Modelling the Chemical Evolution of the Milky Way

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KITP: Back to the Galaxy II

Outline of the talk

- Basic tools to build chemical evolution models
- Basic Equations
- Scenarios for the formation of the Milky Way
- Comparison of results from various models
- Comparison theory versus observations
- Conclusions

Basic Tools

- Initial conditions
- The SFH, namely star formation rate (SFR) and initial mass function (IMF)
- Stellar yields: element production from stars
- Supernovae of different type and their products
- Stellar lifetimes
- Gas flows: infall, inflow, outflow

Star Formation Rate

- The most common parametrization is the Schmidt (1959) law where the SFR is proportional to some power (k=2) of the gas density

$$SFR = \nu \sigma_{gas}^{k}$$

- Kennicutt (1998) suggested k=1.4 from star forming galaxies, but also a law depending of the rotation angular speed of gas

$$SFR = 0.017 \Omega_{gas} \sigma_{gas} \propto R^{-1} \sigma_{gas}$$

- Other parameters such as gas temperature, viscosity and magnetic field are usually ignored

Star Formation Rate

- Star formation rate taking feedback into account (Talbot & Arnett 1971; Dopita &Ryder 1994):

$$SFR = \nu \sigma_{tot}^{k_1} \sigma_{gas}^{k_2}$$

SFR induced by spiral density waves (Wyse & Silk, 1989: Prantzos 2000):

$$SFR = aV(R)R^{-1}\sigma_{gas}^{1.5}$$

Initial Mass Function

- The IMF is generally a power law:

$$\varphi(M) = aM^{-(1+x)}$$

- In the solar vicinity it is a multi-slope function (e.g. Scalo 1986; Kroupa et al. 1993). The normalization is:

$$a\int_0^\infty M\varphi(M)dM = 1$$

The Infall Law

- The infall rate can simply be constant in space and time
- Or described by an exponential law:

$$IR = A(R)e^{-t/\tau(R)}$$

- In principle, the infall law should depend on the DM halo (see Colavitti & al. 2008)

The Outflow Law

- The rate of gas loss from a galaxy through a galactic wind can be expressed as proportional to the SFR (see Martin, 2000):

$$W = -\lambda SFR$$

- Where lambda is a free parameter equal or larger than 1

Stellar Yields

- Low and intermediate mass stars (0.8-8 Msun): produce He, N, C and heavy s-process elements. They die as C-O white dwarfs, when single, and can die as Type Ia SNe when binaries and produce 0.6 Msun of Fe!

- Massive stars (M>8-10 Msun): they produce mainly alpha-elements (O, Ne,Mg, Si, S, Ca), some Fe, light s-process elements and r-process elements and explode as core-collapse SNe

Type Ia Supernovae

- Type Ia SNe are believed to originate from C-O WDs in binary systems exploding when they reach the Chandrasekhar mass
- Two possible channels lead to this: Single Degenerate- the WD explodes after accreting matter from a RG or MS companion (Whelan & Iben 1974), or Double Degenerate- two WDs explode after merging (Iben & Tutukov, 1984)
- Explosion times from 30-31 Myr to a Hubble and several Hubble (DD) times. Prompt Type Ia SNe have been observed (Mannucci et al.2005)

Basic Equations

$$
\begin{aligned}
&\dot{G}_i(t) = -\psi(t)X_i(t) \\
&+ \int_{M_L}^{M_{Bm}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm \\
&+A \int_{M_{Bm}}^{M_{BM}} \phi(m) \\
&\cdot[\int_{\mu_{min}}^{0.5} f(\mu)\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})d\mu]dm \\
&+B \int_{M_{Bm}}^{M_{BM}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm \\
&+ \int_{M_{BM}}^{M_U} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)dm \\
&+X_{A_i}A(t) - X_iW(t)
\end{aligned}
$$

Formation of the Milky Way: the old scenario

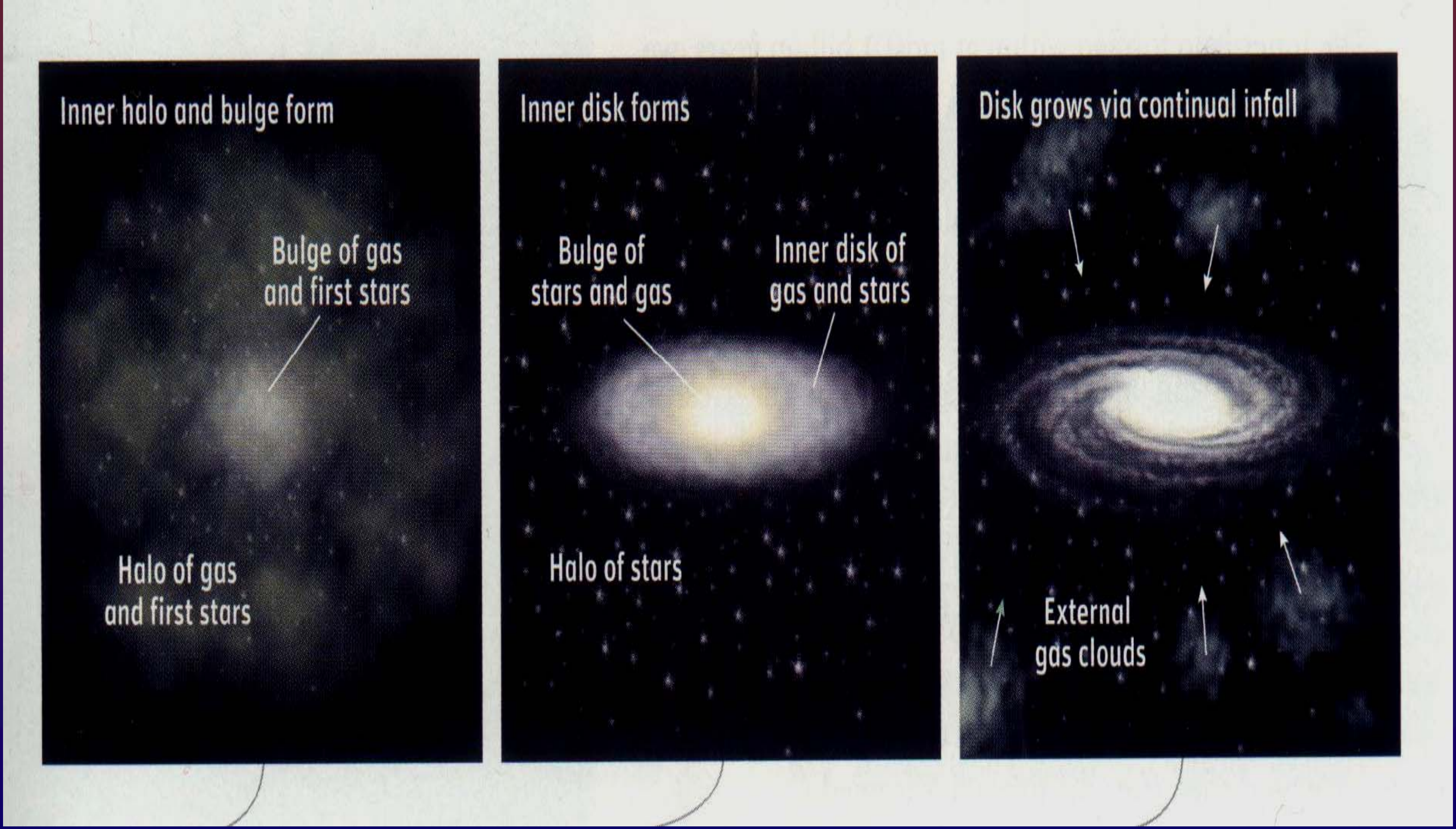
The Formation of the Milky Way

- Eggen, Lynden-Bell & Sandage (1962) suggested a rapid collapse lasting 300 Myr for the formation of the Galaxy
- Searle & Zinn (1978) proposed a central collapse but also that the outer halo formed by merging of large fragments taking place over a timescale > 1Gyr
- In the hierarchical structure formation the Halo should have formed by mergers of stellar subunits such as the dwarf galaxies. Evidence for accretion in the outer Halo (Carollo et al. 07)

