Abundances and chemical evolution models

Physics of Galaxies 2013

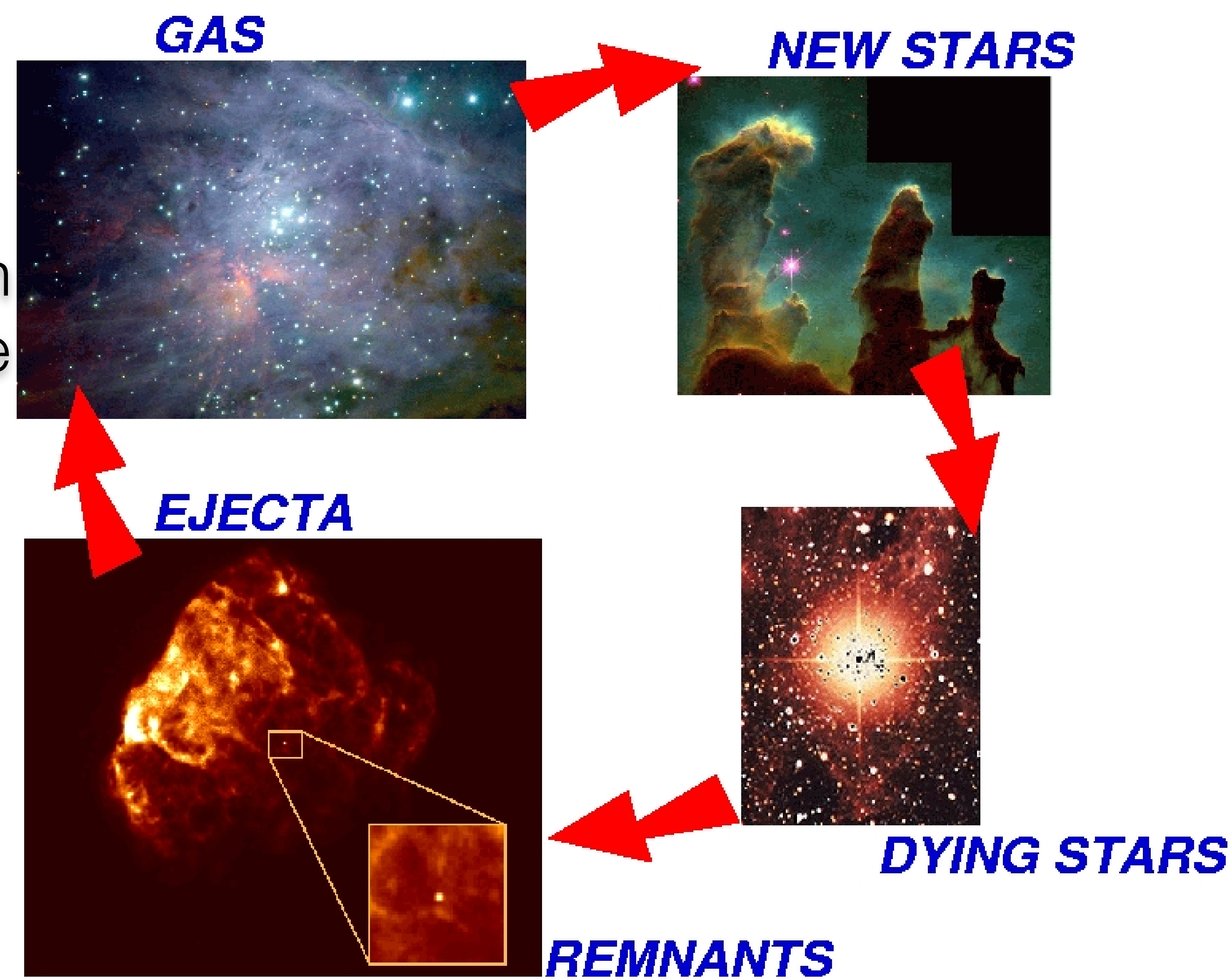
part 6 (out of order!)

