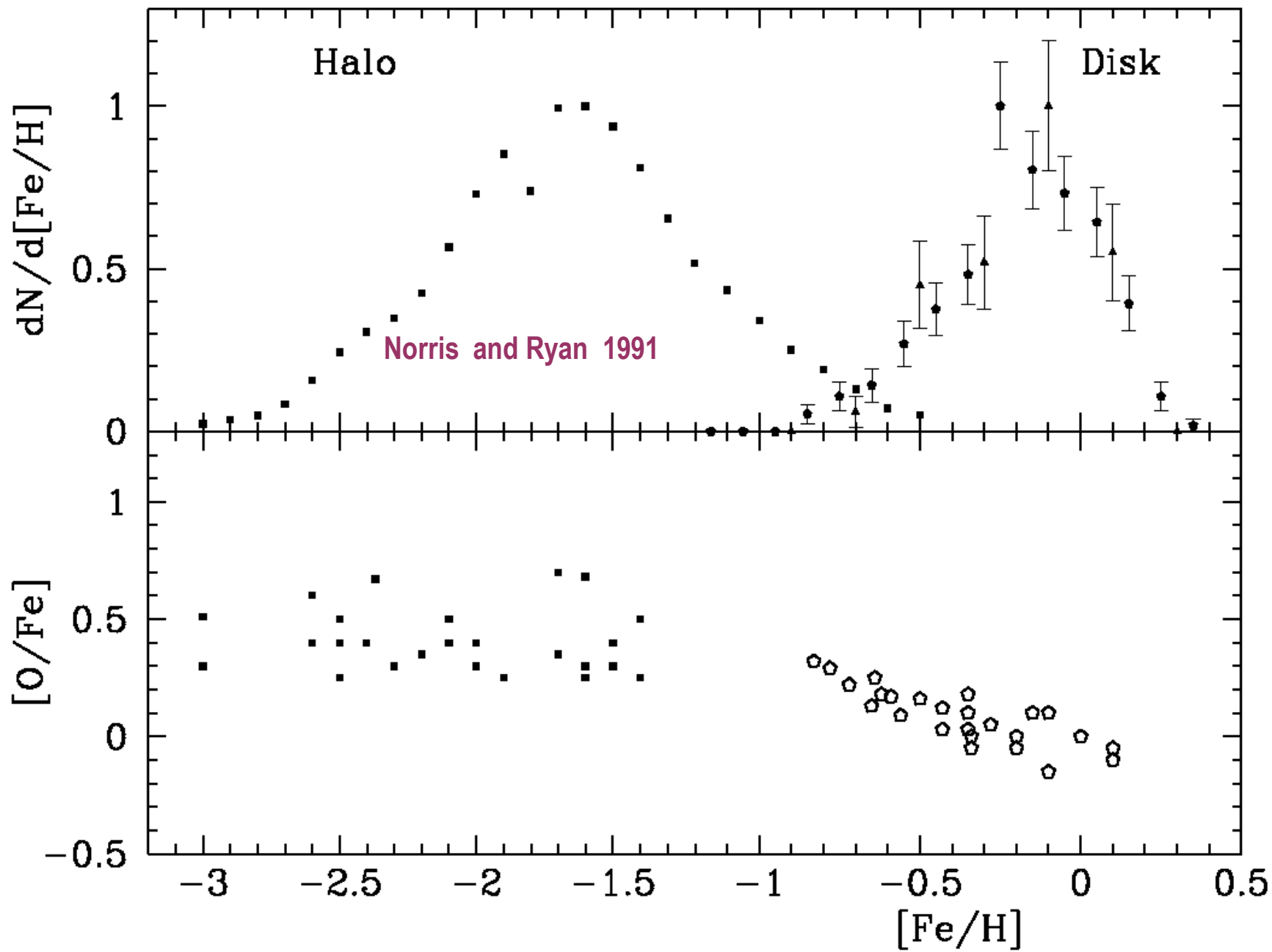
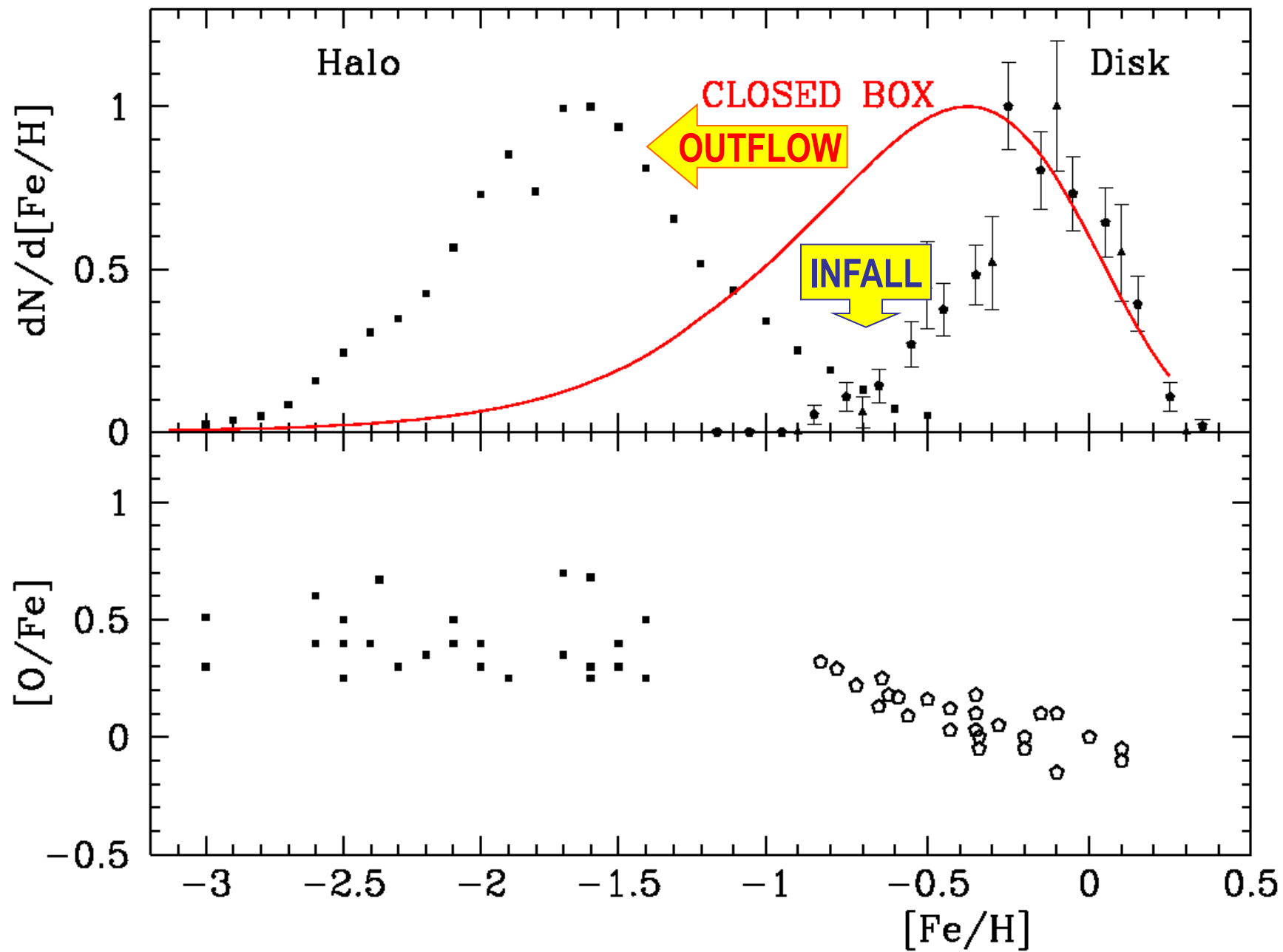


GALACTIC CHEMICAL EVOLUTION

Part IV : Dwarf spheroidals and the halo metallicity distribution





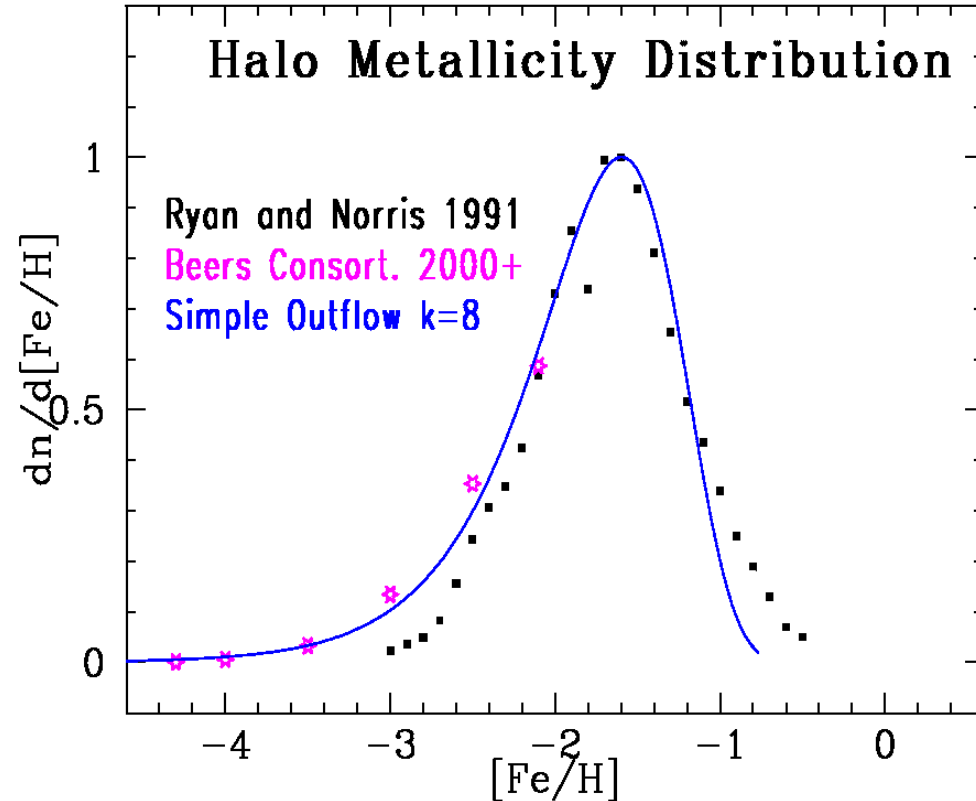
The MW Halo Metallicity Distribution (HMD)

The observed metallicity distribution (MD) of field halo stars is characterized by:

1) A peak at $[Fe/H] = -1.6$ implying a reduced effective yield

$$p_{EFF} \sim p_0/9$$

most easily interpreted in a Simple model with Outflow rate = 8 SFR (Hartwick 1975)



In a simple model with Outflow rate = k SFR :

$$X = p \frac{1-R}{1+k-R} \ln(1/\sigma)$$

$$p_{Eff} = p \frac{1-R}{1+k-R}$$

2) A very smooth shape; is it compatible with the formation of the Halo from hierarchical merging plus tidal disruption of many small fragments ?

Formation of a disk galaxy in the Cold Dark Matter (CDM) scenario of hierarchical merging

M. Steinmetz



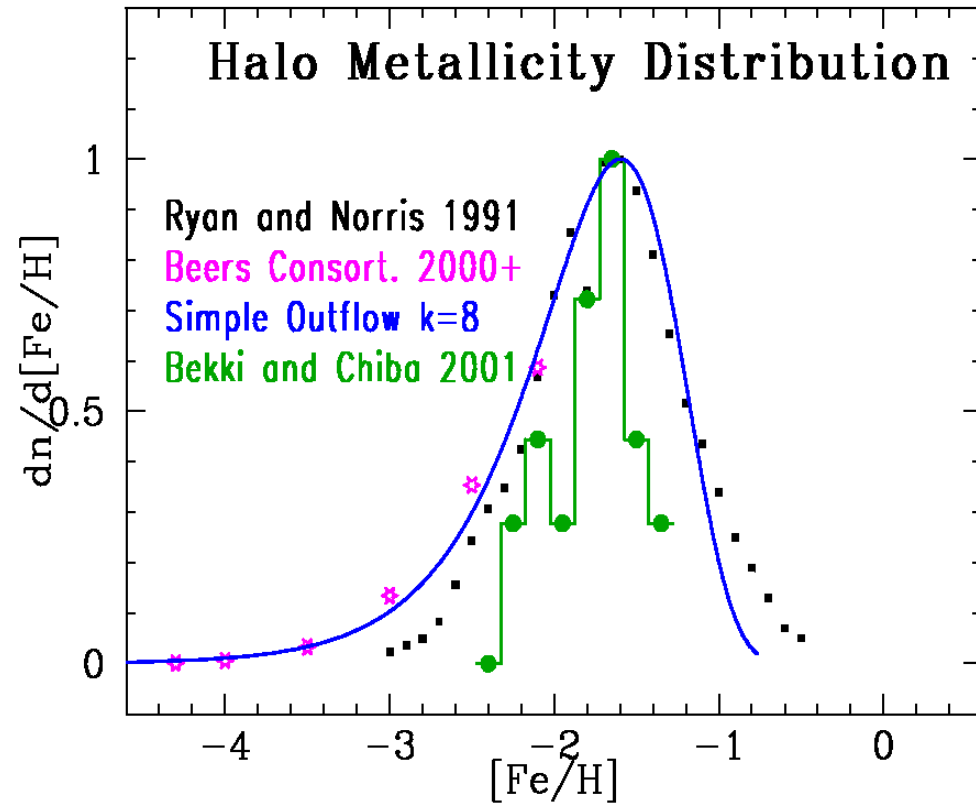
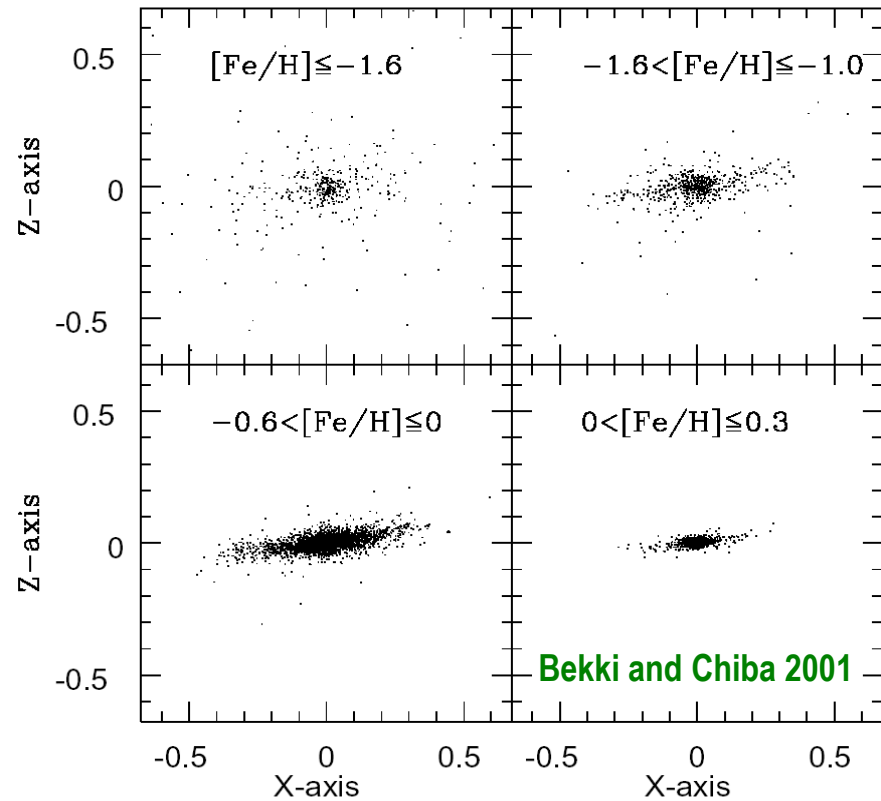
$z: 49.5$

Face on

Edge on

Dark matter properly treated (just gravity) but baryonic physics (star-gas feedback) is poorly understood

The MW Halo Metallicity Distribution (HMD)



Early dynamical models of Halo formation in CDM scenario reproduce the peak (reduced yield) of the observed Z-distribution, but it is not clear why...

A reduced effective yield is obtained due to mass loss, not through feedback from SN, but through tidal disruption of mergers

The shape and smoothness of the observed Z-distribution are not reproduced

Is it a generic feature of the scenario (e.g. last merger of two major subsystems), or is it due to insufficient numerical resolution?

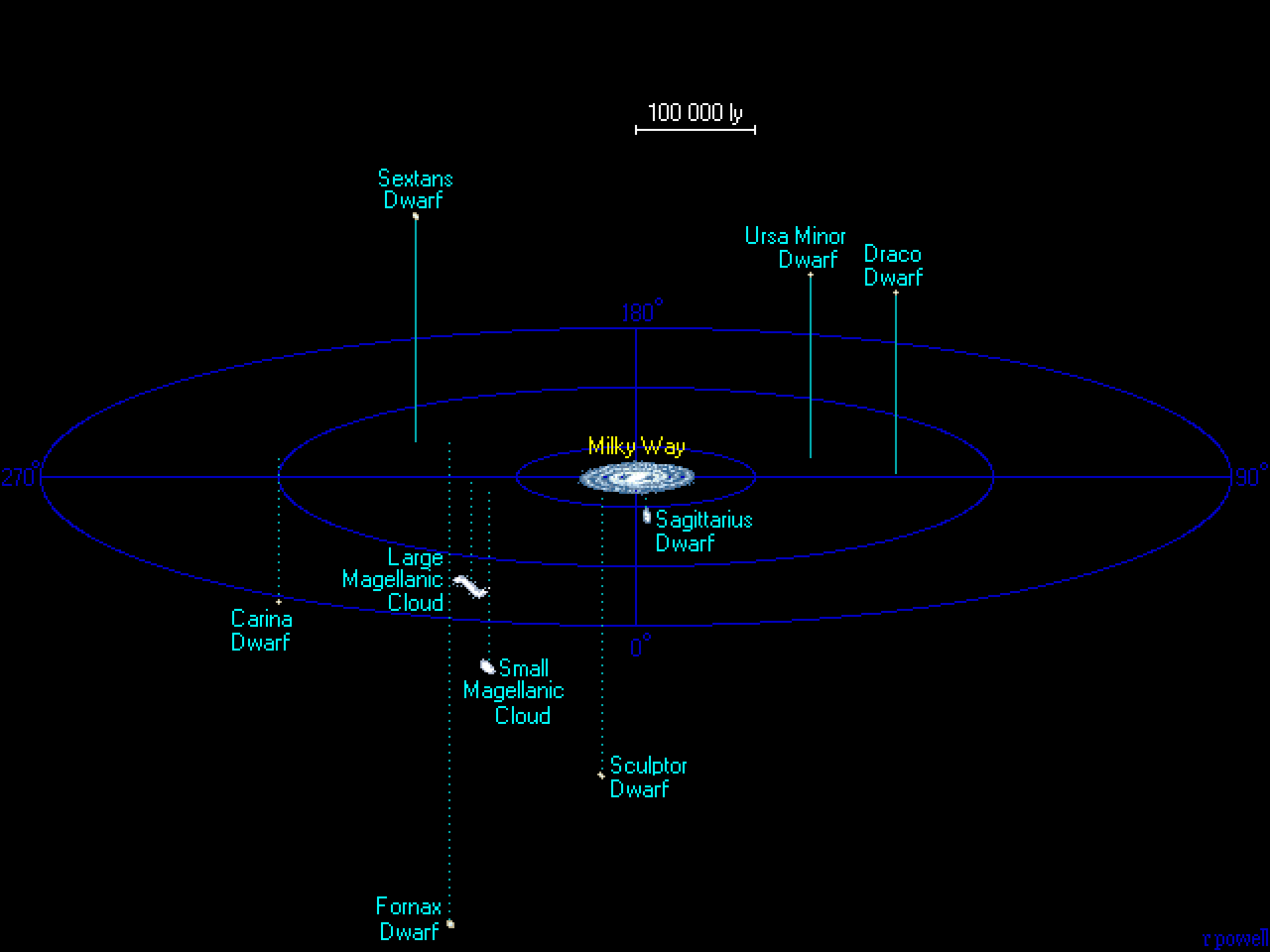
Ingredients required to evaluate the halo MD as a sum of MDs of sub-haloes in the hierarchical merging paradigm :

1) Shape of sub-halo MD

2) Dependence of sub-halo MD on sub-halo mass

3) Baryon mass distribution of sub-haloes

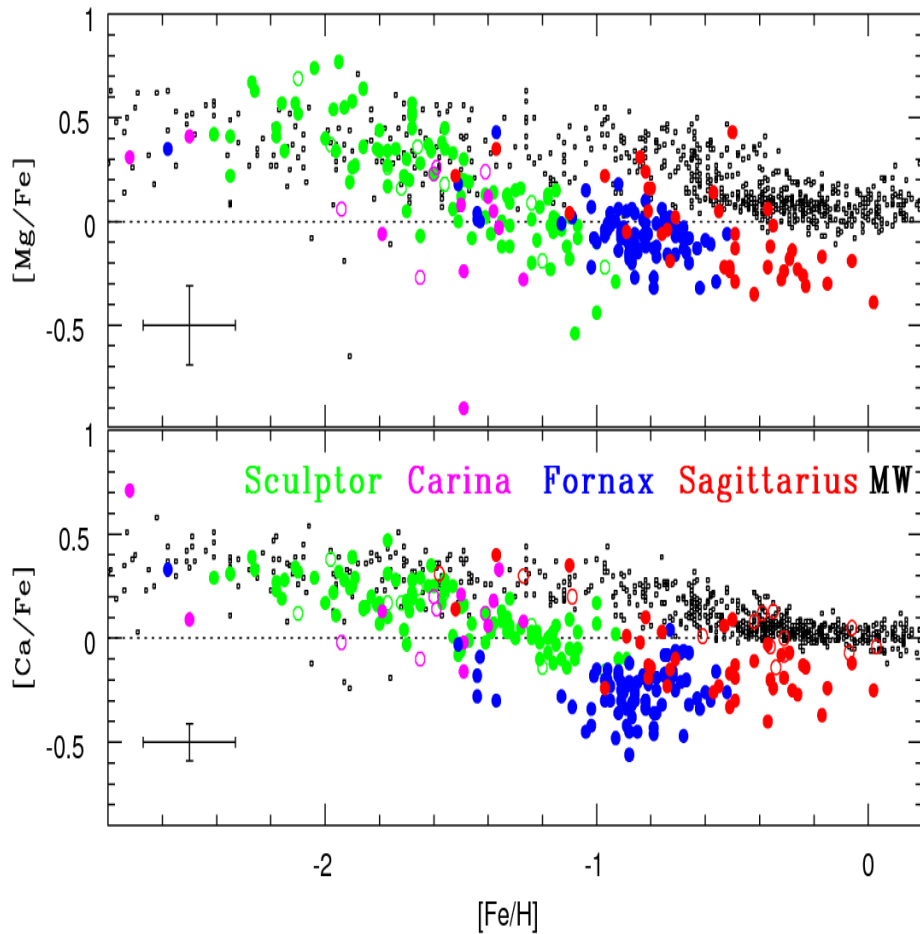
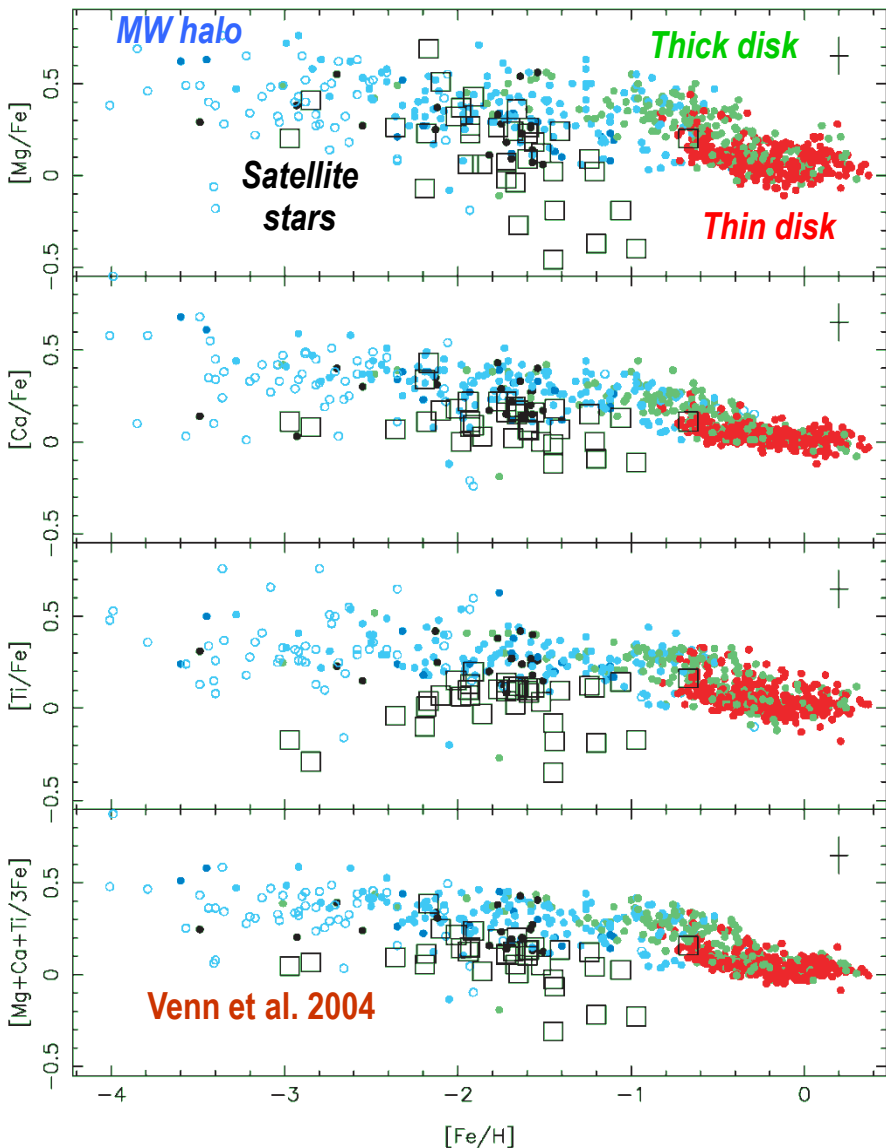
**For the former two ingredients,
one may get inspiration by observations
of nearby dwarf galaxies (satellites of Milky Way)**

