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Formation of Galactic Halo Globular Clusters through Self-Enrichment

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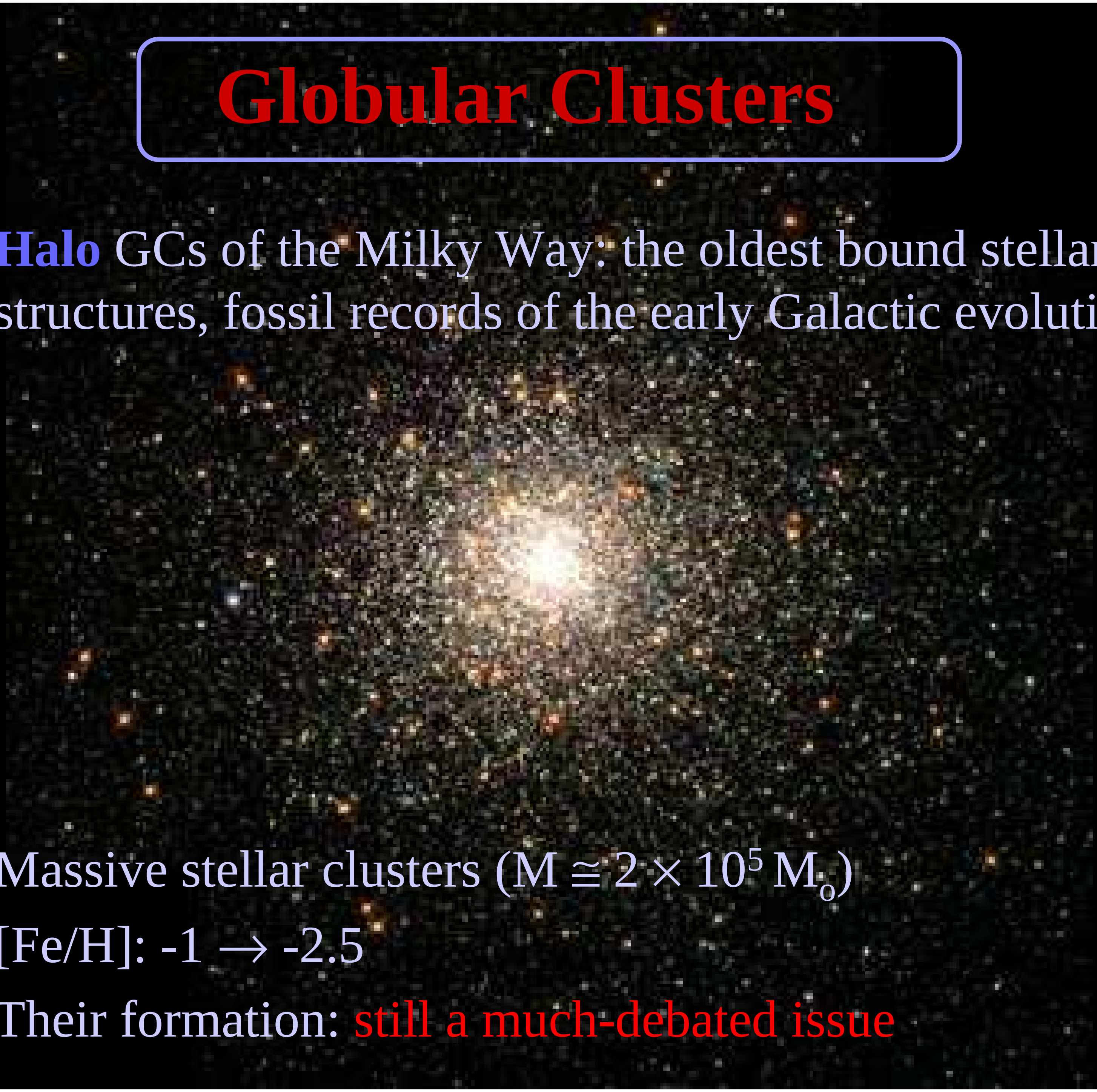
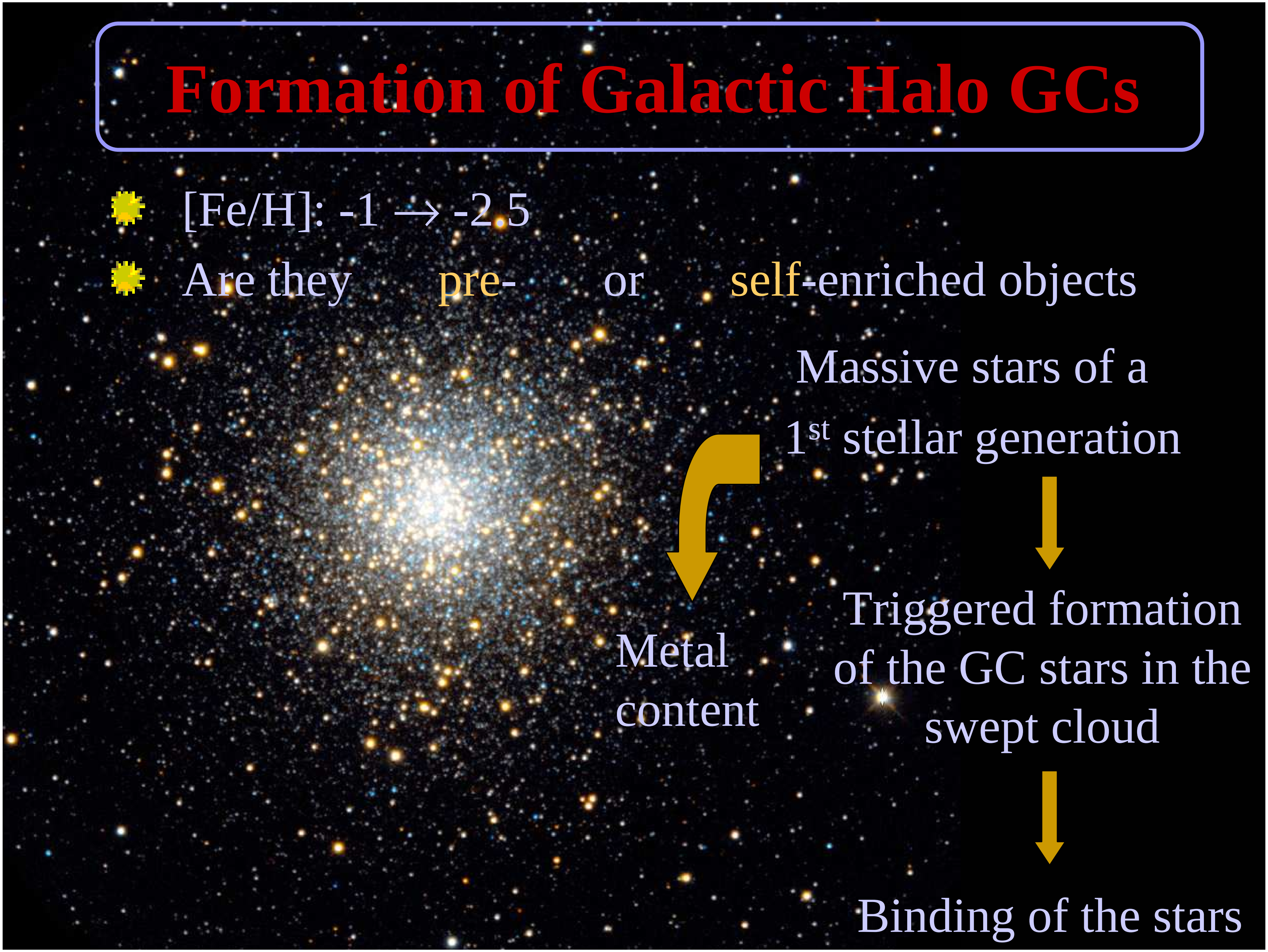
Peer-reviewed papers and proceedings are available at :
http://vela.astro.ulg.ac.be/themes/stellar/halos/index.html

Globular Clusters



- **Halo** GCs of the Milky Way: the oldest bound stellar structures, fossil records of the early Galactic evolution
- Massive stellar clusters ($M \cong 2 \times 10^5 M_o$)
- [Fe/H]: -1 → -2.5
- Their formation: still a much-debated issue

Formation of Galactic Halo GCs



- [Fe/H]: -1 → -2.5
- Are they pre- or self-enriched objects

Massive stars of a 1st stellar generation

↓

Triggered formation of the GC stars in the swept cloud

↓

Binding of the stars

Metal content

Outline

- **The Self-Enrichment model**

  Were the Proto-Globular Cluster Clouds able to sustain a SNII phase ?

- **The Metallicity Gradient**

  First consequence of the self-enrichment model

- **The Mass-Metallicity Relation**

  Second consequence of the self-enrichment model

- **The Transverse Collapse of the Supershell**

  Is there an episode of triggered star formation within the shell ?

- **M82 B: an Extragalactic System of Massive Stellar Clusters**

  The formation of massive clusters is not restricted to the protogalactic era

The Self-Enrichment Model

- Galactic halo GCs: expands the Fall & Rees (1985) model
- Collapse of the protogalaxy:
  cold $(T \sim 10^4$ K) and dense clouds embedded in a
  hot $(T \sim 10^6$ K) and diffuse protogalactic background
- Primordial medium $(Z = 0)$
- Cold Clouds = GC progenitors = PGCCs
  - Iso-T spheres in hydrostatic equilibrium
  - Pressure equilibrium → $P(R) = P_h$

$$M = \sqrt{\frac{2}{\pi}}\left(\frac{\boxed{kT}}{\mu m_H}\right)^2 G^{-3/2}\,\boxed{P_h^{-1/2}}$$

$$R = \sqrt{\frac{1}{2\pi}}\left(\frac{\boxed{kT}}{\mu m_H}\right) G^{-1/2}\,\boxed{P_h^{-1/2}}$$

First Stellar Generation (Z=0)

- Formation of a first stellar generation in the central regions of each PGCC
- Type II Supernovae
  - Chemical enrichment of the primordial cloud up to the present GC metallicity

Self-Enrichment

→ the cloud is its own source of chemical enrichment

  - PGCC → expanding shell ≡ compressed layer of gas

Triggered formation of a second stellar generation with $Z \neq 0$

→ Shell of stars = Proto-Globular Cluster

Cayrel (1986), Brown, Burkert & Truran (1991, 1995)

Dynamical Constraint on the SNII Number

- Recurrent argument **against** self-enrichment:

  binding energy of GCs < kinetic energy of a single SN

  $$\frac{GM_{GC}^2}{R_{GC}} = 10^{50}\,\mathrm{ergs} < E_{SNII} = 10^{51}\,\mathrm{ergs}$$

  a still gaseous proto-cluster is immediately disrupted:
  GCs are not self-enriched systems (e.g. Meylan & Heggie 1997)

- **BUT:** released kinetic energy ≠ kinetic energy of the ISM
  ⇒ other criterion for disruption:
  progenitor cloud binding energy ↔ shell kinetic energy

  $$\frac{GM^2}{R} = \frac{1}{2} M_s(t_{em}) \dot{R}_s(t_{em})$$

Parmentier et al. 1999, A&A 352, 138

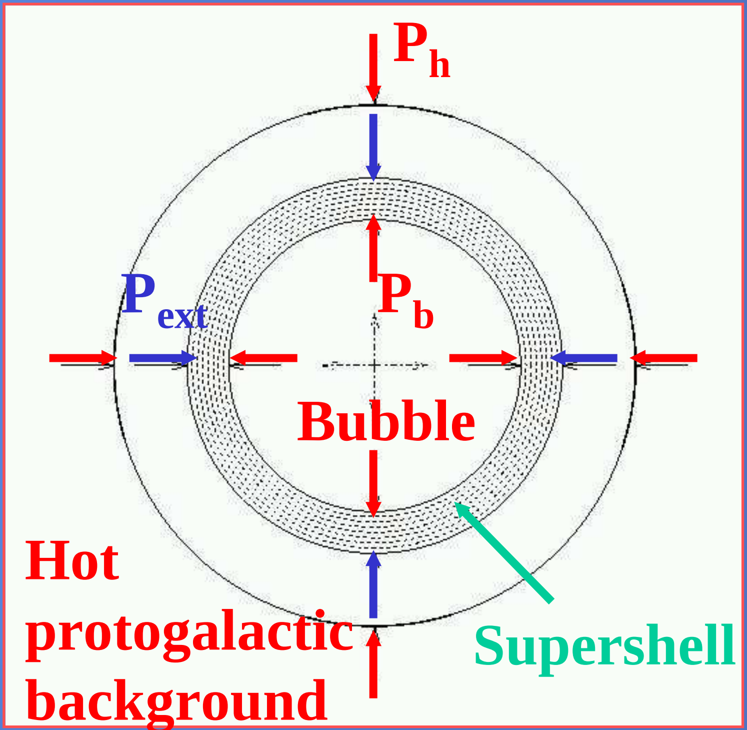
Supershell Propagation through the PGCC : $\dot{R}_S = \dot{R}_S(N_{SNII})$

$$\dot{E}_b = \dot{E}_0 - 4\pi R_s^2 P_b \dot{R}_s$$

$$\frac{4\pi}{3} R_s^3 P_b = \frac{2}{3} E_b$$

$$\frac{d}{dt}\left[M_s \dot{R}_s\right] = 4\pi R_s^2 (P_b - P_{ext}) - \frac{GM_s^2}{2R_s^2}$$

