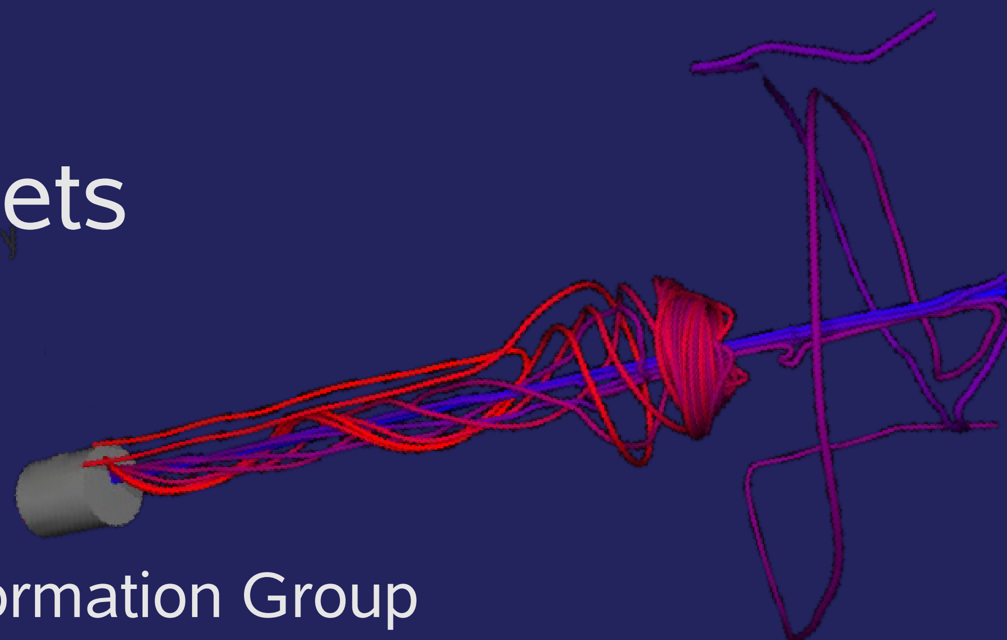
Magnetic Fields in Large-scale Jets



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Theoretical Structure Formation Group
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Martin Krause (MPE Garching)
Sadegh Khochfar (MPE Garching)

Outline

- Jet – Galaxy/ISM interaction
- X-ray cavities
- Turbulent cocoons
- Efficient thermalization
- Magnetic fields: stabilization & amplification of fields
- Ongoing work

most results:
Gaibler, Krause, Camenzind (submitted to MNRAS, 2009)

Why Jets?

- Massive elliptical galaxies formed already at high redshift
  Most massive SMBH also form early

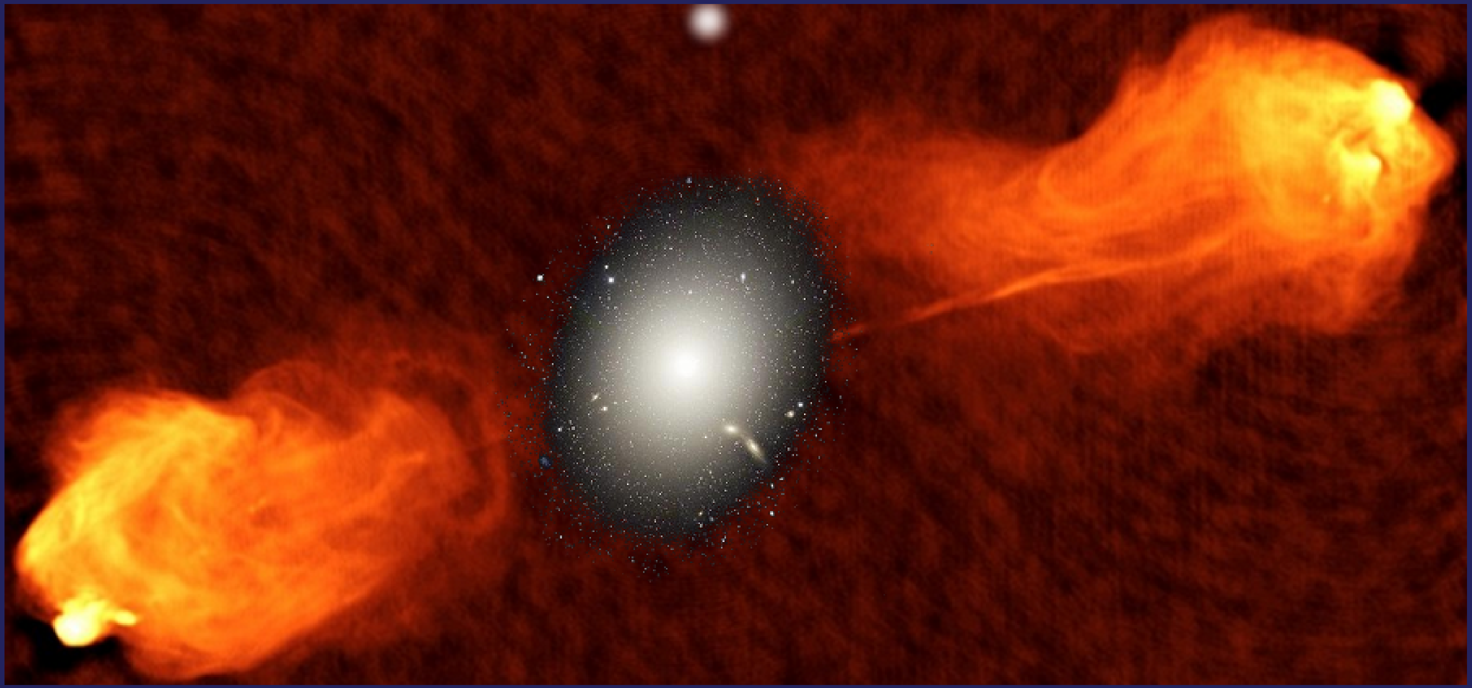
- Can AGN feedback get it done?
  - quench star formation in massive ellipticals
    (negative feedback)
  - trigger star formation by jet activity
    (positive feedback)

- Open questions (cf. Joe Silk's talk):
  - star formation efficiency depends on turbulence in ISM
  - magnetic fields important to regulate SF
  - evidence for jet-triggered star formation:
    is that an option for early and strong SF?

- $\longrightarrow$ Jet feedback has to be examined in detail (resolved!)

Jet – Galaxy Interaction

- well-collimated beams
- only minor interaction with galaxy once they broke out???



Cyg A @ 5 GHz (with giant elliptical overlay, M87)
Perley+ 1984

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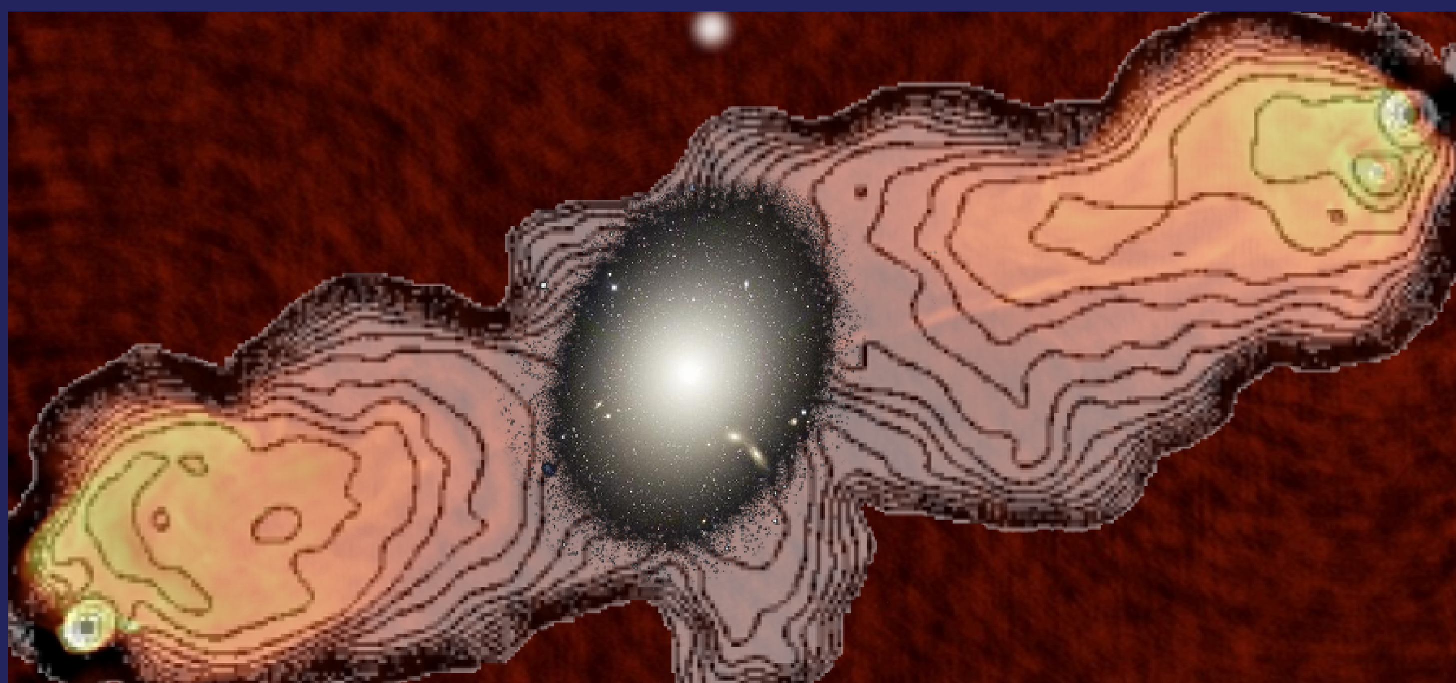


No!

