

Physics of galaxies: some basis

I: Galactic (Chemical) Evolution; introduction, examples, abundance measurements, definitions, IMF, SFR, returned fraction.

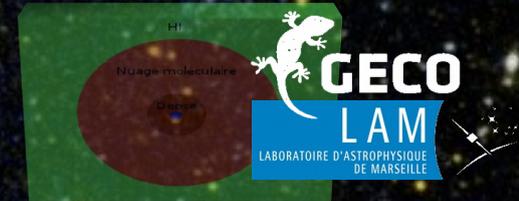
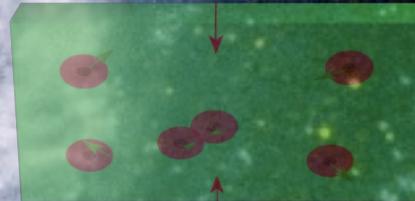
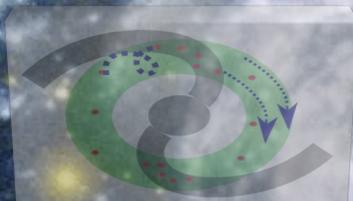
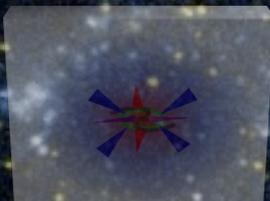
II: Star Formation Laws; threshold, resolution effects, star formation laws, state of the art of observations, gas measurements.

III: Outskirts of galaxies: truncations, anti-truncations, XUV disks, HI, CGM, shells,

*Complementary lectures:
Véronique Buat
Measuring Star Formation Rate
Stellar Masses, SEDs...*



*Samuel Boissier,
Laboratoire d'Astrophysique de Marseille - LAM
Galaxies, Etoiles et Cosmologie group - GECO*



GALACTIC CHEMICAL EVOLUTION

**a) Transformation of the universe
and chemical evolution**



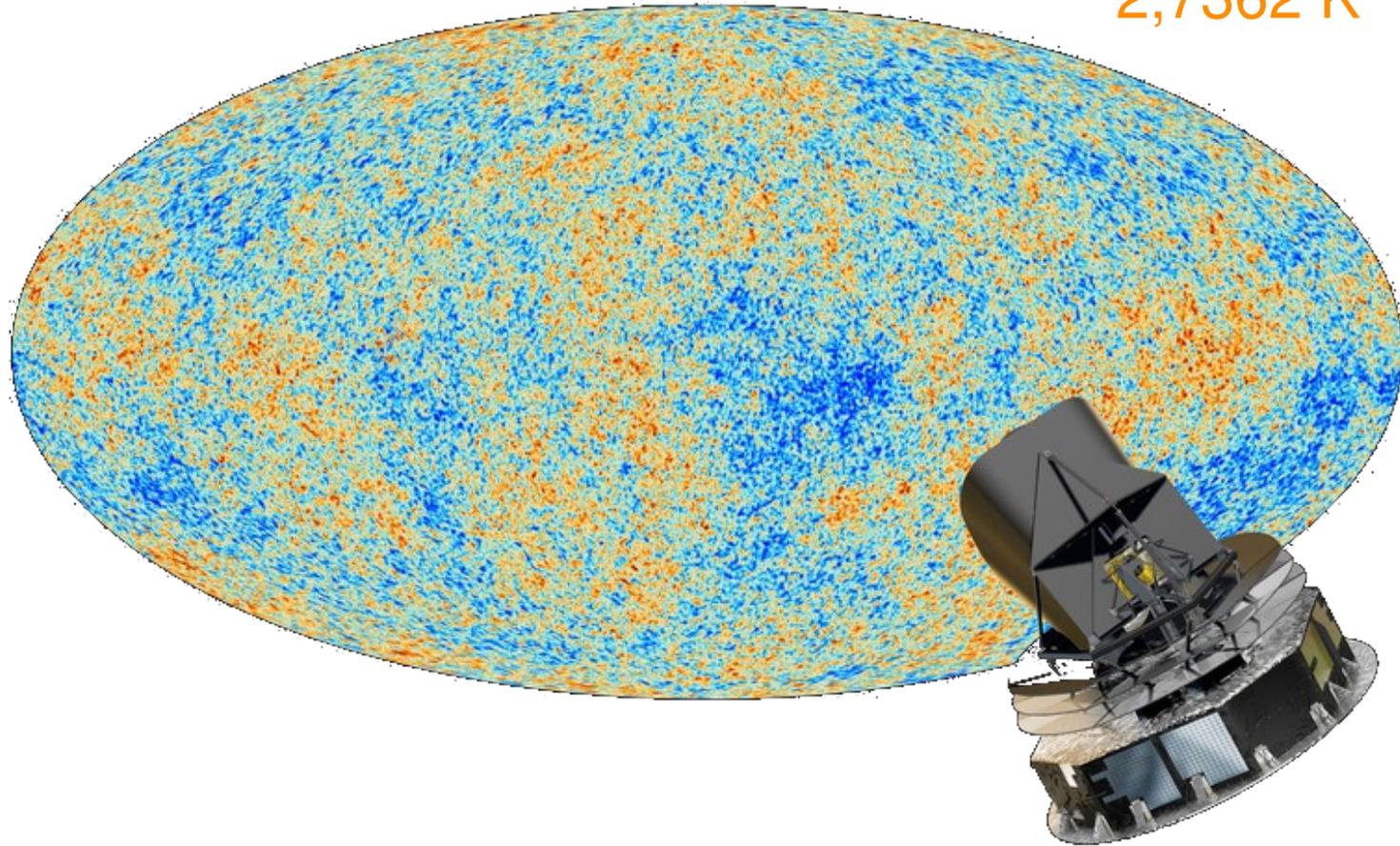
The primordial universe

The cosmological model and the observational constraints point to the big bang scenario...

... in which the universe evolves from a hot dense uniform state

2,7358 K

2,7362 K



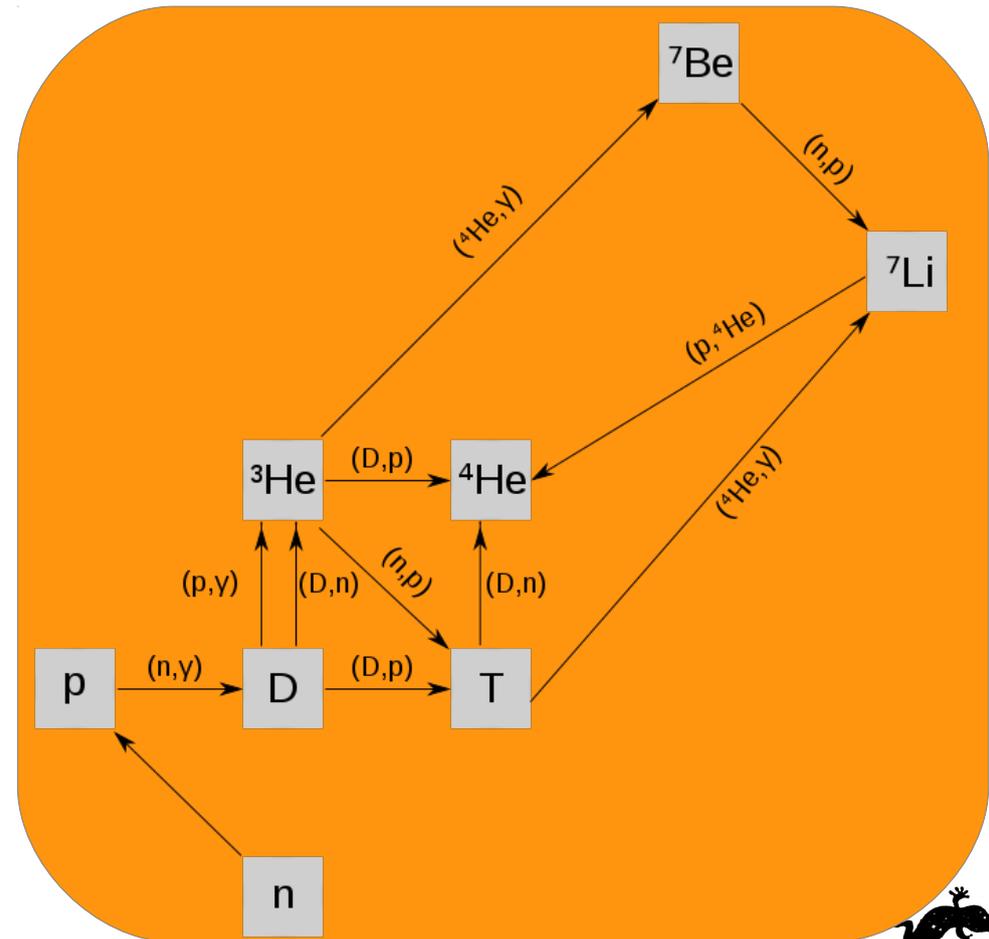
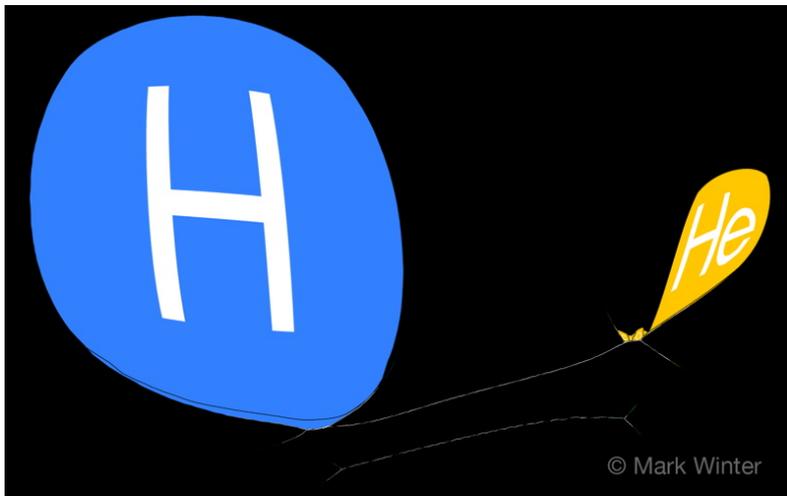
*Cosmological Background
(Planck satellite)*

The primordial universe

Mendeliev table in the primordial universe

A stylized Mendeliev table from the primordial universe. The table is dark blue with green boxes for the elements. The first row contains Hydrogen (H) and Helium (He). The second row contains Lithium (Li). The table is labeled with Roman numerals I through XVIII. The word 'HELIUM' is written in a green box above the Helium element.

Primordial nucleosynthesis :
In this hot dense state,
nuclear reactions allow the
formation of H, He, Li.

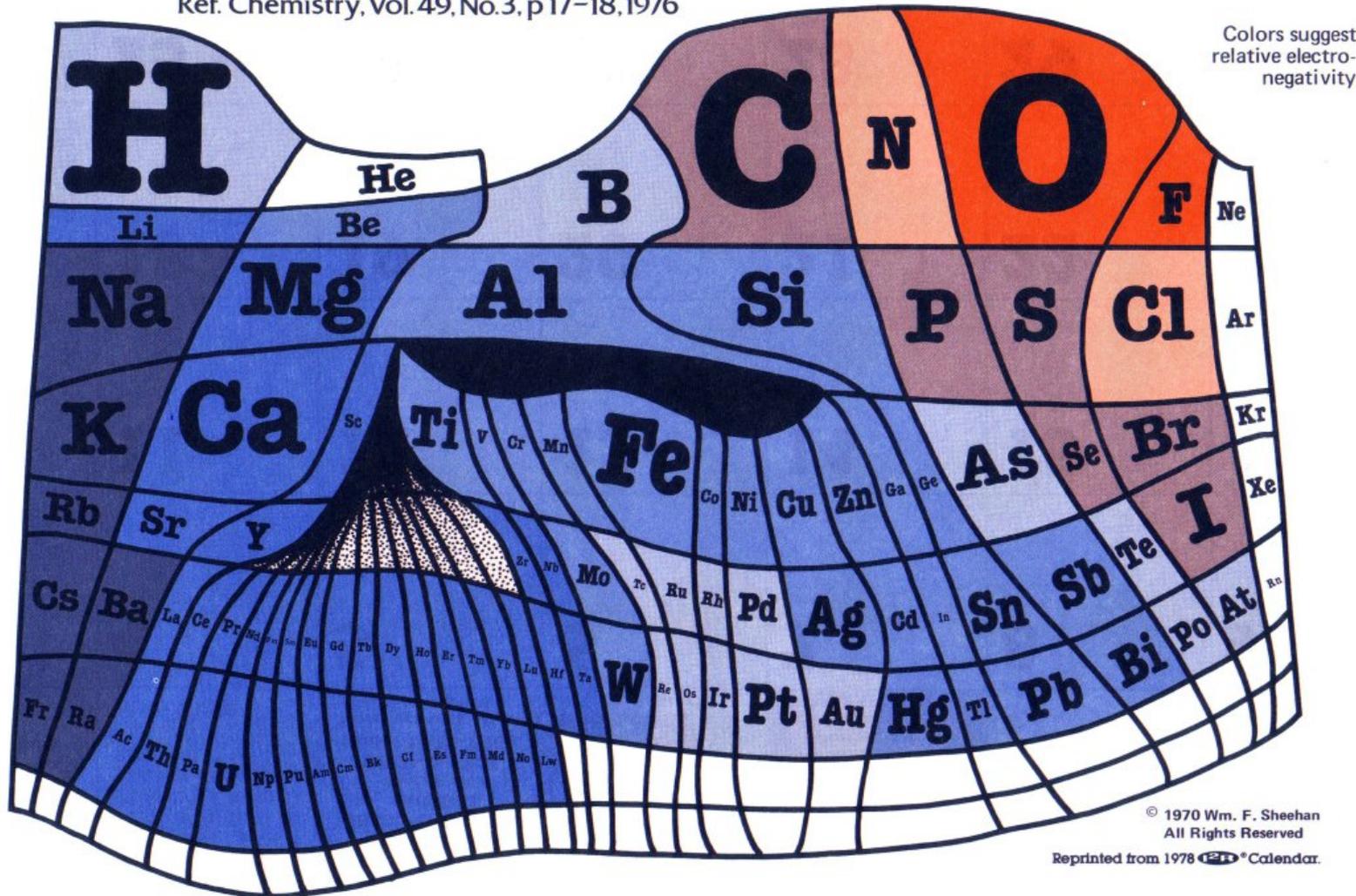


Today's universe

earth

The Elements According to Relative Abundance

A Periodic Chart by Prof. Wm. F. Sheehan, University of Santa Clara, CA 95053
Ref. Chemistry, Vol. 49, No. 3, p 17-18, 1976



Roughly, the size of an element's own niche ("I almost wrote square") is proportioned to its abundance on Earth's surface, and in addition, certain chemical similarities (e.g., Be and Al, or B and Si) are sug-

gested by the positioning of neighbors. The chart emphasizes that in real life a chemist will probably meet O, Si, Al, . . . and that he better do something about it. Periodic tables based upon elemental abundance would, of course, vary from planet to planet. . . W.F.S.

NOTE: TO ACCOMMODATE ALL ELEMENTS SOME DISTORTIONS WERE NECESSARY, FOR EXAMPLE SOME ELEMENTS DO NOT OCCUR NATURALLY.