Different Approaches to the MW Formation

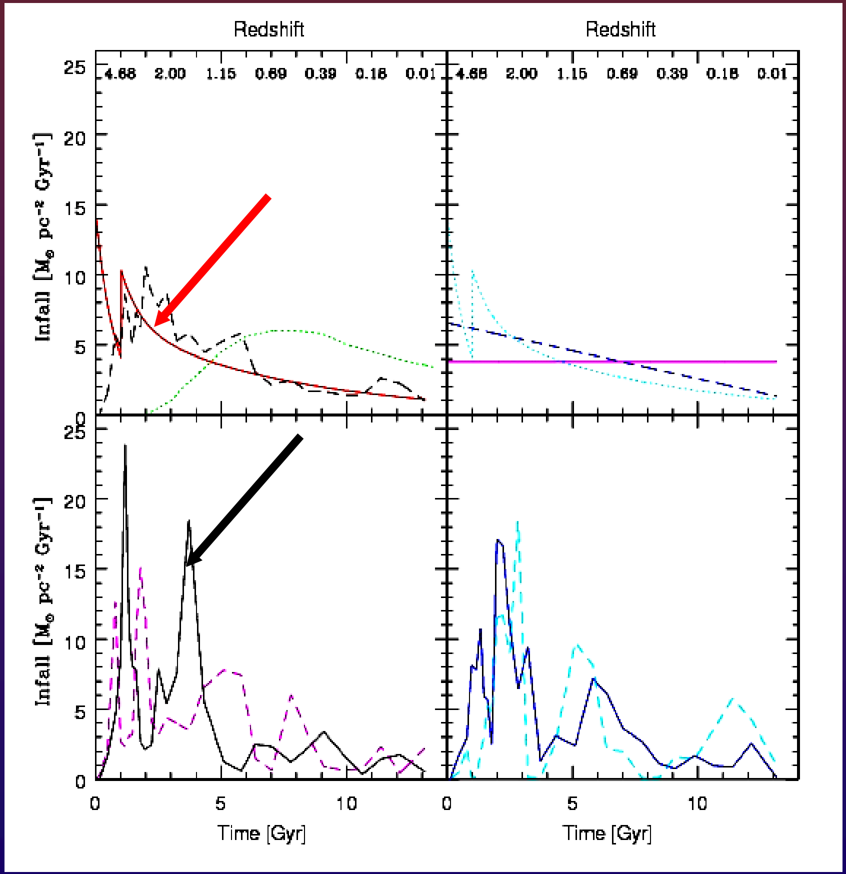
- Two-infall approach: halo and disk form out of two different gas infall episodes (e.g. Chiappini, FM & Gratton 1997; Chang & al. 1999; Alibès & al. 2001)
- Stochastic approach: mixing not efficient in the early Halo phases (e.g. Tsujimoto et al. 1999; Argast et al. 2000; Oey 2000; Cescutti 2008)
- Hierarchical formation of the Halo (e.g. Bekki & Chiba 01; Robertson & al. 05; Font & al. 2006)
- Stellar dynamics included (Schoenrich & Binney, 2008)

The Two-Infall Model



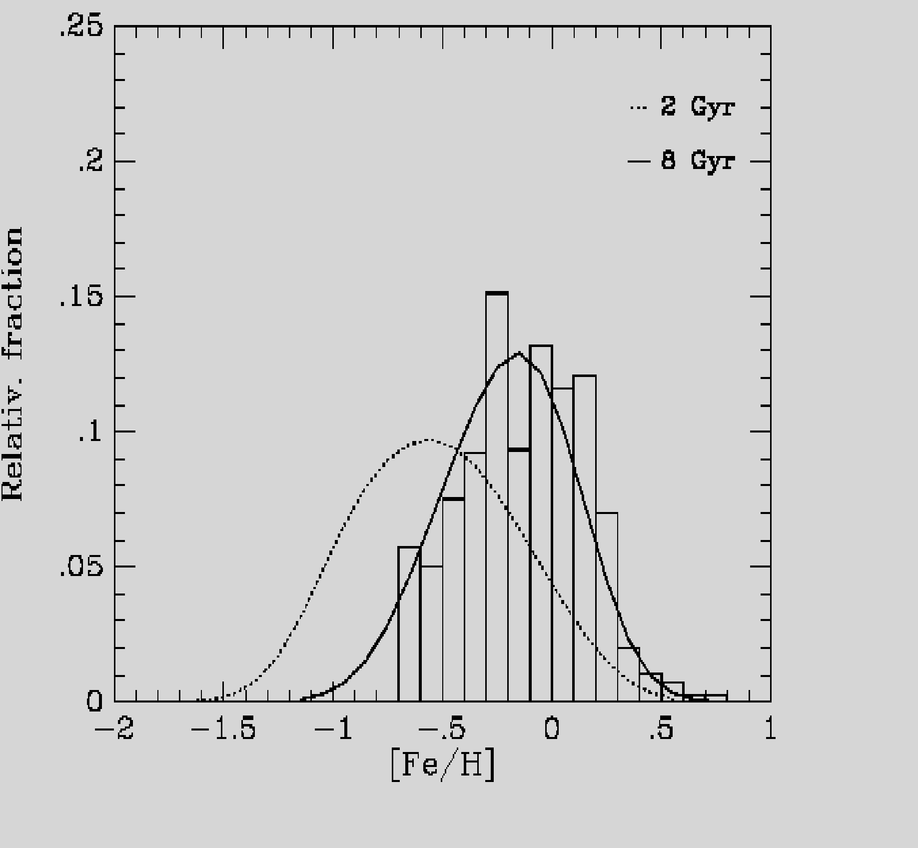
Cosmological Infall Law

- The Chiappini et al. 97 two-infall law is the red curve at the top left
- Cosmological simulations (Colavitti, FM & Murante 2008, Colavitti poster) assuming that the growth of baryonic mass is similar to that of DM
- It predicts a growth of mass similar to the two-infall model!



