ENIGMA Cork MHD
III. Application
MHD Jet Simulations

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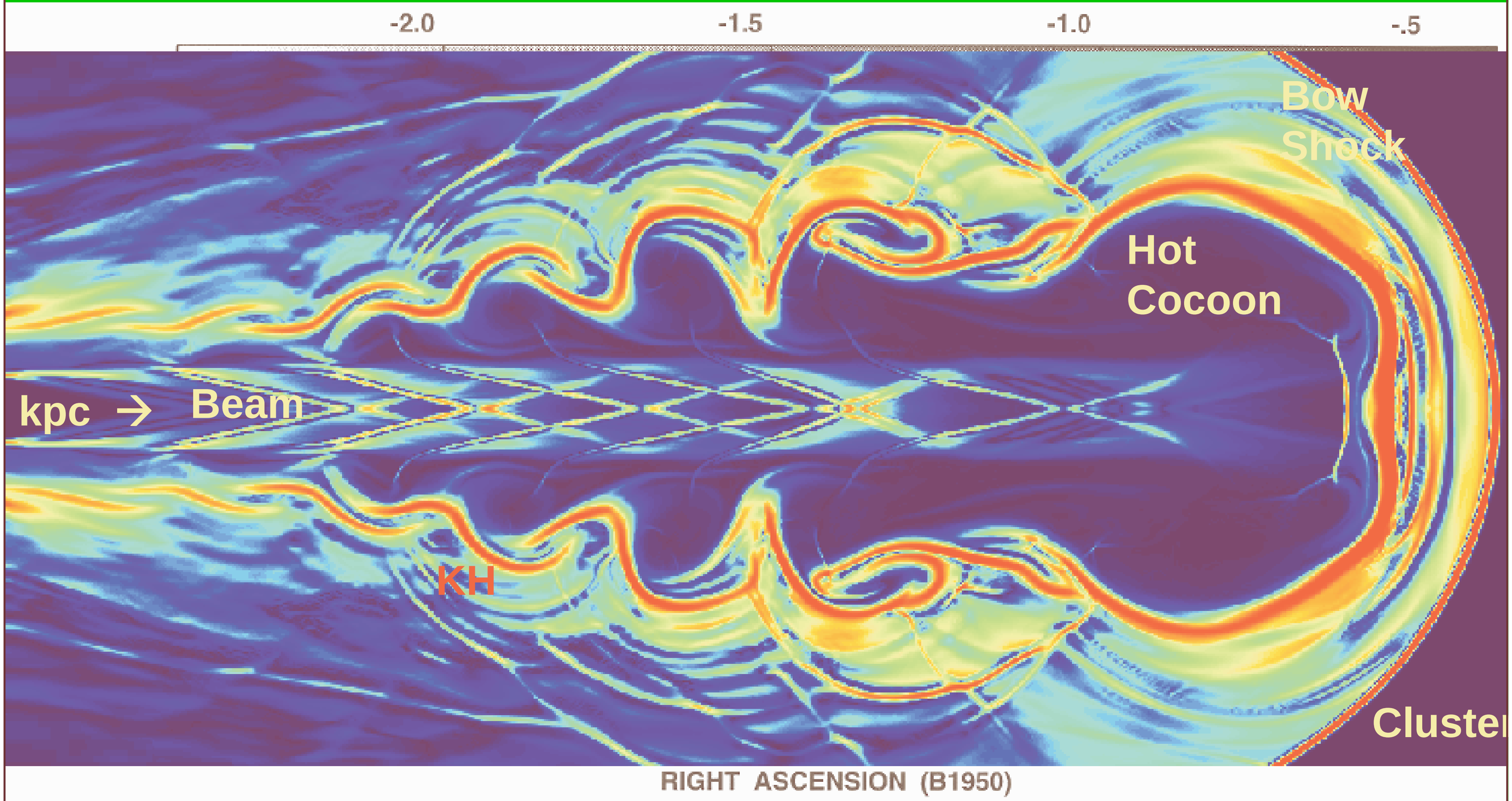
[Martin Krause,
Volker Gaibler]
LSW Königstuhl, ZAH

Do we understand Cygnus A ?



→ Not at all !

Lorentz factor = 1.04, v_J = 0.28 c, Mach = 6
[Hughes 1996] 6 ppb

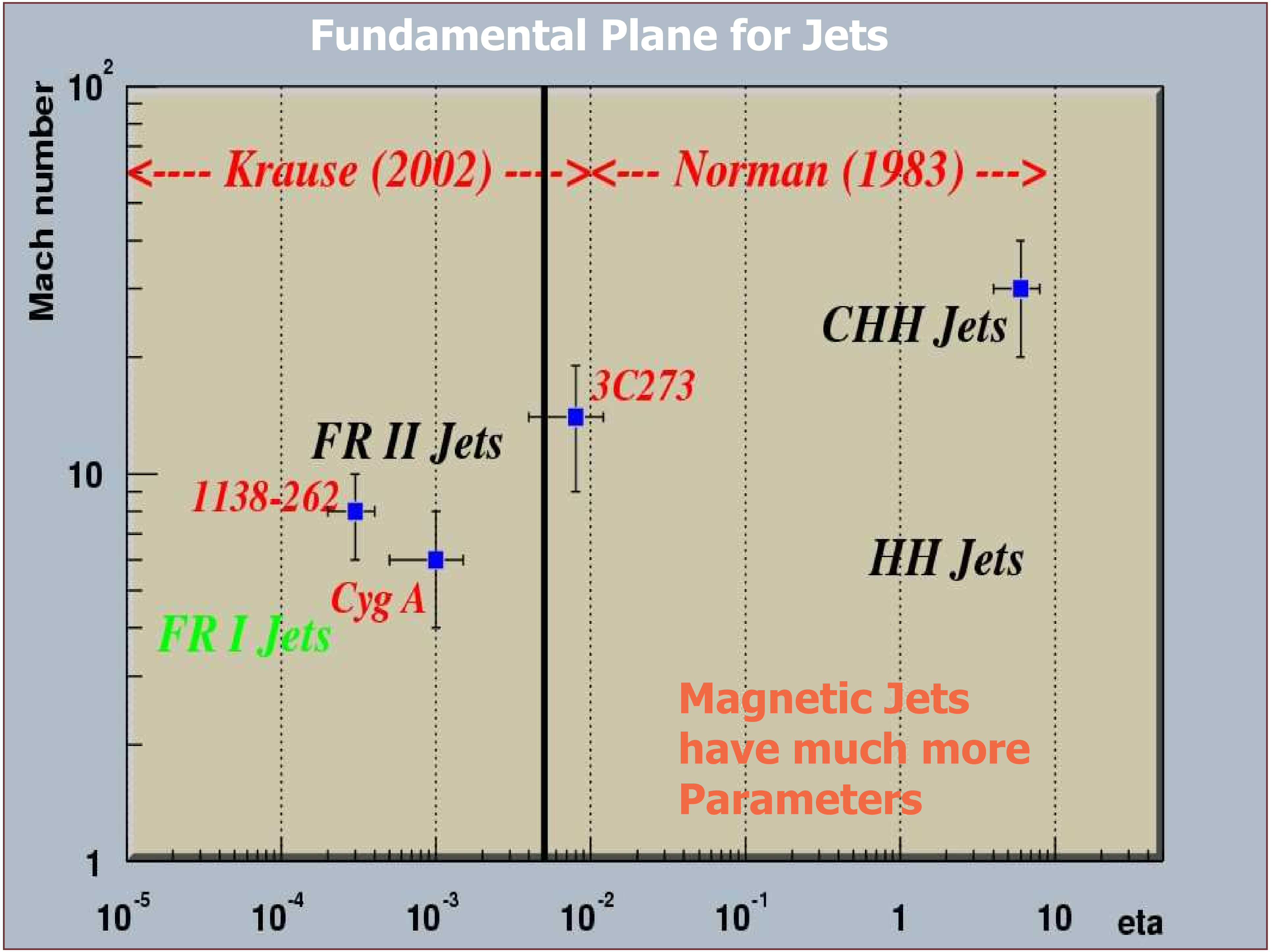
$$V_{Head} = V_{Beam} \frac{\sqrt{\eta \epsilon}}{1 + \sqrt{\eta \epsilon}} \quad ; \quad M >> 1$$

$$\eta = \rho_B h_B \Gamma_B^2 / \rho_G$$: density contrast

$$V_{Beam} = 100 \frac{kpc}{Myr} \sqrt{\frac{10^{-4}}{\eta \epsilon}} \frac{V_{Head}}{kpc/Myr}$$

Bow shock in Cyg A is a weak shock !!!

$c = 307$ kpc/Myr ; $c_{S,Gas} = 0.6$ kpc/Myr

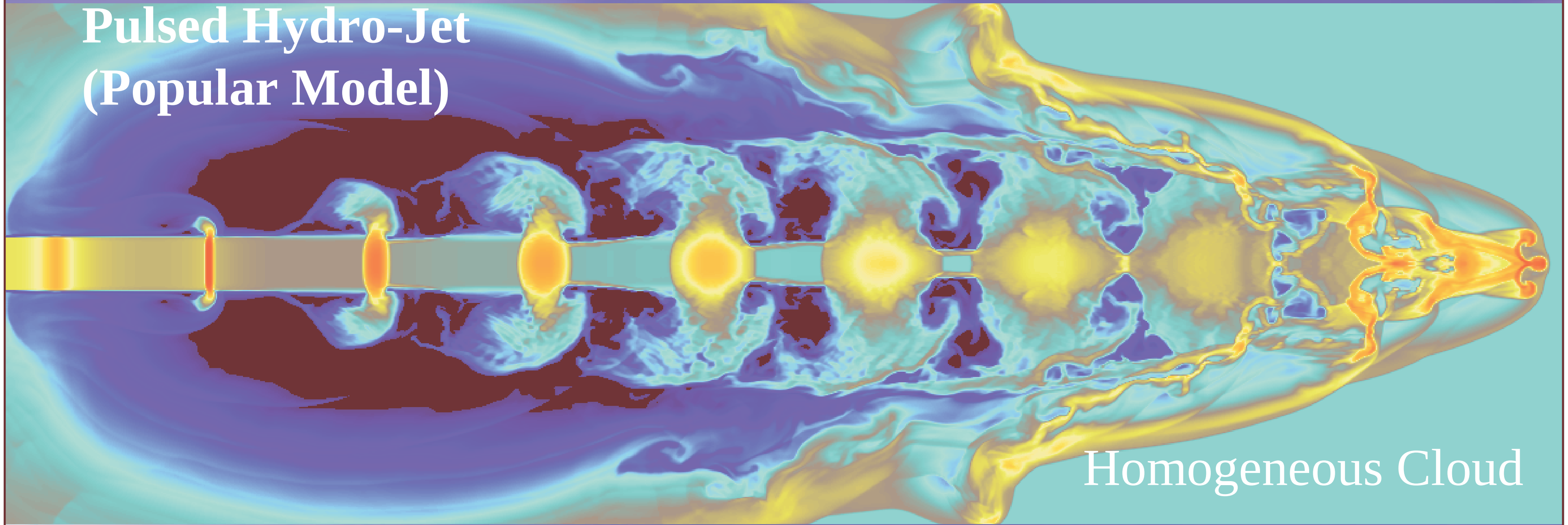

Fundamental Plane for Jets
Mach number
eta
<---- Krause (2002) ----><--- Norman (1983) --->
CHH Jets
3C273
FR II Jets
1138-262
Cyg A
FR I Jets
HH Jets
Magnetic Jets have much more Parameters
10^2
10
1
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10

