

Galactic Chemical Evolution

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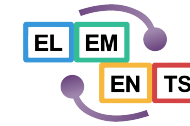
A link between observations and Galaxy evolution

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Introduction: chemical evolution of galaxies



- The evolution of the Galaxy is closely connected to the evolution of its stellar population
- Stars in the Galaxy born, evolve and die and enrich the ISM with their chemical products
- The distribution and evolution of the chemical products depend on both the dynamical Galaxy evolution and the stellar evolution
- We need a field which is able to understand both the dynamical effect of Galaxy evolution and the stellar evolution and nucleosynthesis

Introduction: chemical evolution of galaxies



molecular clouds

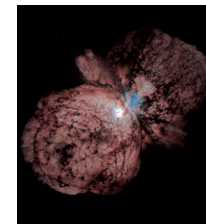


stellar death



formation of stars

cool down



ejecta



The astronomers periodic table

¹ H
Hydrogen
(Hydrogen)
1.0

² He
Helium
(Helium)
4.0

Atomic Number (Tau Tirohi)	22
Symbol (Tirohi)	Ti
Kupu Ingirihi (English Name)	Titanium
Kupu Māori (Māori Name)	Tirotiroti
Atomic Mass (Tau Karahi)	47.9



METALS

Any value in brackets is the mass of the most stable or best known isotope for elements which do not occur naturally.

Non-Metals	Transitional Metals	Metalloids	Halogens
Alkali Metals	Rare Earth	Other Metals	Noble Gases
Alkaline Earth Metals	Lanthanide Series (Rare Earth)	Actinium Series (Rare Earth)	

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Introduction: chemical evolution of galaxies

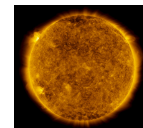


molecular cloud



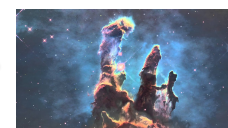
$$Z = Z_0$$

star



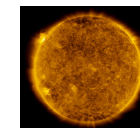
$$Z = Z_0$$

molecular cloud



$$Z = Z_1$$

star

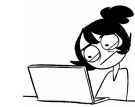


$$Z = Z_1$$

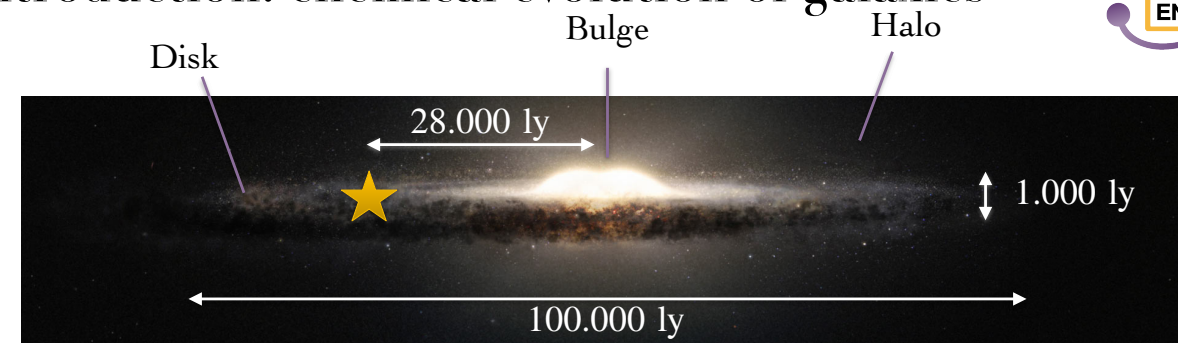
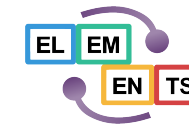


