Evolution of Galaxies:
Chemodynamical models

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Limitations of ‘classical’ models

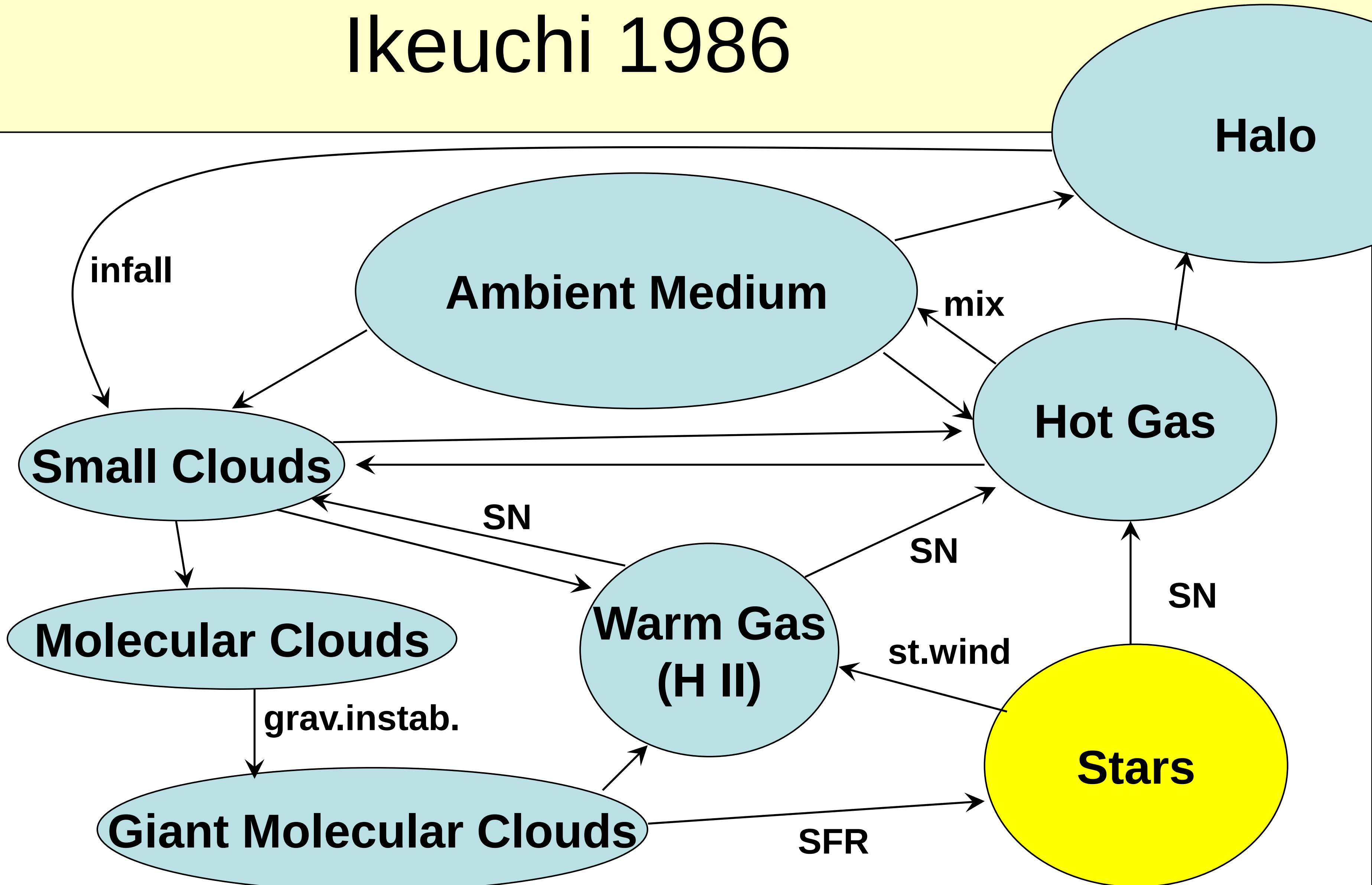
- With sufficient flexibility in the prescriptions and number of free parameters, one can well represent (any) observations …
- Models ARE not unique:
  - G dwarf « problem »
  - abundance gradients
  - mass-metallicity relation…
- Physical meaning of parameters:
  - Why is SF timescale abt. 3 Gyrs in MWG?
  - Yield = true or effective?

Larson1969ff: monolithic collapse

- collapse from Jean-instable protogalactic cloud of gas clumps
- clumps dissipate kinetic energy by cloud-cloud collisions
- star formation via power-law density dependence
- ➔ spherical models reproduce well properties of elliptical (deVaucouleurs profile) ☺ ☺ ☺

- ➔ but one needs to terminate evolution by SN driven outflows
- ➔ 2D rotating models flatten and require strong viscosity
- ➔ 2D models for disk galaxies require time-dependent viscosity and SFR …☹ ☹ ☹

Complexity of multiphase ISM: Ikeuchi 1986

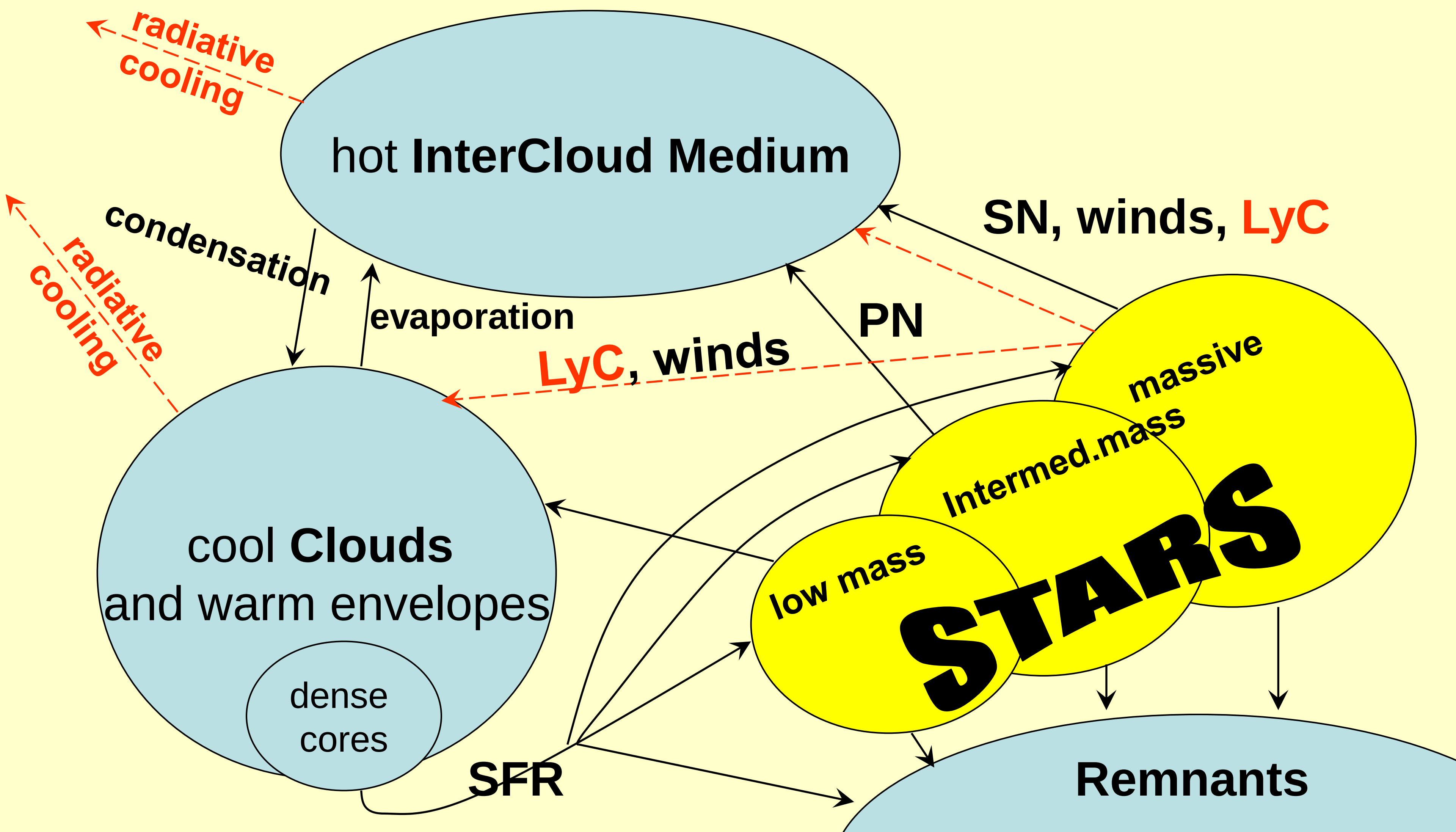


Chemodynamical Approach
(1990ff, Hensler, Burkert, Theis, …)

- Rationale: describe physical processes as completely as (today) possible
- ‘Chemistry’: yields etc. as in ‘classical’ models
- Global dynamics (‘Larson’, 1+2 D)
  - Stars (collisionless Boltzmann, 2^{nd} moments)
  - Clouds (Boltzmann with collision terms)
  - Hot gas (hydrodynamics)
- Gas-star interactions: multiphase ISM
  - Network of gas/star interactions
  - All rate coefficients from theory or direct observation

- NO free fit parameters (except total mass …)

Chemodynamics network

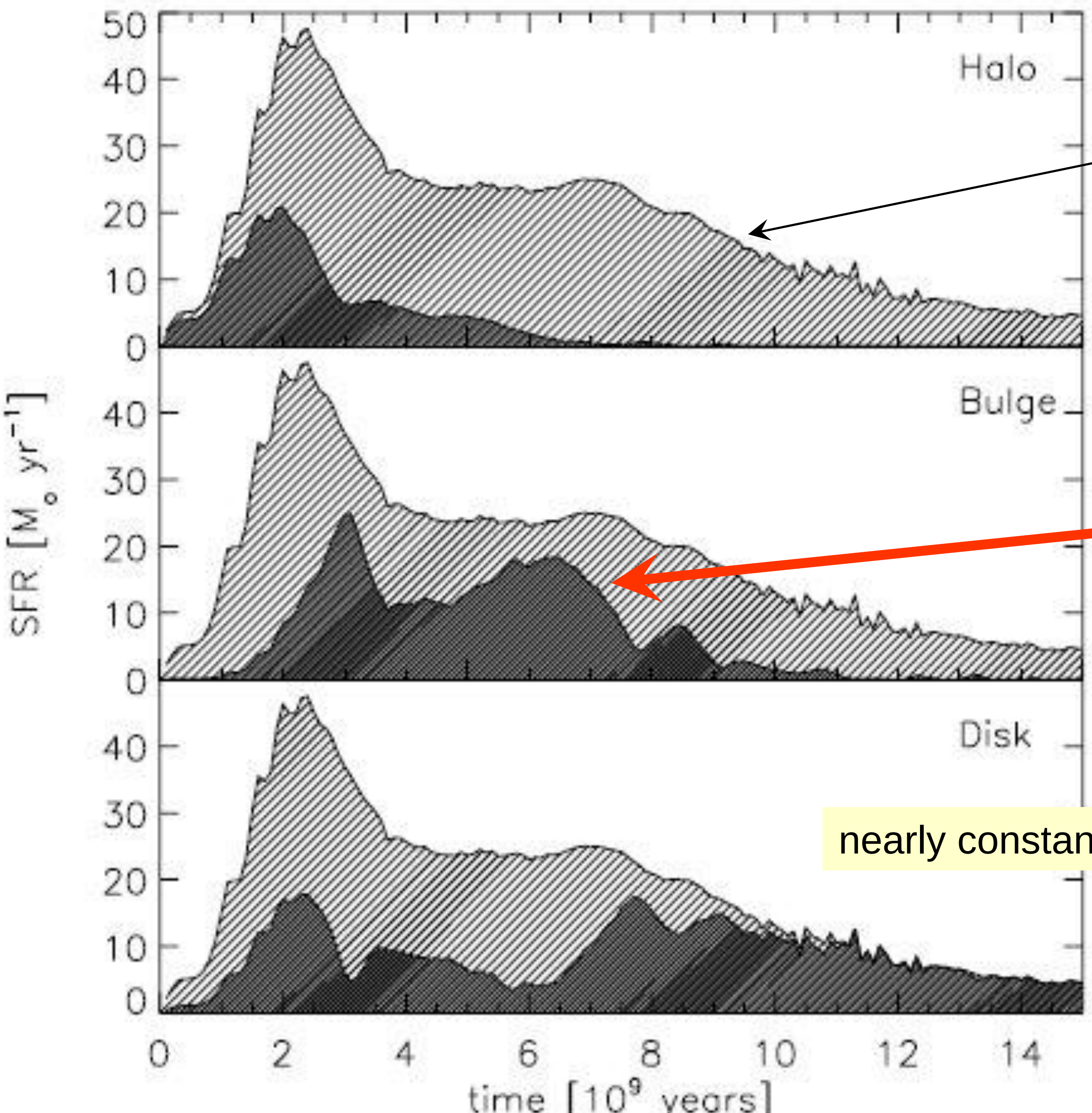


Chemodynamics: Samland's 1994 Milky Way Model

Evolutionary phases:

- Central collapse ➔ strong star formation ➔ outflow of hot metal-rich gas
- Settling of the rotating disk
- Outflowing hot gas condenses in exterior regions ➔ metal-polluted infall into disk

