

# Effects of radial flows of gas and galactic fountains on the chemical evolution of galaxies

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- 1 Galactic fountains
  - The Milky Way: Spitoni et al. (2008)
  - M31: Spitoni et al. (2013)
  - The Galactic fountain delay model for the MW
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## 1 Galactic fountains

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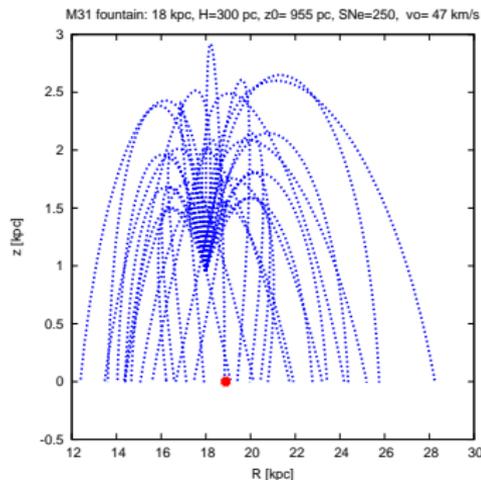
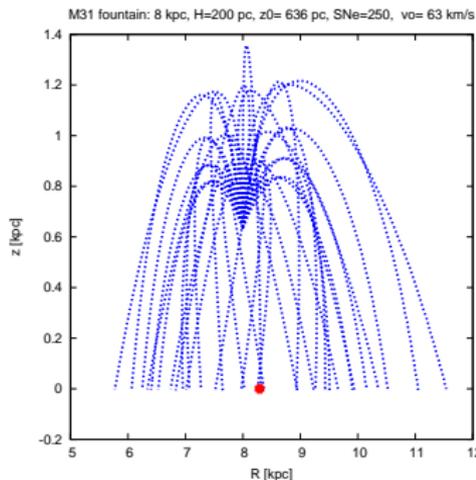
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## 3 Summary



M31: Spitoni et al. (2013)

M31: 8 kpc ( $H=200$  pc), 18 kpc ( $H=300$  pc)

- 8 kpc: The superbubble is already fragmented in clouds when its top reaches  $z = 636$  pc this phase lasts 11.7 Myr. The average landing coordinate is 8.29 kpc (only  $\Delta R=0.29$  kpc). The average orbit time is 42.7 Myr.
- 18 kpc: The superbubble is already fragmented in clouds when its top reaches  $z = 955$  pc ( $\simeq 3H$ ). This phase lasts 22.9 Myr. The average landing coordinate is 18.89 kpc (only  $\Delta R=0.89$  kpc). The average orbit time is 147.1 Myr.

## The prescriptions of the model of Spitoni et al. (2009)

- We applied the delay on the two infall model of François et al (2004) (an updated version of Chiappini et al. 2001)
- We considered the delay only for massive stars  $M > 8M_{\odot}$ .
- We computed this effect only on thin disk stars (e. g. only for stars born after the halo-thick disk transition) because the “break out” event, necessary for a galactic fountain, requires that the OB associations sit on a plane stratified disk where the density decreases along the z-axis.
- Time delay: 0.1, 0.2, 0.5, 1.0 Gyr (... a delay of 1.0 Gyr can be obtained in case of a OB association composed by  $10^4$  SNe).

## The Galactic fountain delay model for the MW

# The delay produced by Galactic fountain in the MW (Spitoni et al. 2008)

$$\langle t_{total} \rangle = t_{final} + \langle t_{orbit} \rangle$$

The average time  $\langle t_{total} \rangle$  [Myr].

	4 kpc	8 kpc	12 kpc
10 SNe	43	53	75
50 SNe	36	54	87
100 SNe	36	57	96
500 SNe	38	75	133

The maximum  $t_{total}$  as a function of the galactocentric distance.

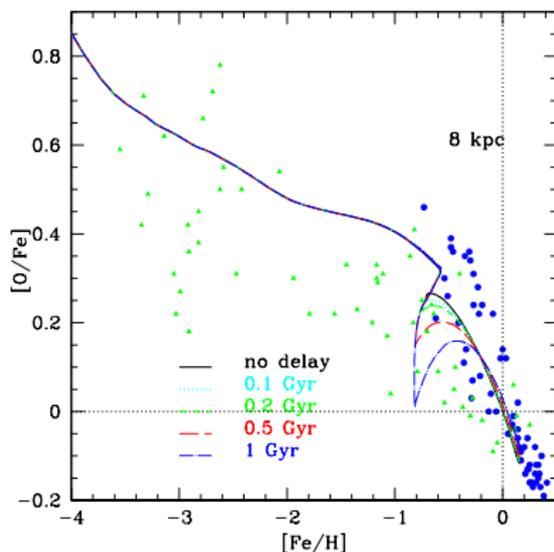
	4 kpc	8 kpc	12 kpc
Maximum delay	48 Myr	114 Myr	245 Myr

