Star Formation and Chemical Enrichment

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Formation and Evolution of Galaxies 2023/24 Q1
Rijksuniversiteit Groningen

Star Formation

Star Formation

- Star formation defines the visible properties of galaxies and this means that any theory of galaxy formation needs to include a theory of how stars form…

- A full understanding of star formation in a cosmological framework is challenging - the typical mass of gas in a galaxy is ~$10^{11}M_\odot$ with a density of ~10^{-24} g cm^{-3}, and for a typical star this is ~$1M_\odot$ and ~1g cm^{-3} → *11 orders of magnitude in mass and 24 in density*

- Gas on the scale of the Milky Way can cool and collapse very quickly. So one of the challenges for a theory of galaxy formation and evolution is actually how to *STOP a galaxy turning all its gas into stars all in one go at the beginning*

- As gas cools it looses pressure support and flows to centre of a galaxy (or halo), causing density to increase. Once this density increases sufficiently the gas becomes self gravitating and collapses under its own gravity.

- In the presence of efficient cooling self-gravitating gas is unstable and can collapse catastrophically. This leads to the formation of dense, cold gas clouds within which star formation can occur.

Lessons from SF in the MW

- The ISM is constituted by HI, HII and H_2 (~30%) and dust (1%)
- Star formation occurs in molecular clouds
  - it occurs within the dense parts of molecular clouds
  - only molecular gas can cool below 100 K and therefore collapse under its own gravity: Jeans criteria, Bonnor-Ebert
  - atomic gas does not emit efficiently at these temperatures but molecular gas does, mostly with roto-vibrational transitions. The more its emits the more it cools, the more its density increases (so gravity increases). At some point gravity will exceed the pressure, the equilibrium is broken and collapse starts.

- H_2 forms on dust grains most efficiently. It can be destroyed by the radiation field, but deep inside molecular clouds it is self-shielded
- Inferred lifetimes for MCs are ~ 10^7 yrs, from association to young (and not old) clusters

SF timescales in molecular clouds

$$\tau_{\rm ff} = \left(\frac{3\pi}{32G\overline{\rho}}\right)^{1/2} \simeq 3.6\times10^{6}\,{\rm yr}\left(\frac{n_{\rm H_2}}{100\,{\rm cm^{-3}}}\right)^{-1/2}.$$

- The free fall time is considerably shorter than the MCs inferred lifetimes

- Thus molecular clouds must be supported against gravitational collapse by non-thermal pressure. e.g., turbulence and/or magnetic fields of 10-100μG

- The measured galactic SF timescale is $\tau_{\rm SF} \equiv M_{\rm gas}/\dot{M}_{\rm gas}$

- For disk galaxies like Milky Way this is t_{SF} ~10^9 yr and >> t_{ff}

- In starbursts the timescales are comparable

- Star formation is not very efficient in disks: $E = t_{ff}/t_{SF}$ ~ 0.002
    - “slow”: including magnetic fields
    - “inefficient”: turbulence, self-regulation (HII regions and winds from young stars)

SF and galaxy evolution

- Related to the formation of molecular clouds
    - thermal instability
    - instabilities in self-gravitating disks
    - gas compression (e.g. on spiral arms, during mergers)
- Process of star formation is not very well-understood
- what determines the efficiencies and timescales?
- We assume that for understanding large scale effects of galaxy evolution we do not need to go into the specific small scale details of star formation.
- We have to find scaling laws and look at global properties

Need to understand how the GLOBAL properties of star formation averaged over a large volume of gas, depend on the GLOBAL properties of the gas, such as mass, density, temperature and chemical composition.

Empirical SF laws

$$\boxed{\dot{\Sigma}_\star = \dot{M}_\star / \mathrm{area}}$$

SFR, Σ, in terms of mass in stars formed per unit area per unit time

$$\boxed{\tau_{\mathrm{SF}} = \Sigma_{\mathrm{gas}} / \dot{\Sigma}_\star}$$

τ_{SF} : Gas consumption timescale

Since the most obvious requirement for star formation is the presence of gas, it is only logical to look at the relation between SFR and surface density of gas:

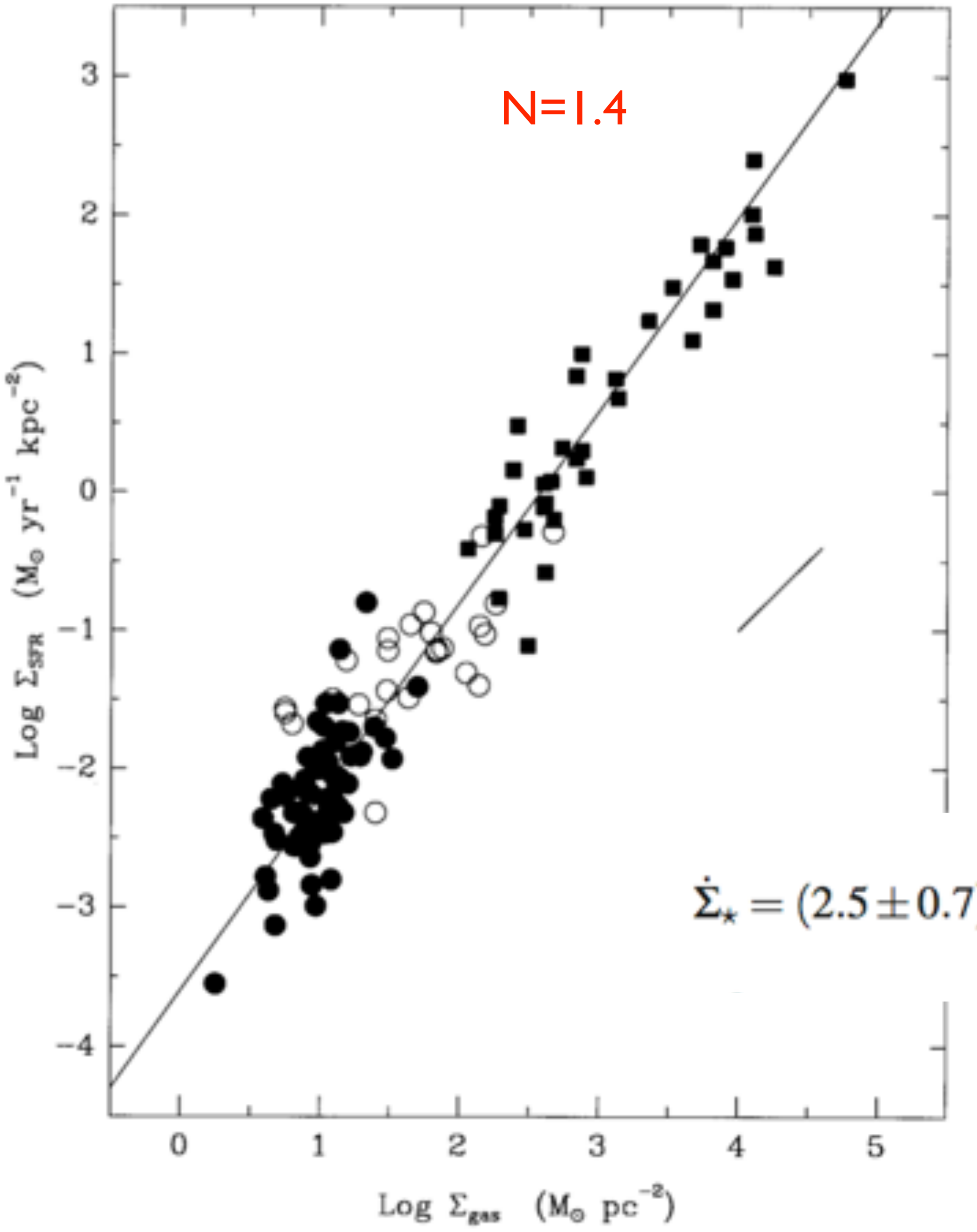
$$\dot{\Sigma}_\star \propto \Sigma_{\mathrm{gas}}^{\mathrm{N}}$$

Schmidt (1959)
N=2

Kennicutt-Schmidt law

Normal disk, filled circles; starburst, squares; Open circles are the centres of normal disk galaxies.

Kennicutt-Schmidt law



The study of star formation in normal spiral galaxies and also starbursts have shown Schmidt "law" is a surprisingly good description of global SFRs (averaged over entire star forming disc)

$$\dot{\Sigma}_\star = (2.5\pm0.7)\times10^{-4}\left(\frac{\Sigma_{\rm gas}}{M_\odot\,{\rm pc}^{-2}}\right)^{1.4\pm0.15} M_\odot\,{\rm yr}^{-1}\,{\rm kpc}^{-2}$$

$$\Sigma_{\rm gas} = \Sigma_{\rm HI} + \Sigma_{\rm H_2}$$

Kennicutt (1998) ApJ, 498, 541

KS law - interpretation

SFR is controlled by the self-gravity of the gas. This would mean that the rate of star formation will be proportional to the gas mass divided by the time scale for gravitational collapse (free-fall time).

$$\tau_{\rm ff} \propto 1/\sqrt{\bar{\rho}}$$

$$\dot{\rho}_\star = \varepsilon_{\rm SF} \frac{\rho_{\rm gas}}{\tau_{\rm ff}} \propto \rho_{\rm gas}^{1.5}$$

ε is the free-fall time of the gas divided by gas consumption time, or star formation efficiency

If all galaxies have approx. same scale height, this implies: $\dot{\Sigma}_\star \propto \Sigma_{gas}^{1.5}$

in good agreement with empirical law

However, this interpretation implies $\varepsilon_{\rm SF} \ll 1$

Which suggests that self gravity isn't the only important process.

Perhaps only a small fraction of gas participates in star formation, or the star formation time scale is τ/ε. In either case – additional physics required to explain empirical law.

Kennicutt (1998) ApJ, 498, 541

Summary of SF laws

Global star formation laws averaged over whole disk – really need to understand the importance of different physical parameters (gas density, orbital time scales) on smaller spatial scales.

$$\dot{\Sigma}_\star \approx 0.017 \Sigma_{\rm gas} \Omega$$

This relation valid from galaxy to galaxy but not within a galaxy, meaning that the orbital time seems to have no impact on LOCAL star-formation efficiency.

Leroy et al. (2008) AJ, 136, 2782

$\dot{\Sigma}_\star - \Sigma_{\rm gas}$ on the other hand does change within a galaxy.

A single power law is a poor fit, as there is a break at low gas surface densities. This corresponds to an abrupt truncation in the SFR.

It can be seen that looking at the relations with atomic and molecular gas separately, that molecular gas correlates much better with SFR.

$$\dot{\Sigma}_\star = (7 \pm 3) \times 10^{-4} \left(\frac{\Sigma_{\rm H_2}}{\rm M_\odot \, pc^{-2}} \right)^{1.0 \pm 0.2} \rm M_\odot \, yr^{-1} \, kpc^{-2}$$

Schmidt law for molecular gas

Two laws: 1. for transformation from atomic into molecular gas

2. formation of stars from molecular gas

Bigiel et al. (2008) AJ, 136, 2846

SF tracers

UV Continuum (1250-2500A) :

Number of massive stars in a galaxy is directly proportional to the current SFR, as long as it is not absorbed on the way. Only possible from the ground for z=1-5. For z<1 need space telescope. Assuming time scale ~10^8 yr, or longer:

$$\frac{\dot{M}_\star}{\mathrm{M_\odot\,yr^{-1}}} \approx 1.4 \times 10^{-28} \left(\frac{L_\mathrm{UV}}{\mathrm{erg\,s^{-1}\,Hz^{-1}}}\right)$$

Nebular Emission Lines:

The ISM around young, massive stars is ionised by Lyman continuum photons produced by these stars, giving rise to HII regions. The recombination of this ionised gas produces H emission lines (e.g., Hα but also Hβ, Pα, Pβ, Brα, Brγ), which can be used as SFR diagnostic, because their flux is proportional to the Lyman continuum flux from young (<2×10^7yr) massive (>$10M_\odot$) stars.

$$\frac{\dot{M}_\star}{\mathrm{M_\odot\,yr^{-1}}} \approx 7.9 \times 10^{-42} \left(\frac{L_{\mathrm{H}\alpha}}{\mathrm{erg\,s^{-1}}}\right)$$

Forbidden lines:

For galaxies with z>0.5, Hα emission is redshifted out of optical. The strongest feature in the blue is [OII]λ3727 forbidden line doublet. Unfortunately luminosities do not depend only on the local radiation field, but also the ionization state and metallicity of ISM. It has been successfully empirically calibrated, and can be used out to z=1.6 (in the optical).

$$\frac{\dot{M}_\star}{\mathrm{M_\odot\,yr^{-1}}} \approx 1.4 \times 10^{-41} \left(\frac{L_\mathrm{OII}}{\mathrm{erg\,s^{-1}}}\right)$$

Kennicutt (1998) ARAA, 36, 189

SF tracers (cont.)

FIR Continuum (8-1000µm):

Typically the ISM associated with star forming regions can be quite dusty, so a significant fraction of the UV photons produced by massive stars is absorbed. This heats the dust and is subsequently re-emitted in the FIR. This does depend on opacity of dust, if it is not optically thick, need to specify the escape fraction. There is a also a contribution due to older stars. Works well for short duration intense star formation, ie., starbursts (10-100Myr old).

$$\frac{\dot{M}_\star}{\mathrm{M_\odot\,yr^{-1}}} \approx 4.5 \times 10^{-44} \left(\frac{L_{\mathrm{FIR}}}{\mathrm{erg\,s^{-1}}} \right)$$

Kennicutt (1998) ARAA, 36, 189

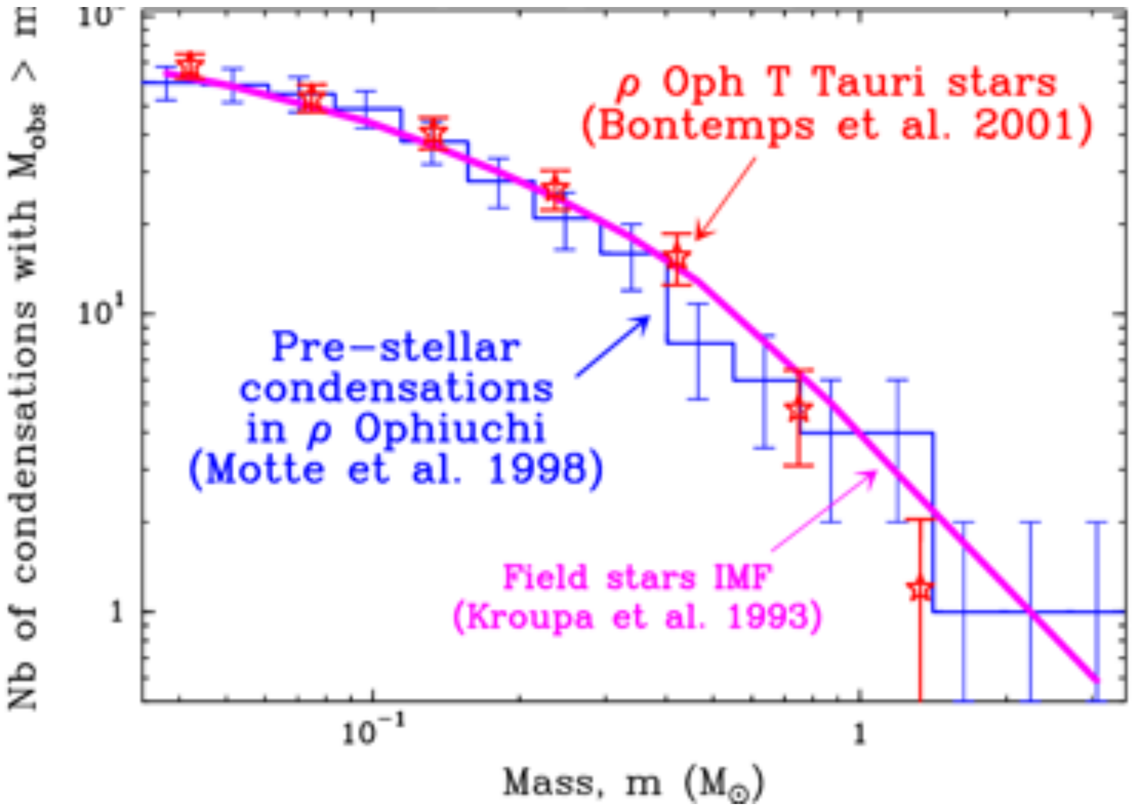
The initial mass function (IMF)

