Radioactive nuclei from *cosmochronology* to *habitability*

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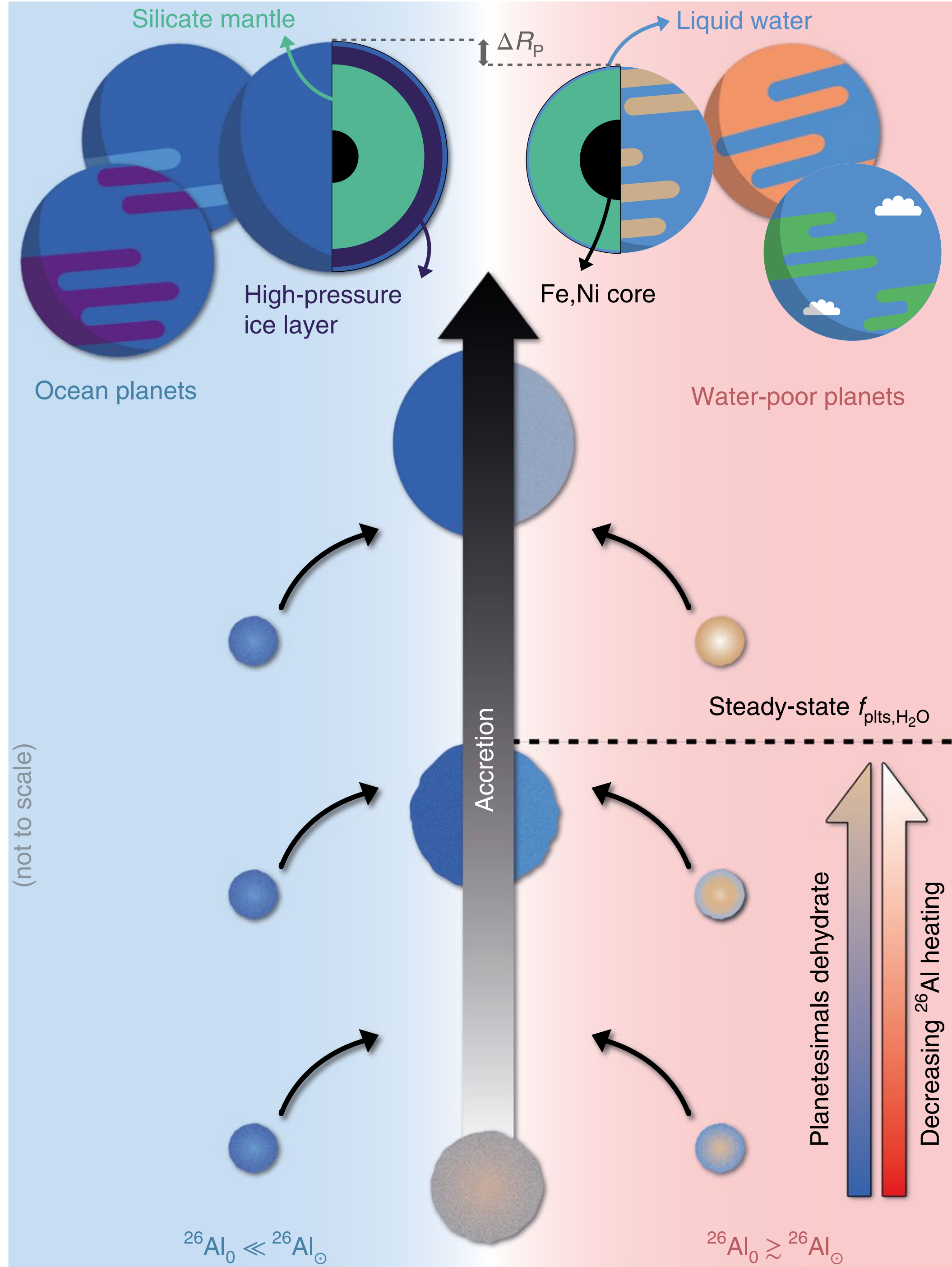
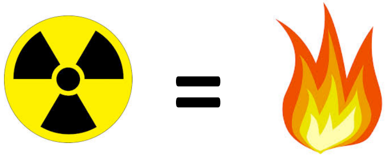
Why are radioactive nuclei important to build terrestrial habitable planets?

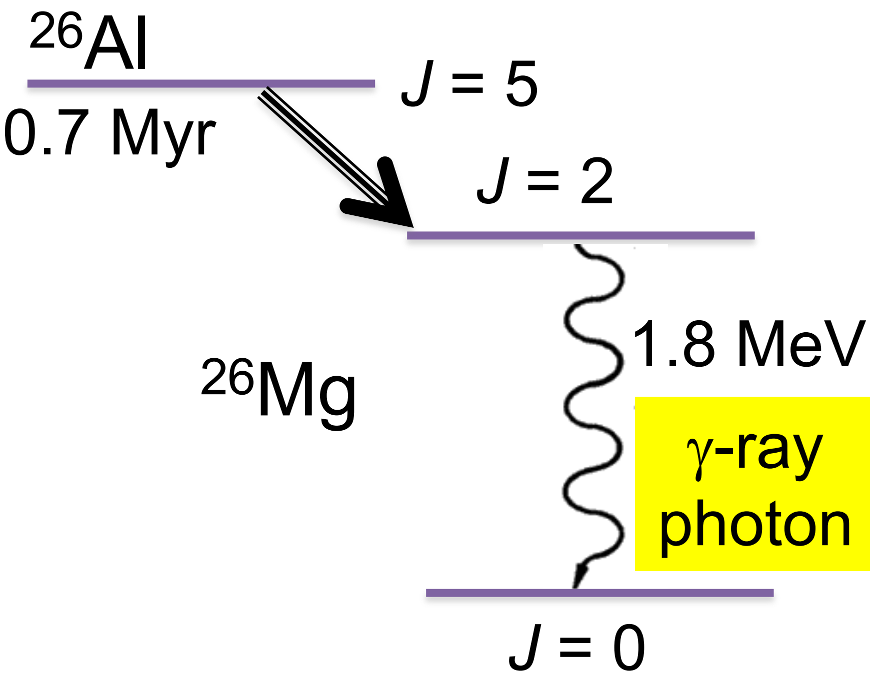
Lichtenberg et al. (2019) calculated the effect of different initial abundances in the planet building blocks of the **radioactive nucleus ^{26}Al** (half life = 0.7 Myr)

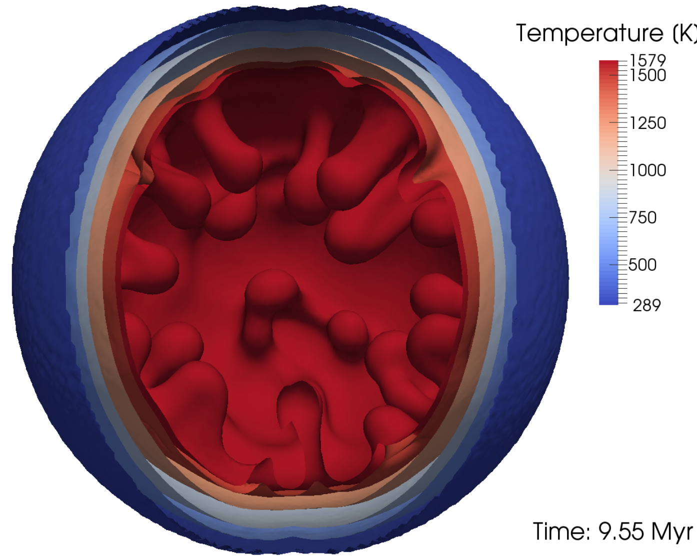
See also Ciesla et al. (2015, ApJ)



Radioactive decay can generate heat!







Lichtenberg et al. 2016 (Icarus)

The radioactive decay of ^{26}Al in the early Solar System was a main **source of heat in planetesimals**, altering their thermo-mechanical evolution and outgassing volatiles.

Where did this nucleus came from?

Are other planetary systems born rich in ^{26}Al?

Stellar origin hypotheses for the presence of ^{26}Al in the early Solar System

"LOCAL": A nearby dying star injected the radionuclides into the protosolar nebula (***early*** injection) or disk (***late*** injection)

Cameron & Truran 1977 … Hester et al. 2004 … Wasserburg et al. 2006 … Lugaro et al. 2012 … Pan et al. 2012 … Gounelle 2015 … Goodson et al. 2016

"GLOBAL": During **the evolution of the molecular cloud** many stars died within it and polluted with radionuclides the gas from which new stars formed

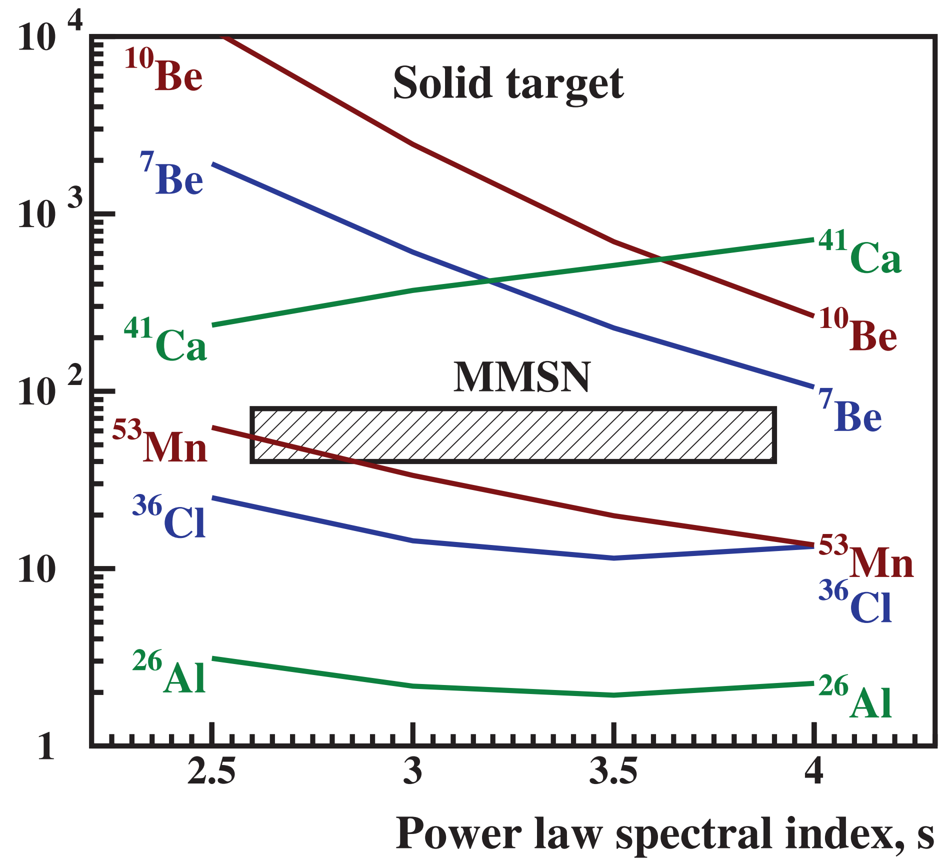
Gaidos et al. 2009 … Vasileiadis et al. 2013 … Young 2014, 2016 … Kuffmeier et al. 2016

