The Chemical Enrichment of the MW

A local benchmark to cosmology

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Heidelberg, 08.12.2009

The "Archaeological" approach can be powerful to study:

The nature of the First Stars

Signs of fast rotators in the early universe

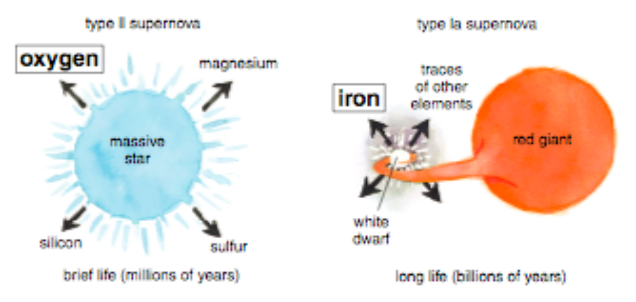
The ultimate goal: Tying together studies of 'galactic archaeology' with observations and cosmological simulations of galaxies forming at high z

Abundance Patterns - halo/thin/thick disk and bulge: building blocks - gas or stars?

Does the MW fit into the CDM picture?

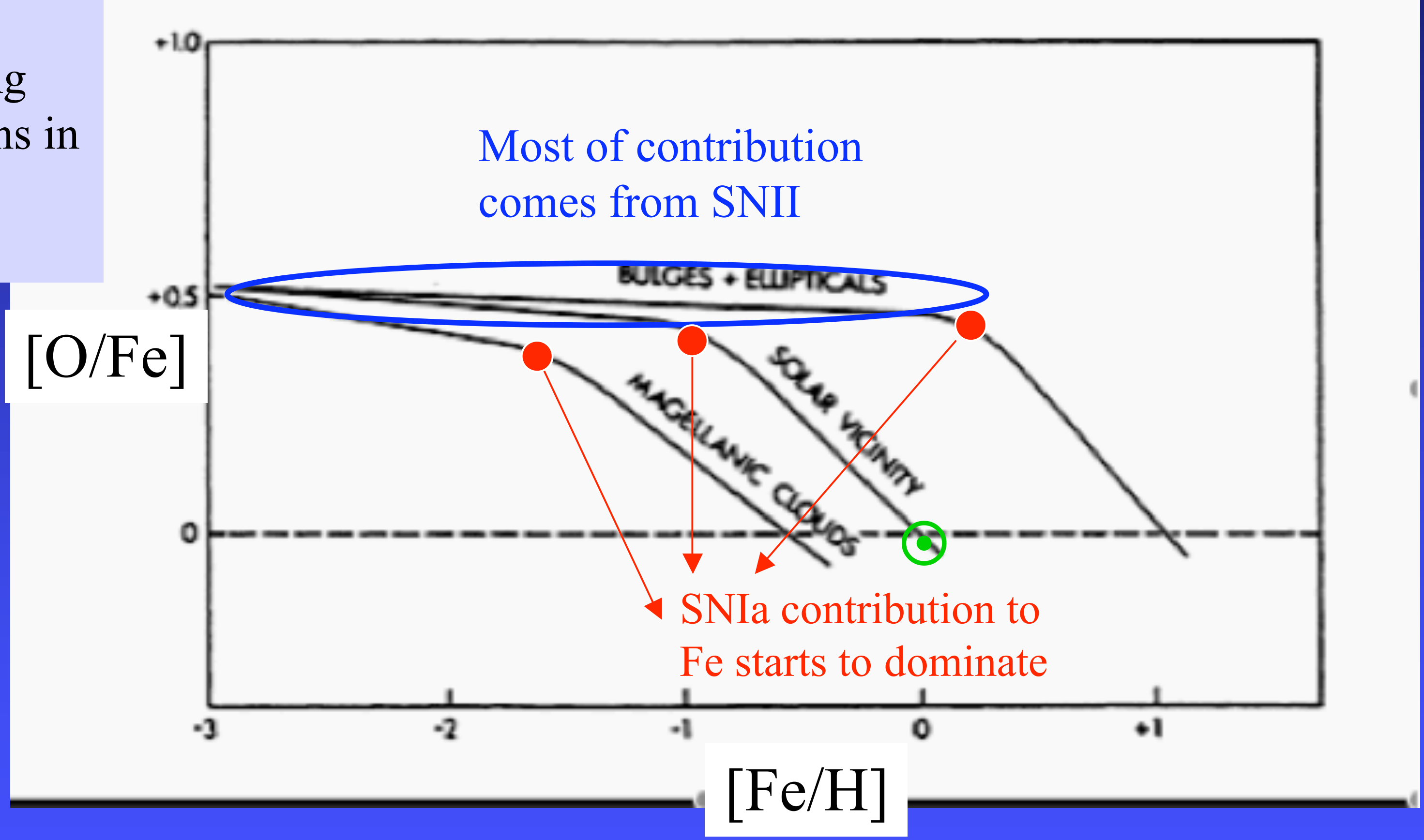
Abundance Ratios as “Cosmic Clocks”

- Different chemical elements -> restored to the ISM on different timescales by stars of different **lifetimes weighted by an IMF**
- ISM will be enriched **faster** in elements produced by **massive stars (alpha-elements)** and more **slowly** in elements produced by **type Ia SNe and low- and intermediate mass stars (Fe, C)**
- **The enrichment of elements coming from massive stars will last only while the SF is active**



Fe comes both from SNII and SNIa, whereas O comes from SNII

Diagram representing observations in different galaxies



Most of contribution comes from SNII

SNIa contribution to Fe starts to dominate

[O/Fe] vs. [Fe/H] in different galaxies

Precise Abundances + Large samples

Better constraints!

-Thick vs. Thin disk vs. Bulge

- Disk radial gradients

- Halo - Very-metal-poor

Window into the early chemical enrichment of the Universe

Formation of the MW

Two Infall (Chiappini et al. 1997, 2001)

Bulge+thick disk - FAST FORMATION

Thin disk - SLOW FORMATION

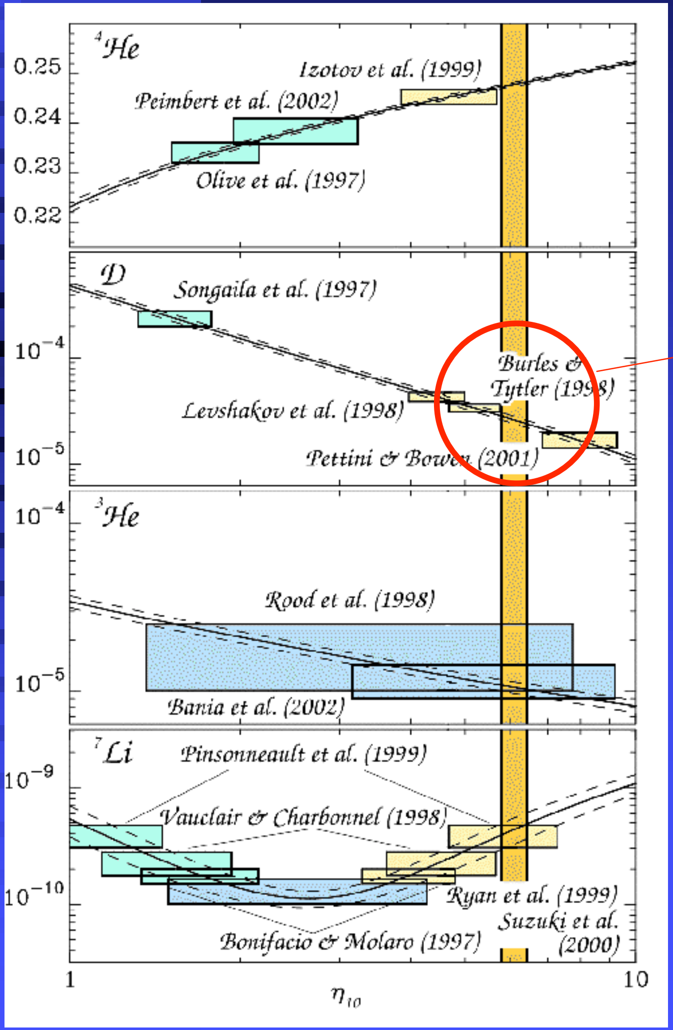
Why a Two Infall Model ?

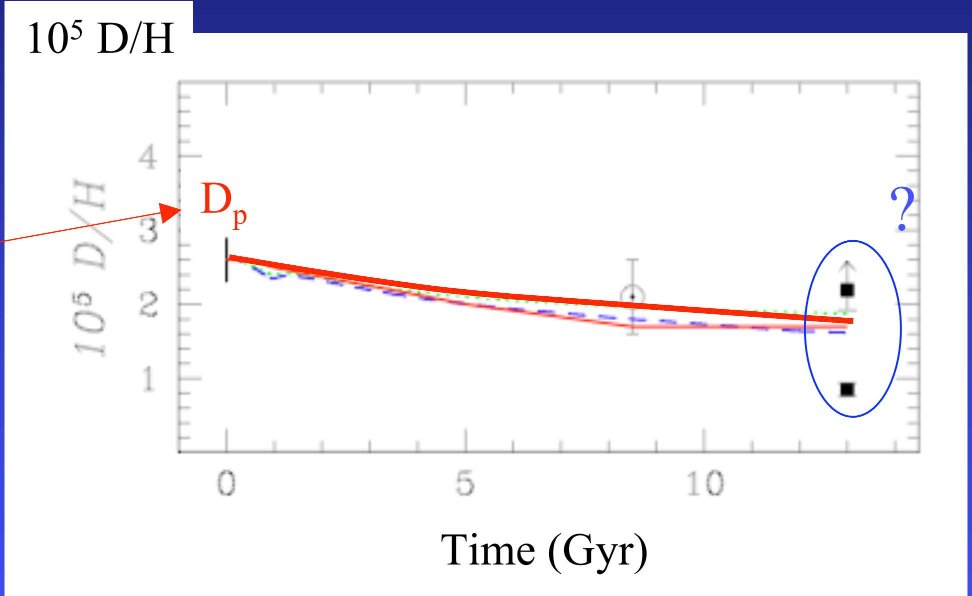
1. G dwarf metallicity distribution + D abundance: imply a long timescale for the formation of the thin disk via slow infall of metal-poor gas
2. Halo/Thick disk vs. thin disk discontinuity in abundance ratios (Gratton et al. 1996, Fuhrmann 1998)

1. D Evolution and G(K)-dwarf Metallicity Distribution

Deuterium destroyed in stellar interiors → Its quantity in the ISM decreases from its primordial value to the current ISM value (FUSE)

Big Bang Nucleosynthesis





Romano, Tosi, Chiappini & Matteucci. 2006

Before WMAP: Measuring primordial abundances of ^{4}He, D, ^{3}He and ^{7}Li to constrain the cosmic baryon density
After WMAP: We know primordial abundances

Infall needed to explain G-dwarf metallicity distribution and D abundance

$f = A\ \exp(-t/\tau)$

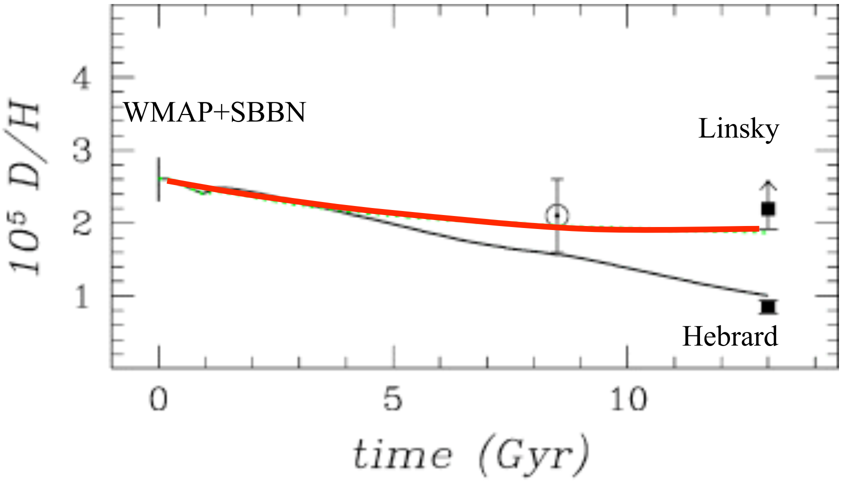
None of CE models have $D_p/D_{ISM} > 1.5$

(Romano, Tosi, Chiappini, Matteucci 2006)