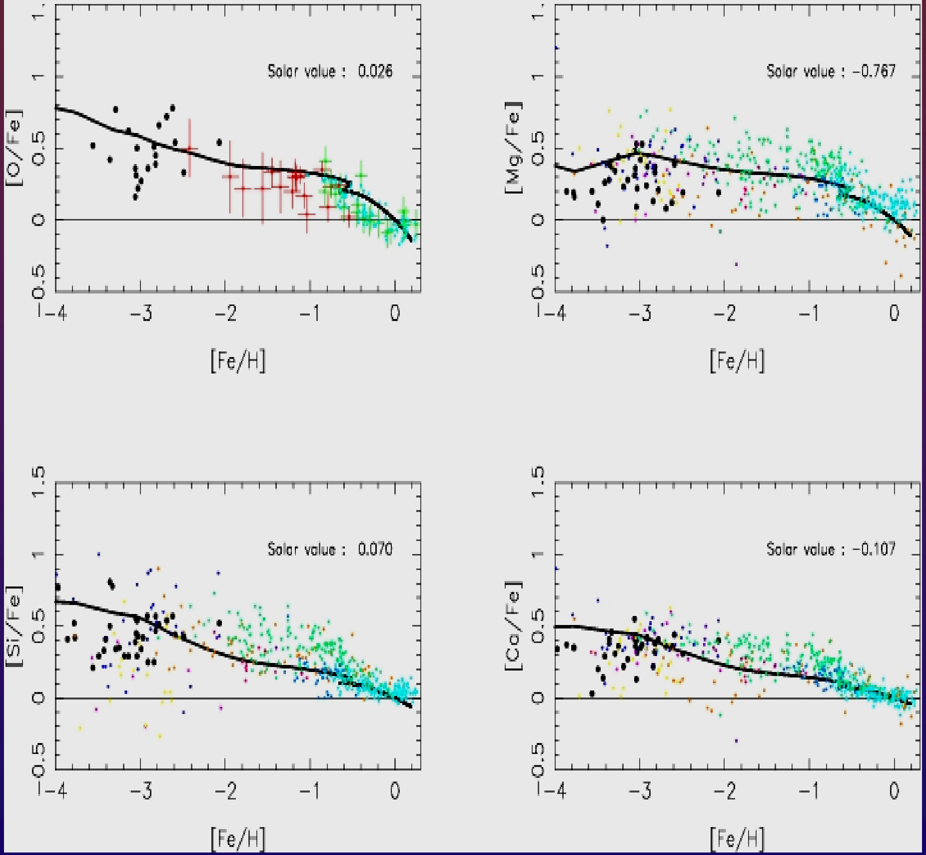
Predictions & Observations

- G-dwarf metallicity distribution in the solar vicinity: data from Kotoneva & al. (2002)
- Models by Chiappini et al. (1997) with different timescales of disk formation at 8 Kpc
- A timescale of 8 Gyr produces a good fit



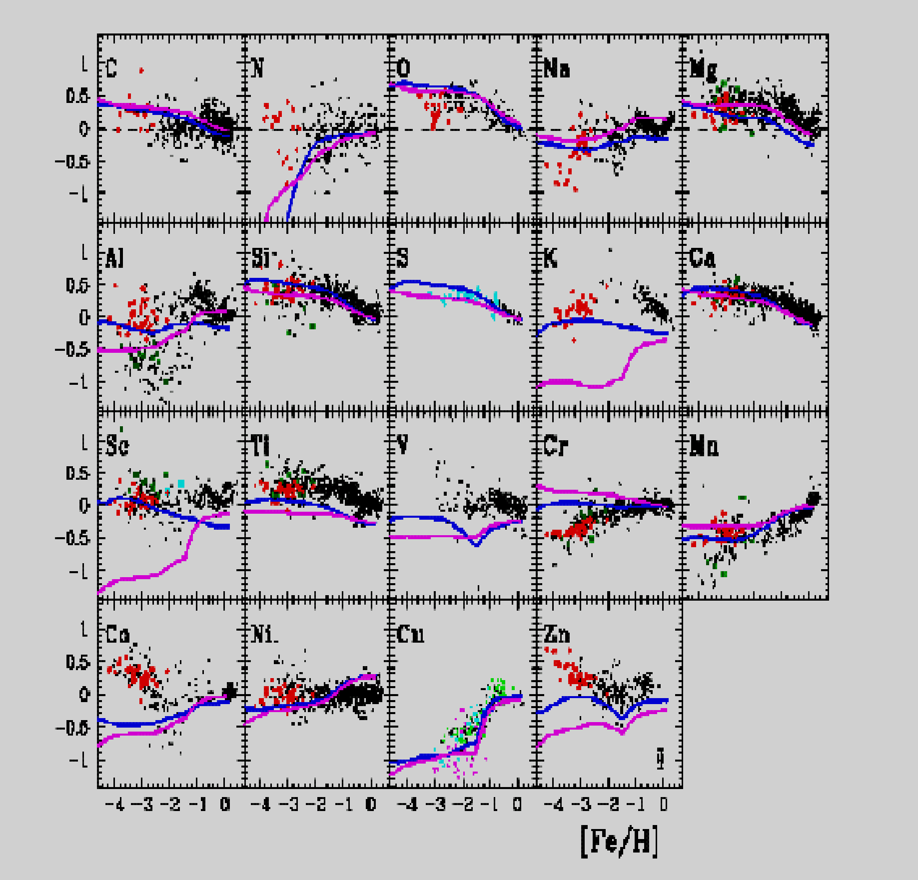
Predictions & Observations

- Results from the two-infall model (Francois & al. 2004). Woosley & Weaver 1995 (WW95) yields with some corrections
- We can infer the timescale for the Halo formation (1-1.5 Gyr)
- The observed spread in the [O,Mg/Fe] ratios at very low metallicities < than predicted with inhomogeneous models (e.g. Argast et al. 2000)



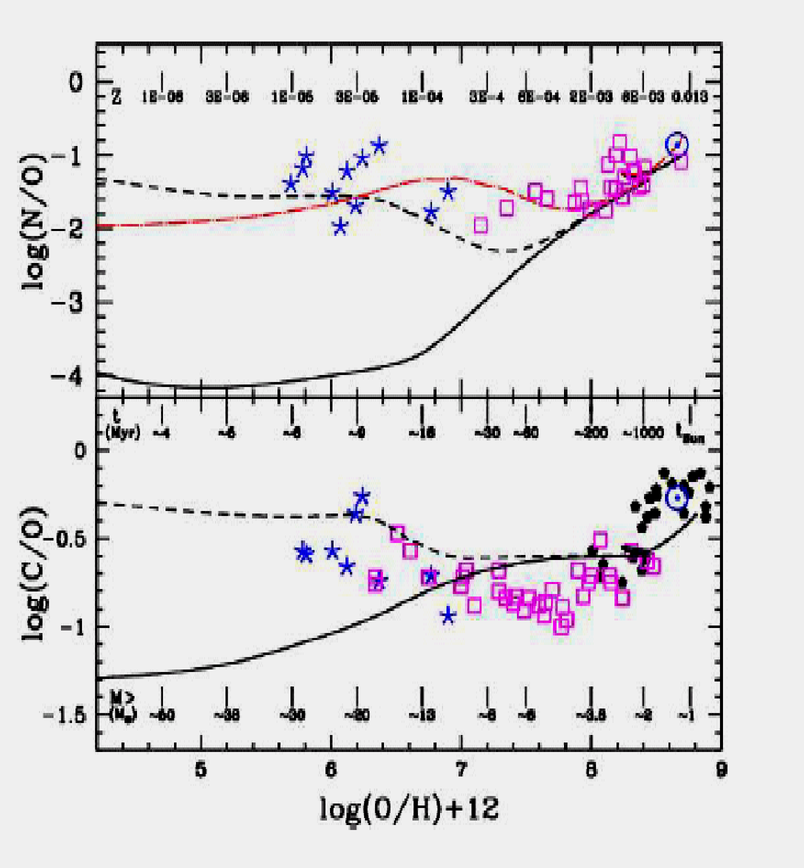
Uncertainties in the Yields

- The alpha/Fe ratios are well reproduced
- There are still uncertainties for Fe-peak elements
- Pink lines : yields from Chieffi& Limongi (2004); blue lines yields from WW95. Figure from Prentzos (2007)



