Dynamics of gas and cosmic rays inside the huge radio-x-ay cavity of Cygnus a: similarities with the Fermi Bubbles

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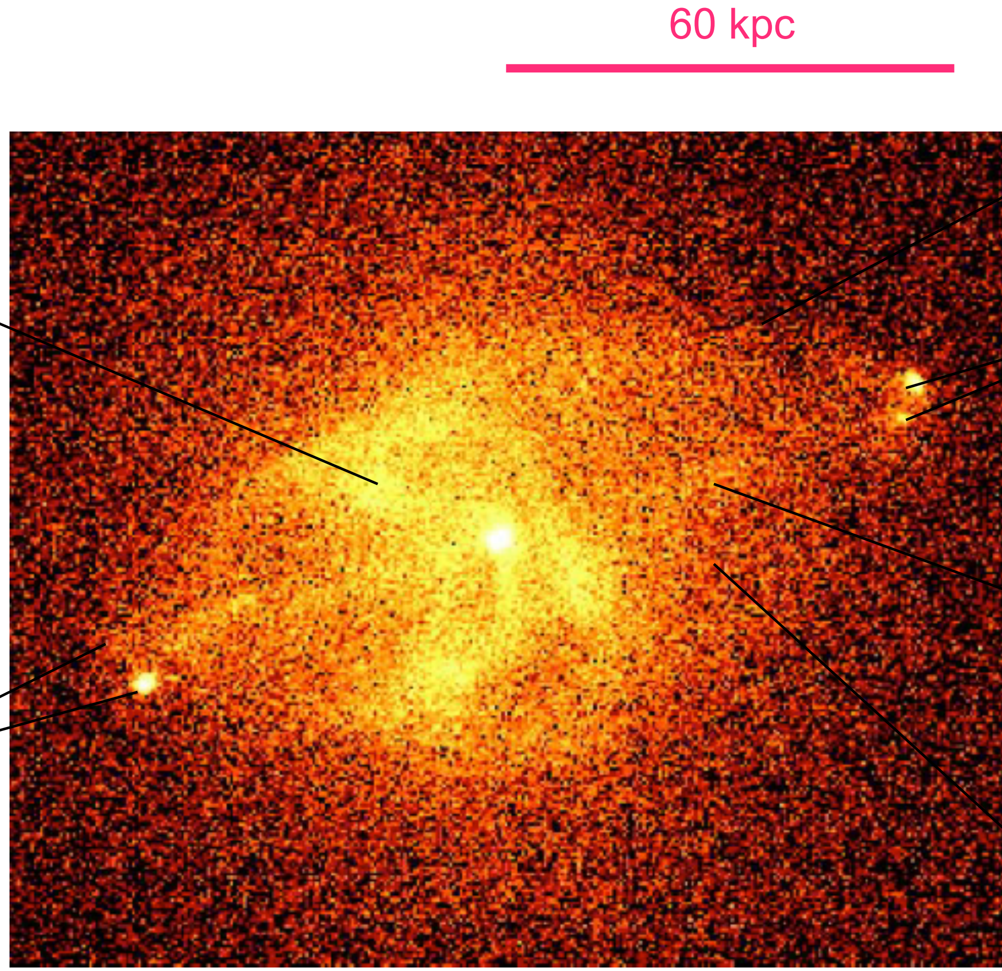
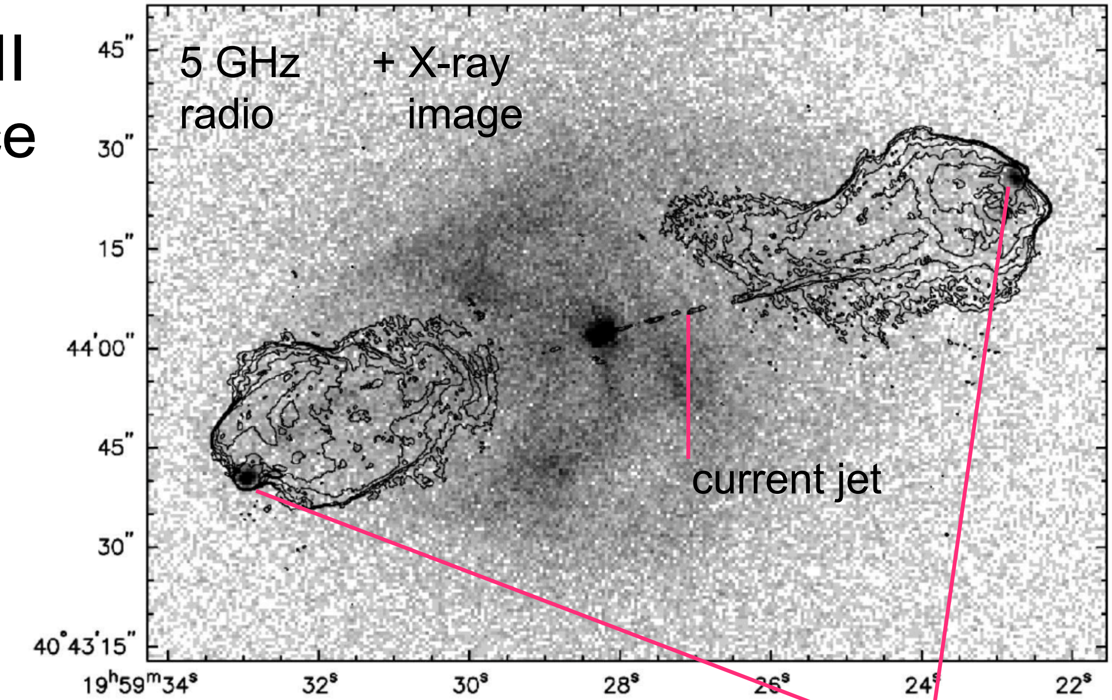
Chandra X-ray image of Cygnus A



