How AGN Jets Heat the Intracluster Medium -- Insights from Simulations

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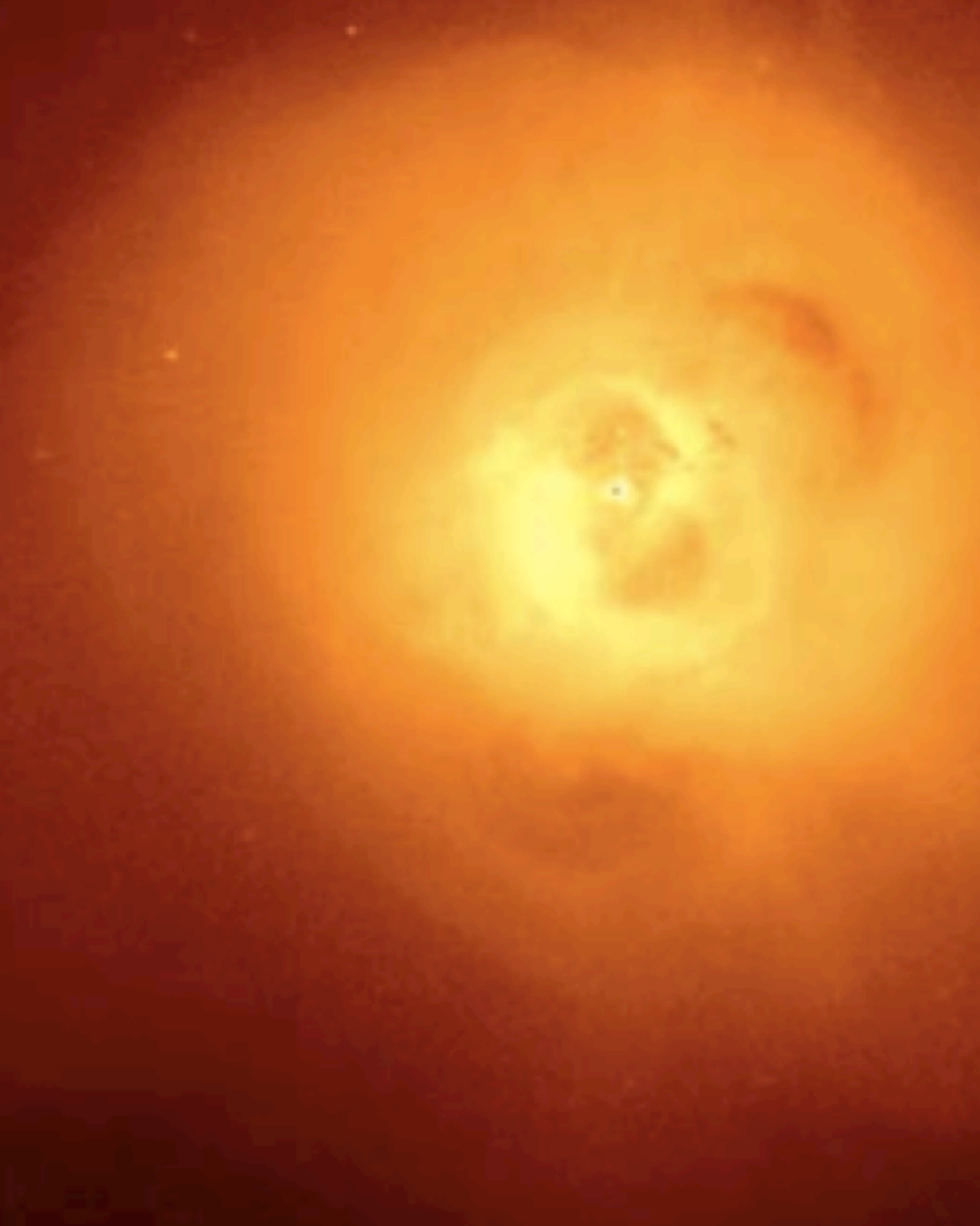
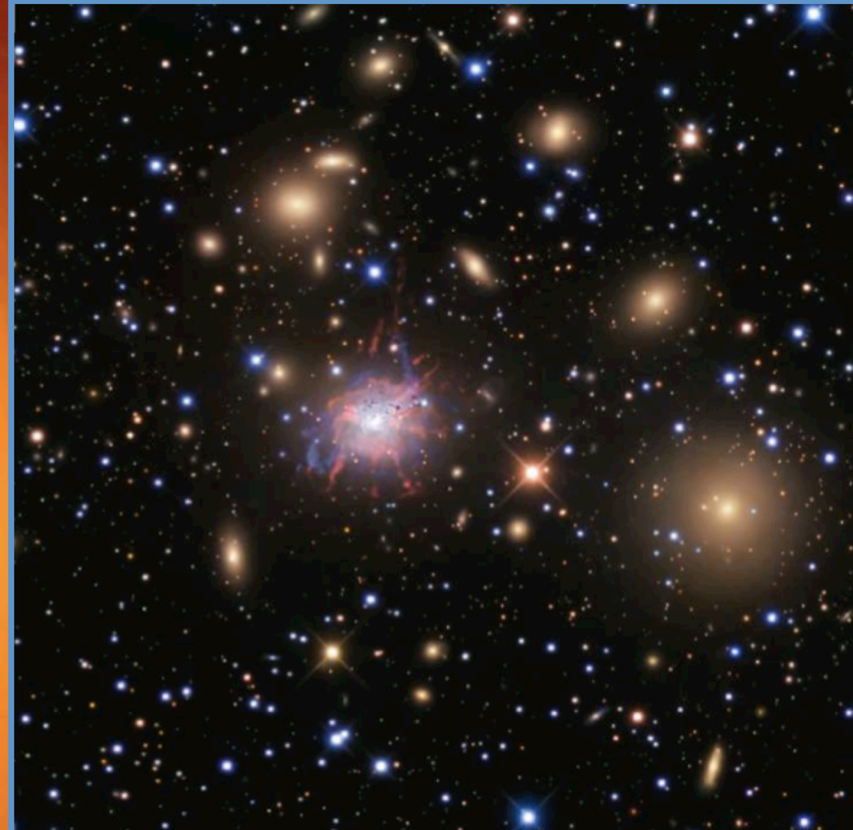
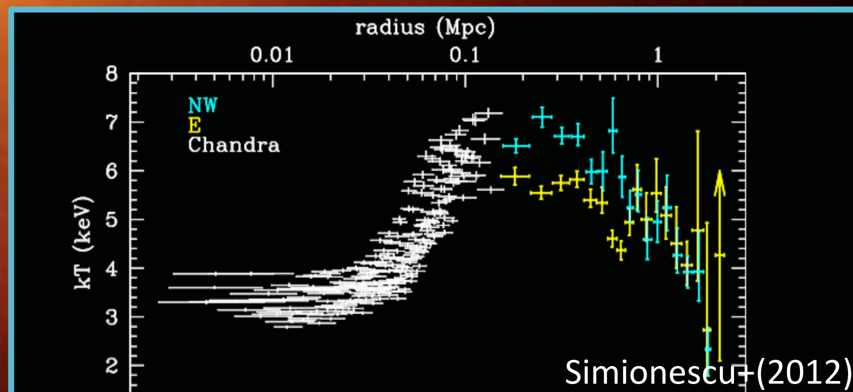
Physics of the ICM, Aug. 24, 2016

Ref: Yang & Reynolds, 2016, ApJ in press
(astro-ph://1605.01725)

Perseus cluster (Fabian+ 2010)



