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Some considerations on abundance gradients in galaxies

Final remarks

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Abstract. We discuss the main physical processes which can be responsible for the formation of abundance gradients in galaxies. In particular, we show results relative to the gradients in the Milky Way thin disk and compare them with observations of HII regions, planetary nebulae (PNe), open clusters and Cepheids.We conclude that the inside-out formation of the disk is a necessary assumption but is not enough to reproduce the observed gradients. The addiction of one or more of the following processes, such as radial gas flows, variable efficiency of star formation with Galactic radius and a threshold gas density for star formation, are necessary. Finally, we discuss high red-shift abundance gradients and the predictions of chemical evolution models.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: abundances – Cosmology: observations

1. Introduction

Abundance gradients are measured in the Milky Way disk as well as in disks of spirals and also in elliptical galaxies and indicate that the concentration of metals decreases with the galactocentric distance. By interpreting abundance gradients, we gain insight on the mechanisms of formation of galaxies. Abundance gradients in the Galactic disk are traced by HII regions, planetary nebulae (PNe), B stars, open clusters and Cepheids. In the past years, a great deal of chemical evolution models and cosmological simulations, predicting abundance gradients in galaxies, has appeared (Palla et al. (2020); Vincenzo & Kobayashi (2018); Grisoni et al. (2018); Cavichia et al. (2014); Mott et al. (2013); Pilkington et al. (2012); Bilitewski & Schönrich (2012); Spitoni & Matteucci (2011); Colavitti et al. (2009); Portinari & Chiosi (2000); Chiappini et al. (2001); Boissier & Prantzos (1999); Matteucci & Francois (1989)). The physical processes which concur to the gradient formation are: i) an inside-out formation of galaxy disks (Larson (1976); Matteucci & Francois (1989)), where the innermost regions form by a faster gas accretion than the outermost ones. This can be obtained by assuming a time scale of gas accretion increasing with Galactocentric distance (Matteucci & Francois (1989); Chiappini et al. (2001)),ii) A threshold gas density for star formation (Chiappini et al. (2001)), iii) a variable efficiency of star formation along the galaxy disk (Colavitti et al. (2009); Palla et al. (2020)). Concerning high redshift abundance gradients, we remind the paper by Cresci et al. (2010), where a gradient inversion was observed in the O gradient at red-shift $z \sim 3$, only 2 Gyr after the Big Bang. In other words, at $z \sim 3$ the O gradient decreases towards the galaxy centre. This fact has been explained by the large gas accretion occurring at early times in spiral disks (see also Mott et al. (2013)). We will discuss in the next Sections the results on abundance gradients in the Milky Way obtained by various chemical models, and try to infer constraints on both stellar nucleosynthesis and disk formation.

2. Gradient predictions from chemical evolution models

Among the first papers suggesting inside-out disk formation to reproduce abundance gradients along the Galactic disk were Matteucci & Francois (1989); Chiappini et al. (2001). In Chiappini et al. (2001), it was adopted the two-infall model of Chiappini et al. (1997), where two major episodes of gas accretion were considered. The timescale for gas accretion in the first episode was assumed to be shorter and the star formation rate (SFR) higher than in the second episode. In particular, the timescale for the formation of the disk at the solar ring was estimated to be 7 – 8 Gyr. The first episode formed the halo and thick disk, while the second formed the thin disk. A timescale for gas accretion increasing with Galactocentric distance plus a threshold gas density for star formation (Kennicutt (1989)) were also adopted. The increasing timescale with Galactocentric distance, simulates an inside-out disk formation. This hypothesis, suggested first by Larson (1976), has a physical basis, since tidal forces are more intense in the innermost regions of the disk, thus attracting more extra-galactic gas.