- Central star formation continues for long time

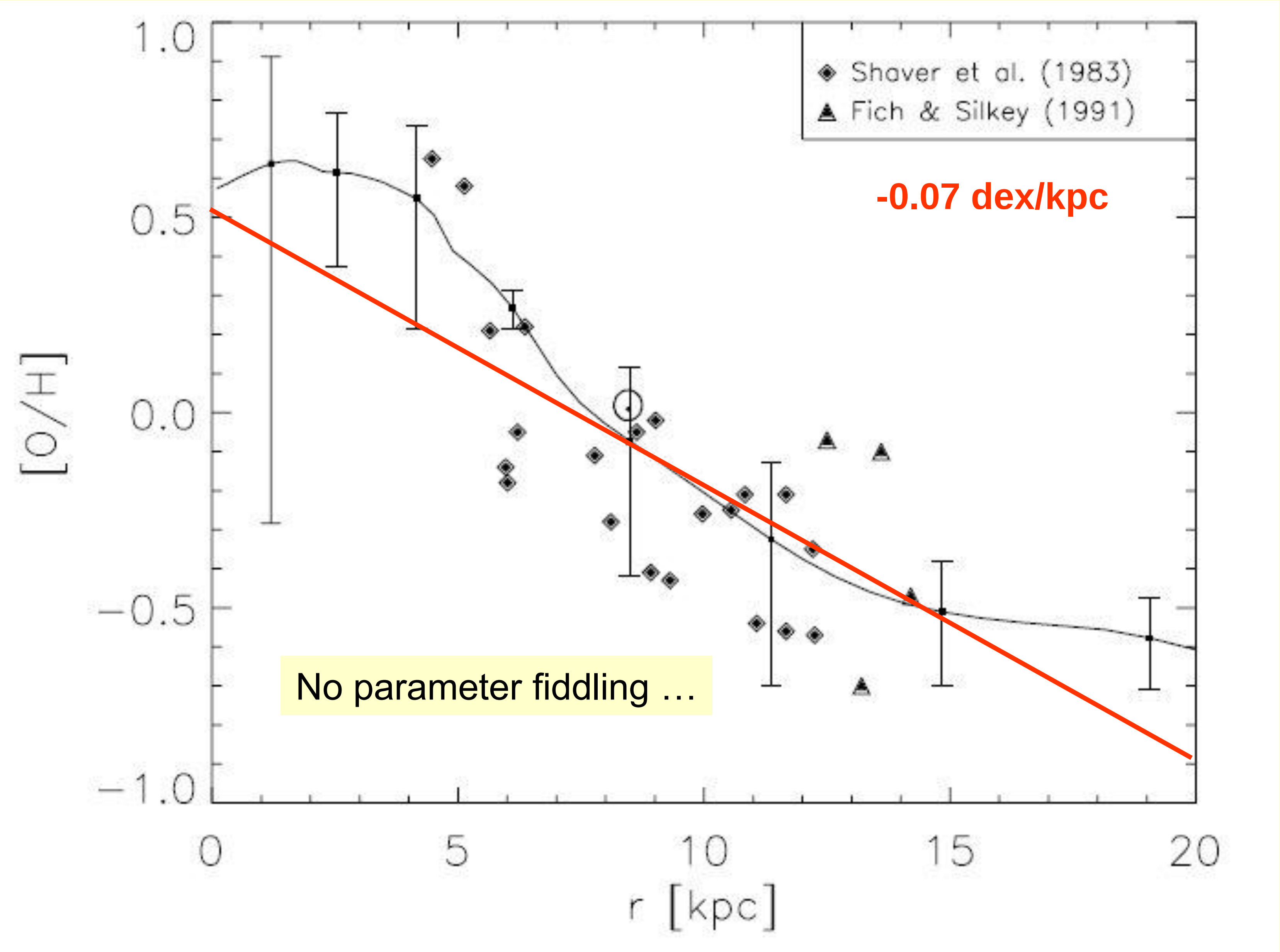


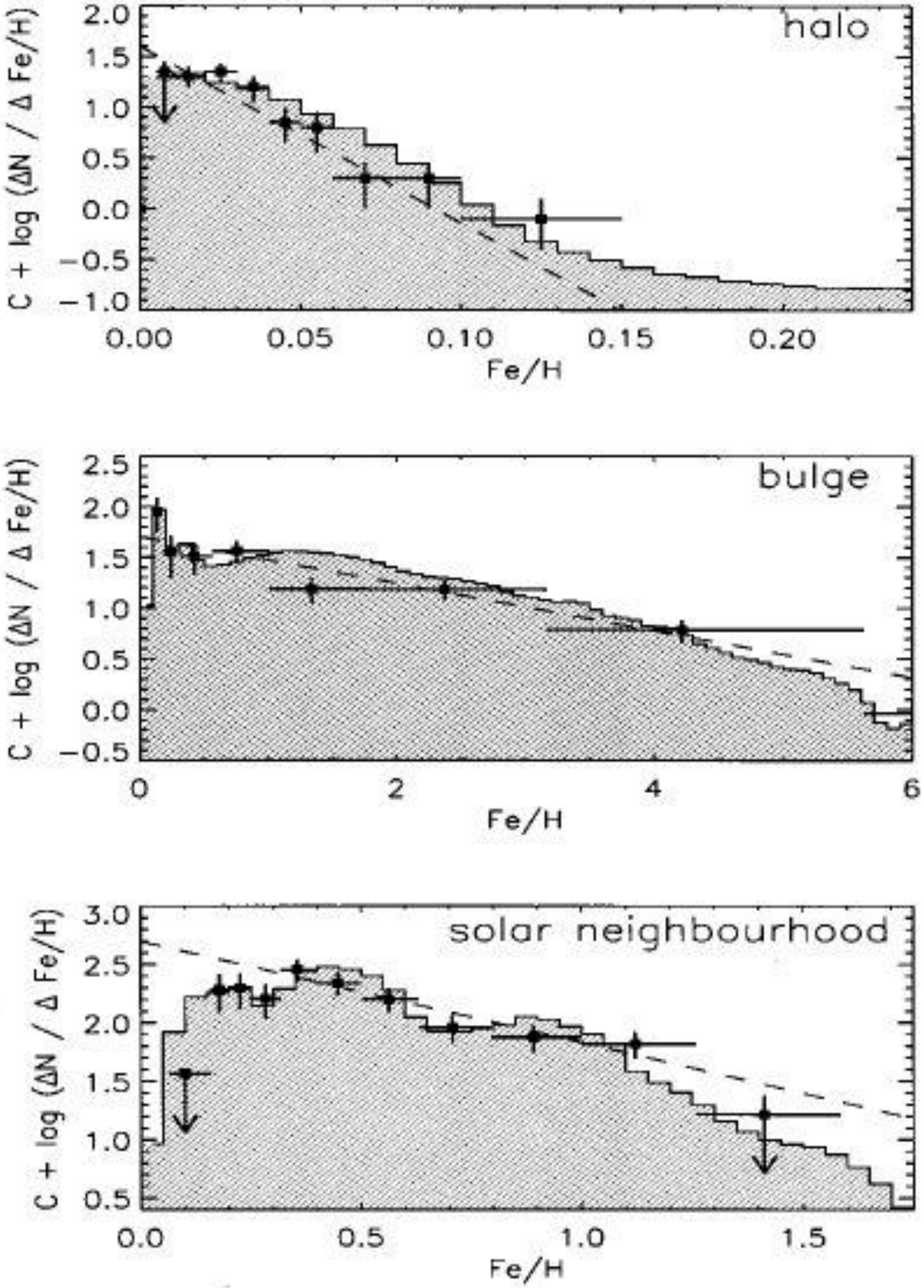
Total SFR

SF in bulge continues for a long time

nearly constant SF in disk

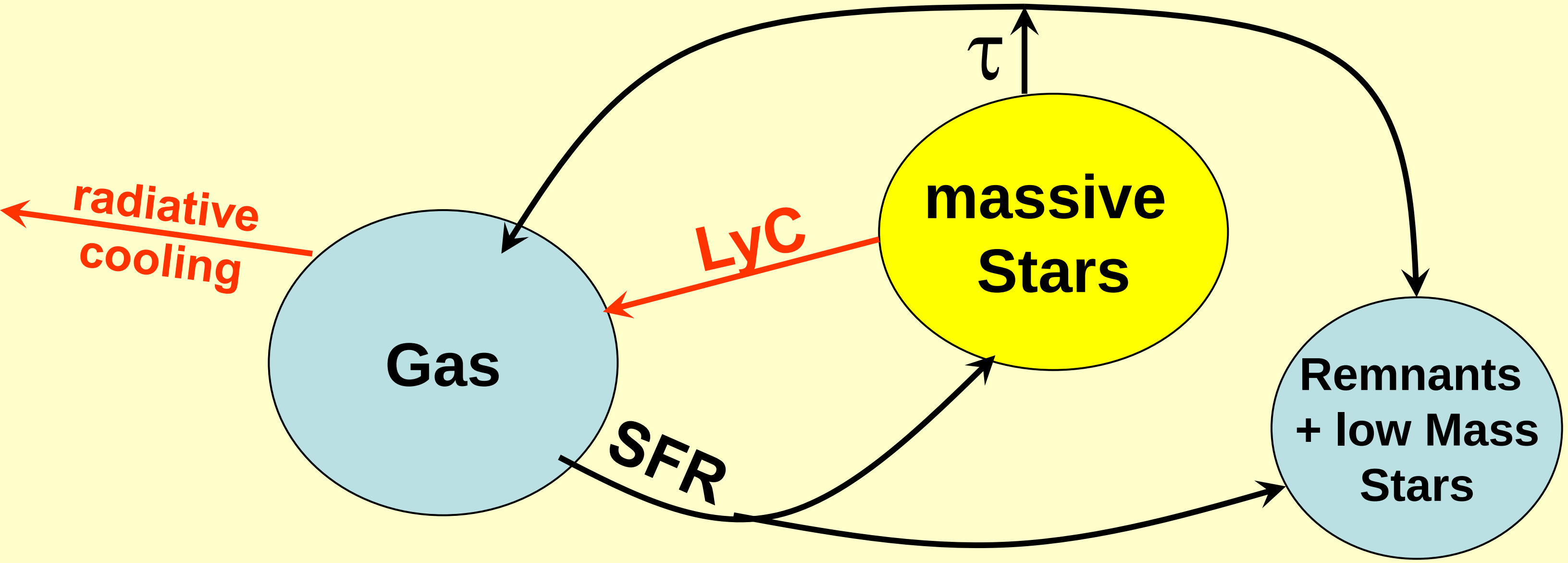
The present abundance gradient in the cloudy medium





- Stellar ADFs the three components are explained with the same IMF and nucleosynthesis
- global gasflows ➔ different effective yields

… how does it work?



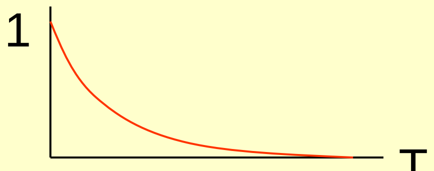
Gas mass: $dg/dt = -\Psi + s\eta/\tau$

Massive star mass: $ds/dt = \xi\Psi - s/\tau$

Gas internal energy: $de/dt = hs - g^2\Lambda(T)$ $e = 3k_B\, gT/2m$

SFR: $\Psi = C\, g^n * e^{-T/1000\ K}$

efficiency factor
=fraction of gas in molecules:



In most situations, the characteristic time scale for energy balance (ccoling time) is shorter than that for star formation ➔ assume thermal equilibrium

$$0 = de/dt = sh - g^2\Lambda(T)$$

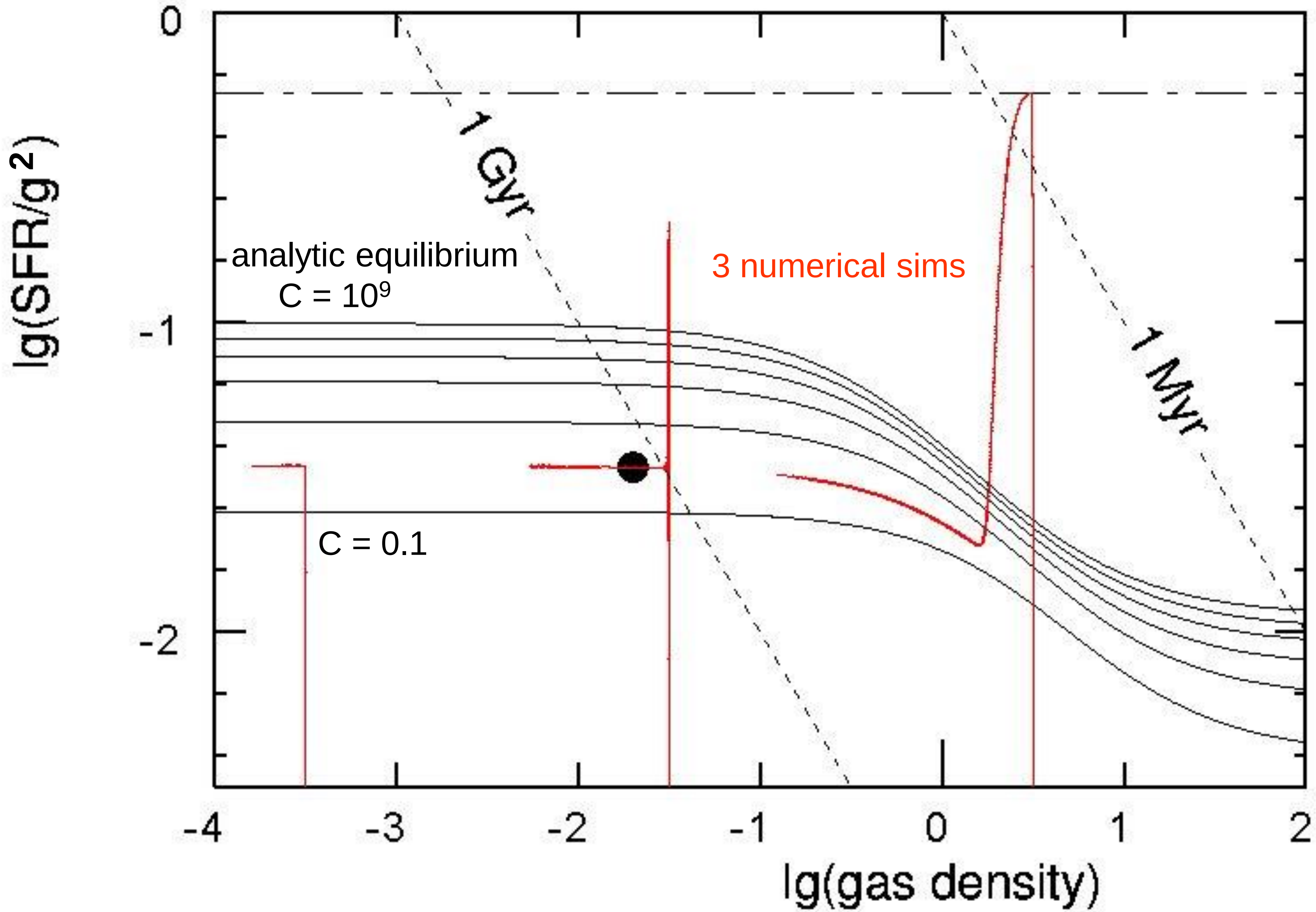
➔ $x := s/g^2$ new system variable

There does exist an equilibrium $dx/dt = 0$ which is

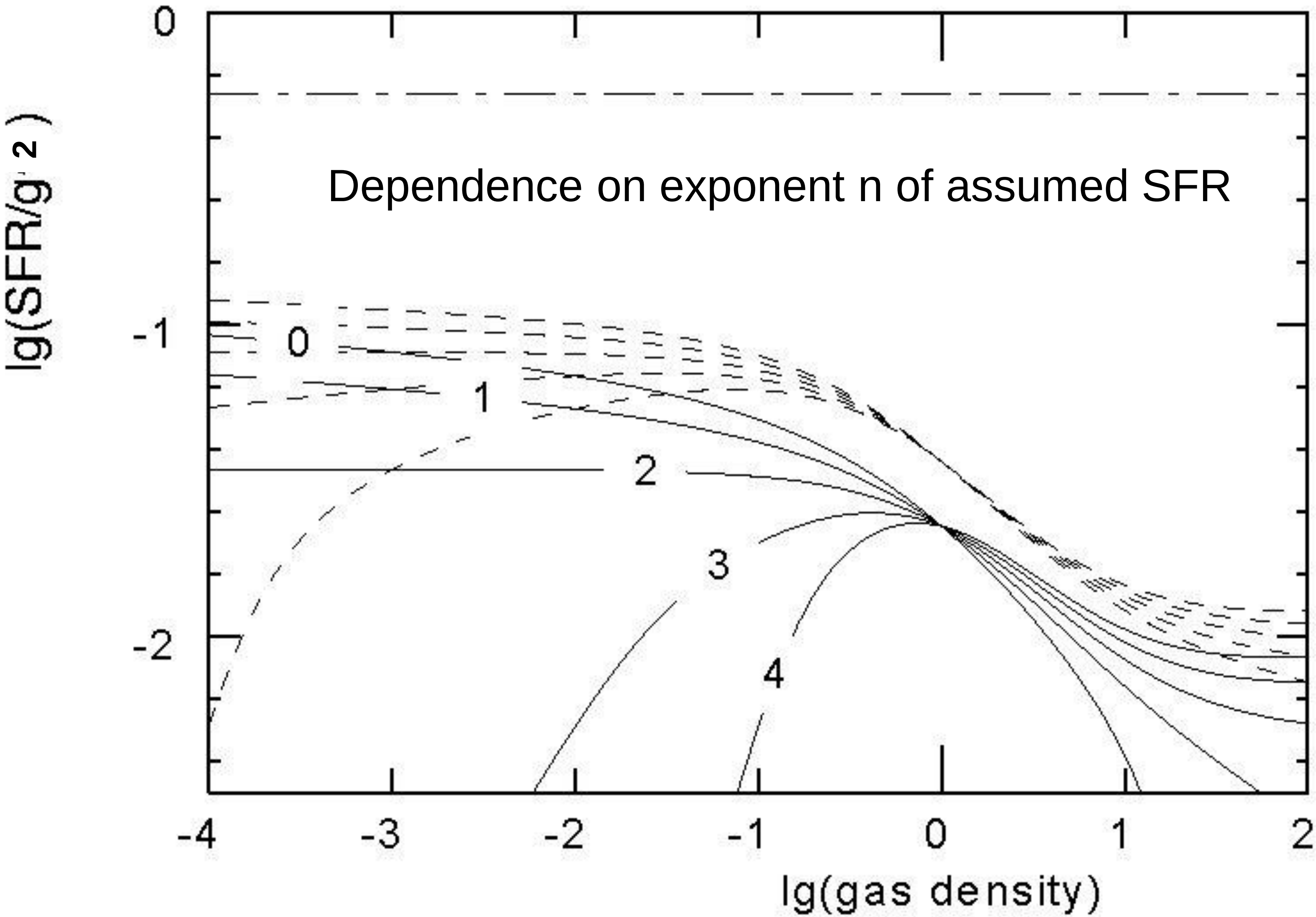
$$\Psi_{eq} = g^2 \frac{\Lambda(T)}{h\xi\tau} \frac{1 + 2gx\eta}{1 + 2gx/\eta\xi}$$