located at center of cluster of mass ~10^{15} M_{sun}

Cygnus A is a classic FRII double lobe radio source

age of Cygnus A event is ~10^7 yrs
from sync. losses
Mach no. of bow shock

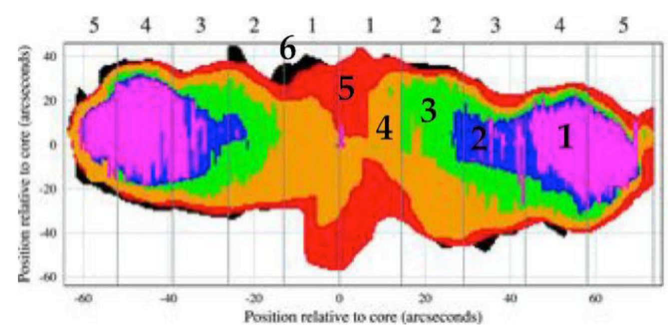


radio hotspots

jet volume is small -- no hotspot yet

high energy CRes emit at high-ν closer to hotspot

1 15 GHz
2 8
3 5
4 1.34
5 0.33
6 0.15

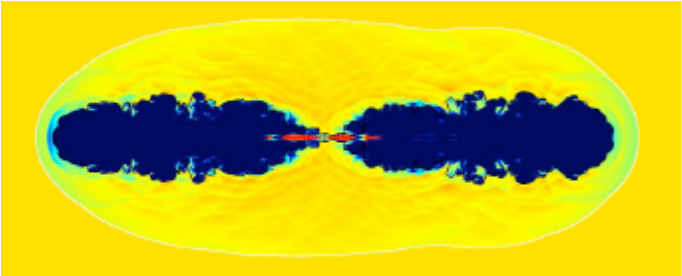


6 radio images super-imposed

well-ordered radio electron ages

three most recent jet-driven FRII lobe calculations

2D hydro

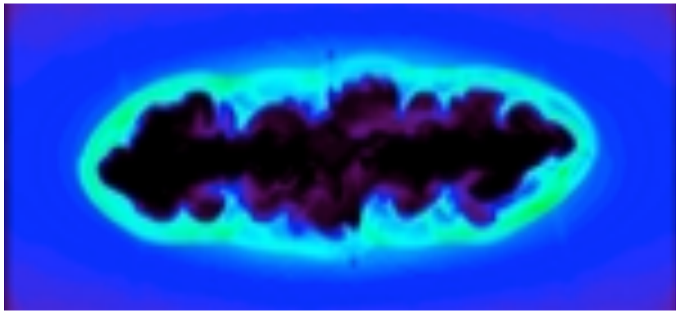


2013

radio cavities are dynamically chaotic

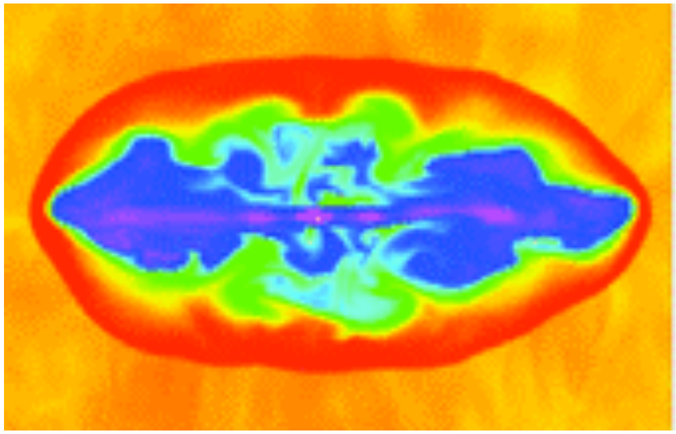
radio electron ages will be mixed

3D MHD



2011

3D MHD



2011

it’s time for a more realistic computation!

2D axisymmetric computations with a relativistic component

gas: $P = (\gamma - 1)e \quad \gamma = 5/3$

CRs: $P_c = (\gamma_c - 1)e_c \quad \gamma_c = 4/3$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = -\nabla(P + P_c) - \rho\nabla\Phi$$

$$+ \nabla \cdot \mathbf{\Pi} + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B}$$

viscous force

ignore Lorentz force: observe $B^2/8\pi << e_c$

thermal energy density

$$\frac{\partial e}{\partial t} + \nabla \cdot \mathbf{u}e = -P(\nabla \cdot \mathbf{u}) - \mathcal{L}_{rad} + \mathbf{\Pi} : \nabla\mathbf{u}$$

ignore radiation losses: small during t_{age} ~10^7 yrs

viscous dissipation

CR energy density*

$$\frac{\partial e_c}{\partial t} + \nabla \cdot \mathbf{u}e_c = -P_c(\nabla \cdot \mathbf{u}) + \nabla \cdot (\kappa \nabla e_c)$$

ignore CR diffusion: small during t_{age} if κ ~10^{28} cm^2/s as in Milky Way also: no age mixing

passive frozen-in field

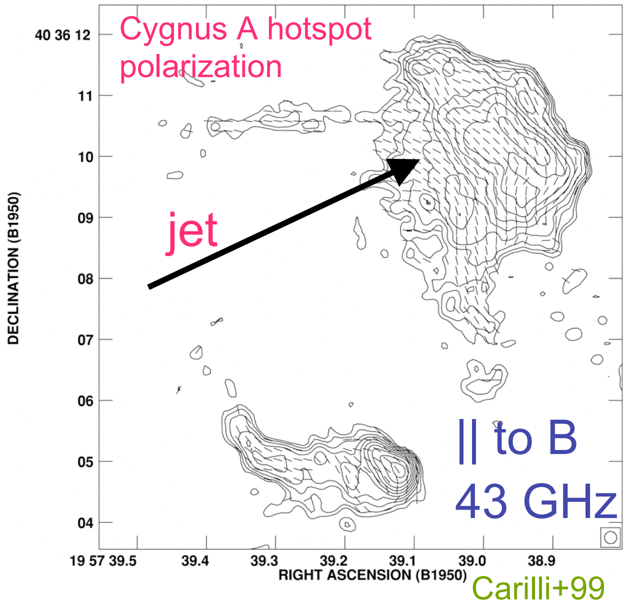
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) \qquad \nabla \cdot \mathbf{B} = 0$$

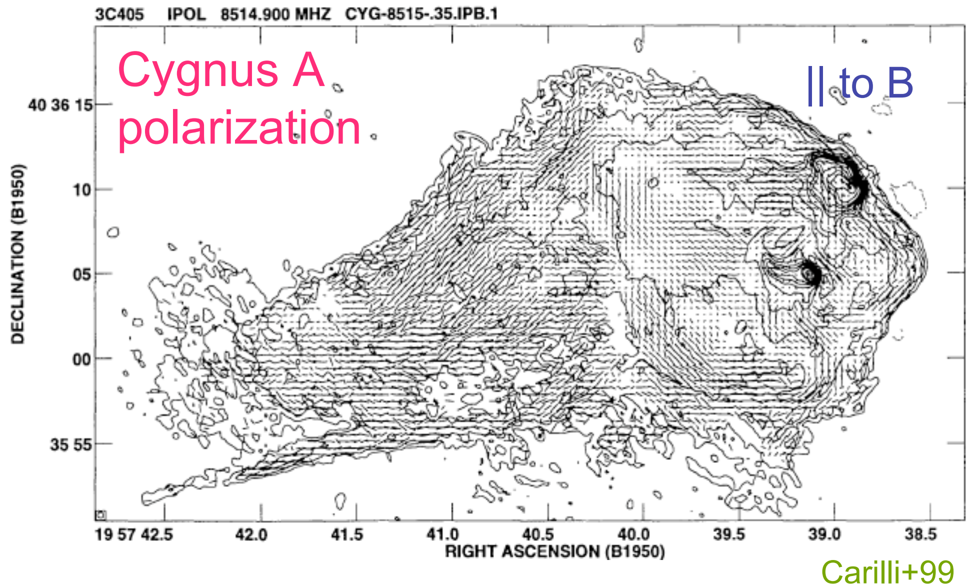
*expect $P_c > P$

radio polarization observations

hotspot field is largely ~ toroidal

but non-toroidal fields appear downstream





assume a purely toroidal field

poloidal fields cannot be used in moving hotspot sources without violating divB=0 – true for all common MHD codes

assume a hotspot-driven flow: jet is not explicitly computed

this is OK since:

- jet occupies a negligible volume
- hotspots are brighter than jets: e_c & B are well observed

in hotspot-driven flows:

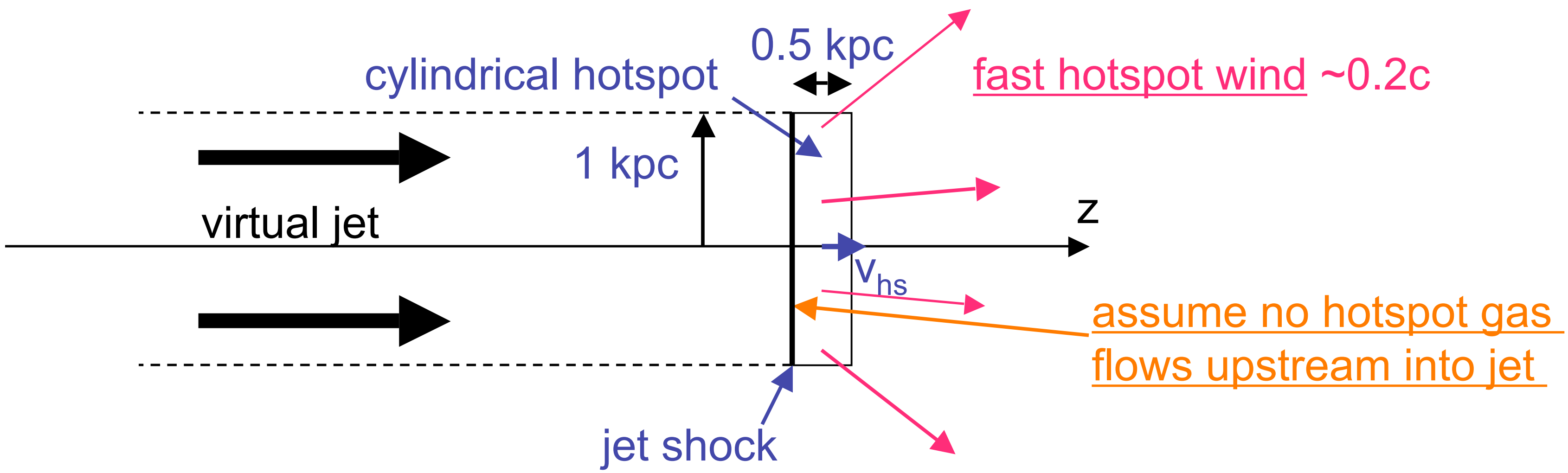
- all plasma, CRs & field in cavity come from the hotspot

at each time step moving hotspot is injected with

(1) 10^{46} erg/s of relativistic CRs to fill Cygnus A radio cavity volume in 10^7 yrs
(2) 1 M_{sun}/year of non-relativistic gas with v_{hs} -- for B to freeze onto
(3) toroidal hotspot field is reset to observed value: B_{hs} ~ 200 μG

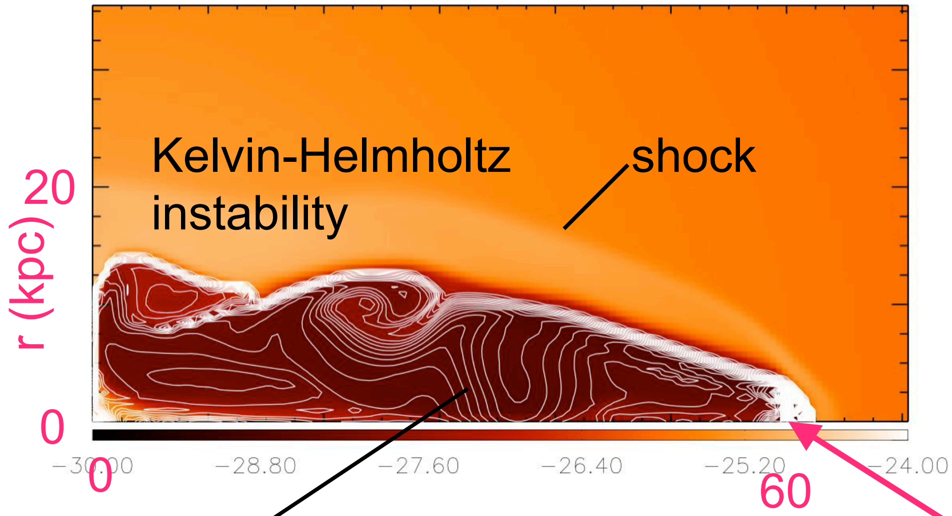
hotspot source zones move on the grid at constant velocity along z-axis:

v_{hs} = 60kpc/10^7yrs = 5800 km/s



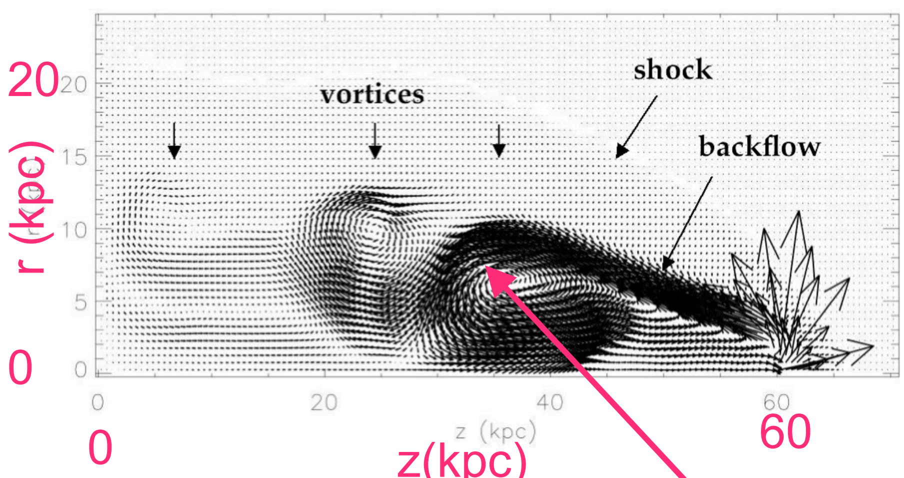
after 10^7 yrs:

density



gas density with CR energy density contours

velocity



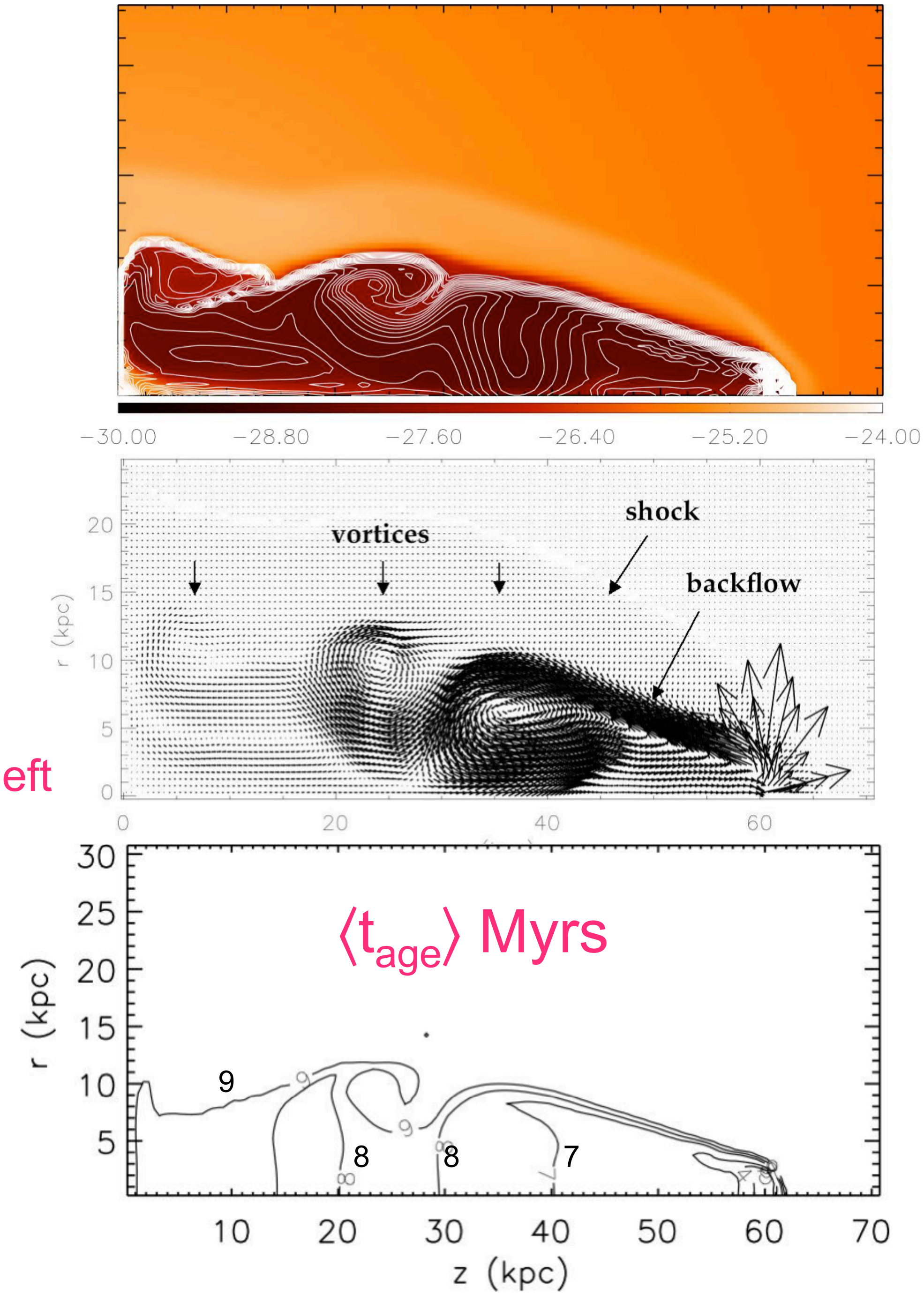
boundary backflow disturbed by internal KH vortices

Kelvin Helmholtz instability first occurs inside cavity, not at cavity boundary density

velocity

advect time CRs left hotspot t_{hs}

projected CR age 10 - t_{hs} weighted along los by synchrotron emission

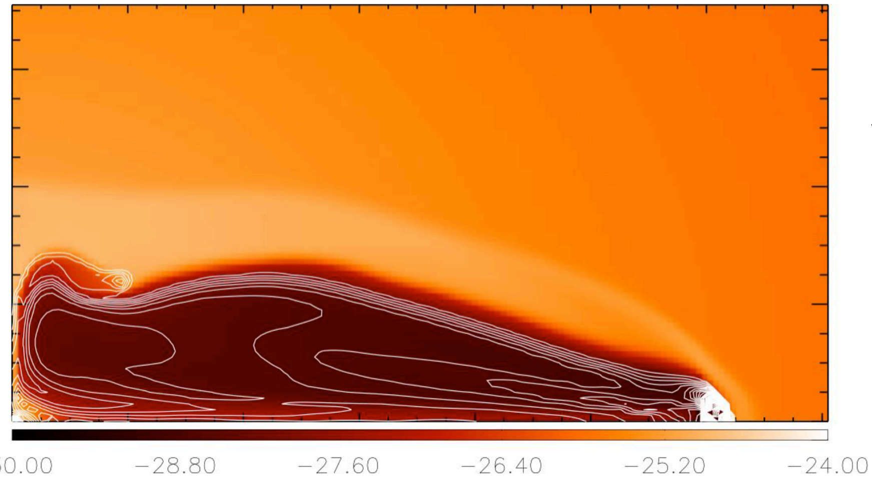


projected sync. age is <u>not monotonic</u> as in Cygnus A

Must stop KH with (huge) B or viscosity…

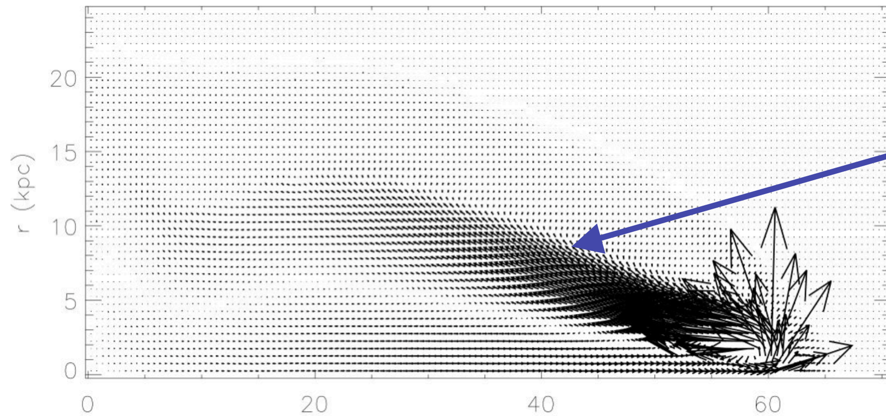
Repeat with viscosity
t = 10^7 yrs

density



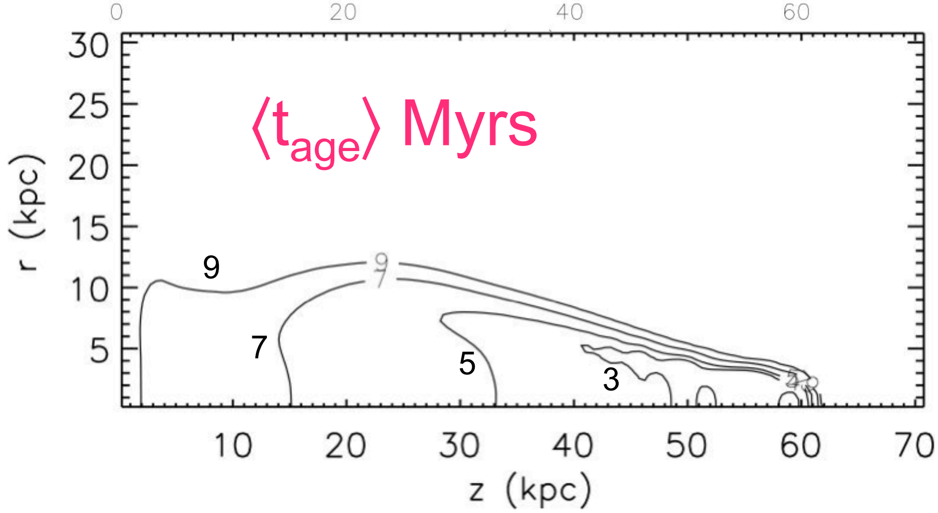
KH is suppressed with small viscosity
μ = 30 gm/(cm s)

