3. The physics of star formation and feedback

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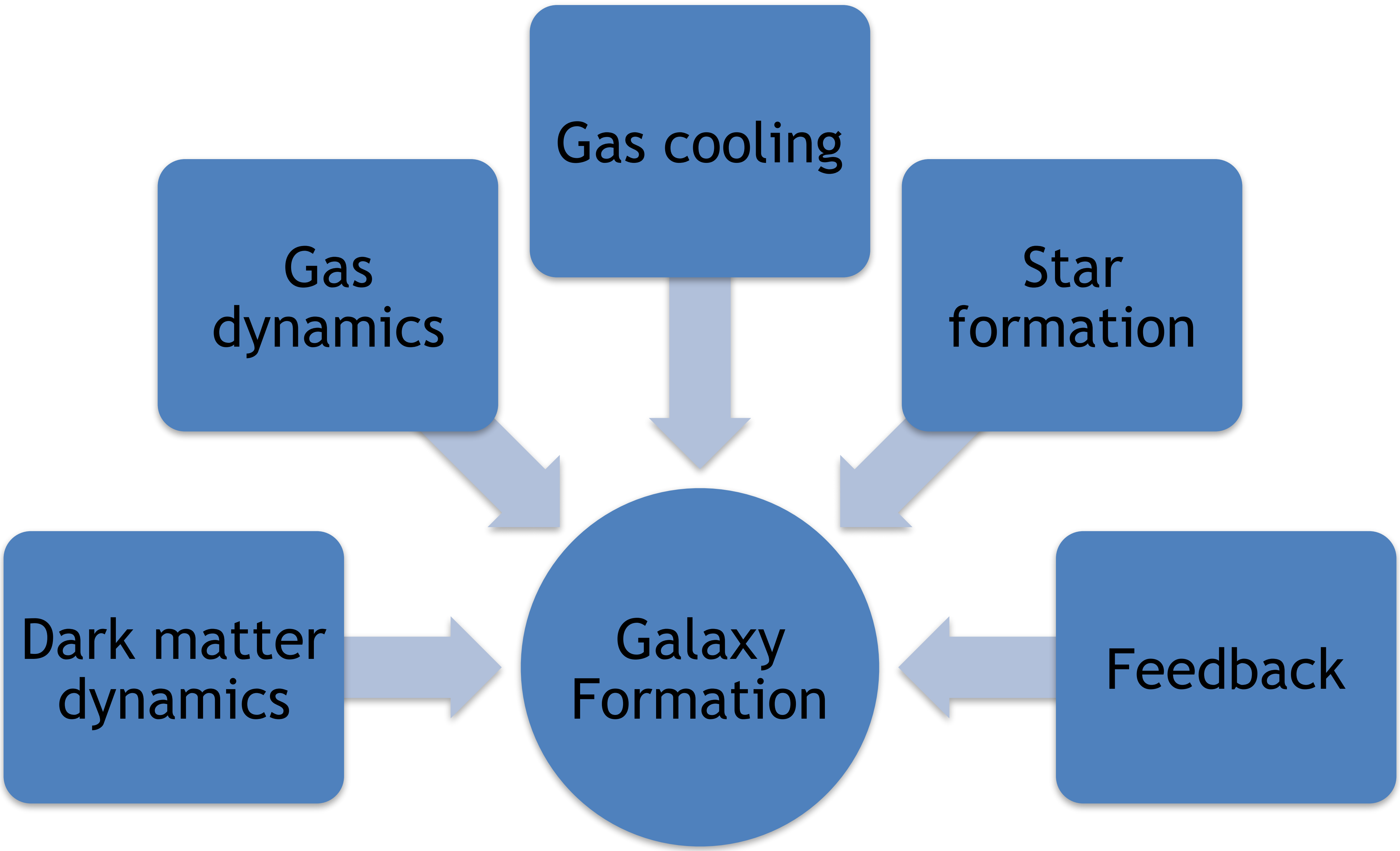
A Physical model for galaxy formation



Gas physics

- Physics relevant for galaxy formation.
- Physical models at resolved scales.

- Radiative cooling and heating
- Star formation
- Feedback

Equations of Gasdynamics

$$\frac{\partial \rho_G}{\partial t} + \nabla(\rho_G \vec{u}) = \left(\frac{\partial \rho_G}{\partial t}\right)_{SF} + \left(\frac{\partial \rho_G}{\partial t}\right)_{FB}$$

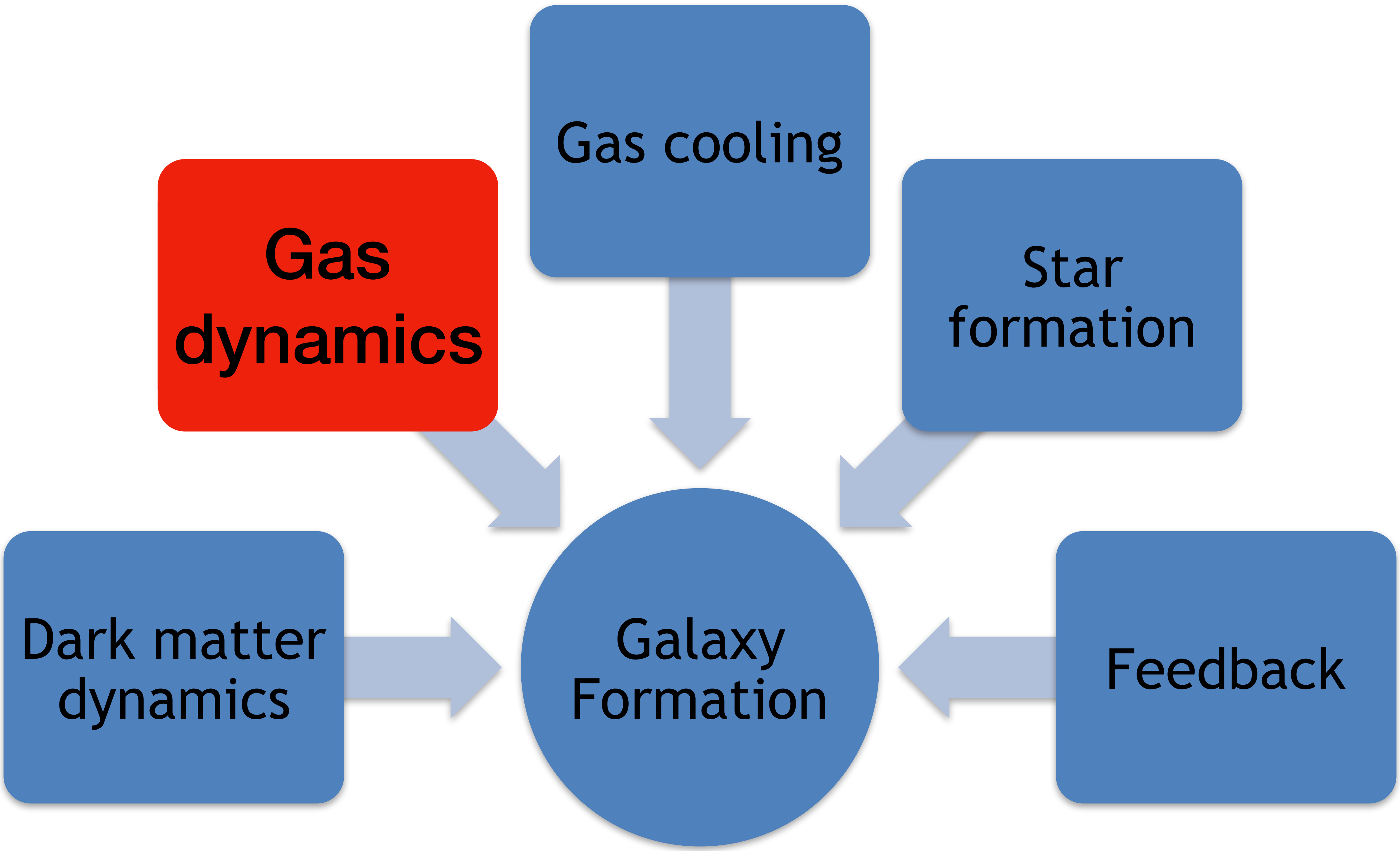
$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} = -\nabla\phi - \frac{\nabla P}{\rho_G} + \left(\frac{\partial \vec{u}}{\partial t}\right)_{SF} + \left(\frac{\partial \vec{u}}{\partial t}\right)_{FB}$$

$$\frac{\partial E}{\partial t} + \nabla\left[(E+P)\vec{u}\right] = -\rho_G \vec{u}\nabla\phi + \Gamma + L + \left(\frac{\partial E}{\partial t}\right)_{SF} + \left(\frac{\partial E}{\partial t}\right)_{FB}$$

$$\nabla^2\phi = 4\pi G(\rho_T + 3P_T/c^2) - \Lambda$$

$$E = \rho_G\left(\varepsilon + \frac{u^2}{2}\right), \quad \varepsilon = \frac{1}{\gamma - 1}\frac{P}{\rho_G}$$

A Physical model for galaxy formation



Shock Heating

Consider a gas cloud of mass $M_{\rm gas}$ falling into a halo of mass $M_{\rm h}$ with velocity $v_{\rm in}$

At some point the gas is shocked; either close to center, where flow lines converge, or at the accretion shock, which is typically located close to the virial radius.

