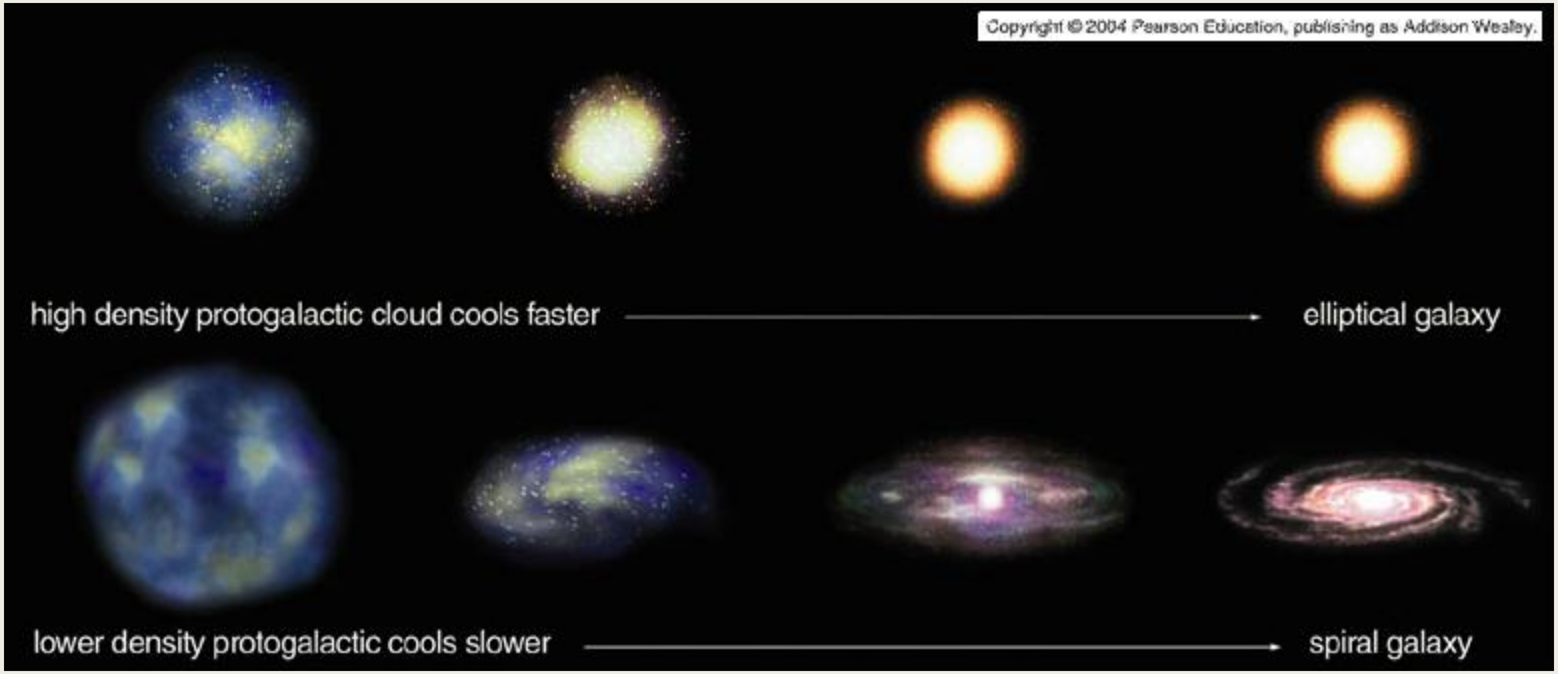
GALACTIC CHEMICAL EVOLUTION
I.

Lezione VIII- Fisica delle Galassie
Pagel “Nucleosynthesis and Chemical evolution of Galaxies”, cap. 8
And
“The Formation and
Evolution of the Milky Way”
C. Chiappini 2001

Laura Magrini

Aims of a Galactic chemical evolution model (GCE)

- Describe the spatial and temporal evolution:
  - *Star formation process*
  - ***Gas** and stellar content*
  - *Chemical composition and dust*



Ingredients of a Galactic chemical evolution model (GCE)

- Initial conditions: how galaxies are assembled
- Star formation model: how the gas is transformed into stars
- The initial mass function: which stars are formed from gas
- The stellar yields: AGB, Type II and Ia Supernova-different progenitors
- The different stellar life-times: time scales of ISM pollution
- Pristine or enriched gas accretion (Infall)
- Outflows (Supernovas and AGN feedbacks)

Ingredients of a Galactic chemical evolution model (GCE)

- Initial conditions: Initial conditions:
  - → *Usually assumes that in a galaxy all the mass is initially in the form of gas*
  - → *Primordial composition: abundances from Big Bang nucleosynthesis*

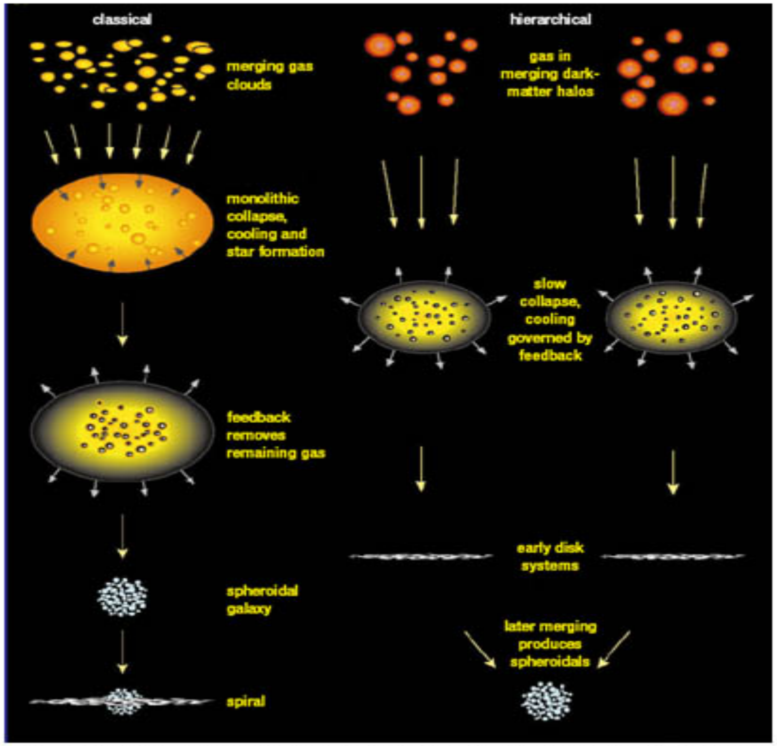


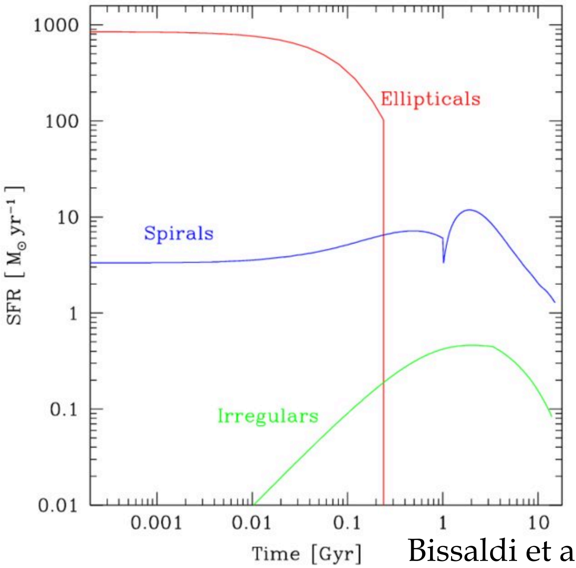
Figure 1: The two competing models of galaxy formation and evolution that could produce the galaxies we observe today. The classical 'top down' or monolithic model is shown on the left. This involves the collapse of a large cloud over time. The hierarchical or 'bottom up' model is shown on the right and involves successive mergers of small bodies[1].¶

How initial condition are settled has important cosmological implications

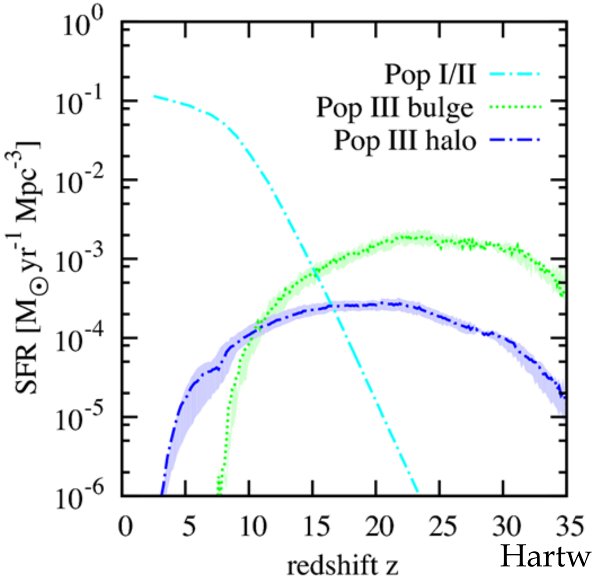
- Classical monolithical collapse → no pre-enrichment
- Hierarchical assembly → gas enriched in previous small galaxies in which star formation was activated

Ingredients of a Galactic chemical evolution model (GCE)

- Star formation rate (SFR):
  - → *How much gas is converted into stars per years ($M_\odot$/yr)?*
    - → *$SFR=f(t, M_{gas}, \rho_{gas})$*
    - → *Depends on galaxy type (Elliptical, Spiral, …)*
    - → *within a galaxy, depends on the galactic component (disc, halo, bulge)*



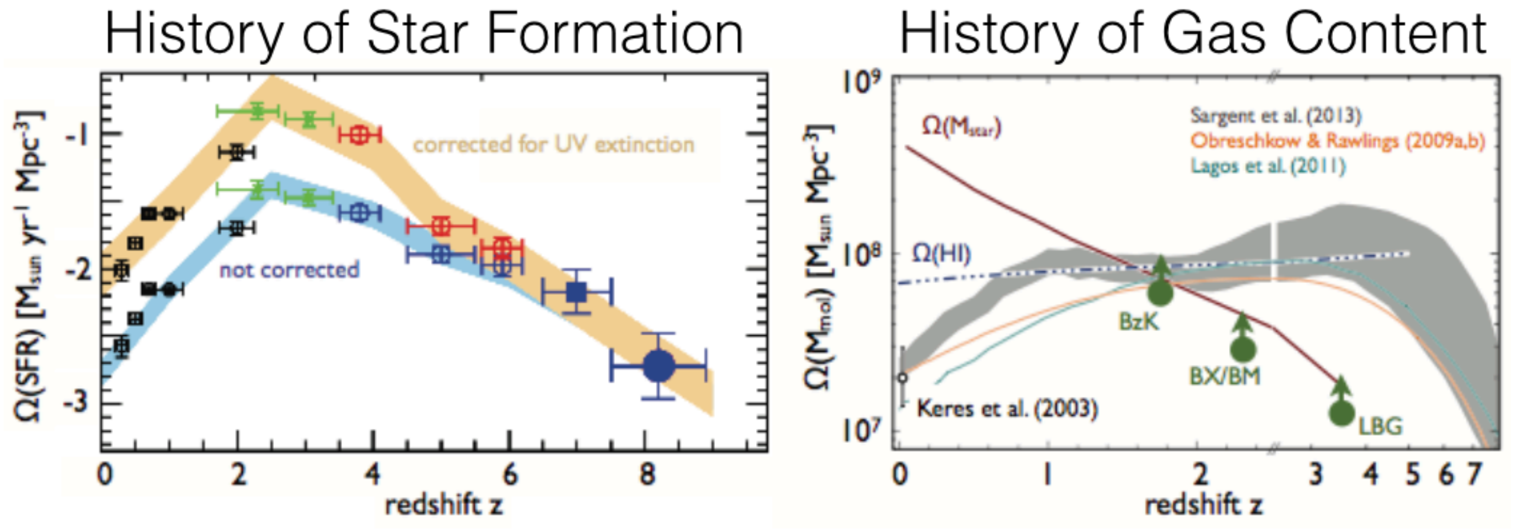
Bissaldi et al. 2007



Hartwig et al. 2015

Ingredients of a Galactic chemical evolution model (GCE)