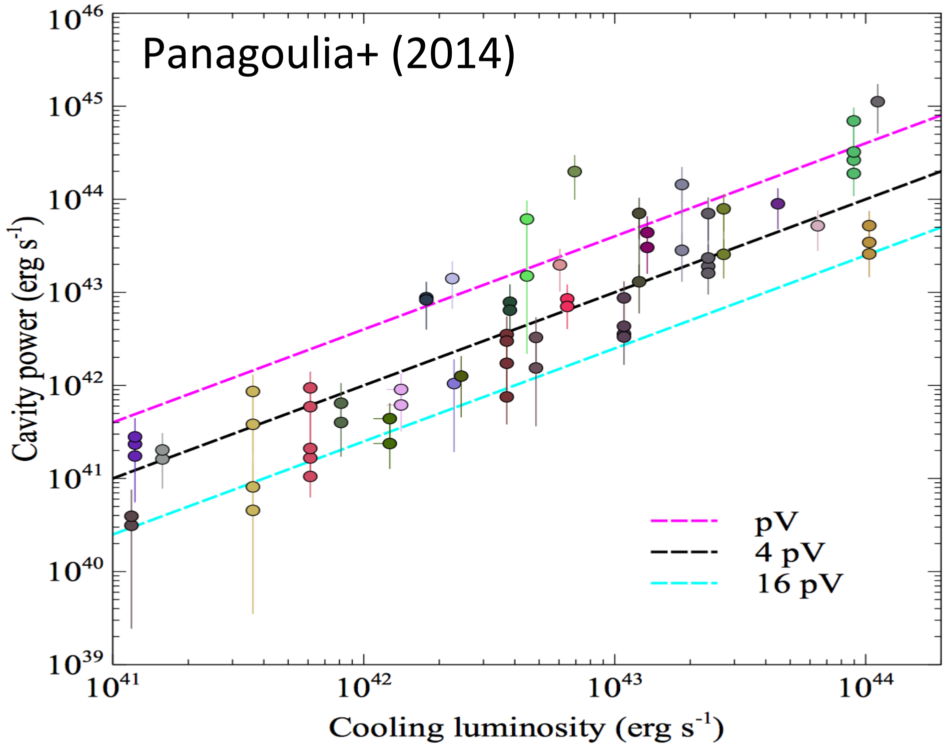




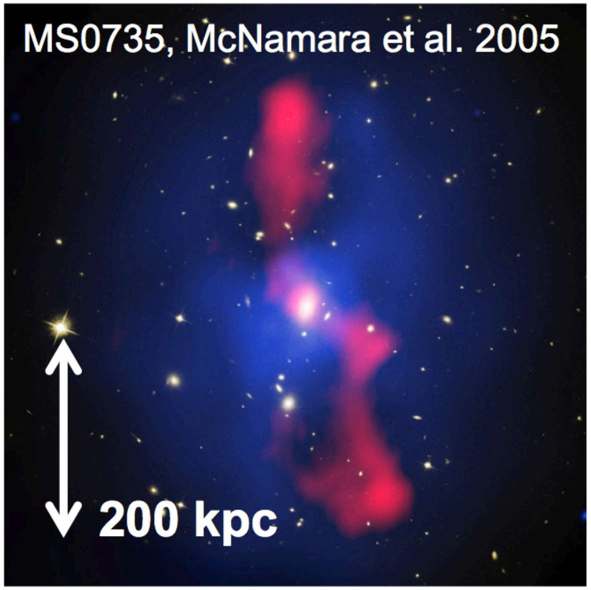
Simionescu+(2012)

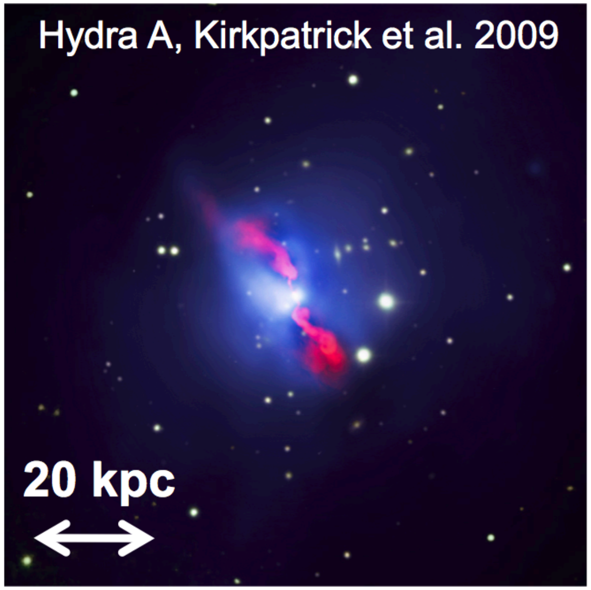
AGN Feedback

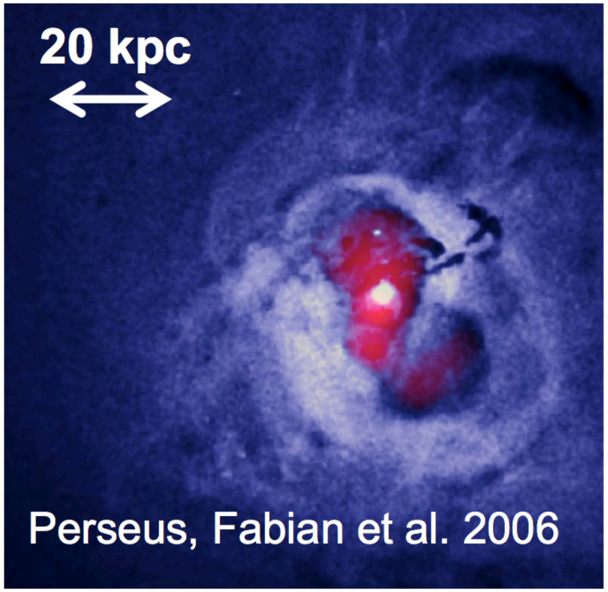
- Radio bubbles
- $P_{cav} \sim L_{cool}$



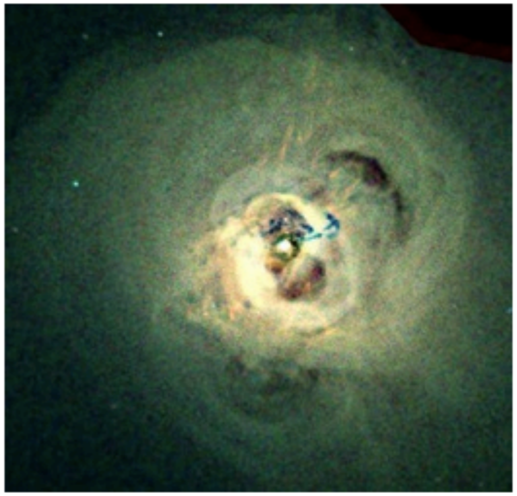
Courtesy of J.Hlavacek-Larrondo



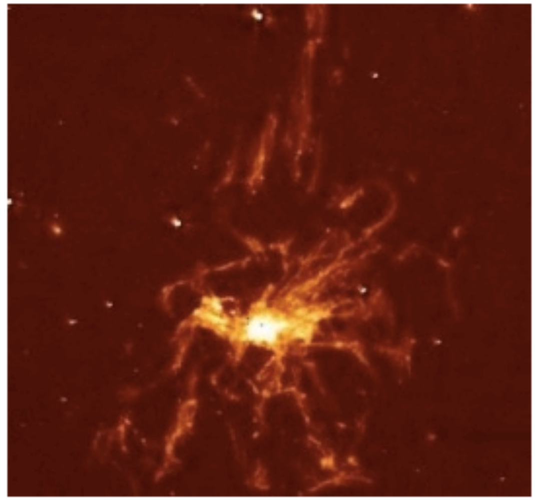




Success of AGN simulations



X-ray observations of Perseus

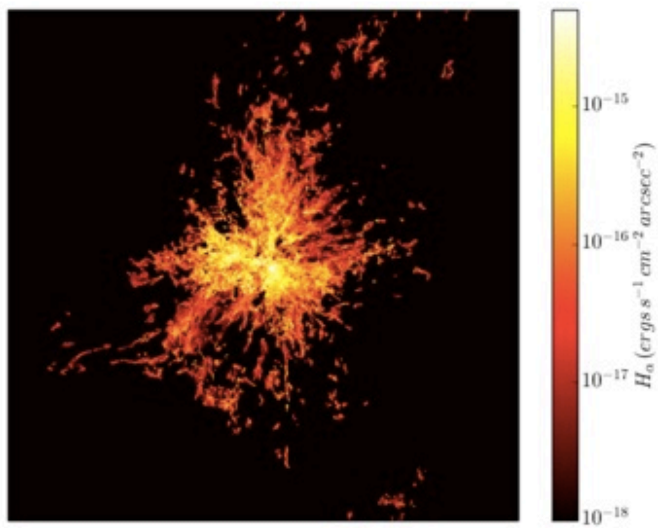


Hα observations of Perseus

- ❖ Hydrodynamic
- ❖ Thermal instabilities and cold gas accretion
- ❖ Momentum-driven Jets

(McCourt+, Gaspari+, Li+, Voit+, Meece+, Prasad+)