The equilibrium star formation rate follows a quadratic ‘Schmidt’ (power) law, independent of the assumed SFR

➔ Self-regulated star formation



Köppen, Theis, Hensler 1995



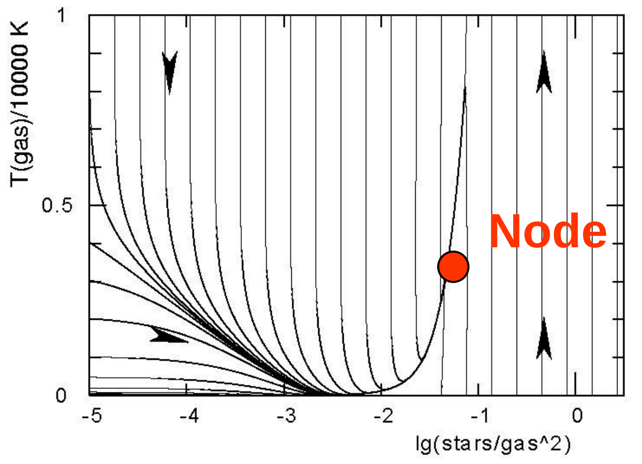
Köppen, Theis, Hensler 1995

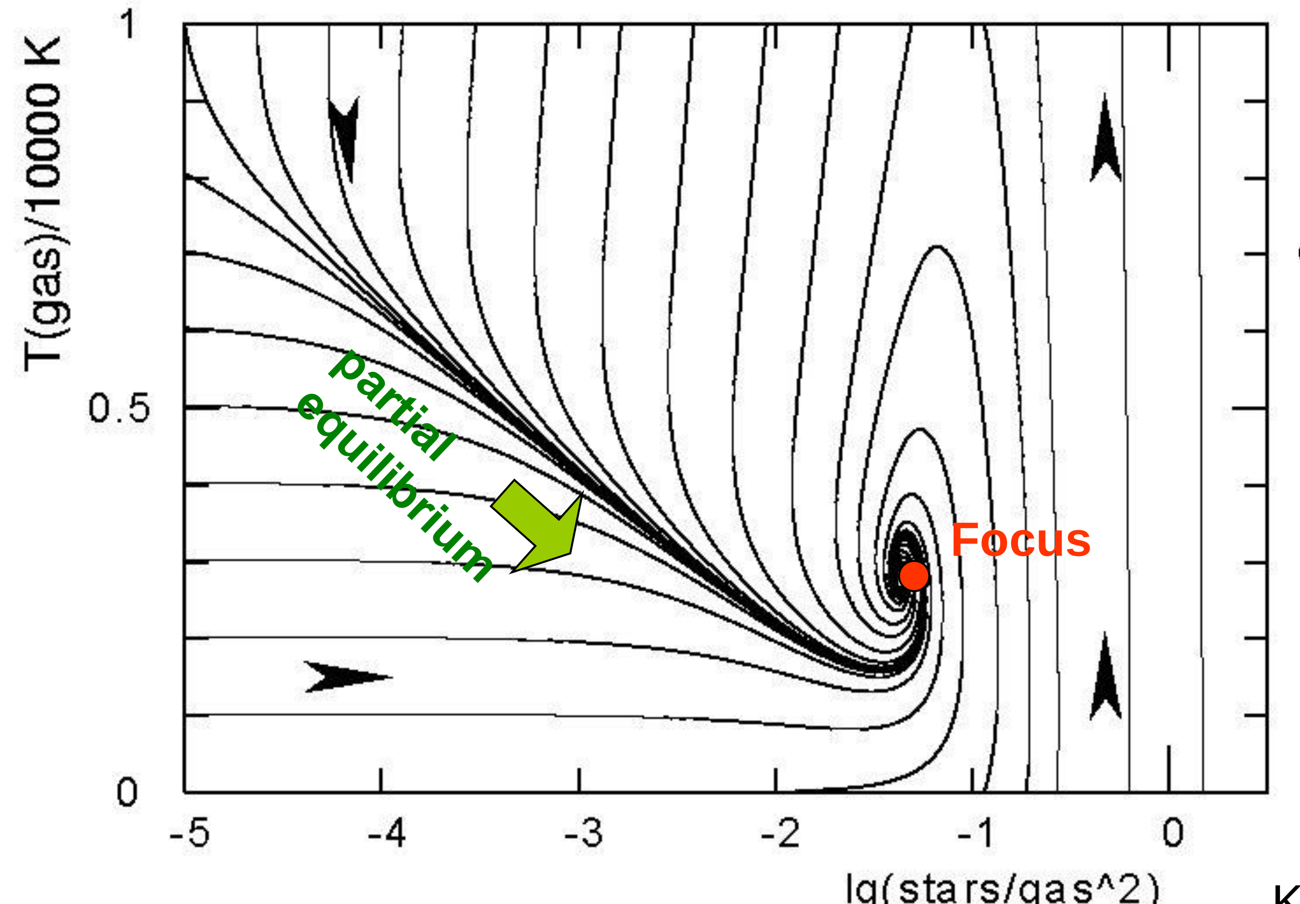
Stability analysis

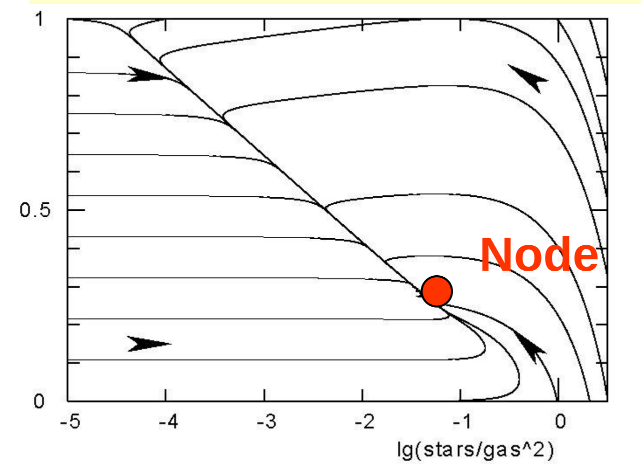
- **locally (**analytically**)**
- **globally**

➔ always stable

- **gas density**
- **parameters of recipes**







Köppen, Theis, Hensler 1995

Our System: $(x = s/g^2 \quad e = bgT)$

$\dot{g} = \cdots$ slow $\Rightarrow$ g = control parameter

$$\left.\begin{aligned}\dot{x} &= \dot{x}(x,e,g)\\ \dot{e} &= \dot{e}(x,e,g)\end{aligned}\right\}\text{fast}\Big\} \quad \text{equilibrium } \dot{x} = \dot{e} = 0$$

Local Stability:

Linearization about equilibrium: $x = x_0 + \tilde{x}e^{\lambda t} \ldots$

(λ are Eigenvalues of Jacobi matrix)

e.g.

$$2\,\mathrm{Re}(\lambda) = -\frac{\xi + 4x_0 g\xi\eta + 4x_0^2 g^2\eta}{\tau(\xi + 2x_0 g)} - \frac{g}{b}\underbrace{\frac{\partial\Lambda}{\partial T}}_{>0} < 0$$

ALWAYS < 0

i.e. STABLE

for all g

for all parameters $\tau, \xi, \eta, \ldots$

det J > 0 $\Rightarrow$ Never a saddle point

Complex eigenvalues between $g \approx 10^{-3} \ldots 10^{-1} \frac{M_\odot}{pc^3}$

(strongly damped oscillations around equilibrium: "Focus": $\tau_{decay} \lesssim \frac{1}{4}\tau_{period}$)

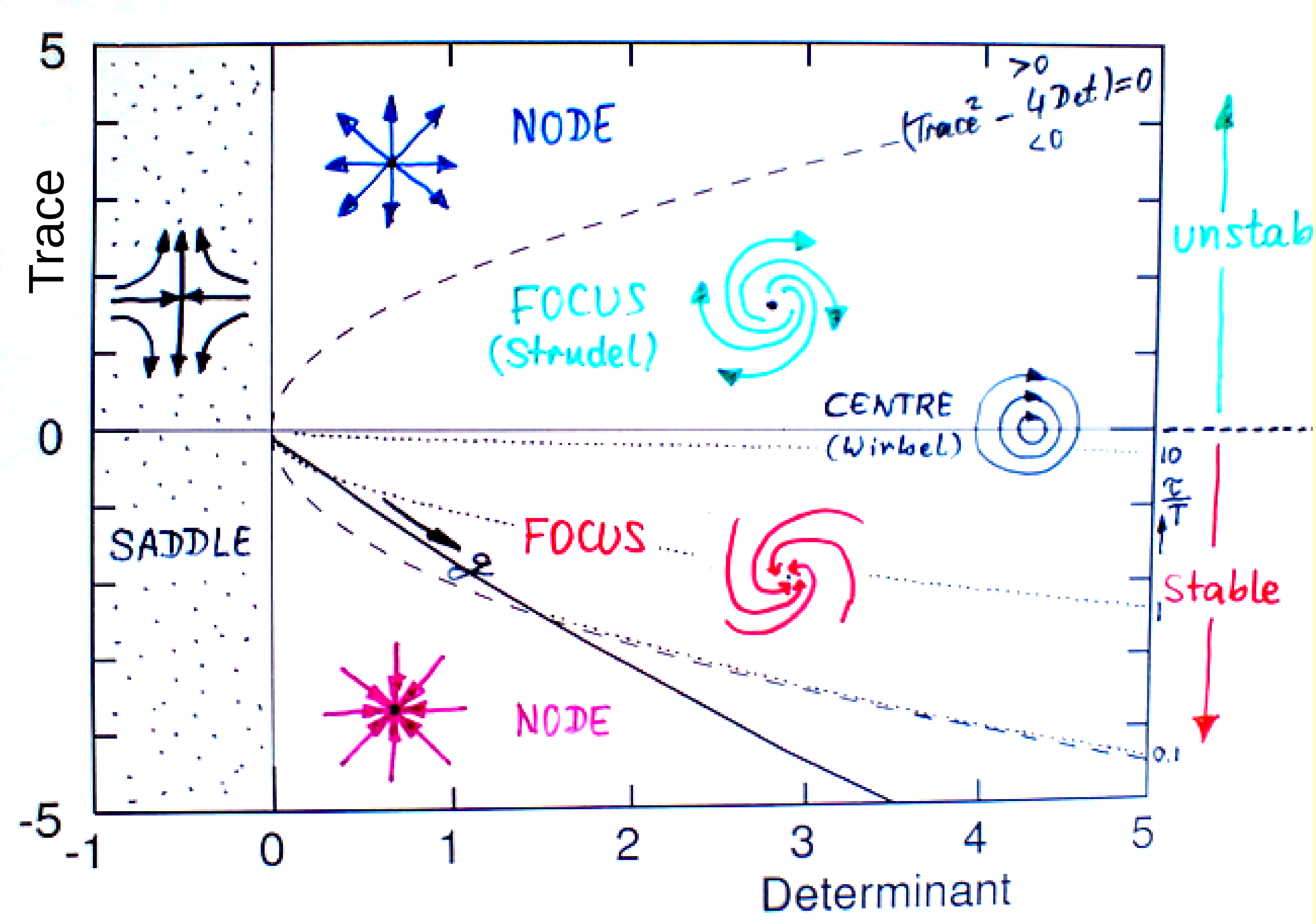
For the system

$$\dot{x} = f(x,y)$$
$$\dot{y} = g(x,y)$$

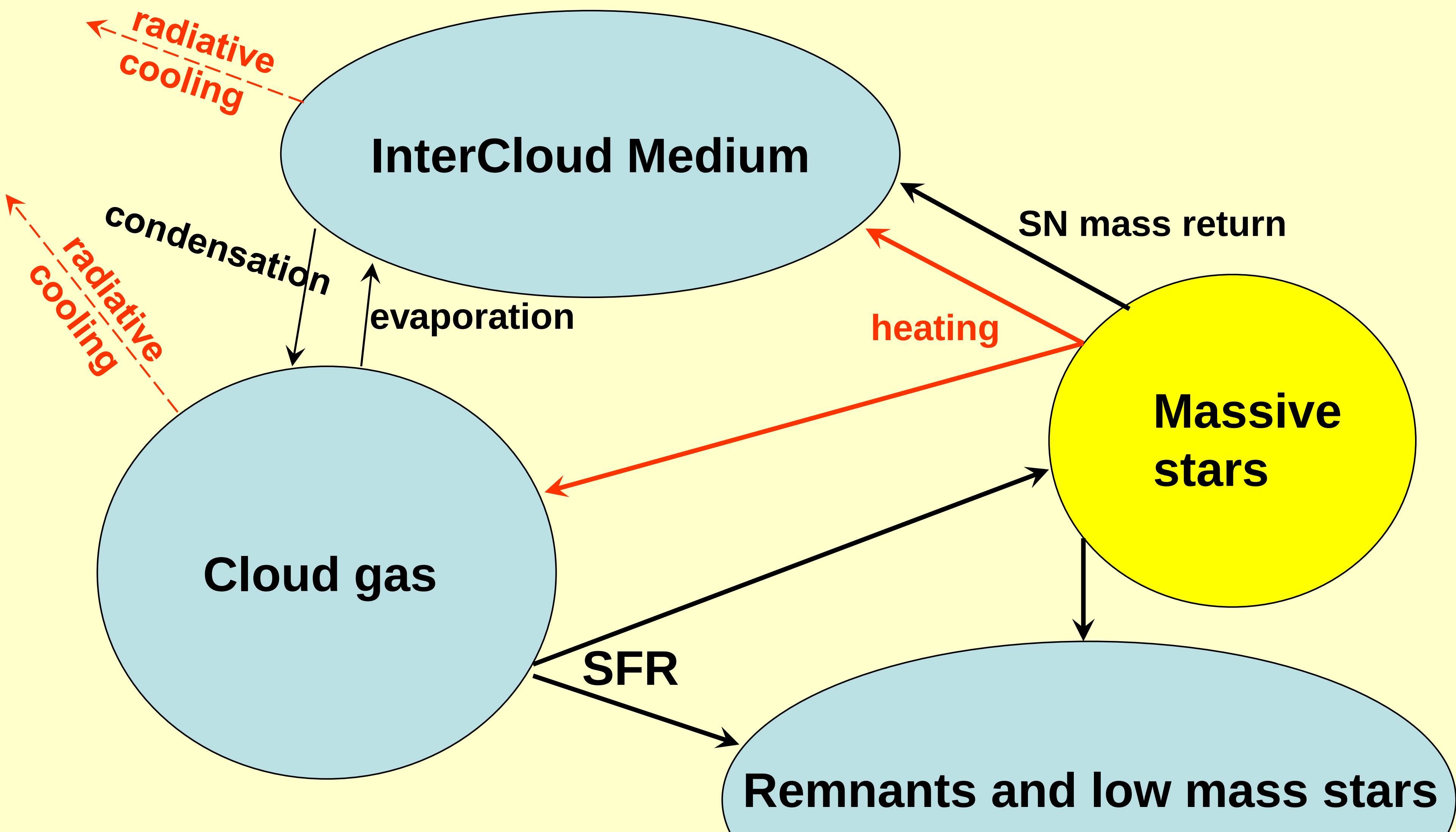
the Jacobi matrix is

$$J = \begin{pmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} \end{pmatrix}$$

Parameters of Jacobi matrix



More complete network:



To cut a long story short …
there is a hierarchy of equilibria:

Consumption of cloud gas by star formation
abt.1000 Myr ➔ clouds(t)

