

Chemical Evolution Models

Thomas Bilitewski, 15.12.2010

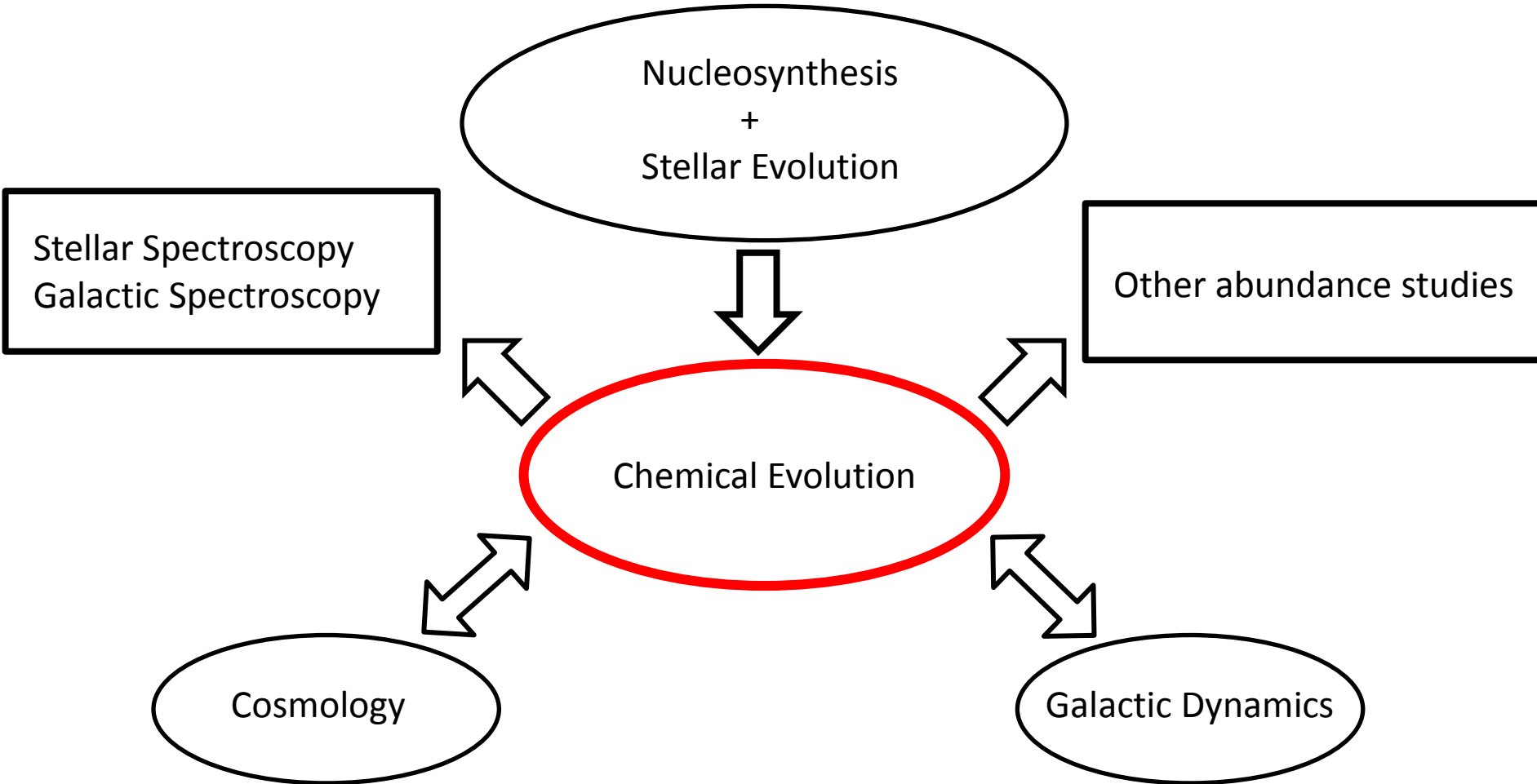
Outline

- What is chemical evolution
- Nucleosynthesis:
 - Local abundances
 - Stellar evolution
 - Synthesis of elemental elements
- Chemical evolution models:
 - Assumptions
 - Analytical models
 - Simulations

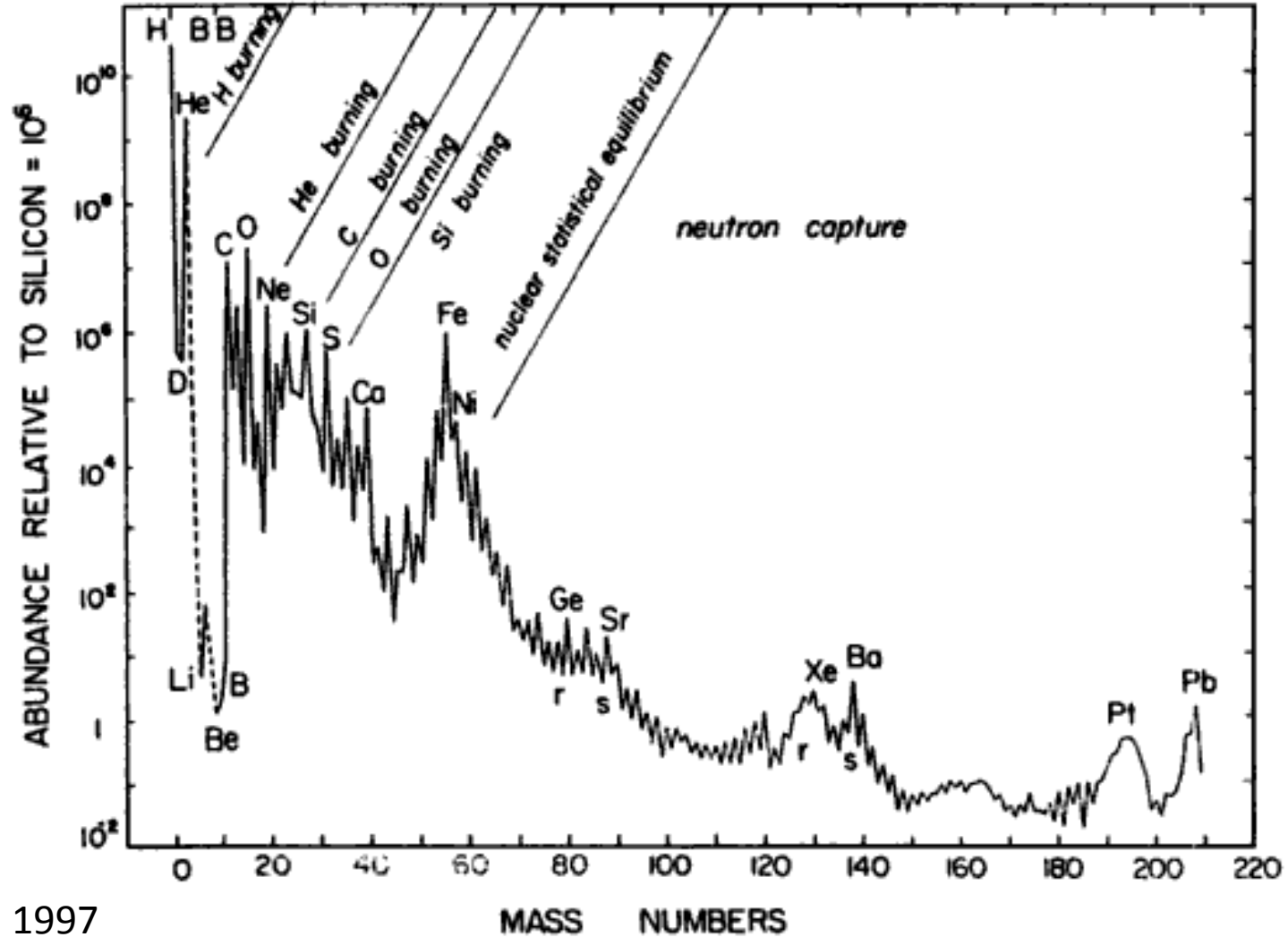
Chemical Evolution

- CE tries to model the evolution of elemental abundances in the universe and in galaxies
- It requires knowledge of nucleosynthesis & stellar evolution and galactic dynamics & evolution

CE and related fields

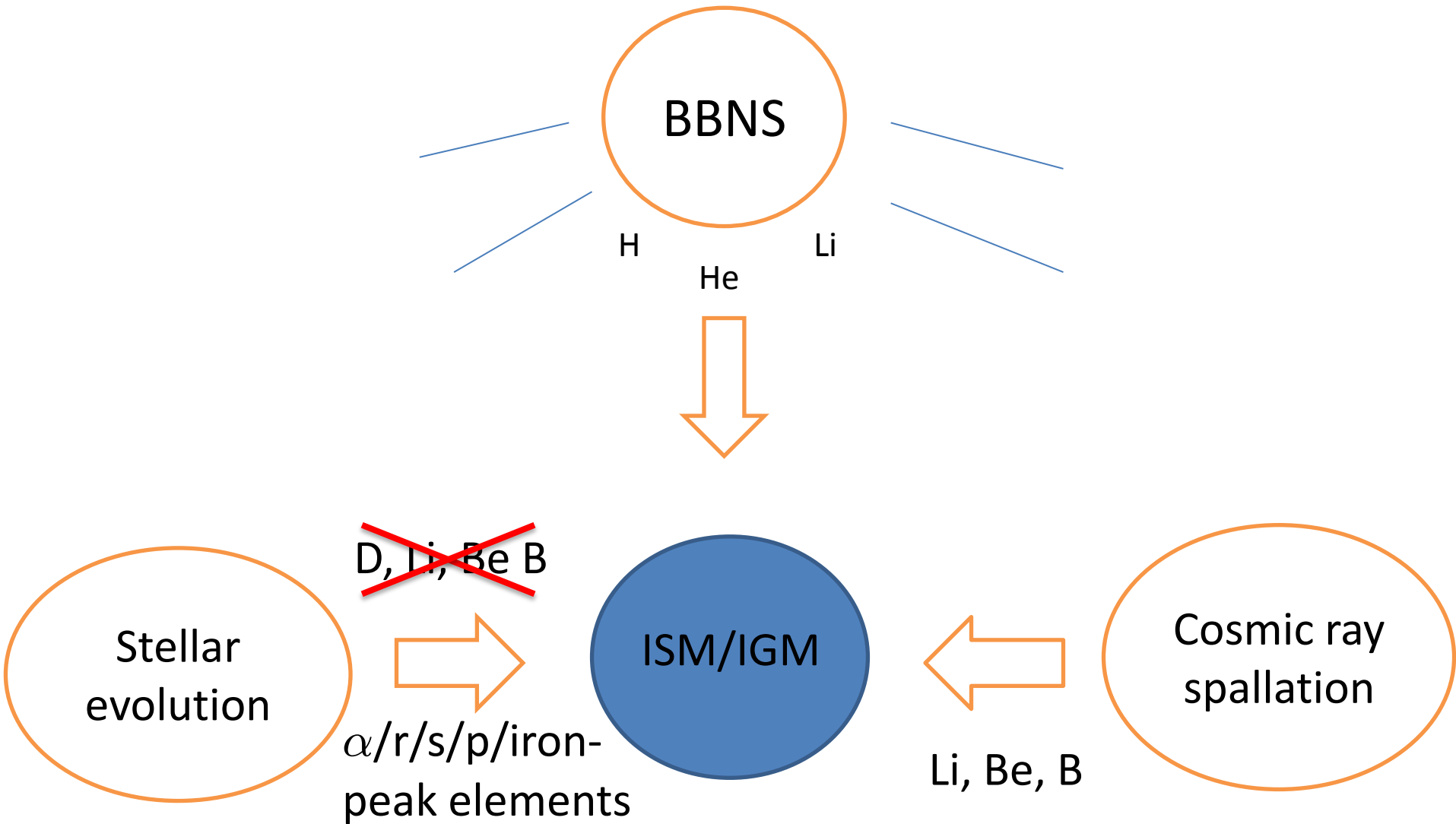


Local abundances



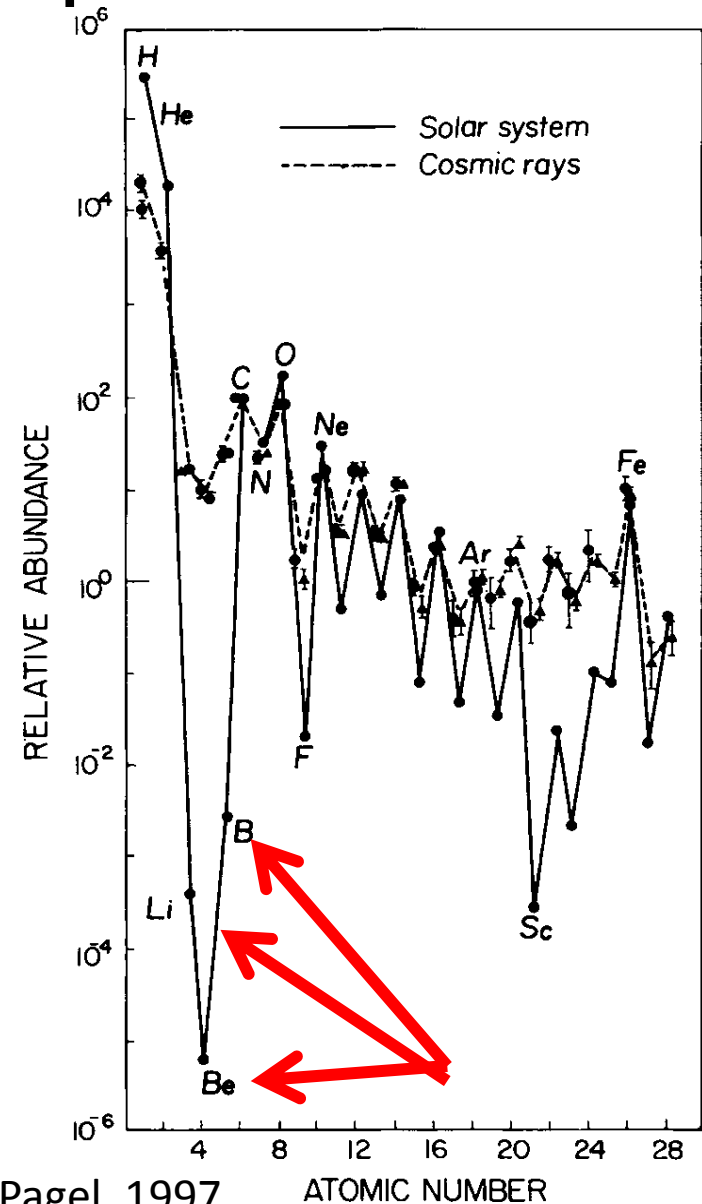
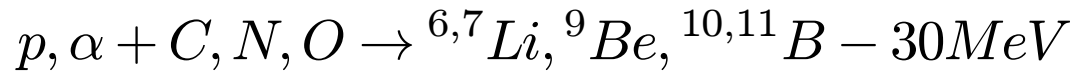
Pagel, 1997

Origin of elements



Cosmic ray spallation products

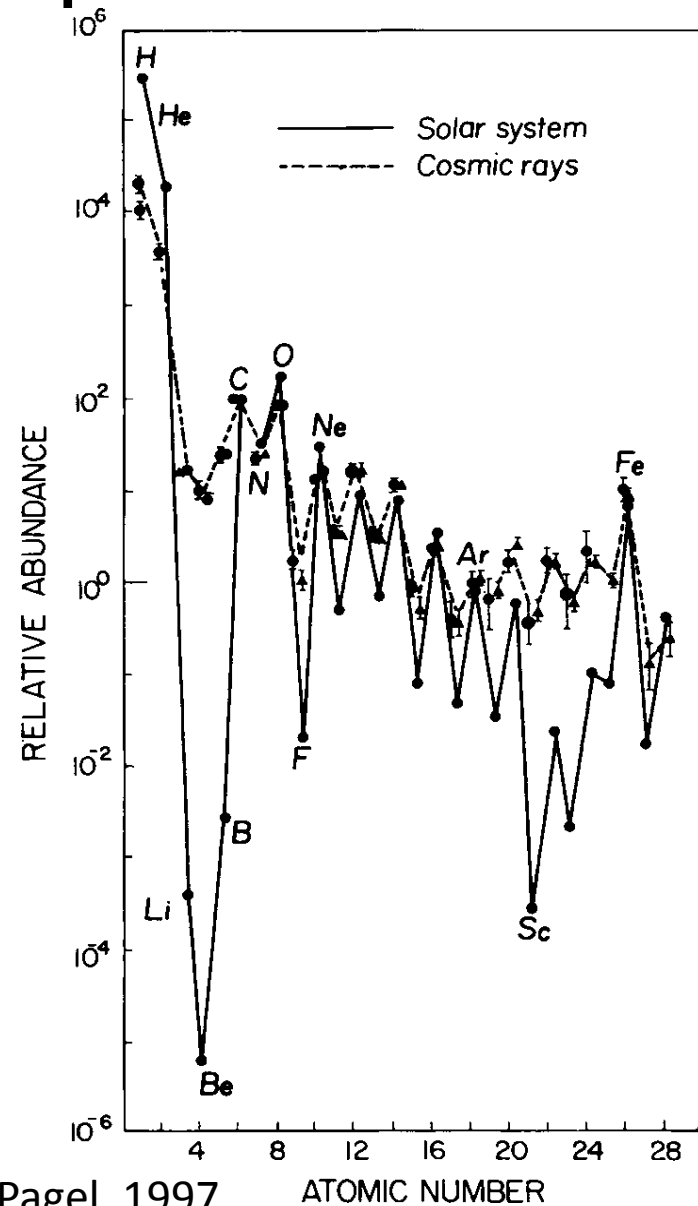
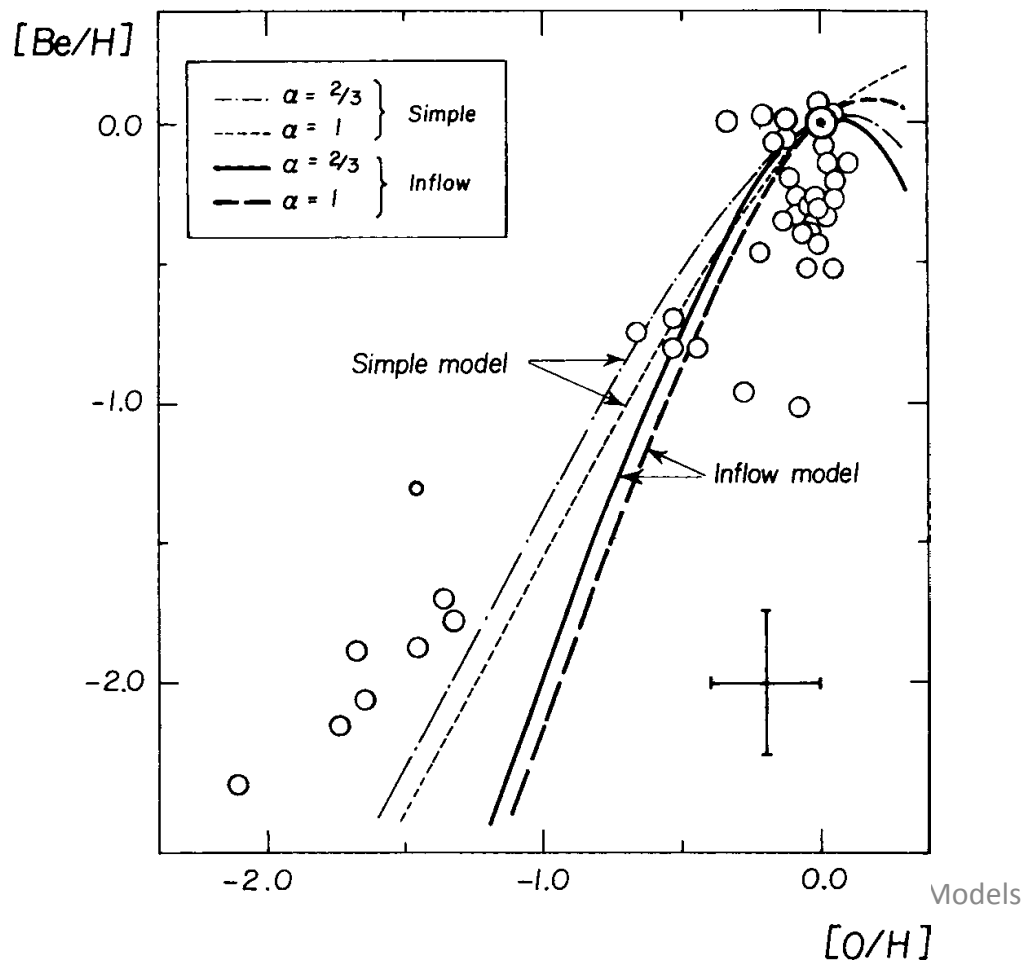
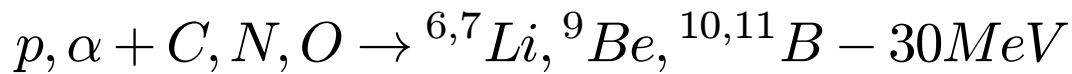
Li, Be, B