Solar origin hypotheses for the presence of ^{26}Al in the early Solar System (see next talk)

Basic idea: fast protons and ^{3}He can interact with material and produce ^{26}Al (non-thermal *spallation* reactions). E.g., Lee et al. (1998) , Jacquet et al. (2019), Gaches et al. (2020, next talk).

General main problems:

1. The maximum mass of chondritic material bearing ^{26}Al (in Earth masses) is always well below the total number needed to cover the rocky component of the minimum-mass solar nebula (MMSN), Duprat & Tatischeff (2007).
2. There is co-production of other radioactive isotopes: significative production of ^{26}Al leads to an overproduction of ^{10}Be (e.g., Sossi et al 2017)



Stellar origin hypotheses for the presence of ^{26}Al in the early Solar System

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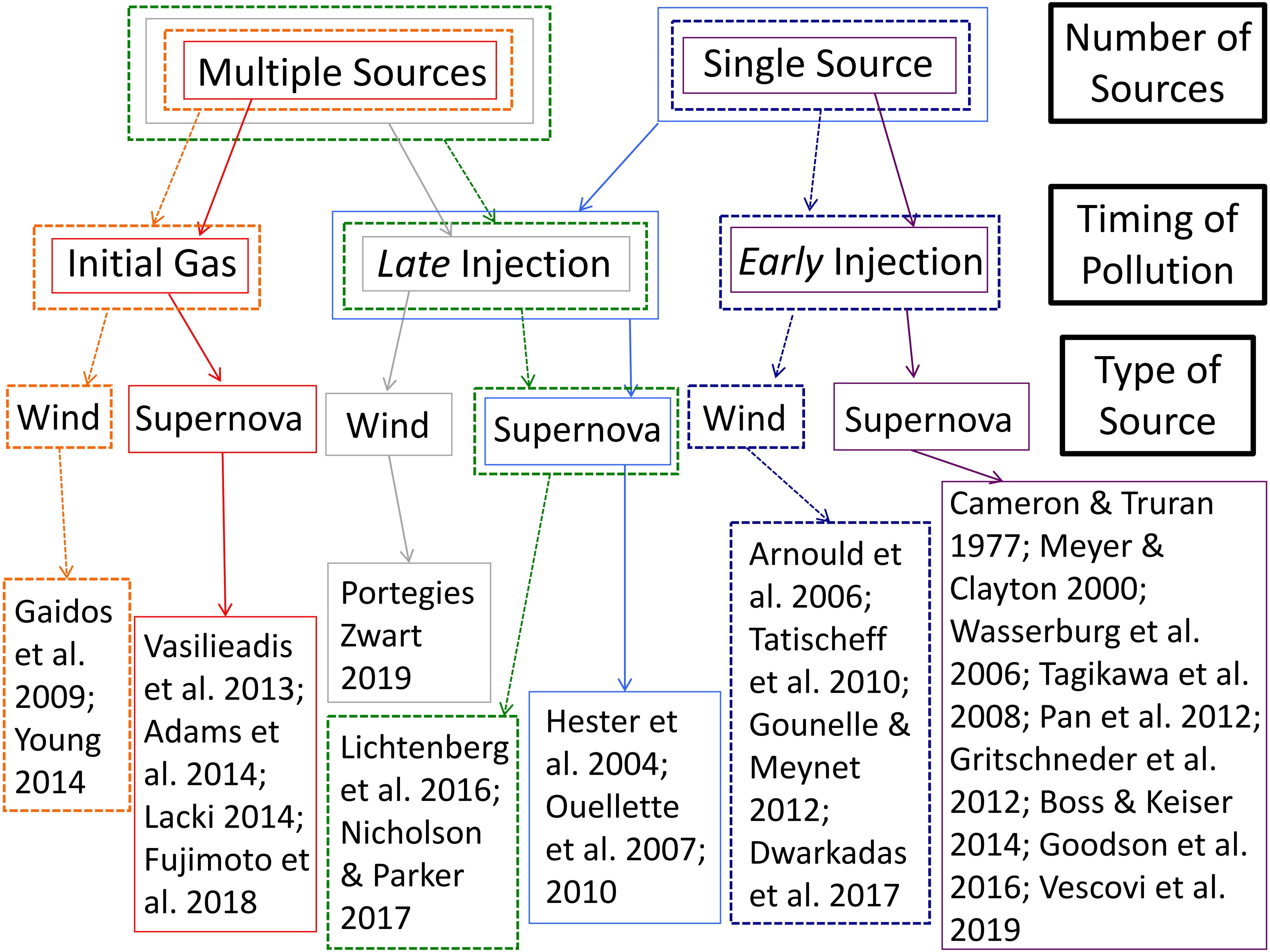
Multiple Sources
Single Source
Number of Sources
Initial Gas
Late Injection
Early Injection
Timing of Pollution
Wind
Supernova
Wind
Supernova
Wind
Supernova
Type of Source
Gaidos et al. 2009; Young 2014
Vasilieadis et al. 2013; Adams et al. 2014; Lacki 2014; Fujimoto et al. 2018
Portegies Zwart 2019
Lichtenberg et al. 2016; Nicholson & Parker 2017
Hester et al. 2004; Ouellette et al. 2007; 2010
Arnould et al. 2006; Tatischeff et al. 2010; Gounelle & Meynet 2012; Dwarkadas et al. 2017
Cameron & Truran 1977; Meyer & Clayton 2000; Wasserburg et al. 2006; Tagikawa et al. 2008; Pan et al. 2012; Gritschneder et al. 2012; Boss & Keiser 2014; Goodson et al. 2016; Vescovi et al. 2019

Multiple Sources

Single Source

Number of Sources

Initia

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ource

Wind

No consensus on a more than 40-year-old question!

Each of these scenario will come with a different answer to the question if ***are other planetary systems born rich in ^{26}Al?***

Gaidos et al. 2009; Young 2014

Lacki 2014; Fujimoto et al. 2018

Nicholson & Parker 2017

Ouellette et al. 2007; 2010

2012; Dwarkadas et al. 2017

Truran
&
;
et al.
wa et al.
al. 2012;
et al.
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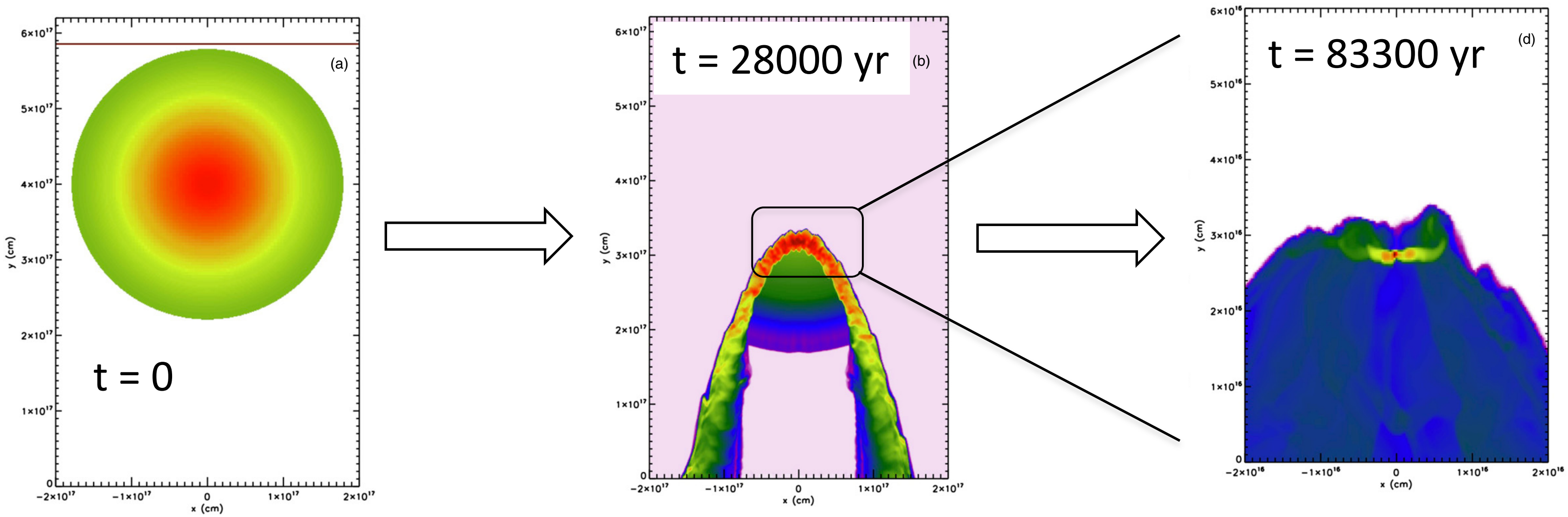
Examples of the local scenario:

