Origin of Short-lived Radio nuclides in the Early Solar System

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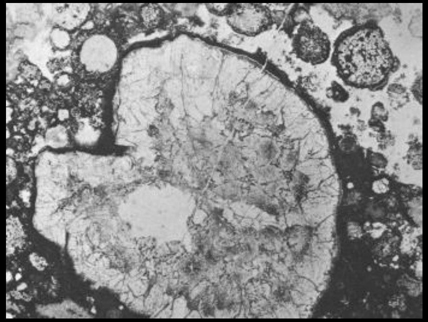
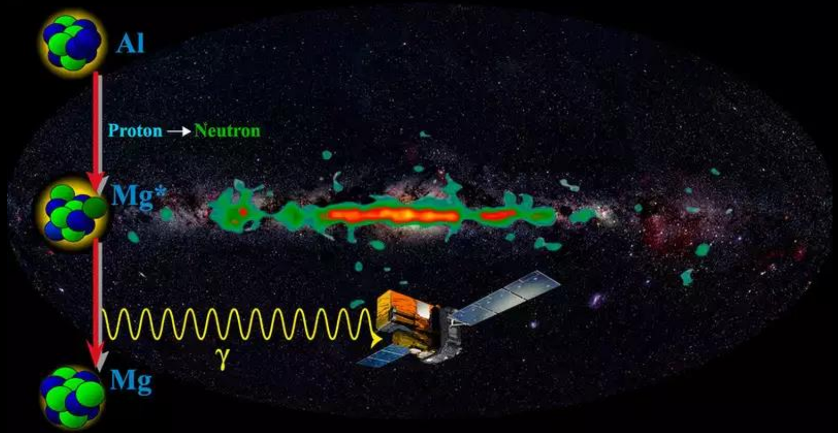




Contents

Introduction to Galactic Chemical evolution (GCE) models

- Homogeneous GCE models
- Predicted Star formation rate and Supernova rates in the galaxy
- Abundance of Short-lived radionuclides(SLRs) ^{26}Al, ^{41}Ca, ^{36}Cl, ^{53}Mn and ^{60}Fe in the Galaxy

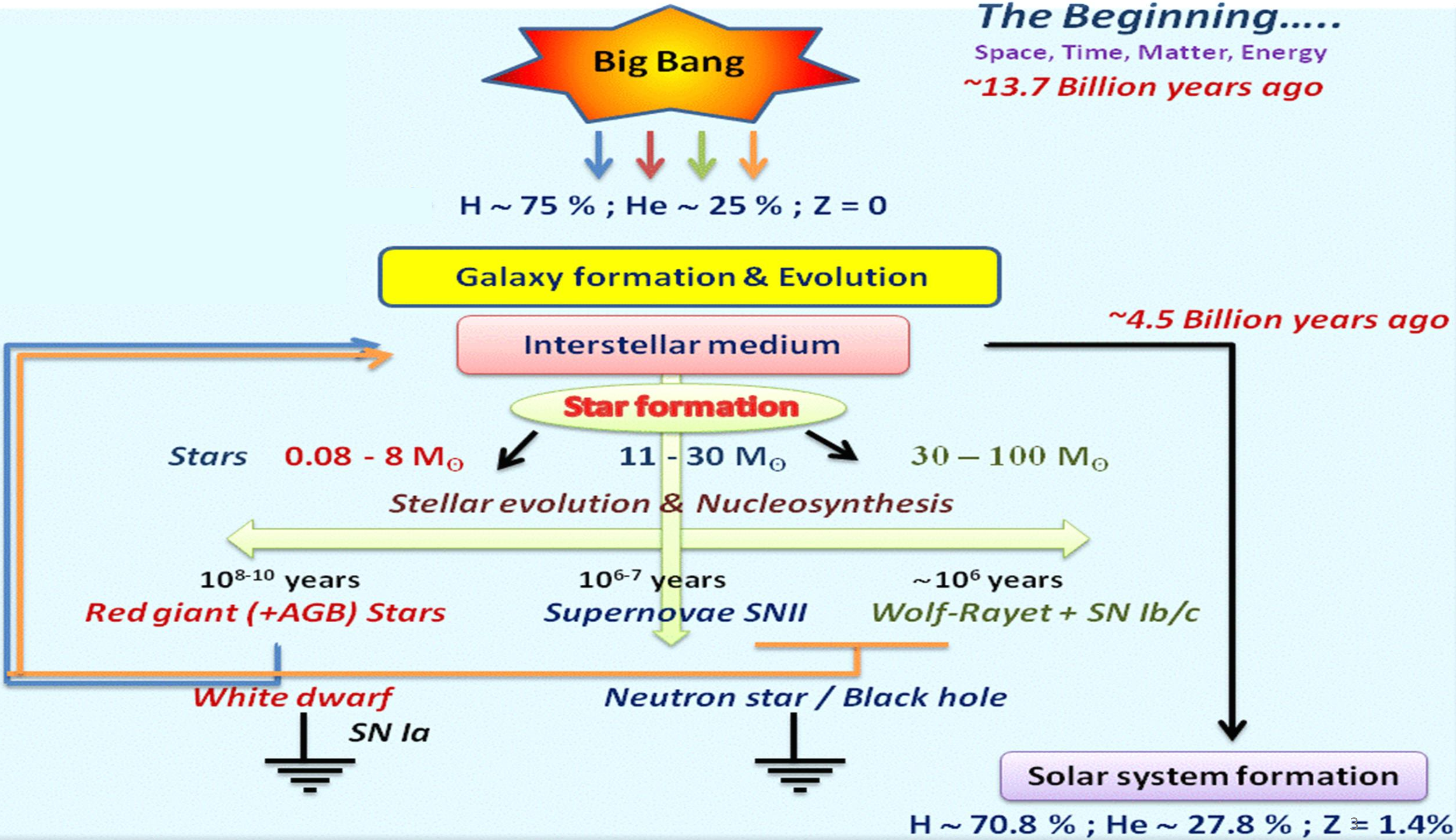
Astrophysical Origin of SLRs in Early Solar System

- Heterogeneous GCE model for the solar neighborhood

The Beginning…..

