Radio galaxies in clusters – cosmic weather stations or novel probes of cluster physics?

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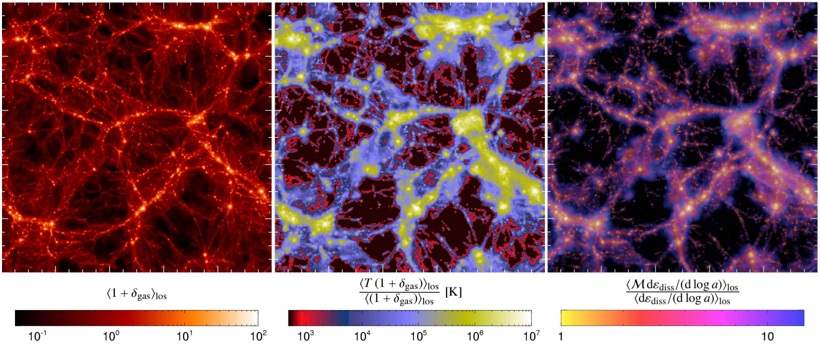
Outline

1. Radio Galaxies in Clusters
   - Introduction
   - A puzzling radio galaxy
   - Bubble-shock interaction
2. Probing accretion shocks
   - Perseus accretion shock
   - Vision and Speculations
   - Conclusions

The structure of our Universe – a “cosmic web”

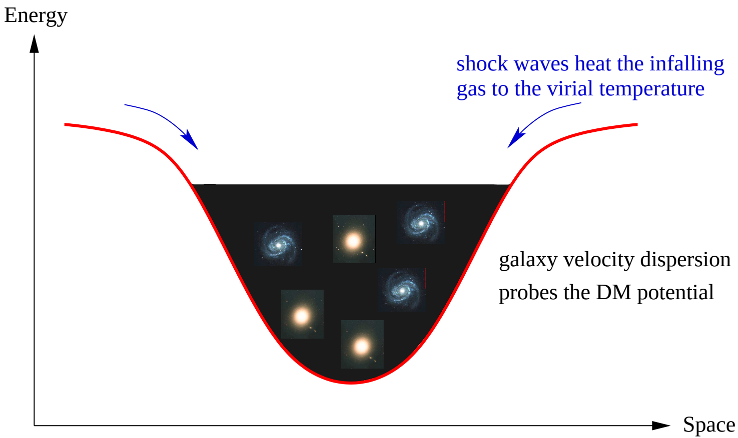


Left: projected gas density in a cosmological simulation ($L = 100\,h^{-1}$ Mpc, $z = 0$).
Middle: gas temperature of the gravitationally heated intergalactic medium.
Right: structure formation shocks, color coded by Mach number.

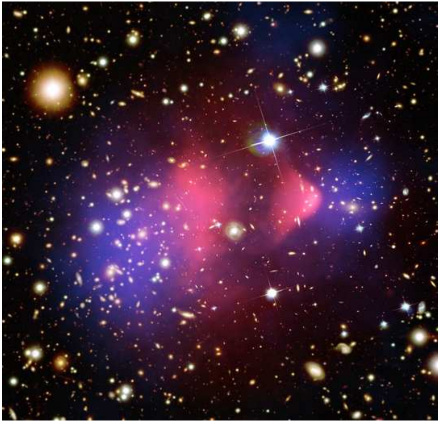
(C.P. et al. 2006)

A theorist's perspective of a galaxy cluster . . .

Galaxy clusters are dynamically evolving dark matter potential wells:

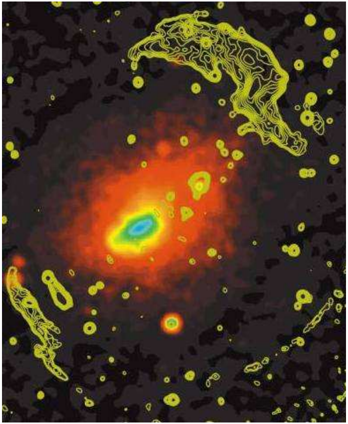


. . . and how the observer's Universe looks like



1E 0657-56 ("Bullet cluster")

(X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.)



