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The Effects of Galactic Fountains on the Chemical Evolution of Galaxies

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Outline

- The galactic fountains: an overview
- Galactic fountains and their connection with HVCs and IVCs
  - The superbubble evolution: the Kompaneets approximation
  - Abundances of Fe and O in the superbubble
  - Comparison with HVC and IVC observations
- Summary I
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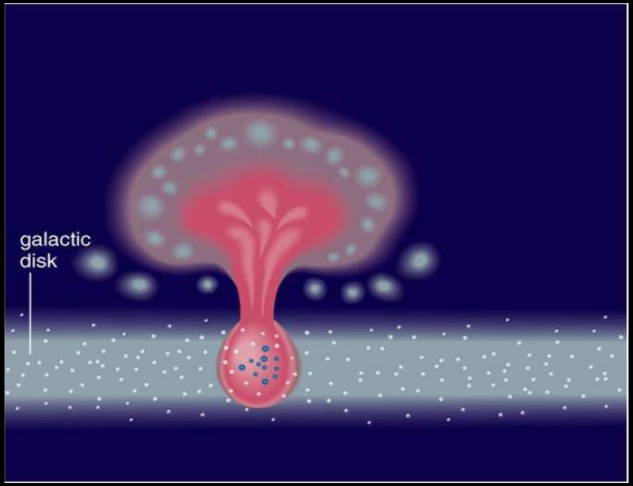
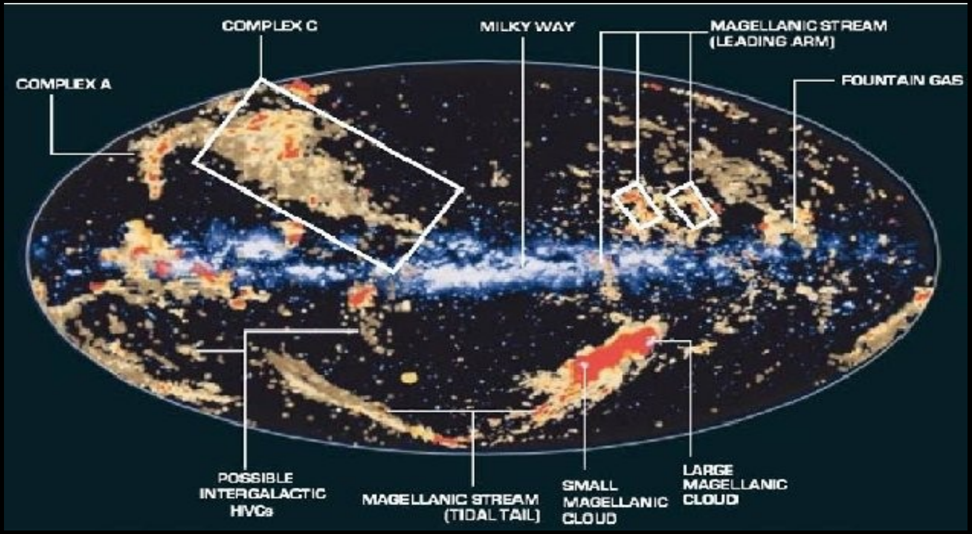
  - A detailed chemical evolution model for the MW
- Effects of Galactic Fountains: delayed chemical enrichment in the MW
- Summary II
- Future perspectives: effects of radial flows on the chemical evolution of the disk Galaxy

The Galactic fountain: an overview





(Gouveia Dal Pino et al. 2008)

- Sequential explosions of SNe from an OB association create a superbubble.

- An observed feature which seems to be correlated to gas circulation in galactic fountains are the so-called intermediate and high-velocity-clouds (IVCs and HVCs, respectively).

Galactic fountains and their connection with high and intermediate velocity clouds

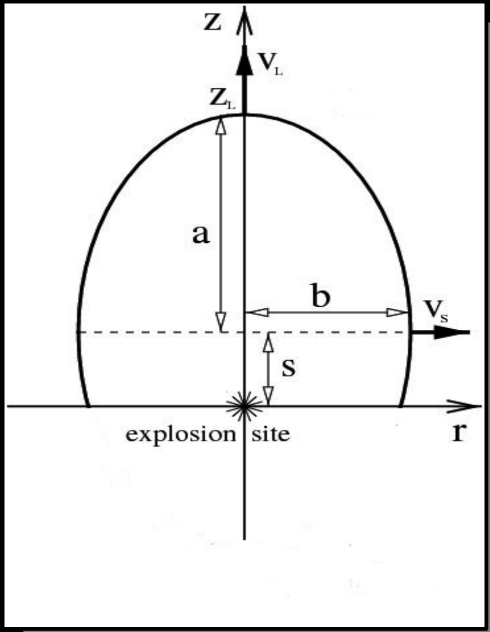
*(**Spitoni, E.**, Recchi, S., Matteucci, F., 2008, A&A, 484, 743)*

The superbubble evolution: the Kompaneets (1960) approximation in our model

(an analytic expression)

- Uniform pressure within the superbubble
- Superbubble expansion in a direction normal to the local surface
- Internal pressure dominates the external pressure
- Superbubble expansion in a exponential atmosphere

$$\rho(z) = \rho_0 exp(-z/H),$$



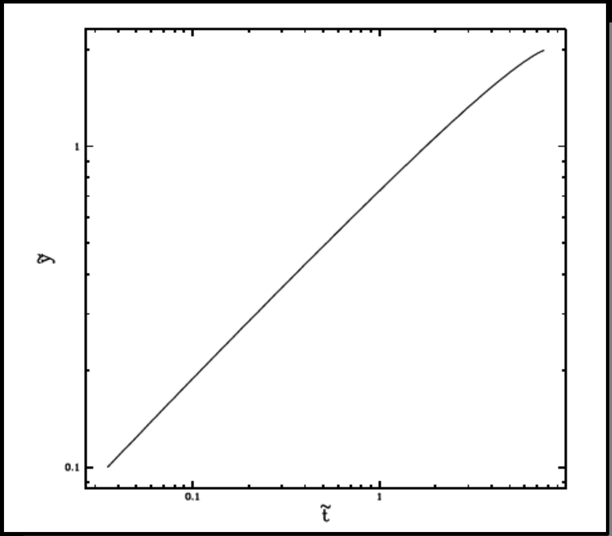
analytic expressions:

for the top side:

$$z_L = -2H \ln\left(1 - \frac{y}{2H}\right)$$

and for the semi-minor axis b:

$$b = 2H \arcsin\left(\frac{y}{2H}\right).$$

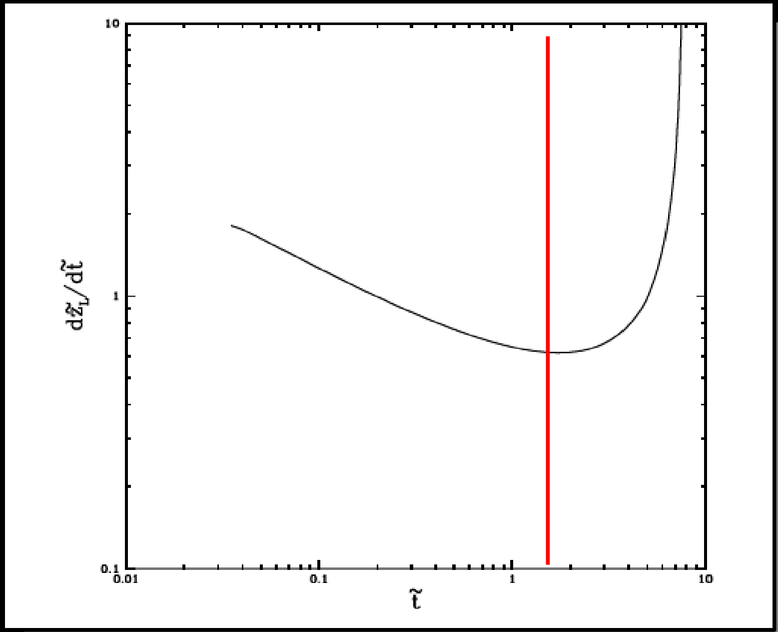


$$y = \int_0^t \sqrt{\frac{\gamma^2 - 1}{2}\frac{E_{\rm th}}{\rho_0 \Omega}}\, dt$$

$$\frac{dE_{th}}{dt} = L_0 - P\frac{d\Omega}{dt}$$

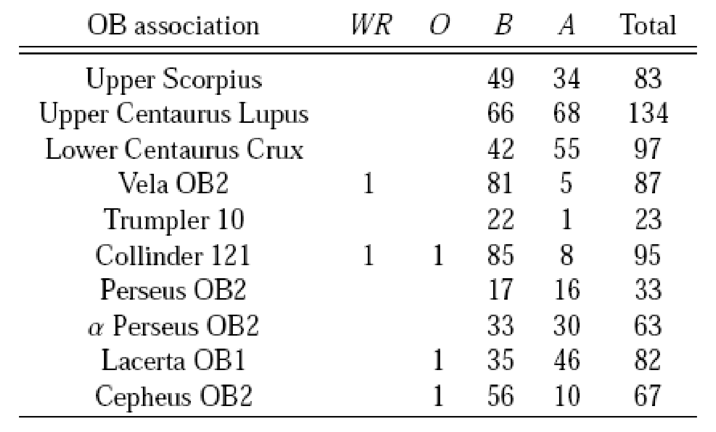
$$P = (\gamma - 1)\,\frac{E_{\rm th}}{\Omega}$$

- There is a typical timescale at which the superbubble "blows out" (e.g. the transition from deceleration to acceleration upwards).