Herbig-Haro Flows

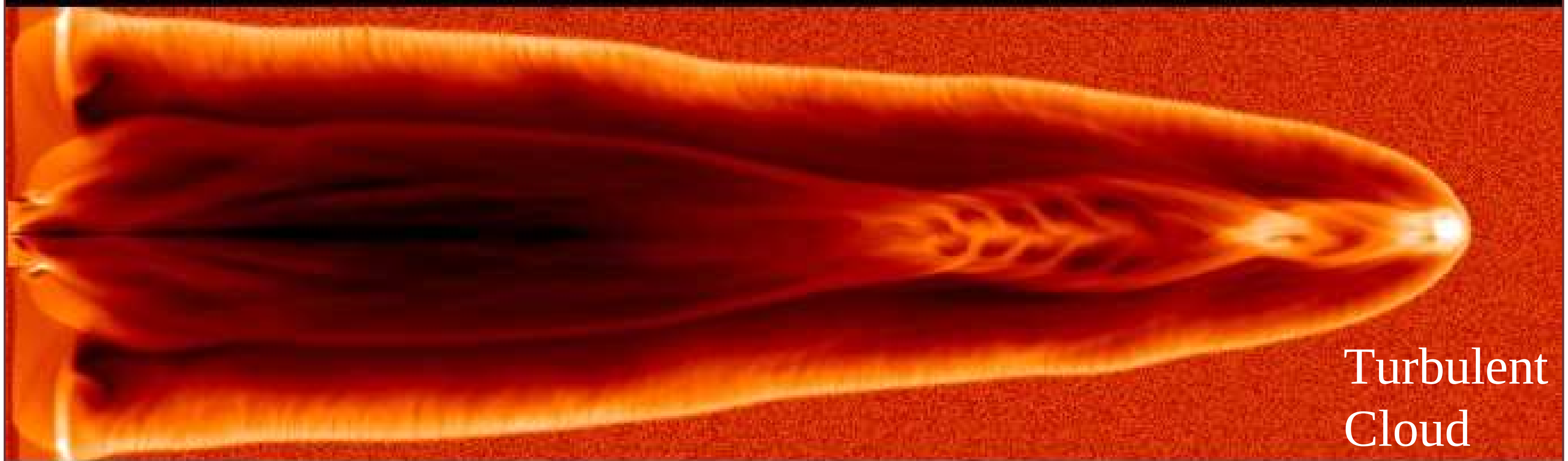
HH 111

Almost 50 years ago, George Herbig and Guillermo Haro independently discovered a number of compact nebulae with peculiar spectra near dark clouds.

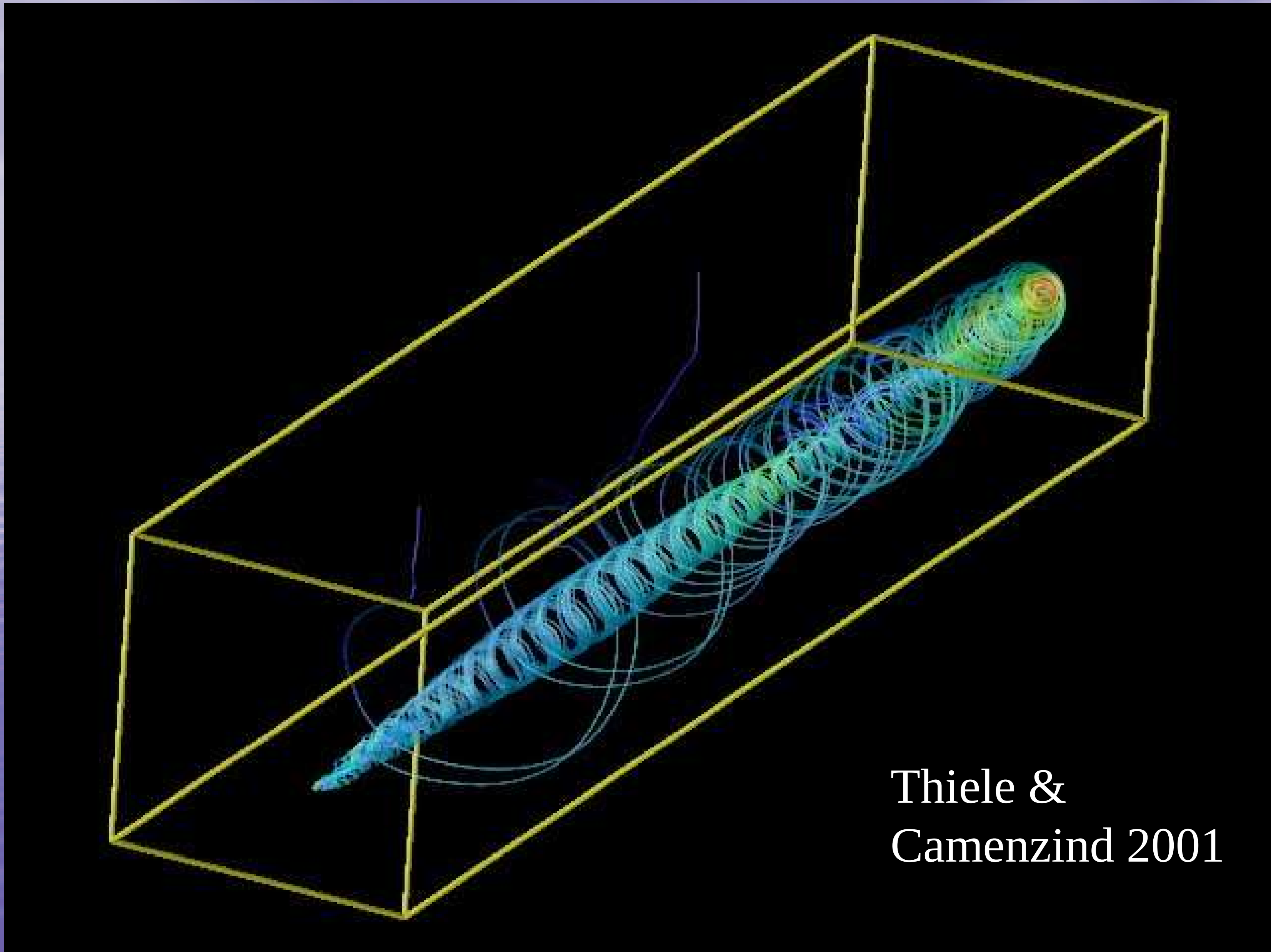
The large range of excitation conditions requires bow shocks and other complex morphologies. By the early 1980s, several Herbig-Haro (HH) objects were shown to be highly collimated jets of partially ionized plasma moving away from young stars at speeds of 100 to over 1000 km/s (R. Mundt, MPIA Heidelberg; Bo Reipurth at ESO).

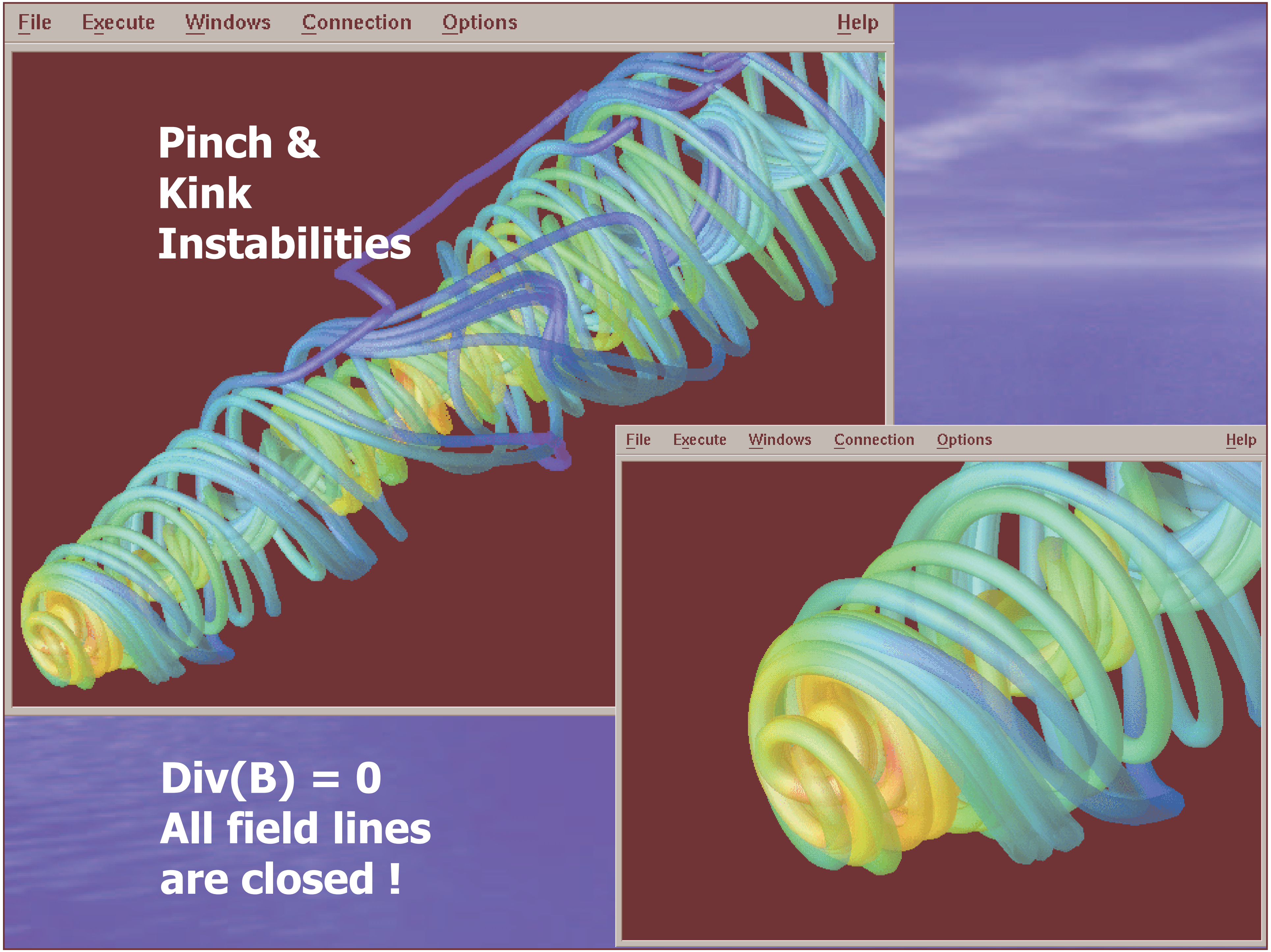


Overpressured Magnetic Jet (LSW Model; Camenzind 1990)



