Large-scale shocks and extragalactic cosmic rays

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in collaboration with

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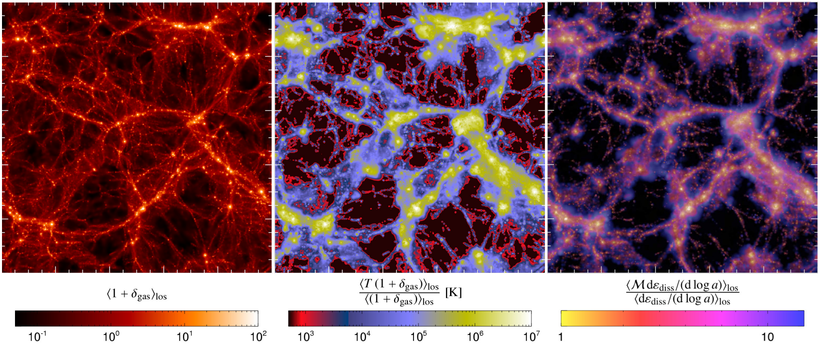
Outline

1. Cosmological simulations
   - Introduction
   - Physics in simulations
   - Cosmic rays in galaxy clusters
2. Cosmic-ray signatures
   - Multi messenger approach
   - Radio emission
   - Gamma rays
3. Large-scale shocks
   - Radio galaxies in clusters
   - Probing accretion shocks
   - Vision and Speculations

The structure of our Universe – a “cosmic web”

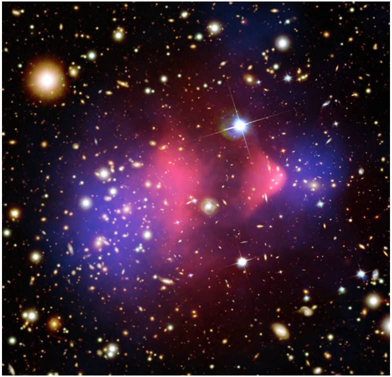


Left: projected gas density in a cosmological simulation ($L = 100\,h^{-1}$ Mpc, $z = 0$).
Middle: gas temperature of the gravitationally heated intergalactic medium.
Right: structure formation shocks, color coded by Mach number.

(C.P. et al. 2006)

Galaxy cluster evolution

- cluster mergers are the most energetic events in the Universe (after the Big Bang)
  $\rightarrow$ shocks and turbulence

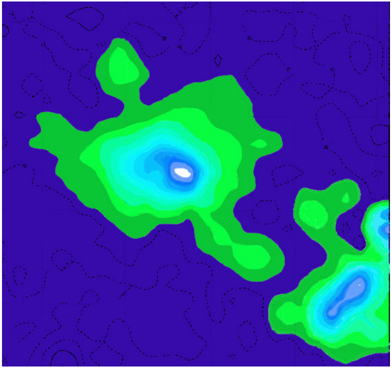


'Bullet cluster'

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

Galaxy cluster evolution

- cluster mergers are the most energetic events in the Universe (after the Big Bang)
  $\rightarrow$ shocks and turbulence
- accompanied by enigmatic cluster radio halos and relics
  $\rightarrow$ existence of relativistic electrons and magnetic fields

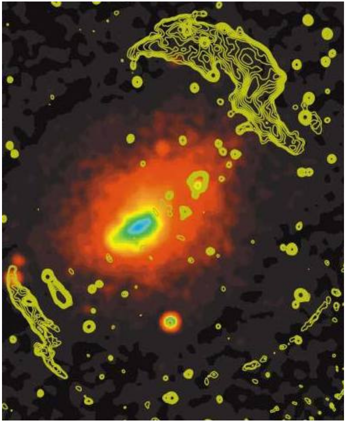


giant radio halo and relic in Coma

Effelsberg/Deiss

Galaxy cluster evolution

- cluster mergers are the most energetic events in the Universe (after the Big Bang)
  $\rightarrow$ shocks and turbulence
- accompanied by enigmatic cluster radio halos and relics
  $\rightarrow$ existence of relativistic electrons and magnetic fields
- laboratories for cluster formation and high-energy astrophysics:
  $\rightarrow$ particle acceleration and cosmic magnetism