Chemical evolution

- Why do we care?
    - **All** elements heavier than Li were formed **by *nucleosynthesis* in stars**
    - The differences in the compositions in stars tell us about *when* and *how* the stars were made

The life cycle of gas and stars in galaxies

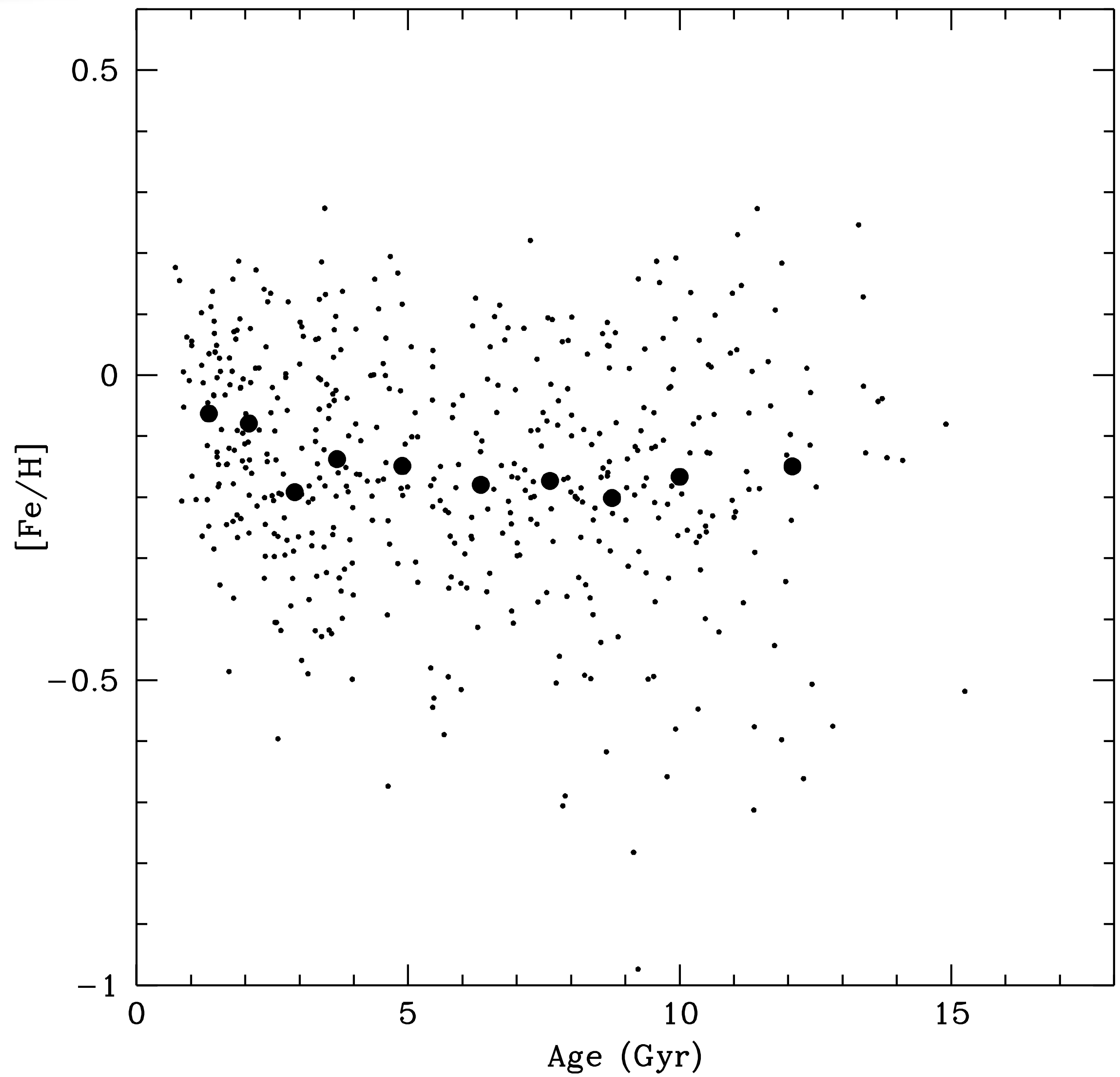
- Gas is turned into stars (somehow)
- Stars burn H into He and then He into C and then, if massive enough, C into heavier elements, all the way to Fe in the most massive stars
- These elements are returned to the interstellar medium at the end of the stars' lives through winds or supernovae



notice the scatter at old ages!