Closed Magnetic Structure




File
Execute
Windows
Connection
Options
Help
Pinch &
Kink
Instabilities
File
Execute
Windows
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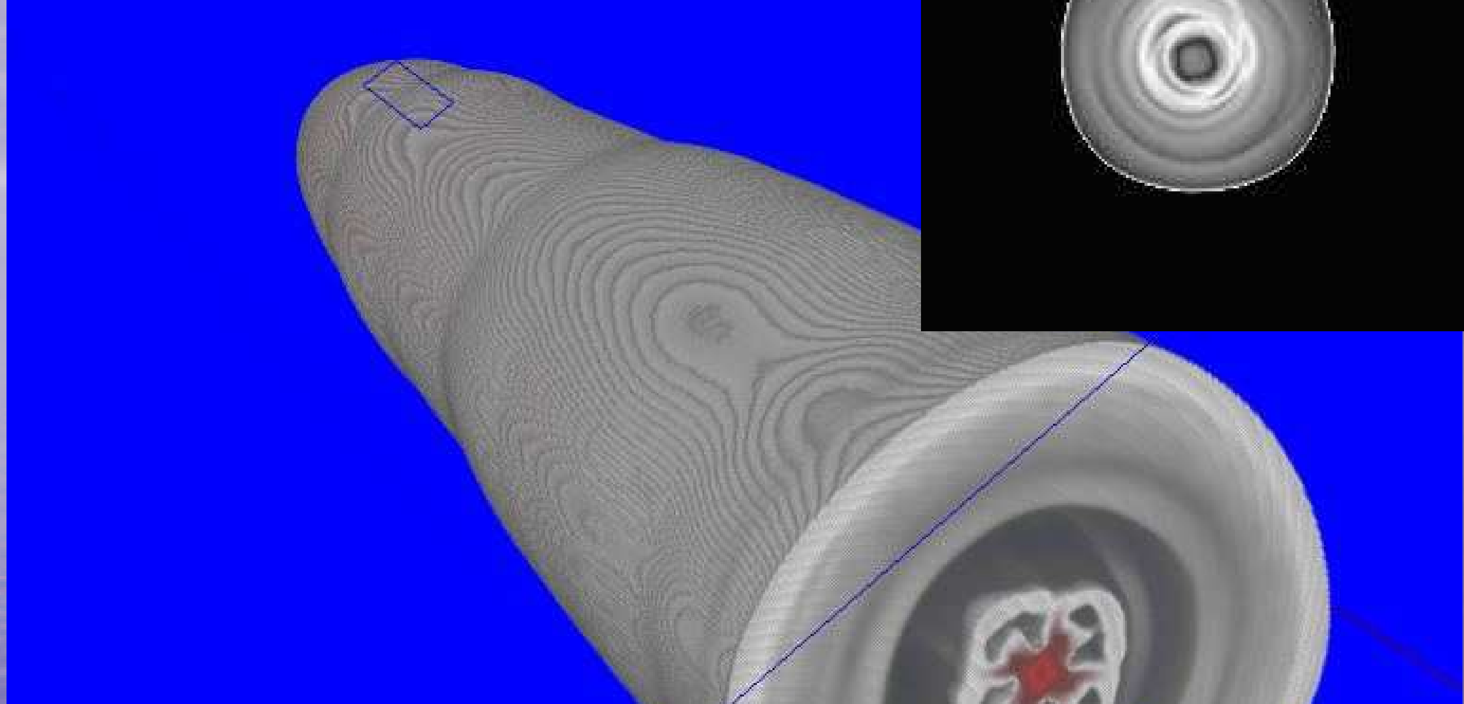
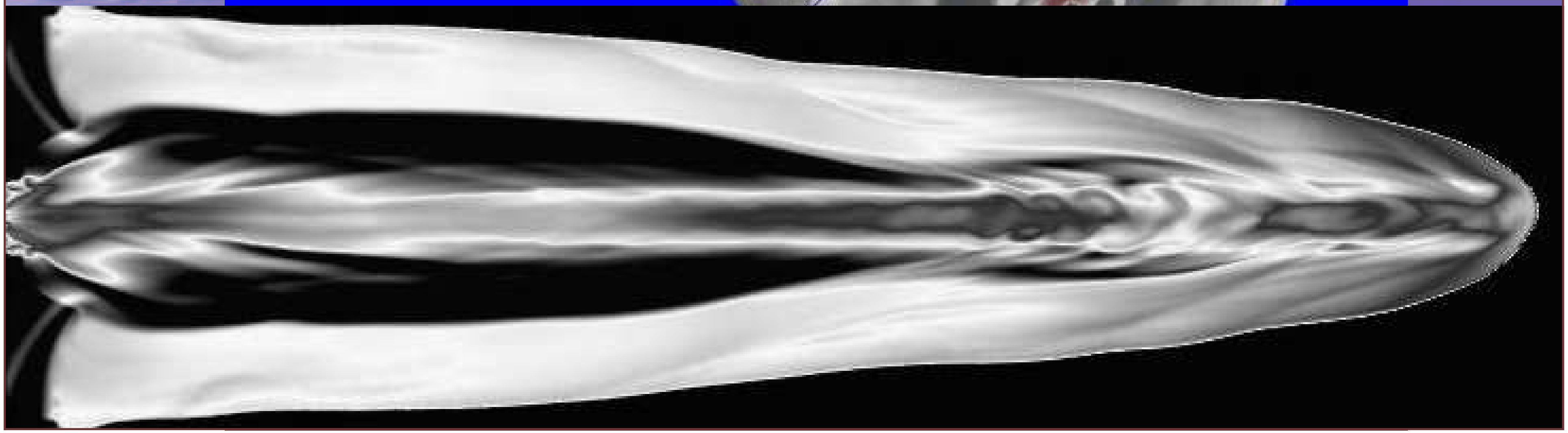
Options
Help
Div(B) = 0
All field lines
are closed !

3D MHD Jet in Turbulent Cloud





2) How does the IGM change by the jet impact?
It depends ...

Basic parameter : the density contrast jet / IGM η

Constraints:

non-relativistic jet

$$L = \pi\, r_{\mathrm{j}}^{2}\, \rho_{\mathrm{j}}\, v_{\mathrm{j}}^{3}$$

$$\eta = \rho_{\mathrm{j}} / \rho_{0}$$

$$\rightarrow \eta = 6 \times 10^{-3}\, L_{47}\, r_{\mathrm{kpc}}^{-2}\, (n_{0} / 0.2\ \mathrm{cm}^{-3})^{-1}\, (v / 0.5c)^{-3}$$

relativistic jet

$$L = 2\pi\, r_{\mathrm{j}}^{2}\, \rho_{\mathrm{j}}\, \Gamma\, (\Gamma\, h - 1)\, \beta\, c^{3}$$

$$\eta = \Gamma^{2}\, h\, \rho_{\mathrm{j}} / \rho_{0}$$

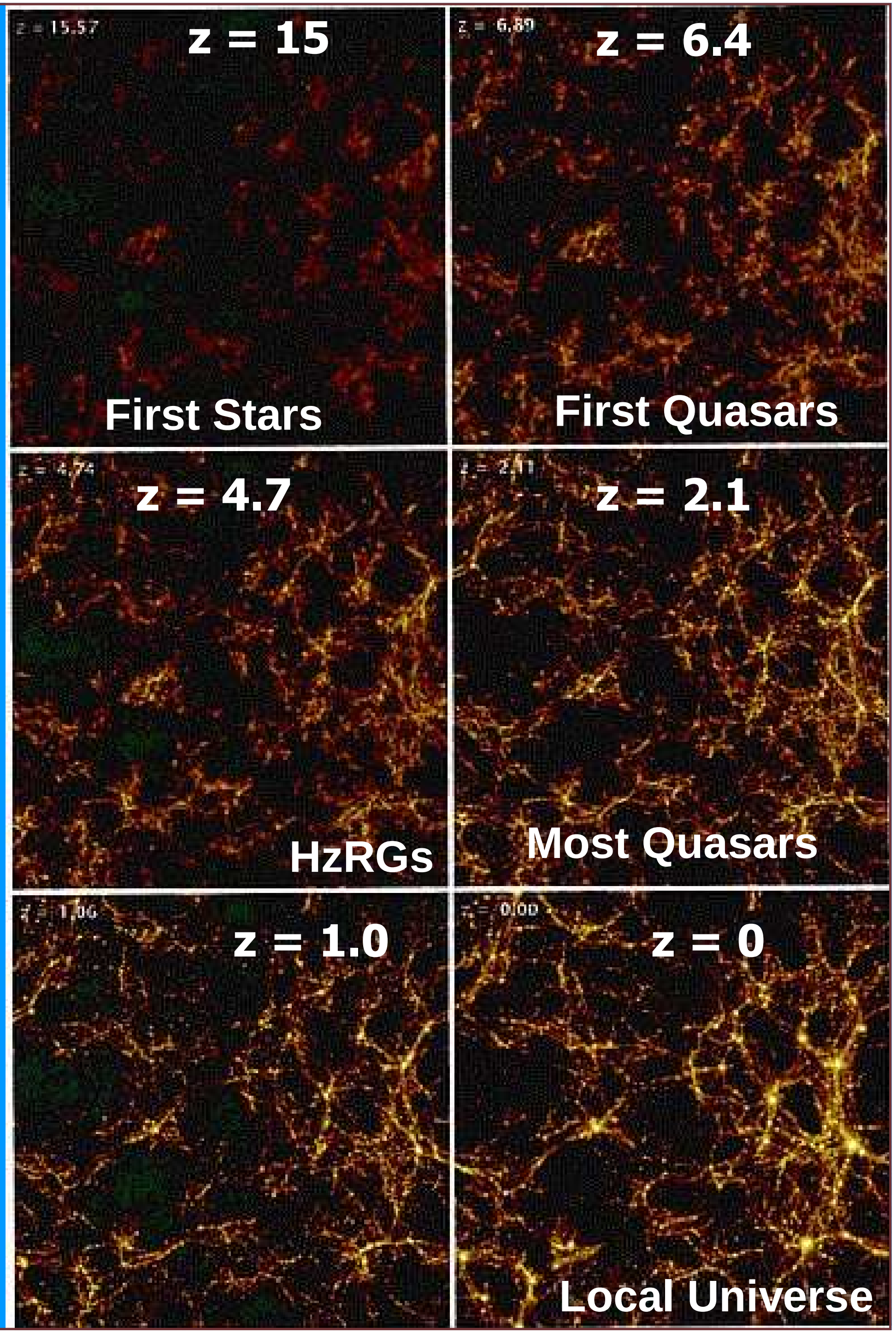
$$\rightarrow \eta = 4 \times 10^{-4}\, L_{47}\, r_{\mathrm{kpc}}^{-2}\, (n_{0} / 0.2\, \mathrm{cm}^{-3})^{-1}\, \beta^{-1}$$

Essentials

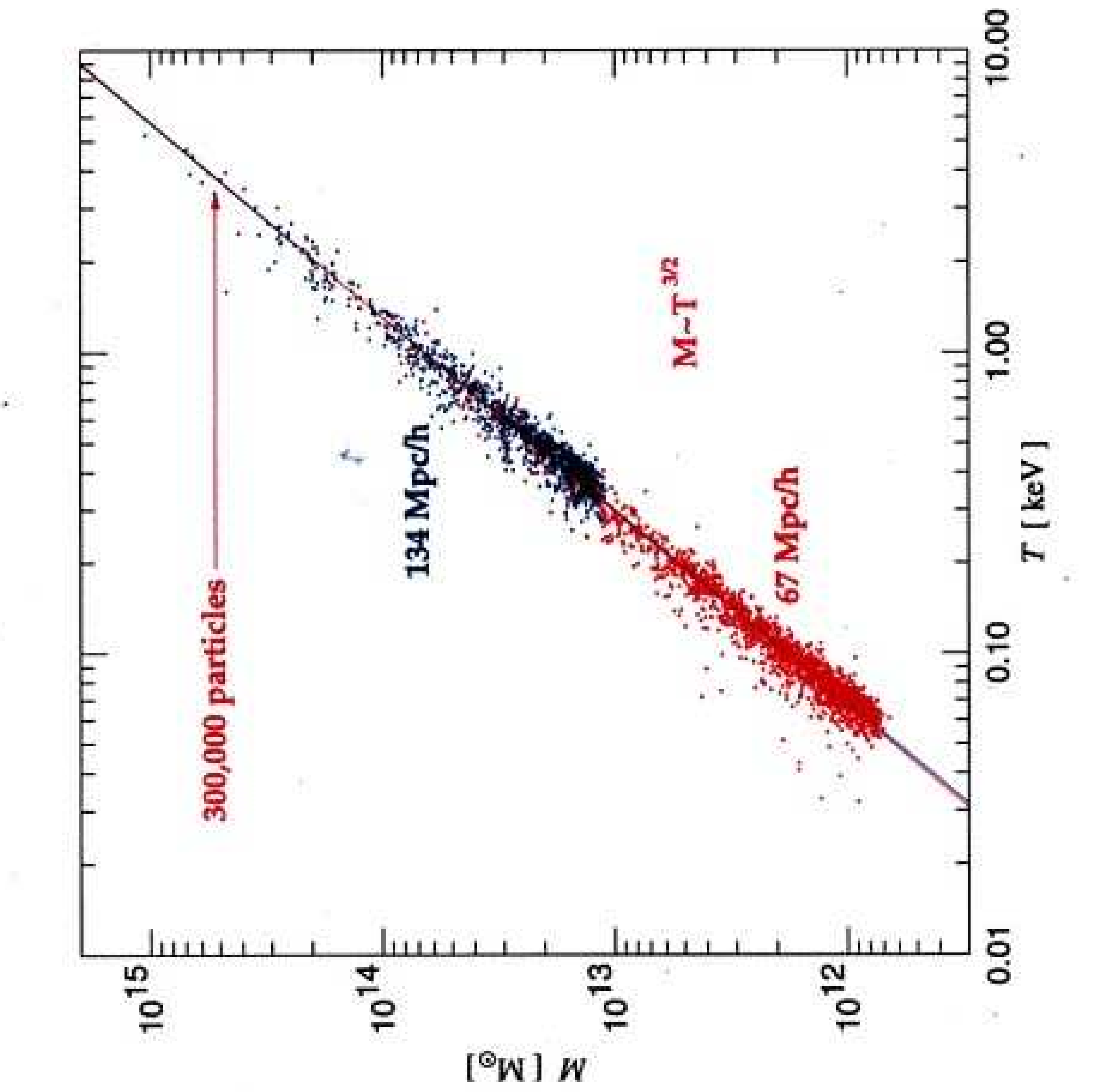
- Cluster gas properties are essential for understanding their JETs (density contrast and profile, temperature, magnetic fields);
- Low η Jets → 3 Phase Model of JET evolution: From the Sedov-phase over the cigar-phase towards the bubble-phase;
- Do we now understand Cygnus A ?
- The Bubble-Phase of JET-activity is now a very active field of research (Perseus).

