The dessert !

Lectures - III & IV

❑ Numerical Models - One example

❑ Applying it to the MW (lots of observations!)

- The solar vicinity:
  - ✓ thin disk
  - ✓ thick disk
  - ✓ halo (later!)

- Leaving the solar vicinity (much less observations…)
  - ✓ the bulge
  - ✓ the whole disk (gradients)

The halo and the First Stars

Lecture III

Brief Intro to Numerical Models

The particular formalism of the Trieste group (Matteucci 2001) has been applied for galaxies of different morphological types:

Spirals (MW), Ellipticals, bulges, dSphs, BCGs, DLAs, Lyman-Break, etc.

Very important role of τ_m ! No I.R.A.

Formalism to include SNIa

(Matteucci & Greggio 1986)

✓ M_B: total mass of the binary system

✓ M_{BM} and M_{Bm} mass limits to form a binary system which can lead to a SNIa taken to be around 3 and 16 $M_\odot$

✓ A: Fraction of systems with total mass in the appropriate mass range which eventually succeed in giving rise to a SNIa event. $A \approx 0.05\text{-}0.09$

✓ τ_{m2} : lifetime of the secondary star from the binary system which regulates the clock for the explosion (the more massive)

✓ $f(\mu)$: distribution function of the mass fraction of the secondary

$$f(\mu) = 2^{1+\gamma} (1+\gamma)\, \mu^{\gamma} \qquad \gamma=2$$

(Greggio & Renzini 1983)

$$\mu = m_2 / M_B$$

$dG_i/dt = d(X_iM_g)/dt$ = rate of time variation of the gas fraction in the form of an element *i*

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

1st term: Gas is consumed to form stars

Min mass to form a SNIa = 3 M☉

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

Lowest mass contributing to CE = 0.8M☉

2nd term: Rate at which *i* is restored to the ISM by stars in the mass range M_L and M_{Bm} not forming SNIa

$$+A\int_{M_{Bm}}^{M_{BM}} \phi(m)$$

3rd term: Rate at which *i* is restored to the ISM by SNIa

$$\cdot\left[\int_{\mu_{min}}^{0.5} f(\mu)\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})d\mu\right]dm$$

4th term: Rate at which *i* is restored by stars in the same mass range as above, but which do not give a SNIa (either single or binaries)

Largest mass contributing to CE = 16 M☉

B=1-A

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

5th term: Rate at which *i* is restored by stars more massive than M_{Bm}

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

$$+X_{A_i}A(t) - X_iW(t)$$

6th and 7th terms: Rate at which *i* is accreted via infall or leaves the system via winds

Lecture III
Chemical properties of the MW

A local benchmark to cosmology

Constraints on galaxy formation and on the origin of the elements

Applying these models to the MW

Goals : a) constrain the stellar yields, b) constrain the SFH/ enrichment timescales, c) constrain infall/outflows

Different components required different initial conditions, flow history, star formation efficiency

But… same nucleosynthesis, same stellar inputs, same IMF (?), same Star Formation law

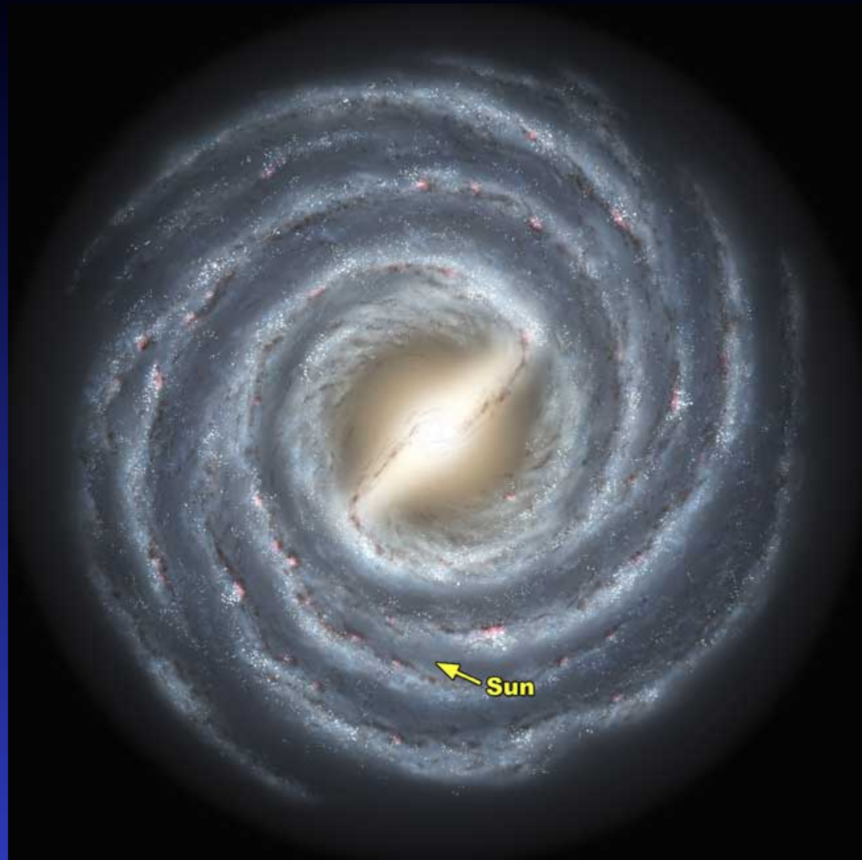
Powerful approach if many observation constraints:
It is the case in the solar vicinity, especially for thin disk!

