How AGN Jets Heat the Intracluster Medium

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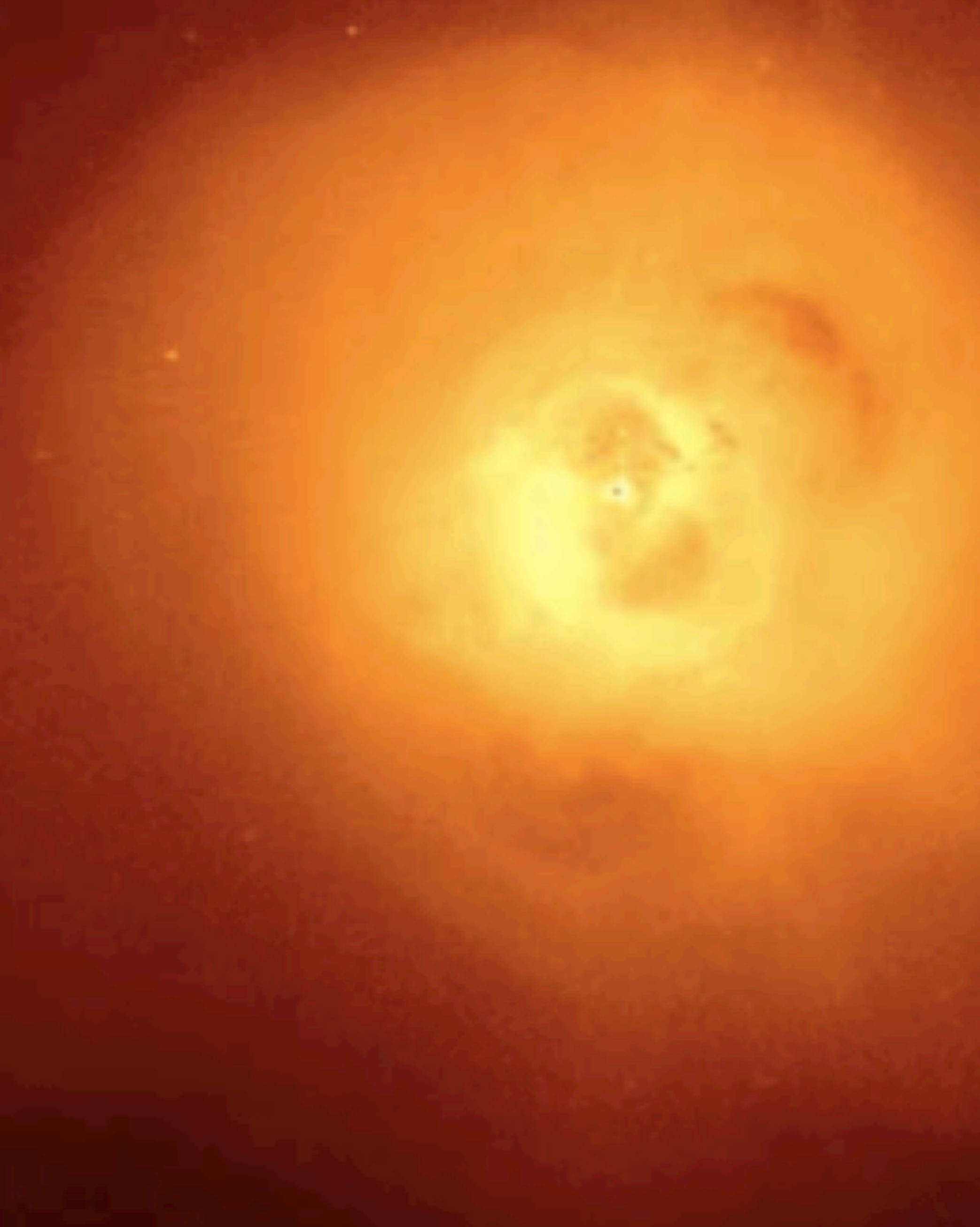
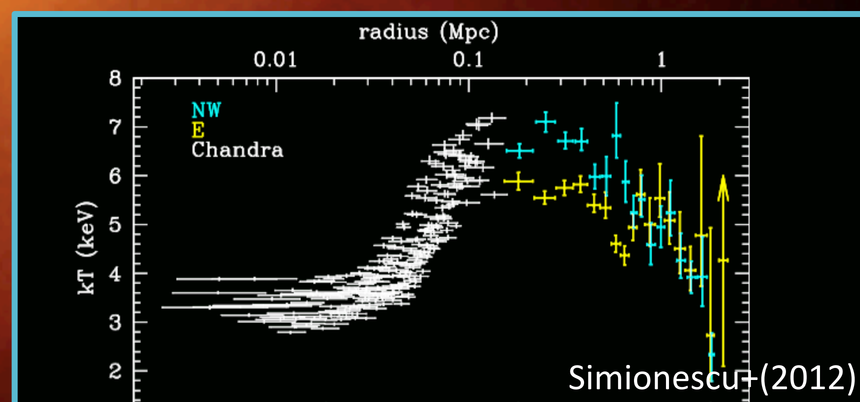
Ref: Yang & Reynolds, 2016, ApJ, 829, 90
(astro-ph://1605.01725)

Perseus cluster (Fabian+ 2010)



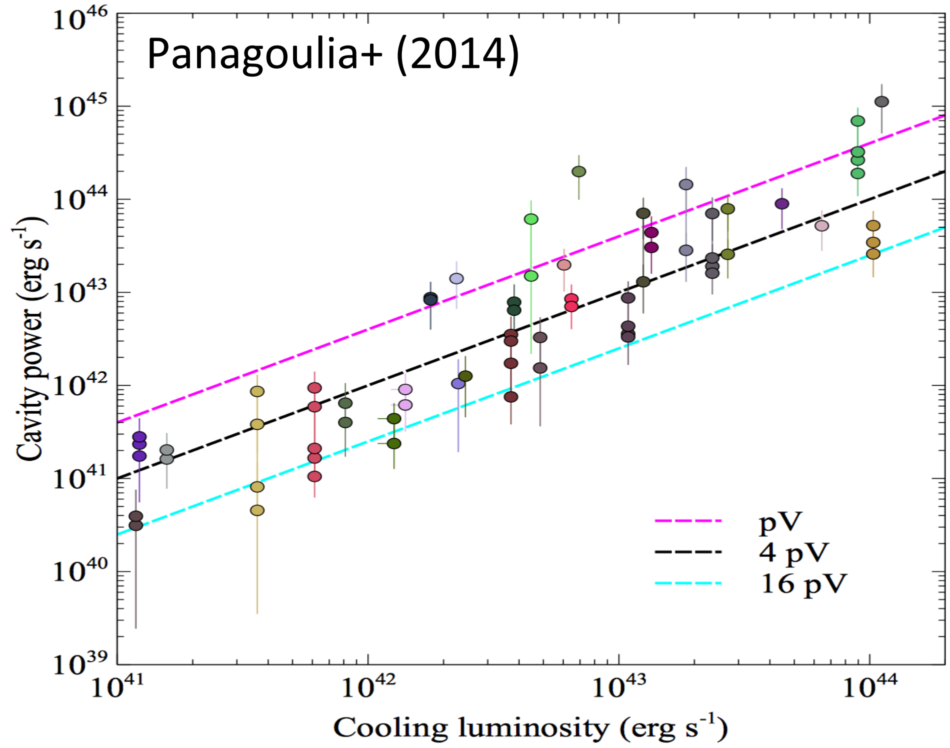


Simionescu+(2012)