- Number of massive stars in a OB association

SNe	L_0 [erg s^{-1}]
10	10^{37}
50	5×10^{37}
100	10^{38}
500	5×10^{38}



OB association	*WR*	*O*	*B*	*A*	Total
Upper Scorpius			49	34	83
Upper Centaurus Lupus			66	68	134
Lower Centaurus Crux			42	55	97
Vela OB2	1		81	5	87
Trumpler 10			22	1	23
Collinder 121	1	1	85	8	95
Perseus OB2			17	16	33
α Perseus OB2			33	30	63
Lacerta OB1		1	35	46	82
Cepheus OB2		1	56	10	67

De Zeeuw et al. (1998)

- ISM height scale *H*: we adopted the vertical distributions of the various interstellar components in the solar neighborhood reported by Cox (2005)

$$H = \frac{1}{\rho_0} \int_0^\infty \sum_{i=1}^{6} \rho_i(z)\, dz \simeq 141\mathrm{pc}.$$

The ISM density profile along the Galaxy radius is taken by Wolfire et al. (2003)

- Due to the *Raileigh-Taylor instabilities* the supershell fragments and we consider the formation of clouds with an initial velocity given by the top site velocity of the supershell at the moment of fragmentation

- At the time at which the cloud is thrown, the supershell presents:

$z_L = 448$ pc $\qquad$ $b = 259$ pc

($z_L \sim 3H$ in agreement with Mac Low & McCray 1988)

Results: cloud velocities and masses

4 kpc

SNe	t_{final} [Myr]	v_n [km s^{-1}]
10	22.89	23
50	13.39	39
100	10.63	49
500	6.21	83

8 kpc

SNe	t_{final} [Myr]	v_n [km s^{-1}]
10	19.04	27
50	11.13	46
100	8.84	58
500	5.17	100

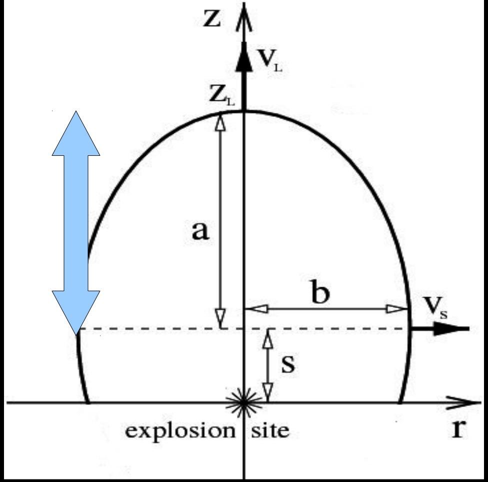
12 kpc

SNe	t_{final} [Myr]	v_n [km s^{-1}]
10	16.68	31
50	9.77	53
100	7.74	67
500	4.52	114

$$M_4\,(z > 0) = 10.07 \times 10^5\, M_\odot,$$
$$M_8\,(z > 0) = 5.79 \times 10^5\, M_\odot,$$
$$M_{12}\,(z > 0) = 3.89 \times 10^5\, M_\odot.$$

- We assume that the part of the ISM swept up mass into the thin supershell that could fragment and move upwards is the mass included above the *s* height

$$M_{cloud_{R_0=4}} = 2.17 \times 10^5 M_\odot,$$
$$M_{cloud_{R_0=8}} = 1.24 \times 10^5 M_\odot,$$
$$M_{cloud_{R_0=12}} = 0.84 \times 10^5 M_\odot.$$



Abundances of Fe and O in the superbubble

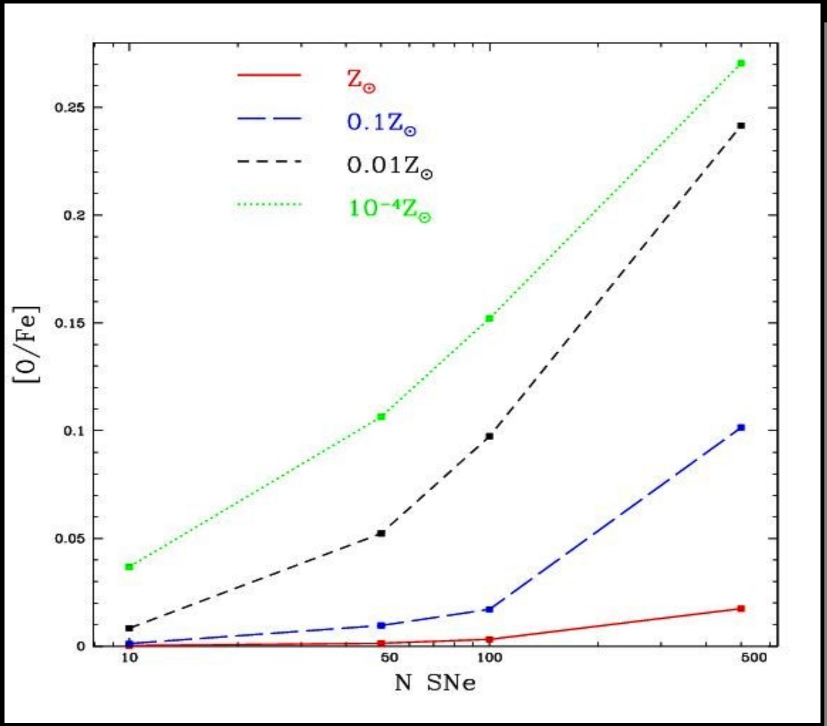
- The mass of metals ejected by SNe is given by: $M_{el_*} = \int_{M_{inf}}^{40} m_{el}(m)\phi(m)\,dm,$
  - The lower mass limit corresponds to the time at which the cloud forms (M< M_{inf} are still alive at the time of cloud formation).
  - IMF Salpeter (1955) $\int_{8}^{40} \phi(m)\,dm = A \int_{8}^{40} m^{-2.35}\,dm = S\,Ne$.
  - Yields from Woosley & Weaver (1995) , solar abundances given by Anders & Grevesse (1989).
  - All the amount of the ejected metals end up in the supershell.

(*an upper-limit estimate*)

$$M_{shell-el} = M_{shell} * Z_{el} + M_{el*}$$

Stellar yields at 4 different metallicities with the assumption that the ISM in the disk has the same metallicity as the OB association:

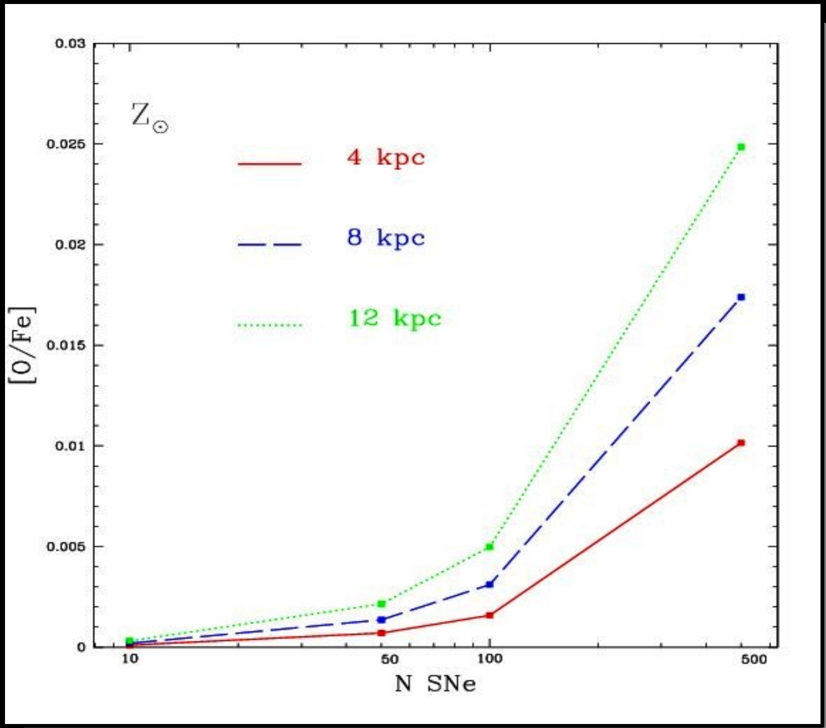
$Z_{\odot}$ $0.1\,Z_{\odot}$ $0.01\,Z_{\odot}$ $10^{4}\,Z_{\odot}$

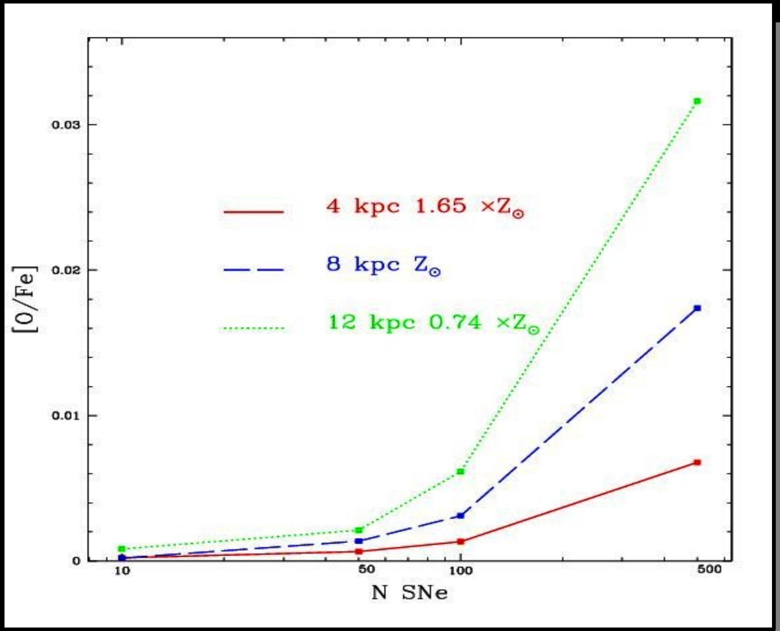


$$[O/Fe] = \log\left(\frac{M_{ShellO_{16}}}{M_{ShellFe_{56}}}\right) - \log\left(\frac{O_{16_\odot}}{Fe_{56_\odot}}\right)$$

- Significant overabundances of *O* relative to *Fe* are found only in case of a large number of SNe and low initial metallicity (8 kpc).