One single supernova triggering the collapse of the presolar cloud core and injecting material with a shock wave

(Alan Boss et al. series of many papers, see also Gritschneder et al. 2012)



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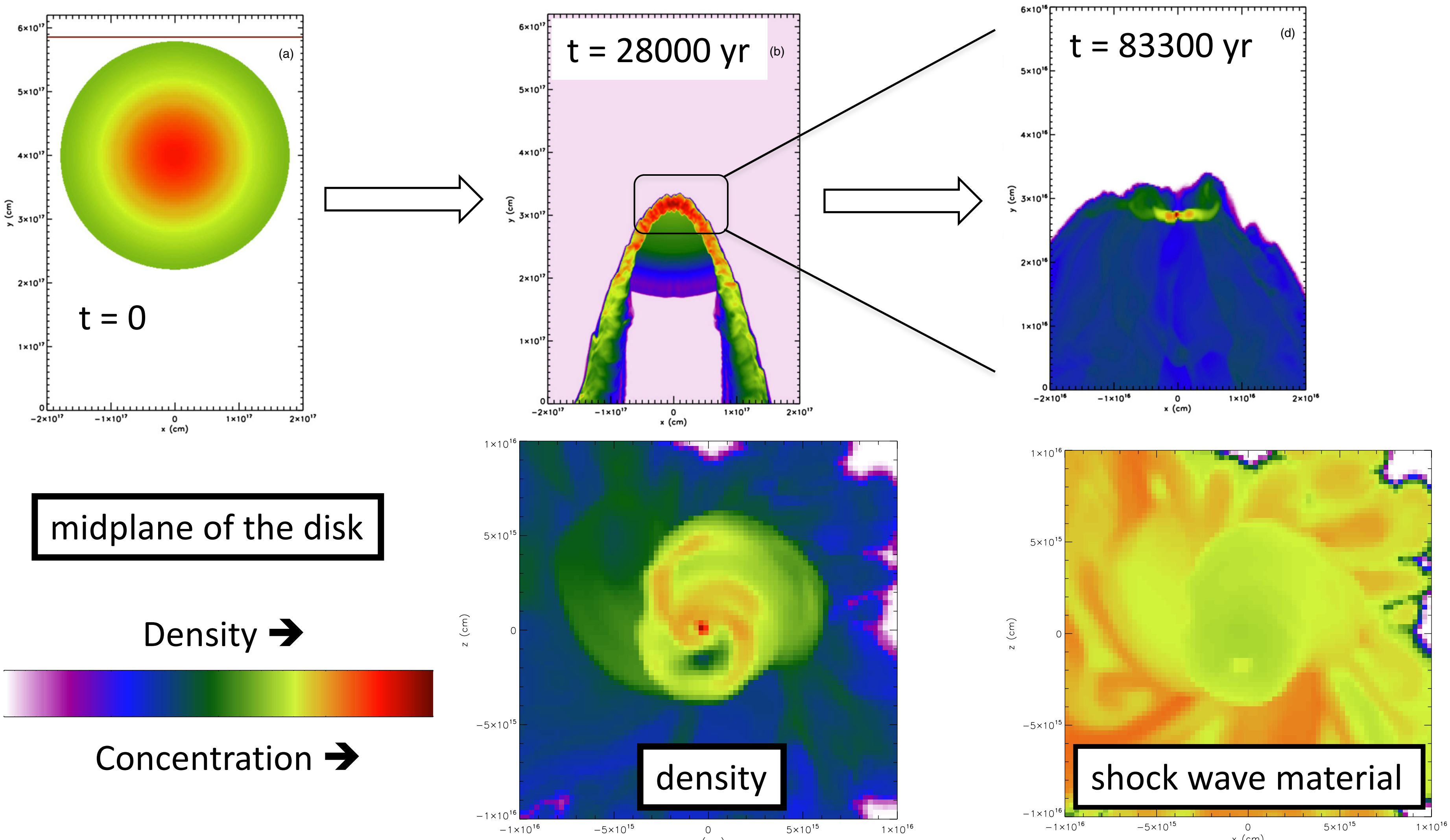
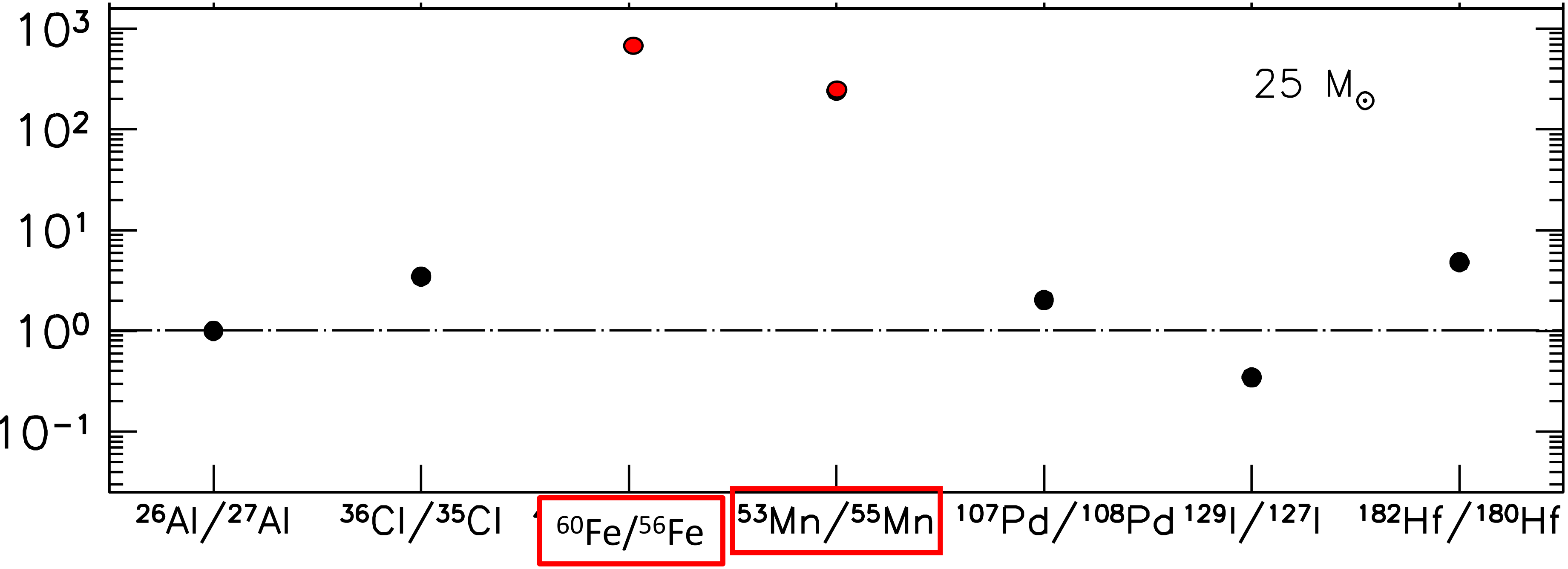


The general problem with supernovae:

They do not produce short-lived radionuclides in the proportion needed to reproduce their observed abundances in the early Solar System (typically…)

Predicted ratio / early Solar System ratio, normalised such as =1 for $^{26}Al/^{27}Al$



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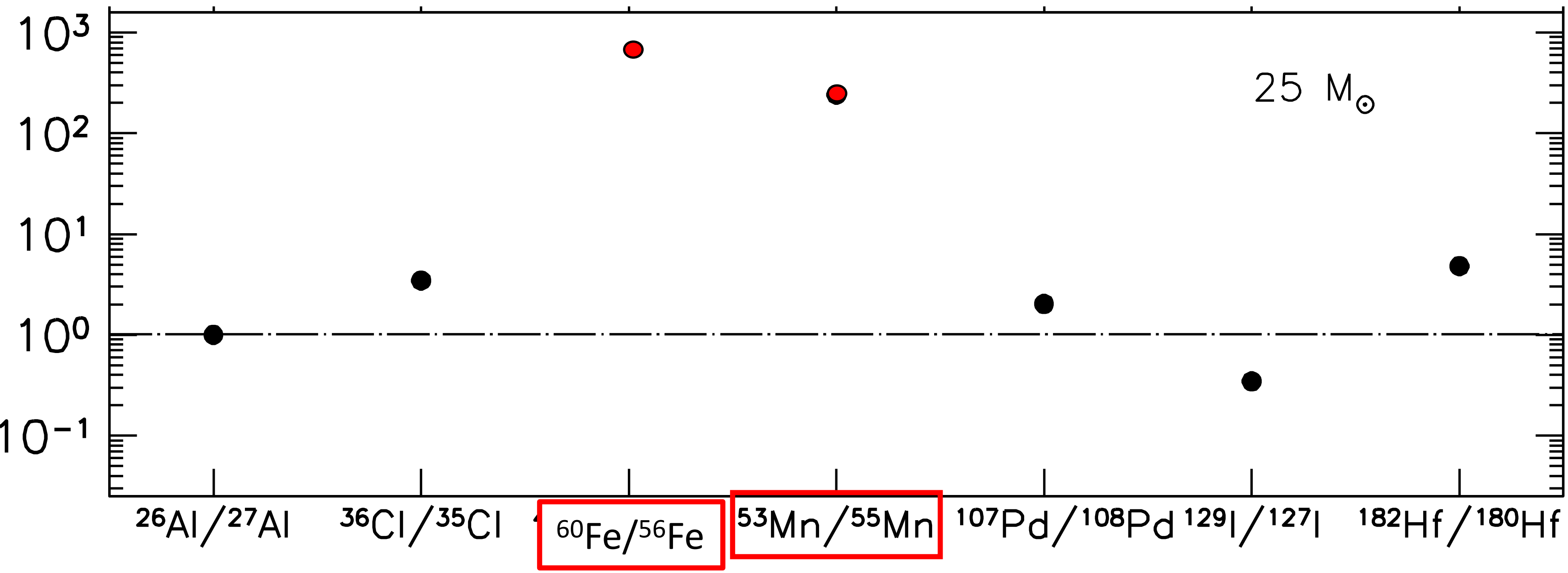
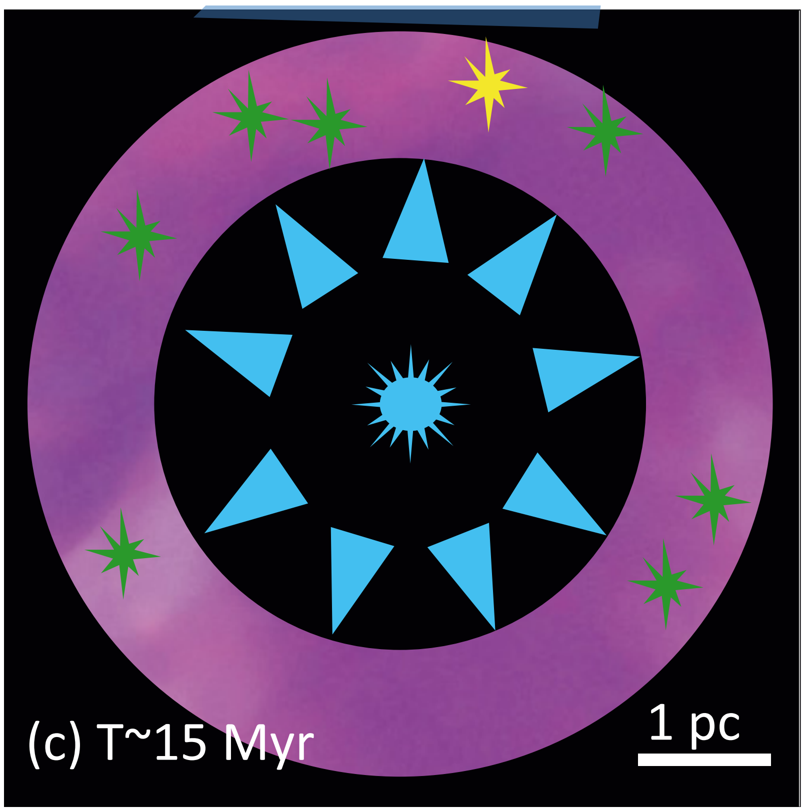


