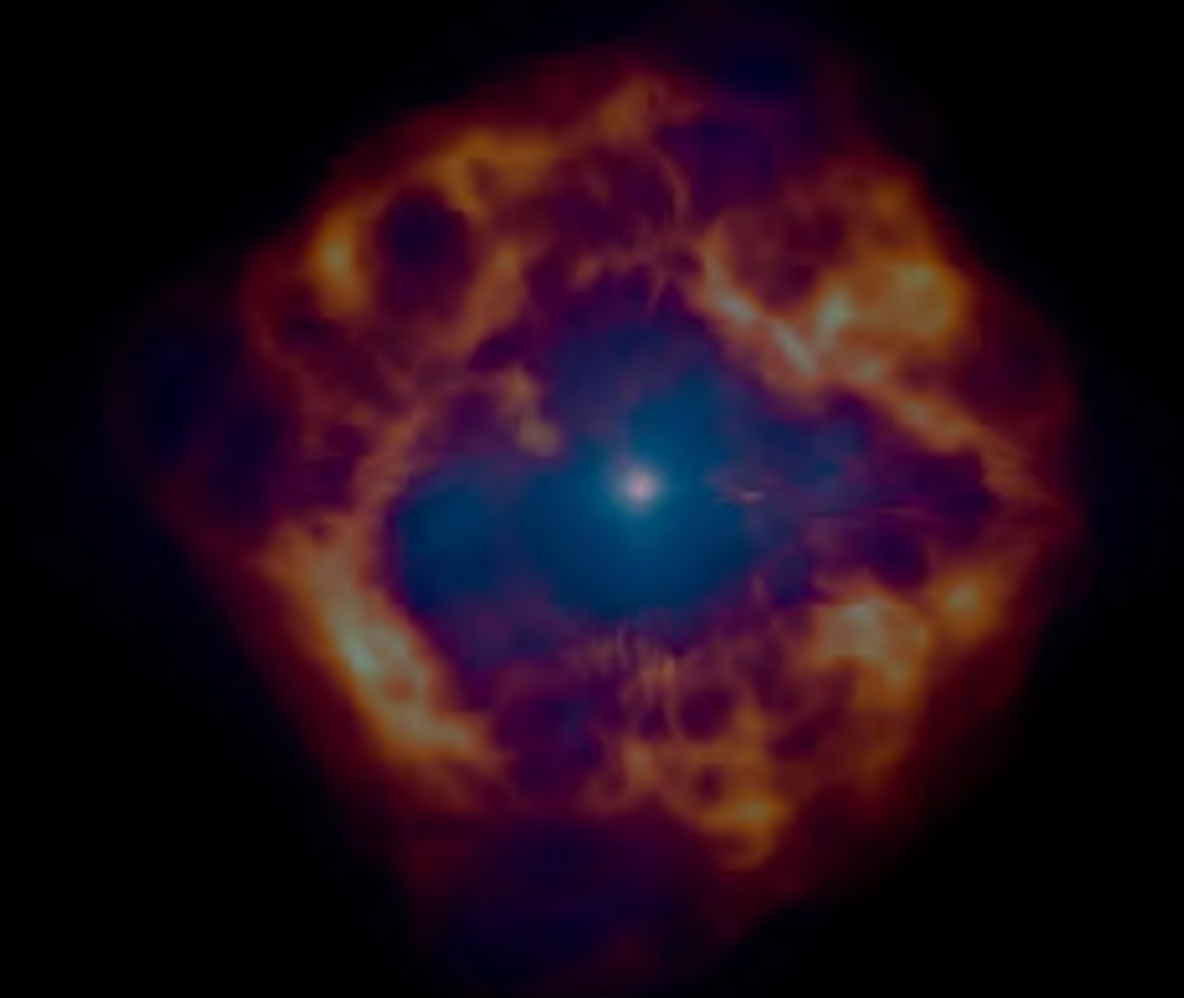
Gas evolution around young star clusters in the presence of cosmic rays



Siddhartha Gupta

Indian Institute of Science & Raman Research Institute, India

http://www.rri.res.in/~siddhartha

16 September 2019

StarFormMapper Conference, York

Acknowledgement

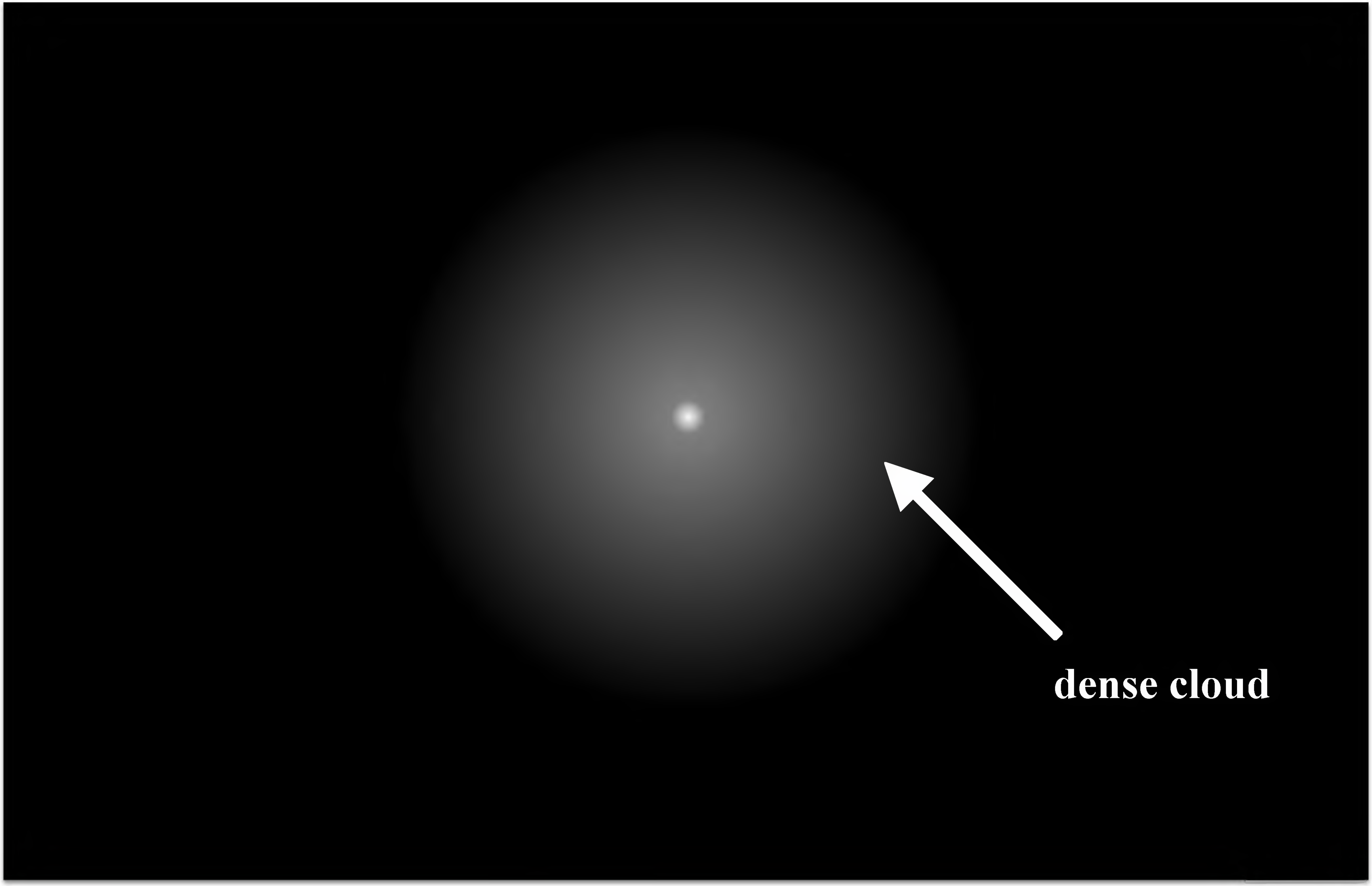
Biman Nath (RRI, India) & Prateek Sharma (IISc, India)

Andrea Mignone (Turin University, Italy)

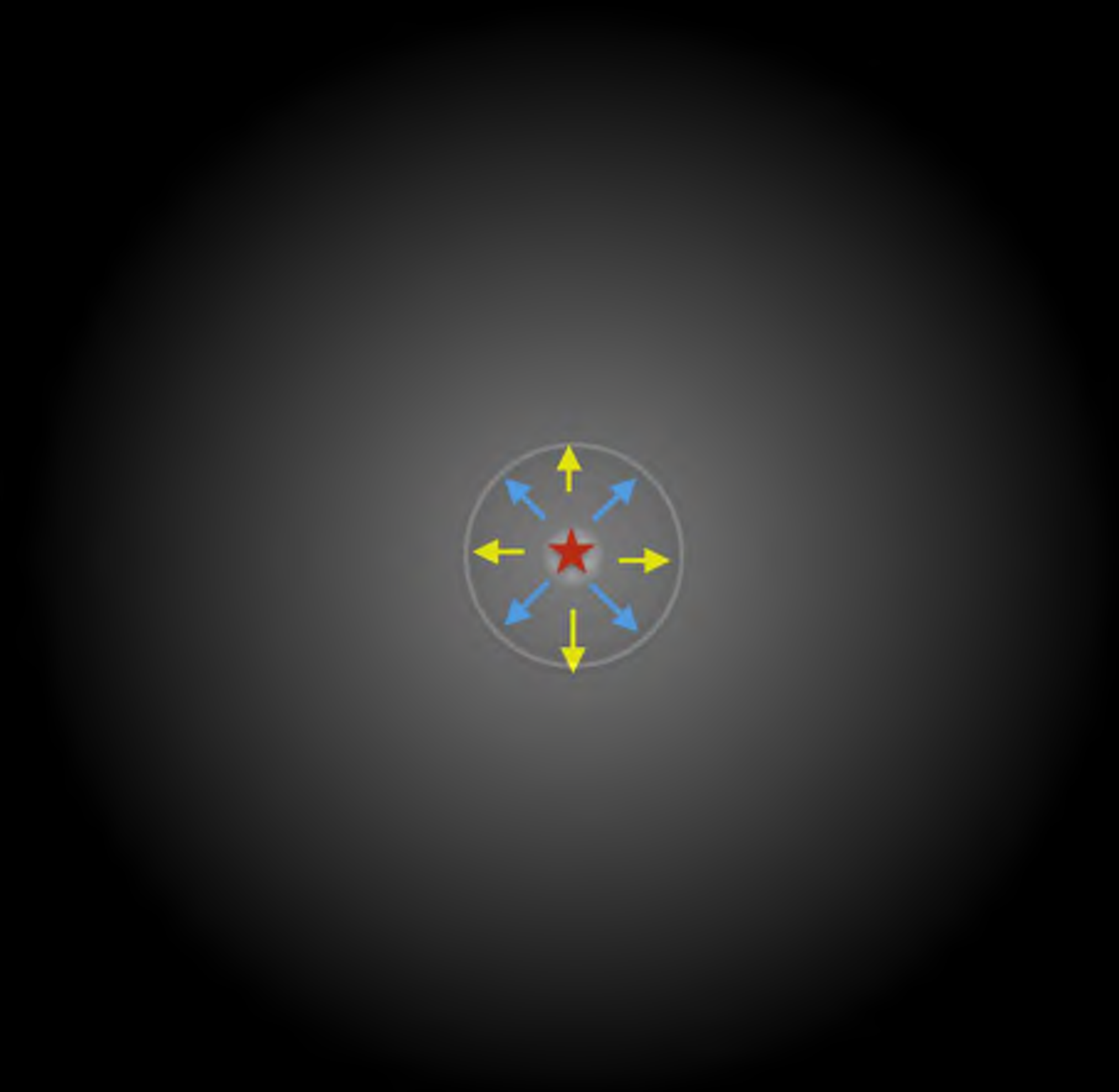
David Eichler (Ben-Gurion University, Israel)

Yuri Shchekinov (P. N. Lebedev Physical Institute, Russia)

