Jet power - what do you do with it?

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12th Birmingham-Nottingham Extragalactic Workshop - AGN: populations, parameters and power - 28th Sep. 2010

Overview

- Hydrodynamic simulation: Fanaroff-Riley class I and II jets
- Power channels: cavity, cocoon, shocks
- Interaction of a jet with a gaseous galactic disk

Fanaroff-Riley class II

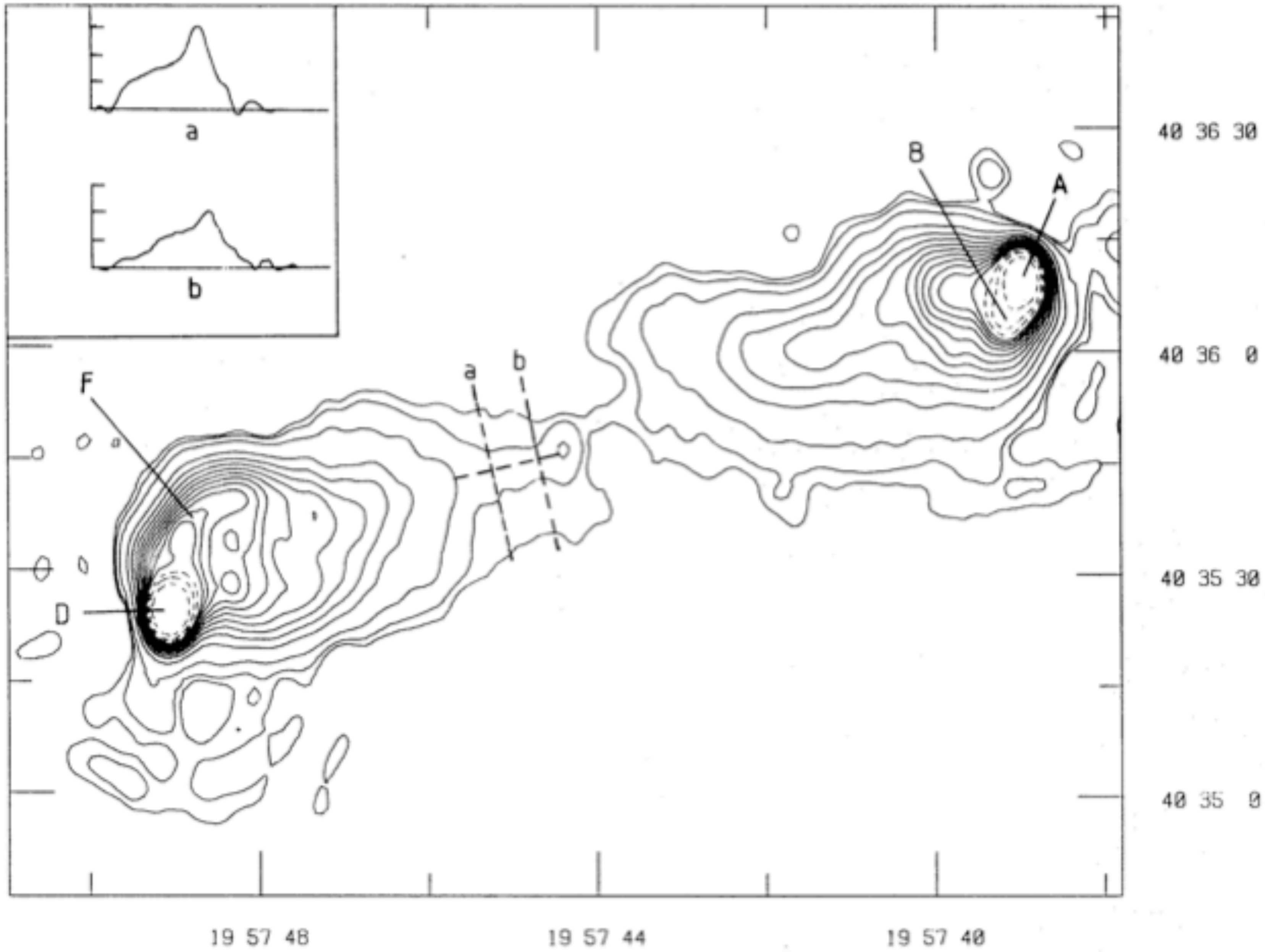
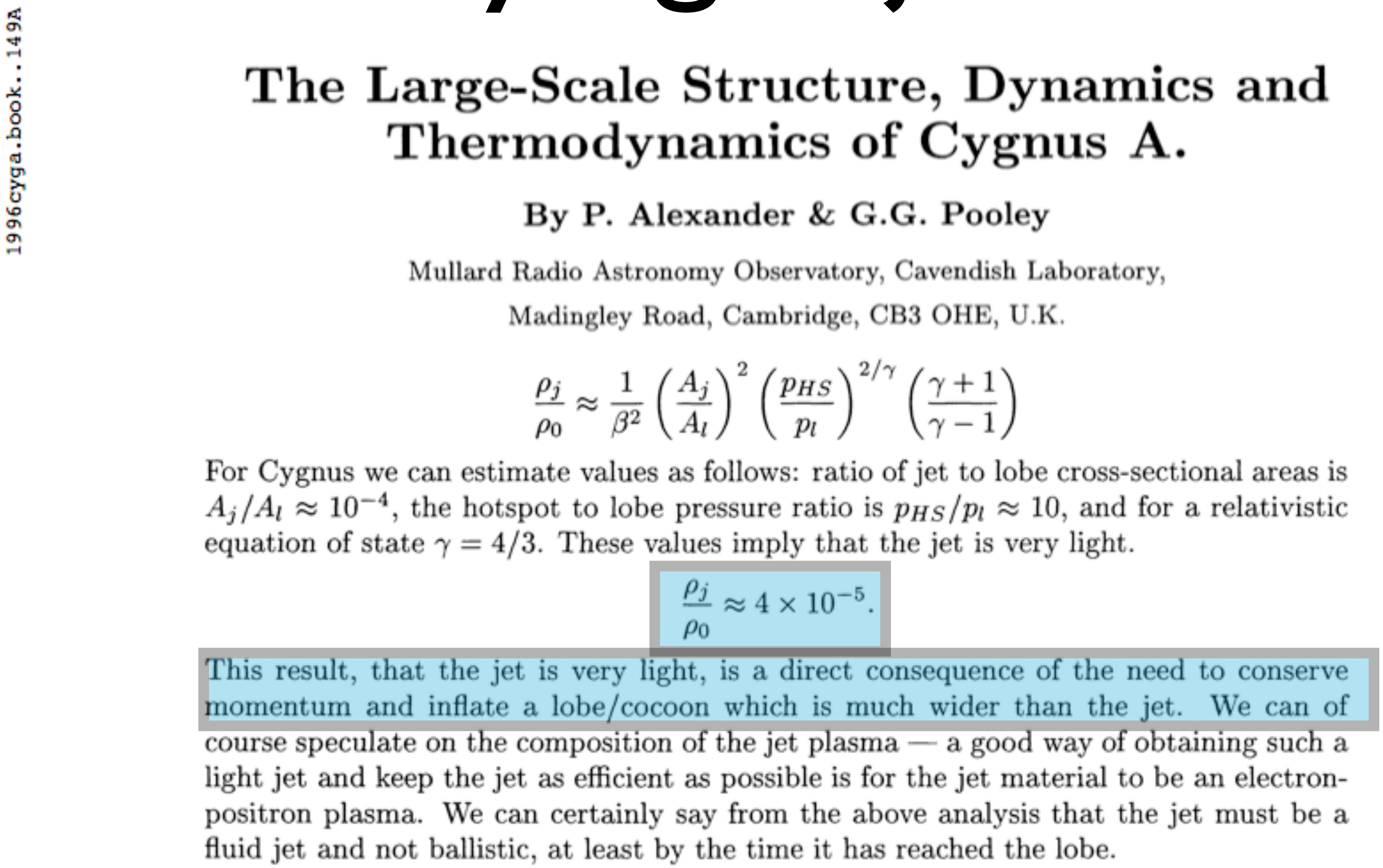


Figure 1a. Full-resolution 2.7-GHz map. Contour levels: 0.2 0.4 1.0 3.0 5.0 7.0 9.0 11.0 13.0 15.0 17.0 19.0 21.0; dashed: 25.0 30.0 40.0 Jy/beam. The inset shows two south to north cross-sections through the bridge between the Sf lobe and the central component. The marks are at intervals of 250 mJy/beam. Residual small phase errors are responsible for the lower dynamic range (600 : 1) near to the hotspots

Alexander, Brown & Scott 1984
Cambridge 5-km radio telescope
Cygnus A @ 2.7 GHz

Wide lobes / cocoons: very light jets



The Large-Scale Structure, Dynamics and Thermodynamics of Cygnus A.

By P. Alexander & G.G. Pooley

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$$\frac{\rho_j}{\rho_0} \approx \frac{1}{\beta^2}\left(\frac{A_j}{A_l}\right)^2 \left(\frac{p_{HS}}{p_l}\right)^{2/\gamma} \left(\frac{\gamma+1}{\gamma-1}\right)$$

For Cygnus we can estimate values as follows: ratio of jet to lobe cross-sectional areas is $A_j/A_l \approx 10^{-4}$, the hotspot to lobe pressure ratio is $p_{HS}/p_l \approx 10$, and for a relativistic equation of state $\gamma = 4/3$. These values imply that the jet is very light.

$$\frac{\rho_j}{\rho_0} \approx 4 \times 10^{-5}.$$

This result, that the jet is very light, is a direct consequence of the need to conserve momentum and inflate a lobe/cocoon which is much wider than the jet. We can of course speculate on the composition of the jet plasma — a good way of obtaining such a light jet and keep the jet as efficient as possible is for the jet material to be an electron-positron plasma. We can certainly say from the above analysis that the jet must be a fluid jet and not ballistic, at least by the time it has reached the lobe.

