AGN Feedback and Cooling Flows: The failure of simple hydrodynamic models

Unjournal Club

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Outline

- Introduction
- Code
- Model
- Cooling
- Different types of feedback
- Problems
- Other ways out
- Conclusion

ICM

- The Intracluster Medium (ICM) in rich relaxed clusters is cooling.
- Most of the baryonic mass of the cluster is in ICM (most of the mass is in the dark matter).
- Cools through thermal bremsstrahlung (proportional to n^2).

Cool gas?

- But where is this cool gas?
- Gas is not seen below about $\sim \frac{1}{3} T_{virial}$.
- No reservoirs of cool gas.
  - No enhanced star formation or giant clouds.
  - Elliptical galaxies in cluster centers are not still forming.

Galaxy Formation

- So really, we are not just talking about cluster gas.
- This is also a problem of why do massive galaxies have a maximum size.

Cooling Flow

- This is the Cooling Flow problem.
- Occurs over wide range of cluster masses and temperature.
- Therefore, any solution must has some form of self regulation.

AGN

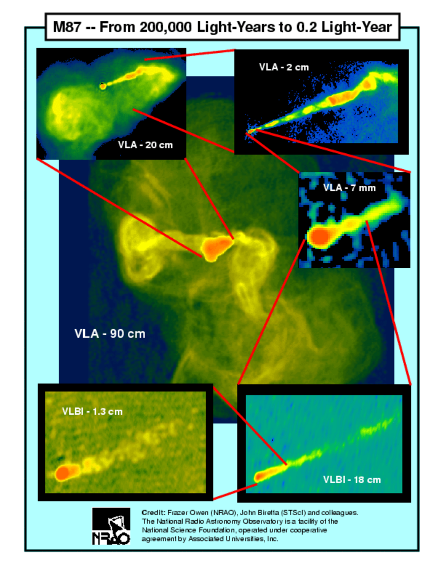
- AGN are an attractive solution.
- Their energy injection is on the same order of the cooling luminosity ($\sim 10^{45} - 10^{46}$ erg s^{-1}).
- Occur in the center of central elliptical galaxy.
  - Right where heating is needed.
- Fed by accretion of gas, so regulation may come naturally.
- Lots of signs of interaction between AGN and gas.

Interactions

- Ghost bubbles
- Ripples
- Shells
- Filaments

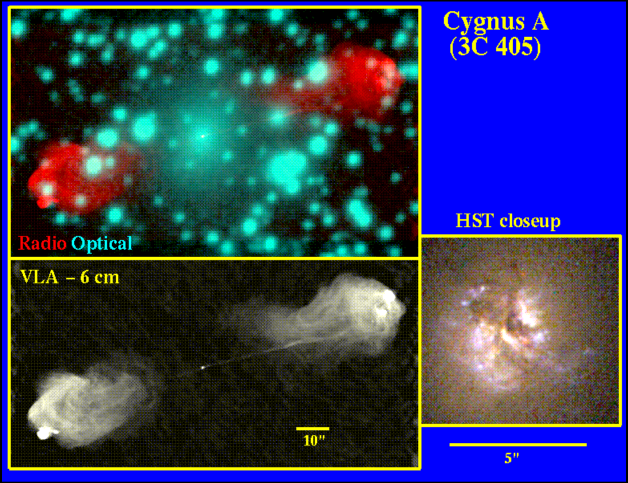
First some real objects:

M87 in Virgo



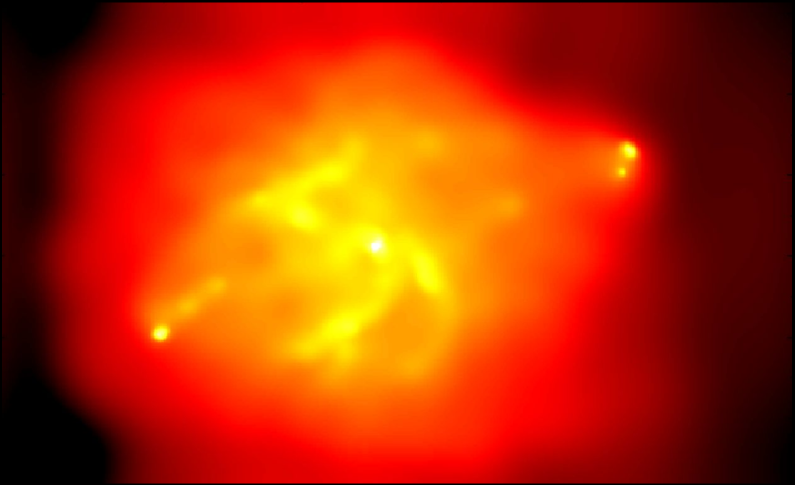
M87 -- From 200,000 Light-Years to 0.2 Light-Year
VLA - 2 cm
VLA - 20 cm
VLA - 7 mm
VLA - 90 cm
VLBI - 1.3 cm
VLBI - 18 cm
Credit: Frazer Owen (NRAO), John Biretta (STScI) and colleagues.
The National Radio Astronomy Observatory is a facility of the
National Science Foundation, operated under cooperative
agreement by Associated Universities, Inc.