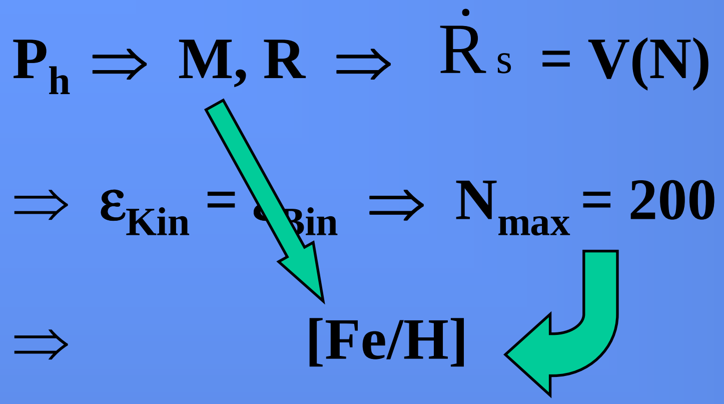
$$M_s(t) = \frac{M}{R} R_s(t)$$



Castor, McCray & Weaver (1975)

$$\dot{N} = cst \Rightarrow \dot{R}_s(t) = V \Rightarrow \boxed{3V^3 + 3\left(\frac{kT}{\mu m_H} + \frac{GM}{2R}\right)V = 2\dot{N}\frac{R}{M}}$$

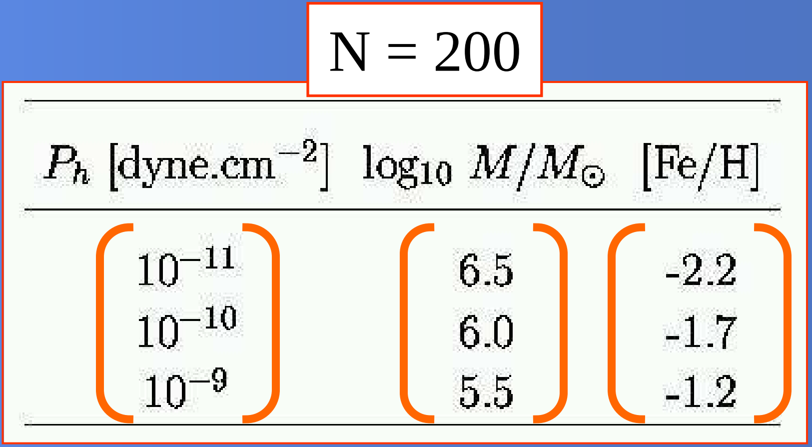
Dynamical Constraint and Self-Enrichment Level



$P_h \Rightarrow M, R \Rightarrow \dot{R}_s = V(N)$

$\Rightarrow \varepsilon_{Kin} = \varepsilon_{Bin} \Rightarrow N_{max} = 200$

$\Rightarrow$ [Fe/H]



N = 200

P_h [dyne.cm^{-2}]	$\log_{10} M/M_\odot$	[Fe/H]
10^{-11}	6.5	-2.2
10^{-10}	6.0	-1.7
10^{-9}	5.5	-1.2

- PGCC masses (within F&R) can be self-enriched up to Galactic halo metallicities

Observational Tests

- Dependence of the self-enrichment level on the hot protogalactic background pressure, P_h

$\Rightarrow$ Metallicity gradient

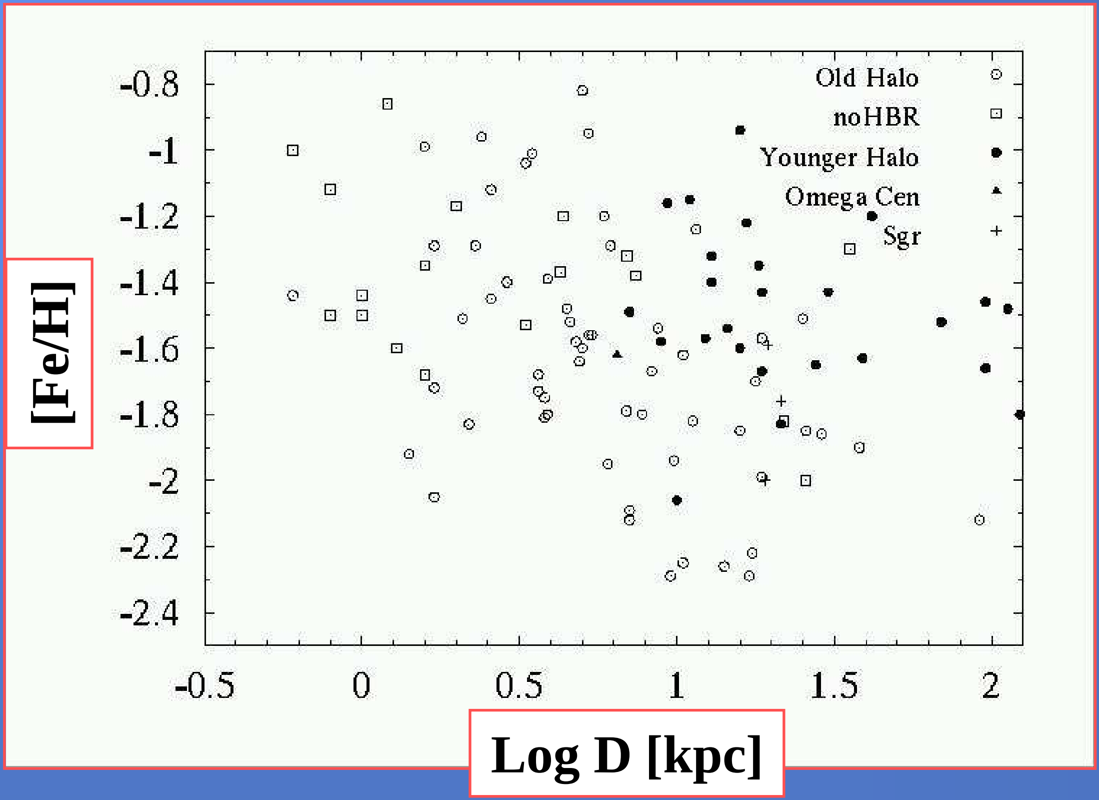
- Relation between the PGCC mass and their self-enrichment level

$\Rightarrow$ Mass-metallicity relationship

The Metallicity Gradient

- **Is there a Metallicity Gradient ?**

  - Whole Galactic halo:
    No clear-cut
    metallicity gradient



Linear Pearson correlation coefficient: **-0.3**

But: the Galactic halo is made of two sub-populations

Based on differences such as:

- the HB morphology (Lee et al. 1993),
- the age (Rosenberg et al. 1999),
- the kinematics & orbit shape (Dinescu et al. 1999),
- the galactocentric distance & spatial distribution (Hartwick 1987),

Zinn (1993):

Galactic Halo =

Old Halo

GCs formed during the collapse of the protogalactic cloud

\+

Younger Halo

- GCs formed in satellite systems and accreted later on

e.g.: dwarf galaxy Sagittarius
⇒ M54, Arp2, Ter7, Ter8 included in the halo (Ibata et al. 1994)

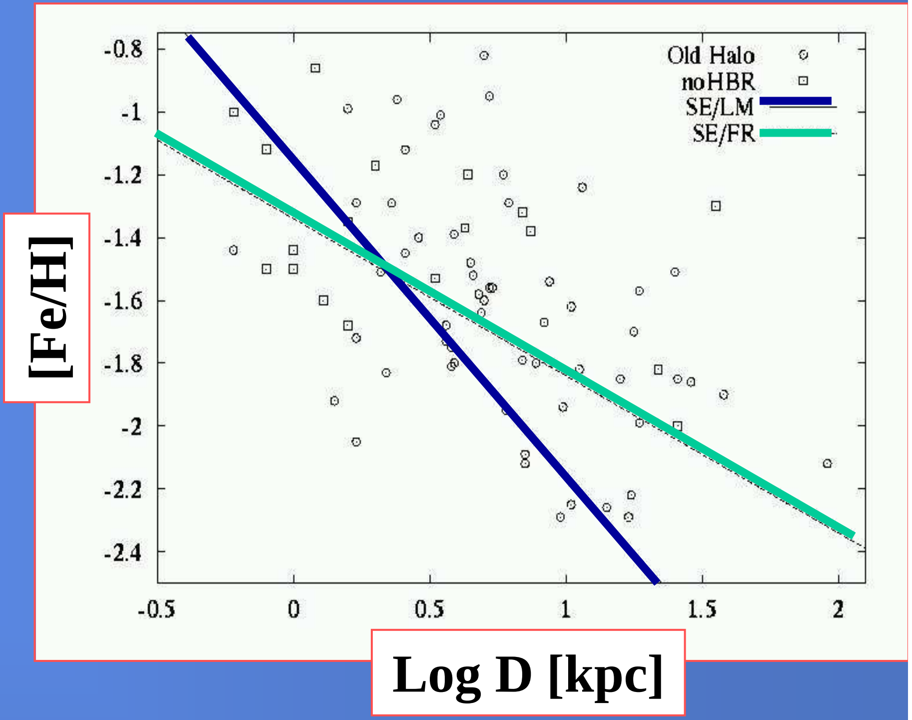
- **“contamination”of the genuine Galactic GCS**

Comparison between the Model and the OH Gradient

- In contrast with the whole halo, the **Old Halo** exhibits a **significant metallicity gradient**

Linear Pearson correlation coef.:

$r = -0.5$ with $\wp = 99.999\%$



- Relation between [Fe/H] and P_h (self-enrichment, N=200)

$$[Fe/H] = 3.3 + 0.5 \log P_h$$

No need for an age-metallicity relation

Parmentier et al. 2000, A&A 363, 526

The Mass-Metallicity Relation

- **The lack of a Mass-Metallicity Relation against Self-Enrichment**
  - At first glance, no mass(luminosity)-metallicity relation among any GCS ⇒ also an often used argument against the self-enrichment hypothesis *(e.g. Djorgovski & Meylan 1994)*
  - Dwarf galaxies exhibit a well-defined mass-metallicity relation in the sense that the most metal-poor are the dimmest ones.

▲ To compare GCs and dwarfs does not make sense !

No DM	DM
1 burst SF	Several bursts SF
$\Delta[\mathrm{Fe/H}] \leq 0.1$dex	$\Delta[\mathrm{Fe/H}] \approx 1$dex

- “More massive objects are better able to retain their metal-enriched ejecta”

  ⇒ Should [Fe/H] increase with M in case of self-enrichment ?