Pagel, 1997

Cosmic ray spallation products

Li, Be, B



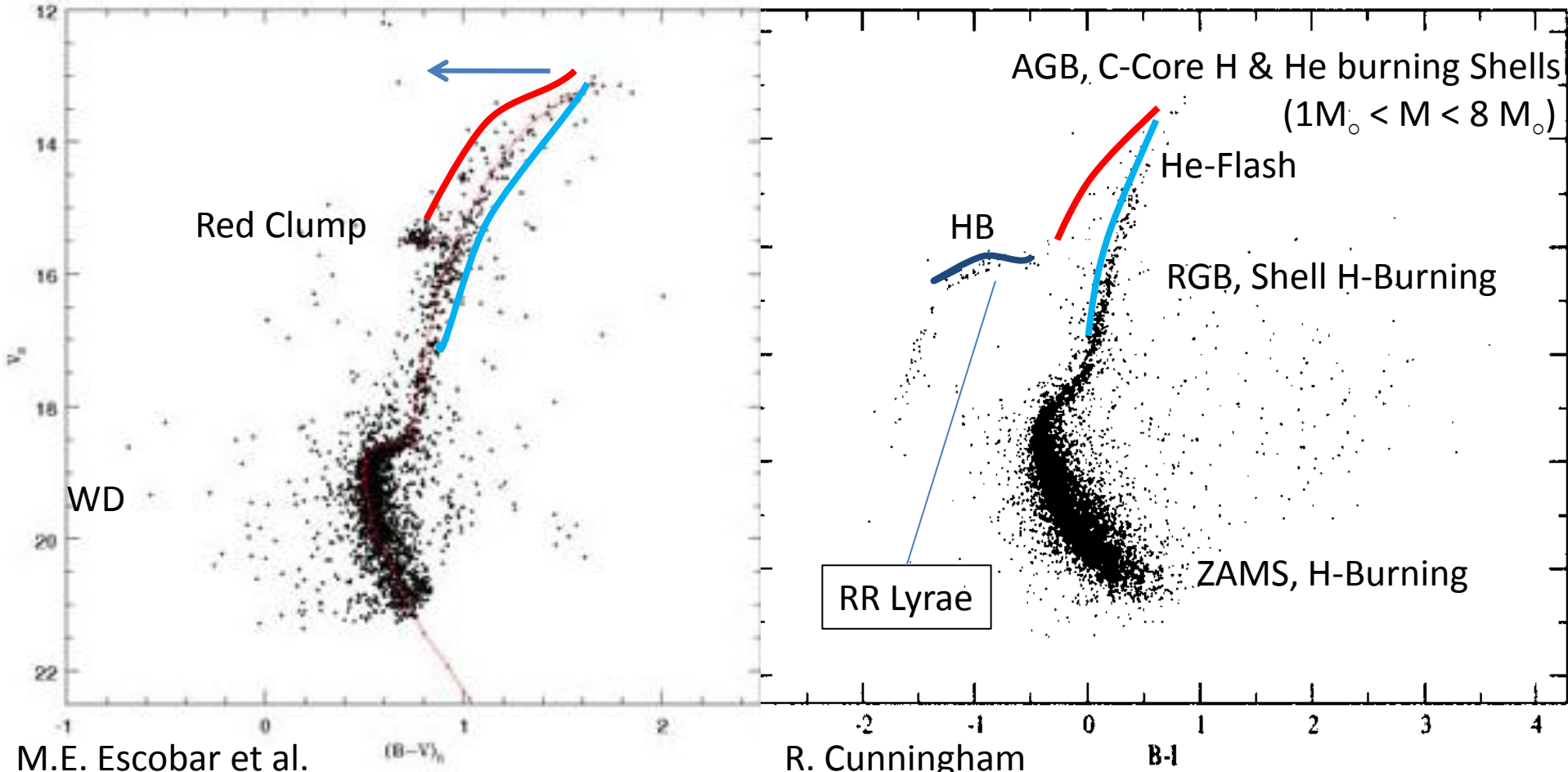
Pagel, 1997

ATOMIC NUMBER

Stellar evolution

M 69, metal-rich

M15 metal-poor

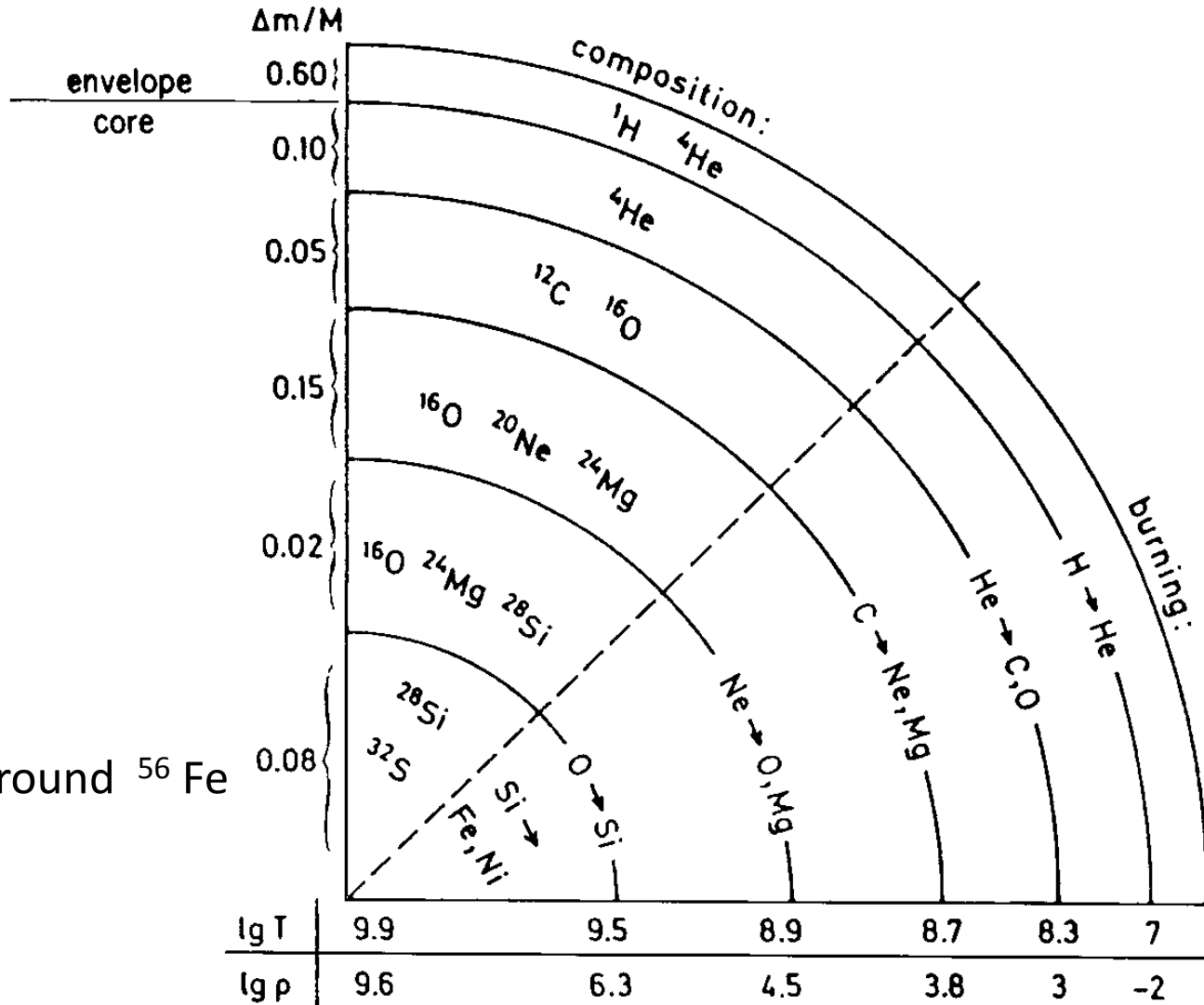


M.E. Escobar et al.

R. Cunningham

Shell structure

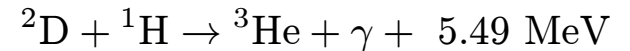
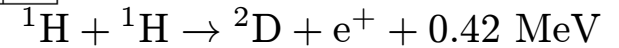
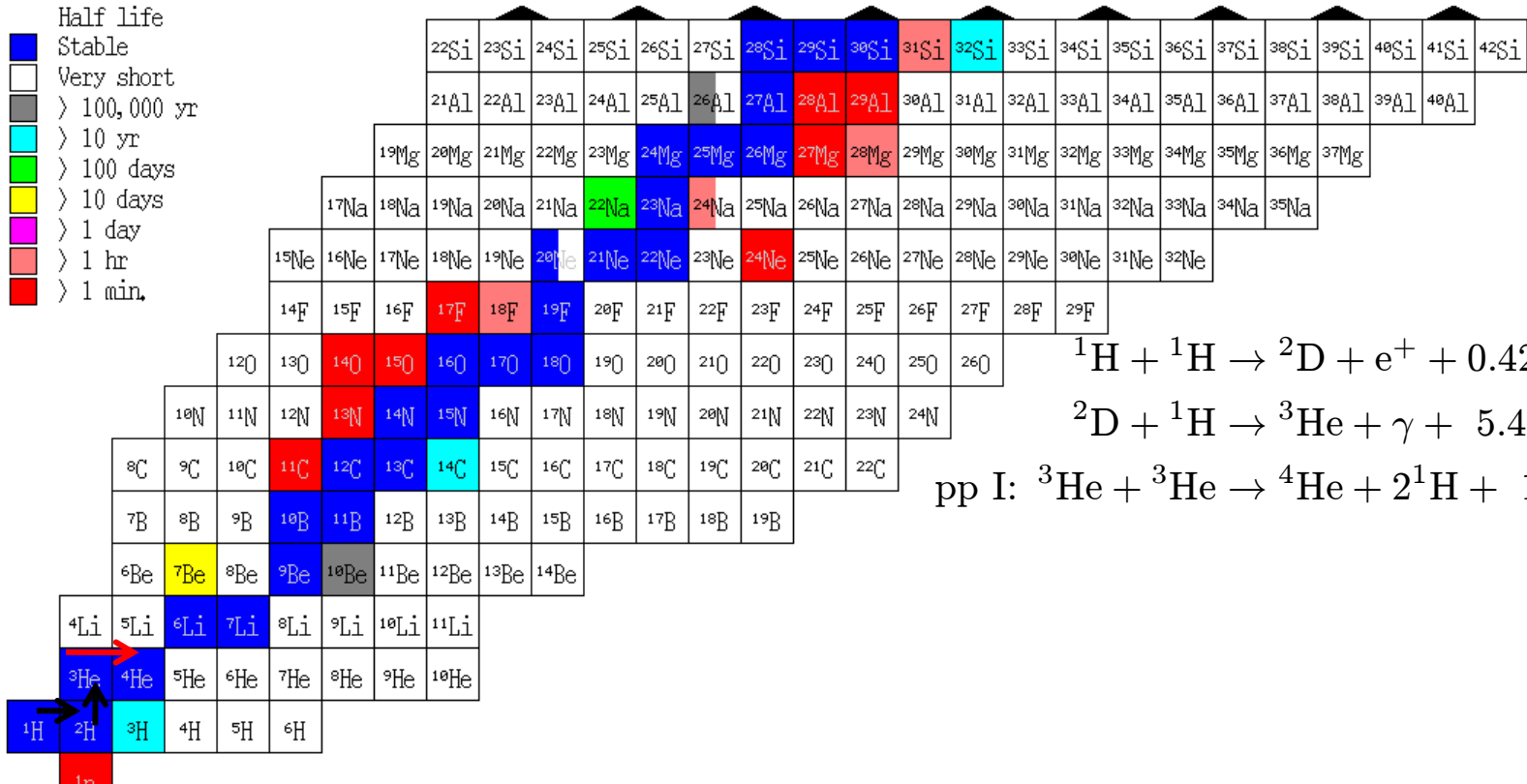
$M > 8M_{\odot}$



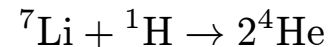
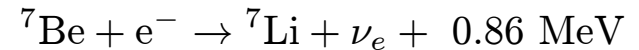
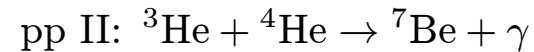
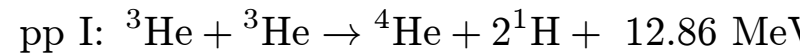
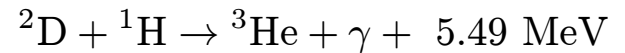
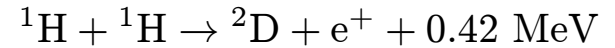
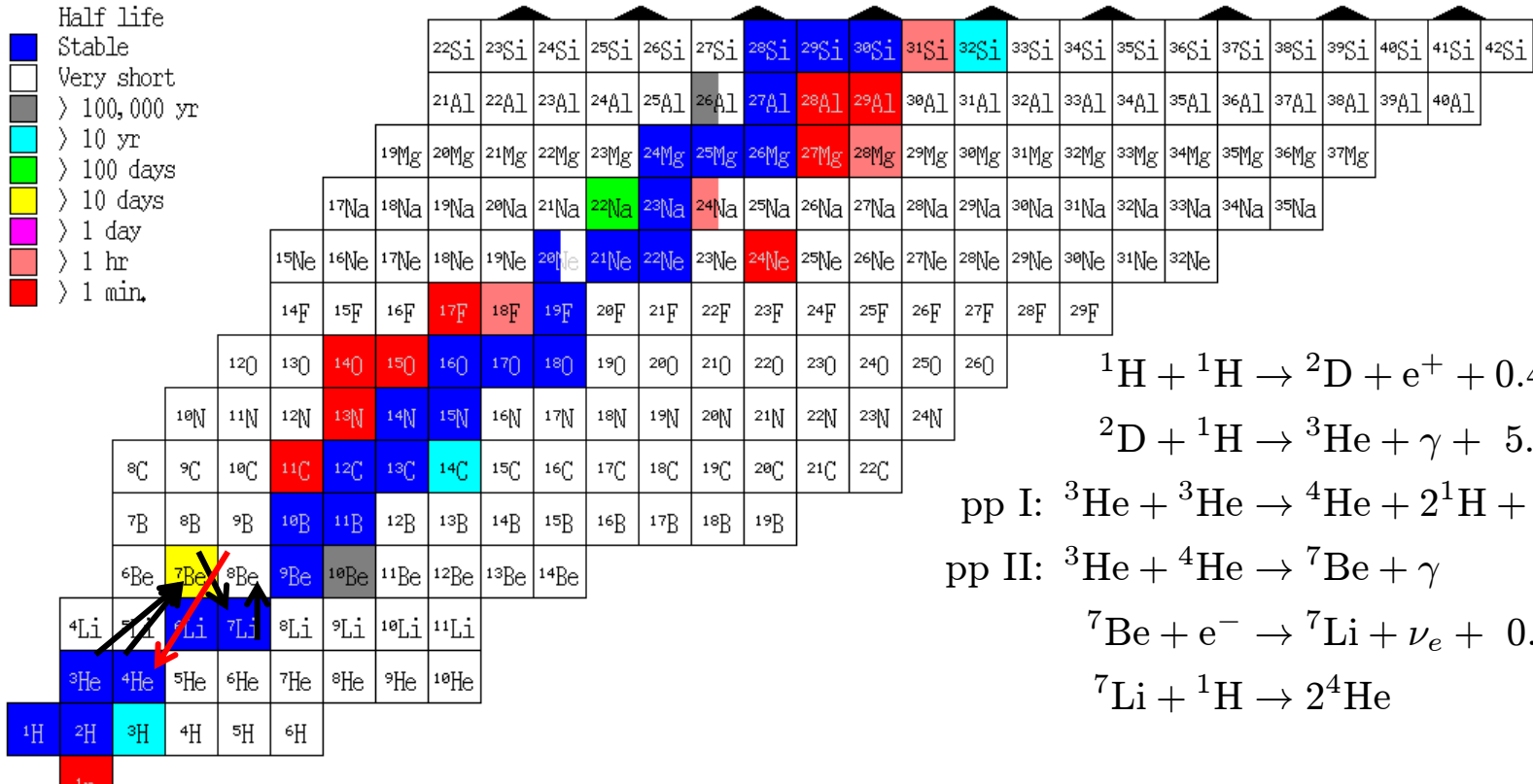
Fusion stops around ^{56}Fe
 → Iron-peak

