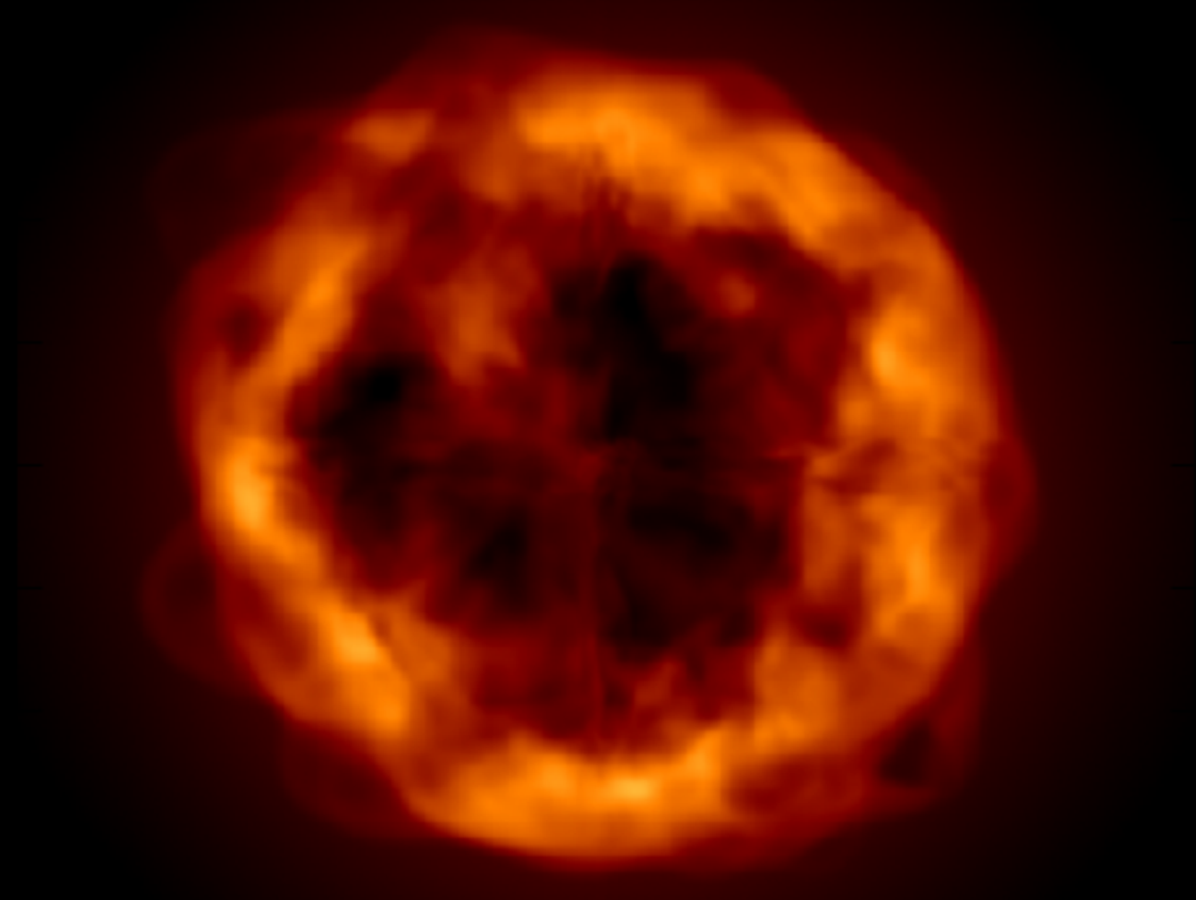
Cosmic rays from young star clusters:
clues from multi-wavelength observations



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Cosmic Rays and the InterStellar Medium Conference, Grenoble, France

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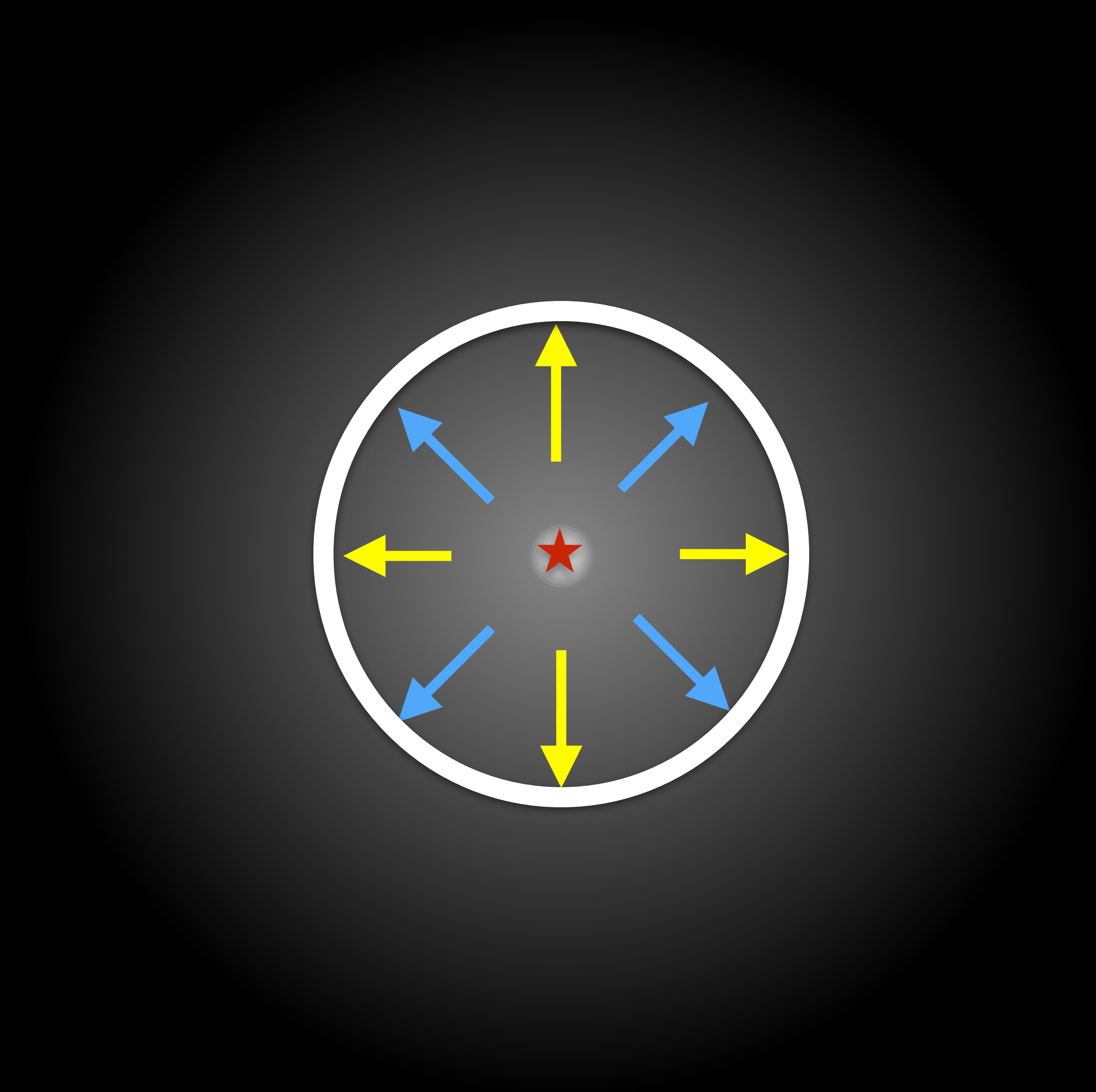
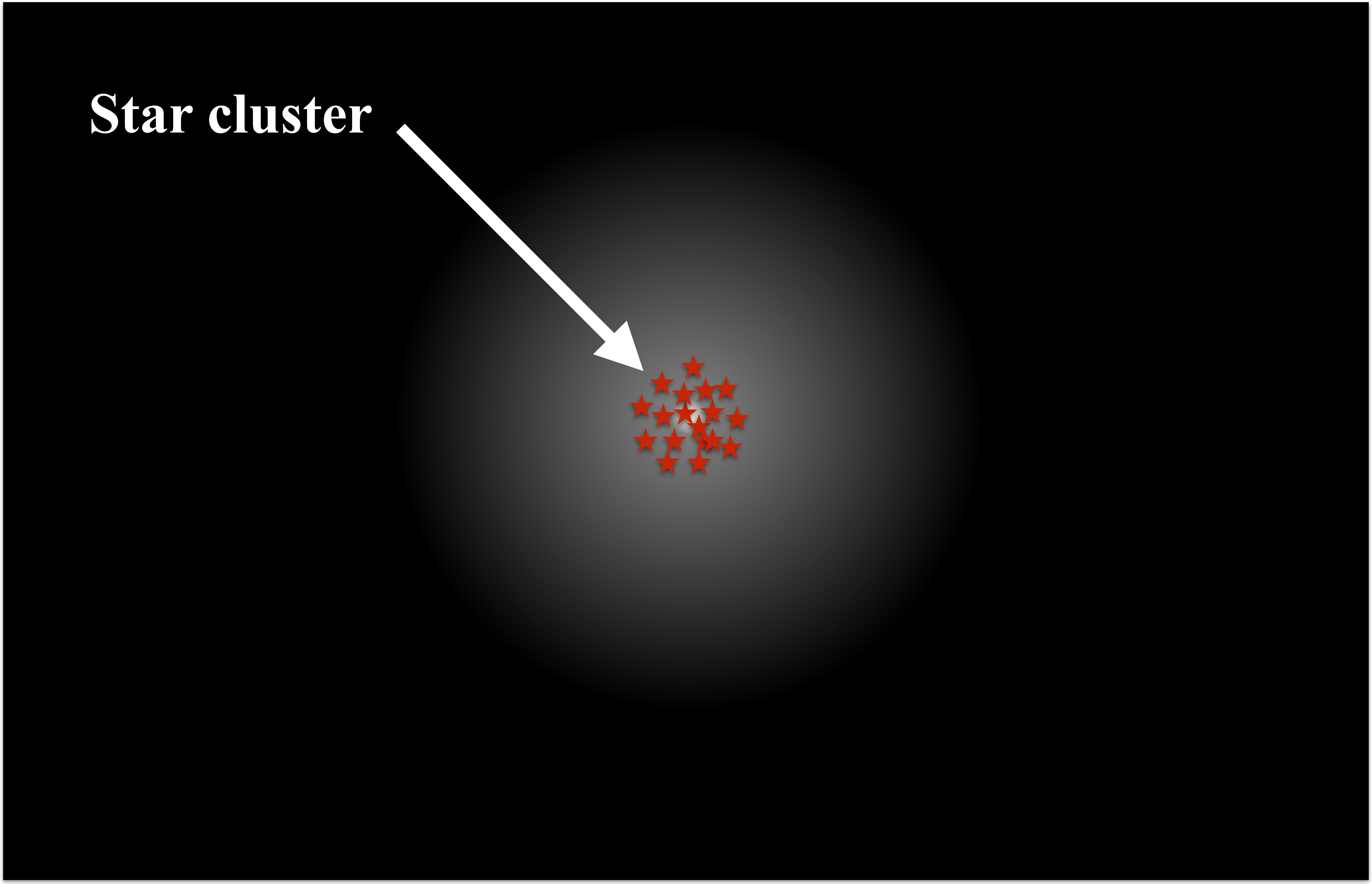
Andrea Mignone (Turin University, Italy)

