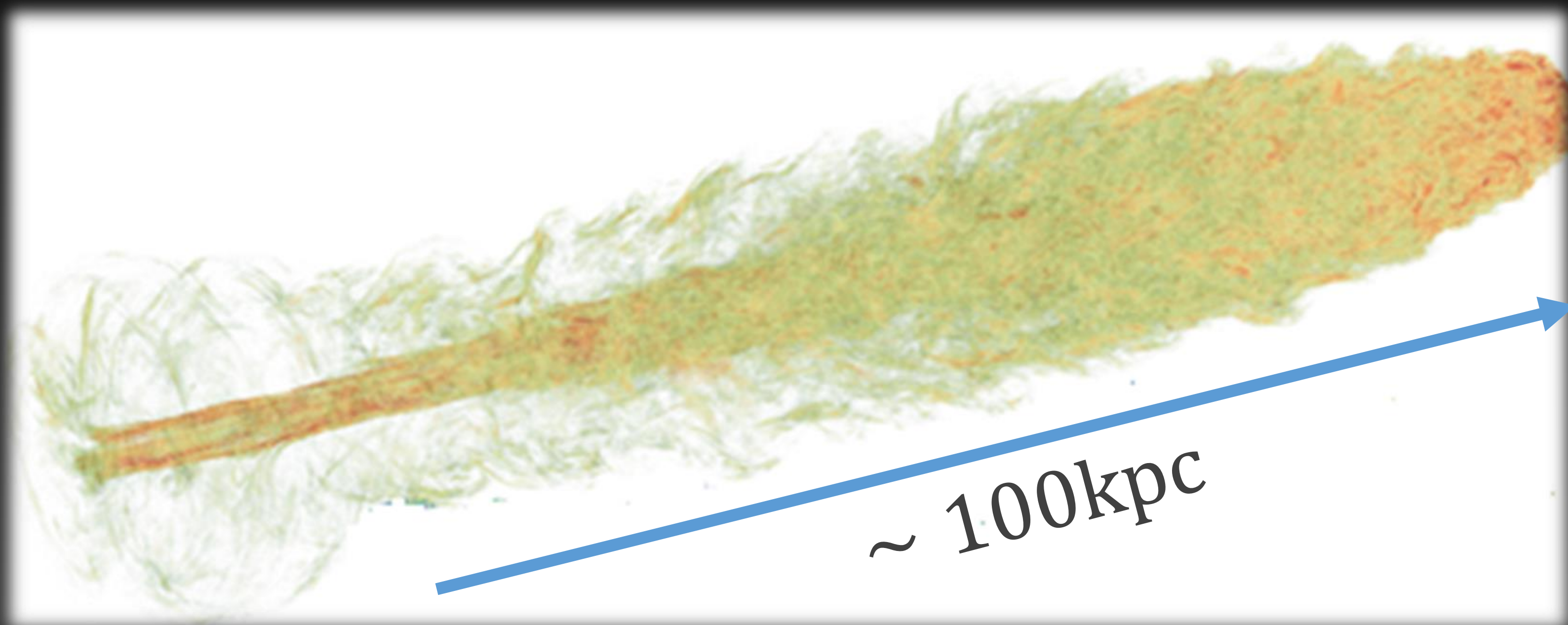
Preliminary

Three dimensional modeling of FR-II jets using two-temperature MHD simulation



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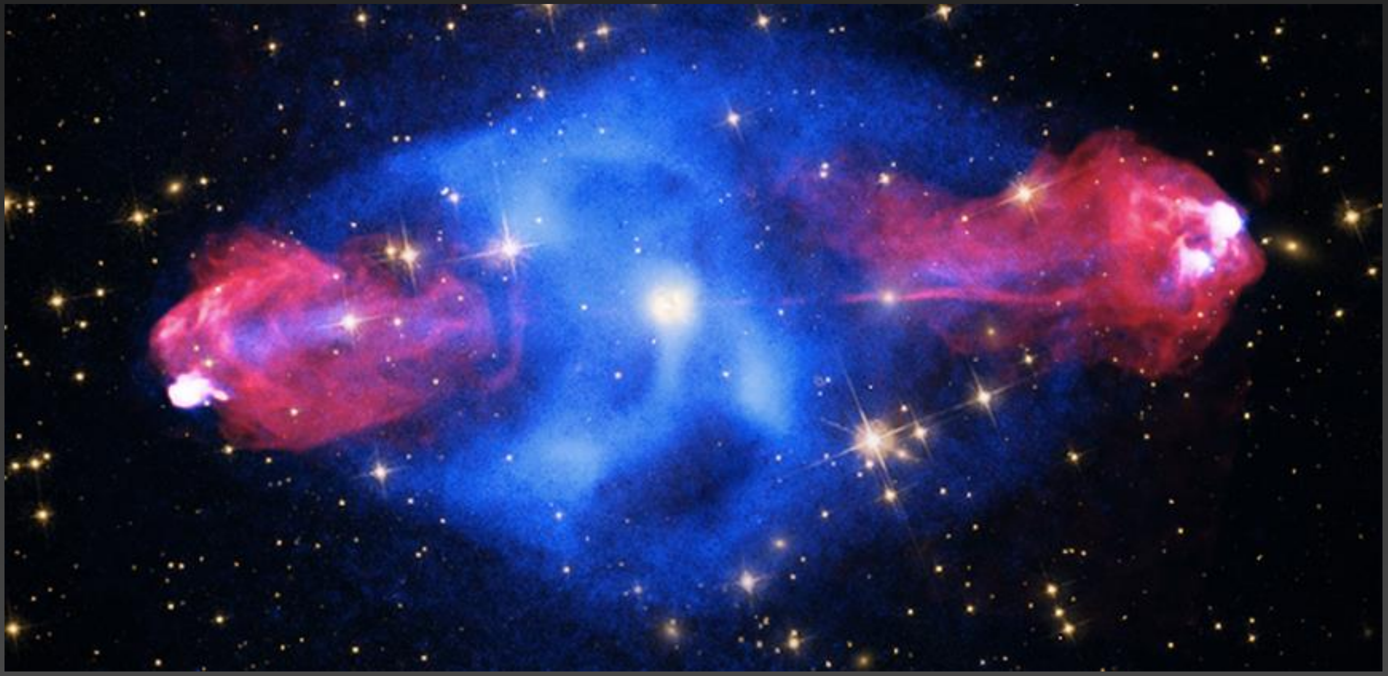
1. Introduction - FR II Radio Galaxies -