- Field Star IMF is within errors same as that inferred for Orion Nebula Cluster and other nearby star forming regions
- It has a power law (Salpeter) down to about 0.5-1 $M_\odot$ with most mass in solar mass stars but most luminosity at high M

$$\Phi(\log m) = dN/d\log m \propto m^{-\Gamma}$$

Salpeter 1955
$\Gamma=1.35$

Condensations mass spectrum in ρ Oph



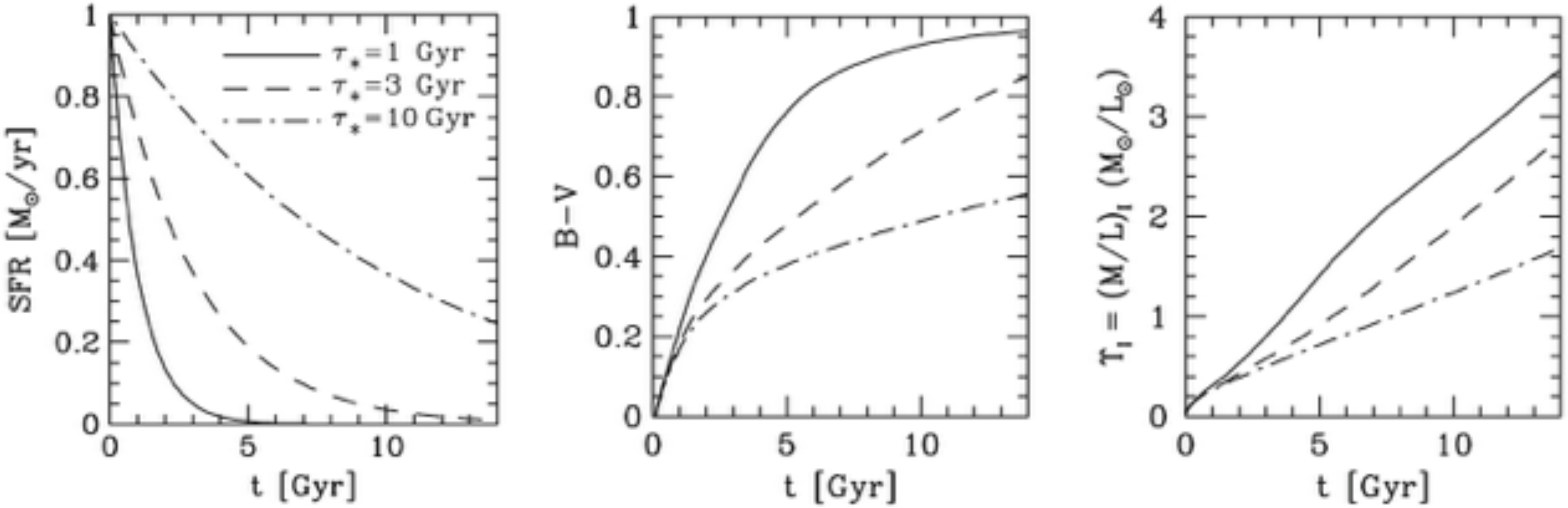
(see also Testi & Sargent 1998; Motte et al. 2001)

Submm continuum surveys of nearby proto-clusters suggest that the mass distribution of pre-stellar condensations mimics the form of the stellar IMF

⇒ **The IMF is at least partly determined by fragmentation at the pre-stellar stage.**

Star formation histories (SFH)

How to determine physical properties of galaxies (e.g., stellar masses and SFHs) from quantities that are directly observed (e.g., luminosity, spectrum). These observed quantities are convolutions of the SFH, IMF, dust extinction, etc.

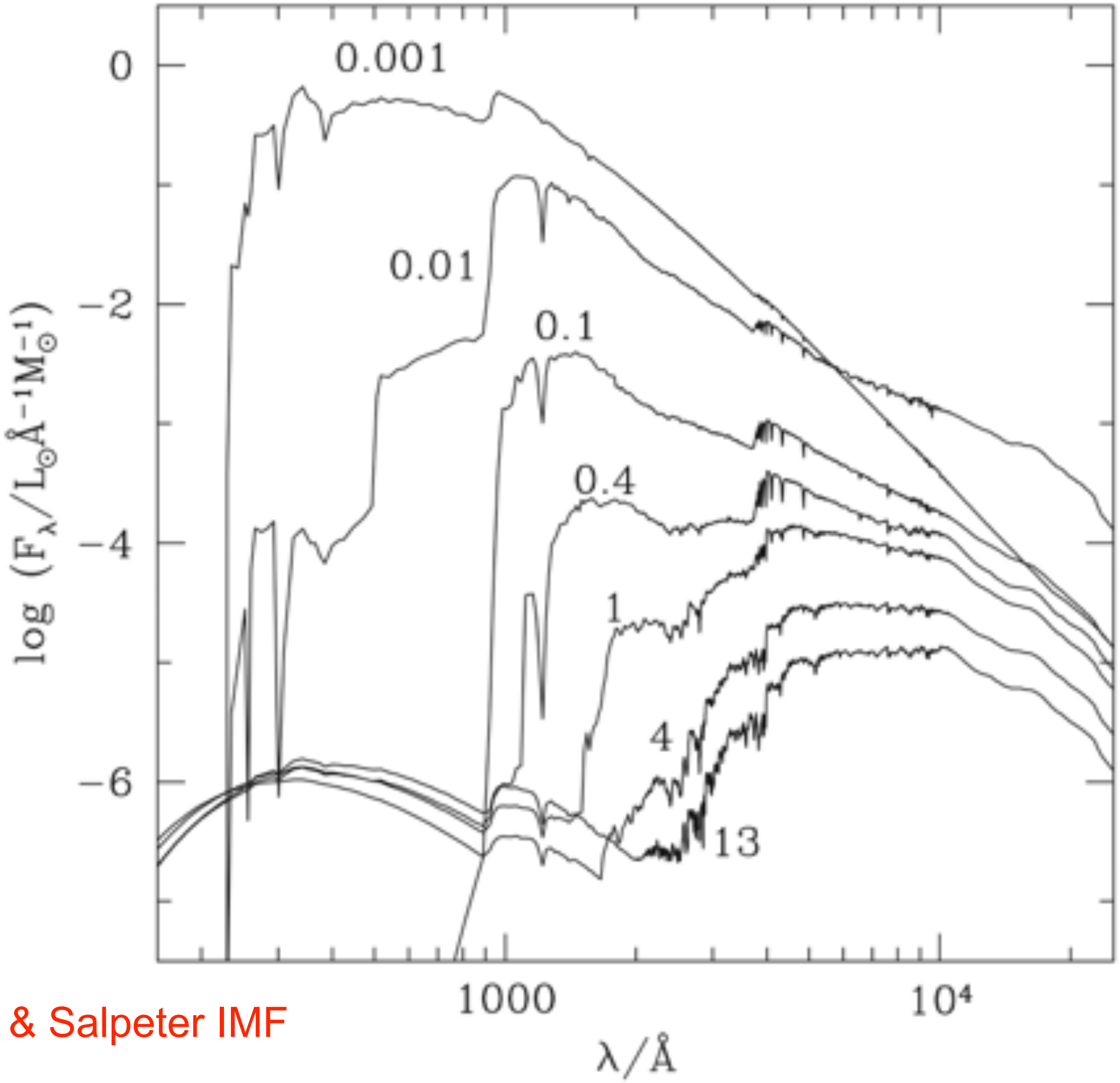


Exponential SFHs of the form:

$$\Psi(t) = \frac{1}{\tau_\star} \exp\left(-\frac{t}{\tau_\star}\right)$$

$\tau_\star$ characteristic SF time scale

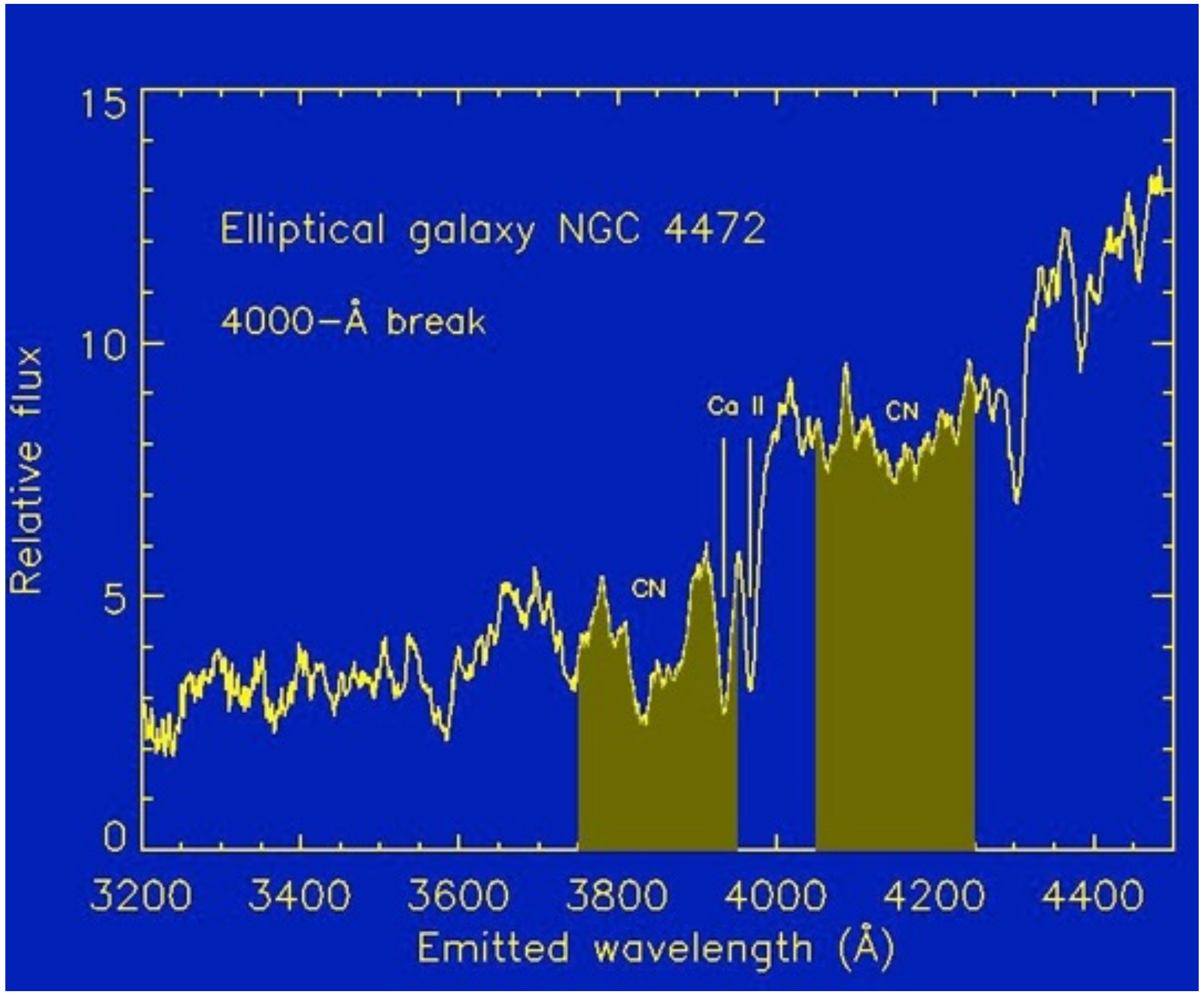
Single stellar population - spectral evolution



Solar metallicity & Salpeter IMF

Predicted spectra of coeval stellar population (no dust): 1, 10, 100, 400 Myr, 1, 4, 13 Gyr

Passive galaxy SEDs - the 4000 Angstrom break



- Caused by:
  - **absorption** of high energy radiation by **metals** in the stellar atmospheres
  - the **lack of hot blue stars**
- Hence:
  - Ellipticals => A strong 4000A-Break
  - Spirals => A weak 4000A-Break
  - Irregulars => No 4000A-Break

Stellar population synthesis

An indispensable tool for most studies of the galaxy population.

Star formation histories.

Stellar masses

Stellar ages.

The history of chemical enrichment

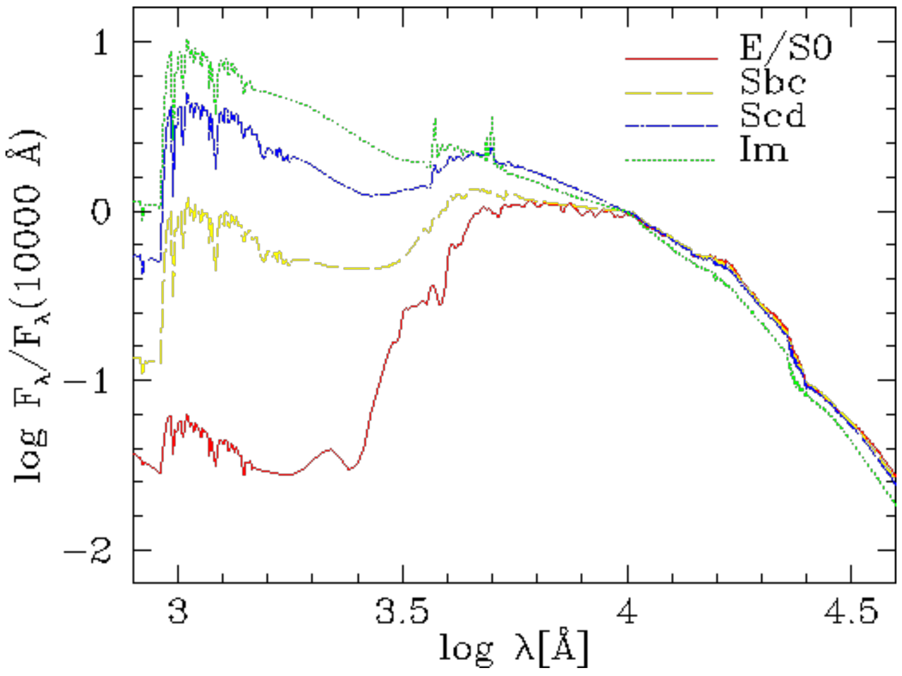
The assembly of mass in the Universe

Dust content of distant galaxies

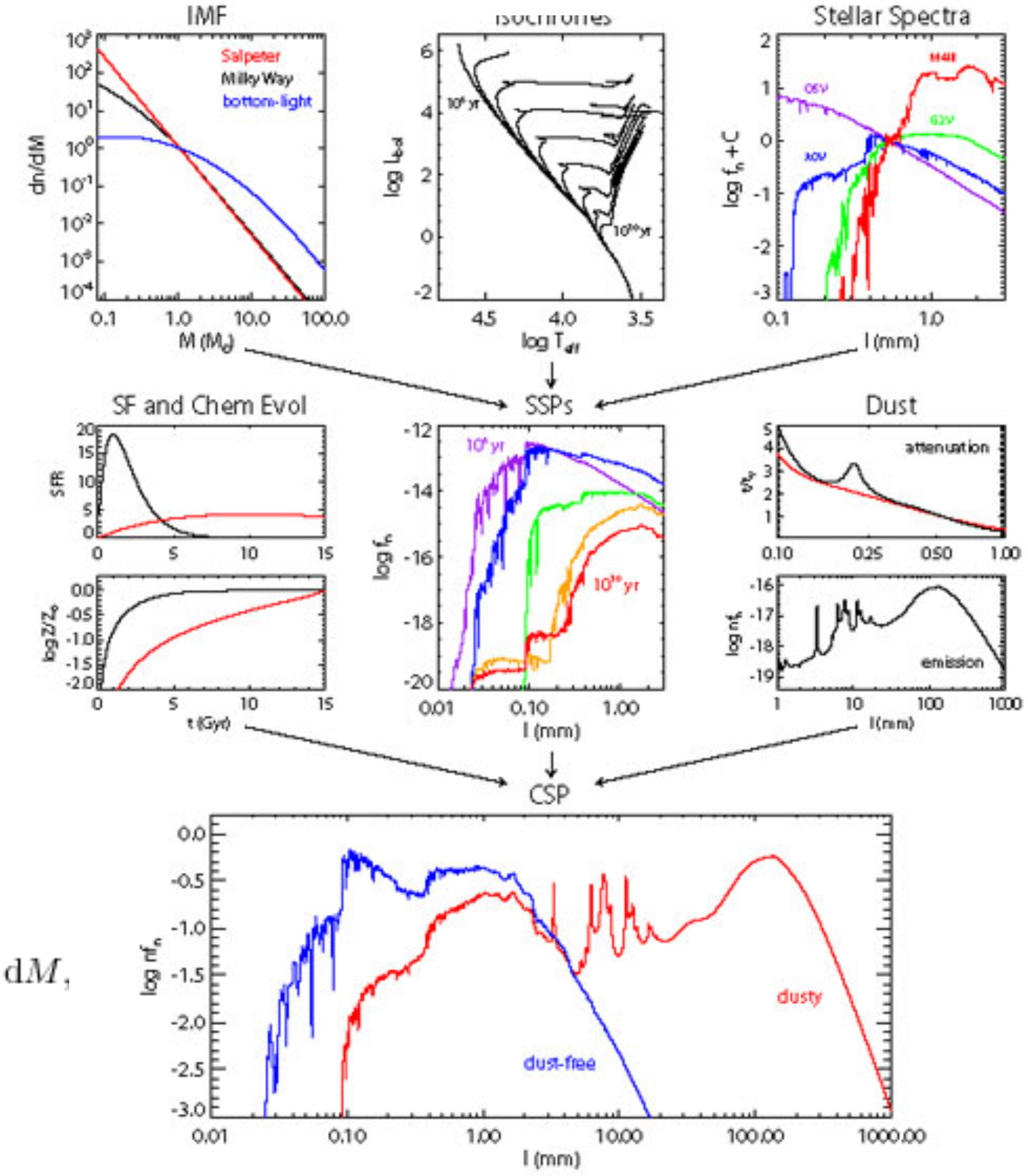
But in reverse, it can also be informed by galaxy observations - learning about complex, rare & important stages of stellar evolution.