The Galactic fountain delay model for the MW

# The chemical evolution equation + time delay from galactic fountains

$$\begin{aligned}
 \dot{G}_i(r, t) = & -\psi(r, t)X_i(r, t) \\
 & + \int_{M_L}^{M_{BM}} \psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm \\
 & + A_{Ia} \int_{M_{BM}}^{M_{BM}} \phi(M_B) \cdot \left[ \int_{\mu_m}^{0.5} f(\mu) \psi(r, t - \tau_{m2}) Q_{mi}^{SNIa}(t - \tau_{m2}) d\mu \right] dM_B \\
 & + (1 - A_{Ia}) \int_{M_{BM}}^{M_{BM}} \psi(r, t - \tau_m - \Delta t_1) Q_{mi}(t - \tau_m - \Delta t_1) \phi(m) dm \\
 & + \int_{M_{BM}}^{M_U} \psi(r, t - \tau_m - \Delta t_1) Q_{mi}(t - \tau_m - \Delta t_1) \phi(m) dm \\
 & + X_{A_j} B(r, t)
 \end{aligned}$$

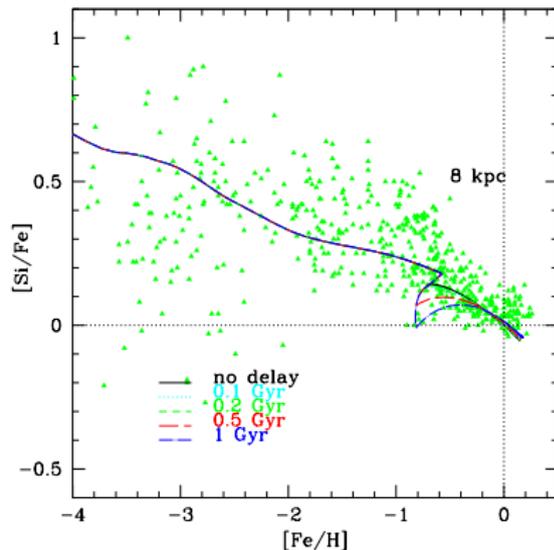
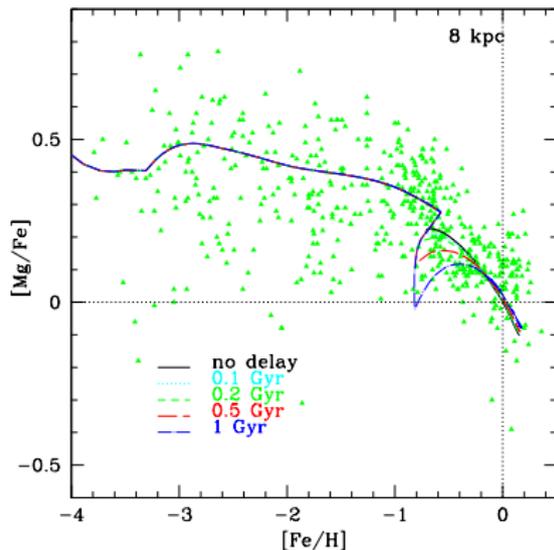
## Galactic fountain delay model results: Spitoni et al. (2009)



Data Bensby (2004), Francois et al. (2004).