Milky Way

Local Benchmark to Cosmology

Access to detailed ages + abundances + space velocities for individual stars

GAIA



Record of continuous star formation during the past 13 Gyrs

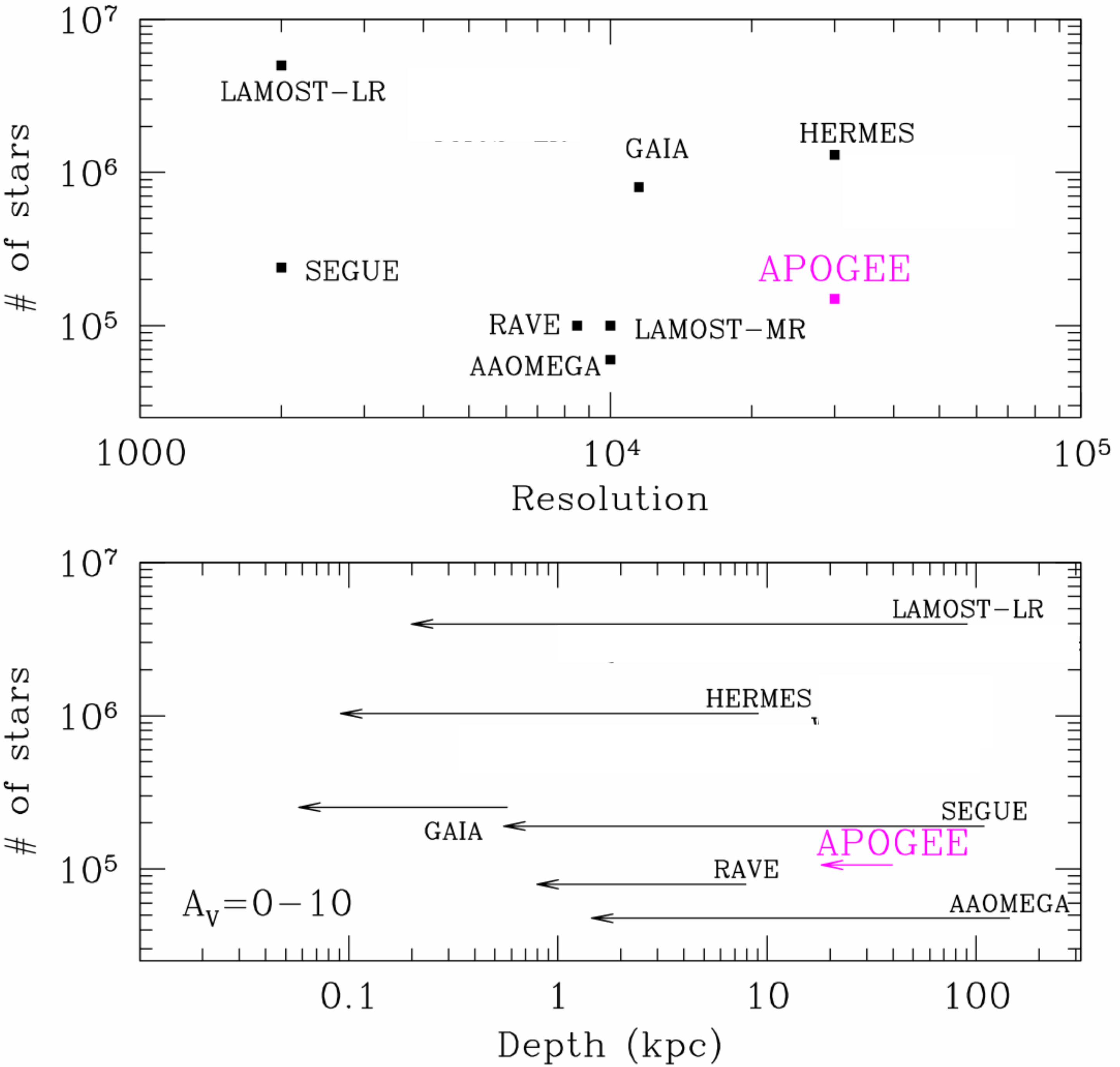
Bonus: Origin of chemical elements

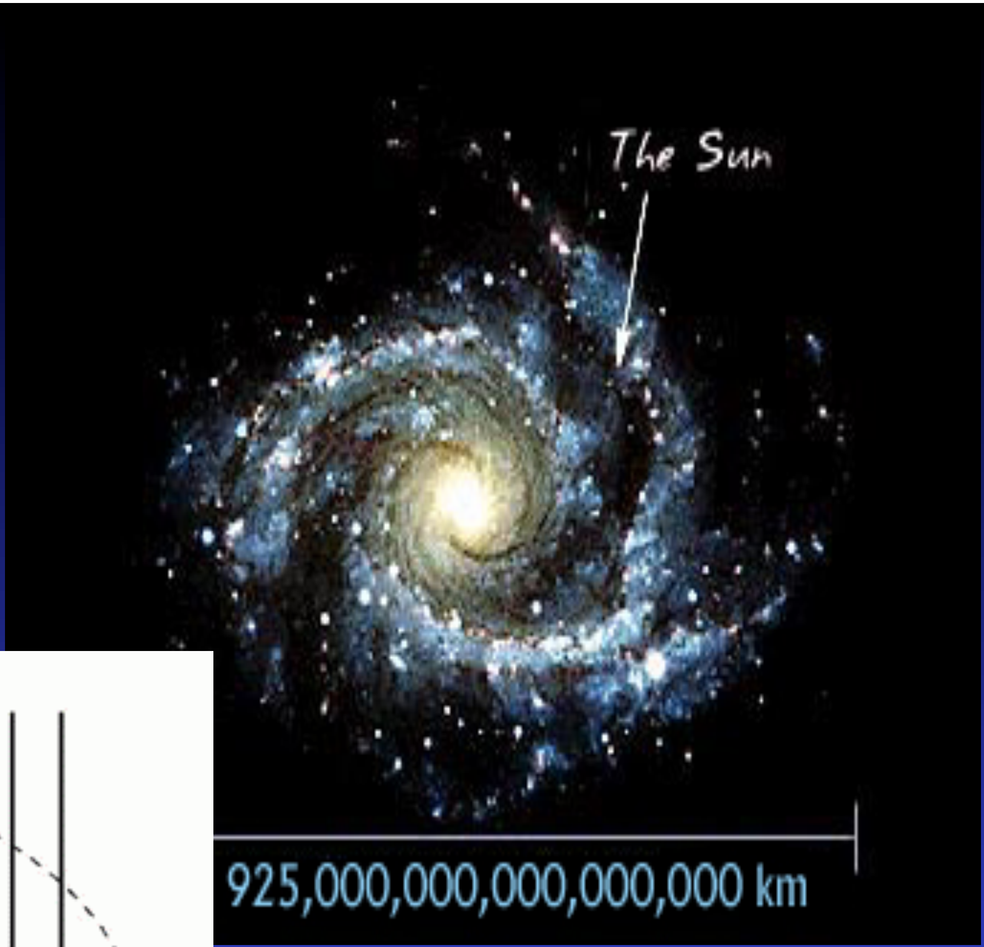
Rosetta Stone of Chemical Evolution

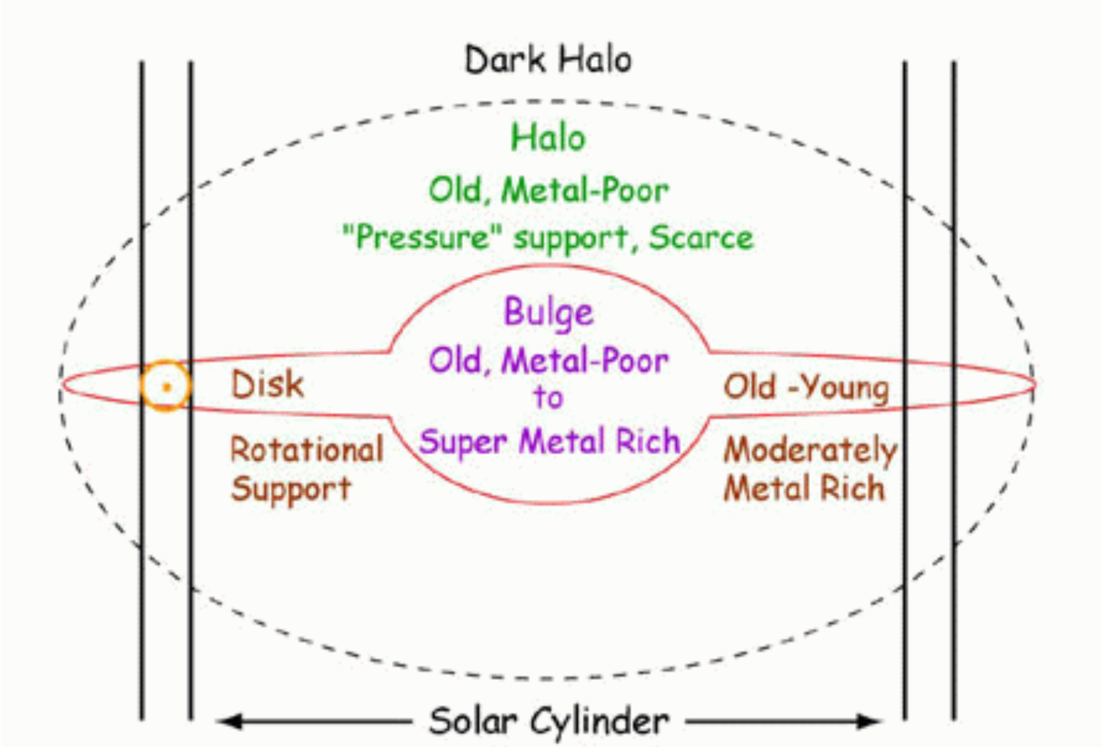
Test for LambdaCDM scenario…

From Majewski

SURVEYS



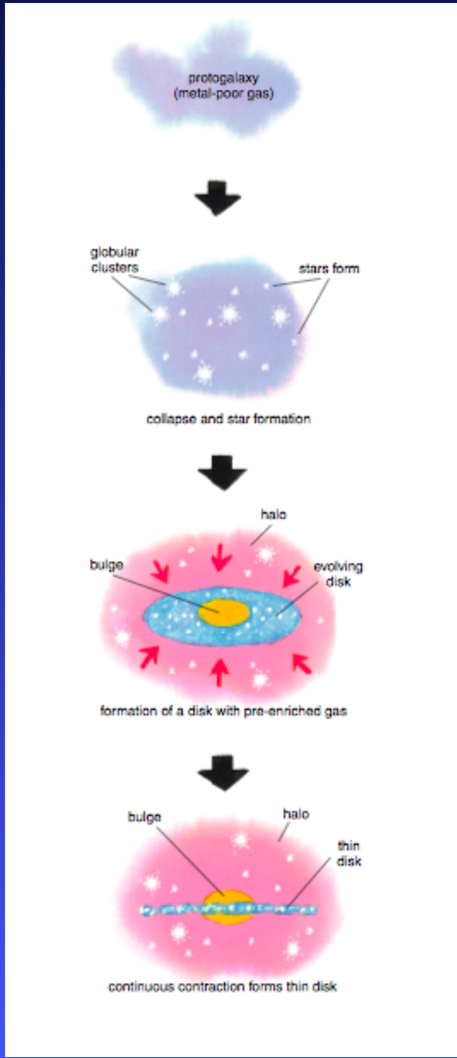




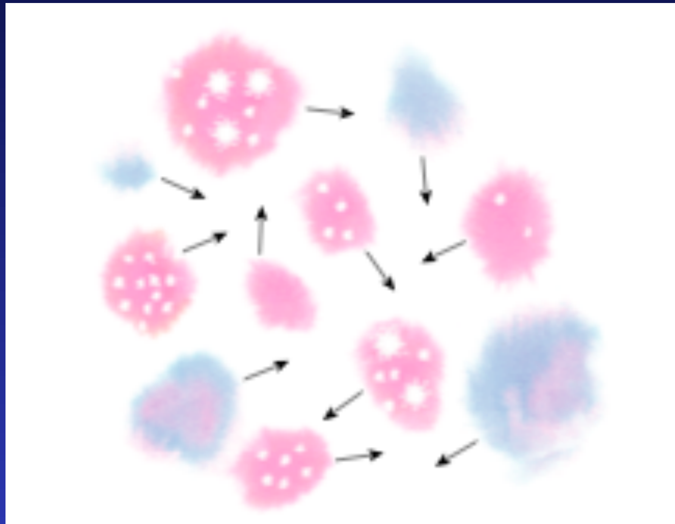
Prantzos 2007

Early ideas on the MW formation

Eggen, Lynden-bell & Sandage (1962) suggested a rapid collapse lasting 300 Myr



Searly & Zinn (1978) proposed that outer halo formed by mergers



Protogalactic fragments in various stages of evolution

New data convincingly show that the thin disk formed by slow gas accretion (Infall)

