

ASTR 610

Theory of Galaxy Formation

Lecture 17: Feedback

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Feedback

In this lecture we discuss feedback, focussing mainly on supernove feedback. After describing blastwaves, we show that efficient SN feedback requires an ISM in which most of the volume is in the hot phase. We discuss how this may come about because of stellar evolution & radiation...

Topics that will be covered include:

- Energy Budgets (SN & AGN)
- Galactic Winds & Mass Loading
- Modelling SN feedback
- Rayleigh-Taylor instability
- Theory of blastwaves
- SNR overlap & ISM structure
- Radiation Pressure

Some Feedback Please

One of the most important problems in Galaxy Formation is the **overcooling** problem. Preventing overcooling requires some heat input. According to the current paradigm, the main heating mechanisms are **feedback** from star formation and AGN activity.



The Starburst Dwarf Galaxy M82

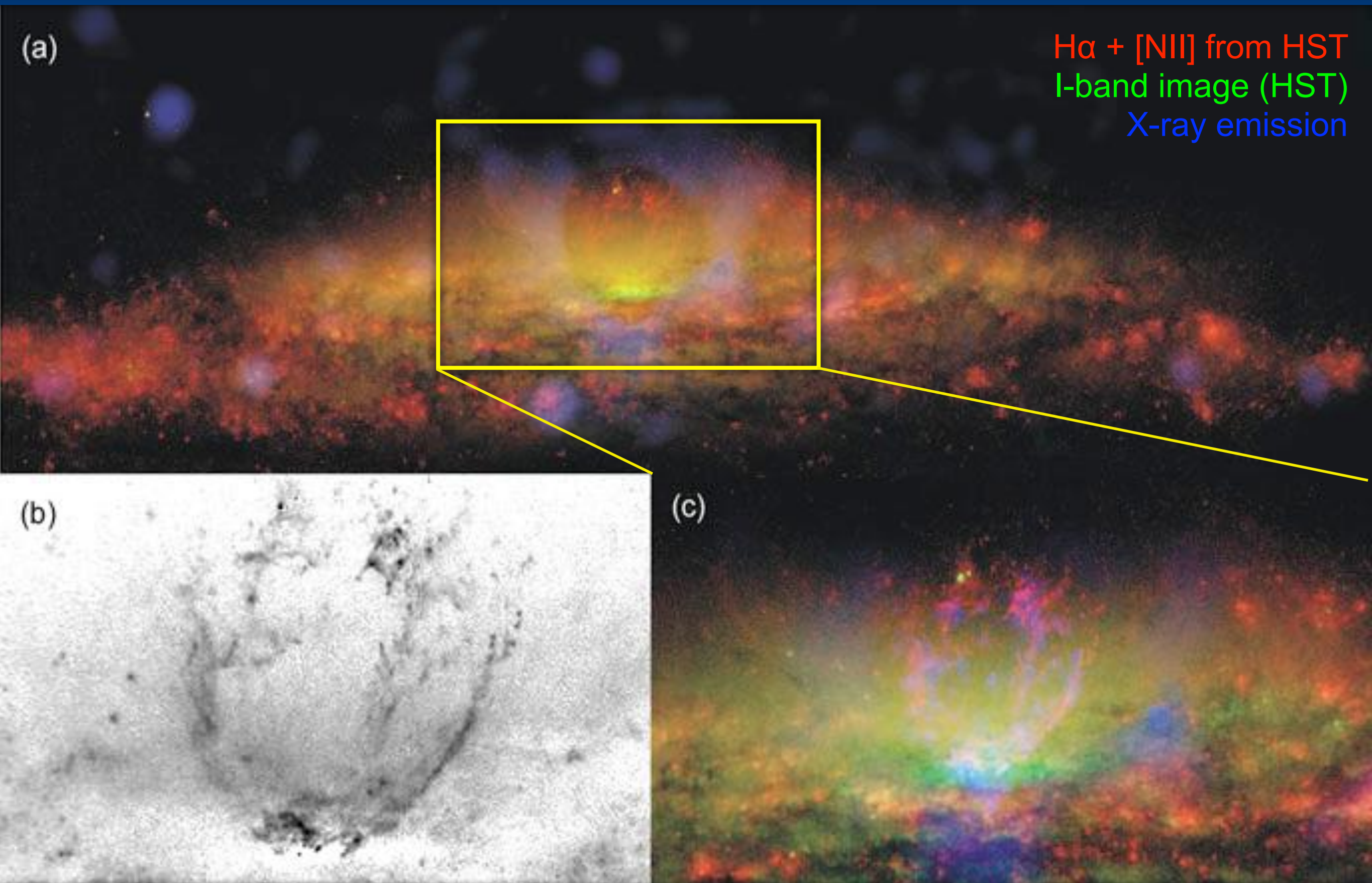


H α emission from WYIN Telescope
optical star light (BVI) from HST
(courtesy: Smith, Gallagher, & Westmoquette).

The Starburst Dwarf Galaxy M82



NGC 3079



Supernova Feedback (ejection)

To get a feel for whether the energy input from SN can be relevant for galaxy formation, imagine ejecting a mass M_{ej} from the center of a NFW dark matter halo.

This requires an energy injection of $E_{\text{ej}} = \frac{1}{2} M_{\text{ej}} V_{\text{esc}}^2$. Using that, to a good approximation, the escape velocity from the center of a NFW halo is $V_{\text{esc}} \simeq \sqrt{6c} V_{\text{vir}}$ where c is the halo concentration parameter, we have that $E_{\text{ej}} \simeq 3c M_{\text{ej}} V_{\text{vir}}^2$

The energy available from SN is $E_{\text{fb}} = \varepsilon_{\text{SN}} \zeta M_* E_{\text{SN}}$

$\varepsilon_{\text{SN}} \leq 1$ = fraction of SN energy available for feedback (not just radiated away)

$\zeta \simeq 0.01 M_{\odot}^{-1}$ = number of SN produced per Solar mass of stars formed (IMF dependent)

$E_{\text{SN}} \simeq 10^{51} \text{ erg}$ = energy supplied per SN

Equating E_{fb} to E_{ej} we obtain that

$$\frac{M_{\text{ej}}}{M_*} \simeq 0.4 \varepsilon_{\text{SN}} \left(\frac{c}{10} \right)^{-1} \left(\frac{V_{\text{vir}}}{200 \text{ km/s}} \right)^{-2}$$



Hence, even if 100% of the SN energy can be converted into kinetic energy of a galactic wind, SN can only eject about 40% of the stellar mass from a MW-sized halo.

This efficiency increases with decreasing halo mass; for $V_{\text{vir}} = 50 \text{ km/s}$ we have that $M_{\text{ej}} \leq 6.4 M_*$

Supernova Feedback (reheating)

Rather than ejecting gas from the halo, SN energy can also be used to reheat gas.

The **internal energy** of gas is $E_{\text{int}} = \frac{3}{2} M_{\text{gas}} \frac{k_B T}{\mu m_p}$.

Imagine we want to reheat this gas from an initial temperature of $T_{\text{init}} = 10^4 \text{ K}$ to the virial temperature of the halo, $T_{\text{vir}} = \frac{\mu m_p}{2 k_B} V_{\text{vir}}^2$

This requires an energy

$$E_{\text{reheat}} = \frac{3}{2} M_{\text{gas}} \frac{k_B (T_{\text{vir}} - T_{\text{init}})}{\mu m_p} = \frac{3}{4} M_{\text{gas}} V_{\text{vir}}^2 \left(1 - \frac{T_{\text{init}}}{T_{\text{vir}}} \right)$$

Equating E_{reheat} to E_{fb} yields

$$\frac{M_{\text{gas}}}{M_*} \simeq 17 \epsilon_{\text{SN}} \left(\frac{V_{\text{vir}}}{200 \text{ km/s}} \right)^{-2} \left(1 - \frac{T_{\text{init}}}{T_{\text{vir}}} \right)^{-1}$$

Hence, in a MW halo, **SN** can reheat up to $17 M_{\odot}$ for every Solar mass of stars formed.

Reheating is more efficient than ejecting gas, by roughly factor $(V_{\text{esc}}/V_{\text{vir}})^2 \simeq 6$

The all important question for gauging the potential impact of SN feedback is

what is the SN feedback efficiency parameter ϵ_{SN}

As we will see, depending on the ISM and SF conditions, $0.01 < \epsilon_{\text{SN}} \leq 1$

AGN Feedback

What about feedback from AGN?

The energy output from an AGN (over its lifetime) is

$$E_{\text{AGN}} \sim 0.1 M_{\text{BH}} c^2$$

where we have assumed that roughly 10% of the rest-mass energy is radiated away. If we assume that a fraction ε_{AGN} of this radiation is used to reheat gas or to eject it from the halo, and we use that $M_{\text{BH}} \simeq 0.002 M_{\text{bulge}}$ we obtain that

$$\frac{E_{\text{AGN}}}{E_{\text{SN}}} \sim 36 \frac{\varepsilon_{\text{AGN}}}{\varepsilon_{\text{SN}}} \left(\frac{M_{\text{bulge}}}{M_*} \right)$$

If $\varepsilon_{\text{AGN}} \sim \varepsilon_{\text{SN}}$ AGN feedback can be order of magnitude more efficient than SN feedback

Key question: what is a realistic value for ε_{AGN}

NOTE: fact that we can see AGN implies that ε_{AGN} has to be significantly smaller than unity

Mass Loading & Scaling Relations

Let \dot{M}_w be the rate at which mass is ejected into a galactic wind that emerges from a galaxy due to SN feedback. The ratio $\eta \equiv \dot{M}_w / \dot{M}_*$ is called the **mass loading** of the wind, and is the parameter of importance for galaxy formation.