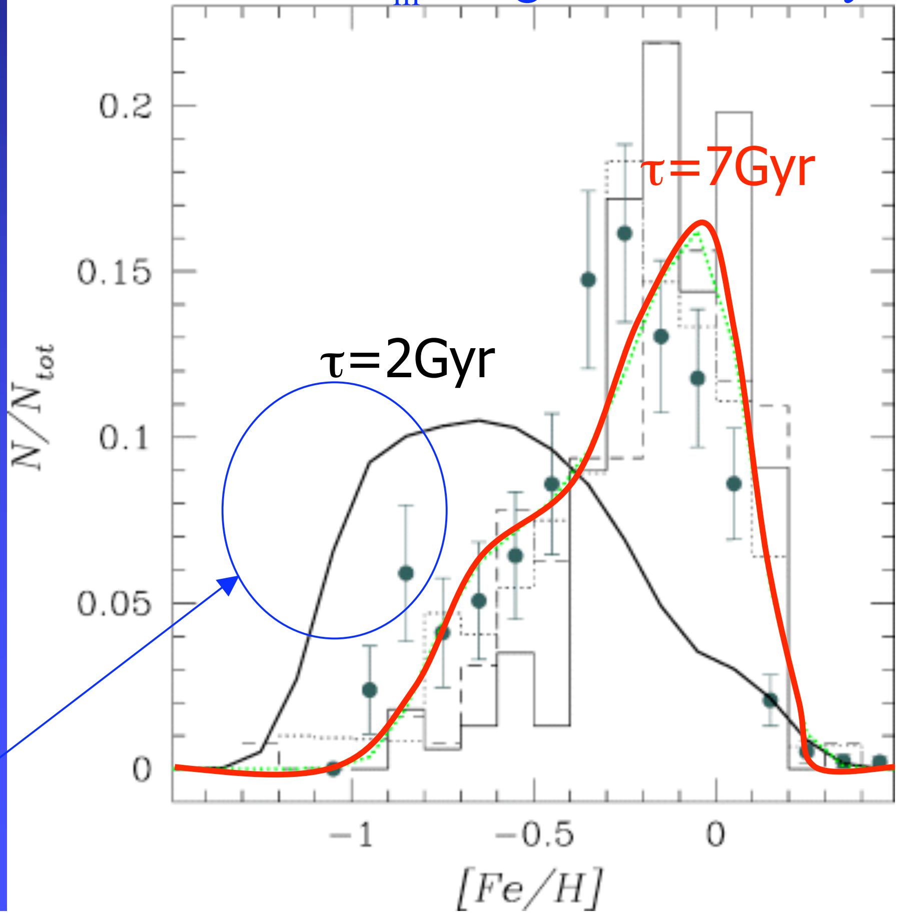
If we try to increase the D consumption by increasing the SFR or making a faster infall we contradict other constraints such as the G-dwarf metallicity distribution.

Lower value now attributed D depletion on dust grains (Linsky et al. 2006)

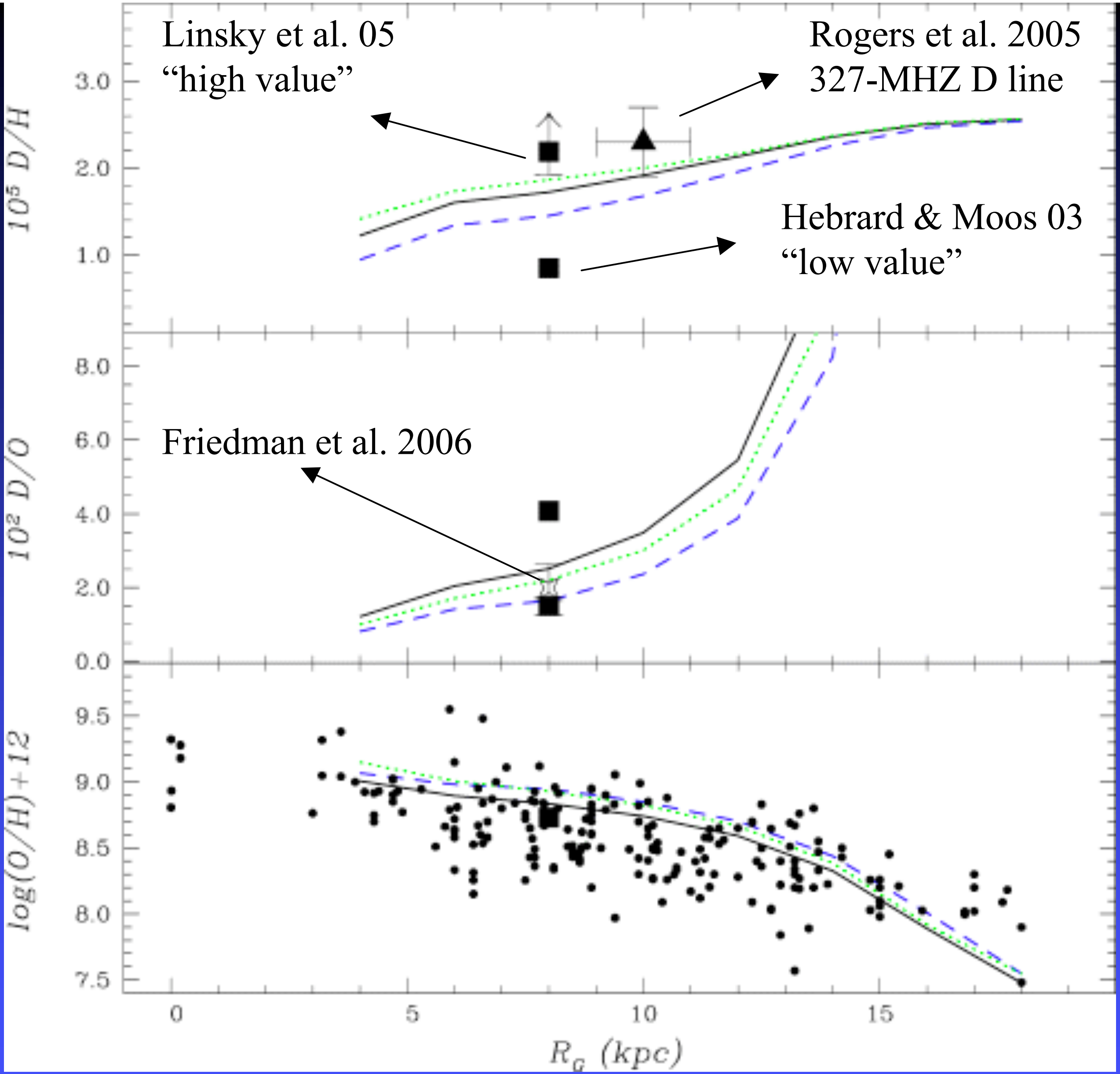
G-dwarf Problem: Simple model and/or fast accretion predicts too many metal poor stars, not observed!



Stars with τ_m > Age of the Galaxy



Models: Chiappini et al. (2002)



Linsky et al. 05
“high value”

Rogers et al. 2005
327-MHZ D line

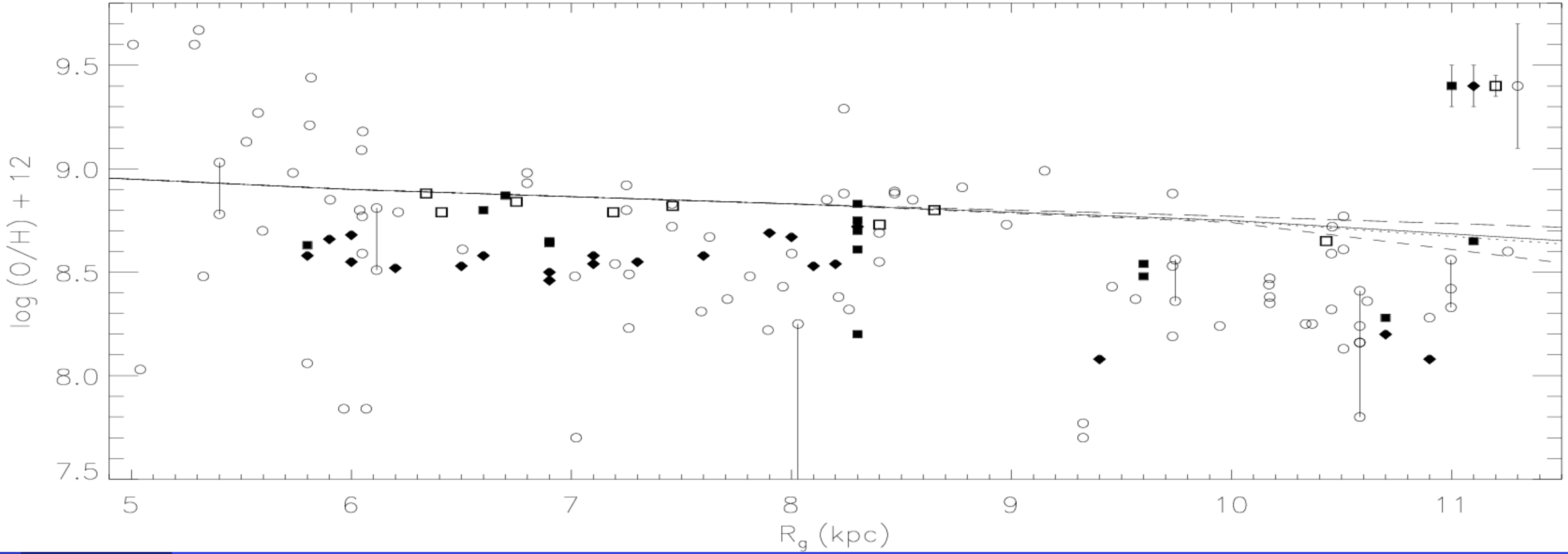
Hebrard & Moos 03
“low value”

Friedman et al. 2006

Cescutti, Matteucci, Francois & Chiappini 2007: abundance gradients for O, Mg, Si, S, Ca, Sc, Ti, Co, V, Fe, Ni, Zn, Cu, Mn, Cr, Ba, La, Eu (based on the timescale law of Chiappini et al. 2001)

Galactic Abundance Gradients

Literature: HII regions & B-stars



HII Regions:
○ Rudolph et al. (2006)
□ Esteban et al. (2005)

Models:
Chiappini et al. (2001)

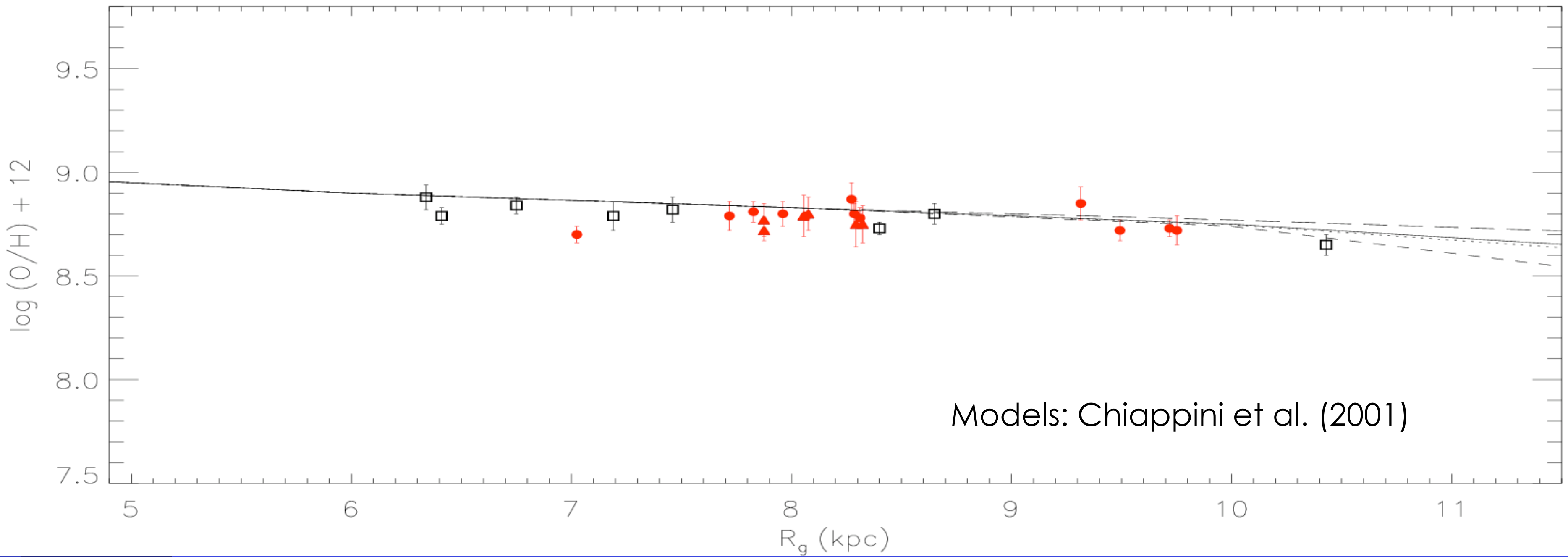
B-Stars (NLTE):
■ Gummersbach et al. (1998)
◆ Daflon & Cunha (2004)

- large scatter @ every R

(From Przybilla 2008)

Galactic Abundance Gradients

Pryzbilla & col: B-stars + BA-supergiants & HII-regions (Esteban+ 2005)