The predicted gradients were fitting the data available at that time and predicted that gradients should steepen with cosmic time. In that model the efficiency of star formation, namely the star formation rate per unit mass of gas, was assumed constant with Galactocentric radius. However, in Boissier & Prantzos (1999); Colavitti et al. (2009) it was shown that, assuming a variable star formation efficiency along the Galactic disk, the abundance gradients should instead flatten with time. Therefore, by establishing the evolution of gradients with time would impose constraints on the star formation rate (SFR). In Figure 1 we show the recent results by Palla et al. (2020), who adopted a revised version of the two-infall model adapted to the thick and thin disk. It is evident from Figure 1, that a model with only inside-out disk formation and threshold in the gas density for star formation are not able to reproduce the most recent data on abundance gradients. A variable efficiency of star formation or radial gas flows are instead necessary to fit the data. In fact, in Figure 1 the black continuous lines represent the predictions of the disk model MWA which assumes only inside-out formation for the disk. The other lines represent models where different prescriptions for variable efficiency of star formation (left panel) or for radial gas flows (right panel) are considered. In Figure 2 we show an even more recent comparison theory-observations for the Mg gradient in the Milky Way from Spitoni et al. (2021), where the observed gradient is reproduced by assuming an inside-out disk formation and a variable efficiency of star formation as a function of the Galactocentric distance.

2.1. Gradients of different chemical elements and abundance ratios

All gradient of metals along the Milky Way disk are negative, but the slope can change for each element. In particular, the gradients of elements formed on long timescales, such as N and Fe, are generally steeper than gradients formed on short timescales, such as oxygen. In Figures 3 and 4 we show the predicted and observed gradients of O and Fe in the Milky Way

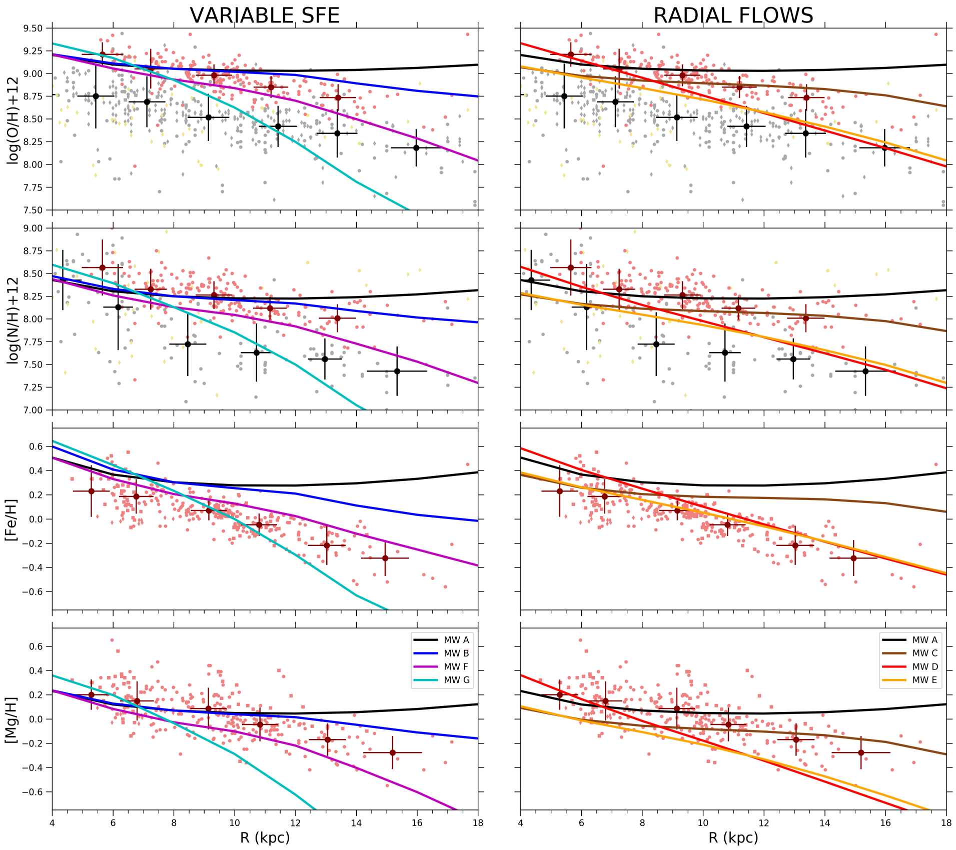

Fig. 1. Abundance gradients for the Milky Way disk. Comparison between theory and observations. For details on models and data see Palla et al. (2020). Model MW A contains only inside-out formation of the thin disk and no radial gas flows, constant efficiency of star formation with Galactocentric distance; Model MW B is like MW A but it assumes a variable star formation efficiency; Model MW C has inside-out, constant star formation efficiency and radial gas flows with constant velocity: Model MW D is like Model MW C but with a variable velocity for radial gas flows; Model MW E is like Model MW D but with a different law for the variation of the velocity of radial flows; Model MW F is like Model MW C but with variable efficiency of star formation; Model MW G is like Model MW D but with variable star formation efficiency.