Molecular Cloud - Star - Feedback

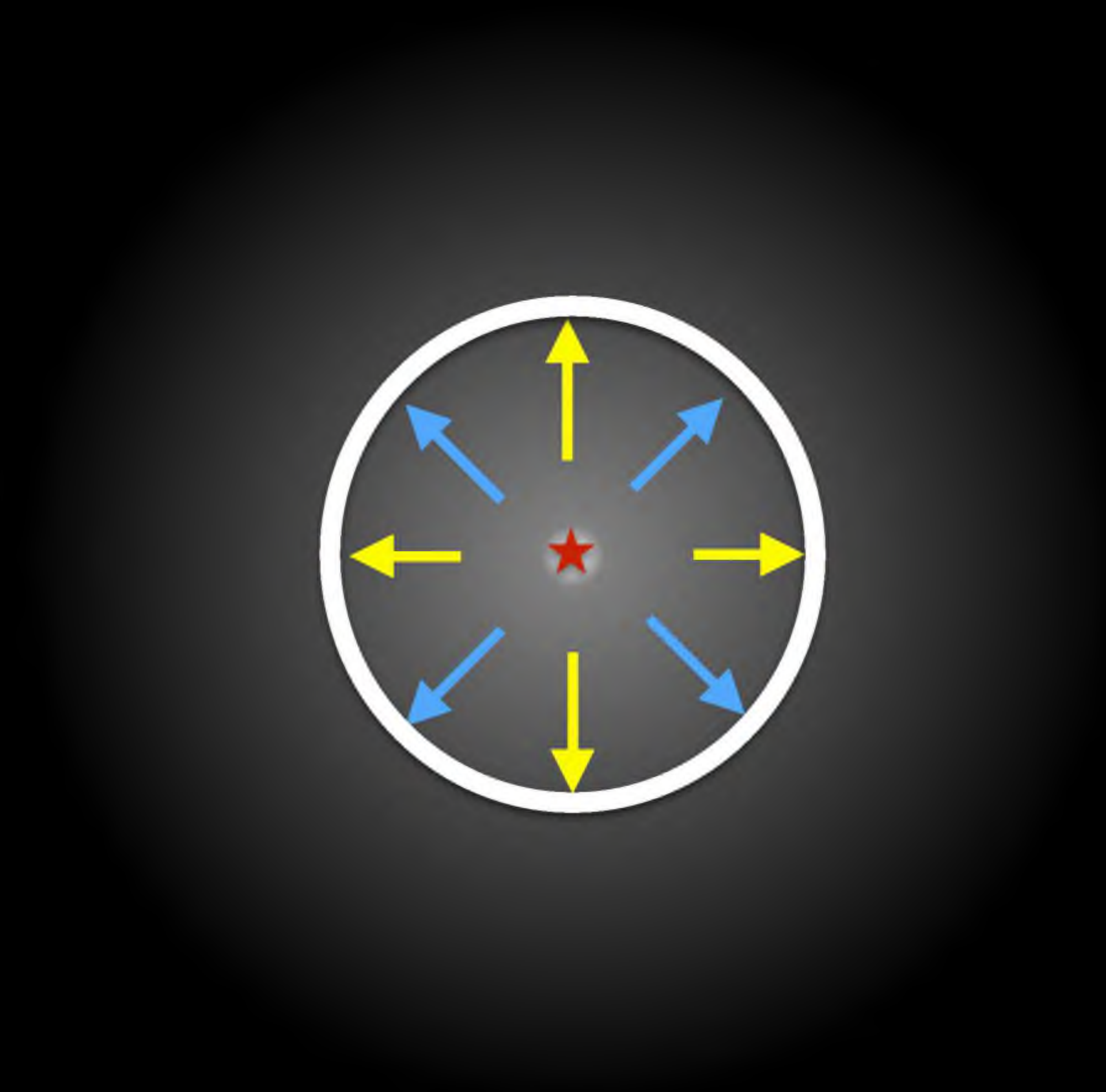


Molecular Cloud - Star - Feedback



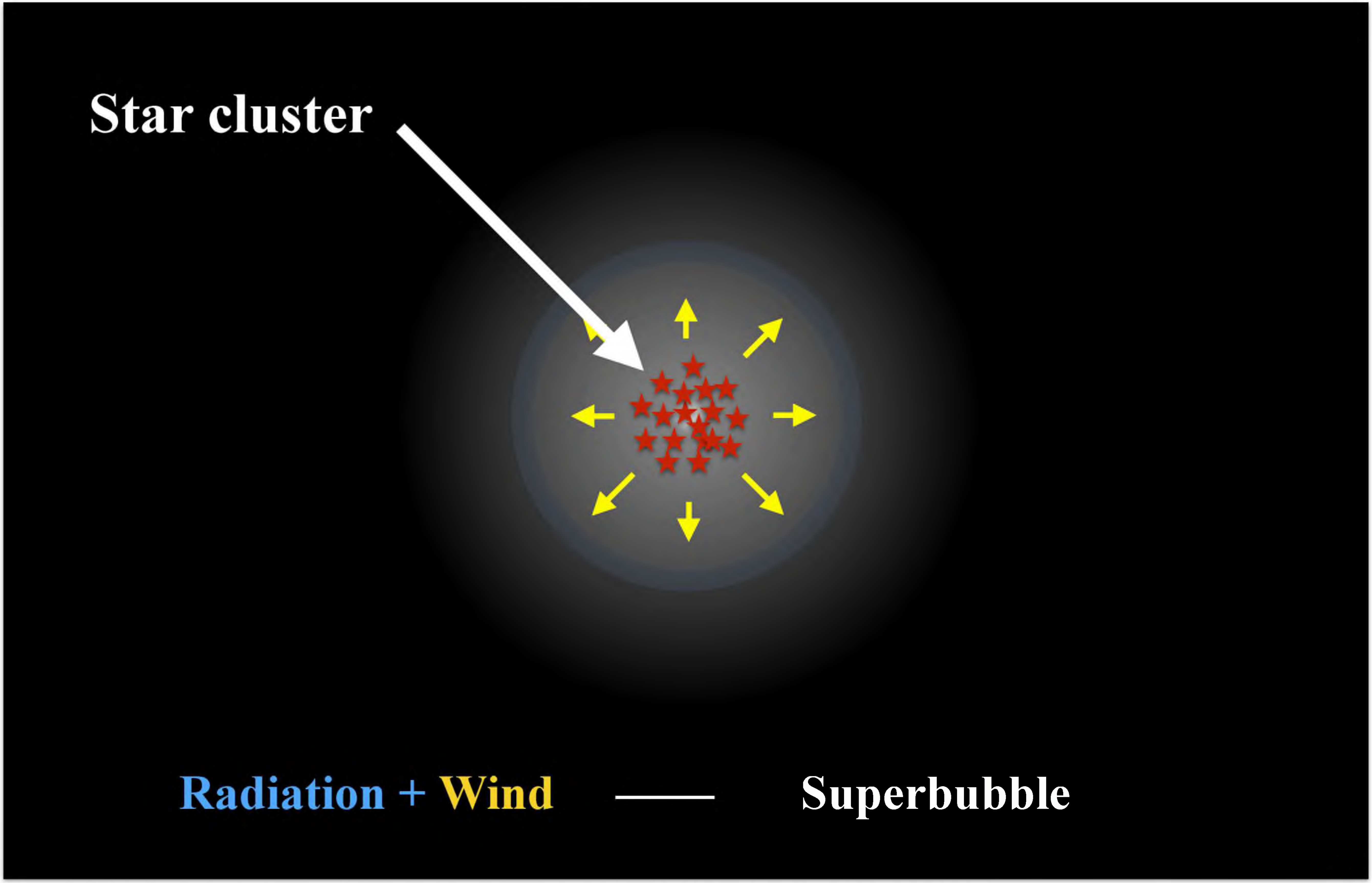
Radiation, Wind

Molecular Cloud - Star - Feedback

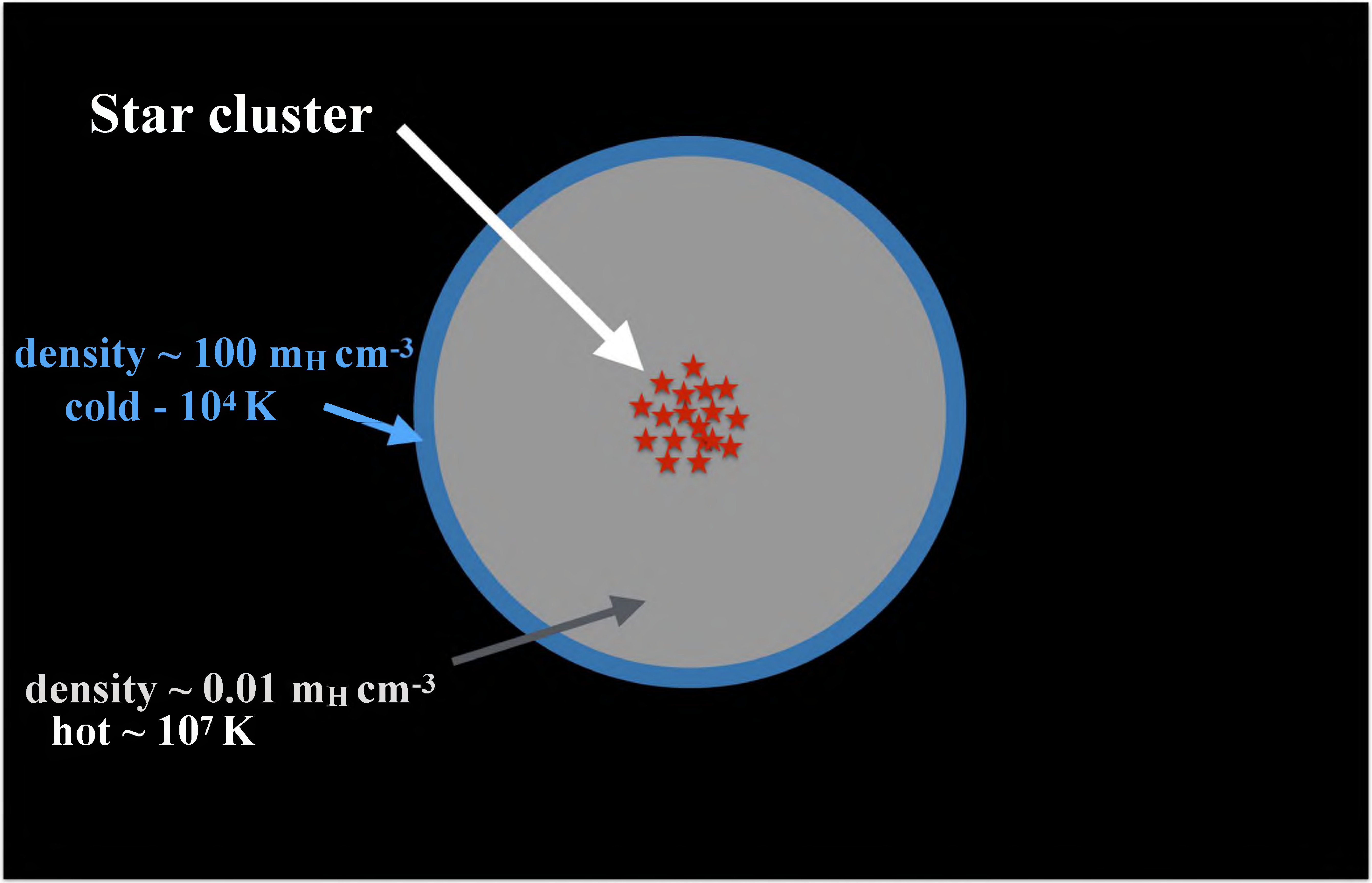


Radiation, Wind —— Interstellar bubble

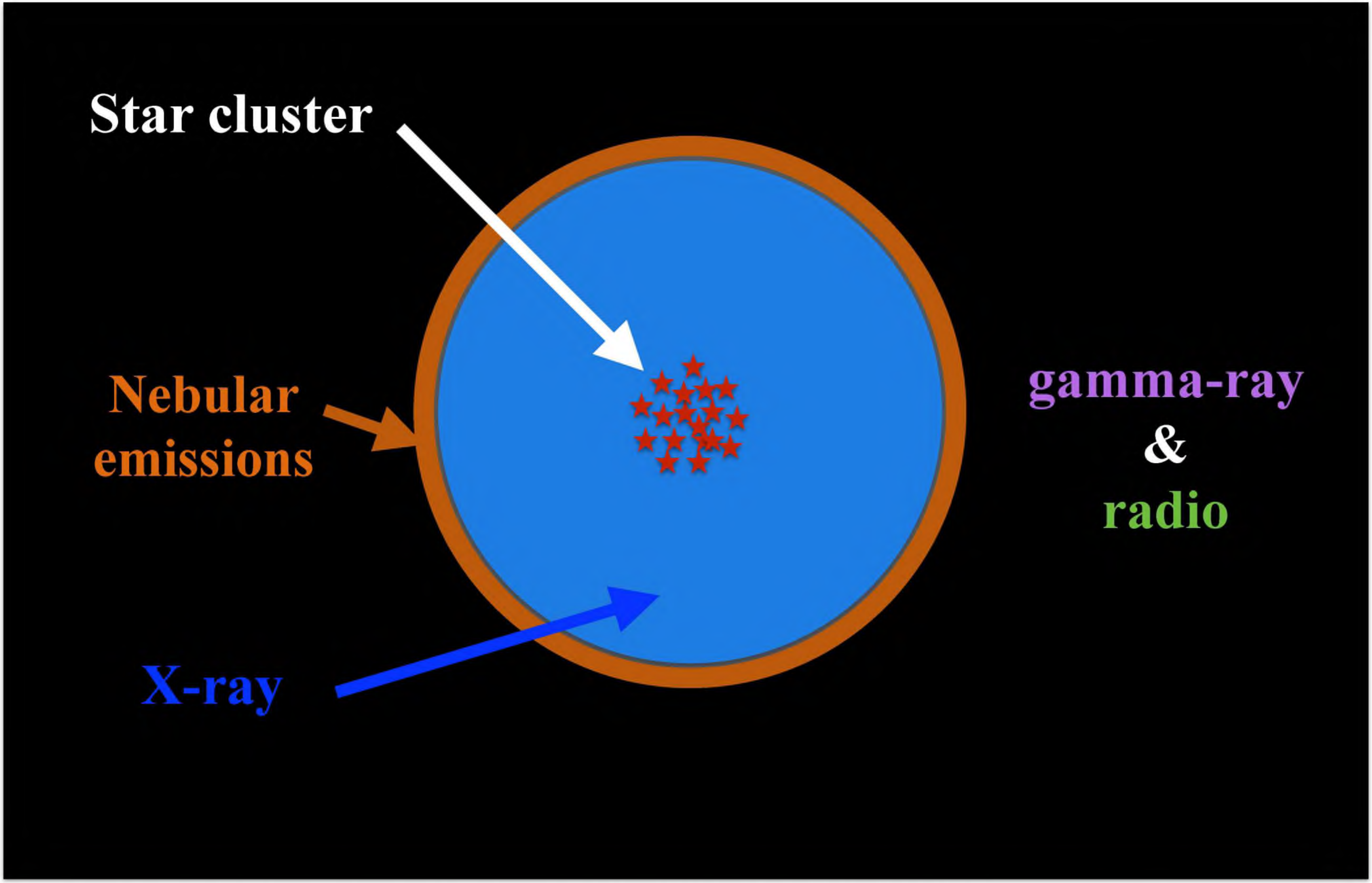
Molecular Cloud - Stars - Feedback



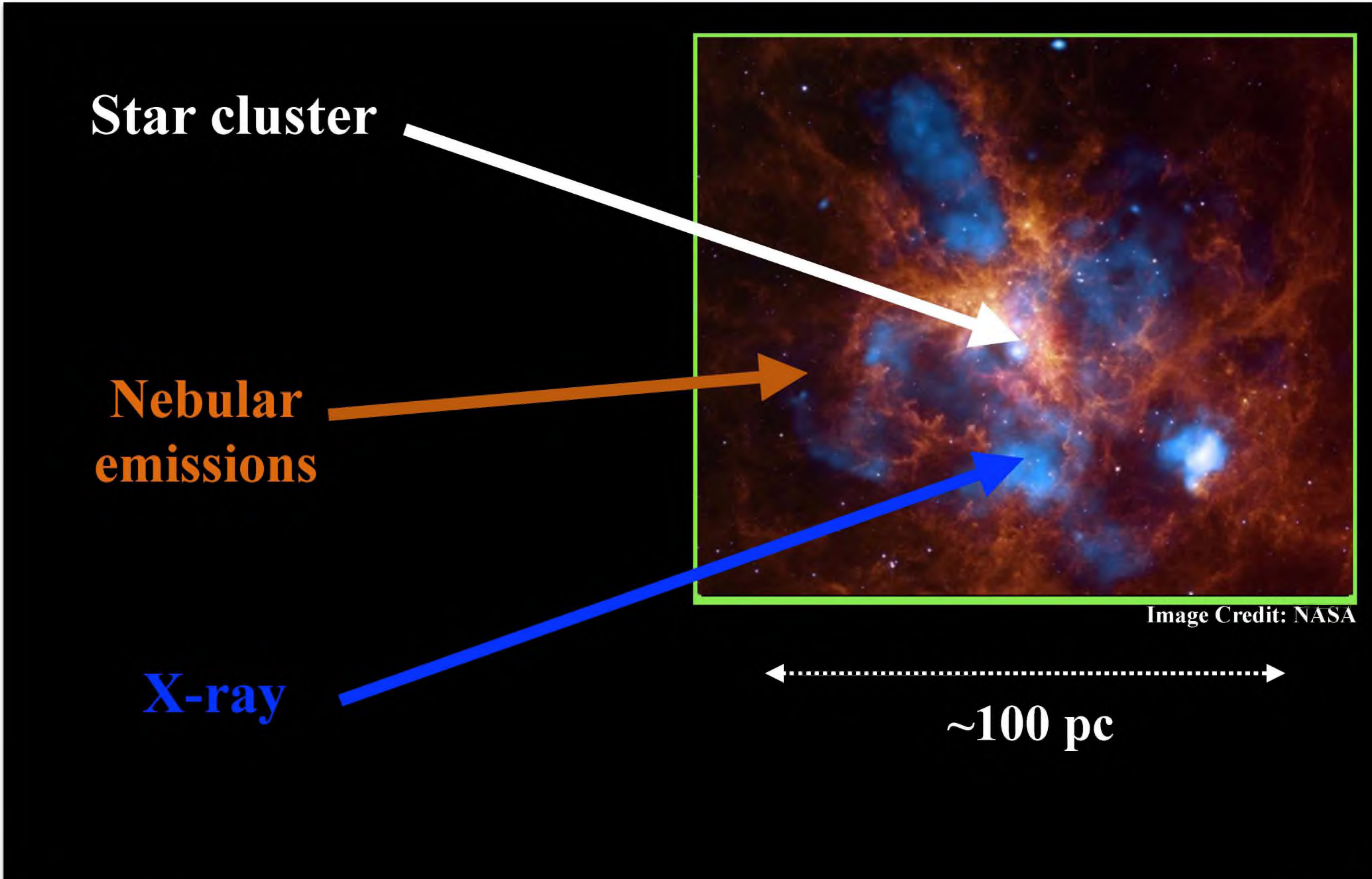
Molecular Cloud - Stars - Feedback



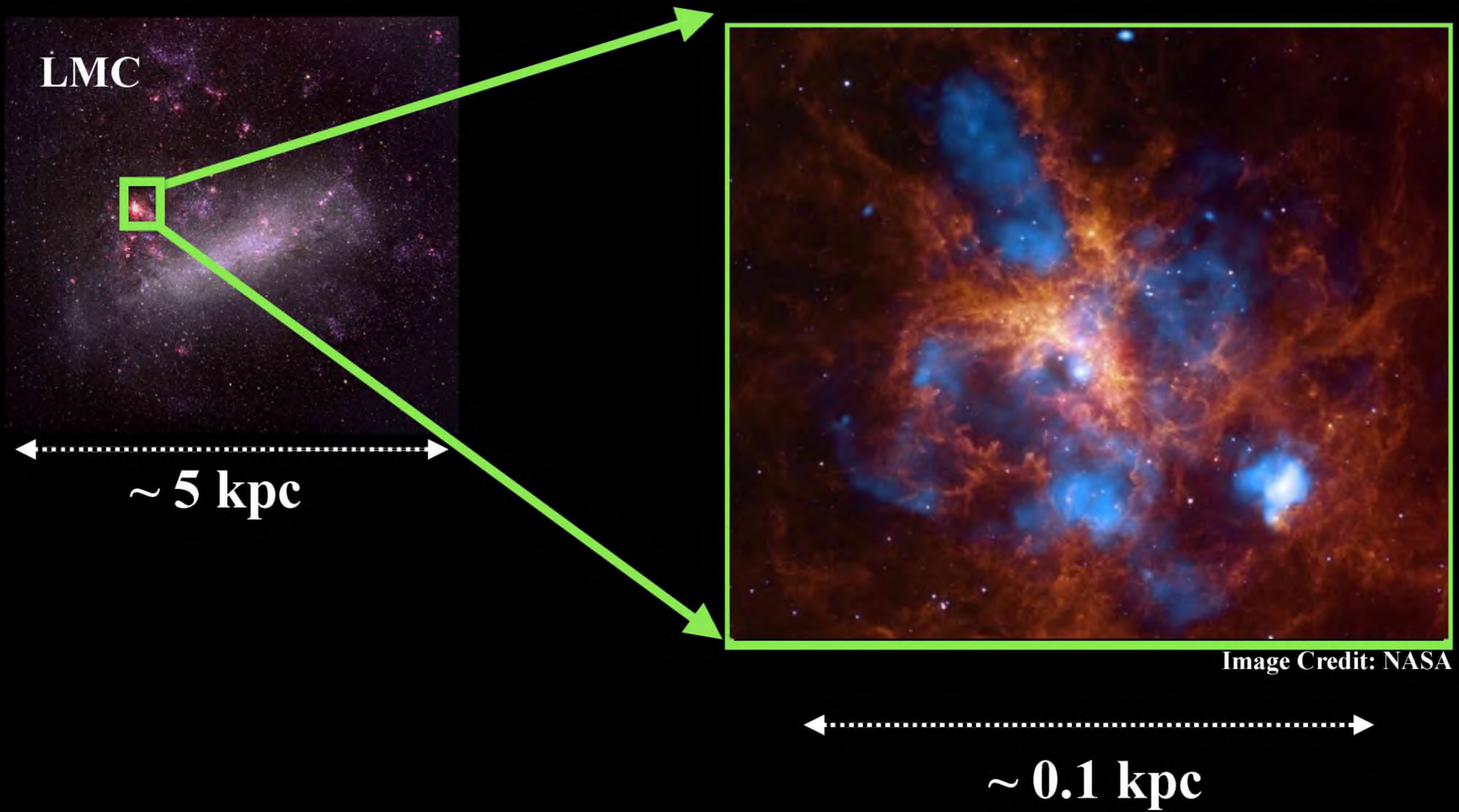
Star cluster driven structure



Star cluster driven structure



Diameter ~ 100 times smaller than a galaxy



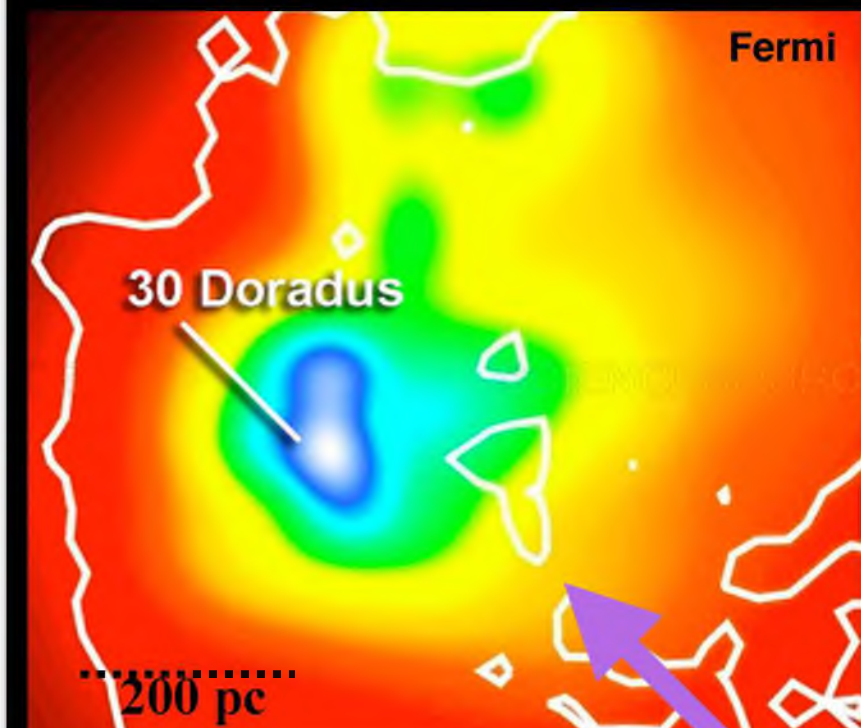
Building block of a galaxy