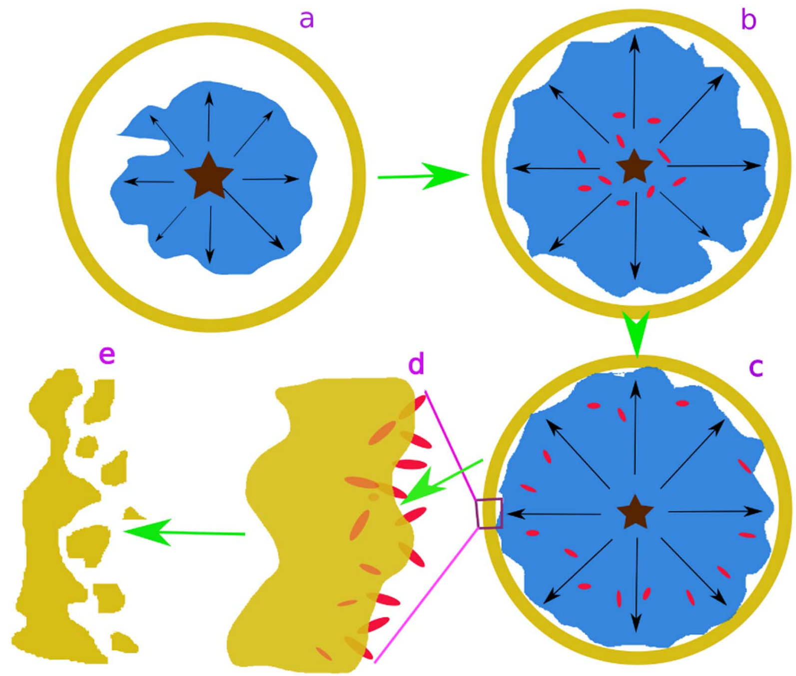
This is why people have turned to Wolf-Rayet stars winds, i.e., massive star winds, because these eject ^{26}Al but no ^{53}Mn and ^{60}Fe

Examples of the local scenario:

Birth of the Sun in the circumstellar dense shell produced by the interaction of the winds of a Wolf-Rayet star and the molecular cloud gas

(Gounelle & Meynet 2012, see also Dwarkadas et al. 2017)





Not modelled how to inject the shell material in the early Solar System material

Examples of the global scenario:

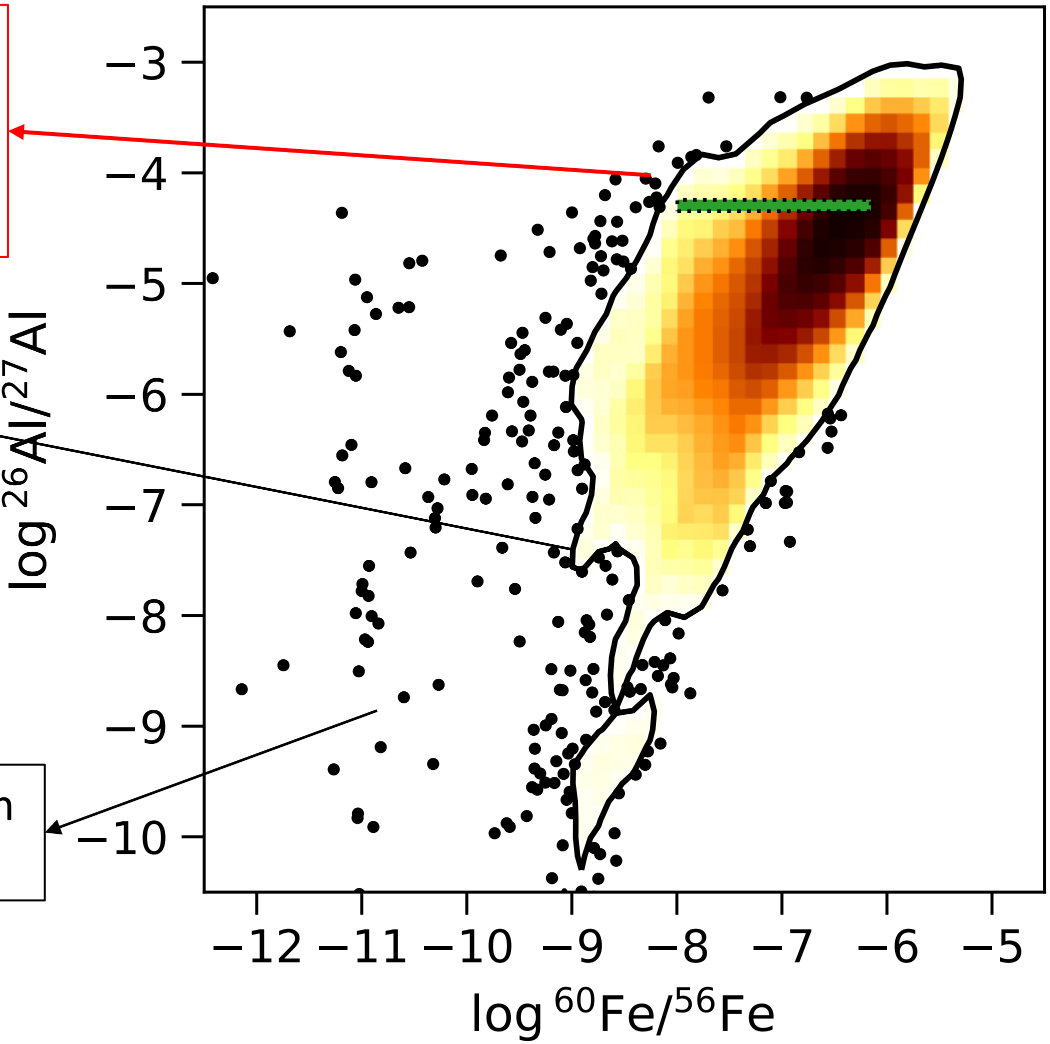
Evolution of ^{26}Al and ^{60}Fe in the galactic interstellar medium from high-resolution chemohydrodynamical simulations

(Fujimoto et al. 2018)

Early Solar System values, adjusted by me to account for the latest results and a correct normalization of the supernova yields

