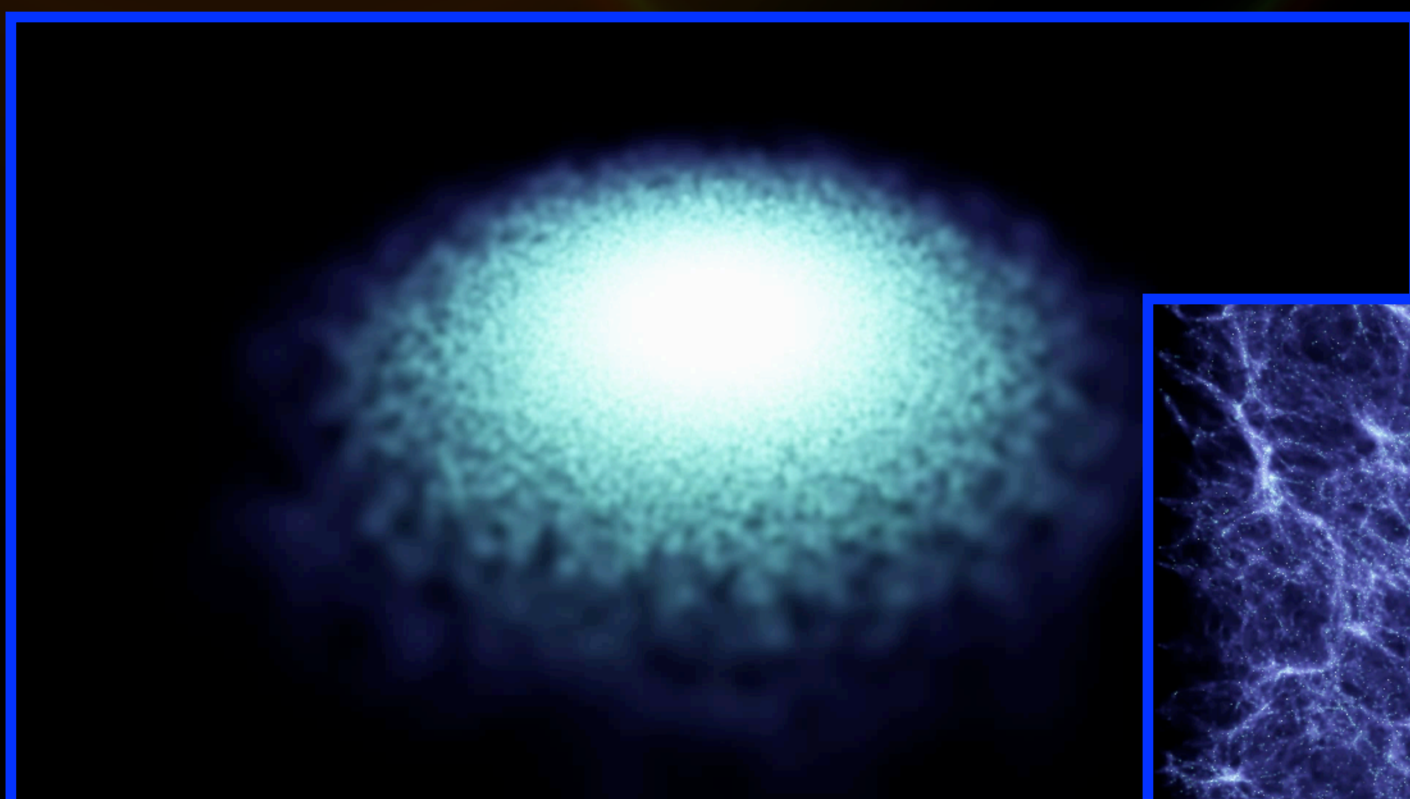
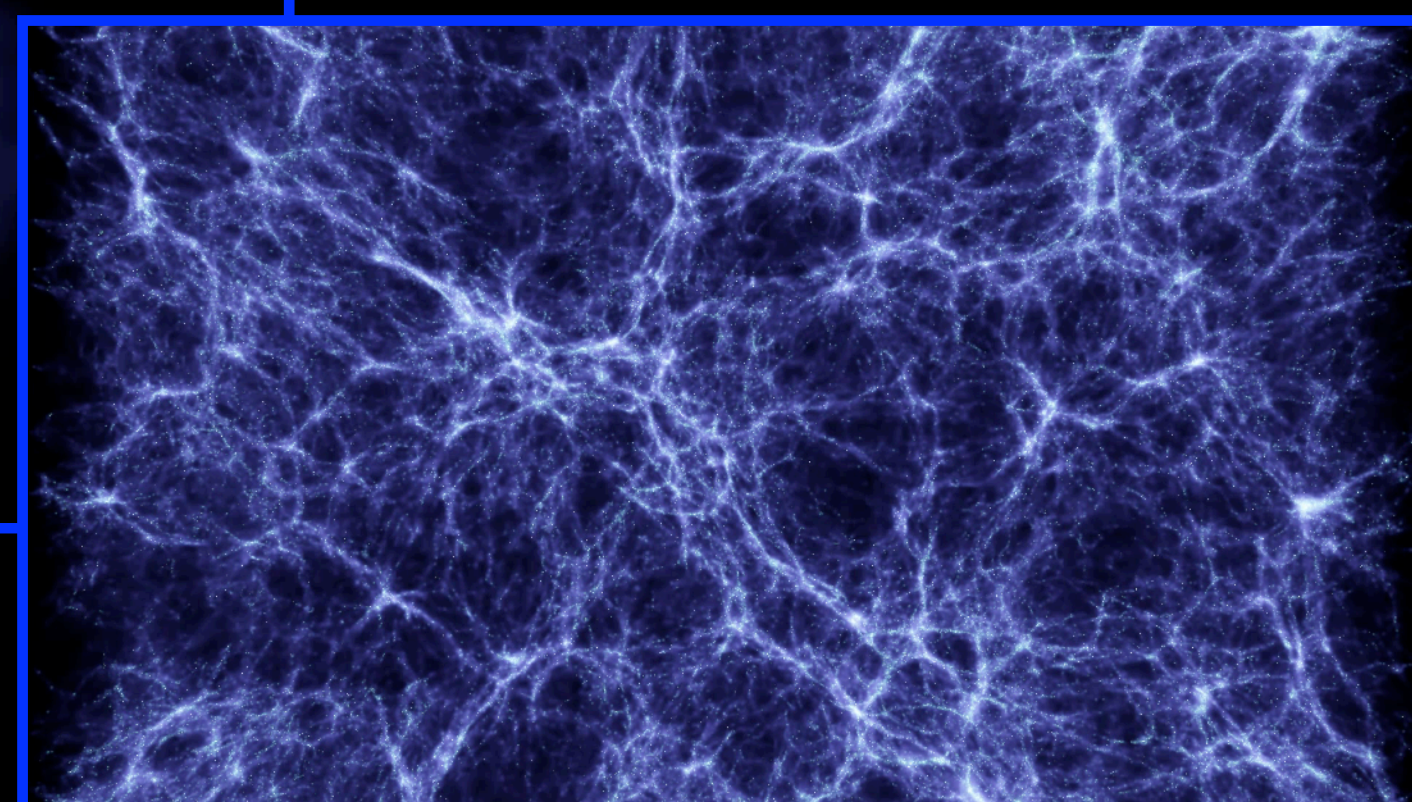
Tools of the Trade: Galactic Chemical Evolution

Prof Brad Gibson

Director, E.A. Milne Centre for Astrophysics
Head of Physics, University of Hull





Galactic Archaeology:
Mining the Fossil Record of Disk Galaxies

...the ways in which we trace the formation and evolution of galaxies...

Observations

Structure | **Chemistry** | **Kinematics**

Modeling

Galactic Archaeology:
Mining the Fossil Record of Disk Galaxies

Structure | **Chemistry** | **Kinematics**

- DM vs stars vs gas
- gradients (vertical and radial)
- bulge-to-disk ratios
- abundance patterns
- thick vs thin disks
- stellar populations
- warps, lopsidedness
- disk heating
- radial migration
- anomalous velocity clouds
- age-metallicity relation
- metallicity distribution functions
- isotopic patterns
- streams and debris
- gas infall and mass assembly
- star formation histories
- dust
- scaling relations

Galactic Archaeology:
Mining the Fossil Record of Disk Galaxies

Structure | **Chemistry** | **Kinematics**

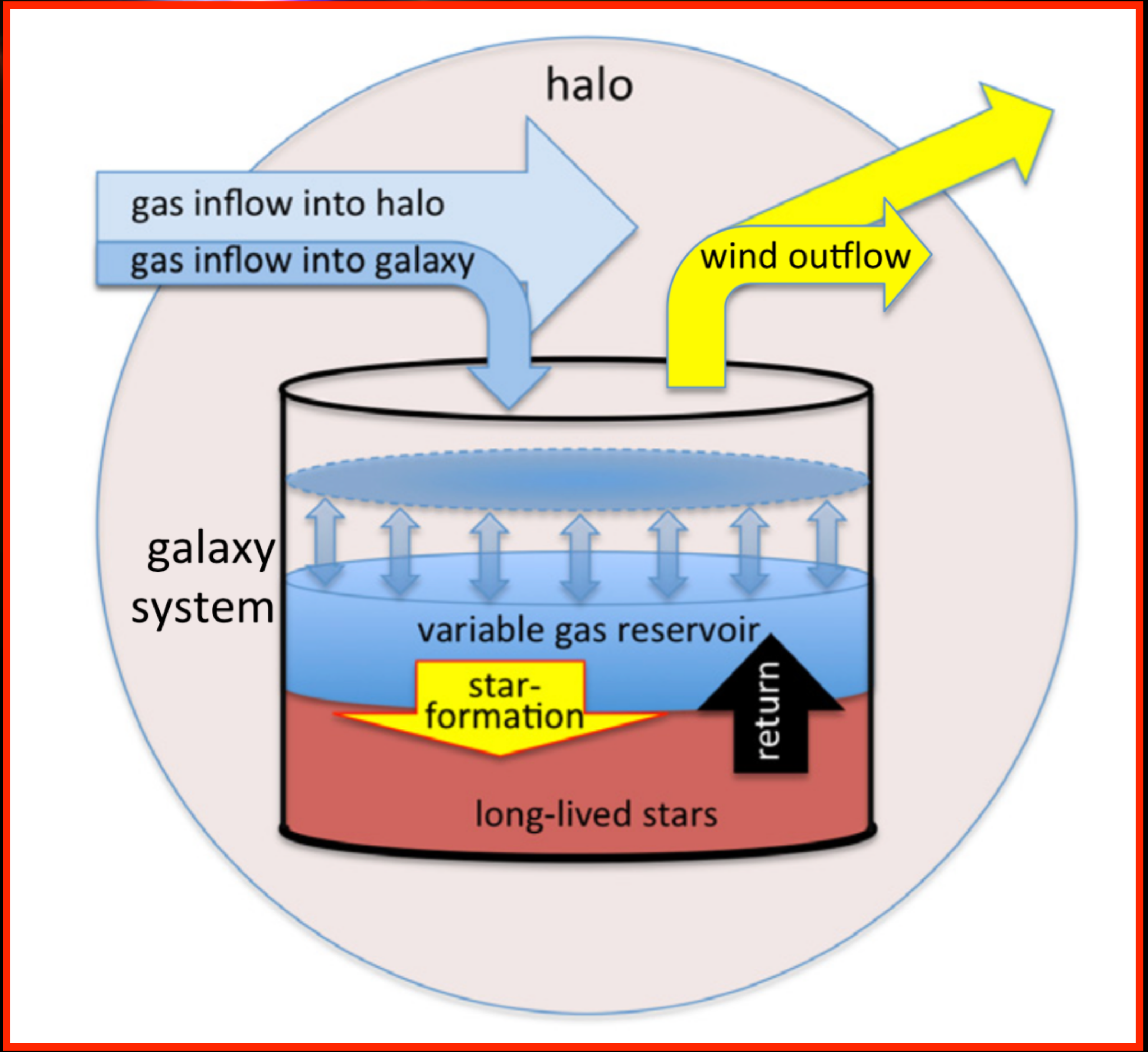
- DM vs stars vs gas
- gradients (vertical and radial)
- bulge-to-disk ratios
- abundance patterns
- thick vs thin disks
- stellar populations
- warps, lopsidedness
- disk heating
- radial migration

- anomalous velocity clouds
- age-metallicity relation
- metallicity distribution functions
- isotopic patterns
- streams and debris
- gas infall and mass assembly
- star formation histories
- dust
- scaling relations

Some questions today for which you should come away with answers...

- What is “chemical evolution” and why is it useful?
- What does “inside-out” galaxy formation mean?
- What is a “closed box” model?
- What is an “Initial Mass Function”?
- What is the “G-dwarf Problem”?
- What is the “Instantaneous Recycling Approximation”?
- What is “Prompt Initial Enrichment”?
- What are “High-Velocity Clouds”?
- How do supernovae act as clocks for age-dating galaxies?
- How can chemical evolution aid stellar evolution?
- What is a “Galactic Wind”?

Building a Framework to Explore Galactic Chemical Evolution

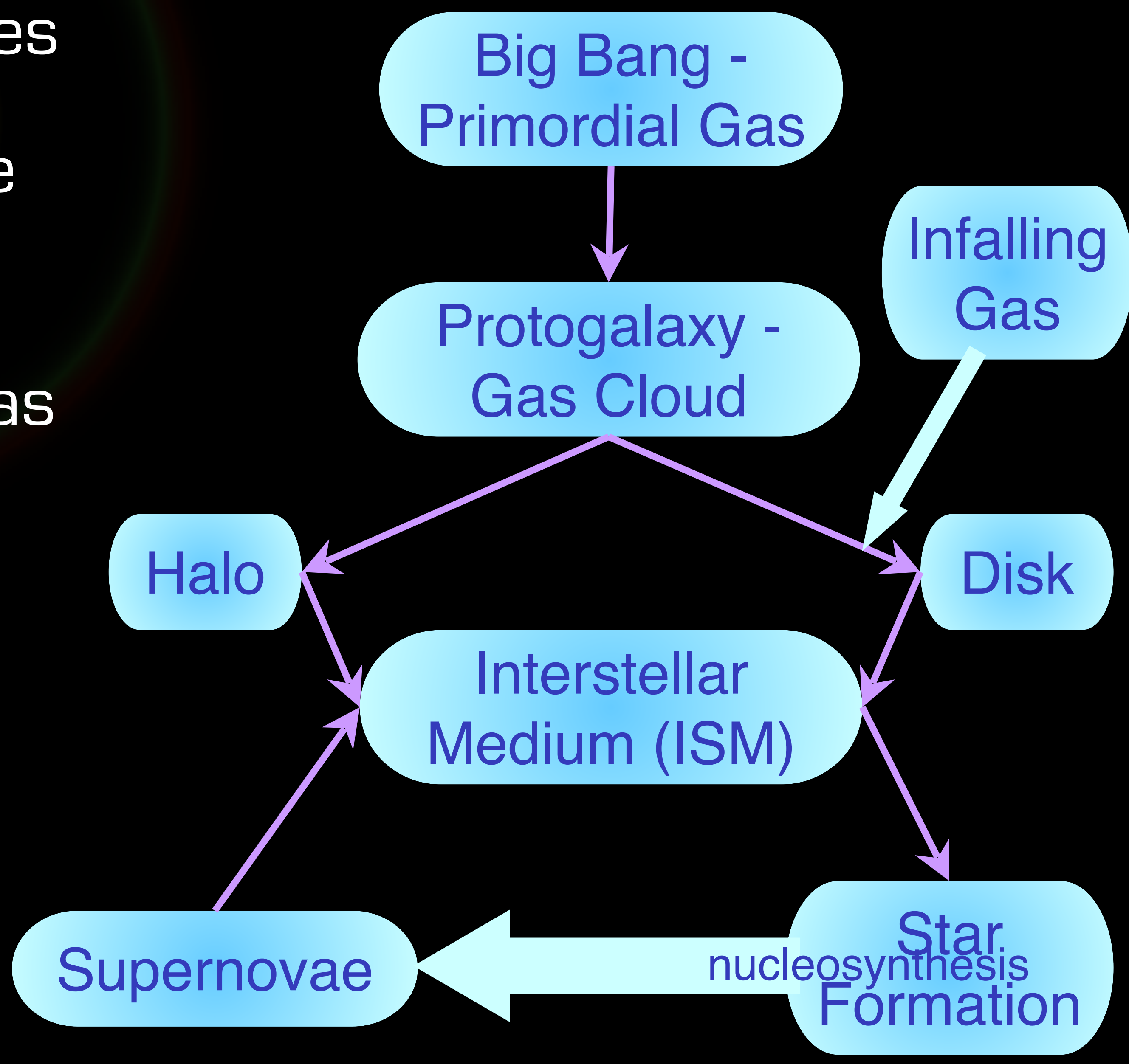


Lilly et al (2013)

- Galactic Chemical Evolution is a powerful mechanism for tracing the time evolution of the chemical elements' appearance throughout the Milky Way
- these elements are the building blocks of planets, galaxies, and (ultimately) us

Galaxy Formation and Evolution

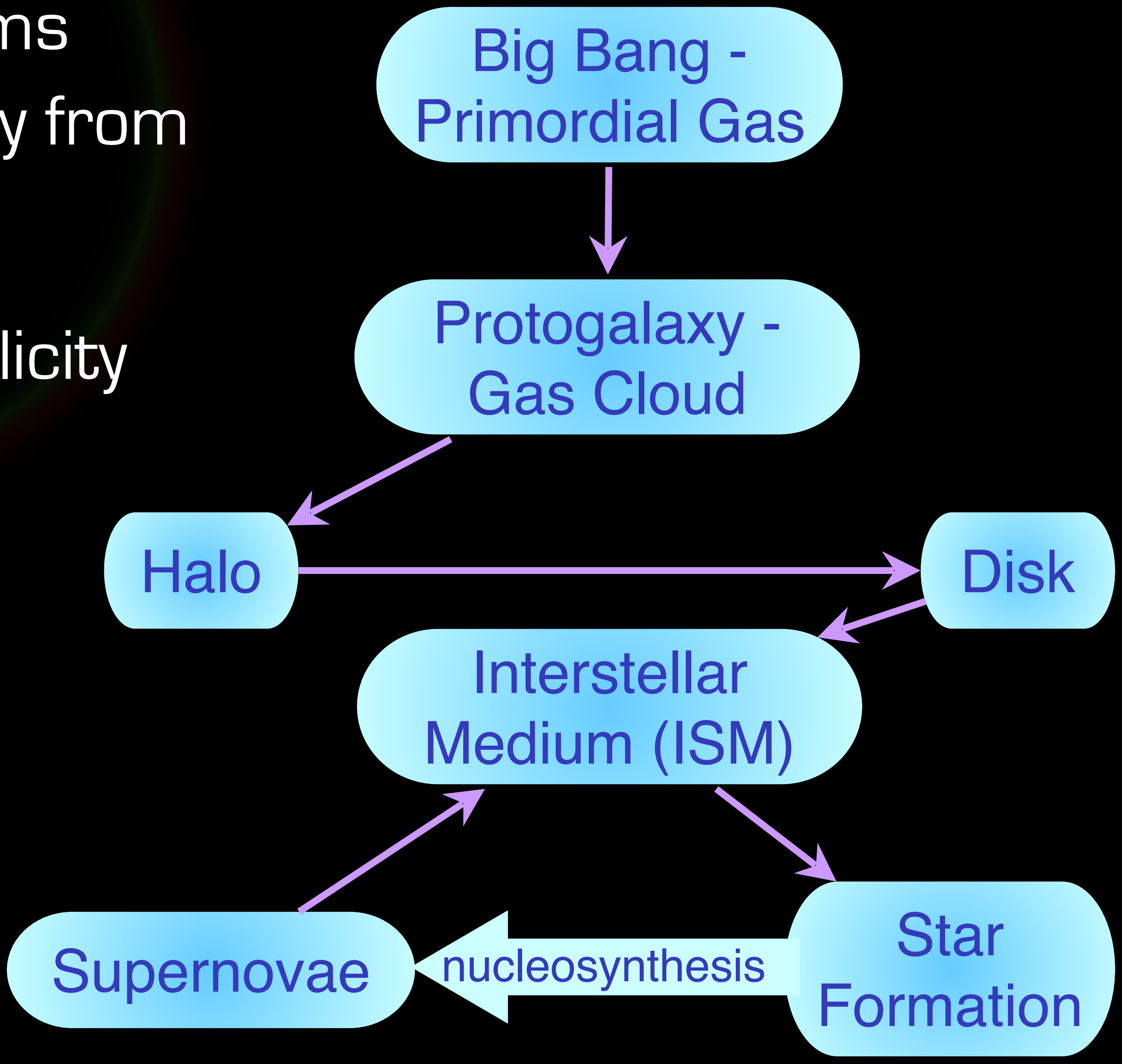
- cloud of primordial gas collapses
- stars form, evolve & synthesise heavier elements
- stars die, ejecting metal rich gas (and energy)
- new stars form
- meanwhile, the galaxy accretes more material