- found *everywhere* in a galaxy.
- help to understand galaxy evolution.

Stellar activities cause γ-ray, X-ray, radio emission

- A star cluster contains: ~ 10 — 1000 O/B stars.
- Wind mechanical power (L_w) ~ 10^{37} — 10^{39} erg s^{-1}
- Stellar radiation bolometric luminosity (L_{bol}) ~ 500 L_w

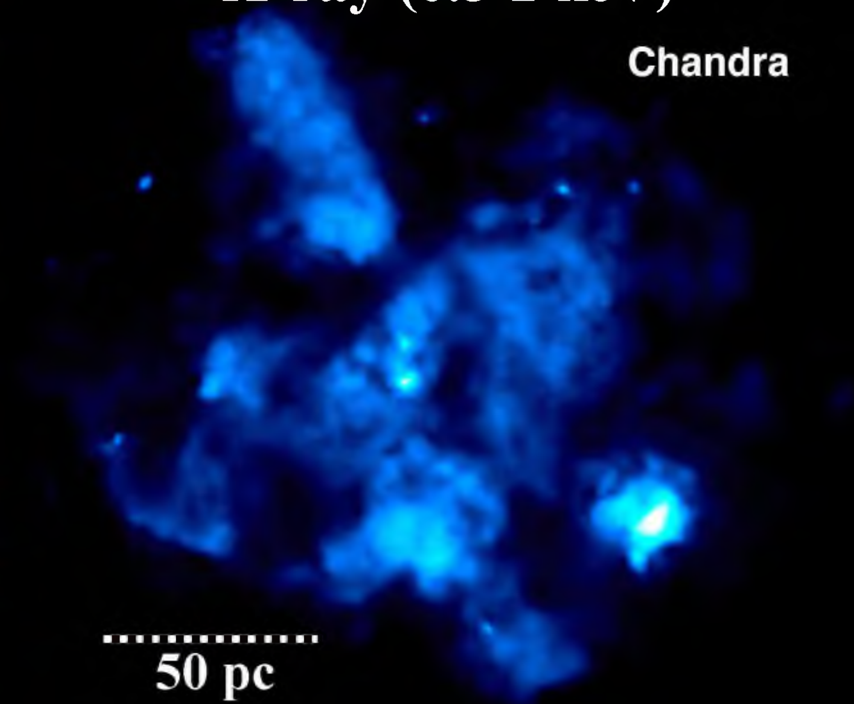
gamma-ray (0.1-200 GeV)



L_γ ~ 0.7% L_w

(Abdo et al. 2010)

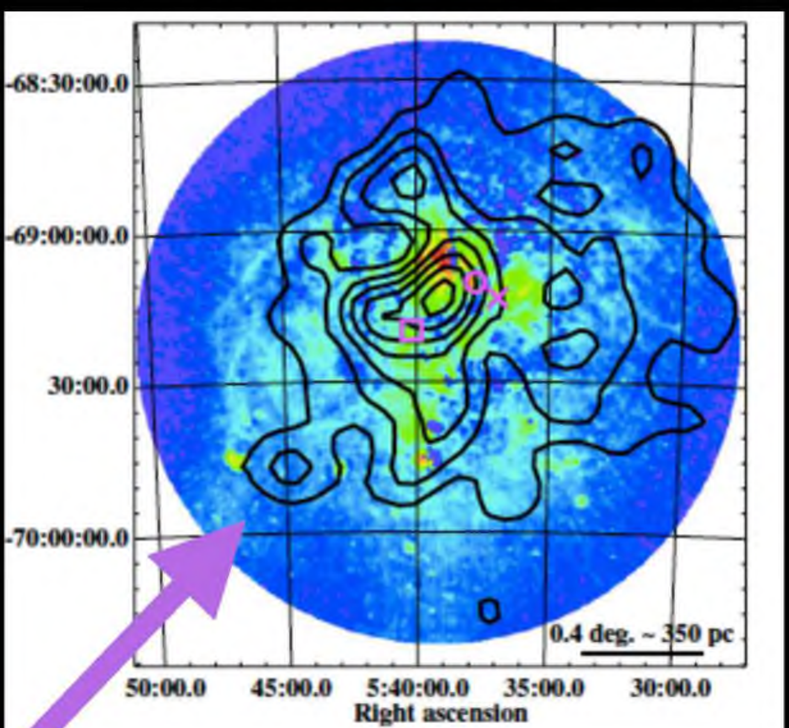
X-ray (0.5-2 keV)



L_X ~ 0.1% L_w

(Lopez et al. 2011)

non-thermal radio (1.4 GHz)



L_R (1.4 GHz) ~ 0.01% L_w

(Murphy et al 2012, Hughes et al. 2007)

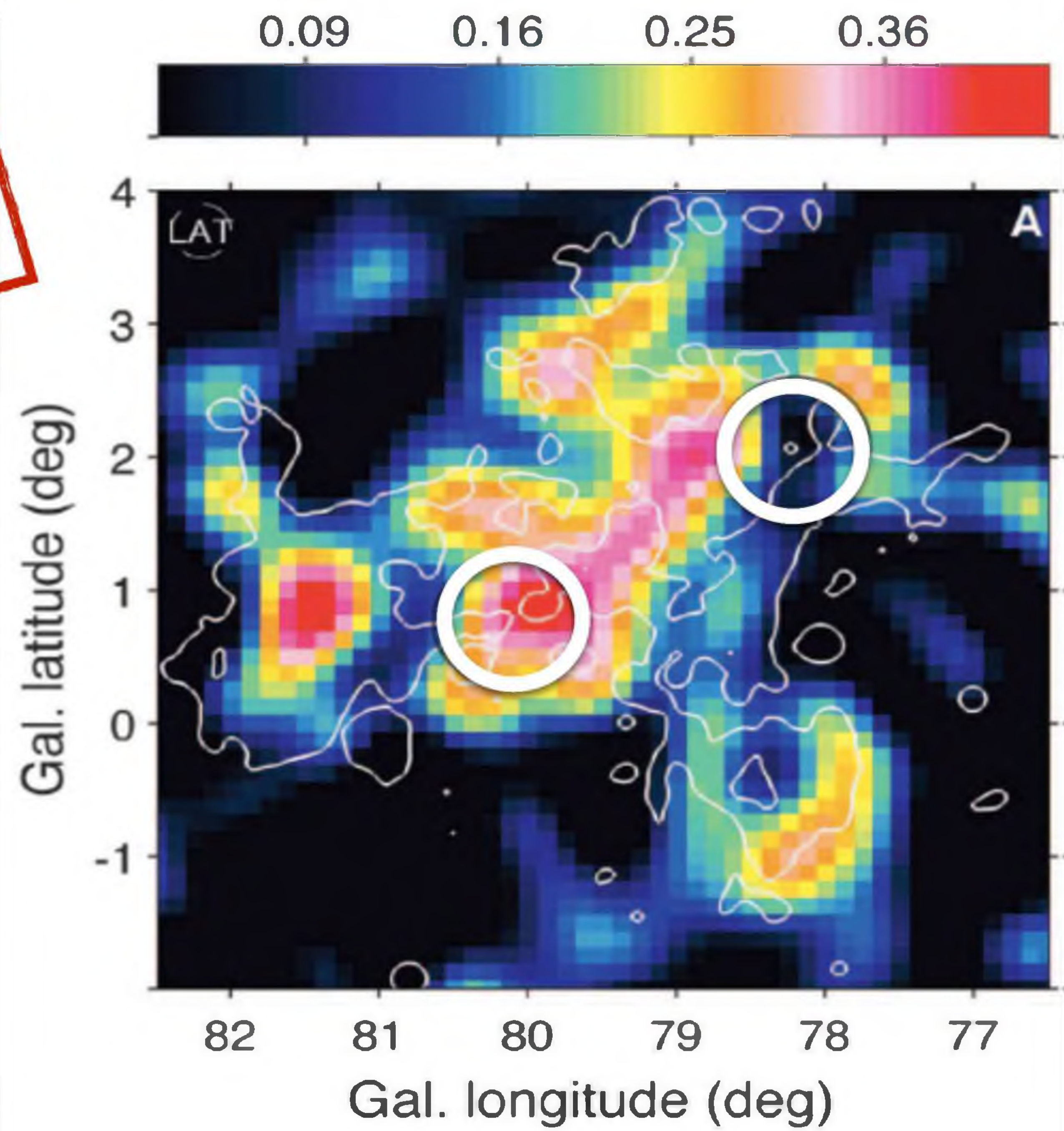
Evidence of cosmic ray (CR) acceleration ?