↓

Two Infall Model

(Chiappini, Matteucci, Gratton 1997)

Halo and thin-disk phases disentangled: solar vicinity did not form from halo gas but mainly from extragalactic material

Chiappini 2001, American Scientist, Issue Nov/Dec
Chiappini 2004, Sky & Telescope

Two Infall Model:

First "Infall"

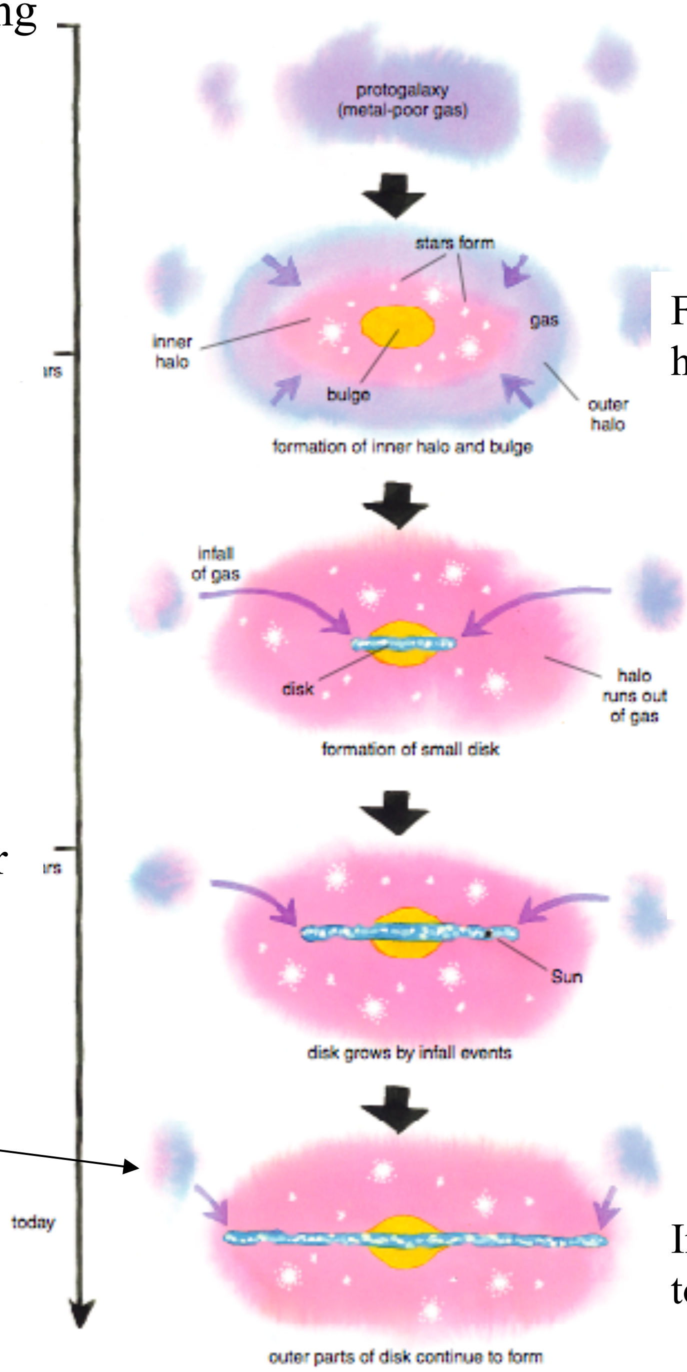
Second Infall

Present infall rate 0.2 M⊙/yr in the whole disk

Big Bang

≈1Gyr

≈9 Gyr



Protogalaxy: Metal Poor Gas

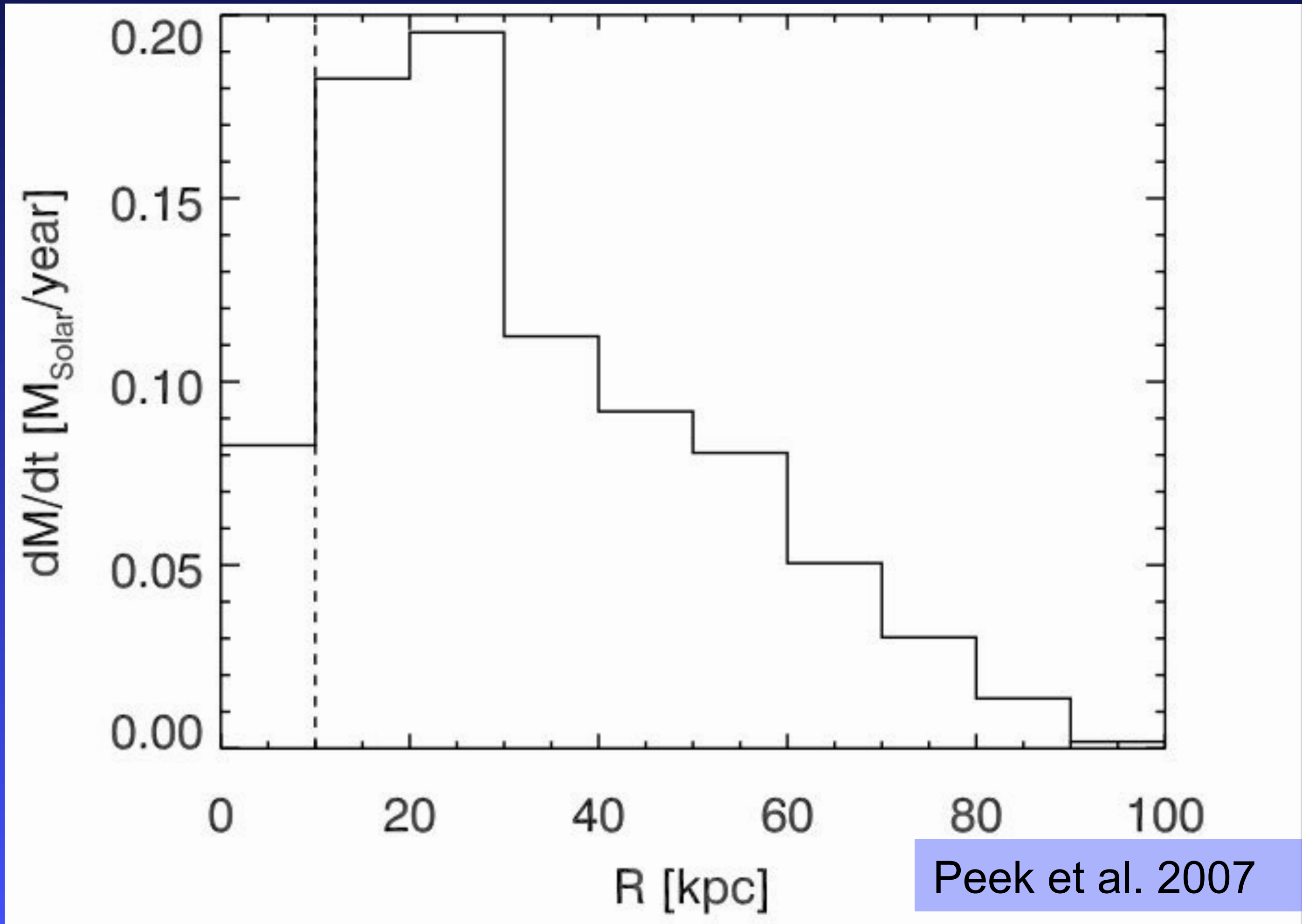
Formation of inner halo and bulge

Formation of disk

Disk grows

Infall continues to build disk

Present Accretion Rate onto the MW from condensing halo clouds: 0.2 M⊙/yr



Peek et al. 2007

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 implied a long timescale for the formation of the thin disk (Rocha-Pinto & Maciel 1996)

