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3D Magnetohydrodynamics Simulations of *Cluster Radio Sources*

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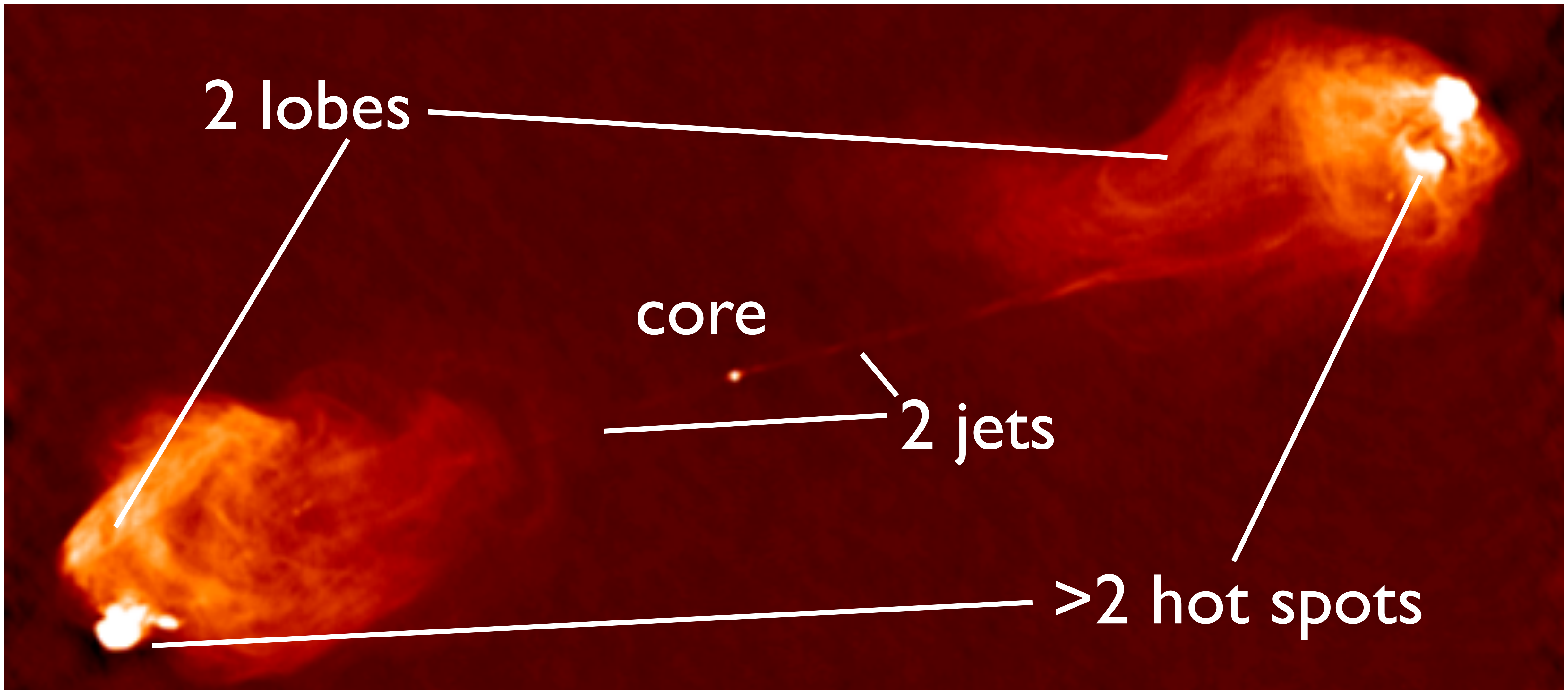
Excellence Cluster Universe

with: Paul Alexander, Hans Böhringer, Gayoung Chon,
Martin Hardcastle, Daniel Hopton, Julia Riley, Joachim Trümper