  (e.g. McLaughlin 1997, Barmby et al.2000)

  - Not necessarily: if a more massive object is indeed better able to retain more SN ejecta, this larger amount of metallic ejecta is mixed with a larger amount of gas

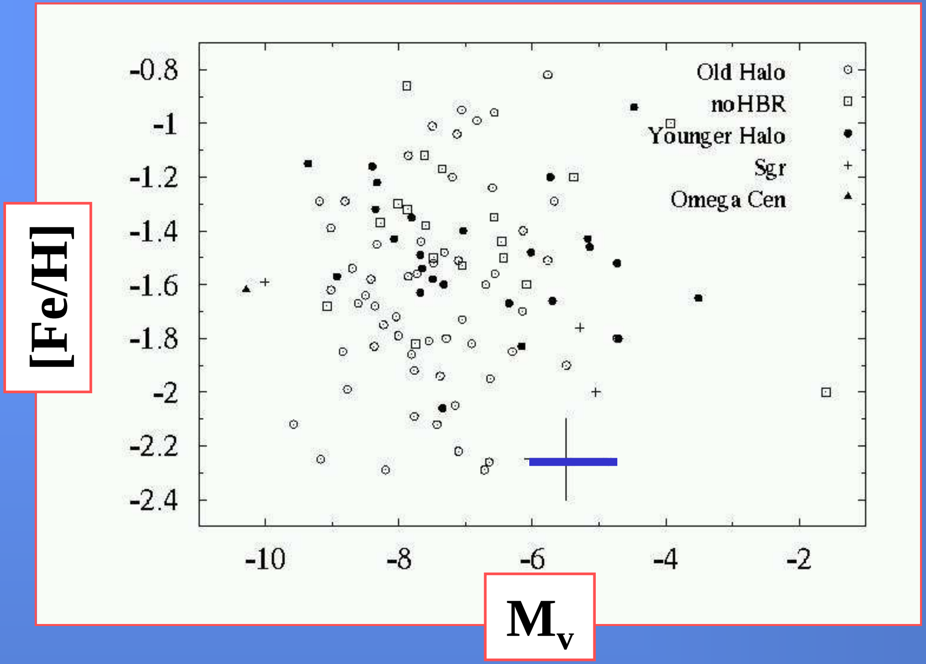
    ⇒ no firm conclusion about [Fe/H] since

    it depends on the ratio of two increased quantities !

  - This SE model (N=200): the most metal-rich proto-GCs are the least massive ones.

$$\boxed{[\mathrm{Fe/H}] = 4.35 - \log M}$$

Is there a Luminosity-Metallicity Correlation ?

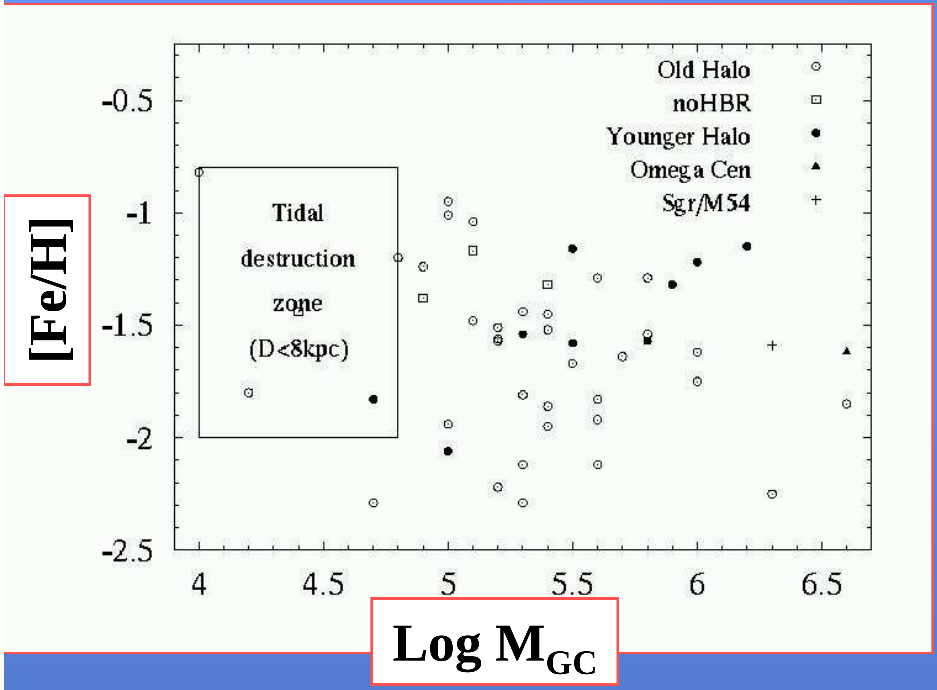


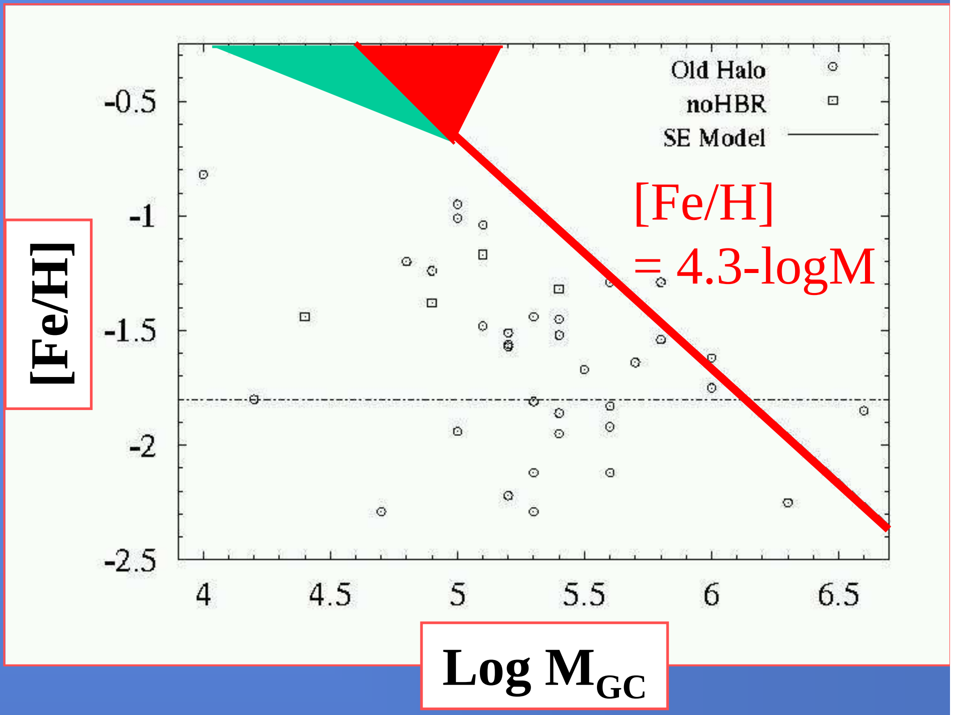
- Halo GCS = OH (formed “in situ”, °) + YH (accreted, •)

  The search of a mass-metallicity relation should be restricted to the OH subsystem
- Dispersion in the GC mass-to-light ratio *(e.g. Pryor & Meylan 1993)*
- The mass-metallicity relation applies to the gaseous progenitors of GCs ⇒ Second stellar generation SFE

Comparison of the Model with the Observations

- *Pryor & Meylan 1993:* the most complete and homogeneous set of GC masses





- Halo GCs (49 GCs)
- Old Halo (°) + Younger Halo (•)
- Pearson cor. coef.: -0.15

- Old Halo GCs (38 GCs)
- SE model ↔ Permitted area
- Pearson cor. coef.: -0.35

  with ℘ = 96.92%

Parmentier & Gilmore 2001, A&A 378, 97

The Transverse Collapse of the Shell

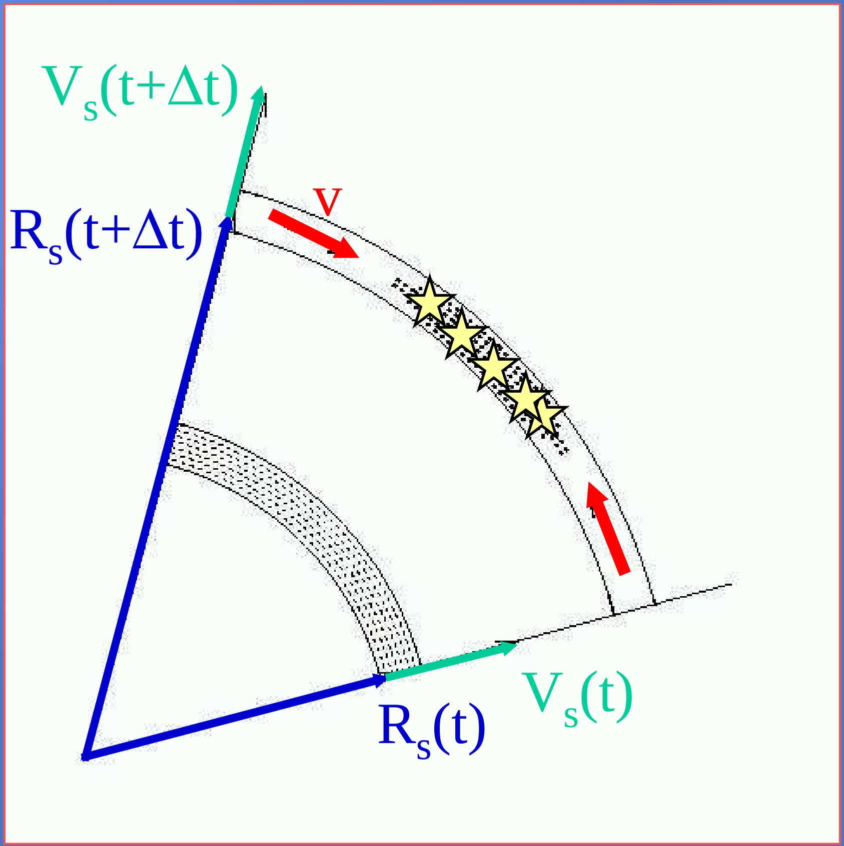
→ **Is there a second stellar generation ?**

Study of the ability of the

supershell to undergo a

transverse collapse

⇒ Triggered star formation

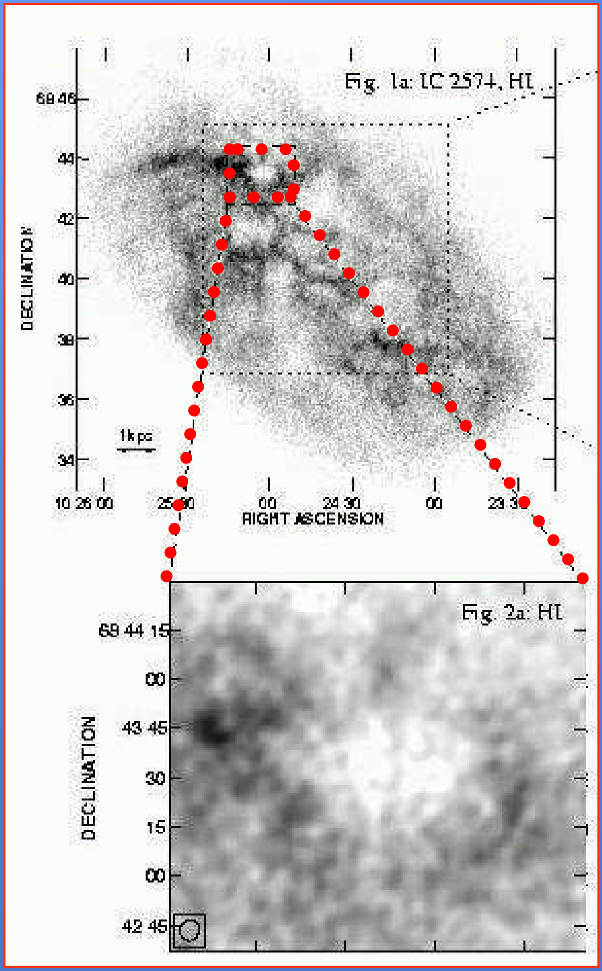


Observational Evidence of Triggered Star Formation

Galactic disc and dwarf galaxies: e.g. IC2574 *(Walter et al. 1998)*

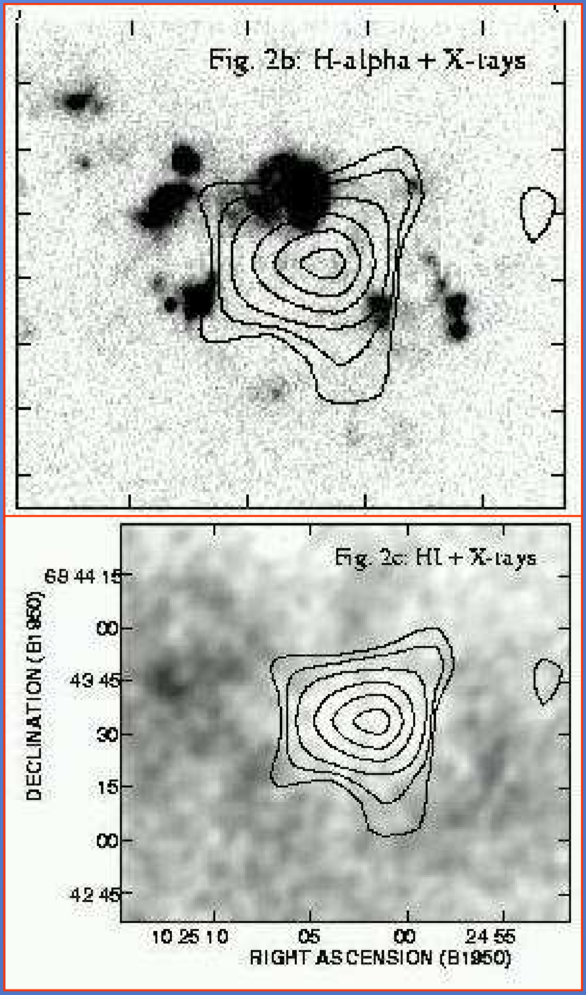
IC2574: HI

HI void
⇒ bubble



Hα
⇒ shell

X-rays
⇒ bubble



Transverse Flows within a Shell

- For transverse flow of gas in the shell *(e.g. Elmegreen 1994)*:

  - Perturbed equation of continuity

$$\boxed{\frac{\partial \sigma_1}{\partial t} = -2\frac{V_s}{R_s}\sigma_1 - \sigma_0 \nabla_T . v}$$

Stretching of the perturbed region with the shell expansion ($V_s > 0$) >< Congergence of the perturbed flows in the shell

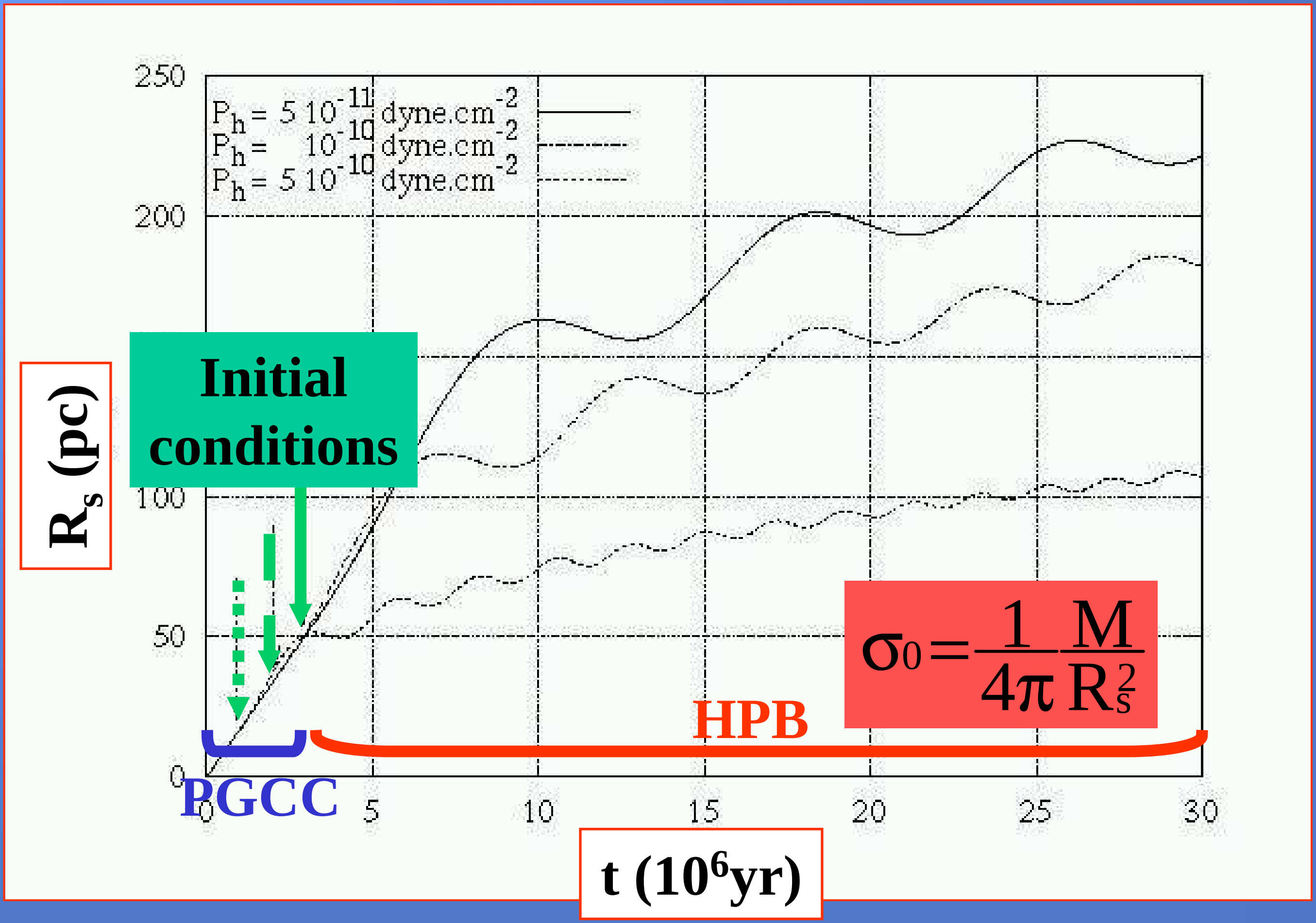
  - Perturbed equation of momentum

$$\boxed{\sigma_0 \frac{\partial v}{\partial t} = -\sigma_0 \frac{V_s}{R_s} v - c_s^2 \nabla \sigma_1 + \sigma_0 g_1}$$

Stretching of the perturbed region with the shell expansion ($V_s > 0$) & Internal pressure >< Perturbed (transverse) gravity

$$g_1 = -2\pi i G \sigma_1 \qquad \sigma_0 = \frac{1}{4\pi}\frac{M}{R_s^2}$$

Shell radius with time



$$\sigma_0 = \frac{1}{4\pi}\frac{M}{R_s^2}$$

Development with Time of the Collapse

- Numerical integration over time of the perturbed equations
  - Perturbed quantities: $\sigma_1 = \tilde{\sigma}_1(t)e^{-i\eta\phi}$ and $v = \tilde{v}(t)e^{-i\eta\phi}e^{i\Delta\phi}$

    $\eta = 2\pi R_s/\lambda$ = number of forming clumps along a shell circumference
  - Perturbed equation of continuity: $\boxed{\frac{\partial\tilde{\sigma}_1}{\partial t} = -2\frac{V_s}{R_s}\tilde{\sigma}_1 + \sigma_0\frac{i\eta}{R_s}\tilde{v}e^{i\Delta\phi}}$
  - Perturbed equation of momentum:

$$\boxed{\frac{\partial\tilde{v}}{\partial t} = -\frac{V_s}{R_s}\tilde{v} + \frac{i\eta c_s^2}{R_s\sigma_0}\tilde{\sigma}_1 e^{-i\Delta\phi} - 2\pi i G\tilde{\sigma}_1 e^{-i\Delta\phi}}$$

- Parameters controling the shell transverse collapse:

  § $\tilde{\sigma}_1^{init} = \tilde{\sigma}_1(t_{em})$

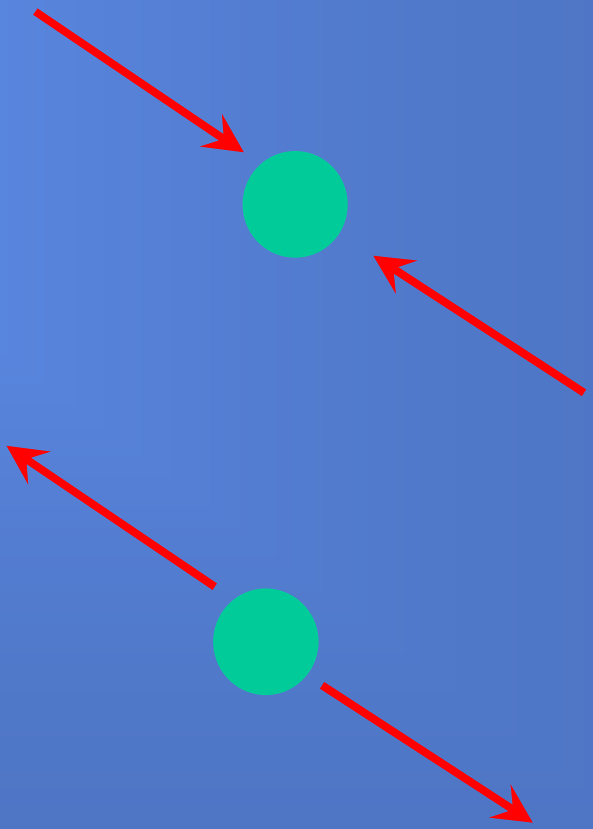
  § $\tilde{v}^{init} = \tilde{v}(t_{em})$

  § $\Delta\phi$

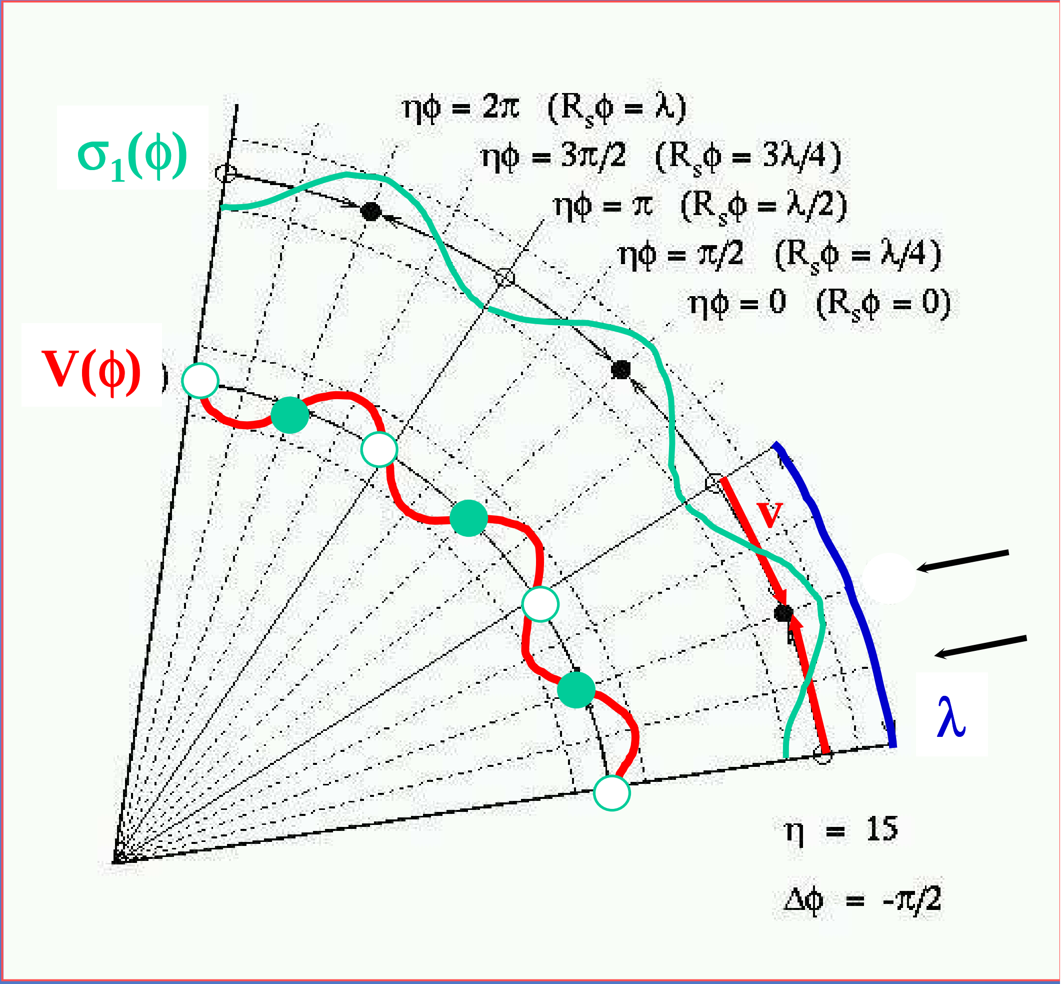
  § η

  § c_s

$$\begin{tikzcd}
§\ N \arrow[r] & R_s \arrow[dr] & \\
 & & \sigma_0 \\
§\ P_h \arrow[r] \arrow[uur] & M \arrow[ur] &
\end{tikzcd}$$