Synthetic X-ray composite image of the central 50 kpc region

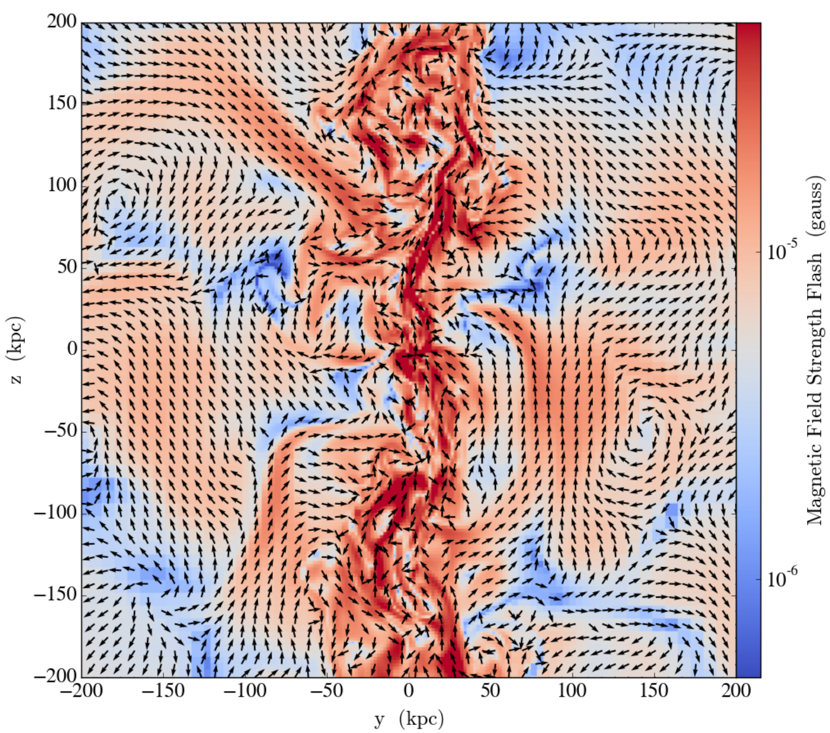


Synthetic Hα map

Role of conduction?

❖ Anisotropic conduction -> HBI (Quataert 2007) -> B field wrapping

B field



Yang & Reynolds (2016)

*Assuming Spitzer conductivity along B

❖ HBI is suppressed using realistic beta

$$l_{\rm crit} \simeq 84\ {\rm kpc}\left(\frac{\beta}{200}\right)^{-1/2}\left(\frac{g}{10^{-8}\ {\rm cm\ s^{-1}}}\right)^{1/2} \times\left(\frac{T}{4\ {\rm keV}}\right)\left(\frac{dT/dr}{4\ {\rm keV}/100\ {\rm kpc}}\right)^{-1/2}.$$

❖ AGN-driven turbulence randomizes field lines such that f_{sp}~1/3

$$Q_{\rm cond} = -f_{\rm sp}\chi\partial T/\partial r$$

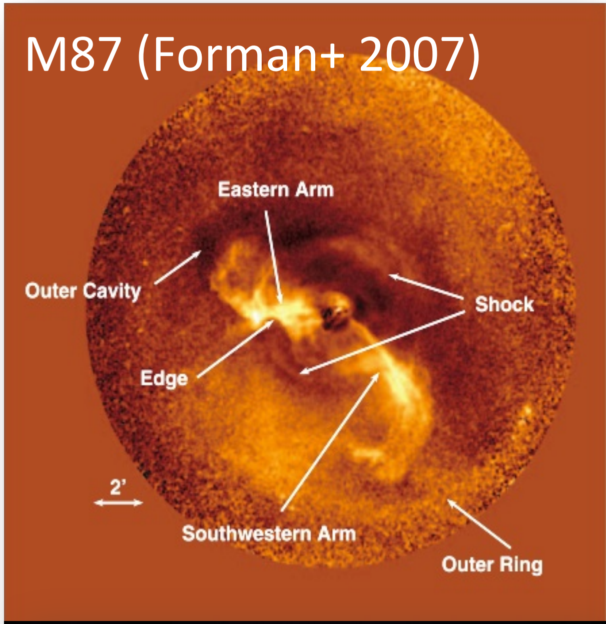
❖ Conductive heating contributes to 10%~50% of radiative losses

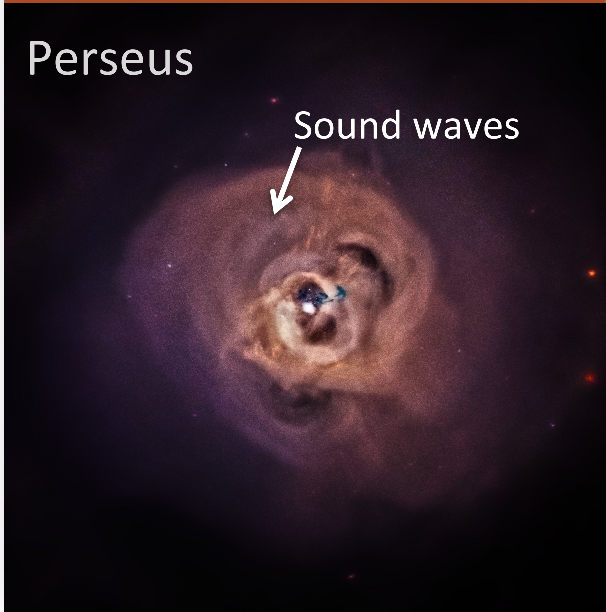
How AGN jets heat the ICM?

- Possible heating mechanisms:
  - Cavity heating (Churazov+ 2001)
  - Weak shocks (Fabian+ 2003)
  - Sound waves (Fabian+ 2005)
  - Turbulence dissipation (Zhuravleva+ 2014)
  - Mixing with hot bubble gas (Hillel+ 2016)
  - Cosmic-ray heating (Guo+ 2008, Pfrommer+2013)

How to distribute heat radially and isotropically?

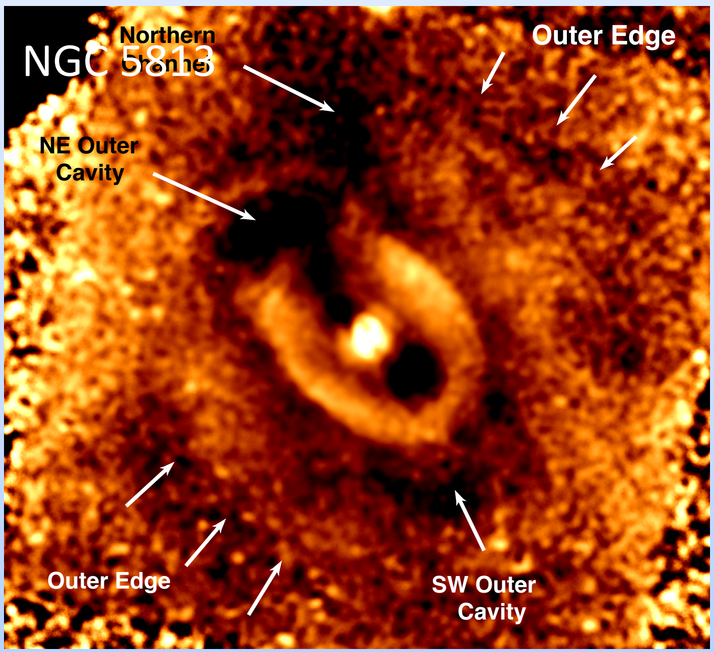
Which mechanisms are dominant?





How AGN jets heat the ICM?

Statement 1: Shock heating is enough to balance radiative cooling (Randall+ 2015)



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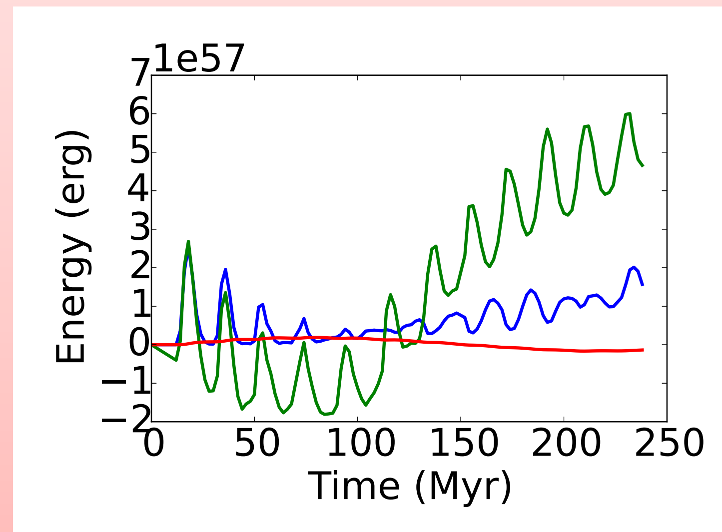
OR

Statement 2: Bubble mixing is more efficient than shock heating (Hillel+ 2016)



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  - ~~Cosmic ray heating (Guo+ 2008)~~

How to distribute heat radially and isotropically?