If we assume that the shock thermalizes all the kinetic energy of the gas cloud, so that $\langle v_{\rm gas}\rangle \simeq 0$ after it is shocked (a reasonable assumption), and that $v_{\rm in}^2 \gg \frac{k_{\rm B} T_{\rm in}}{\mu m_{\rm p}}$ (so that internal energy of infalling gas can be ignored) then the internal energy of the shocked gas is equal to the kinetic energy of the gas at infall:

$$E_{\rm int,sh} = \frac{3}{2} N\, k_{\rm B}\, T_{\rm sh} = \frac{1}{2} M_{\rm gas} v_{\rm in}^2$$

where $N = M_{\rm gas}/(\mu m_{\rm p})$ is the number of gas particles, and we have assumed a mono-atomic gas, for which $\gamma = 5/3$

$$T_{\rm sh} = \frac{\mu m_{\rm p}}{3 k_{\rm B}} v_{\rm in}^2$$

If the gas falls in from large distance (where $\Phi(r) \simeq 0$), and has negligible, initial velocity, then

$$v_{\rm in} \simeq v_{\rm esc}(r_{\rm sh}) = \sqrt{2|\Phi(r_{\rm sh})|}$$

Shock Heating

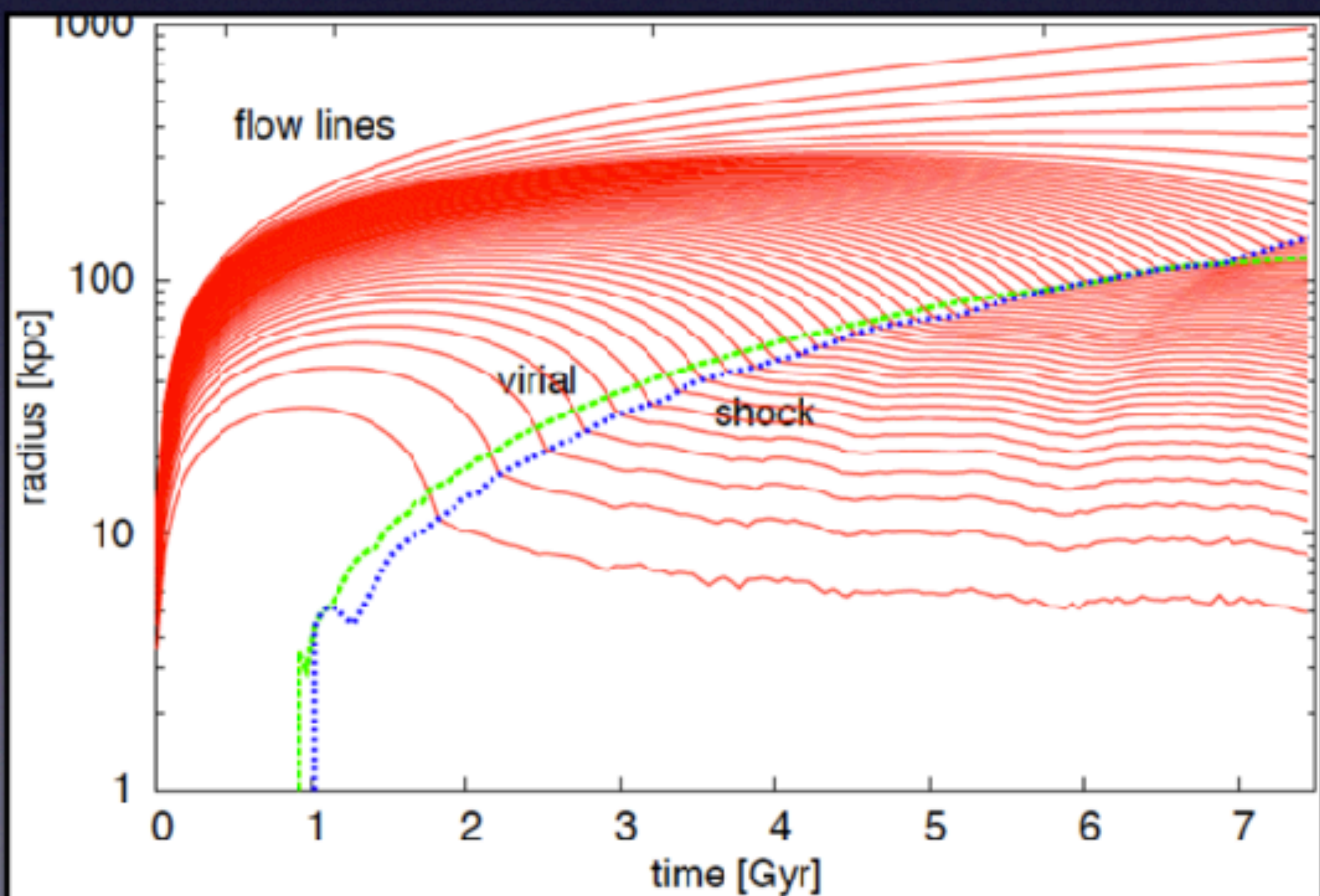
If we assume that $r_{\rm sh} = r_{\rm vir}$ (a common assumption), then $v_{\rm in}^2 = \zeta \dfrac{G M_{\rm vir}}{r_{\rm vir}} = \zeta V_{\rm vir}^2$

Here $\zeta = \mathcal{O}(1)$ is a parameter that depends on the detailed density profile of the halo.

The temperature of the shocked gas in a halo with virial velocity $V_{\rm vir}$ is

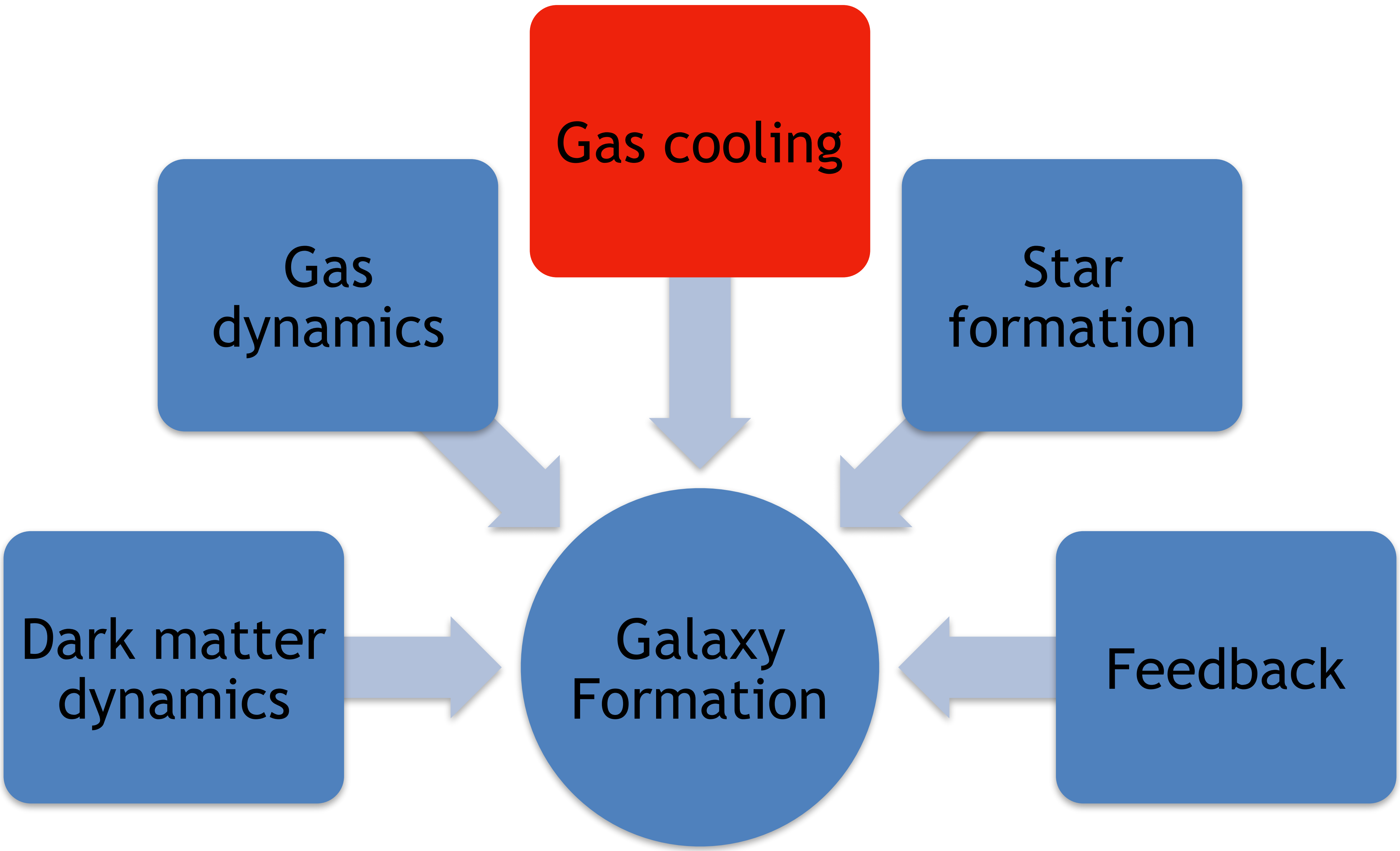
$$T_{\rm sh} \simeq \frac{\zeta}{3} \frac{\mu m_{\rm p}}{k_{\rm B}} V_{\rm vir}^2$$

Source: Birnboim & Dekel, 2003, MNRAS, 345, 349



The build-up of a virial shock (discontinuity in velocity) at around the virial radius in a collapsing structure. Based on 1D calculations in an expanding Universe...