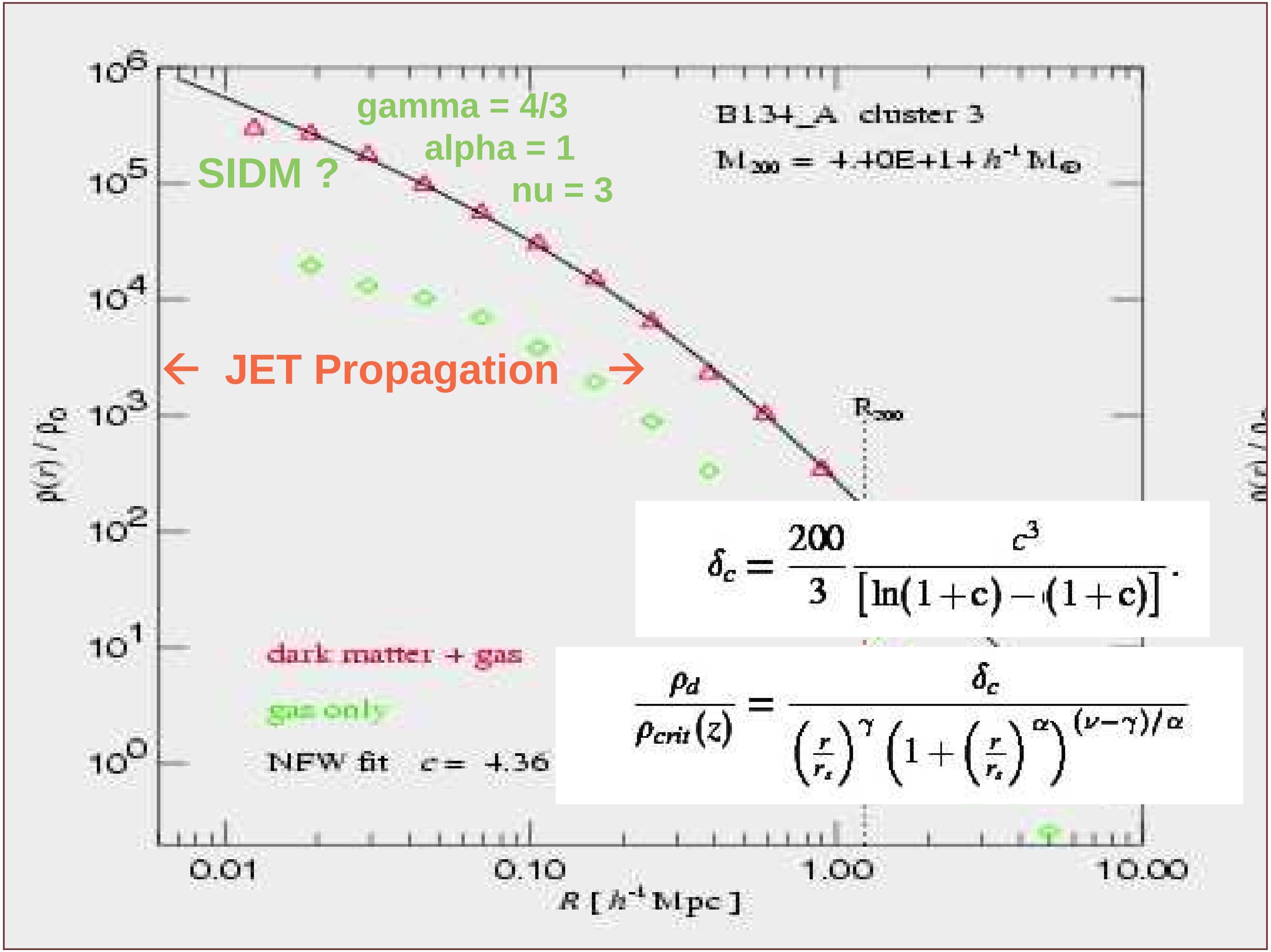
Cluster Evolution

- Clusters form in the high density peaks of cosmic density perturbations (M. White et al. 2001; Millenium Run 2005).
- Standard cosmology: LCDM Parameters:
- 0.67, 0.3, 0.7, 0.040, 1
- 200 x 200 x 33 Mpc
- Gas distribution ->



Temperature vs Cluster Mass





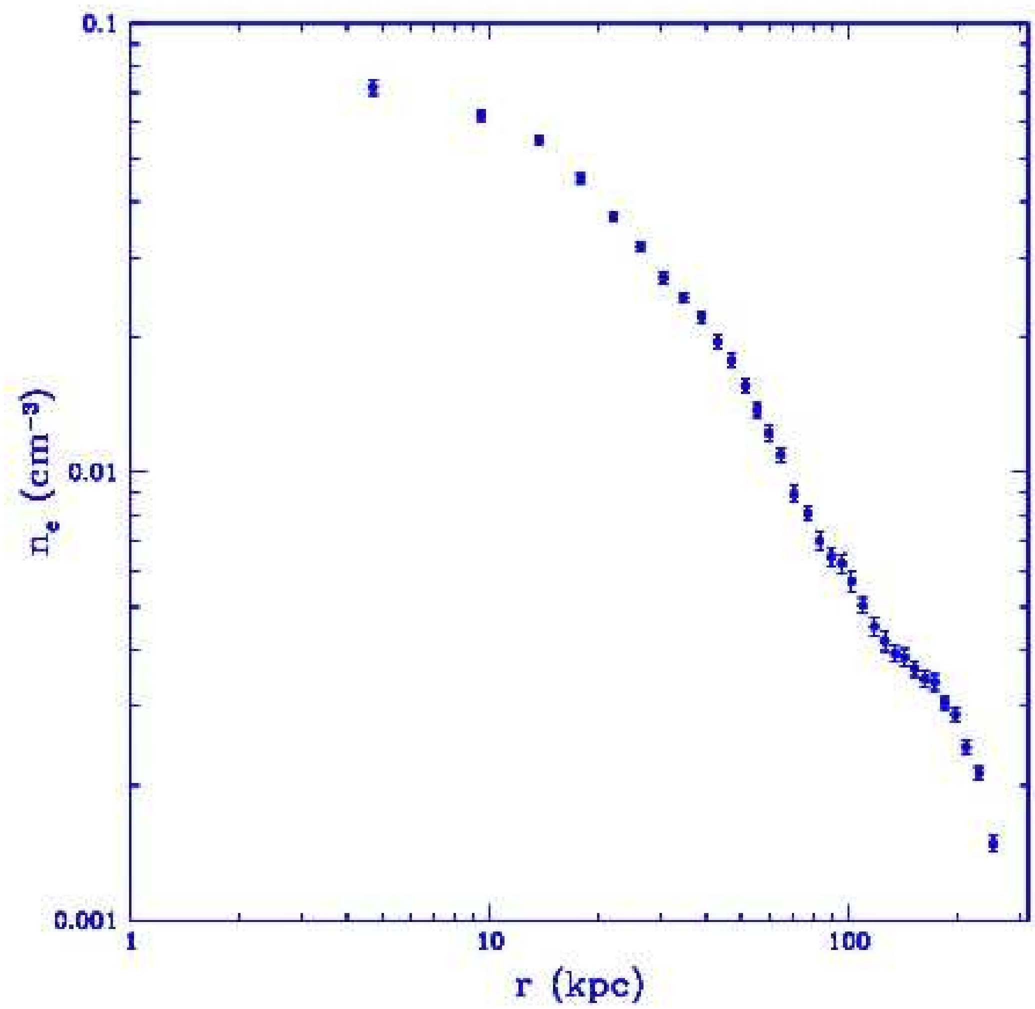
$$\delta_c = \frac{200}{3}\frac{c^3}{[\ln(1+c)-(1+c)]}.$$

$$\frac{\rho_d}{\rho_{crit}(z)} = \frac{\delta_c}{\left(\frac{r}{r_s}\right)^{\gamma}\left(1+\left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\nu-\gamma)/\alpha}}$$

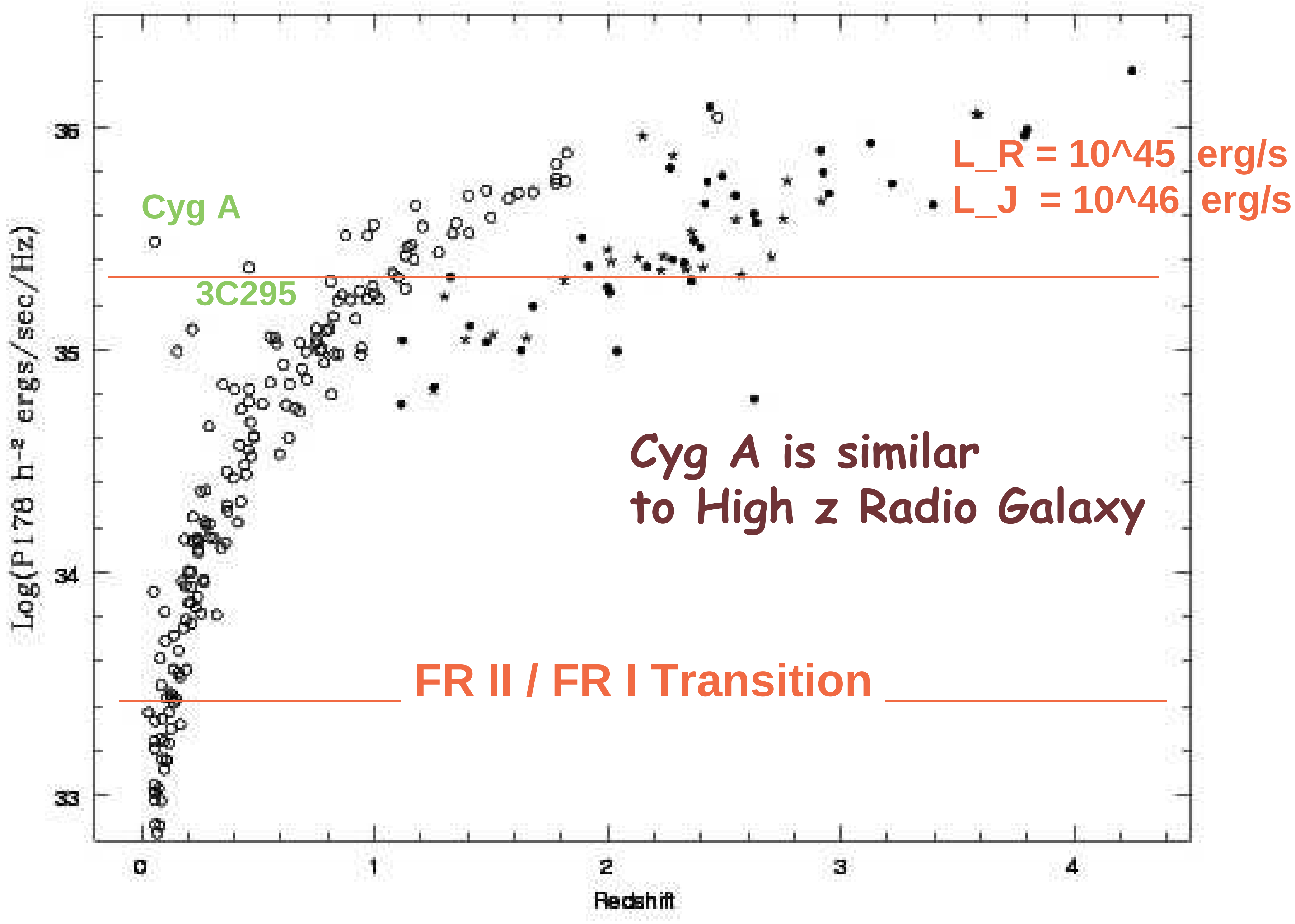
Typical Density Profile in a Cluster (Hydra, CXO)