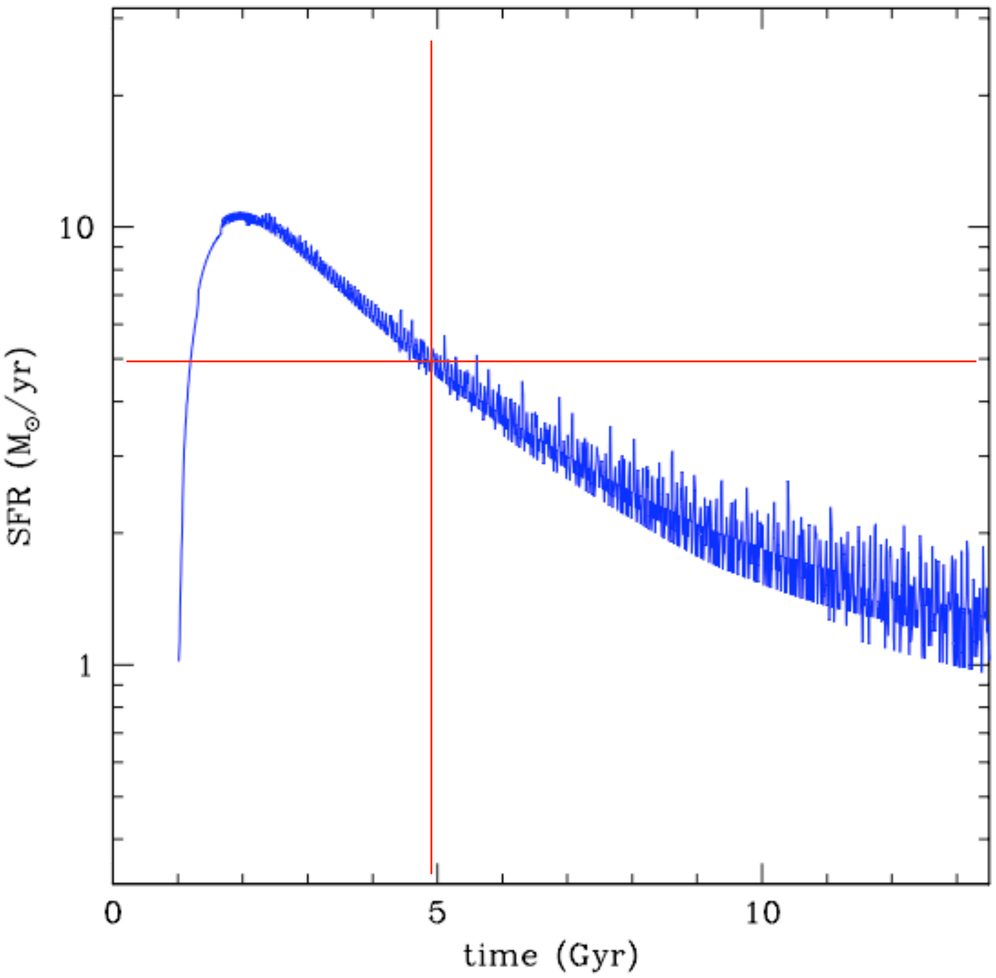
- chemical homogeneity of solar neighbourhood: 3rd independent indicators (B stars, BA SG and HII-regions)
- near-solar abundances over ~4kpc
- flat abundance gradient

➡ tight observational constraints for Galactochemical evolution

Friedrich-Alexander-Universität
Erlangen-Nürnberg

(From Przybilla 2008)

The MW in the Cosmological Context



Similar of SFR in Spirals @ z=1 (Bell 2007)

5 Msun/yr @ z=1

How much enrichment from t_{sun} to t_{now}?

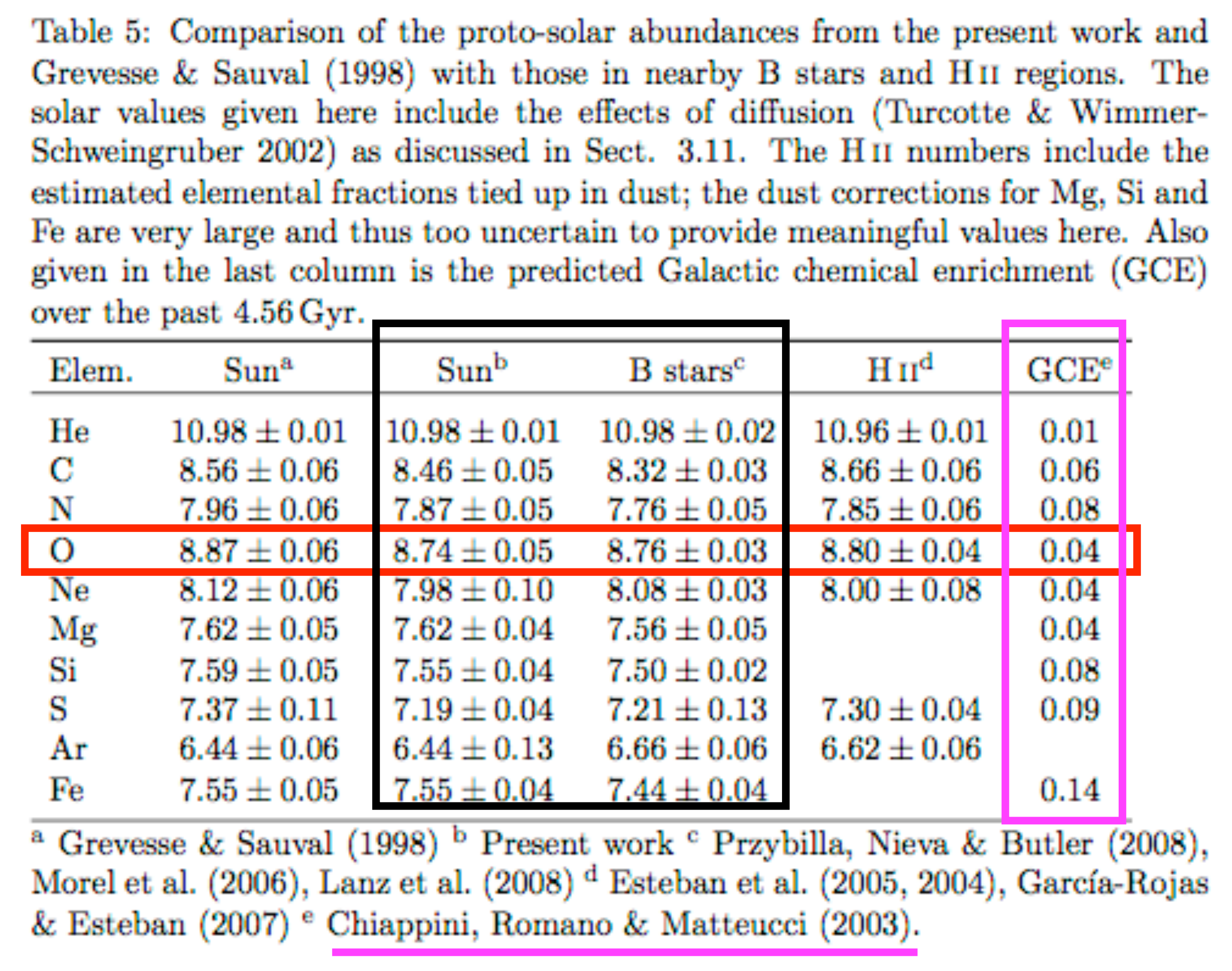


Table 5: Comparison of the proto-solar abundances from the present work and Grevesse & Sauval (1998) with those in nearby B stars and H II regions. The solar values given here include the effects of diffusion (Turcotte & Wimmer-Schweingruber 2002) as discussed in Sect. 3.11. The H II numbers include the estimated elemental fractions tied up in dust; the dust corrections for Mg, Si and Fe are very large and thus too uncertain to provide meaningful values here. Also given in the last column is the predicted Galactic chemical enrichment (GCE) over the past 4.56 Gyr.

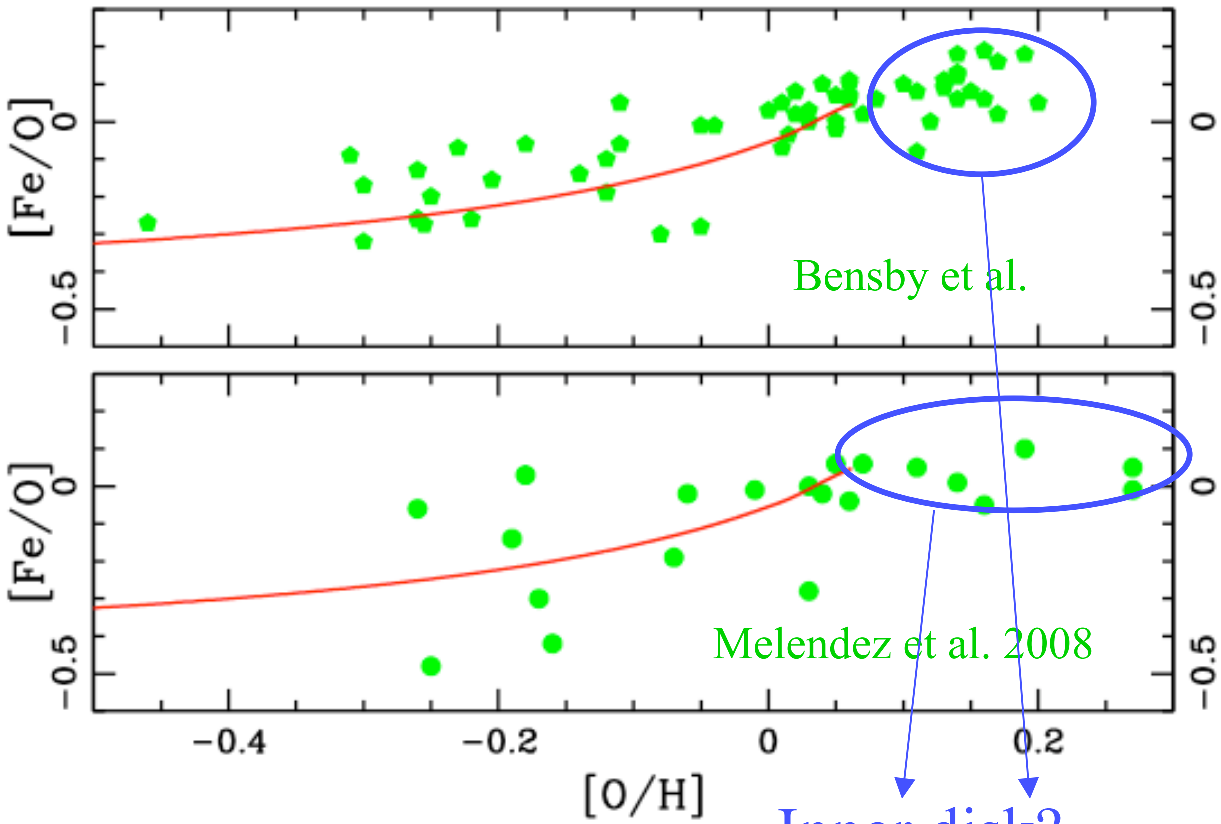
Elem.	Sun[a]	Sun[b]	B stars[c]	H II[d]	GCE[e]
He	10.98 ± 0.01	10.98 ± 0.01	10.98 ± 0.02	10.96 ± 0.01	0.01
C	8.56 ± 0.06	8.46 ± 0.05	8.32 ± 0.03	8.66 ± 0.06	0.06
N	7.96 ± 0.06	7.87 ± 0.05	7.76 ± 0.05	7.85 ± 0.06	0.08
O	8.87 ± 0.06	8.74 ± 0.05	8.76 ± 0.03	8.80 ± 0.04	0.04
Ne	8.12 ± 0.06	7.98 ± 0.10	8.08 ± 0.03	8.00 ± 0.08	0.04
Mg	7.62 ± 0.05	7.62 ± 0.04	7.56 ± 0.05		0.04
Si	7.59 ± 0.05	7.55 ± 0.04	7.50 ± 0.02		0.08
S	7.37 ± 0.11	7.19 ± 0.04	7.21 ± 0.13	7.30 ± 0.04	0.09
Ar	6.44 ± 0.06	6.44 ± 0.13	6.66 ± 0.06	6.62 ± 0.06	
Fe	7.55 ± 0.05	7.55 ± 0.04	7.44 ± 0.04		0.14

[a] Grevesse & Sauval (1998) [b] Present work [c] Przybilla, Nieva & Butler (2008), Morel et al. (2006), Lanz et al. (2008) [d] Esteban et al. (2005, 2004), García-Rojas & Esteban (2007) [e] Chiappini, Romano & Matteucci (2003).

Asplund et al. 2009

Some stellar migration?

Sun [a,b]	Orion [c] B stars vs. HII region	ISM [d] Absorption lines
8.66	8.65-8.8	8.53-8.61 + dust
8.77	8.51 (CEL) + dust 8.65 (RL) + dust	



Inner disk?