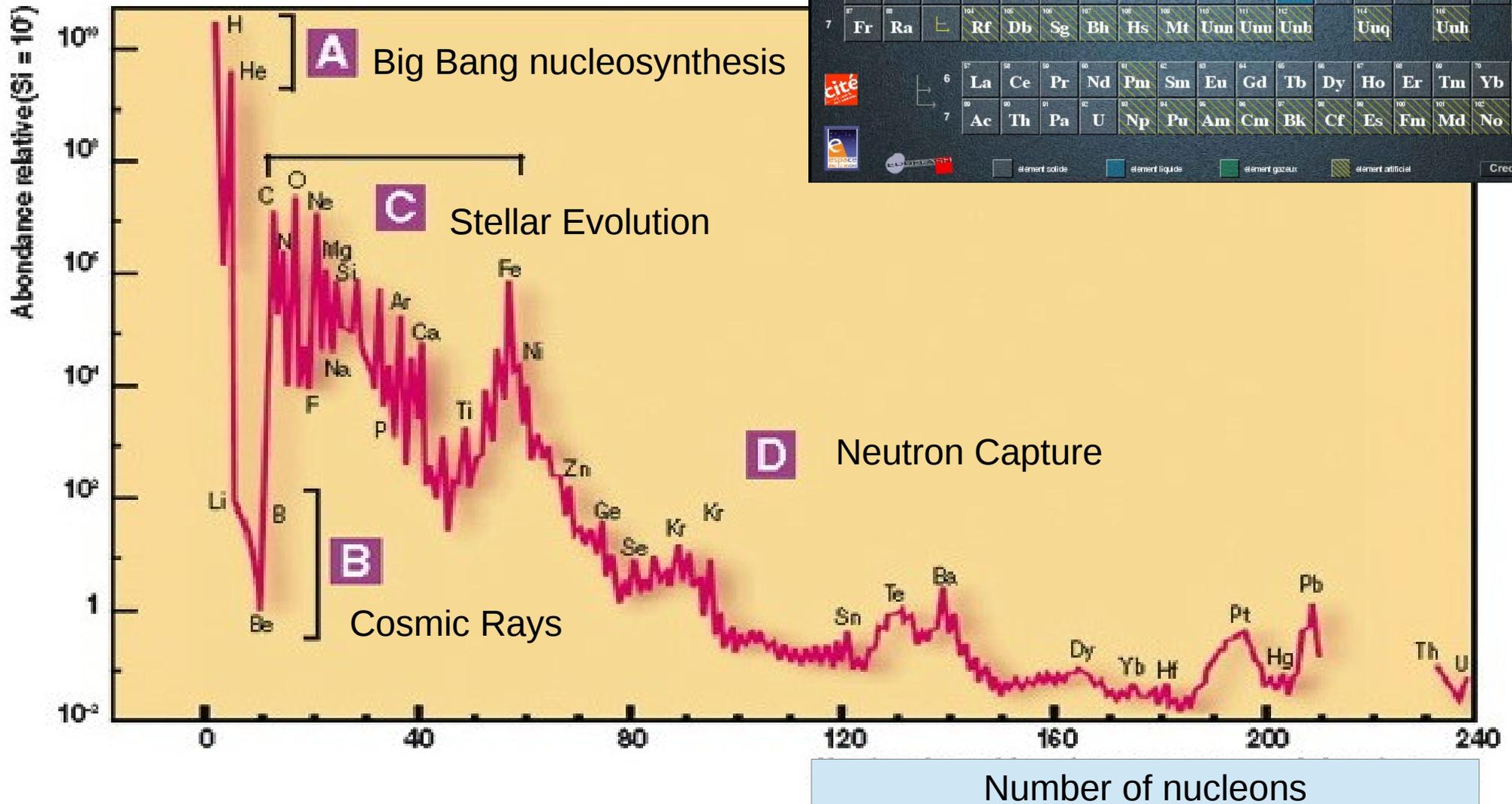


primordial universe



Today's universe

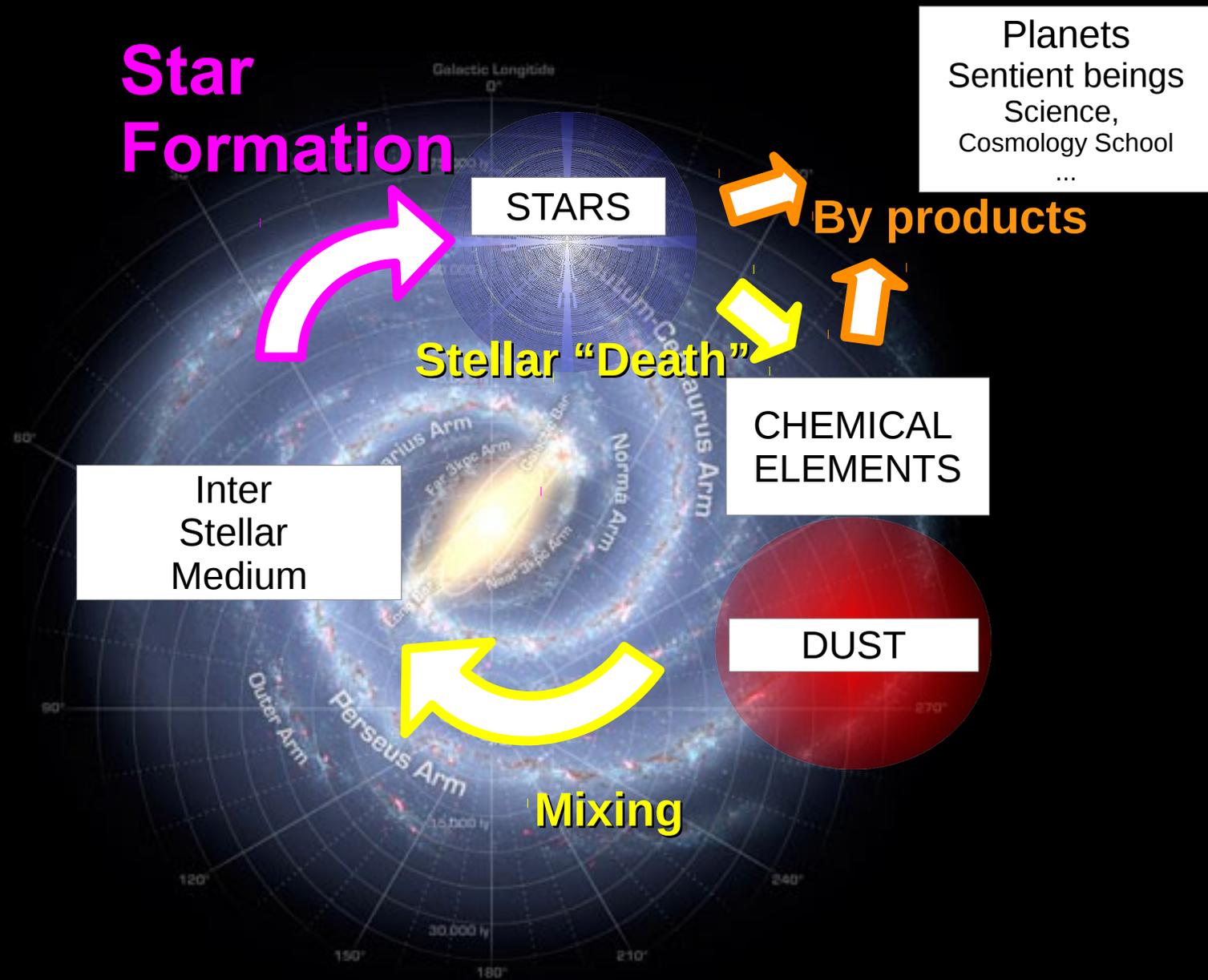
Abundances of elements



Today's universe

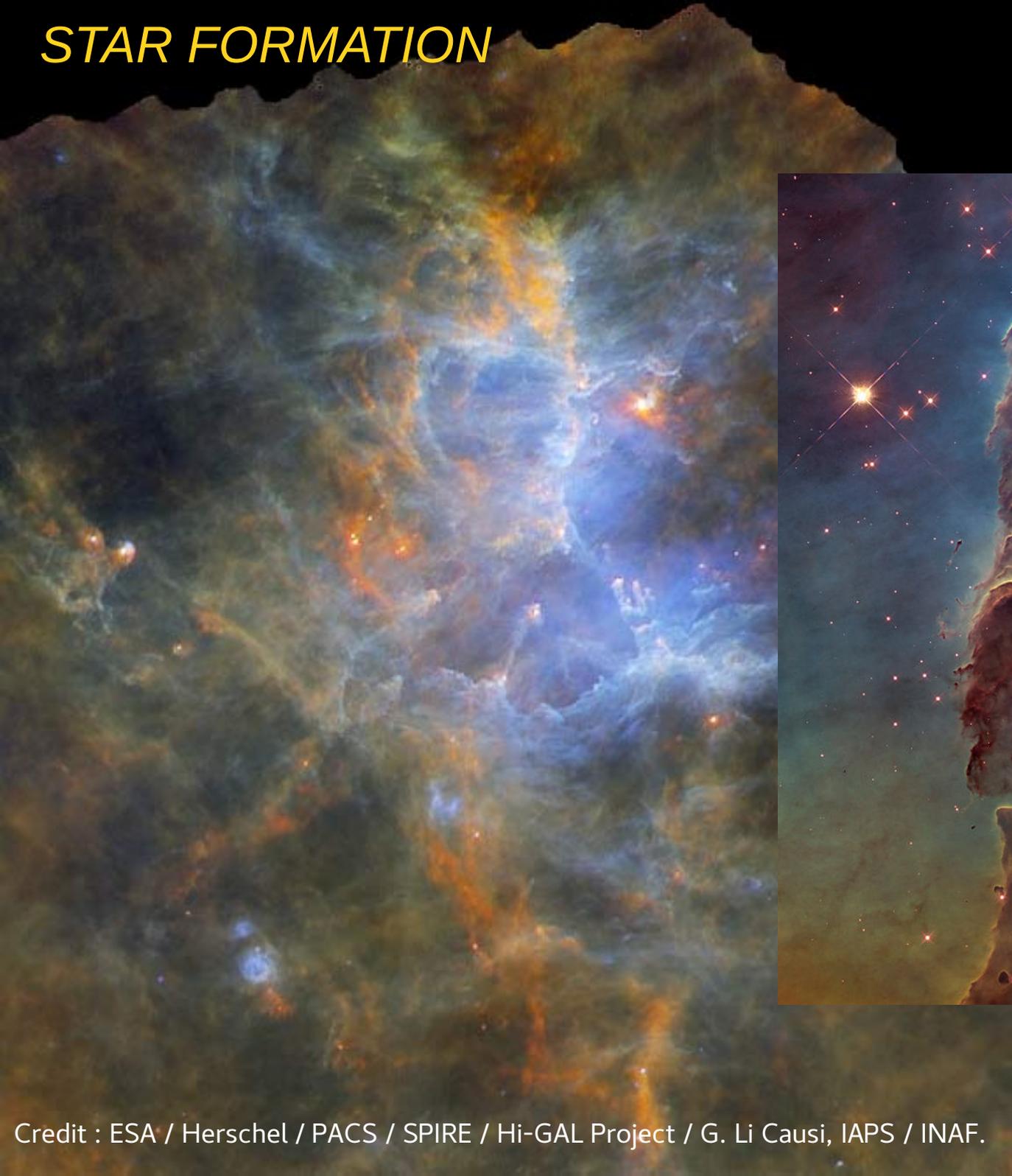


The cycle of transformation within galaxies



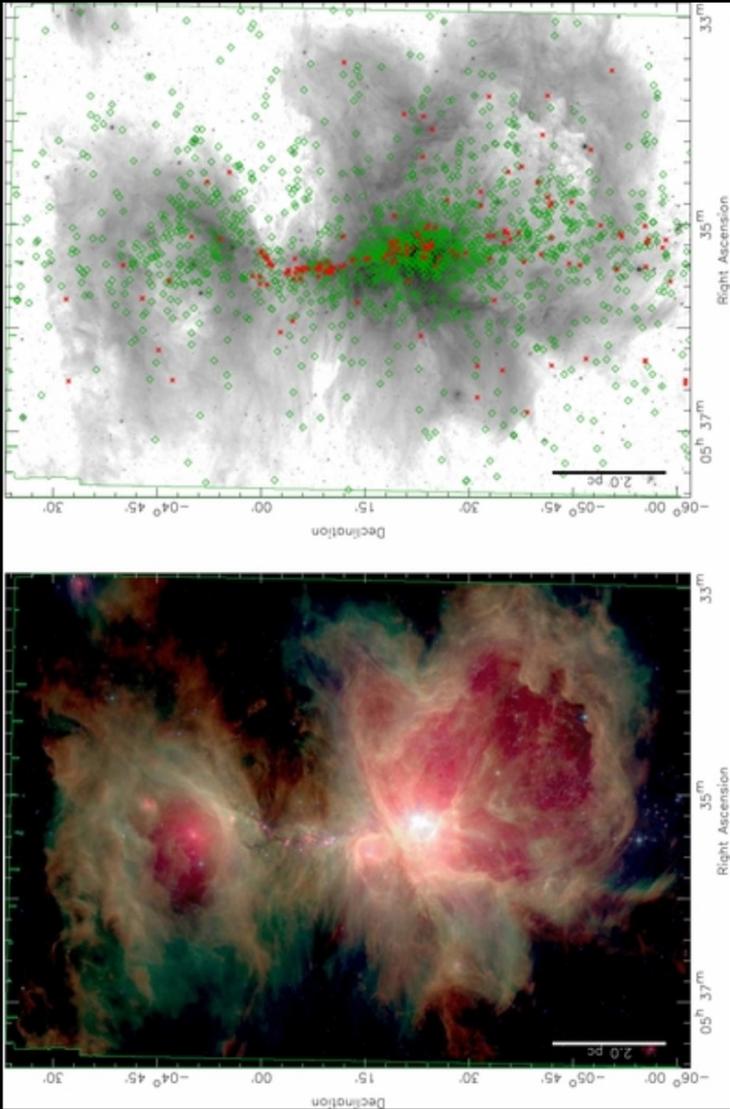
STAR FORMATION

M16



HST

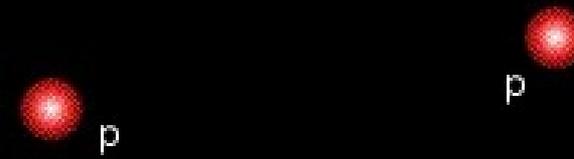
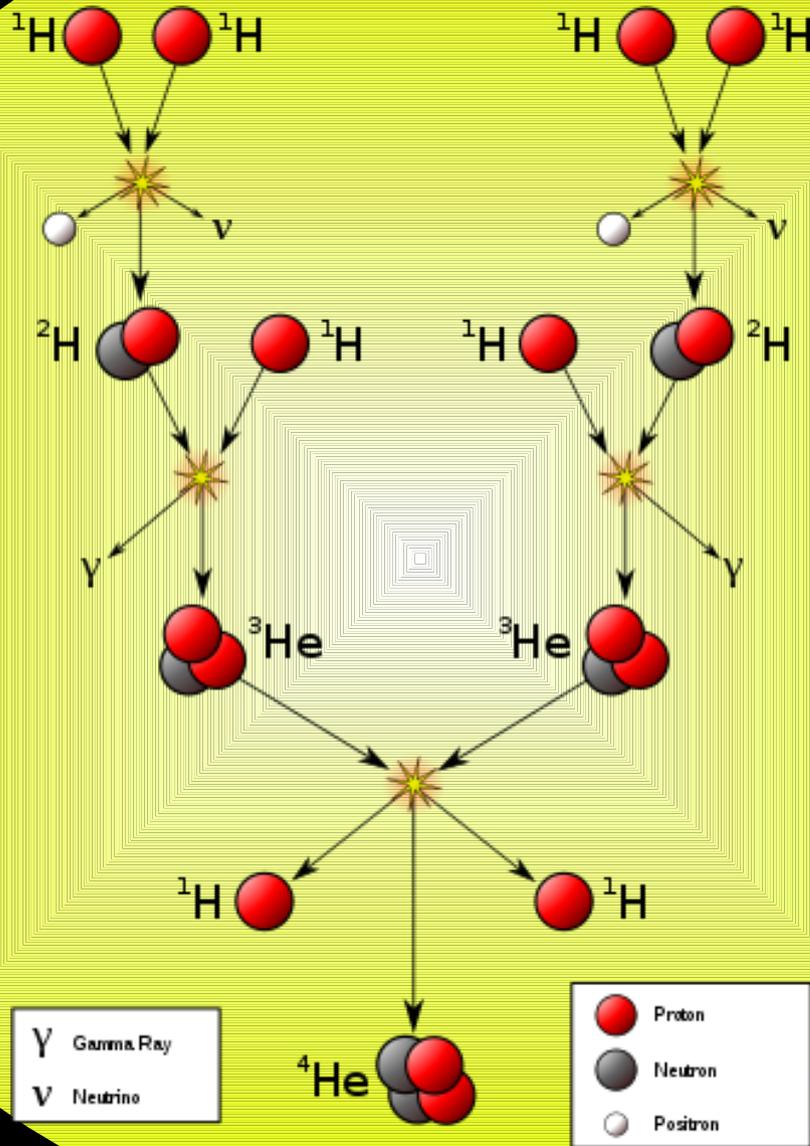
STAR FORMATION



FORMATION OF ELEMENTS IN STARS

Stellar nucleosynthesis

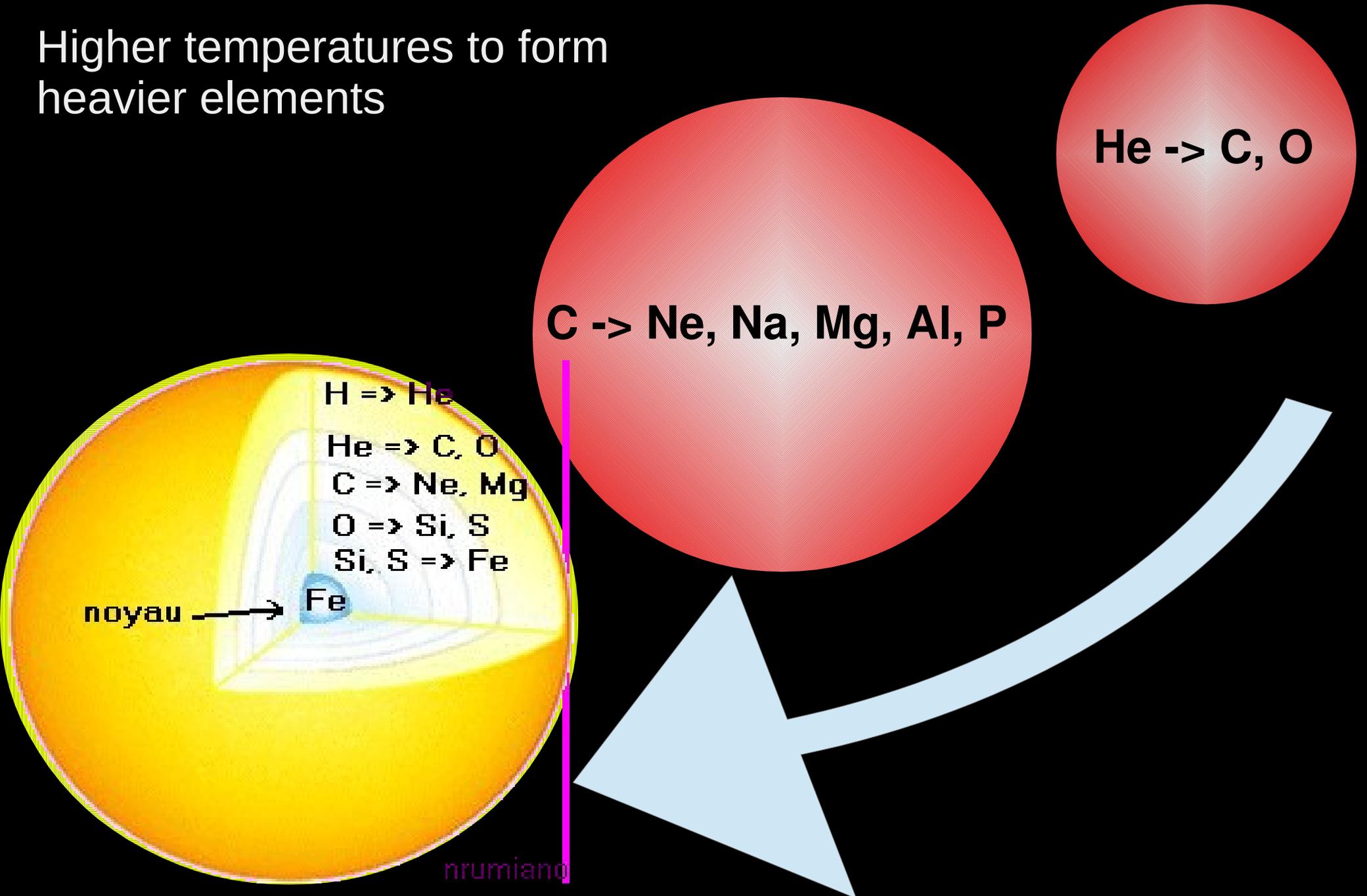
Exemple : proton-proton chain of reactions.

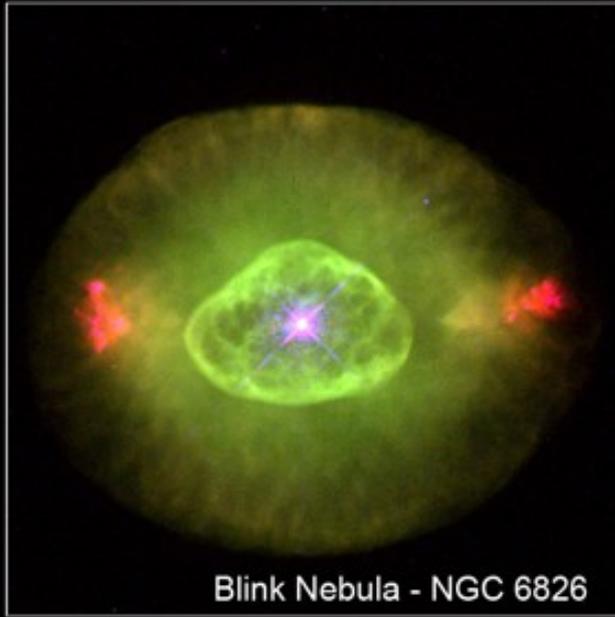


FORMATION OF THE ELEMENTS

Stellar nucleosynthesis

Higher temperatures to form heavier elements





Blink Nebula - NGC 6826



Nébuleuse de l'Oeil de Chat - NGC6543



Nébuleuse Dumbbell - M27

Planetary neabulae

Intermediate mass stars eject outer regions at the end of their exsistence



Nébuleuse de la Lyre - M57



Nébuleuse de l'Eskimo - NGC2392

Dispersion of heavy elements in the interstellar medium

Supernova

Massive stars
explode as core-
collapse supernovae



Note : other type of Sns are Ia : linked to binary stars,
and are important source of Iron (discussed later)

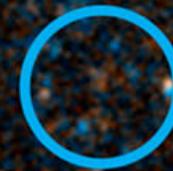
N6946-BH1
HST WFPC2

2007



N6946-BH1
HST WFC3/UVIS

2015

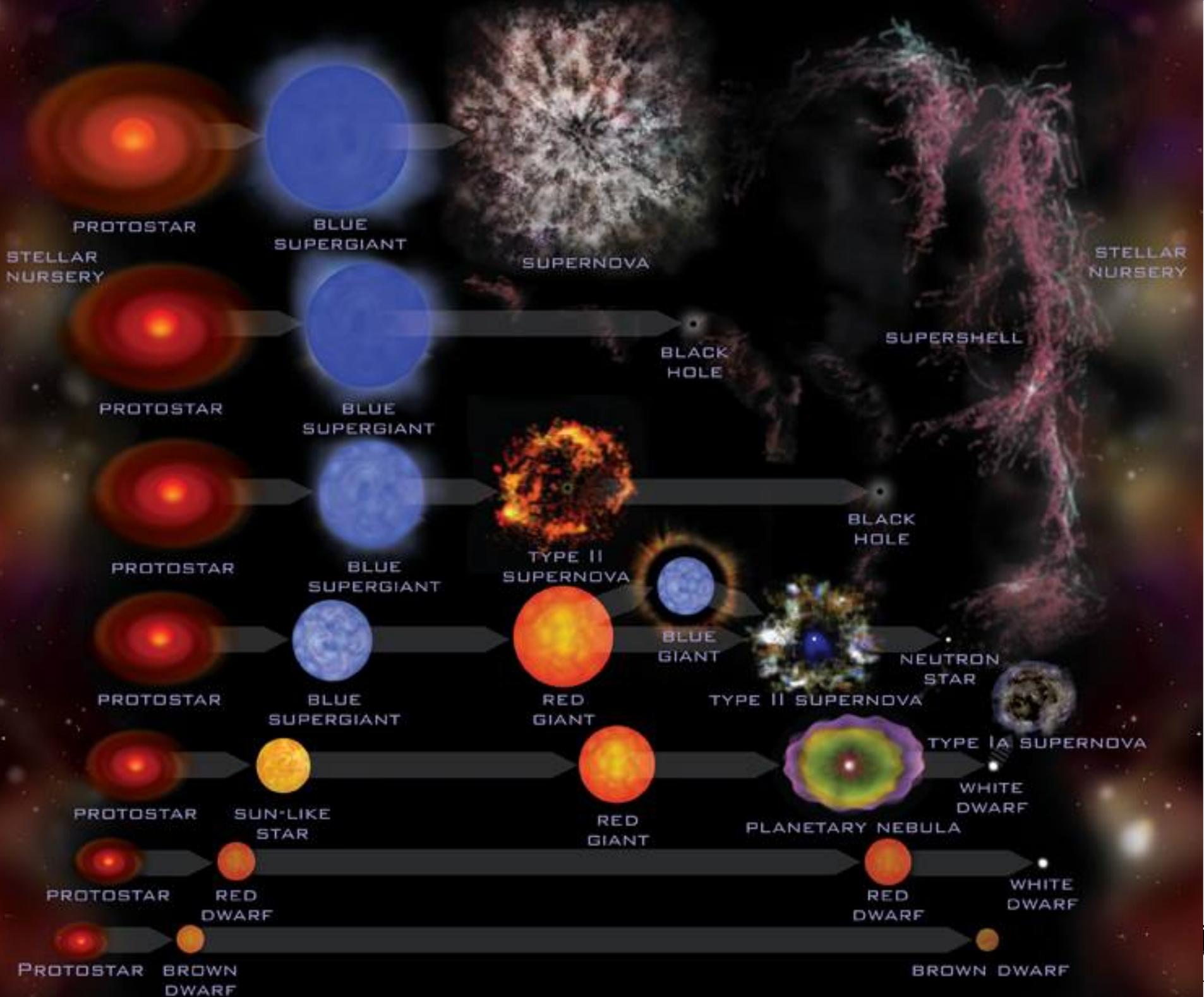


NASA/ESA/C. Kochanek (OSU)