A Physical model for galaxy formation



Radiative cooling/heating

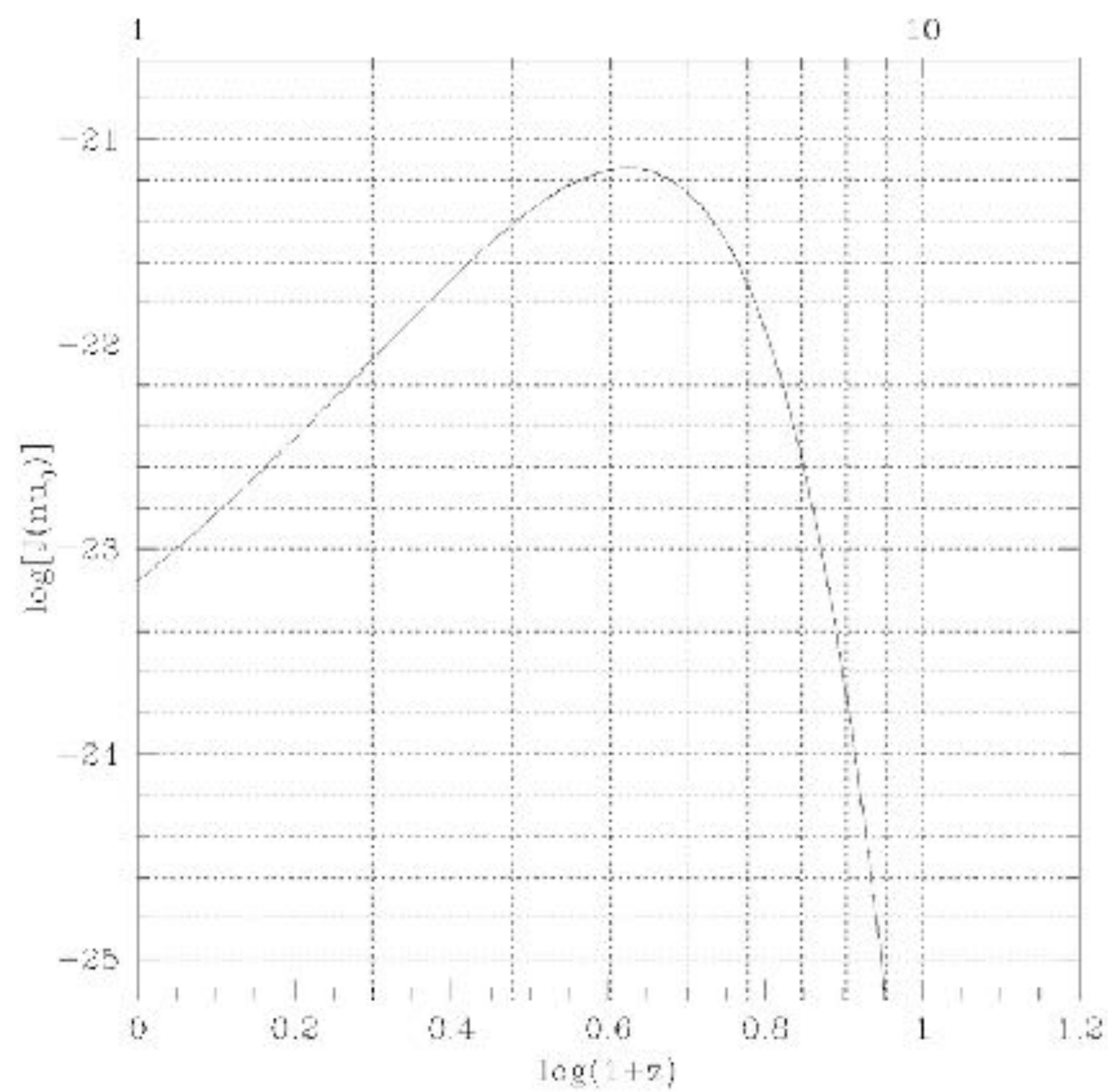
- Interactions of gas with radiation:
- Uniform ionizing UV background.
- Radiative cooling of gas.

Cosmological UV background

- Spectral shape:

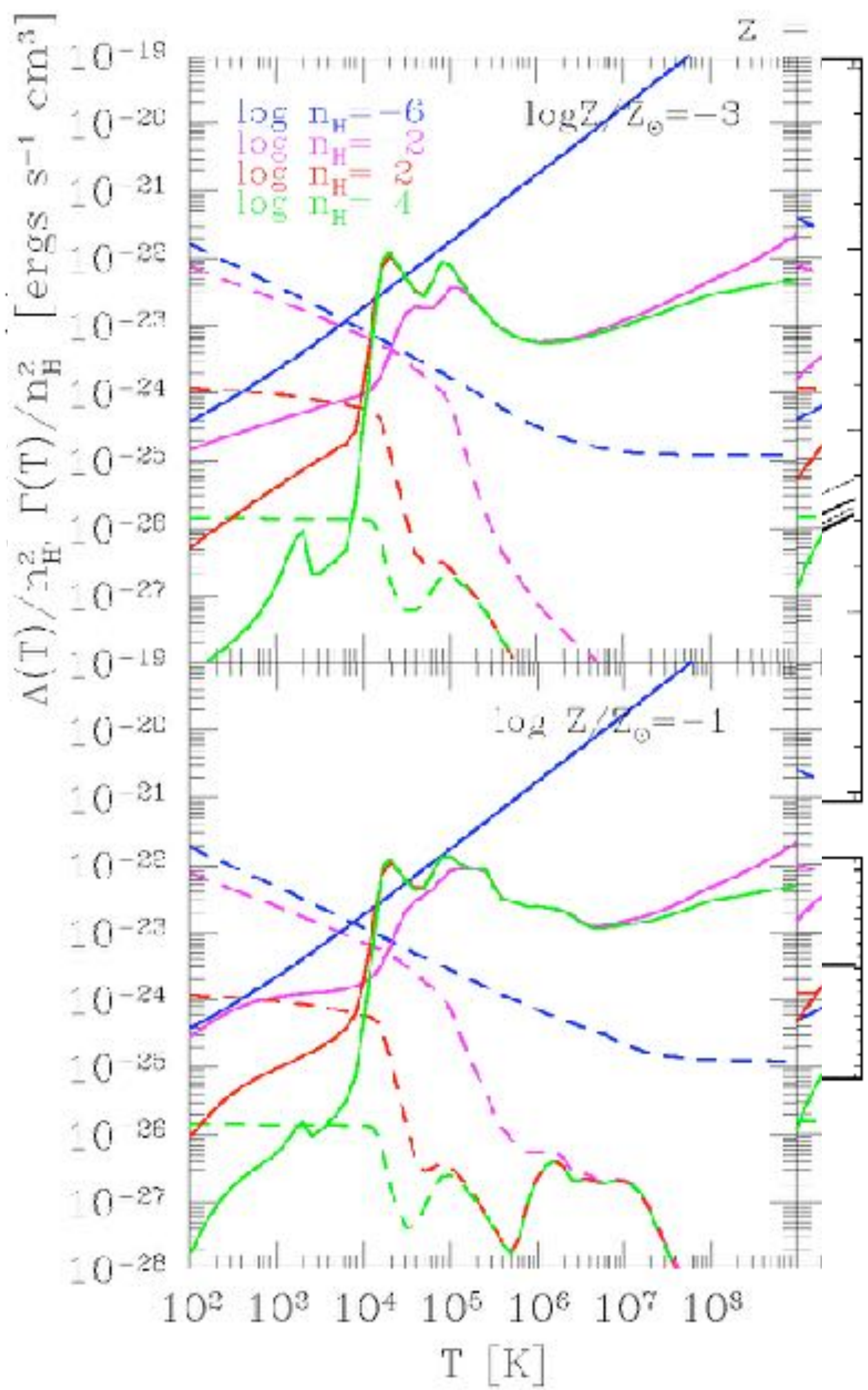
$$J(\nu, z) = J(\nu_0, z)\left(\frac{\nu}{\nu_0}\right)^{-\alpha}$$

- Model of $J(\nu_0,z)$ from Haardt & Madau (1996).
- Gas self-shielding:
  - Reduced UV background for $n>n_{TH}$