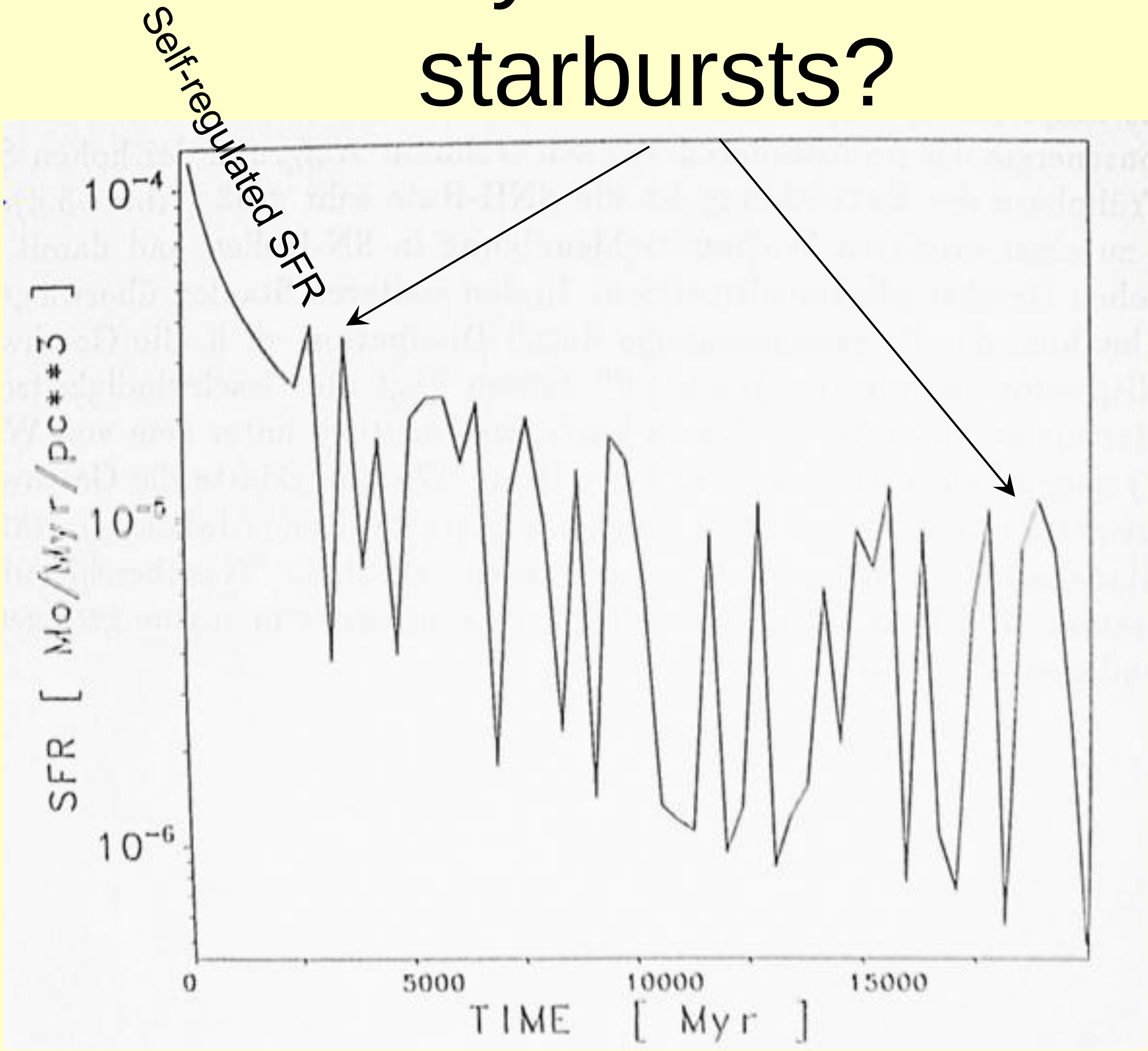
Equilibrium Condensation = Evaporation
abt.100 Myr ➔ gas/clouds ≈ 0.001

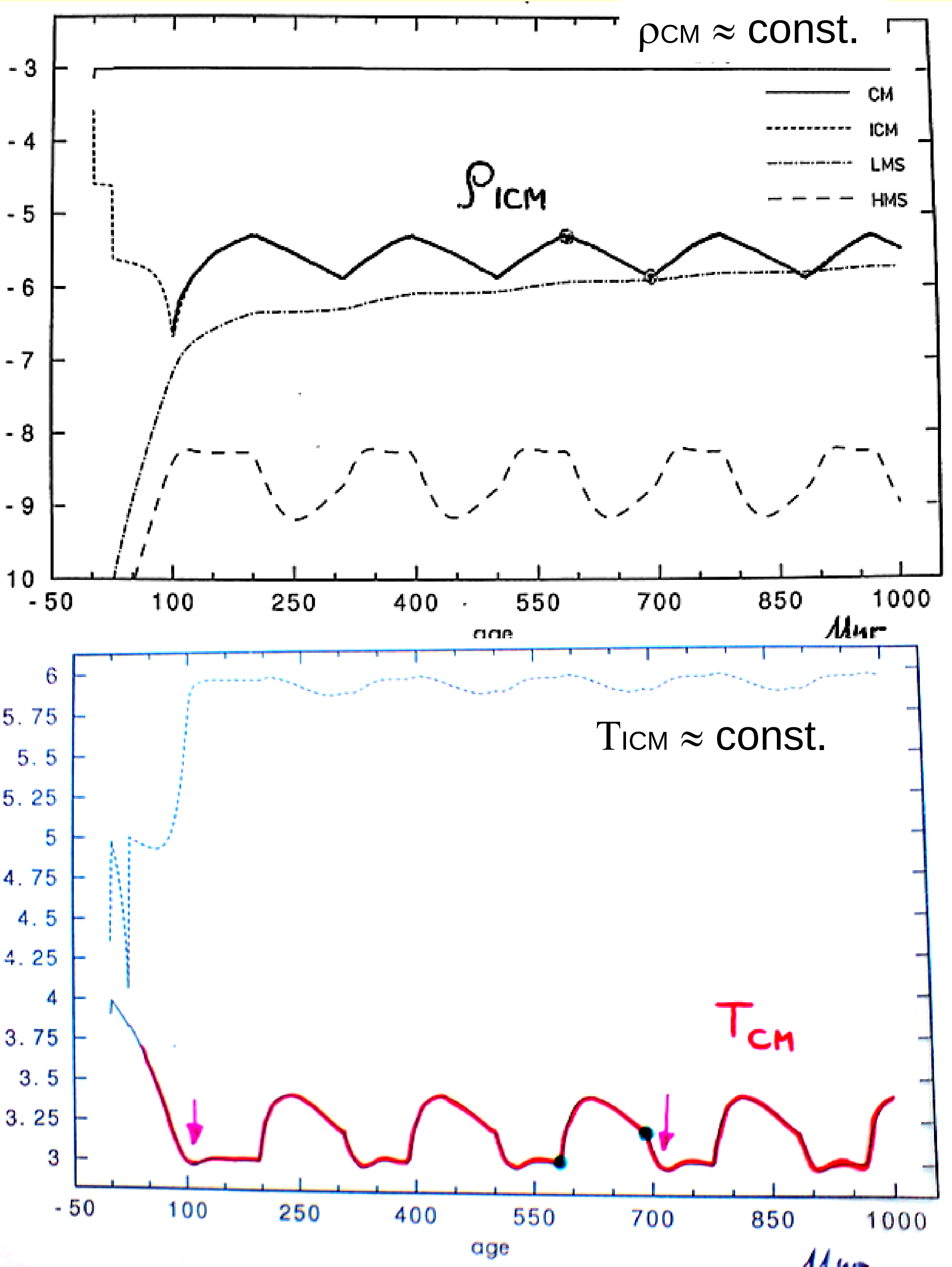
Thermal equilibrium in cloud gas: Heating = Cooling
abt.1 Myr ➔ T

Here's the long story:

- Early models showed strongly fluctuating star formation: « starbursts »?
- … interesting and enjoyable analysis …
- They are non-linear oscillations between evaporation and condensation, caused by a small physical inconsistency of network equations … condensed gas hadn't cooled
- They were not starbursts but interruptions of the self-regulated SF

Chemodynamical model: starbursts?



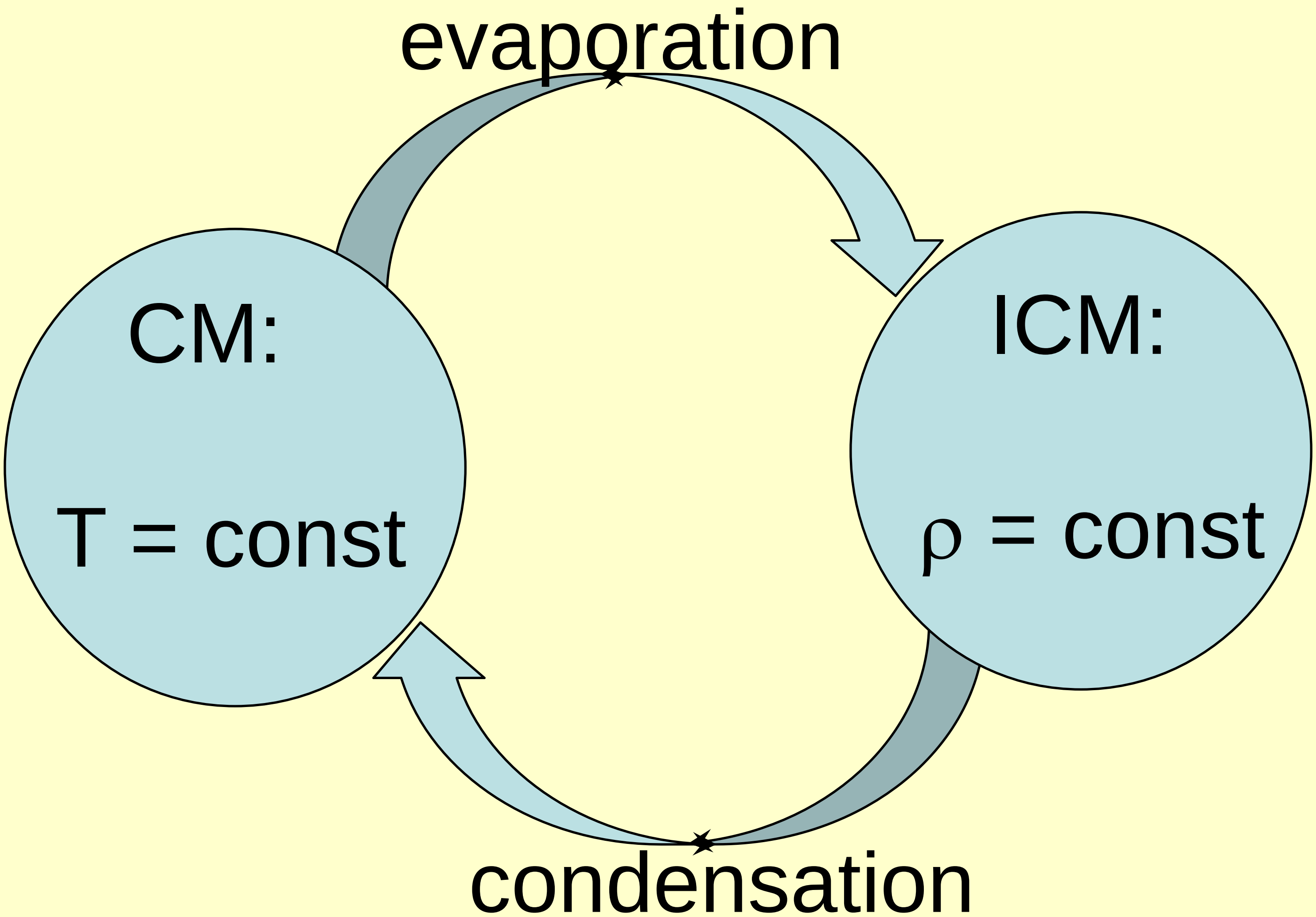


Ditto, zoomed

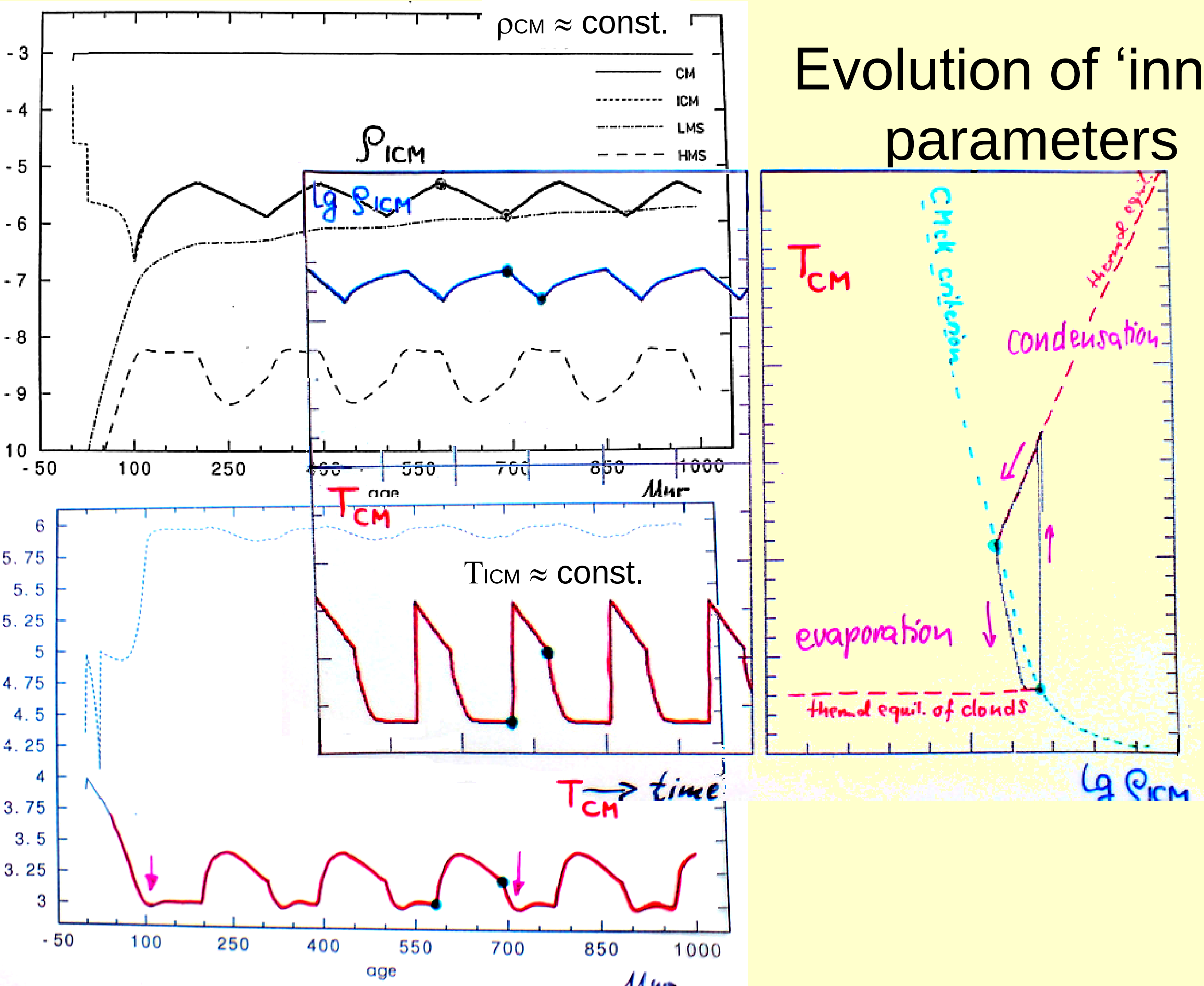
...

non-linear oscillations!

