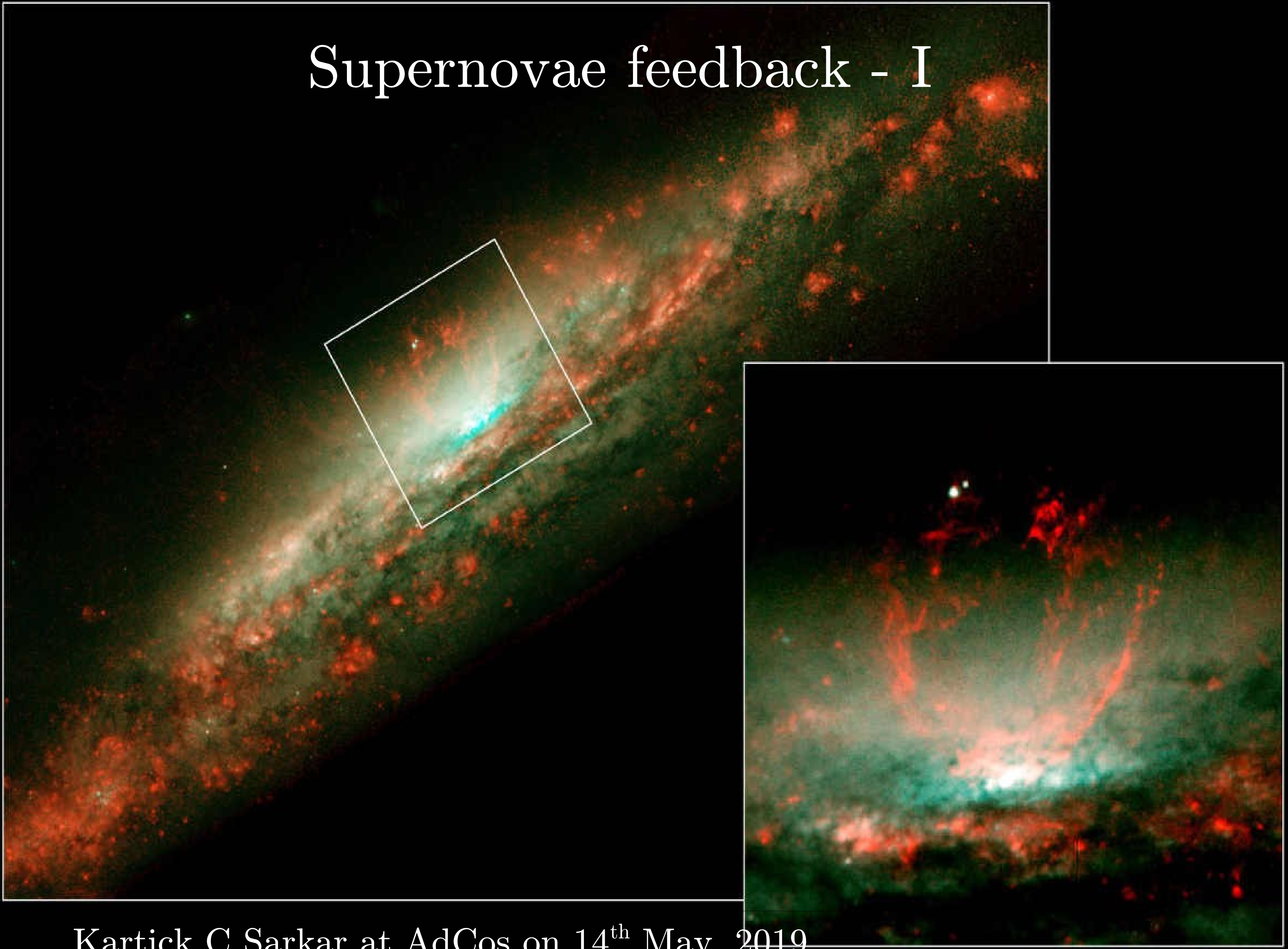
Supernovae feedback - I



Kartick C Sarkar at AdCos on 14th May, 2019

Content

1. What is a supernova?

2. Why do we need them?

3. Single supernova (SN)
   - Expansion in interstellar medium
   - Kennicutt-Schmidt law from SN

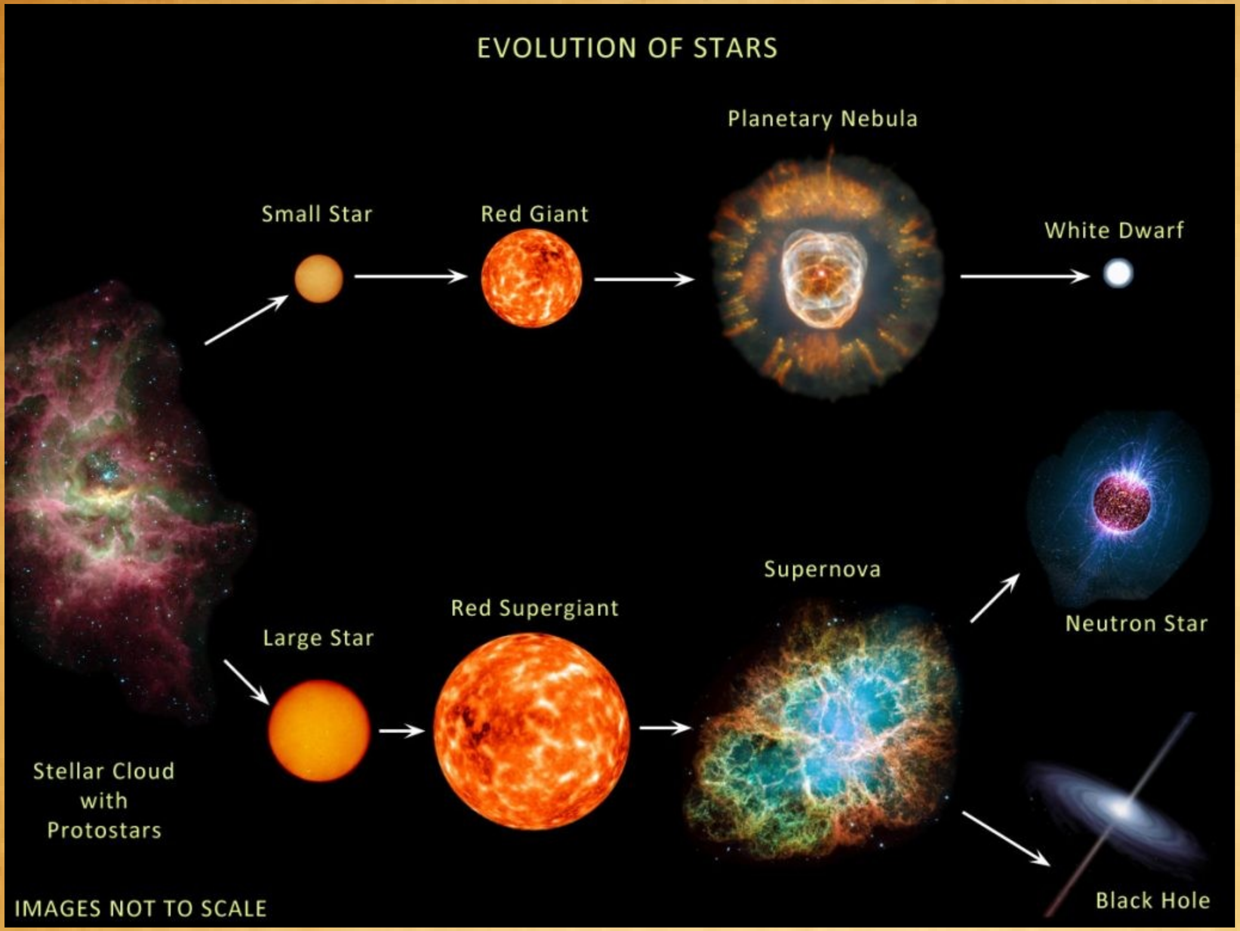
4. Supernovae united: Superbubble

5. Rebellation of supernovae: breaking out

6. A superbubble in our Galaxy

7. Other effects of SNe

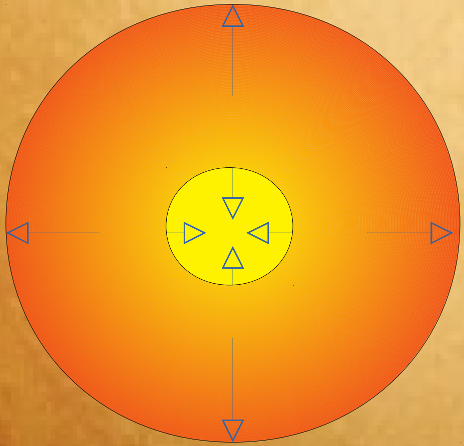
What is a supernova?

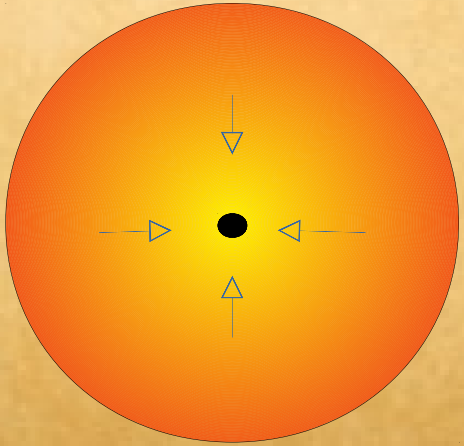


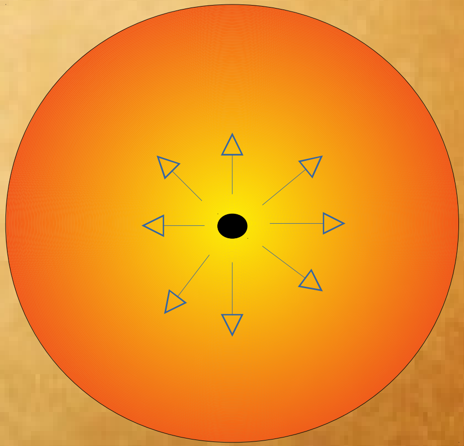
$M < 8\,M_\odot$

$8\,M_\odot < M < 15\,M_\odot$

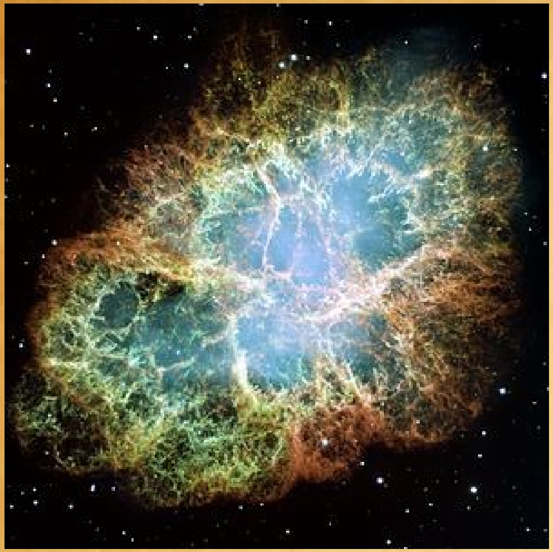
$M > 15\,M_\odot$







What is a supernova?



Crab nebula

G299

W49B

Massive stars burn fast and produce SNe within ~10 Myr

Means, any massive star that we see must be young (< 10 Myr)

Initial Mass function:

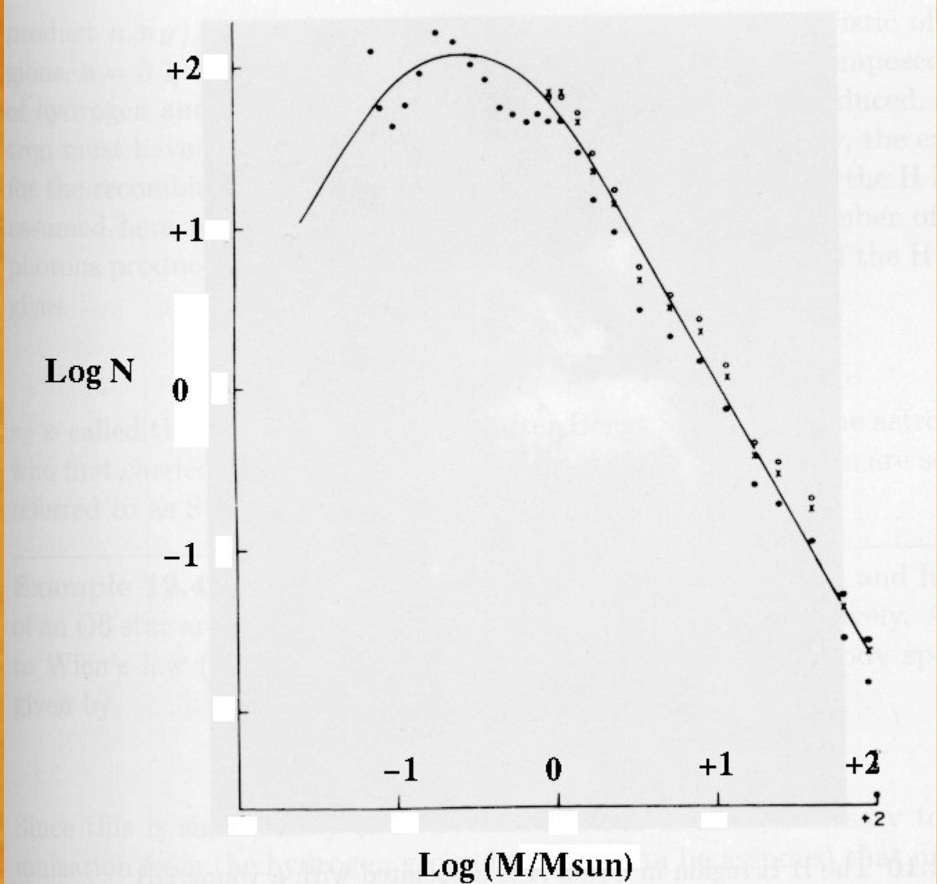


Figure 12.9 The initial mass function, ξ, shows the number of stars per unit area of the Milky Way's disk per unit interval of logarithmic mass that is produced in different mass intervals. Masses are in solar units. (Figure adapted from Rana, *Astron. Astrophys.*, *184*, 104, 1987.)

