Chemical Evolution of Galaxies and JWST Surprises (?)

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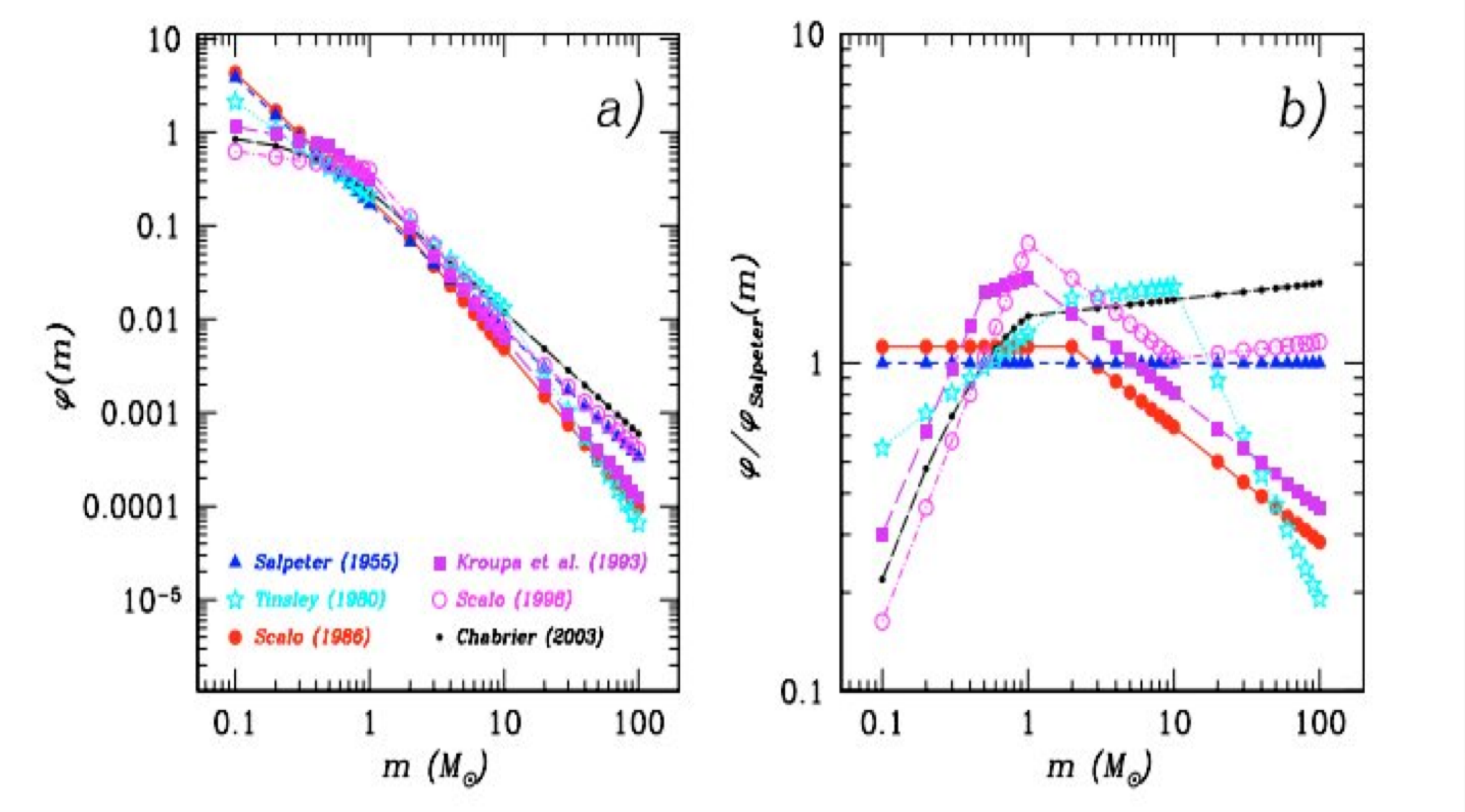
Basic Ingredients of Chemical Evolution

- Initial conditions (open/closed-box; initial chemical composition)
- The stellar birthrate function: SFRxIMF
- The stellar yields (i.e. the mass restored into the ISM by a star of a given mass in the form of a given chemical element
- Gas flows: infall, outflow, inflow

The Initial Mass Function

- Several IMFs have been derived for the solar vicinity and are expressed as a power law



Parametrizations of SFR and gas flows

- The SFR is often assumed to be a Schmidt-Kennicutt law (k=1.4)

$$SFR = \nu \sigma_g^k$$

- The Infall rate is often an exponential law

$$IR = Ae^{-t/\tau}$$

- The outflow rate is proportional to the SFR

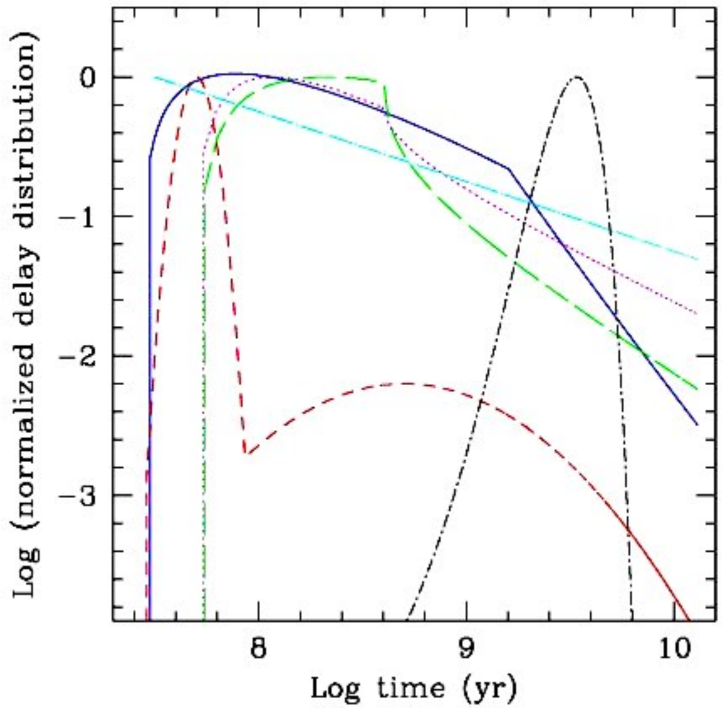
$$WR = -\omega \cdot SFR$$

The Stellar Yields

- Low and intermediate mass stars (0.8-8 Msun): produce He, N, C and heavy s-process elements and die as C-O WDs
- Massive stars (M>8-10 Msun, CC-SNe): produce alpha-elements (O, Mg..), some Fe, light s-process elements and r-process elements . They end as Type II, Ib, Ic SNe
- Type Ia SNe (WDs in binary systems) produce mainly Fe (0.6-0.7Msun per SN, mild dependence on stellar metallicity)
- Merging neutron stars (MNS) do produce r and s-process elements