Probability density contour of newly formed stars

Individual newly formed stars in sparse regions



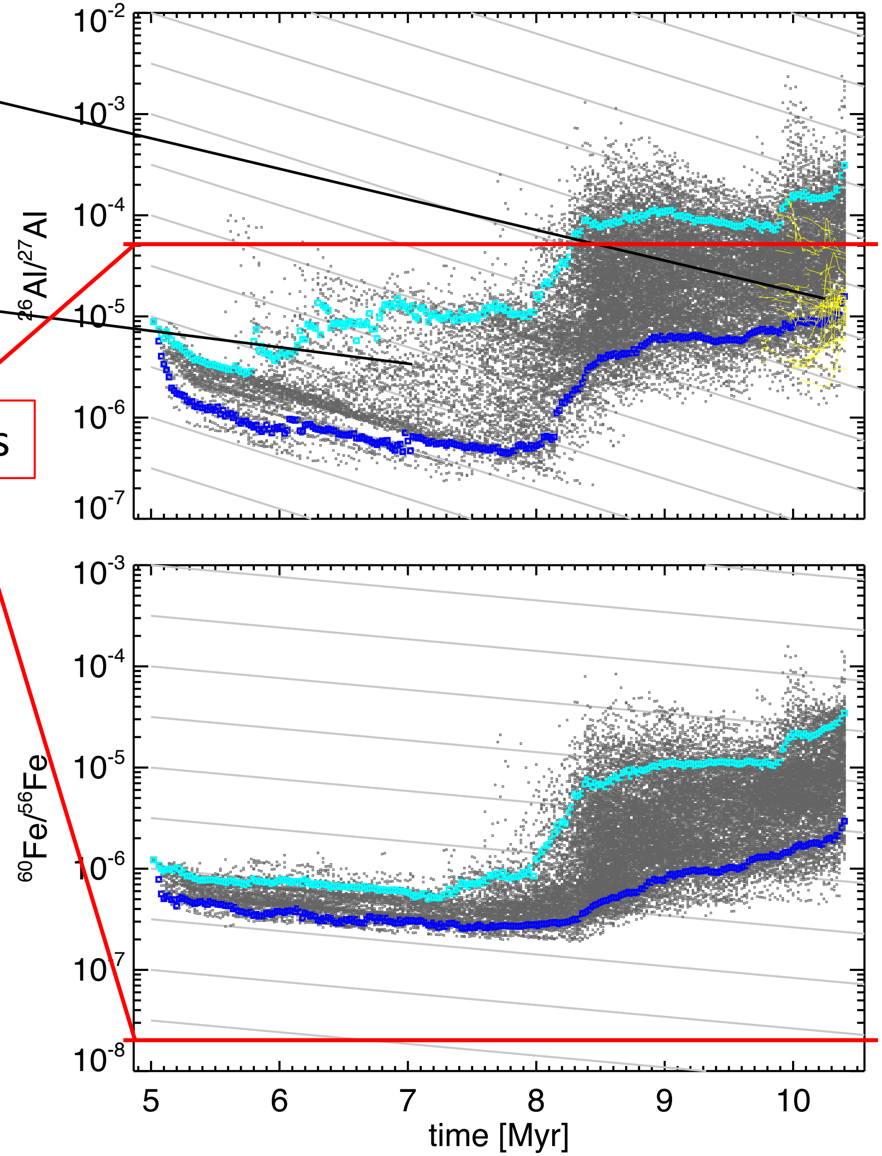
Examples of the global scenario:

Abundance of ^{26}Al and ^{60}Fe in evolving giant molecular clouds from high-resolution RAMSES simulations (Vasilieadis et al. 2013)

Yellow: Gas accreting to sink particles (individual stars)

Grey: Dense star-forming clumps

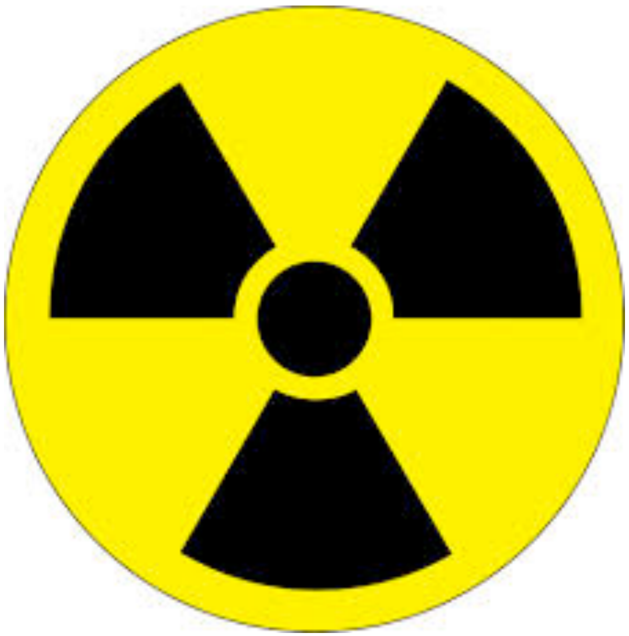
Early Solar System values



The usual supernova problem of making too much ^{60}Fe!

We need one special supernova for the local scenario (e.g., Takigawa et al. 2008) or we need to get rid of supernovae in the global scenario (e.g., Gaidos et al. 2009, Young 2014)

What can I do about this problem? ***Cosmochronology!***



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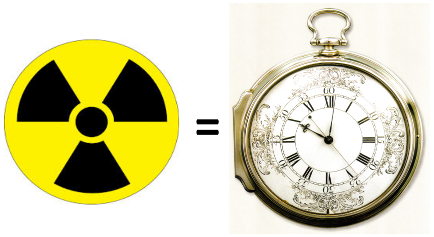
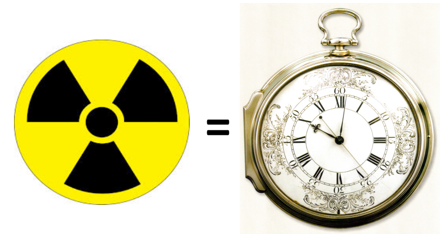
Isotope	τ (Myr)	Reference isotope	Initial Solar System ratio
^{247}Cm	22.5	^{235}U	$(5.6 \pm 0.3) \times 10^{-5}$ (5%)
^{244}Pu	80	^{238}U	$(7 \pm 1) \times 10^{-3}$ (14%)
^{182}Hf	13	^{180}Hf	$(1.018 \pm 0.043) \times 10^{-4}$ (4%)
^{146}Sm	98 or 149	^{146}Sm	$(8.28 \pm 0.44) \times 10^{-3}$ (5%)
^{129}I	23	^{127}I	$(1.28 \pm 0.03) \times 10^{-4}$ (2%)
^{107}Pd	9.4	^{108}Pd	$(6.6 \pm 0.4) \times 10^{-5}$ (6%)
^{92}Nb	50	^{92}Mo	$(3.33 \pm 0.68) \times 10^{-5}$ (20%)
^{53}Mn	5.3	^{55}Mn	$(6.28 \pm 0.66) \times 10^{-6}$ (10%)
^{60}Fe	3.8	^{56}Fe	$(1.01 \pm 0.27) \times 10^{-8}$ (26%)
^{26}Al	1.03	^{27}Al	$(5.23 \pm 0.13) \times 10^{-5}$ (2.5%)

Etc etc …

What time do we want to measure?



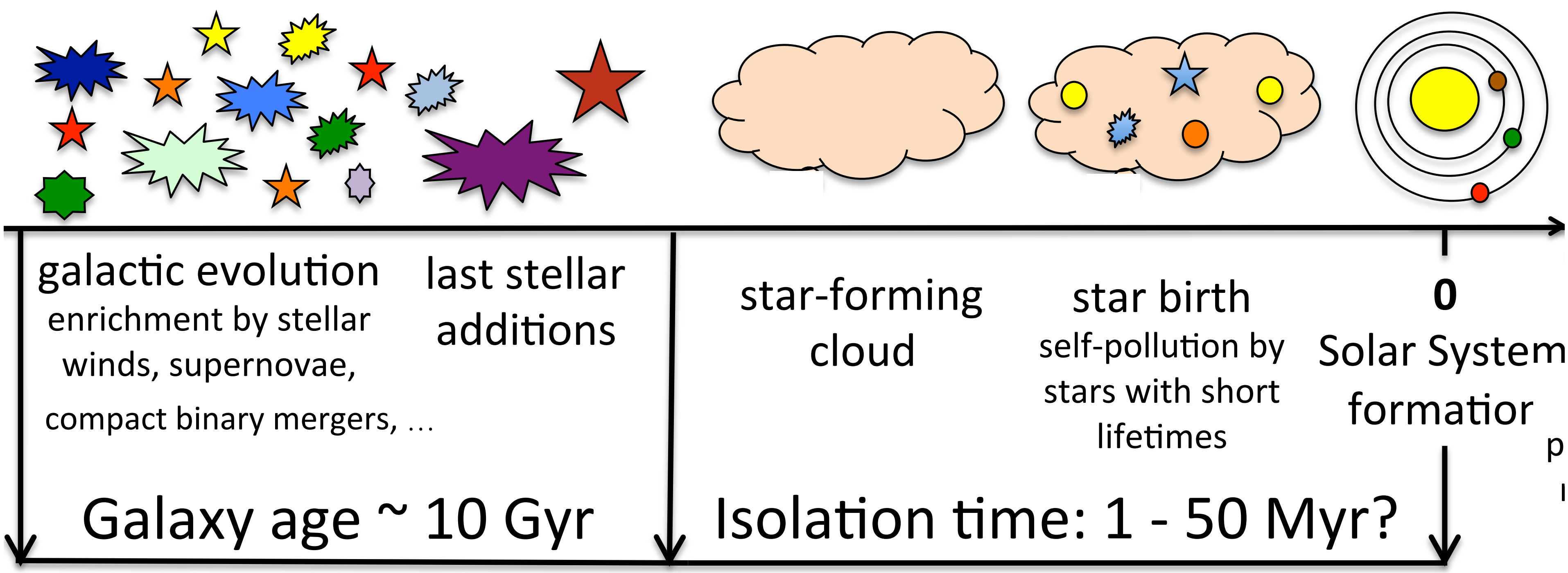
What time do we want to measure?