Space, Time, Matter, Energy

~13.7 Billion years ago



Big Bang

H ~ 75 % ; He ~ 25 % ; Z = 0

Galaxy formation & Evolution

~4.5 Billion years ago

Interstellar medium

Star formation

Stars $0.08 - 8\ M_\odot$ $11 - 30\ M_\odot$ $30 - 100\ M_\odot$

Stellar evolution & Nucleosynthesis

10^{8-10} years 10^{6-7} years $\sim 10^{6}$ years

Red giant (+AGB) Stars *Supernovae SNII* *Wolf-Rayet + SN Ib/c*

White dwarf *Neutron star / Black hole*

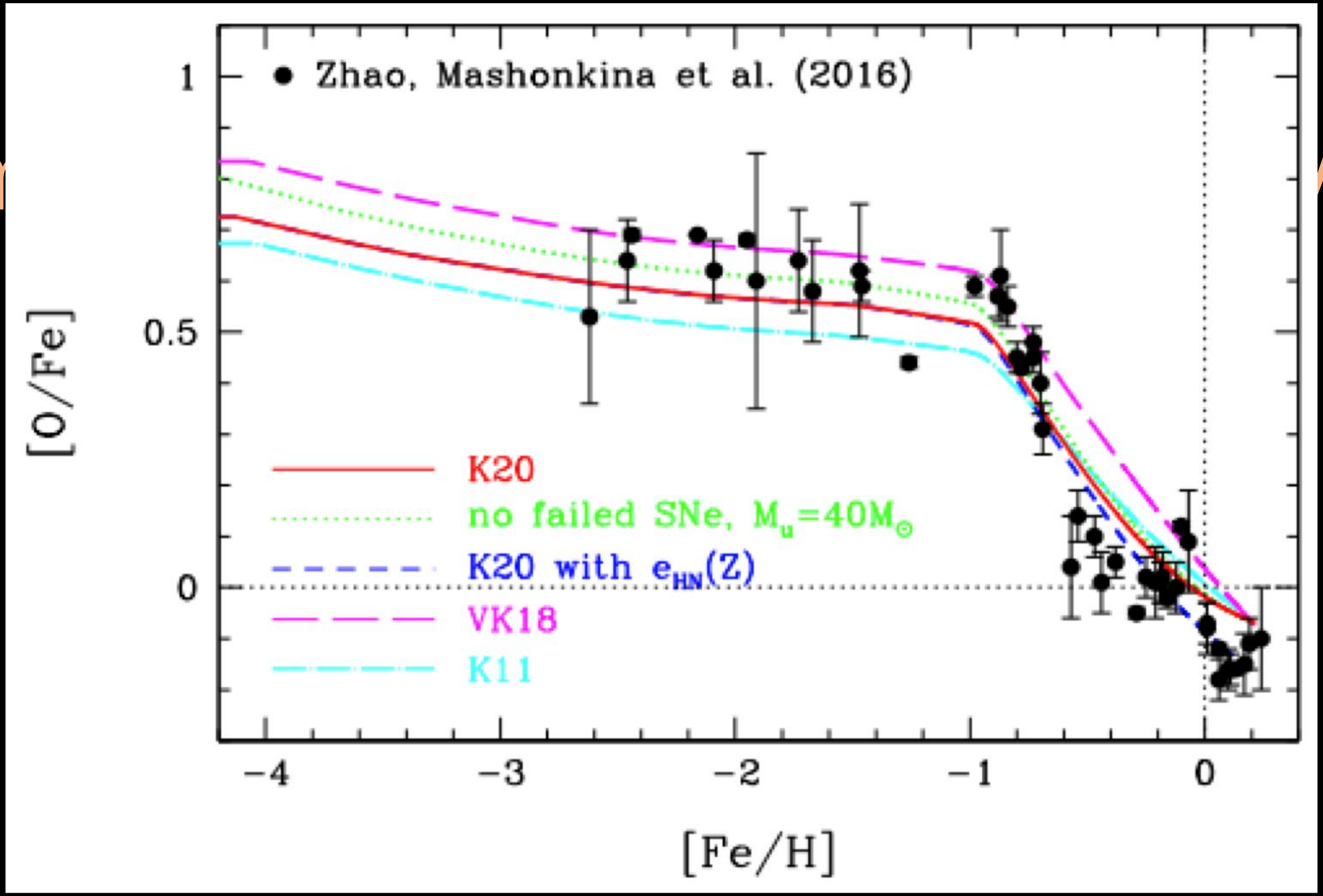
SN Ia

Solar system formation

H ~ 70.8 % ; He ~ 27.8 % ; Z = 1.4%

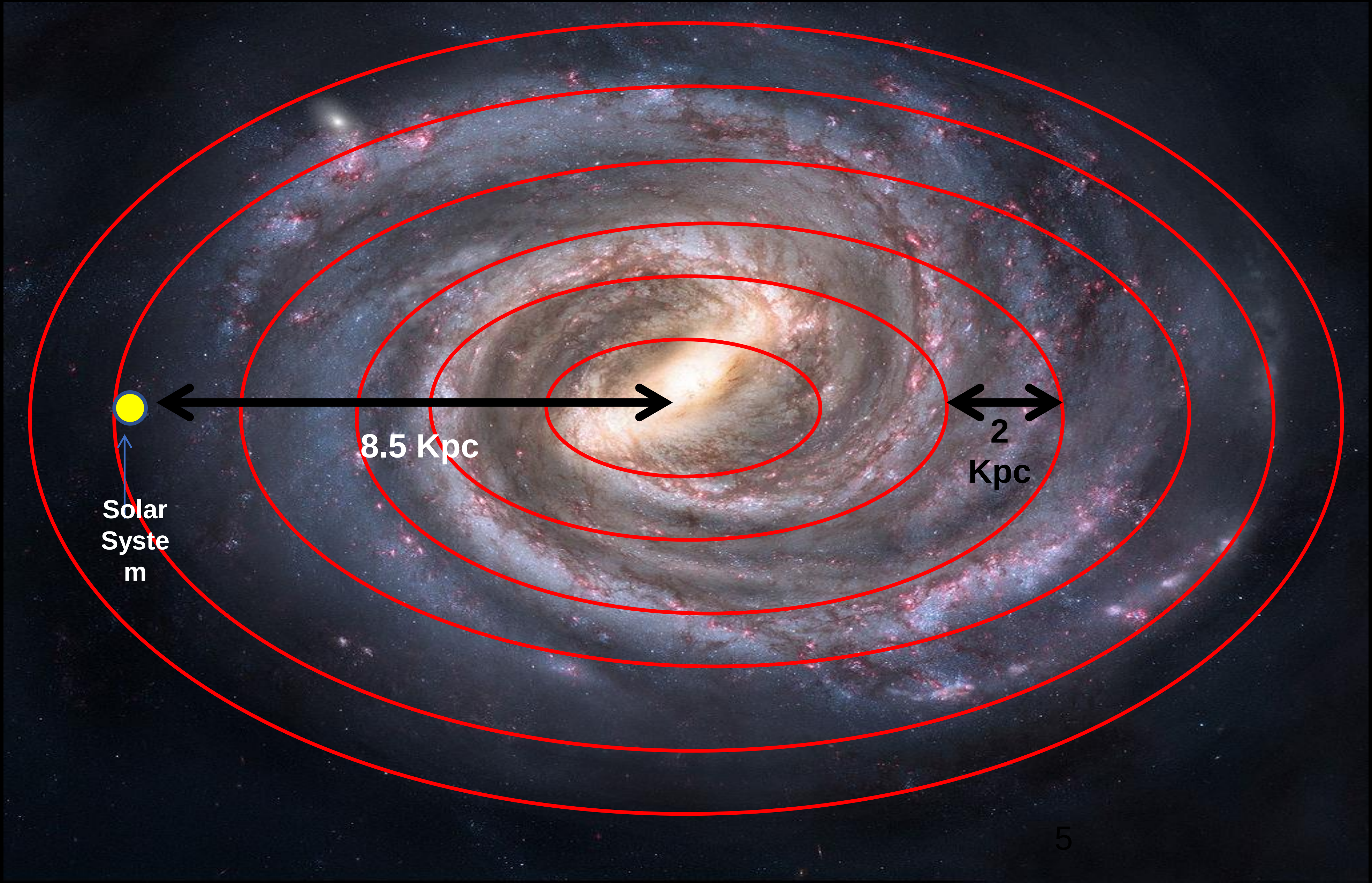
Why is GCE important to study Short-lived Radio nuclides?