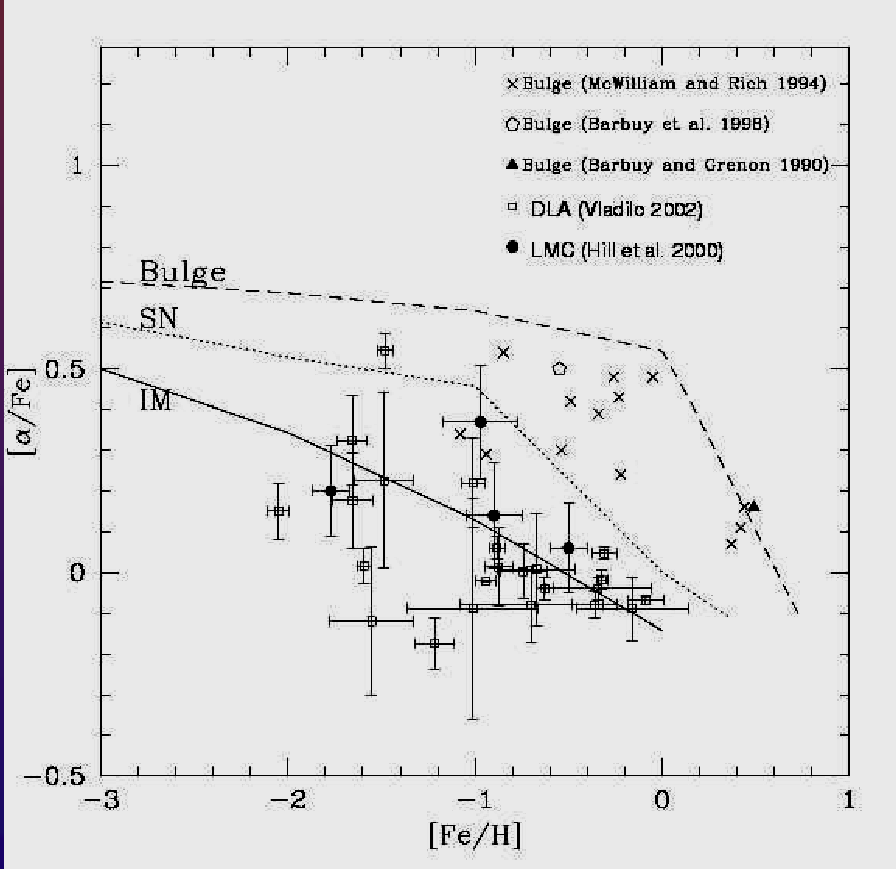
C & N evolution

- Primary nitrogen from rotating very metal poor massive stars is required to explain N/O at low metallicity
- Models from Chiappini et al. (2006) (dashed lines) including primary N from rotating massive stars
- Large squares from Israelian et al. 04; asterisks from Spite et al. 05; pentagons from Nissen 04

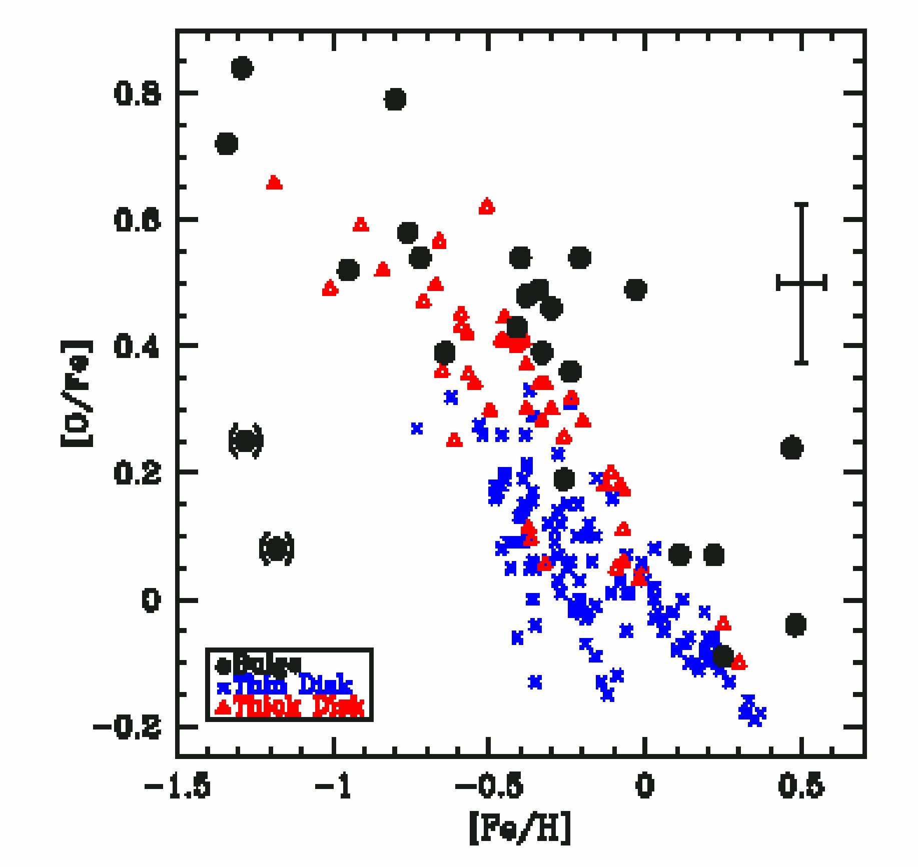


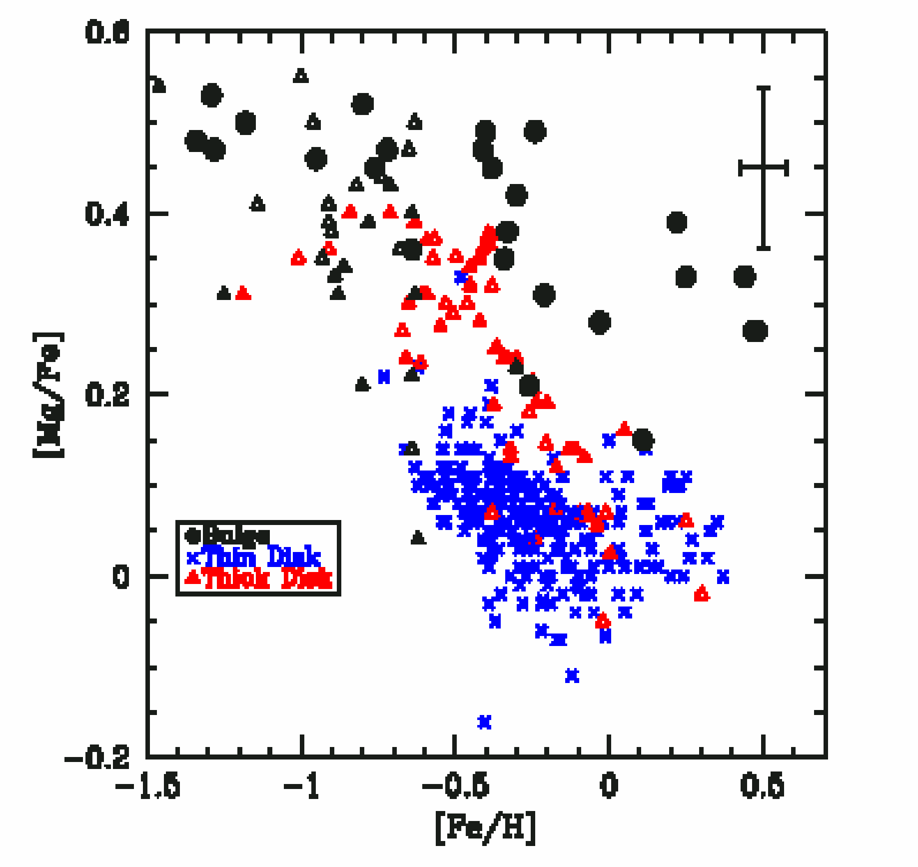
The Time-Delay Model

- Predicted [alpha/Fe] ratios for different SFR histories (a more modern version of Matteucci & Brocato 1990)
- A strong starburst (dashed line), a SFR like in the solar vicinity (dotted) and a slow SFR (continuous) like in Magellanic Irregulars or Dwarf Spheroidals