velocity



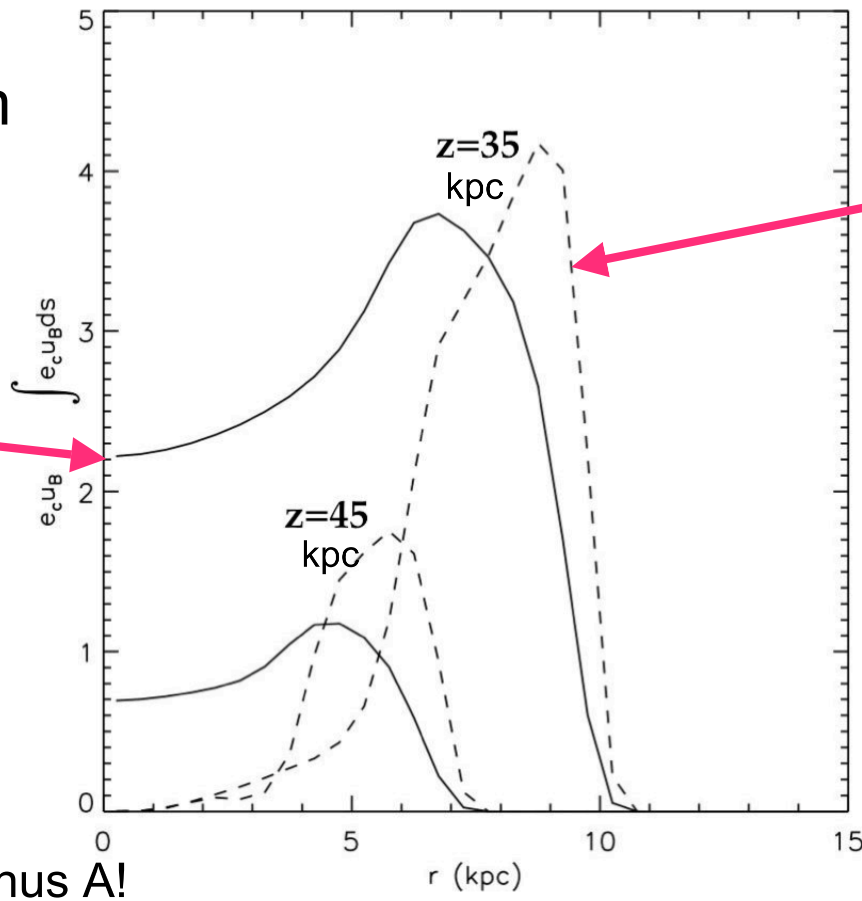
first computation of smooth boundary backflow!

projected CR age 10 - t_{hs} weighted along los by synchrotron emission



now CR age varies monotonically as in Cygnus A synchrotron emission from computed boundary backflow

sync. surface brightness $\int e_c u_B \, ds$



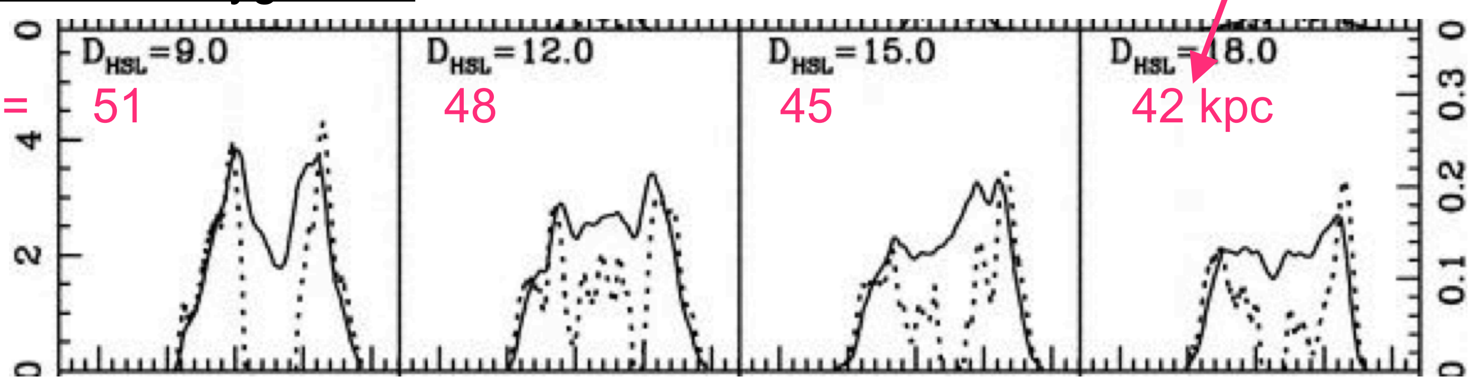
$e_c u_B$ (proxy for sync. emissivity) peaks at radio lobe boundary

$$\boxed{u_B = \frac{B^2}{8\pi}}$$

z kpc from center

is observed in Cygnus A!

z =



-20 0 20
arcsec (kpc)

Carvalho+05

1.3GHz

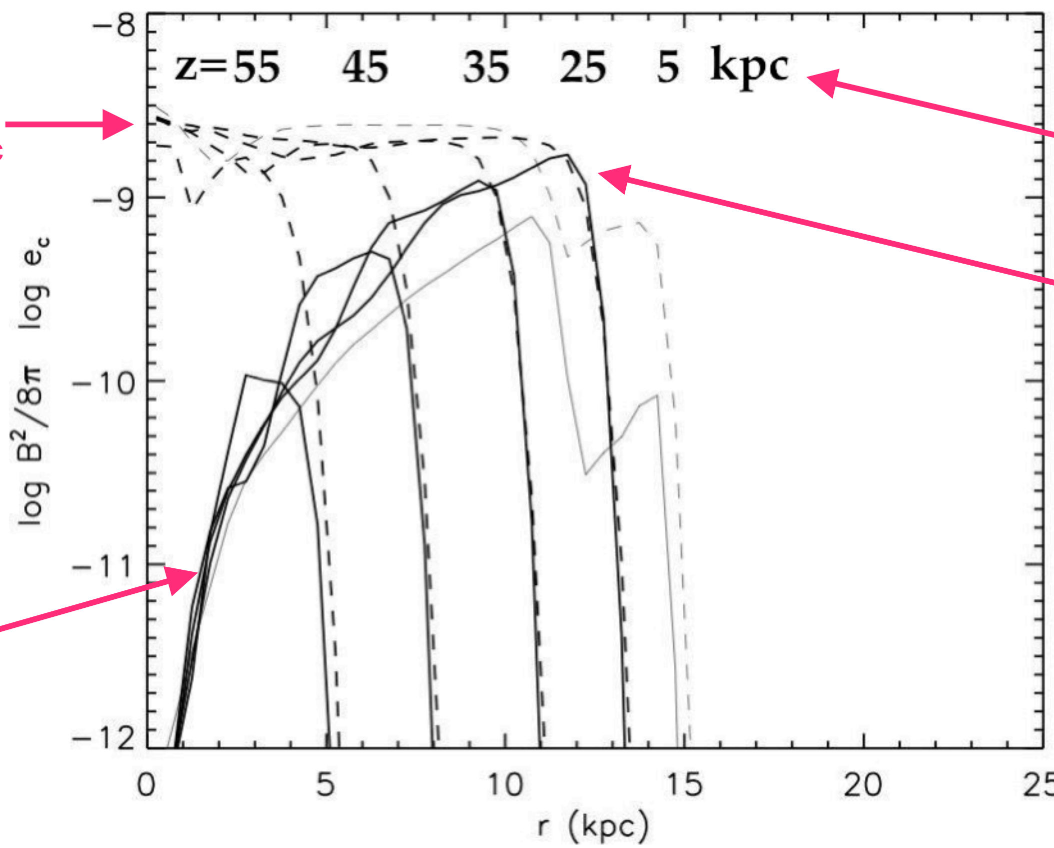
radio emission from active FRII radio lobes
along boundary backflow is very limb-brightened

similar to γ-ray IC emission in the Fermi bubbles for first time: can connect observed B_{hs} and $B_{backflow}$

