Some Observational Constraints on Chemical Evolution

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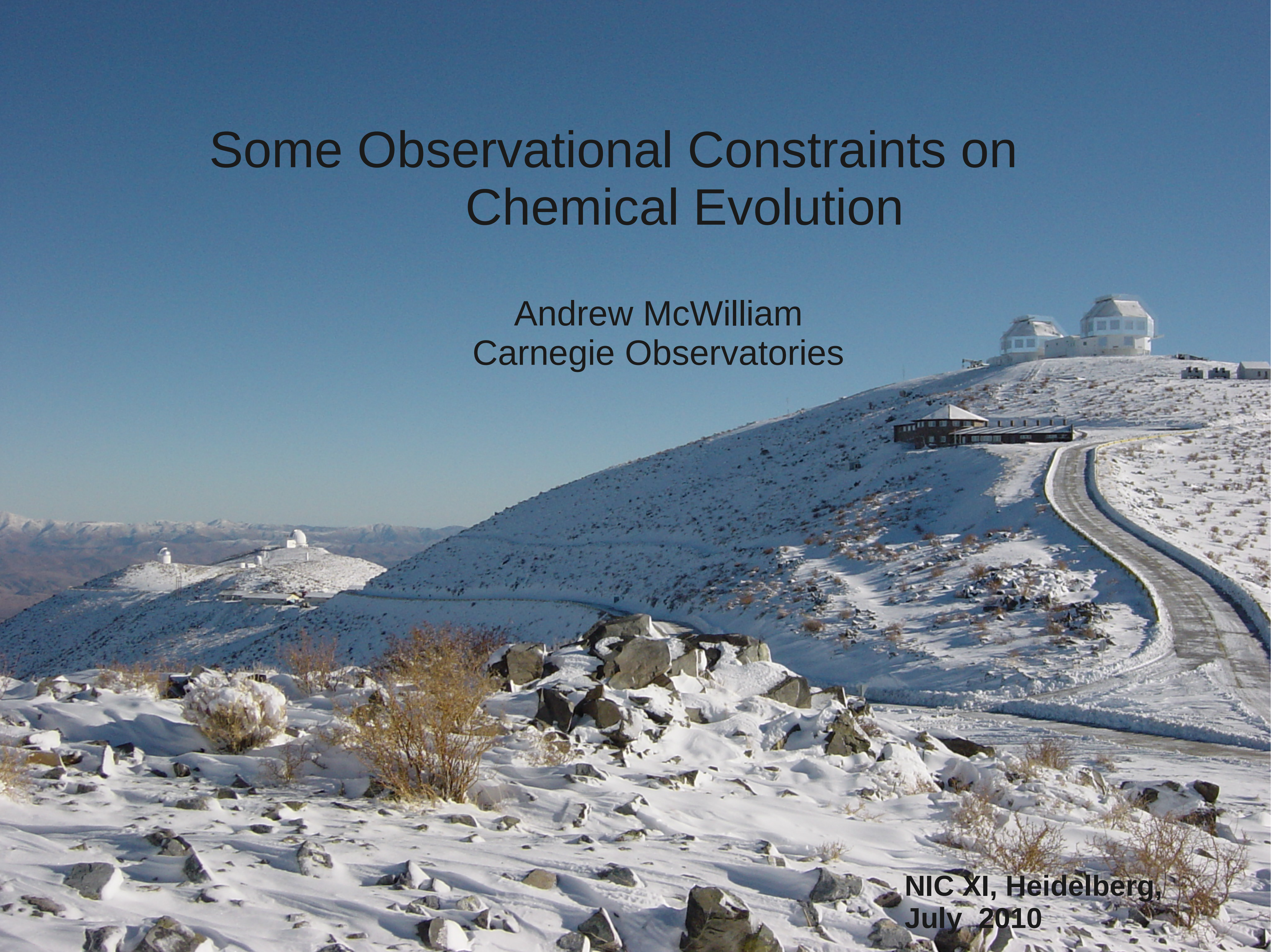
Carnegie Observatories



NIC XI, Heidelberg,
July 2010

Why Study Chemical Evolution?

To understand nucleosynthesis and stellar yields.

To understand the role of environment on chemical enrichment.

To understand how galaxies evolved.

Chemical Evolution and Stellar yields must be solved simultaneously

Use the chemical fossil record to probe galaxy evolution

but

Understand nucleosynthesis yields via dependence on environment

→ **probe many different environments**
(thin/thick disk, inner/outer disk, halo, bulge, GCs, other galaxies)

→ **RGB stars are bright, trace age of Universe, many species**

Goal to measure formation timescales, SFR, IMF, inflows, outflows, accretion

Use simple arguments and clear observational results

Simple model: constant gas consumption rate, stellar generations, “yield”,
instantaneous re-cycling, mixing, etc...
(van den Bergh 1962, Schmidt 1963, Searle & Sargent 1972)

(missing critical detail but useful for learning about CE)

- linear age-metallicity relation
- normal metallicity distribution function
- mean metallicity = yield

Metallicity Distribution Function is useful:

Halo metallicity ~-1.6 much less than solar neighborhood → **outflow**

G-dwarf Problem (paucity of low-metallicity disk stars) → **inflow**

Metal-poor dwarf galaxies with gas (e.g. LMC, SMC) → **low SFR**
& Carbon stars

Bulge [Fe/H]~solar (but if not much SNIa) **IMF?,** massive inflow?

Alpha Elements (e.g. O, Mg, Si, Ca,Ti)

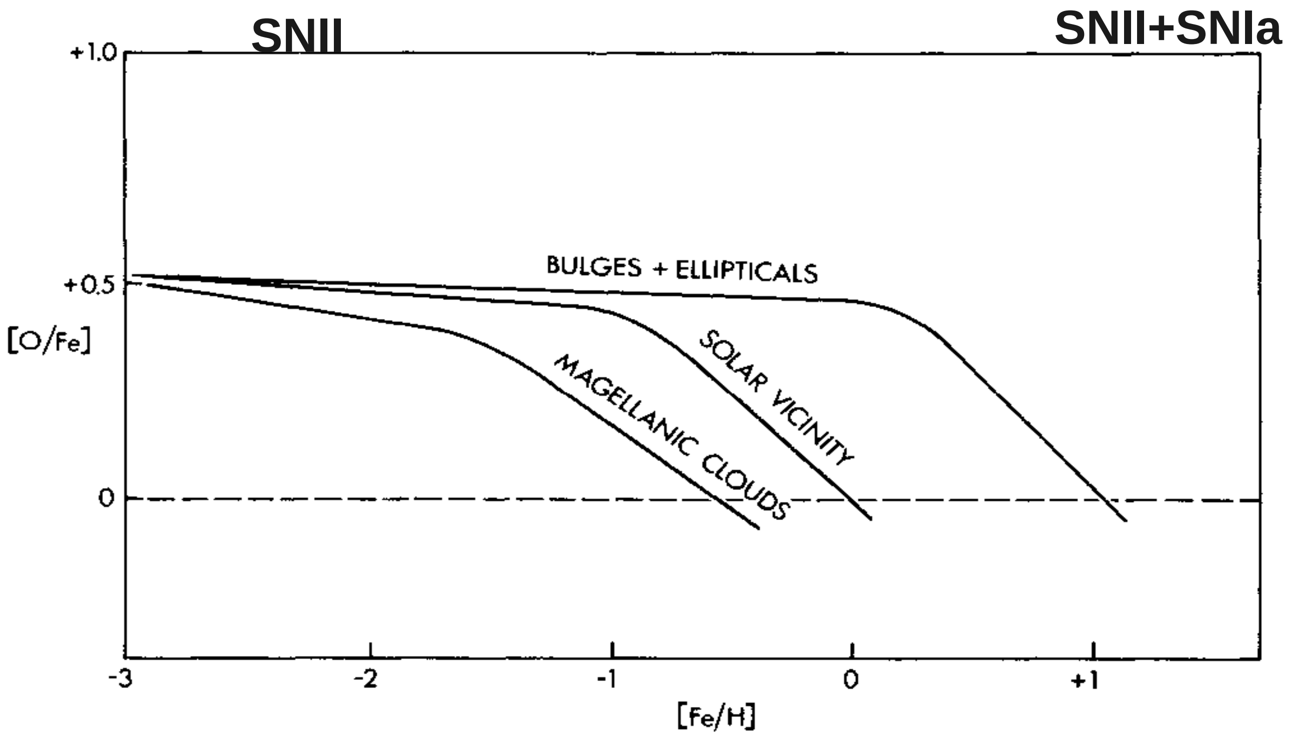


FIG. 4.—A sketch of the predicted [O/Fe] vs. [Fe/H] relations in different systems as a consequence of their different [Fe/H]-*t* relations.

(c.f. Tinsley 1979)

IMF ↑

SFR →

[O/Fe] dependence on SFR (Matteucci & Brocato 1990)

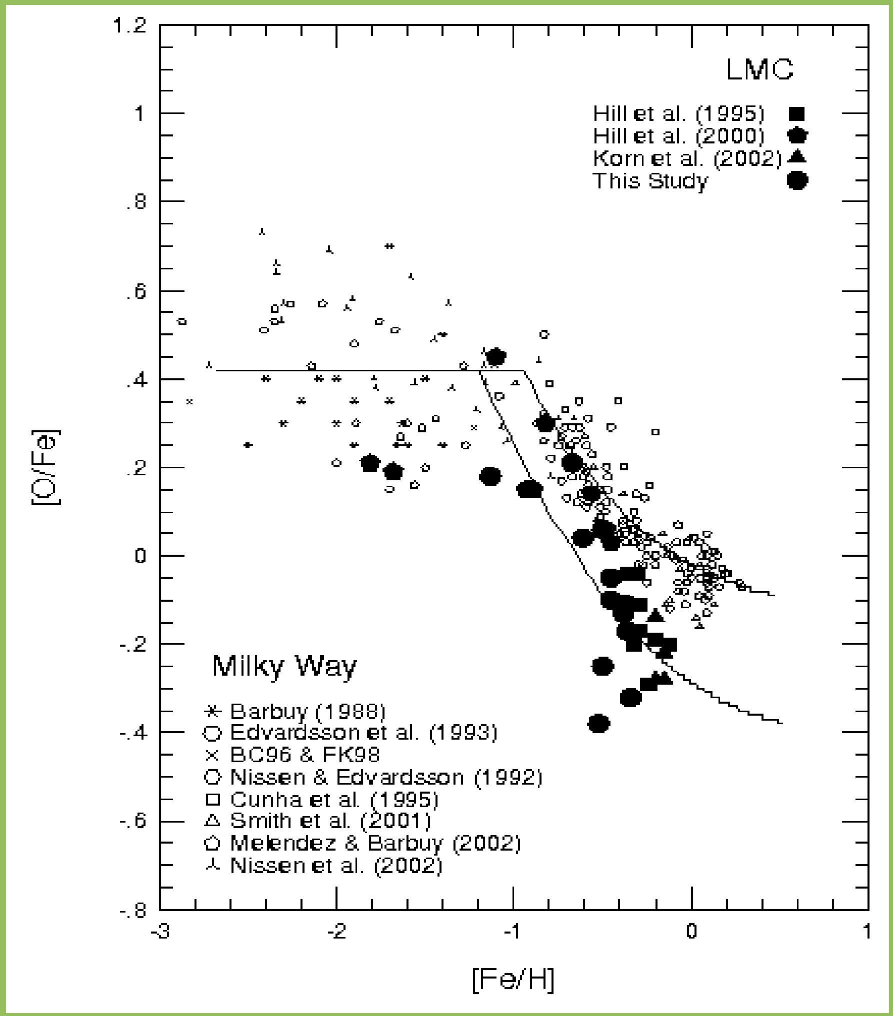
Expect [α/Fe] enhanced in bulge, low in dwarf galaxies.

High SFR → short formation timescale

(Knee ~ 1Gyr?)