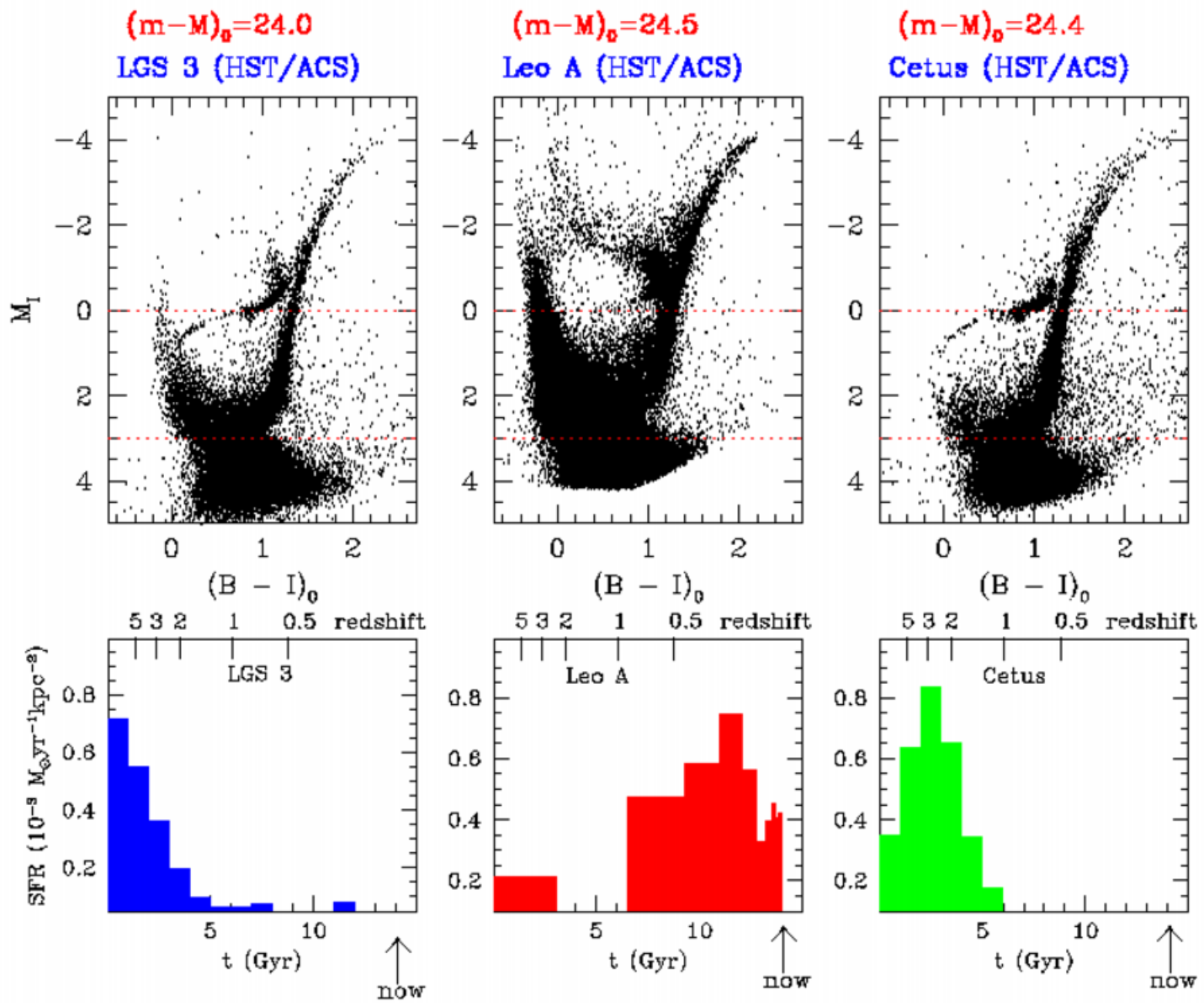


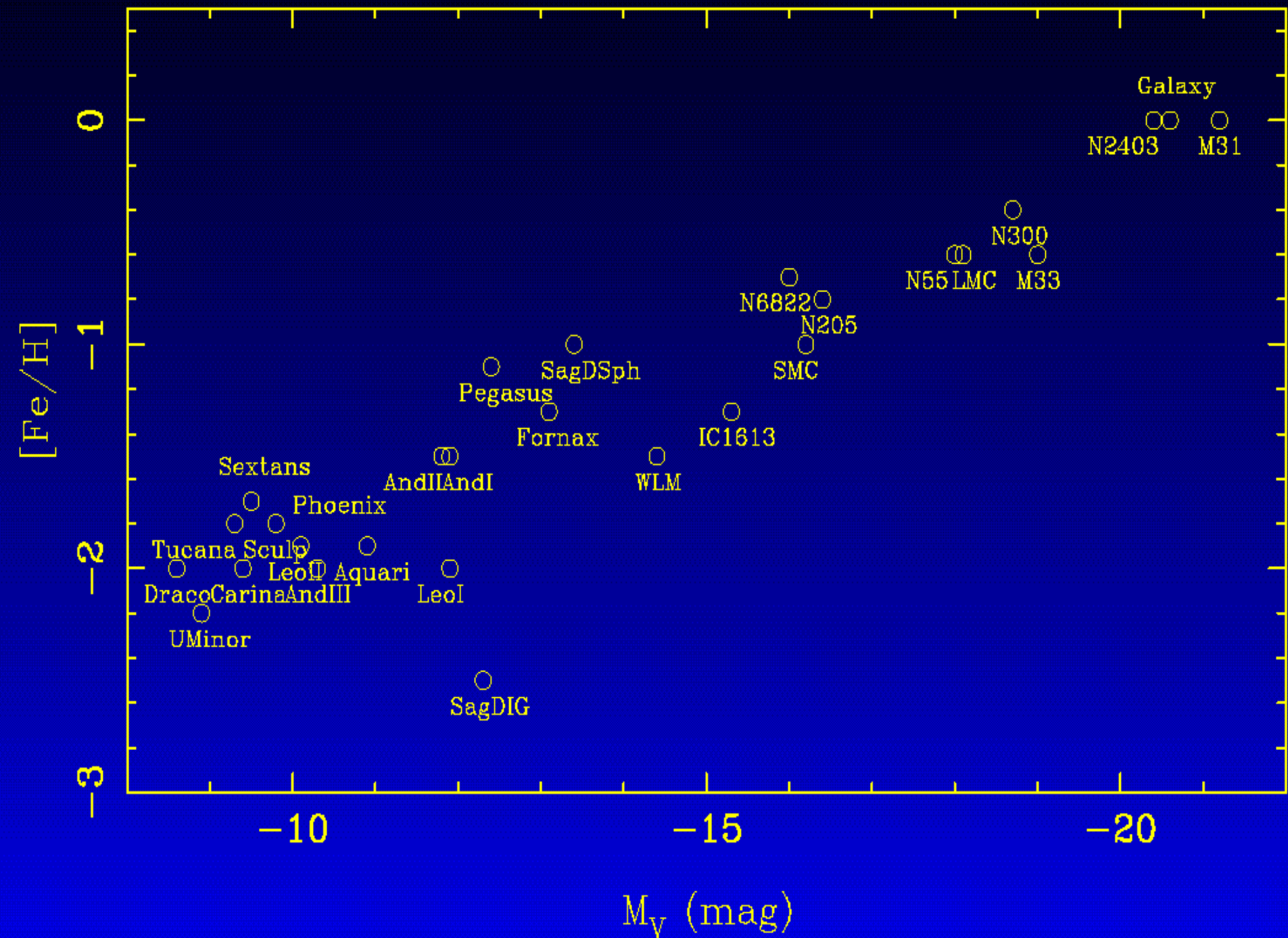
**Present day dwarf satellites of MW
cannot be the building blocks
of MW halo
(abundance ratios: Fe from SNIa)**

**The building blocks (sub-haloes)
of MW halo must have evolved
UNAFFECTED by SNIa ejecta
[short timescales (< 1 Gyr)**

**(alternatively, SNIa ejecta
preferentially lost from those systems)**







The MDs of dSph satellites
of the MW

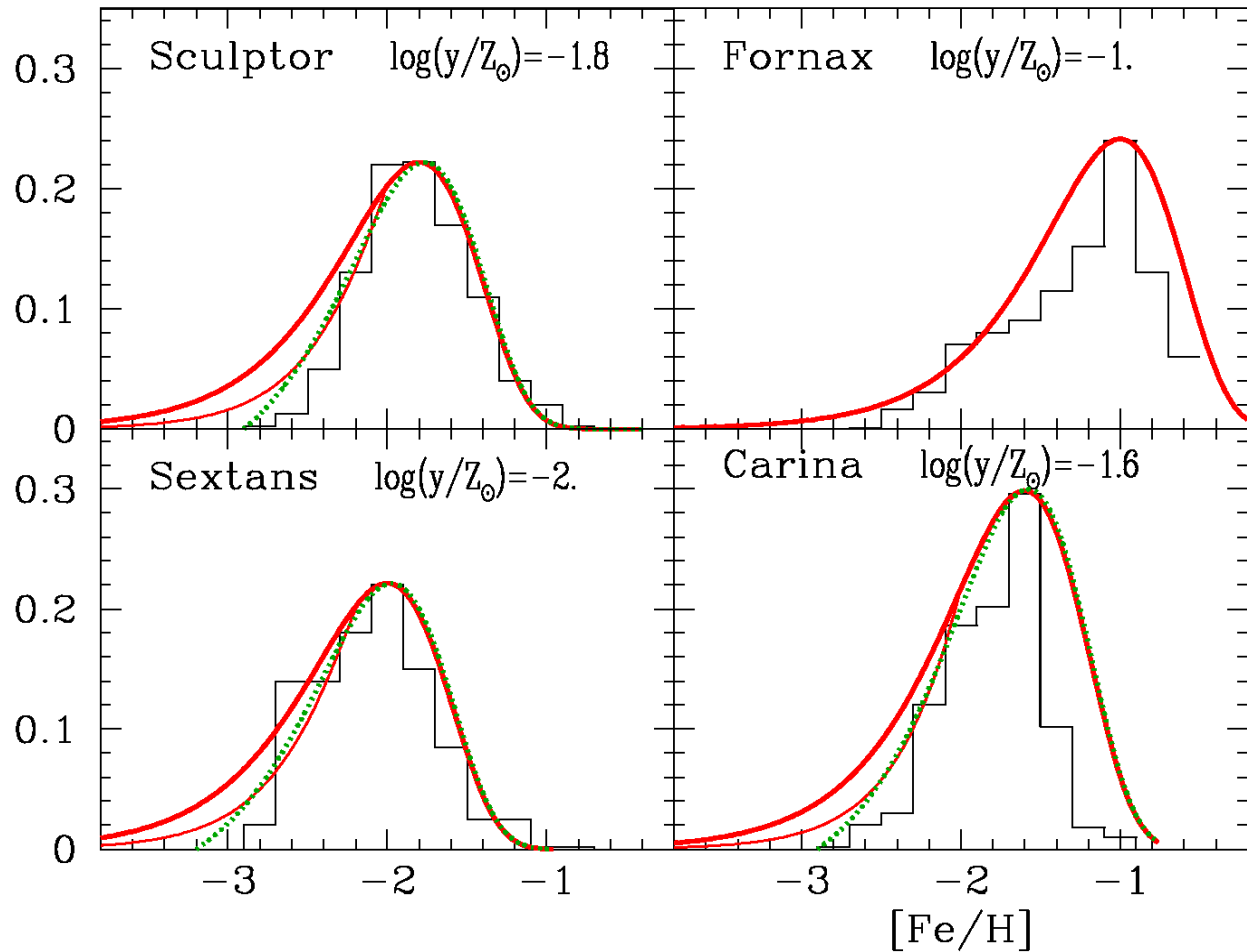
can be well described by the
simple model with outflow

AND either

- pre-enrichment
(*Helmi et al. 2006*)

- early infall
(*Prantzos 2007*)

- both
(*Salvadori et al. 2008*)



—

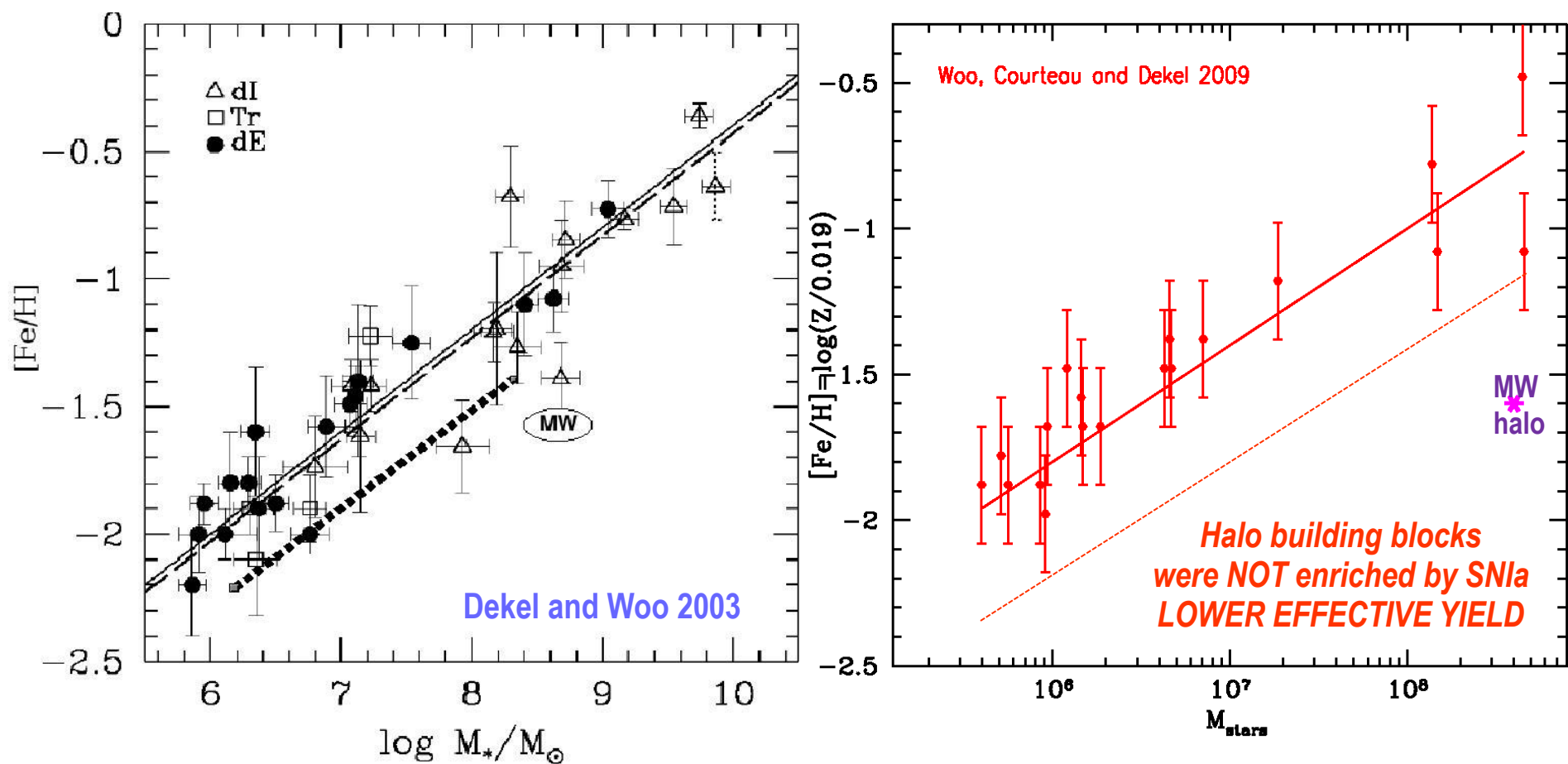
Simple model with Outflow

—

Simple model with Outflow + a phase of Early Infall

⋯

Simple model with Outflow + initial [Fe/H] = -3



Local dwarf spheroidals today display a *Mass - (stellar) metallicity* relationship which may be explained by SN feedback, inducing stronger mass loss in less massive galaxies (Dekel and Silk 1985, Dekel and Woo 2003) and resulting in a *reduced effective yield*

$$p_{eff}(M) = p_0 \frac{1-R}{1-R+k(M)} \quad \text{Assuming that } \text{Outflow rate} = k(M) * \text{SFR}$$

N. B. The Milky Way halo (considered as a single entity) is found BELOW that relationship (steeper IMF, OR abnormally high mass loss for its mass, OR... ???)

Ingredients required to evaluate the halo MD as a sum of MDs of sub-haloes in the hierarchical merging paradigm :

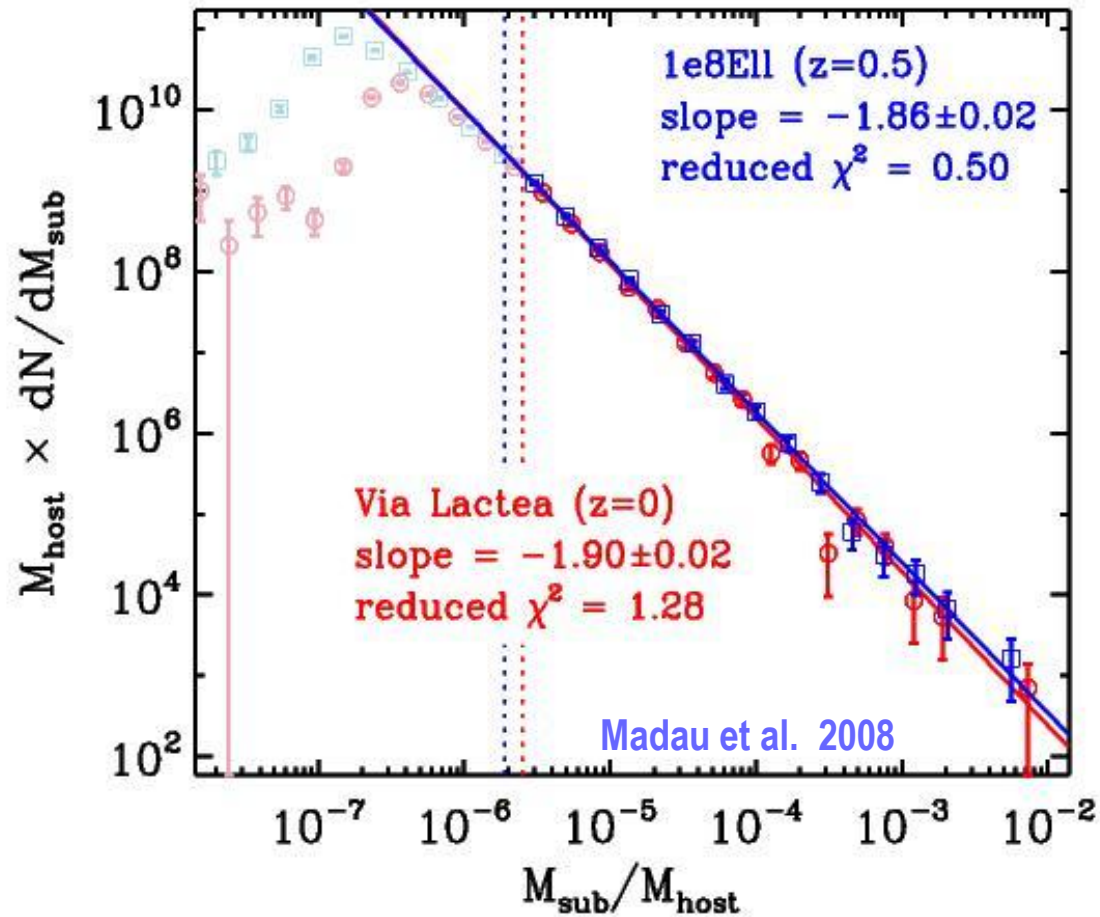
1) Shape of sub-halo MD

2) Dependence of sub-halo MD on sub-halo mass

3) Baryon mass distribution of sub-haloes

**For the former two ingredients,
one may get inspiration by observations
of nearby dwarf galaxies (satellites of Milky Way)**

For the latter: results of numerical simulations



Dark halo distribution function

Simulations find that for the dark matter sub-haloes

$$dN/dM \propto M^{-1.9}$$

(Diemand et al. 2006, Madau et al. 2008)