- Therefore the chemical abundance of the gas – and the next generation of stars – should increase as a function of time
  - ...in the absence of gas flowing into the the system...
- “Metallicity” is thus a kind of **clock**... sort of!

The age–metallicity relation from the Geneva-Copenhagen survey (Nordström et al. 2004)



The build-up of metals in a stellar population

- "Galactic Chemical Evolution" (GCE) models
- The simplest model for chemical enrichment in a galaxy is the **closed-box model**, in which the galaxy is considered to a single "box" ("one zone") *with no inflow or outflow*
  - **Assume:**
    - Gas is well-mixed
    - Metals are returned to gas faster than the star-formation timescale ("instantaneous recycling")

- Definitions:
  - $M_{TOT}=M_g(t)+M_s(t)$, where $M_g(t)$ is the mass of gas at time t and $M_s(t)$ is the mass in unevolved stars at t
  - $M_Z(t)$ is the mass of metals in the gas
  - $Z=Z_{gas}=M_Z(t)/M_g(t)$ is the metallicity in the gas (the mass fraction in metals; $Z_\odot \approx 0.019$) and $Z=0$ at $t=0$
  - δM_s is the net flow of gas into stars at each new generation of stars
  - $y\delta M_s$ is the mass of new metals released back into the ISM after each generation, so y is the **yield**: the fraction of stellar mass returned to the gas as metals

- The mass fraction of metals locked up in the low-mass stars (and remnants) is $Z\delta M_s$

returned by supernovae

- Now, in each generation, $\delta M_Z = y\delta M_s - Z\delta M_s$

locked up in new low-mass stars

- so $\delta Z = \delta\left(\frac{M_Z}{M_g}\right) = \frac{\delta M_Z}{M_g} - \frac{M_Z}{M_g^2}\delta M_g$
- or $\delta Z = \frac{1}{M_g}(\delta M_Z - Z\delta M_g)$
- now, note that $\delta M_s = -\delta M_g$, since M_{TOT} is constant, so

$$\delta M_Z = -y\delta M_g + Z\delta M_g$$

- Substituting, we find $\delta Z = \frac{1}{M_g}(-y\delta M_g + Z\delta M_g - Z\delta M_g)$
- And so $\delta Z = -y\frac{\delta M_g}{M_g}$
- Finally, we have $$\boxed{Z(t) = -y \ln\left[\frac{M_g(t)}{M_{\rm tot}}\right]}$$

  if *y* does not depend on time

  - We often write $M_g/M_{TOT}=\mu$, the **gas fraction**
  - Note that this is unphysical: $Z \to \infty$ as $M_g \to 0$
- In a closed box, *metallicity grows with time*

- How do the metallicities of the stars evolve in a closed box?
  - The mass of stars $M_s(t)$ formed before time t, and so with metallicity $<Z(t)$ is just $M_g(0)–M_g(t)$ and therefore