Pagal, 1997

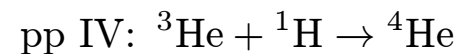
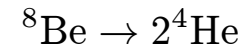
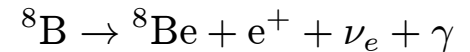
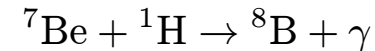
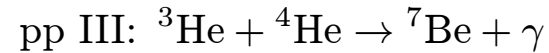
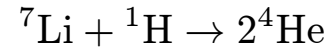
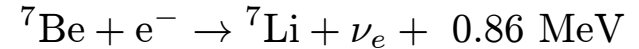
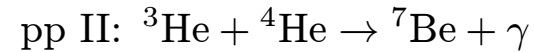
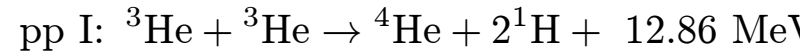
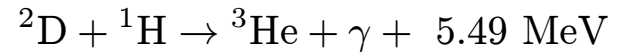
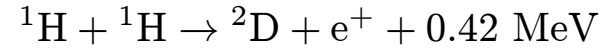
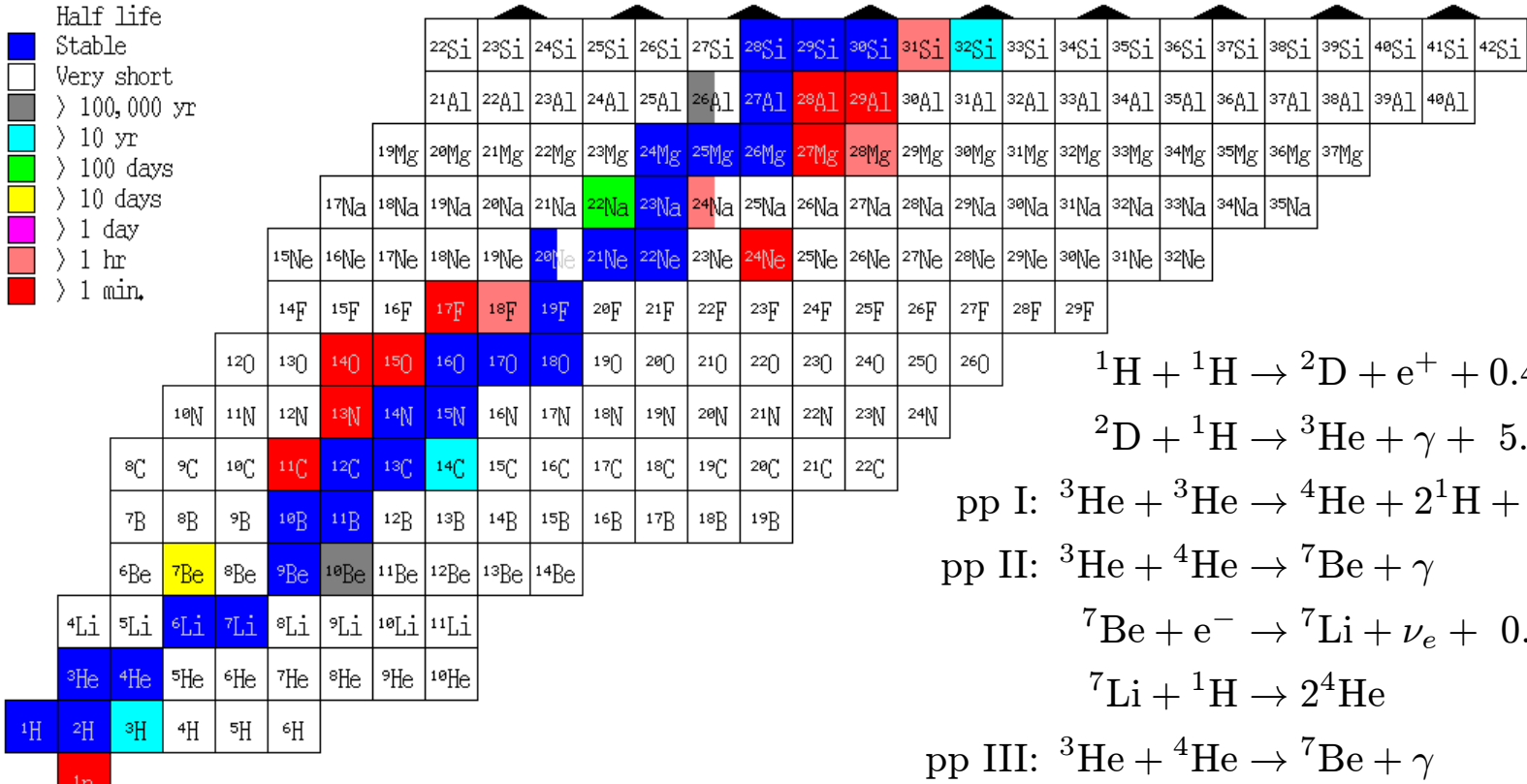
H-Burning (ppl-chain)



H-Burning (ppII-chain)

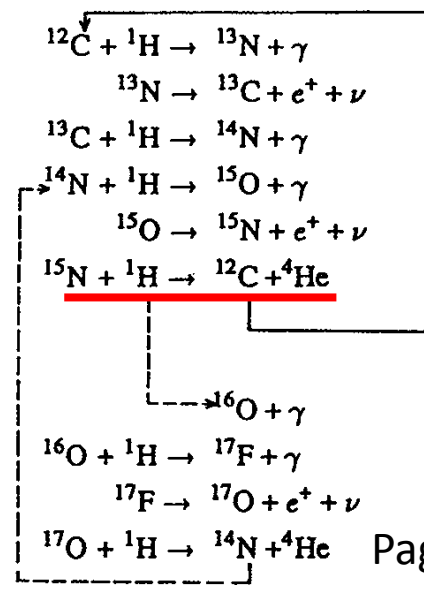
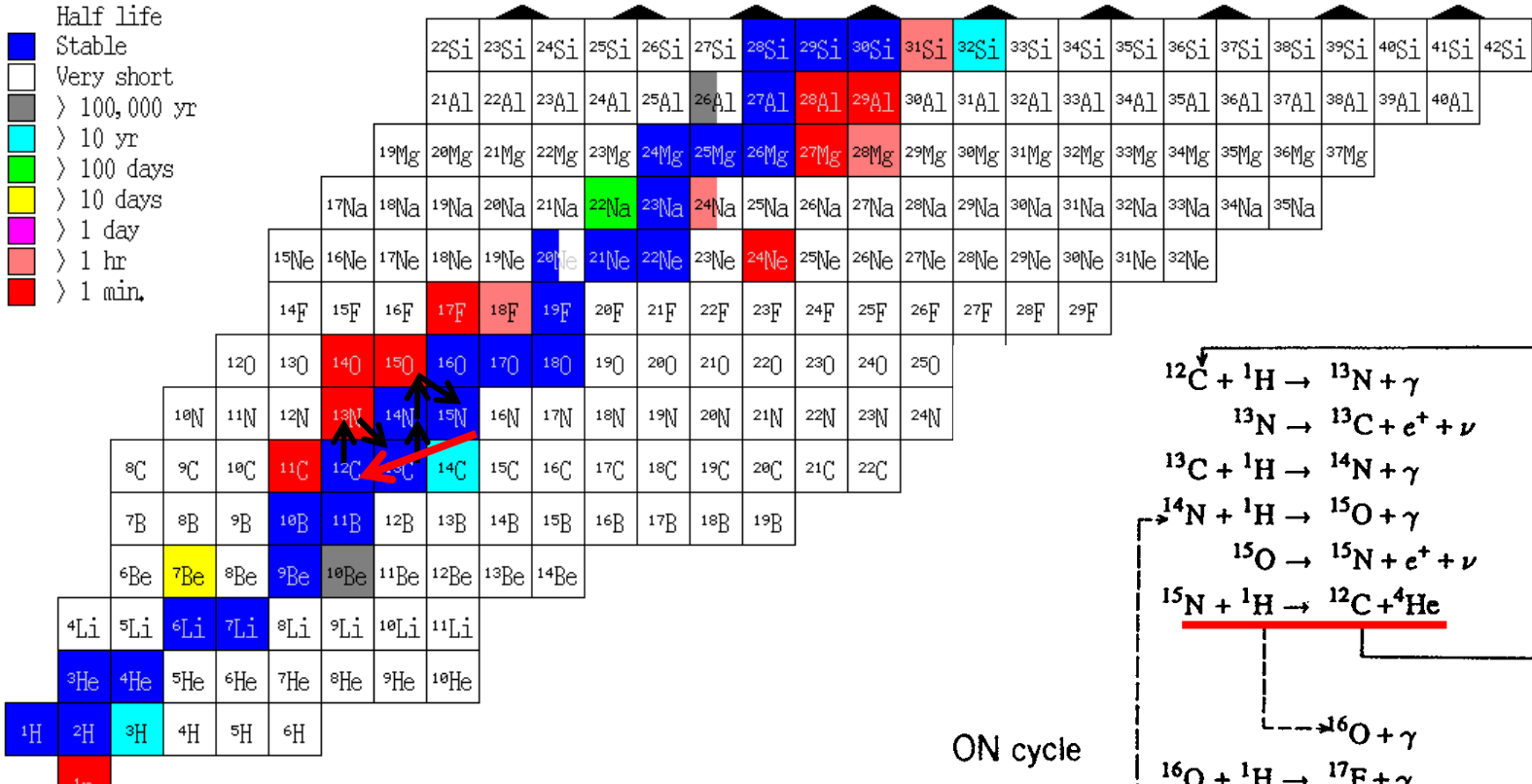


H-Burning (pp-chain)



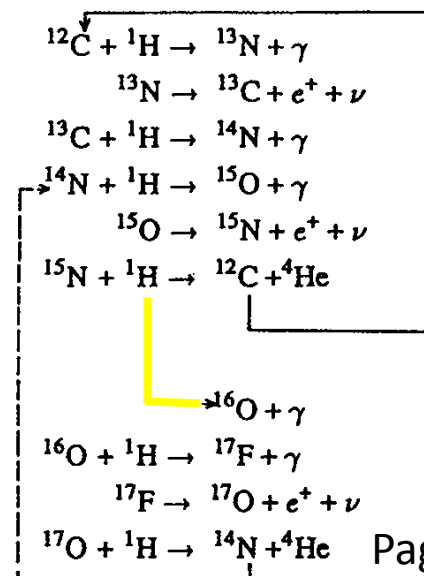
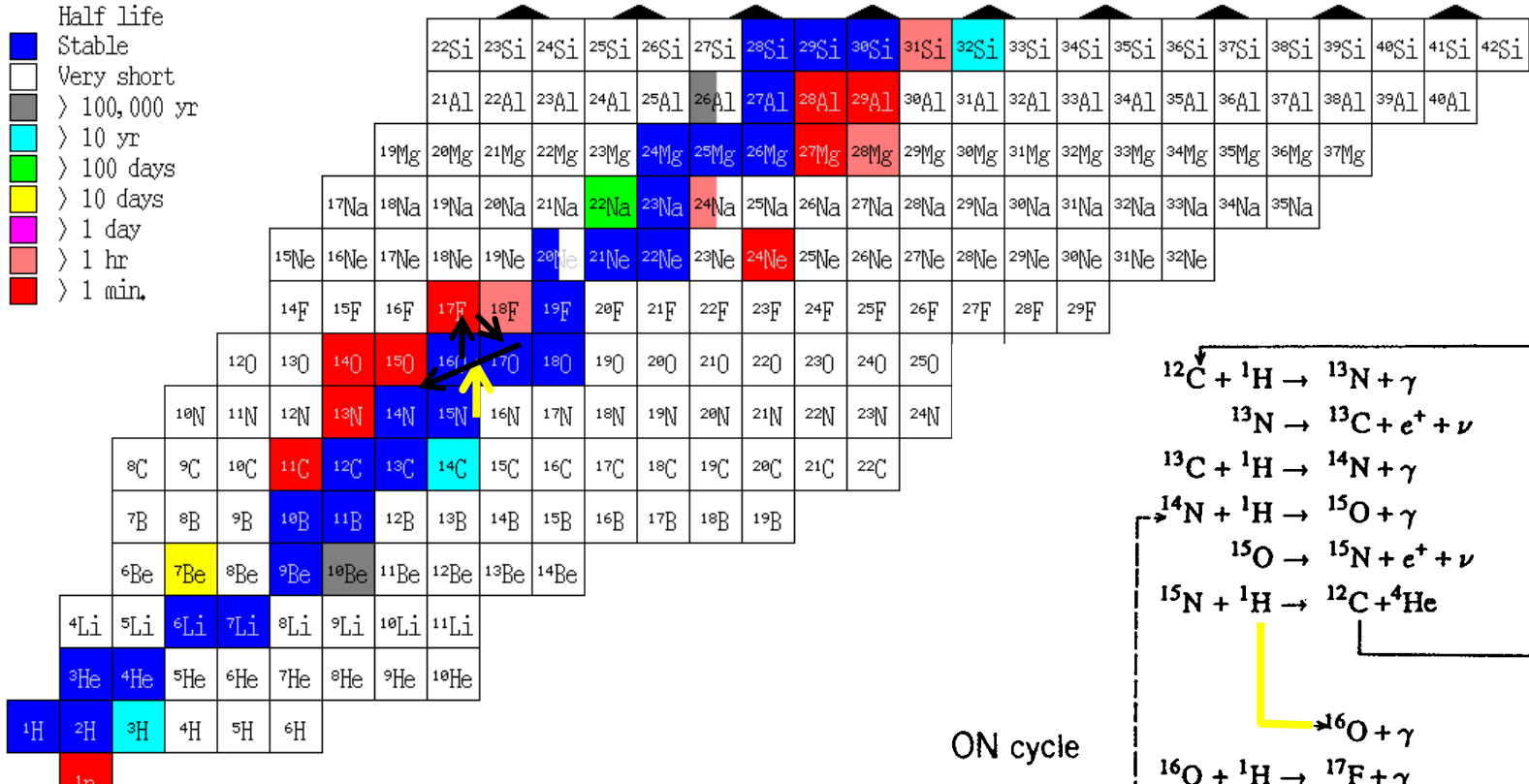
H-Burning (CNO-cycle)

- Half life
- Stable
 - Very short
 - > 100,000 yr
 - > 10 yr
 - > 100 days
 - > 10 days
 - > 1 day
 - > 1 hr
 - > 1 min.

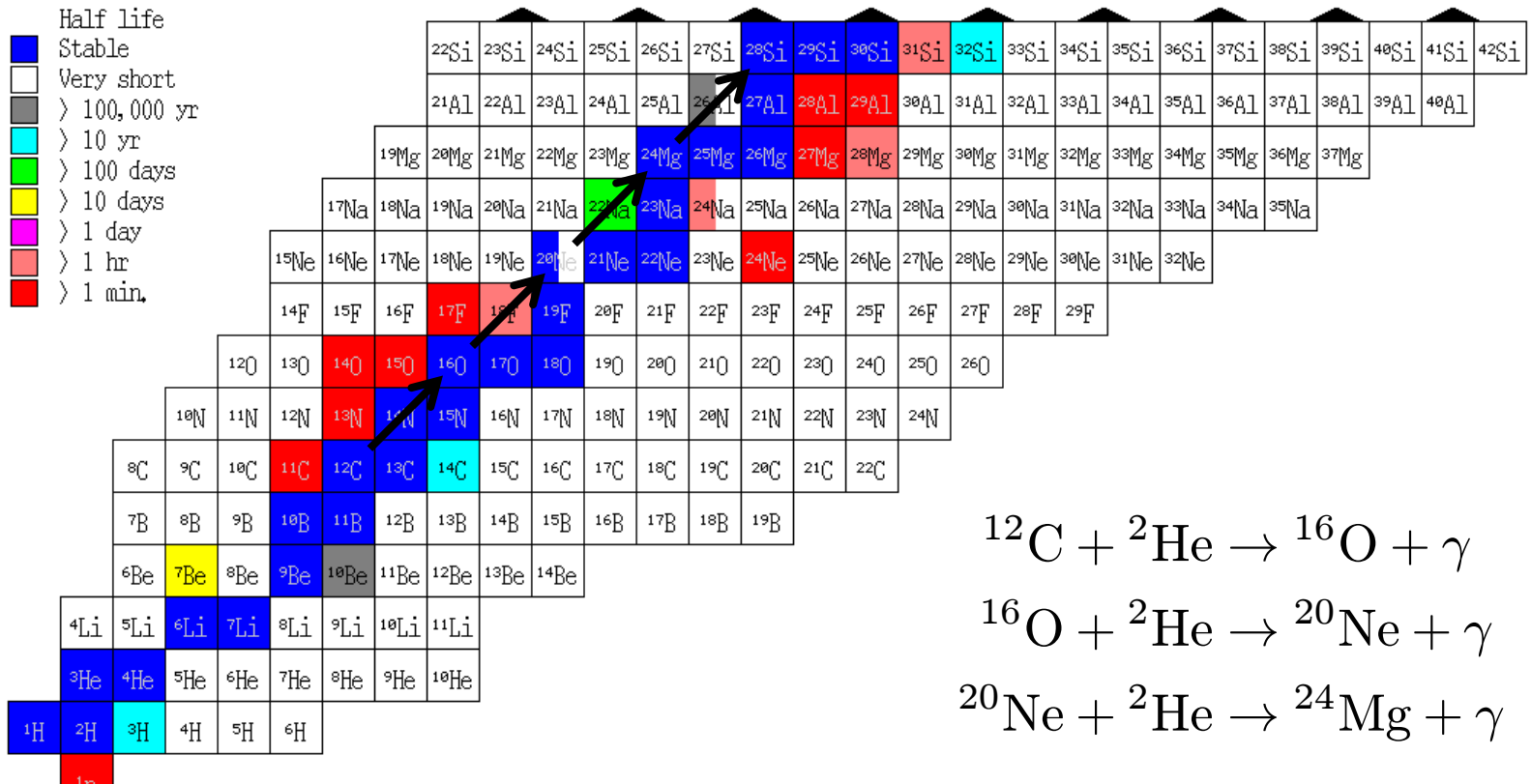


H-Burning (CNO-cycle)

- Half life
- Stable
 - Very short
 - > 100,000 yr
 - > 10 yr
 - > 100 days
 - > 10 days
 - > 1 day
 - > 1 hr
 - > 1 min.



