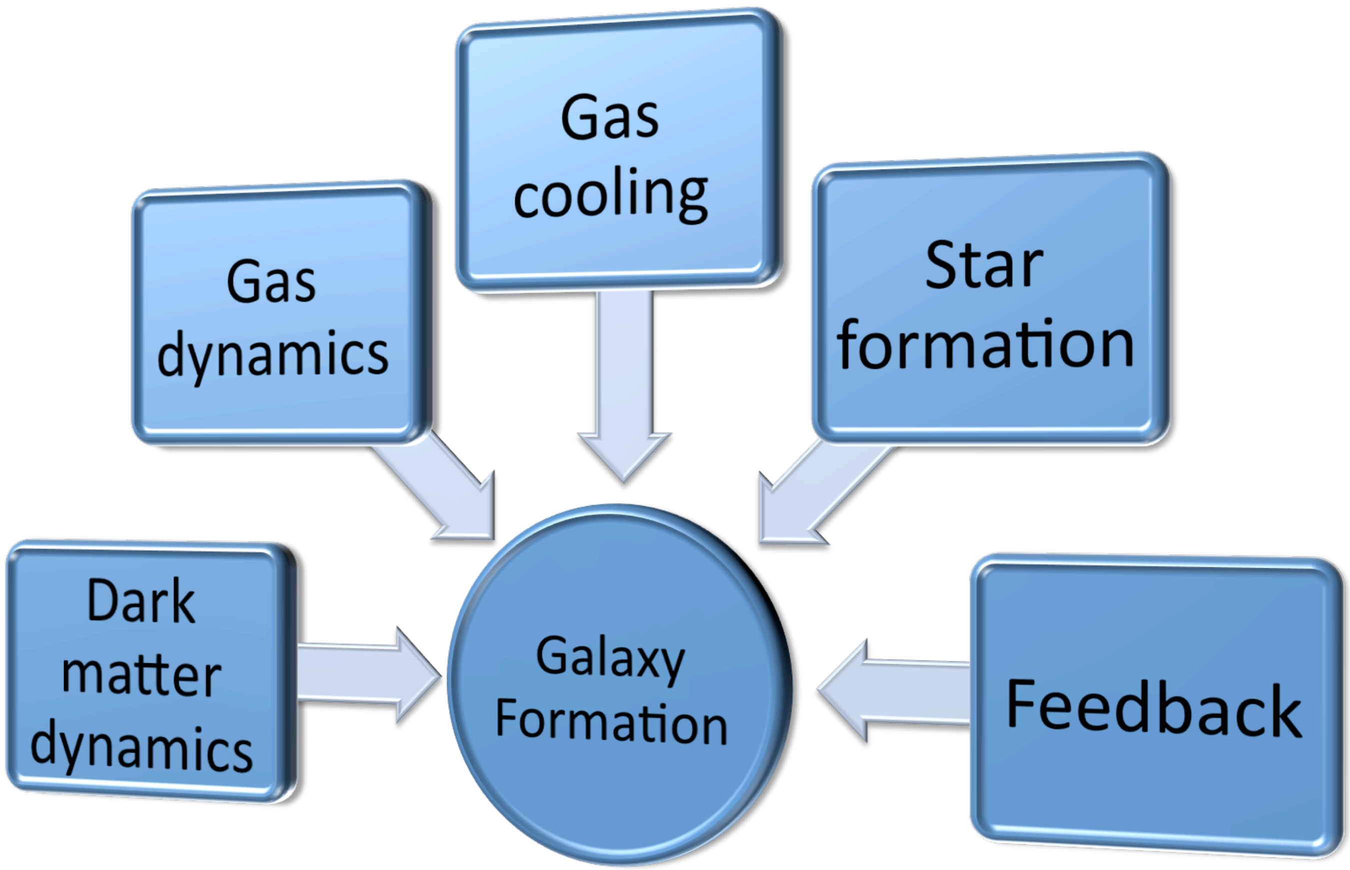
Galaxy formation simulations done with ART (II)

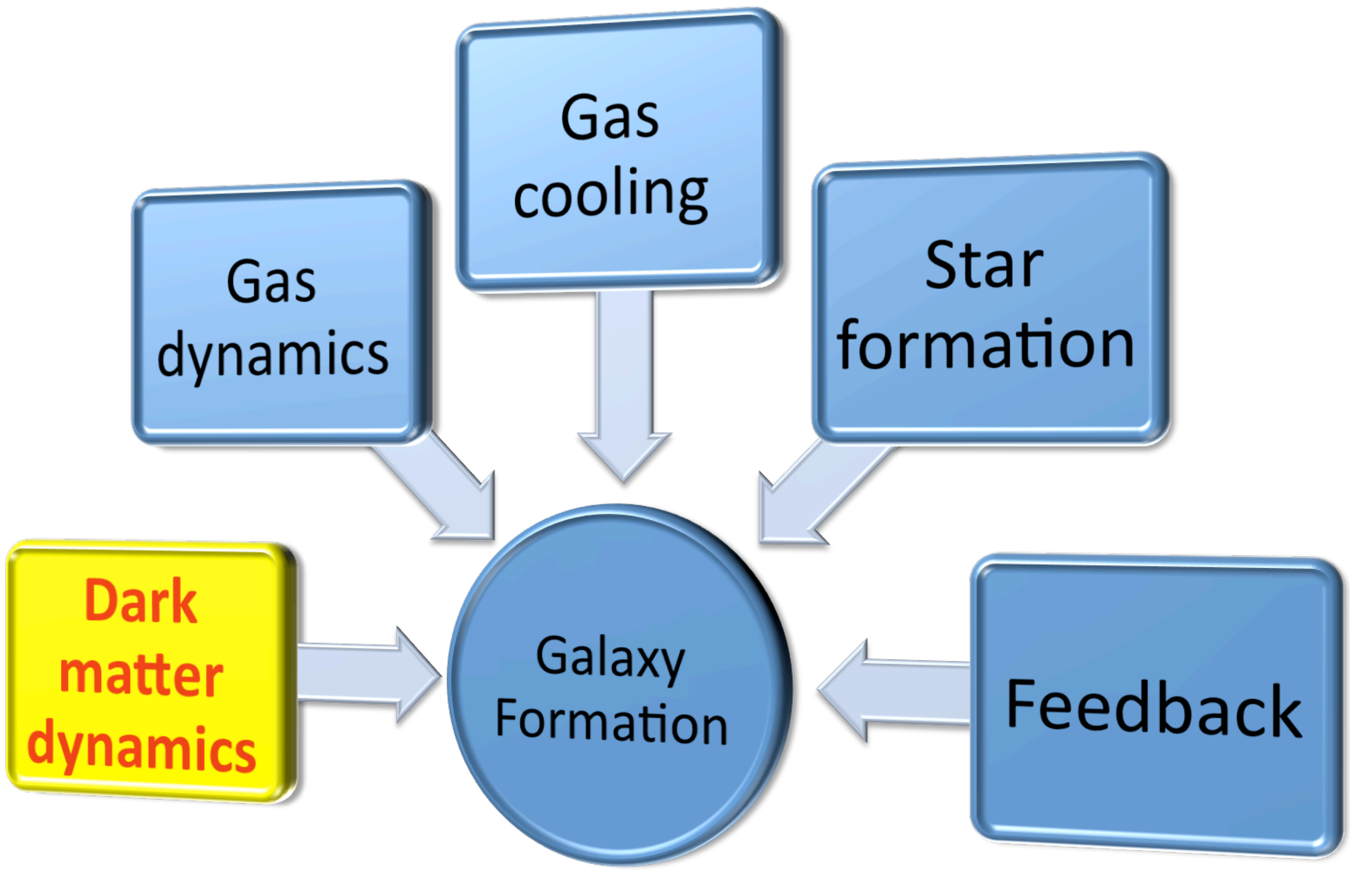
Daniel Ceverino

Santa Cruz school, 2010

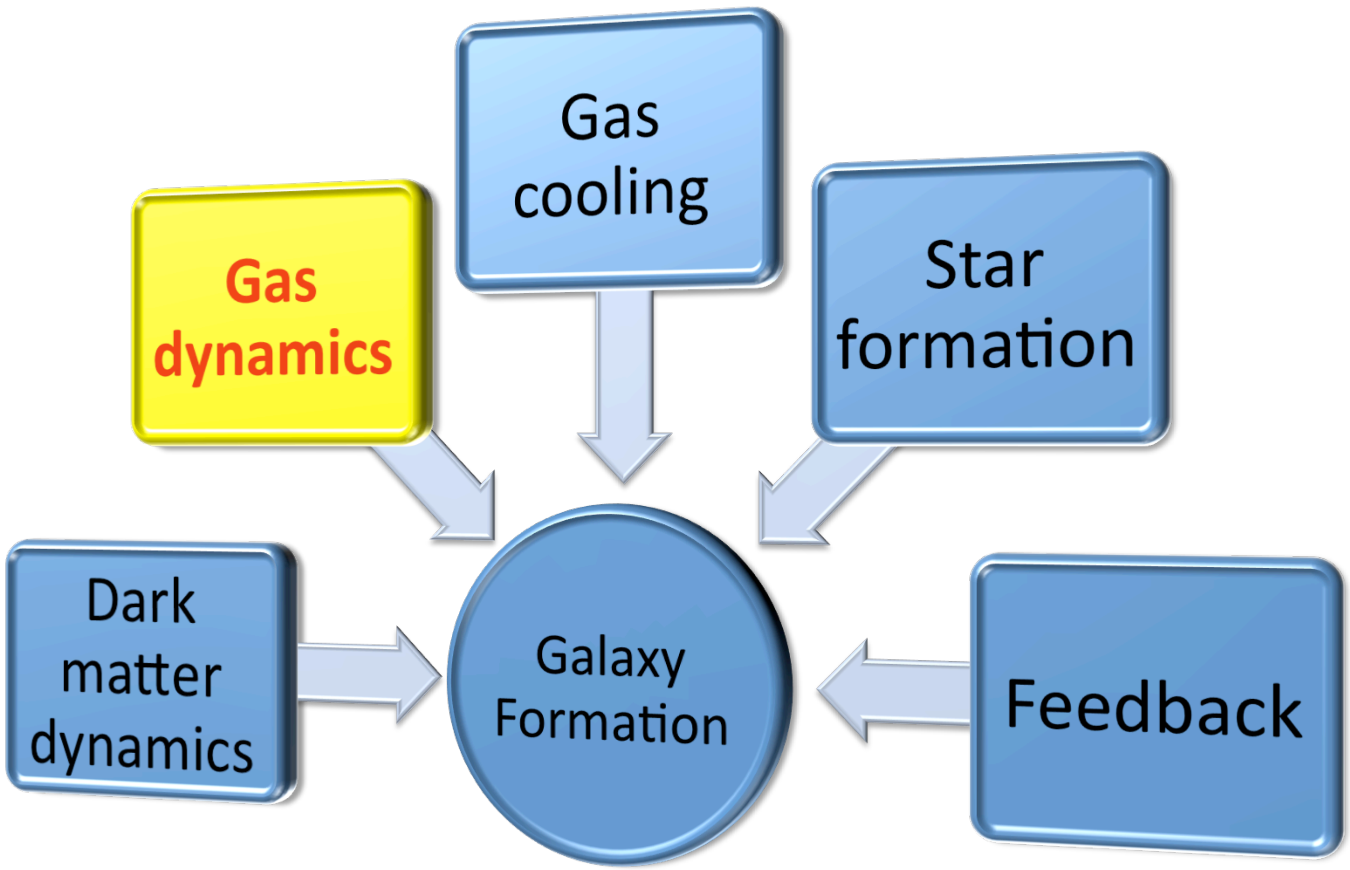
A Physical model for galaxy formation



Physical models for galaxy formation



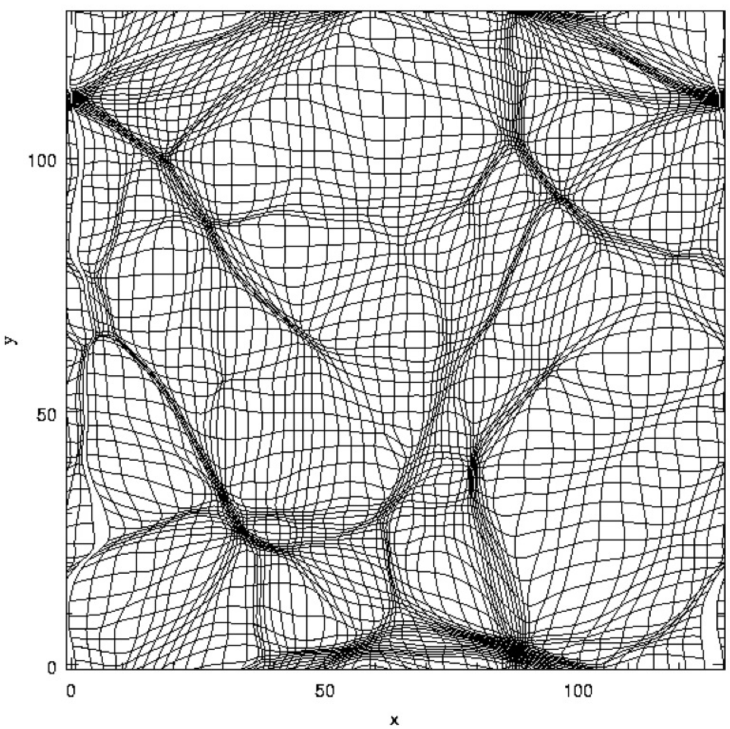
Physical models for galaxy formation

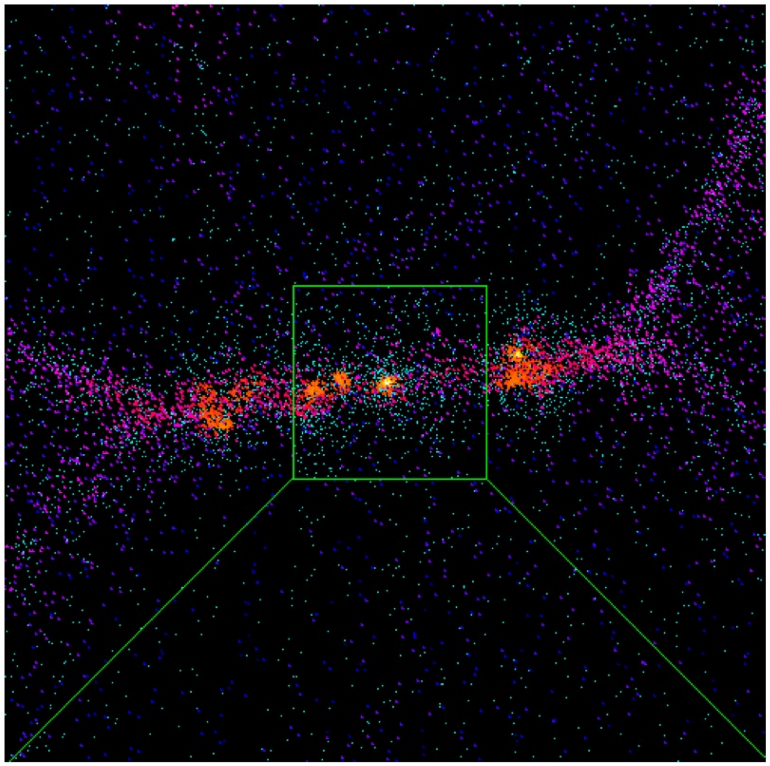


Lagrangian Approach

- Smoothed Lagrangian Hydrodynamics (SLH)
  [Gnedin 1996; Pen 1997]

- Smoothed Particle Hydrodynamics (SPH)





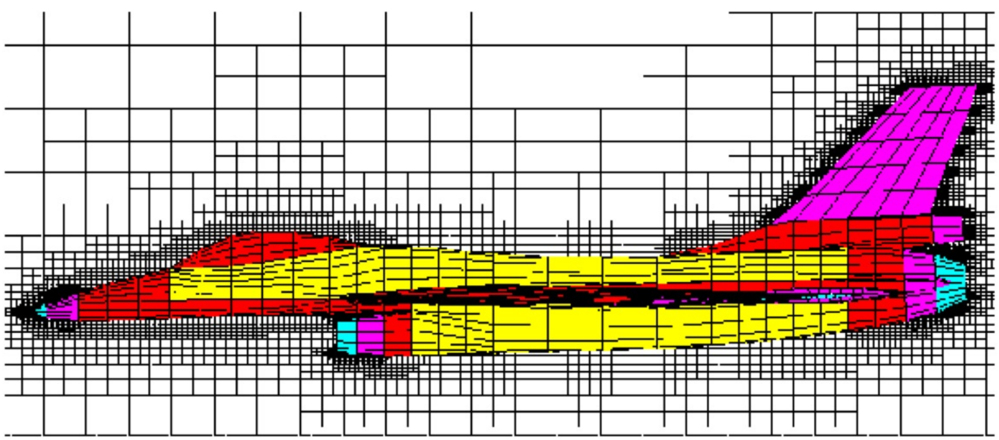
The AMR Approach

- Efficient, reliable finite element methods *for uniform grids* have been developed for solving the Poisson and gasdynamics equations.