Abell 3667

(radio: Johnston-Hollitt. X-ray: ROSAT/PSPC.)

Wish list for shocks

What we would like to measure and hope to infer:

- jump conditions: shock strength
- upstream properties: infalling warm-hot intergalactic medium
- post- and pre-shock conditions: geometry, obliquity
- shock curvature: vorticity and B field generation
- post-shock turbulence: power spectrum, non-thermal pressure support
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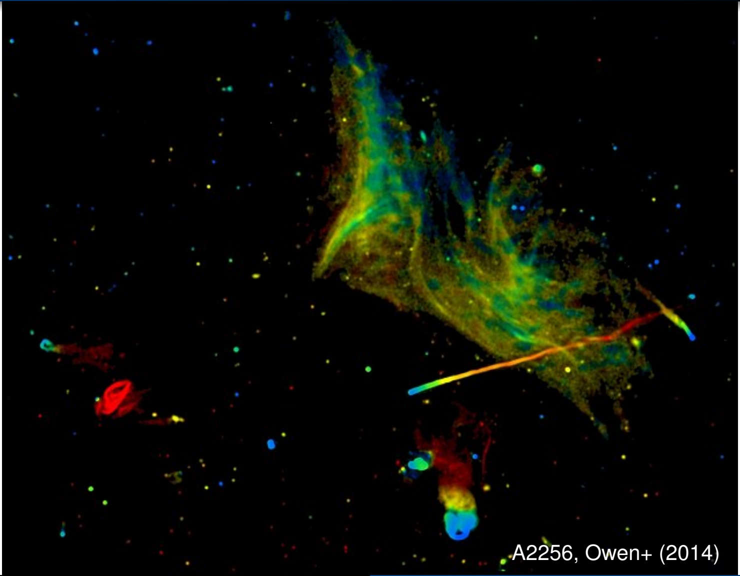
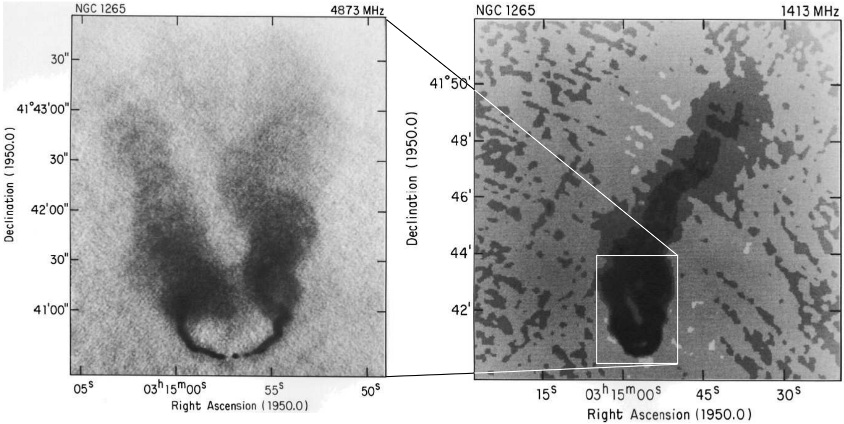
X-rays give limited insight → new complementary tools!

Radio galaxies in merging clusters



Total synchrotron intensity of NGC 1265

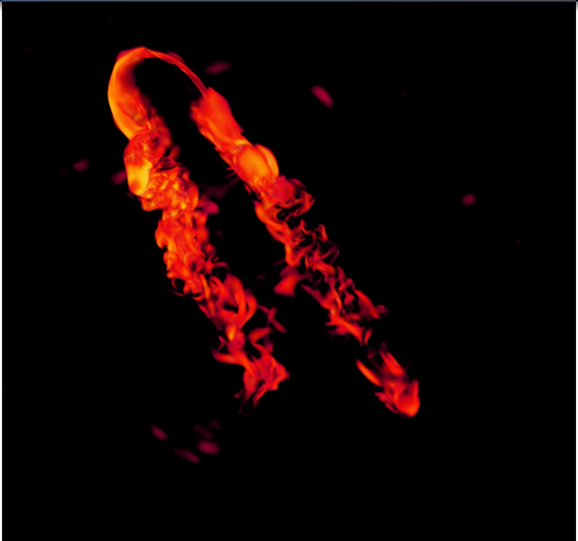


NGC 1265 – a radio galaxy in the Perseus cluster at 4.9 GHz *(left)* and 1.4 GHz *(right)*

