Aspects of AGN feedback and magnetic field influences

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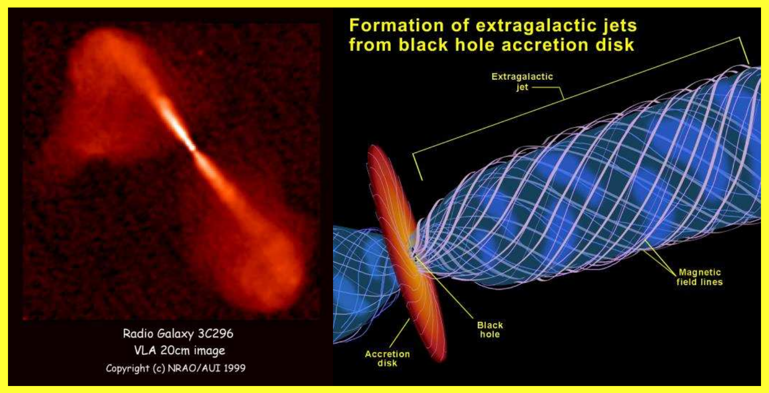
Motivation: Astrophysical jets

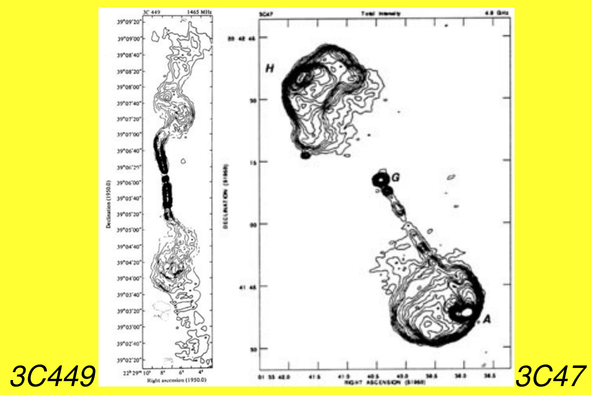
- Jets (+ accretion disks) at galactic scales



$\Rightarrow$ accretion on massive black holes ($10^8 M_\odot$)
$\Rightarrow$ jet lengths: pc (3.26 light-year) to megaparsecs
$\Rightarrow$ nonthermal (synchrotron) radio emission $\rightarrow$ **B**
$\Rightarrow$ relativistic flows, Lorentz factors $\Gamma \simeq \mathcal{O}(10)$

Fanaroff-Riley classification for AGN jets

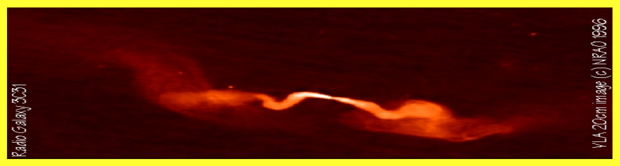
- Fanaroff-Riley 1974: correlation **radio luminosity** - positions high-low surface brightness



$\Rightarrow$ Class I – Class II transition: at well-defined $L_{178\mathrm{Mhz}}$

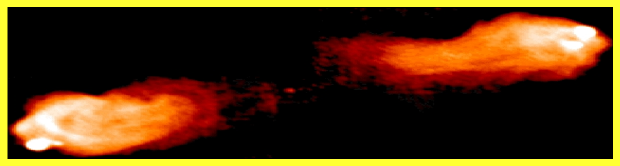
Fanaroff-Riley 1974 classification

- morphology **radio maps**: Class I – Class II transit at well-defined radio luminosity $L_{178\mathrm{Mhz}}$
- FR I: brightest near core, jets in 80 %, **relativistic at parsec scale while diffuse and subrelativistic at kpc**



3C31

- FR II: emit in **lobes, hot spots**; narrow, highly relativistic jet

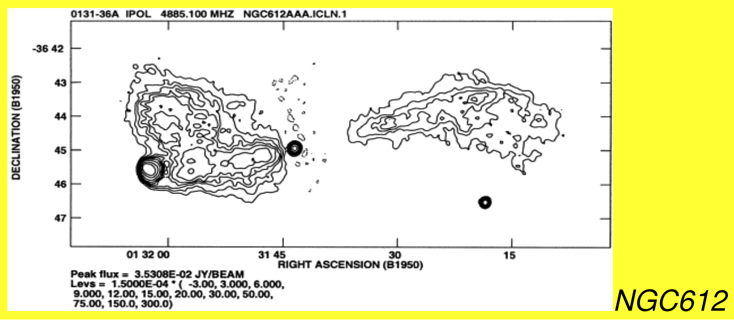


Cygnus A

- relation radio appearance - **IGM energy transport/deposition**

HYMORS

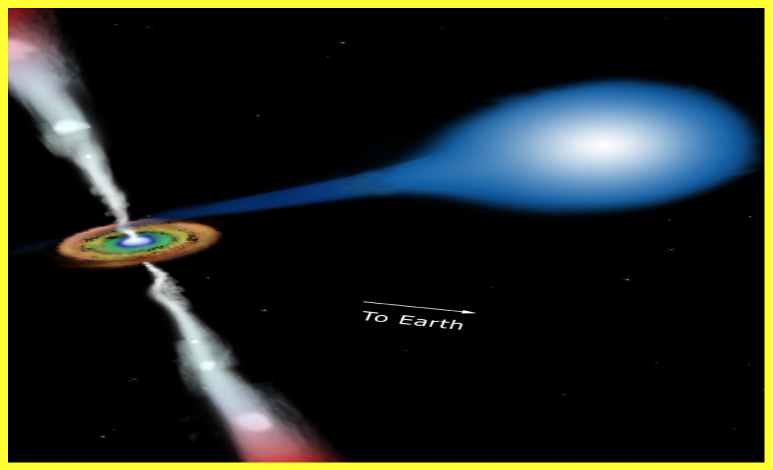
- Gopal-Krishna & Wiita 2002: **Hy**brid **Mo**rphology **R**adio **S**ources
  - ⇒ FR I appearance on one side, FR II characteristics
  - ⇒ FR I/II relates to **ambient medium differences**



  - ⇒ FR II lobe with hotspot to SE, diffuse jet to NW (FR I)
  - ⇒ source yields 'identical' launch conditions at each side

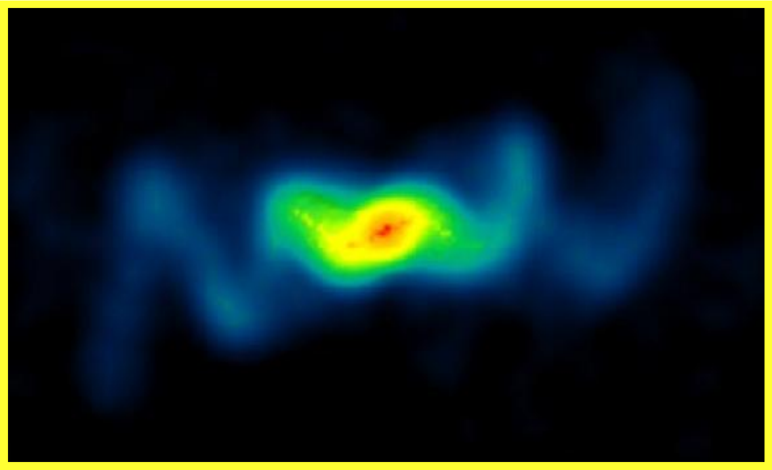
Jets at all scales

- X-ray binary: AGN jet analogue at smaller scale & in fast-forward: archetype system: SS433 at 5.5 kpc distance