❑ To m ystem



Kobayashi et al. 2020

Modelling Approach



Gas accretion models

Different types of infall mechanism have been studied in several models to explore the accretion growth of the Galaxy. Most of the successful models use simple *exponentially decreasing* infall rates.

1. Two-infall

$$\frac{d\sigma(r,t)}{dt} = A(r)e^{-(t/t_T)} + B(r)\,e^{-((t-t_{max})/t_D)}$$

Where

$$A(r) = \frac{\sigma_T(r,t_G)}{t_T(1 - e^{-t_G/t_T})}$$

$$B(r) = \frac{\sigma(r,t_G) - \sigma_T(r,t_G)}{t_D(1 - e^{-((t-t_{max})/t_D)})}$$

'Inside-out' scenario

$$t_D(r) = 1.033\left(\frac{r}{kpc}\right) - 1.267\ \mathrm{Gyr}$$

Chiappini et al. 1997

2. Three-infall

$$\frac{d\sigma(r,t)}{dt} = A(r)e^{-(t/t_H)} + B(r)e^{-((t-t_{maxH})/t_T)} + C(r)e^{-((t-t_{maxT})/t_D)}$$

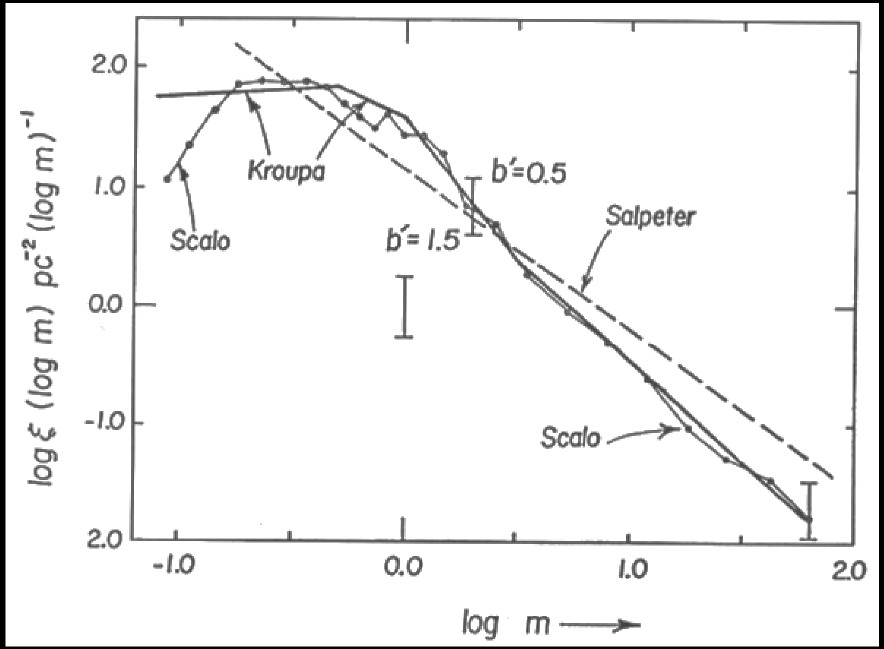
Micali et al. 2013

Stellar Birth Rate Functions

Initial mass Function (IMF)

$$\varphi_n(m) = Am^{-(1+x)}$$

Scalo 1986, 1998



From Pagel 1997, "NucJeosynthesis and Chemical Evolution of Galaxies"

The stellar population evolution of the 0.8, 1, and 1.25 $M_\odot$ is monitored over the Galactic evolution to understand the G-dwarf metallicity distribution.

Star Formation Rate (SFR)

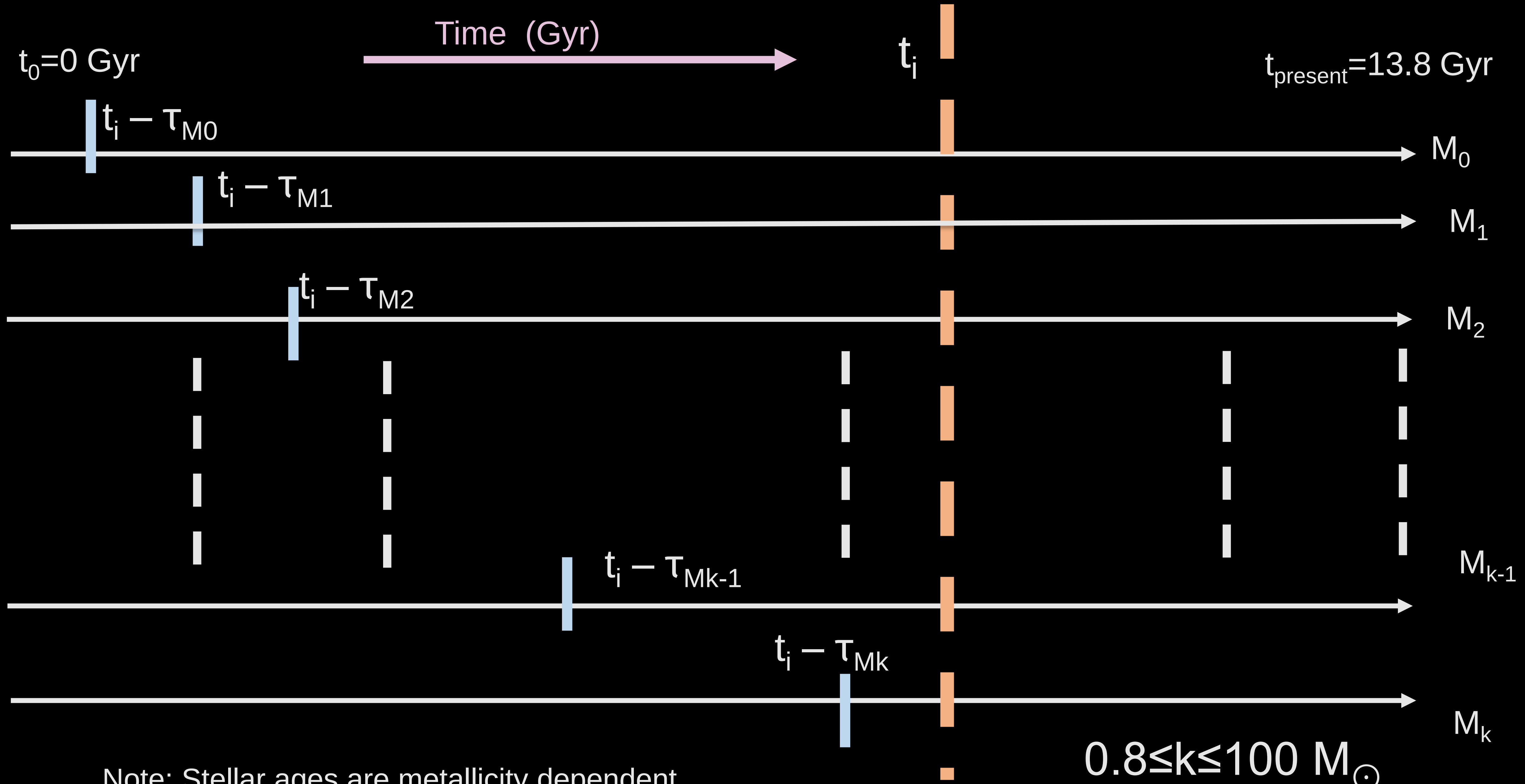
$$SFR(r,t) = \nu(t)\eta(r)\frac{\sigma^{n}(r,t)\sigma_{gas}^{m}(r,t)}{\sigma^{n+m-1}(r,t)} M_{\odot} pc^{-2} Myr^{-1}$$