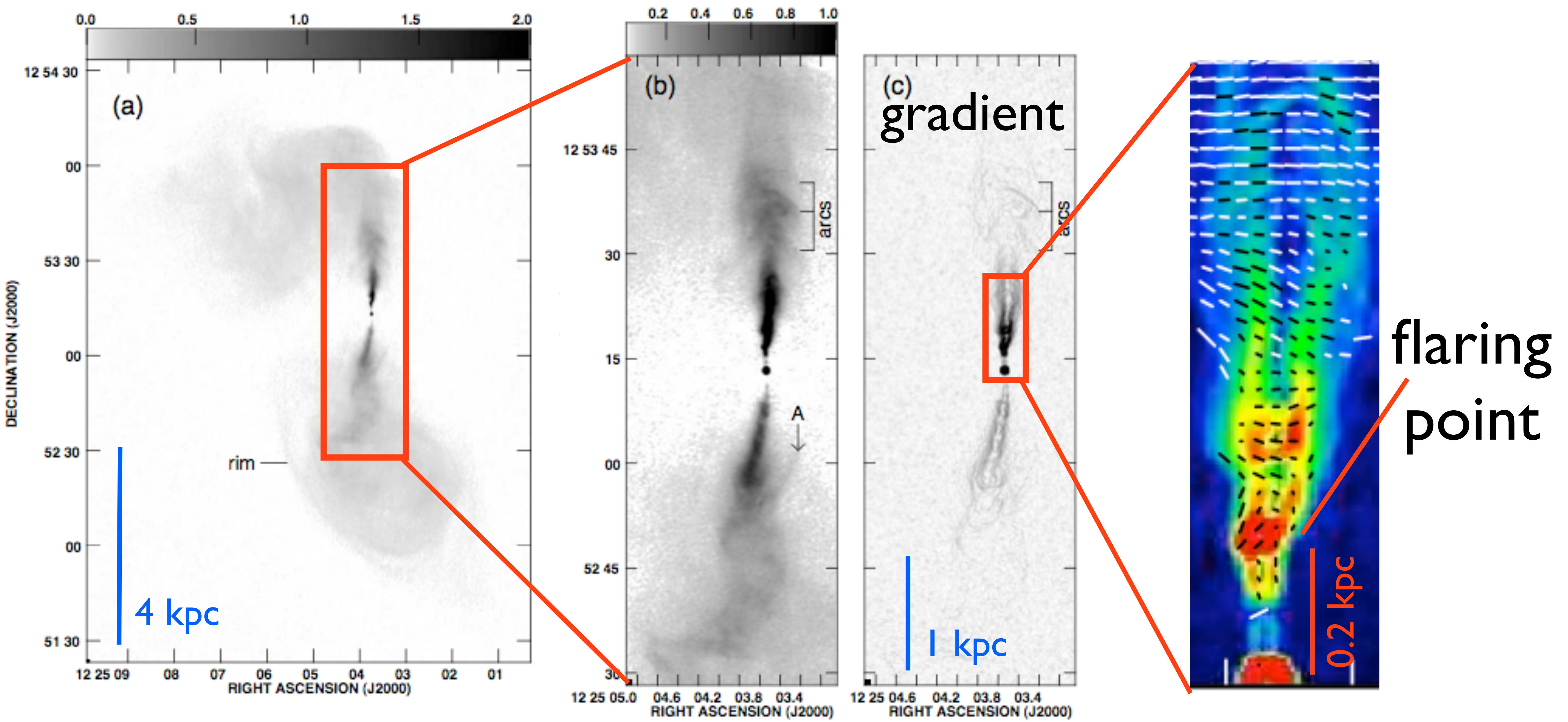
A radio source



Cygnus A, courtesy: Chris Carilli

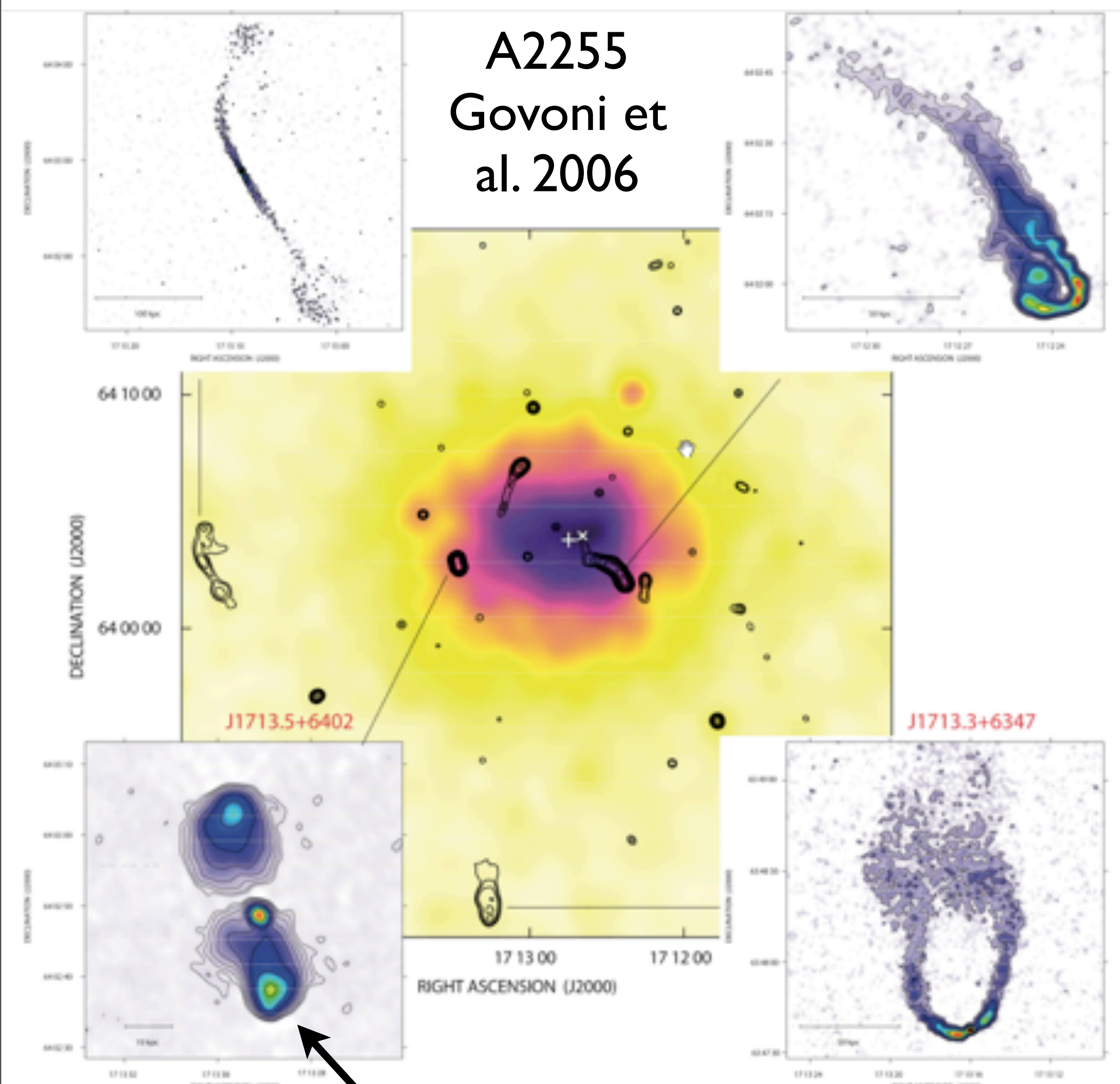
Fanaroff Riley (1974) class II

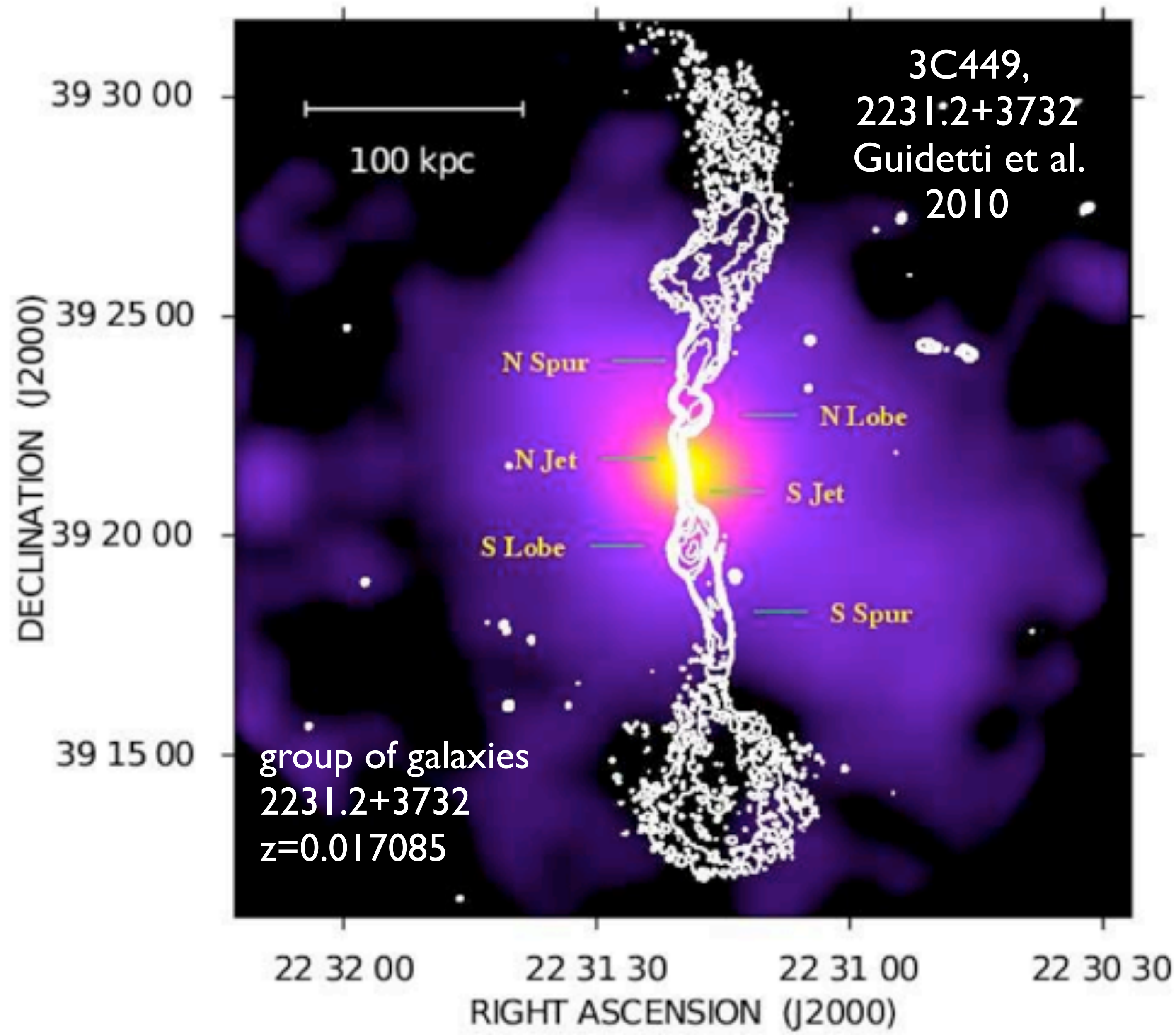
Fanaroff Riley class I



M84, 5 GHz, Laing+ 2011

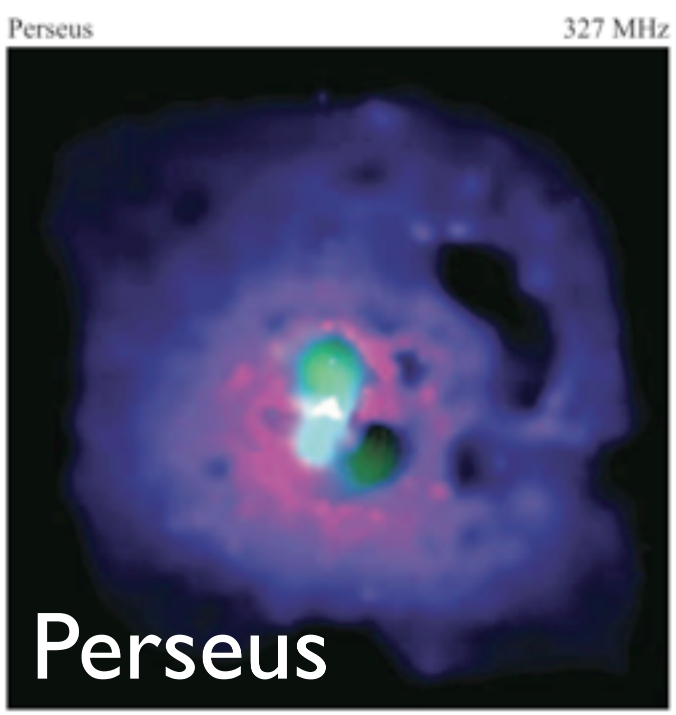
Cluster radio sources





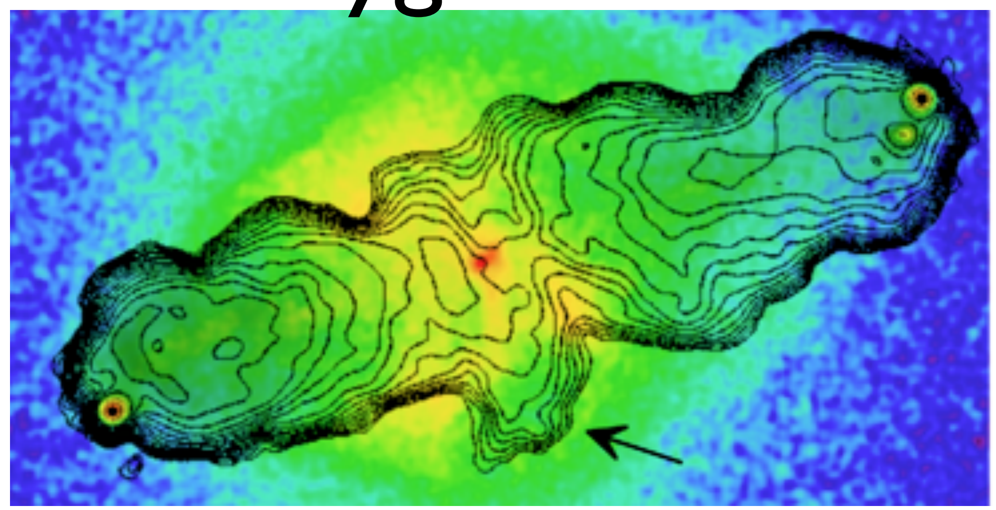
Some FR II - mostly FR I

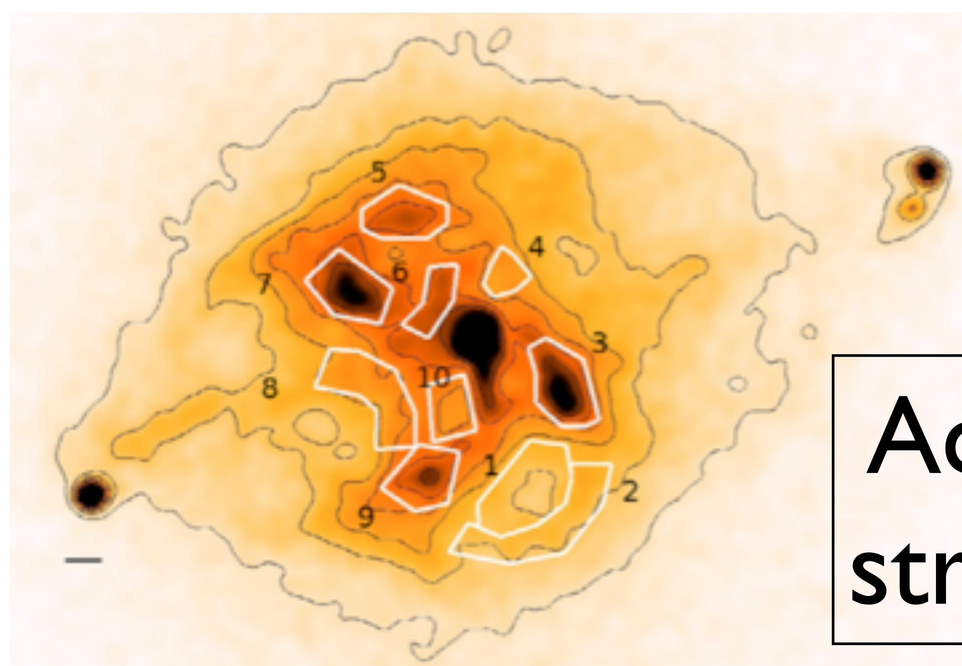
X-ray cavities & shocks



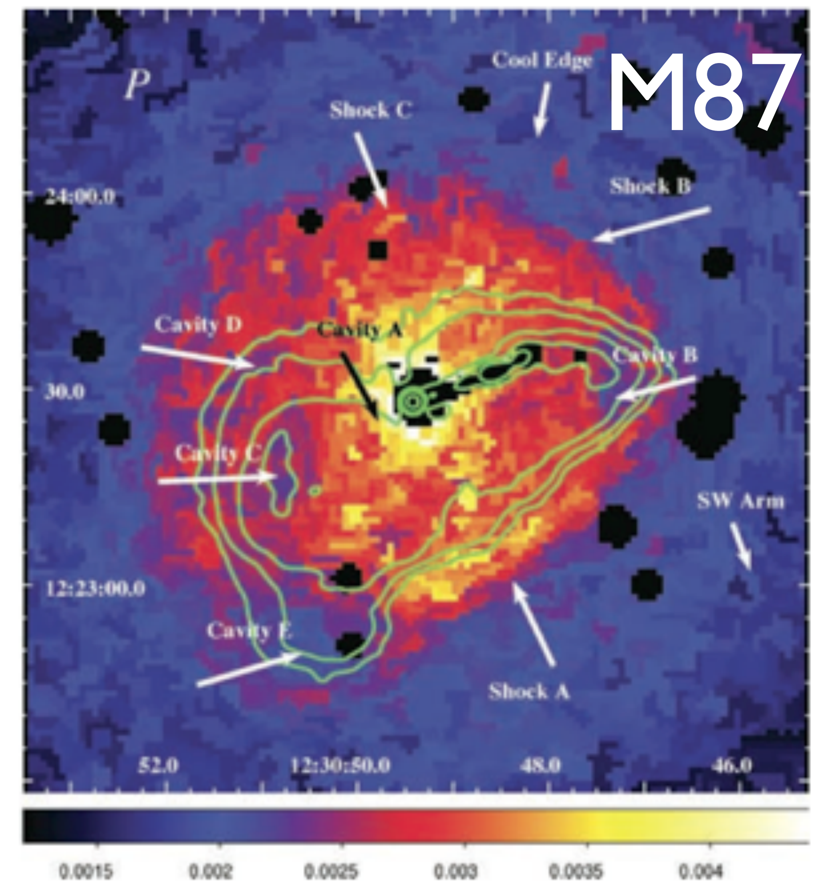
Birzan+2008

Cygnus A





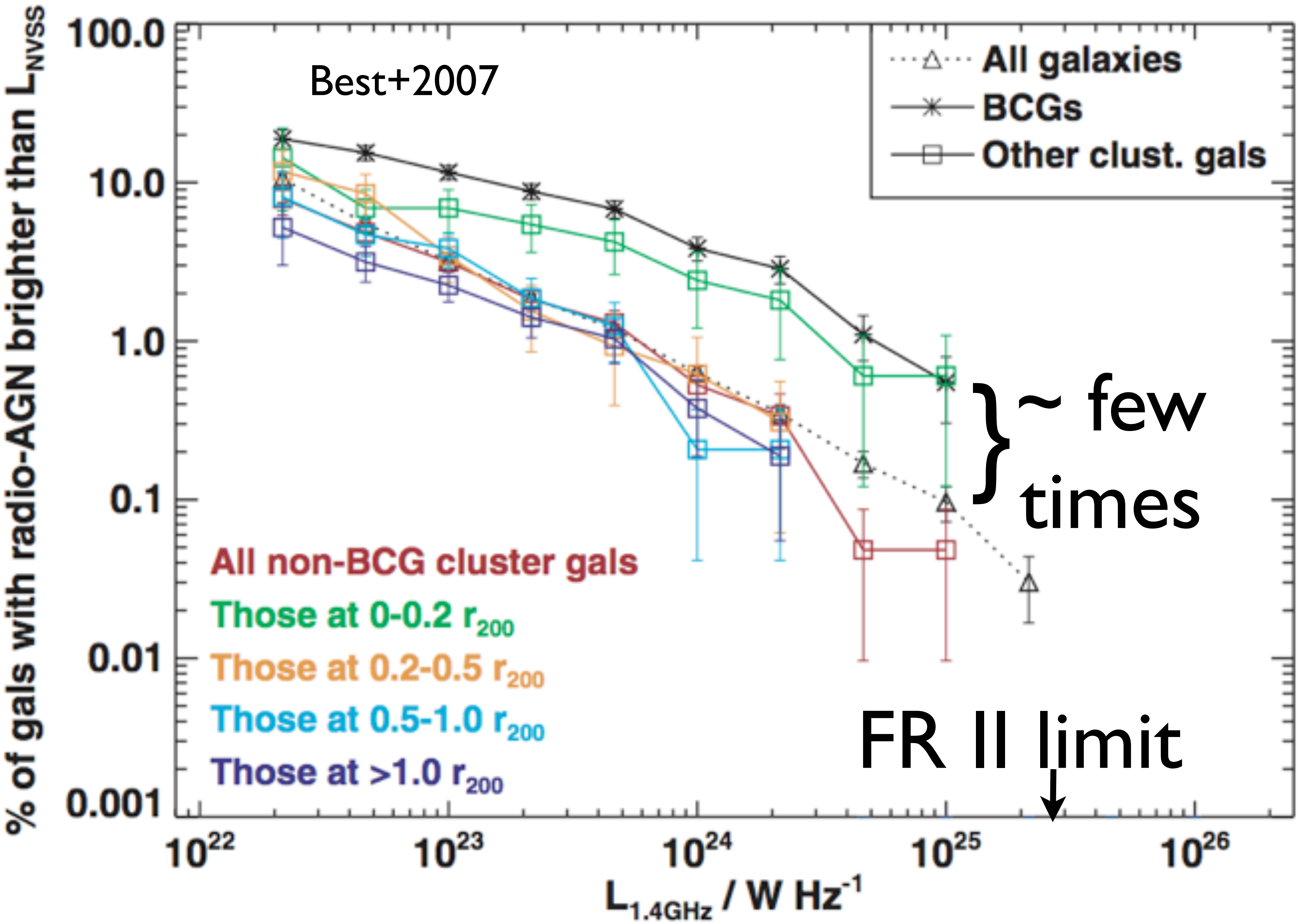
Chon, Böhringer, Krause & Trümper 2012



Million+2010

Active radio sources:
strong impact on ICM

Central cluster galaxies: more radio loud

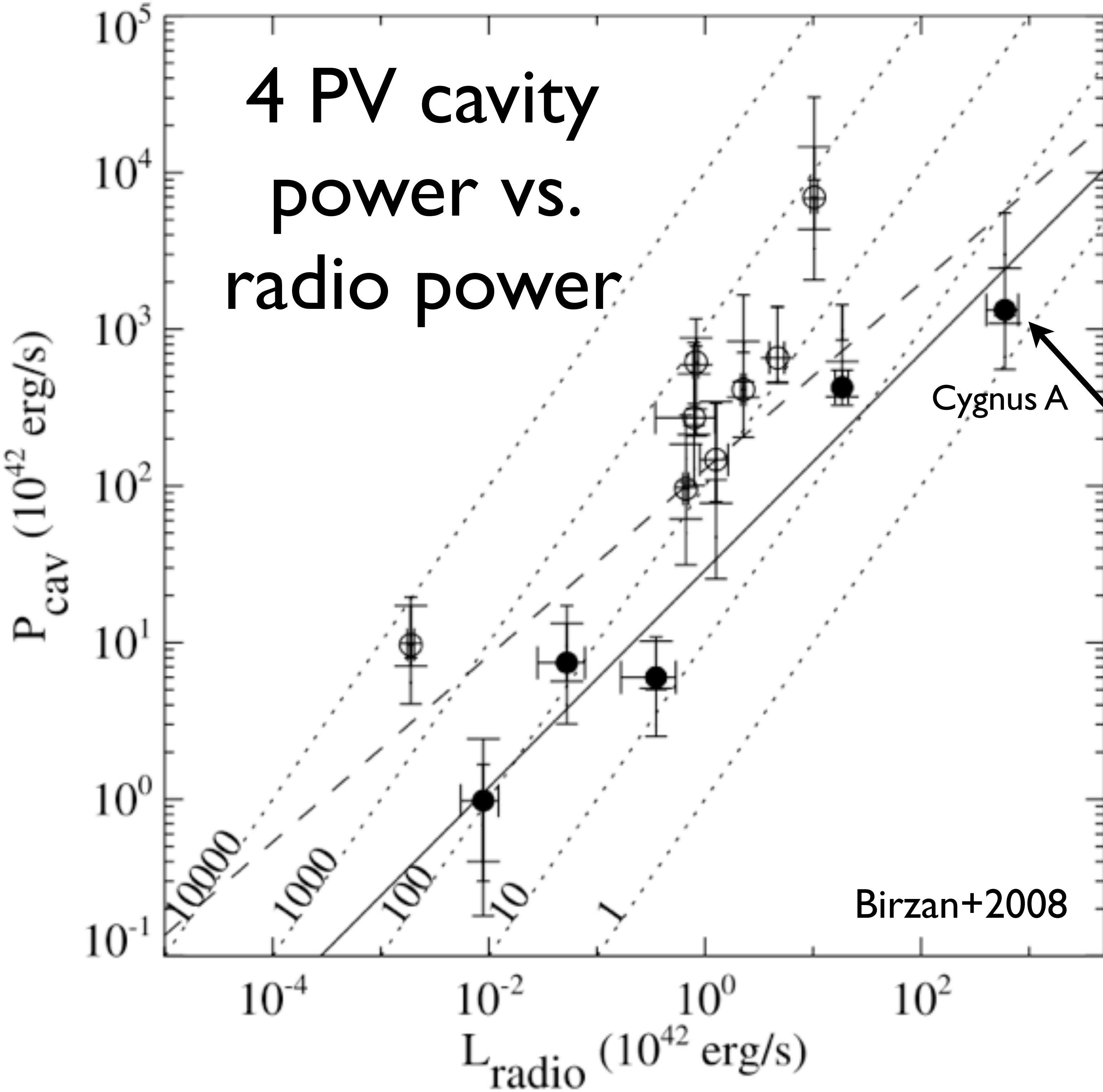


Duty cycle

- BCG: ~30%
- Core: ~10-20 %
- Outskirts: <≈ 10 %
- Optical AGN independent of radio AGN (Shabala+ 2008)