Most of FR II sources have powerful jets

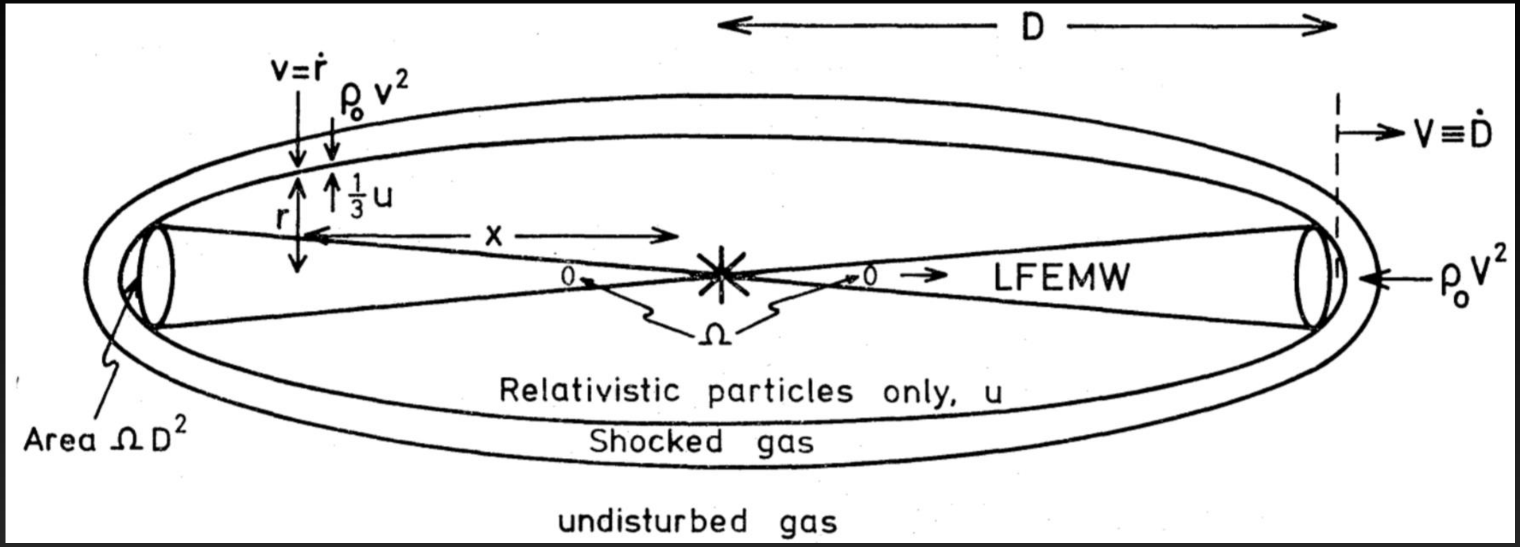
- Edge brightened sources (hotspot, Radio-lobe)
Synchrotron radiation from relativistic electrons in the magnetic fields of lobes.

- Diffuse thermal X-ray emitted like a rugby ball.



Blue:X-ray, Red: Radio

1. Introduction - FR II Radio Galaxies -



Classical theory of FR II jets (e.g., Scheuer 1974)

- Jets convert kinetic energy into particles and internal energy at the terminal shocks = Hotspots

- The hot plasma through the hotspots back towards to the nucleus, spreading out = Radio-lobe (Cocoon)

- The layer of shocked plasma emitted diffuse X-ray.

1. Introduction - Two-temperature plasma -

X-ray cavity in the galaxy cluster

-> Jet plasma is hotter and lighter than ICM

$[\ n_{\rm ICM} \sim 10^{-2} - 10^{-3}{\rm cm}^{-3}, T_{\rm ICM} \sim 10^{7} - 10^{8}{\rm K}\ ]$

- Relaxation time scale of electrons and ions through Coulomb coupling is longer than the propagation time scale.

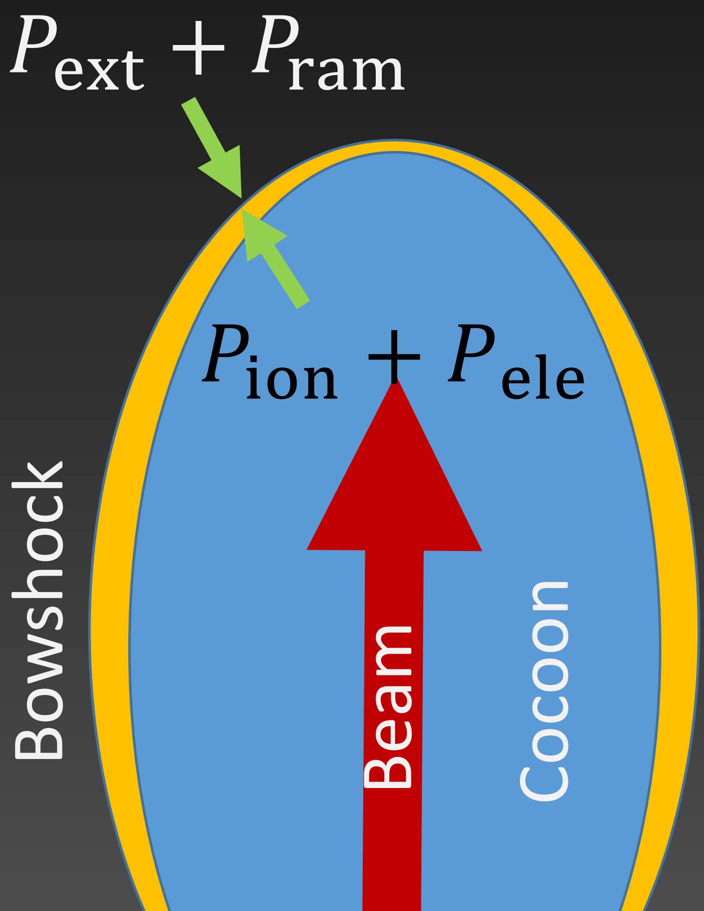
$$\tau_{\rm ei} \geq \tau_{\rm dyn} \qquad \tau_{\rm ei} \propto n^{-1} T_{\rm e}^{3/2}$$

- Electrons and ions could be decoupled in jets.

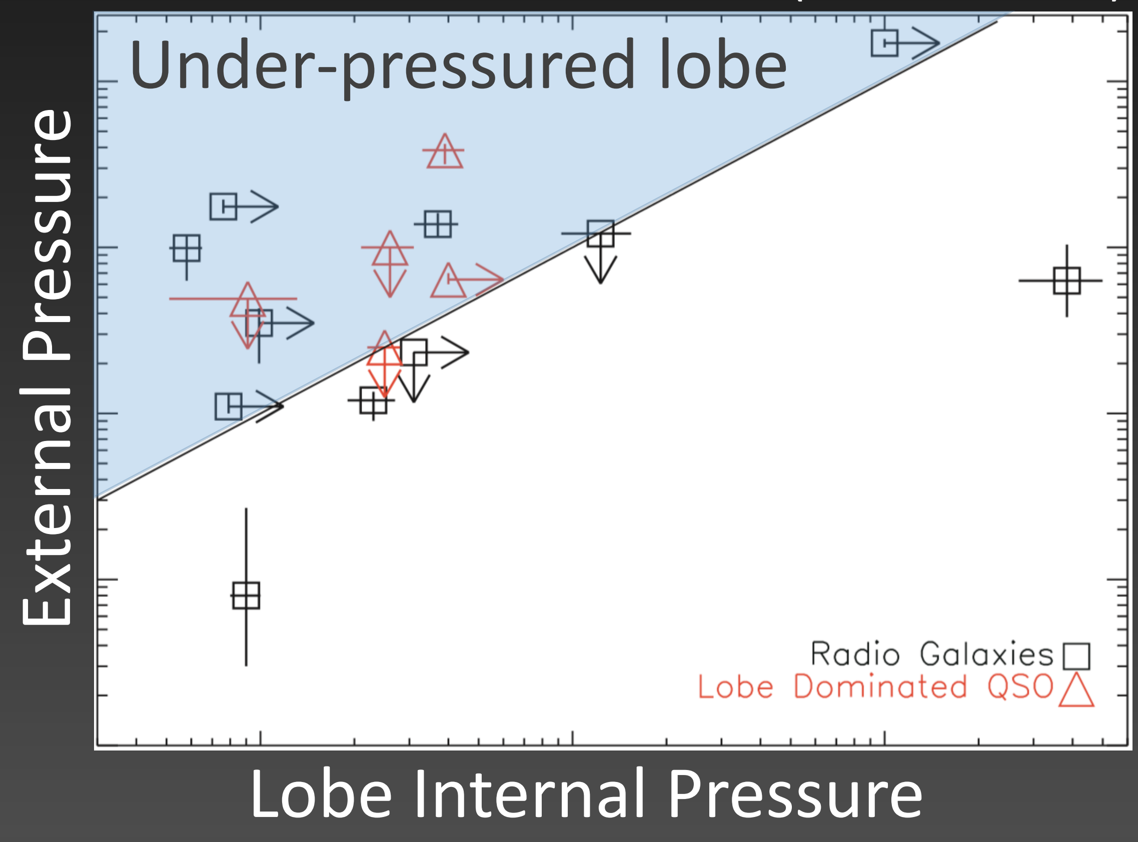
$$\rightarrow \quad p_{\rm electron} \neq p_{\rm ion}$$

1. Introduction - Energetics of radio-lobe -

- Pressure balance of radio-lobe, $P_{\rm ext} \leq P_{\rm ion} + P_{\rm ele}$
- The under-pressured lobe indicate the existence of the non-radiating ions in the FR-II jets.