Since we lack proper, theoretical understanding of how **galactic winds** emerge, and numerical simulations lack the spatial resolution (and physics) to treat **SN feedback** from first principles, a number of different heuristic approaches have been used:

Energy-Driven Winds

$$v_w \propto V_{\text{vir}}$$

$$\eta \propto V_{\text{vir}}^{-2}$$

Momentum-Driven Winds

$$v_w \propto V_{\text{vir}}$$

$$\eta \propto V_{\text{vir}}^{-1}$$

Constant Winds Models

$$v_w = \text{constant}$$

$$\eta = \text{constant}$$

Power-Law Wind Models

$$v_w \propto V_{\text{vir}}$$

$$\eta \propto V_{\text{vir}}^{-\alpha_{\text{fb}}}$$

In what follows we discuss each of these four **wind models** in turn...

Mass Loading & Scaling Relations

Energy-Driven Winds

Assuming that $v_w \propto V_{\text{vir}}$ and that the kinematics are governed by energy conservation results in a wind model with $\eta \propto V_{\text{vir}}^{-2}$:

$$\begin{array}{l} \dot{E}_w = \frac{1}{2} \dot{M}_w v_w^2 \\ \dot{E}_{\text{SN}} = \varepsilon_{\text{SN}} \zeta \dot{M}_* E_{\text{SN}} \end{array} \quad \longrightarrow \quad \eta = \eta_0 \left(\frac{V_{\text{vir}}}{200 \text{ km/s}} \right)^{-2}$$

$$\text{Here } \eta_0 = \frac{2 \varepsilon_{\text{SN}} \zeta E_{\text{SN}}}{(200 \text{ km/s})^2} \simeq 25 \varepsilon_{\text{SN}} \left(\frac{\zeta}{0.01 M_{\odot}^{-1}} \right) \left(\frac{E_{\text{SN}}}{10^{51} \text{ erg}} \right)$$

This particular wind-model is used abundantly in (semi)-analytical models of galaxy formation. In order for these models to have a sufficiently strong impact on the [galaxy stellar mass function](#) (i.e., strong suppression of galaxy formation in low mass haloes), the models typically require $\varepsilon_{\text{SN}} \sim 1$

Mass Loading & Scaling Relations

Momentum-Driven Winds

Similar to energy-driven wind models, these models assume that $v_w \propto V_{\text{vir}}$. However, here the assumption is made that the wind kinematics are governed by momentum conservation, which results in $\eta \propto V_{\text{vir}}^{-1}$.

$$\begin{array}{l} \dot{M}_w v_w \propto \dot{M}_* \\ v_w \propto V_{\text{vir}} \end{array} \quad \Rightarrow \quad \eta = \eta_0 \left(\frac{V_{\text{vir}}}{200 \text{ km/s}} \right)^{-1}$$

This model has been advocated by Murray et al. (2005) and is motivated by the idea that winds may be driven by radiation pressure acting on dust grains.

Since this model predicts a weaker scaling with halo mass, it generally results in stellar mass functions that are steeper at the low mass end than those resulting from models that invoke energy-driven winds.

It has been argued that momentum-driven winds are more successful in reproducing the size-mass relation of disk galaxies (Dutton & vdBosch 2009), and the enrichment of the high-z IGM (Oppenheimer & Dave 2006)

Mass Loading & Scaling Relations

Constant Wind Velocity

These models assume that both the wind velocity v_w and the mass loading η are constant, independent of halo mass.

The rationale of this model is that galactic winds arise due to **local** physics associated with **SN**. Locality is assumed to imply no scaling with global potential.

Example: the SPH code Gadget-2 (Springel & Hernquist 2003)

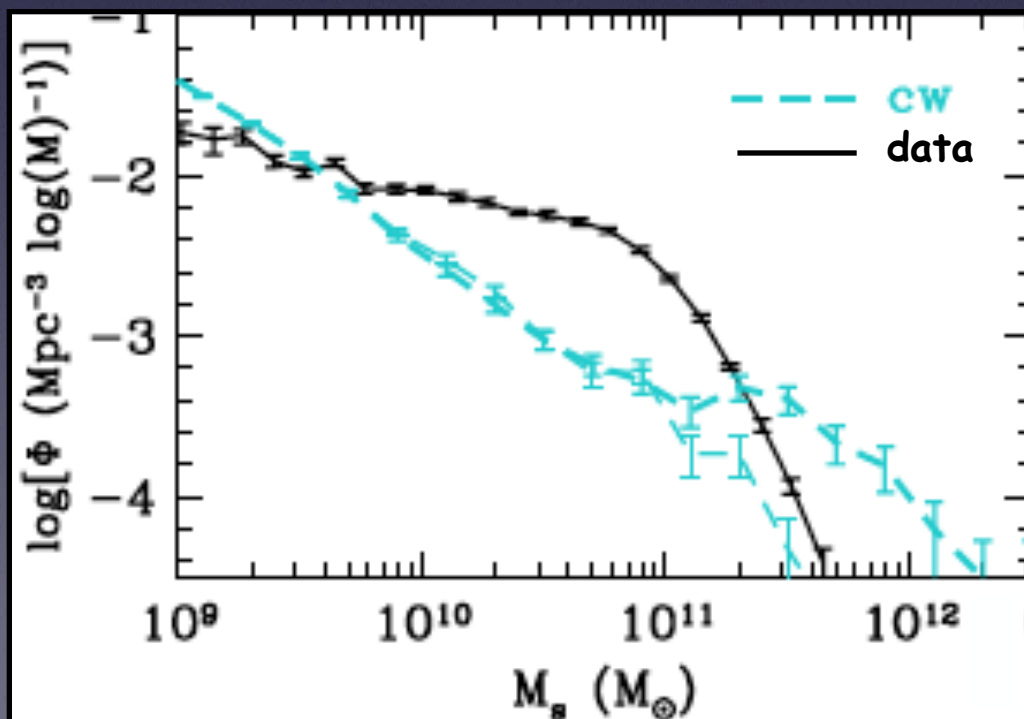
$$v_w = 484 \text{ km/s}$$

$$\eta = 2$$

energy conservation

$$\varepsilon_{\text{SN}} \simeq 0.5$$

i.e., in this particular wind model ~50% of **SN energy** is tapped to drive wind



As shown by Oppenheimer et al. (2010), this wind model fails extremely poorly in reproducing the stellar mass function at the low mass end (much too steep). This demonstrates that, as eluded to above, **mass loading** needs to increase with decreasing halo mass...

Mass Loading & Scaling Relations

Power-Law Wind Models

Lacking a proper theory for how **SN feedback** operates, several authors have used this 'freedom' to adopt a more flexible scaling relation. In particular, several **SAMs** model **SN feedback** using a wind model with

$$\eta = \eta_0 \left(\frac{V_{\text{vir}}}{200 \text{ km/s}} \right)^{-\alpha_{\text{fb}}}$$

and treat both η_0 and α_{fb} as free parameters.

Examples are the **SAM** of Cole et al. (1994), who adopt $\alpha_{\text{fb}} = 5.5$, and the more recent **SAM** of Guo et al. (2011), who adopt $\alpha_{\text{fb}} = 3.5$. For comparison, momentum and energy-driven winds have $\alpha_{\text{fb}} = 1.0$ and 2.0 , respectively.

These large values of α_{fb} are typically required to obtain a good match to the luminosity (or stellar mass) function at the faint end...

NOTE: SAMs adopt different strategies for treating galactic winds:

retention/reheating: wind material is added to hot gas in the halo

(r)ejection: wind material is removed from halo altogether

SN feedback in simulations

In numerical (hydrodynamical) simulations of galaxy formation, the two most often used approaches to modelling SN feedback are:

Thermal Feedback

a fraction $\varepsilon_{\text{SN}} \leq 1$ of the SN energy is given to neighboring gas particles in the form of thermal energy.

Problem: gas in star forming region is dense, causing rapid cooling. Consequently, most SN energy is rapidly radiated away, before it has a chance to do much...

Solution: turn off radiative cooling for receptor particles for some time interval Δt , to allow thermal pressure to disperse gas to lower densities...

Kinetic Feedback

a fraction $\varepsilon_{\text{SN}} \leq 1$ of the SN energy is given to neighboring gas particles in the form of kinetic energy. Wind velocity has to be put in by hand...

Problem: gas in star forming region is dense, preventing gas from escaping to large distances...

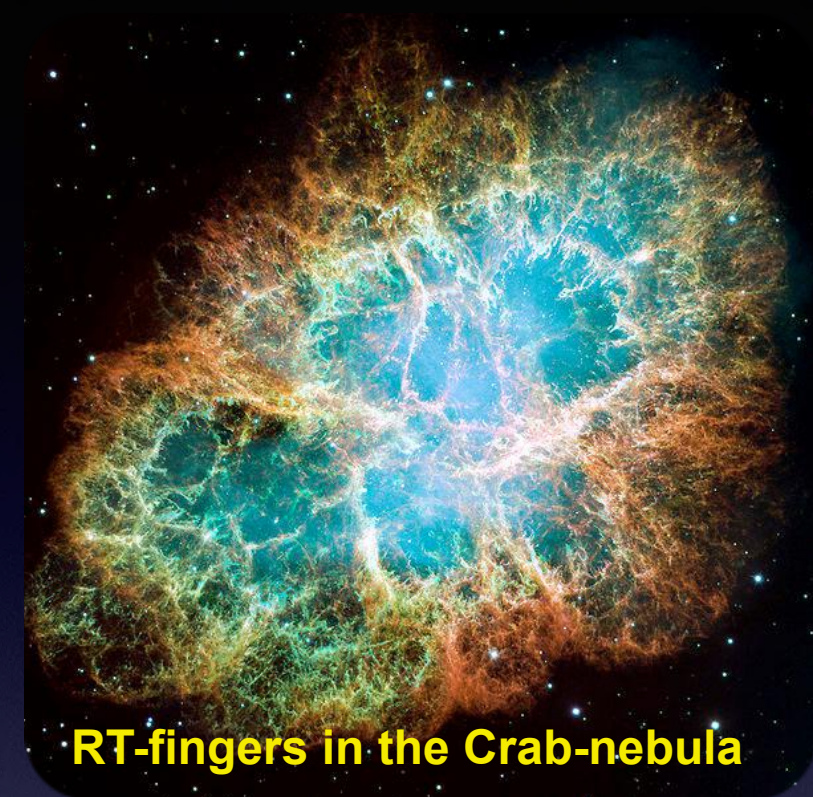
Solution: turn off hydrodynamics for receptor particles for some time interval Δt , to allow kinematic motion to disperse gas to lower densities...