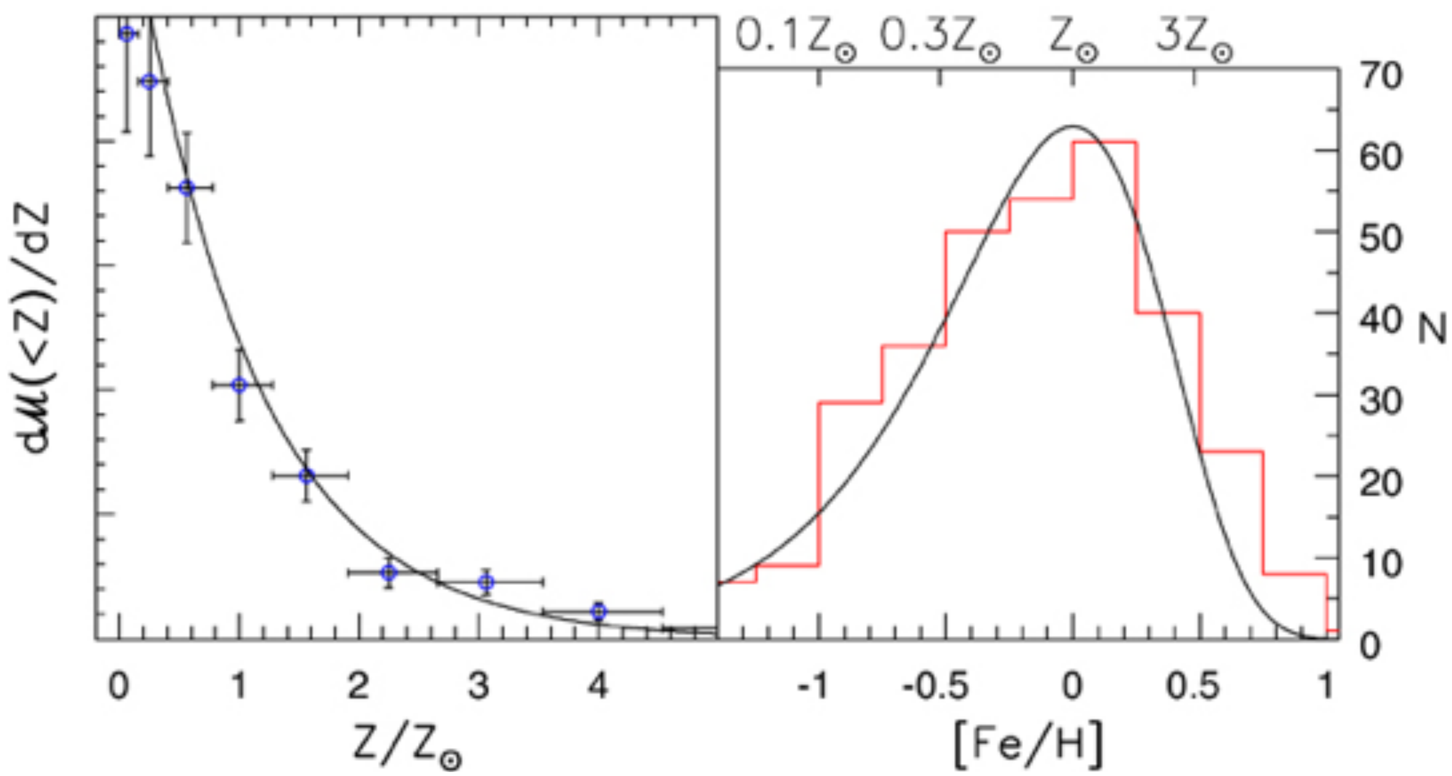
$$M_s(< Z) = M_g(0)[1 - \exp(-Z/y)]$$

    - Note the lack of an explicit time here! So when the gas density is high relative to the number of stars formed, the abundance of metals is low.
  - Once the gas is all consumed, the mass of stars with metallicities in $(Z, Z+dZ)$ is just

$$dM_s(< Z) \propto \exp(-Z/y)dZ$$

The closed-box model and the Galactic bulge

- Comparing a closed-box model with the distribution of metallicities in the bulge, a very good fit can be found with $y = Z_\odot$ and $Z(t) = 0$



The closed-box model and the thin disk

- Let's derive the yield for the Solar neighborhood in the closed box model: $Z(t) = -y \ln[M_g(t)/M_{\rm tot}]$
  - For t=today, Z~$0.7Z_\odot$
  - The total mass is $M_{\rm g}$(today)+$M_{\rm S}$(today)~10 $M_\odot/pc^2$ + 40 $M_\odot/pc^2$=50 $M_\odot/pc^2$
  - Thus we find y=0.43 $Z_\odot$