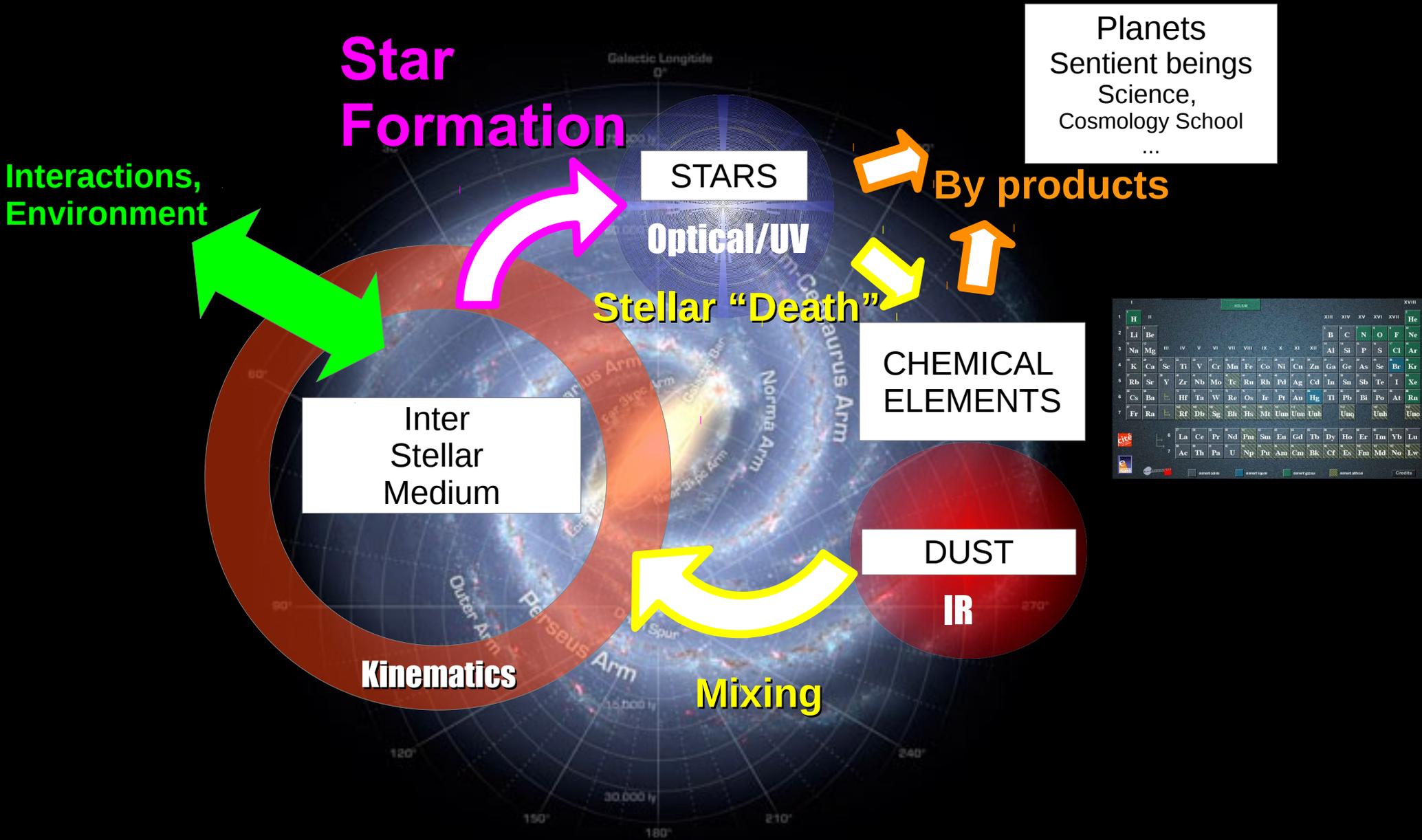
Disparition of a massive star : direct formation of a black hole ?



(c) Chandra



The cycle of transformation within galaxies



Interlude : a bit of history

SYNTHESIS OF THE ELEMENTS IN STARS

E. Marqaret Burbidge, G. R. Burbidge,
William A. Fowler and F. Hoyle

KELLOGG RADIATION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Burbidge, Burbidge, Fowler, Hoyle (1957)



Interlude : a bit of history

SYNTHESIS OF THE ELEMENTS IN STARS

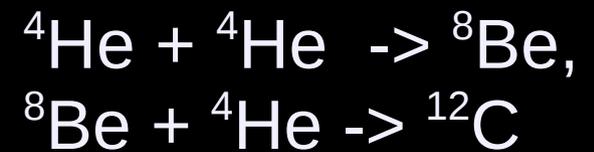
E. Margaret Burbidge, G. R. Burbidge,
William A. Fowler and F. Hoyle

KELLOGG RADIATION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Burbidge, Burbidge, Fowler, Hoyle (1957)



Salpeter (1951):



Interlude : a bit of history

SYNTHESIS OF THE ELEMENTS IN STARS

E. Margaret Burbidge, G. R. Burbidge,
William A. Fowler and F. Hoyle

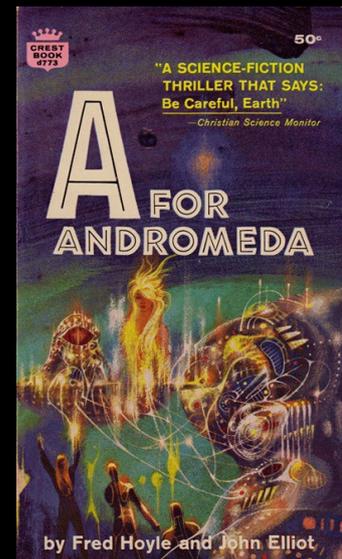
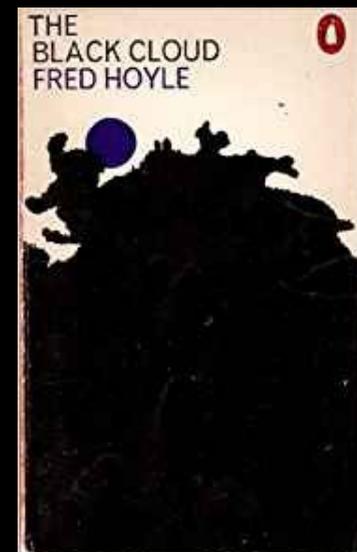


MOUNT WILSON AND PALOMAR OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
CALIFORNIA INSTITUTE OF TECHNOLOGY

Fred Hoyle :

- Motivation to prove that elements were made in stars, not in a “*Big Bang*” !
- Majority of elements made in stars indeed
- but the most abundant ones during the Big Bang.

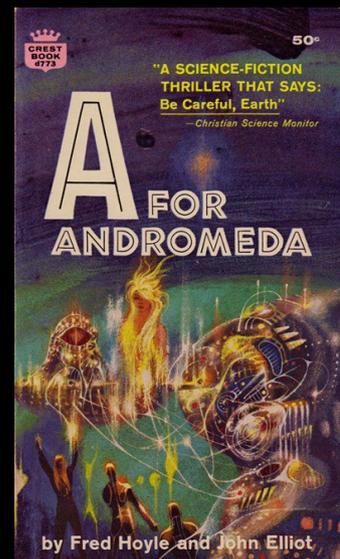
(was also a
Science-
Fiction
author!)



Interlude : a bit of history

3rd COSMOLOGY SCHOOL

Cracow, Poland
10-23.07.2017



GALACTIC CHEMICAL EVOLUTION

- a) Transformation of the universe and chemical evolution
- b) How to use chemical evolution traces to learn about galaxy evolution



In the Milky Way:

Many constraints,
especially: abundances
in stars

Goswami & Prantzos 2000

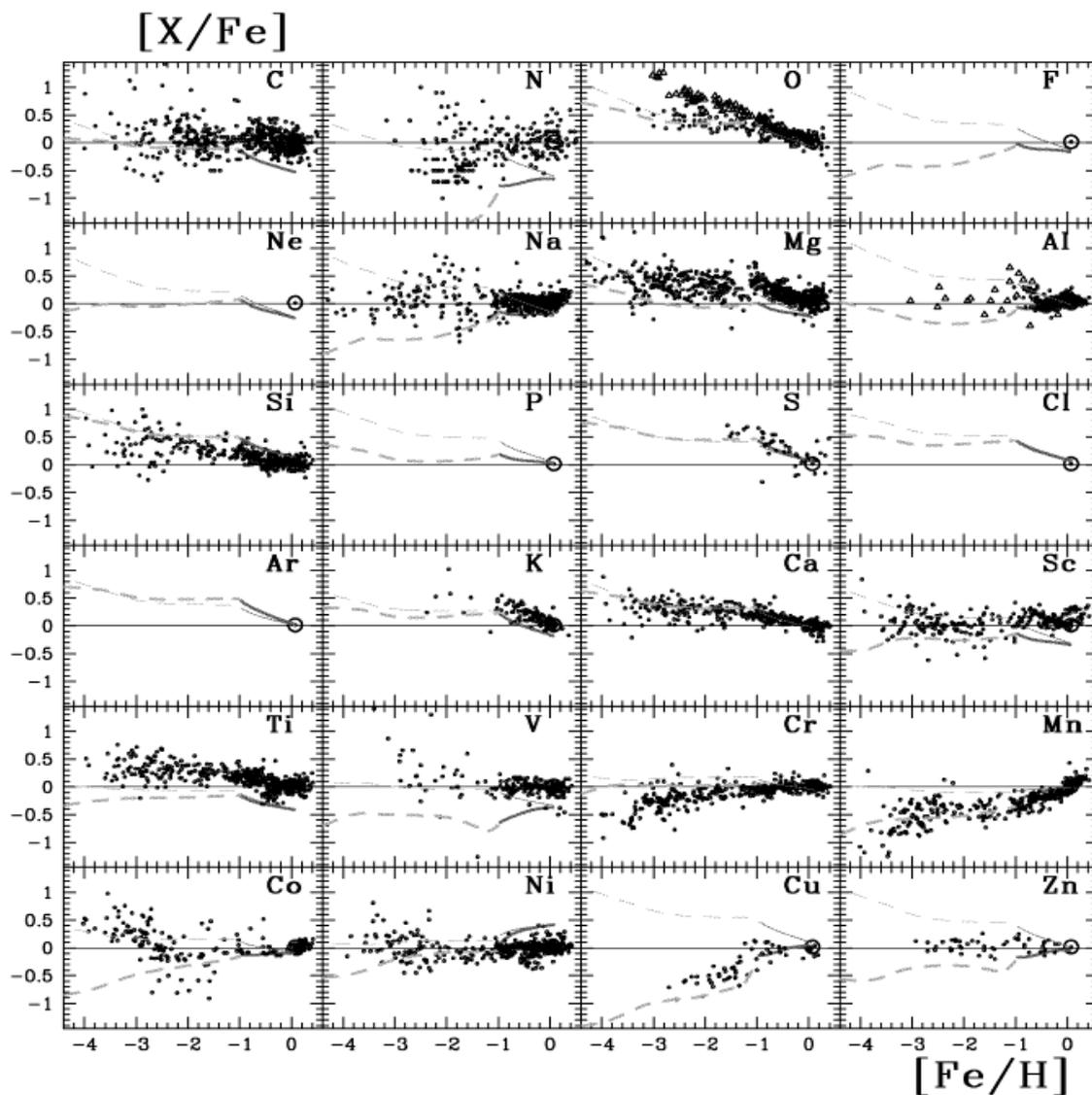
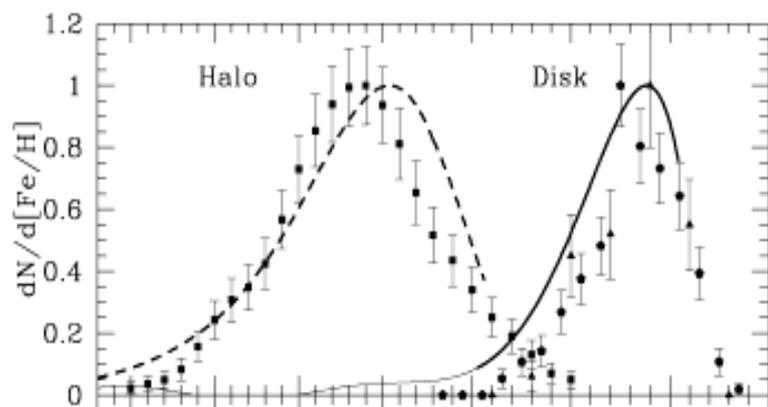
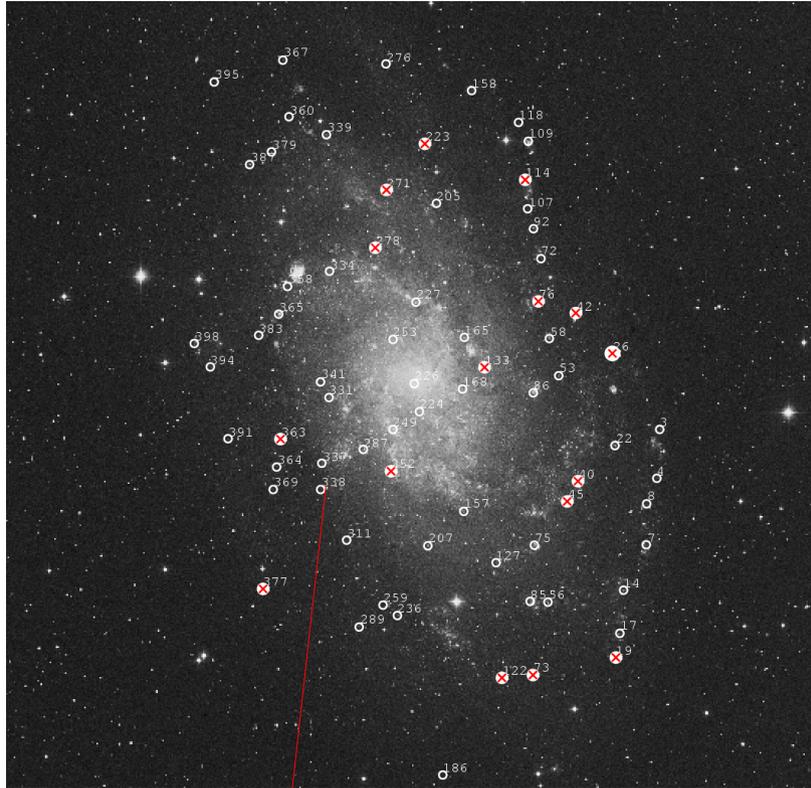


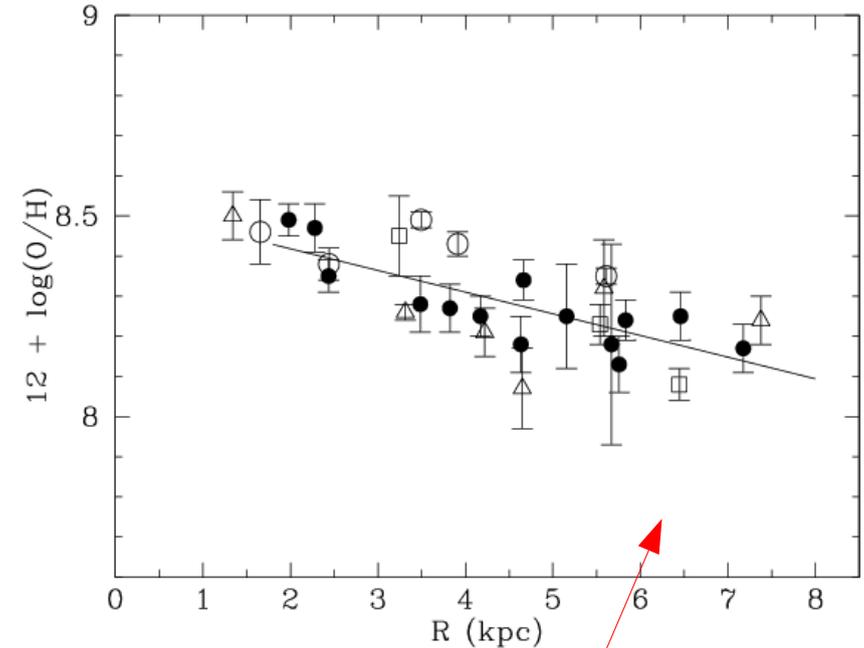
Fig. 7. Abundance ratios $[X/Fe]$ of stars in the halo and the local disk, as a function of $[Fe/H]$. Theoretical results are obtained with models that treat properly the halo (*dashed curve* assuming *outflow*) and the disk (*solid curve* assuming *slow infall*). Two sets of massive star yields are used, both from WW1995: at constant (=solar) metallicity (*thin curves*, Case A, only for illustration purposes) and at variable metallicity (*thick curves*, the reference Case B). Yields of the W7 and W70 models of Iwamoto et al. (1999) for SNIa are used in both cases (properly interpolated as a function of metallicity); intermediate mass stars are not considered. It should be noted that WW1995 yields of Fe have been divided by 2, in order to obtain the observed α/Fe ratio in halo stars. Model trends below $[Fe/H]=-3$ are due to the finite lifetime of stars ($[Fe/H]=-4$ is attained at 10 Myr, corresponding to the lifetime of stars with mass $> 20M_{\odot}$, while $[Fe/H]=-3$ is attained at 20 Myr, corresponding to the lifetime of $\sim 10M_{\odot}$ stars). In view of the yield uncertainties of individual stars (Sect. 2) and of the uncertainties in the timescales at those early times of the halo evolution, those trends *should not be considered as significant*. The observed data points in the figure are taken from sources listed in Table 1. Observed abundance ratios of $[O/Fe]$ from Israelian et al. (1998) and Boesgaard et al. (1999) are shown by *open triangles*; they suggest a trend quite different from all other α -elements. The *open triangles* in the $[Al/Fe]$ panel correspond to observed data with NLTE corrections (from Baumüller & Gehren 1997).