SED models

Empirical



Synthetic



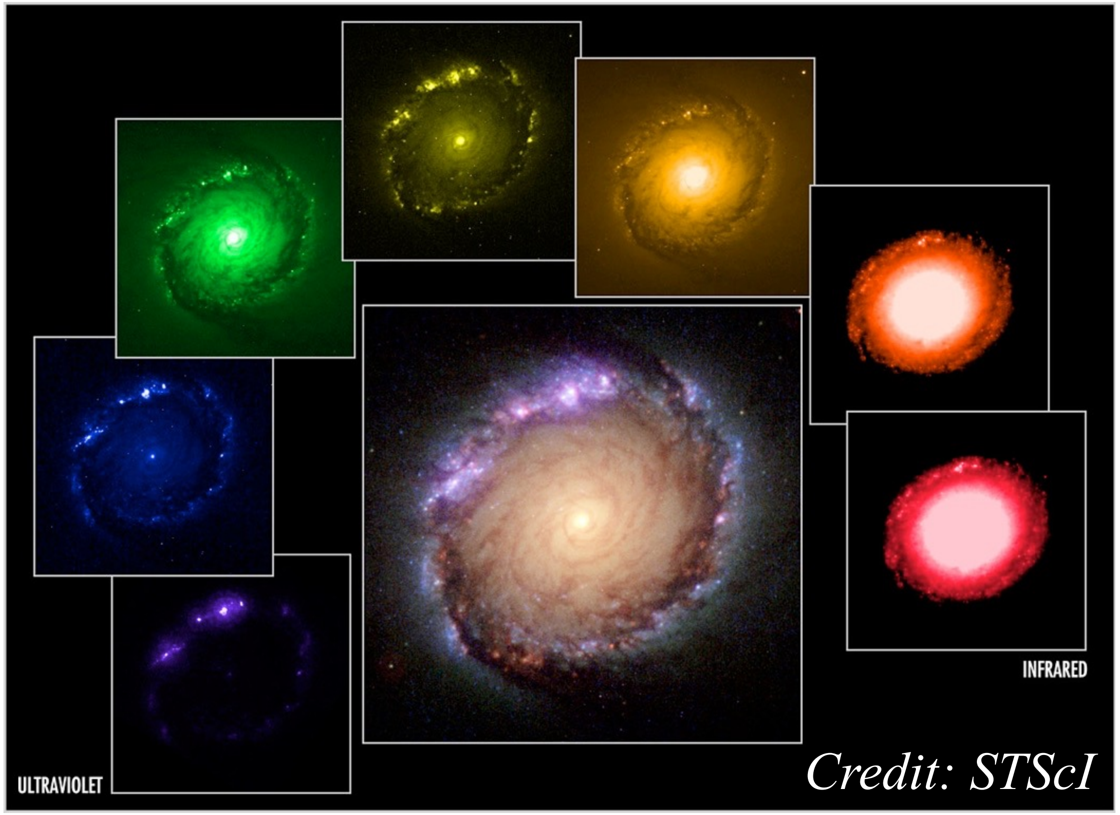
$$f_{\rm SSP}(t,Z) = \int_{m_{\rm lo}}^{m_{\rm up}(t)} f_{\rm star}\left[T_{\rm eff}(M), \log g(M)\,|\,t, Z\right]\Phi(M)\,{\rm d}M,$$

stellar spectrum

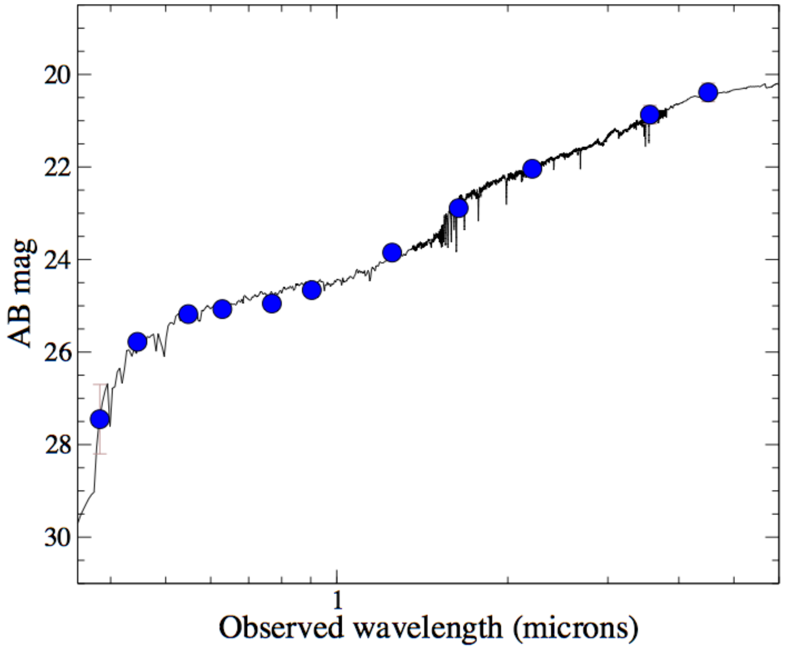
IMF

Credit: J. Walcher

Spectral energy distribution (SED) fitting



Credit: STScI



Photometric redshift → *'cheap' alternative to spectroscopic redshifts*

Age

Dust Extinction

Stellar Mass

From SF to passivity - indicators

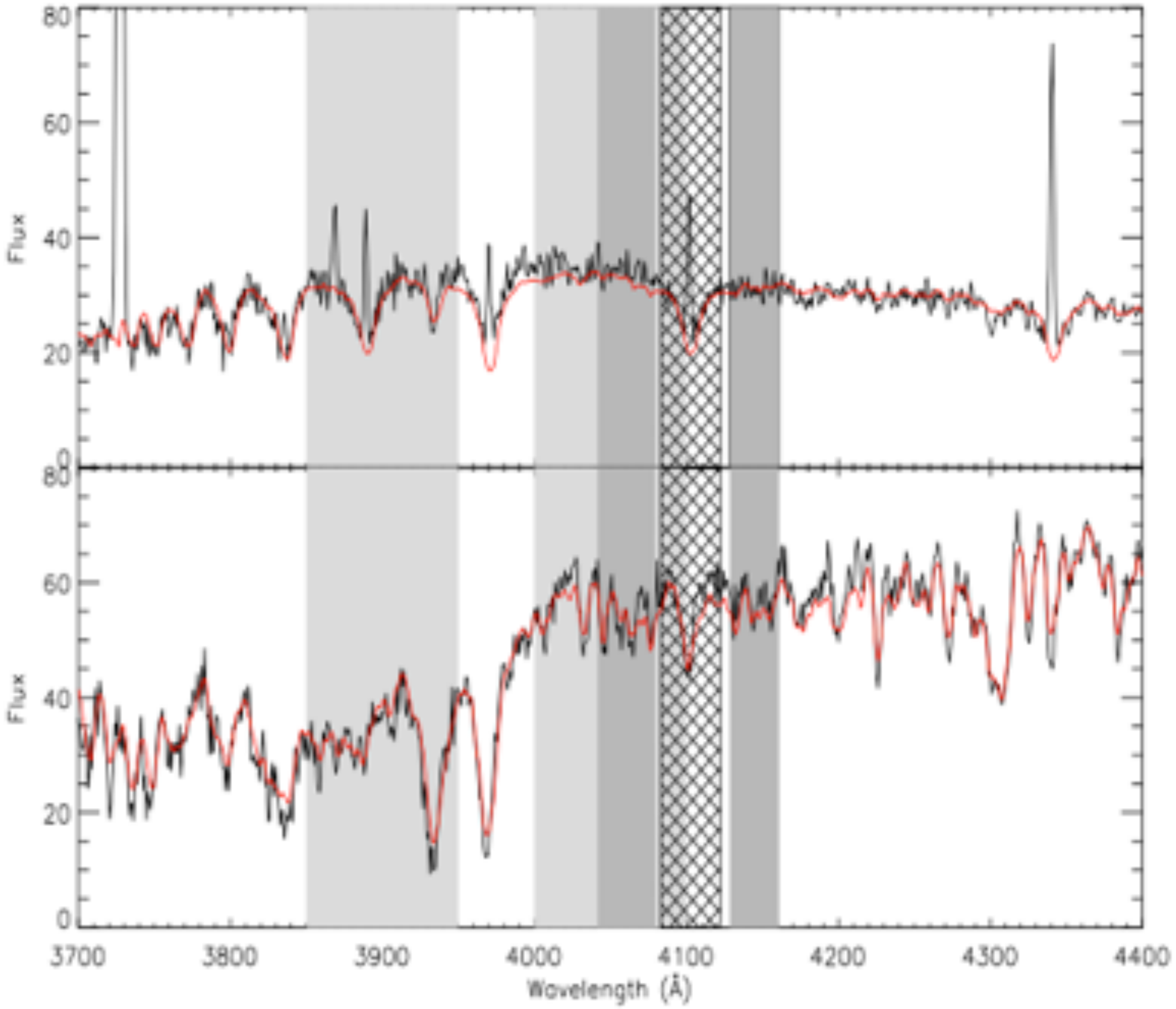


Figure 1: SDSS spectra of a late-type galaxy (top) and an early-type galaxy (bottom) are plotted over the interval 3700-4400 Å in the restframe. The red line shows our best fit BC2002 model spectrum. The light grey shaded regions indicate the bandpasses over which the $D_n(4000)$ index is measured. The dark grey regions show the pseudocontinua for the $H\delta_A$ index, while the hatched region shows the $H\delta_A$ bandpass.

D(4000) and H-delta - constrain SFHs, dust attenuation and stellar masses of galaxies.

Kauffmann et al. 2003 MNRAS, 341, 33

From SF to passivity - time evolution

Kauffmann et al. 2003a MNRAS, 341, 33

Different Spectral Libraries

Different Z

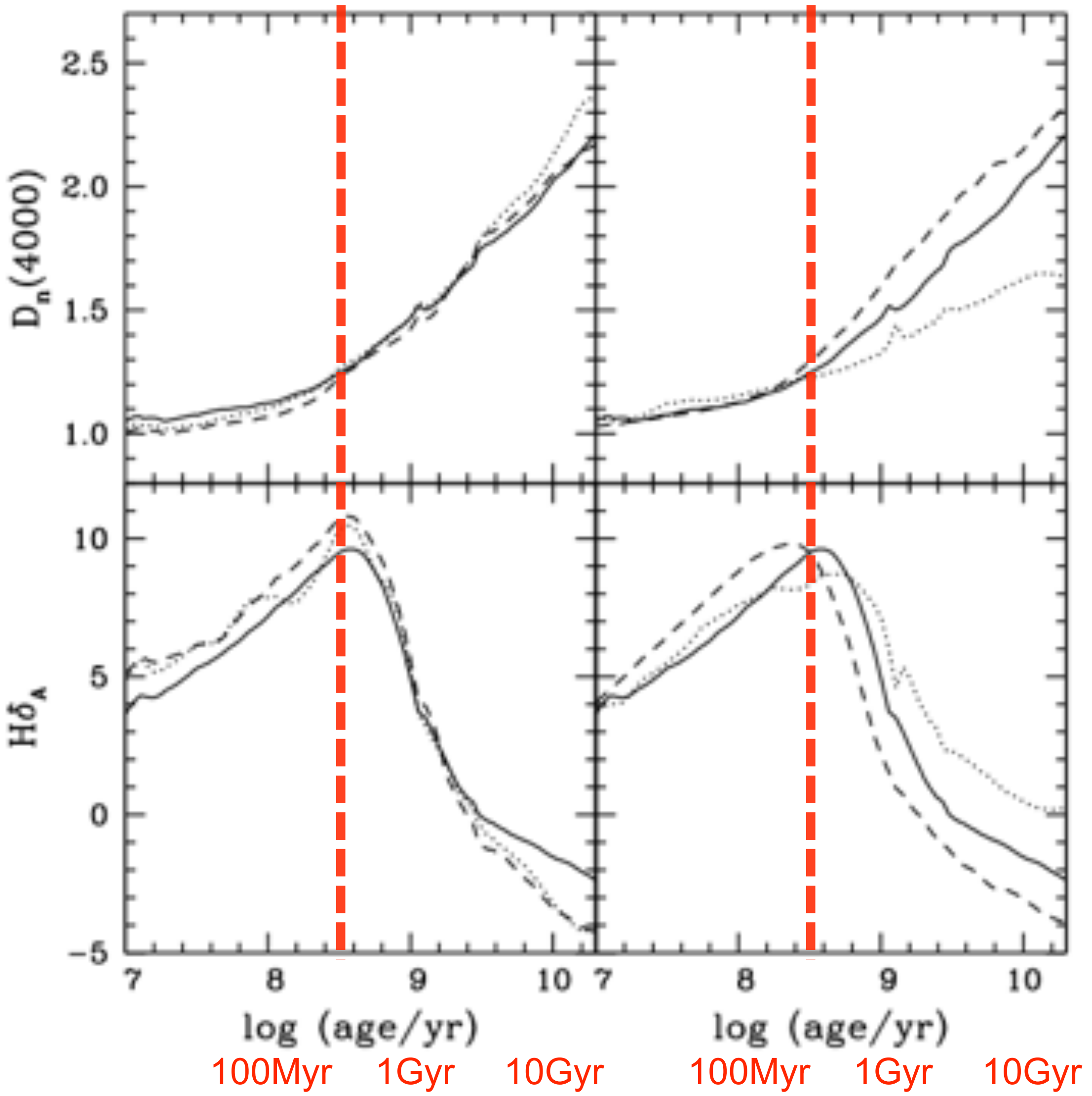
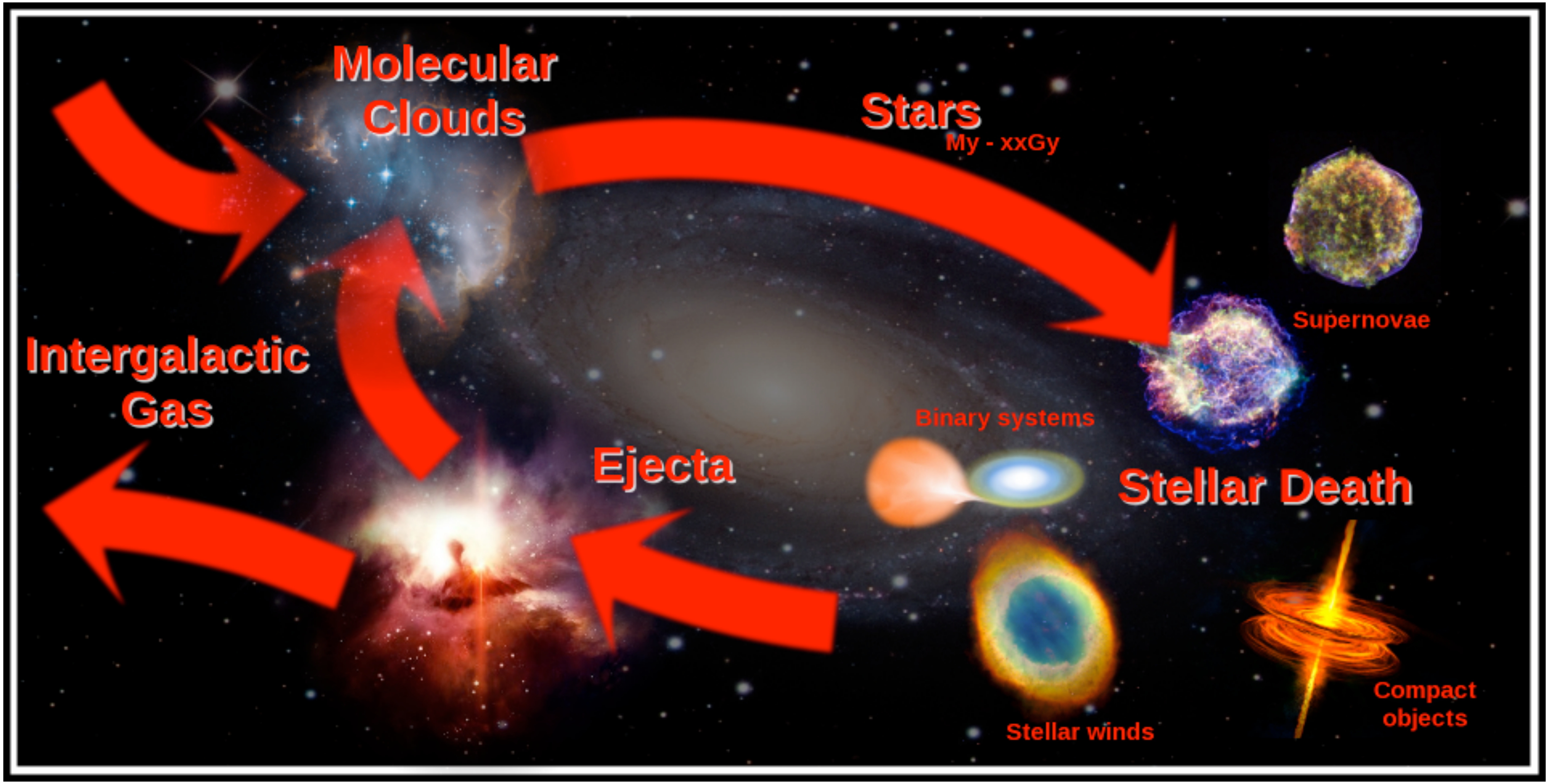