Whole galaxy contained in cocoon

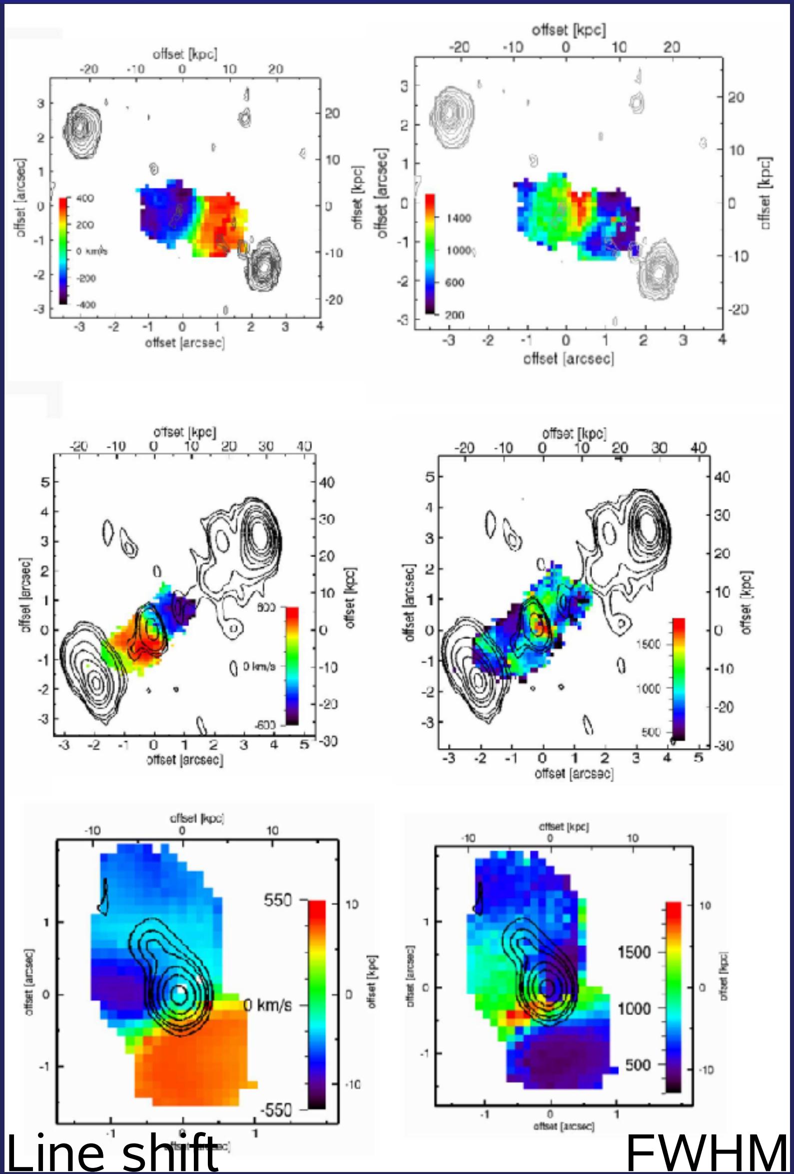
Cyg A @ 5 GHz
Perley+ 1984

Cyg A @ 327 MHz contour overlay
Lazio+ 2006

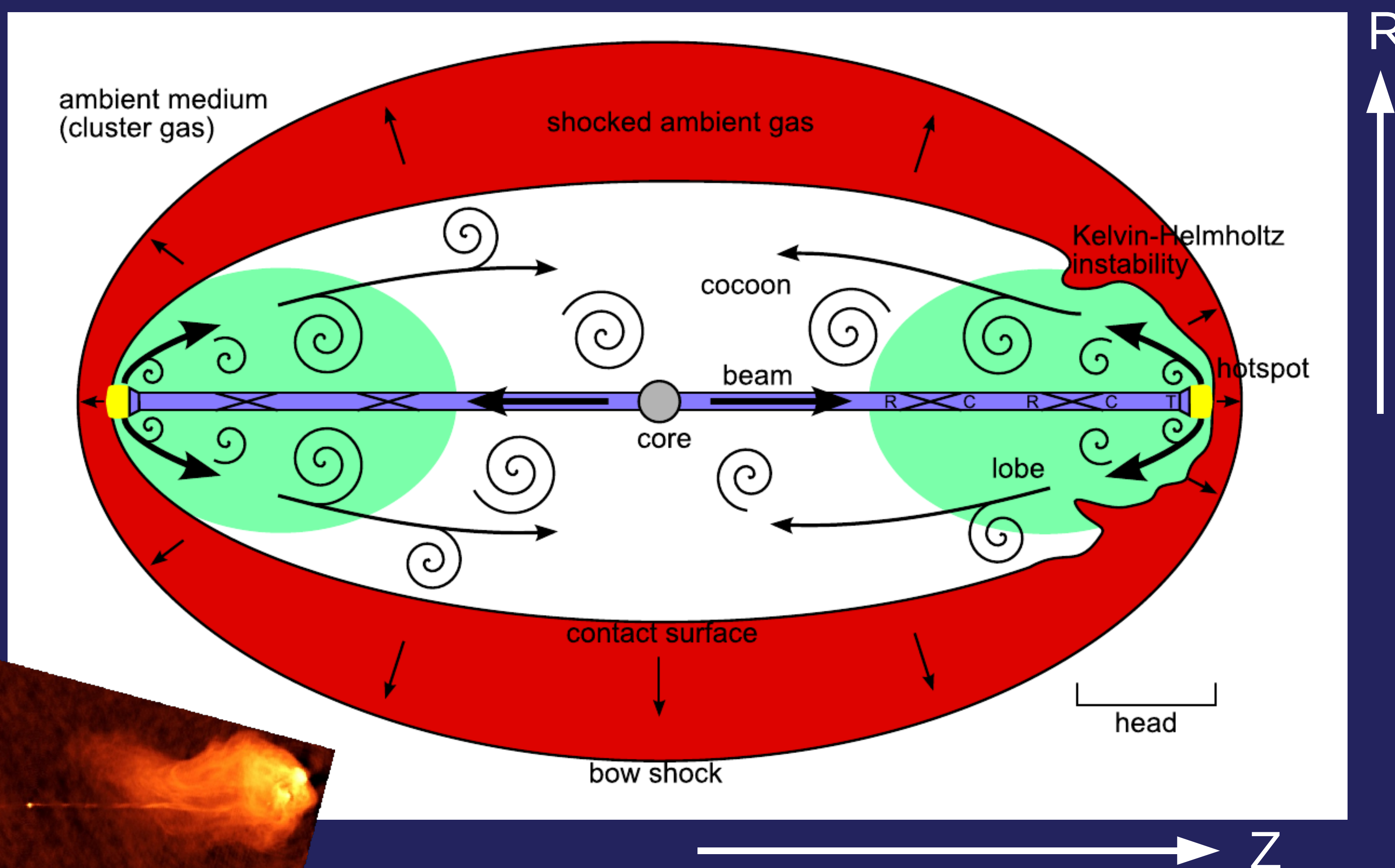
High-z Radio Galaxies

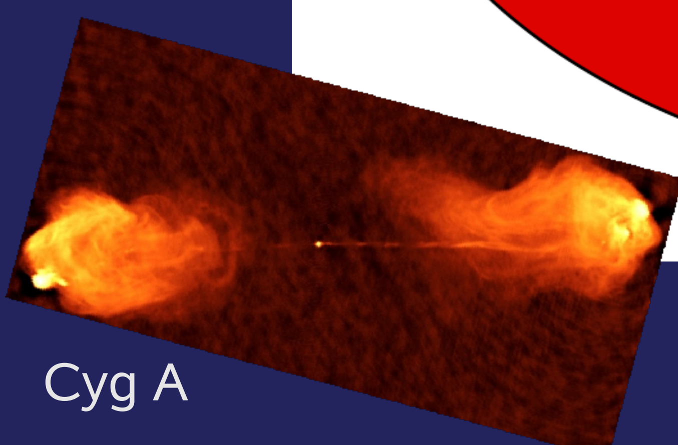
- Extended Emission Line Regions aligned with jets
- Outflows
- Highly turbulent motion (~ 1000 km/s)