$$\frac{dN}{dM} \propto M^{-2.3} \quad for \quad M > 1\, M_\odot$$

Number of SNe for a young star cluster

$$N_{sn} = \frac{\int_{8\,M_\odot}^{100\,M_\odot} \frac{dN}{dM}\, dM}{\int_{0.1\,M_\odot}^{100\,M_\odot} M \frac{dN}{dM}\, dM} = \frac{1}{120\, M_\odot}$$

Our galaxy has SN-rate of 1 per century

If there are 10^{10} such galaxies in the Universe then the SN rate is

3 SN/s

Content

1. What is a supernova?

2. Why do we need them?

3. Single supernova (SN)
   - Expansion in interstellar medium
   - Kennicutt-Schmidt law from SN

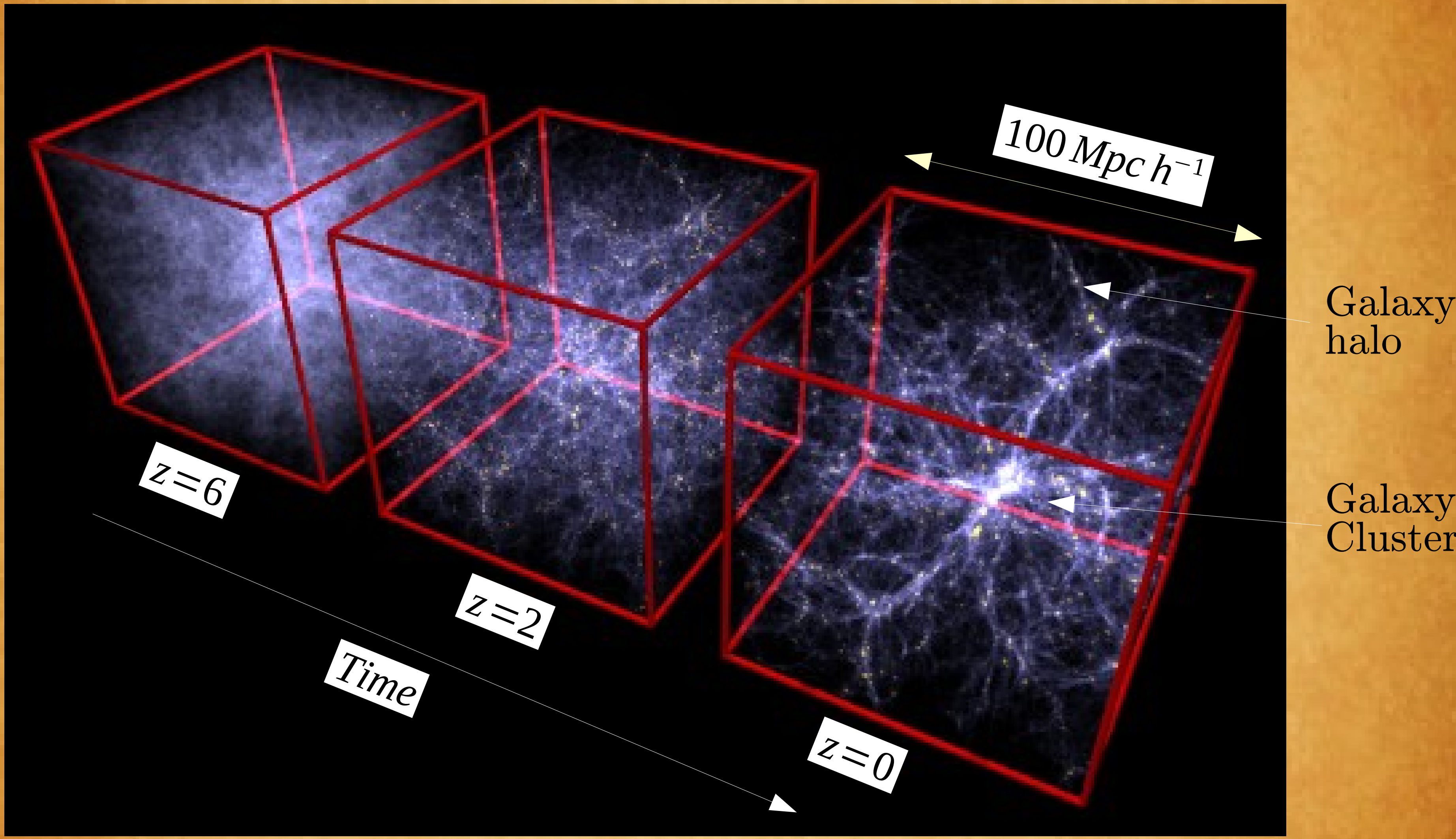
4. Supernovae united: Superbubble

5. Rebellation of supernovae: breaking out

6. A superbubble in our Galaxy

7. Other effects of SNe

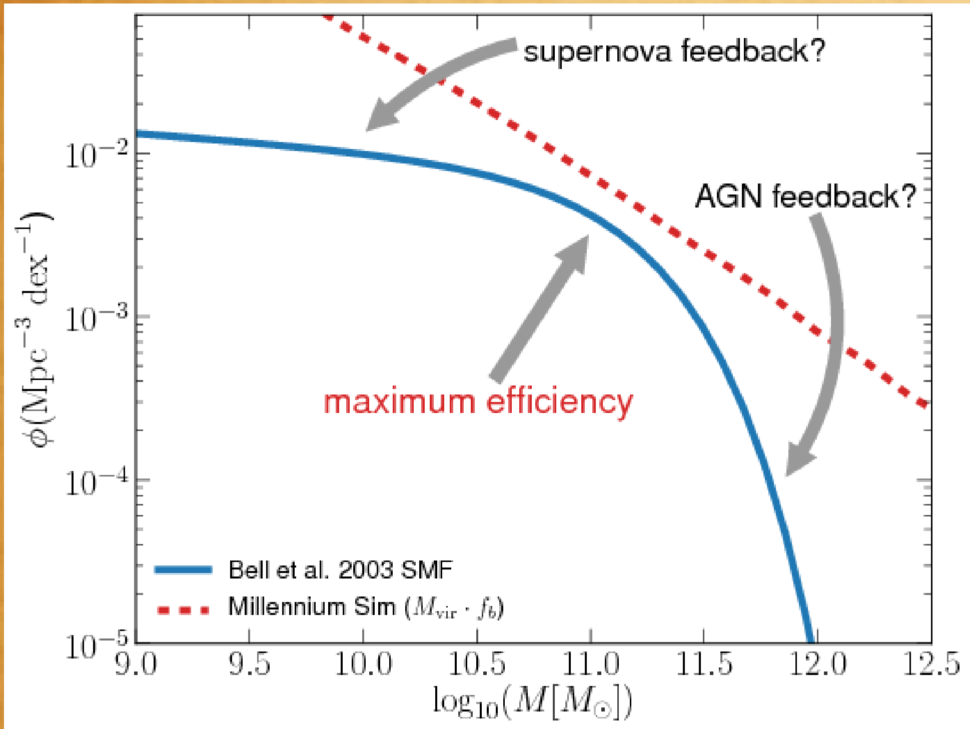
Dark matter only simulation



Millennium simulation team, MPA

Why do we need feedback ?

Number of Galaxies per volume

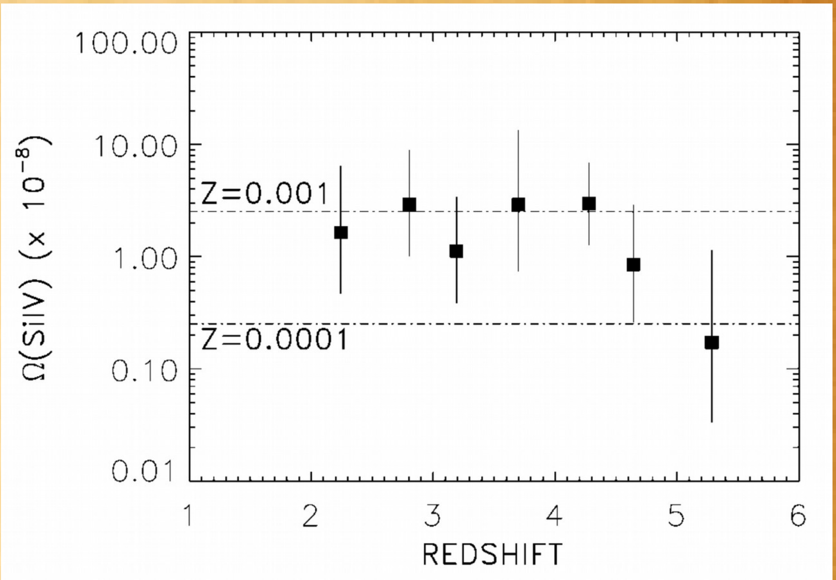


Mutch et. al., (2013)

$$M_* \ vs \ \frac{dn_{gal}}{d \log M_*}$$

Observed stellar mass function vs theoretical prediction: observed star formation efficiency is much smaller than the predicted one from dark matter only simulations

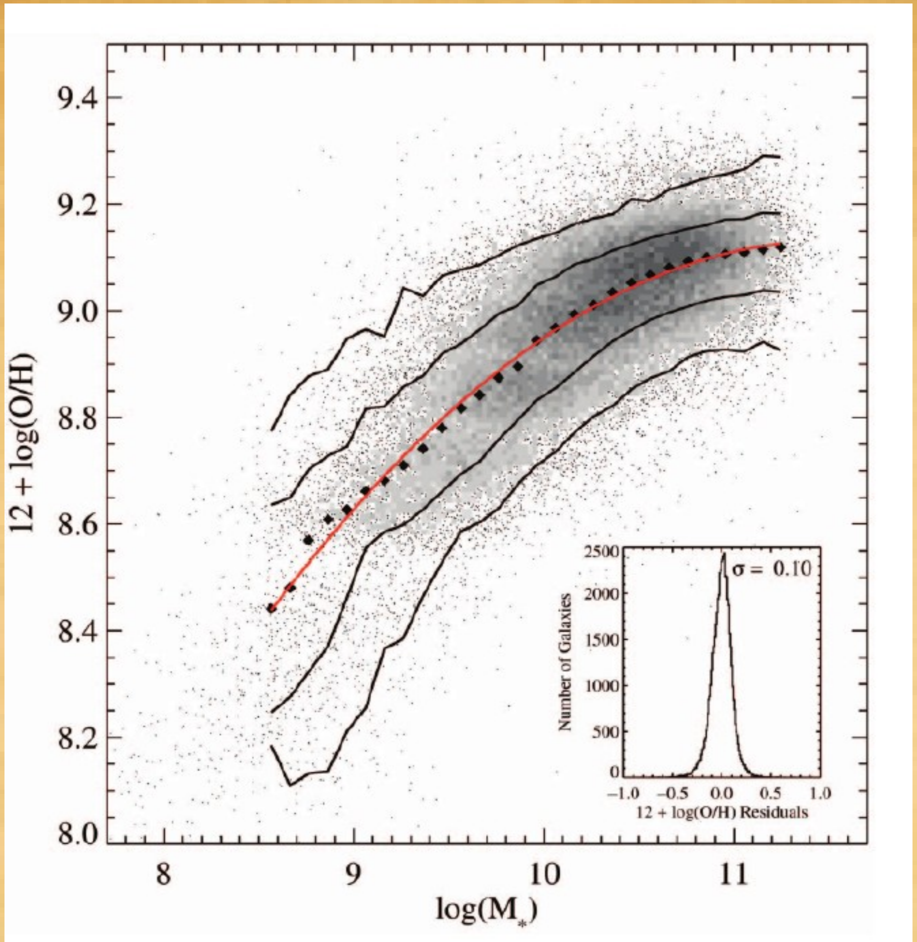
Metallicity



Songaila (2001)

Presence of metals outside galaxies indicate outflow from galaxies

Why do we need feedback ?



Observed gas phase metallicity vs stellar mass of galaxies:
Low mass galaxies loose metals and massive galaxies keep their metals. Signature of some activity at the galaxy that Drives these metals out

Content

1. What is a supernova?

2. Why do we need them?

3. Single supernova (SN)
- Expansion in interstellar medium
- Kennicutt-Schmidt law from SN

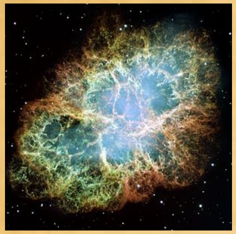
4. Supernovae united: Superbubble

5. Rebellation of supernovae: breaking out

6. A superbubble in our Galaxy

7. Other effects of SNe

Energatics of a supernova?