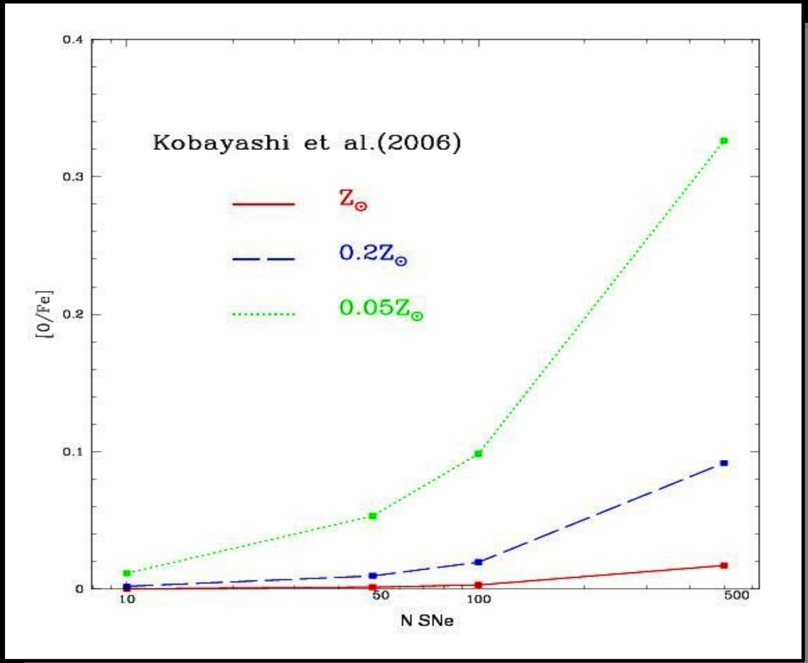
- Larger radial coordinates yield a larger [*O/Fe*] because the amount of swept-up pristine gas is smaller and therefore the new α elements ejected by SNe are less diluted.





- For the ISM metallicities we used the average observed values as a function of galactocentric distance, by analysing Galactic Cepheids (Andrievsky et al. 2002; Cescutti et al. 2006).

- Model results using the yields of Kobayashi et al. (2006) for the solar neighborhood.



Calculation of the orbits of the clouds

- *Ballistic models* describe the extra-planar gas as an inhomogeneous collection of clouds subject only to the potential of the Galaxy.

- *Hybrid ballistic-fluid stationary model* the clouds are subject also to the viscous interaction with the extra-planar gas.

The estimated *drag time* was taken from Barnabè et al. (2005): the scale time after which the relative circular motion between the cloud and the extra planar halo becomes equal to zero.

$$t_{\mathrm{drag}} \approx 2.7 \times 10^{8} \left(\frac{\tilde{M}_5}{n_{\mathrm{p}}} \right)^{1/3} \mathrm{yr},$$

$$\mathbf{a}_{drag} \equiv -\frac{\mathbf{v} - \mathbf{v}_g}{t_{drag}}$$

Initial conditions of the cloud

- The clouds have different initial velocity modulus $||\mathbf{v}_{\mathbf{o}}||=v_n$ and masses depending on the the number of SNe in the OB association and the initial throwing radial coordinate.

- Since the $||\mathbf{v}_{\mathbf{o}}||$ velocities are relative to the LSR for the throwing radial coordinate R_0 in the inertial reference frame of the simulation we have:

$$\mathbf{v}_{\mathbf{i}}= \mathbf{v}_{\mathbf{o}}+\mathbf{v}_{\mathbf{c}}(R_o,0)\hat{e}_{\boldsymbol{\varphi}}$$

- The direction of throwing cannot be known a priori: for each velocity modulus v_n we calculated a fountain composed of 33 different direction of throwing.

Galaxy model

$$\Phi_M(R,z) = -\frac{GM_d}{\sqrt{R^2 + \left(a + \sqrt{z^2 + b^2}\right)^2}}.$$

$$\Phi_{dm}(r) = -4\pi r_{dm,0}^2 \rho_{dm,0} \frac{\ln(1+x)}{x},$$

$$\Phi_b(r) = -\frac{GM_b}{r_{b,0} + r}$$

- Galaxy disk

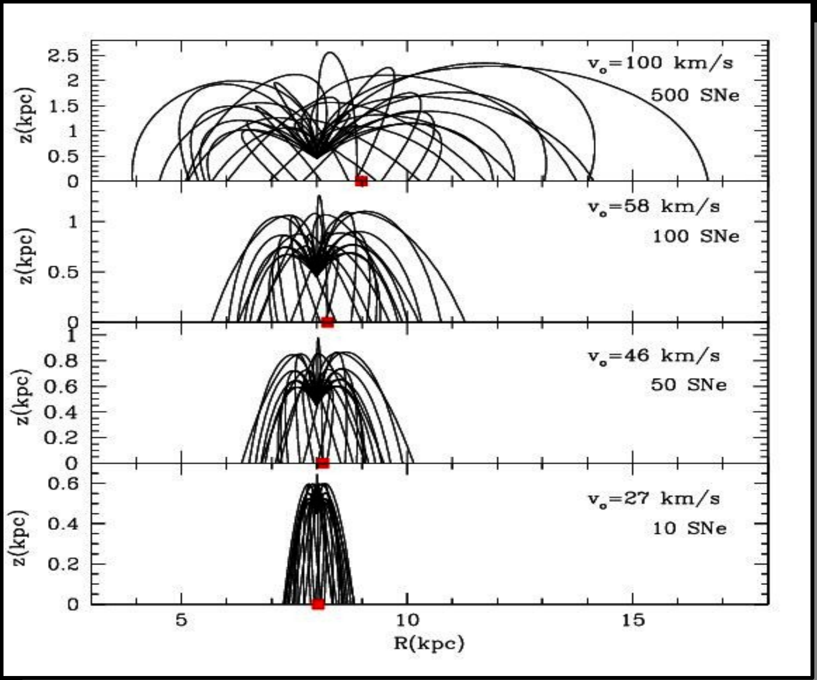
  Miyamoto & Nagai (1975)
- DM halo

  Navarro et al. (1996)
- Bulge

  Hernquist (1990)

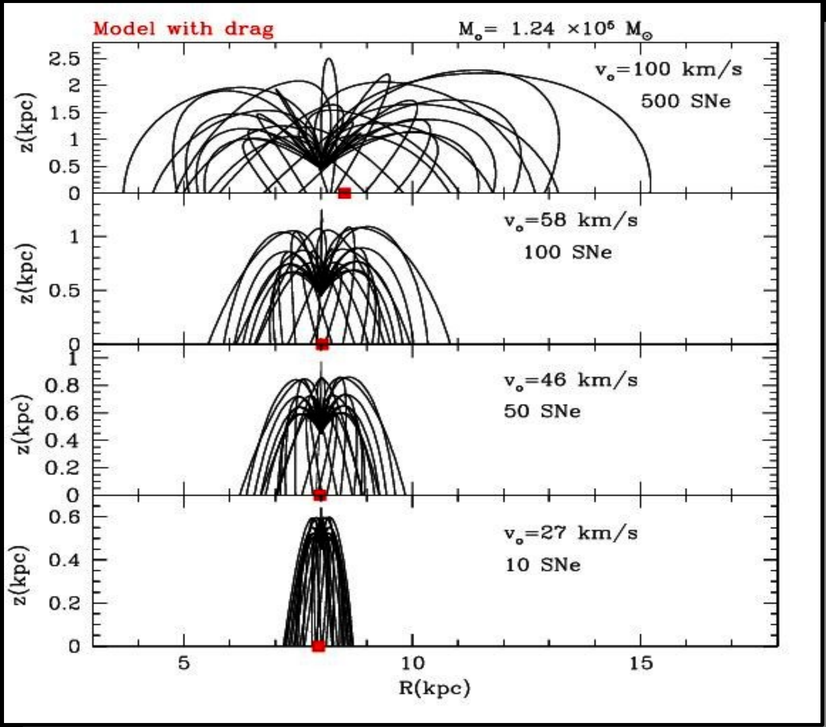
- Also we have considered a isothermal gas halo over the disk with the follow field density:

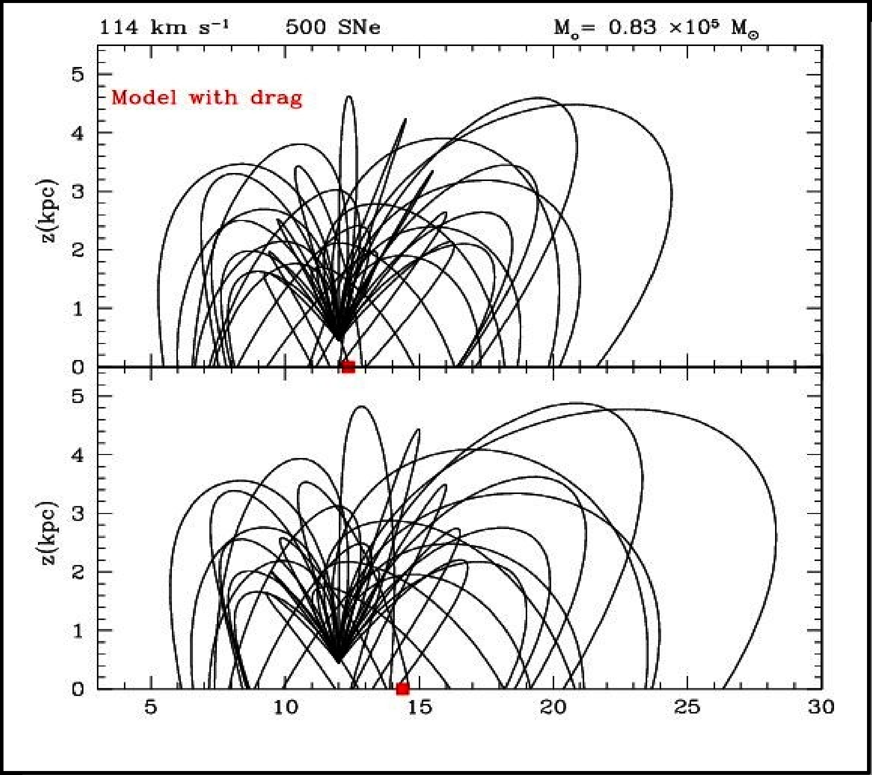
$$\rho(R,z) = \rho_o e^{(-\Phi_{tot}+\Phi_0)/\beta_0},$$



- The clouds are preferentially thrown outwards, but their final average landing coordinates differ by **1 kpc** at most from the throwing coordinate (confirmed by Melioli et al. 2009).

