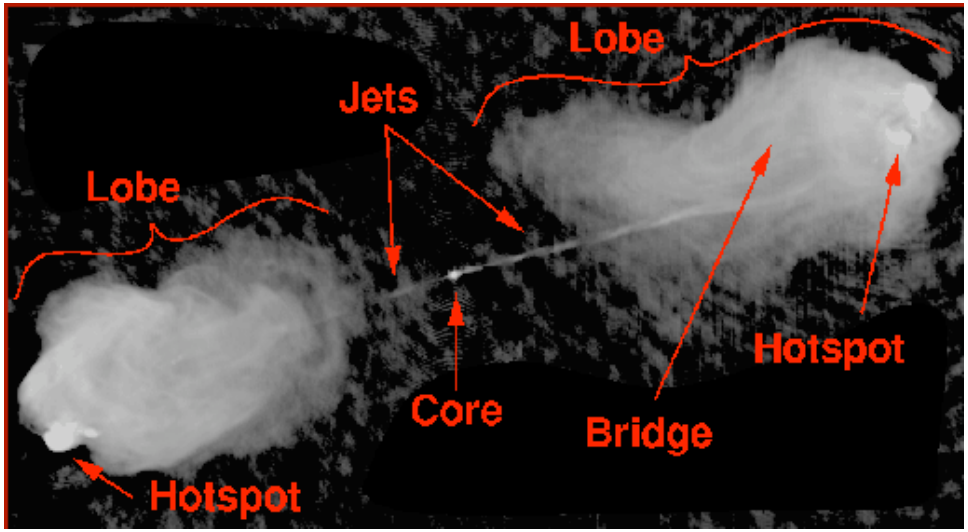
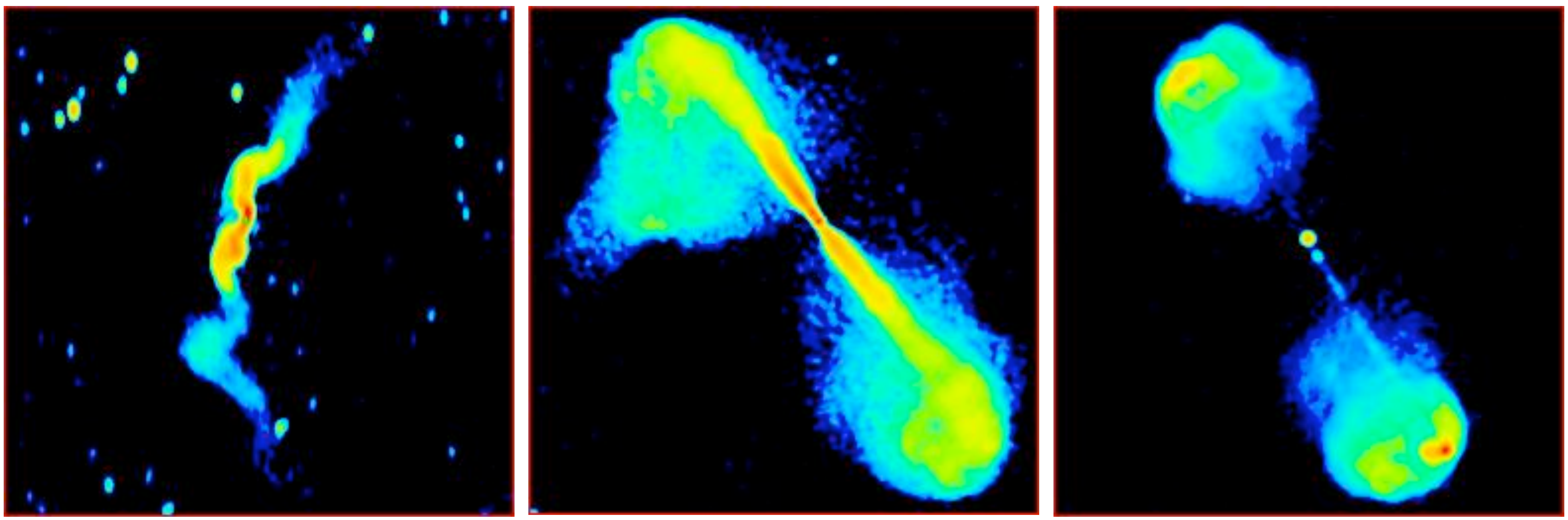
Summary: Jets, Outflows and Cosmic Structure Formation

- **Team members:** Paul Bellan, Jean Eilek, Tom Jones, Phil Kronberg, Sergey Lebedev, Hui Li, Richard Lovelace, Sean Matt, Pat Hartigan
- Contacted about ~ 80 members in the community and got ~ 40 contributions

Impact on Structure Formation

- Interaction w. Intra-Cluster Medium (ICM)
- ICM as a plasma astrophysics laboratory
- Magnetic fields in Inter-Galactic Medium (IGM)



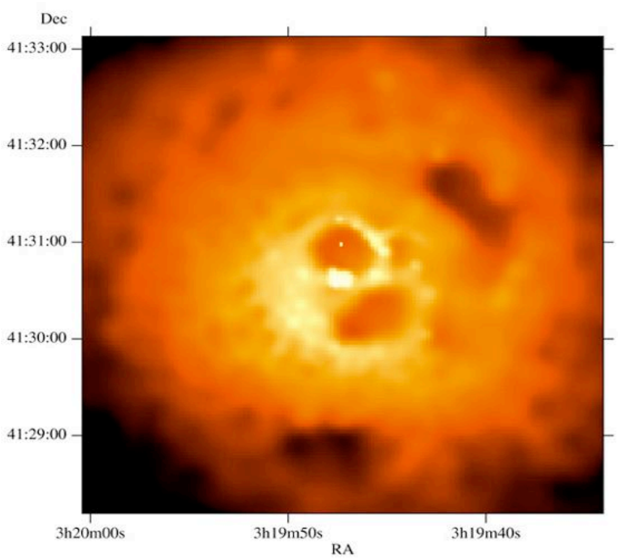


FR I radio galaxies

FR II radio galaxies

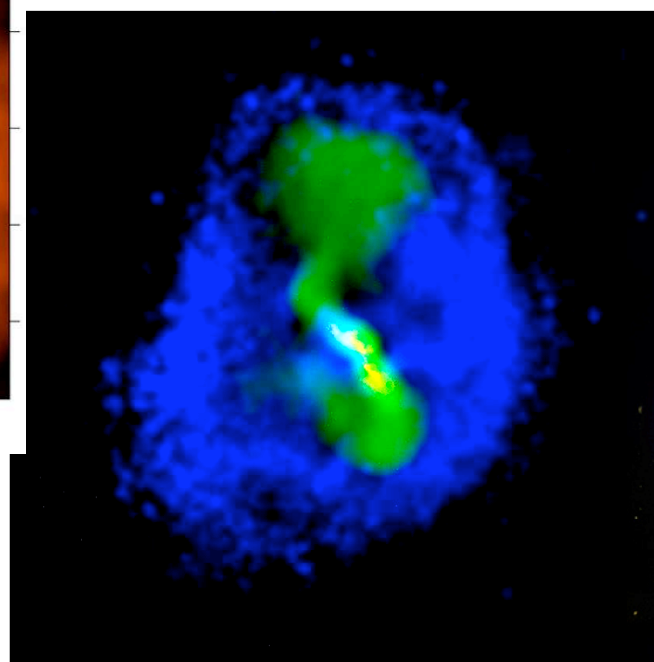
Jets and Lobes interacting with Galaxy Clusters

Perseus (Fabian et al.)



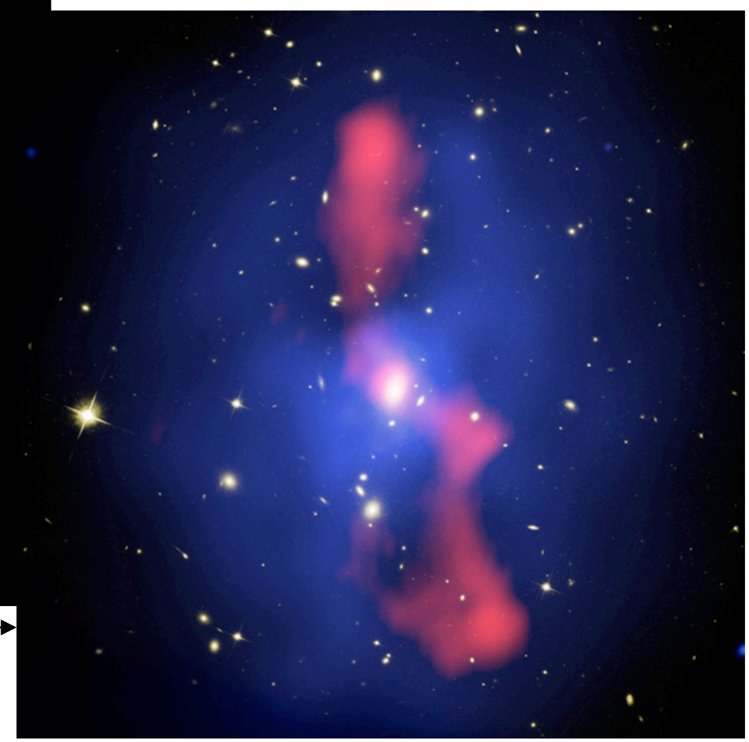
~ 200 Kpc

Hydra A (Wise et al.)