The Searle-Zinn Picture

Galaxy Formation and Evolution

- in the ELS picture, the halo forms rapidly and the disk successively from pre-enriched (halo) gas
- halo star kinematics and metallicity (predicted to be) closely correlated

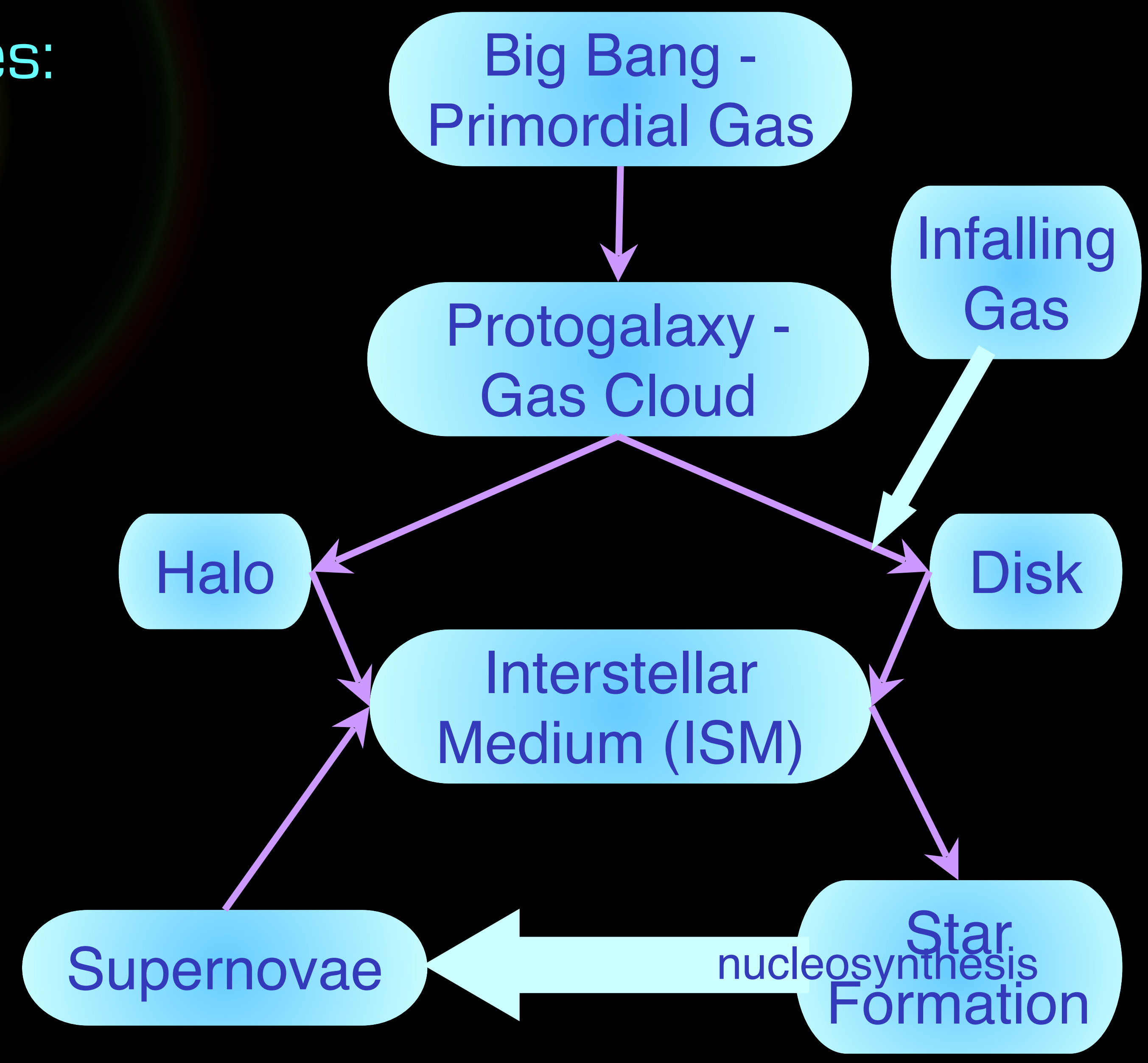


The ELS Picture

Galaxy Formation and Evolution

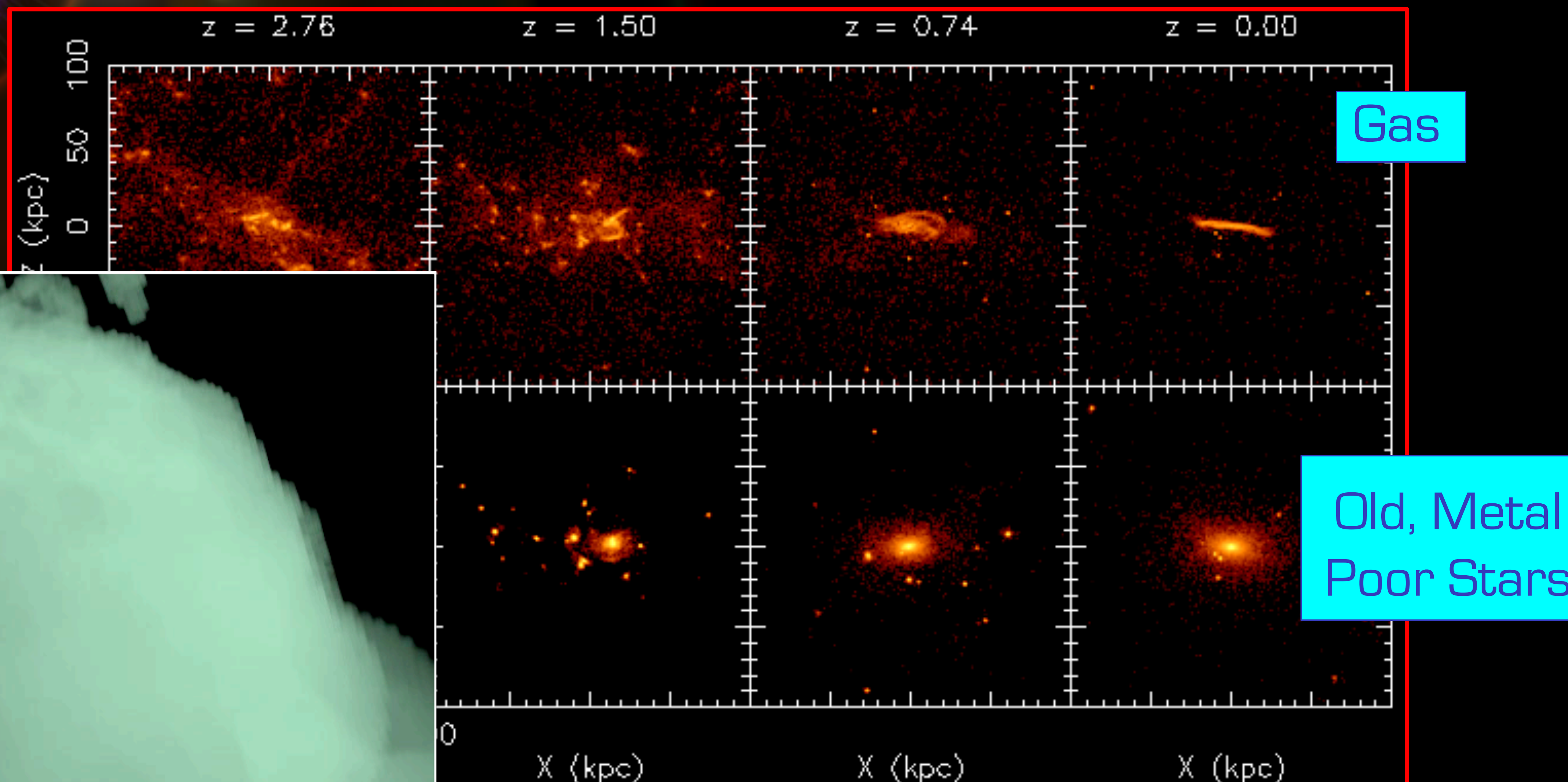
Four complementary approaches:

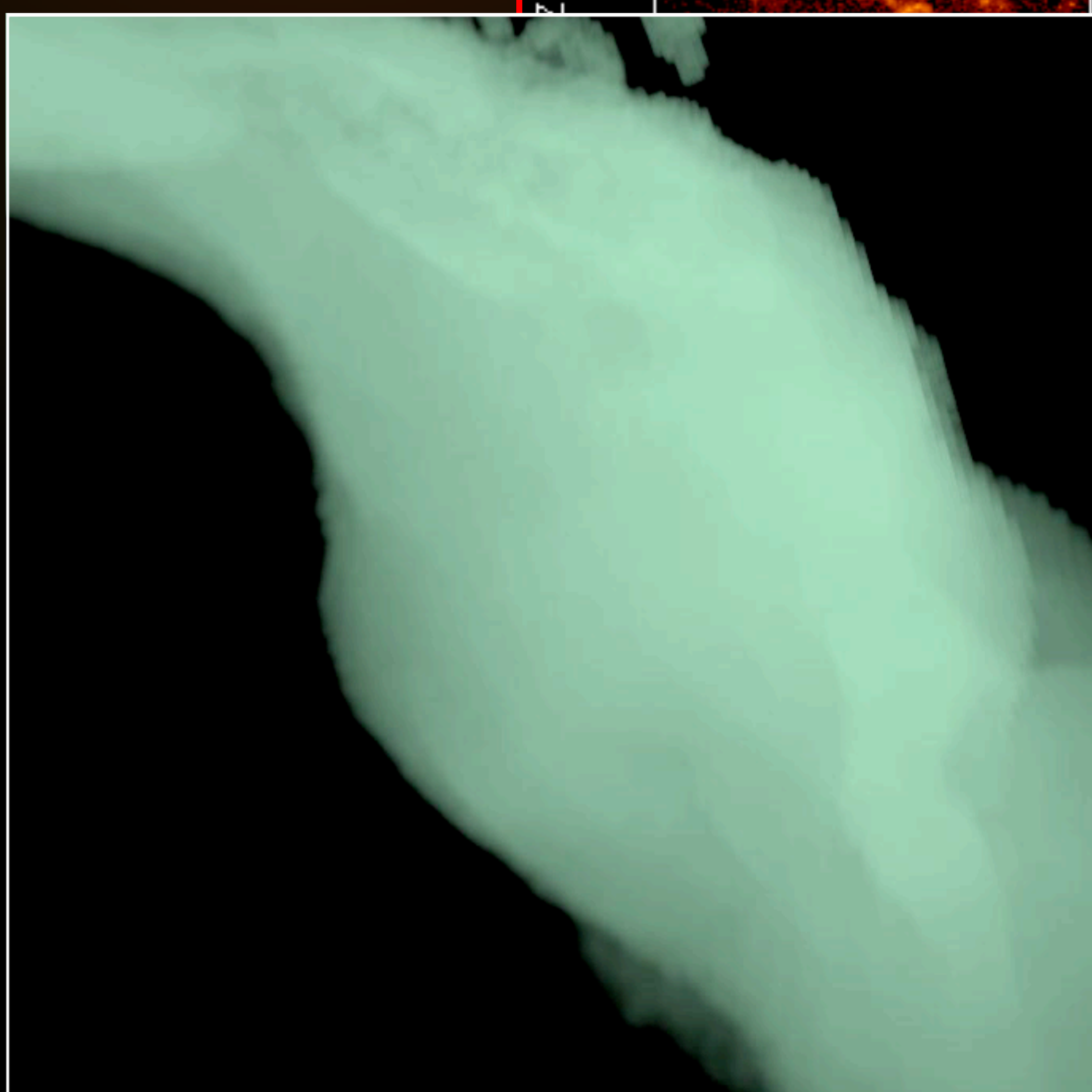
- Observational
- "Computational"



Galaxy Formation Simulations

Kawata & Gibson (2003,2005)

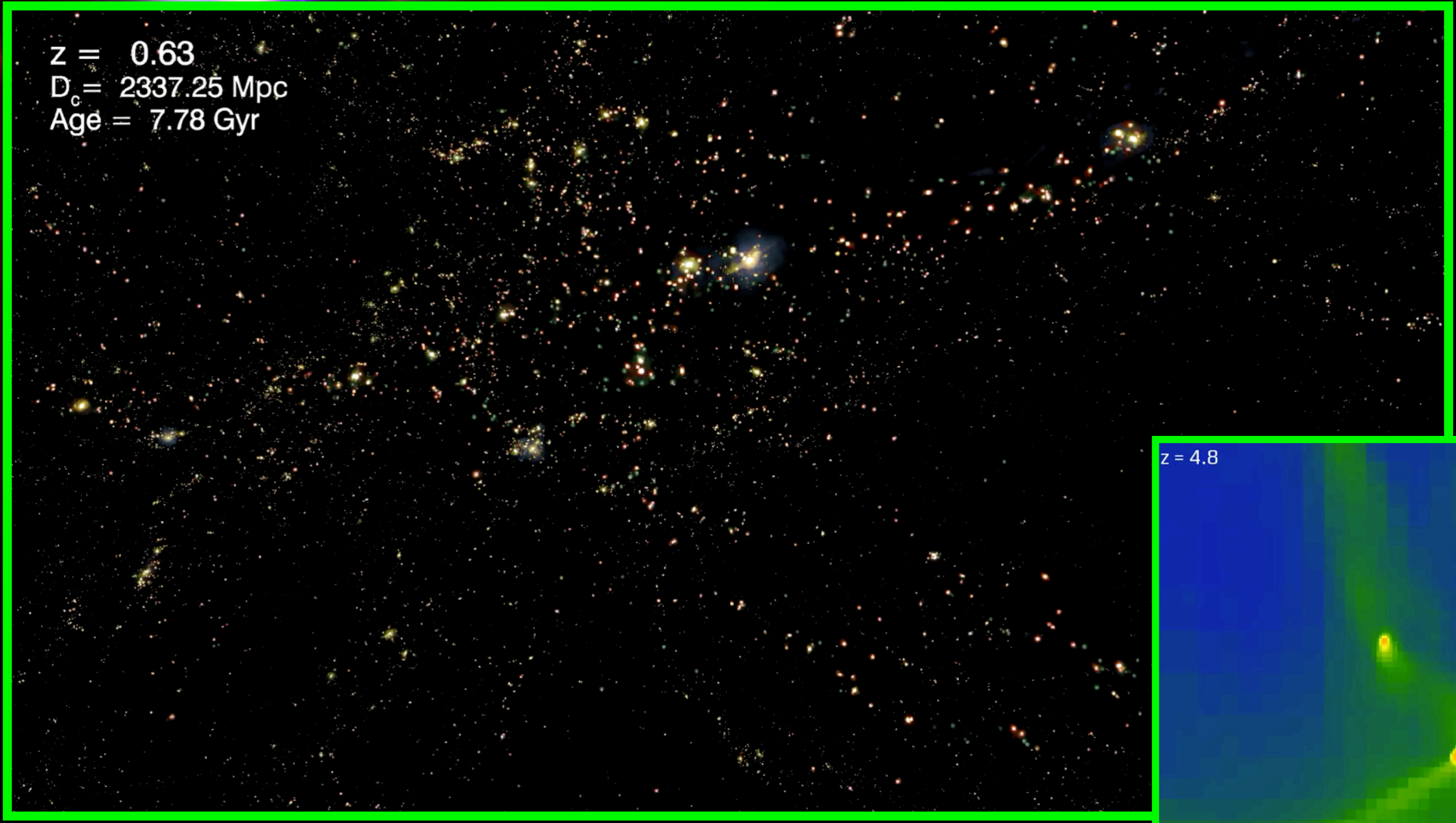


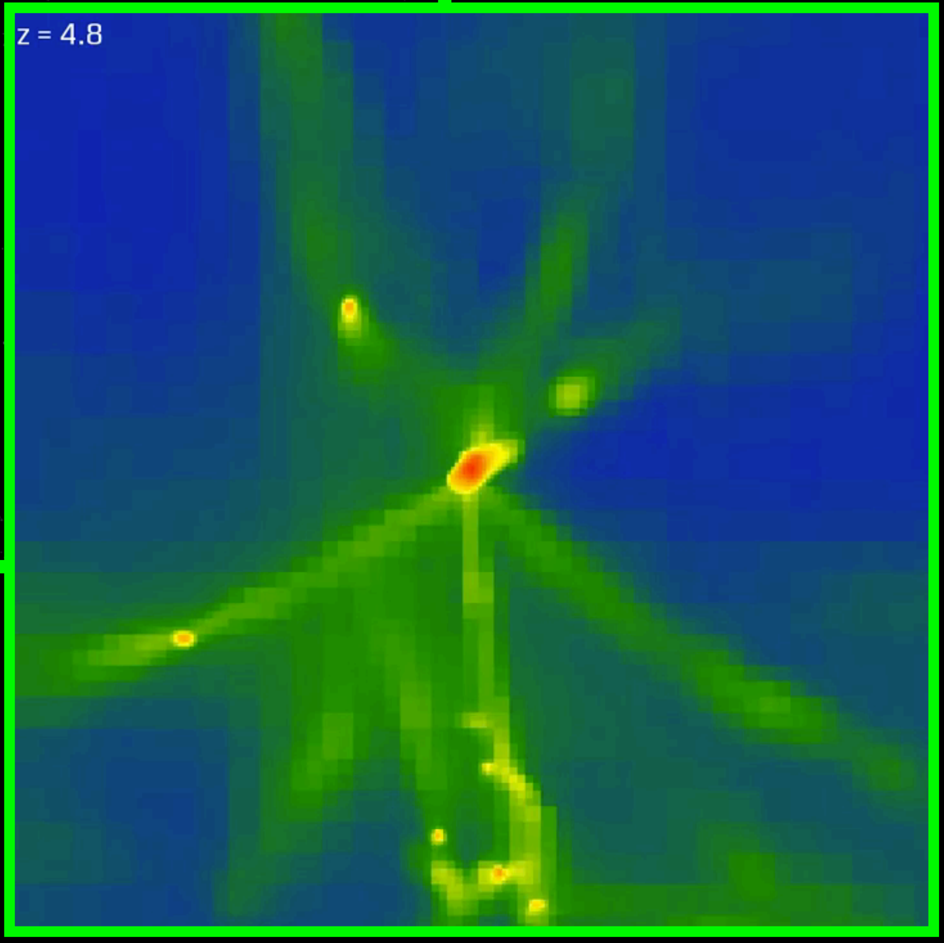


- density-dependent star formation and feedback implemented, in order to trace the metal distribution in galaxies, clusters, and the IGM