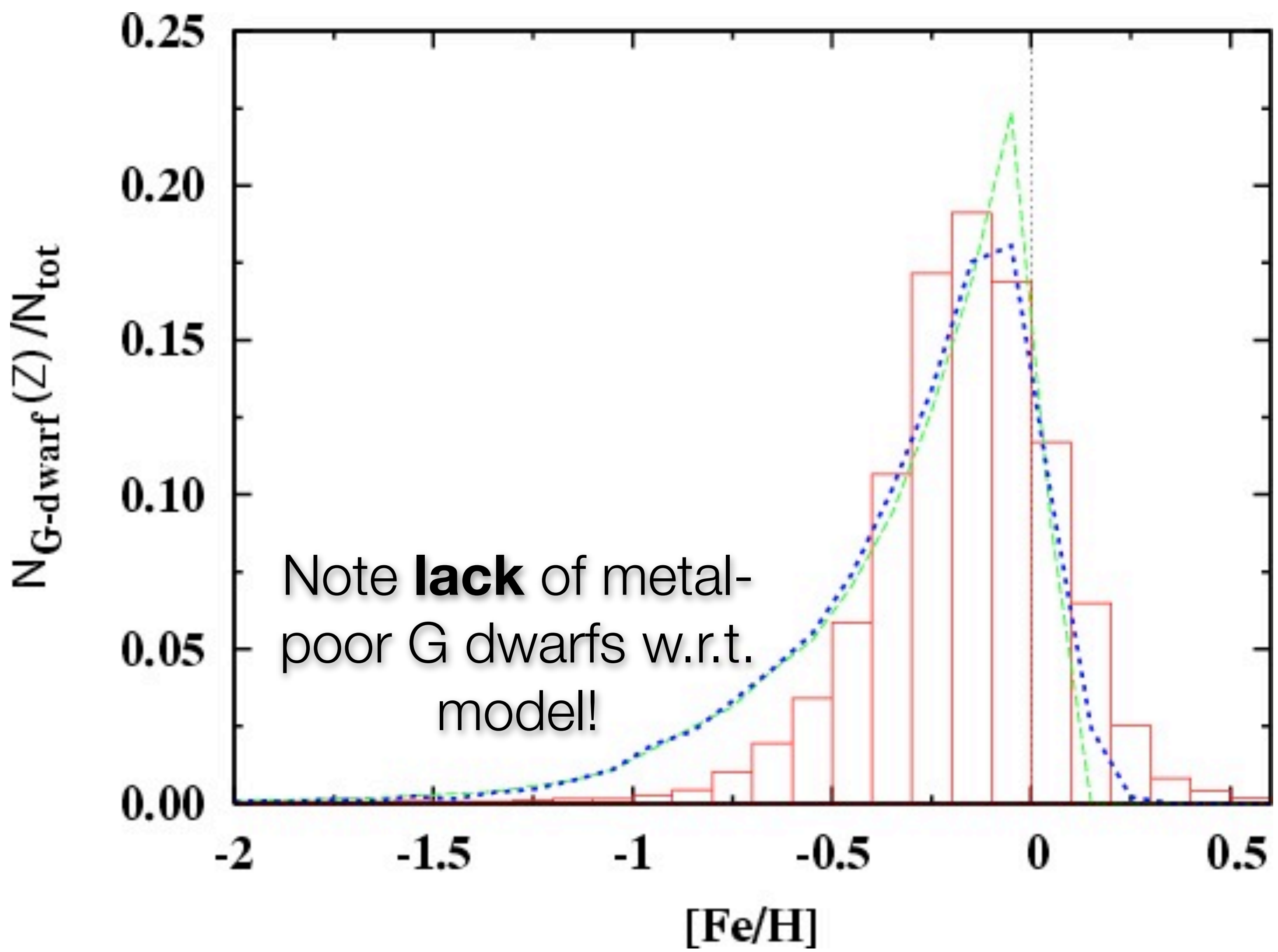
The G dwarf problem

- Now let's ask how many long-lived stars we should see with $Z<0.25\ Z_\odot$:

$$\frac{M_s(<0.25Z_\odot)}{M_s(<0.7Z_\odot)} = \frac{1-\exp(-0.25Z_\odot/y)}{1-\exp(-0.7Z_\odot/y)} \approx 0.55$$

  - so **55%** of the stars in the Solar neighborhood should have $Z< Z_\odot/4$
  - but we only see **~2%** of the local F and G stars with these metallicities!