Consistent with feedback loop idea: radio AGN (only) couples to ICM

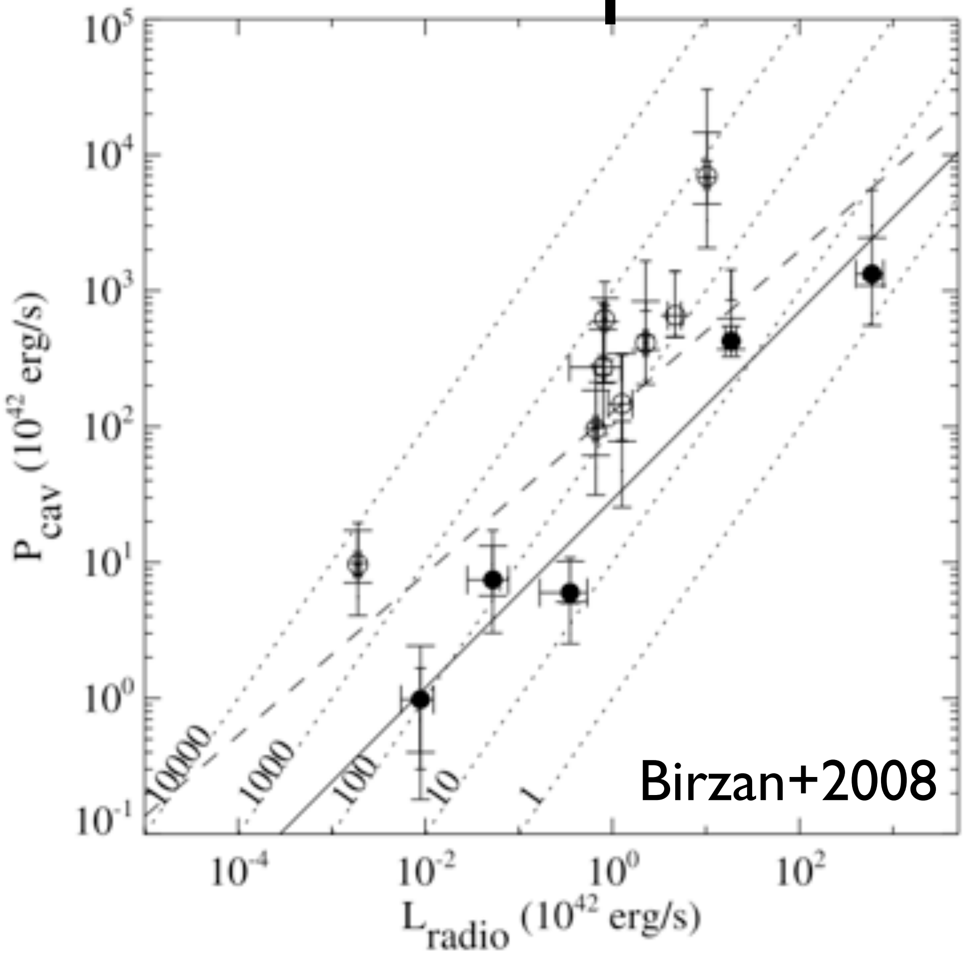
Cavity power



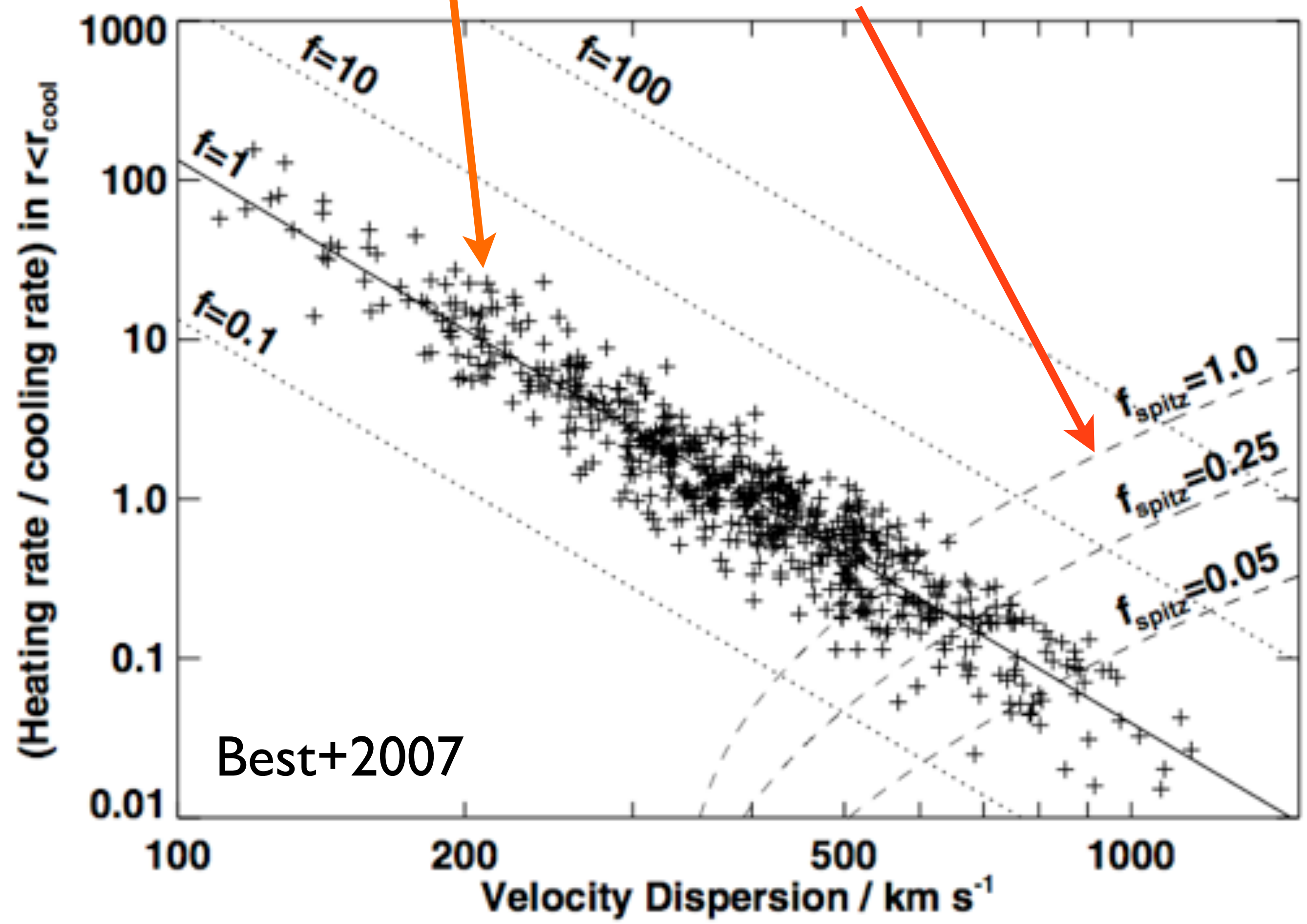
- Volume (X-ray cavity) x ext. pressure = energy
- neglects shocks
- active sources: x 10-100, detailed models: Kaiser & Alexander 1999, Zanni+2003, Krause 2005

Heating / cooling balance?

4 PV cavity power vs. radio power



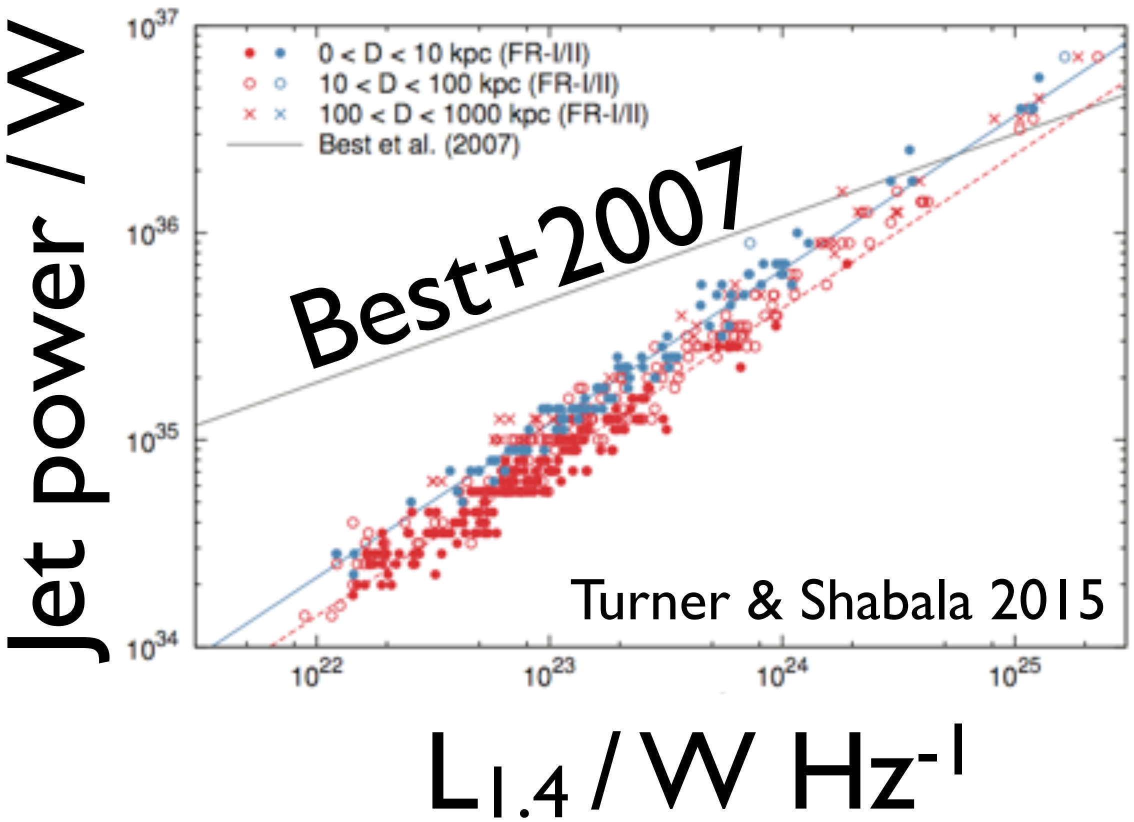
Radio sources + conduction

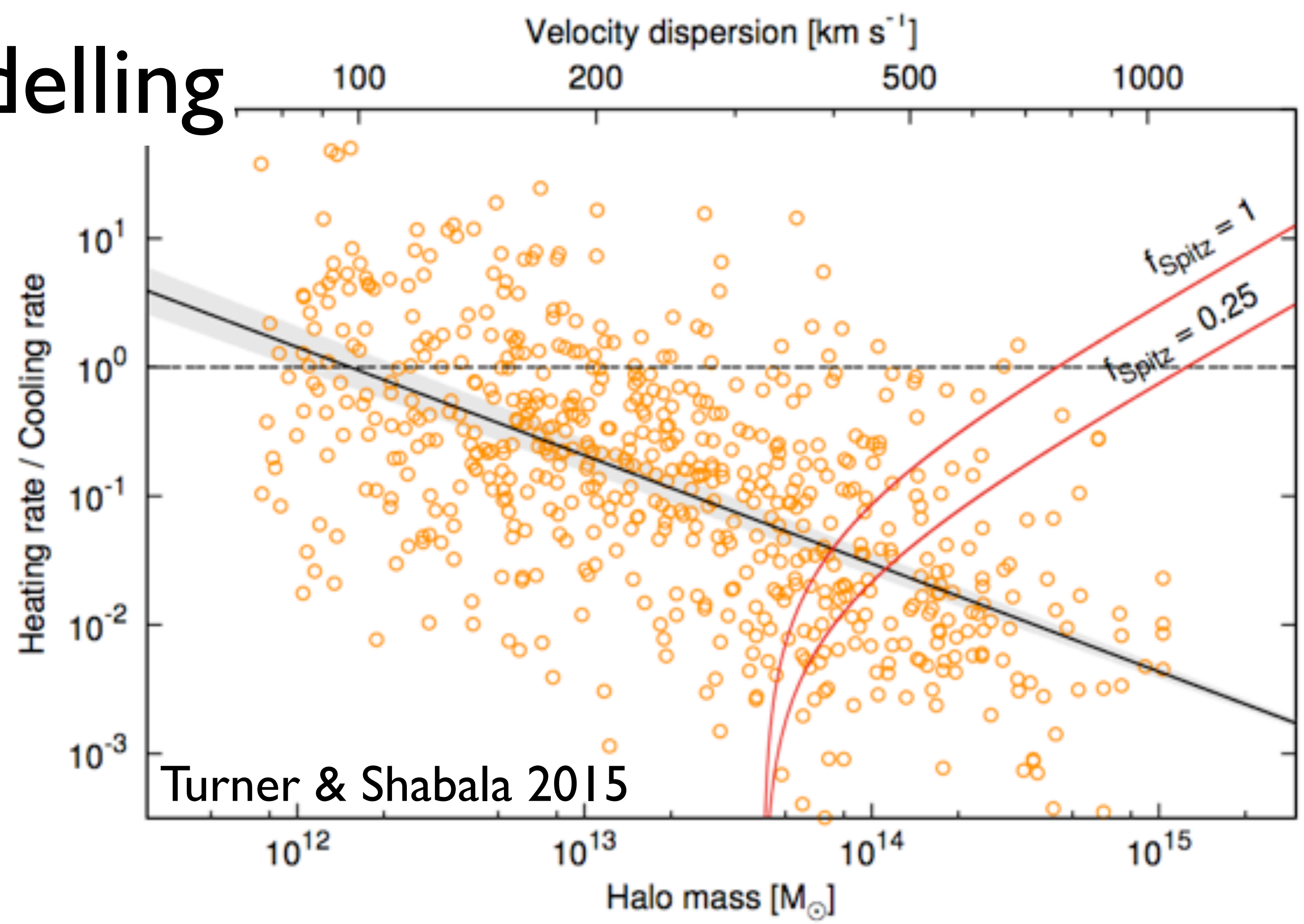


No!(?) But large modelling uncertainties.

Heating / cooling balance?

Self-similar / analytic modelling





Change radio source model: yes!

(with conduction in massive clusters)

Questions

- Observations ⇔ jet energy flux ?
- Jet energy flux ⇔ ICM heating (radius) ?
- Jet morphological type ⇔ AGN type ?

Jet modelling

Jet-environment interaction

- Scheuer 1974: cocoon & cavity formation / jet collimation by cocoon
- Falle 1991, Kaiser & Alexander 1997, Komissarov & Falle 1998: identified critical scale L1, after which self-similarity, crucial factor: self-collimation by cocoon pressure
- Simulations: self-similar evol. confirmed when inc. self-col. by cocoon pressure (Komissarov & Falle 1998)
- Deviations from self-similarity at outer scale L2 (Alexander 2002, Hardcastle & Krause 2013)

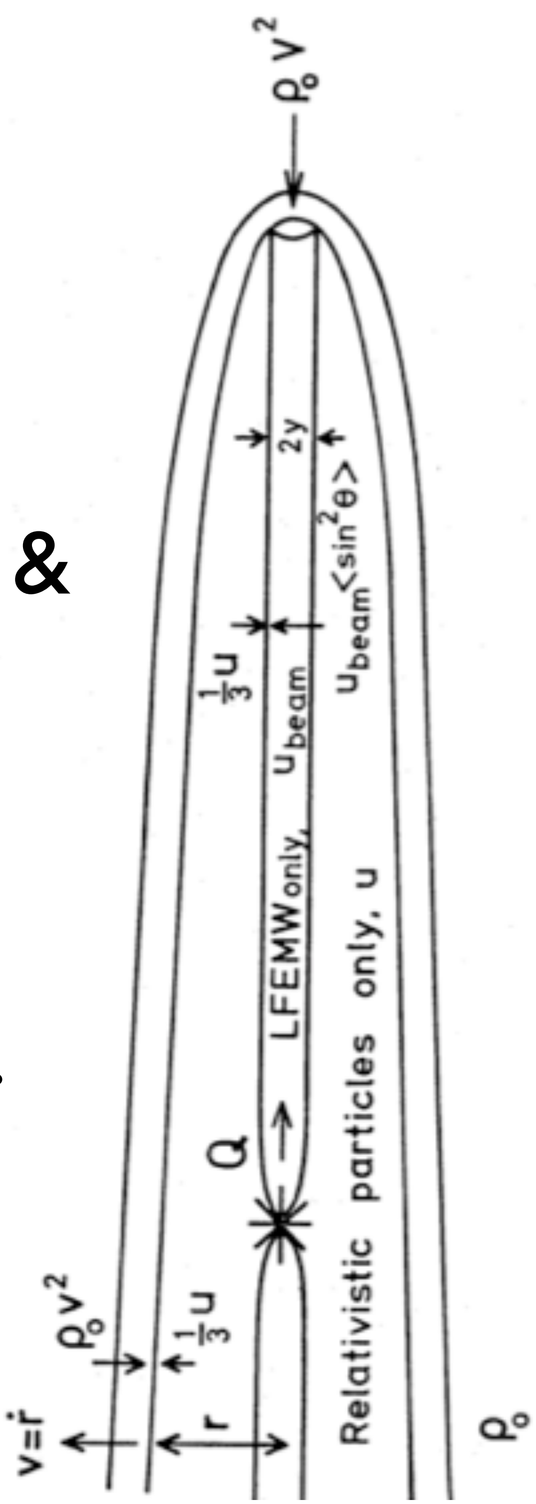
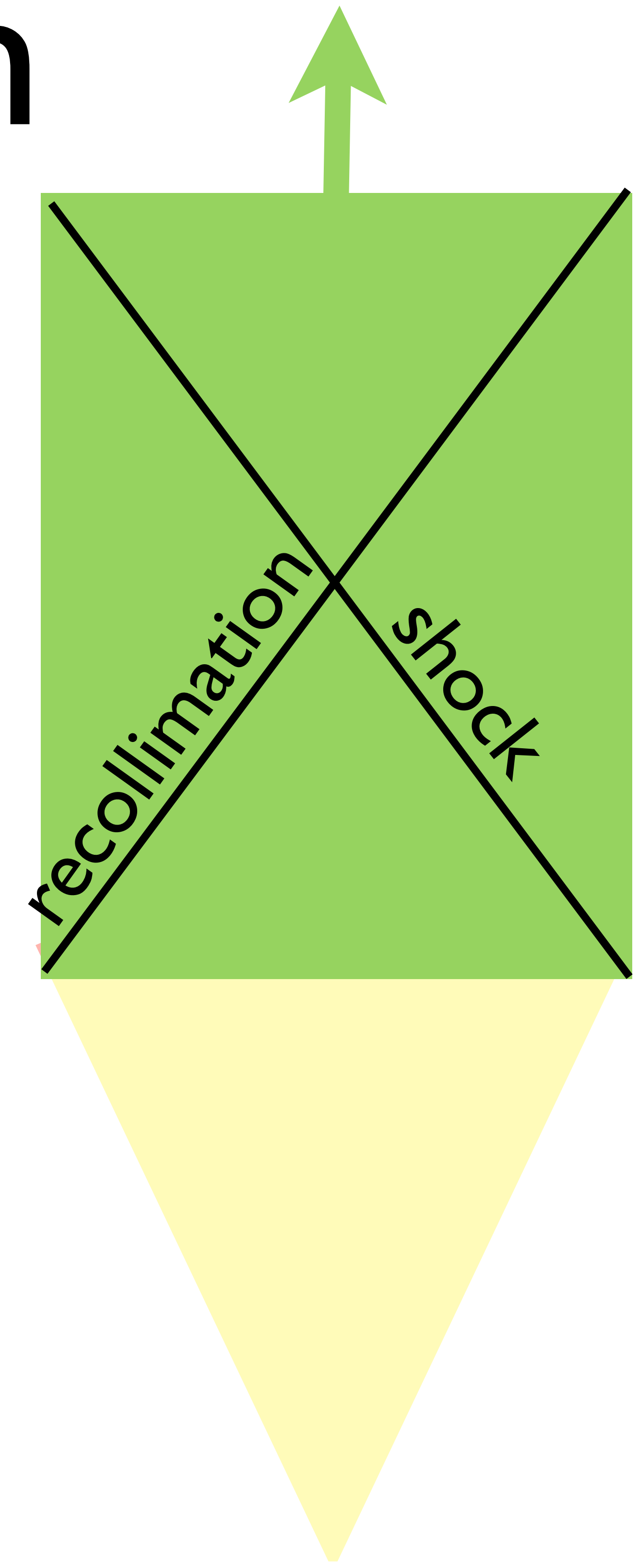


