Two-temperature MHD simulations of extragalactic jets.

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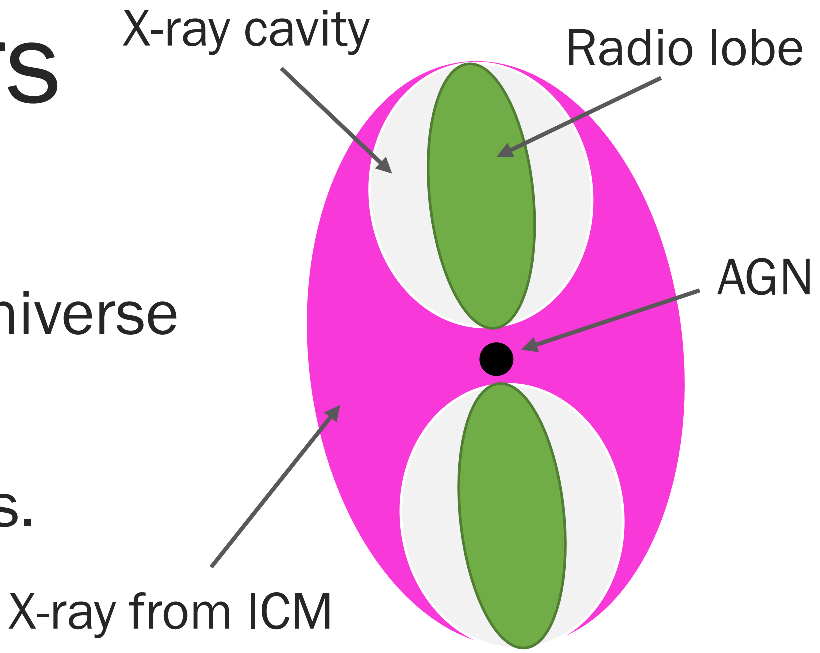
Jets in galaxy clusters

- Radio-mode (jet-driven) AGN feedback [McNarama & Nulsen 2012]

⇒ The maintenance of massive galaxies in the present-day Universe

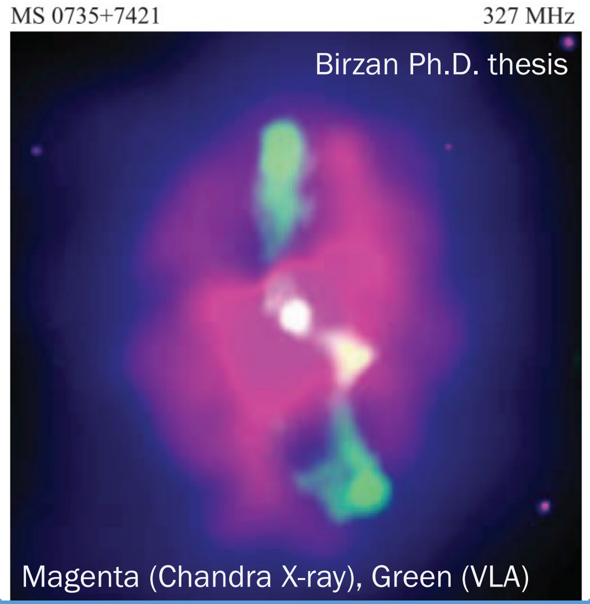
- Continuous particle (re-)acceleration in kpc-scale jets

⇒ Promising candidates for extra-galactic cosmic-ray particles.



kpc-scale jet components

<u>Radio Lobe and X-ray Cavity = Cocoon (composed of the jetted gas)</u>
store enormous amounts of energy as relativistic electrons and magnetic fields, which are transported by the jet.



Clue about the physical nature of jets
(Compsiton, Magnetic fields, Particles energy etc.…)

Two-Temperature Plasma

■ Relaxation Time scale of e-p coupling via Coulomb collisions

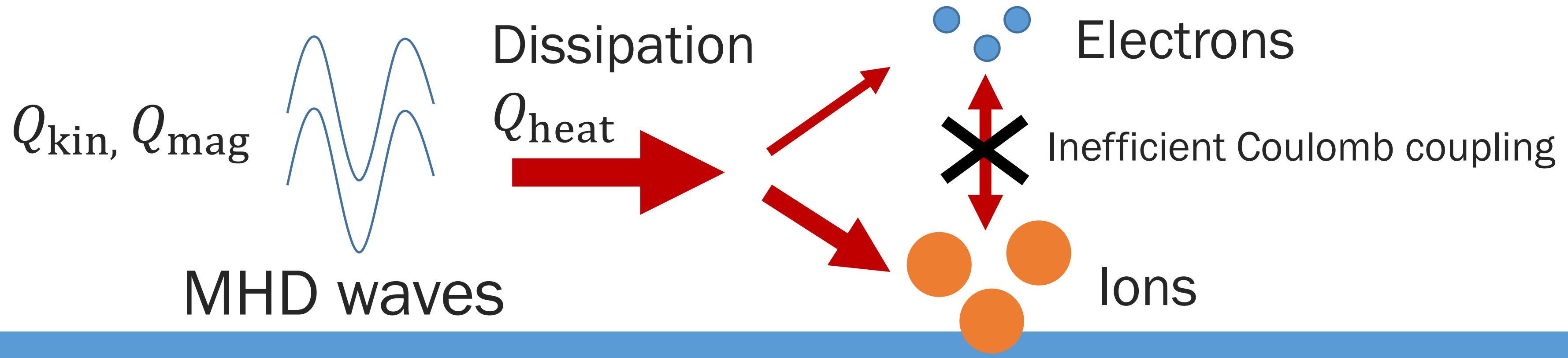
$$t_{ei} = 2.0 \times 10^8 \ \mathrm{yr} \left(\frac{n_i}{10^{-3}\ \mathrm{cm}^{-3}}\right)^{-1} \left(\frac{T_e}{10^8\ \mathrm{K}}\right)^{3/2} .$$

Detection of X-ray Cavity indicates that jet plasma is hotter and lighter than ICM.

ICM： $n_{\mathrm{ICM}} \sim 10^{-2} - 10^{-3}$
$T_{\mathrm{ICM}} \sim$ a few KeV

Jet ： $n < 10^{-3}, T_{\mathrm{e}} > 10^{9}\mathrm{K}$
$\rightarrow t_{\mathrm{ei}} \gg 10^{10}\mathrm{yr}$ (>> Outburst Age!!)

