

AGN Feedback, Cooling Flows, and Cosmic Rays in Galaxy Clusters

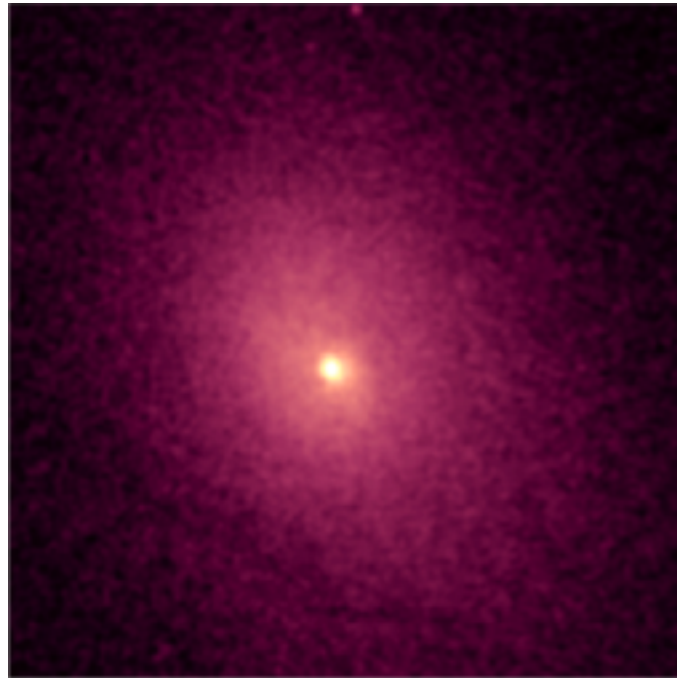
Fulai Guo

(UC Santa Cruz)

Collaborators: William G Mathews (UCSC)
S. Peng Oh (UCSB)

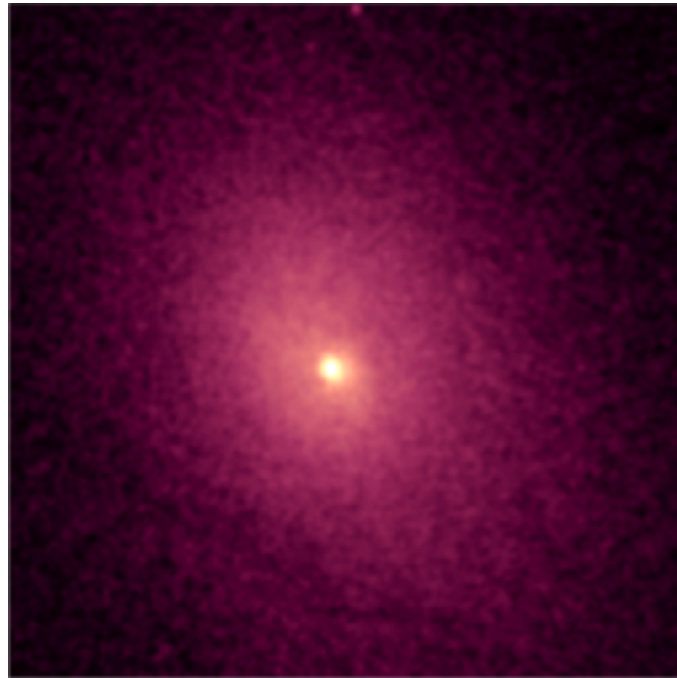
the 2nd ICM theory/computation workshop, Ann Arbor, 08/30/2012

(1) Why is AGN feedback important in galaxy clusters?



Abell 2029; X-ray image

(1) ~~Why~~ Is AGN feedback important in galaxy clusters?

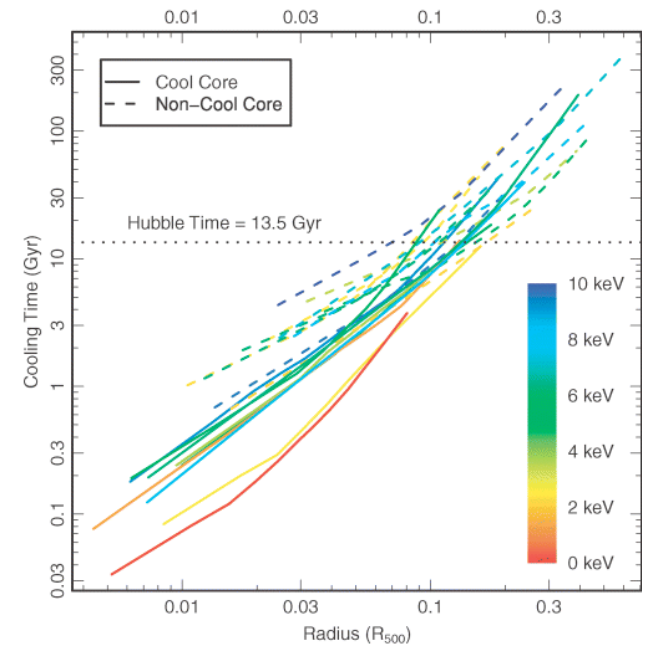


Abell 2029; X-ray image

(1) Is AGN feedback important in galaxy clusters?

Theoretically, an ideal candidate to solve the cooling flow problem

Cooling time



Radius (R_{500})

Sanderson et al. 2006

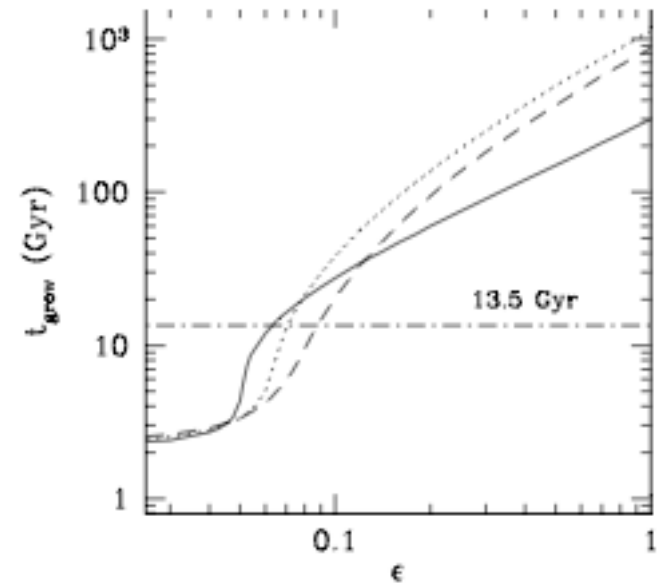
(1) Is AGN feedback important in galaxy clusters?