a toroidal field increases in decelerating flow $u_z \perp B$

radio lobe CR pressure is nearly uniform

$3P_c$



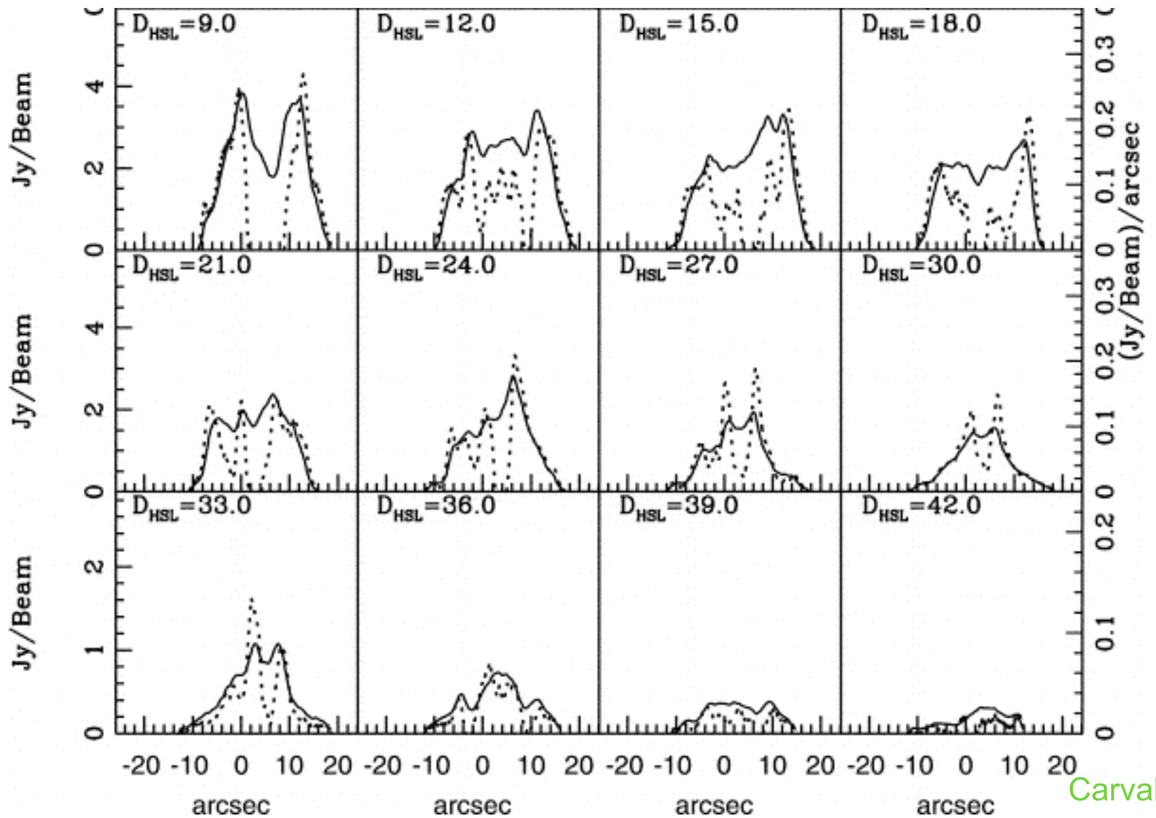
kpc from center

backflowing field

$\frac{B^2}{8\pi}$

backflowing toroidal magnetic field Is ~20X too large and the computed radio emissivity $e_c u_B$ increases along decelerating boundary backflow

but observed radio emissivity $e_c u_B$ in Cygnus A
decreases along boundary backflow



Carvalho+05

1.3GHz

possible solutions:

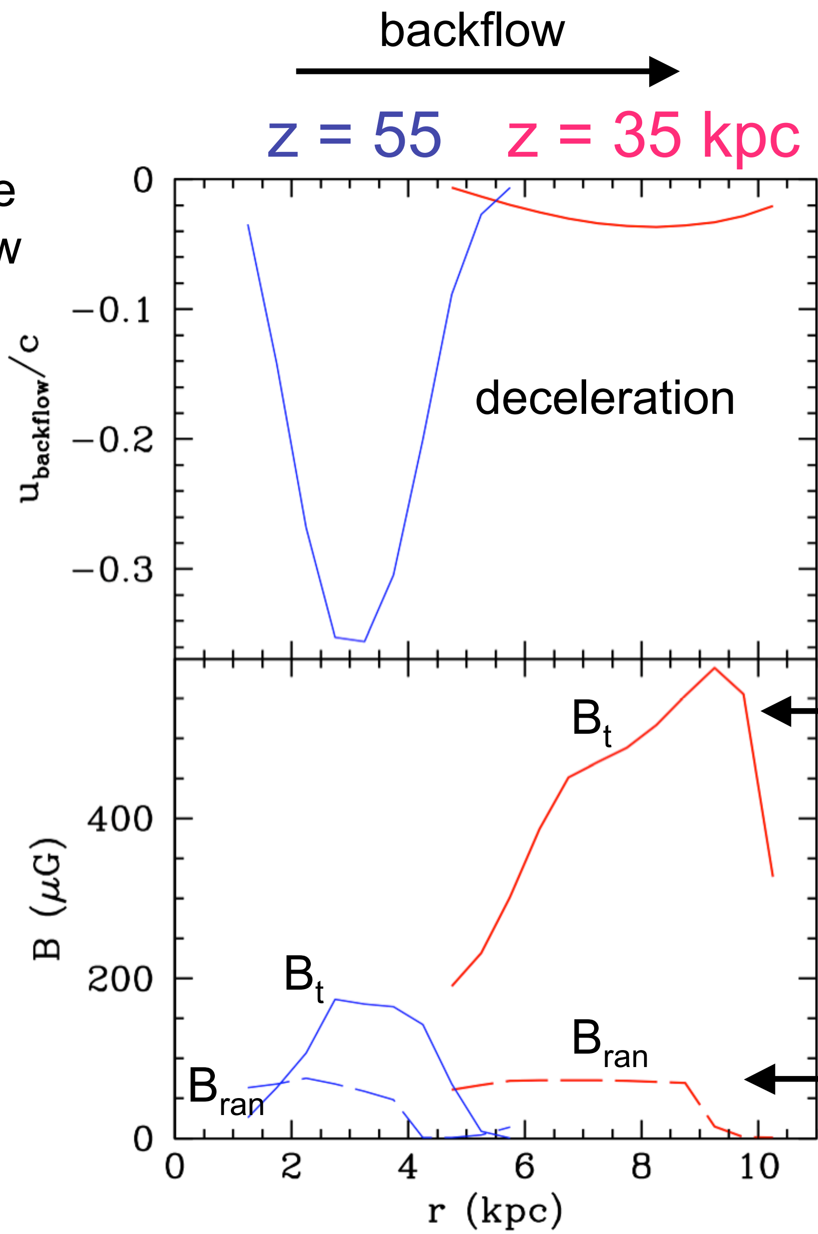
replace $e_c u_B$ with $\int n(\gamma,\mathbf{r},t)\, \varepsilon(\gamma,u_B)\, d\gamma$
include CRe diffusion
B(t) from hotspot may decay?
B field may be disordered

if B field is randomized along the backflow: $\boxed{B_{ran} = B_{hs}(\rho/\rho_{hs})^{2/3}}$

(flux-conserving)