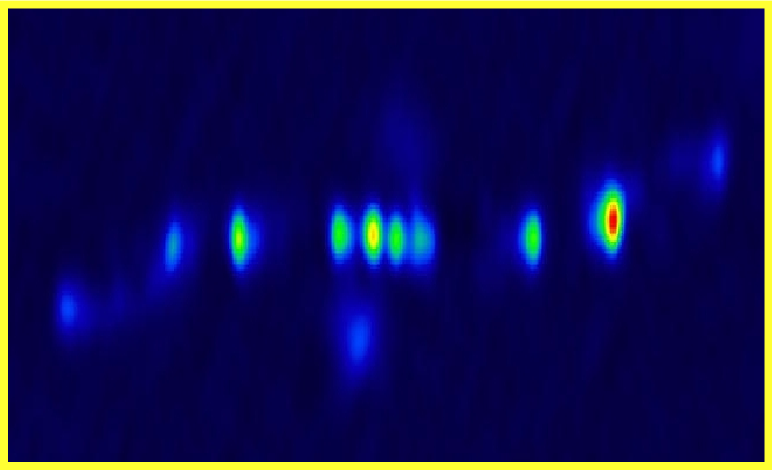


- microquasar XRB system SS433: observed down to sub-parsec scale! mildly relativistic speeds

  $\Rightarrow$ VLA scale (order 0.1 pc)



- down to VLBA scale ($\sim$ 0.026 pc), individual blobs $\sim$ 200 AU



$\Rightarrow$ **SS433 VLBA movie 42 day**

- precessing jet, geometry known, 165 day period!

AGN and XRB Jet challenges

- Newtonian to Relativistic 2D and 3D (M)HD simulations
- How do highly energetic flows decelerate (especially FR II)?

  ⇒ **where is energy deposited**, efficiency?
- **Role of (inner) jet structure on mixing?**

  ⇒ cylindrical to conical jets, steady to varying, radial structure & mixing, 2D to 3D [precession]?
- Example study of **conical non-relativistic hydro jets and FR I/II variation**: Krause et al. '12

  ⇒ FLASH simulations in axisymmetry

  ⇒ seek connections between jet parameters and radio source morphology

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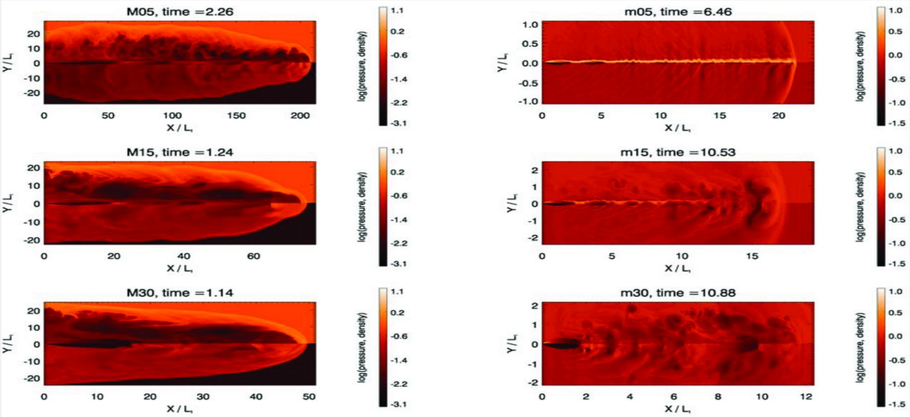
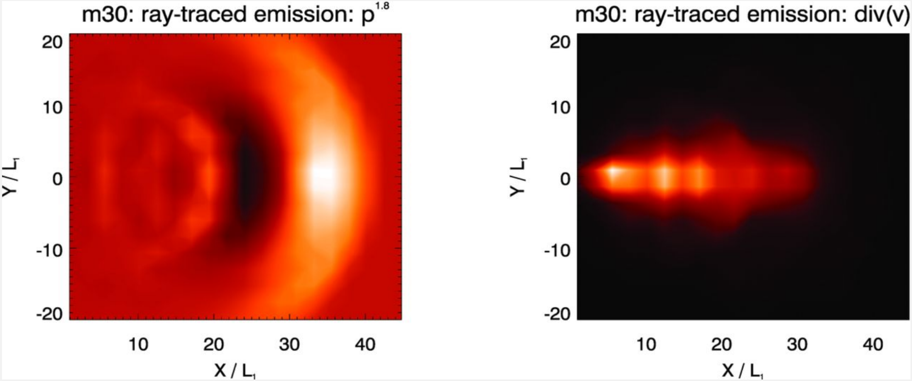
Krause et al. '12



- six 2D HD conical jets $5-30^{\circ}$ in constant medium: $\neq$ scales
  - $\Rightarrow$ jet sideways ram pressure $\approx$ ambient p: can recollimate
  - $\Rightarrow$ where jet density drops below ambient density
  - $\Rightarrow$ where uncollimated ram pressure falls below external p

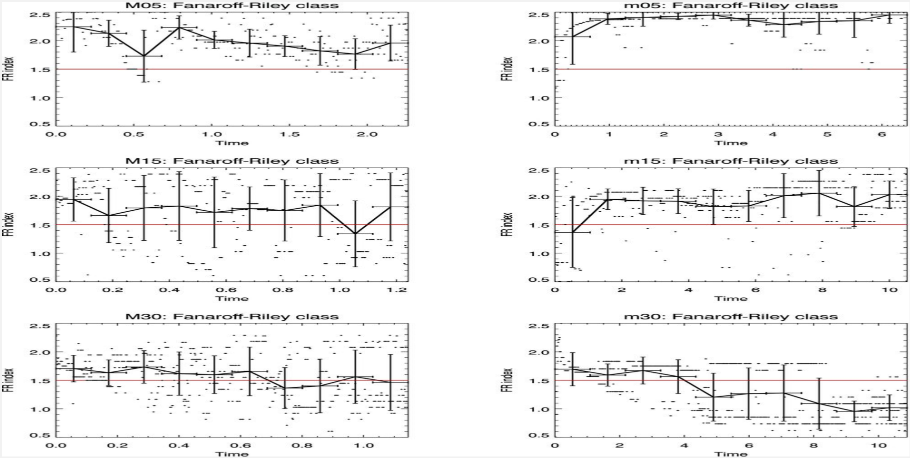
Krause et al. '12



- mimic LOS integrated 'emissivity': use $p^{1.8}$ versus $\nabla \cdot \mathbf{v}$
  $\Rightarrow$ compression highlights shocks, sets extent + brightest feature along x, defines index

$$FR = 2x_{\rm bright}/x_{\rm size} + 0.5$$

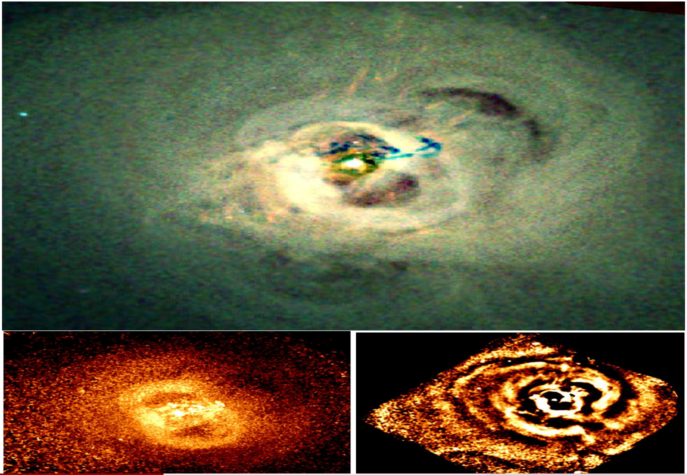
Krause et al. '12



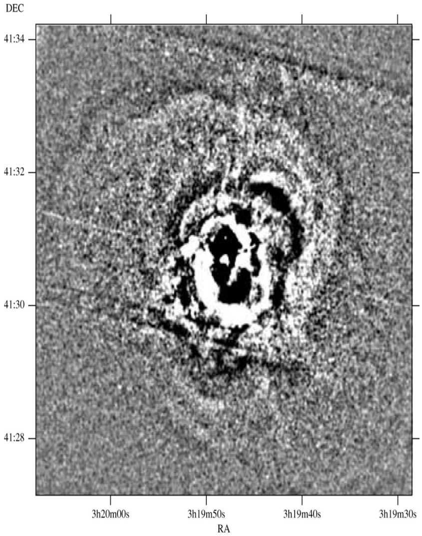
- FR index can vary from FR II (>1.5) to FR I
  - ⇒ low opening angles stay FR II
  - ⇒ large opening angle can become FR I