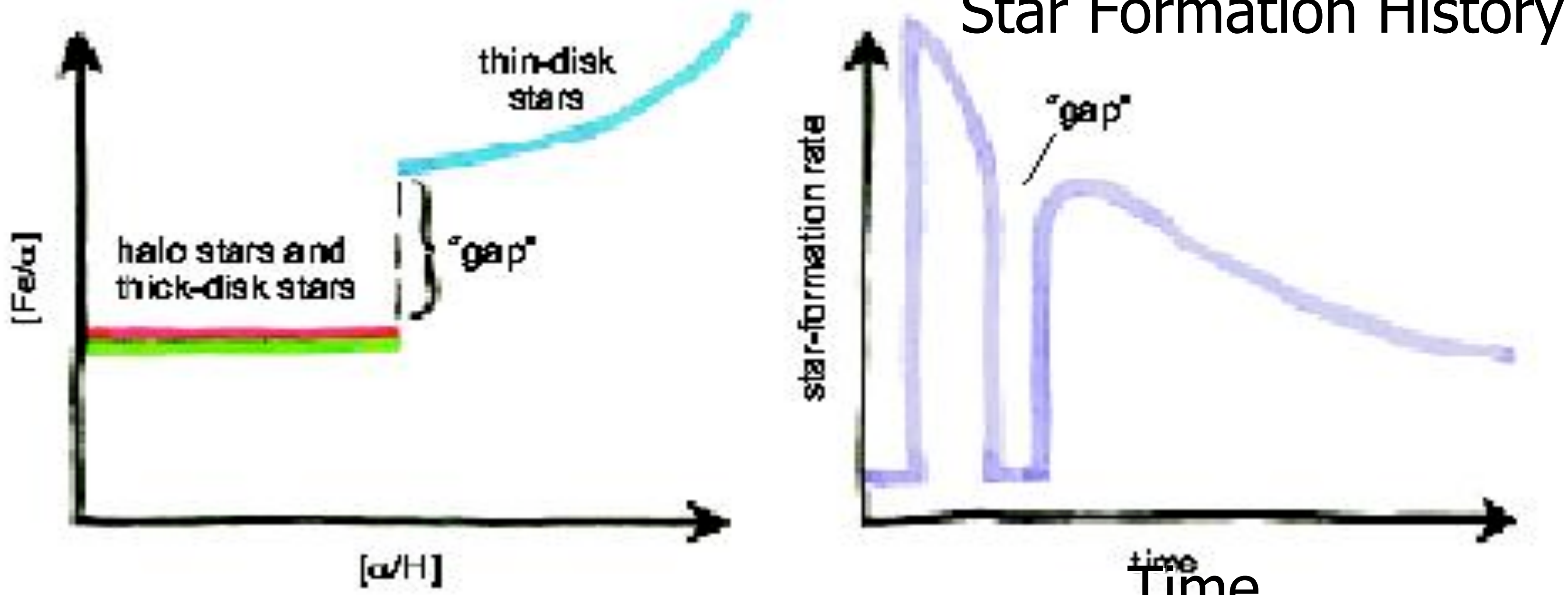
a.Asplund et al. 2005
b.Caffau et al. 2008
c.Simon-Diaz et al. 2008 (prep)
d.Hebrard (priv. Com.)

2. Discontinuity in the Abundance Ratios

[Fe/α]

(Chiappini 2001 Am.Sci.)

Star Formation History

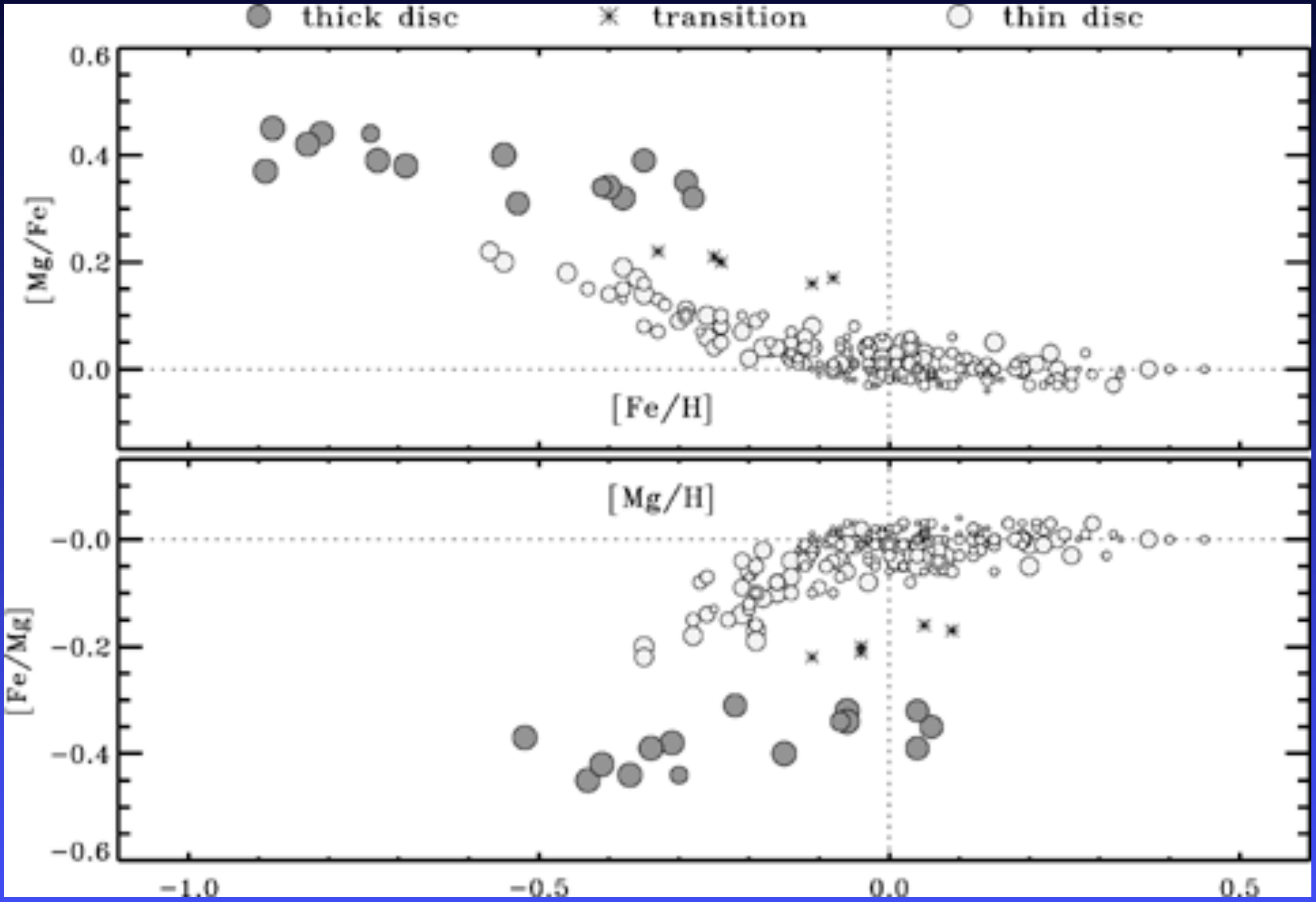


[α/H] (by instance O)

Time

This behavior is expect to show up more clearly for a ratio between an element restored on long timescales to the ISM (e.g. Fe, C) and an element ejected in short timescales (e.g. O)

Fuhrmann 2008 - Volume complete sample



Lack of scatter (10000 lower than metallicity range!)

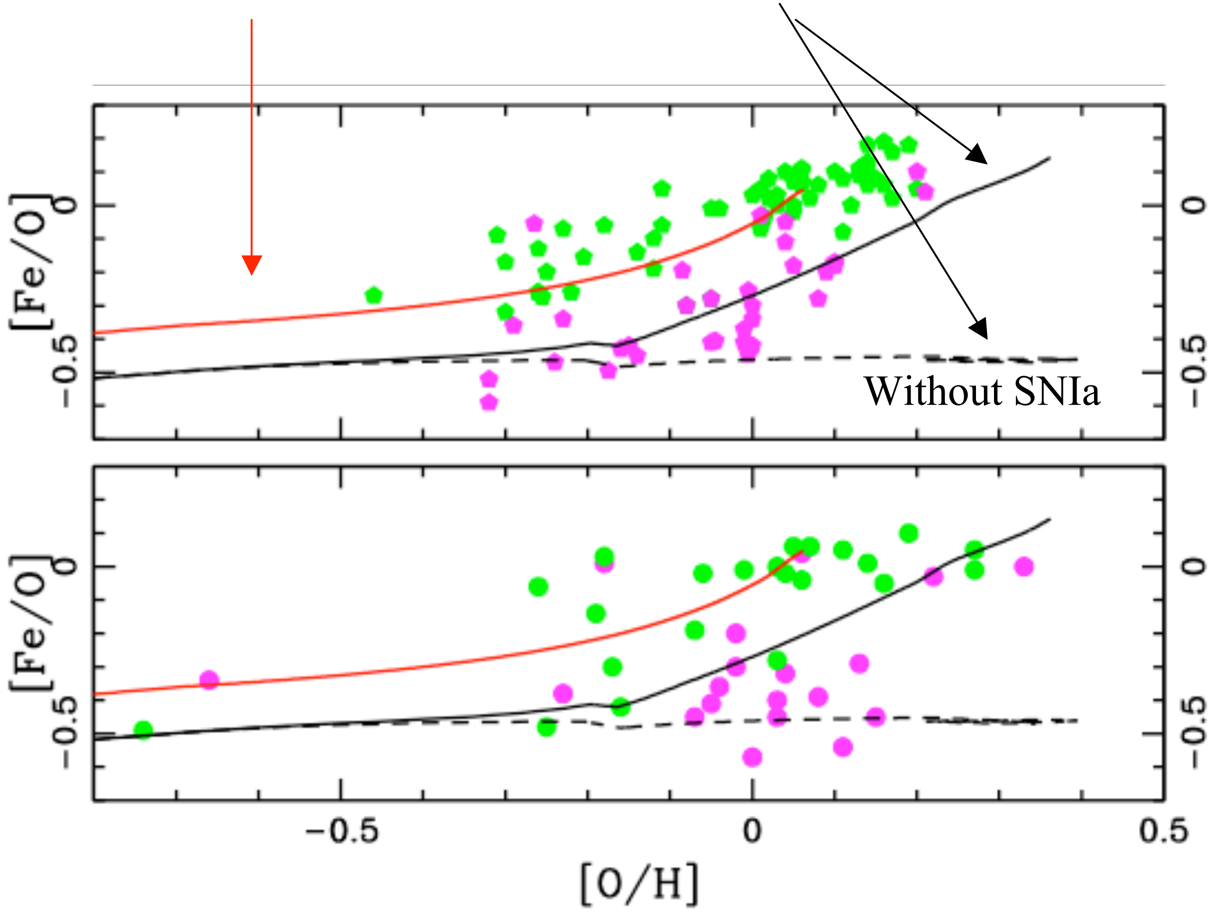
Halo, Thick disk, Thin disk: cannot have been made by uncorrelated systems
Suggestions of an age gap between thick disk and oldest stars in thin disks
(Liu & Charboyer 2000, Sandage et al. 2003, Bernkopf & Furhmann 2006)

Green dots: Thin disk data
Magenta dots: Thick disk data

# THICK DISK
SFE = 10 x SFE_thin disk
τ = 0.4 Gyrs (Thin = 7 Gyrs)

Thin disk model

Thick disk model



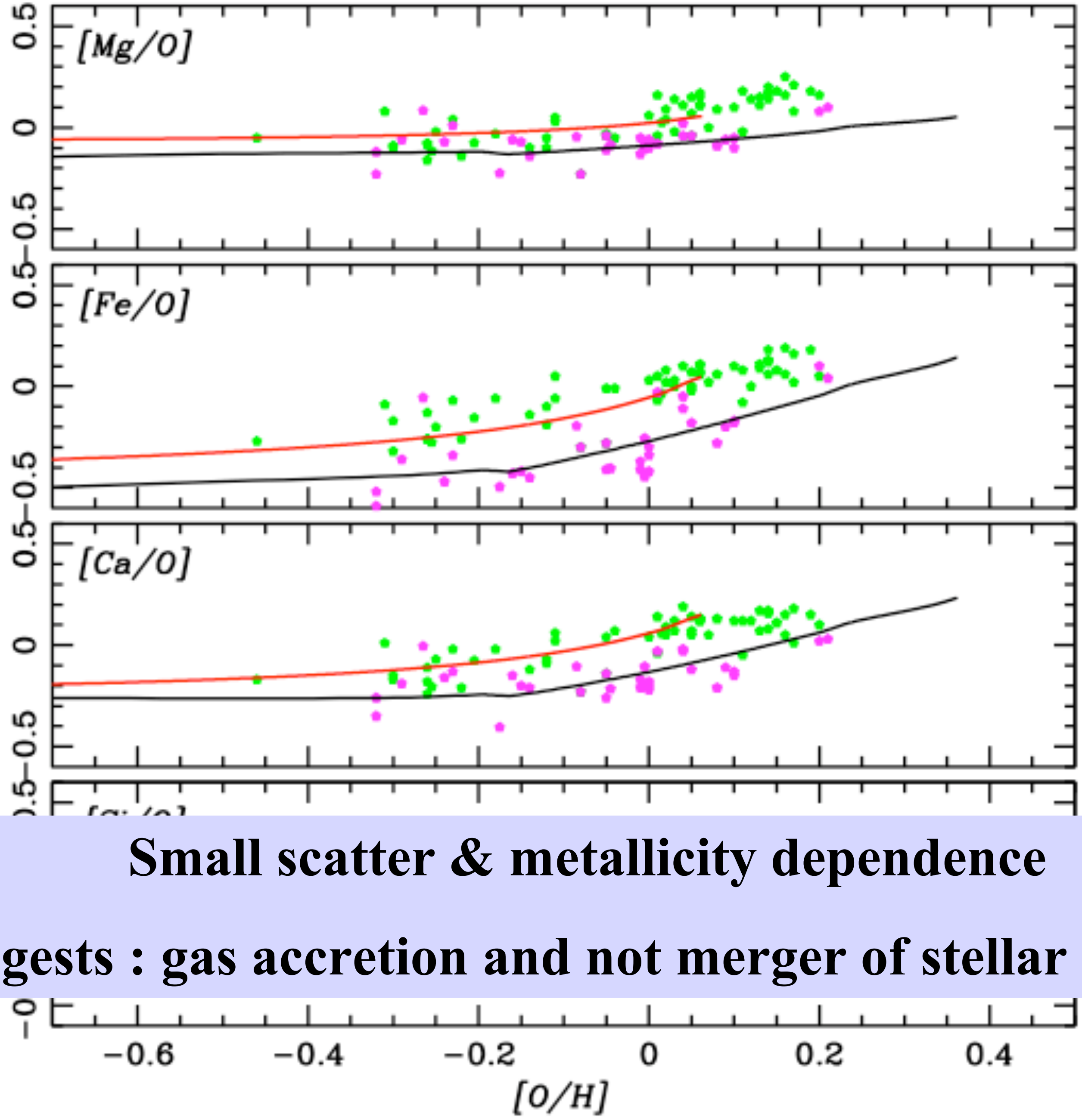
Without SNIa

True thick disk stars: up to which metallicity?