Electrons and protons (ions) could be decoupled in jets



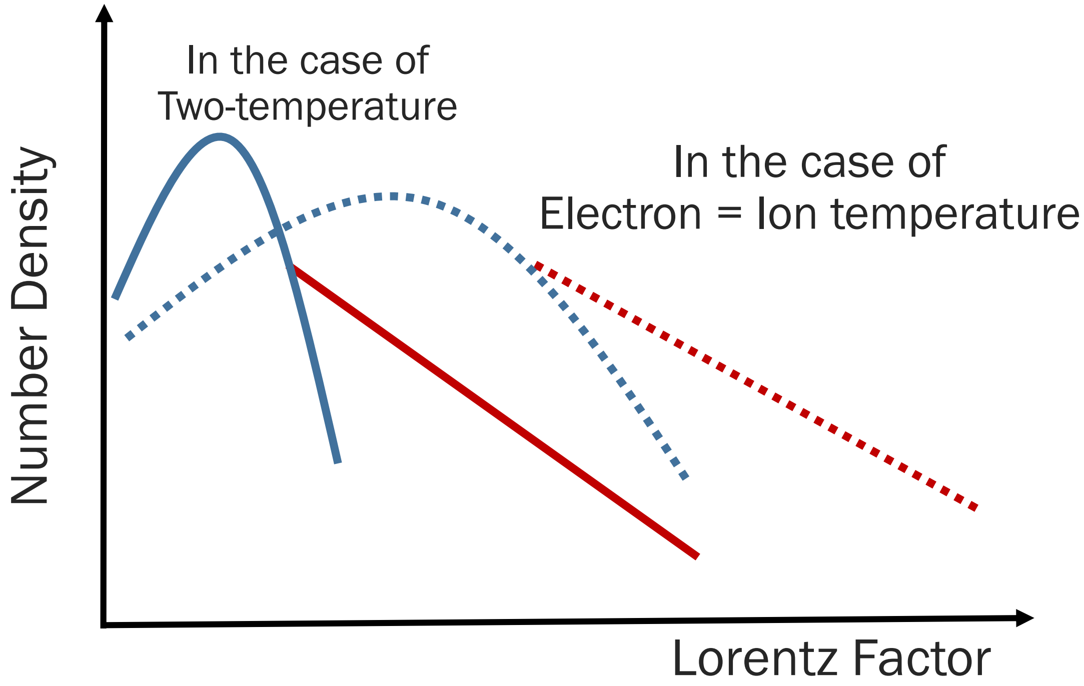
Importance of two-temp. plasma for jets

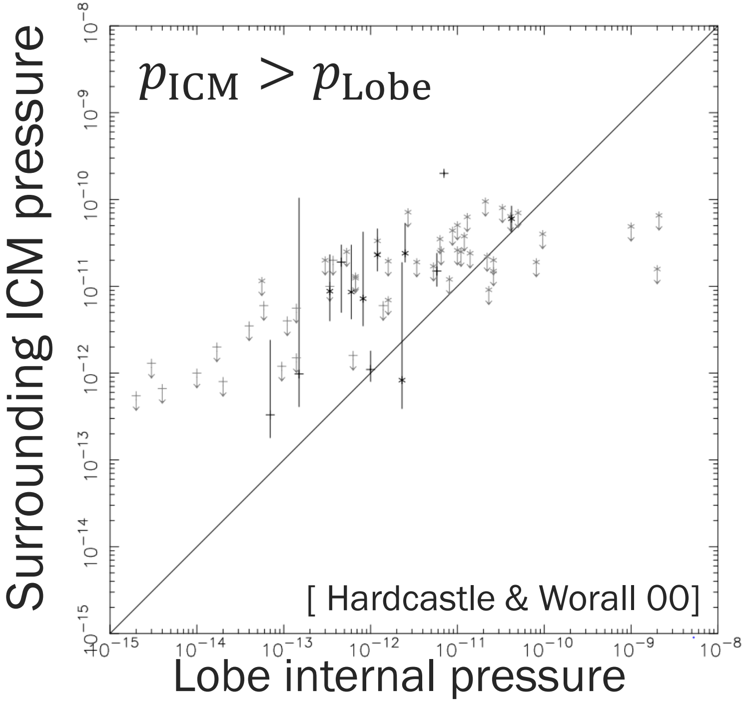
Our ultimate goal is to construct dynamical modeling with non-thermal transport

→ We firstly should obtain "exact" electron temperature in the jet

- A part of thermal electrons are accelerated into the non-thermal distributions.
- The existence of thermal protons and electrons are supported by previous studies.

[e.g., Ito+ 08, Kino & Takahara 08]





(Not include thermal and protons pressure)

Energy estimation of jets

- $P_{\mathrm{cav}} - L_{\mathrm{radio}}$ relation [Birzan 2004, 2008]

$P_{\mathrm{cav}} = 4pVt_{\mathrm{age}}^{-1}$: Lower limit for mechanical power
⇒ Required energy to support the cavity

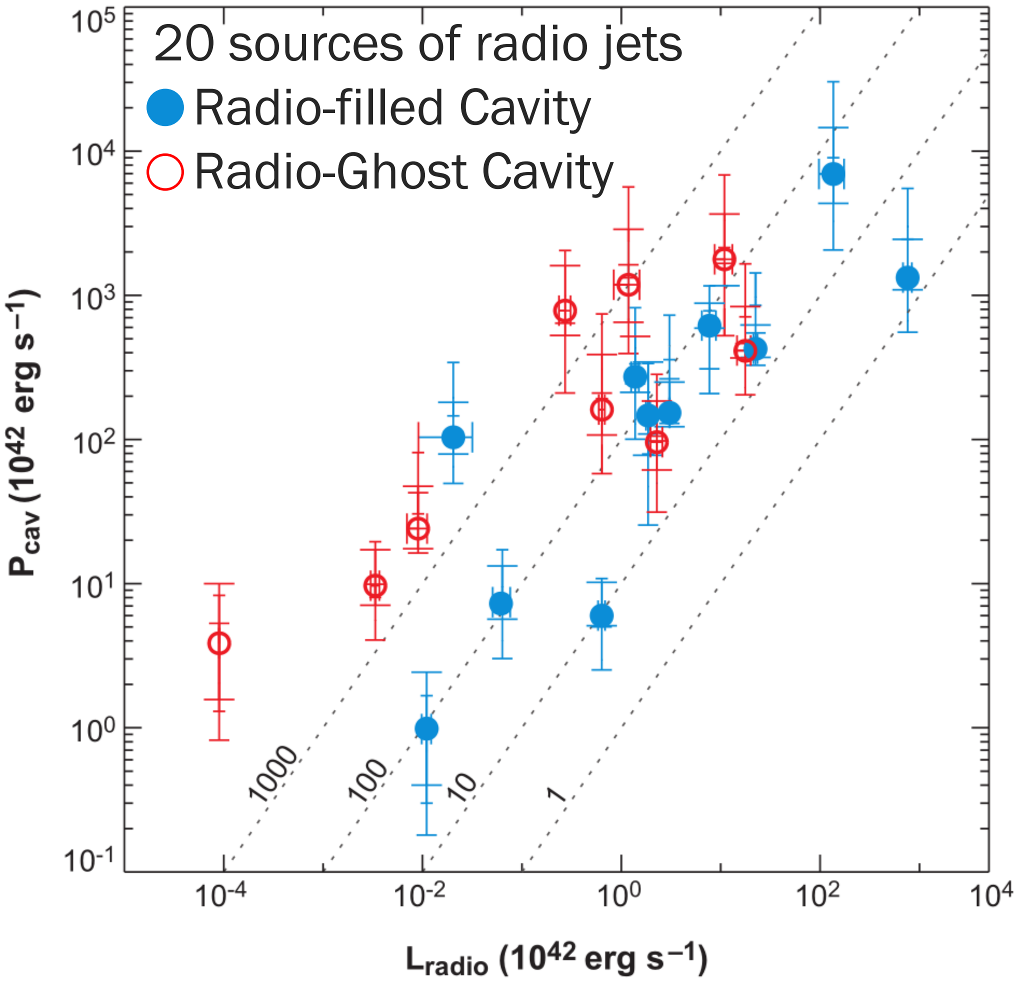
L_{radio} : Radio synchrotron energy from lobe
⇒ Magnetic × non-thermal electrons energies

Exist of large scatter $P_{\mathrm{cav}} \sim (1-1000) L_{\mathrm{radio}}$,
But, a large proportion of radiative inefficient lobes

$$P_{\mathrm{cav}} \gg L_{\mathrm{radio}}$$

The factor of large scatters
✓ <u>Contribution of gas pressure from protons</u>
✓ Electron radiative cooling
✓ The estimation of jet's age etc....

Jet mechanical power $(U_p + U_e)$



Radio power ($U_{\mathrm{mag}} \times U_e$)

Motivations

- The two-temperature plasma is maintain for long time because of relaxation time is longer than jets dynamical time scale.
- When plasma is heated, jet and surrounding ICM have two-temperature.