Rayleigh-Taylor Instability

Realistic winds are subject to **Rayleigh-Taylor (RT) instability**:

This instability arises when lower density gas pushes higher density gas, i.e., when a hot 'bubble' tries to disperse a shell of dense (cold) material: **RT 'fingers'** appear, ultimately allowing the hot gas to escape. This depressurizes the bubble, stalling the cold shell...

If galactic winds consist of hot bubbles pushing shells of cold material outwards, mass loading efficiencies are naturally restricted to $\eta \lesssim 1$



RT-fingers in the Crab-nebula

[see Mac-Low & Ferrara (1999) for a more detailed discussion]

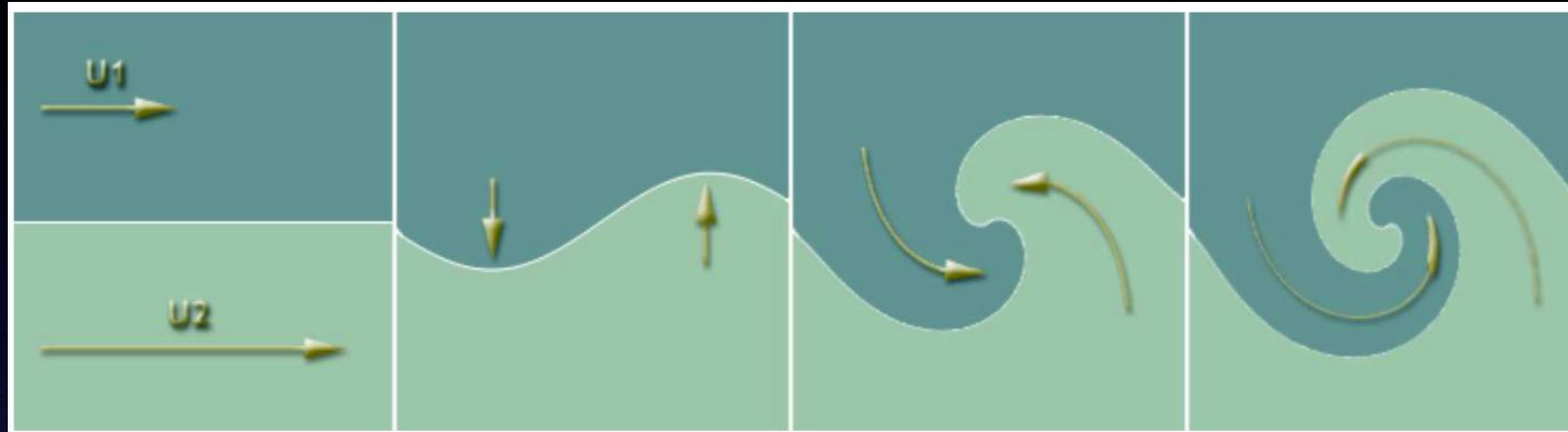


Although, as we will see, realistic galactic winds most likely have a different morphology, be aware that **Lagrangian**, particle-based codes such as **SPH** often lack ability to properly model **RT instabilities**....

Consequently, they are likely to overestimate **mass loading** efficiencies.

Kelvin-Helmholtz Instability & Cloud Crushing

Two fluids with different densities moving past each other are subject to the **Kelvin-Helmholtz (KH) instability**



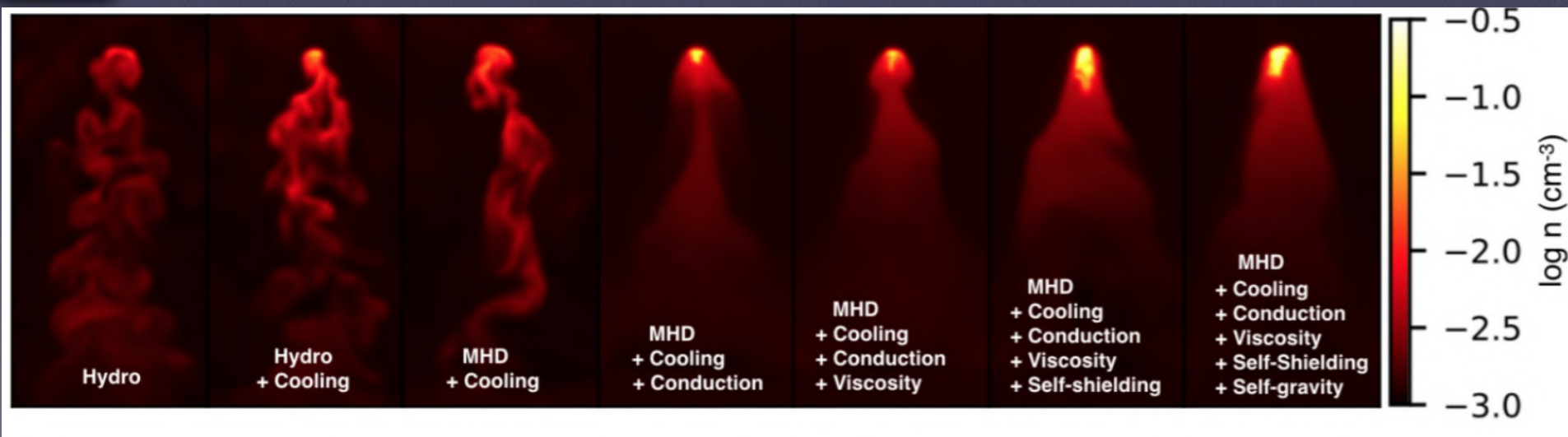
KH instability in Jupiter's atmosphere



KH instabilities occur when a galactic winds blows past a cold cloud. Without cooling & magnetic fields the clouds will disrupt in roughly one cloud sound crossing time (**cloud crushing problem**).

You can't lift cold gas with hot wind, but you can destroy cold clouds, and entrail & mix the cold gas in the hot wind. Recent work, though, suggest that with cooling and/or magnetic fields, clouds can be accelerated by winds.....

[see Gronke & Oh (2018) for a more detailed discussion]



<https://www.youtube.com/watch?v=ejCzlwIT--w>

Blastwaves



To consider the impact of a **SN**, consider the simplest case of a single **SN** going off (with spherical symmetry) in a **uniform** medium with hydrogen number density **n_H** and temperature **T** .

The light emitted by a **SN** is spectacular, but at **$\sim 10^{49}$ erg**, it is negligible compared to the **kinetic energy** in its ejecta, which is **$\sim 10^{51}$ erg**. This is the energy we want to tap for our feedback...In what follows we write **$E_{\text{SN}} = 10^{51} E_{51}$ erg**

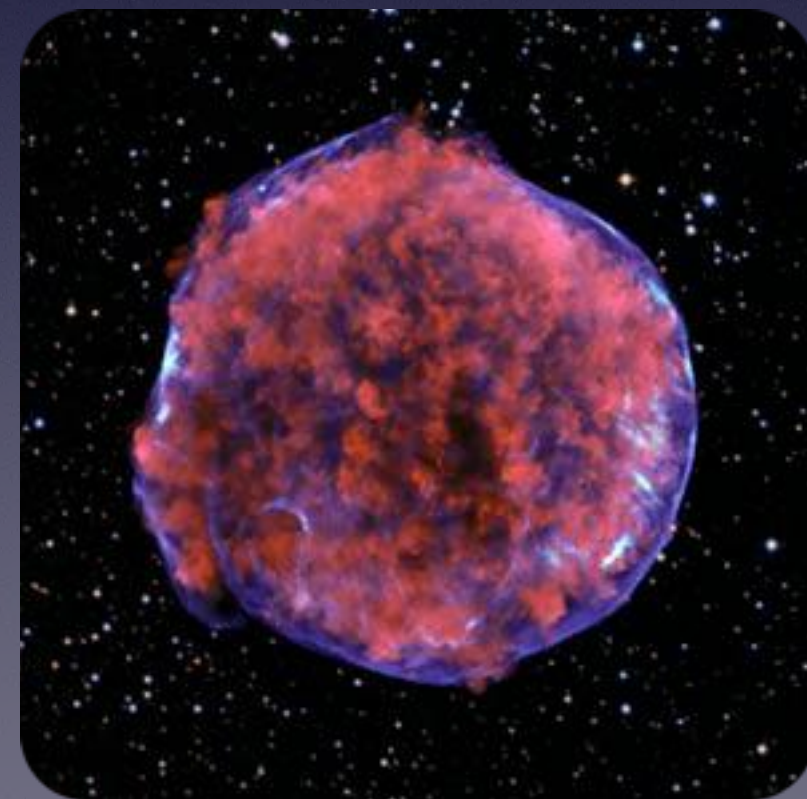
Depending on type of SN, the ejecta mass ranges from **$\sim 1.4 M_\odot$** (type Ia) to **$\sim 10\text{-}20 M_\odot$** (type II). The RMS velocity of ejecta is

$$\langle v_{\text{ej}} \rangle = \left(\frac{2 E_{\text{SN}}}{M_{\text{ej}}} \right)^{1/2} \simeq 10^4 \text{ km/s} \left(\frac{M_{\text{ej}}}{M_\odot} \right)^{-1/2}$$

This is much larger than the sound speed in the surrounding medium, which is of the order **$c_s \sim 0.2$ km/s** for the dense, **cold** medium (**$T=10$ K**) to **~ 6 km/s** for the **warm** medium (**$T = 10^4$ K**)



The SN will drive a fast shock into the ISM = blastwave



Blastwaves

Evolution of SN blastwave consists of 4 well-defined stages:

- free expansion phase
- adiabatic or Sedov-Taylor phase
- radiative stage
- momentum or snowplow phase