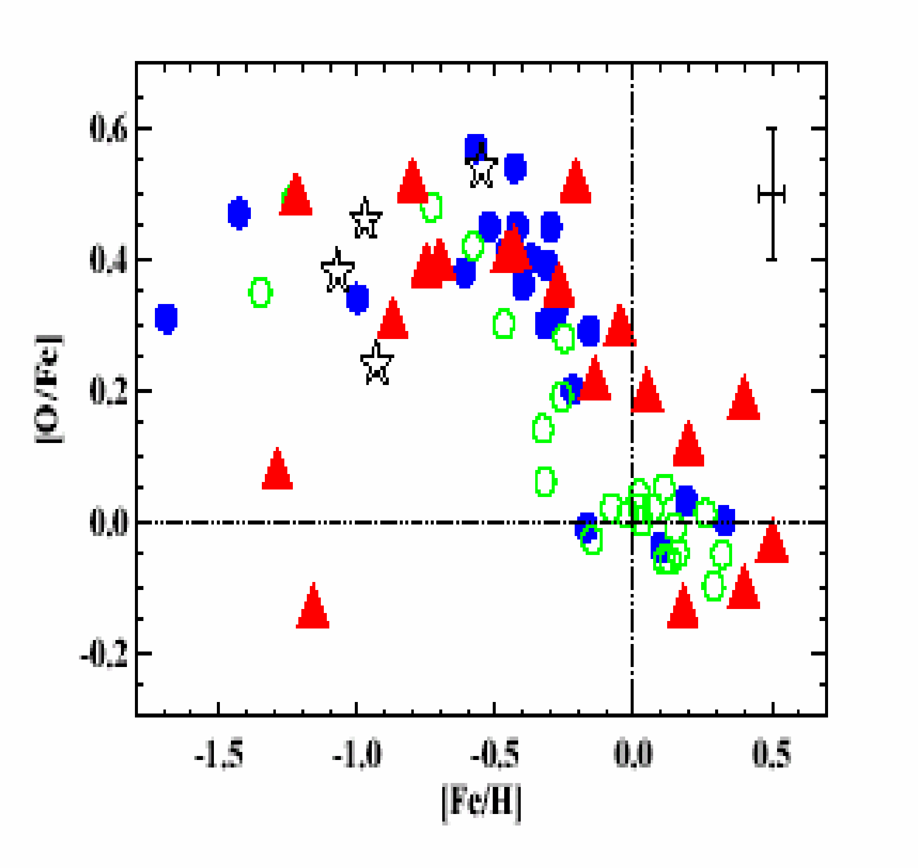
Thin-Thick Disk and Bulge (Fulbright et al. 2007)





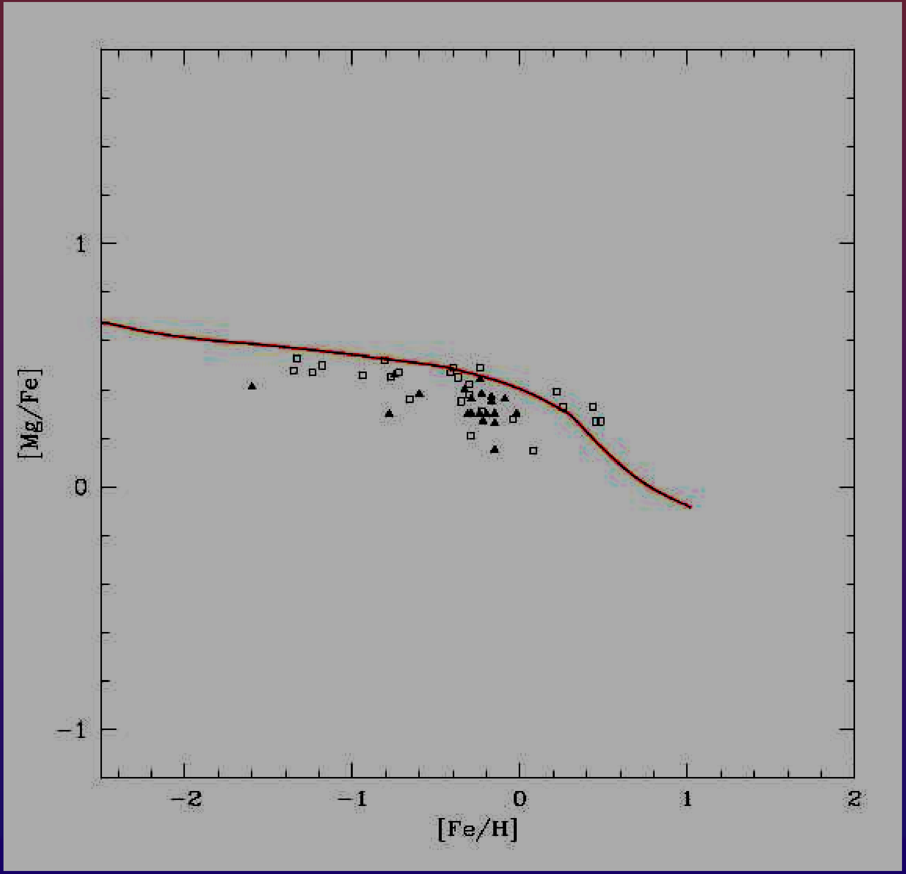
Again Thin-Thick Disk -Bulge

- Thick disk stars have higher [O/Fe] than thin disk stars (Bensby et al. 2004, Melendez et al. 2008). Thick disk evolved faster
- Bulge stars have higher [O/Fe] ratios than the thick disk stars (Fulbright et al. 07; Lecurer et al. 07). Bulge stars (red) have the same [O/Fe] of thick disk stars (blue) (Melendez et al. 2008)

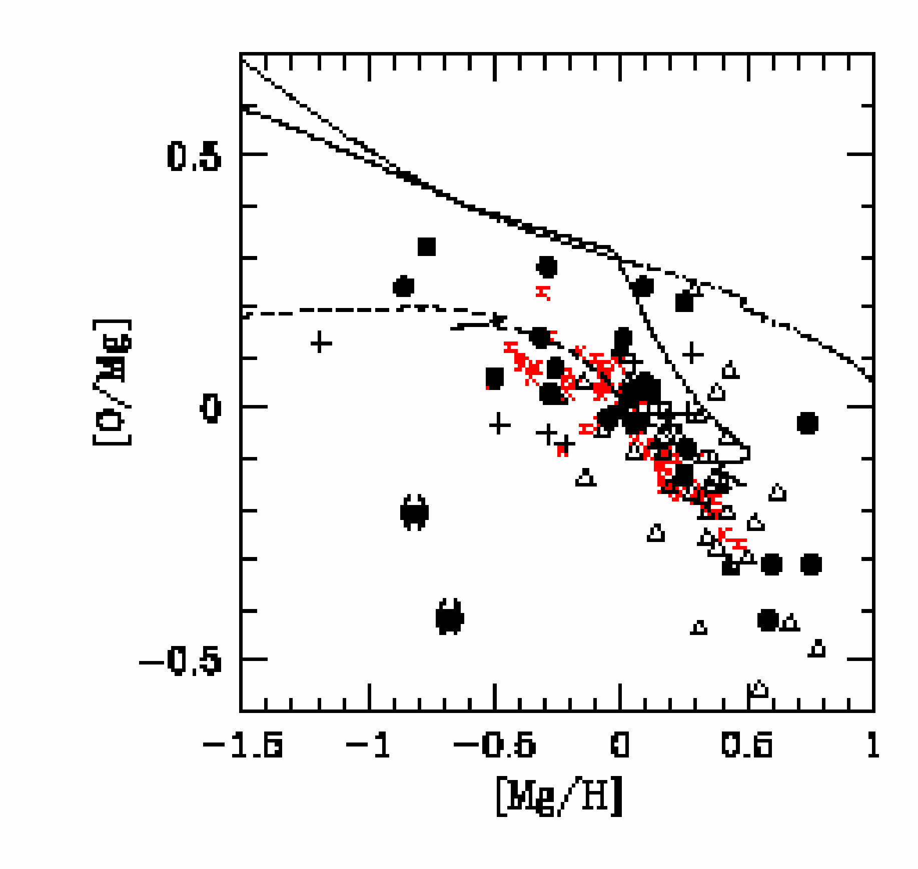


Predictions for the Bulge

- Model (red, Ballero et al. 2006): fast Bulge formation (0.3 Gyr) and flatter IMF
- Predicts large Mg to Fe for a large Fe interval
- Turning point at larger than solar Fe. Mg flatter than O (effect of the time-delay model)
- Data from Zoccali et al. 06; Fulbright et al. 06, 07;Origlia & Rich (04, 05)