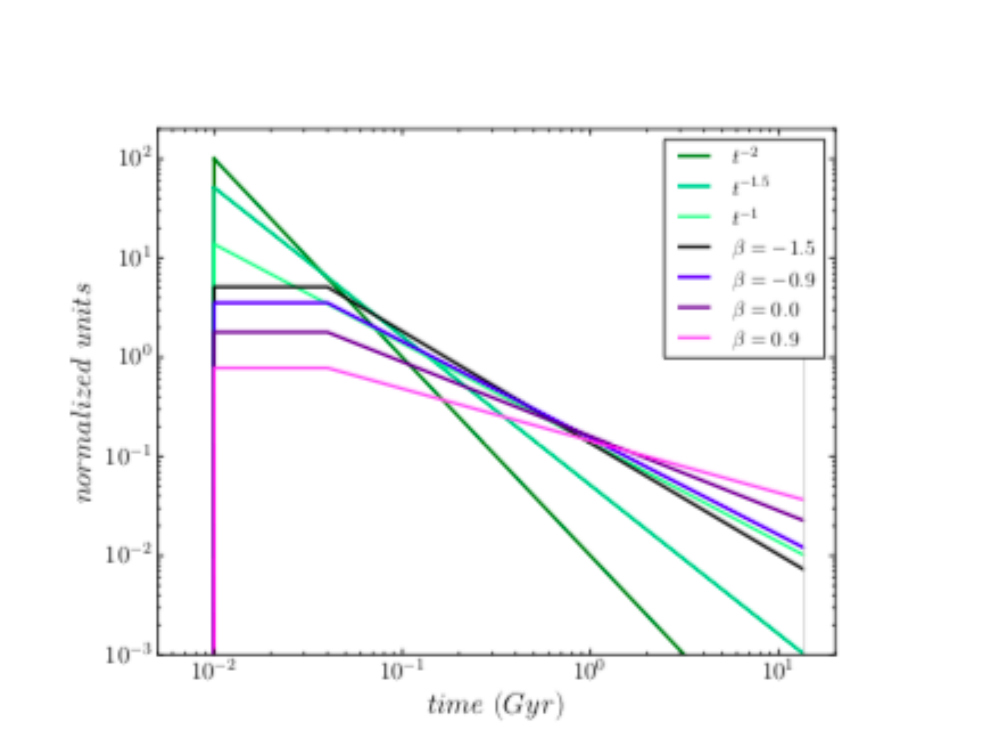
Delay time distributions for Type Ia SNe (SD, DD and empirical DTDs). Minimum delay 35Myr

- The SD model (black continuous line), the DD model (green dashed), the bimodal (Mannucci+06, red short-dashed), the cosmologically derived (Strolger+04,black dashed-dotted)
- The best progenitor models are SD and DD



Delay time distributions for Merging Neutron Stars (MNS) (Simonetti+2019; Greggio+2020)

- Three DTDs are described by simple power law functions
- The other four DTDs are derived for different values of the beta parameter describing the initial separation the MNS system
- The best is beta=-1.5 to reproduce Eu, together with MRD SNe