(Belsole+ 2007)



1. Introduction - Energetics of radio-lobe -

- Pressure balance of radio-lobe, $P_{\mathrm{ext}} \leq P_{\mathrm{ion}} + P_{\mathrm{ele}}$

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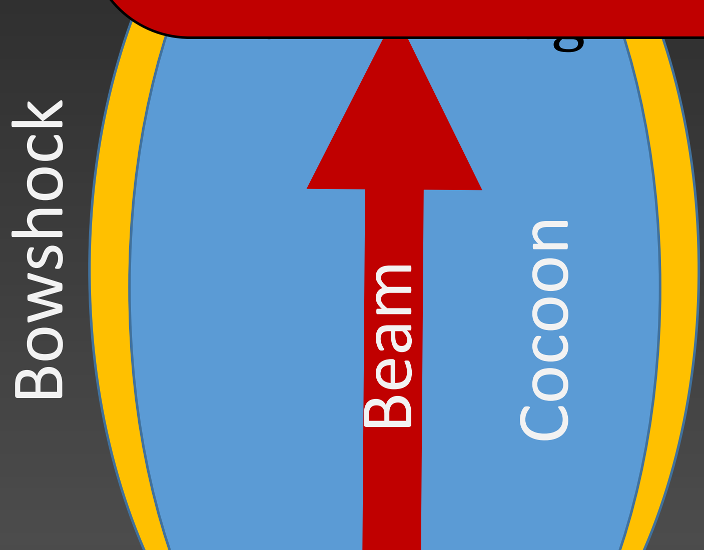
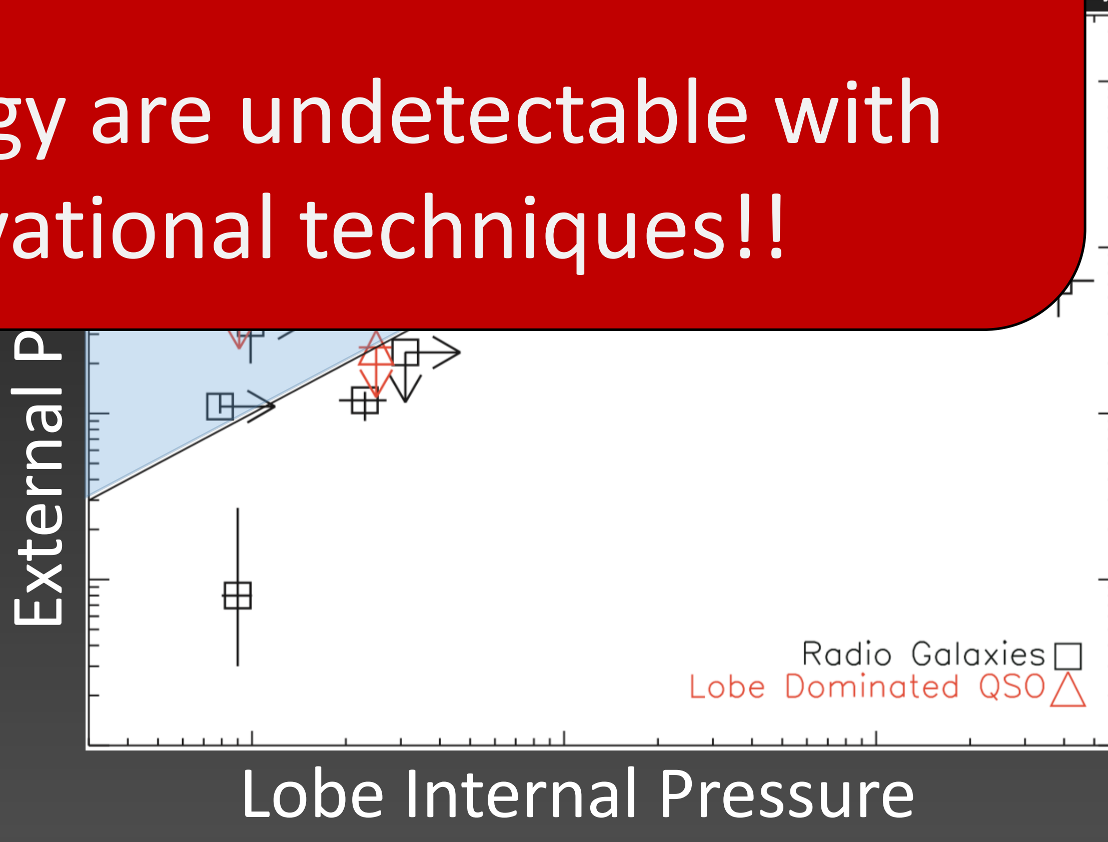
- We can only estimate electron energy through radiation.

- The ion energy are undetectable with current observational techniques!!





1. Introduction - Motivations -

We investigate

- the spatial energy distribution of electron and ion through two-temperature MHD jets simulation.
- the pressure balance between jet and surrounding medium, especially possibility of electron under-pressured lobe.

Method

- Basic equations
- The fraction of electron heating
- Model

2. Method - Basic equations -

Assumption

- Electron-Ion plasma, $n = n_{\mathrm{i}} = n_{\mathrm{e}}$
- One fluid approximation
- Electron and Ion have distinct temperature

MHD Eqs. + Electron and Ion. energy Eqs.

$$
\begin{cases}
nT_{\mathrm{i}} \dfrac{ds_{\mathrm{i}}}{dt} = -q^{\mathrm{ie}} + (1 - f_{\mathrm{e}}) q^{\mathrm{heat}} \\
nT_{\mathrm{e}} \dfrac{ds_{\mathrm{e}}}{dt} = +q^{\mathrm{ie}} + f_{\mathrm{e}} q^{\mathrm{heat}} - q^{\mathrm{rad}}
\end{cases}
$$

[Colulomb] [Dissipation] [Radiation]

2. Method - The fraction of electron heating -

Model 1: Turbulent dissipation into the electron and ions.