Talbot and Arnett (1975); Alibes 2001

- The radial and the temporal dependence of the normalized SFR is incorporated by defining the star formation efficiency parameters, *η*(*r*) and *v*(*t*), respectively.

- v(t) is 2 during the initial 1 Gyr and unity for the evolution subsequent to 1 Gyr.

Stellar Ejecta



Time (Gyr)

t_0=0 Gyr

t_i

$t_{present}$=13.8 Gyr

$t_i - \tau_{M0}$

M_0

$t_i - \tau_{M1}$

M_1

$t_i - \tau_{M2}$

M_2

$t_i - \tau_{Mk-1}$

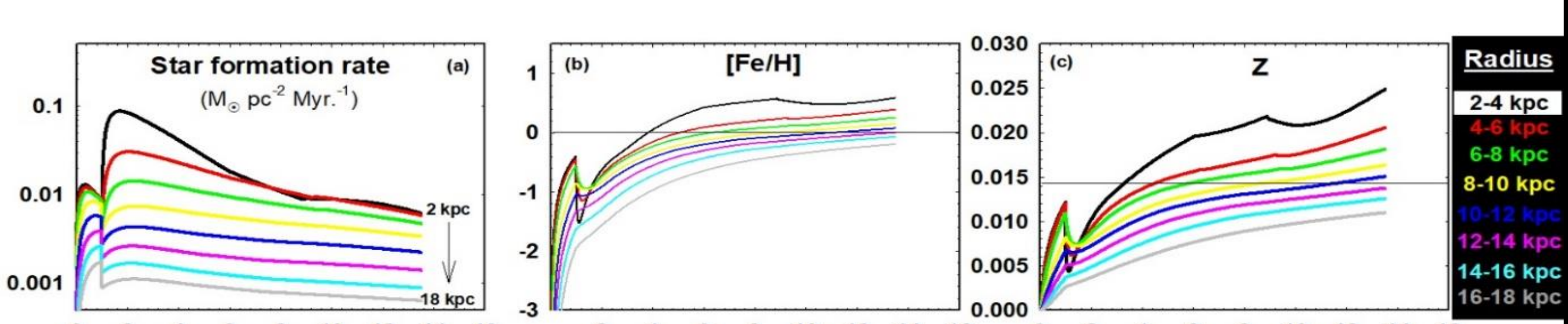
M_{k-1}

$t_i - \tau_{Mk}$

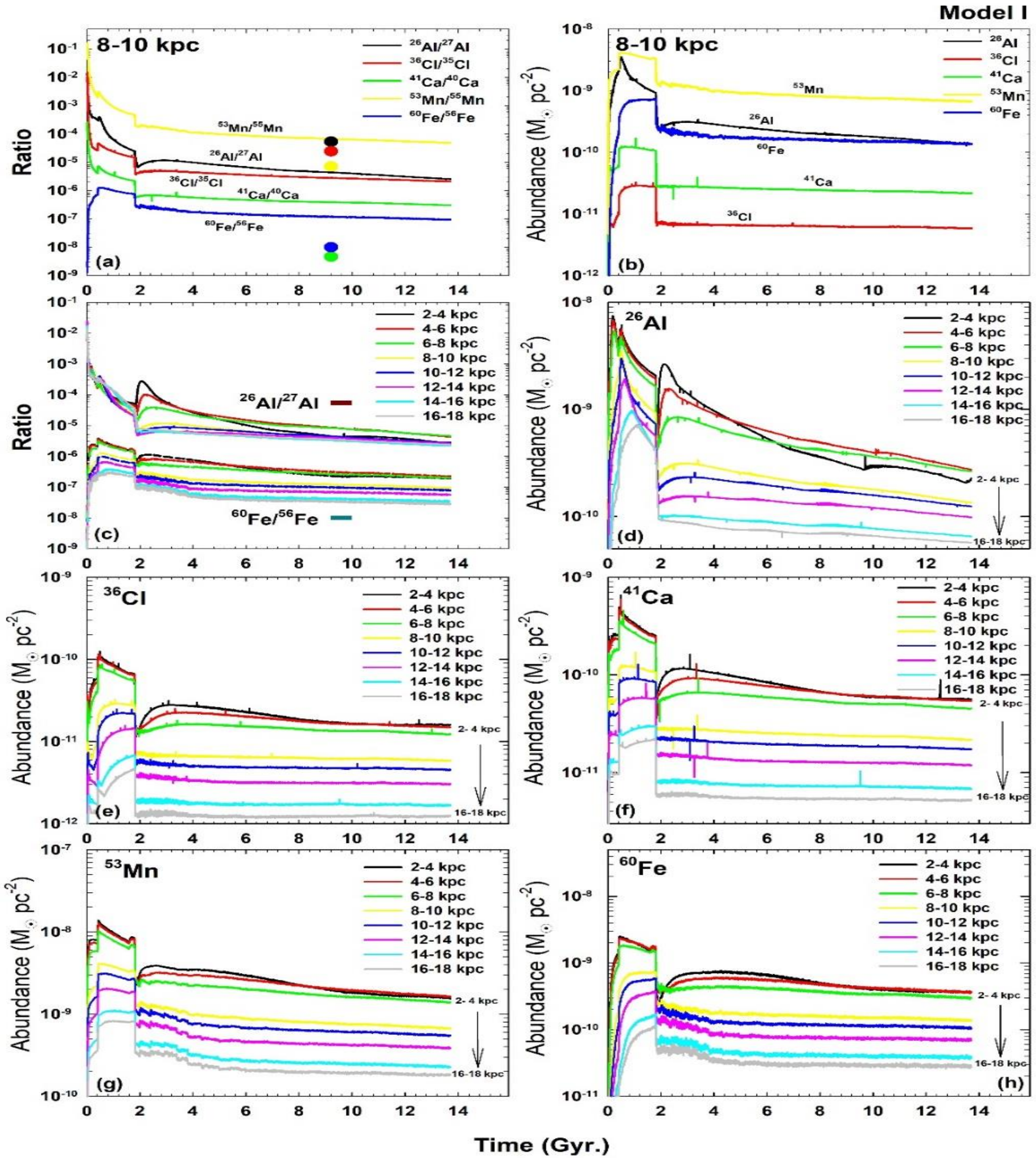
M_k

$0.8 \leq k \leq 100\ M_\odot$

Note: Stellar ages are metallicity dependent



Sahijpal and Kaur, 2018, MNRAS



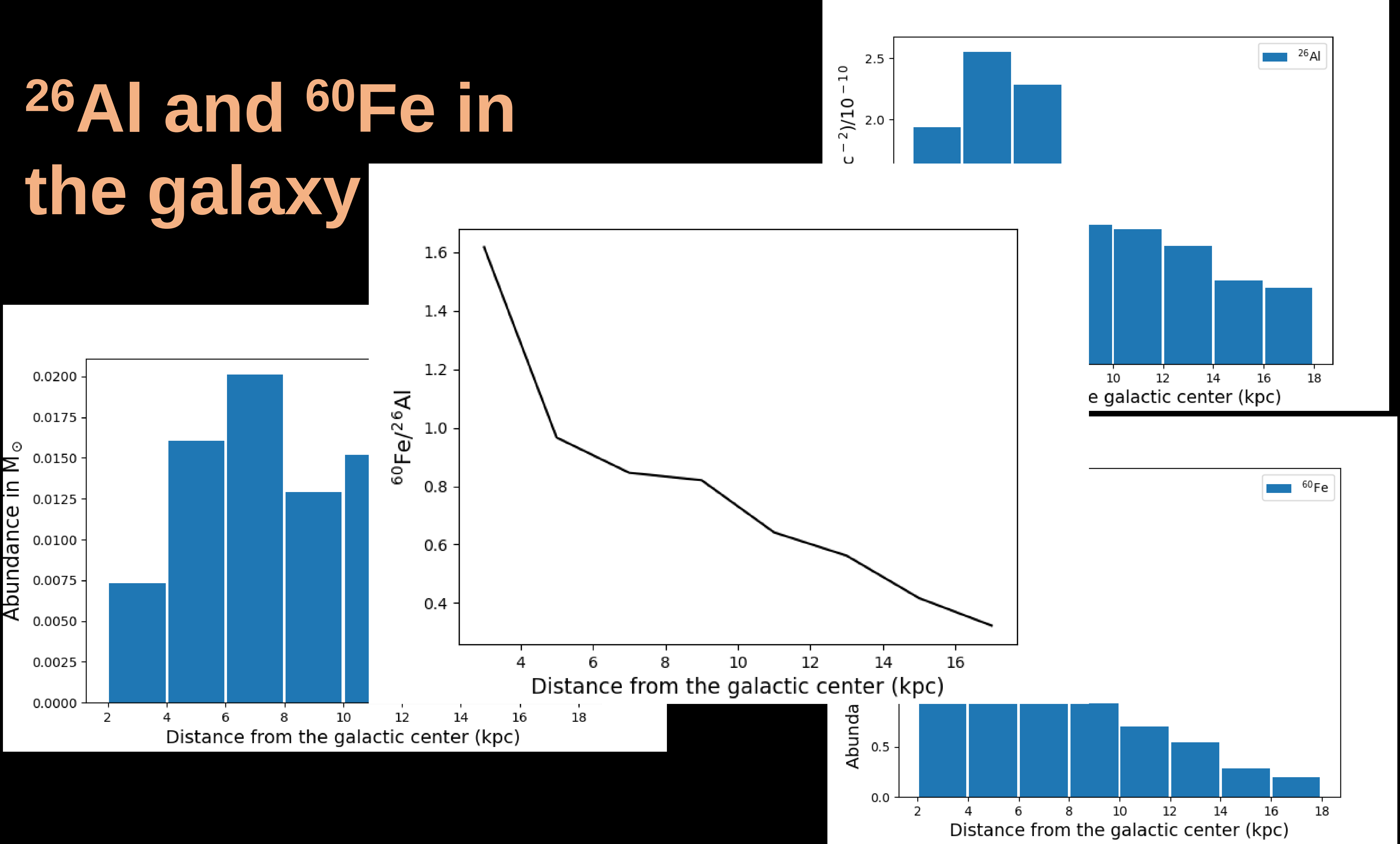
Homo-GCE trends for SLRs

- The average *Homo*-GCE trends of SLRs follow the star formation rate (Fujimoto et al. 2018).

- In general, the average GCE trends show that the production of SLRs is high in the inner regions of the Galaxy and gradually reduces towards the outer regions on account of comparatively low star formation