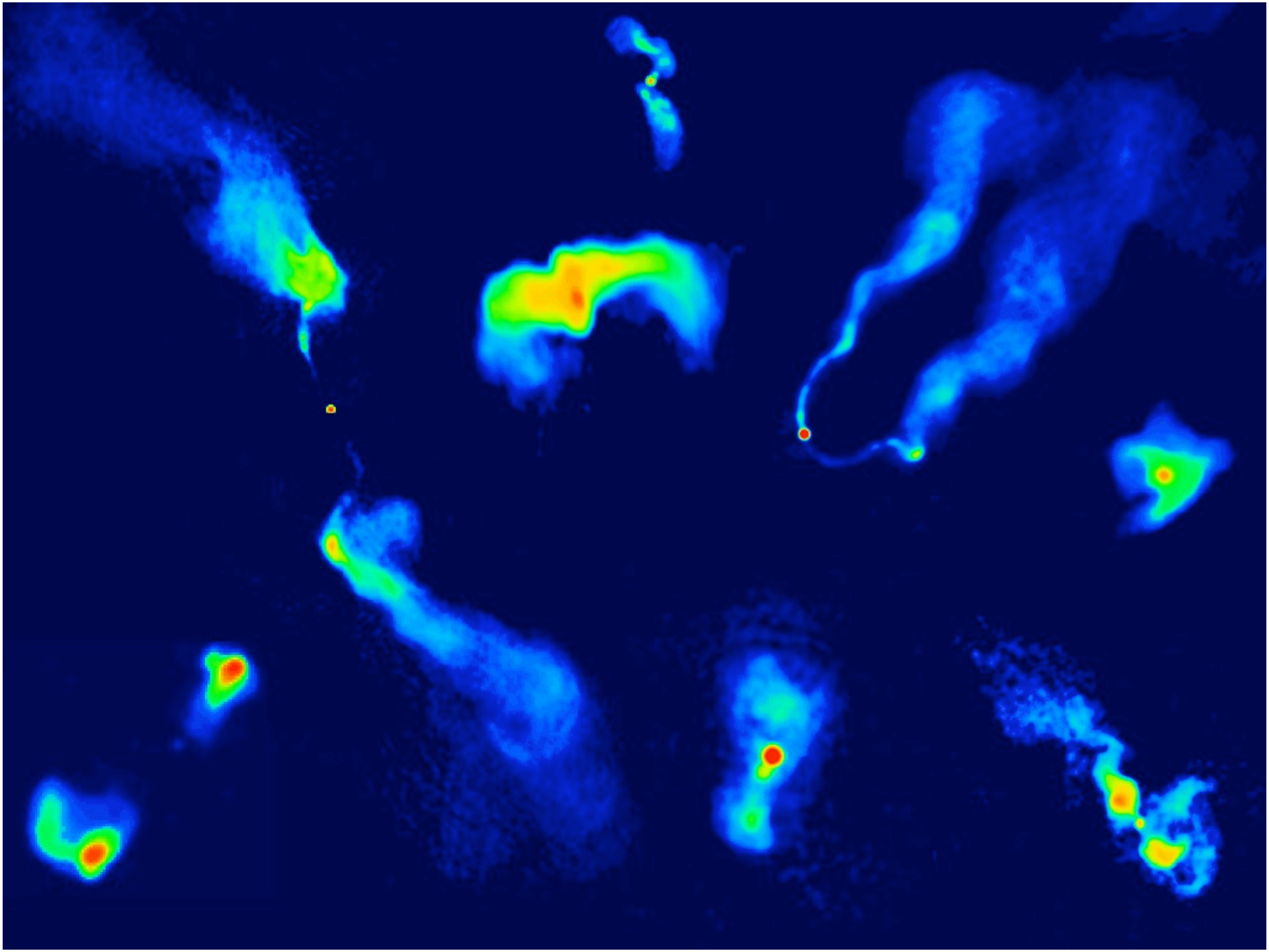


~ 400 Kpc

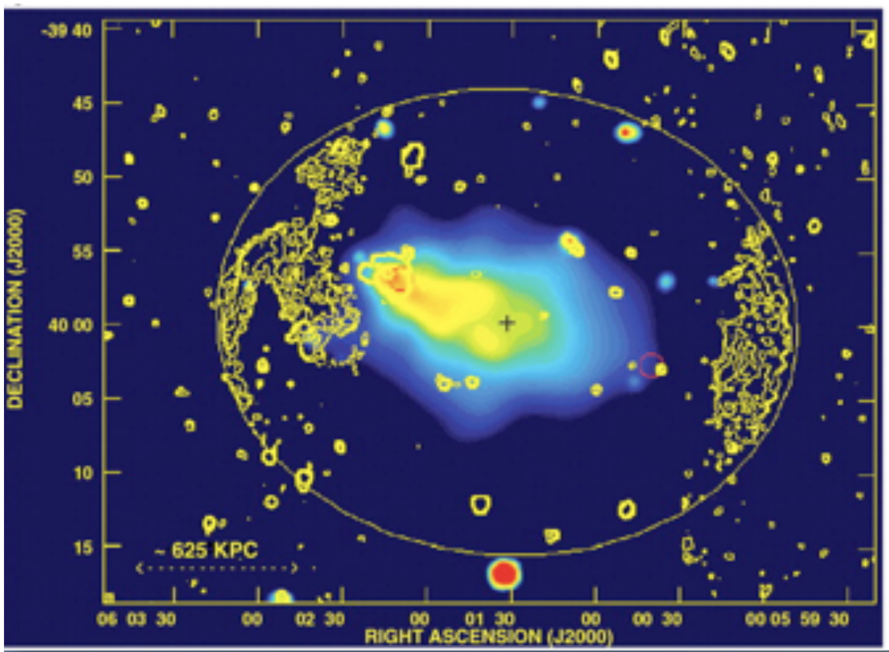
MS0735.6+7421
(McNamara et al.)

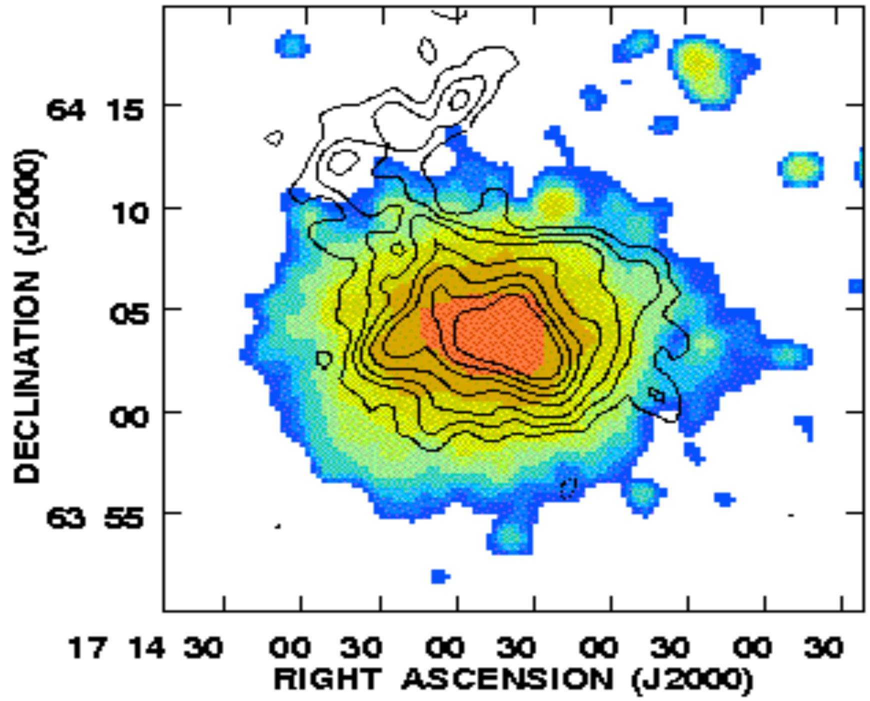


~ Mpc



On Cluster Scale …

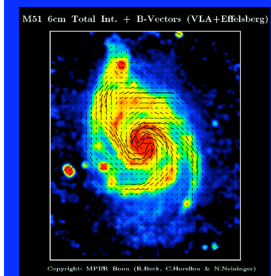


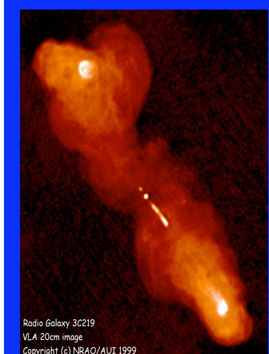


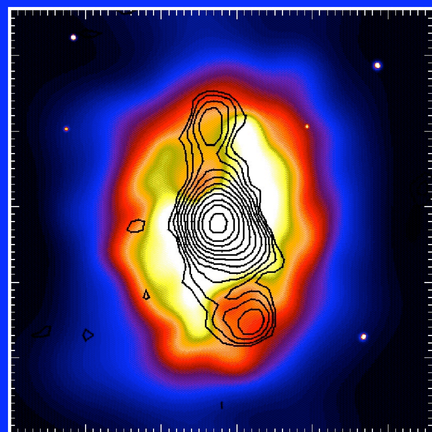
Implications:

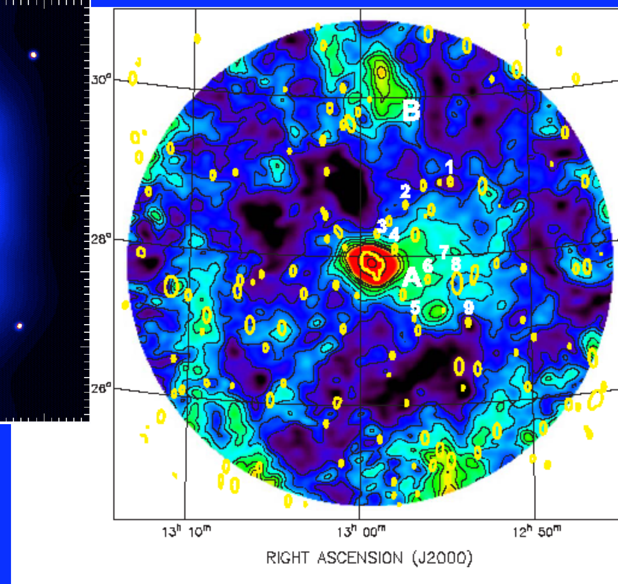
- cluster wide (Mpc) magnetic fields
- total magnetic energy ~10^{61} ergs
- energization of particles in 10^8 yrs

Individual Galaxy | Galaxy Clusters | Super-Galactic Filaments | The Magnetized Universe (???)