Nesvadba+ 2008



Morphology

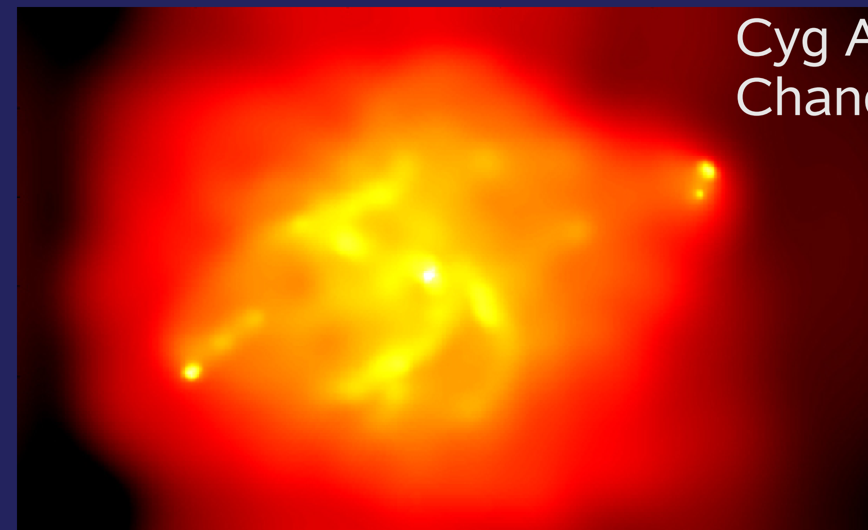


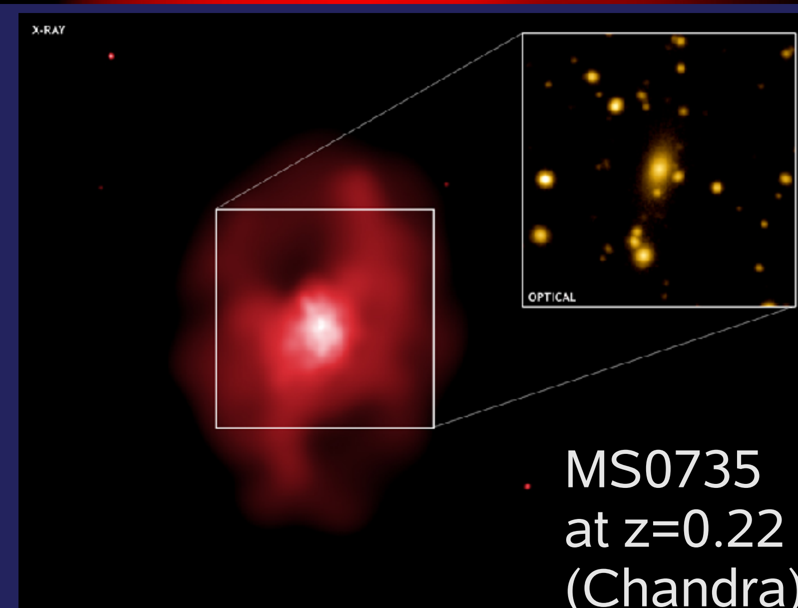


Cyg A

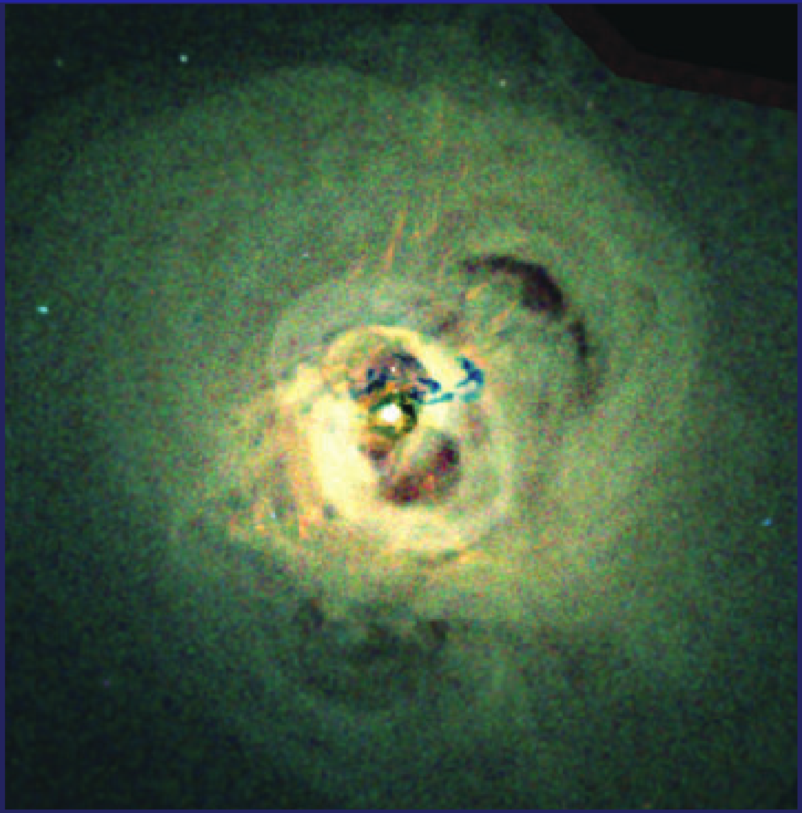
Ambient Gas & Cavities

- Thermal ambient gas:
  ICM in bremsstrahlung
- Cavities:
  ambient gas displaced
  by cocoon
- Relativistic particles
  synchrotron & inverse compton
  (beam and cocoon)



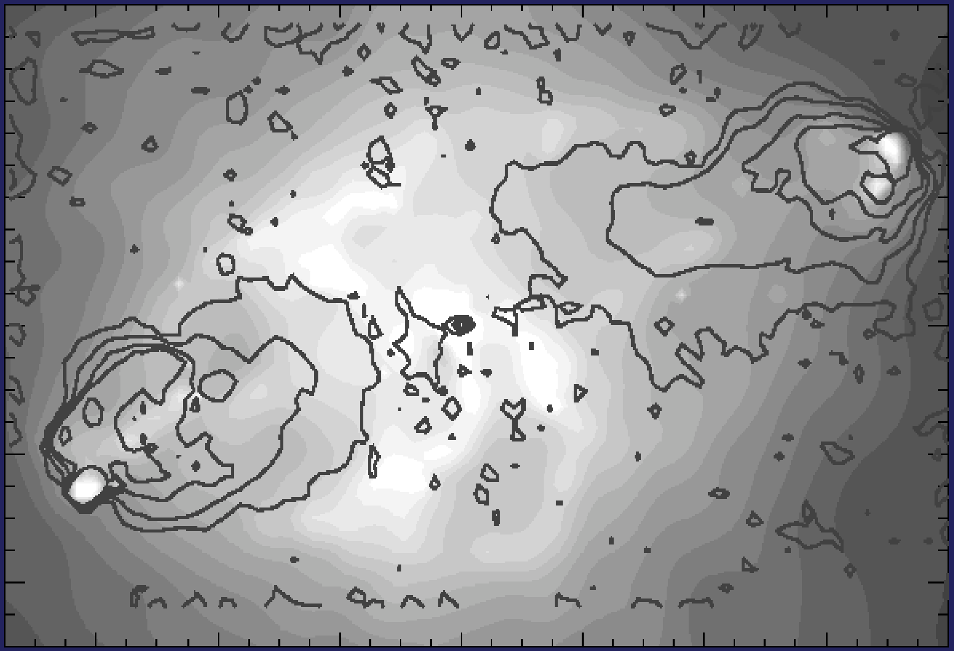


Jets and Cavities



Perseus A
(Fabian+ 2006)
z=0.0183
pV ~ 2 x 10^{59} erg
power 10^{44-45} erg/s

Cygnus A
(Wilson/Carilli/Perley)
z=0.0561
enthalpy 3 x 10^{60} erg
power 1.3 x 10^{45} erg/s



Very Light Jets

- Important: Density contrast: $\eta = \rho_{jet} / \rho_{ambient}$

our study:
$10^{-1} \ldots 10^{-4}$
under-dense jets

- AGN jets:
  despite their power very underdense on large scales!
  - mildly relativistic speeds of the beam plasma
  - but propagation much slower than jet speed
  - strong backflow
  - wide cocoons (Norman+ 1983)
- Estimate jet densities:
  - jet power, mass flux and jet speed
  - comparison to Eddington accretion limit
  - hotspot pressures (ram pressure)
  - propagation speeds