O'Dea & Owen (1986)

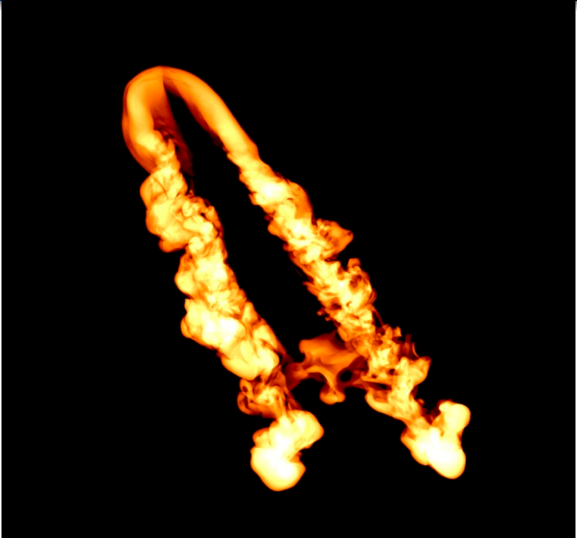
HITS

Bipolar AGN jets in an ICM wind: magnetic field



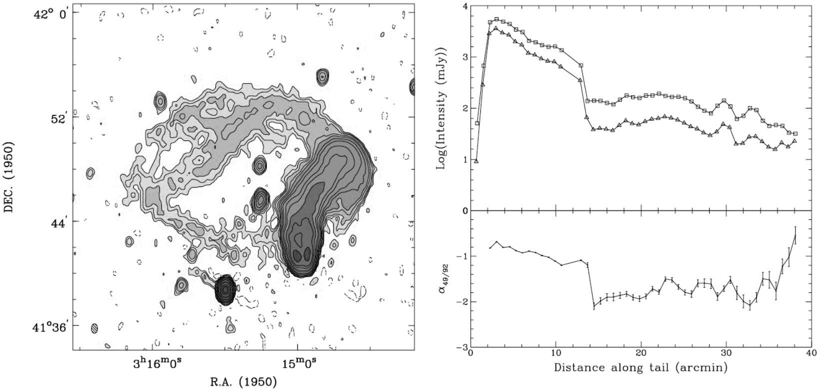
credit: Porter, Mendygral & Jones

Bipolar AGN jets in an ICM wind: synthetic radio



credit: Porter, Mendygral & Jones

Radio properties of NGC 1265



Sijbring & de Bruyn (1998): *left:* radio intensity $I_{600\,\mathrm{MHz}}$; *right:* variations of $I_{600\,\mathrm{MHz}}$ *(triangles)*, $I_{150\,\mathrm{MHz}}$ *(squares)* and spectral index *(bottom)* along the tail

Previous models of NGC 1265 and why they fail

1. chance superposition of several independent head-tail galaxies
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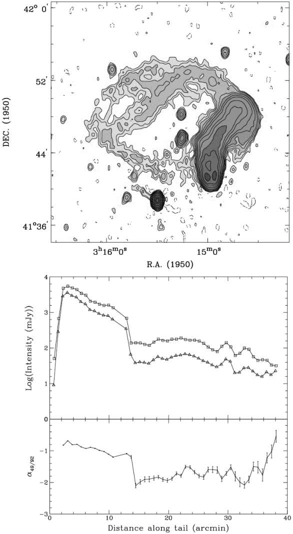
4. 'radio tail' outlines ballistic orbit of NGC 1265
   → *requires dark object with* $M \gtrsim M_{\mathrm{NGC\ 1265}} \simeq 3 \times 10^{12} M_\odot$ *orbiting the galaxy, no explanation of change of orbit and same challenges regarding electron cooling and re-acceleration*