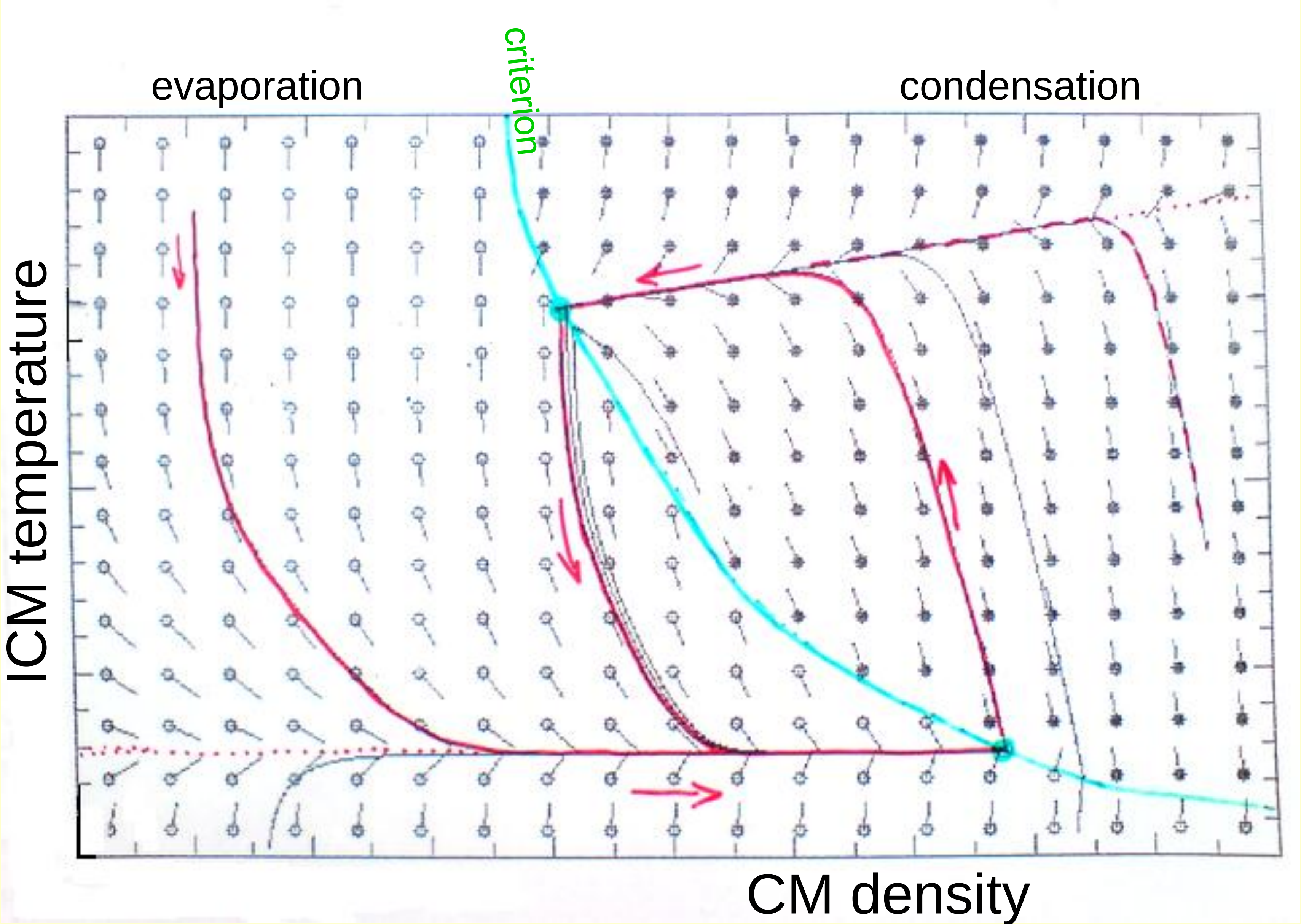
Apply simplifications

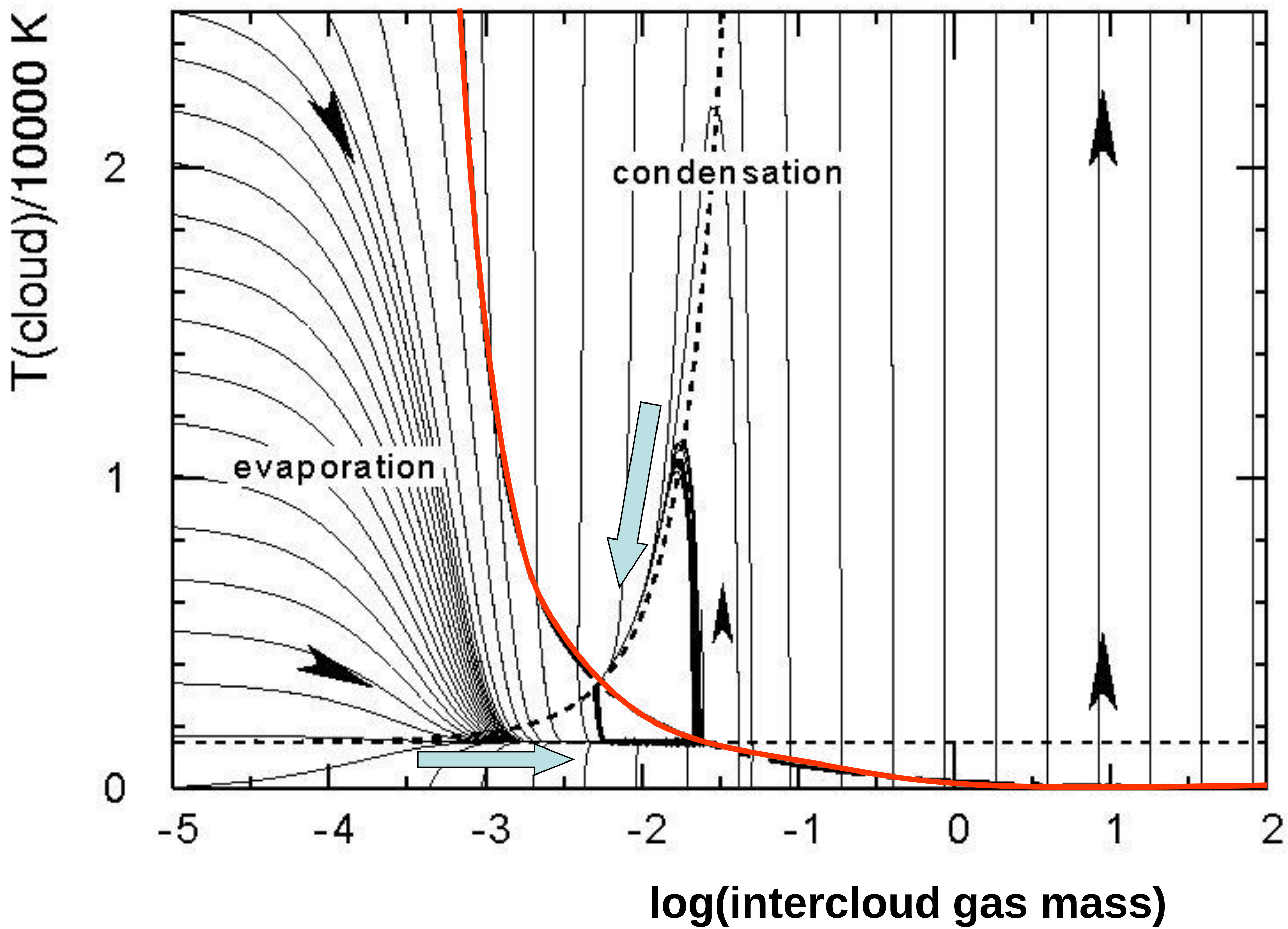


Evolution of 'inner' parameters

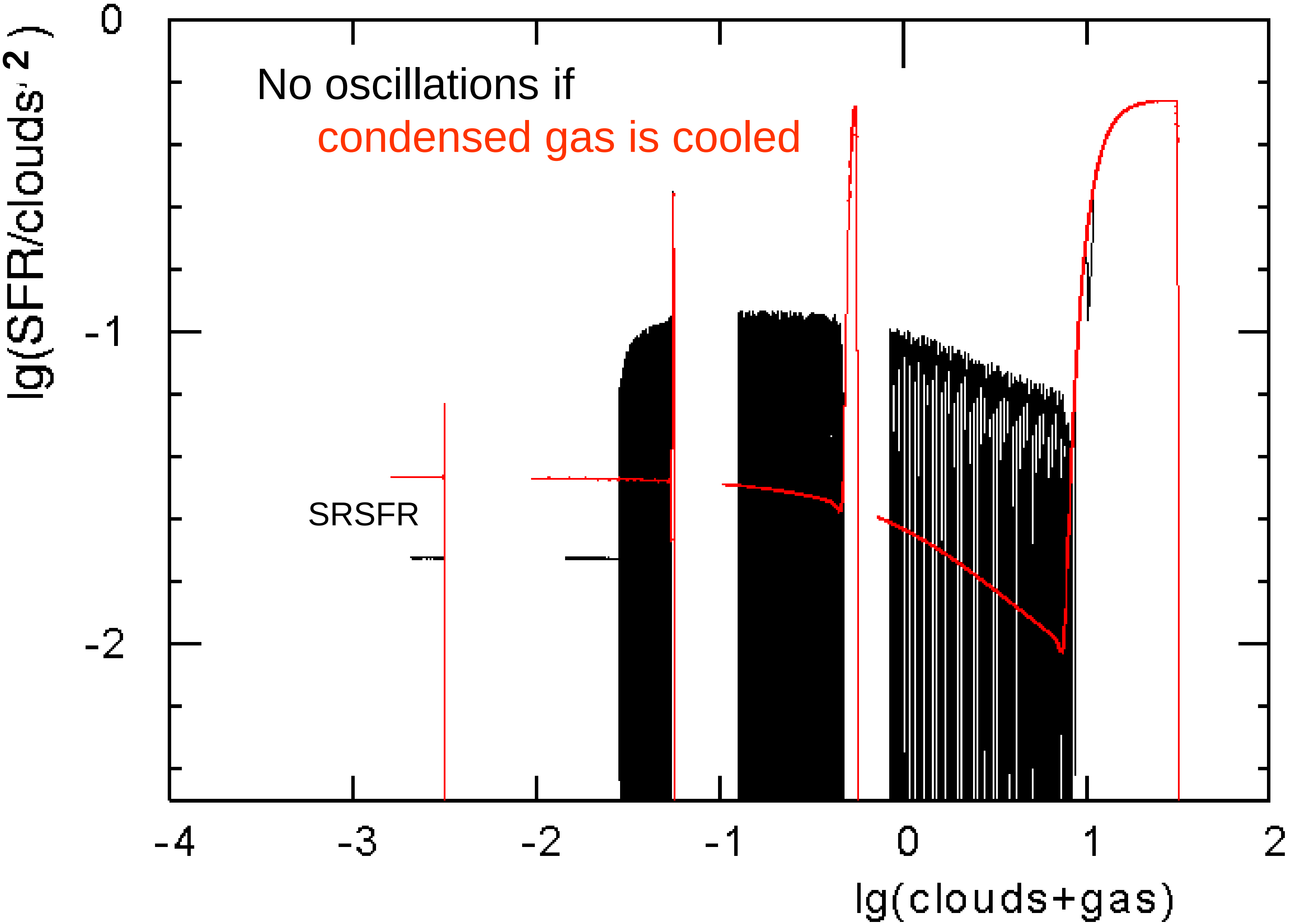


Sufficient to study flow field





T(cloud)/10000 K
2
1
0
condensation
evaporation
-5
-4
-3
-2
-1
0
1
2
log(intercloud gas mass)


No oscillations if
condensed gas is cooled
SRSFR
lg(SFR/clouds^2)
lg(clouds+gas)
0
-1
-2
-4
-3
-2
-1
0
1
2

The origin of the ‘trouble’

III. CLASSICAL EVAPORATION

a) Evaporation Rates

Throughout §§ III and IV we shall consider the evaporation of a spherical cloud of radius R embedded in a hot gas which has density n_f and temperature T_f far from the cloud, under the assumption that radiation, ionization, and magnetic fields may be neglected. (Ionization may be neglected if the surface of the cloud is ionized or if the ambient plasma is very hot, $kT_f \gg 1$ Ryd.) We seek time-independent solutions for the mass loss rate

$$\dot{m} = 4\pi r^2 \rho v \tag{11}$$

which are eigenvalues of the energy conservation equation

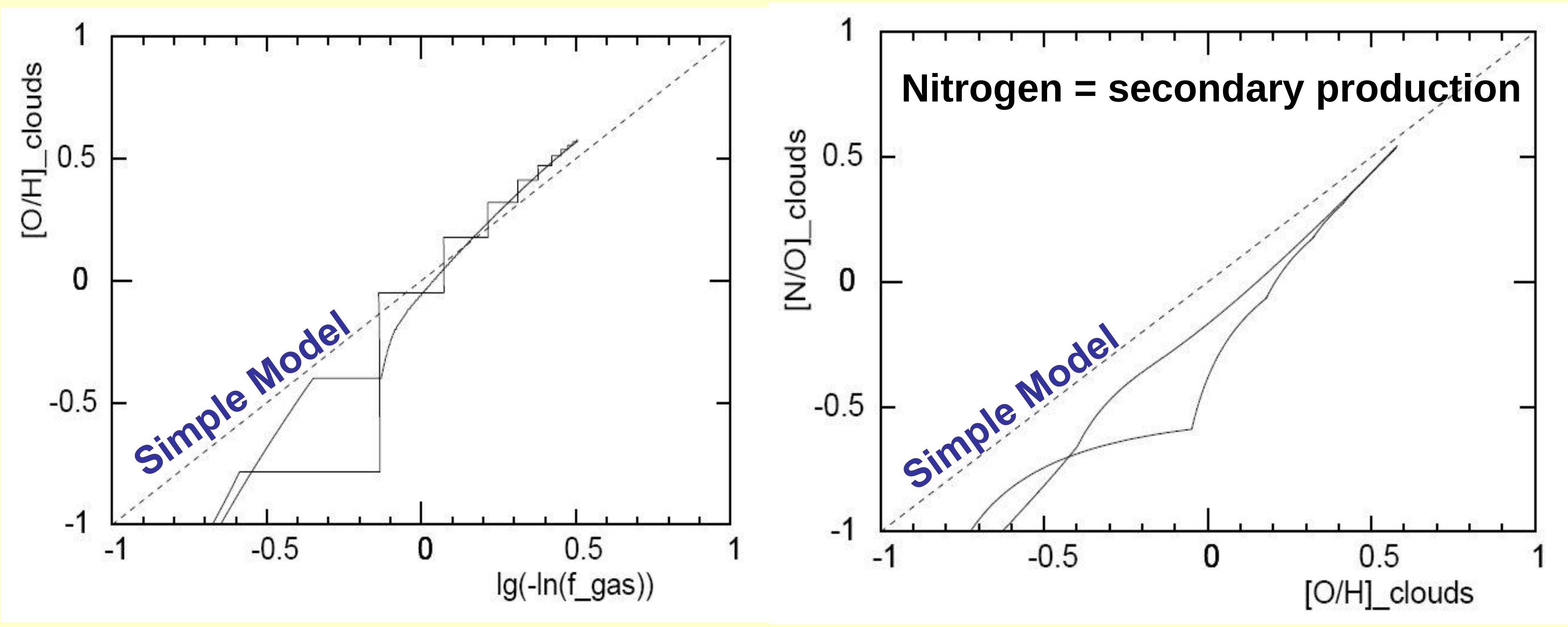
$$\nabla \cdot \rho \boldsymbol{v}(\tfrac{1}{2}v^2 + 5c^2/2) + \nabla \cdot \boldsymbol{q} = 0 \tag{12}$$

subject to the boundary condition that T approaches T_f as r approaches infinity and $T \sim 0$ at $r = R$. Such solutions may be found only for spherical geometries, and the solutions described are not directly applicable to plane or cylindrical cases. (Time-independent solutions for the latter two cases exist only if T is constrained to approach T_f at a finite distance from the cloud.) For simplicity of notation we define the

Derivation of the formulae for evaporation and condensation rates **did** include energy conservation

Cowie & McKee 1977

As far as the cloud phase (HII regions) is concerned ..