Numerical models confirm: lighter (& faster) jets -> wider cocoons

- e.g. Norman et al. 1983
- parameters: $\eta=\rho_j/\rho_a$, M: int. Mach
- gen. agreement / source structure

tuning η

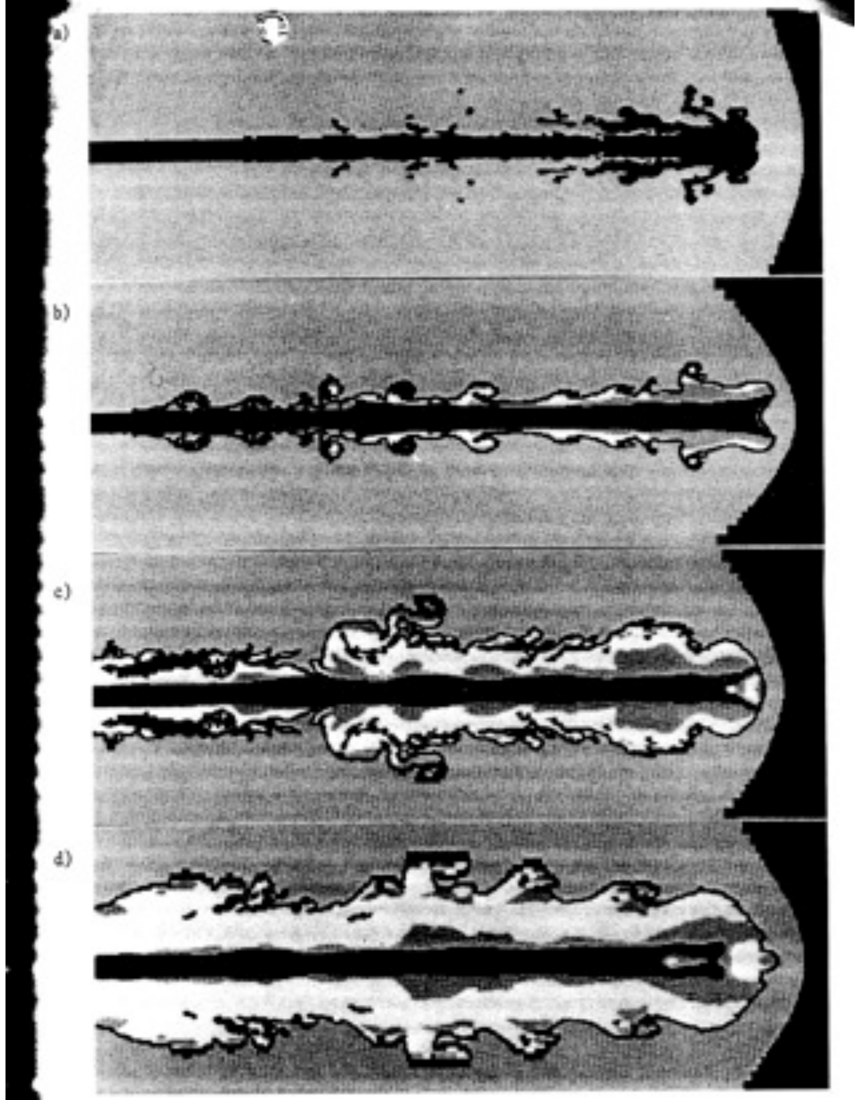


Figure 15. Naked beams and thick cocoons: a sequence of Mach 6 jets h different densities. a)ρ_b/ρ_m = 10, b) ρ_b/ρ_m = 1, c) ρ_b/ρ_m = 0.1, d) ρ_b/ρ_m = 0.01. Backflow (white regions) is stronglydependent on den

tuning M

OPAGATION AND MORPHOLOGY OF PRESSURE-CONFINED SUPERSONIC JETS

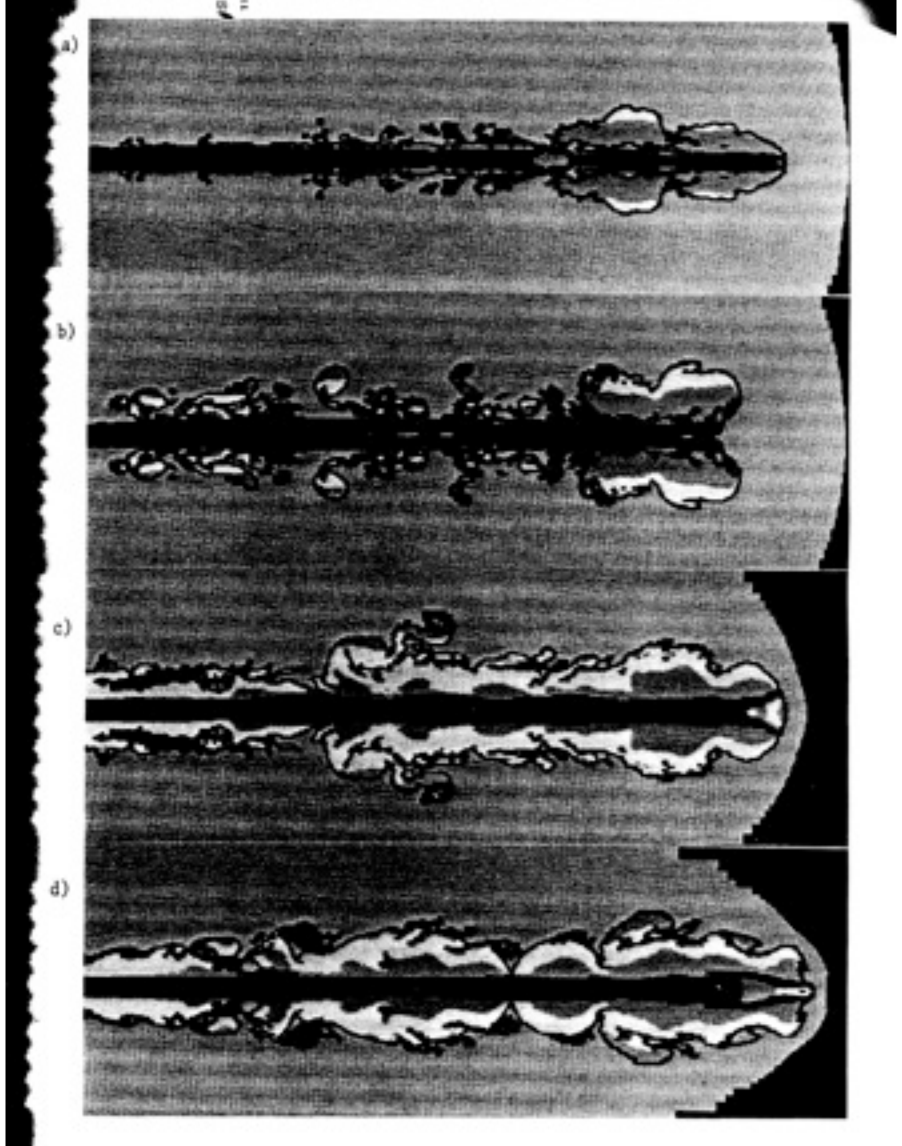
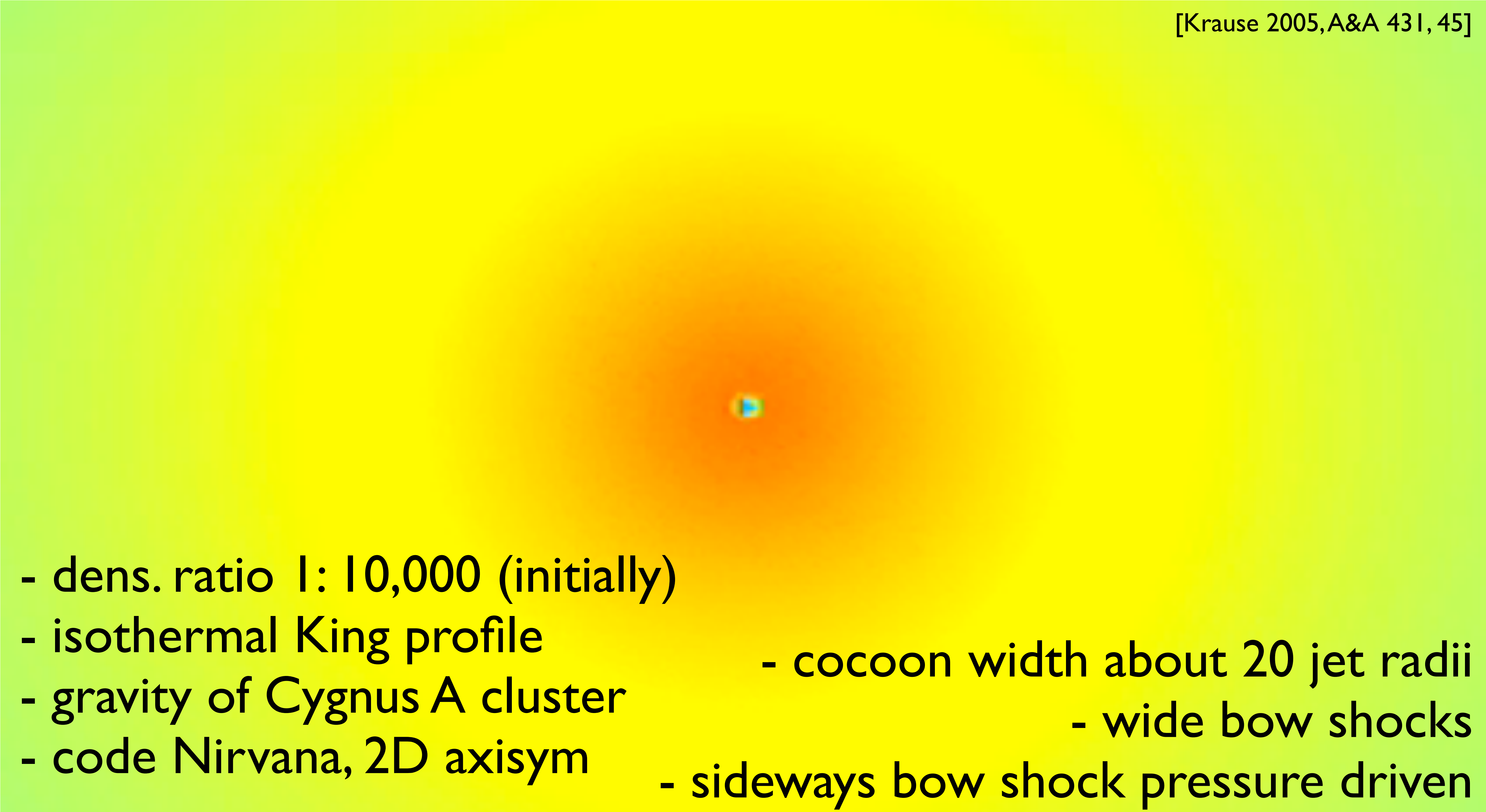


Figure 16. Lobes and unstable cocoons: a sequence of ρ_b/ρ_m = 0.1 jets having different Mach numbers. a) M_b = 1.5, b) M_b = 3, c) M_b = 6, d)