Theoretically, an ideal candidate to solve the cooling flow problem

The feedback mechanism is the key to stably maintain clusters in the cool core state

$$\underline{L_{\text{agn}} = -\epsilon \dot{M}_{\text{in}} c^2}$$

Instability growth time



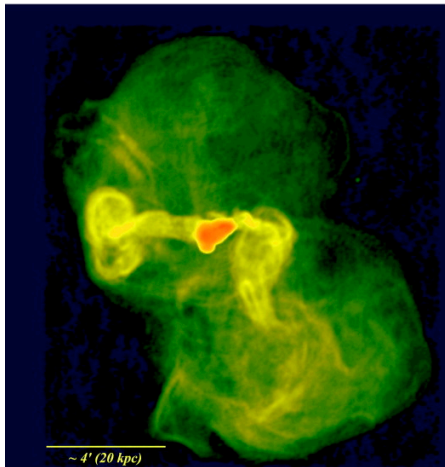
Feedback efficiency

Guo, Oh & Ruszkowski 2008

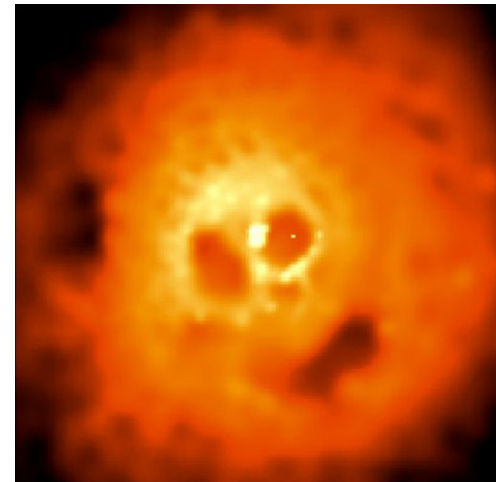
(1) Is AGN feedback important in galaxy clusters?

Theoretically, an ideal candidate to solve the cooling flow problem

Observationally, AGN feedback events have been detected in many clusters in radio and X-ray

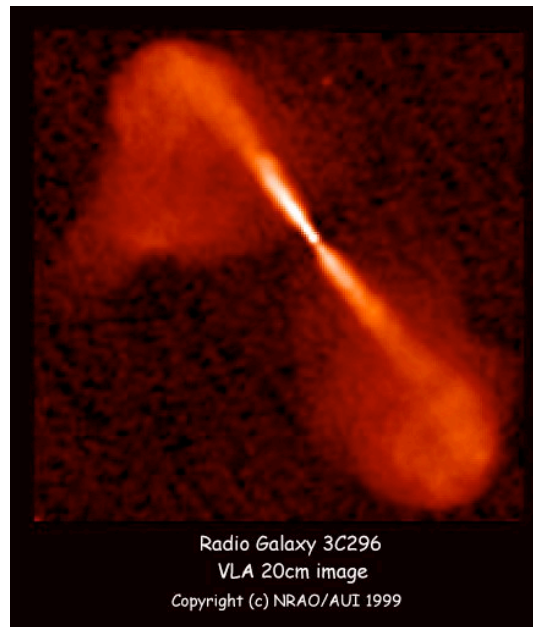


M87 at 90 cm (Owen et al 2000)



Chandra image of Perseus Cluster

(2) How are AGN feedback events triggered?



20 cm radio image of 3C296
(Image courtesy of NRAO/AUI)

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Hot mode versus cold mode

Both hot gas and cold gas are present in many cool cores of galaxy clusters

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To complete the feedback loop, AGN feedback should be triggered while hot gas cools.

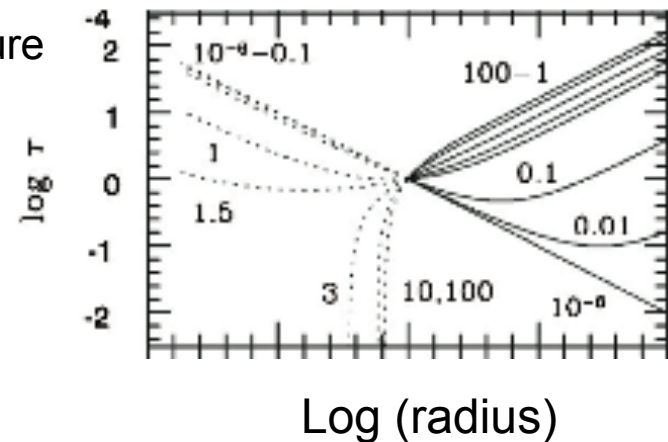
(2) How are AGN feedback events triggered?

Hot mode vs cold mode

The flow fate is determined by a dimensionless parameter a , evaluated at the sonic point:

$$a = 0.1008 \frac{(\dot{M}/M_{\odot} \text{ yr}^{-1})(\Lambda/10^{-23} \text{ erg cm}^3 \text{ s}^{-1})}{(T_s/10^7 \text{ K})(M/10^9 M_{\odot})},$$

Temperature



Mathews & Guo (2012)

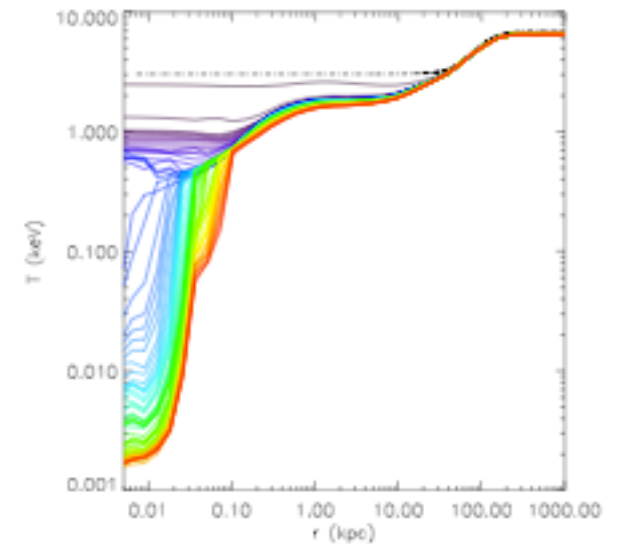
(2) How are AGN feedback events triggered?

Hot mode vs cold mode

Quataert & Narayan (2000) argued that hot mode accretion dominates in galaxy clusters such as Virgo

Li & Bryan (2012) shows with 3D simulations that hot gas cools off before accreted by black holes