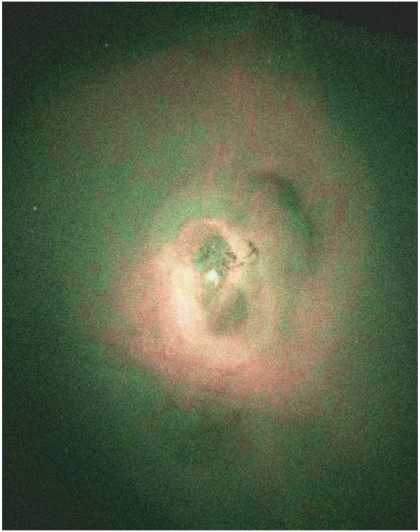
Kinetic feedback

- FR II jets pump $\mathcal{O}(10^{46})\,\mathrm{erg\,s^{-1}}$ in IGM
  $\Rightarrow$ shock-reheat IGM, blowing large-scale bubbles
- galaxy NGC 1275 jet activity affects Perseus cluster *Fabian '03*

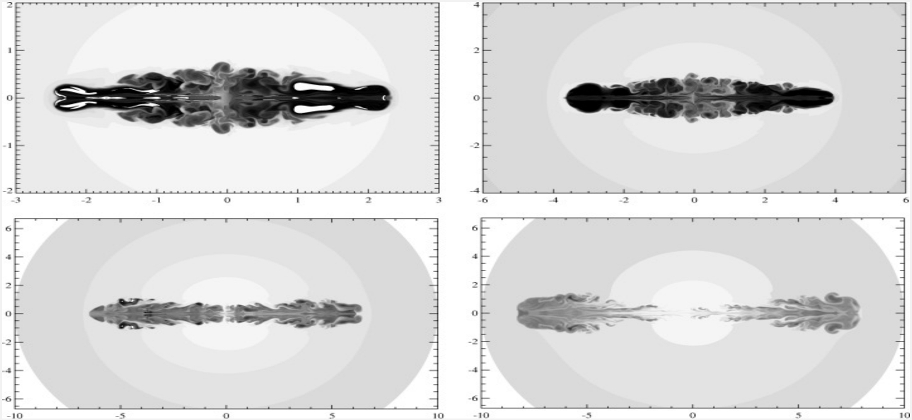


- *Fabian et al '03* subtracted images, Chandra 0.3-0.7 keV (right)



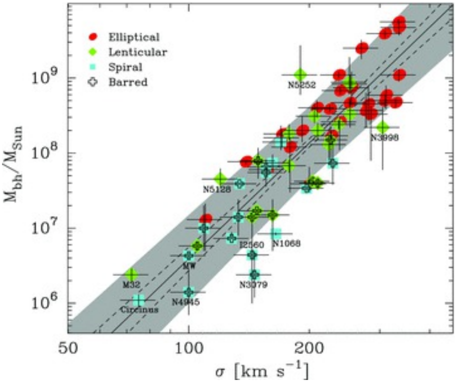


Reynolds et al. '02



- 2D HD conical jets (15°) injected in (externally stratified) $\rho(r)$, active to passive jet phase, address dead radio galaxy aspects
  - $\Rightarrow$ cocoon expands, to buoyant stage (Rayleigh-Taylor)
  - $\Rightarrow$ endstate with 20-fold raised entropy in atmosphere

Graham et al. '11



- observational evidence for AGN feedback: $M_{bh} - \sigma$ relation

  $\Rightarrow$ 64 galaxies with known black hole mass, updated study

$$\log(M_{bh}/M_{\odot}) = 8.13 + 5.13 \log[\sigma/200\,\mathrm{km\,s^{-1}}]$$

- stellar velocity dispersion σ: spread of (stellar) velocities, for interior of host galaxy (is function of radial distance, generally)

  $\Rightarrow$ several methods exist, e.g. Tonry & Davies 1979

  $\Rightarrow$ use spectroscopic data $g(n)$ (intensity versus wavelength bin) of galaxy, correlated to template spectrum $t(n)$ (at zero redshift and instrumental broadening) $\rightarrow$ cross-correlate over wavelength bins $\sum_m g(m)t(m-n)$ (so that its Fourier transform becomes product of FTs) $\rightarrow$ assume $g(n) \approx \alpha t(n) * b(n-\delta)$ multiple α, shifted by δ and broadened by convolution with symmetric function $b(n)$ with dispersion σ (Gaussian bell)

  $\Rightarrow$ least square fit determines α, δ, widths in $g(n)$ and $t(n)$ determines dispersion σ

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- Expected $M_{bh} \propto \sigma^5$: Silk & Rees 1998

$\Rightarrow$ first objects to form are supermassive BH, they merge, grow, feedback on star formation rate (SFR)

$\Rightarrow$ escape speed σ from mass within radius $M(r) = 2r\sigma^2/G$

$\Rightarrow$ isothermal bulge $T = \sigma^2 m_p/3k$, density $\rho(r) \propto \sigma^2/r^2$

$\Rightarrow$ protogalactic wind will sweep up gas, with velocity that can exceed escape speed from galaxy when

$$M_{bh} > (\sigma/500\,\mathrm{km\,s^{-1}})^5\, 8 \times 10^8 M_\odot$$

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- Expected $M_{bh} \propto \sigma^4$: Fabian 1999
  - $\Rightarrow$ uses momentum balance instead of energy arguments
  - $\Rightarrow$ outward radiation pressure versus inward gravity
- distinguish **radiative or wind mode** versus **kinetic mode**
  - $\Rightarrow$ in kinetic mode: galaxy feeds back energy in surroundings which balances cooling otherwise expected in surrounding gas
  - $\Rightarrow$ kinetic mode blows bubbles, FR I in blown cavity

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- cosmological evolutions follow dark matter, gas, star dynamics

  ⇒ popular using SPH (Gadget2 etc)

  ⇒ need handle feedback at **subgridscale** resolutions, also SFR parametrized, feedback from supernovae

  ⇒ **parametrize**....when accrete on BH, how BH merge, how BH release part of this energy in surroundings