Horizon Run 5: State of the Art

Lee, ...,Gibson et al. (2021)



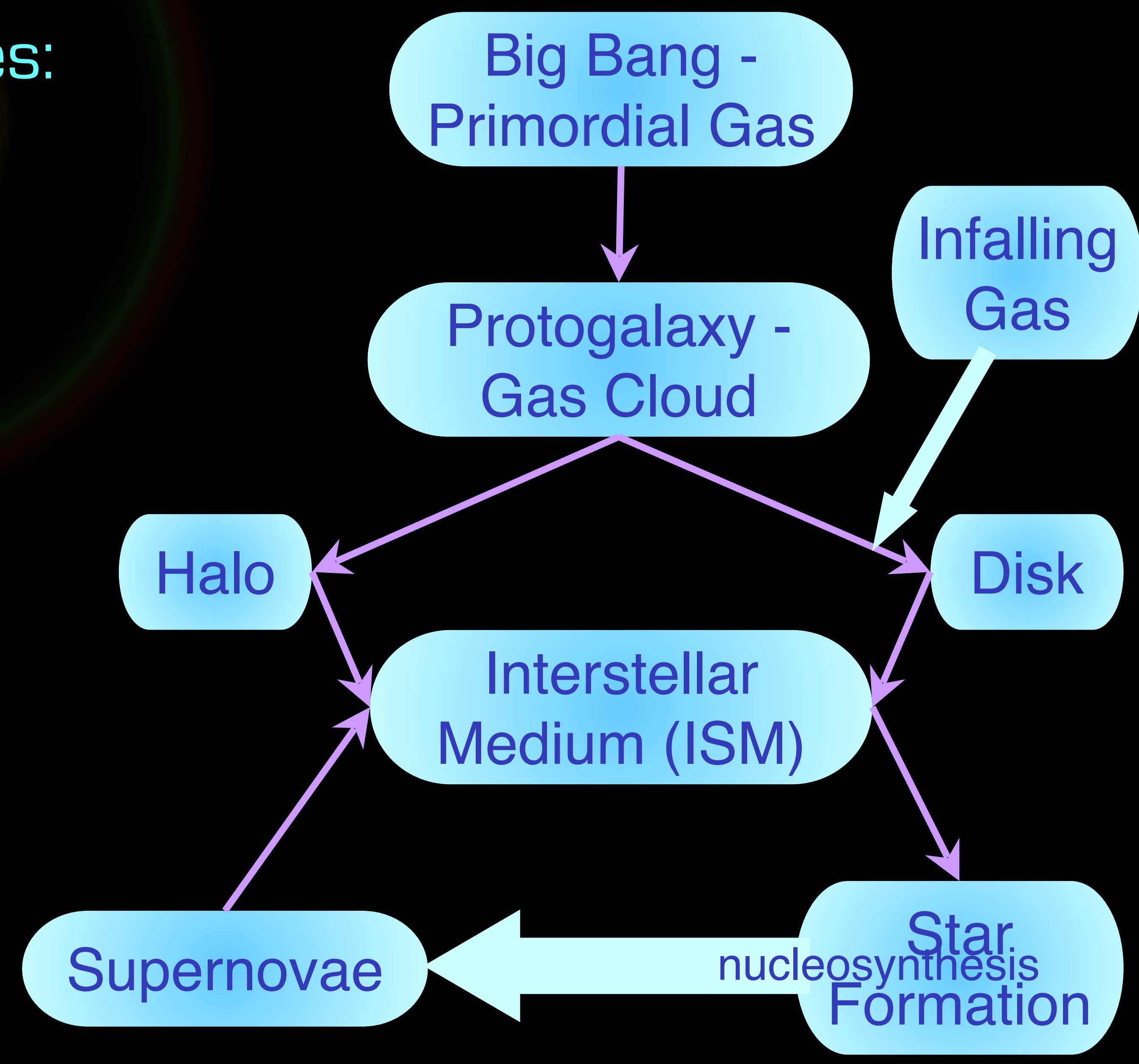


- the Horizon Run is an unprecedented simulation, 1000x larger than anything attempted before

Galaxy Formation and Evolution

Four complementary approaches:

- Observational
- “Computational”
- Semi-Analytical
- “Analytical”



Basic Parameters of Galactic Chemical Evolution

To put together a basic model for the chemical evolution of galaxies, one needs a few ingredients:

- initial conditions
  Big Bang Nucleosynthesis; Prompt Initial Enrichment
- birthrate function
  star formation rate; initial mass function
- (stellar) nucleosynthesis
  supernovae; stellar winds; binary stars
- gas flows
  infall; outflowing super-winds; radial flows

Basic Equations of Chemical Evolution

The chemical evolution of a simple "closed box" system (i.e., no infall or outflow from the region under consideration) can be modeled with the use of only two simple(-ish) equations:

Rate of change of the gas mass $M_g(t)$ →

$$\frac{\mathrm{d}M_{\mathrm{g}}(t)}{\mathrm{d}t} = -\psi(t) + E(t),$$

Rate of change of the mass of metals in the ISM $M_Z(t)$ →

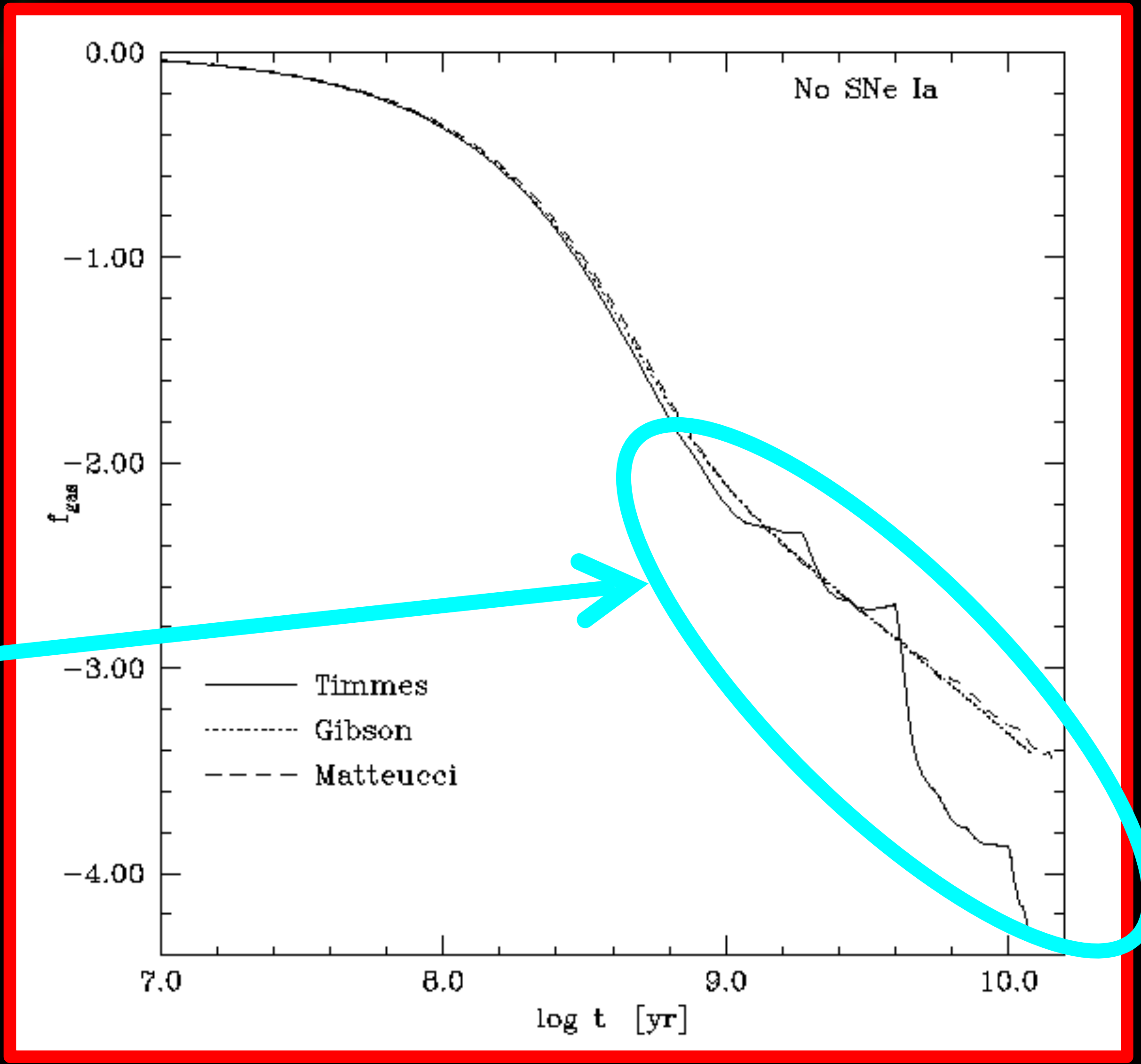
$$\frac{\mathrm{d}M_{\mathrm{Z}}(t)}{\mathrm{d}t} = -\mathrm{Z}(t)\psi(t) + E_{\mathrm{Z}}(t),$$

A Very Simple GCE Model

Gibson (1997)

- evolution of the gas mass fraction $f_g = M_g / M_G$ for a closed-box model, ignoring Type Ia SNe, and assuming a Salpeter IMF (single power law of slope 1.35) and a Schmidt Law of slope k=1

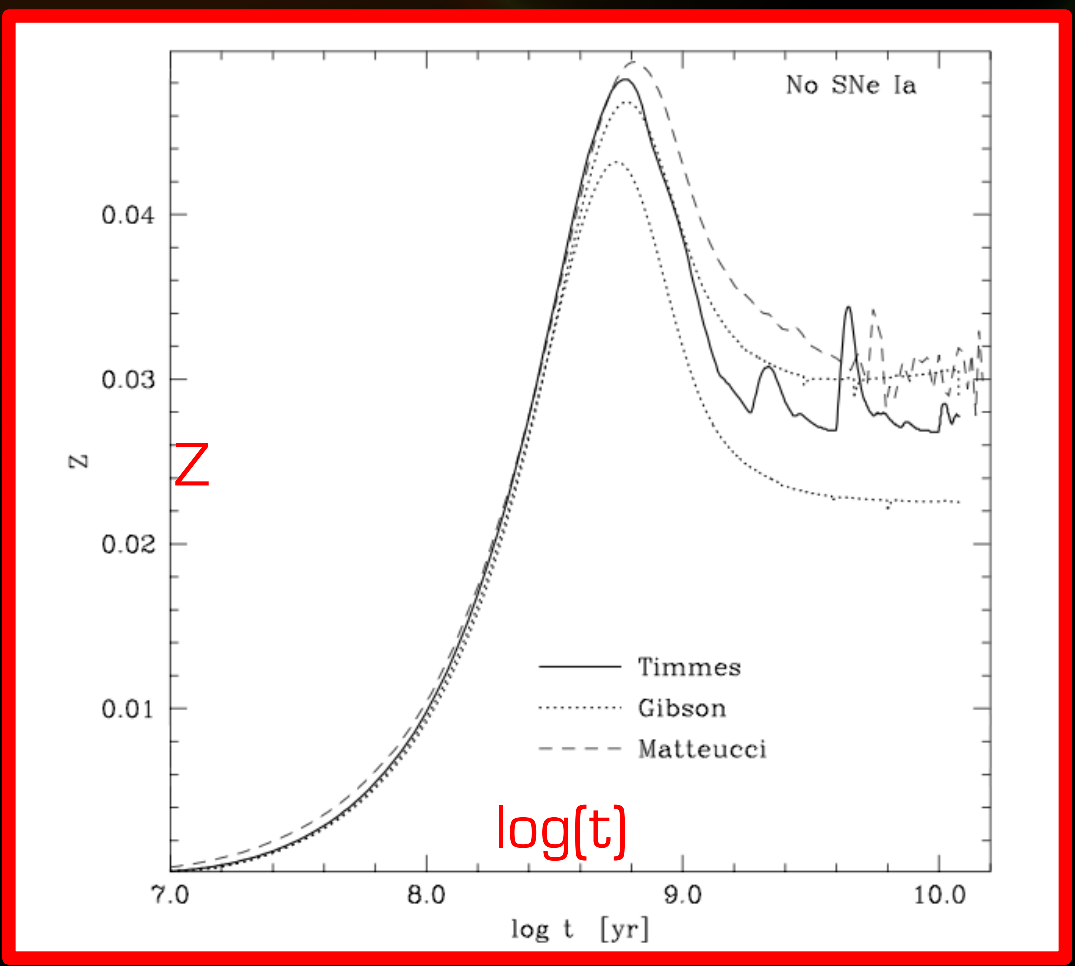
- three different chemical evolution codes are compared here; that of Timmes et al shows numerical instabililites at gas fractions below ~1%.

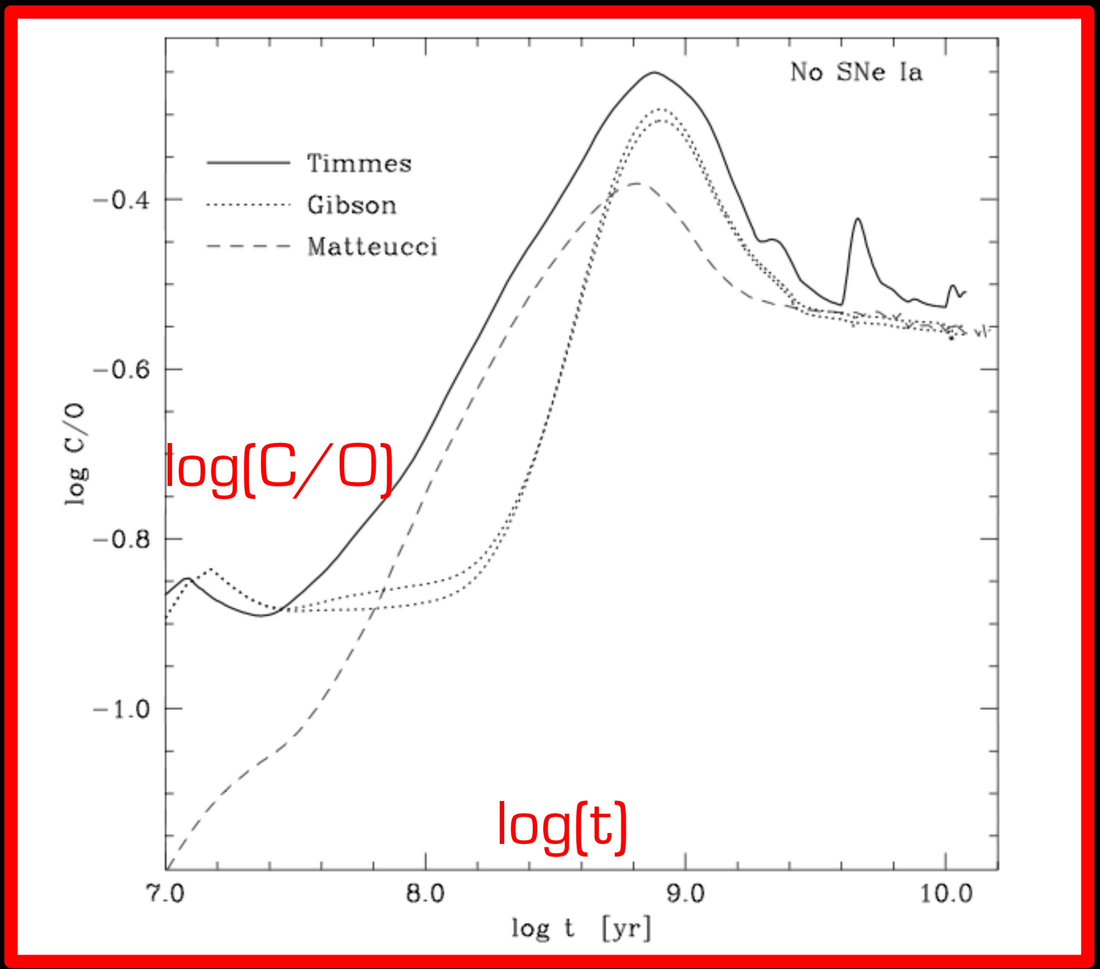


A Very Simple GCE Model

Gibson (1997)

- evolution of the gas mass fraction $f_g=M_g/M_G$ for a closed-box model, ignoring Type Ia SNe, and assuming a Salpeter IMF (single power law of slope 1.35) and a Schmidt Law of slope k=1





Evolution of the Gas Mass

The first of the fundamental equations governs the rate of change of system gas mass (gas being the fuel for star formation).

Gas accretion rate: $M_\odot/yr$

$$\frac{\mathrm{d}M_{\mathrm{g}}(t)}{\mathrm{d}t} = -\psi(t) + E(t) + A(t) - W(t)$$

Gas outflow rate: $M_\odot/yr$

Rate of change of the gas mass: $M_\odot/yr$

Star formation rate: $M_\odot/yr$

Gas returned to the ISM from dying stars: $M_\odot/yr$

Star formation reduces the available gas mass (hence the negative sign), as does any outflow from the system, while the gas returned by supernovae and planetary nebulae increases the system gas mass, as does the continual replenishment due to infalling gas.

The Birthrate Function: B(m,t)

$$B(m,t) = \psi(t)\varphi(m)dtdm$$

Star Formation Rate

Initial Mass Function

The Star Formation Rate: $\Psi(t)$

The microphysics of star formation cannot be treated in any sophisticated manner within models of galaxy formation and evolution.