Figure 2: **Left:** The evolution of $D_n(4000)$ and $H\delta_A$ following an instantaneous, solar-metallicity burst of star formation. Solid lines show results from BC2002+STELIB, the dotted line shows results if the Pickles (1998) library is used, and the dashed line is for the Jacoby, Hunter & Christensen (1984) library. **Right:** The evolution of $D_n(4000)$ and $H\delta_A$ for bursts of different metallicity. The solid line is a solar metallicity model, the dotted line is a 20 percent solar model and the dashed line as a 2.5 solar model.

Stellar/AGN Feedback

Matter cycle within galaxies



Credit: R. Longland

Stellar Feedback

- As the stars evolve they return mass and energy to the ISM
  - winds: E_{kin}~ $4 \times 10^{50} (M_{\rm wind}/10\,{\rm M}_\odot)(v_\infty/2000\,{\rm km\,s^{-1}})^2\,{\rm erg}$
  - SN explosions: $E_{\rm SN} = E_{51} \times 10^{51}\,{\rm erg}, \quad \text{with} \quad E_{51} \sim 1.0.$
- This impacts both
  - chemical evolution
  - subsequent star formation (source of heating)
  - dynamics of the gas

  For example, the binding energy of the gas of a dwarf galaxy of 10^7 M_{sun} and R ~ 1 kpc is E_{bin} ~ GM^2/R ~ 8 x 10^{51} erg → very comparable to E_{SN}!
- Modeling the poorly understood physics that couple feedback, cooling of gas and star formation is extremely difficult
  - prescriptions are global and heuristic

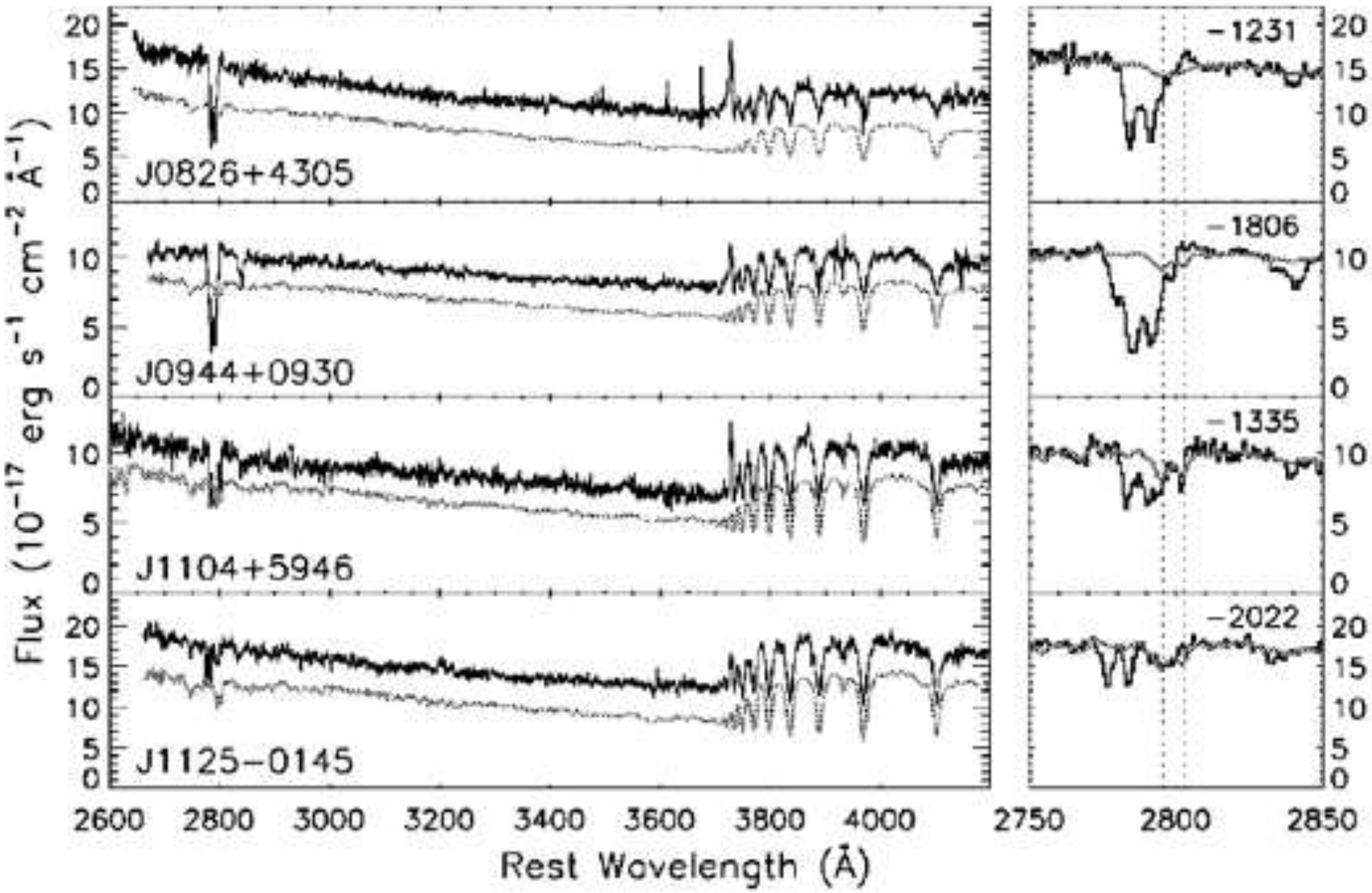
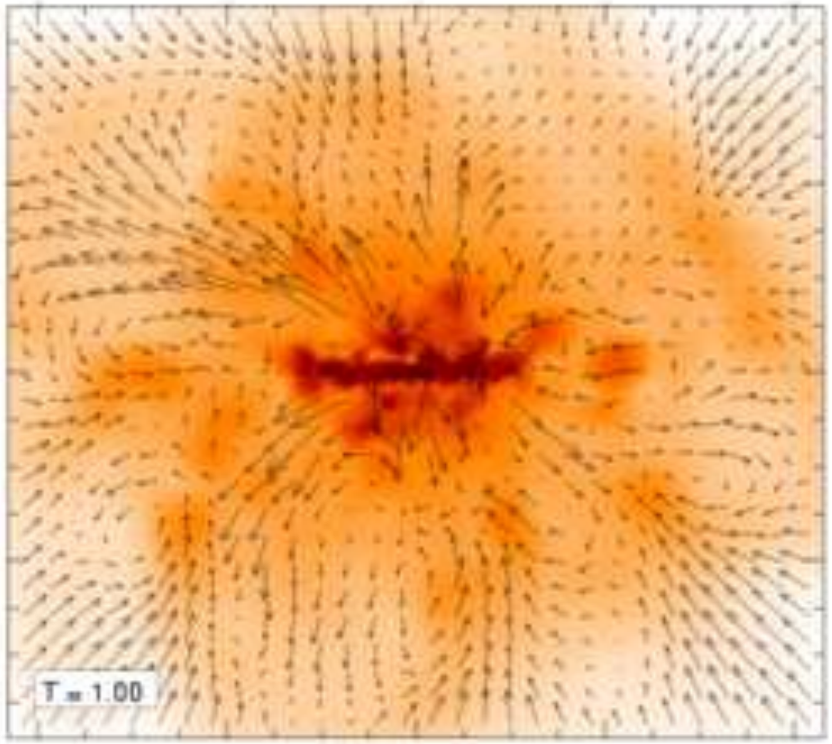


FIG. 1.—Example spectra (*black*) and continuum model fits (*gray*). In the left panel, the continuum models are offset for clarity. The right panel highlights the region around the Mg II doublet. Dotted lines mark the rest wavelength of Mg II. The presence of blueshifted lines indicates an outflow. The velocity of the most blueshifted component is given in kilometers per second in the upper right corner.

Tremonti et al. 2007

Feedback/galactic wind issues



Can supernova feedback drive galactic winds?

Can these reproduce the mass-element abundance relation?

Can they enrich intergalactic gas with heavy elements?

Can these enhance formation of disks over bulges?

What about feedback from Active Galactic Nuclei?

$$\dot{M}_{\text{wind}} \propto \dot{E}_{\text{SN}} / V_{\text{esc}}^{2}$$
$$\propto \dot{M}_{*} / V_{c}^{2}$$

AGN feedback

Also in AGNs there are indications of outflows induced by activity near the SMBH

The process is poorly understood but feedback by AGN is likely important

(especially for preventing cooling and star formation in the most massive galaxies)

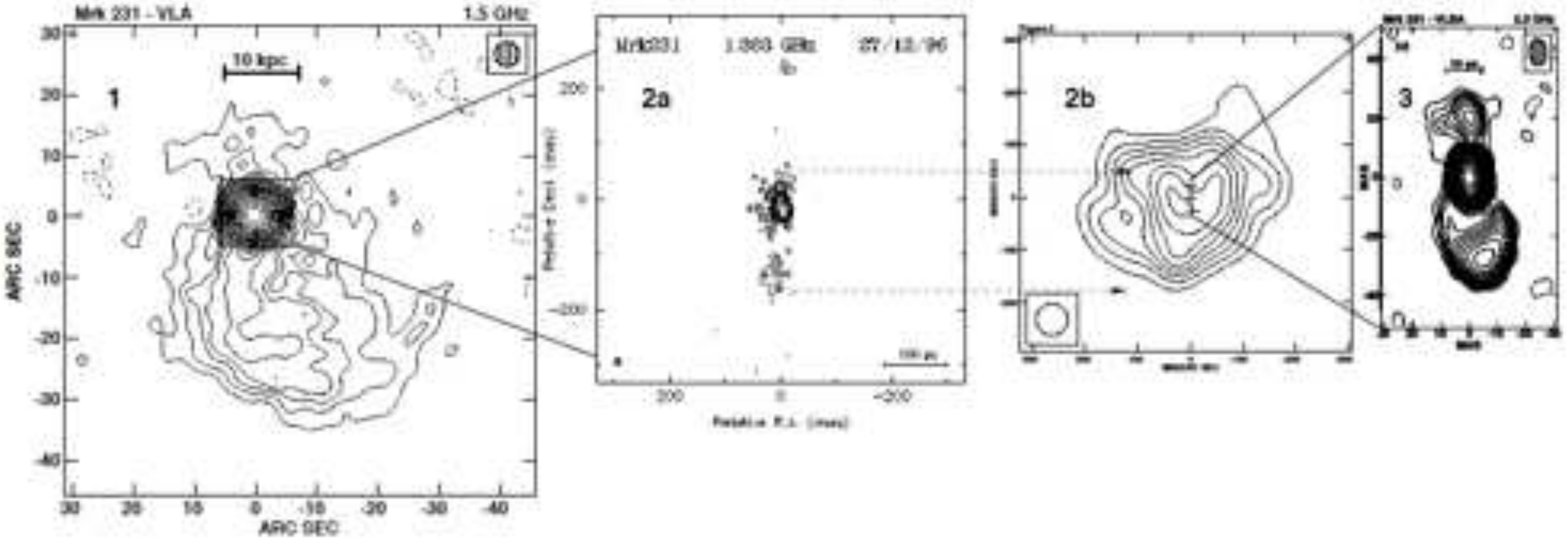


Fig. 1. Overview of the radio continuum structures of Mrk 231 ranging from tens of kpc to the inner tens of pc regions (at the distance of Mrk 231 1" corresponds to 0.867 kpc). The images, taken from Ulvestad, Wrobel, & Carilli (1999); Carilli et al. (1998); Taylor et al. (1999) (©AAS, reproduced with permission), show the presence of different structures, see text for details. The disk-like structure (Panels 2b) aligned almost E-W has been detected after the subtraction of the brighter nuclear structure (Panel 3). For details, see description in the text.