How energy partition between electrons and ions while jets propagate in kpc-scale??

We must investigate that the spatial energy distribution of both electrons and protons by conducting two-temperature MHD jets simulation.

Basic Equations

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\boldsymbol{v}) = 0, \quad m_{\mathrm{i}} n \left[\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v}\right] = -\nabla p_{\mathrm{gas}} - \nabla\left(\frac{B^2}{8\pi}\right) + \frac{1}{4\pi}(\boldsymbol{B} \cdot \nabla)\boldsymbol{B},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}), \quad \frac{\partial E}{\partial t} + \nabla \cdot \left[\boldsymbol{v}\left(E + p_{\mathrm{gas}} + \frac{B^2}{8\pi}\right) - \frac{\boldsymbol{B}(\boldsymbol{v} \cdot \boldsymbol{B})}{4\pi}\right] = -q_{\mathrm{rad}}$$

$n, m_{\mathrm{i}}, \boldsymbol{v}, \boldsymbol{B}, p_{\mathrm{gas}}, E$: Number density, Proton mass, bulk velocity, Magnetic fields, Gas pressure, Total energy

Single temperature plasma ($p_{\mathrm{i}} = p_{\mathrm{e}}$) → Two-temperature plasma ($p_{\mathrm{i}} \neq p_{\mathrm{e}}$)

Energy evolution for electrons and ions self-consistently

$$p_{\mathrm{gas}} = p_{\mathrm{i}} + p_{\mathrm{e}}, \quad E = \frac{\rho v^2}{2} + \frac{p_{\mathrm{i}}}{\gamma_{\mathrm{i}} - 1} + \frac{p_{\mathrm{e}}}{\gamma_{\mathrm{e}} - 1} + \frac{B^2}{8\pi}$$

$$T_{\mathrm{e}} \frac{ds_{\mathrm{e}}}{dt} = f_{\mathrm{e}}\, Q_{\mathrm{heat}} + q_{\mathrm{ie}} - q_{\mathrm{rad}},$$

$$T_{\mathrm{i}} \frac{ds_{\mathrm{i}}}{dt} = (1 - f_{\mathrm{e}})\, Q_{\mathrm{heat}} - q_{\mathrm{ie}},$$

$$Q_{\mathrm{heat}} \xrightarrow{f_e} Q_{\mathrm{ele.}}$$

$$Q_{\mathrm{heat}} \xrightarrow{1 - f_e} Q_{\mathrm{ion}}$$

Coulomb coupling rate : $q_{\mathrm{ie}} \propto (T_{\mathrm{i}} - T_{\mathrm{e}})n^2$

Bremsstrahlung loss rate : $q_{ie} \propto n^2\sqrt{T_e}$

[Stepney & Guilbert 1983, Dermer+ 1991]

Dissipative heating for electrons, f_e

MHD turbulence Model

Alfvenic turbulence heating rate using gyrokinetic model. [Kawazura+ 18, 20]

$$f_{\rm e}|_{\rm turb} \equiv \frac{Q_{\rm e}}{Q_{\rm e}+Q_{\rm i}} = \frac{1}{1+Q_{\rm i}/Q_{\rm e}}, \quad \frac{Q_{\rm i}}{Q_{\rm e}} = \frac{35}{1+(\beta_{\rm i}/15)^{-1.5}\exp\left(-0.1T_{\rm e}/T_{\rm i}\right)}$$

Low $\beta_{\rm i}$ ($\mathrm{B}^2/8\pi < p_{\rm ion}$) $\Rightarrow$ Heat electrons, High $\beta_{\rm i}$ $\Rightarrow$ Heat ions

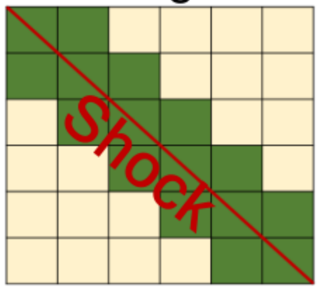
Shock heating Model

An appropriate value that explains the observations is $\xi = 0.05$.

ξ: ion to electron heat transfer ratio at shock layer.

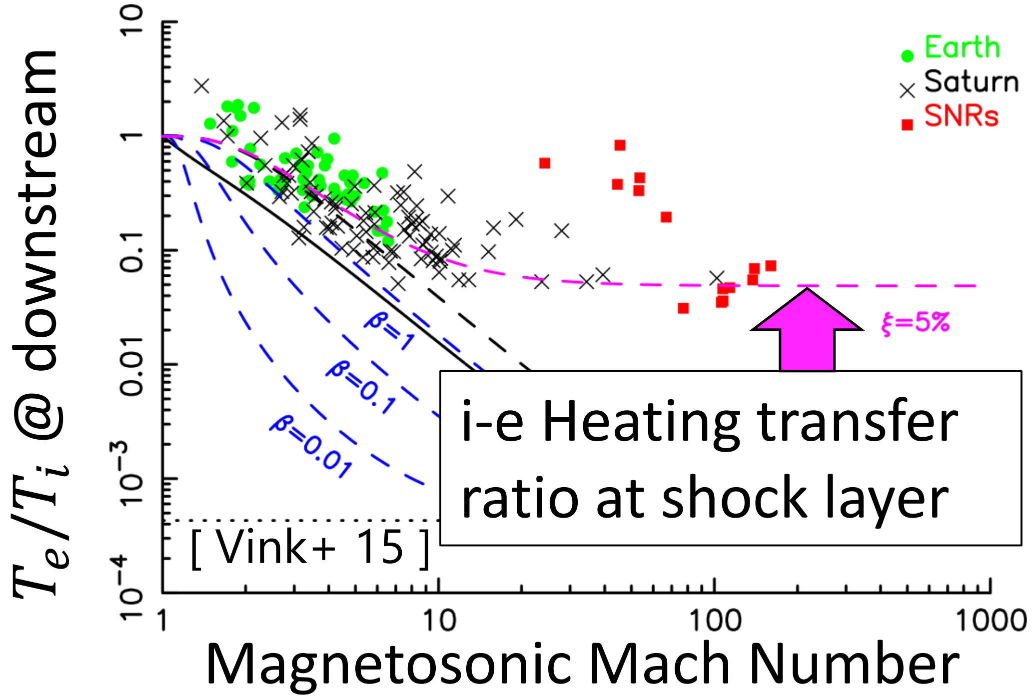
$$f_{\rm e}|_{\rm shock} = 0.05$$

MHD grids



Normal zone $f_{\rm e} = f_{\rm e}|_{\rm turb}$

Shock zone $f_{\rm e} = f_{\rm e}|_{\rm shock}$



Simulation Setup

MHD Code：CANS+ (Matsumoto+ 19)