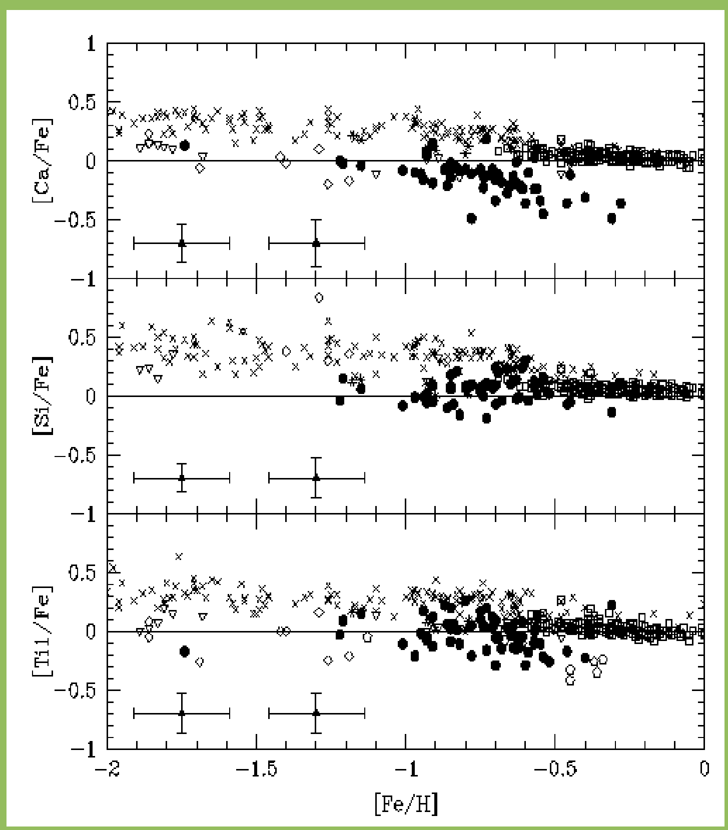
LMC Alpha Abundances

Smith et al. (2002)



Hill et al. (2000) LMC GCs
Smith et al. (2002)

Pompeia et al. (2008)



(O slightly deficient)

Alpha elements in other Dwarf Galaxies

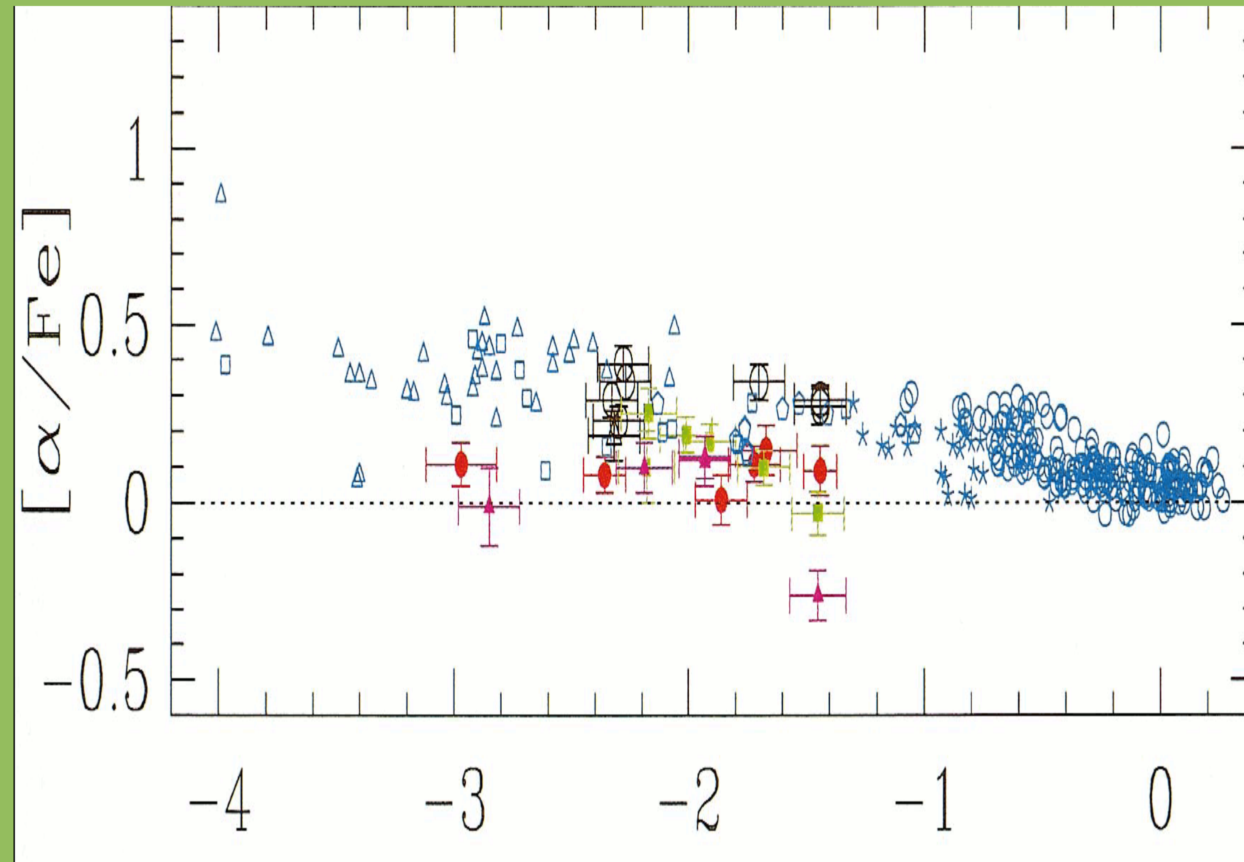
Shetrone et al. (2001)

Draco, Ursa Minor, Sextans dSphs

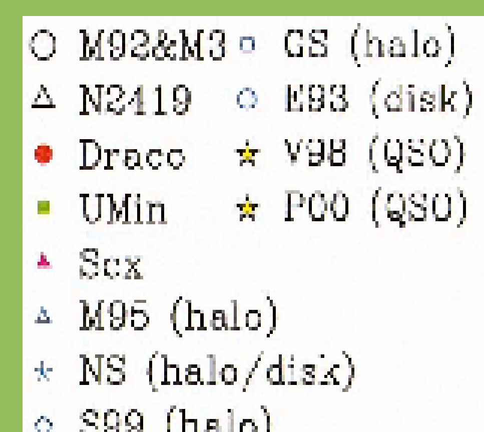
Ca, Ti, Mg low but not Si (O in Draco)

Na low, but Al enhanced

Y low, Ba normal

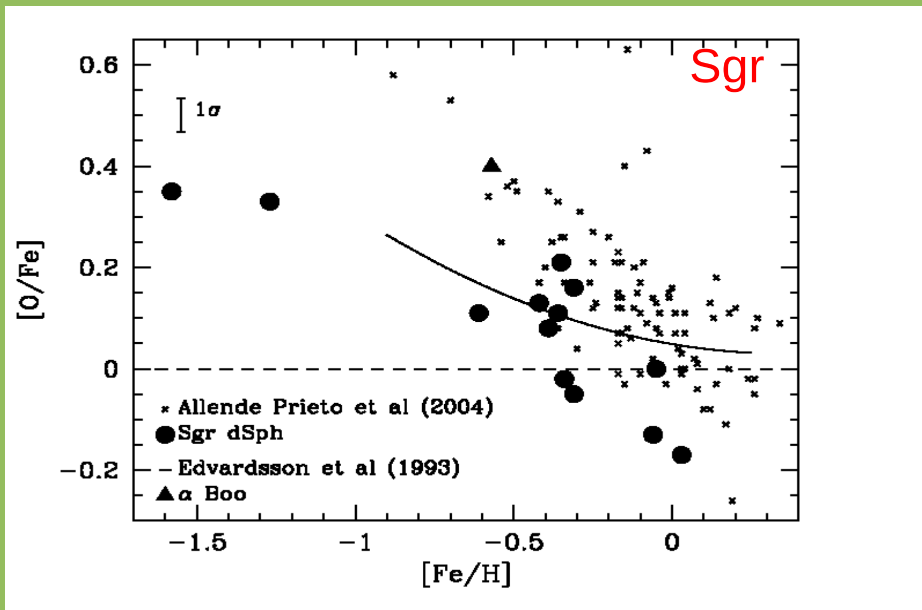


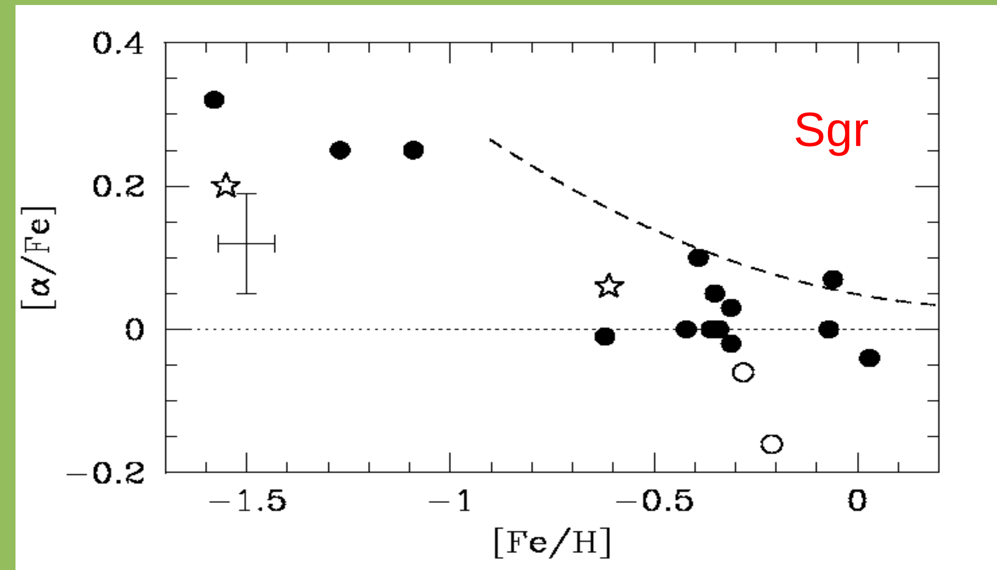
★Where α = (Mg+Ca+Ti)/3

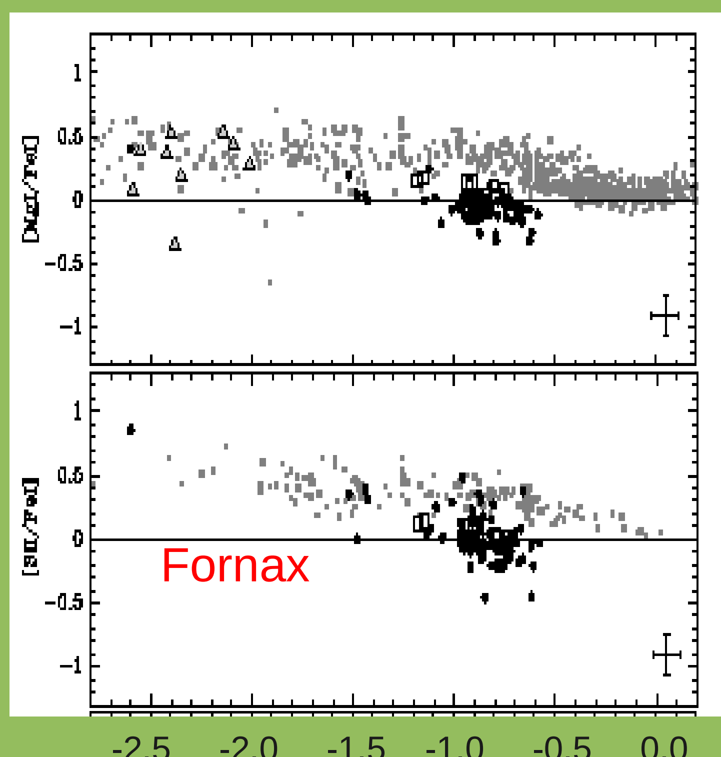


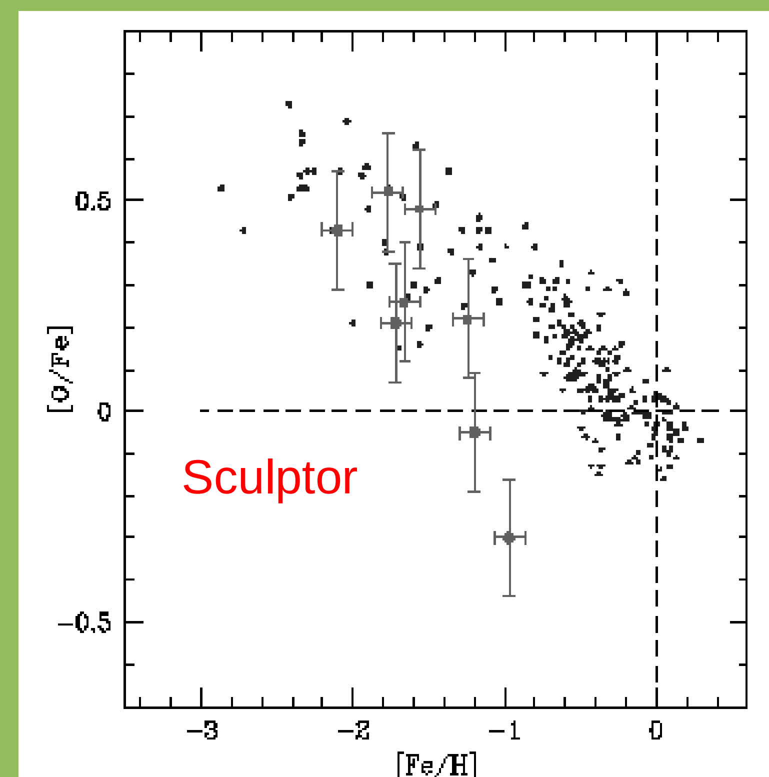
McWilliam & Smecker-Hane(2005)
Smecker-Hane & McWilliam(2002)

also: Sbordone et al. (2007), Carretta et al. (2010)