- So the simple closed-box model is clearly wrong for the Solar neighborhood!
- Possible solutions:
  - No G dwarfs made at early times (too extreme?)
  - Yield decreases with increasing *Z* (disagrees with SN yields)
  - Disk pre-enrichment: disk is polluted by spheroid
  - Disk infall and enrichment



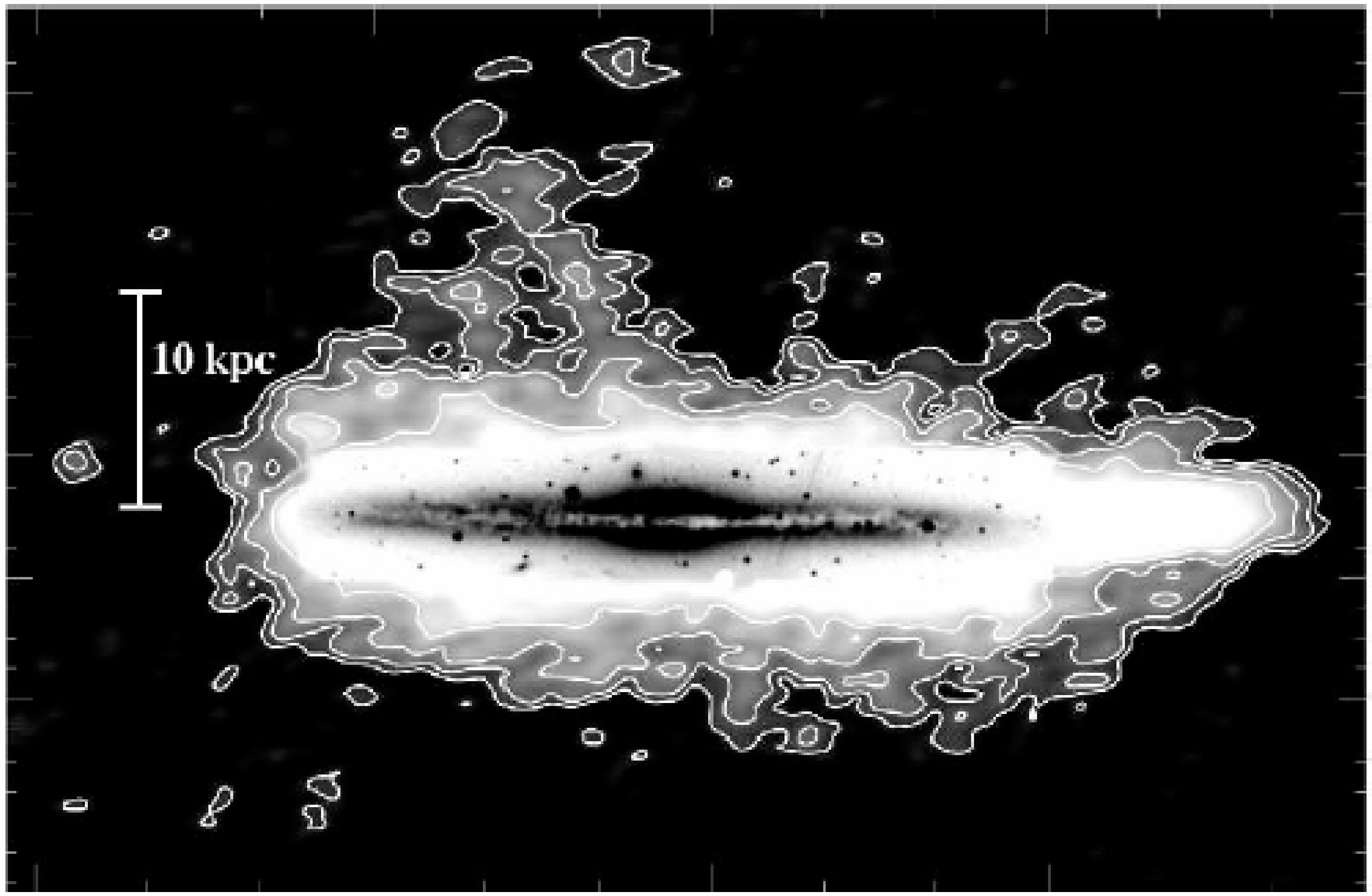
- Pre-enrichment does a reasonable job: if $Z(0) \approx 0.15\ Z_\odot$, then G dwarf problem is mostly resolved
- The G dwarf problem means that the Solar neighborhood *was not always like it is now!*
    - **Something** was very different – nucleosynthesis gives us an important clue to galaxy evolution!