Bensby and collab.:
above solar

Ramirez et al.:
up to a factor of 2
below solar (-0.3dex)

Bensby & Feltzing data



Small scatter & metallicity dependence

Suggests : gas accretion and not merger of stellar systems

Thick disk/Bulge similarities

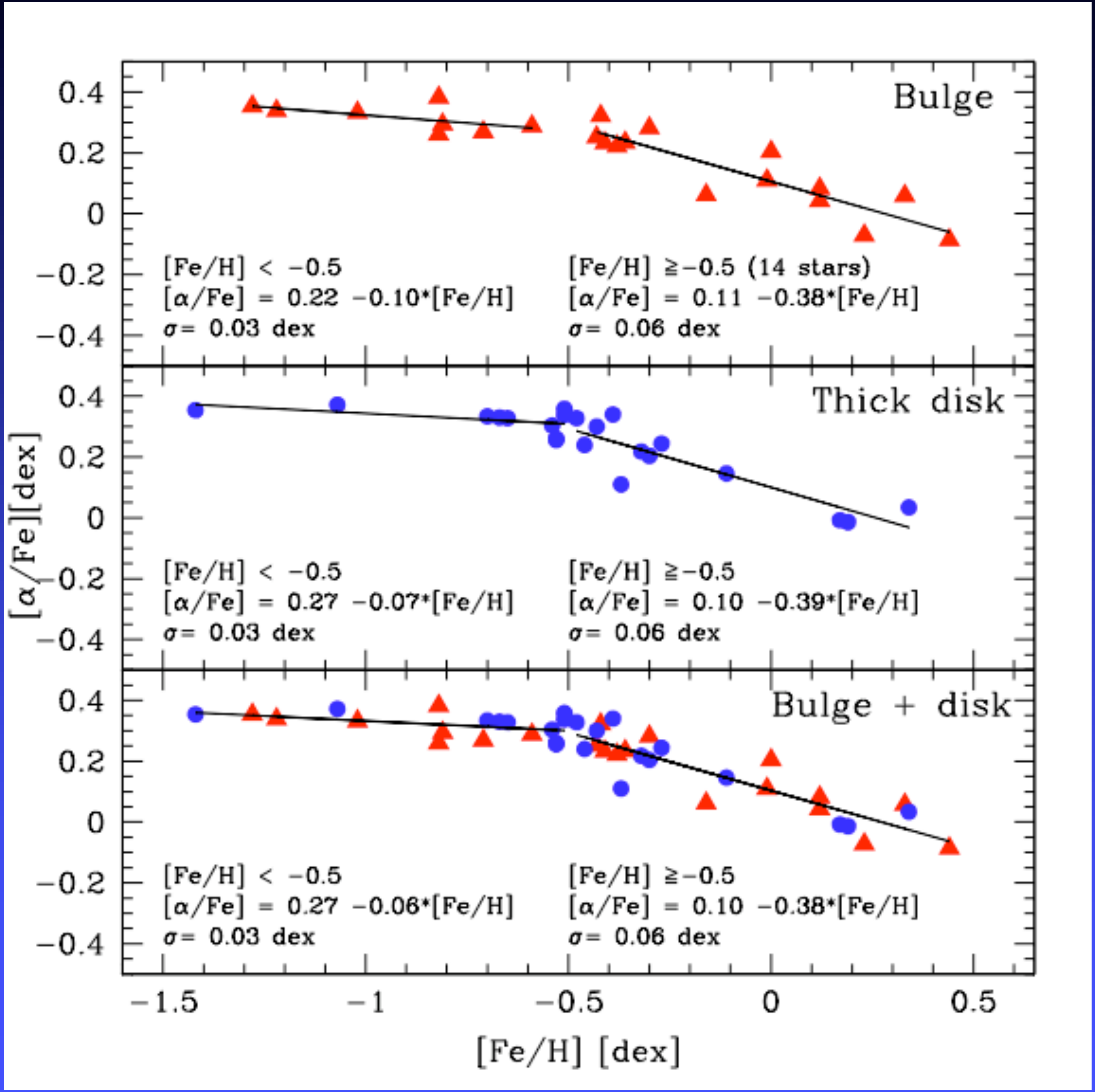
Recent Results: Despite the very different mean metallicities, the Bulge and Thick Disk abundance ratios are similar!

Meléndez, J.; Asplund, M.; Alves-Brito, A.; Cunha, K.; Barbuy, B.; Bessell, M. S.; Chiappini, C.; Freeman, K. C.; Ramírez, I.; Smith, V. V.; Yong, D. 2008 A&A Letters

Cescutti, Matteucci, McWilliam & Chiappini, 2009, A&A

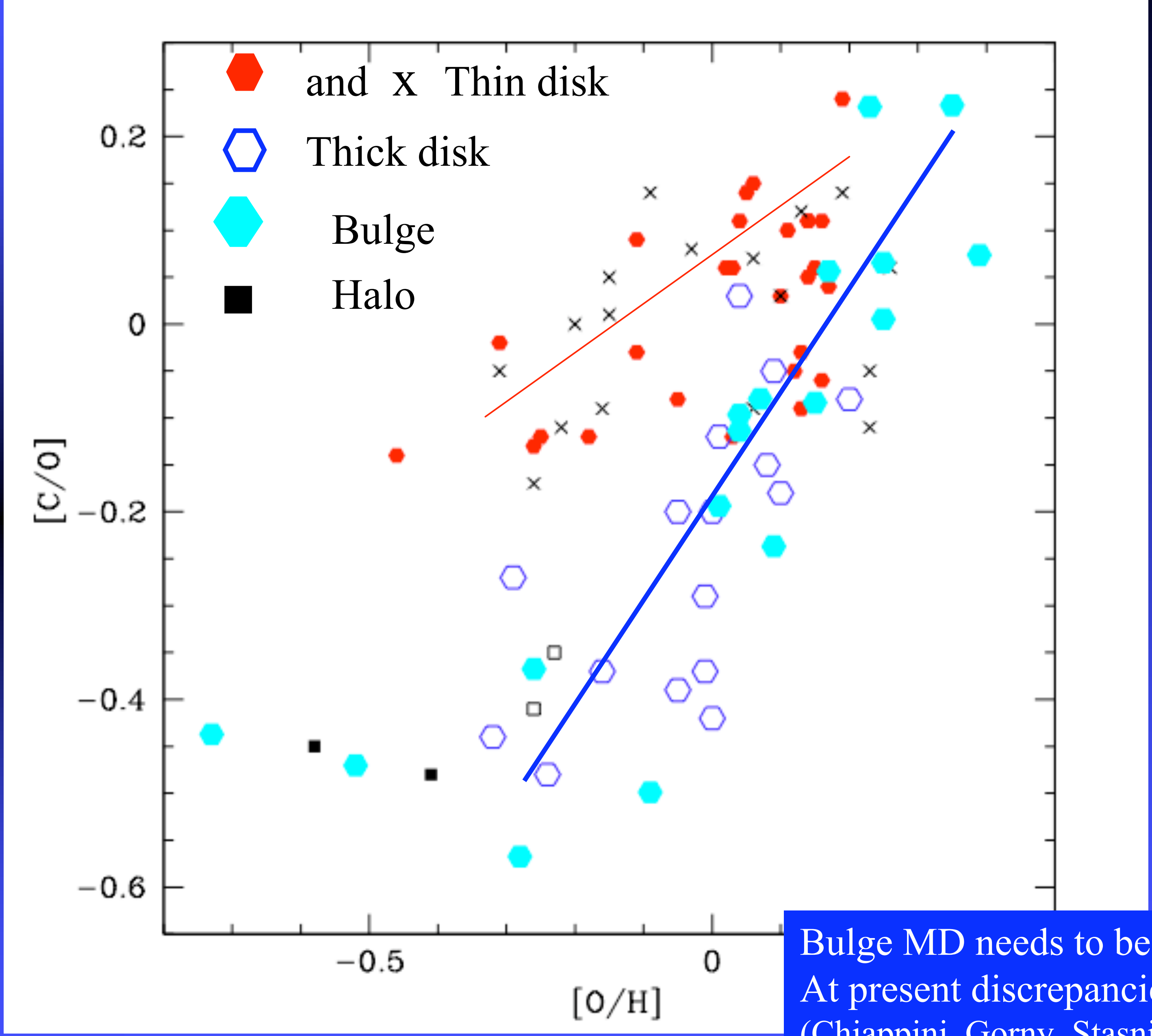
Alvez Britto et al. 2010, A&A (submitted)

Suggest similar IMFs and formations timescales for bulge & thick disk



Alves-Brito et al. 2010, Melendez et al. 2008 A&A Letters

Cescutti, Matteucci, McWilliam & Chiappini 2009 A&A



Bulge and
Thick disk
show the same
C/O vs. O/H !

Bulge MD needs to be better constrained.
At present discrepancies giants/PNe/dwarfs
(Chiappini, Gorny, Stasniska & Barbuy 2009)

Summary of main conclusions for MW from pure chemical arguments

(Chiappini 2009, Chiappini et al. 2010 in prep)

-The thin disk formed by slow gas accretion (Infall)

- The thick disk formed by fast GAS accretion

- Short timescale for gas accretion < 1Gyr)
- SFE_thick_disk = 10 x SFE_thin_disk

- Formation timescales of thick disk & bulge were similar

Same IMF but different SFEs?

Encouraging agreement with high-z observations (e.g. Genzel et al. 2008) and disk/bulge formation simulations

(Elmegreen & collaborators)

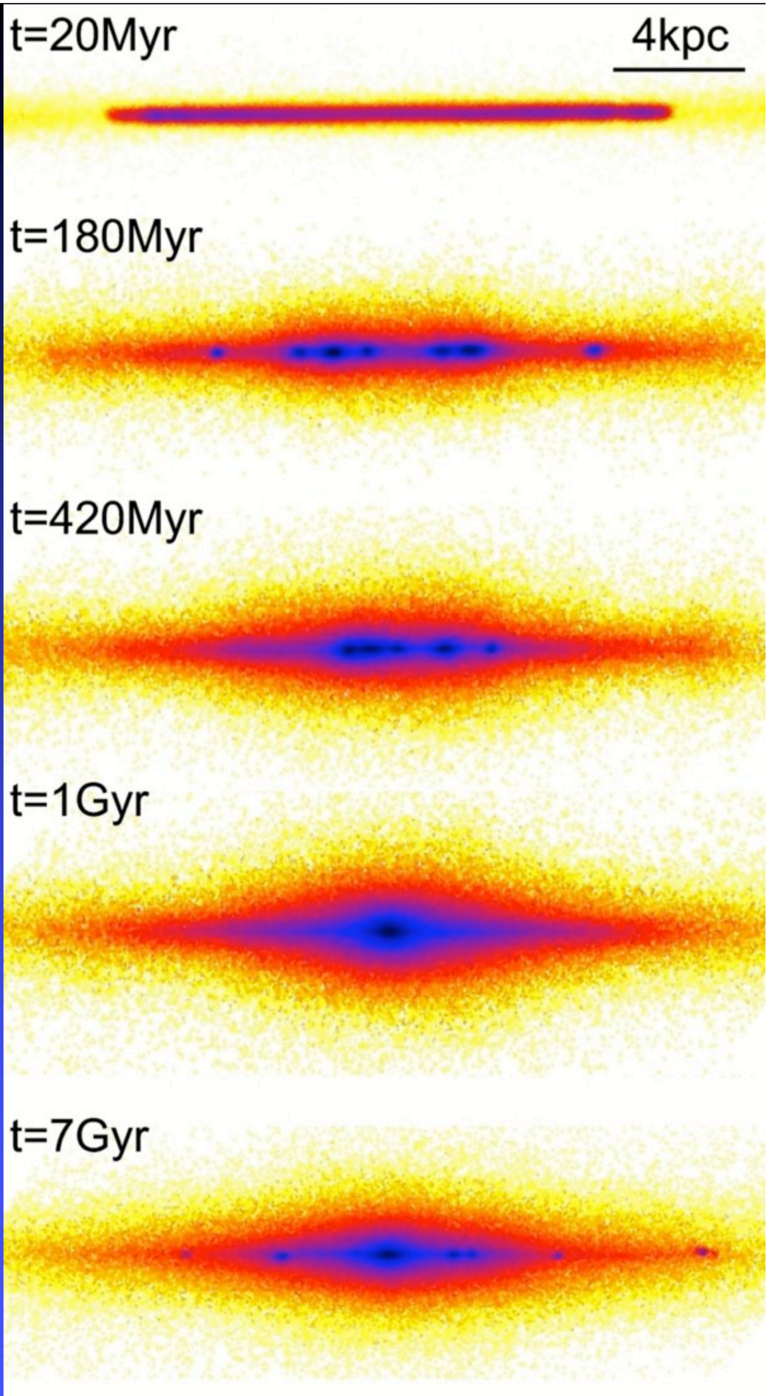
High z Observations

- ❑ SINS Survey (Genzel & collab): Turbulent rotating star forming disks + bulge at z=2
- ❑ Chain Galaxies in HUDF (Elmegreen & collab) : Star formation clumps aligned on a plane