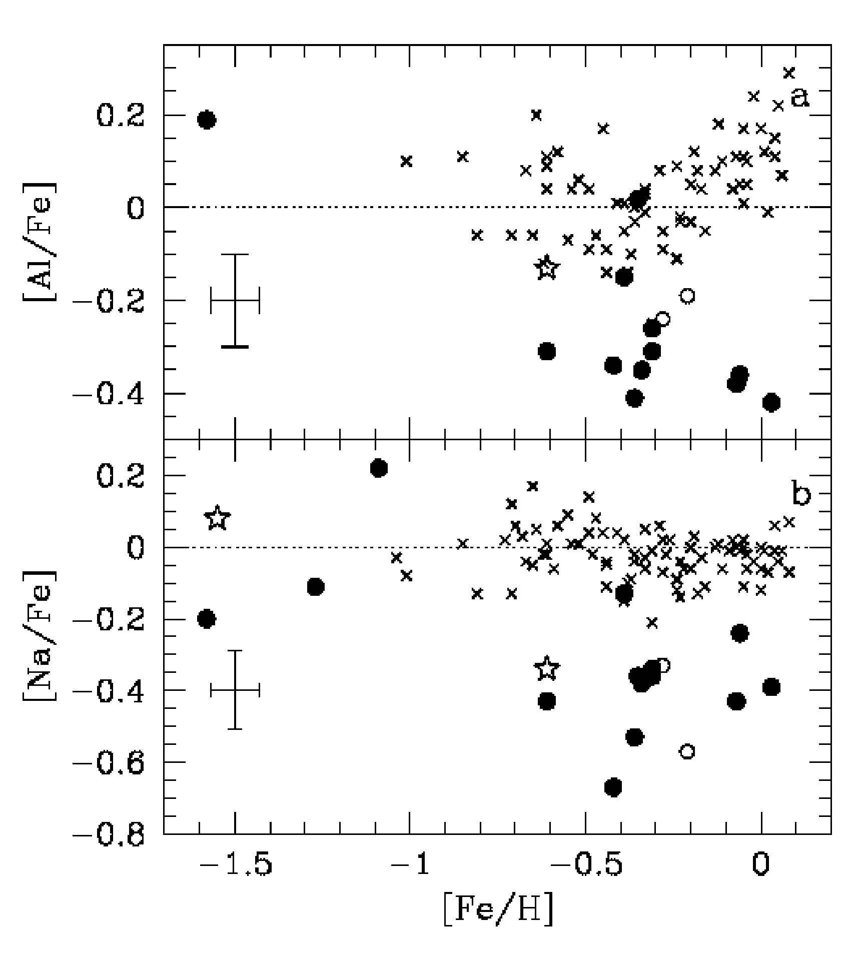


Letarte et al. (2010)

Geisler et al .(2005)

Al and Na Deficiencies

Sgr dSph



Smecker-Hane & McWilliam(2002)

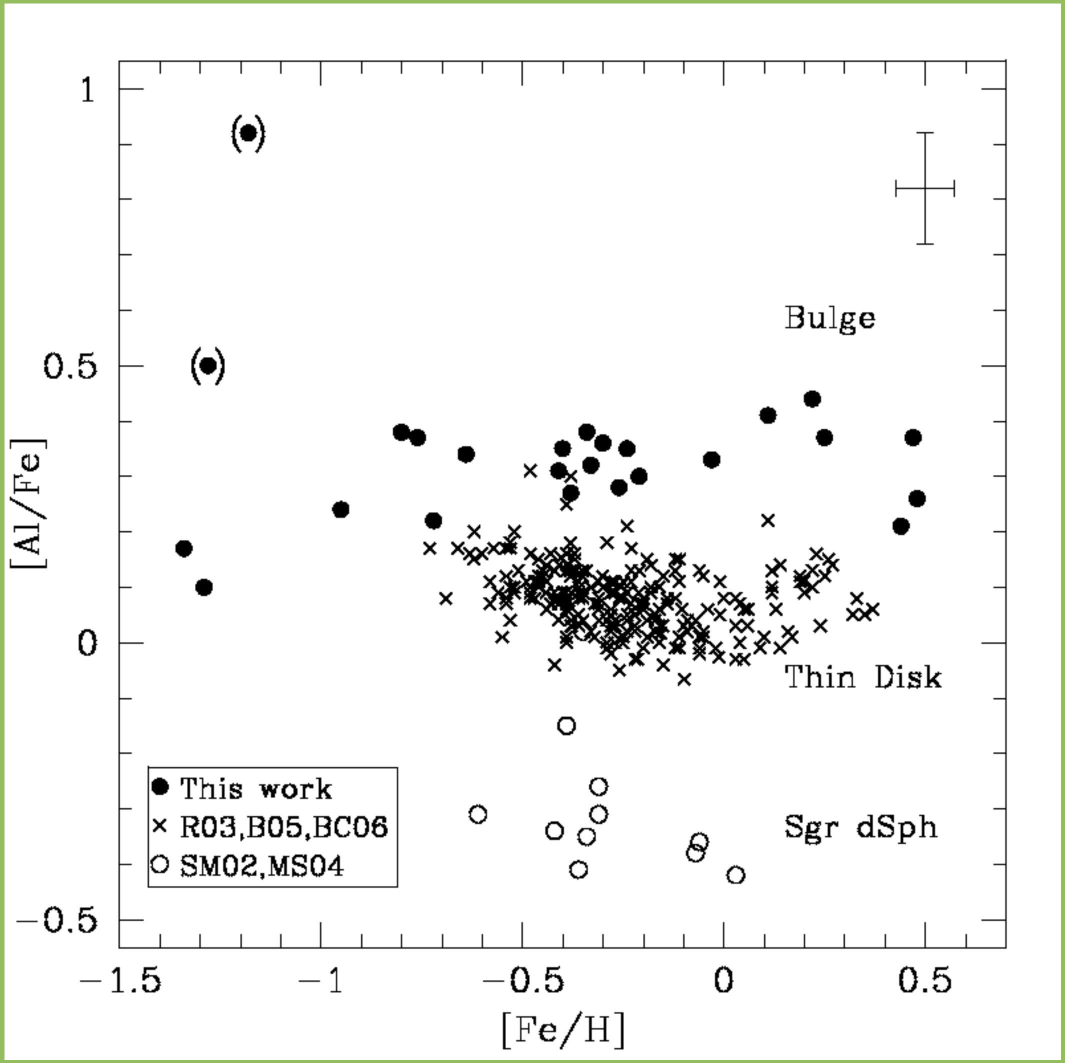
Bonifacio et al (2000)

Agree: Sbordone et al. (2007),
Unclear: Carretta et al. (2010)

✶ Consistent with lack of massive star nucleosynthesis products.

Al and Na made in massive stars, although proton-burning can contribute a secondary component.

* [Al/Fe] varies strongly as a function of environment



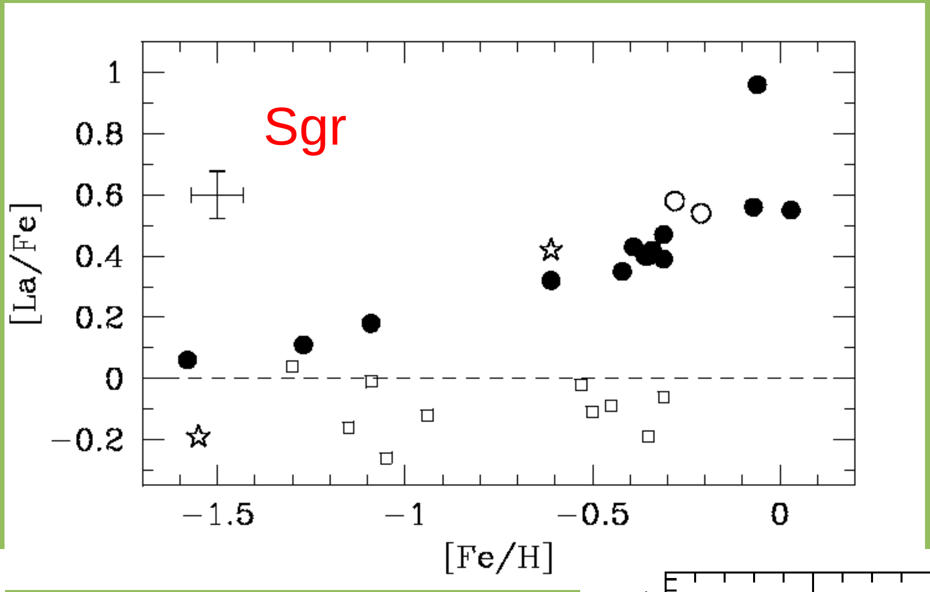
Bulge – Sgr ~ 0.8 dex

~85% Fe in Sgr from SNIa ?

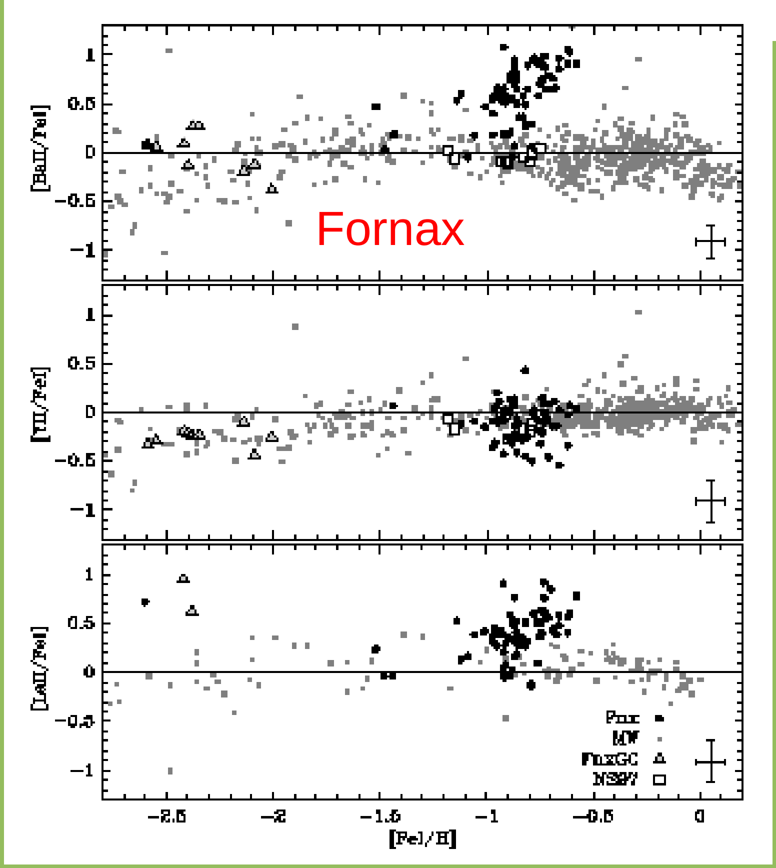
non-LTE not a problem!