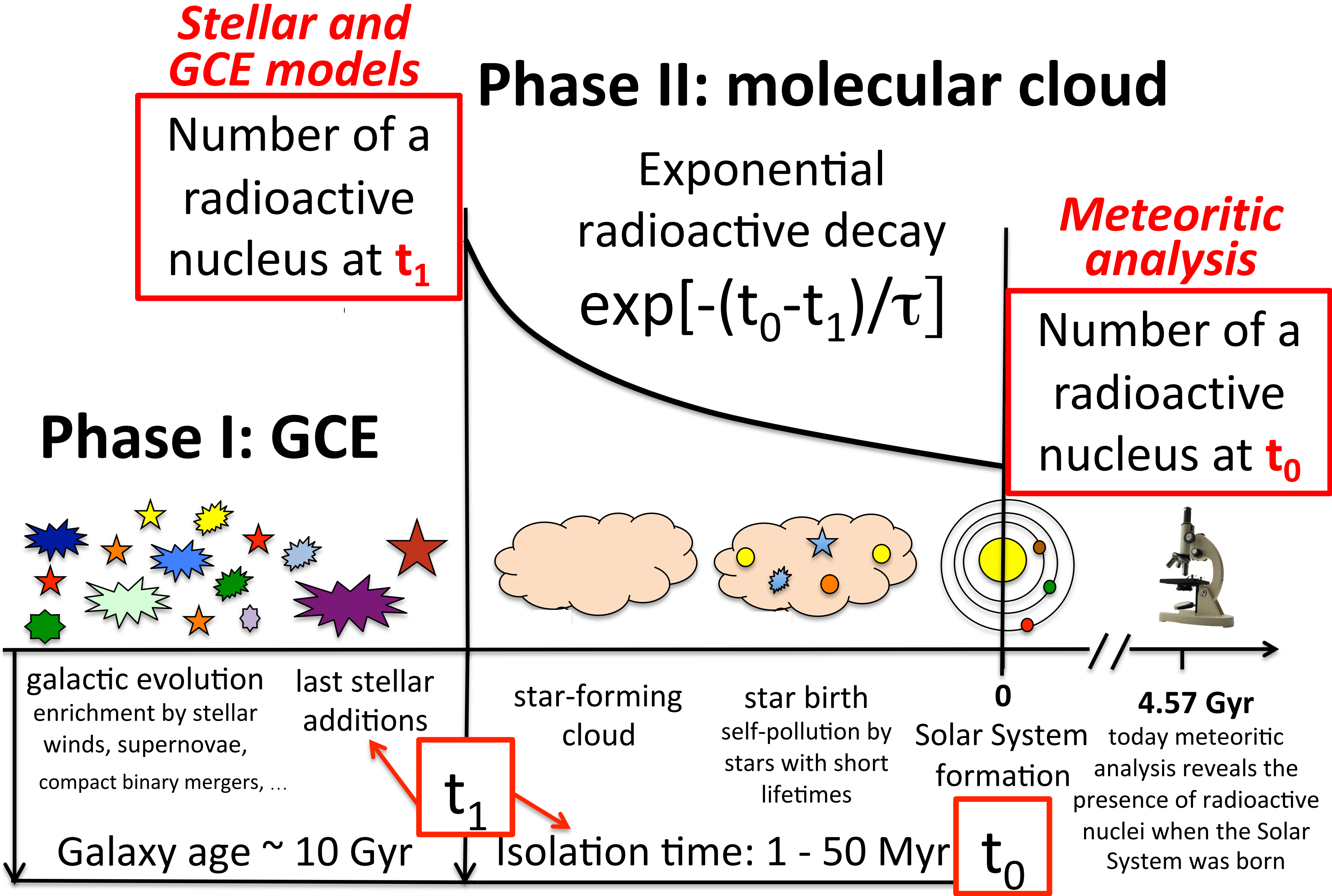
Galactic Chemical Evolution

Phase I: GCE

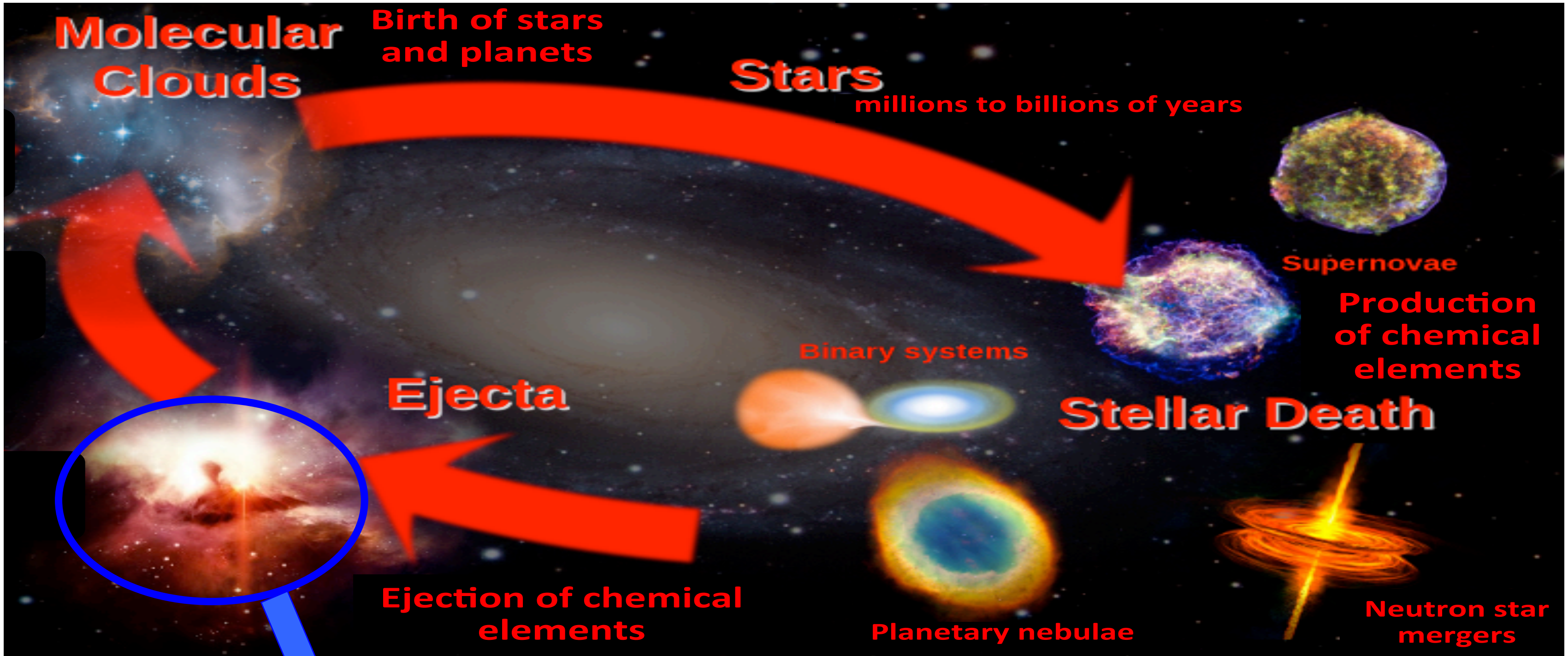
Phase II: molecular cloud

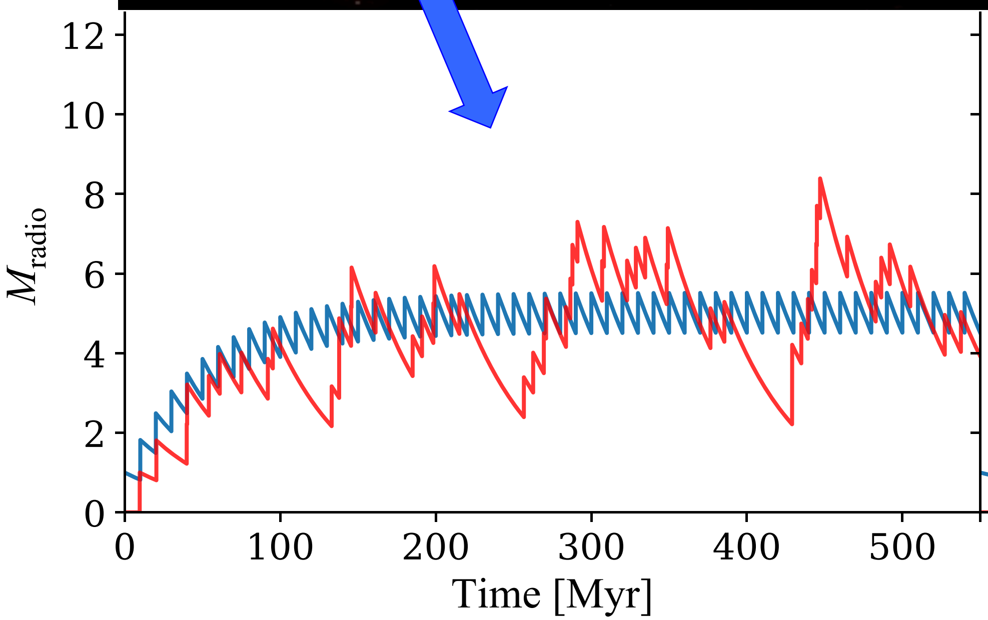


How to use radioactive decay to measure time



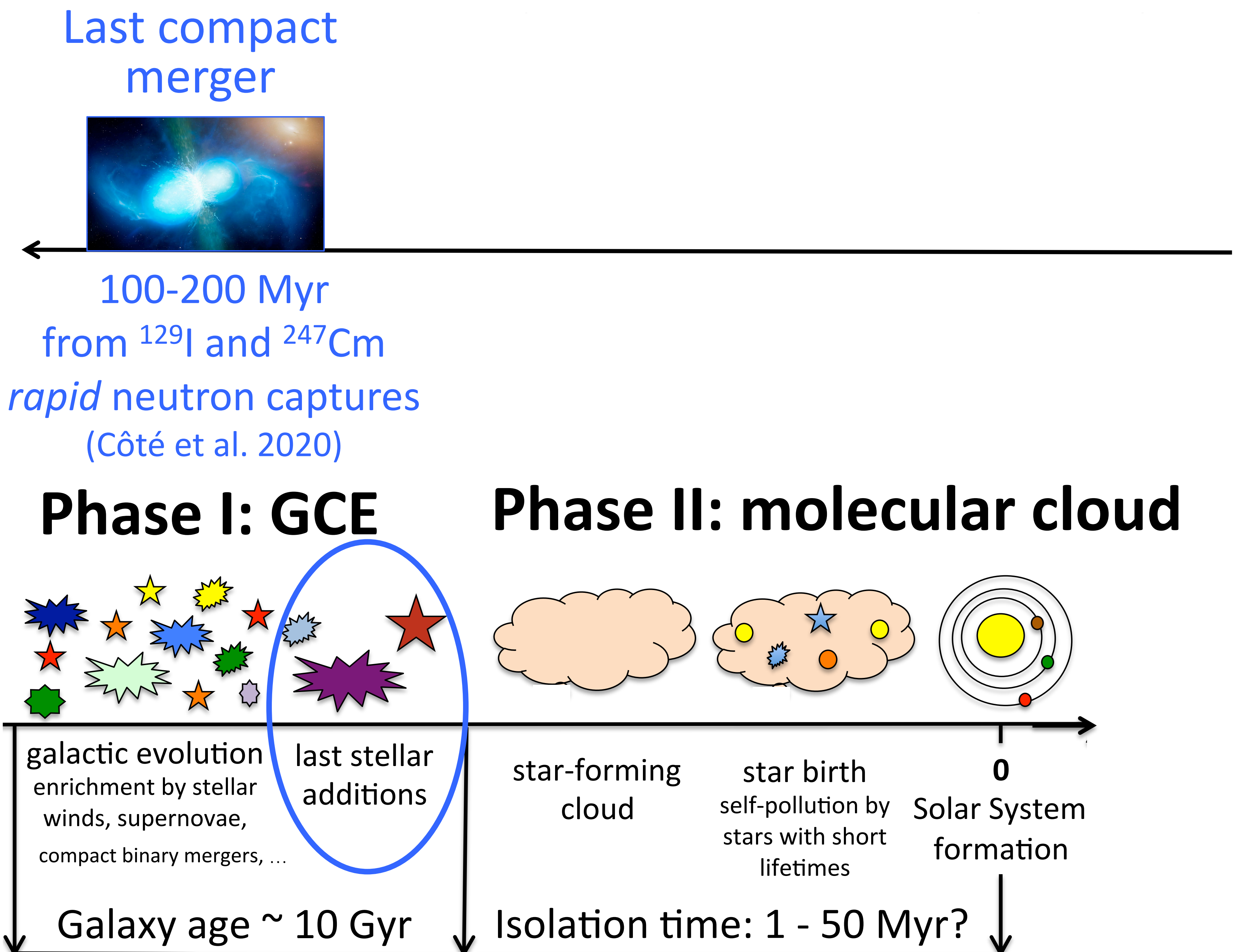
Phase I: Chemical Evolution of the Milky Way Galaxy