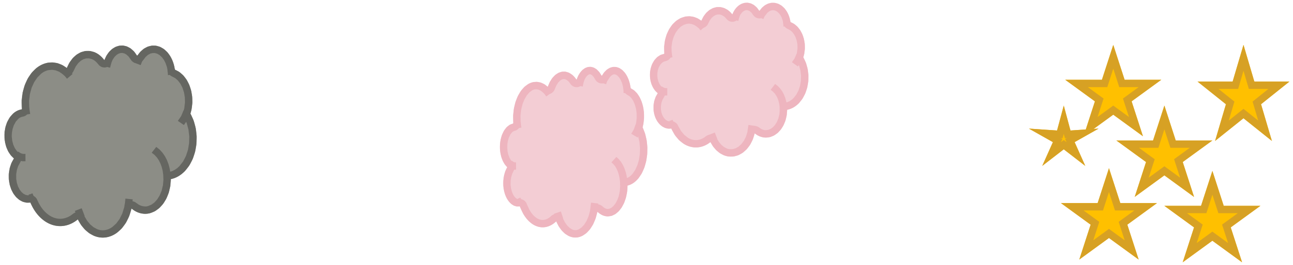
- Universal Star formation rate (SFR):
- total star formation rate density (SFRD) of the universe as a function of redshift as traced by deep UV/optical surveys and molecular gas content of galaxies − the fuel for star formation



Casey et al. 2015

Ingredients of a Galactic chemical evolution model (GCE)

- Star formation rate (SFR):
- How it can be approximated in GCE models



Atomic gas (g) → Molecular clouds (c) → Stars (s)

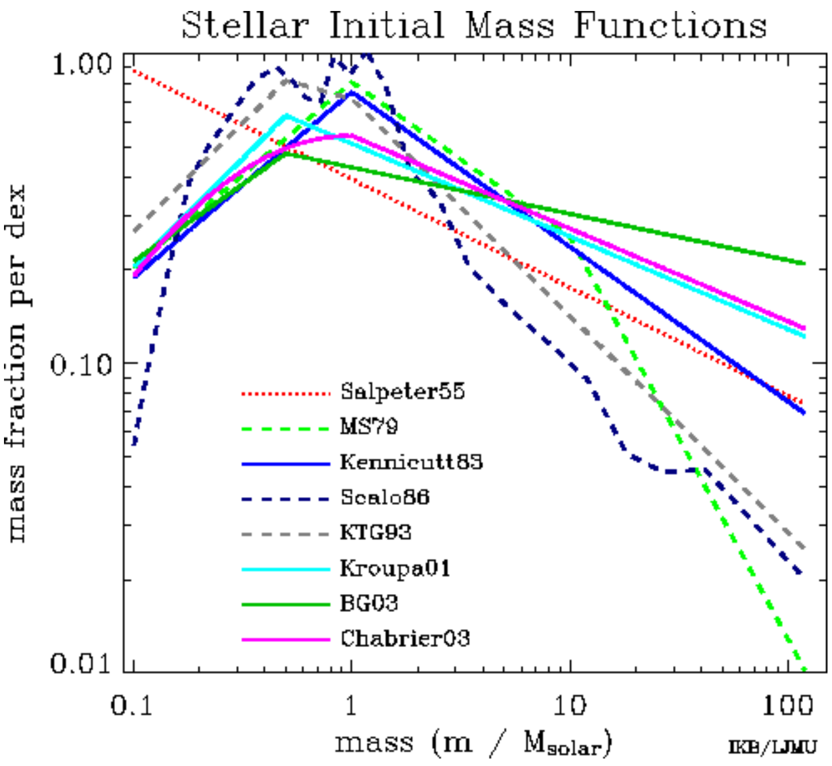
From atomic to molecular gas → $\propto g^{n}$ with $n \sim 1.5$ (Kennitcut-Schmidt law)

From molecular gas to stars → $\propto c^{2}$ cloud collisions (mainly in spiral arms)

Ingredients of a Galactic chemical evolution model (GCE)

- Initial mass function (IMF):

  → *Relative birth of stars with different initial masses*



- For M > 1 (with M initial stellar mass in $M_\odot$) the IMF is approximately a power law:

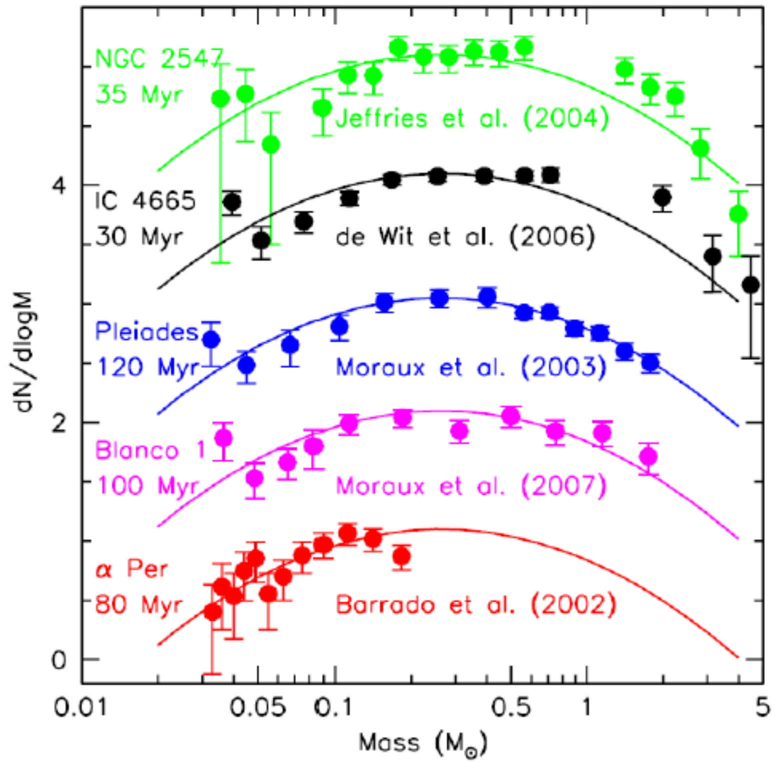
$$\phi(m)=dN/dm=m^{-(1+x)}$$

with x from 1.2 to 1.7

- Different parametrizations of the IMF imply different balance between low-mass and high-mass stars
- Different evolution → different chemical products

Ingredients of a Galactic chemical evolution model (GCE)

- Initial mass function (IMF):



E. Moraux

Studies of the field, local young clusters and associations, and old globular clusters suggest that the vast majority were drawn from a "universal" IMF (Bastian et al. 2010)

However….

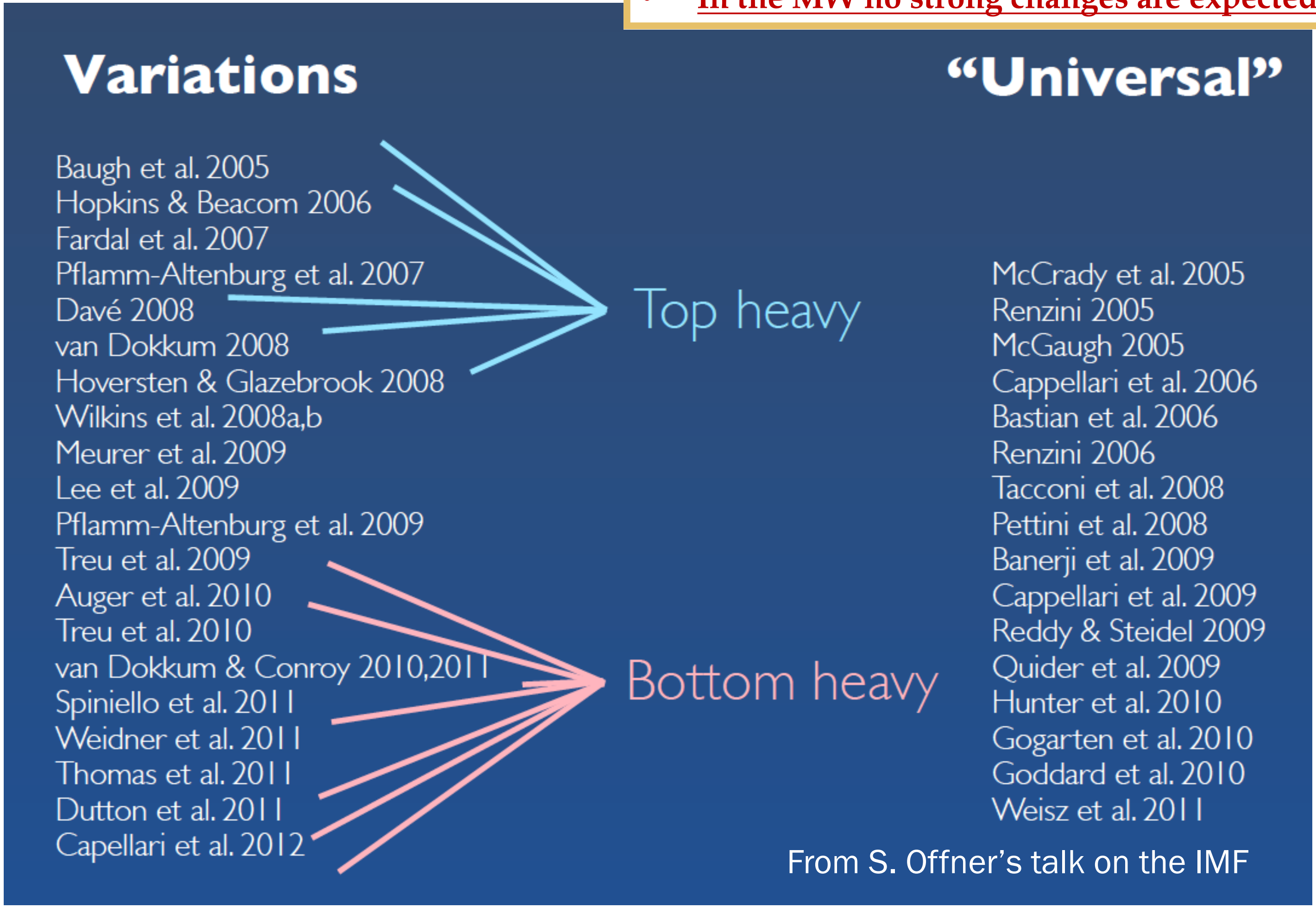
we do not know what happens in different conditions (e.g., other galaxies, different regions of our Galaxy, etc.)

Ingredients of a Galactic chemical evolution model (GCE)

From models:

- Initial mass function (IMF):

- Variation in metallicity by a factor of 20 does not change the IMF
- Need to go to much lower metallicities $(< 10^{-5} Z_{\odot})$ before changes are seen
- **In the MW no strong changes are expected**



Variations

Baugh et al. 2005
Hopkins & Beacom 2006
Fardal et al. 2007
Pflamm-Altenburg et al. 2007
Davé 2008
van Dokkum 2008
Hoversten & Glazebrook 2008
Wilkins et al. 2008a,b
Meurer et al. 2009
Lee et al. 2009
Pflamm-Altenburg et al. 2009
Treu et al. 2009
Auger et al. 2010
Treu et al. 2010
van Dokkum & Conroy 2010,2011
Spiniello et al. 2011
Weidner et al. 2011
Thomas et al. 2011
Dutton et al. 2011
Capellari et al. 2012

Top heavy

Bottom heavy

"Universal"

McCrady et al. 2005
Renzini 2005
McGaugh 2005
Cappellari et al. 2006
Bastian et al. 2006
Renzini 2006
Tacconi et al. 2008
Pettini et al. 2008
Banerji et al. 2009
Cappellari et al. 2009
Reddy & Steidel 2009
Quider et al. 2009
Hunter et al. 2010
Gogarten et al. 2010
Goddard et al. 2010
Weisz et al. 2011

From S. Offner's talk on the IMF

Ingredients of a Galactic chemical evolution model (GCE)

- Products of stellar evolution:

Three classes of stars:

1. Massive stars:

→ $M > 8\ M_\odot$ and lifetime $< 10^8$ yr

→ compared to the Galactic timescale, instantaneously recycle their ejecta (SNe, stellar winds) after they form

2. Intermediate-mass stars:

→ $1\ M_\odot < M < 8\ M_\odot$ and 10^8 yr < lifetime < 10^{10} yr

→ **significant delay in recycling their ejecta**

3. Low-mass stars:

→ $M < 1\ M_\odot$ and lifetime $> 10^{10}$ yr

→ do not evolve and recycle, only serve to lock up gas (but act as important tracers of the chemical history of the Galaxy)

Ingredients of a Galactic chemical evolution model (GCE)

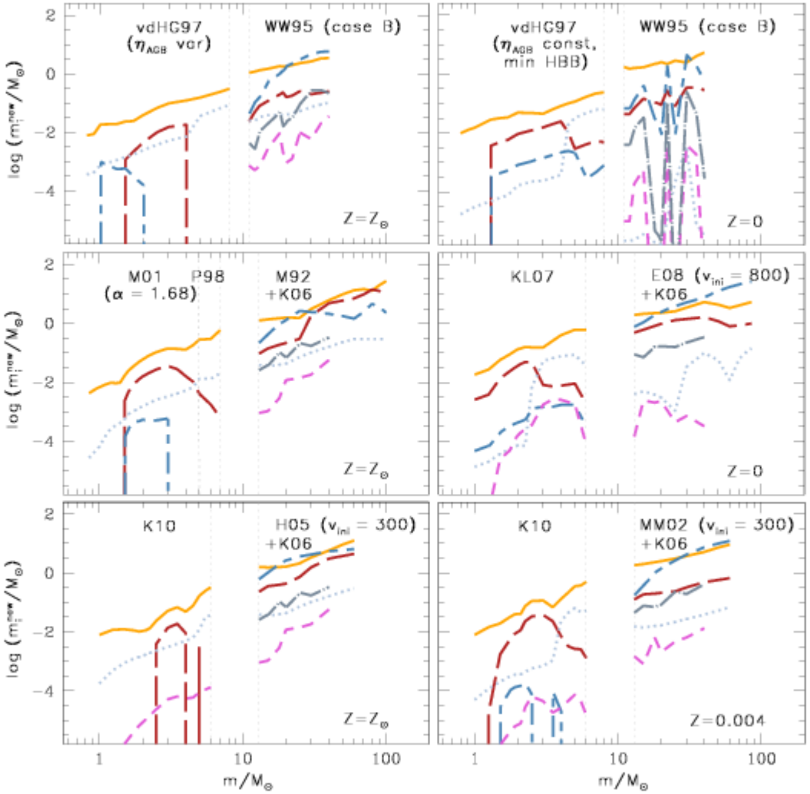
- Products of stellar evolution:

For a star of given initial mass and metallicity:

- how much mass is ejected into the ISM at the end of their evolution?