Stellar activit … dio emission

- Typically, a star cl
- Wind mechanical … $(10^3 - 10^5)\ L_\odot$
- Stellar radiation b … $(10^6 - 10^8)\ L_\odot$

Photon count map 10-100 GeV

A Cocoon of Freshly Accelerated Cosmic Rays Detected by Fermi in the Cygnus Superbubble



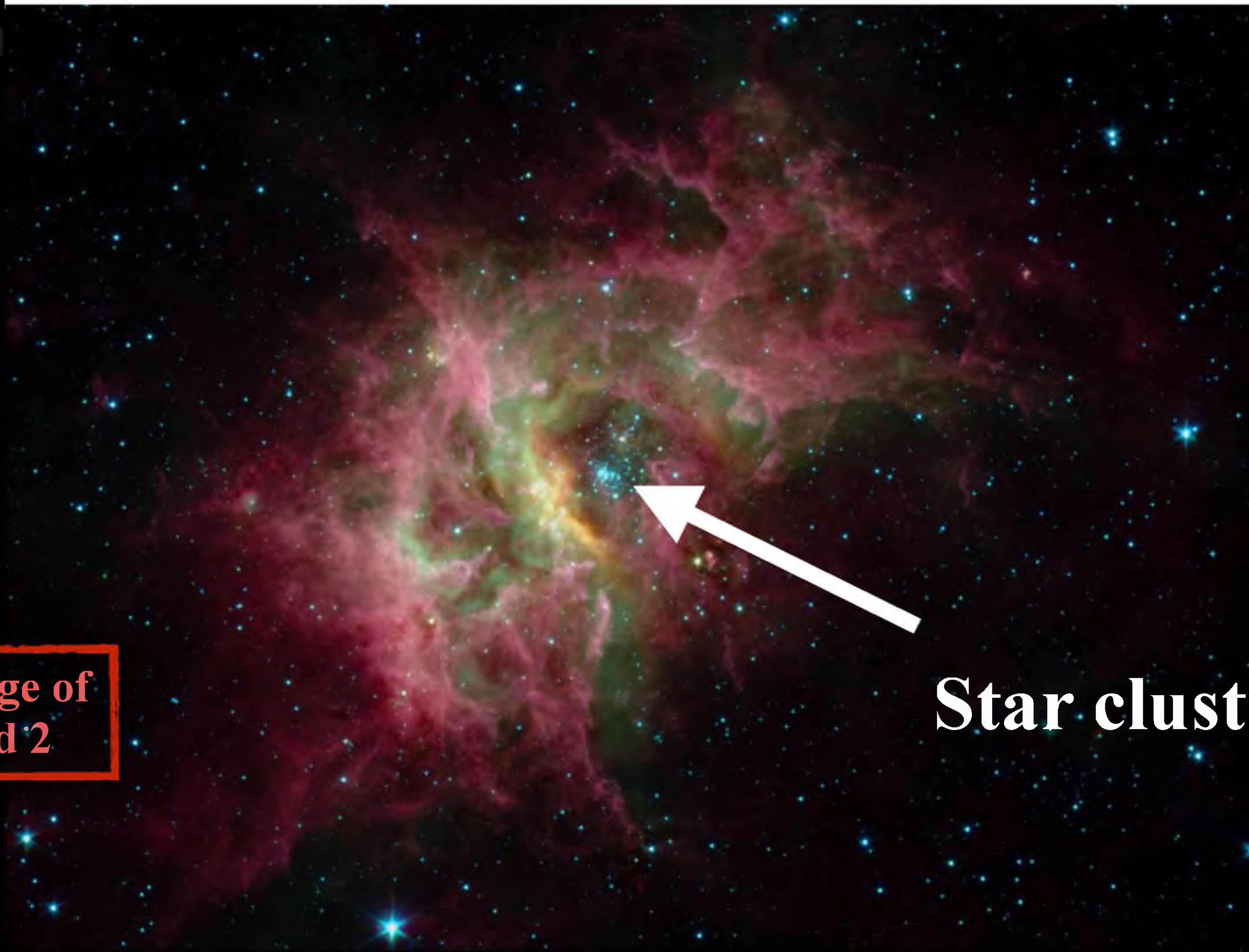
Ackermann et al. 2011 Science, 334, 1103

Stellar ac… …mission

- Typically, …
- Wind mec…
- Stellar rad…

Diffuse γ-ray emission in the vicinity of young star cluster Westerlund 2

Yang, de Ona Wilhelmi & Aharonian A&A 611, A77 (2018)



Infrared image of Westerlund 2

Image credit: E. Churchwell, NASA

Questions to be answered

1. How does cosmic ray acceleration affect the structure of superbubble?

2. Impact on multi-wavelength luminosities.

Theoretical modeling

1. Mass
2. Momentum
3. Energy

Drury & Völk (1981), Drury & Falle (1986)

Two-fluid equations:
Moment of Boltzmann equation +
Fokker-Planck CR transport equation.

Equations solved …

Spitzer (1962)

Cloudy (Ferland et al 1998)

1. Mass
2. Momentum — CR term
3. Energy — CR term — Thermal conduction — Cooling + Heating
4. CR Energy — CR diffusion — CR Cooling

Drury & Voelk (1981)

Guo & Oh (2008)

Equations solved …

1. $\frac{\partial\rho}{\partial t} + \vec{\nabla}.(\rho\,\vec{v}) = S_\rho$

2. $\frac{\partial}{\partial t}(\rho\,\vec{v}) + \vec{\nabla}.(\rho\,\vec{v}\otimes\vec{v} + p_{\rm tot}) = \rho\vec{g}$

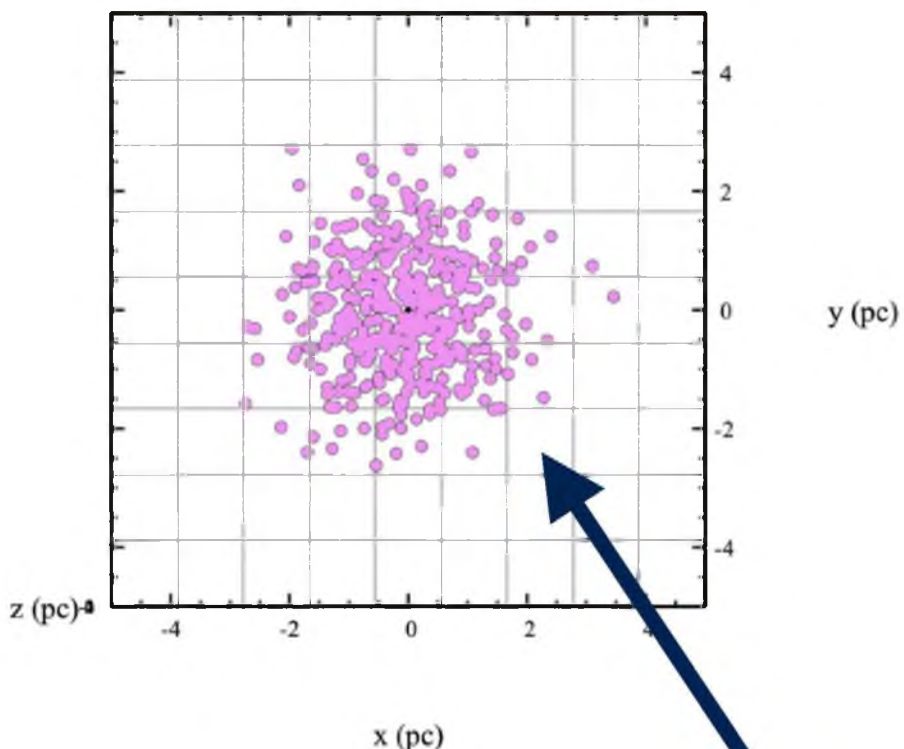
3. $\frac{\partial e_{\rm tot}}{\partial t} + \vec{\nabla}.\left[(e_{\rm tot} + p_{\rm tot})\,\vec{v} + \vec{F}_{\rm t} + \vec{F}_{\rm crd}\right] = \rho\vec{v}.\vec{g} + S_{\rm e} - q_{\rm th}^{\rm eff}$

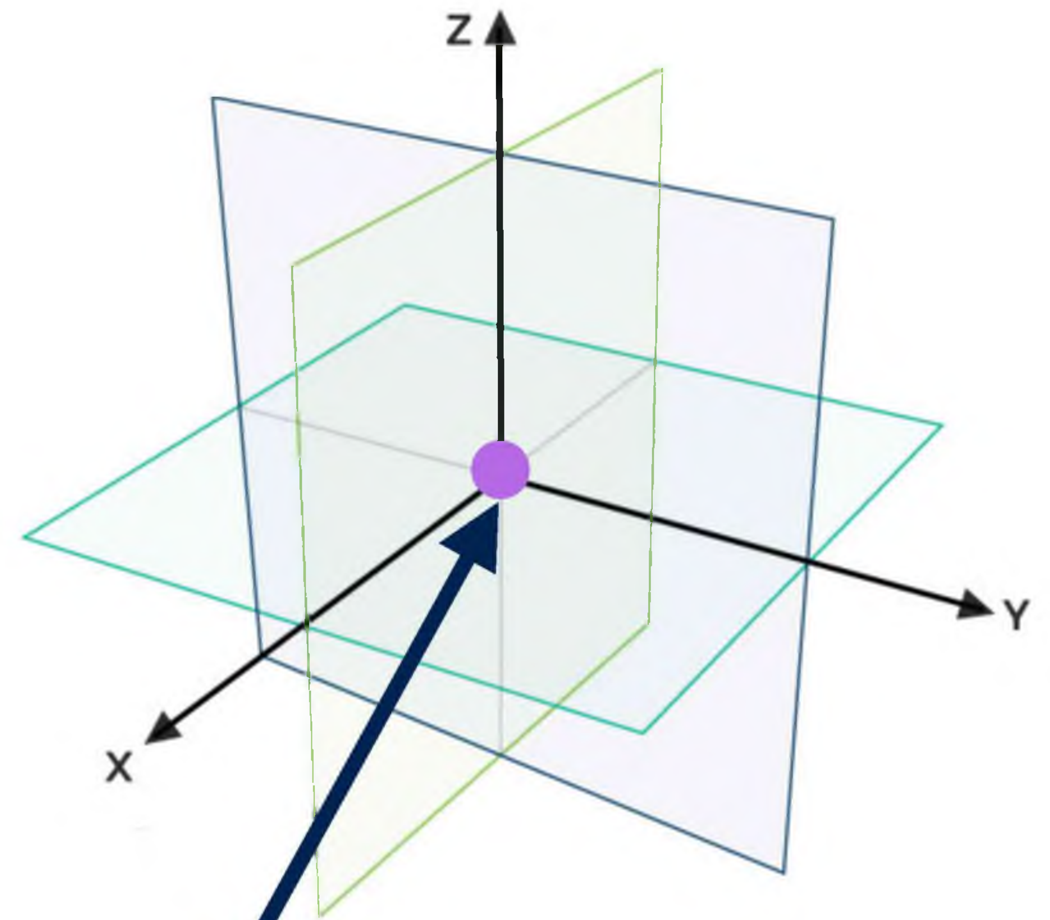
4. $\frac{\partial\, e_{\rm cr}}{\partial t} + \vec{\nabla}.\left[e_{\rm cr}\,\vec{v} + \vec{F}_{\rm crd}\right] = -p_{\rm cr}\vec{\nabla}.\vec{v} + S_{\rm cr} - q_{\rm cr}$

Implemented two-fluid eqs in the PLUTO code

Gupta, S., Sharma, P & Mignone, A. (arXiv:1906.07200)

Simulation set-up





Stars

grid resolution

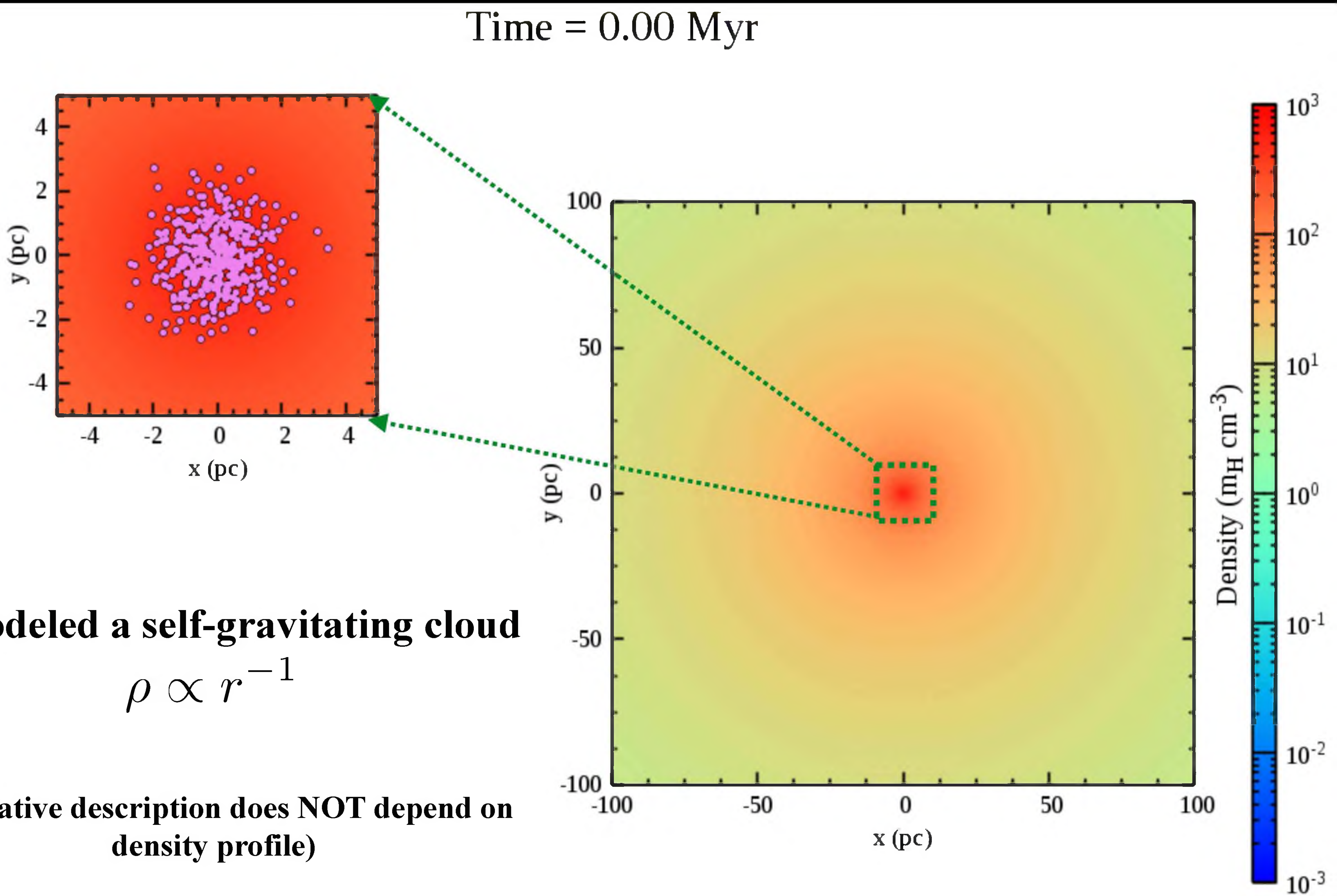
central 5 pc region

$\Delta r = 0.1\,\mathrm{pc}$

other region

$\Delta r \approx 0.5\,\mathrm{pc}$

Ambient density profile

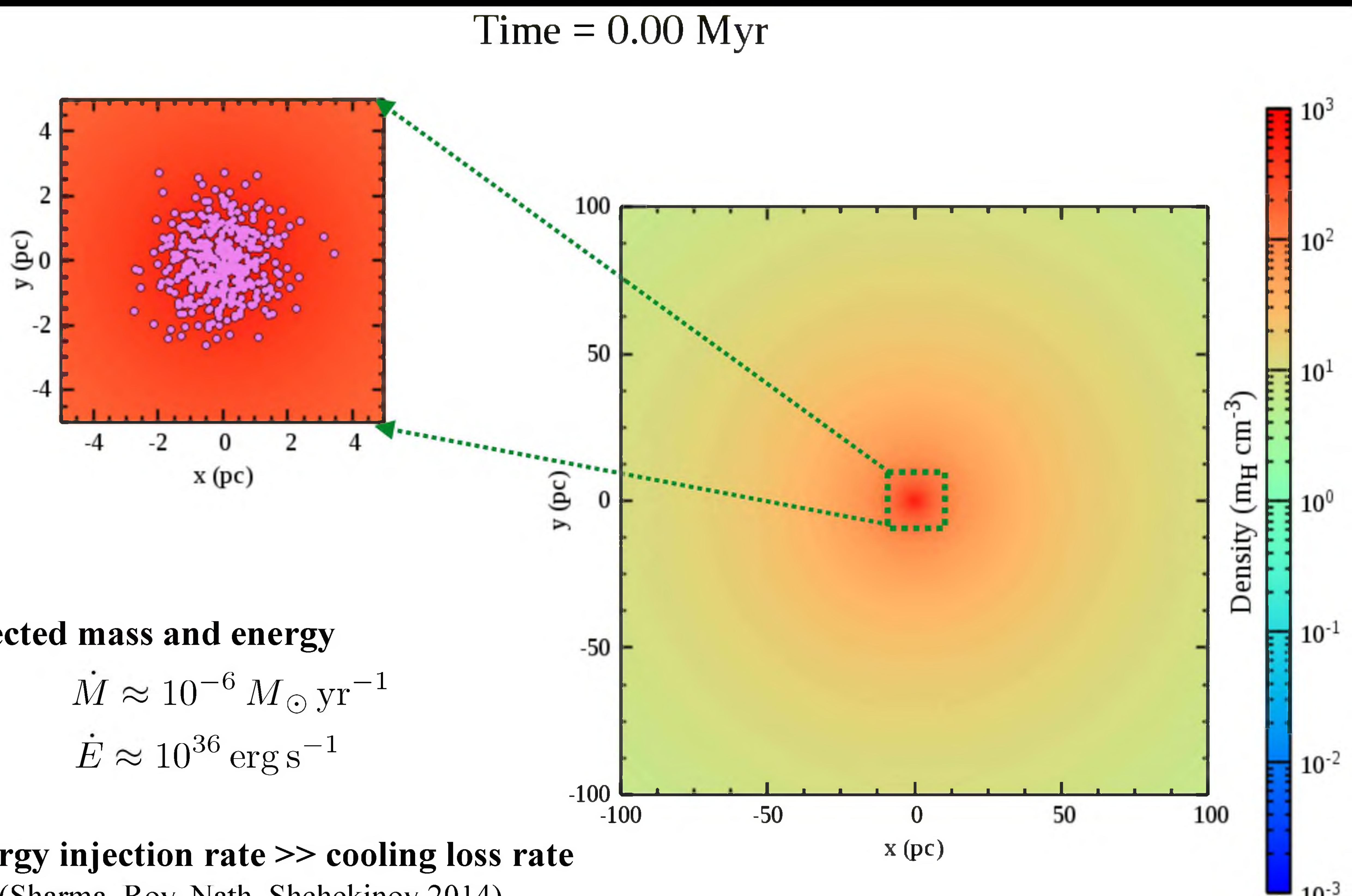


- **modeled a self-gravitating cloud**

$$\rho \propto r^{-1}$$

(qualitative description does NOT depend on density profile)