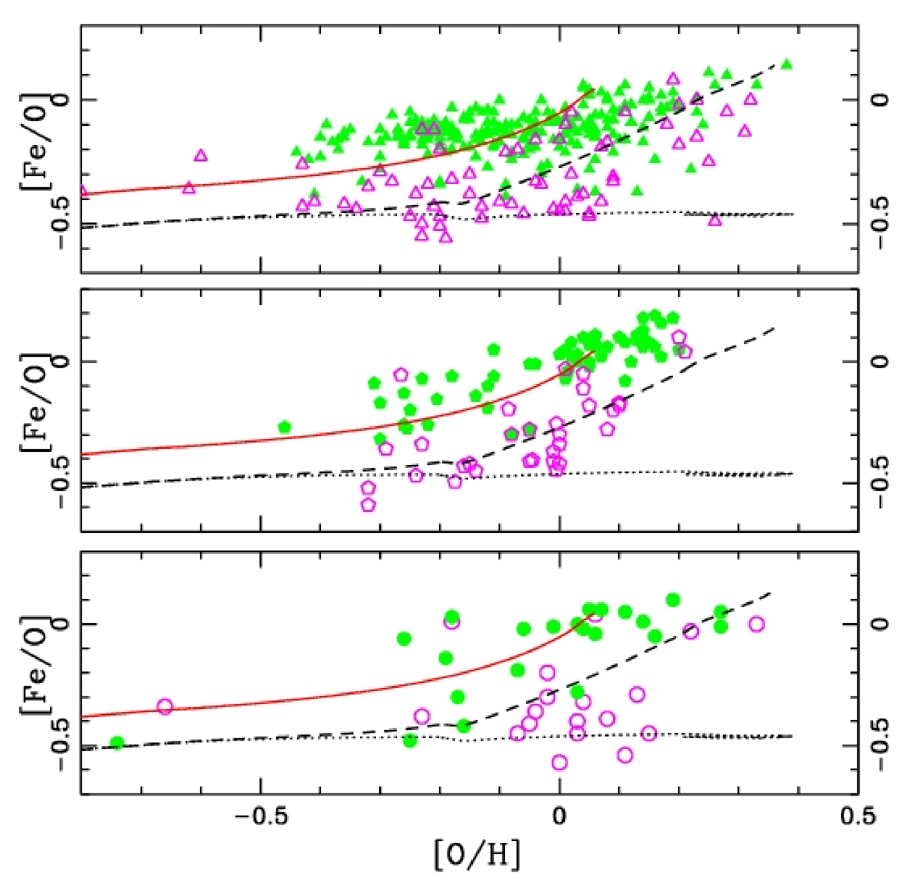
Predictions for the Bulge and Thin Disk



- McWilliam et al. (2008) showed that the steep decline observed in [O/Mg] can be explained by adopting the yields of O from Maeder (92) with mass loss for Z>Zsun
- Black points are Bulge stars and Red are thin disk stars

The Thick Disk

- Abundances in the thin disk (green) and abundances in the thick disk (pink)
- Models from Chiappini (2008) where the thick disk (dashed line) forms by gas infall occurring on much shorter timescales than the Local thin disk (continuous line)
- The dotted line is a thick disk model without SNe Ia



Timescales from Galactic Astro-Archaeology

- The inner stellar Halo must have formed on a timescale of 1.5 Gyr whereas the outer Halo must have formed on a longer timescale (inside-out Halo formation)
- The Local disk must have assembled on a time scale from 6-8 Gyr (agreement with chemo-dynamical models)
- The thick disk must have formed more quickly than the thin disk (2 Gyr?)
- The Bulge must have formed on a time no longer than 0.3-0.5 Gyr
- The thin disk formed inside out with longer timescales in the outer parts where it is still forming now

Abundance Gradients in the Thin Disk

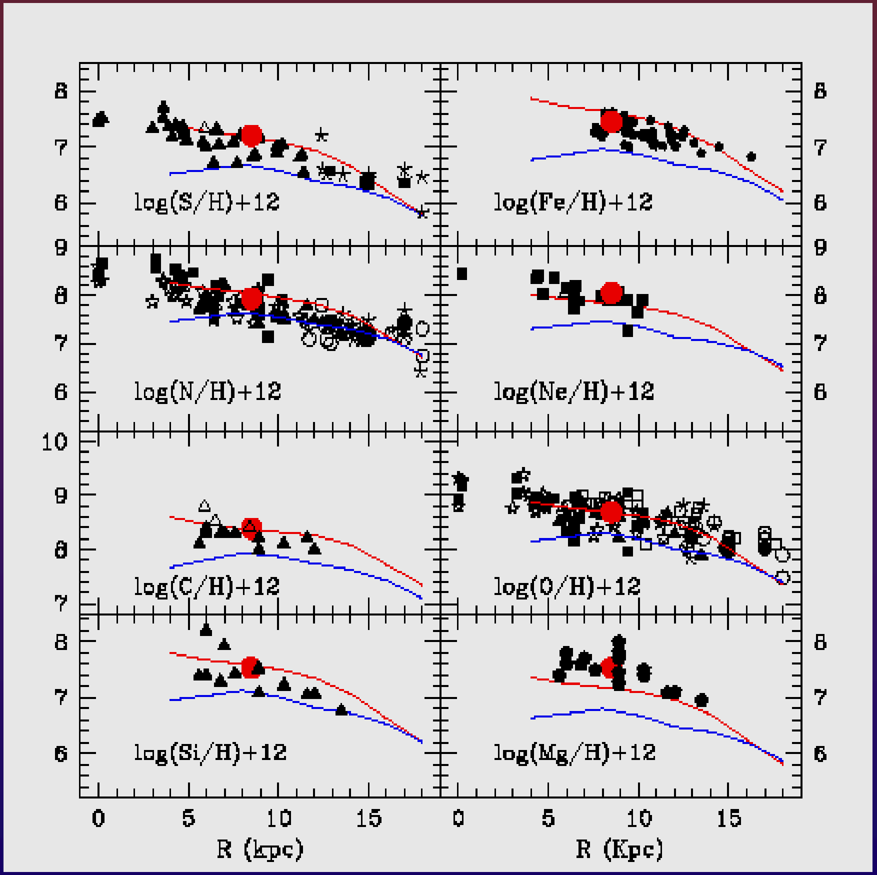
- If the disk formed inside-out, the abundance gradients are well reproduced . Observational evidence from Munoz-Mateos et al. (2007)
- A way of achieving this is to assume the timescale for disk formation to increase linearly with galactocentric distance(Matteucci & Francois 89; Boissier & Prantzos, 99; Chiappini & al. 01). For example:

$$\tau_d(R) = 0.875R - 0.75$$

- Modest radial flows can also reproduce the gradients with a constant timescale for disk formation (Portinari& Chiosi, 2000)