$1\,SN \approx 10^{53}\,erg$

$99\,\%$ Neutrino emission

$1\%\ (\approx 10^{51}\,erg)$ Mechanical energy in the form of high velocity ejecta

The total light emission by Sun

$$E_{\odot} = L_{\odot} \times 10\ Gyr = 2\times 10^{33}\ erg\ s^{-1} \times 10\ Gyr \approx 6\times 10^{50}\ erg$$

We expect a prominent effect on the interstellar medium

Phases of a supernova?

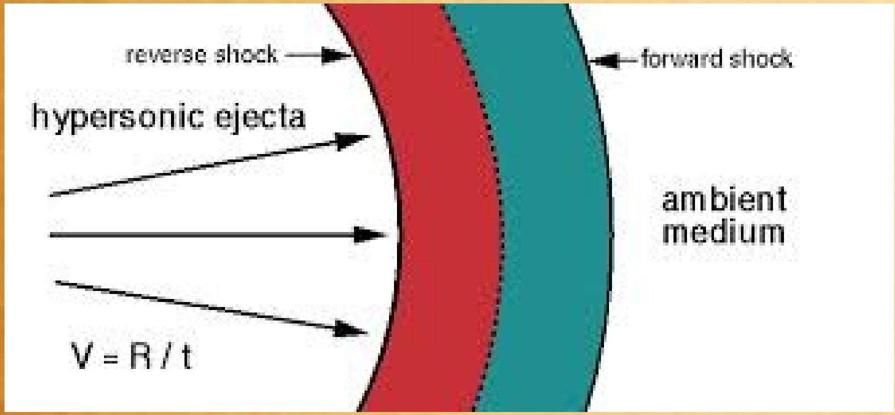
A SN has total energy of $E_{sn} \approx 10^{51} erg$

And total ejected mass of $M_{ej} \approx 2 - 10\, M_{\odot}$

$$v_{ej} = \left(\frac{2 E_{sn}}{M_{ej}} \right)^{1/2} = 10^4 \; km \; s^{-1} \; E_{51}^{1/2} \left(\frac{M_{ej}}{M_{\odot}} \right)^{1/2}$$

$$E_{51} \approx \frac{E_{sn}}{10^{51}}$$

$$c_{ism} \approx 10 \; km \; s^{-1}$$



Free expansion

$$R = v_{ej} \times t$$

$$\Rightarrow \rho_{ej} \propto R^{-3} \propto t^{-3}$$

$$\Rightarrow P_{ram} \propto \rho_{ej} v_{ej}^2 \propto t^{-3}$$

Thermal pressure of the accumulated matter soon exceeds the ram pressure of the wind. This happens when the mass of the accumulated matter equals the ejecta mass, i.e.

$$M_{ej} = \frac{4}{3} \pi R_1^3 \rho_0$$

$$R_1 = 1.9 \; pc \left(\frac{M_{ej}}{M_{\odot}} \right)^{1/3} n_0^{-1/3}$$

End of free expansion

$$M_{ej} = \frac{4}{3}\pi R_1^3 \rho_0$$

$$R_1 = 1.9\ pc \left(\frac{M_{ej}}{M_\odot}\right)^{1/3} n_0^{-1/3}$$

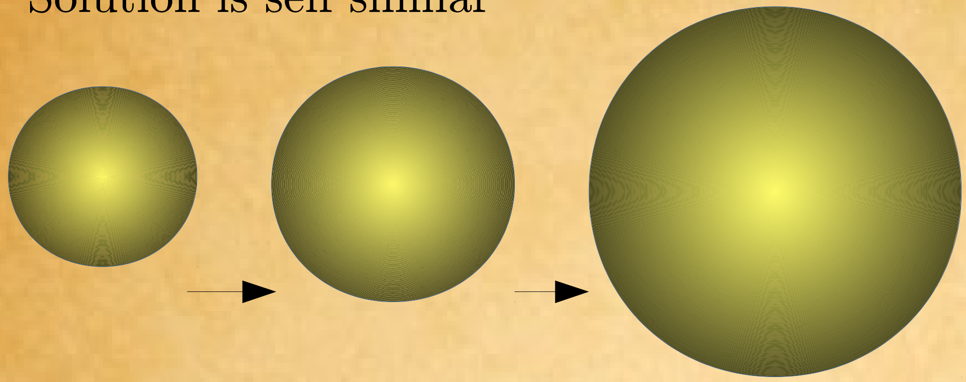
This means a time of $t_1 = \frac{R_1}{v_{ej}} = 186\ yr \left(\frac{M_{ej}}{M_\odot}\right)^{5/6} E_{51}^{-1/2} n_0^{-1/3}$

After this phase, the kinetic energy almost completely converts into thermal energy and supernova can then be assumed as a **point explosion** and the evolution can be well approximated by blast wave solution. This phase is called the

Sedov-Taylor phase

Sedov-Taylor phase

Solution is self similar



$$\rho(r) = \rho_0 \, f(x) \quad ,$$
$$v(r) = \frac{R_s}{t} \, g(x) \quad ,$$
$$p(r) = \frac{\rho_0 R_s^2}{t^2} \, h(x) \quad ,$$

In such a case a simple simensional analysis gives

$$R_s = A \, E^{\alpha} \, \rho^{\beta} \, t^{\eta}$$

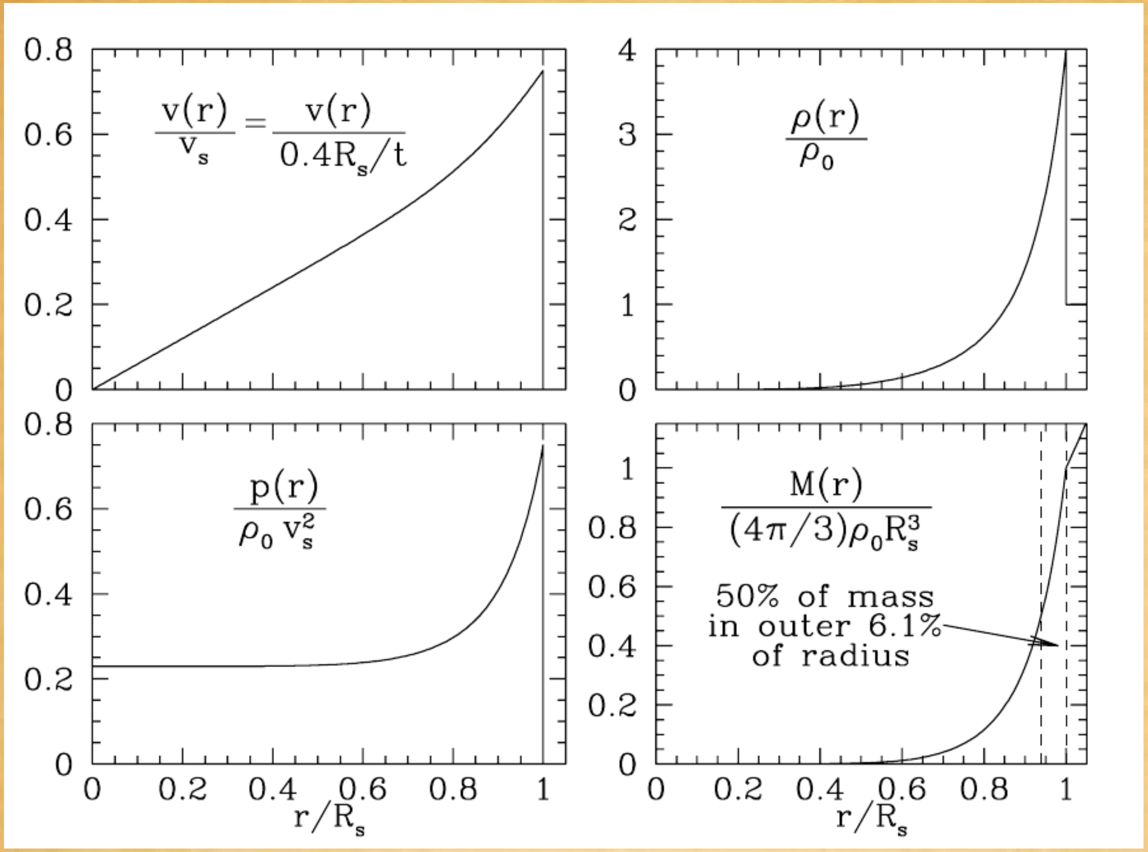
$$R_s = A \, E^{1/5} \, \rho_0^{-1/5} \, t^{2/5}$$

Shock radius $\quad R_s = 1.54 \times 10^{19} \, \mathrm{cm} \, E_{51}^{1/5} n_0^{-1/5} t_3^{2/5} \quad ,$

Shock velocity $\quad v_s = 1950 \, \mathrm{km \, s^{-1}} \, E_{51}^{1/5} n_0^{-1/5} t_3^{-3/5} \quad ,$

Shock temperature $\quad T_s = 5.25 \times 10^7 \, \mathrm{K} \, E_{51}^{2/5} n_0^{-2/5} t_3^{-6/5} \quad ,$ (Strong shock limit)

Sedov-Taylor phase



Full profile in the Sedov-Taylor phase B Draine

However, This will not last for long as the shocked gas will cool and the assumption of self-similarity breaks down

Radiative cooling

Free-Free, Free-bound, bound-bound processes

$$\Lambda \approx C\, T_6^{-0.7} n_{\rm H} n_e \quad , \quad C = 1.1 \times 10^{-22}\, {\rm erg\, cm^3\, s^{-1}}$$ $10^5 K < T < 3\times10^6 K$

With time, density increase, temperature decreases
So, cooling becomes important

Fractional energy loss via radiation

$$\frac{\Delta E(t)}{E_0} \approx -2.38 \times 10^{-6} n_0^{1.68} E_{51}^{-0.68} t_3^{3.04}$$

Start of cooling at $t_{\rm rad} = 49.3 \times 10^3\, {\rm yr}\, E_{51}^{0.22} n_0^{-0.55}$,

Shock radius $R_{\rm rad} = 7.32 \times 10^{19}\, {\rm cm}\, E_{51}^{0.29} n_0^{-0.42}$,

Shock velocity $v_s(t_{\rm rad}) = 188\, {\rm km\, s^{-1}}\, \left(E_{51}/n_0^2\right)^{0.07}$,

Shock temperature $T_s(t_{\rm rad}) = 4.86 \times 10^5\, {\rm K}\, \left(E_{51}/n_0^2\right)^{0.13}$,

Snow-plow phase

Once the shock cools, it becomes a thin shell. The shock is then only pushed by the hot gas pressure inside. The shock only accumulates more and more matter in it.

The gas pressure inside undergoes adiabatic expansion $pV^\gamma = const,$

The equation of motion for the shell is then

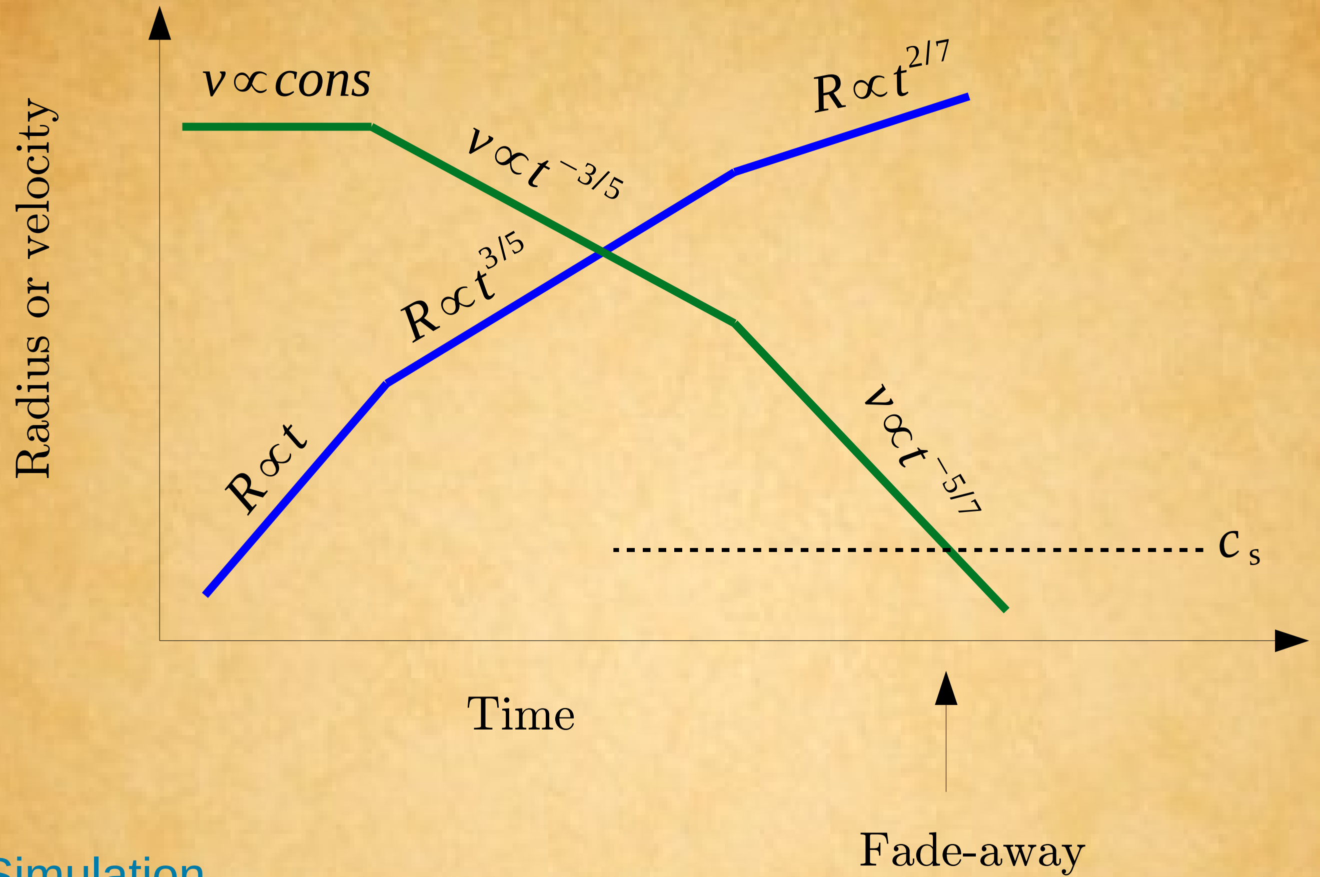
$$\frac{d}{dt}(M_s v_s) \approx p_i 4\pi R_s^2 = 4\pi p_0(t_{\rm rad}) R_{\rm rad}^5 R_s^{-3}$$

Assume the solution to be $R_s \propto t^\eta.$

$$R_s \approx R_s(t_{\rm rad})(t/t_{\rm rad})^{2/7} \quad ,$$

$$v_s \approx \frac{2}{7}\frac{R_s}{t} = \frac{2}{7}\frac{R_s(t_{\rm rad})}{t_{\rm rad}}\left(\frac{t}{t_{\rm rad}}\right)^{-5/7}$$

Phases of a supernova?