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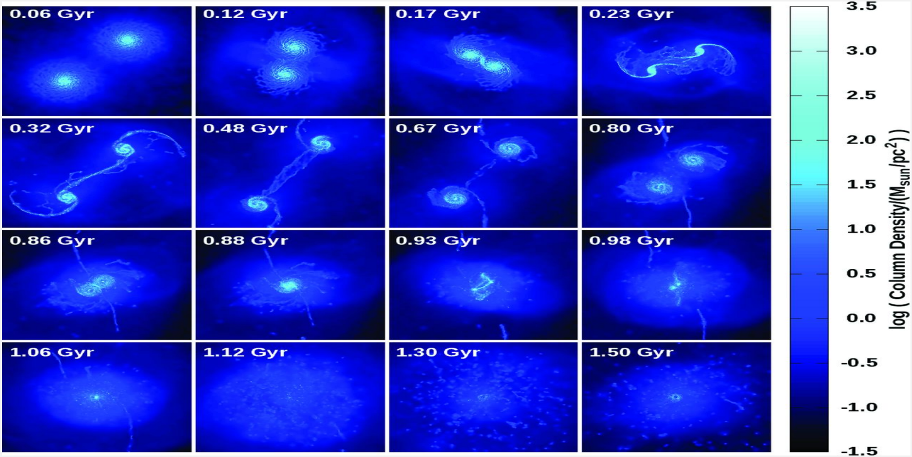
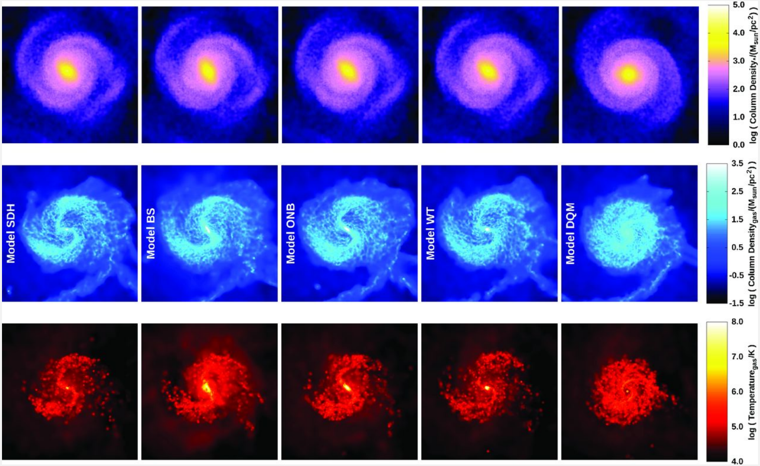
Wurster et al. '13



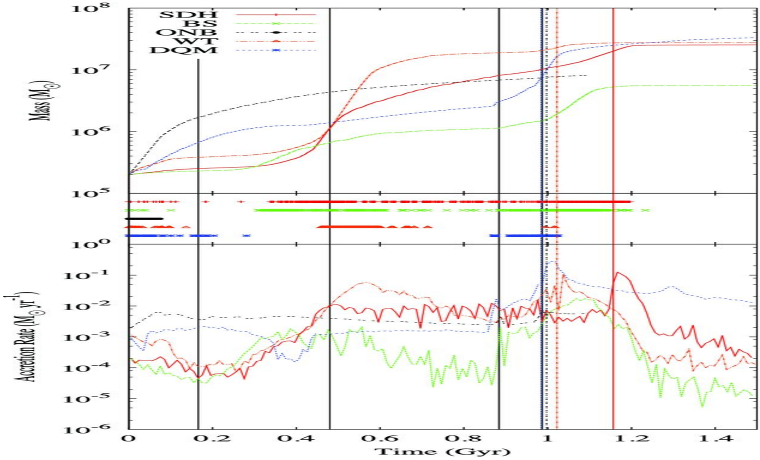
- HYDRA: N-body + SPH simulate gas-star-dark matter evolution
  - $\Rightarrow$ simulate merger event of 2 galaxies, each with central BH
  - $\Rightarrow$ parametrized 'star formation rate' and feedback

Wurster et al. '13



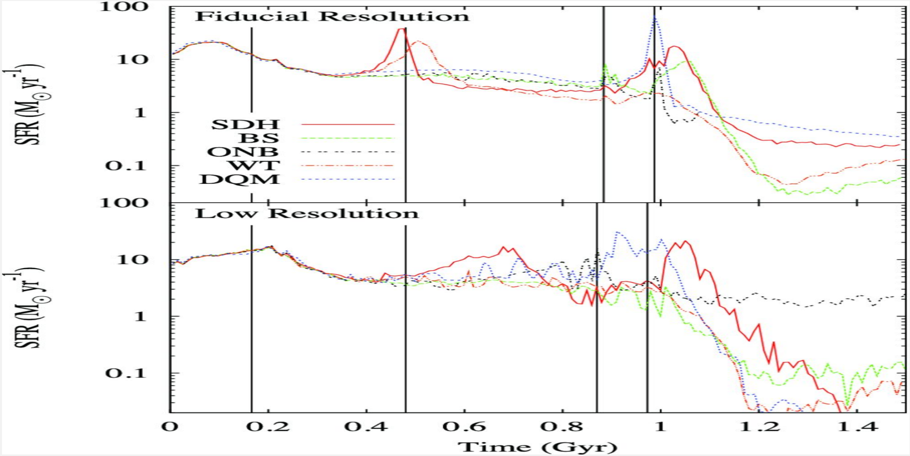
- 5 means for parametrizing feedback: zoom on one galaxy at time of first maximal separation (apoapsis, 480 Myr)

Wurster et al. ’13



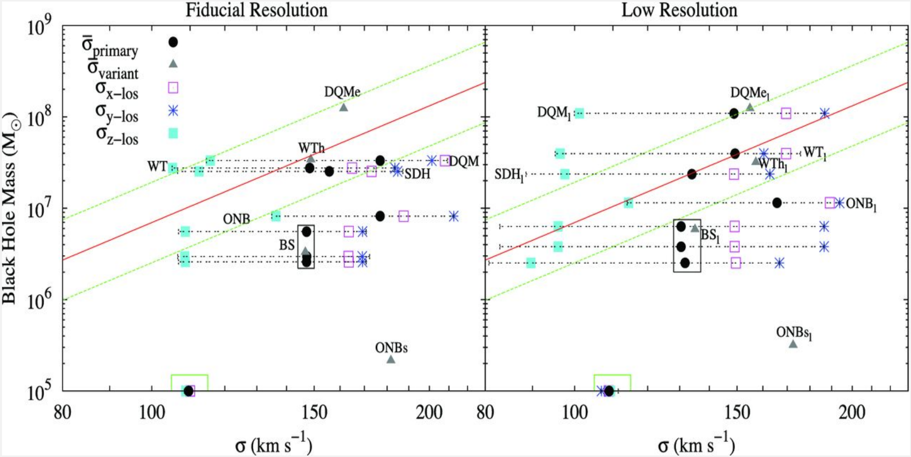
- dramatic differences in BH mass growth, accretion rate on BH (model BS does not -yet-show BH merger)

Wurster et al. '13



- different star formation rates (between models and resolution): note logarithmic scale: orders of magnitude!

Wurster et al. ’13



- can ‘reproduce’ $M_{bh} - \sigma$ relations

- magnetic field?

Sutter et al. '12

- 3D MHD-AMR (Flash): isolated galaxy cluster with injected kinetic, thermal, magnetic energy

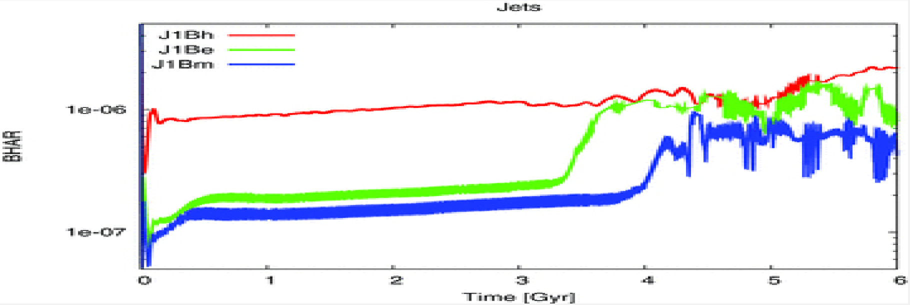
  $\Rightarrow$ cluster mass $10^{14} M_{\odot}$, with $3 \times 10^{9} M_{\odot}$ BH