- **Is the Universe Magnetized ? To What Level?**
- **What are the Plasma Physics Processes that Governed and Impacted the Structure Formation?**

Cosmology MHD Code

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla \bullet (\rho \mathbf{v}) = 0$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \frac{1}{a}\nabla \bullet \left[\rho \mathbf{v}\mathbf{v} + P_g + \frac{B^2}{2} - \mathbf{B}\mathbf{B}\right] = -\frac{\dot{a}}{a}\rho \mathbf{v} - \frac{1}{a}\rho \nabla \Phi$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \bullet \left[\left(E + P_g + \frac{B^2}{2}\right)\mathbf{v} - (\mathbf{v} \bullet \mathbf{B})\mathbf{B}\right] = -2\frac{\dot{a}}{a}E - \frac{1}{a}\rho \mathbf{v} \bullet \nabla \Phi + \frac{1}{2}\frac{\dot{a}}{a}B^2$$

$$\frac{\partial \mathbf{B}}{\partial t} = \frac{1}{a}\nabla \times (\mathbf{v} \times \mathbf{B}) - \frac{1}{2}\frac{\dot{a}}{a}\mathbf{B}, \qquad E = \frac{1}{2}\rho \mathbf{v}^2 + \frac{P_g}{\gamma - 1} + \frac{B^2}{2}$$

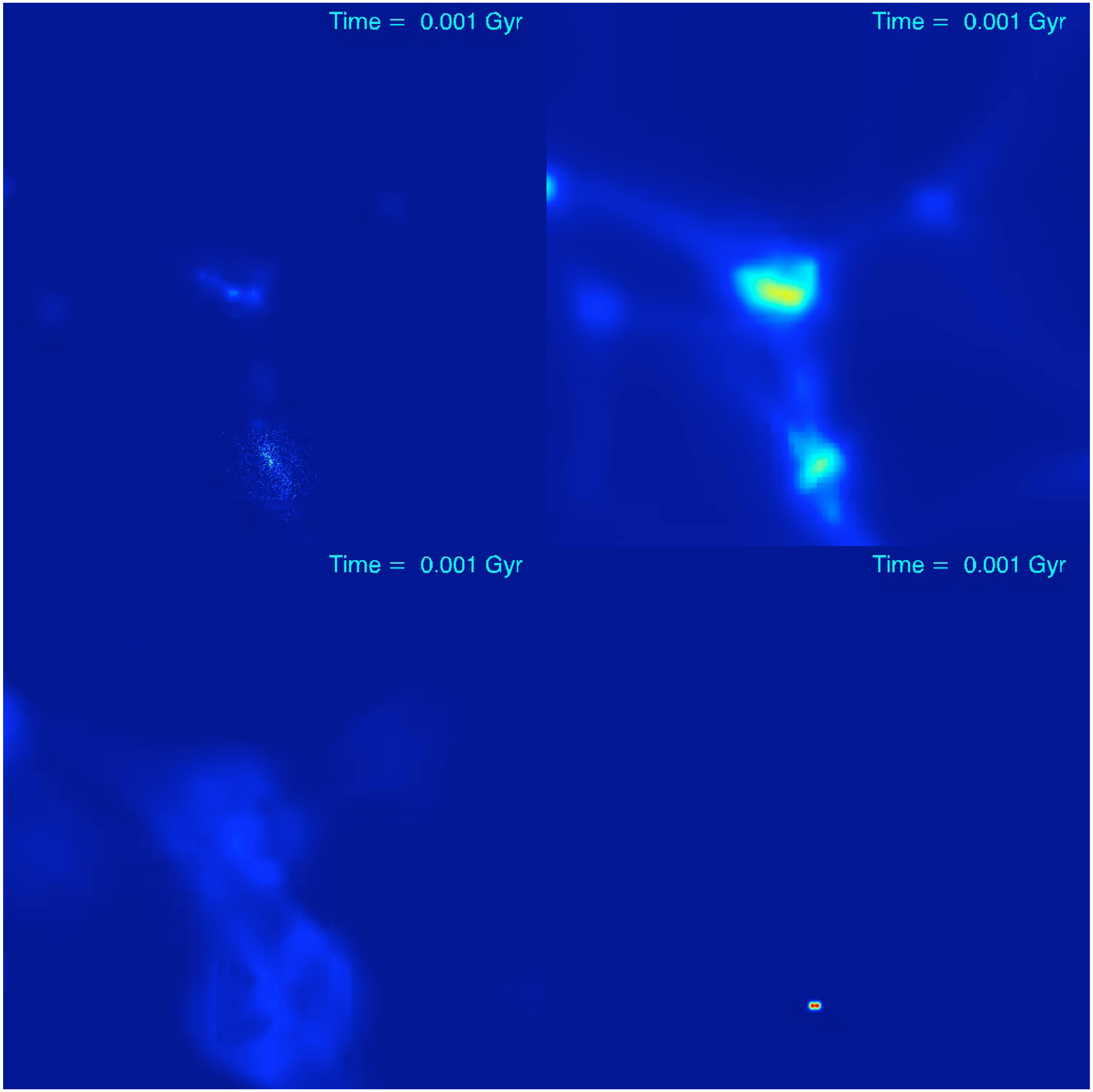
$\rho, P_g, \mathbf{B}$ **: comoving density, pressures;** $\mathbf{v}$ **: proper peculiar velocity**

Cosmo-MHD: Li, Li, Cen (2008, ApJS)

ENZO+MHD: Collins et al. (2010, method paper)

Dark matter

baryons



T

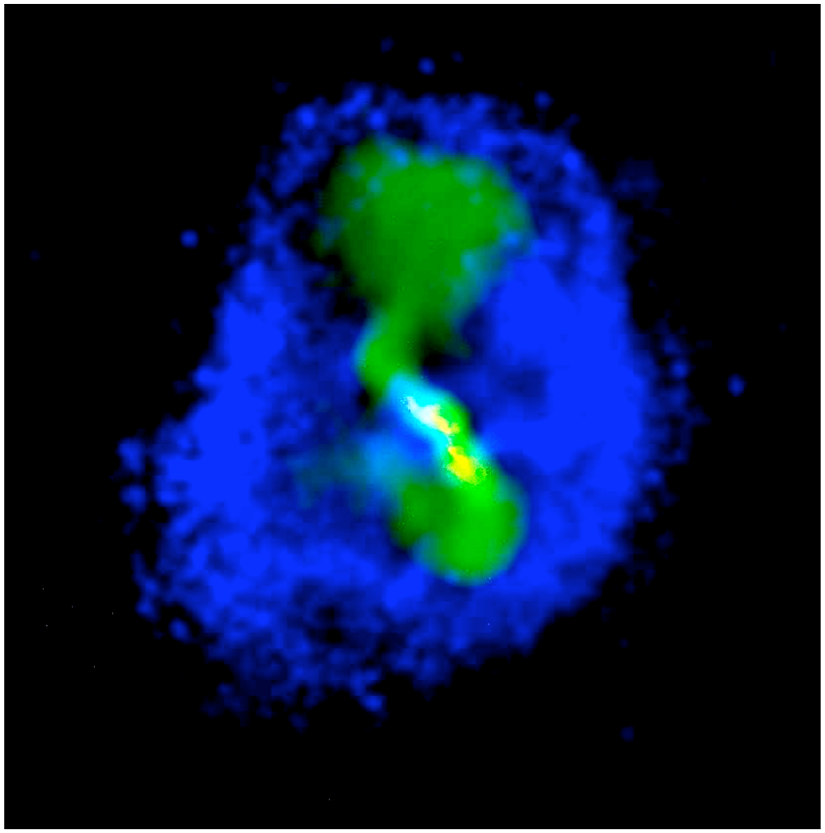
magnetic fields

AGN @ z=3

Some Specific Opportunities

- Observations (see Phil's talk)
- Experiments (see Paul and Sergey's talk)
- YSO jets (see Sean/Pat's talk)
- AGN jets theory/simulation (Richard's talk)

#1: Hydra Challenge



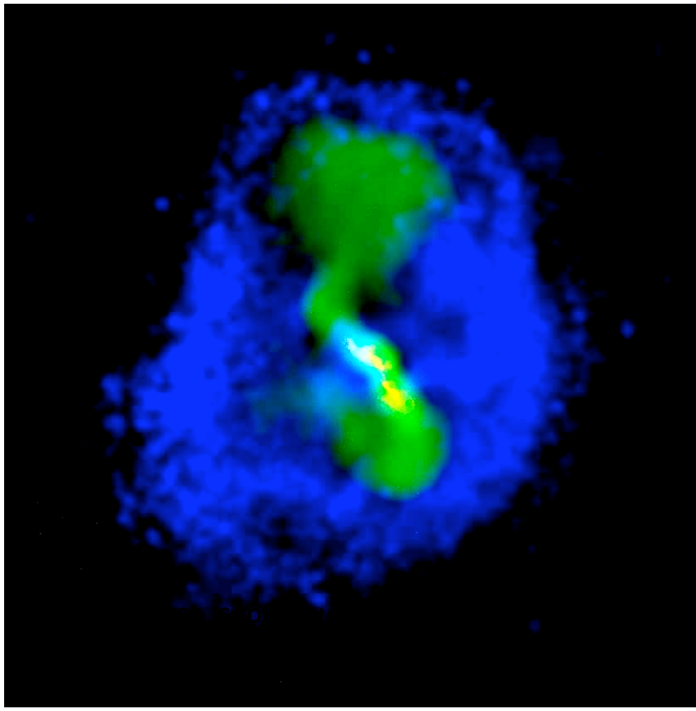
- Large-scale structure of jet/lobes
- Background plasma conditions are relatively well measured
- Need observations, simulations and lab experiments

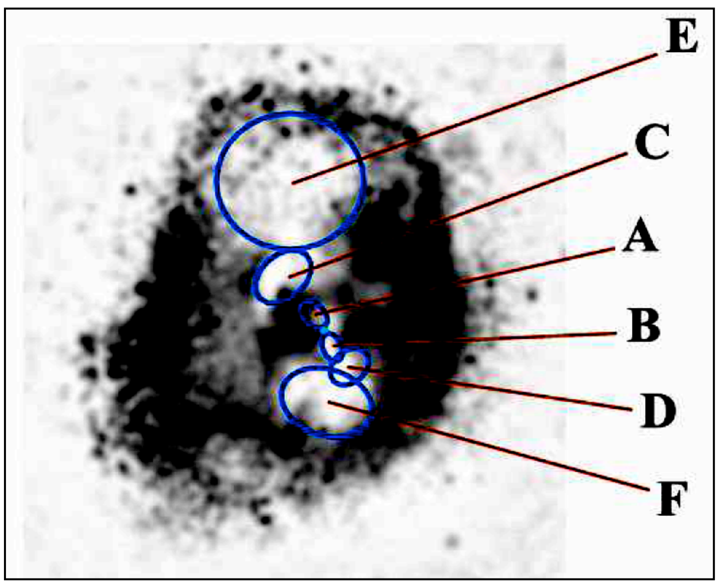
Goals:

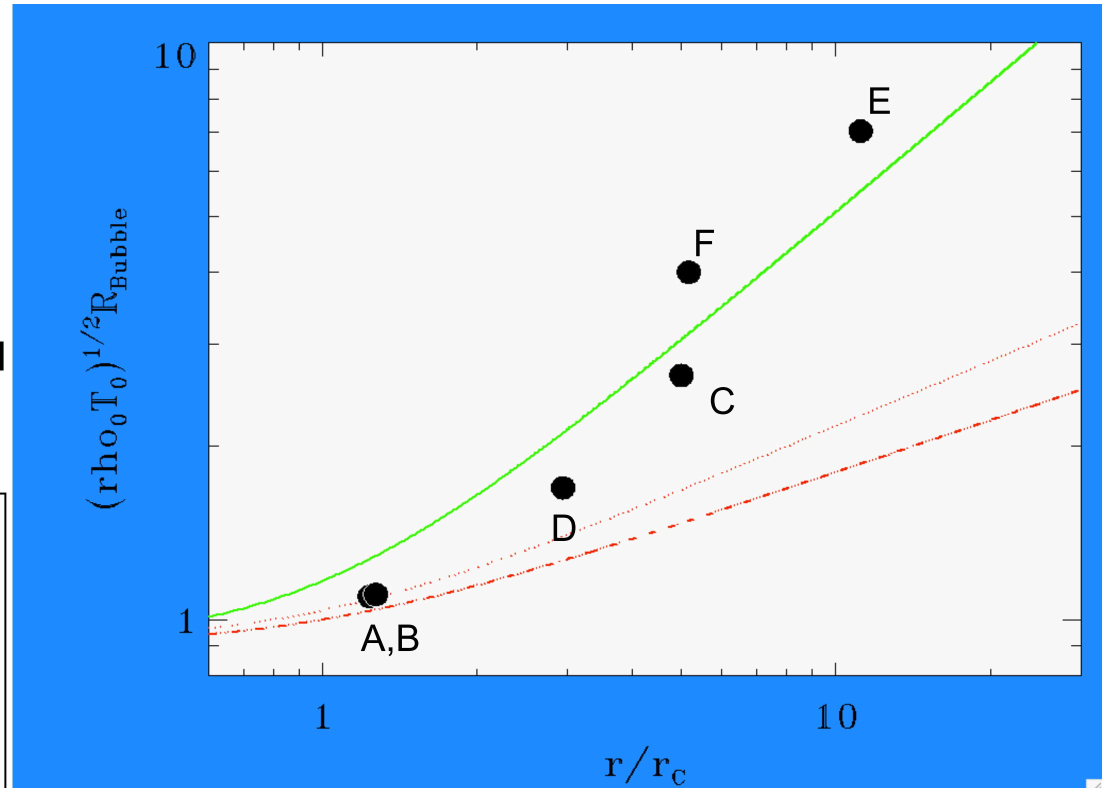
1)Understand the large scale morphology

2) Understand the energy exchange with background plasmas

Bubbles in Hydra A



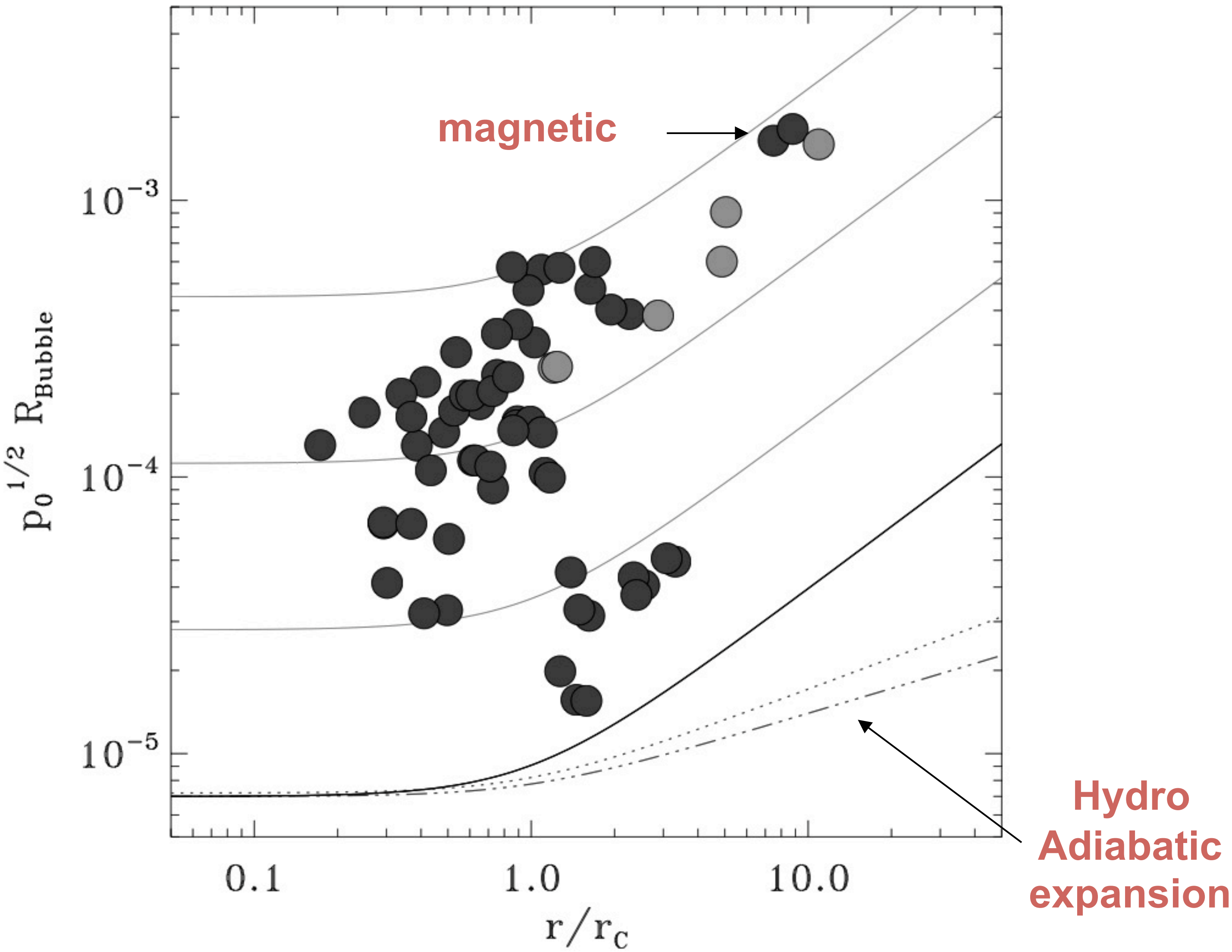




Diehl, Li, et al. 2008

Analysis of ~70 Bubbles in 32 Clusters

(Diehl, HL, et al. 2008)



#2: Intra-Cluster Medium Challenge
EVLA

- An order-of-magnitude improvement in number of clusters,
- Embedded and background radio galaxies,
- Synchrotron cluster emission

Abell 2255

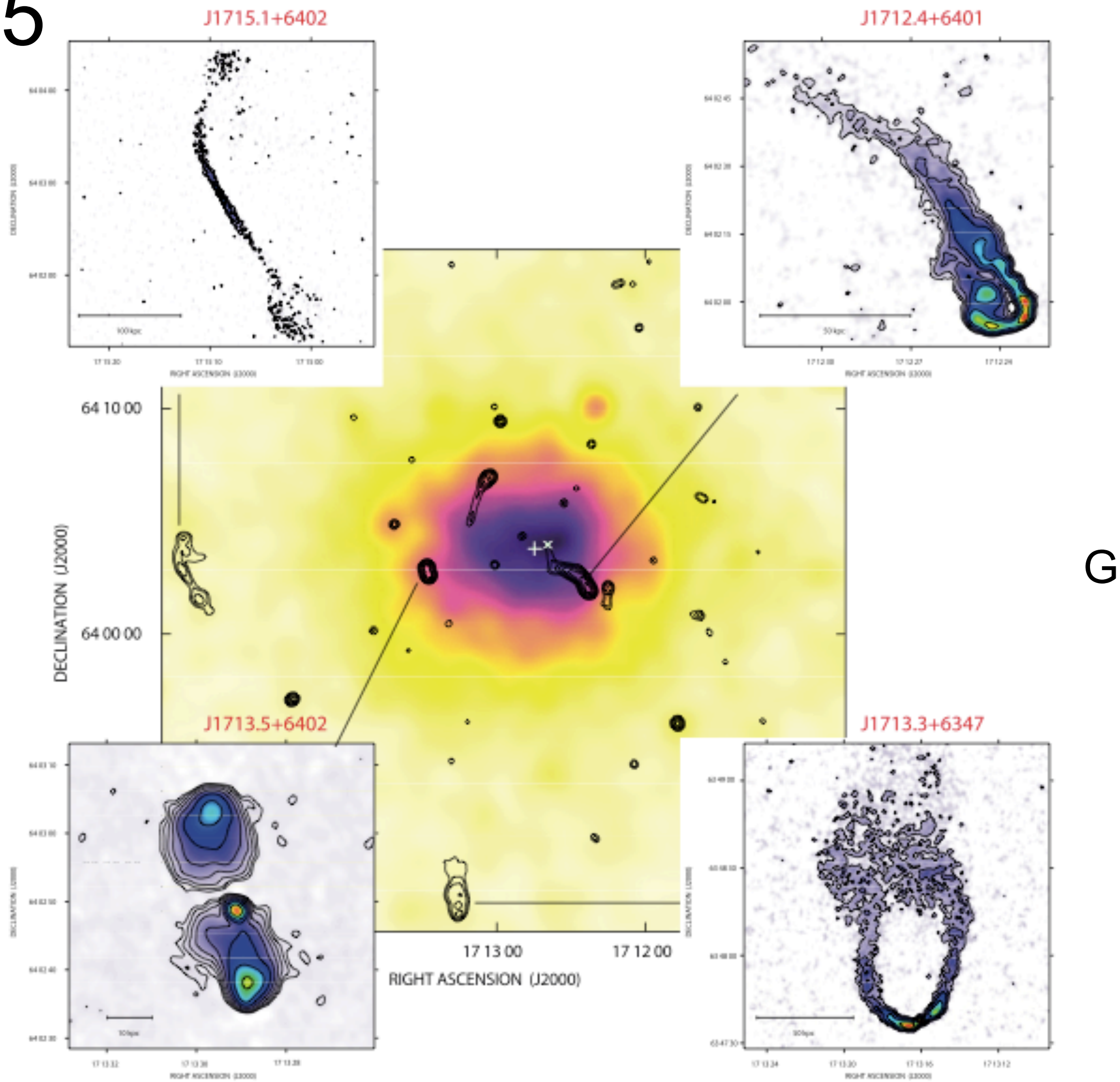
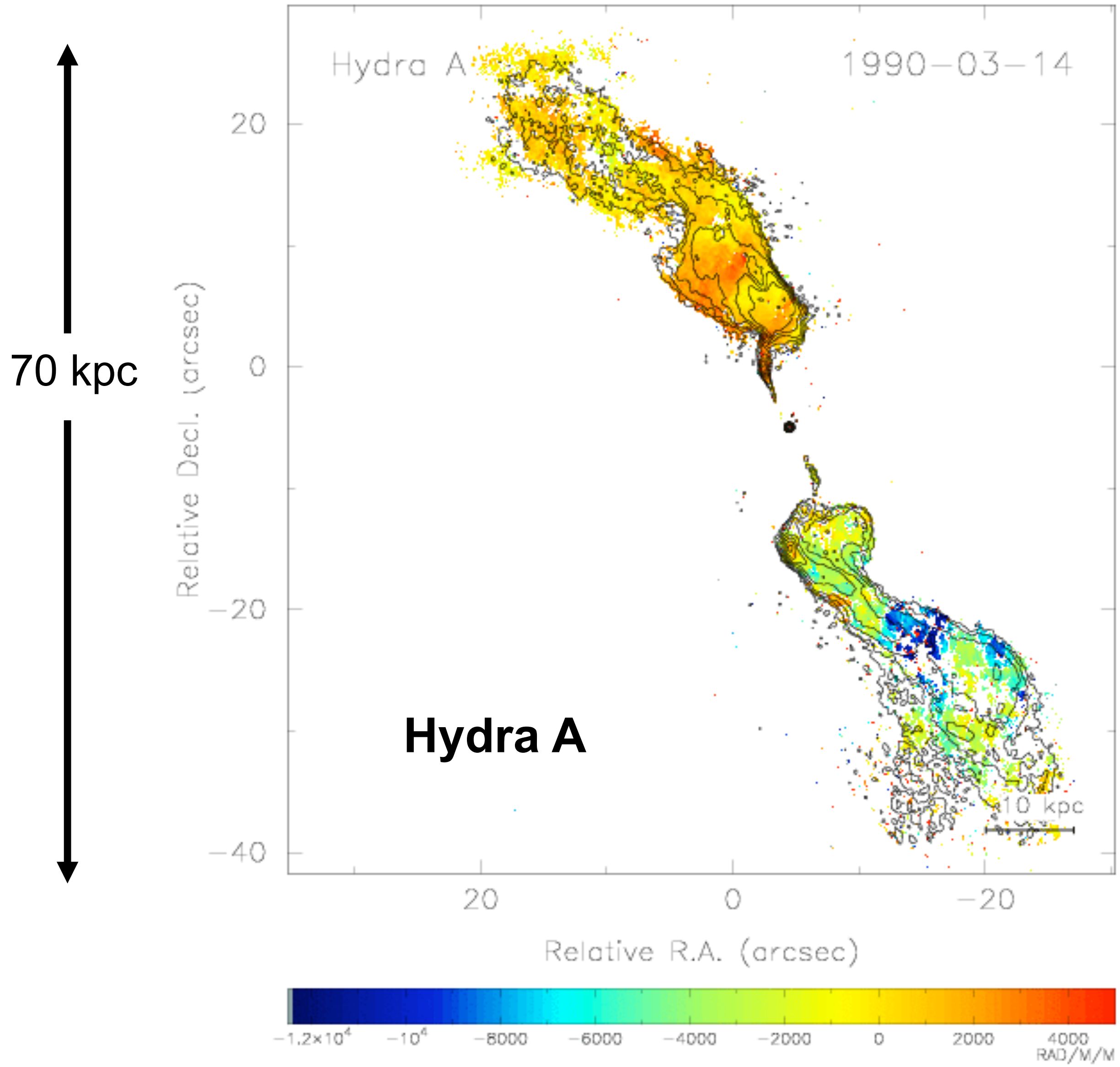