- He
- C
- N
- O
- Na
- Mg

- Ejected masses of newly produced elements as a function of the stellar initial mass, from different authors



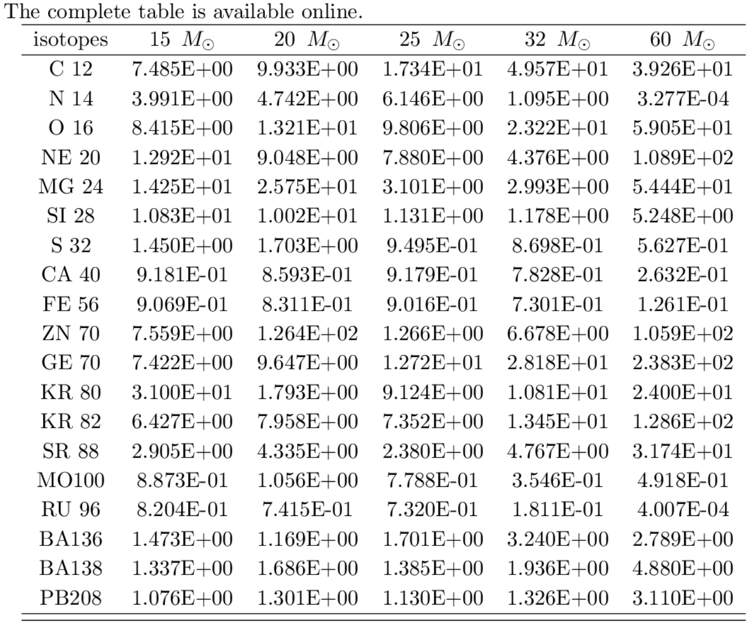
Romano et al. (2010)

Ingredients of a Galactic chemical evolution model (GCE)

- Products of stellar evolution:

For a star of given initial mass and metallicity:

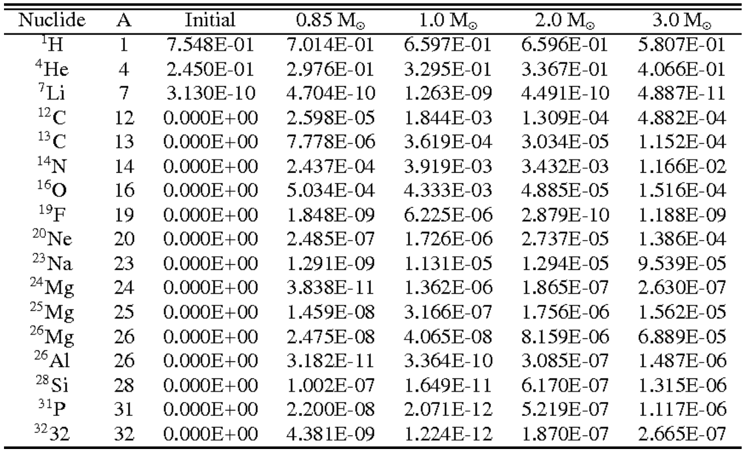
- in the form of which elements/isotopes?



The complete table is available online.

isotopes	15 $M_\odot$	20 $M_\odot$	25 $M_\odot$	32 $M_\odot$	60 $M_\odot$
C 12	7.485E+00	9.933E+00	1.734E+01	4.957E+01	3.926E+01
N 14	3.991E+00	4.742E+00	6.146E+00	1.095E+00	3.277E-04
O 16	8.415E+00	1.321E+01	9.806E+00	2.322E+01	5.905E+01
NE 20	1.292E+01	9.048E+00	7.880E+00	4.376E+00	1.089E+02
MG 24	1.425E+01	2.575E+01	3.101E+00	2.993E+00	5.444E+01
SI 28	1.083E+01	1.002E+01	1.131E+00	1.178E+00	5.248E+00
S 32	1.450E+00	1.703E+00	9.495E-01	8.698E-01	5.627E-01
CA 40	9.181E-01	8.593E-01	9.179E-01	7.828E-01	2.632E-01
FE 56	9.069E-01	8.311E-01	9.016E-01	7.301E-01	1.261E-01
ZN 70	7.559E+00	1.264E+02	1.266E+00	6.678E+00	1.059E+02
GE 70	7.422E+00	9.647E+00	1.272E+01	2.818E+01	2.383E+02
KR 80	3.100E+01	1.793E+00	9.124E+00	1.081E+01	2.400E+01
KR 82	6.427E+00	7.958E+00	7.352E+00	1.345E+01	1.286E+02
SR 88	2.905E+00	4.335E+00	2.380E+00	4.767E+00	3.174E+01
MO100	8.873E-01	1.056E+00	7.788E-01	3.546E-01	4.918E-01
RU 96	8.204E-01	7.415E-01	7.320E-01	1.811E-01	4.007E-04
BA136	1.473E+00	1.169E+00	1.701E+00	3.240E+00	2.789E+00
BA138	1.337E+00	1.686E+00	1.385E+00	1.936E+00	4.880E+00
PB208	1.076E+00	1.301E+00	1.130E+00	1.326E+00	3.110E+00

Pignatari et al. 2016



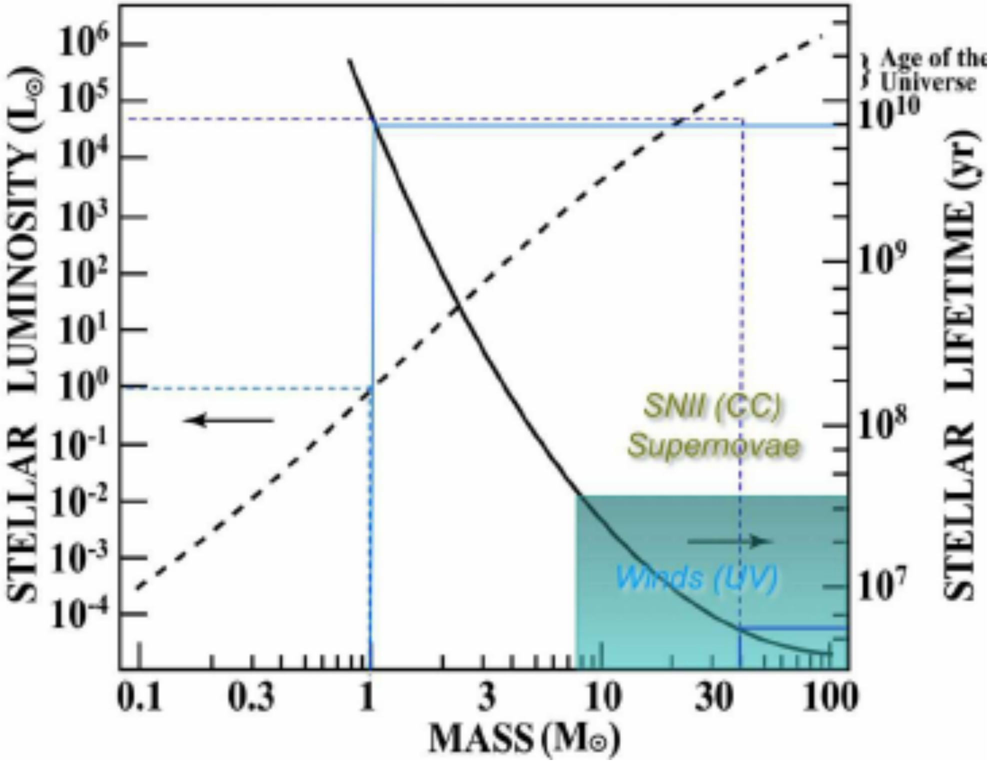
Nuclide	A	Initial	0.85 $M_\odot$	1.0 $M_\odot$	2.0 $M_\odot$	3.0 $M_\odot$
^{1}H	1	7.548E-01	7.014E-01	6.597E-01	6.596E-01	5.807E-01
^{4}He	4	2.450E-01	2.976E-01	3.295E-01	3.367E-01	4.066E-01
^{7}Li	7	3.130E-10	4.704E-10	1.263E-09	4.491E-10	4.887E-11
^{12}C	12	0.000E+00	2.598E-05	1.844E-03	1.309E-04	4.882E-04
^{13}C	13	0.000E+00	7.778E-06	3.619E-04	3.034E-05	1.152E-04
^{14}N	14	0.000E+00	2.437E-04	3.919E-03	3.432E-03	1.166E-02
^{16}O	16	0.000E+00	5.034E-04	4.333E-03	4.885E-05	1.516E-04
^{19}F	19	0.000E+00	1.848E-09	6.225E-06	2.879E-10	1.188E-09
^{20}Ne	20	0.000E+00	2.485E-07	1.726E-06	2.737E-05	1.386E-04
^{23}Na	23	0.000E+00	1.291E-09	1.131E-05	1.294E-05	9.539E-05
^{24}Mg	24	0.000E+00	3.838E-11	1.362E-06	1.865E-07	2.630E-07
^{25}Mg	25	0.000E+00	1.459E-08	3.166E-07	1.756E-06	1.562E-05
^{26}Mg	26	0.000E+00	2.475E-08	4.065E-08	8.159E-06	6.889E-05
^{26}Al	26	0.000E+00	3.182E-11	3.364E-10	3.085E-07	1.487E-06
^{28}Si	28	0.000E+00	1.002E-07	1.649E-11	6.170E-07	1.315E-06
^{31}P	31	0.000E+00	2.200E-08	2.071E-12	5.219E-07	1.117E-06
^{32}32	32	0.000E+00	4.381E-09	1.224E-12	1.870E-07	2.665E-07

Ingredients of a Galactic chemical evolution model (GCE)

- Products of stellar evolution:

For a star of given initial mass and metallicity:

- after how much time?