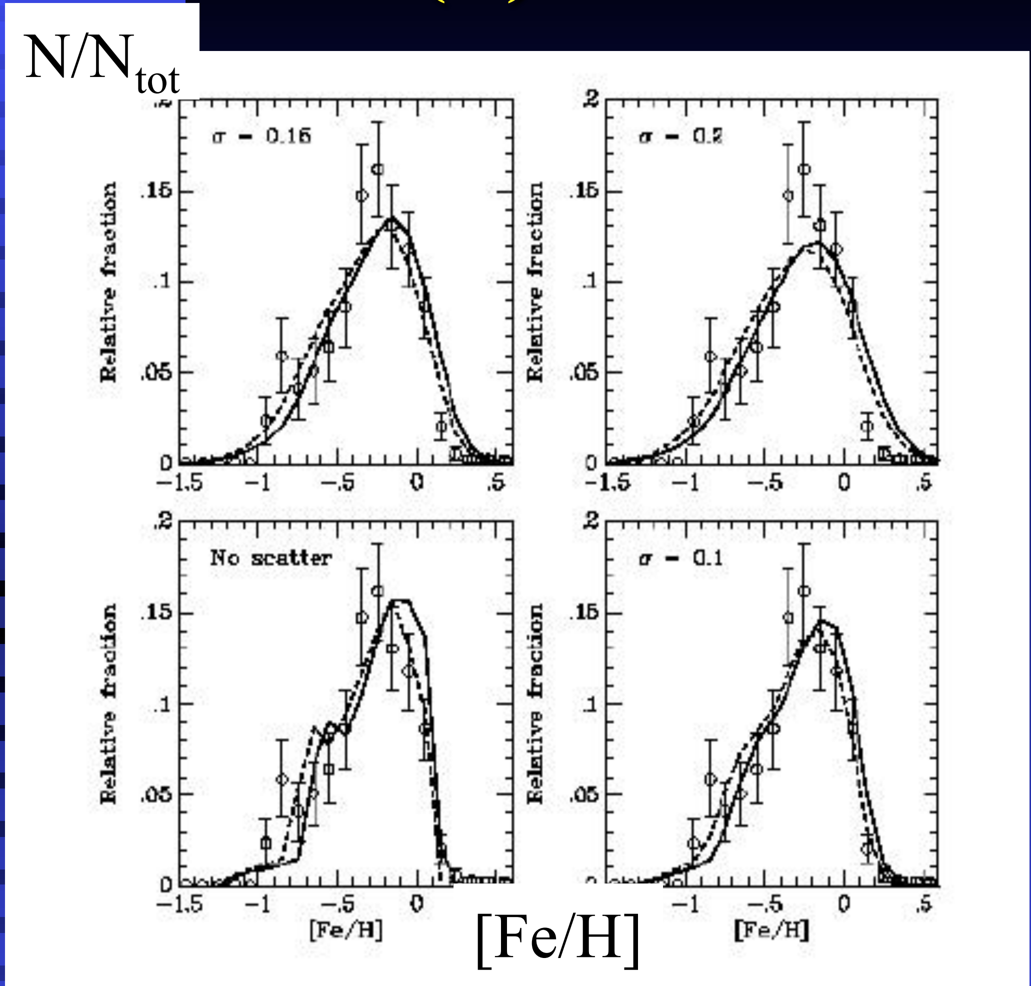
2. Halo/Thick disk vs. thin disk discontinuity in abundance ratios (Gratton et al. 1996, Fuhrmann 1998)

→ a) There is a gap in the plots
[Fe/O] vs. [O/H]
[Fe/Mg] vs. [Mg/H]

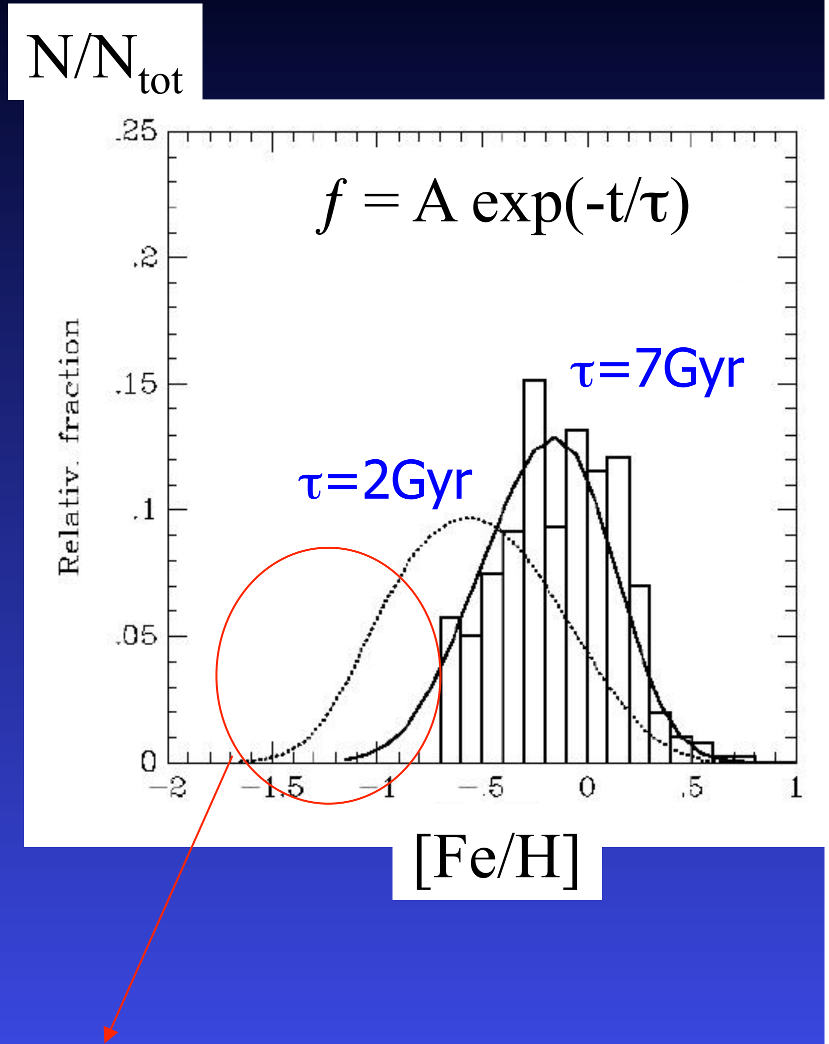
→ b) Halo and thick disk formed fast

Thin disk did not form from halo gas → Two Infalls

1. G(K)-dwarf Metallicity Distribution



Kotoneva, Flynn, Chiappini, Matteucci (2002)



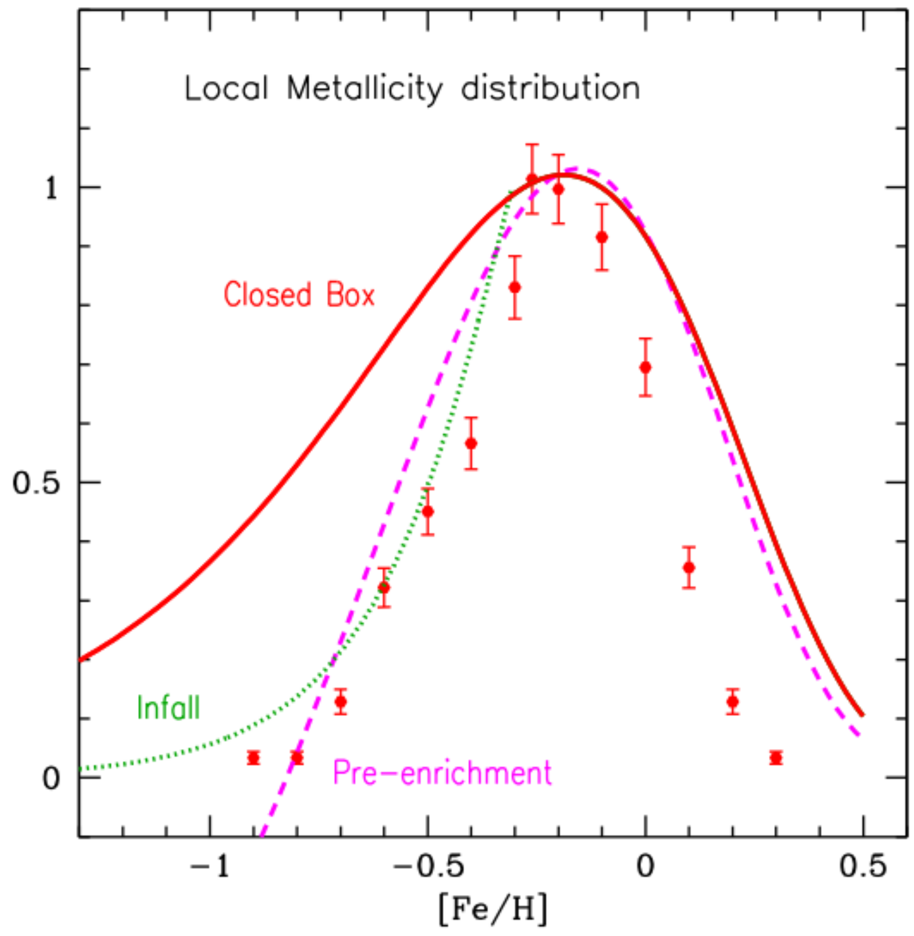
Stars with τ_m > Age of the Galaxy

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

Classical Solutions to the G-dwarf Problem:

a) pre-enrichment
b) Infall of metal poor gas

(from Prantzos 2007)