  $\Rightarrow$ still parametrizes at subgrid, e.g. α multiple of Bondi accretion rate on BH

$$\dot{M}_{bh} = \alpha 4\pi G^2 M_{bh}^2 \frac{\rho}{c_s^3}$$

- feedback as source terms in mass, momentum, energy, and **B**

Sutter et al. '12

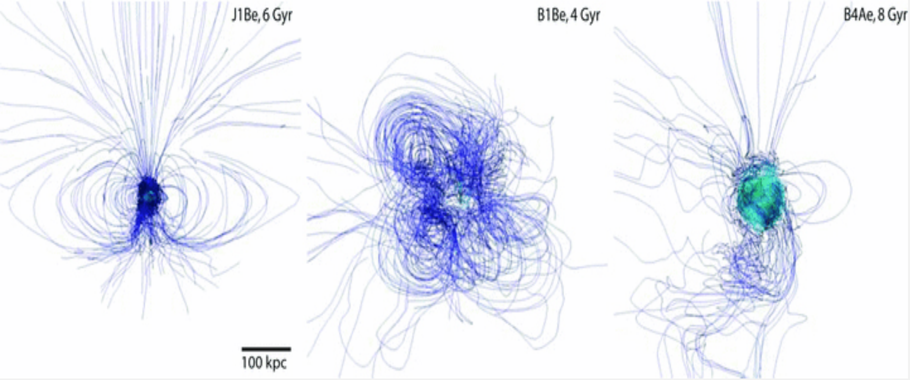


- compare HD (red) with 'Jet' cases (equipartition to pure magnetic energy injected)

  $\Rightarrow$ injected field unwinds, drives gas from center, reduces accretion rate, shown is ratio to Eddington accretion rate

$$\dot{M}_{\rm Edd} = \frac{4\pi G M_{bh} m_p}{0.1 \sigma_T c}$$

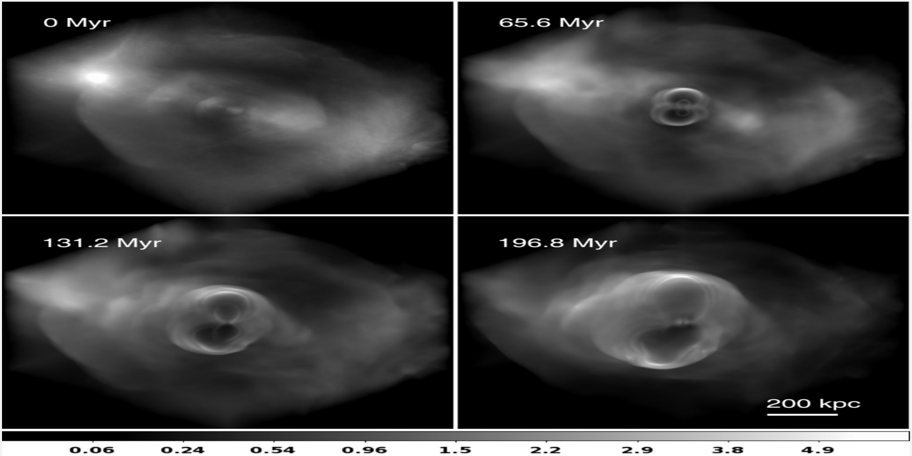
Sutter et al. '12



- injected field varies from directed jet (left) to randomly superposed bubbles (middle) to fixed bubbles (right)

  $\Rightarrow$ field entanglement for superposed bubble injection causes near hydro behavior!

Mendygral et al. '12



- 3D MHD: intermittent jets injected through galaxy cluster
  - $\Rightarrow$ latter extracted from earlier SPH cosmological simulation
  - $\Rightarrow$ synthetic X-ray view (ray-trace$\propto n^2/\sqrt{T}$): cavities/ripples!

- **Pros**: **B** start to be incorporated, high β no excuse for neglect!
  - $\Rightarrow$ Mendygral: speeds order 400 $\mathrm{km\,s^{-1}}$ modify jets/lobes!
  - $\Rightarrow$ Sutter: field topology can regulate environmental impact
- **Cons**: multiscale (spatial and temporal) aspect!
  - $\Rightarrow$ neglect of relativistic treatment of flows

- no models (yet?) that take into account knowledge gained on role of **B** field in accretion disks, jet launch, jet stability and propagation, mixing efficiencies . . .
- own work: typically looks at these latter aspects

  ⇒ start with relativistic HD models jet propagation/mixing (AGN to XRB)

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AGN and XRB Jet challenges

- How do highly energetic flows decelerate (especially FR II)?
  $\Rightarrow$ where is energy deposited, efficiency?
- **Role of inner jet structure on mixing?**
  $\Rightarrow$ cylindrical to conical jets, steady to varying, radial structure & mixing, 2D to 3D?
- Relativistic 2D and 3D (M)HD simulations
  $\Rightarrow$ precession, non-axisymmetric instabilities: 3D!

Special relativity and (M)HD

- **special relativistic treatment** $\rightarrow$ flat Minkowski space-time
  $\Rightarrow$ particle, tensorial energy-momentum conservation
- ideal MHD (full Maxwell): vanishing **E** in comoving frame

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B}$$

  $\Rightarrow$ use fixed Lorentz frame, 1+3 split (time space), find

$$\partial_t \mathbf{U} + \nabla \cdot \mathbf{F}(\mathbf{U}) = \mathbf{0}$$

  $\Rightarrow$ shock-capturing conservative schemes, hyperbolic PDEs
- **MPI-AMRVAC** HTML documentation info at
  http://homes.esat.kuleuven.be/~keppens
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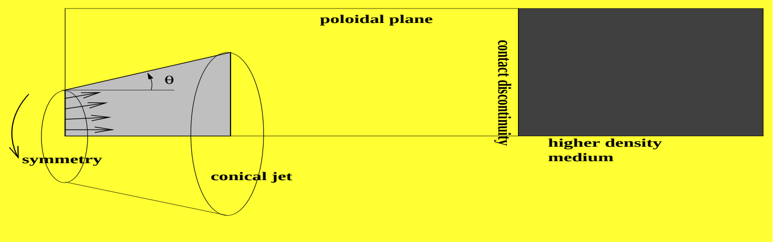
Model parameters

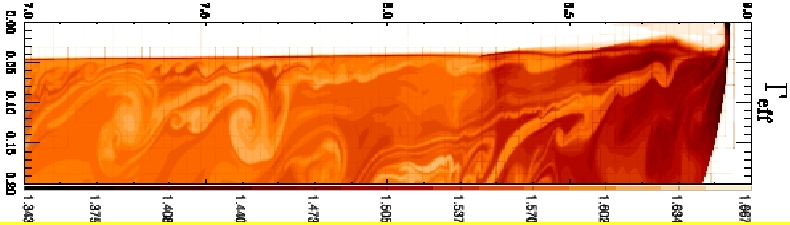
- jet kinetic energy & Lorentz factor Γ (order 10-20)
- ratio between jet/IGM inertia (density contrast)
- opening angle: cylindrical/conical models



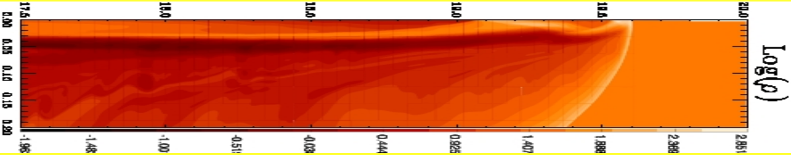
- external medium stratification: include **density discontinuities**

  ⇒ seperating differing regions of influence

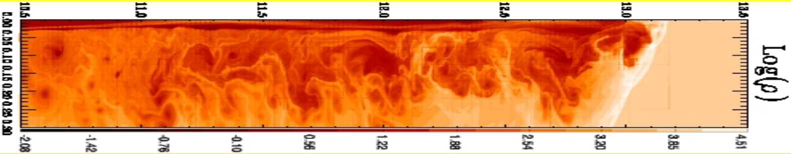
- **Relativistically correct ideal gas: effective $\gamma(T)$**
  - $\Rightarrow$ polytropic index: affects compression rate, shock strength
- Application: **AGN jets encountering density discontinuity**
  - $\Rightarrow$ possible source for sudden deceleration of FR I jets
  - $\Rightarrow$ **simulate jet propagation through layered media**
  - $\Rightarrow$ $\Gamma \simeq 20$ beam Lorentz factor, $L_{\mathrm{Jet,Kin}} \sim 10^{46} \mathrm{e}rgs/s$.
- lower region: lighter medium $\rho_{\mathrm{Low}}/\rho_b = 0.1496$
  - $\Rightarrow$ **zoom on jet head before jump encounter**