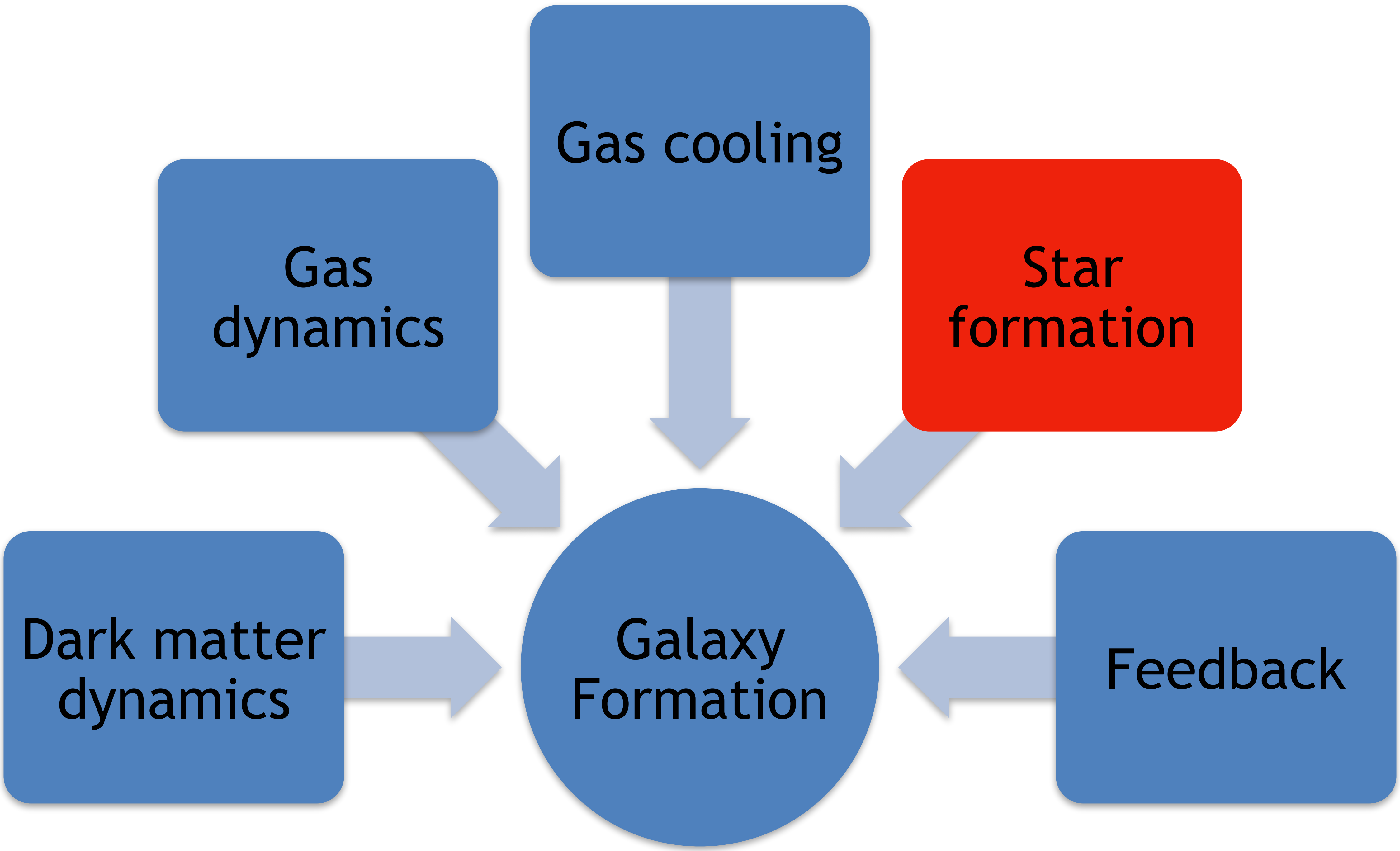


Radiative cooling

- Cooling of a plasma with a given metallicity.
- Molecular cooling.
- Tabulated cooling/heating rates from CLOUDY
- They depend on the local conditions of the gas.



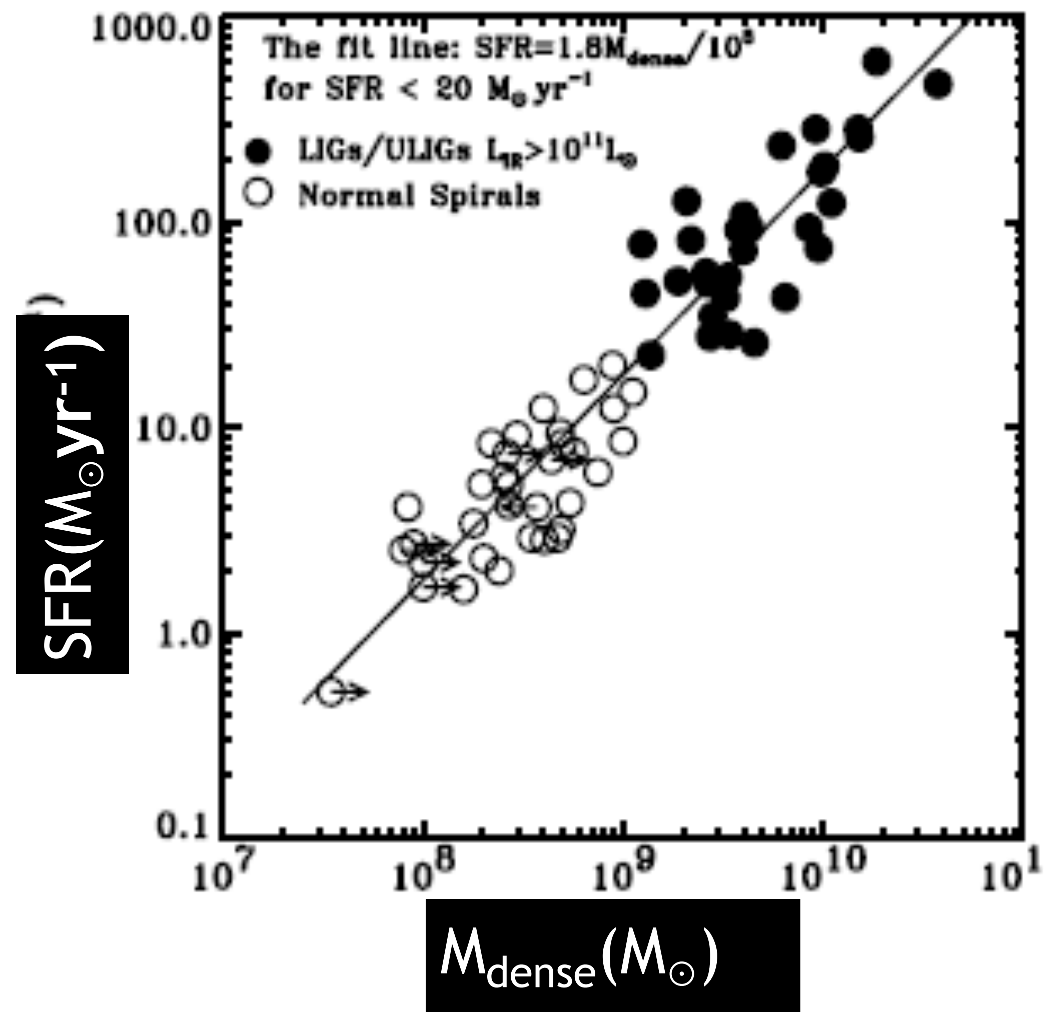
A Physical model for galaxy formation



Star formation

- A complex process.
- Global star formation law: star formation averaged over galactic scales.

- The star formation rate is proportional to the mass in molecular cores traced by HCN emission (Gao & Solomon 2004).