$$t_{\text{Hubble}} \simeq 13.7 \text{ Gyr}$$

present
time



Introduction: chemical evolution of galaxies



$1 M_{\odot}$



$t_{life} \simeq 10 \text{ Gyr}$

$10 M_{\odot}$



$t_{life} \simeq 32 \text{ Myr}$

$100 M_{\odot}$



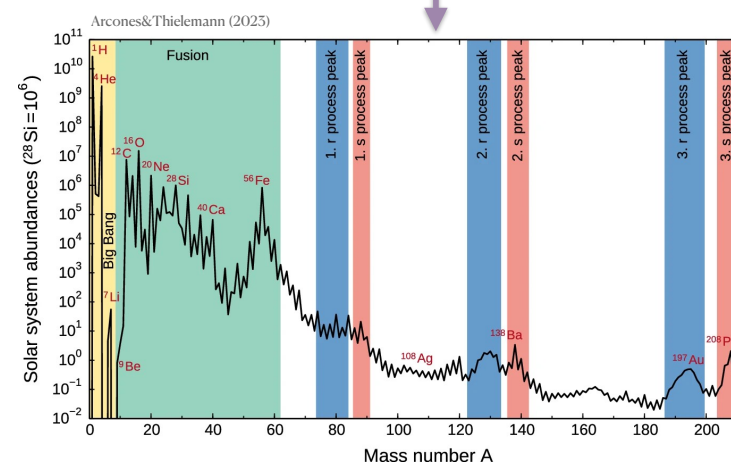
$t_{life} \simeq 0.1 \text{ Myr}$

Introduction: chemical evolution of galaxies



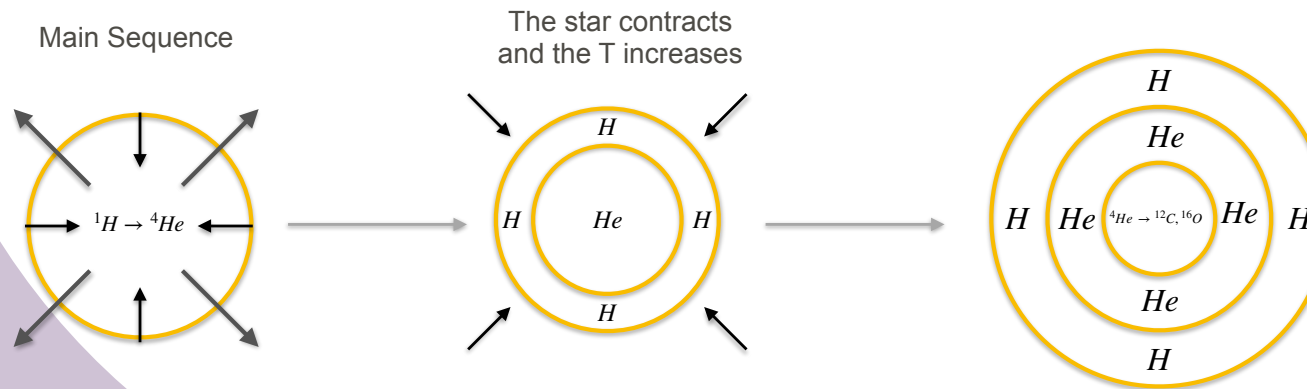
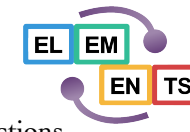
by observing the Sun we
get this

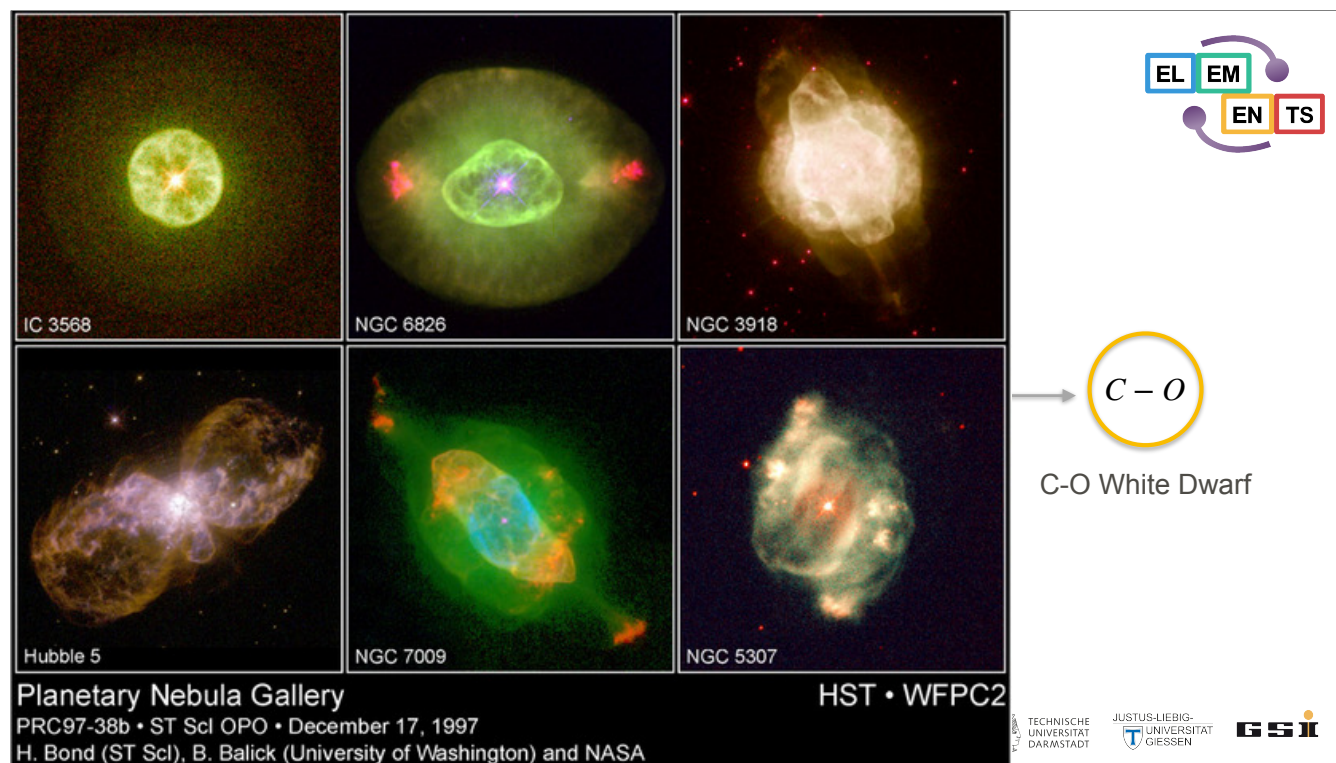
- The abundance of elements in the stellar photosphere near the surface of a star remains unchanged over the lifetime of a star
- The observed heavy-metal abundances of stars *today* measure the abundances of the ISM *when the star was formed*