$\rho_{hs}(t)$ is known at retarded time

negative backflow velocity



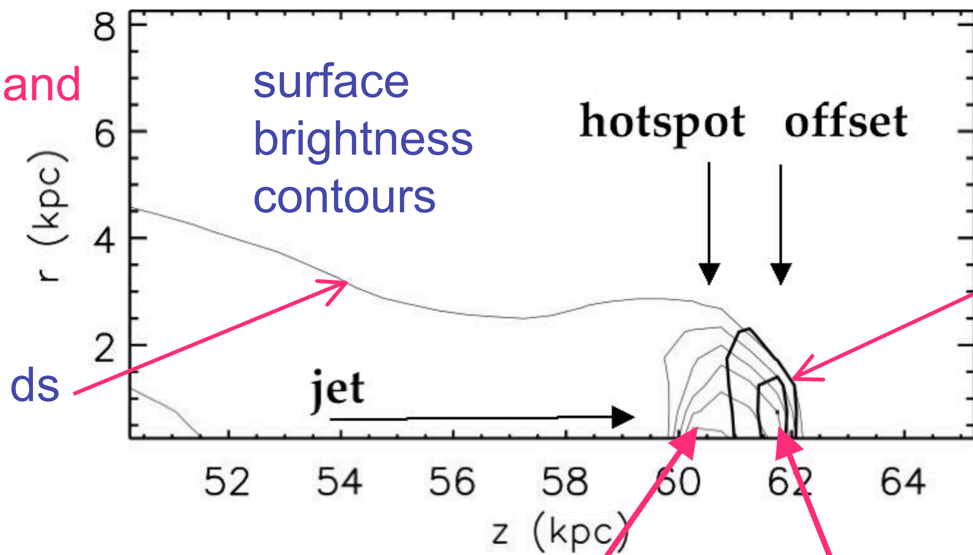
frozen-in toroidal field becomes much too large

assume B_{hs} = 200 μG for both fields (too large?)

a random ~70 μG field may be consistent with observed hs and lobe fields

non-thermal radio and X-ray emission near hotspot

B in hotspot wind grows exponentially as wind decelerates and compresses against dense (shocked) cluster gas ahead



$\int e_c\, u_{cmb}\, ds$

$\int e_c\, u_B\, ds$

HOTSPOT

weak radio sync.

$\int e_c\, u_B\, ds$ <<

OFFSET

strong radio sync.

$\int e_c u_B\, ds$

strong X-ray

synchroton self-Compton (SSC)

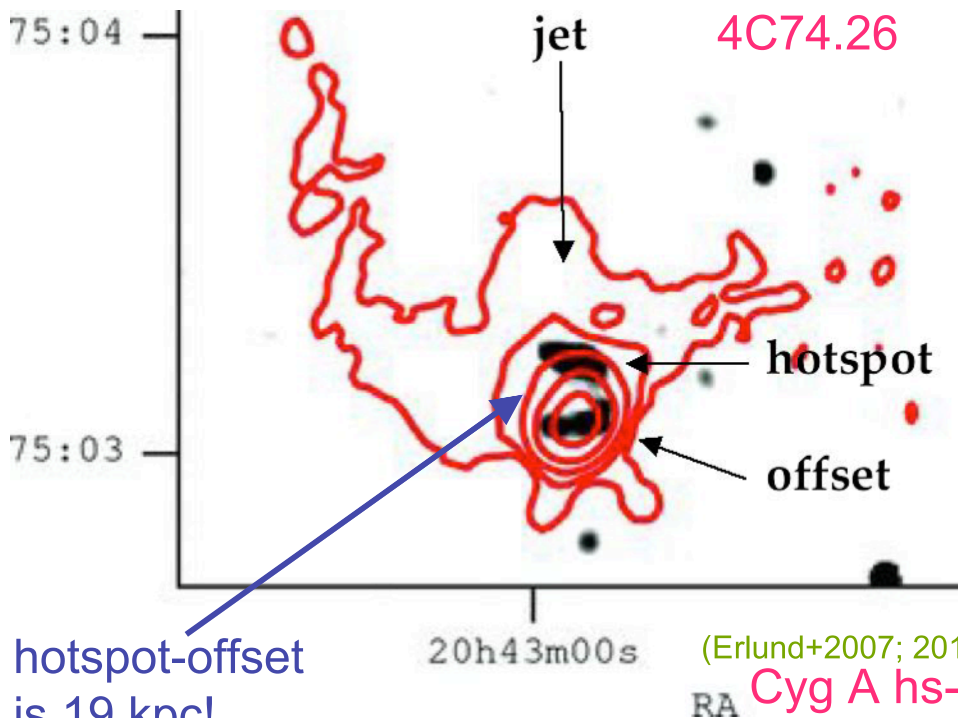
$\int e_c u_{sy}\, ds$ $\quad u_{sy} \sim L_{sy}(r/c)/V$

the brightest radio & X-ray emission is

not from the hotspot

but from the arc-shaped offset compression ~1.5 kpc ahead compare the incredibly powerful FRII hotspot in 4C74.26

500 kpc from its cluster center   <u>can observe both hotspot and offset</u>



hotspot-offset
is 19 kpc!