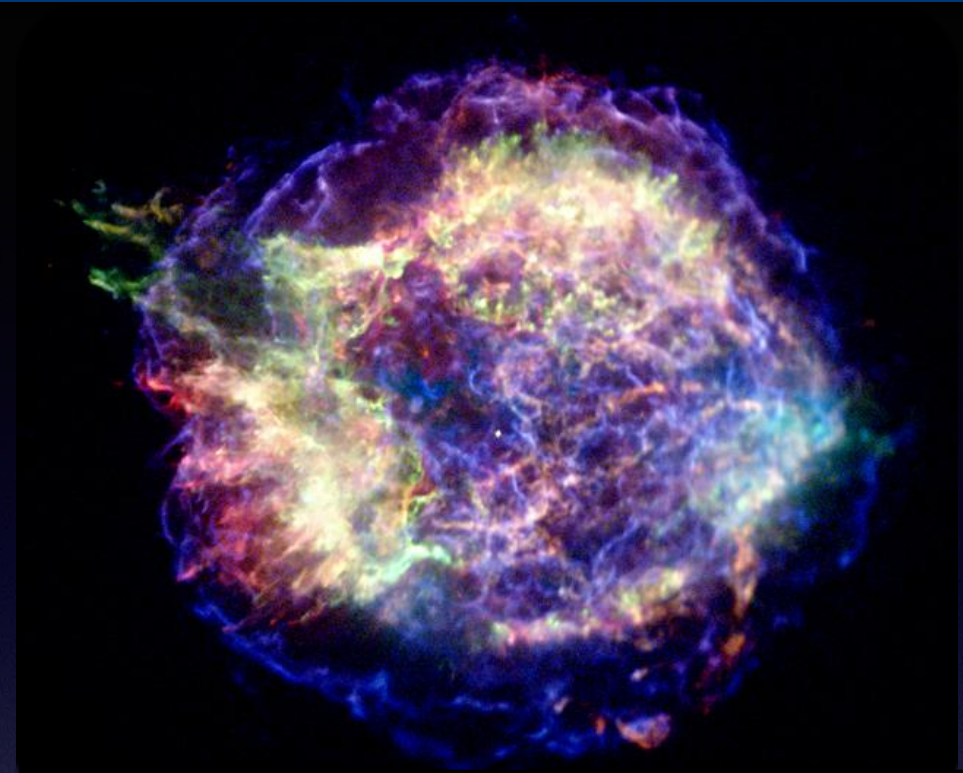
We now briefly describe these phases in turn:

The Free Expansion Phase

Immediately after explosion, the gas swept up by shock is still smaller than mass of ejecta. At this stage, remnant is in free (ballistic) expansion with constant velocity...

Free expansion terminates when $M_{\text{sh}} \equiv \frac{4\pi}{3} r_{\text{sh}}^3 \rho = M_{\text{ej}}$ which happens when

$$t_f \approx 189 \text{ yr} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{5/6} \left(\frac{n_{\text{H}}}{\text{cm}^{-3}} \right)^{-1/3} E_{51}$$
$$r_{\text{sh}} \approx 1.9 \text{ pc} \left(\frac{M_{\text{ej}}}{M_{\odot}} \right)^{1/3} \left(\frac{n_{\text{H}}}{\text{cm}^{-3}} \right)^{-1/3}$$

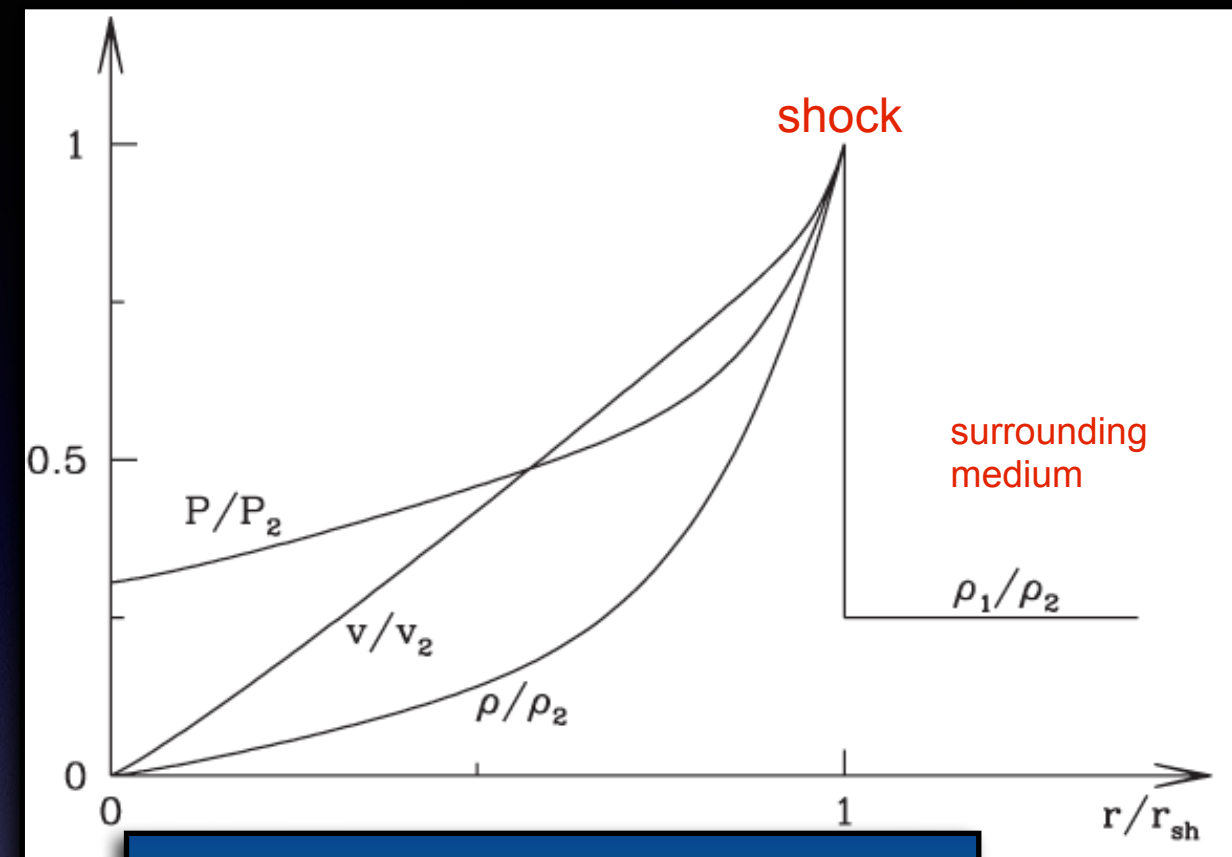


Cas A: Remnant of SN that exploded ~1689 and is still in free expansion phase

Blastwaves

The Sedov-Taylor Phase

As long as radiative losses can be neglected, the next stage of blastwave explosion is **adiabatic expansion**. During this phase the evolution is described by a **similarity solution** that is entirely set by the energy of the explosion and the density of surrounding medium (see MBW §8.6.1 for details)



Self-similar blastwave solution during the adiabatic Sedov-Taylor phase

$$r_{sh} \approx 32 \text{ pc } E_{51}^{1/5} \left(\frac{n_H}{\text{cm}^{-3}} \right)^{-1/5} \left(\frac{t}{10^5 \text{ yr}} \right)^{2/5}$$
$$v_{sh} \approx 124 \text{ km/s } E_{51}^{1/5} \left(\frac{n_H}{\text{cm}^{-3}} \right)^{-1/5} \left(\frac{t}{10^5 \text{ yr}} \right)^{-3/5}$$

This similarity solution was found independently by Taylor (1950) and Sedov (1959) in connection with the development of nuclear weapons...

Blastwaves

The Radiative Phase

The shocked material is heated to high temperatures. Directly behind the shock $T_s = \frac{3}{16} \frac{\mu m_p}{k_B} v_{sh}^2$, and the temperature increases towards the center. This hot material cools radiatively. Once the radiative losses become of order 20-30% of explosion energy, the blastwave enters the radiative phase....

This happens roughly when

$$\begin{aligned} t_{\text{rad}} &\approx 4.3 \times 10^4 \text{ yr } E_{51}^{0.22} \left(\frac{n_H}{\text{cm}^{-3}} \right)^{-0.56} \\ r_{\text{sh}}(t_{\text{rad}}) &\approx 23 \text{ pc } E_{51}^{0.29} \left(\frac{n_H}{\text{cm}^{-3}} \right)^{-0.42} \\ v_{\text{sh}}(t_{\text{rad}}) &\approx 200 \text{ km/s } E_{51}^{0.07} \left(\frac{n_H}{\text{cm}^{-3}} \right)^{0.13} \end{aligned}$$

Since density is highest just behind shock, cooling is most efficient there. The blastwave leaves Taylor-Sedov phase and enters the snowplow phase, with a dense shell of cool gas enclosing a hot central volume where cooling is important. The name 'snowplow' refers to fact that the dense shell 'sweeps up' the ambient gas...

Blastwaves

The Snowplow Phase

Initially the shell is pushed forward by the **pressure** of the hot gas behind the shock. However, **cooling** continues to a point where the interior pressure becomes negligible.

From that point on, the ambient gas is swept up by the **inertia** of the moving shell.



The evolution is now governed by momentum conservation: $M_{\text{sh}} v_{\text{sh}} = \text{constant}$

The '**snowplow**' phase continues until $v_{\text{sh}} \sim c_s$, i.e., the shock speed becomes comparable to the **sound speed** of the surrounding medium. At this point the shock wave turns into a sound wave, and the blastwave '**fades away**'. This signals the end of the blastwave...

The kinetic energy of the shell is now transferred to the **ISM**. Detailed calculations show that the kinetic energy at fading is **~ 0.01** of the initial explosion energy



In this scenario $\varepsilon_{\text{SN}} \sim 0.01$; almost all **SN energy** is radiated away...



Towards Higher Efficiency: Overlapping SNR

In order to make **SN feedback** more efficient, one needs to ensure that another **SN** goes off inside the **SNR** before it has radiated away most of its energy.