Abundance gradients

M33



Magrini et al. 2007, A&A 470, 865–874

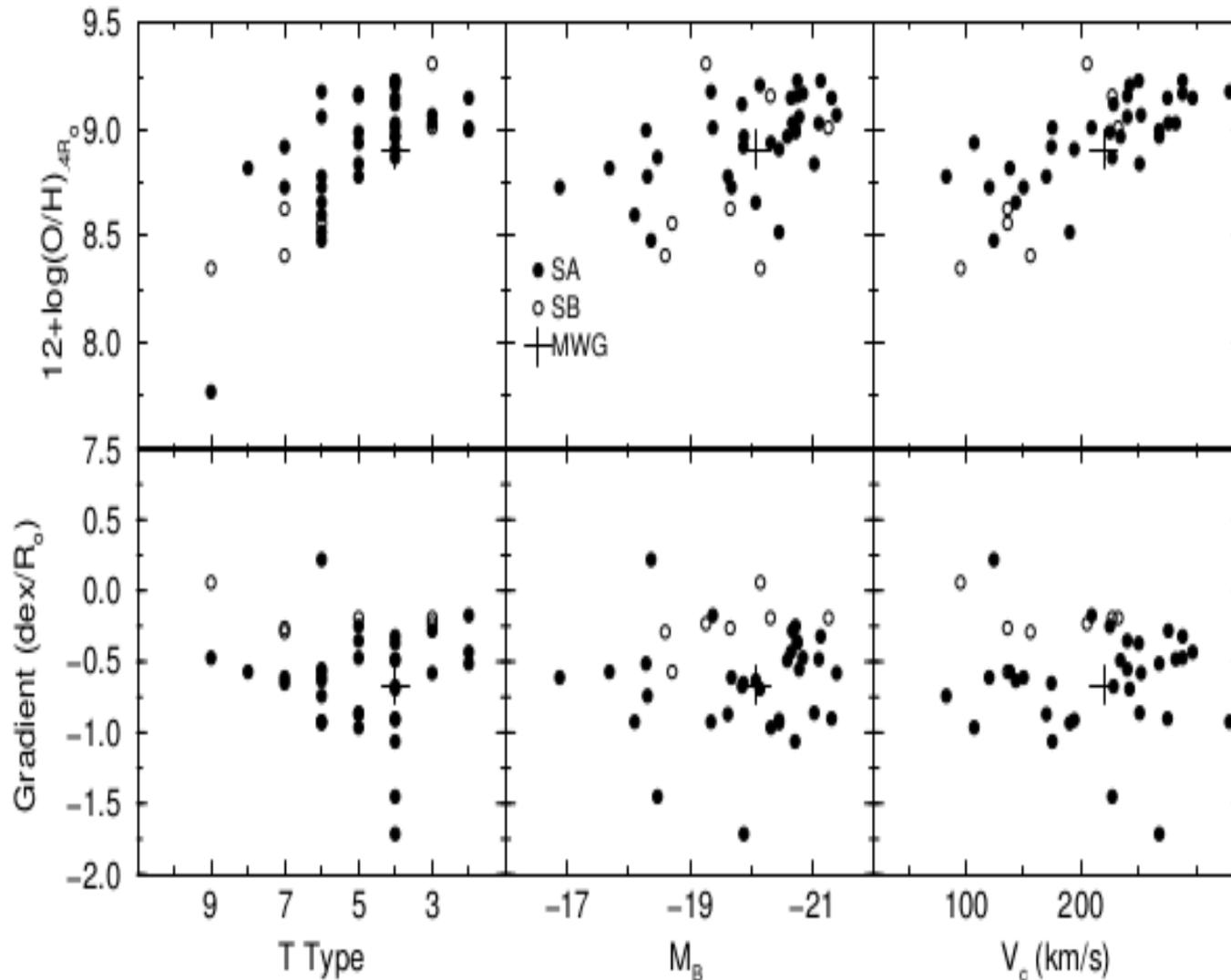


HII regions spectroscopy : **line emission** measurements:
tracers of metallicity in the gas

Same thing can be done in many nearby galaxies
(see NED LEVEL5 NASA database for collection of abundance gradients)



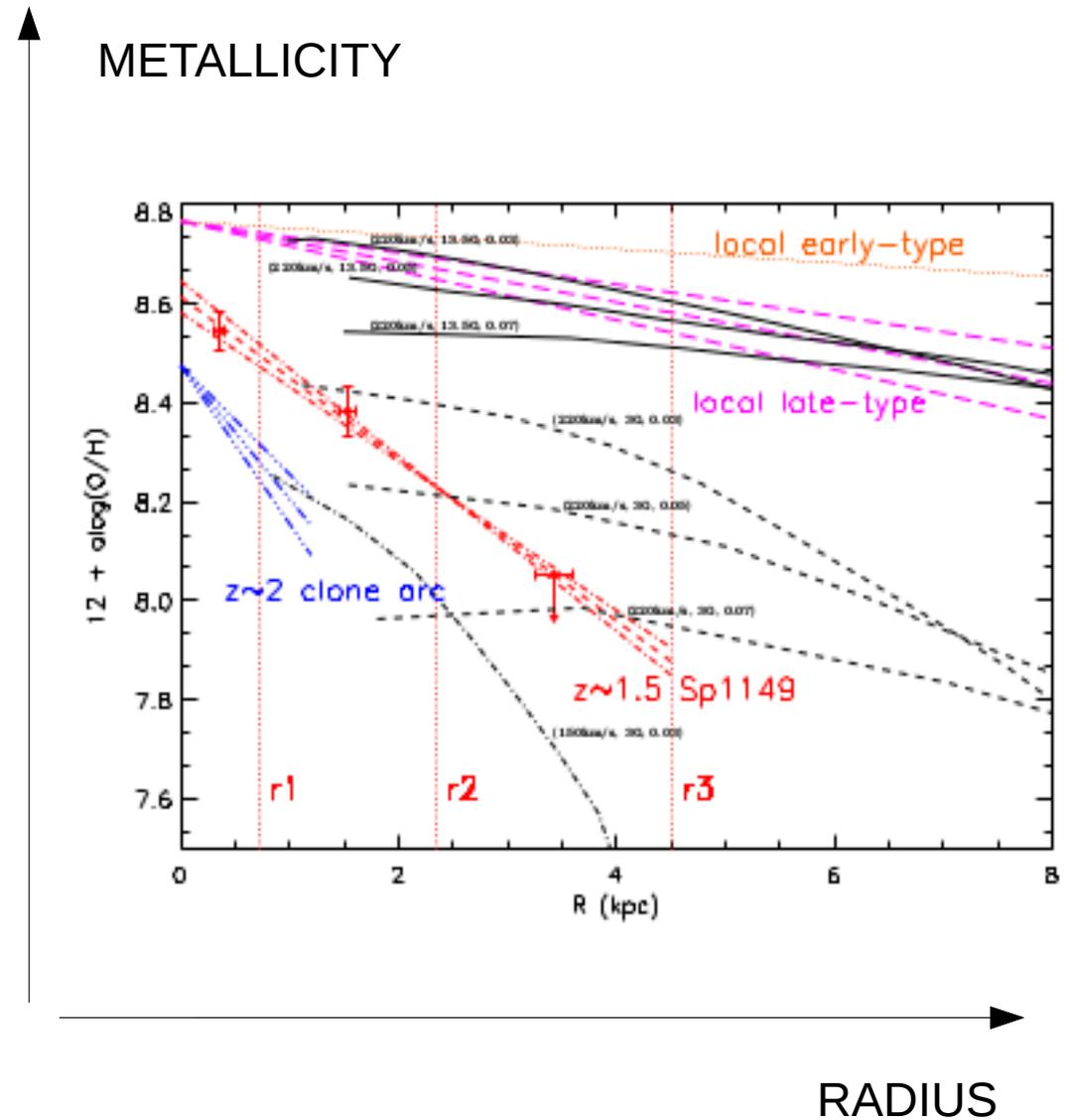
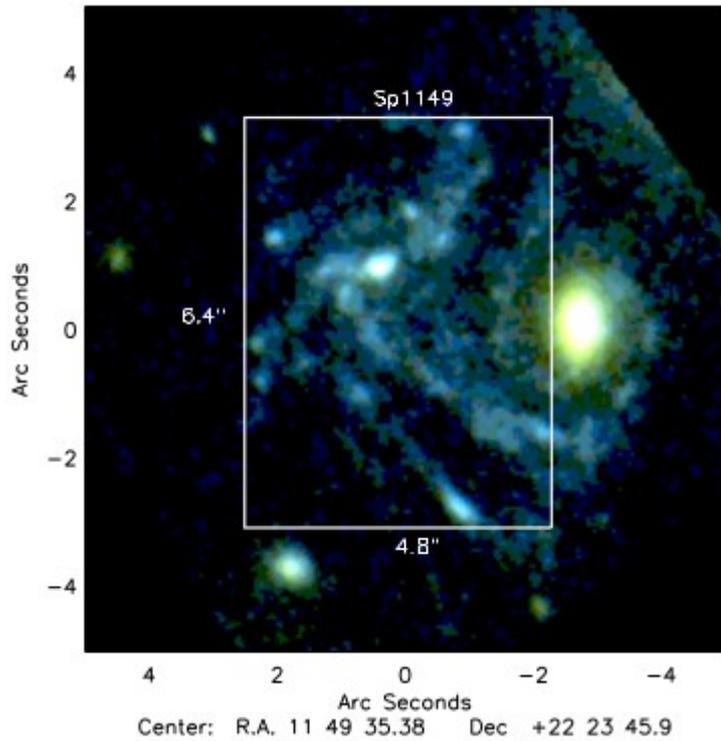
Abundance gradients in the local universe



A typical metallicity (at a relative radius) varies with type, magnitude, rotational velocity or mass.

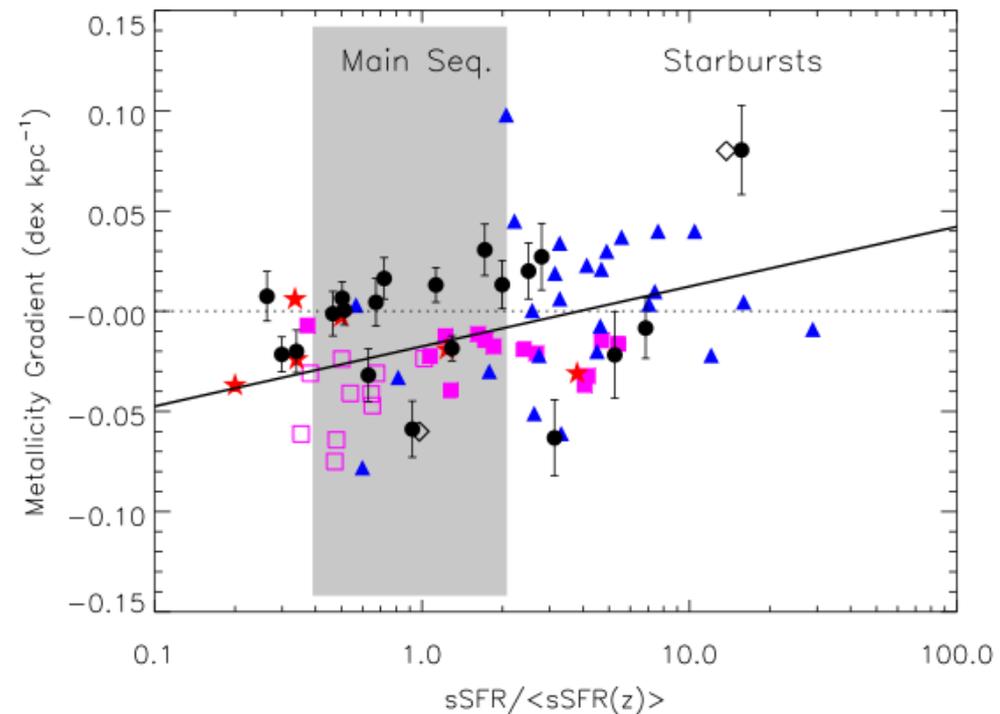
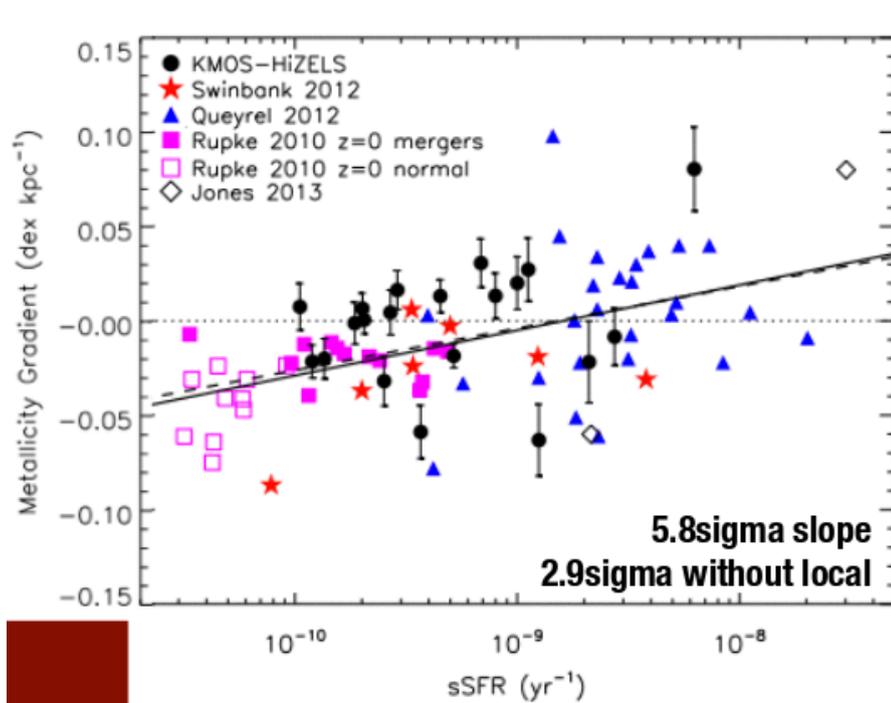
Gradients tend to have similar values when expressed in dex/scalelength !

Abundance gradients in distant galaxies



Abundance gradients in distant galaxies

Stott et al. 2014 from K-mos 3D survey:



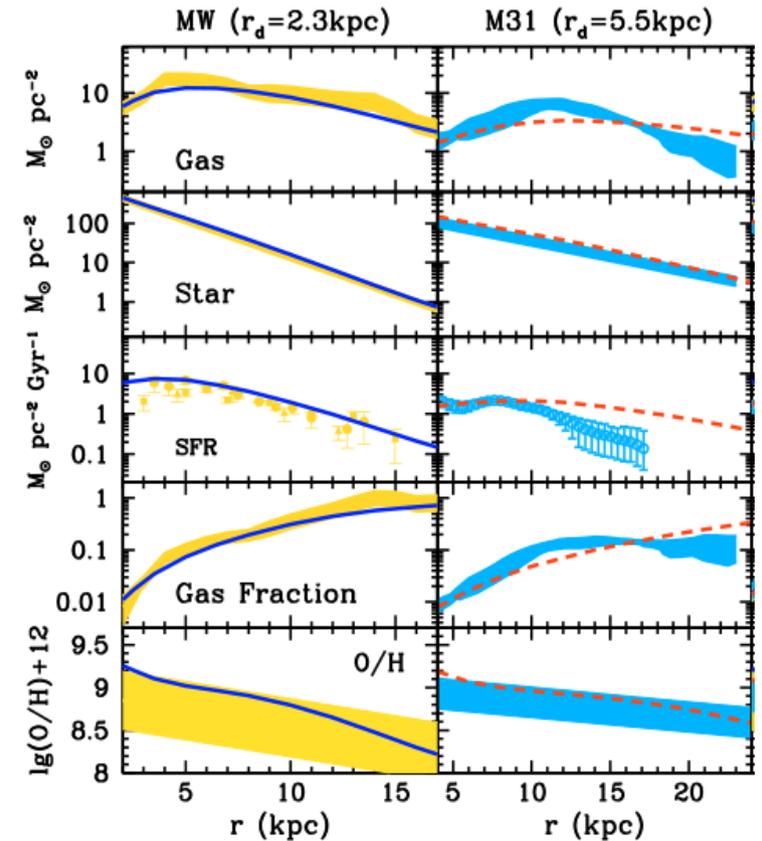
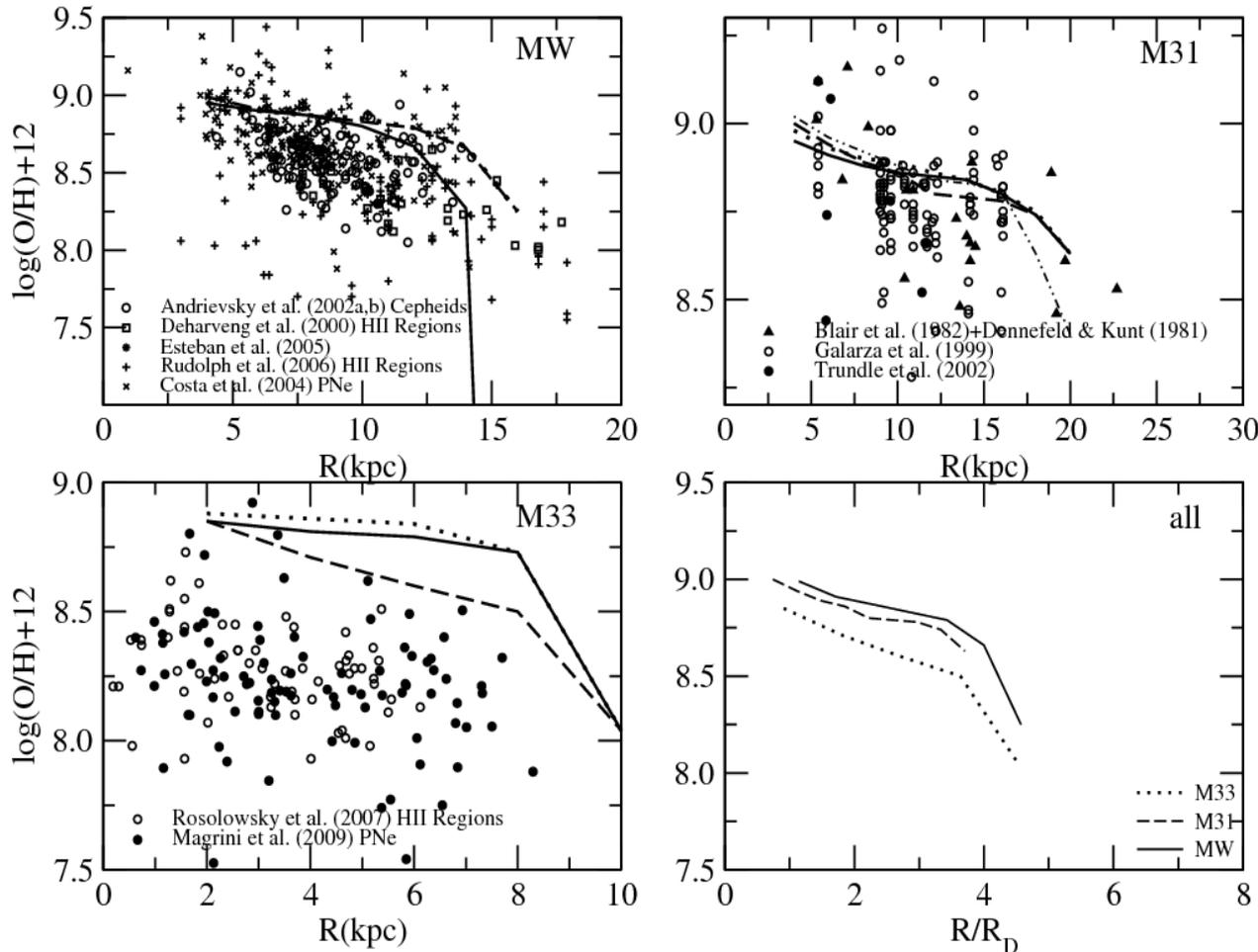
→ Flat gradients in a sample of high redshift galaxies ?

But only from one metallicity indicator,
beam smearing corrections

Chemical Evolution in MW, M31, M33

Constraints on the disks evolution : profiles
(abundances, stellar mass, gas mass, SFR ...)