Requirements for any model of NGC 1265

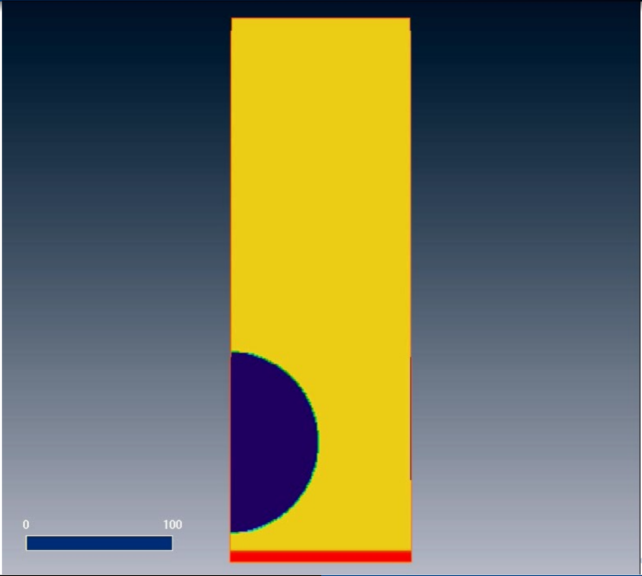


- bright narrow angle tail radio jet: synchrotron cooling
- transition region: change of winding direction and sharp drop in S_ν and α
- coherent properties along the dim radio ring, confined morphology

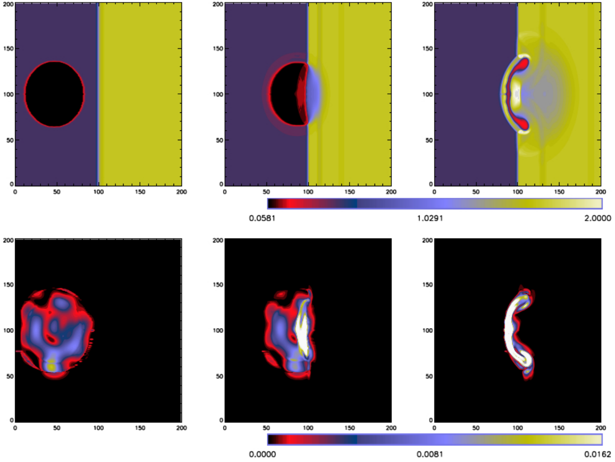
$\rightarrow$ *we are looking at 2 electron populations in projection possibly suggesting 2 different epochs of feedback:*

$\rightarrow$ active jet + detached radio bubble that recently got energized coherently across 300 kpc $\rightarrow$ shock?

Shock overruns an aged radio bubble (C.P. & Jones 2011)

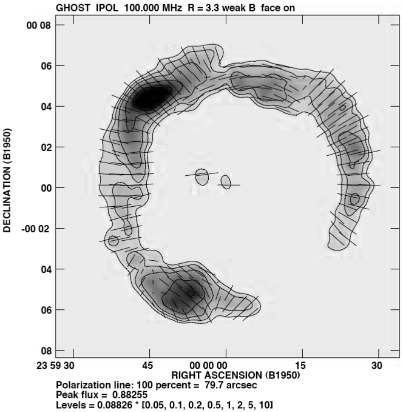


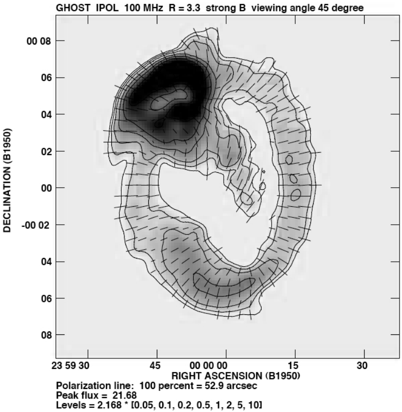
Bubble transformation to vortex ring



Enßlin & Brüggen (2002): gas density *(top)* and magnetic energy density *(bottom)*