Cygnus A



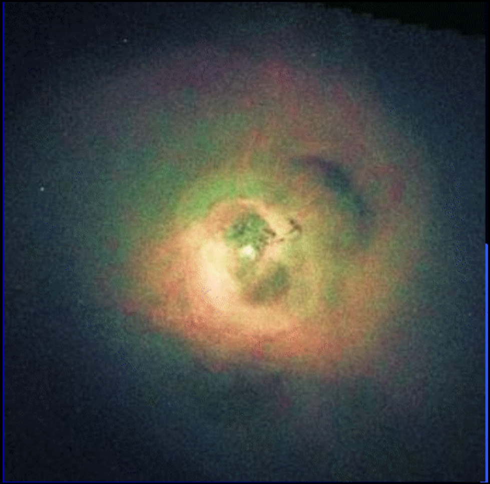
taken from http://www.astr.ua.edu/keel/agn/

Cygnus A in X-Ray



Chandra image from Wilson et al.

Core Region of Perseus Cluster



Perseus cluster Chandra X-ray Observatory (Fabian et al. 2003).

ZEUS-MP

- Parallel version of the Zeus code (Stone and Norman 1992a and b).
- Modified from NCSA version.
- Publicly available.
- http://www.astro.umd.edu/~vernaleo/zeusmp.html

Code Continued

- Fully (only) 3D.
- Eulerian Fixed Grid.
- Covariant formalism.
- 2nd order upwind scheme.
- Solves standard equations of (magneto) hydrodynamics.
- Primarily used on local Beowulf cluster (the Borg), but also tested on GNU/Linux workstations and OS X laptop.

Cluster Setup

- Spherical Polar Grid.
- $200 \times 200 \times 100$
- Enhanced resolution near center and near jet axis.
- Spherically Symmetric.
- Initially Isothermal.

β-Model Atmosphere

$$\rho(r) = \frac{1}{[1 + (\frac{r}{r_0})^2]^{3/4}}$$

and

$$r_{core} = 100 kpc$$

Cooling

Thermal bremsstrahlung for cluster gas:

$$\Lambda = [C_1(k_B T)^\alpha + C_2(k_B T)^\beta + C_3] 0.704 \left(\frac{\rho}{m_p}\right)^2 \times 10^{-22} \text{ ergs cm}^{-3} s^{-1}$$

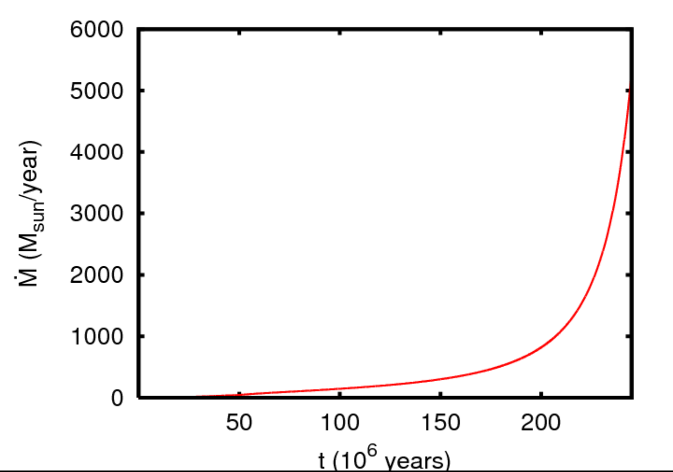
with $C_1 = 8.6 \times 10^{-3}$, $C_2 = 5.8 \times 10^{-2}$, $C_3 = 6.4 \times 10^{-2}$, $\alpha = -1.7$, and $\beta = 0.5$.

This is the same cooling function from Ruszkowski and Begelman 2002.