Properties of toy-model stellar subhaloes

But lower mass sub-haloes are preferentially affected by outflow, and the baryonic mass distribution of sub-haloes will be flatter than the one of dark matter (*Prantzos 2008*)

$$\frac{dN}{dM_*} \propto M_*^{-1.2}$$

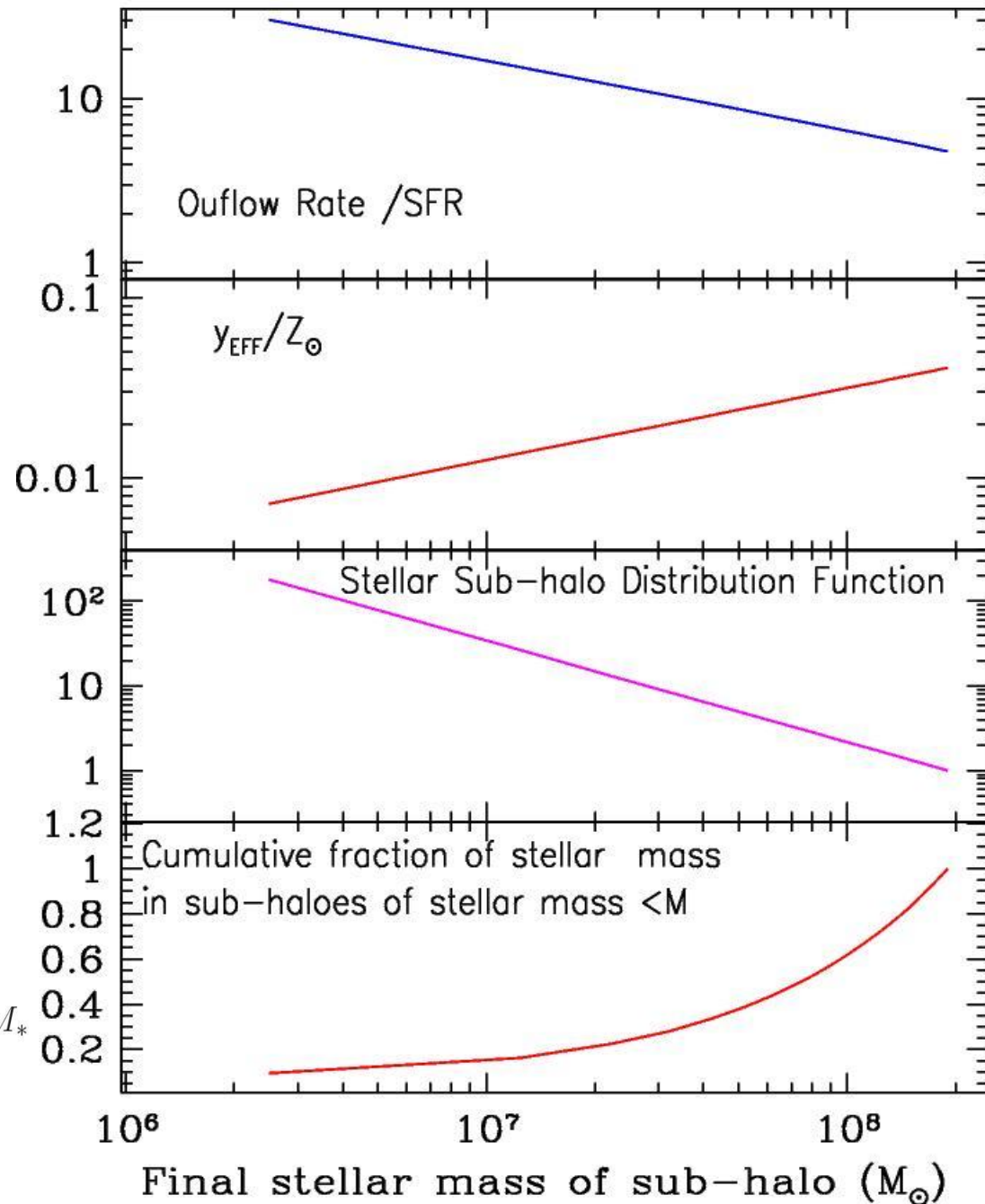
Normalization: Total halo mass

$$M_{*Halos} = 4 \cdot 10^8 M_{\odot} \text{ (Bell et al. 2007)}$$

$$M_{*Halos} = \int_{M_1}^{M_2} \frac{dN}{dM_*} M_* dM_*$$

Metallicity distribution of halo
= Sum of MDs of sub-haloes

$$\frac{d(n/n_1)}{d(\log Z)} = \int_{M_1}^{M_2} \frac{d[n(M_*)/n_1(M_*)]}{d(\log Z)} \frac{dN}{dM_*} M_* dM_*$$

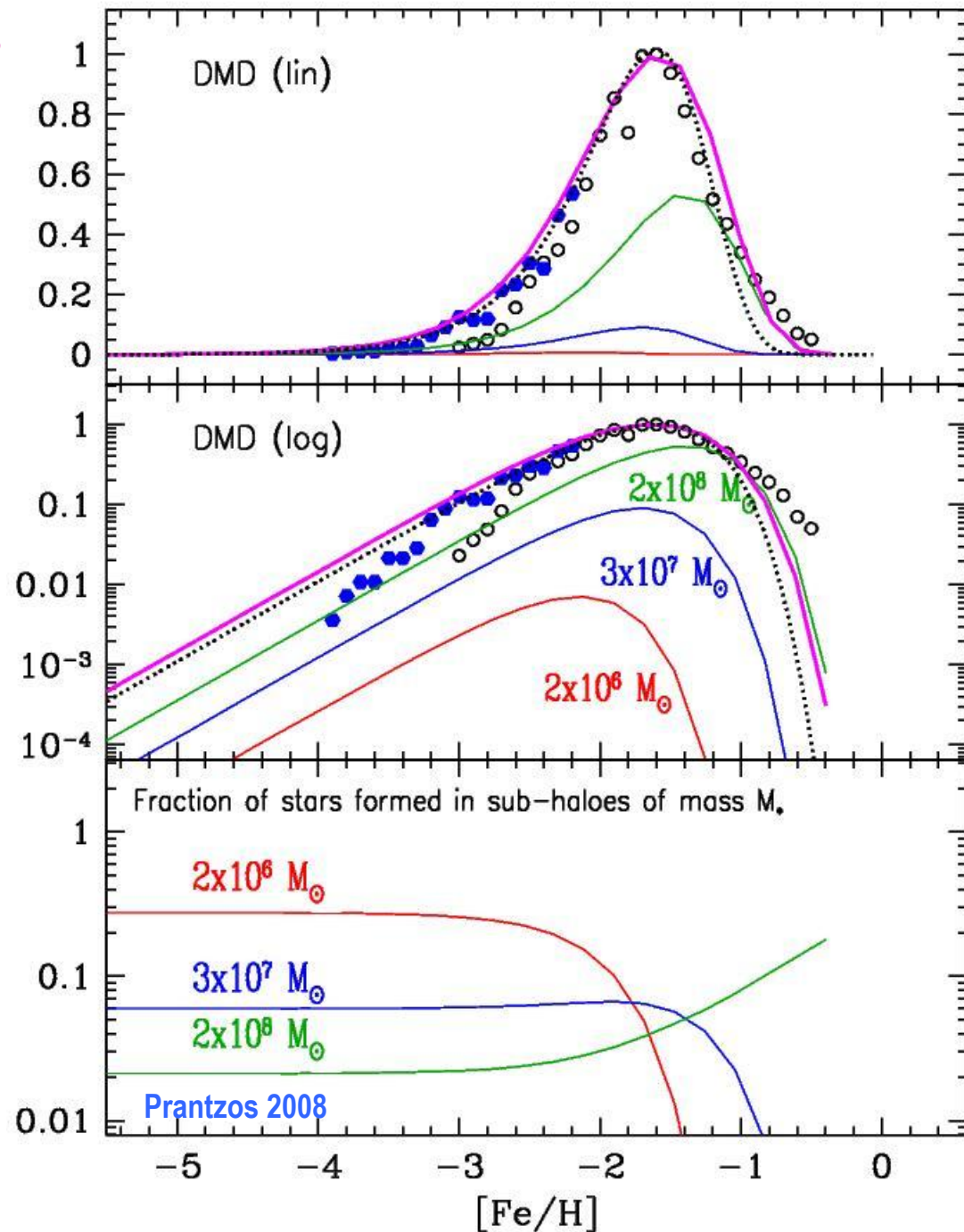


The halo MD may result as the sum of the MDs of ~a few dozens of small galaxies (sub-haloes of $10^6 - 10^8 M_\odot$),

each one with an effective yield obtained from the observed *mass-metallicity relation* for local dwarf spheroidals

and with an appropriate number distribution

Most of the lowest metallicity stars of the halo ($[Fe/H] < -2$) have been formed in the numerous, smallest sub-haloes, while its high metallicity tail was formed in a COUPLE of relatively massive, sub-haloes

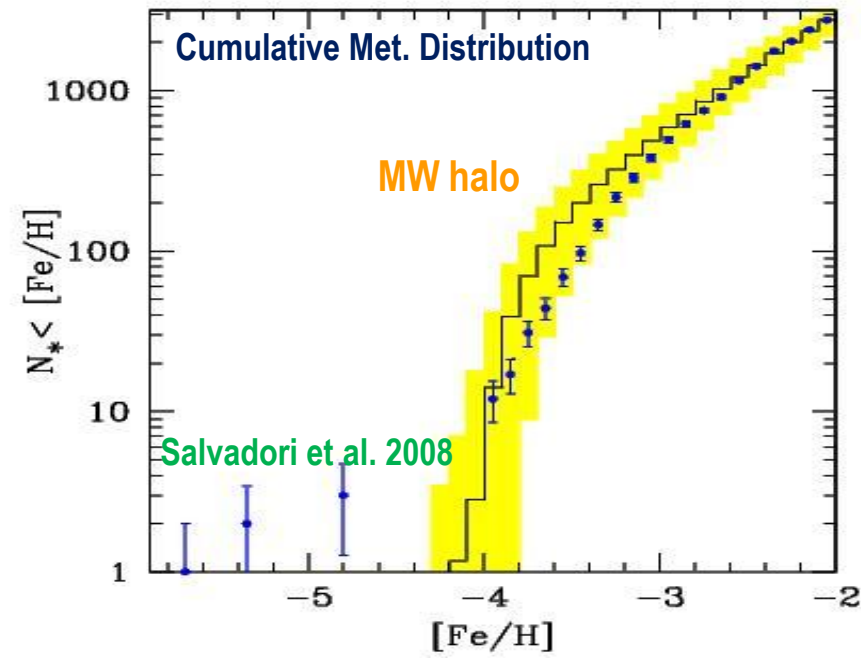
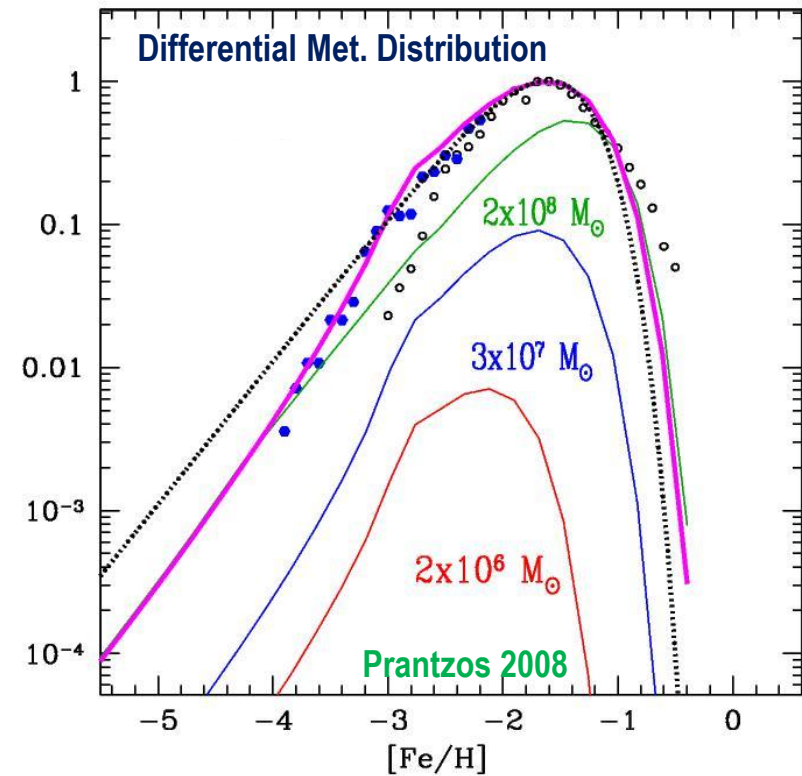


The low metallicity tail of the MW halo MD deviates from the simple outflow model and could be described by:

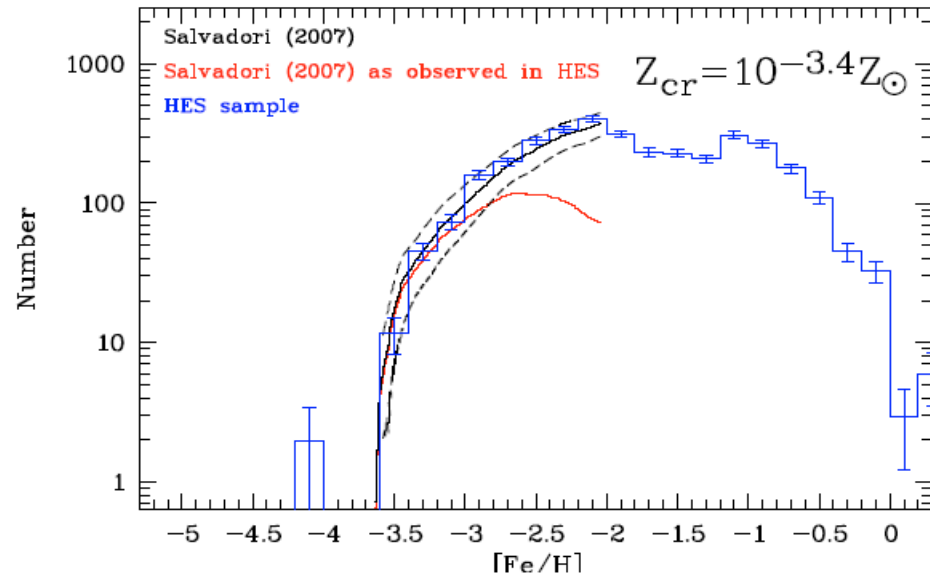
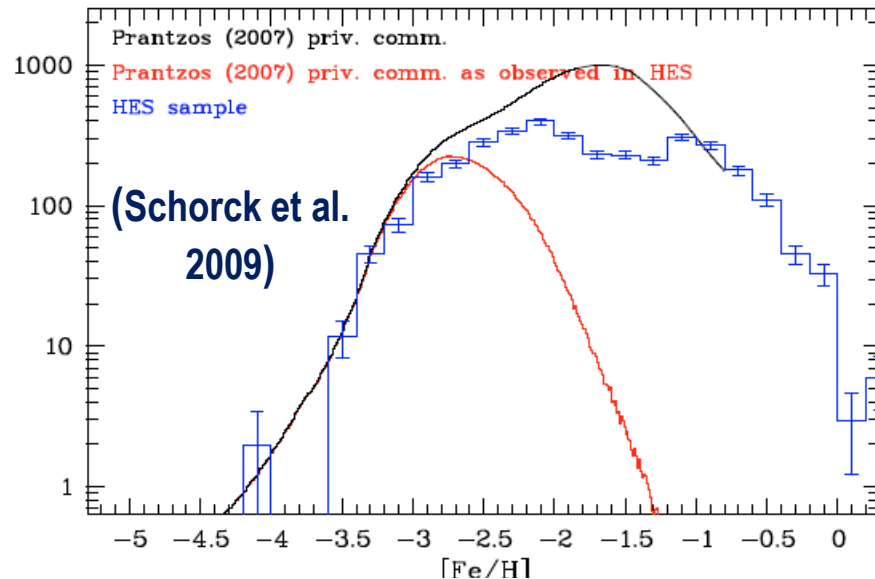
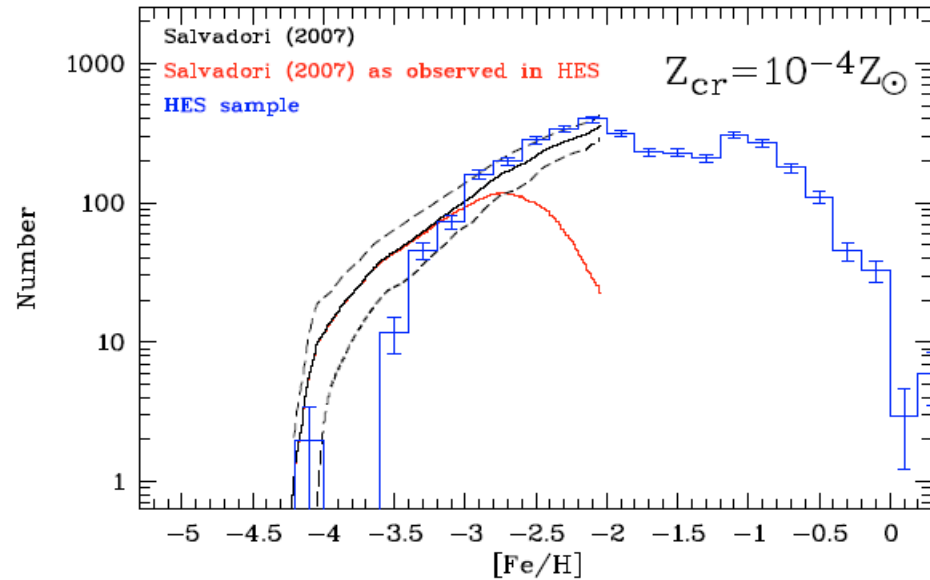
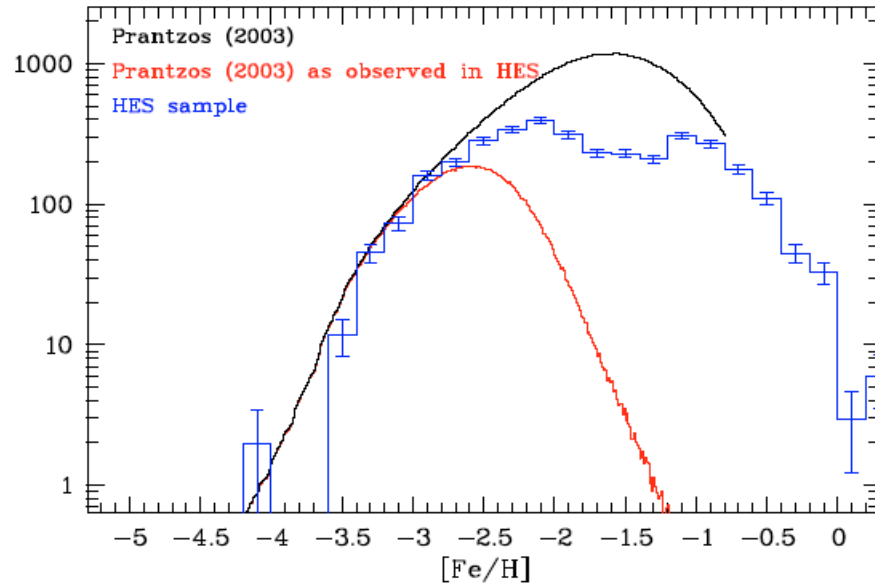
1) an early infall phase for all the sub-haloes and for their sum (<100 Myr, *Prantzos 2003, 2008*)

In that case, differences between Z_{MIN} of halo ($[\text{Fe}/\text{H}] \sim -4$) and luminous present-day dSphs ($[\text{Fe}/\text{H}] \sim -3$) are due to more prolonged infall in the case of present-day luminous dSphs

2) A non-zero initial metallicity $[\text{Fe}/\text{H}] \sim -4$ for the MW sub-haloes vs $[\text{Fe}/\text{H}] \sim -3$ for the dSphs, due to late formation of the dSphs from a more enriched intragalactic medium (*Salvadori et al. 2007, 2008*)



Comparison to Hamburg-ESO survey – 1600 stars (Schorck et al. 2009)



Did the Galaxy halo start its evolution with $[\text{Fe}/\text{H}] = -3.5$
(metallicity of intergalactic medium at that time) ?

SUMMARY OF HALO MD

Halo metallicity distribution compatible with hierarchical merging
assuming sub-halo properties (MD and $p_{\text{Eff}}(M)$) similar to those of dSphs (Outflow)

The metal-poorest halo ($[\text{Fe}/\text{H}] < -2$) stars were formed
in the numerous low mass ($< 10^7 M_{\odot}$) satellites
and the metal-richest halo stars ($[\text{Fe}/\text{H}] > -1.5$)
in a couple of massive ($\sim 10^8 M_{\odot}$) rapidly evolved, satellites

Early infall probably required in both MW sub-haloes and dSphs to explain their metal-poor MD;

Unclear whether a “floor” metallicity is seen in dSphs

IMPLICATIONS FOR EVOLUTION OF ABUNDANCE RATIOS ?