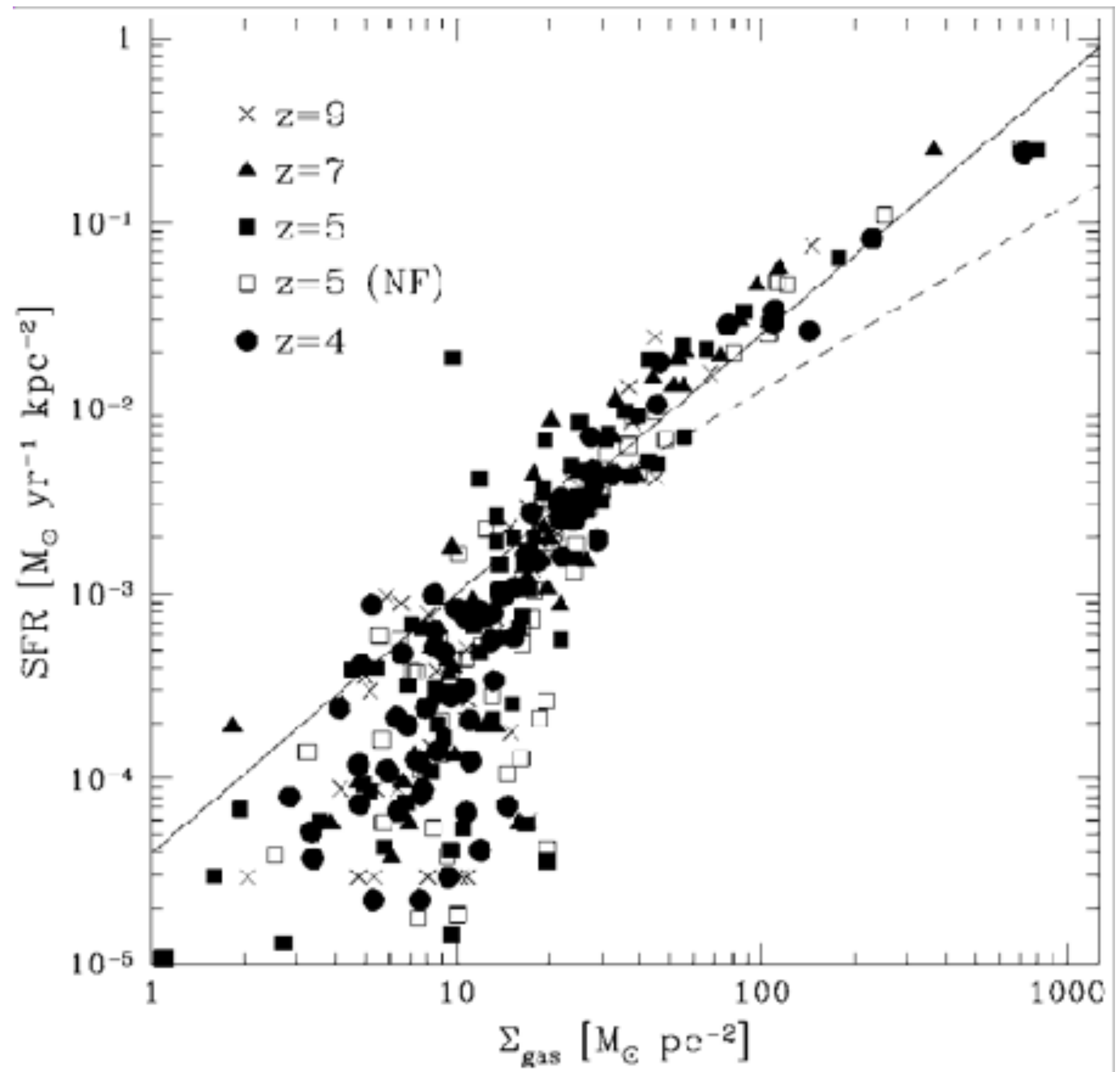


Model for star formation.

- Free parameter, τ:

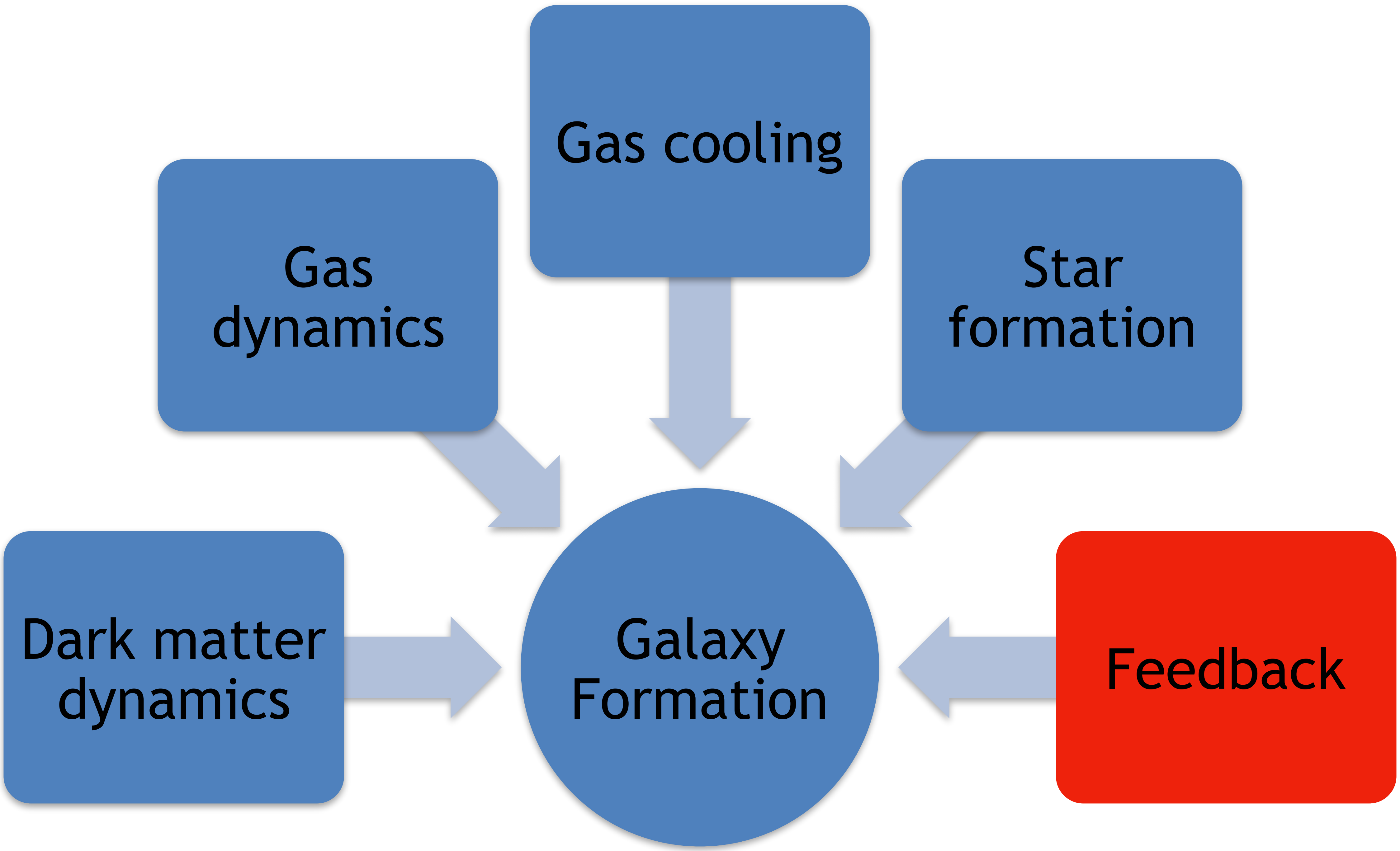
$$\dot{\rho}_* = \frac{\rho_G}{\tau}$$

- Density and temperature thresholds.
- Stellar particle → single population with a Miller-Scallo IMF.
- The code reproduce the Kennicutt empirical law



Kravtsov 2003

A Physical model for galaxy formation



Stellar Feedback

- Thermal energy from stellar winds and supernova explosions:

  $E_{th} = \varepsilon_* 10^{51}$ erg

- Injection of mass and heavy elements.
- Two different time scales: SNII & SNIa

Feedback heating vs radiative cooling

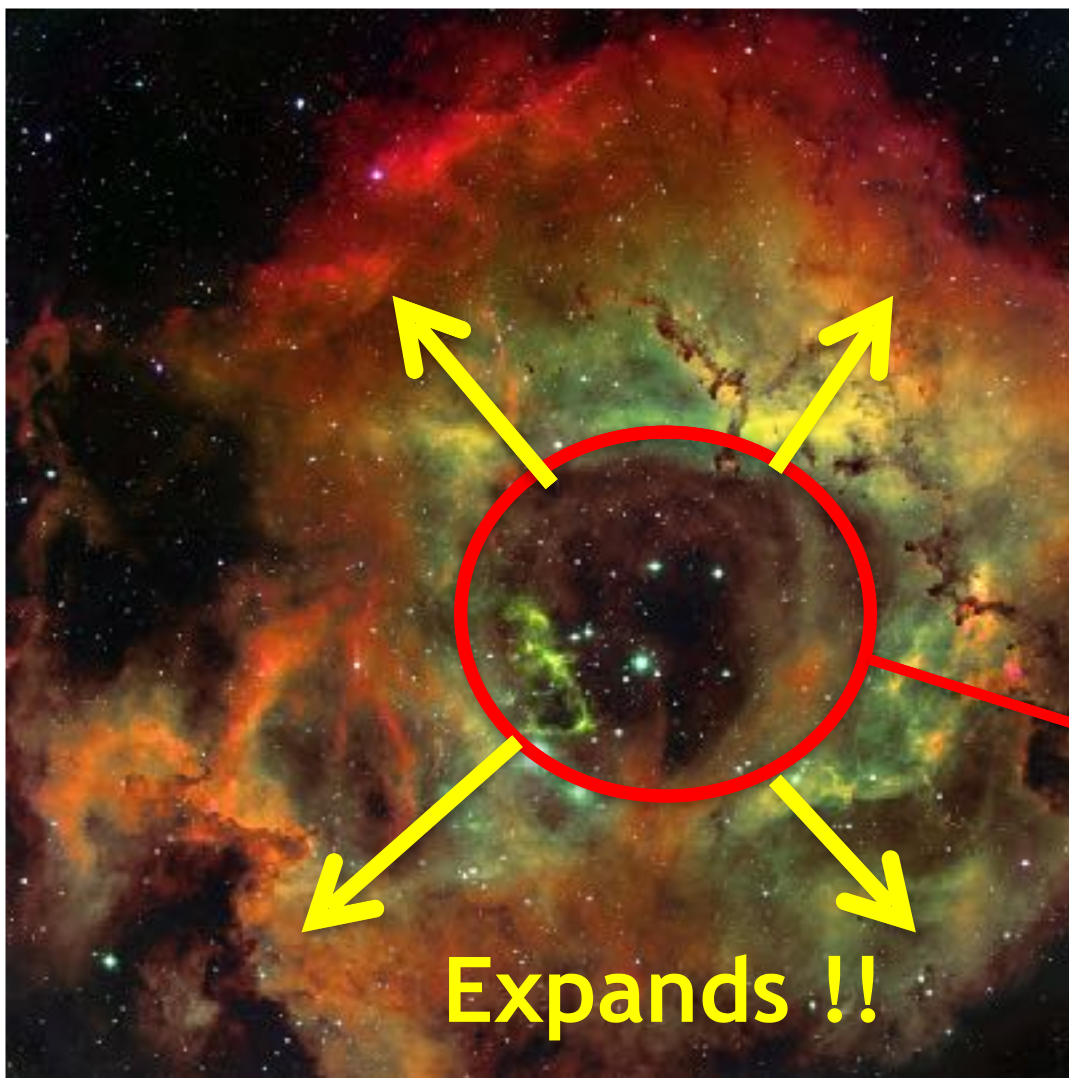
$$\frac{\partial e}{\partial t} = \Gamma - L$$