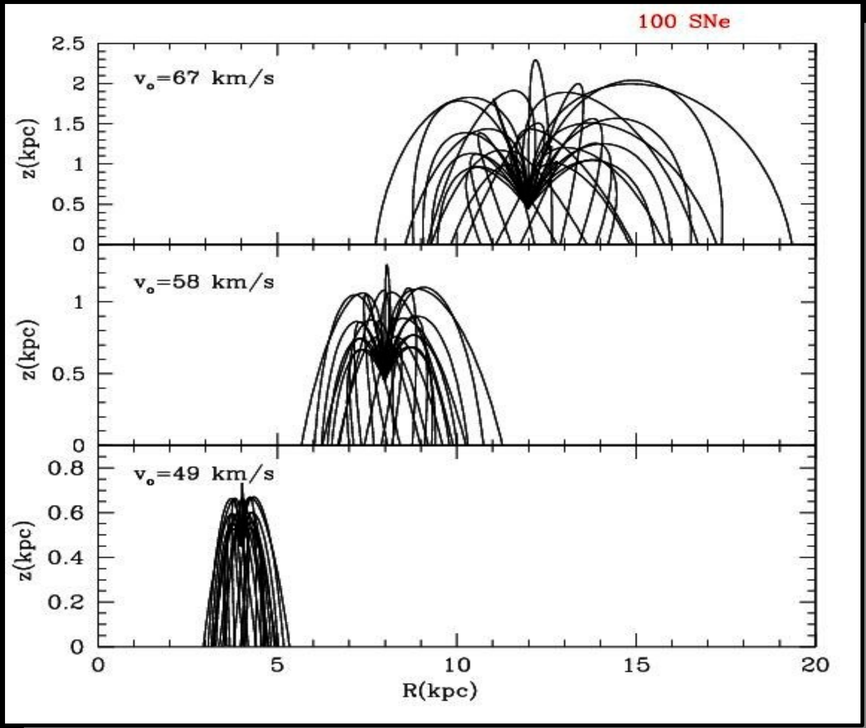
- For the range of initial velocities considered, the effect of a viscous term in the motion equation is weak.

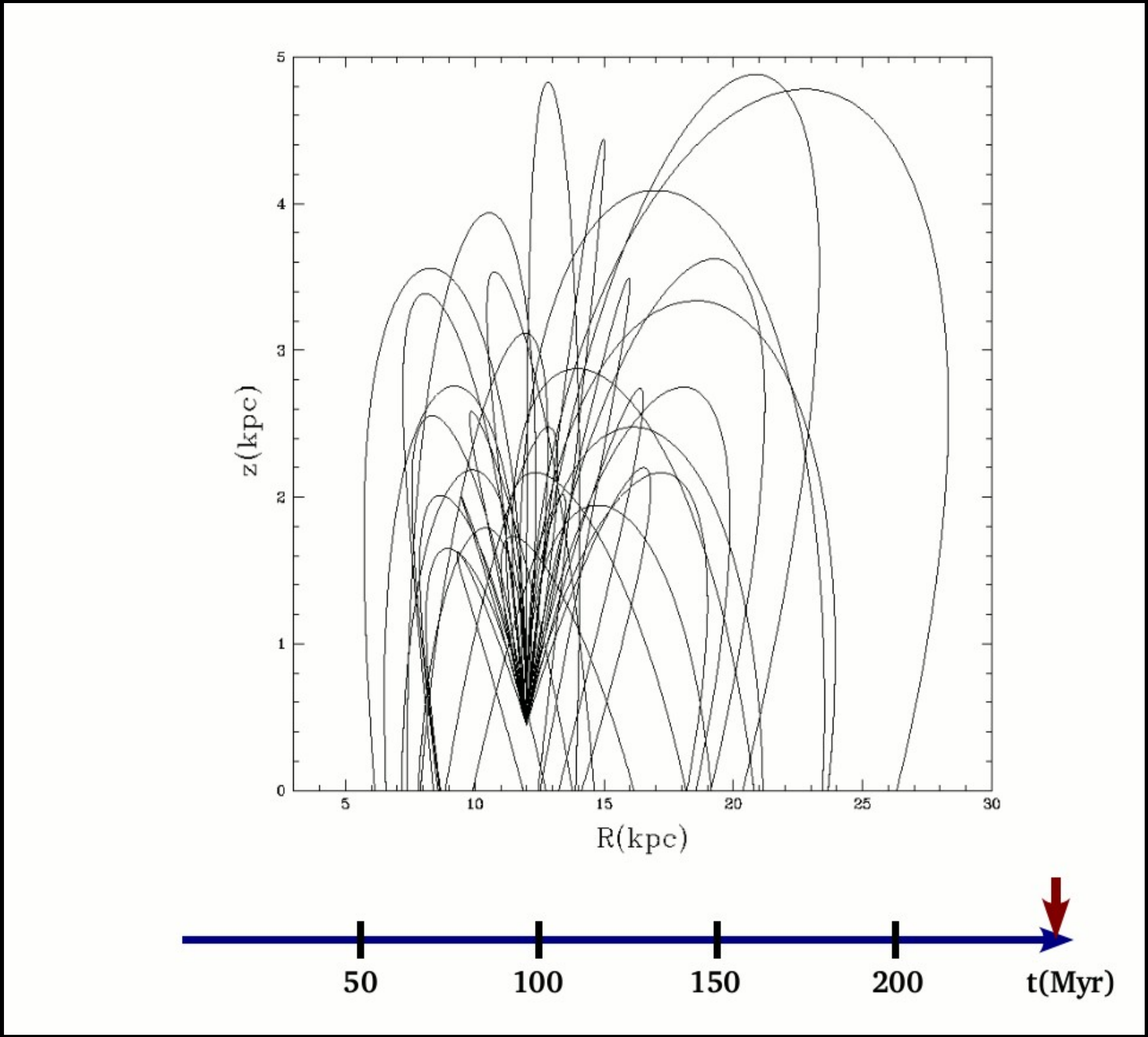




- Fountains that reach the maximum height in our model.

- The most realistic number of massive stars in OB associations in our Galaxy is about 100.





500 SNe, 12 kpc

v_0=114 km s^{-1}

Estimate of the Galactic fountain delay

$$< t_{total} > = t_{final} + < t_{orbit} >$$

- Model assumptions:
  - Single OB association
  - Kompaneets (1960) approximation
  - Galaxy potential:

    Miyamoto & Nagai (1975),
    Hernquist (1990),
    Navarro et al. (1996).

$< t_{total} >$ [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

[Myr]	4 kpc	8 kpc	12 kpc
MAXIMUM DELAY	48	114	245

The effect of dust

- The disruption time-scale

$$\tau_{\mathrm{destr},i} = (\epsilon M_{\mathrm{SNR}})^{-1} \cdot \frac{\sigma_{\mathrm{ISM}}}{R_{\mathrm{SN}}}$$

(Calura et al. 2008)

We obtain that $\tau_{\mathrm{destr,i}} \sim 0.7$ Myr. This timescale is considerably shorter than the time necessary for the formation of a RT instable supershell in our model

- The accretion time-scale

$$\tau_{\mathrm{accr}} = \tau_0/(1 - X_{\mathrm{d}})$$

(Dwek et al. 1998)

τ_0 = 50- 200 Myr. If we calculate the time necessary to accrete 10 times the initial dust fraction (e.g. Xd/Xd,0 = 10), we get: $t = 2.3\tau_0$. This time is greater than the average time of the cloud orbits, therefore we can conclude that the depletion of metals into dust does not play a important role in the supershell evolution.

Comparison with HVC and IVC observations

(data: Wakker et al. 2007, Richter et al. 2001)

Complex C (HVC)

Observations

IV Arch (IVC)

Mass: 0.7 -6 * 10^6 $M_\odot$ Velocity: -114 km s^{-1}
Position: R<14 kpc, z=3-9 kpc
[*O/Fe*]=0.12 dex

z-height bracket 0.8-1.5 kpc (probably as part of a Galactic fountain)

[*O/Fe*]=0.22 dex

Our models

Maximum Mass: 2.* 10^5 $M_\odot$

Maximum Height: 4.4 kpc

500 SN, 12 kpc and $Z=0.1*Z_\odot$: [O/Fe]=0.13 dex.

BUT

The most likely metallicity at 12 kpc is $0.74*Z_\odot$:

500 SNe [*O/Fe*]=0.03 dex

$Z=0.01*Z_\odot$ [*O/Fe*]=0.24 dex, 500 SN 8 kpc

- We can rule out a Galactic origin for the Complex C HVC

- It is quite unlikely that the initial metallicity of an OB association is nowadays as low as $0.01*Z_\odot$

Summary I

- If the initial metallicity of the OB association is solar, the pollution from the dying stars has a negligible effect on the chemical composition of the clouds.
- Both in the ballistic and in the viscous interaction models the maximum height reached by the clouds is not very large.
- The clouds are generally directed outwards but the average landing coordinates differ from the throwing coordinates by 1 kpc at most therefore it is unlikely that galactic fountains affect abundance gradients .
- It is unlikely that the two studied clouds are originated in a Galactic fountain motion.