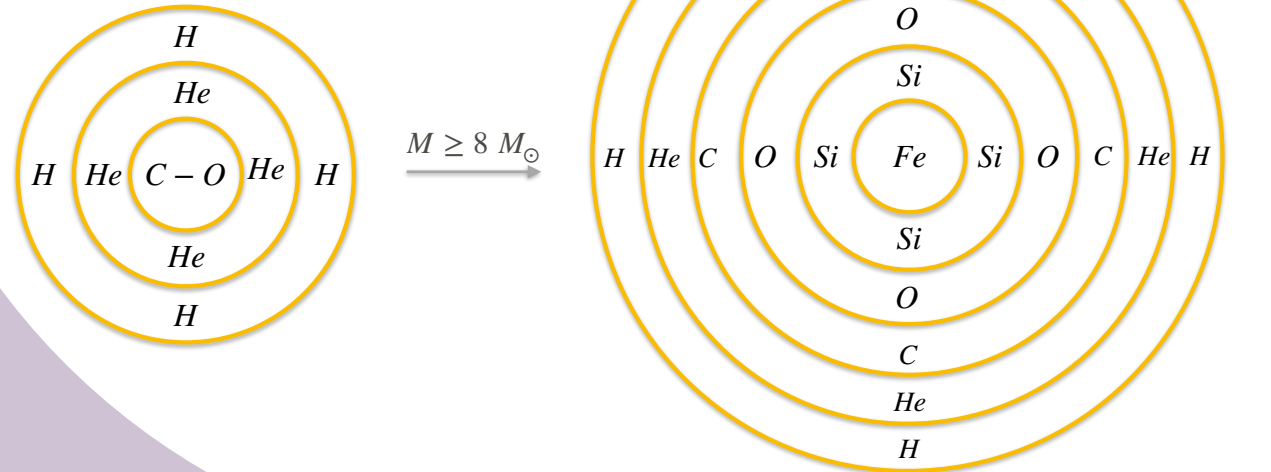
Introduction: stellar evolution

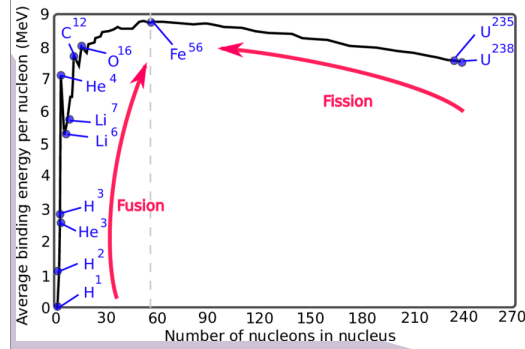
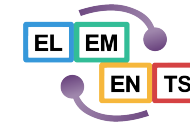
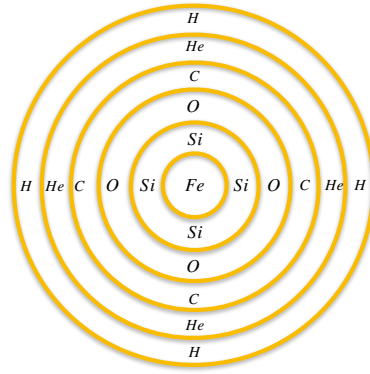
The gravitational force is balanced by the gas pressure generated by thermonuclear fusion reactions





Can reach T high enough to
ignite C into the core

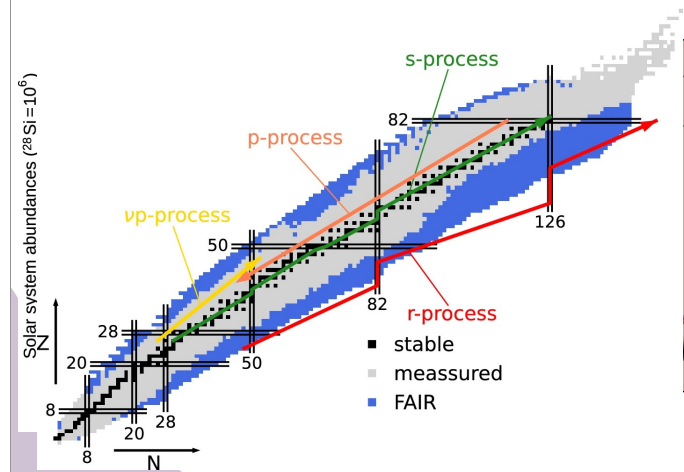
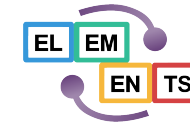




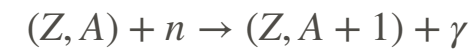
1. Thermonuclear reactions cease in the center and the gravitational pressure can no longer be counteracted
2. The core contracts until $\rho \simeq 10^{14} \text{ g/cm}^3$
3. Nuclear interactions involve a repulsive force which causes the collapse to stop
4. The stop produces a bounce and a shock wave is launched outwards in radius

Explosive Nucleosynthesis - CC-SNe

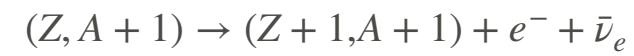
Neutron capture process



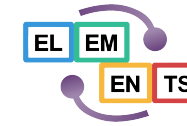
Neutron Capture Processes



The new nucleus may be unstable to β decay (one n is transformed into one p)



Neutron capture elements



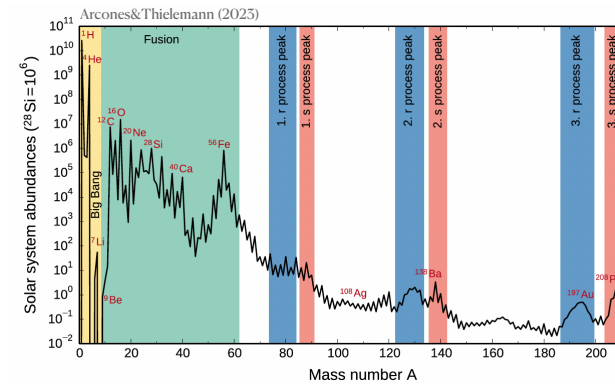
Weak s-process: (rotating) massive stars
($M > 8 M_{\odot}$) - neutrons released from the reaction
 $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$

s-process: the unstable nuclide created by neutron capture will decay in a stable nuclide before it has time to capture another neutron