Ambient density profile



- **injected mass and energy**

$$\dot{M} \approx 10^{-6}\, M_\odot\, \mathrm{yr}^{-1}$$

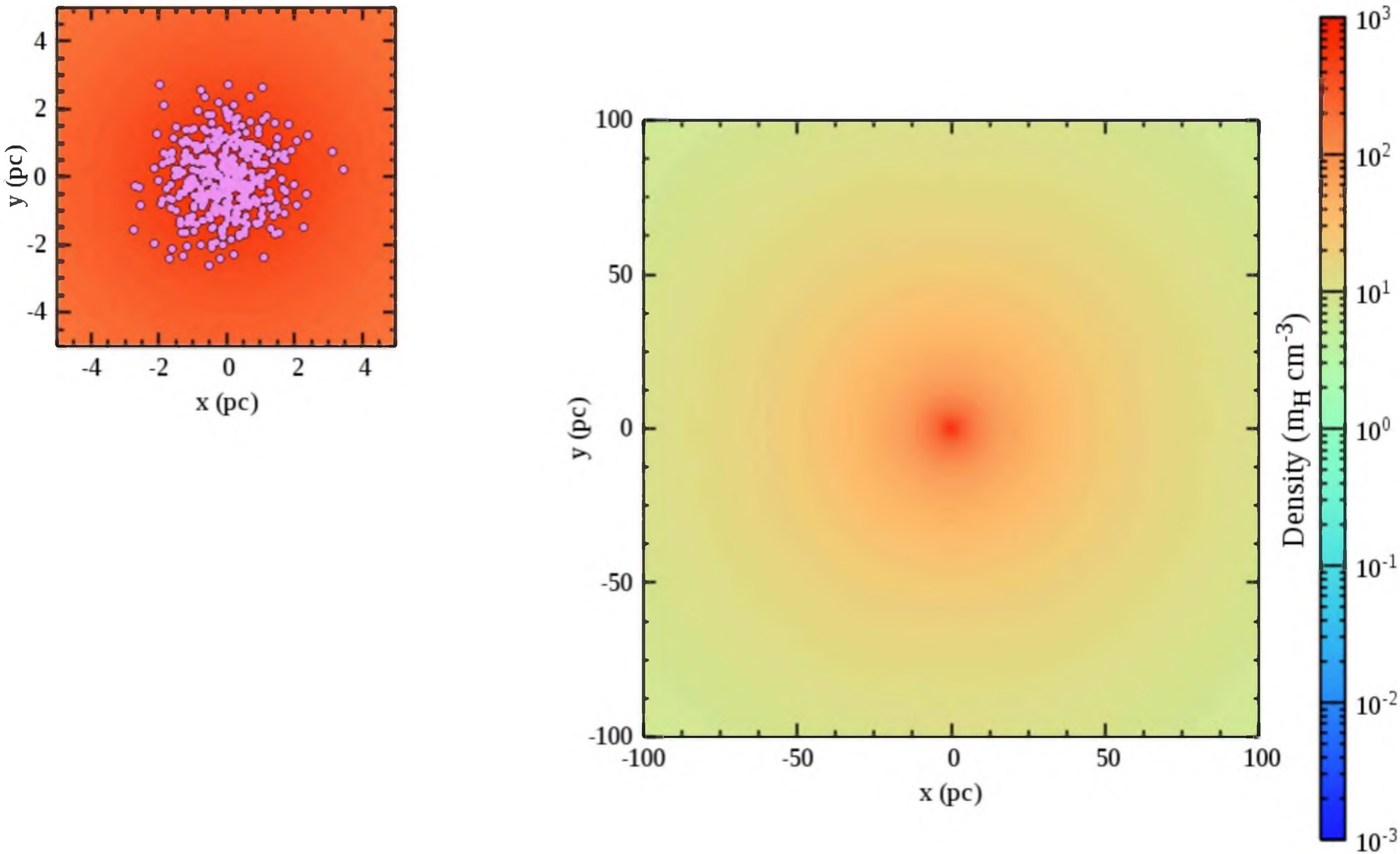
$$\dot{E} \approx 10^{36}\, \mathrm{erg\, s}^{-1}$$

- **energy injection rate >> cooling loss rate**

(Sharma, Roy, Nath, Shchekinov 2014)

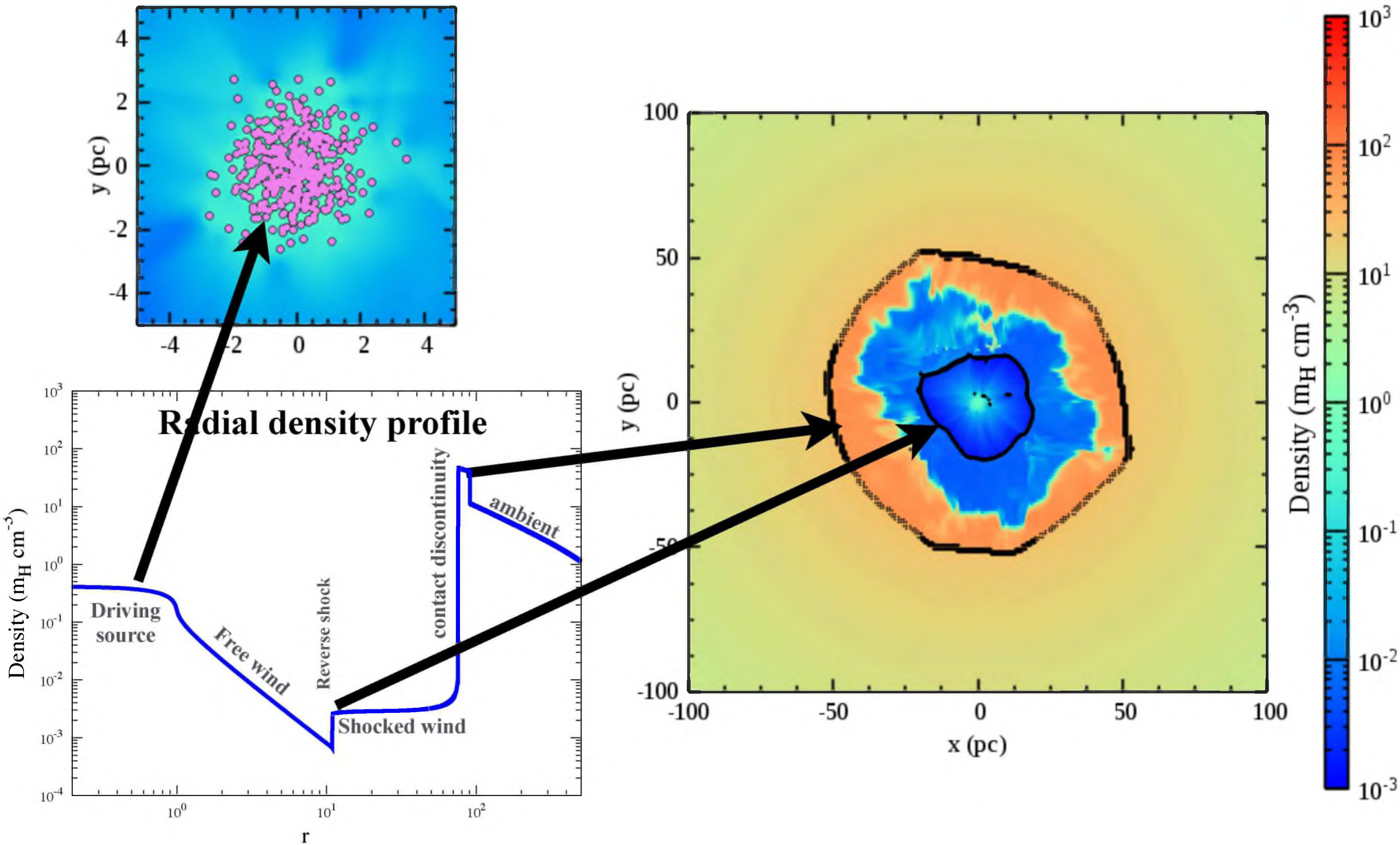
Evolution of superbubble

Time = 0.00 Myr



Density structure

Time = 2.15 Myr

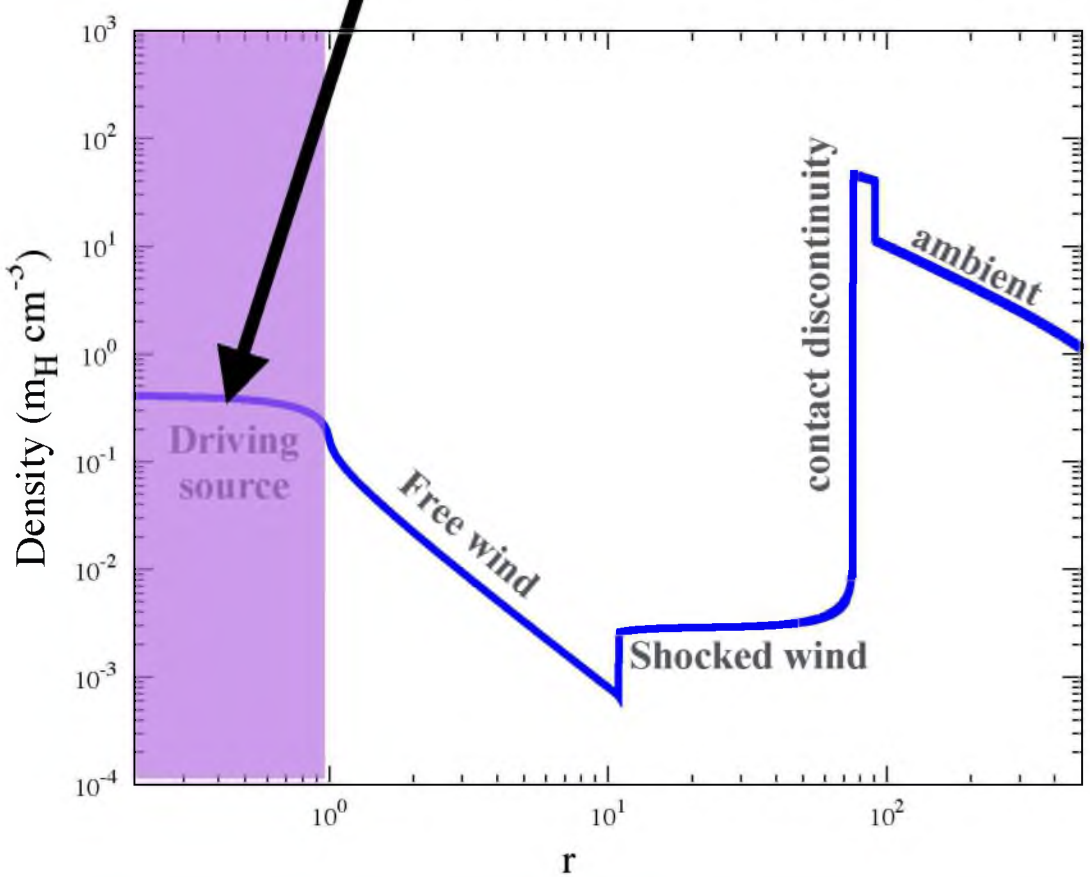


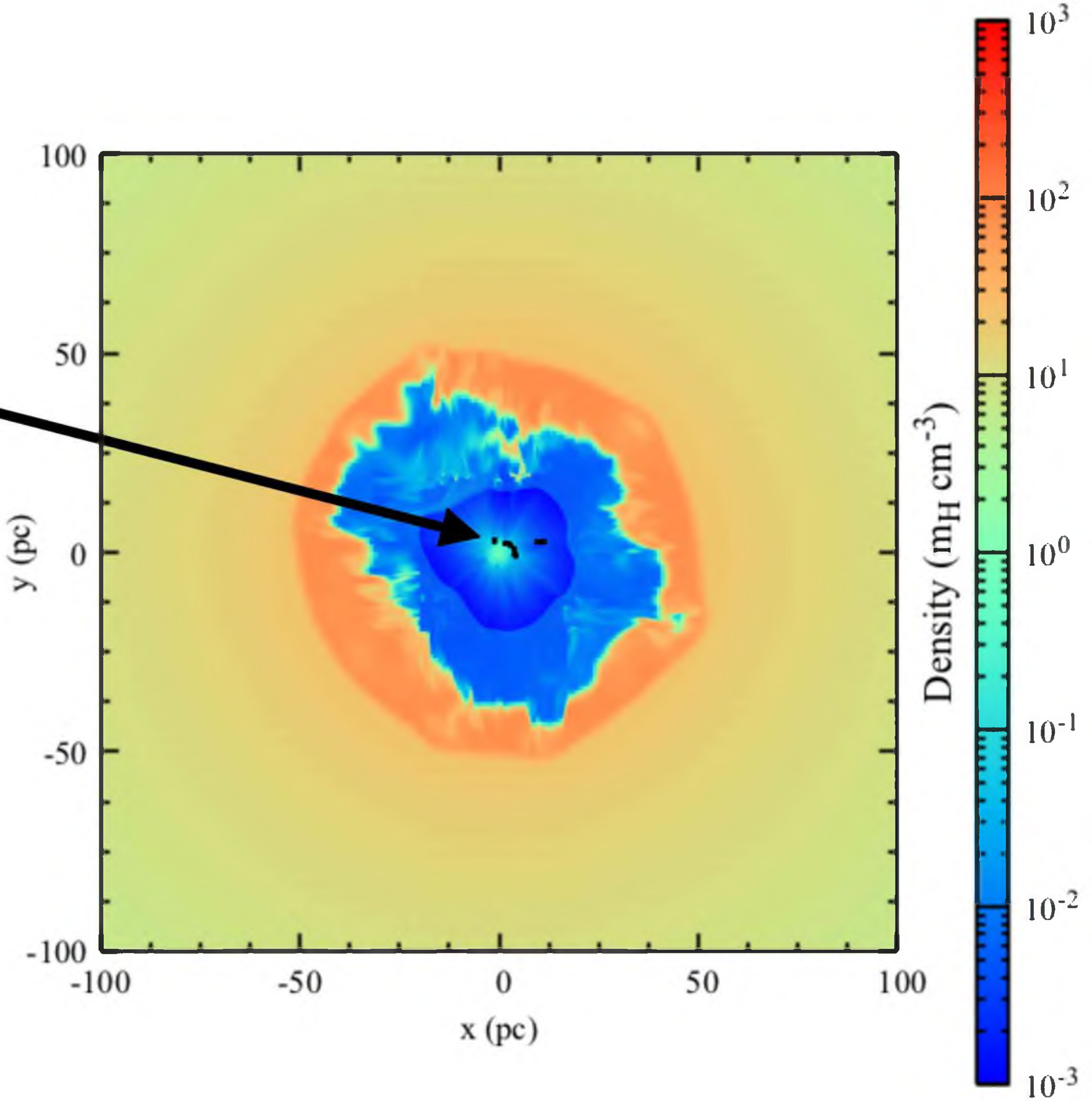
Cosmic ray injection: wind driving region?