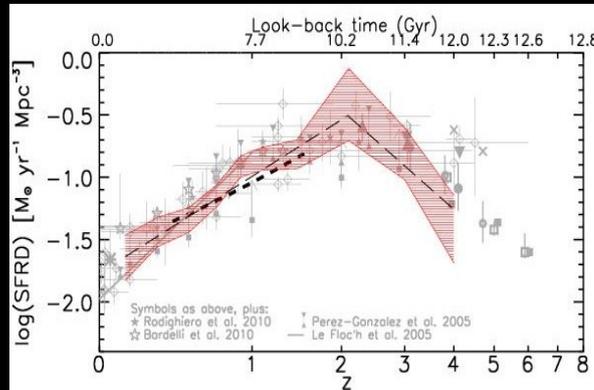
Marcon-Uchida, Matteucci & Costa 2010



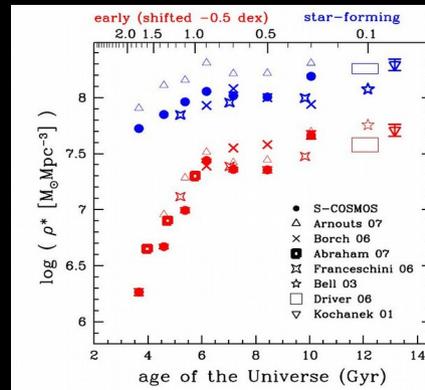
Yin et al. (2013)



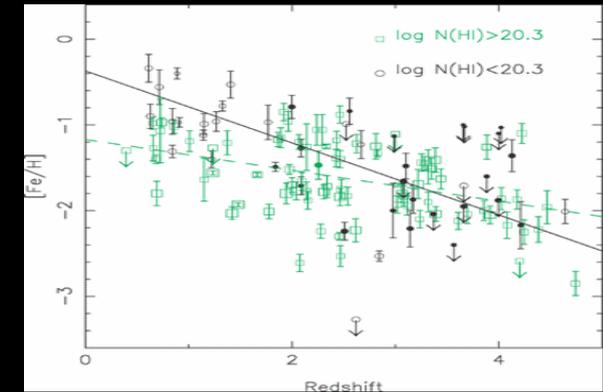
“Cosmic” chemical evolution: evolution with redshift (or with the age of the universe) of densities averaged over large volumes in the universe



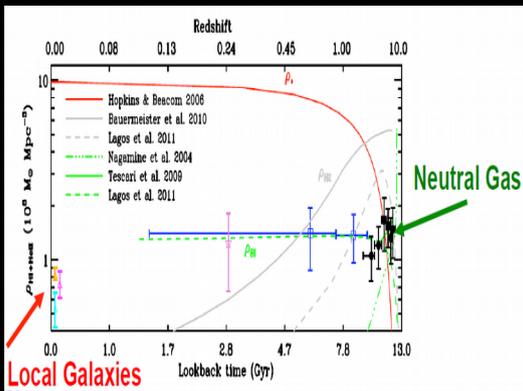
STAR FORMATION
(Cucciati et al., 2012;
Burgarella et al. 2013)



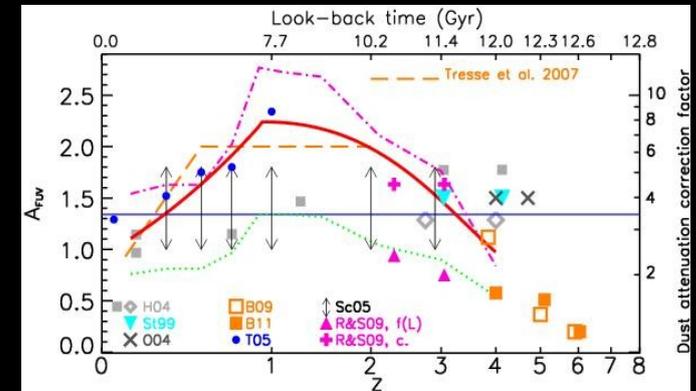
STELLAR MASS
(Ilbert et al., 2010)



ABUNDANCES
(Péroux et al., 2012)



GAS (Zafar et al., 2012)



DUST (Cucciati et al., 2012;
Heinis et al., 2015)

GALACTIC CHEMICAL EVOLUTION

- a) Transformation of the universe and chemical evolution
- b) How to use chemical evolution traces to learn about galaxy evolution
- c) **Measuring Abundances**



An abundance of notations

- **X = mass fraction**

- X_i for element i
- X for Hydrogen
- Y for Helium
- Z for all “metals”
- $X+Y+Z=1$

(Solar -Asplund et al. 2009)

- $X=0.7154,$
 $Y=0.2703,$
 $Z=0.0142$ ~~0.02~~

- **N = Number**

- N_i for element i

Usually wrt a reference:

e.g. N_o/N_H in $12+\log(O/H)$

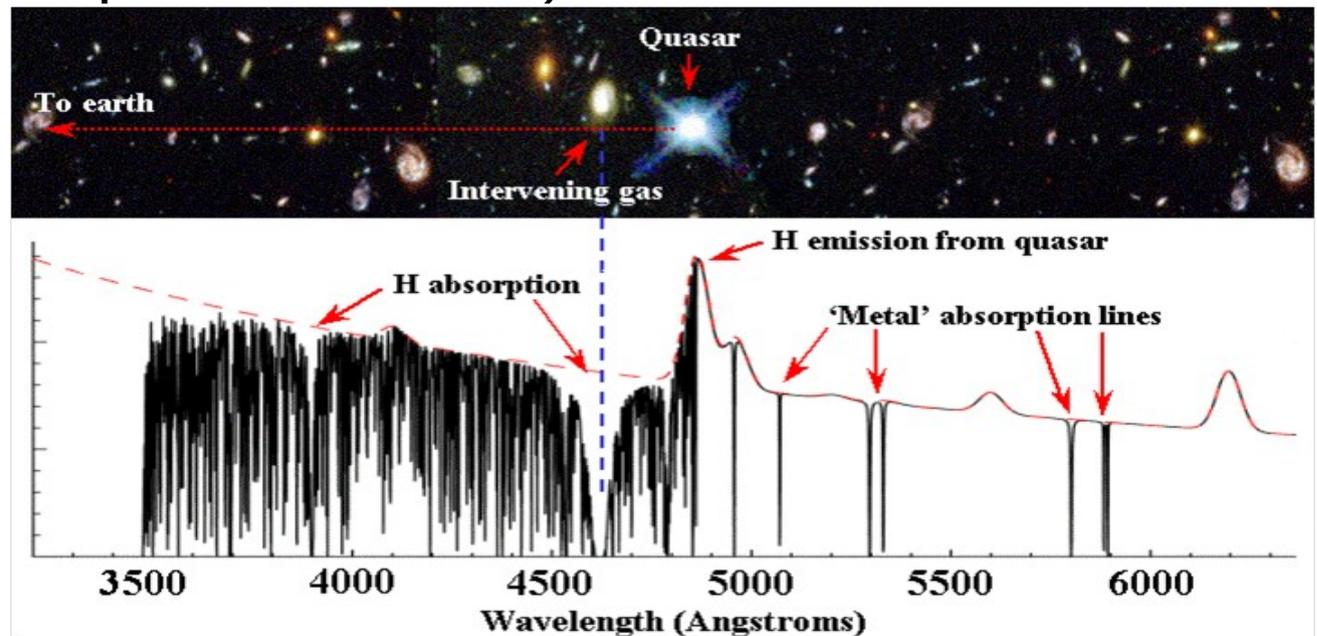
- **“Relative to solar”:**

- Z / Z_{sun}
- $[X_i/X_j]=\log(X_i/X_j)-\log(X_i/X_j)_{sun}$
- e.g. In the stars of the Milky Way,
 $[O/Fe]$ is found between 0 and 1
 $[Fe/H]$ between -5 and 0



Measuring abundances

- Abundances in Stars (in the MW & very nearby galaxies)
- Average metallicity in a stellar population of a galaxy:
stellar population synthesis techniques
- **Abundances in the gas.**
 - In emission
 - In absorption: powerful technique to probe the high z universe (Lyman Alpha forest, DLA)



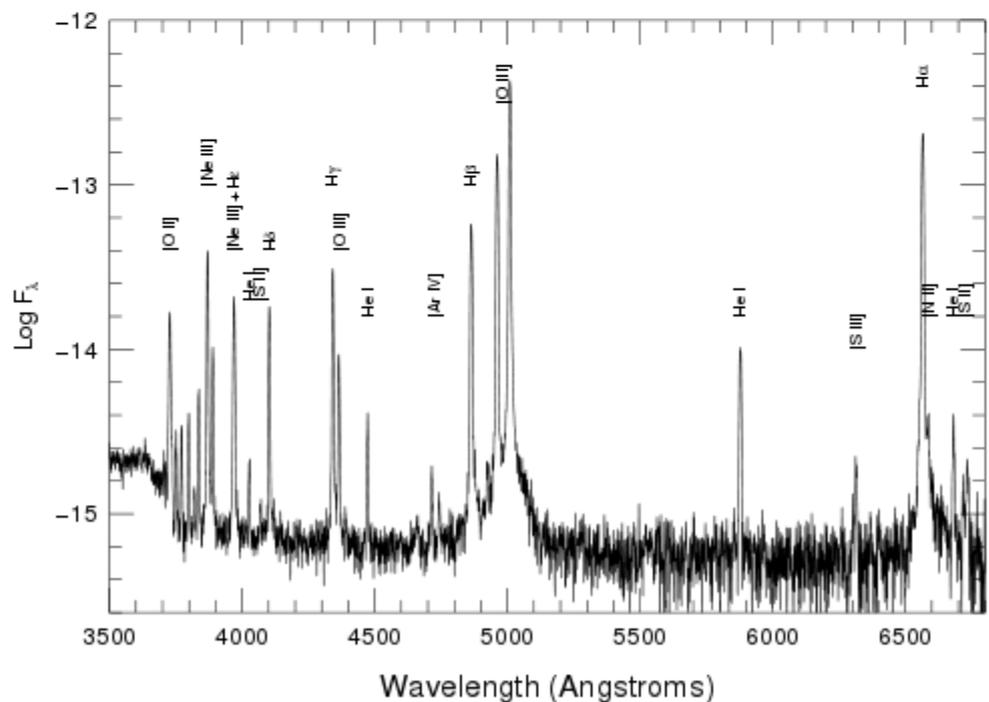
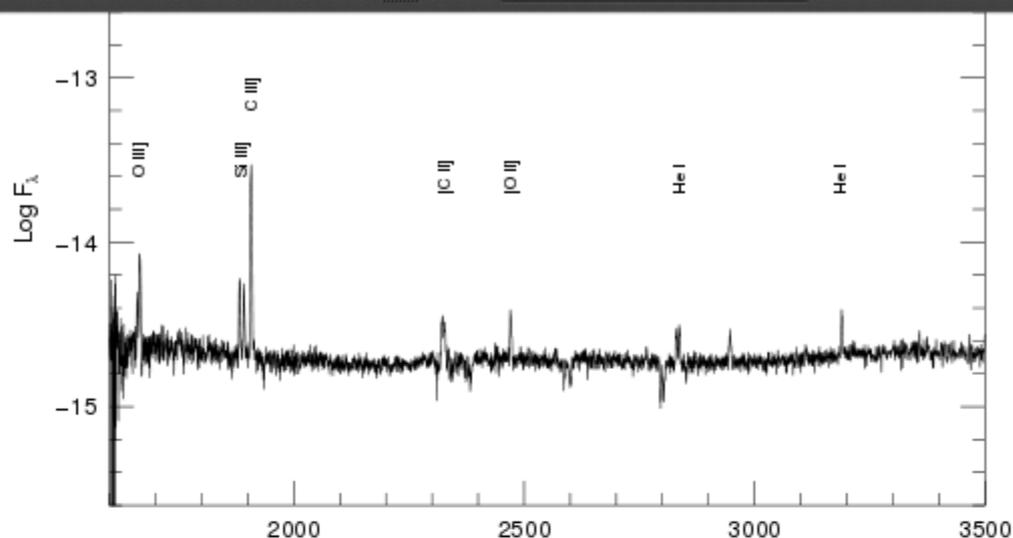
Measuring abundances

Emission lines (from individual HII regions, or global spectra of galaxies)

$$\frac{N(X^{+i})}{N(H^+)} = \frac{I(\lambda)}{I(H\beta)} \frac{\epsilon(H\beta)}{\epsilon(\lambda)}$$

Atomic Properties

Te



Garnett 2002

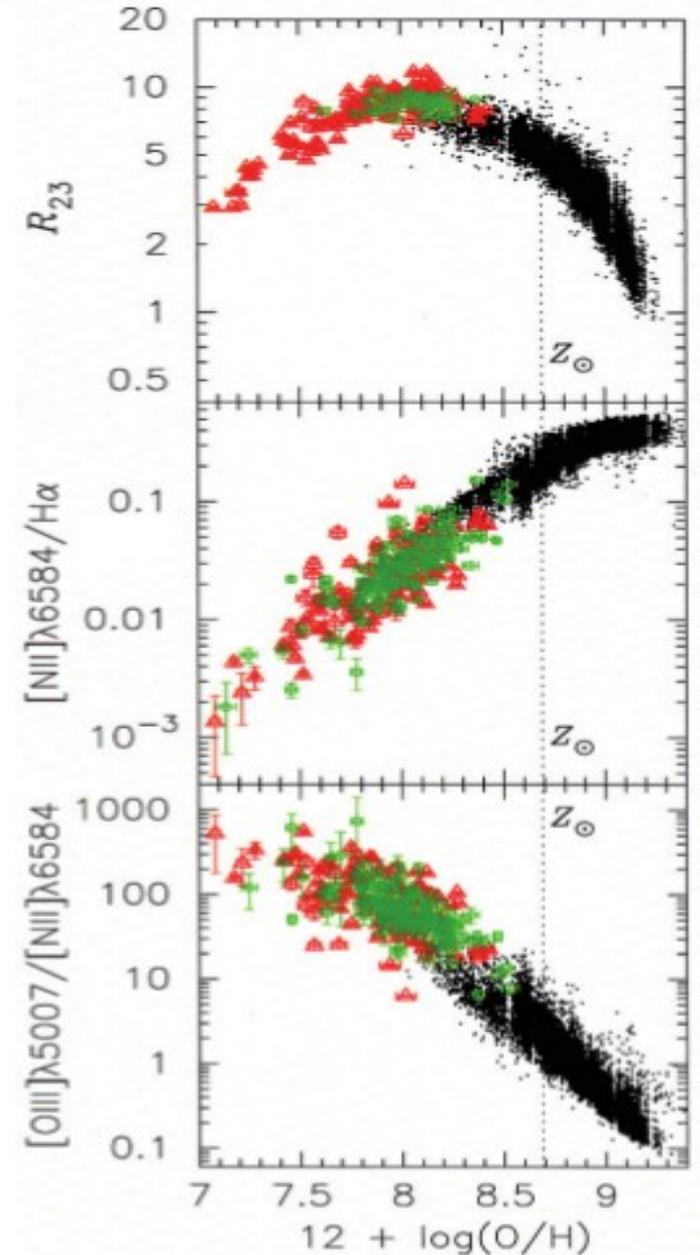


Measuring abundances

In the absence of Te-sensitive lines: use of
“strong lines” empirical indicators

$$R_{23} = \frac{I([\text{O II}]\lambda 3727) + I([\text{O III}]\lambda\lambda 4959, 5007)}{H\beta}$$

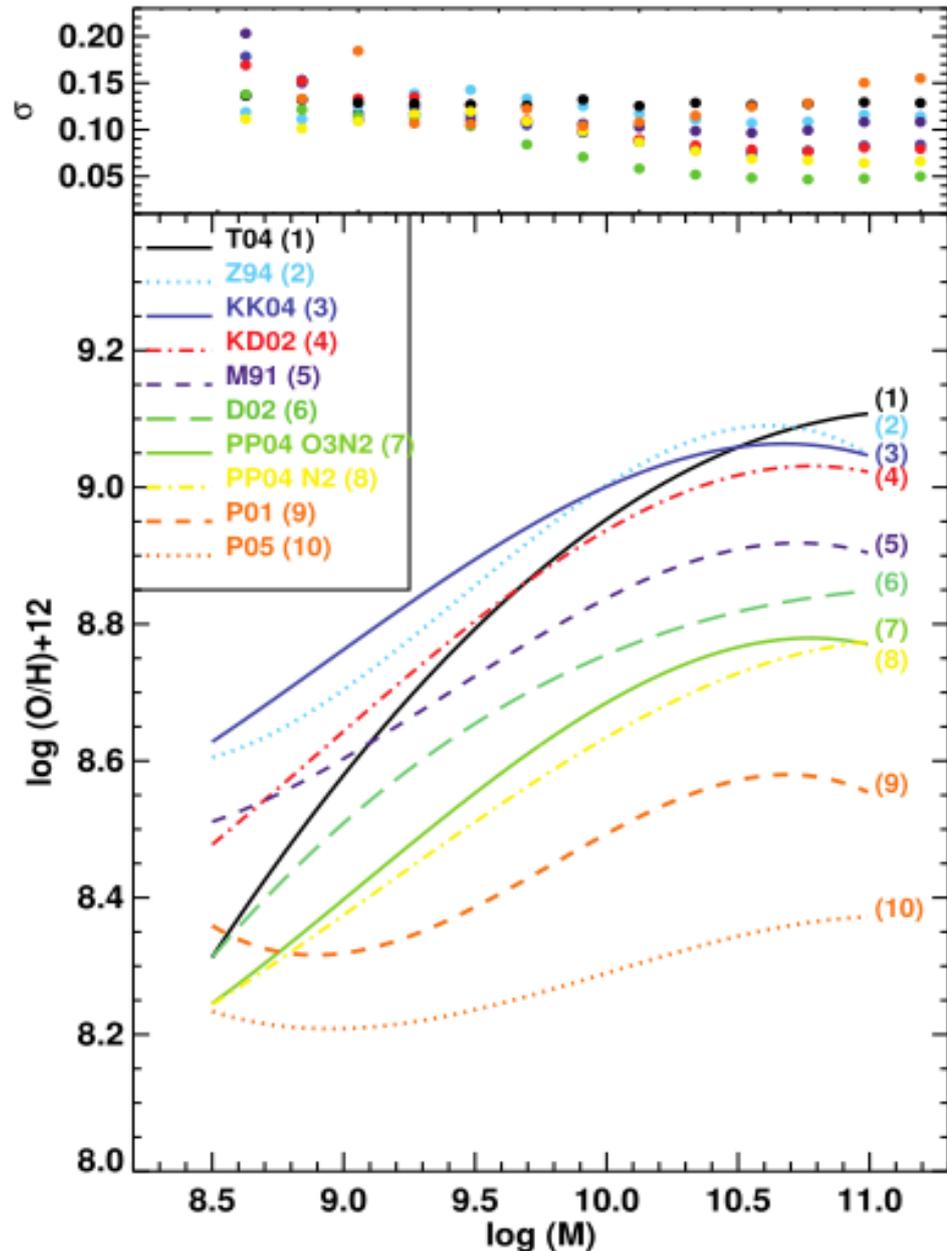
Double-branch : other
diagnostics



Gas metallicity measurements

(Kewley Elysson 2008)

ID	Emission Lines	Calibration Class
T04 ^a	[O II], H β , [O III], H α , [N II], [S II]	Theoretical
Z94	R_{23}	Theoretical
KK04	R_{23} , [O III]/[O II]	Theoretical
KD02	[N II]/[O II], R_{23} , [O III]/[O II]	Theoretical
M91	R_{23} , [O III]/[O II]	Theoretical
D02	[N II]/H α	Combined
PP04	[N II]/H α , [O III]/H β	Empirical
PP04	[N II]/H α	Empirical
P01, P05	R_{23} , [O III]/[O II]	Empirical
T_e	[O III] $\lambda\lambda 4363$, [O III] $\lambda\lambda 4959, 5007$	Direct



GALACTIC CHEMICAL EVOLUTION

- a) Transformation of the universe and chemical evolution
- b) How to use chemical evolution traces to learn about galaxy evolution
- c) Measuring Abundances
- d) Formalism of Galactic Chemical Evolution



A FEW REFERENCES

- Pagel : nucleosynthesis & chemical evolution of galaxies
- Matteucci : chemical evolution of galaxies
- Tinsley 1980, fundamentals of cosmic physics
- An introduction by Nikos Prantzos: Prantzos (2007)
<http://fr.arxiv.org/abs/0709.0833>

How many stars form with mass M at time t ?

$$dN(M,t) = \text{form}(M,t) dM dt$$

$\psi(t)$

Star Formation Rate
($M_{\text{sol}} \text{ yr}^{-1}$)

$\phi(M)$

Initial Mass Function
Description

$$\int_{M_l}^{M_u} M \phi(M) dM = 1$$

m : total mass

m_g : gas mass

m^* : stellar mass

f : gas infall rate

o : gas outflow rate

E : mass ejected from stars

X_i : fraction of mass in form of element "i" in the gas

E_i : mass ejected in form of element "i"

Y_i : yield of a star of mass M for the element "i"

*WARNING : many Definition of "yields" :
net yield, true yield, effective yield*

τ_M : lifetime of a star of mass M

C : mass of compact remnant of a star



GCE

$$\frac{dm}{dt} = [\cancel{f} - o]$$

infall outflow

Closed Box :

$$f=0$$

$$o=0$$



GCE

$$\frac{dm_G}{dt} = -\Psi + E + [f - o]$$

$$E(t) = \int_{M_t}^{M_U} (M - C_M) \Psi(t - \tau_M) \Phi(M) dM$$



GCE

$$\frac{d(m_G X_i)}{dt} = -\Psi X_i + E_i + [fX_{i,f} - oX_{i,o}]$$

$$E_i(t) = \int_{M_t}^{M_U} Y_i(M) \Psi(t - \tau_M) \Phi(M) dM$$

$$Y_i(M) = y_i(M) + (M - C_M) X_i(t - \tau_M).$$

“Primary” yield depend only of M but “secondary” yields can depend on Xi



GCE

Instantaneous Recycling Approximation (IRA)

(good for O, for large gas fraction >50 %, still ok down to >~ 20%)

- Massive stars explodes « instantaneously » $\tau_M = 0$
- Others are “everlasting”

$$E(t) = \int_{M_t}^{M_U} (M - C_M) \Psi(t - \tau_M) \Phi(M) dM$$

Returned Fraction $R \sim 0.3-0.4$

$$E(t) = \psi(t)R$$

$$R = \int_{M_T}^{M_U} (M - C_M) \Phi(M) dM$$

$$E_{\dot{i}}(t) = R \psi(t) X_{\dot{i}}(t) + (1 - R) p_{\dot{i}} \psi(t)$$

$$p_{\dot{i}} = \frac{1}{1 - R} \int_{m_t}^{m_s} y_{\dot{i}}(m) \phi(m) dm.$$

GCE

In closed box :

$$X_i(t) - X_i(0) = -p_i \ln(\sigma_g(t))$$

$\sigma_g = M_g/M$ (fraction de gaz)

This relation links the gas fraction and the abundance ,
independently of the details of the history of star
formation !