- With $\boxed{\Delta\phi = -\pi/2:}$ convergence of the transverse flows towards the initial clump



$$\sigma_1 = \tilde{\sigma}_1(t)e^{-i\eta\phi}$$

$$v = \tilde{v}(t)e^{-i\eta\phi}e^{i\Delta\phi}$$

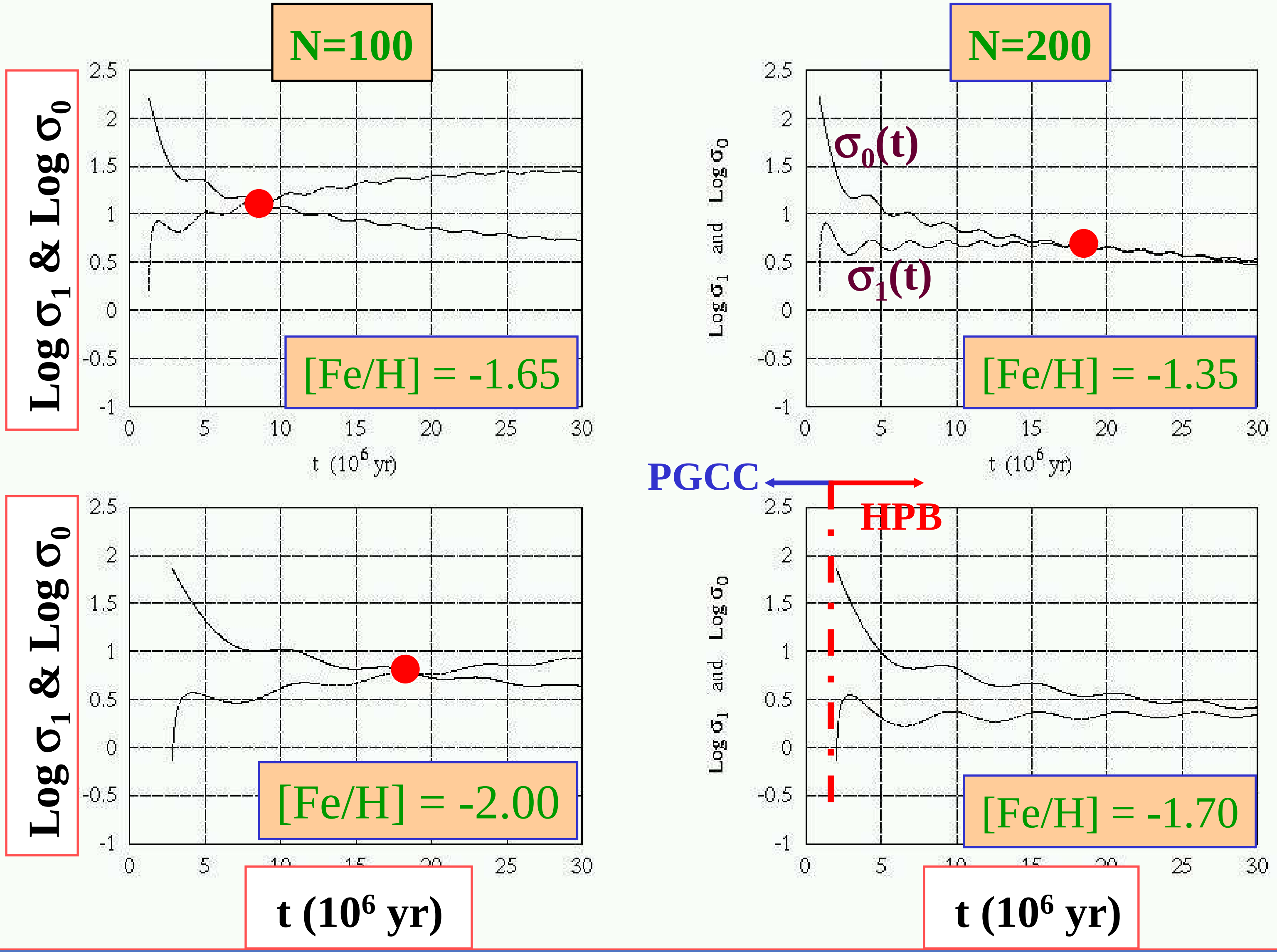
$$\boxed{\frac{\partial\tilde{\sigma}_1}{\partial t} = -2\frac{V_s}{R_s}\tilde{\sigma}_1 + \sigma_0\frac{i\eta}{R_s}\tilde{v}e^{i\Delta\phi}}$$

$$\boxed{\frac{\partial\tilde{v}}{\partial t} = -\frac{V_s}{R_s}\tilde{v} + \frac{i\eta c_s^2}{R_s\sigma_0}\tilde{\sigma}_1 e^{-i\Delta\phi} - 2\pi i G\tilde{\sigma}_1 e^{-i\Delta\phi}}$$

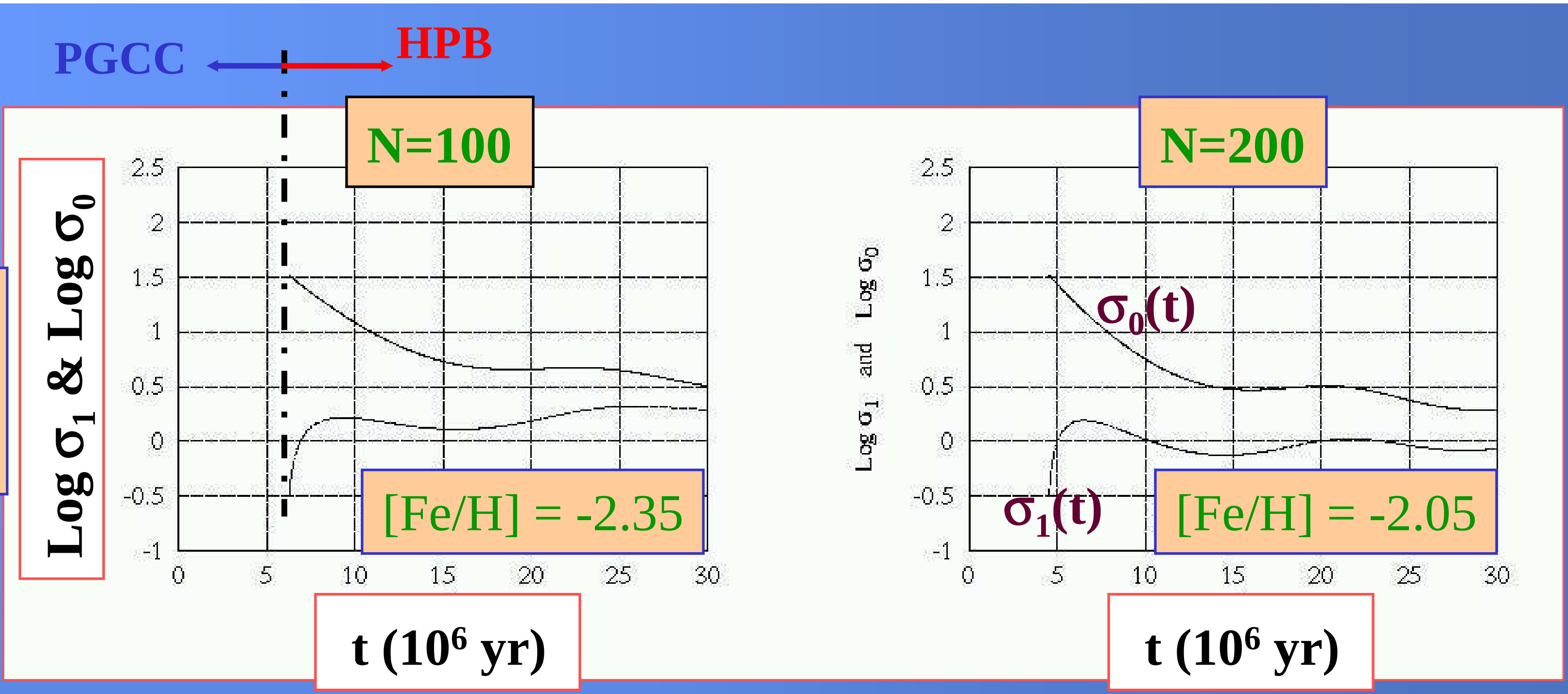
$\eta = 14 \quad \tilde{v}(t_{em}) = 0.02\dot{R}_s(t_{em}) \quad \tilde{\sigma}_1(t_{em}) = 0.01\sigma_0(t_{em}) \quad c_s = 1\,\mathrm{km.s}^{-1} \quad \Delta\phi = -\pi/2$

$P_h =$
5×10^{-10}
$\mathrm{dyne.cm}^{-2}$

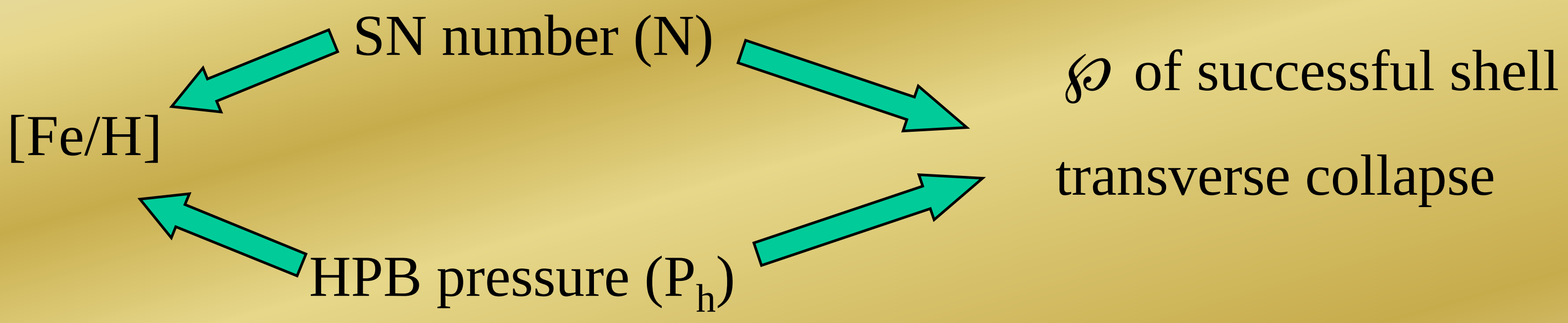
$P_h =$
10^{-10}
$\mathrm{dyne.cm}^{-2}$



$P_h = 2 \times 10^{-11}$ dyne.cm^{-2}



- Shell transverse collapse ↔ Halo Metallicity Distribution


SN number (N)

[Fe/H]