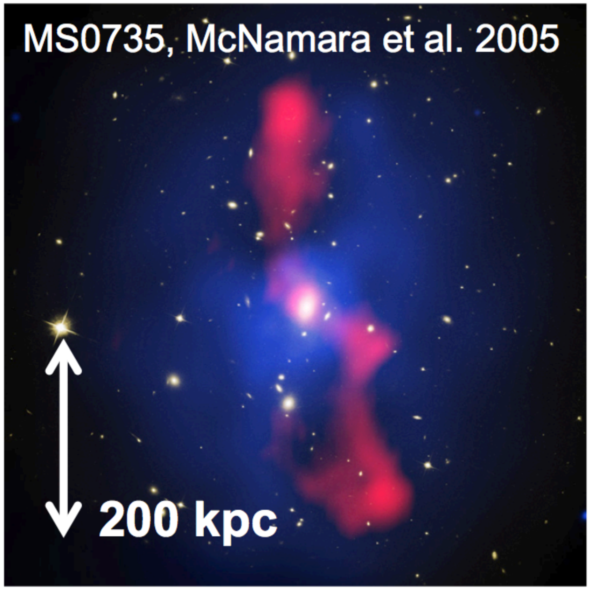
AGN Feedback

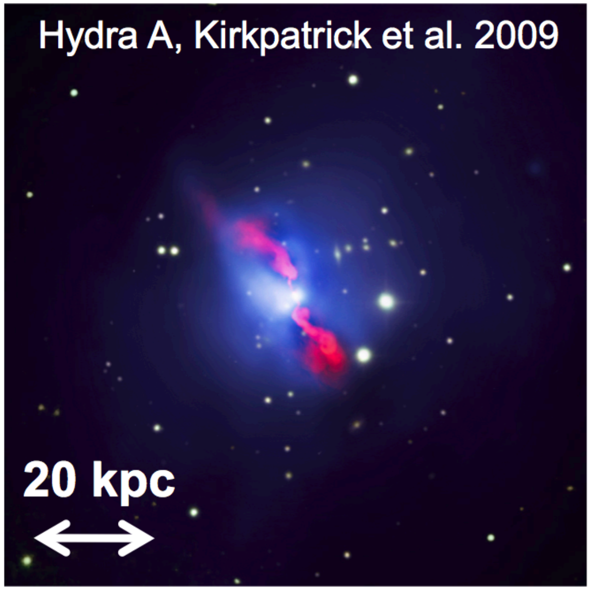
❖ Radio bubbles

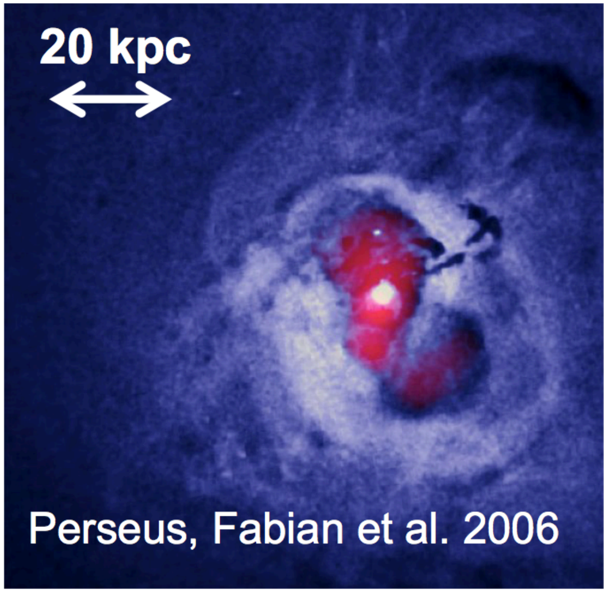
❖ $P_{cav} \sim L_{cool}$



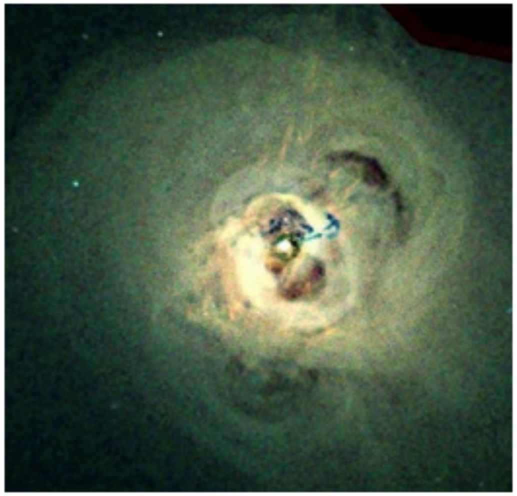
Courtesy of J.Hlavacek-Larrondo



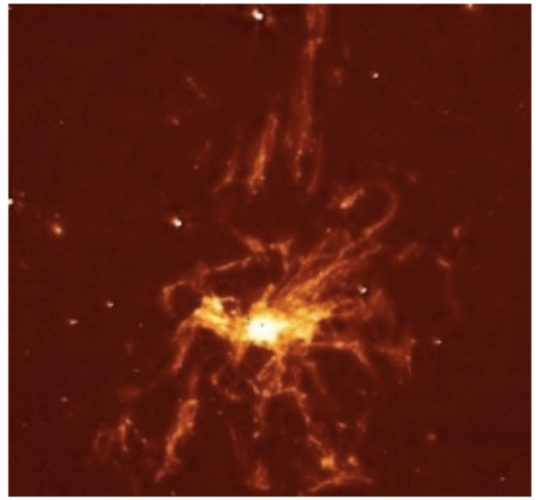




Success of AGN simulations

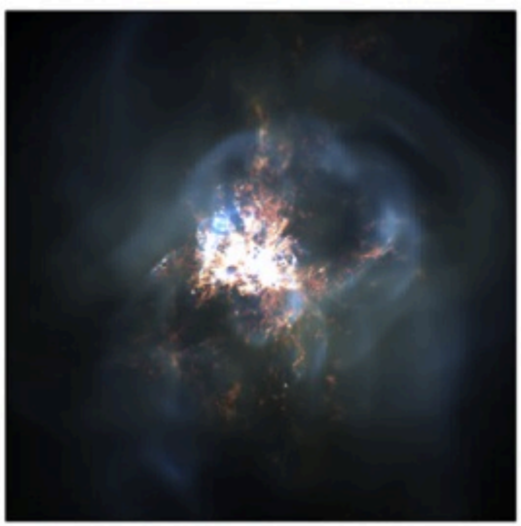


X-ray observations of Perseus

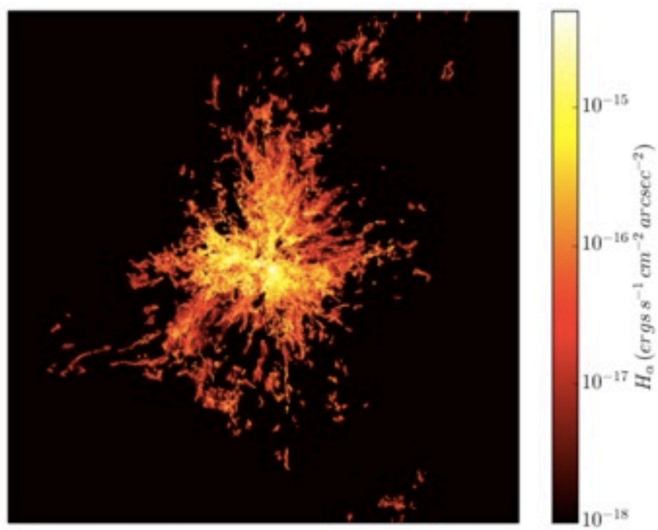


Hα observations of Perseus

- Hydrodynamic
- Cold gas accretion
- Momentum-driven Jets



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



Synthetic Hα map

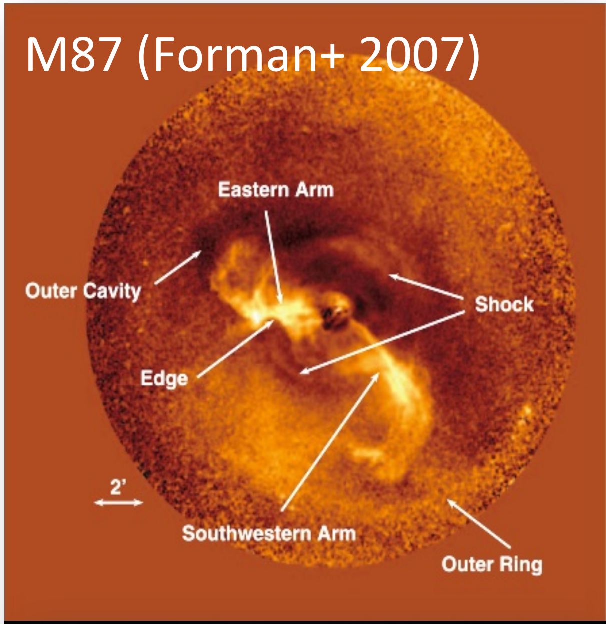
Gaspari+ (2011, 2012)
Li+ (2014, 2015)