$v_{outflow}$ ~ 1300 km/s

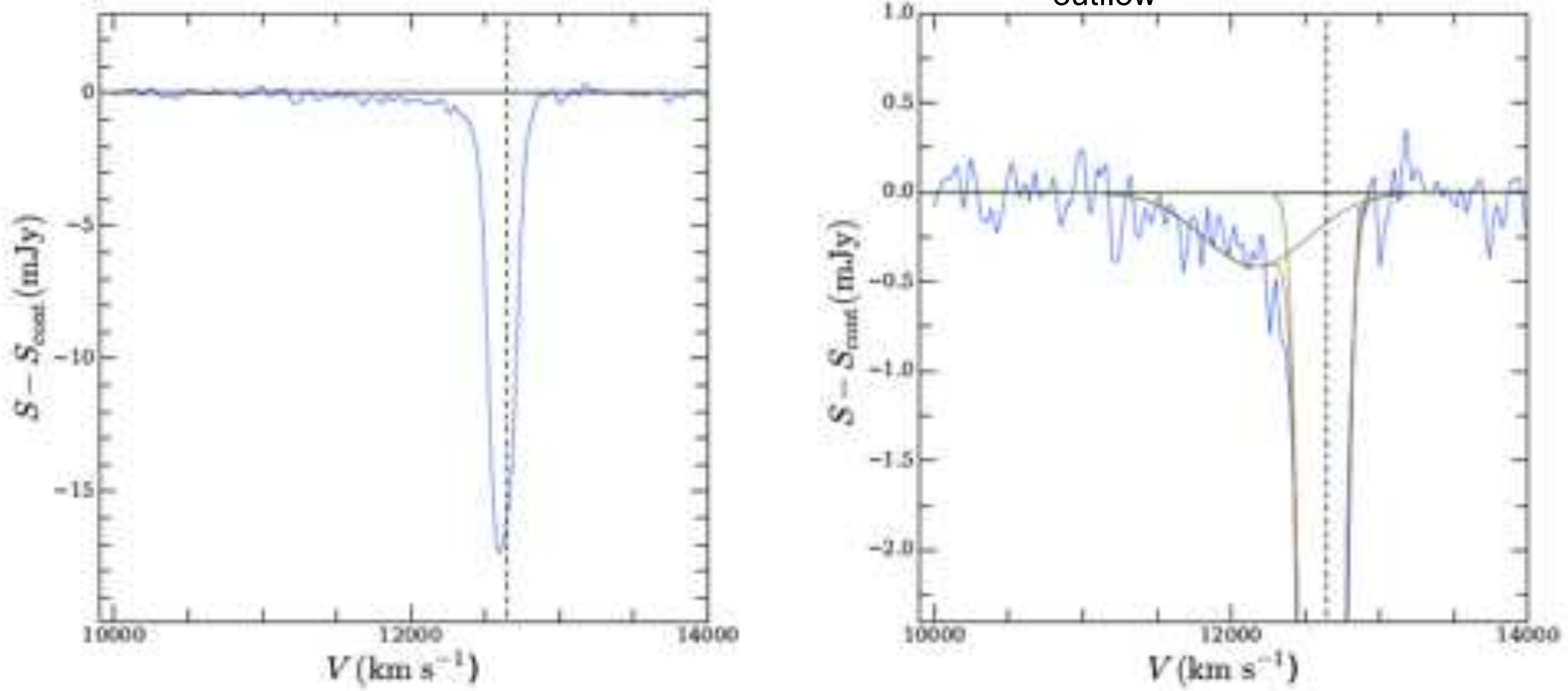


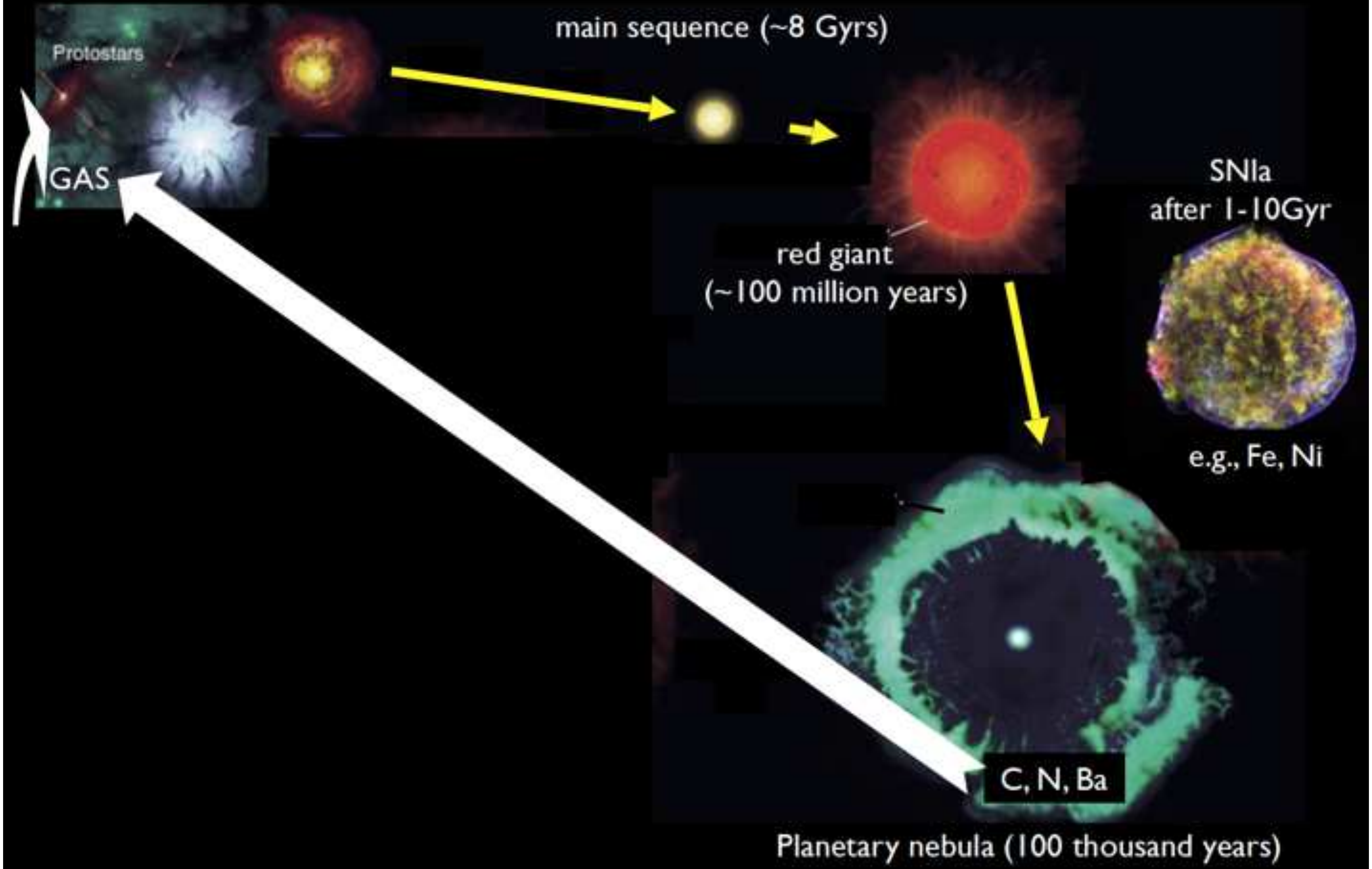
Fig. 4. **Left:** H I absorption profile from the VLA data. The shallow broad absorption is visible at velocities below ~ 12250 km s^{-1}. The dashed line indicate the systemic velocity of Mrk 231. **Right:** Zoom-in of the H I absorption profile from the VLA data, that better shows the blueshifted wing. Superposed is the Gaussian fit of the broad component discussed in the text.

Morganti et al. 2016

Chemical Enrichment

Nucleosynthesis

LOW MASS STAR (the Sun)



Protostars

GAS

main sequence (~8 Gyrs)

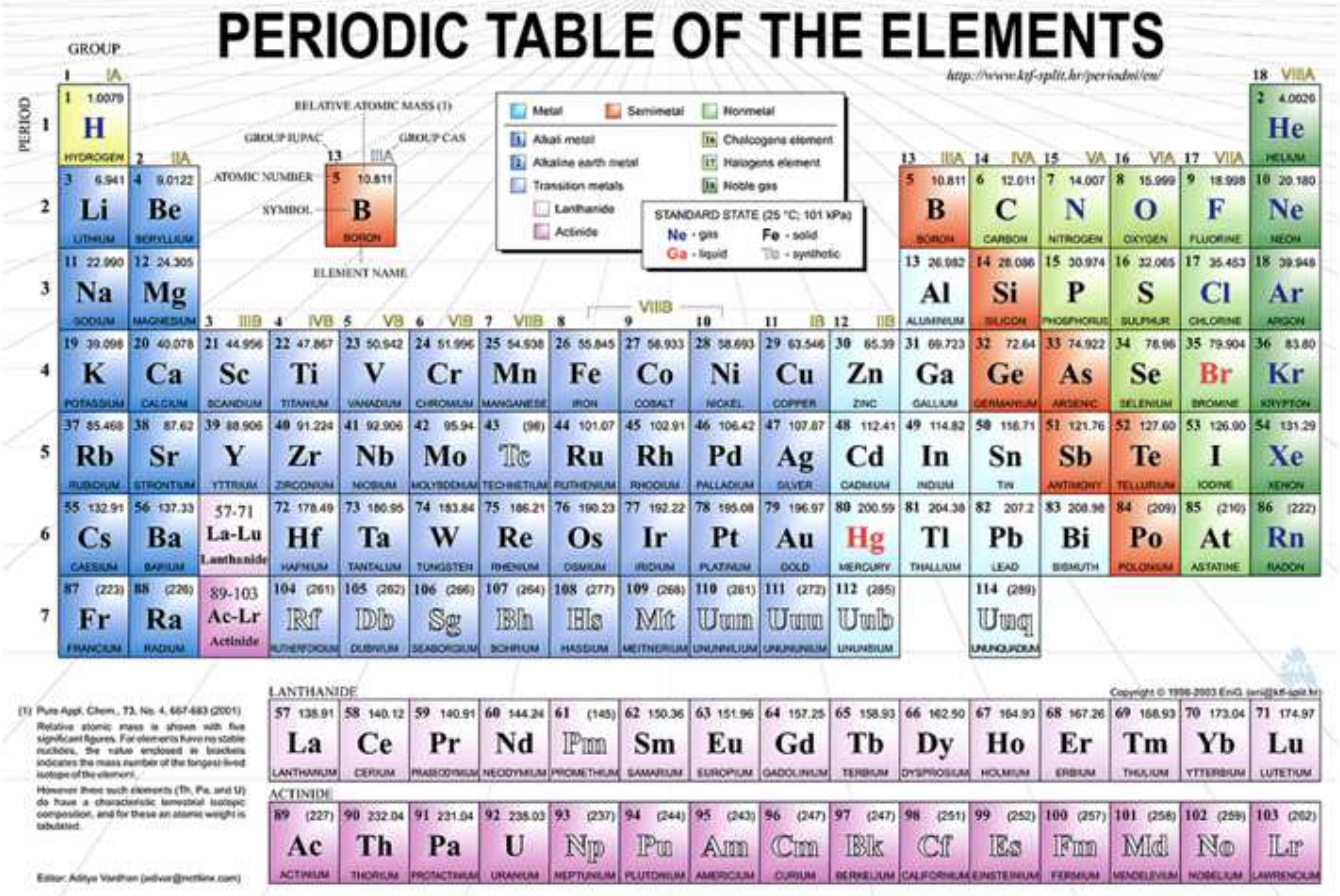
red giant
(~100 million years)

SNIa
after 1-10Gyr

e.g., Fe, Ni

C, N, Ba

Planetary nebula (100 thousand years)



PERIODIC TABLE OF THE ELEMENTS

http://www.ktf-split.hr/periodni/en/

GROUP

RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME

13 IIIA
5 10.811 B BORON

- Metal
- Semimetal
- Nonmetal
- 1 Alkali metal
- 2 Alkaline earth metal
- Transition metals
- Lanthanide
- Actinide
- 16 Chalcogens element
- 17 Halogens element
- 18 Noble gas

STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic

PERIOD	1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1	1 1.0079 H HYDROGEN																	2 4.0026 He HELIUM
2	3 6.941 Li LITHIUM	4 9.0122 Be BERYLLIUM											5 10.811 B BORON	6 12.011 C CARBON	7 14.007 N NITROGEN	8 15.999 O OXYGEN	9 18.998 F FLUORINE	10 20.180 Ne NEON
3	11 22.990 Na SODIUM	12 24.305 Mg MAGNESIUM											13 26.982 Al ALUMINIUM	14 28.086 Si SILICON	15 30.974 P PHOSPHORUS	16 32.065 S SULPHUR	17 35.453 Cl CHLORINE	18 39.948 Ar ARGON
4	19 39.098 K POTASSIUM	20 40.078 Ca CALCIUM	21 44.956 Sc SCANDIUM	22 47.867 Ti TITANIUM	23 50.942 V VANADIUM	24 51.996 Cr CHROMIUM	25 54.938 Mn MANGANESE	26 55.845 Fe IRON	27 58.933 Co COBALT	28 58.693 Ni NICKEL	29 63.546 Cu COPPER	30 65.39 Zn ZINC	31 69.723 Ga GALLIUM	32 72.64 Ge GERMANIUM	33 74.922 As ARSENIC	34 78.96 Se SELENIUM	35 79.904 Br BROMINE	36 83.80 Kr KRYPTON
5	37 85.468 Rb RUBIDIUM	38 87.62 Sr STRONTIUM	39 88.906 Y YTTRIUM	40 91.224 Zr ZIRCONIUM	41 92.906 Nb NIOBIUM	42 95.94 Mo MOLYBDENUM	43 (98) Tc TECHNETIUM	44 101.07 Ru RUTHENIUM	45 102.91 Rh RHODIUM	46 106.42 Pd PALLADIUM	47 107.87 Ag SILVER	48 112.41 Cd CADMIUM	49 114.82 In INDIUM	50 118.71 Sn TIN	51 121.76 Sb ANTIMONY	52 127.60 Te TELLURIUM	53 126.90 I IODINE	54 131.29 Xe XENON
6	55 132.91 Cs CAESIUM	56 137.33 Ba BARIUM	57-71 La-Lu Lanthanide	72 178.49 Hf HAFNIUM	73 180.95 Ta TANTALUM	74 183.84 W TUNGSTEN	75 186.21 Re RHENIUM	76 190.23 Os OSMIUM	77 192.22 Ir IRIDIUM	78 195.08 Pt PLATINUM	79 196.97 Au GOLD	80 200.59 Hg MERCURY	81 204.38 Tl THALLIUM	82 207.2 Pb LEAD	83 208.98 Bi BISMUTH	84 (209) Po POLONIUM	85 (210) At ASTATINE	86 (222) Rn RADON
7	87 (223) Fr FRANCIUM	88 (226) Ra RADIUM	89-103 Ac-Lr Actinide	104 (261) Rf RUTHERFORDIUM	105 (262) Db DUBNIUM	106 (266) Sg SEABORGIUM	107 (264) Bh BOHRIUM	108 (277) Hs HASSIUM	109 (268) Mt MEITNERIUM	110 (281) Uun UNUNNILIUM	111 (272) Uuu UNUNUNIUM	112 (285) Uub UNUNBIUM		114 (289) Uuq UNUNQUADIUM				

LANTHANIDE

57 138.91 La LANTHANUM	58 140.12 Ce CERIUM	59 140.91 Pr PRASEODYMIUM	60 144.24 Nd NEODYMIUM	61 (145) Pm PROMETHIUM	62 150.36 Sm SAMARIUM	63 151.96 Eu EUROPIUM	64 157.25 Gd GADOLINIUM	65 158.93 Tb TERBIUM	66 162.50 Dy DYSPROSIUM	67 164.93 Ho HOLMIUM	68 167.26 Er ERBIUM	69 168.93 Tm THULIUM	70 173.04 Yb YTTERBIUM	71 174.97 Lu LUTETIUM