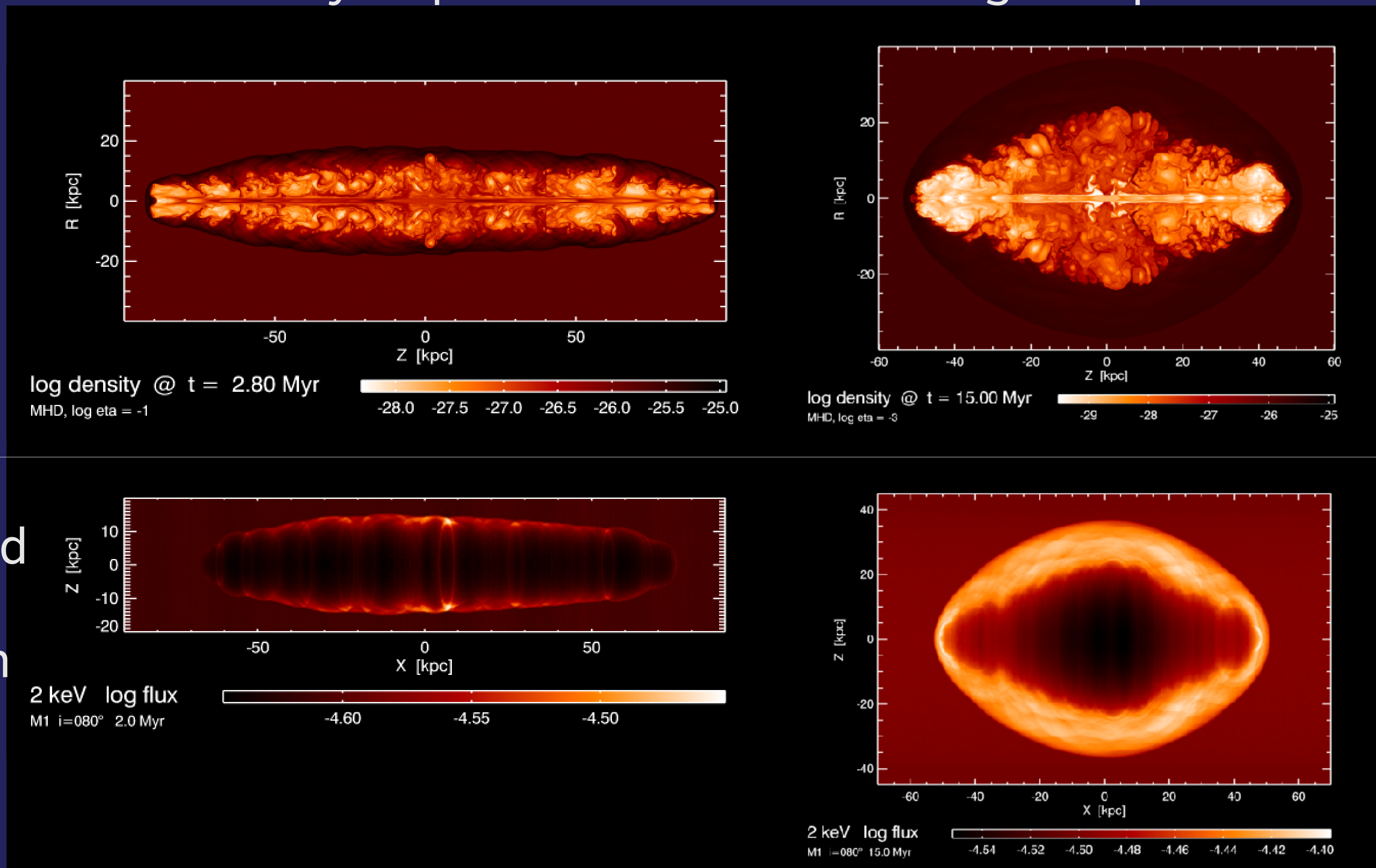
generally $\eta < 10^{-2}$

Density Contrast

"Heavy" $\eta = 10^{-1}$ "Light" $\eta = 10^{-3}$

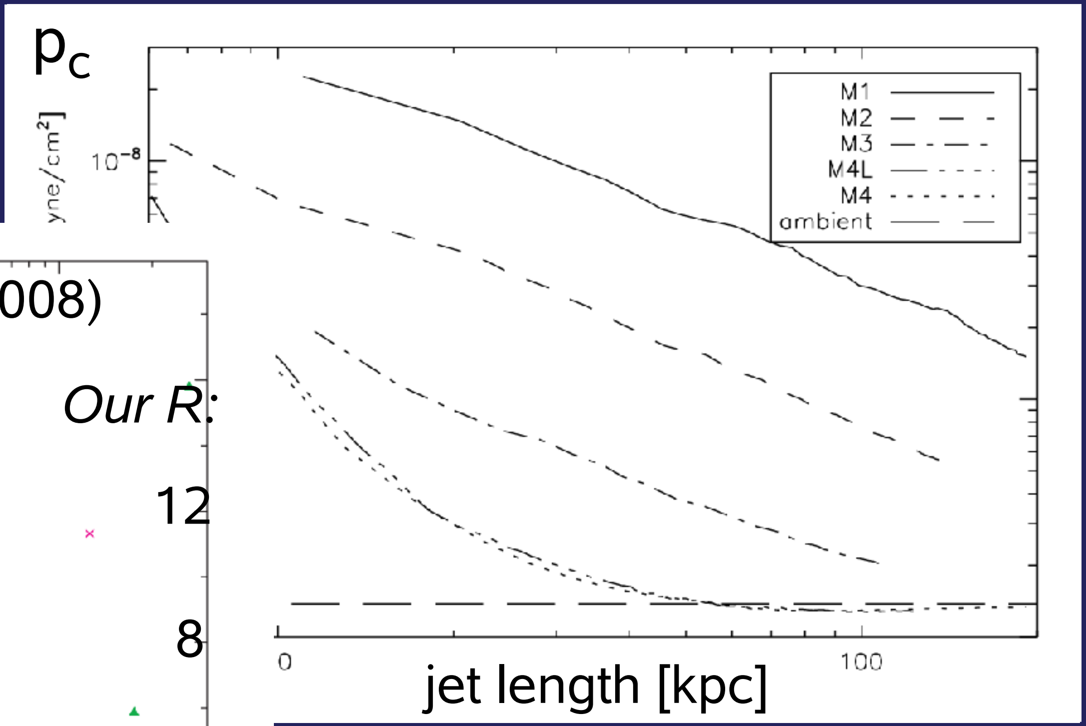
density

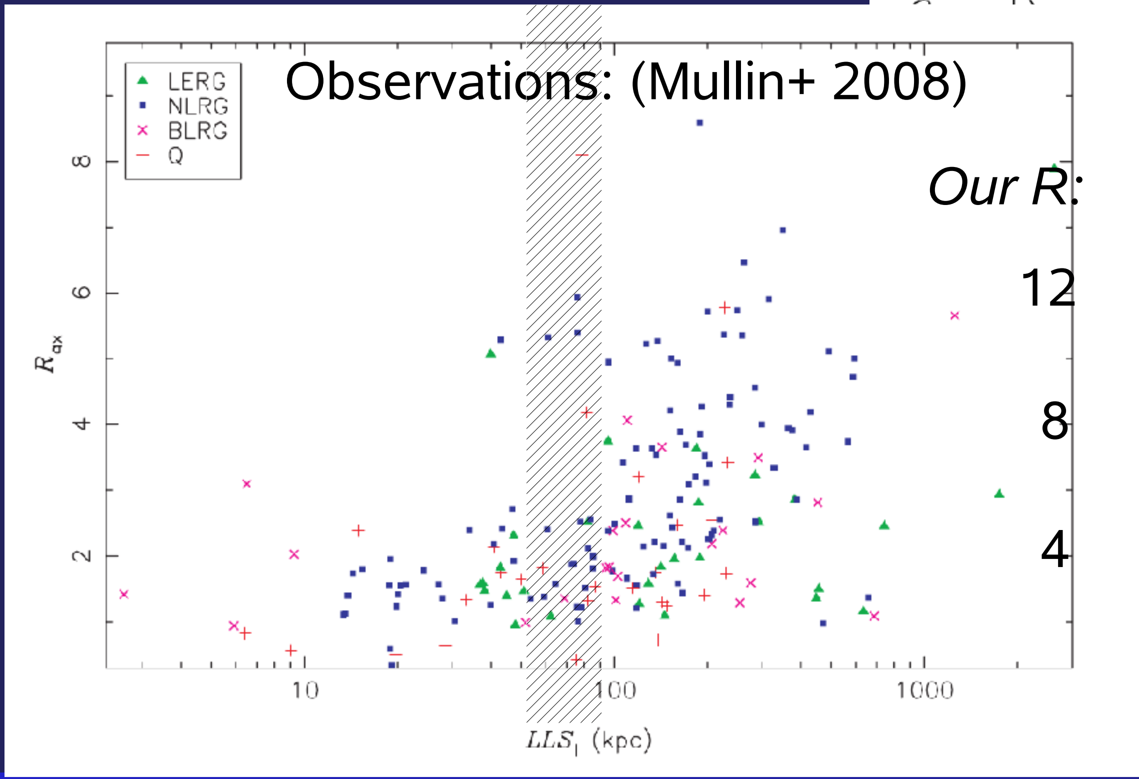
simulated X-ray emission



Cocoon Pressure

- selfsimilar models:
  $p_c \sim L_j^{2/3}$ length$^{-4/3}$
  aspect ratio = const





Jet – Galaxy Interaction

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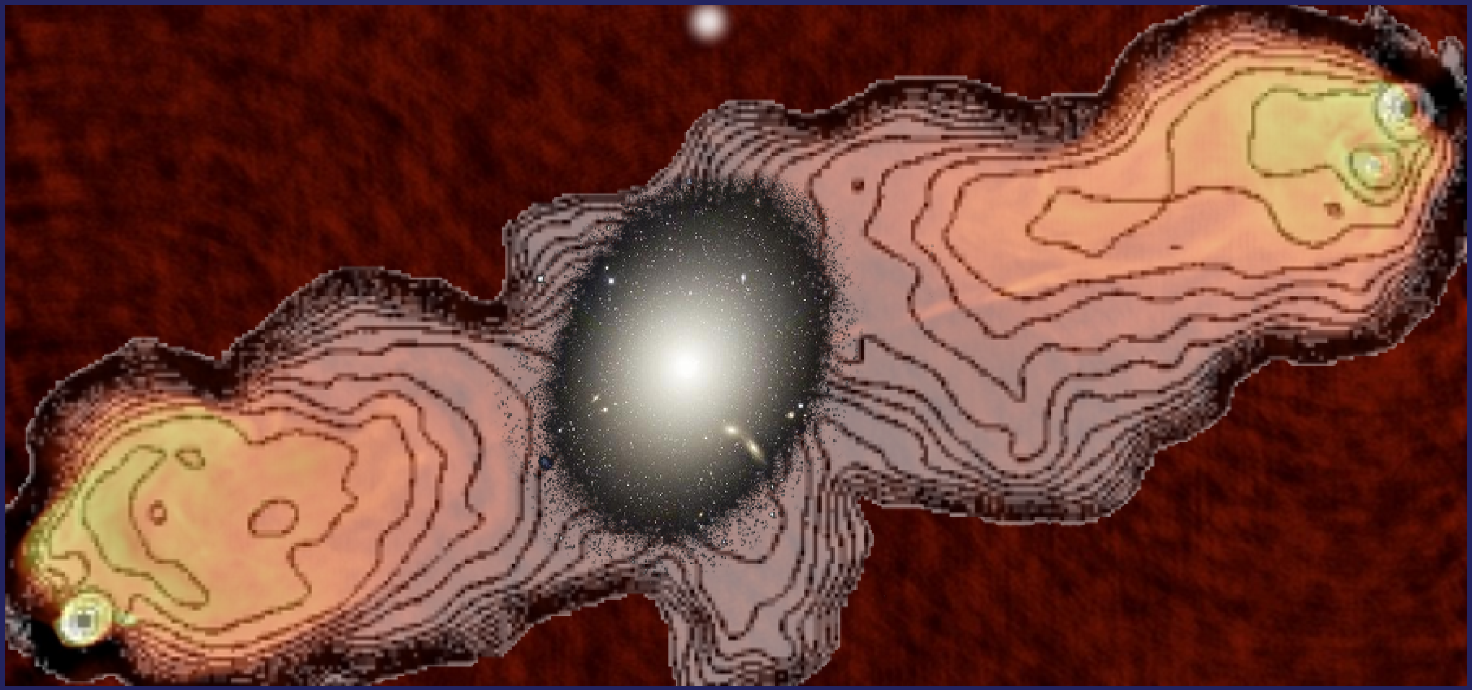


No!