(Kawazura+ 2019)

$$f_\mathrm{e} = f_\mathrm{e}(T_\mathrm{e}/T_\mathrm{i}, \beta_\mathrm{i})$$

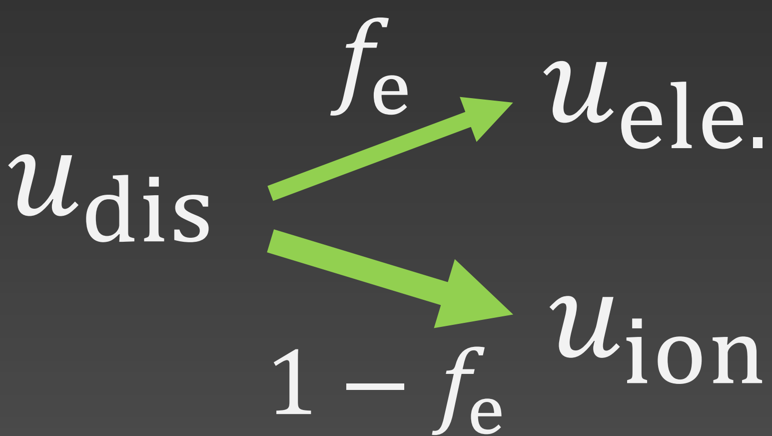
Magnetic energy dominant region : $f_\mathrm{e} \to 1$ (electron heating),

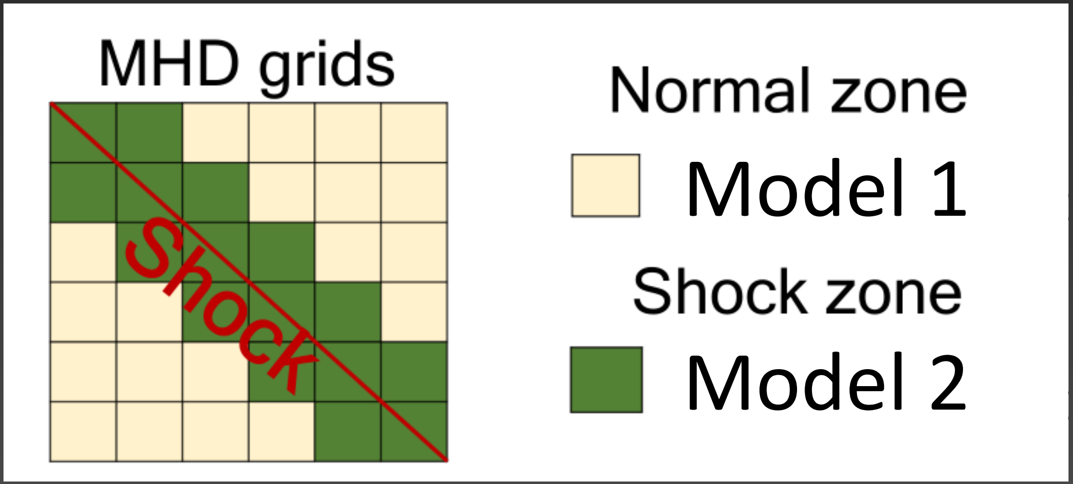
Thermal energy dominant region : $f_\mathrm{e} \to 0$ (ion heating)

Model 2: Dissipation in collisonless shock.

$f_\mathrm{e} = 0.05$ Shocks heat ions (e.g., Ghavamian+2013, Matsukiyo+2010).

$$0 < f_\mathrm{e} < 1$$

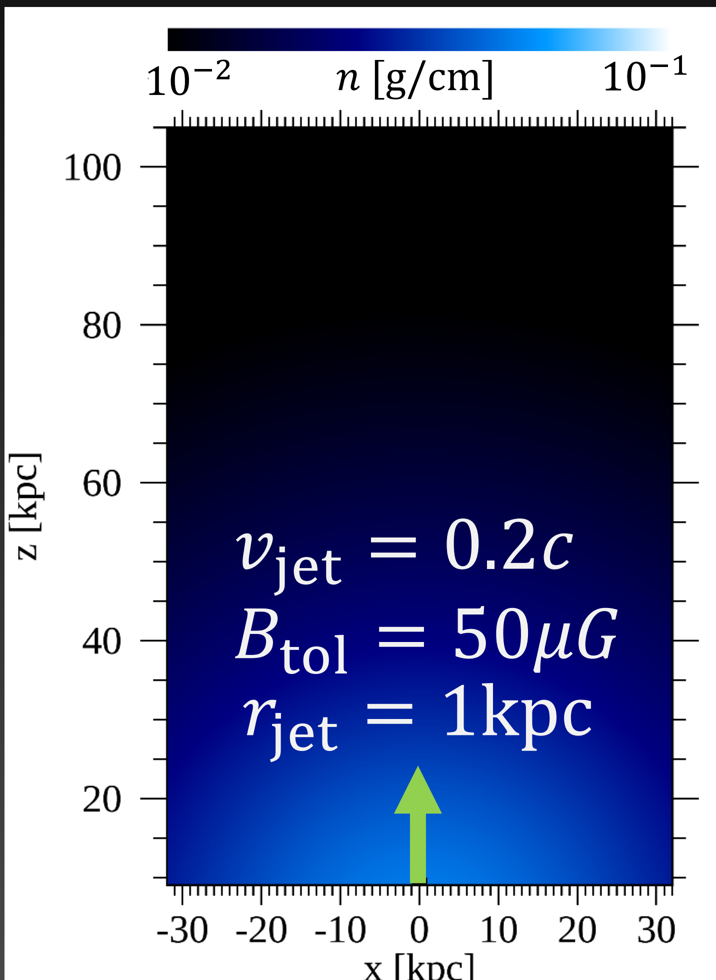




2. Method - Model -

MHD CODE : CANS+ (Matsumoto+2019, Ohmura+ 2019)

Uniform Grids: (800,800,1200)



Jets parameter

$$L_{\rm kin} = 2.0 \times 10^{46} {\rm erg/s}$$

$$T_{\rm e} = T_{\rm i} = 3.0 \times 10^{9} {\rm K}$$

Initial ICM profile

β-profile (King+ 1972)

$$\rho(r) = \rho_0 \{1 + (r/r_{\rm c})^2\}^{-3\beta/2}$$

$$T_{\rm e} = T_{\rm i} = 2.3 \times 10^{7} {\rm K}\ (2{\rm KeV})$$

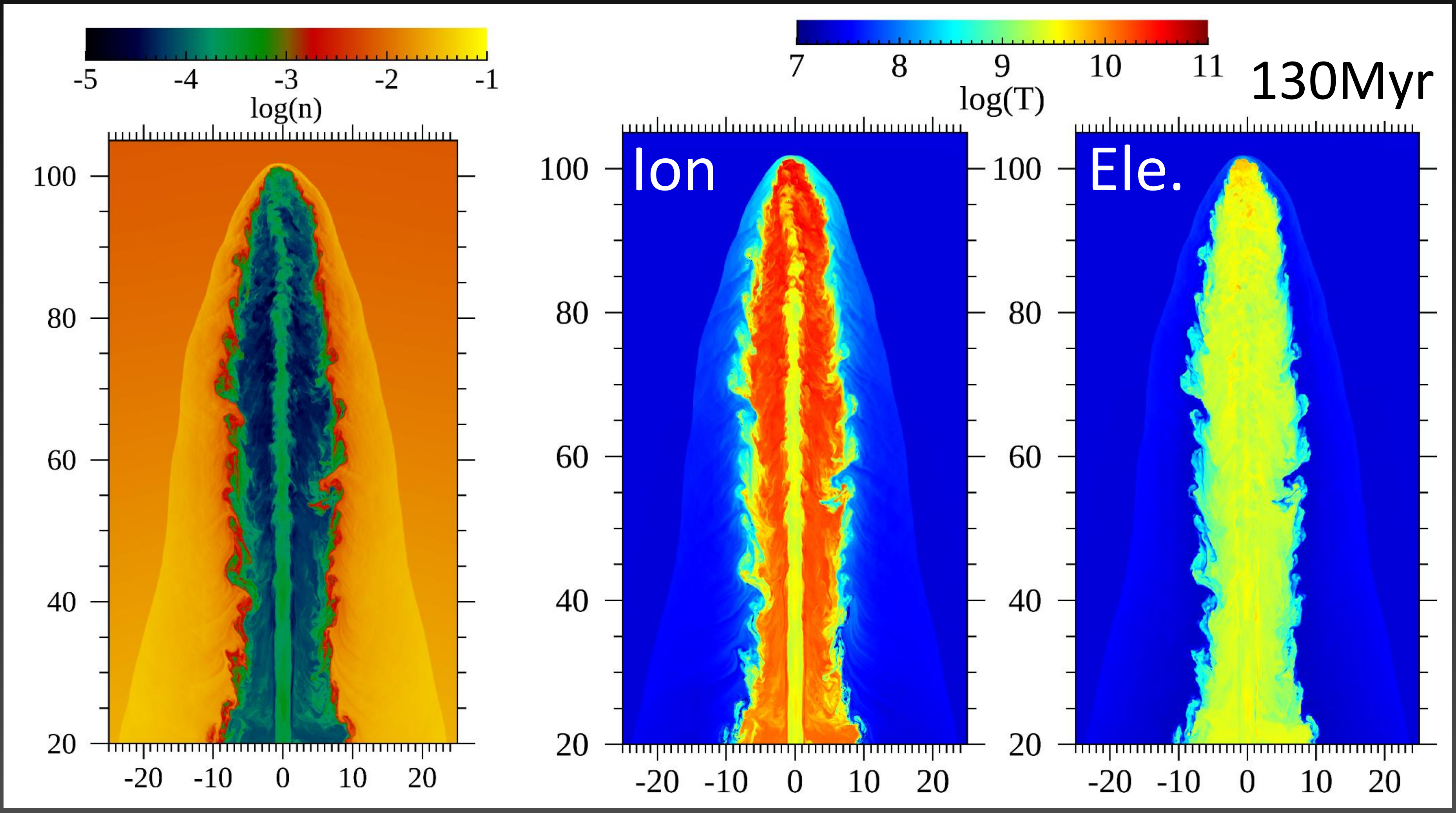
$\rho_0 = 8.35 \times 10^{-26} {\rm g/cc}, r_{\rm c} = 30{\rm kpc}, \beta = 1/2$