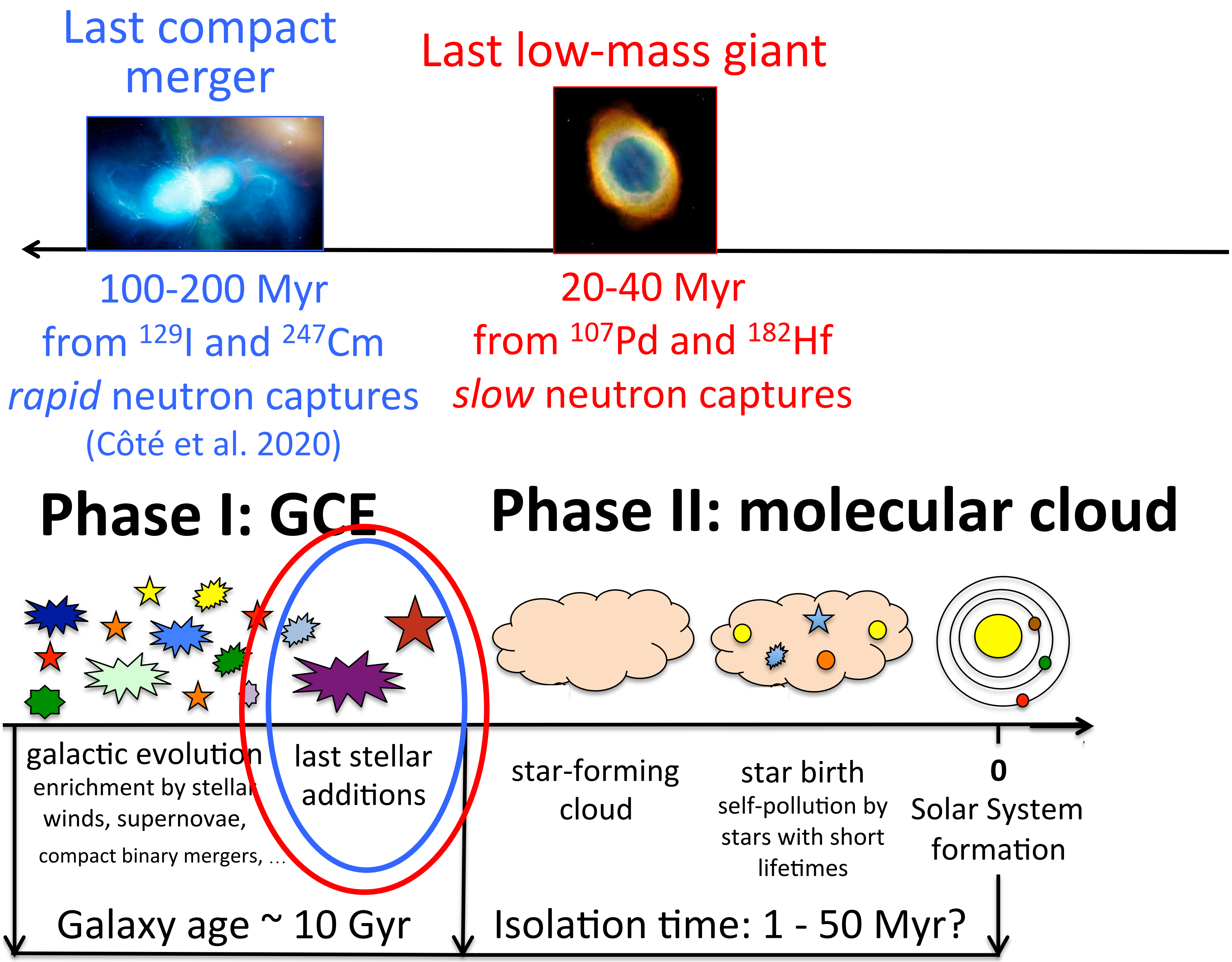


Evolution of the mass of a radioactive nucleus in a ***inhomogenous*** interstellar medium. We need statistical methods.

Côté, Lugaro et al. 2019, ApJ
Cote, Yagüe, Világos, Lugaro 2019, ApJ



Last compact merger
100-200 Myr
from ^{129}I and ^{247}Cm
rapid neutron captures
(Côté et al. 2020)
Phase I: GCE
Phase II: molecular cloud
galactic evolution
enrichment by stellar winds, supernovae,
compact binary mergers, …
last stellar additions
star-forming cloud
star birth
self-pollution by stars with short lifetimes
0
Solar System formation
Galaxy age ~ 10 Gyr
Isolation time: 1 - 50 Myr?