This requires a SN rate

$$\zeta \dot{\rho}_* \geq \frac{3}{4\pi R_{\text{SN}}^3 t_{\text{SN}}}$$

If we set R_{SN} and t_{SN} to be the shock radius and time at the onset of the radiative phase, i.e., $t_{\text{SN}} = t_{\text{rad}}$ and $R_{\text{SN}} = r_{\text{sh}}(t_{\text{rad}})$, and we write $\dot{\Sigma}_* = \dot{\rho}_*/2H$ with H the scale-height of the disk, then we obtain

$$\dot{\Sigma}_* > 18.3 M_{\odot} \text{kpc}^{-2} \text{yr}^{-1} \left(\frac{H}{0.2 \text{kpc}} \right) \left(\frac{\zeta}{10^{-2} M_{\odot}^{-1}} \right)^{-1} \left(\frac{n_{\text{H}}}{\text{cm}^{-3}} \right)^{1.82}$$

Such a high **SFR** is indicative of a **starburst galaxy**. However, those systems typically have most of their gas in dense, molecular form with $n_{\text{H}} \sim 100 \text{ cm}^{-3}$. For **SNR** to overlap in such high densities requires even higher **SFRs** with $\dot{\Sigma}_* > 4.4 \times 10^3 M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$ which is too extreme, even for a **starburst galaxy**...

Towards Higher Efficiency: Overlapping SNR

However, if we can arrange for the SN to go off in a hot, low density medium ($T \sim 10^6 \text{K}$, $n_{\text{H}} \sim 10^{-2} \text{cm}^{-3}$) then we only require a SFR of

$$\dot{\Sigma}_* > 4.2 \times 10^{-3} M_{\odot} \text{kpc}^{-2} \text{yr}^{-1}$$



According to Kennicutt-Schmidt law, this requires $\Sigma_{\text{gas}} > 7 M_{\odot} \text{pc}^{-2}$ which is of order the star formation threshold density....



SN feedback can be an efficient feedback mechanism, with $\epsilon_{\text{SN}} \simeq 1$ as long as most of the volume of the ISM is in the hot phase ($T \sim 10^6 \text{K}$, $n_{\text{H}} \sim 10^{-2} \text{cm}^{-3}$).



NOTE: in this picture, SN feedback heats the ISM, maintaining it in a hot phase. If the temperature of this phase exceeds the virial temperature of the halo, the pressure of the gas will drive itself out of the halo (\sim outflow). If $T < T_{\text{vir}}$, the main impact of SN feedback is to reheat the gas, thereby regulating the star formation efficiency...

The Three-Phase Medium of the ISM

Developed by **McKee & Ostriker** in 1977, according to this model the ISM consists of 3 phases, with most of the volume in the hot phase, which is maintained & pressurized by **SN**....



Chris McKee



Jerry Ostriker

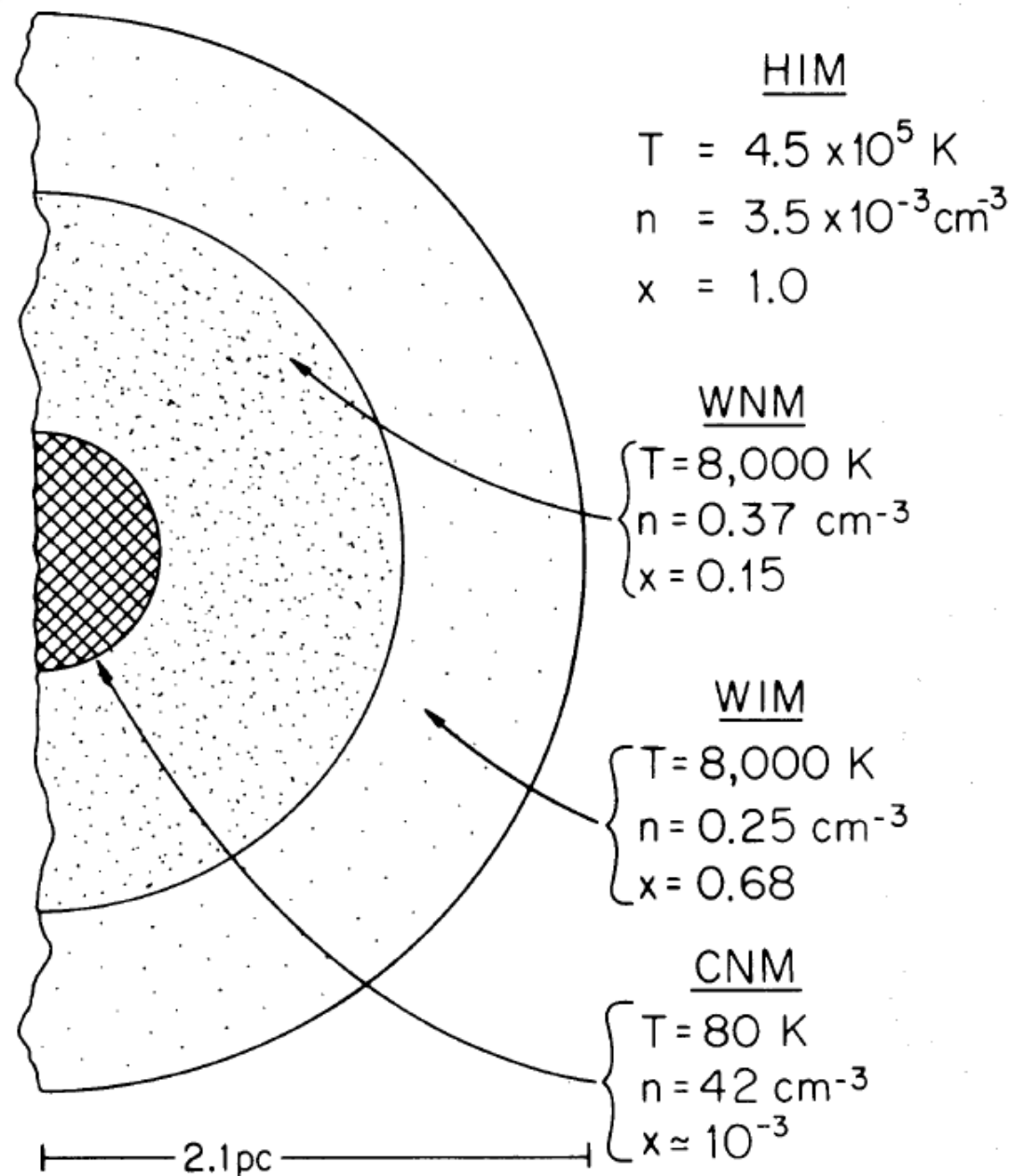
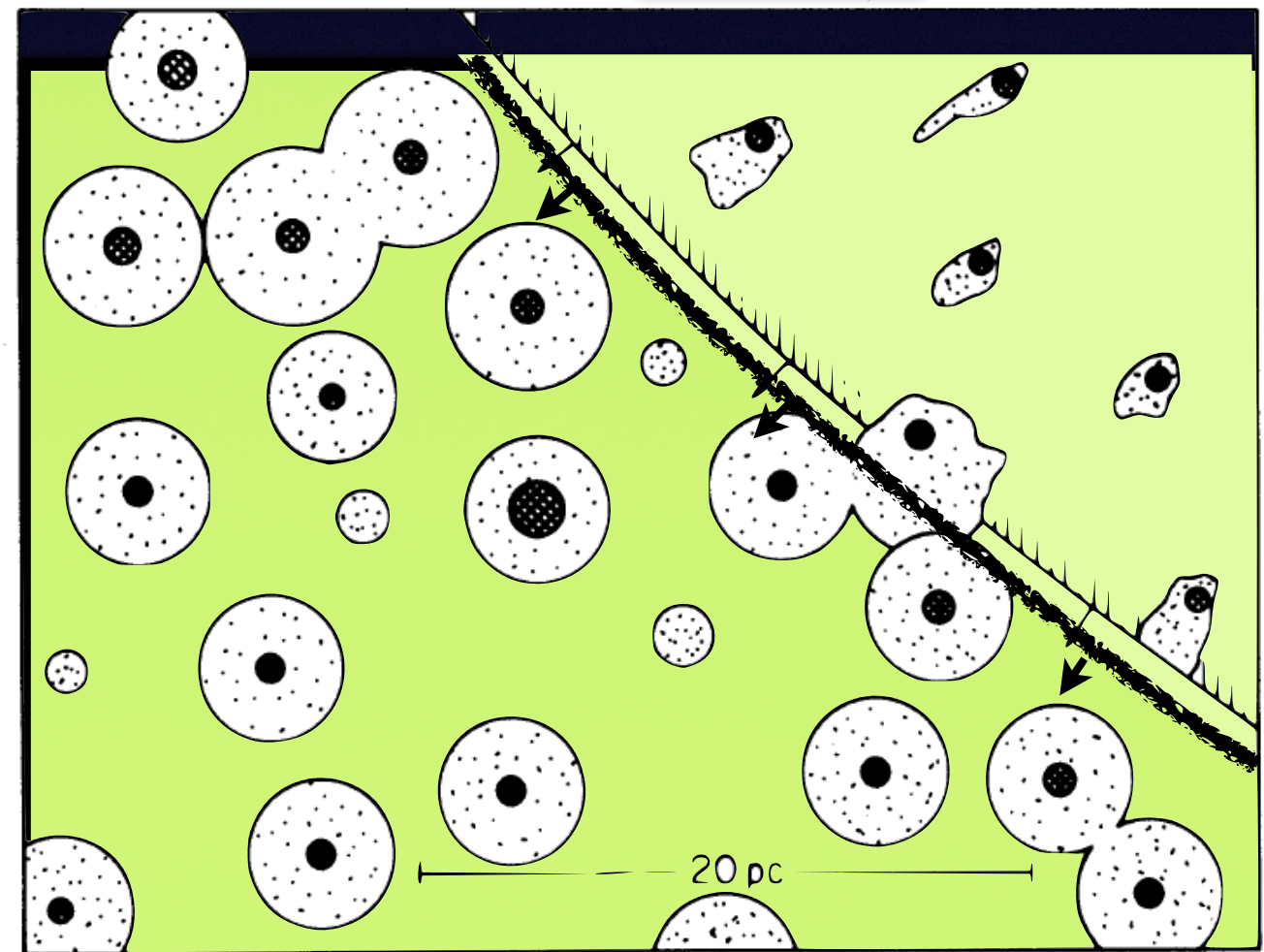