disk (Mott et al. (2013)). The data shown in those two figures are from Galactic Cepheids. The model predictions reported in the figures refer to a best model with radial gas flows plus inside-out (continuous lines) and to a model only with inside-out (dashed lines). It is clear that the Fe gradient is slightly steeper than the O one and that the sole inside-out mechanism is not enough to reproduce the gradient in the outermost disk regions. Again, although the inside out formation is a physical process that should be active, it is not the sole cause of abundance gradients in our Galaxy.

Concerning gradients of abundance ratios, they are predicted to be flat if the two elements are produced on the same timescales

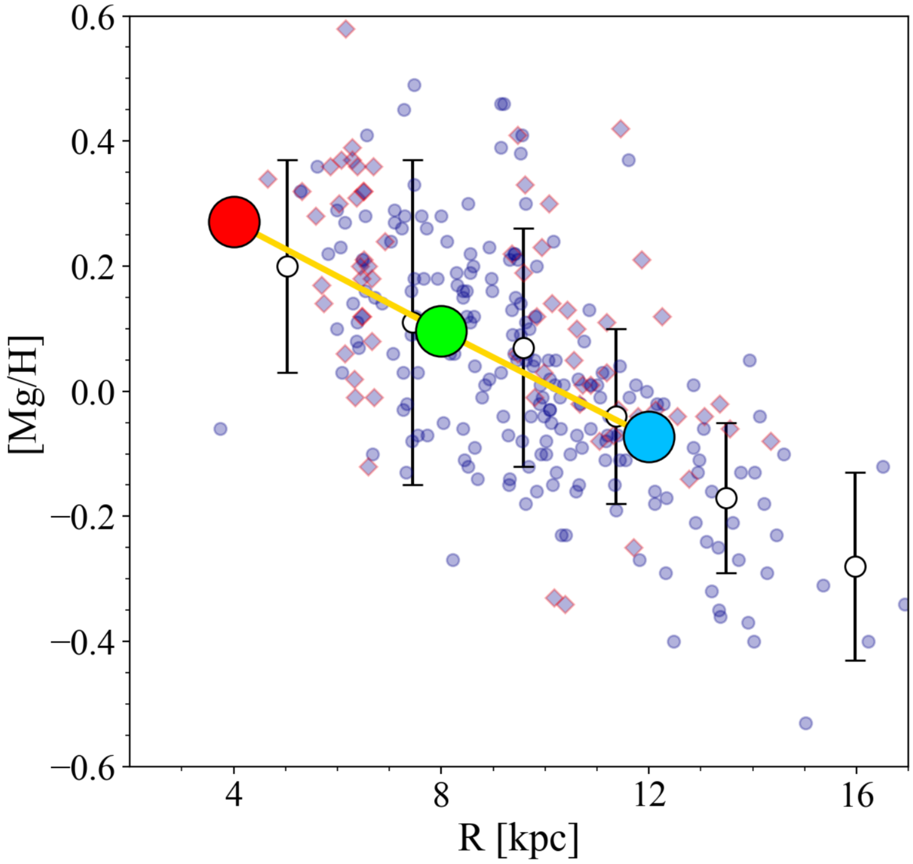

Fig. 2. The Mg gradient in the Milky Way disk.For details on the model and data see Spitoni et al. (2021). The model presented here assumes inside-out disk formation and variable efficiency of star formation along the disk, but no radial gas flows.