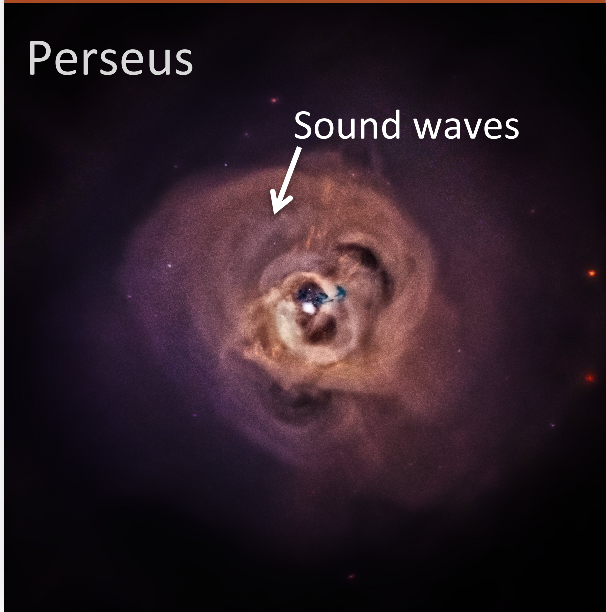
How AGN jets heat the ICM?

- 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?

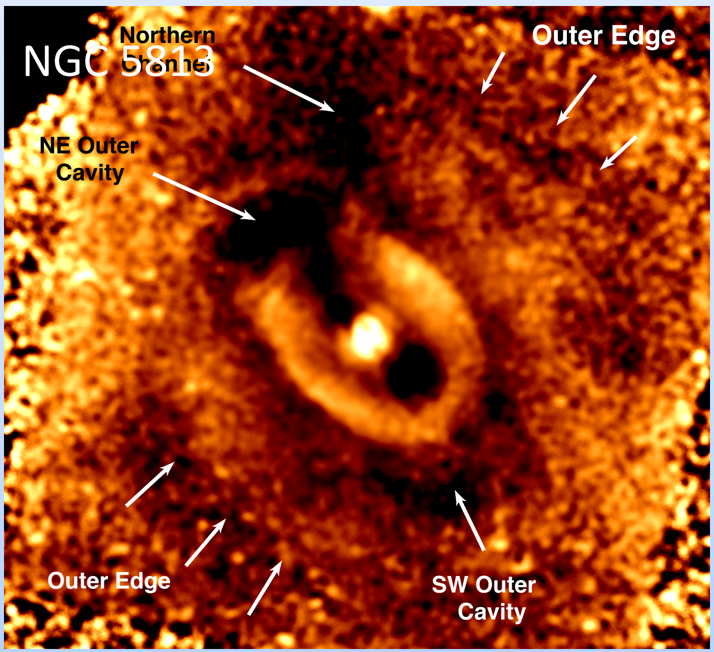
Which mechanisms are dominant?





How AGN jets heat the ICM?

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



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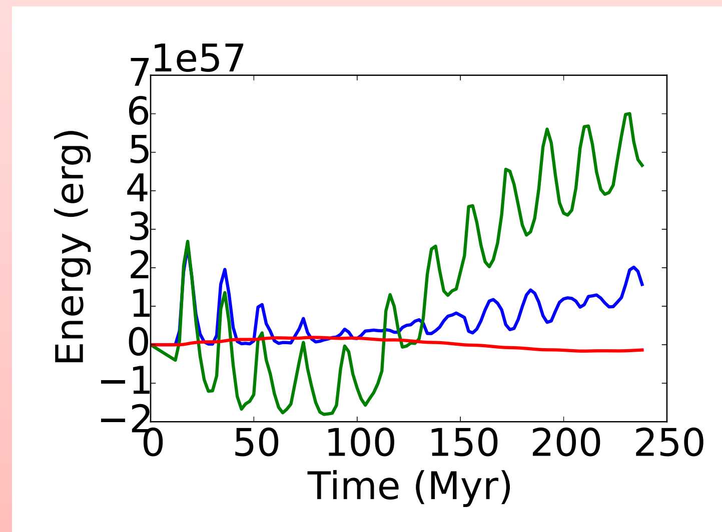
Statement 2: Bubble mixing is more efficient than shock heating (Hillel+ 2016)