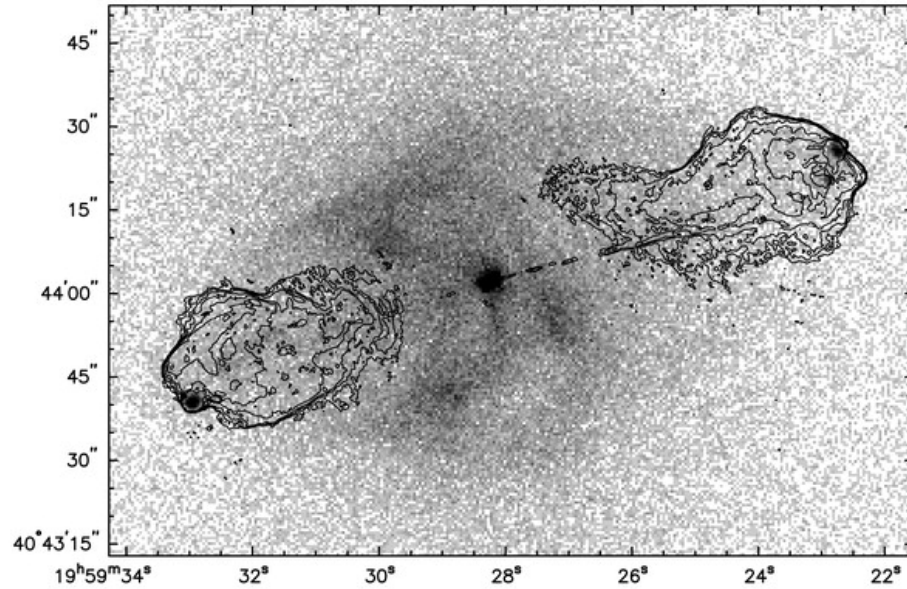
Temperature



radius

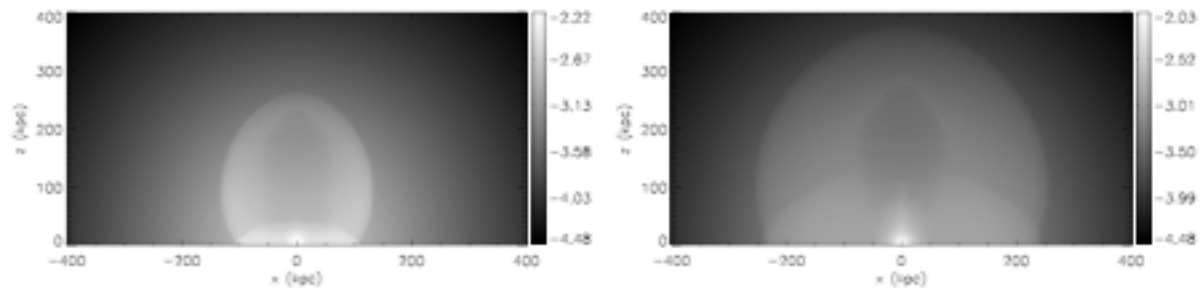
Li & Bryan (2012)

(3) How does AGN feedback heat hot gas?



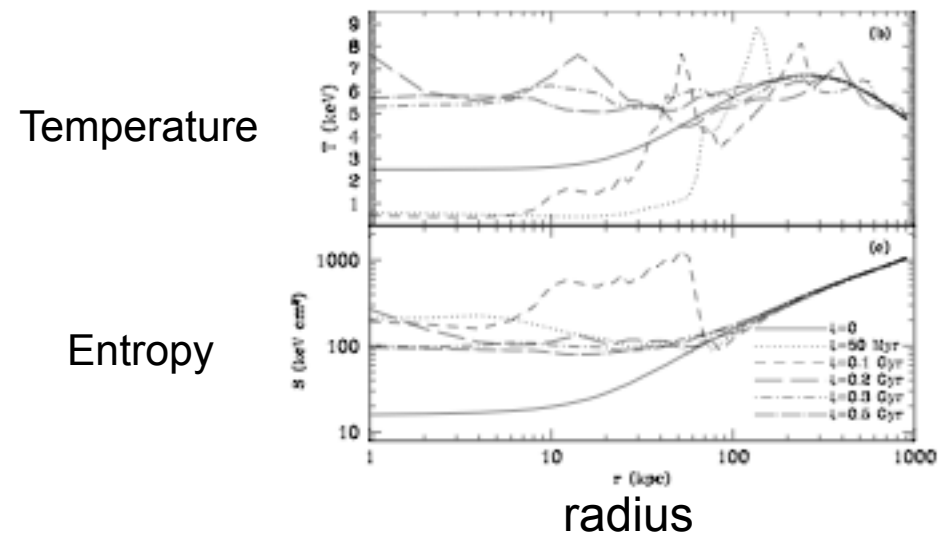
Cygnus A; 6 cm contours in X-ray image,
Wilson et al 2006

(3) How does AGN feedback heat hot gas?



Shocks are produced by AGN feedback events (Guo & Mathews 2010a)

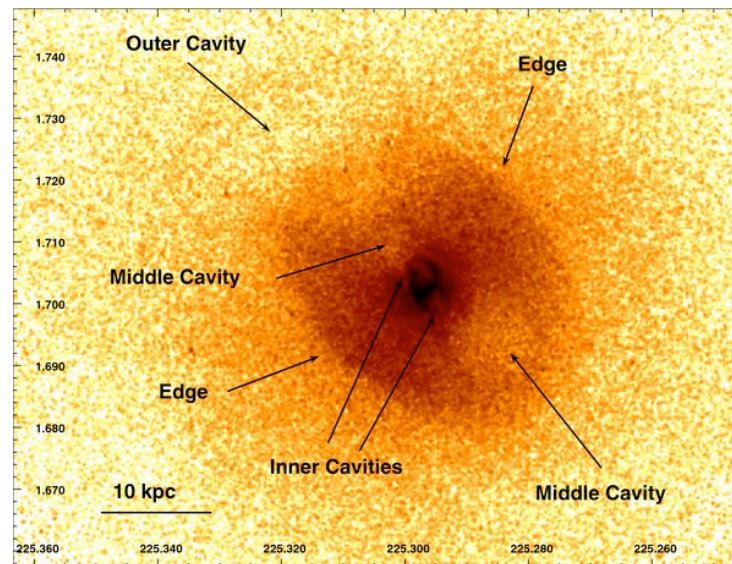
(3) How does AGN feedback heat hot gas?



For very powerful events, shocks may even destroy cool cores, producing non-cool core systems (Guo & Mathews 2010b)

(3) How does AGN feedback heat hot gas?

Shocks are also seen in deep X-ray images



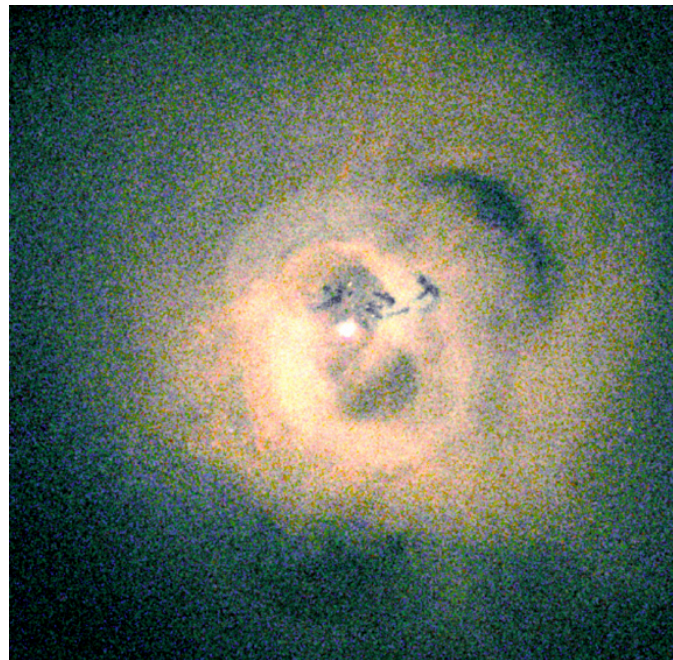
0.3-2 keV *Chandra* image of NGC 5813 (Randall+11)

(3) How does AGN feedback heat hot gas?