Molecular Cloud - Star - Feedback

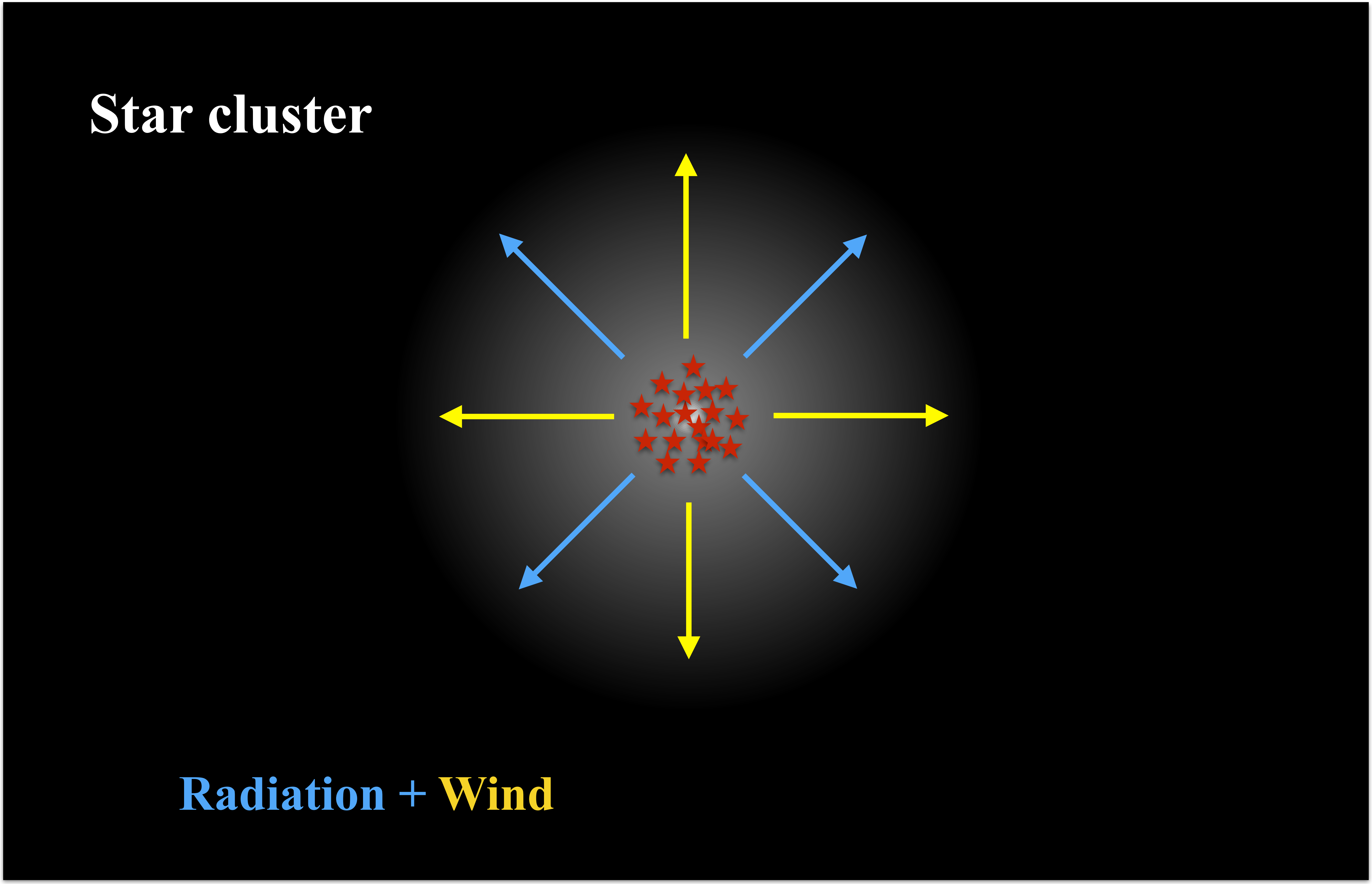


Radiation, Wind —— Interstellar bubble

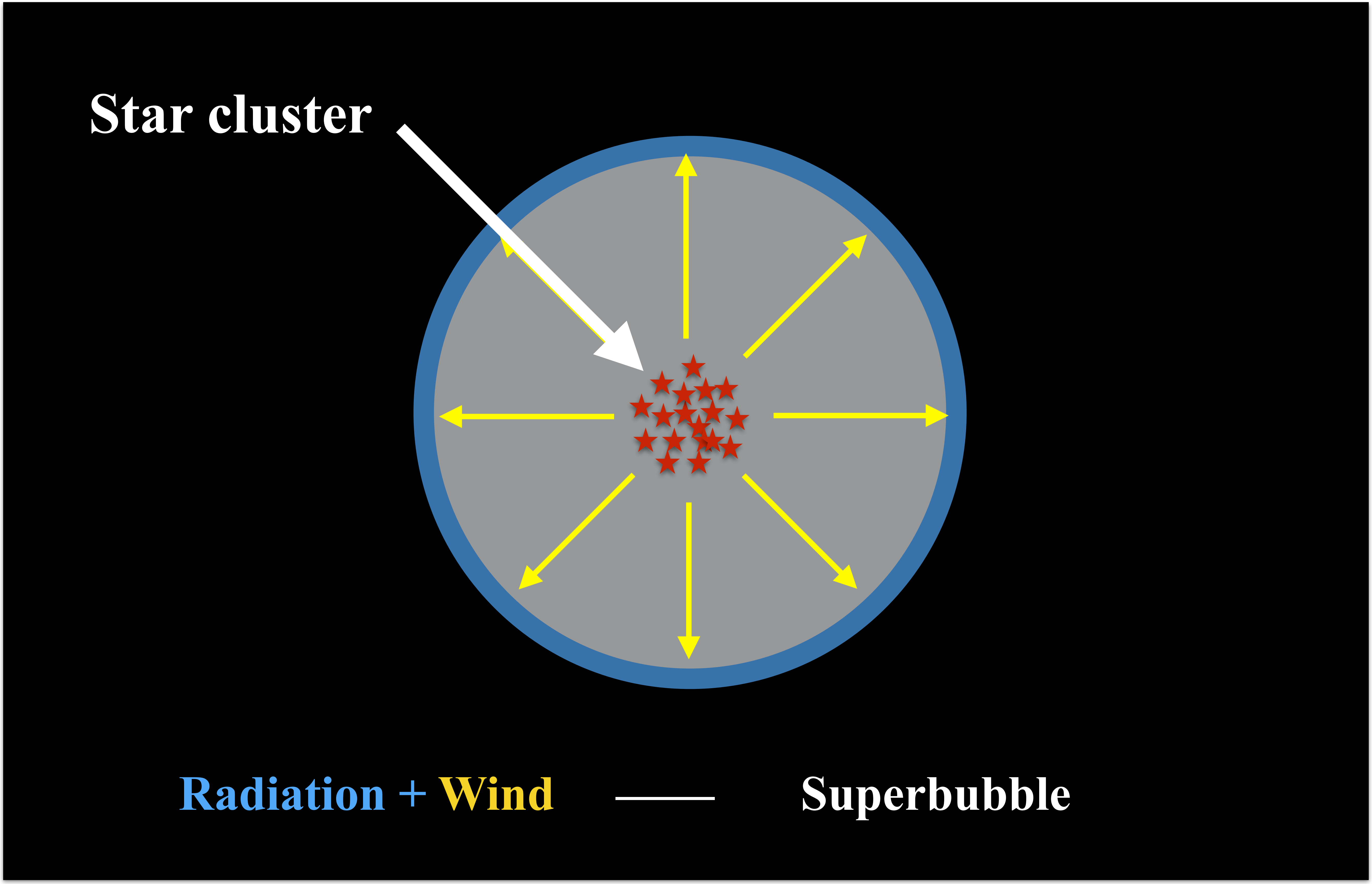
Molecular Cloud - Stars - Feedback



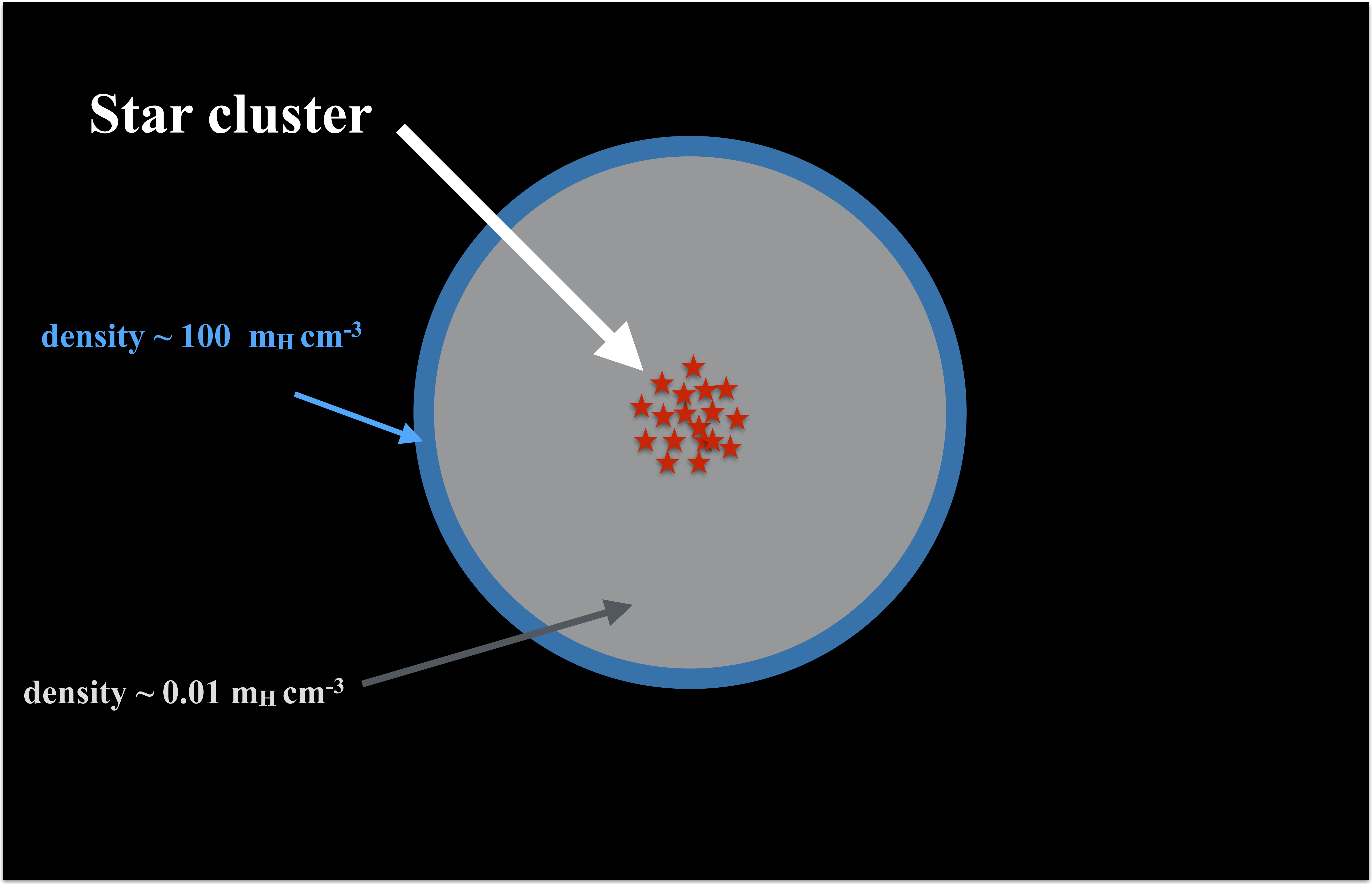
Molecular Cloud - Stars - Feedback



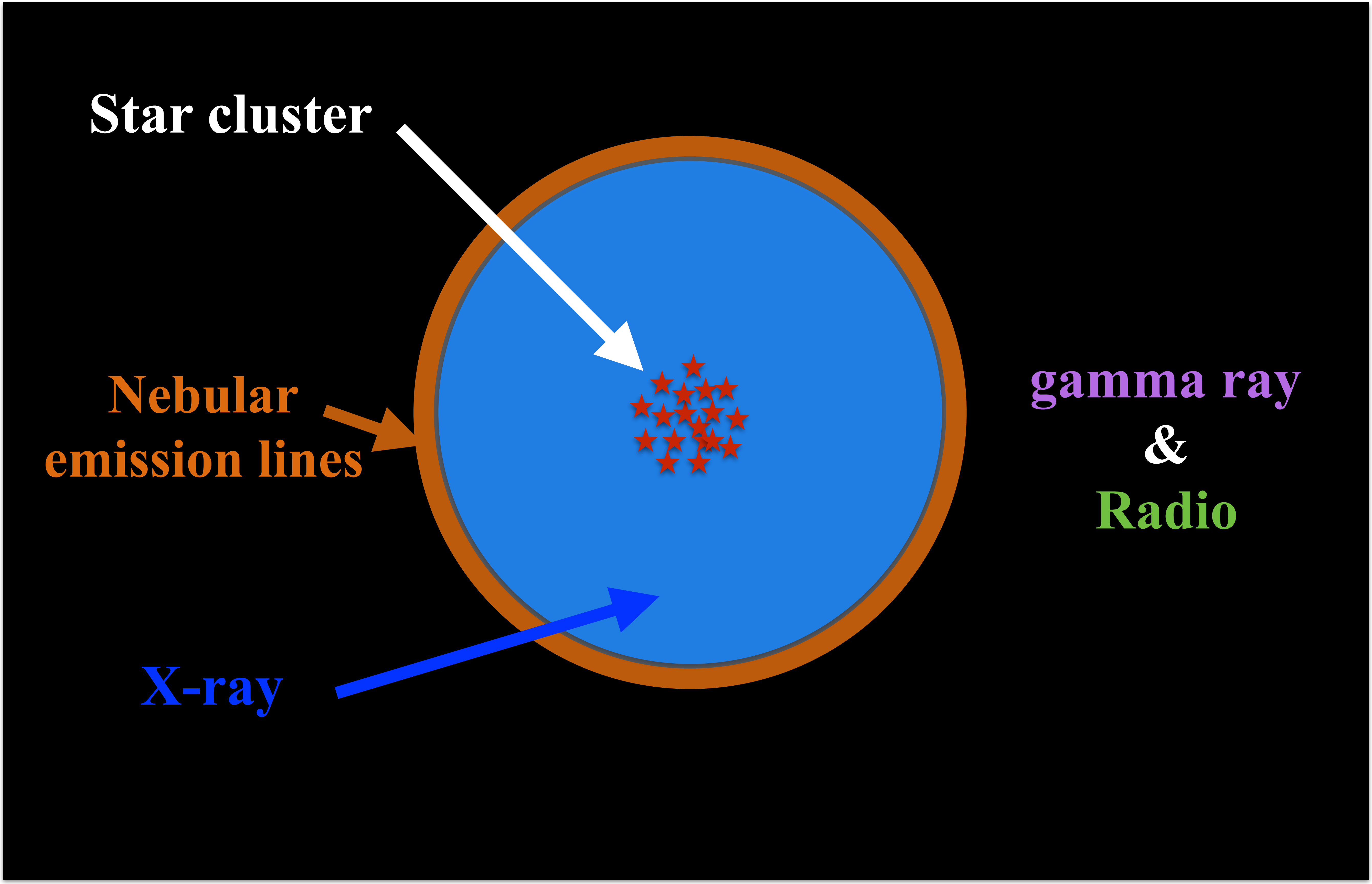
Molecular Cloud - Stars - Feedback



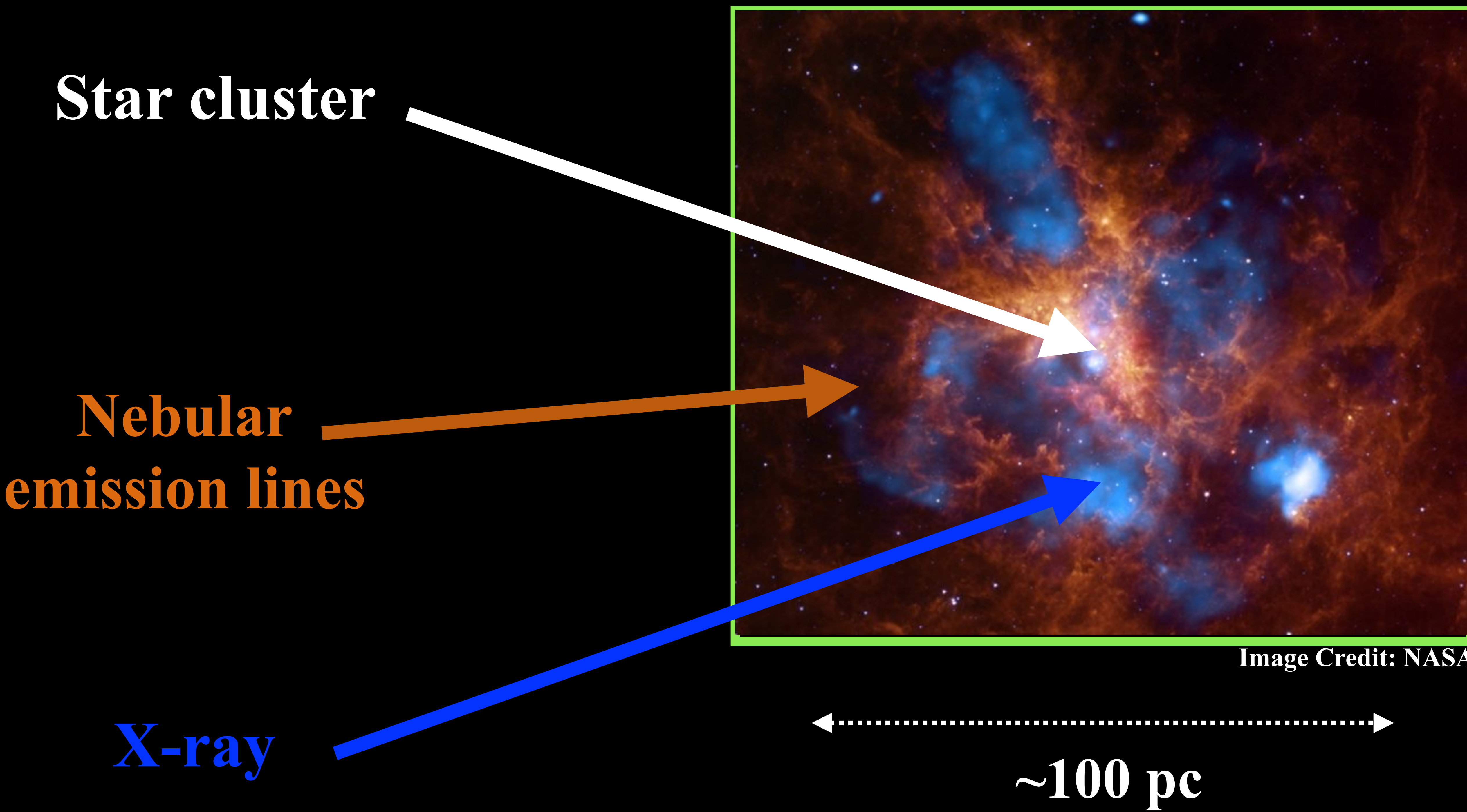
Molecular Cloud - Stars - Feedback



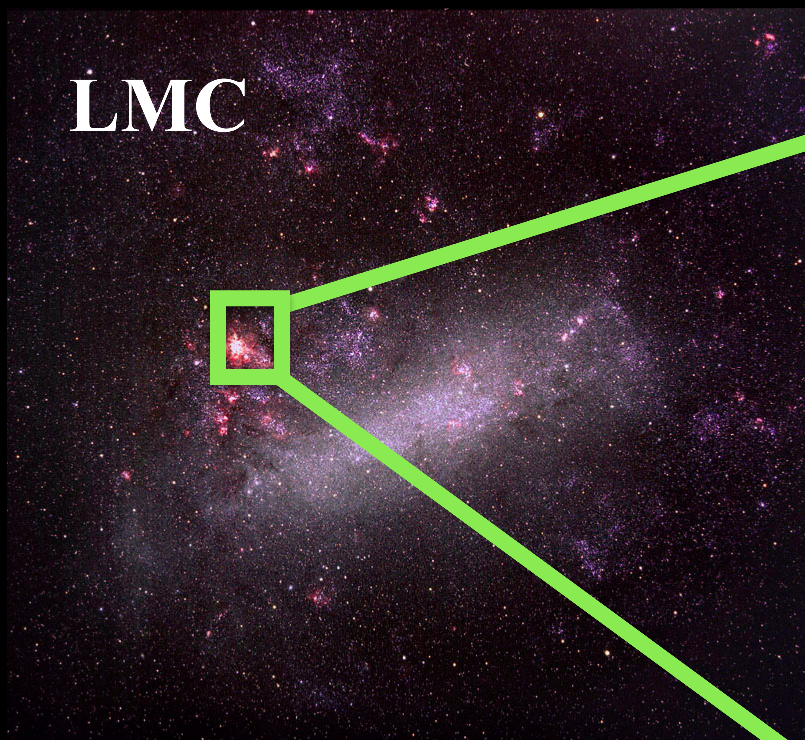
Star cluster driven structure



Star cluster driven structure



Diameter ~ 100 times smaller than a galaxy



~ 5 kpc

Image Credit: NASA

~ 0.1 kpc

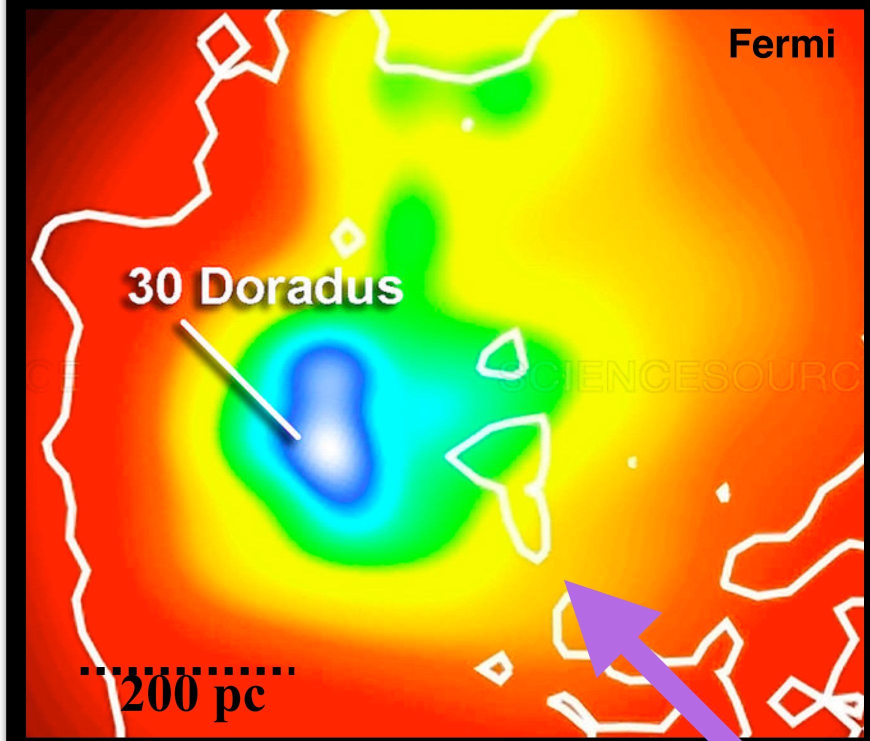
Building block of a galaxy

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

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

- Typically, a star cluster is made of ~ 10 - 1000 OB stars
- Wind mechanical power (L_w) ~ 10^{37} — 10^{39} erg s^{-1} ~ 2 (10^3 - 10^5) $L_\odot$
- Stellar radiation bolometric luminosity (L_{bol}) ~ 500 L_w ~ (10^6 - 10^8) $L_\odot$

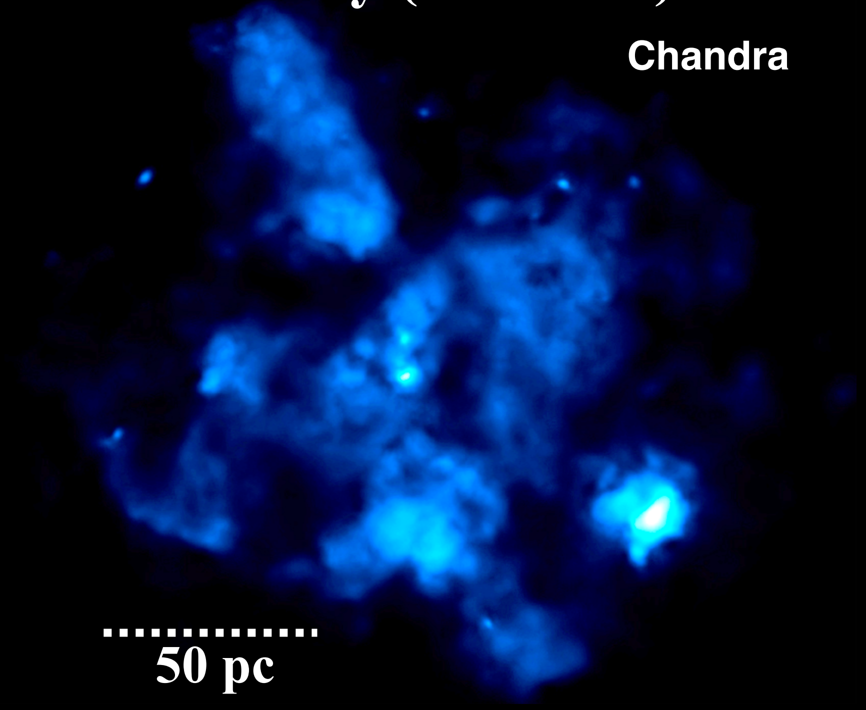
gamma-ray (0.1-200 GeV)



L_γ ~ 1% L_w

(Abdo et al. 2010; Knödlseder 2013)

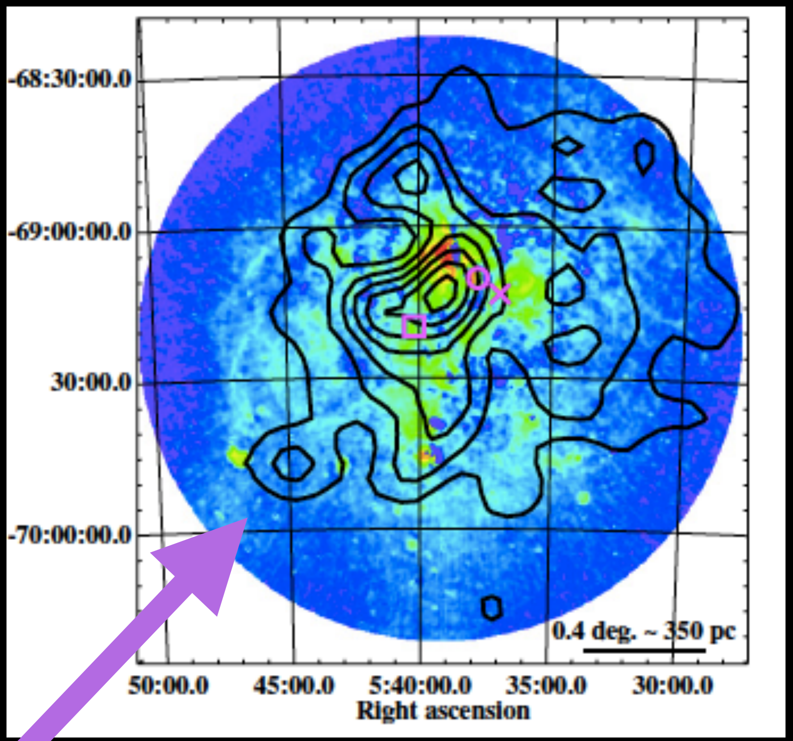
X-ray (0.5-2 keV)



L_X ~ 0.5% 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)

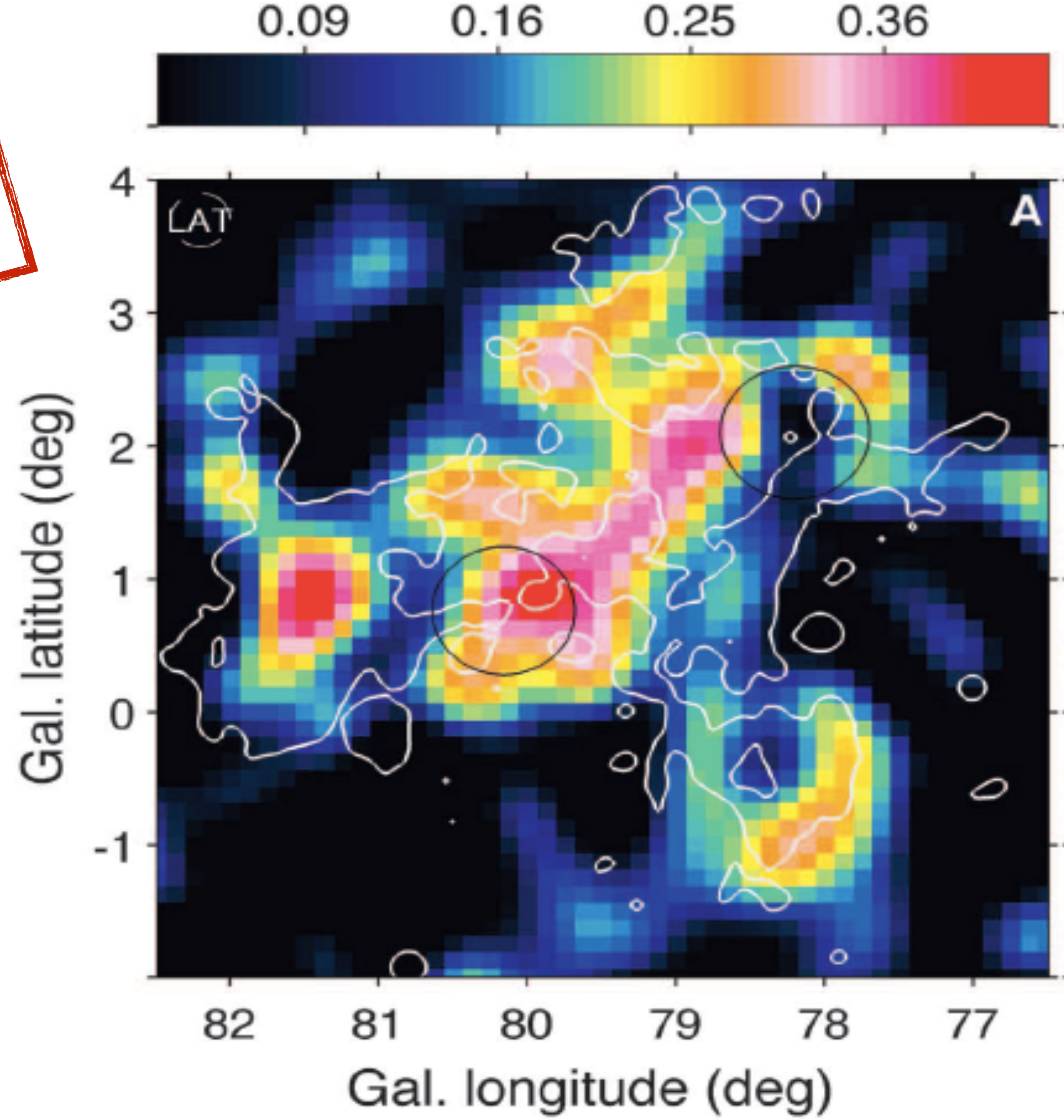
Evidence of cosmic ray acceleration

Stellar activit… dio emission

- Typically, a star cl…
- Wind mechanical … $(10^3 - 10^5)\ L_\odot$
- Stellar radiation b… $0^6 - 10^8)\ L_\odot$

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

- Typically, a
- Wind mech
- 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. Can we model it from multi-wavelength luminosities?