Simulation

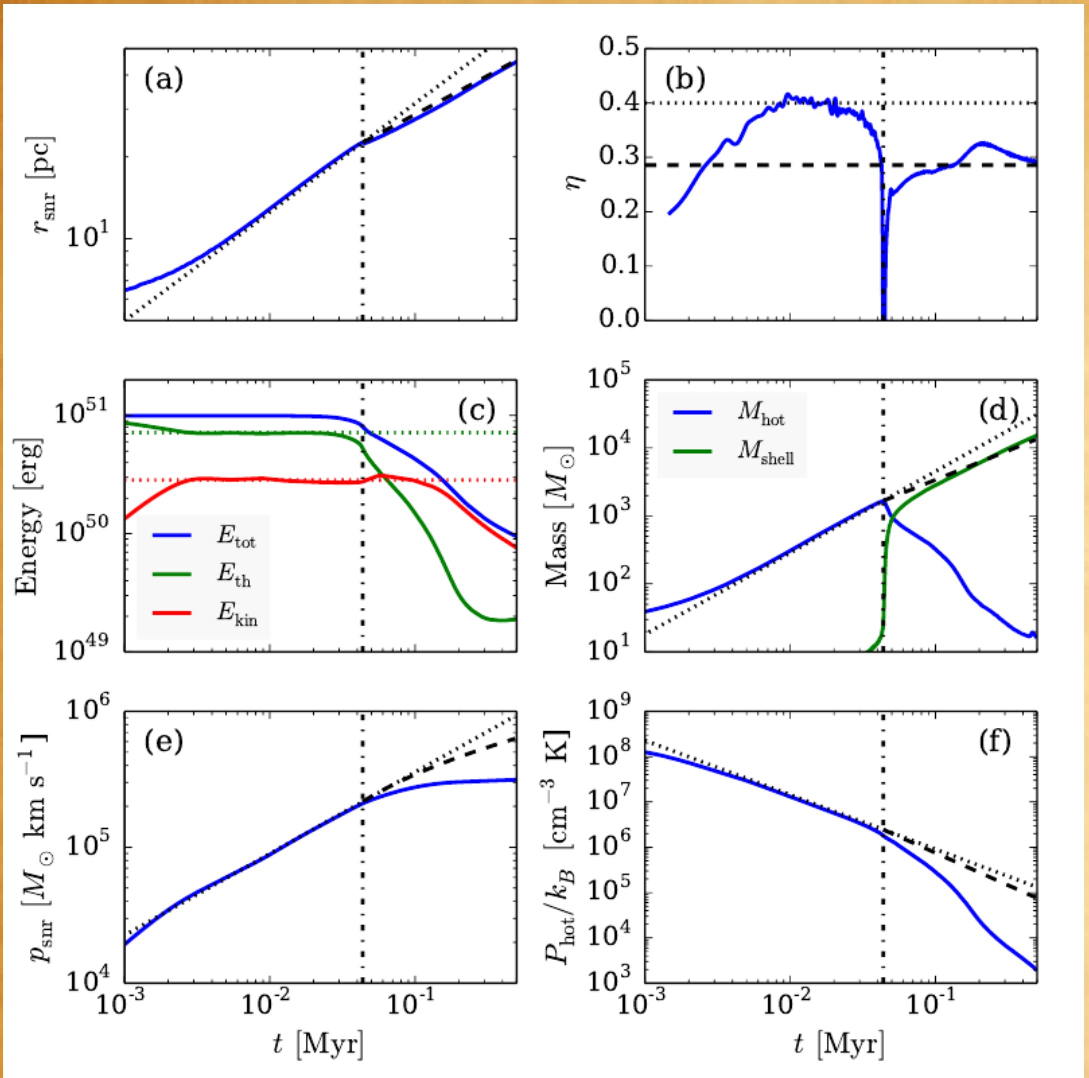
Fade-away time

$$t_f \simeq 1.87\,\mathrm{Myr}\,e_{51}^{0.32} c_1^{-7/5}\, n_0^{-0.37}\,,$$

Fade-away radius

$$R_f \simeq 69.0\,\mathrm{pc}\,e_{51}^{0.32} c_1^{-2/5}\, n_0^{-0.37}\,.$$

Energatics and momentum from a SN



Kim & Ostriker, 2015

Energy retained

Kinetic = 10%

Thermal = 2%

Content

1. What is a supernova?

2. Why do we need them?

3. Single supernova (SN)
   - Expansion in interstellar medium
   - **Kennicutt-Schmidt law from SN**

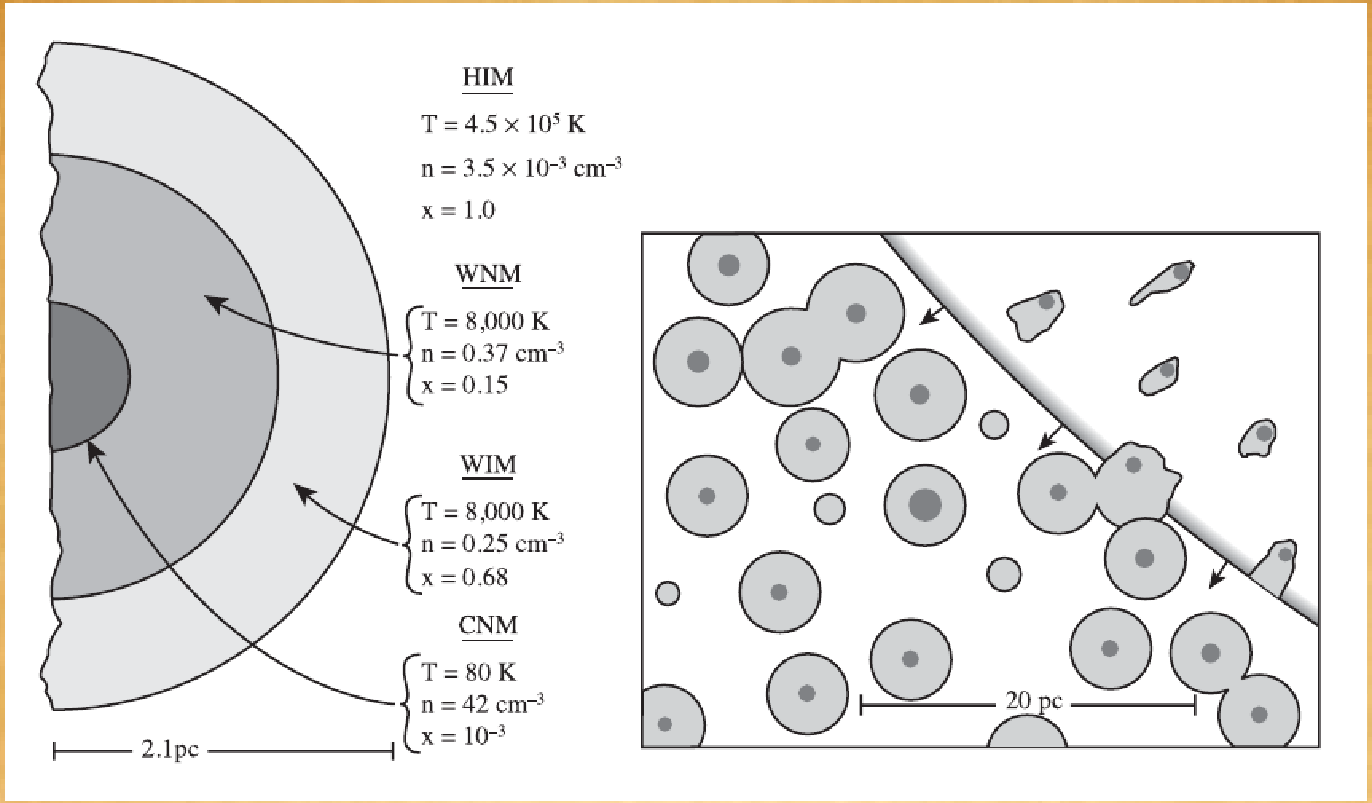
4. Supernovae united: Superbubble

5. Rebellation of supernovae: breaking out

6. A superbubble in our Galaxy

7. Other effects of SNe

Effect of star formation



Propagation of shock in the interstellar medium prevents star formation

Fig credit: McKee & Ostriker, 1977

Volume filling factor

Volume of each such shocked region is $V_{sn} = \frac{4}{3}\pi R_f^3$

They hang around for a time of t_f

Now, if the SN rate per unit volume is S

Then the volume filling factor is $f = V_{sn} \times S \times t_f$

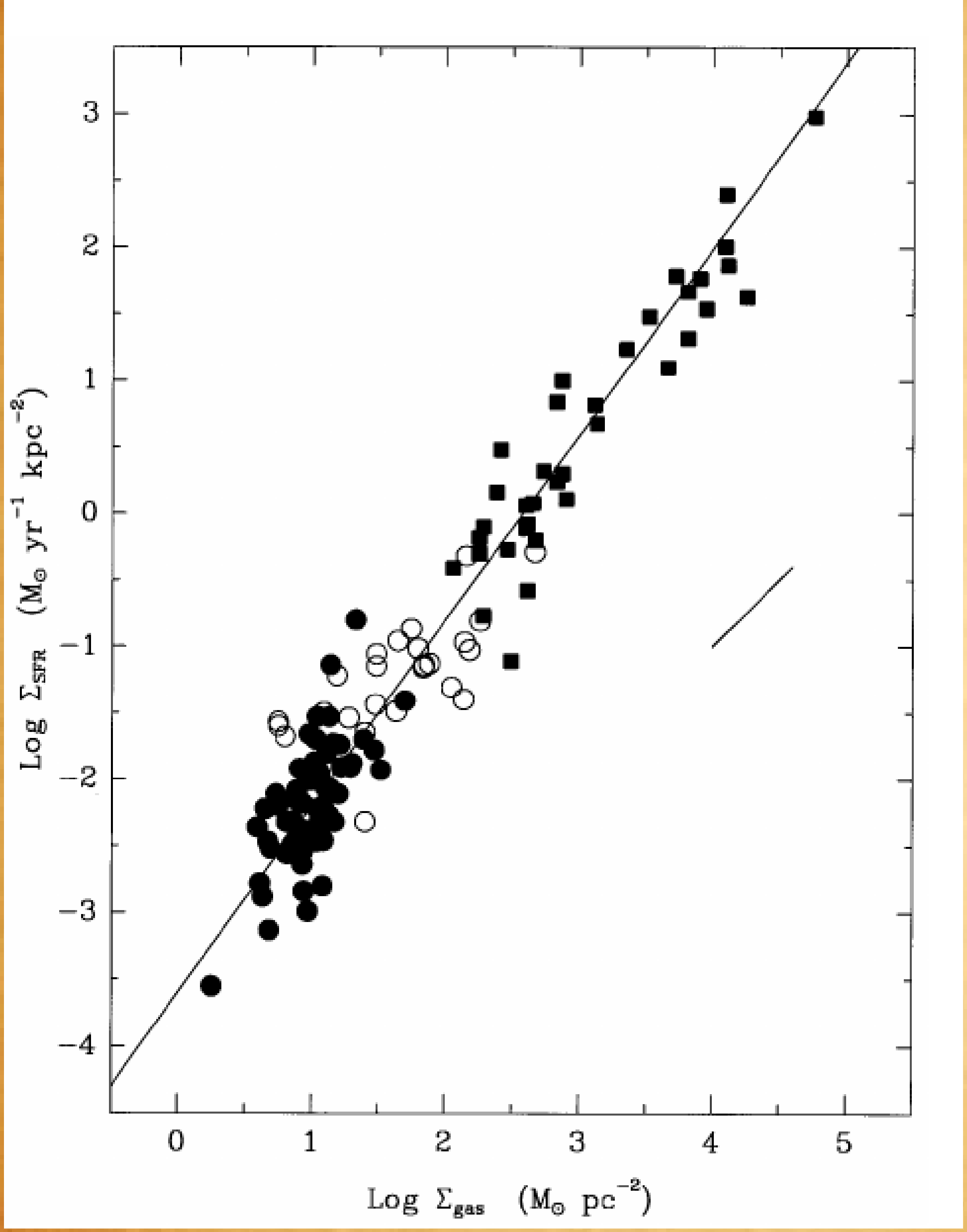
$$= 0.24\, e_{51}^{1.26} c_1^{-2.6}\, S_{-4}\, n_0^{-1.48}$$