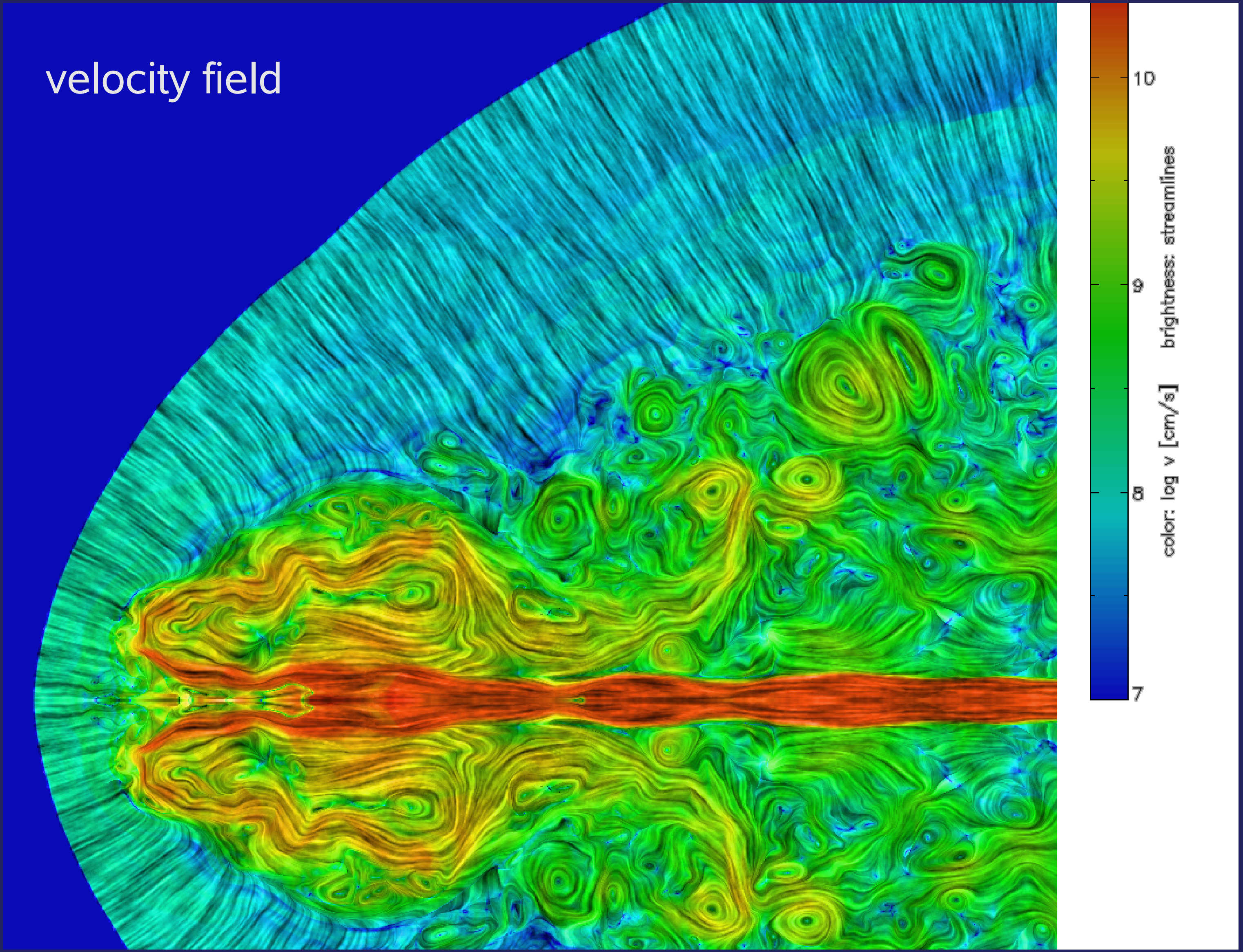
Whole galaxy contained in cocoon

Cyg A @ 5 GHz
Perley+ 1984

Cyg A @ 327 MHz contour overlay
Lazio+ 2006

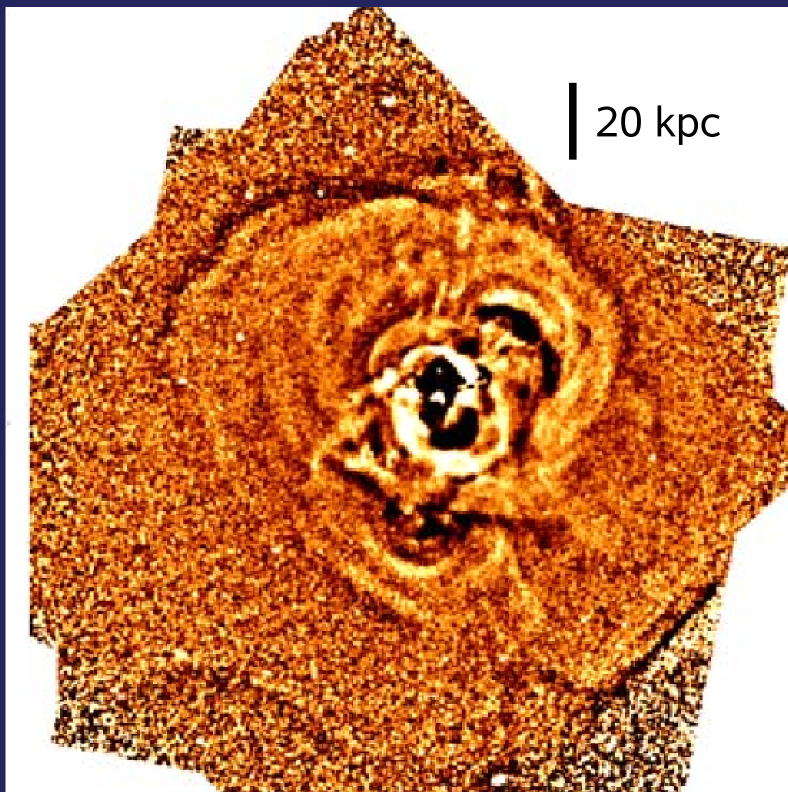
Cocoon Turbulence

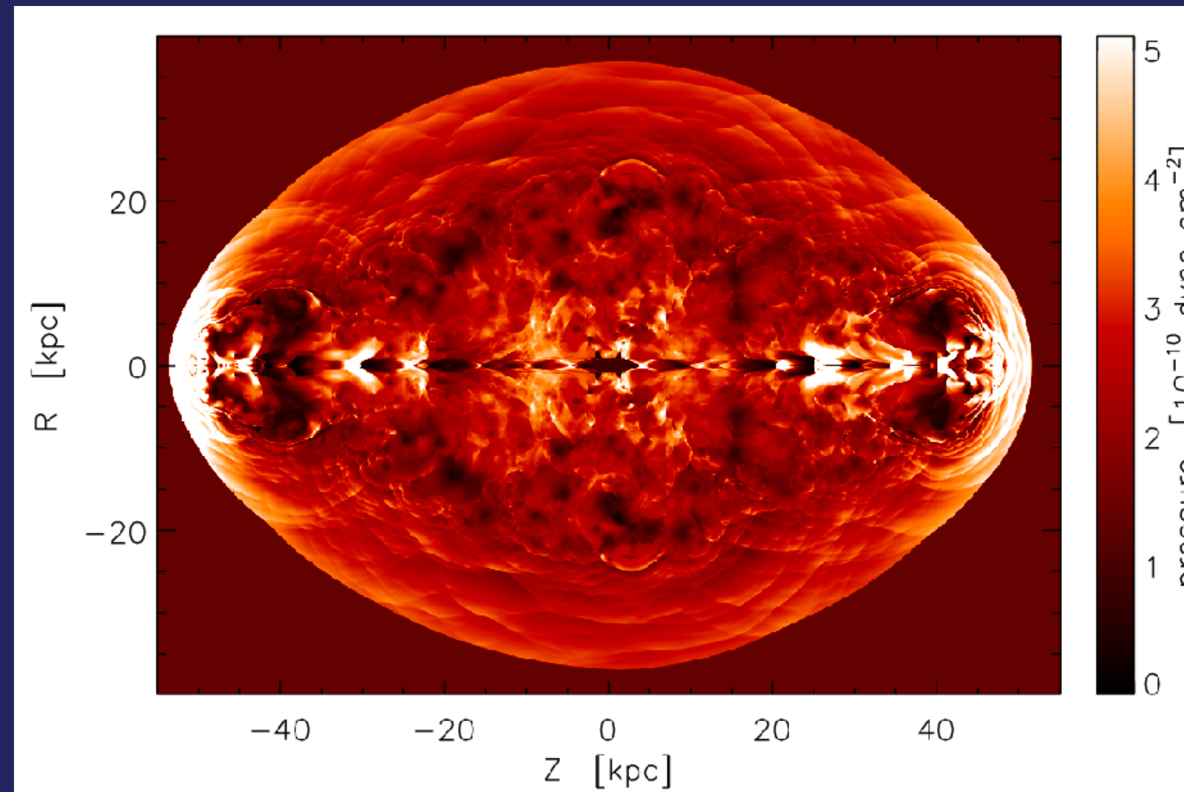
- strong backflow
- highly turbulent cocoon!
- interaction with ISM
- Creation of multi-phase turbulence in cocoon (M. Krause)



[animation]

Cocoon Turbulence





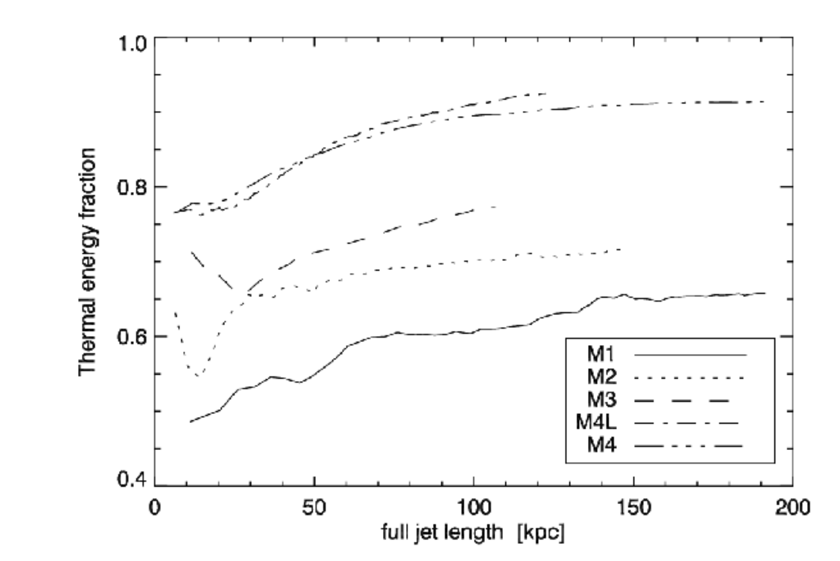
waves and ripples in
Perseus A
Fabian+ 2006