- **preformed jet head: ultrarelativistic state in shocked, swept-up ISM**, affects dynamics as it penetrates denser region
  - ⇒ **consider two density contrast: both higher density**
- Case I: contrast $\rho_{\rm up}/\rho_b = 4.687$ time $t = 380$



  - ⇒ knot formation, fairly stable beam remains
- Case II: contrast $\rho_{\rm up}/\rho_b = 671.22$ time $t = 300$

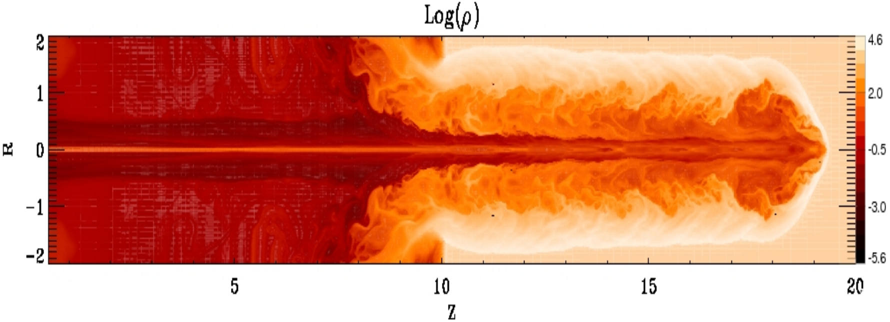


  - ⇒ turbulent cocoon, backflow (KH), axial jet confinement

- differences between **low-high energy jets:** 10^{43} **or** $10^{46}\mathrm{ergs/s}$
  - $\Rightarrow$ jet beam kinetic luminosity

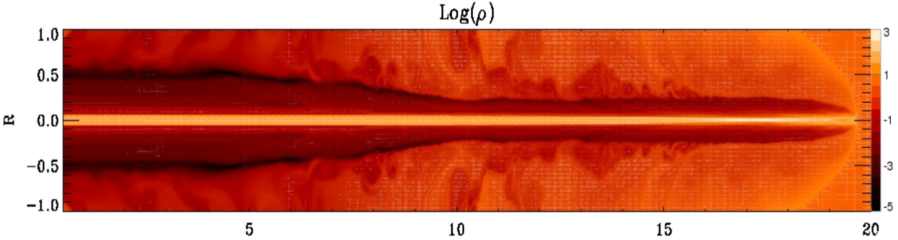
$$L_{\mathrm{jet,Kin}} = (\Gamma_{\mathrm{b}}\, h_{\mathrm{b}} - 1)\, \rho_{\mathrm{b}} \Gamma_{\mathrm{b}} \pi\, R_{\mathrm{b}}^2 v_{\mathrm{b}}$$

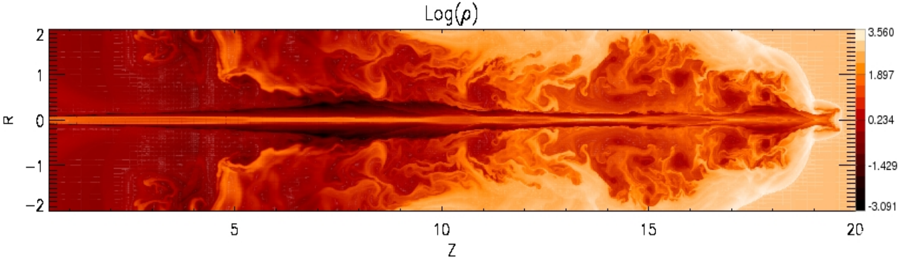
  - $\Rightarrow$ 10 models, **varying** $\Gamma_{\mathrm{b}} = 10 - 20$ **and** $\theta = 0 - 1$
  - $\Rightarrow$ with/out ρ variation, Case II $10^{46}\mathrm{ergs/s}$ at $t = 900$



$\Rightarrow$ **FR II jet at first, then dramatic slowdown to FR I**

- high energy jets: need significant contrast for FR I transition

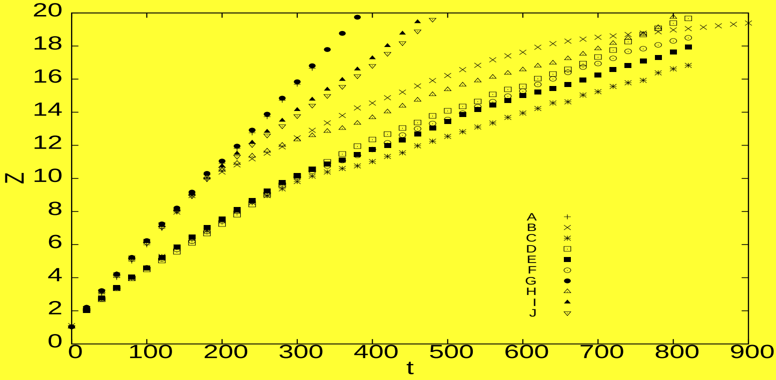




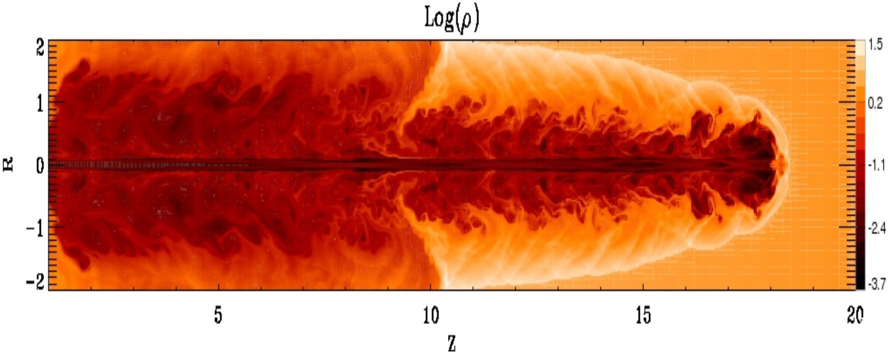
$\Rightarrow$ $\Gamma = 10$, **density jump 10-1000**, IGM stratification effects

A&A 491, 321-337 (2008)

- overall findings on jet deceleration
  - ⇒ **FR II-FR I transition feasible at large density contrast**
  - ⇒ FR I changeover: relativistic at pc to subrelativistic at kpc



- FR I low energy jets: **Richtmeyer-Meshkov instability** as shock passes CD



$\Rightarrow$ all **high-resolution, grid-adaptive computations, effective resolutions of** 3000 $\times$ 5000, **4 to 6 refinement levels**

$\Rightarrow$ typical execution times: **4 days on 64 processors**

- previous models: IGM discontinuous 2-layer structure
  - $\Rightarrow$ jet is (nearly) cylindrical
  - $\Rightarrow$ from overdense jet to light jet conditions
  - $\Rightarrow$ upper medium either uniform or decreasing with distance
- Recently: *Monceau-Baroux et al., A&A 545, A62, 2012*
  - $\Rightarrow$ **explore FR II jets, at large opening angle** $(5-10^\circ)$
  - $\Rightarrow$ enter a decreasing density (King atmosphere) ISM/IGM