Effects of Galactic Fountains on the chemical evolution of the MW

*(**Spitoni, E.**, Matteucci, F., Recchi.S., Cescutti, G., Pipino, A., 2009 A&A, 504, 87)*

- *To take into account the effects of galactic fountains we consider a delay in the chemical enrichment of the MW (the relaxation of the IMA)*
  - Most of the chemical evolution models adopt the IMA. In the past there have been only a few attempts to relax the IMA because of:
    - Difficulties in estimating the dispersion time and mixing of the chemical elements (Roy & Kunth 1995)
    - Models which retain IMA provide an excellent fit of the data in the MW (François et al. 2004)
- We also tested another cause for the relaxation of the IMA: the chemical enrichment delay due to gas cooling.

The detailed two infall chemical evolution model

(Francois et al. 2004)

- Two-infall model

$$A(r,t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{max})/\tau_D(r)}$$

- Inside-out formation

$$\tau_D = 1.033r(\mathrm{kpc}) - 1.267 \ \mathrm{Gyr}$$

- SFR ~ $\nu \sigma_G^{1.5}$
- Threshold in the star formation if $\sigma_G < 7 \ M_{sun} \ pc^{-2}$ thin disk

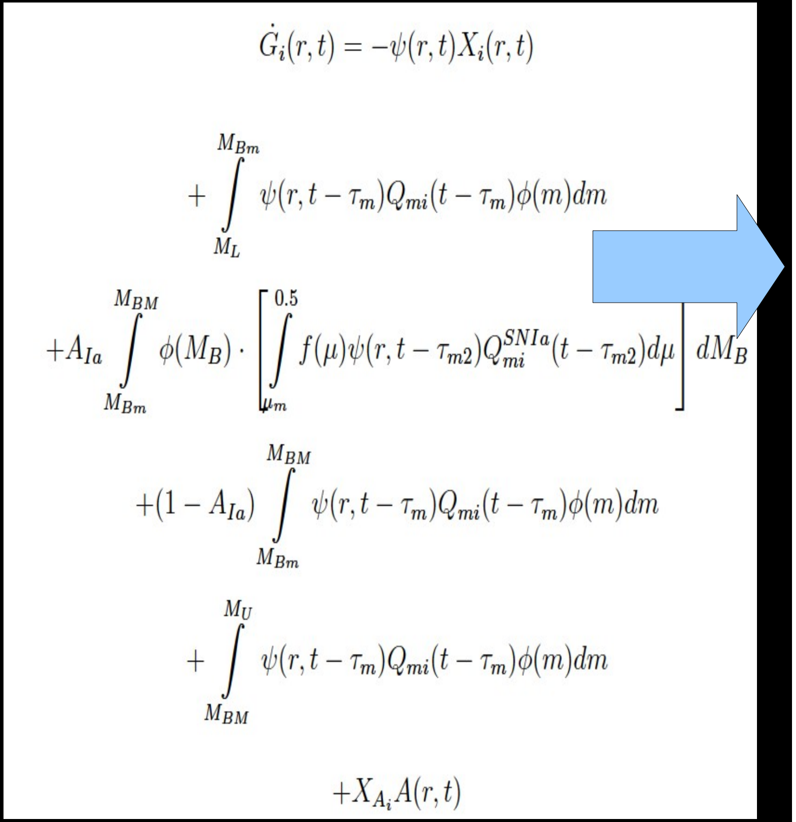
  $\sigma_G < 4 \ M_{sun} \ pc^{-2}$ halo-thick disk
- Galactic disk divided into rings, 2kpc wide, without any exchange of matter

Description of the Galactic fountain delay model

- We considered the delay only for massive stars M> 8 $M_\odot$.
- 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 association 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).

Galactic fountain time delay model

Reference model



$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t)$$

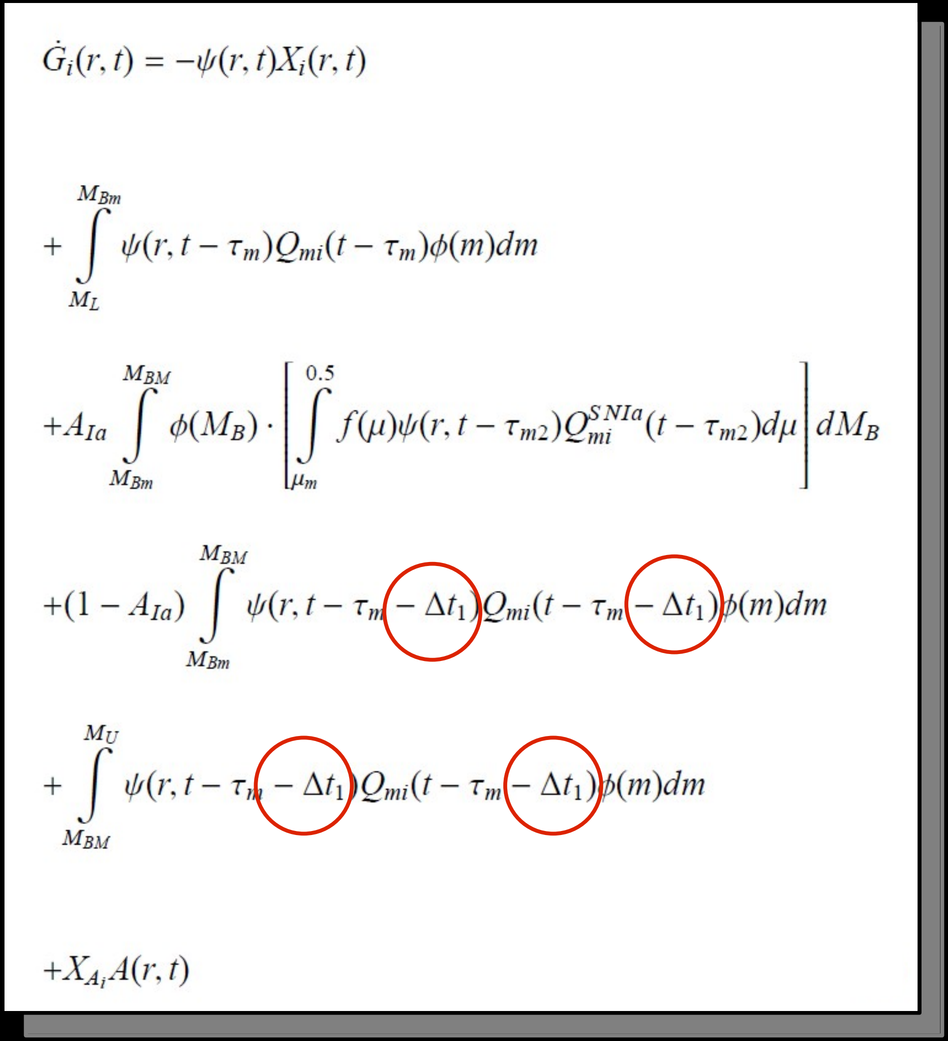
$$+\int_{M_L}^{M_{Bm}} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

$$+A_{Ia}\int_{M_{Bm}}^{M_{BM}} \phi(M_B)\cdot\left[\int_{\mu_m}^{0.5} f(\mu)\psi(r,t-\tau_{m2})Q_{mi}^{SNIa}(t-\tau_{m2})d\mu\right] dM_B$$

$$+(1-A_{Ia})\int_{M_{Bm}}^{M_{BM}} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

$$+\int_{M_{BM}}^{M_U} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

$$+X_{A_i}A(r,t)$$



$$\dot{G}_i(r,t) = -\psi(r,t)X_i(r,t)$$

$$+\int_{M_L}^{M_{Bm}} \psi(r,t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm$$

$$+A_{Ia}\int_{M_{Bm}}^{M_{BM}} \phi(M_B)\cdot\left[\int_{\mu_m}^{0.5} f(\mu)\psi(r,t-\tau_{m2})Q_{mi}^{SNIa}(t-\tau_{m2})d\mu\right] dM_B$$

$$+(1-A_{Ia})\int_{M_{Bm}}^{M_{BM}} \psi(r,t-\tau_m \boxed{-\Delta t_1})Q_{mi}(t-\tau_m \boxed{-\Delta t_1})\phi(m)dm$$

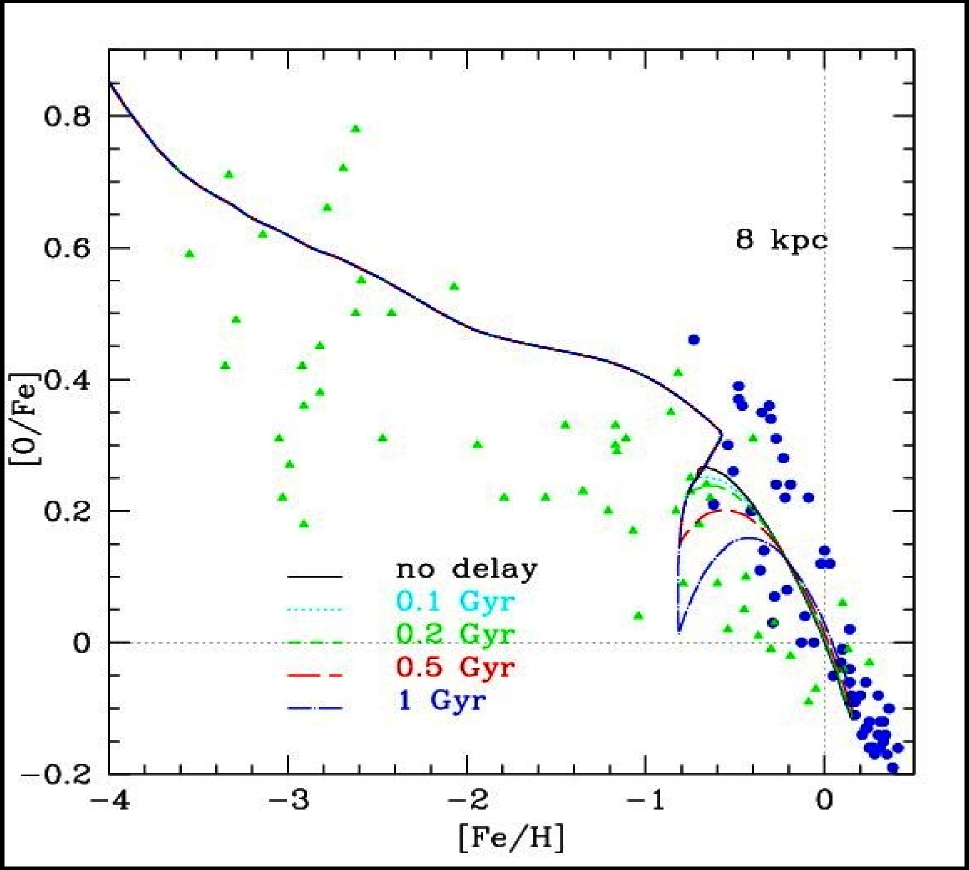
$$+\int_{M_{BM}}^{M_U} \psi(r,t-\tau_m \boxed{-\Delta t_1})Q_{mi}(t-\tau_m \boxed{-\Delta t_1})\phi(m)dm$$