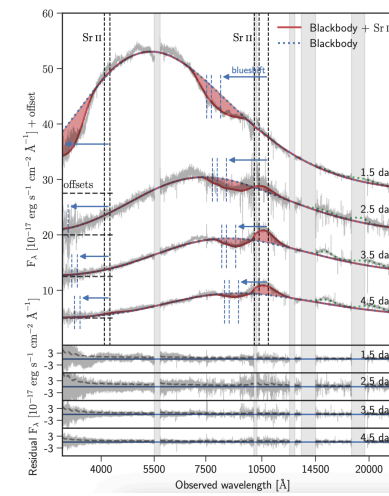
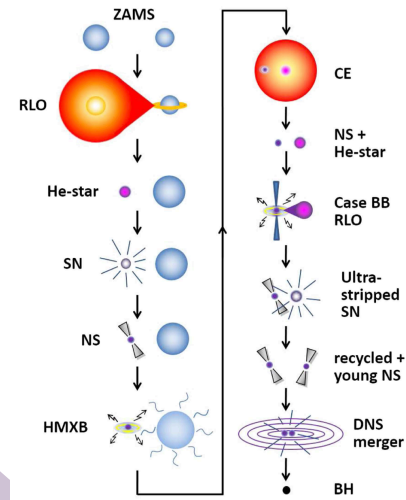
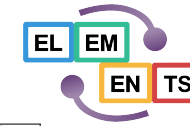
Main s-process: Low-intermediate mass stars (LIMS, $M < 8 M_{\odot}$) during the AGB phase - neutrons released from the reactions $^{13}\text{C}(\alpha, n)^{16}\text{O}$, $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$

r-process: there is time for multiple neutron captures before the first β -decay occurs

Strong s-process: Low-metallicity low-mass AGB stars - neutrons released from the reactions $^{13}\text{C}(\alpha, n)^{16}\text{O}$, $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$



Neutron star mergers (MNS)



Neutron star mergers (MNS)



Delay time for MNS: $\tau = \tau_s + \tau_{gw}$

τ_s lifetime of the secondary component

τ_{gw} gravitational radiation delay

Landau&Lifshitz (1966)

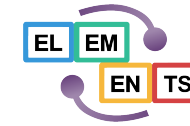
$$\tau_{gw} = \frac{0.15A^4}{m_1m_2(m_1 + m_2)}Gyr$$

Simonetti et al. (2019)

$$\tau_{gw} = \frac{0.6A^4}{M^3}Gyr$$

$$df(\tau_{gw}) = df(A, M) = g(A)h(M)dAdM$$
$$\begin{cases} g(A) \propto A^\beta \\ h(M) \propto const. \end{cases}$$

Neutron star mergers (MNS)



SF history

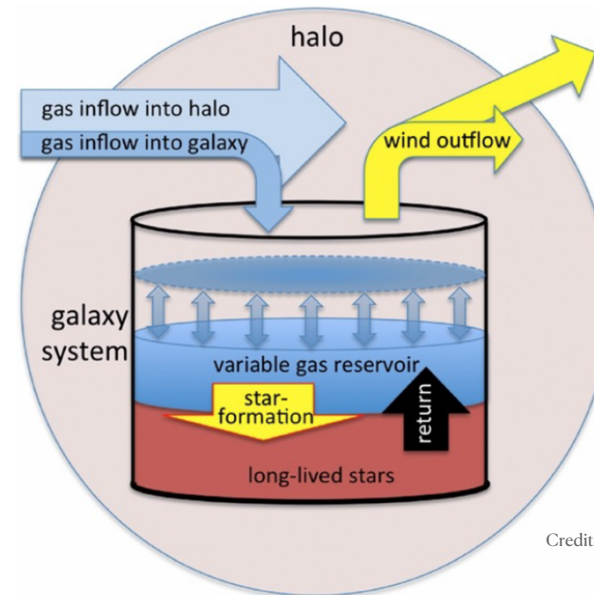
$$R_{MNS}(t) = k_{\alpha} \int_{\tau_i}^{\min(t, \tau_x)} \alpha_{MNS}(\tau) \psi(t - \tau) f_{MNS}(\tau) d\tau$$

$$\int_{9M_{\odot}}^{50M_{\odot}} \varphi(m) dm$$

the fraction stars in the correct mass range which can give rise to a merging event

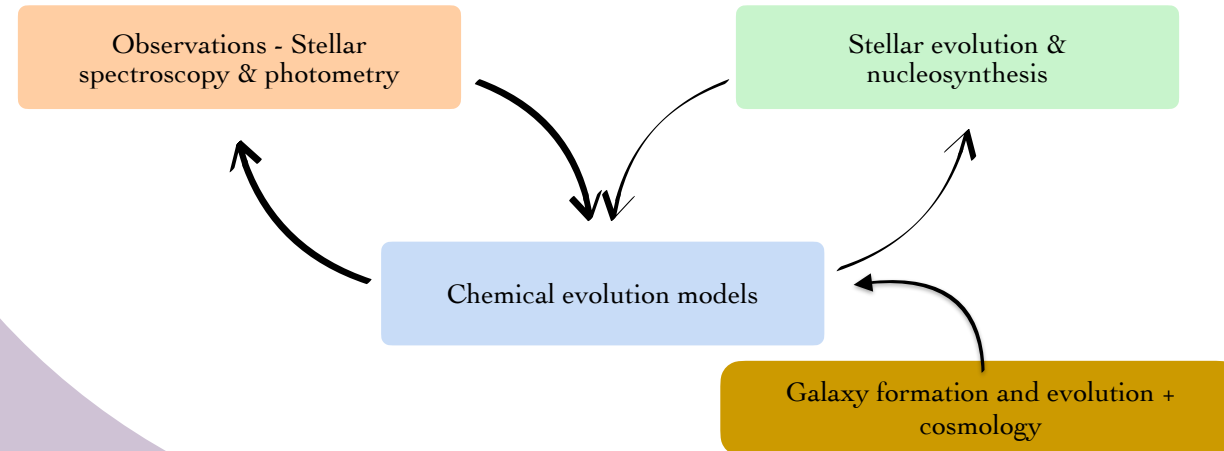
delay time distribution (DTD)