$$\Gamma = \rho_* \Gamma'$$

$$L = n_H^2 L'$$

In the beginning…

Rosette Nebula



there was an
Overheated,
Overpressure,
bubble
expanding in a molecular
cloud

Feedback: two conditions

1) Create overpressured region: **Heating > Cooling**

$$n_H \Lambda' \leq \frac{\rho_{*,\mathrm{young}}}{\rho_{\mathrm{gas}}} \mu_H m_H \Gamma'$$

$$\left(\frac{n_H}{0.1\,\mathrm{cm}^{-3}}\right)\left(\frac{\Lambda'}{10^{-22}\,\mathrm{erg\,s^{-1}\,cm^{-3}}}\right) \leq \left(\frac{\rho_{*,\mathrm{young}}}{\rho_{\mathrm{gas}}}\right)\left(\frac{\Gamma'}{10^{34}\,\mathrm{erg\,s^{-1}\,M_\odot^{-1}}}\right)$$

Difficult to satisfy this condition for $T_{gas} > 10^4$K; need very low gas density. Temperature regime 100-10000 K is crucial for initial stage of formation of superbubbles

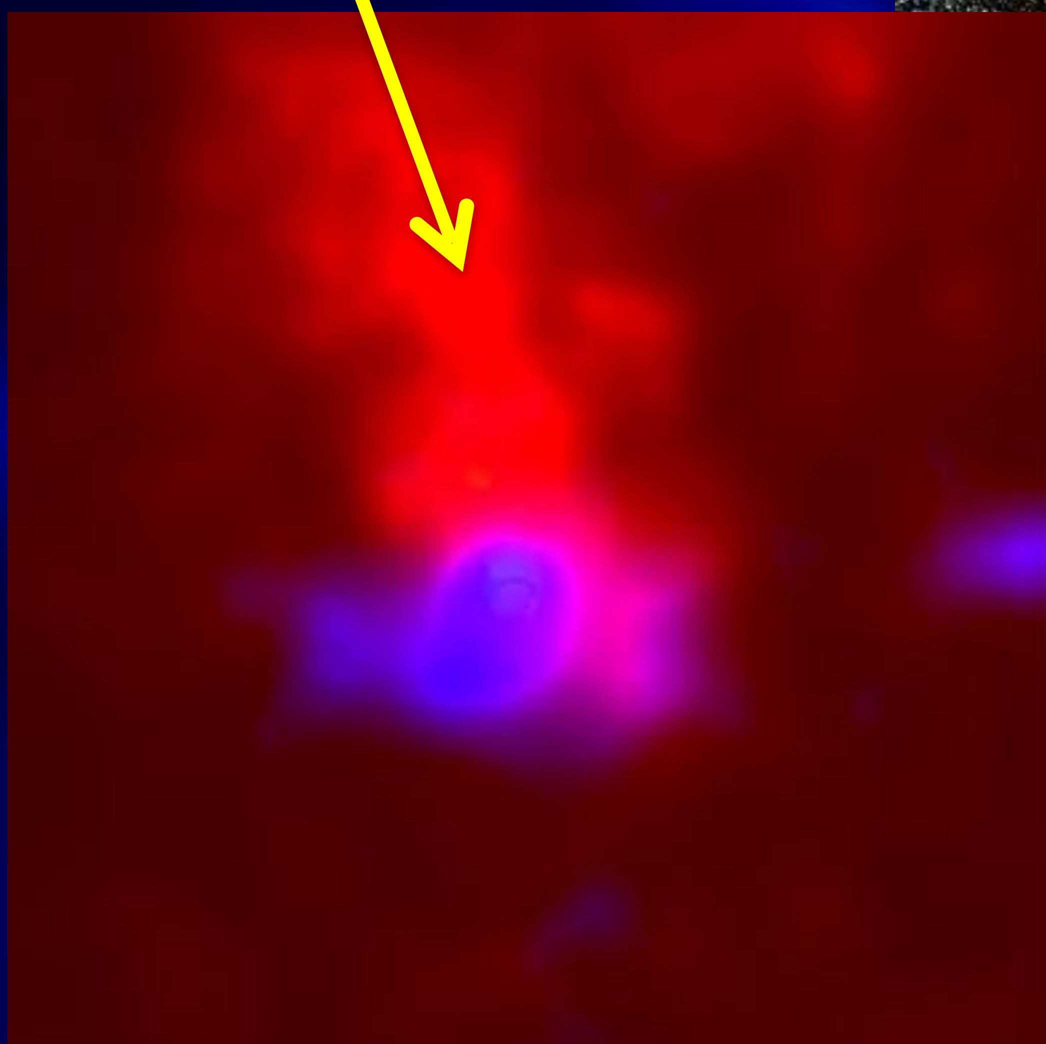
2) Pressure gradient > gravity force: **AntiJeans regime**

$$\Delta P/k \geq \frac{4\pi}{3k} G(\rho R)^2 = 10^{-1}(n_H R_{pc})^2 \rightarrow \left(\frac{X_{pc}}{75\,\mathrm{pc}}\right)^2 \leq \left(\frac{T}{10^4\,\mathrm{K}}\right)\left(\frac{n_H}{10\,\mathrm{cm}^{-3}}\right)^{-1}$$

Limits on resolution: X < 70pc Need balance of force resolution X and threshold of star formation nH

Champagne flow

10^7 degrees gas



X-rays from Chandra
(Townsley et al. 2003)