Case I:

$$\dot{E}_{\rm cr} = \epsilon_{\rm cr}\,\dot{E}$$

$$\epsilon_{\rm cr} \approx 0.01 - 0.2$$

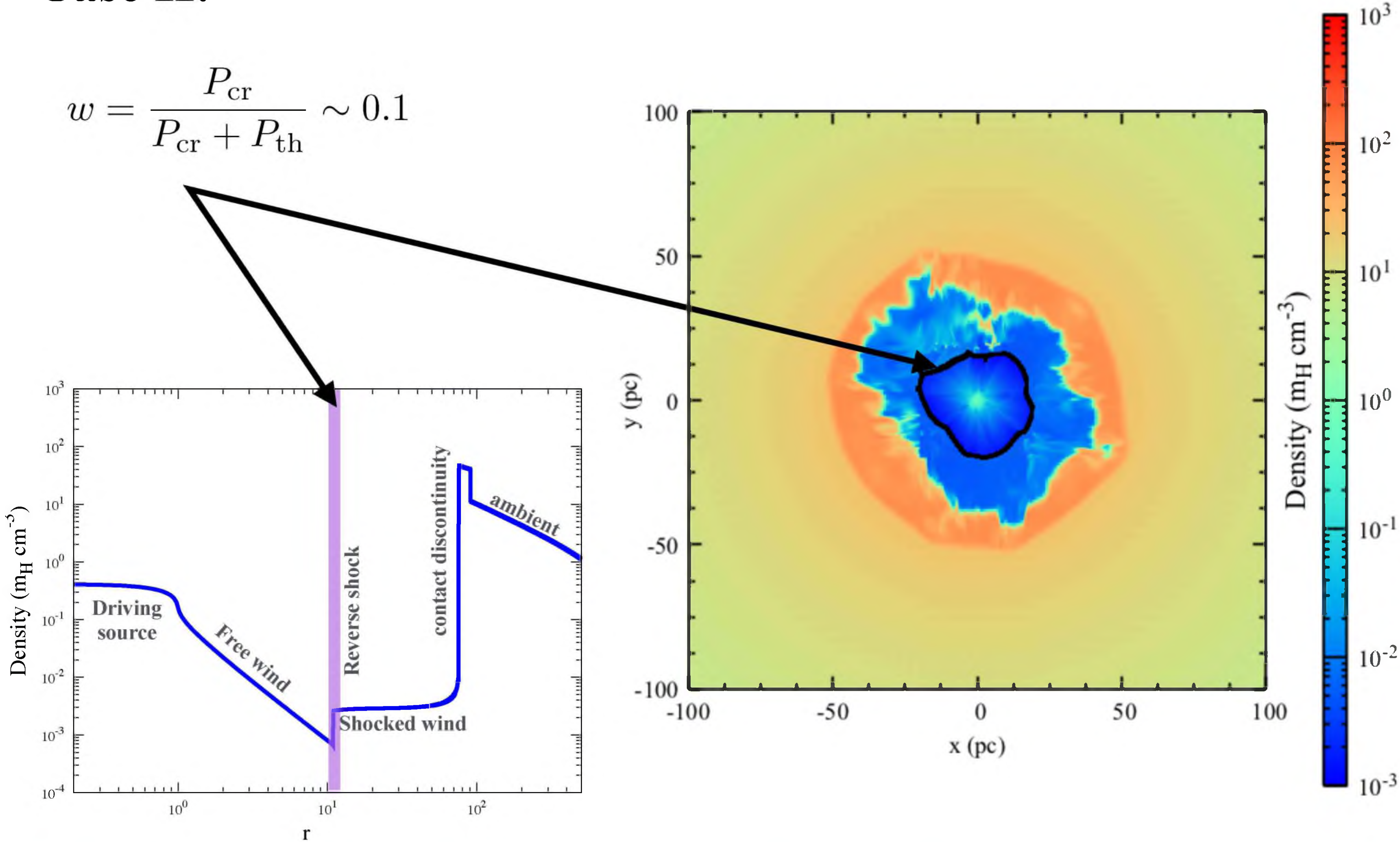




Cosmic ray injection: reverse & forward shock?

Case II:

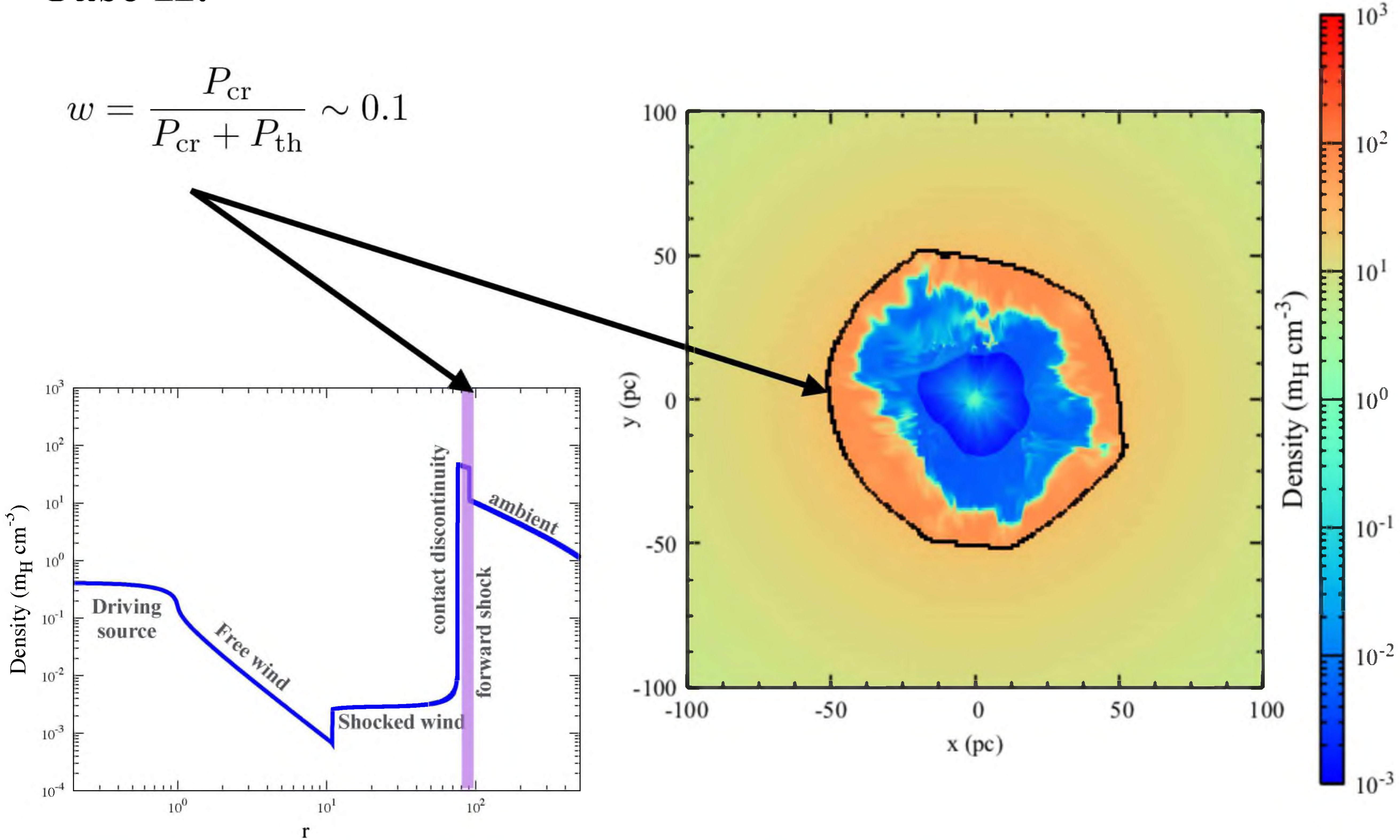
$$w = \frac{P_{\rm cr}}{P_{\rm cr} + P_{\rm th}} \sim 0.1$$



Cosmic ray injection: reverse & forward shock?

Case II:

$$w = \frac{P_{\rm cr}}{P_{\rm cr} + P_{\rm th}} \sim 0.1$$



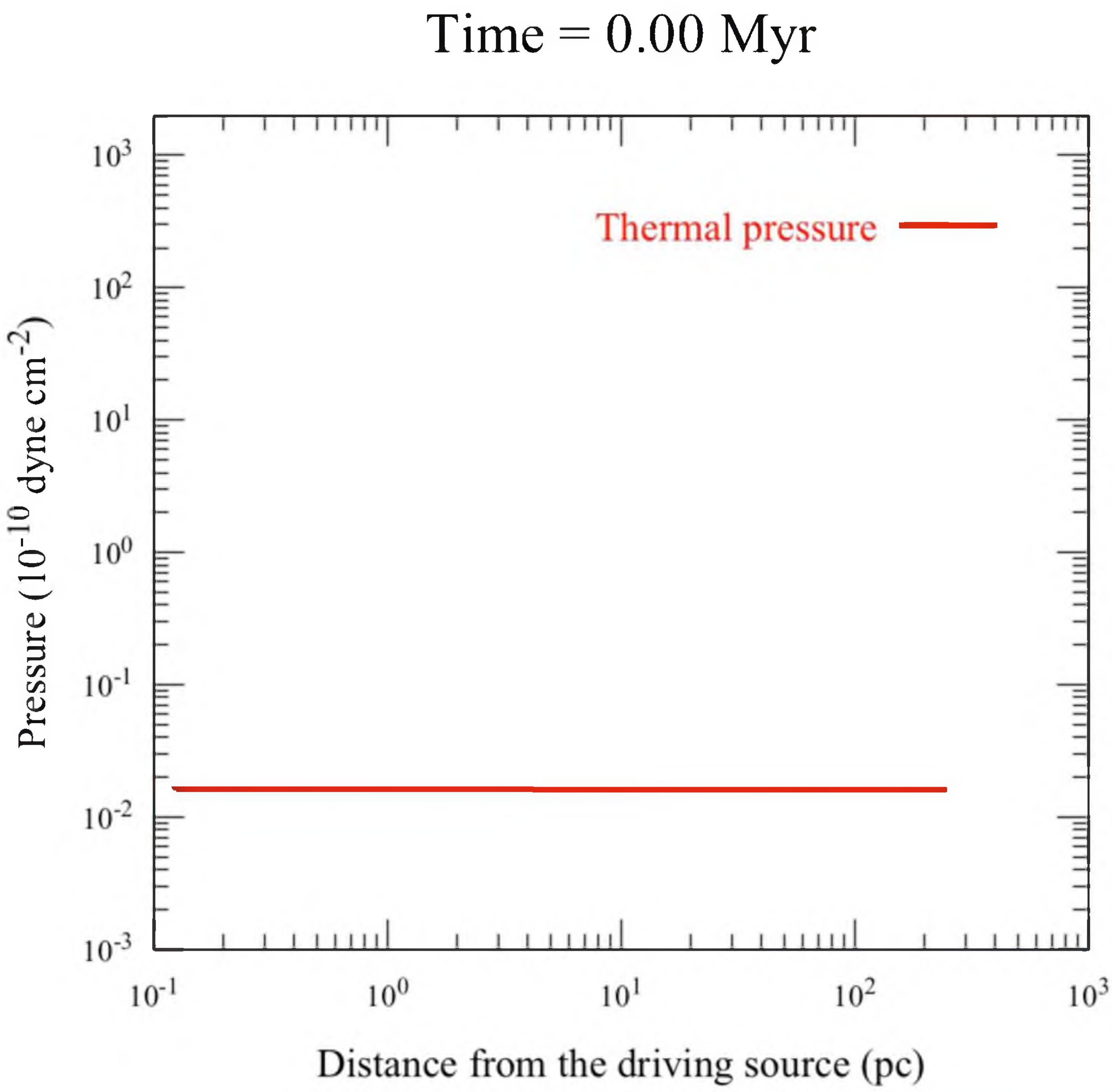
Confusion: where to inject cosmic rays …

Cluster core ?

Reverse and forward shocks?

we investigate two cases separately.

One-fluid model (without cosmic rays)



- **Evolution of Mach number**

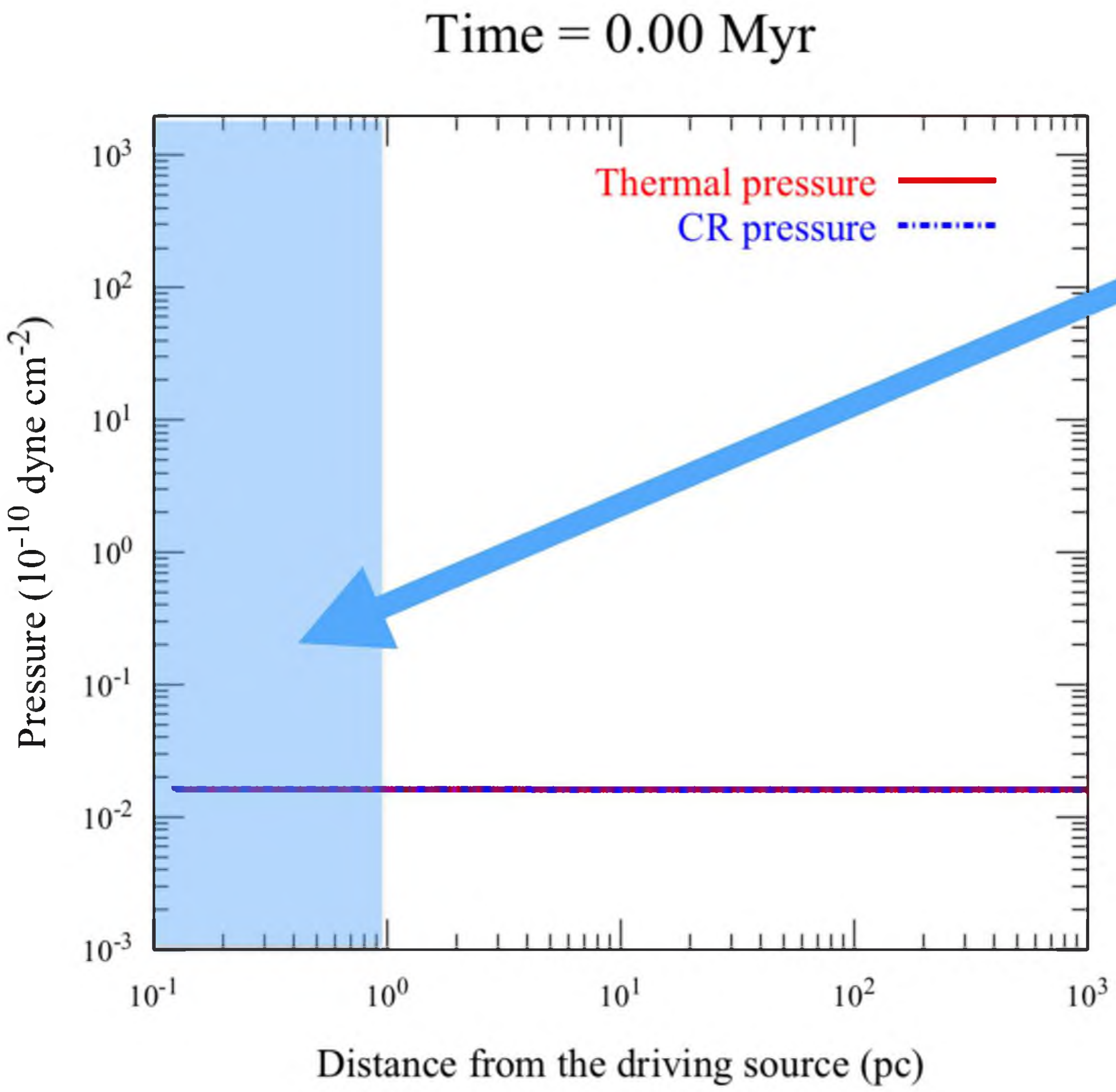
$$\mathcal{M} = \frac{\text{Shock speed}}{\text{sound speed}}$$