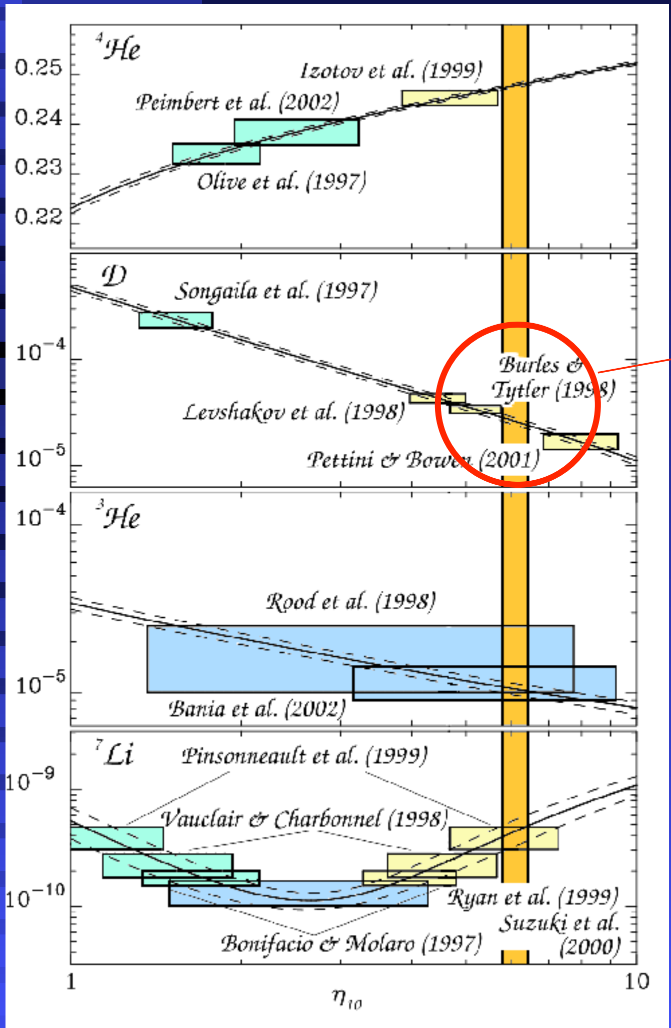


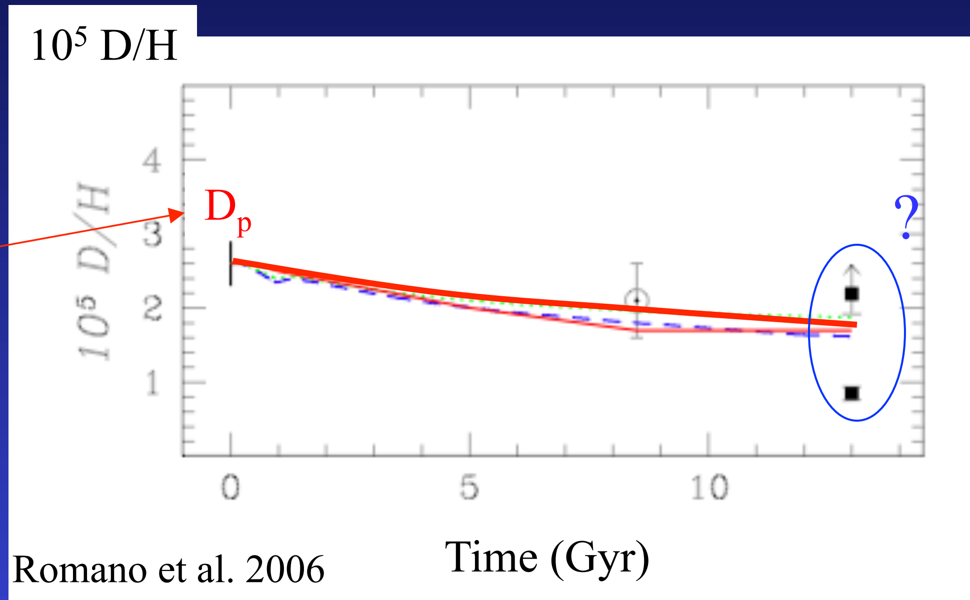
Data: Holmberg et al. 2007

The D Evolution

Deuterium destroyed in stellar interiors → Its quantity in the ISM decreases from its primordial value to the current values measured recently by FUSE

Big Bang Nucleosynthesis





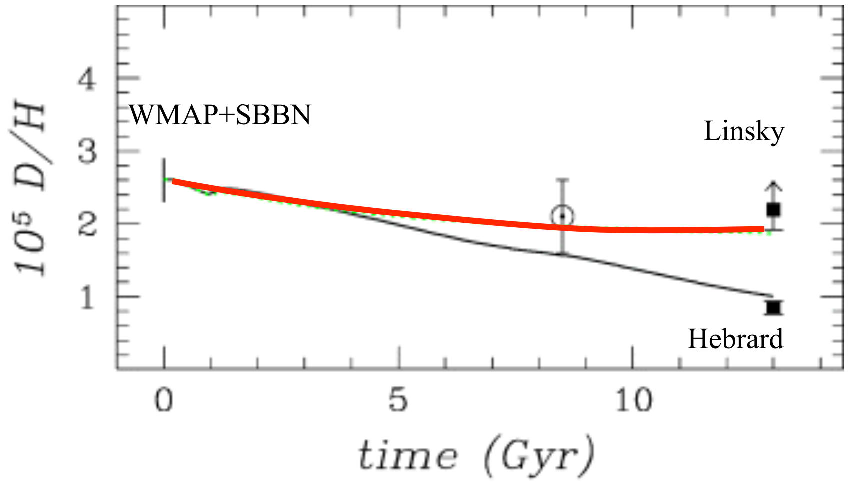
Before WMAP: Measuring primordial abundances of ^{4}He, D, ^{3}He and ^{7}Li to constrain the cosmic baryon density

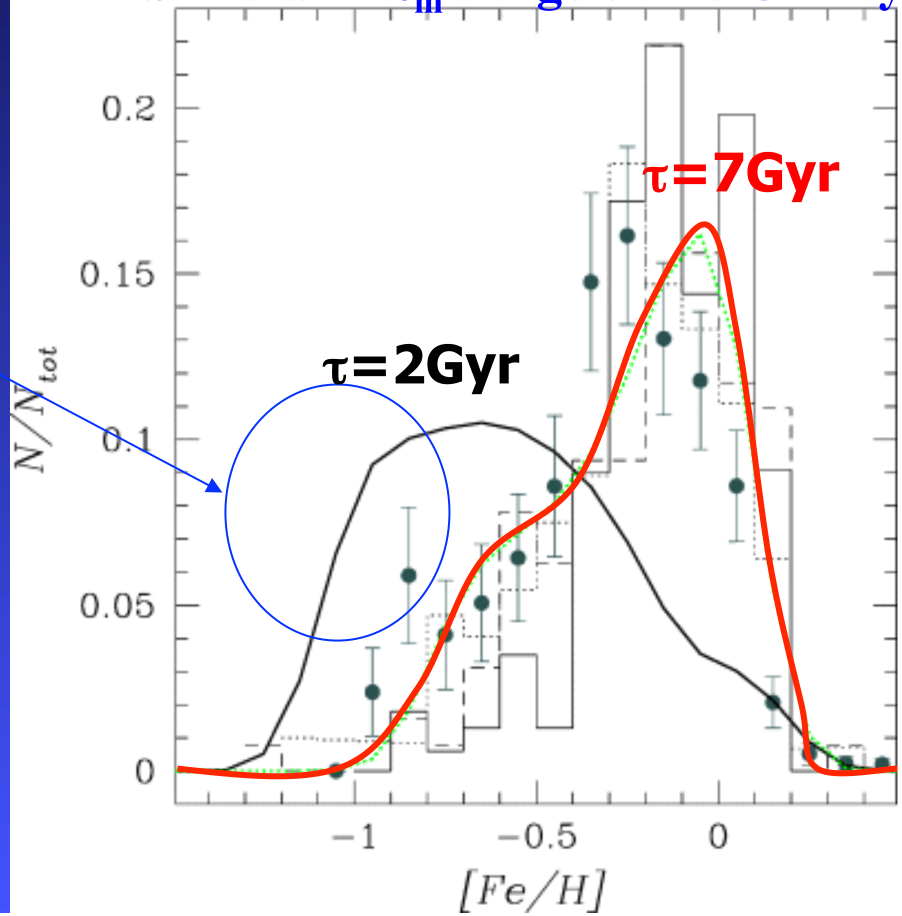
After WMAP: We know primordial abundances

Infall needed to explain D/H and the metallicity distribution of long living stars