GCE

One more assumption
(schmidt like law)

$$\psi(t) = \epsilon M_G(t)$$

$$\sigma_g(t) = \exp(-\epsilon (1 - R) t)$$

$$X_i(t) = X_i(0) + p_i \epsilon (1 - R) t$$

GCE

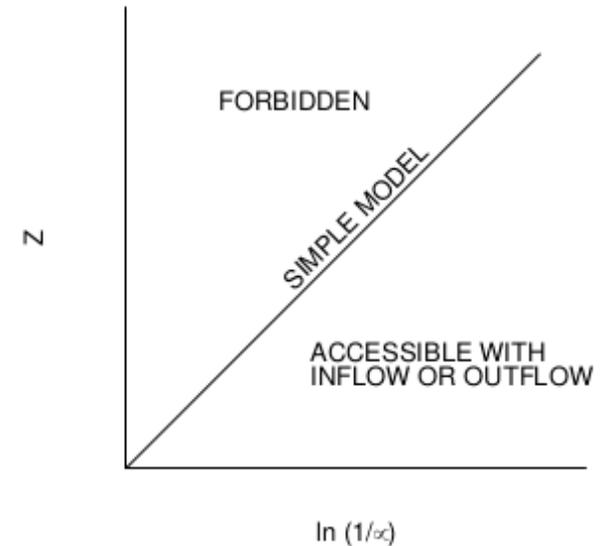
With IRA, it is possible to obtain similar relations under various assumptions :

- **infall** ($f=-\text{SFR}$)
- **outflows** ($o=\alpha \text{ SFR}$)

$$\sigma_g(t) = \frac{1}{1 + \epsilon (1 - R) t}$$

$$Z(t) = [Z(0) - (p_X + Z_f)] \exp(-\epsilon (1 - R) t) + (p_X + Z_f)$$

$$Z(t) = [Z(0) - (p_X + Z_f)] \exp\left(1 - \frac{1}{\sigma}\right) + (p_X + Z_f)$$



GARNETT 2002
Edmunds et al.
1990

$$\sigma_g(t) = \frac{R - 1 - \alpha}{(R - 1) \exp(-\epsilon (R - 1 - \alpha) t) - \alpha}$$

$$Z(t) = Z(0) + p_X \epsilon (1 - R) t$$

$$Z(t) = Z(0) + p_X \frac{1 - R}{1 - R + \alpha} \ln \left[\left(\frac{1}{\sigma} + \frac{\alpha}{R - 1 - \alpha} \right) \left(\frac{1 - R + \alpha}{1 - R} \right) \right]$$

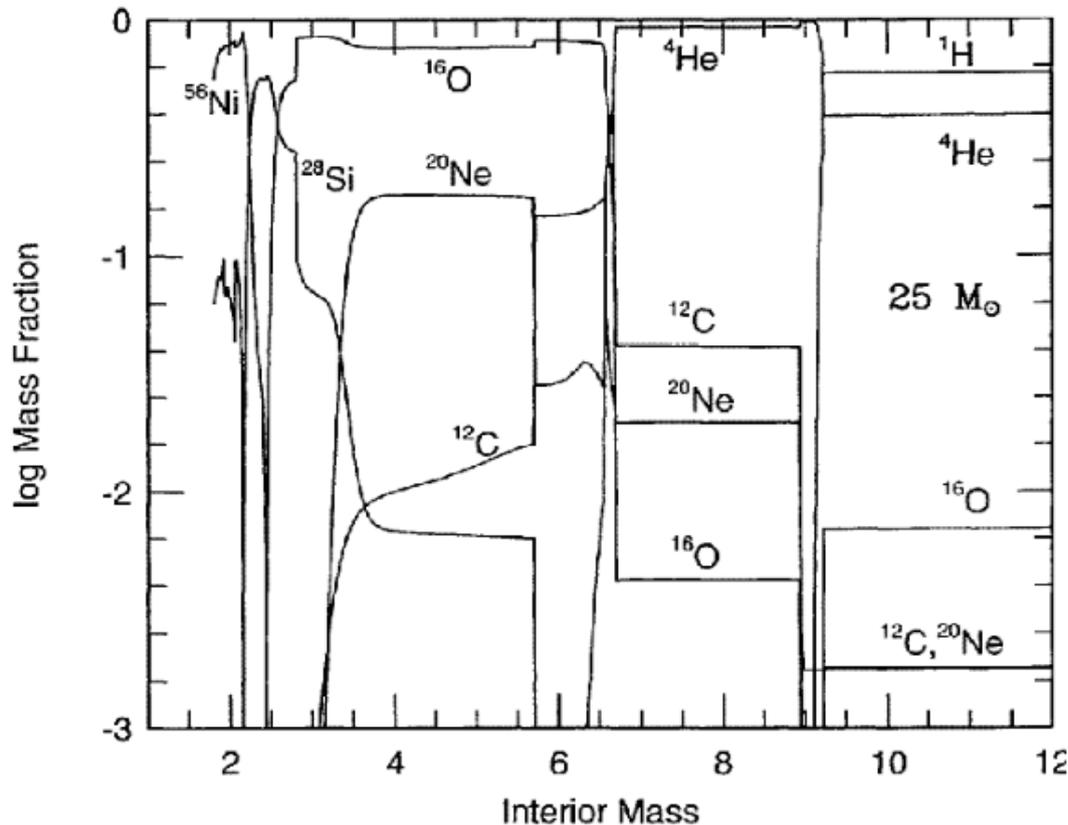


GALACTIC CHEMICAL EVOLUTION

- a) Transformation of the universe and chemical evolution
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- Yields from massive stars



Yields quite uncertain
(factor 2 for O)

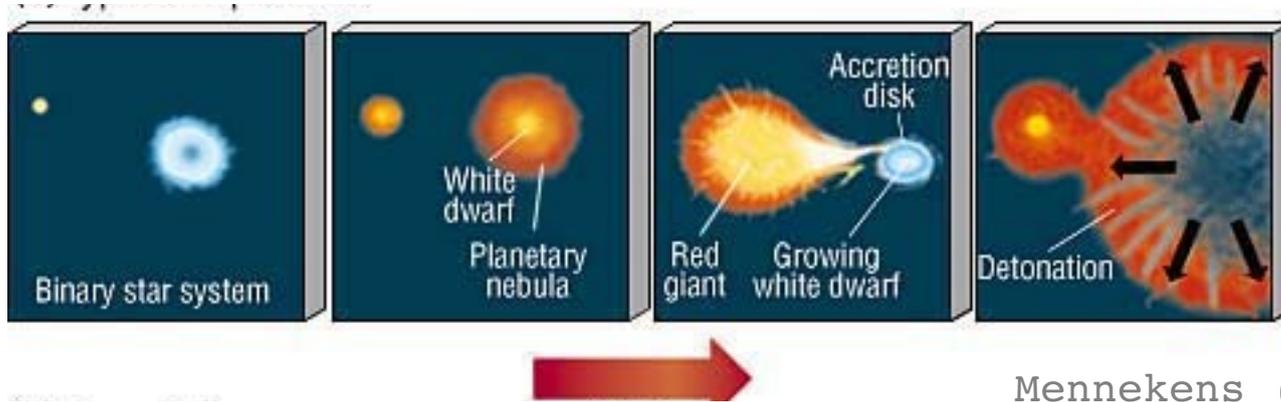
Fig. 3. Interior composition of a $25 M_{\odot}$ star after its explosion; only major isotopes are displayed (from Woosley and Weaver 1995).

- Yields from intermediate-mass stars

Even more uncertain

Contributions to H,C,N,O isotopes, s-process elements

- Yields from SN Ia



Mennekens (IAP Progenitor meeting)

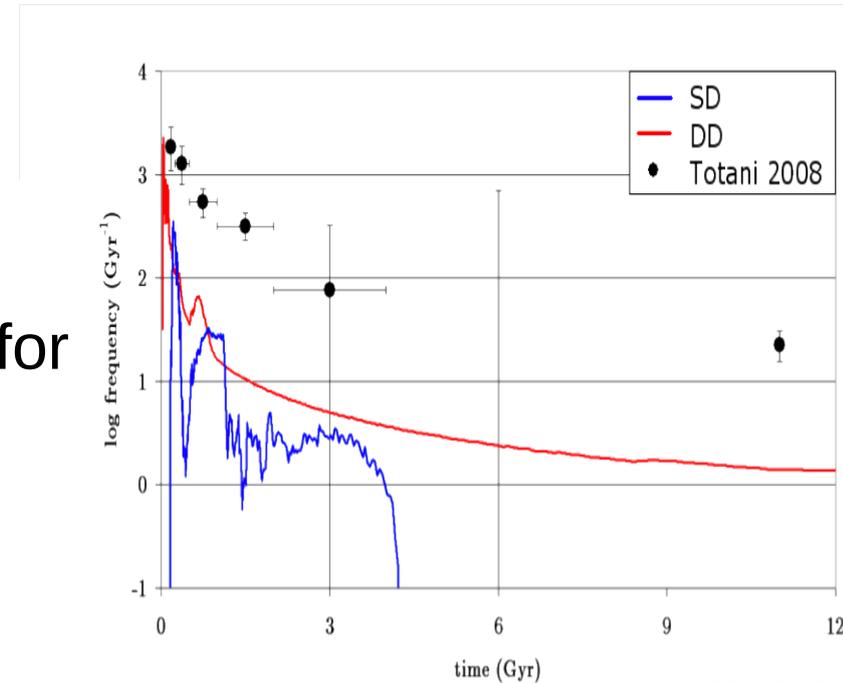
Dominates Fe production, with a delay with respect to star formation !

Prescription for inclusion in models

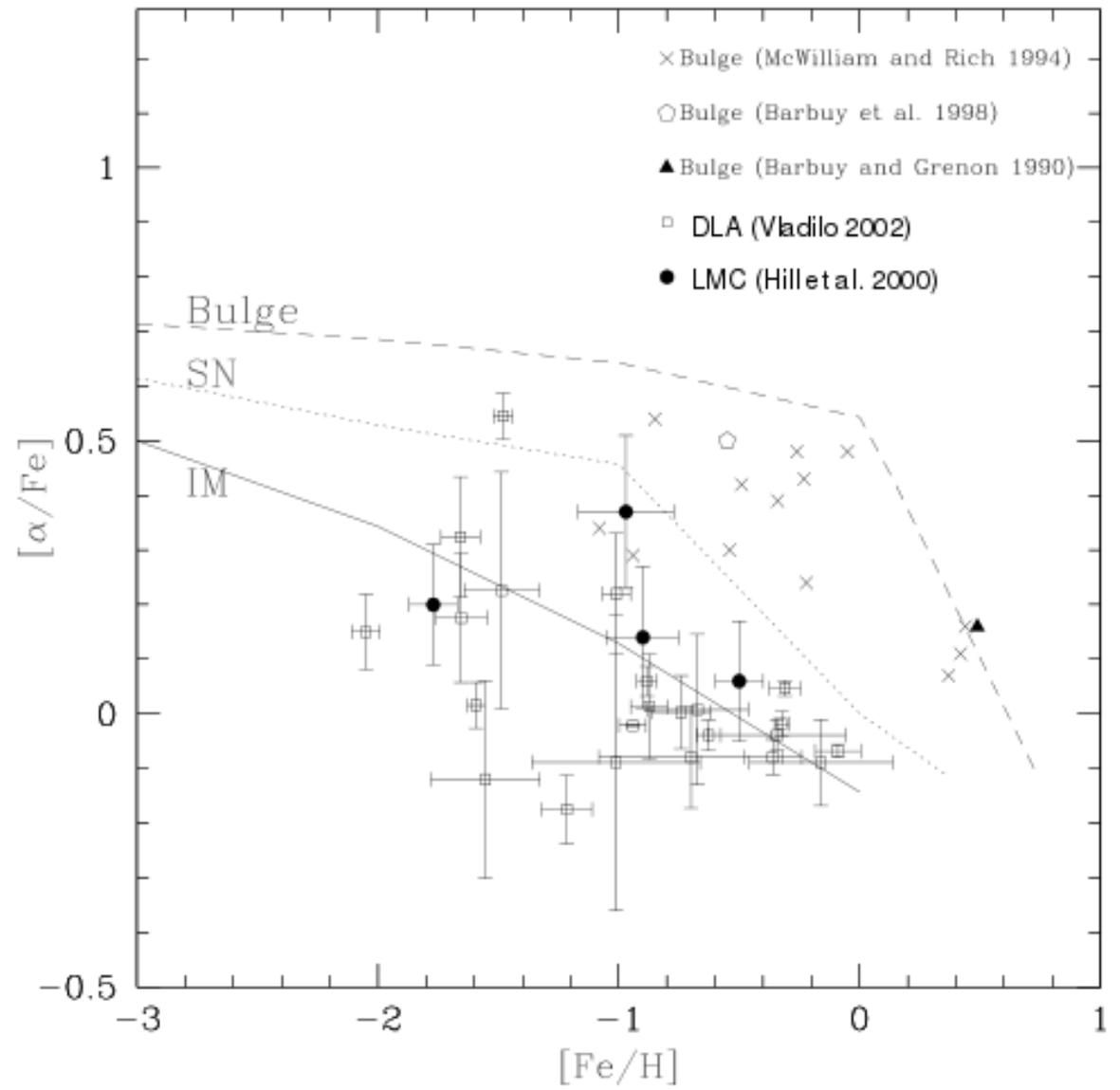
- Greggio & Renzini 1983:
Based on binary system, evolution time for The primary star...

- Sannapieco & Bildsten 2005

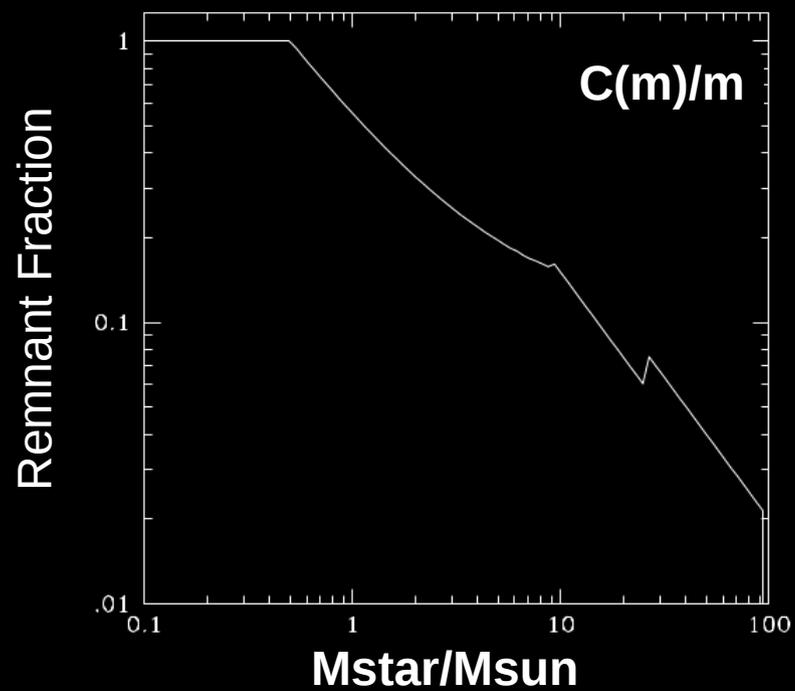
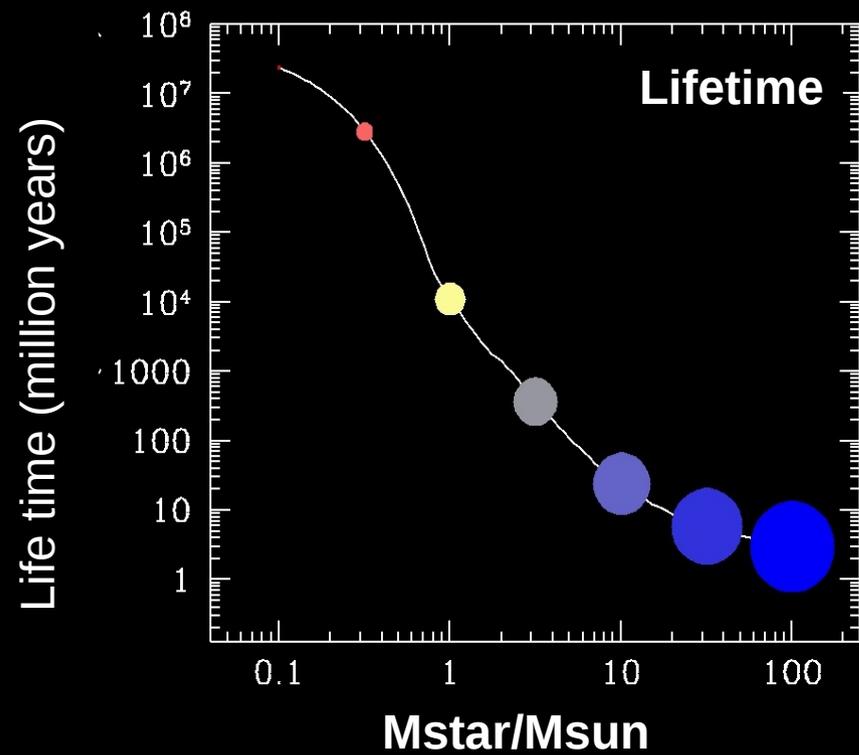
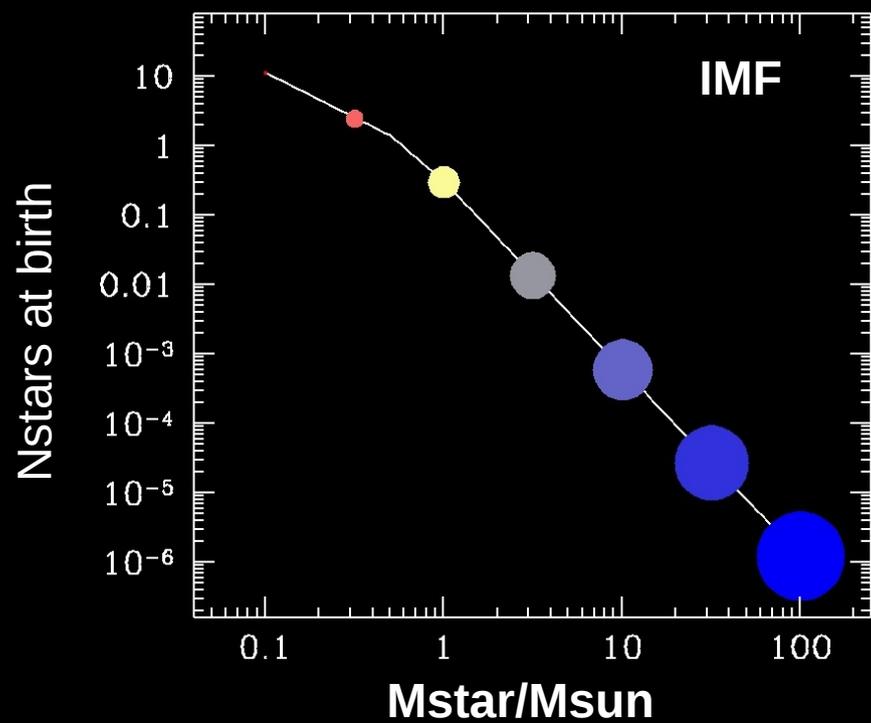
$$\frac{\text{SNR}_{\text{Ia}}(t)}{(100 \text{ yr})^{-1}} = A \left[\frac{M_{\star}(t)}{10^{10} M_{\odot}} \right] + B \left[\frac{\dot{M}_{\star}(t)}{10^{10} M_{\odot} \text{ Gyr}^{-1}} \right], \quad (1)$$



This delay in combination with different star formation histories can explain trends in e.g. O/Fe vs Fe/H