Forward shock decreases ↓

Reverse shock increases ↑

$$\mathcal{M} \simeq 8.15\,\eta^{-2/15} R_{\rm src,pc}^{-2/3}\,\rho_2^{-1/5}\,\dot{M}_{-4}^{1/6}\,L_{39}^{1/30}\,t_6^{4/15}$$

Case I: CR injection in cluster core region



$$\dot{E}_{cr} = \epsilon_{cr}\, \dot{E}$$

$$\epsilon_{cr} = 0.1$$

- **Evolution of Mach number**

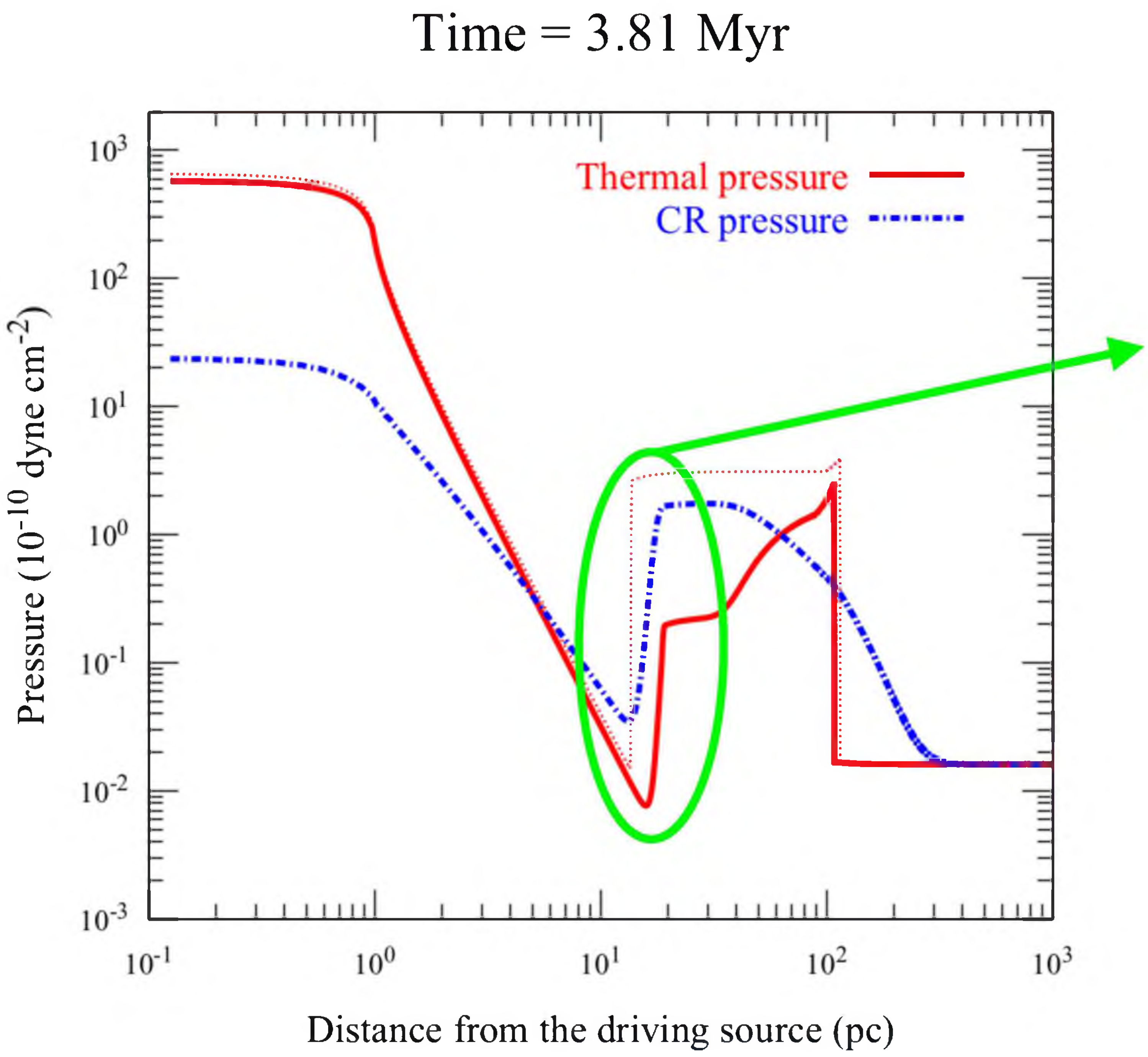
$$\mathcal{M} = \frac{\text{Shock speed}}{\text{sound speed}}$$

Forward shock decreases ↓

Reverse shock increases ↑

Gupta, S., **Nath, B. B., Sharma, P. & Eichler, D. 2018a, MNRAS**

Case I: CR injection in cluster core region



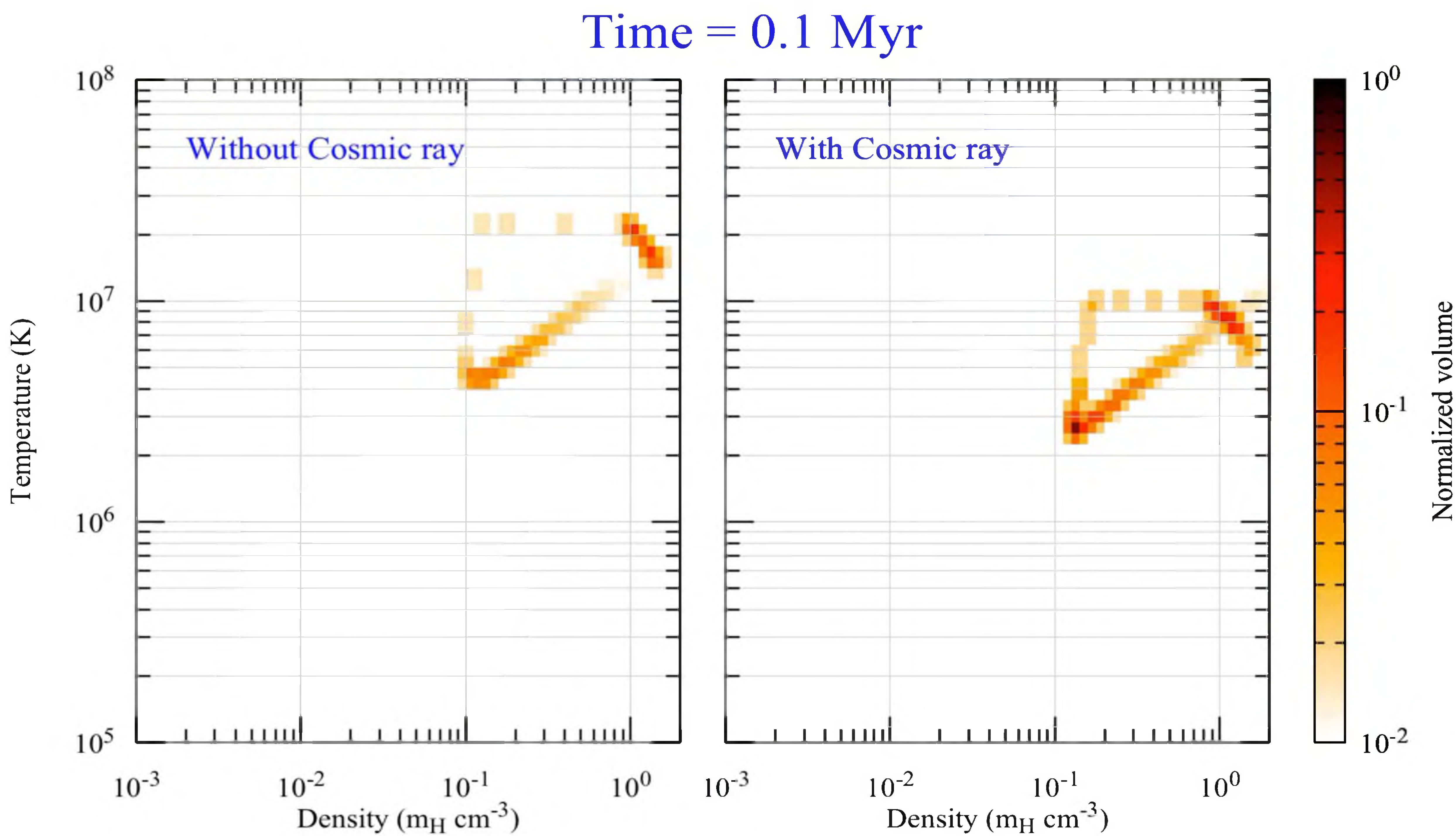
- two-fluid diffusive shock Re-acceleration —
  (Drury & Volk 1981, Becker & Kazanas 2001)

CR diffusion coefficient:

$$10^{26} \lesssim \frac{\kappa_{cr}}{\mathrm{cm^2\,s^{-1}}} \lesssim 3 \times 10^{27}$$

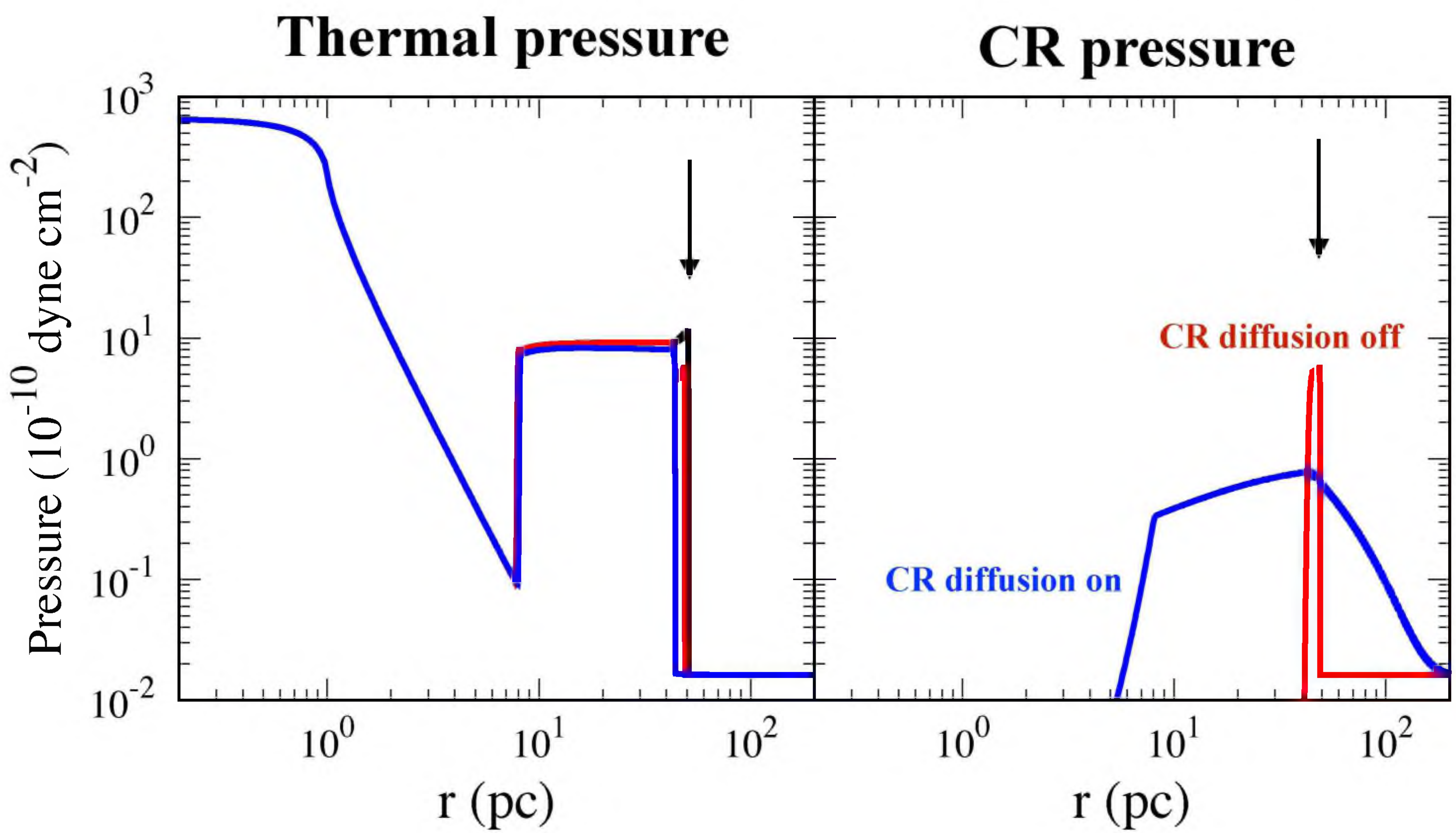
Gupta, S., Nath, B. B., Sharma, P. & Eichler, D. 2018a, MNRAS

CRs reduce hot gas temperature …



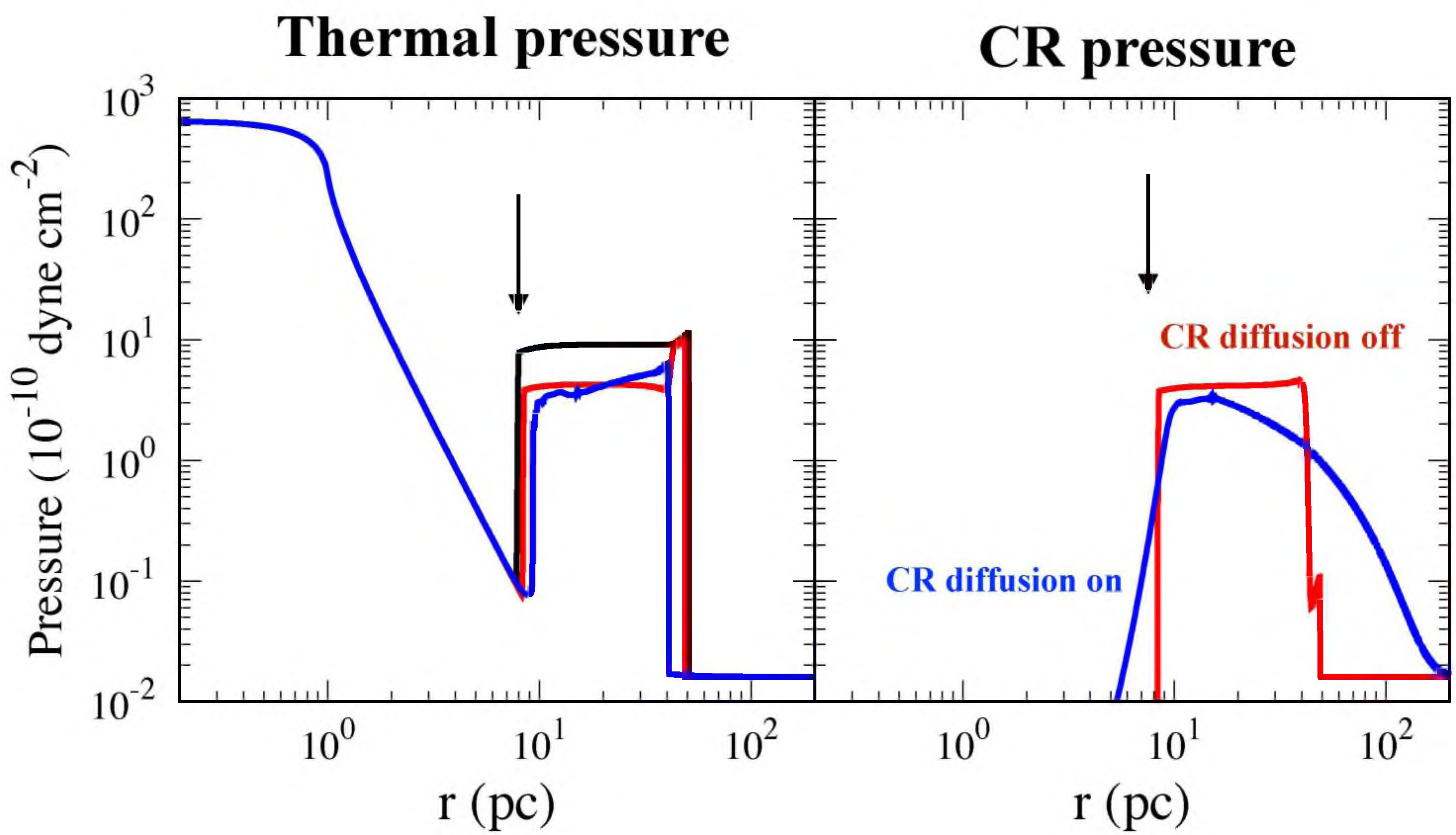
[Gupta, S.](), Nath, B. B., Sharma, P. & Eichler, D. 2018a, MNRAS

Case II.A: CR injection at forward shock



- Injection at forward shock does NOT change interior structure.