40 pc
10 pc

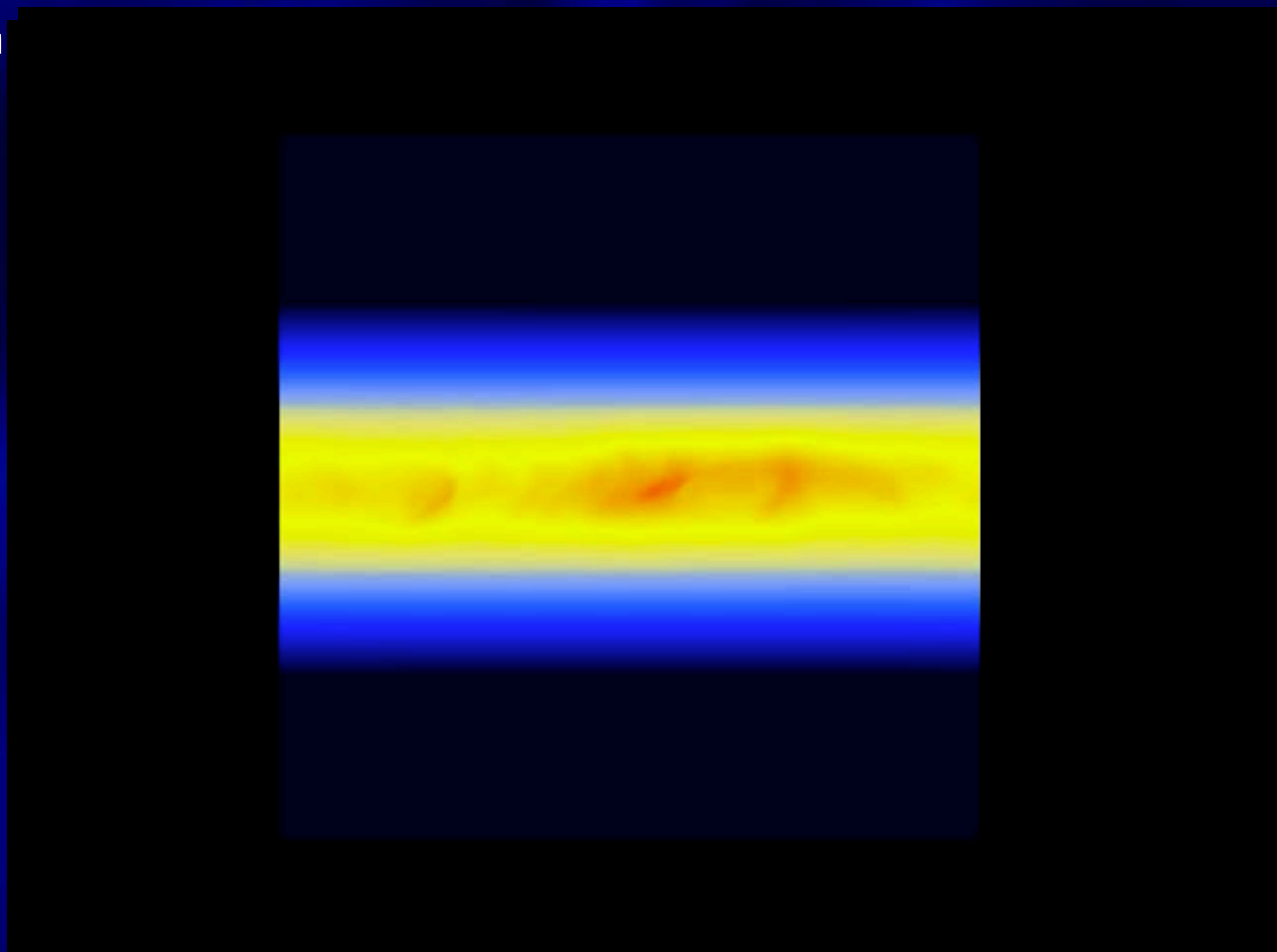
M17, Horseshoe Nebula

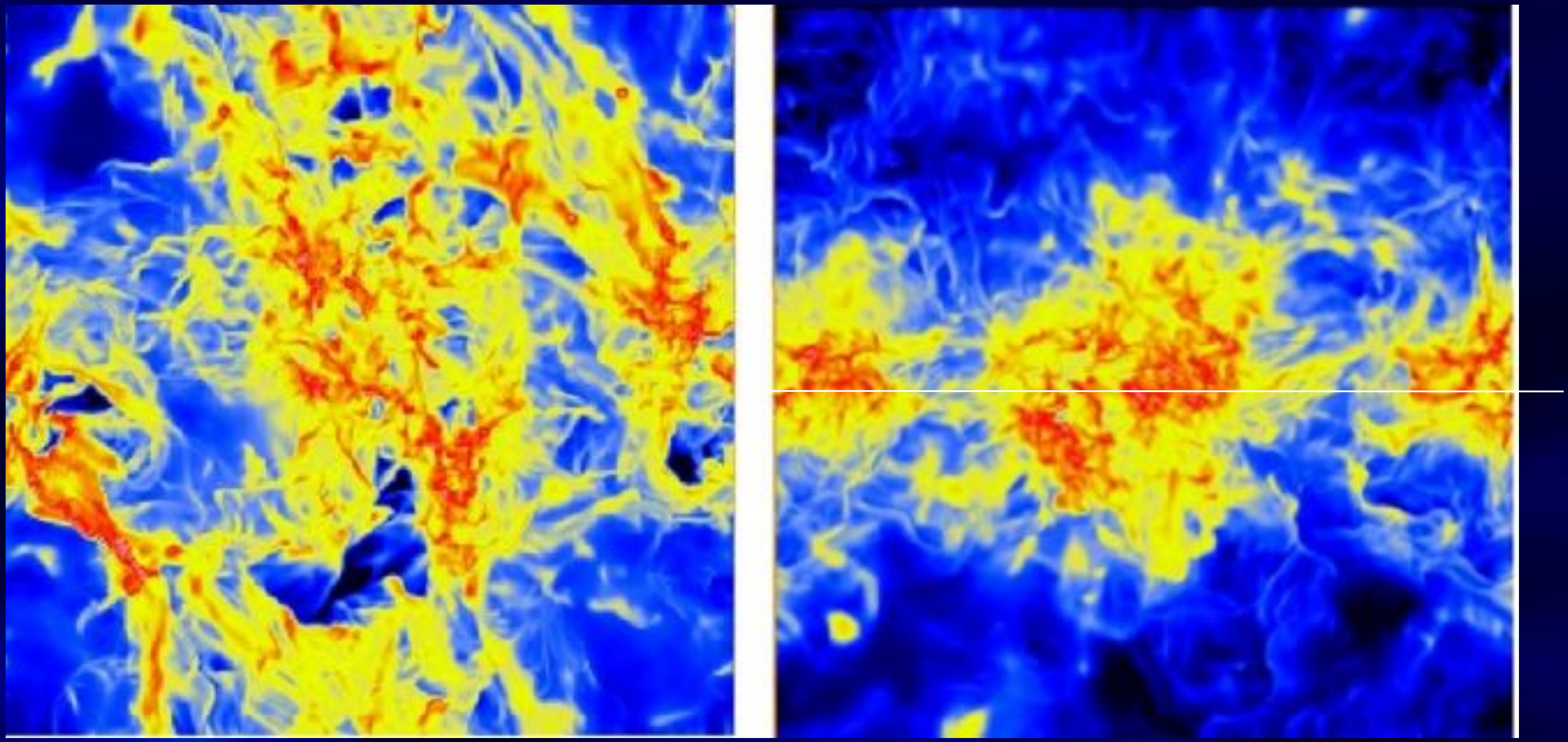
A piece of a galactic disk

8 pc resolution

Projected density

4 Kpc





Projection to the disk plane

Projection along the disk plane

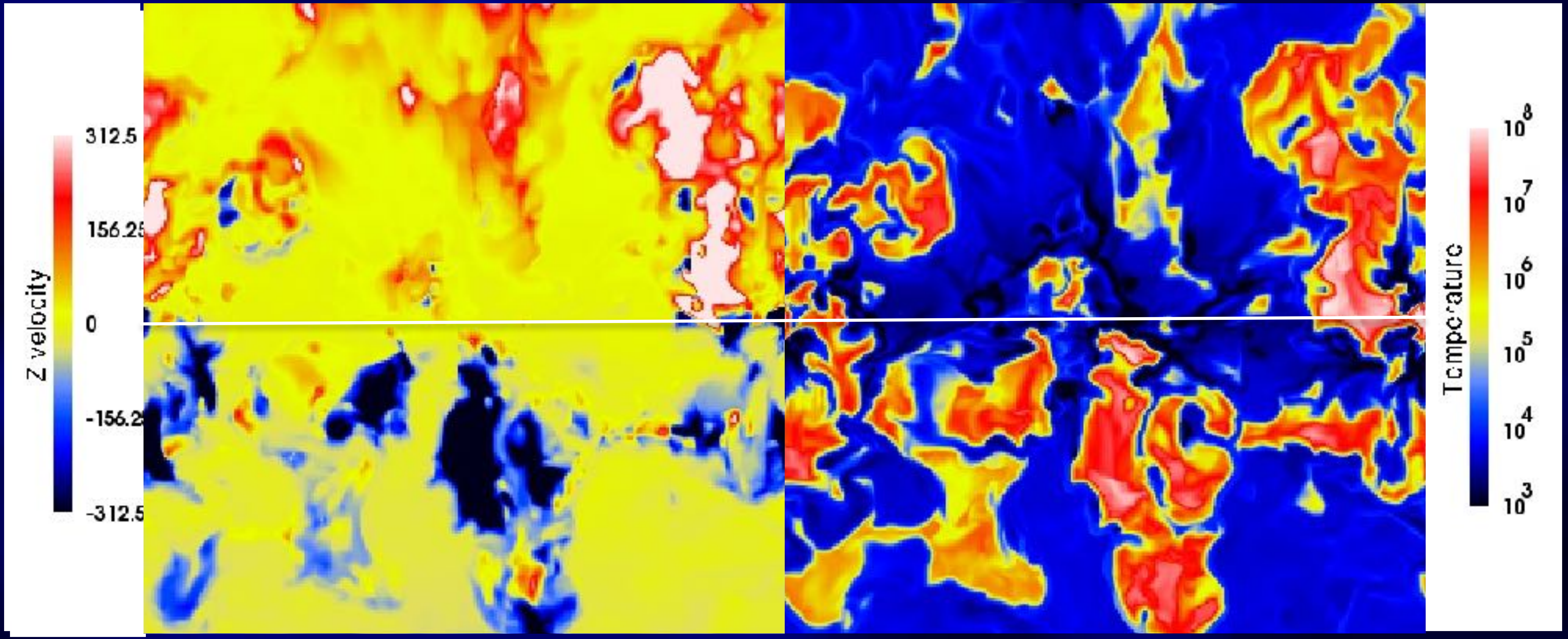
Projected density

Advanced stages: fully turbulent ISM

Super-bubbles and galactic chimneys

4x4 Kpc² Slices perpendicular to the disk plane

8 pc resolution



The effect of the stellar feedback in the ISM (Ceverino & Klypin 2009):

A multiphase medium: Cold ($T<10^3$ K) gas, Warm ($10^3 < T < 10^4$ K) and Hot ($T> 10^4$ K) gas.