FIG. 4. *Model B.*

Jet-environment interaction



- Outflows with opening angle < π

  +L1: wind mass = swept up mass

  -L1a:
  sideways pressure = ambient pressure
  ⇒ recollimation

  -L1b:
  jet density = ambient density
  ⇒ cocoon formation

  -L1c:
  forward ram pressure = amb. pressure
  ⇒ hot spot limit unless collimated

Jet-environment interaction

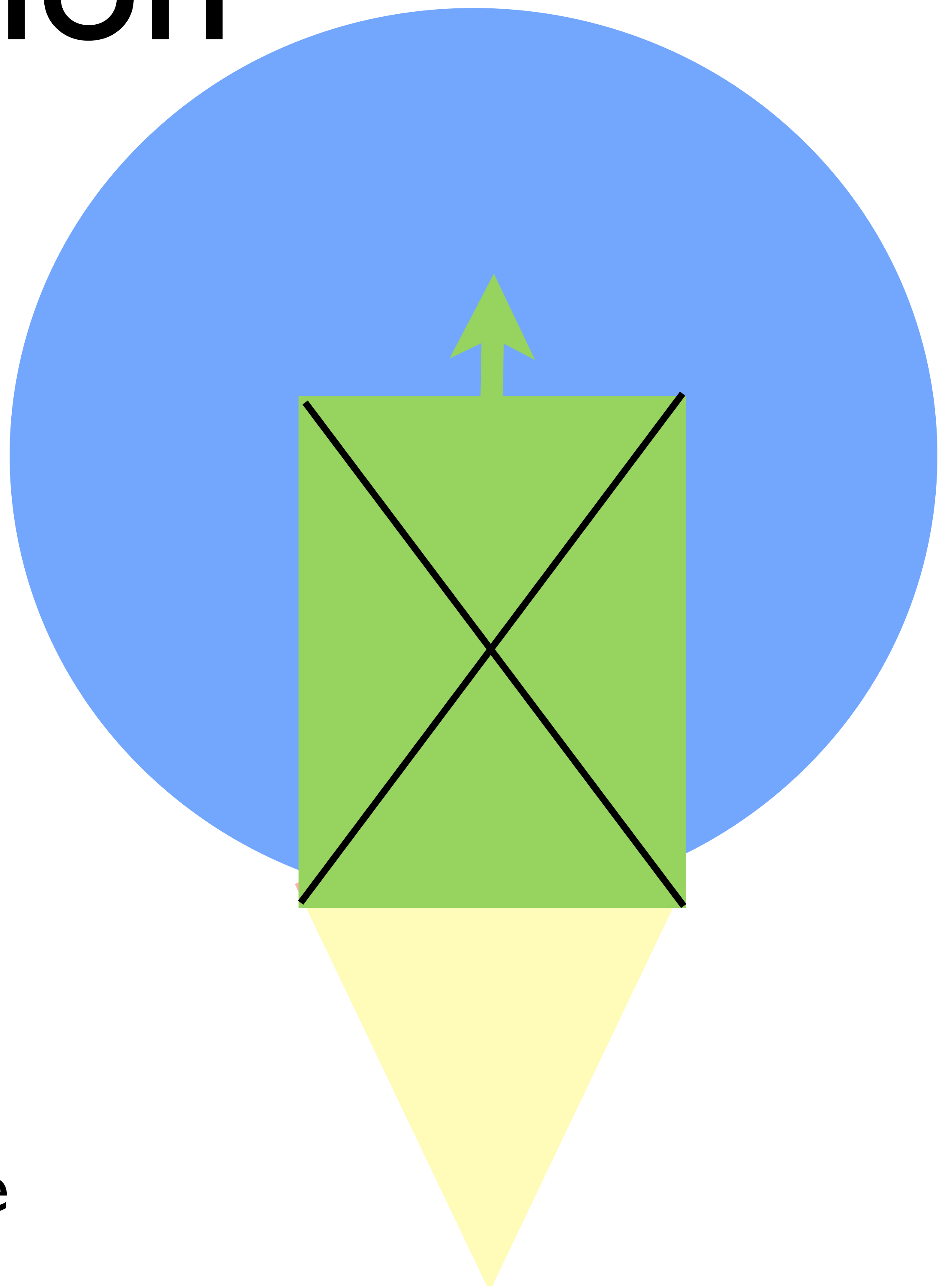
- Outflows with opening angle < π

  +L1: wind mass = swept up mass

  -L1a:
  sideways pressure = ambient pressure
  ⇒ recollimation

  -L1b:
  jet density = ambient density
  ⇒ cocoon / lobe formation

  -L1c:
  forward ram pressure = amb. pressure
  ⇒ hot spot limit unless collimated



Jet-environment interaction

- Outflows with opening angle < π

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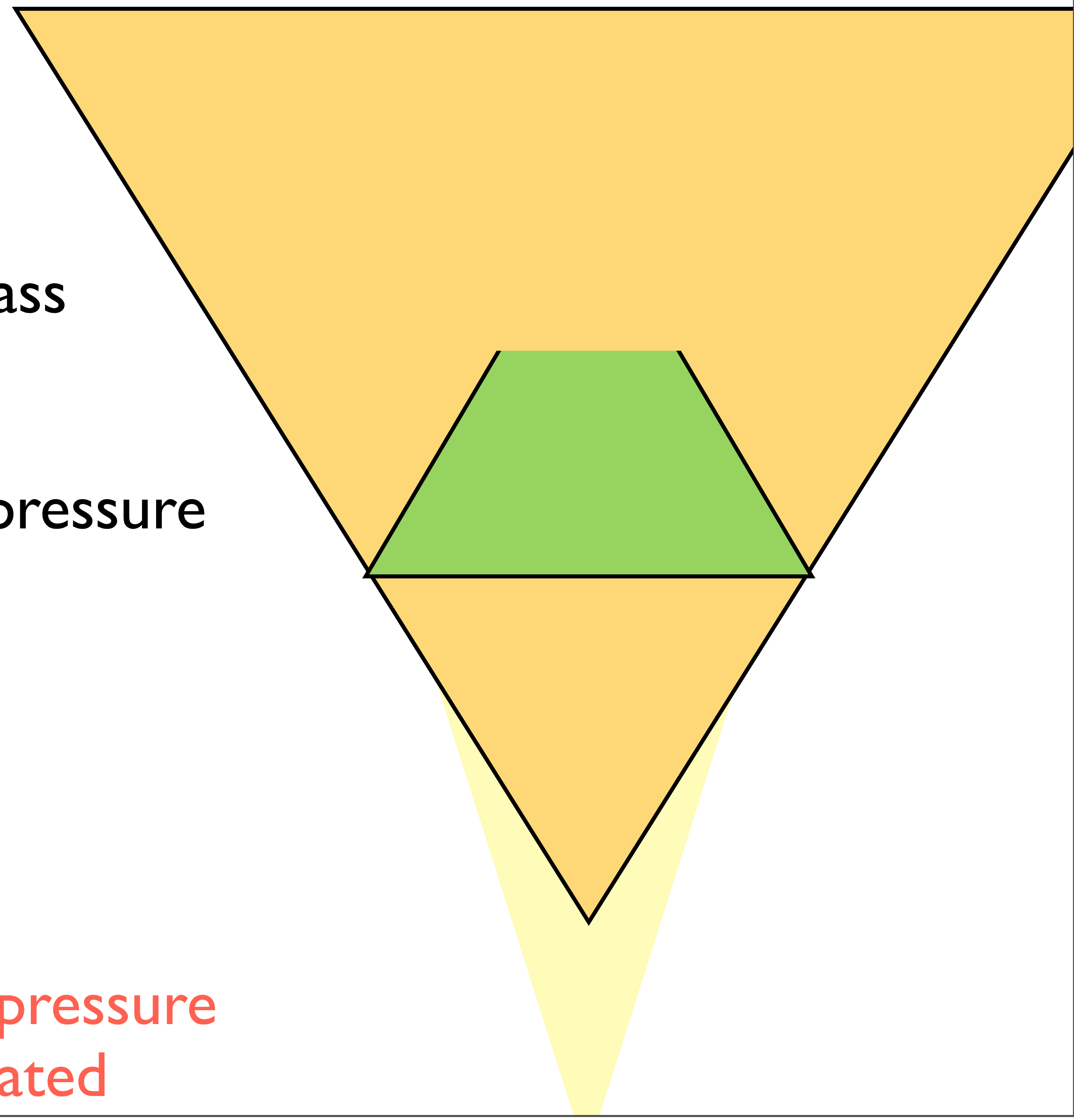
  ⇒ hot spot limit unless collimated



Collimation (or not) by ambient pressure

- Initially conical beam, density & ram pressure $\propto r^{-2}$
- 3 parameters: solid angle $\Omega(\theta)$, external Mach number M_x, scale L1

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

Simulations

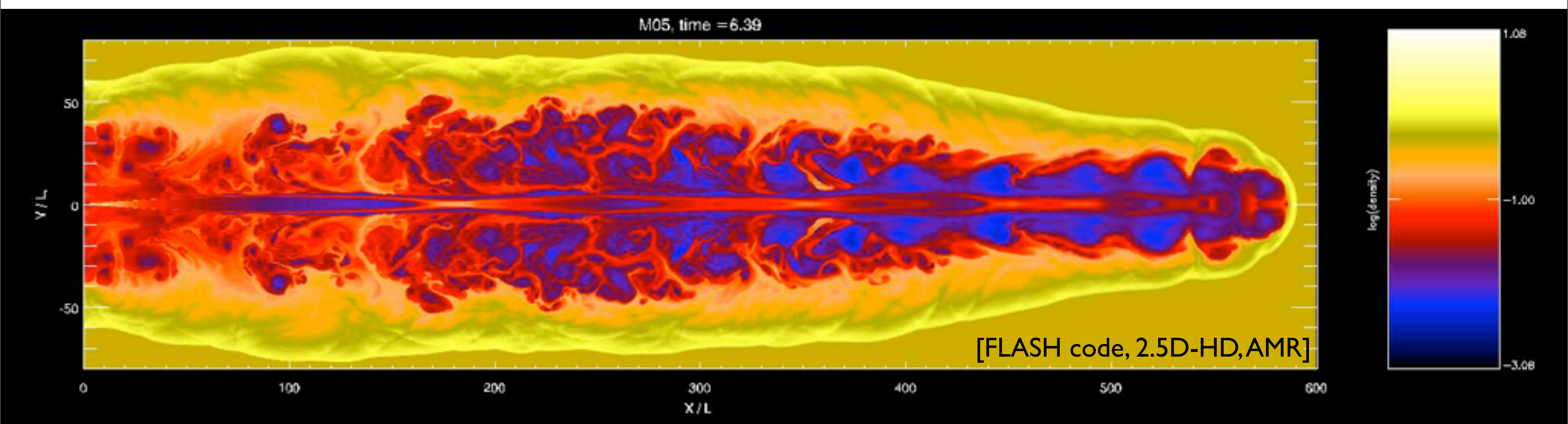
- Standard hydrodynamics:
  - mass conservation
  - momentum conservation
  - energy conservation
- 2.5D (axisymmetric) + AMR
- FLASH-code

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:

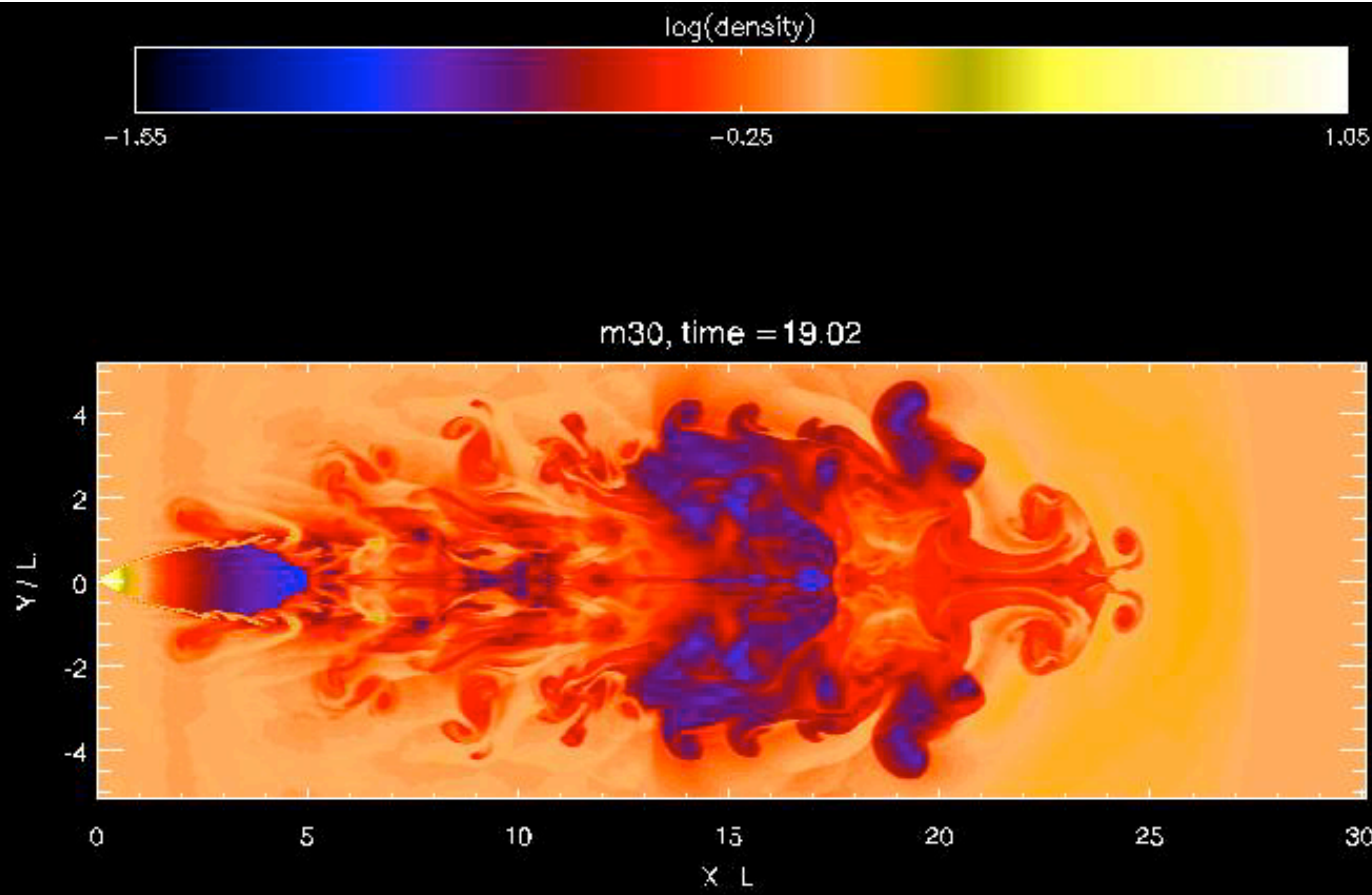
$$\eta = \left(\frac{L_{1b}}{L_{1a}}\right)^2 = \frac{1}{\gamma \sin^2\theta M_x^2}$$