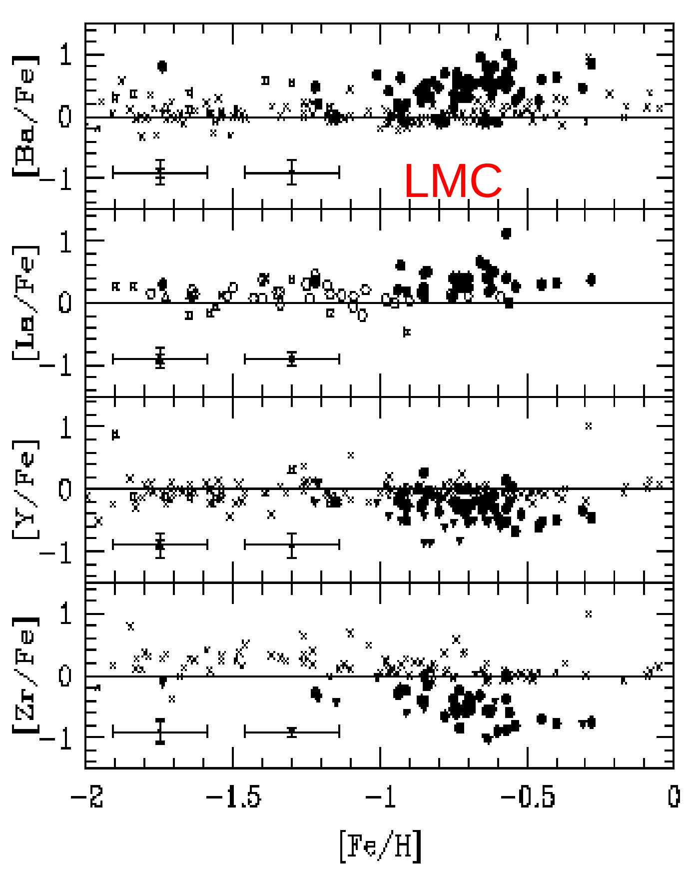
S-Process Enchancements in Dwarf Galaxies

McWilliam & Smecker Hane (2005)



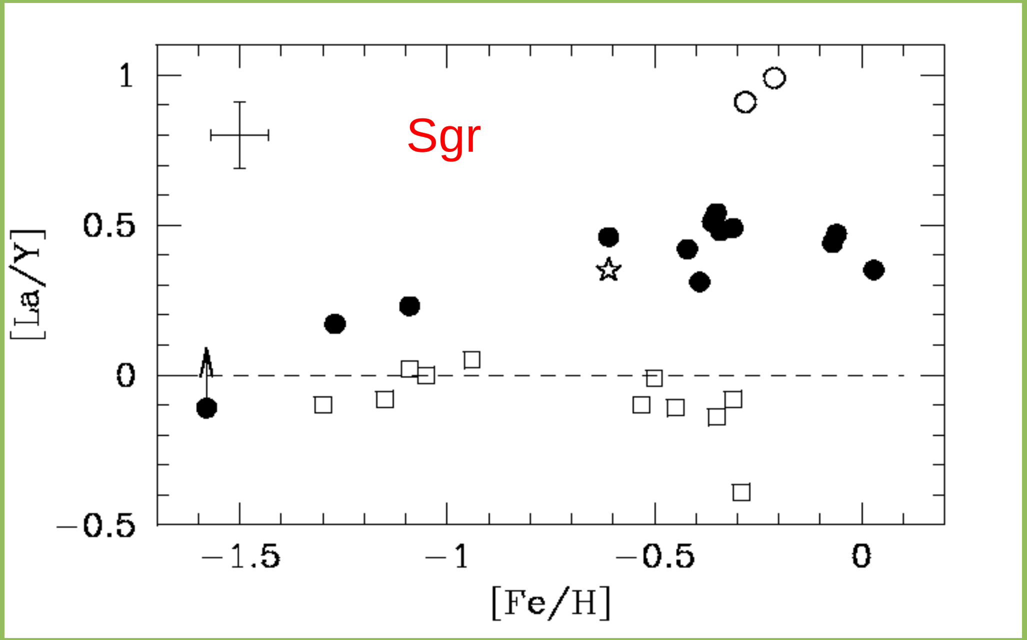
Letarte et al (2010)





Pompeia et al. (2008)

*High hs/ls indicates low [Fe/H] AGB star nucleosynthesis



[La/Y] indicates lower [Fe/H] than the stars!

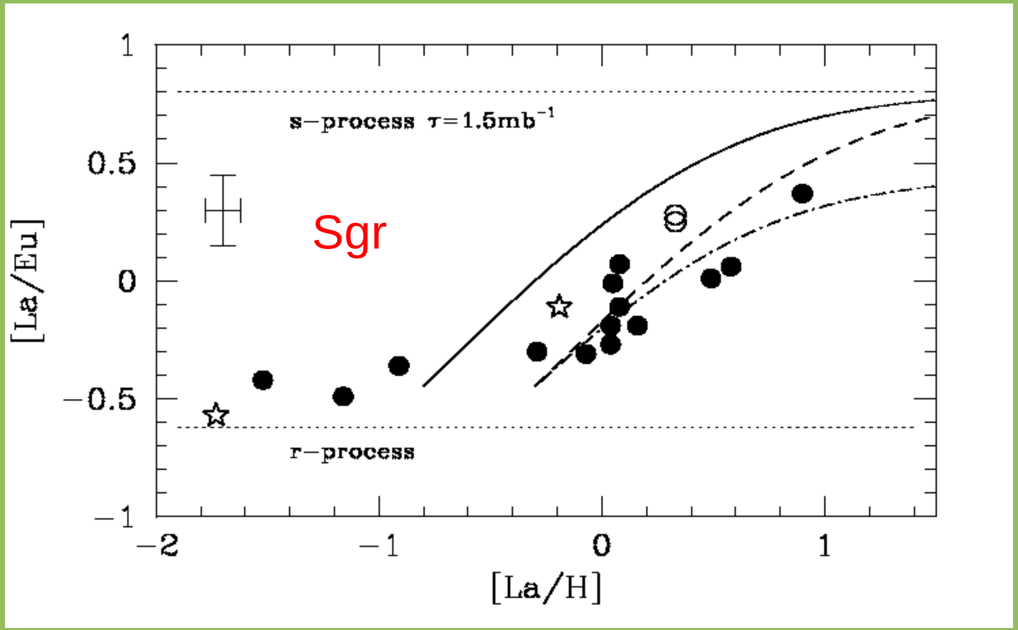
Suggests primordial s-process from previous metal-poor AGB stars
(similar to LMC & Fornax)

How could this happen?

Leaky box Chemical Evolution

left little gas at high [Fe/H] and a lot of old, metal-poor, AGB stars

Should be a large population of stars near [Fe/H]~-1 or -0.6.

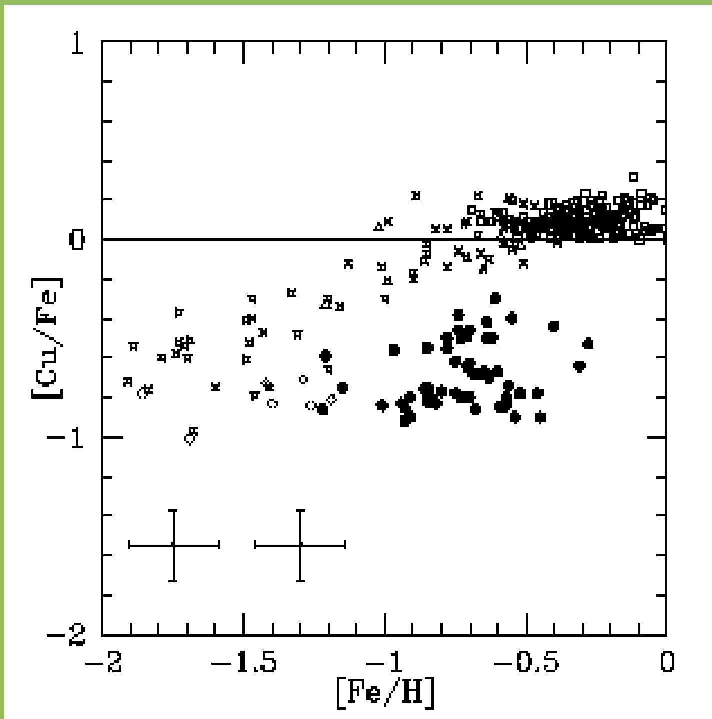


≥95% s-process

Cu traces massive stars (Bisterzo et al. 2004)

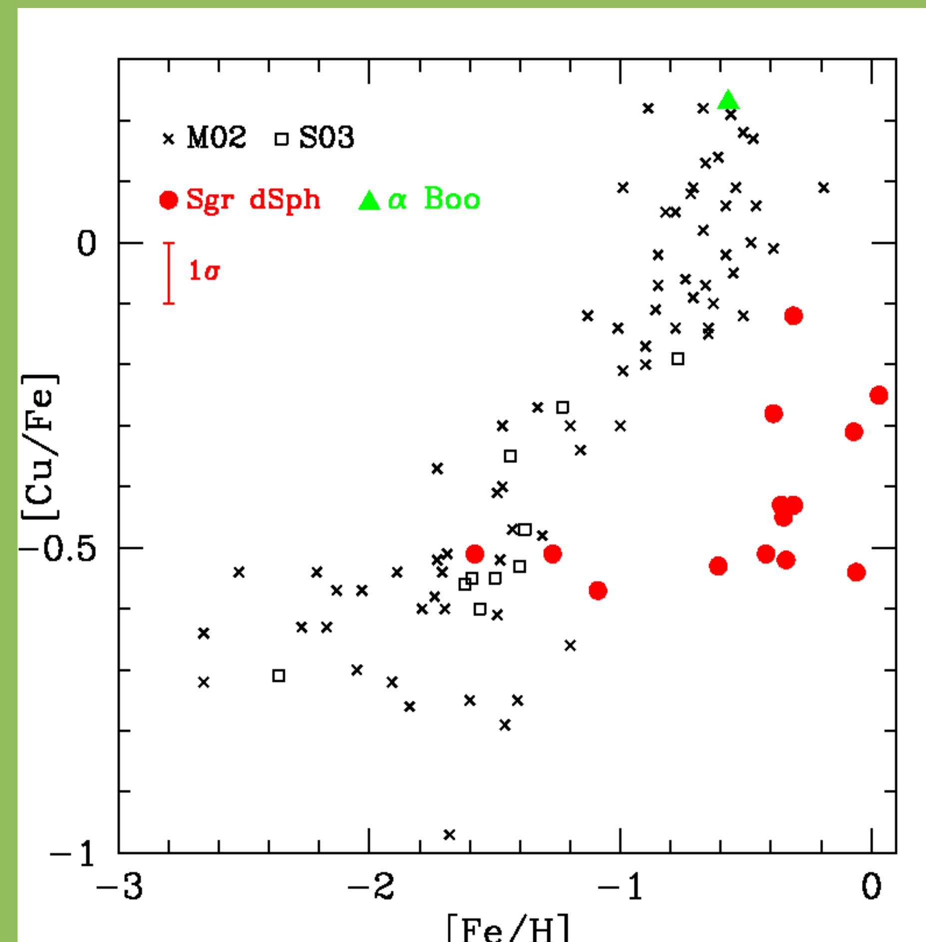
(metallicity-dependent sr-process)

LMC

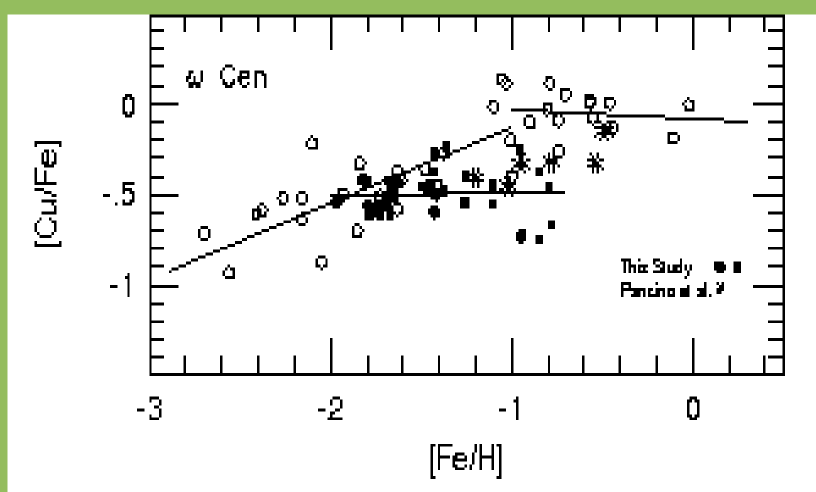


Pompeia et al. (2008)