INTERPRETATION: Buildup of the central disks and bulges of massive galaxies at z~2 driven by the early secular evolution of gas-rich 'proto'-disks. Disks highly turbulent due to rapid 'cold' accretion flows along filaments of the cosmic web => dynamical friction and viscous processes proceed on a time scale of <1 Gyr, at least an order of magnitude faster than in z~0 disk galaxies

(e.g. Bournaud & Elmegreen 2009 ApJL)

We are seeing thick disks, with assembly timescales of a few Myrs, with apparent no major mergers



The Halo

The nature of the First Stars

Signs of fast rotators in the early universe

Context

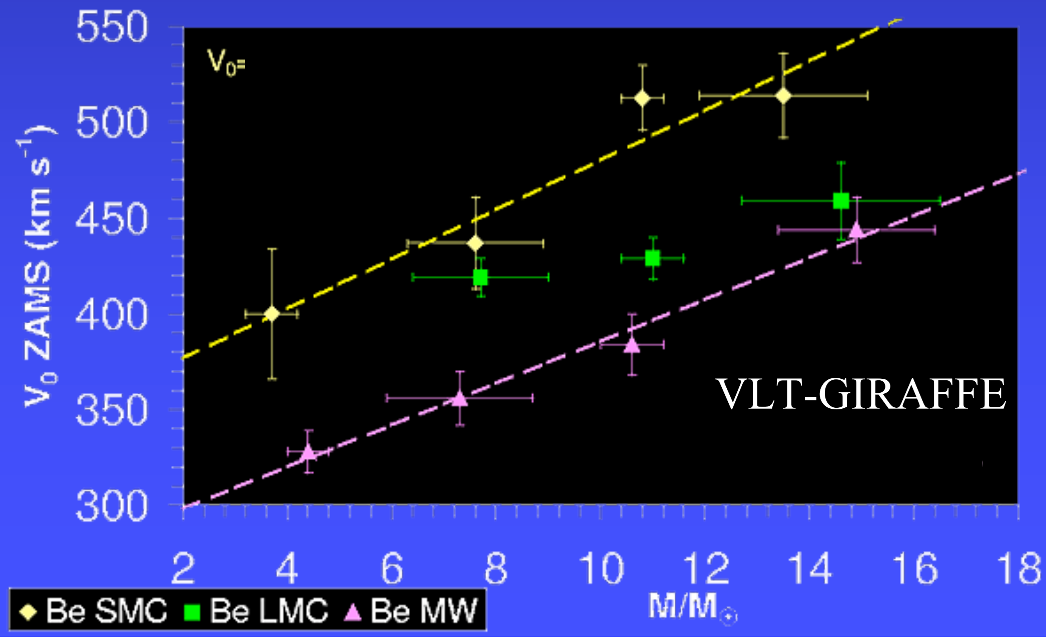
Geneva Models - Stellar Rotation/Mass-loss:
Can explain observed stellar properties that models without rotation/mass-loss cannot:

polar winds, stellar shape, larger temperature at poles, WR/O vs. Z, SNIbc/SNII vs. Z, Be fraction vs. Z…

@ low Z stars rotate faster (more compact)

- Mokiem et al. (2006): Excess of fast rotating O-type unevolved stars in SMC with respect to the Galaxy

Martayan et al. (2007): <Vrot> ⇑ from MW -> LMC -> SMC



Stellar Models as inputs to CEMs:

Approach: to use stellar models that account for observations in the Local Universe + predictions made by these models at very low Z ($< 10^{-5}$)

Important consequences for the chemical enrichment in the early Universe!

Fast rotators!

@ very low Z stars are more compact and could rotate at 600-800km/s
(Hirschi 2007)

Why 600-800 km/s?
Assumption: J_{ini} = constant

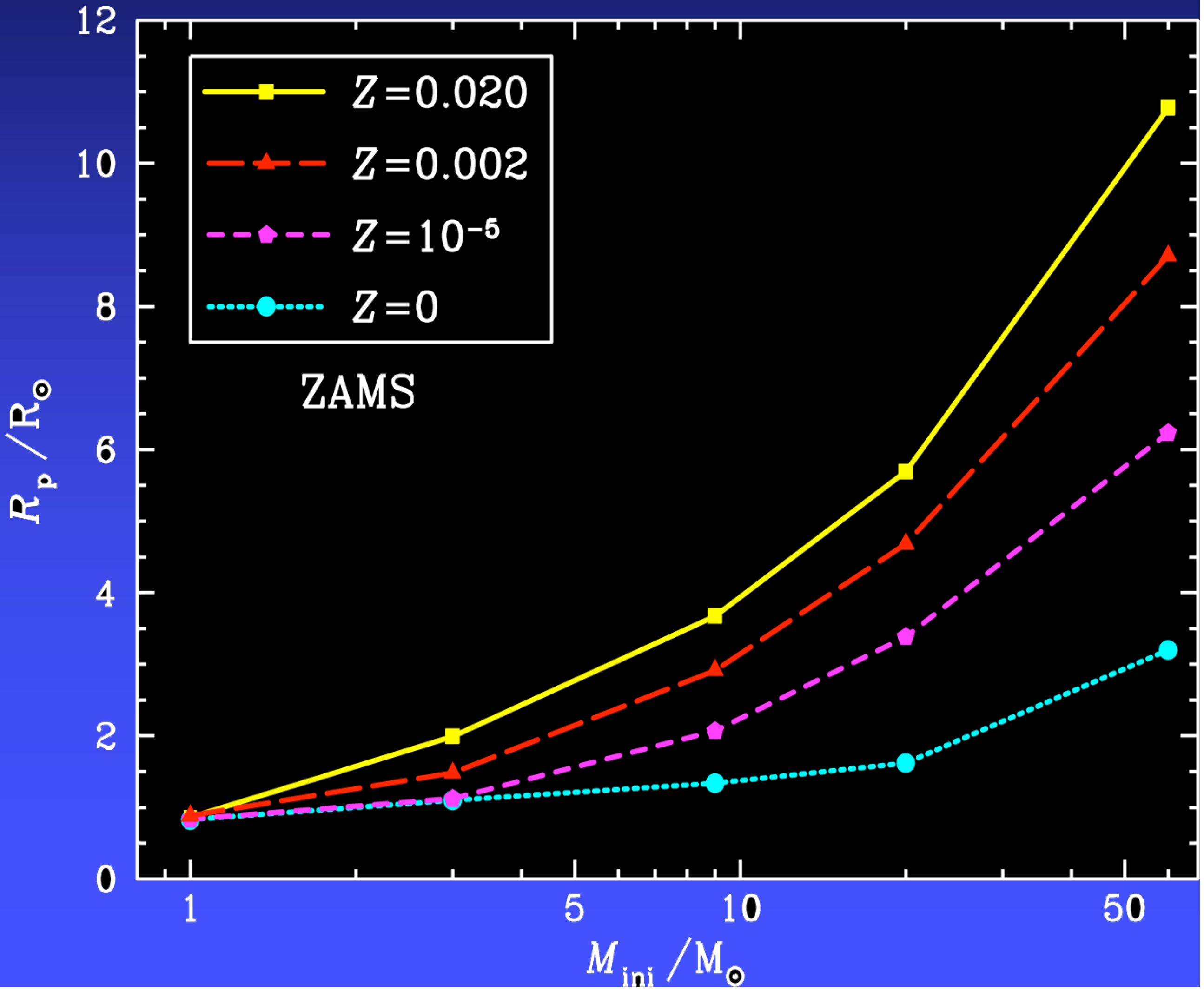
M_{ini}= 20 M_{sun}: R(Z=10^{-8}) = R(Z=solar)/4

Mixing -> increases when: M ↑ Vrot ↑ Z ↓ ➡ More N! (and ^{13}C)

- Rotation,-> velocity gradients inside star -> diffusion of C and O produced in the He burning core into the H burning-shell
- Formation of primary ^{14}N and ^{13}C.
- Part of ^{14}N is converted into ^{22}Ne: a neutron source for s-process in massive stars
- Stellar surface enhancement in CNO -> strong mass loss

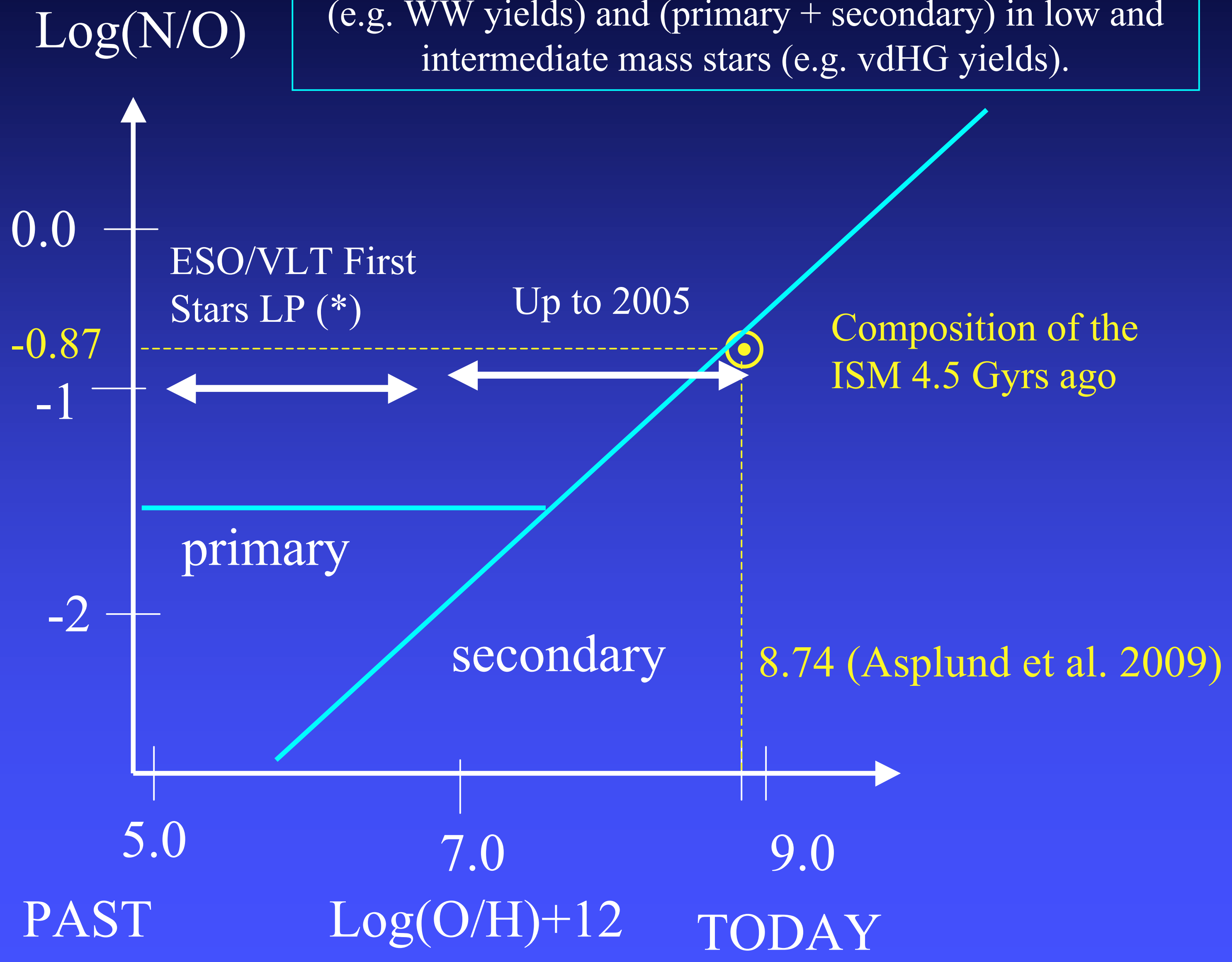
- M_{ini}= 20 M_{sun}:

V_{ini}	Z_{ini}	J_{ini} [10^{53} erg s]
300	solar	0.36
300	10^{-8}	0.18
600	10^{-8}	0.33



Secondary/primary vs. primary element

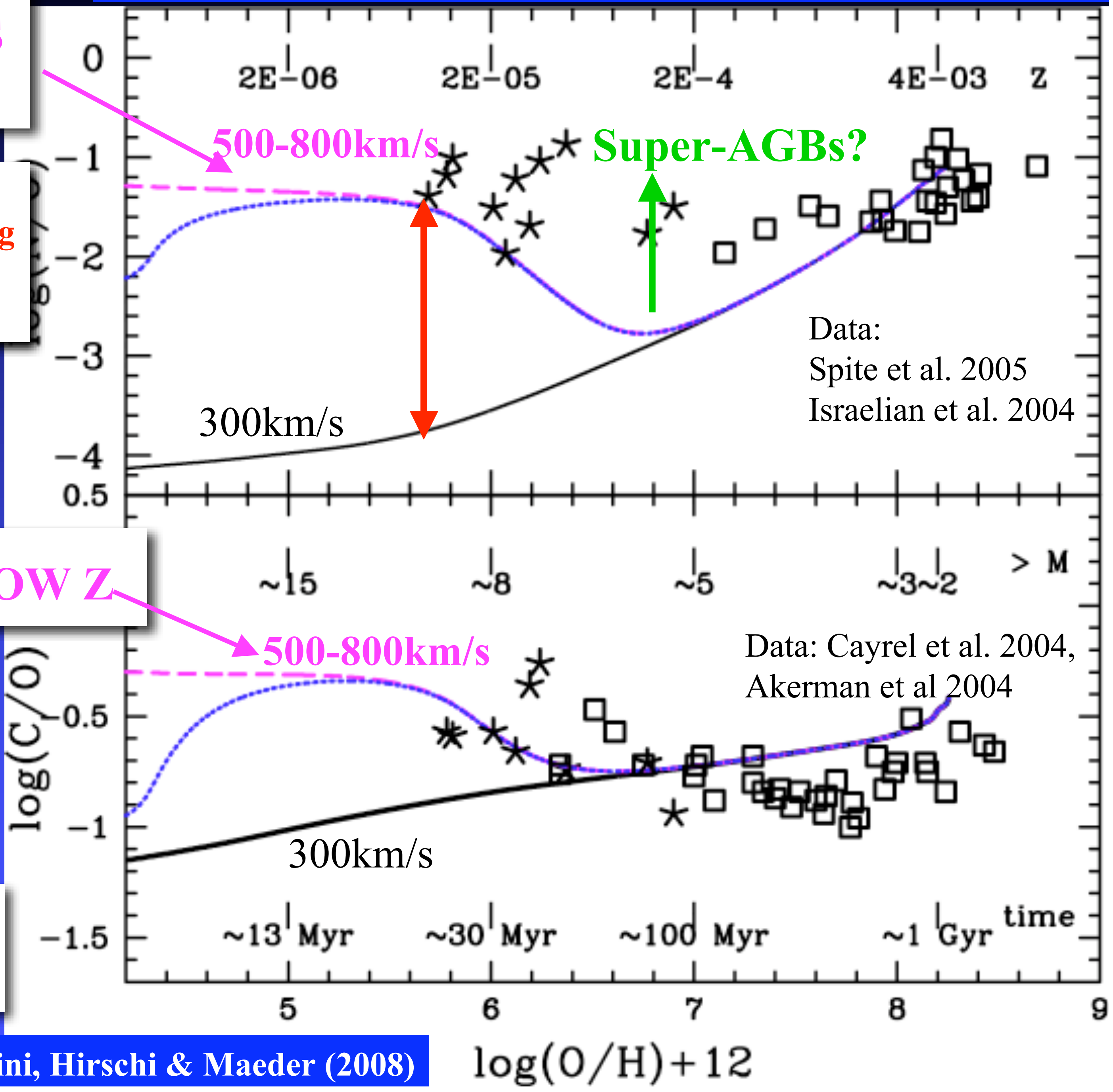
"Standard Stellar Models": N secondary in massive stars (e.g. WW yields) and (primary + secondary) in low and intermediate mass stars (e.g. vdHG yields).



(*) Cayrel et al. 2004, Spite et al. (2005, 2006); Lai et al. (2008)

IF WE CONSIDER FAST ROTATORS @ at very low Z

Chiappini, Hirschi, Meynet, Ekstroem, Maeder, Matteucci (2006a,b)



500-800km/s

Super-AGBs?

Data:
Spite et al. 2005
Israelian et al. 2004

^{14}N/O @ [Fe/H]=-3 increases by 3 orders of mag upon the inclusion of fast rotators!

C/O UPTURN @ LOW Z

500-800km/s

Data: Cayrel et al. 2004,
Akerman et al 2004

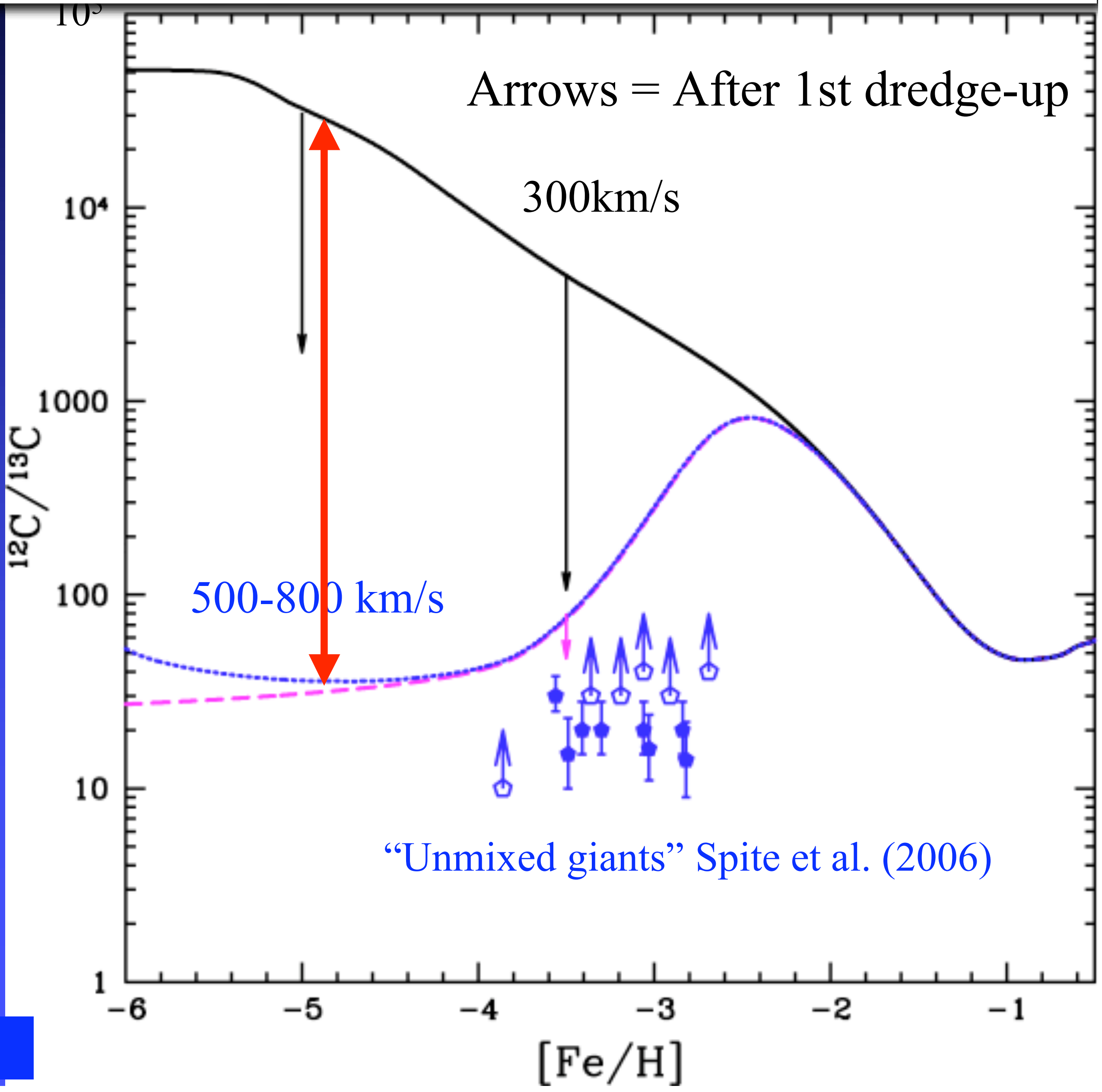
Small effect of Pop III (Z=0)

Ekstroem, Meynet, Chiappini, Hirschi & Maeder (2008)

The expected $^{12}C/^{13}C$ ratio @ [Fe/H]=-5 drops by 4 orders of mag upon the inclusion of fast rotators!

There should be an impact on the C isotopic ratios as well Mixing will produce not only N but also ^{13}C!

In this framework massive stars can explain low $^{12}C/^{13}C$ @ low [Fe/H] (< -3) without invoking AGB contribution to the ISM enrichment compatible with observations (Melendez & Cohen 2007)



[X/H]=log(X/H)-log(X/H)_Sun

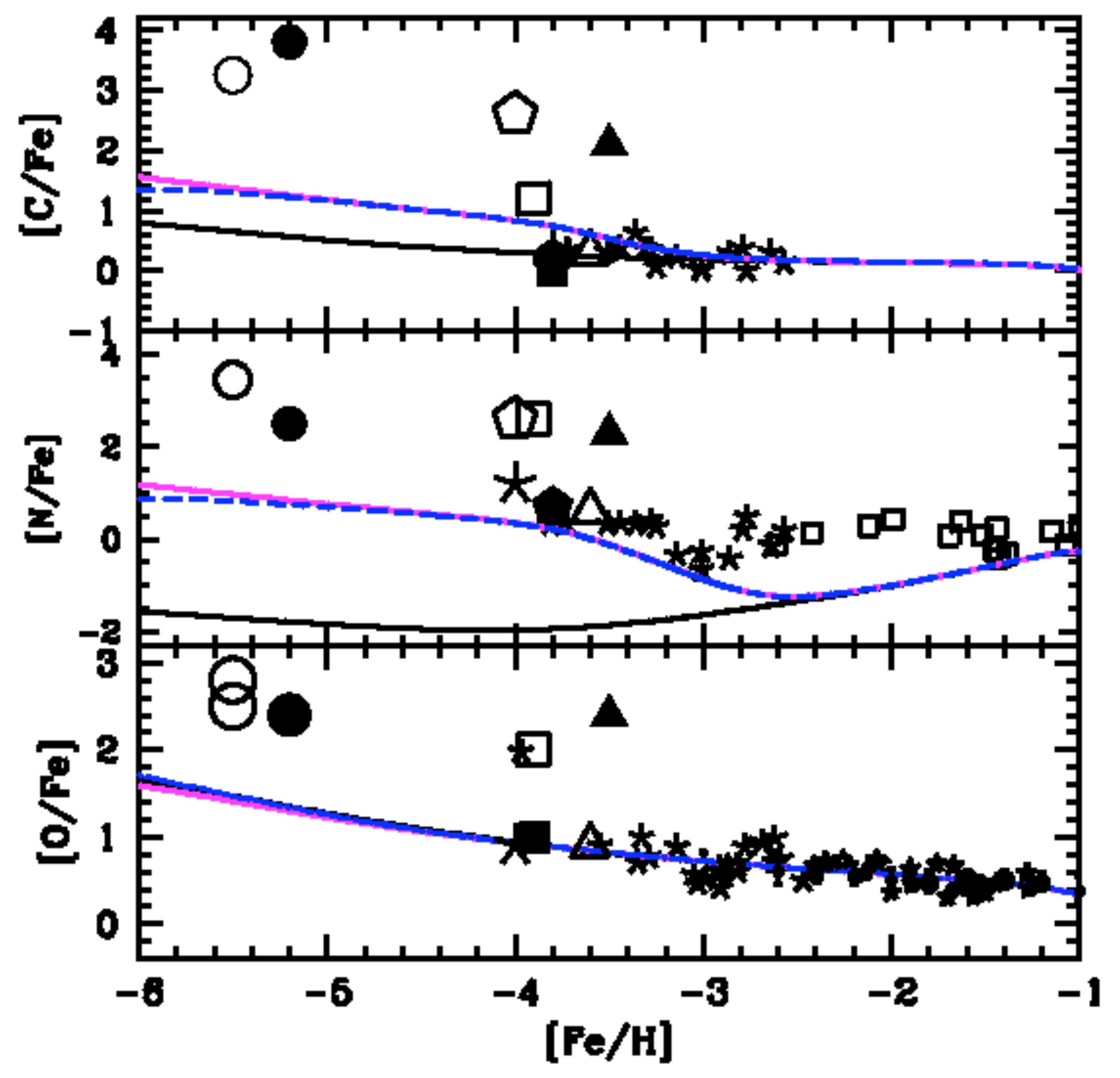
Chiappini et al. (2008, A&A Letter)