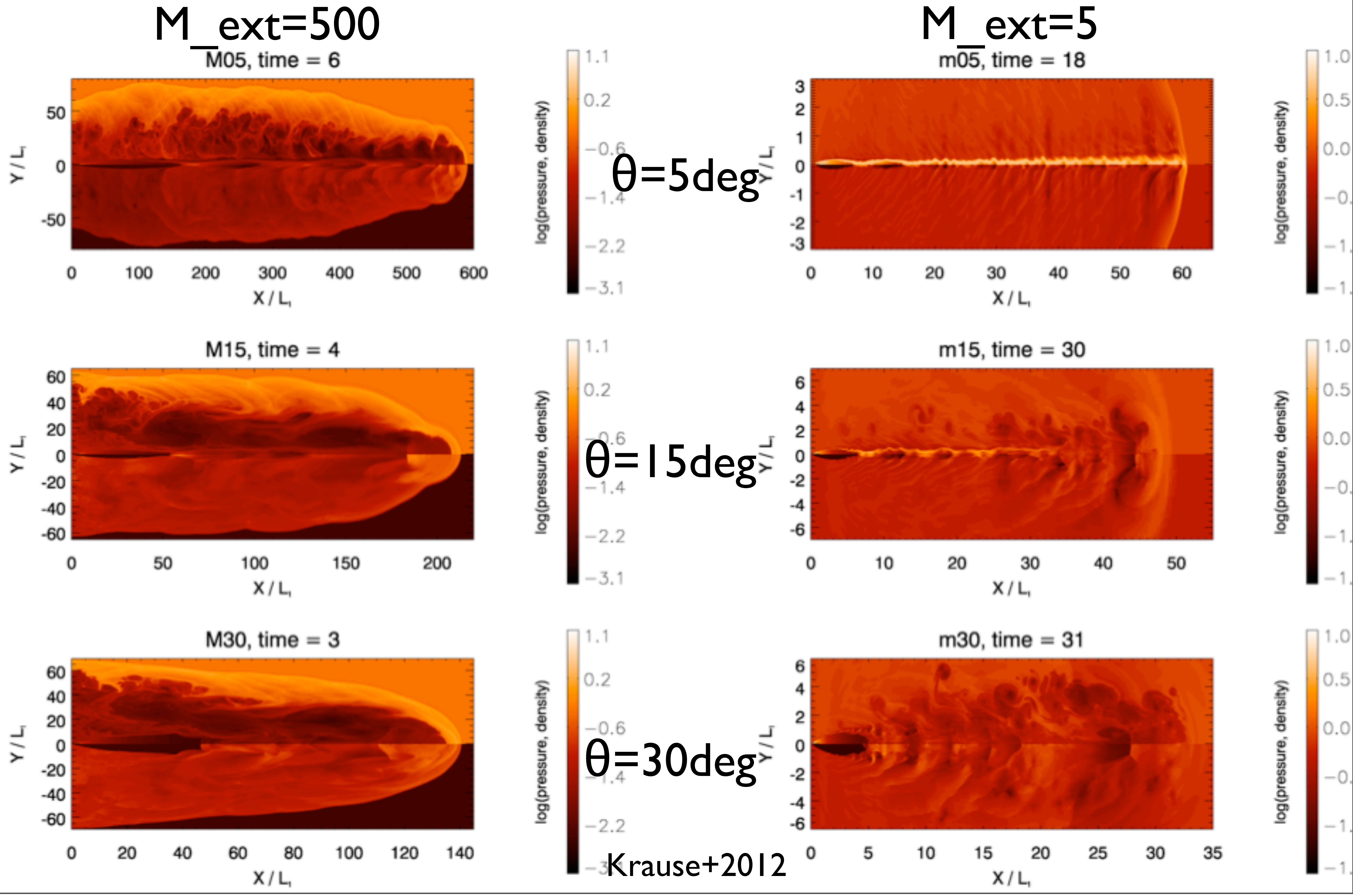
FR I recipe

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

FR I recipe

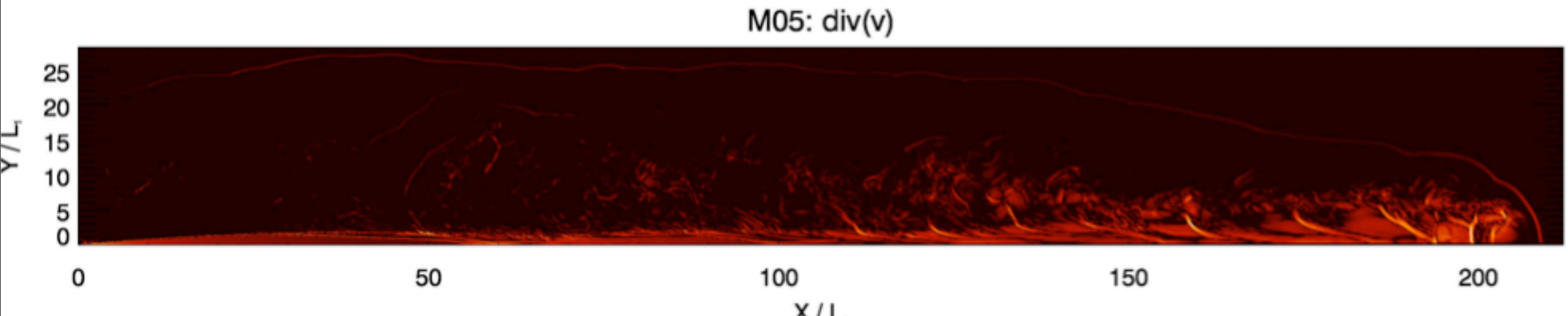

log(density)
−1.55
−0.25
1.05
m30, time =19.02
Y / L
4
2
0
-2
-4
0
5
10
15
20
25
30
X L

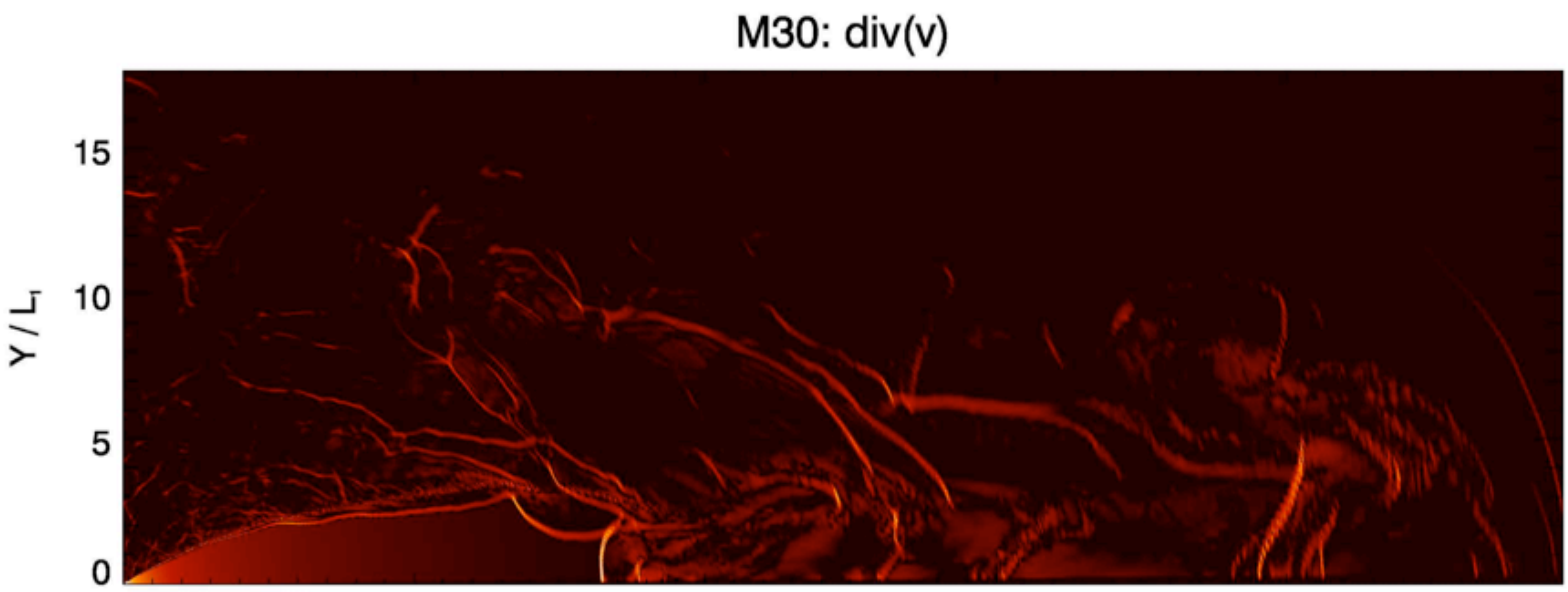
Range of morphologies



Quantifying emission:

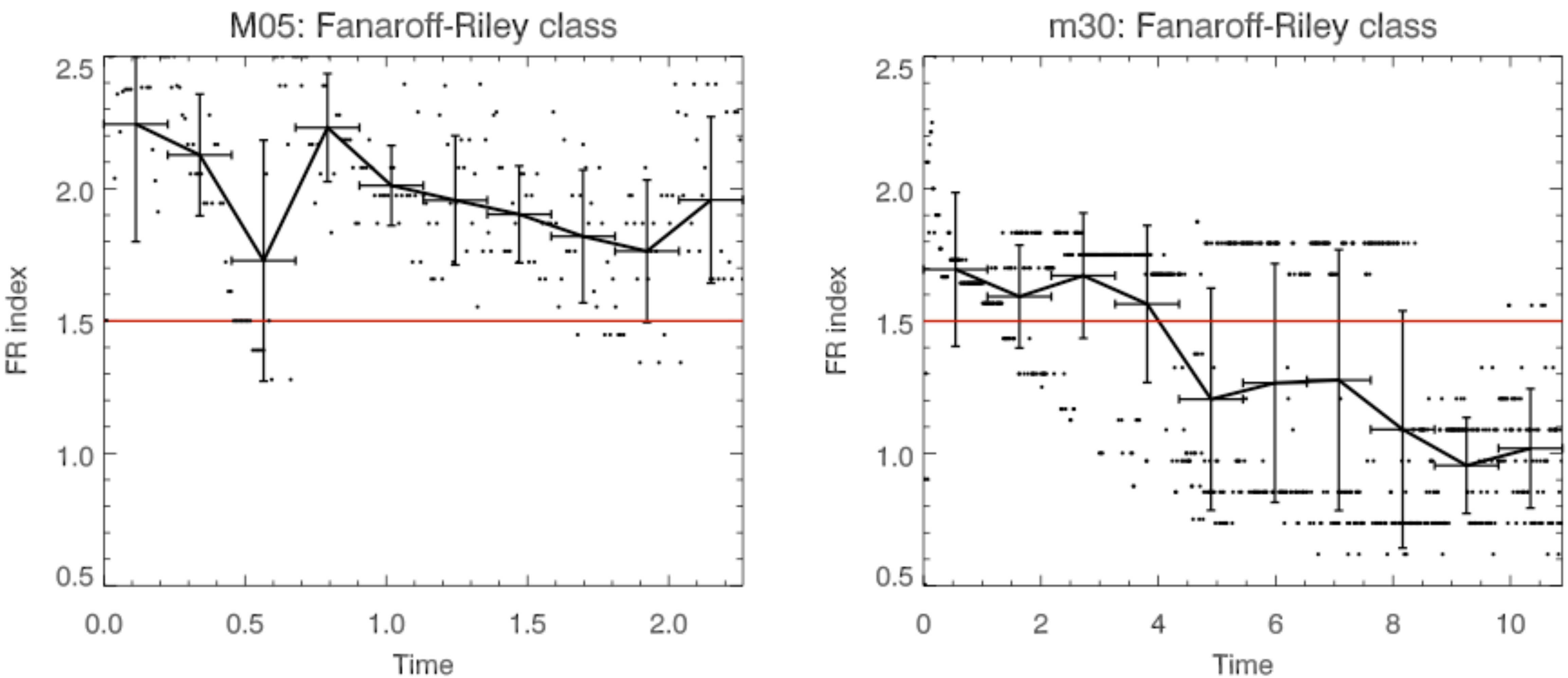
- assume emission prop to div(v) (particle acceleration at shocks):





FR classification

(transform 3D, project surface brightness)



$$FR = 2x_{\text{bright}}/x_{\text{size}} + 1/2$$

Questions

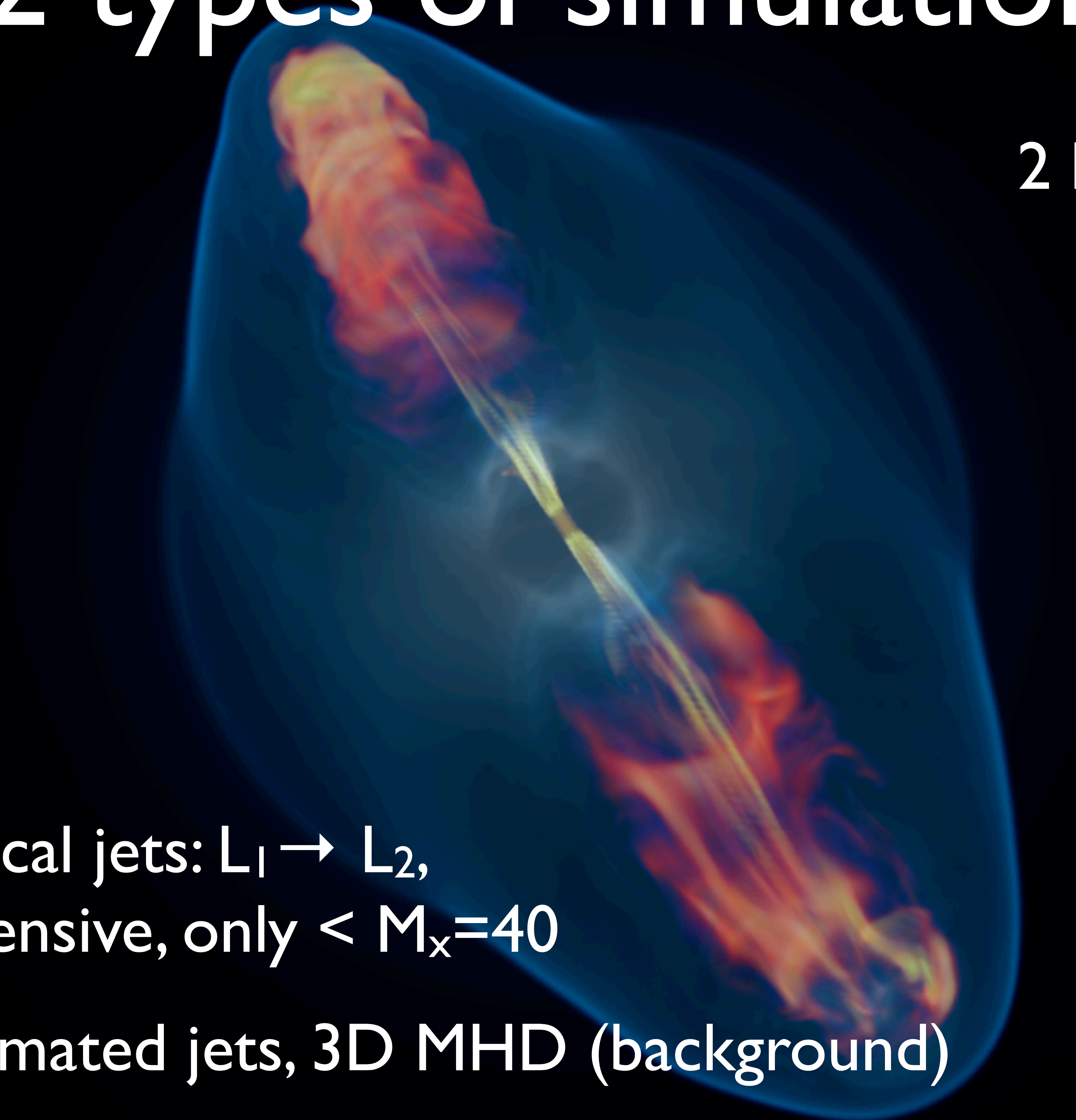
- Jet morphological type ⇔ AGN type ?