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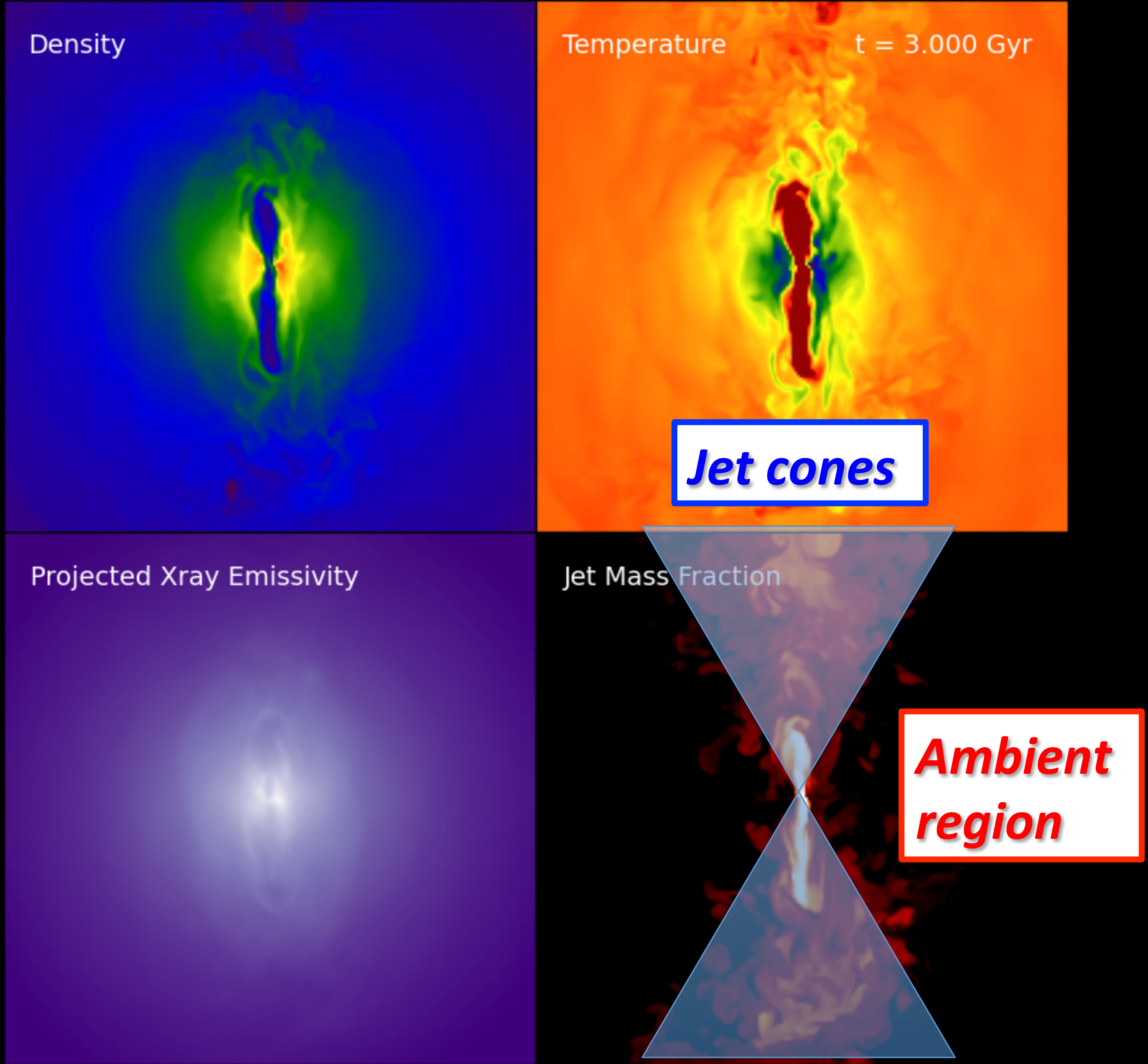
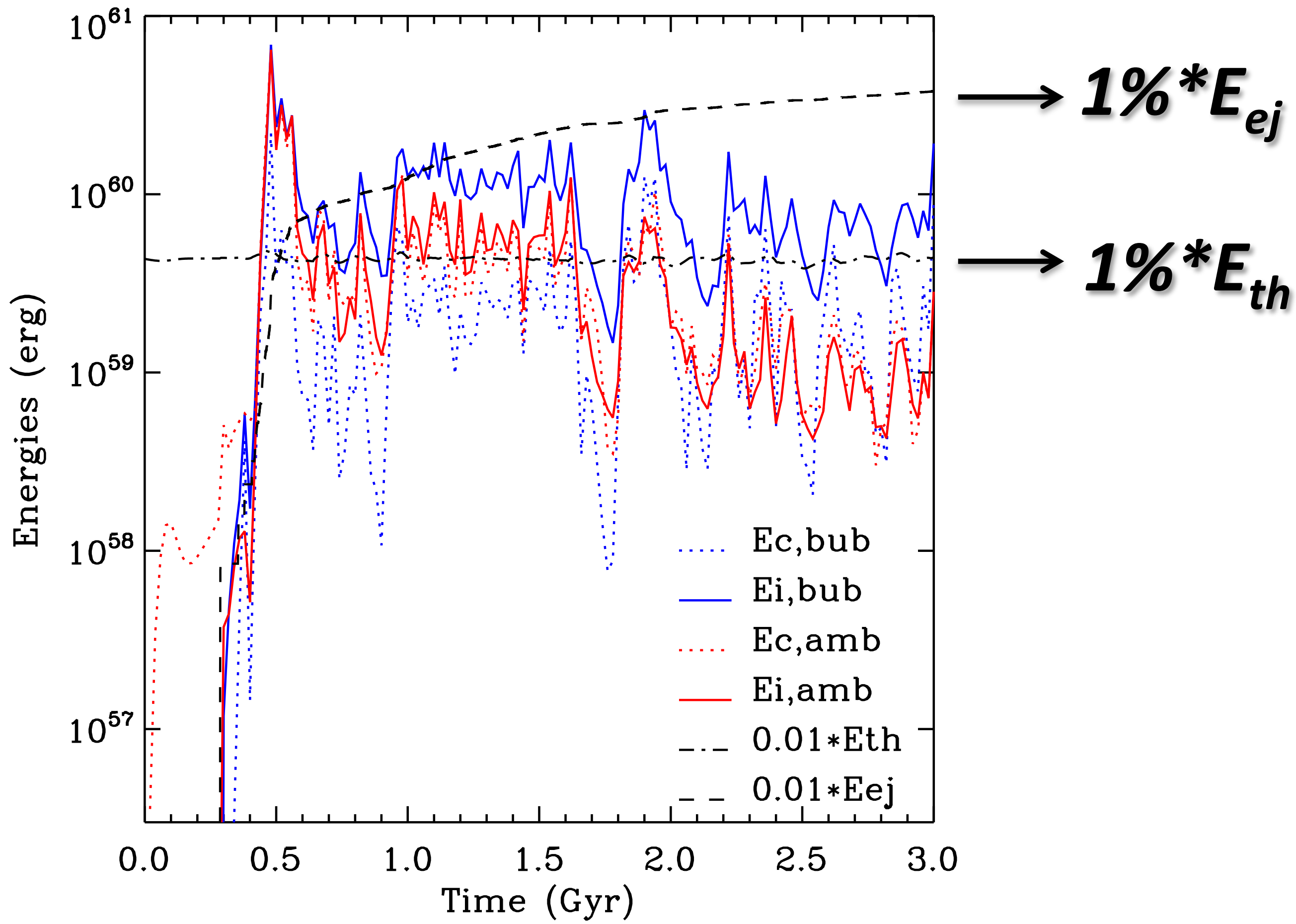
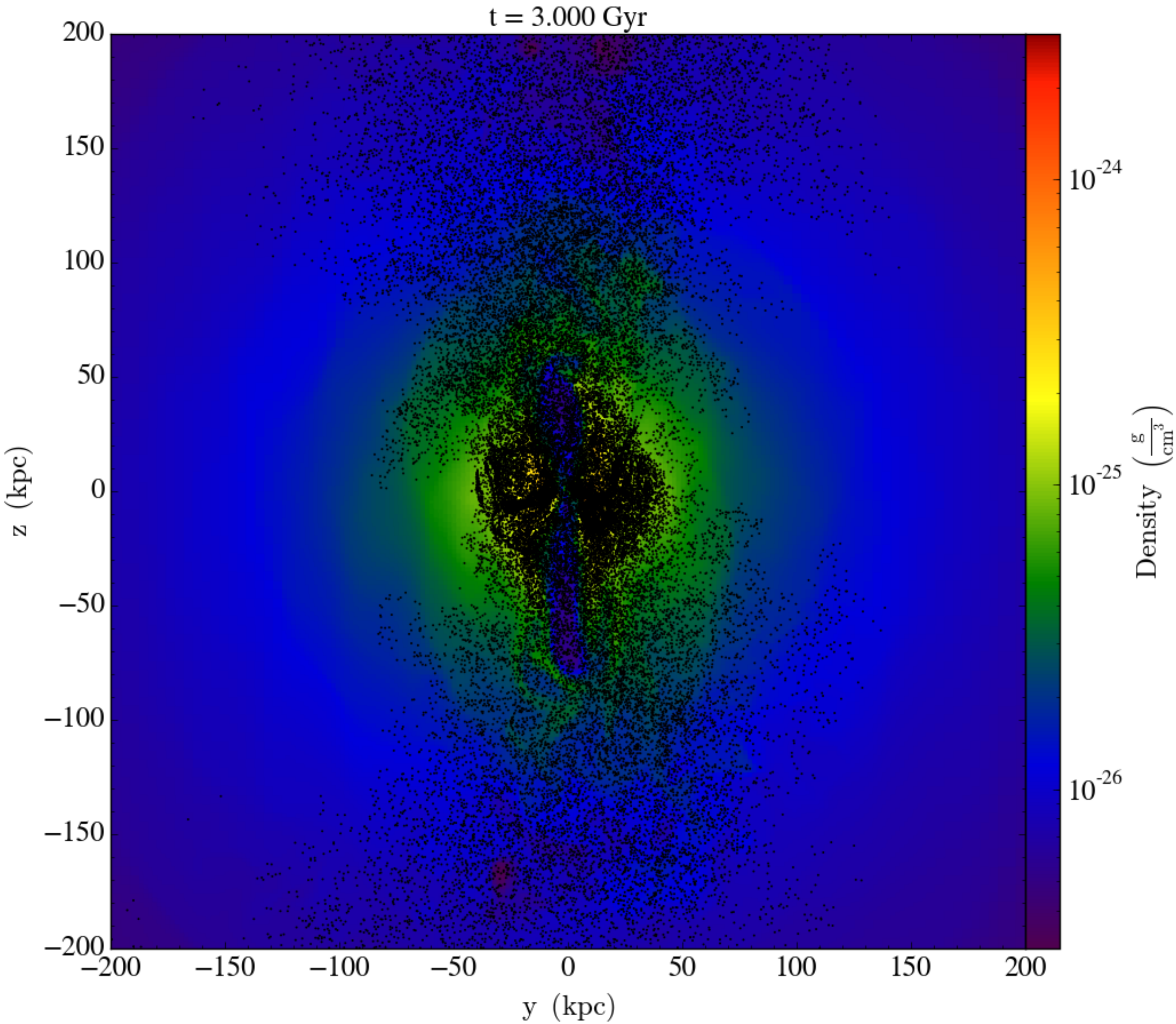
Goal – Gain insights from hydro simulations of self-regulated AGN feedback!