Results

- Overview
- Energetics in jets
- Under-pressured lobe

3. Results - Overview -

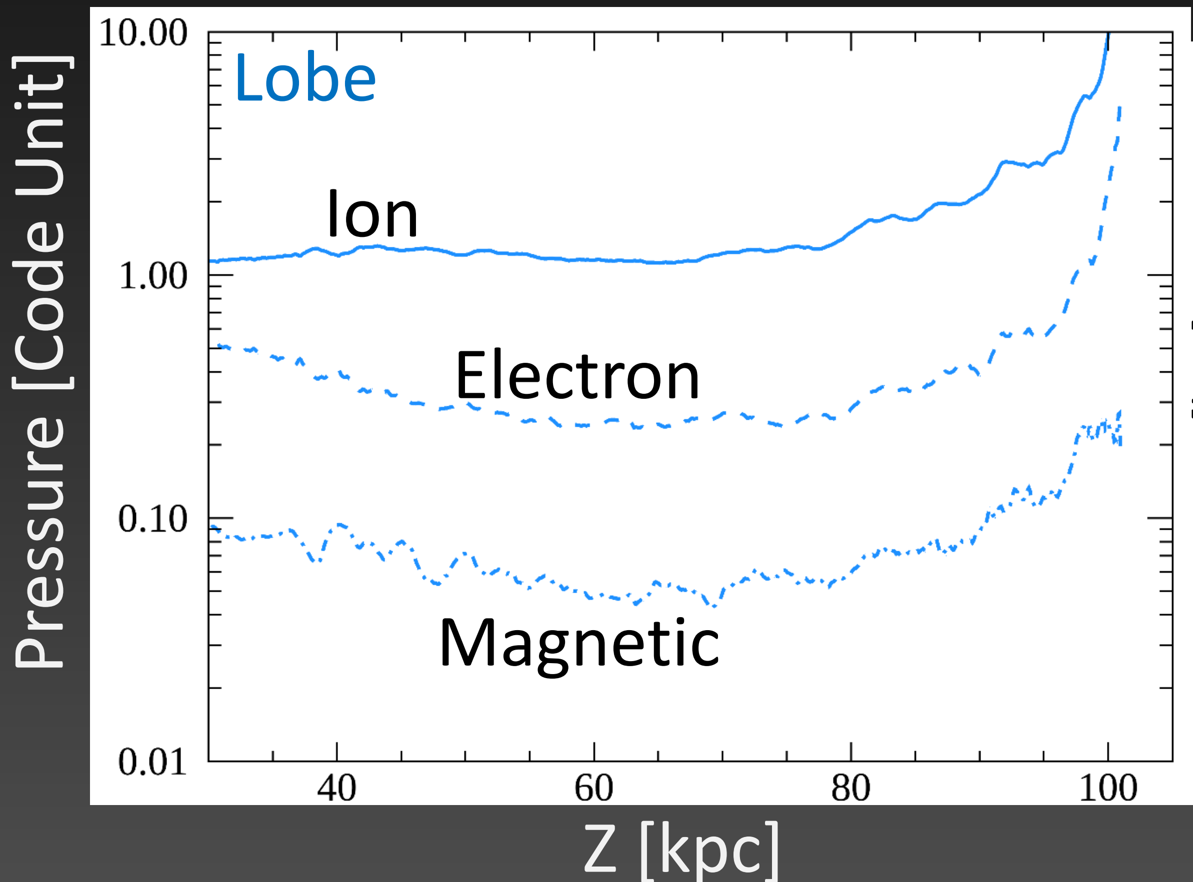
- Beam can reach termination, and form the terminal shocked.
- The most of heating energy goes to ions.

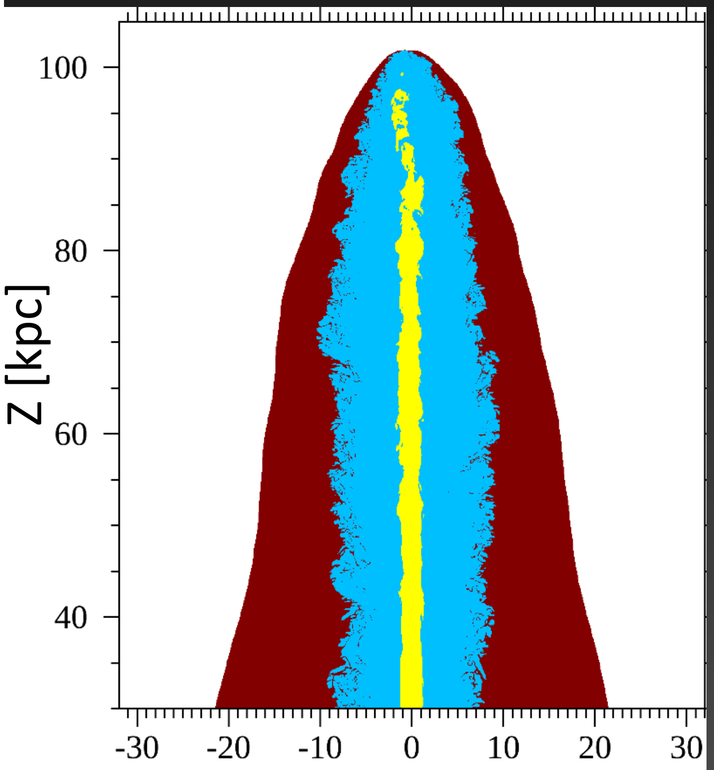


3. Results - Energetics in jets -

Volume-weighted pressure in radio-lobe.