It is seen in galaxy simulations that this volume filling factor is

$$f = 0.5$$

$$\Rightarrow S \propto n_0^{1.48}$$

Kennicutt-Schmidt law



$$\Sigma_{sfr} \propto \Sigma_{gas}^{1.4}$$

$$\Rightarrow S_{sn} \propto n_{gas}^{1.4}$$

An alternative explanation for the KS law

Kennicutt, 1998

Content

1. What is a supernova?

2. Why do we need them?

3. Single supernova (SN)
   - Expansion in interstellar medium
   - Kennicutt-Schmidt law from SN

4. **Supernovae united: Superbubble**

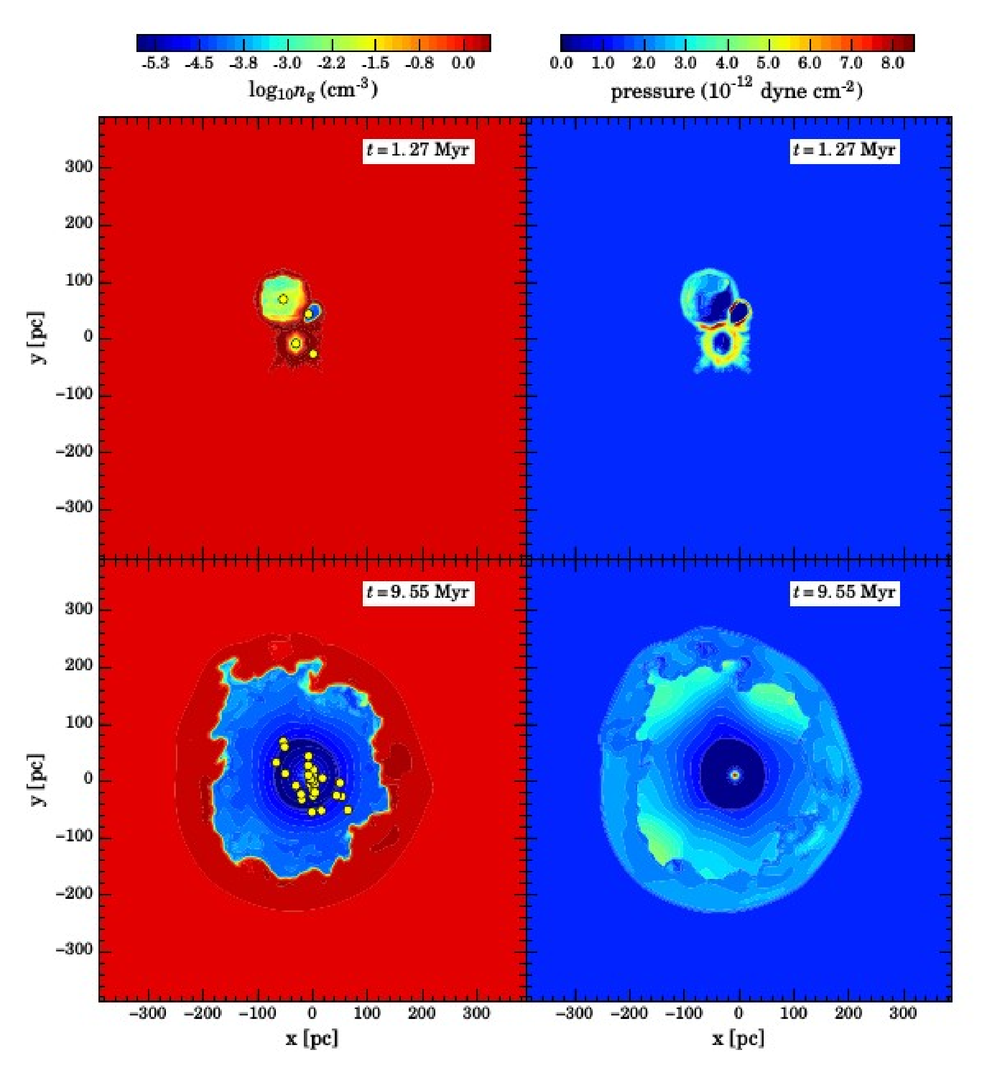
5. Rebellation of supernovae: breaking out

6. A superbubble in our Galaxy

7. Other effects of SNe

Stars like to form in clusters

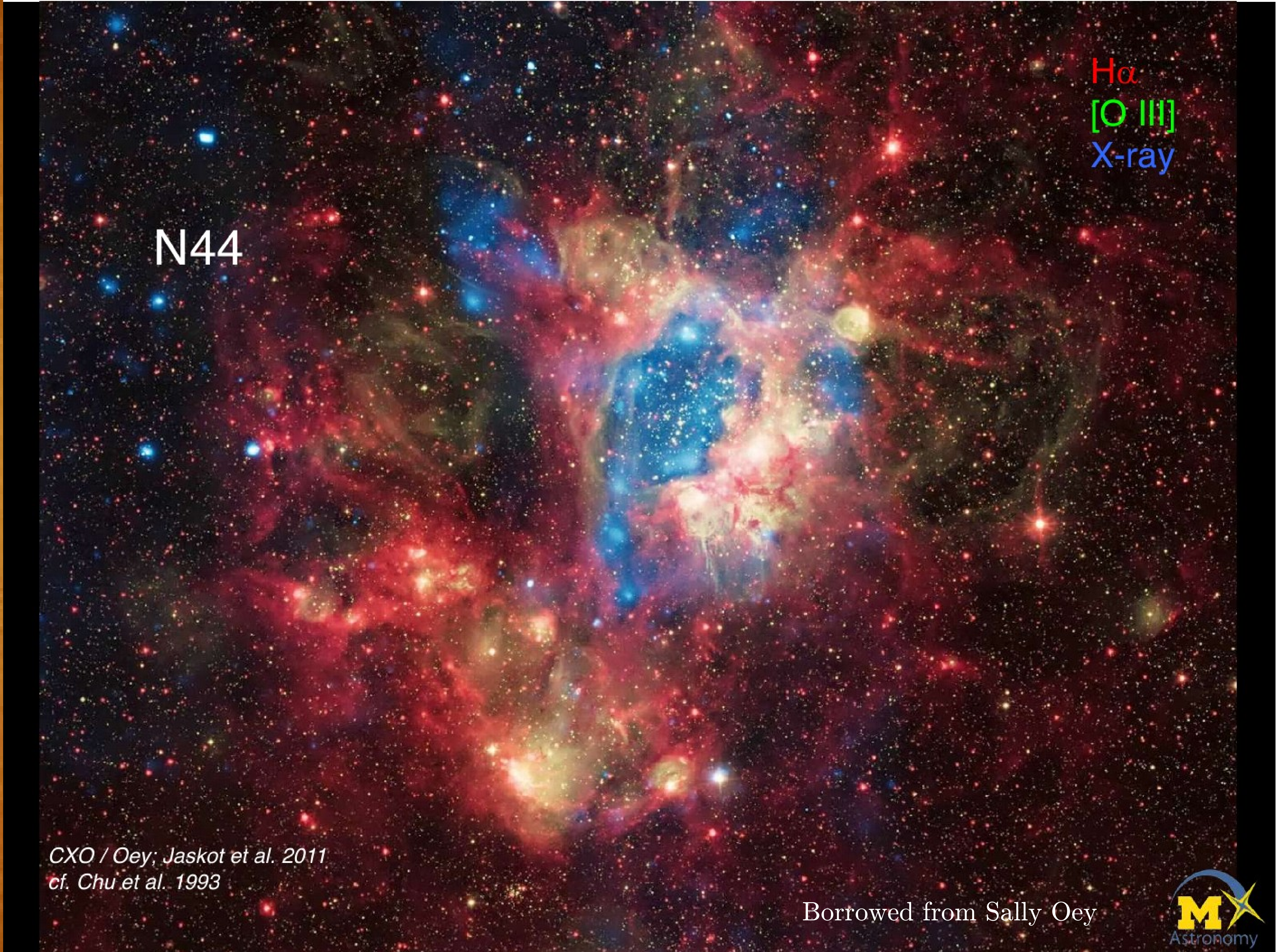
So do then SNe



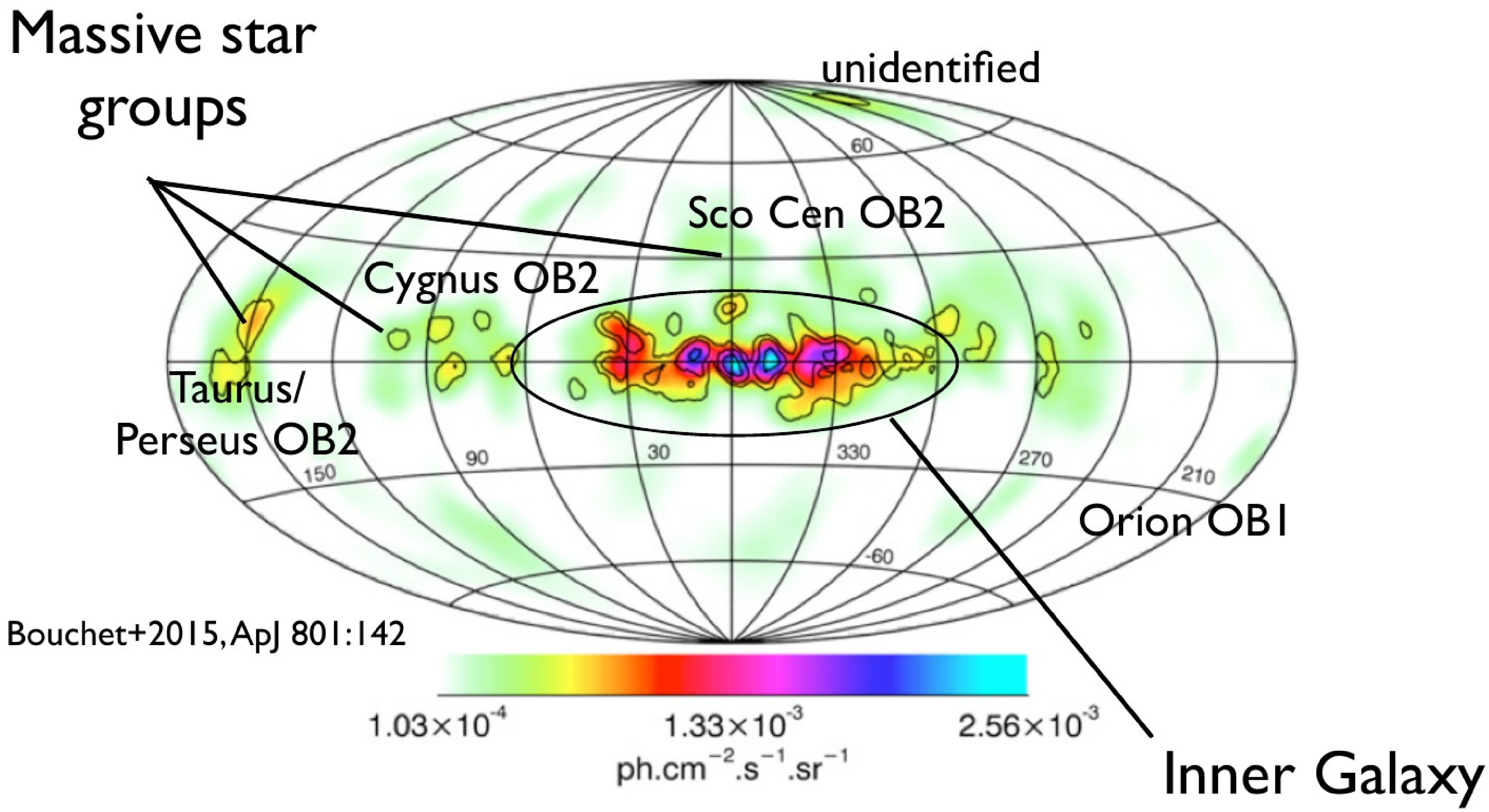
Trapezium cluster in Orion nebula

Play movie from Martin Krause

Overlap pf Supernovae, (Yadav etal., 2016)