Red contours: radio observations 1.4GHz

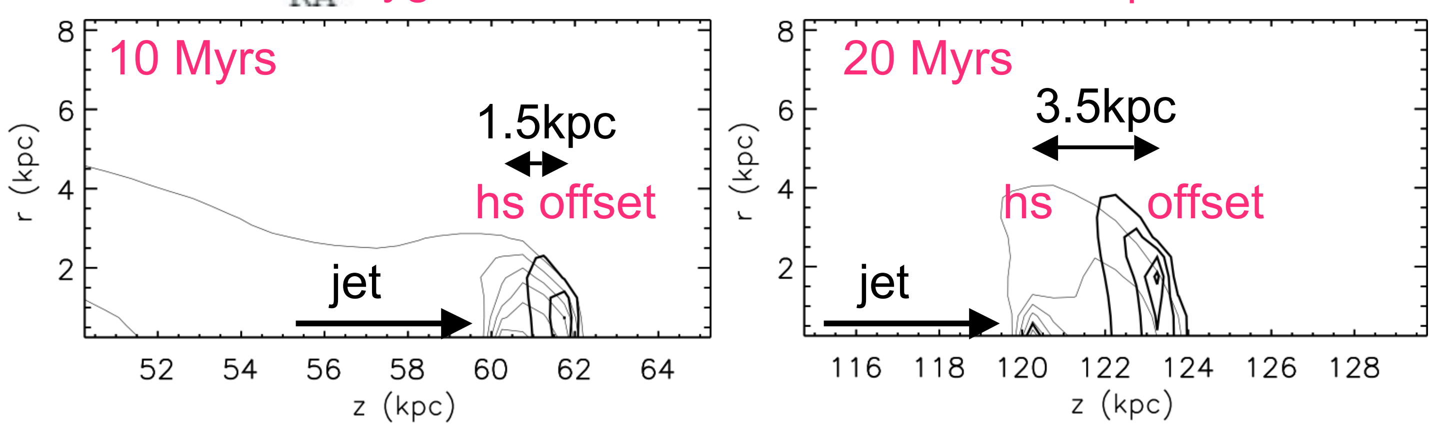
Grey scale: X-ray image

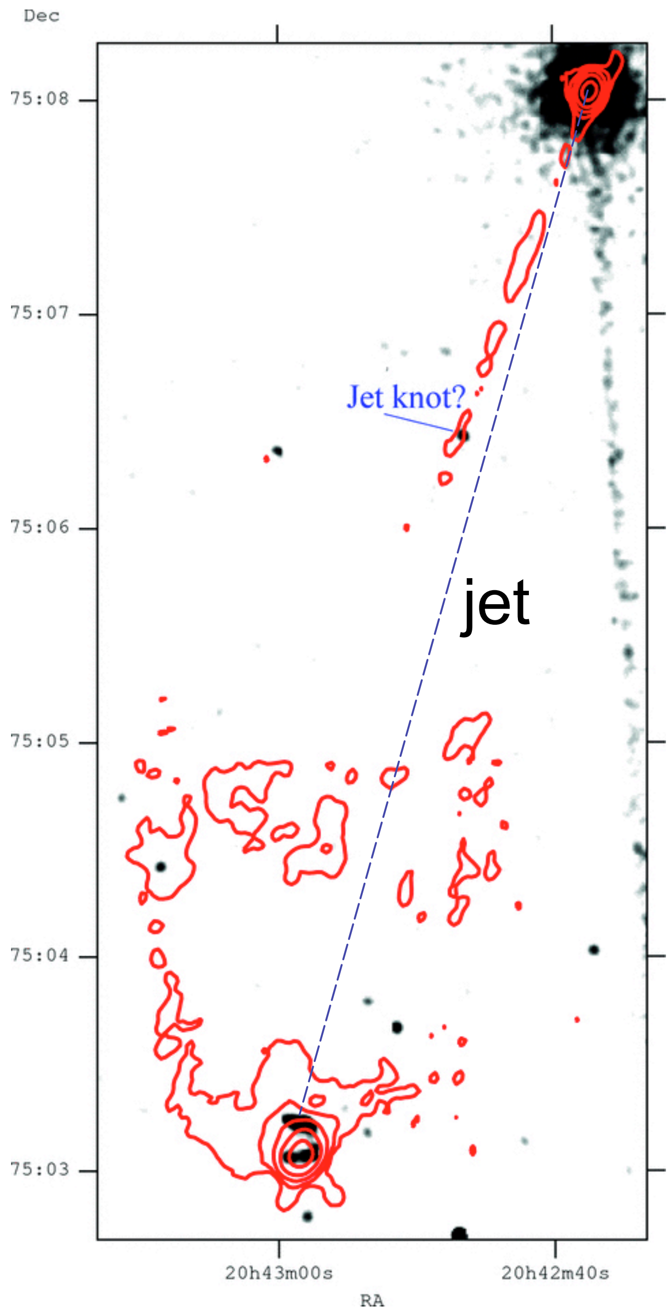
<u>X-ray sync. emission</u> from hotspot?

radio sync. & X-ray SSC
from arc-shaped offset

(Erlund+2007; 2010)

Cyg A hs-offset increases as cluster ρ decreases:





hotspot elongated
perpendicular
to jet

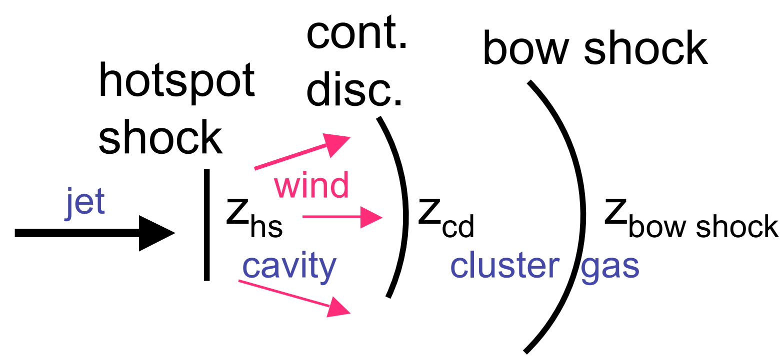
tilted offset X-ray
and radio emission
indicates inclination
of local cavity wall

subsonic communication determines hotspot-offset distance

consider 1D flow along jet direction

Mach number in frame of cavity-cluster contact discontinuity $u_z(z_{cd})$

$$\mathcal{M} = \frac{u_z(z) - u_z(z_{cd})}{c_s} < 1$$

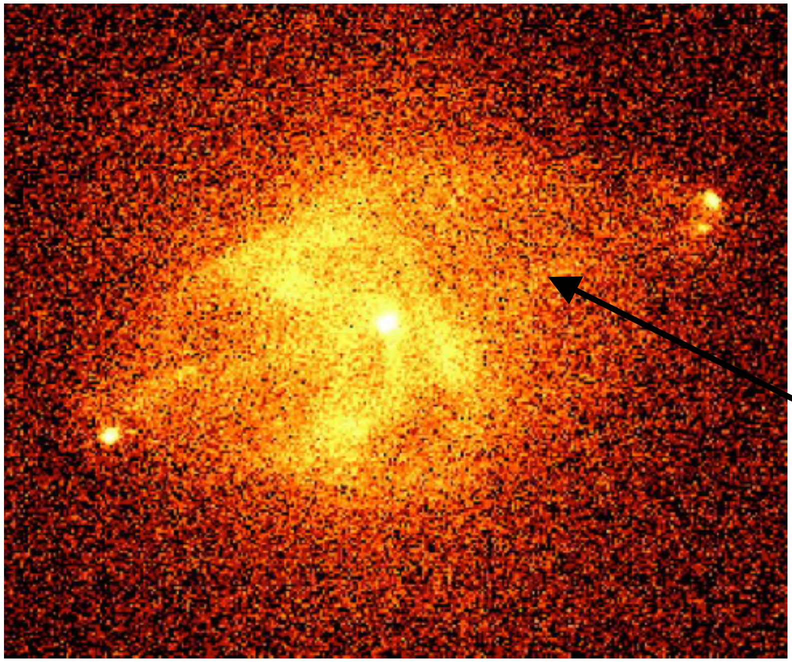


is subsonic between the hotspot shock and cluster gas bow shock.

in our calculation the hotspot is required to move at constant velocity, but

- in reality the hotspot shock can back off from the cavity boundary until the recoil momentum of the hotspot wind balances the jet momentum

Possible explanation of multiple hotspots (common in FRIIs)



multiple hotspots:
- jets must relocate abruptly in ~10^5 yrs
- jet fragments still activate visible hotspots

thermal X-ray filaments lie exactly along the same symmetry axis as the non-thermal jet

low-momentum jets may be deflected by scattering off density inhomogeneities in the thermal filaments

some conclusions of hotspot-driven FRII evolution:

- KH instabilities inside the radio lobe must be damped
  to reproduce smooth radial variation of radio electron ages
  viscous damping more likely than magnetic damping?

- radio synchrotron emission occurs in a narrow boundary backflow.
  sync. emission in active radio lobes is hollow – as observed

- the bright radio-X-ray "hotspots" in Cygnus A
  are offset ahead of the true post-shock hotspot
  brightest radio sync. and X-ray SSC emission
  comes from compression of the hotspot wind

- the observed hotspot magnetic field, if toroidal,
  evolves into lobe fields much larger than observed
  lobe B may be random -- replace $e_c u_B$ with $\int n(\gamma,\mathbf{r},t)\ \varepsilon(\gamma,u_B)\ d\gamma$ --
  include CRe diffusion -- B(t) from hotspot may decay

- computed flow is subsonic between jet shock and cluster bow shock,
  allowing the hotspot-offset distance to adjust to the jet momentum

- multiple hotspots commonly observed in FRII sources
  may result from occasional deflections of low momentum jets
  by thermal filaments that also lie along the jet axis