(see Esteban's talk at this conference). If instead, the two elements are produced on different timescales, such as N and Fe, where N is produced mainly by low and intermediate mass stars (0.8-8$M_\odot$) and partly by massive stars ($M > 8M_\odot$), whereas O is entirely produced by massive stars, the gradient can be steeper. However, since N in massive stars is likely to be produced as a primary element (no dependence on the initial stellar metallicity), then we expect the N/O gradient at high red-hift to be flat. Hayden-Pawson in the talk at this conference showed that high red-shift gradients are rather flat. This confirms indeed the theoretical expectation of primary N from massive stars, first suggested by Matteucci (1986) and later confirmed by stellar evolutionary models of massive stars with rotation by Meynet & Maeder (2002).

In Figure 5, we report the results of Grisoni et al. (2018) for the [Mg/Fe] vs.[Fe/H] relation as function of the Galactocentric distance, for three different models describing the evolution of the thin disk. In particular, the model labelled 2IMA is a classical two-infall model with constant efficiency of star formation and no radial gas flows. The Model 1IMA is a one-infall model (a unique gas accretion episode

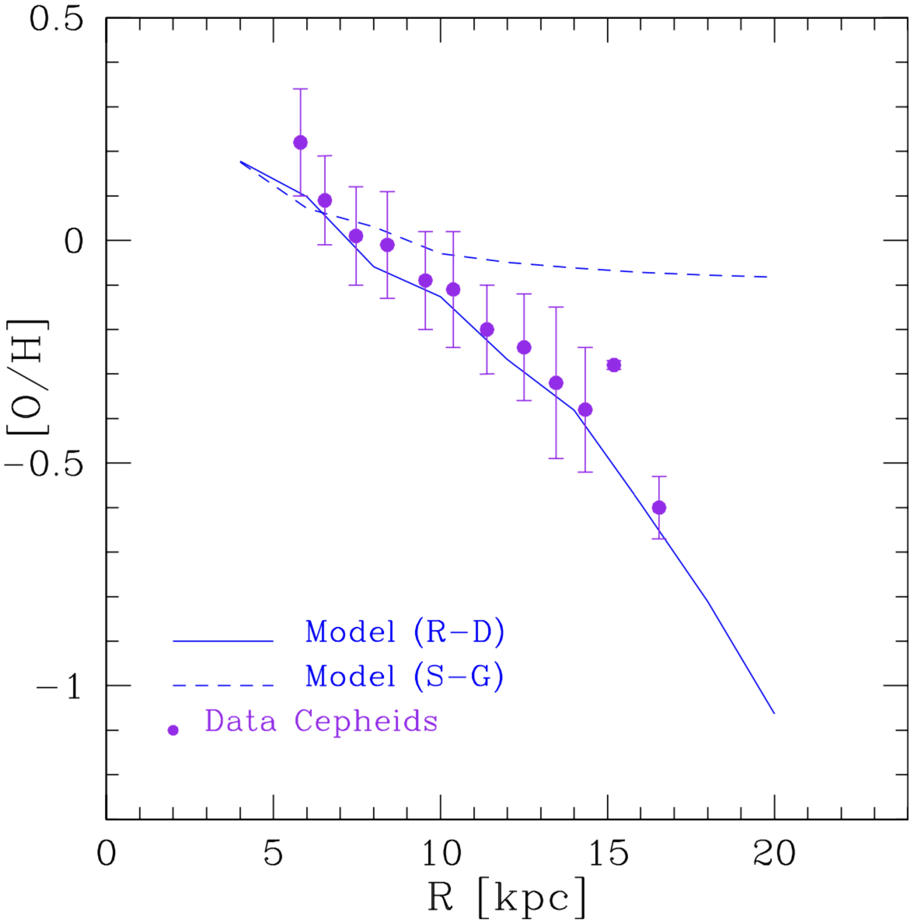

Fig. 3. The O gradient in the Milky Way disk. Figure from Mott et al. (2013)). The data are from Luck & Lambert (2011). Model (R-D) contains inside-out disk formation, constant efficiency of star formation and radial gas flows; Model (S-G) is like Model (R-D) without radial gas flows. As one can see, the model with inside out disk formation, constant star formation efficiency and no radial gas flows does not reproduce the data.