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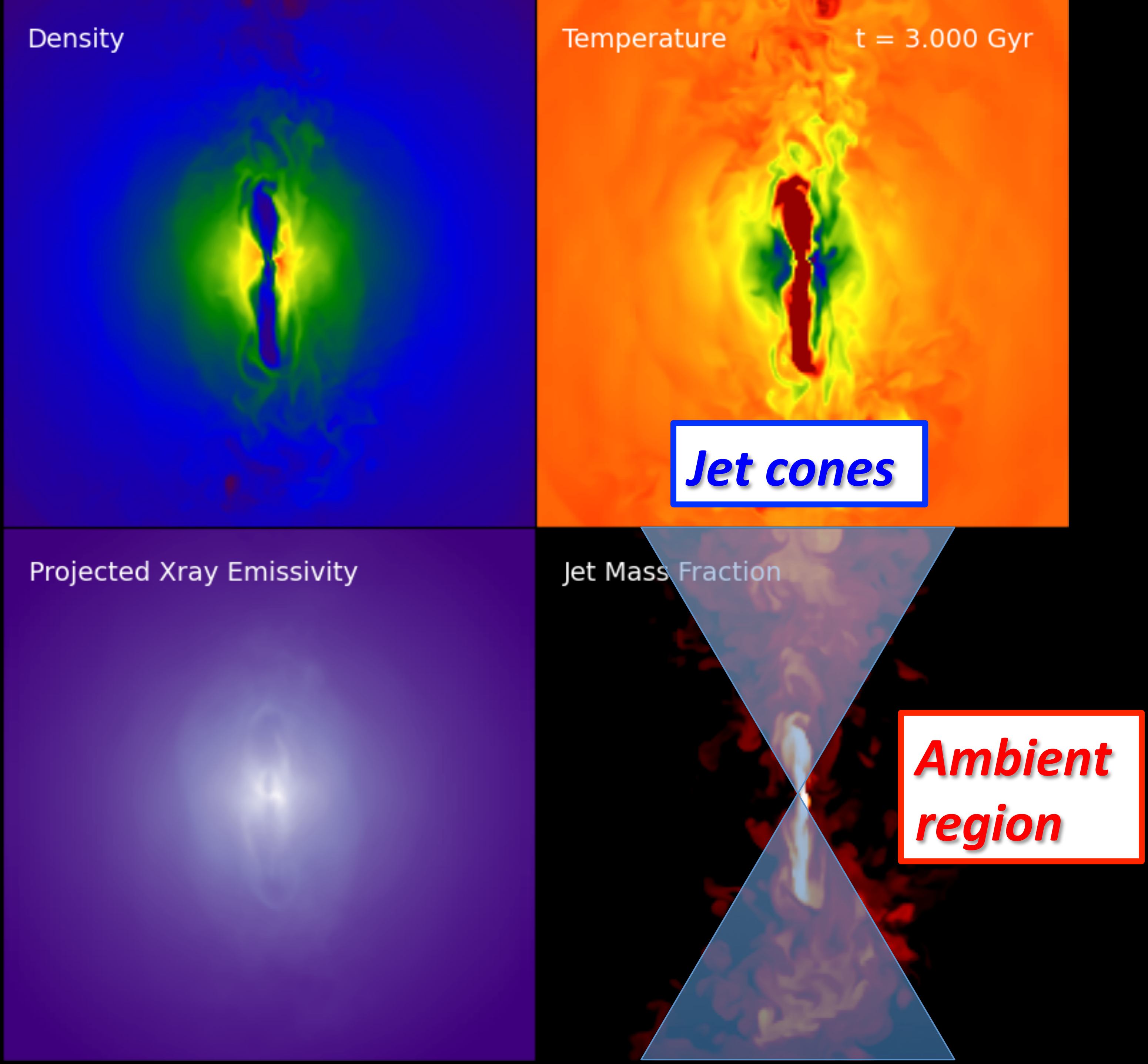
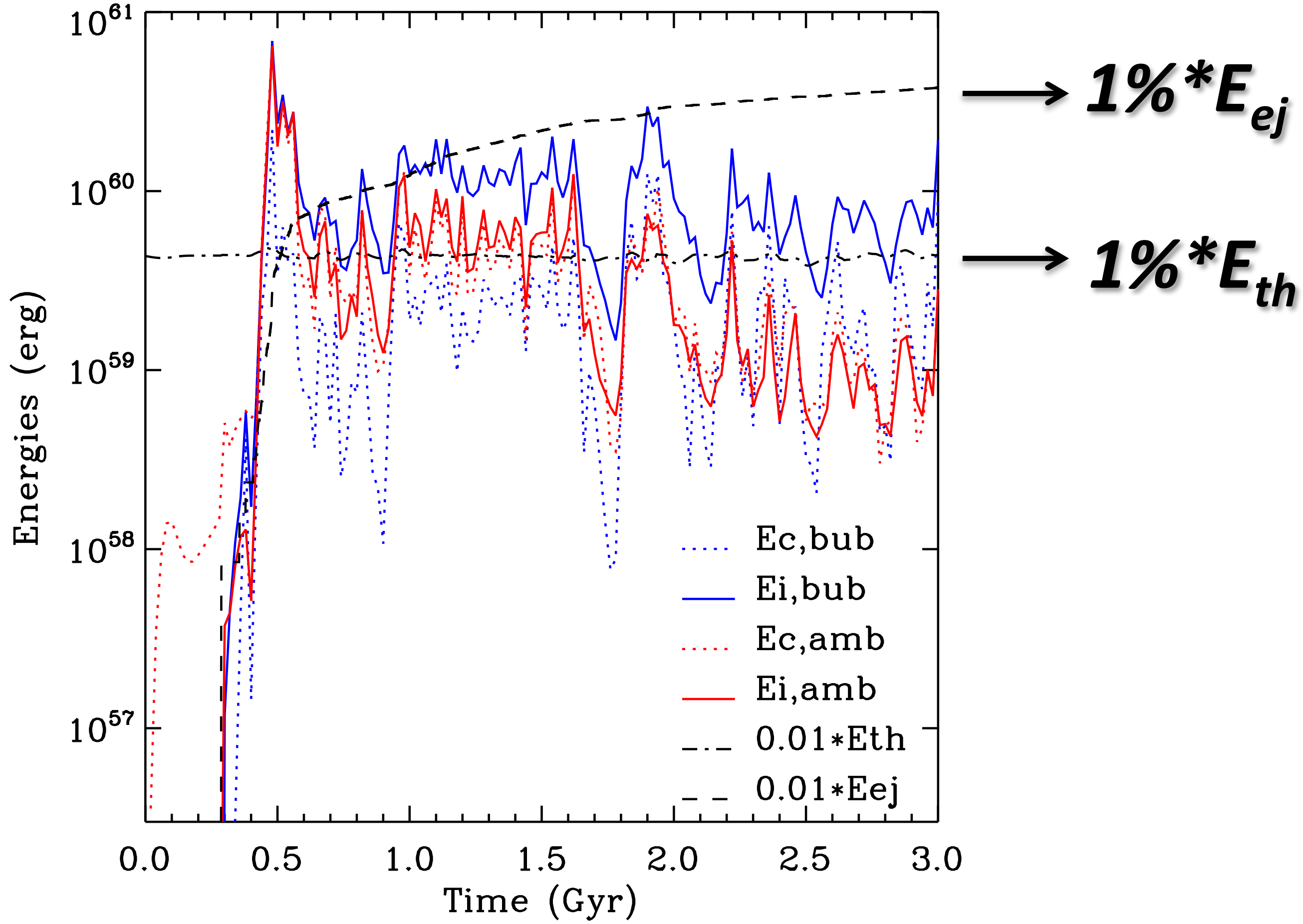
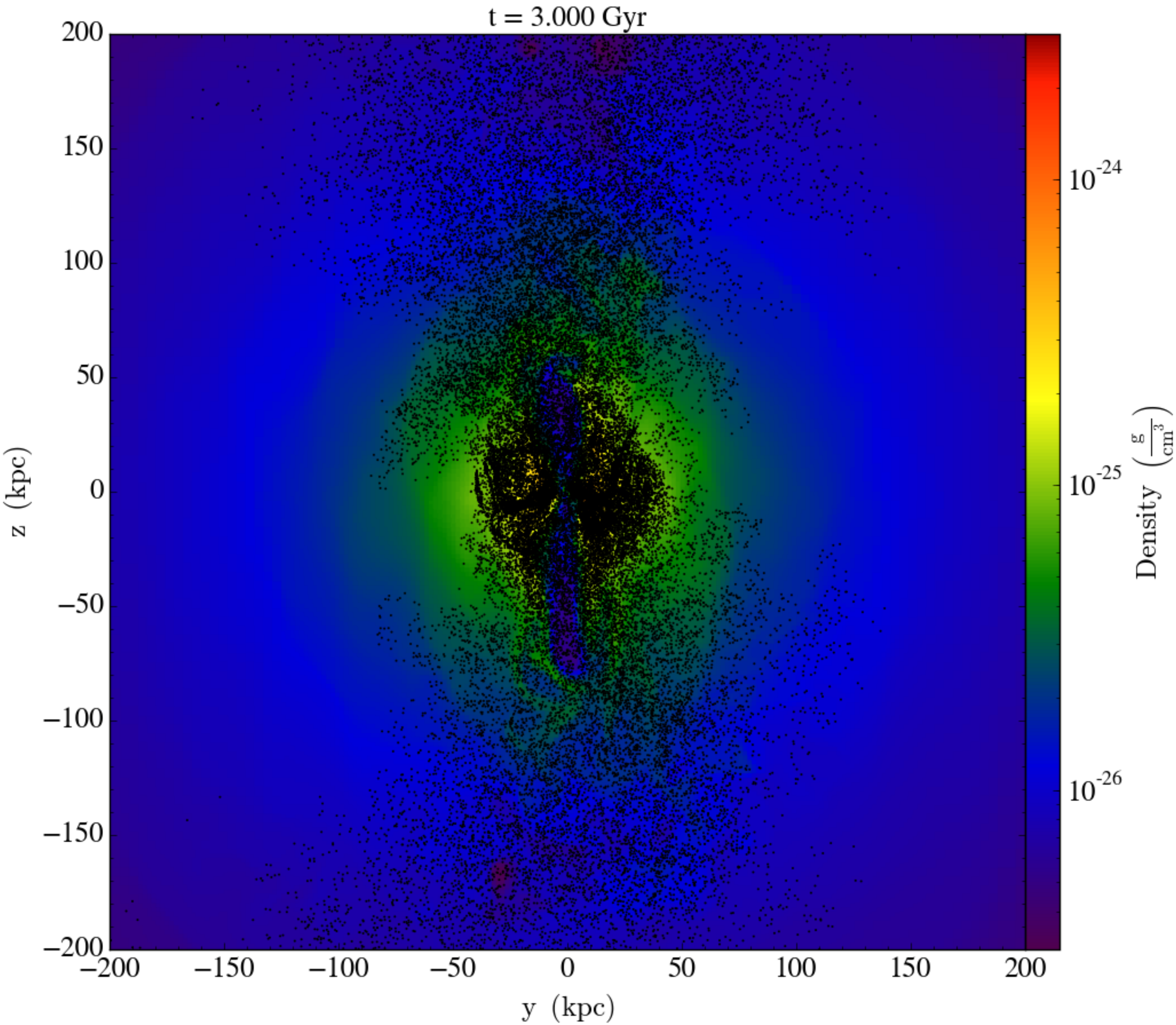
Goal – Gain insights from hydro simulations of self-regulated AGN feedback!