Introduction: chemical evolution of galaxies



Credits: Lilly et al. (2013)

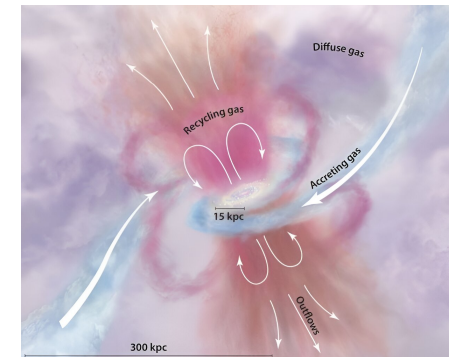
Introduction: chemical evolution of galaxies



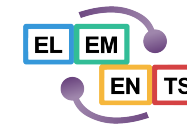
Basic ingredients of chemical evolution



- Boundaries of the system: closed or open model →
 - Infall/outflow of gas
 - Mergers with other galaxies
- Chemical composition of the infalling gas →
 - Primordial composition (H, He, Li, Be)
 - Pre-enriched
- Gas flows and their chemical composition



Basic ingredients of chemical evolution

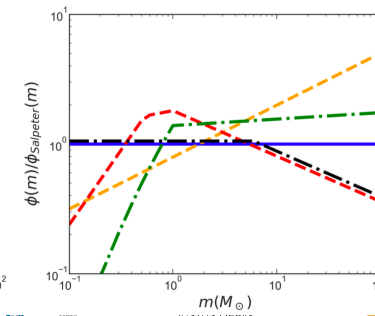
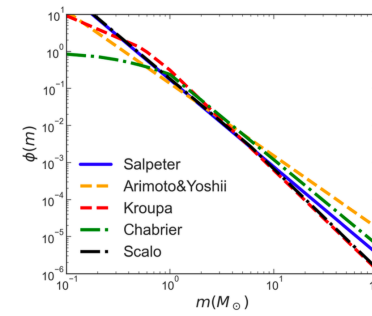
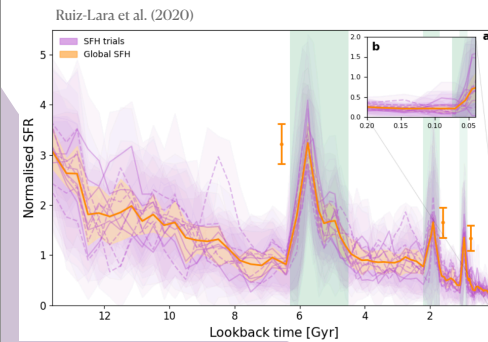


- Stellar birthrate function

$$B(m, t) = \phi(m)\psi(t)dm dt$$

Star formation rate
(SFR)

Initial mass function
(IMF)

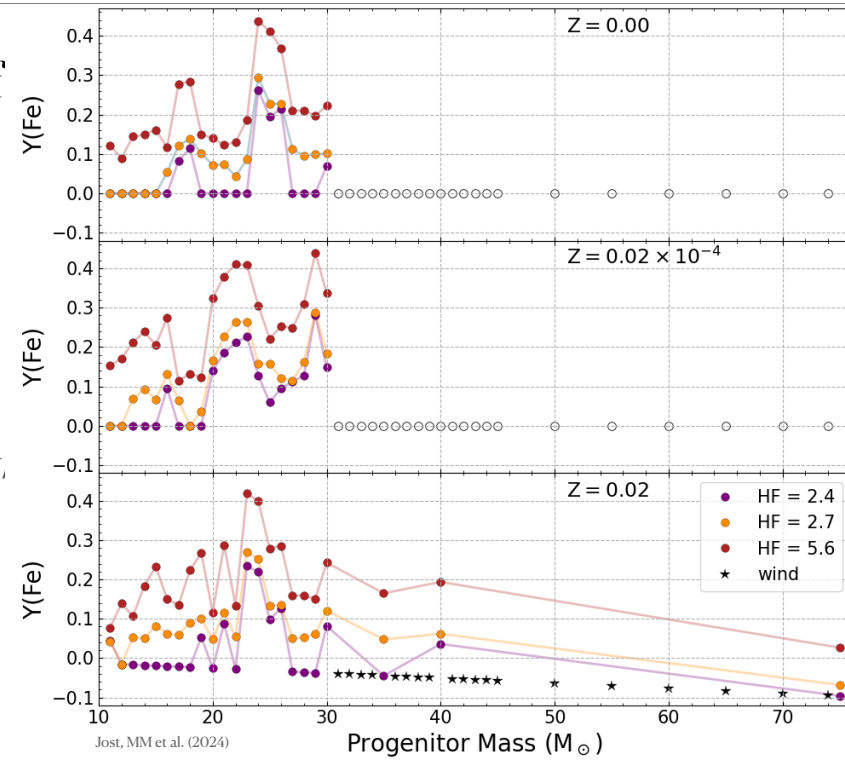


Basic ingredients of

- Stellar yields

Massive stars ($M > 8 M_{\odot}$) →

Low-intermediate mass stars ($0.3 \leq M_i$)