α -elements

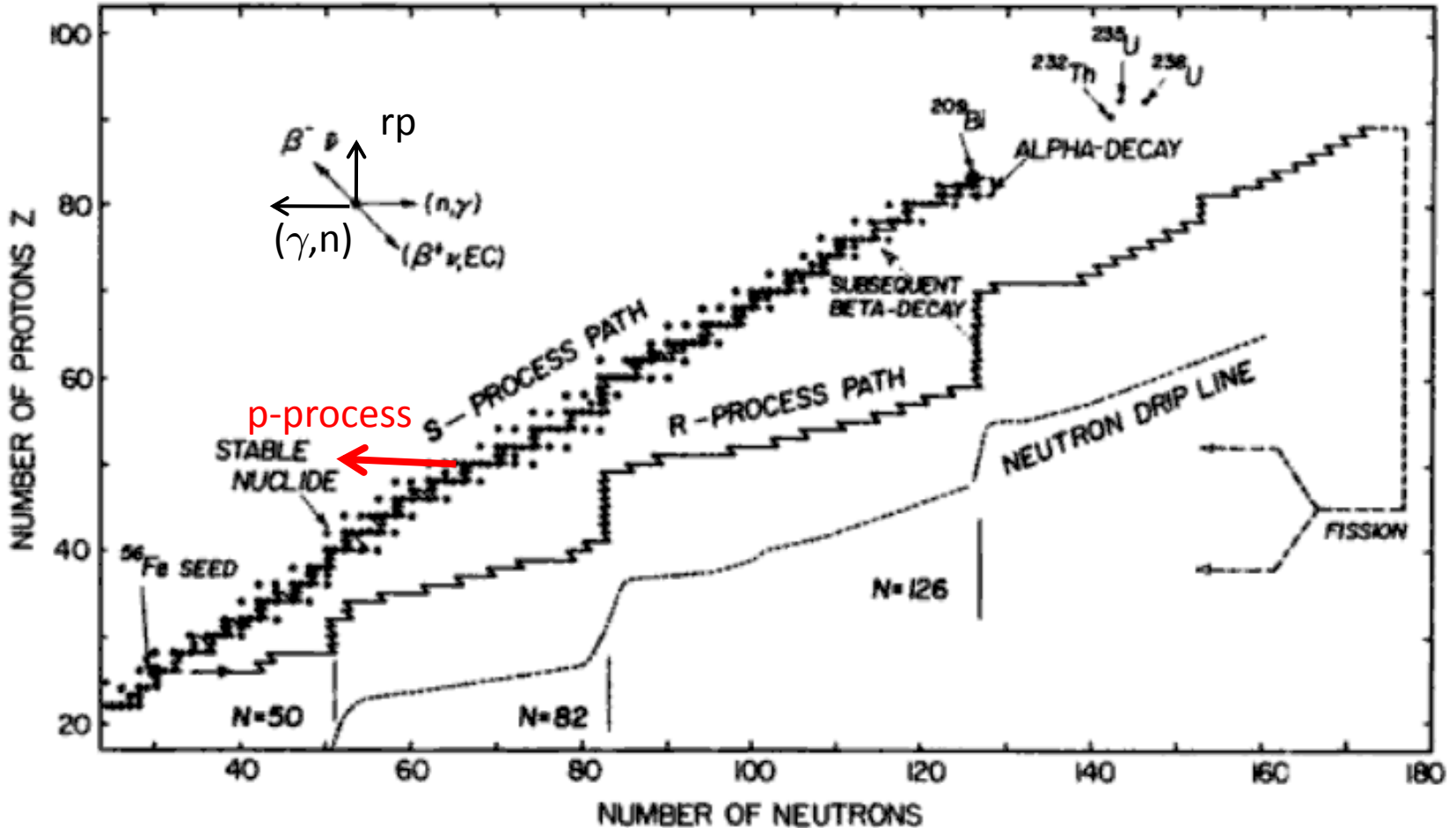


Higher α -elements (Si, S, Ar, Ca, Ti,...,Ni)

s-/r-/p/rp-process

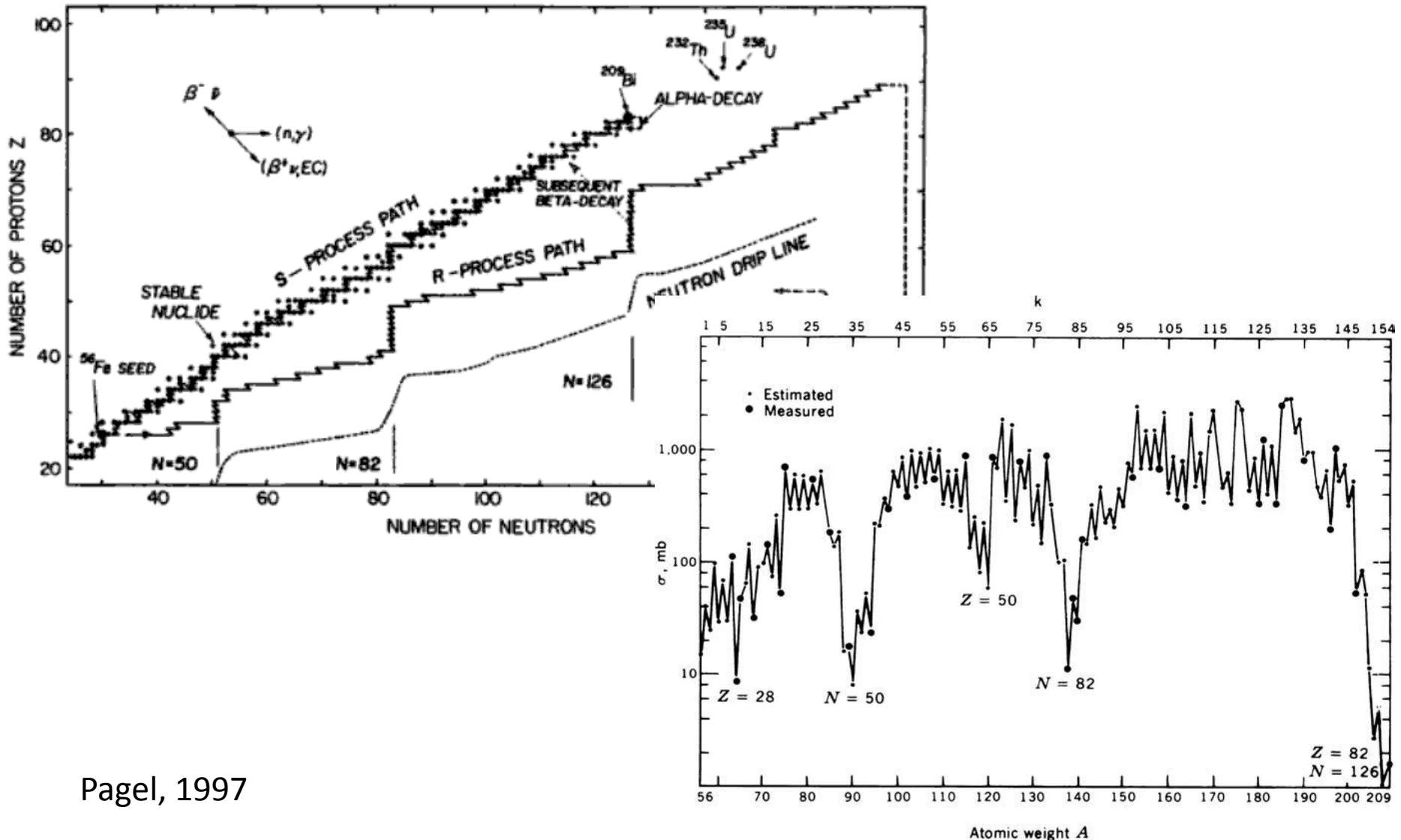
- s-process:
 - slow neutron capture compared to β -decay, nuclides are built ascending the β -stability valley up to ^{209}Bi
- r-process:
 - rapid capture builds neutron-rich, very unstable nuclides up to $A=270$
 - β -decay and fission leads to nuclides on neutron-rich side of stability valley
- p-process:
 - Create proton-rich nuclei by photodisintegration : (γ, α) , (γ, n)
- rp-process:
 - rapid proton capture

r/s/p/rp-process



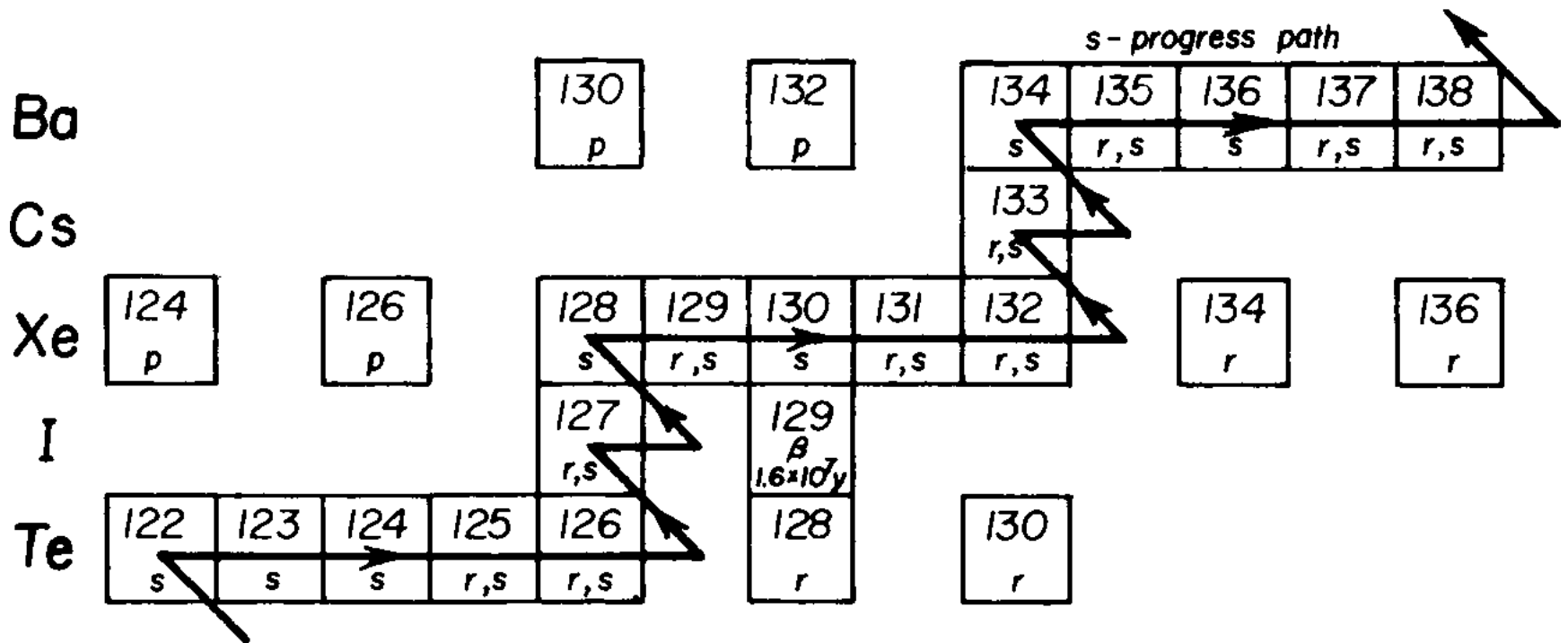
Pagel, 1997

Neutron capture cross-section



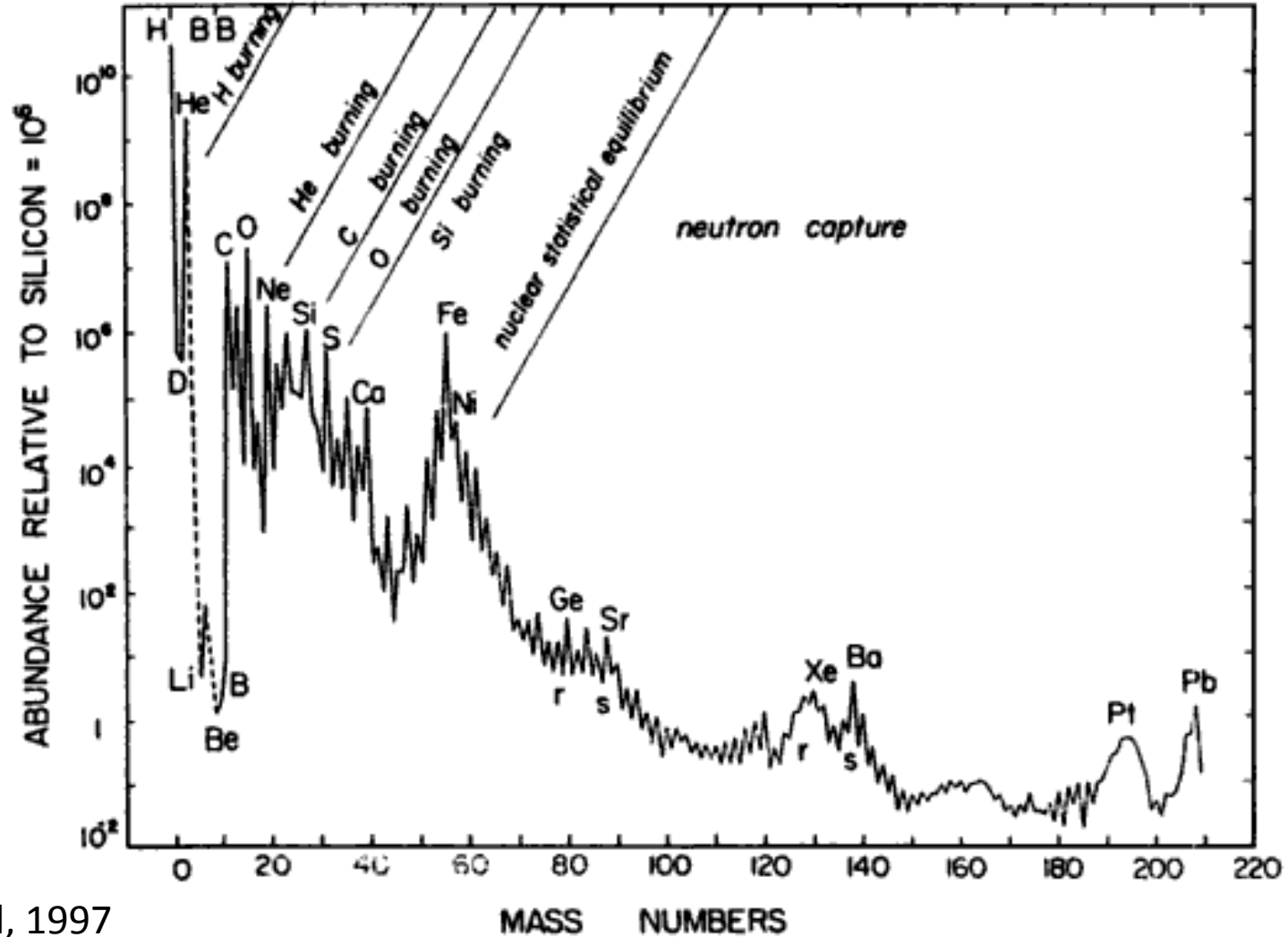
Pagel, 1997

r-,s-,p-elements



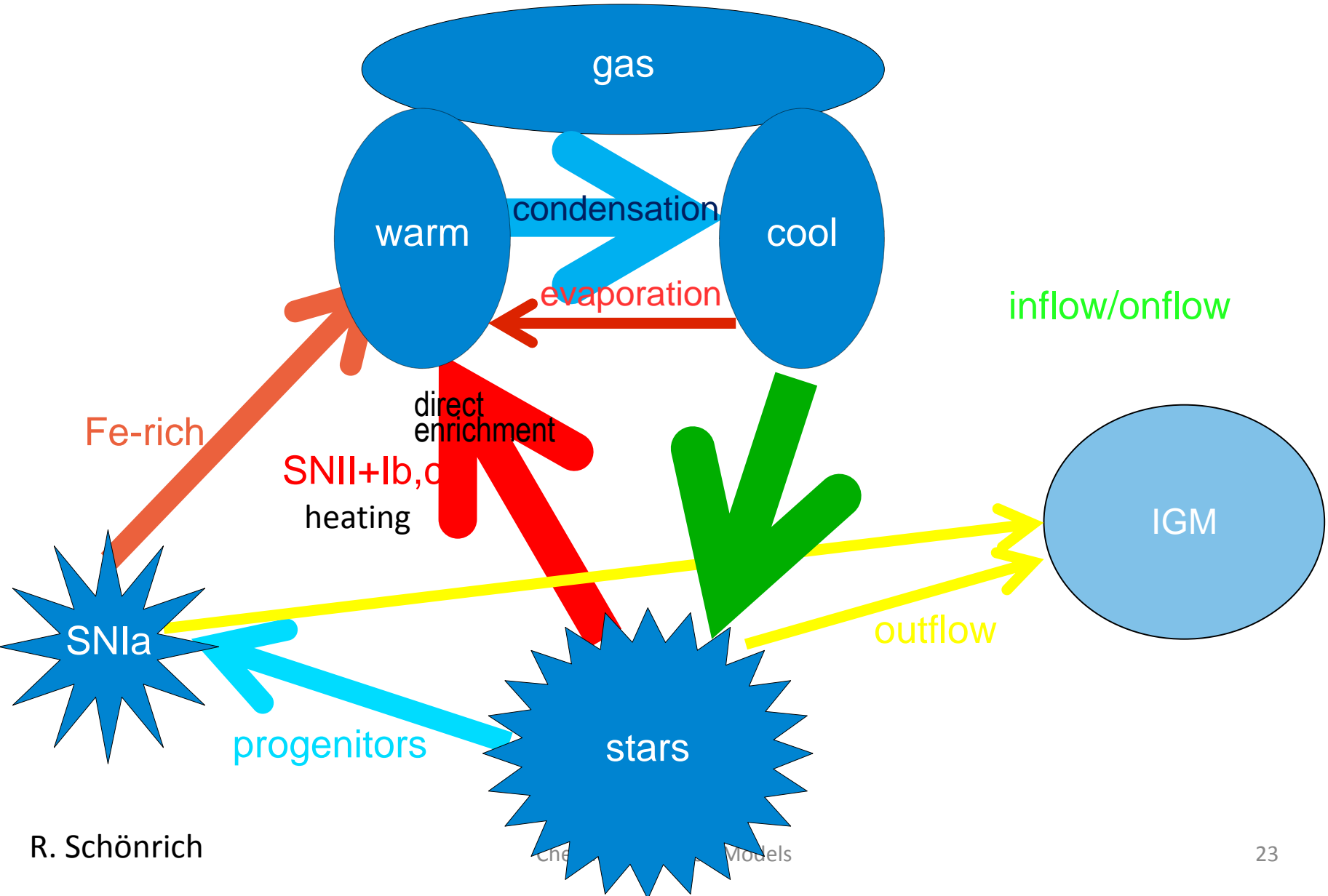
Pagel, 1997

Local abundances



Pagel, 1997

Chemical evolution modelling



Main ingredients

- Initial conditions
 - eg. primordial gas or initial enrichment
- Stellar yield rates
- IMF
- SFR
- Assumptions about all other relevant processes