ICM

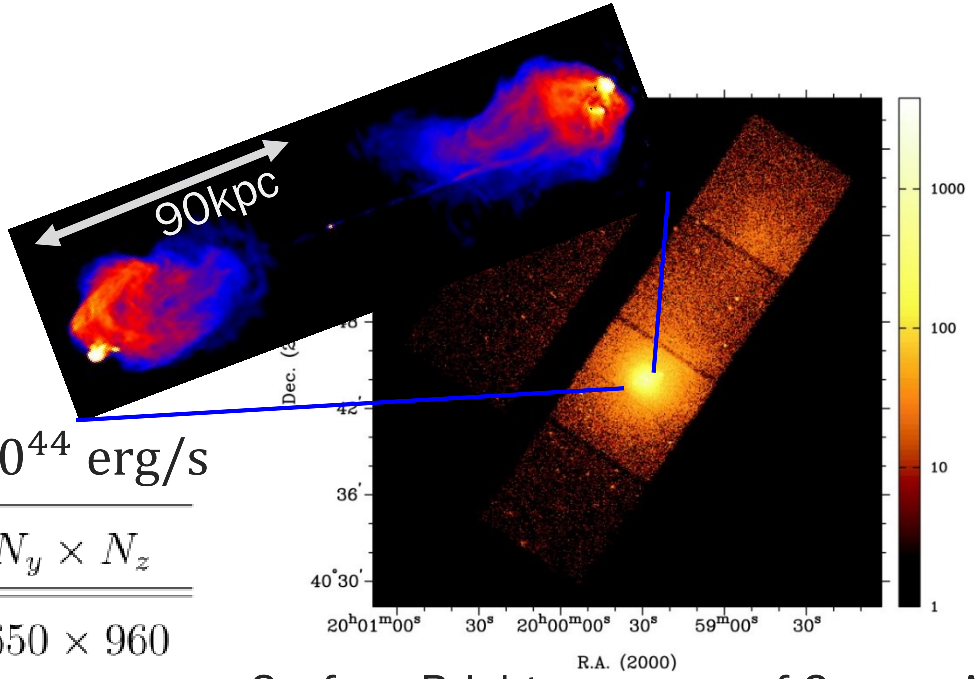
Density and pressure profile・・・isothermal β-model

$$\rho_{\mathrm{ICM}}(r) = \rho_0 \left[1 + \left(\frac{r}{r_{\mathrm{c}}}\right)^2\right]^{-3\beta/2}$$

Core density	$\rho_0 = 8.35 \times 10^{-26}\ \mathrm{g/cm^3}$	, $\beta = 0.5$
Core radius	$r_{\mathrm{c}} = 20\ \mathrm{kpc}$	, Temperature $T_{\mathrm{e}} = T_{\mathrm{i}} = 5\ \mathrm{keV}$

Jets Model

To generate jets, we inject supersonic magnetized flow ($x^2 + y^2 < 1\ \mathrm{kpc}$, and $\mathrm{z} = 0\ \mathrm{kpc}$)



Surface Brightness map of Cygnus A
Chandra 0.75-8KeV (Smith+ 2012)

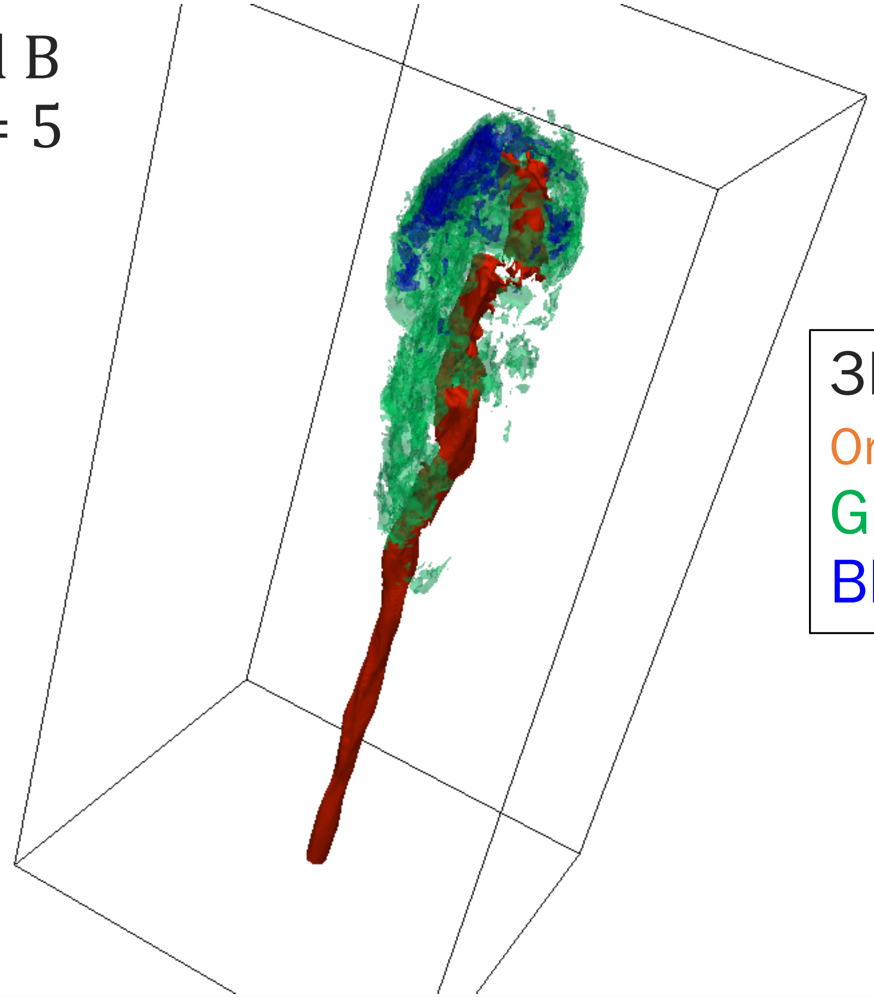
Velocity $v_z = 0.3c$, Tempearure $T_{\mathrm{e}} = T_{\mathrm{i}} = 1.0 \times 10^{10}\ \mathrm{K}$,
Kinetic energy $L_{\mathrm{kin}} = 5 \times 10^{45}\ \mathrm{erg/s}$, Thermal energy $L_{\mathrm{th}} = 4 \times 10^{44}\ \mathrm{erg/s}$

Model	$\beta_{\mathrm{gas,jet}}$	$\mathcal{M}_{\mathrm{A}}$	$\mathrm{B_{jet}}$ [μG]	$L_x \times L_y \times L_z$ [kpc]	$N_x \times N_y \times N_z$
A	1	4.9	138	$64 \times 65 \times 96$	$640 \times 650 \times 960$
B	5	11	62	$64 \times 64 \times 96$	$640 \times 640 \times 960$
C	100	49	14	$64 \times 65 \times 96$	$640 \times 650 \times 960$

Jets dynamics

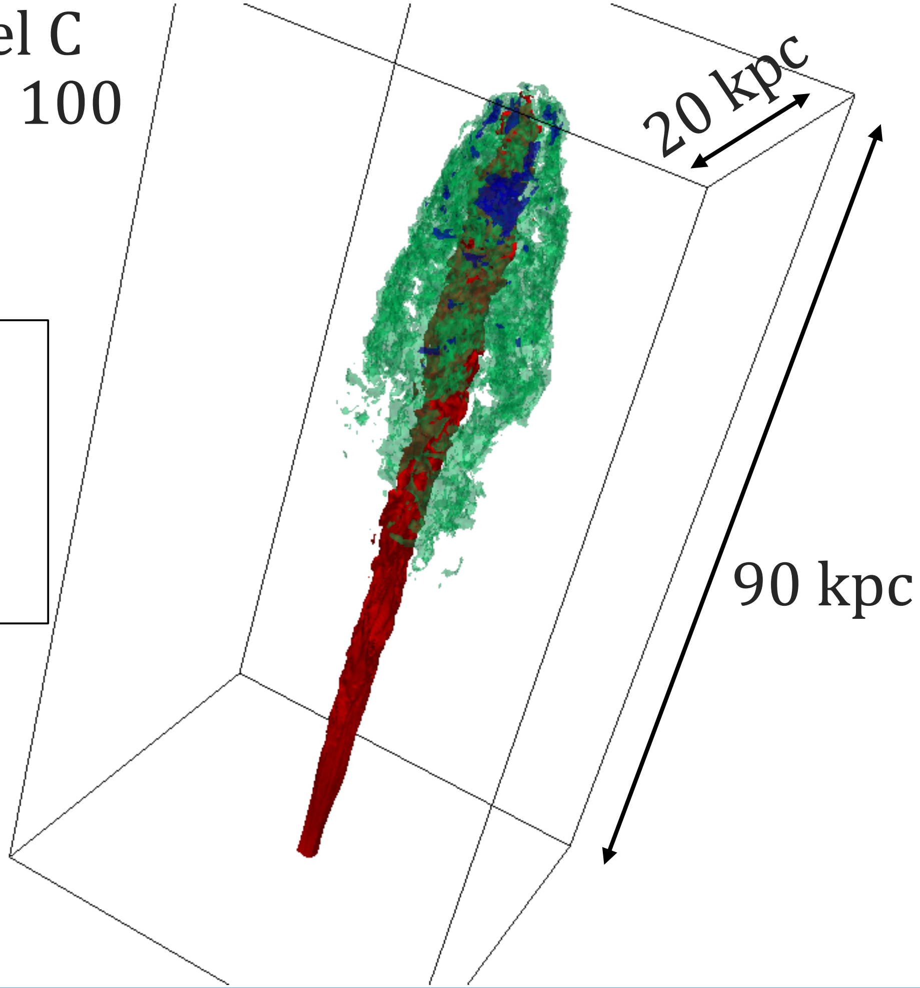
$\beta_{\mathrm{gas}} = 5$ ： current-drive kink mode, $\beta_{\mathrm{gas}} = 100$ ： Kelvin-Helmholtz ・ Rayleight-Taylor modes