Equations of chemical evolution

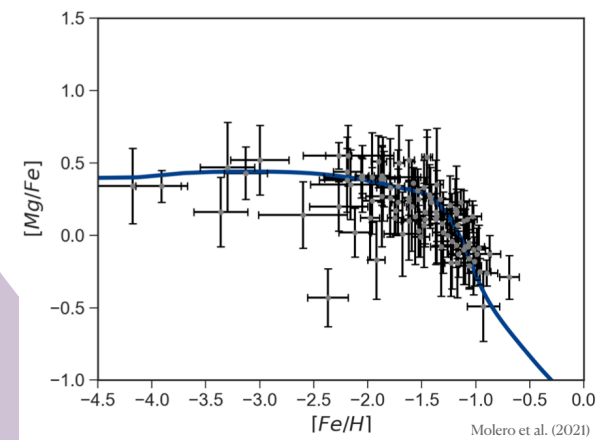
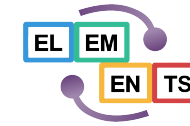


- The evolution of the mass of gas in the form of the chemical element i

$$\dot{M}_{\text{gas},i}(R, \theta, t) = \underbrace{-\psi(R, \theta, t)X_i(R, \theta, t)}_{\substack{\downarrow \\ \text{lost of gas because of SF} \\ \text{processes}}} + \underbrace{X_{i,A}A(R, \theta, t)}_{\substack{\downarrow \\ \text{accretion of gas} \\ \text{through infall}}} - \underbrace{X_i(R, \theta, t)W(R, \theta, t)}_{\substack{\downarrow \\ \text{lost of gas} \\ \text{galactic winds}}} - \underbrace{X_i(R, \theta, t)\dot{M}_{BH}(R, \theta, t)}_{\substack{\downarrow \\ \text{lost by feeding the} \\ \text{central BH}}} + \underbrace{\dot{R}_i(R, \theta, t)}_{\substack{\downarrow \\ \text{restitution of gas} \\ \text{from stars}}}$$

The time-delay model

$$[X/H] = \log(X/H) - \log(X/H)_{\odot}$$



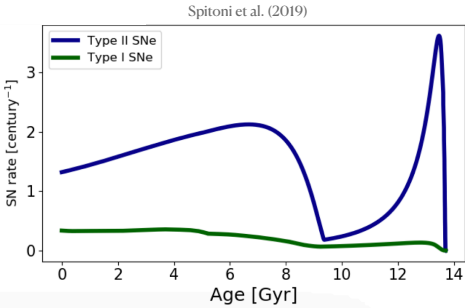
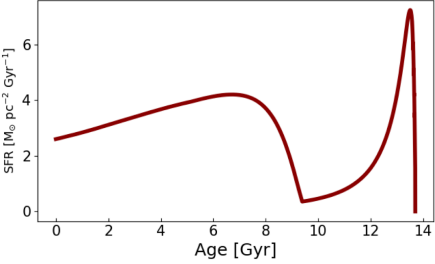
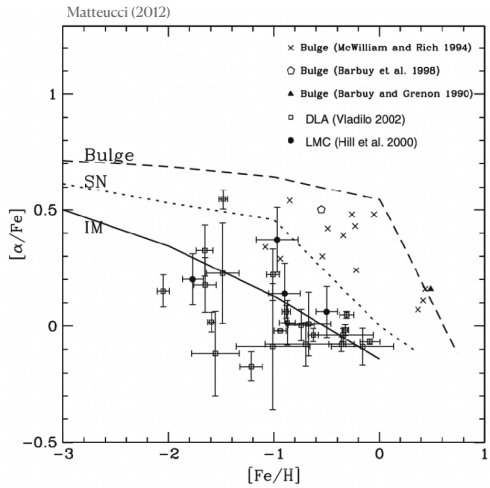
Massive stars: short lifetimes
important Fe and Mg producers

Type Ia SNe: long lifetimes
main Fe producers

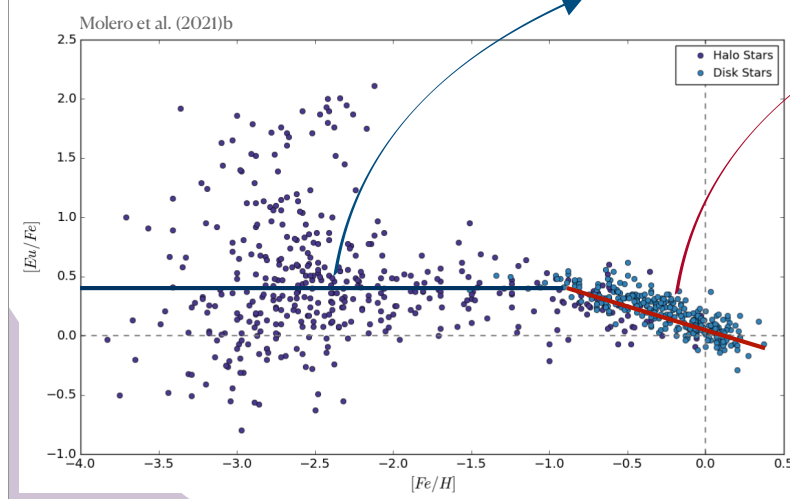
The time-delay model



$$[X/H] = \log(X/H) - \log(X/H)_{\odot}$$



Applications: the $[\text{Eu}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$



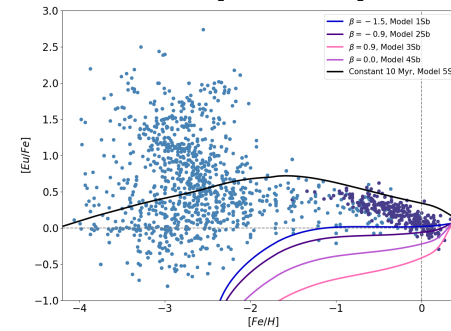
Fe from SNE Ia

Quick sources: massive stars and/or MNS
with a constant delay for merging

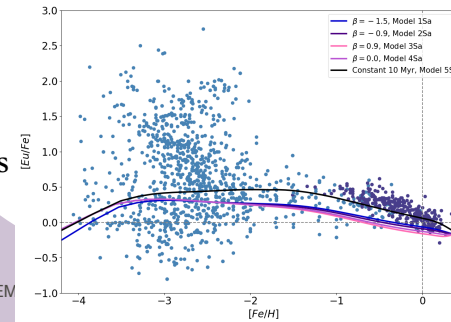
Applications: the $[\text{Eu}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$