--- Shocks heat the hot gas

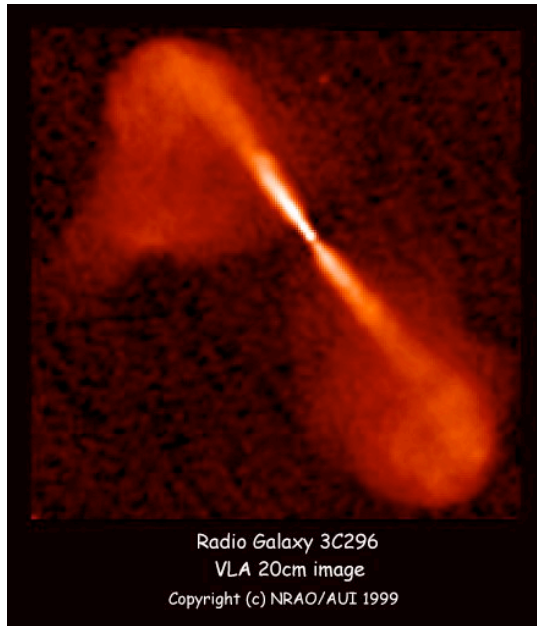
--- AGN bubbles also contain a significant amount of AGN energy, but it is unclear how much of this energy can be delivered to hot gas in cool cores

(4) What physical processes are important in AGN feedback events?

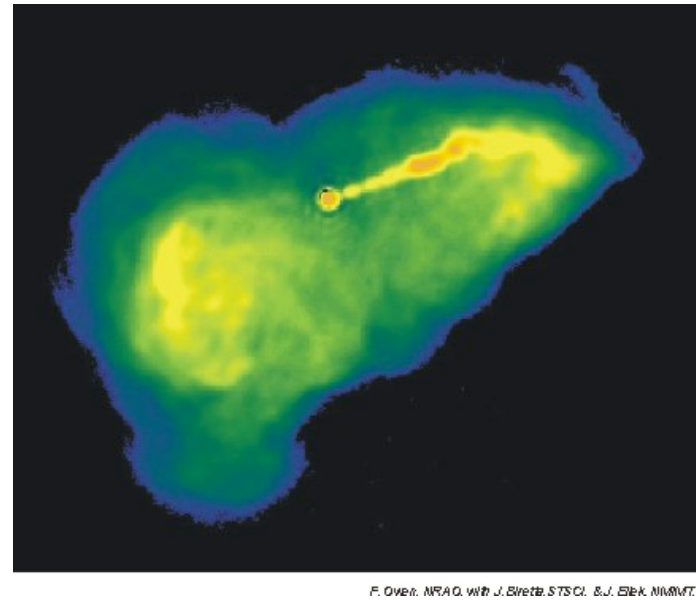


Chandra X-ray image of Perseus cluster
(Credit: NASA/CXC/IoA/A.Fabian et al.)

X-ray cavities, radio bubbles are likely produced by AGN jets



20 cm radio image of 3C296
(Image courtesy of NRAO/AUI)



M87, VLA 20 cm

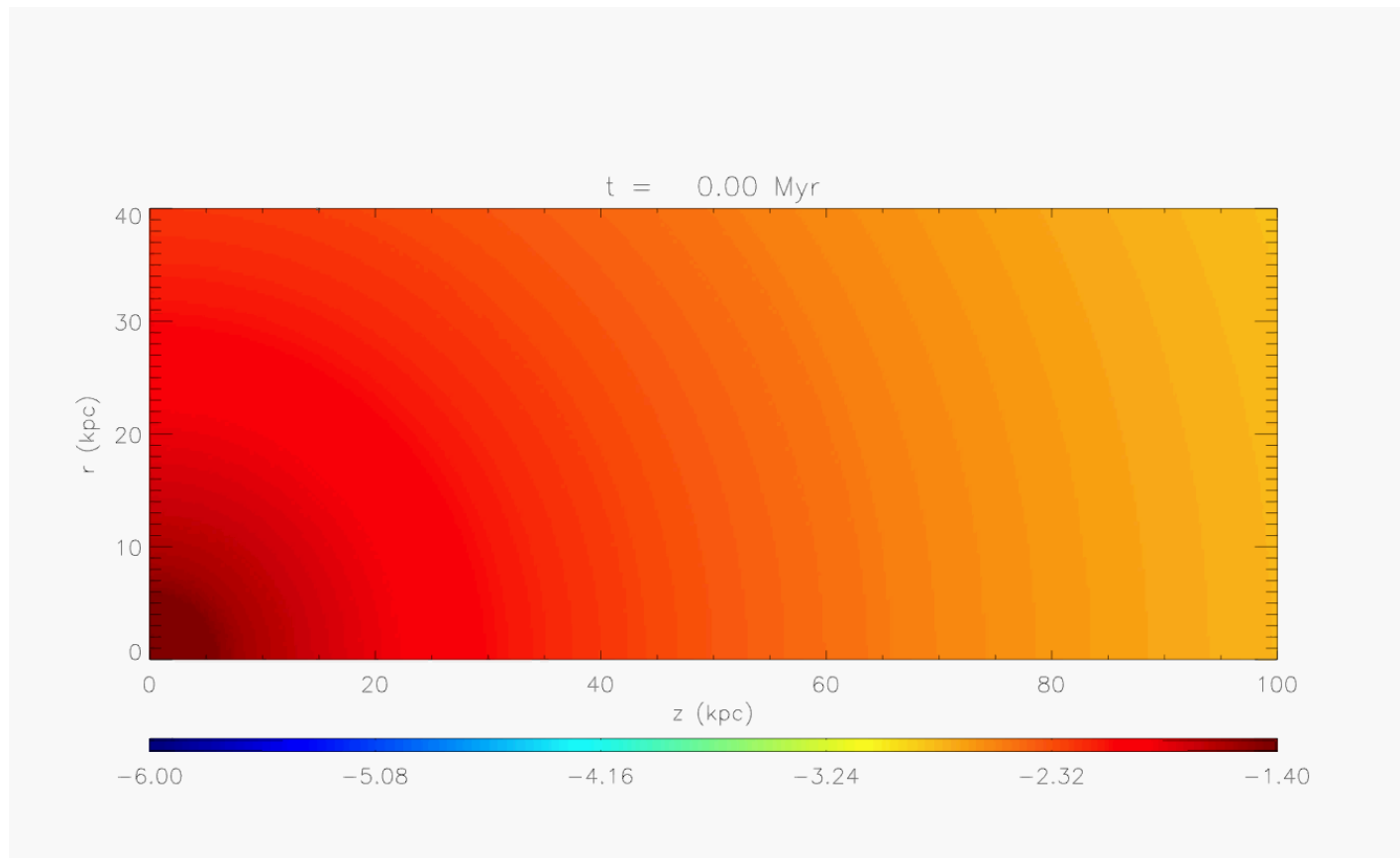
AGN jets are observed through non-thermal emissions. **Are cosmic rays and magnetic fields dynamically important in jet evolution?**



20 cm radio image of 3C296
(Image courtesy of NRAO/AUI)

It is not easy to form 'fat' bubbles by AGN jets

Thermal gas distribution (density)

