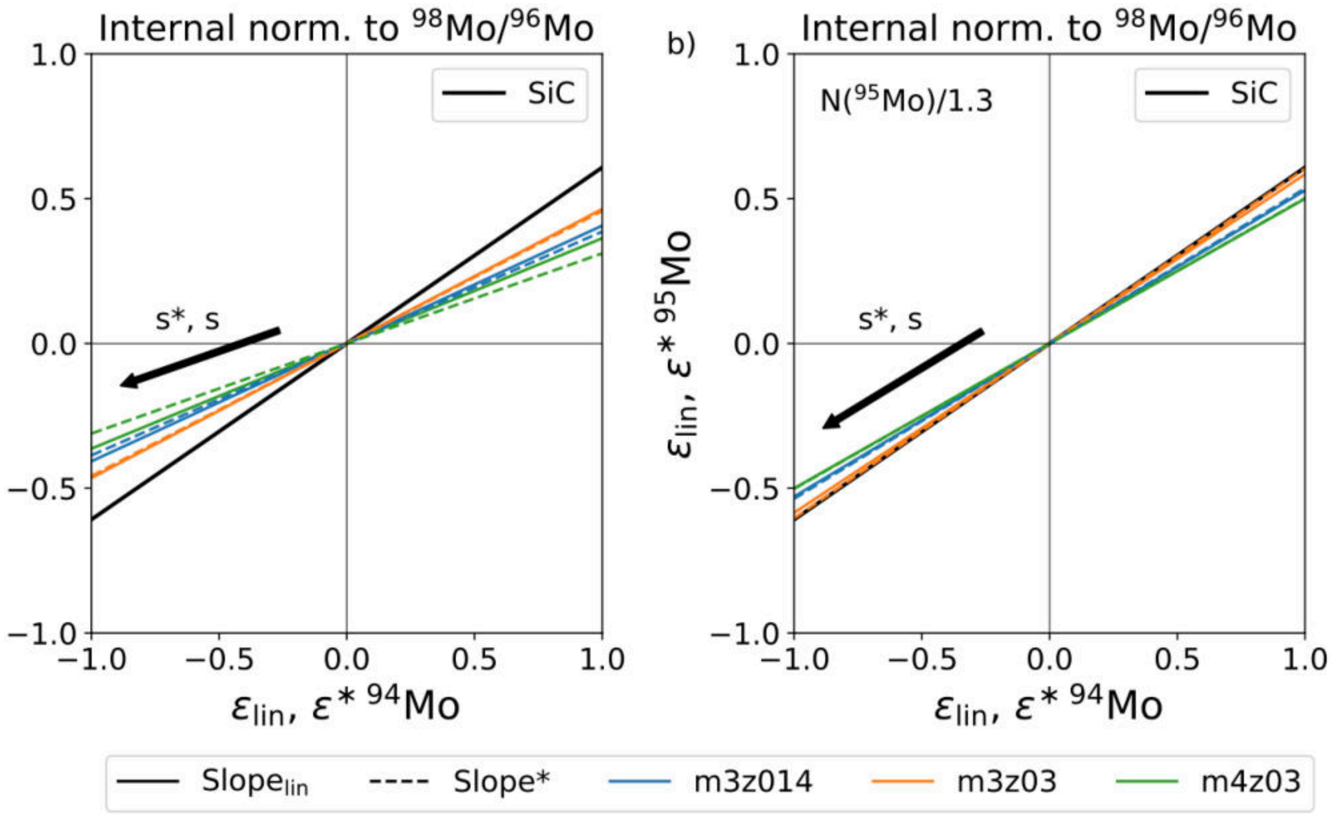


Neutron source reaction rates, and neutron-capture cross sections needed!