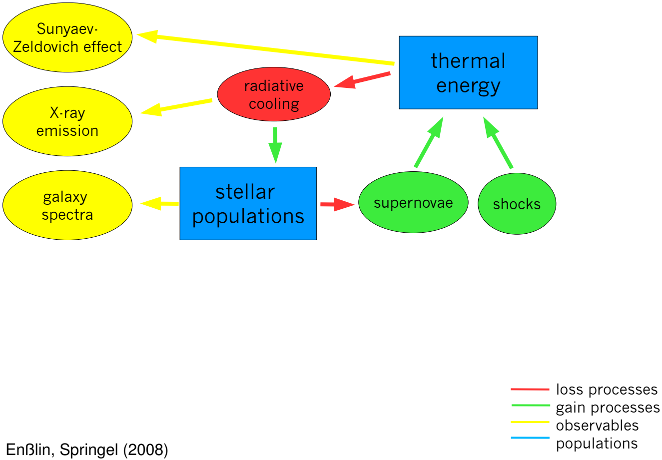


giant radio relic in Abell 3667

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

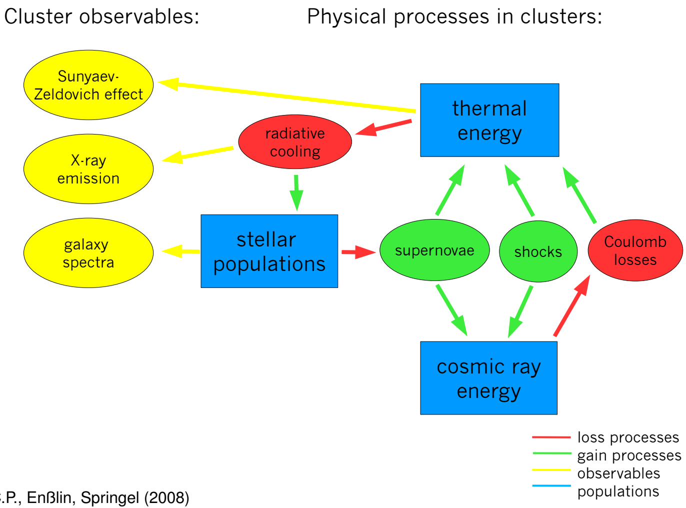
Cosmological simulations – flowchart

Cluster observables: Physical processes in clusters:



C.P., Enßlin, Springel (2008)

Cosmological simulations with cosmic ray physics



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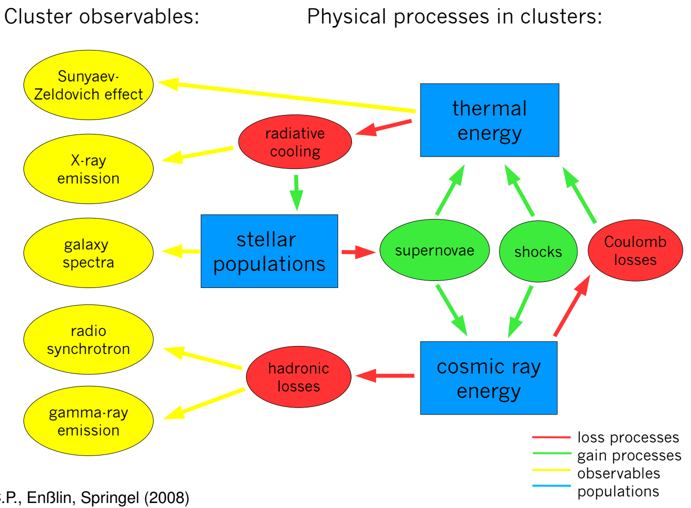
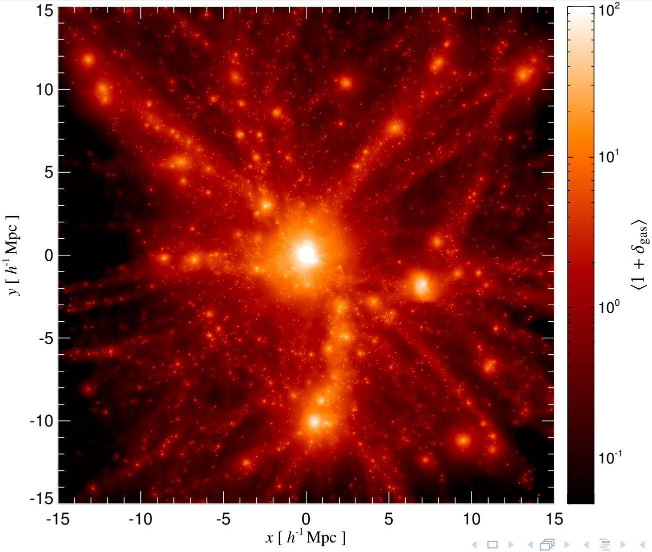