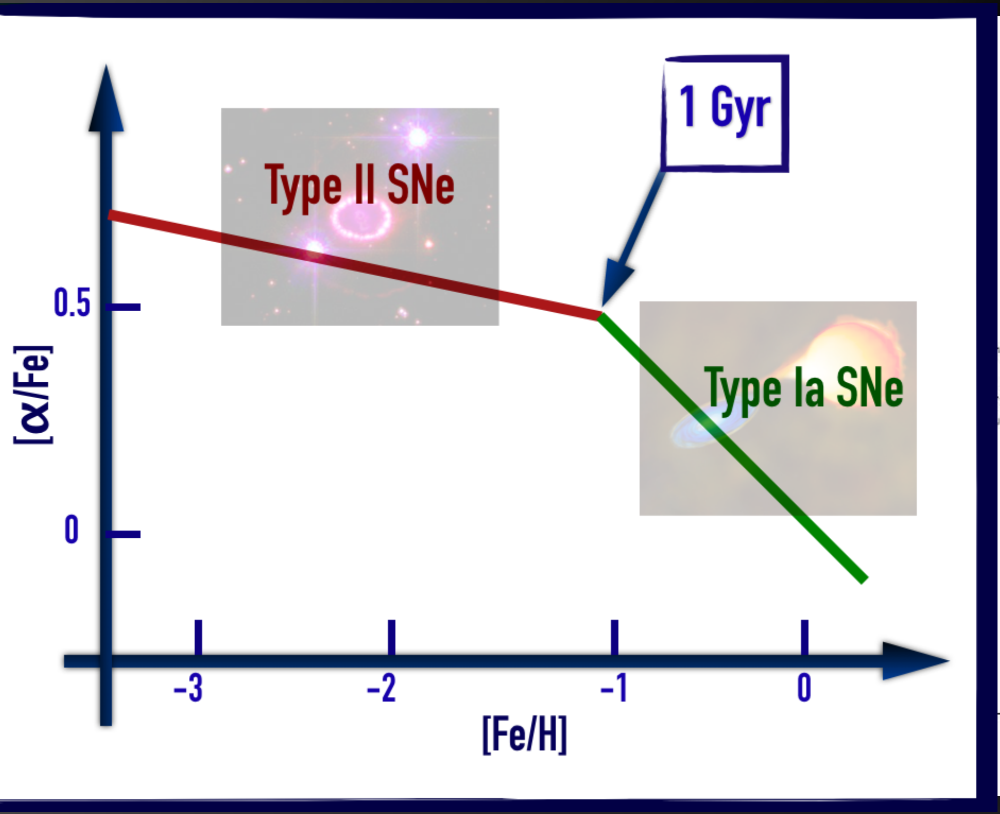
Basic Equation of Chemical Evolution

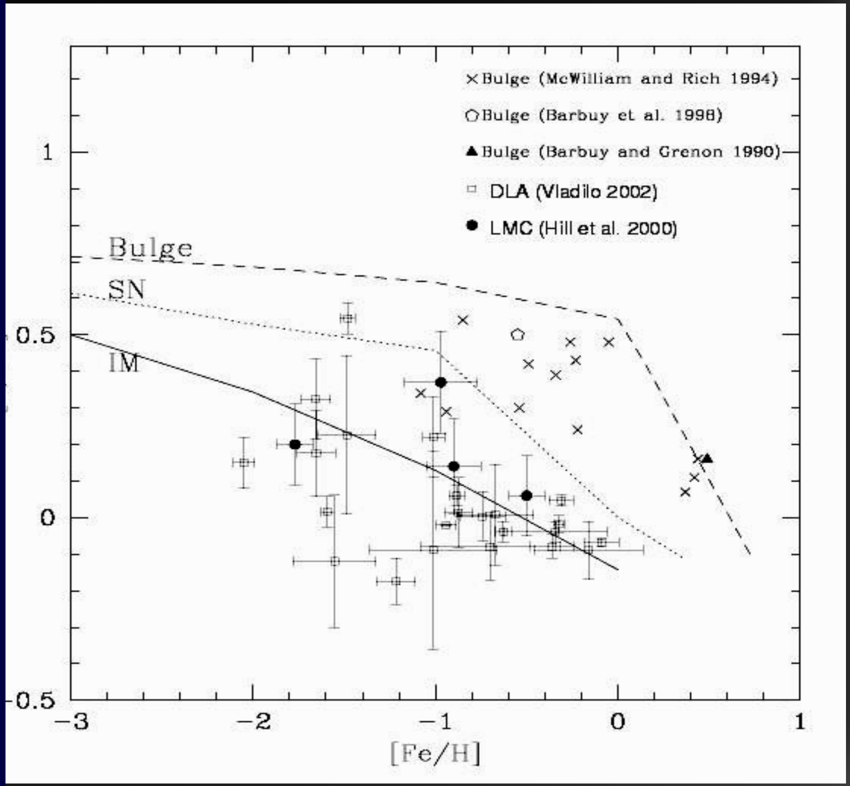
- The variation of the gas fraction in the form of the element i:

$$\dot{G}_i(t) = -\dot{G}_i^{SF} + \dot{G}_i^{prod} + \dot{G}_i^{infall} - \dot{G}_i^{wind}$$

- One equation for each chemical species i (H, D, He, metals)
- The various terms represent the gas in the form of the species i subtracted to the ISM from star formation, the gas restored by dying stars, the infalling and outflowing gas

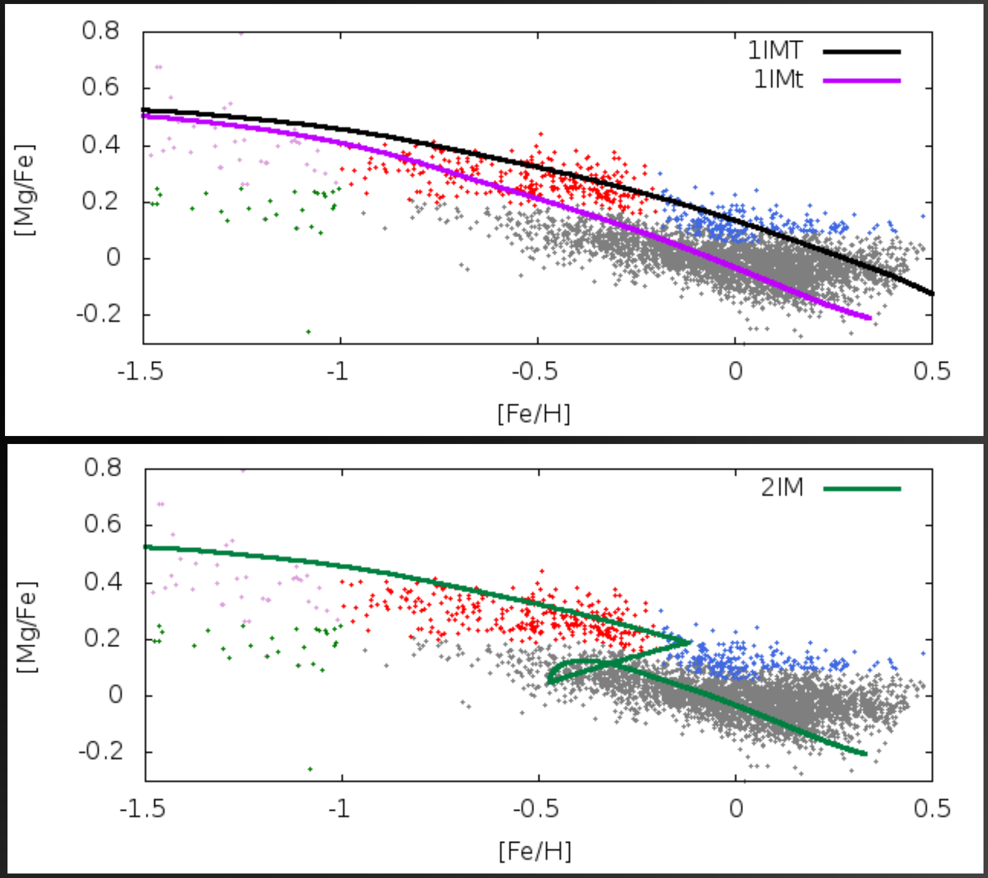
Time-delay model and the [X/Fe]vs [Fe/H] diagram in different galaxies (FM+1990;FM2012)