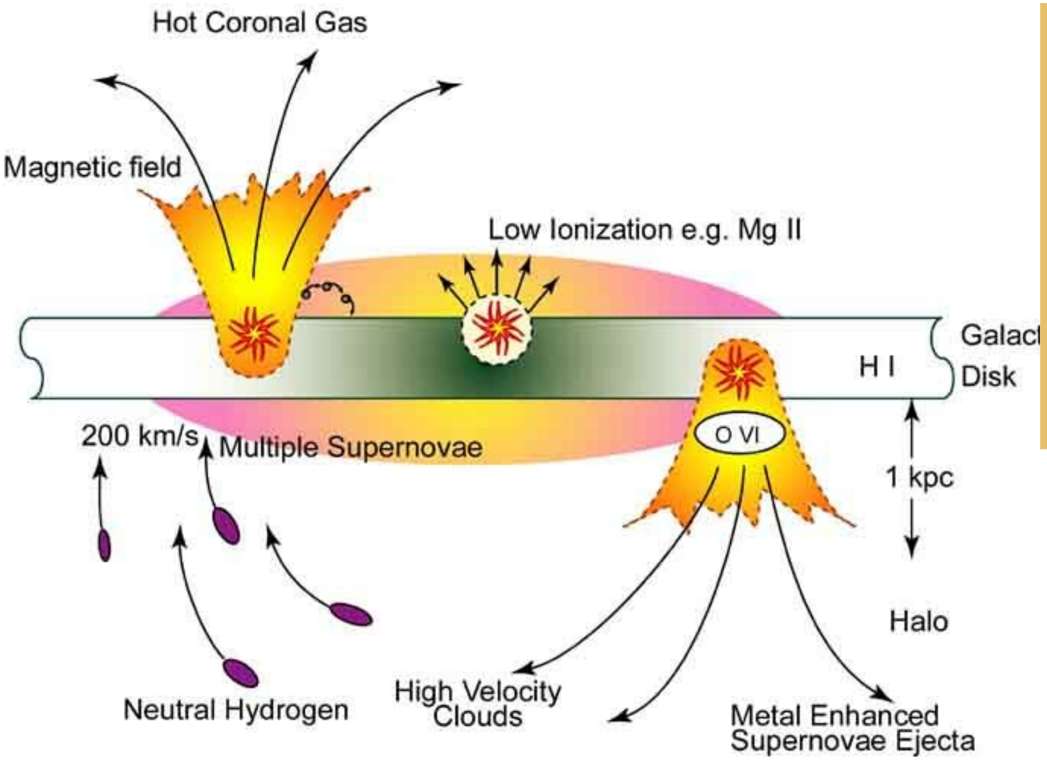
Montmerle 2011

Ingredients of a Galactic chemical evolution model (GCE)

- General Galactic processes:

– *mixing between different phases of the interstellar medium,*

– *large-scale flows within the galaxy and exchange of material with the intergalactic medium.*



Supernova explosions can break through the galactic disk and inject hot gas into a galactic corona

- driving a "Galactic fountain", wherein the gas cools and condenses
- recycles matter into the Galactic disk

FIMS, Space Science Lab, NASA

GCE basic equations:

- The variables of the system:

- *The total mass of the system M*→ only baryonic mass, non-baryonic dark matter is not considered
- *The mass fraction of 'gas', g* [in some models divided by phases, atomic and molecular gas]
- *The mass fraction of stars, s* → includes also remnants, as white dwarfs and neutron stars
- *The abundance, Z, of a given element*

- Mass equations:

$$M=g+s$$

$$dM/dt=F-E$$

where

- F is the rate of accretion of material from outside the system (infall)
- E is the ejection rate, e.g. in a galactic wind

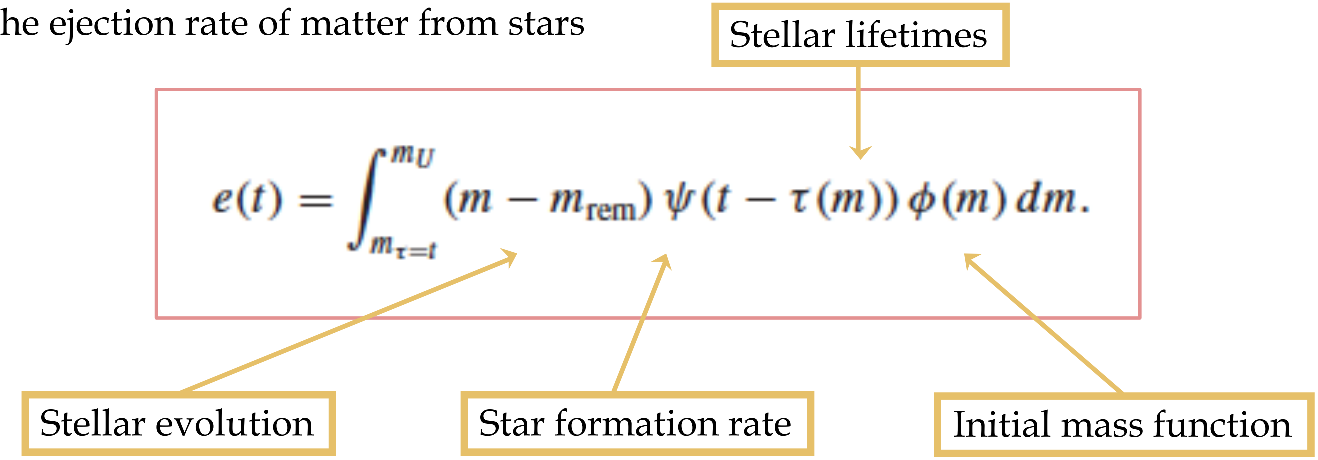
GCE basic equations:

- Gas equation:

$$dg/dt=F-E+e-\psi$$

where

- ○ ψ is the Star Formation Rate (SFR) by mass
- ○ e is the ejection rate of matter from stars



Stellar lifetimes

$$e(t)=\int_{m_{\tau=t}}^{m_U}(m-m_{\mathrm{rem}})\,\psi(t-\tau(m))\,\phi(m)\,dm.$$

Stellar evolution

Star formation rate

Initial mass function

GCE basic equations:

- Star equation:

$$ds/dt = \psi - e$$

where

- ψ is the Star Formation Rate (SFR) by mass
- e is the ejection rate of matter from stars

- Note that the gas and star equations are coupled:

$$dg/dt = F - E + e - \psi \quad \text{and} \quad ds/dt = \psi - e$$

→ *Gas is subtracted to form new stars*

→ *Evolved stars eject gas which is injected in the interstellar medium*

GCE basic equations:

- Metallicity equation:

$$\frac{d}{dt}(gZ) = e_Z - Z\psi + Z_F F - Z_E E$$

where

- *e_z is the total amount of the element ejected from stars*
- *$Z\psi$ is the loss of the considered element to the ISM due to star formation*
- *$Z_F F$ is the addition to the element abundance from inflowing material*
- *Z_E E is the loss by a galactic wind*

e_z (t) element ejected from stars

SFR

Lifetime

IMF

$$e_Z(t) = \int_{m_{\tau=t}}^{m_U} [(m - m_{\rm rem})Z(t - \tau(m)) + mq_Z(m)]\,\psi(t - \tau(m))\,\phi(m)dm$$

Recycling without production

Newly produced and ejected material

GCE basic equations:

- Return fraction (R) and lock-up fraction (α=1-R)

R is the mass fraction of a generation of stars that is returned to the interstellar medium, and it increases with time as progressively smaller stars complete their evolution, while α correspondingly decreases

Lock-up fraction

$$\alpha = 1 - F_M(> m_\tau) + \int_{m_\tau}^{m_U} m_{\mathrm{rem}}(m)\,\phi(m)dm,$$

Fraction returned to gas

Fraction in remnants

- Where the mass fraction FM of a generation of stars that is born with stellar masses above some limit is:

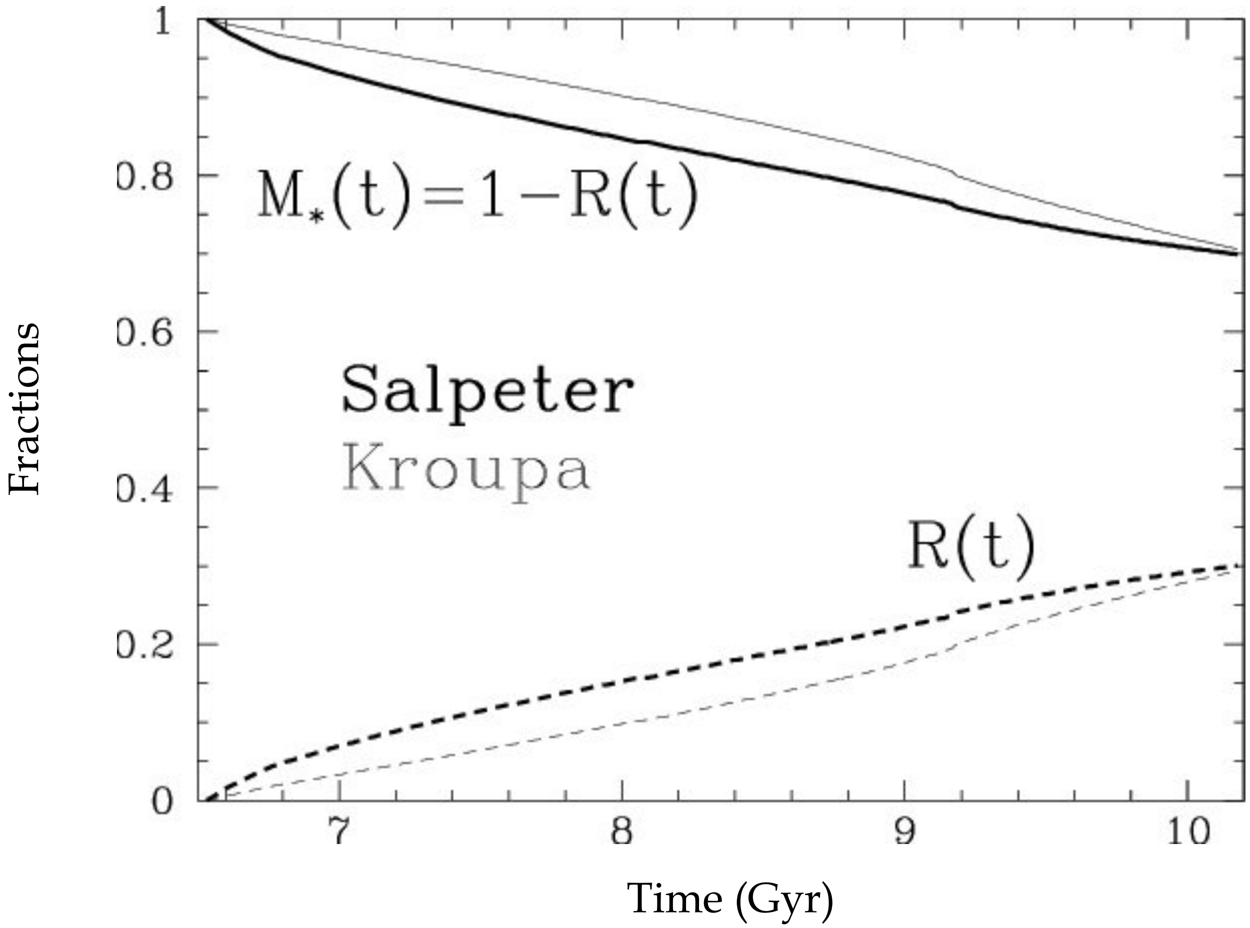
$$F_M(> m) = \int_{m}^{m_U} m'\phi(m')dm'.$$

Mass fraction of stars above a certain mass, that will evolve, and release their mass in the ISM

- Stars with lifetime shorter than the age of the system (so they have time to evolve…and to eject processed gas in the ISM)

GCE basic equations:

- Return fraction (R) and lock-up fraction α=1-R



Locked in long=living stars and in remnants→ decreases with time

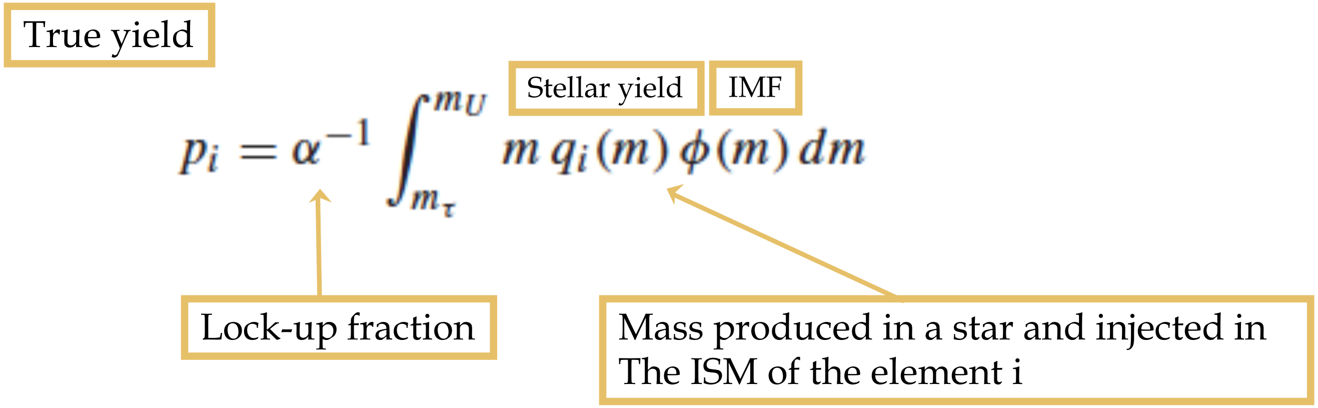
Returned to the ISM → increases with time

Portinari+03

GCE basic equations:

- True yield

The yield p of primary elements produced by massive stars, e.g. oxygen, which is defined as the **mass of element freshly produced and ejected by a generation of stars** in units of the mass that remains locked in long-lived stars and compact remnants **(lock-up fraction)**



True yield

Stellar yield

IMF

$$p_i = \alpha^{-1} \int_{m_\tau}^{m_U} m\, q_i(m)\, \phi(m)\, dm$$

Lock-up fraction

Mass produced in a star and injected in
The ISM of the element i

For instance, for oxygen the true yield is 0.006.