- The *Adaptive Mesh Refinement* (AMR) methods increase the dynamic range of grid-based numerical algorithms beyond the limits imposed by existing hardware.

- The methods have numerous applications in different fields of physics, engineering, etc.

- Now gaining popularity in astrophysics and cosmology



The AMR Approach

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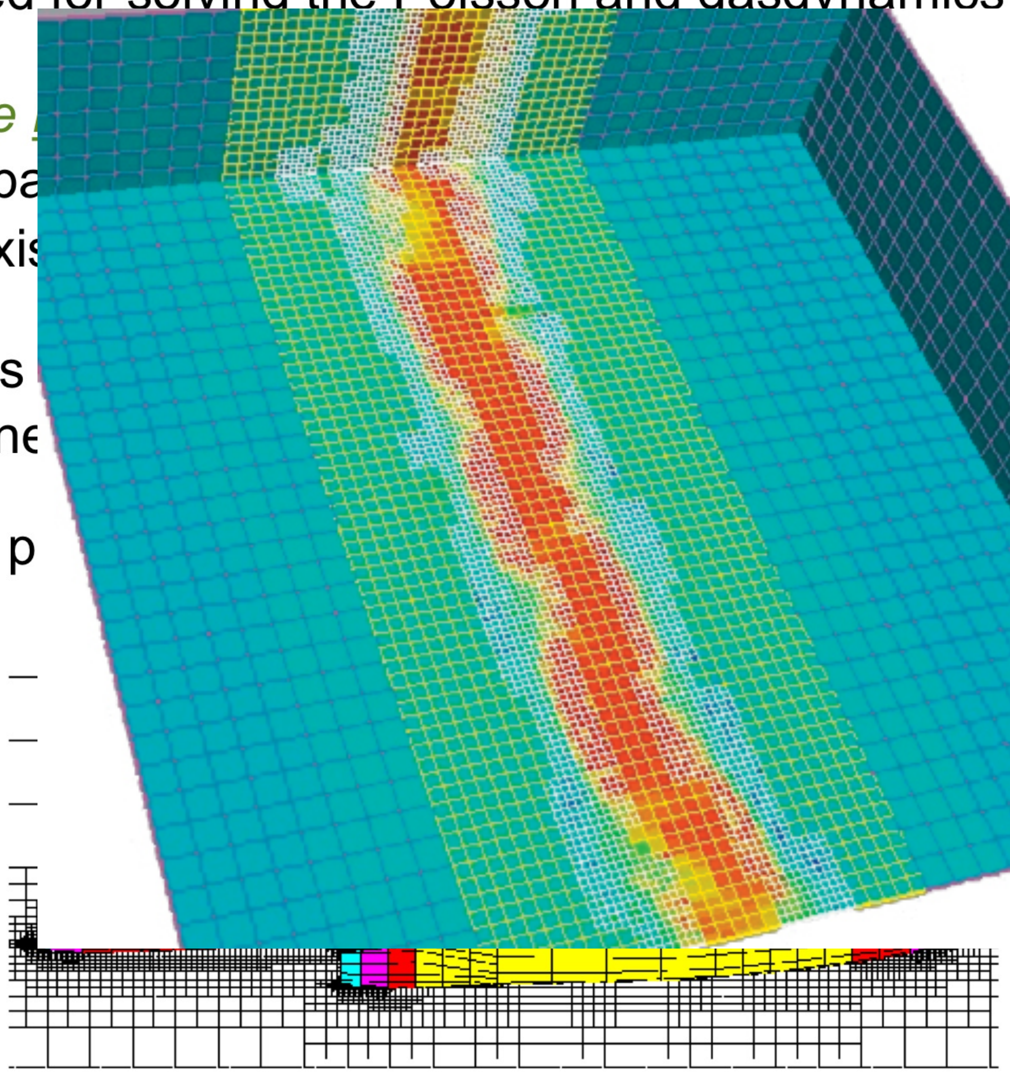
- The *Adaptive* … e the dynamic range of grid-ba… s imposed by exis…

- The methods … elds of physics, engine…

- Now gaining p…



Solving equation of gasdynamics
a crash course in shock-capturing Eulerian methods

$$\frac{\partial \rho}{\partial t} + \nabla \rho \mathbf{u} = 0,$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla \Phi - \frac{\nabla P}{\rho},$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\mathbf{u}] = -\rho \mathbf{u} \cdot \nabla \Phi.$$

- these are equations of Eulerian gasdynamics – they describe evolution of gas properties at a fixed point in space.

- look simple enough – so what is the deal with the vast literature and research on the computational fluid dynamics (CFD) for the past 60 years?

Solving equation of gasdynamics
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- naïve discretization of these equations does not work because flows often develop discontinuities and numerical derivatives “blow up”

- one can introduce artificial viscosity to “smear” the discontinuities, the price is the loss of accuracy and resolution

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a crash course in shock-capturing Eulerian methods

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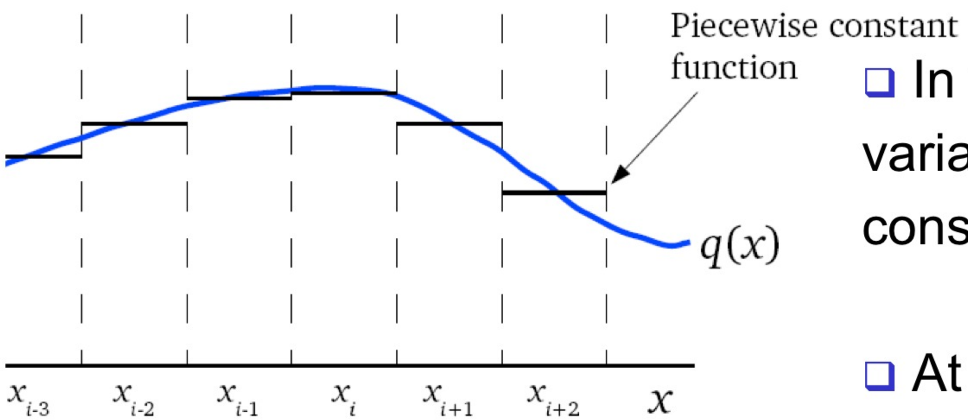


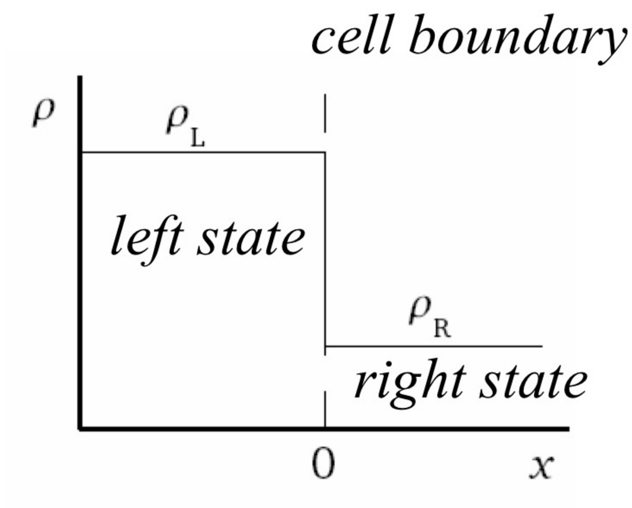
- Some other schemes (e.g., Lax-Wendroff) were proposed but none were really satisfactory

- In 1959, Godunov proposed a radically different scheme for solving these equations

- In the original Godunov's method variables were assumed to be constant in each cell.

- At each cell interface the fluxes of variables are computed by solving the Riemann boundary problem

Solving equation of gasdynamics



variable *flux* *source*

$$\frac{\partial \mathcal{U}}{\partial t} = \frac{\partial \mathcal{F}}{\partial x} + \mathcal{S}$$

$$\mathcal{F} = (\rho v_x, (E+P)v_x, \rho v_x^2, \rho v_x v_y, \rho v_x v_z)$$

$$\mathcal{S} = (0, \rho v_x g_x, \rho g_x, 0, 0)$$

- Find a set of intermediate states (one for each characteristic) that connect left and right states and satisfy physical conditions (e.g., shock jump conditions)

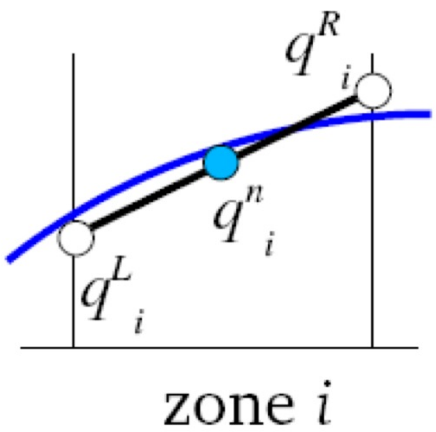
- solve for conservation equations for the fluxes through cell interface given the boundary conditions on the left and on the right of the interface

- update physical variables in cells around the interface

$$\bar{\boldsymbol{q}}_i^L = \boldsymbol{q}_i^L + \frac{\Delta t}{2\Delta x}[\boldsymbol{F}(\boldsymbol{q}_i^L) - \boldsymbol{F}(\boldsymbol{q}_i^R)]$$

$$\bar{\boldsymbol{q}}_i^R = \boldsymbol{q}_i^R + \frac{\Delta t}{2\Delta x}[\boldsymbol{F}(\boldsymbol{q}_i^L) - \boldsymbol{F}(\boldsymbol{q}_i^R)]$$

Solving equation of gasdynamics
a crash course in shock-capturing Eulerian methods



variable *flux* *source*

$$\underbrace{\frac{\partial \mathcal{U}}{\partial t}}_{\text{variable}} = \underbrace{\frac{\partial \mathcal{F}}{\partial x}}_{\text{flux}} + \underbrace{\mathcal{S}}_{\text{source}}$$

$$\mathcal{F} = (\rho v_x, (E+P)v_x, \rho v_x^2, \rho v_x v_y, \rho v_x v_z)$$

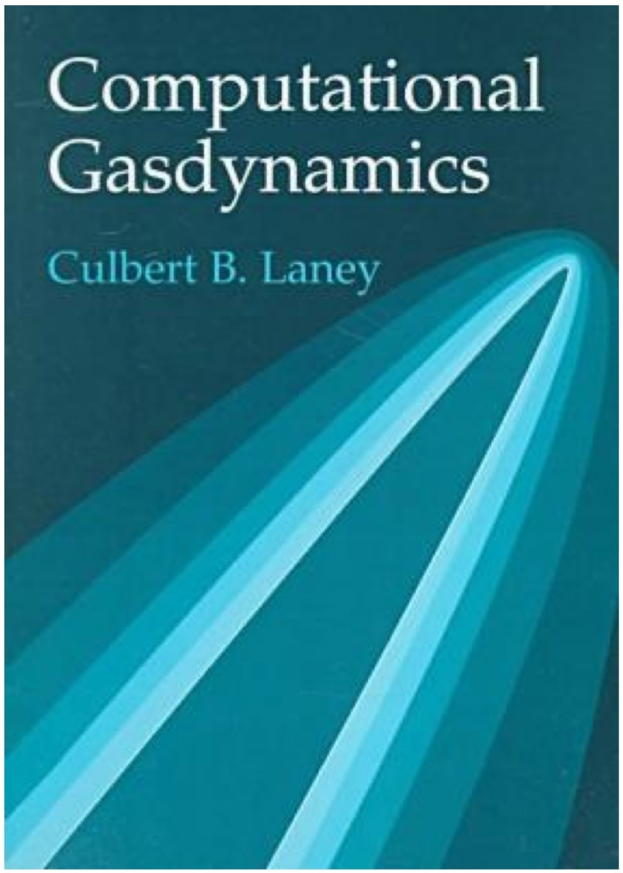
$$\mathcal{S} = (0, \rho v_x g_x, \rho g_x, 0, 0)$$

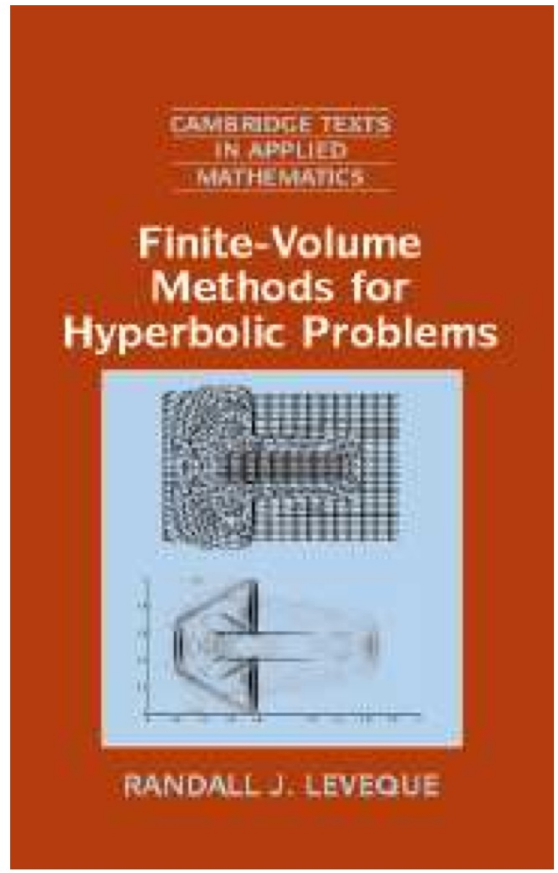
- In the ART code the left and right states are constructed by linear extrapolation (the change of variables is represented by piecewise linear function) and exact Riemann solver is used

- higher order reconstruction is possible (e.g., piecewise parabolic method – PPM)

- however, advatantage of higher order with AMR is dubious (e.g. Zhang & McFadyen 2006)

good books on Eulerian gasdynamics methods:





Gas physics

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

- Radiative cooling and heating
- Star formation
- Feedback

Gasdynamical equations

$$\frac{\partial \rho_G}{\partial t} + \nabla(\rho_G \vec{u}) = \left(\frac{\partial \rho_G}{\partial t}\right)_{\substack{\text{Star}\\ \text{formation}}} + \left(\frac{\partial \rho_G}{\partial t}\right)_{\substack{\text{Stellar}\\ \text{mass}\\ \text{looses}}}$$