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)

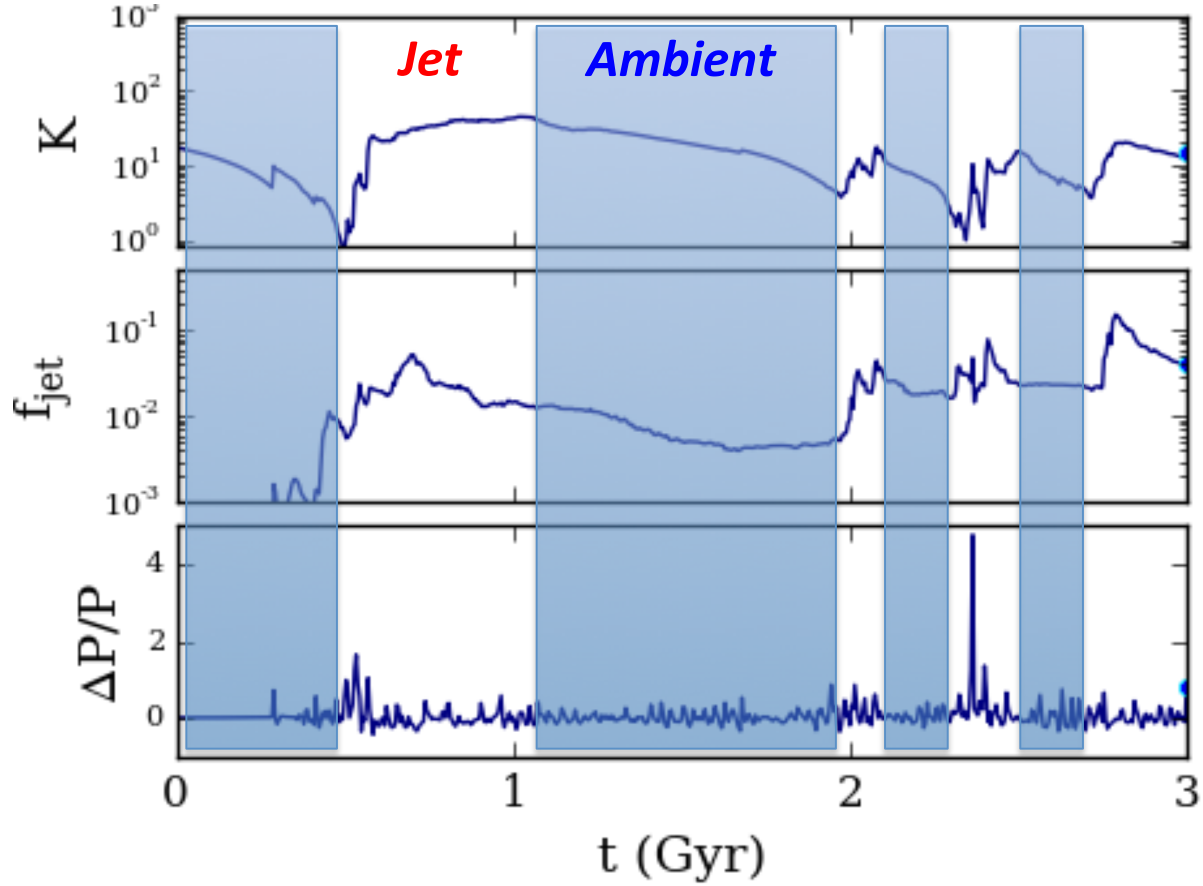


t = 3.000 Gyr
200
150
100
50
0
−50
−100
−150
−200
z (kpc)
−200
−150
−100
−50
0
50
100
150
200
y (kpc)
10^{-24}
10^{-25}
10^{-26}
Density $\left(\frac{g}{cm^3}\right)$