Case II.B: CR injection at reverse shock



- Injection at reverse shock *reduces* thermal energy.

Take home message

1. **How does cosmic ray acceleration affect the structure of superbubble?**

   Cosmic rays modify internal structure

Next — Impact on multi-wavelength luminosities.

Ref. : Gupta, S., Nath, B. B., Sharma, P. & Eichler, D. 2018a, MNRAS

Multi-wavelength luminosities

Gamma Ray

X - Ray

Radio

Gamma ray

Hadronic:

$$p\text{-}p,\ p\text{-}\alpha,\ \alpha\text{-}p \longrightarrow \begin{cases} \pi^{\pm} \longrightarrow \mu + \nu_{-} \\ \pi^{0} \longrightarrow \gamma + \gamma \end{cases}$$

$$L_{\gamma}^{\mathrm{H}} \propto (\text{volume}) \times (\text{mass density}) \times (\text{CR energy density})$$

Leptonic

Photons gain energy via inverse Compton scattering

$$L_{\gamma}^{\mathrm{IC}} \propto (\text{volume}) \times (\text{radiation energy density}) \times (\text{CR e}^{-}\ \text{energy density})$$

stellar radiation, IR >> CMB

Take home message

- **both processes are important for smaller bubbles.**

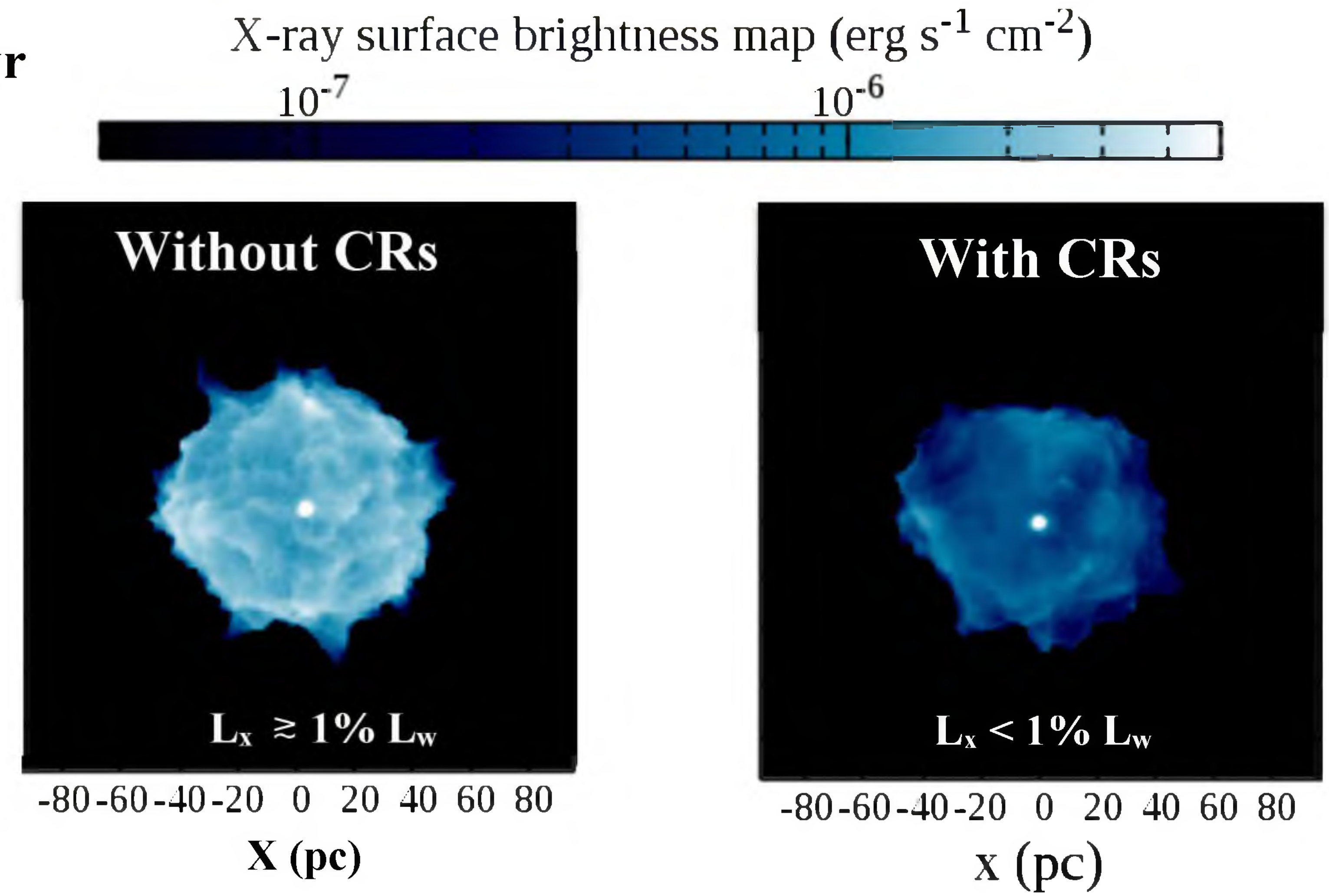
Gamma Ray

Luminosity up to ~ 1% L_w

Ref. : **Gupta, S.**, Nath, B. B., and Sharma, P. 2018b, MNRAS

X-ray (0.5-2 keV)

Time = 3 Myr



- **X-ray luminosity:** $L_X \propto \int_V dV \; \rho^2 \Lambda(T, Z)$ **(Mekal plasma model)**

- **Cosmic rays reduce X-ray luminosity.**

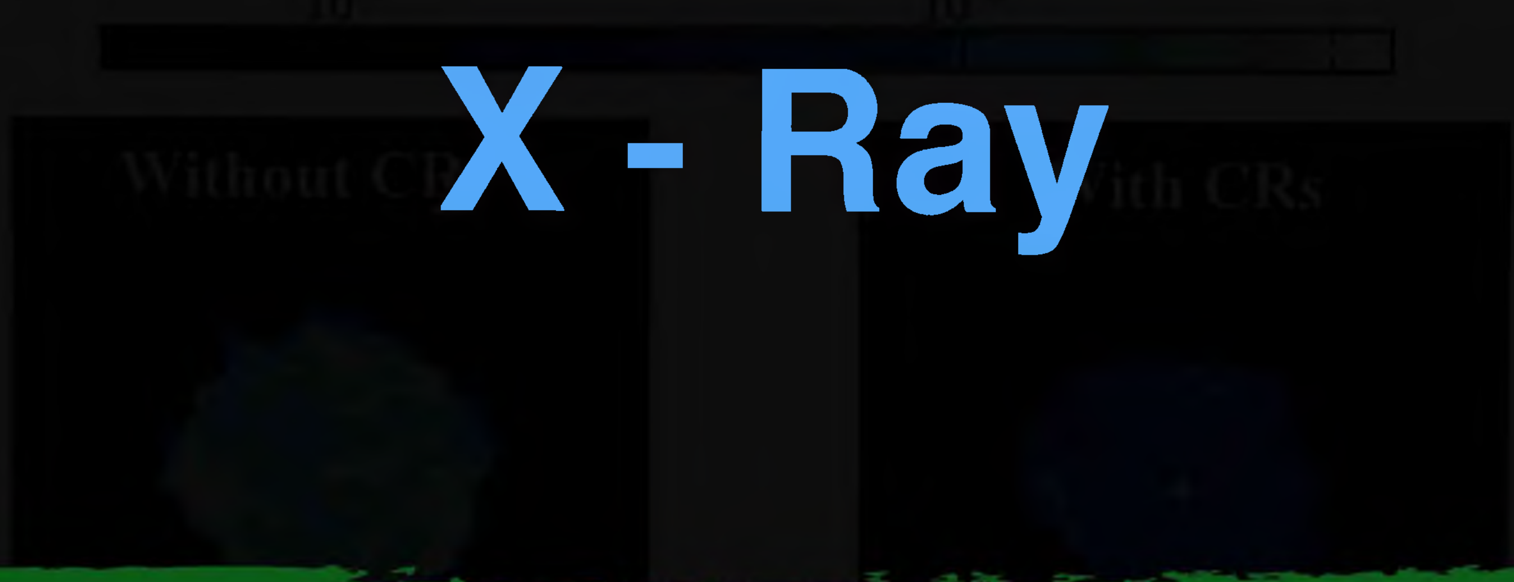
X - Ray

CRs reduce X-ray luminosity

Ref. : **Gupta, S.**, Nath, B. B., and Sharma, P. 2018b, MNRAS

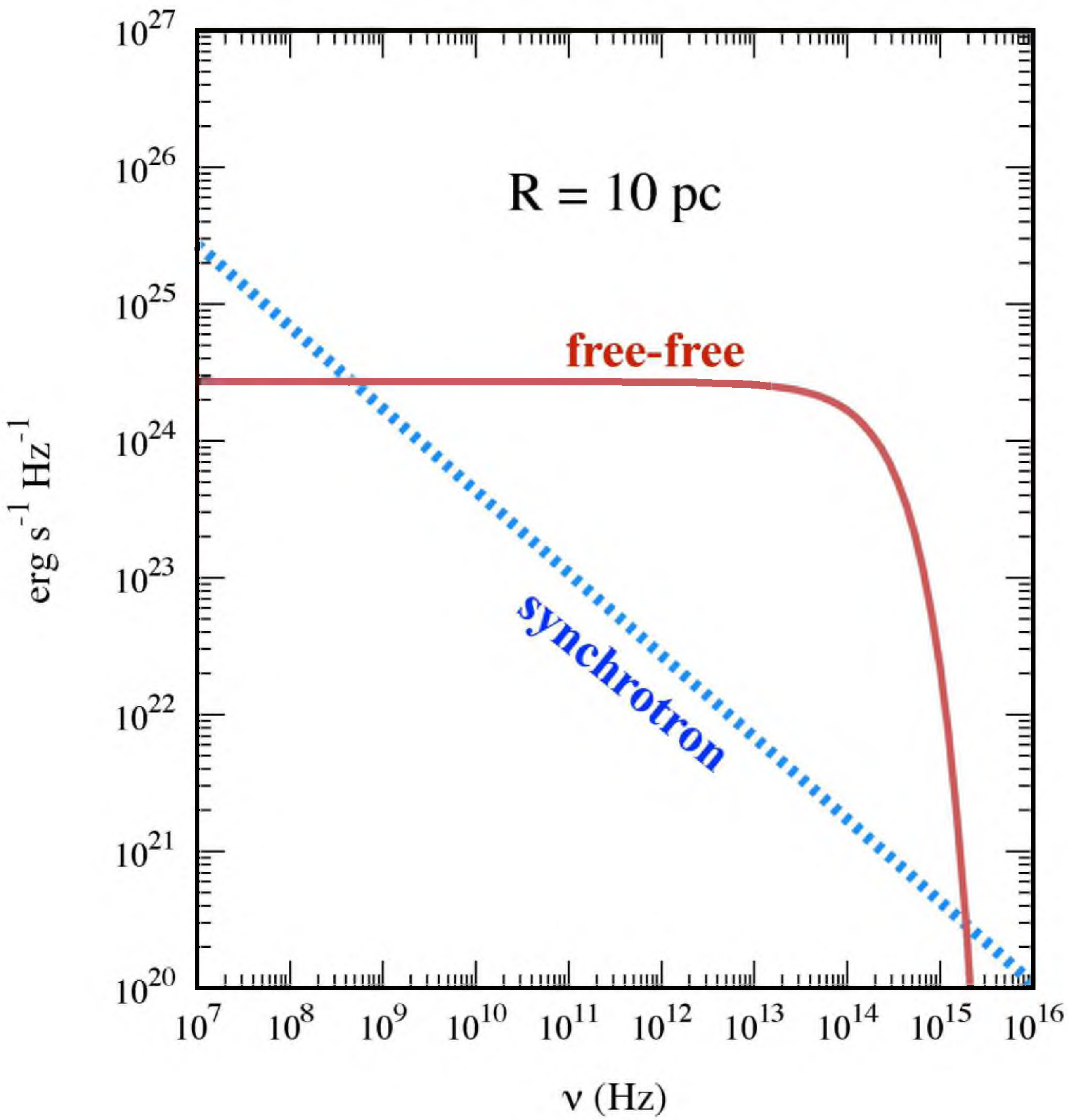
X-ray (0.5-2 keV)

Time = 3 Myr



- X-ray luminosity: $L_X \propto \int_V dV\, \rho^2 \Lambda(T, Z)$ (Mekal plasma model)
- Cosmic rays reduce X-ray luminosity.

Radio emission



Take home message

- Thermal (f-f) and non-thermal (synch.) radio are comparable.

Impact on multi-wavelength luminosities

A. Two-fluid model reproduces the observed gamma-ray and X-ray luminosities.

B. Radio may not be a good diagnostics.

Take home message

Where we are …

1. Applied the two-fluid (gas + CRs) model to star clusters for the *first time*.
2. CR acceleration from multi-wavelength observations.
3. Implemented two-fluid equations in the PLUTO code.

This study has improved our understanding of wind-ISM interaction in presence of Cosmic rays.

what's next …

Magnetized bubble — needs input from observation — CR-MHD / PIC.

http://www.rri.res.in/~siddhartha

Important references

1. Becker, P. A. & Kazanas, D. 2001 ApJ, 546, 429
2. Drury, L. O'C. & Volk, J. H. 1981 ApJ, 248, 344
3. Gupta. S., Sharma, P., Mignone, A. (arXiv:1906.07200)
4. Gupta. S., Nath, B. B., Sharma, P. 2018, MNRAS, 479, 5220
5. Gupta. S., Nath, B. B., Sharma, P. & Eichler, D. 2018, MNRAS, 473, 1537
6. Pfrommer, C., Pakmor, R., Schaal, K., Simpson, C. M. et al.2017 MNRAS, 465, 4500
7. Weaver, R., McCray, R., Castor, J., Shapiro, P., Moore, R., 1977, ApJ, 218, 377