Model B
$\beta_{\mathrm{gas}} = 5$



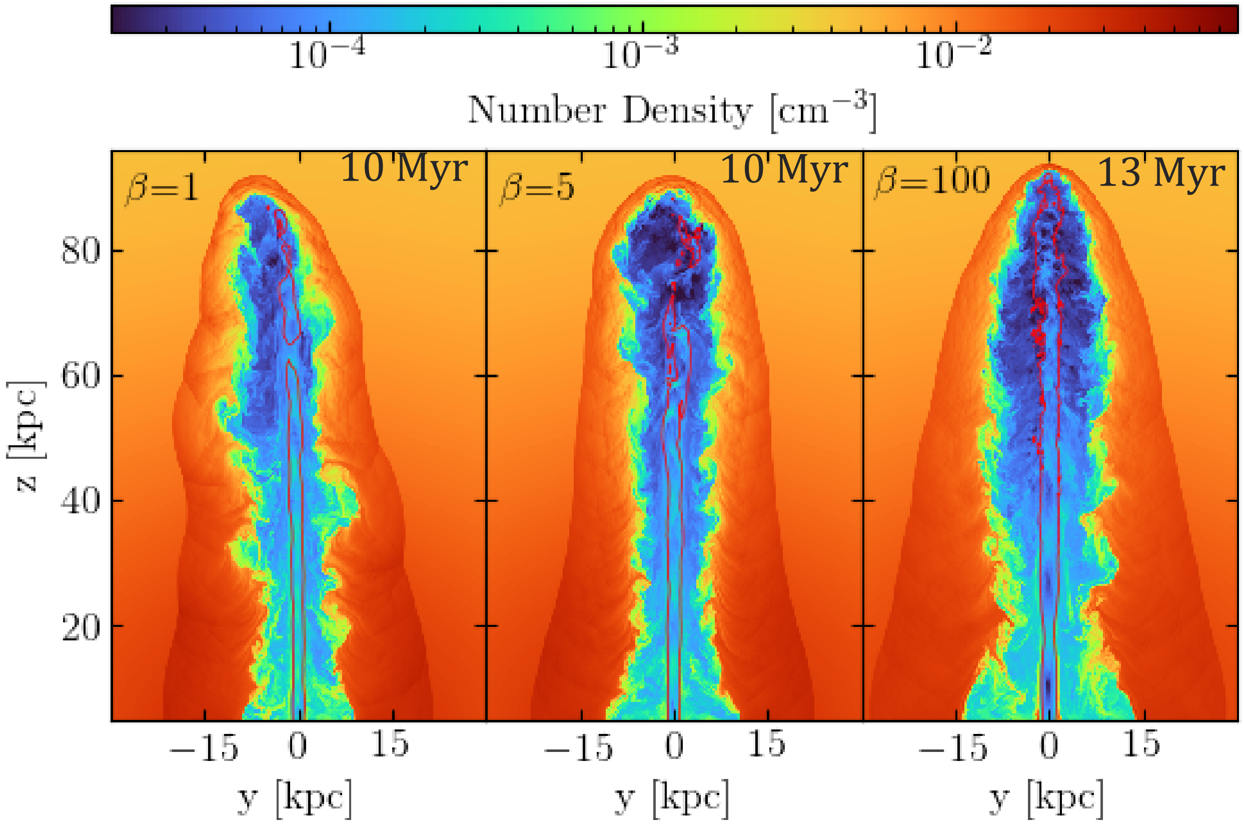
3D isosurface
Orange ： $0.2c$
Green ： $-0.05c$
Blue ： $-0.1c$