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} = -\nabla\Phi - \frac{\nabla P}{\rho_G} + \left(\frac{\partial \vec{u}}{\partial t}\right)_{\substack{\text{Star}\\ \text{formation}}} + \left(\frac{\partial \vec{u}}{\partial t}\right)_{\substack{\text{Stellar}\\ \text{mass}\\ \text{looses}}}$$

$$\frac{\partial E}{\partial t} + \nabla\left[(E + P)\vec{u}\right] = -\rho_G \vec{u}\nabla\Phi + \Gamma + L + \left(\frac{\partial E}{\partial t}\right)_{\substack{\text{Star}\\ \text{formation}}} + \left(\frac{\partial E}{\partial t}\right)_{\substack{\text{Stellar}\\ \text{mass}\\ \text{looses}}}$$

$$\nabla^2\Phi = 4\pi G(\rho_{Tot} + 3P_{Tot}/c^2) - \Lambda$$

$$E = \rho_G(\varepsilon + \frac{u^2}{2})$$

$$\varepsilon = \frac{1}{\gamma - 1}\frac{P}{\rho_G}$$

Source terms

$$\left(\frac{\partial \rho_*}{\partial t}\right)_{\substack{\text{Star}\\\text{formation}}} = \begin{Bmatrix} \dfrac{\rho_{gas}}{\tau} & , \text{ If } T < T_* \;\&\; \rho > \rho_* \\ 0 & , \text{Otherwise} \end{Bmatrix} = -\left(\frac{\partial \rho_G}{\partial t}\right)_{\substack{\text{Star}\\\text{formation}}}$$

$$\left(\frac{\partial \rho_G}{\partial t}\right)_{\substack{\text{Stellar}\\\text{mass}\\\text{losses}}} = \int_0^t \left(\frac{\partial \rho_*(t')}{\partial t}\right)_{\substack{\text{Star}\\\text{formation}}} R_*(t-t')dt' = -\left(\frac{\partial \rho_*}{\partial t}\right)_{\substack{\text{Stellar}\\\text{mass}\\\text{losses}}}$$

$$\left(\frac{\partial \vec{u}}{\partial t}\right)_{\substack{\text{Star}\\\text{formation}}} = -\frac{1}{\rho}\left(\frac{\partial \rho_*}{\partial t}\right)_{\substack{\text{Star}\\\text{formation}}} \vec{u}$$

$$\left(\frac{\partial \vec{u}}{\partial t}\right)_{\substack{\text{Stellar}\\\text{mass}\\\text{losses}}} = \frac{1}{\rho}\left(\frac{\partial \rho_G}{\partial t}\right)_{\substack{\text{Stellar}\\\text{mass}\\\text{losses}}} \left\langle \vec{v}_* \right\rangle$$

$$\left(\frac{\partial E}{\partial t}\right)_{\substack{\text{Star}\\\text{formation}}} = -\frac{1}{\rho}\left(\frac{\partial \rho_*}{\partial t}\right)_{\substack{\text{Star}\\\text{formation}}} E$$

$$\left(\frac{\partial E}{\partial t}\right)_{\substack{\text{Stellar}\\\text{mass}\\\text{losses}}} = \left(\frac{\partial \rho_G}{\partial t}\right)_{\substack{\text{Stellar}\\\text{mass}\\\text{losses}}} \left(\vec{u}\cdot\left\langle \vec{v}_* \right\rangle + \frac{1}{2}u^2\right)$$

Cooling and heating rates

$$\Gamma(\rho_G, T, Z, z) = \Gamma_{\text{Compton}} + \Gamma_{\text{UV}} + \Gamma_{\text{Feedback}}$$

$$L(\rho_G, T, Z, z) = L_{\text{Compton}} + L_{\substack{\text{Line}\\ \text{cooling}}}$$

$$\frac{Z}{Z_{\text{Solar}}} = \log\left(\frac{\rho_{\text{Metals from SNII}} + \rho_{\text{Metals from SNIa}}}{\rho_G}\right)$$

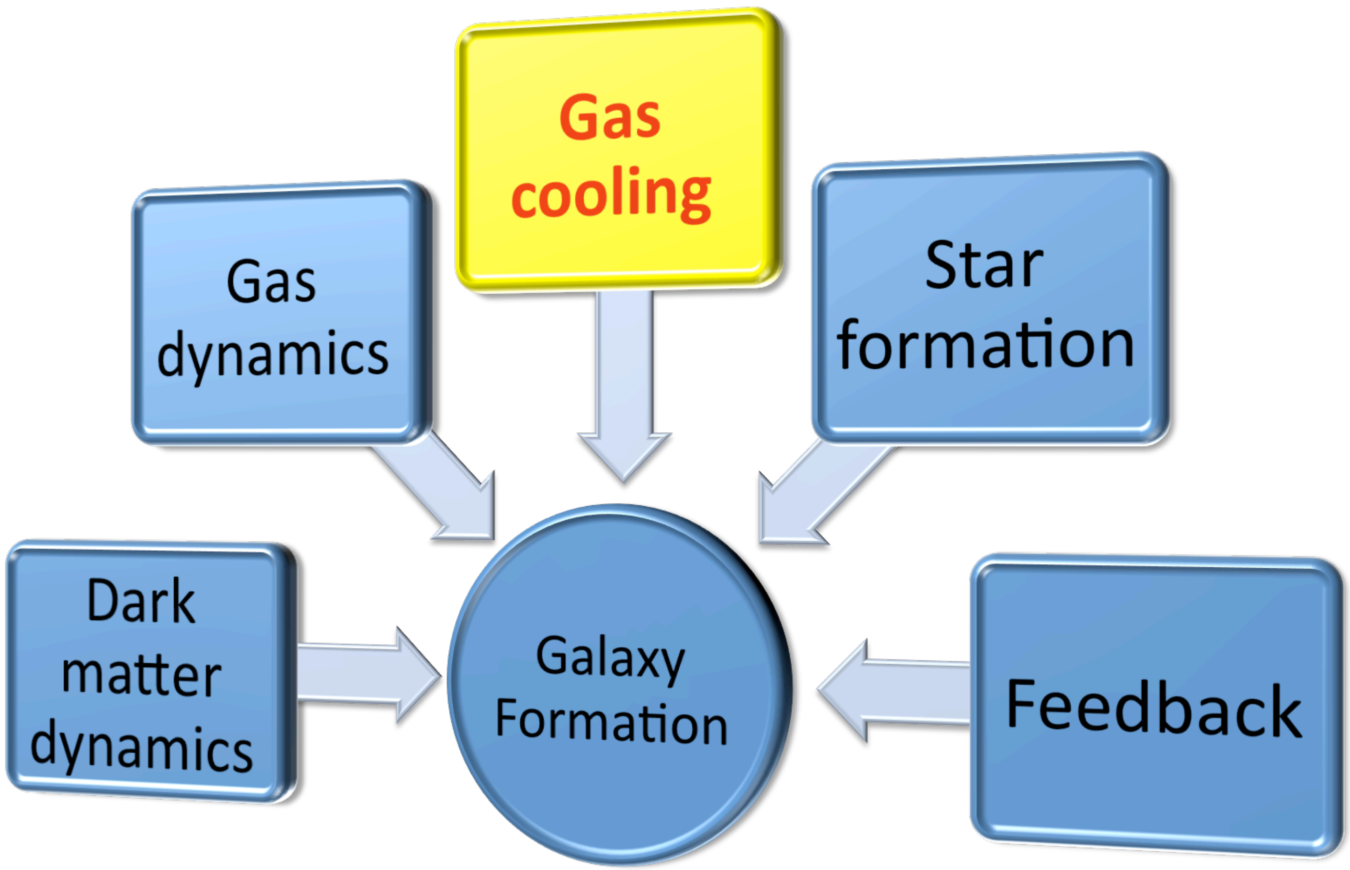
$$\Gamma_{\text{Feedback}} = \Gamma_{\text{SNII}} + \Gamma_{\text{SNIa}}$$

$$\Gamma_{\text{SNII}} = \varepsilon_F \frac{dn_{\text{SNII}}}{dt}$$

$$\Gamma_{\text{SNIa}} = \varepsilon_F \frac{dn_{\text{SNIa}}}{dt}$$

- Equations for metals in gas and stars.

Physical models for galaxy formation



Radiative cooling/heating

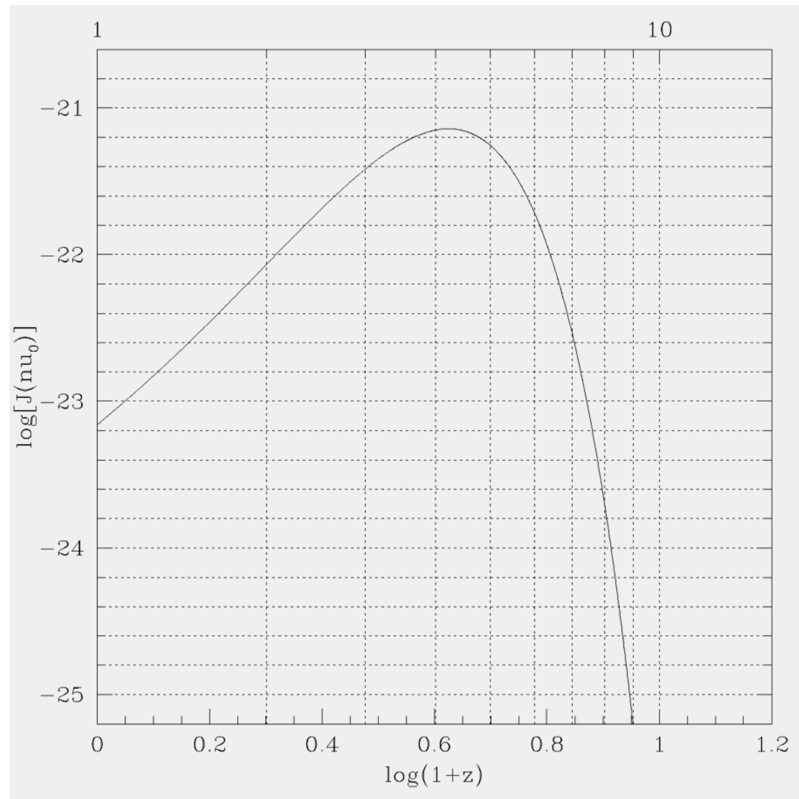
- Interactions of gas with radiation:
- Uniform ionizing UV background.
- Radiative cooling of gas.

Cosmological UV background

- Spectral shape:

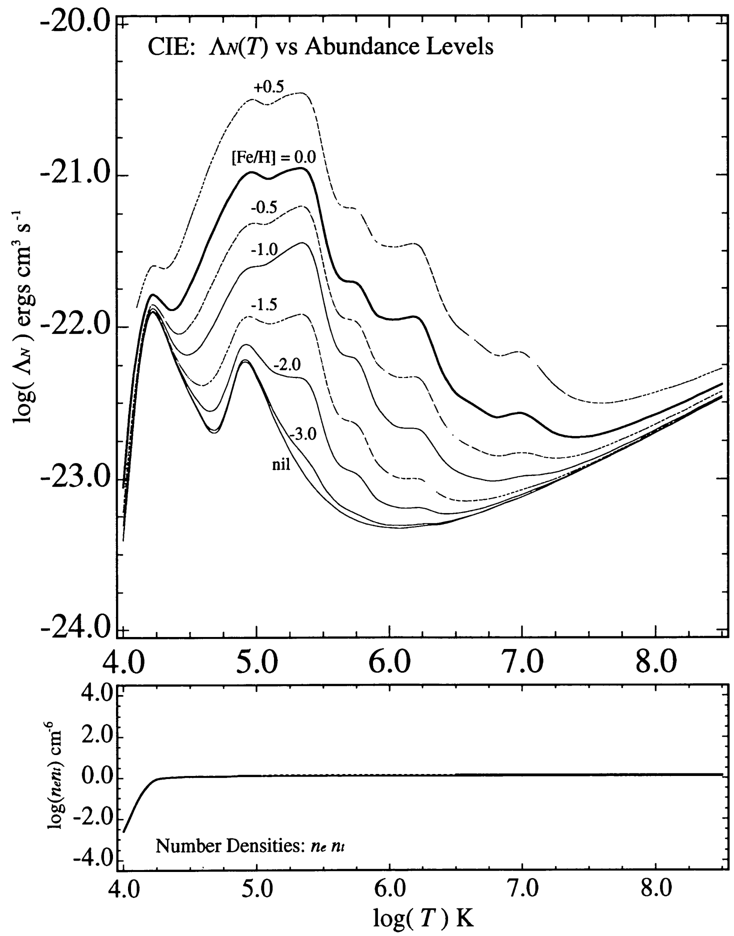
$$J(\nu, z) = J(\nu_0, z)\left(\frac{\nu}{\nu_0}\right)^{-\alpha}$$

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



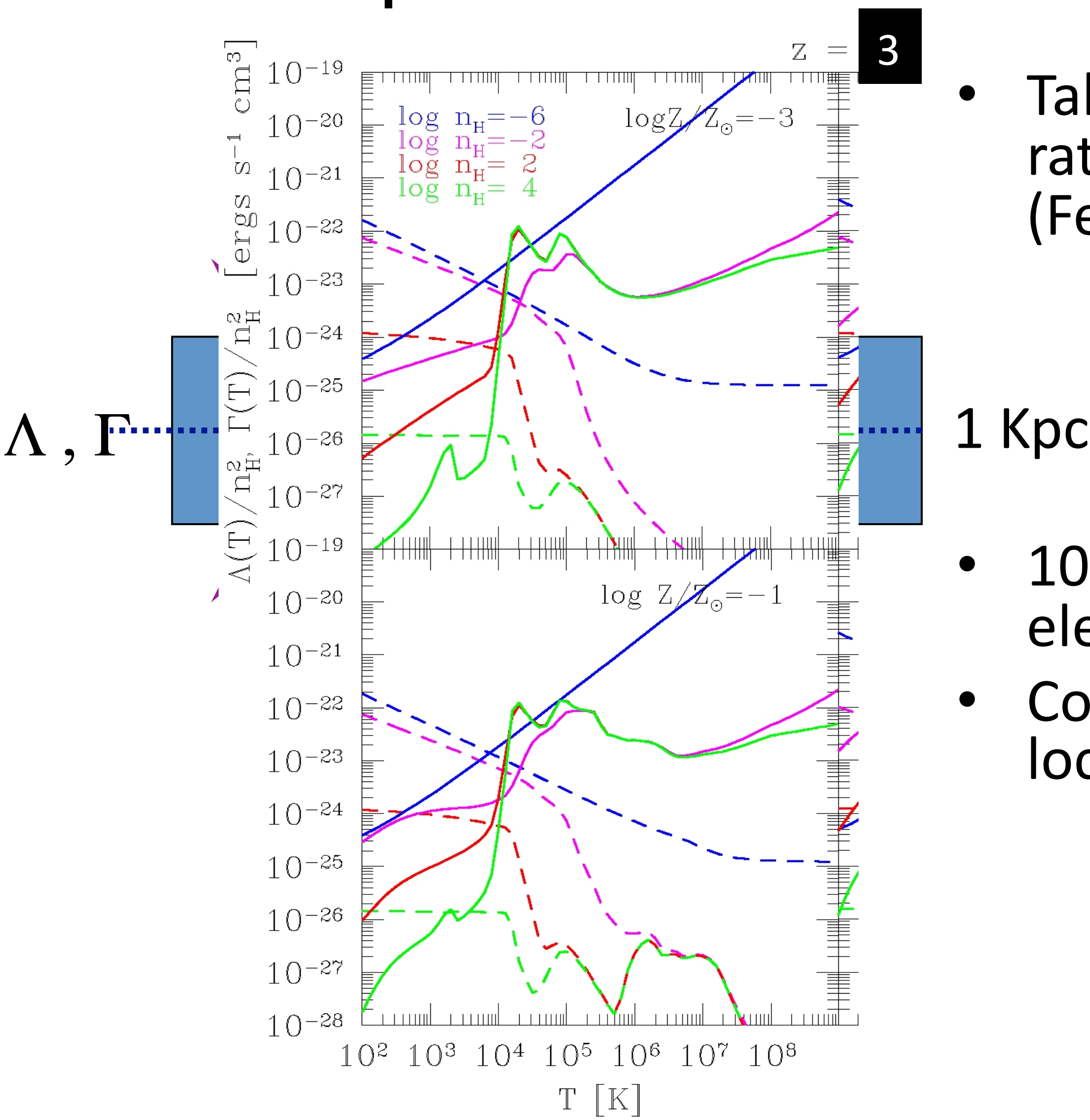
Radiative cooling

- Cooling of a plasma with a given metallicity.
- Molecular cooling.