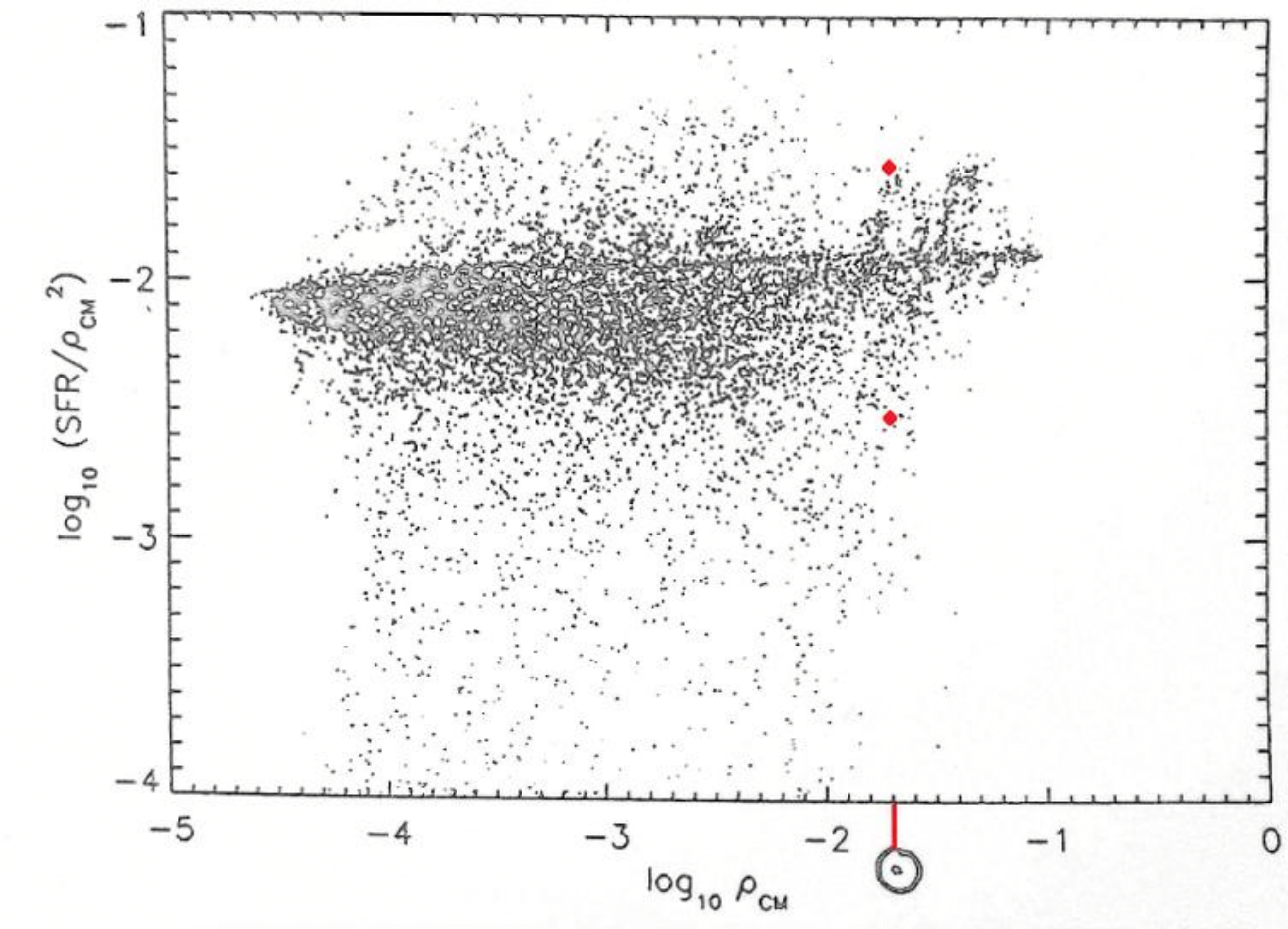


… a closed box chemodynamical model is very close to the closed-box Simple Model

… even the version with oscillations

Köppen, Theis, Hensler 1998

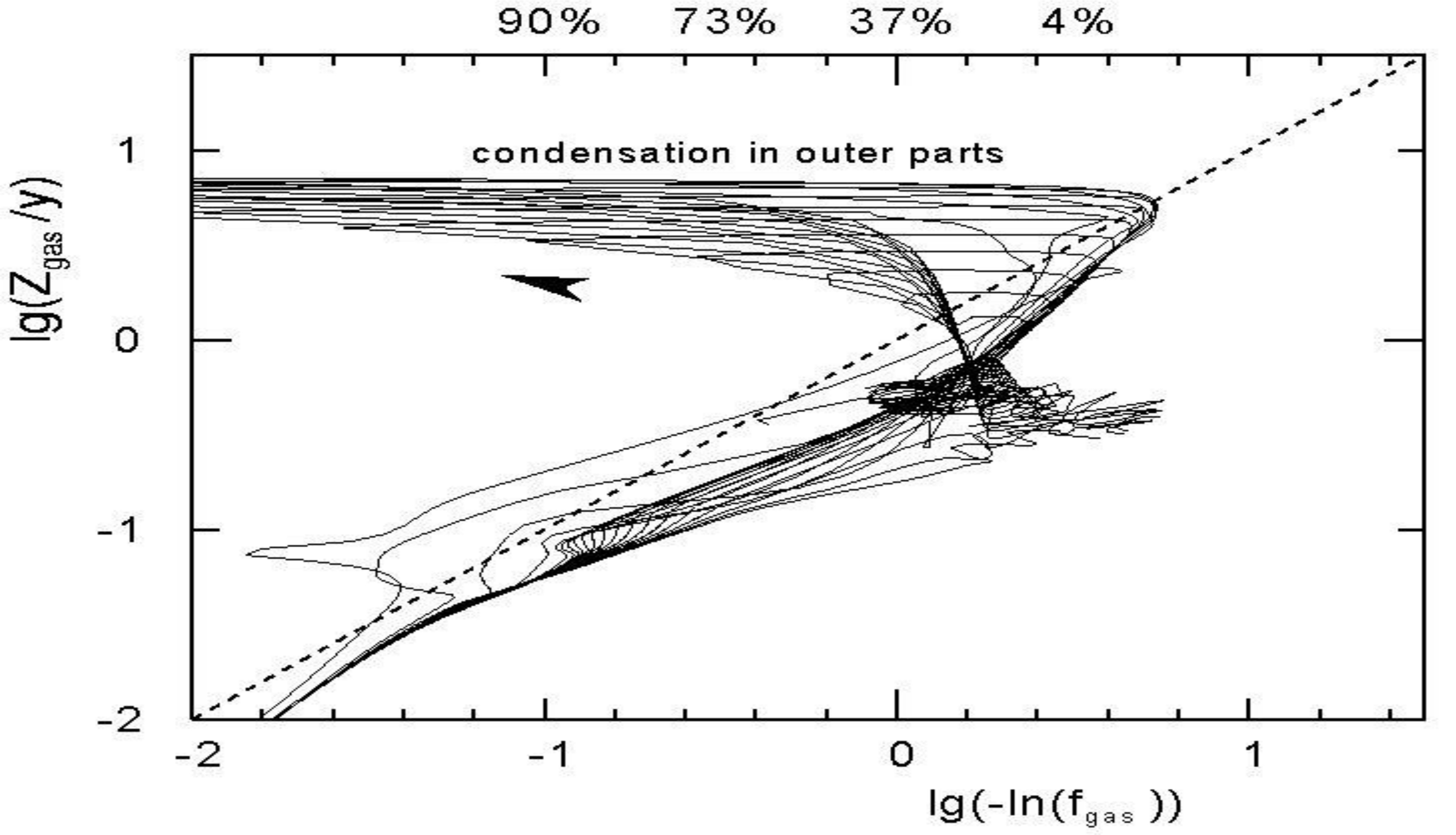
Samland's model



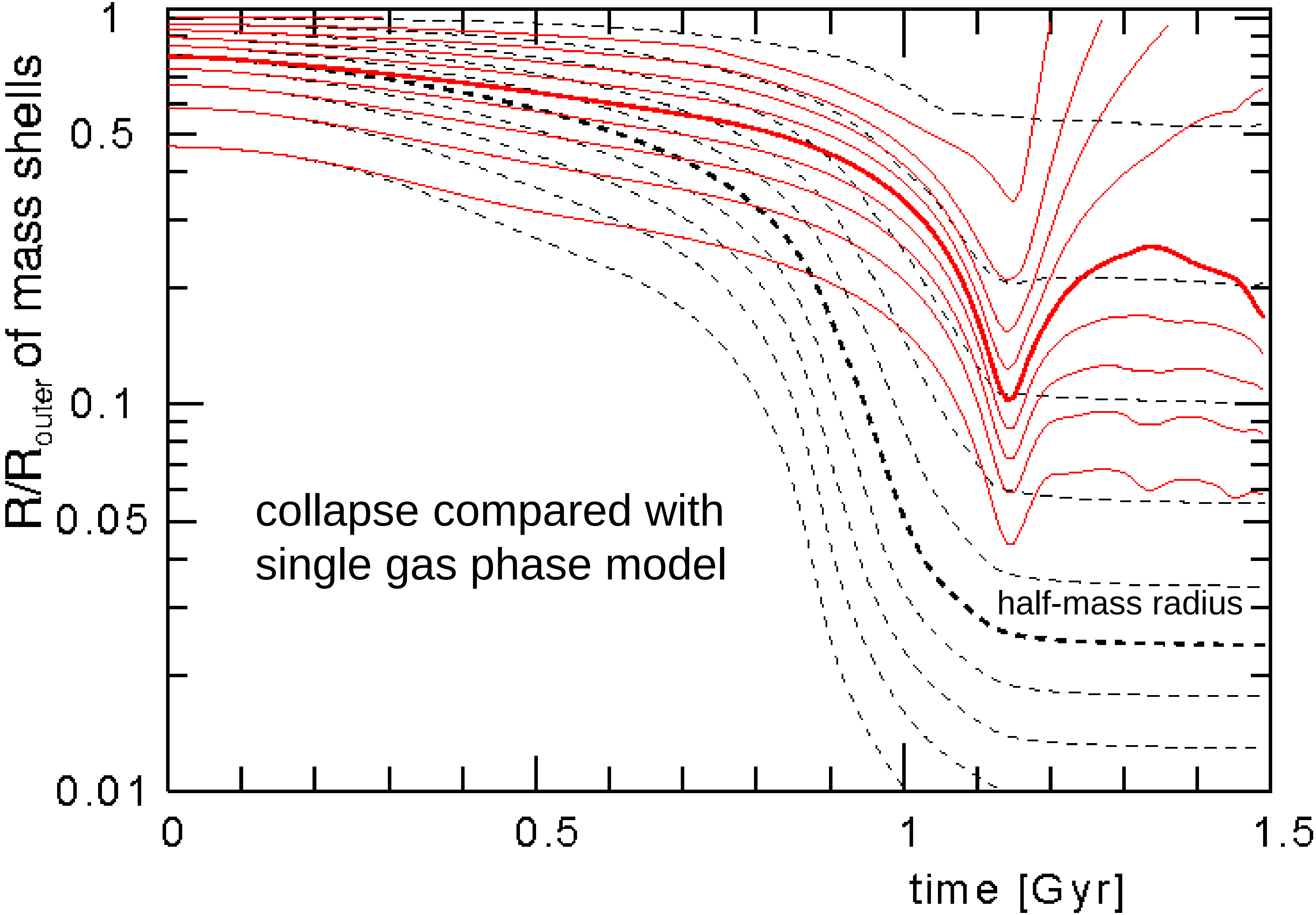
➔ For most of the time most of the volume elements are in self-regulated star formation, with SFR $\propto$ ρ^2

Dynamics

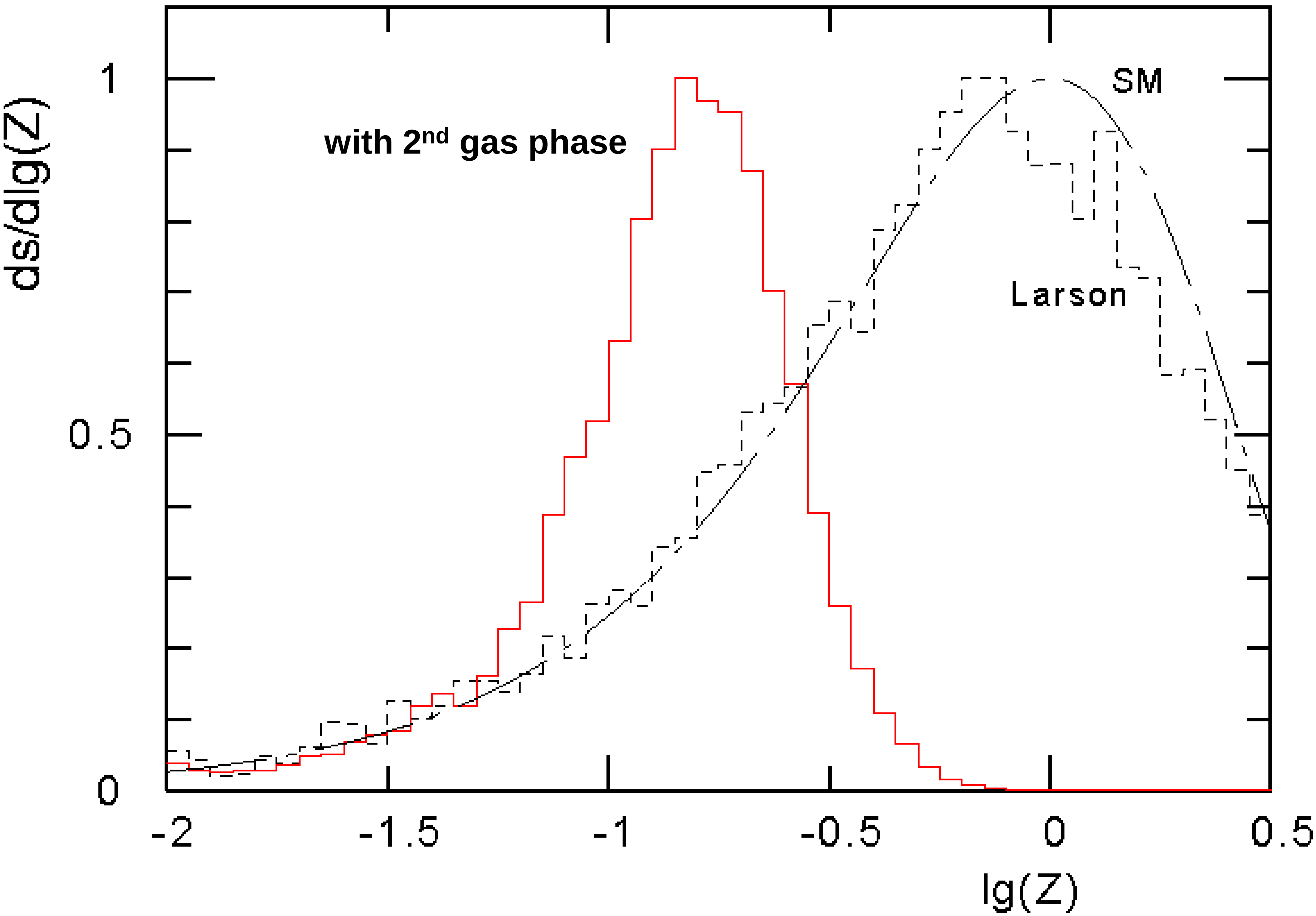
Let us add a 2nd gas phase to a spherical collapse 'Larson' model



Mass loss !!!



R/R$_{outer}$ of mass shells
1
0.5
0.1
0.05
0.01
0
0.5
1
1.5
time [Gyr]
collapse compared with
single gas phase model
half-mass radius



ds/dlg(Z)
1
0.5
0
with 2nd gas phase
SM
Larson
-2
-1.5
-1
-0.5
0
0.5
lg(Z)

Current models ….