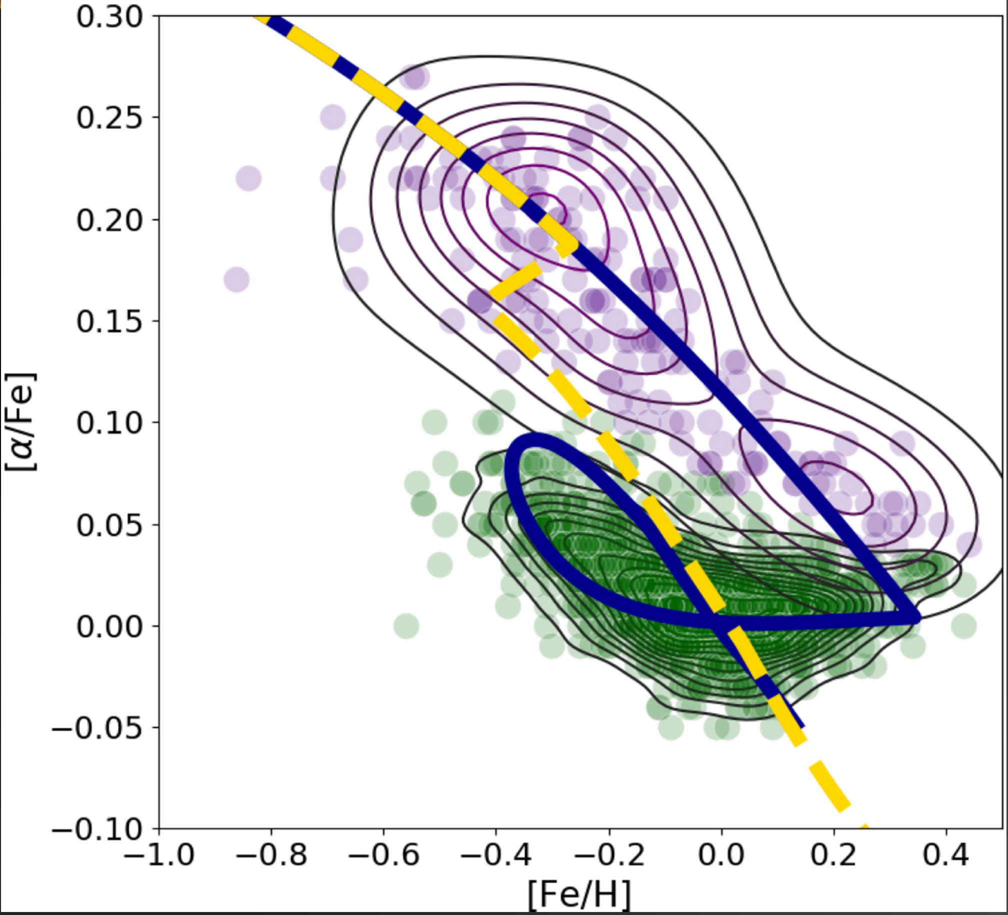
The Milky Way:bimodality in [alpha/Fe] in thick and thin disks

- Grisoni+2017 tried to reproduce the observed bimodality in the [alpha/Fe] ratios in the thick and thin disks from AMBRE survey (de Laverny+2013)
- Here are two possible explanations: I) the parallel model (upper panel), ii) the two-infall model (bottom panel)



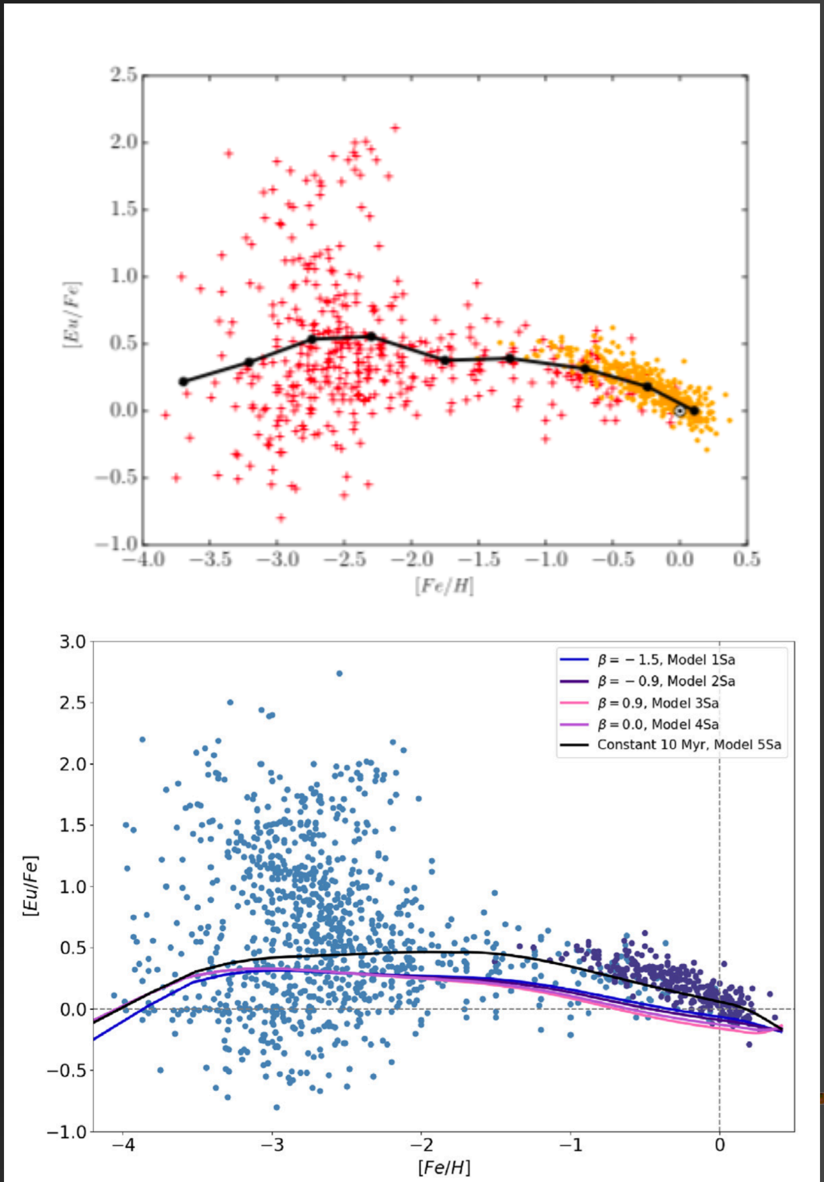
Spitoni+2019 and APOGEE data

- APOGEE data show again a strong bimodality in [alpha/Fe] ratios
- Spitoni+19 suggested a two infall model with a gap in SF of 4.3 Gyr between the formation of the thick and thin disk
- Other explanation: stellar migration(Buck20; Sharma+20), outflow (Vincenzo+21)