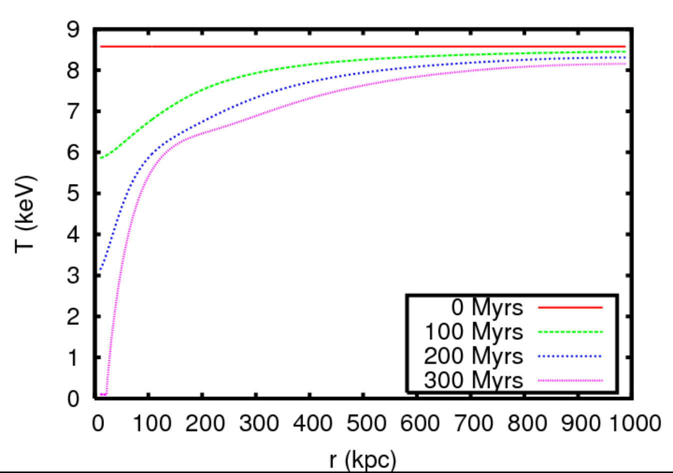
Pure Cooling

- As a reference case, a cluster simulation with cooling but no AGN was run.
- Mass accretion across inner boundary of the simulation was calculated as diagnostic of cooling flow.

Mass accretion



Radial Temperature Dependence



Cooling Catastrophe

- As expected, with nothing to stop it, cooling runs away to unrealistic (i.e., detectable) levels.
- Happens in around 250 Myrs.
- Thanks to n^2 cooling law, it gets quicker and eventually runs away.

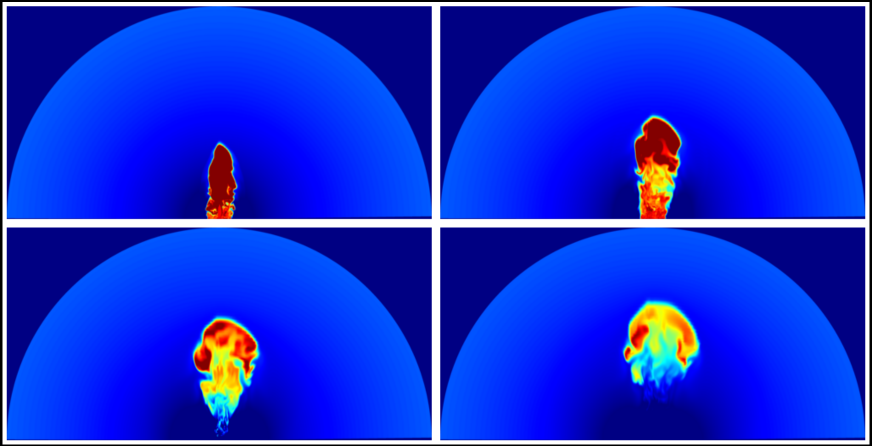
Feedback types

- Single Jet
- Instantaneous Feedback
- Delayed Feedback
- Feedback and Rotation

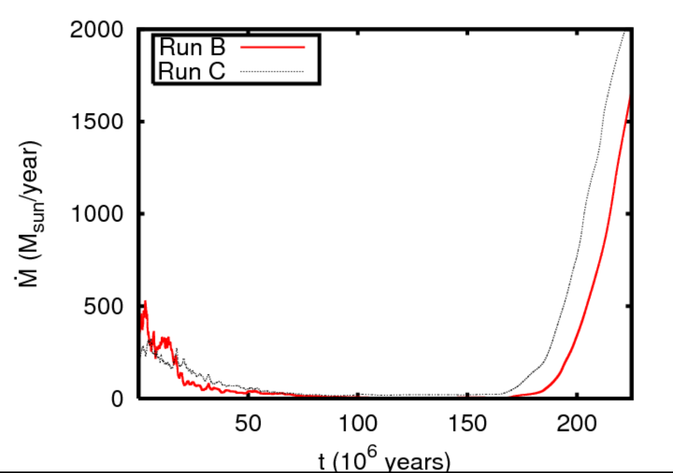
Single Jet

- Jet is low density material injected at a small opening angle at inner edge of grid.
- Jet Kinetic Luminosity of 9.8×10^{45} erg s^{-1}.
- Jet is active for 100 Myrs.