Theoretical modeling

1. Mass

2. Momentum

3. Energy

- usually do not include effects of relativistic particles
- Need a system that has both thermal fluid and CRs.

Theoretical modeling

1. Mass
2. Momentum
3. Energy

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

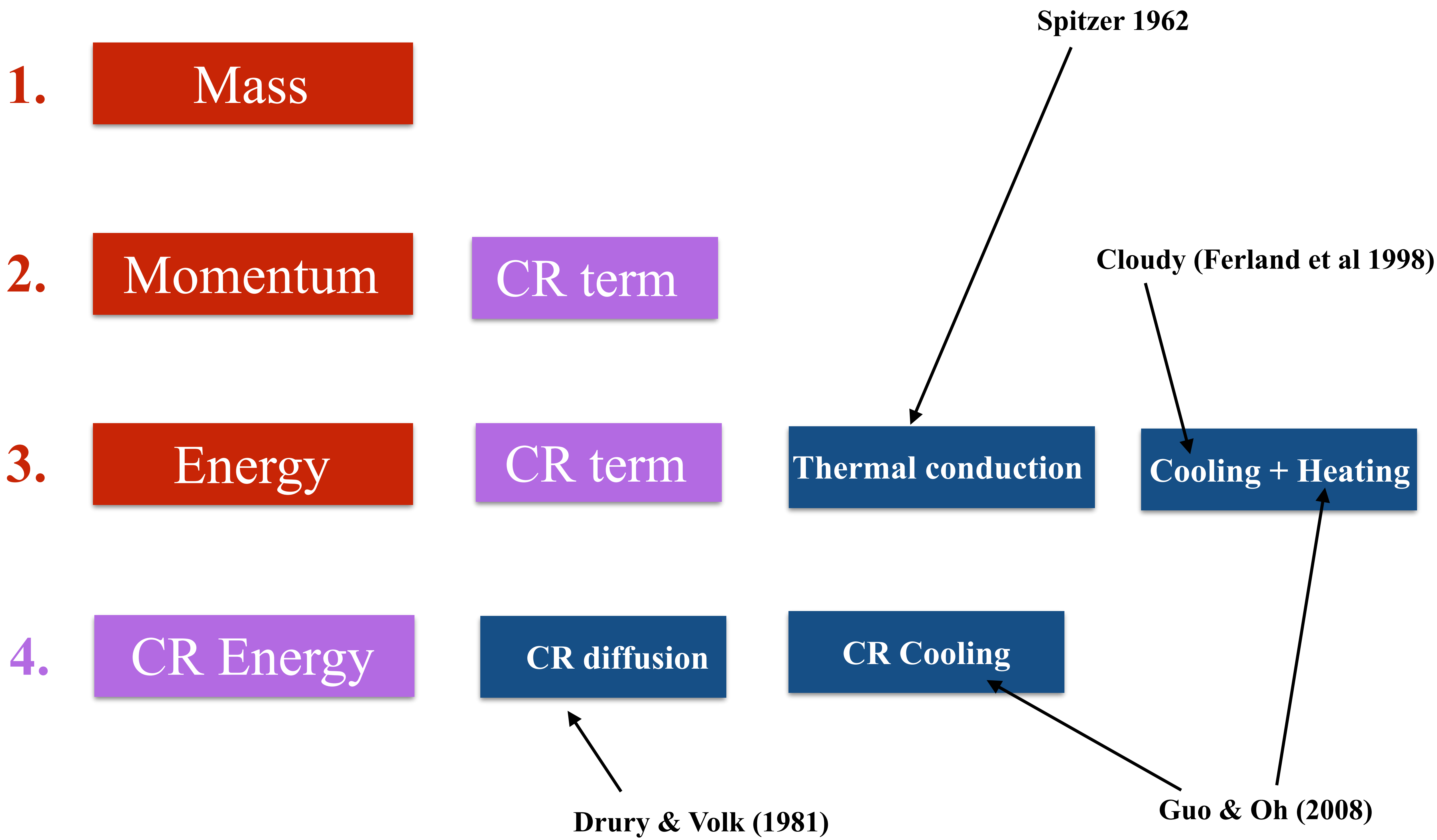
Two-fluid equations:
Moment of Boltzmann equation +
Fokker-Planck CR transport equation.

Equations solved …

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

(e.g. Pfrommer et al. 2006; Salem & Bryan 2013; Booth et al. 2013)

Equations solved …



Equations solved …

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

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

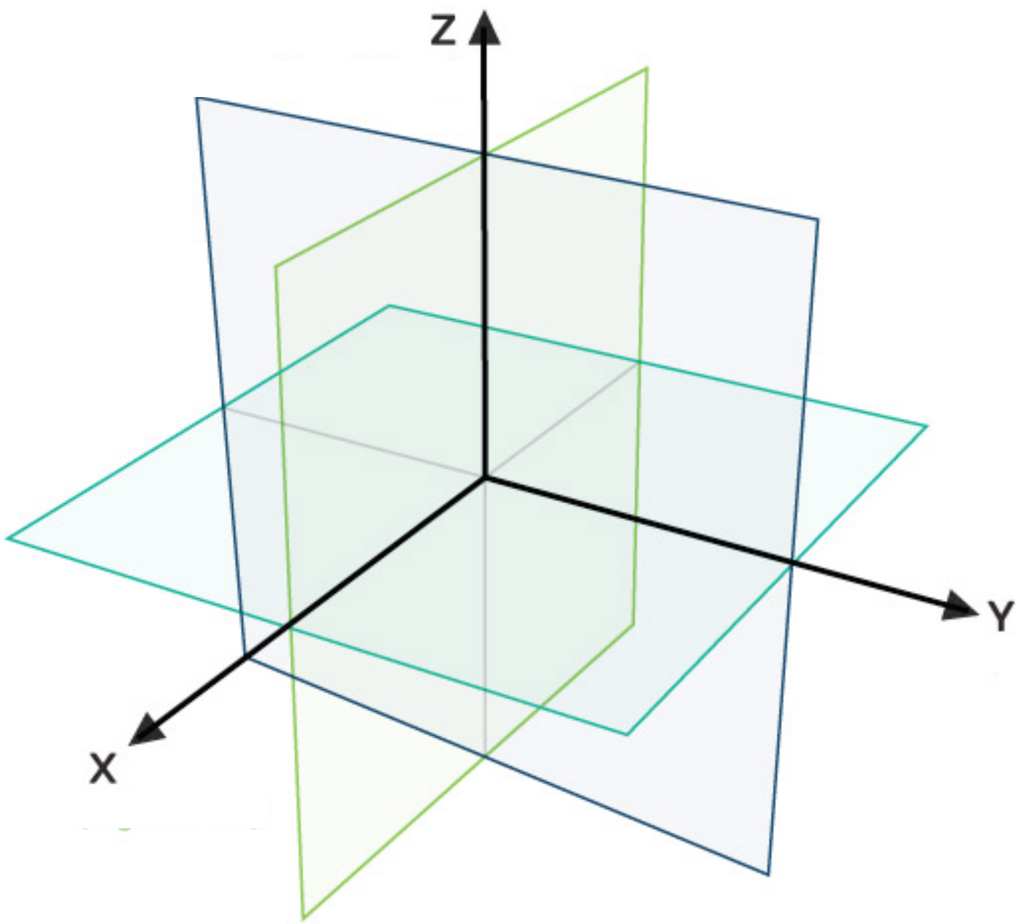
3. $$\frac{\partial e_{\rm tot}}{\partial t} + \vec{\nabla}.\left[(e_{\rm tot} + p_{\rm tot})\,\vec{v} + \vec{F}_{\rm t} + \vec{F}_{\rm crd}\right] = \rho\vec{v}.\vec{g} + S_{\rm e} - q_{\rm th}^{\rm eff}$$