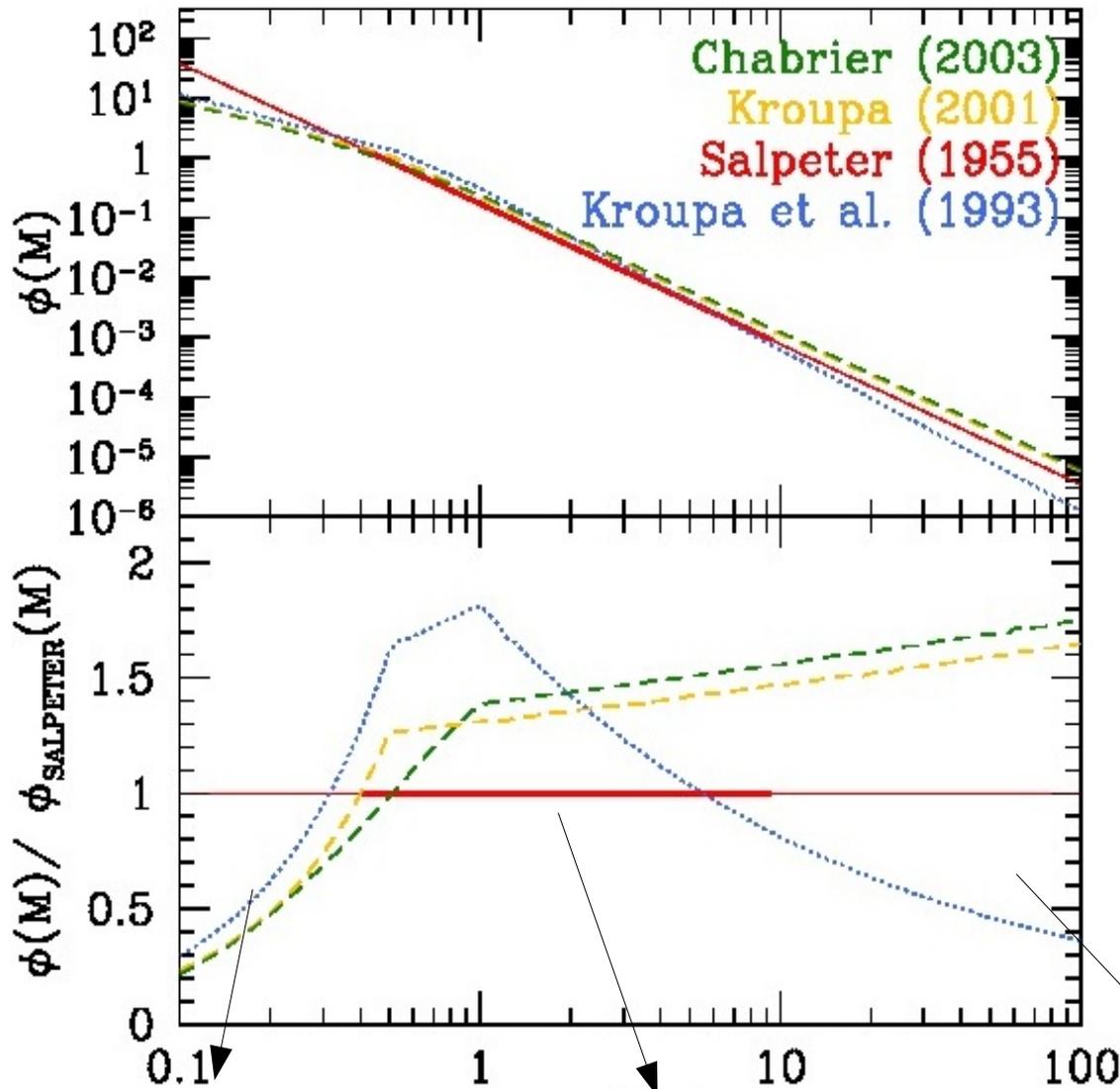


IMF, Lifetimes, Remnant mass



$$\Phi(M) = \frac{dN}{dM} = A M^{-(1+X)}$$

Slope of the Salpeter IMF: $X = 1.35$



Low Mass Stars
fraction of mass locked
and the NIR output

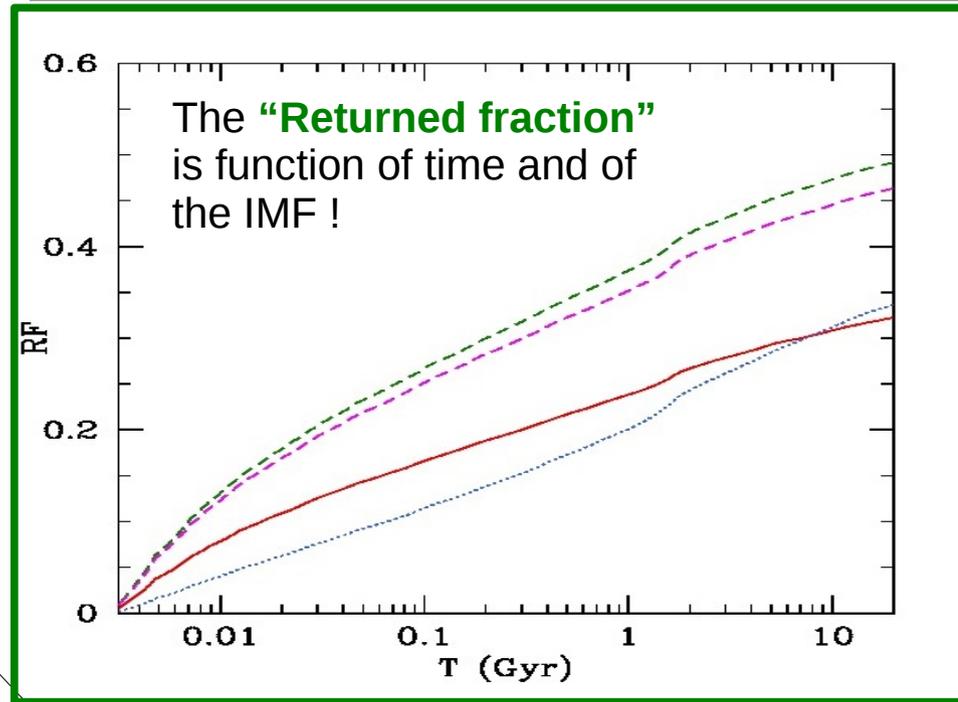
Intermediate Mass Stars:
during some phases,
important light providers

Massive stars:
light output in SFR
tracers, metal output

Conversions SFR
(see lecture by V. Buat)

Boissier 2013

ψ (Kroupa 2001)	x 1.5	=	ψ (Salpeter)
ψ (Kroupa 2001)	x 1.59	=	ψ (truncated Salpeter)
ψ (Chabrier 2003)	x 1.5	=	ψ (Salpeter)
ψ (Kroupa 2001)	x 1.5	=	ψ (Salpeter)
ψ (Kroupa 2001)	x 0.88	=	ψ (Chabrier 2003)



Is the IMF universal ? Constant in time ?

- The Integrated Galaxial Initial Mass Function of stars

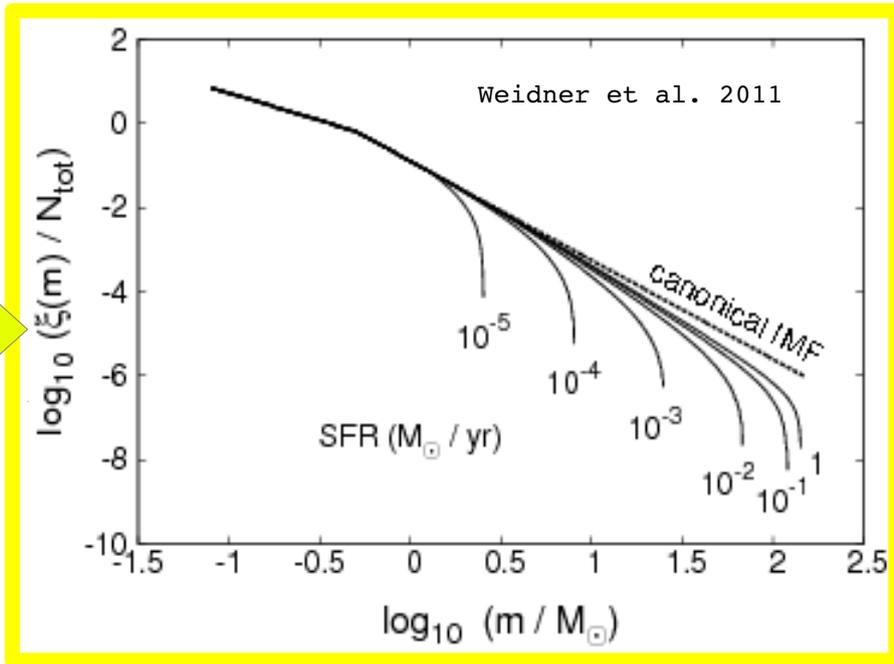
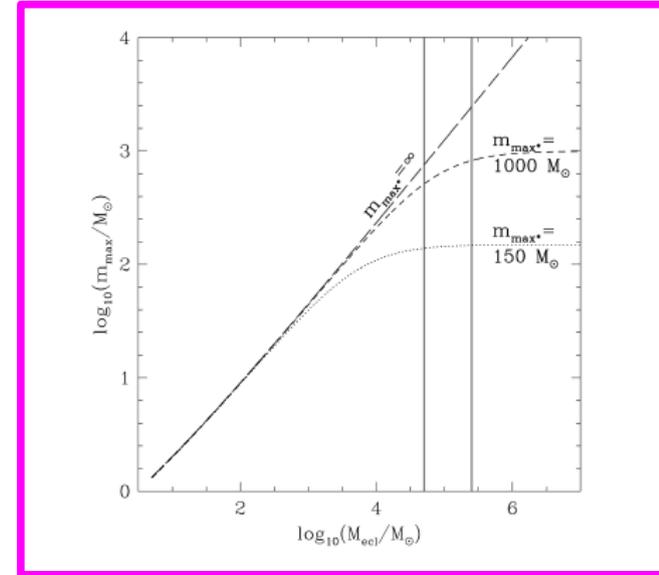
(e.g. Weidner & Kroupa 2005)

Basics : stars form within clusters

$$\xi_{\text{IGIMF}}(m, t) = \int_{M_{\text{ecl}, \text{min}}}^{M_{\text{ecl}, \text{max}}(\text{SFR}(t))} \xi(m \leq m_{\text{max}}) \xi_{\text{ecl}}(M_{\text{ecl}}) dM_{\text{ecl}}.$$

Maximum mass of a cluster: Cluster mass function

$$\log M_{\text{ecl}, \text{max}} = \log k_{\text{ML}} + (0.75 \pm 0.03) \log \text{SFR} + (6.77 \pm 0.02),$$



- Evolution with redshift ?
e.g. Wilkins et al. 2008
But see Ilbert et al. 2013



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- f) The “galactic” ingredients



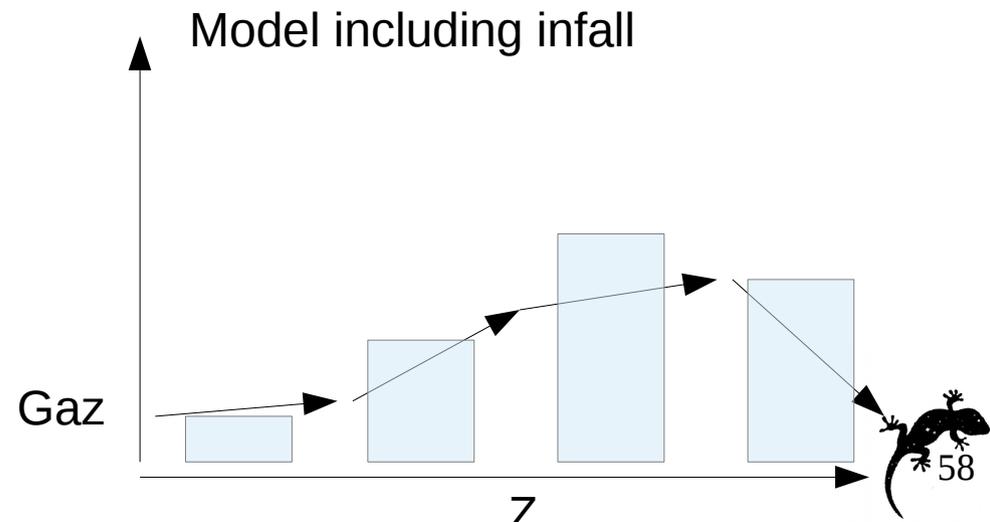
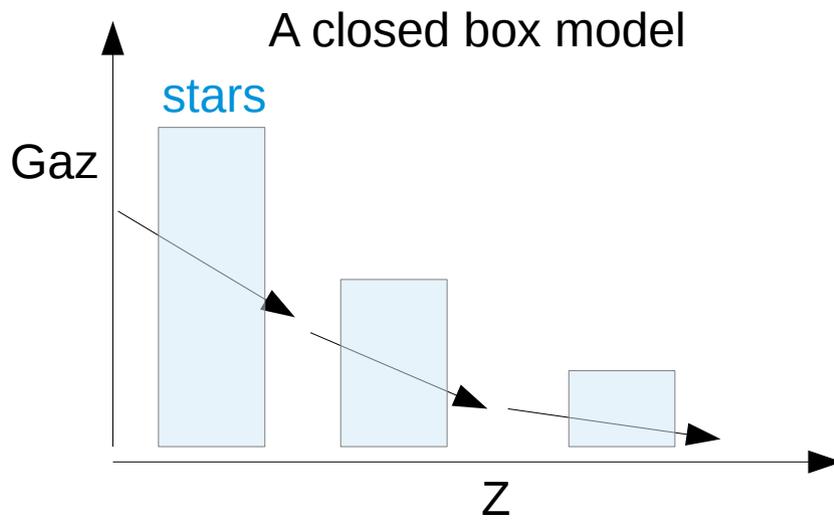
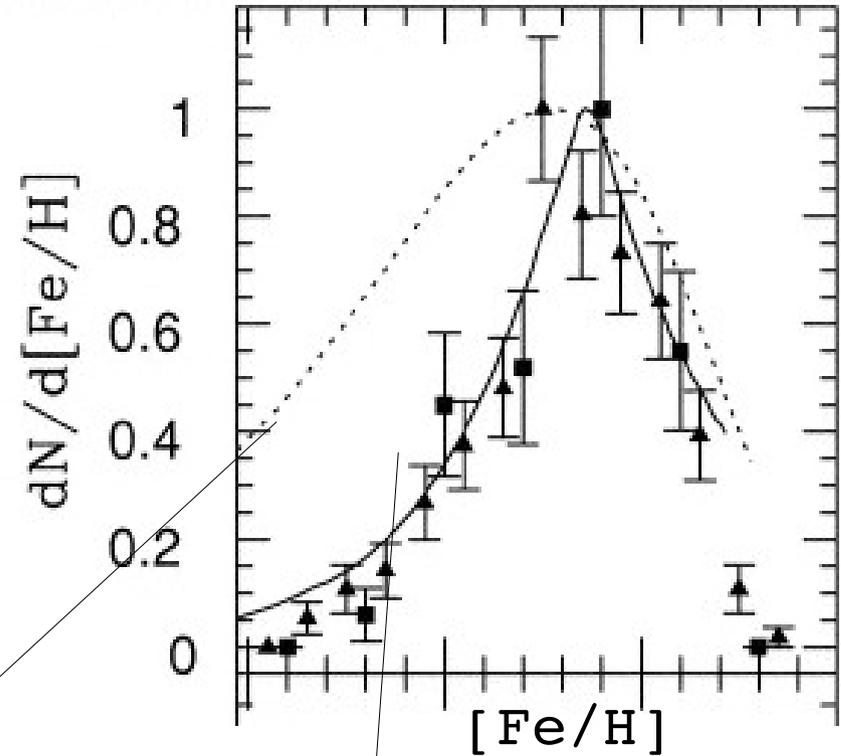
“Galactic” Ingredients

- Infall
 - In the MW: the G-dwarf problems
 - In other galaxies : History of accretion (backward, vs “cosmological”)
- Outflows
 - Winds from massive stars vs potential of the galaxies
- The Star Formation Rate :
 - see next lecture!

Infall in the Milky Way

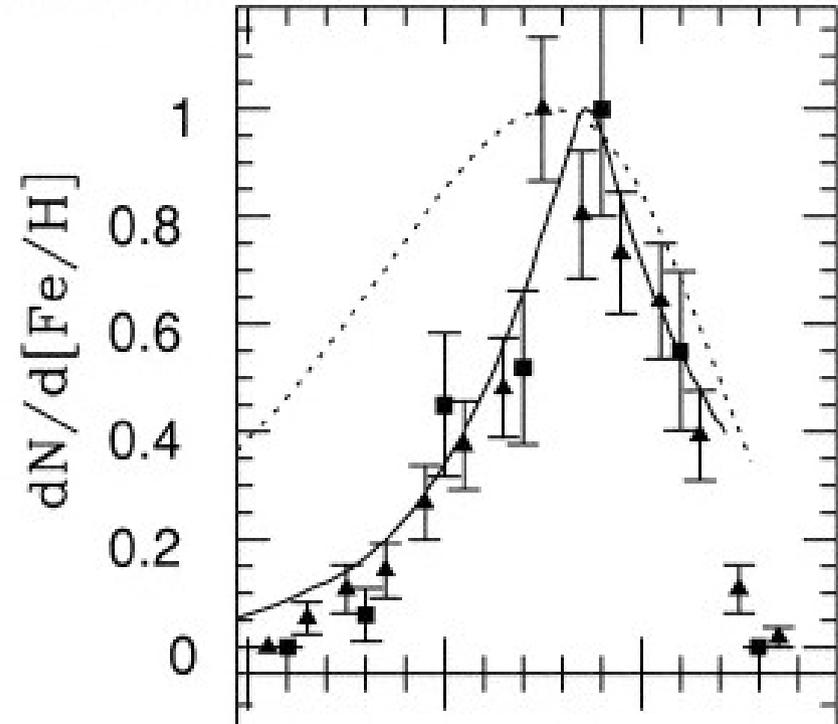
e.g. Prantzos & Silk 1998

“The G-Dwarf problem” in the solar neighborhood.



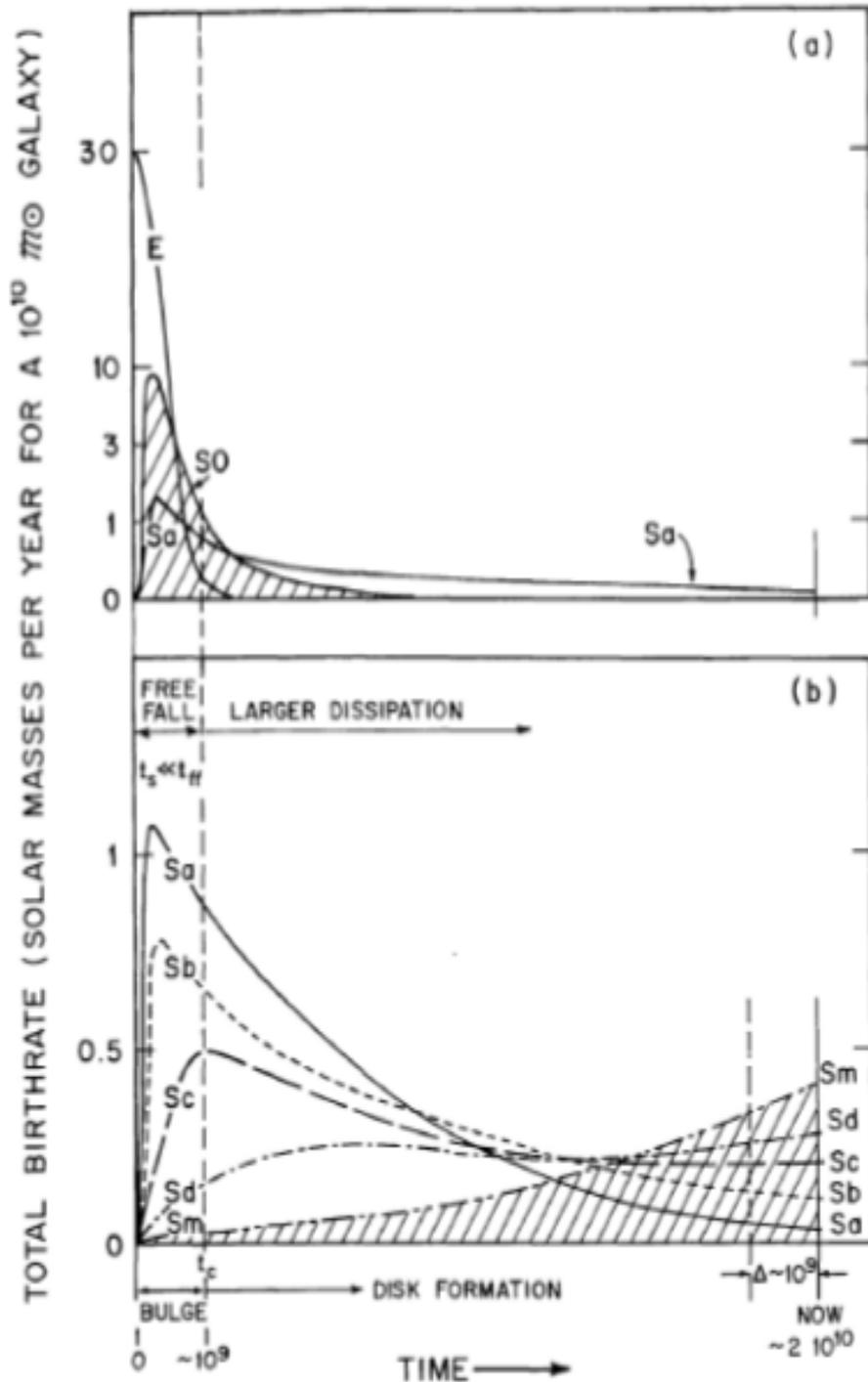
Infall in the Milky Way

“The G-Dwarf problem” in the solar neighborhood.