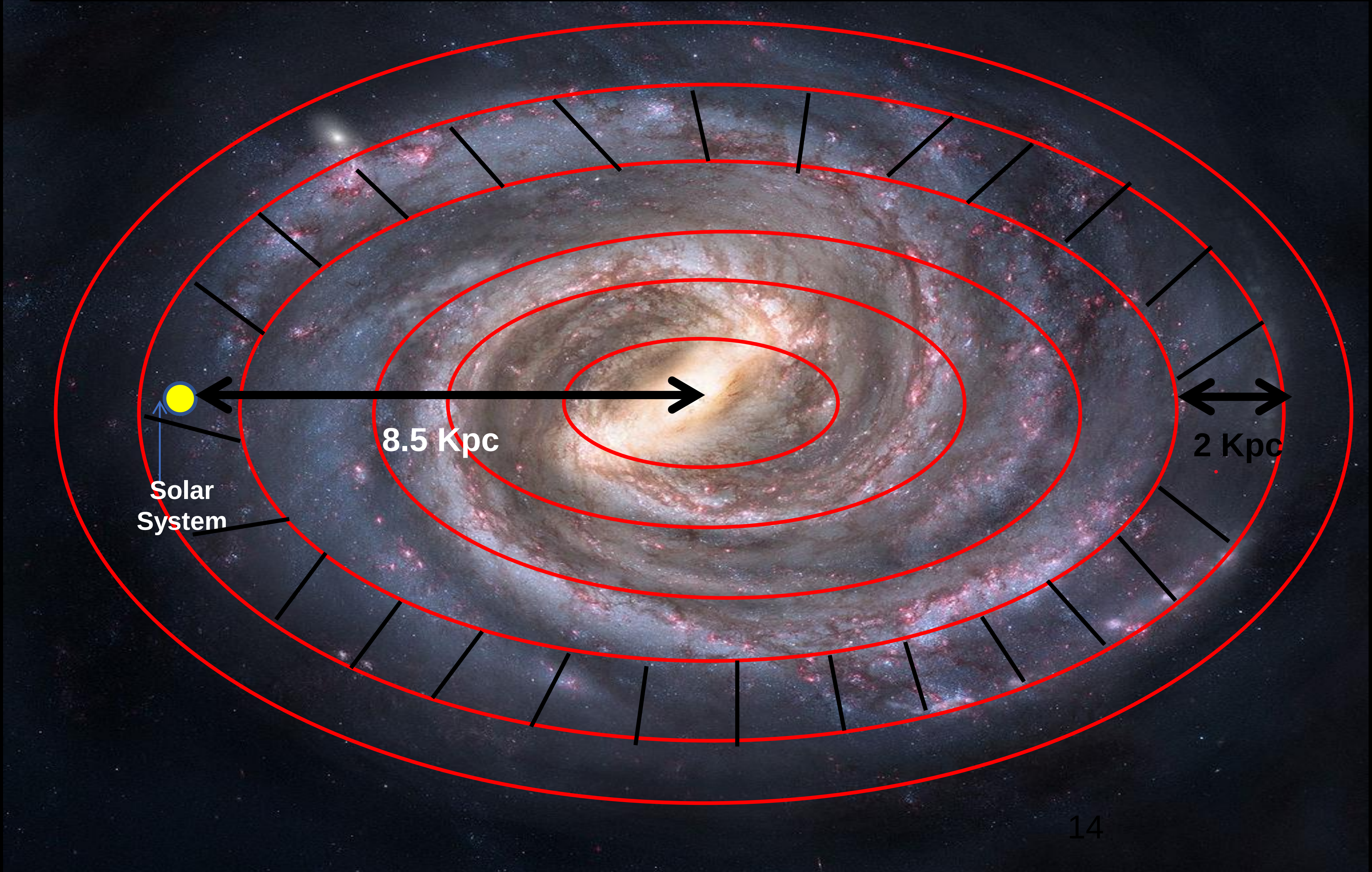
Kaur, T., & Sahijpal, S., 2019a,b

^{26}Al and ^{60}Fe in the galaxy



SLR ratio	Model I	Assume initial value in the early solar system	Reference
^{26}Al/^{27}Al (τ ~1.05 Myr)	4.4×10^{-6} $2.6\times10^{-6}{}^{\$}$	4.0×10^{-6} 8.4×10^{-6}	Diehl et al. 2006; Huss et al. 2009
^{36}Cl/^{35}Cl (τ ~0.43 Myr)	2.8×10^{-6}	$(2.44\pm0.65)\times10^{-5}$	Tang et al. (2017)
^{41}Ca/^{40}Ca (τ ~0.15 Myr)	3.9×10^{-7}	$(4.6\pm1.9)\times10^{-9}$	Liu (2017)
^{53}Mn/^{55}Mn (τ ~5.34 Myr)	6.7×10^{-5}	$(7\pm1)\times10^{-6}$	Tissot et al. (2017)
^{60}Fe/^{56}Fe (τ ~3.75 Myr)	1.2×10^{-7} $9.2\times10^{-8}{}^{\$}$	4.4×10^{-8} 2.7×10^{-7}	Diehl et al. 2006; Huss et al. 2009

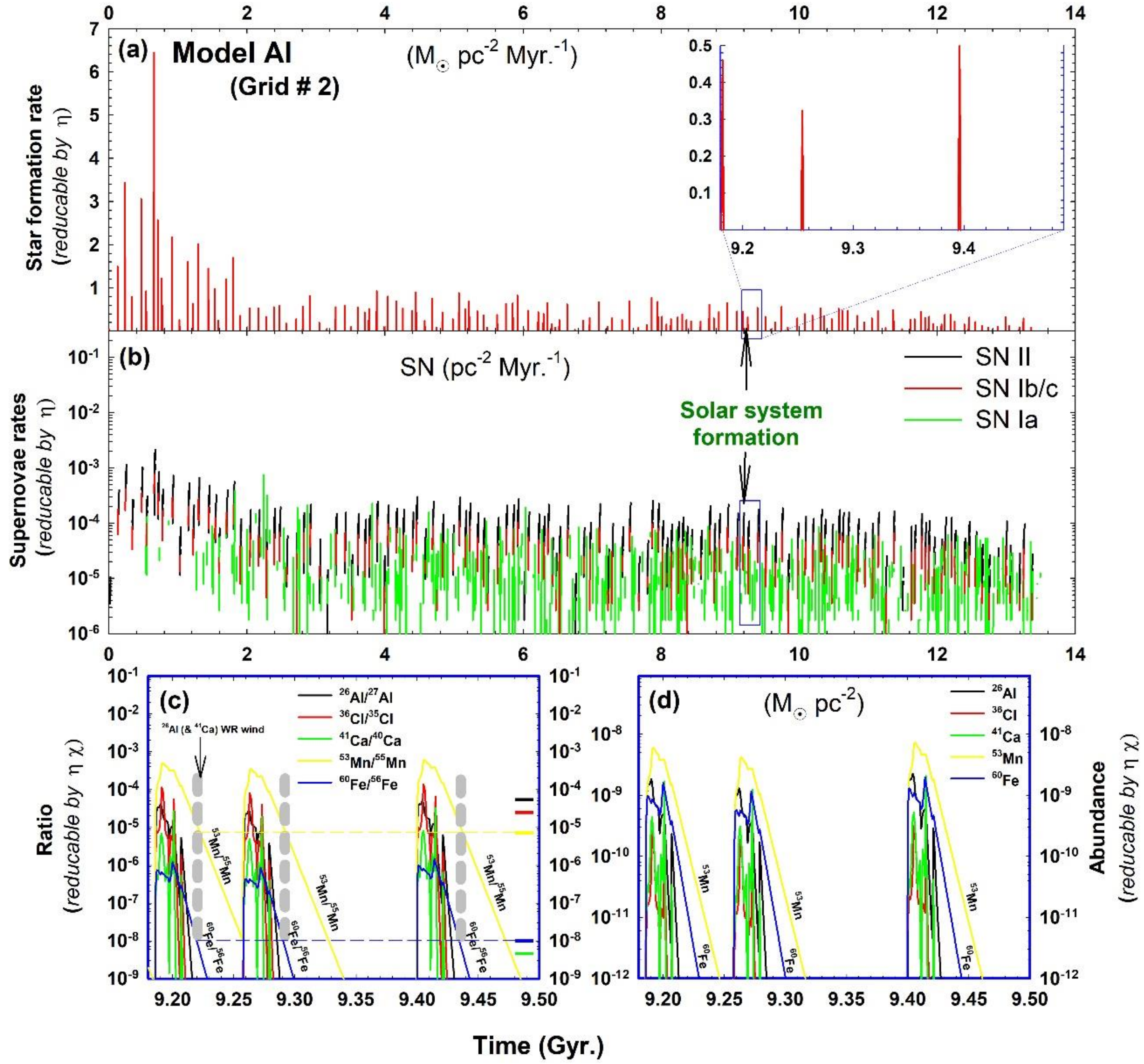
Heterogeneous GCE Approach



Model Parameters for Heter GCE models

Heter-GCE model	Total grids within solar annular ring	Grid size (kpc^2)	Time period for the formation of a cluster within a grid	Average mass ($M_\odot$) of stellar cluster formed after ~9 Gyr Range is also presented