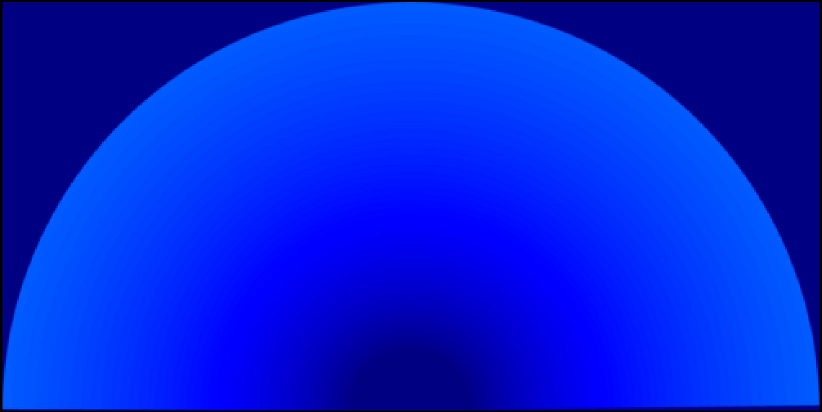
Single Jet Images



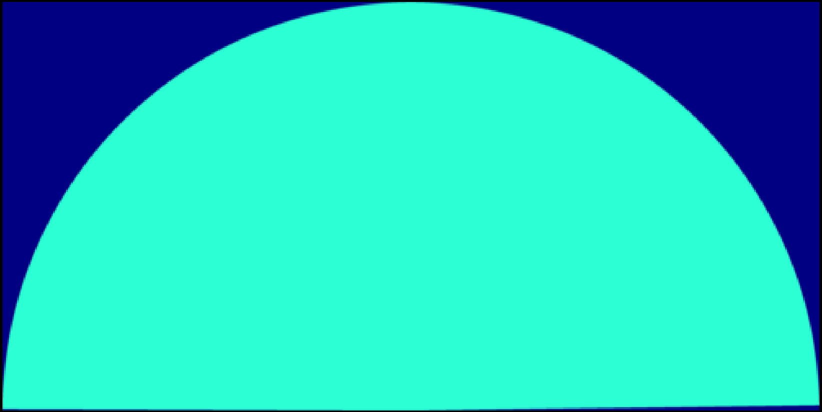
Delayed but not stopped



Single Jet Entropy



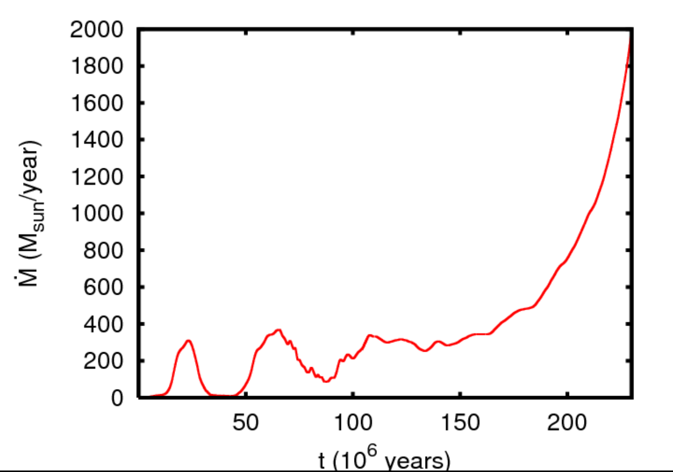
Single Jet Temperature



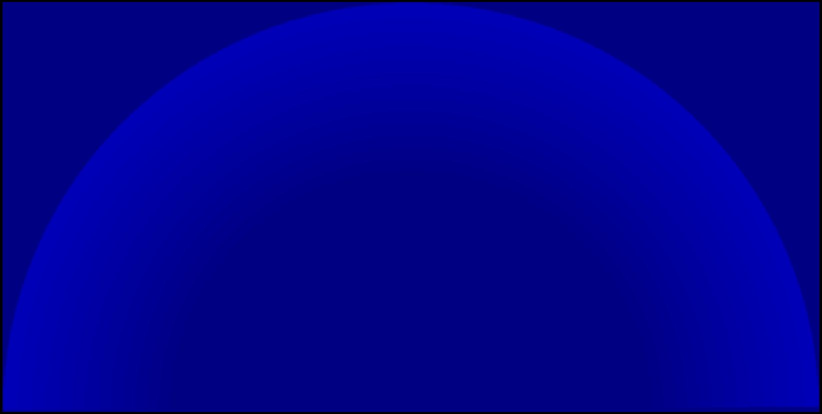
Feedback

- To simulate the supermassive blackhole, we take the $\dot{M}$ from the inner boundary and assume it is converted into energy which goes into powering a jet.
- $v_{jet} = \left(\frac{2\eta \dot{M} c^2}{A\rho}\right)^{\frac{1}{3}}$
- Realistically, there are lots of places where we lose efficiency, so we should be significantly below the theoretical max of $\eta = 0.1$.
- Most runs done with $\eta = 0.0001$ or 0.00001.