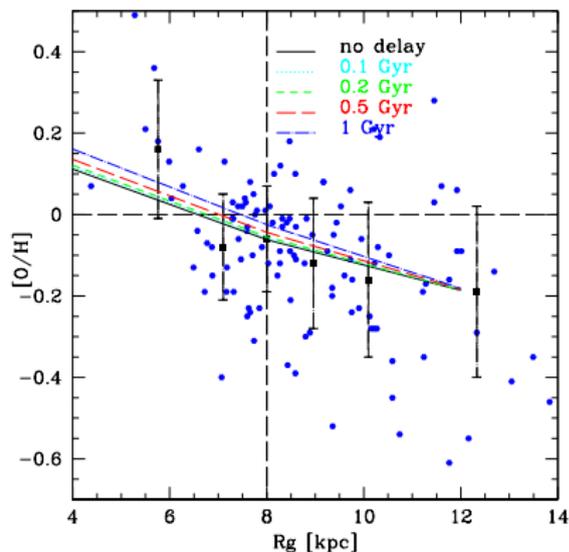
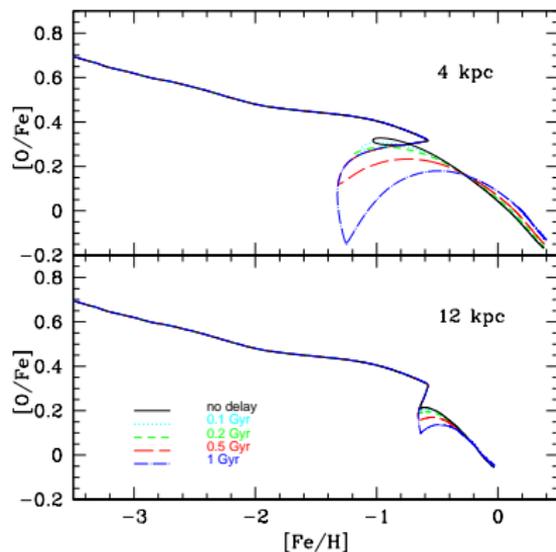
- The main feature of the galactic fountain is an enhancement of the drop in the  $[O/Fe]$  ratio. The galactic fountain delay has the effect of increasing the period during which there is no pollution from type II SNe.
- Type Ia SNe are not affected by the delay
- The maximum possible delay must be lower than 1.0 Gyr

## Galactic fountain delay model results: Spitoni et al. (2009)



- The effect of the galactic fountain depends on the considered element. Si, which is also produced by type Ia SNe in a non negligible amount, shows a smaller drop of the  $[Si/Fe]$  quantity compared to O and Mg.

## Galactic fountain delay model results: Spitoni et al. (2009)



- The effect depends on the galactocentric distance.
- The time delay produced by a galactic fountain has a negligible effect on the abundance gradient in the Galaxy disk

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# The radial inflow as a consequence of the infall

- The majority of chemical evolution models assume that the Galactic disk forms by means of infall of gas and divide the disk into several independent rings without exchange of matter between them
- However, if gas infall is important, the Galactic disk is not adequately described by a simple multi-zone model with separated zones (Mayor & Vigroux 1981). To maintain consistency, **radial gas flows have to be taken into account** as a dynamical consequence of infall. Lacey & Fall (1985) estimated that the gas inflow velocity is up to a few  $\text{km s}^{-1}$ .

# The implementation of radial inflows in Spitoni et al. (2011)

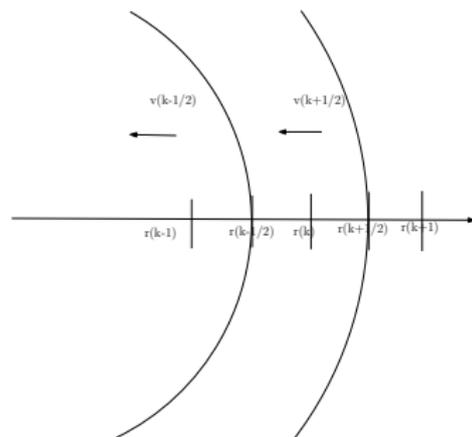
- Radial inflows with a flux  $F(r)$ , contribute to altering the gas surface density in the  $k$ -th shell in according to (Portinari & Chiosi 2000)

$$\left[ \frac{d\sigma_{gk}}{dt} \right]_{rf} = - \frac{1}{\pi \left( r_{k+\frac{1}{2}}^2 - r_{k-\frac{1}{2}}^2 \right)} \left[ F(r_{k+\frac{1}{2}}) - F(r_{k-\frac{1}{2}}) \right]$$

where the gas flows can be written as:

$$F(r_{k+\frac{1}{2}}) = 2\pi r_{k+\frac{1}{2}} v_{k+\frac{1}{2}} [\sigma_{g(k+1)}],$$

$$F(r_{k-\frac{1}{2}}) = 2\pi r_{k-\frac{1}{2}} v_{k-\frac{1}{2}} [\sigma_{g(k)}].$$



We find that:

$$\left( r_{k+\frac{1}{2}}^2 - r_{k-\frac{1}{2}}^2 \right) = \frac{r_{k+1} - r_{k-1}}{2} \left( r_k + \frac{r_{k-1} + r_{k+1}}{2} \right).$$