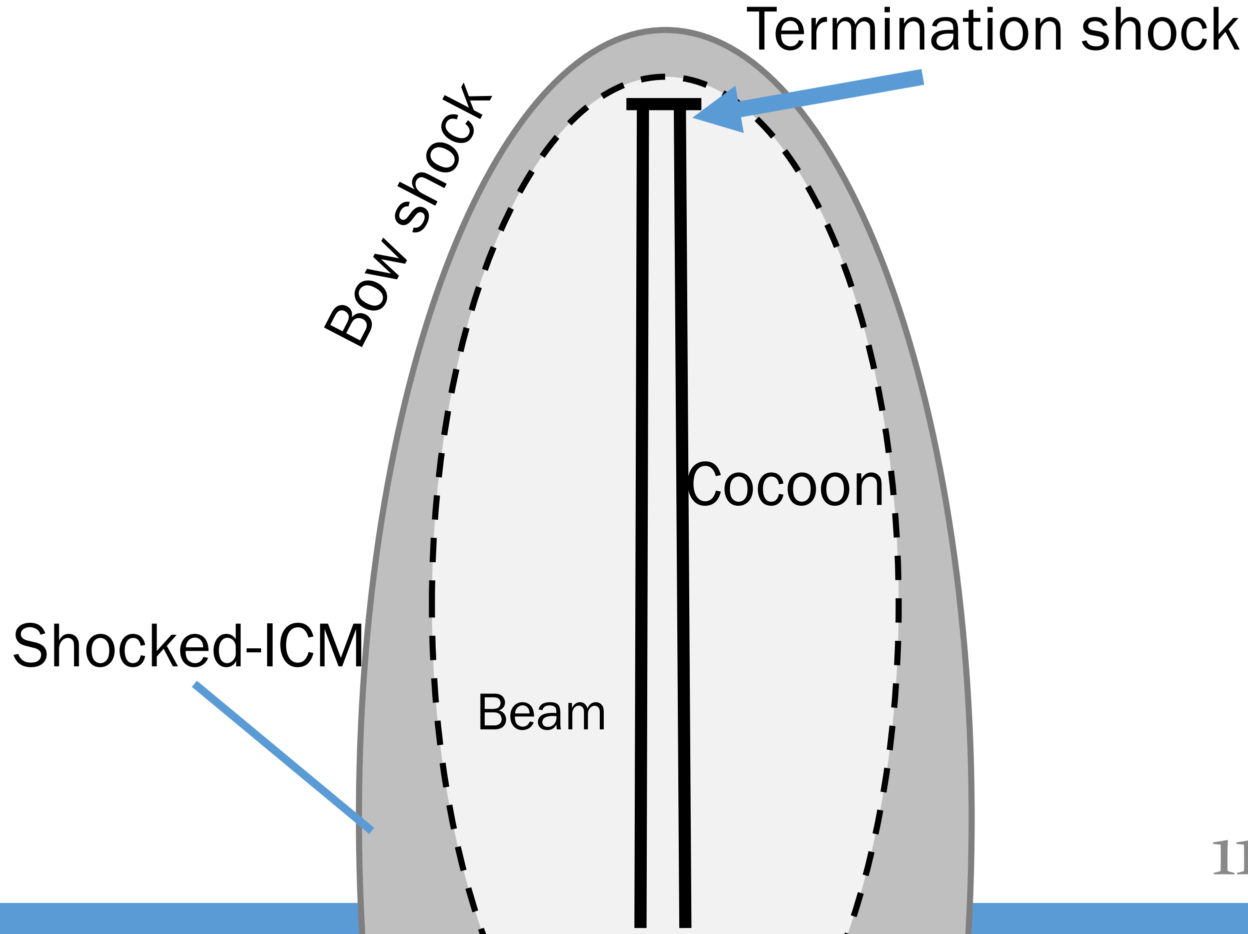
Model C
$\beta_{\mathrm{gas}} = 100$



Morphology

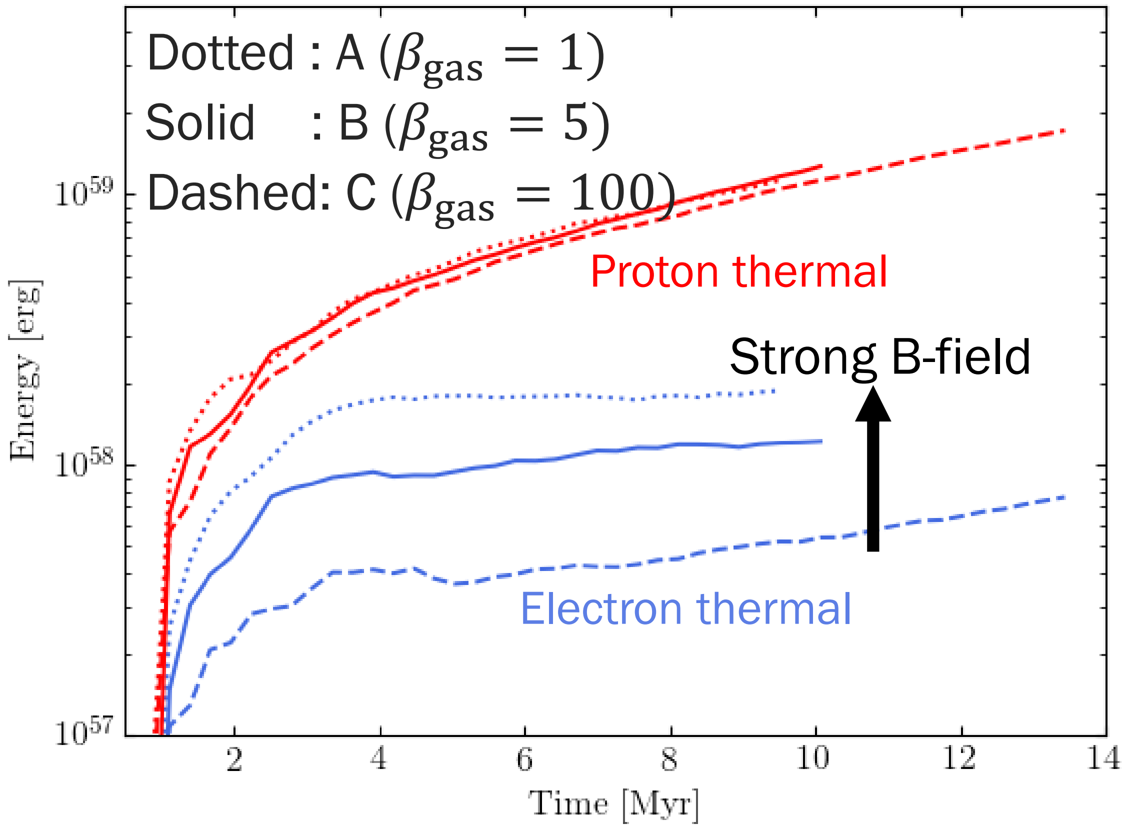
- Shocked-jet gas is referred as ‘Cocoon’ (Low-density cavity and Radio lobe)
- The jet magnetization impact the development of instabilities modes
- Large-scale morphologies are affected by non-axisymmetric motion

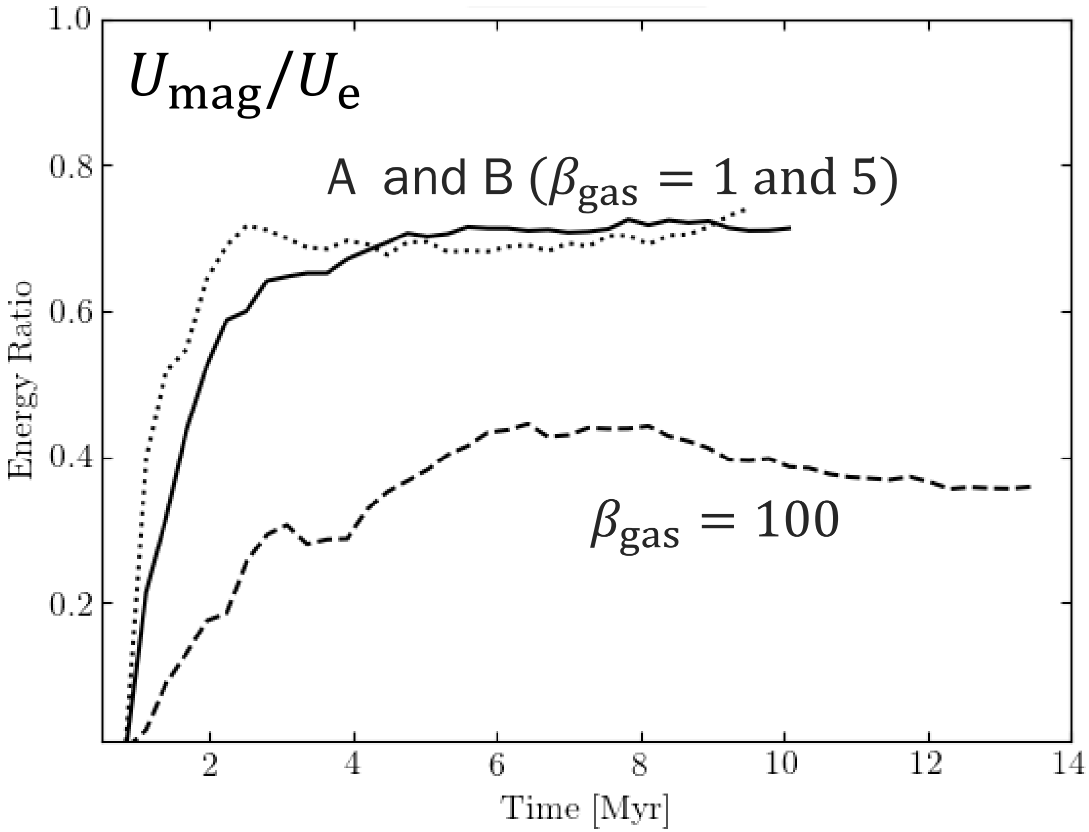




Jets energetics

- Kinetic and Magnetic energies are dissipated at shocks and turbulence
- Protons are energetically dominant over the electrons in the cocoons.
- The electron temperatures are proportional to magnetic energy (Electron heating model : $f_{e,\mathrm{turb}} \propto U_{\mathrm{mag}}$)
- In the case of model $\beta_{\mathrm{gas}} = 1$ and 5, $U_{\mathrm{mag}}/U_{\mathrm{e}}$= constant. ~0.7