during which thick and thin disk form in sequence) with constant star formation efficiency and no radial flows, the model 1IMB is one-infall and has a variable efficiency of star formation and no radial flows, the modek 1IMC is one-infall and has radial gas flows but constant star formation efficiency, model 1IMD is one infall and assumes both variable efficiency and radial gas flows. The predictions of the [Mg/Fe] vs. [Fe/H] relations correspond to three different thin disk rings at 4, 8 and 14 Kpc from the Galactic center. The model predictions are compared to data from APOGEE (Hayden et al. (2015)). Looking at Figure 5, we can see that one-infall models with both variable star formation efficiency and radial gas flows does not reproduce the data, especially at large Galactocentric distances. The model with only variable efficiency of star formation does well reproduce the data, although at 14

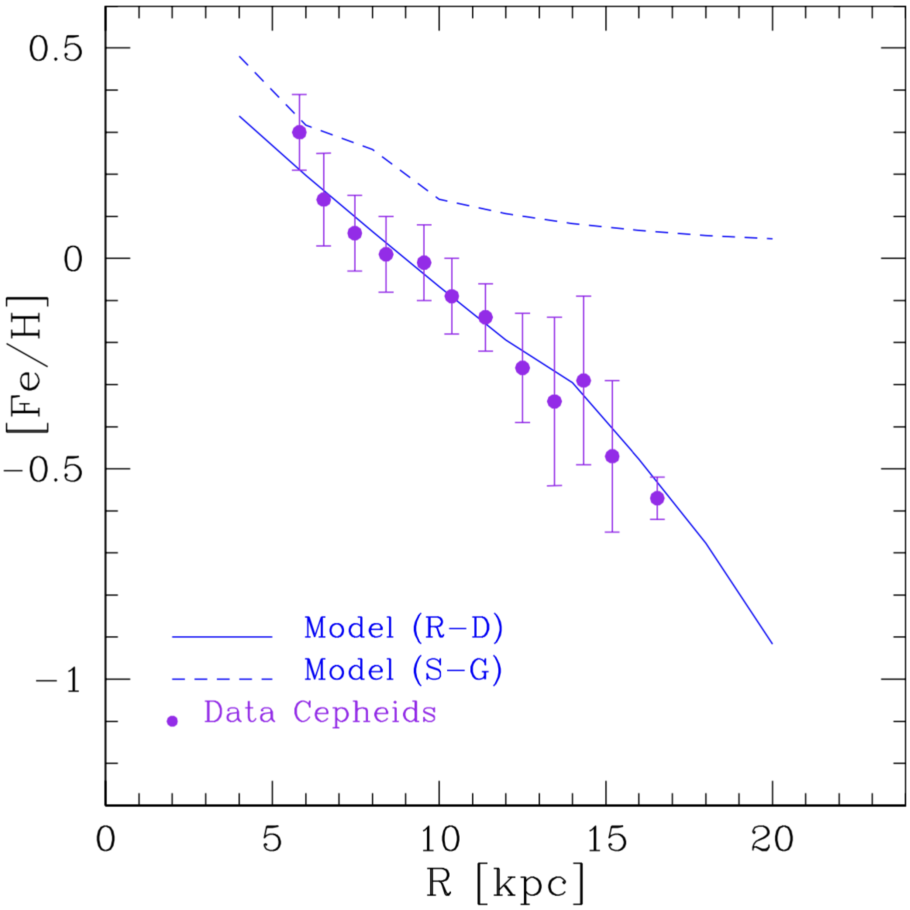

Fig. 4. The Fe gradient in the Milky Way disk. Figure from Mott et al. (2013)). The data are from Luck & Lambert (2011). Te model are the same as in Figure 3.

kpc the predicted [Fe/H] does not cover the observed range, but on the other hand it reproduces at best the observed gradients of the abundances of single elements (see also Figure 1). Therefore, we can conclude, from Grisoni's paper, that a model with variable efficiency of star formation along the thin disk can well reproduce the gradients of single elements and abundance ratios.