The best we can hope for is a reasonable parametrisation. Several of the more "famous" include:

- Exponentially decreasing

$$SFR = \nu e^{-t/\tau_*}$$

Milky Way $\Rightarrow \tau_* = 5\text{-}15$ Gyr

$\nu \equiv$ SF efficiency $[t^{-1}]$

- Schmidt Law

$$SFR = \nu \sigma_{gas}^{k}$$

Disks $\Rightarrow k \approx 1.4$

The Star Formation Rate: Ψ(t)

- Dopita & Ryder

$$SFR = \nu \sigma_{tot}^{k_1} \sigma_{gas}^{k_2}$$

Disks ⇒ $k_1 \approx 0.5$ and $k_2 \approx 1.5$

- Kennicutt

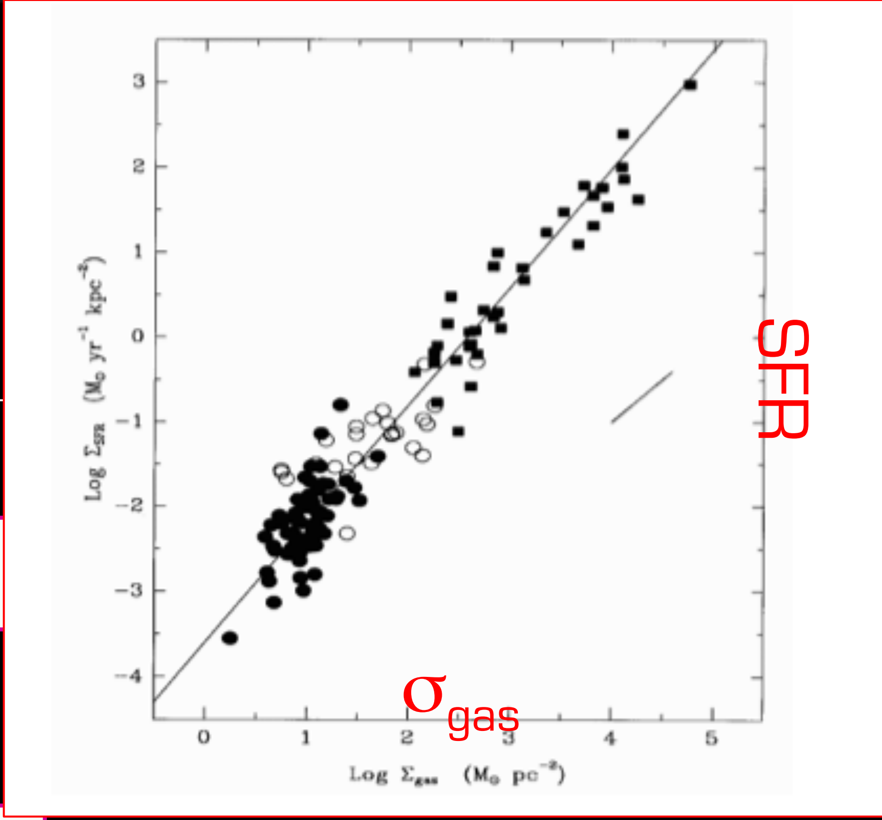
$$SFR = 0.017 \Omega_{gas} \sigma_{gas} \propto R^{-1} \sigma_{gas}$$

Disks ⇒ $k \approx 1.0$-1.5

$$\sigma_{th} = 7 M_{\odot} pc^{-2}$$

⇒ star formation threshold

Boundary Conditions on $\Psi(t)$



- Hα flux from HII regions $\propto$ SFR

$$SFR(M_\odot yr^{-1}) = 7.9 \cdot 10^{-42} L_{H_\alpha}(ergs^{-1})$$

- UV continuum $\propto$ SFR

$$SFR(M_\odot yr^{-1}) = 0.9 \cdot 10^{-6} \frac{L(UV)}{L_{bol_\odot}}$$

- counts of supergiants in nearby galaxies $\propto$ SFR
- integrated colours and spectra $\Rightarrow$ young:old stars $\Rightarrow$ SFR_0/<SFR>
- radio emission from HII regions $\Rightarrow$ SFR

Local solar neighbourhood (for Milky Way models):

$$SFR = 2 - 10 \mathrm{M_\odot pc^{-2} Gyr^{-1}}$$

Gas Ejection Rate: E(t)

Gibson (1997)

The gas ejection rate E(t) looks scary at first glance, but it simply represents the amount of mass returned to the ISM at time t from low mass single stars, intermediate mass binaries, intermediate mass single stars, and high mass single stars.

$$\frac{\mathrm{d}M_{\mathrm{g}}(t)}{\mathrm{d}t} = -\psi(t) + E(t),$$

$$\begin{aligned} E(t) = & \int_{m_l}^{m_{\mathrm{Bm}}} \phi(m)\psi(t-\tau_m)R(m)\mathrm{d}m \\ & + A\int_{m_2}^{m_{\mathrm{BM}}} \phi(m)\left\{\int_{\mu_m}^{0.5} f(\mu)\psi(t-\tau_{m_2})R(m_2)\mathrm{d}\mu\right\}\mathrm{d}m \\ & + (1-A)\int_{m_2}^{m_{\mathrm{BM}}} \phi(m)\psi(t-\tau_m)R(m)\mathrm{d}m \\ & + \int_{m_3}^{m_U} \phi(m)\psi(t-\tau_m)R(m)\mathrm{d}m \end{aligned}$$

A=fraction of mass in the 3-16 $M_\odot$ range

locked up in Type Ia (binary) supernovae progenitors

Gas Ejection Rate: E(t)

There are really only three key terms governing the gas ejection rate E(t):

$$\int_{m^1}^{m_{\mathrm{Bm}}} \phi(m)\psi(t-\tau_m)R(m)\mathrm{d}m$$

Initial mass function (distribution of stellar masses in a given stellar generation)

Star formation rate at the time that the presently dying star of mass m was born

Fractional mass returned to ISM by star of mass m at the end of its lifetime τ_m

$\tau_m \equiv 0 \Rightarrow$ instantaneous recycling approximation

Let's now examine these three terms in turn.

The Initial Mass Function: $\phi(m)$

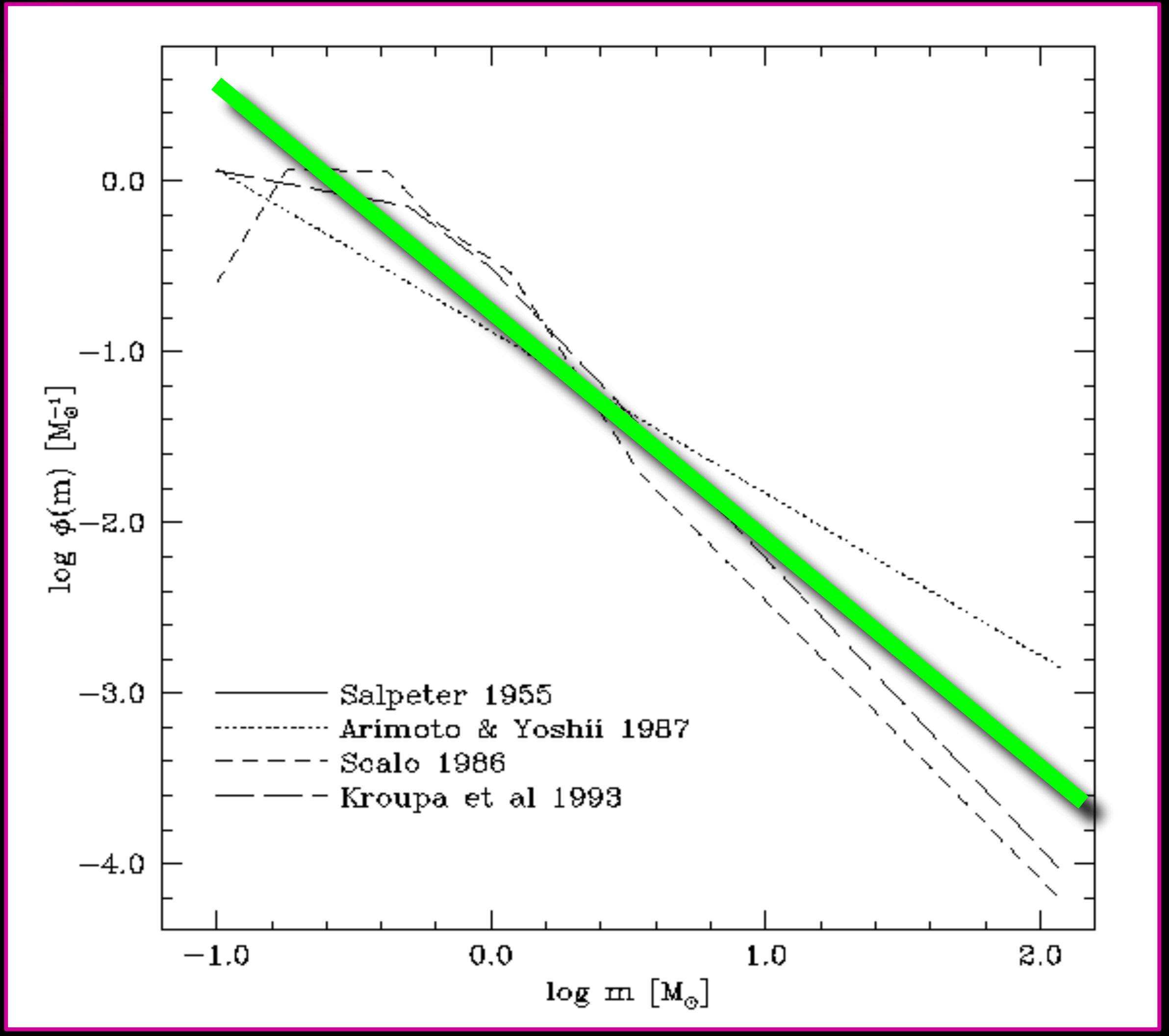
The IMF describes the relative birth-rates of stars with different initial mass m. Its derivation is based upon taking the observed present-day mass distribution of stars, and then making a series of "corrections" taking into account evolved/extinct stars, in order to infer the IMF.

$\varphi(m)$ is generally written as a power-law function in mass (or as a series of power-laws), normalised to unity, of the form:

$$\boxed{\phi_i(m) = k_i m^{-x_i},}$$

The Initial Mass Function: $\phi(m)$

The standard bearer in terms of IMF is that derived by Edwin Salpeter in 1955. His analysis of the local solar neighbourhood led him to conclude that a single power law of slope x=1.35 was an adequate representation of the IMF.



Since then, a number of refinements have occurred, the majority of which have reduced the relative fraction of massive (>12$M_\odot$) stars in a given stellar generation f_m from ~11% to ~5% (by mass).

IMF	$f_m(m \geq 12 M_\odot)$
AY87	0.364
S55	0.113
KTG93	0.062
S86	0.038

The Accretion Rate: A(t)

Ongoing accretion is a natural part of the SZ picture and is, in fact, required of chemical evolution models of the Milky Way - specifically, to solve the so-called "G-dwarf Problem" (the overproduction of metal-poor stars which plagues closed-box models).

Th

ar

Is there any evidence of this infall?

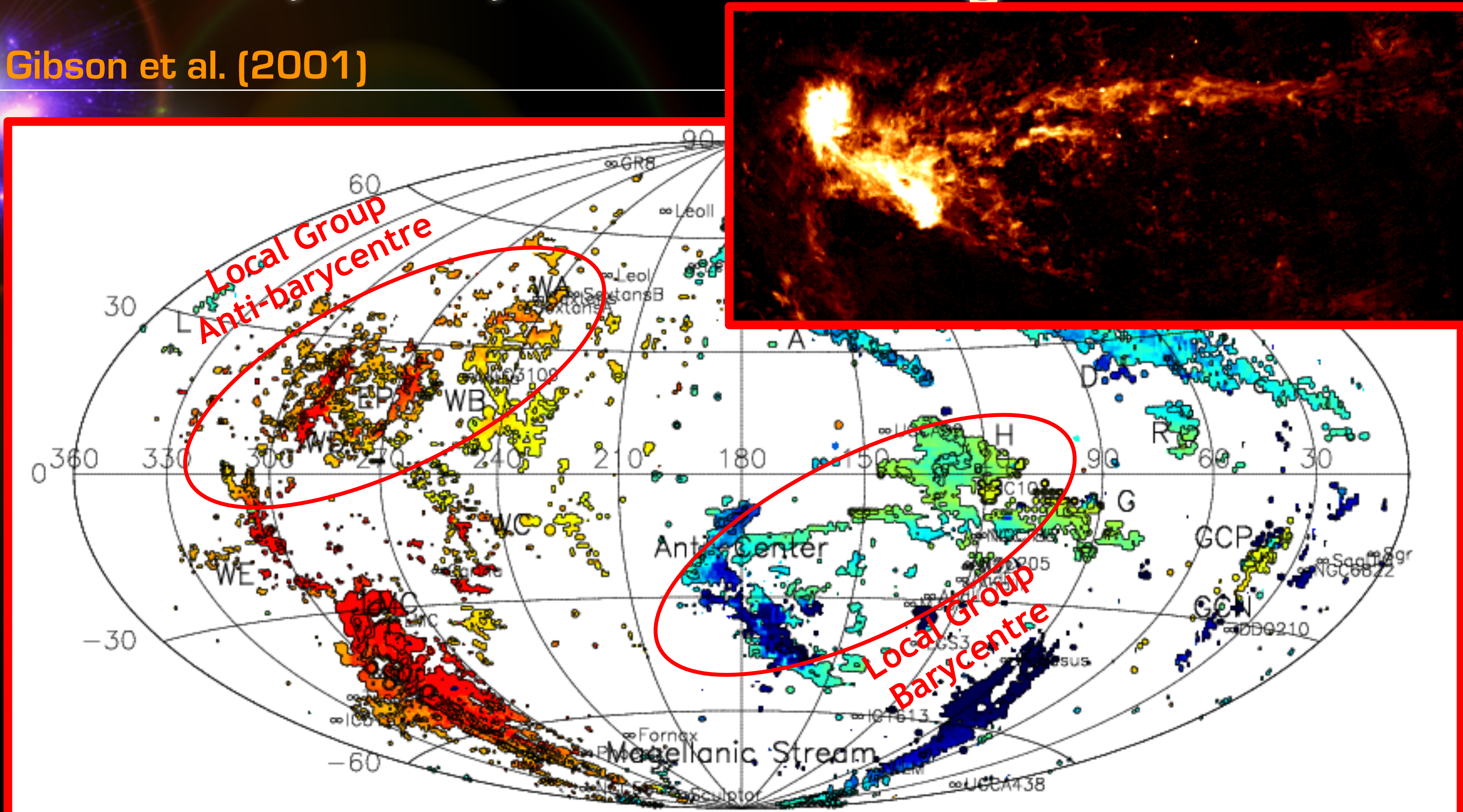
$$\frac{\mathrm{d}M_g(t)}{\mathrm{d}t} = -\psi(t) + E(t) + A(t)$$

$$A(t) = A(R)e^{-t/\tau(R)}$$

Boundary Condition: $\sigma_{tot}(R,t_G)$

Accretion, HVCs, and the Missing Satellites?

Gibson et al. (2001)



- kinematics inconsistent with Galactic rotation ($|v_{LSR}| > 100$ km/s)
- large sky covering factor (>40%)
- 60% of HVC HI flux from Mag Stream (15% from Complex C)
- origin scenarios: fountains (kpc), condensed halo gas (10s of kpc), tidal debris (10s of kpc), building blocks (Mpc)?

(there are 1000s of them...)

Evolution of the Metal Mass of the ISM

The second of the fundamental equations governs the rate of change of metal mass in the ISM and is a direct analog of the first equation (governing the evolution of the gas mass):

$Z(0)\neq 0 \Rightarrow$ prompt initial enrichment

Metallicity of ISM: $Z(t)=M_Z(t)/M_g(t)$

Metallicity of infalling gas

$$\frac{\mathrm{d}M_\mathrm{Z}(t)}{\mathrm{d}t} = -\mathrm{Z}(t)\psi(t) + E_\mathrm{Z}(t) + Z_{inf}(t)\,A(t)$$

Rate of change of the ISM metal mass: $M_\odot/yr$

Star formation rate: $M_\odot/yr$

Metals returned to the ISM from dying stars: $M_\odot/yr$

The Metal Ejection Rate: $E_Z(t)$

Gibson (1997)

The ISM metal mass ejection rate $E_Z(t)$ is also a direct parallel to that seen for the evolution of the gas ejection rate:

$$\frac{\mathrm{d}M_Z(t)}{\mathrm{d}t} = -Z(t)\psi(t) + E_Z(t),$$

$$\begin{aligned} E_Z(t) = & \int_{m^1}^{m_{\mathrm{Bm}}} \frac{\phi(m)}{m} \psi(t-\tau_m) m_{Z,m}^{\mathrm{ej}} \mathrm{d}m \\ & + A \int_{m^2}^{m_{\mathrm{BM}}} \frac{\phi(m)}{m} \left\{ \int_{\mu_m}^{0.5} f(\mu) \psi(t-\tau_{m_2}) m_{Z,m_1}^{\mathrm{ej}} \mathrm{d}\mu \right\} \mathrm{d}m \\ & + (1-A) \int_{m^2}^{m_{\mathrm{BM}}} \frac{\phi(m)}{m} \psi(t-\tau_m) m_{Z,m}^{\mathrm{ej}} \mathrm{d}m \\ & + \int_{m^3}^{m_{\mathrm{U}}} \frac{\phi(m)}{m} \psi(t-\tau_m) m_{Z,m}^{\mathrm{ej}} \mathrm{d}m. \end{aligned}$$

A=fraction of mass in the 3-16 $M_{\odot}$ range

locked up in binary Type Ia supernovae progenitors

The Metal Ejection Rate: $E_Z(t)$

We have already examined the IMF $\varphi(m)$, star formation rate $\psi(t)$, and stellar lifetime τ_m in relation to the gas ejection rate equation. The key new ingredient here is the mass of metals ejected from a star of given mass m and metallicity Z:

$$\int_{m^1}^{m_{\mathrm{Bm}}} \frac{\phi(m)}{m} \psi(t - \tau_m) m_{\mathrm{Z},m}^{\mathrm{ej}} \mathrm{d}m$$

The predicted values of $m^{ej}_{Z,m}$ - or the stellar yield - depend upon the physics of stellar evolution, and are fundamental to any chemical evolution analysis.

Stellar Nucleosynthesis SItes

Supernovae (SNe) represent the death throes of massive (>8 $M_\odot$) stars

→ Type II SNe

and low mass (1-8 $M_\odot$) stellar binaries

→ Type Ia SNe

The primary discriminant between the main SN families - Types I and II - is the presence (Type II), or lack thereof (Type I), of hydrogen in the observed spectrum.

Stellar Nucleosynthesis Sites

In stars of mass less than 8 $M_{\odot}$, core burning is halted by the formation of a degenerate CO core which later becomes a white dwarf.

Stars of mass greater than 8 $M_{\odot}$ though <u>can</u> ignite carbon.

The evolution of the stellar interior is <u>greatly</u> accelerated from here on out ...

→ driven primarily by neutrino emission at the extreme temperatures involved in the core

Stellar Nucleosynthesis Sites

Type II Supernovae

α-elements (O,Ne,Mg,Si,S,Ca); some Fe; s-process ($A<90$); r-process

Type Ia Supernovae

Fe-peak elements

Low- and Intermediate-Mass Stars

^4He,C,N,s-process ($A>90$)

Type II Supernovae Yields

Gibson, Loewenstein & Mushotzky (1997)

There are a number of excellent stellar yield compilations available, each which approach the physics of stellar evolution in their own unique manner - these compilations include those of Arnett (1996: A96), Langer & Hankel (1995: LH95), Maeder (1992: M92), Tsujimoto et al. (1995: T95), and Woosley & Weaver (1995: W95).

Mass loss? | Reaction Rate | Unprocessed ejecta included? | Explosive nucleosynthesis included?

Yield Source	$\dot{M}$(?)	Convection	$^{12}C(\alpha,\gamma)^{16}O$	Z	m^{unp}(?)	exp nuc(?)	init state
T95	N	Sch	C85	$Z_\odot$	N	Y	He
M92	Y	Sch+over	C85	$Z_\odot/20$	N	N	ZAMS
W95	N	Led+semi	0.74×C85	$Z_\odot/10$	Y	Y	ZAMS
A96	N	ad+chem hom+semi hom	0.74×C85	$Z_\odot$	Y	N	ZAMS
LH95	Y	~Led+semi	0.74×C85	$Z_\odot/10$	Y	N	ZAMS

Type II Supernovae Yields

Gibson, Loewenstein & Mushotzky (1997)

The different input physics manifests itself in different predictions for the nucleosynthetic yields. Shown below are the IMF-weighted yield predictions for various elements.

Some elements appear more robust to the subtleties of the input physics (e.g. Si, S), while others can vary by factors of two-to-three between the compilations (e.g. Fe, O, Mg, Ne).