Simulations of very light jets



[Krause 2005, A&A 431, 45]

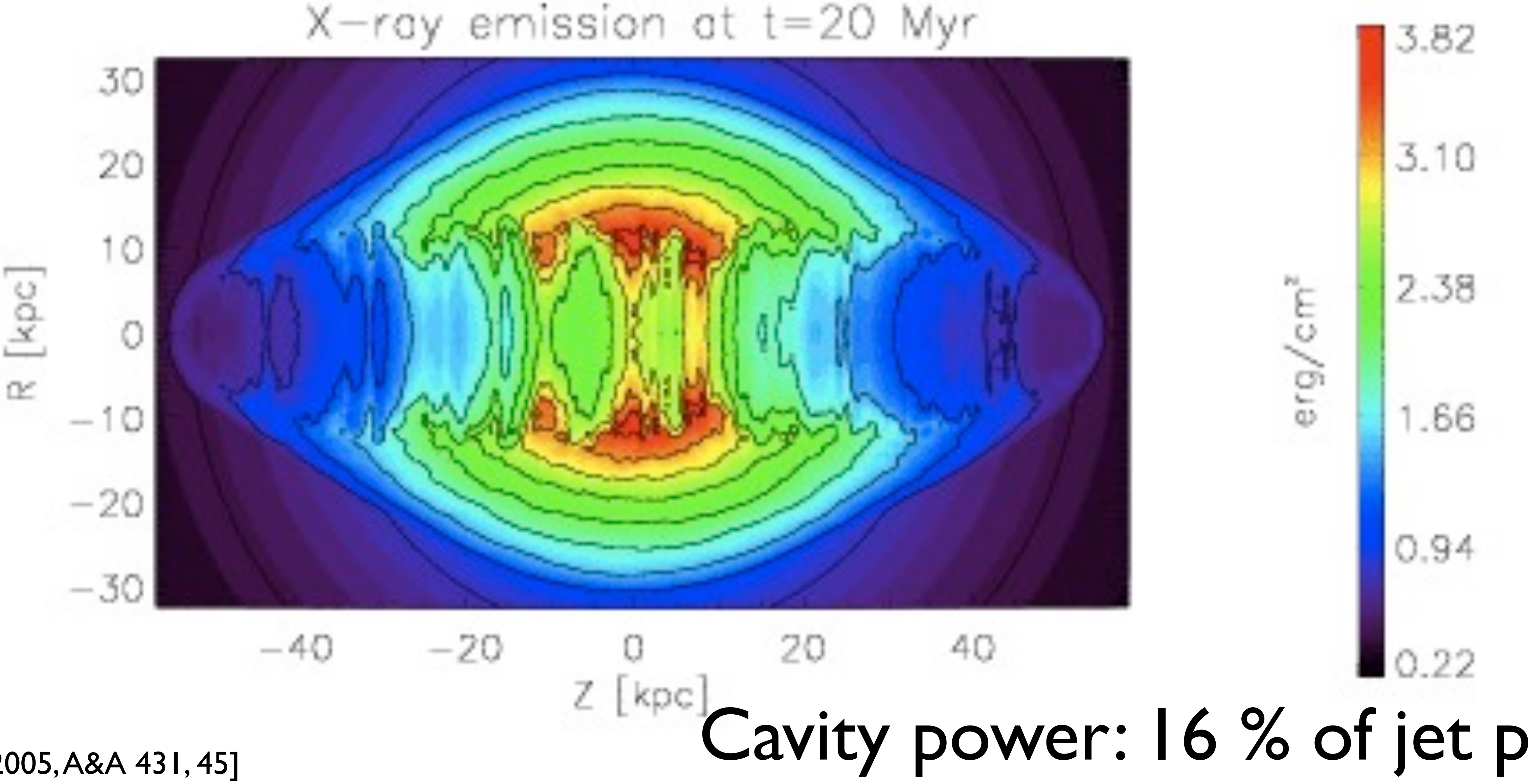
- dens. ratio 1: 10,000 (initially)
- isothermal King profile
- gravity of Cygnus A cluster
- code Nirvana, 2D axisym

- cocoon width about 20 jet radii
- wide bow shocks
- sideways bow shock pressure driven

Example Simulation, 2D, $\eta_0=10^{-4}$: X-ray isophotes

Shocked external gas region becomes wide for low jet density and late times

-> X-ray cavities, Elliptical X-ray isophotes



Cavity power: 16 % of jet power

[Krause 2005, A&A 431, 45]

Sideways expansion: blast wave solutions for all density profiles

- blastwave derivation: force ballance at bow shock:

$$\frac{\partial}{\partial t}\left(\mathcal{M}v\right) = S\left(p_{\rm int} - p_{\rm ext}\right)$$

- general solution in Krause 2003 & 2005:

$$\int_0^r \mathcal{M}(r) r dr = 2\int_0^t dt_1 \int_0^{t_1} E(t_2) dt_2 .$$

- constant density (here: L=power)

$$r \quad = \quad \left(\frac{5L}{4\pi\rho_0}\right)^{1/5} t^{3/5}$$

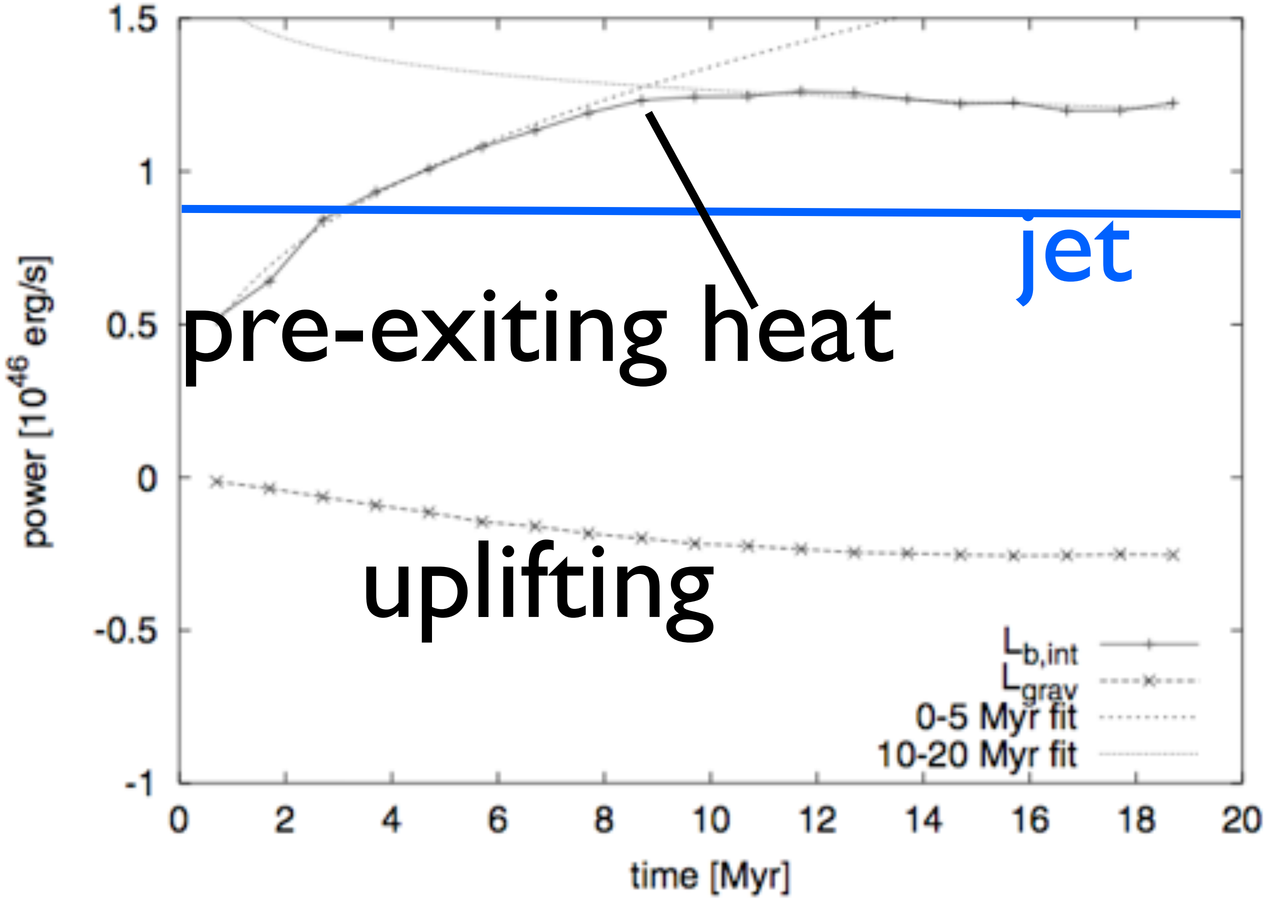
- example: beta profile

$$\rho(r) = \rho_0 \left(1 + \left(\frac{r}{r_0}\right)^2\right)^{-3\beta/2} \qquad t = \sqrt[3]{\frac{12\pi\rho_0 r_0^5}{\mathcal{L}} Y}$$