  Correlated:

  FR I: wide opening angle, ADAF, hot-mode accretion, low jet power, FR II when small

  large-scale FR II: narrow opening angle, opt. AGN, cold-mode accretion, SF galaxies

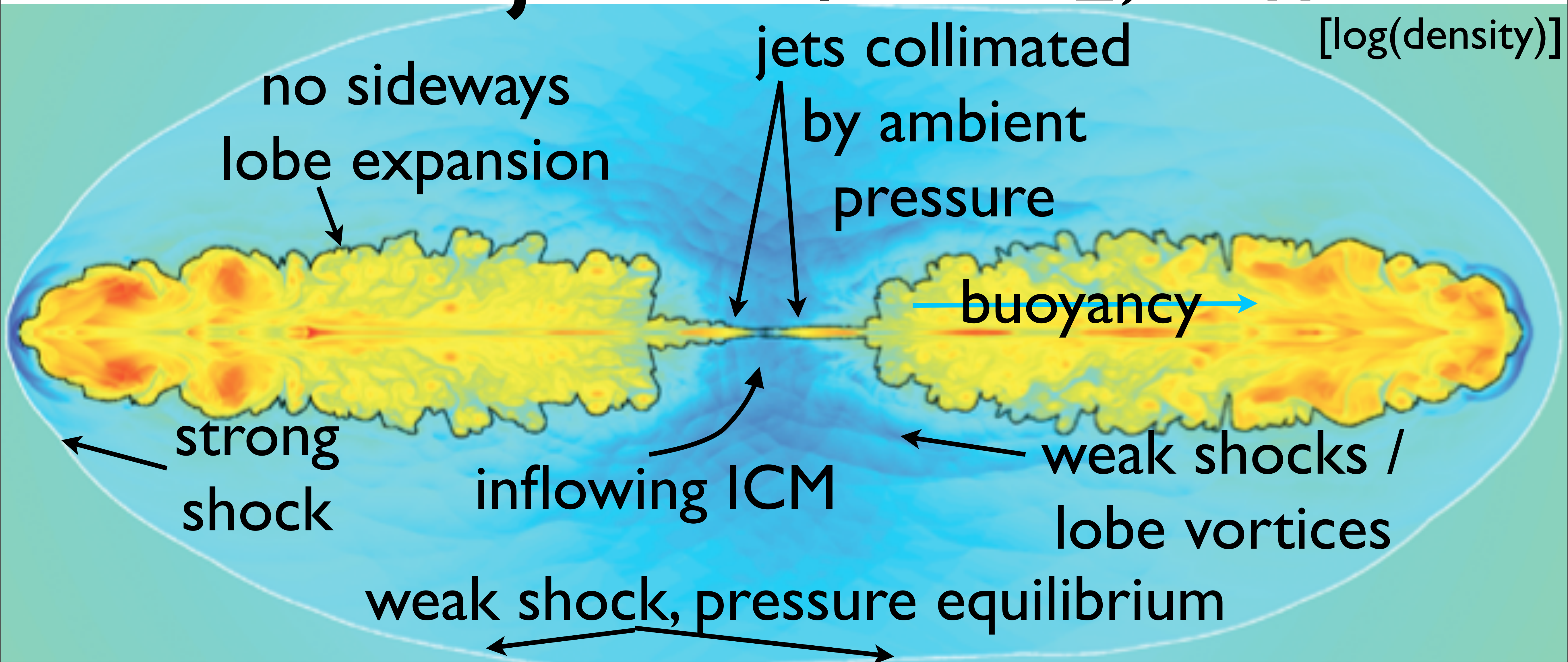
2 types of simulations



2 keV cluster

- conical jets: $L_1 \rightarrow L_2$,
  expensive, only < M_x=40
- collimated jets, 3D MHD (background)

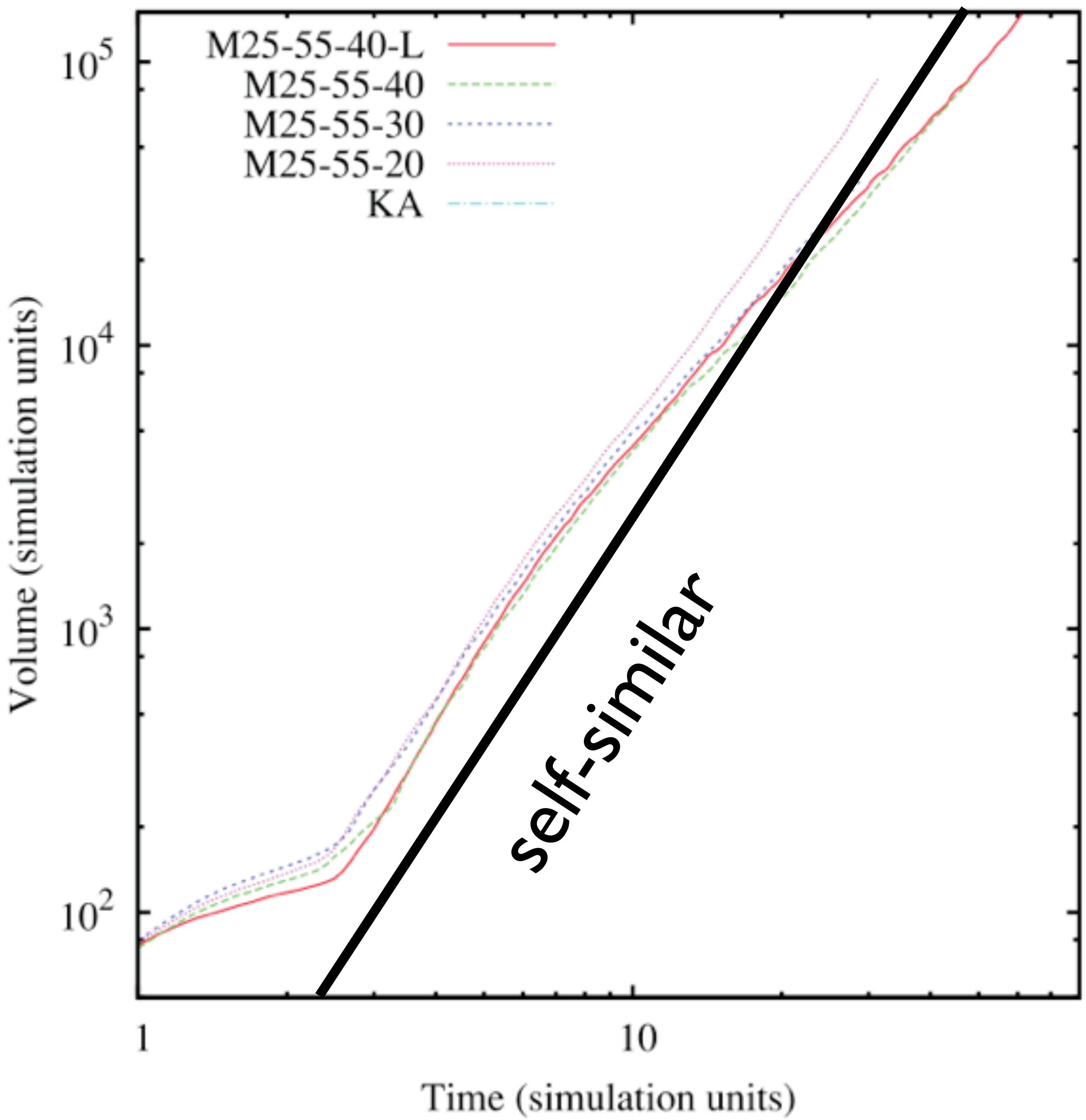
Conical jets: $L_1 \rightarrow L_2$, M_x=40



- above: L > L_2, as typically observed
- beta-profile, beta = 0.35, 0.55, 0.75, 0.90

$$n = n_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta/2}$$

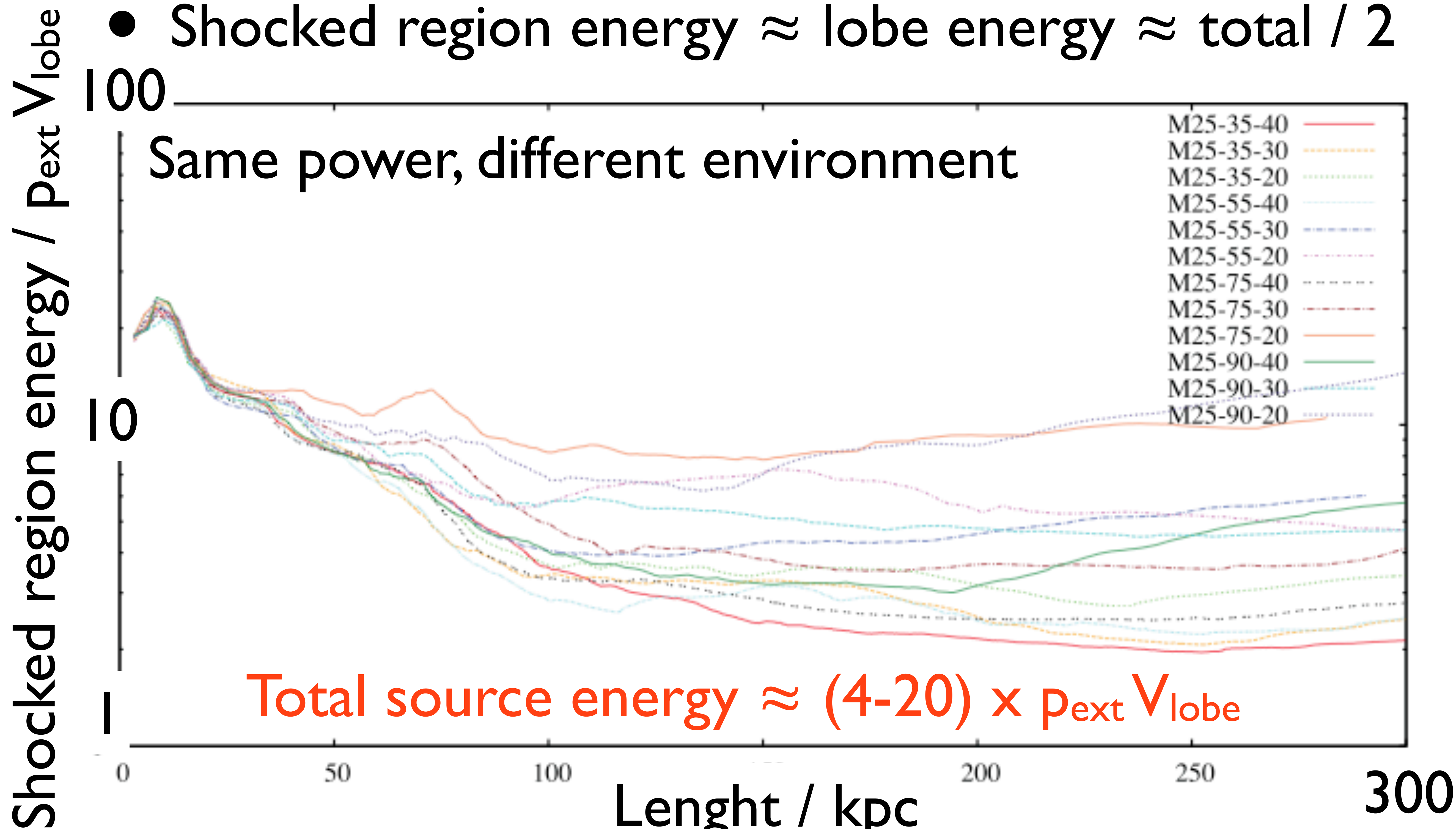
Lobe volume



- Lobe volume grows slower than self-similar
- Radio emission overpredicted by self-similar models
- true jet power > jet power (self-sim)