Type II SNe Yields

Yield Source	$< y_{Fe,SNII} >$	$< y_{O,SNII} >$	$< y_{Si,SNII} >$	$< y_{Mg,SNII} >$	$< y_{Ne,SNII} >$	$< y_{S,SNII} >$
A96	0.071	0.593	n/a	0.054	0.101	n/a
T95	0.121	1.777	0.133	0.118	0.232	0.040
T95+M92	0.121	0.923	n/a	n/a	n/a	n/a
W95;A;$10^{-4}Z_\odot$	0.073	0.806	0.104	0.036	0.095	0.059
W95;B;$10^{-4}Z_\odot$	0.085	1.455	0.118	0.066	0.223	0.065
W95;A;$Z_\odot$	0.113	1.217	0.124	0.065	0.181	0.058
W95;B;$Z_\odot$	0.141	1.664	0.143	0.094	0.265	0.064

Yield Source	$< y_{Fe,SNIa} >$	$< y_{O,SNIa} >$	$< y_{Si,SNIa} >$	$< y_{Mg,SNIa} >$	$< y_{Ne,SNIa} >$	$< y_{S,SNIa} >$
TNH93	0.744	0.148	0.158	0.009	0.005	0.086

Type Ia SNe Yields

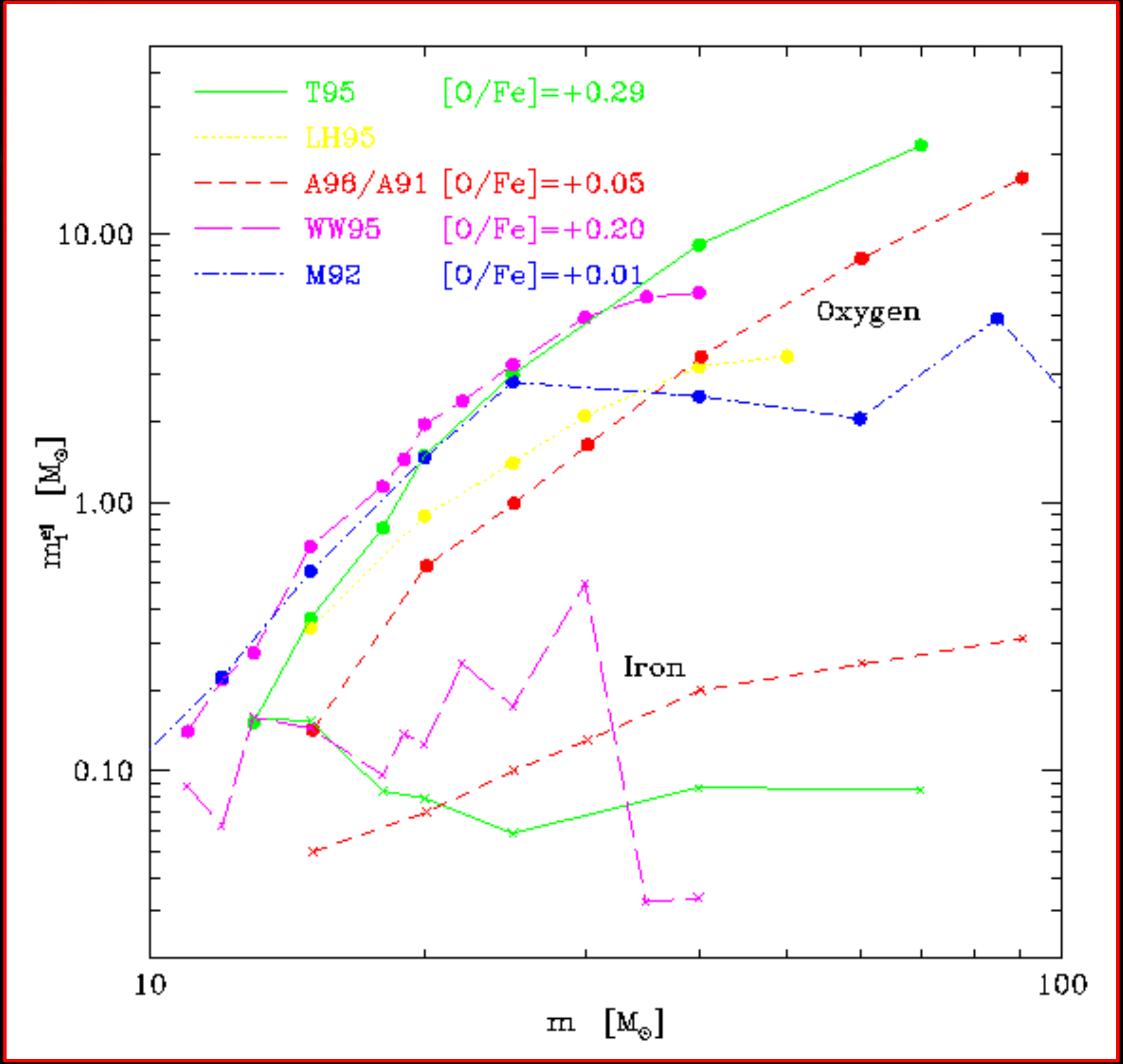
Type II Supernovae Yields

Gibson (2002)

Elements which are produced primarily via hydrostatic burning in the outer layers (e.g. oxygen) show an increasing trend with increasing mass.

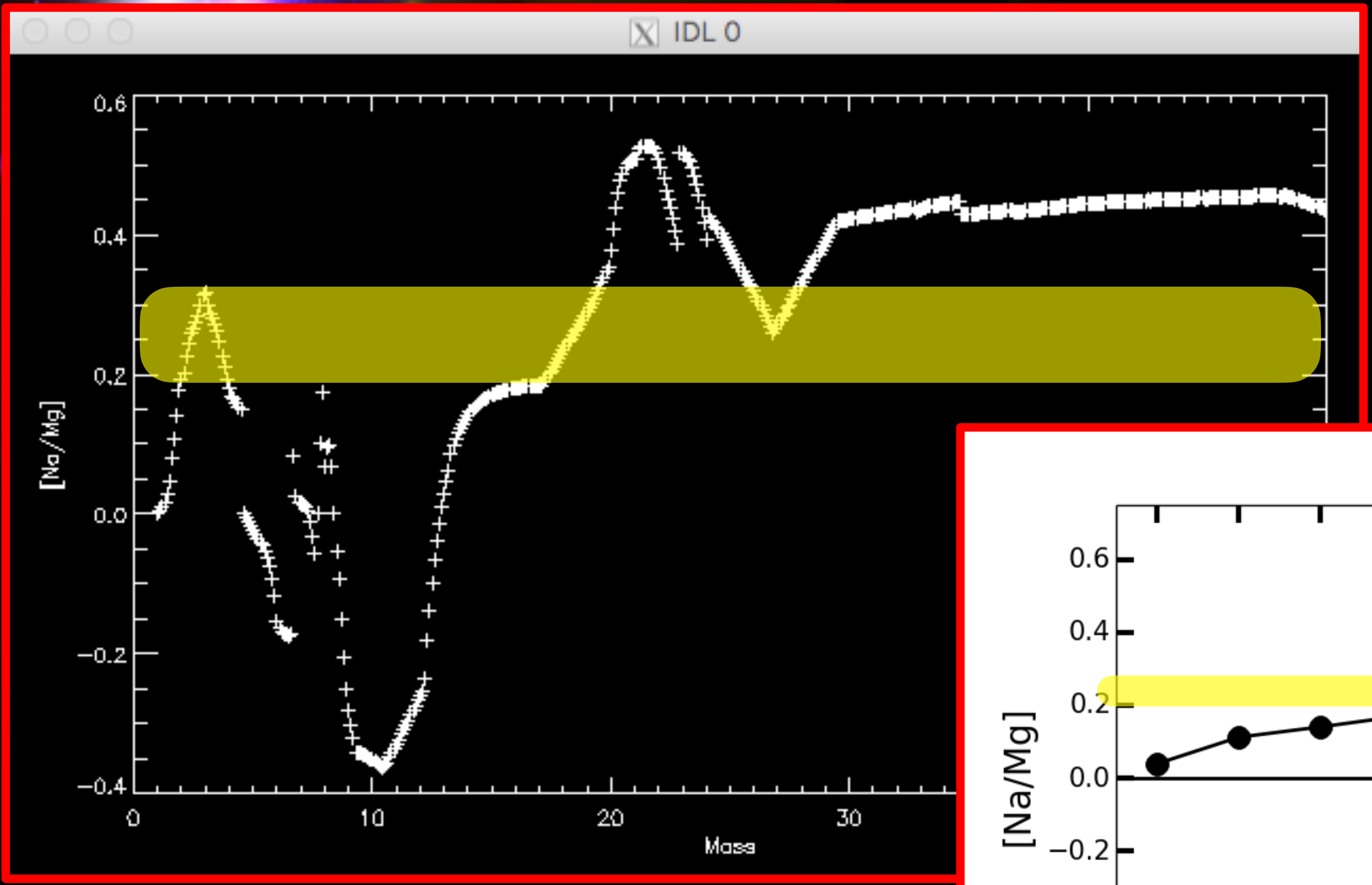
Conversely, elements produced primarily via explosive nucleosynthesis in the core and inner layers (e.g. iron), are less dependent upon the stellar mass m.

These trends hold regardless of yield compilation.



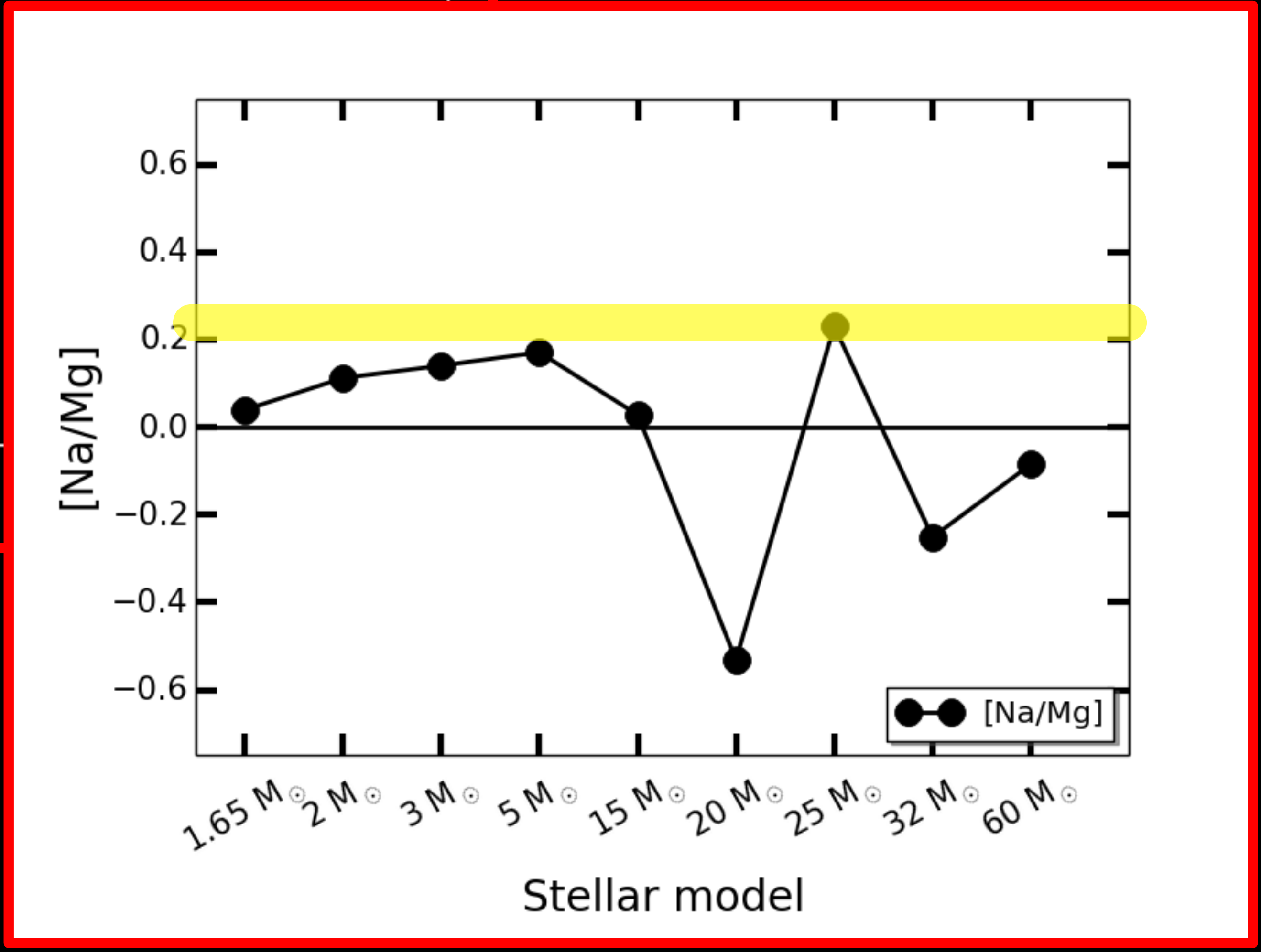
Cautionary Statement: Stellar Yields

NuGrid (Pignatari et al. 2016) is changing the landscape but we are not there yet…



Karakas (2010) +
Chieffi & Limongi (2004)

- M87:
  [Na/Mg] ~ +0.2 - +0.3



Pignatari et al (2016)

Galactic Winds

The first of the fundamental equations governs the rate of change of system gas mass (gas being the fuel for star formation).

Gas accretion rate: $M_\odot/yr$

$$\frac{dM_g(t)}{dt} = -\psi(t) + E(t) + A(t) - W(t)$$

Gas outflow rate: $M_\odot/yr$

Rate of change of the gas mass: $M_\odot/yr$

Star formation rate: $M_\odot/yr$

Gas returned to the ISM from dying stars: $M_\odot/yr$

Star formation reduces the available gas mass (hence the negative sign), as does any outflow from the system, while the gas returned by supernovae and planetary nebulae increases the system gas mass, as does the continual replenishment due to infalling gas.

Galactic Winds

Supernovae deposit not only the products of nucleosynthesis back into the interstellar medium (ISM), but also thermal and mechanical energy.

Signatures of this energy deposition are manifest in:

- increased turbulence of the ISM (impacting upon star formation)
- X-ray emission associated with hot gas within supernova remnants
- the powering of galactic winds, chimneys, holes, and fountains

Galactic Winds

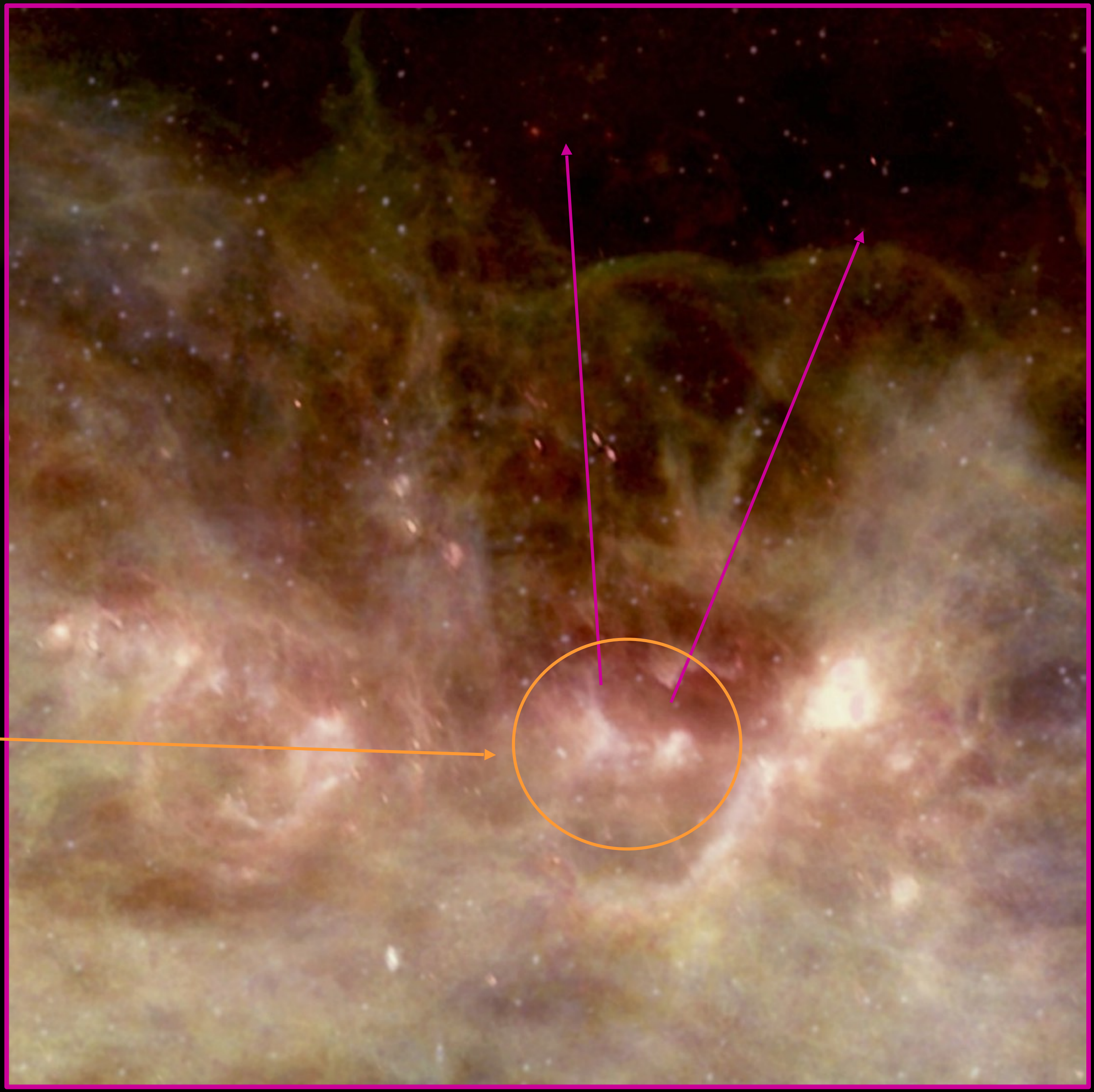
Galactic winds are exactly what the name imply … a wind carrying supernova ejecta and swept-up ISM gas, powered from behind by energy from the supernova explosion itself.

Galactic-scale winds can potentially evacuate all of the ISM associated with a galaxy, leading to pollution of the intracluster medium of galaxy clusters (or the intergalactic medium as a whole).

Galactic Winds

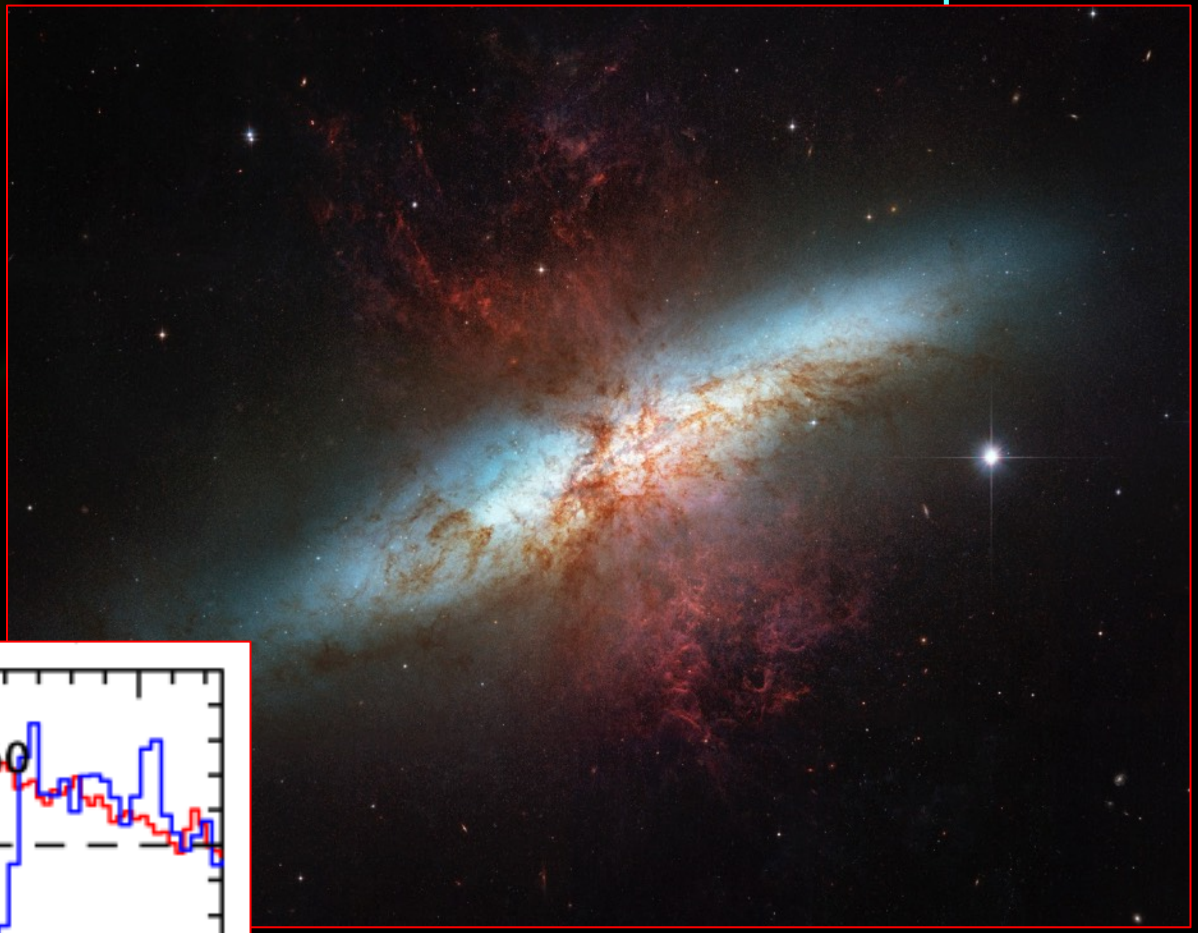
The W4 chimney (or superbubble) is funnelling hot gas from the Galactic disk to the lower halo.