It means that 0.6% of the mass of stars in a generation is ejected in the ISM as oxygen

The instantaneous recycling approximation (IRA)

- It assumes that all processes **involving stellar evolution, nucleosynthesis and recycling take place instantaneously on the timescale of galactic evolution**

- It is often quite good for products of massive-star evolution, like oxygen

- But it not adequate for elements like: iron, nitrogen, s-process → produced on time-scales of several Gyr

- In the instantaneous recycling approximation (IRA):

  → α (lock-up mass in form of stars) and p (yields of ejected elements in the ISM) do not depend explicitly on time

  → stellar evolution timescales are considered negligible

The instantaneous recycling approximation

$$M(t) = s(t) + g(t) = M_0 - M_{\rm ej} + M_{\rm accr}$$

The total mass of the galaxy

$$dg/dt = F - E - ds/dt$$

The differential equation for the gas

with F infall and E outflow

→ the stellar lifetimes do not appear

→ The gas is expelled from stars without any delay

$$s(t) = \alpha S(t),$$

S(t) is the mass of all stars born up to t,

s(t) is the mass still in form of stars or remnants

α lockup fraction

New production

Lock-up in stars

Infall

$$\frac{d}{dS}(gZ) = q + RZ - Z - Z_E \frac{E}{\psi} + Z_F \frac{F}{\psi}$$

Abundance of an element

Recycling from evolved stars

Ejection

The time-delay and the IRA approaches

As a function of time

$$\frac{d}{dt}(gZ) = e_Z - Z\psi + Z_F F - Z_E E$$

$$e_Z(t) = \int_{m_{\tau=t}}^{m_U} [(m - m_{\mathrm{rem}})Z(t - \tau(m)) + m q_Z(m)]\, \psi(t - \tau(m))\, \phi(m) dm$$

Recycling without production

Newly produced and ejected material

As a function of S

New production

Lock-up in stars

Infall

$$\frac{d}{dS}(gZ) = q + RZ - Z - Z_E \frac{E}{\psi} + Z_F \frac{F}{\psi}$$

Recycling

Ejection

Abundance of an element

The I.R.A. states that all the stars with masses < 1 $M_\odot$ live forever but also that the stars with masses > 1 $M_\odot$ die instantaneously (poor approximation)

The simple model

Assumptions of the **Simple model**:

1. The system is isolated with a constant total mass, i.e. no inflows or outflows

$$g(t) + s(t) = M = \text{const.}$$

2. The system is well mixed at all times (for gas and new stars)

3. The system starts as pure gas with primordial abundances, i.e.

$$g(0) = M; \quad Z(0) = S(0) = 0.$$

4. The IMF and nucleosynthetic yields of stars with given initial mass are unchanged

The simple model

The equations of the Simple model:

$$dg = -ds$$

→ In the Simple Model (with IRA)

$$g\frac{dZ}{ds} = p + (Z_F - Z)\,\cancel{\frac{dM_{\text{accr}}}{ds}}.$$

IRA model with inflow and outflow

$$g\frac{dZ}{ds} = p + \cancel{(Z_F - Z)}\,\cancel{\frac{dM_{\text{accr}}}{ds}}.$$

Simple model with IRA

P →mass of element freshly produced and ejected by a generation of stars

The simple model

The equations of the Simple model for the gas:

$$g\frac{dZ}{ds} = -g\frac{dZ}{dg} = p,$$

→ In the Simple Model (with IRA)

→ Integrating:

$$Z = -p ln\frac{g(t)}{g(0)} = -p ln \mu$$

→with μ gas fraction M/g

→ g(0) is the total mass of the system (no exchanges)→ initial mass=final mass=g(t)+s(t)=g(0)

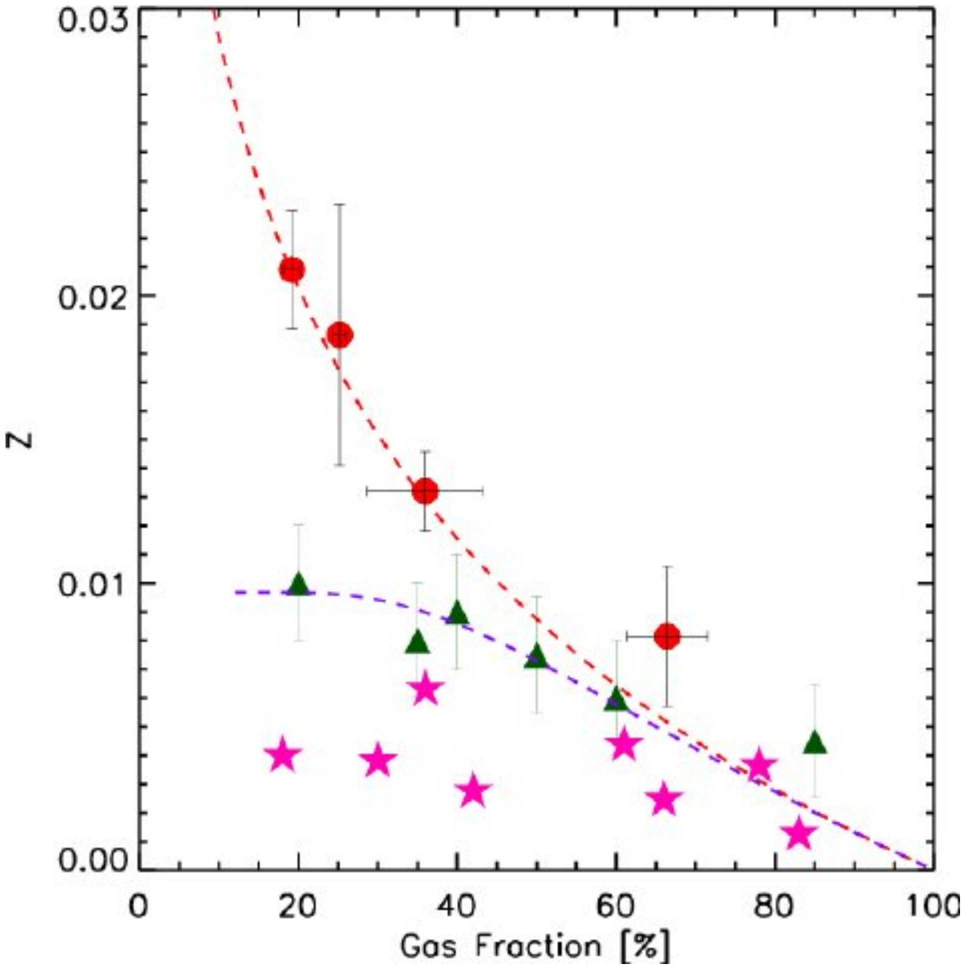
$$Z = p\ ln\ (M/g)$$

$$Z = p\ ln\ (1/\mu)$$

The abundance (Z) in the gas increases with decreasing gas fraction

The simple model

- **the observed metallicity of the <u>gas</u> in the system is directly related to the logarithm of the fraction of the mass still remaining in gaseous form** (defined as μ)



→ Simple model

→ Infall model

→ The red dashed line is the theoretical relation in the case of a closed-box model [Simple model]

→ The violet dashed line is a model with infall and outflow

<u>**Comparison with observations indicates that the simple model does not work in many cases**</u>

The simple model

The equations of the Simple model for the stars:

The Mean Stellar Metallicity

→ For the average abundance of a stellar population

$$\langle z \rangle = \frac{1}{s}\int_0^s z(s')ds' = 1 + \frac{\mu \ln \mu}{1-\mu}$$

$$\rightarrow 1, \quad \text{for } \mu < 0.1$$

With z=Z/p and p is the true yield

This means that the mean metallicity of a system, *Z*, approaches the yield, *p*, as the gas is used up, so the gas fraction goes toward zero.

The simple model

The equations of the Simple model for the stars:

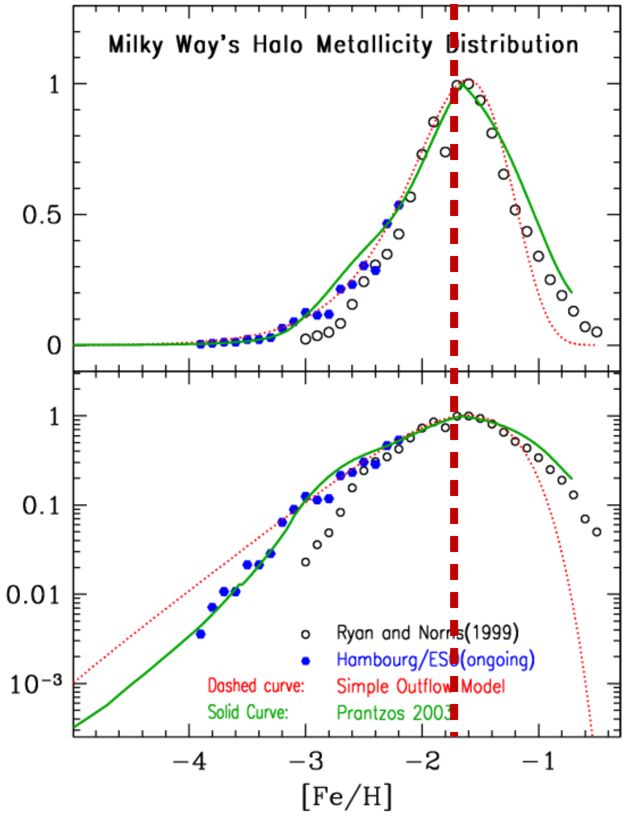
The Mean Metallicity Problem: why is it a ‘problem’?

→ Then why **don't** the halo, disk populations, dSph galaxies, all of which have μ nearly or equal to zero, have **exactly the same MDF**?

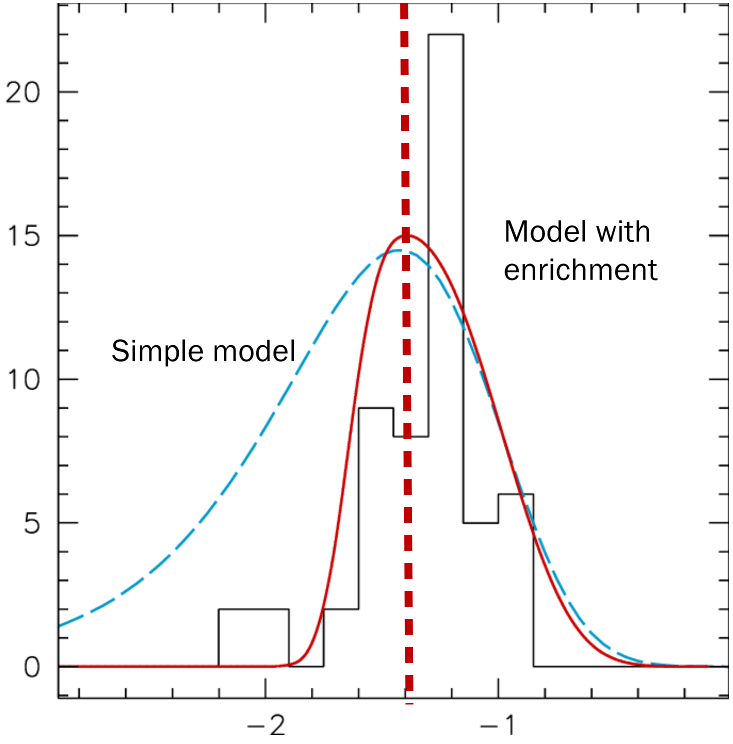
- The obvious differences in the MDFs of the different stellar populations points to the fact that a **"closed-box" treatment is not appropriate for each of these populations** (considered separately).
- Clearly the differences can be explained if the different populations, and especially the halo, lost gas and therefore was not able to reach the same net metal production as it would had it retained gas.
- Similarly, for dwarf Spheroidal galaxies, gas must have been lost during their evolution.
- → *see next plots*

The simple model

The Mean Metallicity Problem: why is it a ‘problem’?



Differential metallicity distribution of field halo stars in linear and logarithmic scales. Data are from Ryan and Norris (1991) and the Hamburg/ESO project



The MDF of Leo I RGB stars on the [M/H] metallicity scale, compared with a simple model with a low effective yield (dashed line) and a model with a prompt initial enrichment (solid line). (from Gullieuszik et al. 2009)

The leaky model

The Mean Metallicity Problem: why is it a ‘problem’?

The can be solved with modifications to the closed box scenario that allows outflows and inflows of gas, as a ***leaky box model*** where some mass is driven out from the system, i.e. from supernovae.

Usually, it is assumed that the rate at which supernovae drive gas out of the system is a function of the star formation rate:

$$M_{tot}(t)=M_{tot}(0)-\eta\ M_s(t)$$

where η is a constant

As in the closed box, we can compute the metallicity as a function of the gas fraction:

$$dZ/dg=-p/\mu\ 1/(1+\eta)$$

Where p is the yield, μ is the gas fraction and η is the outflow rate

The leaky model

The Mean Metallicity Problem: why is it a ‘problem’?