FIG. 1



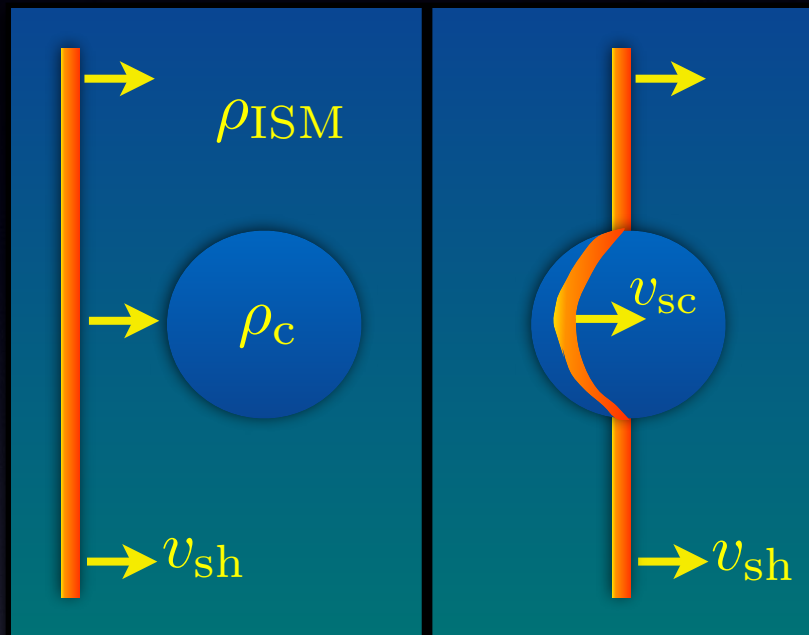
A CLOSE UP VIEW

FIG. 2

Source: McKee & Ostriker, 1977, ApJ, 218, 148

Blast Waves in Inhomogeneous Medium

In our treatment of blastwaves, we assumed they explode within a **homogeneous** medium. In reality, the medium will be highly **inhomogeneous**. What happens when the blastwave shockfront runs over a dense cloud of gas?



clouds can be shredded or evaporated, adding mass to wind. The material that remains as a dense, bound clump is accelerated to wind velocity due to shock and ram pressure...

- when shock 'hits' cloud, it sets off shock wave within cloud with velocity $v_{sc} \approx \sqrt{\rho_{ICM}/\rho_c} v_{sh}$
 - ➡ Mach number of shock same in ICM as in cloud..
- shock passing through cloud will set cloud in motion
- velocity gradients in cloud (induced by shock) may 'shred' cloud if its self-gravity or magnetic field is too small
- after blastwave has passed cloud is engulfed in hot gas
- thermal conduction** and **Kelvin-Helmholtz instabilities** due to hot wind can lead to **evaporation** of cloud material, resulting in mass loss from cloud, and mass loading of wind.
- temperature of wind decreases, since thermal energy is now shared by more particles; higher density also promotes cooling

Stellar Winds & Radiation Pressure

But....if the presence of a hot medium requires **SN** overlap, and for **SN** to overlap requires a hot medium, we have ourselves a classical chicken & egg problem...

The solution to this problem requires additional feedback mechanisms. These include **photo-ionization**, **proto-stellar jets**, **stellar winds** (shocks), and **radiation pressure**. The combined effect of these processes is to clear-out SF regions from dense, cold material so that once the SN go off, they do so in a low-density, hot environment...



The **radiation pressure** pushes on **dust**, resulting in a force:

$$F_{\text{rad}} = (1 + \tau_{\text{IR}}) \frac{L}{c}$$

The first factor L/c represents momentum imparted by optical/UV photons absorbed by **dust**, which re-radiates in the IR.

The factor $\tau_{\text{IR}} L/c$ accounts for the momentum imparted by the total number of IR photons absorbed/scattered.