Passive tracers –
the Lagrangian view

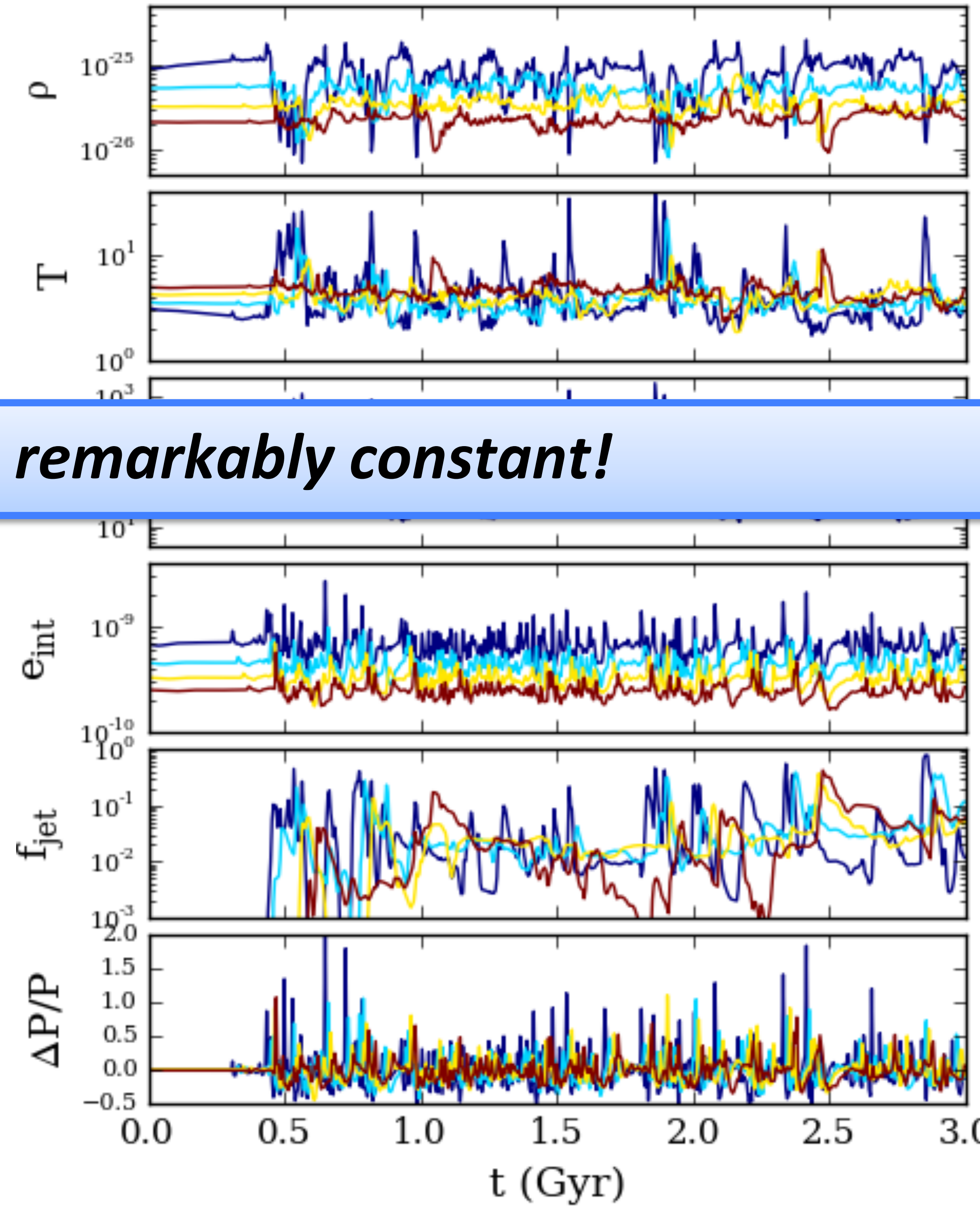
$$K \equiv \frac{T}{n_e^{2/3}}$$

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

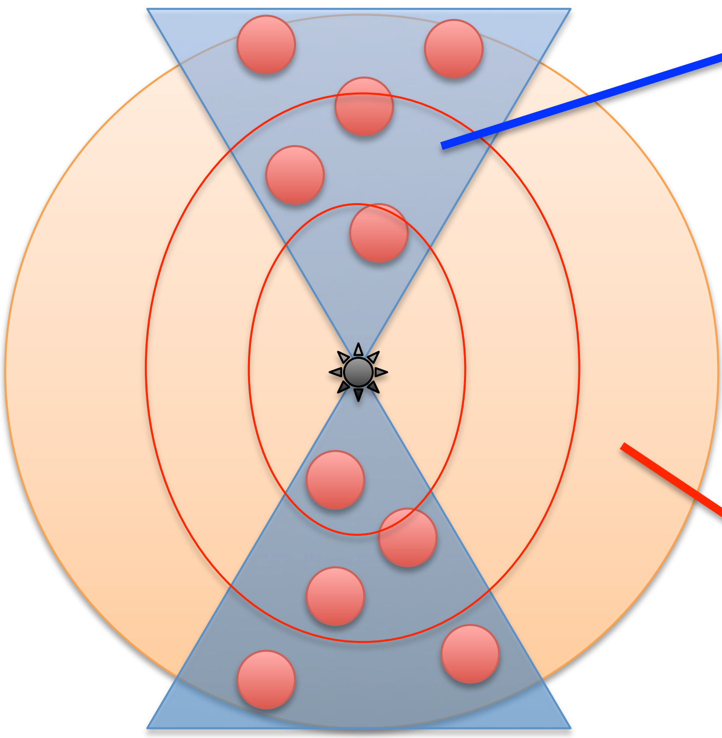


- ***Heating done by bubble mixing and shocks***
- ***Mixing more efficient, but shocks more frequent***
- ***Net cooling in amb. region; net heating in jet cones***

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

Transport by advection or convection

Adiabatic compression or expansion

Heating and Cooling

≈ 0

Transport & adiabatic processes important!!

$\neq 0$

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

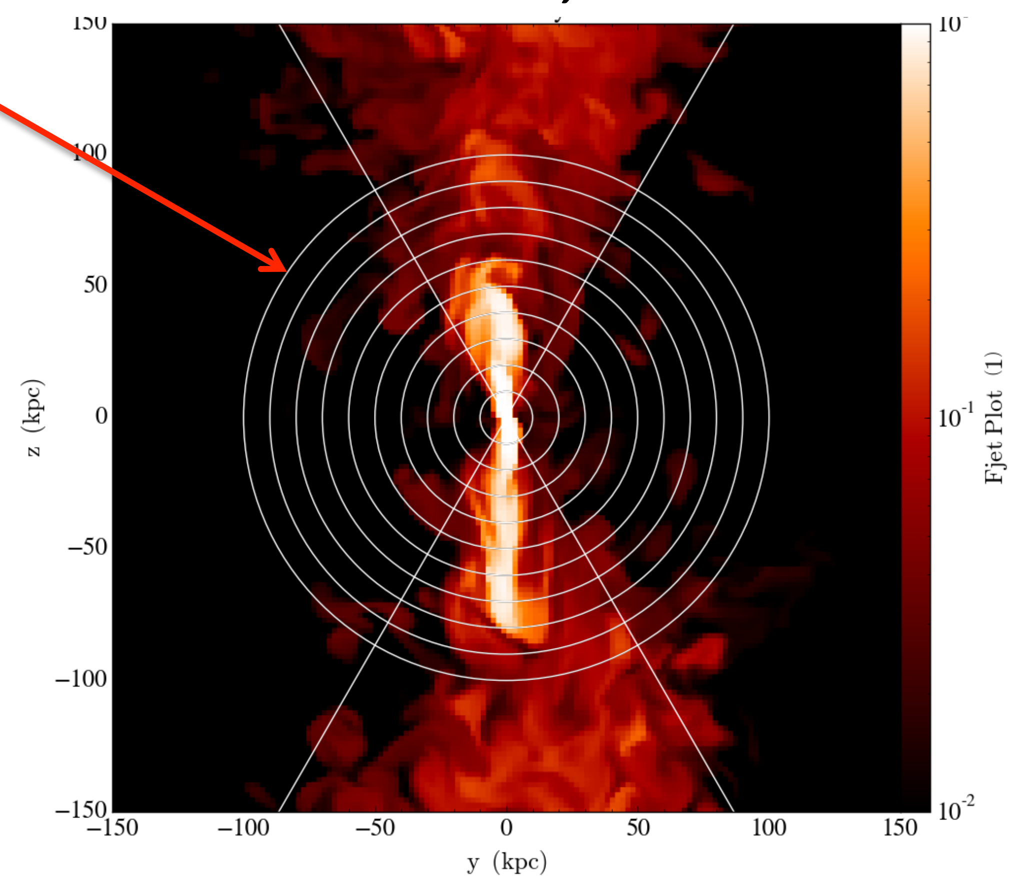
$$\alpha \in \{transport, adiabatic, mixing, shocks, cooling\}$$