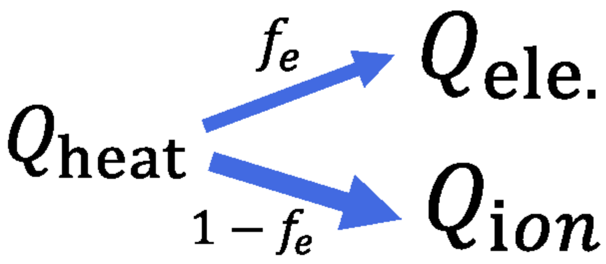


Jets energetics

MHD turbulence Model

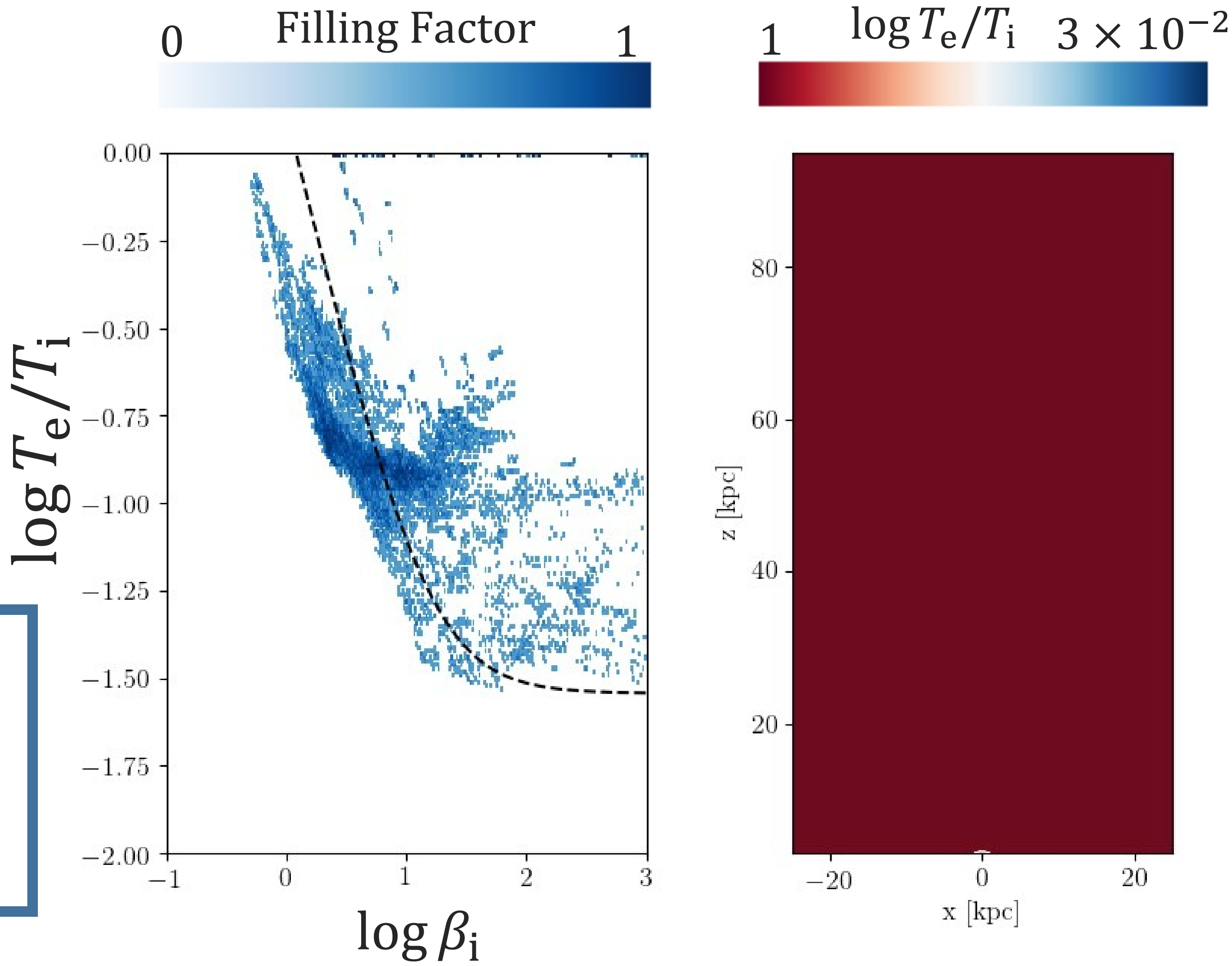
$$f_{\mathrm{e}}|_{\mathrm{turb}} \equiv \frac{Q_{\mathrm{e}}}{Q_{\mathrm{e}} + Q_{\mathrm{i}}} = \frac{1}{1 + Q_{\mathrm{i}}/Q_{\mathrm{e}}}$$

$$\frac{Q_{\mathrm{i}}}{Q_{\mathrm{e}}} = \frac{35}{1 + (\beta_{\mathrm{i}}/15)^{-1.5} \exp\left(-0.1 T_{\mathrm{e}}/T_{\mathrm{i}}\right)}$$