2.2. Evolution of gradients with time

How do gradients evolve in time? Do they steepen or flatten? The answers to these questions are not yet clear since we lack data for gradients at different cosmic epochs. However, with the advent of asteroseismology the stellar ages are better known and Casali (this conference) showed that the gradient of [Fe/H] seem to flatten in time (see also Kaur's talk). From the theoretical point of view the gradient evolution crucially depends upon the assumed star formation and gas accretion laws. A variable efficiency of star formation along the disk can

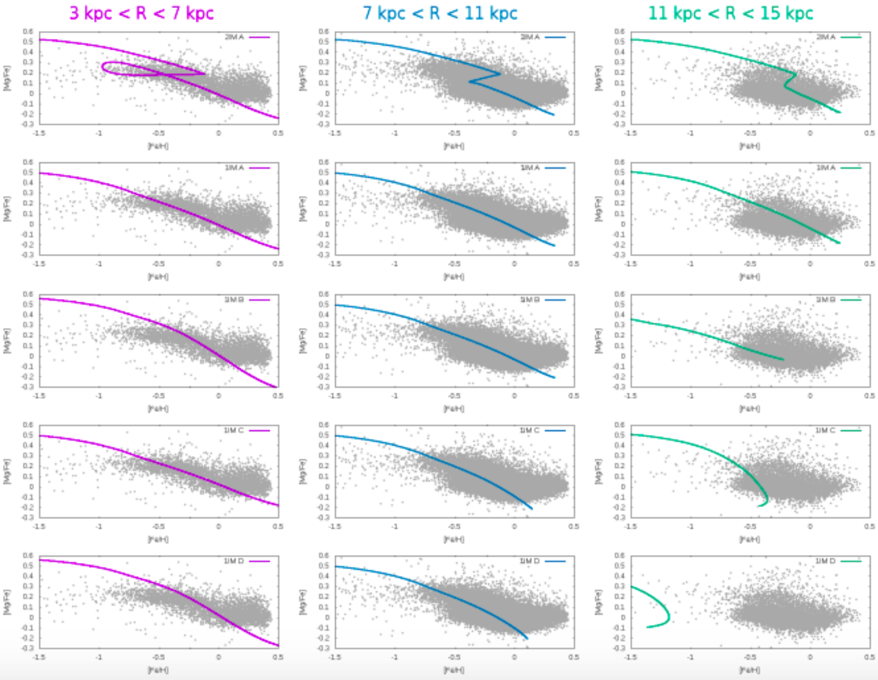

Fig. 5. Observed and predicted abundance patterns of [Mg/Fe] vs. [Fe/H]. The data are from Hayden et al. (2015) and are divided as follows: 3-7 kpc (left panels), 7-11 kpc (central panels), 11-15 kpc (right panels). The predictions (see text) are from model 2IM A (upper panels), 1IM A (second panels), 1IM B (third panels), 1IM C (fourth panels), 1IM D (fifth panels) at different Galactocentric distances: 4 kpc (magenta line), 8 (blue line), 14 (green line). The Figure is from Grisoni et al. (2018).The data are from Hayden et al. (2015).

produce a flattening of the gradient with time, while a constant star formation efficiency produces a steepening. Also gas accretion which varies in time can strongly affect the gradient evolution and even produce an inversion of gradients, as we will see in the next Section.

3. High red-shift gradients

Mott et al. (2013) predicted the gradient evolution with cosmic time (red-shift) for a Milky Way-like galaxy (see Figure 6). The adopted model was the two-infall one including radial gas flows along the thin disk as well as constant star formation efficiency with Galactic radius. They found that at red-shift $z > 3$ the O gradient has indeed an inversion towards the center. This inversion can be explained by the adopted two-infall model of Chiappini et al. (1997), in which the gas accretion rate at the beginning of the formation of the disk is high. Because of that, the dilution, due to the primordial accreting gas, predominates over the chemical enrichment due to star formation. At later times, the chemical enrichment takes over the gas accretion, which decreases following an exponential law, and the O abundance starts increasing towards the center, and the gradient steepens in time. Therefore, there is a possible explanation to the gradient inversion at high red-shift, if more data will confirm it.