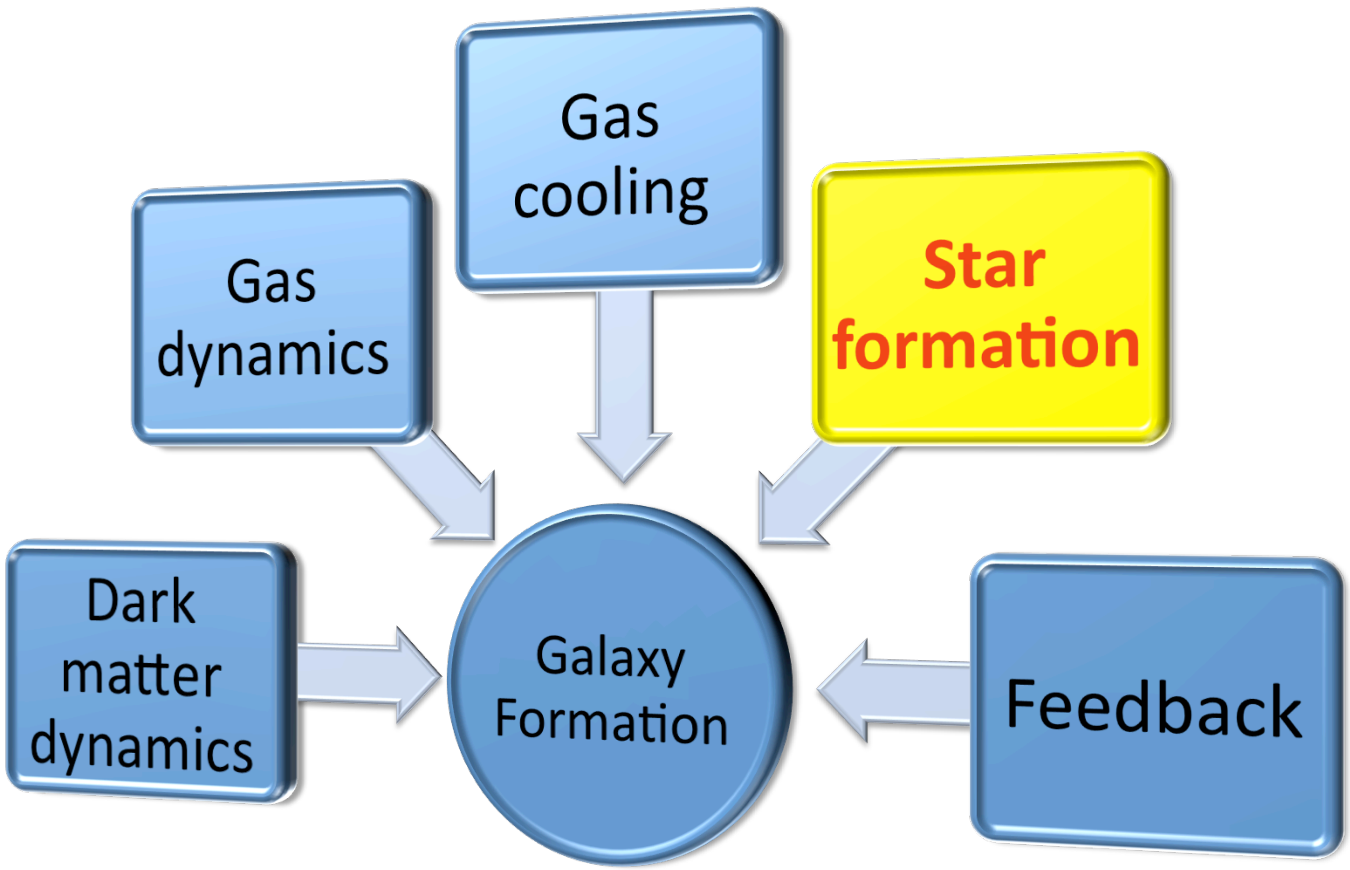
Sutherland & Dopita (1993)

How is radiative cooling/heating implemented in the code? Cloudy



- Tabulated cooling/heating rates (Λ/Γ) from CLOUDY (Ferland 1998) for given…
  - Hydrogen density.
  - Temperature.
  - Metallicity.
  - UV background intensity.
- 10^4 emision lines from 30 elements.
- Cooling rates depend on the local conditions of the gas.

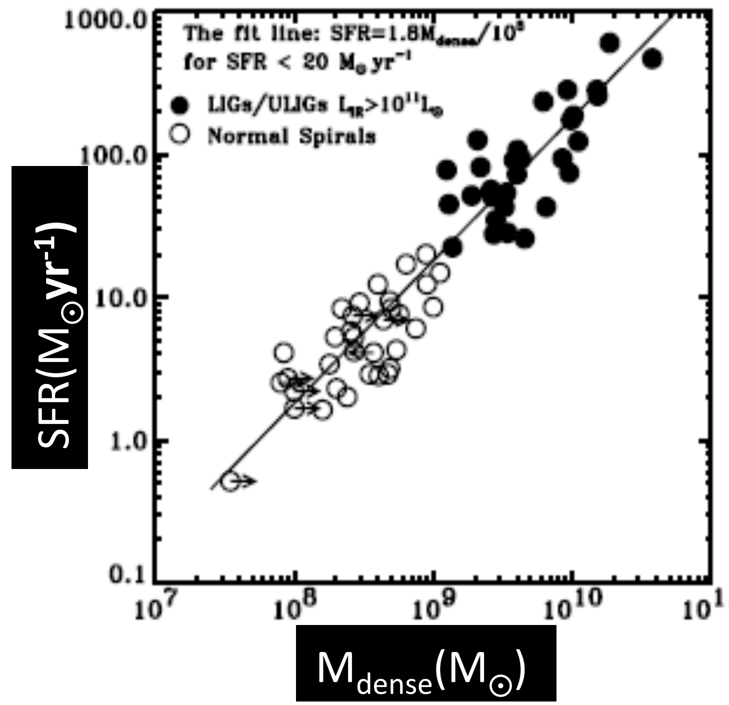
Physical models for galaxy formation



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).



star formation in nutshell

convert gas mass into collisionless stellar particles in cold, dense regions according to rate:

$$\dot{\rho}_* = C_* \left(\frac{\rho_{\rm gas}}{\rho_0} \right)^\alpha, \quad T < T_*, \quad \rho_{\rm gas} > \rho_*$$

Starformation in simulations: challenges

- although the parameters of a SF recipe can be tuned to reproduce the Kennicutt's law, the actual star formation in simulations depends on gas density and local dynamical time – both resolution-dependent quantities

- the parameters and star formation will thus in general be resolution-dependent

- moreover, the star formation law itself may depend on the scales resolved in a simulation (observationally, the situation is not yet clear, and so far we only have observational guidance only at z~0).

- feedback is also strongly resolution dependent because resolution determines the mass of gas to which the energy is deposited.

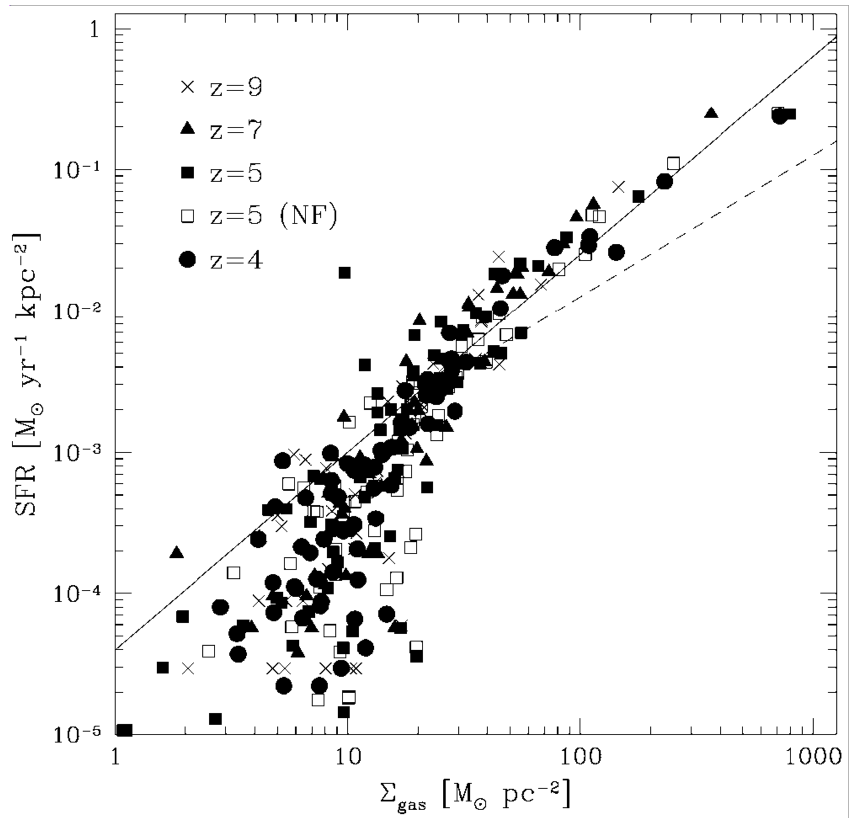
Recipe for star formation.

- Free parameter, τ:

$$\dot{\rho}_{stars} = \frac{\rho_{gas}}{\tau}$$

- Density and temperature thresholds.

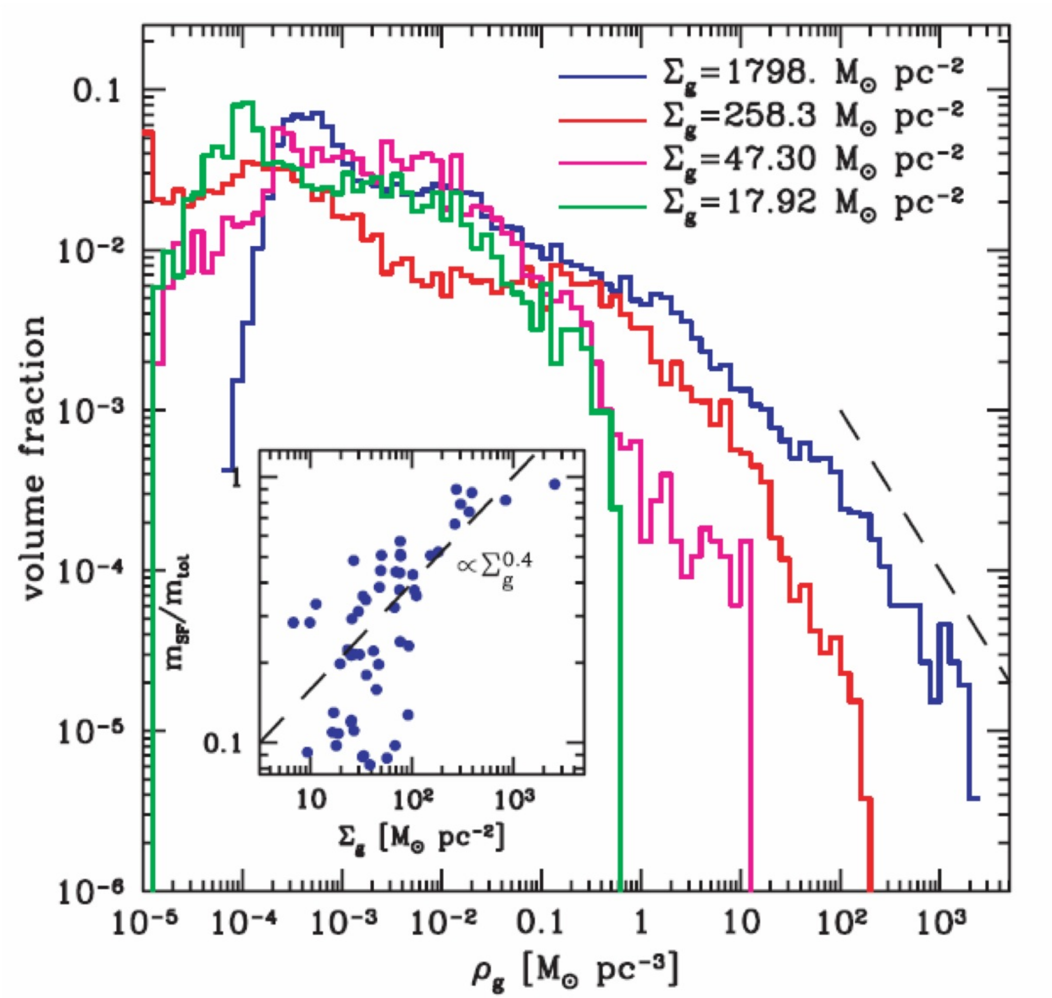
- Stellar particle → single population with a Miller-Scallo IMF.
- The code reproduce the Kennicutt empirical law



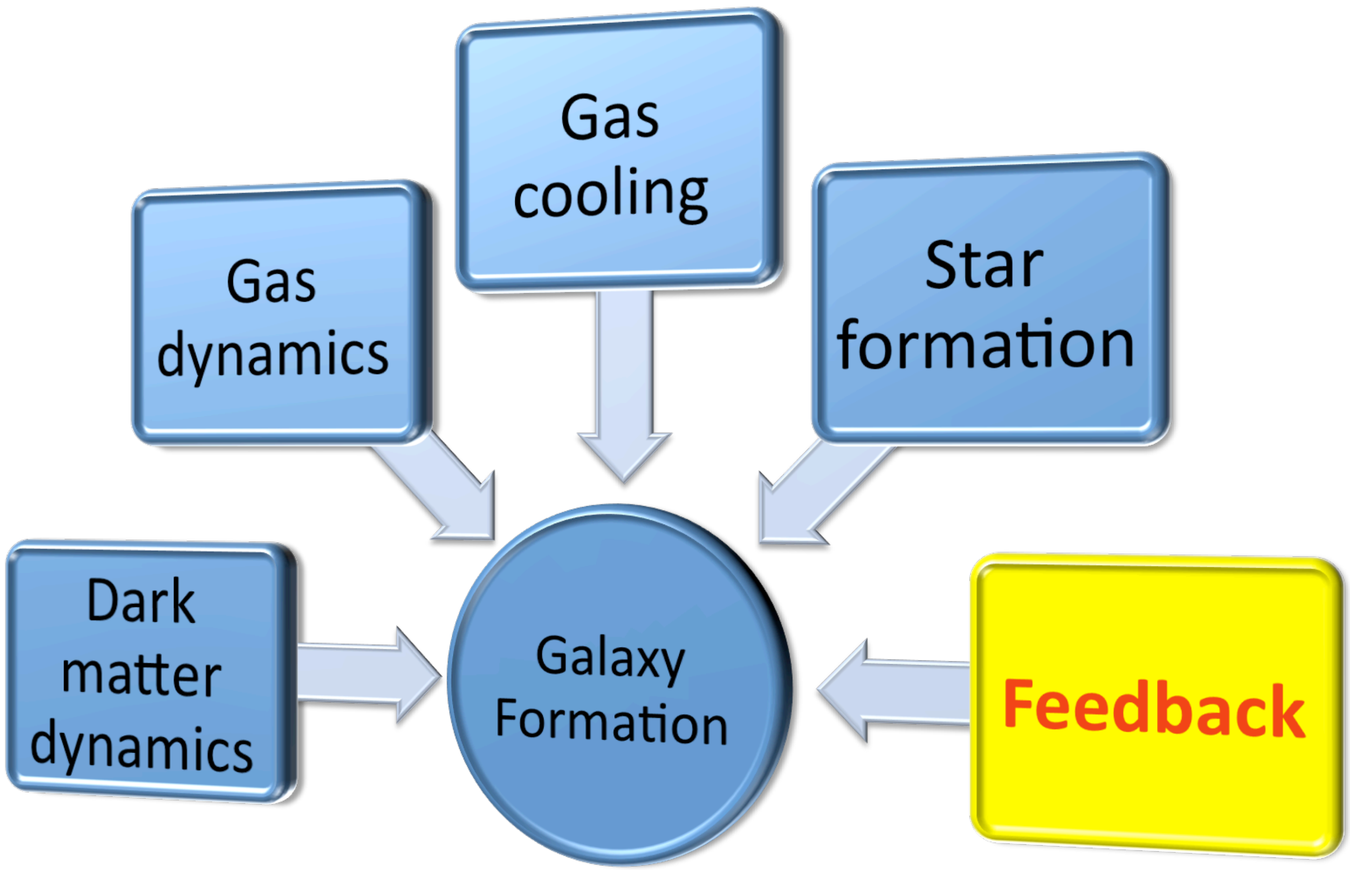
Kravtsov 2003

A possible explanation for the origin of n=1.4 in the Kennicutt's law

pdf of gas density



Physical models 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

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

Feedback heating vs radiative cooling

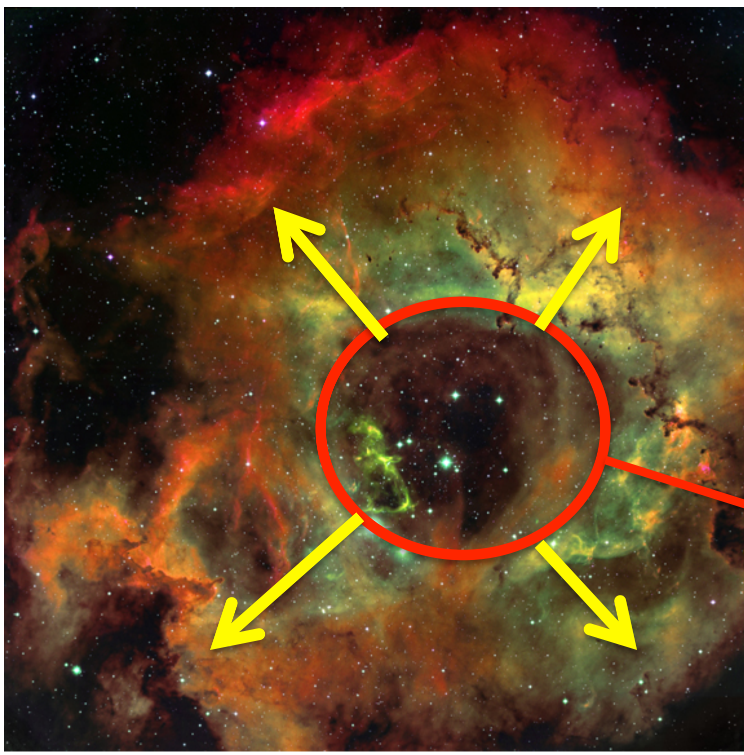
$$\text{Heating rate}: \quad \Gamma = \rho_{\text{Stars}}\, \Gamma'$$