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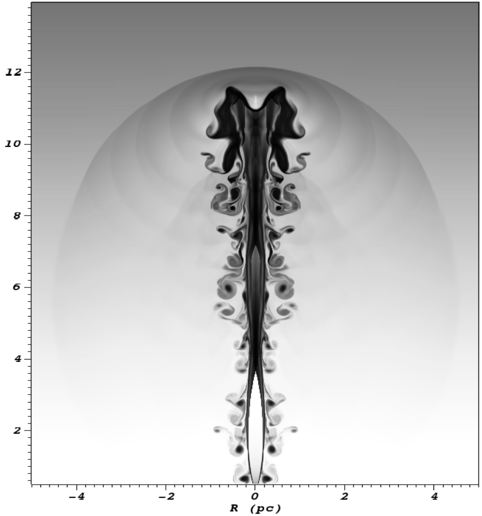
- finite angle jets: recollimation leading to ‘static’ shock patterns
  ⇒ Fermi acceleration sites for particles, nodes



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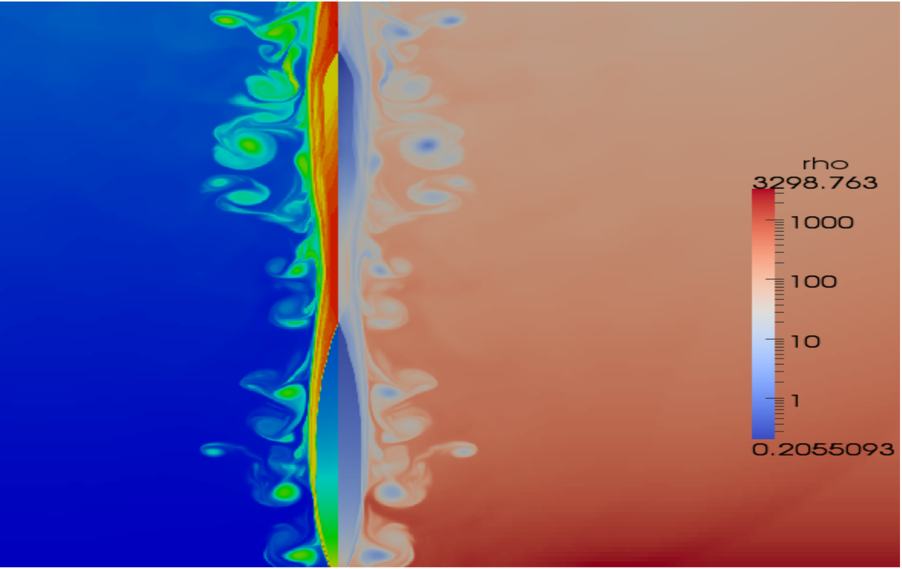
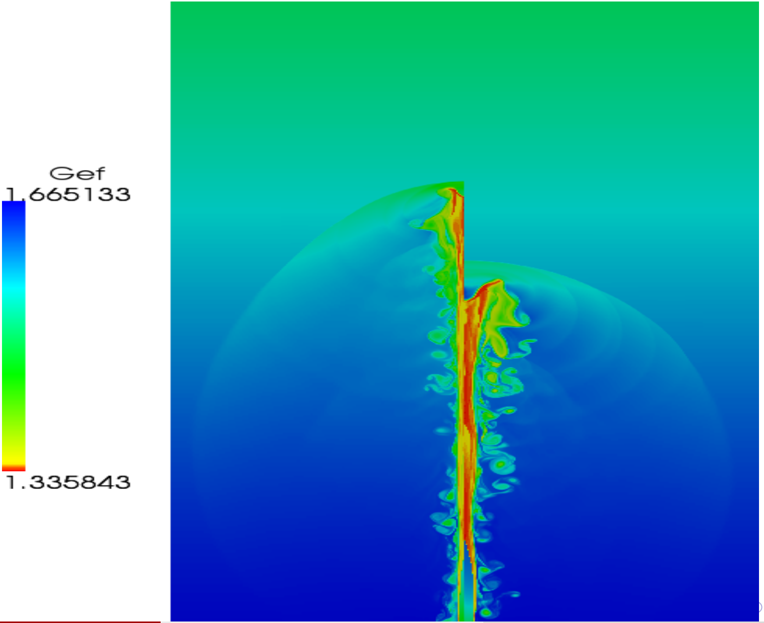
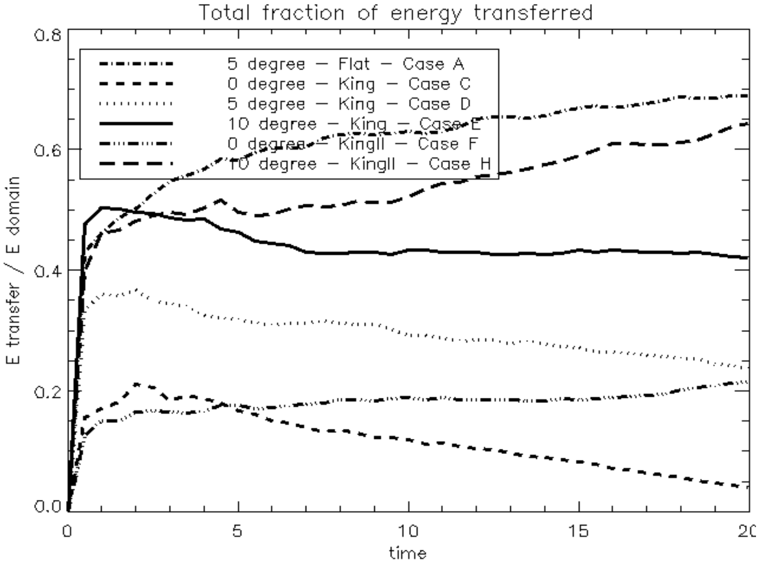


- compare (effective polytropic index) view for 5° to 10°



- quantitative comparisons: identify shocked ISM, jet beam, instability mixing zone with instantaneous masks

- use masks to quantify volumes, energy content, energy transfer
  - ⇒ example for energy into mixing/shocked ISM



- main findings:

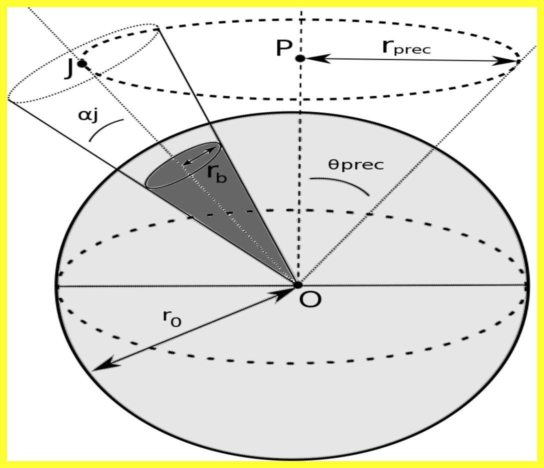
  ⇒ wider opening angle jets decelerate faster, and are accompanied by a larger mixing zone

  ⇒ **energy transfer mainly happens in shocked ISM region, by cocoon traversing waves and at frontal bow shock**

  ⇒ **finite opening angle jets can get up to 70% of their energy fed into shocked ISM** regions

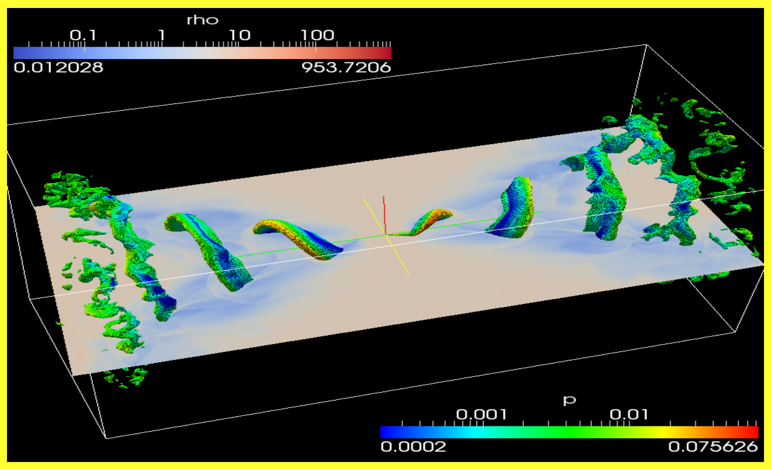
SS433 jet simulations

- 3D hydro runs at mildly relativistic SS433 case (Monceau-Baroux et al, '13 in revision)
  - ⇒ need to handle jet precession, inner boundary region