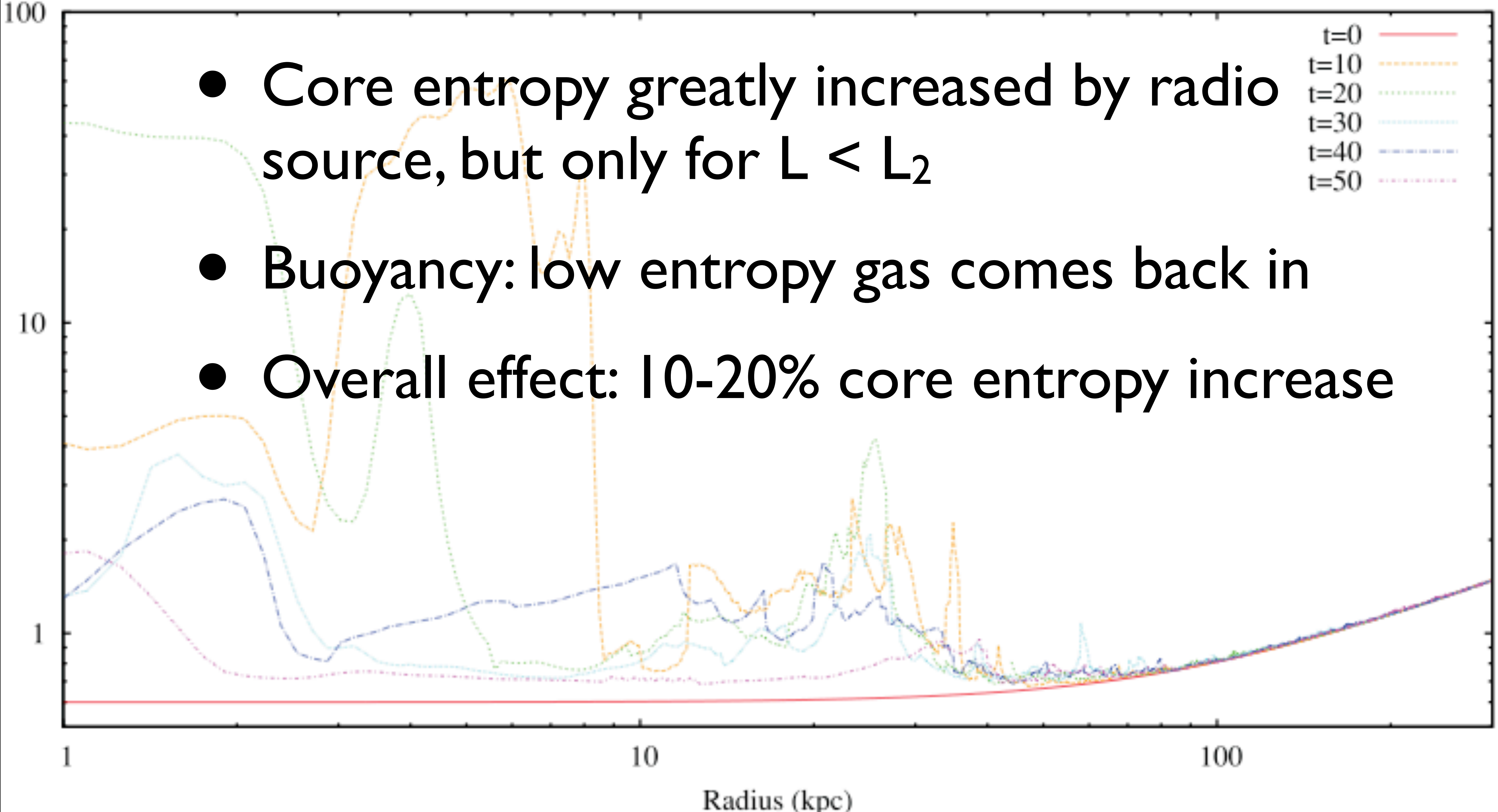
Cavity power estimates

- Shocked region energy ≈ lobe energy ≈ total / 2

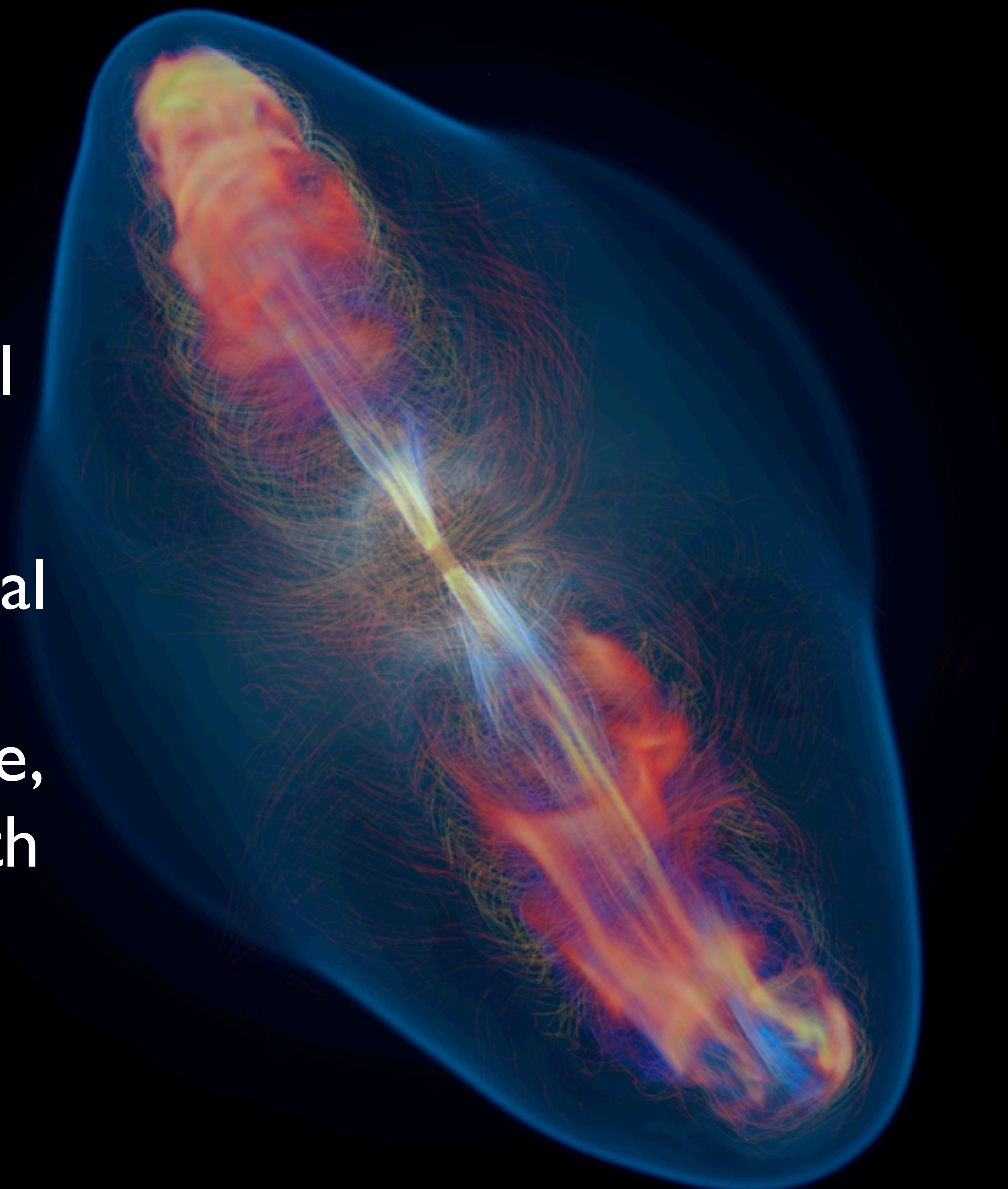


Entropy profile

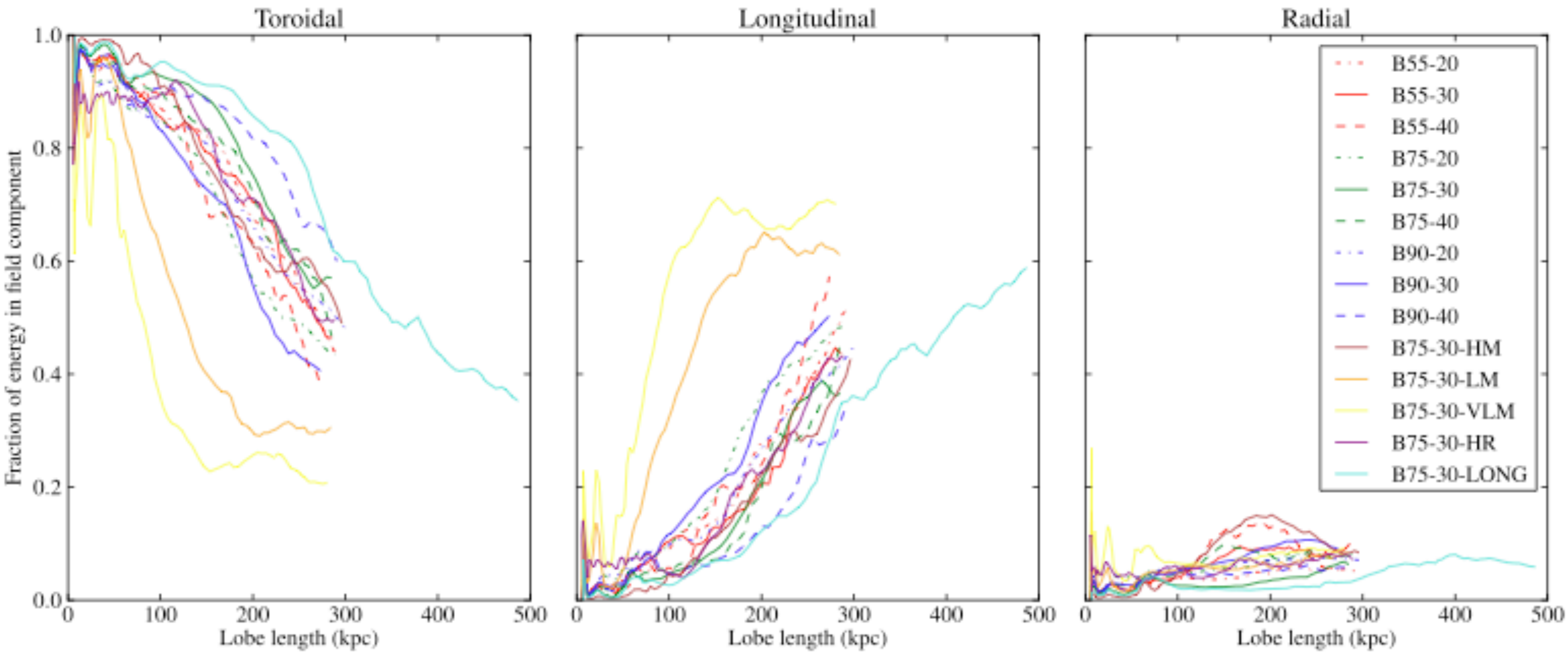
- Core entropy greatly increased by radio source, but only for $L < L_2$
- Buoyancy: low entropy gas comes back in
- Overall effect: 10-20% core entropy increase



- Magnetic fields
- 3D crucial
- init:
  jet: toroidal
  ambient: turbulence, scaled with density



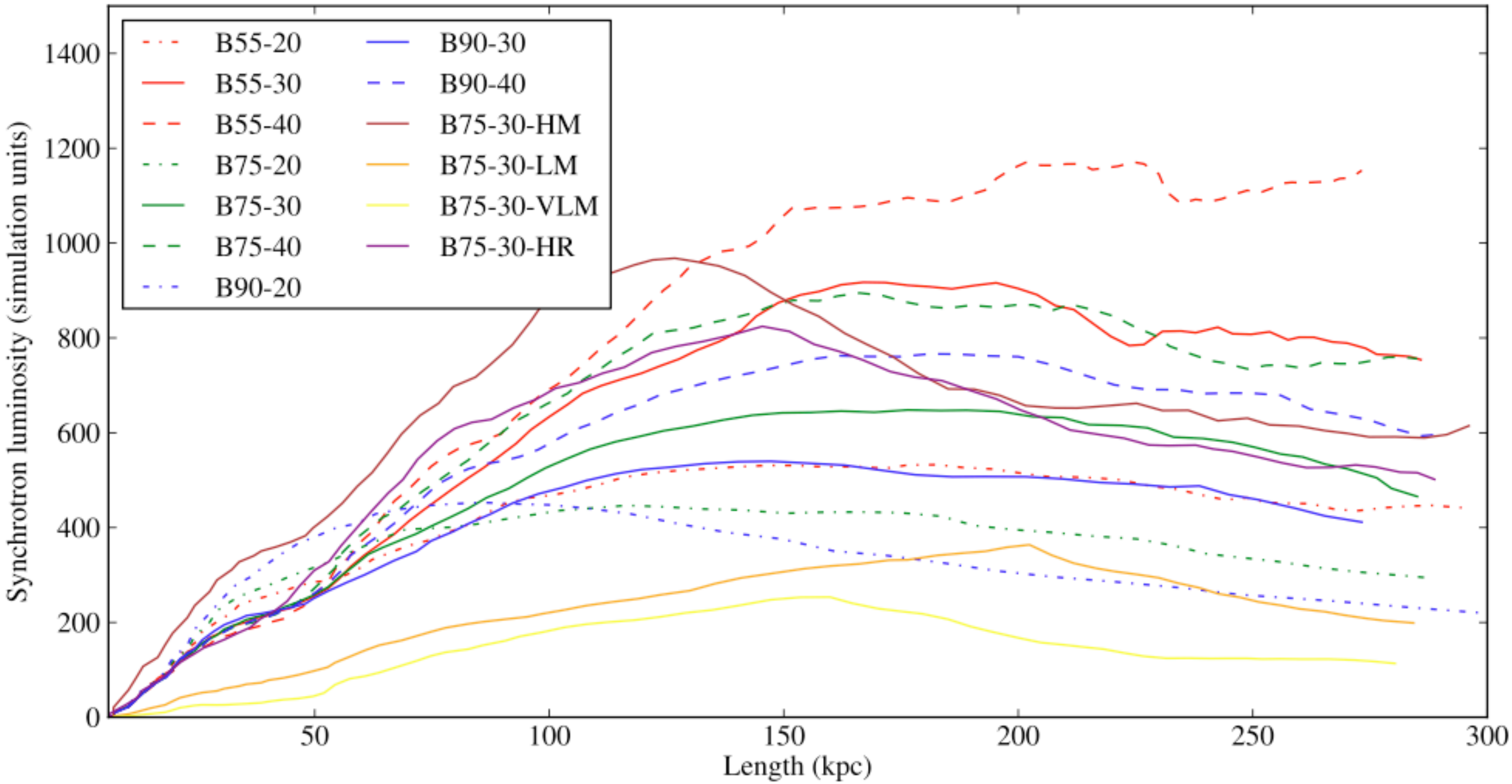
Magnetic topology: lobe magnetic energy fractions



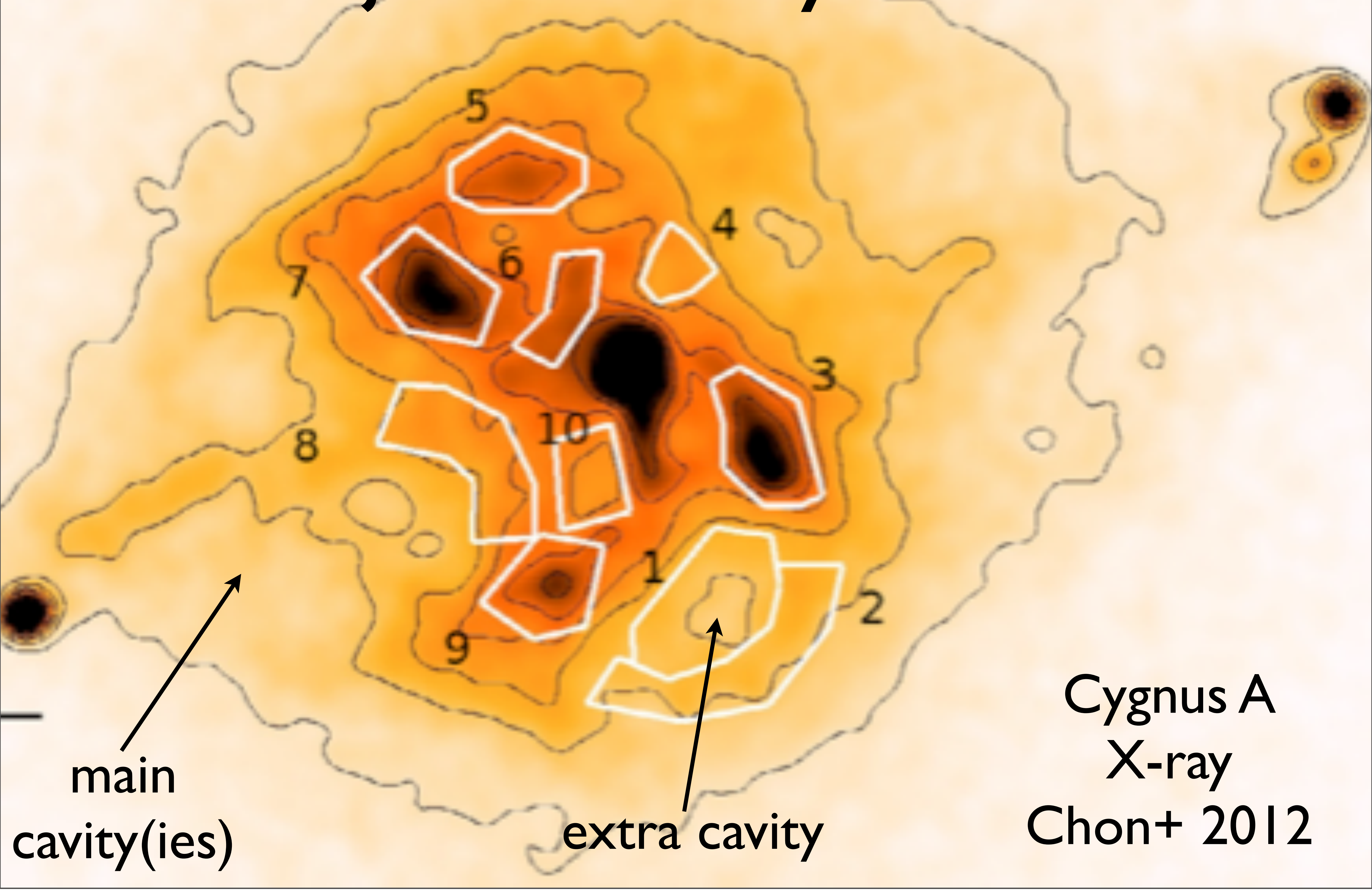
- Convergence: 1/3 toroidal, 2/3 longitudinal

Luminosity-length diagram

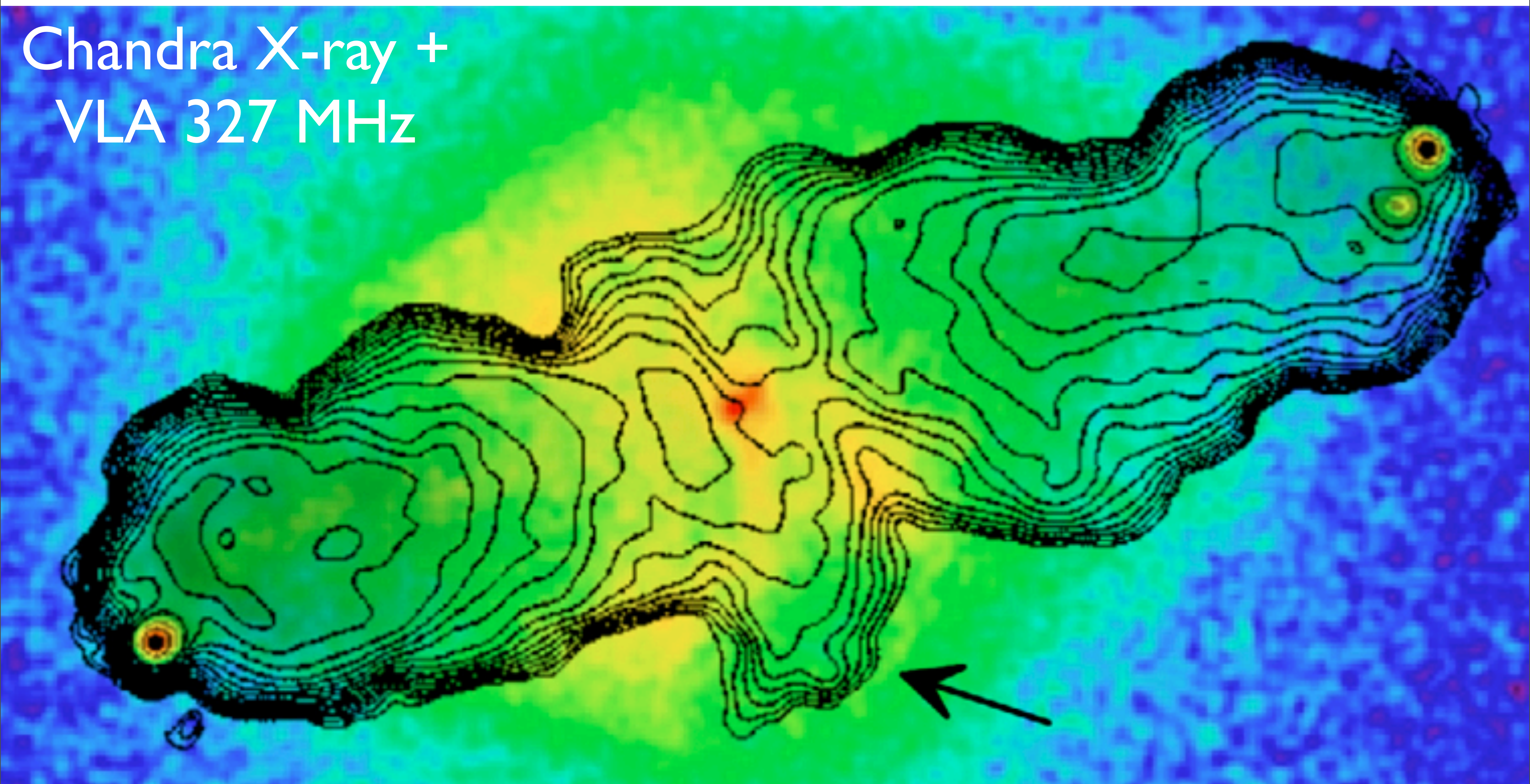
- same jet power/ ≈ factor 6 difference due to each, environment & jet field strength