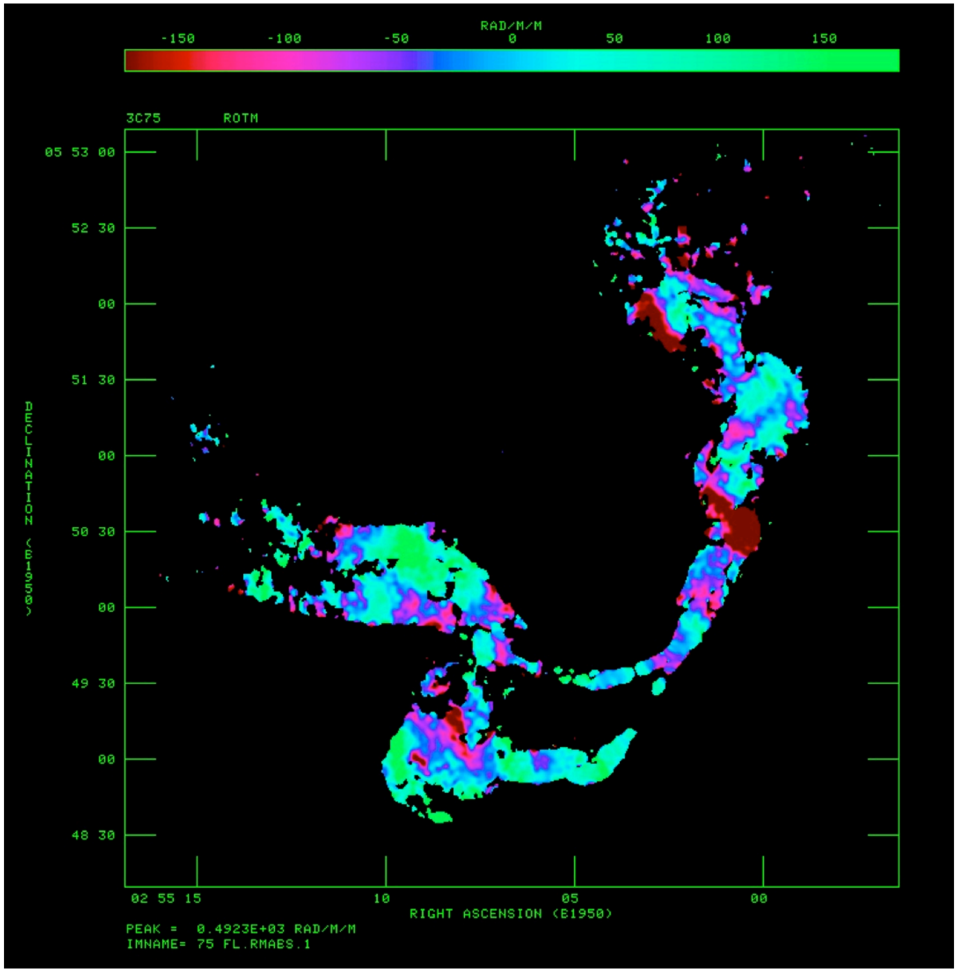
Fig. 1. Radio contours of the A2255 cluster of galaxies obtained at 20 cm (Govoni et al. 2005) overlaid on the ROSAT X-ray image. The white symbols + and × indicate the position of the cluster X-ray centroid and peak respectively. The radio image at 20 cm has a *FWHM* of 15″ × 15″. The radio contours are: 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, 25.6, and 51.2 mJy/beam. The sensitivity (1σ) is 0.016 mJy/beam. For graphical reasons the first contour is at 25σ therefore we see only the radio galaxies of the cluster while the low brightness, diffuse emissions (radio halo and relic) are not visible here. Pointed high resolution observations at 6 cm of four cluster radio galaxies are inset. The radio contours at 6 cm are: 0.06, 0.12, 0.24, 0.48, 0.96, 1.92, 3.84, and 7.68 mJy/beam. See Table 2 for more information (e.g. resolution, sensitivity, peak brightness) of these observations.

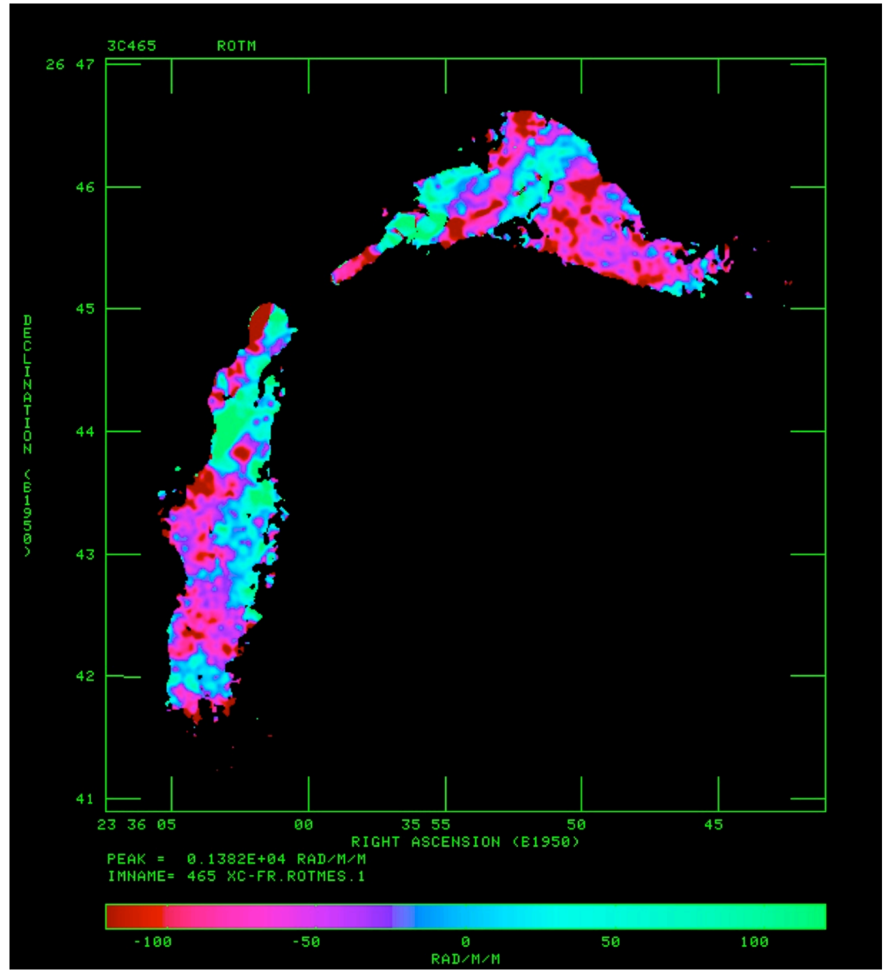
Govoni et al. 2006



- **Energy and Flux**
- **ICM magnetic turbulence?**

(Taylor & Perley'93; Colgate & Li'00)