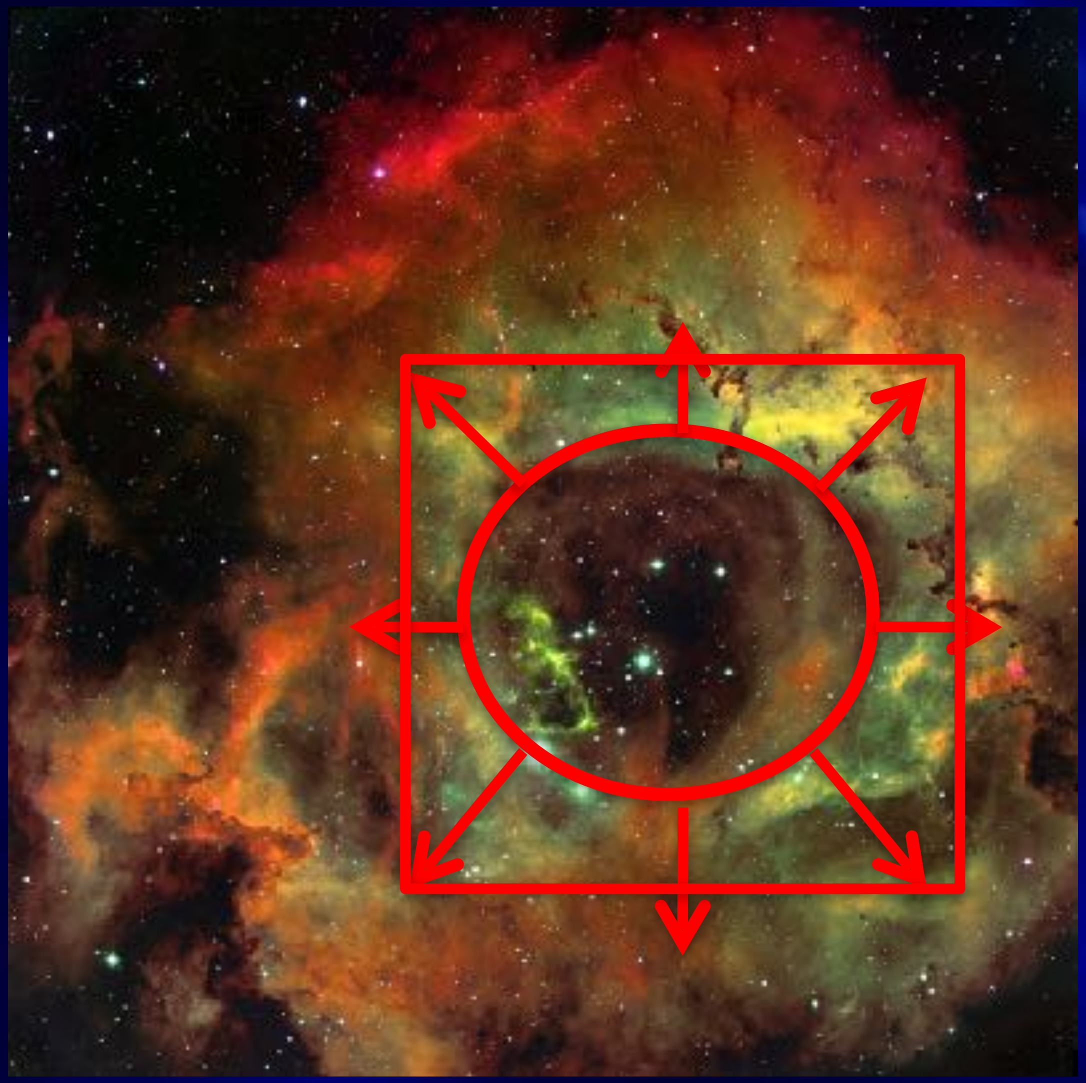
Summary on supernovae feedback

- Stellar feedback maintains a 3-phase ISM.
- It generates super-bubbles and galactic chimneys.
- Low star formation rates.
- Supernova-driven turbulent ISM.

Radiative feedback

Rosette Nebula

40 pc



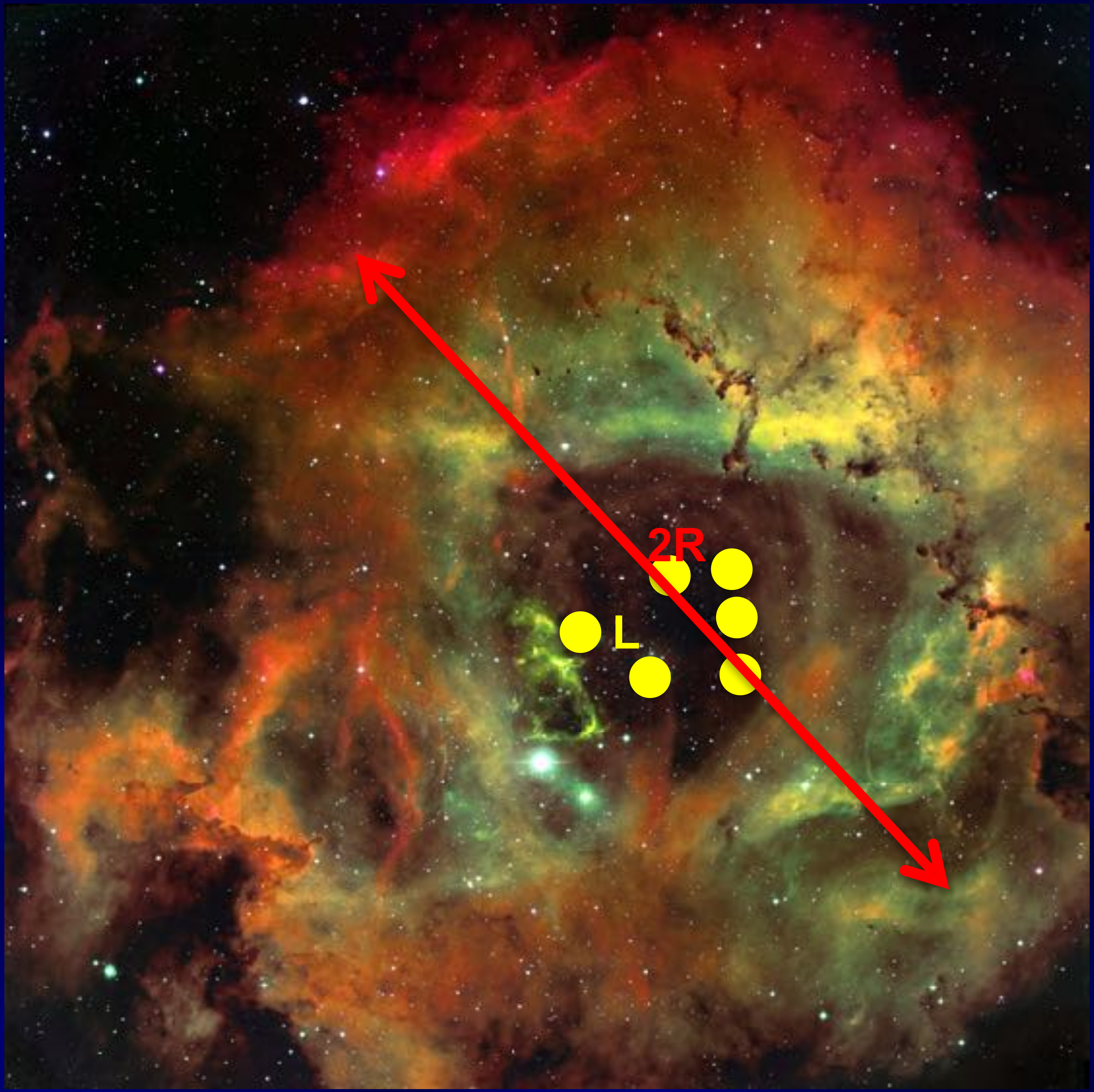
No Supernova explosion yet
- Stellar winds
- Thermal pressure
- Radiation pressure
  - from ionizing photons

Typical resolution of our zoom-in, cosmological simulation: ~ 20 pc

- At low column densities

$P_{rad} \alpha (1-\exp(-\tau))$

- Optically thin
- No effect from radiation pressure



- At high column densities
- Add pressure

$$P_{rad} = L / (R^2 c)$$

$$L = M_* \Gamma$$

Γ = cte for 5 Myr

column densities $>10^{21}$ cm^{-2}

No free parameters

Ceverino et al. 2014

+ photoionization and photoheating
+ unresolved supernovae shells

Three take-home messages

- The Interaction of gas with radiation is important
- The formation of stars is a complex process
- Feedback is a ‘melting pot’ of many diverse processes

Third Tutorial Section

List of projects

- 1. Accretion rate onto halos and onto galaxies: DM, gas, stars
- 2. Interaction of cold flows and Disk.
- 3. Angular momentum: in cold flows vs disk
- 4. Basic Structure of galaxies: Density profiles of gas, stars, DM. f_b?
- 5. Kinematics of gas: disk rotation curve, velocity dispersion
- 6. Kinematics of stars: bulge/disk decomposition
- 7. Gas outflows