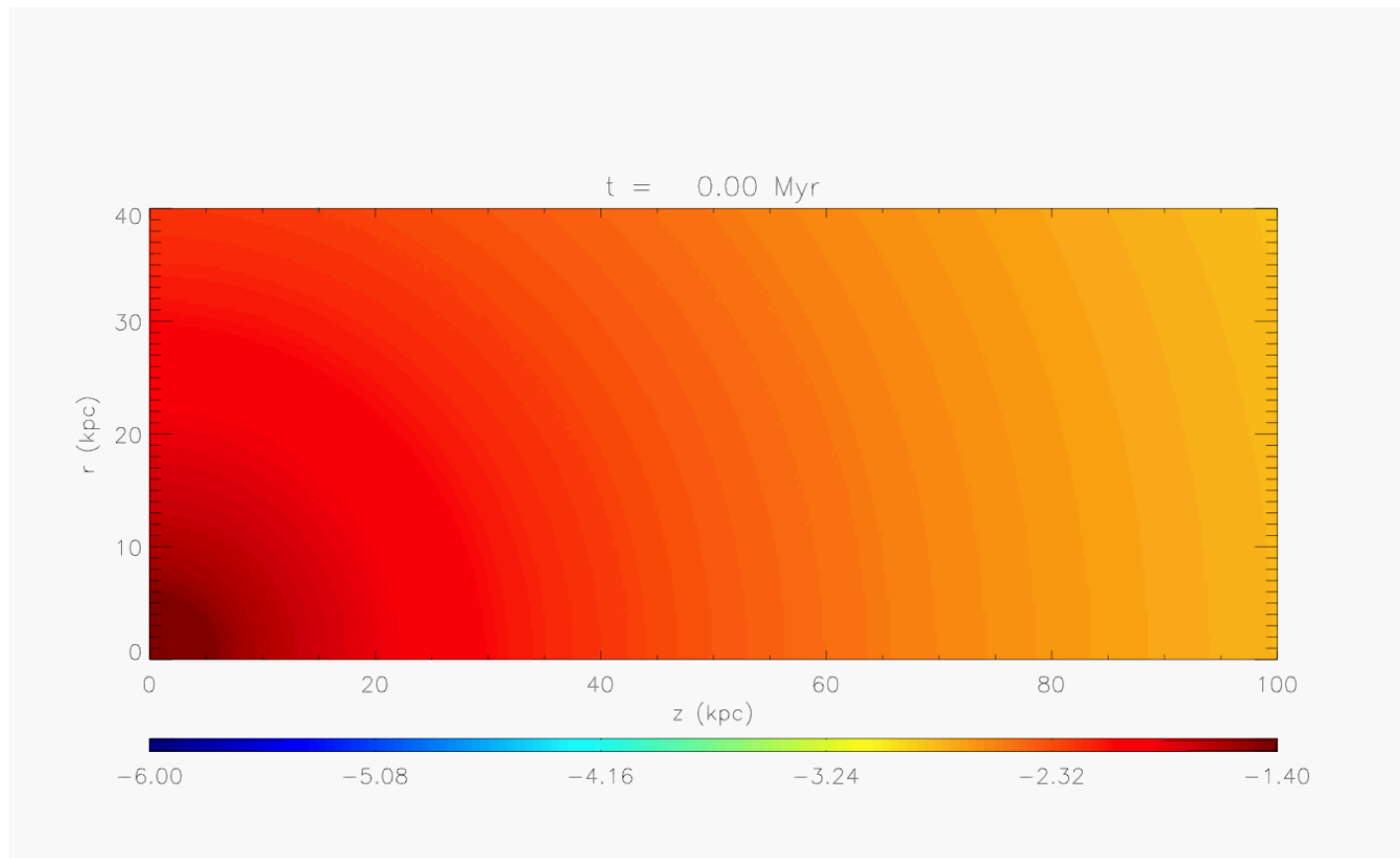


Thermal jet active for 10 Myr (the jet density contrast=0.01)

Guo & Mathews 2011

To form a fat bubble, the ratio of momentum flux to energy flux in the jet should be small.

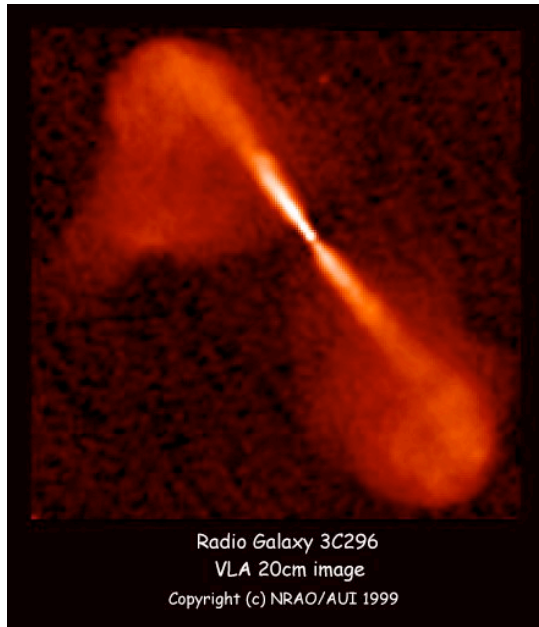
One option to fulfill this requirement is a jet energetically dominated by cosmic rays



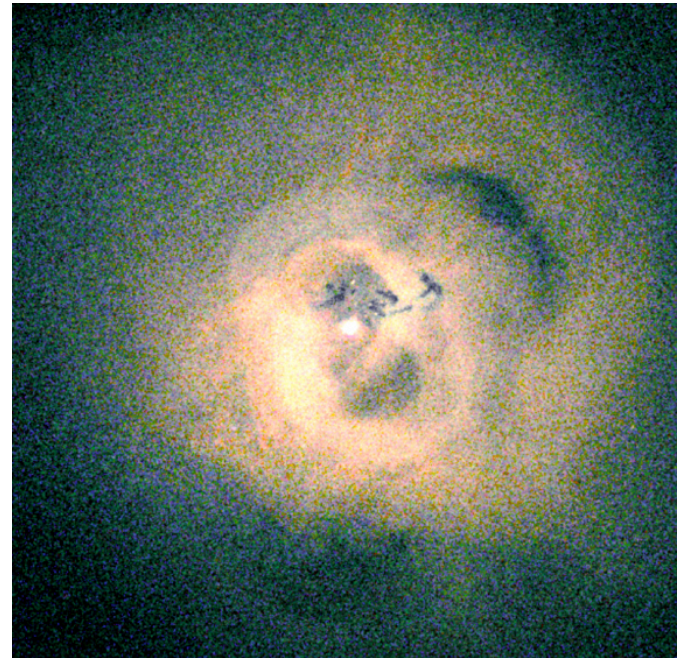
CR-dominated jet active for 10 Myr (the jet density contrast=0.0001)

Guo & Mathews 2011

To firmly determine if cosmic rays play a dynamically important role, we need to compare with observations