Recalling that  $G_i(r, t) = [\sigma_g(r, t)X_i(r, t)]/\sigma_A(r)$ , we obtain the radial flow term to be added into the chemical evolution equation:

$$\left[ \frac{d}{dt} G_i(r_k, t) \right]_{rf} = -\beta_k G_i(r_k, t) + \gamma_k G_i(r_{k+1}, t),$$

where  $\beta_k$  and  $\gamma_k$  are, respectively:

$$\beta_k = -\frac{2}{r_k + \frac{r_{k-1} + r_{k+1}}{2}} \times \left[ v_{k-\frac{1}{2}} \frac{r_{k-1} + r_k}{r_{k+1} - r_{k-1}} \right]$$

$$\gamma_k = -\frac{2}{r_k + \frac{r_{k-1} + r_{k+1}}{2}} \times \left[ v_{k+\frac{1}{2}} \frac{r_k + r_{k+1}}{r_{k+1} - r_{k-1}} \right] \frac{\sigma_{A(k+1)}}{\sigma_{Ak}},$$

and  $\sigma_{A(k+1)}$  and  $\sigma_{Ak}$  are the actual density profile at the radius  $r_{k+1}$  and  $r_k$ , respectively.



The chemical evolution models with the radial inflow of gas

# The chemical evolution equation + radial flows

$$\begin{aligned}
 \dot{G}_i(r, t) = & -\psi(r, t)X_i(r, t) \\
 & + \int_{M_L}^{M_{BM}} \psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm \\
 & + A_{Ia} \int_{M_{BM}}^{M_{BM}} \phi(M_B) \cdot \left[ \int_{\mu_m}^{0.5} f(\mu) \psi(r, t - \tau_{m2}) Q_{mi}^{SNIa}(t - \tau_{m2}) d\mu \right] dM_B \\
 & + (1 - A_{Ia}) \int_{M_{BM}}^{M_{BM}} \psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm \\
 & + \int_{M_{BM}}^{M_U} \psi(r, t - \tau_m) Q_{mi}(t - \tau_m) \phi(m) dm \\
 & + X_{A_j} B(r, t) \\
 & + \left[ \frac{d}{dt} G_i(r, t) \right]_{rf}
 \end{aligned}$$

## The models we report here from Spitoni &amp; Matteucci (2011)

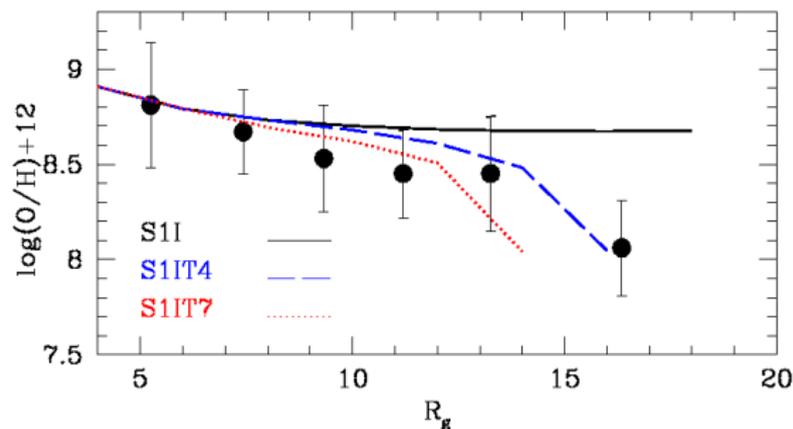
Models	Infall type	$\tau_d$	Threshold	Radial inflow
S11	1 infall	1.033 R (kpc) -1.27 Gyr	no	/
S11T4	1 infall	1.033 R (kpc) -1.27 Gyr	$4 M_{\odot} \text{pc}^{-2}$	/
S11T7	1 infall	1.033 R (kpc) -1.27 Gyr	$7 M_{\odot} \text{pc}^{-2}$	/
R111	1 infall	1.033 R (kpc) -1.27 Gyr	no	$-1 \text{ km s}^{-1}$
R11L	1 infall	1.033 R (kpc) -1.27 Gyr	no	linear inflow

## Observational data

- For the Galactic abundance gradient of oxygen, we use the following set of data: Deharveng et al. (2000), Esteban et al. (2005), Rudolph et al. (2006), who analyzed the Galactic HII regions; Costa et al. (2004) who studied planetary nebulae (PNe).

The MW one infall model: Spitoni & Matteucci (2011)

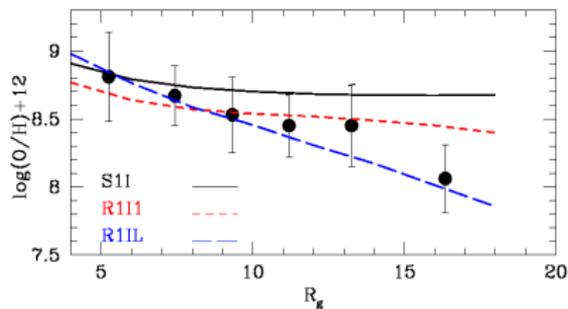
## The “static” 1 infall model results Spitoni & Matteucci (2011)



- Even if we consider a model with an inside-out formation the gradient obtained with a one-infall model without a threshold is too flat.
- The slope for galactocentric distances between 4 and 14 kpc can be reproduced if we consider the model with a threshold in the SF. However, since the surface gas mass density in the outer parts of the disk is too small, there is no SF in this region, hence neither metal production nor chemical evolution.