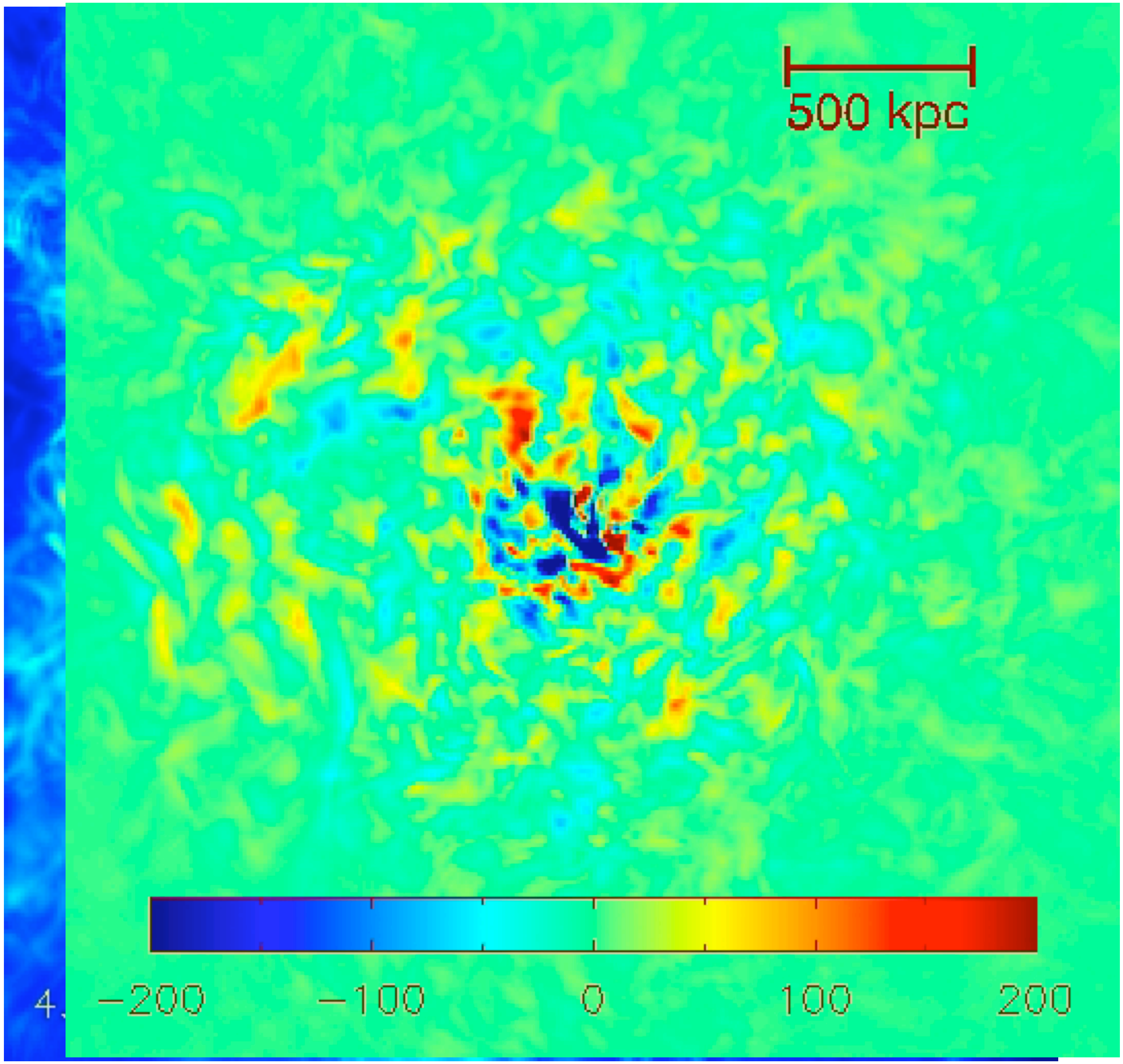


Abell 400

Abell 2634

Eilek & Owen 2002

Faraday Rotation Measure

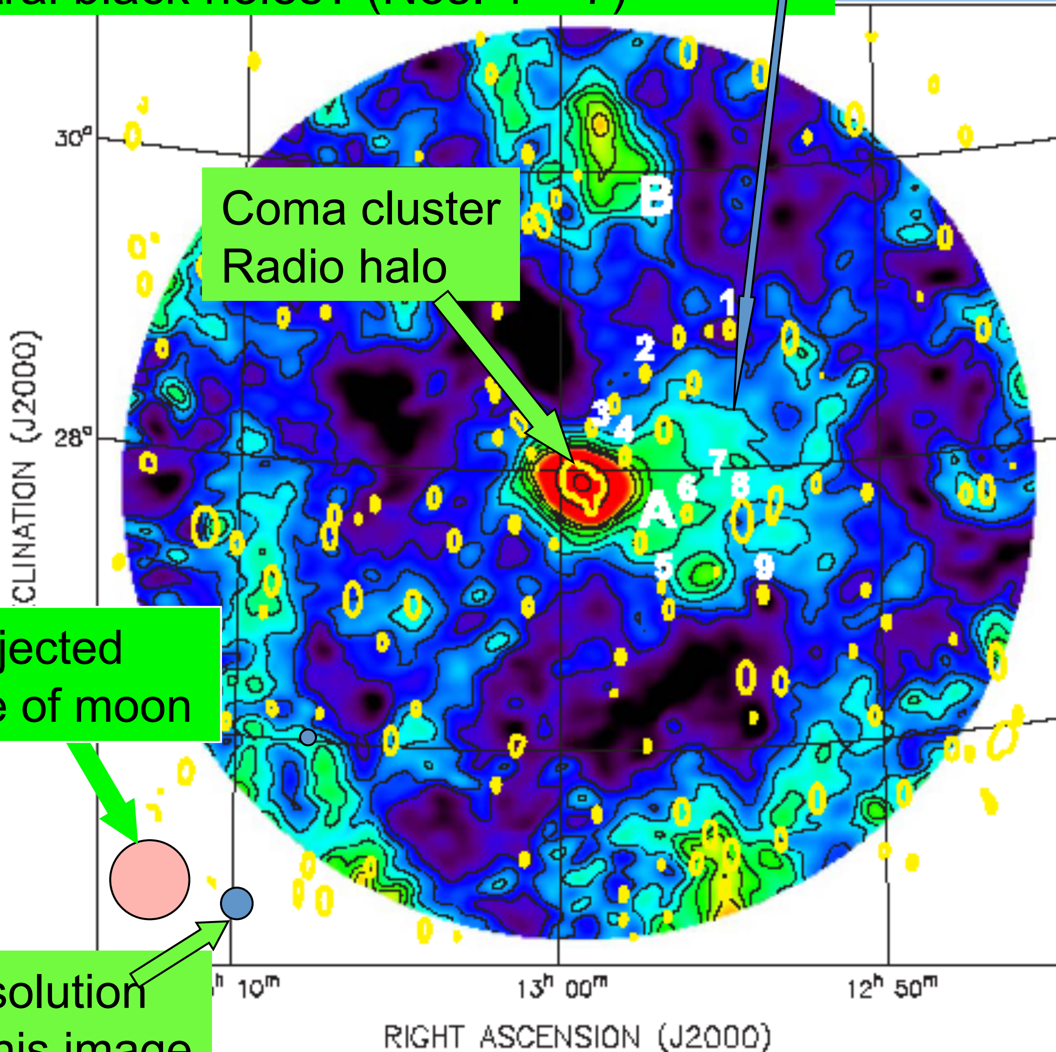


Xu, HL, et al. 2009

COMBINED Arecibo-DRAO image, smoothed to *10' (Arecibo) resolution*

P. Kronberg, R. Kothes, C. Salter, & P. Perillat ApJ 659, 267, 2007

Collective energization of several galactic central black holes? (Nos. 1 – 7)



REMOVED:

- *Discrete sources*
- *CMB + linear plane Milky Way foreground*

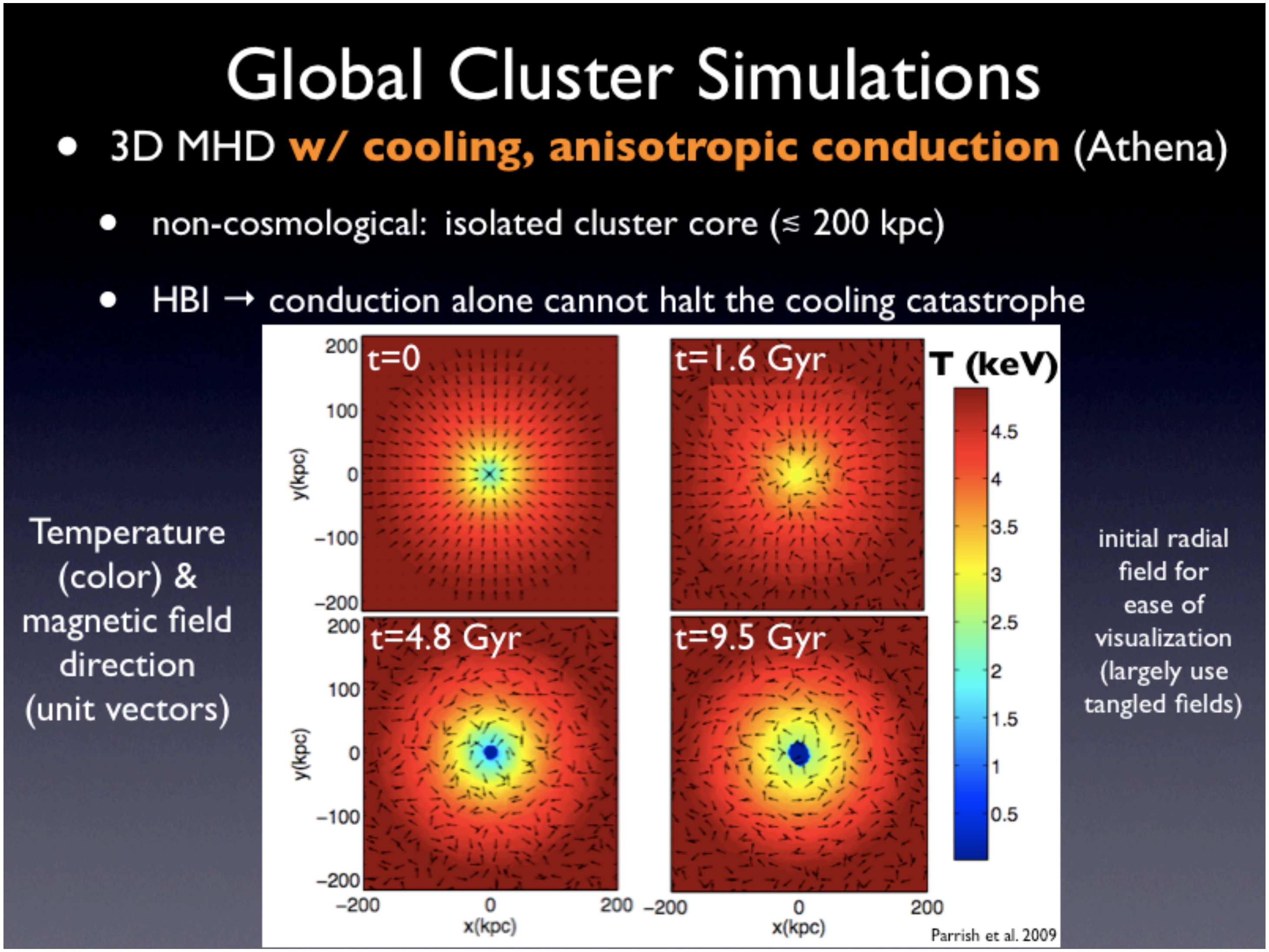
Strongest discrete sources re-overlaid as yellow ellipses

- *Black contours at 1.4, 1.9, 2.4, 2.9, 3.4, 3.9, 4.4, 10, 40K*
- *σ ≈ 250mK at 430 MHz*

Region A (2 – 3 Mpc in extent) requires a distributed "fresh" energy source – plausibly provided by the ~ 7 embedded, radio galaxies.