GALACTIC CHEMICAL EVOLUTION

Part V : The Milky Way disk

Representations of a disk (Milky Way) galaxy

0 - D



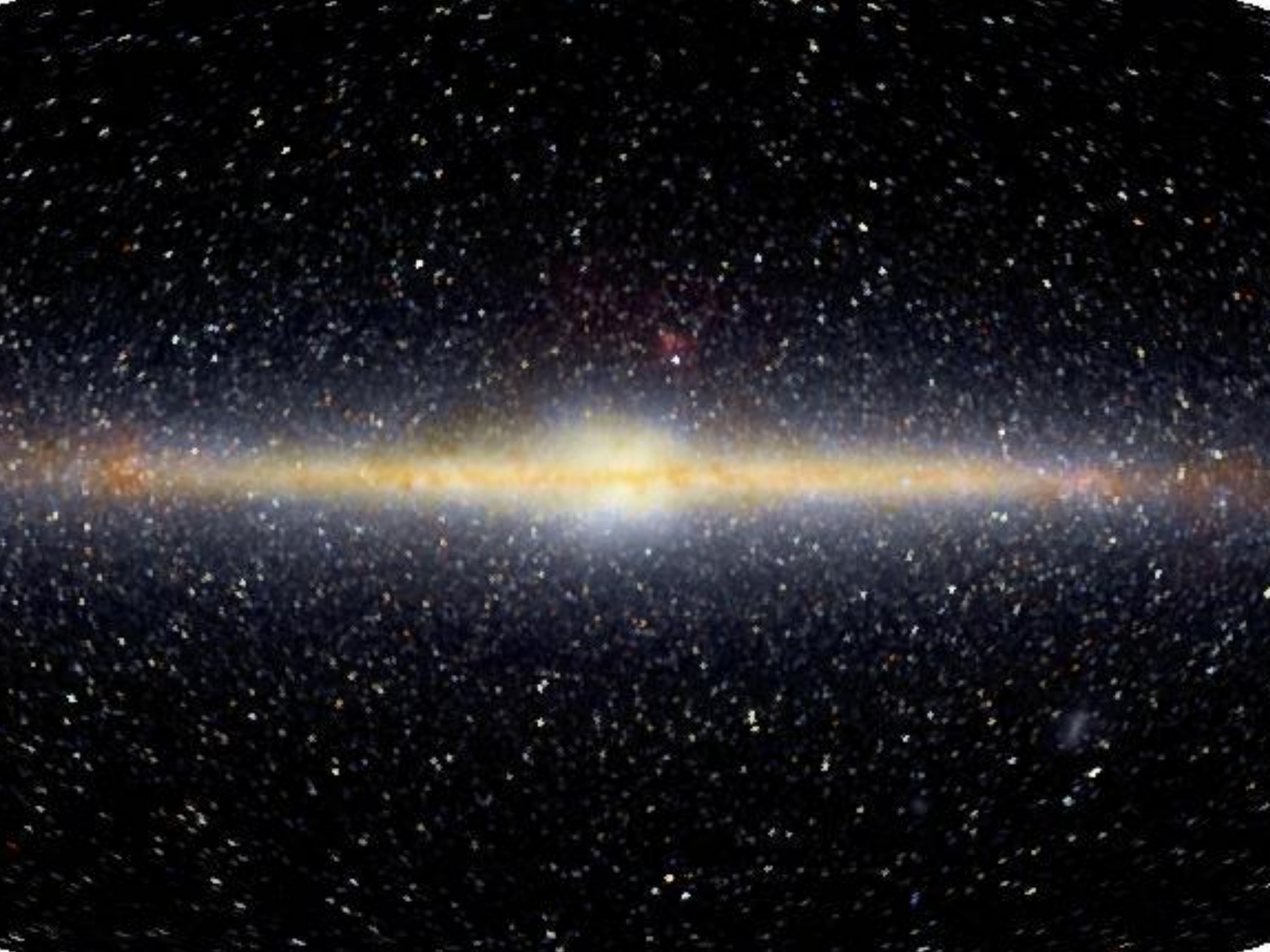
Point box

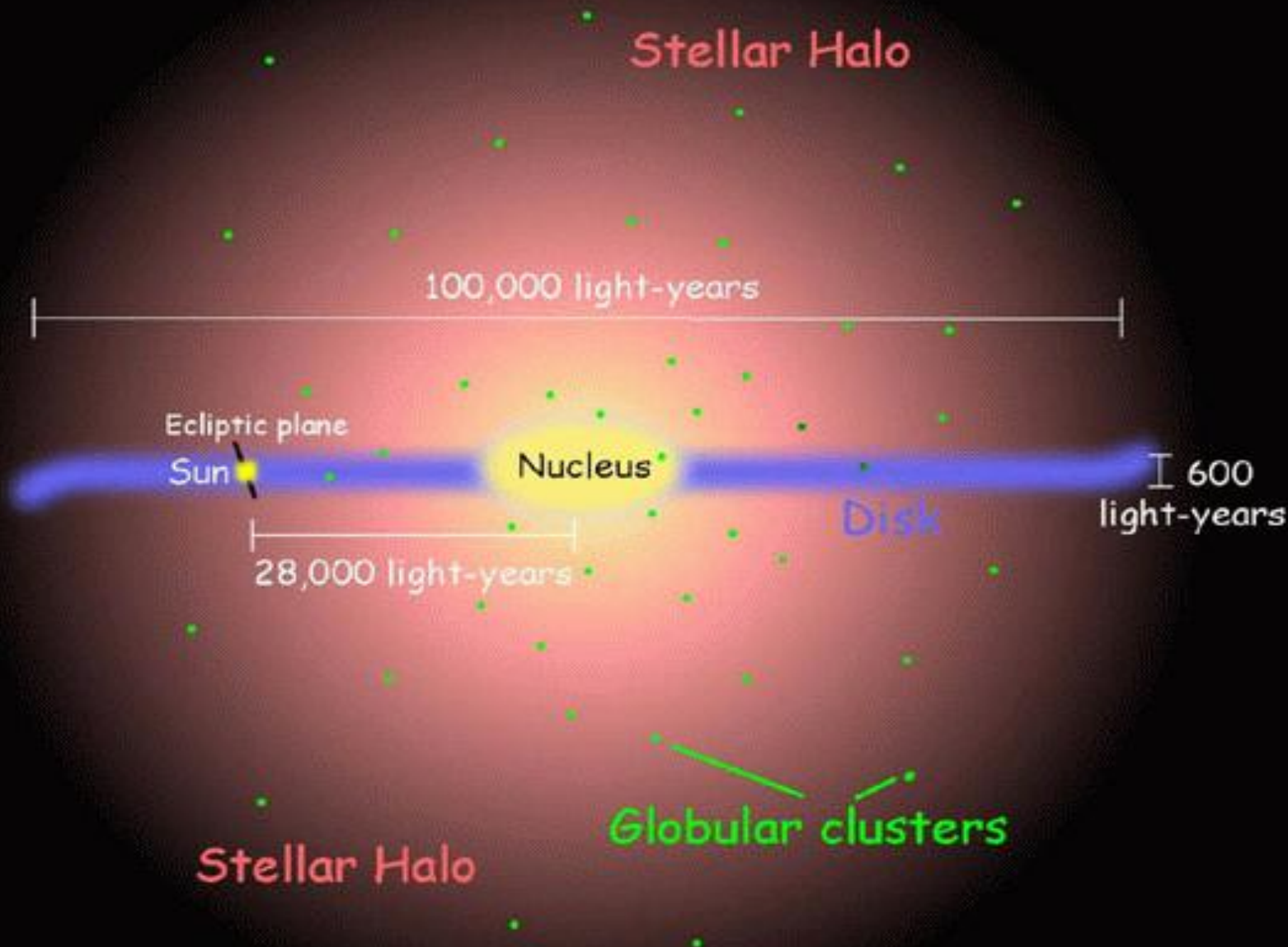
Global properties:

Mass (Gas, Stars), Metallicity, SF and SN rates

Luminosity (various λ -bands), Spectra

Evolution = $f(t)$ only



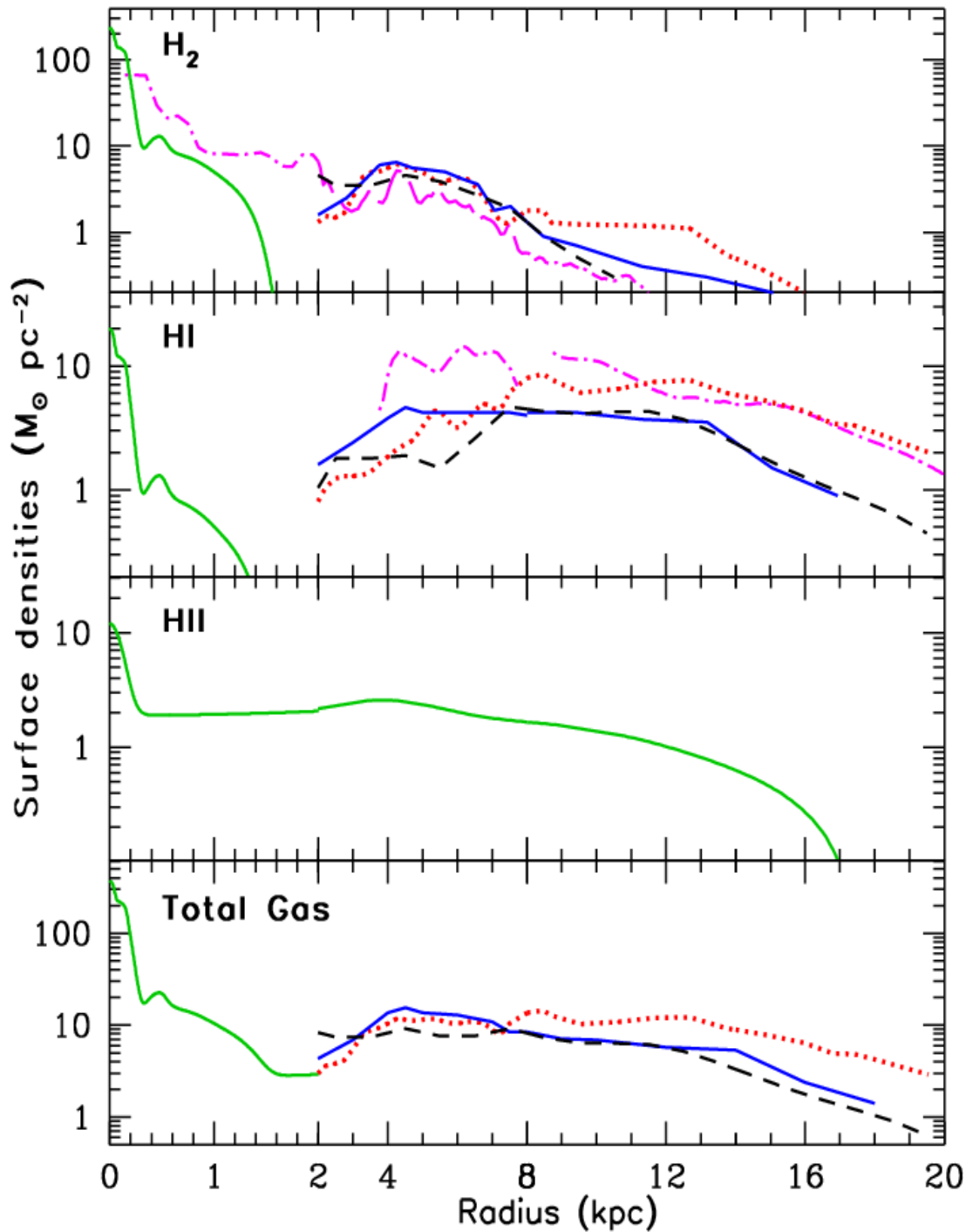


- Local disk (8 kpc from GC): Composition of nearby young stars and gas is ~ solar
(But: older stars are more metal poor, by a factor up to ten)
- Inner Galactic disk: metal rich young stars and gas (up to 3 times solar)
- Outer Galactic disk: metal poor young stars and gas (down to 1/3 solar)



**The Milky Way disk:
Spiral structure, but
radial symmetry assumed
(azimuthally averaged quantities)**

The Milky Way disk: (1) Gas profiles



Relatively flat,
except for molecular gas
in inner disk

The Milky Way disk: (2) Star and SFR profiles

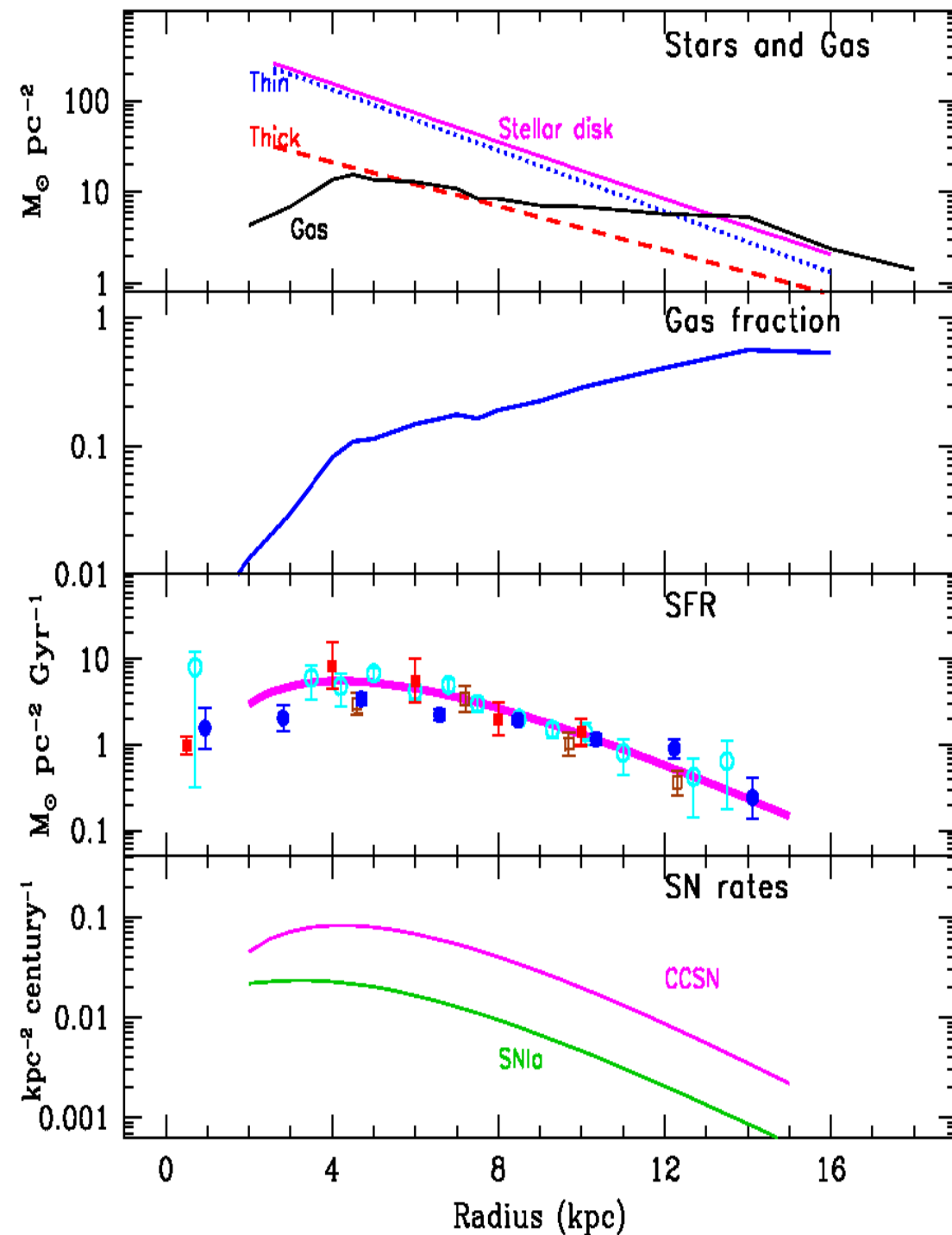
Exponential stellar profile
 $\Sigma(R) = \Sigma_0 \exp(-R/S_R)$
with $S_R \sim 2.5$ kpc

Gas Mass $\sim 10^{10} M_\odot$

Star Mass $\sim 4 \cdot 10^{10} M_\odot$

Inner disk more “processed”
than outer disk
(gas fraction profile)

No information on past history
Only present day profiles



Radial dependence of SFR

Ohnisi (1975), Wyse and Silk (1989):

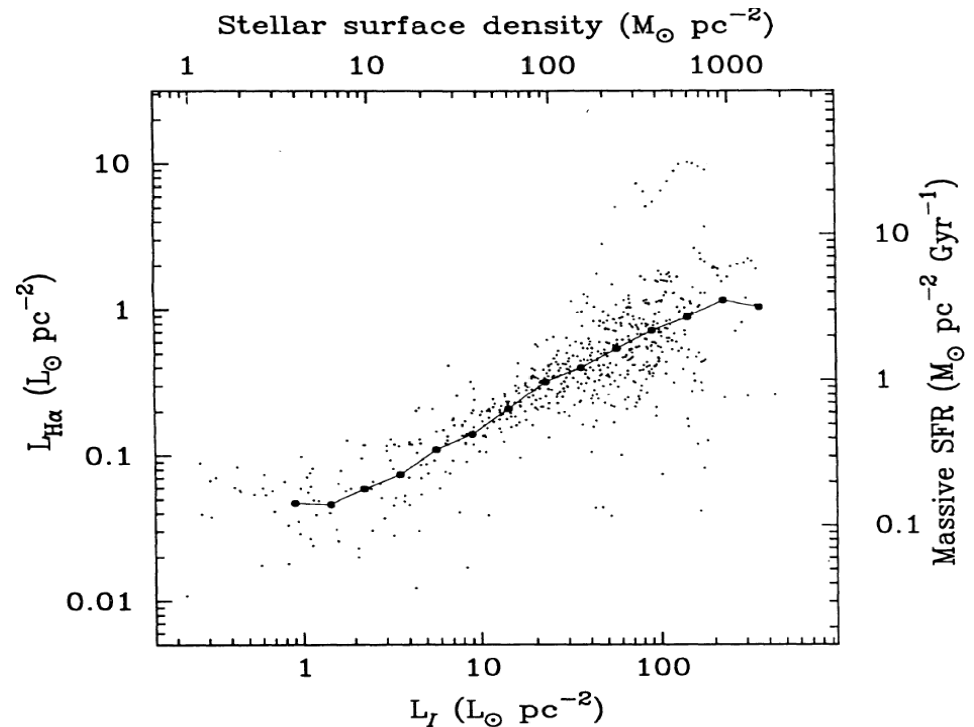
SFR induced by spiral density waves,
hitting the ISM with frequency $\Omega - \Omega_p$
[$\Omega = V(R)/R$ and Ω_p = frequency of spiral pattern]

For $V(R) \cong \text{const}$ and $\Omega_p \ll \Omega$
 $\text{SFR} \propto V(R)/R \propto R^{-1}$

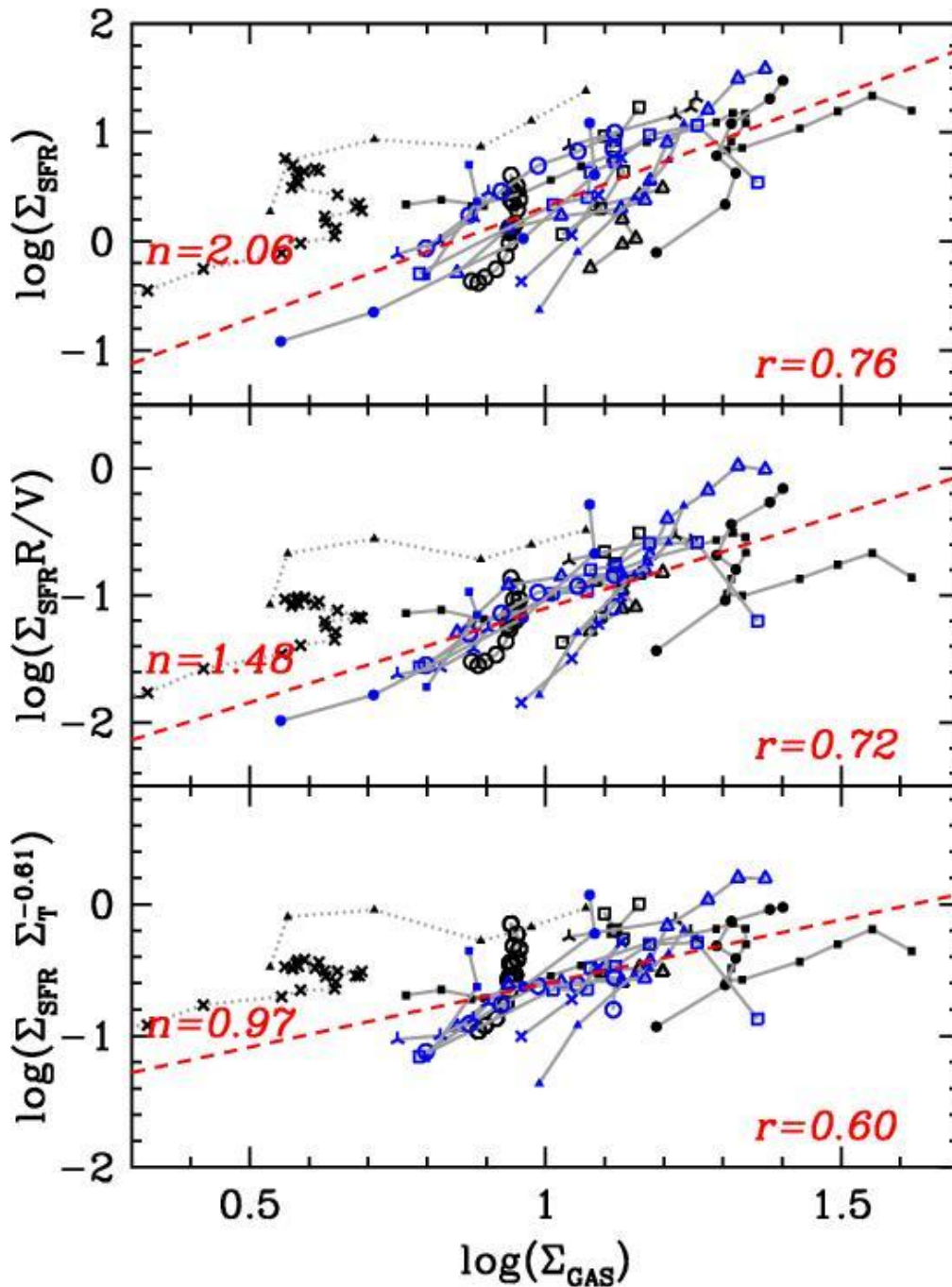
Dopita and Ryder (1994)

$$\text{SFR} \propto \Sigma_{\text{GAS}}^N \Sigma_{\text{TOT}}^M$$

$1.5 \leq N+M \leq 2.5$
 $N=5/3$ and $M=1/3$
or $N=1$ and $M=0.5$



Testing the SFR laws (Boissier et al. 2003)



1) Pure Schmidt law

$$\text{SFR} \propto \Sigma_{\text{GAS}}^N$$

$$N = 2$$

2) Induced by spiral waves

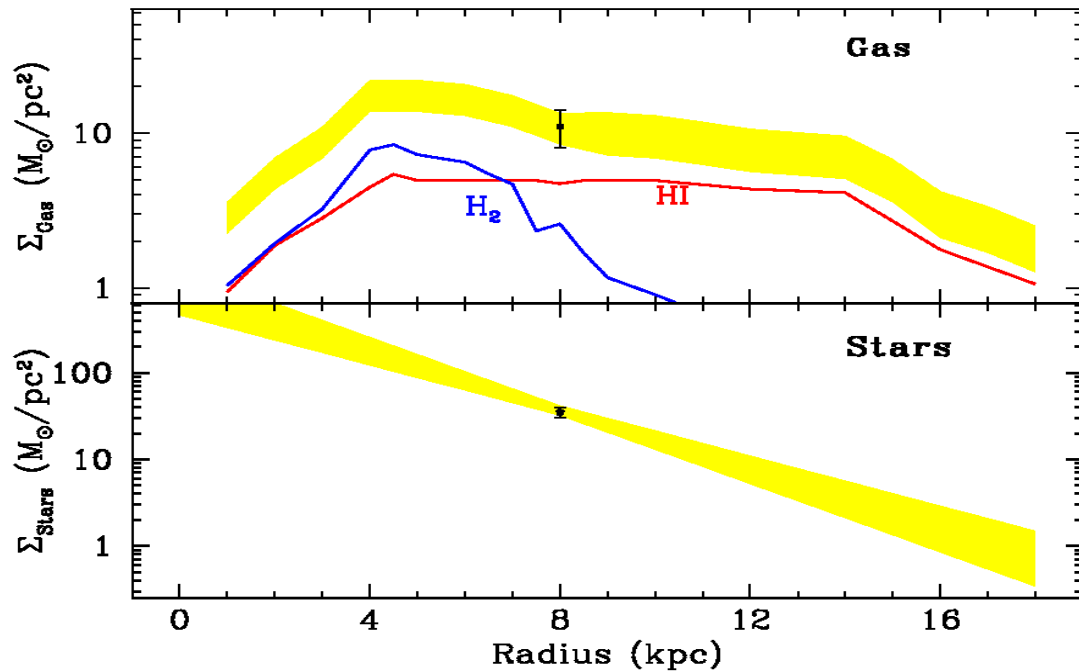
$$\text{SFR} \propto \Sigma_{\text{GAS}}^N \quad V/R$$