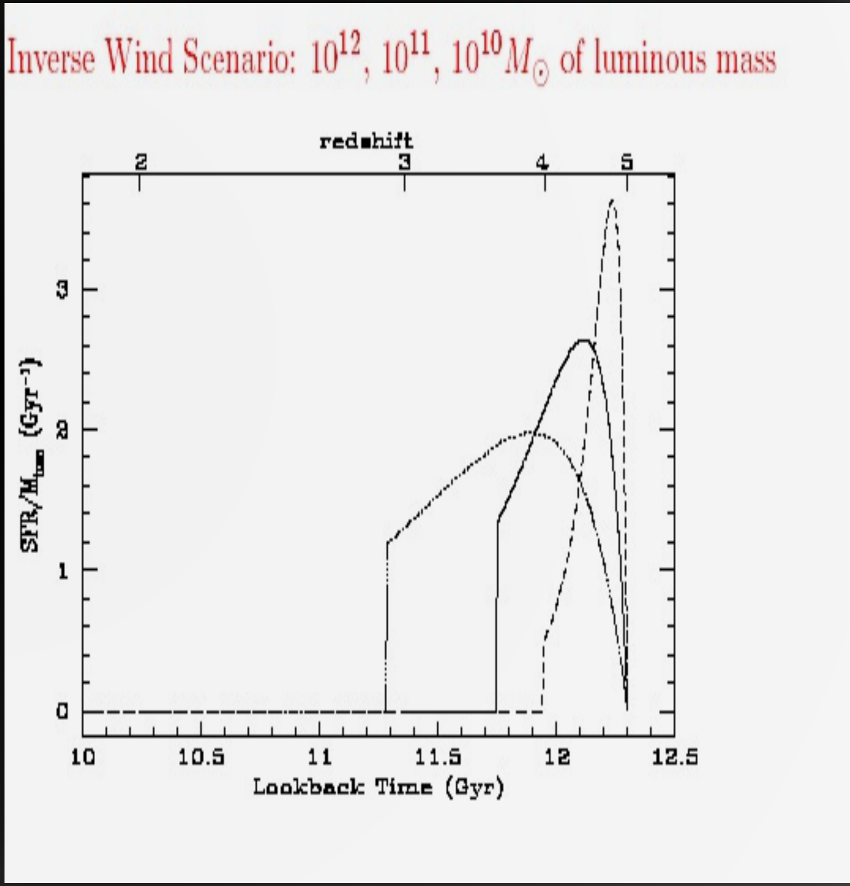
Heavy elements and merging neutron stars

- Eu behaves as an alpha-element, overabundant relatives to Fe at low metallicity, although a large spread is present (black line is data best fit)
- This requires an early source of Eu
- Here are models with a DTD for MNS plus core-collapse SNe acting at early times (FM+2014; Simonetti+ 2019; Molero et al. 2020)



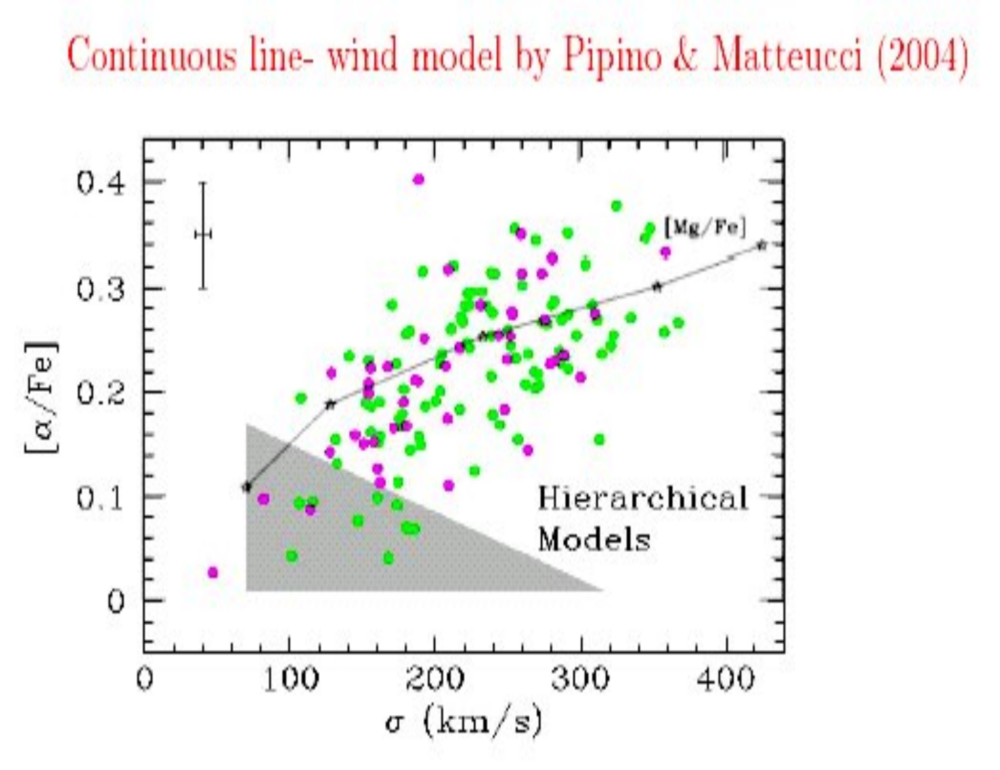
Elliptical galaxies

- Ellipticals evolve very quickly with high SFR quenched by galactic winds (timescale< 1Gyr)
- FM (1994) and Pipino & FM (2004) suggested that SF efficiency increases with galactic mass
- Thus galactic winds develop first in more massive galaxies (inverse wind scenario)
- We can call it downsizing in SF. Massive ellipticals are older than less massive ones and form faster
- In agreement with observations (Thomas,06)
- Very recently JWST has detected massive galaxies at z=10! (see Menci+2022; Labbè+2023)