Sgr dSph



McWilliam & Smecker Hane (2005)



Also in Omega Cen: Cunha et al. (2002)

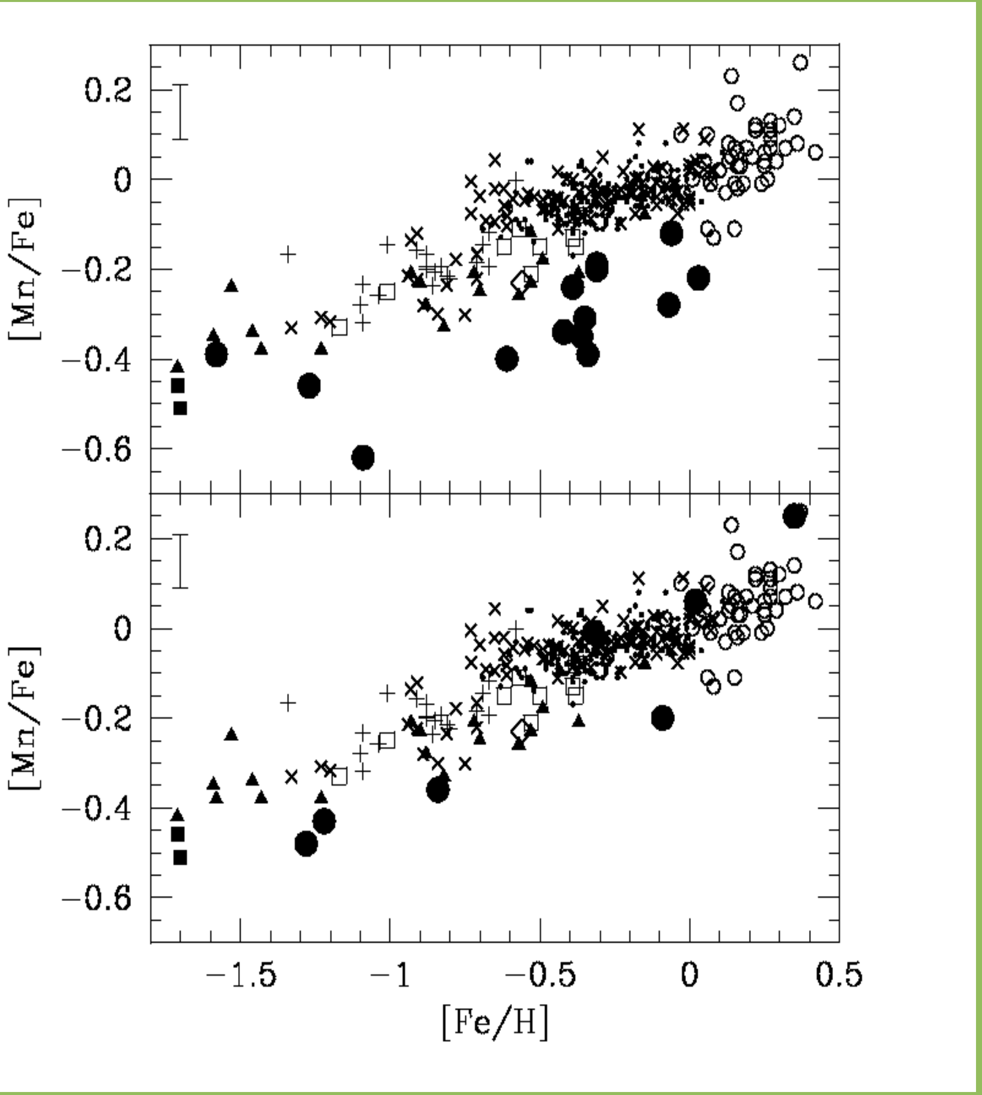
Confirmed by Carretta et al (2010)

Low [Mn/Fe] suggests metal-poor SNIa in Sgr dSph

(Arnett 1971: metal-dependent Mn/Fe yields)

Sgr deficient [Mn/Fe]

Bulge normal [Mn/Fe]



Also seen in Omega Cen (Cunha et al. 2010), which shows other similar abundance patterns (e.g. s-process, and Cu/Fe).

McWilliam, Rich & Smecker Hane (2003)

Carretta et al. (2010) disagree !

A Qualitative Model For Dwarf Galaxy Evolution

My dwarf galaxy evolution scenario is one of a low SFR leaky box. Many metal-poor stars formed early-on, during the gas rich phase, but due to continuous gas loss, as high [Fe/H] was approached the nucoeosynthesis products from massive stars (on-going SF) was overwhelmed by s-process from a relatively large population of metal-poor AGB stars.

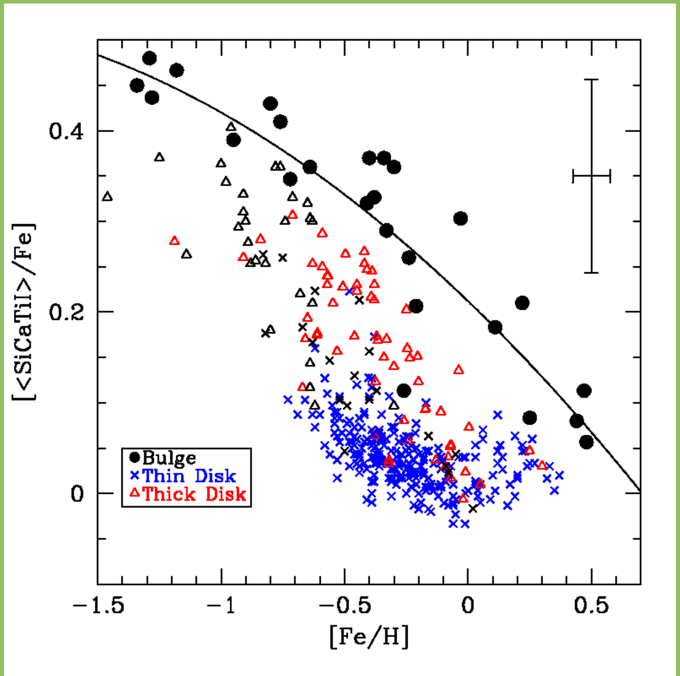
Iron-peak elements were dominated by metal-poor SNIa.

This qualitatively explains the abundance anomalies outlined here.

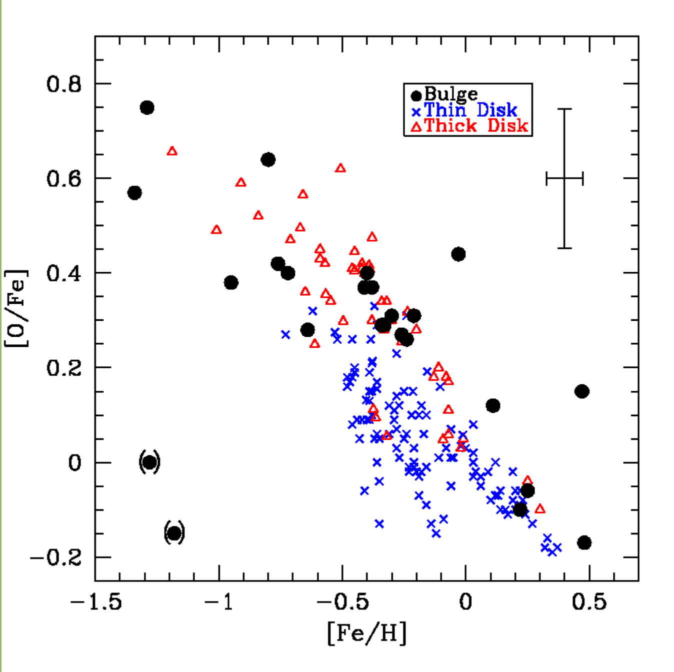
This leaky box scenario should occur for most low-mass systems, perhaps less extreme for the more massive dwarf galaxies.

Bulge Alpha Elements

Fulbright, McWilliam & Rich (2007)

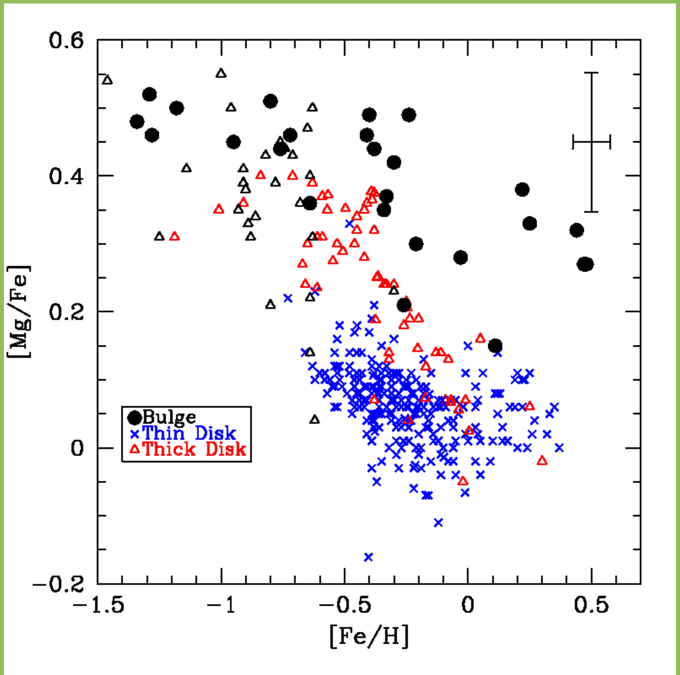


ΔO~0.8 dex



Δ(SiCaTi)~0.4 dex

ΔMg~0.2-0.35dex



If [α/Fe] decline due to SNIa Fe, why does Δε vary?
(some Si,Ca & Ti also made in SNIa)

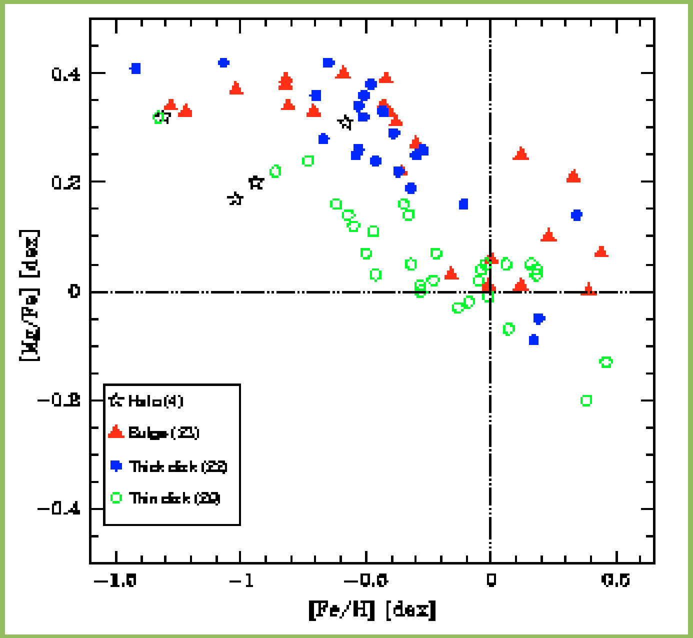
O and Mg both hydrostatic alphas! (not made in SNIa)

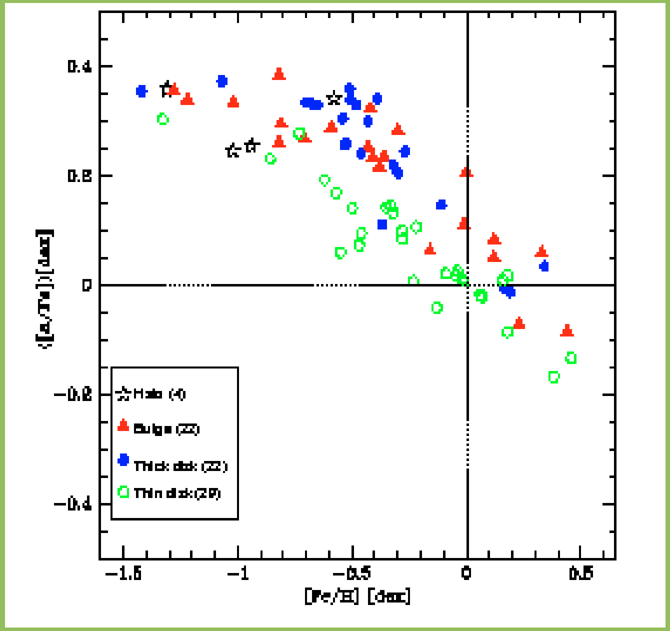
If the SiCaTi/Fe decline not due to SNIa Fe, then metallicity-dependent yields

Discord Among The Bulge Alpha Measurements

Alves Brito et al. (2010)

Mg/Fe trend similar to other alphas.