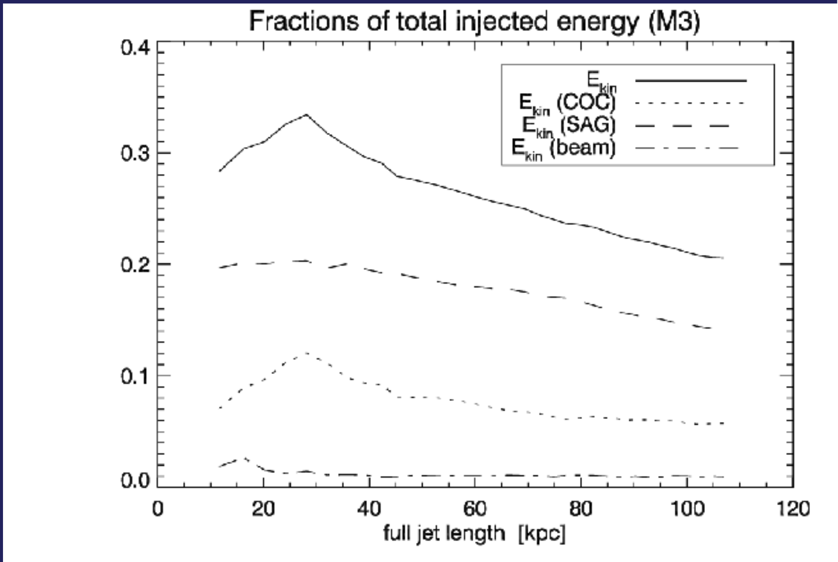
pressure map

- travelling sound waves in shocked ambient gas
- weak bow shock softly turns into sound wave!
- dissipation / heating?

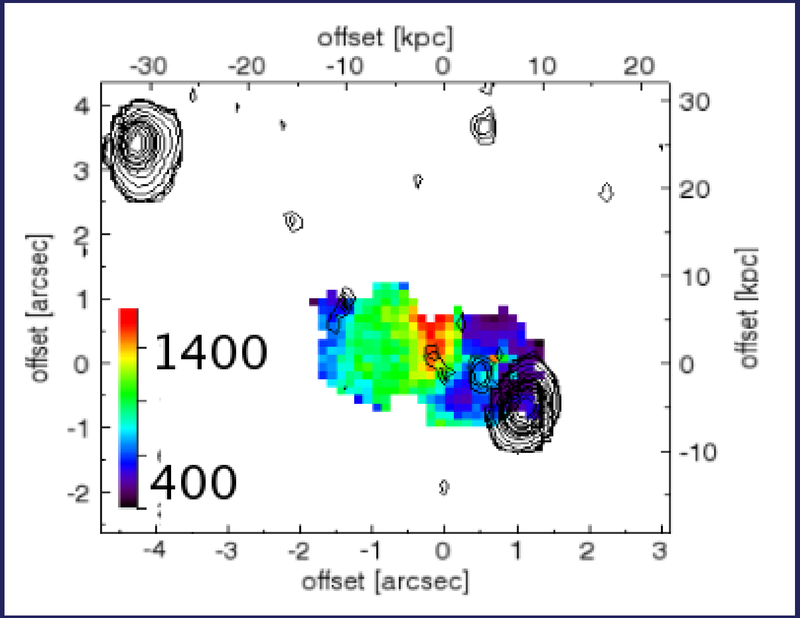
Energy Budget

- light jets:
  high thermalization efficiency
  hot radio plasma cavity
  & heated ambient gas (hot phase)
- thermalization ~ 80%
  (half cocoon, half ambient)
  Zanni+ 2005:
  up to 75% irreversibly dissipated
- several percent of total power
  contained in cocoon turbulence
  may stir up ISM





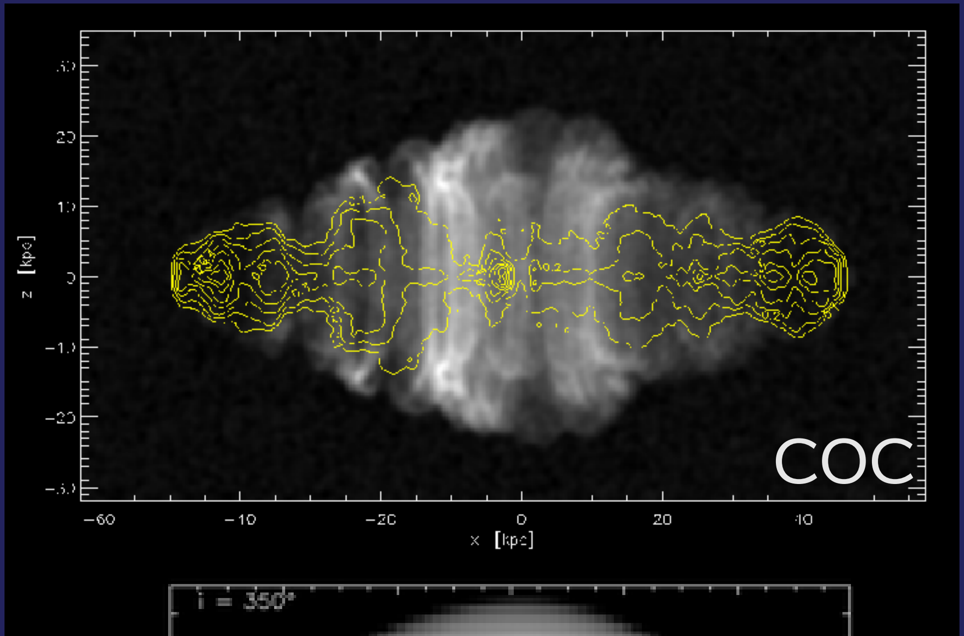
Location of the Emission Line Gas

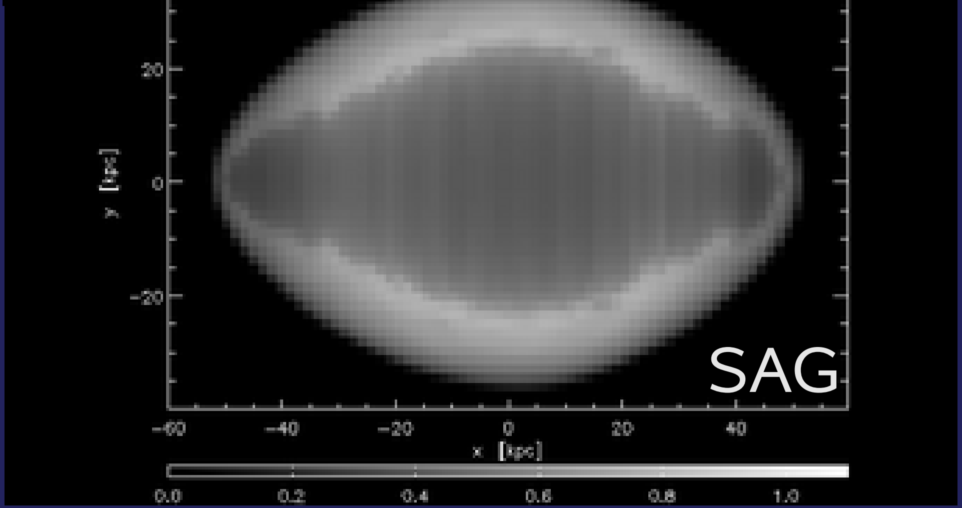


O III FWHM
km/s

project with N. Nesvadba

multi-phase medium
simulations: Martin Krause





Magnetic Fields

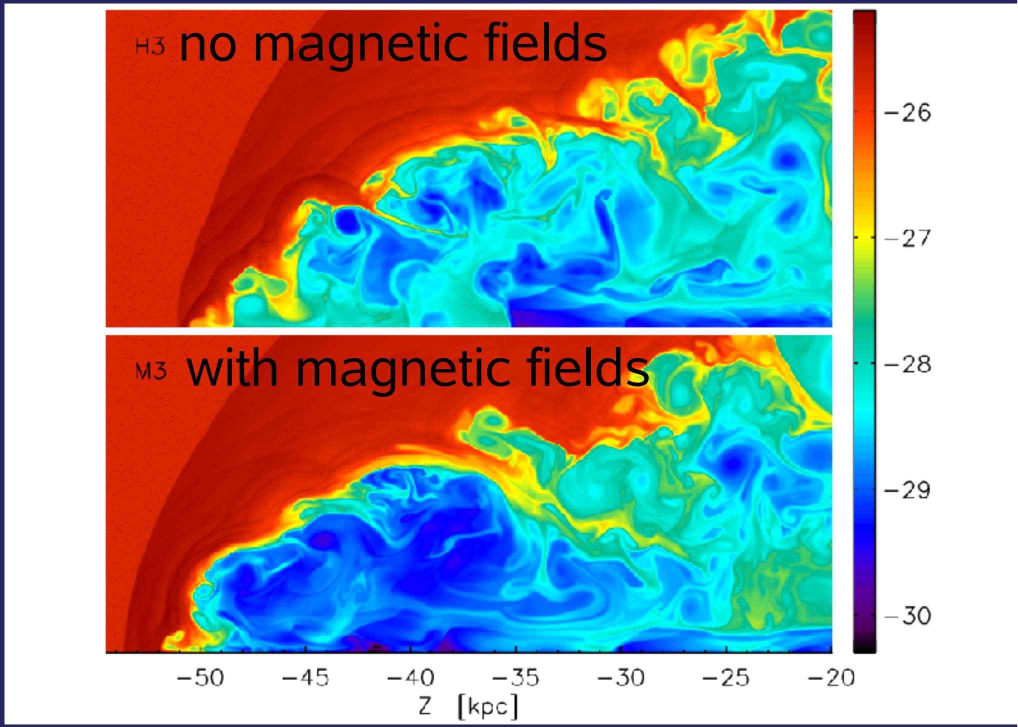
- Why magnetic fields?
  - synchrotron emission $\longrightarrow$ they must be there!
  - what is their effect?