The leaky model

The mean stellar metallicity is:

$$\overline{Z}_s = \frac{p}{1+\eta}$$

- if the system loses no gas, η = 0 and we have the simple (closed) box solution
- At the other extreme, if supernovae are efficient in removing gas, η >> 1 and the mean abundance becomes *p* / η (reduced effective yield).

Thus, the **effective yield declines as the metal-enriched gas leaves the system**.

The leaky model

The Mean Metallicity Problem: why is it a ‘problem’?

The leaky model

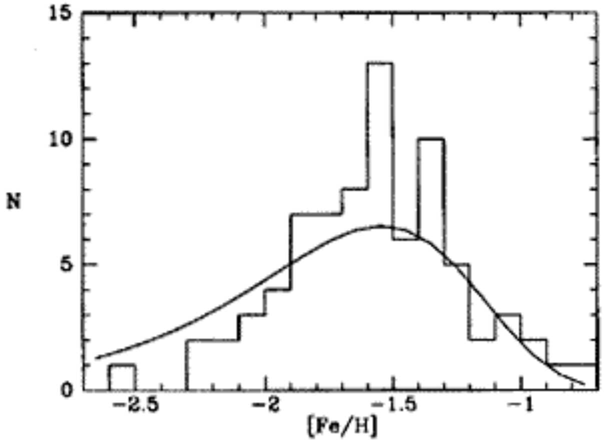


Figure 10.39 The metallicity distribution of the more metal-poor globular clusters shown in Figure 10.32 (histogram) is reasonably well fitted by the prediction [equation (5.43)] of the leaky-box model with effective yield $p_{\text{eff}} \equiv p/(1+c) = 5.7 \times 10^{-4}$ (curve).

if $p \sim 0.02$ (which is the solar abundance), then you find that for the same p you need a halo η of ten or more to get down to a halo mean metallicity.

The metallicity distribution for the halo can be reasonably explained with a leaky box model that has an effective yield of:

$$p_{eff} = p \,/\, (1 + \eta) = 5.7 \text{ x } 10^{-4}$$

The leaky model

Where has the Halo gas gone?

The leaky box model can explain the MDF of the halo. Where did all of that gas lost by the halo end up?

- The mass of bulge is close to estimated mass lost from halo (~2-3 x 10^{10} solar masses)
- The angular momentum distribution of the halo and bulge are more similar than are the halo and disk populations

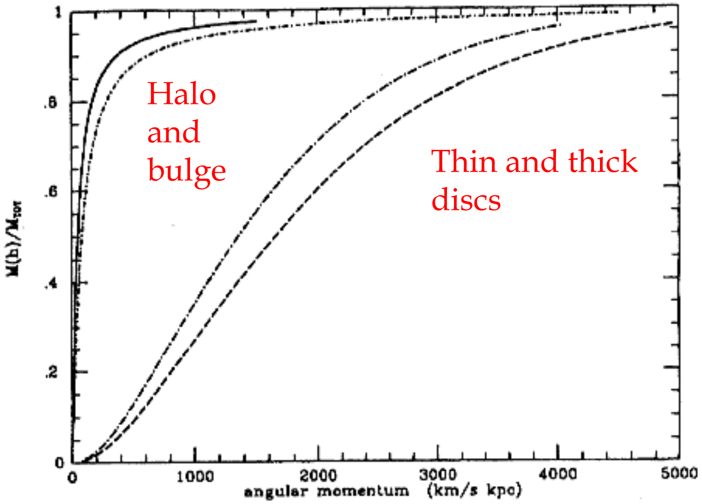
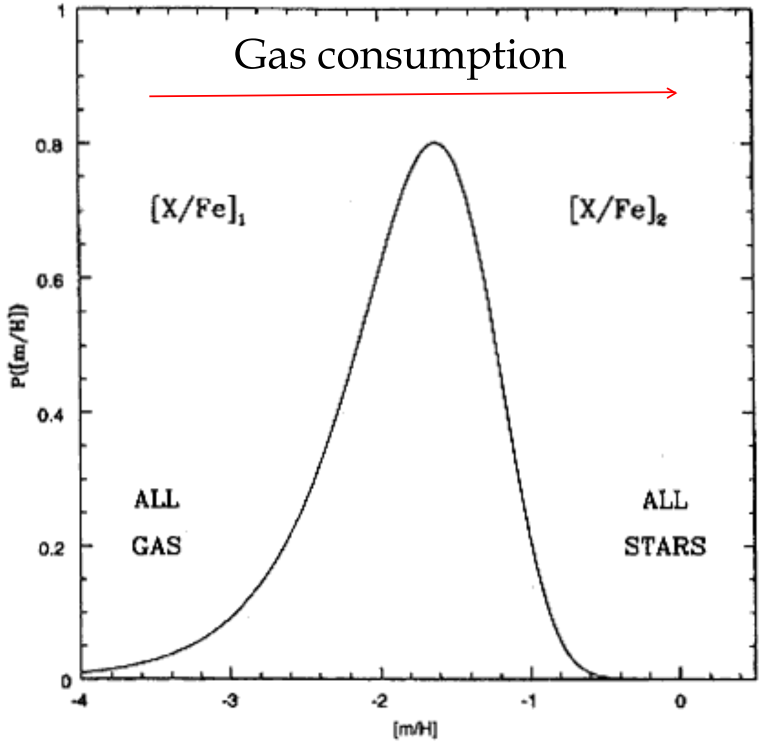


Fig. 35. The angular momentum distributions of the halo, bulge, and disk populations, according to Wyse & Gilmore (1992). The *solid line* is the normalized angular momentum distribution for the bulge, the *short dash-dot curve* is for the spheroid/halo, the *long dash-dot curve* is for the thick disk, and the *dashed line* is for the thin disk

The simple model

The Metallicity distribution function (MDF) in the MW disc



- Initially, the probability of finding a star of any metallicity, including low, is small.
- As more gas is converted into stars, the system becomes more enriched and the probability of finding a more enriched star increases.
- When more than half of the gas has been converted into stars, the number of stars of higher metallicity declines (less gas, less star formation).
- As the gas gets used up, fewer and fewer increasingly enriched stars can be made.
- **The final MDF has a long tail to *low* metallicities.**

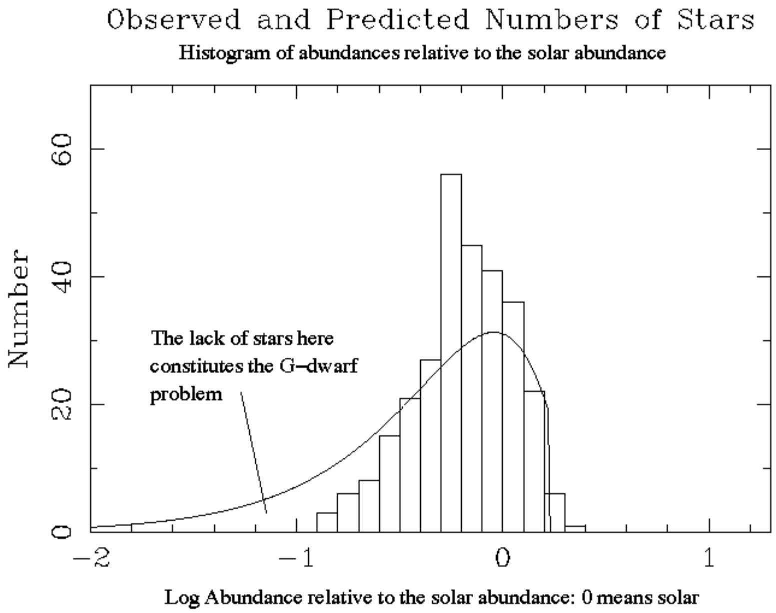
The simple model

The G-dwarfs problem

In the calculation for the solar neighborhood, where the gas fraction is μ ~ 0.1, we find that:

- about half of the stars in the solar neighborhood should have about 1/4 the metallicity of the most metal rich local stars ([Fe/H] ~ +0.2).
- Thus we expect about 1/2 of the local stars to have metallicity [Fe/H] < -0.4 or so.

Instead, we have far fewer than this



Failure of the simple model

The G-dwarfs problem

The observed lack of metal-poor stars in our Galaxy.

There are expected to be some stars that formed early in the life of our Galaxy and, if of less than one solar mass, have not yet evolved away from the Main Sequence.

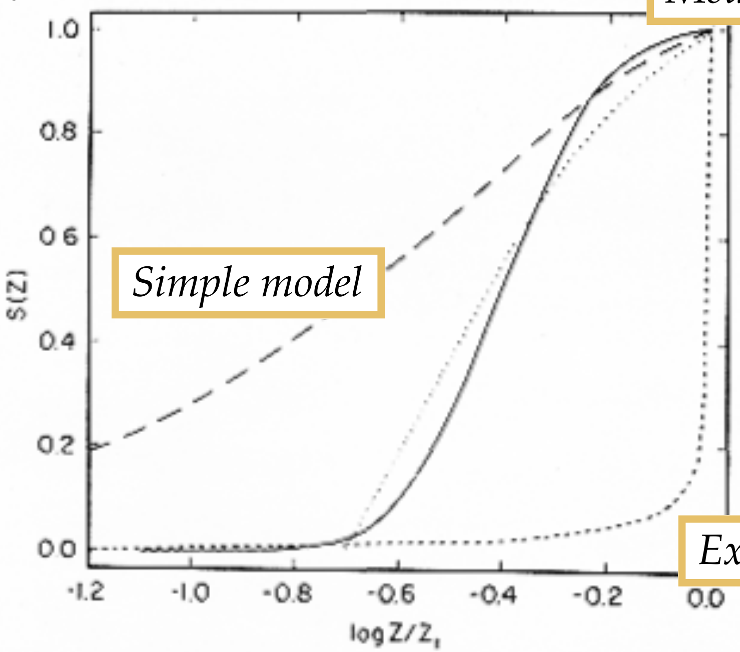
There should thus be a population of low-mass stars that display the very low metal abundances expected to be typical of the conditions at the time of the formation of the Galaxy.

The lack of observed stars of the expected metallicity can be explained relaxing the Simple model and allowing the **existence of slow infall of pre-enriched gas.**

Failure of the simple model

The G-dwarfs problem

Tinsley 1980



Model with gas pre-enriched

Simple model

Extreme infall model

FIGURE 8 Cumulative stellar metallicity distributions. $S(Z)$ is the fraction of stars that have metallicities $\leqslant Z$, with a maximum value Z_1. *Solid line:* log-normal representation of the data for stars in the solar neighborhood; Z_1 is taken as $2 \cdot Z_\odot$ since more metal-rich stars are very rare; $\langle \log Z/Z_\odot \rangle = -0.1$, and $\sigma(\log Z/Z_\odot) = 0.15$, allowing for observational errors (e.g., Pagel, 1979a). *Long dashes:* the "simple" model for chemical evolution (Section 4.2). *Short dashes:* an extreme infall model (Section 4.2.1). *Dots:* a model with a finite initial metallicity (Section 4.2.2).

Failure of the simple model

The G-dwarfs problem: possible solutions

i) A **variable yield**, p with Z, which is the same as saying that the IMF changes with metallicity.

- *bimodal star formation* where the early, metal-poor IMF only made higher mass stars, then the G-dwarf problem could be solved within a closed-box context.

ii) Infall of gas onto the disk.

iii) A **larger "closed-box" :**

Thin, thick discs, and halo considered together. That is, the thin disc gas started out ***pre-enriched.***

The "closed box" may have to be enlarged to be the Milky Way itself.

Failure of the simple model

The G-dwarfs problem: the infall solution

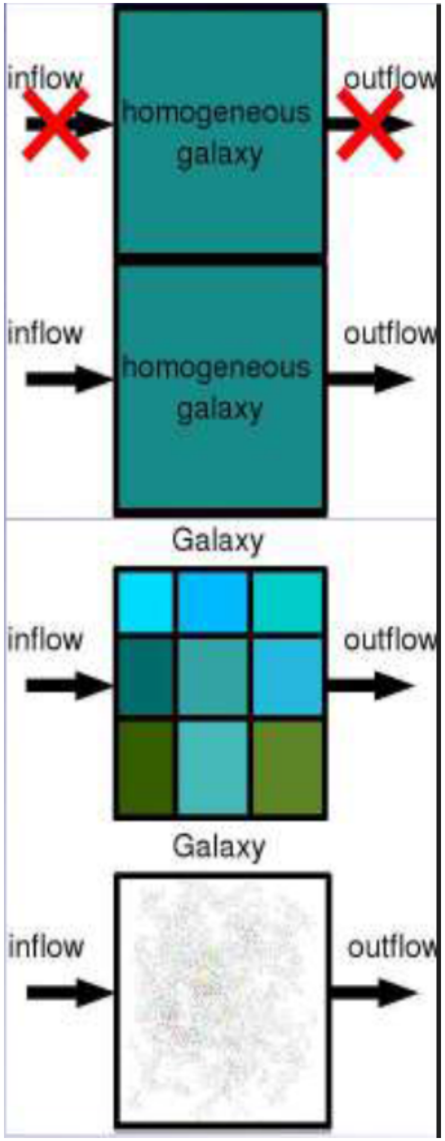
Starting with the work of Larson (1972) in connection with dynamical models of galaxy formation, it has been a popular idea to account **for the G-dwarf metallicity distribution on the basis of inflow models**, i.e. formation of the Galactic disk by gradual accretion of unprocessed or partially processed material which only starts to form stars after it has fallen into the disk, as was first proposed by Oort (1966) as an explanation of the high-velocity H I clouds.