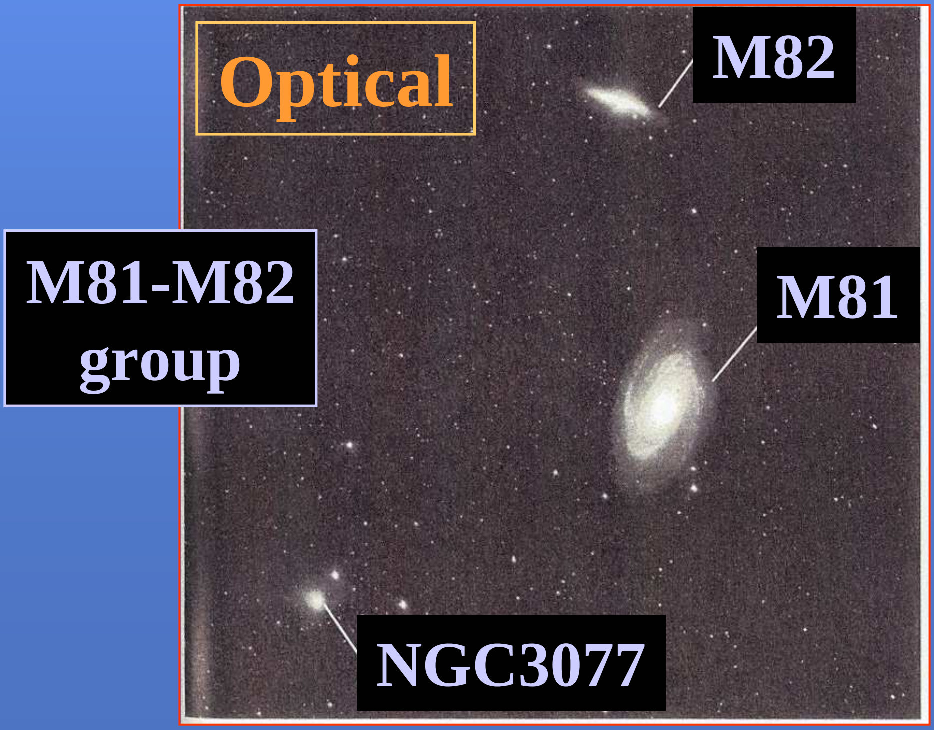
HPB pressure (P_h)

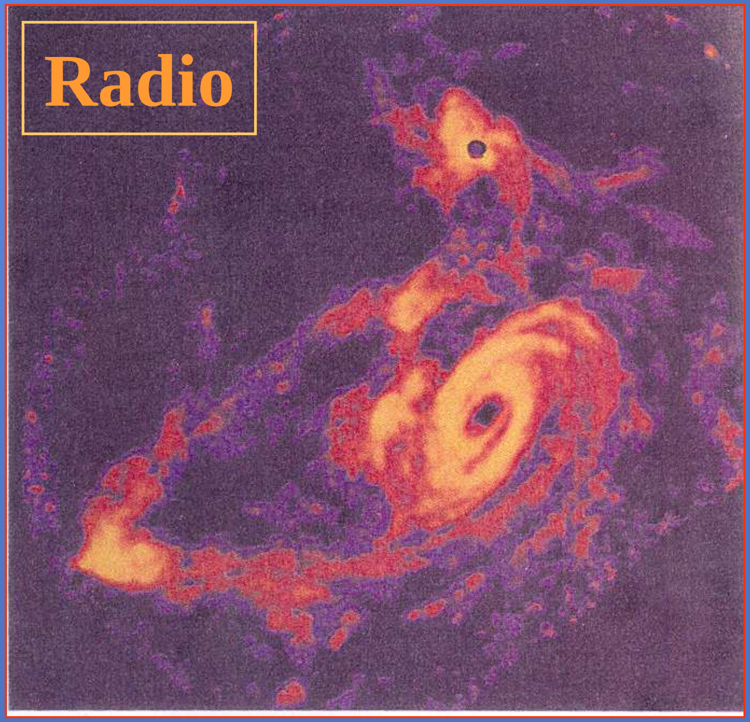
℘ of successful shell transverse collapse

→ **Open the way to the understanding of the MDF**

M82 B: an extragalactic system of massive stellar clusters

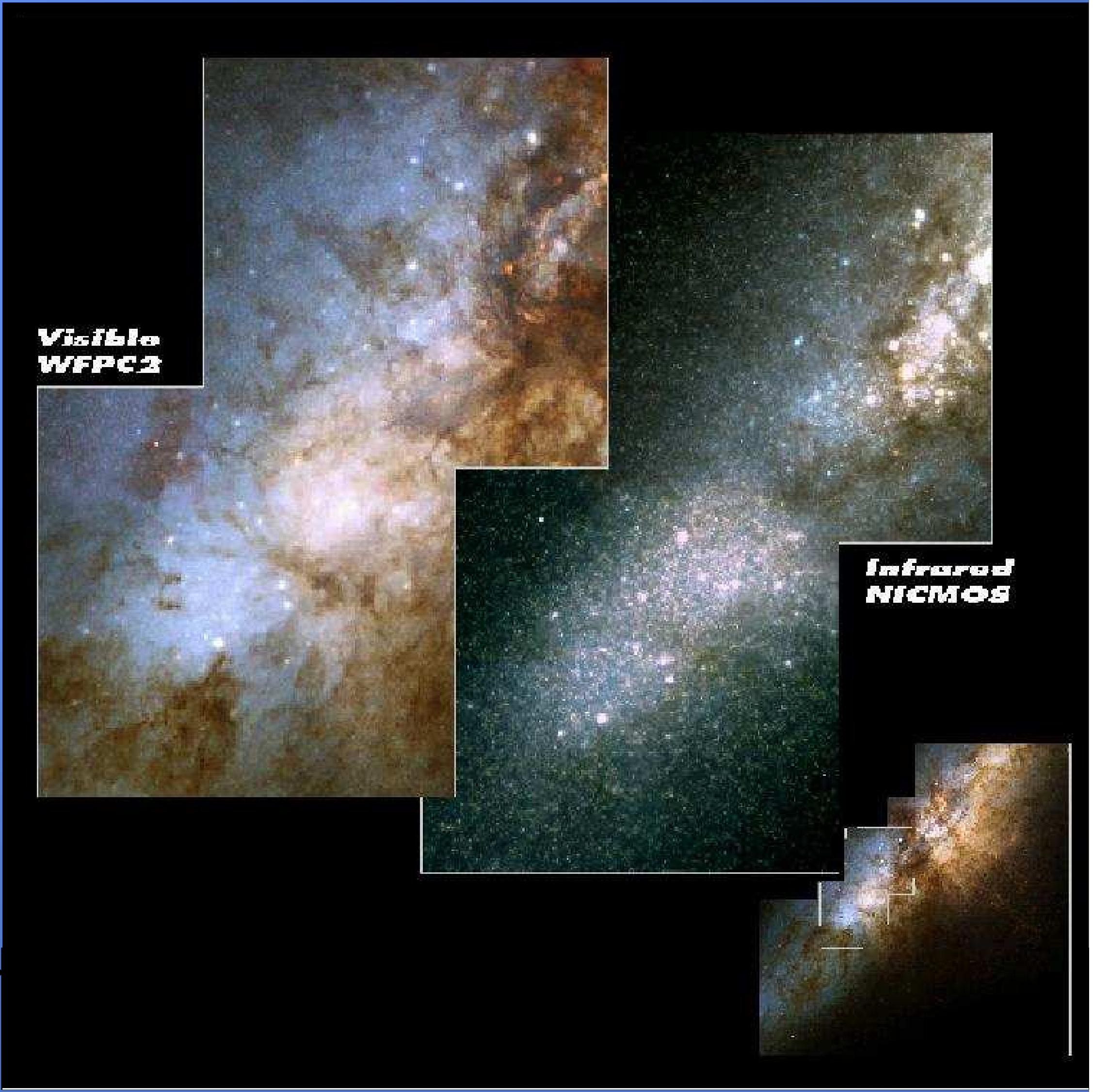
- **HST:** the formation of massive stellar clusters is not restricted to the protogalactic epoch. Current formation sites: merging galaxies (e.g. the Antennae) and interacting galaxies (e.g. M82).





The Starburst galaxy M82

- M82-M81 (D = 3.6Mpc): the closest group of interacting galaxies
- M82 central regions: active starburst →
- M82 B:
  - several 100 Myr old starburst
  - *de Grijs, O'Connell & Gallagher 2001:* → HST optical + near-IR
  - 100 massive star clusters



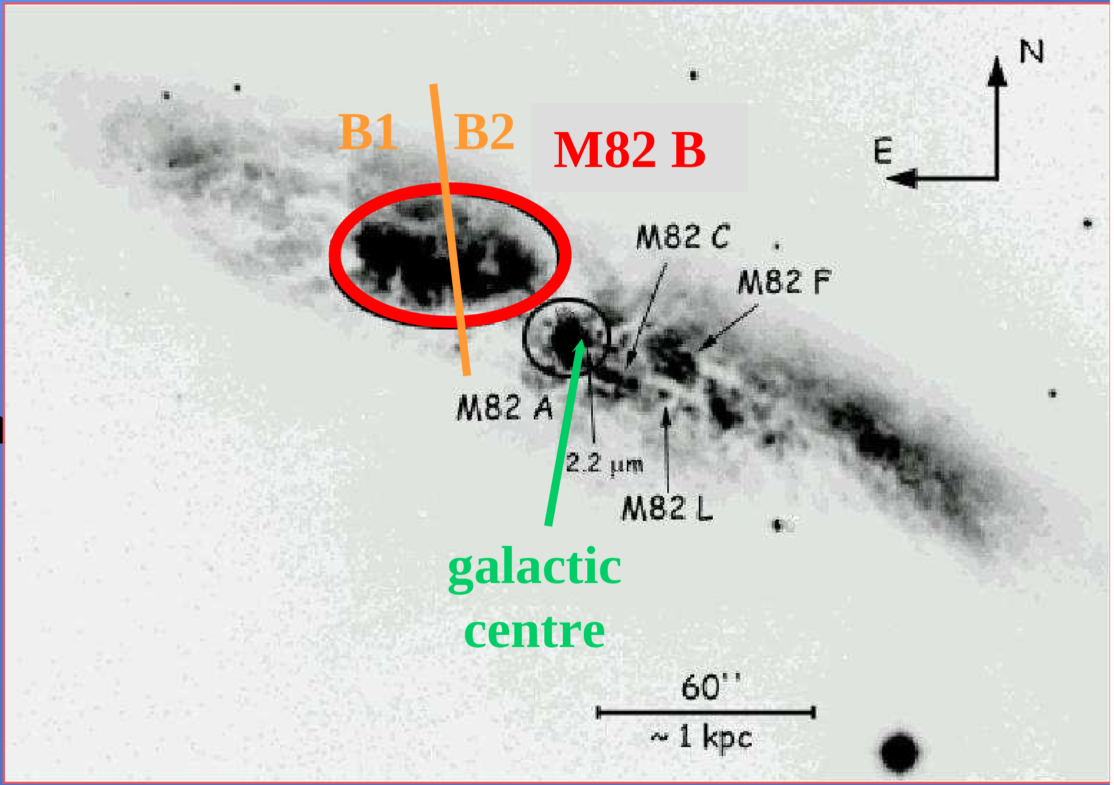
Spectral Synthesis → M82 B History

- Spectral synthesis:
  - Computes the evolution with time/vs metallicity of the photometric properties of a stellar population.
  - Compare the observed cluster photometry to the theory.
  - Bruzual & Charlot (1996):