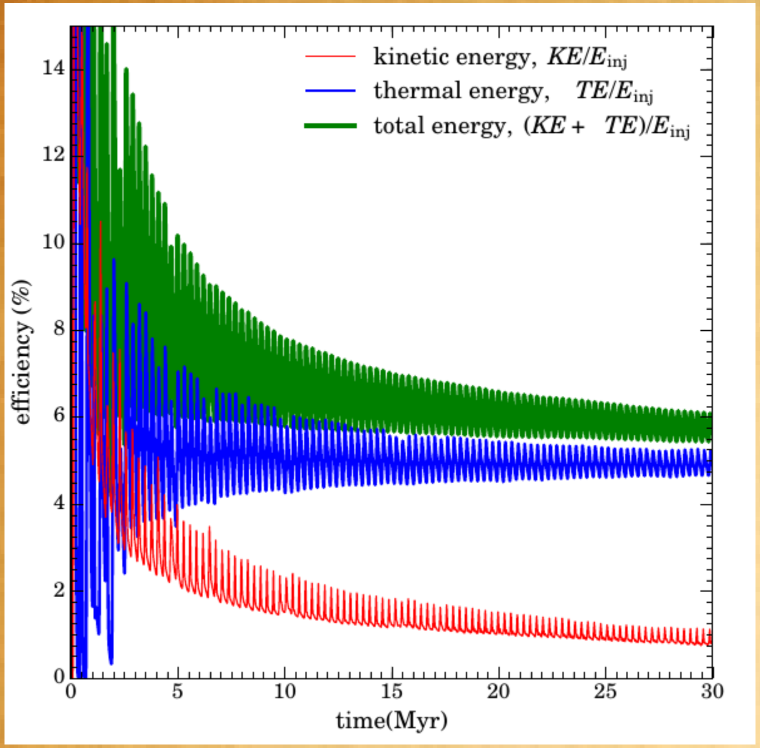

Hα
[O III]
X-ray
N44
CXO / Oey; Jaskot et al. 2011
cf. Chu et al. 1993
Borrowed from Sally Oey
Astronomy

^{26}Al emission sites

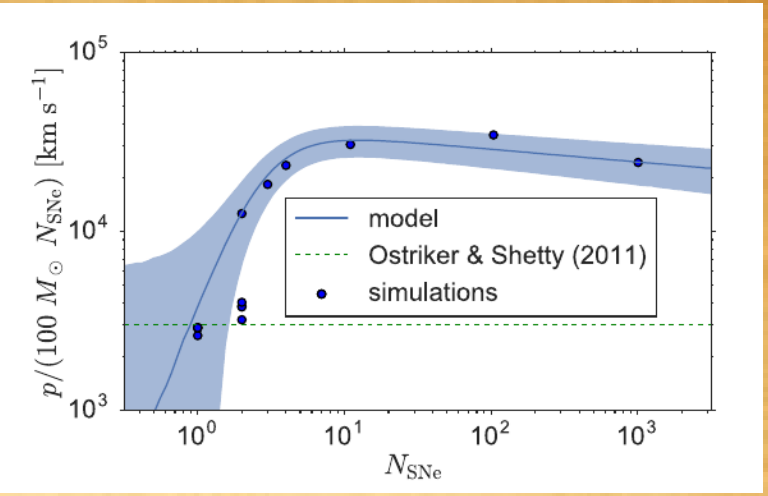


Bouchet+2015, ApJ 801:142

Supernovae united



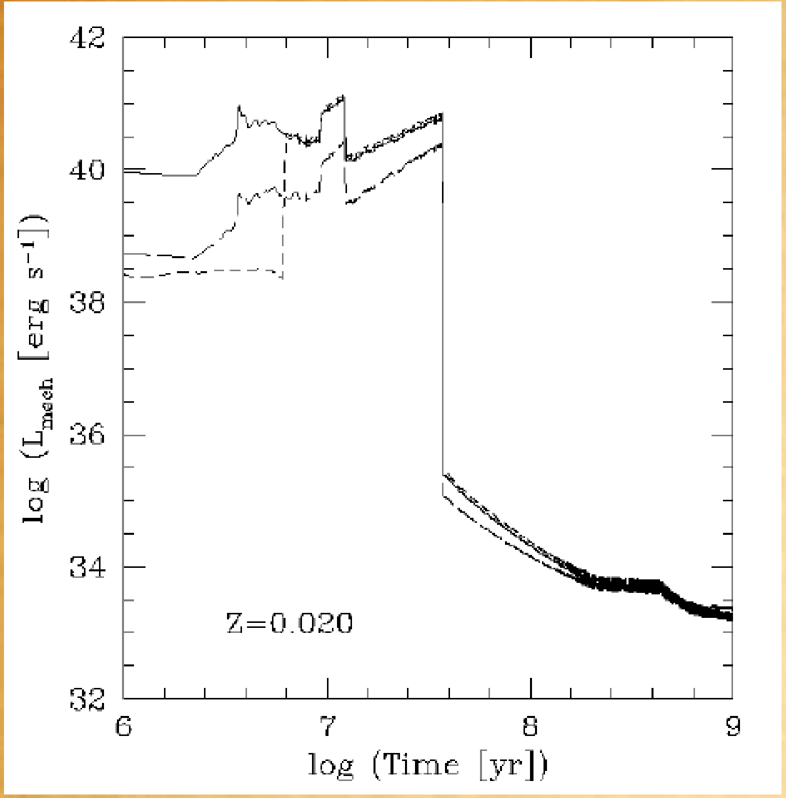
SNe in a cluster saves larger amount of energy

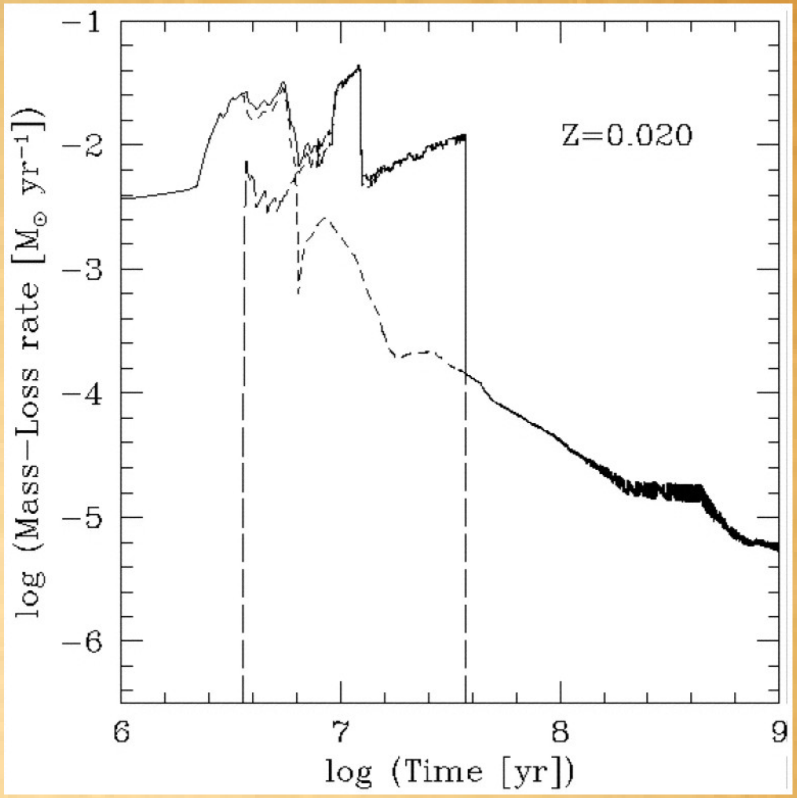


SNe in a cluster saves produces more momentum per SNe

Yadav et.al., 2016; Gentry et.al., 2016;

Supernovae united





A burst of star formation, forming a 10^6 M_{sun} cluster

Mechanical energy output and the mass loss rate is const for first 30 Myr

$$L = \frac{1}{2}\dot{M}\,v_w^2$$

$$\Rightarrow v_w = \sqrt{\frac{2\ L}{\dot{M}}} \approx 2000\ \ km\ s^{-1}\ \ L_{40}^{1/2}\left(\frac{\dot{M}}{0.01\,M_\odot\,yr^{-1}}\right)^{-1/2}$$

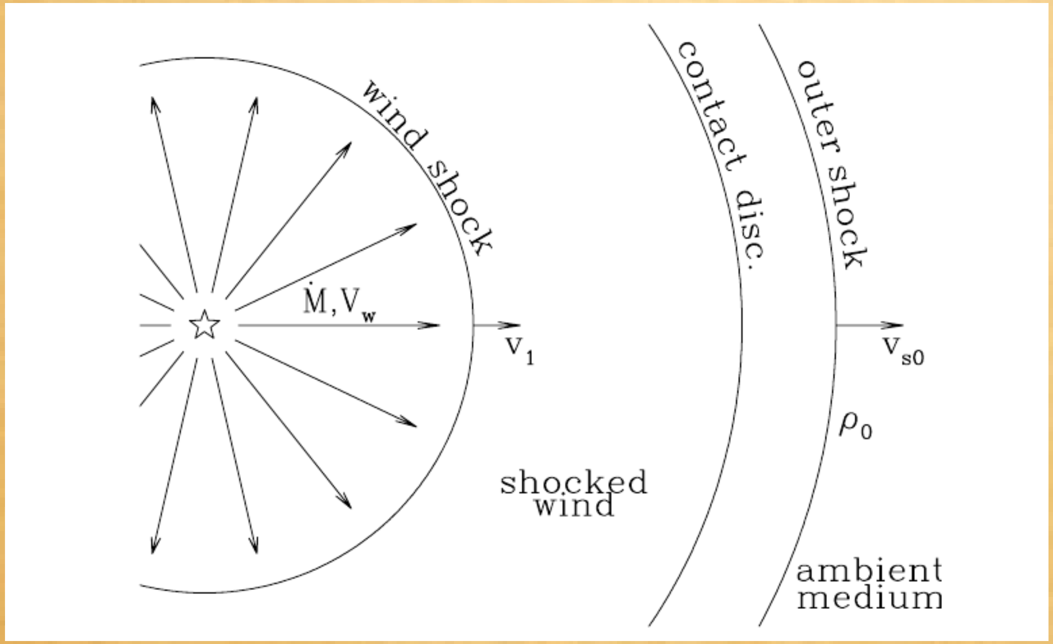
Leitherer et al., 1999

The wind in this case first goes through the **free expansion phase** and then to an **energy conserving phase** where the solution is self similar (remember the dimensional analysis)

The shock radius and velocity are given as (remember the dimenaional analysis)

$$R_s \approx \left(\frac{L t^3}{\rho_0}\right)^{1/5} = 250 \; pc \; L_{40}^{1/5} t_{Myr}^{3/5} n_0^{-1/5}$$

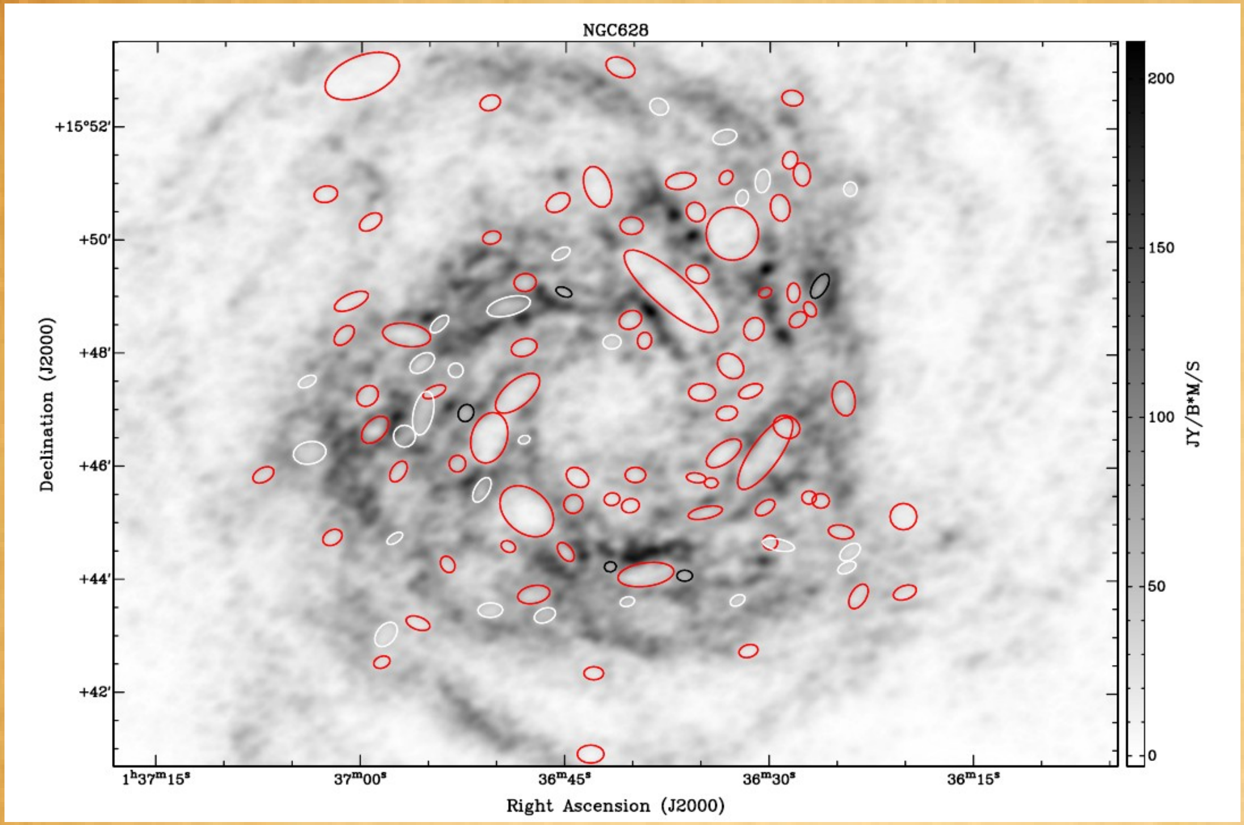
$$v_s \approx \frac{3}{5}\frac{R}{t} = 130 \; km \; s^{-1} \; L_{40}^{1/3} n_0^{-1/3} R_{250\,pc}^{-2/3}$$