Model AI (WW95+K10)	100	1.13	50-150 Myr Entire cluster forms within 1 Myr	3.3×10^5 Range: 3×10^4 - 6×10^5
Model BI (WW95+K10)	400	0.28	25-75 Myr Entire cluster forms within 1 Myr	4.2×10^4 Range: 2×10^3 - 1×10^5
Model CI (WW95+K10)	400	0.28	50-100 Myr Entire cluster forms over 3 Myr	6.3×10^4 Range: 1×10^4 - 1×10^5
Model DI (WW95+K10)	400	0.28	50-100 Myr Entire cluster forms over 10 Myr with a gap of 1 Myr after each 2 Myr	8.4×10^4 Range: 4×10^4 - 1×10^5
Model DIII (LC18+K10) 0 km s^{-1} rotational velocity	400	0.28	50-100 Myr Entire cluster forms over 10 Myr with a gap of 1 Myr after each 2 Myr	8.4×10^4 Range: 4×10^4 - 1×10^5
Model DIV (LC18+K10) 300 km s^{-1} rotational velocity	400	0.28	50-100 Myr Entire cluster forms over 10 Myr with a gap of 1 Myr after each 2 Myr	8.4×10^4 Range: 4×10^4 - 1×10^5
Model EI (WW95+K10)	800	0.14	50-110 Myr Entire cluster forms within 1 Myr	3.3×10^4 Range: 6×10^3 - 7×10^4