$$\text{Cooling rate}: \quad L = n_H^2 L'(T, n_H, Z, z)$$

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

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**

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

$$\left(\frac{n_H}{0.1\,\mathrm{cm}^{-3}}\right)\left(\frac{\Lambda'}{10^{-22}\,\mathrm{erg\,s^{-1}\,cm^{-3}}}\right) \leq$$

$$\left(\frac{\rho_{*,\mathrm{young}}}{\rho_{\mathrm{gas}}}\right)\left(\frac{\Gamma'}{10^{34}\,\mathrm{erg\,s^{-1}\,M_\odot^{-1}}}\right)$$

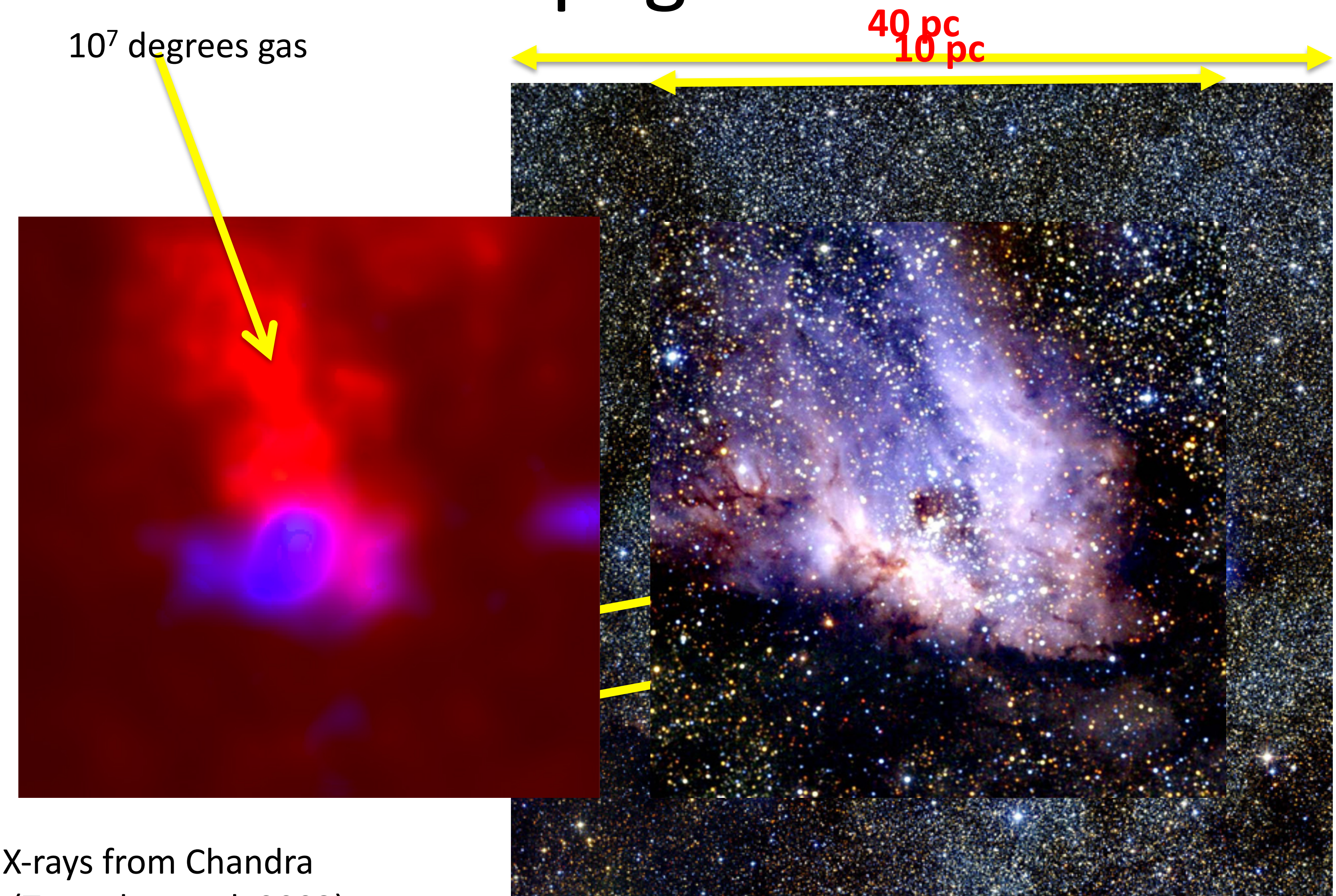
Difficult to satisfy this condition for $T_{gas} > 10^4$K; need very low gas density. Temperature regime 100-10000 K is crucial for initial stage of formation of superbubbles

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

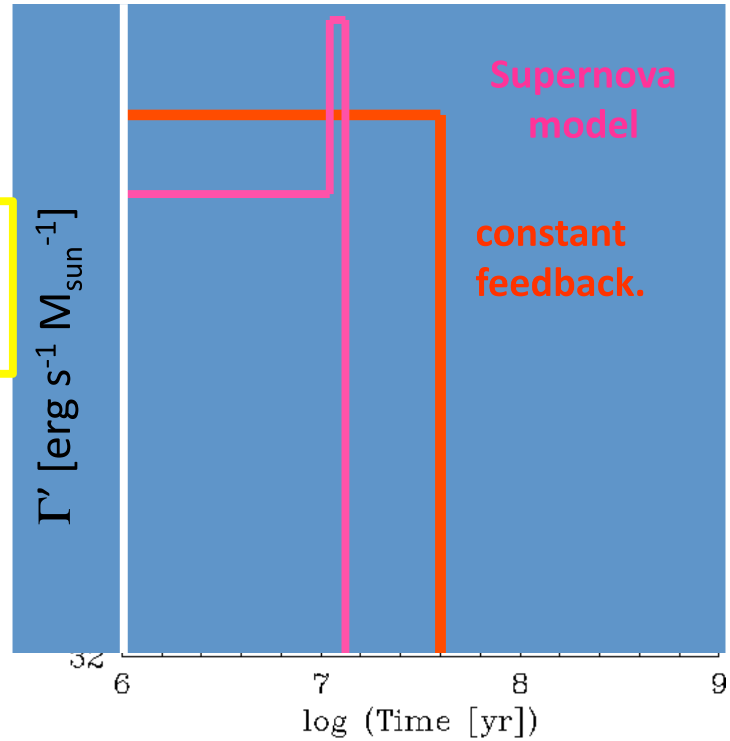
Champagne flow



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

M17, Horseshoe Nebula

OUR MODEL OF STELLAR FEEDBACK

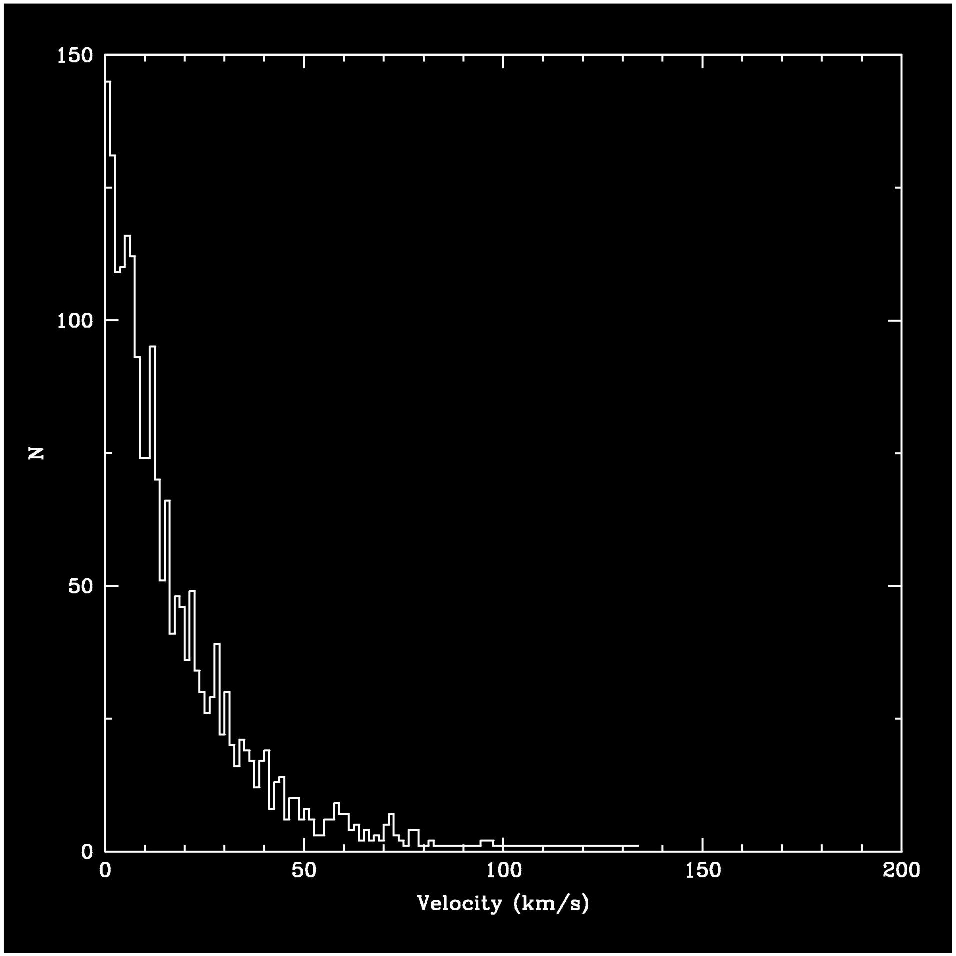


Leitherer et al.1999

$$\text{Heating rate}: \quad \Gamma = \rho_{\mathrm{Stars}}\, \Gamma'$$

$$\text{Cooling rate}: \quad L = n_H^2 L'(T, n_H, Z, z)$$

Runaway stars



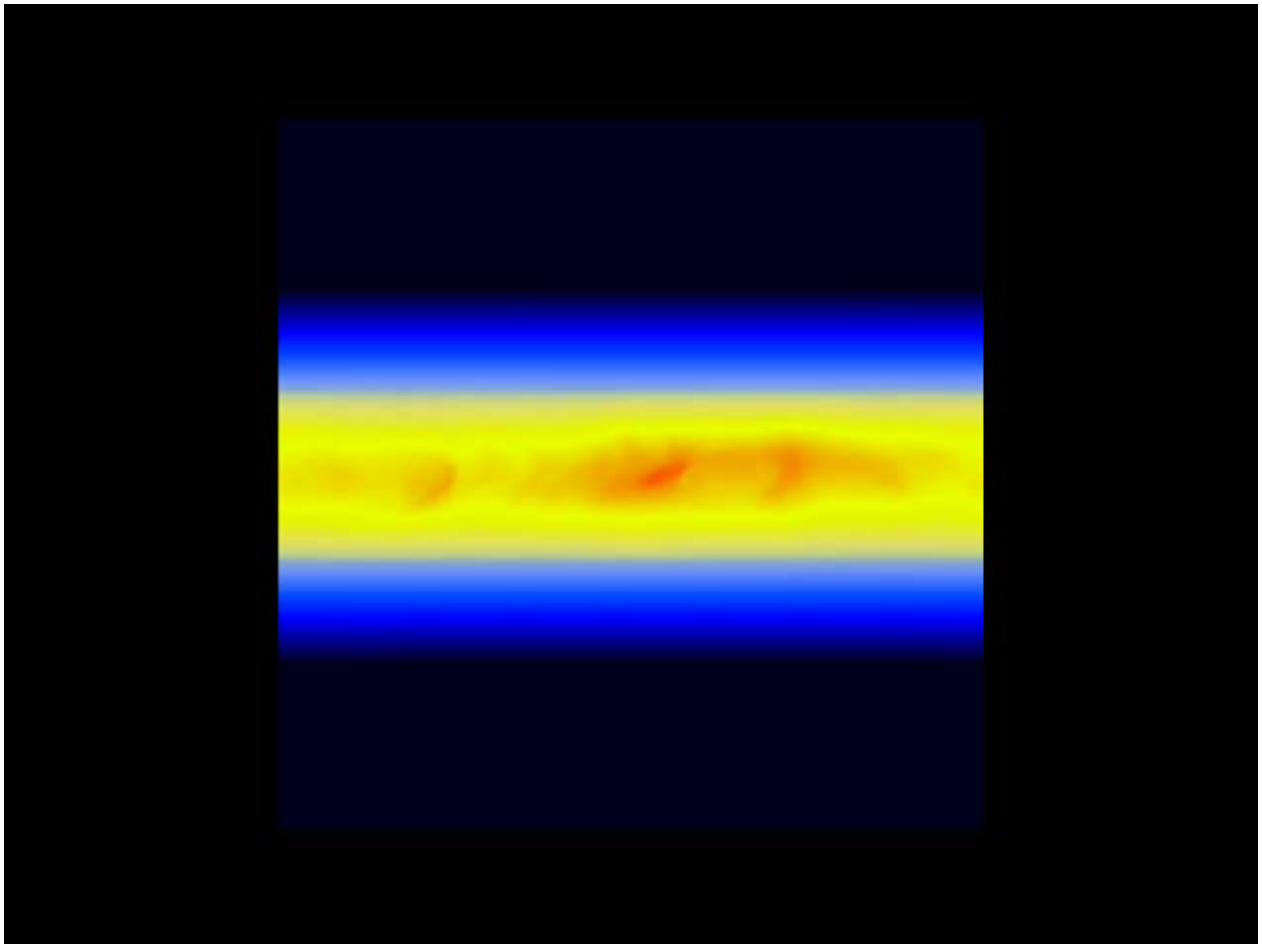
- 20%-30% of massive stars are found in the field rather than in clusters (Gies, 1987)
- 10 % have high velocities (v> 40 km/s)
- Exponential distribution of peculiar velocities (v_{Scale}=17 km/s)