- Topology:
  - infer from polarization measurements
  - mostly axial in beam, perpendicular at hotspots
  - stretched tangled fields? helical fields?

- Assume helical fields
  - effects found should also be relevant for tangled fields
  - resolve magnetic field structure well
  - magnetic field confined to jet (by setup)
  - sub-equipartition

Magnetic Fields: Stabilization

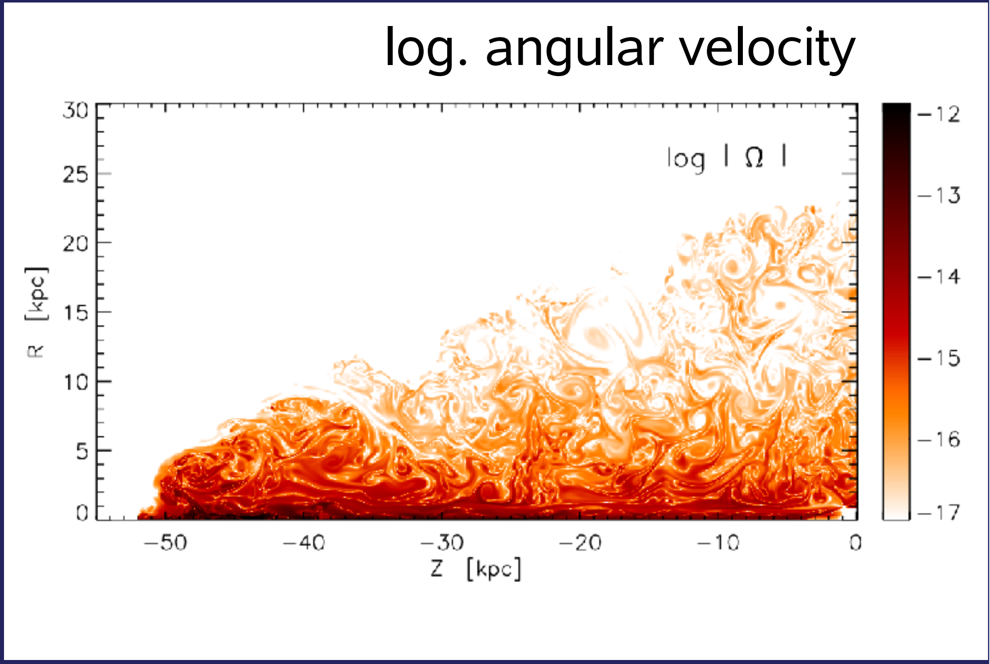
- M3: plasma beta = 8.1 (injected)
- comparison HD – MHD
  - damp KH shear instability (field lines resist bending)
  - less entrainment
  - stabilization in cocoon not enough?



M3 density

Step 1: Beam Rotation

- initially: beam has no rotation, but helical field
- plasma rotation:
  "MHD angular momentum conservation"
  (exchange of
  magnetic field and
  plasma angular momentum)