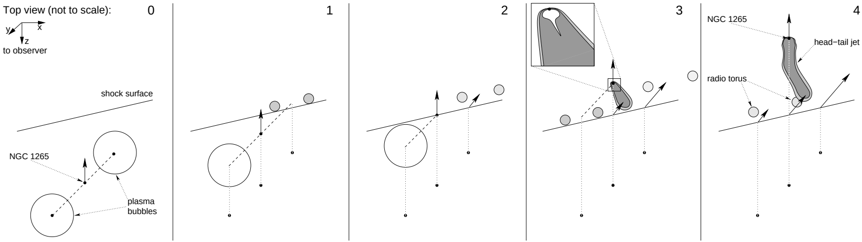
Synthetic radio emission of shock-transformed bubble





Enßlin & Brüggen (2002): total 100 MHz intensity and polarization E-vectors, strong shock/weak *B* *(left)* and strong shock/strong *B* model *(right)*

Cartoon of the time evolution of NGC 1265

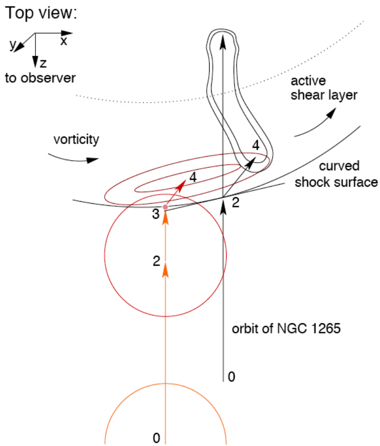


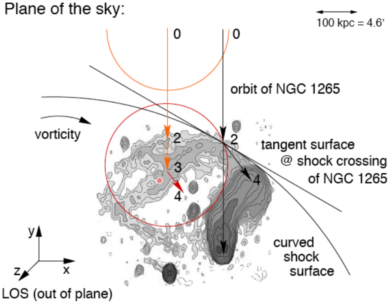
C.P. & Jones (2011)

NGC 1265 as a perfect probe of a shock

- **idea:**
  - galaxy velocity not affected by shock
    $\rightarrow$ pre-shock conditions
  - tail & torus as tracers of the post-shock flow
- **assumptions:**
  - shock surface $\|$ gravitational equipotential surface of Perseus
  - recent jet launched shortly after shock crossing
- **method:**
  - extrapolating position and velocity back in time
  - employing conservation laws at oblique shock
  - iterate until convergence

Derived geometry for NGC 1265

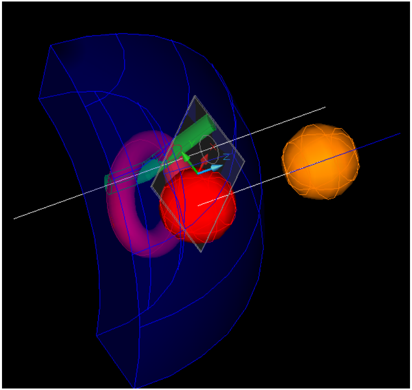




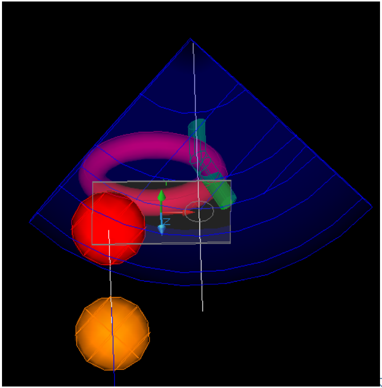
C.P. & Jones (2011)

A 3D model for NGC 1265

3D model:



top view:



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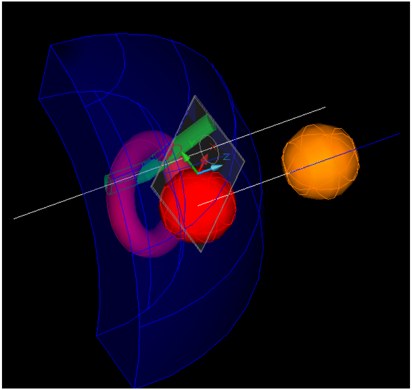
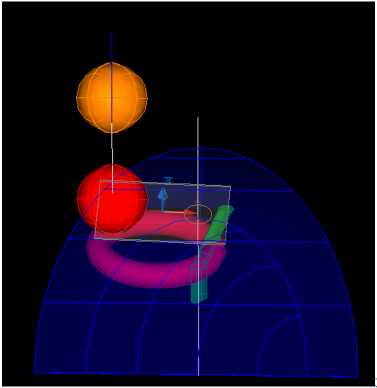


observer's view:



Shock strength and jump conditions

- shock compresses relativistic bubble adiabatically: $P_2/P_1 = C^{4/3}$
- bubble compression factor:

$$C = \frac{V_{\text{bubble}}}{V_{\text{torus}}} = \frac{\frac{4}{3}\pi R^3}{2\pi^2 R r_{\text{min}}^2} = \frac{2}{3\pi}\left(\frac{R}{r_{\text{min}}}\right)^2 \simeq 10$$

- assuming pressure equilibrium → shock jumps:

$$\frac{P_2}{P_1} \simeq 21.5, \quad \frac{\rho_2}{\rho_1} \simeq 3.4, \quad \frac{T_2}{T_1} \simeq 6.3, \quad \text{and } \mathcal{M} \simeq 4.2$$

C.P. & Jones (2011)

Perseus accretion shock and WHIM properties

- jet has low Faraday RM → NGC 1265 on near side of Perseus
  NGC 1265 redshifted w/r to Perseus → infalling system
  → shock likely the accretion shock
- extrapolating X-ray n- and T-profiles to R_{200} & shock jumps:
  → upper limits on infalling warm-hot intergalactic medium

$$\begin{aligned} kT_1 &\lesssim 0.4\,\mathrm{keV} \\ n_1 &\lesssim 5\times10^{-5}\,\mathrm{cm}^{-3} \\ P_1 &\lesssim 3.6\times10^{-14}\,\mathrm{erg\,cm}^{-3} \end{aligned}$$

C.P. & Jones (2011)

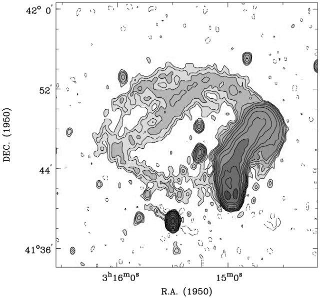
Shear flows and shock curvature

- ellipticity of radio torus (magnitude and orientation) & bending direction of tail
  $\rightarrow$ excludes projection effects
  $\rightarrow$ evidence for post-shock shear flow
- shock curvature injects vorticity that shears the gas westwards:

$$\frac{\varepsilon_{\mathrm{shear}}}{\varepsilon_{\mathrm{th,2}}} = \frac{\mu m_{\mathrm{p}} v_\perp^2}{3kT_2} \simeq 0.14,$$

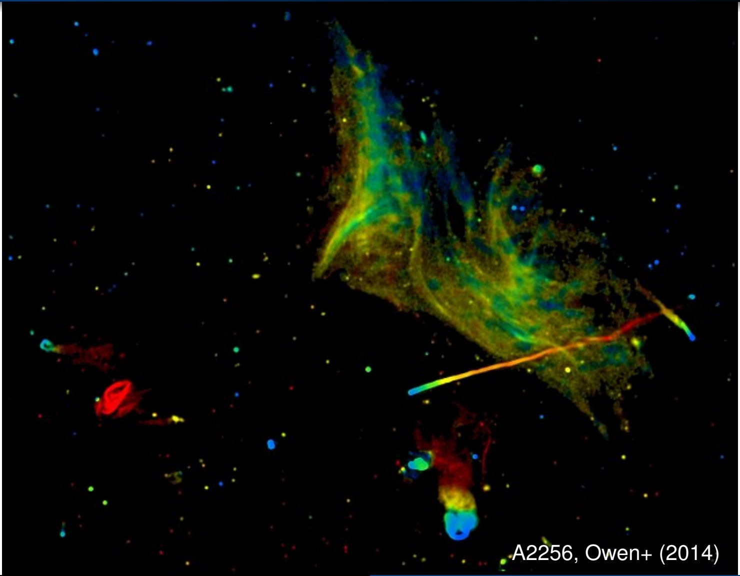
with $kT_2 \simeq 2.4\,\mathrm{keV}$ and $v_\perp \simeq 400\,\mathrm{km/s}$