Results for Heter-GCE models



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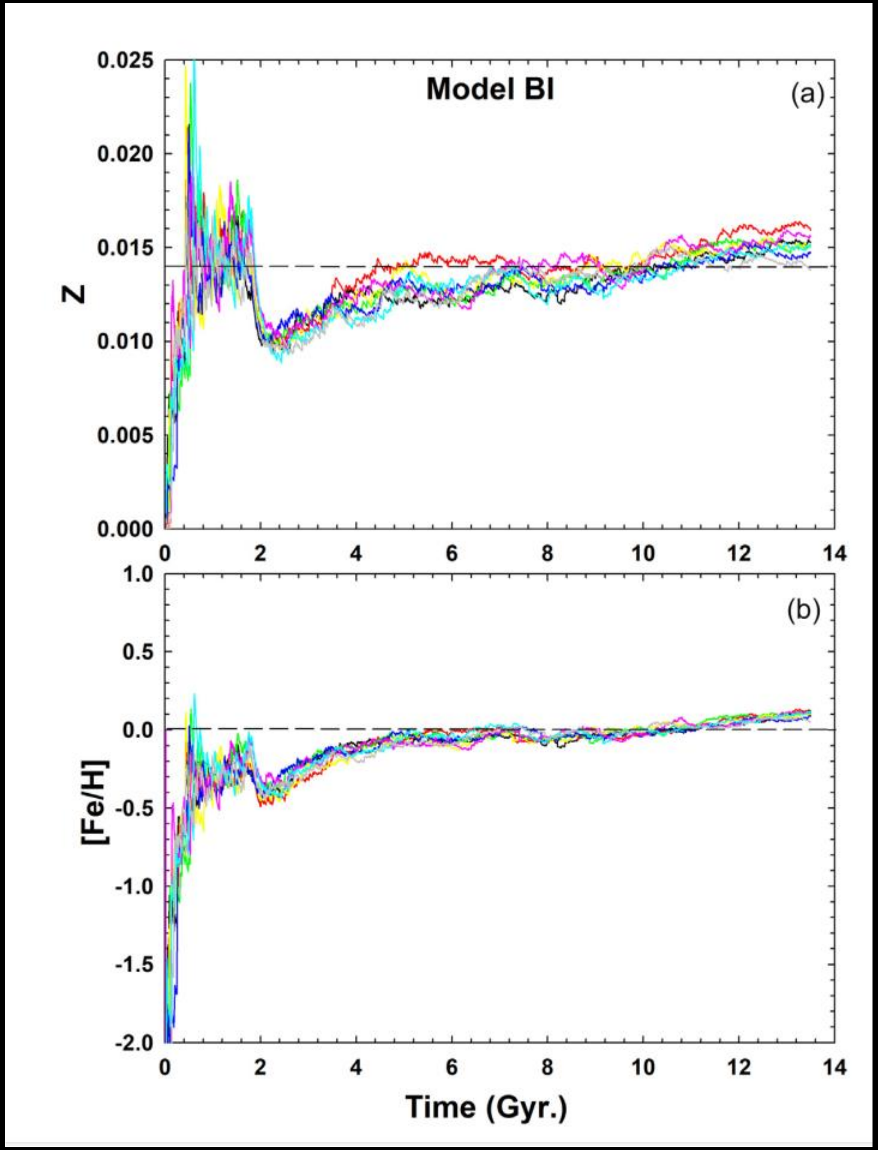

The metallicity Z,and [Fe/H] of the Heter-GCE Model

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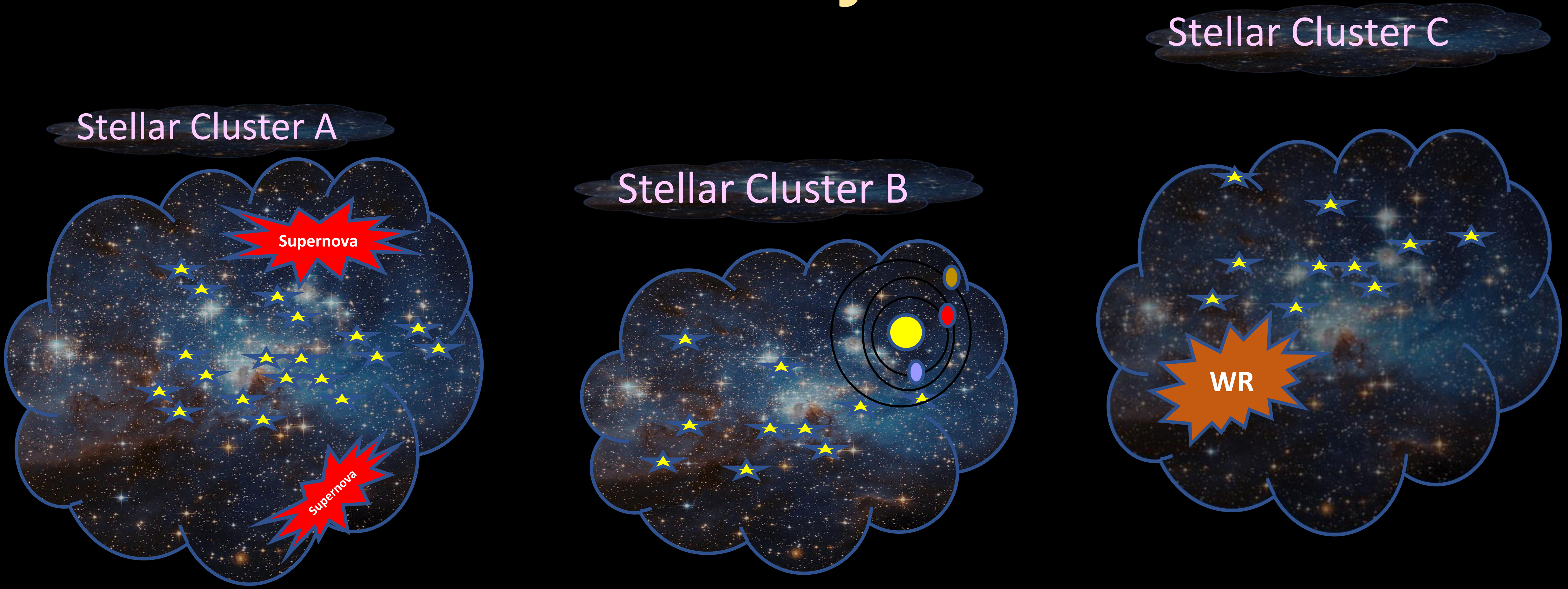
One of the Plausible Scenarios for the formation of the Solar System



Sahijpal & Soni 2006; Dwarkadas et al. 2017; Kaur & Sahijpal 2019; Kaur 2021

Conclusion

- The abundance distribution of Short-lived radio nuclides in the entire galaxy from GCE contribution shows co-relation with Star Formation Rate.
- Our Solar System gradually formed as a natural consequence of evolution of the Milky Way Galaxy.
- The decaying ^{60}Fe and ^{53}Mn remnants from the evolved massive stars from the cluster probably contaminated the local medium associated with the presolar molecular cloud.
- The stellar contribution of ^{26}Al (and probably ^{41}Ca) to ESS in the proposed scenario would require the role of an independent Wolf- Rayet wind.
- The production of ^{36}Cl along with ^{7,10}Be can be explained by local irradiation scenarios in the ESS.