Castor etal, 1975; Weaver etal, 1977

Content

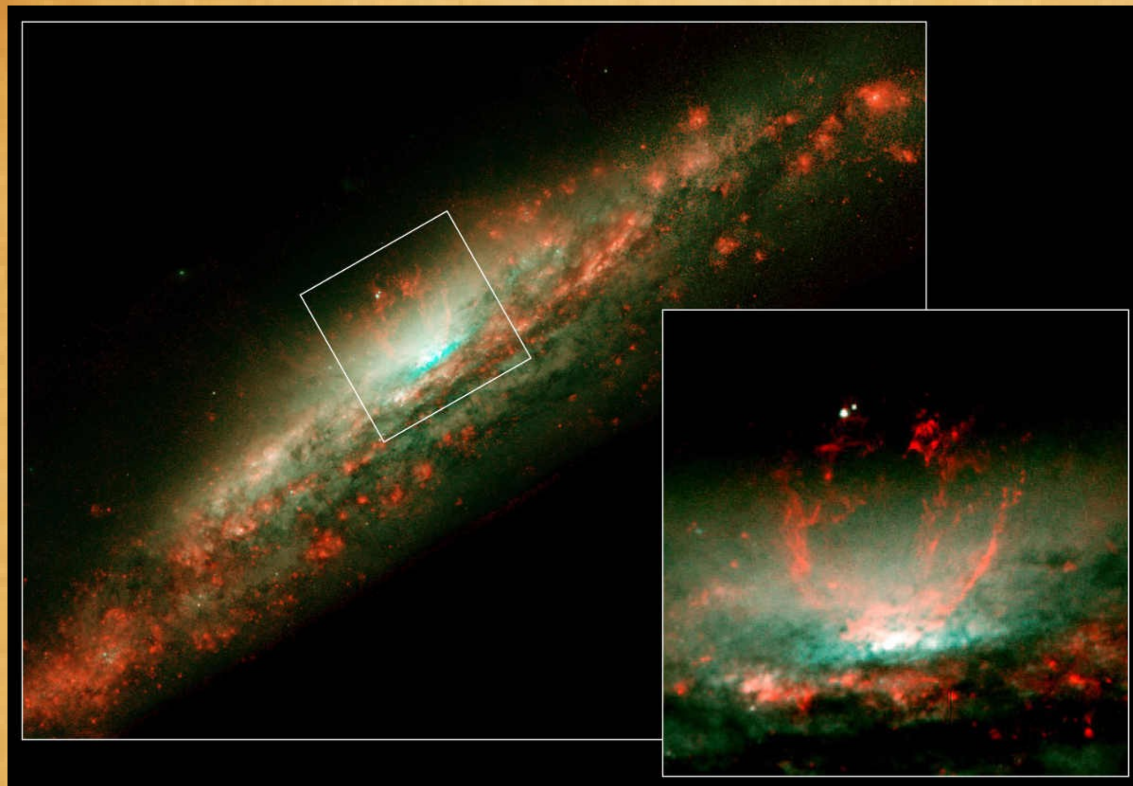
The interstellar medium in disky: Some bubbles stay, some escape



HI observation of galaxy NGC628

Break-out

The interstellar medium in disky: Some bubbles stay, some escape



NGC 3079: red-H-alpha emission; green/blue- starlight

Below a minimum number of Sne the bubble does not break out

In summary, superwinds are ubiquitous in galaxies with star-formation-rates per unit area $\Sigma_* \geq 10^{-1}\ M_\odot\ yr^{-1}\ kpc^{-2}$. Starbursts and the Lyman Break galaxies surpass this threshold, while the disks of ordinary present-day spiral galaxies do not (Kennicutt 1998).

NASA/STScI-2001-28; Heckman, 2002

Break-out

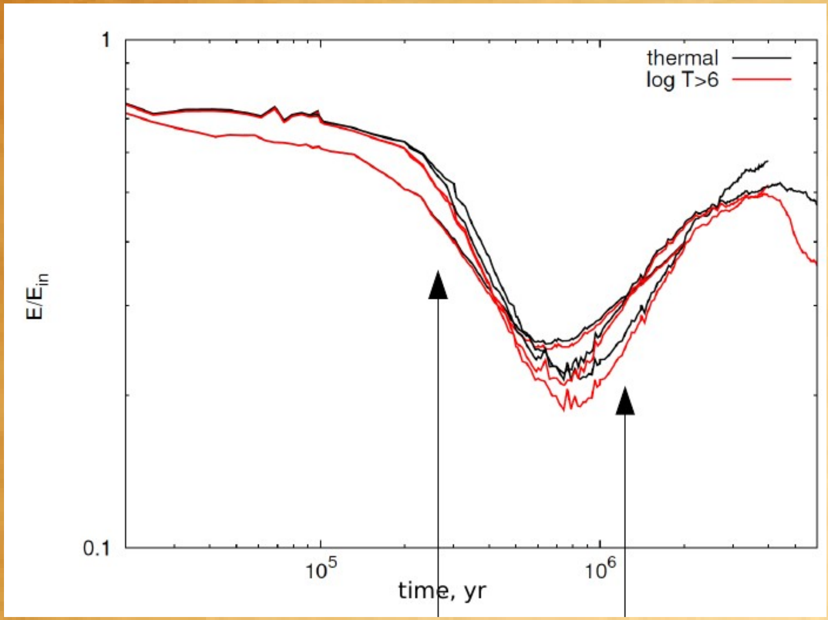
The interstellar medium in disky: Some bubbles stay, some escape

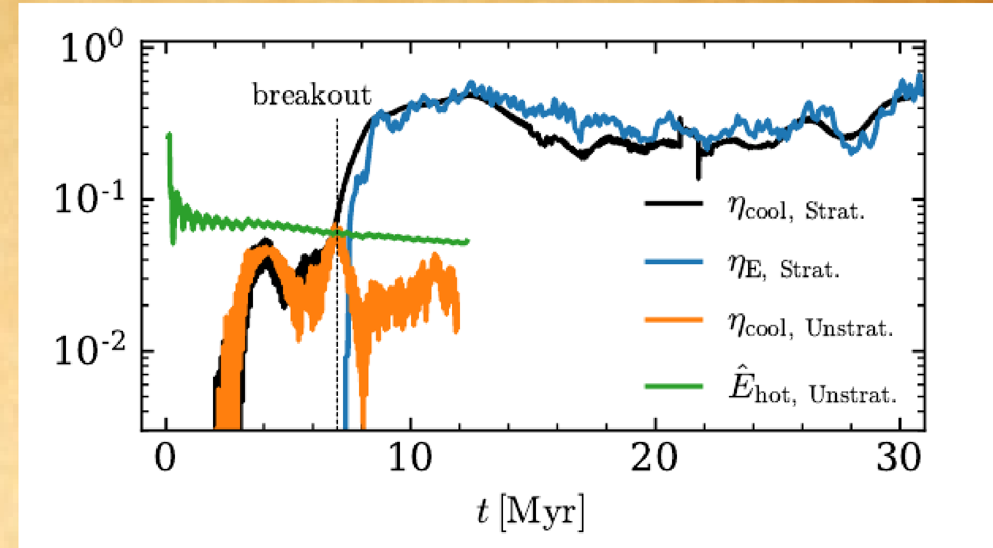
M82: red-H-alpha; green- starlight; blue-Xray

Play EHR simulation

NASA/JPL-Caltech/STScI/CXC/UofA

The interstellar medium in disky: Some bubbles stay, some escape





Clustered SNe in a stratified medium saves larger amount of energy

Vasilev et. al., 2018; Fielding et. al., 2018

Content

1. What is a supernova?

2. Why do we need them?

3. Single supernova (SN)
   - Expansion in interstellar medium
   - Kennicutt-Schmidt law from SN

4. Supernovae united: Superbubble

5. Rebellation of supernovae: breaking out

6. A superbubble in our Galaxy

7. Other effects of SNe

Bubbles in our Galaxy

Given this information, we can easily calculate if a galaxy is likey to produce Wind or not

Milky-Way has a star formation rate of $2-3\ M_{\odot}\ yr^{-1}$ within approx 10 kpc

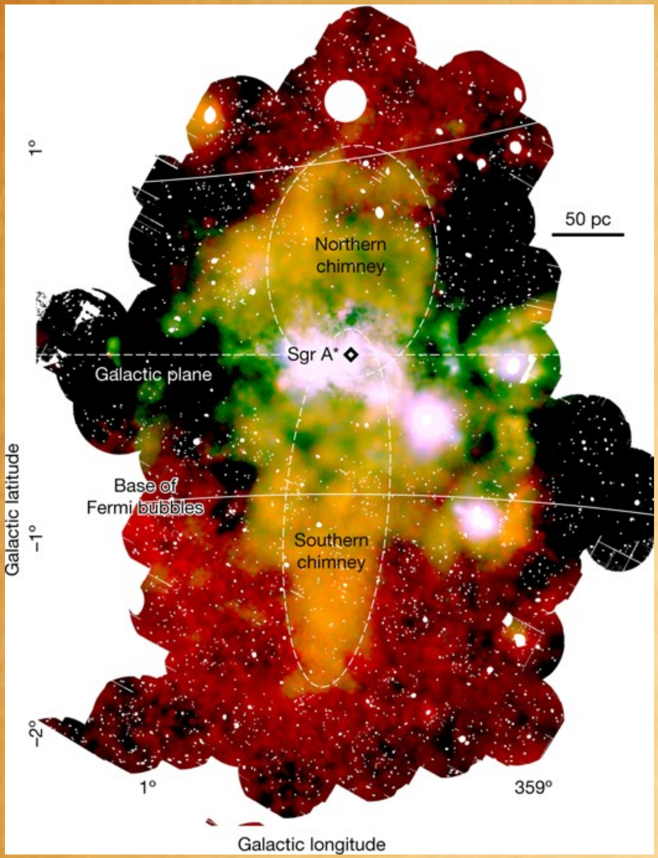
$\Rightarrow \Sigma_{sfr} \approx 10^{-2} M_{\odot}\, yr^{-1} kpc^{-2}$ **There is no disc-wide outflow**

Milky-Way central 100 pc has a star formation rate of $\approx 0.1\ M_{\odot}\ yr^{-1}$

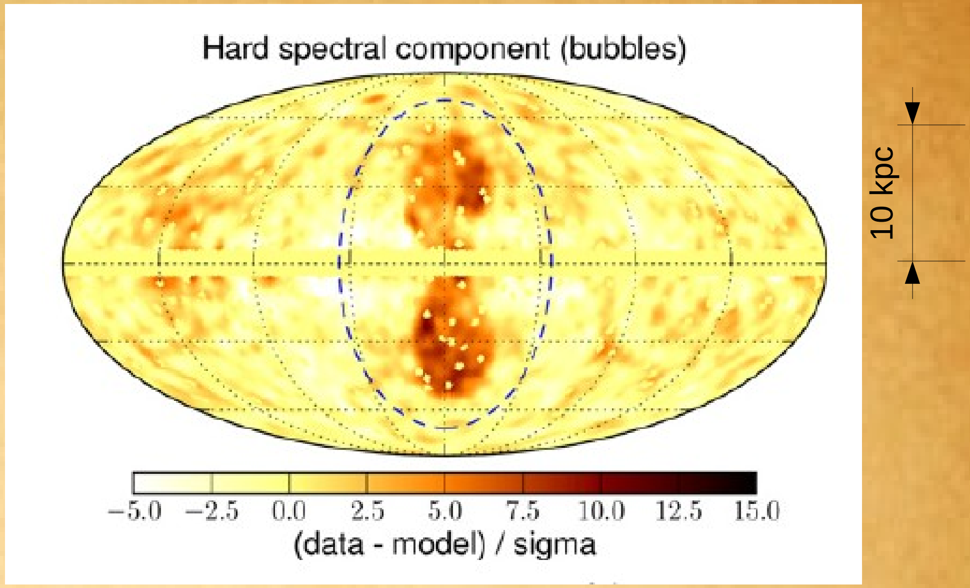
$\Rightarrow \Sigma_{sfr} \approx 3\, M_{\odot}\, yr^{-1} kpc^{-2}$ **There can be outflow from the center**

NASA/CXC/UMass/D. Wang et al.; Optical: NASA/ESA/STScI/D.Wang et al.; IR: NASA/JPL-Caltech/SSC/S.Stolovy

Fermi Bubbles



X-ray outflow at the Galactic centre



Gamma-ray emission from the expanded bubble

The central black hole ?

The supernovae ?