$$N = 1.5$$

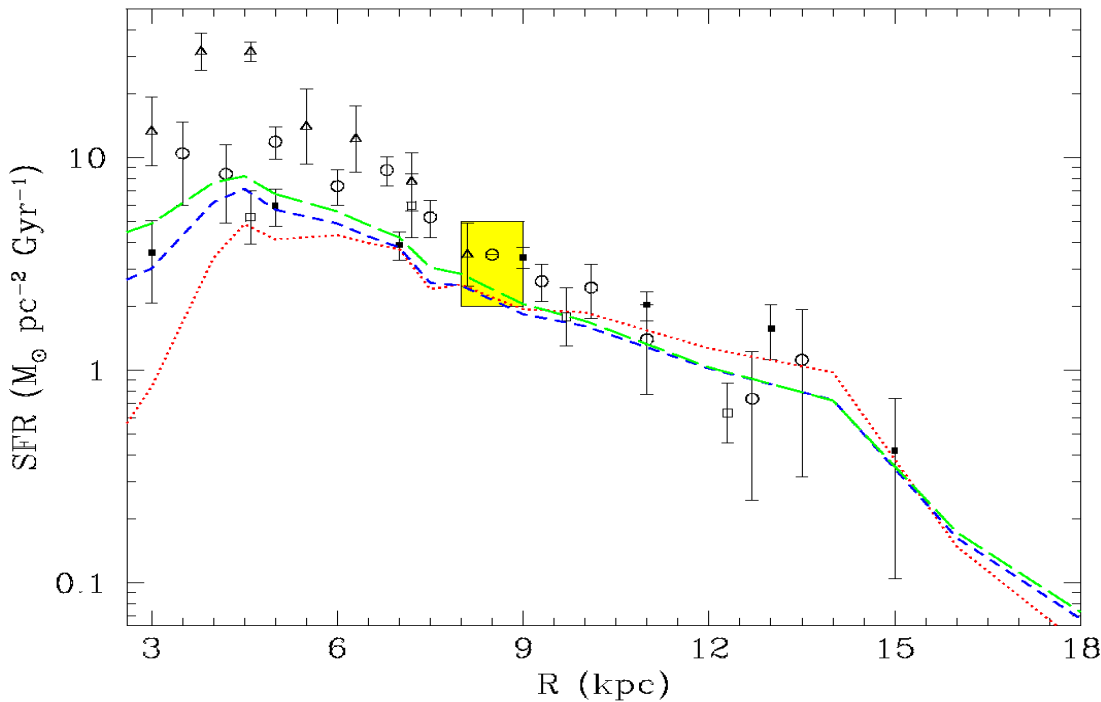
3) Modified by total mass

$$\text{SFR} \propto \Sigma_{\text{GAS}}^N \quad \Sigma_{\text{TOT}}^{0.5}$$

$$N = 1.$$

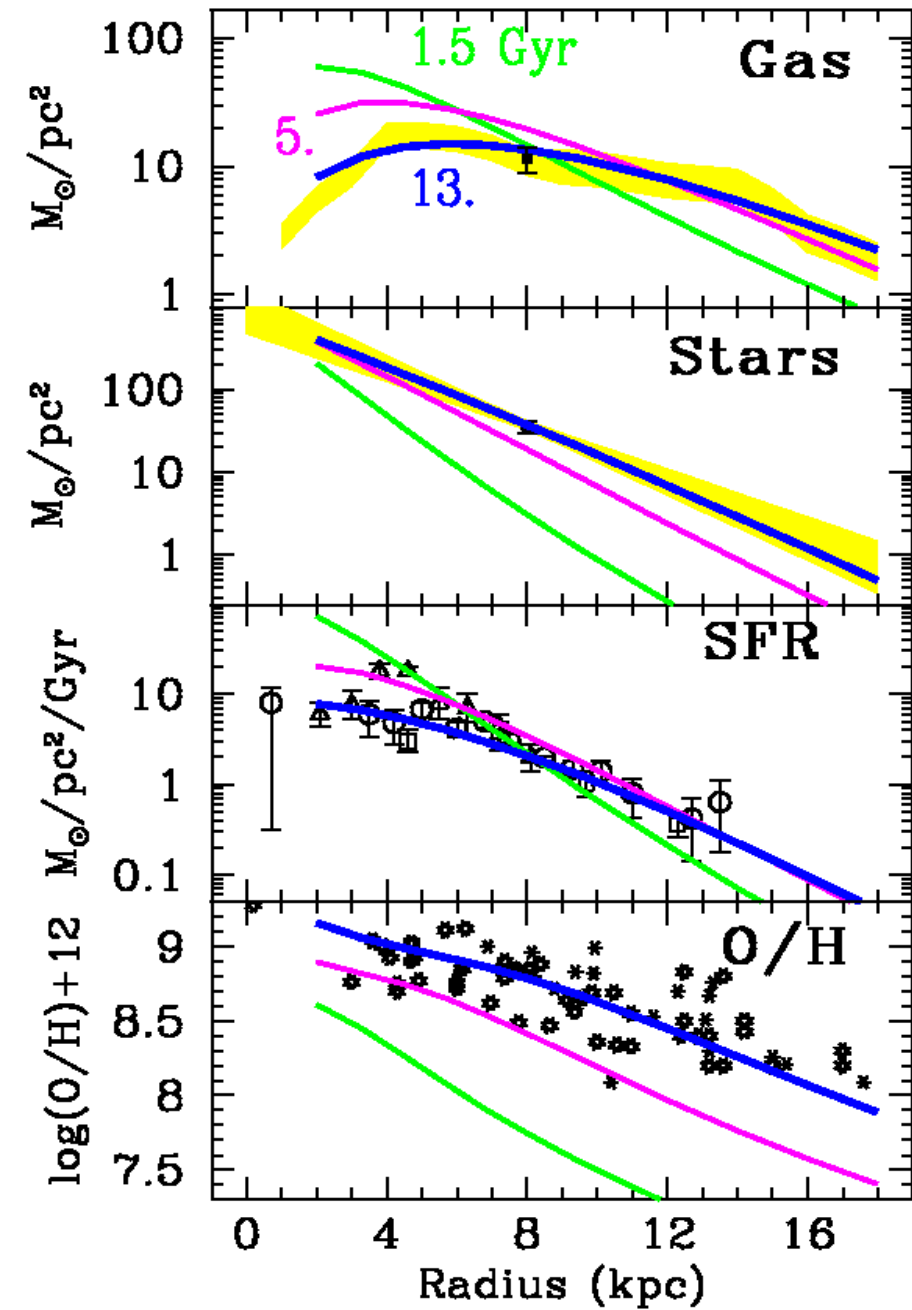


Application of the derived SFR laws to the case of the Milky Way disk

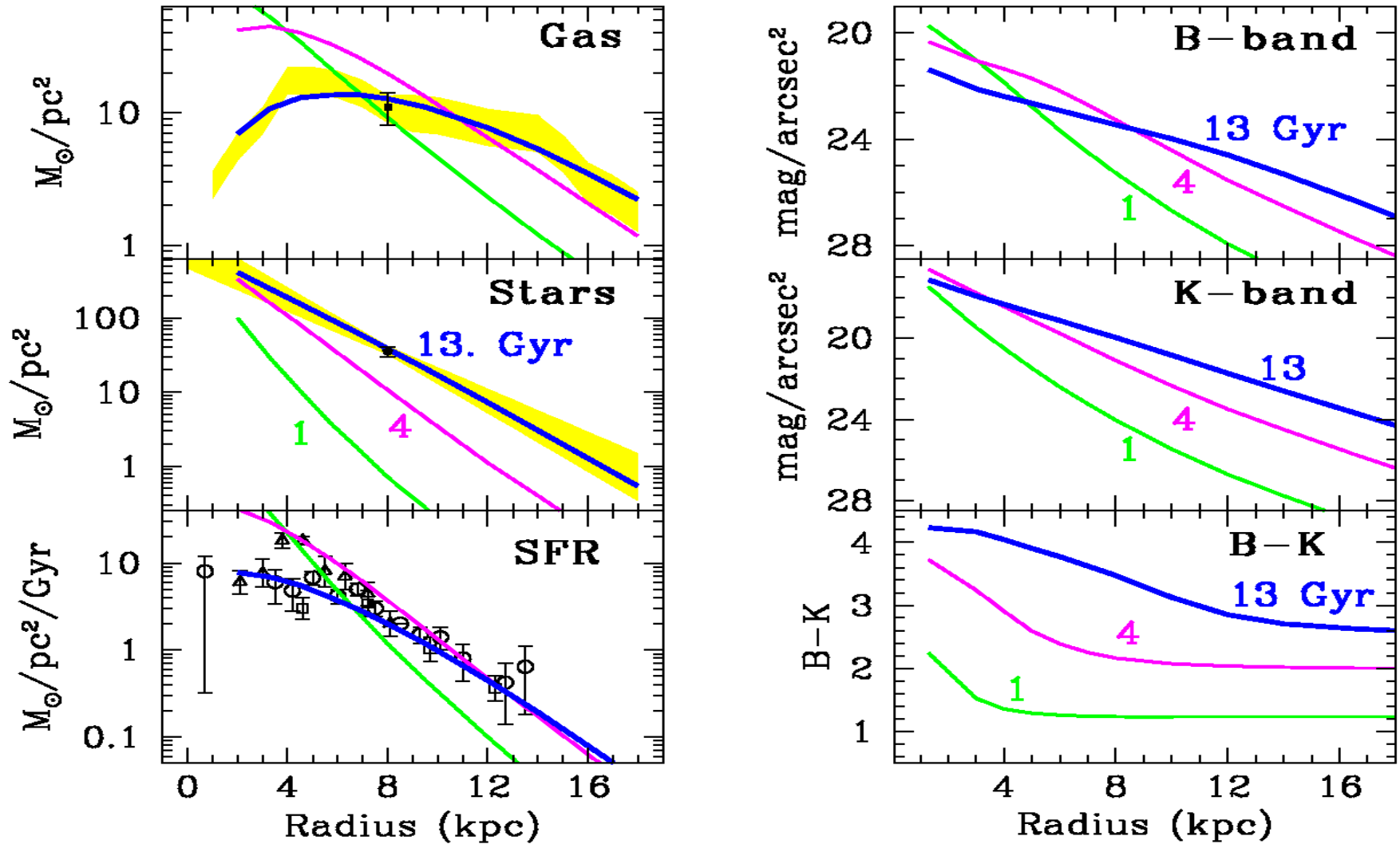


All three SFR laws give fair fits to the data, (except, perhaps, for the pure Schmidt law ($N=2$), which fails in the molecular ring)

The Milky Way disk: (4) Evolution

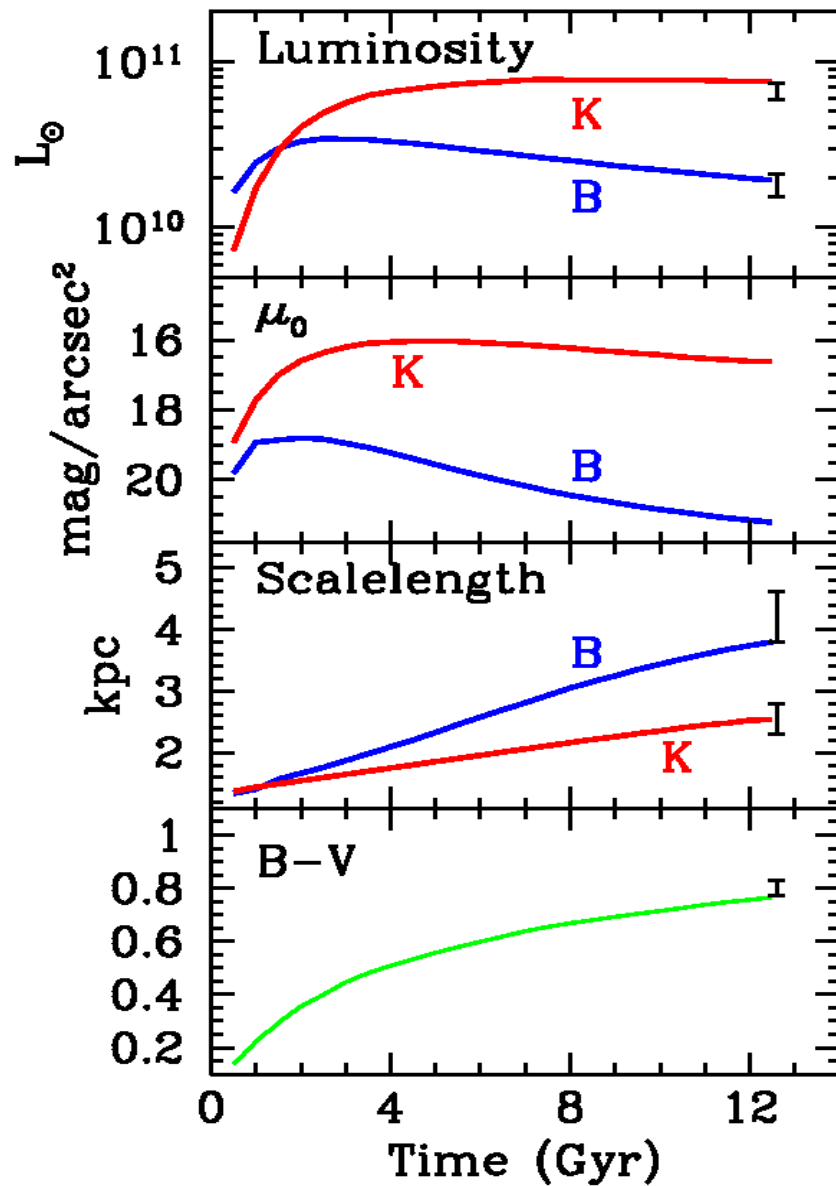
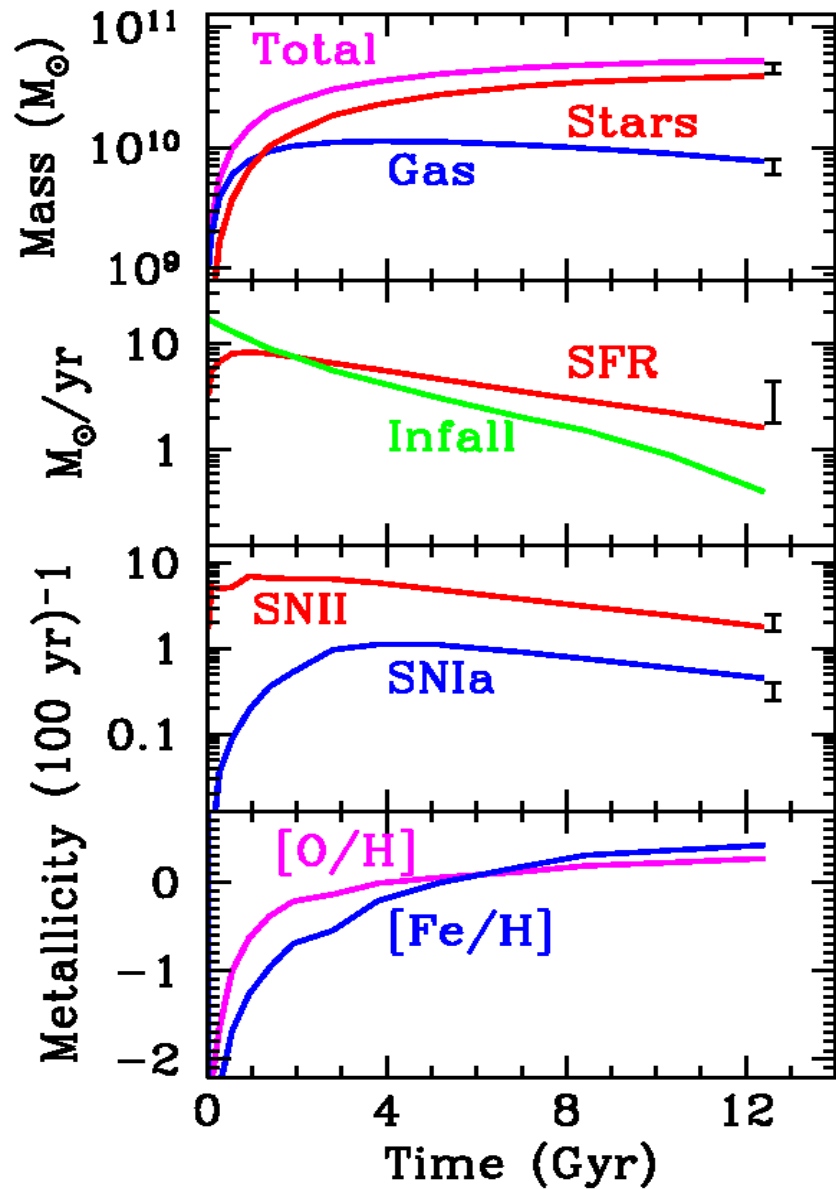


The Milky Way disk (5) Evolution



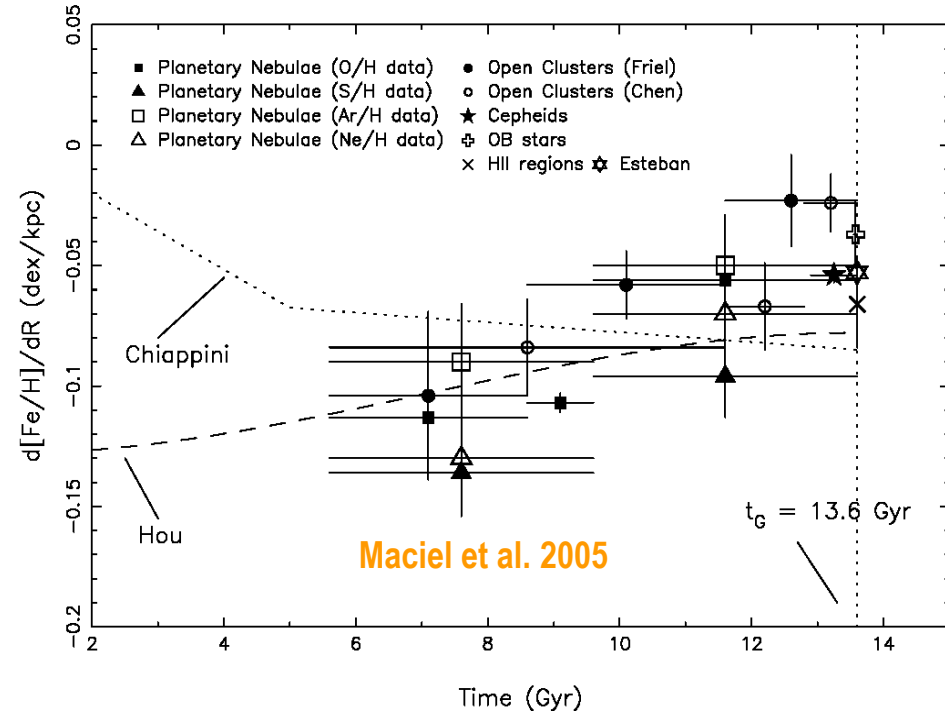
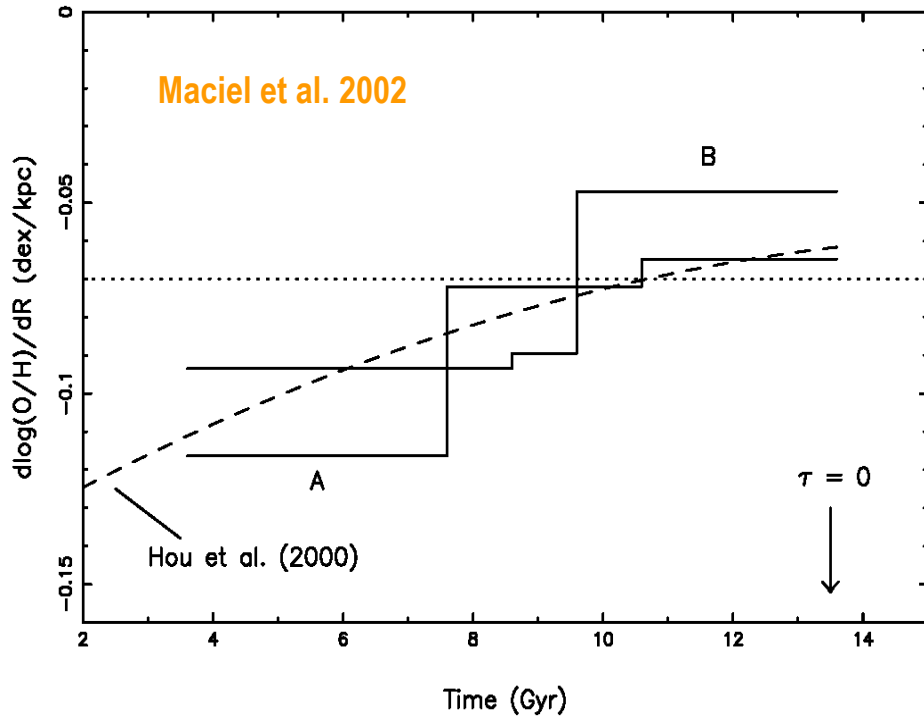
Inside-Out formation and radially varying SFR efficiency required to reproduce observed SFR, gas and colour profiles (Scalelengths: $R_B \approx 4$ kpc, $R_K \approx 2.5$ kpc)
(Boissier and Prantzos 1999)

The Milky Way disk (6) Global evolution



The Milky Way disk (7)

Evolution of the metallicity profile



“Observed” evolution of O gradient:

$d[d\log(O/H)/dR]/dt \sim 0.004$ dex/kpc/Gyr

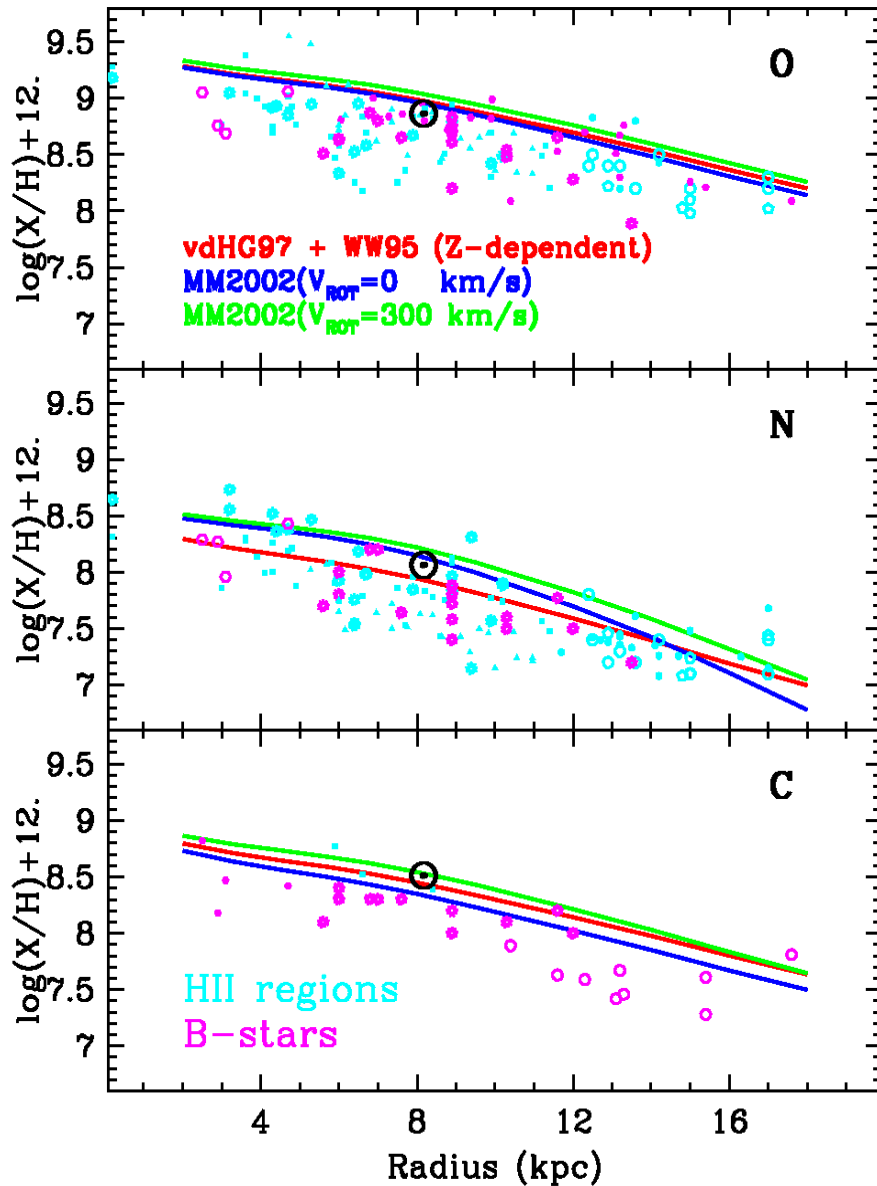
In broad agreement with theory

Also for Fe

But: large uncertainties in both abundance gradient (abundances, distances) and age determinations

The Milky Way disk (8)

Abundance gradients of CNO in Milky Way disk



$$d\log(\text{O}/\text{H})/dR = -0.07 \text{ dex/kpc}$$

**BUT: what is the true value
of the Galactic abundance gradient ?**

The Milky Way disk (9)