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

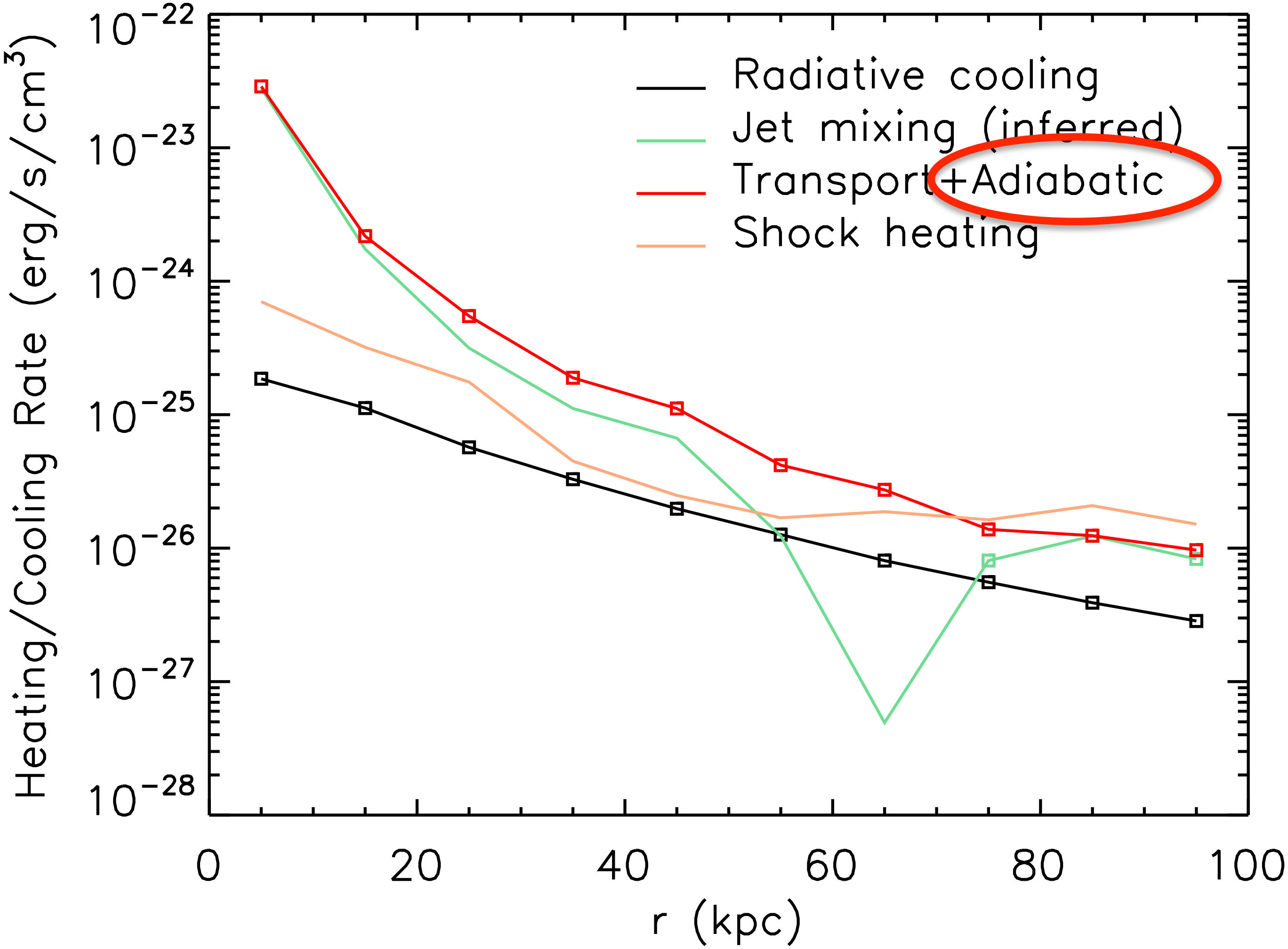
$$\Rightarrow < \varepsilon_{\alpha,i} >_t$$

20 sectors:

Cones vs. Ambient, 10 radial bins



H/C processes – Jet cones



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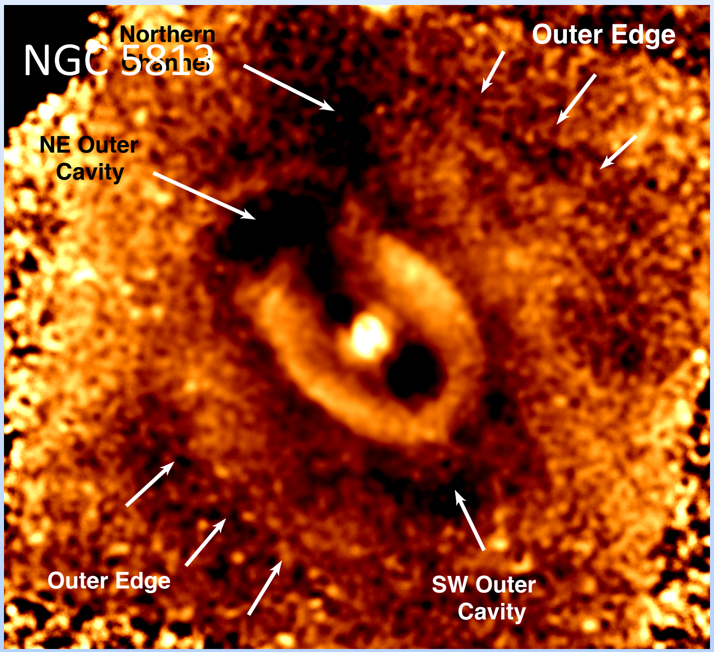

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AND

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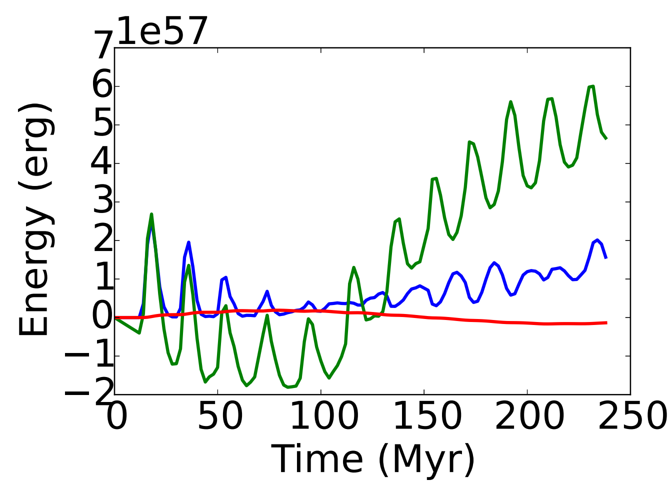
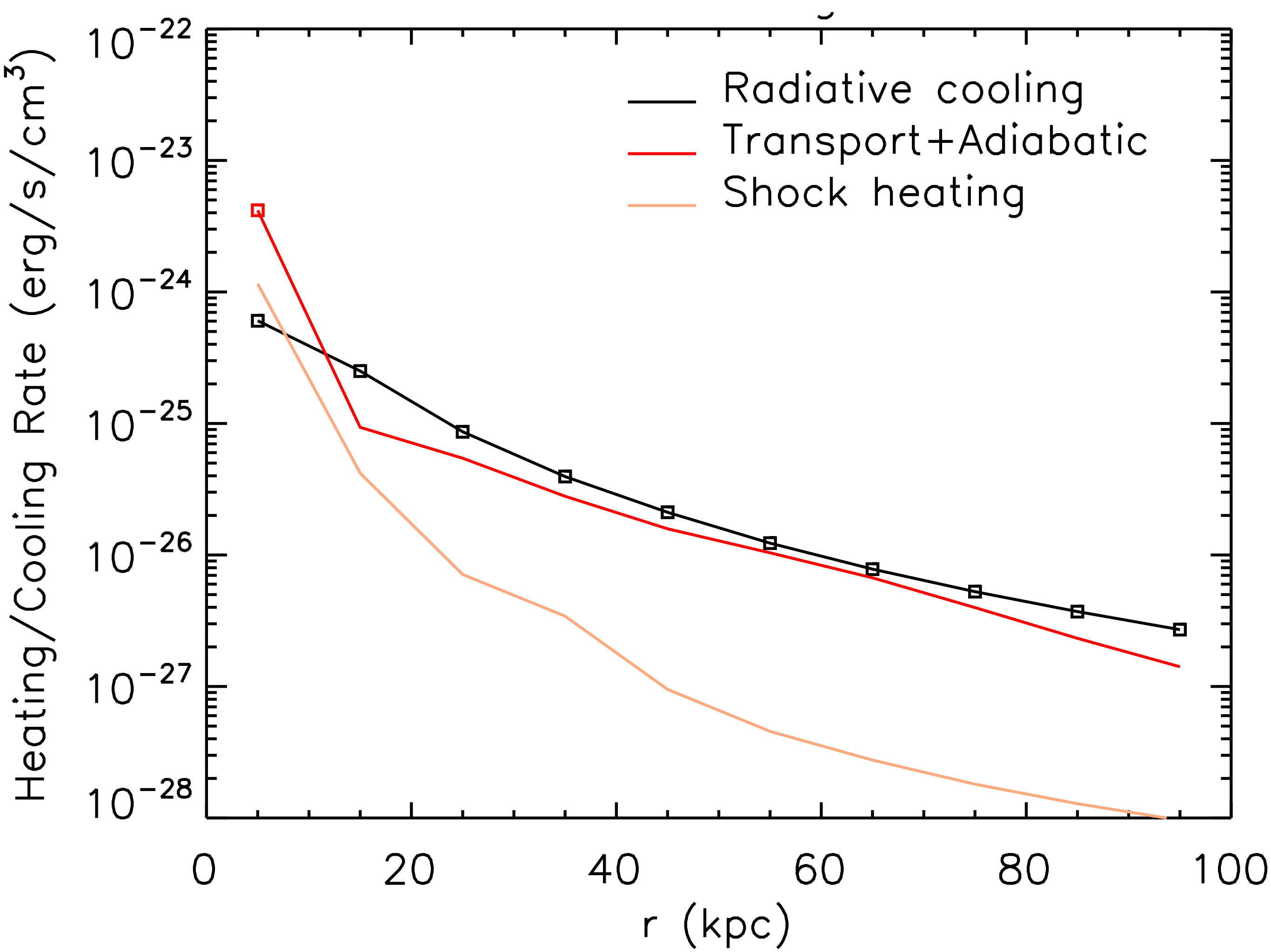