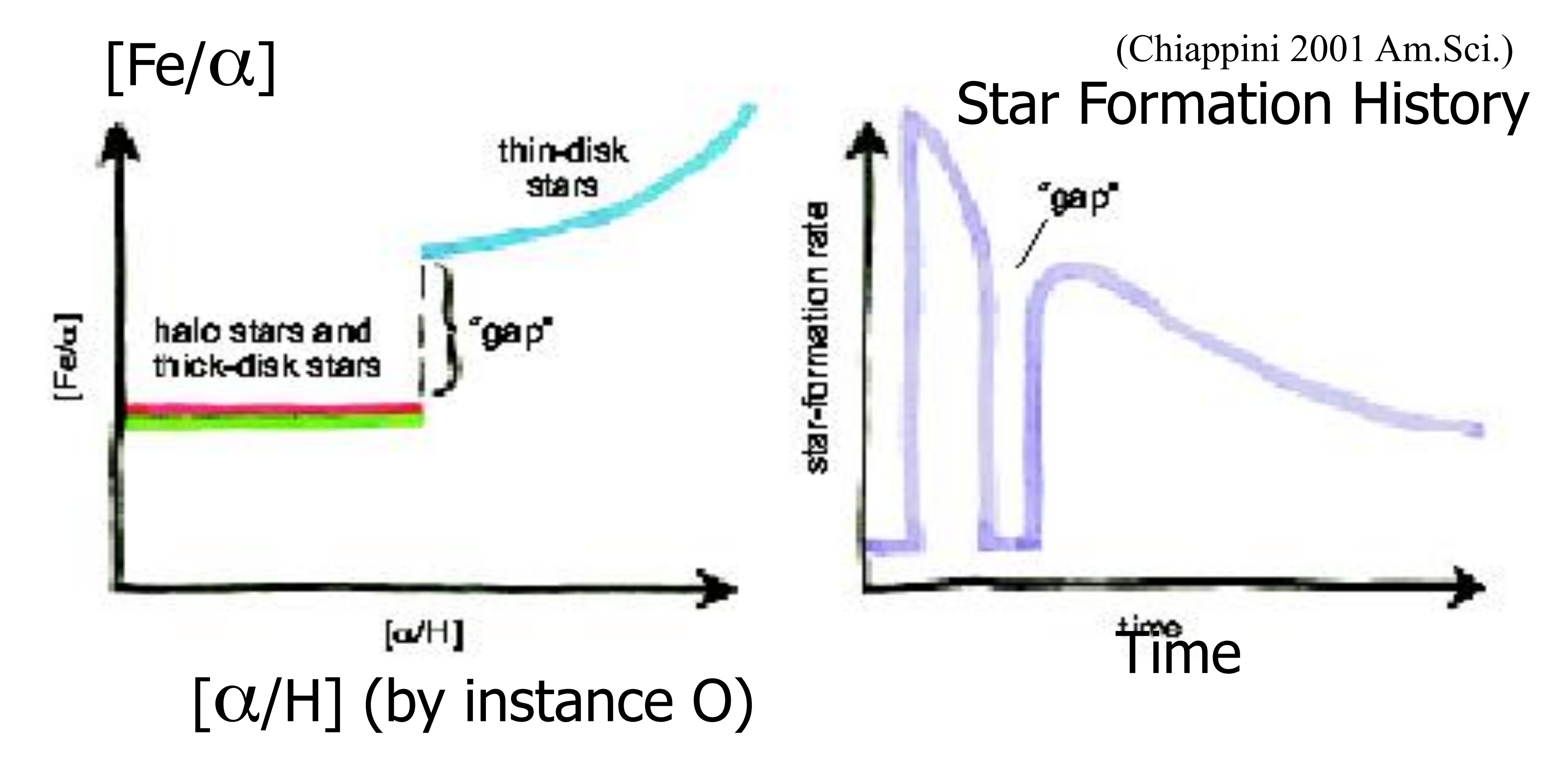
$$f = A \exp(-t/\tau)$$

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



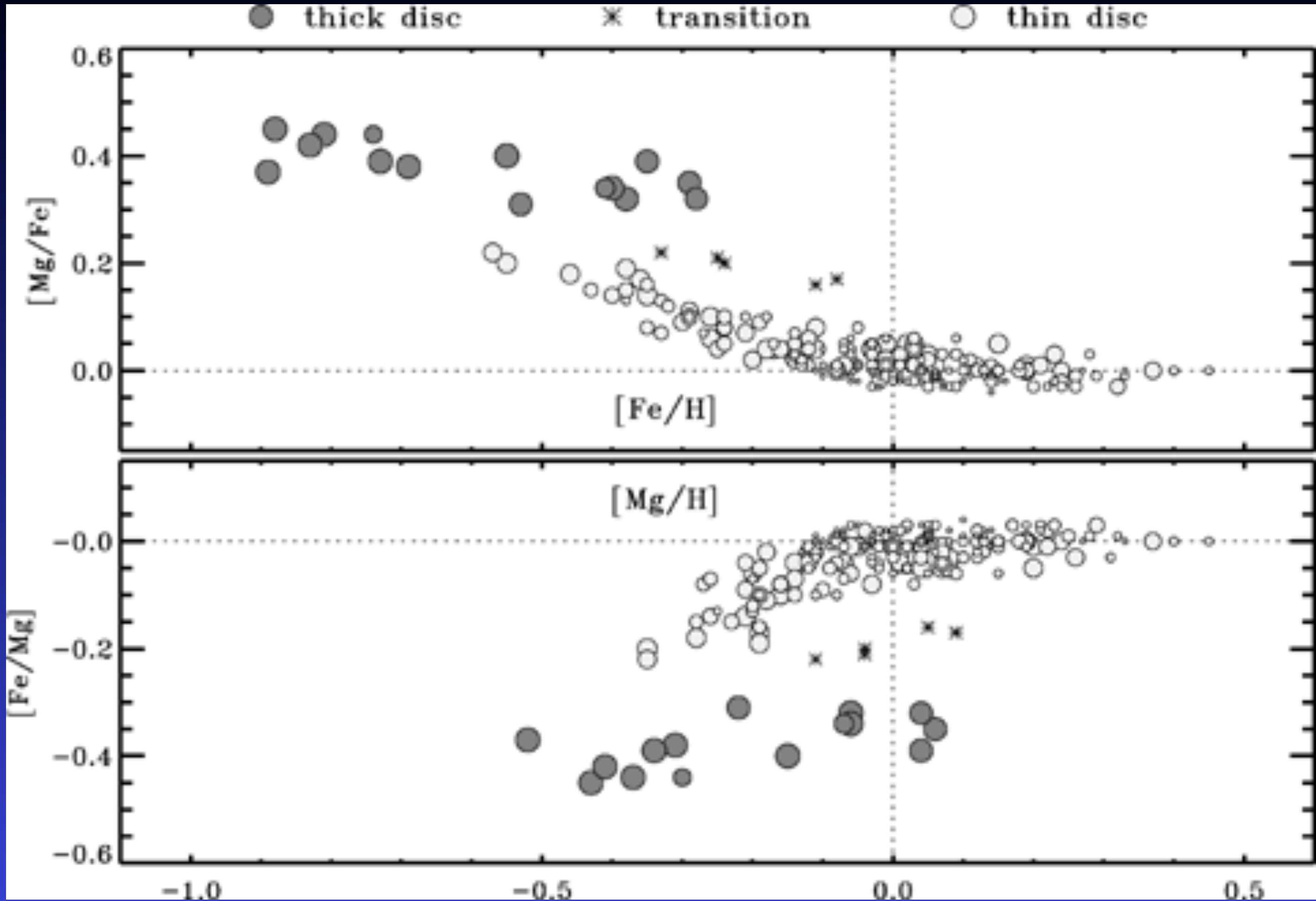


2. Discontinuity in the Abundance Ratios



This behaviour 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

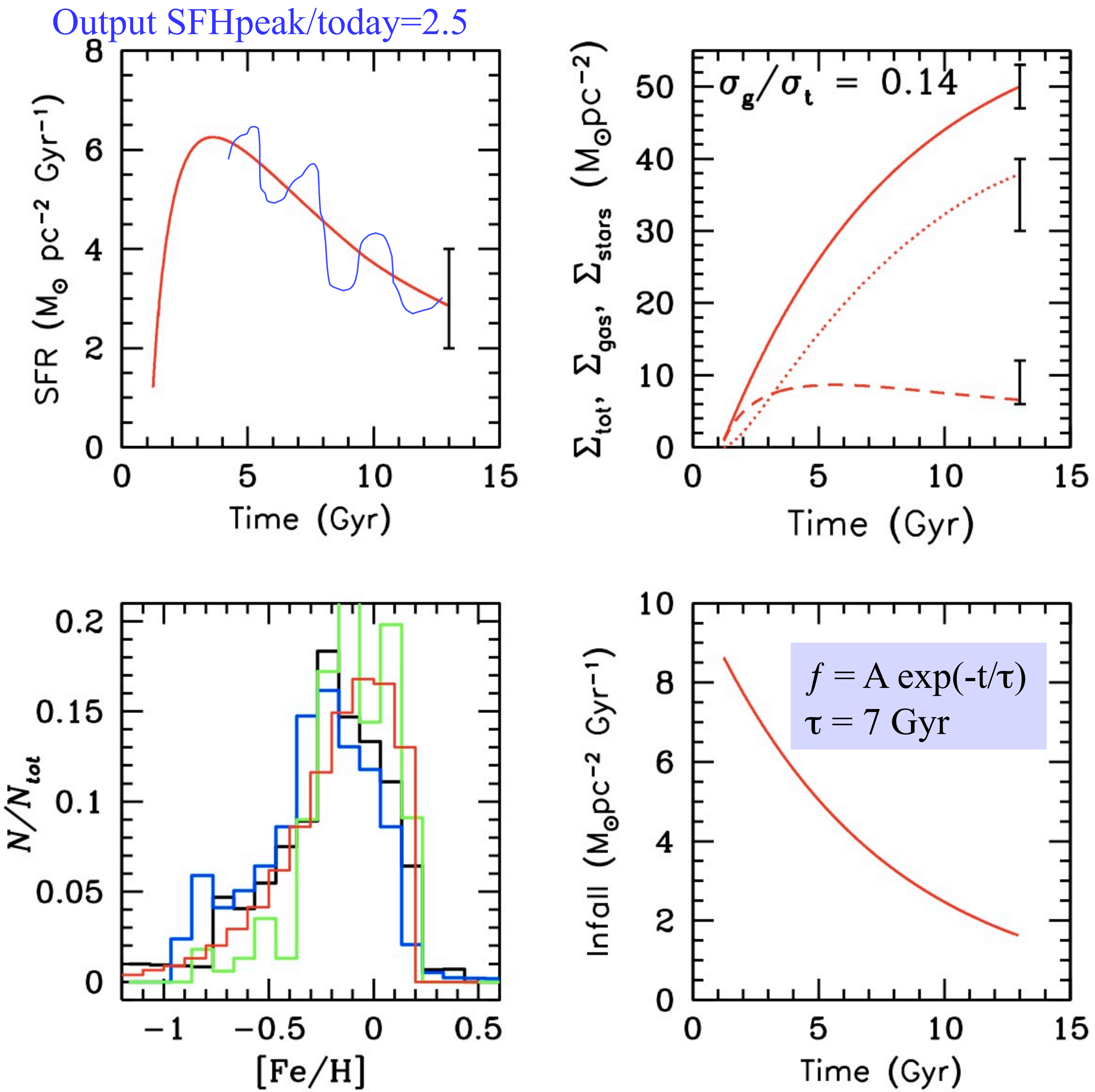


Lack of scatter (10000 lower than metallicity range!)

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)



Thin Disk

Many constraints!

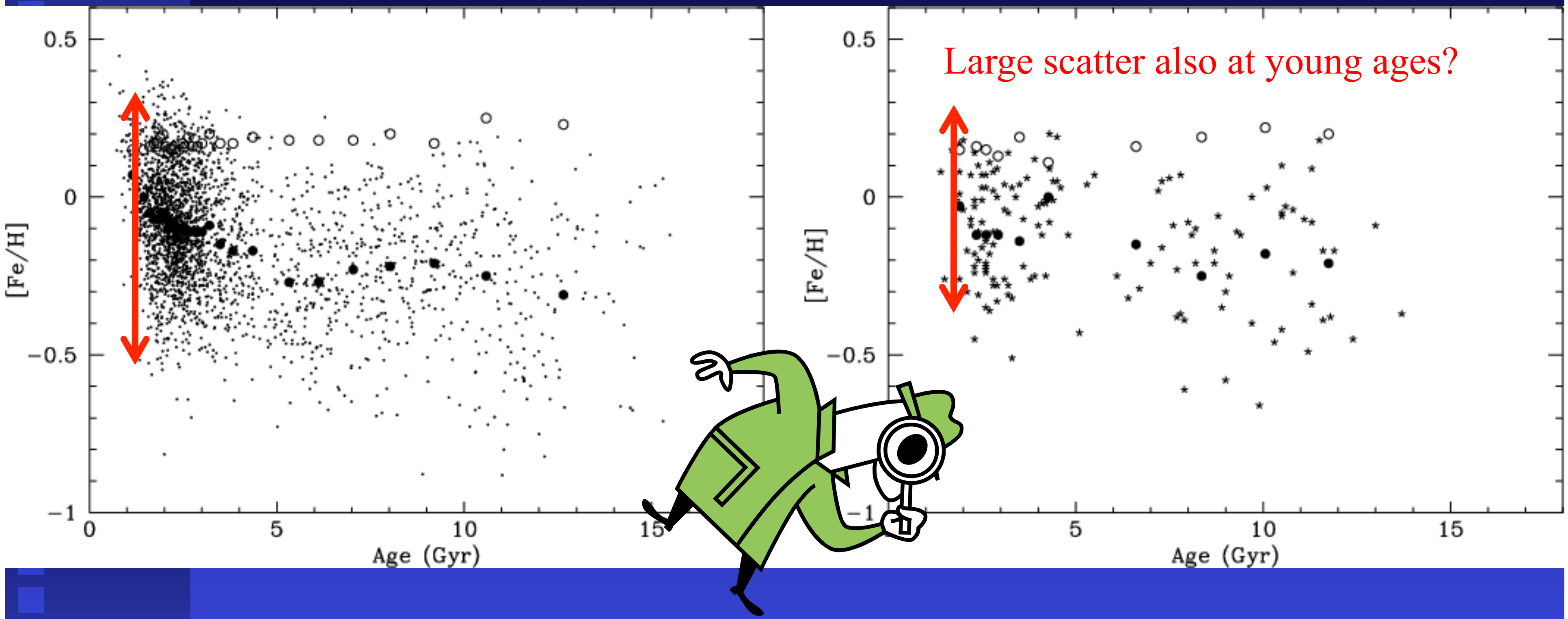
Gas, stars, total mass
MDs, AMR,
SFR today,
SN rates I and Ia,