Density
Temperature
t = 3.000 Gyr
Jet cones
Projected Xray Emissivity
Jet Mass Fraction
Ambient region

Turbulence dissipation -> Not likely



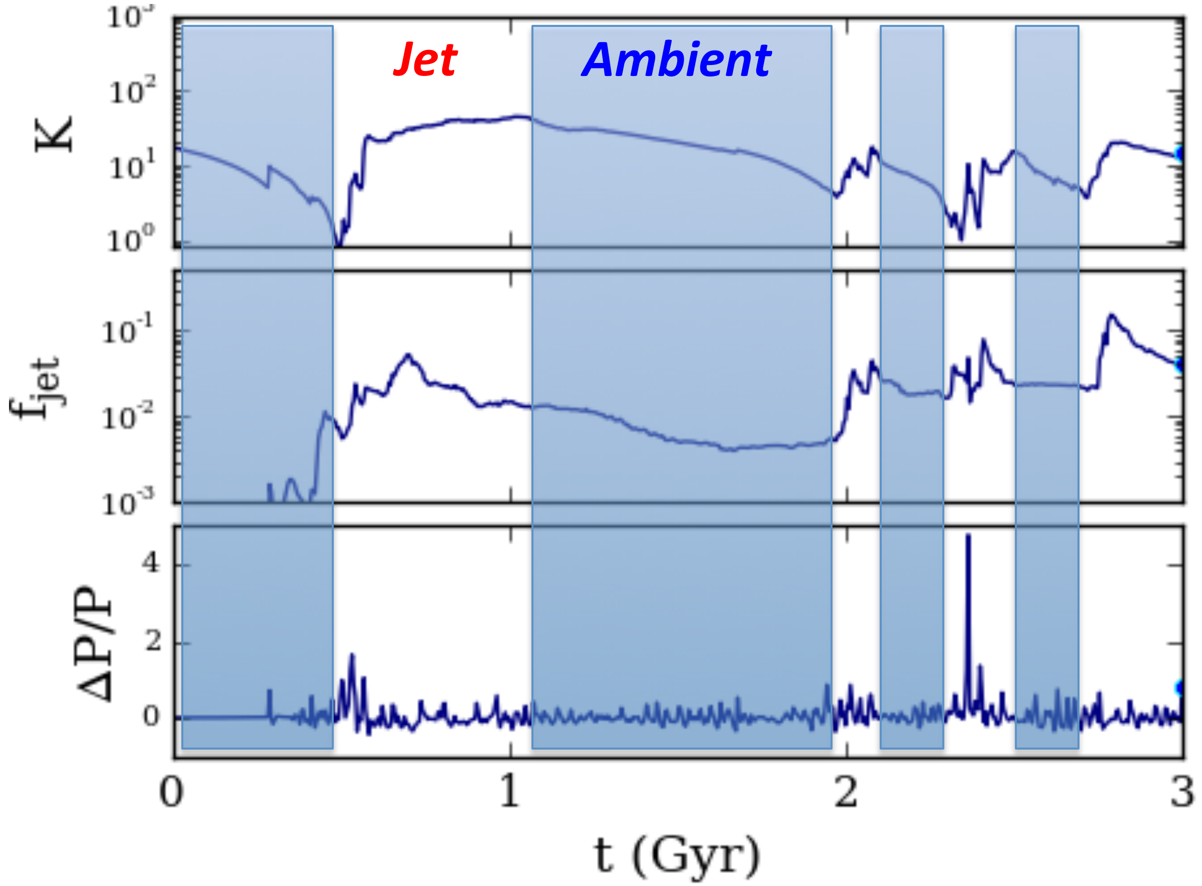
- Turbulent energy ~few percent of thermal energy (Hitomi 2016)
- Turbulent energy only ~1% of injected AGN energy (Reynolds+ 2015)


t = 3.000 Gyr
z (kpc)
y (kpc)
Density $\left(\frac{g}{cm^3}\right)$
10^{-24}
10^{-25}
10^{-26}
200
150
100
50
0
−50
−100
−150
−200
−200
−150
−100
−50
0
50
100
150
200