Alpha elements are enhanced, wrt thin disk,
but similar to thick disk.

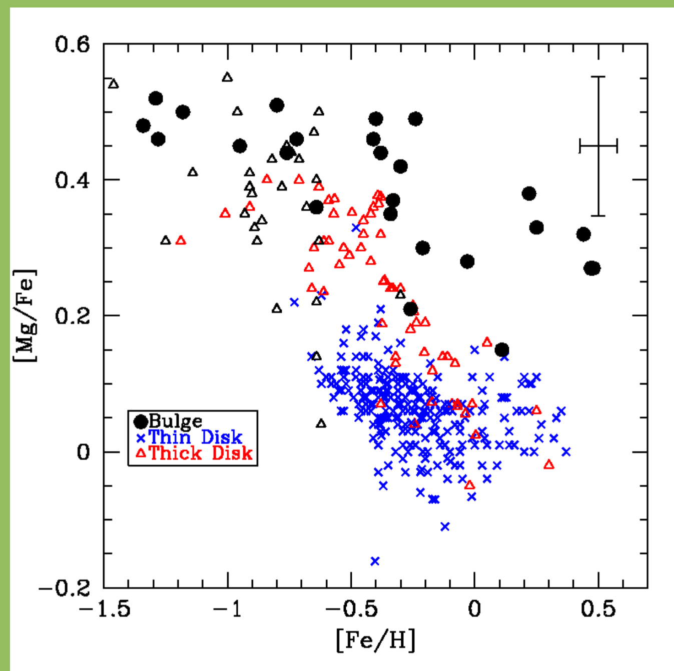
Similar to Matteucci & Brocato (1990) expectations,
but different from FMR07 results.

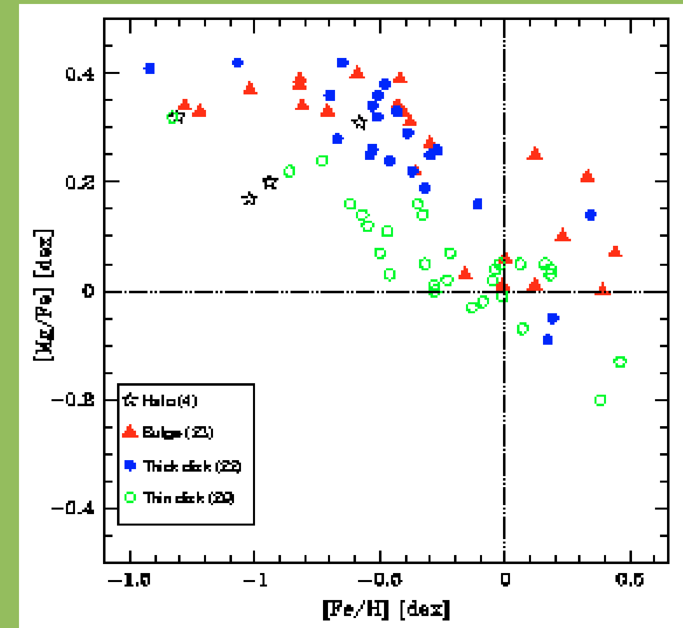
Discord Among The Bulge Alpha Measurements

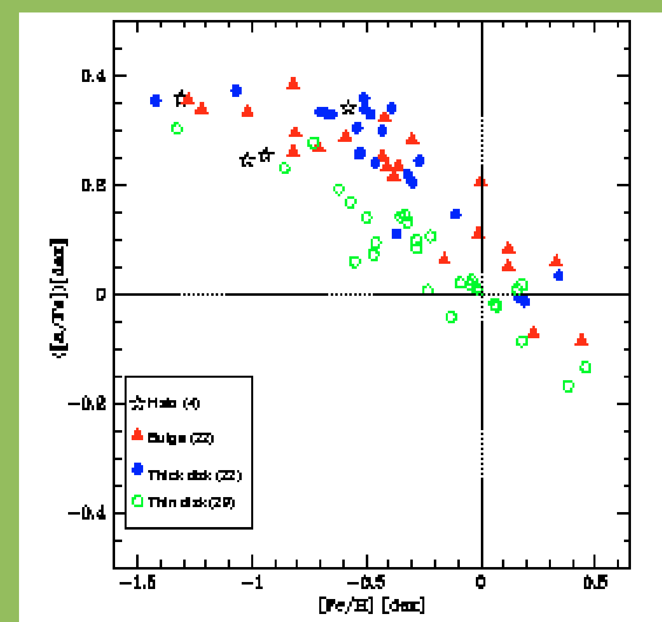
Alves Brito et al. (2010)

Mg/Fe trend similar to other alphas.

0.1 dex shift ?
cf FMR07







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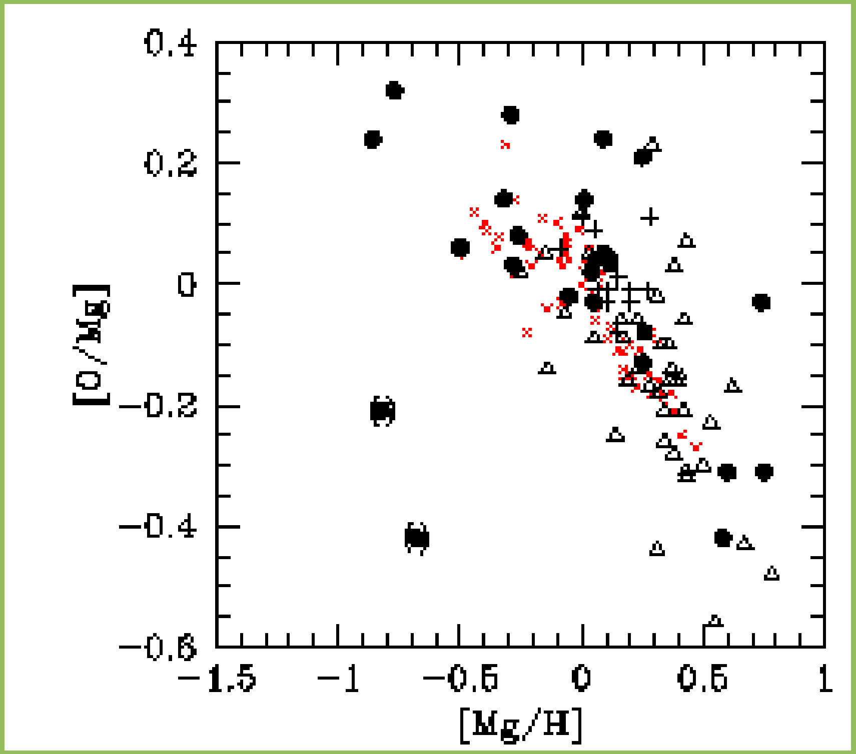
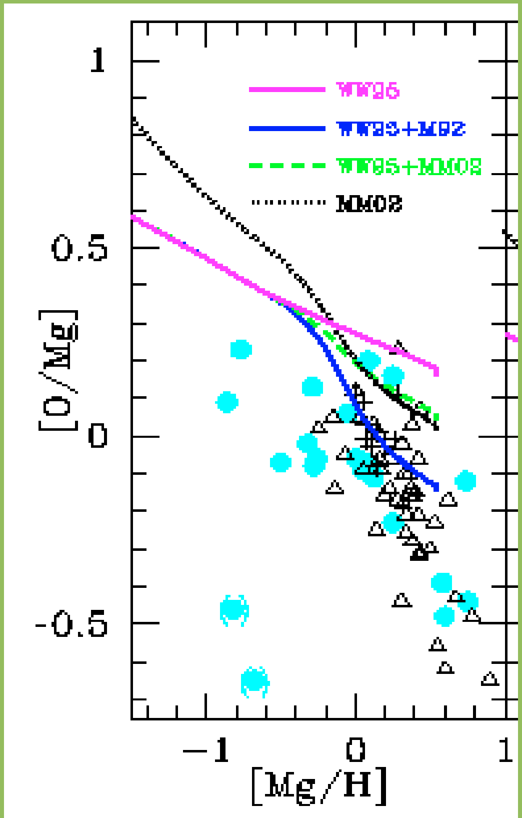
Bulge and Disk [O/Mg]



McWilliam et al. (2008)

Bulge [O/Mg]



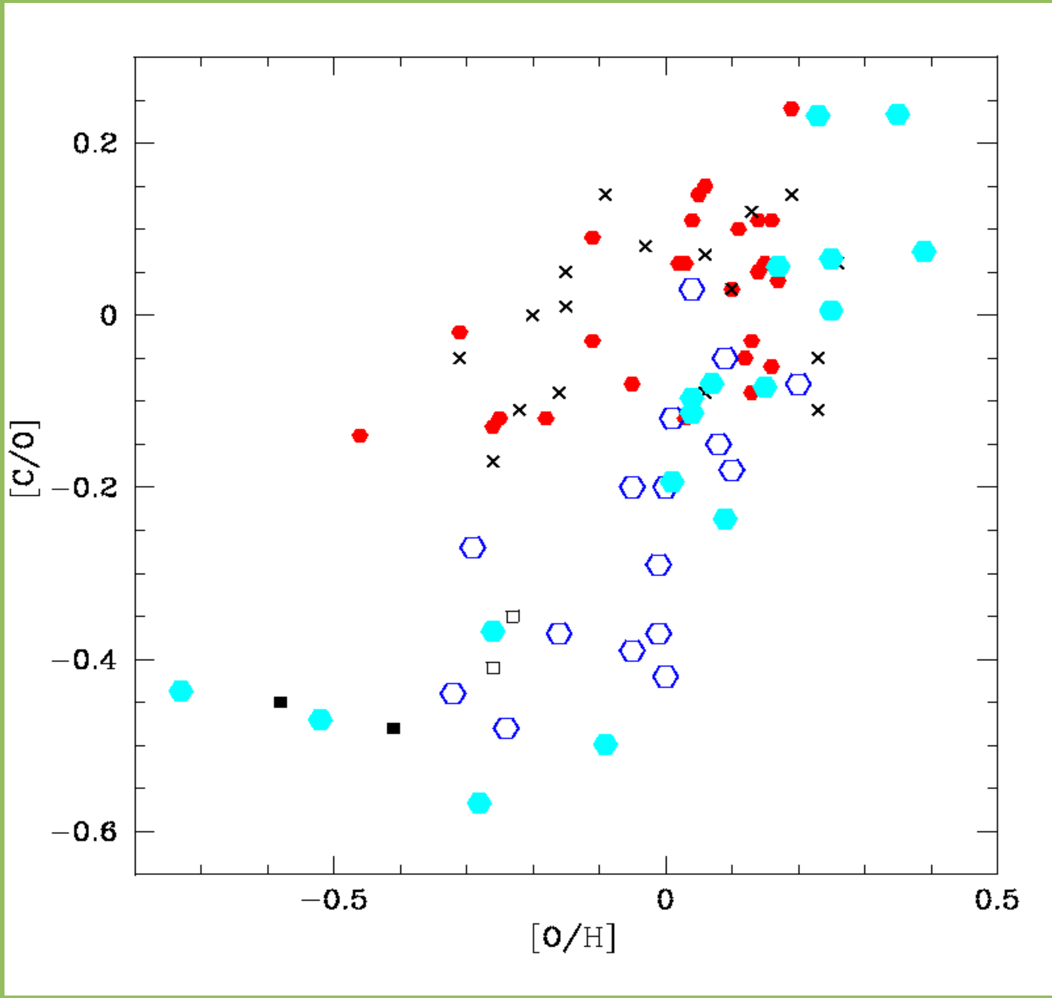
Cescutti et al. (2009)

[O/Mg] in disk and bulge show similar, downward, trend.