The wind is being driven by the young open cluster OCl 352 in the centre of this neutral hydrogen image.

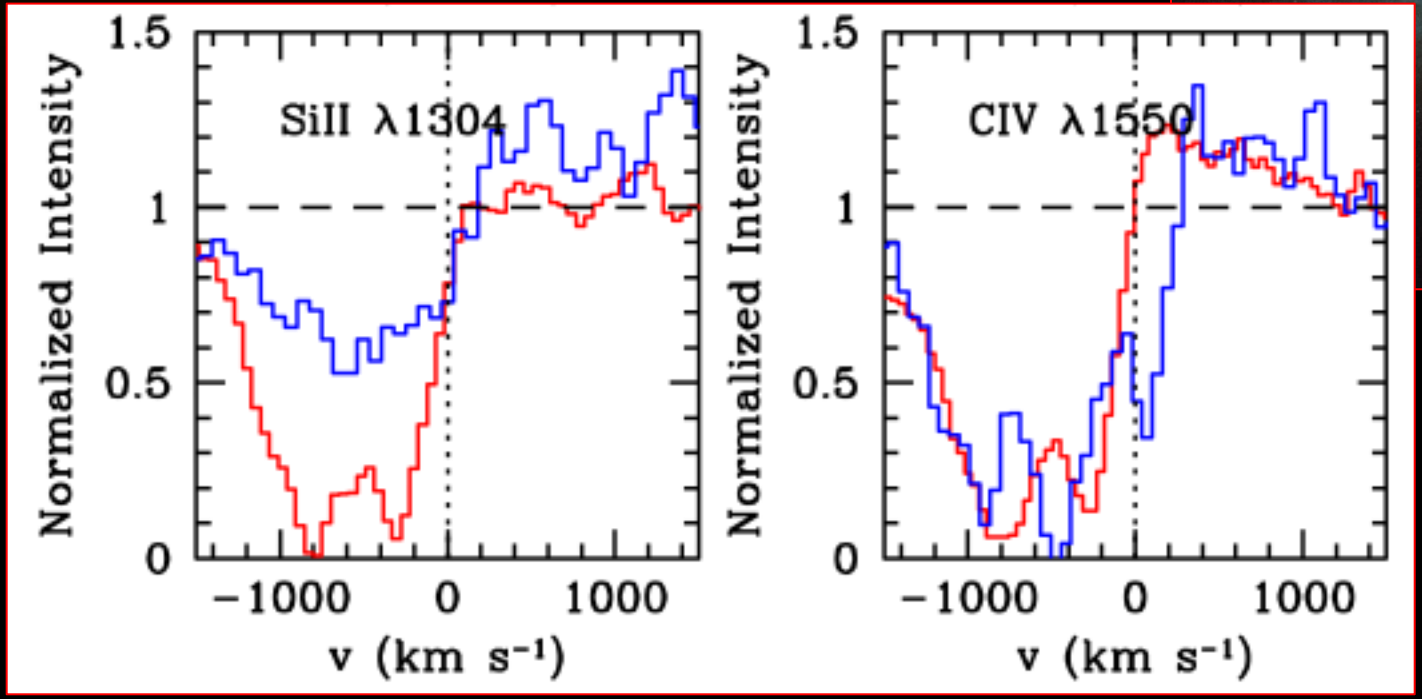


Galactic Winds

M82 Superwind

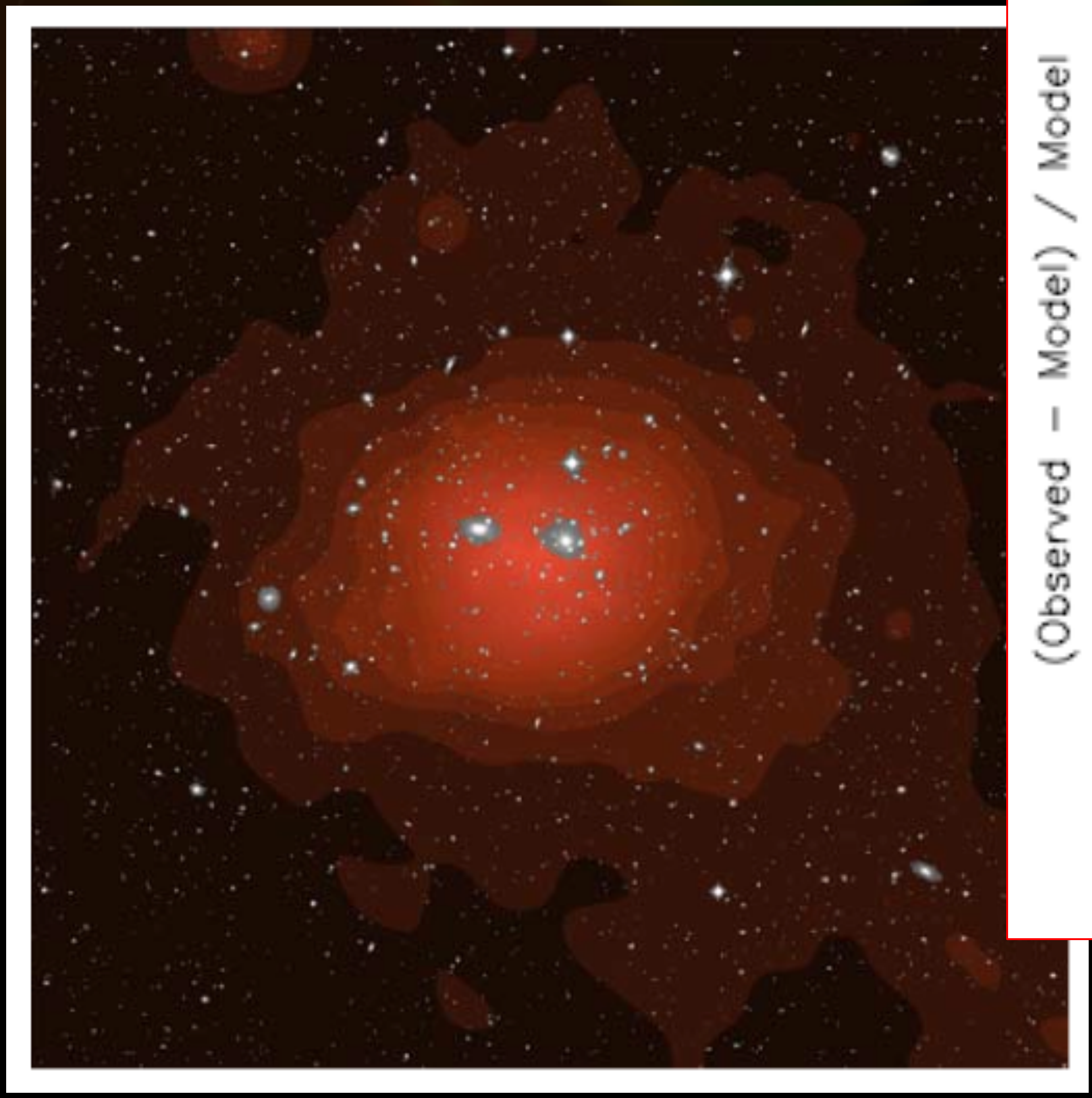


Two high-z Lyman Break Galaxies showing superwinds being driven with velocties upwards of ~1000 km/s

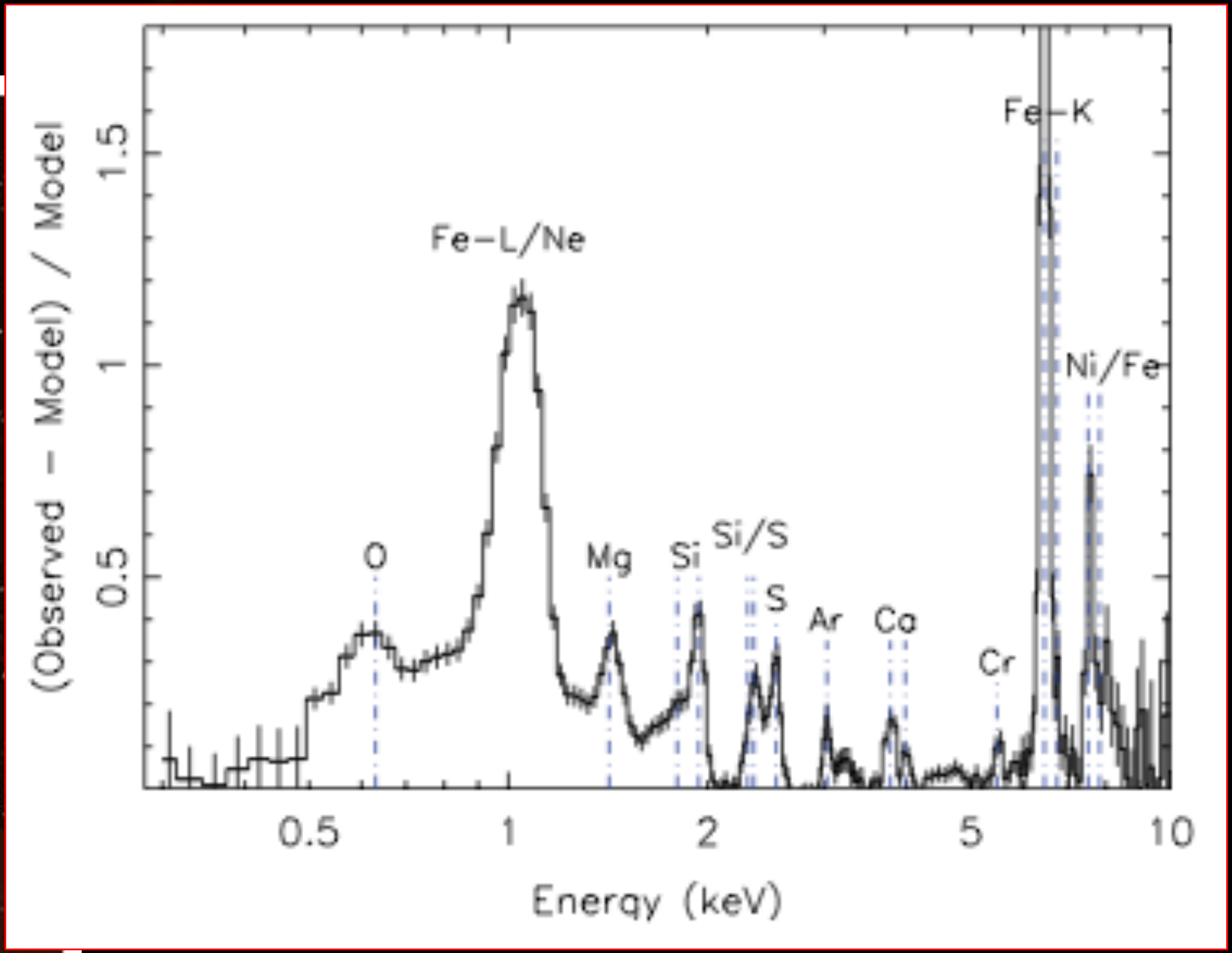


Metal-enriched Gas in Galaxy Clusters

X-ray observations of cluster gas show significant quantities of Fe, Si, O, Mg, and other heavy elements.



Coma Cluster in X-rays (w/ROSAT)



2A 0335+096 (w/XMM)

Galactic Chemical Evolution in One Slide

Semi-numerical Galactic Chemical Evolution codes boil down to a single 1st-order delay differential equation:

Evolution of element 'i'

$$\frac{\mathrm{d}G_i(t)}{\mathrm{d}t} = -\psi(t)X_i(t)$$

Depletion due to star formation

$$+\int_{M_L}^{M_{B_m}} \psi(t-\tau_m)Q_{\mathrm{mi}}(t-\tau_m)\phi(m)\mathrm{d}m$$

Low mass single stars

$$+A\int_{M_{B_m}}^{M_{B_M}} \phi(m)\left[\int_{\mu_{\mathrm{m}}}^{0.5} f(\mu)Q_{\mathrm{mi}}(t-\tau_{\mathrm{m}_2})\psi(t-\tau_{\mathrm{m}_2})\mathrm{d}\mu\right]\mathrm{d}m$$

SNe Ia

$$+(1-A)\int_{\mathrm{M_{B_m}}}^{M_{\mathrm{B_M}}} \psi(t-\tau_m)Q_{\mathrm{mi}}(t-\tau_m)\phi(m)\mathrm{d}m$$

Intermediate mass single stars

$$+\int_{\mathrm{M_{B_M}}}^{M_U} \psi(t-\tau_m)Q_{\mathrm{mi}}(t-\tau_m)\phi(m)\mathrm{d}m$$

SNe II

$$+\left(\frac{\mathrm{d}G_i(t)}{\mathrm{d}t}\right)_{\mathrm{infall}} - W(t)X_i(t) + \left(\frac{\mathrm{d}G_i(t)}{\mathrm{d}t}\right)_{\mathrm{acc}}, \qquad (1)$$

Early Infall Outflow Secondary Accretion

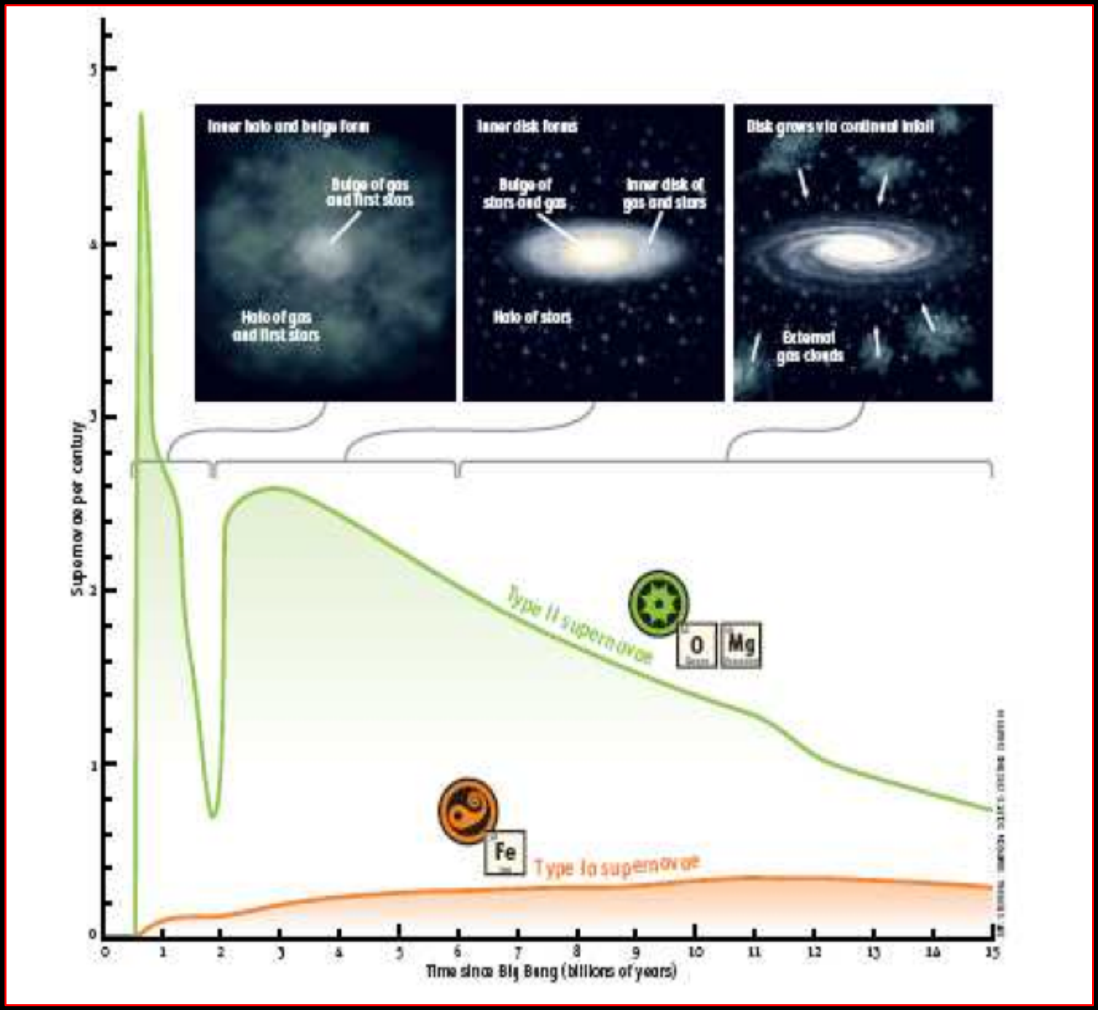
Spiral Galaxies

The tools described thus far - the so-called "simple, one-zone, closed-box" model - are adequate for (relatively) simple elliptical galaxies ... this is not the case for structurally complicated systems such as spiral galaxies.

Instead, more sophisticated "dual-infall" models are (generally) favoured.