→ Used to determine total cluster Mass

→ Input for Jet Simulation

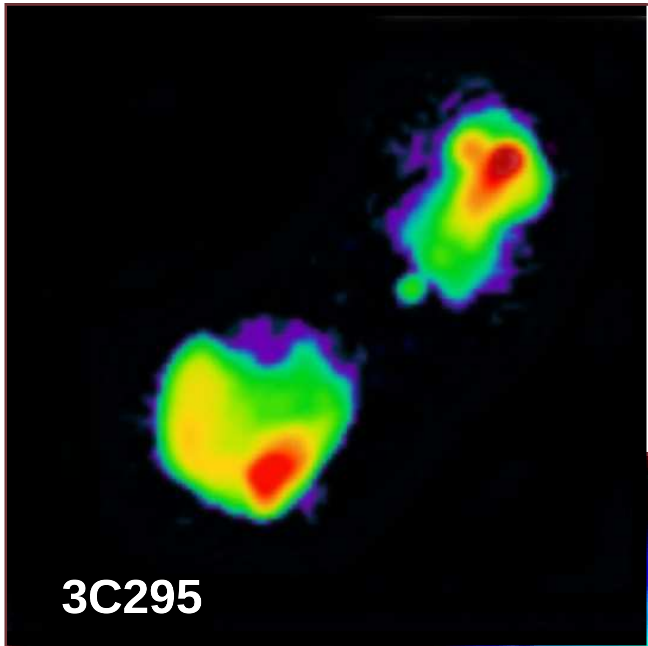


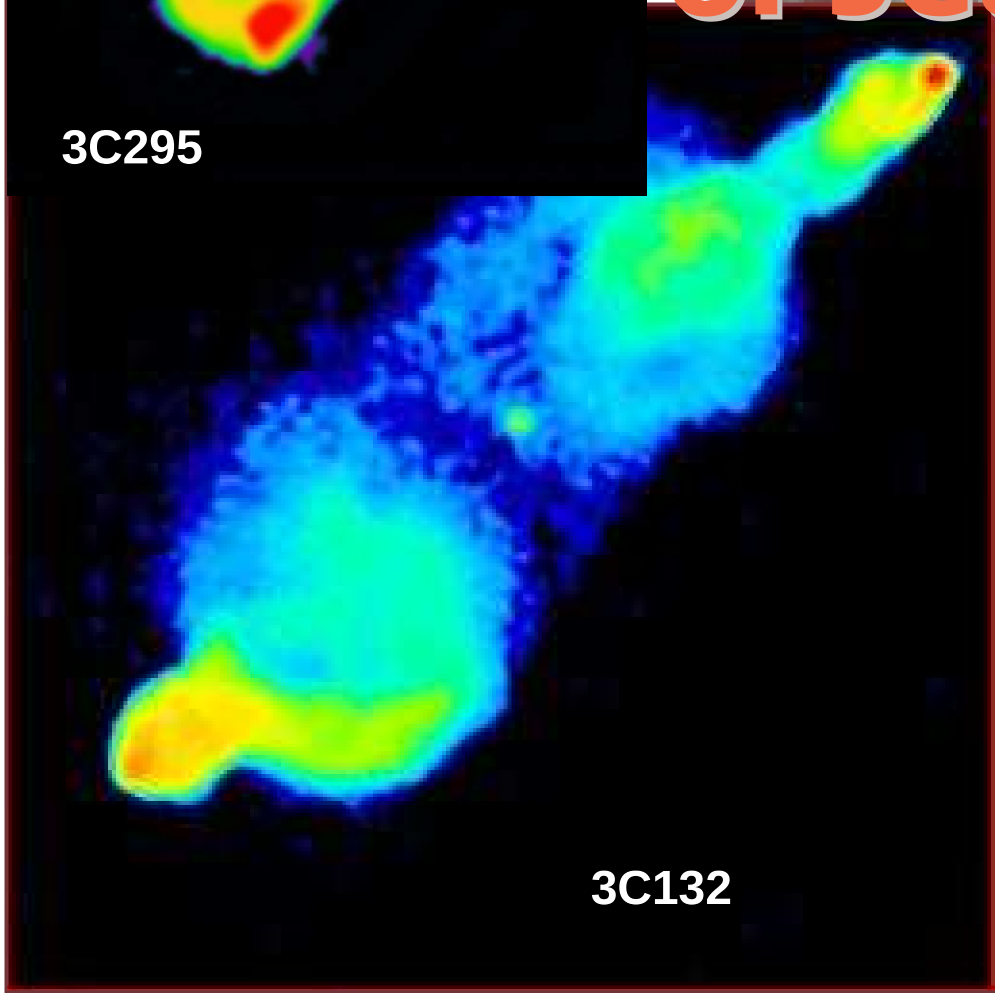
$$M_{tot}(<r) = -\frac{kTr}{\mu m_p G}\left(\frac{d\ ln\ \rho_{gas}}{d\ ln\ r} + \frac{d\ ln\ T}{d\ ln\ r}\right)$$

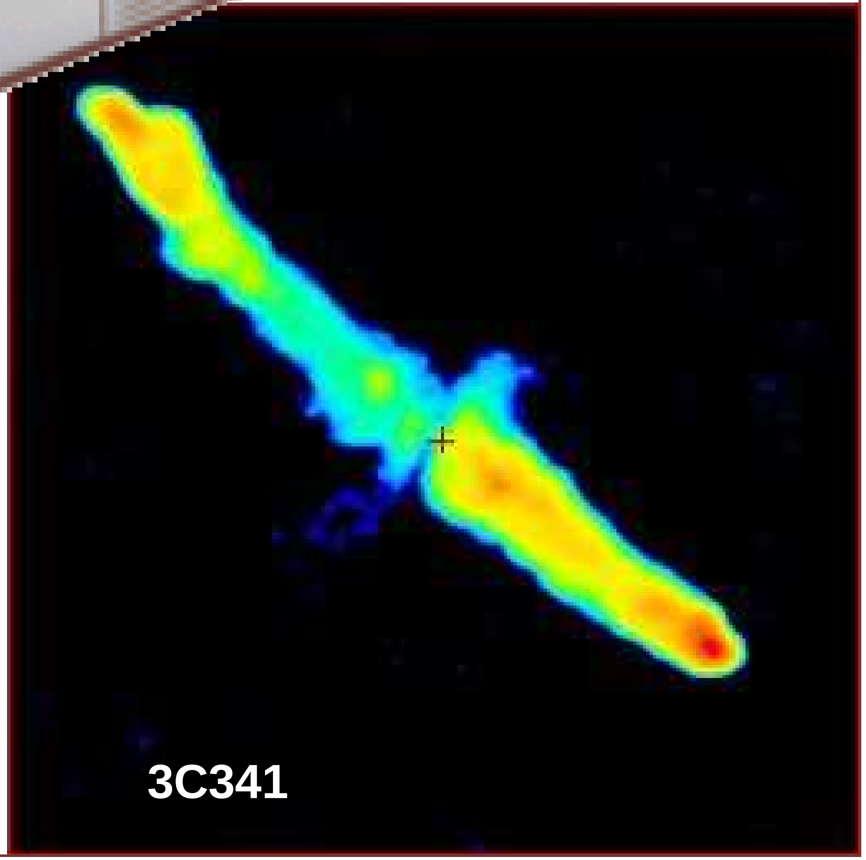


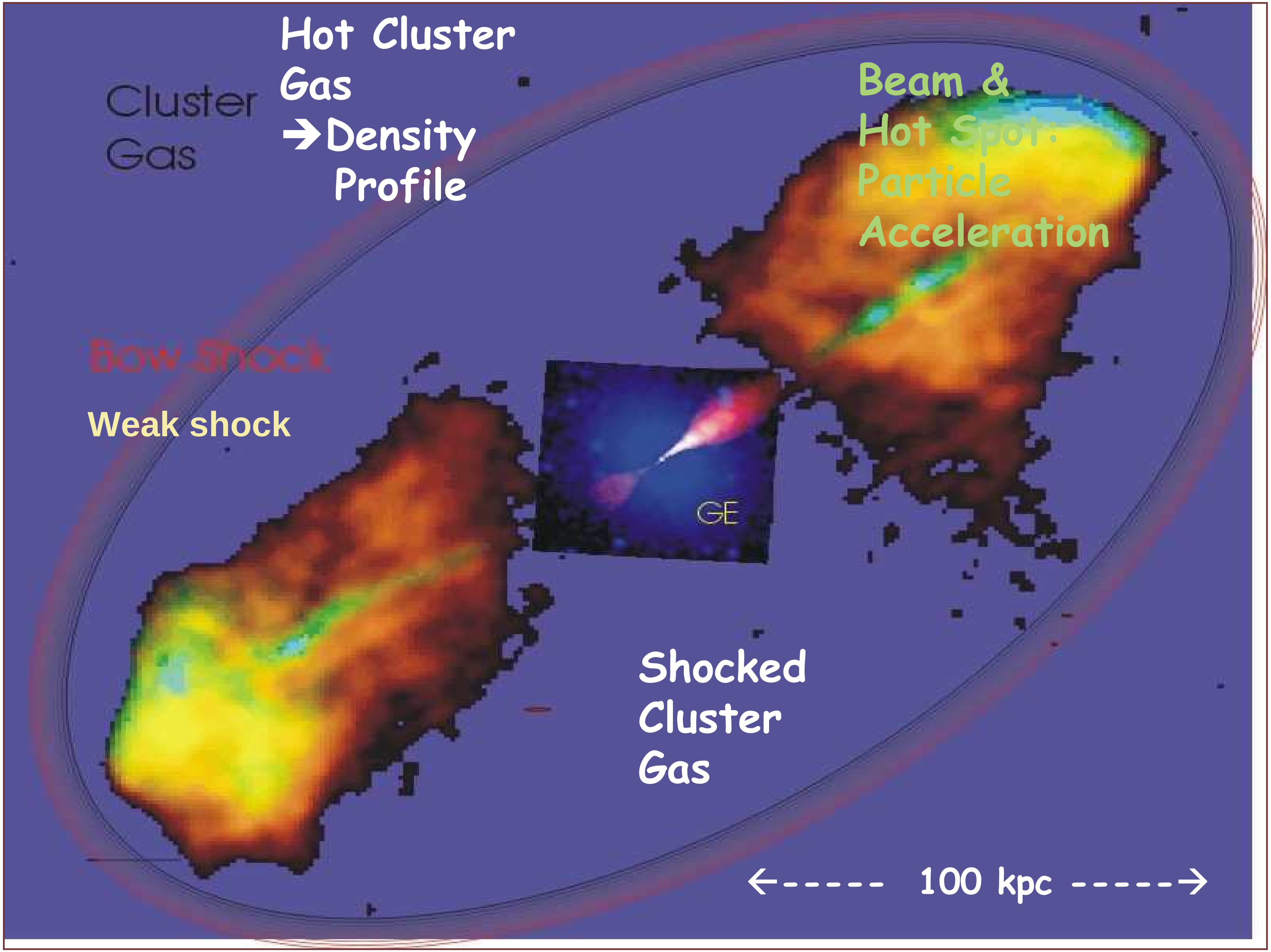
Cyg A
3C295
L_R = 10^45 erg/s
L_J = 10^46 erg/s
Cyg A is similar
to High z Radio Galaxy
FR II / FR I Transition
Log(P178 h⁻² ergs/sec/Hz)
Redshift
33
34
35
36
0
1
2
3
4