Stellar yields

- Theoretically these could be calculated from the above processes
- Issues:
 - Incomplete knowledge of reaction rates/cross sections
 - No good theory of mixing
 - Formation of black holes, Hypernovae, fall-back line
 - Unclear explosion conditions
 - Magnetic fields, rotation
 - Binary systems

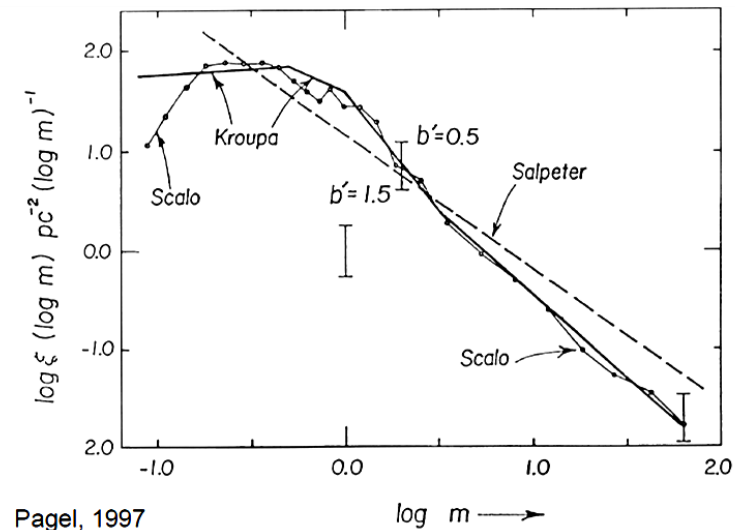
Initial mass function

- Gives the relative birthrate of stars in a mass intervall

$$\Phi(m) = dN/dm \quad \xi(m) = dN/d\log(m) = m dN/dm$$

$$\int_{min}^{max} \xi(m) dm = 1$$

- Observations: luminosity function
- Approximations are (piecewise) power laws
 - Salpeter IMF: $\xi(m) \propto m^{-1.35}$
 - Scalo IMF
 - Kroupa-IMF
- Consequences for CE:
 - Dependence of stellar evolution on mass
- Issues:
 - IMF at low metallicities and time dependence
 - IBP for binaries
 - time dependence of SFR
 - Corrections for evolved stars, unresolved binaries



Star formation rate

- SFR describes the amount of cold gas transformed into stars
- No simple law expected as it may depend on
 - time, gas mass/density
 - total surface density
 - galactic rotation constants
 - Morphology of galaxy
 - other processes: mergers etc

- Approximations:

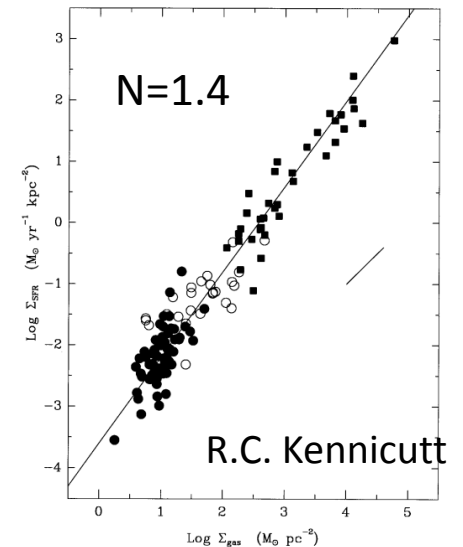
- Exponential decay
- Schmidt-Kennicutt laws: Power laws in the surface density

$$\Sigma_{SFR} = A \cdot \Sigma_{gas}^N$$

- These may also include thresholds or be piecewise defined

- Consequences:

- Increasing SFR leads to decreasing metallicity and vice versa



Basic CE equations

- Total mass is given by : $M = g + s$
- Inflows F increase while outflows E decrease the gas mass(g), star formation(Ψ) traps gas in stars and during evolution processed materials are ejected (e)

$$dM/dt = F - E$$

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

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

- The abundance of a stable nuclide is given by

$$d(gZ)/dt = e_Z - Z\Psi + Z_F F - Z_E E$$

Basic CE equations

- The total ejected mass is given by :

$$e(t) = \int_{m_{\tau=t}}^{max} (m - m_{rem}) \Psi(t - \tau(m)) \Phi(m) dm$$

- The ejected mass of a specific nuclide is :

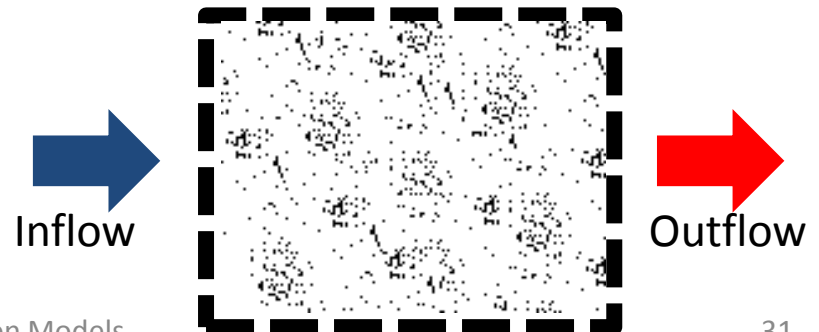
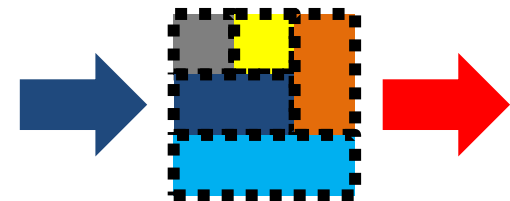
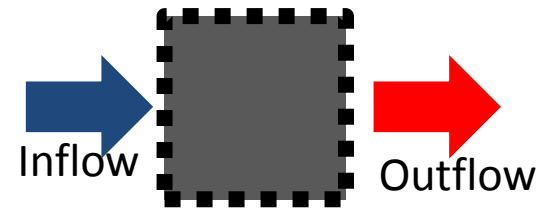
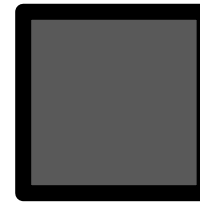
$$e_Z(t) = \int_{m_{\tau=t}}^{max} [(m - m_{rem}) Z(t - \tau(m)) + m q_Z(m)] \Psi(t - \tau(m)) \Phi(m) dm$$

Instantaneous recycling

- Assumption: All processes of stellar evolution take place instantaneously compared to galactic evolution
- This allows analytical treatment of the equations
- Issues:
 - Problems describing nuclides that are produced by stars that have long evolution times (eg. Fe), SN
 - Distorts CE processes

Types of GCE models

- Homogeneous Models:
 - No kinematics
 - a. Isolated system (closed box)
 - b. In- and outflow (open box)
- Inhomogenous Models:
 - separate system into different parts and model each as a box
 - possible couplings include mass-, energy or momentum-transfer
 - No kinematics
- Chemo-dynamical models:
 - Analytical and N-Body simulations
 - Both include kinematics
 - complete simulation of the galaxy and its components with interactions



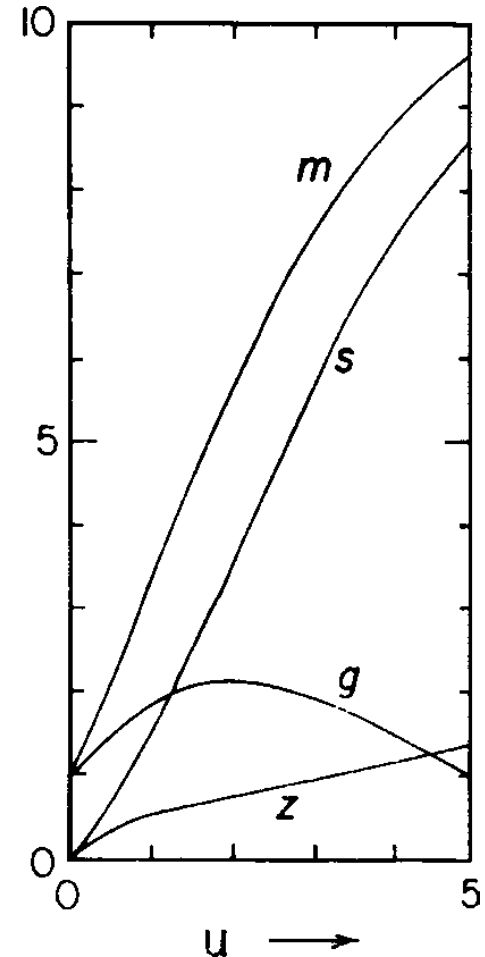
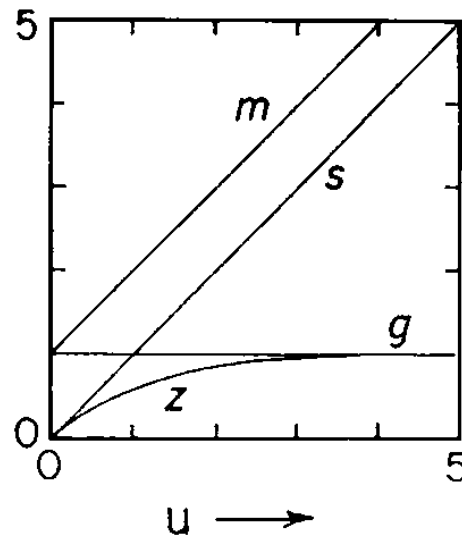
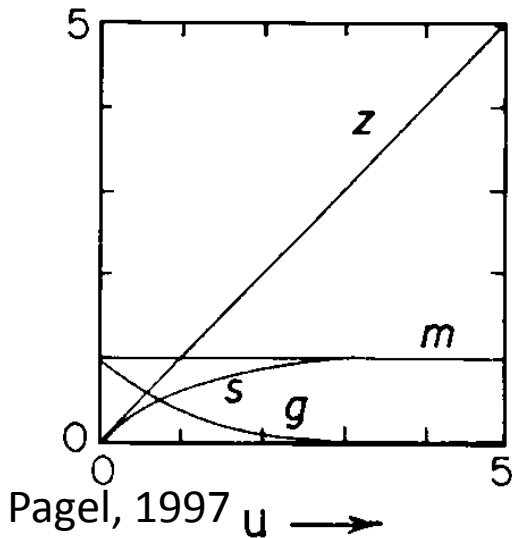
One-zone models predictions

m, s, g are the total, star and gas mass
 z is metallicity

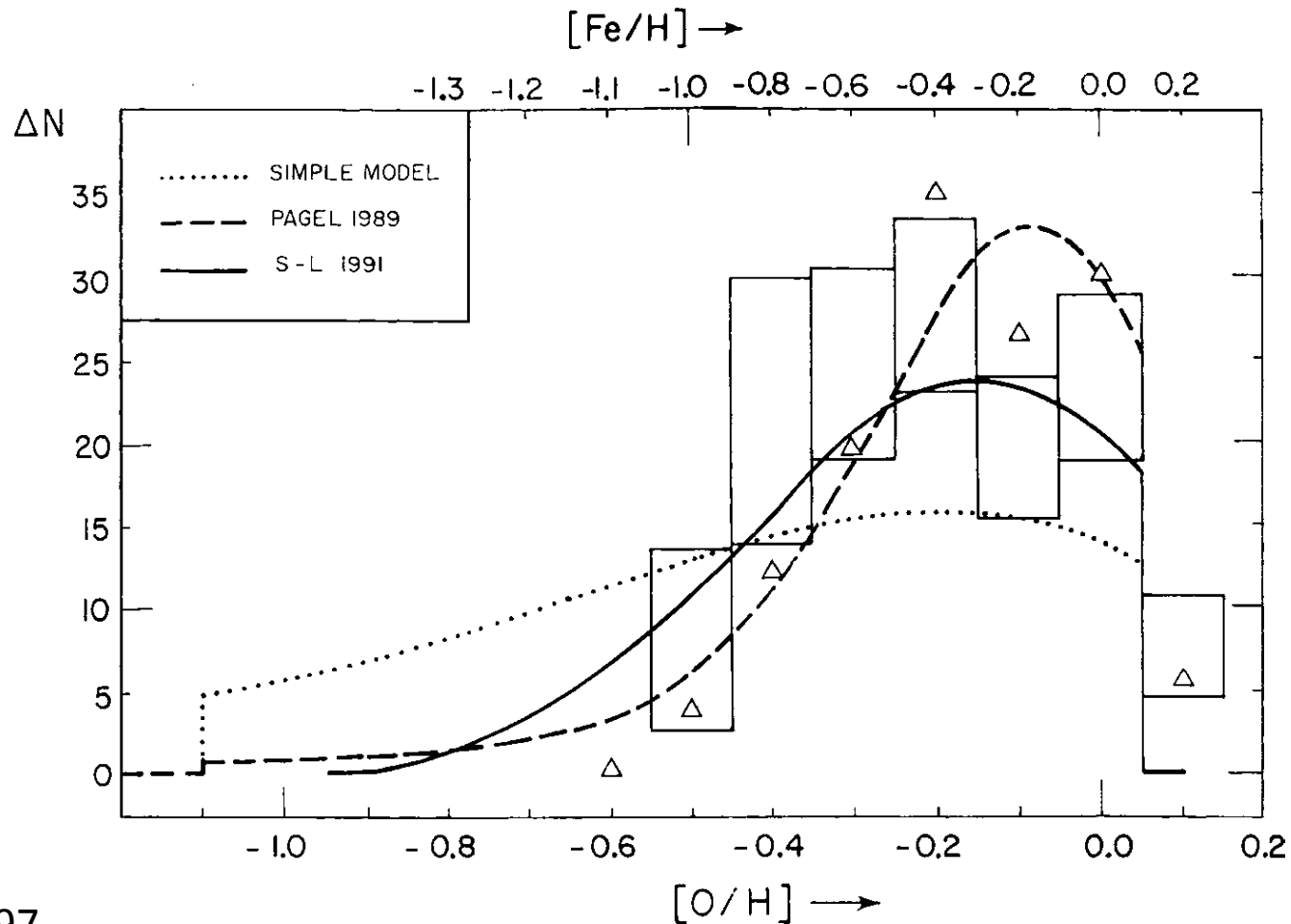
$$u = \int_0^t \omega(\tau) d\tau \quad \omega \text{ is transition probability gas to star}$$