The MW one infall model: Spitoni & Matteucci (2011)

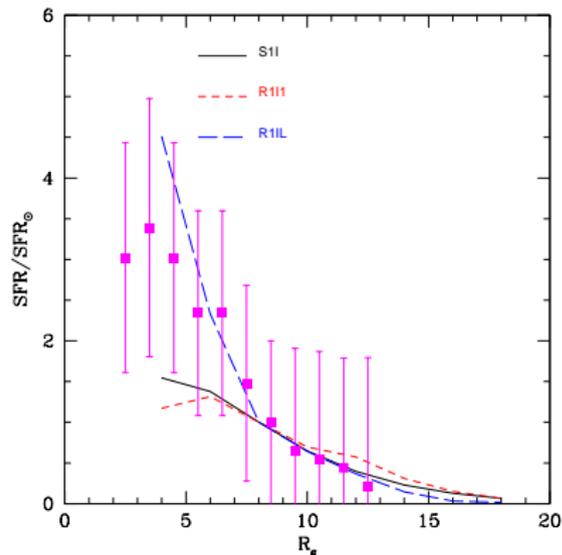
## The 1 infall model with a “linear” radial inflow



- With the model R1IL, we are able to fit quite well the data of HII regions and PNe assuming a linearly increasing flow velocity toward the outer regions given by:

$$v_R = (R_g/4) - 1.$$

- Velocities span the range between 0 and 3.8 km/s (in accordance with the results of Schönrich & Binney 2009).



Data taken by Rana (1991)

The MW two infall model: Mott et al. (2013)

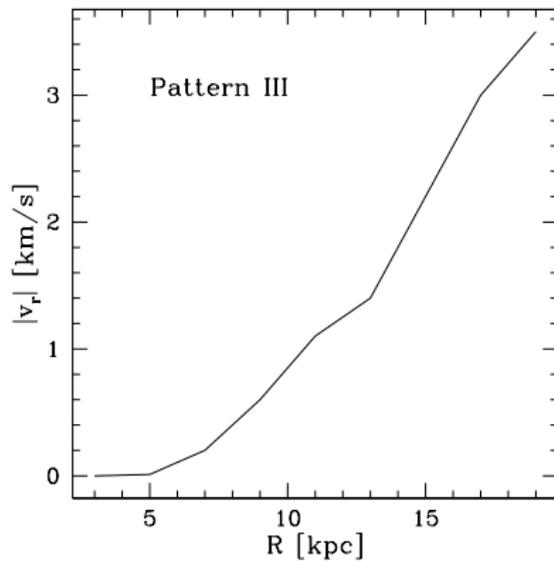
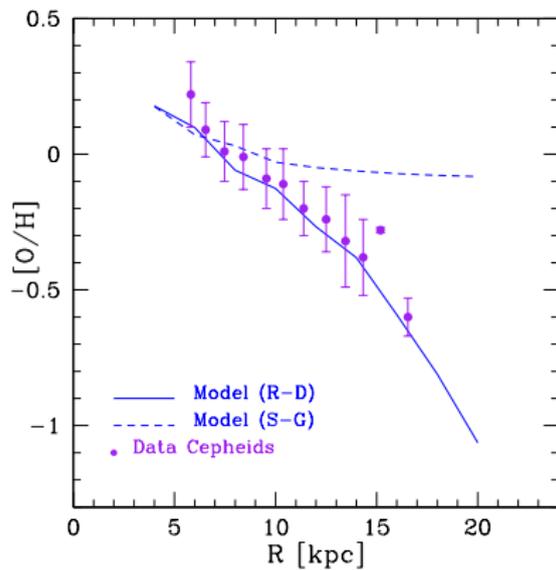
## The Best model R-D of Mott et al. 2013

Model	Threshold [ $M_{\odot} \text{ pc}^{-2}$ ]	$\tau_d$ (I-O) [Gyr]	$\sigma_h(r)$ [ $M_{\odot} \text{ pc}^{-2}$ ]	SFE $v$ [ $\text{Gyr}^{-1}$ ]	Radial inflow
S-G	/	1.033 R (kpc) -1.27 Gyr	17 if $R \leq 8$ kpc 0.01 if $R \geq 10$	1	/
R-D	/	1.033 R (kpc) -1.27 Gyr	17 if $R \leq 8$ kpc 0.01 if $R \geq 10$	1	pattern III