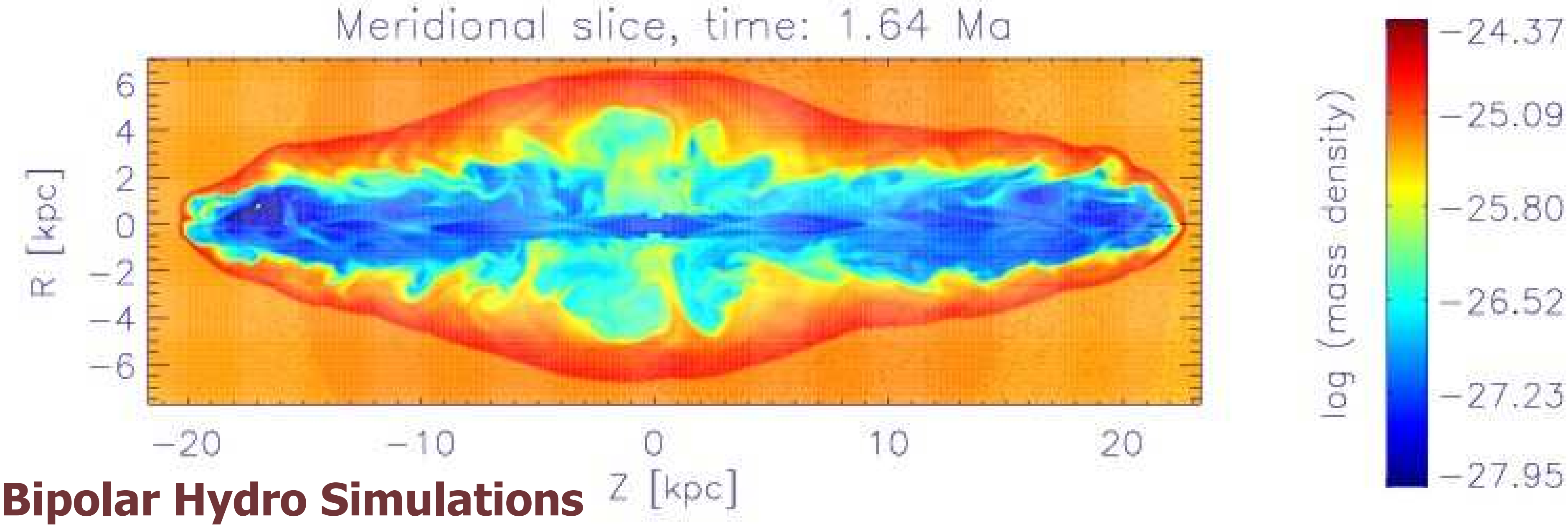
3 Phase-Evolution of Jets



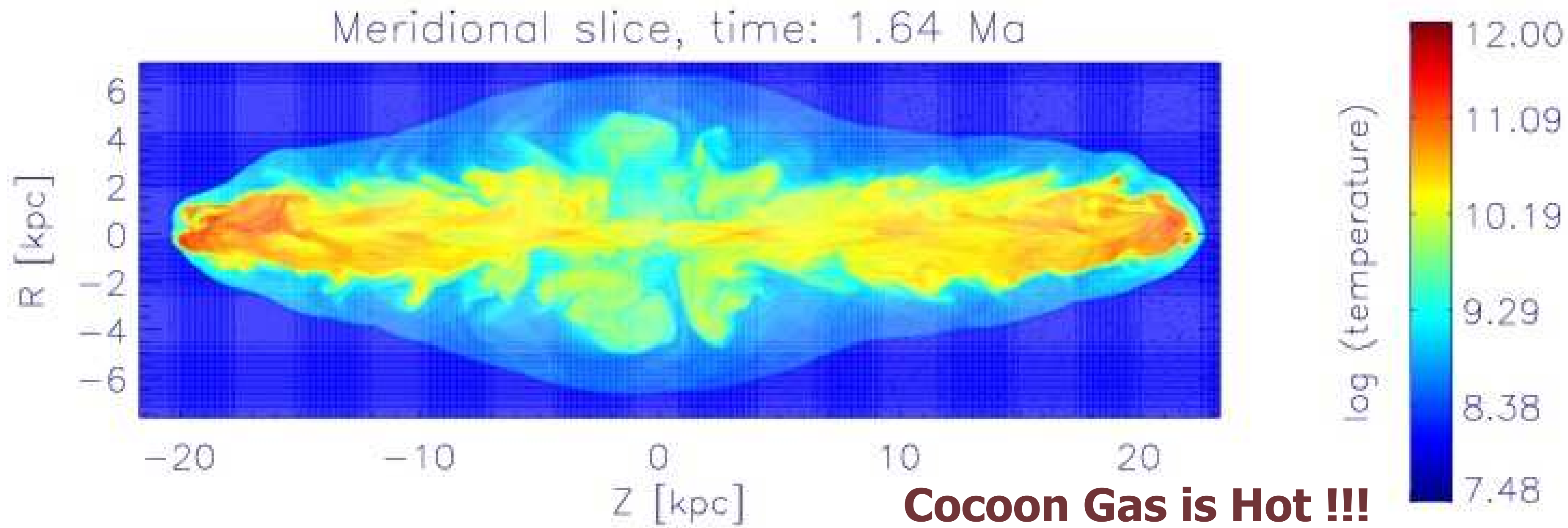




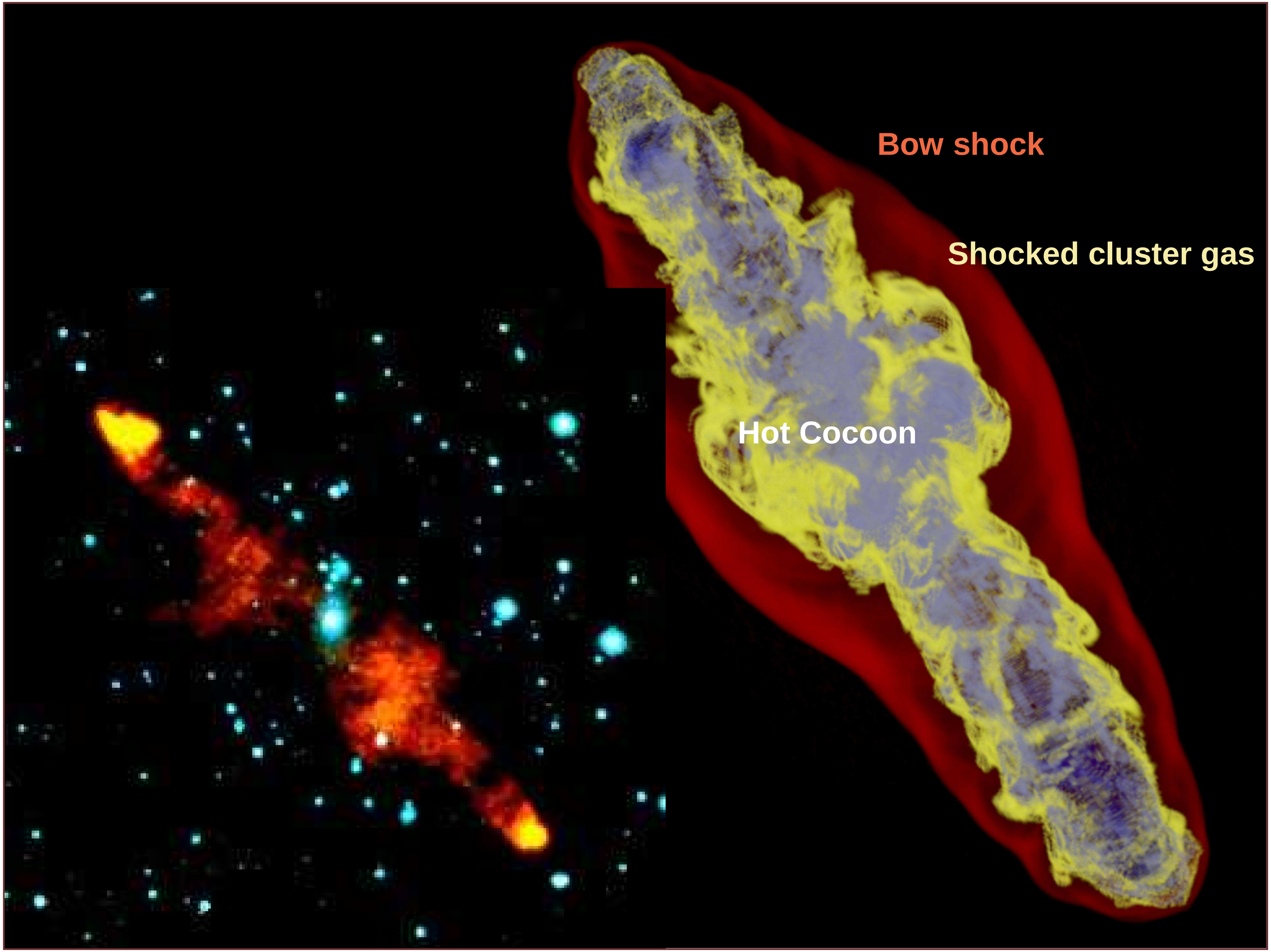

Hot Cluster Gas
→Density Profile
Cluster Gas
Beam & Hot Spot: Particle Acceleration
Bow Shock
Weak shock
GE
Shocked Cluster Gas
←----- 100 kpc -----→



Bipolar Hydro Simulations



Cocoon Gas is Hot !!!


Bow shock
Shocked cluster gas
Hot Cocoon

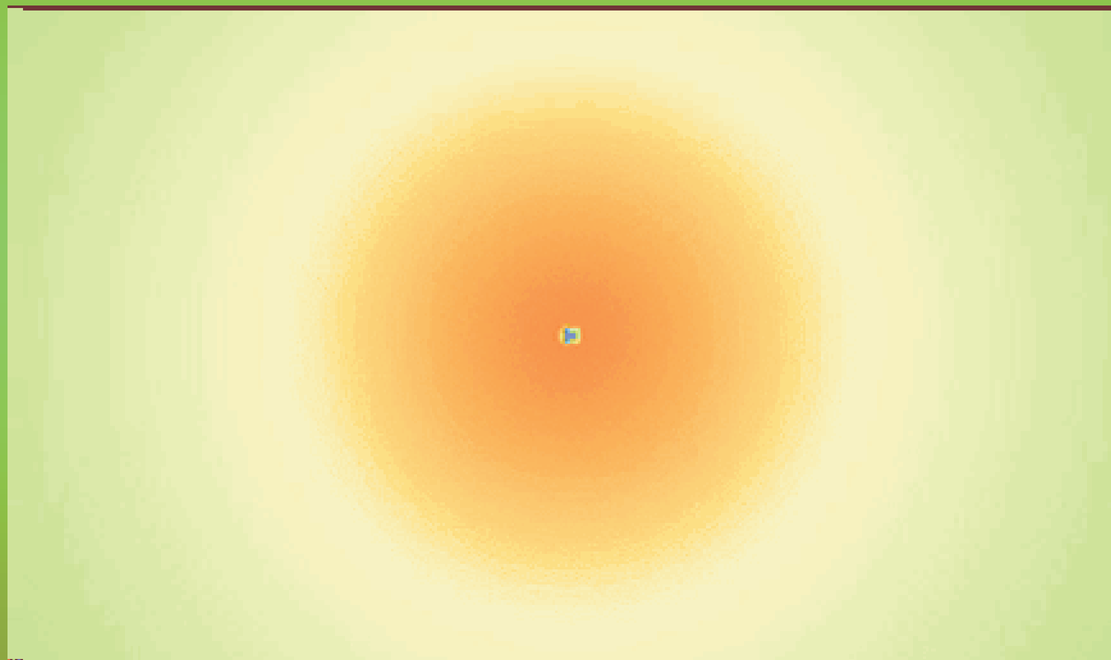
The Present State of Cygnus A

- Cygnus A is in a cluster: M(R < 500 kpc) = 2 x 10^{14} M_Sun (Smith et al. 2002);
- Gas density profile is shallower than given by ROSAT observations: $n_{Gas} \sim r^{-1.4}$
- The synchrotron-age of Cyg A (27 Myr) is compatible with the Sedov-phase:
- → if the density profile was as flat as measured by Chandra;
- → core density is about 0.1 cm^{-3}, L_{Jet} = 1 x 10^{46} erg/s;
- → the eastern Jet is just on the way to break out.
- → Cocoon cylindrical: due to magnetic confinement ? or due to low Mach numbers ?