only MNS



MNS +
Massive stars



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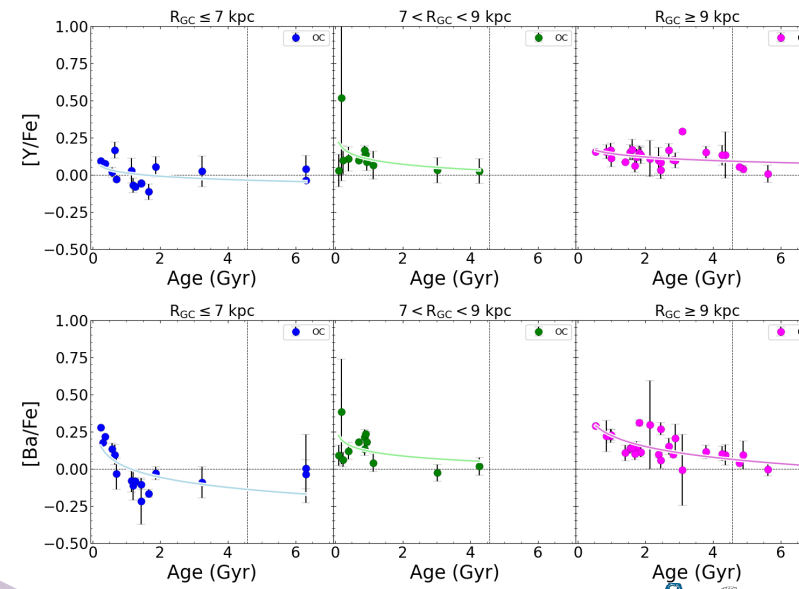
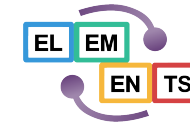
- MNS sole producers of Eu: model with a constant and short delay
- MS co-produce Eu with MNS, they become the main production site and dominate the relation

Either NS all merge on short timescales or they cannot be the major producers of Eu

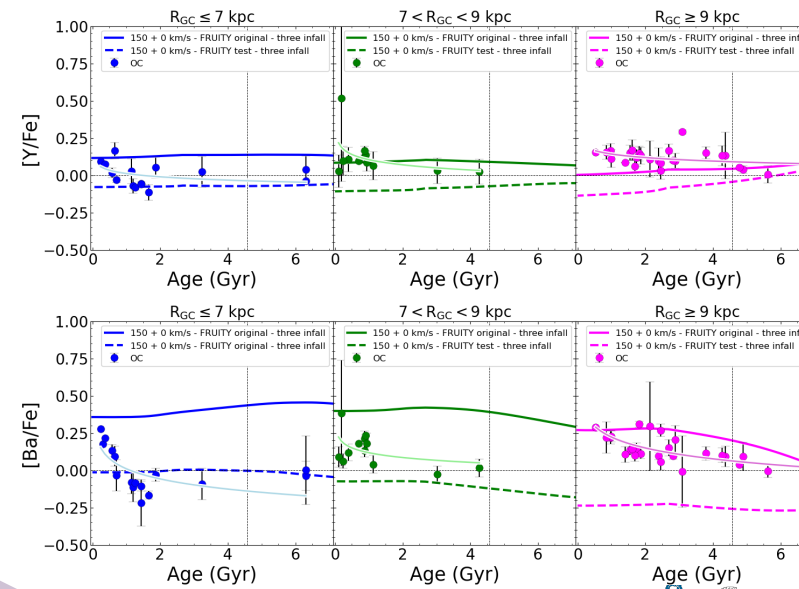
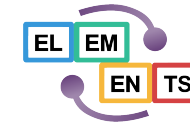
e.g.,
Matteucci+14, Cescutti+15, Wehmeyer+15, Cotè+19, Si
monetti+19, Kobayashi+20, Cavallo+21, Molero+21a,b,
Van der Swaelmen+23



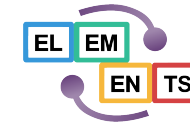
Applications: the $[s/Fe]$ vs. Age



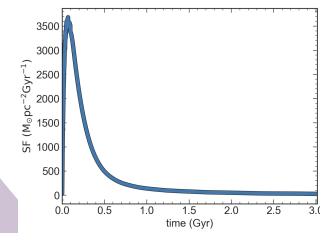
Applications: the $[s/Fe]$ vs. Age



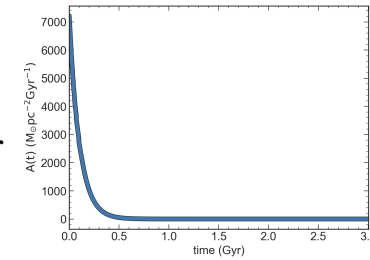
Applications: the Galactic bulge



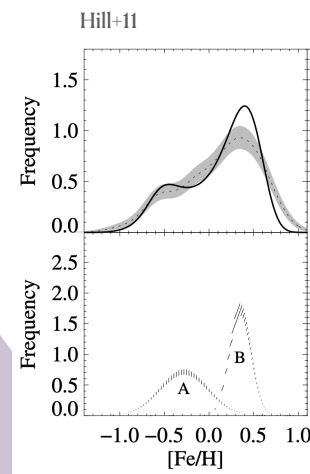
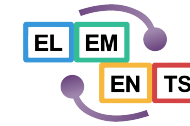
$$\dot{M}_{\text{gas},i}(R, \theta, t) = -\psi(R, \theta, t)X_i(R, \theta, t) + X_{i,A}A(R, \theta, t) - X_i(R, \theta, t)W(R, \theta, t) - X_i(R, \theta, t)\dot{M}_{BH}(R, \theta, t) + \dot{R}_i(R, \theta, t)$$