H/C processes – Ambient region



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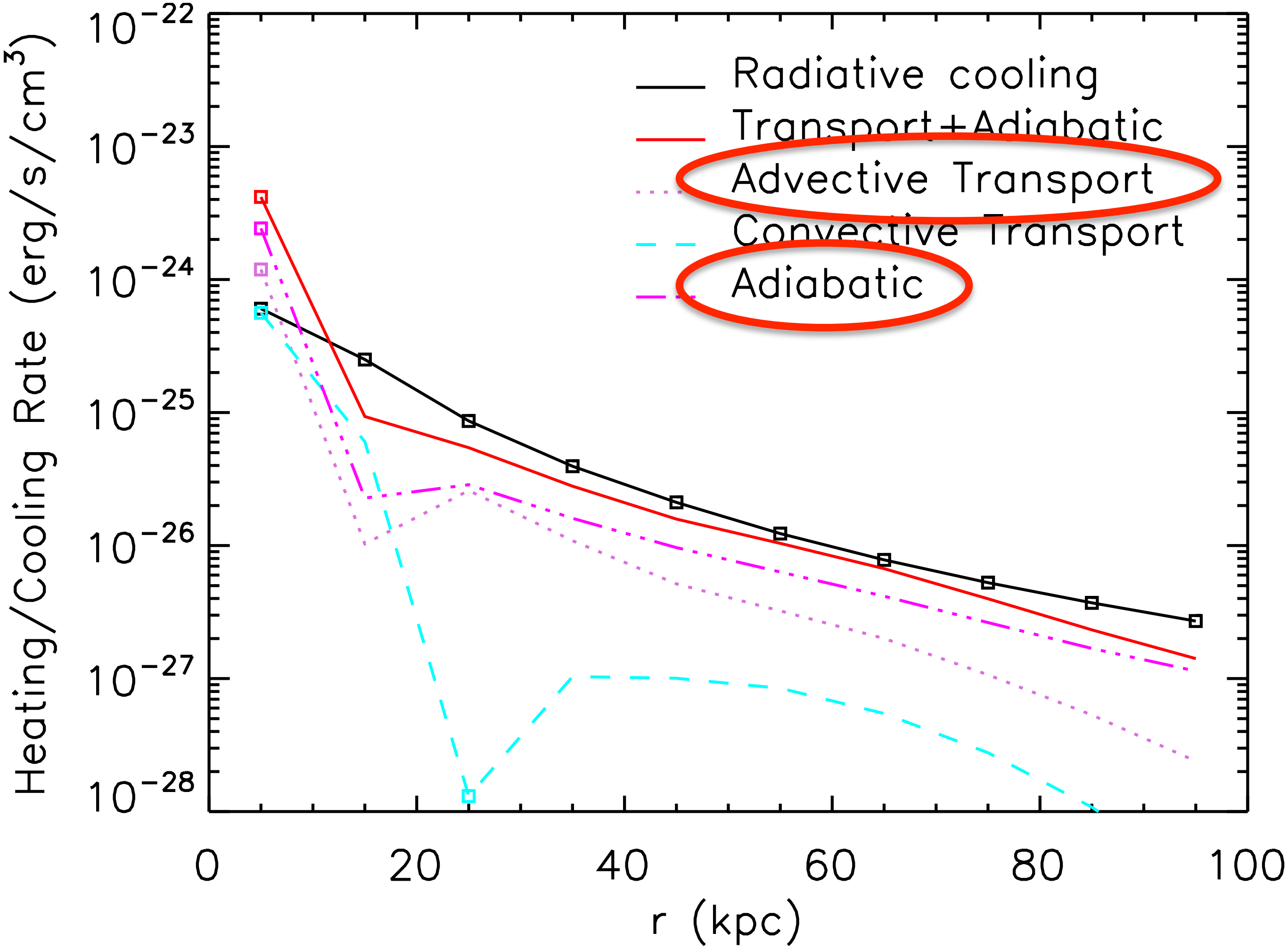
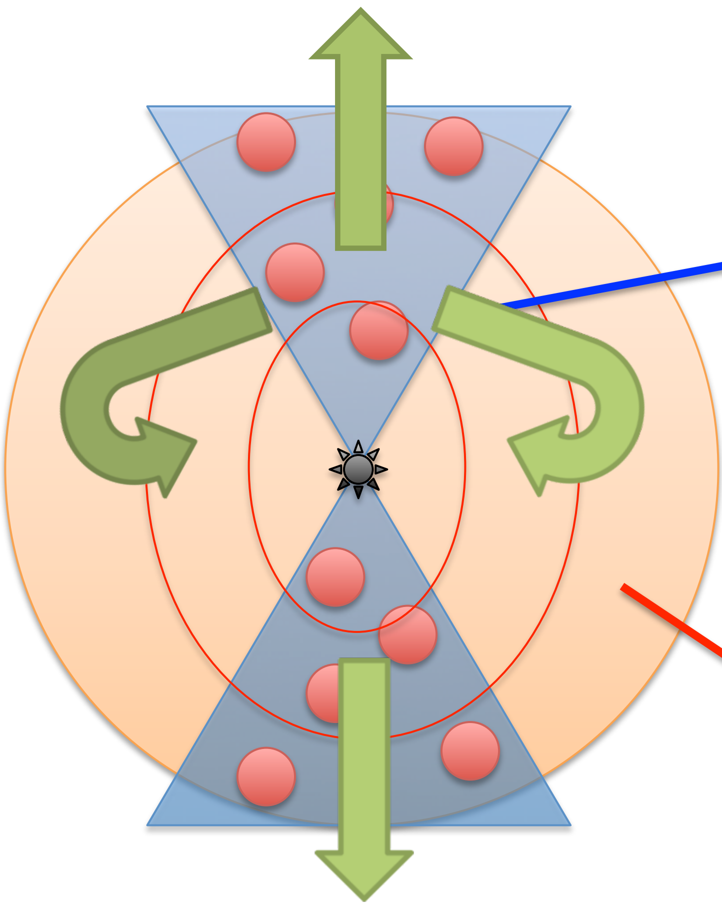


A model of ``gentle circulation”



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”

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 heatin