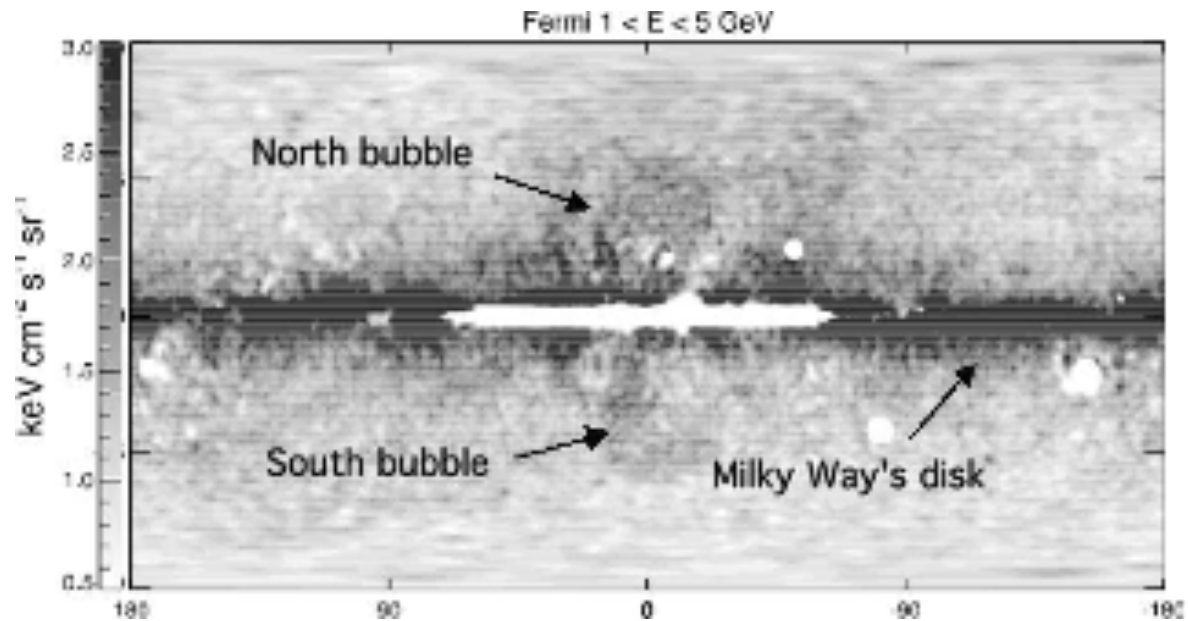
20 cm radio image of 3C296
(Image courtesy of NRAO/AUI)



Chandra X-ray image of Perseus cluster
(Credit: NASA/CXC/IoA/A.Fabian et al.)

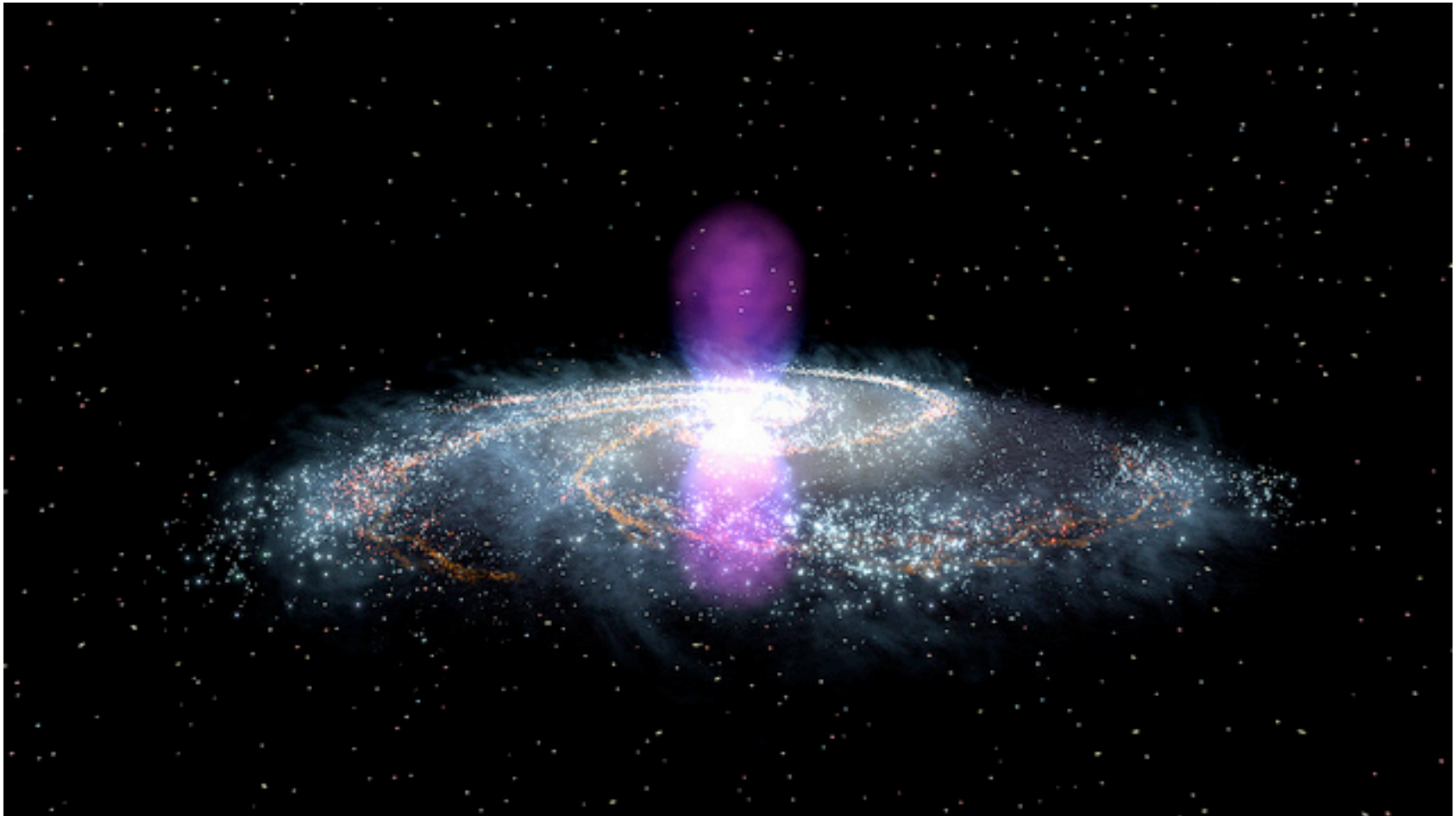
The Fermi Bubbles in the Milky Way

A similar AGN bubble?