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

Implemented two-fluid solver in PLUTO

Mignone et al. 2007; Gupta et al. in prep

Simulation set-up



grid resolution

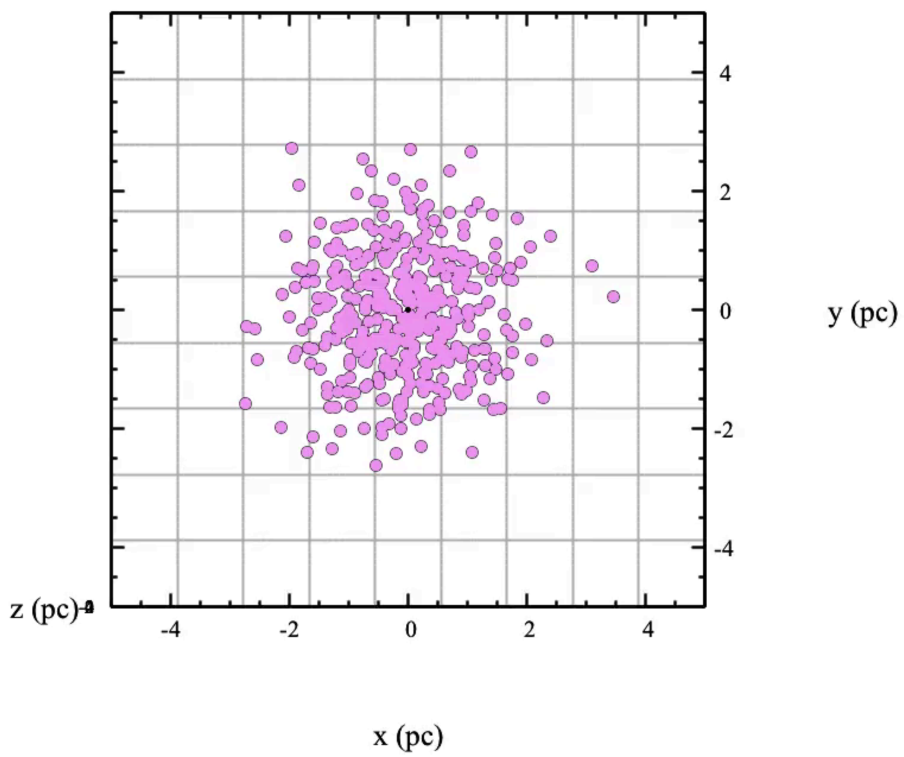
central region

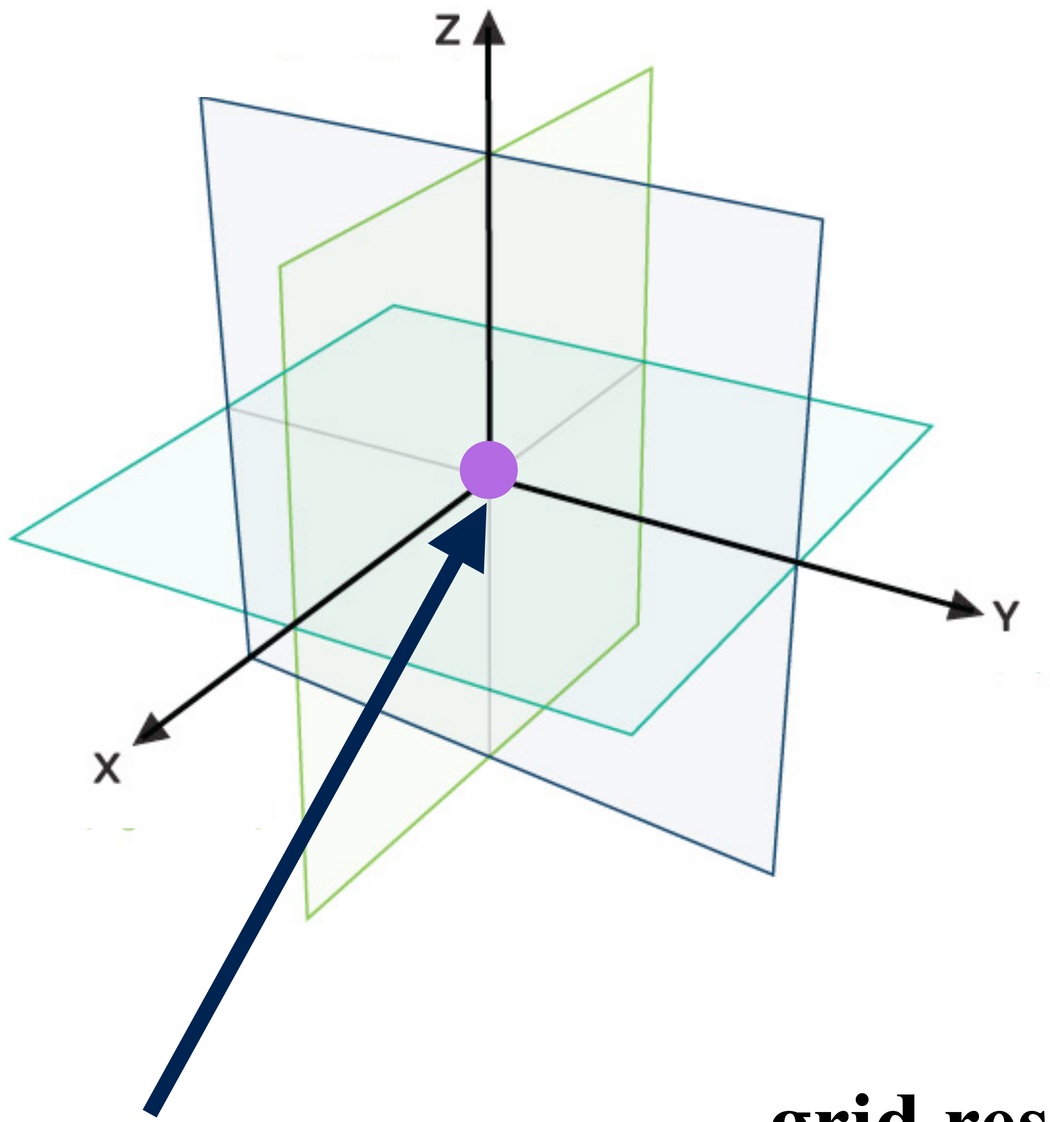
$\Delta r = 0.1\,\mathrm{pc}$

other region

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

Simulation set-up





Stars

grid resolution

central region

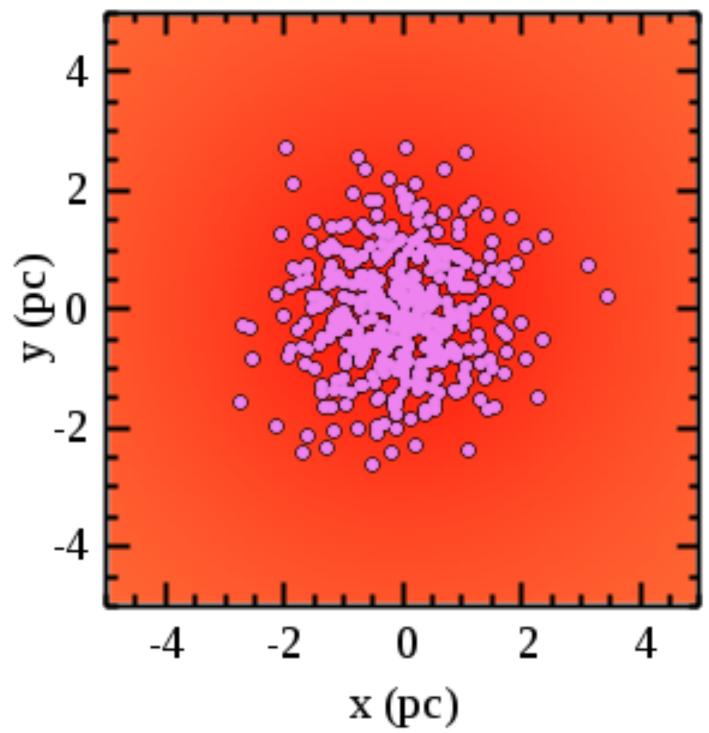
$\Delta r = 0.1\,\mathrm{pc}$

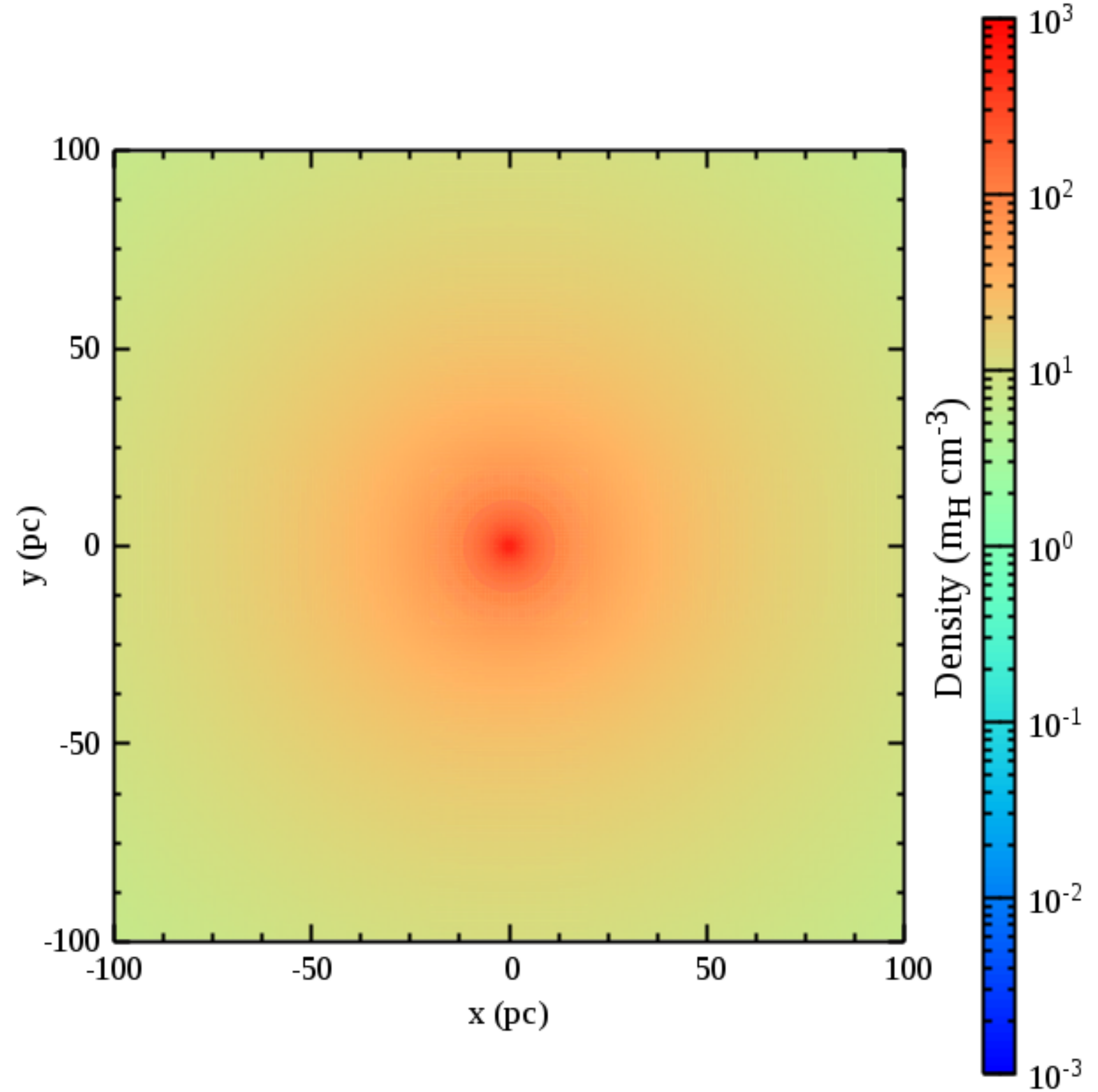
other region

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

Ambient density profile

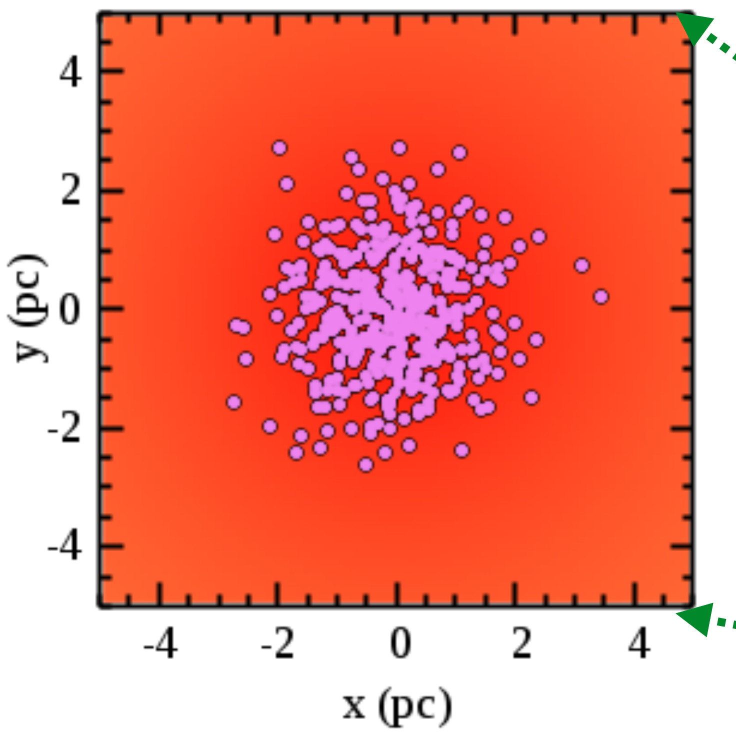
Time = 0.00 Myr

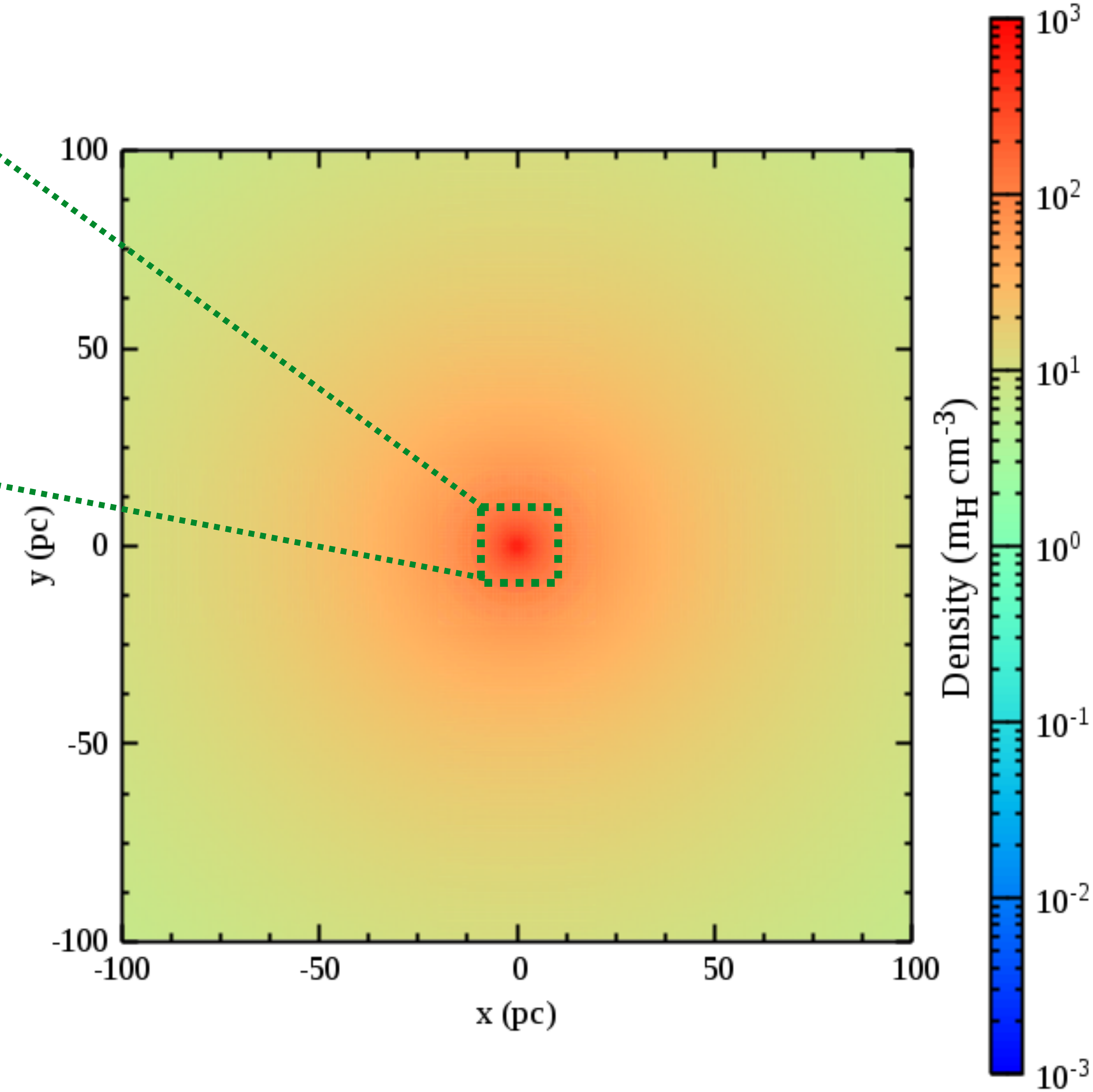




Ambient density profile

Time = 0.00 Myr

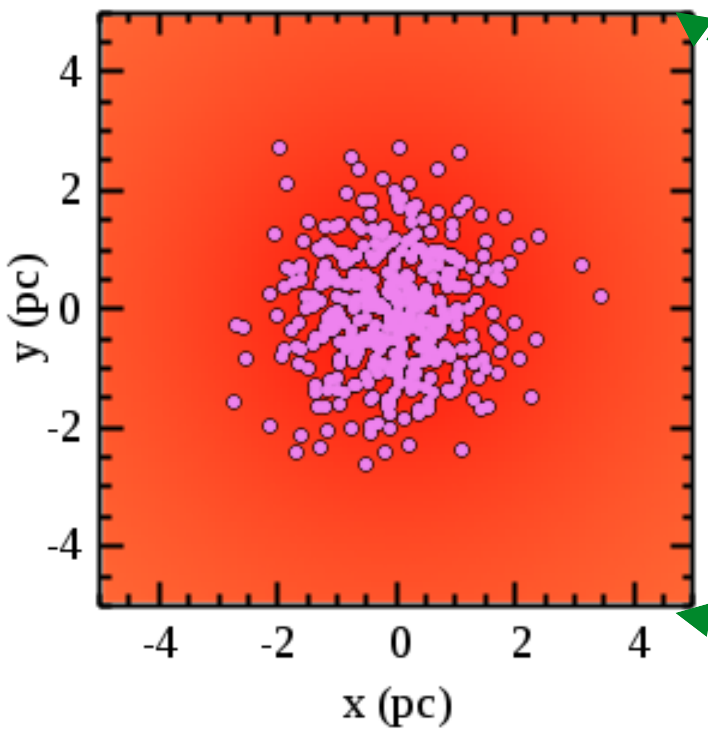


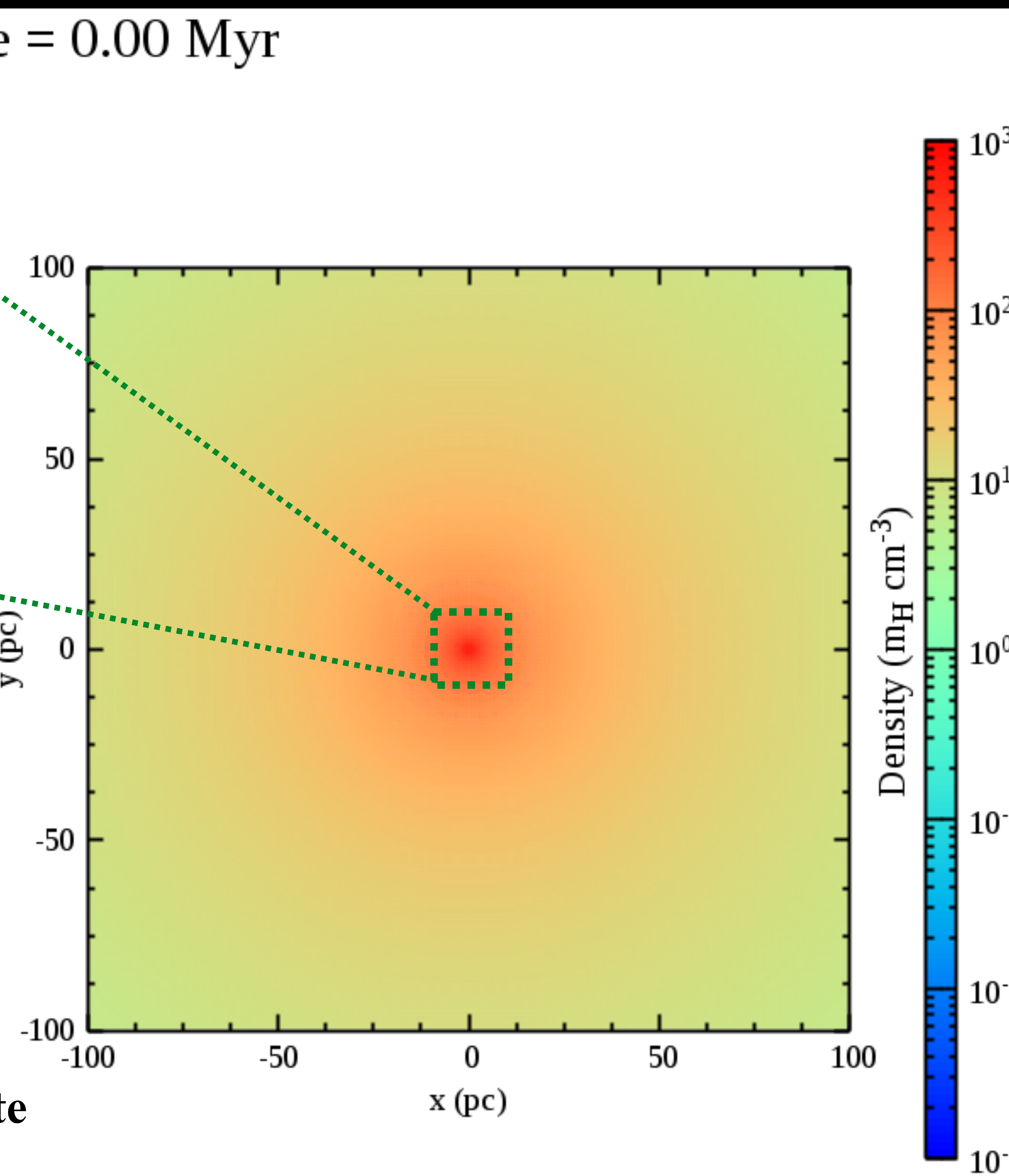


- **modeled a self-gravitating cloud**

$$\rho \propto r^{-1}$$ **(Solomon et al. 1987)**

Ambient density profile





- **injected mass and energy**

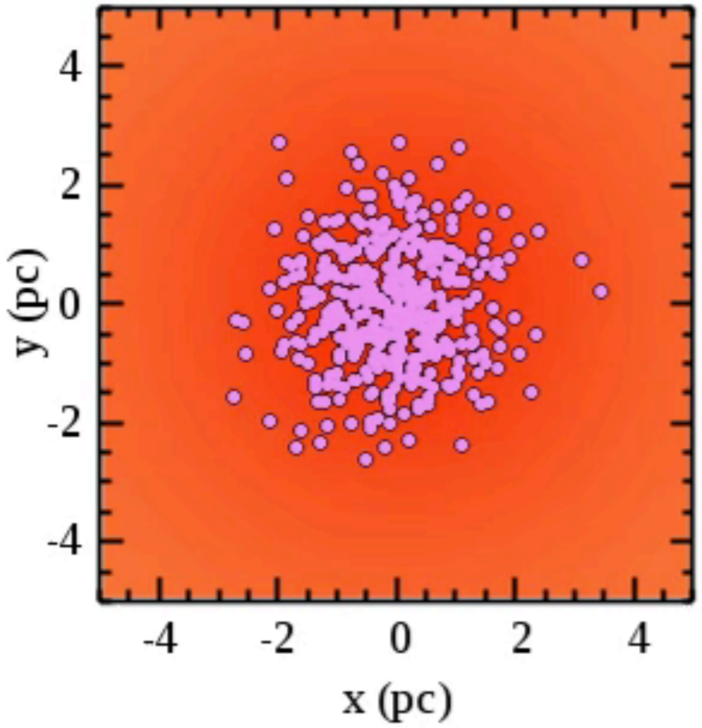
$$\dot{M} \approx 10^{-6}\, M_\odot\, \mathrm{yr}^{-1}$$

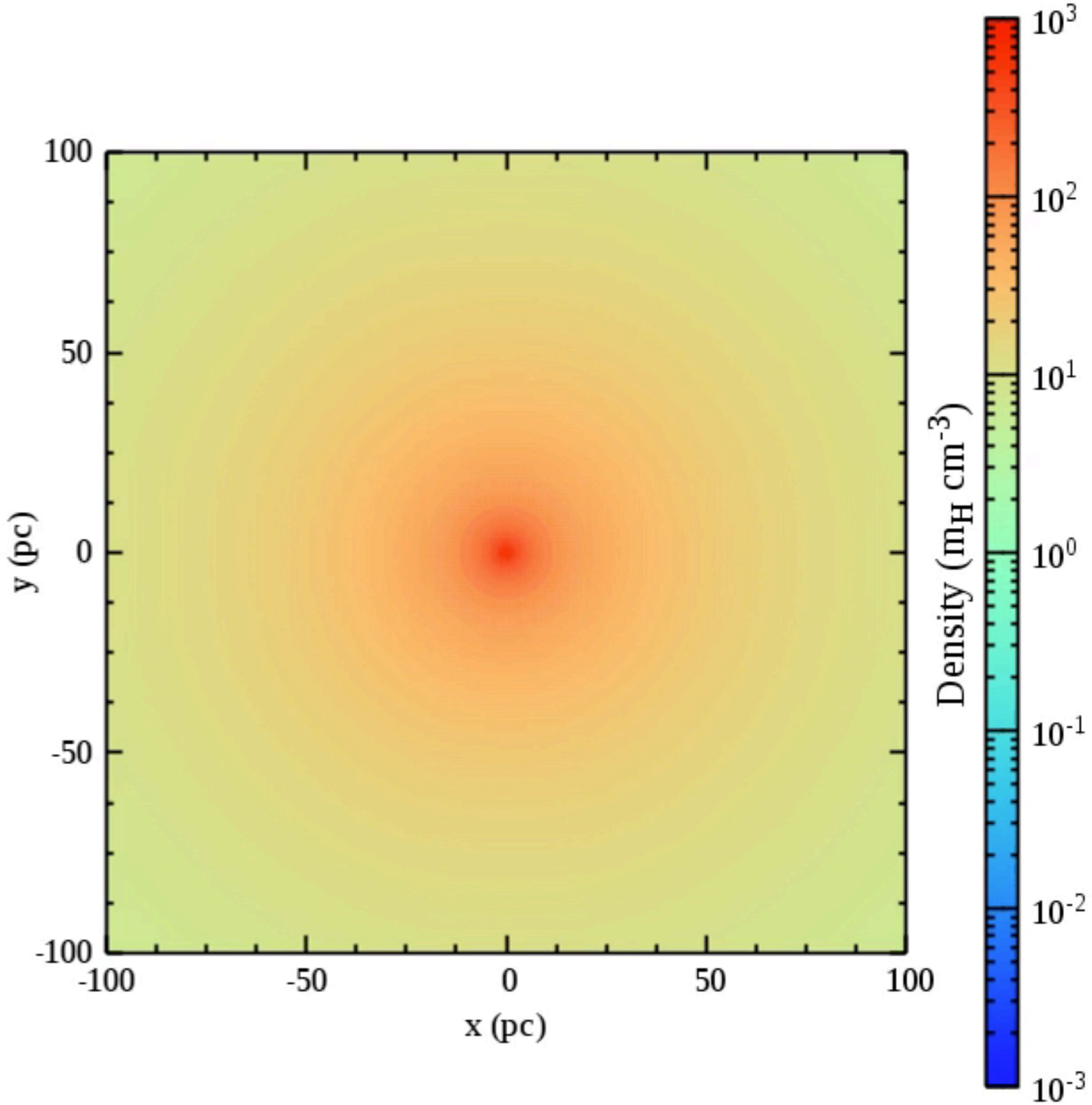
$$\dot{E} \approx 10^{36}\, \mathrm{erg\, s}^{-1}$$

- **energy injection rate >> cooling loss rate**
  (Sharma, Roy, Nath, Shchekinov 2014)