But see Haywood et al. 2014:
The thick disk is a significant contributor
And stellar migration can change the picture.

Infall in nearby galaxies

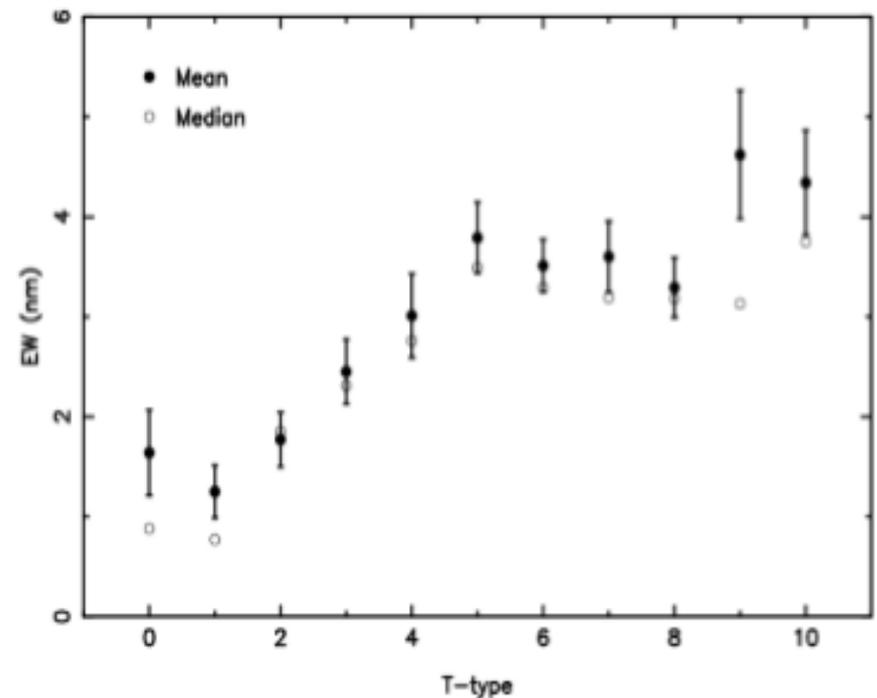


$$b = \text{SFR} / \langle \text{SFR} \rangle$$

$$\text{SSFR} = \text{SFR} / M^*$$

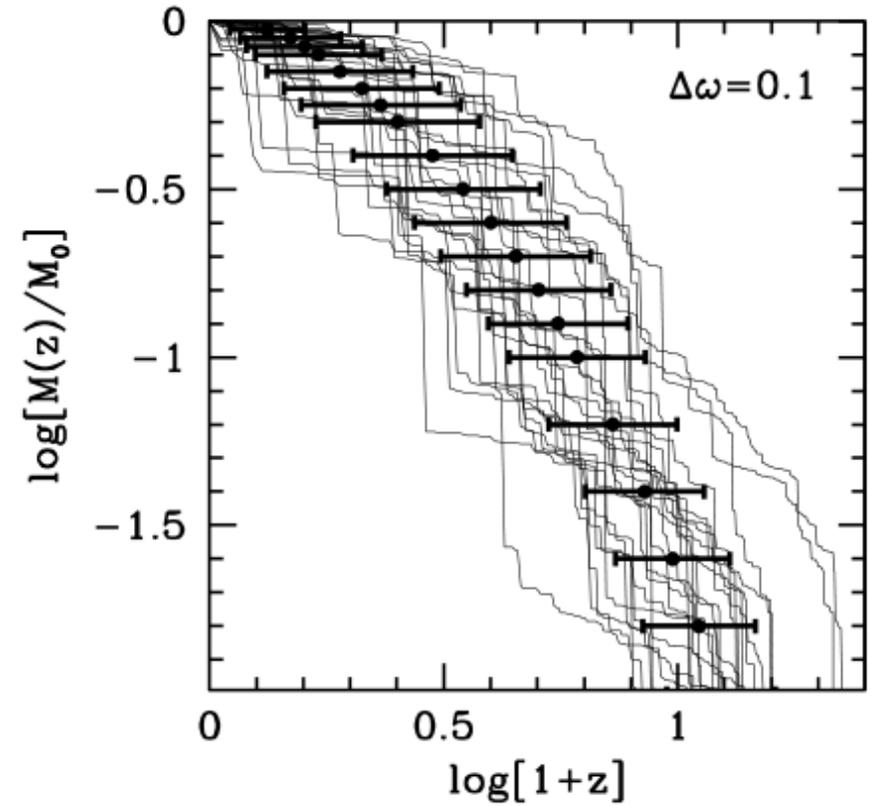
$$\text{IRA: } b = T (1 - R) \text{ SSFR}$$

Indicates long time-scales for SFR history of spirals
 -> long “formation” time



Infall in a cosmological context

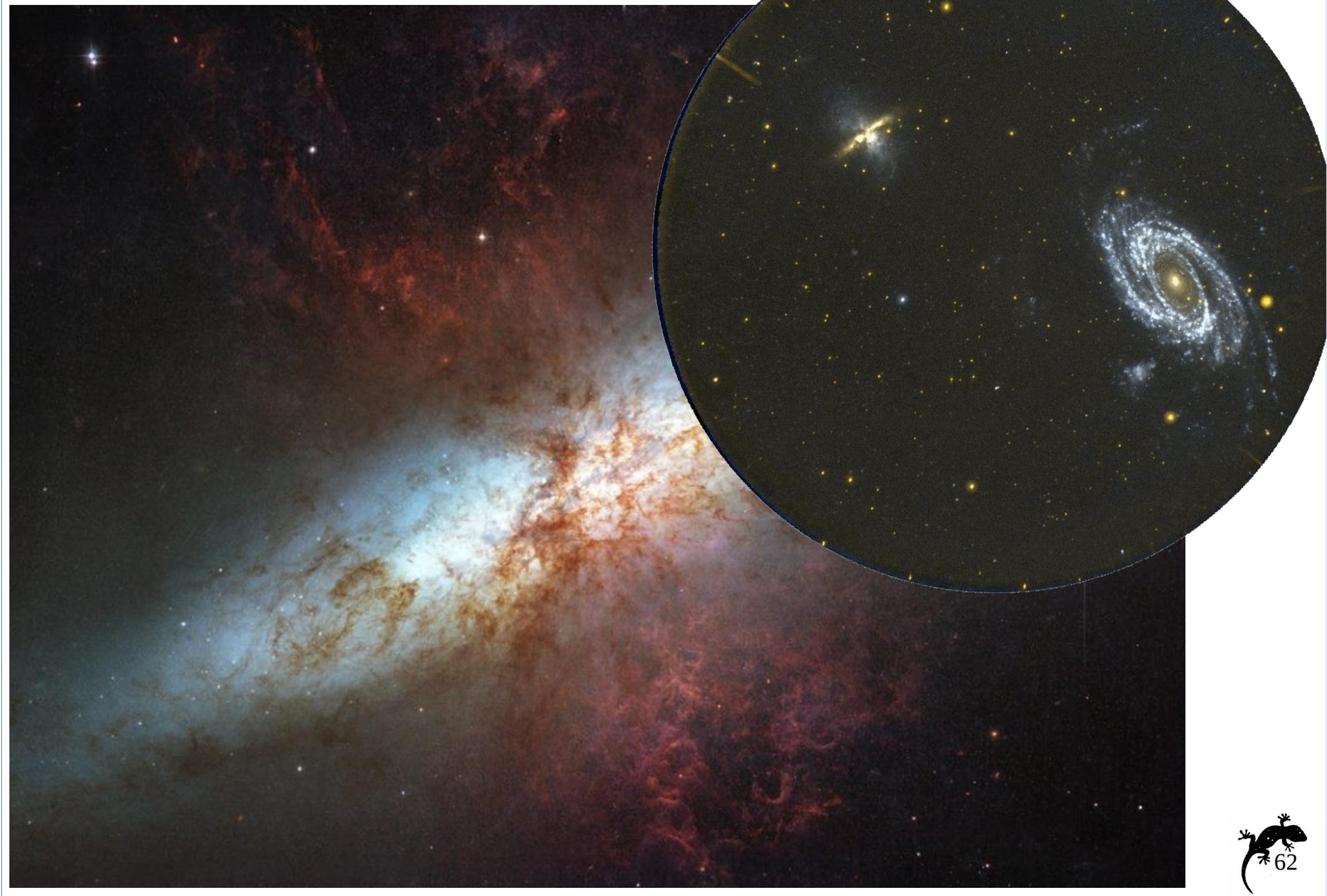
See other lectures !



Van Den Bosch 2001



Outflows in the nearby universe



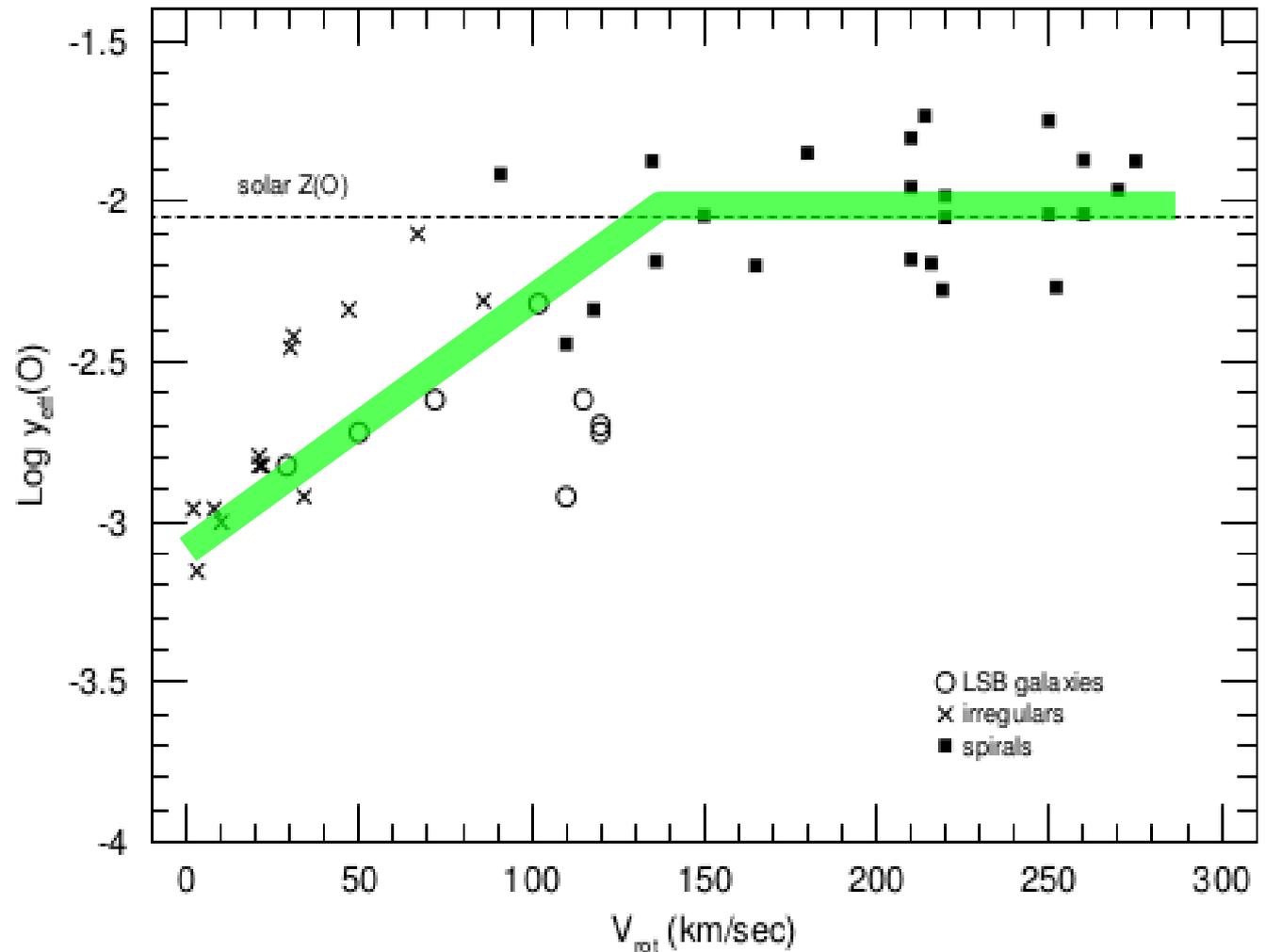
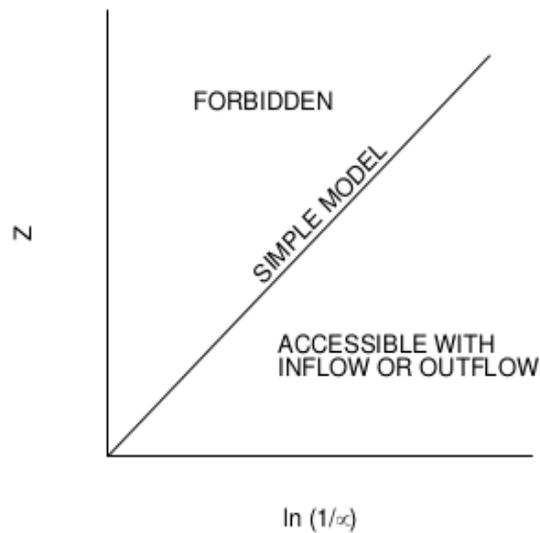
Outflows in the nearby universe

Observations

$$Z_X(t) - Z_X(0) = -p_X \ln(\sigma_a(t))$$

Garnett 2002

Definition of
"effective yield"



Outflows in the distant universe

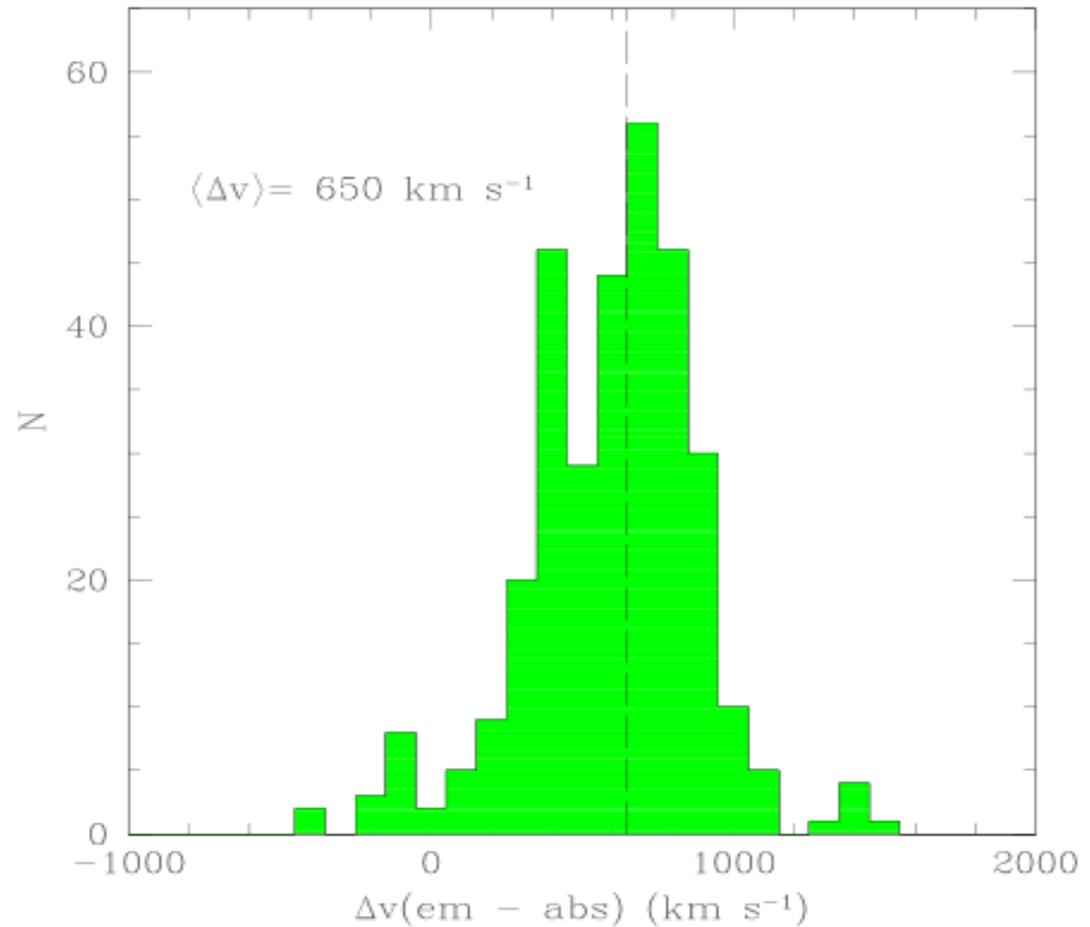
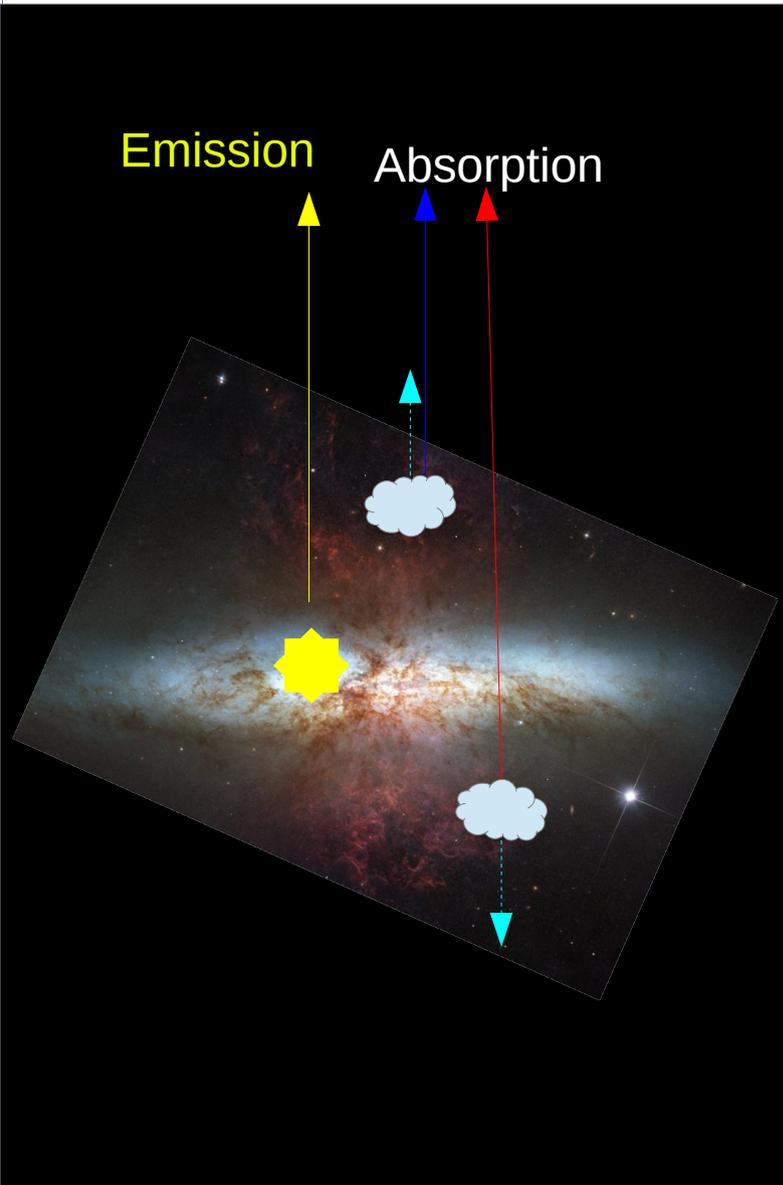


FIG. 1.— The distribution of velocity offsets between Ly α emission and low-ionization interstellar absorption. The most straightforward indication that LBGs are experiencing large-scale outflows of their interstellar material is the velocity offset measured in individual spectra between Ly α emission and interstellar absorption lines. This histogram shows the distribution of velocity offsets for the 323 galaxies with spectra in which both types of features are detected. The mean velocity offset (redshift difference) is $\Delta v = 650 \text{ km s}^{-1}$ ($\Delta z = 0.008$).

Shapley et al. 2003

Sugahara et al. 2017 : evolution with redshift in z 0-2.

A galactic ingredient

... THE **S**tar **F**ormation **R**ate

See next lecture