Leaky-box model: the effect of outflow

- We know that many galaxies have strong **outflows** of gas, generally caused by intense star formation or AGN
- What effect does this have on the chemical evolution?

Accreting-box model: the effects of inflow

- At the same time, it has become clear that galaxies also **accrete** gas
  - What affect does this **inflow** have on the chemical evolution?



Generalizing the one-zone model

- First, let's define the **inflowing** gas to have a mass $\delta M_{\rm in}=f\delta M_{\rm s}$ with metallicity $Z_{\rm in}$ and the **outflowing** gas to have a mass $\delta M_{\rm out}=g\delta M_{\rm s}$ with metallicity $Z_{\rm out}$
- Then it is possible to show that

$$\delta Z = \frac{1}{M_g}[(y + fZ_{\rm in} - Z - gZ_{\rm out})\delta M_{\rm TOT} - (y + fZ_{\rm in} - gZ_{\rm out})\delta M_{\rm g}]$$

- In general, this equation can only be solved **only** if $M_{\rm TOT}$ and $M_{\rm g}$ are specified functions of time.
  - But there are two special cases of interest...

The leaky-box model

- In this case, $\delta M_{\mathrm{TOT}} \approx 0$, and $f=0$, $g \neq 0$, and $Z_{\mathrm{out}} = Z_{\mathrm{SN}}$, so that the SN ejecta leave directly *before* mixing into the ISM
  - note that this prescription violates $M_{\mathrm{TOT}} \sim$ constant, but effect is small at early times
- then $Z(t) = -(y - gZ_{\mathrm{out}}) \ln[M_g(t)/M_{\mathrm{tot}}]$
  - Compared to the closed-box model, the only thing that happens is that the *yield is reduced* by $-gZ_{\mathrm{out}}$
    - explains low apparent yield in dwarf galaxies

The accreting-box model

- When the infall is small and balances star formation, $\delta M_s \approx 0$; also assume that Z_{in}=constant and $Z_{out}=Z$ (well mixed)
    - As $t \to \infty,\ M_{\rm TOT} \gg M_g$ and
$$Z \to \frac{y + f Z_{\rm in}}{1+g}$$
    - If $Z_{in}=0$ ("pristine" gas), $g=0$, and $f=1$, then
$$Z \to y$$

- The mass in stars more metal-poor than Z is $M_s(<Z)=M_{TOT}(Z)-M_g$ which is

$$M_s(<Z) = -M_g \ln\left(1 - \frac{Z}{y}\right)$$

- Then the yield can be determined from the metallicity: in the Solar neighborhood, $Z=0.7Z_\odot$, then $y\approx0.71Z_\odot$, so the fraction of stars with $Z<Z_\odot/4$ is

$$M_s(< Z_\odot/4) = 0.43M_g \approx 0.09M_{\rm tot} \approx 0.11M_s$$

  - So about 11% of the dwarf stars should be more metal-poor than $0.25Z_\odot$, in better agreement with the observations!

- Finally, don’t forget about the thick disk!
    - Lots of metal-poor dwarfs there — good way to help solve the G dwarf problem...