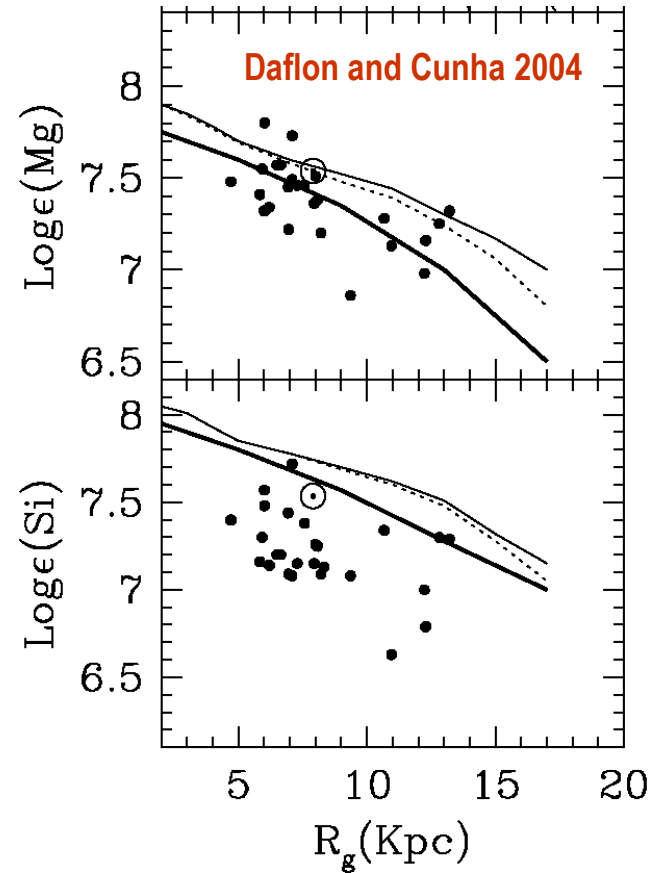
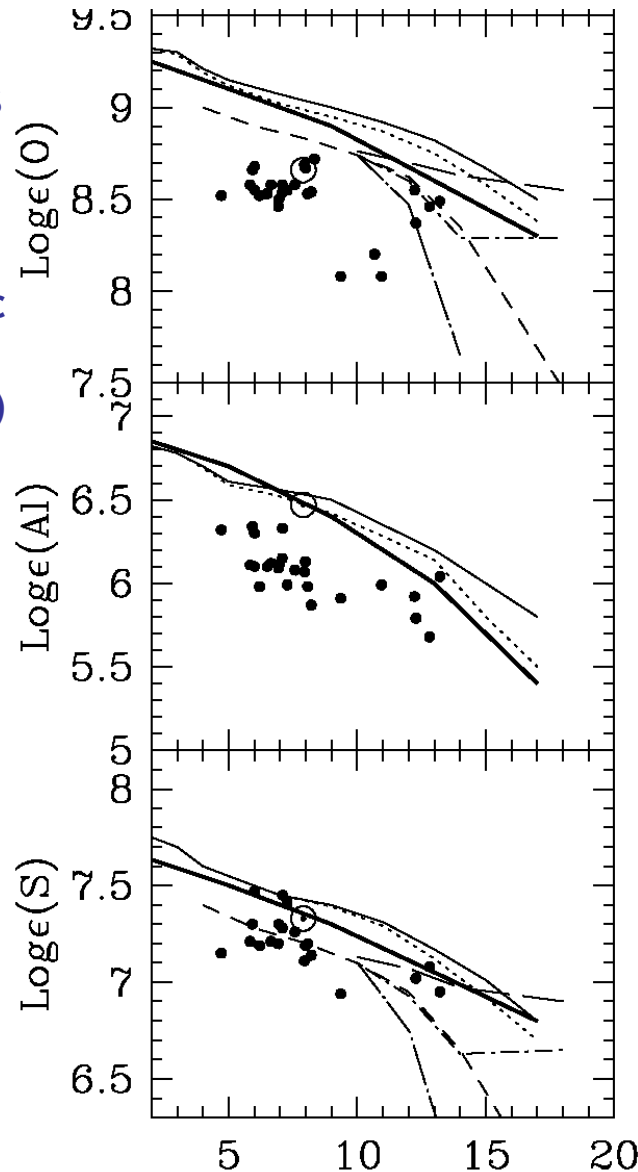
Recent observations of OB stars
 suggest a gradient of
 $d\log(O/H)/dR \sim -0.033 \text{ dex/kpc}$
 (about half the canonical value)

for oxygen,

and slightly larger

for other elements

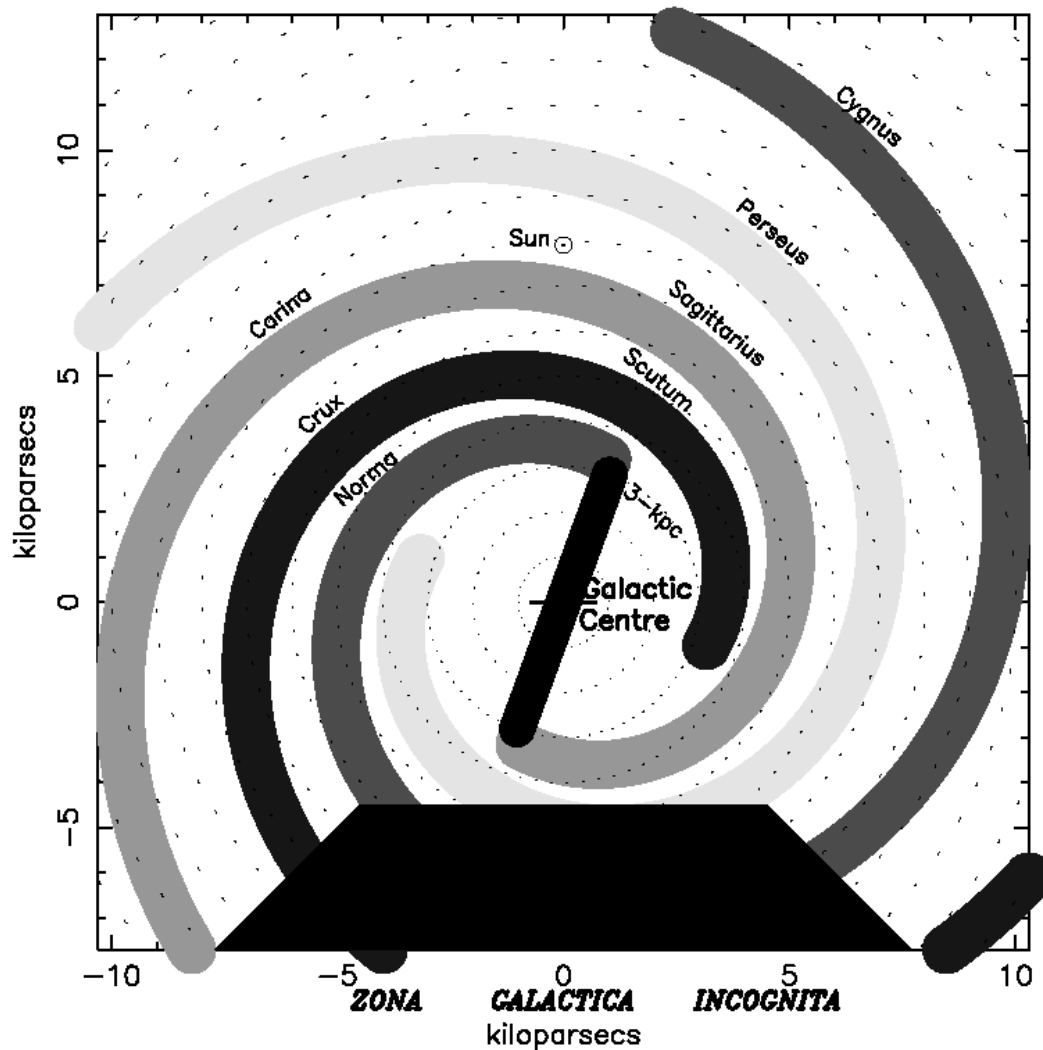
(Daflon and Cunha 2004)



- Chiappini et al. 2001, model A
- Chiappini et al. 2001, model B
- Chiappini et al. 2001, model C
- Chiappini et al. 2001, model D
- Alibes et al. 2001, primordial
- Alibes et al. 2001, enriched
- Hou et al. 2000

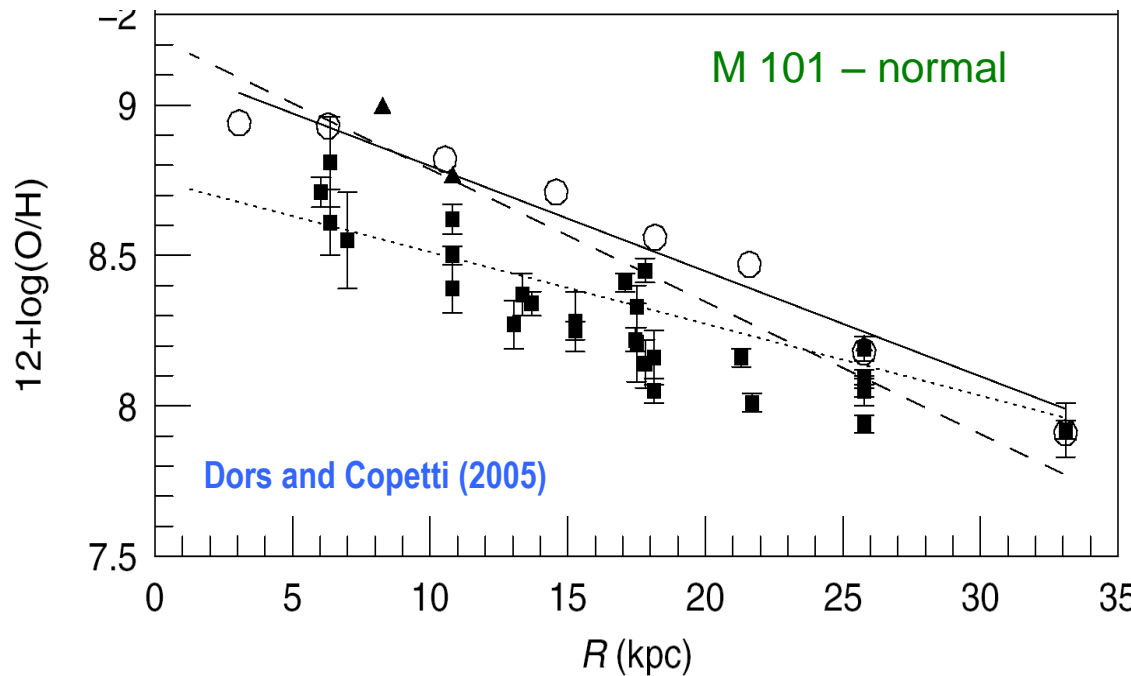
The Milky Way disk (10)

The value of the abundance gradient is crucial regarding the action of a galactic bar
A bar drives (metal-poor) gas from the outer disk inwards, and this radial inflow tends to reduce abundance gradients

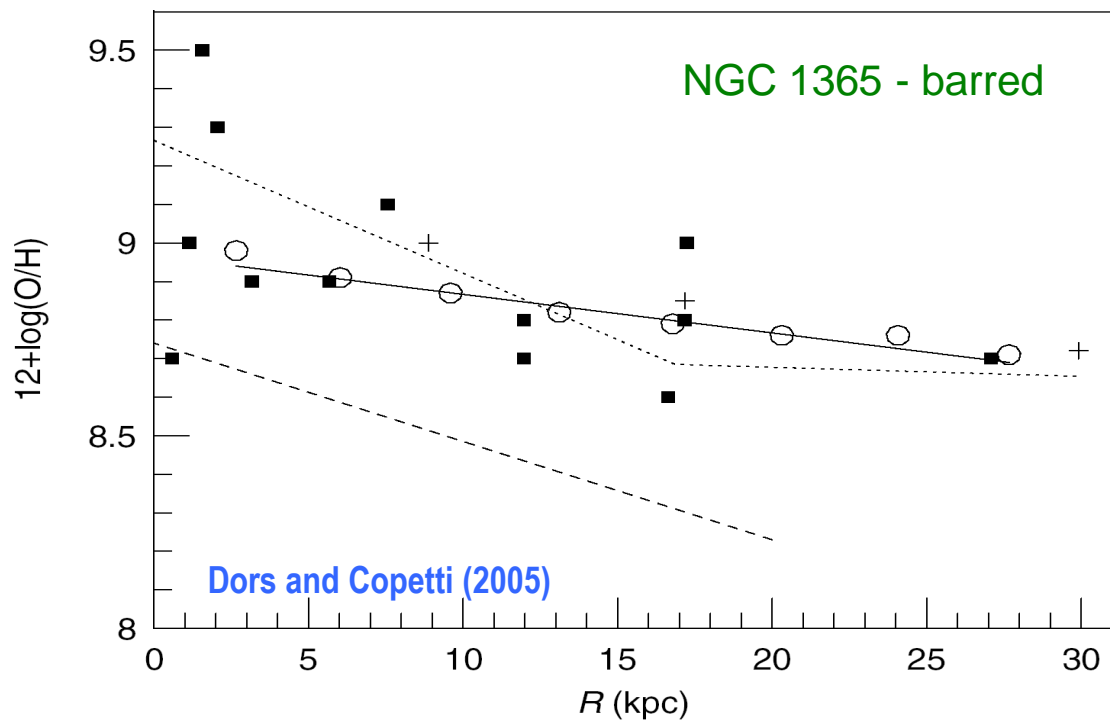


The importance of the Galactic bar is not well established yet

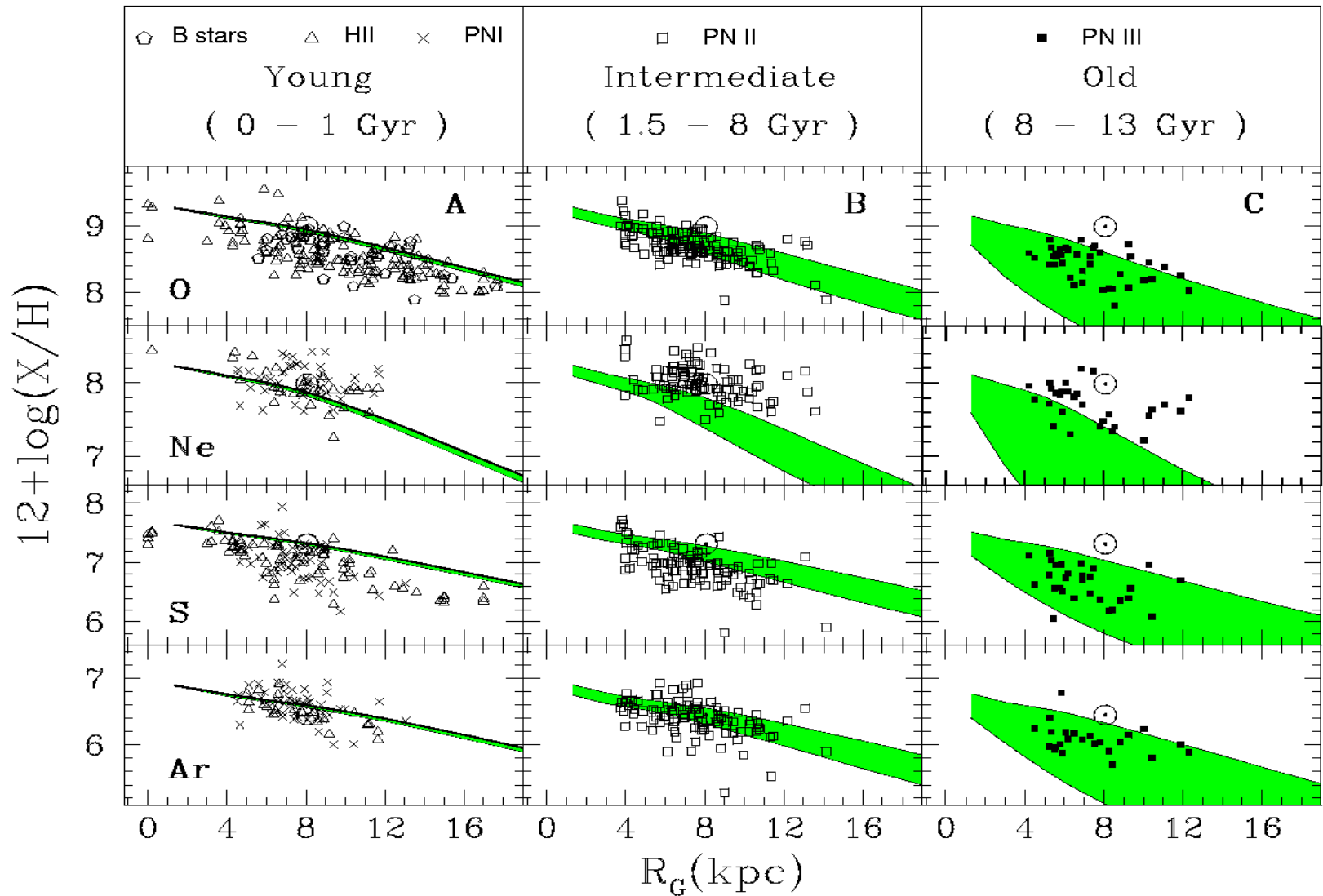
Normal disk galaxies have stronger abundance gradients



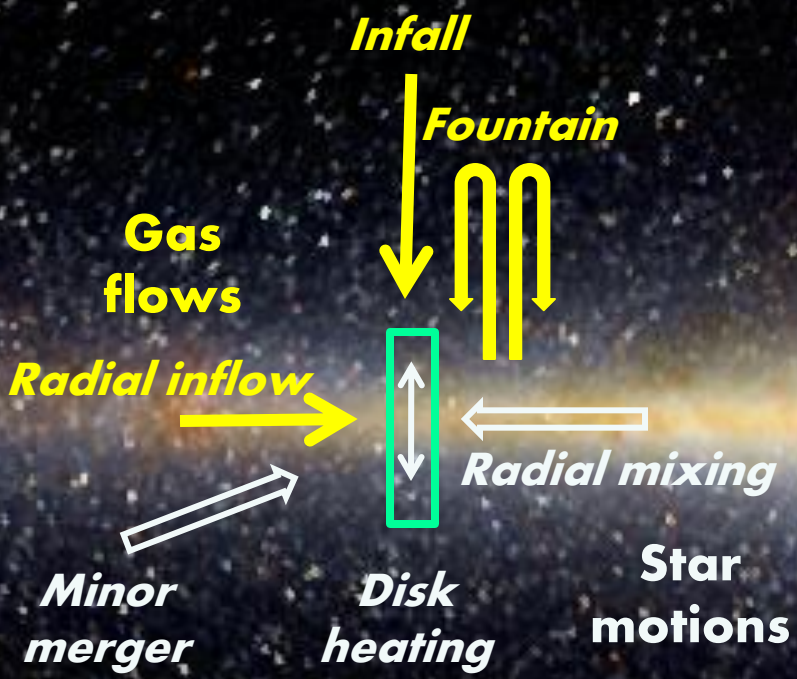
Barred disk galaxies tend to have smaller abundance gradients than non-barred ones



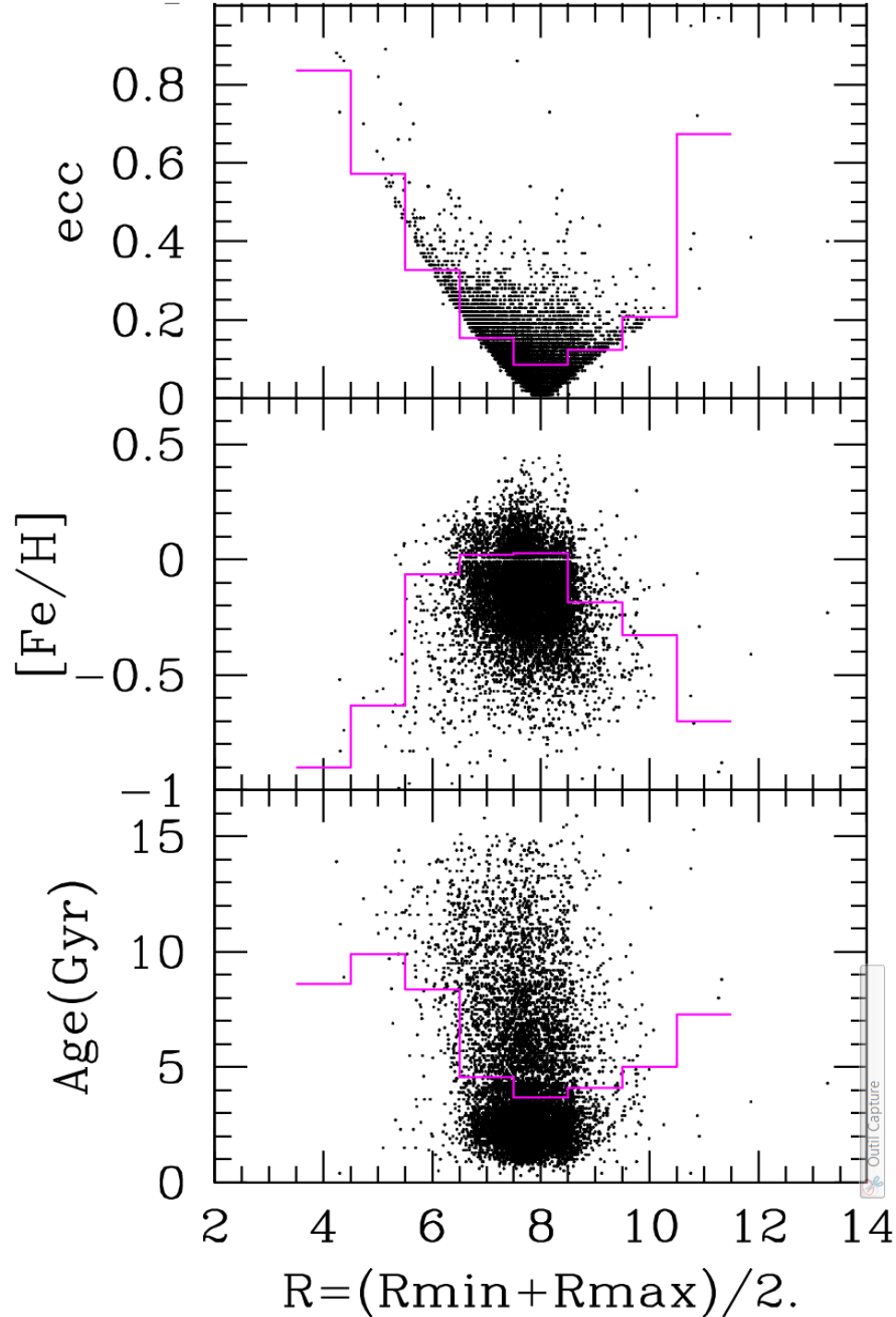
Evolution of abundance gradients in Milky Way disk (*Hou et al. 2000*)