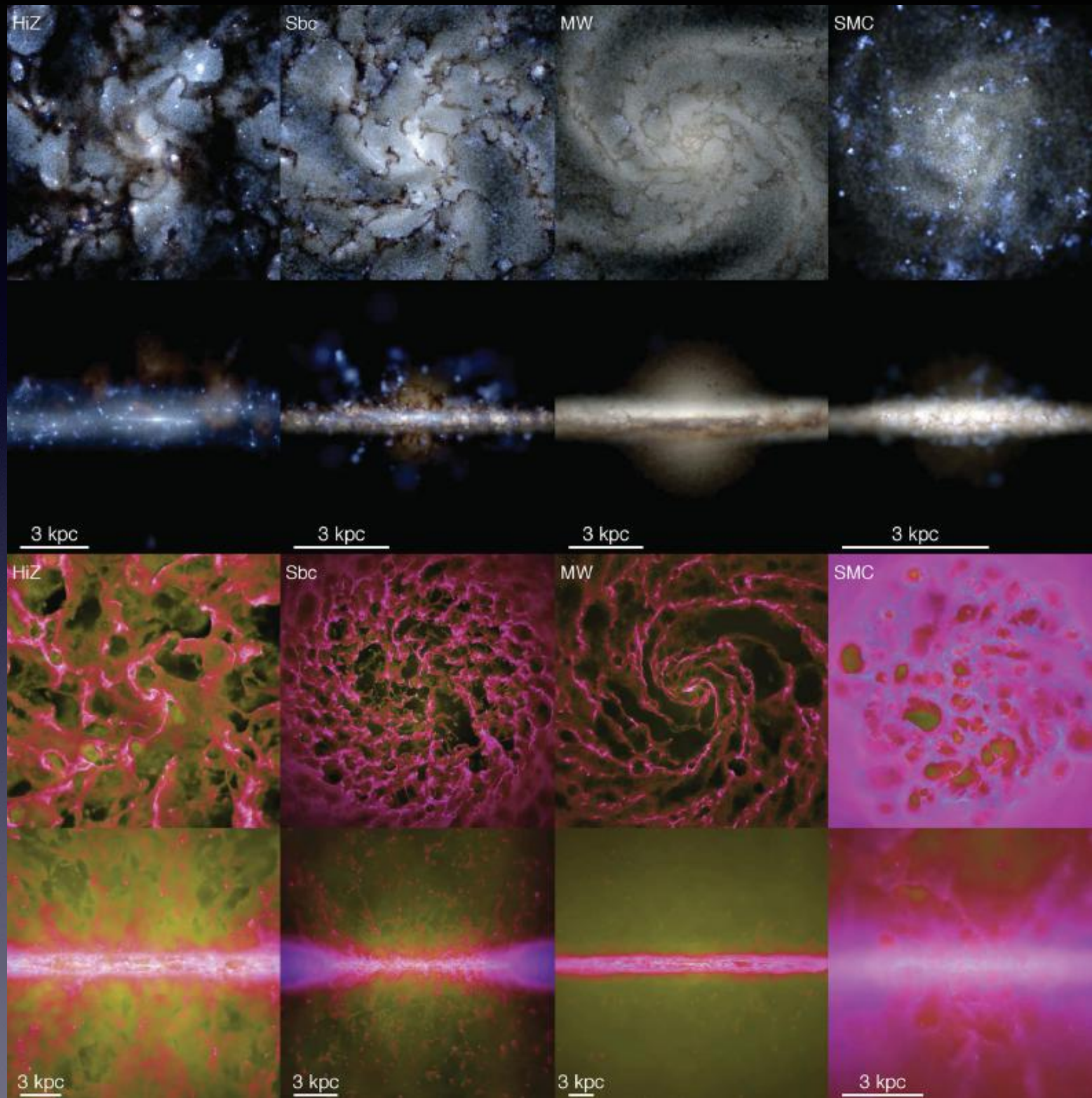
Radiation Pressure at Work



Radiation Pressure at Work



Simulations of Stellar Feedback

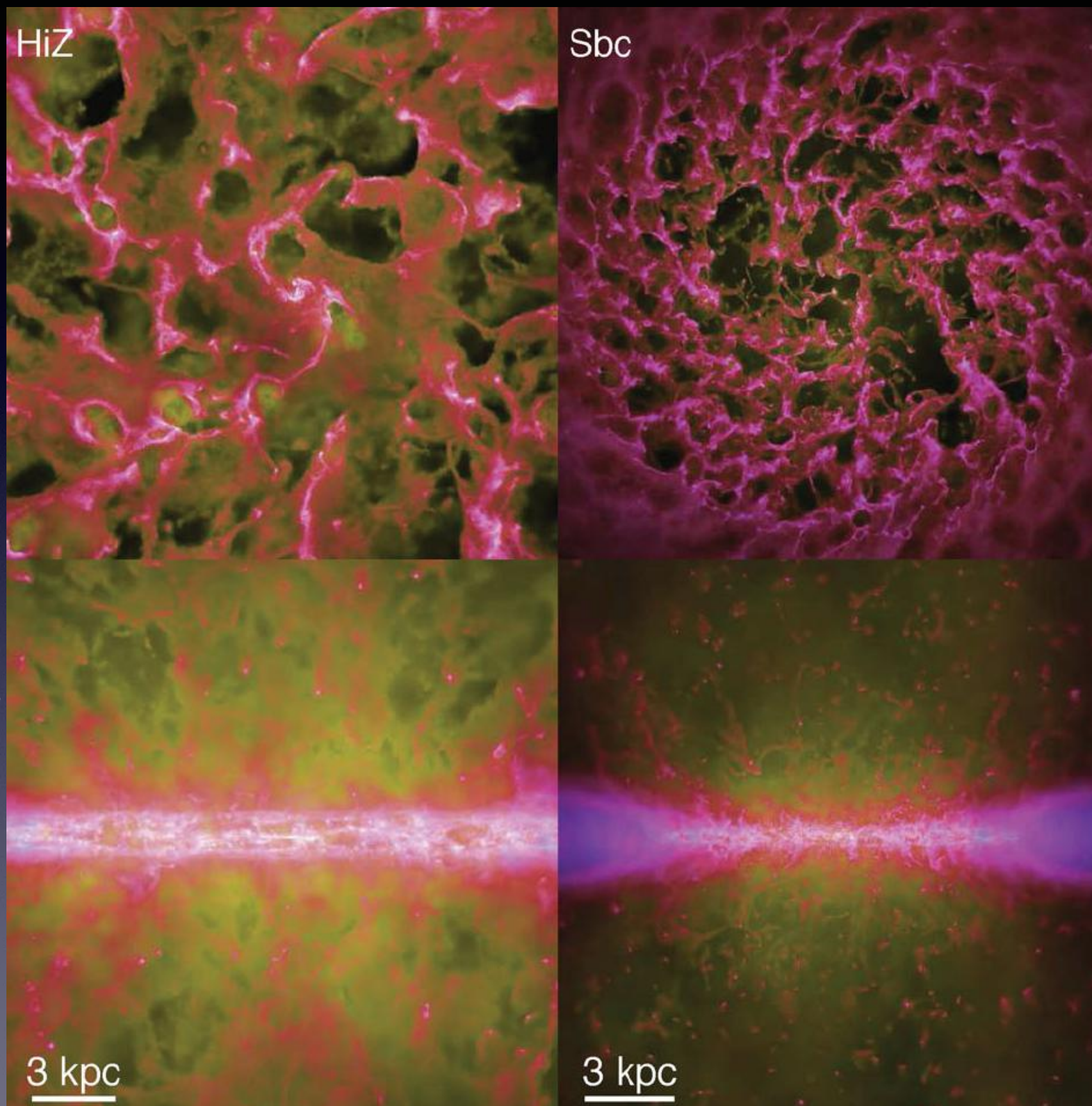


A recent set of simulations by Hopkins, Quataert & Murray (2012) shows that including **radiation pressure** and other stellar feedback processes, in addition to **SN feedback**, are crucial for obtaining successful galactic winds.

Figure shows results for four different systems: a high-z starburst galaxy, a bursting Sbc galaxy, a MW-like analog and a SMC-like analog.

Upper two rows show mock ugr composite image of stars + dust. **Bottom two rows** show gas; pink and yellow colors indicate warm (10^4 - 10^5 K) and hot ($>10^6$ K) gas, respectively.

Starburst Mode

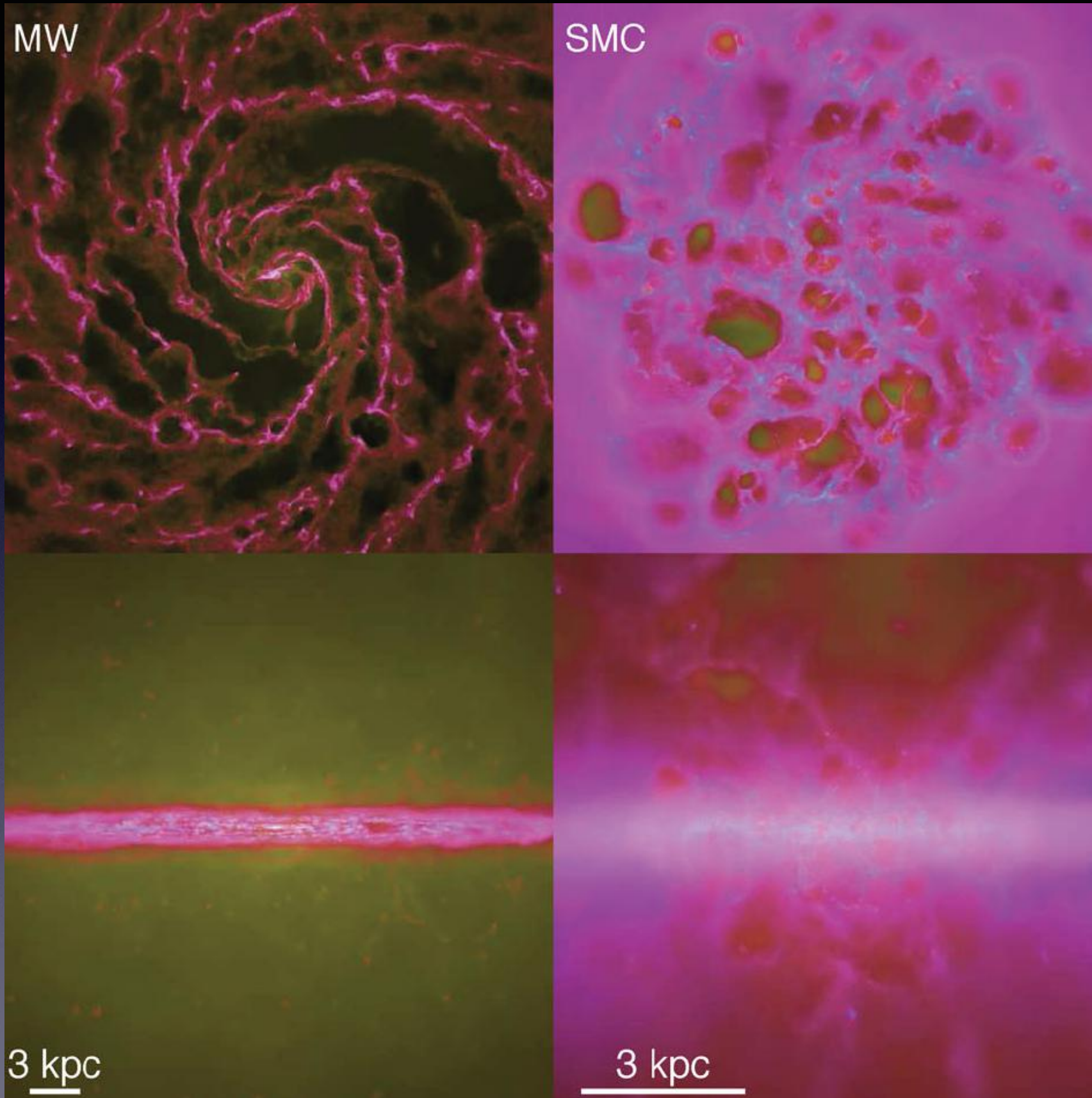


Note how most of volume is occupied by hot gas bubbles resulting from **SN explosions**. ISM is clearly multi-phase & turbulent...

Most of the mass is in cold-phase (in form of **GMCS**) which occupy tiny volume, and are therefore barely visible...

Note how hot gas, heated by **SN**, is **vented** out of disk, pushing warm gas with it, resulting in **galactic outflow**. Most of the mass (volume) of wind is in warm/cold (hot) phase. The warm/cold gas in wind is mainly accelerated by radiation pressure..

Normal Star Formation Mode



In the case of a 'normal' **MW**, the gas morphology more closely follows stars in a global **spiral pattern**. The wind is primarily hot **SN-driven bubbles** venting out, with little cold/warm material


In the case of a **SMC**-analogue dwarf, the disc is thick with irregular star formation and large **bubbles** from overlapping **SNe**. Wind is prominent and contains mix of hot gas and **entrained** cold/warm material in filaments/loops/arcs...