[alpha/Fe] ratios in ellipticals

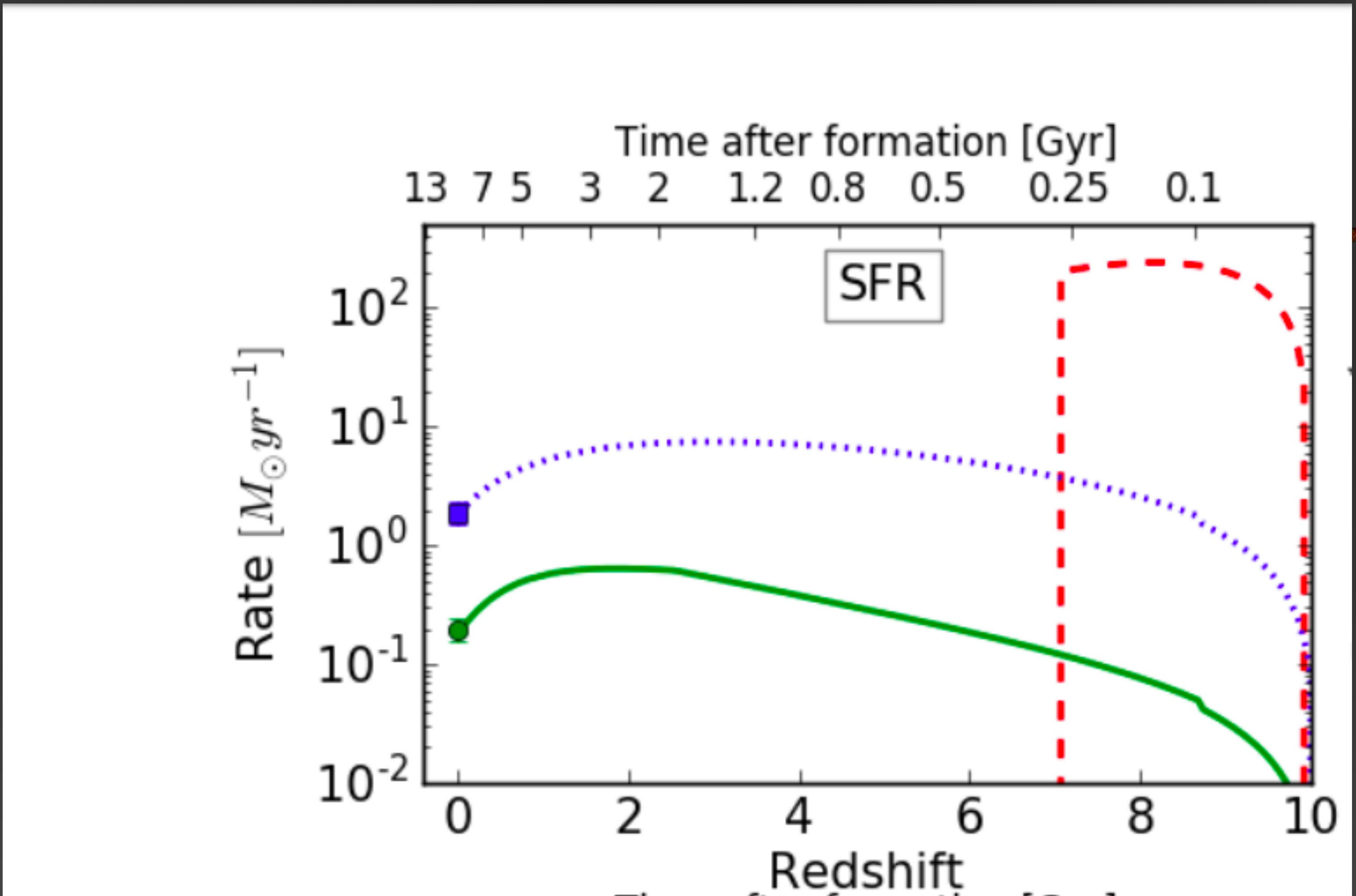
- The [alpha/Fe] ratios increase with galactic mass in ellipticals
- Downsizing in SF (SF efficiency increasing with mass) produces naturally this results.
- A consequence of the time-delay model
- Figure adapted from Thomas et al. (2002)
- More recent models for ellipticals with SN and AGN feedback confirm the fast evolution on times <1Gyr (Molero, FM, Ciotti, 2023)



Cosmic Metal Enrichment

- Cosmic metal enrichment is the chemical evolution in a unitary volume (1 Mpc^3) of the Universe
- A possible method consists in computing the chemical evolution of different galaxies and then weight their contributions on their number density at any redshift (Calura +FM 2004; Gioannini+2017; Molero+2020)
- The galaxy number density will depend on the luminosity function and the assumed galaxy formation scenario

Star formation histories for galaxies of different morphological type (Ell red; Sp blue; Irr green)



The Gioannini et al.(2017) method

- The cosmic star formation rate (CSFR) is computed as:

$$CSFR = \sum_k \psi_k(t) \cdot n_k$$

- With n_k being the number density of the k_{th} type of galaxy

The Gioannini et al. (2017) method

- The cosmic mean metallicity (CMM) can be defined as:

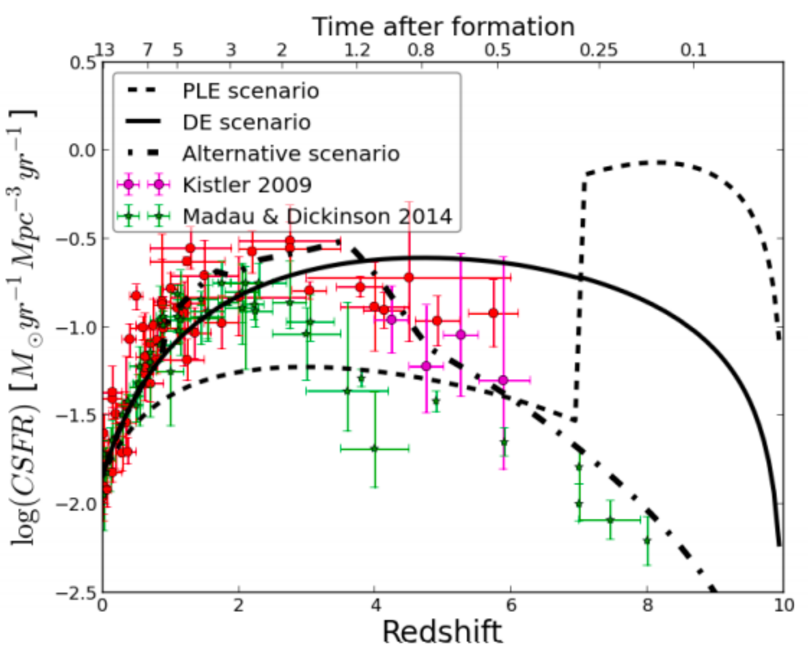
$$< Z_{cosmic}(t) >= \frac{\sum_k Z_k(t) n_k(t)}{\sum_k n_k(t)}$$