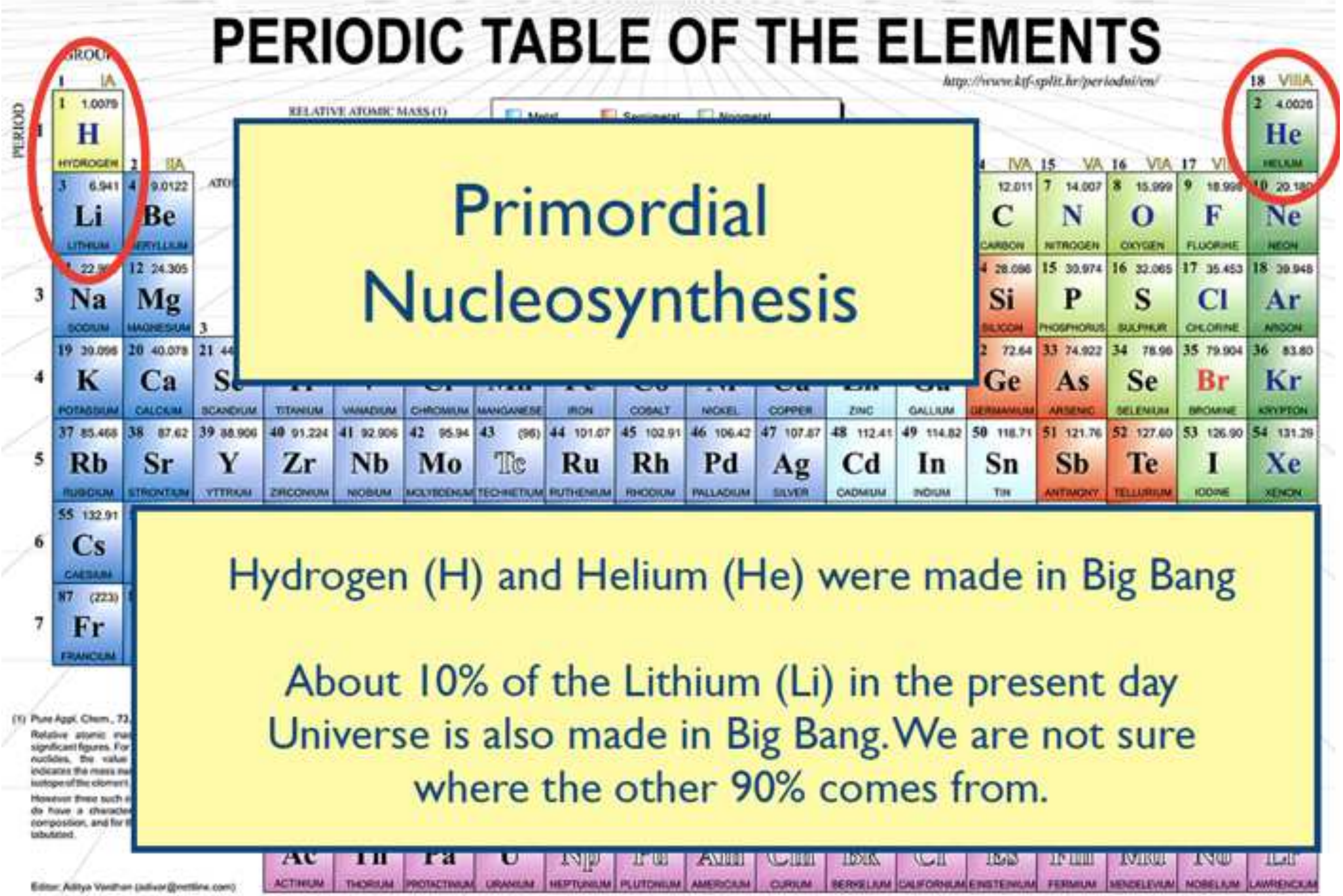
ACTINIDE

89 (227) Ac ACTINIUM	90 232.04 Th THORIUM	91 231.04 Pa PROTACTINIUM	92 238.03 U URANIUM	93 (237) Np NEPTUNIUM	94 (244) Pu PLUTONIUM	95 (243) Am AMERICIUM	96 (247) Cm CURIUM	97 (247) Bk BERKELIUM	98 (251) Cf CALIFORNIUM	99 (252) Es EINSTEINIUM	100 (257) Fm FERMIUM	101 (258) Md MENDELEVIUM	102 (259) No NOBELIUM	103 (262) Lr LAWRENCIUM

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@nettlinx.com)

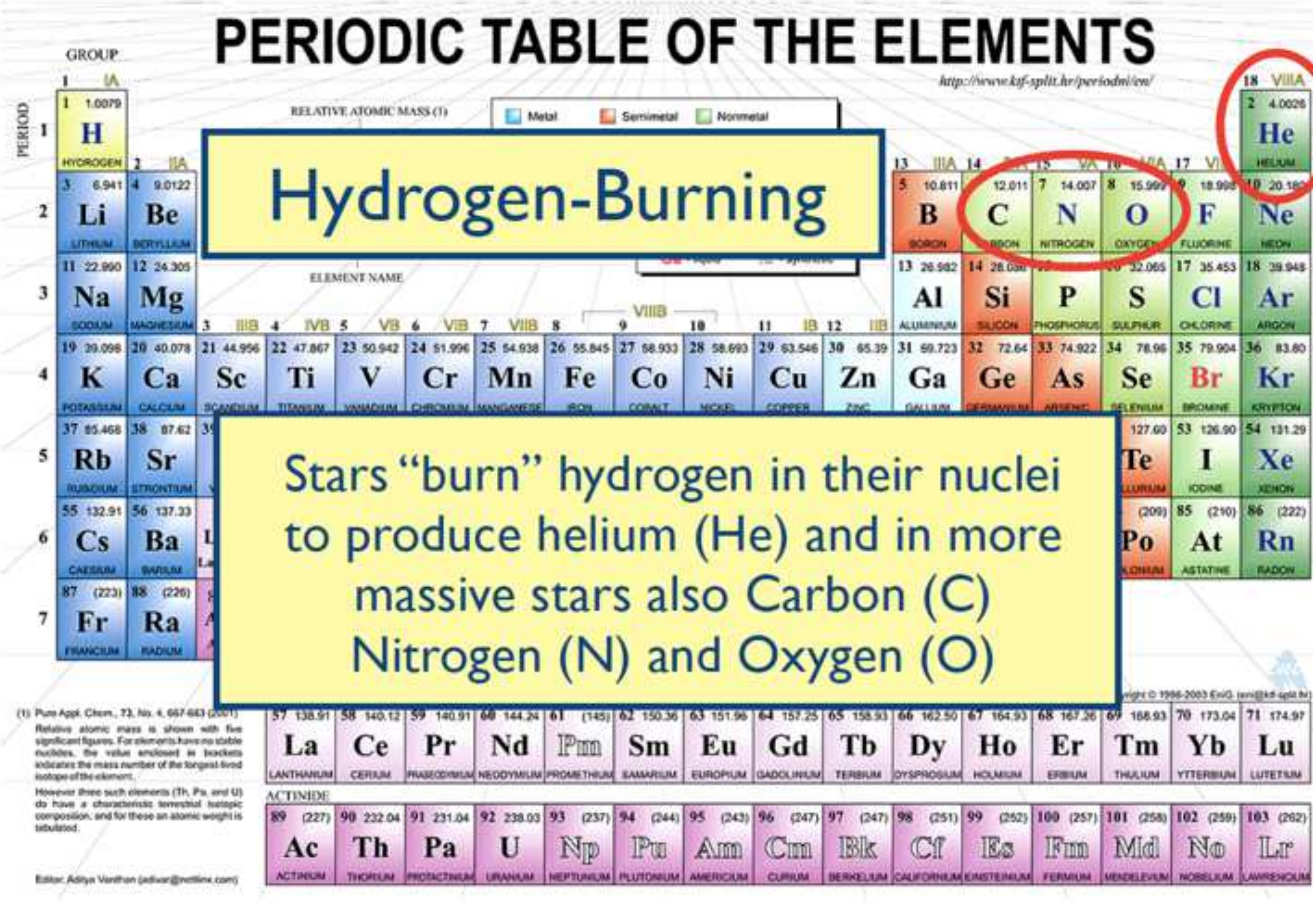


Primordial Nucleosynthesis

Hydrogen (H) and Helium (He) were made in Big Bang

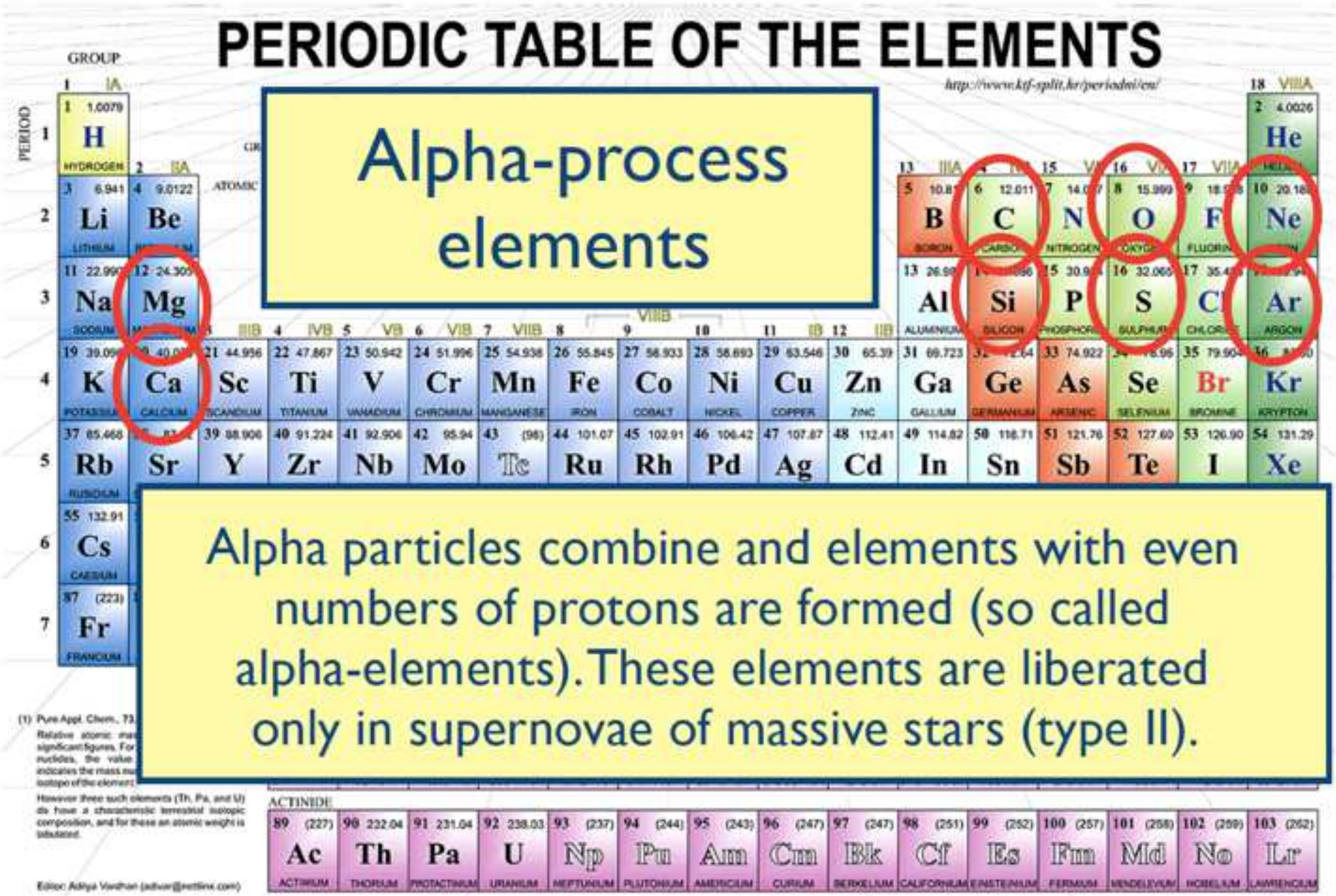
About 10% of the Lithium (Li) in the present day Universe is also made in Big Bang. We are not sure where the other 90% comes from.

Hydrogen-Burning

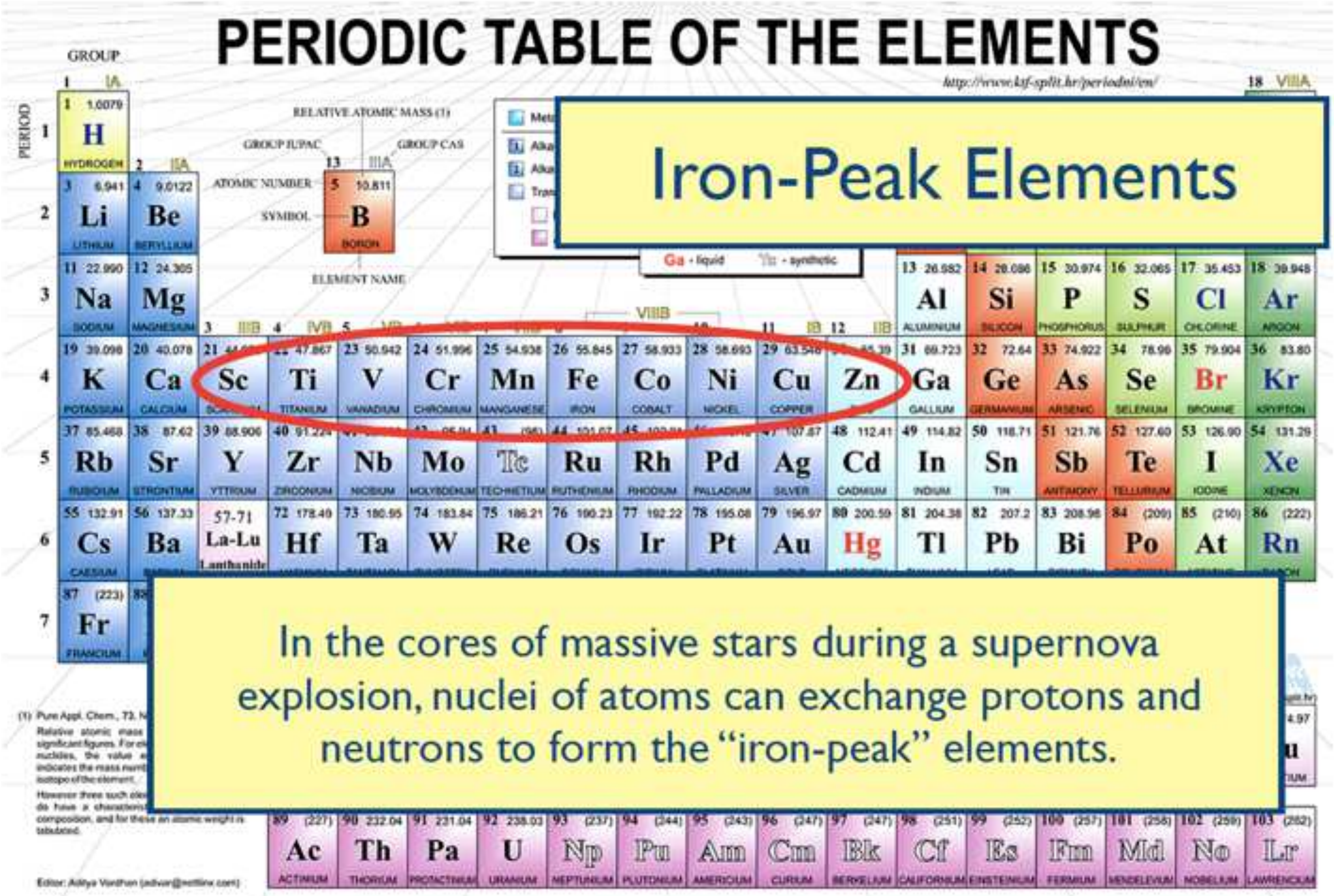


Stars "burn" hydrogen in their nuclei to produce helium (He) and in more massive stars also Carbon (C) Nitrogen (N) and Oxygen (O)