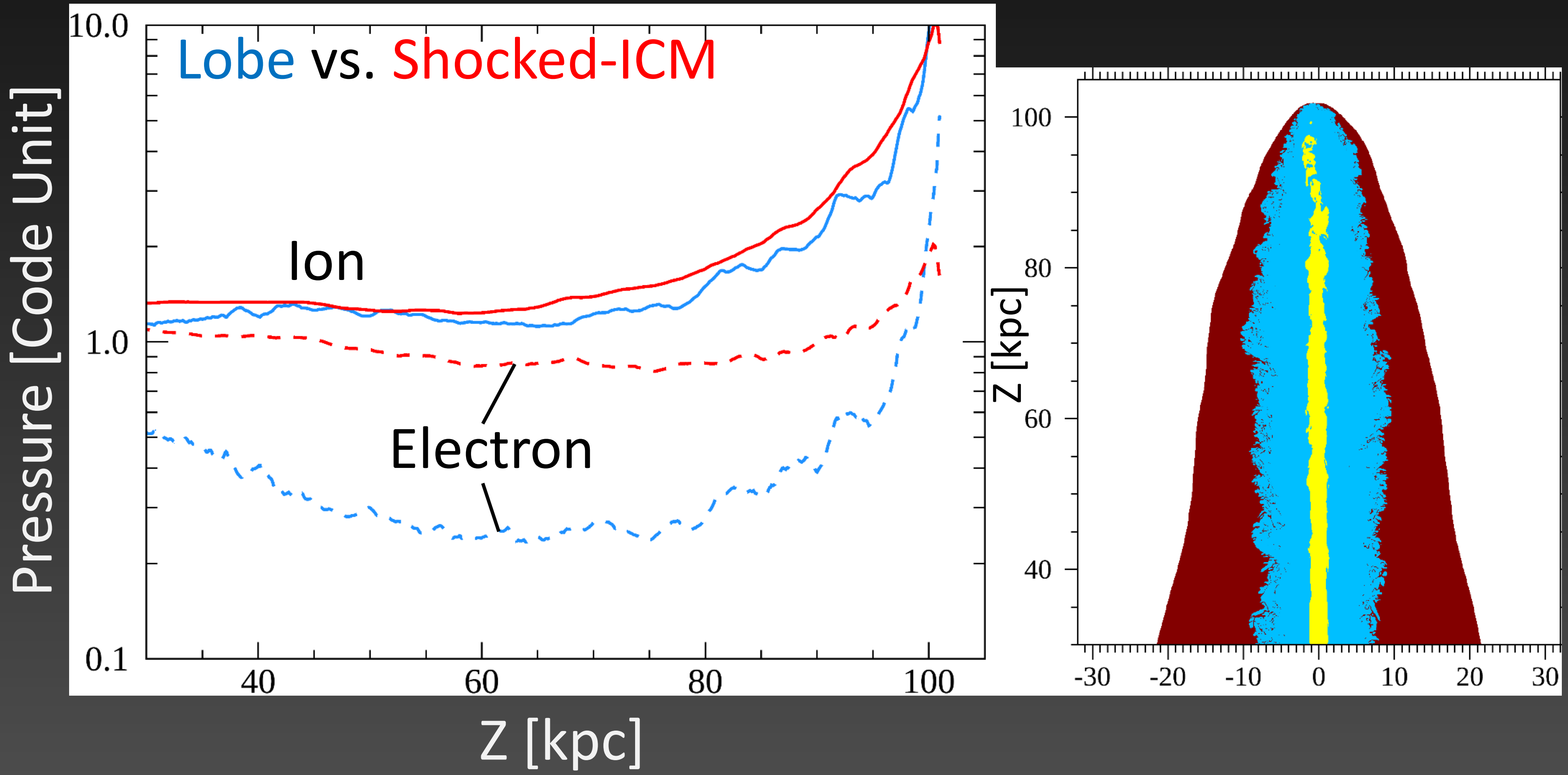
$$P_{\mathrm{i,e,B}}(z) = \frac{\int p_{\mathrm{i,e,B}} 2\pi r dr dz}{\int 2\pi r dr dz} \qquad p_B = B^2/8\pi$$