$$+X_{A_i}A(r,t)$$

Results

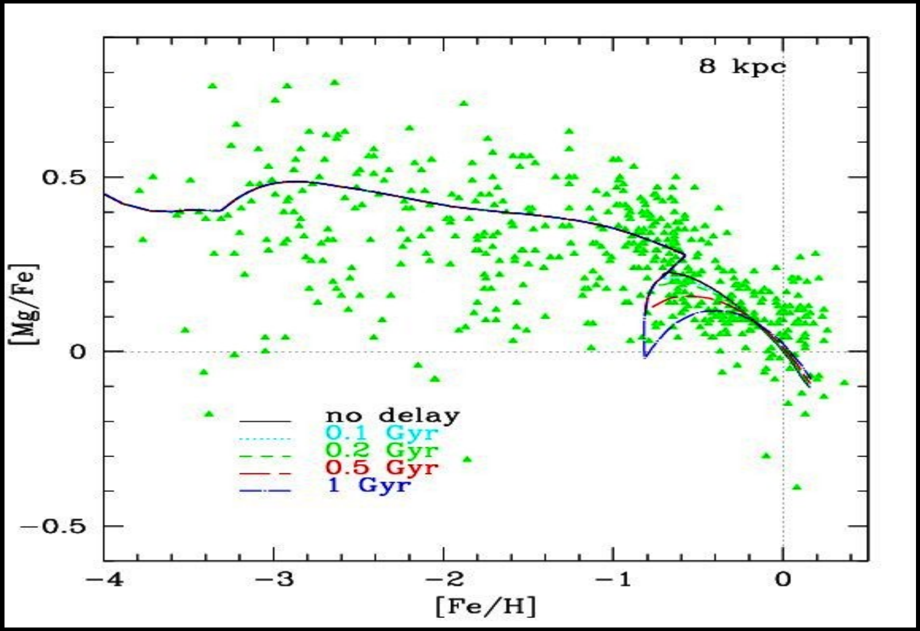
8 kpc

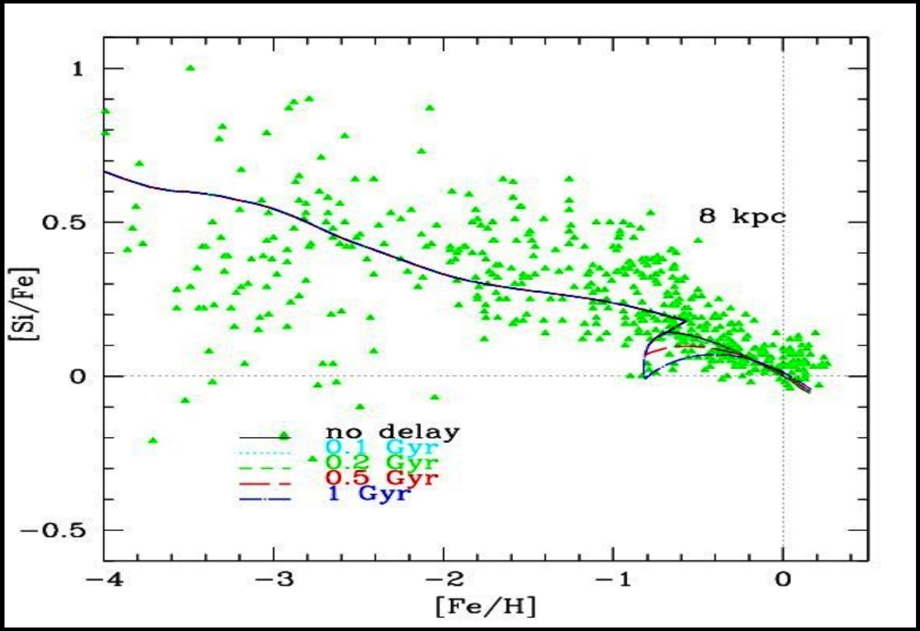
[el/Fe]/ [Fe/H]



Data: Bensby (2004), François et al. (2004)

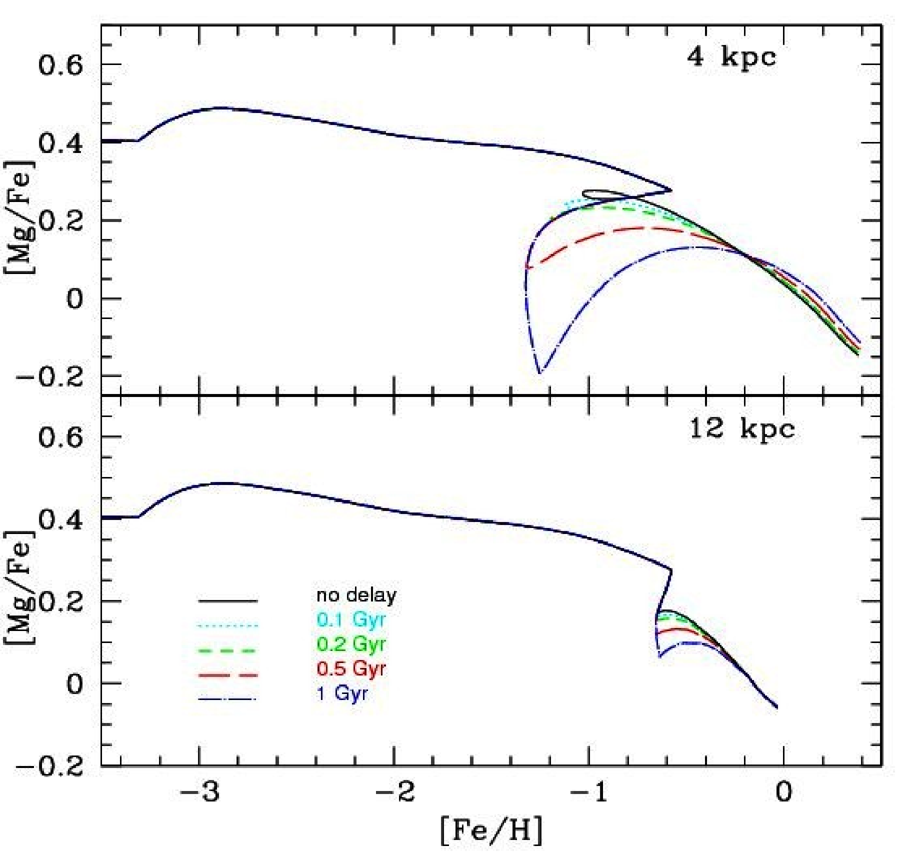
- The main feature of the galactic fountain is an enhancement of the drop in the [O/Fe] ratio. The galactic fountain delay has the effect of increasing the period during which there is no pollution from type II SNe.
- Type Ia SNe are not affected by the delay
- The maximum possible delay must be lower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



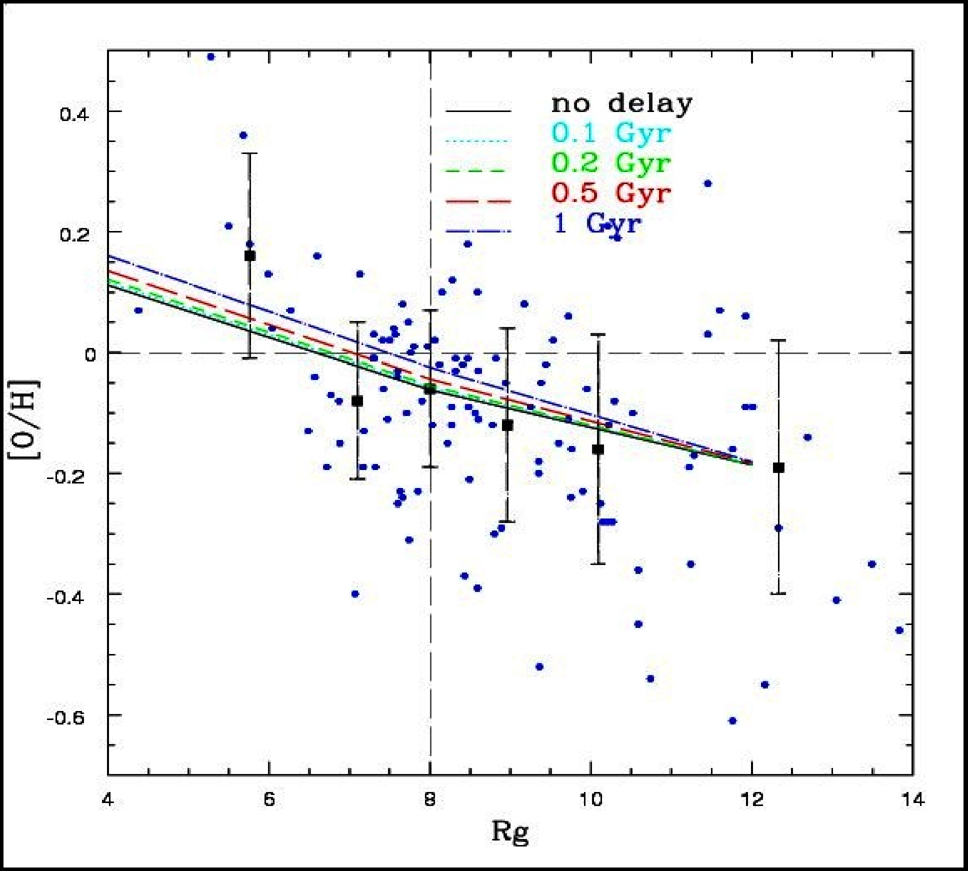


- The effect of the galactic fountain depends on the considered element. Si, which is also produced by type Ia SNe in a non negligible amount, shows a smaller drop of the [Si/Fe] quantity compared to O and Mg.