⇒evolution of the halo and disk are treated independently and form out of two separate infall episodes

⇒ the first (halo and bulge) phase lasts no more than 1-2 Gyrs, while second (thin disk) phase acts over a longer timescale (6-8 Gyrs in the solar neighbourhood)



The Dual-Infall Approach

Fenner & Gibson (2003)

The infall rate term A(r,t) (aside: expanding from single-zone to multi-zone, but the basic equation of GCE applies to each zone) is defined as:

$$A(r,t) = a(r)e^{-t/\tau_H(r)} + b(r)e^{-(t-t_{max})/\tau_D(r)}$$

Halo term: $\tau_H \approx 1$ [Gyr]

Disk term: $\tau_D(r) \approx r$ [Gyr]

Details:

- t_{max} = time of maximum infall in disk phase
- a(r) and b(r) fixed to recover present-day mass surface density in solar neighbourhood

Disk timescale varying with galactocentric distance ⇒ "inside-out" galaxy formation

Formation and Evolution of the Milky Way: Two-Infall Formation

Fenner & Gibson (2003)

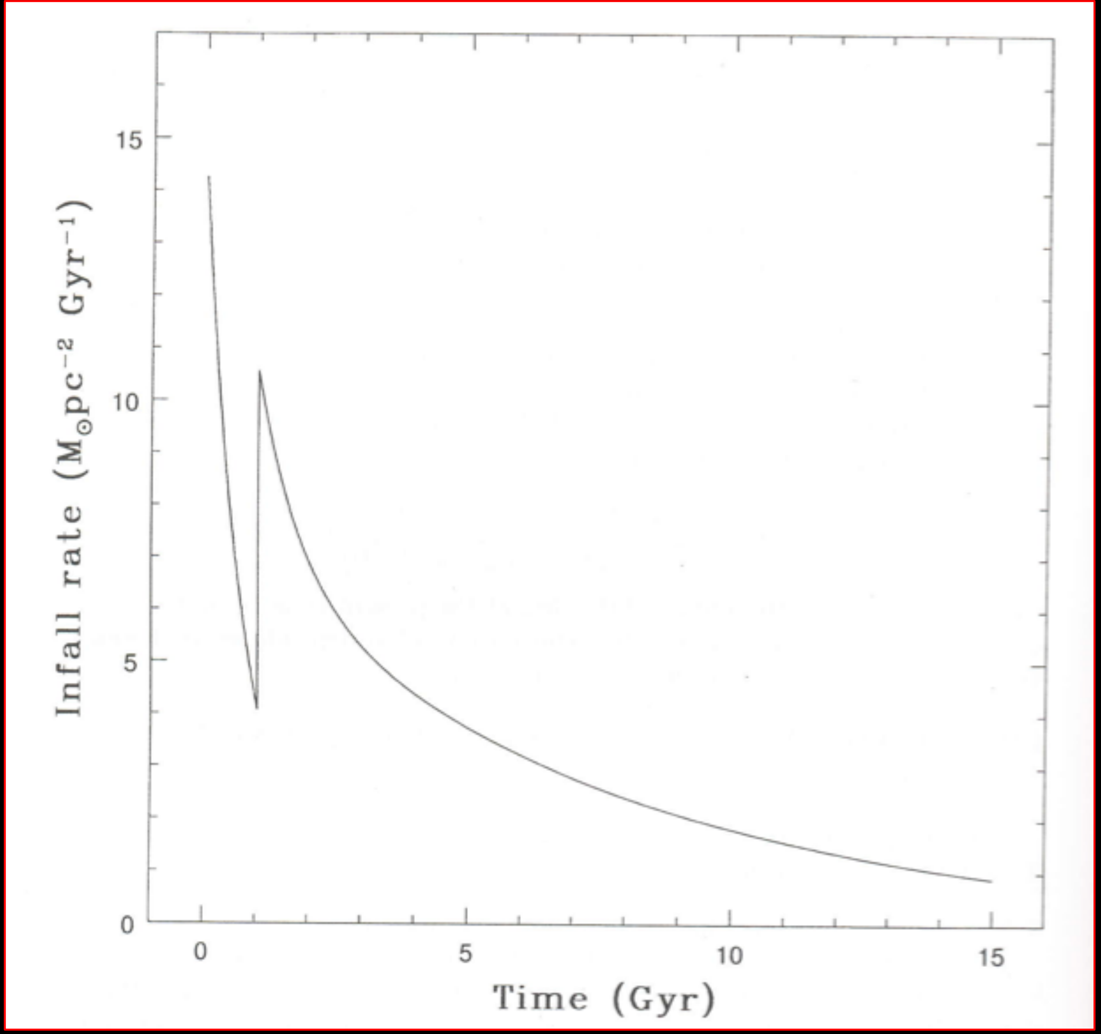
- in particular, the infall rate is expressed as:

$$X_{iA}A(t) = X_{iA}a(r)e^{-t/\tau_1} + X_{iA}b(r)e^{-(t-t_{max})/\tau_2(r)}$$

- $\tau_2(r)$ is a function of radius:

$$\tau_2(r) = 0.875r - 0.75 \ \ Gyr$$

- above gives 6-8Gyr timescale at solar circle
- long timescale means disk did not form out of gas lost by halo
- t_{max} is the time delay before peak of infall during disk phase



Formation and Evolution of the Milky Way: Two-Infall Formation

Fenner & Gibson (2003)

- star formation rate chosen to be function of gas density, as before, but there is a threshold in the gas density below which the SFR is assumed to go to zero:

$$\psi(r,t) = \frac{d\sigma_{gas}(r,t)}{dt} = \nu\left[\frac{\sigma(r,t)\sigma_{gas}(r,t)}{\tilde{\sigma}(\tilde{r},t)^2}\right]^{1.4}\sigma_{gas}(r,t)^{1.5}$$

- when $\sigma_{gas} > \sigma_{th} = 7\ M_{\odot}/pc^2$, and SFR=0, otherwise

Formation and Evolution of the Milky Way: Two-Infall Formation

- now, couple:

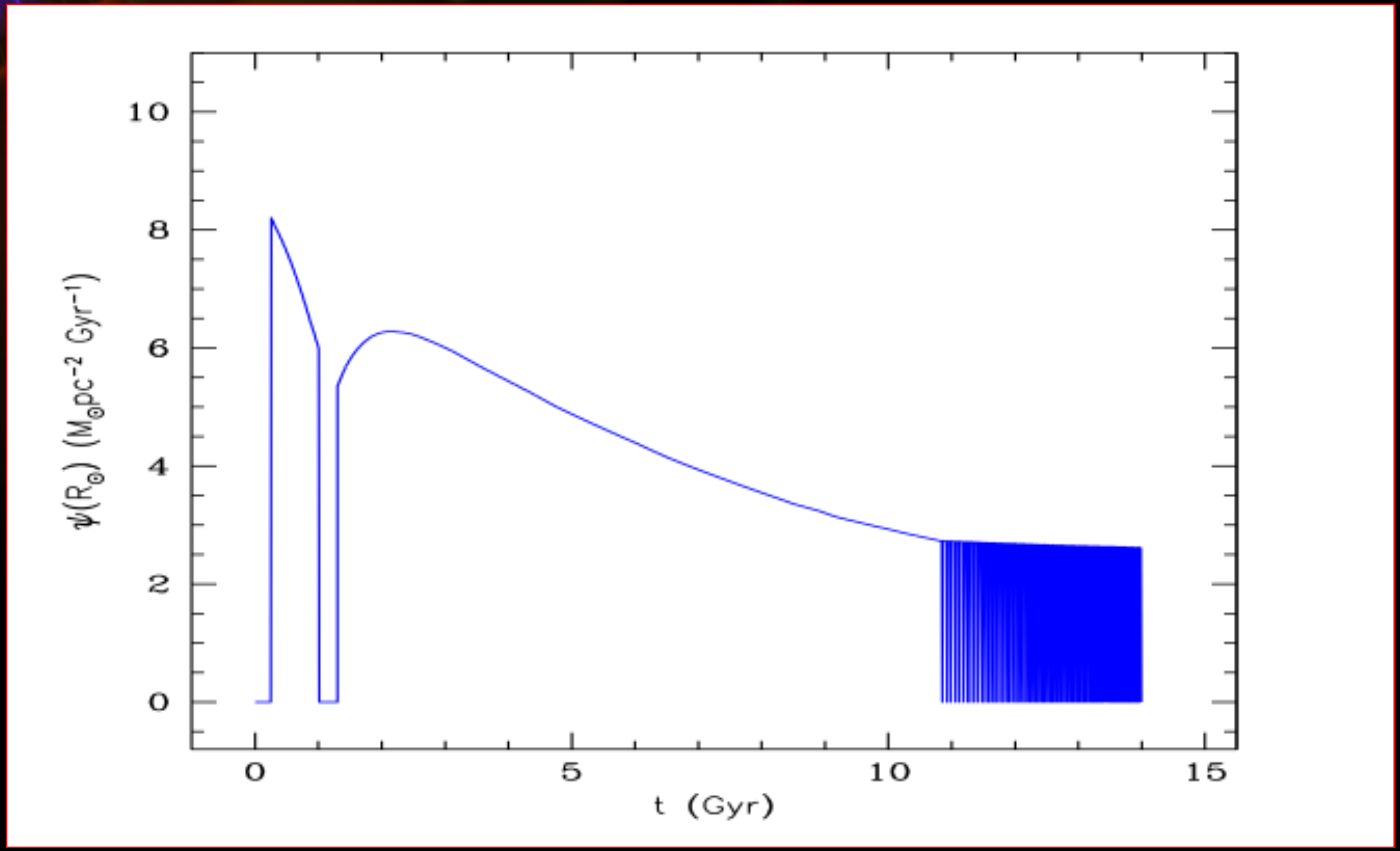
$$X_{iA}A(t) = X_{iA}a(r)e^{-t/\tau_1} + X_{iA}b(r)e^{-(t-t_{max})/\tau_2(r)}$$

- with:

$$\begin{aligned}\dot{\sigma}_i(t) = -\psi(t)X_i(t) + \int_{M_L}^{M_{Bm}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\varphi(m)dm + \\ A\int_{M_{Bm}}^{M_{BM}} \varphi(m)[\int_{\mu_{min}}^{0.5} f(\mu)\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})d\mu]dm + \\ (1-A)\int_{M_{Bm}}^{M_{BM}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\varphi(m)dm + \\ \int_{M_{BM}}^{M_U} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\varphi(m)dm + X_{iA}(t)A(t) - X_i(t)W(t)\end{aligned}$$

The Dual-Infall Approach

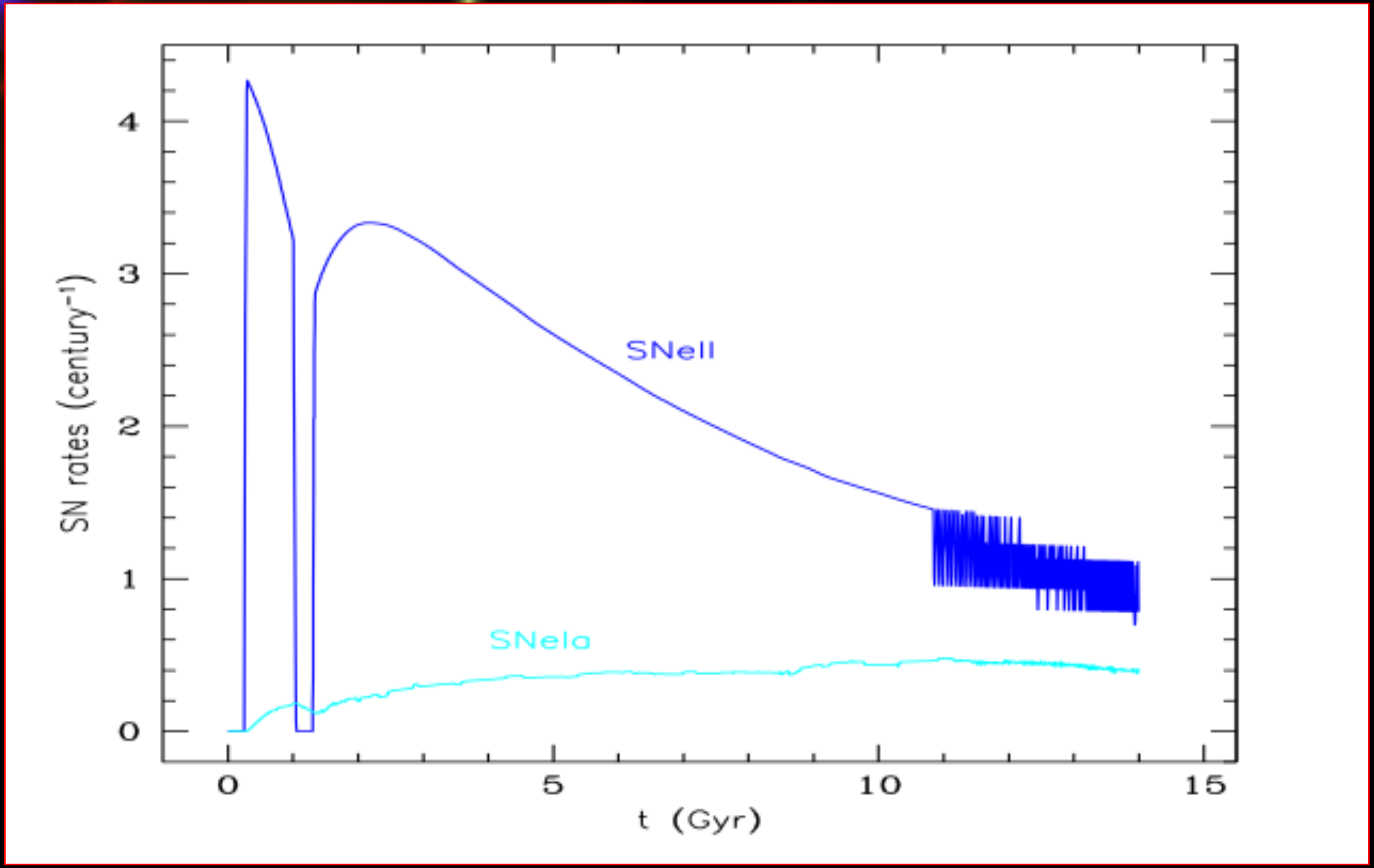
Star formation rate in the solar neighbourhood:



Oscillatory behaviour at lates times and the gap between the halo and disk phases due to the imposition of a star formation threshold

The Dual-Infall Approach

Supernovae rates in the solar neighbourhood:



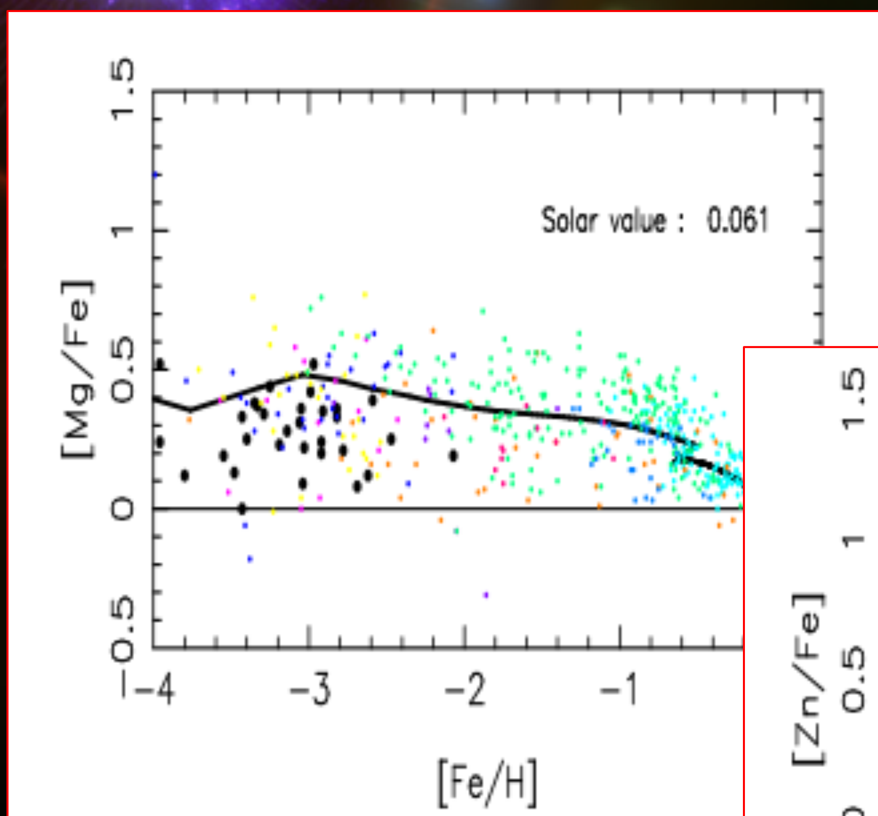
The Dual-Infall Approach

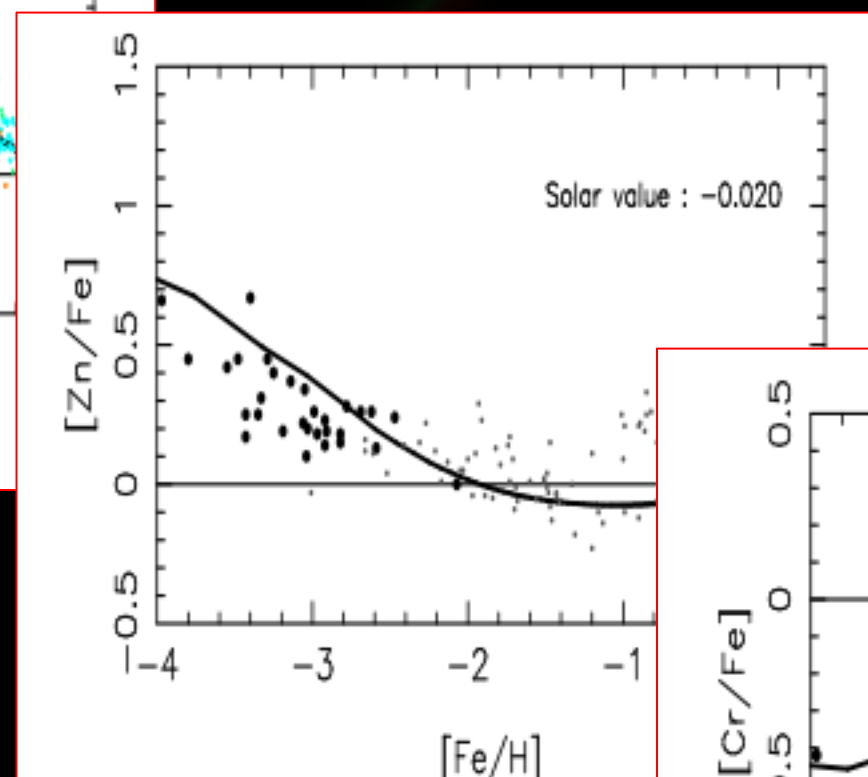
The main observational constraints that any model calibrated upon the solar neighbourhood must be consistent with:

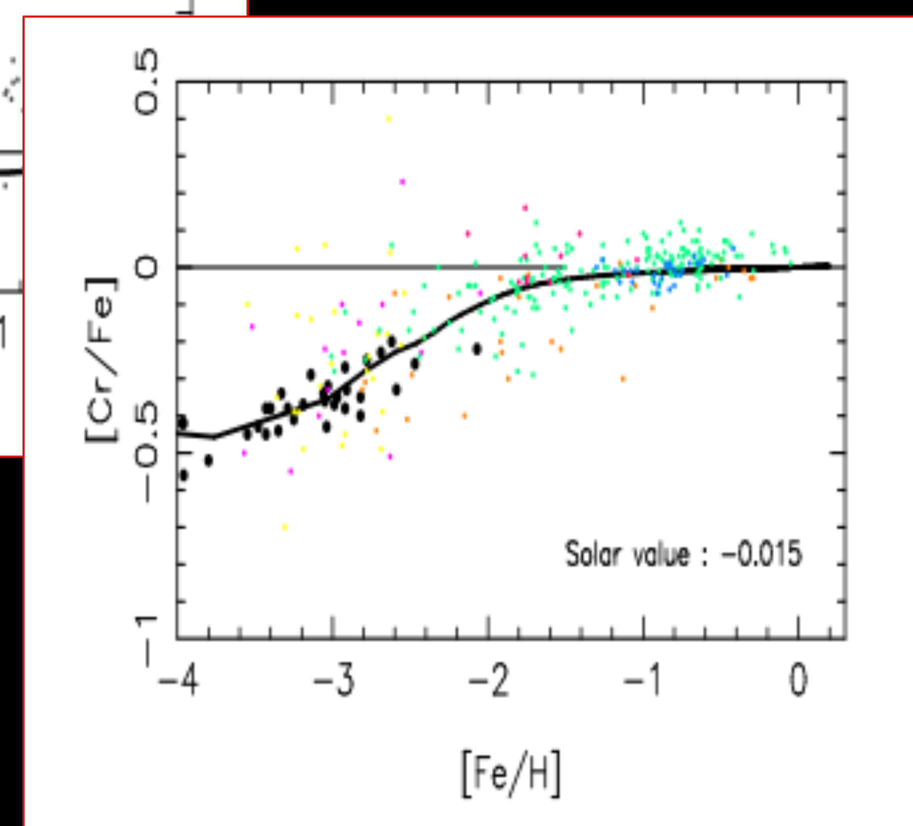
- The present time surface gas density: $\sigma_{gas} = 13 \pm 3 M_{\odot} pc^{-2}$
- The present time surface star density $\sigma_{*} = 43 \pm 5 M_{\odot} pc^{-2}$
- The present time total surface mass density: $\sigma_{tot} = 51 \pm 6 M_{\odot} pc^{-2}$
- The present time SFR: $\psi_o = 2 - 5 M_{\odot} pc^{-2} Gyr^{-1}$
- The present time infall rate: $0.3 - 1.5 M_{\odot} pc^{-2} Gyr^{-1}$
- The present day mass function (PDMF)
- The solar abundances, namely the chemical abundances of the ISM at the time of birth of the solar system 4.5 Gyr ago as well as at the present time abundances
- The observed $[X_i/\mathrm{Fe}]$ vs. [Fe/H] relations
- The G-dwarf metallicity distribution
- The age-metallicity relation