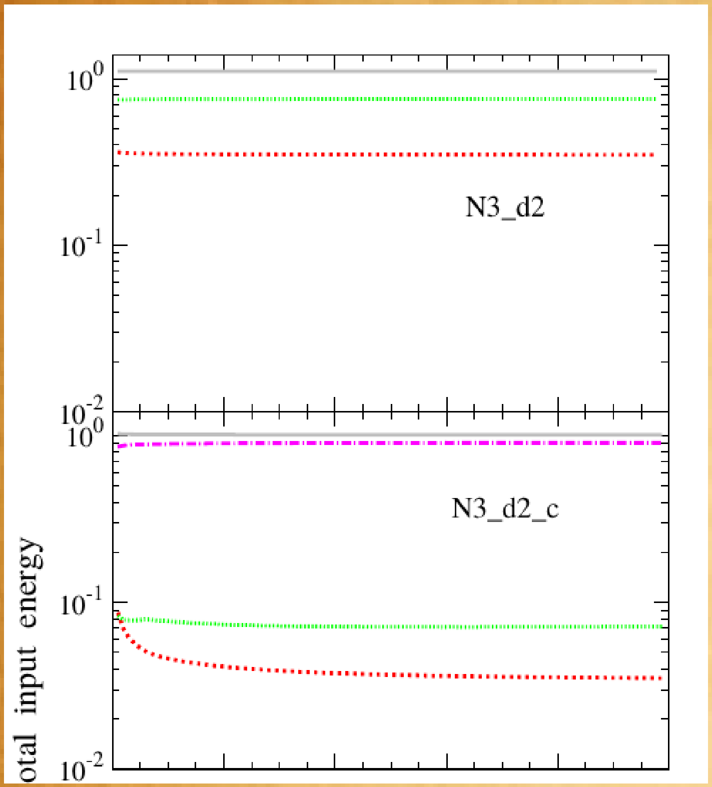
Ponti et. al., 2019; Ackermann et. Al, 2015

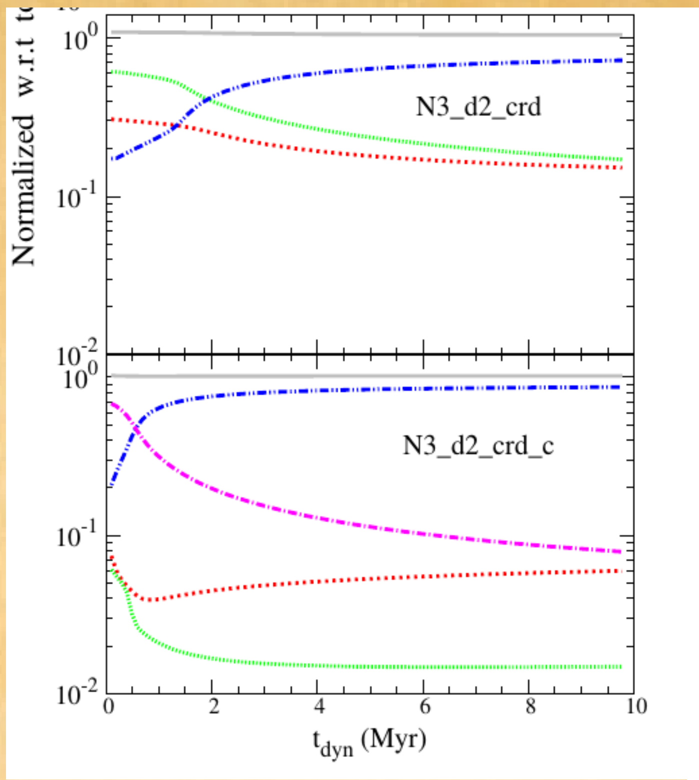
Content

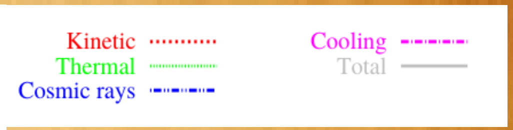
1. What is a supernova?
2. Why do we need them?
3. Single supernova (SN)
   - Expansion in interstellar medium
   - Kennicutt-Schmidt law from SN
4. Supernovae united: Superbubble
5. Rebellation of supernovae: breaking out
6. A superbubble in our Galaxy
7. **Other effects of SNe**

Effects of SNe bubbles in interstellar medium (ISM)

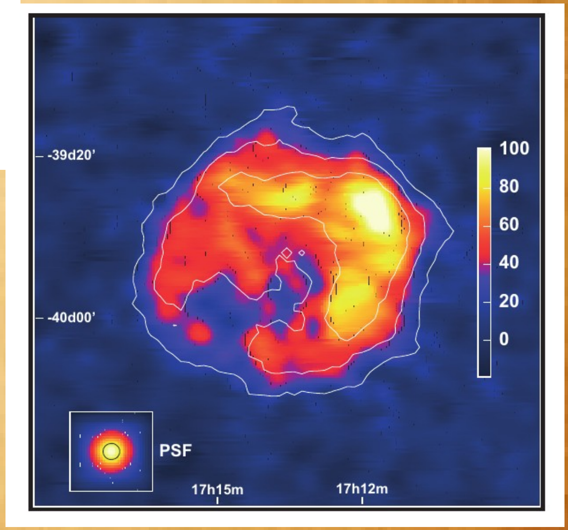
Generating cosmic rays







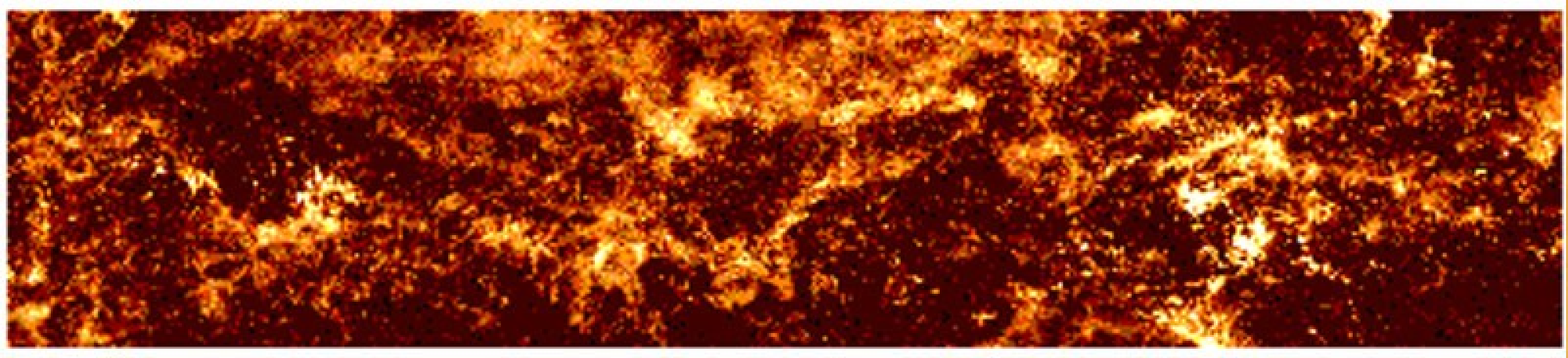
Almost 80% of the superbubble energy is converted into cosmic rays !



Gamma-ray image of SNR RX J1713.7−3946.

Effects of SNe bubbles in interstellar medium (ISM)

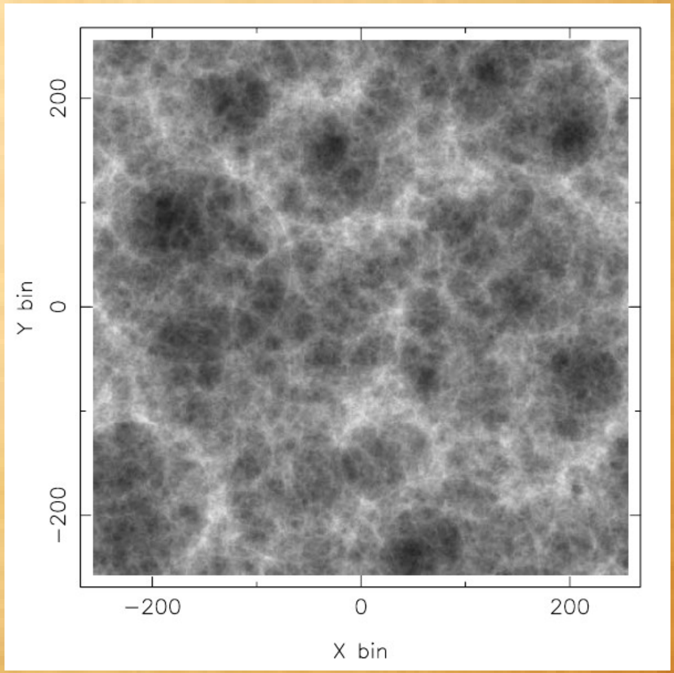
Generating turbulence



Interstellar medium is turbulent (CO map)

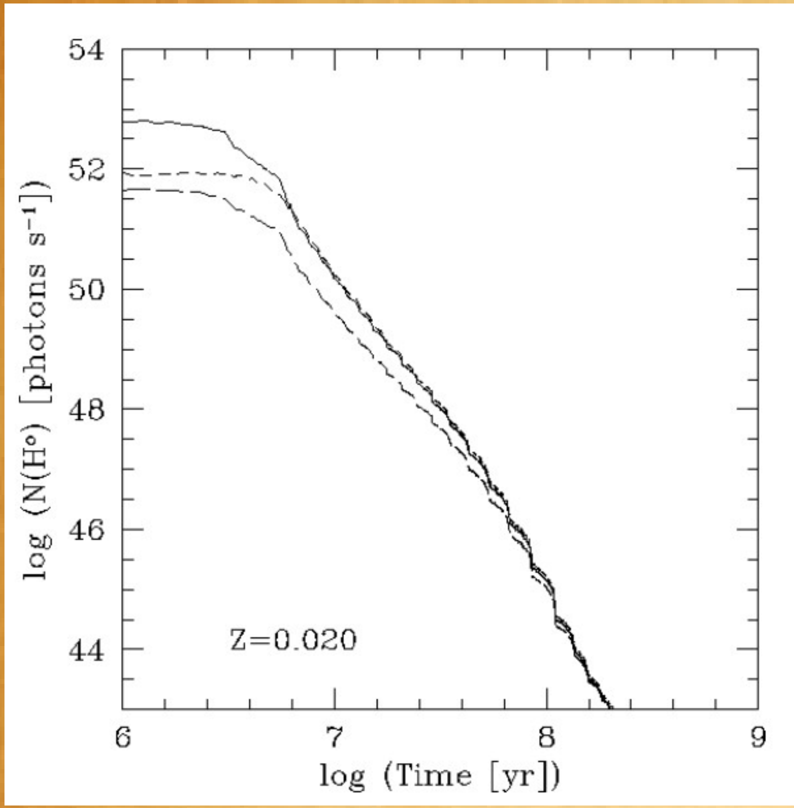
Sne can drive the turbulence in quiscent galaxies

HI column density for randomly exploding Sne in the ISM

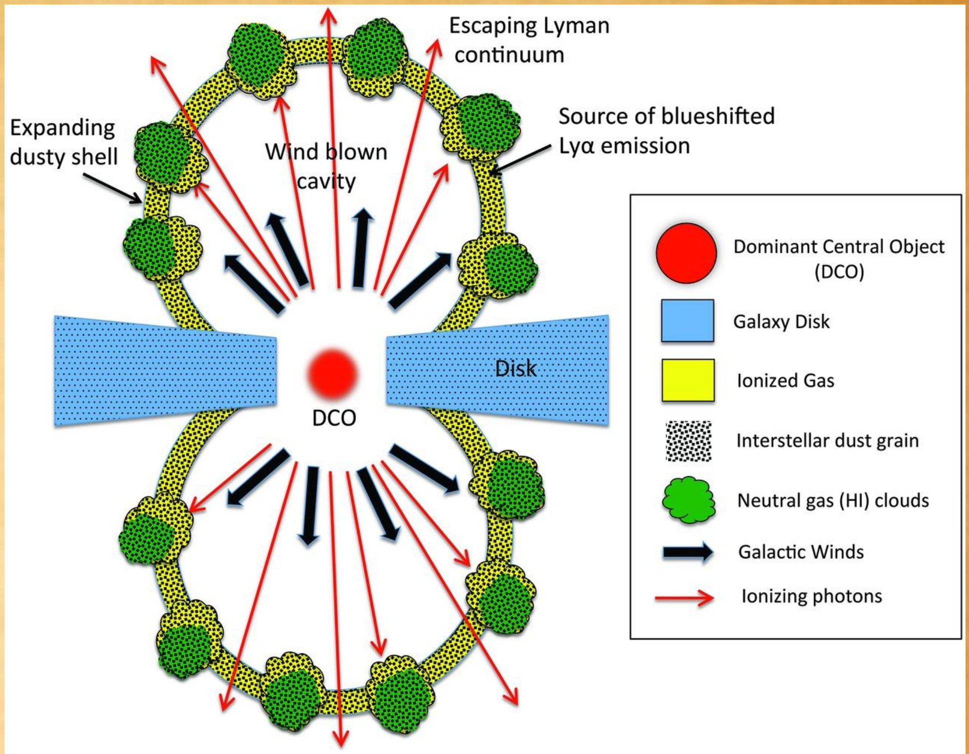


Heyer et al, 1998; Krumholz et.al., 2018; Hodge & Deshpande, 2006;

Effects of SNe bubbles in intergalactic medium (IGM)



Generating ionising photons



Ionising photons escape from galaxy via channels of dusty shell

Leitherer et.al., 1999; Borthakur et. al., 2014

Effects of SNe bubbles in intergalactic medium (IGM)

Ionising photons escape the galaxy and helped ionising the universe

Reionisation simulation

Leitherer et.al., 1999; Borthakur et. al., 2014

Conclusions

- Sne produce thermal energy, kinetic energy, metals, cosmic rays.
- SN can effect the star formation in galaxies (mostly low mass)
- Clusters of Sne produce large scale outflow, disperses metals and ionising photons in the intergalactic medium

Thanks for your attention