Alpha-process elements

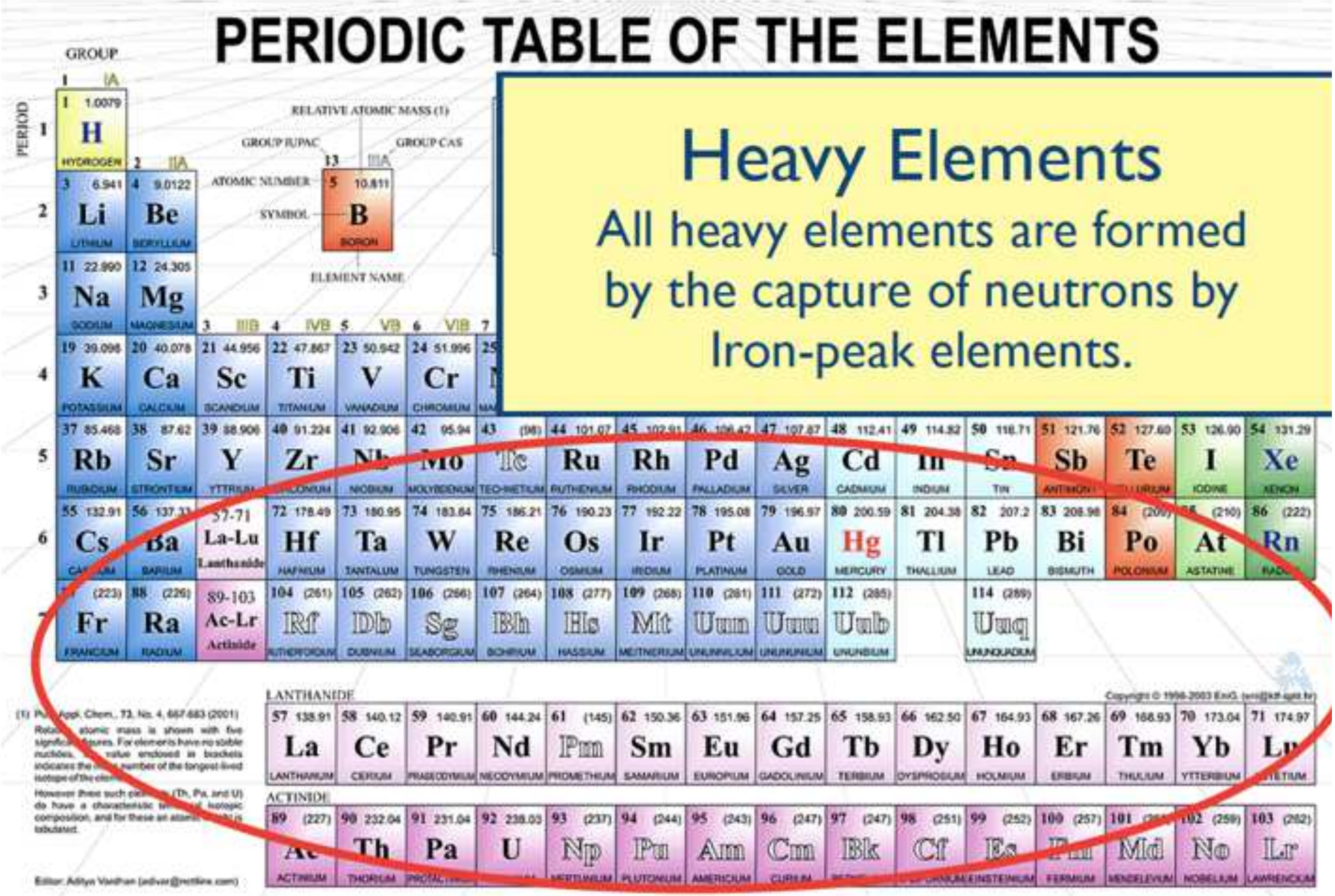


Alpha particles combine and elements with even numbers of protons are formed (so called alpha-elements). These elements are liberated only in supernovae of massive stars (type II).



Iron-Peak Elements

In the cores of massive stars during a supernova explosion, nuclei of atoms can exchange protons and neutrons to form the "iron-peak" elements.



Heavy Elements

All heavy elements are formed by the capture of neutrons by Iron-peak elements.

Chemical Tagging

- Light Elements – e.g., O Na Mg Al
tracers of deep mixing abundances patterns
(globular clusters versus field stars)

- α- Elements – e.g., O Mg Si Ca Ti
dominated by products of Supernovae II

- Iron-peak Elements e.g., V Cr Mn Co Ni Cu Zn
explosive nucleosynthesis (supernovae I)

- Heavy Elements ($Z > 30$)
mix of r- and s- process elements
e.g., s-process e.g., Ba, La (low mass stellar winds)
r-process e.g., Eu (supernovae?)

McWilliam 1997 ARAA, 35, 503
Freeman & Bland-Hawthorn 2002 ARAA, 40, 487

The build up of metals in a galaxy

- The simplest model of build up of metals in a galaxy over time is the **closed-box**
- Assumptions:
  - the galaxy's gas is well-mixed (had the same initial composition everywhere);
  - the (high-mass) stars return their nucleosynthetic products rapidly, much faster than the time to form a significant fraction of the stars.

    This approximation is known as the "**one-zone, instantaneous recycling model**".
  - no gas escapes from or is added to the galaxy

- **The key quantities** are:
  - $M_g(t)$: mass of gas in the galaxy
  - $M_s(t)$: mass locked up in stars throughout the lifetime of the galaxy.
  - $M_h(t)$: total mass of metals in the gas phase
- **The metal abundance of the gas is** $Z(t) = M_h(t)/M_g(t)$

The closed-box model

- Suppose a mass of stars $d'M_s$ is formed at time t. After the high-mass stars have evolved a mass dM_s remains locked up in low-mass stars and in remnants.

- The mass in heavy elements produced by this generation of stars is defined as
  $p\ dM_s$.

  The quantity p is known as the yield of that stellar generation (it represents an average over all stars formed) and depends fundamentally on the initial mass function and on the details of nuclear burning.

- The mass of heavy elements M_h in the interstellar gas changes as the metals produced by the high-mass stars are returned. Some fraction of these heavy elements will still be locked up in the low-mass stars and remnants. This fraction:
  - is proportional to the mass in these stars and remnants dM_s, and
  - has the initial metallicity Z of the gas.

- Hence the total mass in heavy elements which is locked up is $Z\ dM_s$.

- Therefore, the rate of change in the metal content of the gas mass is

$$\boxed{dM_h/dt = p\ dM_s/dt - Z\ dM_s/dt} \qquad (1)$$

$$dM_h/dt = (p - Z)\ dM_s/dt$$

- Mass conservation implies: $\boxed{dM_g/dt + dM_s/dt = 0},$ (2)

- The metallicity of the gas changes by

$$dZ/dt = d(M_h/M_g)/dt \rightarrow \qquad dZ/dt = -p/M_g\ dM_g/dt$$

- If the yield p does not depend on Z, we integrate to obtain the metallicity at time t

$$Z(t) = Z(0) - p * \ln[M_g(t)/M_g(0)]$$

The metallicity of the gas grows with time, as stars are formed and the gas is consumed

- We can also predict the metallicity distribution of the stars. The mass of the stars that have a metallicity less than Z(t) is

$$M_s[< Z(t)] = M_s(t) = M_g(0) - M_g(t) = M_g(0) * [1 - e^{- (Z(t)- Z(0))/p}]$$

- A closed box model seems to reproduce well the metallicity distribution of stars in the bulge of our Galaxy

Rich (1990), ApJ, 362, 604

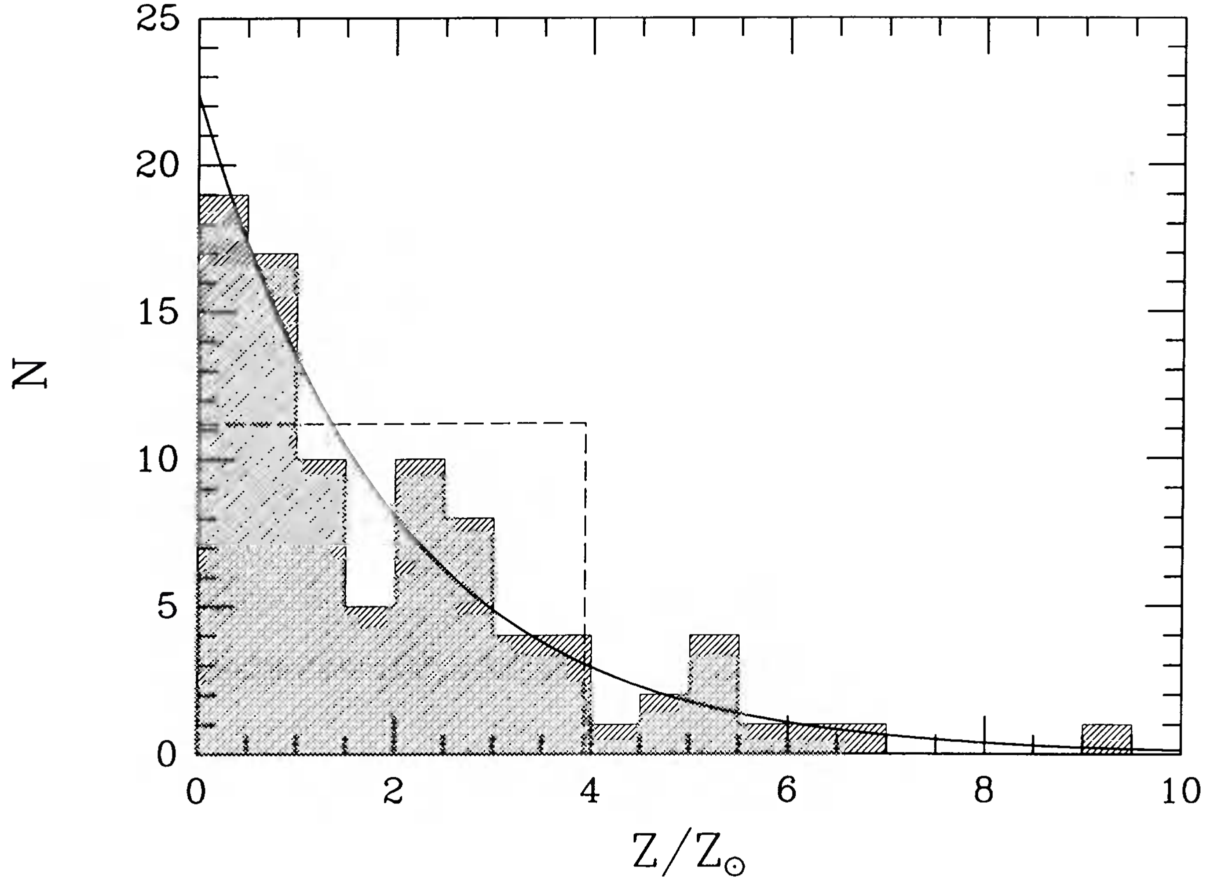


FIG. 8.—Differential abundance distribution of bulge giants compared to two limiting cases of the simple model of chemical evolution. *Solid line*: simple "closed box" model with complete gas consumption; $\langle z \rangle = 2.0 z/z_\odot$. *Dashed line*: Simple model, in the limiting case where a small fraction of the initial volume of gas is converted to stars, the remainder being lost from the system.

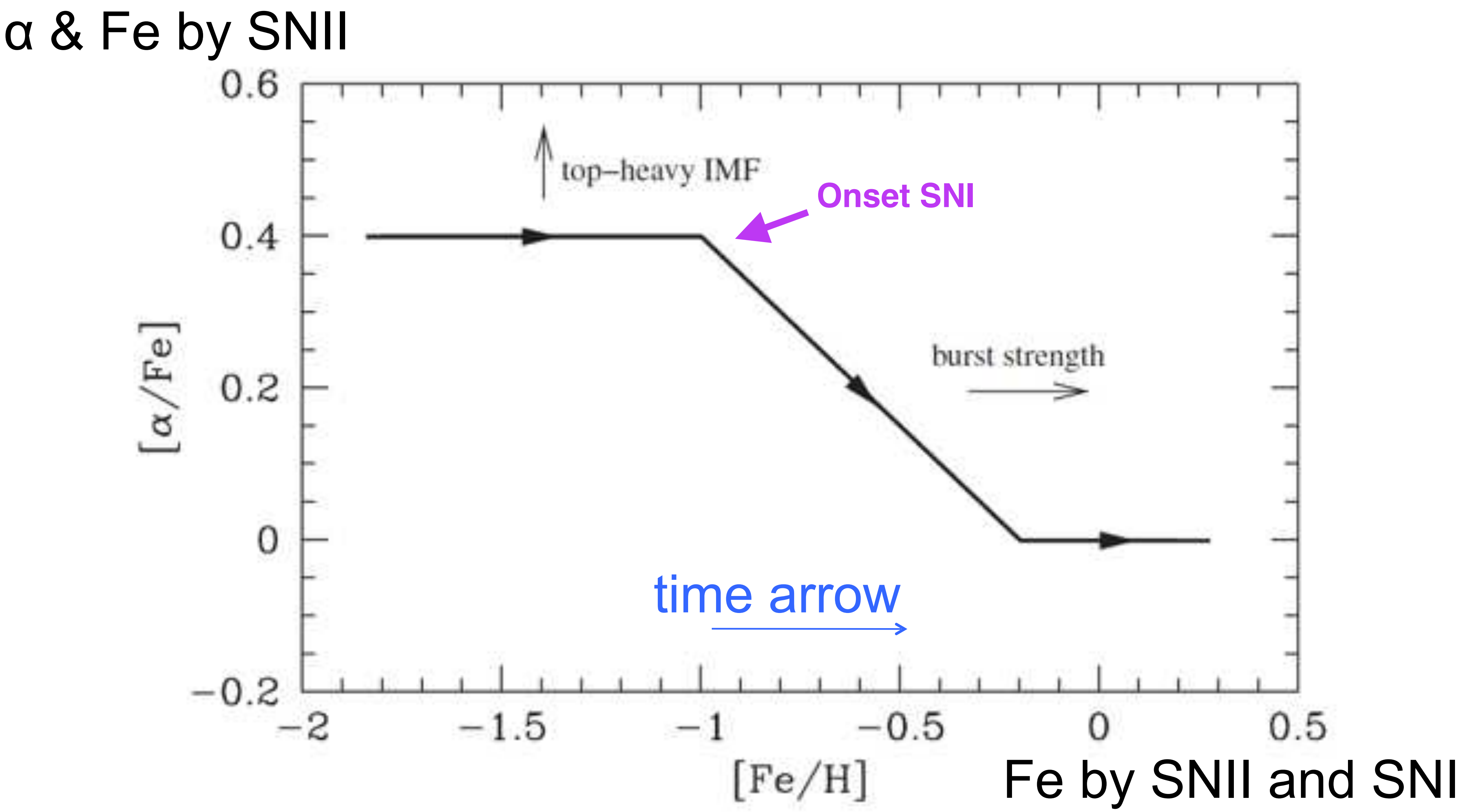
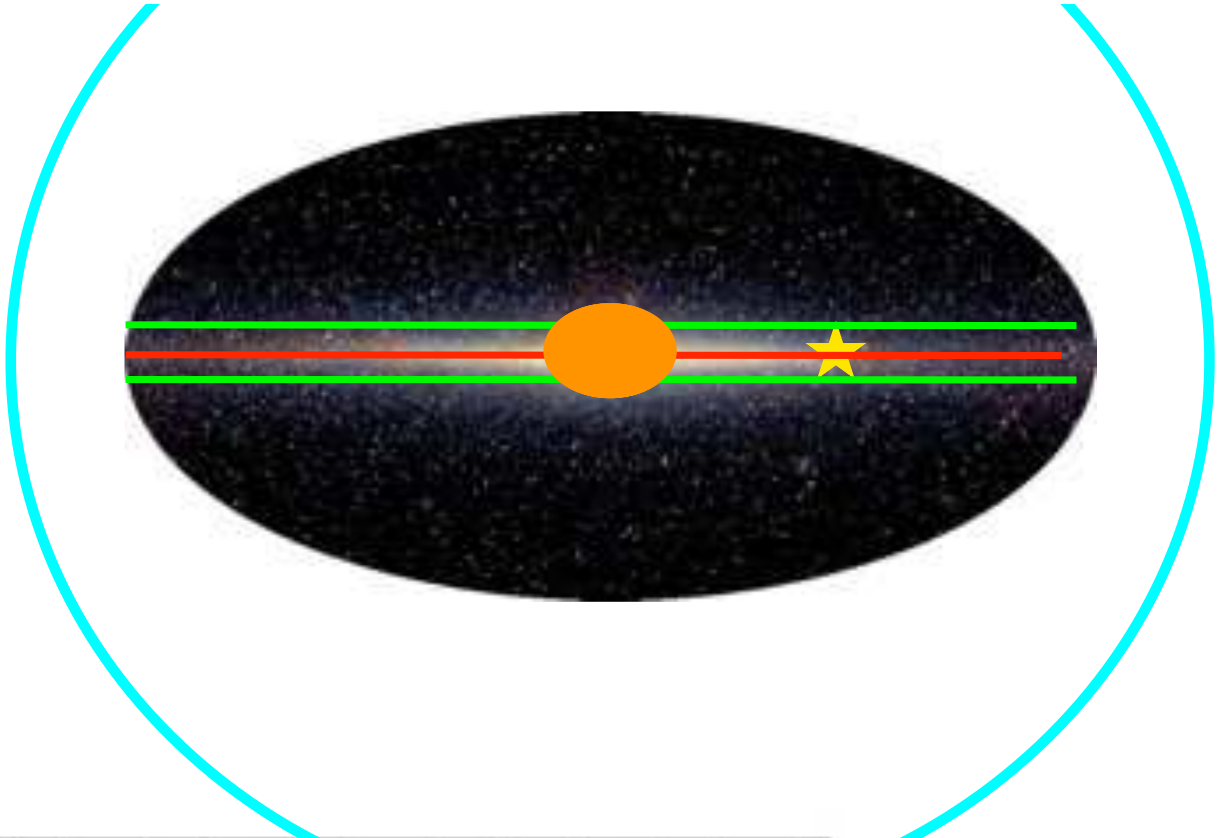
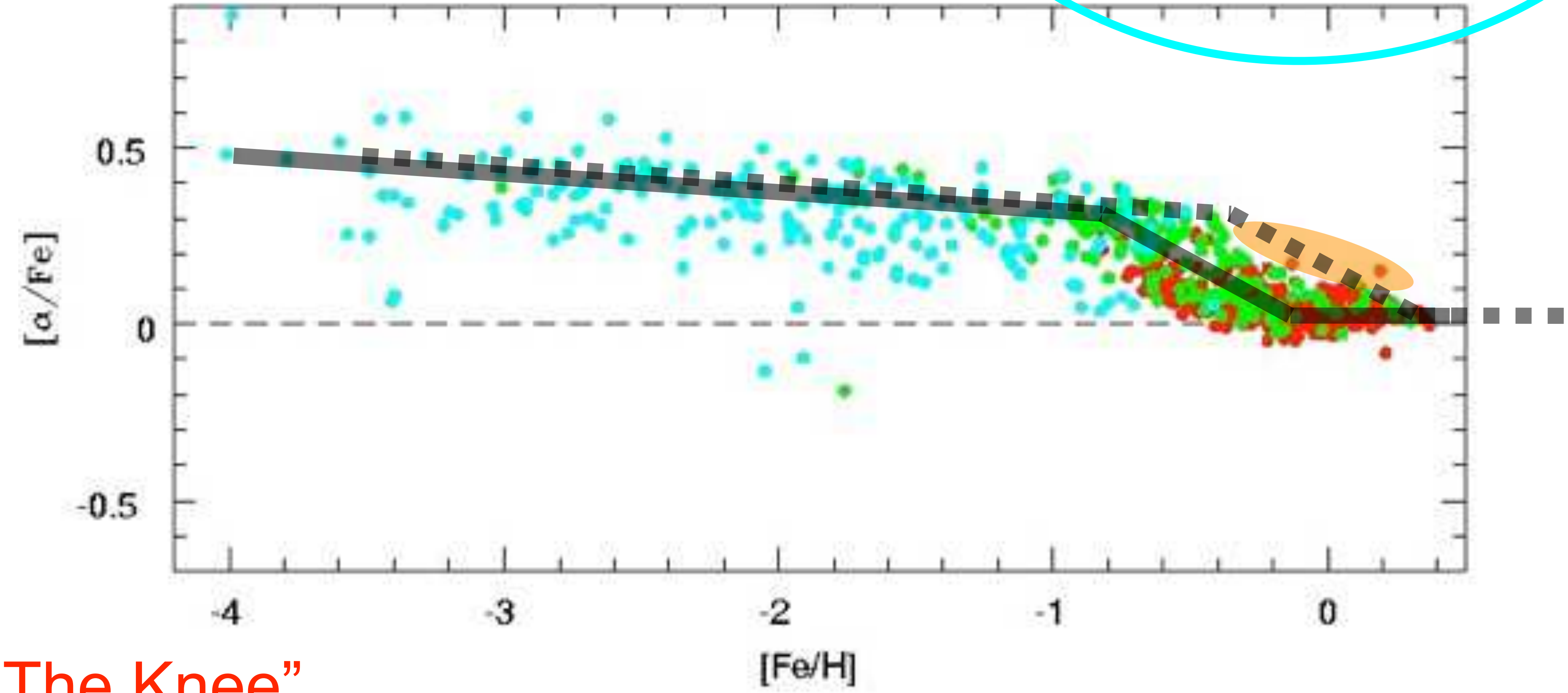