SS433 jet simulations

- 3D hydro runs at more mildly relativistic SS433 case
  $\Rightarrow$ need to handle jet precession, explore sub-parsec scale



- overdense, canonical jet speed: jet/ISM interaction causes slow-down

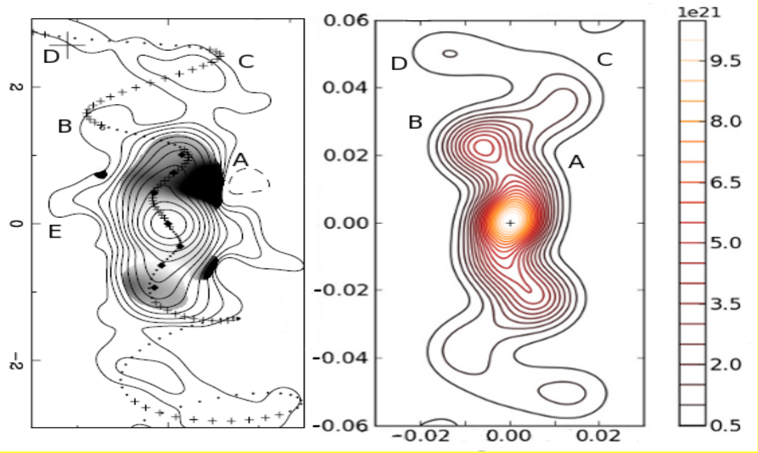
  ⇒ takes longer to build up various windings of helix than estimated from precession/speed

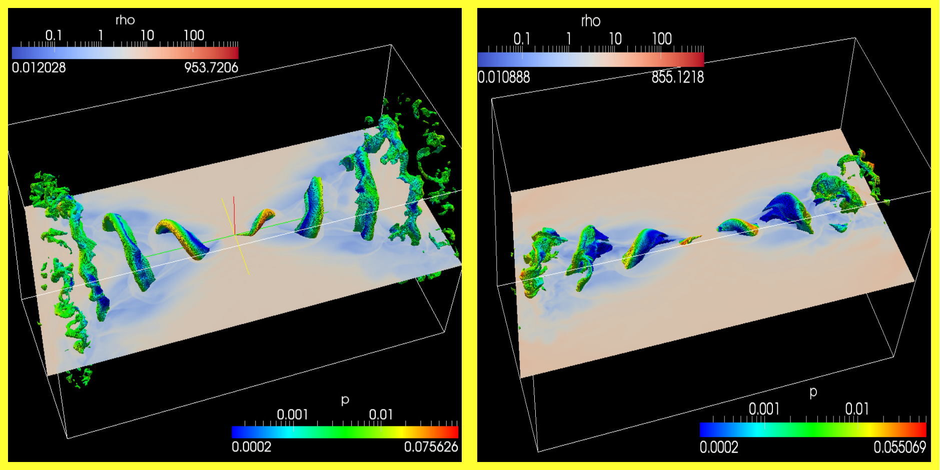
  ⇒ **ss433 jet buildup**

  ⇒ **ss433 density in cross-section**

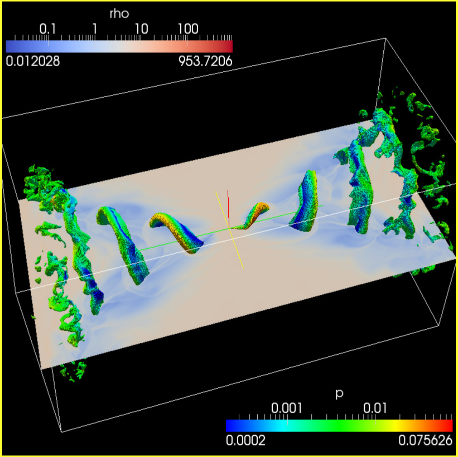
- Radio maps produced, match with observed VLA maps (Monceau-Baroux et al, submitted)

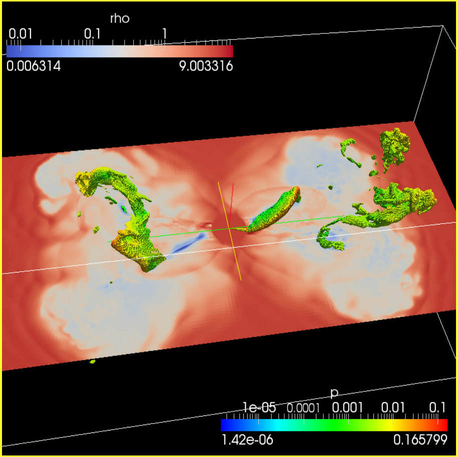
- at canonical 0.26c speed, radio map comparison
  - ⇒ Left: VLA observation (with helix from kinematic model)
  - ⇒ Right: virtual map, sub-parsec scale (source added)



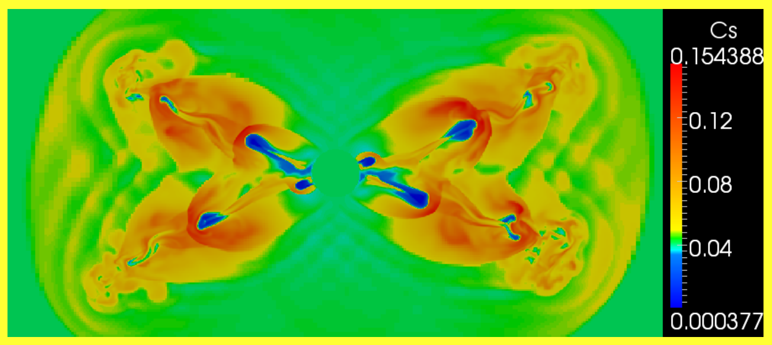


varying the precession angle 20° to 10°...

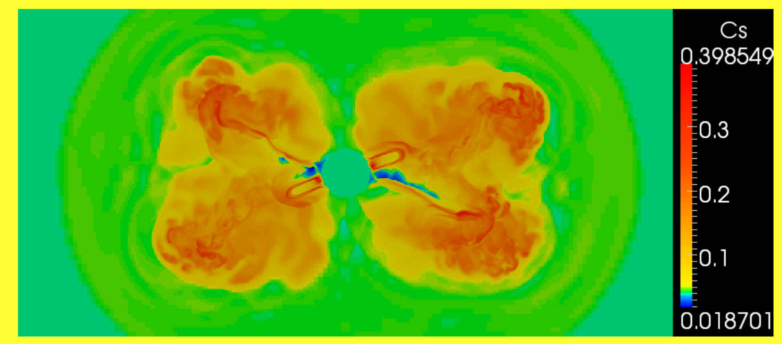




varying the speed form 0.26c to 0.845c . . .



varying the speed **form 0.26c** . . . : over- to underdense, latter first inflates bubble, effective slow-down!



varying the speed **to 0.845c**. . . : over- to underdense, latter first inflates bubble, effective slow-down!

Outlook

- from 2.5D axisymmetric (M)HD to 3D scenarios

  ⇒ can investigate full morphology, stability aspects, mixing
- recent studies explore 3D precessing jet scenarios

  ⇒ synthetic radio views, mimic SS433 conditions
- relativistic MHD runs provide all info for future synthetic polarization views

  ⇒ scale-encompassing studies **must couple launch to far-field feedback aspects**

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