Results at 4 kpc and 12 kpc



- The effect depends on the galactocentric distance: different histories of star formation at different galactocentric radii



Data from Andriesky et al. (2002)

The time delay produced by a galactic fountain has a negligible effect on the abundance gradient in the Galaxy disk,

We also tested the delay in the chemical enrichment due the finite time required to the gas for cooling

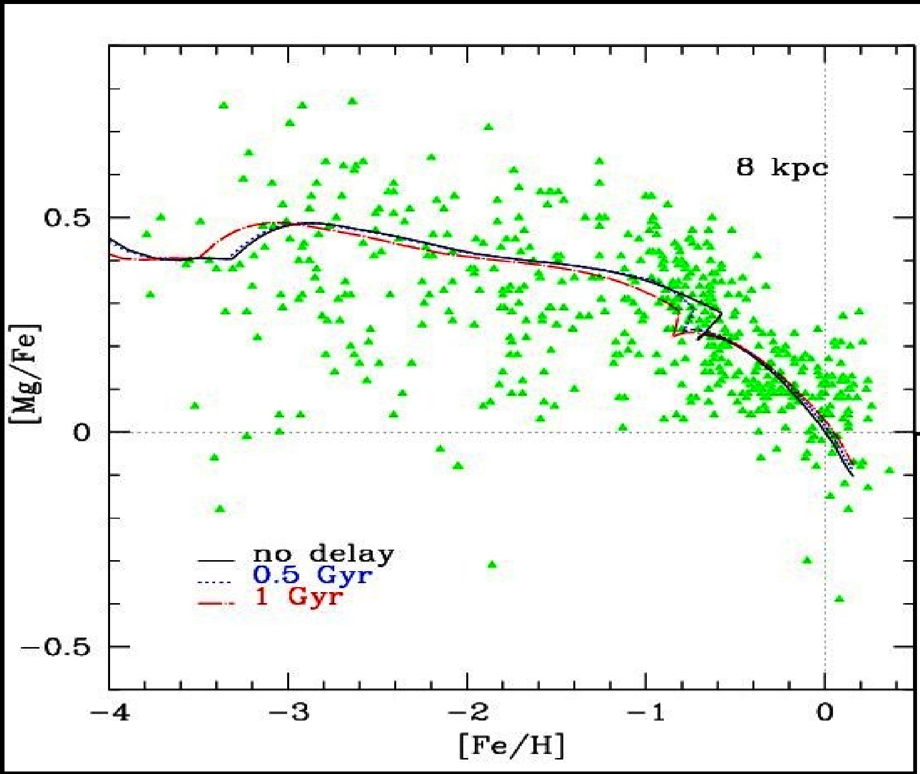
- We considered the delay:

  i) ***for all stars*** (both type II and type Ia SNe),

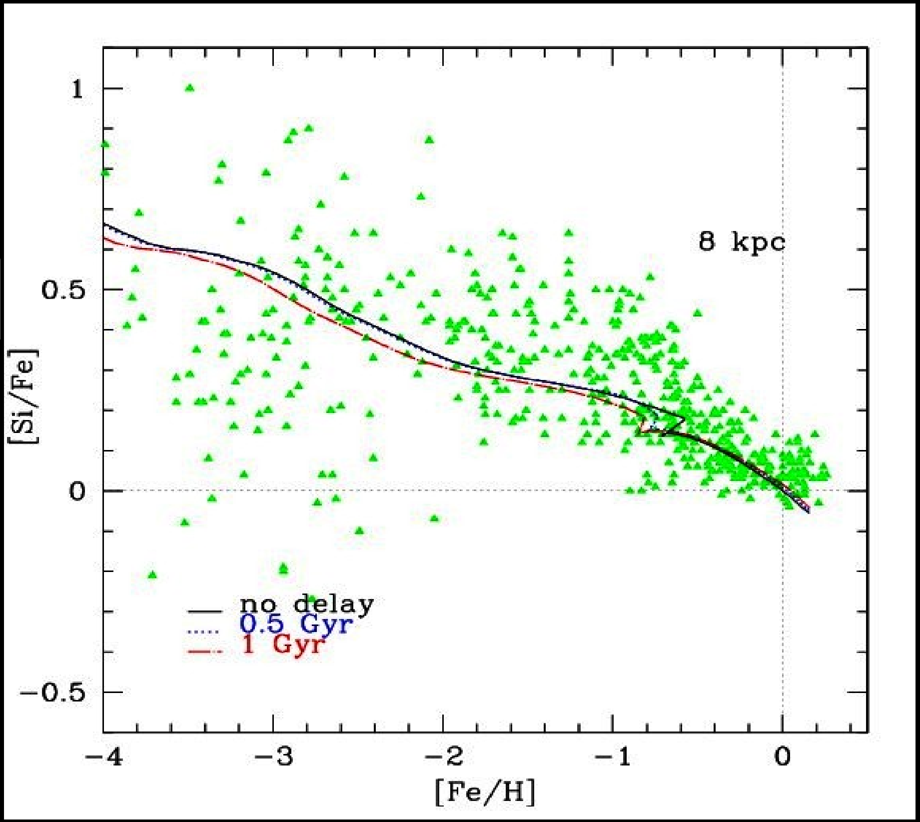
  ii) both halo and disk stars are affected by this delay.

- Time delay: 0.5 Gyr and 1.0 Gyr (Thomas et al. 1998)

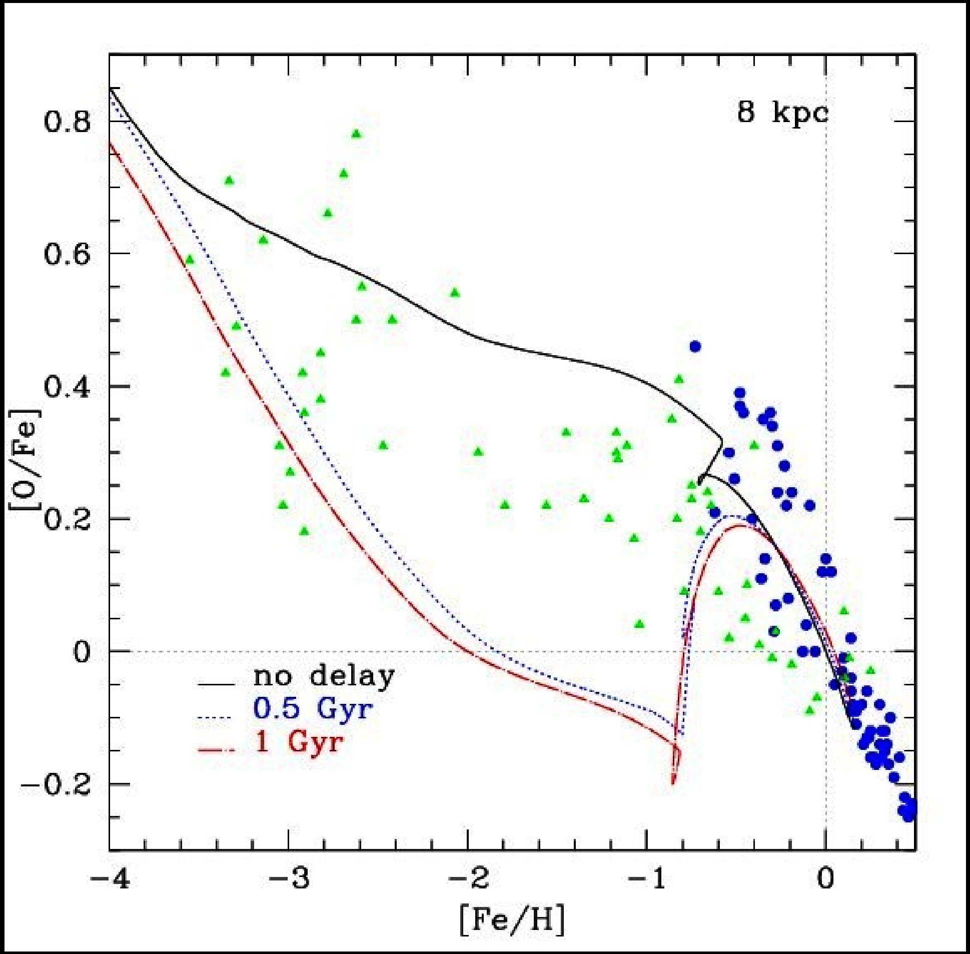
- The metal cooling delay model with the assumed delays has a very small effect.