Fig. 10.10. A schematic of the chemical enrichment pattern of the ISM for a single coeval burst of star formation. Time advances along the thick curve as indicated by the arrows. The thin arrows indicate the impact of making the IMF more top-heavy and of increasing the strength of the burst.

The location of the knee depends on the intensity of SF burst
(or star formation rate/timescale)

Stellar Abundances
in the Milky Way

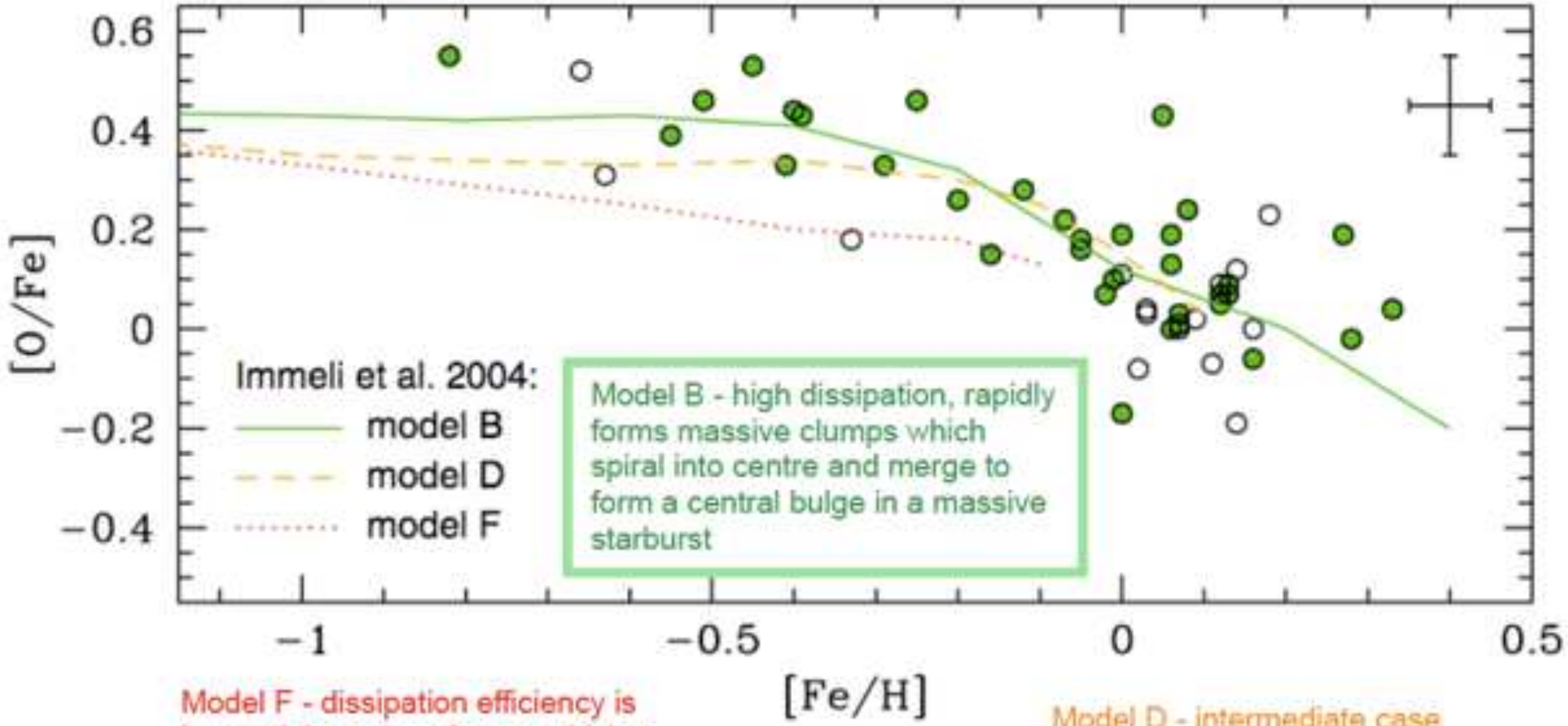




“The Knee”

compilation by Venn et al. 2004

Formation of the Bulge



Model B - high dissipation, rapidly forms massive clumps which spiral into centre and merge to form a central bulge in a massive starburst

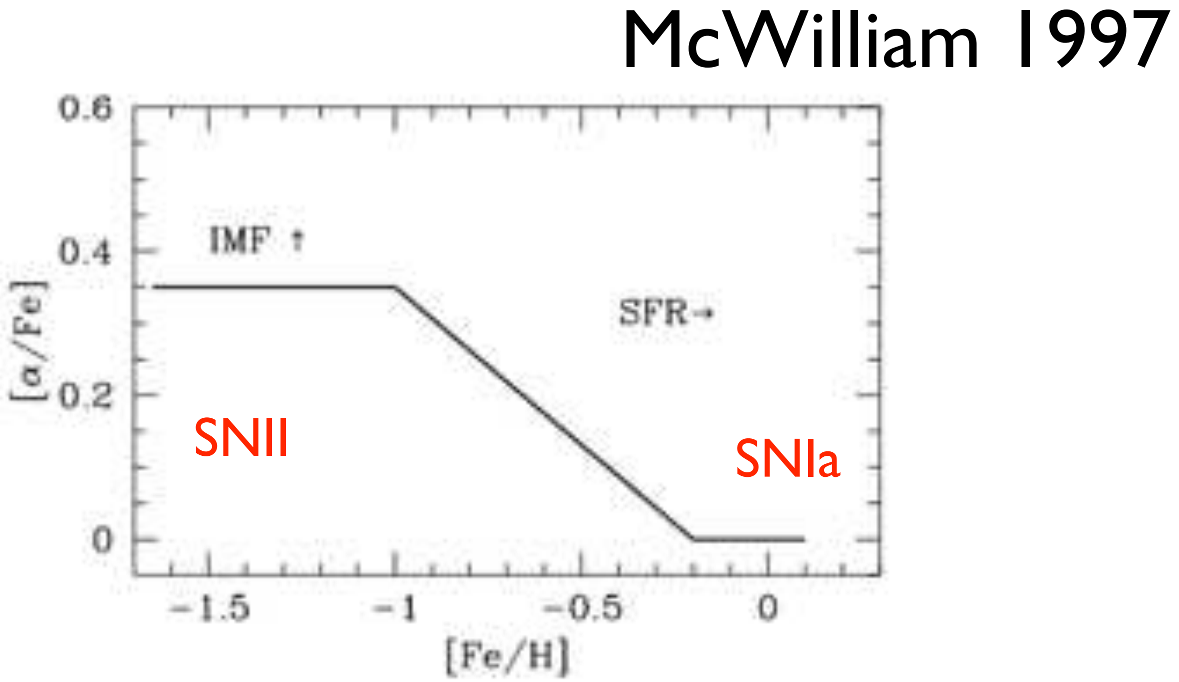
Model F - dissipation efficiency is low and the galaxy forms a thicker disk which at later times through instability forms a bar and then a (pseudo)bulge.

Model D - intermediate case

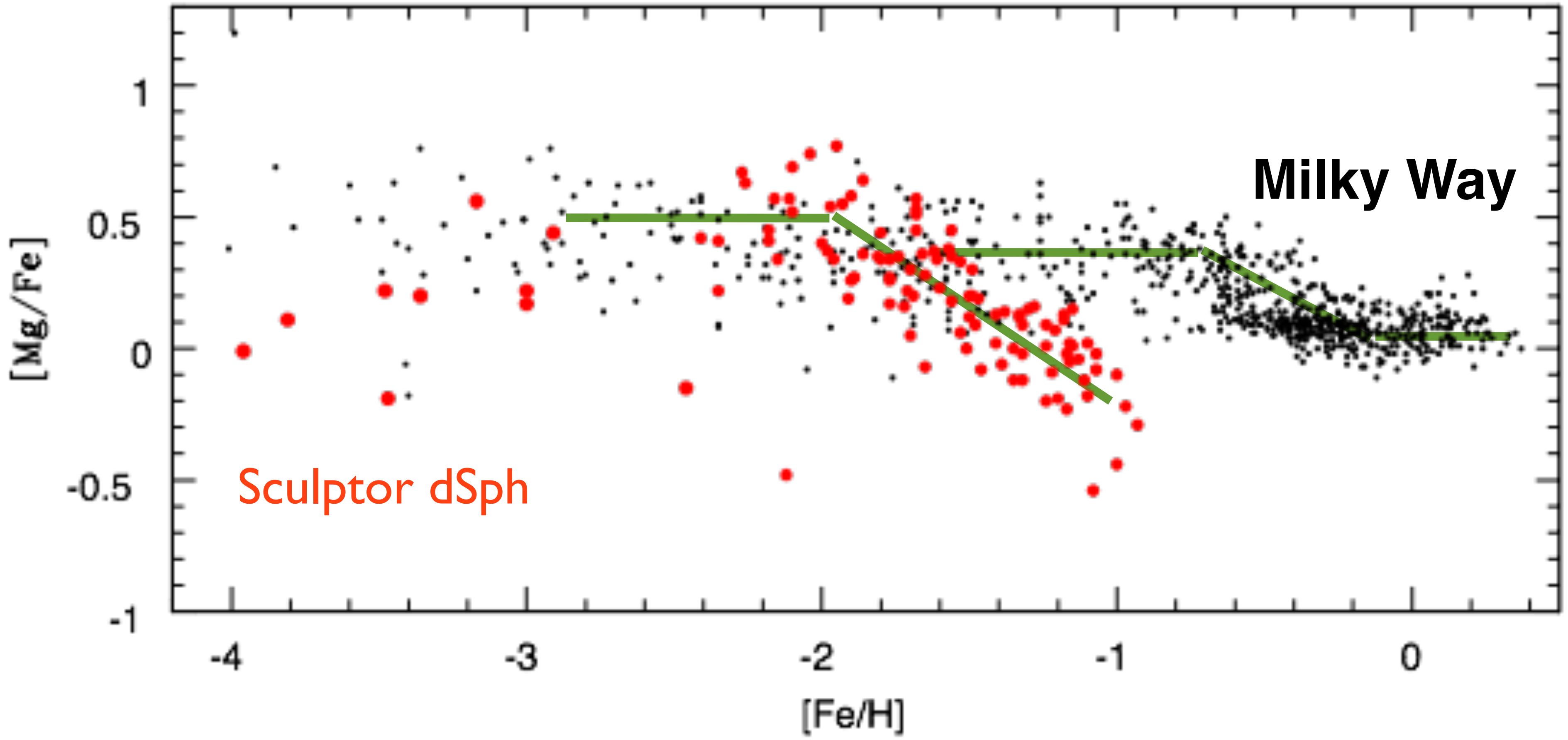
Zoccali et al. 2006 A&AL, 457, 1

Milky Way bulge similar to Early type galaxies, in being α-element enhanced, dominated by old stellar populations and having formed on time scales shorter than 1Gyr (Thomas et al. 2005). Therefore like early type galaxies the bulge is likely to have formed through a series of short starbursts triggered by rapid gas rich mergers when the Universe was only a few Gyr old.

Alpha-Elements: Comparison to a dwarf galaxy


McWilliam 1997

“The Knee”



Tolstoy et al. 2009; Starkenburg et al. 2013