We proposed that this is due to metallicity reduction of O yields, due to winds stripping massive star outer layers, related to the WR phenomenon.

→ **If so, there should be an increase in the [C/O] ratio with metallicity.**

[C/O] in the thin disk, thick disk and bulge



Cescutti et al. (2009) / MFR10

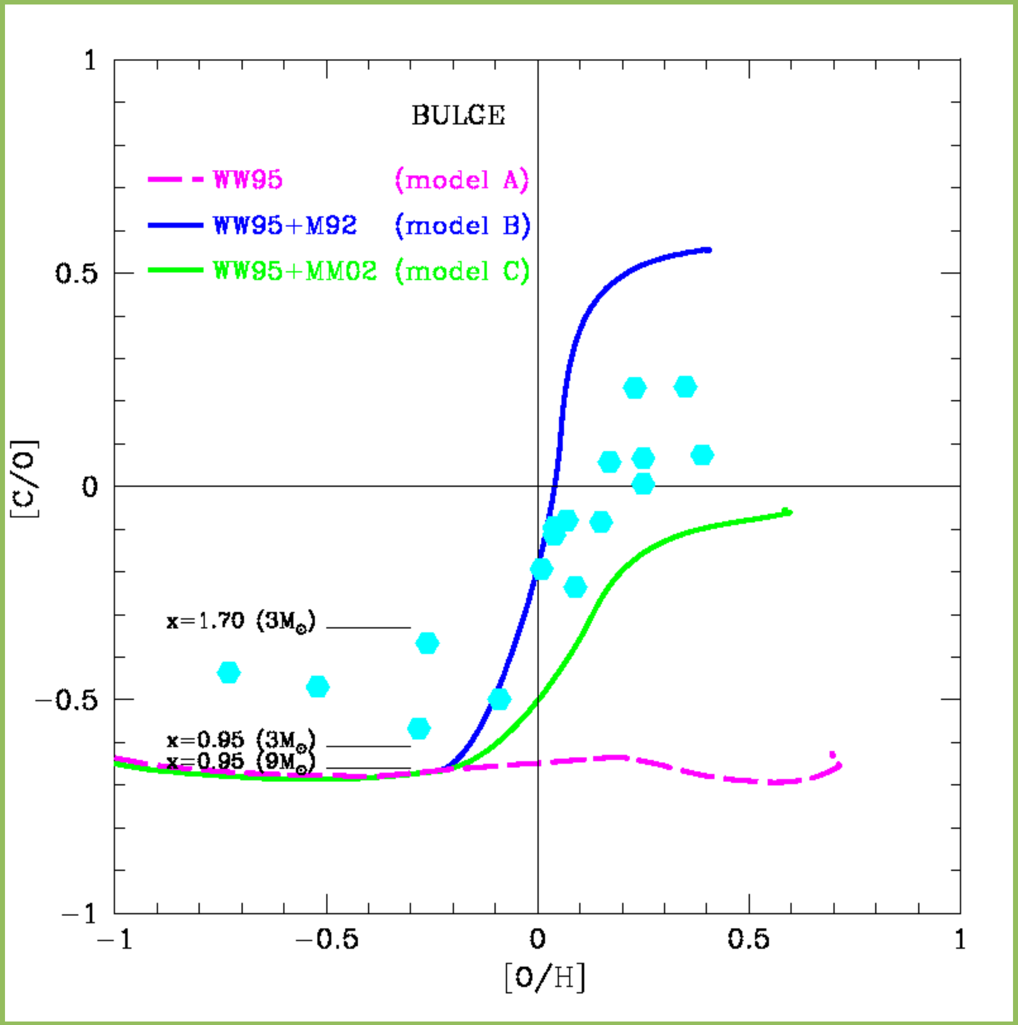
thin disk: red points/black crosses
bulge: filled blue hexagons
thick disk: open blue hexagons

Evidence of timescale difference

(C09, MFR10/Mel08)

***Large [C/O] in Thin Disk from AGB carbon stars**

*Massive star winds decrease oxygen and increase carbon yields (Maeder 1992, Maeder & Meynet 2002)



New MFR09 results +
Cescutti et al. (2009) predictions
with rapid evolution

Problem at low metallicity

Missing a source of C at low z?

Massive binary WR systems?

(C09, MFR09/Mel08)

* Stellar yield predictions including mass-loss via z-dependent winds are roughly consistent with the measured bulge [C/O] vs. [O/H] trend.

Conclusions

1. Dwarf galaxies generally show deficiencies of alpha elements, and Al, Na, and Cu which indicate a paucity of massive star nucelosynthesis, as expected from low SFR in the standard SNII/SNIa scenario.

2. Large s-process enhancements seen in dwarf galaxies suggest leaky-box chemical evolution.   High [Eu/Fe] can be s-process!

3. Deficient [Mn/Fe] ratios in dwarf galaxies suggest nucleosynthesis by metal-poor SNIa.

4. The Galactic bulge and disk O/Mg slope and C/O ratios suggests declining O yields with metallicity, roughly consistent expectations from metallicty-dependent winds, related to WR stars.

5. Dispersion in measured [alpha/Fe] in the bulge. Claims of Mg, Na and Al enhancements in the bulge suggest short formation timescale, and metallicity-dependent yields for explosive alphas (Si, Ca, Ti.)

6. The Galactic bulge [Fe/H] is unexpectedly high for a system that evolved without significant SNIa nucleosynthesis.

→
- **bulge IMF skewed to high mass stars, or**
- **massive SFR and inflow on a short timescale**

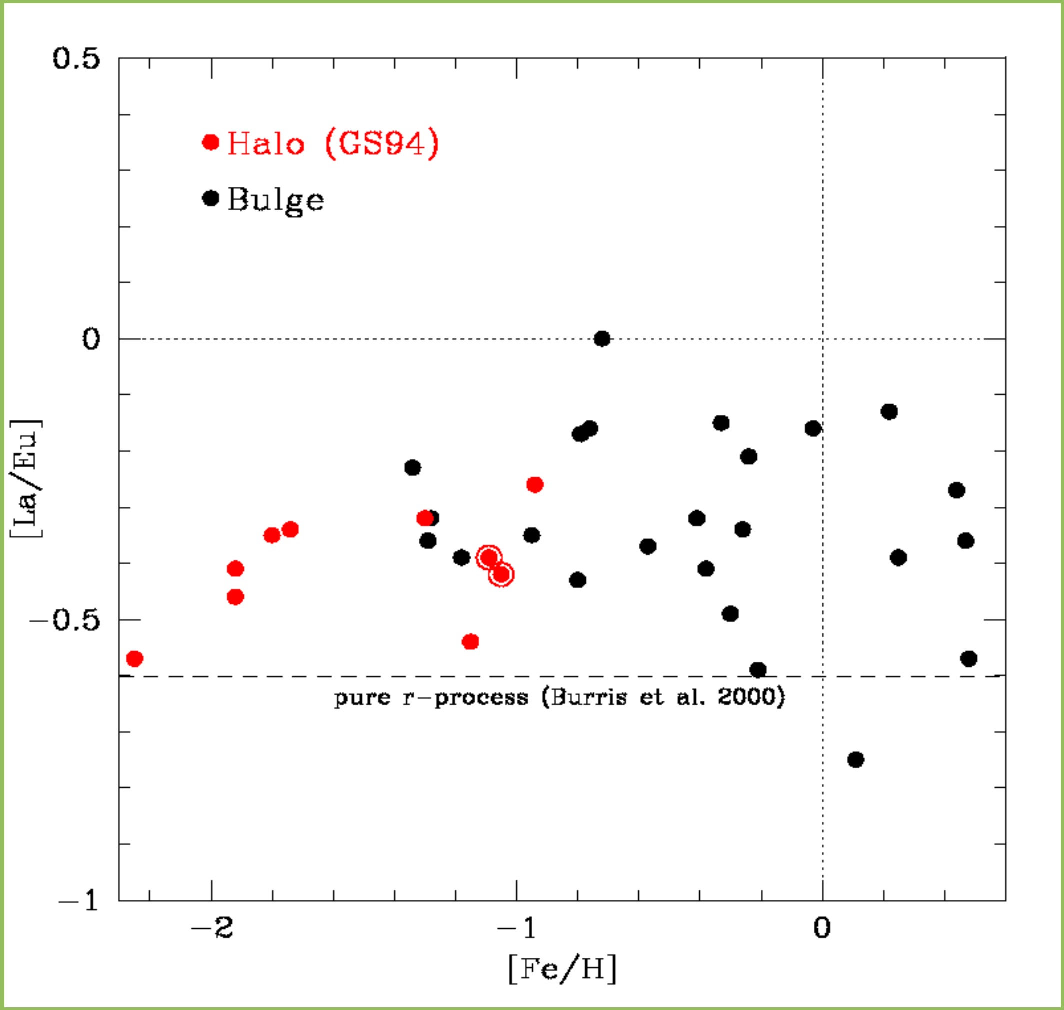
7. [Rb/Fe] in the bulge would provide a useful probe for timescales of intermediate mass AGB stars

More Constraints: Neutron-Capture Elements (FMR09)

Solar System s-process (e.g. La) elements made in low mass (1.3-3Msun) AGB stars on long timescales; r-process elements (e.g. Eu) thought to be made in SNII events.

[La/Eu] → s/r ratio

Bulge is halo-like
→ short timescale



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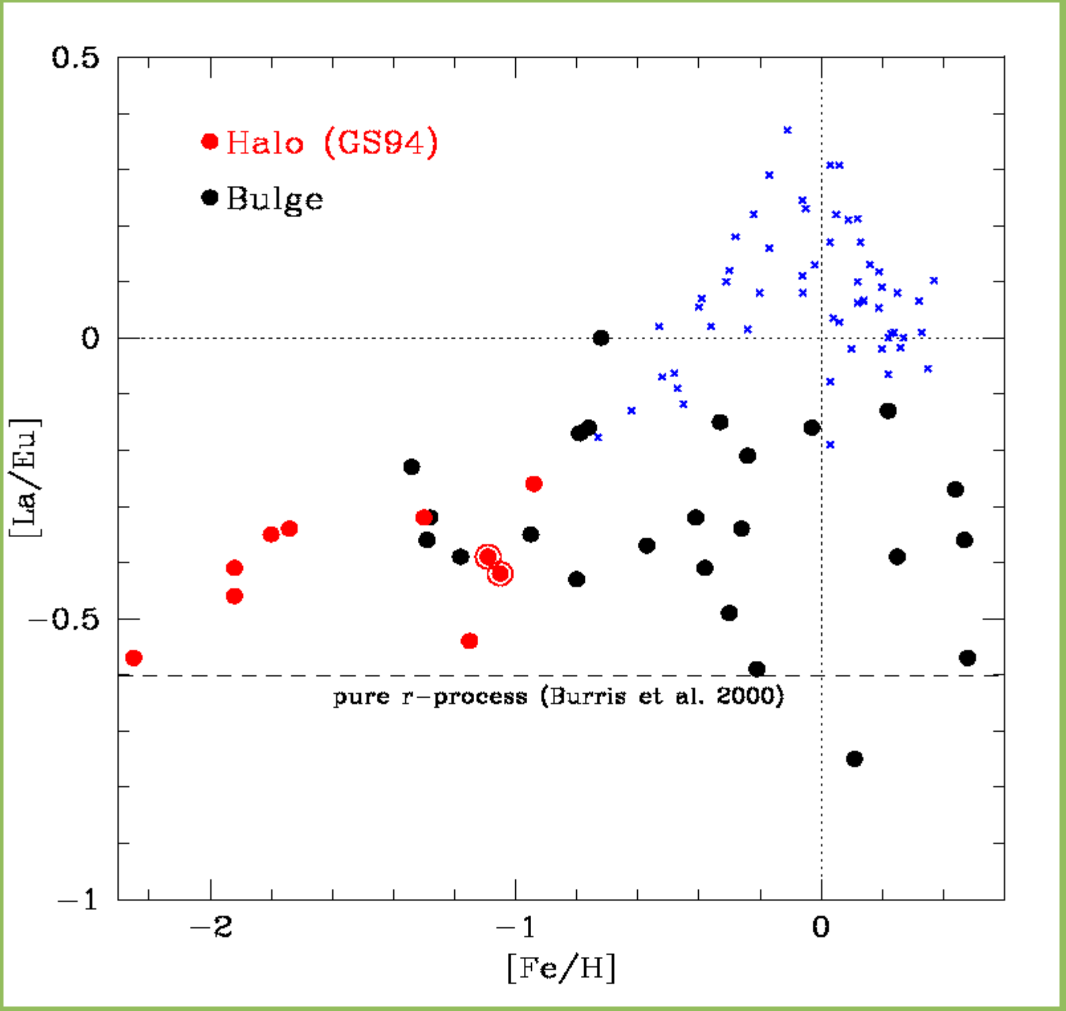