The Dual-Infall Approach

Abundance Patterns in the Solar Neighbourhood



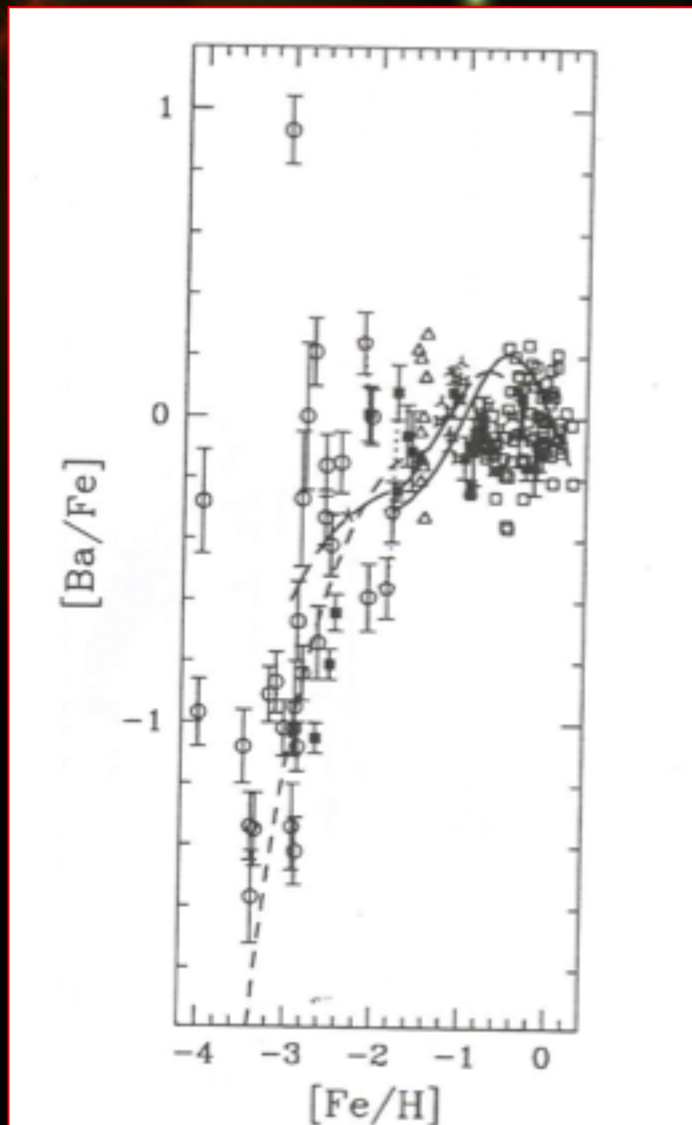


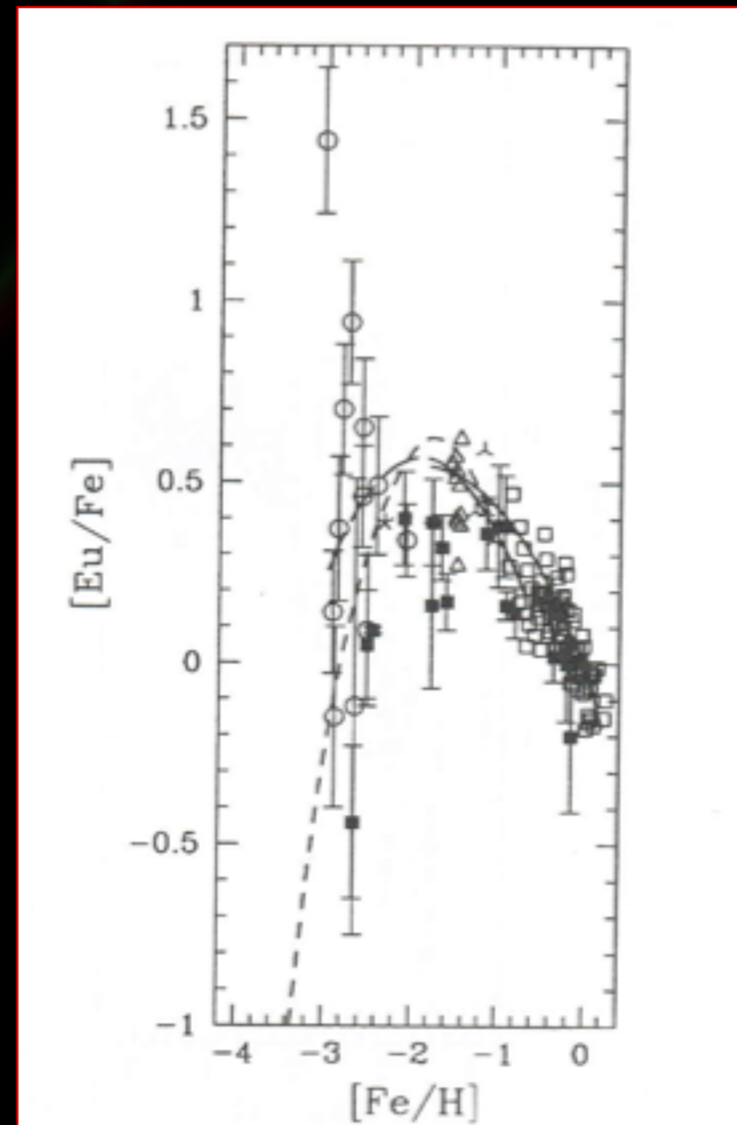


Formation and Evolution of the Milky Way: Evolution of the Solar Neighbourhood

- summarise typical s- and r-process elements (Ba and Eu, respectively)

- Ba at very low [Fe/H] suggests there is also an r-process component
- scatter in Ba at low [Fe/H] not fully understood



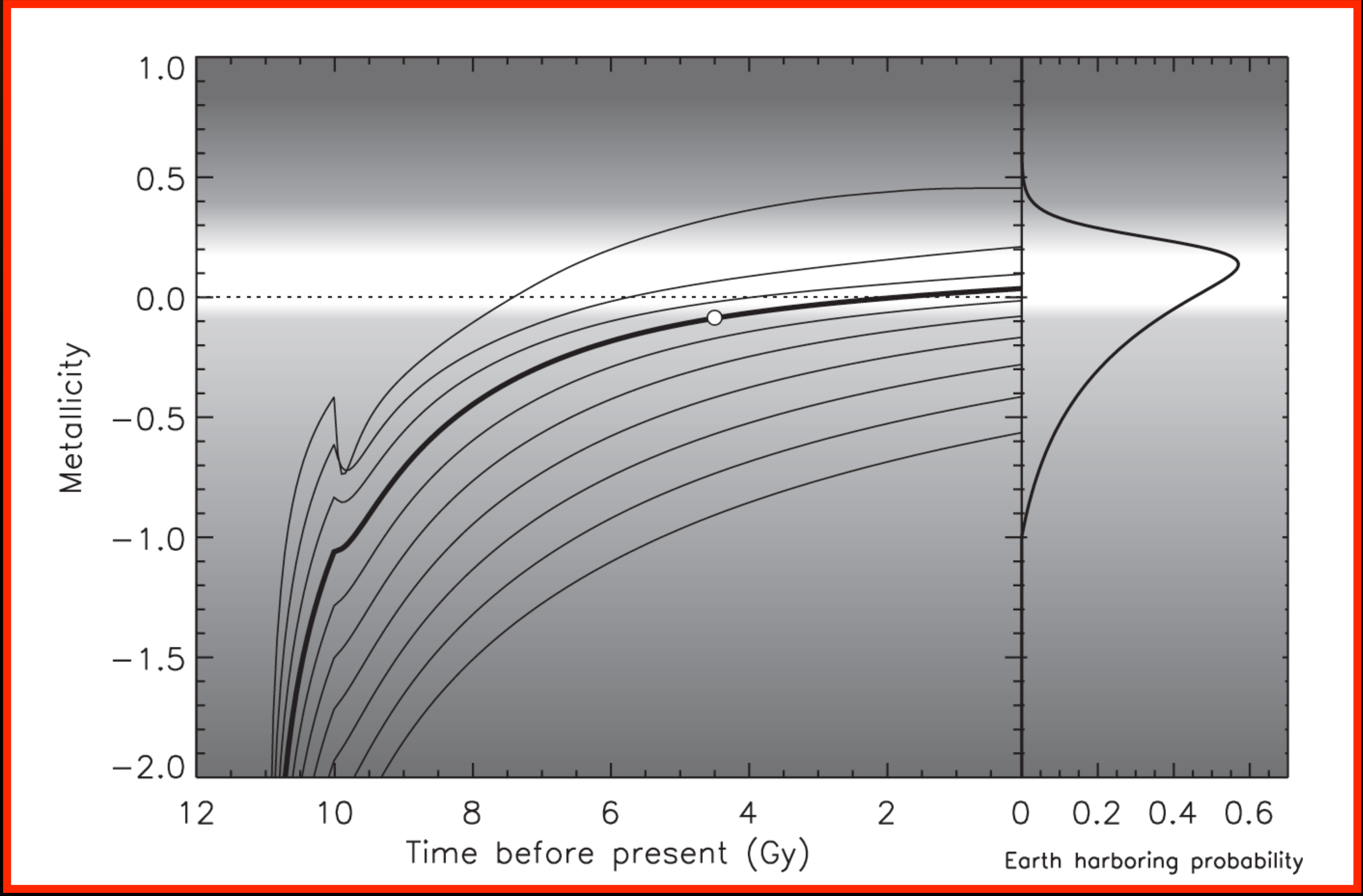


- Eu at very low [Fe/H] suggests it comes from 8-10Msun stars but not the highest mass SNeII (unlike the alpha-elements)

The Dual-Infall Approach

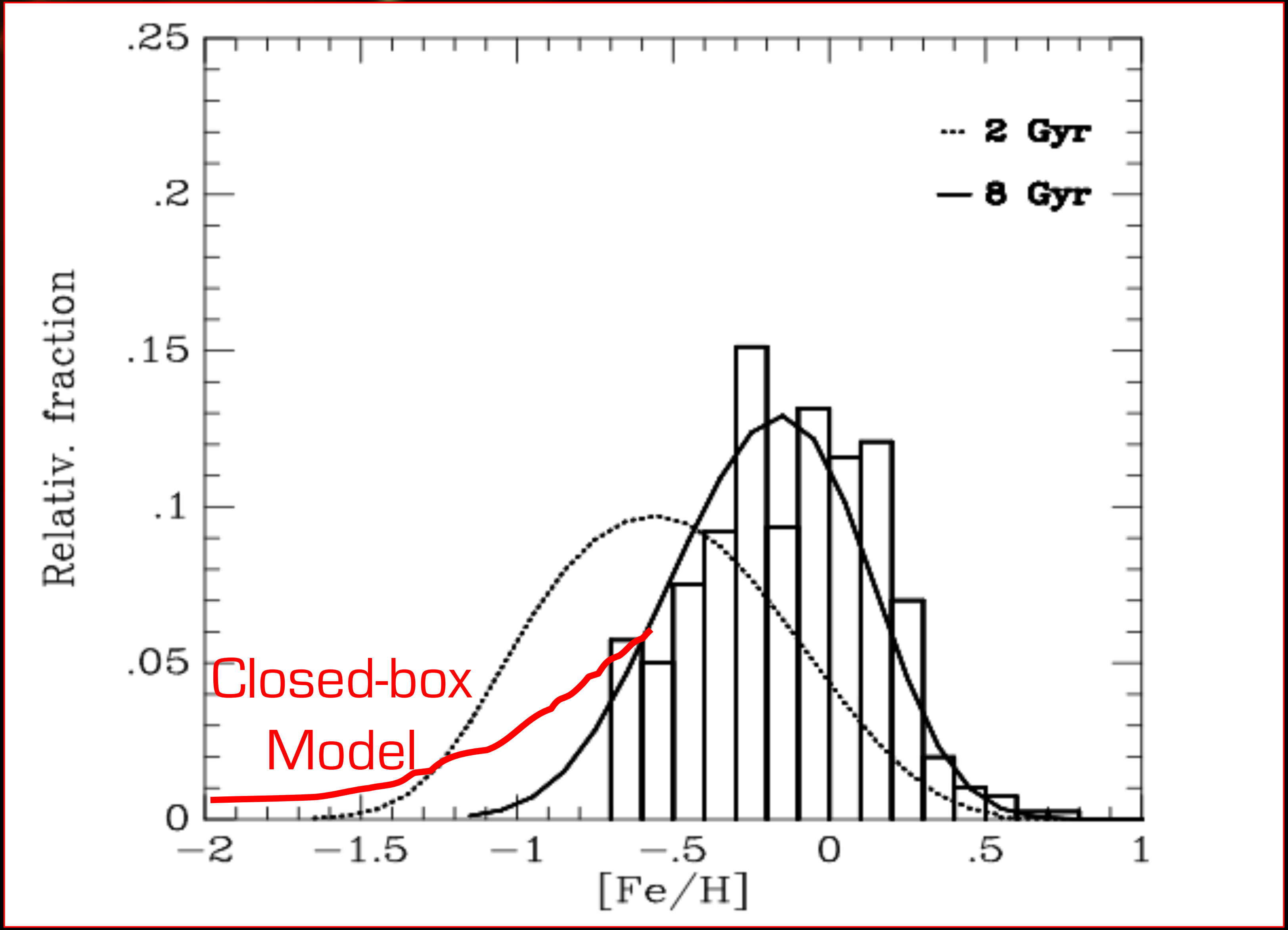
Lineweaver, Fenner & Gibson (2004)

- the age-metallicity relation: rapid increase in metallicity during the ‘halo phase’, followed by relatively gentle increase in metallicity during the ‘disk phase’



The Dual-Infall Approach

The Metallicity Distribution Function:

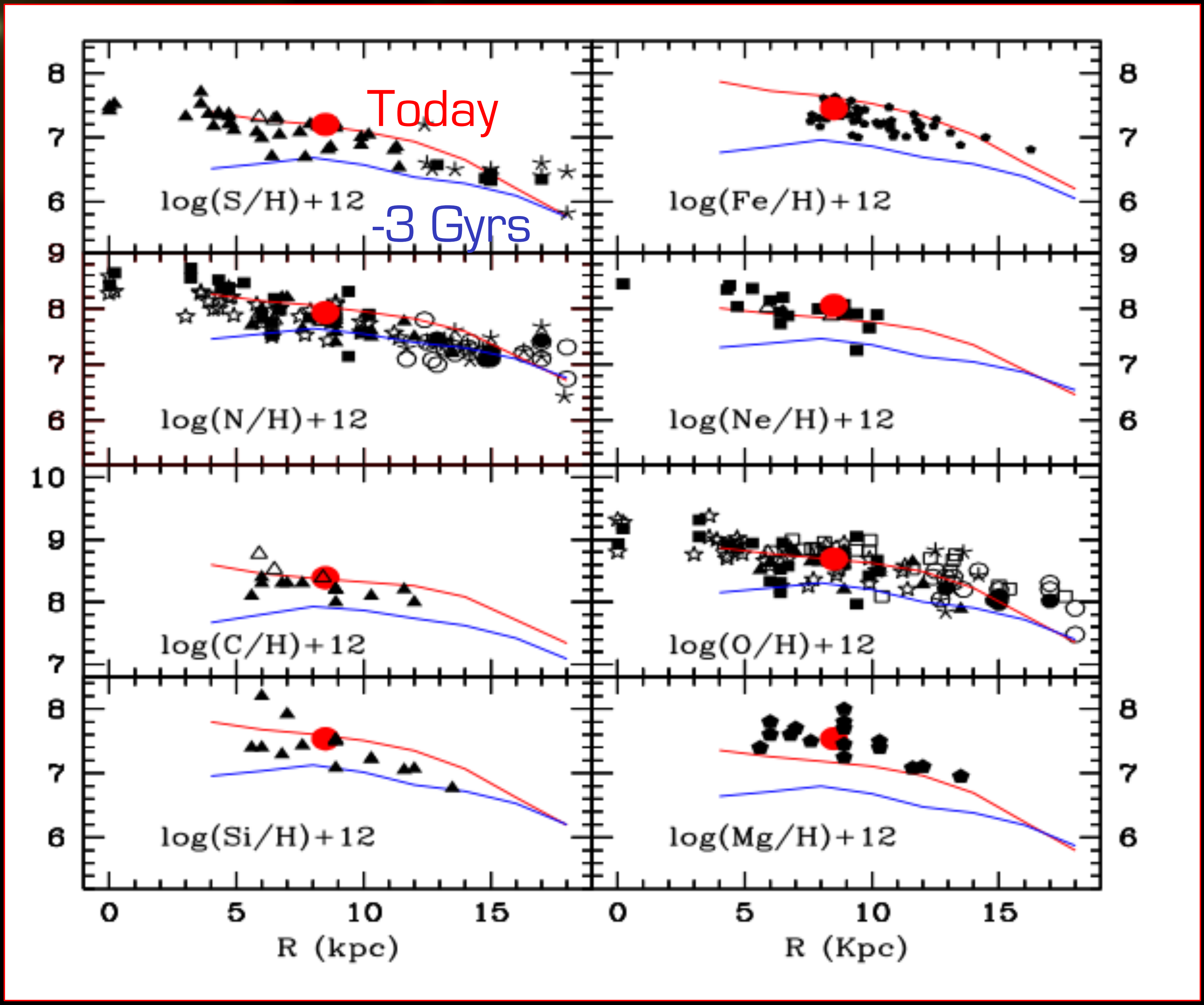


The Dual-Infall Approach

Pilkington et al. (2012); Gibson et al. (2013)

Abundance Gradients

- steepens with age, driven by the "inside-out" form of the imposed infall term



The Dual-Infall Approach

Basic conclusions we can derive about the Milky Way from chemical abundances and galactic chemical evolution:

- The inner halo formed on a timescale of 1-2 Gyr at maximum, the outer halo formed on longer timescales perhaps from accretion of satellites or gas.
- The disk at the solar ring formed on a timescale not shorter than 7 Gyr.
- The whole disk formed inside out with timescales of the order of 2 Gyr or less in the inner regions and 10 Gyr or more in the outermost regions.
- The abundance gradients arise naturally from the assumption of the inside-out formation of the disk. A threshold density for the star formation helps in steepening the gradients in the outer disk regions.
- The bulge is very old and formed very quickly on a timescale smaller than even the inner halo and not larger than 0.5 Gyr.
- The IMF seems to be different in the bulge and the disk, being flatter in the bulge, although more abundance data are necessary before drawing firm conclusions.

GCE: Background Reading

- Gibson et al. (2003)… https://ui.adsabs.harvard.edu/abs/2003PASA...20..401G/abstract
- Molla et al. (2015)… https://ui.adsabs.harvard.edu/abs/2015MNRAS.451.3693M/abstract
- NuPyCEE… https://github.com/NuGrid/NuPyCEE
- ChemPy… https://github.com/bjodah/chempy