- where n_k is the number density of galaxies of morphological type k (k=Ell, Spir, Irr) and Z_k is the metallicity of the k-th type of galaxy

Mean Cosmic Metallicity and Galaxy Formation Scenarios

- The galaxy number density varies with cosmic time in different ways according to different galaxy formation scenarios
- One very simple scenario is the pure luminosity (PLE) evolution with n_k constant in time
- The hierarchical clustering (DE) scenario where ellipticals form later as merging of spirals and n_k varies in time
- An alternative scenario observationally derived (Pozzi+2015) similar to DE

Cosmic star formation rate (Gioannini et al. 2017; Molero et al. 2020)
Three different galaxy formation scenarios



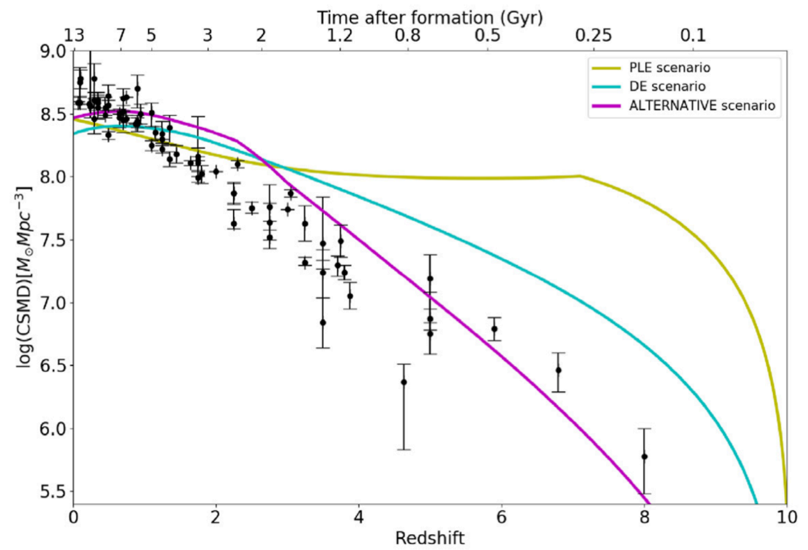
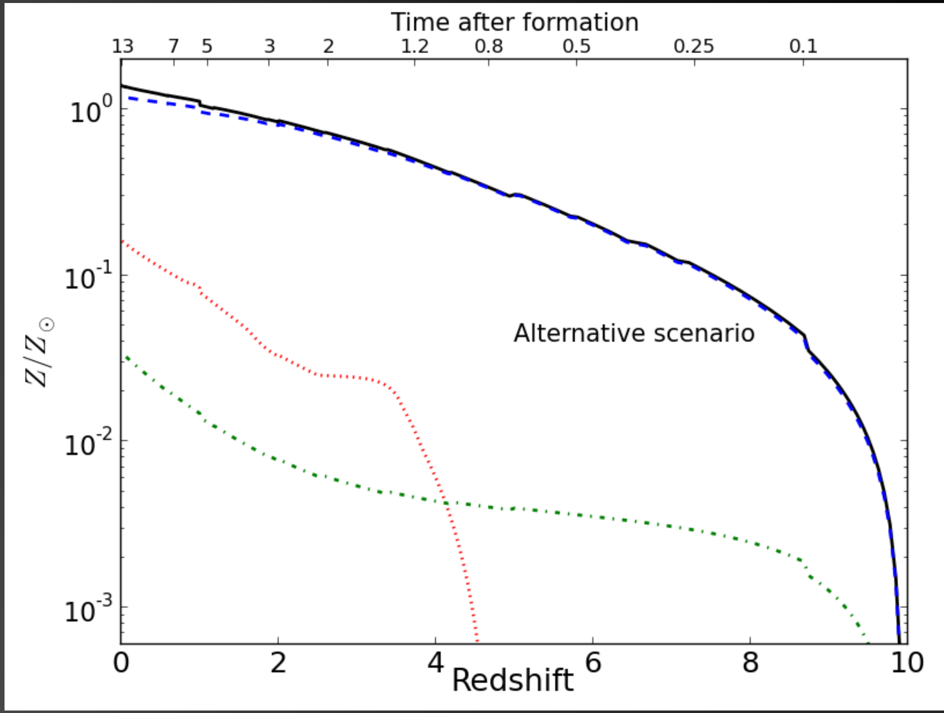
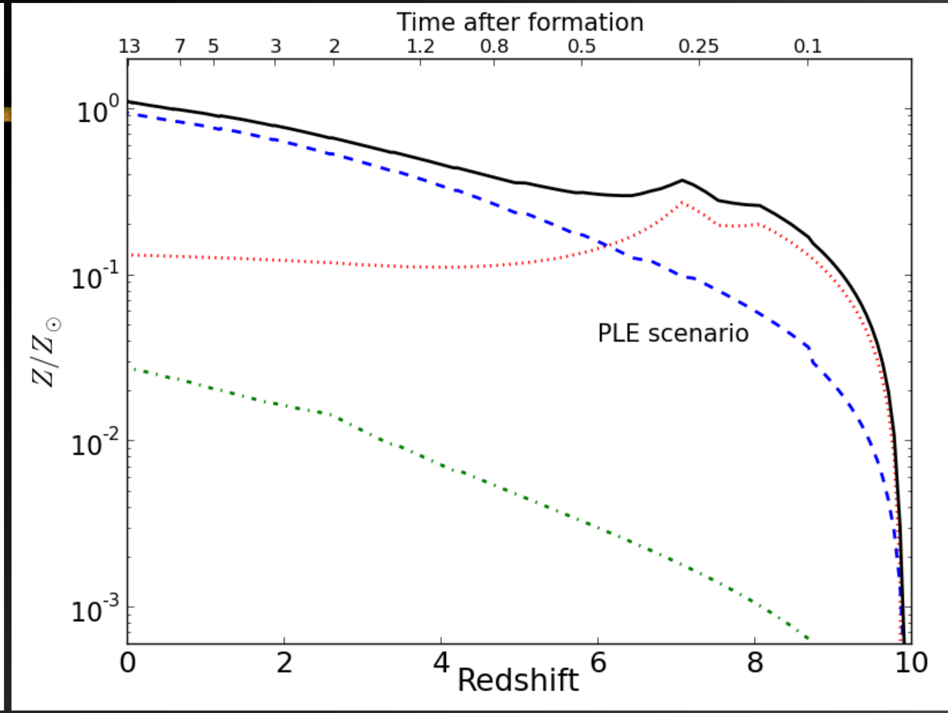