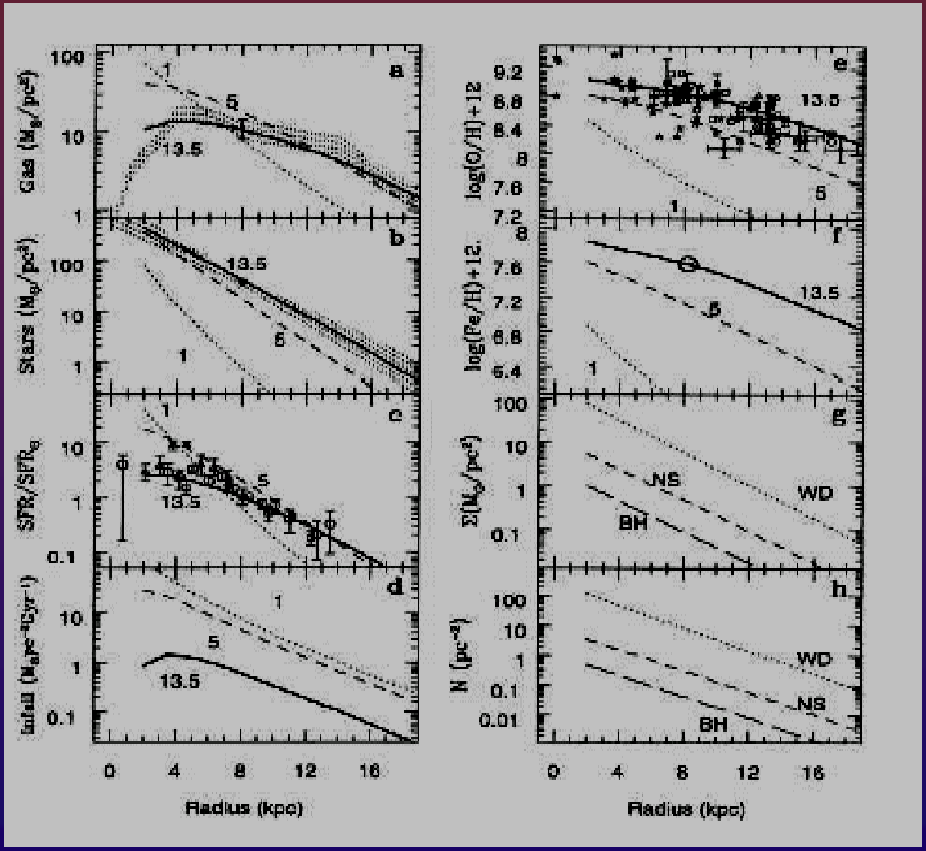
Abundance Gradients

- Predicted and observed abundance gradients from Chiappini, FM & Romano (2001). Threshold density in the SFR
- Data from HII regions, PNe and B stars, red dot is the Sun
- The gradients steepen with time (from blue to red)



Abundance Gradients

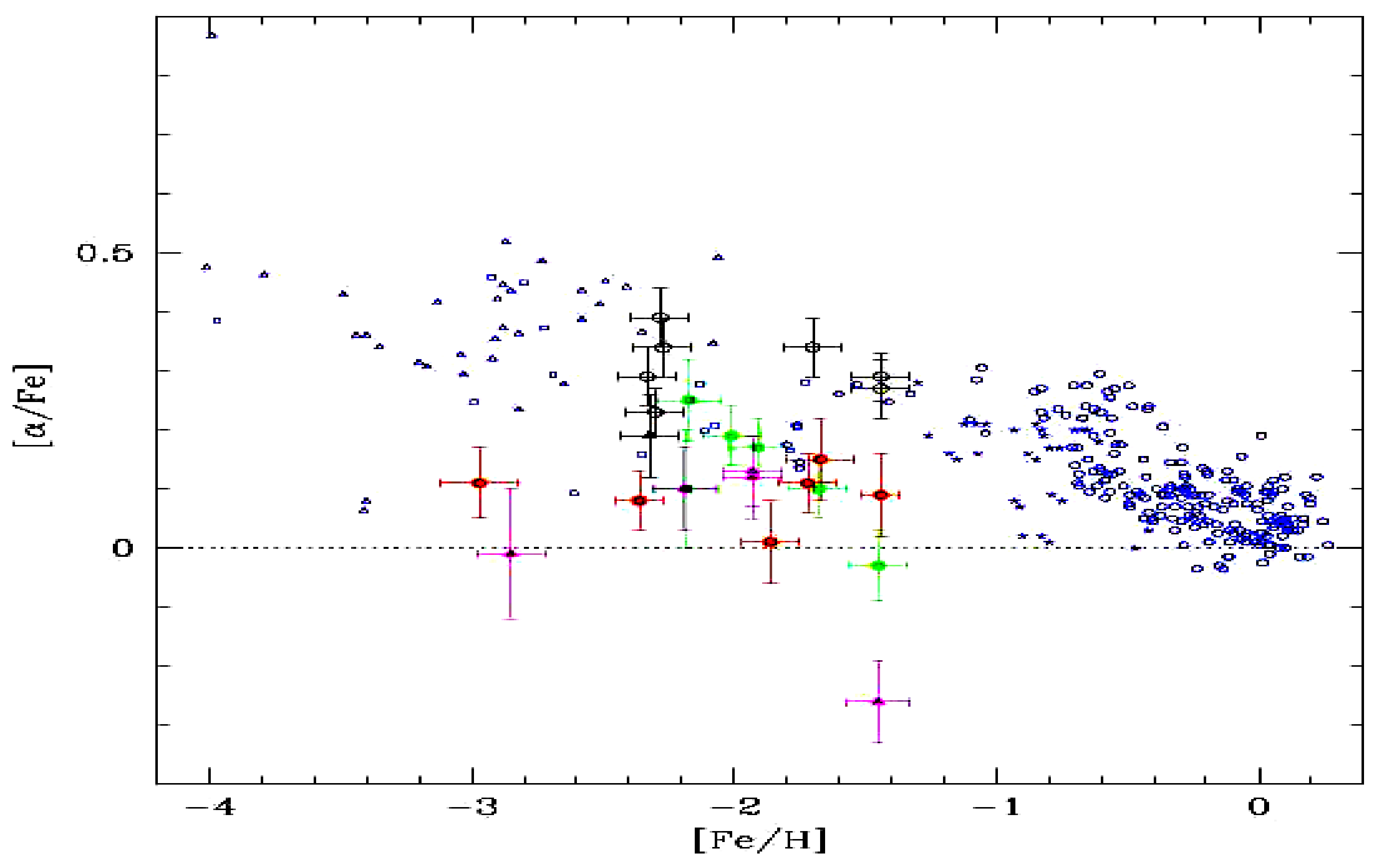
- Predictions from Boissier & Prantzos (1999), no threshold density in the SF
- They predict the gradient to flatten in time
- The difference is due to the effect of the threshold in the SFR



Open Questions in the MW Formation

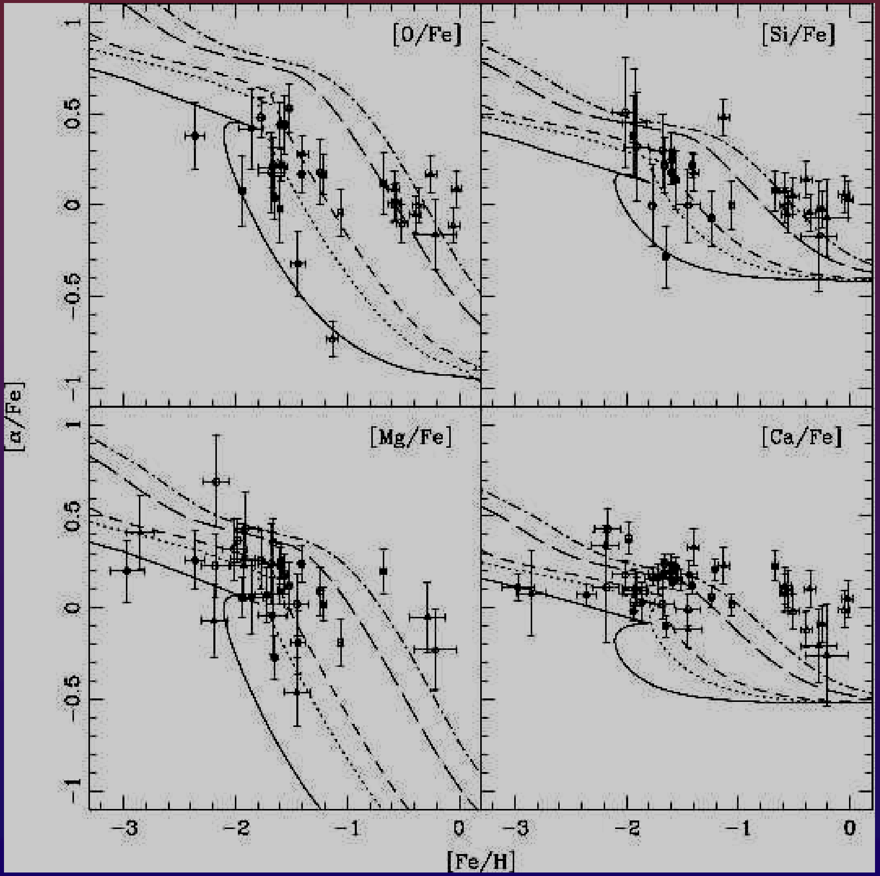
- Did the stellar halo of the MW form by accretion of smaller subsystems or by gas infall?
- Did the galactic thin disk formed by gas accretion occurring inside-out ?
- Did the thick disk formed like the thin disk or was partly or totally accreted?
- Chemical evolution models assume gas accretion whereas hierarchical cosmological models favor the formation by merging of subsystems
- Can the chemical abundances help in discriminating?