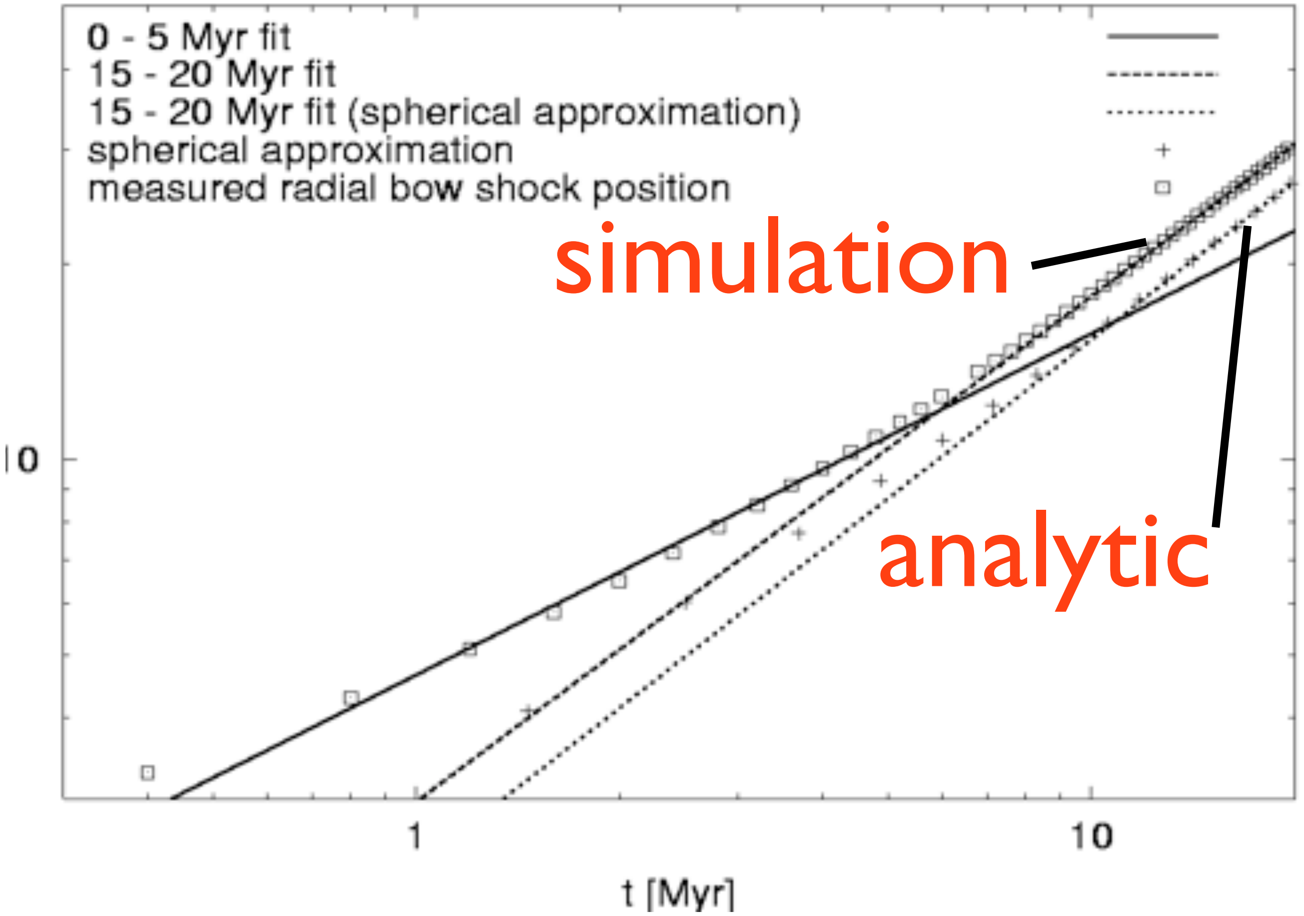
$$Y = \left\{ \begin{array}{l} \frac{1}{8}x(A^3 + A/2) - \frac{1}{4}\mathrm{arcsinh}(x)B \\ \frac{1}{2}\left(\frac{2}{3}xC - \mathrm{arctan(x)}A^2\right) \\ \frac{1}{2}\mathrm{arcsinh}(x)C - \frac{3}{4}xA \end{array} \right\} \mathrm{for}\ 3\beta = \left\{ \begin{array}{l} 1 \\ 2 \\ 3 \end{array} \right. \quad \begin{array}{rcl} A & = & \sqrt{1+x^2} \\ B & = & 3/4 - x^2 \\ C & = & 3/2 + x^2 \\ x & = & r/r_0 . \end{array}$$

Check shock power

Power sources vs. time



Bow shock radius vs. time

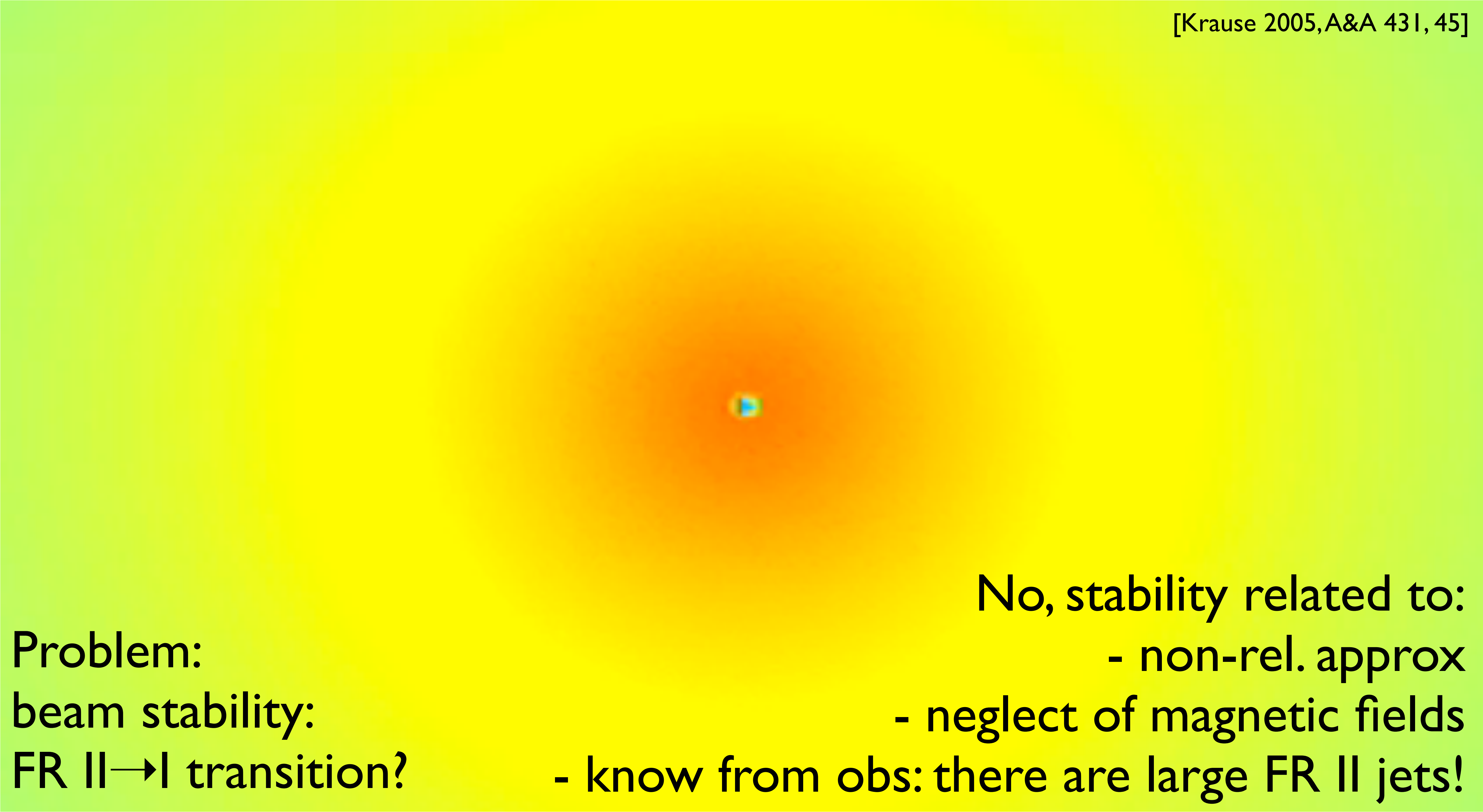


- L=L_jet + L_pre-existing - L_uplift
- Bow shock measurement overestimates L by ≈60%

Power determinations

Source	$\log(Q_0/$ erg/s), authors	$\log(Q_0/$ erg/s), this method	$\log(Q_0\ t/$ erg), authors	$\log(Q_0\ t/$ erg), this method
Cygnus A Wilson et al. 2006	46.1	>47.2	61.1	>62.3
MS 0735.6 +7421 Mc Namara et al. 2005	46.2	45.9	61.8	61.4

Simulations of very light jets

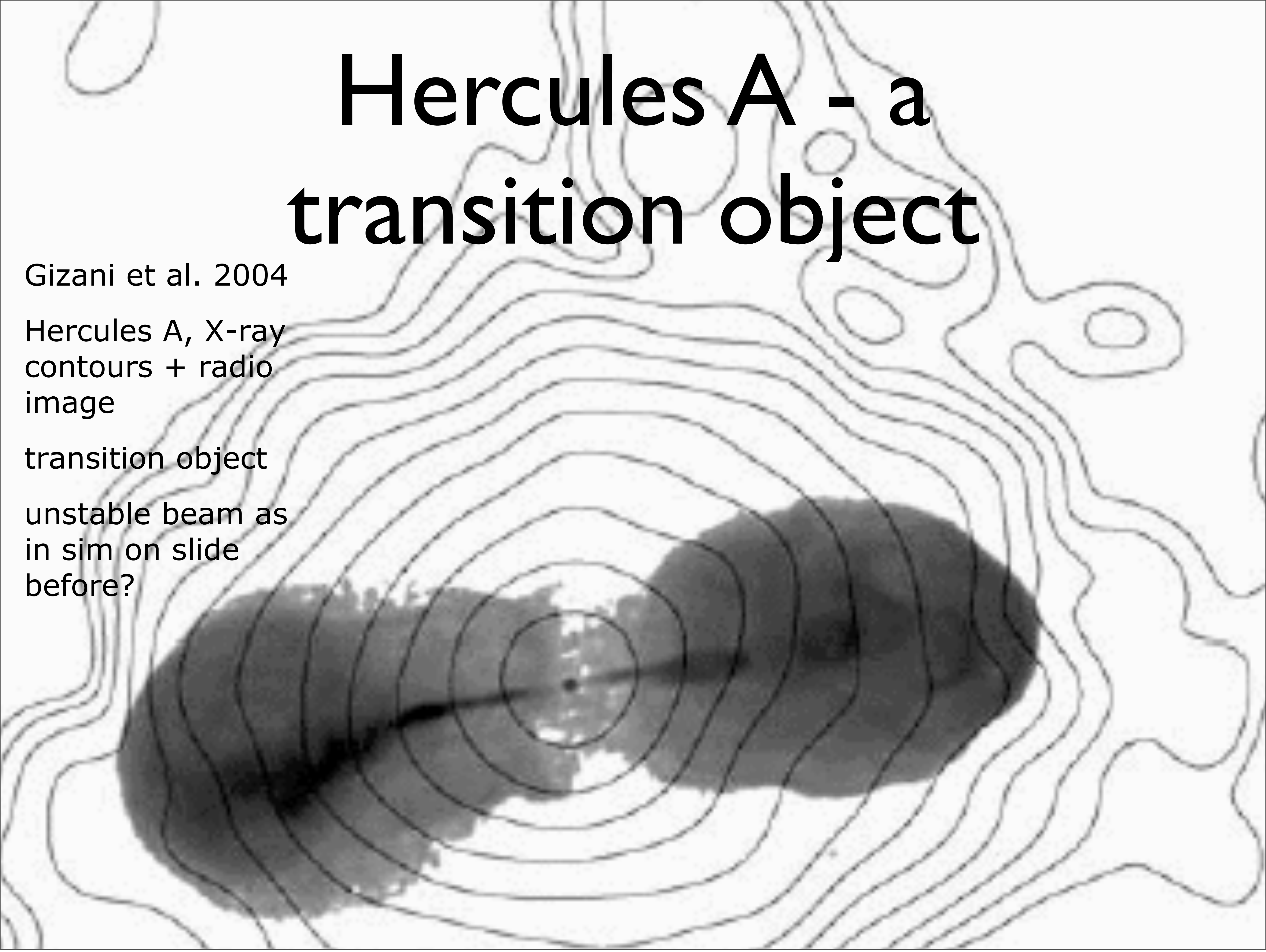


[Krause 2005, A&A 431, 45]

Problem:
beam stability:
FR II→I transition?