In principle, dispersion should increase with age and galactocentric distance





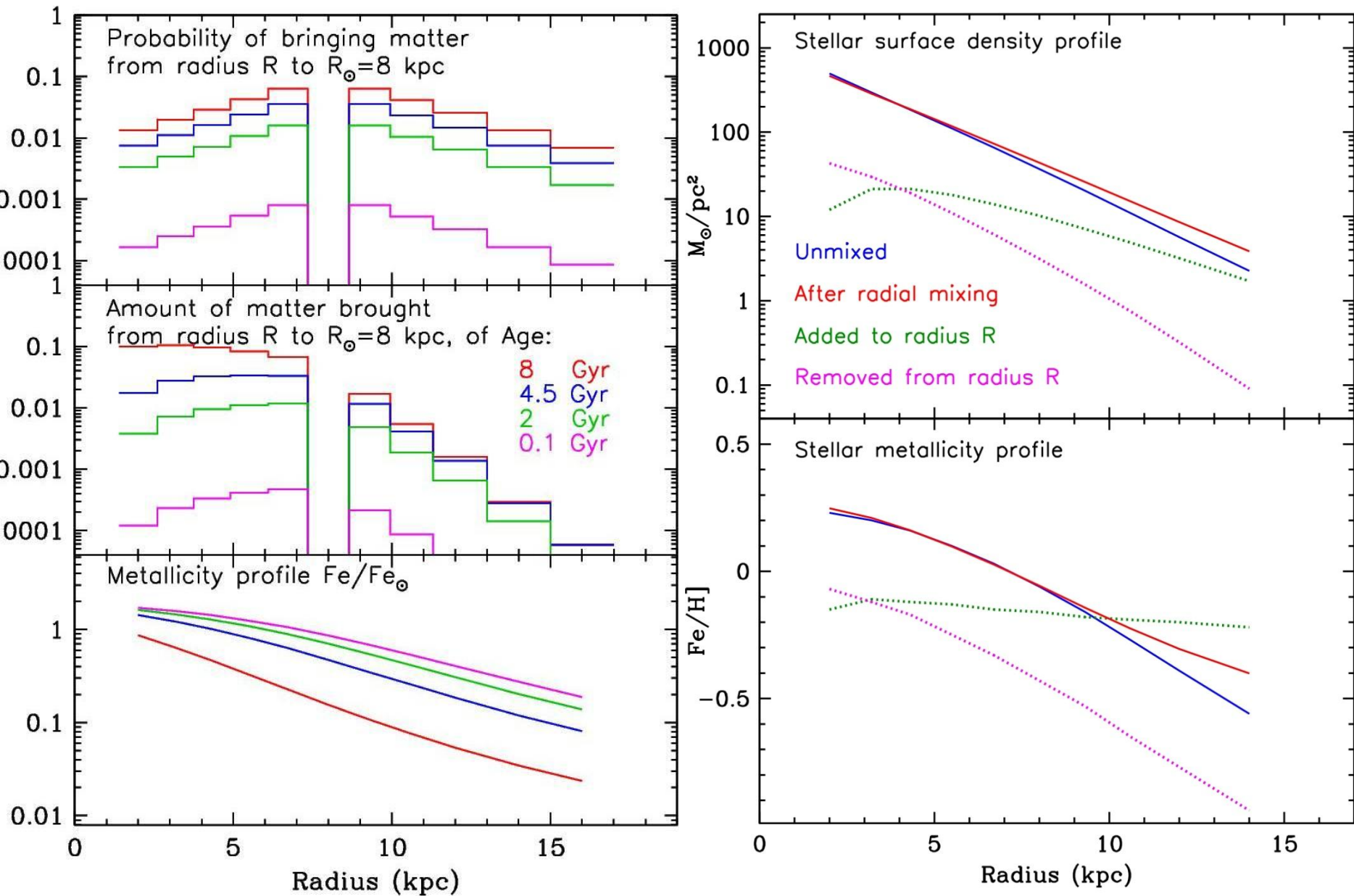


Analysis of kinematics, composition and age of stars in solar neighborhood (<200 pc) from GKS (*Holmberg et al. 2009*) shows that

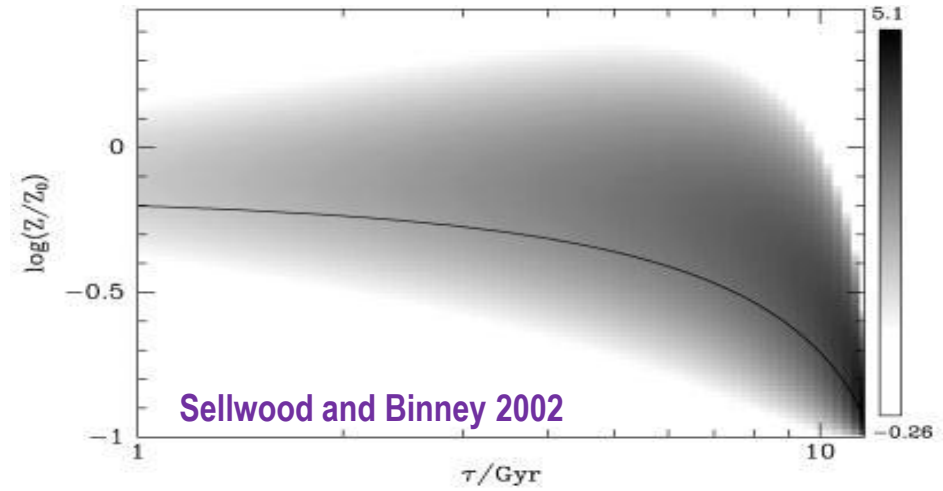
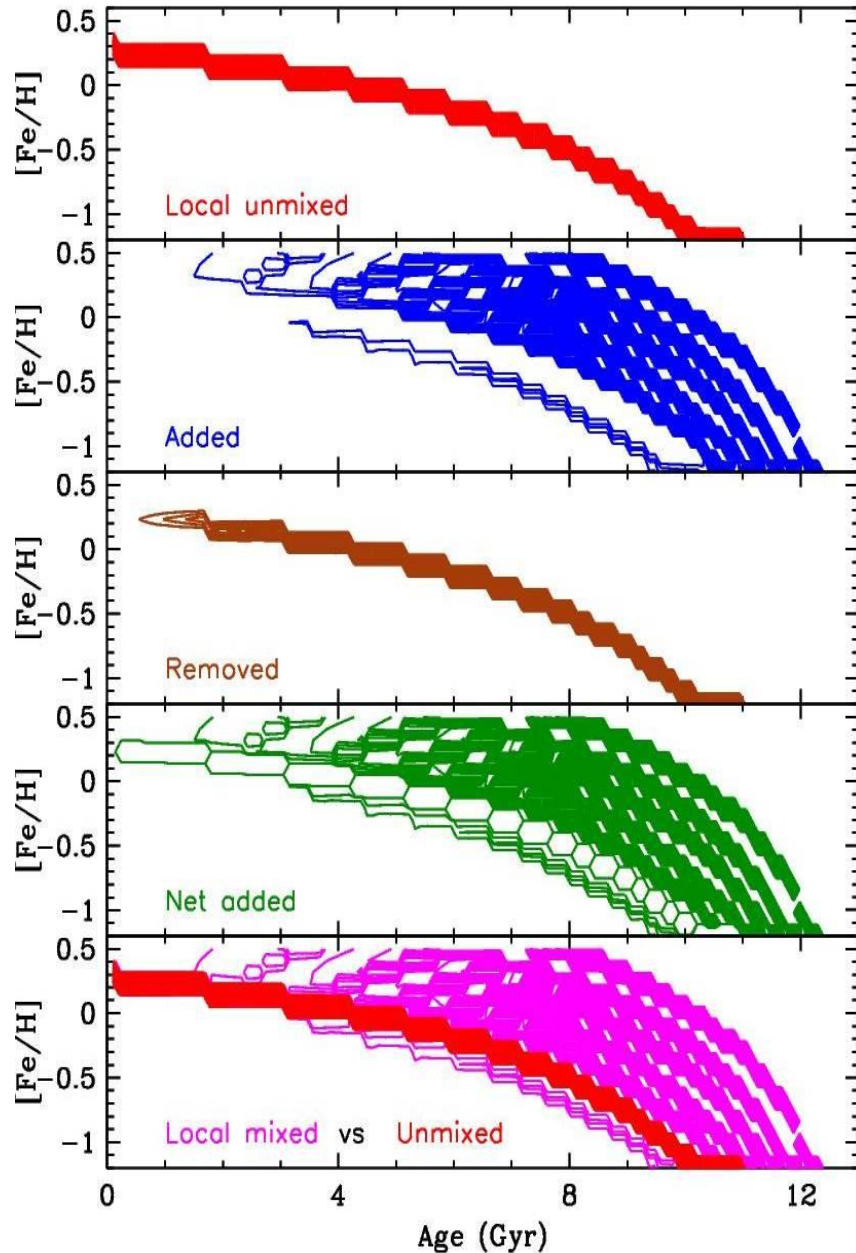
stars with **high eccentricities** (born either in the inner or the outer disk) have **lower metallicities** and **larger ages**, ON AVERAGE, than stars of low eccentricities (born locally)

Such stars are here either due to normal **epicyclic motion** or from **radial migration** (*Sellwood and Binney 2002*)

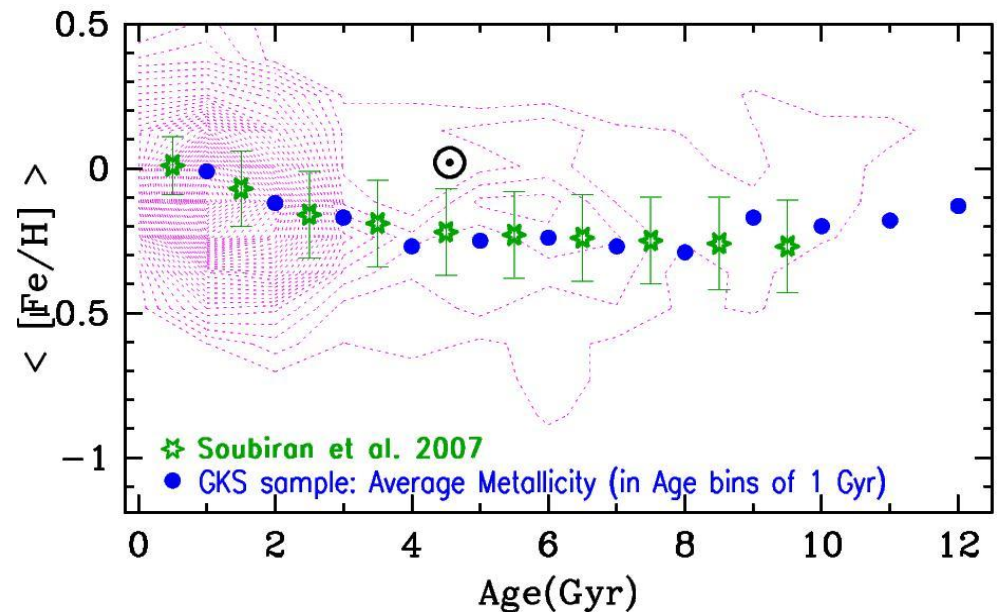
A toy model for radial mixing (a la Sellwood and Binney 2002)



Effect of radial mixing on local age-metallicity relation



Radial mixing may induce dispersion into and slightly alter the average local age-metallicity relation

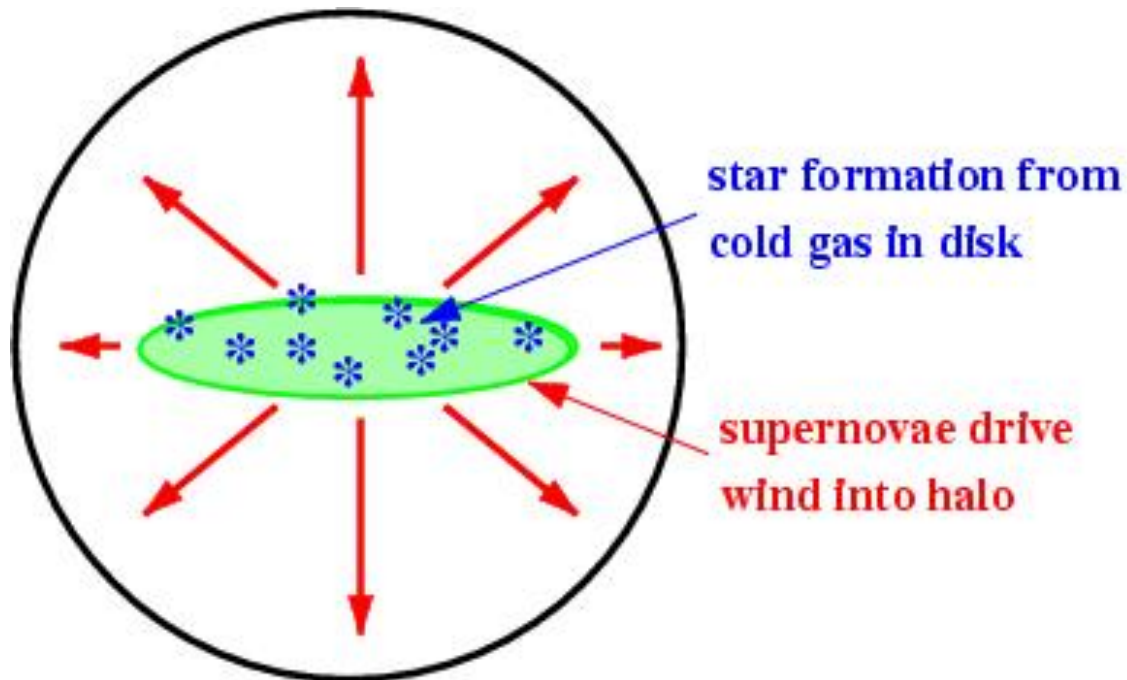
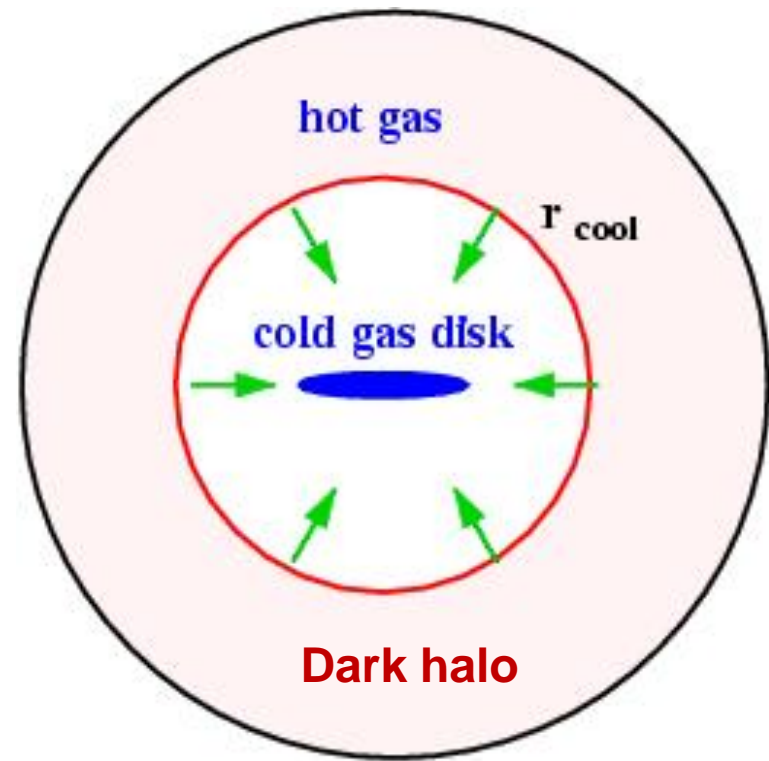


Modern framework of galaxy formation and evolution

In the gravitational potential wells
of Dark matter haloes, baryonic gas falls
and is heated to virial temperature

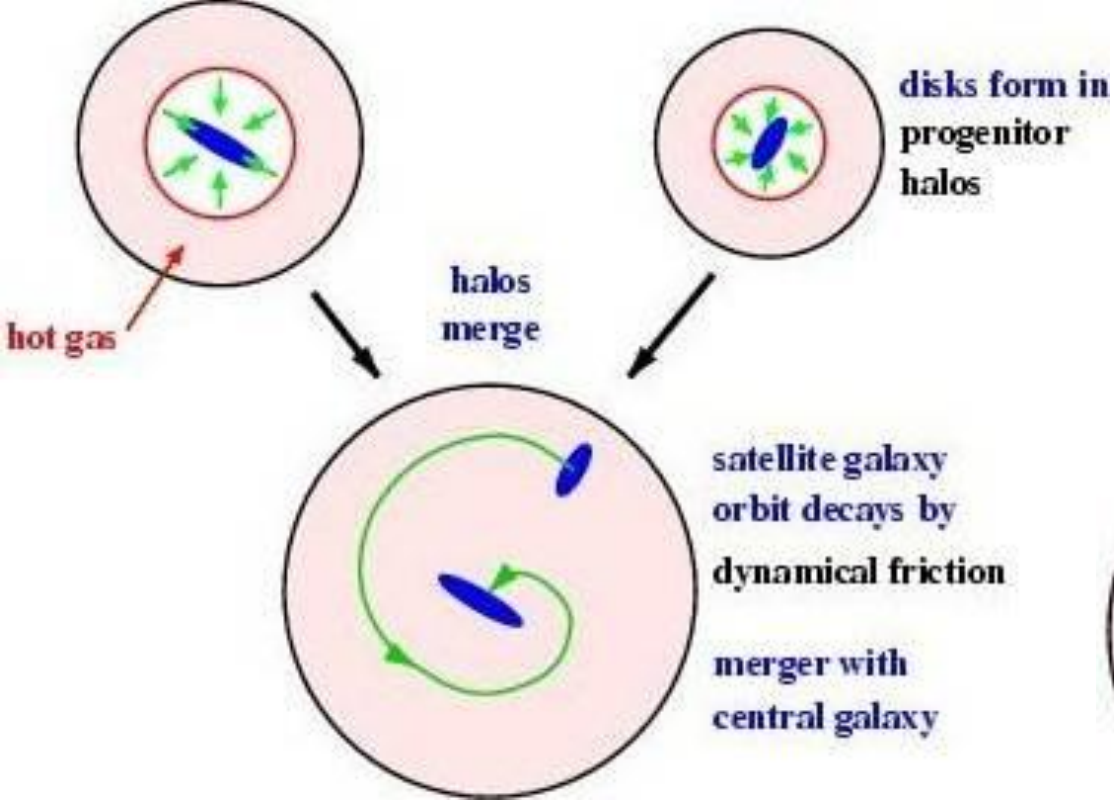
$$kT \sim \frac{1}{2} GM^2/R$$

It dissipates its energy by radiation
(cooling rate \propto density²)
and forms a gaseous disk

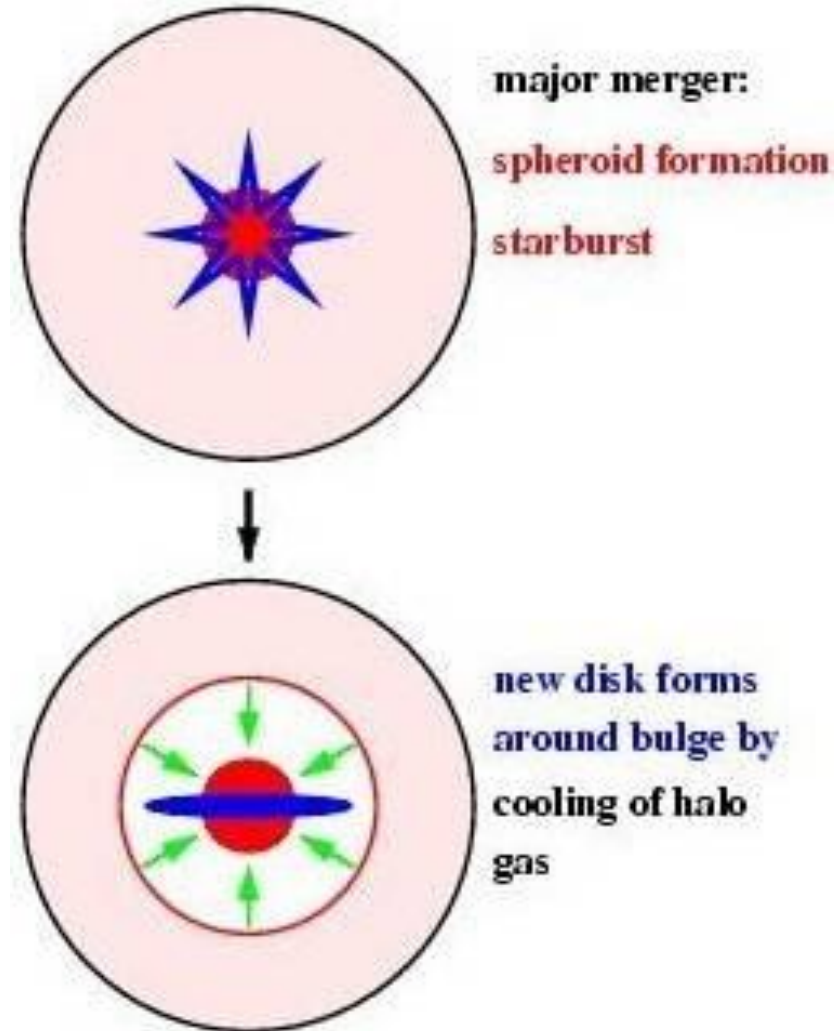


Stars are formed from cold gas
in the disk, inside-outwards

SN heat the gas (feed-back)
(perhaps) stopping temporarily
star formation and
(perhaps) driving galactic winds
and expelling material from
the galaxy



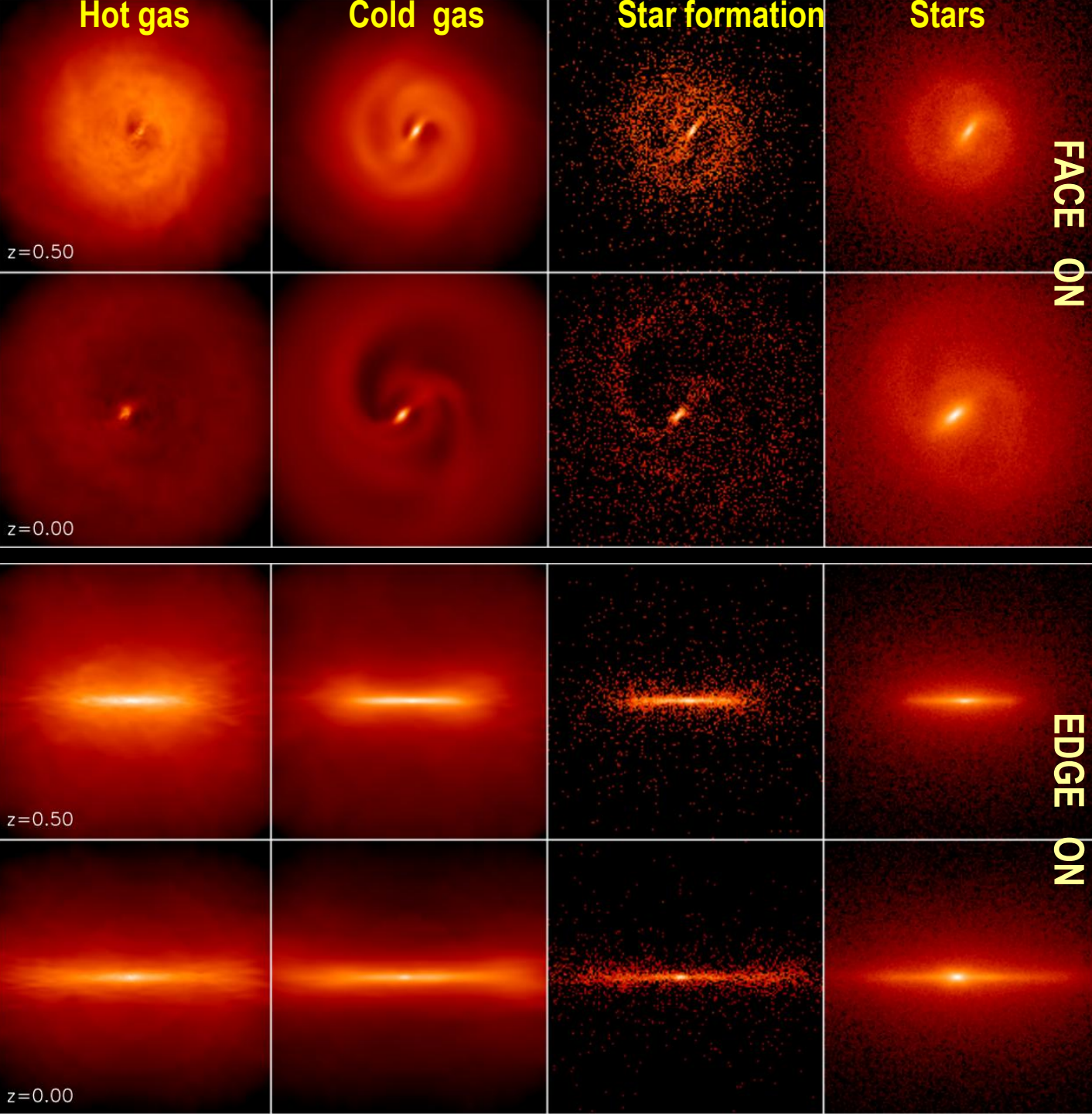
Galaxy interactions and mergers play a key role in the modern framework...