    $(B-V)_0$, $(V-I)_0$, $(V-J)_0$,
    M/L_v vs time t,
    for ≠ metallicities Z

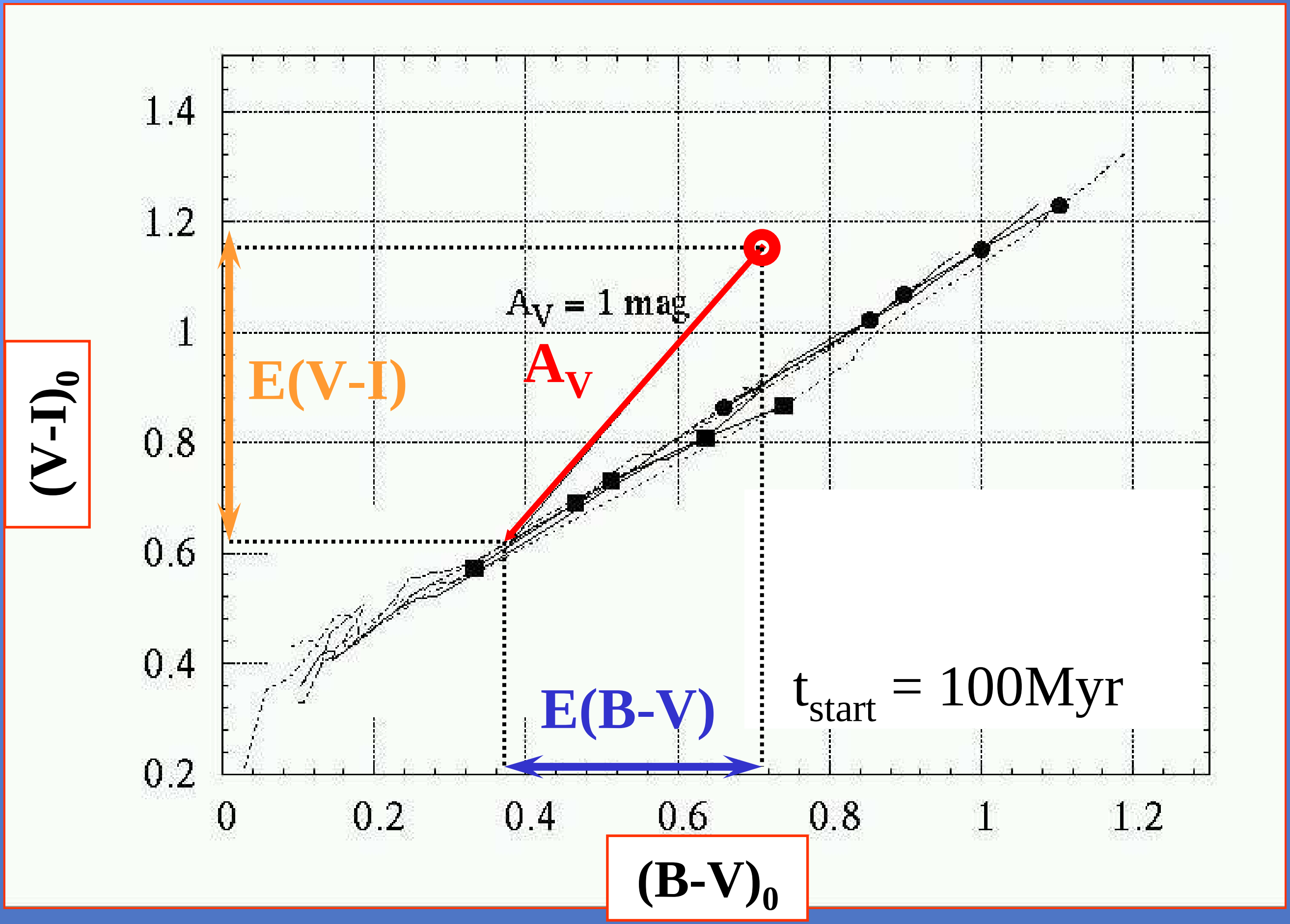
- What we must derive:

  - the foreground extinction
  - the cluster age,
  - the cluster metallicity,
  - the cluster mass.

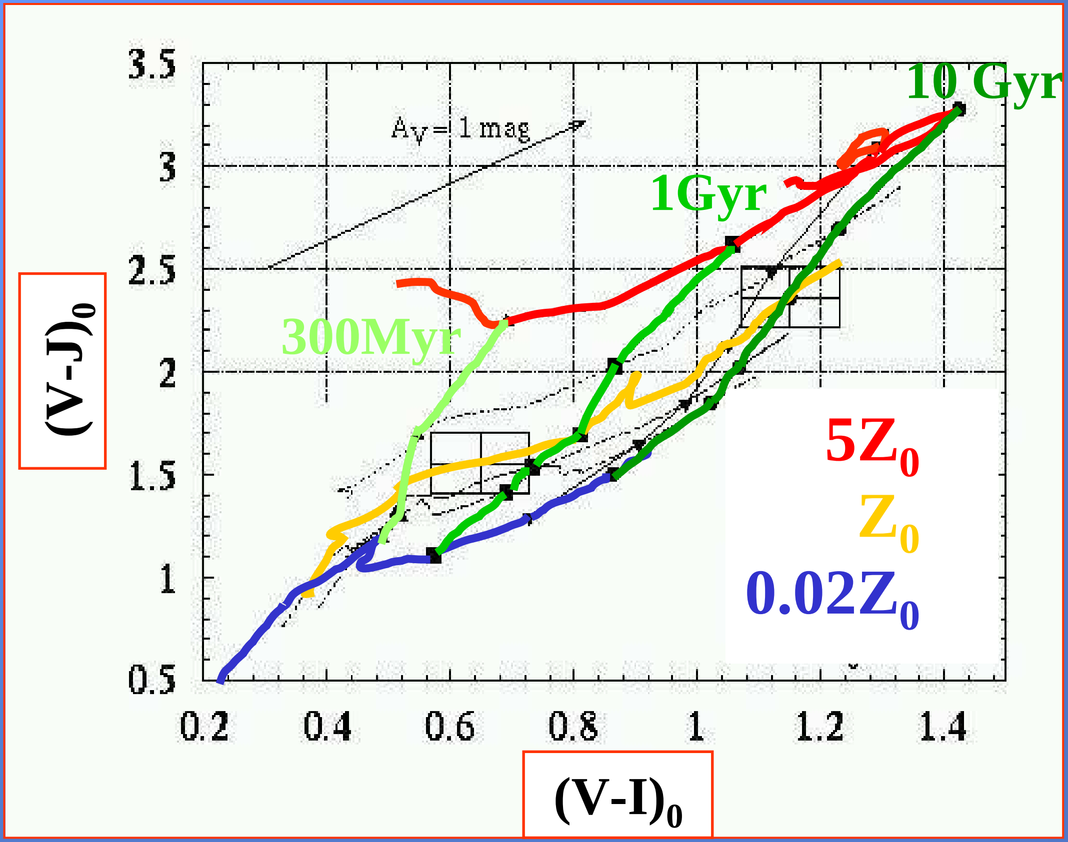


- Extinction estimates: the *BVI* diagram

Aging trajectories for various metallicities

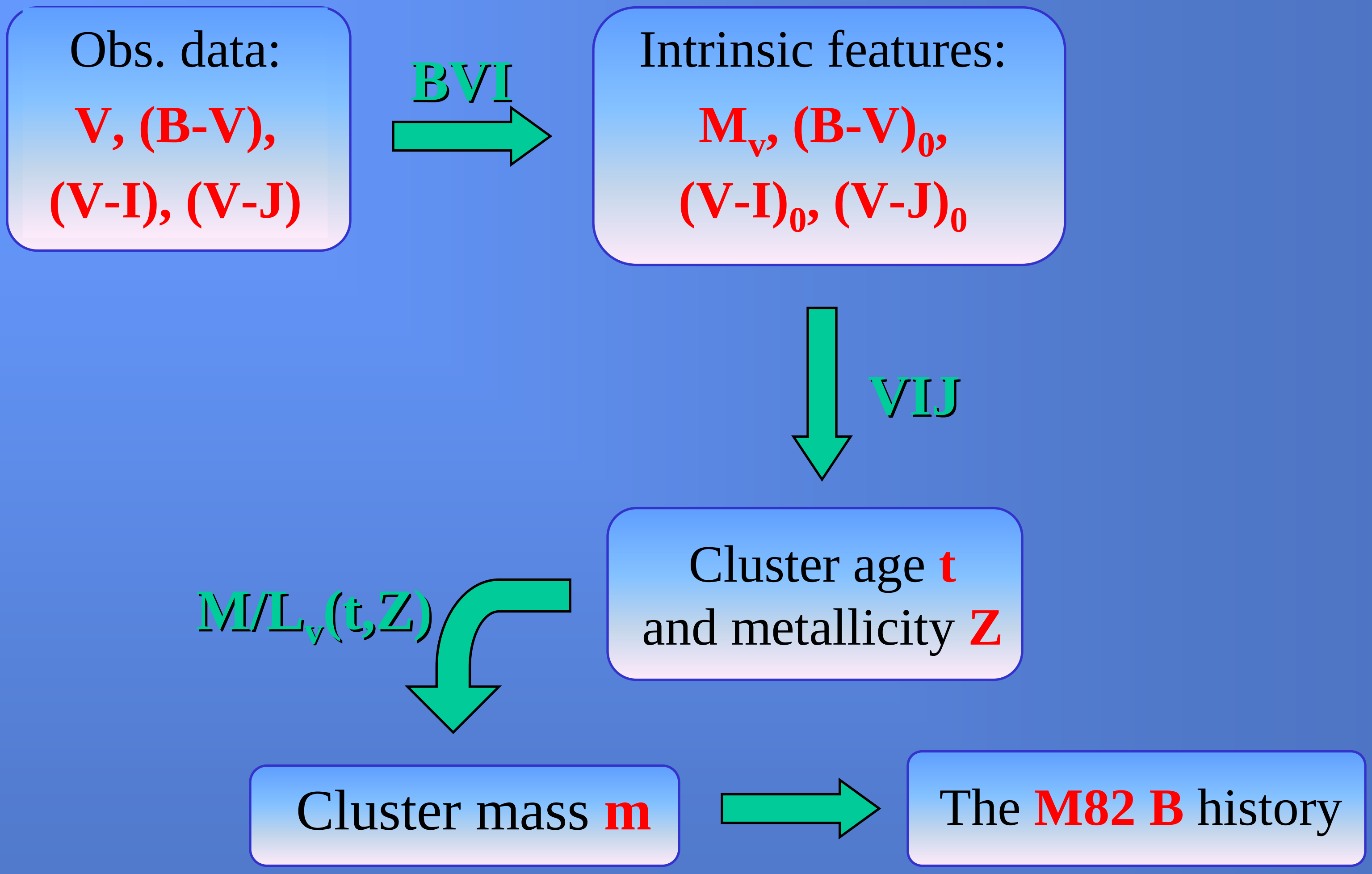


Age & metallicity estimates: the *VIJ* diagram



v $(V-J)_0$ vs $(V-I)_0$: grid drawn by isochrones and isometallicity tracks

⇒ the $(V-J)_0$ vs $(V-I)_0$ diagram is well-suited to disentangle age and metallicity effects



Obs. data:

V, (B-V),
(V-I), (V-J)

BVI

Intrinsic features:

$\mathbf{M_v}$, **(B-V)**$_0$,
(V-I)$_0$, **(V-J)**$_0$

VIJ

Cluster age **t**
and metallicity **Z**

$M/L_v(t,Z)$

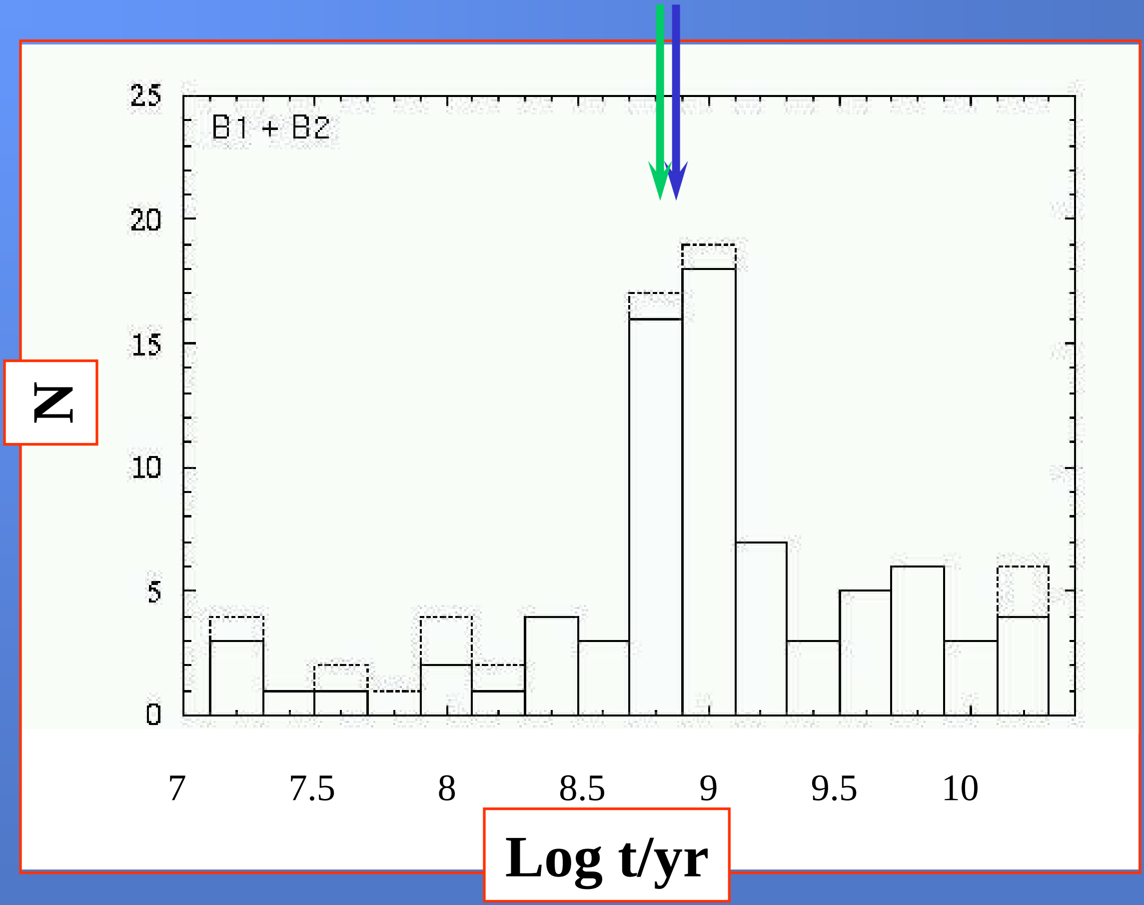
Cluster mass **m**

The **M82 B** history

Parmentier, de Grijs & Gilmore 2003,
MNRAS 342, 208

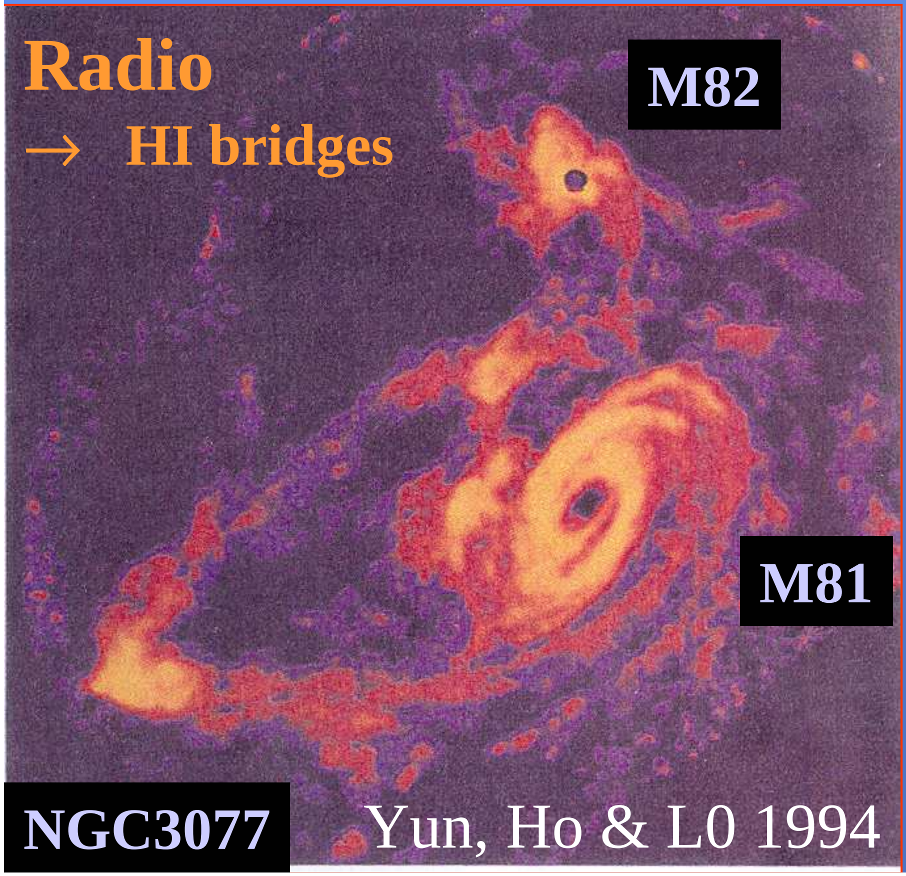
The Cluster History of M82 B

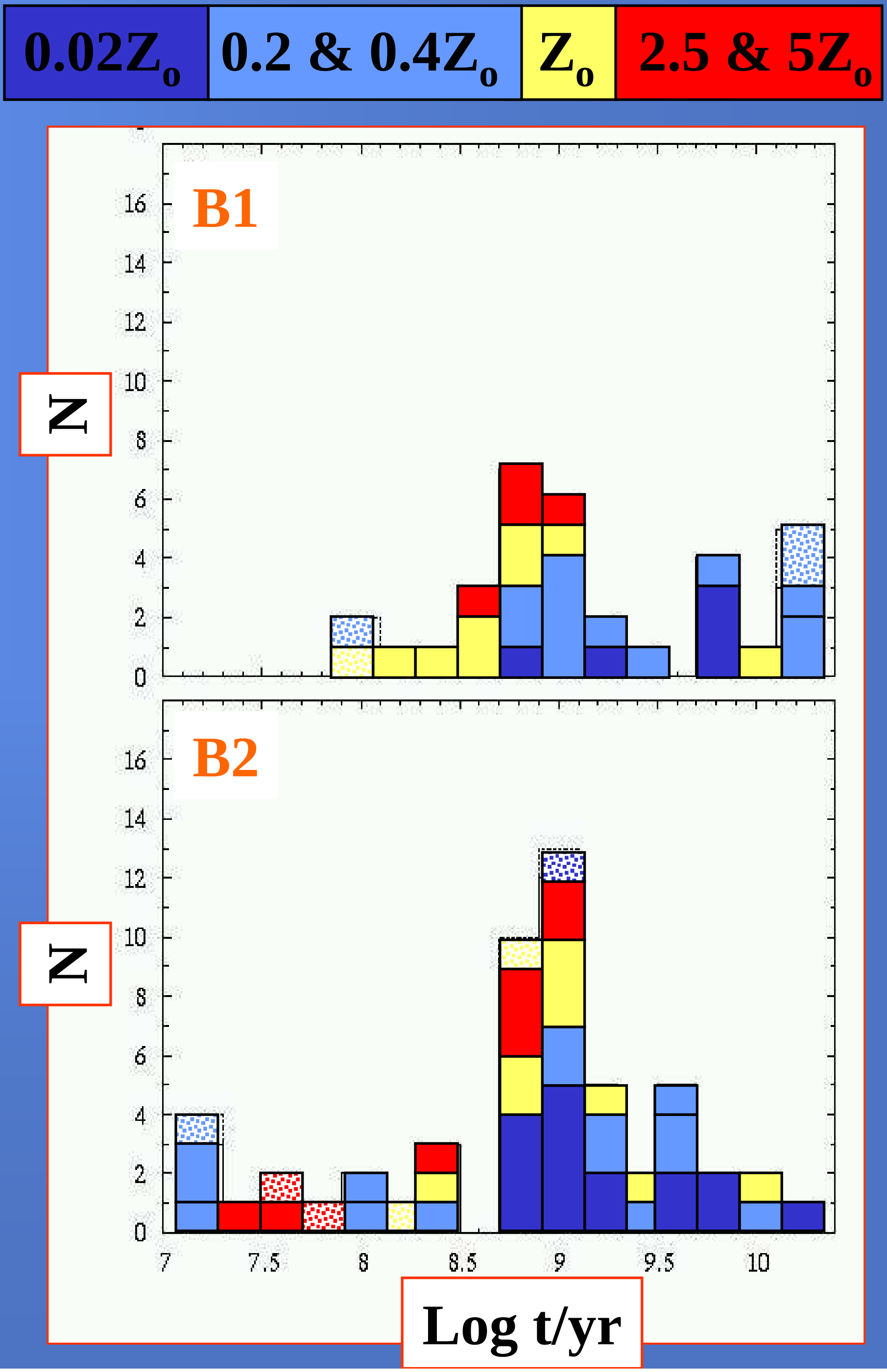
- **Peak of cluster formation**: last perigalactic passage M82/M81



Interactions between galaxies stimulate the formation of stellar clusters

- Chemical evolution
  - **B1**
  - **B2:** infall of “fresh” metal-poor circumgalactic gas about 1Gyr ago





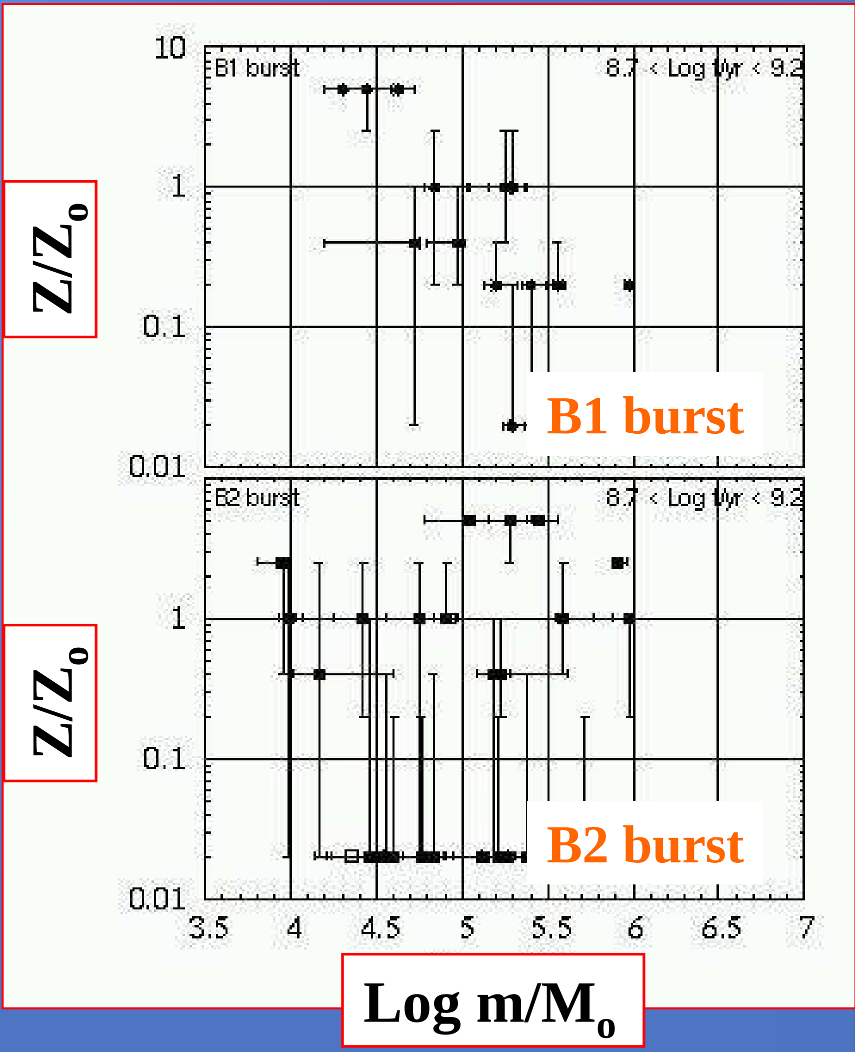
- Do the massive stellar clusters formed during the burst (about 1Gyr ago) arise from a self-enrichment process ?

  ⇒ Search for a mass-metallicity correlation.

V **B1:** r = -0.69 with $\wp$ = 99.8%

⇒ mass-metallicity correlation
in the sense expected by the model

V **B2:** r = -0.15 with $\wp$ = 48%
Pressure of the inter-cloud medium may not have been stable enough due to the circumgalactic gas injection



SE model → progenitor clouds made of non pristine gas

Conclusions and Future Prospects

- ***A priori arguments faced by the self-enrichment scenario may not be true****: good agreement between theory and observations, at least for the Galactic Old Halo.*

  Do not lump all Galactic GCs together (can conceal trends) ***!***

- ***The transverse collapse of the shell****: its ability to form new stars depends on N and* P_h*. Simulations:*

  → *[Fe/H] ranging from –1.2 down to –2.8 are naturally achieved.*

- ***Formation of a bound stellar cluster:*** *next step*