Example: Molybdenum variations in bulk meteorites

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

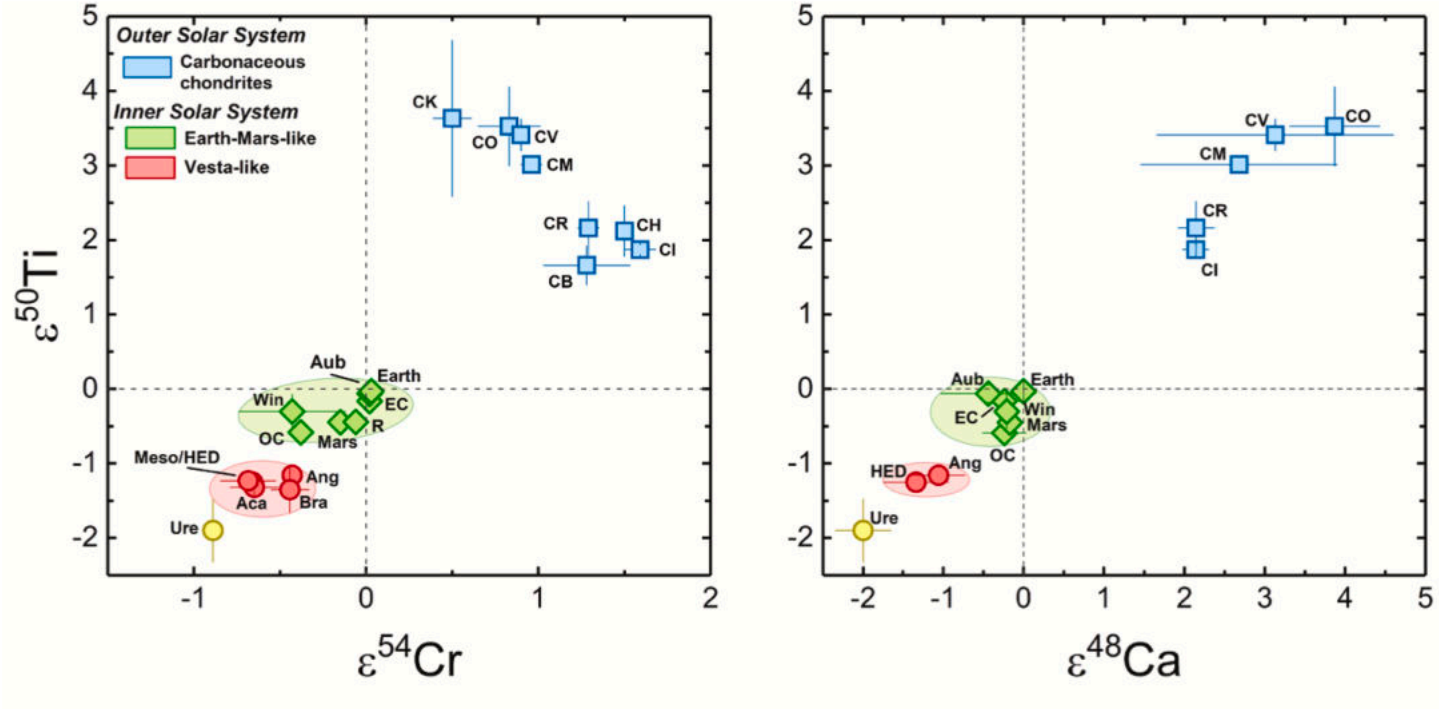




Neutron source reaction rates, and neutron-capture cross sections needed!

Lugaro et al. (2023, EPJA)