... at least for the formation of bulges and ellipticals

Disks have a more quiescent evolution

In any case, baryonic physics is very poorly understood at present



**Samland and Gerhard
2003**



The formation of a Milky Way like galaxy

Galaxy formation simulations created at the

N-body shop

makers of quality galaxies

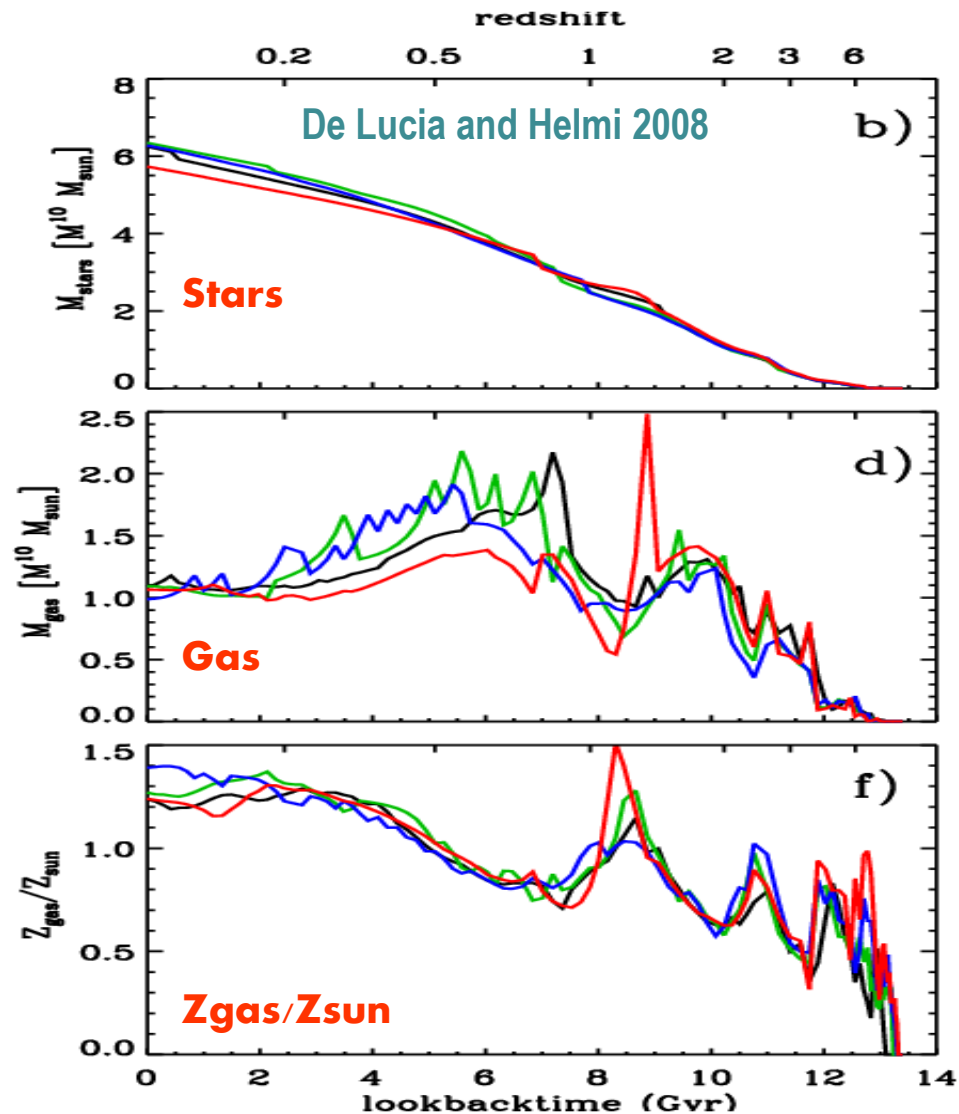
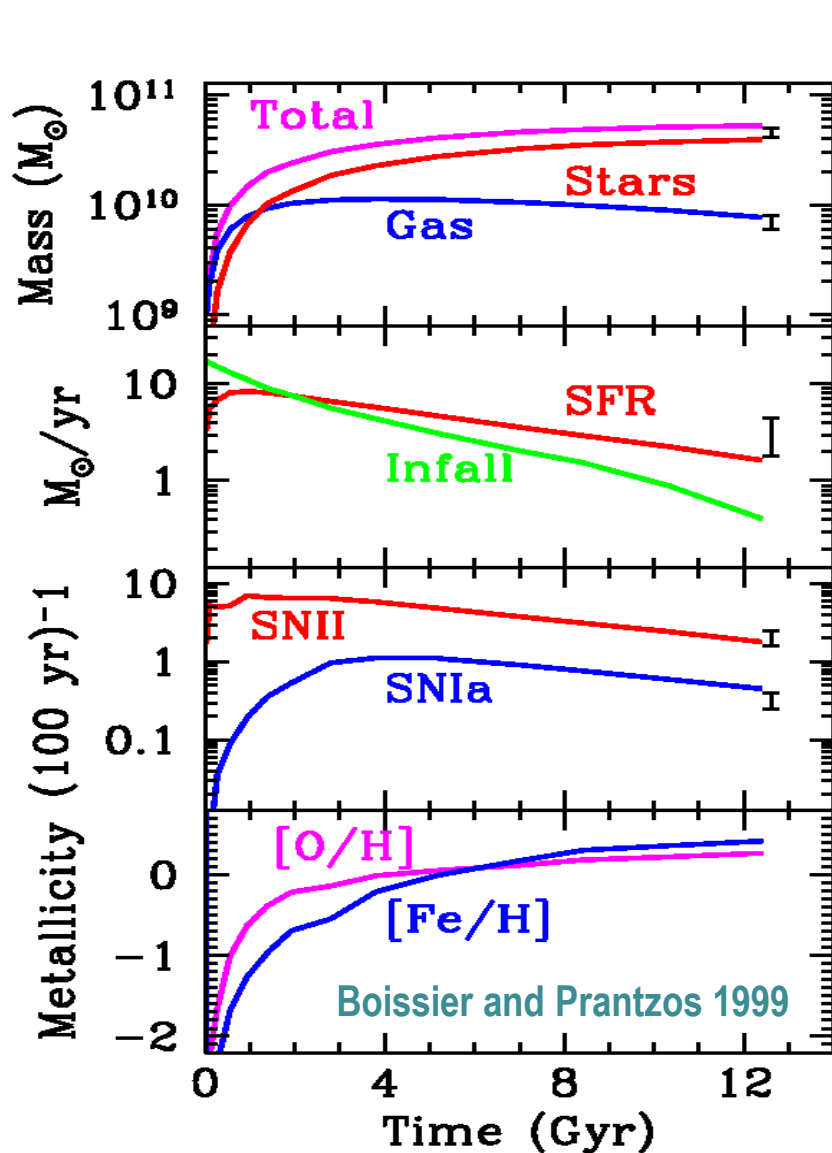
key: gas- green new stars- blue old stars- red

credits: Fabio Governato (University of Washington)
Chris Brook (University of Washington)
James Wadsely (McMaster University)

simulation run at the CINECA supercomputing center, (BO, Italy)
contact: fabio@astro.washington.edu

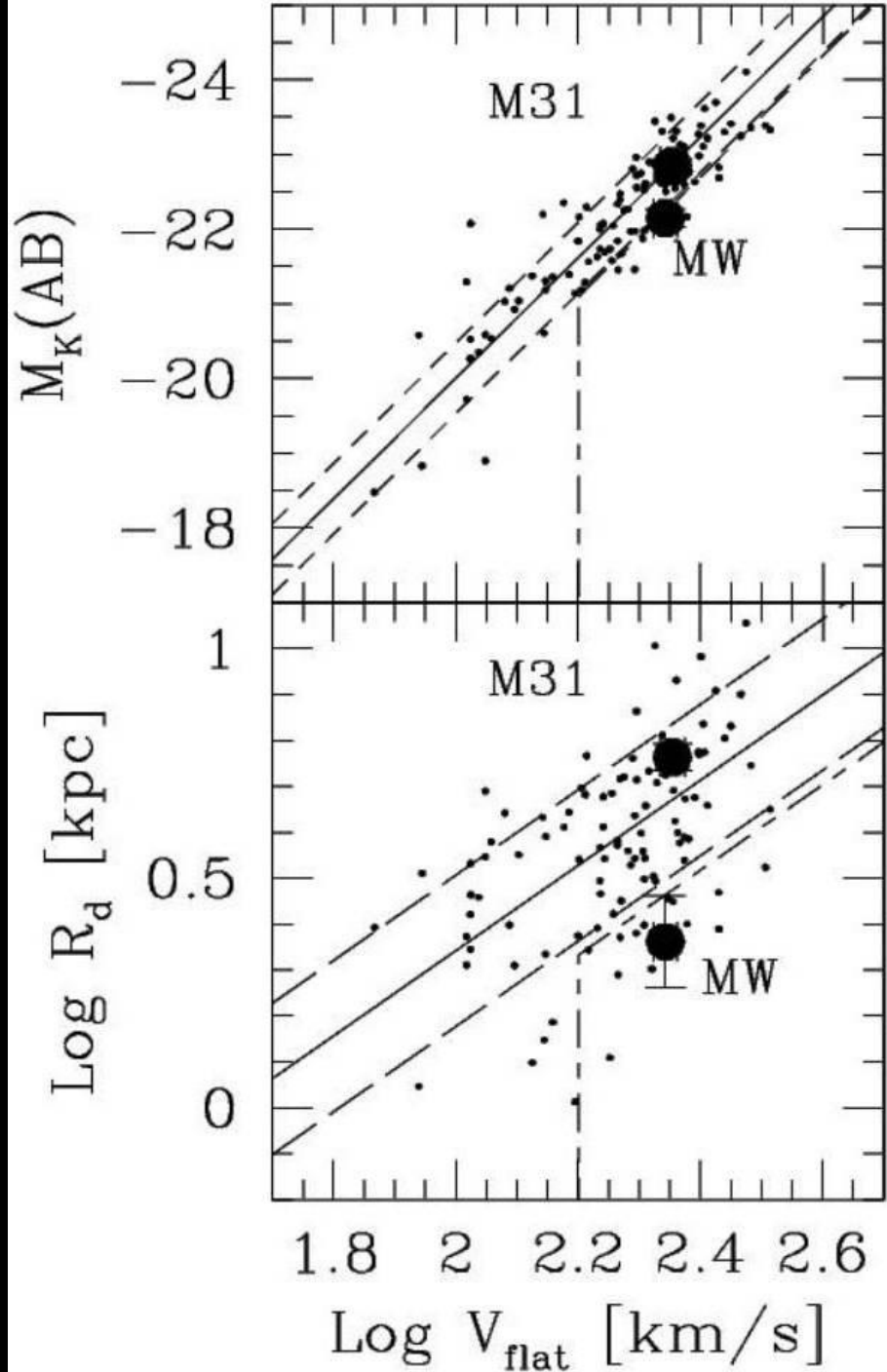
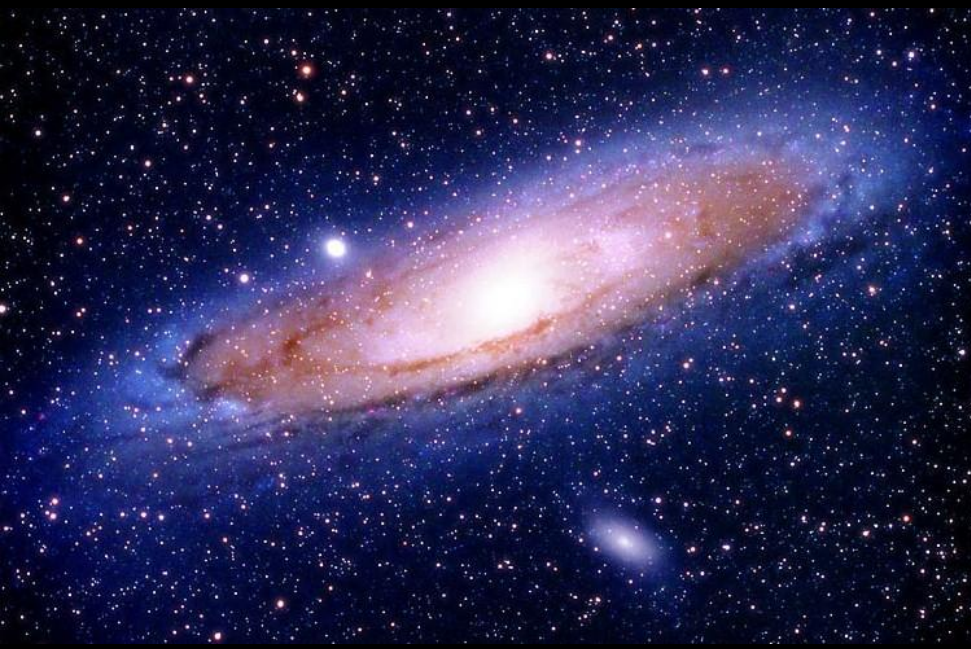
HISTORY OF MILKY WAY DISK... IN THE PAST 10 GYR

M_{STARS} increased by 3-4 ; M_{GAS} remained \sim constant ; Z_{GAS} increased by 2-3



“Old” models constitute a not such a bad approximation of the real (?) situation

How special is the MW ?



Our understanding / modelling of galactic astrophysics (galaxy structure / evolution) is far behind the corresponding ones in stellar astrophysics

| | Star | Galaxy |
|---------------------------------------|---|--|
| Driver of evolution | <p>Nuclear reaction rates</p> <p>$NRR = f(T, \rho, X)$ <i>Well known</i></p> | <p>Star Formation Rate</p> <p>$SFR = f(\text{Gas} \dots \dots \dots)$ <i>Unknown</i></p> |
| Main observational constraints | <p>Hertzsprung–Russel diagram</p> <p><i>Well understood</i></p> | <p>Hubble diagram (?)</p> <p><i>Not yet understood</i></p> |
| Boundary conditions | <p>Zero Age Main Sequence</p> <p><i>Formation / Environment unimportant (except close binaries)</i></p> | <p>Cosmological fluctuation spectrum</p> <p><i>Formation / Environment generally important : gas/star accretion; galaxy interactions</i></p> |

Aims of Galactic Chemical Evolution (GCE) studies

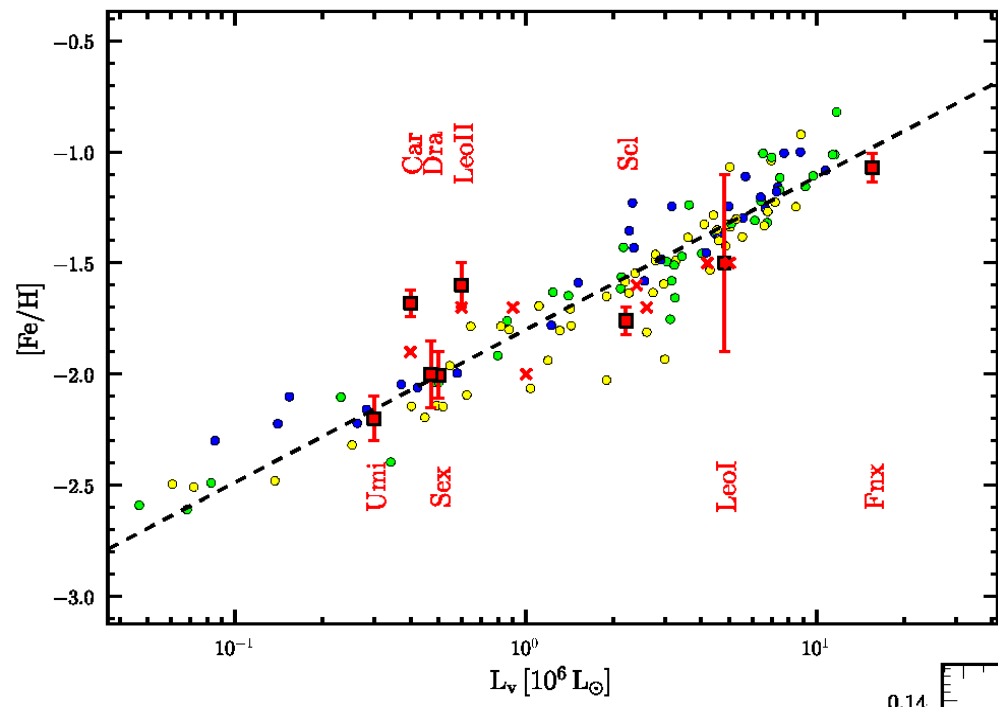
To check / constrain our understanding of stellar nucleosynthesis (i.e. stellar yields), either *statistically* (mean, dispersion) or in *individual objects*

To establish a chronology of events in a given system
e.g. *when* metallicity reached a given value, or *when* some stellar source (SNIa, AGB etc.) became important contributor to the abundance of a given isotope / element

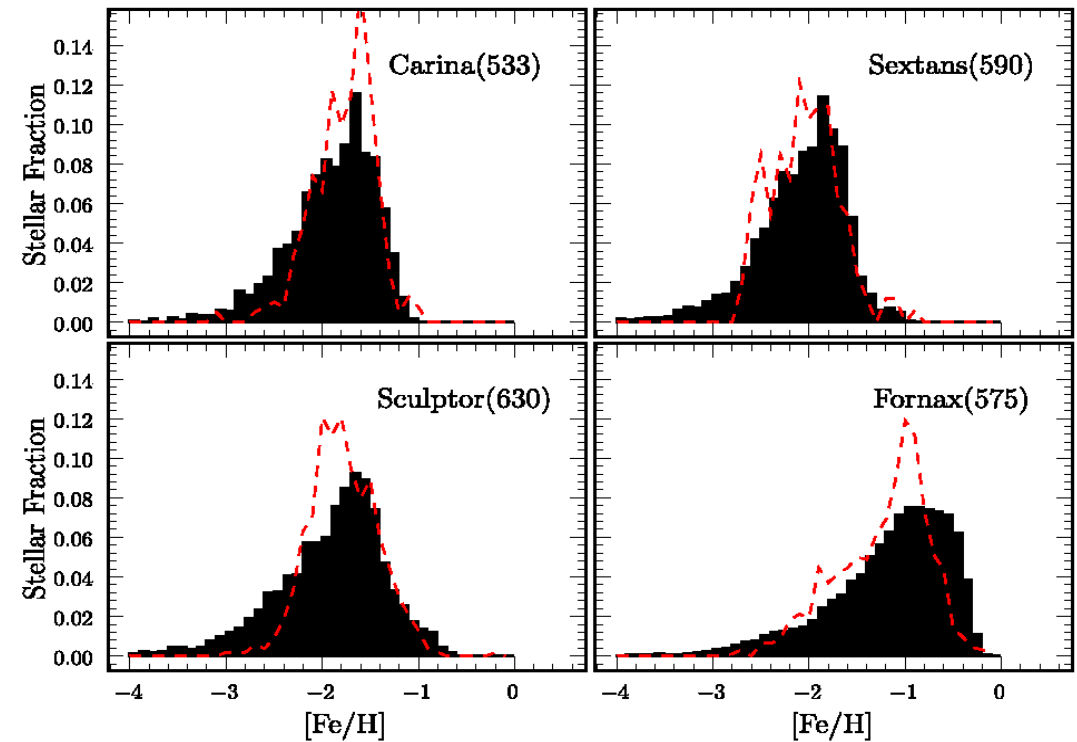
To infer how a system was formed
(*Star Formation Rate, large scale gas movements*)
e.g. slow infall of gas in case of solar neighborhood

In the future, GCE should be used combined to spectrophotometric and dynamical evolution in a cosmological framework for a full understanding of galaxy formation and evolution
WE ARE NOT YET AT THAT POINT

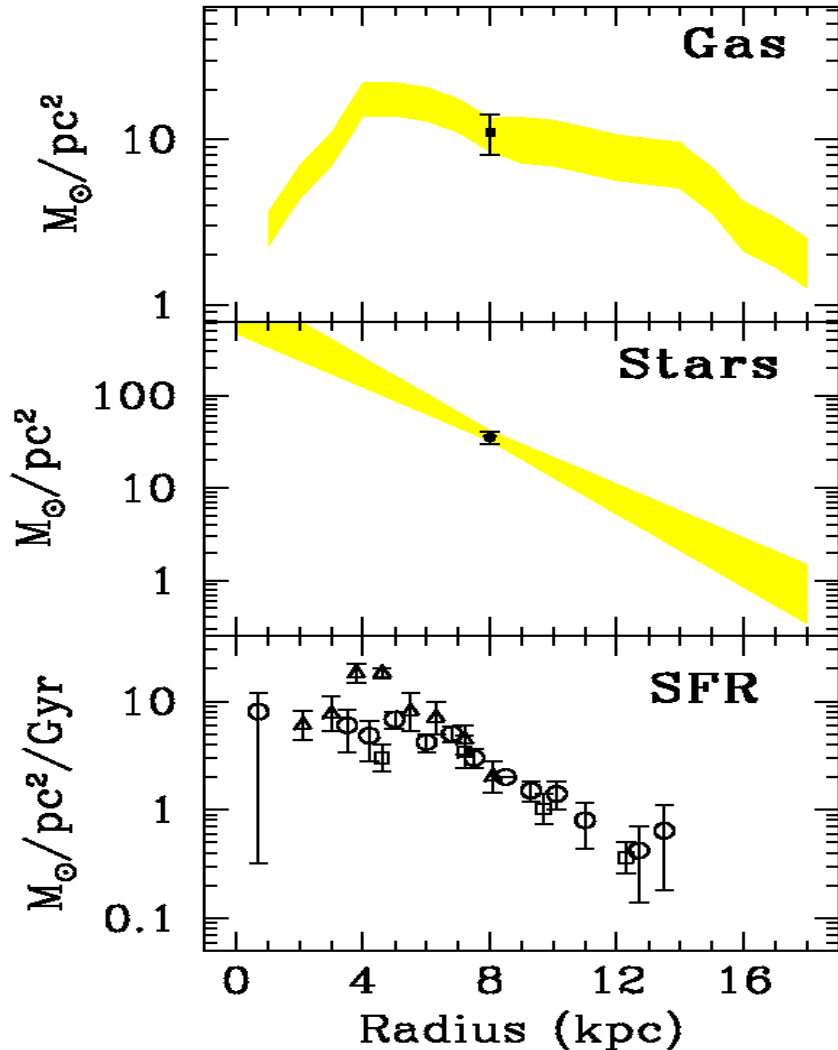
Metallicity – luminosity relationship



Metallicity distributions of dwarf galaxies



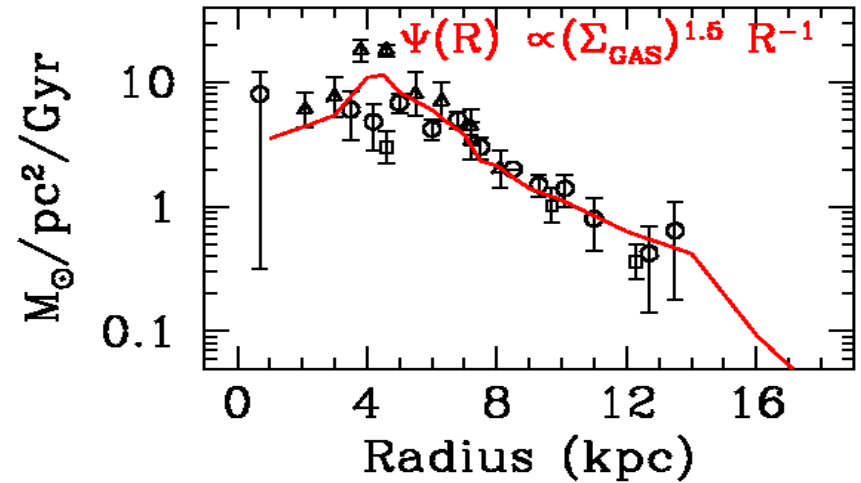
The Milky Way disk: (3) Star formation rate



SFR profile compatible with theory of SF induced by spiral density waves

$$\text{SFR} \propto \Omega = V/R \propto R^{-1}$$

(Onihishi 1975; Wyse and Silk 1986)



Also: compatible with observations of SFR profiles in nearby spirals (Boissier et al. 2003)