C.P. & Jones (2011)

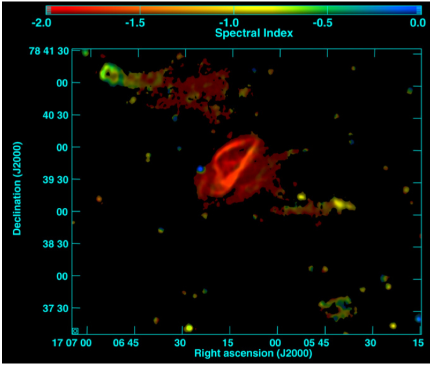


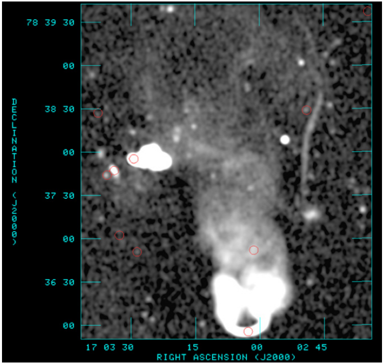
Sijbring & de Bruyn (1998)

Vision and Speculations



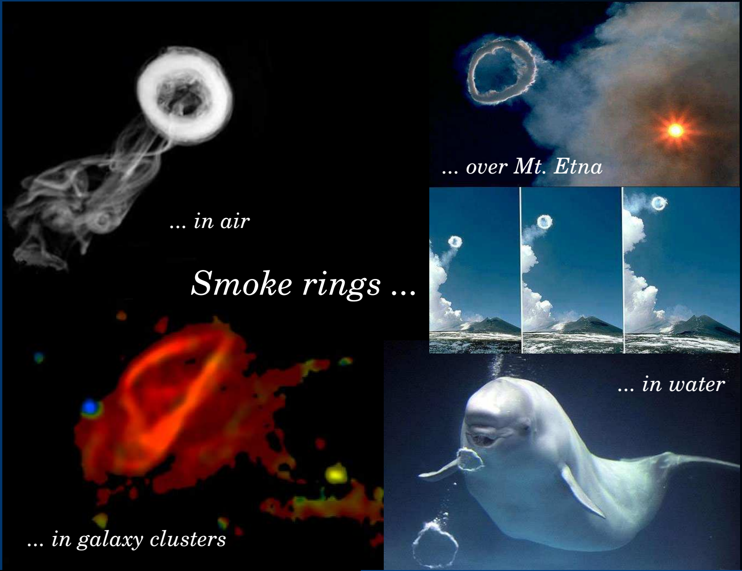
Radio vortex rings in A2256





A2256, Owen+ (2014)

The Universe is full of . . .



Conclusions on radio galaxies as probes of shocks

- consistent 3D model of NGC 1265
- prediction of a very interesting source class for LOFAR/SKA
- radio galaxies as perfect probes of pre- and post-shock flows:
  - hydrodynamic jumps and Mach numbers
  - statistical properties of the infalling WHIM (+ X-rays)
  - estimating the curvature radius of shocks and induced shear flows

→ implications for intra-cluster turbulence as well as generation and amplification of large-scale magnetic fields!

Literature for the talk

- Pfrommer & Jones, 2011, ApJ, 730, 22,
  Radio Galaxy NGC 1265 unveils the Accretion Shock onto the Perseus Galaxy Cluster