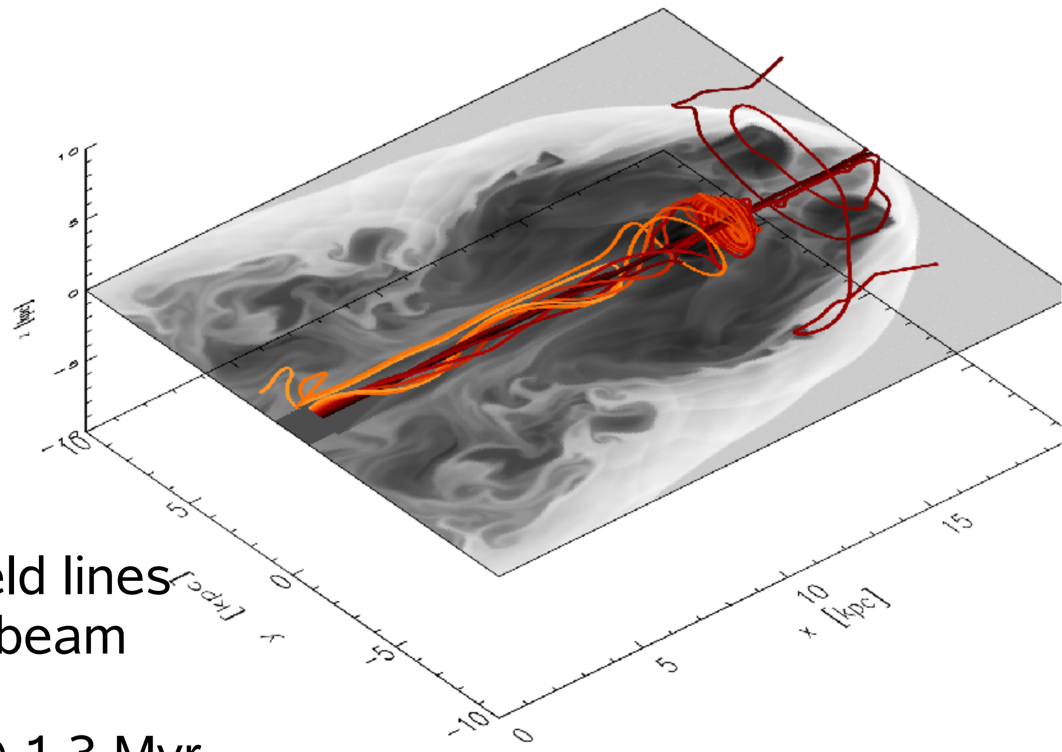


Step 2: Shearing and Field Generation

- backflow:
  plasma streams
  off the axis

- angular momentum
  conservation:
  differential rotation

- shearing:
  kinetic ⟶ magnetic
  amplifies fields

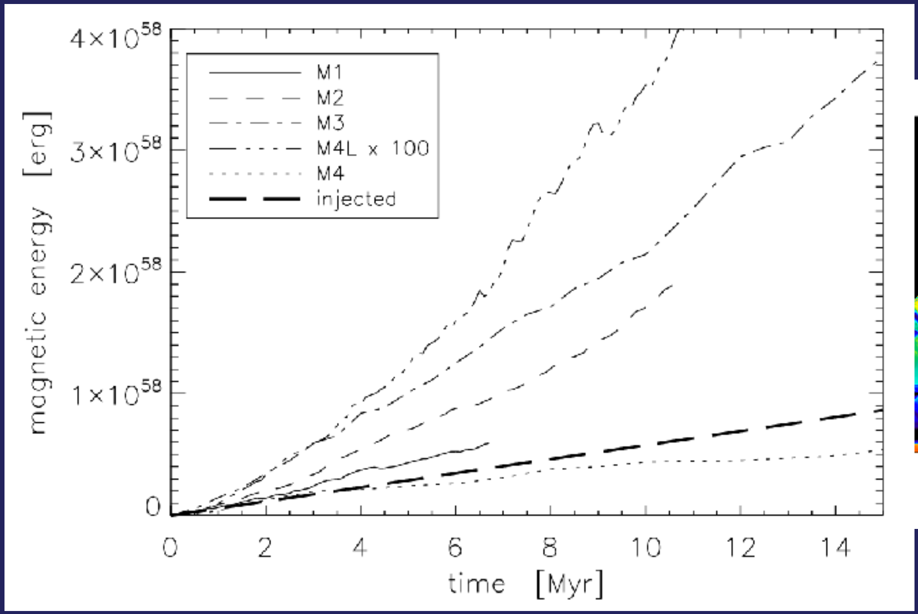


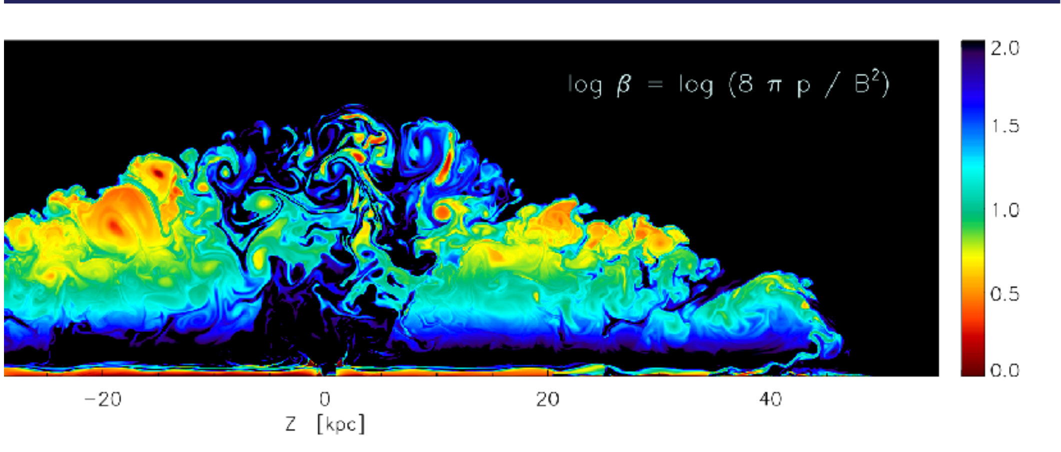
3D field lines
in jet beam

M2 @ 1.3 Myr

Magnetic Field Magnitude

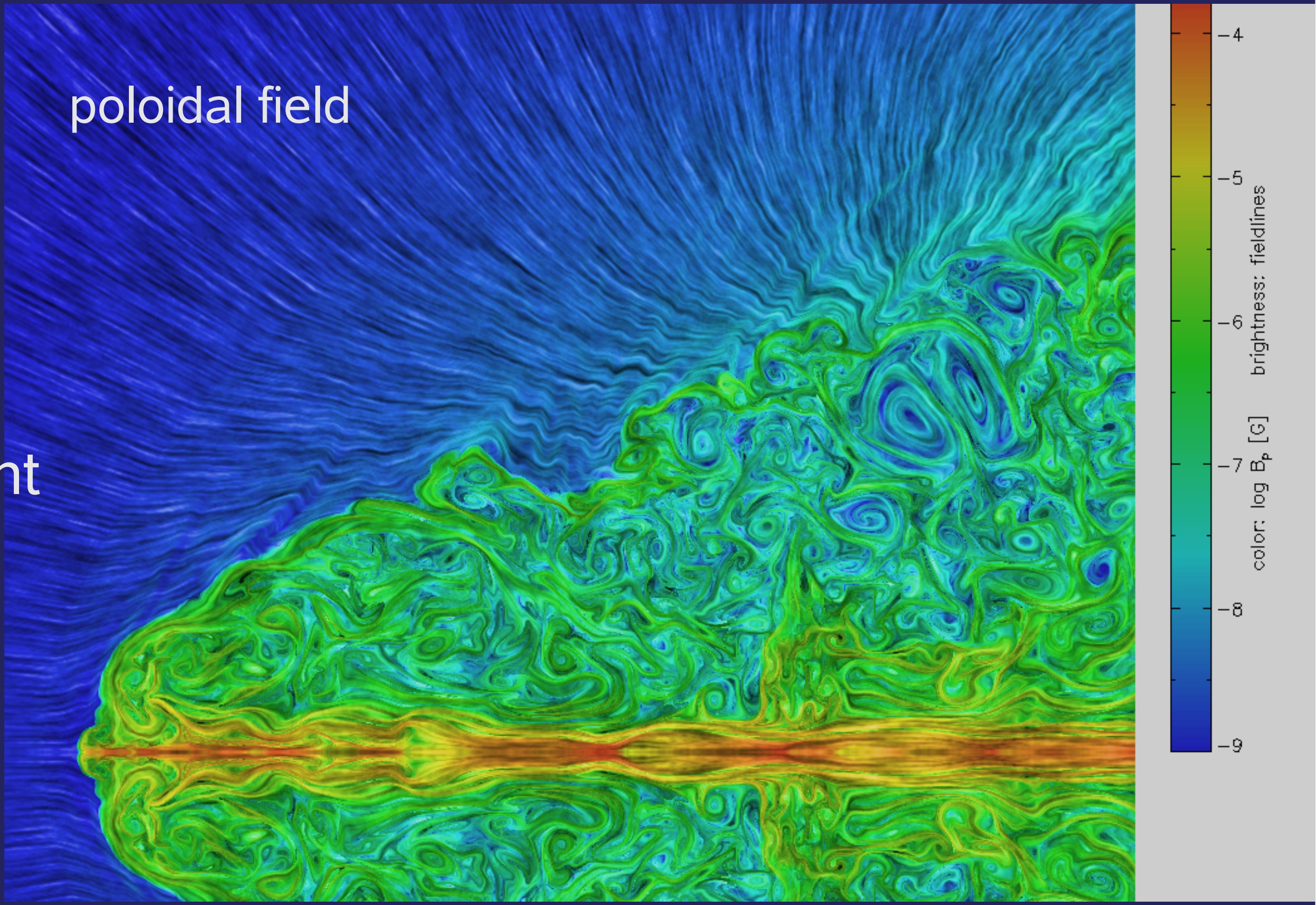
- cocoon:
  much stronger fields than expected from flux conservation
- expectation in 3D:
  also strong fields, but balance poloidal/toroidal,
  turbulent distribution of magnetic fields in cocoon





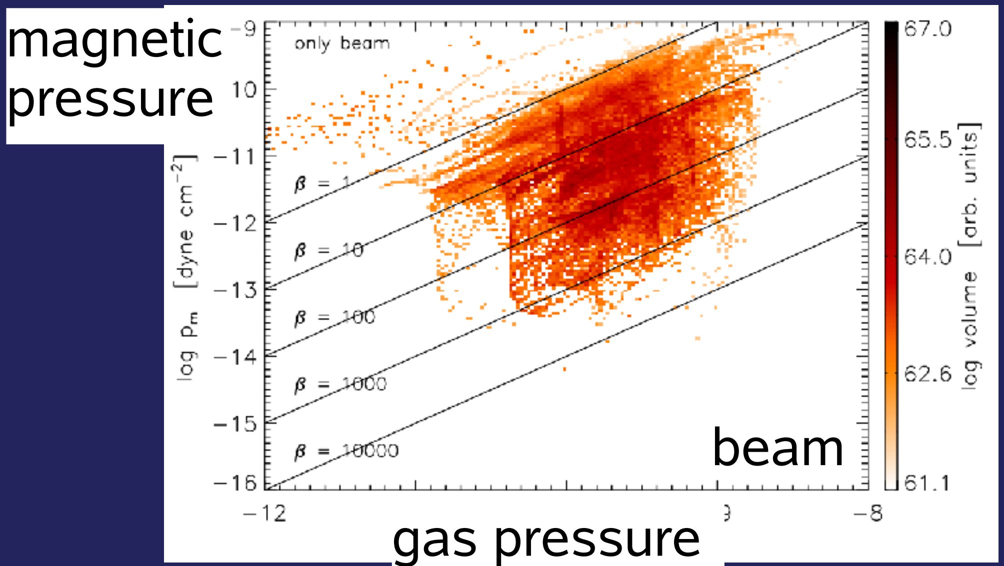
Poloidal Magnetic Field

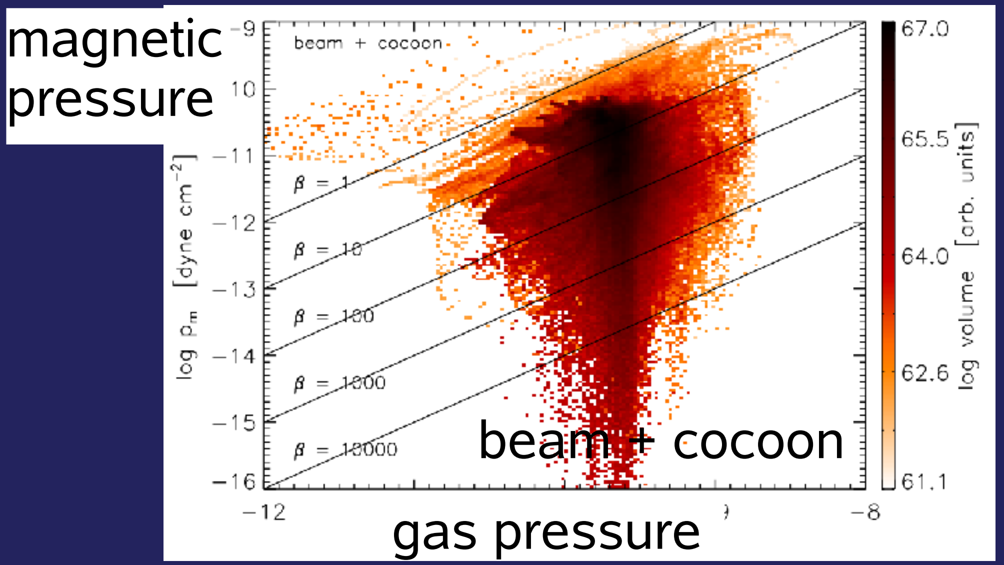
- strong in beam
- highly turbulent
- poloidal component artificially weak in 2.5Dcocoons $\longrightarrow$ 3D



The Question of Equipartition

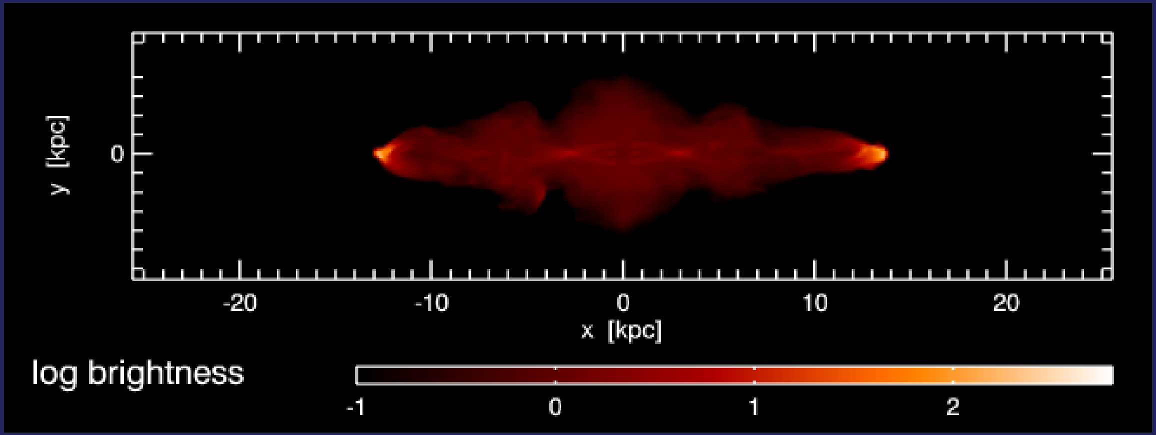
- often assumed:
  equipartition between magnetic field and relativistic particles
- here:
  check magnetic field and plasma pressure (plasma beta)
- beam:
  beta constant across shocks
- cocoon:
  spread

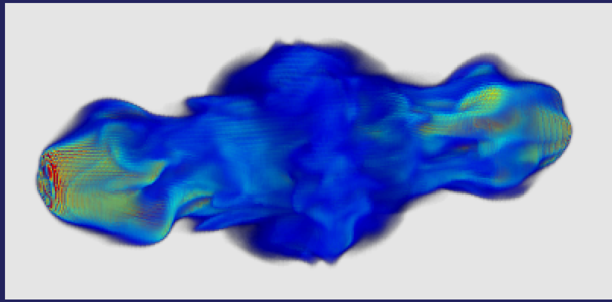




Ongoing Work

- Physical mechanism examined by axisymmetric simulations
- 3D simulations of jets in clumpy medium
  for extended emission line regions in HzRG
- Interaction with cosmological environment
  Self-consistent evolution of jet activity (accretion, spin, ...)





Summary

- cocoon turbulence excites sound waves,
  interactionwith ISM
  thermalization very efficient for very light jets
- magnetic fields stabilize jet head, suppress entrainment
- helical fields & shearing generate magnetic energy:
  damp KH instability and magnetize cocoon
- 3D simulations necessary for realistic turbulent interaction with ISM and cosmological environment