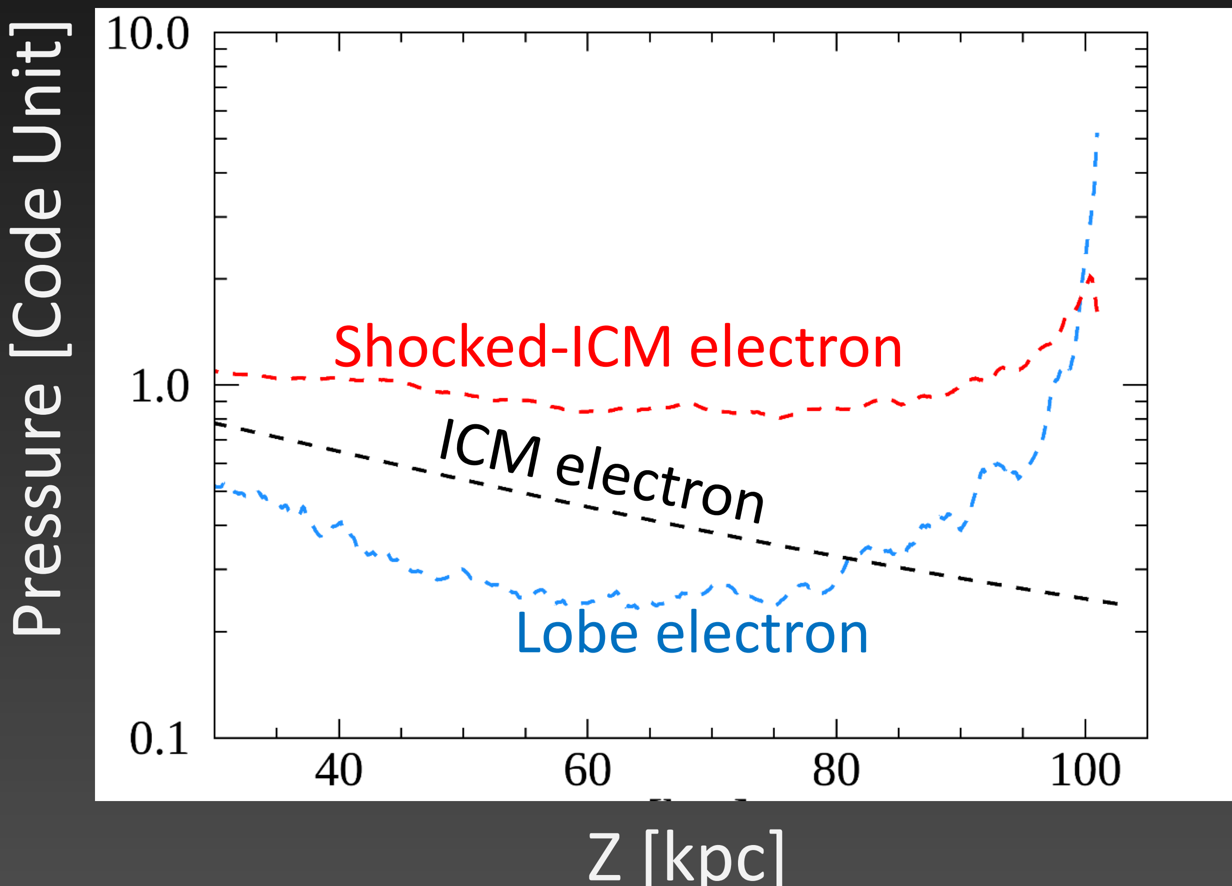
3. Results - Energetics in jets -

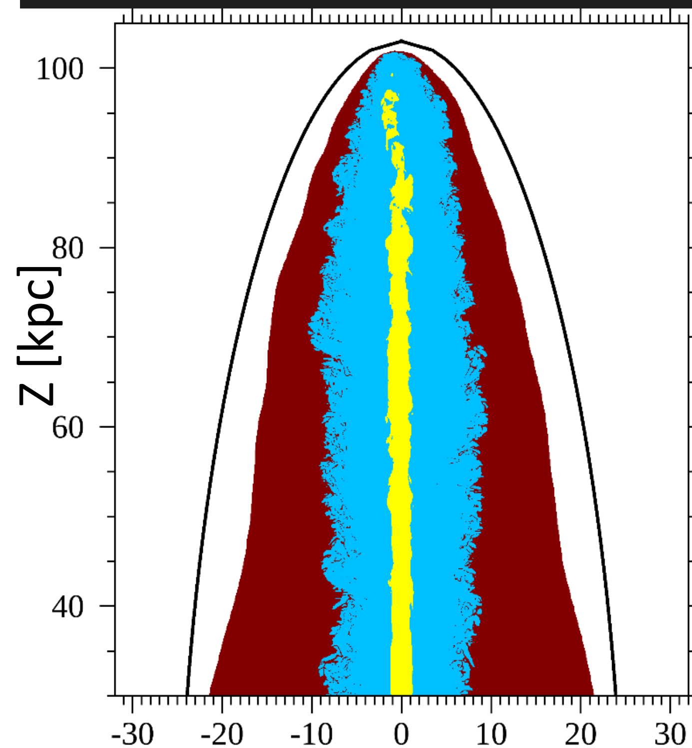
- In shocked-ICM, Ions and electrons decouple by bowshock. But, Coulomb interaction is effective because density is high.
- The lobe electron pressure is lower than shocked-ICM.



3. Results - Energetics in jets -

- Shocked-ICM electron pressure is higher than surrounding electron pressure everywhere.
- Lobe electrons have lower energy than ICM electrons (z<80).



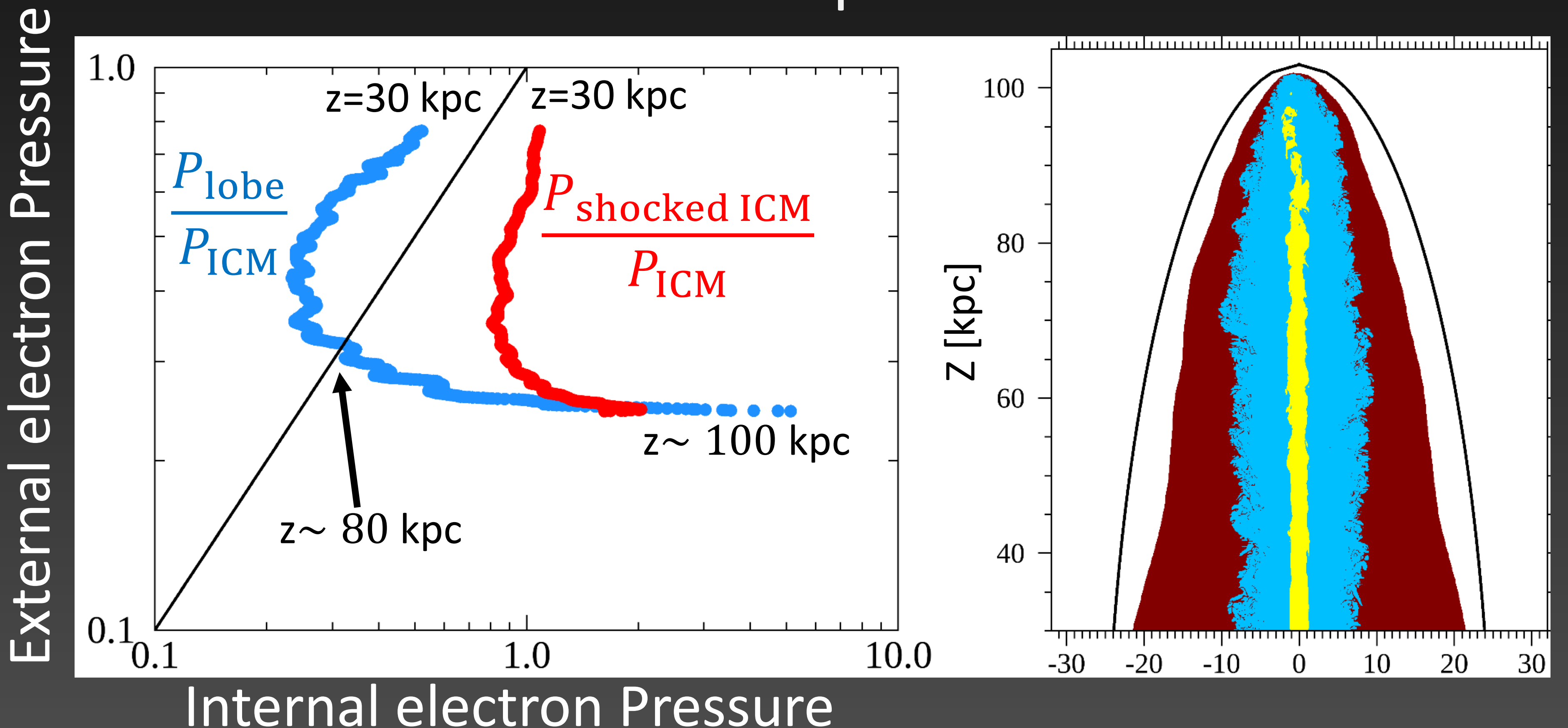


3. Results - Under-pressured lobe -

- Shocked-ICM electron pressure is higher than surrounding electron pressure everywhere.

- On the other hand, lobe electron pressure is low.