Instantaneous Feedback



Instantaneous Feedback Entropy zoomed



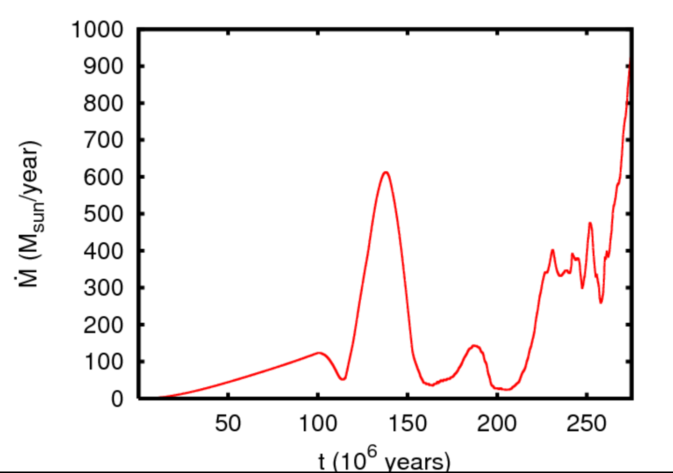
Delayed Feedback

- Accretion takes time.
- Tried a delay of 10 Myrs which is roughly the sound crossing time of the core.
- Also did a delay of 100 Myrs which is closer to the dynamical time for the central galaxy and physically seems plausible.

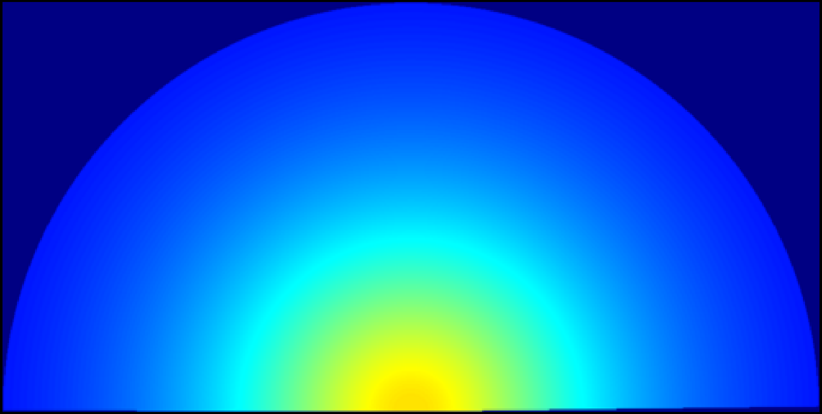
Delayed Feedback Results

- Short delay does basically no better than immediate feedback.
- Long delay can holds off cooling catastrophe until 285 Myrs (about 40 Myrs better than no jet at all).
- In both cases, lower efficiency does slightly better.

Delayed Feedback Mdot



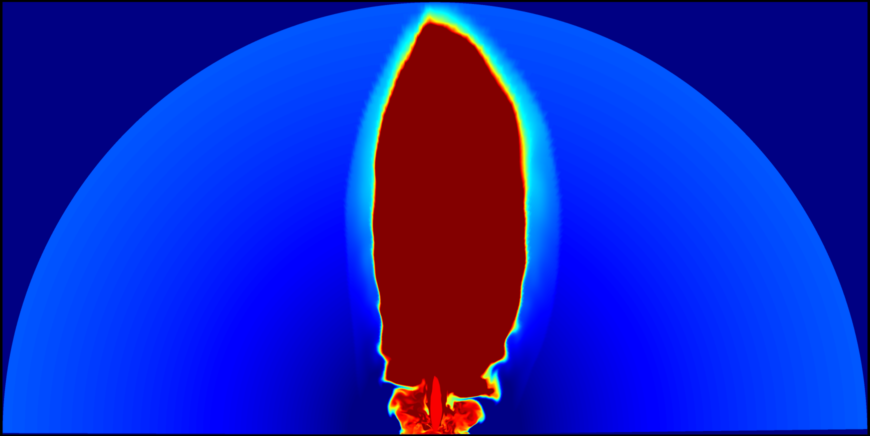
Delayed Feedback Density zoomed



Extreme Cases

- Just for completeness we did delayed feedback with $\eta = 0.1$ and 0.01.
- These both imply perfect or near perfect accretion and don't make much sense physically.
- And they don't really work.
- They can delay catastrophic cooling for 100 Myrs or so, but eventually fail.
- And they don't produce realistic looking structures.