→ the G dwarf problem in the disk is not solved by including effects from the halo (infall of gas or pre-enrichment by the *halo*)

→ Need pre-enrichment from the thick disc

→ Remember the angular momentum of the different Galactic components

Beyond the simple model



- → Closed box: Single zone, no exchange
- → Open box: Single zone, prescription for infall and outflow
- → Multi-zone, with infall and outflow, between zones and with the "exterior"
- → Chemodynamical models

The global picture

The MW is a complex system.

Globally, we can approximate it as a closed box, but each single component has interchange with other and there is an evolutionary sequence among them

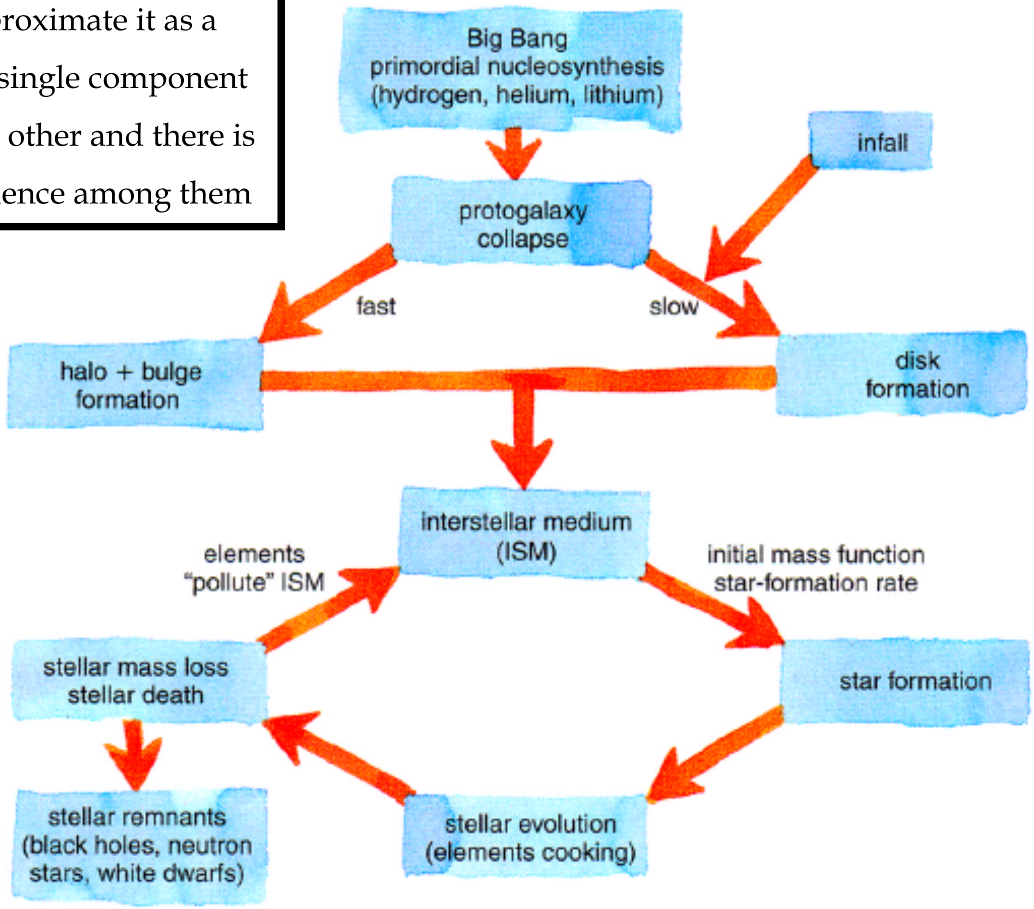
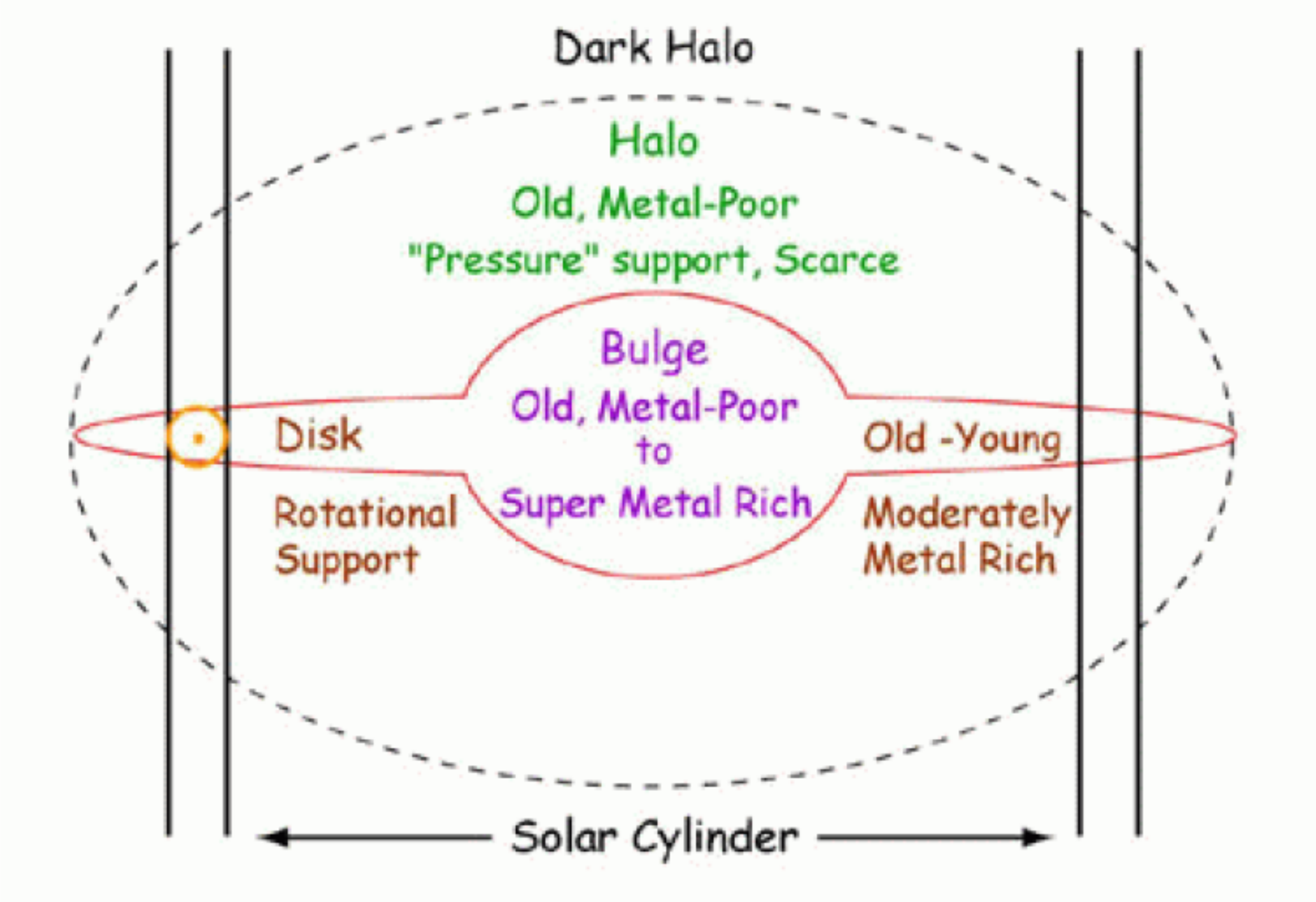


Figure 11. Many factors must be considered in the construction of models that explain the chemical evolution of our galaxy. Not all of these factors are fully understood at this time, which limits the "resolution" of the models—how much of the Galaxy's evolution they can explain. The development of new observatories, however, promises to refine our measures of the Galaxy's chemical and kinematic fine structure, and so our understanding of the processes involved in its evolution.

From Chiappini et al. (2001)

The global picture: the Milky way is not a simple system



From lectures of N. Prantzos 2014

The collapse model

A possible model for the Milky Way

The collapse model by Eggen, Lynden-Bell and Sandage explains the formation of the Milky-Way in a very short timescale (300 Myr)

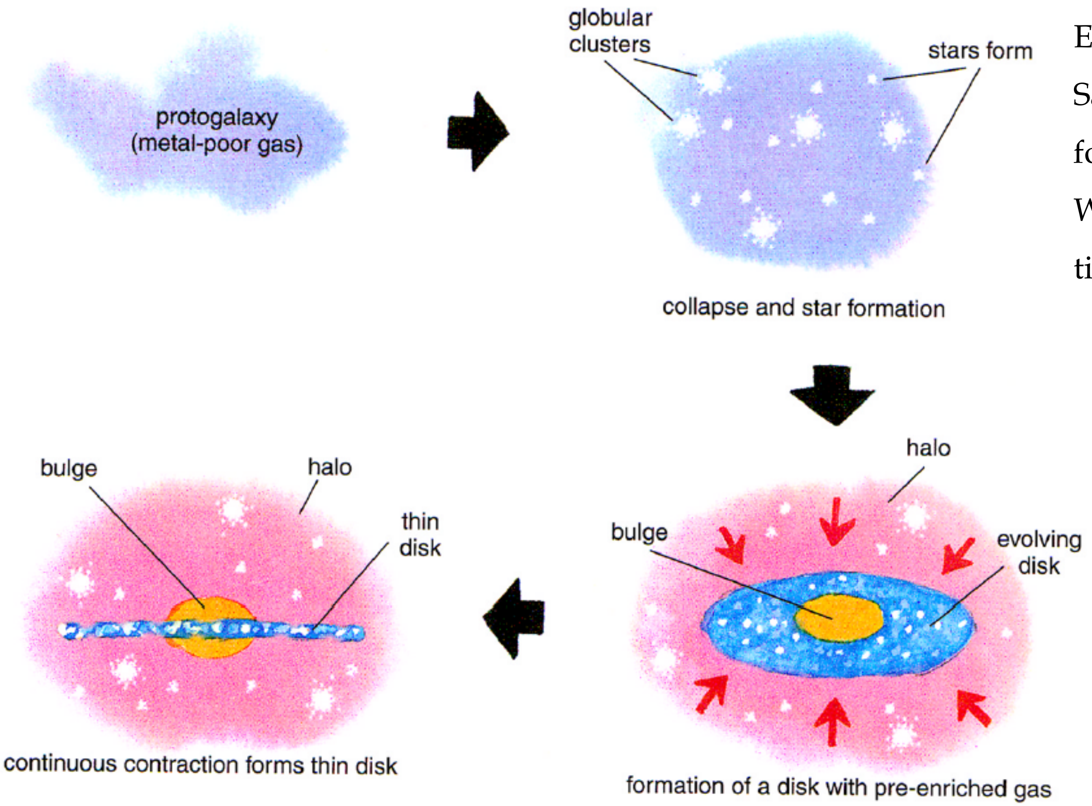


Figure 6. The "ELS" model holds that the Milky Way formed from the rapid collapse of a single cloud of gas. Stars formed early in the collapse maintained the dynamics of the metal-poor gas and so now travel around the Galaxy in elliptical orbits within the halo. As the cloud collapsed *(red arrows)* preferentially along its rotational axis, it formed a disk that had been enriched with the metals produced by the early generations of halo stars.