No, stability related to:
- non-rel. approx
- neglect of magnetic fields
- know from obs: there are large FR II jets!

Hercules A - a transition object



Gizani et al. 2004

Hercules A, X-ray contours + radio image

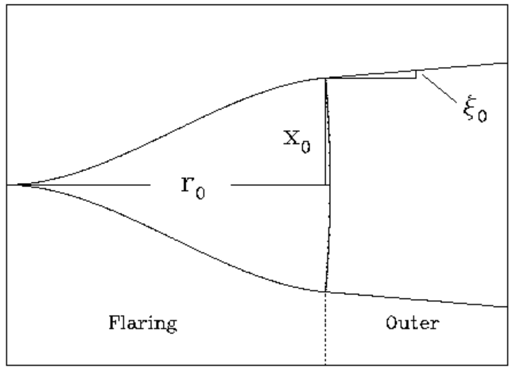
transition object

unstable beam as in sim on slide before?

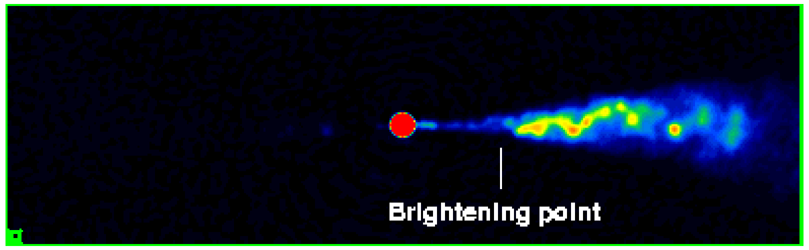
Fanaroff-Riley class I

- lower radio luminosity
- morphology related to jet power and environment

Geometry

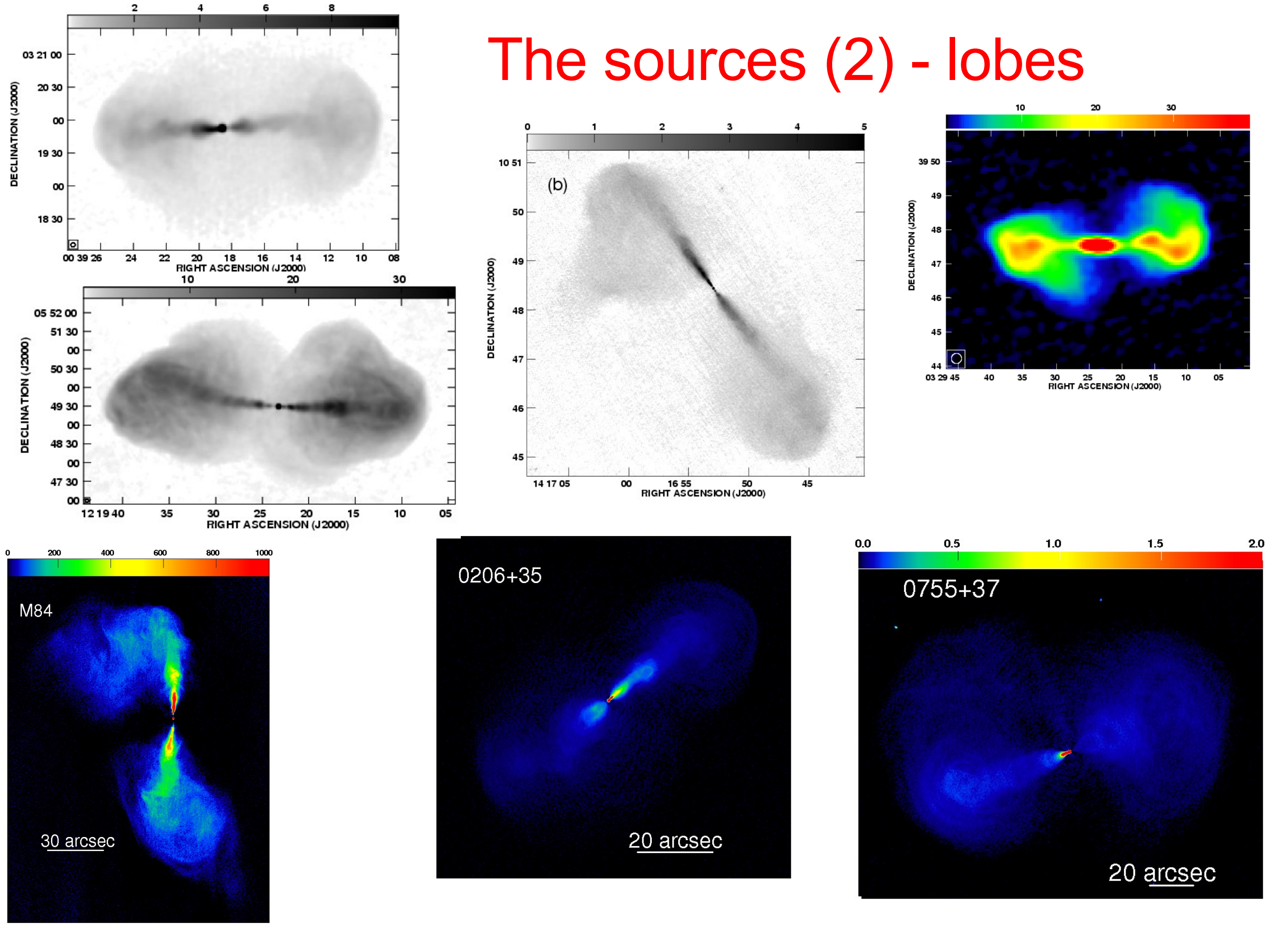


FR1 jets flare and then recollimate



Abrupt brightening close to nucleus

Complex fine structure in bright region



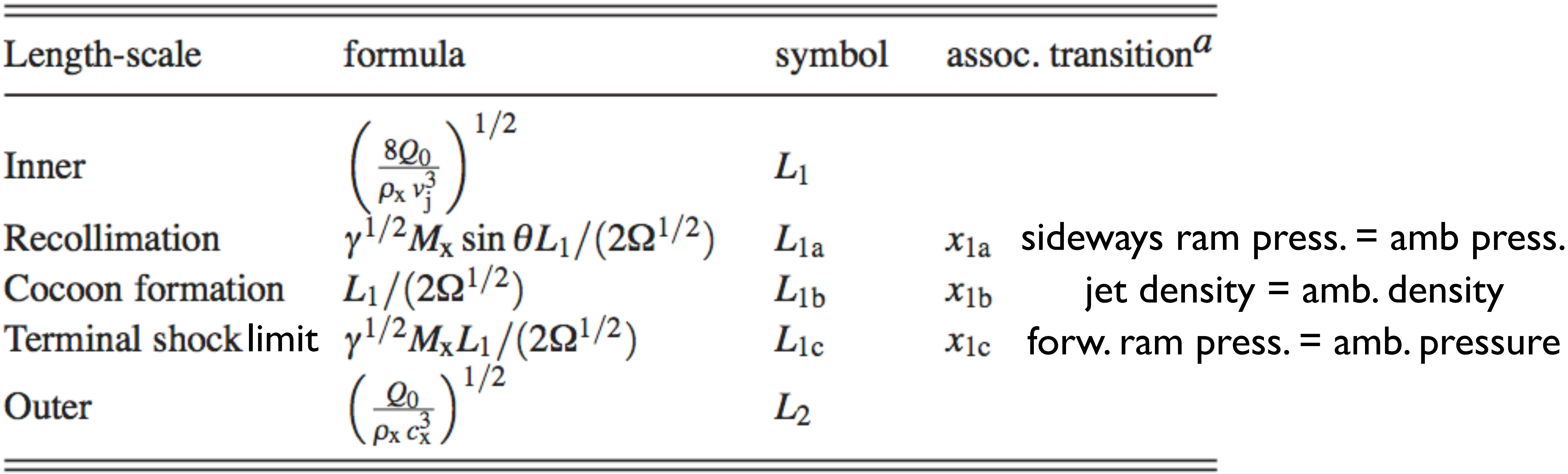
The sources (2) - lobes

[credits: R. Laing]

[Alexander 2006, Krause
Alexander & Riley in prep.]