Simple
model

Extreme inflow
model



One-zone models predictions G-dwarf problem



Pagel, 1997

Distribution function of O-ab. of 132 G-dwarfs in solar cylinder

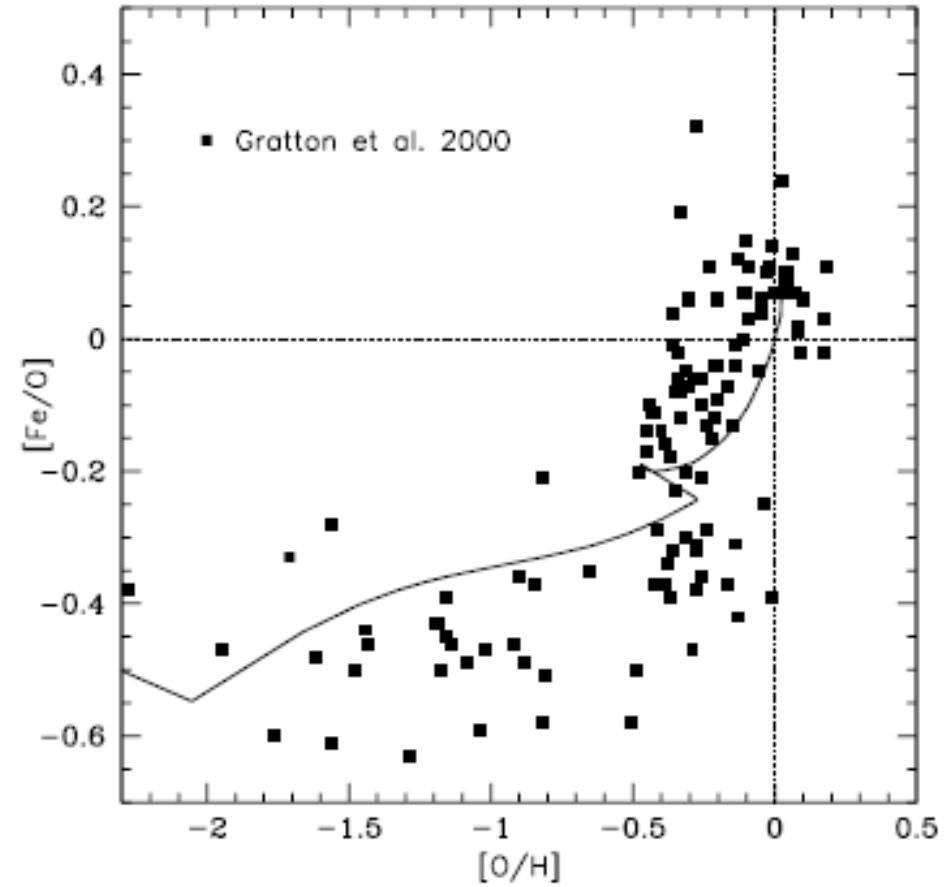
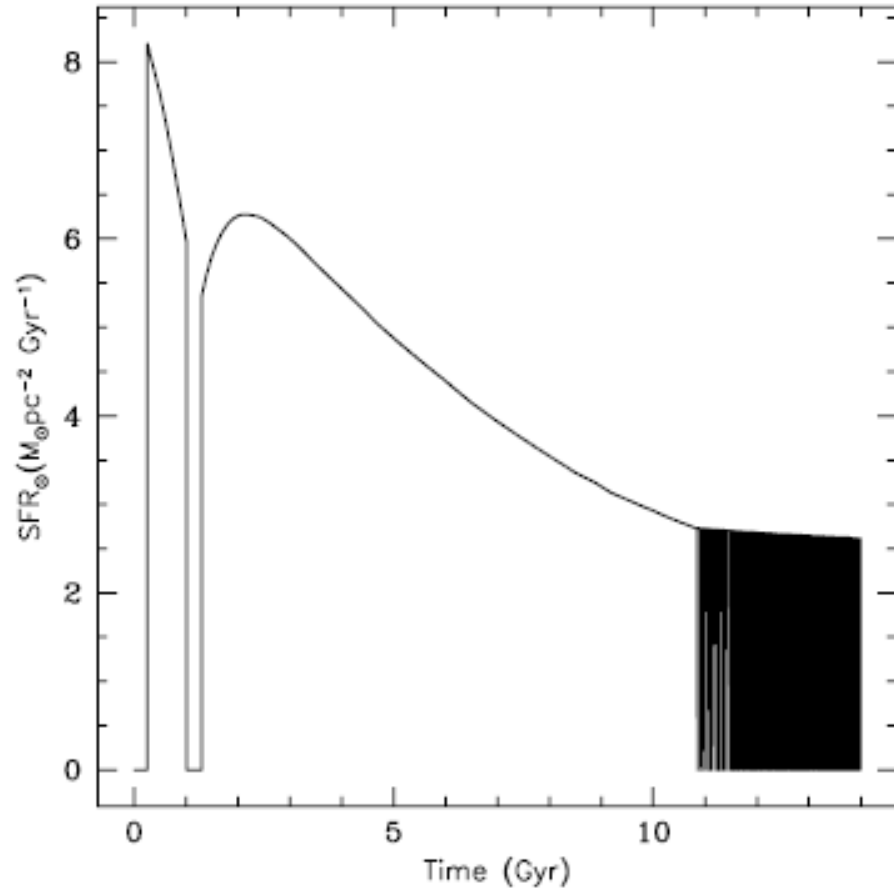
Successes and problems

- Analytical models allow understanding of parameters
- Predicts age-metallicity relation
- Fails to explain G-dwarf problem
- Oversimplified:
 - No gradients
 - Integrated quantities
 - Doesn't allow for complex galactic structure

Multi-Zone model

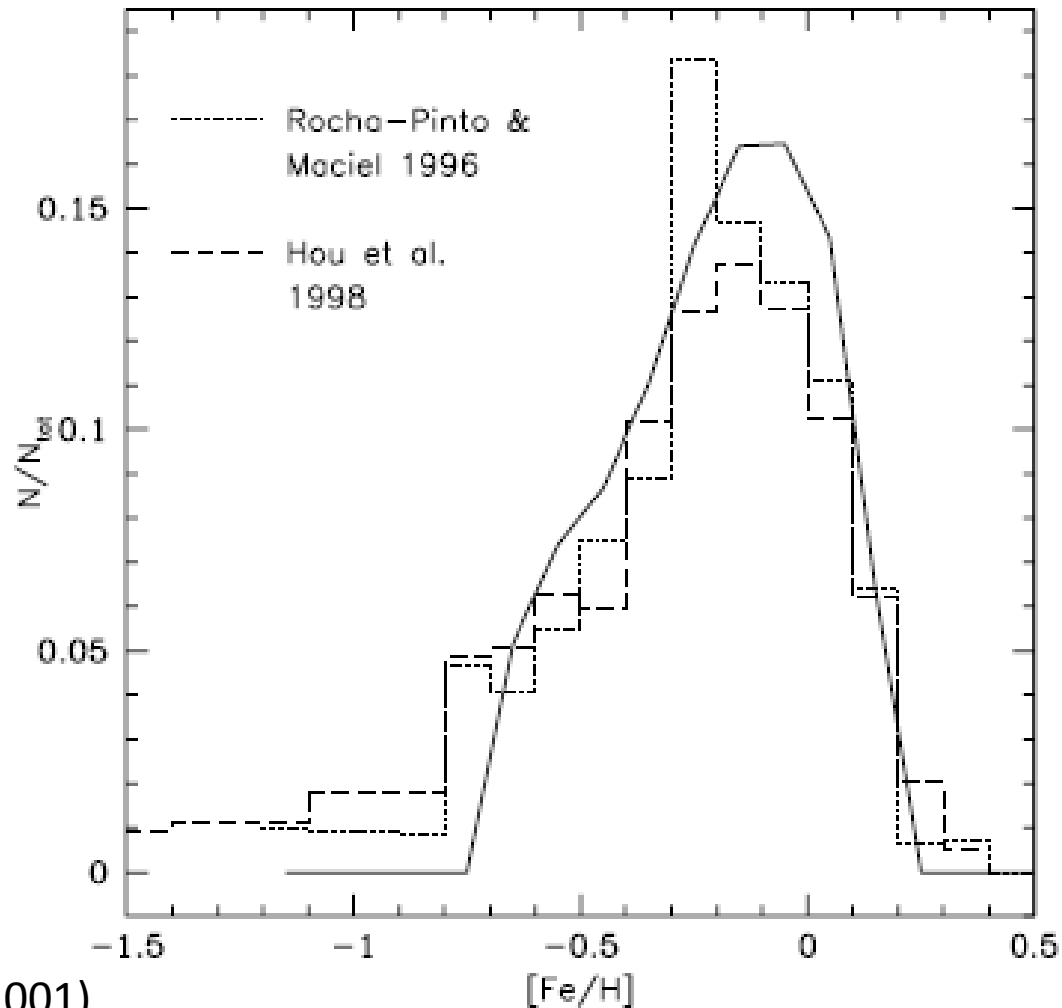
- C.Chiappini, F.Matteucci & R.Gratton (1997)
- C.Chiappini, F.Matteucci & D.Romano (2001)
 - Two infall episodes to create halo&bulge (fast) and disk(slow)
 - Model disk as several independent rings
 - Scalo IMF and power law SFR with threshold
 - Fit to abundance, gas profiles in MW disk

SFR & abundance plane [O/H],[Fe/O]



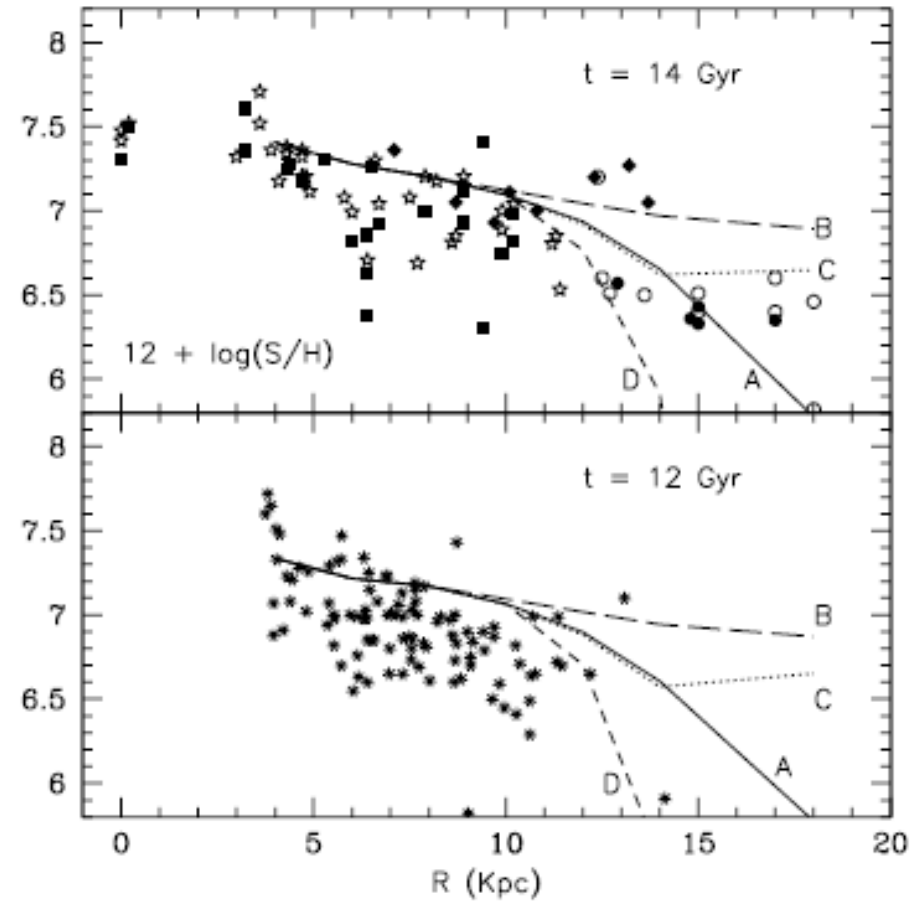
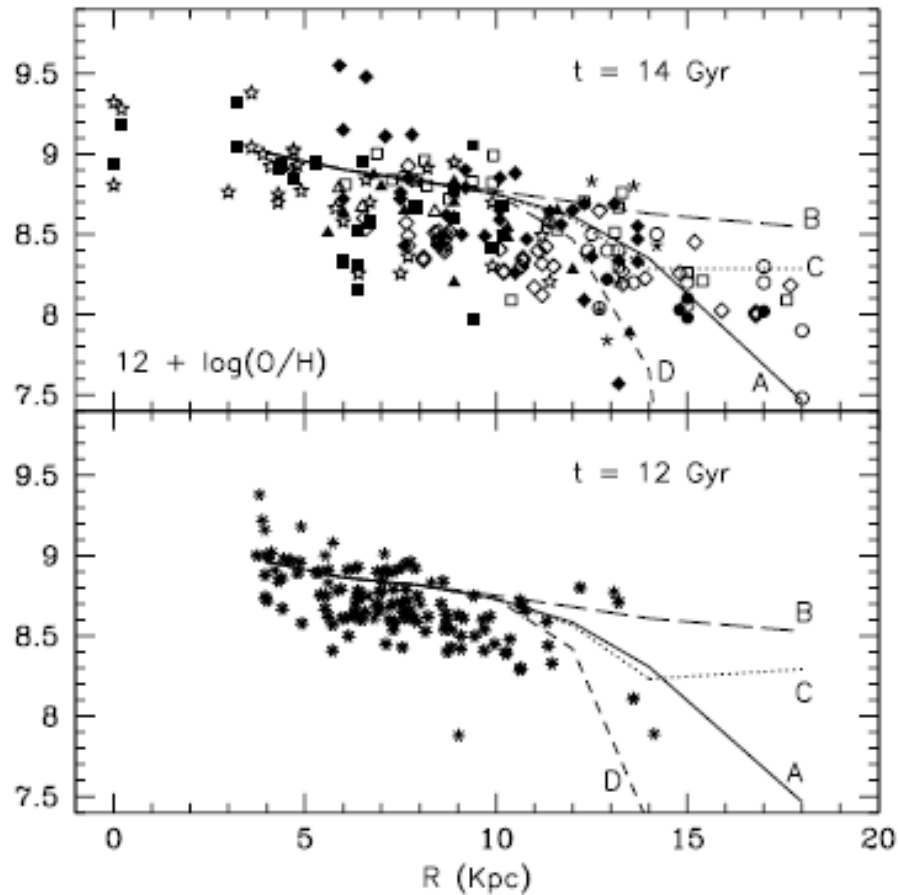
C.C., F.M. & D.R. (2001)

G-dwarf metallicity distribution fct



C.C., F.M. & D.R. (2001)

Abundance gradients



C.C., F.M. & D.R. (2001)

Successes and problems

- Reproduce observed G-dwarf distribution
- Reproduce solar abundances up to a factor of 2
- Issues:
 - Discrepancy between observed and predicted abundances
 - CE parametrized by infall
 - Independent rings, no mixing effects
 - “Oscillating” SFR
 - Lack of observational data to constrain models

Chemo-dynamical model

- Self consistent model of the galaxy with some of its parts and interactions
- Samland & Gerhard, 2003:
 - Assume average dark halo formation history
 - Stellar evolution depends only on initial mass and metallicity
 - 2-phase ISM with hot gas containing cold and warm clouds
 - Models for evaporation & condensation
 - Self-regulation (star formation, heating)

Chemo-dynamical model results

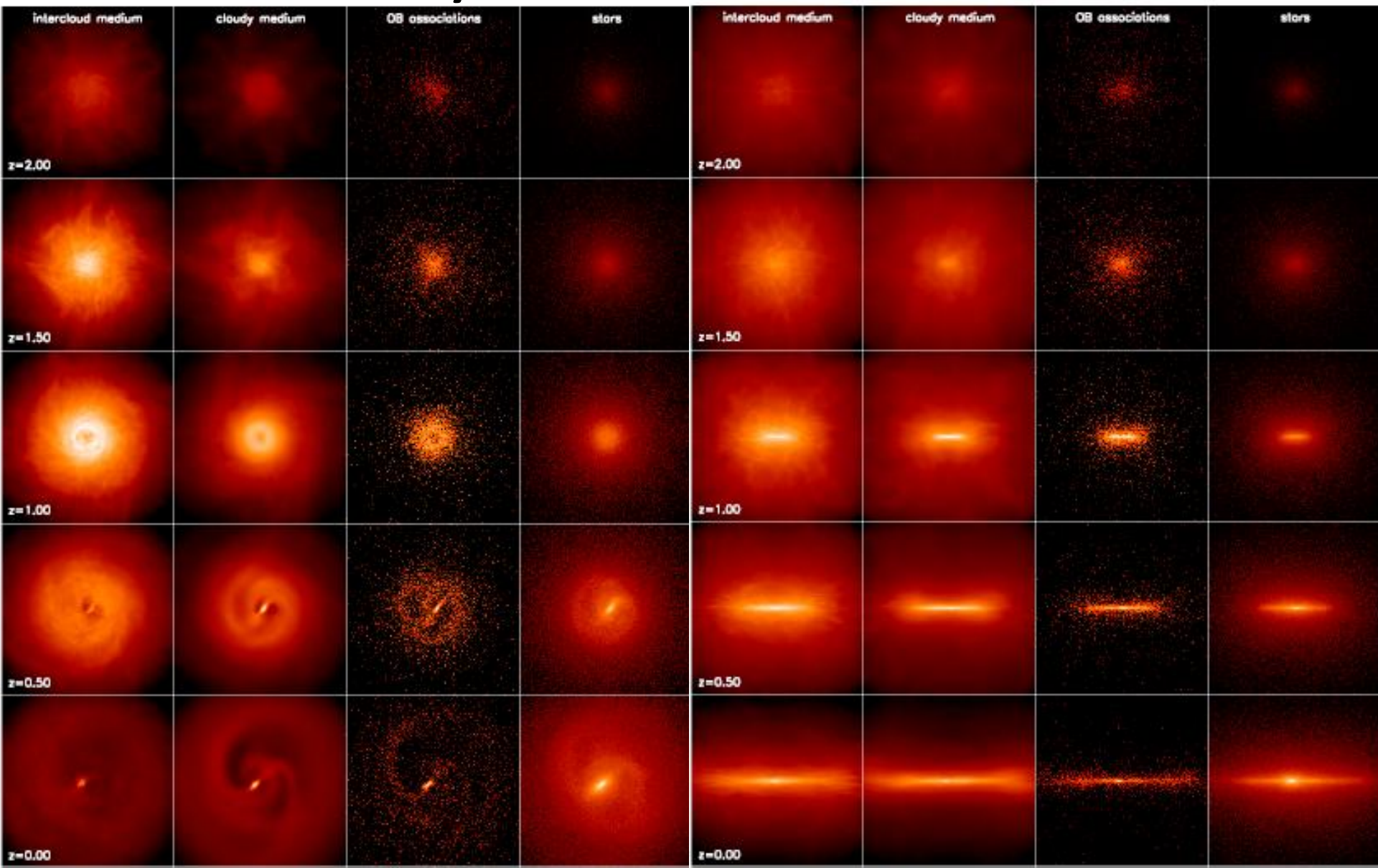
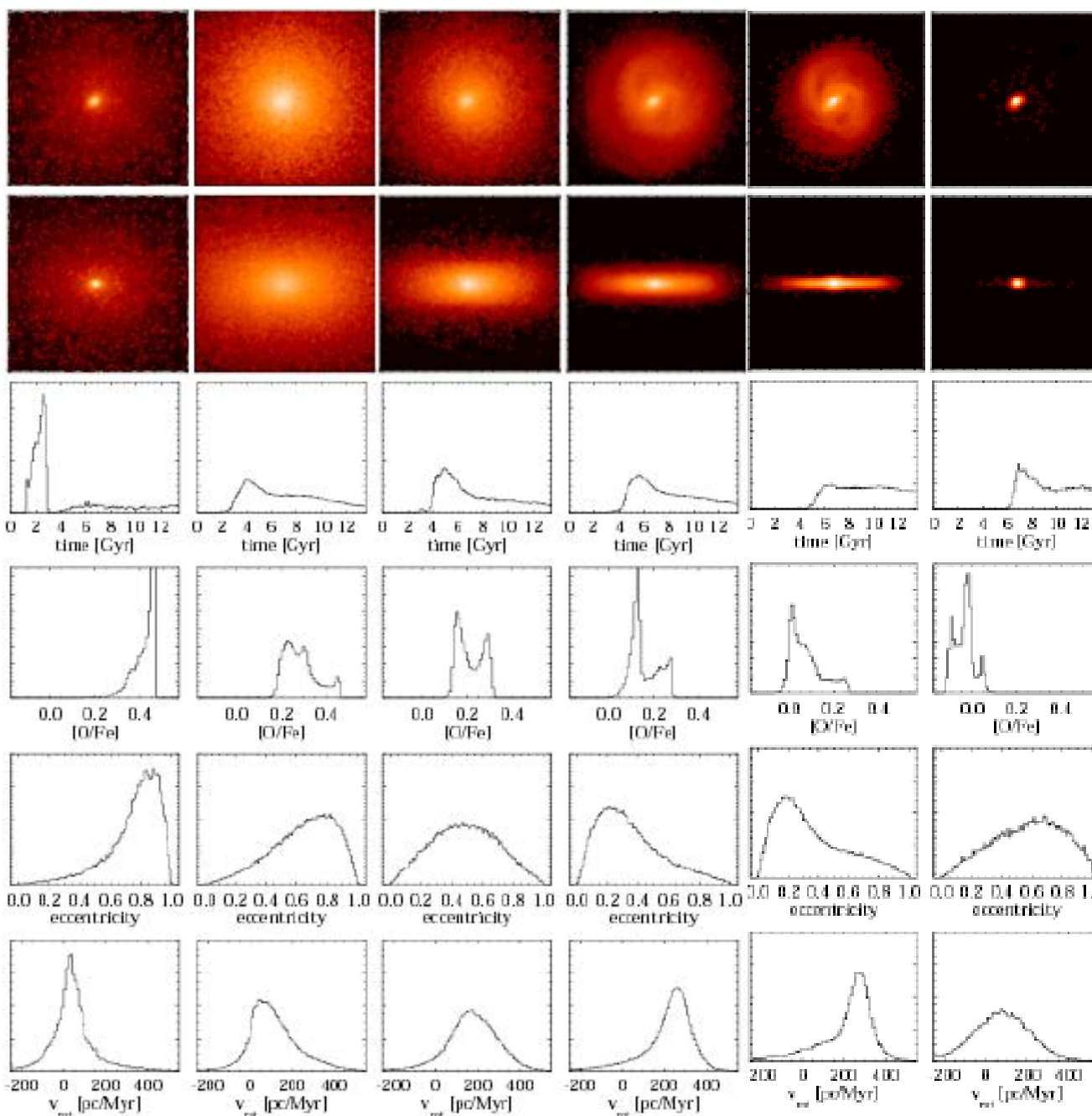
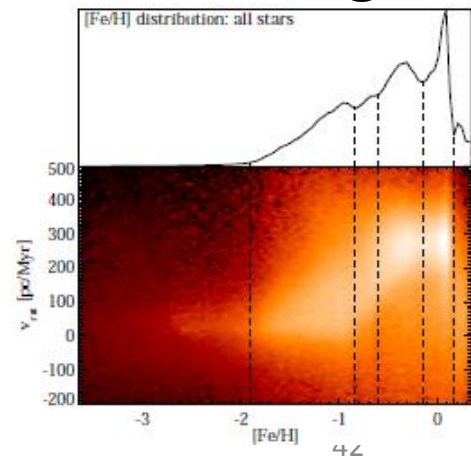