4. Conclusions

Here is the summary of what discussed above:

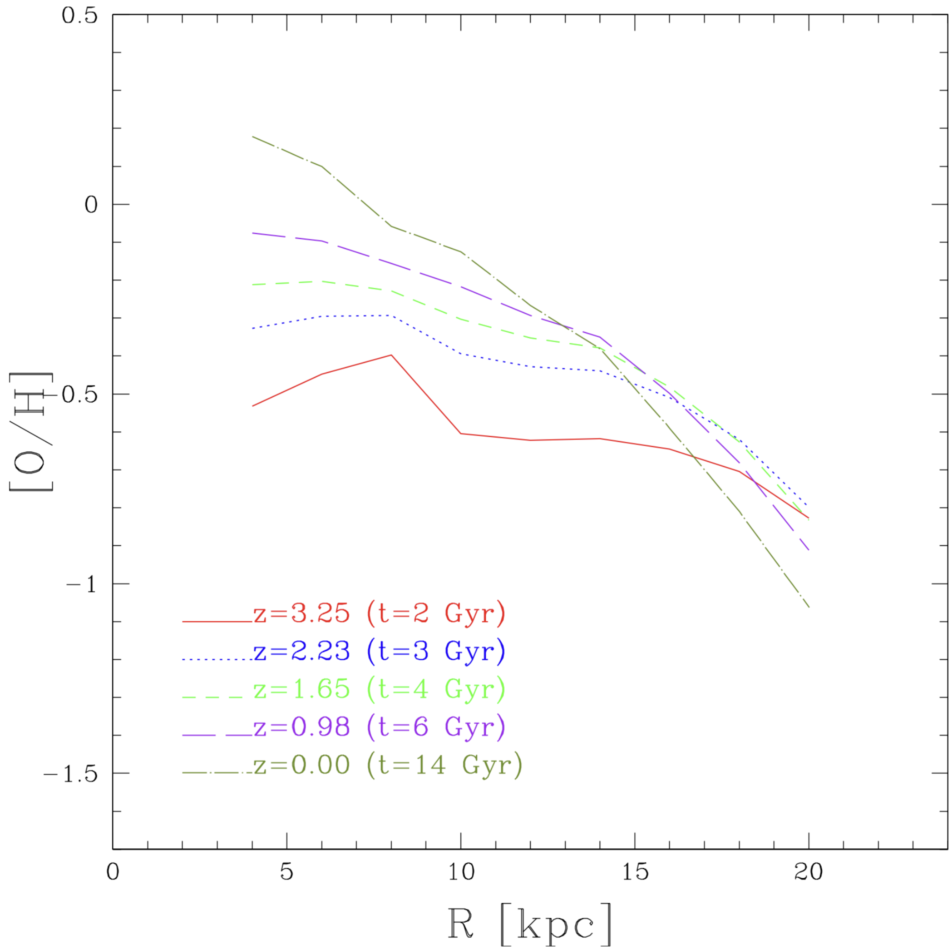

Fig. 6. The predicted evolution of the O gradient with cosmic time in the Milky Way disk. Figure from Mott et al. (2013)). The various curves refer to gradients at different red-shifts, as indicated in the Figure. The Model reported here is Model (R-D), shown in Figure 4.

- Abundance gradients are strong tools to impose constraints on the formation of galaxy disks and in general on galaxy formation. An inside out disk formation is required from physical arguments and it favors the formation of abundance gradients.
- Stellar migration can flatten gradients (see Minchev's talk) whereas gas radial migration steepen them (see Palla's talk).
- We cannot reproduce abundance gradients only with inside-out and/or gas threshold for star formation. Only the presence of radial gas flows or variable efficiency of star formation along the disc can reproduce the data (Palla's and Spitoni's talks).
- Still open is the question of the evolution of gradients in time from the observational point of view, but stellar ages with asteroseismology seem to be a very promising way to solve it (Casali's and Valentini's talks).
- Li gradient along the thin Galactic disk suggests a nova rate flattening in time (see Romano's talk).

- The observed gradient inversion at high red-shift, if confirmed, could be due to the strong infall rate that formed the disk at early times.

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