Collimation (or not) by ambient pressure

- Initially conical beam, density & ram pressure $\propto r^{-2}$
- 3 parameters: solid angle Ω, external Mach number M-ext, scale L1



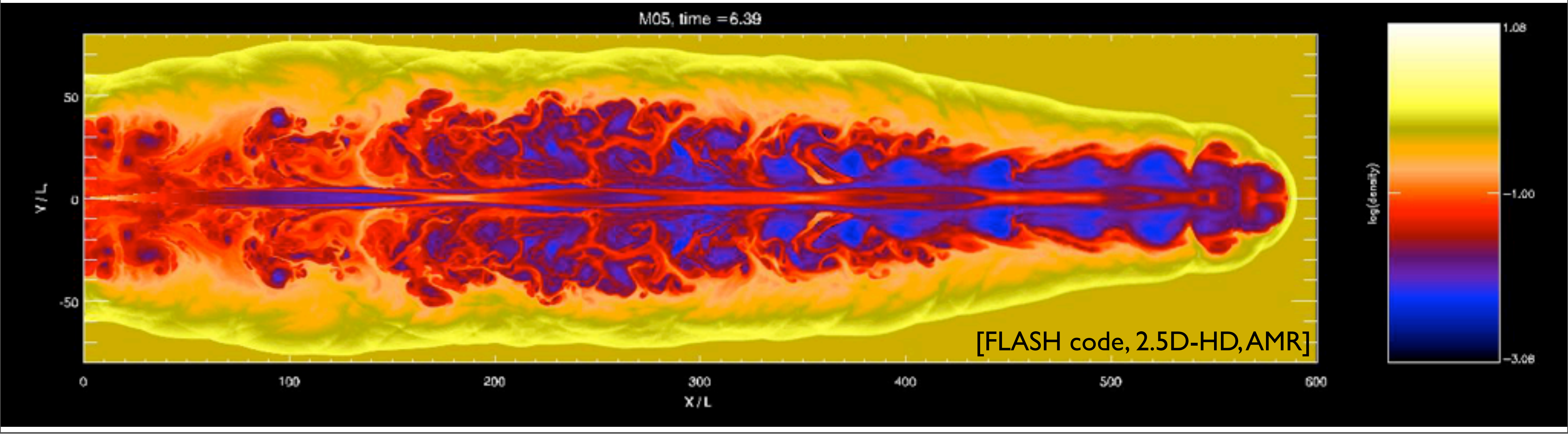
Length-scale	formula	symbol	assoc. transition^a	
Inner	$\left(\frac{8Q_0}{\rho_x v_j^3}\right)^{1/2}$	L_1		
Recollimation	$\gamma^{1/2} M_x \sin\theta L_1/(2\Omega^{1/2})$	L_{1a}	x_{1a}	sideways ram press. = amb press.
Cocoon formation	$L_1/(2\Omega^{1/2})$	L_{1b}	x_{1b}	jet density = amb. density
Terminal shock limit	$\gamma^{1/2} M_x L_1/(2\Omega^{1/2})$	L_{1c}	x_{1c}	forw. ram press. = amb. pressure
Outer	$\left(\frac{Q_0}{\rho_x c_x^3}\right)^{1/2}$	L_2		

FR II recipe

- 1st: form cocoon (L1b)
- 2nd: collimate (L1a)
- 3rd: have terminal shock (L1c)
- i.e. arrange: L1b < L1a < L1c

- Density ratio set by current external Mach number:

$$\eta = \left(\frac{L_{1\mathrm{b}}}{L_{1\mathrm{a}}}\right)^2 = \frac{1}{\gamma \sin^2\theta M_{\mathrm{x}}^2}$$

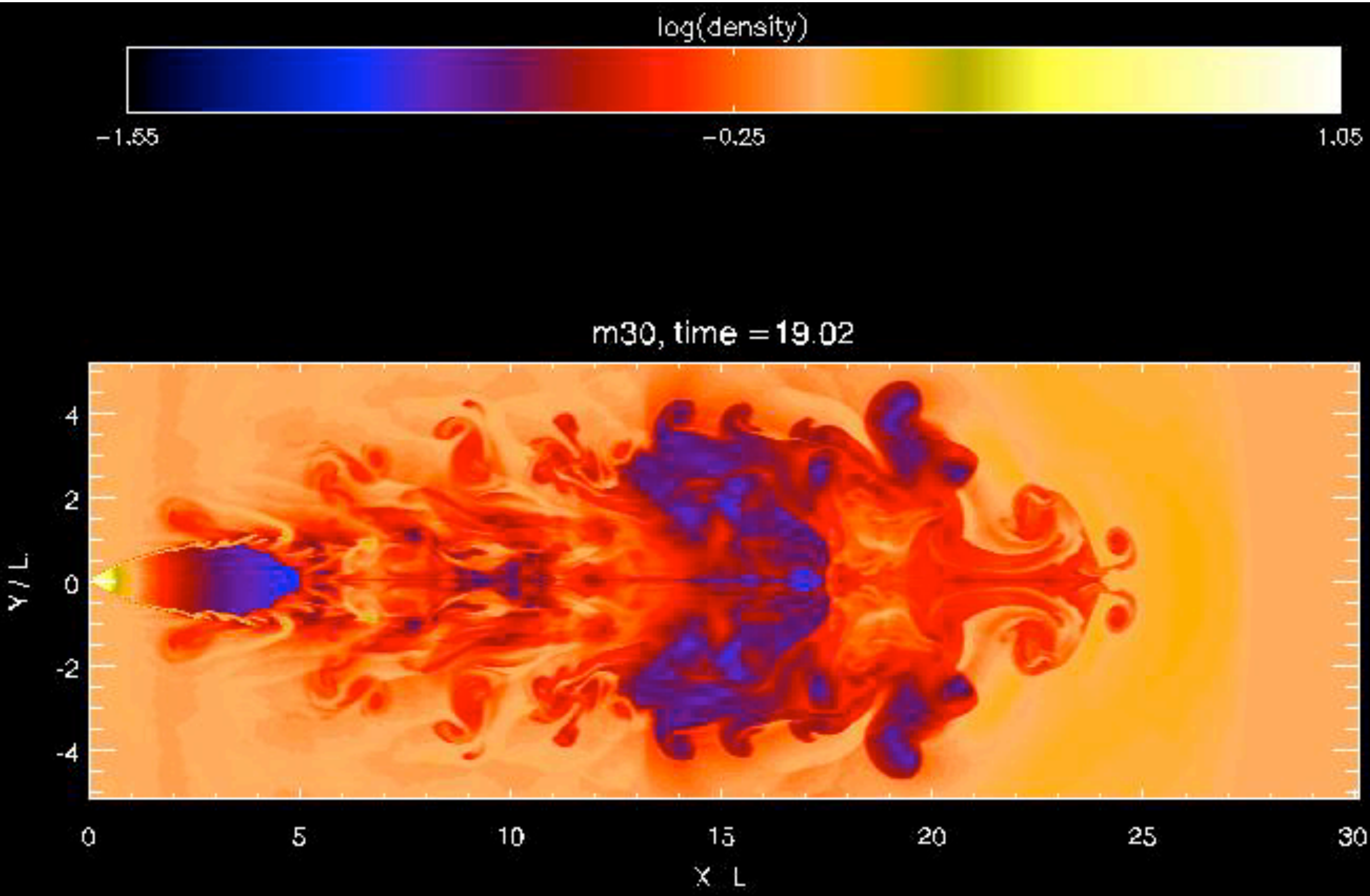


[FLASH code, 2.5D-HD, AMR]

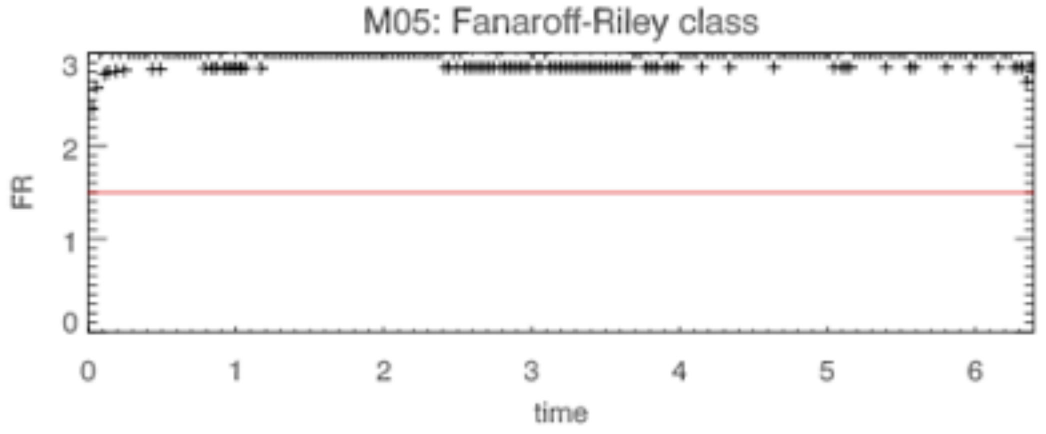
Simple minded FR I recipe

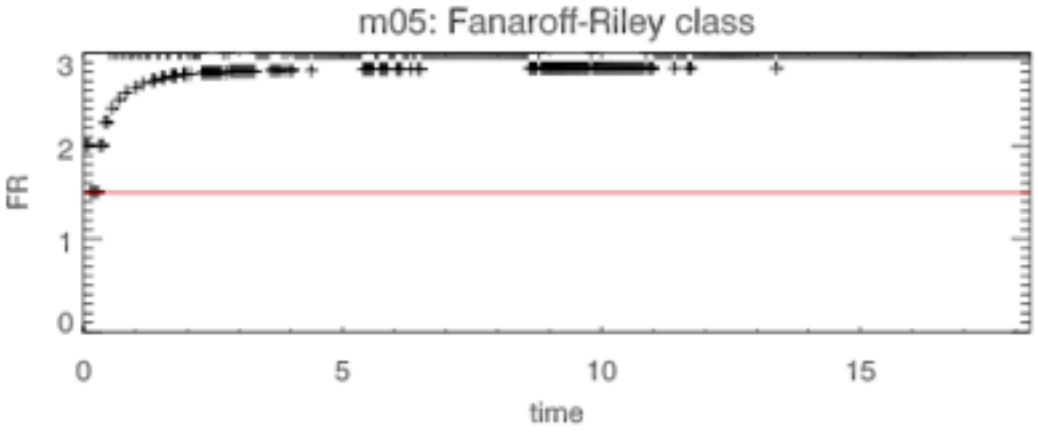
- 1st: form cocoon (L1b)
- 2nd: have terminal shock
- 3rd: (try to) re-collimate