Fig. 7. Face-on surface density of the ionized gas, the cloudy medium, the OB-associations and the stars at different redshifts. Each column shows the evolution of one component between redshift $z = 2$ and $z = 0$. Each panel has a size of 50×50 kpc.



f.l.t.r.:

- 1: Extreme halo
- 2: Inner halo
- 3: Metal-weak thick disk
- 4: Thick disk
- 5: Thin disk
- 6: Inner bulge



Suceses and problems

- Gives a plausible galaxy formation history including the distinct parts of our galaxy (bulge, bar, disk)
- Metal enrichment history roughly consistent with observations
- Reproduces oxygen distribution of G-dwarfs

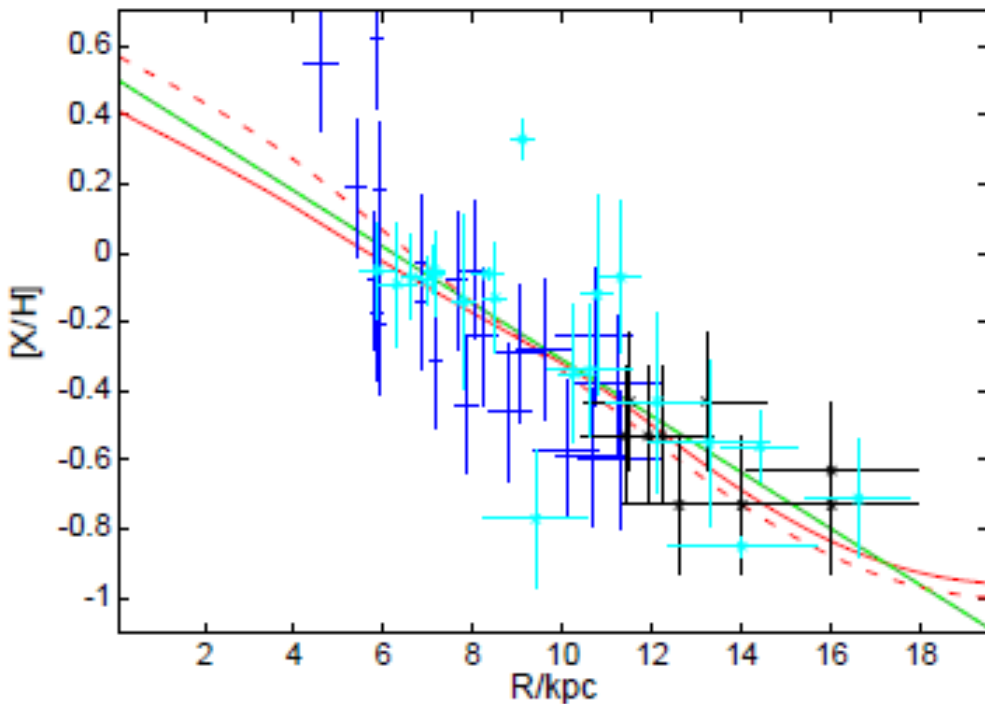
- Lack of computing power to simulate 3-phase model and formation of halo
- Unclear input physics
- No merging processes included
- **Many parameters**, initial data
- **Low spatial resolution**

Analytical chemo-dynamical model

- Schönrich, Binney (2009):
 - model evolution of galactic disk separated into 80 annuli
 - Allow migration of stars between annuli (churning and blurring)
 - Radial gas transport
 - 2 interstellar gas medium
 - Complete kinematical treatment
 - Compare it to Geneva-Copenhagen sample (~ 14000 stars)

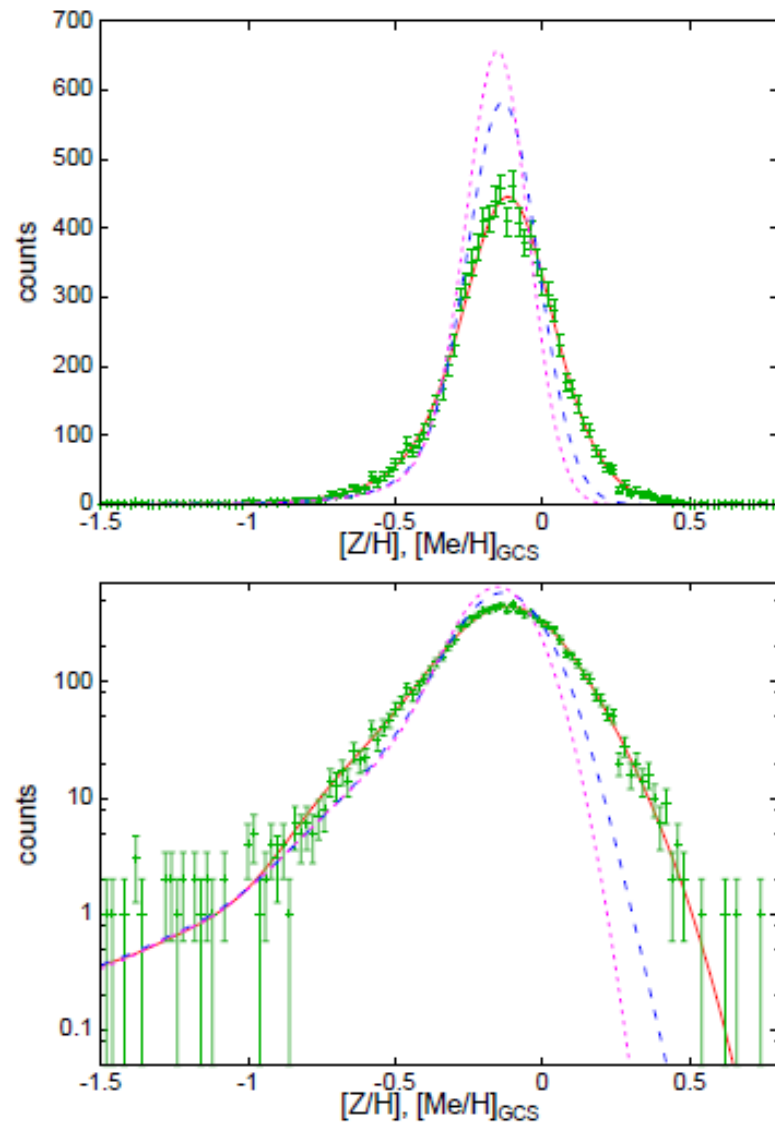
Results

Metallicity of ISM

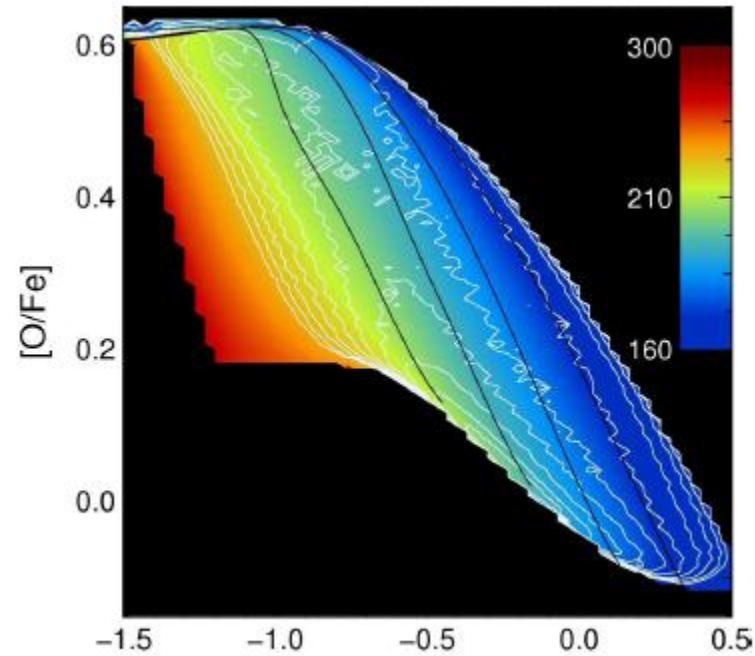


Schönrich, Binney (2009)

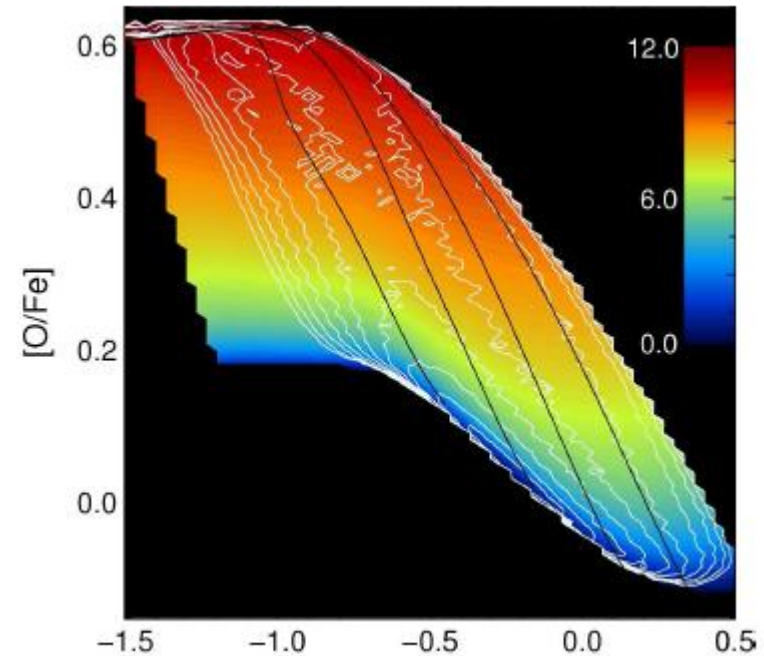
Metallicity distribution



Abundance plane with kinematics



Contour=density $[Fe/H]$
Colour=av. rot. velocity



Contour=density $[Fe/H]$
Colour=age

Schönrich, Binney (2009)

Bimodal structure

Suceses and problems

- High quality fits to observed abundances with few parameters
- Allows analytical relations and studies of effects of parameters on results
- Allows resolution of solar system
- Demonstrates importance of radial flows
- Proofs existence of radial migration

- Only simulates the disk (no bar, bulge, halo)
- Severe simplifications in kinematics
- Highly insufficient knowledge of infall and radial flows

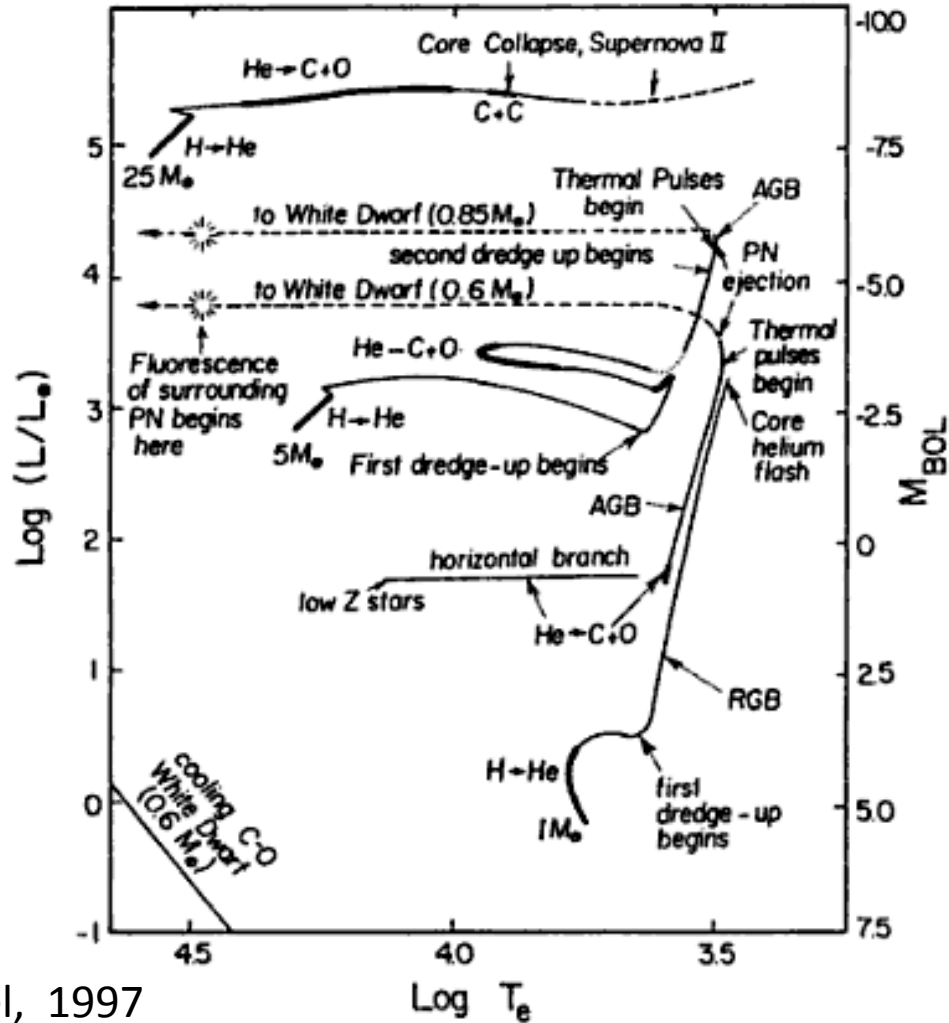
Conclusions

- CE reproduces the evolution of many observable parameters such as star formation, stellar populations and abundances
- CE might in the future give us a complete history of our galaxy
- Analytical models and N-Body simulations can be used complementarily
- Major issues:
 - Limited data on galactic abundances, star formation history, infall and outflows
 - stellar evolution: cross sections, mixing, SN, BH&NS formation, binary effects
 - Cosmology: initial data (halo)
 - Kinematics