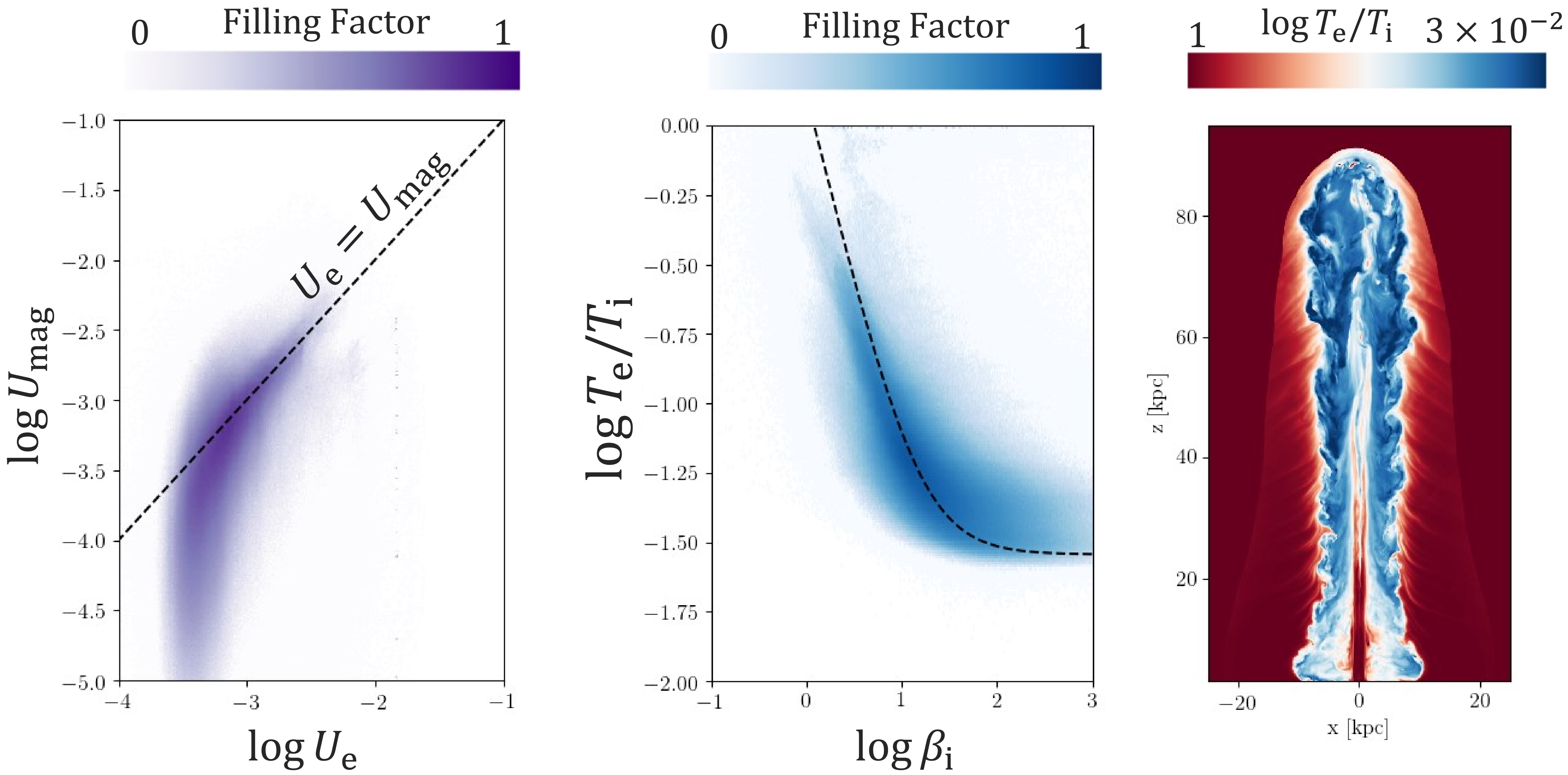


$$\frac{U_{\mathrm{e}}}{U_{\mathrm{i}}} \approx \left(\frac{T_{\mathrm{e}}}{T_{\mathrm{i}}}\right)_{eq} = \frac{f_{\mathrm{e,turb}}(\beta_{\mathrm{i}})}{1 + f_{\mathrm{e,turb}}(\beta_{\mathrm{i}})}, \beta_{\mathrm{i}} \sim \frac{U_{\mathrm{i}}}{U_{mag}}$$

Three energies are related by turbulence heating.
$U_e, U_i, U_{\mathrm{mag}}$



Jets energetics



Discussion $P_{\mathrm{cav}} - L_{\mathrm{radio}}$ relation

■ Radio Synchrotron Power ：$L_{\mathrm{radio}} \propto U_{e,Nth} B_{\perp}^{0.5(p+1)} \nu^{-0.5(p-1)},\ dN = N^{-p} dE$

Assumptions：$U_{e,Nth} = \begin{cases} \eta U_e\ \ (2T) \\ \eta U_p\ (1T) \end{cases}, \eta = 0.2,\ p = -2,\ \nu = 155\mathrm{MHz}$

■ Mechanical Energy：$P_{cavity} = 4pV t_{\mathrm{age}}^{-1}$

$t_{\mathrm{age}} = \frac{L}{C_s}, C_s^2 = \frac{p_{\mathrm{gas}}}{\rho_{\mathrm{gas}}},\ L$: Propagation distance

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Result

- $P_{\mathrm{cav}} < 10^{-1} L_{\mathrm{jet}}$

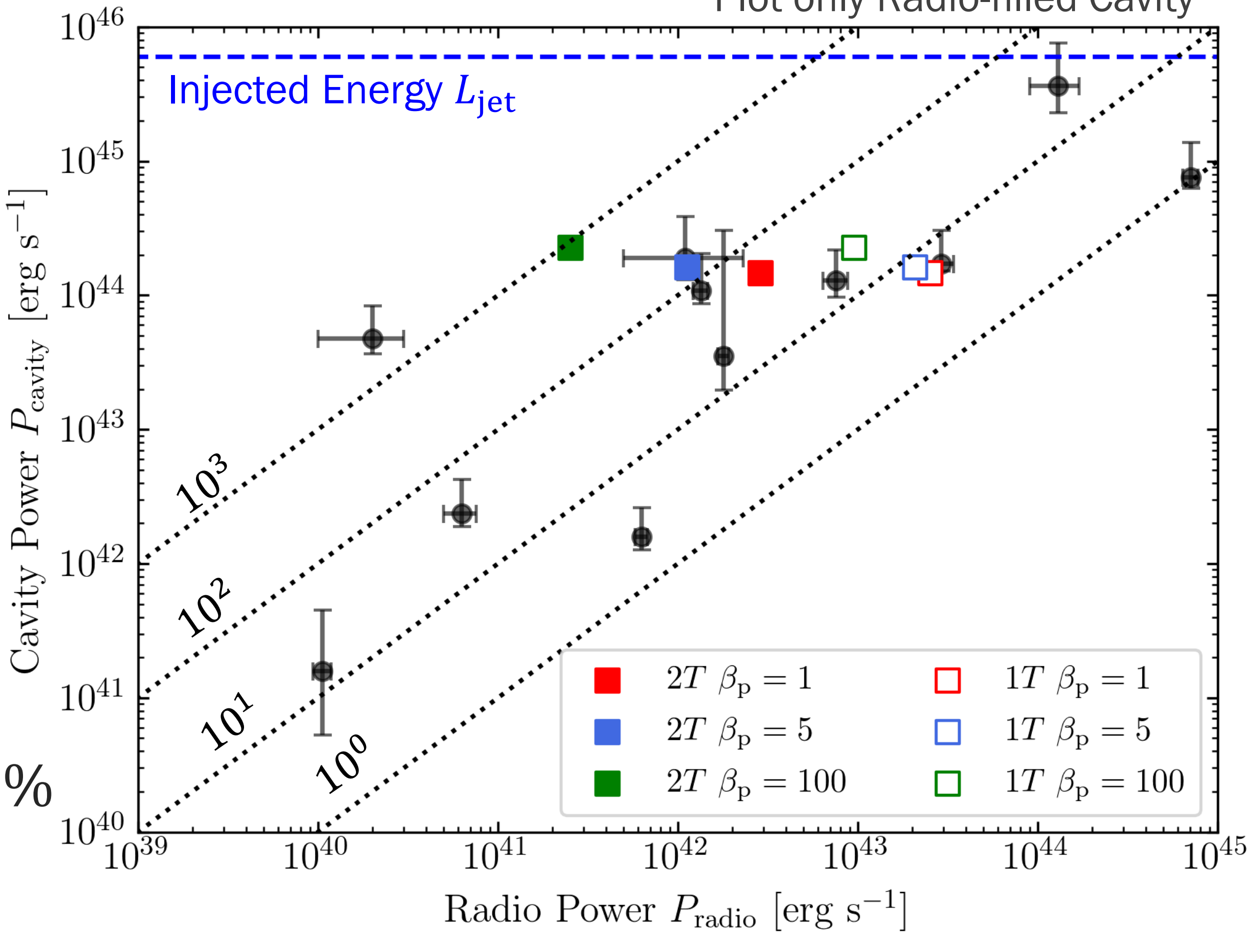
  ⇒ ▪ Energy transportation from jets to ICM

  ▪ Overestimate jet's age $t_{\mathrm{sim}} < 0.3 t_{\mathrm{age}}$

Singe-Temperature Model $L_{\mathrm{radio}}/L_{jet} \sim 1\%$

Two-Temperature Model $L_{\mathrm{radio}}/L_{jet} \sim (0.01 - 0.1)\%$

Plot only Radio-filled Cavity



Summary

- We investigate the energy budgets of jets by conducting two-temperature MHD simulations that evolve the entropy equations of electrons and ions in a self-consistent manner.
- Magnetic fields are play significant role in the jet dynamics and electron heating. Higher-magnetized jets suffer from non-axisymmetric mode
- Shocked-electron stored in the cocoon evolve toward energy equipartition with magnetic energy through turbulent dissipation. As a result, we find that $U_{\rm ion} \gg U_e \sim U_{\rm mag}$

Future Works

- Non-thermal particles transport
- Relativistic jets model
- Pair-dominated jets $(e^{\pm} - p)$

Ions take on the expansion of cocoon!!