Last compact merger
Last low-mass giant
100-200 Myr
from ^{129}I and ^{247}Cm
rapid neutron captures
(Côté et al. 2020)
20-40 Myr
from ^{107}Pd and ^{182}Hf
slow neutron captures
Phase I: GCE
Phase II: molecular cloud
galactic evolution
enrichment by stellar winds, supernovae, compact binary mergers, …
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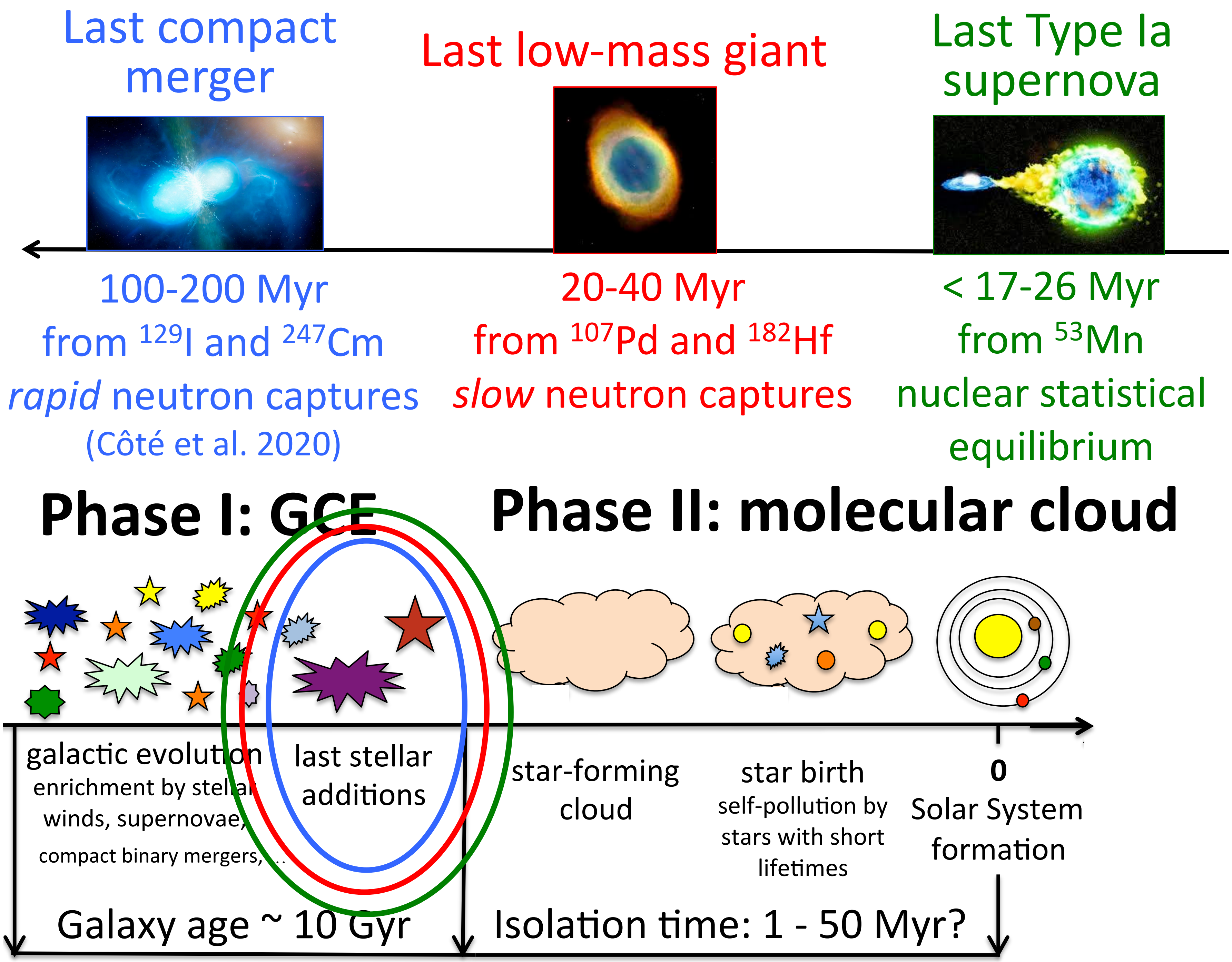
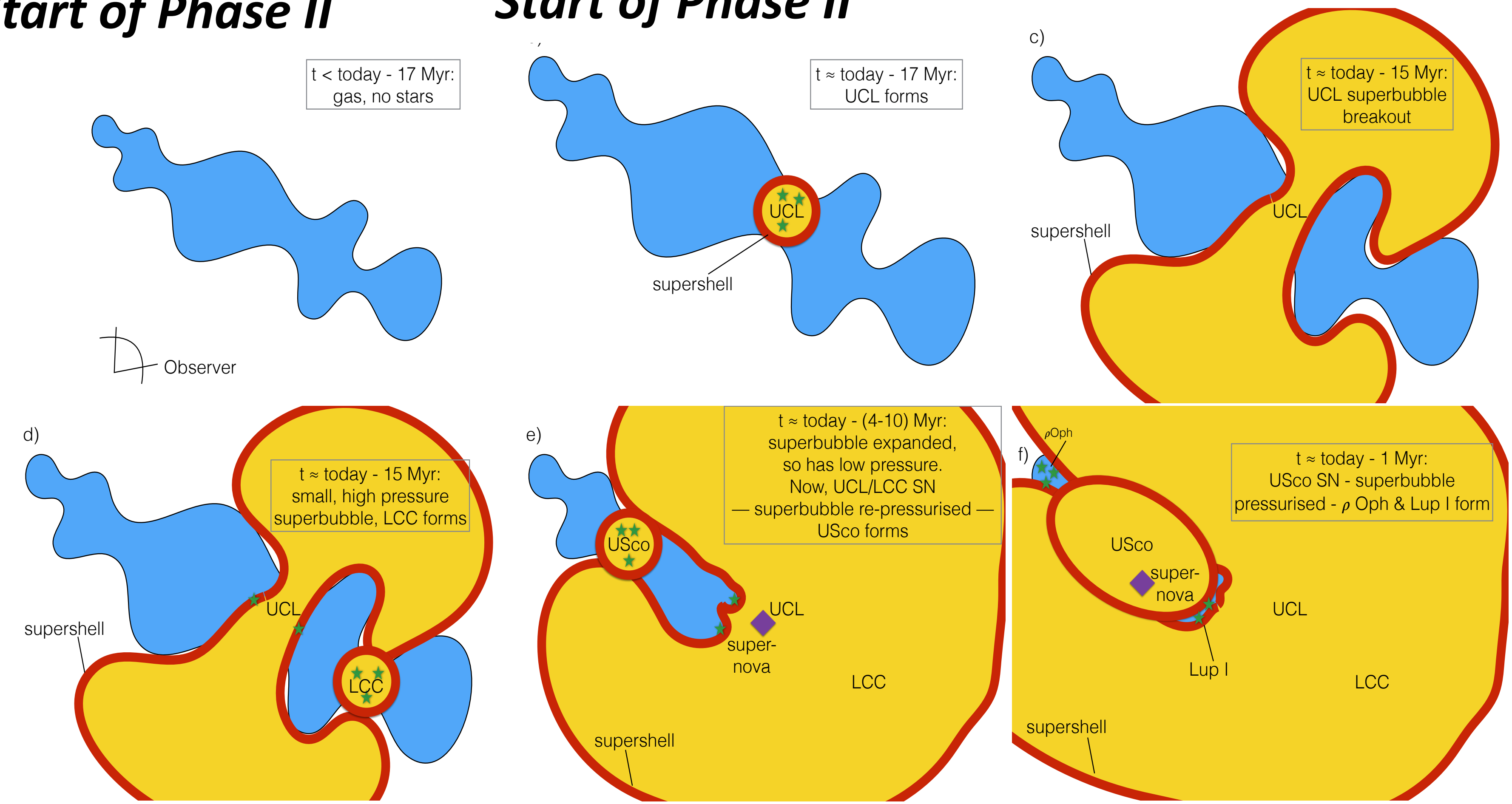


Last compact merger
Last low-mass giant
Last Type Ia supernova
100-200 Myr
from ^{129}I and ^{247}Cm
rapid neutron captures
(Côté et al. 2020)
20-40 Myr
from ^{107}Pd and ^{182}Hf
slow neutron captures
< 17-26 Myr
from ^{53}Mn
nuclear statistical equilibrium
Phase I: GCE
Phase II: molecular cloud
galactic evolution
enrichment by stellar winds, supernovae, compact binary mergers, ...
last stellar additions
star-forming cloud
star birth
self-pollution by stars with short lifetimes
0
Solar System formation
Galaxy age ~ 10 Gyr
Isolation time: 1 - 50 Myr?

Characterising the timescale of Phase II

e.g. Scorpius Centaurus OB2 (Krause et al. 2018, A&A)

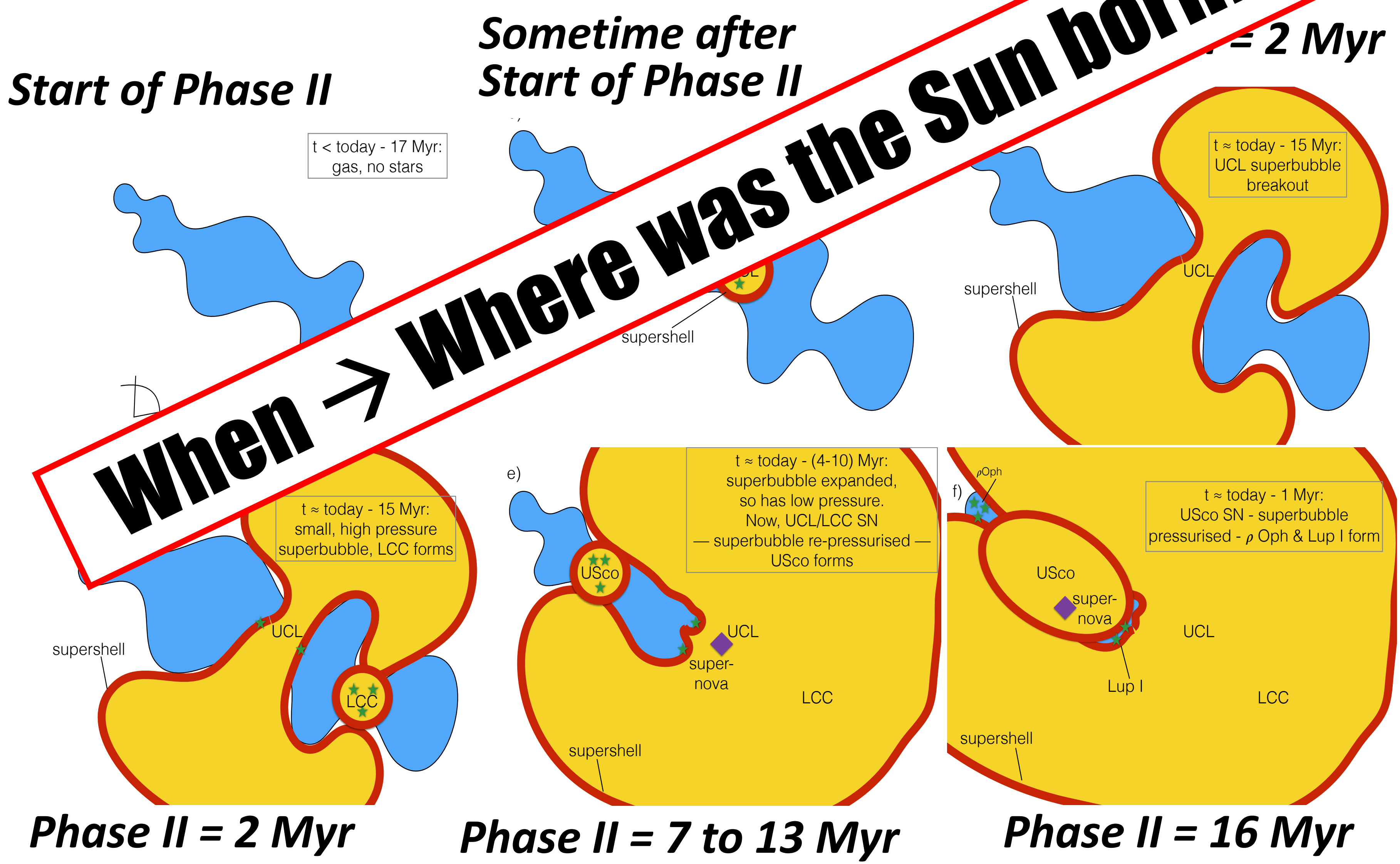
Start of Phase II | ***Sometime after Start of Phase II*** | ***Phase II = 2 Myr***



Phase II = 2 Myr | ***Phase II = 7 to 13 Myr*** | ***Phase II = 16 Myr***

Characterising the timescale of Phase II

e.g. Scorpius Centaurus OB2 (Krause et al. 20 A)



Take-away messages:

- There is **no consensus** on the origin of the radioactive heat source ^{26}Al in the early Solar System and we do not know if other planetary systems are also born rich in ^{26}Al.
- But, we can use other radionuclides to investigate **the environment of the Sun's birth and therefore the origin of ^{26}Al** by measuring how long the presolar matter spent inside a molecular cloud before the formation of the Sun.
- To address all these question **stellar nucleosynthesis** is the core knowledge and detailed models of **the *radioactive* evolution of the Milky Way** are needed

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