Solar abundances,
ISM abundances,
Abundance trends of elements of different formation site

+ scatter in [X/Y] vs. [Y/H]

Timescale compatible with cosmologically motivated infall laws + needed to explain D evolution (see IAU 268)

Age-Metallicity Relation: is all the scatter real?

(Holmberg et al. 2009)



Left: AMR for single stars with error_Age < 25%.

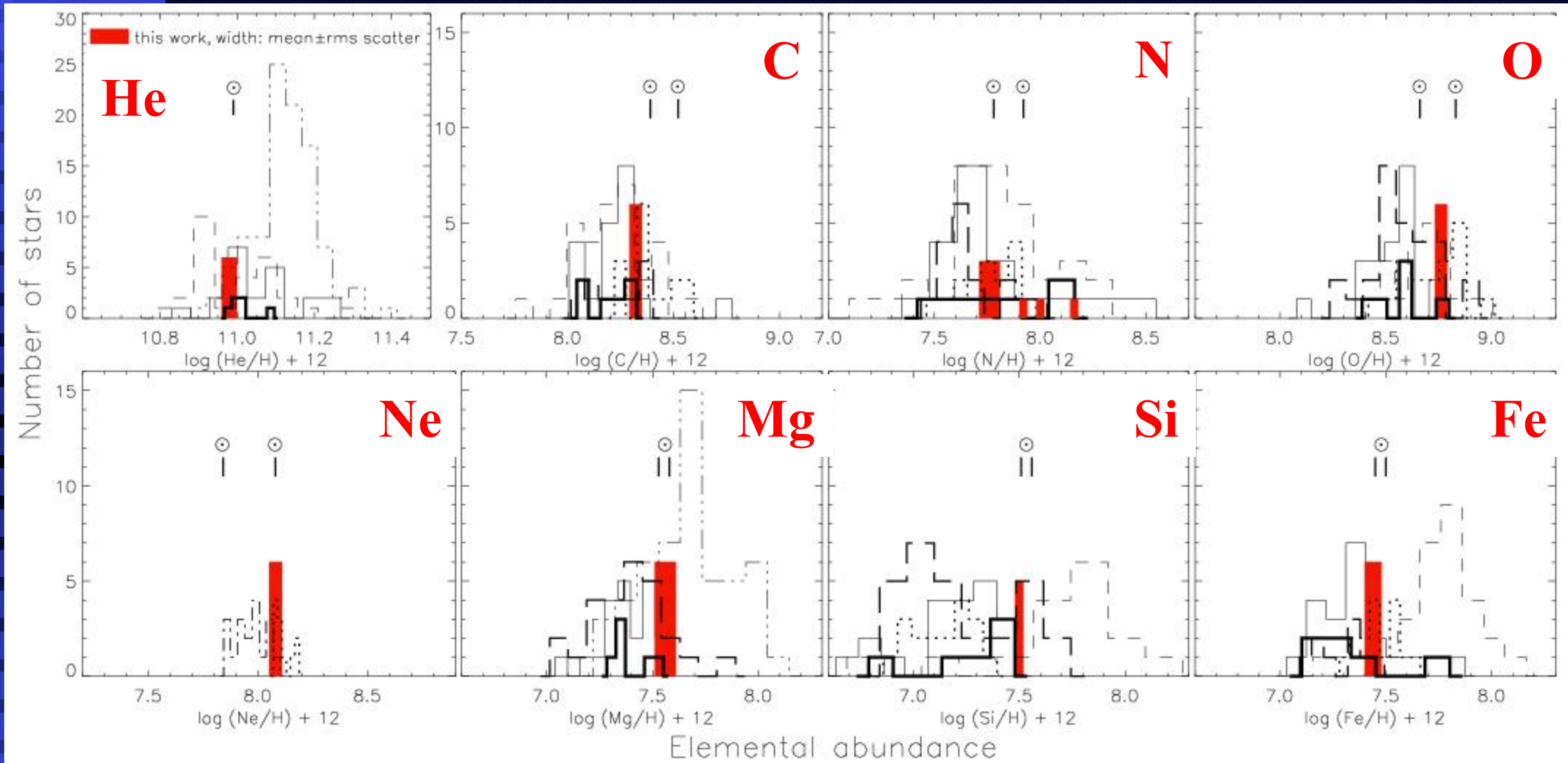
Large filled dots = mean values

Open circles = the dispersions of [Fe/H] in bins with equal numbers of stars.

Right: same, but for stars within 40 pc.