Evolution of superbubble

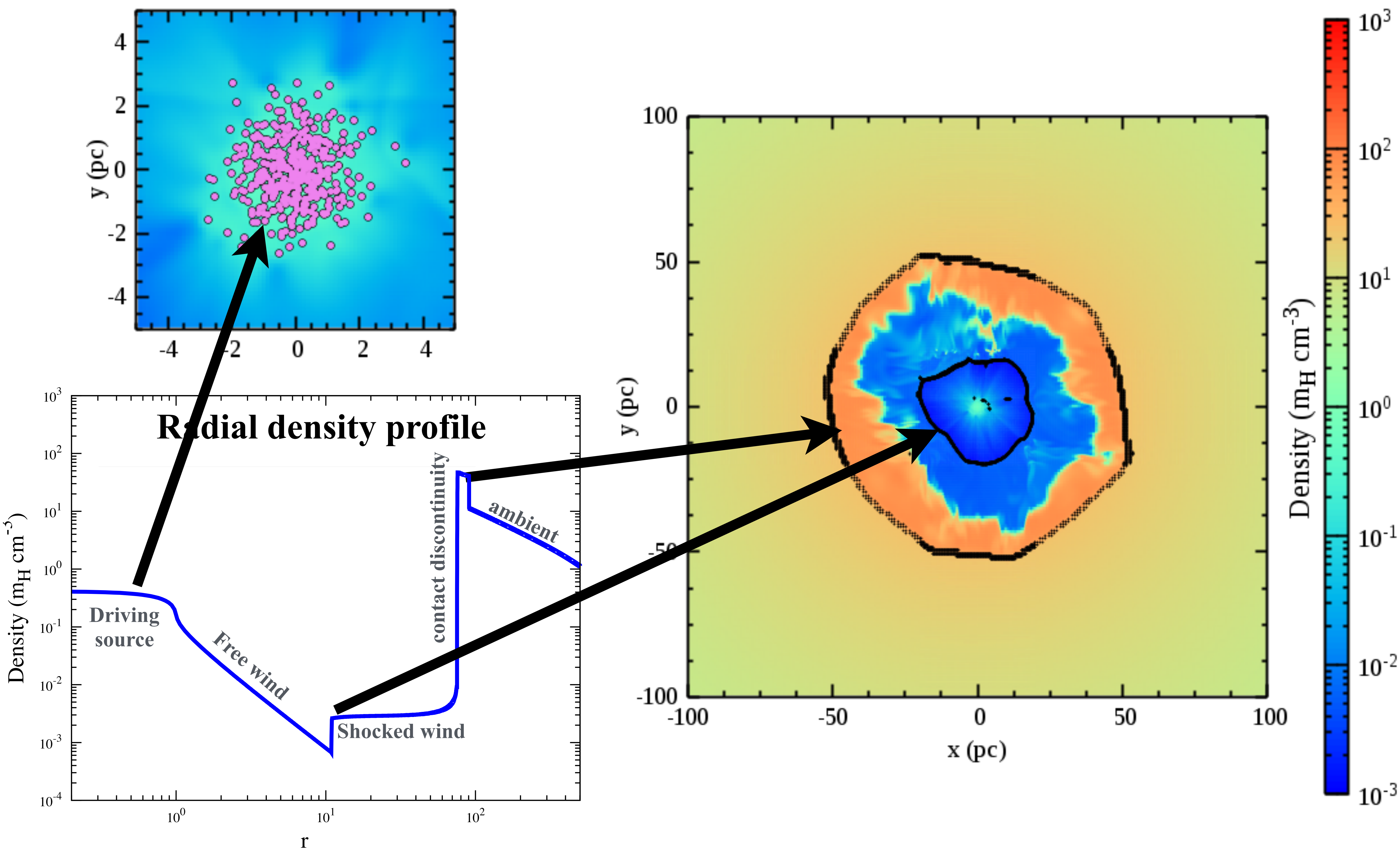
Time = 0.00 Myr





Density structure

Time = 2.15 Myr

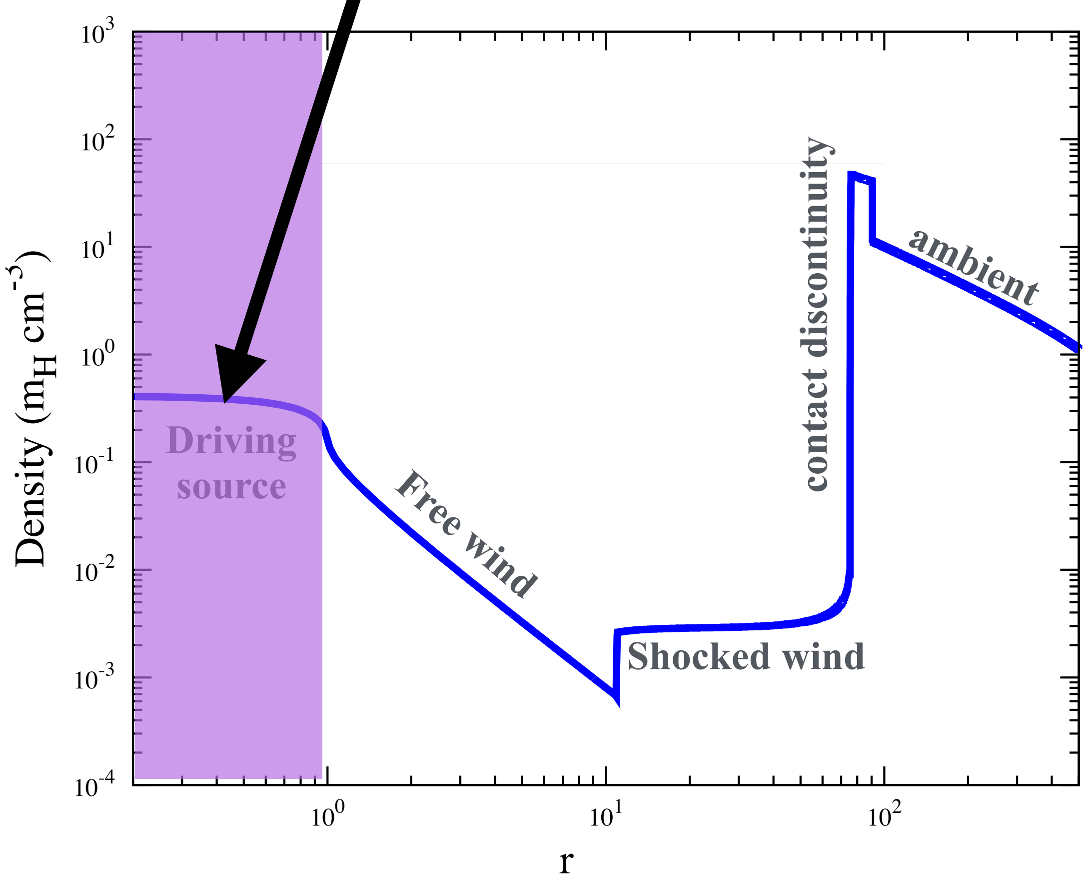


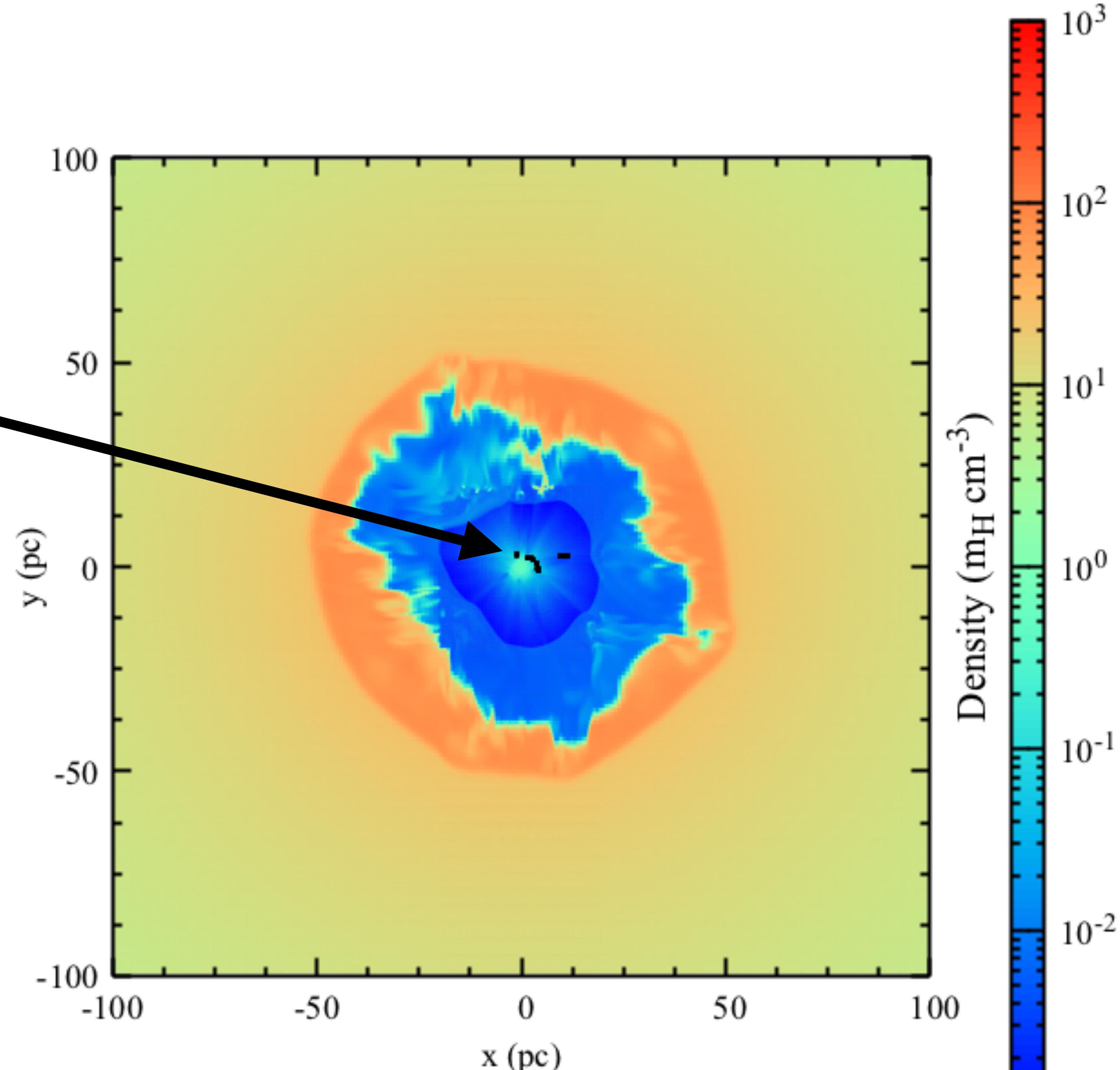
Cosmic ray injection: wind driving region?

Model I:

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

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

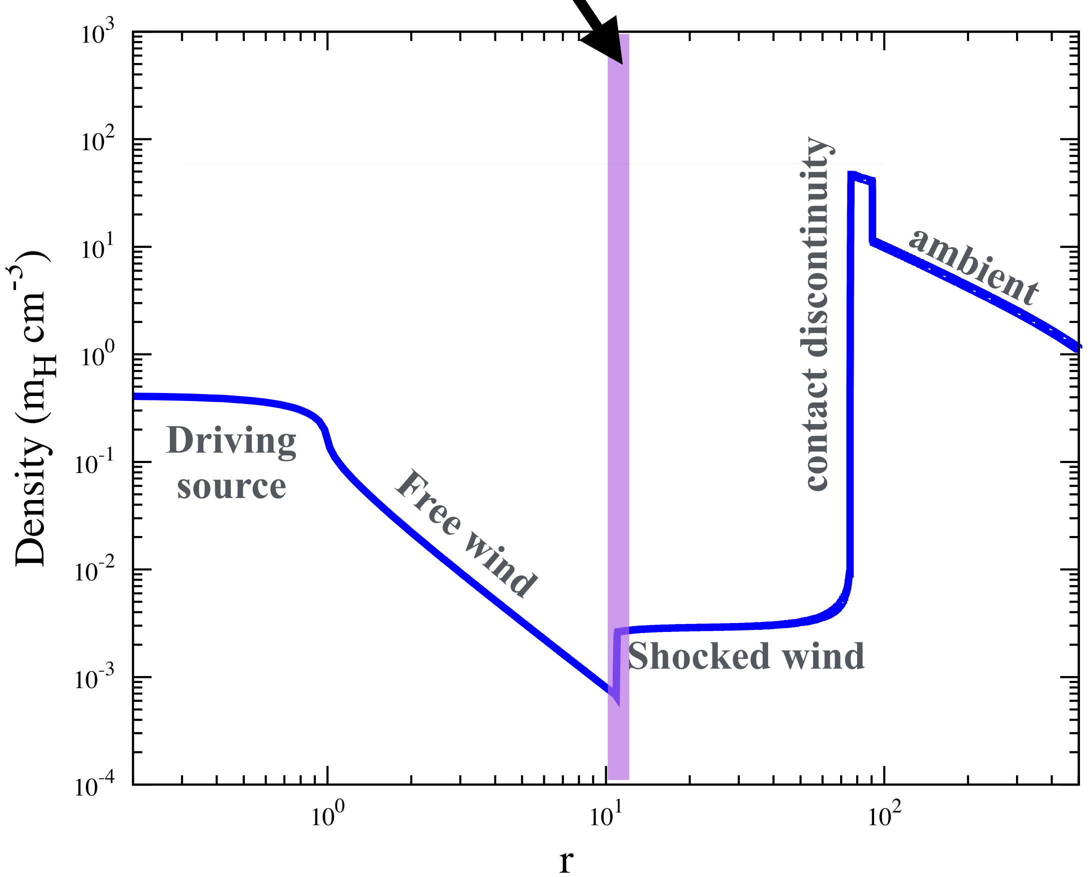


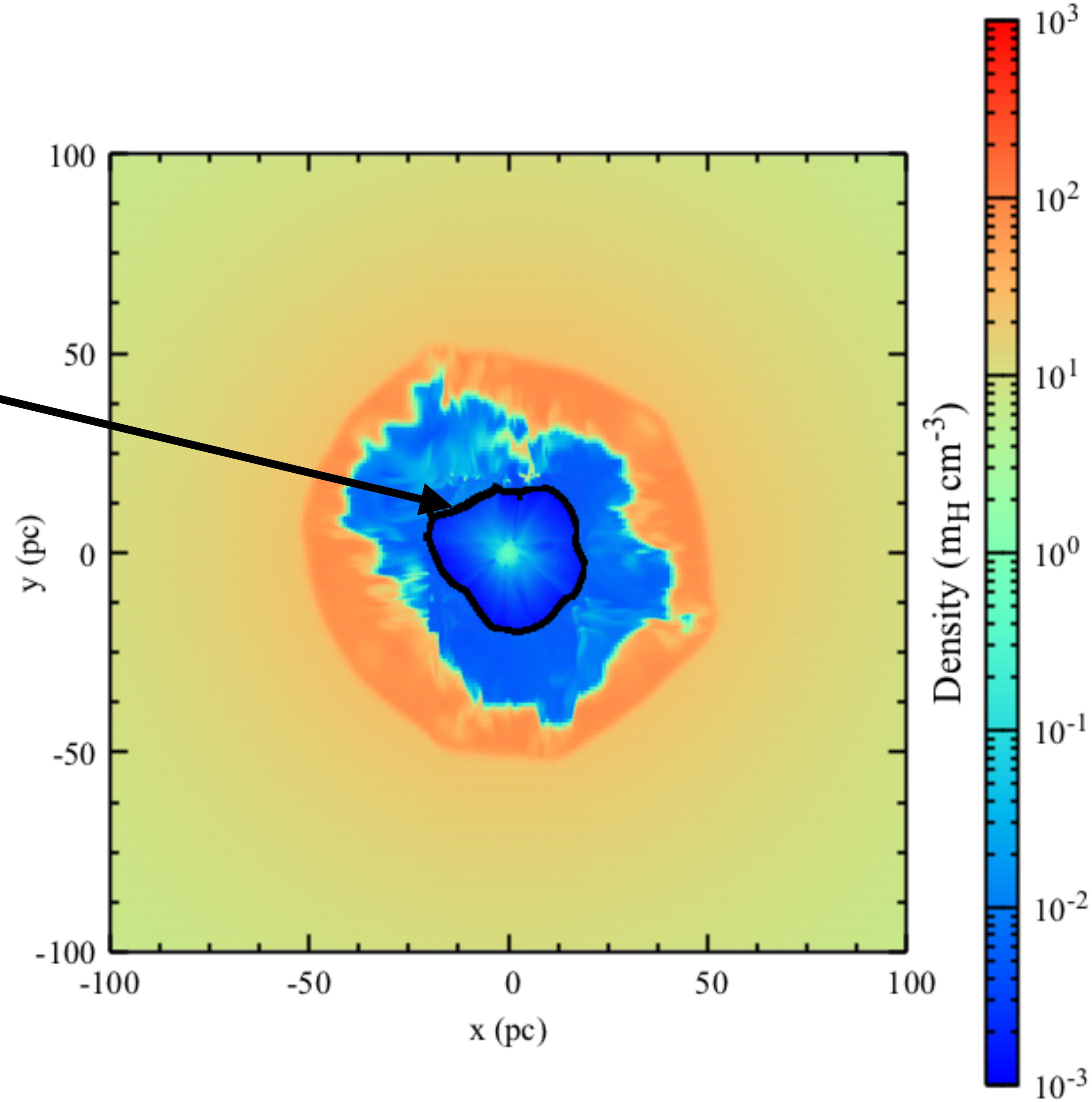


Cosmic ray injection: reverse & forward shock?

Model II:

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





Cosmic ray injection: reverse & forward shock?

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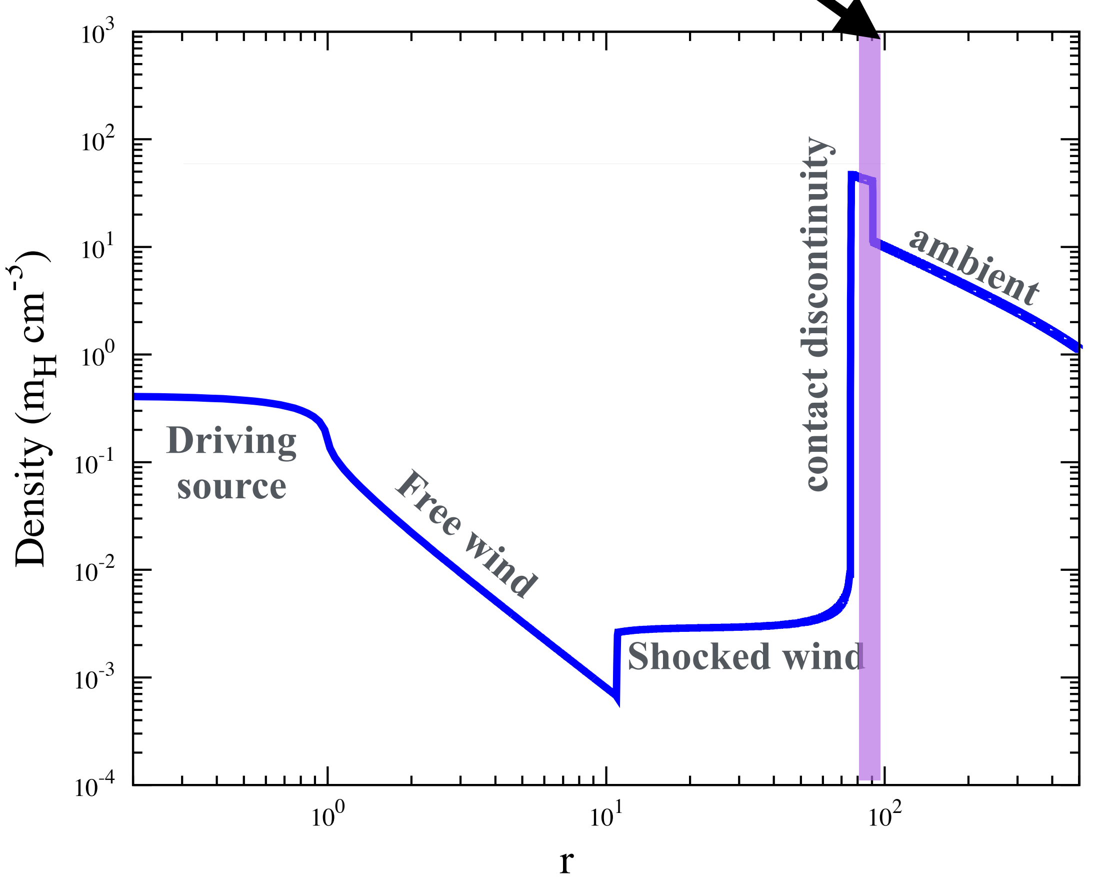
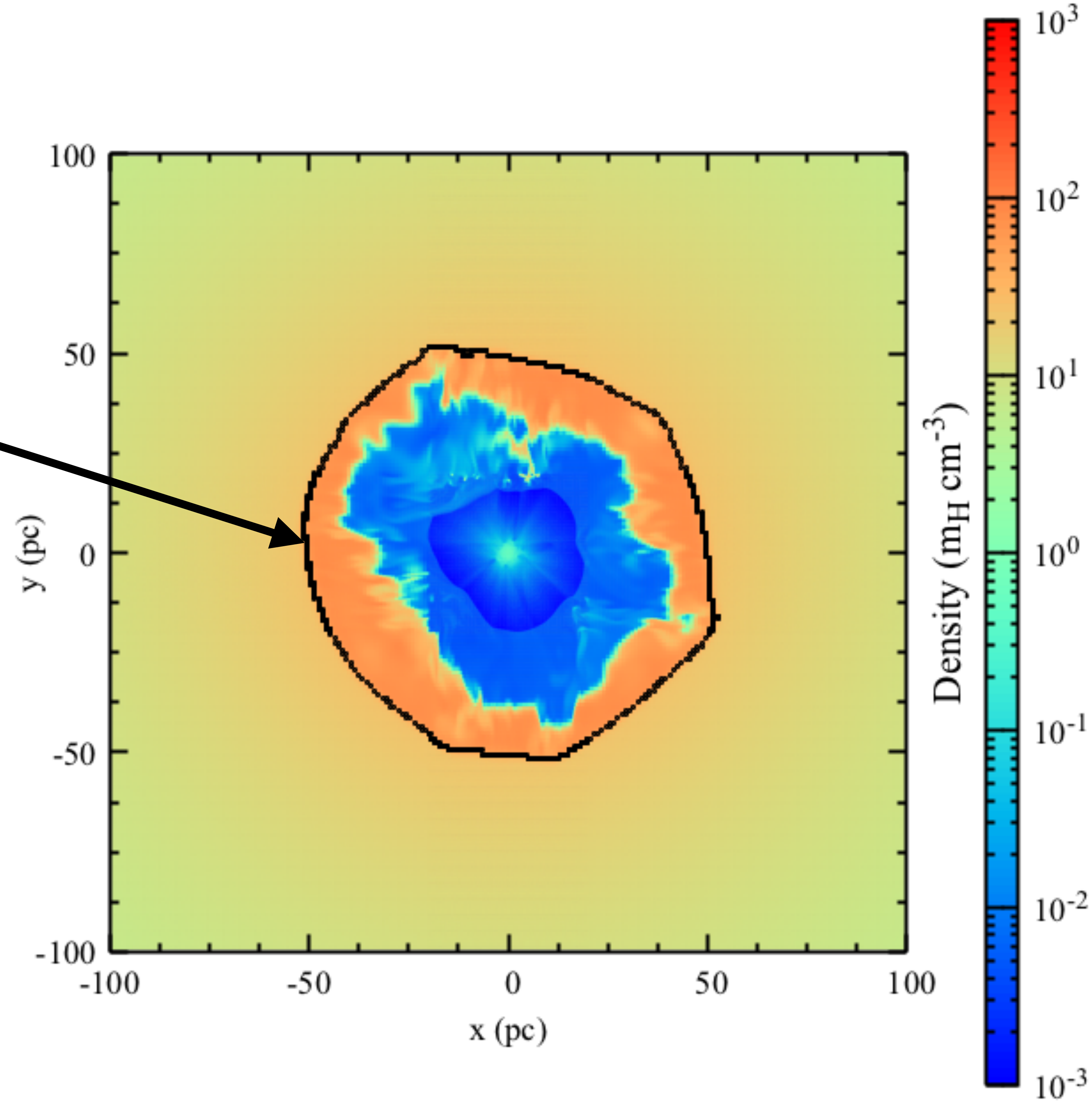