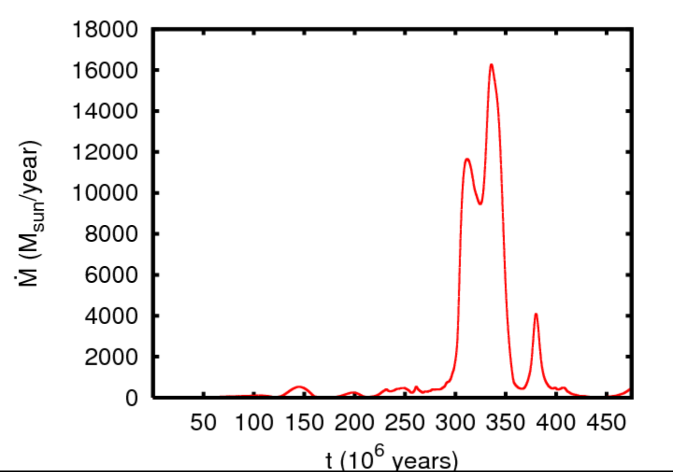
Extreme



Rotation

- What if the cluster is not static?
- We tried setting up some rotation in the cluster.
- Keeping the outer parts rotating slower than the sound speed forces many types to rotate too slowly in the center to change things.
- A partially rotationally supported cluster was the most interesting.

Rotation Mdot



Galactic Disk

- After a short but massive inflow, accretion mostly halts.
- So if this the solution?

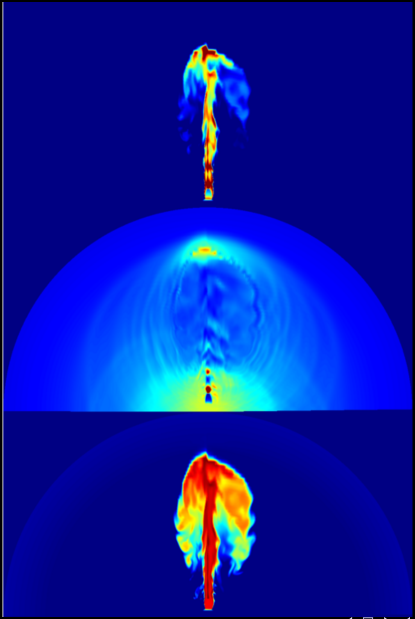
Galactic Disk pt. 2

- This hasn't done exactly what it looks like.
- Low angular momentum material has accreted.
- The rest is cannot accrete.
- Instead it forms a dense, thin cool disk around the center.
- So instead of stopping accretion, we have moved it (and the AGN has little to do with it).

Problems

- Why can we delay but not stop cooling?
- Why do we not get the nice recurring AGN bursts we expected?
- And some recent observational work by Bîrzan, et al. 2004 casts some doubt on AGN having enough power to completely balance cooling anyway.

Channels and Deposition



Bubbles

- Lots of other authors (including us) have done better with bubbles.
- But we have shown bubbles cannot capture the behavior of jet inflated bubbles.
- Must include dynamics of jet if we want a trustworthy solution.

Parameter Space

- Is there a solution hiding somewhere else in our parameter space?
- These are long simulations, and there are lots of things to vary.
- But it doesn't matter.
- This needs to work on cluster of many different masses, so a fine tuned solution is not much better than no solution.

Ways Out

- Thermal Conduction may help.
  - Outer region of cluster is a huge reservoirs of heat.
  - May help distribute energy from AGN.
  - Magnetic fields can complicate this picture.
  - We are currently working on this.
- Viscosity can help dissipate heat, but it is also suppressed by magnetic fields.
- Mergers, dynamical friction, etc.
  - Probably do more in the outer regions where we don't really need the heating.
- Cosmic Rays
  - Not too easy to both heat and not conflict with observations.

Conclusion

We have done high resolution, three dimensional hydrodynamical simulations of jets in cooling flow cluster. We find that when the full dynamics of the jet are included, hydrodynamic jets do not offset cooling, even though they are energetically capable of doing so.