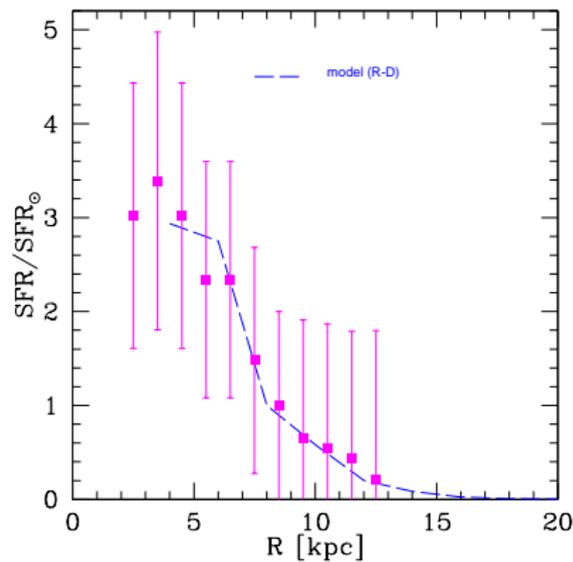
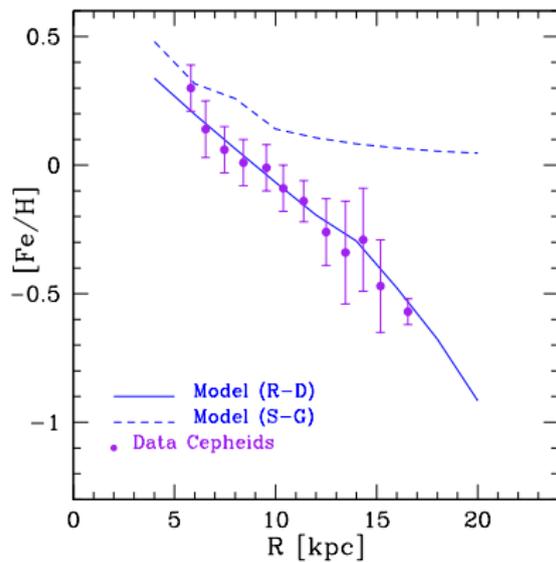
## Observational data

- The data set we used are those presented by Luck & Lambert (2011) which contain a spectroscopic investigation of 238 Cepheids in the northern sky in the Galactocentric distance range 5-17 kpc.

## The MW two infall model: Mott et al. (2013)



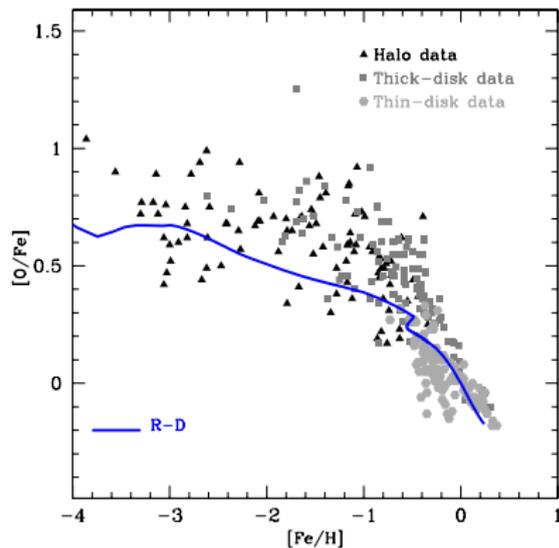
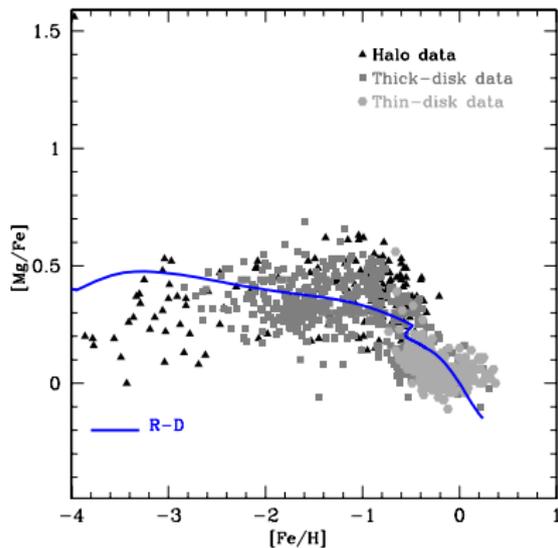
## The MW two infall model: Mott et al. (2013)