→ Under-pressured lobe

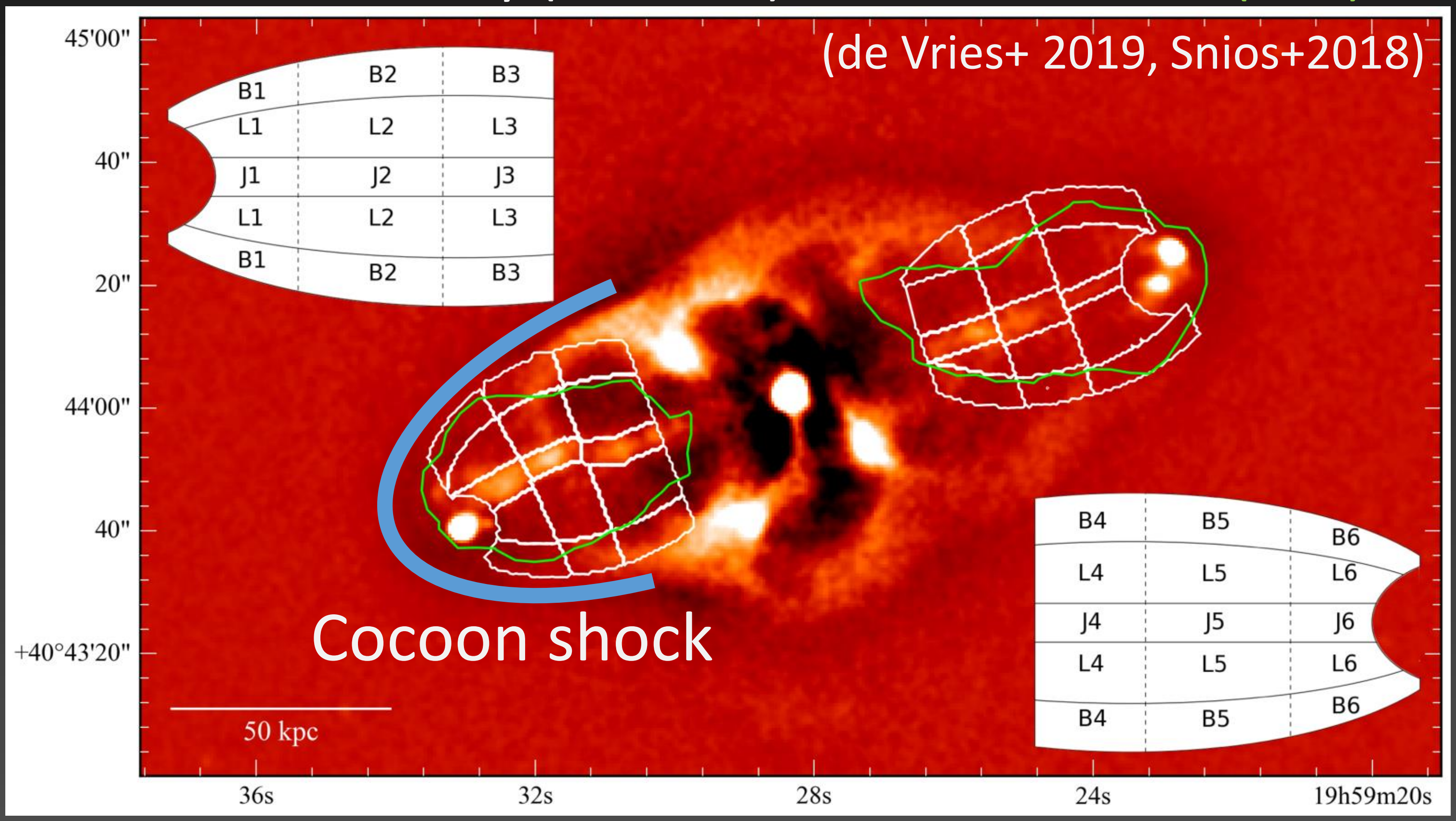


Discussion

4. Discussion - Under-pressured lobe -

- The bow (cocoon) shocks of Cyg.A are clearly seen in high-resolution Chandra observations.
- Shock compression is clearly observed at these shocks.

0.5-7.0 KeV X-ray (Chandra), contour 4.5 GHz (VLA)



4. Discussion - Under-pressured lobe -

- However, the pressure of the eastern lobe, which is estimated by X-ray Inverse Compton, is lower than the rim pressure, *i.e.*, Under-pressured lobe.
- These observational analysis indicates that

$$P_{\rm lobe} < P_{\rm ICM} < P_{\rm shocked-ICM}$$

	$p_{\rm rim}$ [a] (10^{-10} erg cm^{-3})	$\gamma_{\rm min}$ [b]	$p_{\rm IC}$ [c] (10^{-10} erg cm^{-3})
East	10.4 ± 0.4	1	$5.8^{+2.0}_{-1.4}$
		10	$2.2^{+0.4}_{-0.4}$
West	8.4 ± 0.2	1	140^{+1690}_{-116}
		10	18^{+40}_{-10}

(de Vries+ 2019)

4. Discussion - Under-pressured lobe -

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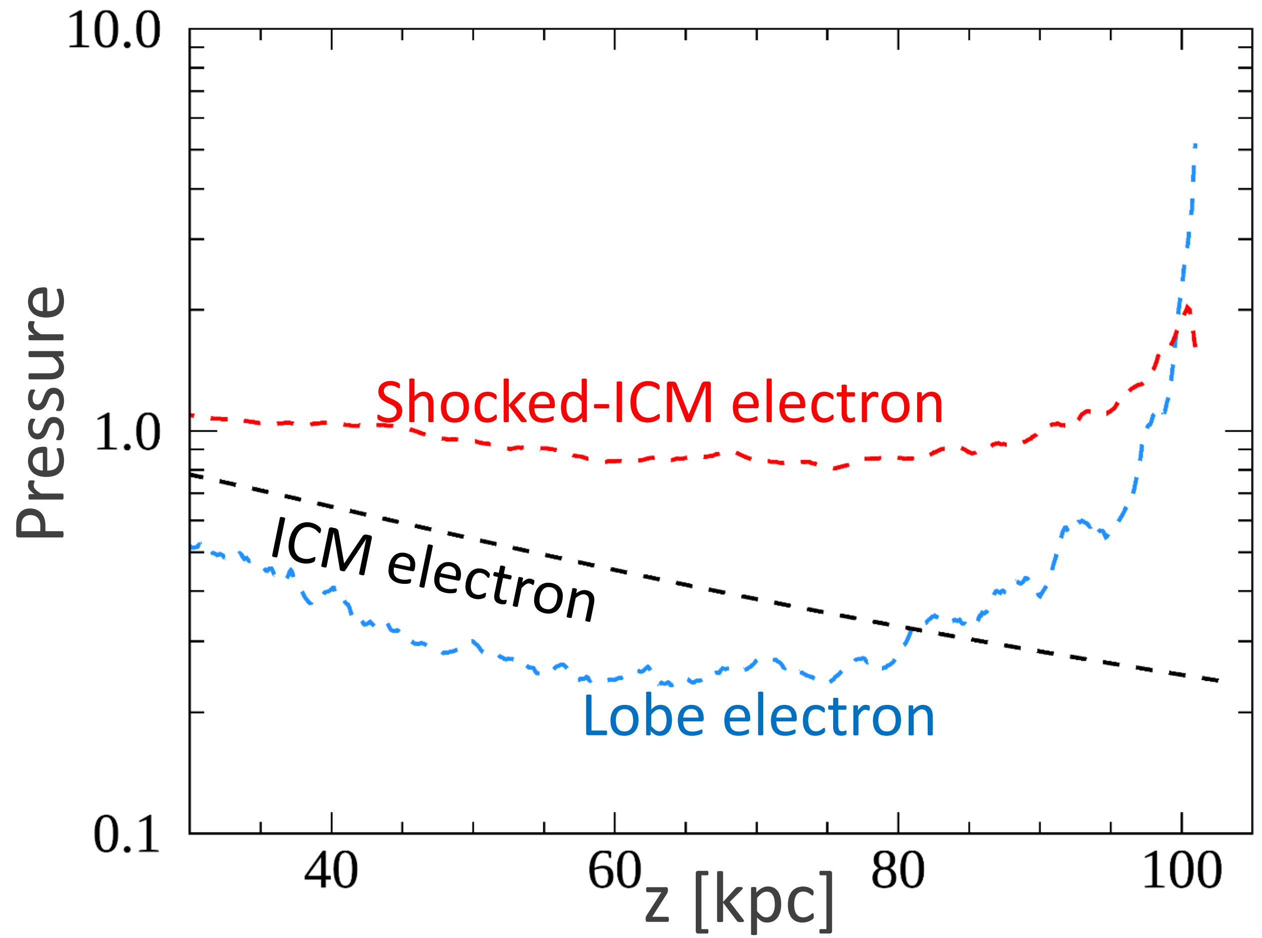
Our two-temperature jets model could explain this pressure condition.

$$P_{\mathrm{lobe}} < P_{\mathrm{ICM}} < P_{\mathrm{shocked-ICM}}$$



5. Summary

- We have carried out high-resolution two-temperature MHD jets propagate simulations.

- Beam, which propagating up to 100 kpc, can reach termination of jets, and terminal shock (hotspot) is formed.

- The magnetic energy is much less than the ion thermal energy, and hence most of heating energy goes to ions.

- The lobe electron pressure is lower than that of shocked-ICM and surrounding ICM, and under-pressured lobe is formed .