[Ba/Eu]

x Thin disk

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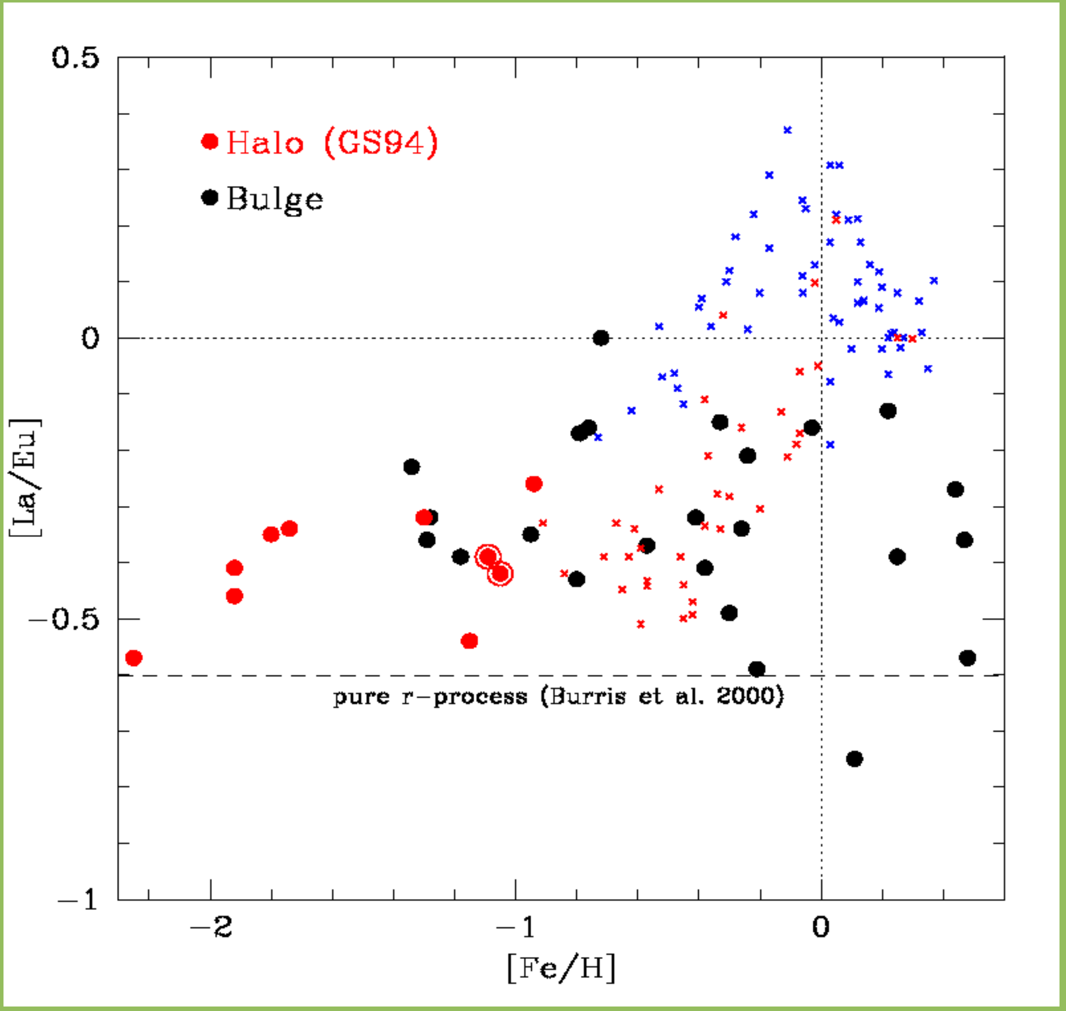
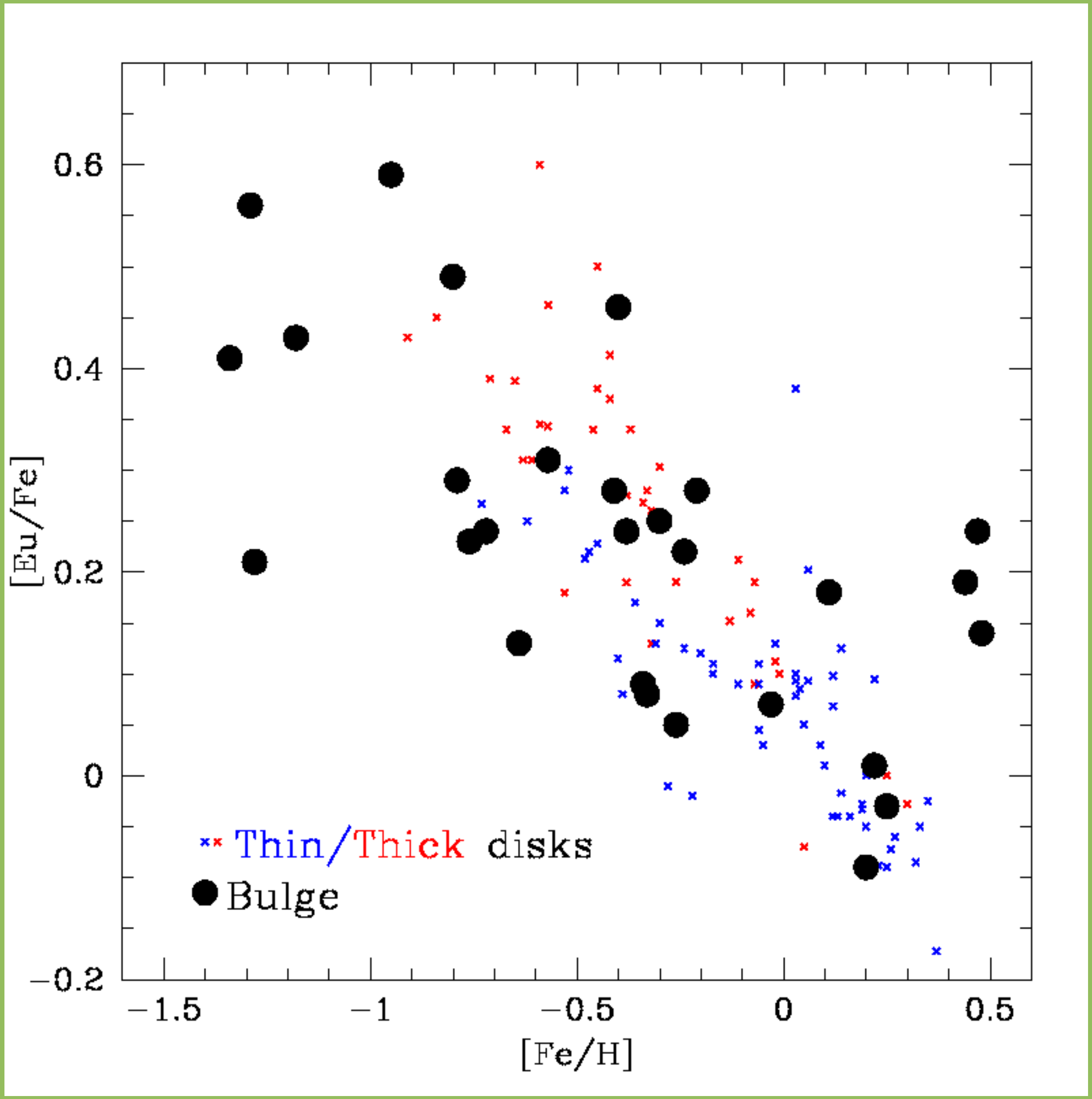


[Ba/Eu]

x Thin disk

x Thick disk

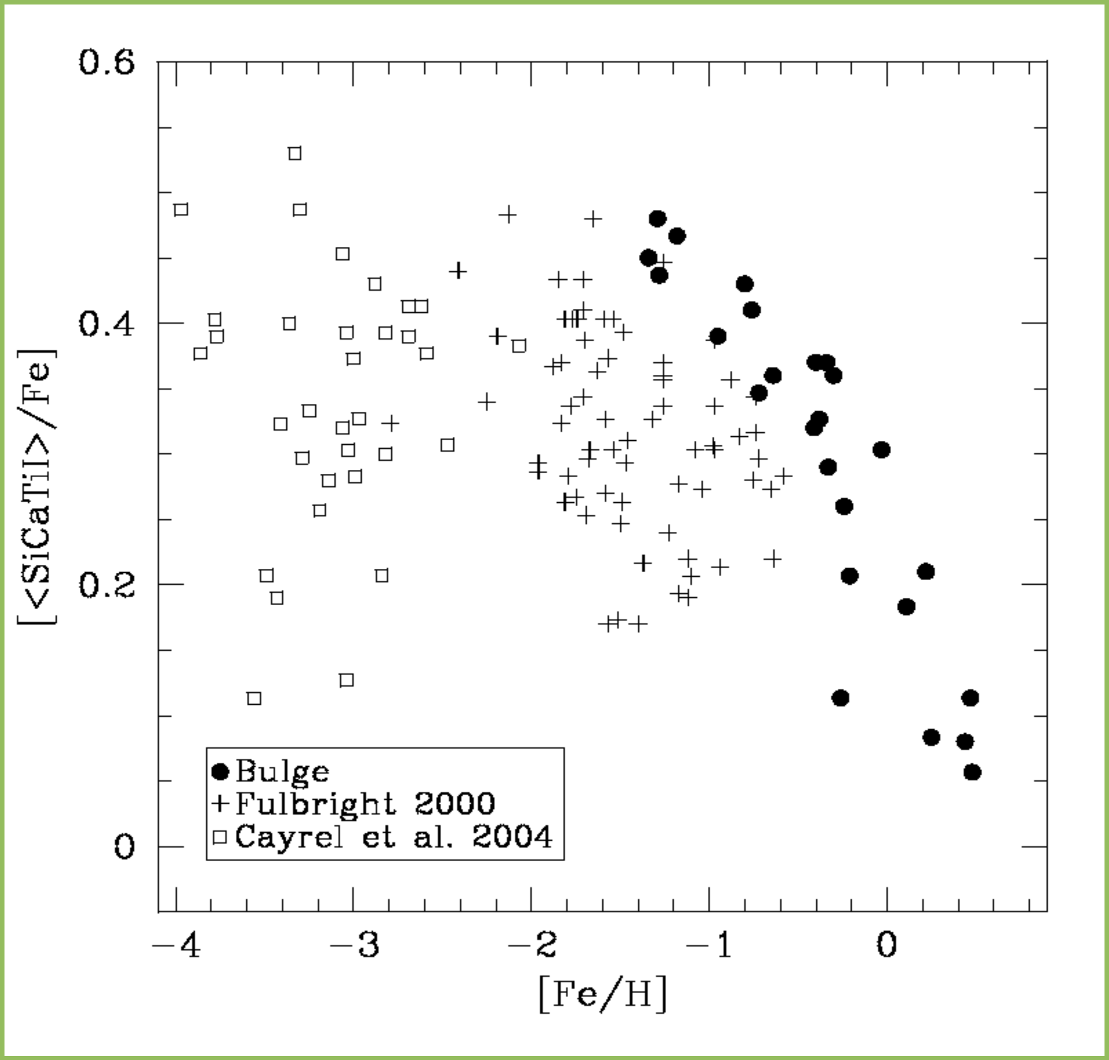
Red Herring? [Eu/Fe] in bulge



Eu/Fe in disk trends like alphas

[Eu/Fe] decline suggests long formation timescale

r-process not understood



Bulge alpha/Fe higher than halo with much less scatter.

→ **Homogeneous bulge evolution**

Consistent with halo accretion

IMF?