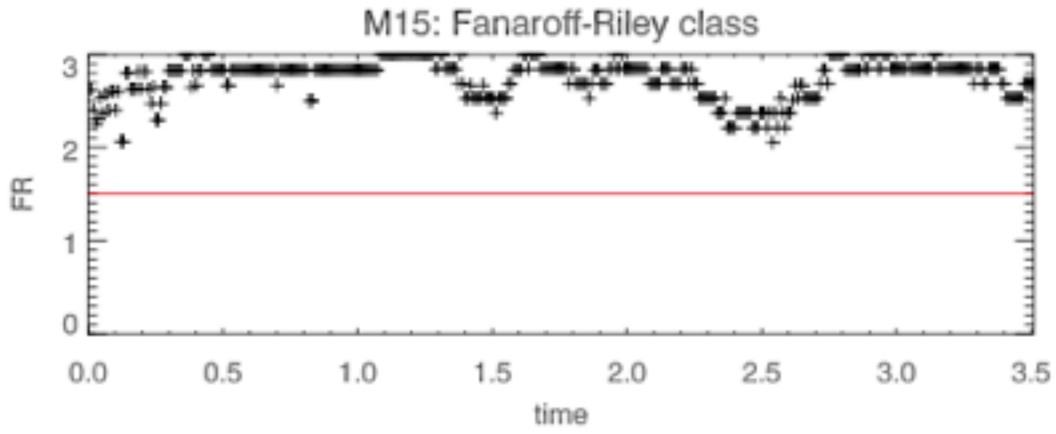
Simple minded FR I

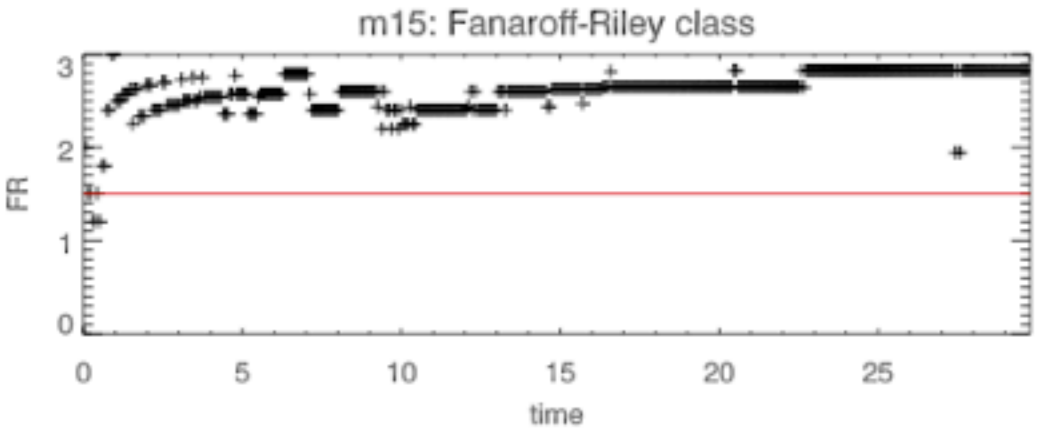


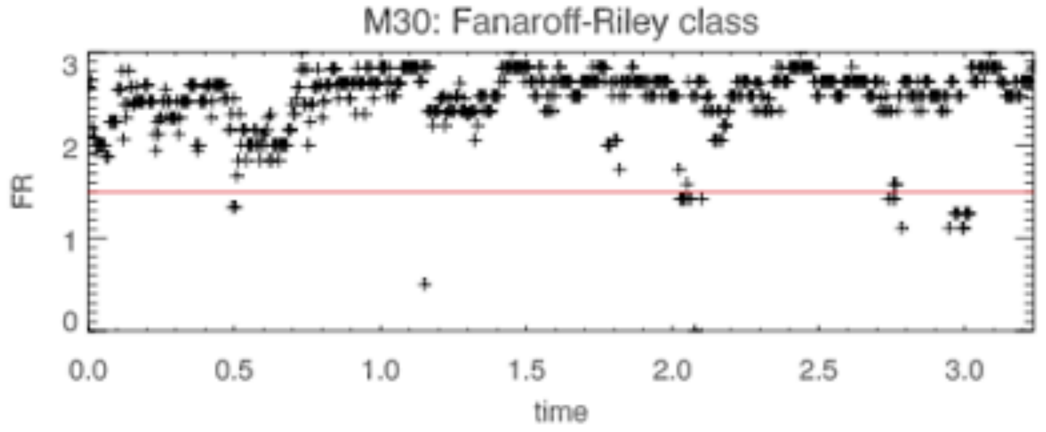
FR class vs. time
em=div(v) $p^{1.8}$

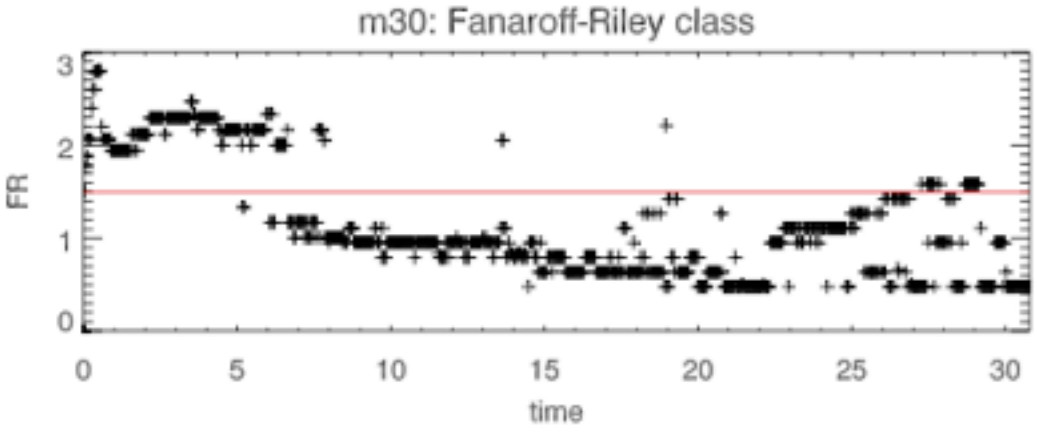












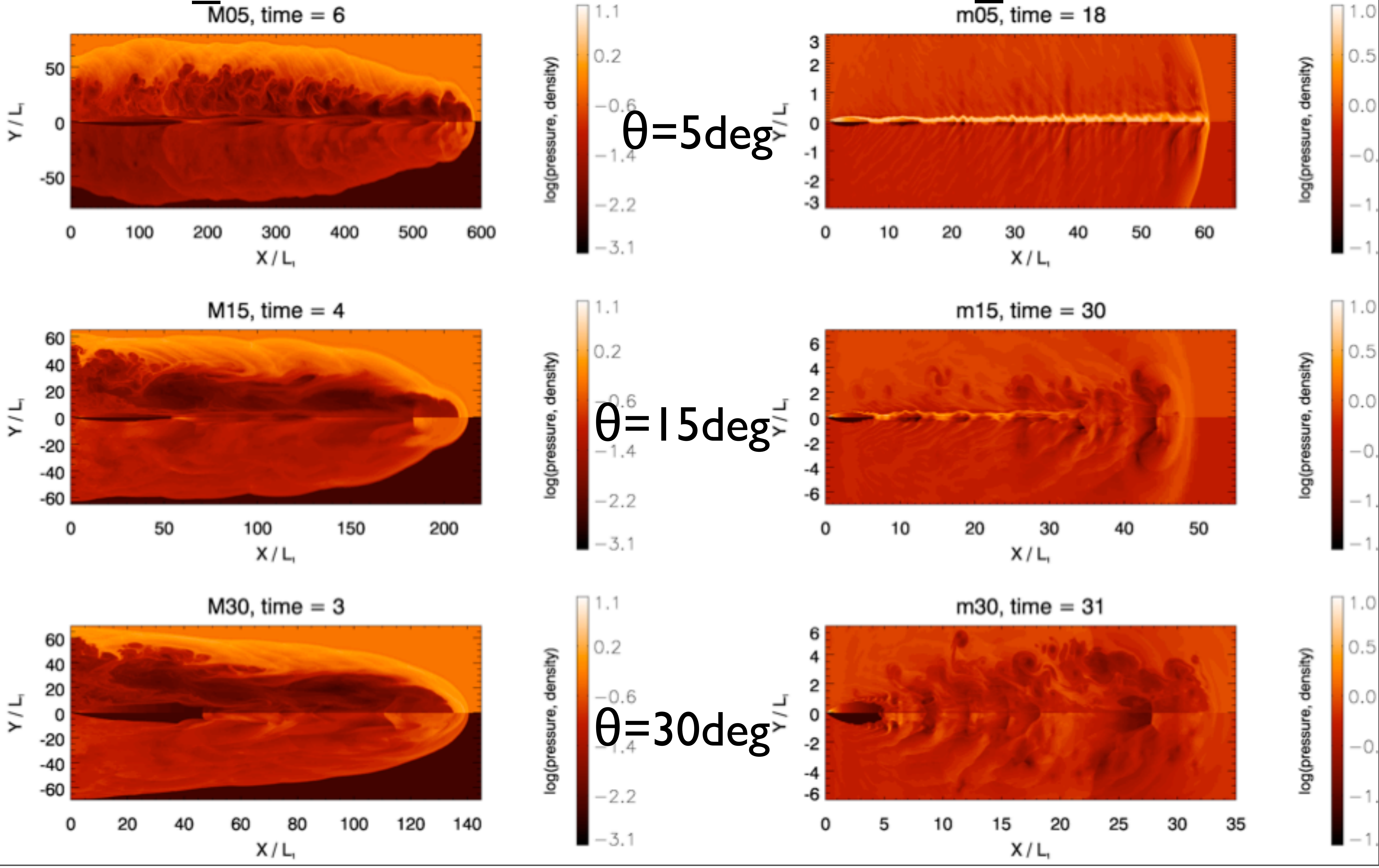
Advanced FR I recipe

- From scales: all lobed sources have FR II phase
- critical for forwardly oriented cocoon: <u>entrainment</u>
- here: entrainment works well because we set parameters to get moderately underdense jet by M-ext=5, realistic: a few 100 (diffcult in sim.)
- real sources: cocoon instability/ Rayleigh-Taylor (Kaiser & Best 2007)