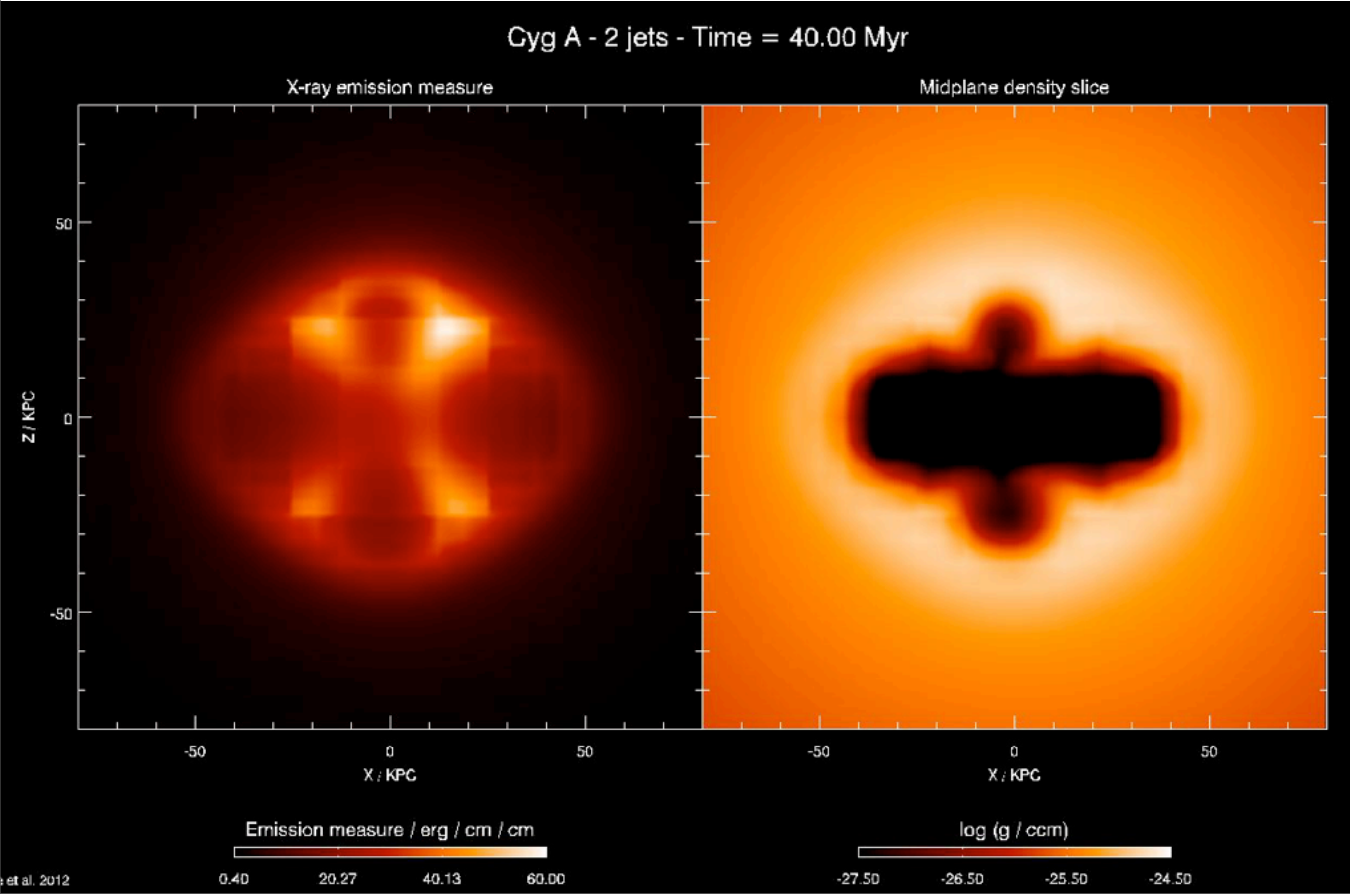
Double jets - binary black holes?



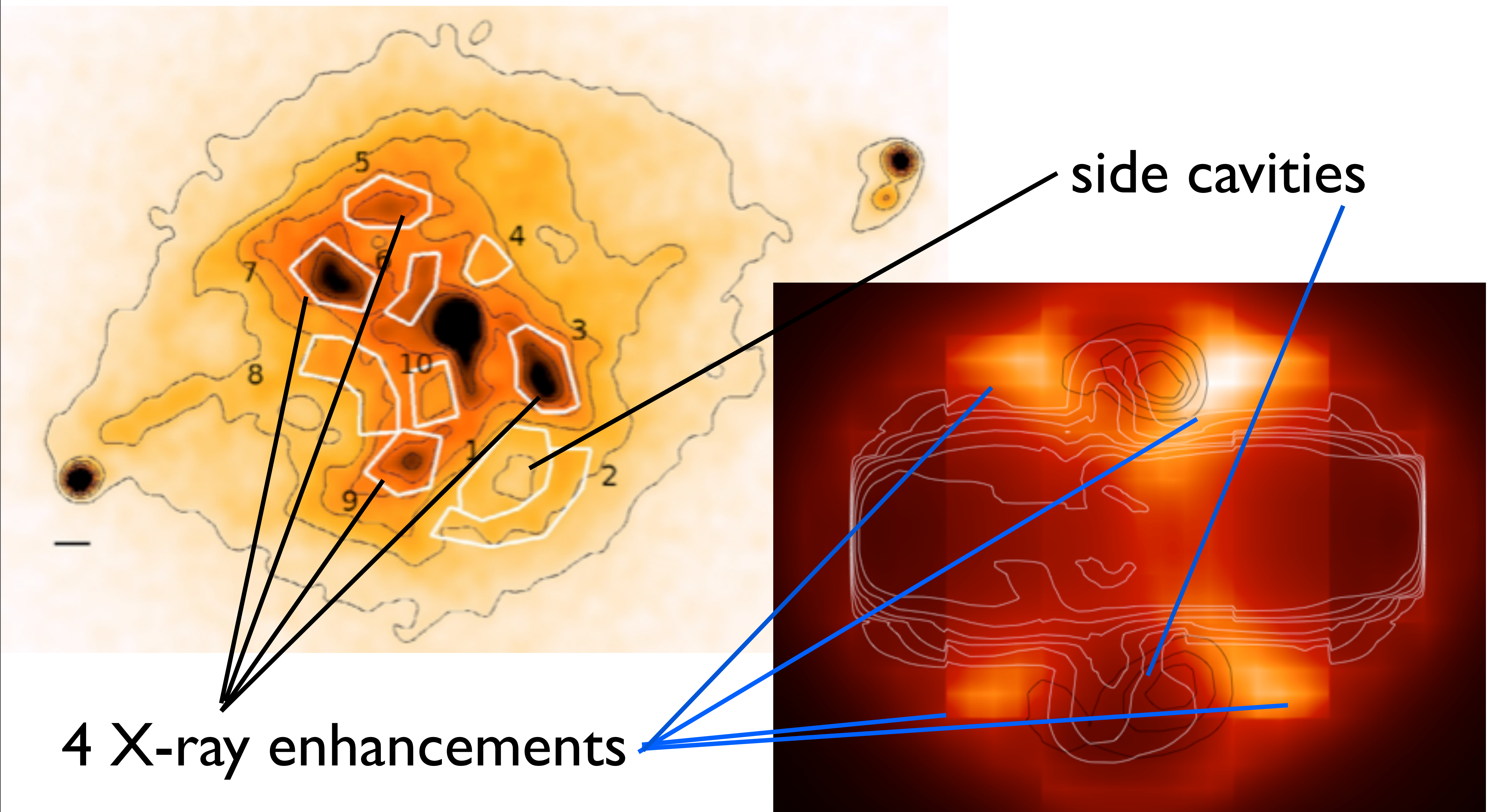
Oldest electrons in this side cavity



3D - 2 jets: 10^{45} erg/s $\perp$ 2×10^{47} erg/s

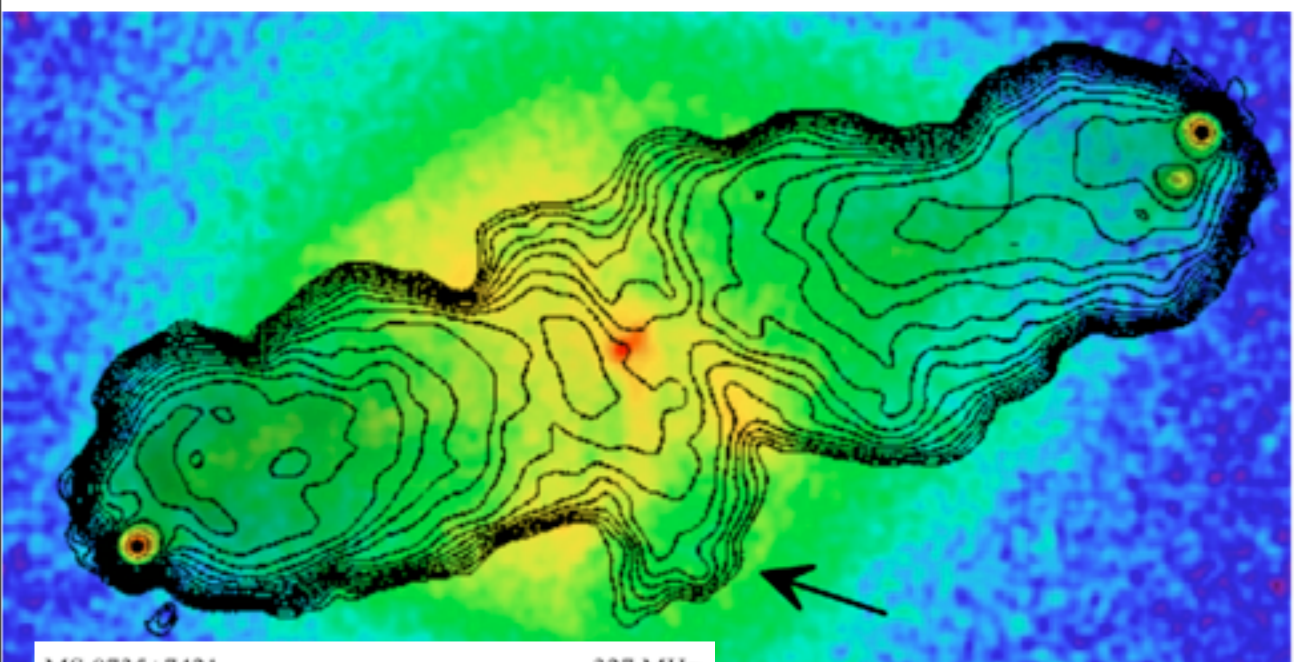


Comparison to 3D simulation: 2 perpendicular jets

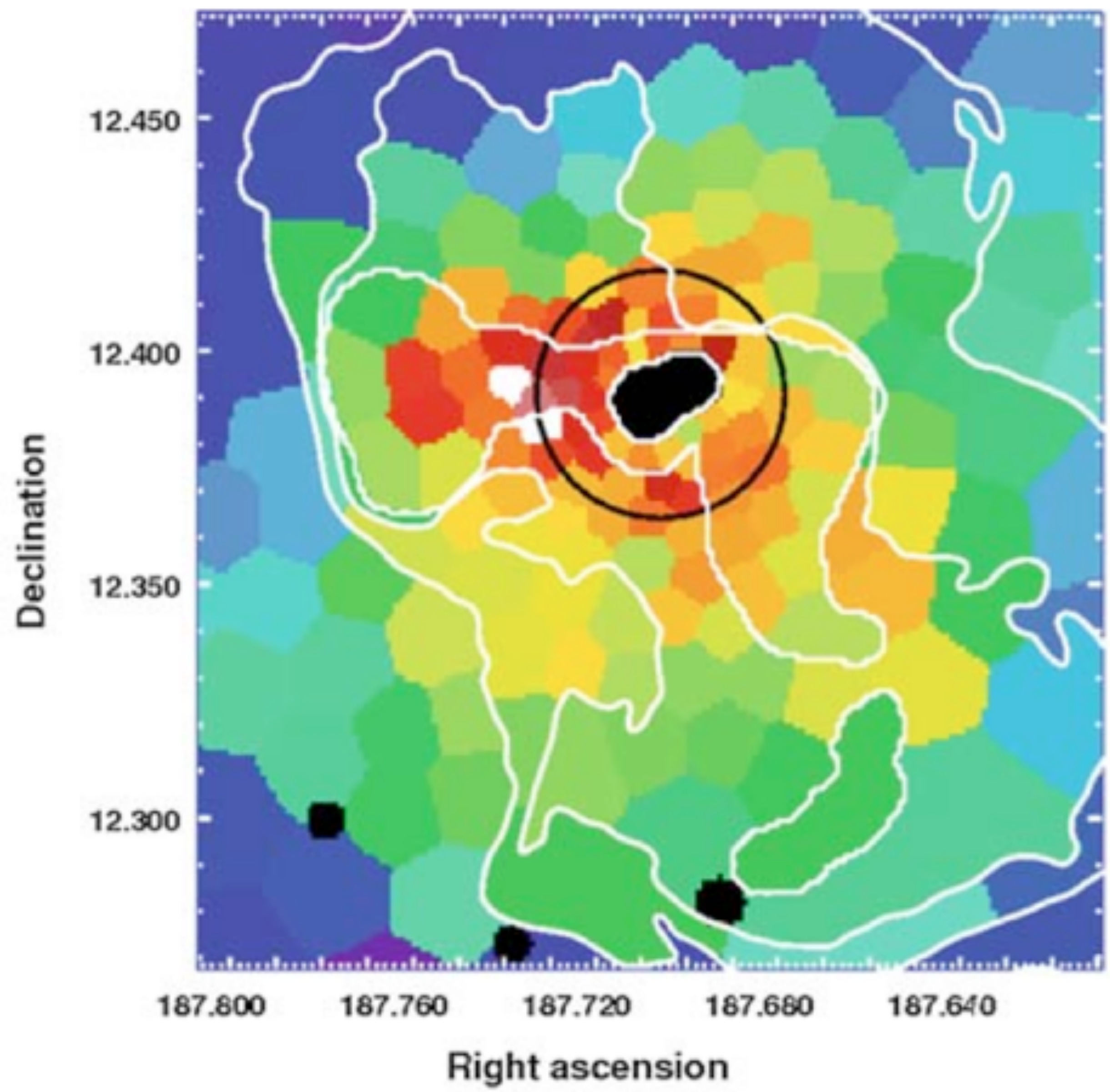


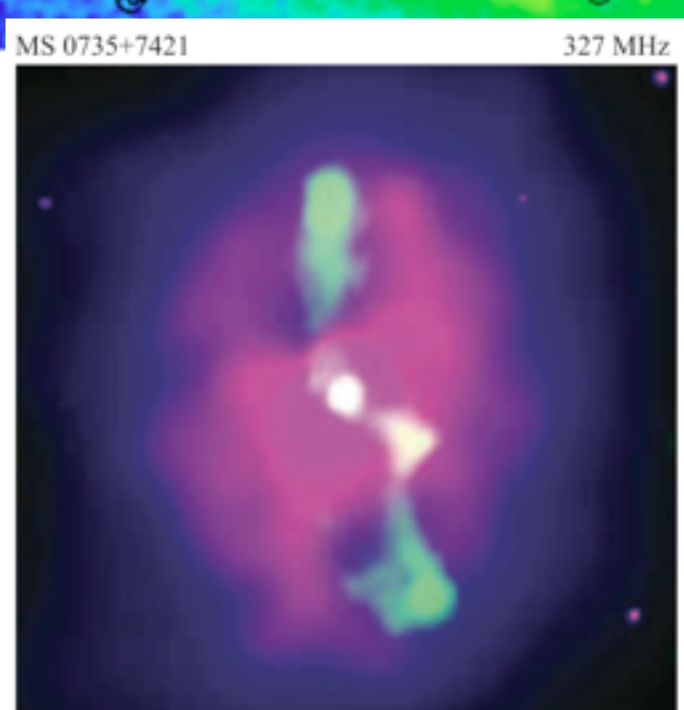
Similar in other sources

Cygnus A



M87 / Virgo





MS 0735+7421

Conclusions I

- Observations ⇔ jet energy flux ?

  E_{jet} = 4-20 pV, L_{radio} (size) ≈ factor 10 scatter / env+mf, self-similar radio source models underestimate jet power

- Jet morphological type ⇔ AGN type ?

  Hot mode acc. ⇒ wide low pow. jets ⇒ FR I (large-sc.)

  Cold mode acc. ⇒ narrow high pow. jets ⇒ FR II

- Jet energy flux ⇔ ICM heating (radius) ?

  Efficient heating for L_1 < size < L_2 ≈ 10s of kpc, only ⇒ need frequent re-triggering (as observed).

Conclusions II

- Magnetic fields in FR II radio lobes turn longitudinal (reproduce polarisarion data)

- Binary black holes might produce radio sources in different directions

References

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  Gayoung Chon, Hans Böhringer, Martin Krause, Joachim Trümper, A&A, 545, L3 (2012)

- *A new connection between the opening angle and the large-scale morphology of extragalactic radio sources*
  M. Krause, P. Alexander, J. Riley, D. Hopton MNRAS, 427, 3196 (2012)

- *Numerical modelling of the lobes of radio galaxies in cluster environments*
  M. J. Hardcastle and M. G. H. Krause, MNRAS, 430, 174 (2013)

- *Numerical modelling of the lobes of radio galaxies in cluster environments II: Magnetic field configuration and observability*
  M. J. Hardcastle & M. G. H. Krause, MNRAS, 443, 1482 (2014)