Large-Scale Simulations on Supercomputers (NEC, HLRS)

Very light
Bipolar Jets:
NEC SX-5
for 1 month
➔ NEC SX-6,
& NEC SX-8

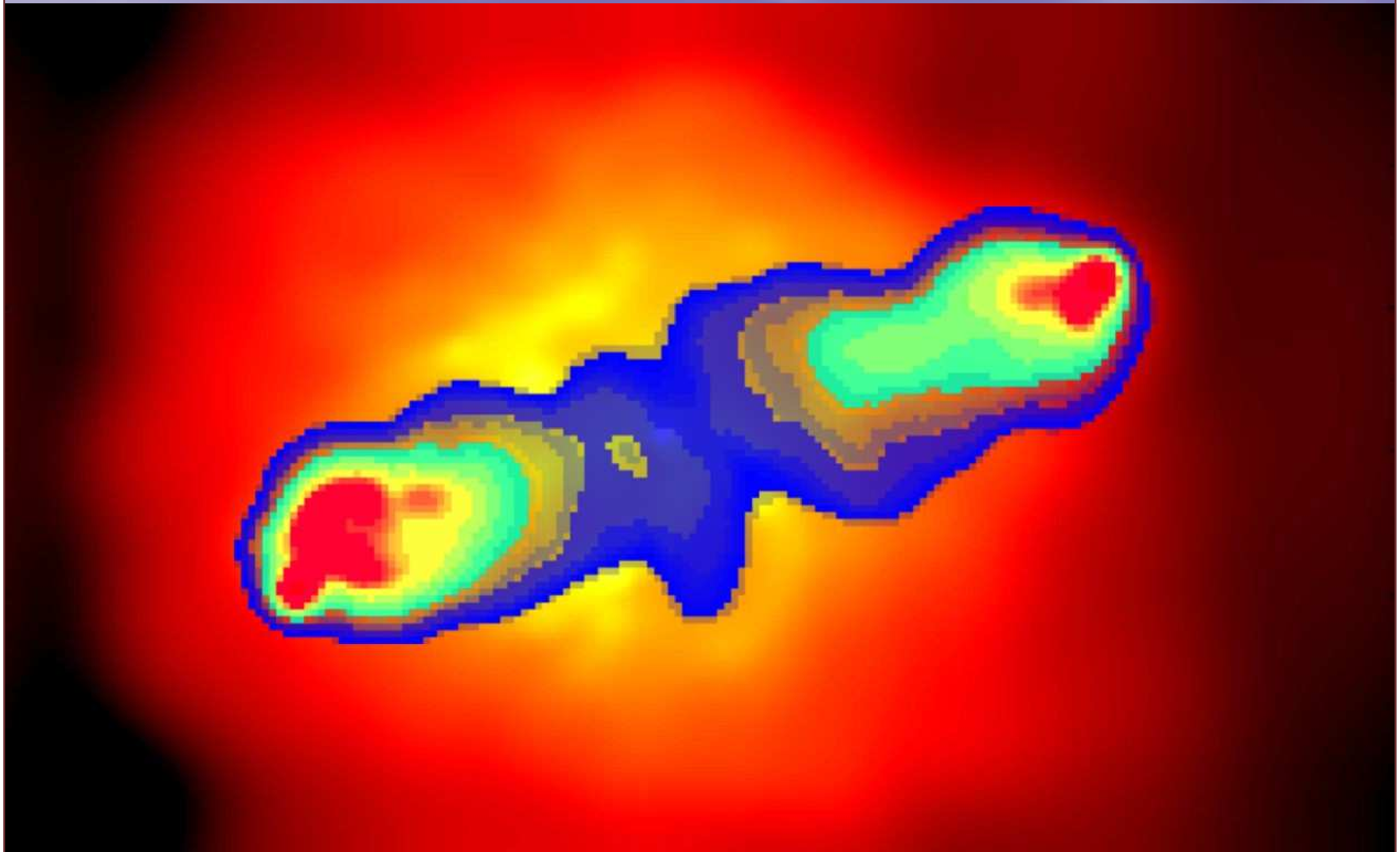
➔20 Mio years
in real life.



Transition from
spherical bubble
➔ cigar-shape.

M. Krause, LSW

Cyg A is at the End in the Sedov-Phase



Chandra

VLA 330 MHz

$$E(t) = L_J\, t$$

$$\rho(r) = \rho_0 \left(R_c / r \right)^{\kappa} , \; \kappa = 1.4 , \; R_c = 10 \text{ kpc}$$

$$R(t) = \left(\frac{(3-\kappa)(5-\kappa)\, L_J}{12\, \pi\, \rho_0\, R_c^{\kappa}} \right)^{\frac{1}{5-\kappa}} t^{\frac{3}{5-\kappa}}$$

$$R(t) = 3.3 \text{ kpc} \left(t \,/\, \text{Myr} \right)^{\frac{1}{1.2}}$$

$$t = 27 \text{ Myr} \rightarrow R = 51 \text{ kpc}$$

Density Contrast Cyg A: $\eta = \dfrac{\rho_J h_J \Gamma^2}{\rho_0}$

$$L_{kin} = \pi R_J^2 \, \Gamma (h_J \Gamma - 1) \, \rho_J \beta \, c^3$$

$$\frac{L_{kin}}{\pi R_J^2 \rho_0 \eta \, c^3} = \beta \left(1 - \frac{1}{h_J \Gamma}\right) = \chi < 1$$

$$\eta = \frac{0.0002}{\chi} \, \frac{L_{kin}}{10^{46} \text{ erg/s}} \, \frac{0.1 \text{ cm}^{-3}}{n_0} \left(\frac{0.55 \text{ kpc}}{R_J} \right)^2$$

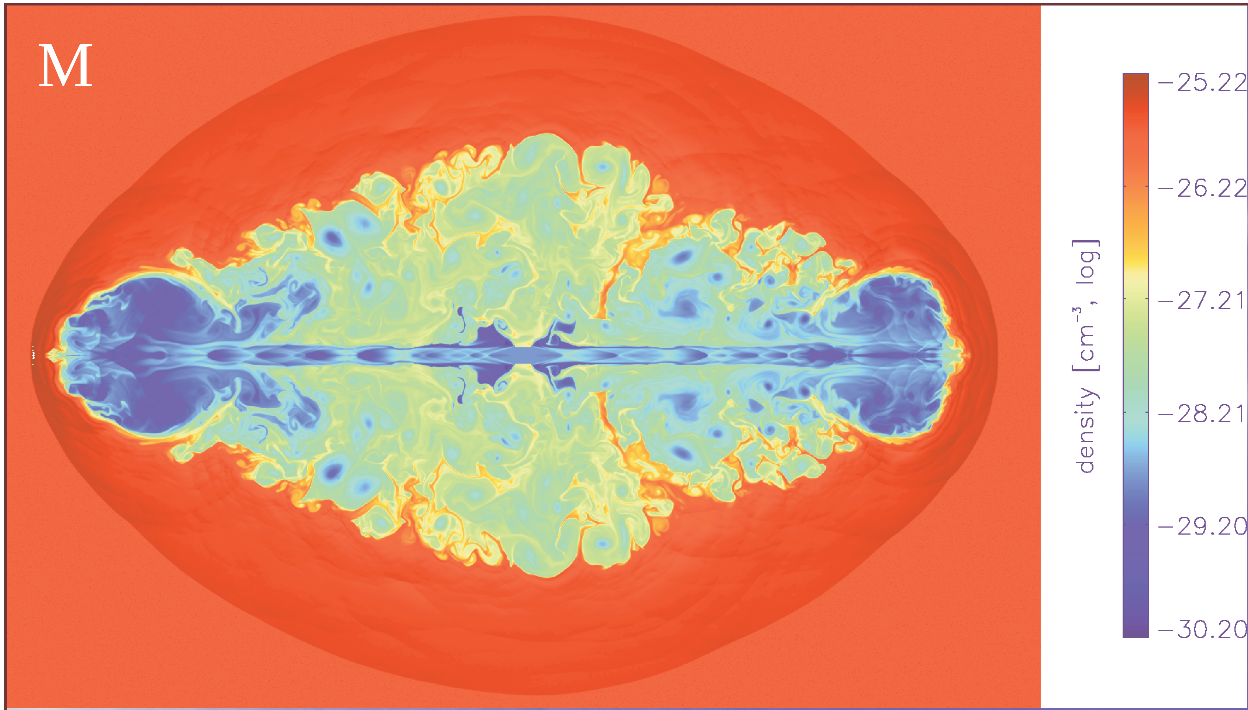
Consistency Check for Cyg A

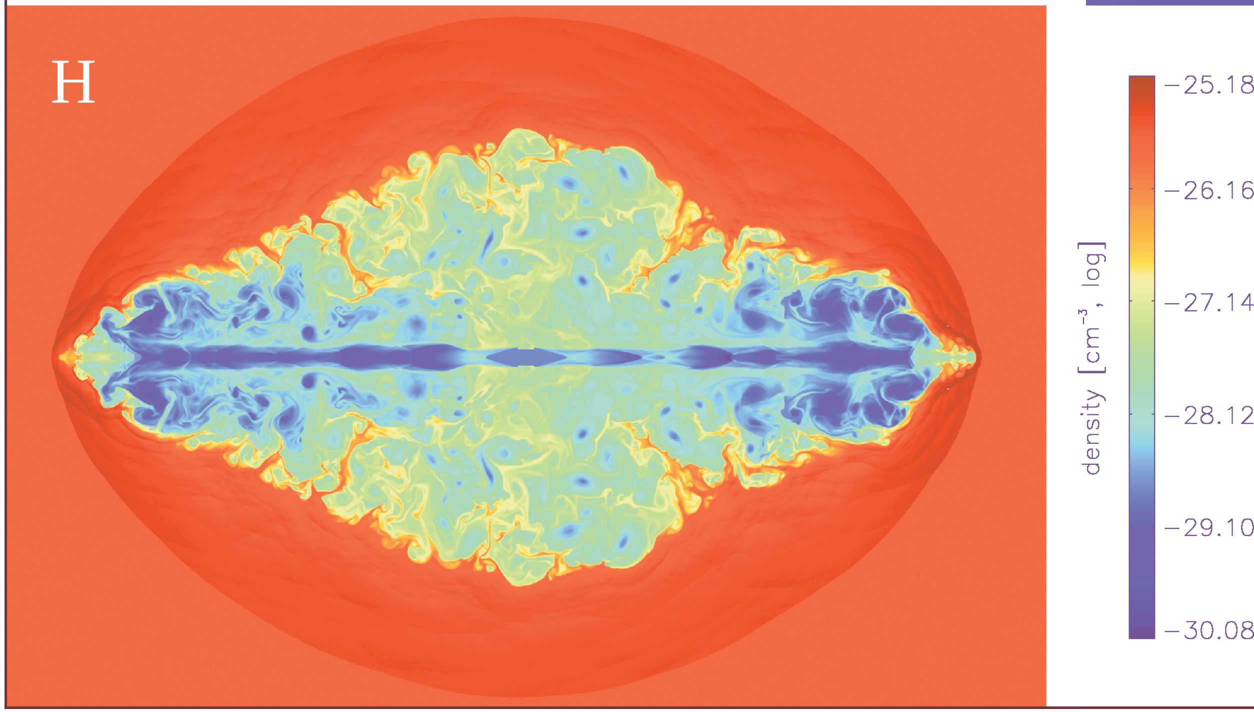
$$\dot{M}_J = \pi R_J^2 \eta \rho_0 \frac{c\beta}{\Gamma h_J} = 0.35\, M_\odot\, yr^{-1} \frac{\eta_{-3}\beta}{\Gamma h_J} \left(\frac{2R_J}{kpc}\right)^2$$

$$L_{kin} = \dot{M}_J c^2 h_J \Gamma \chi / \beta$$

$$L_{kin} = 2\times 10^{46}\ erg/s\ \eta_{-3}\ \chi \frac{n_0}{0.1\ cm^{-3}} \left(\frac{2R_J}{kpc}\right)^2$$