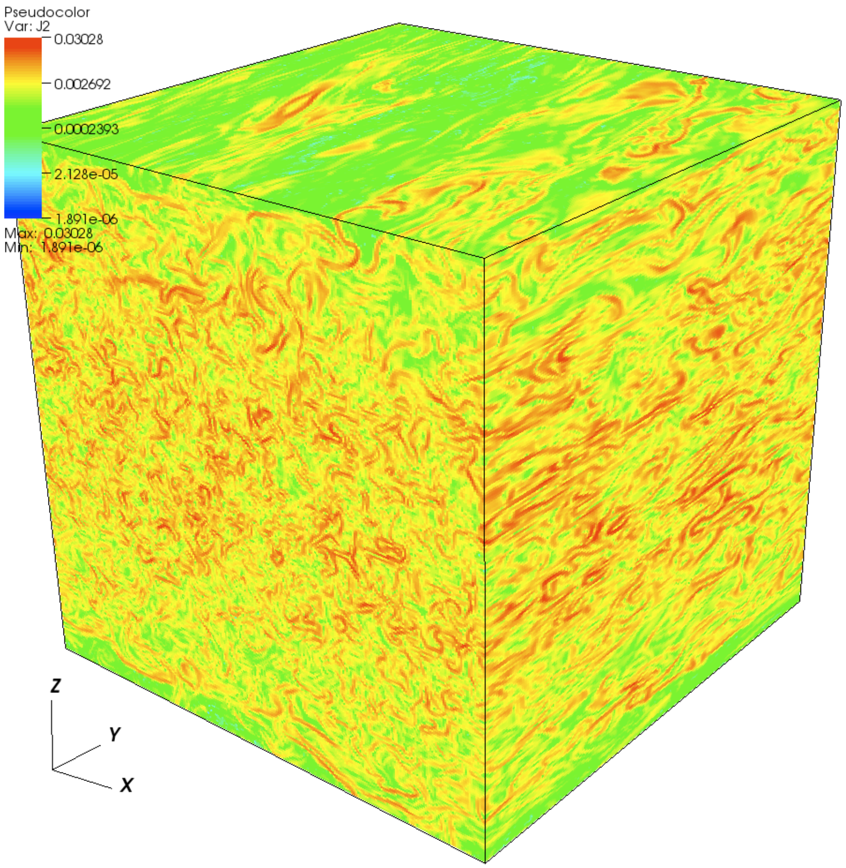
RESULT:
$<|B|> \approx 10^{-7}$G over 2 – 3 Mpc