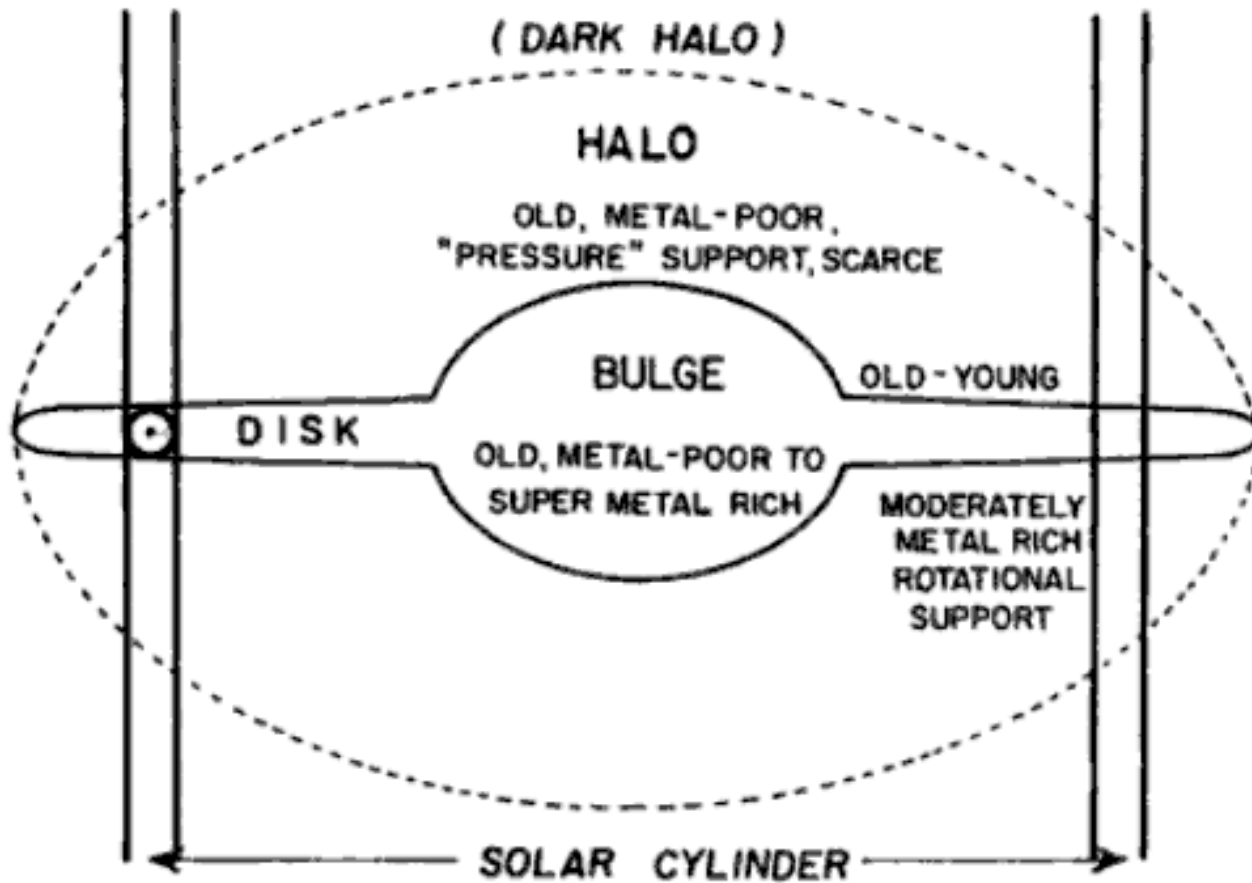
Bibliography

- B.E.J. Pagel, *Nucleosynthesis and Chemical Evolution of Galaxies*, Cambridge University Press, 1997
- R. Schönrich and J. Binney, *MNRAS* 396: 203–222 (2009)
- R. Schönrich and J. Binney, *MNRAS* 399:1145-1156 (2009)
- M.Haywood, *MNRAS*, 371, 1760 (2006)
- B. Nordström et al., *A&A* 418, 989–1019 (2004)
- M. Samland, & O.E. Gerhard, *A&A* 399, 961-982 (2003)
- C.Chiappini, F.Matteucci & D.Romano, *ApJ* 554, 1044-1058 (2001)
- R.C. Kennicutt , *ApJ*, 498, 541 (1998)
- C.Chiappini, F.Matteucci & R.Gratton , *ApJ* 477,765-780(1997)
- A.Maeder, *A&A* 264, 105-120 (1992)
- M. Schmidt, *ApJ*, 137, 758 (1963)
- E.M. Burbidge, G.R. Burbidge, W.A. Fowler, F. Hoyle, *Rev. Mod. Phys.* 29, 547–650 (1957)

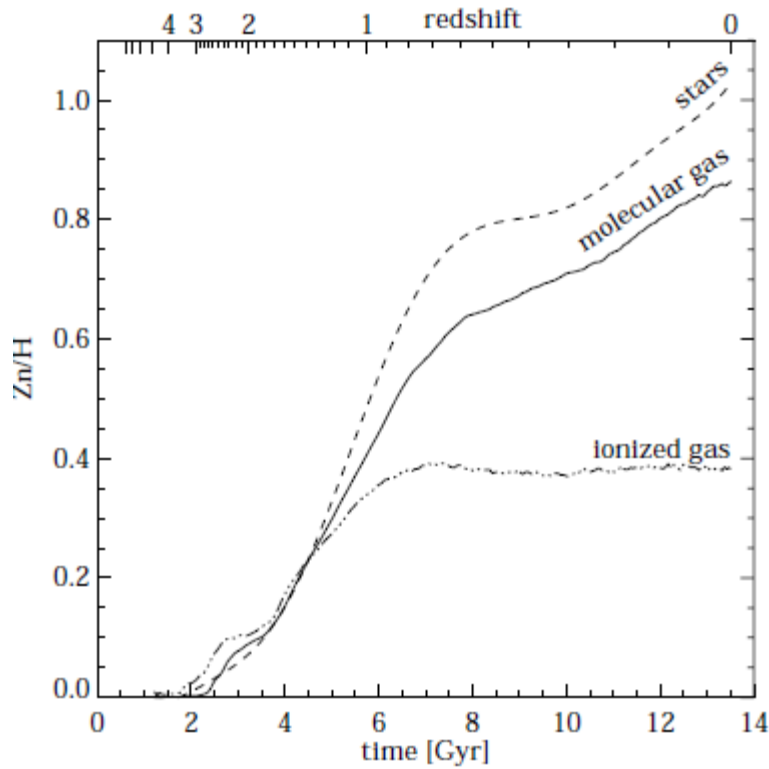
Stellar evolution



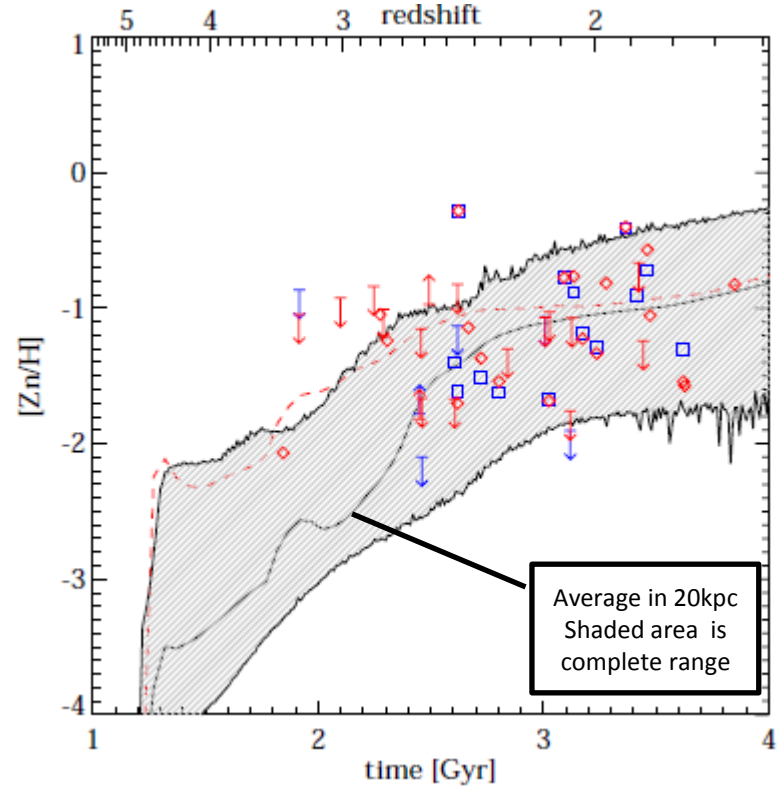
Pagel, 1997



metallicity evolution

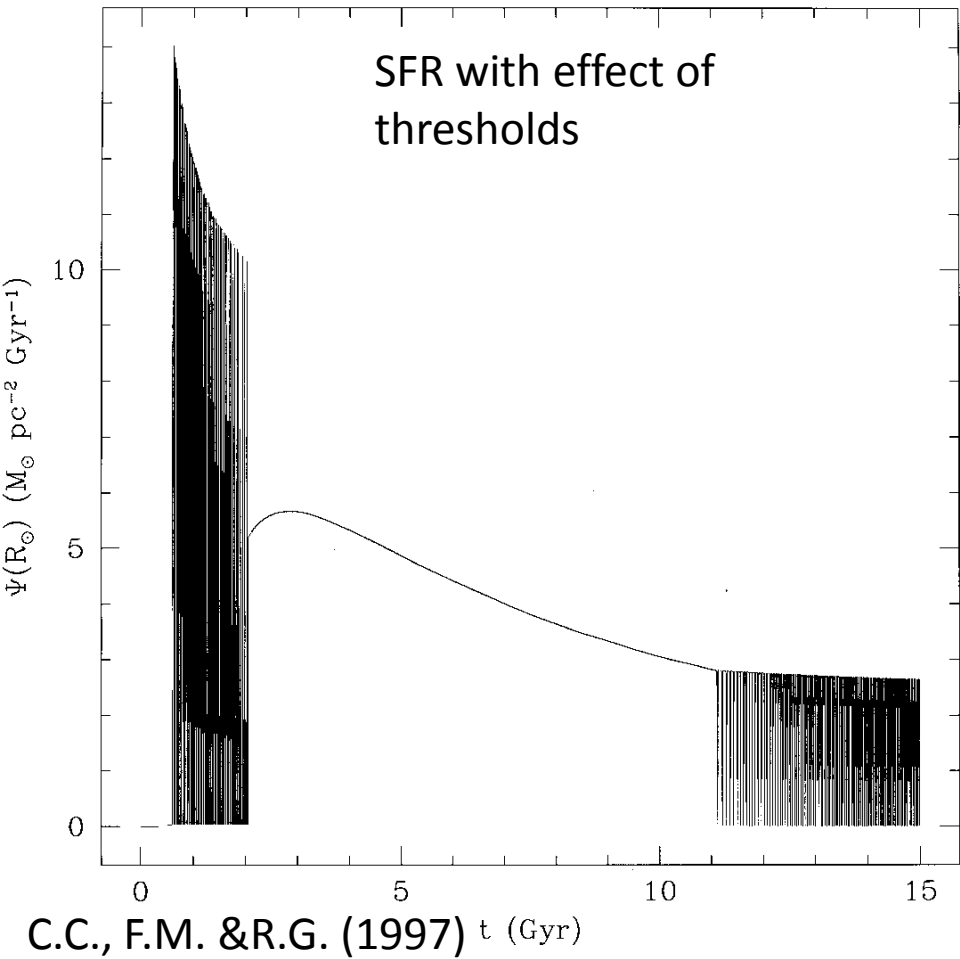


Samland & Gerhard, 2003



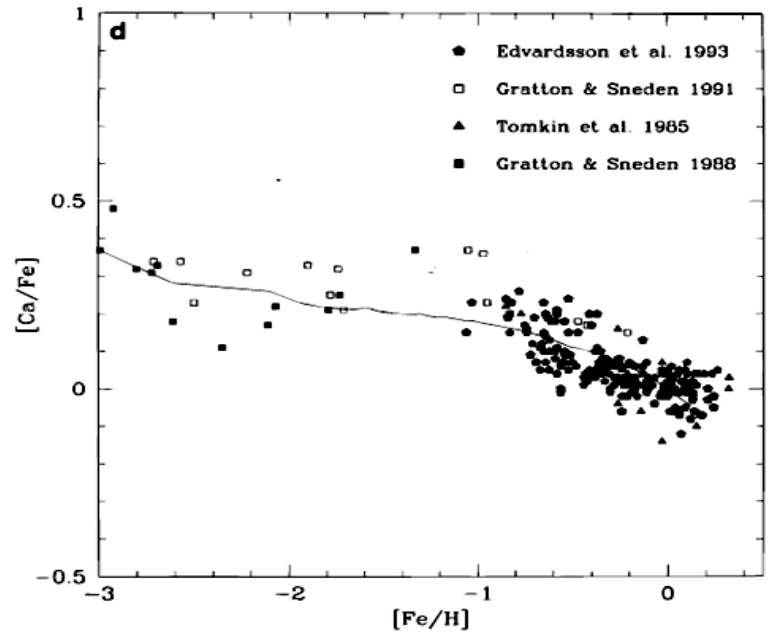
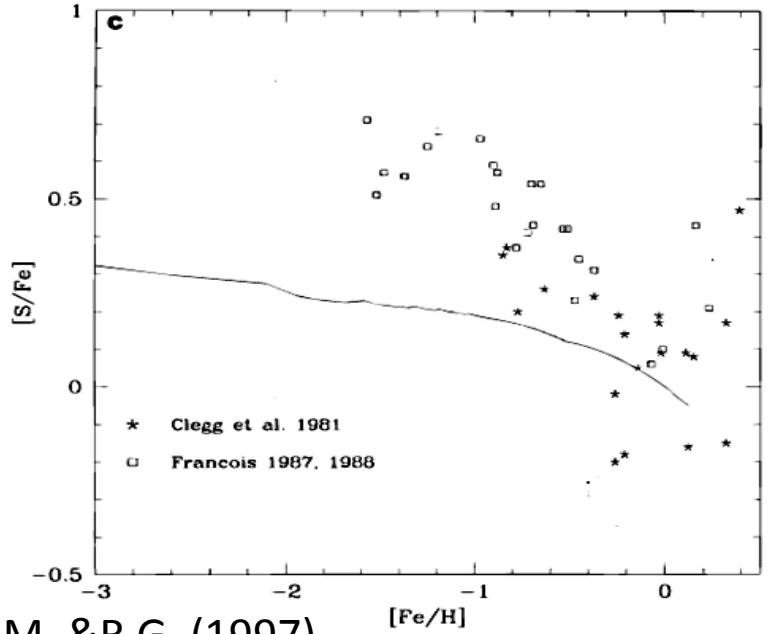
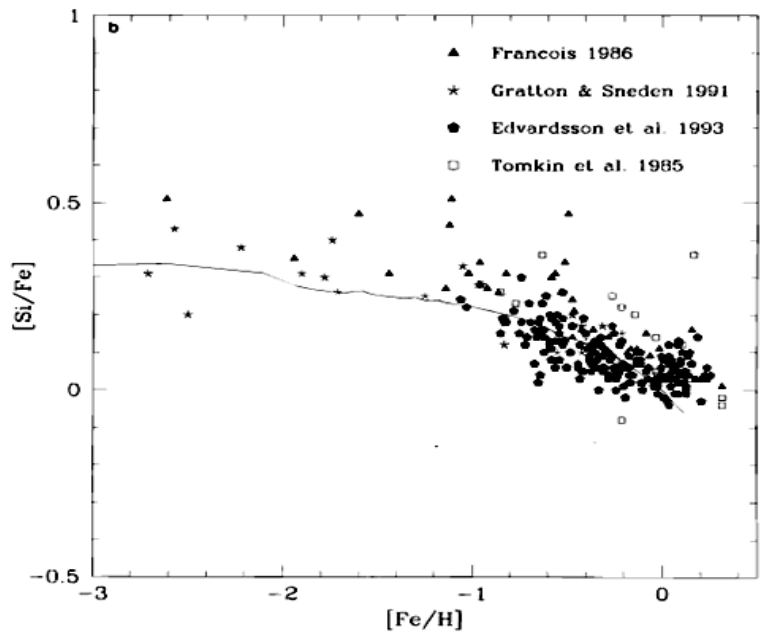
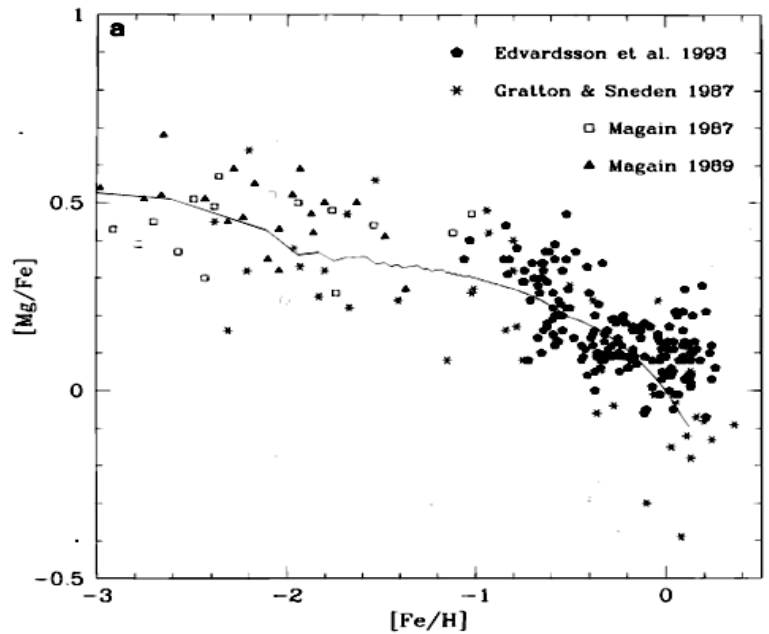
Average in 20kpc
Shaded area is
complete range

Results



SOLAR ABUNDANCES BY MASS

Element	Best Model (A)	Observations ^a
H	0.731	0.702
D	4.630 (-5)	4.80 (-5)
^3He	10.01 (-5)	2.93 (-5)
^4He	2.548 (-1)	2.75 (-1)
^{12}C	1.827 (-3)	3.03 (-3)
^{16}O	7.278 (-3)	9.59 (-3)
^{14}N	1.386 (-3)	1.11 (-3)
^{13}C	4.758 (-5)	3.65 (-5)
Ne	0.942 (-3)	1.62 (-3)
Mg	2.48 (-4)	5.15 (-4)
Si	7.03 (-4)	7.11 (-4)
S	3.071 (-4)	4.18 (-4)
Ca	3.95 (-5)	6.20 (-5)
Fe	1.37 (-3)	1.27 (-3)
Cu	8.18 (-7)	8.40 (-7)
Zn	2.44 (-6)	2.09 (-6)
Z	1.433 (-2)	1.886 (-2)



C.C., F.M. & R.G. (1997)

Self-regulation