From Chiappini et al. (2001)

The collapse model with multiple fragments

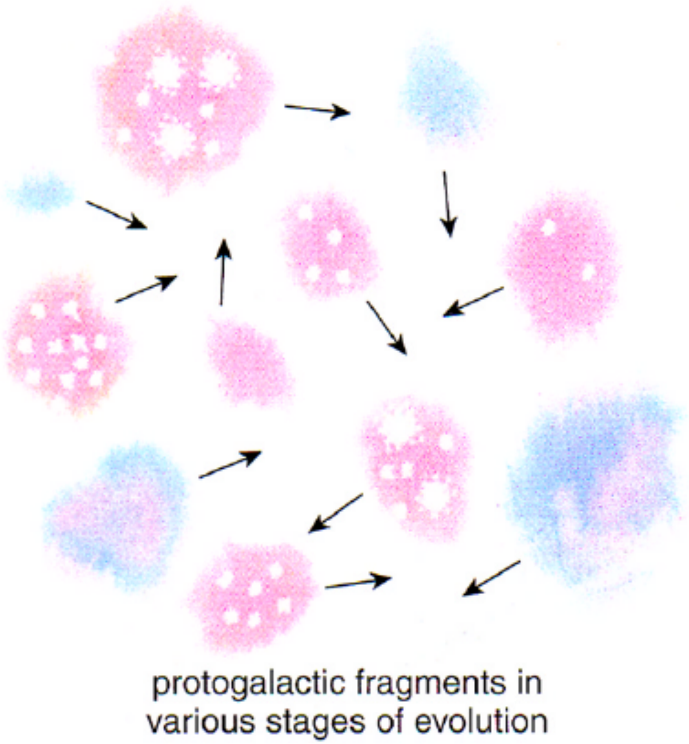


Figure 7. The Searle and Zinn model proposes that the Milky Way formed from an aggregation of several cloud fragments. This model helps to explain the observed differences in the metallicity of globular clusters in the galactic halo. Since each of the cloud fragments had independent histories, some may have evolved more than others, and so have produced objects of greater metallicity.

The timescale proposed by the ELS model was too short.

Observing the metallicity distribution of Globular clusters in the halo, Searle and Zinn proposed a model in which different clouds (with different SFH) were accreted to form the halo (confirmed later by hierarchical formation of structures)

From Chiappini et al. (2001)

Time gaps between the formation of Galactic components

The first models assumed a continuous evolutionary transition in the formation of the thick disk and the thin disk.

However, our Galaxy's formation was neither smooth nor continuous.

→ Observations of the abundances of stars in the halo and in the thick disc, compared with the thin disc stars, shown a different abundance pattern.

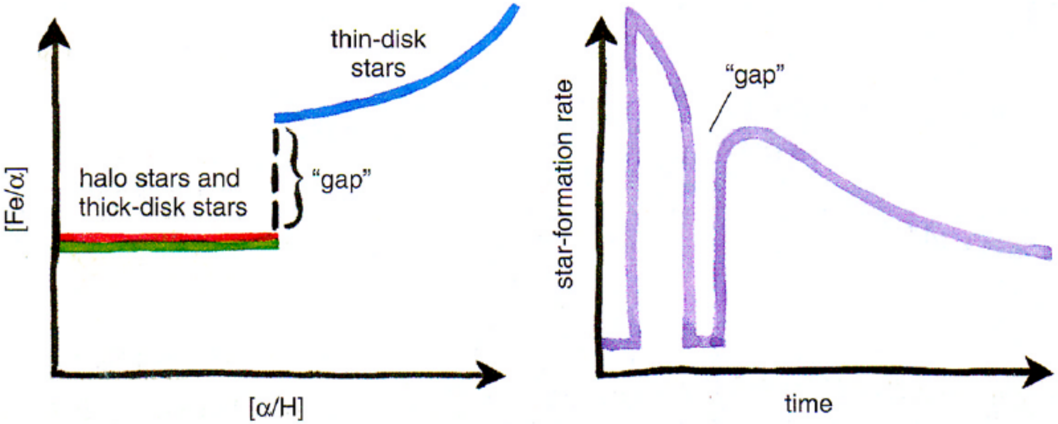


Figure 8. A "gap" in the relative abundances of iron and the alpha (**a**) elements *(left)*, such as oxygen, is interpreted as a period during which the star-formation rate in the Galaxy decreased *(right)*. This is because the alpha elements are produced by the type II supernovae, which are effectively indicators of the star-formation rate. The gap in star formation appeared to occur after the halo and the thick disk literally "ran out of gas," and did not increase again until newly accreted gas settled down to form the thin disk.

The gap in Fe/α can be interpreted as a period in which the SFR of the Galaxy decreased (due to gas consumption)

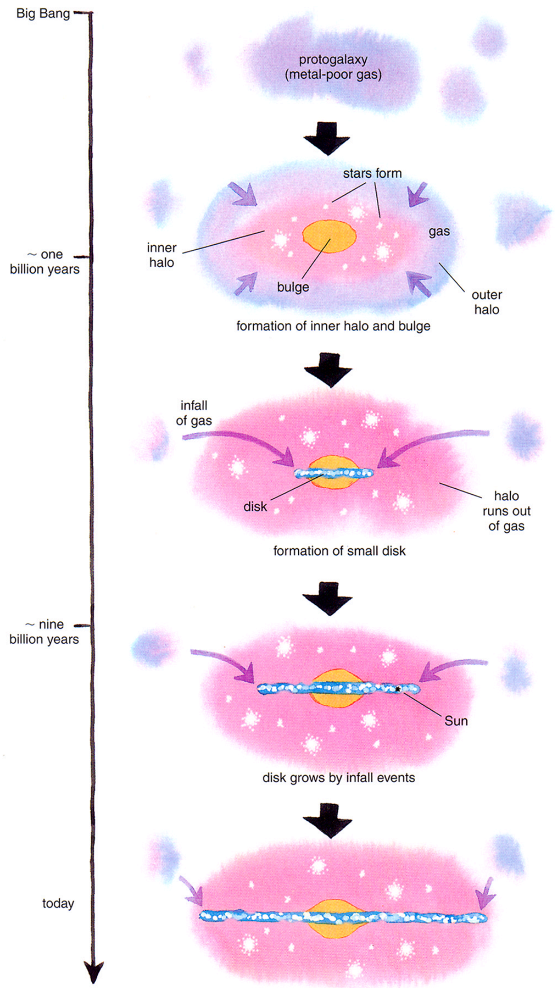
A subsequent infall of gas that formed the thin disc, produced a new burst of star formation

From Chiappini et al. (2001)

The two-infall model

A possible model for the Milky Way

- → An initial collapse formed the halo (and probably part of the thick disk)
- → Star formation in the halo continued until the gas density dropped below a certain threshold.
- → Gas lost by the halo accumulates in the center and so forms the bulge.
- → After the halo forms and star formation ceases, a second infall event forms the thin disk.
- → This event was either a result of a merger with a small galaxy or due to the longer time required for material with a high angular momentum to fall.

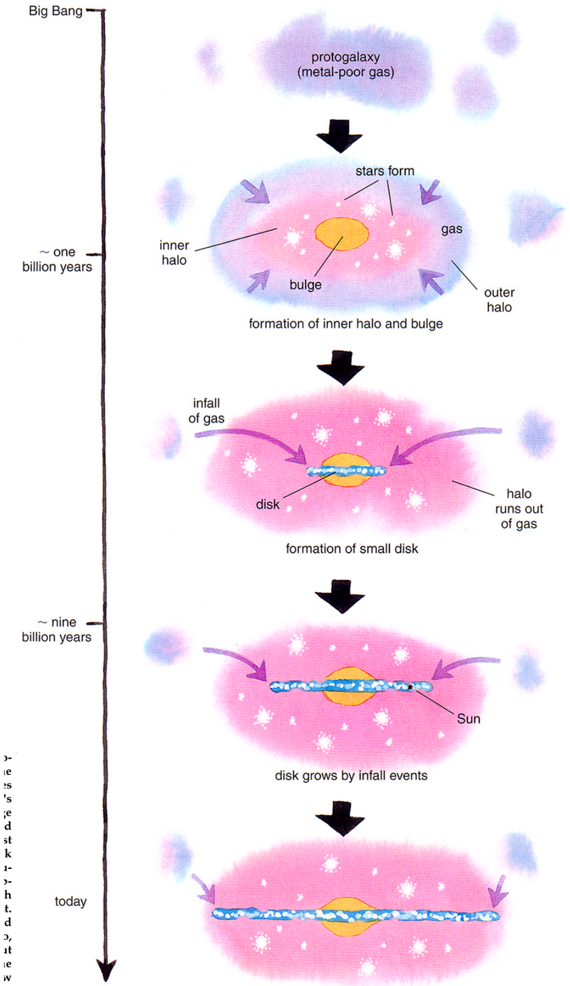


From Chiappini et al. (2001)

The two-infall model

Properties of the disc

- → The disc formed later by the infall of high-angular momentum gas
- → The disc also appears to be evolving "inside-out," with the central-most regions forming first.
- → The formation of the solar neighborhood which began about 10 billion years ago, was completed when the disk was about seven billion years old
- → The outer parts of the disk continue to grow even today with the infall of extragalactic gas clouds.
- → The model can account for the radial distribution of the metallicity, for the G-dwarf distribution, and other features of the MW.



From Chiappini et al. (2001)

The two-infall model

Observational evidence of the continuous infall of gas

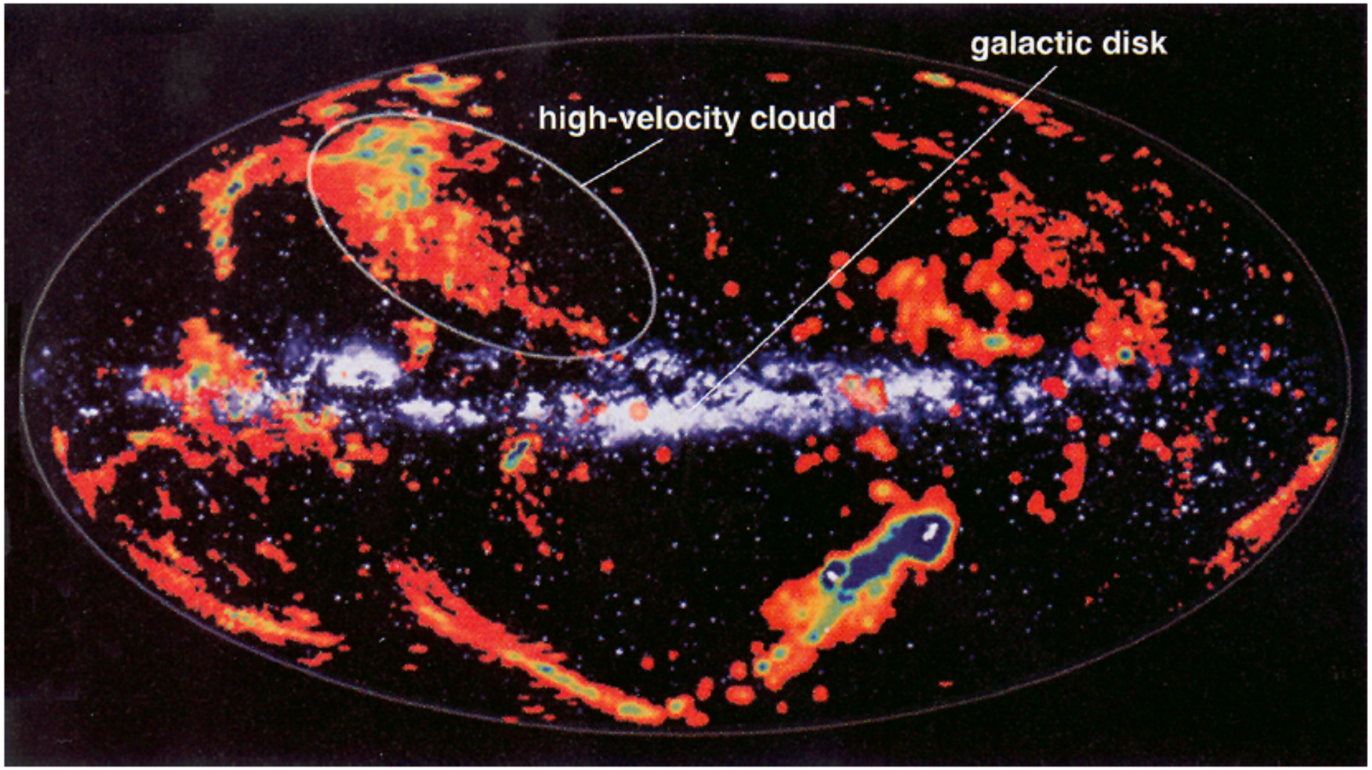


Figure 10. High-velocity clouds, consisting of nebulous blobs of gas, are falling onto the galactic disk from the galactic halo. One interpretation holds that these clouds are evidence that infalling primordial matter maintains the rate of star formation in the galactic disk. Observations suggest that such clouds are indeed replenishing the Galaxy's gas supply at a pace that explains the current rate of star formation in the solar neighborhood—about one new star every year. (Image courtesy of Bart Wakker, University of Wisconsin-Madison, and NASA.)

From Chiappini et al. (2001)

The status of the art and the MW

- From the simple model the **present-time chemodynamical models**, linked to cosmological models (formation of structures, initial conditions)

- The MW is the benchmark for all models: they should be able to reproduce the detailed observations we have from:
  - Stars: ages, kinematics, chemical abundances, density radial profiles
  - Gas: **density radial profiles of molecular and atomic gas, kinematics and abundances → next lecture**
  - Star formation history, star formation rate of the different Galactic component
  - Infall rate from high-velocity clouds
  - And many others….