0 Myr

Gas

MW

10 pc

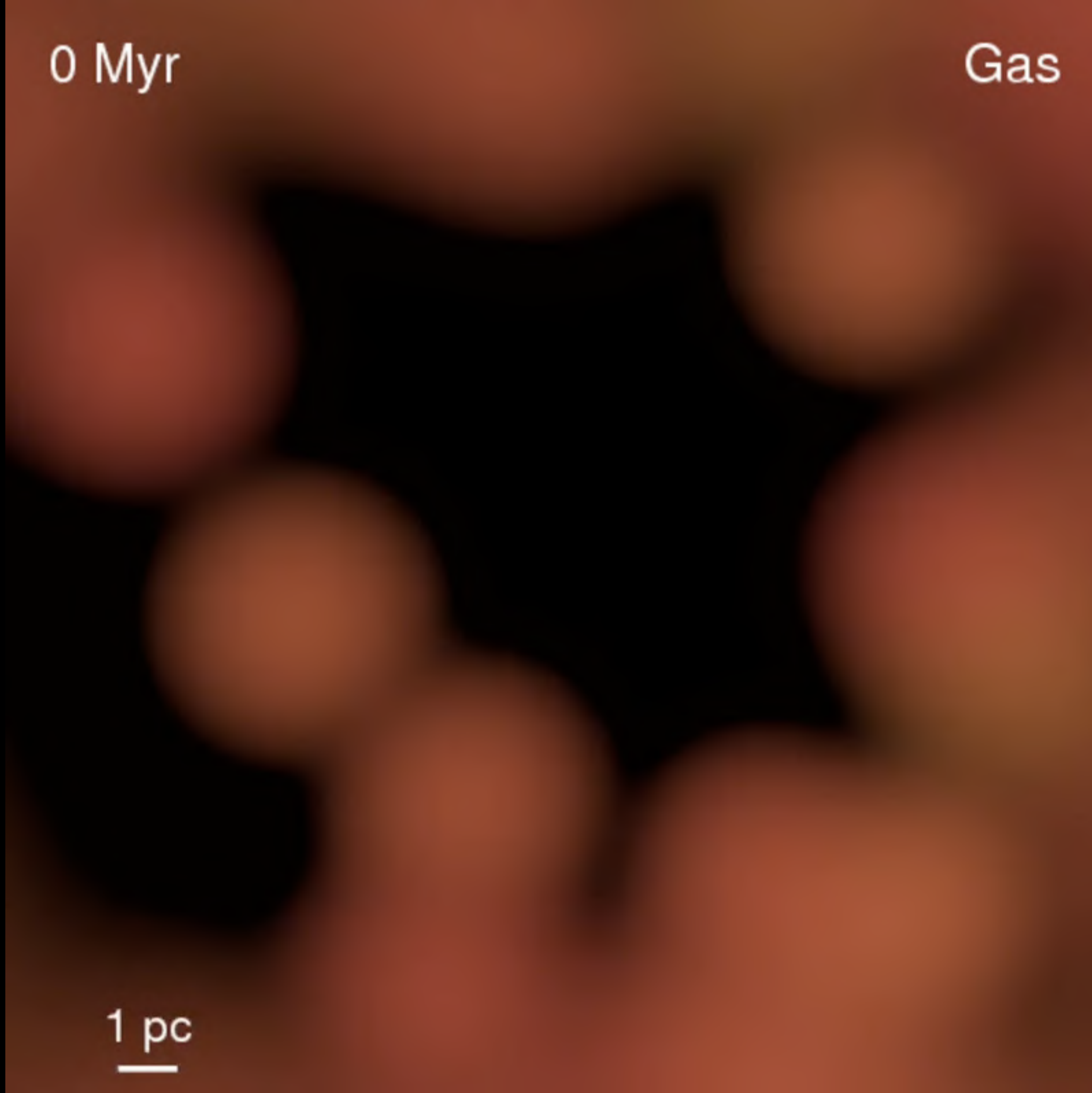


0 Myr

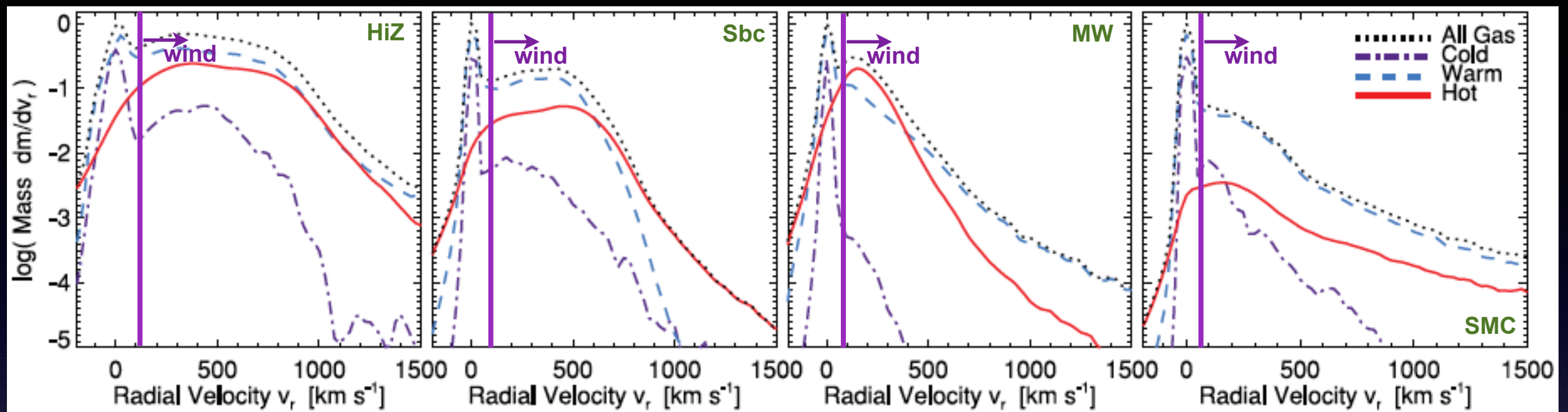
Gas

SMC

1 pc
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The Multi-Phase structure of Winds



Source: Hopkins, Quataert & Murray, 2012, MNRAS, 421, 3522

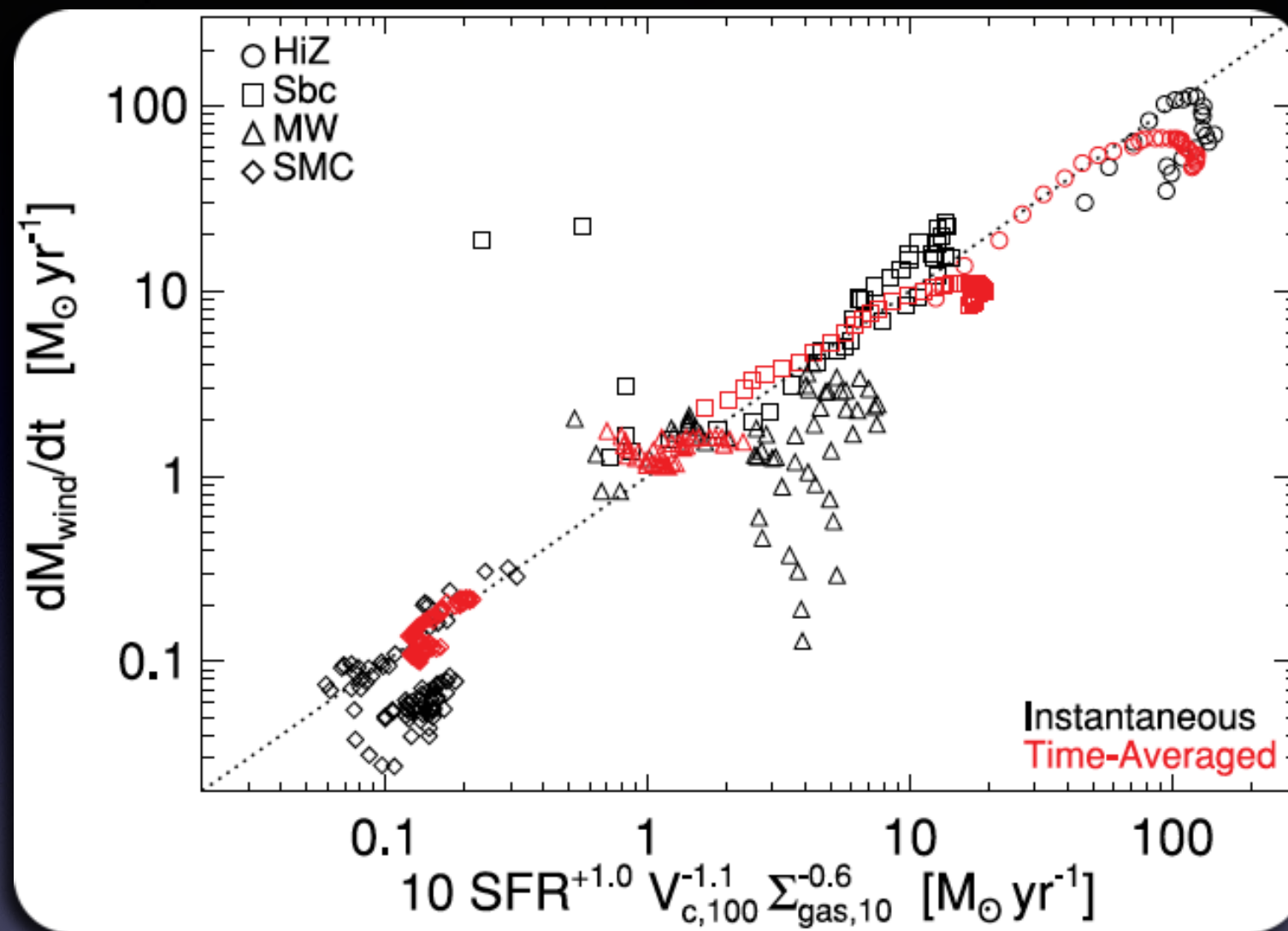
The galactic winds in the Hopkins et al. simulations reach very high velocities. Even cold gas is found with radial velocities that exceeds the escape speed. This is partially cold material that has been accelerated by **blastwave(s) + ram pressure** of hot wind, but also hot material in the wind that is cooling out...

Wind is a mixture of **warm** gas (containing most of the mass) and volume-filling **hot** gas, with a few percent contribution from **cold** gas at all velocities.



Galactic winds themselves are multi-phase structures.

Mass Loading Scaling Relations



Source: Hopkins, Quataert & Murray, 2012, MNRAS, 421, 3522

The winds in the Hopkins et al. simulations have **mass loadings** that scale as

$$\eta \simeq 10 \left(\frac{V_c(R)}{100 \text{ km/s}} \right)^{-1} \left(\frac{\Sigma_{\text{gas}}(R)}{100 M_{\odot} \text{pc}^{-2}} \right)^{-0.5}$$



which is similar to the scaling relations expected for **momentum-driven winds**.

Caveats

Although the simulations by Hopkins et al. look extremely promising, there are a number of caveats to be aware of

- no realistic **boundary conditions** (no external pressure, no infall of new gas)
- **SPH-based**. Doesn't properly account for evaporation, condensation and acceleration of cold clouds (**KH** and **RT** instabilities)
- simulations do not include **metal cooling** (too little cooling)
- no **magnetic fields** or **cosmic rays** have been included
- **radiation pressure** only modeled in crude, approximate way.
In particular, treatment of **T_{IR}** is very uncertain. Hopkins+ assume it can be large, resulting in huge boost, but see Krumholz & Thompson 2012
- implied scaling of **mass loading** with halo mass most likely insufficient to explain faint-end of galaxy luminosity function.

Much work remains....

Summary

- **SN feedback** is essential ingredient of galaxy formation. It helps explain why overall SF efficiency is low, and is invoked to explain why galaxy formation is less efficient in lower mass haloes...
- Unless **SN** go off in hot, low density medium, almost all **SN** energy is radiated away during radiative phase of **blastwave**.
- Efficient **SN feedback** requires three-phase **ISM** envisioned by McKee & Ostriker (1977), with most volume (mass) being in hot (cold) phase.
- **Radiation pressure**, **stellar winds**, and **photo-ionization** seem to be crucial ingredients for paving the way for efficient **SN feedback**.
- Numerical simulations that include wide spectrum of stellar feedback processes yields mass-loading efficiencies that scale similar to **momentum-driven winds**.
- They predict **multi-phase winds**; winds properties depend on **SFR** rate; **radiation pressure** becomes more important in systems with higher **SFRs**.