Figure 12. Cosmic stellar mass density (CSMD) as a function of redshift for the three different cosmological scenarios of galaxy formation. Observational data are a collection from Madau & Dickinson (2014).

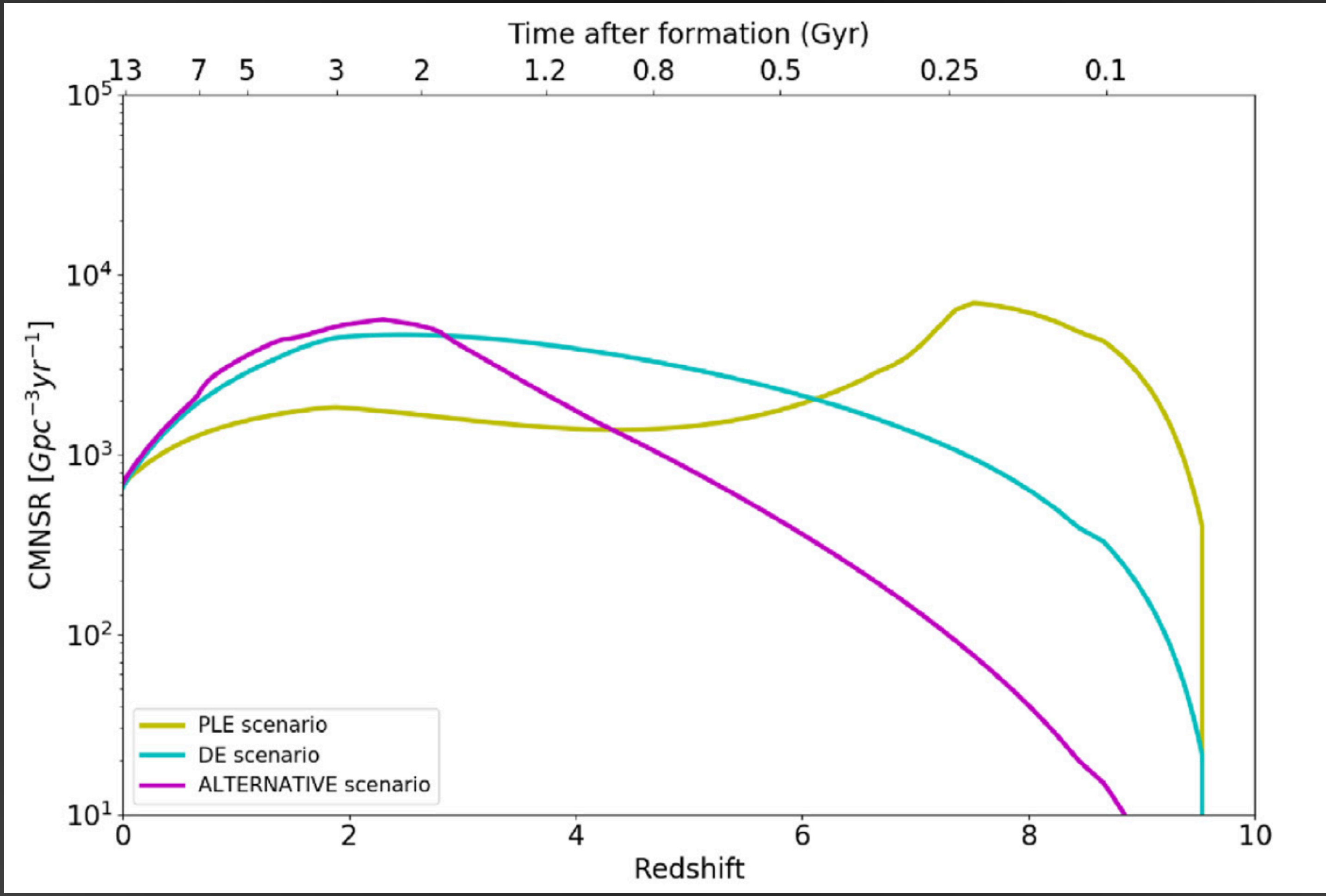
Evolution of average cosmic metallicity (Gioannini+2017)

- Ell-red; Sp-blue; Irr-green, global Z-black; Z_{sun}=0.0134





Predicted Cosmic Rate of Merging Neutron Stars: best DTD for MNS plus CC-SNe (Molero+2020)



Summary

- Astroarchaeology: from abundances and abundance ratios we can infer the typical timescales of formation of galaxies: spheroids formed quickly (< 1 Gyr) while disks formed on much longer timescales (several Gyr and inside-out)
- Massive spheroids already evolved are expected to be found at high z (JWST, and this is the surprise, seems to confirm that)
- The [alpha/Fe] dichotomy in the thick and thin disk stars of the Milky Way can be explained by sharp transitions of either SFR and infall, or outflow and perhaps with a contribution by stellar migration

Summary

- Cosmic metal enrichment depends on the assumed model of galaxy formation, but in any scenario the CAM has increased very fast: after 0.25 Gyr the CAM was already equal or larger than 0.1 solar
- Metallicities measured in galaxies at z=8 with JWST suggest metallicities of 0.3 solar! (Curti et al. 2023)
- Irregular galaxies are negligible metal producers in any scenario, the role of ellipticals is strongly dependent on the assumed scenario for galaxy formation