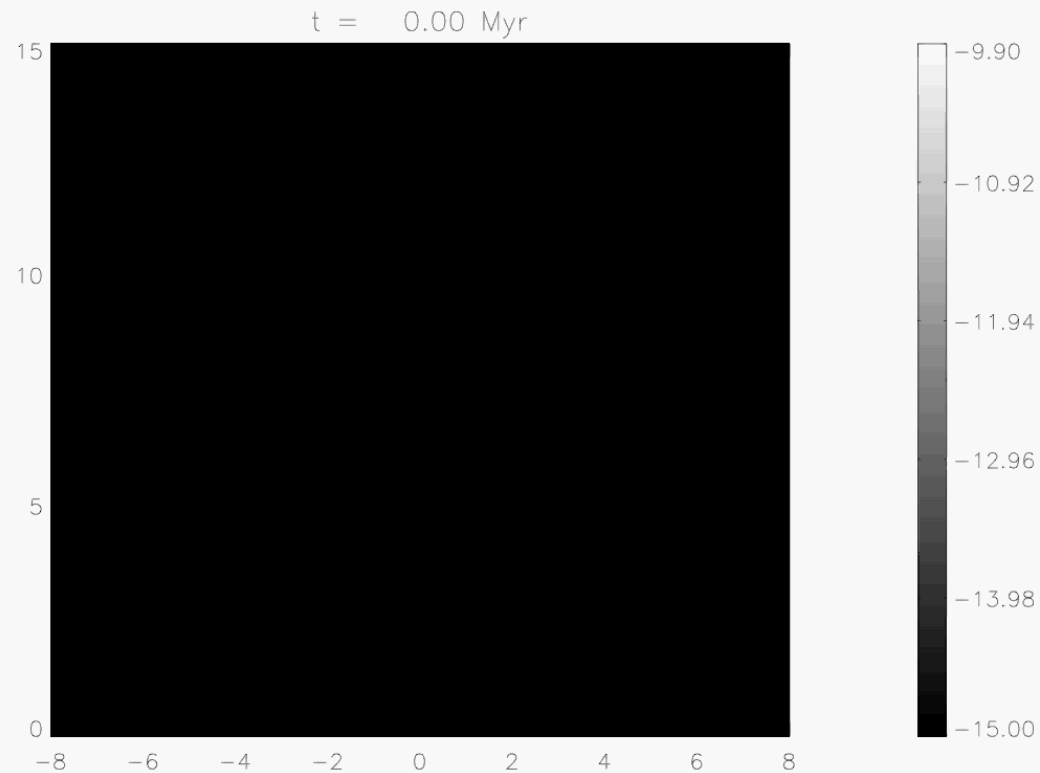
The Fermi bubbles (Su+2010)

An Artist's View of The Fermi Bubbles



(NASA image)

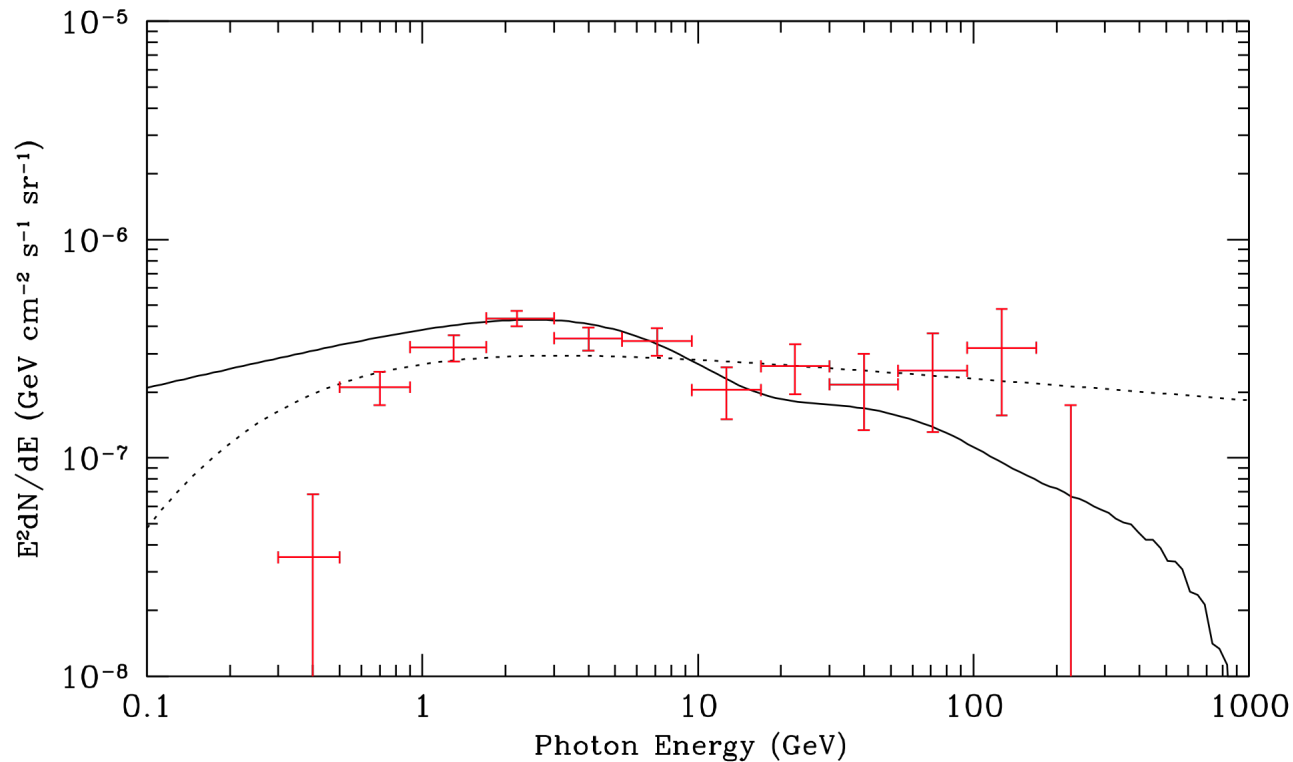
The formation of the Fermi bubble by a typical AGN jet



Cosmic ray distribution

Guo & Mathews 2012; Guo et al 2012

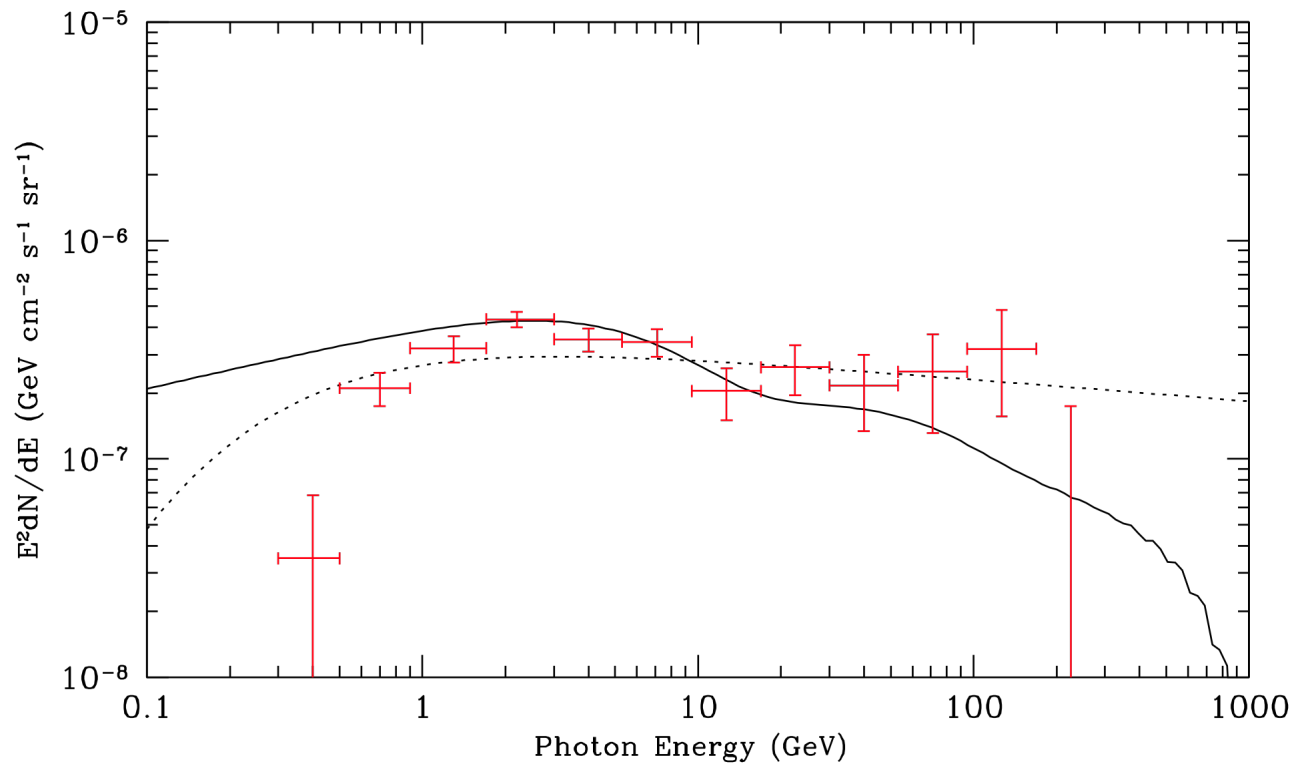
How do our model compare with *Fermi* observations?