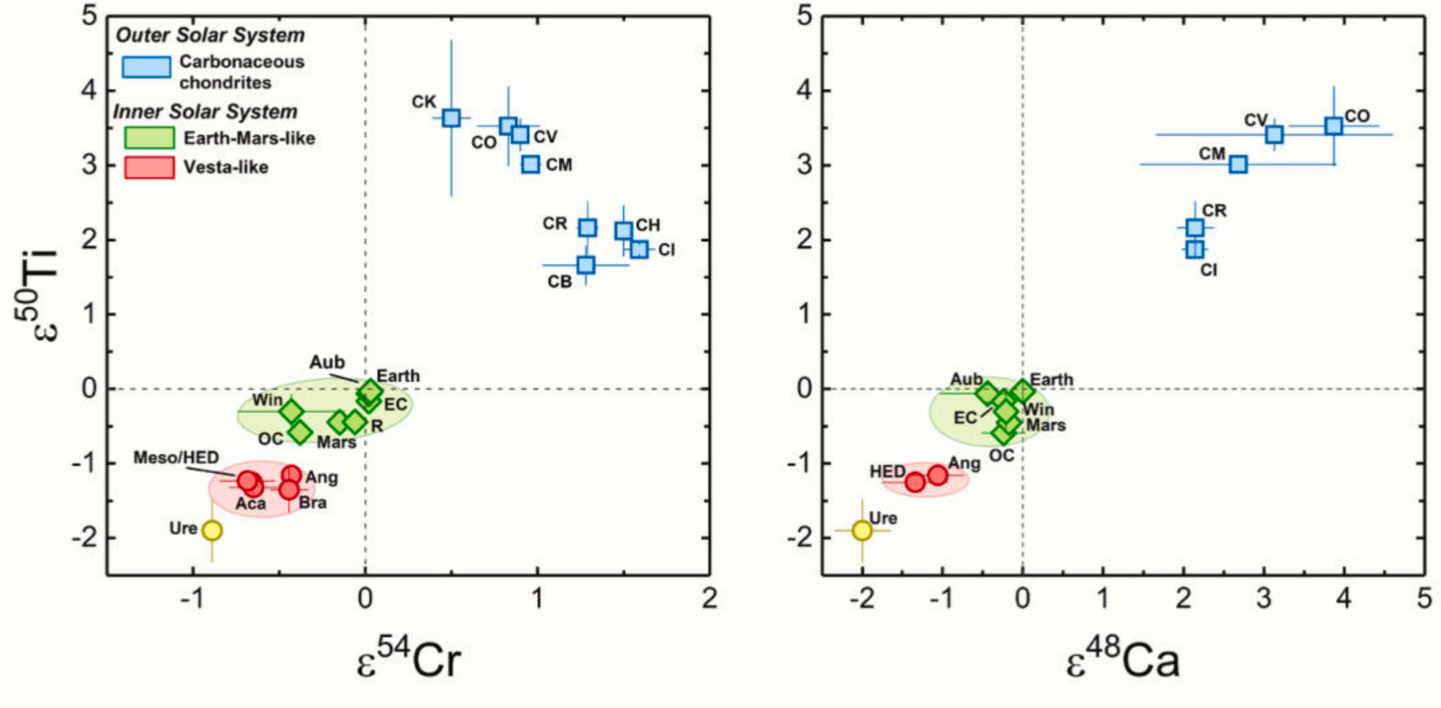
Example: Ca, Ti, Cr variations in bulk meteorites



Neutron source reaction rates, neutron-capture cross sections and decay rates needed!

Figure from Rüfenacht et al. (2023, GCA)

Example: Ca, Ti, Cr variations in bulk meteorites



Neutron source reaction rates, 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**).

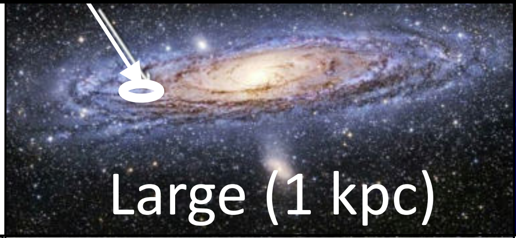
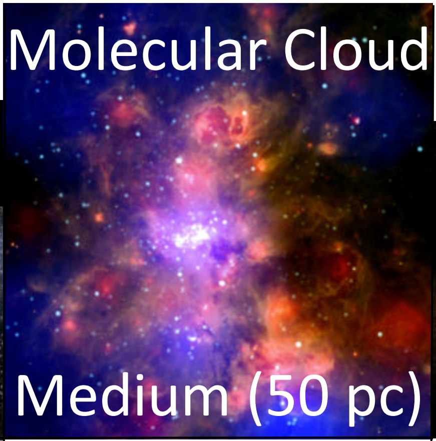
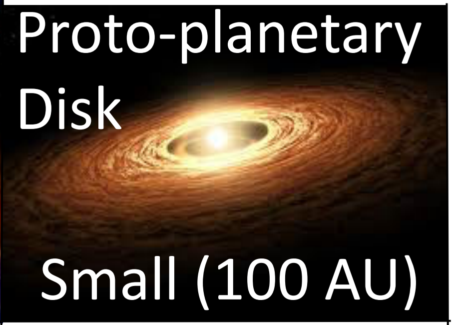
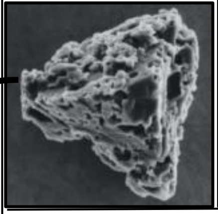
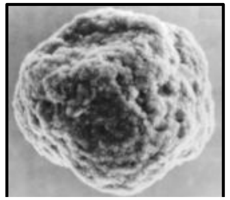
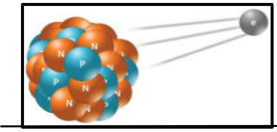
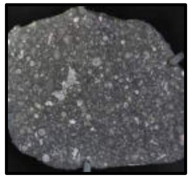
^{50}Ti: Sedyshev *et al.*, Phys. Rev. C (1999).