Passive tracers – the Lagrangian view

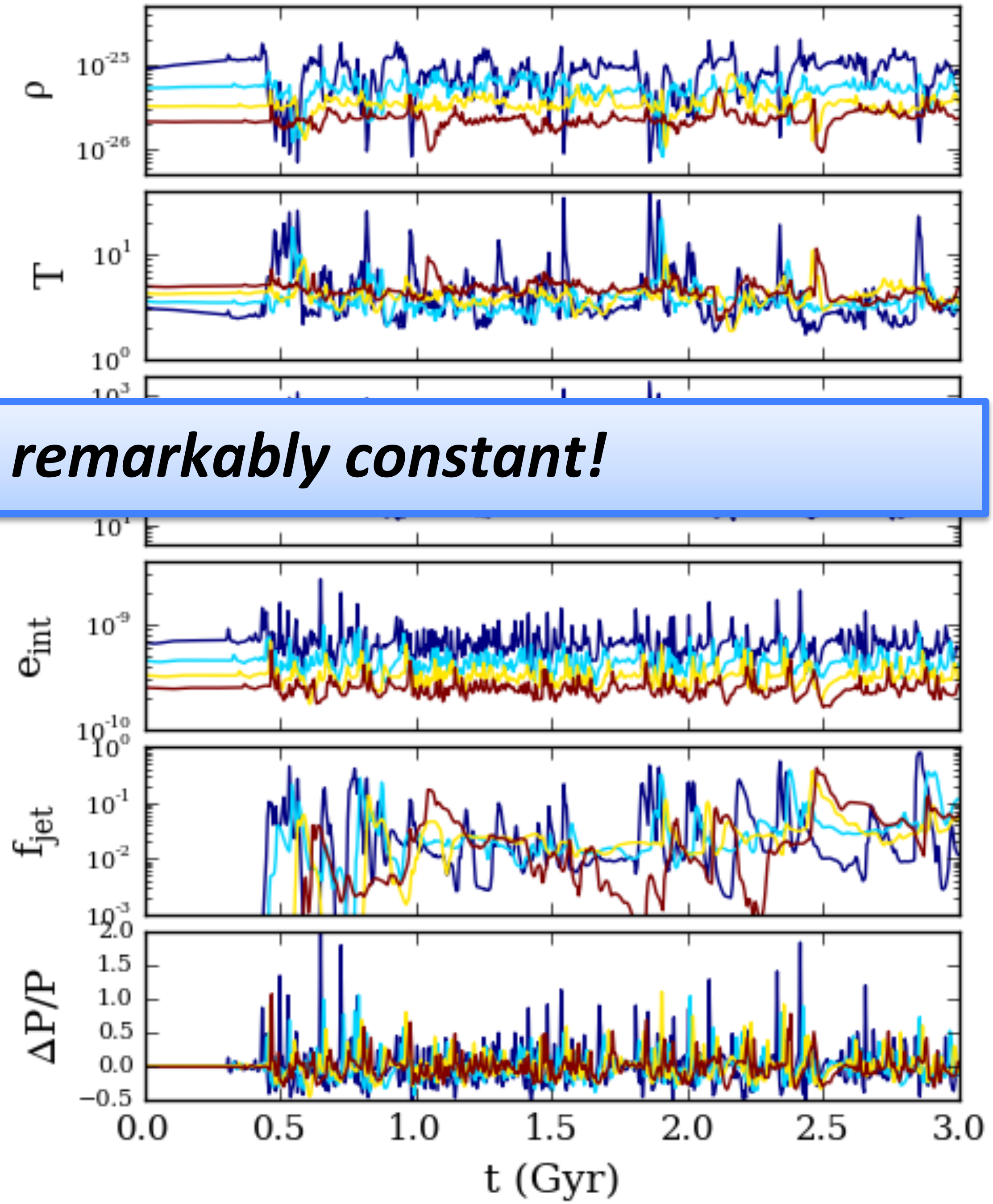
$$K \equiv \frac{T}{n_e^{2/3}}$$

$$\frac{dK}{dt} = H - C$$

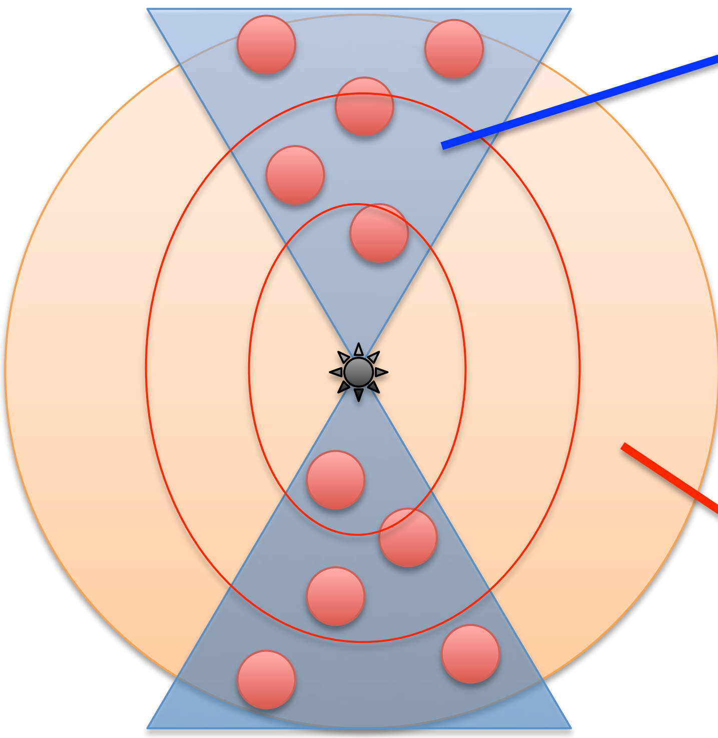


- ***Heating done by bubble mixing and shocks***
- ***Mixing more efficient, but shocks more frequent***
- ***Net cooling in amb. region; net heating in jet cones***

Static tracers – the Eulerian view



❖ ***Hydro variables are remarkably constant!***



Within jet cones:

- ***Net heating* by bubble mixing and shocks**
- ***But T does not increase!?***

Within ambient region:

- ***Net cooling***
- ***But T does not decrease!?***

Gas internal energy equation:

$$\frac{\partial e_i}{\partial t} + \nabla \cdot (e_i \vec{v}) + P(\nabla \cdot \vec{v}) = H - C$$

Change of e_i at a fixed location → ≈ 0

Transport by advection or convection

Adiabatic compression or expansion

→ ***Transport & adiabatic processes important!!***

Heating and Cooling → $\neq 0$

$$\varepsilon_\alpha \rightarrow \left[\frac{\partial e_i}{\partial t} + \nabla\cdot(e_i\vec{v}) + P(\nabla\cdot\vec{v}) = H_{mix} + H_{sh} - C \right]$$

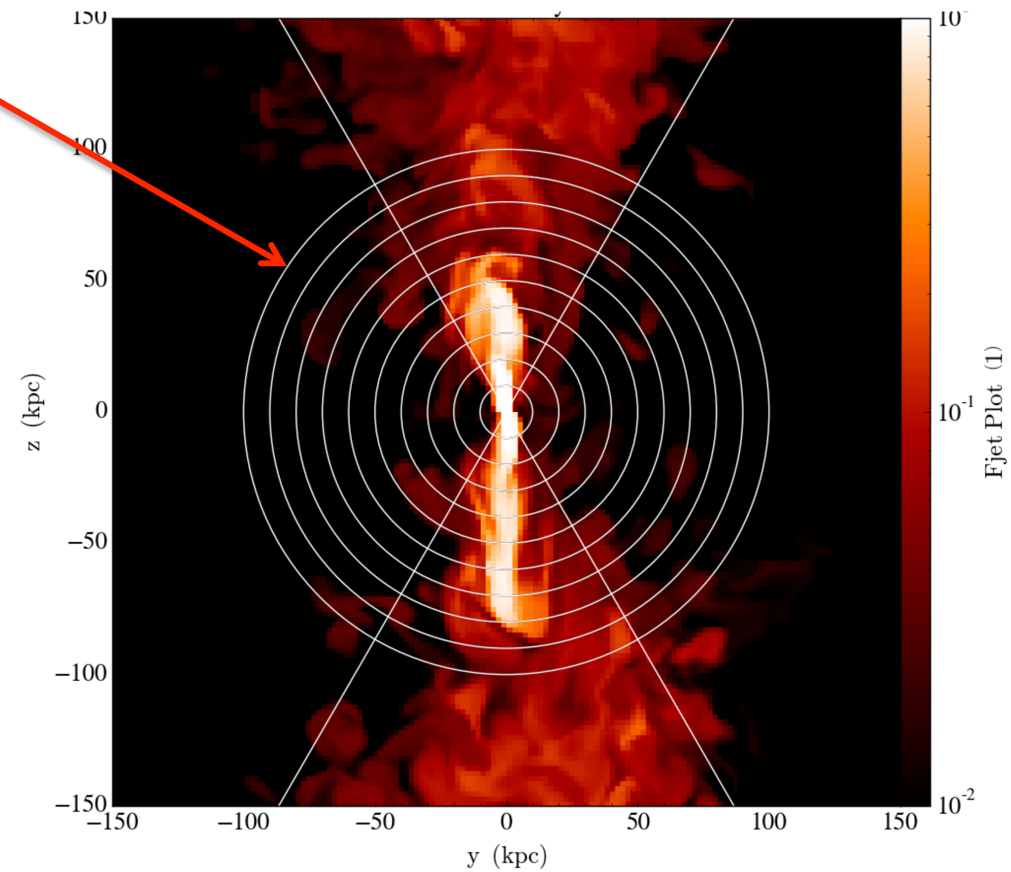
$$\alpha \in \{transport, adiabatic, mixing, shocks, cooling\}$$

$$\Rightarrow \varepsilon_{\alpha,i} = \frac{\int_{V_i} \varepsilon_\alpha \, dV}{V_i}$$