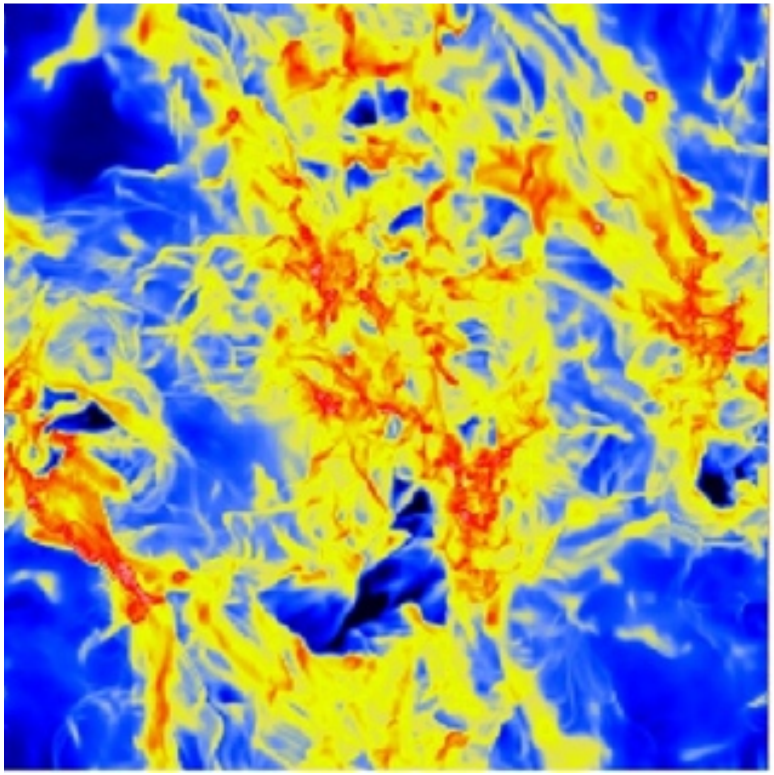
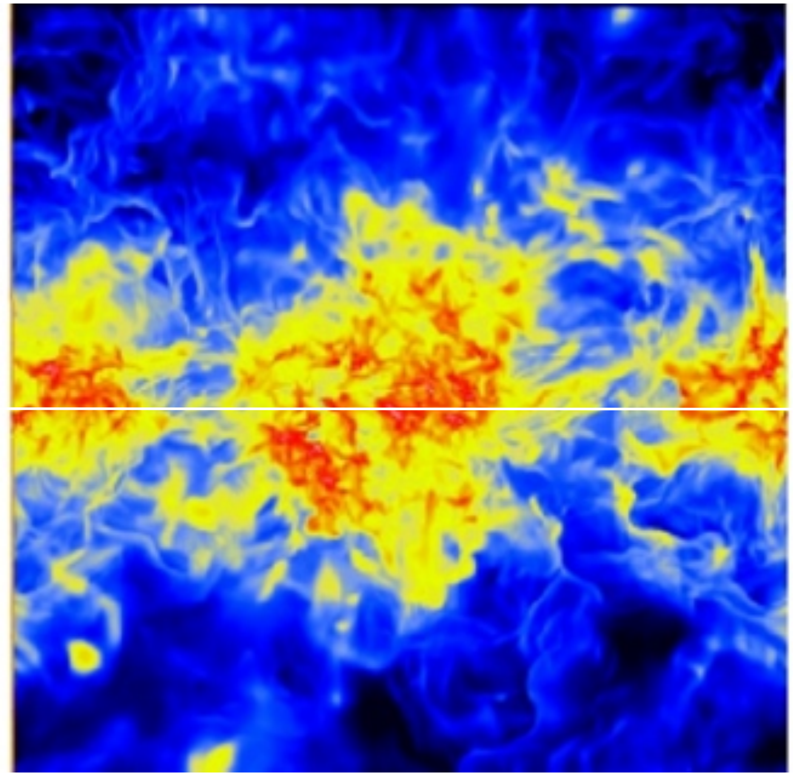
A piece of a galactic disk