^{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**

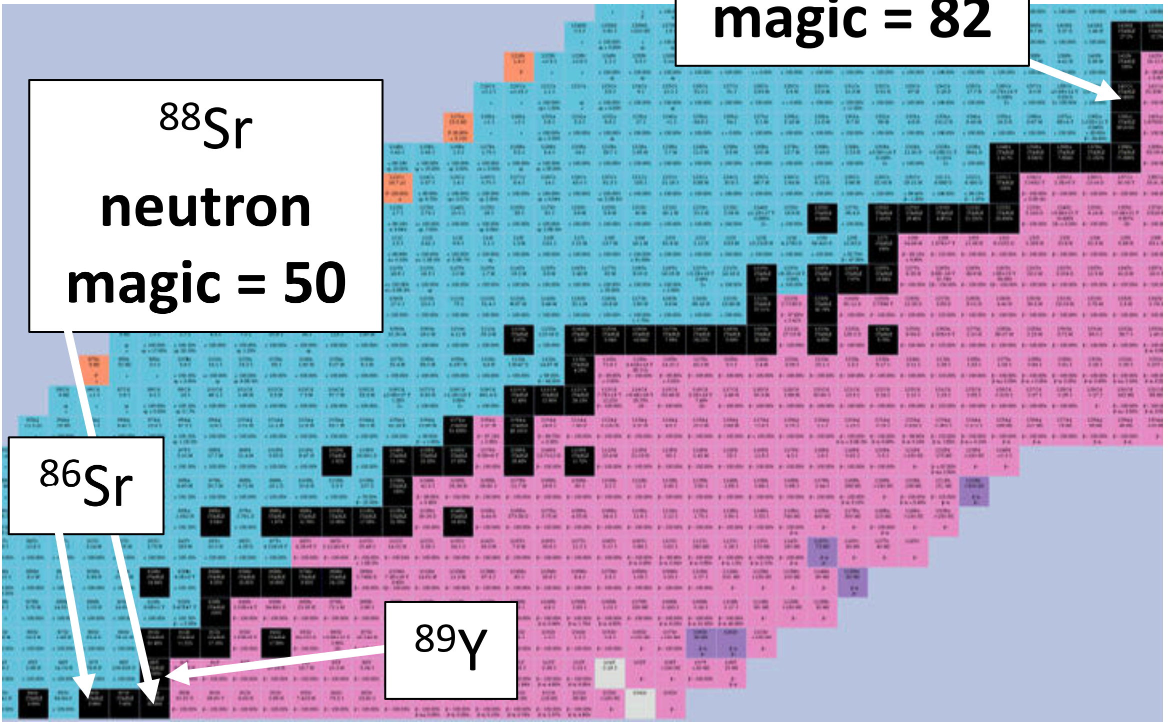
Summary of example cases

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

Thanks to all the collaborators and students!

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)

Neutron captures produce negative $\delta(^{88}Sr/^{86}Sr)$ only when [Ce/Y] is also negative!



^{140}Ce
neutron magic = 82

^{88}Sr
neutron magic = 50

^{86}Sr

^{89}Y