Heat Conduction Problem

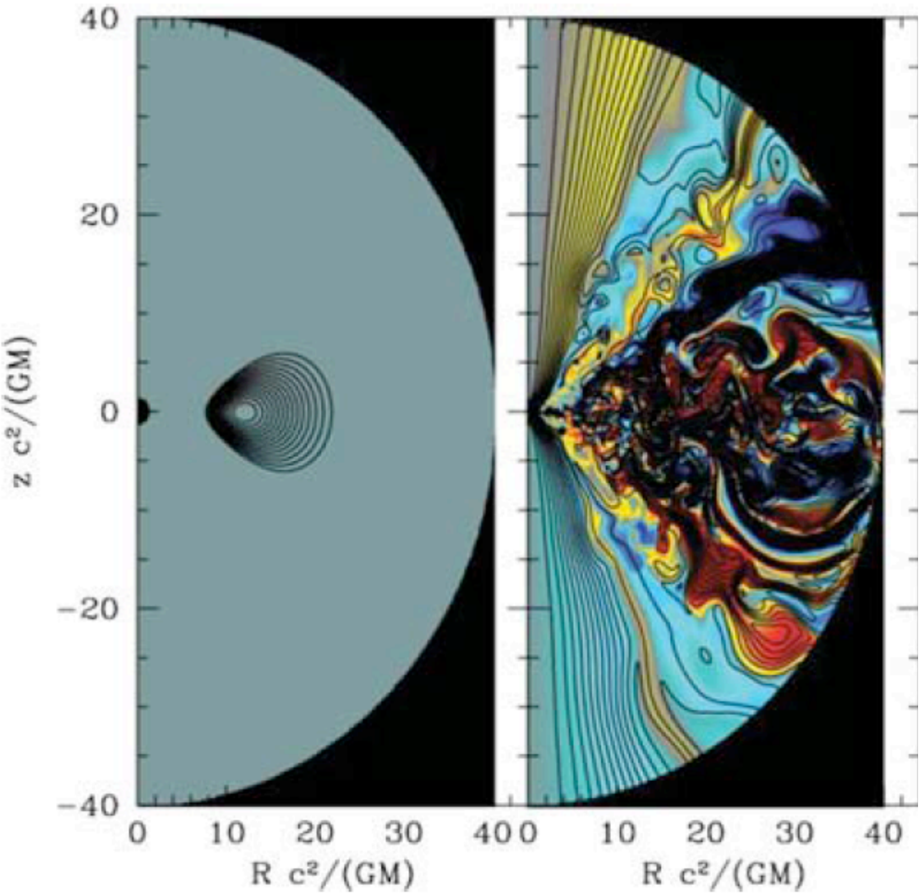


Courtesy E. Quataert

#3: Disk Dynamo and Momentum Transport

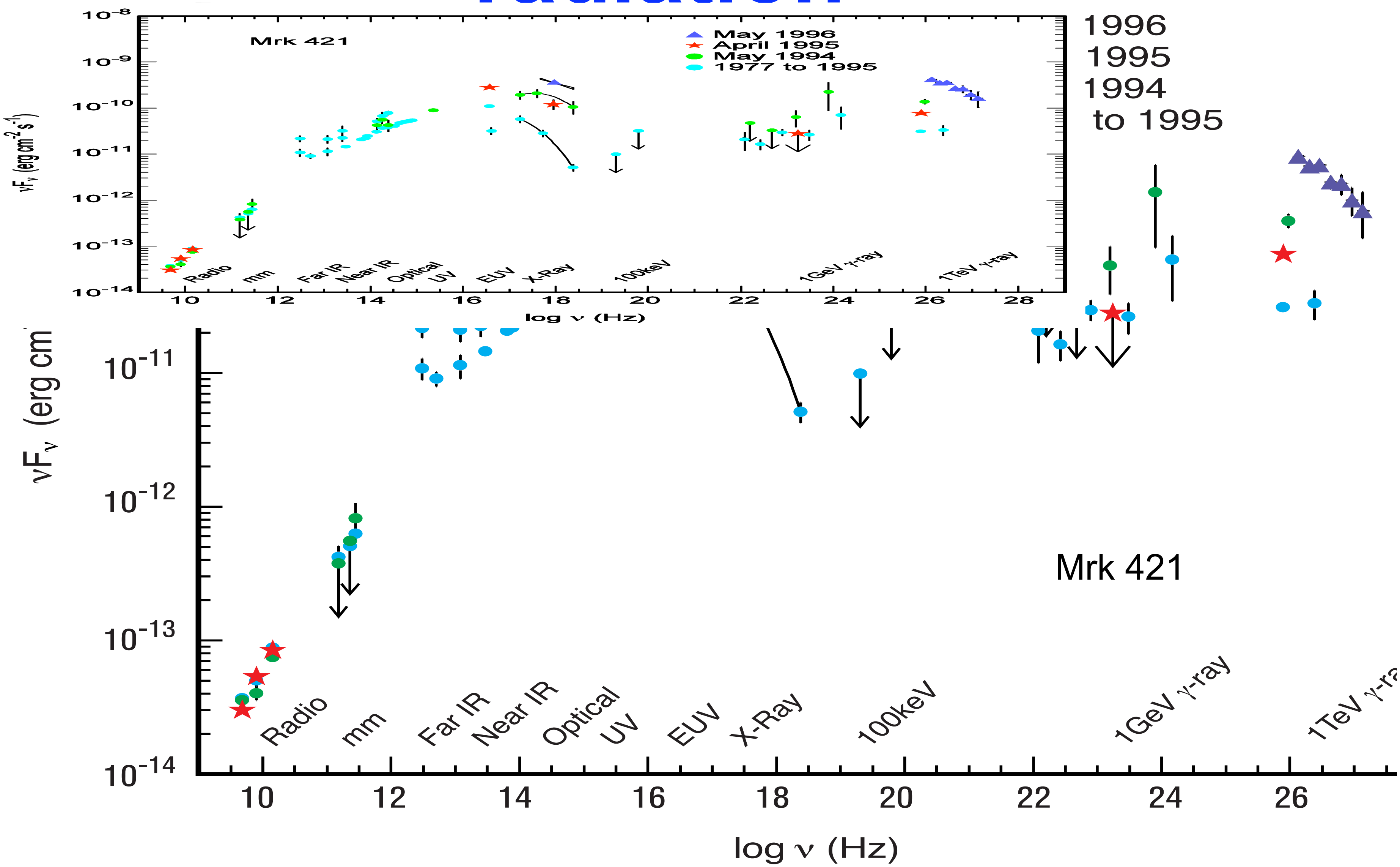


Courtesy: J. Stone



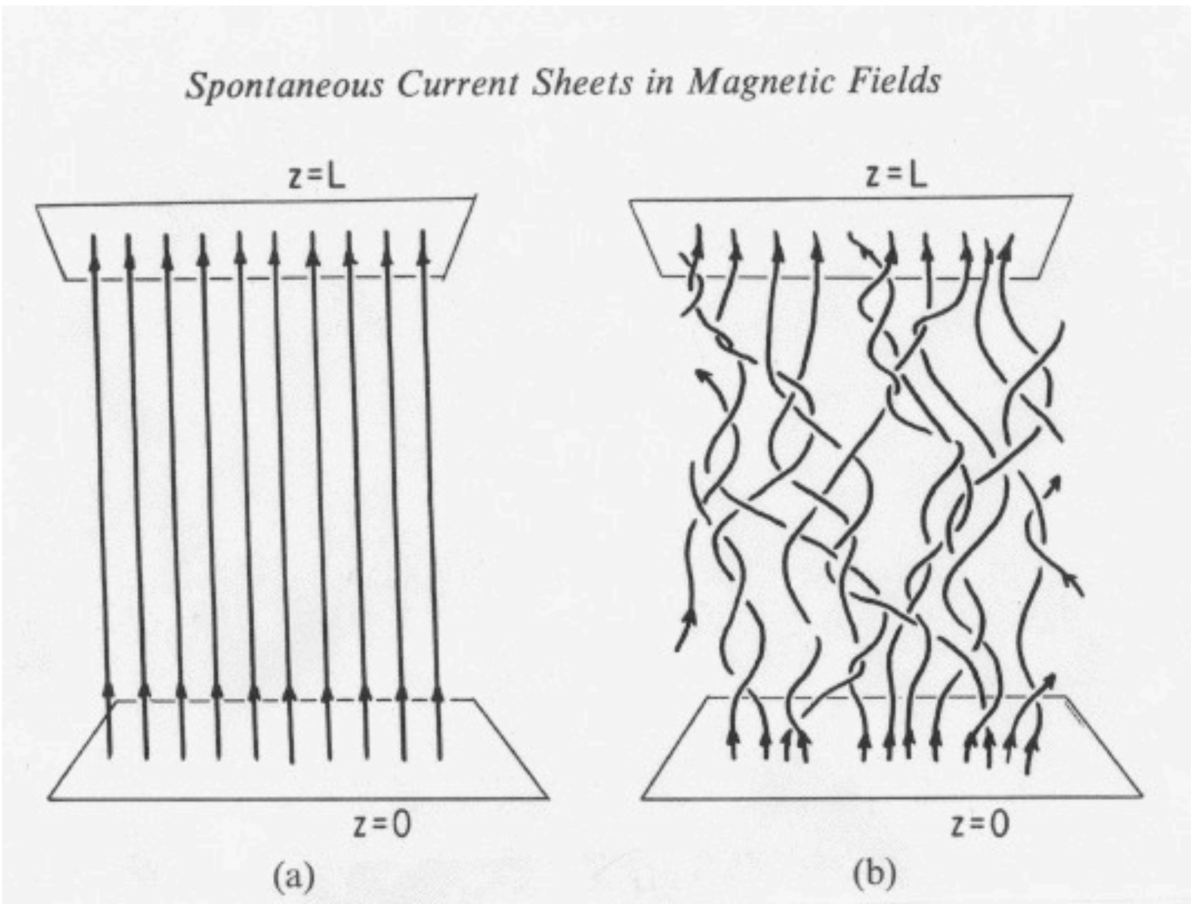
Courtesy: J. McKinney

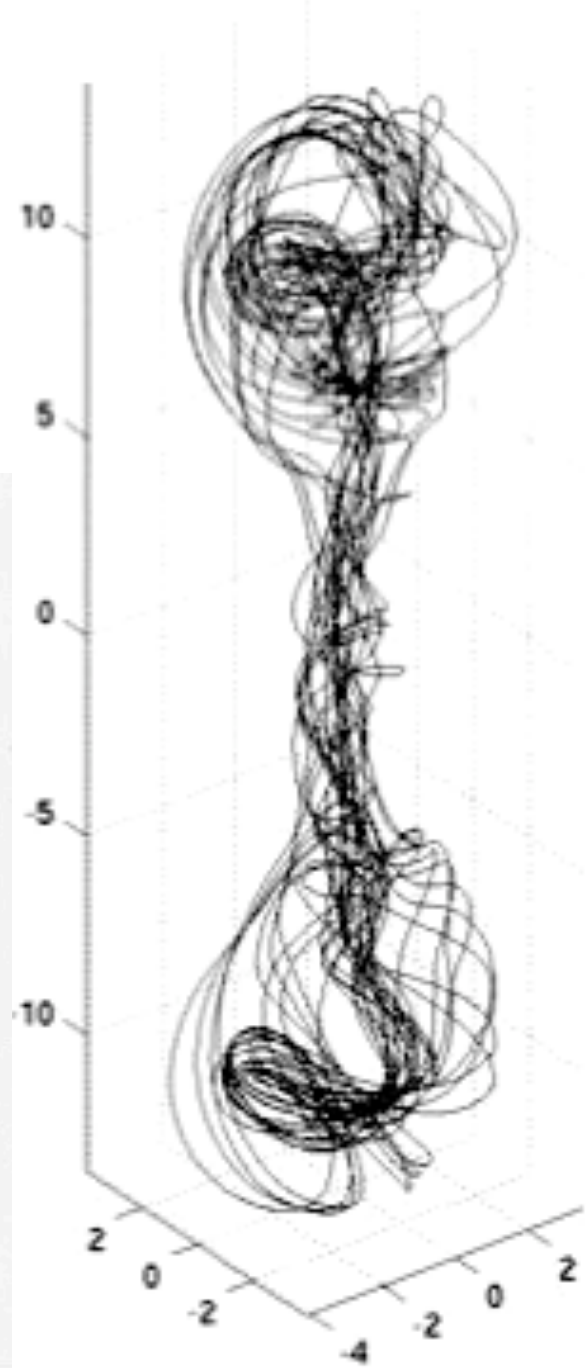
#4: Dissipation in Jets: a) radiation



#4: b) Reconnection in Jets and Lobes

- Similar to Parker Problem?

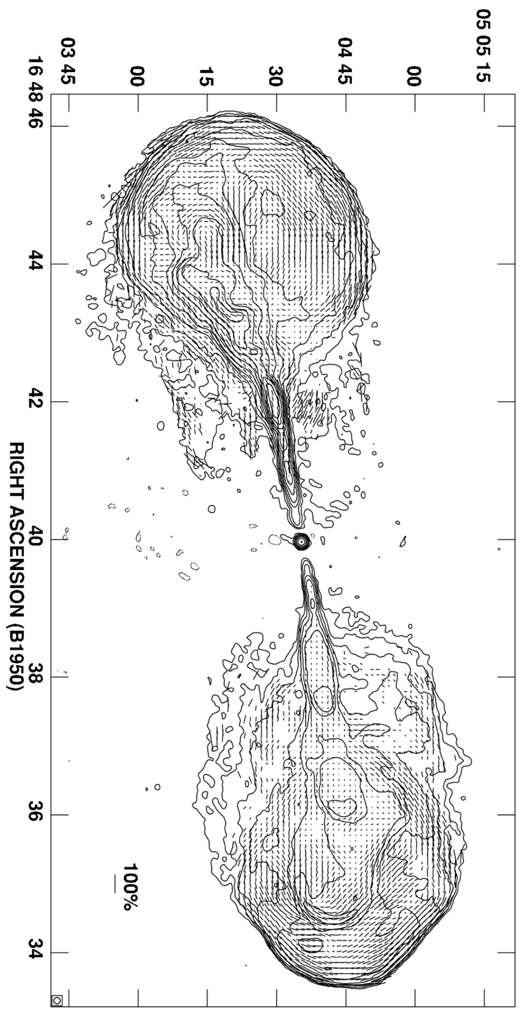




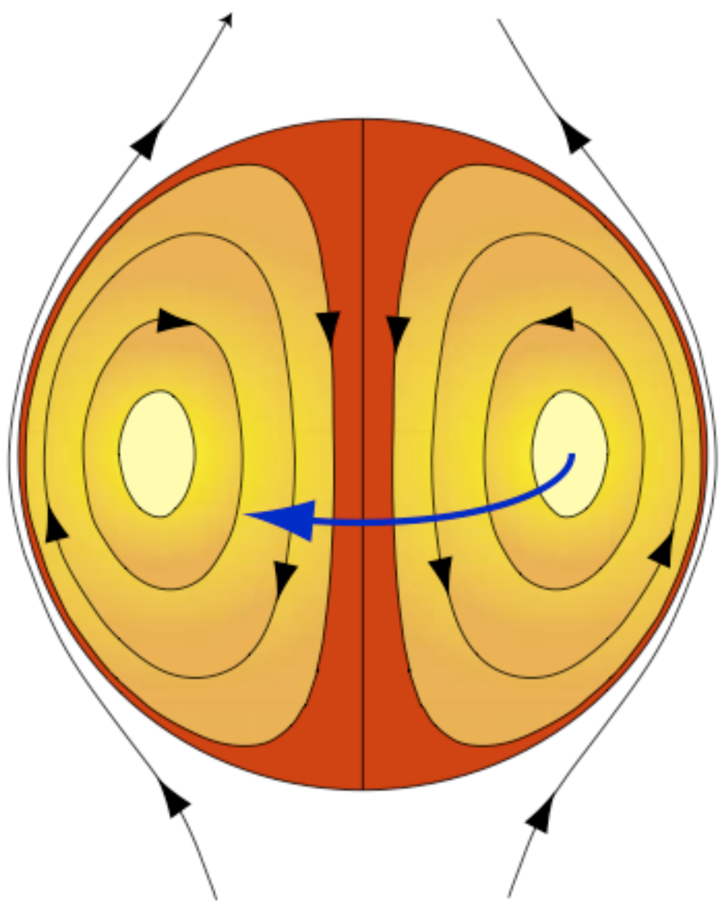
Reconnection in Jets and Lobes

Flux conversion in the lobes?

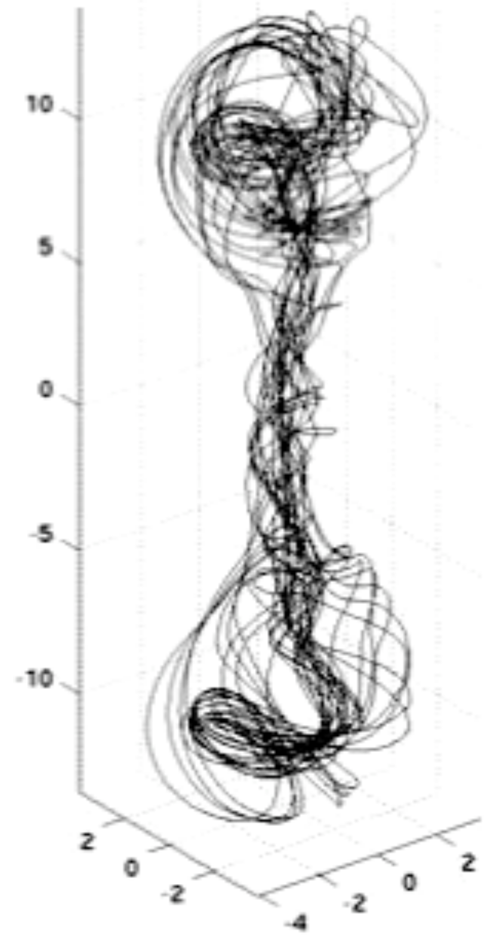
Herc A



spheromak



**modelin
g**



#4: c) Relativistic Fluid-Kinetic Theory

- Need to treat fluid and kinetic physics together (for dissipation physics). Relativistic drift-kinetic or gyro-kinetic?
- Jet "sigma-problem"
- Lack basic theoretical formulation and simulation tools to treat relativistic fluid theory while including relativistic kinetic physics in a self-consistent fashion

A National "Jet" Consortium?

(similar to EU/JetSet team)

- Set up mutual visitor programs, yearly workshop on jet/outflows that include laboratory, observation, plasma theory/ simulation.
- Consortium will ensure much better "coupling" among astronomical and plasma communities
- Perhaps led by DOE/OFES in close collaboration with NSF and NASA.
- Several "Grand Challenges" projects/teams championed by DOE/OFES?