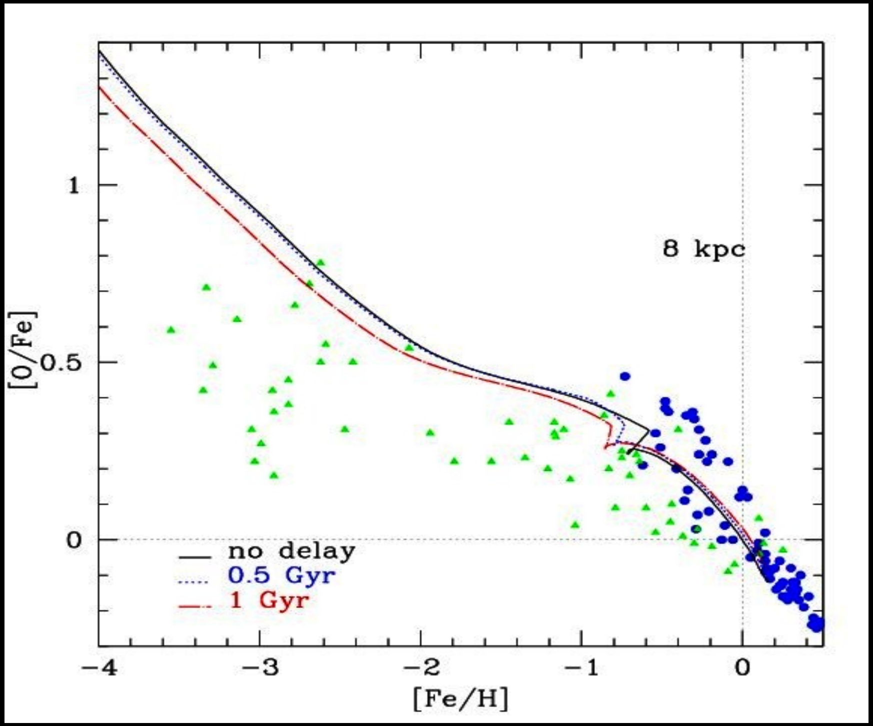
- François et al (2004) nucleosynthesis prescriptions: Mg, Si, Fe yields are not depending on metallicity



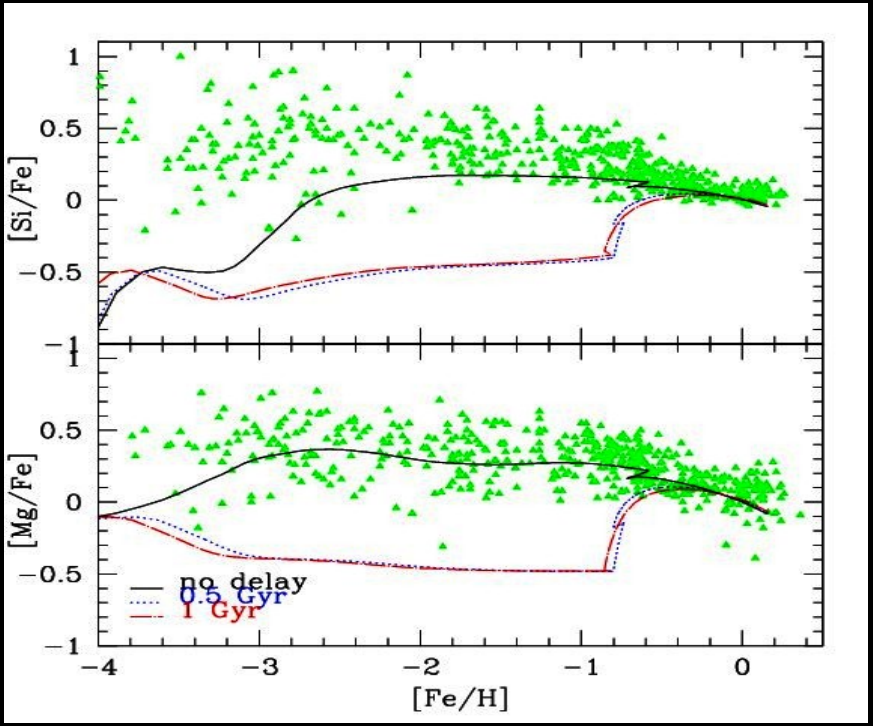
Metallicity dependent oxygen yields of WW95



- The delay induces a situation where the yields for Z ~ 0, which are lower than for the other metallicities, act for a longer time.
- As a consequence the [O/Fe] drops to very low values during the whole halo phase



- [O/Fe] using the yields at the solar metallicity given by WW95.



- Mg, Si using the yields dependent on metallicity given by WW95.

François et al (2004) nucleosynthesis prescriptions are not compatible with a delayed enrichment of the halo.

Summary II

- We showed that in the solar neighbourhood the delay produced by a galactic fountain has a negligible effect on the chemical evolution of all α elements we studied.
- In [el/Fe] versus [Fe/H] relations, the main feature of the galactic fountain is an enhancement of the drop in the [el/Fe] ratios. The galactic fountain delay has the effect of increasing the period during which there is no pollution from type II SNe.
- *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.*
- The metal cooling delay model with the assumed delays has a very small effect on the chemical evolution in the solar neighborhood if yields not depending on metallicity are used.
- On the other hand, in the case of the metal dependent yields of WW95 the results differ substantially from our reference model and do not fit the observations.

Effects of radial flow on the chemical evolution of the disk of Galaxy

*(**Spitoni, E.** Matteucci,, F. Submitted on A&A)*

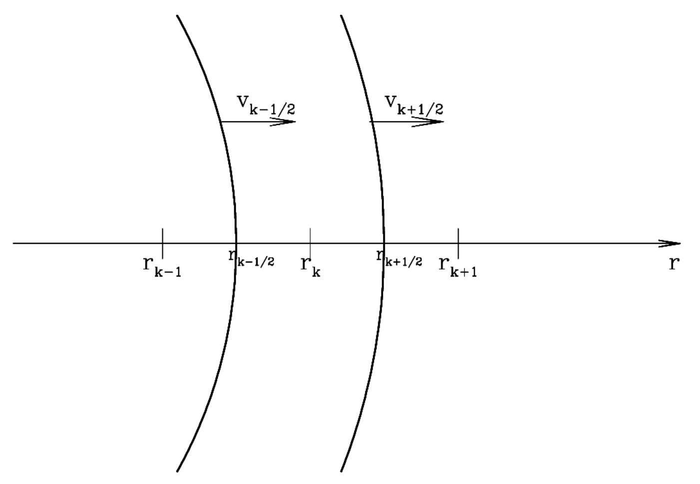
- If gas infall is important, radial gas flows have to be taken into account as a dynamical consequence of infall.

  The infalling gas has a lower angular momentum than the circular motions in the disc, and mixing with the gas in the disc induces a net radial inflow. Lacey & Fall (1985) estimated that the gas inflow velocity is up to a few km s^{-1}

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

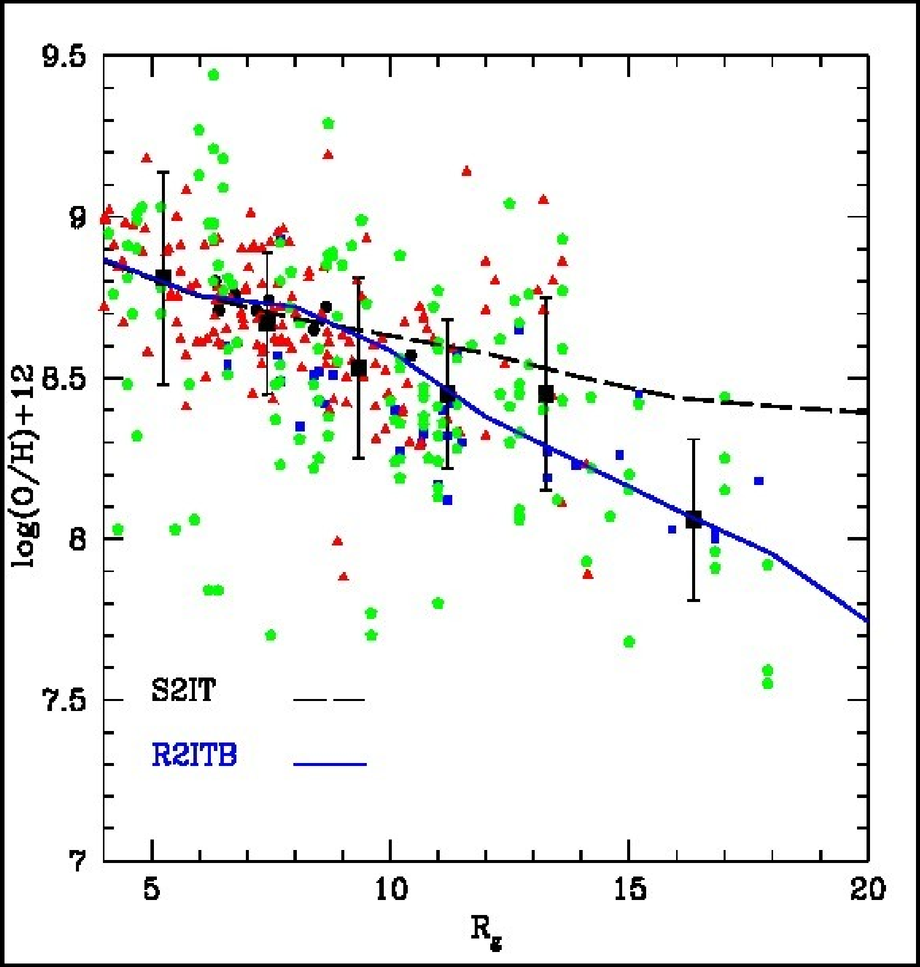
$$\beta_k = -\frac{2}{r_k + \frac{r_{k-1}+r_{k+1}}{2}} \times \left[V_{k-\frac{1}{2}} \frac{r_{k-1} + r_k}{r_{k+1} - r_{k-1}}\right]$$

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



Models	Radial flow
S2IT	NO
R2TB	Inflow with a variable speed

Deharveng et al.(2000) HII Regions
Esteban et al.(2005) HII Regions
Rudolph et al. (2006) HII Regions
Costa et al.(2004) PNe



- The velocity of the inflow decreases linearly inward and spans the range between -3 - 0 km/s