- ‘Chemodynamics’ (global dynamics of gas and stars = ‘Larson’, multi-phase ISM): 1D, 2D, 3D FDM, … stars via N-body

- ‘Chemie’ + Dynamics $\neq$ Chemodynamics

- Hierarchical Clustering Models

Hierarchical galaxy formation

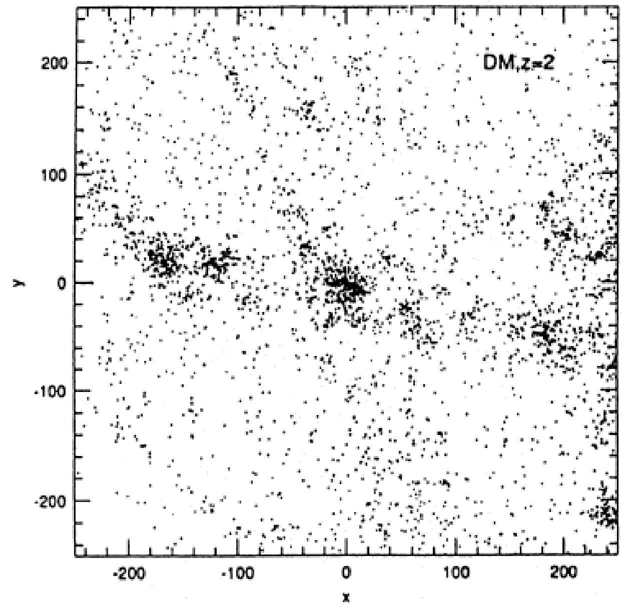
Gravitational instabilities occur on all scales:

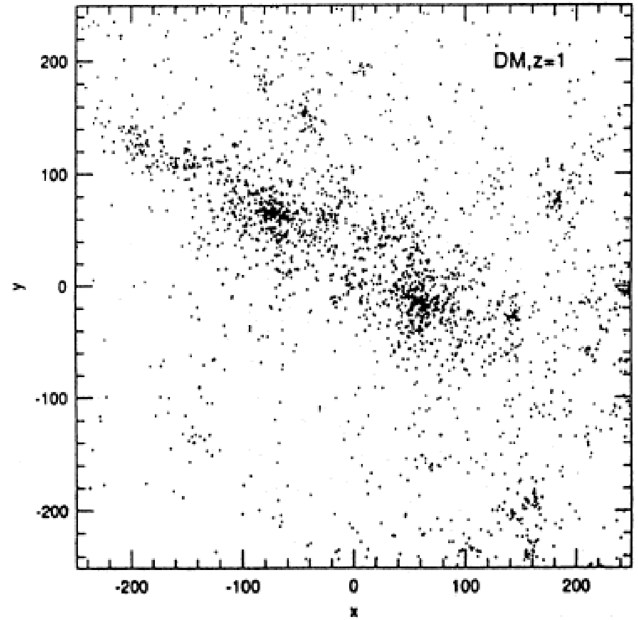
- growth of density fluctuations in universe
- formation & collapse of galaxies
- formation & collapse of gas clouds
- formation & collapse of stars

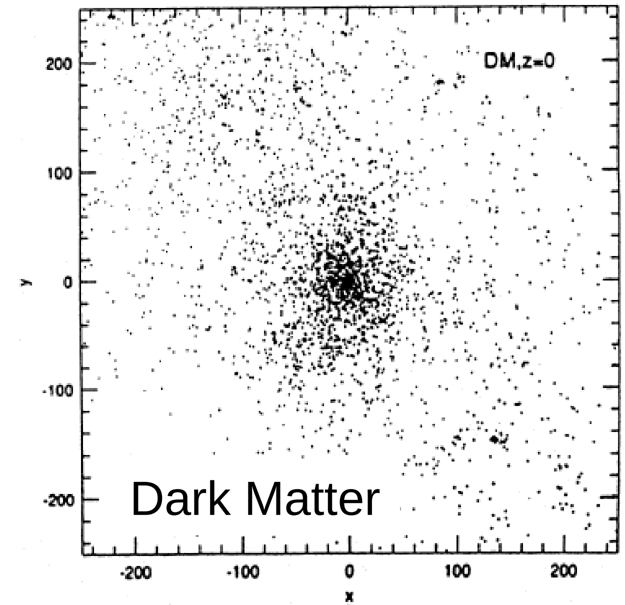
Cold Dark Matter: $\rho_{\mathrm{DM}} \approx 10\ \rho_{\mathrm{(gas+stars)}}$

- galaxies form in dark matter condensations

Method of computation:
SPH for ‘gas’ + N body code for ‘stars’





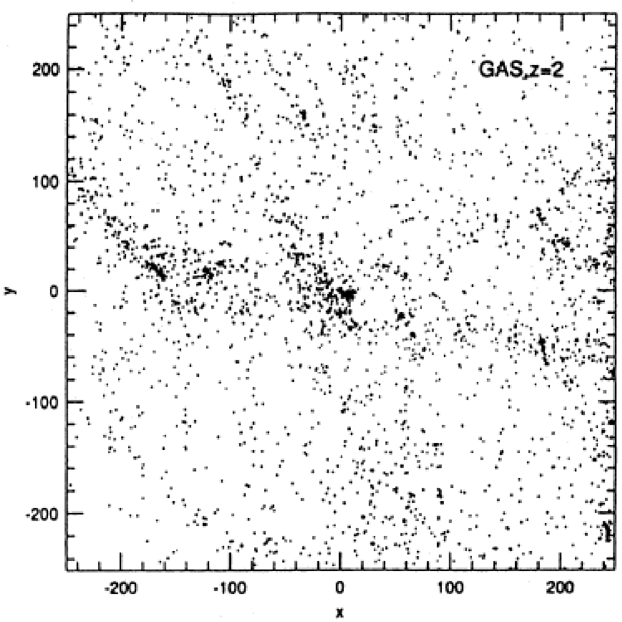


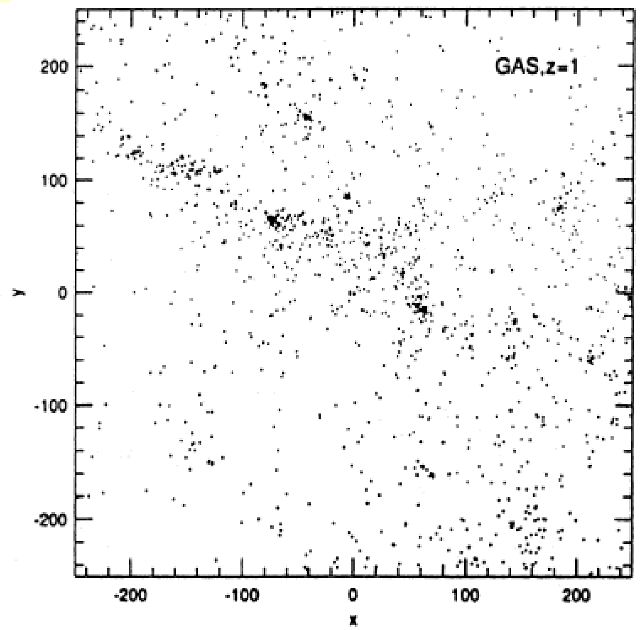
z = 2

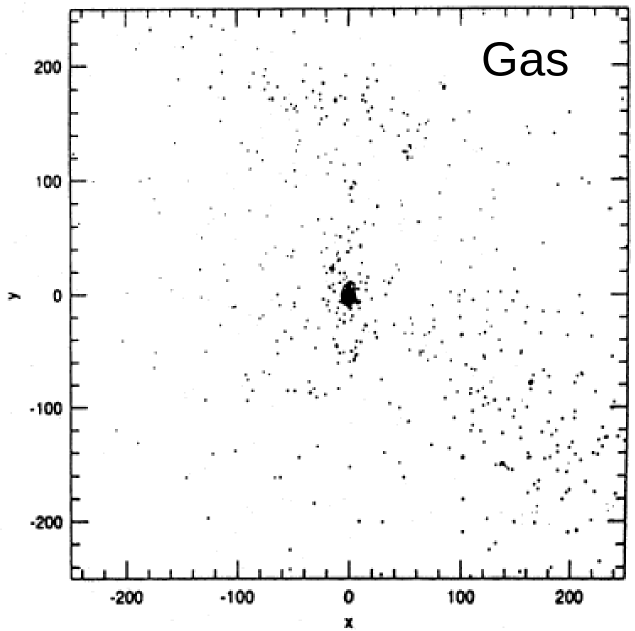
1

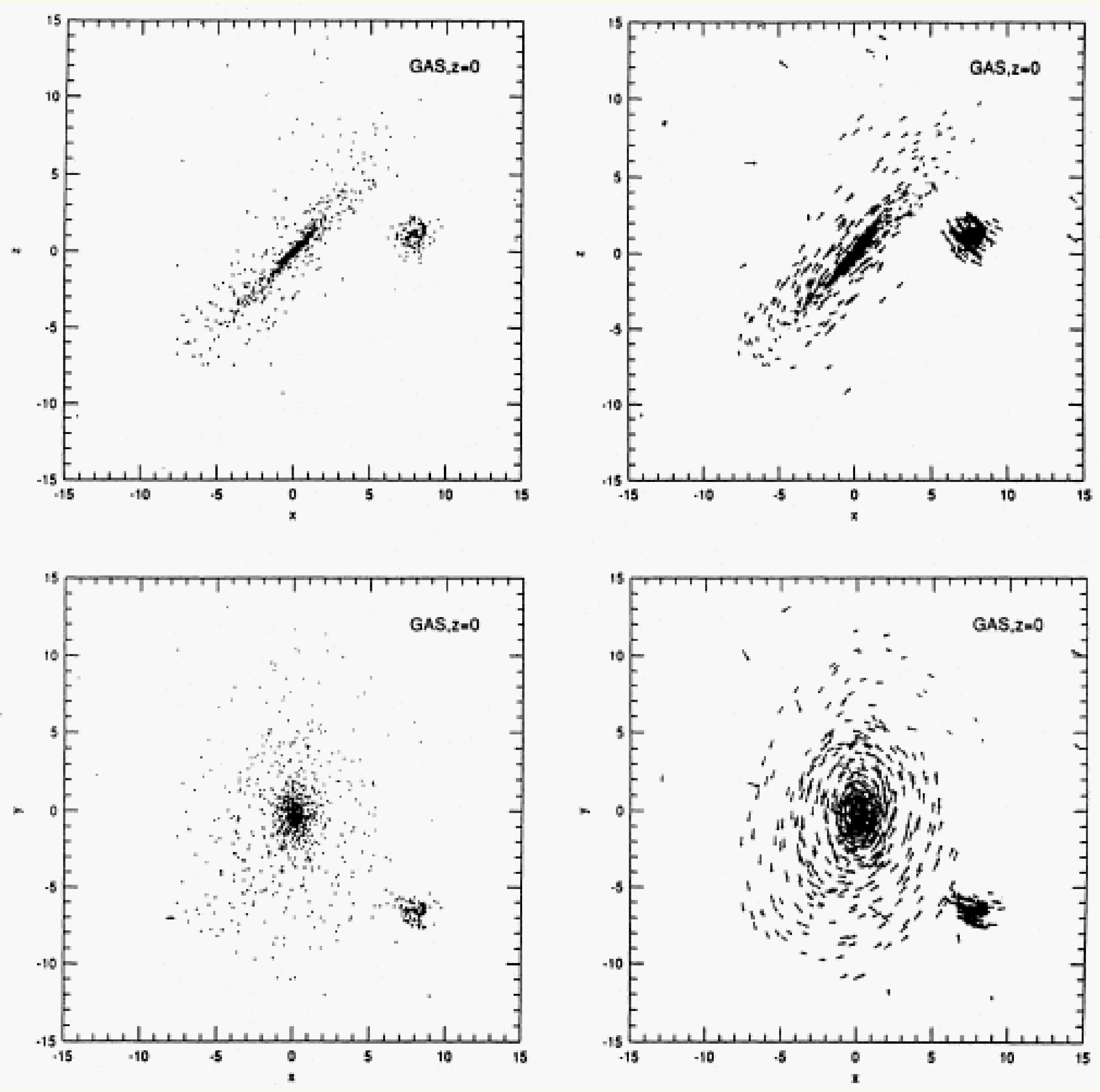
0

Navarro & White 1994







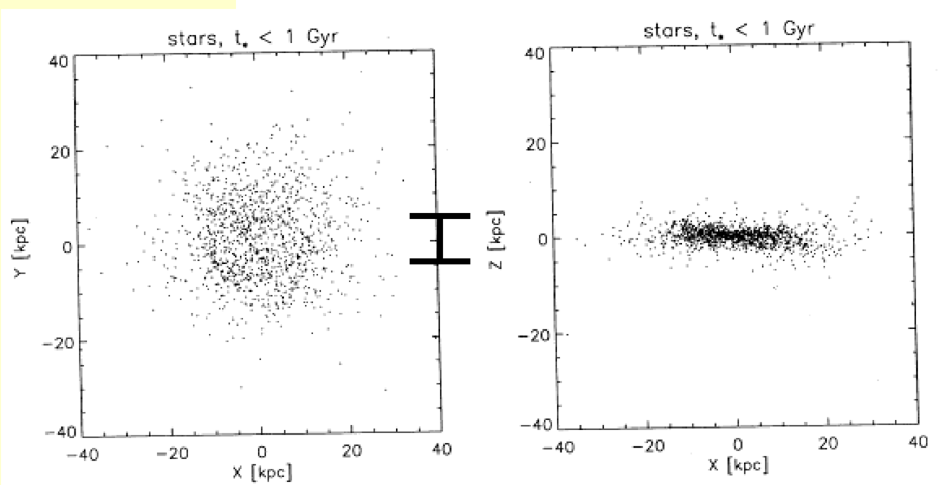


Navarro & White 1994

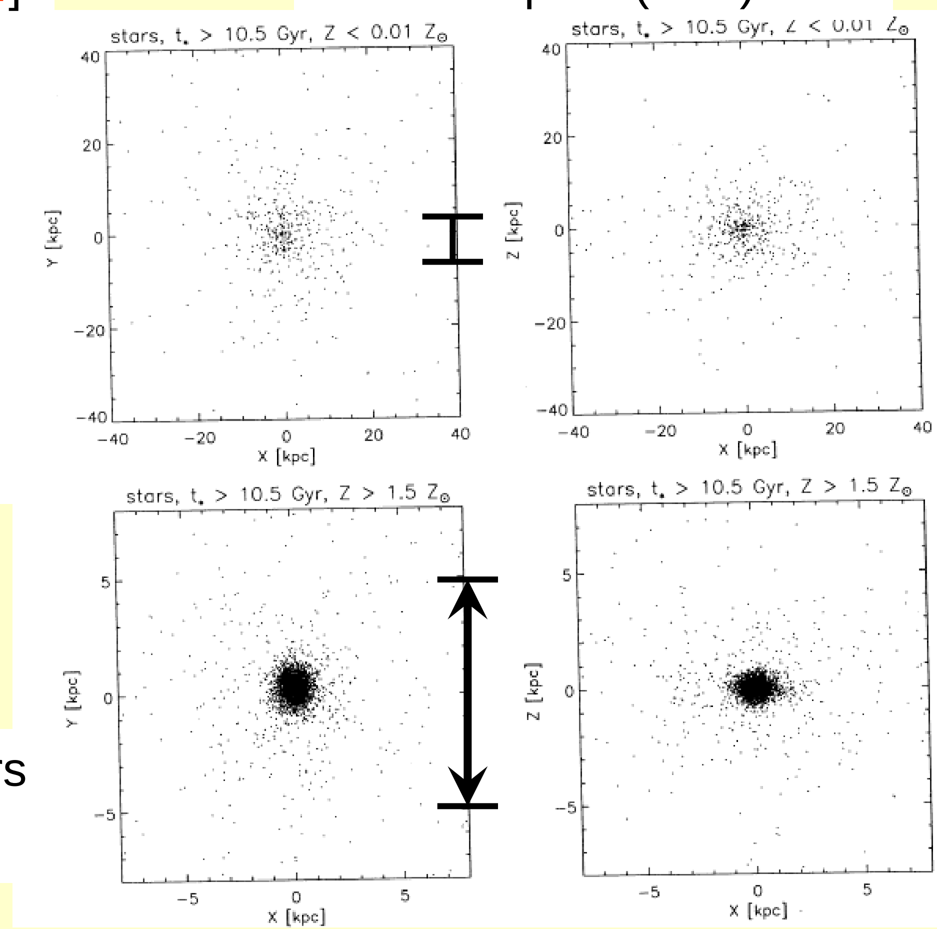
The present state of another simulated galaxy – with chemical evolution (Steinmetz & Müller 1994):

young disk stars

[gas: dlgZ/dr = - 0.05 dex/kpc ☑]