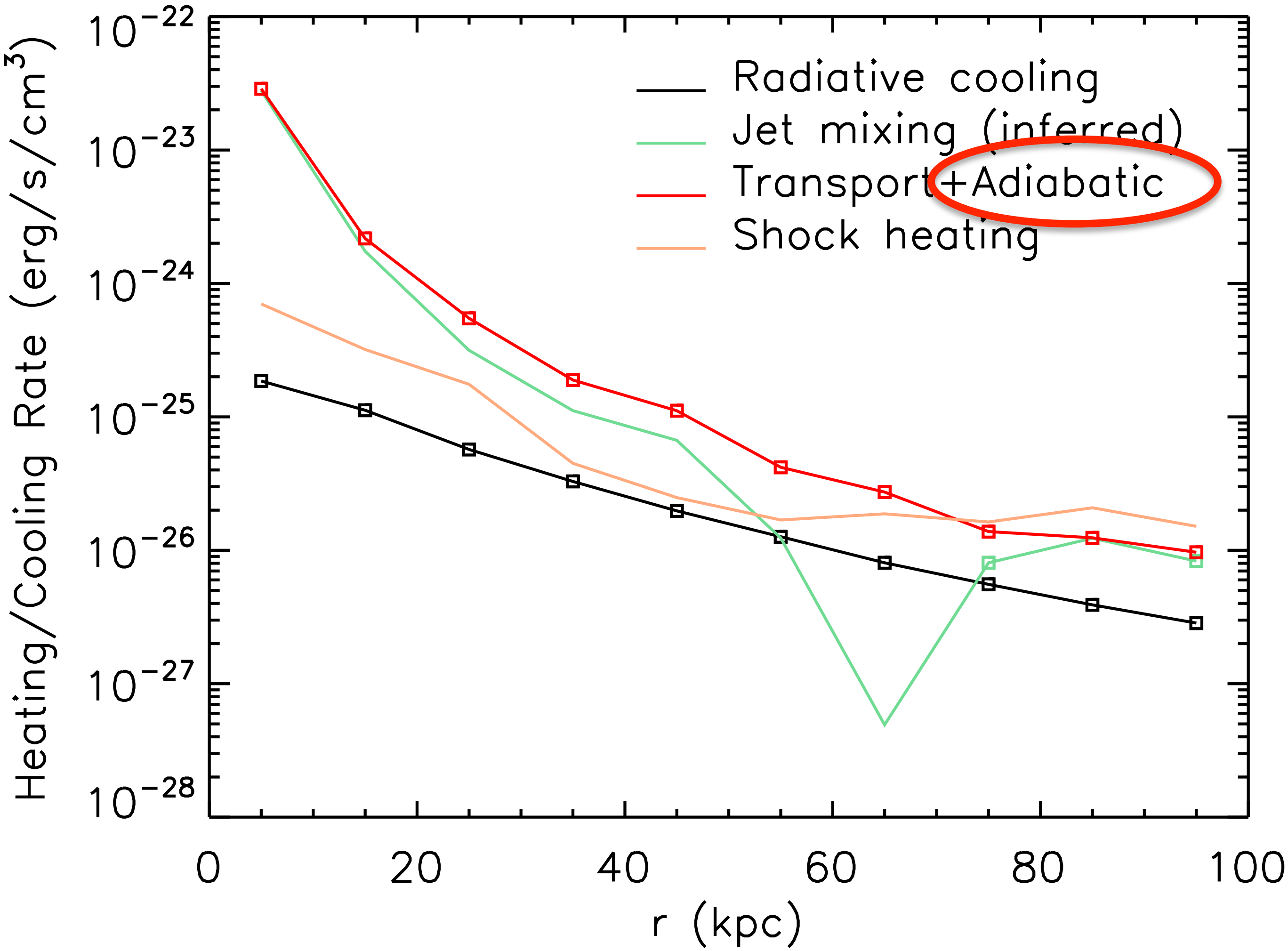
$$\Rightarrow <\varepsilon_{\alpha,i}>_t$$

20 sectors:

Cones vs. Ambient, 10 radial bins



H/C processes – Jet cones



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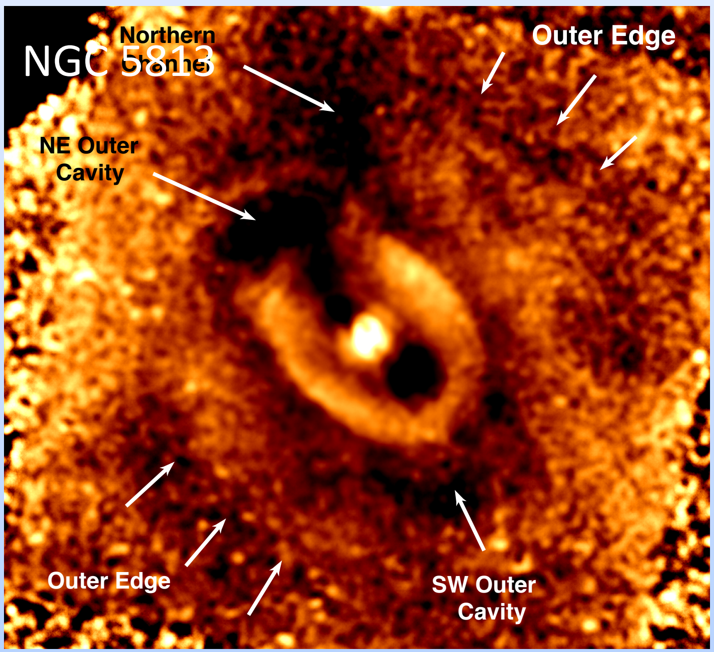

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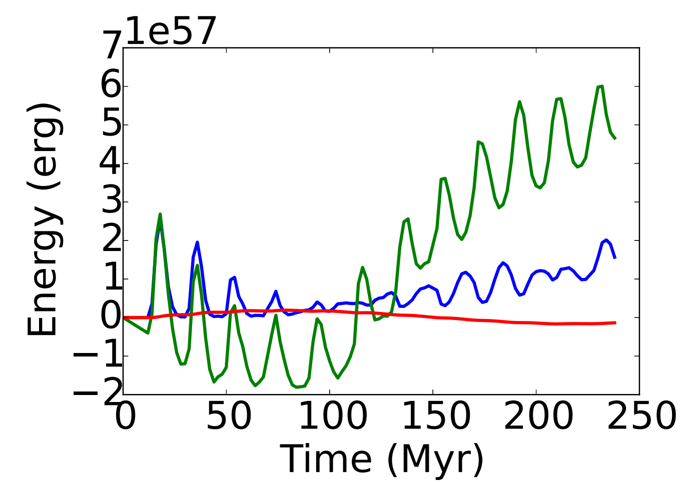
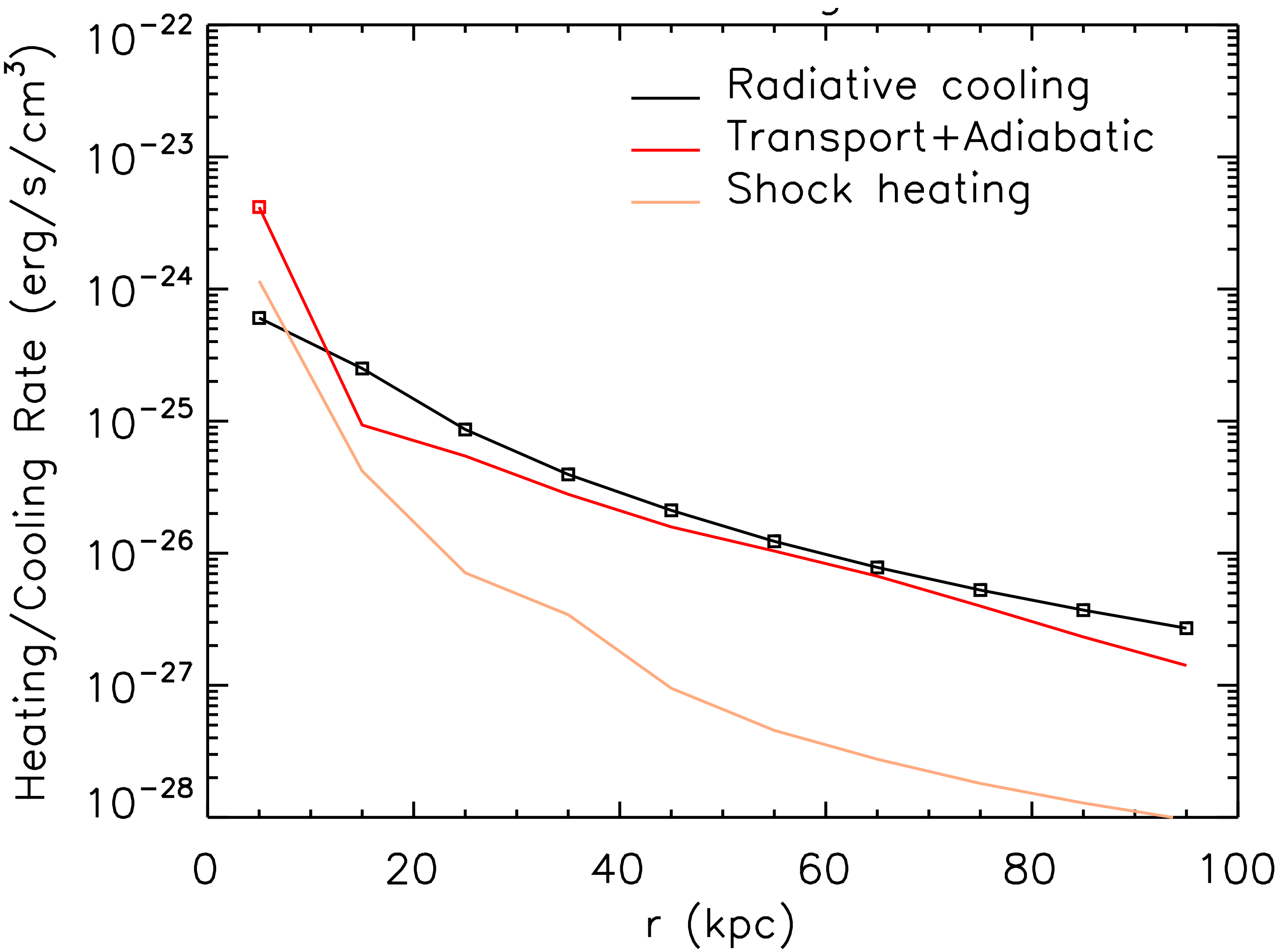