Present-Day Abundances/Solar Neighbourhood: B-Stars

Przybilla, Nieva & Butler (2008)



Improved analysis: chemical homogeneity of the solar neighbourhood

Cosmic abundance standard

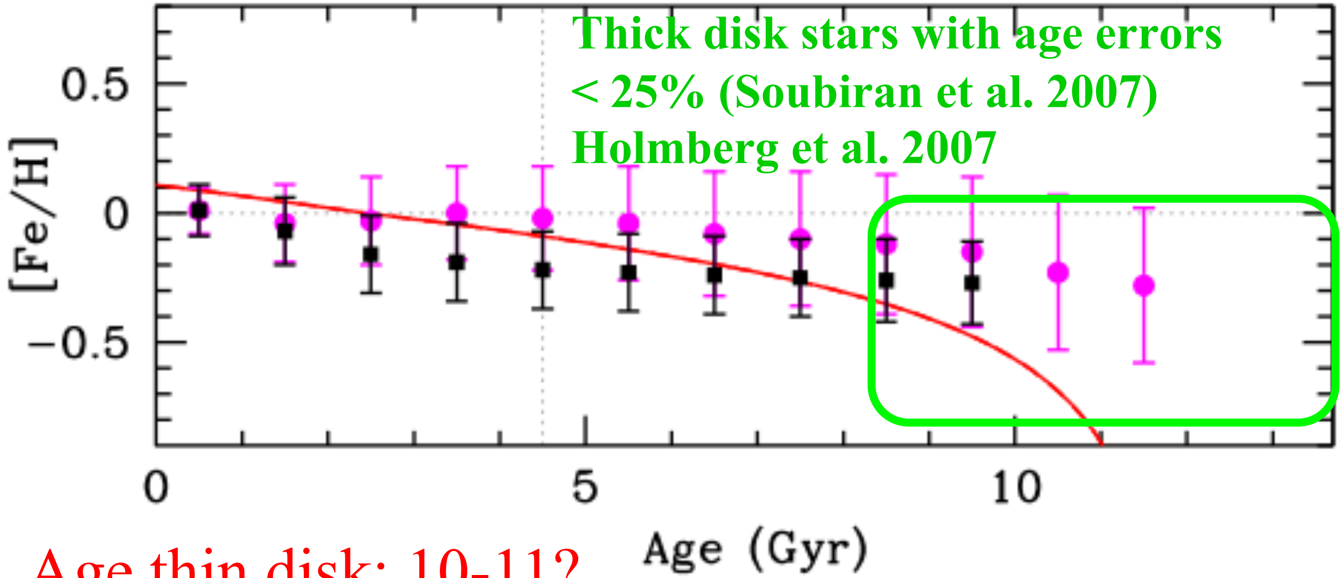
X=0.715 Y=0.271 **Z=0.014**

Friedrich-Alexander-Universität Erlangen-Nürnberg

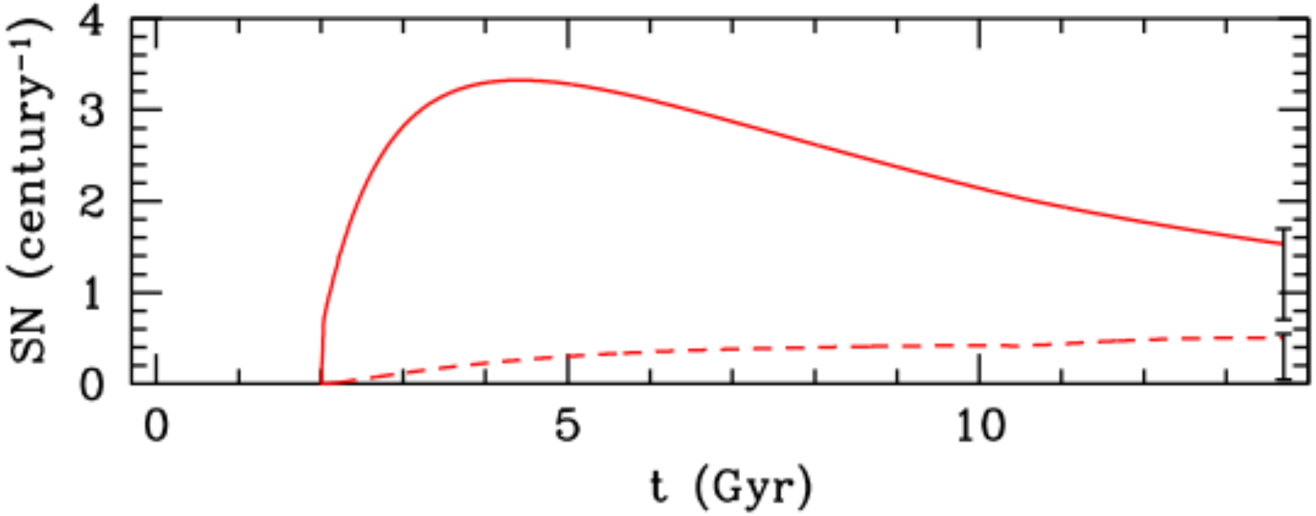
Age-Metallicity Relation

Soubiran et al. 2007: clump stars

da Silva et al. 2006: giants



Age thin disk: 10-11?

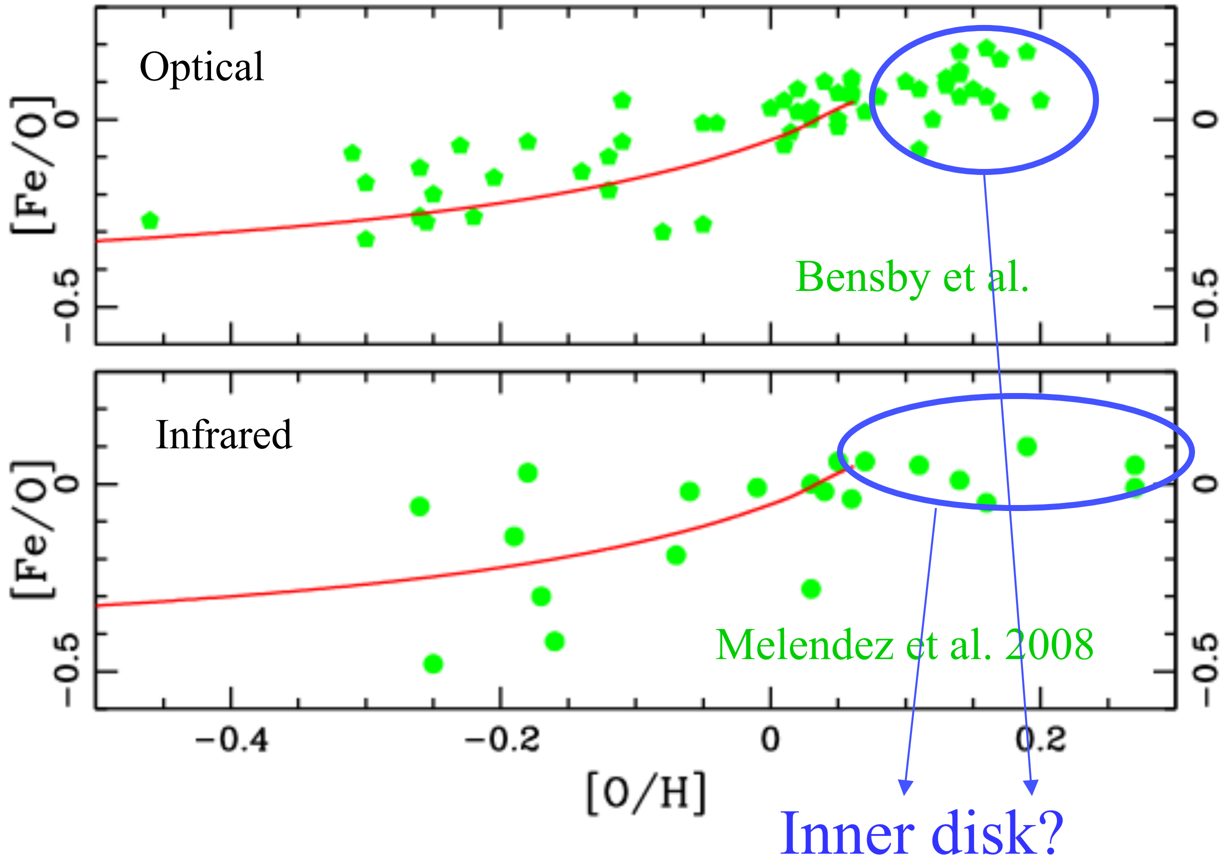


Observations Flatter than models?

Large age uncertainties (especially age > 5 Gyr)

Old ages: mixing with old metal rich stars from inner disk/ bulge + thick disk stars.

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	



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

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

Summary Thin disk

- The long timescale for the thin disk formation: necessary to fit not only the K/G-dwarf MD but also by the solar/present D abundance

- CE models ensuring fit of several INDEPENDENT constraints imply that the SFR has been slowly declining in the last 5 Gyrs.

- However, the "Local" thin disk samples seem to be contaminated by stars coming from inner regions pointing to stellar mixing in the thin disk