$$\chi = \beta \left(1 - \frac{1}{h_J \Gamma}\right) = \frac{1}{3}$$





Magnetic vs. Hydro $\eta=10^{-3}$

Morphology similar

KH instabilities supressed

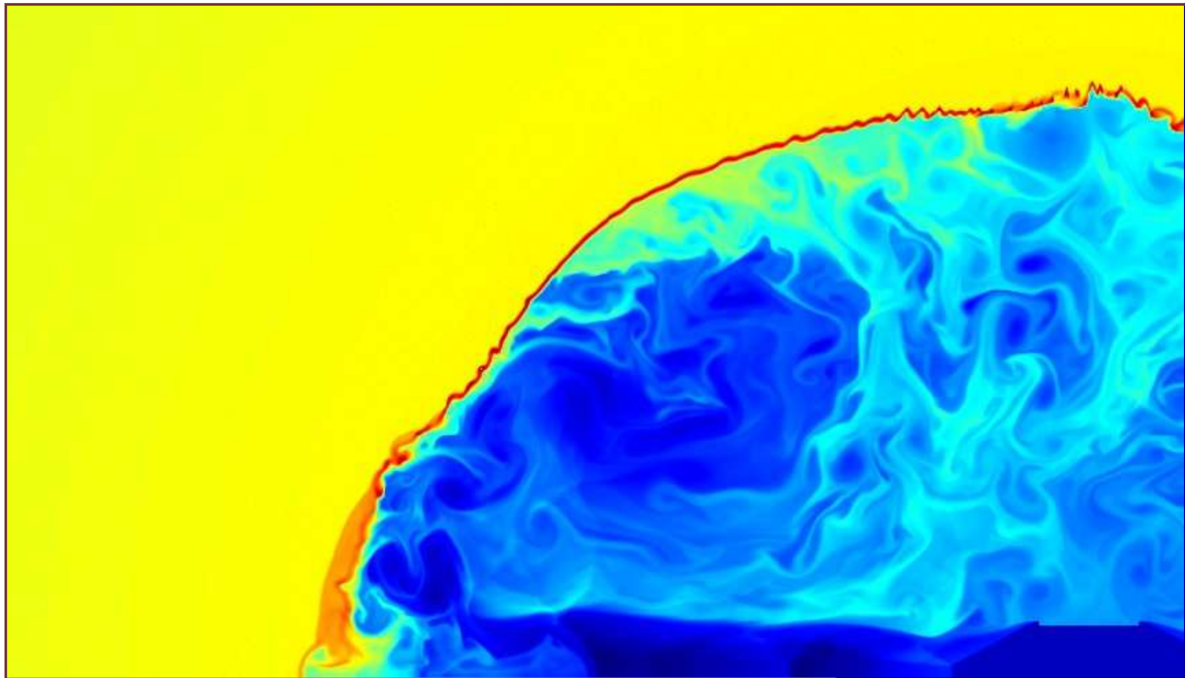
contact discontinuity in head region is more stable.

Cocoon still not cylindrical

M. Krause 2004

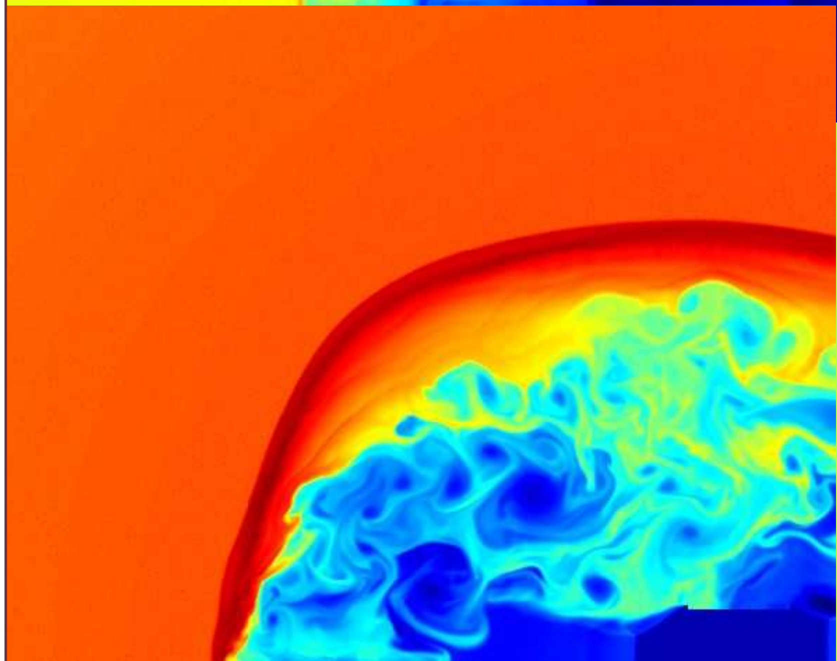
What happens at z > 2 ?

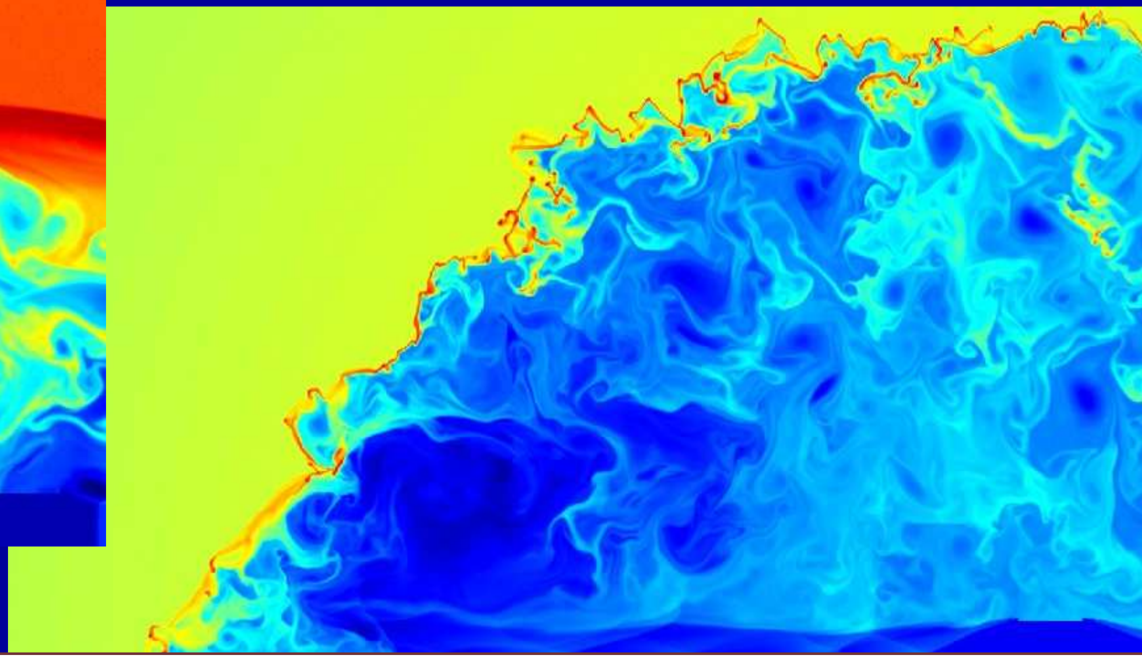
- Background density is higher and ambient temperature lower (virial temperature):
- → eta is even smaller, eta = 0.0001;
- → Sedov phase lasts longer, Jet extension therefore smaller;
- → cooling becomes important;
- → shocked cluster gas cools by Ly alpha emission;
- → structure of the Jet changes;
- → mixing is very efficient.



Density: after
1.4 – 3.0 – 6.8
Mio years
Background:
n = 10 / cm^3

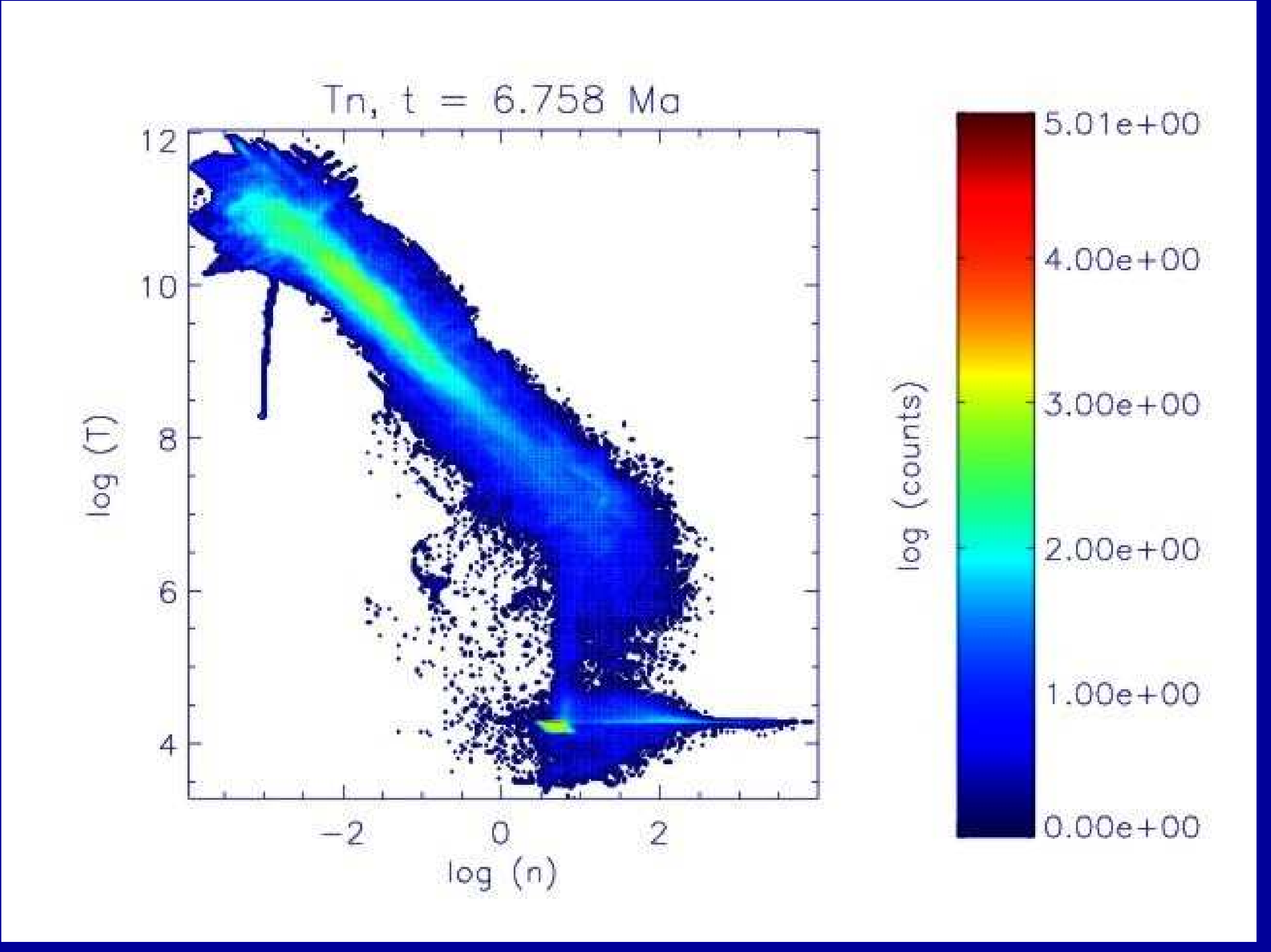
→ Cooling leads to Fragmentation of Bow Shock





M. Krause, LSW

Temperature Diagnostics



What we have achieved

- We extended Jet simulations to $\eta << 0.01$!
- Parameters for Cyg A are now fixed
  → Cyg A is at the end of the Sedov phase;
- Original cluster density profile is crucial;
- At higher redshifts, higher central densities, $n_0 > 1 / cm^3$, → cooling important
  → Ly alpha emission and absorption;
- → mixing of shocked cluster gas with cocoon
  → fingers of cold gas in the cocoon near center;

  → star formation with Jeans mass of 1 Mio solar masses → globular clusters (Krause 2002) ?

Critical Issues

- Magnetic fields have to be included in beam and cocoon → magnetosonic Mach number = 3;
- Beam plasma is always hot – very hot, stays hot → $T_{Beam} > 10^{11}$ K, M = 3 – 6 fixed, not free !
- → Beam/cocoon plasma is a 2-component plasma:
  → ions are thermal and non-relativistic
  → electrons relativistic and bumpy (3C 273 knots) !
- → requires completely new code development in the future: relativistic 2-component MHD codes !
- Understanding of internal knots in Beams (M 87, 3C 273, ...) is in the far future !