Range of morphologies

M_ext=500

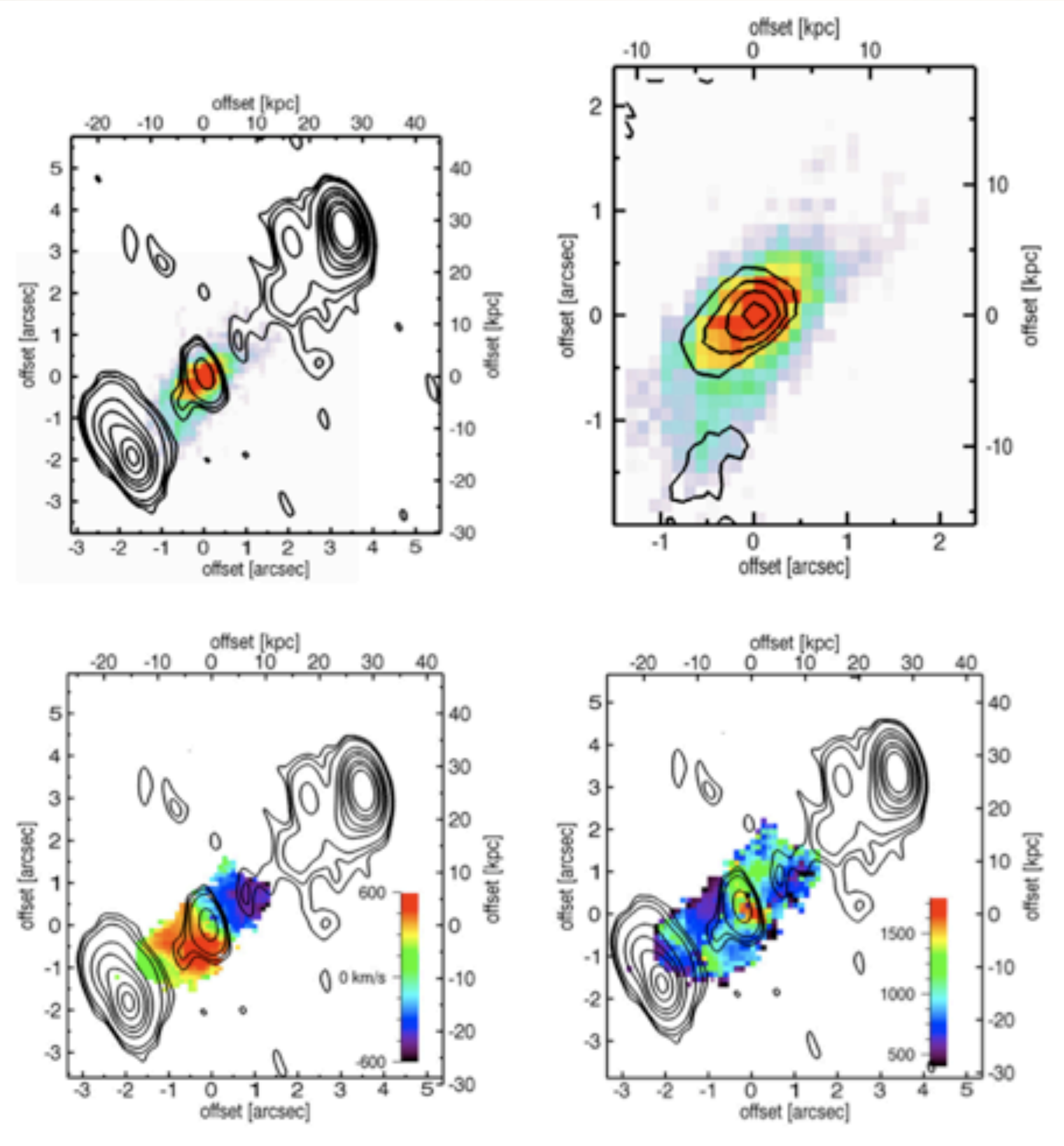
M_ext=5


θ=5deg

θ=15deg

θ=30deg

High redshift radio galaxies



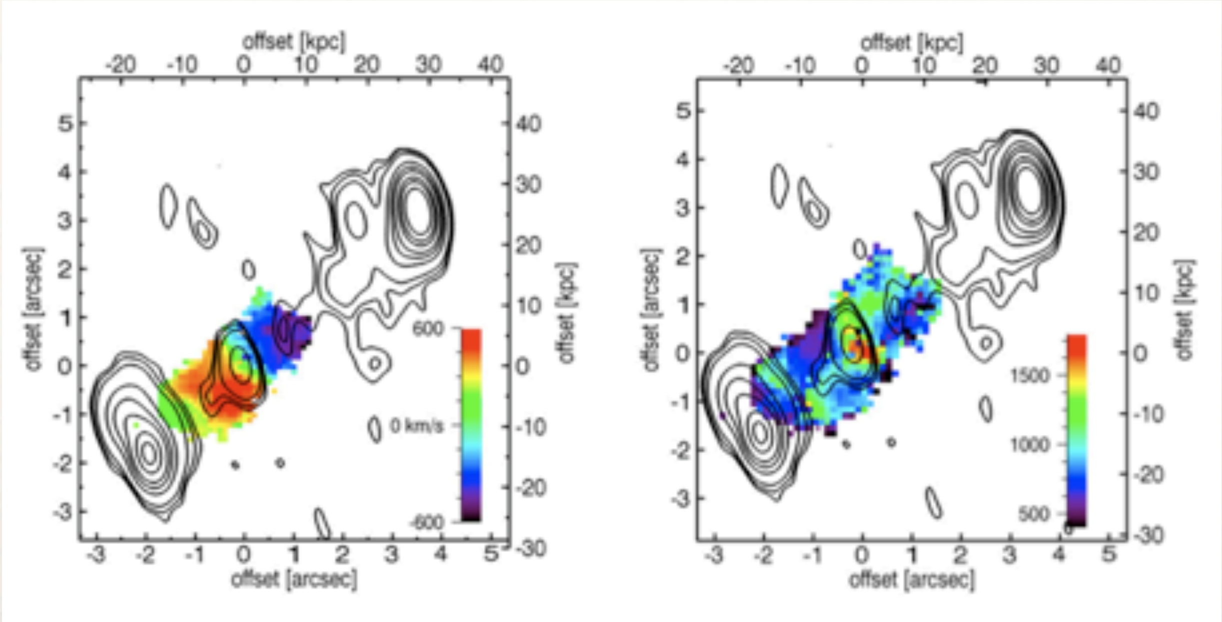
[SINFONI data, Nesvadba et al., 2008]

- z= 2-7
- >10^{10} Msun in gas
- massive host galaxies
- powerful radio sources
- < 100kpc EL haloes, radio aligned
- FWHM: 1000 km/s, super-gravitational
- bulk outflow: 500 km/s

[Krause & Gaibler 2009,
Krause & Alexander 2007]

Key: energy & momentum balance

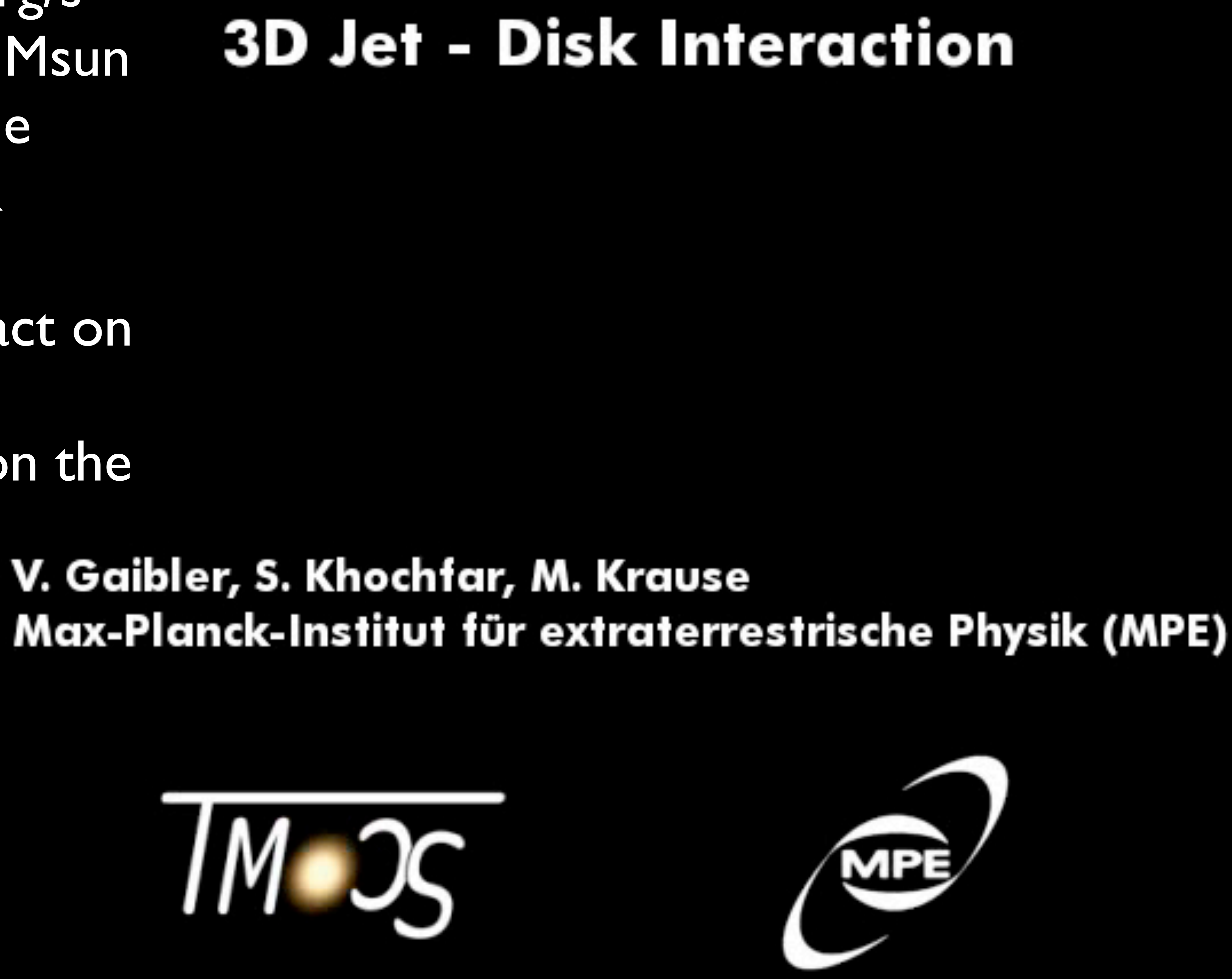
- Compare parameters from X-ray data:
- Momentum:
  - $P_{elg}=10^{51}\ \mathrm{g\ cm\ s^{-1}}\ M_{elg,10}\ v_{elg,500}$
  - $P_{jet}=10^{48}\ \mathrm{g\ cm\ s^{-1}}\ M_{jet,4}\,(\Gamma/3)$
- Energy:
  - $E_{elg}=10^{58}\ \mathrm{erg}\ M_{elg,10}\ v_{elg,500}^2$
  - $E_{jet}\approx 10^{61}\ \mathrm{erg}$
- Cocoon momentum cannot produce bulk speeds
- Energy flux sufficient
- thermal instability induced turbulence (Kritsuk & Norman 2002,2004)?



[Gaibler Khochfar & Krause,
MNRAS accepted]

Q0=6 10^{45} erg/s
M_dsk=10^{11} Msun
RAMSES code
3D HD AMR

- strong impact on disk
- jet power on the small side



3D Jet - Disk Interaction

V. Gaibler, S. Khochfar, M. Krause
Max-Planck-Institut für extraterrestrische Physik (MPE)

Conclusions

- Jet power:
  - drives shocks into ambient gas
  - inflates cocoons
  - determines position of flaring point
  - expels cold ISM
- Can use these tracers to measure it