8 pc resolution

Projected density

4 Kpc





4 kpc

Projection to the disk plane

Projection along the disk plane

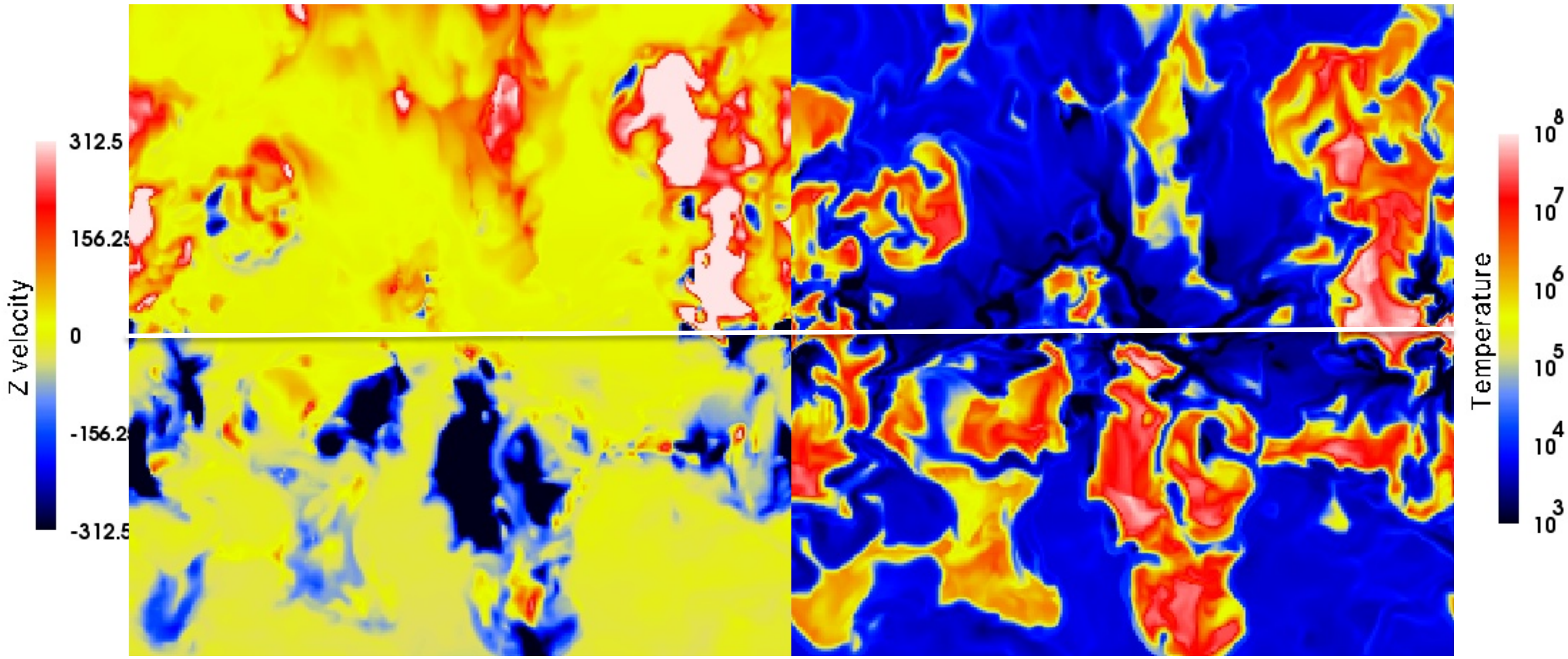
Projected density

Advanced stages: fully turbulent ISM

Super-bubbles and galactic chimneys

4x4 Kpc^2 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 stellar feedback

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

Cosmology: formation of MW galaxy

z=3.5 Major progenitor. 45 pc resolution

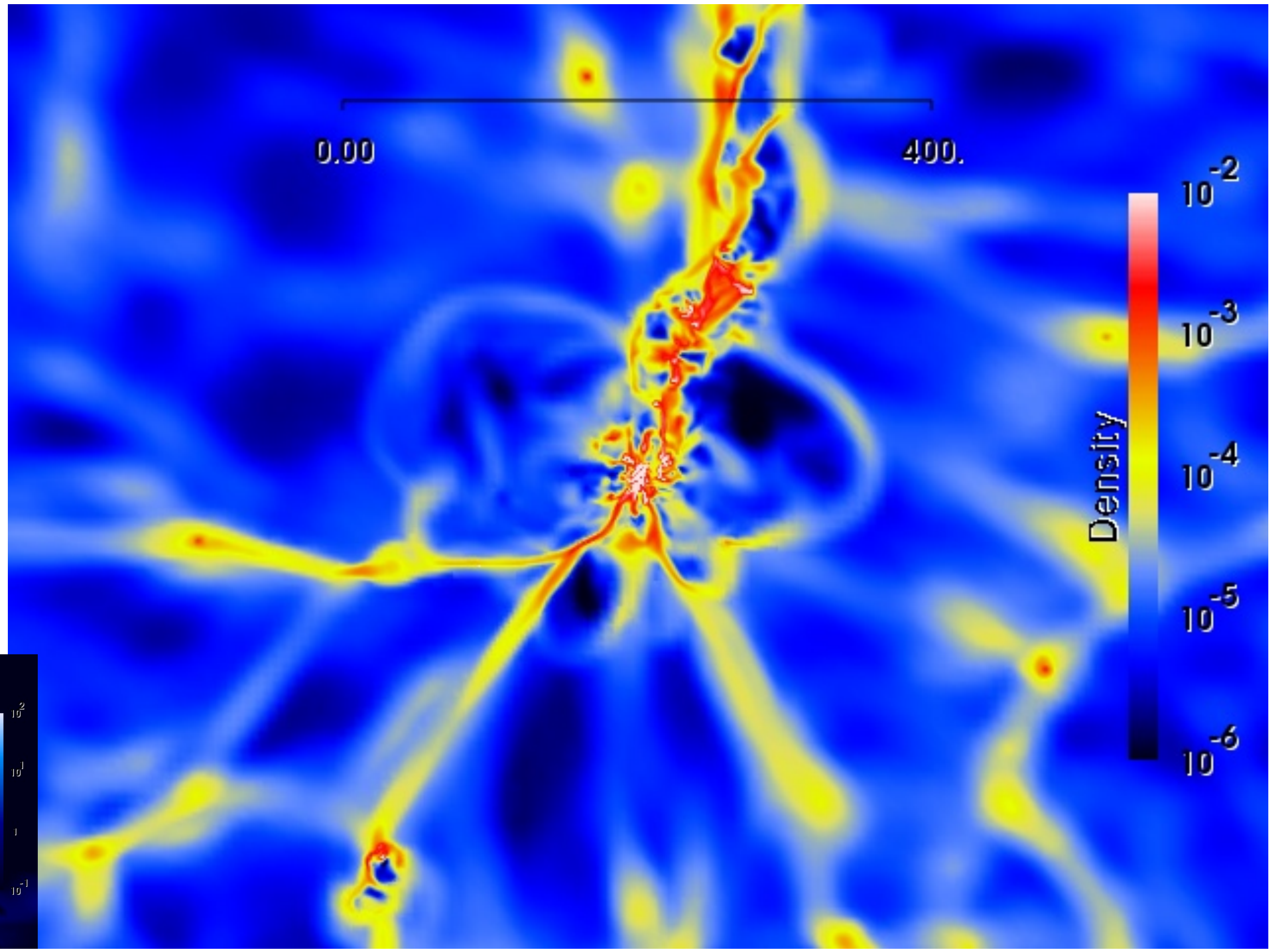
Face-on view SFR =10Msun/year

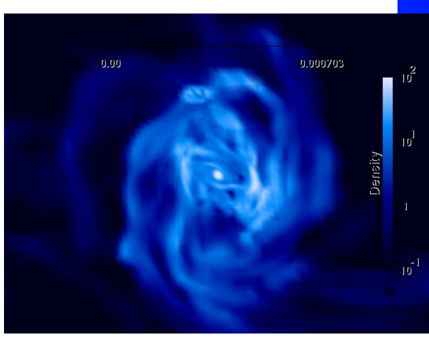
Ceverino & Klypin 2007

400 kpc proper

Cold Flow regime

Slice of gas density



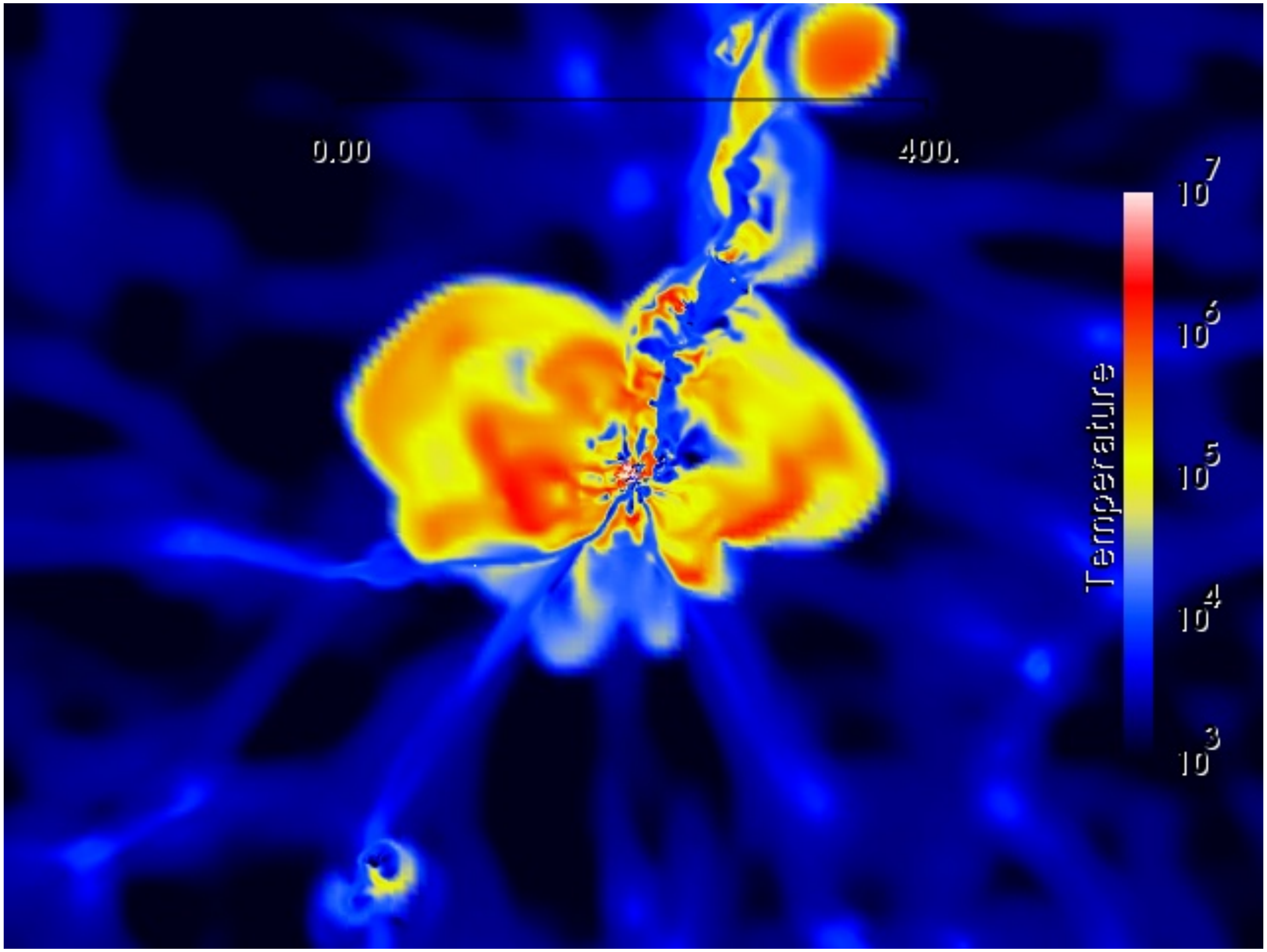


Ceverino & Klypin 2007

z=3.5 Major progenitor of MW. 45 pc resolution
Face-on view

400 kpc proper

Cold Flow regime



Slice of
temperature

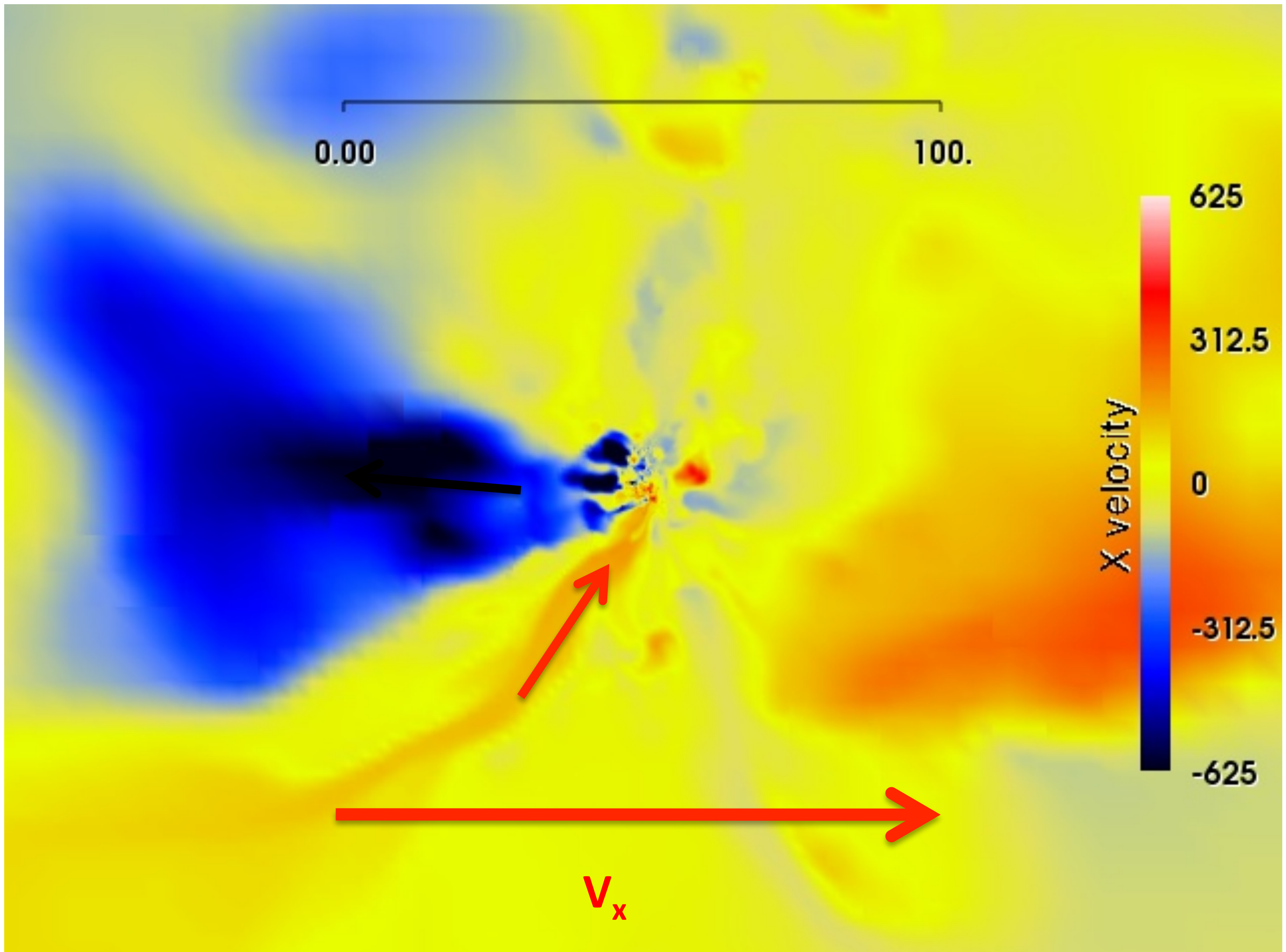
Ceverino & Klypin 2007

z=3.5 Major progenitor of MW. 45 pc resolution

Face-on view

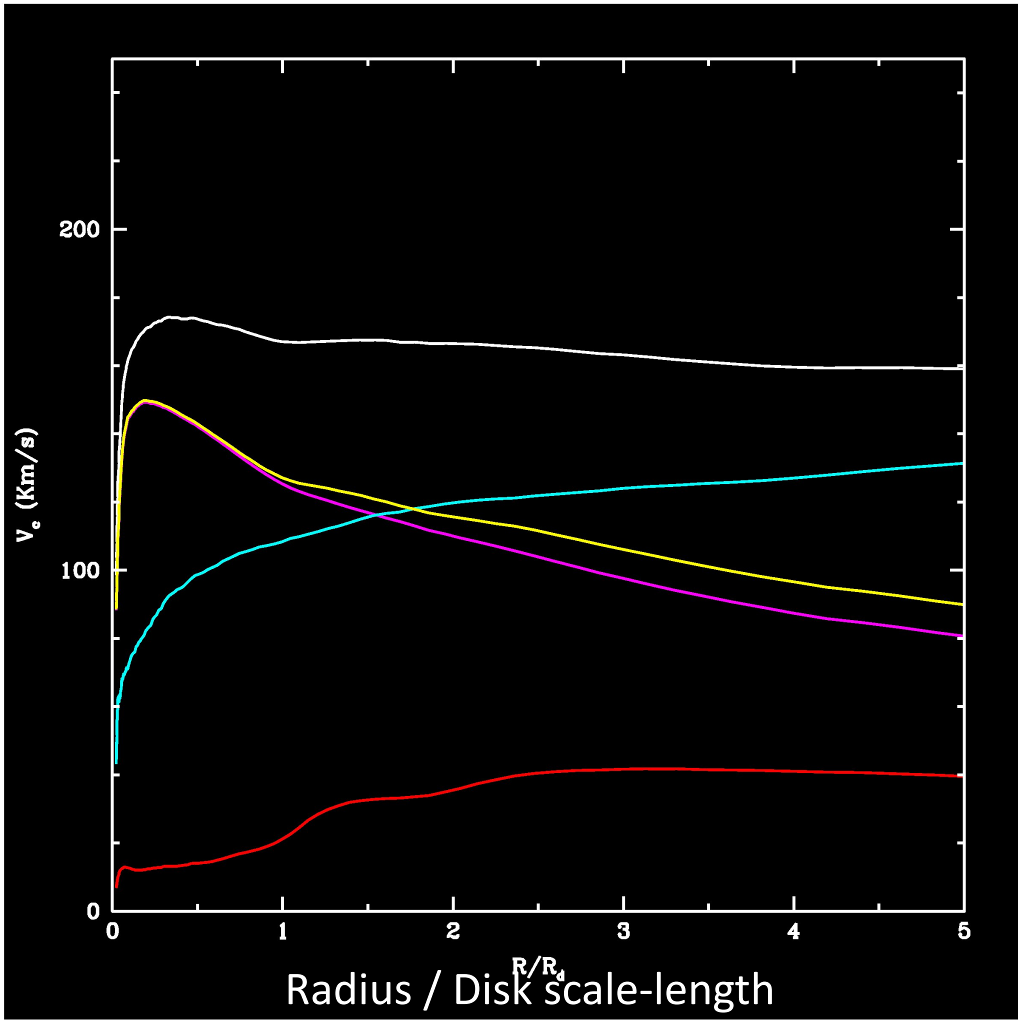
100 kpc proper

Gas velocity
In the
horizontal
direction.



Flat rotation curves are still the most sensitive test for feedback models

Combination of resolution and feedback improves the rotation curves



Resolution 45 pc. Thermal stellar feedback + runaway stars

MW-progenitor at z=3.

Scale-length: R_d=1.4 Kpc

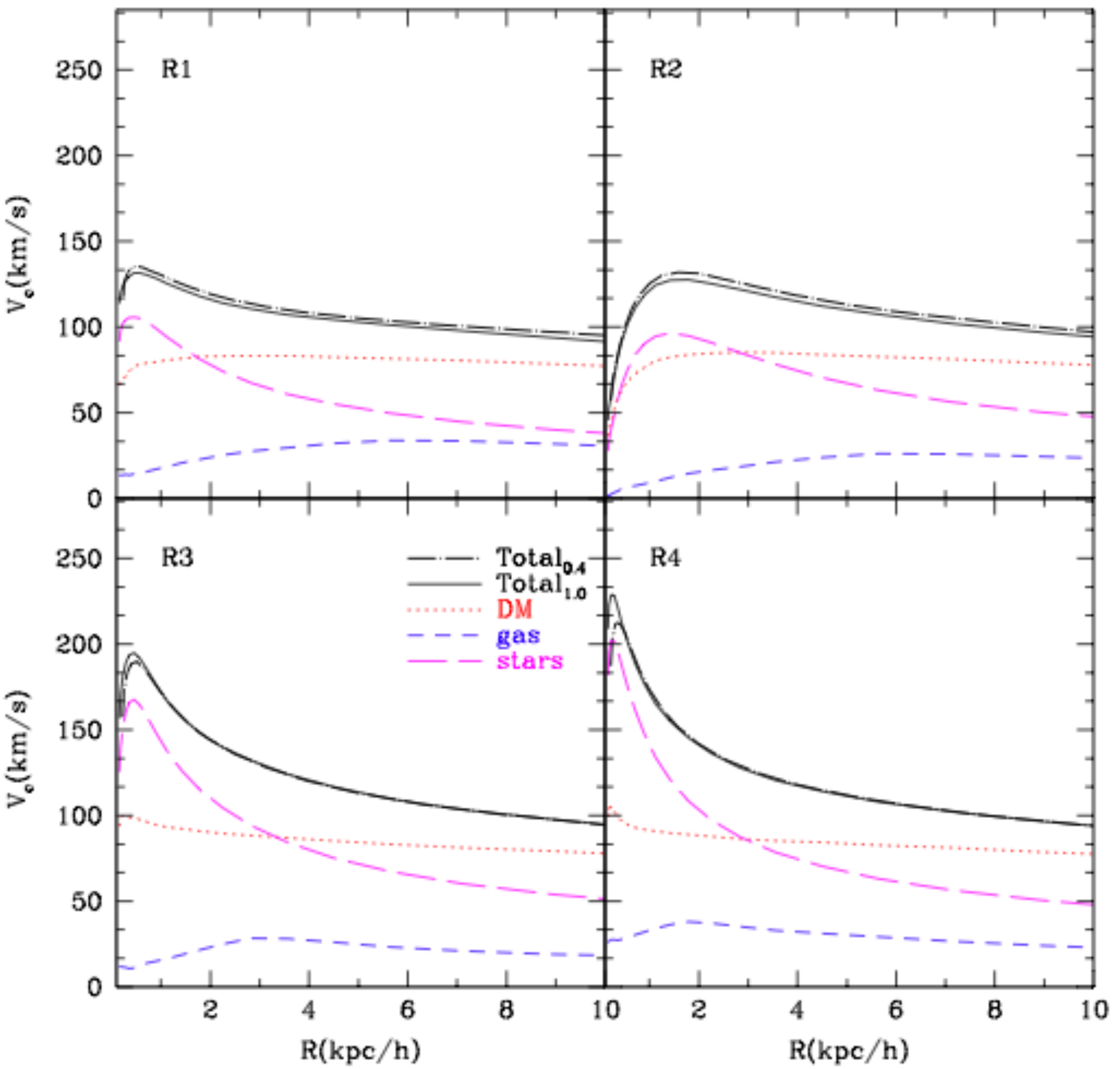
R_{vir}= 40 Kpc

M_{vir}=2 10^{11} $M_\odot$

M_* = 10^{10} $M_\odot$

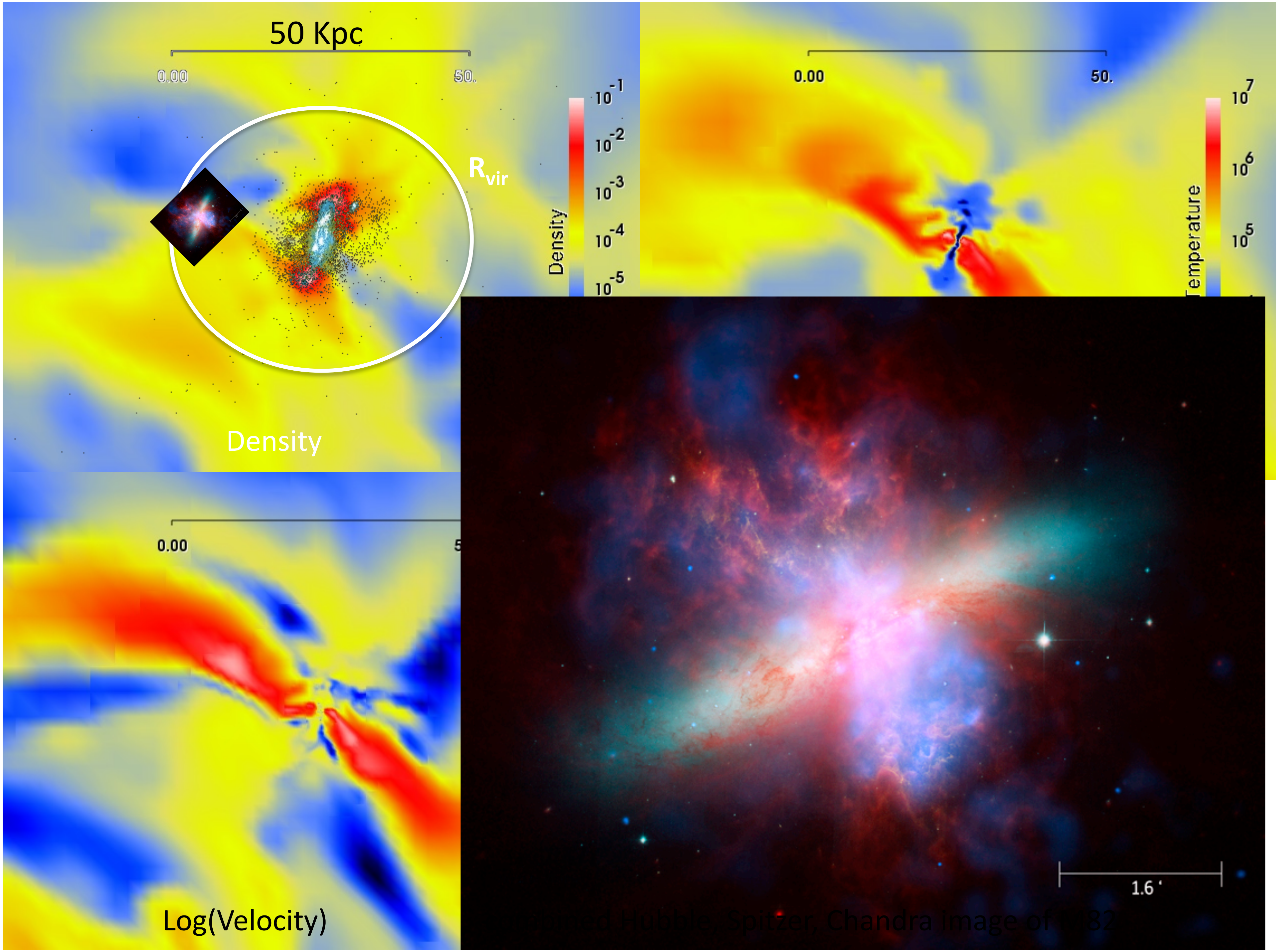
Fraction of cold baryons (stars and cold gas) inside R_{vir} is 0.5 universal = 0.5 Ω_{bar}/Ω_m