[alpha/Fe] Ratios in the MW and dSphs

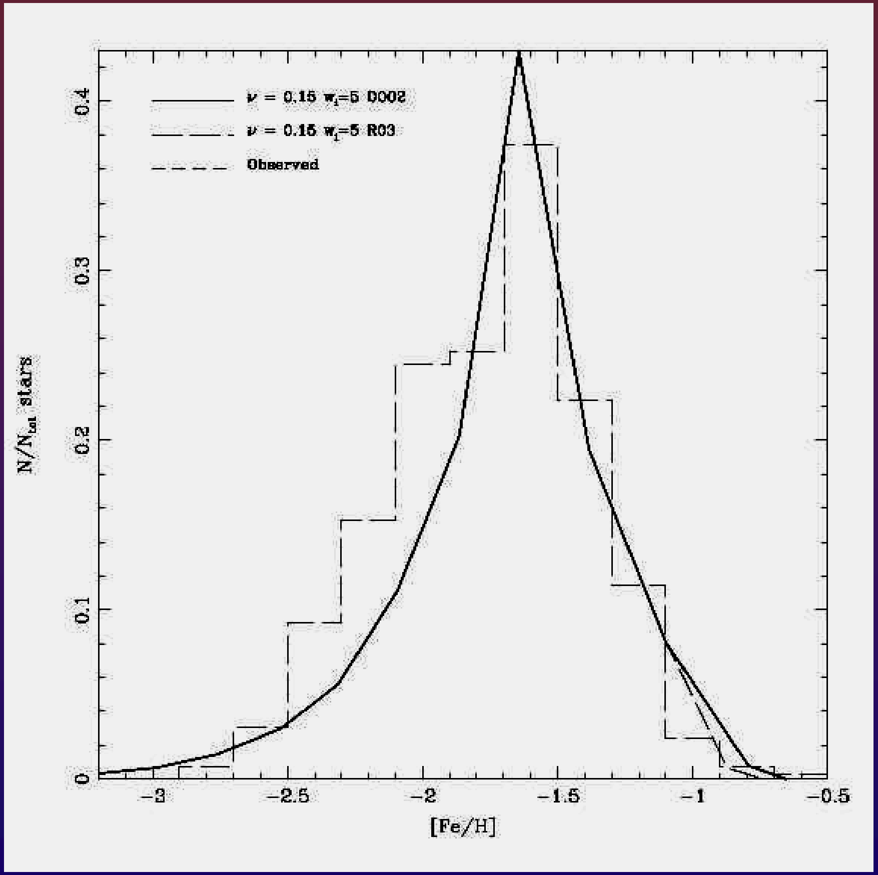


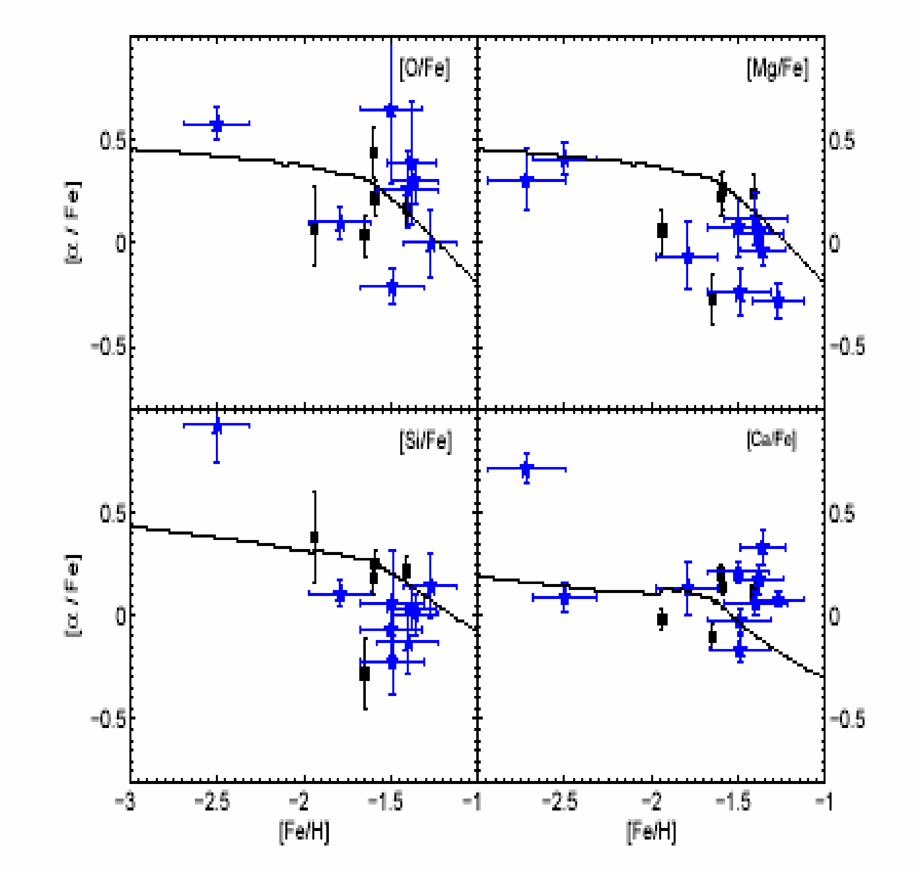
Chemical Evolution of dSphs

- Lanfranchi & Matteucci (2003, 2004) proposed a model which assumes a SF H as derived by the CMDs. Initial baryonic masses 5x10^(8)Msun
- SN feedback induces a strong outflow. DM ten times LM but diffuse (M/L today of the order of 100)
- SFR less efficient that in the MW going on for 8 Gyr
- Models for specific galaxies were computed also



Evolution of Carina –Observations from Koch & al. (2005, 2008)





Summary

- Time-delay model (SN II vs. SN Ia metal production) works well in interpreting abundance ratios in galaxies
- Timescales for the formation of the various Galactic components can be inferred from abundance ratios
- The thin and thick disk abundance ratios suggest a faster formation of the thick disk by gas infall, although the outer thick disk has probably been accreted. The thin disk was formed more slowly by gas infall probably inside-out
- The Bulge should have formed even faster than the inner Halo

Summary

- Local dwarf spheroidal galaxies seem to have formed stars for long periods (several Gyrs) and their star formation must have proceeded much more slowly than in the MW
- Galactic winds and/or gas stripping have also played an important role in the evolution of dSphs
- The Halo might have formed by accretion of satellites. More data on very low metallicity stars in dSphs and in the MW are required to assess this point