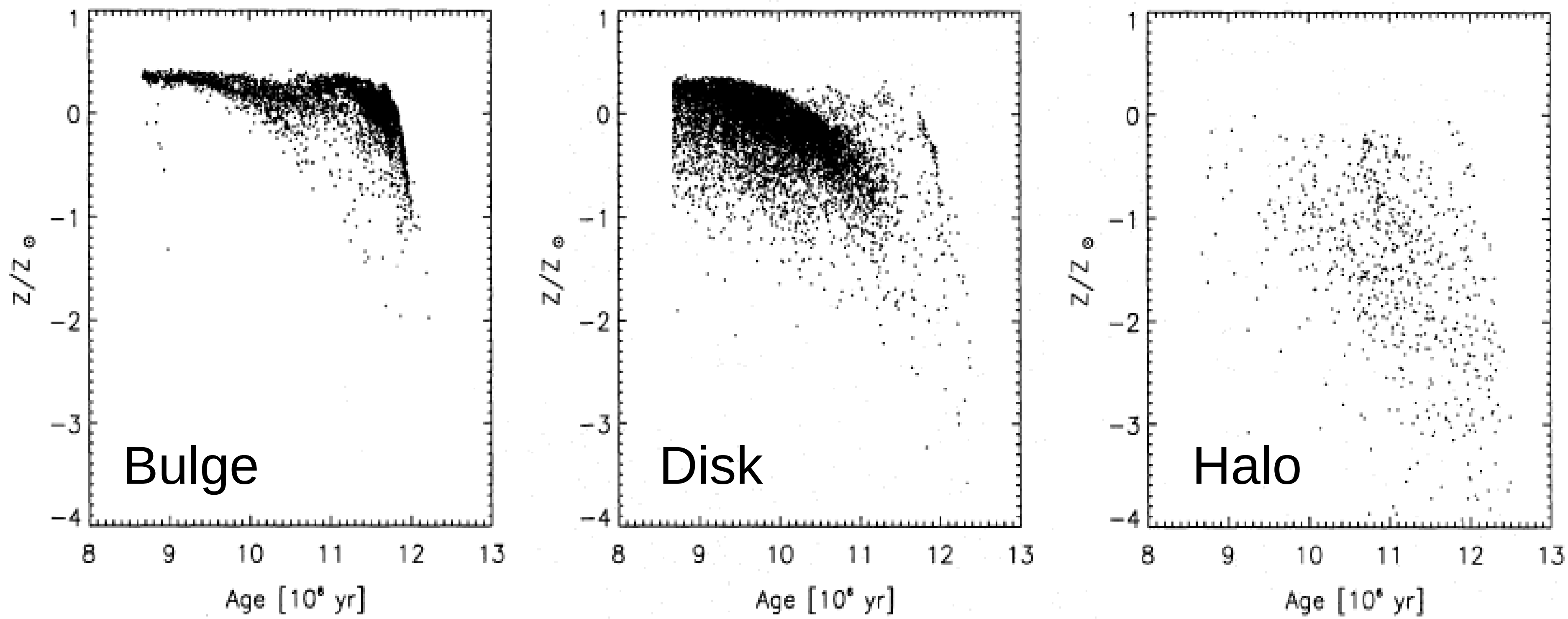
old metal-poor (halo) stars



old metal-rich (bulge) stars

dlgZ/dlg r = - 0.1 ☑

Stellar age-metallicity relations

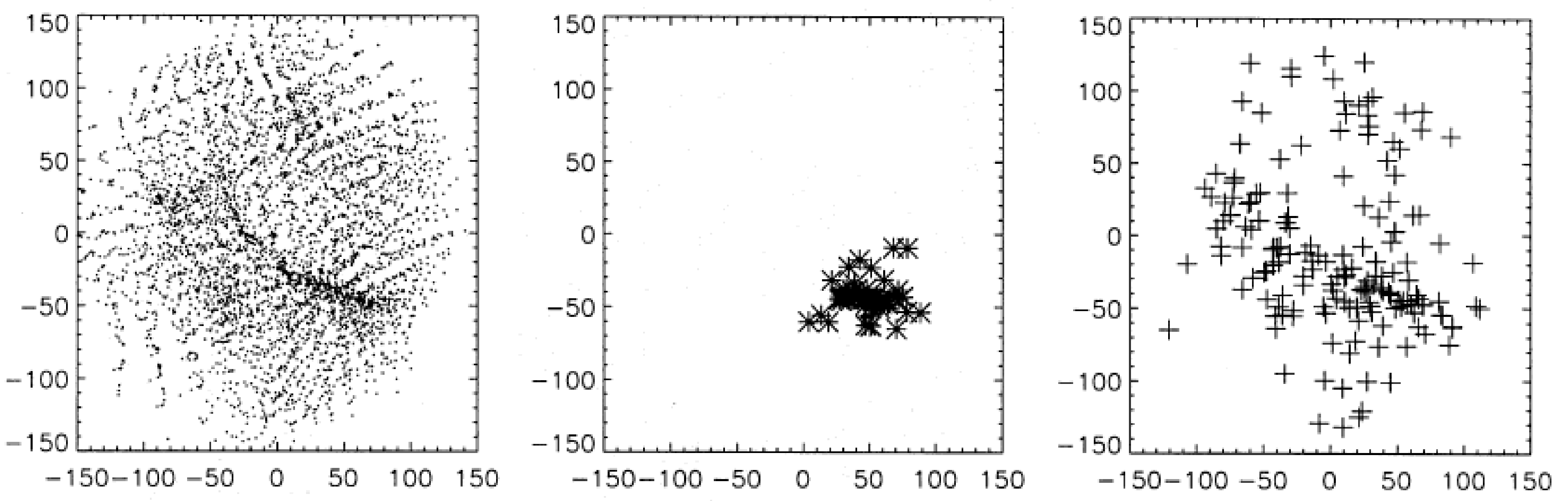


« However, about 13% of the disk stars have metallicities less than 0.25 $Z_{\odot}$, in contrast to the observational limit of 2% in the solar neighbourhood, indicating a G-dwarf-problem »

Steinmetz & Müller 1994

… but not if that problem were merely due to obs. selection (Haywood 2006)!

Initial site of gas cloud determines where a star ends up:



gas particles at z=6

positions of gas particles that will form:

bulge stars

halo stars

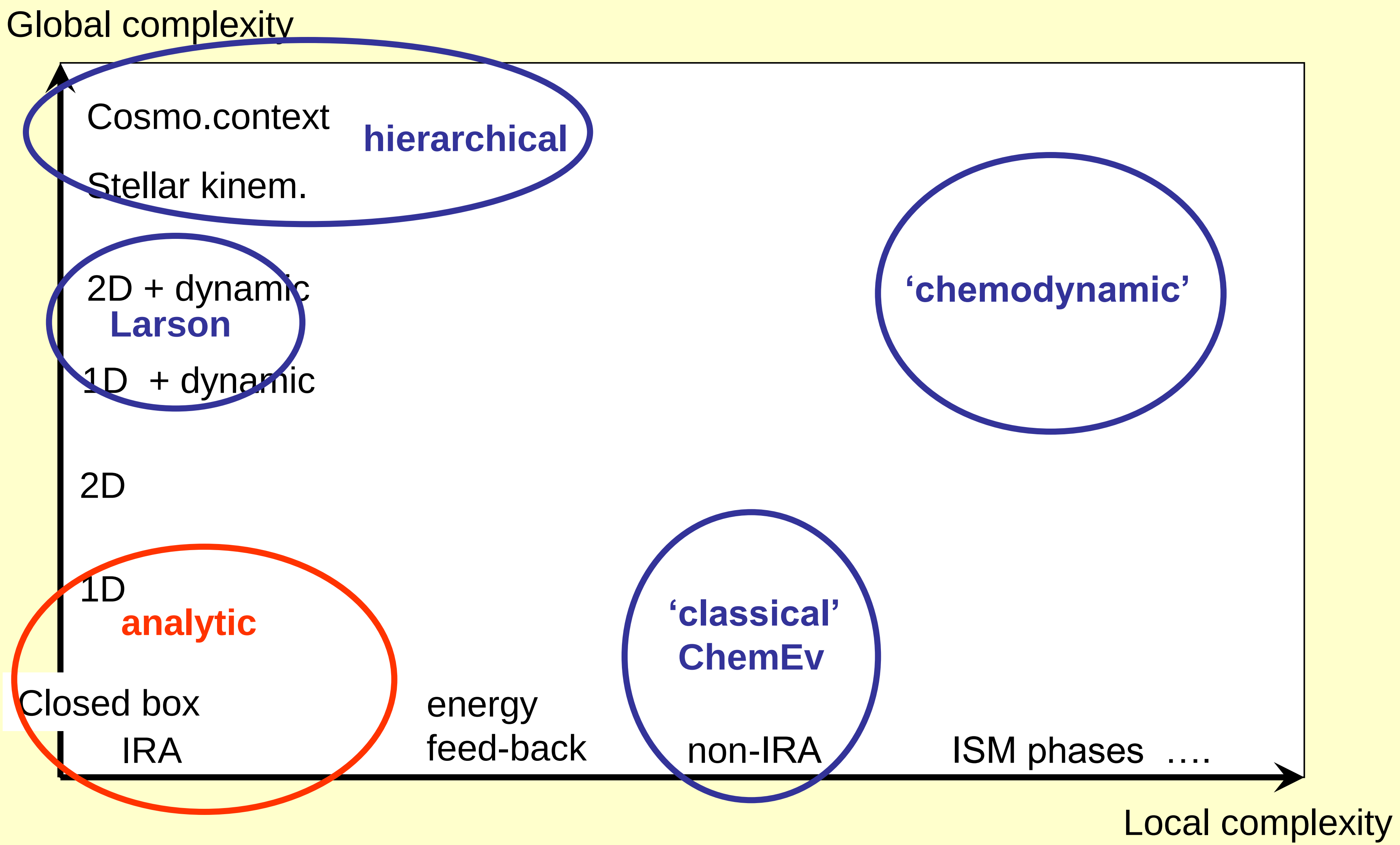
A remark, not a summary

We now have **two** physically motivated but **different** evolution models that explain the observed metallicity gradient in the disk without any fiddling of free parameters:

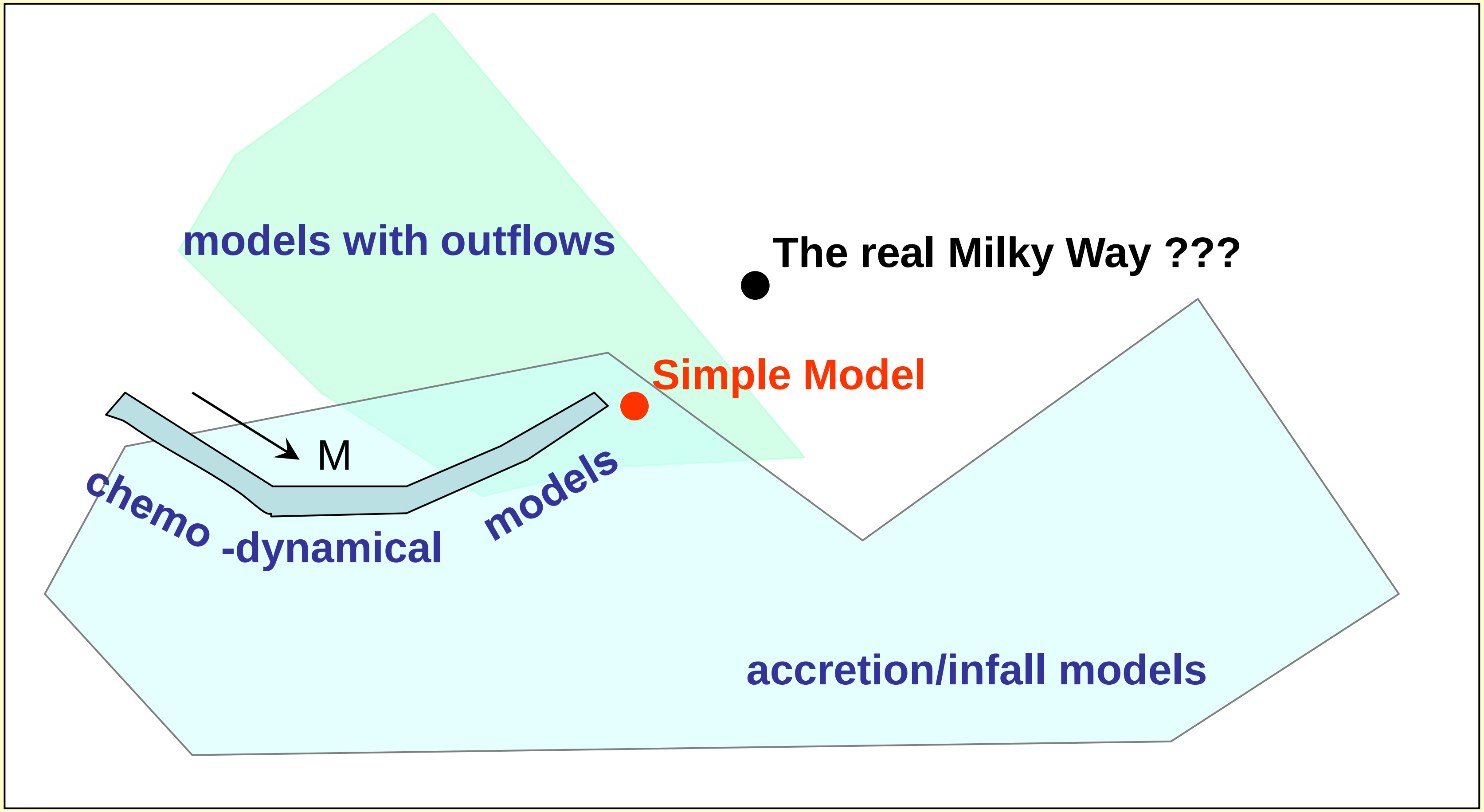
- Samland 94: monolythic collapse, transport of metals in hot ISM phase and mixing with gas to form disk.
- Steinmetz 94: gas assembly in dark matter halo, single gas phase.

Some thoughts about models

Types of models



The space of **all** chemical models



➔ If something holds true for ALL chemical models, it will also be valid for any chemo-dynamical or chemo+dynamics model (irrespective their particular ingredients or recipes …

Inheritance of properties …

Adding another aspect or process to a model

- may leave some behaviour of the solutions unaffected
  - ratio of primary elements = yield ratio
  - Samland’s models are monolythic collapse

- can bring new types of behaviour to the solutions
  - imperfect mixing breaks up relation of secondary and primary elements

Inheritance of properties …

	$Z = -y \ln f$	$A/B = y_A/y_B$	$Z_k/P = P^k$	Gdwarfs
single zone				
with inflow	quite	yes	yes	NO
incom.mix	yes	yes	NO	yes
chemodyn.	yes	yes	yes	yes
1 D				
chemEvol.	quite	yes	yes	NO (Infall)
Larson	NO	yes	yes	yes
Larson+ICM	quite	yes	yes	NO
2 D				
Samland 94	NO	yes	yes	NO: B/D/H

… in chemodynamics …

	SelfRegulated SFR: Ψ α ρ^2	Equilbrium cond./evap. $K^*\rho_{ICM} = E^*\rho_{CM}$
Closed box	yes	yes
2-D Samland 94	yes	yes

Which model for which purpose?

- To explain O/Ne/S/Ar abundance ratios, stellar nucleosynthesis and IMF suffice!
- For relations of metallicity and gas fraction (effective yield) simple (analytical) models will do …
- To estimate the influence of different scenarios and physical processes, models with parametrized recipes might well do

Which model?

- To explore the effect of a process, some parametrized recipe could be helpful
- To see the effects of several physical processes in concert and to get their quantitative result … use models as complete as possible …
- … but be ready to cut down the model into a very simple concept that can help you to understand it

Warnings

- Never interpret numerical results in terms of physics! This is dangerous, especially if the results agree with observations or your expectations …
- I should prefer to understand the maths of a model as thoroughly as possible … irrespective of any approximations or simplifications of the physics necessary to formulate the equations

Where do we stand …

- ‘classical’ chemical evolution can explain observations by a diversity of models with different parametrized processes: ➔

  not unique! …but they’re still useful
- ‘modern’ complex chemical+dynamical models can explain observations by different scenarios and recipes (SF, energy feed-back, …) … hidden parameters? **unique**ness**?**