Parameter study



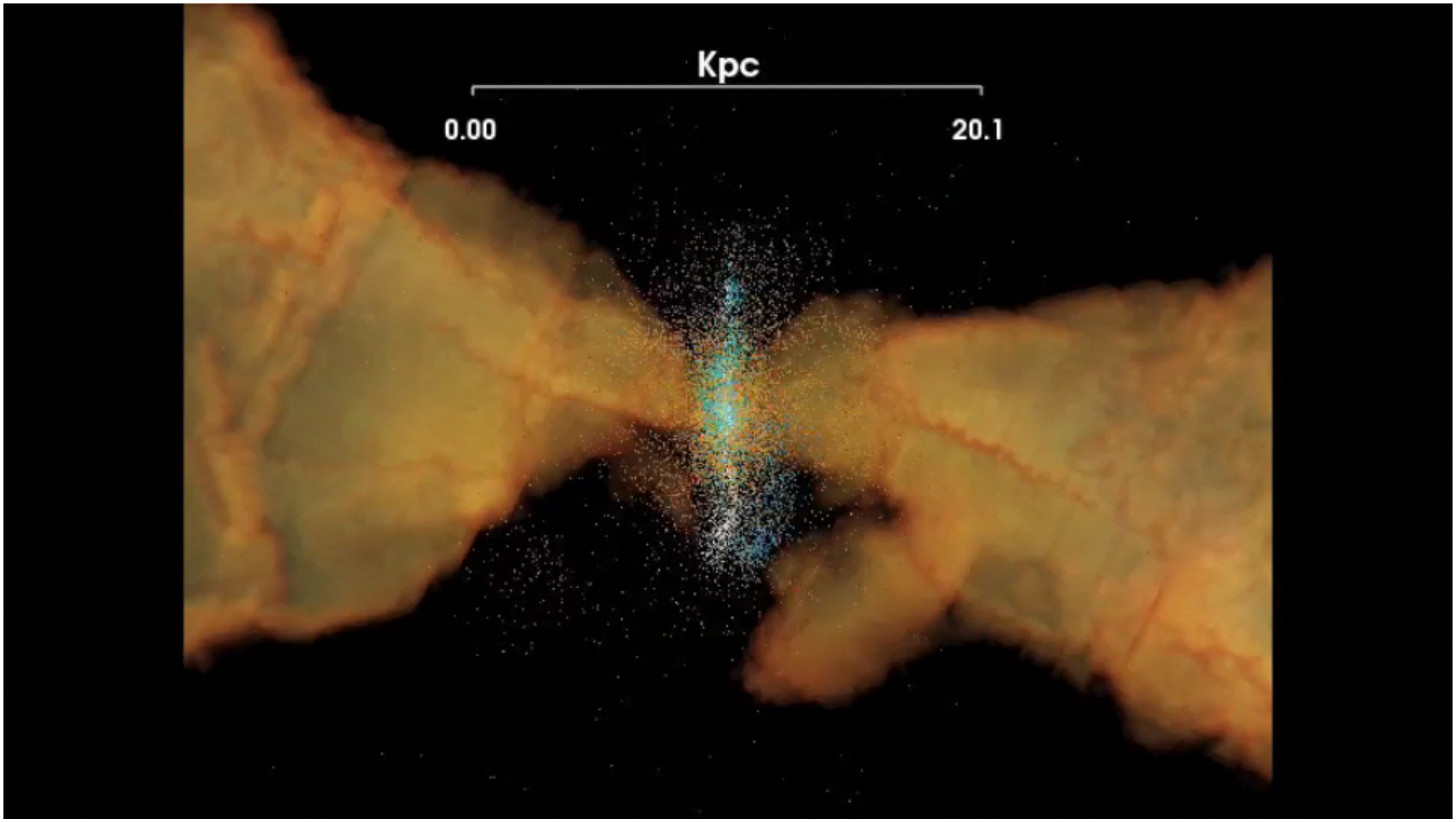
Model	$m_{\star,lim}$ (10^4 $M_\odot$)	n_{SF} (cm^{-3})	$C_\star$ (2.5×10^{-10} yr^{-1})	Cooling	β (10^6 yr)
D1	1.0	50.0	1.0	on	off
D2	8.0	6.25	1.0	on	off
D3	8.0	6.25	1.0	40	off
D4	∞	6.25	none	40	off
R1	1.0	1.0	667.0	on	100.0
R2	1.0	0.1	500.0	40	20.0
R3	1.0	1.0	500.0	40	20.0
R4	1.0	6.25	500.0	40	20.0
Ad	off	off	off	off	off

Colin et al 2010

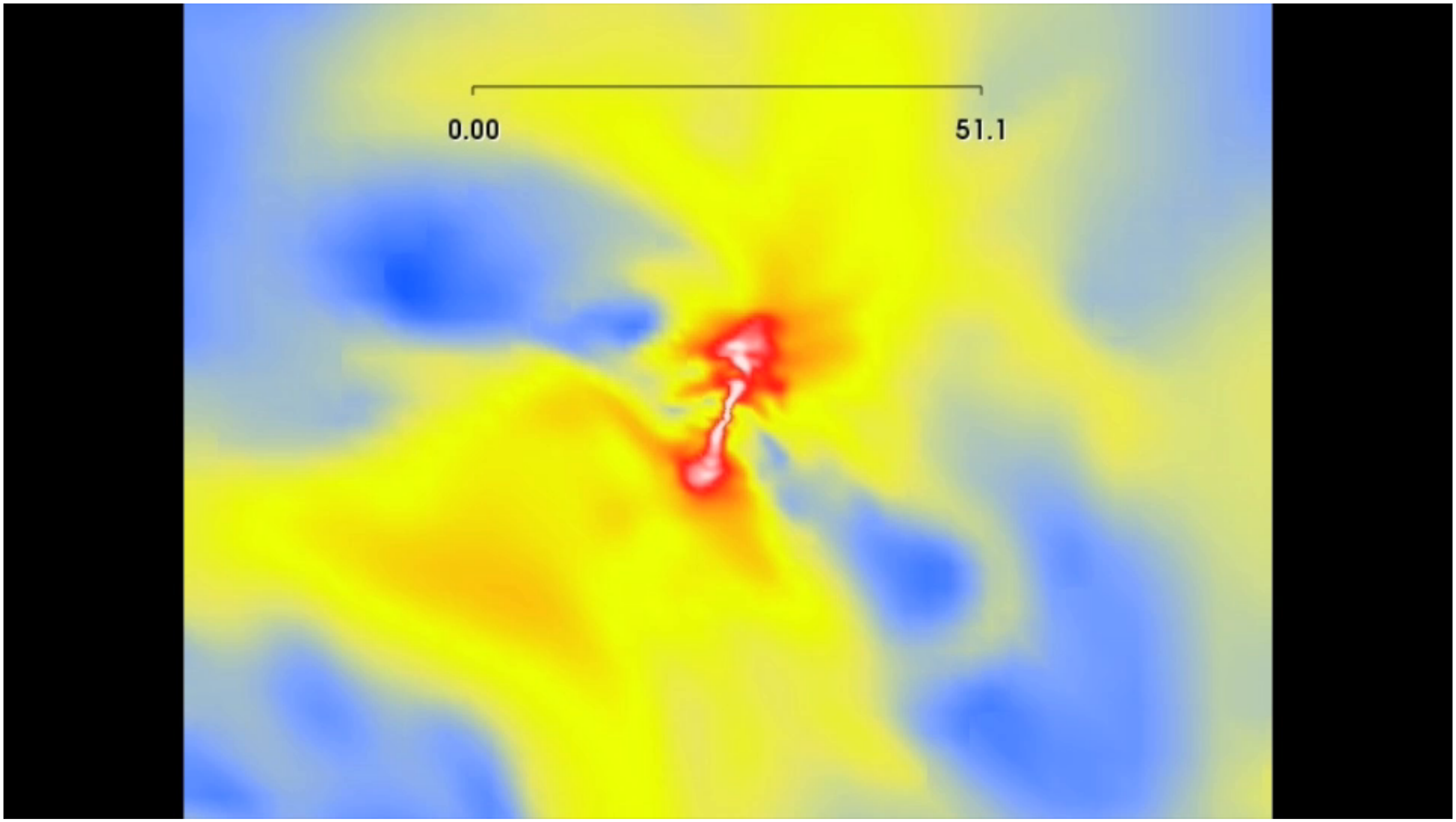

50 Kpc
0.00
50.
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Density
R_{vir}
Density
0.00
50.
10^{7}
10^{6}
10^{5}
Temperature
0.00
Log(Velocity)
1.6 '
Hubble, Spitzer, Chandra image of

Outflows extend beyond the virial radius

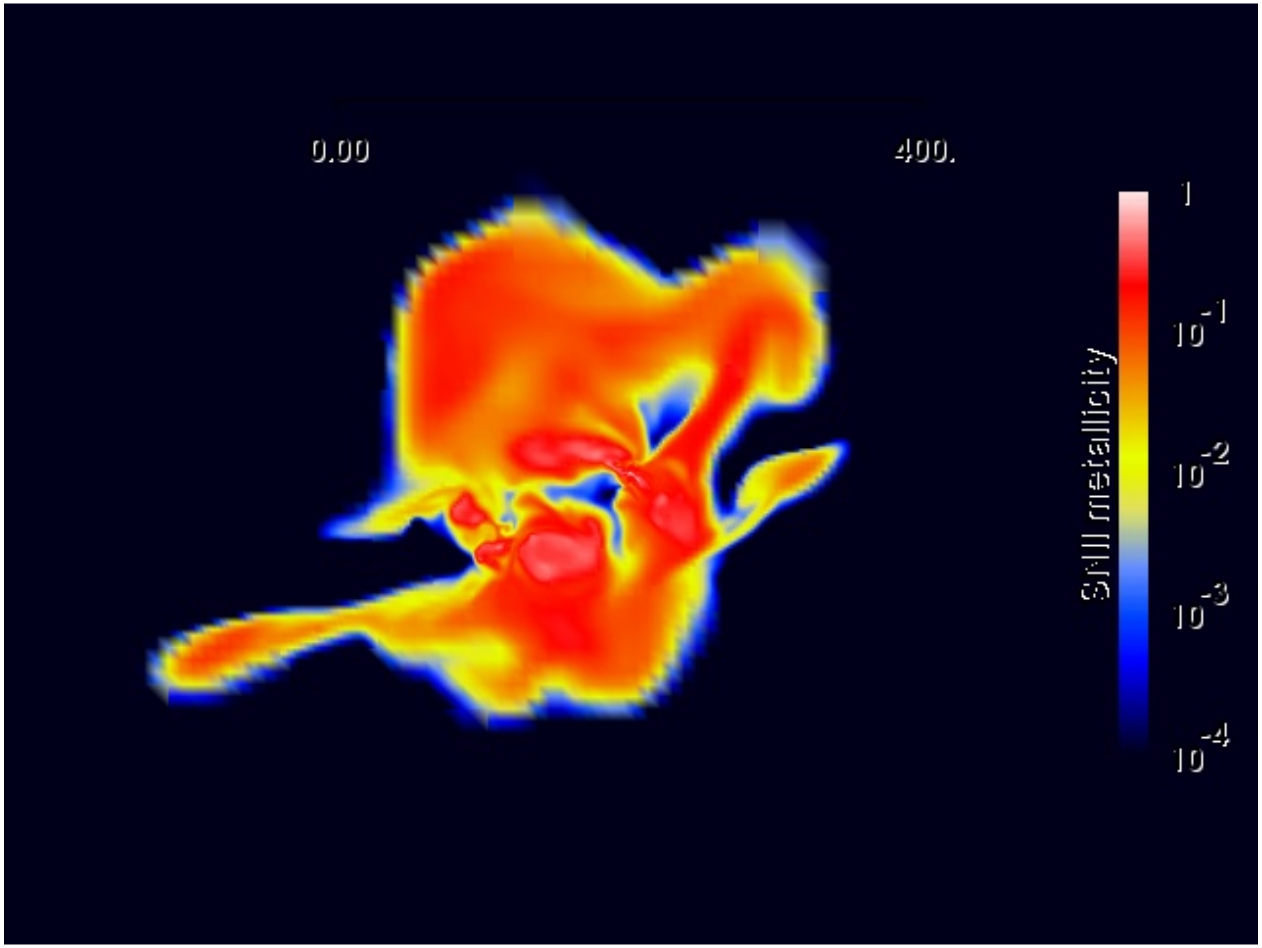
Outflow mass ≈ 10^7 $M_\odot$
Mass loss rate ≈ SFR



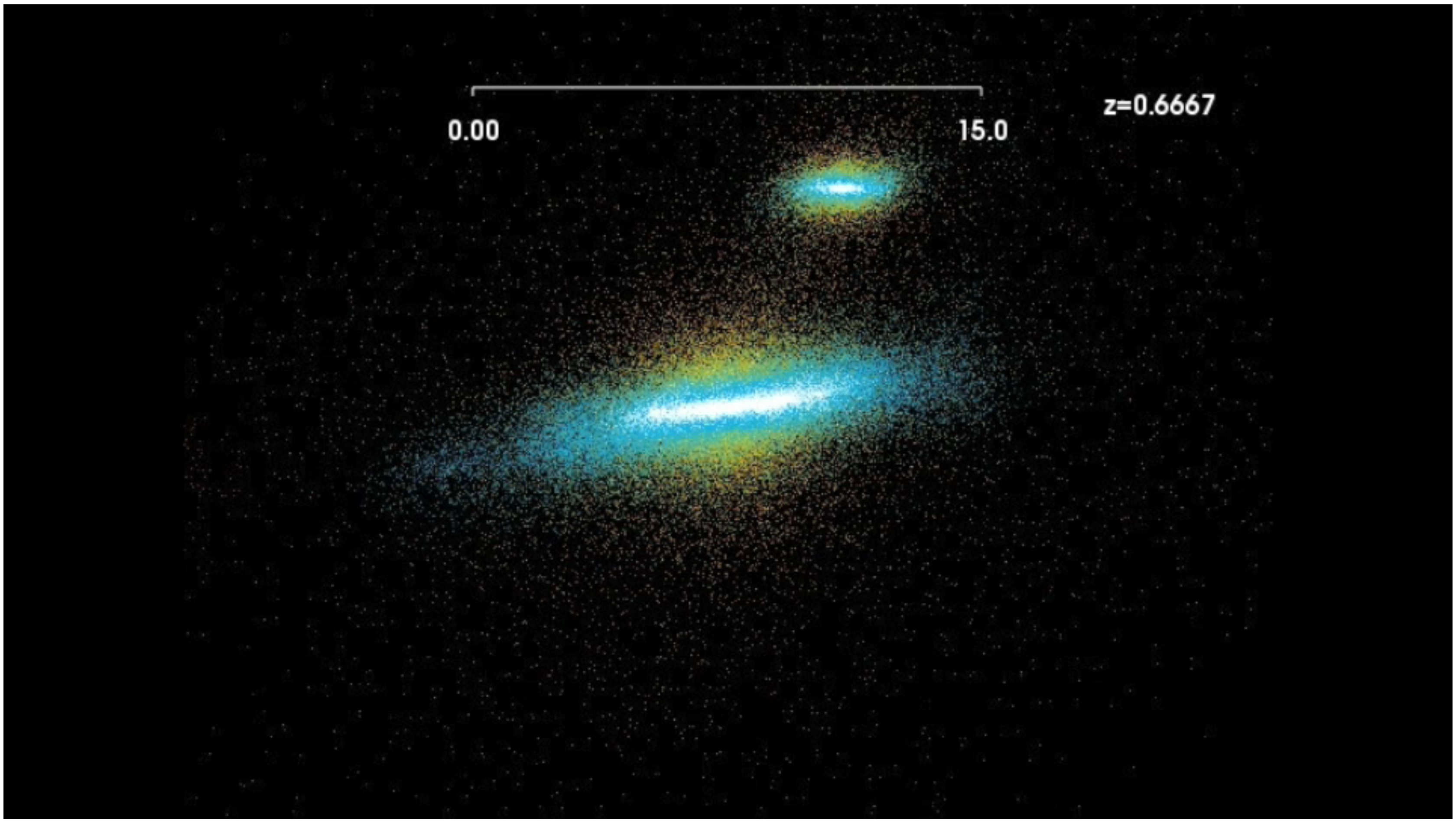
The effect of outflows extends much further



Galactic winds enrich the IGM with metals.



A low-mass spiral galaxy?



Summary

- Key features of the physical model in ART:
  - Cooling below 10^4 K
  - Self-shielding of dense (neutral) gas
  - Runaway stars
- Conditions for feedback efficiency:
  - Overheating regime
  - Expanding bubbles
  - Superbubbles, galactic chimneys and outflows
  - Better rotation curves