The average spectrum of the Fermi Bubbles

Leptonic Scenario (solid line): the required CR electron pressure to produce the observed gamma-ray flux is negligible compared to the total bubble pressure

How do our model compare with *Fermi* observations?



The average spectrum of the Fermi Bubbles

Leptonic Scenario (solid line): the required CR electron pressure to produce the observed gamma-ray flux is negligible compared to the total bubble pressure

Hadronic Scenario (dashed line): the required CR proton pressure is much higher, probably dominating the total bubble pressure.

(4) What physical processes are important in AGN feedback events?

Cosmic ray pressure ?

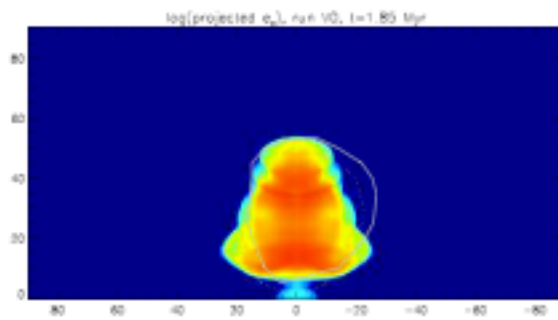
Magnetic fields ?

Shear viscosity ?

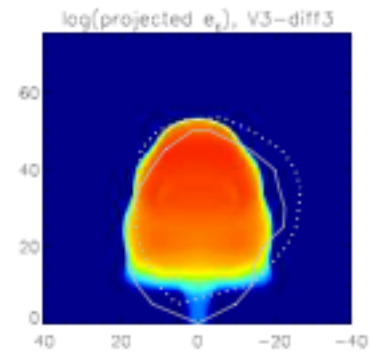
(4) What physical processes are important in AGN feedback events?

Shear viscosity ?

Without viscosity



With viscosity



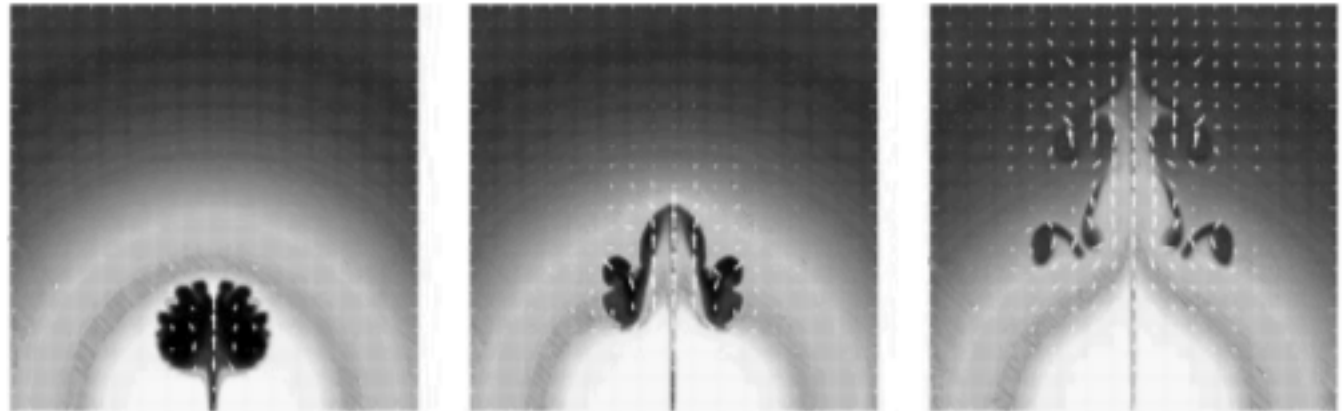
The line-of-sight projected CR energy density in **Galactic coordinates** (Guo et al 2012).

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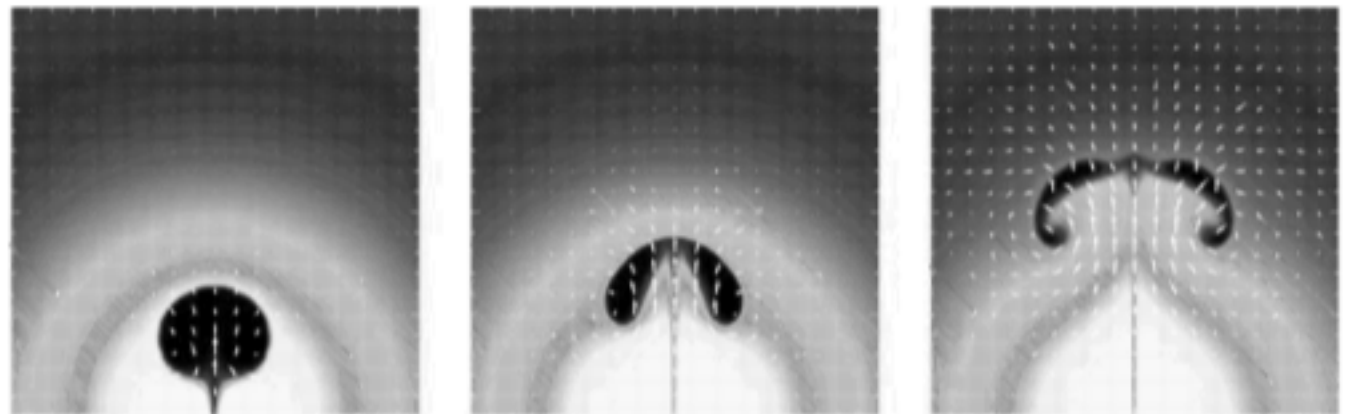
Shear viscosity ?

Reynolds et al 2005

Without viscosity



With viscosity



Summary

- Is AGN feedback important in galaxy clusters?
theory and observations
- How are AGN feedback events triggered?
hot mode vs cold mode
- How does AGN feedback heat hot gas?
weak shocks and ?
- What physical processes are important in AGN feedback events?
cosmic ray physics, magnetic fields, viscosity, ...