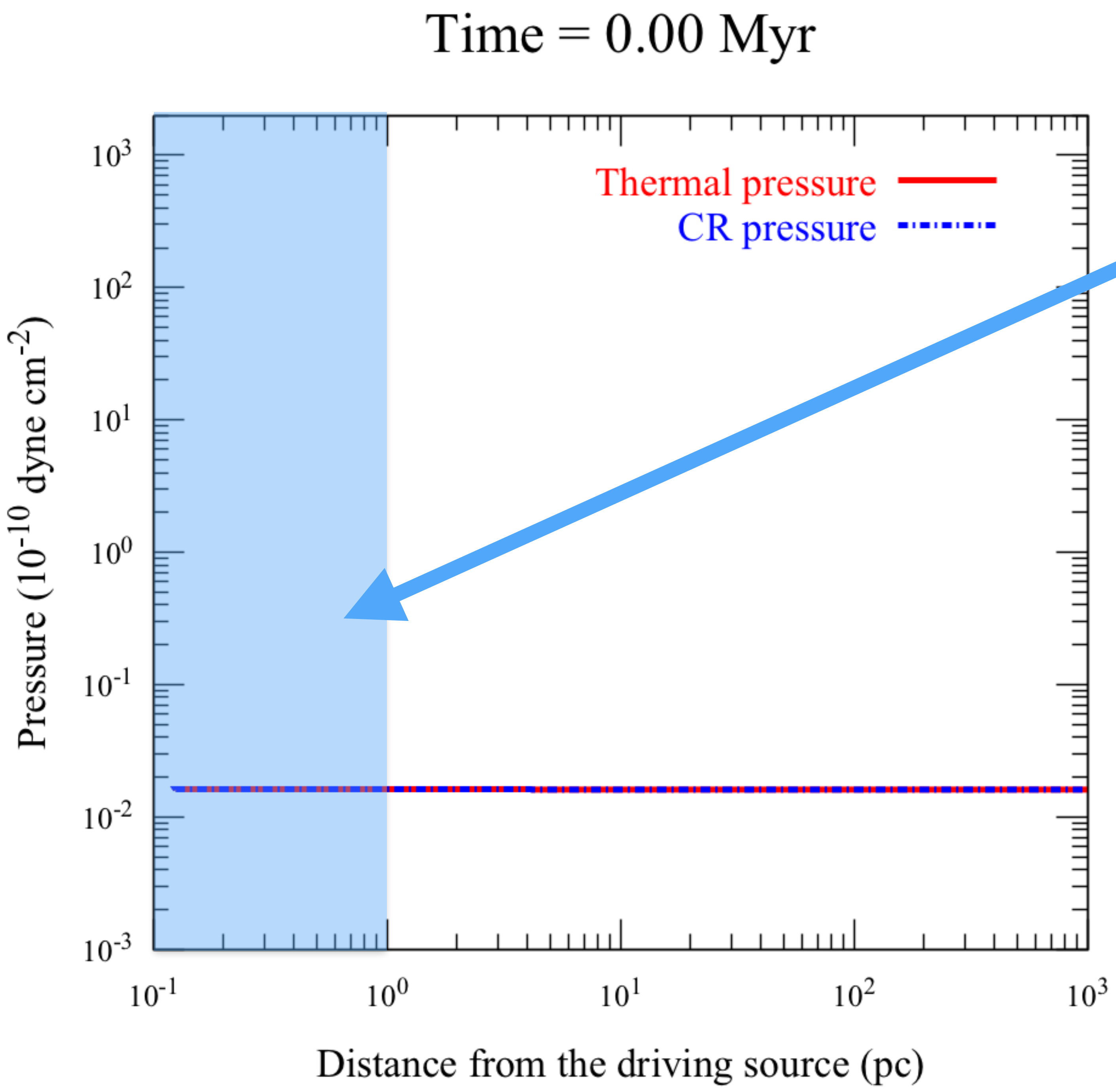
Confusion

Wind driving region?

Reverse and forward shocks?

we investigate two cases separately.

CASE I: CR injection in wind driving region



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

$$\epsilon_{\rm cr} = 0.1$$

- **Mach number Vs time**

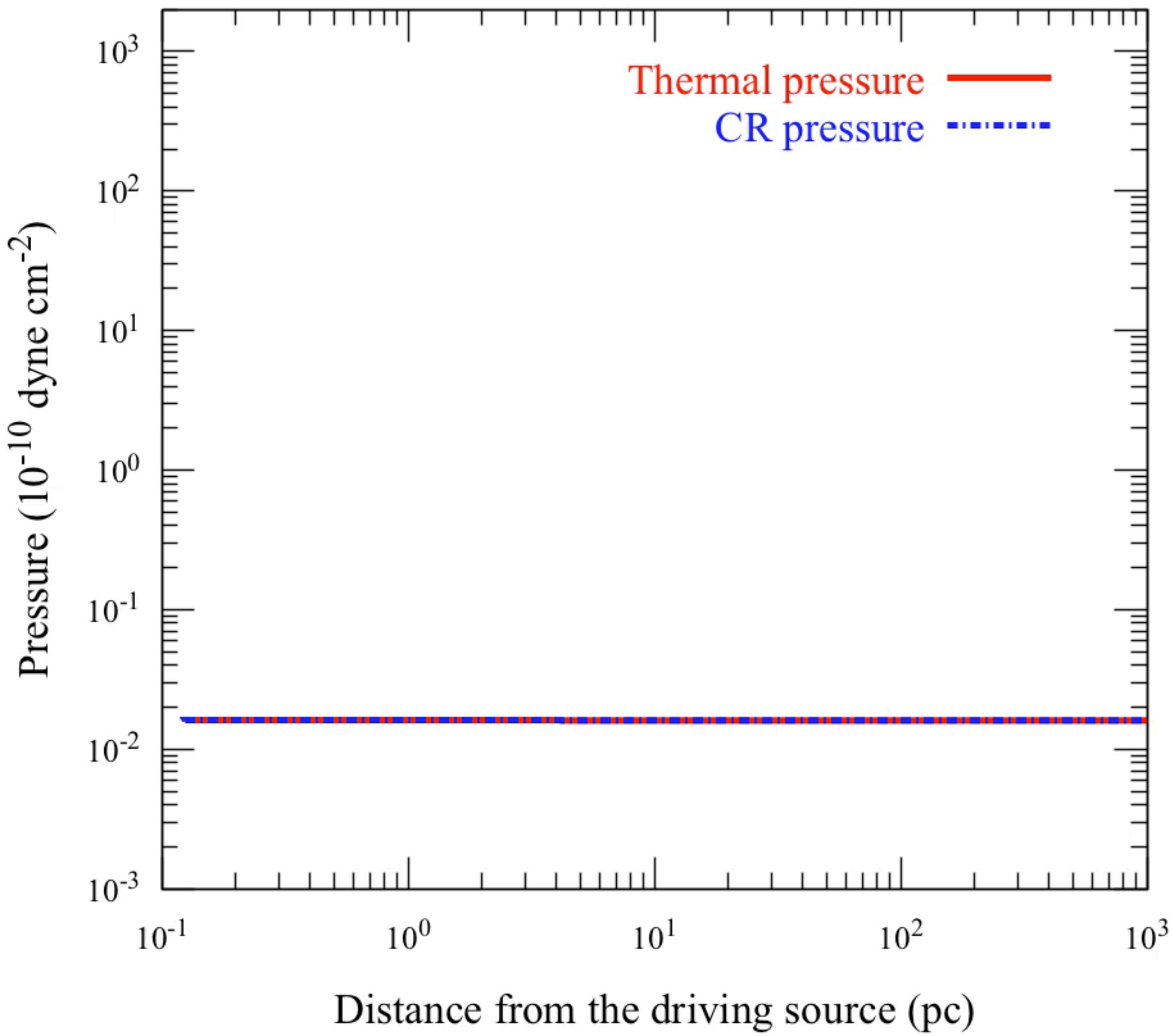
Forward shock decreases ↓

Reverse shock increases ↑
(M~ 10)

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

CASE I: CR injection in wind driving region

Time = 0.00 Myr



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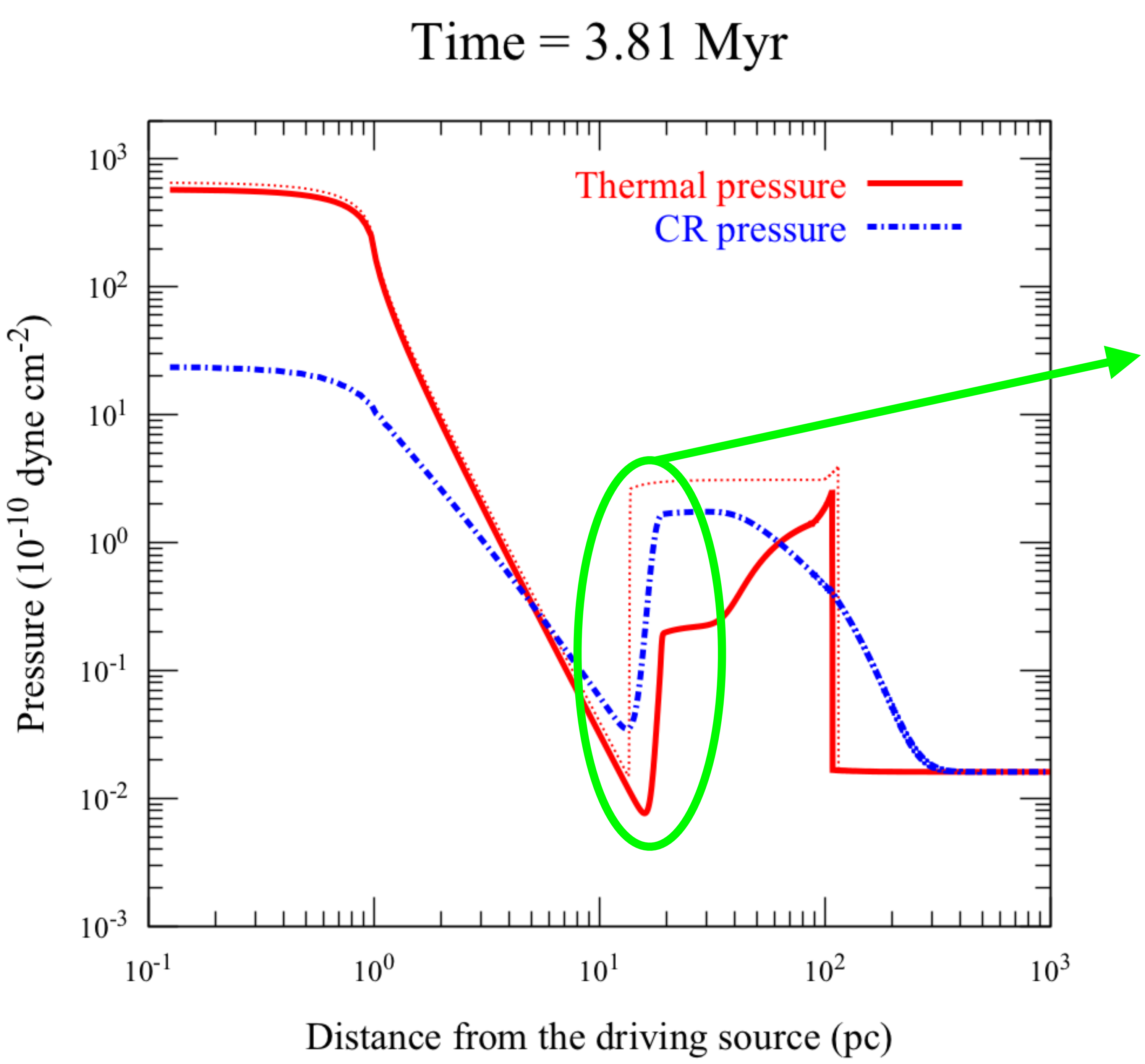


$$\dot{E}_{\rm cr} = \epsilon_{\rm cr}\,\dot{E}$$

$$\epsilon_{\rm cr} = 0.1$$

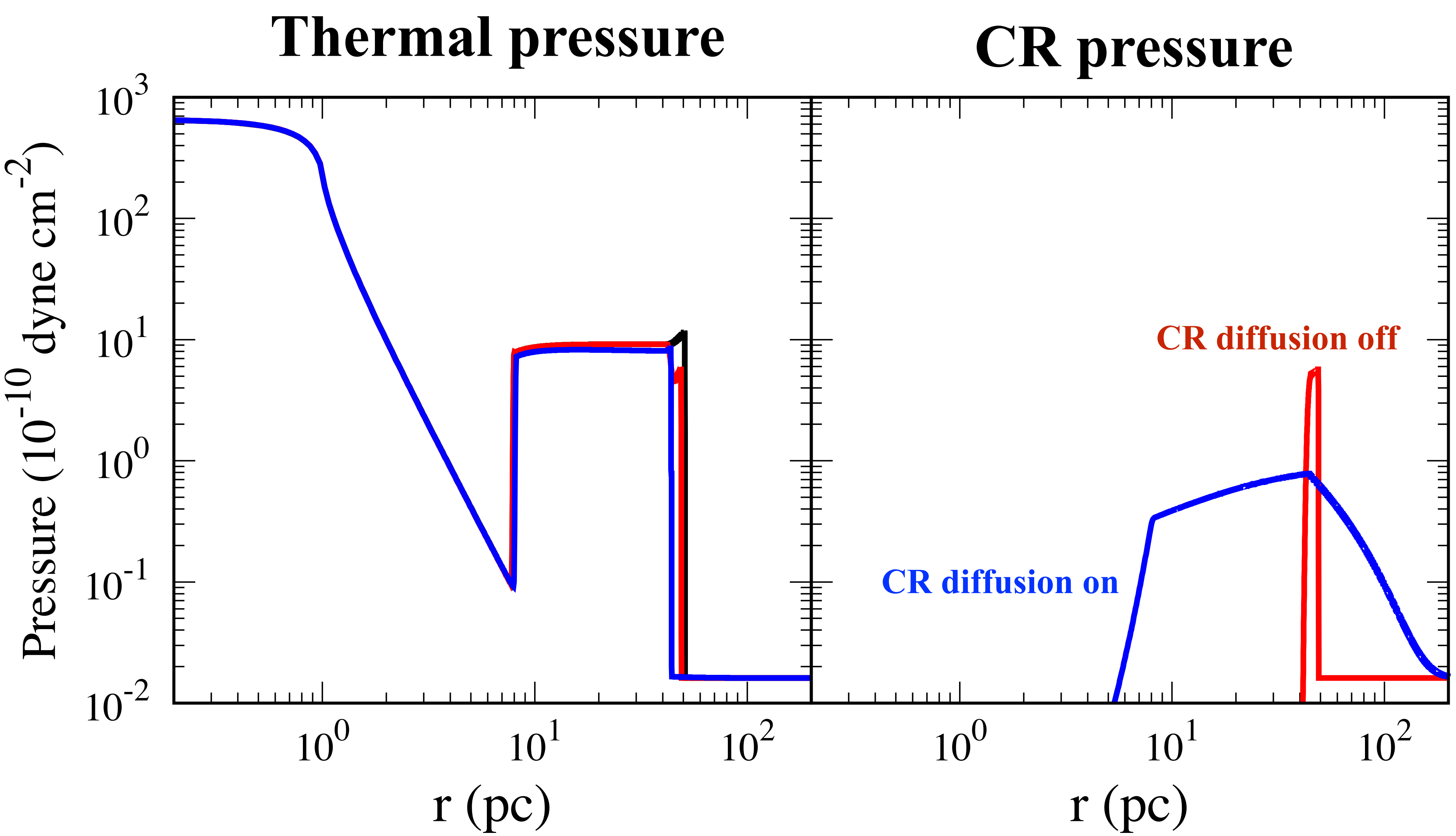
- two-fluid diffusive shock Re-acceleration — **Globally smooth solution** (Drury & Volk 1981, Becker & Kazanas 2001)

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

- thermal energy/X-ray luminosity reduced.

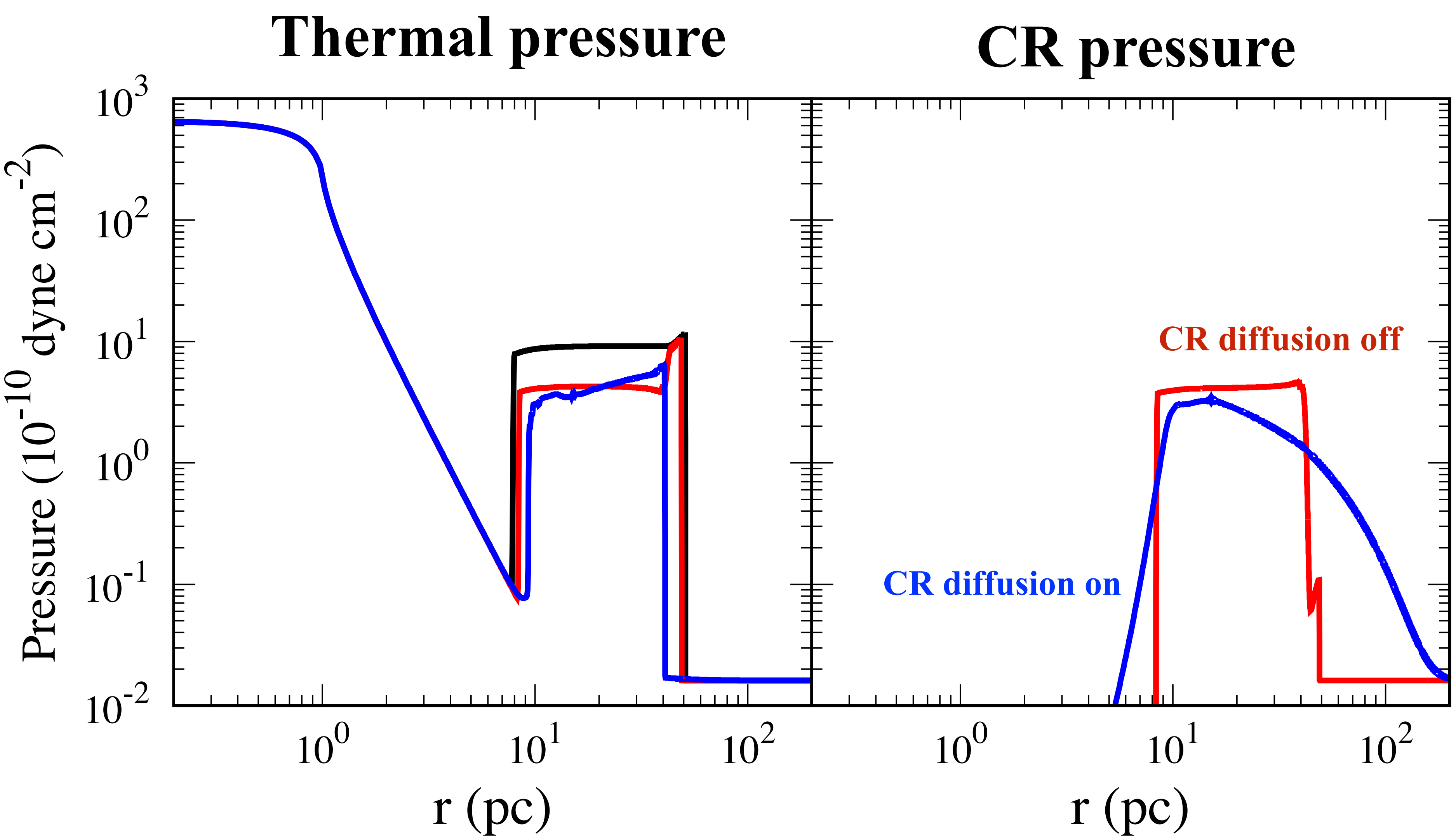
simulation performed using our two-fluid code RAINBOW

CASE IIa: CR injection at forward shock



- Forward shock injection does not change interior structure.