Fast rotators produce stellar winds which are CNO & He rich

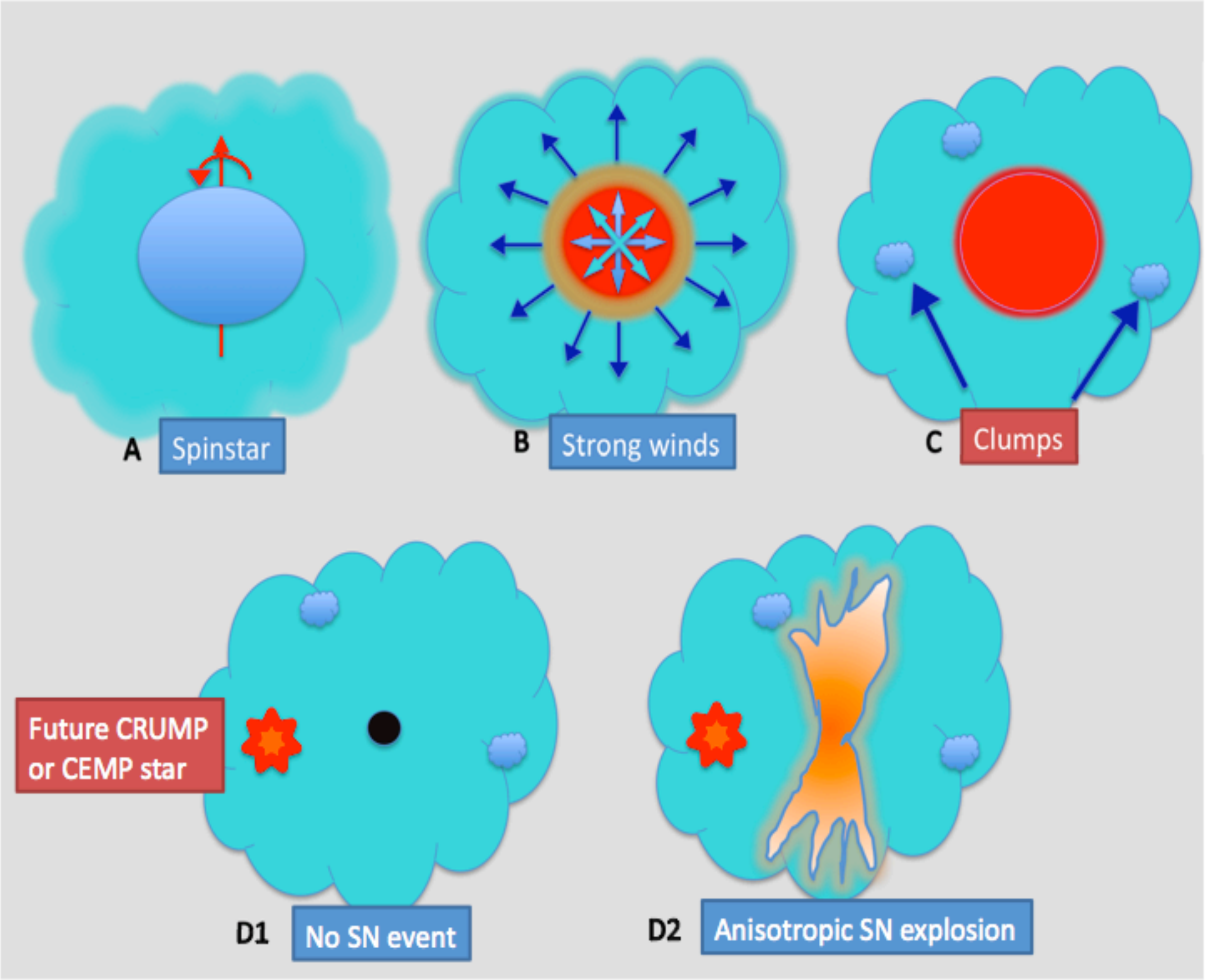
Could be connected with the existence of the CEMP-no stars !

Hirschi (2007):

- Some of the most metal poor CRUMPS could have formed from gas which was mainly enriched by stellar winds of rotating very low metallicity stars



CEMPs-Massive Stellar Winds connection



Meynet et al. 2010 (submitted)

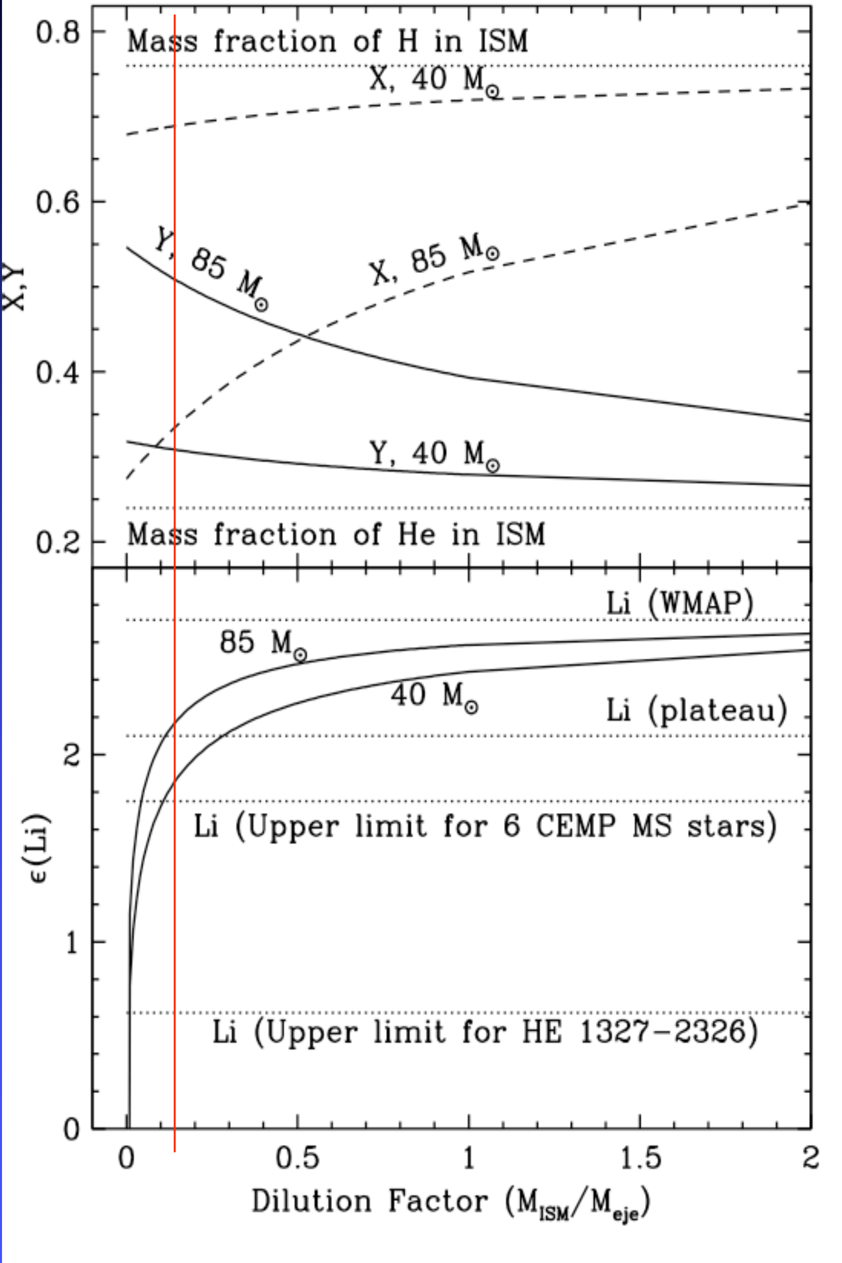
- ☐ Wind material: H-burning products (high [N/C], [N/O], low $^{12}C/^{13}C < 10$) independent of dilution factor

- ☐ Small dilution factor: He-rich, Li-poor

- ☐ Wind + SNe material - requires large dilution to explain CNO - then get larger Li and larger $^{12}C/^{13}C$ ratios (> 30 - also He burning material)

- ☐ Rotation needed in any case to explain high N

He-rich not expected in AGB scenario
Could be a way of discriminating the two possibilities…



SUMMARY

Signatures of fast rotators @ low Z: large N/O & C/O and low $^{12}C/^{13}C$ at low Z in the very metal-poor stars of the MW halo

(Observations from Spite et al. 2005, 2006 - Models from Chiappini et al. 2006ab, 2008)

Impact of “SPINSTARS” @ low Z

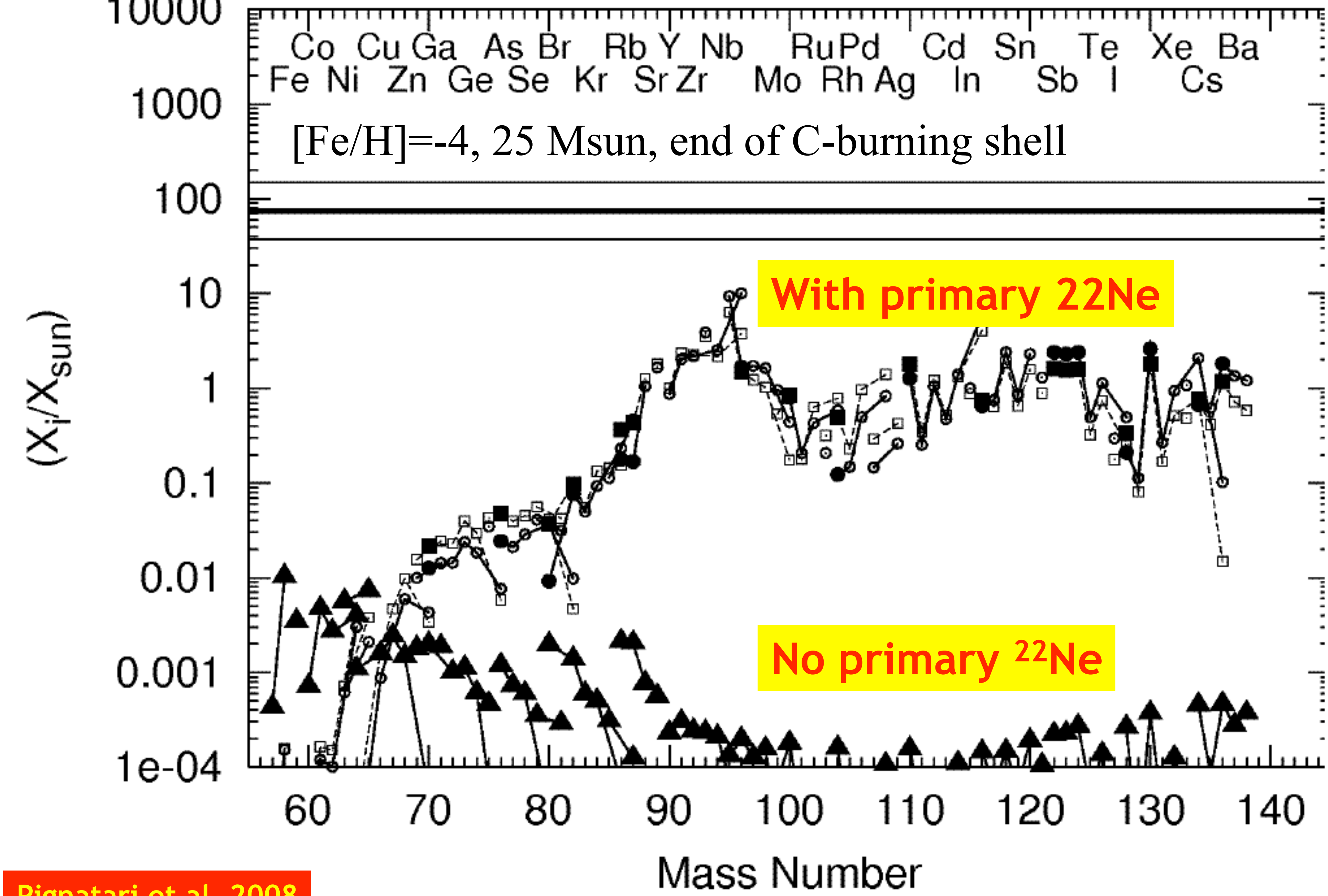
⇒ Could change radically the current numerical simulations for the formation of the first stars and explosion of SNe -> at present they do not consider fast rotation/mass-loss (even at Z=0! Ekstroem, Meynet & Chiappini et al. 2008)

⇒ N/O is usually used as a cosmic clock in several research areas… impact in the interpretation of high z objects - Lyman-break and DLAs, and local star burst galaxies based on integrated spectra (e.g. Levesque et al. 2009 - SB99 with new stellar evolution tracks taking rotation into account).

⇒ Impact on the progenitors of GRBs and their dependency on metallicity (Hirschi et al. 2005, Yoon et al. 2006)

We are looking for other imprints of fast stars! s-process elements? He? Connection with CEMPs?

Fast Rotators can produce s-process elements!



Pignatari et al. 2008