H/C processes – Ambient region



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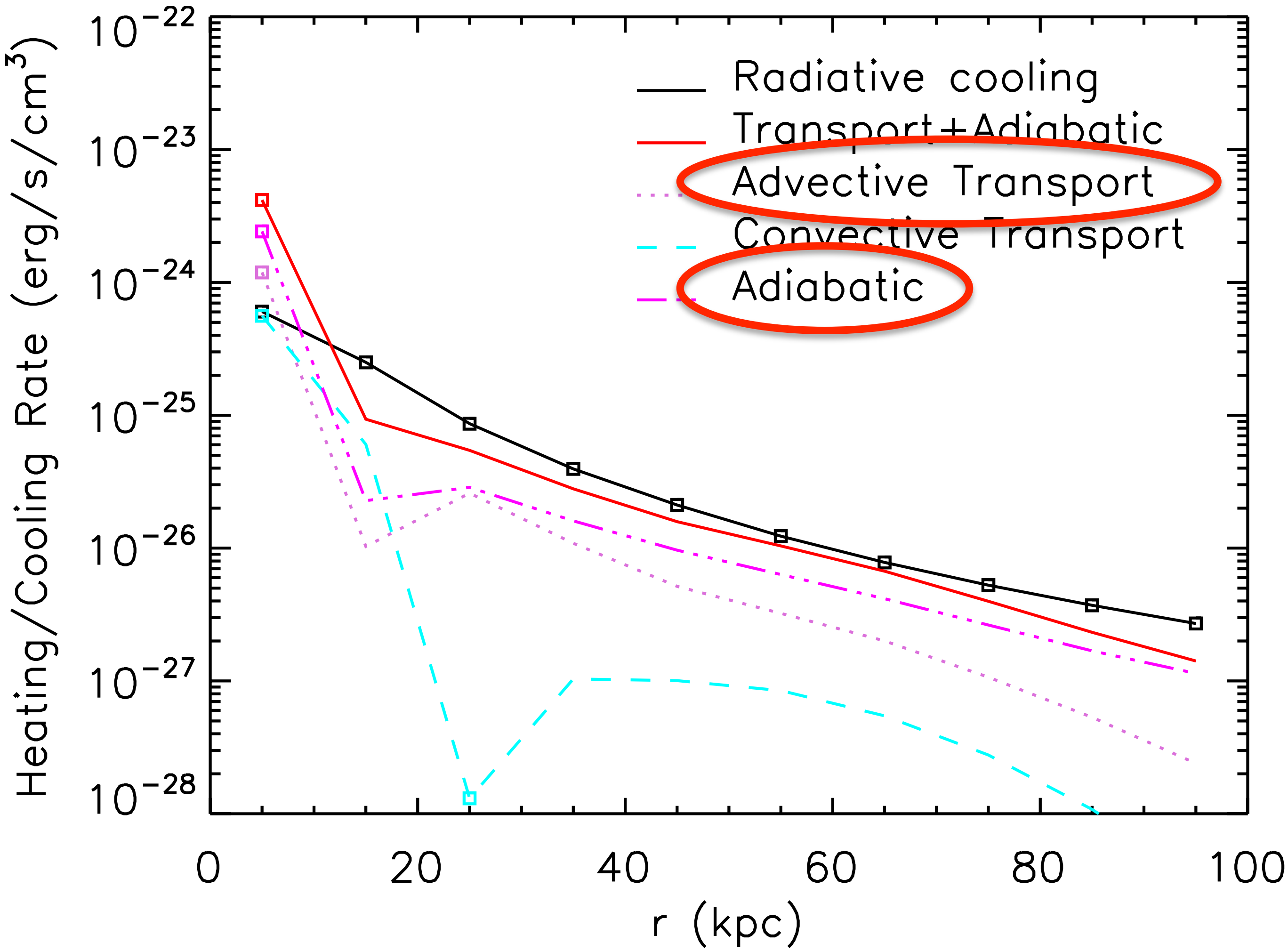
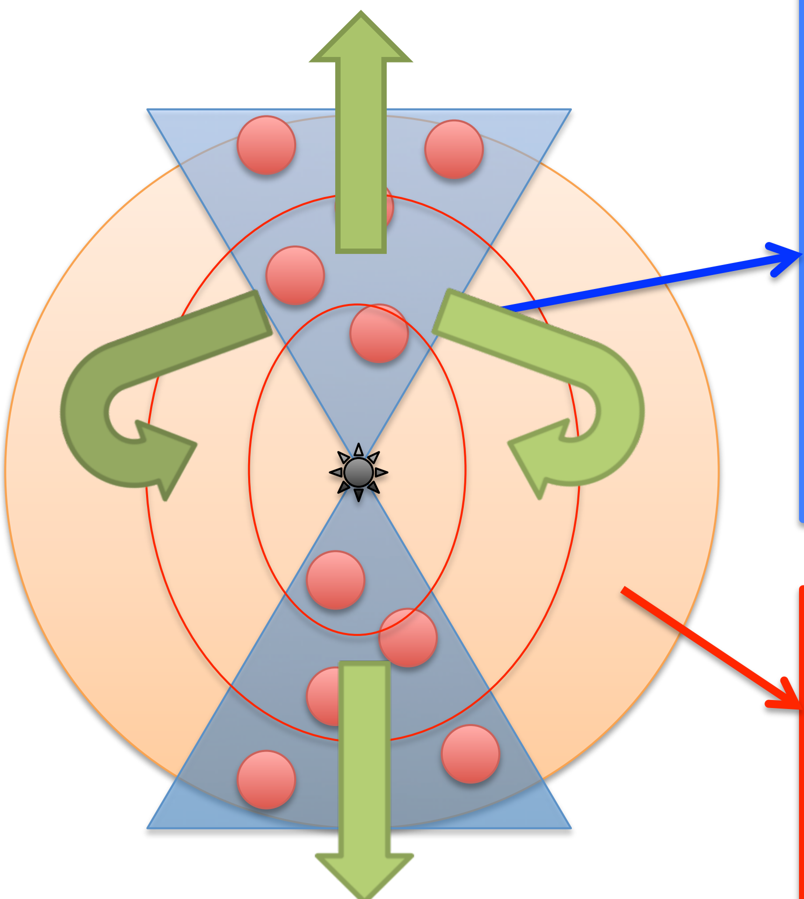


A model of ``gentle circulation"



Within jet cones:

- ***Net heating*** ***by bubble mixing and shocks***
- ***But T does not increase due to adiabatic expansion***

Within ambient region:

- ***Net cooling***
- ***But T does not decrease due to advection & adiabatic compression***

A model of ``gentle circulation”

Open questions

❖ No B fields, conduction, or viscosity:

-> Cavity heating, sound-wave heating

❖ Kinetic feedback assumes hot gas within bubbles

-> Bubble composition still unknown $P_{tot} = P_{th} + P_B + P_{cr}$

-> If CR-dominated, bubble mixing would be inefficient and has to rely on CR heating (see talks by Pfrommer and Ruszkowski)

Summary -- How AGN Jets heat the ICM?

- What mechanisms are dominant?
  -- Heating done by bubble mixing and weak shocks
  -- Turbulent heating is not dominant

- How to distribute heat radially and isotropically?
  - Heating and cooling profiles do not need to balance
  - AGN jets do not need to heat isotropically
  - ICM undergoes ``gentle circulation" that transports and compensates AGN heating

- Future work
  - Include B field, conduction, viscosity, and CRs