CASE IIb: CR injection at reverse shock



- Reverse shock injection reduces thermal energy.

Take home message

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

Effects of CRs depend on CR injection region.

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

Gamma Ray

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

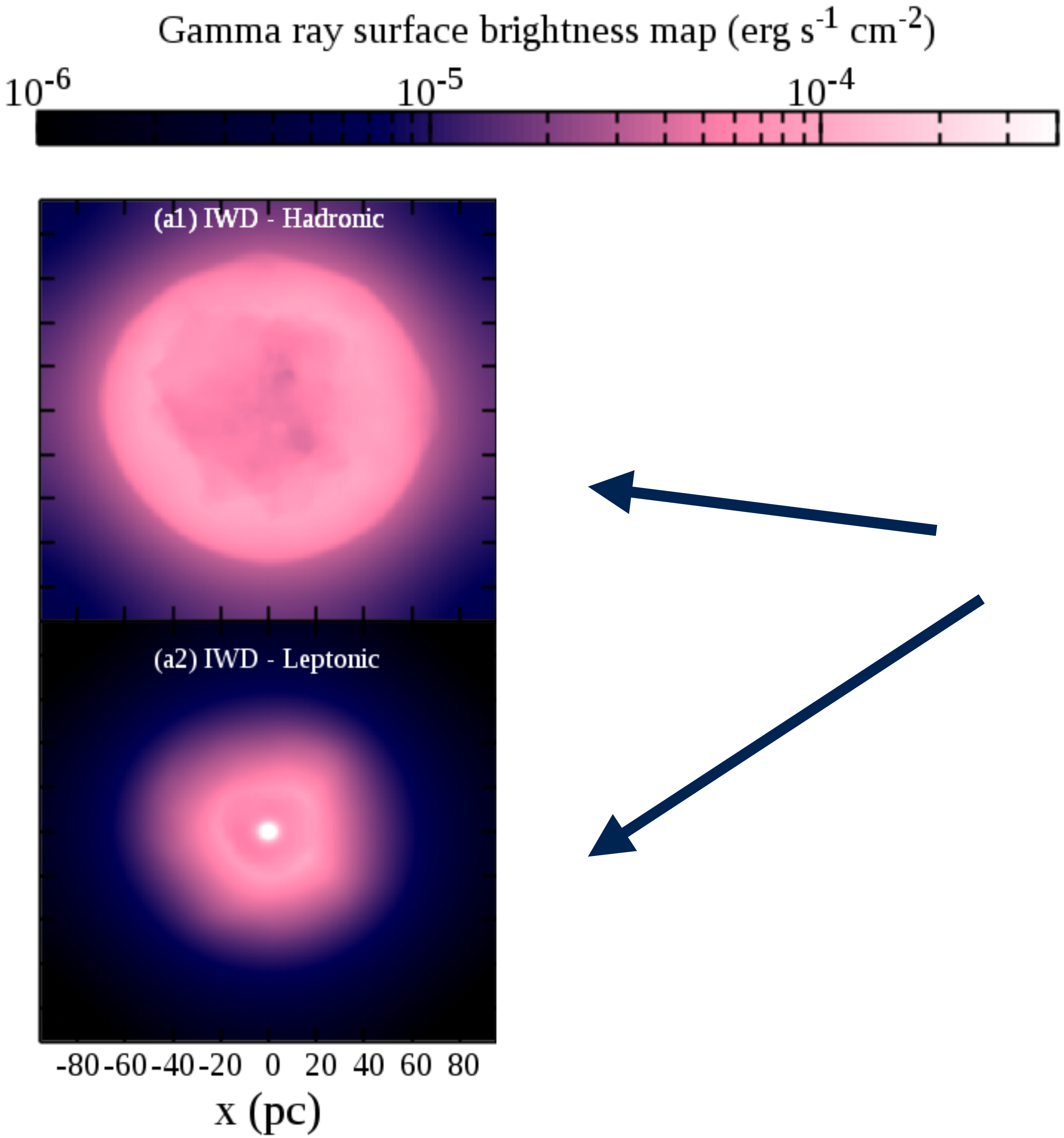
$$L_{\gamma}^{\mathrm{IC}} \propto (\text{volume}) \times (\text{radiation energy density}) \times (\text{CR e}^{-}\ \text{energy density})$$

stellar radiation, IR >> CMB

Take home message

- both processes are important for smaller bubbles (R < 10 pc)

Gamma ray

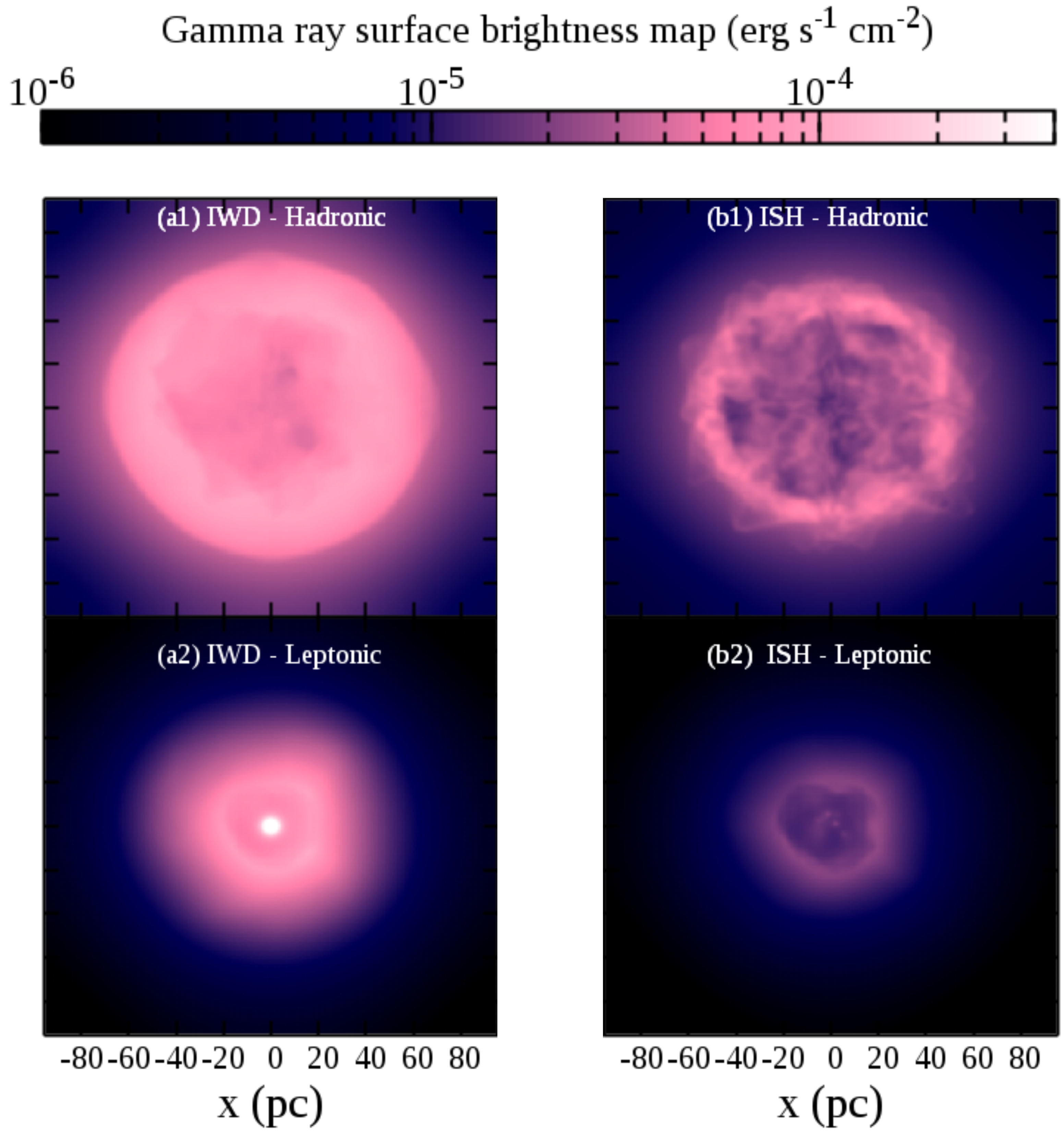


CR injection at wind driving region

$L_\gamma \sim 5\% \, L_w$

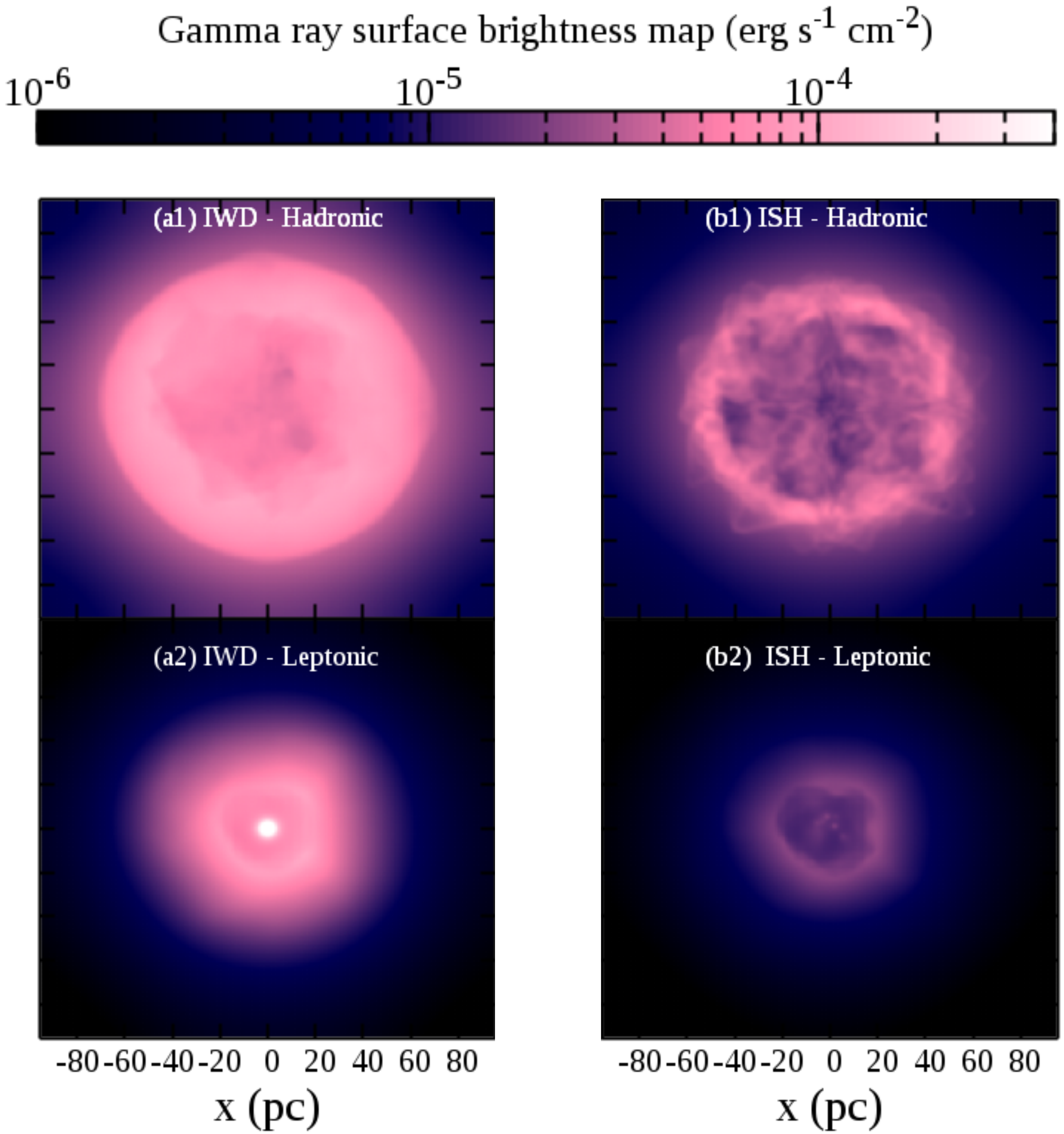
Used prescription: Dermer 1986; Pfrommer & Ensslin 2004

Gamma ray



CR injection at reverse shock and forward shock

Gamma ray



$L_\gamma \sim 1\% \, L_w$

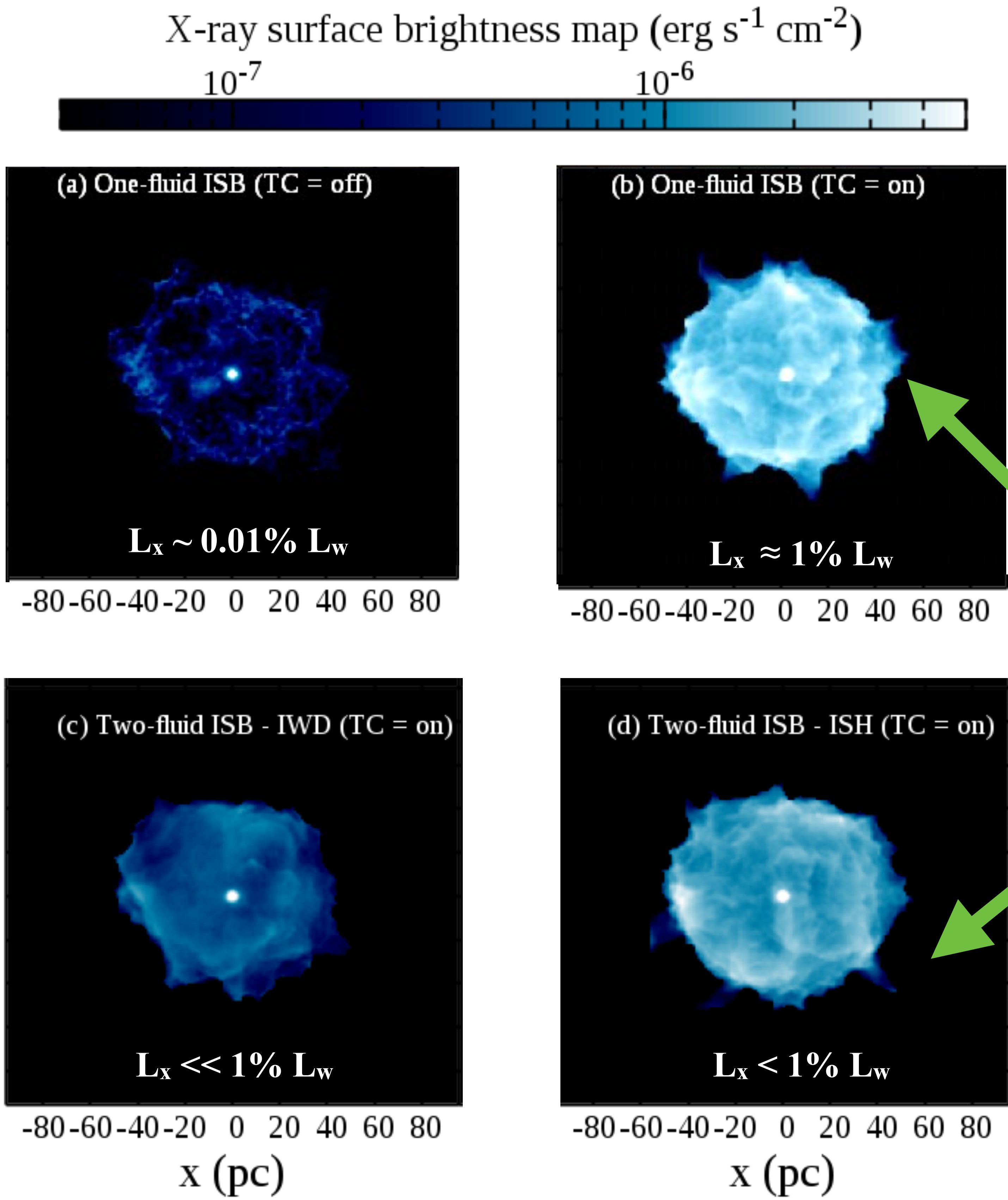
(injection dependent)

preferred model

PIC simulation may help

X - Ray

X-ray (0.5-2 keV)



Take home message

- thermal conduction is important
- over predicts X-ray luminosity?
- preferred model - shock injection
- needs MHD simulations

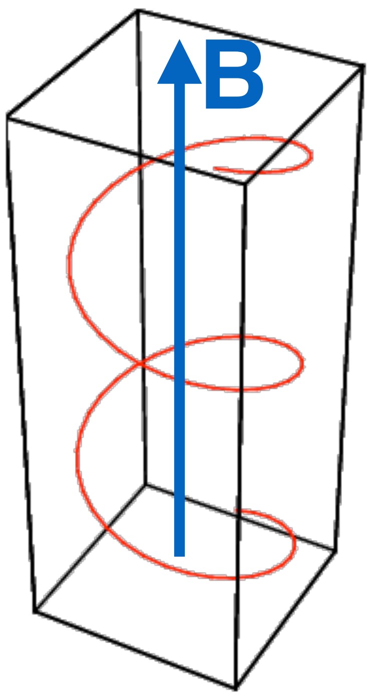
Radio emission

Radio luminosity

Non-Thermal radio:

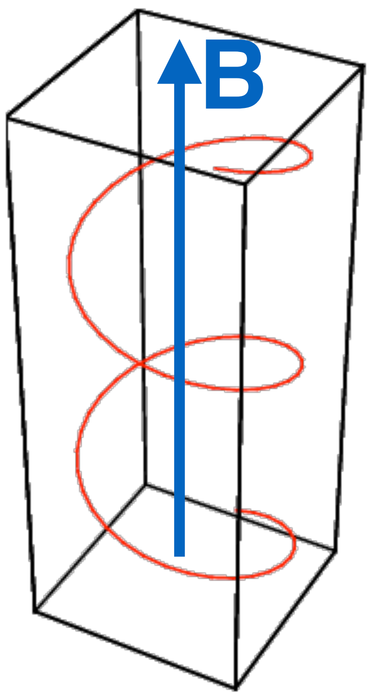
- Synchrotron emission from relativistic electron

$$\frac{dL_{\rm R}}{d\nu} \sim 1.4 \times 10^{24} \left(\frac{R}{10\,{\rm pc}}\right)^{3} \left(\frac{B}{40\mu{\rm G}}\right)^{1.6} \left(\frac{e_{\rm cr\_e}}{10^{-10}{\rm cgs}}\right) \left(\frac{\nu}{1.4{\rm GHz}}\right)^{-0.6} \ {\rm erg\,s^{-1}\,Hz^{-1}}$$



Radio luminosity

Non-Thermal radio:



- Synchrotron emission from relativistic electron

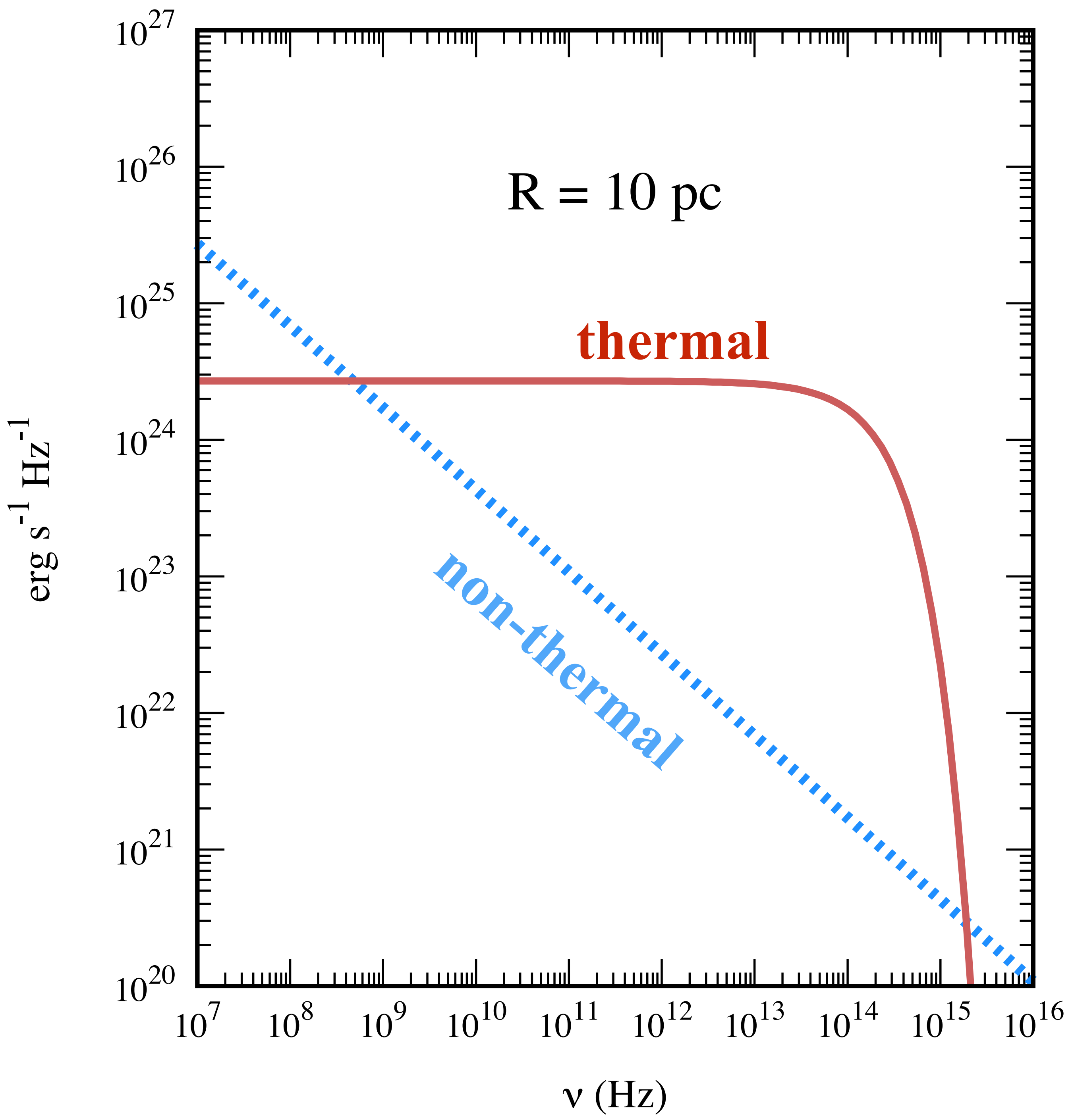
$$\frac{dL_{\rm R}}{d\nu} \sim 1.4 \times 10^{24} \left(\frac{R}{10\,{\rm pc}}\right)^{3} \left(\frac{B}{40\mu{\rm G}}\right)^{1.6} \left(\frac{e_{\rm cr\_e}}{10^{-10}{\rm cgs}}\right) \left(\frac{\nu}{1.4{\rm GHz}}\right)^{-0.6} \ {\rm erg\,s^{-1}\,Hz^{-1}}$$

Thermal radio:

- Bremsstrahlung of thermal electrons

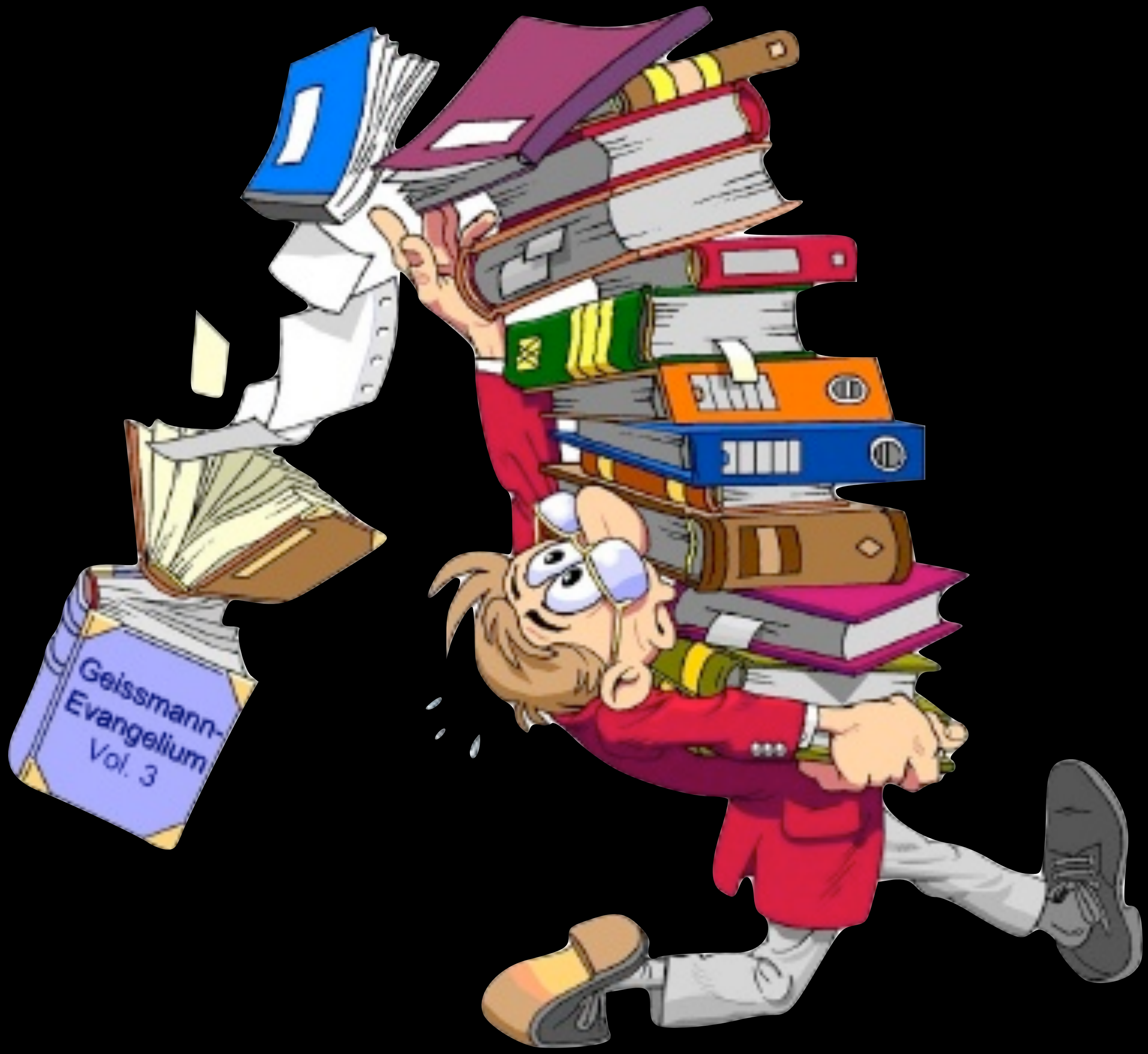
$$\frac{\rm dL}{\rm d\nu}|_{\rm ff} = 2.7 \times 10^{24} \left(\frac{R}{10{\rm pc}}\right) \exp\left[-\frac{h\nu}{k_{\rm B}\,T_4}\right] \ {\rm erg\,s^{-1}\,Hz^{-1}}$$

Radio luminosity: MHD is needed



- **Thermal radio ~ non-thermal radio**

Take home message



Take home message

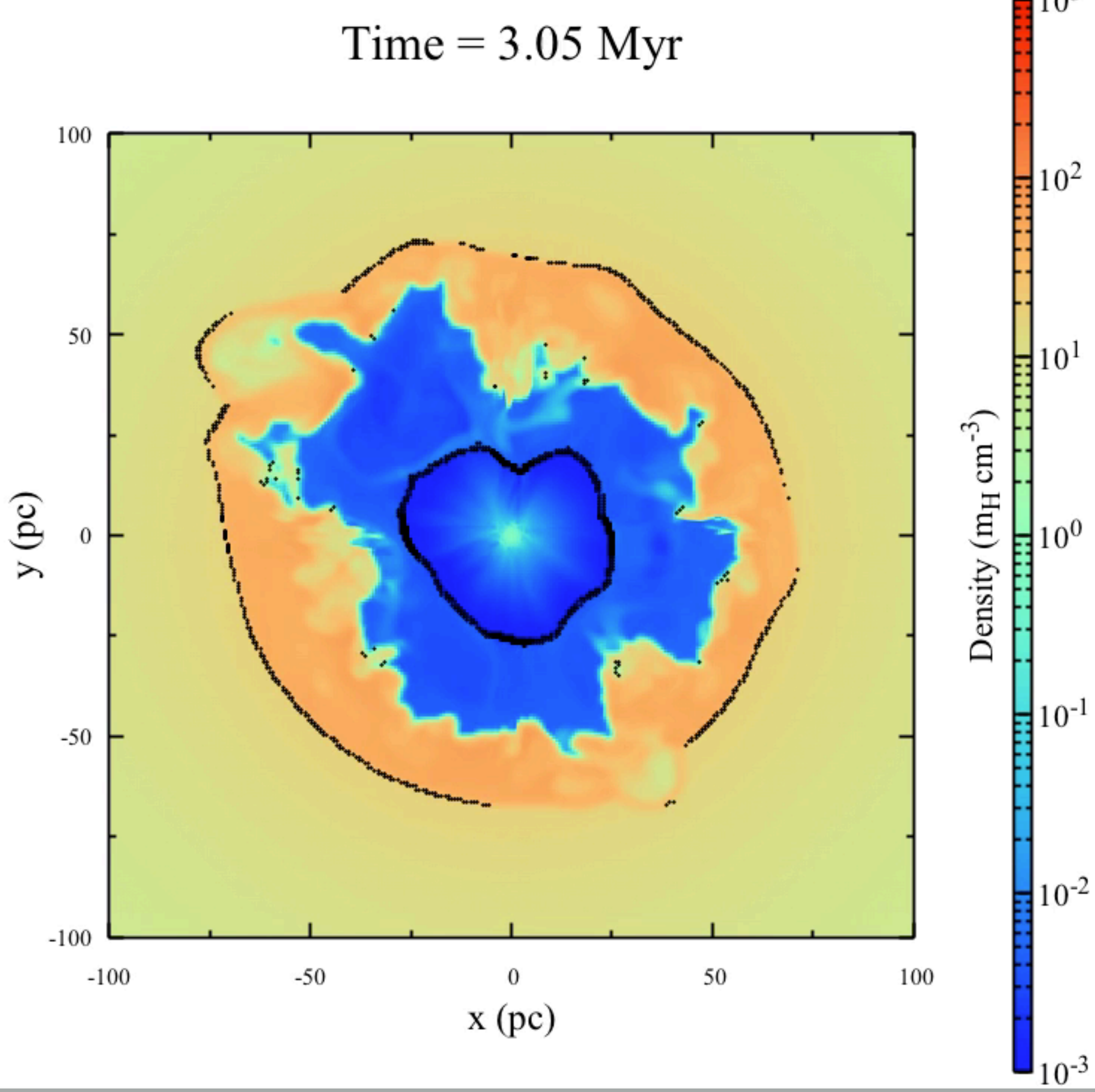
2. Can we model CRA from multi-wavelength luminosities?

A. Gamma-ray and X-ray luminosity can be used to model CR acceleration efficiency.

B. Interpretation of radio observations needs more accurate modeling.

Reference: **Gupta, S.,** Nath, B. & Sharma, P. (arXiv:1804.05877)

Stellar wind + Supernovae



Do all star clusters form reverse (wind termination) shock?

Summary

The effect of CRs in SN blast wave —Chevalier 1983 (also see Diesing & Caprioli: arXiv1804.09731)

We have generalized the interstellar bubble model of Weaver et al. 1977 in presence of cosmic rays.

1. **Star clusters can efficiently accelerate cosmic rays in their wind termination shock.**
2. **This study will be useful to constrain cosmic ray acceleration from multi-wavelength observation.**

What's next?

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

Contribution of star cluster in Galactic CRs.

Important references

1. Chevalier, R. A. 1983, ApJ, 272,765

2. Chevalier, R. A. & Luo D. 1994, ApJ, 421, 225

3. Becker, P. A. & Kazanas, D. 2001 ApJ, 546, 429

4. Drury, L. O'C. & Volk, J. H. 1981 ApJ, 248, 344

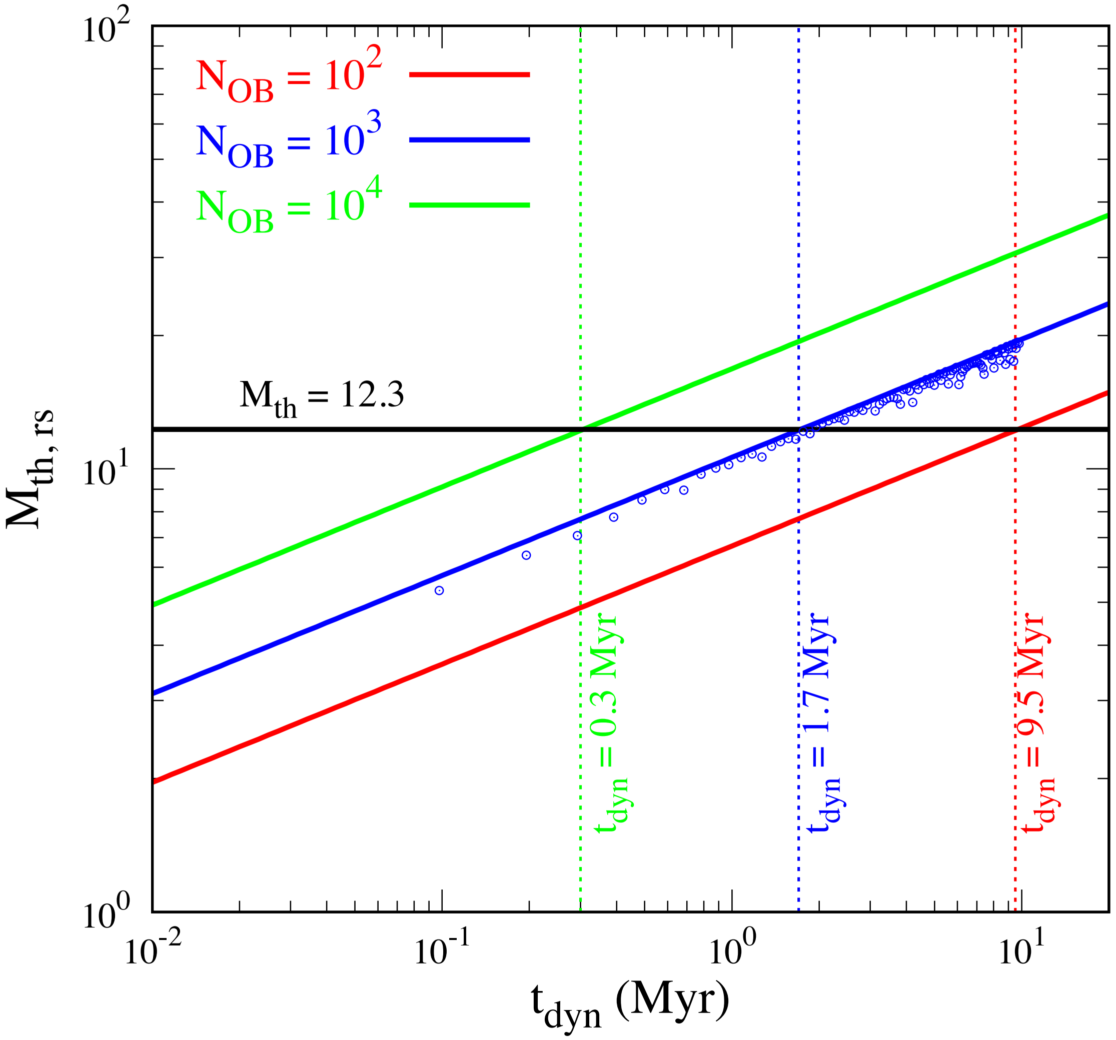
4. Gupta, S., Nath, B. B., Sharma, P. (arXiv:1804.05877)

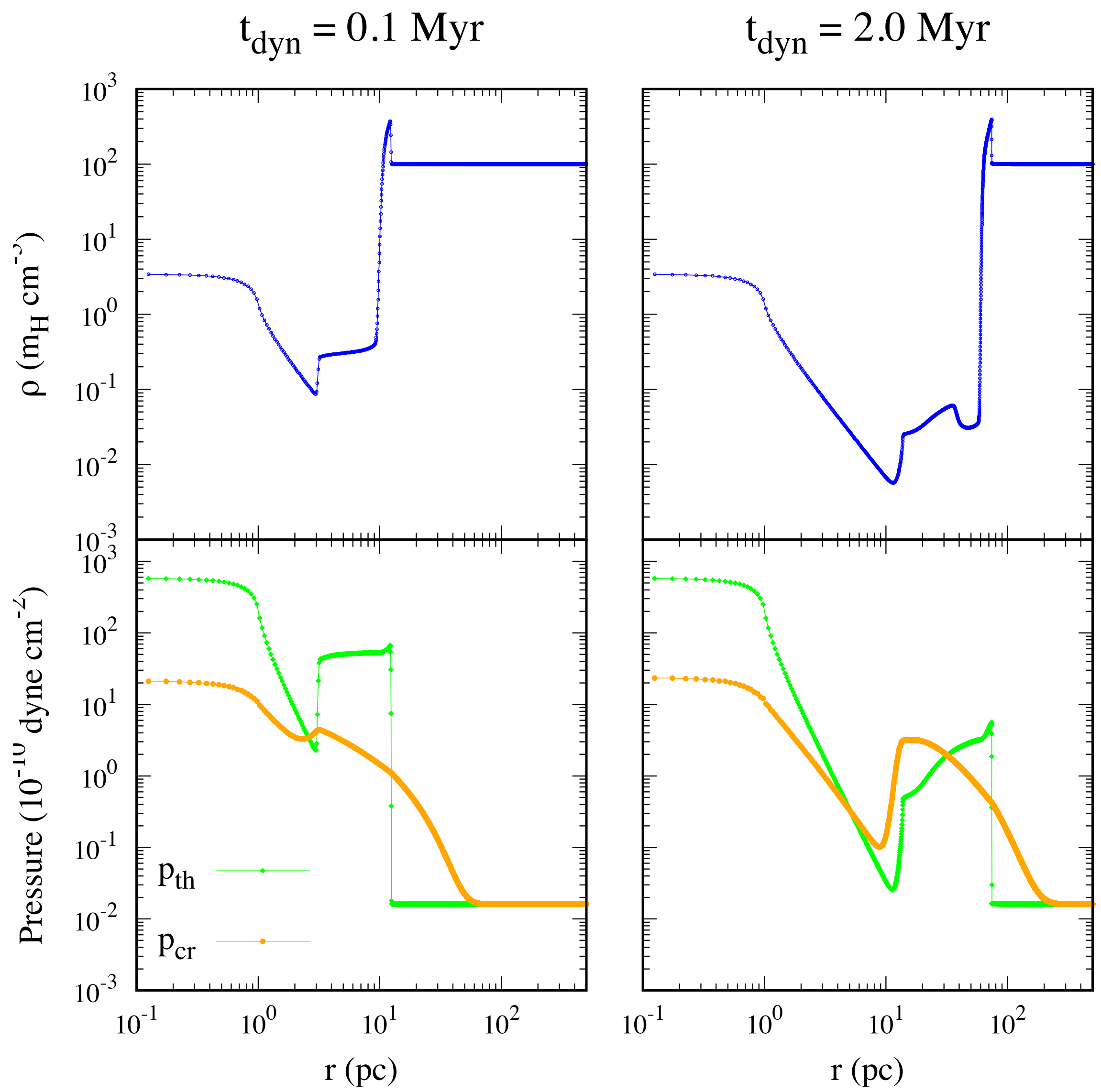
5. Gupta, S., Nath, B. B., Sharma, P. & Eichler, D. 2018, MNRAS, 473, 1537

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

Two-fluid shocks





$$M_{\rm th,rs} = \frac{v_{\rm w}}{a_{\rm th,rs}} \simeq 8.15\,\eta^{-2/15} R_{\rm src,pc}^{-2/3}\,\rho_2^{-1/5}\,\dot{M}_{-4}^{1/6}\,L_{39}^{1/30}\,t_6^{4/15}$$