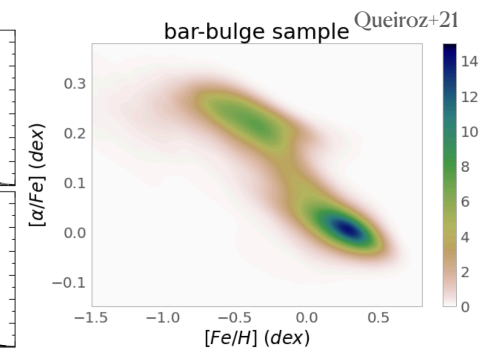
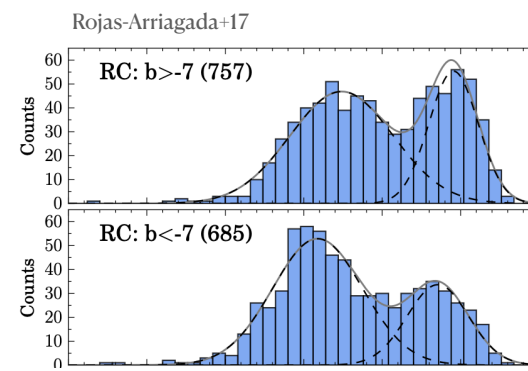
$$\begin{aligned} \dot{M}_{\text{gas},i}(t) &= -\psi(t)X_i(t) + X_{i,A}A(t) + \dot{R}_i(t) \\ &\downarrow \qquad \qquad \qquad \downarrow \\ &= \nu \sigma_{\text{gas}}^k(t), \nu = 25 \text{ Gyr}^{-1} \\ &\qquad \qquad \qquad \propto e^{-\frac{t}{\tau}}, \tau = 0.1 \text{ Gyr} \end{aligned}$$



Applications: the Galactic bulge



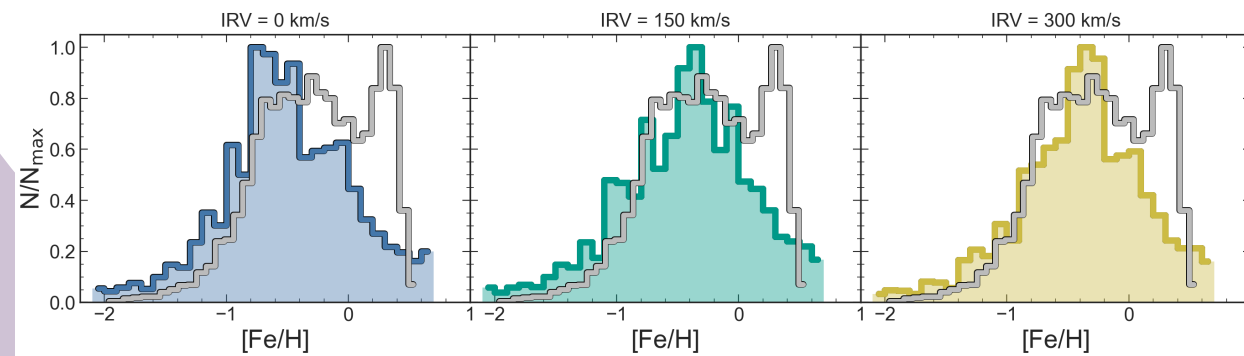
Gonzalez+15, Schultheis+17, Zoccali+17,
Bensby+11,+13,+17, Rojas-Arriagada+19,20,
Queiroz+20, Johnson+20,+22, etc...



Applications: the Galactic bulge



1. Salpeter IMF
2. Massive stars yields from Limongi&Chieffi(2018)
3. Two bursts of SF - delay of 250 Myr



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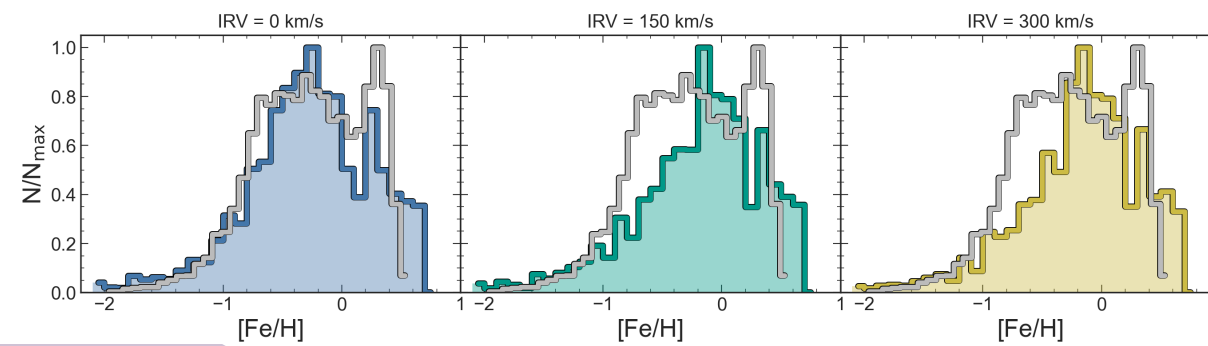
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Applications: the Galactic bulge



1. Chabrier+03 IMF
2. Massive stars yields from Limongi&Chieffi(2018)
3. Two bursts of SF - delay of 250 Myr



Applications: the Galactic bulge



1. Chabrier+03 IMF
2. Massive stars yields from Limongi&Chieffi(2018)
3. Two bursts of SF - delay of 250 Myr

stellar migration