Data taken by Rana (1991)

The MW two infall model: Mott et al. (2013)

# The R-D model for the solar neighborhood: Spitoni & Matteucci (2013, in prep.)

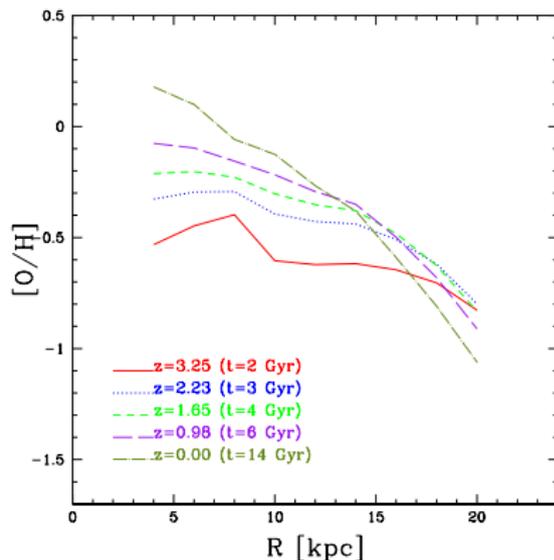


Data taken by Micali et al. (2013)

The MW two infall model: Mott et al. (2013)

# The high redshift inversion of the abundance gradient: Mott et al. (2013)

- Cresci et al. (2010) observed abundance gradient inversion for oxygen at  $z=3$
- R-D model shows this inversion.
- Curir et al. (2012) imposed the high redshift inversion in the abundance gradients to explain the thick disk rotation-metallicity correlation for the MW.



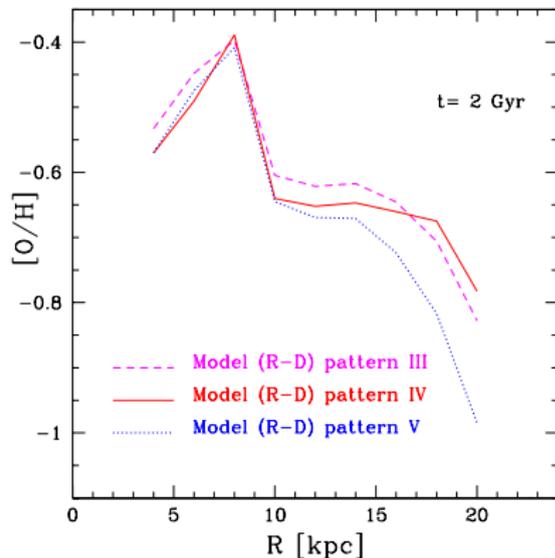
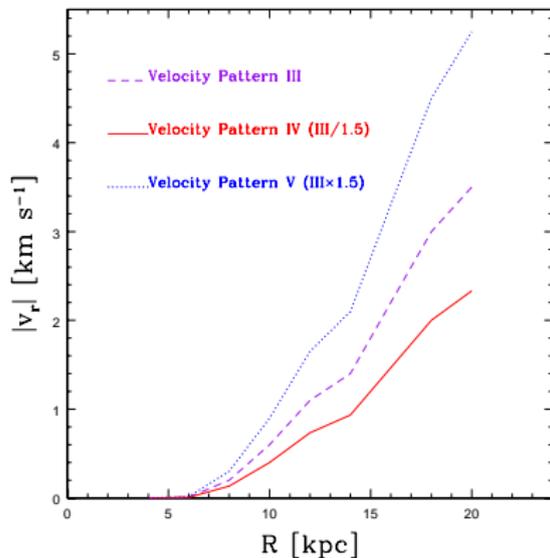
The MW two infall model: Mott et al. (2013)

## The high-redshift inversion with a time dependent radial inflow

- We checked the robustness of our results for the (R-D) model concerning the inversion of gradient at redshift  $z=3$ , considering a time-dependent velocity pattern consistent with the pattern III, and with the work of Bilitewski & Schoenrich (2012).
- We assume for this test the extreme case where the pattern III is the present day law,
- For the model (R-D) we assume that the pattern at the early times up to 2 Gyr follows this equation:

$$v_r(t \leq 2 \text{ Gyr}) = 1.5 \times v_r(\text{patternIII}). \quad (1)$$

## The MW two infall model: Mott et al. (2013)



# The One infall model for M31

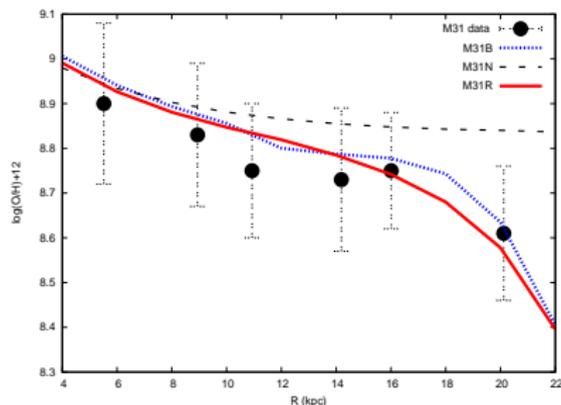
## The models considered in Spitoni et al. (2013)

Models	$\tau_d$	$v$	Threshold	Radial inflow
M31B Marcon-Uchida et al. (2010)	0.62 R (kpc) + 1.62 Gyr	24/R-1.5 Gyr <sup>-1</sup>	5 M <sub>⊙</sub> pc <sup>-2</sup>	no
M31N	0.62 R (kpc) + 1.62 Gyr	2 Gyr <sup>-1</sup>	no	no
M31R	0.62 R (kpc) + 1.62 Gyr	2 Gyr <sup>-1</sup>	no	yes, variable speed

## Observational data

- For the Galactic abundance gradient of oxygen, we use the following set of data: Galarza et al. (1999), Trundle et al. (2002), Blair et al. (1982), and Dennefeld & Kunth (1981) who analyzed the Galactic HII regions.

## The Results for M31: Spitoni et al. (2013)



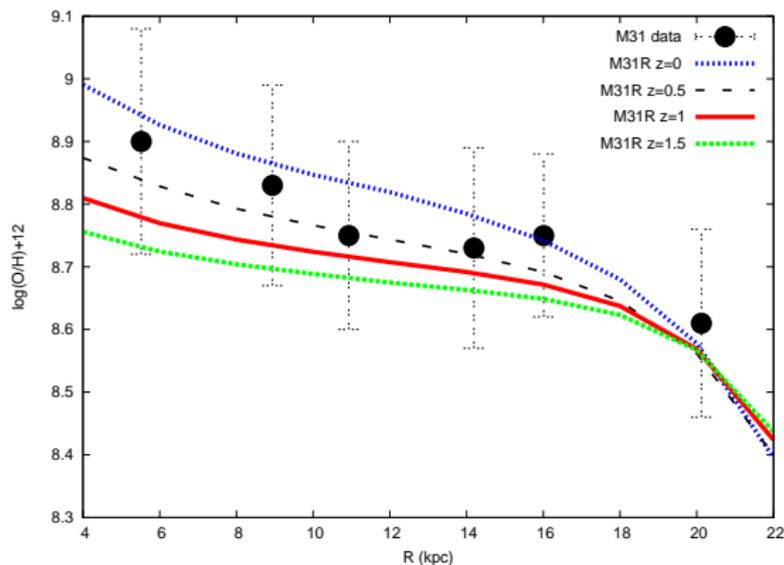
- M31N fails to reproduce the gradient in the outer M31 regions.
- The radial inflow velocity pattern requested to reproduce the data follows this linear relation:

$$|v_r| = 0.05R + 0.45,$$

- The range of velocities spans the range between 0.64 and 1.55 km/s.

The Results for M31: Spitoni et al. (2013)

## The evolution in redshift for the M31R gradient



- For for the model M31R the abundance gradient steepens in time, in accordance with the Chiappini et al. (2001) model.

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# Summary

- We showed that in the solar neighbourhood the delay produced by a galactic fountain has a negligible effect on the chemical evolution of all elements we studied.
- The time delay produced by a galactic fountain originated by an OB association has a negligible effect on the abundance gradients in the Galaxy disk.
- For the one infall models the radial flow velocity that is most consistent with the data varies linearly with the Galactocentric distance and spans a range between 0 and 3.8 km/s for the MW and 0.65–1.55 km/s for M31 (no threshold, with inside-out, and constant SF efficiency  $1 \text{ Gyr}^{-1}$  for MW, and  $2 \text{ Gyr}^{-1}$  for M31).
- The best two-infall model R-D for the MW is able to fit the observation data using a variable but non linear velocity pattern for the gas inflow. The range of velocities spans between 0 and 3.5 km/s.
- In the best two infall model R-D we have the presence of the inversion of gradient at redshift  $z=3$ , confirmed from the observations of Cresci et al. (2010).
- With a time dependent velocity radial inflow, the inversion of the abundance gradient at early times is preserved.