Future work

- To develop a mechanism to incorporate the stellar ejecta dynamics.

- Investigation of the central Bulge+inner disc using heterogeneous models.

- Investigation of the role of Radial Migration for long lived sources of SLRs.

- Explodability and Multiplicity of the Massive stars.

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MNRAS **481,** 5350–5369 (2018)
Advance Access publication 2018 September 26

A Monte Carlo based simulation of the Galactic chemical evolution of the Milky Way Galaxy

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49th Lunar and Planetary Science Conference 2018 (LPI Contrib. No. 2083) **124**

EVOLUTION OF MILKY-WAY GALAXY: THE SOLAR ELEMENTAL ABUNDANCE CONSTRAINTS. S. Sahijpal and Tejpreet Kaur, Dept. of Physics, Panjab University, Chandigarh, India 160014 (sandeep@pu.ac.in).

Chemical evolution of the Milky Way Galaxy: Influence of massive stars and their rotation

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Heterogeneous evolution of the Galaxy and the origin of the short-lived nuclides in the early solar system

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50th Lunar and Planetary Science Conference 2019 (LPI Contrib. No. 2132) **1932.pdf**

SHORT-LIVED RADIONUCLIDES AND THE EVOLUTION OF THE MILKY WAY GALAXY. T. Kaur and S. Sahijpal, Department of Physics, Panjab University, Chandigarh. 160014, India. (sandeep@pu.ac.in)

Thank you for attention

SNIa

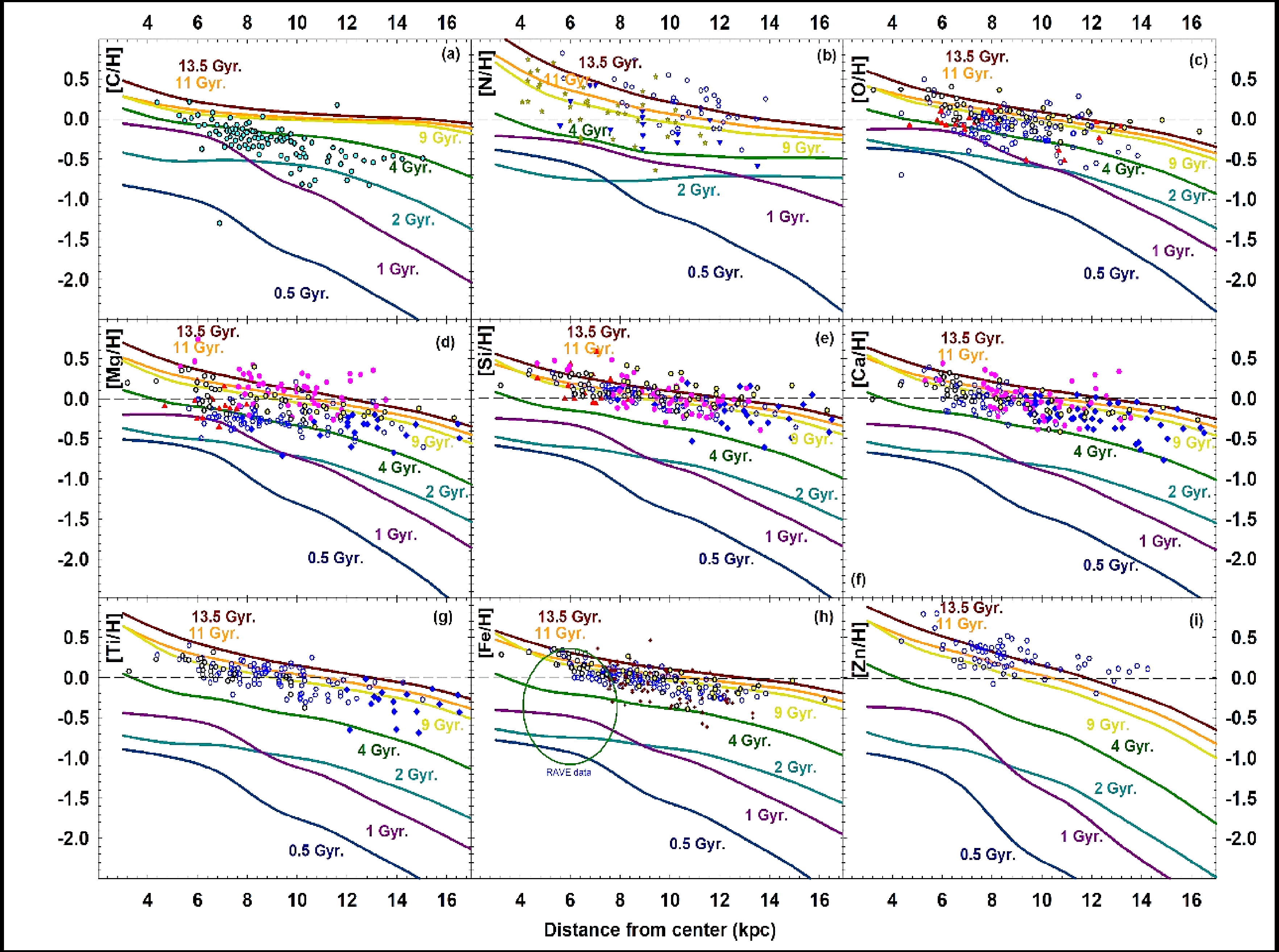
The stellar number distribution function, Gi(t, M), was synthesized for the stars according to the normalized IMF and the metallicity prevailing in the ring at the specific time, t.

A binary stellar population Bi(t, m) { m ⊂ M}, from the stellar number distribution function, Gi(t, M) is evolved with a number fraction, f , of the stars that evolves into binary systems with a definite progenitor of SNe Ia.

The parameter f is treated as a simulation parameter to obtain the solar metallicity has a typical value in the range of 0.02–0.025 in our simulations.

The models with a delay time distribution (DTD) based upon single degenerate (SD) and double-degenerate (DD) are explored to access the SN Ia rates (Matteucci et al. 2009).

Sahijpal & Gupta 2013, Sahijpal & Kaur 2018



Sahijpal and Kaur, 2018, MNRAS