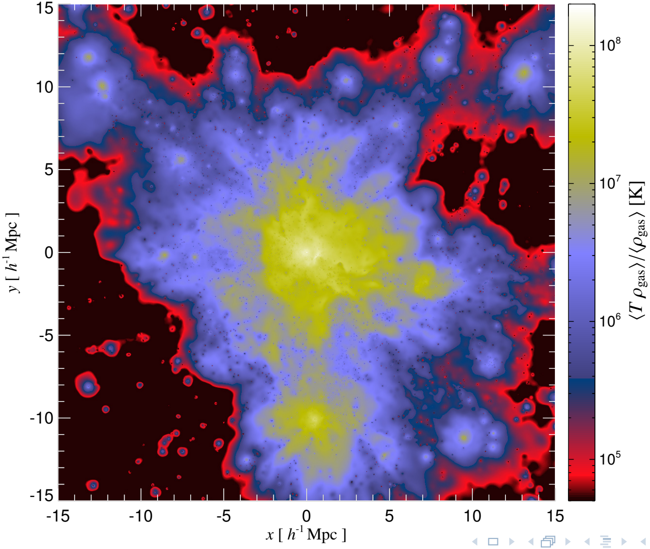
C.P., Enßlin, Springel (2008)

Cosmological cluster simulation: gas density

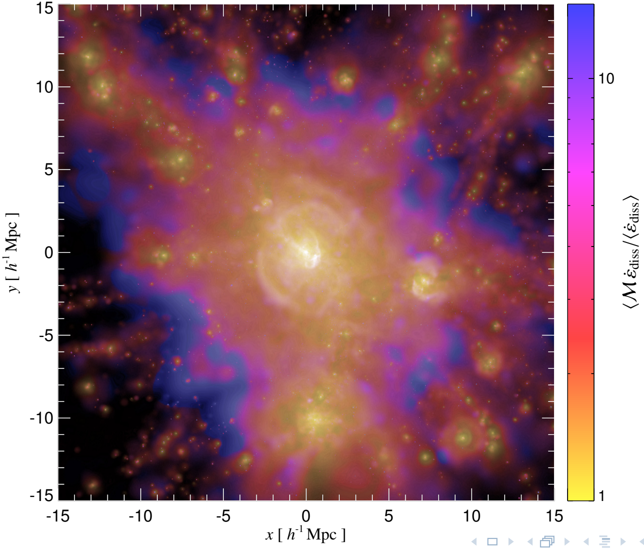


HITS

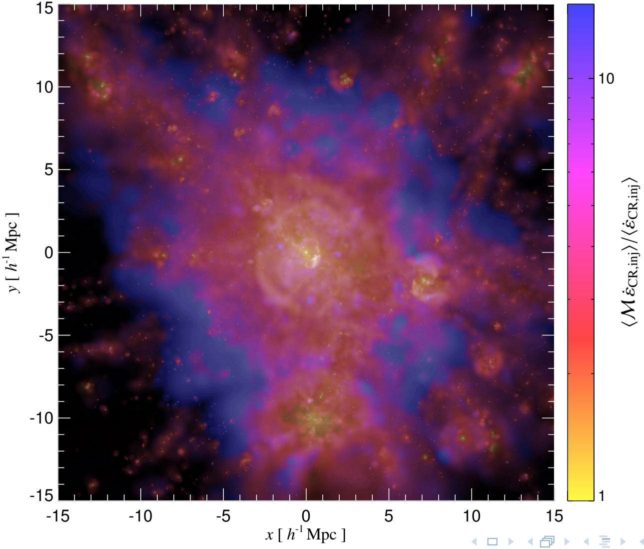
Mass weighted temperature



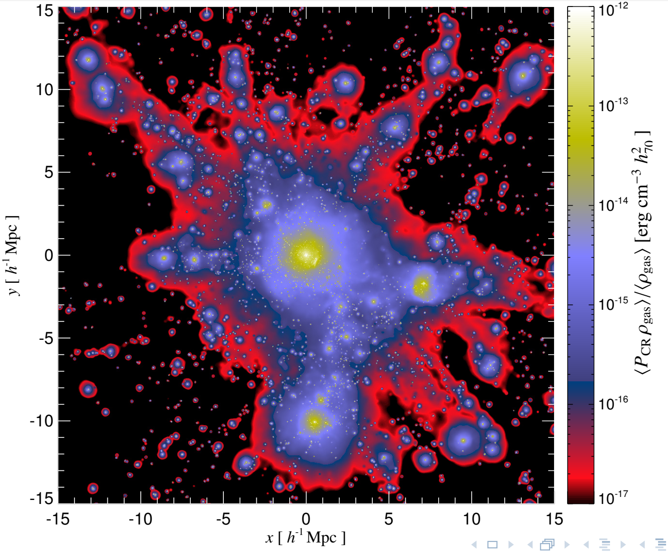
Shock strengths weighted by dissipated energy



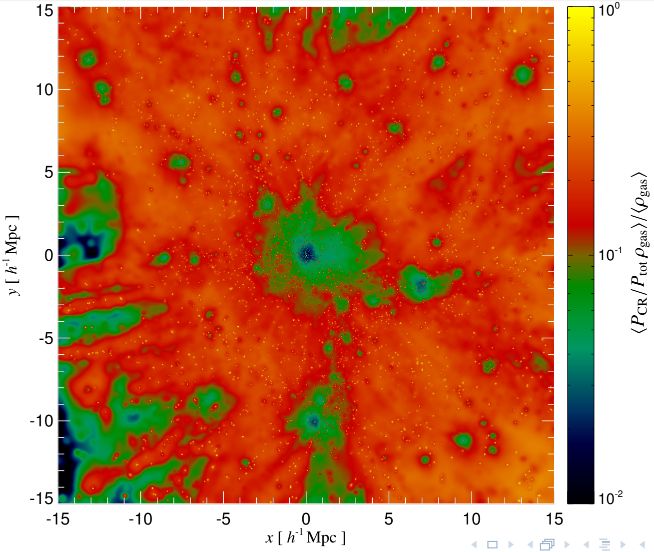
Shock strengths weighted by injected CR energy



Evolved CR pressure

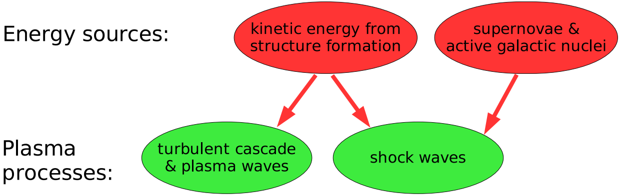


Relative CR pressure $P_{\mathrm{CR}}/P_{\mathrm{total}}$



Multi messenger approach for non-thermal processes

Relativistic populations and radiative processes in clusters:



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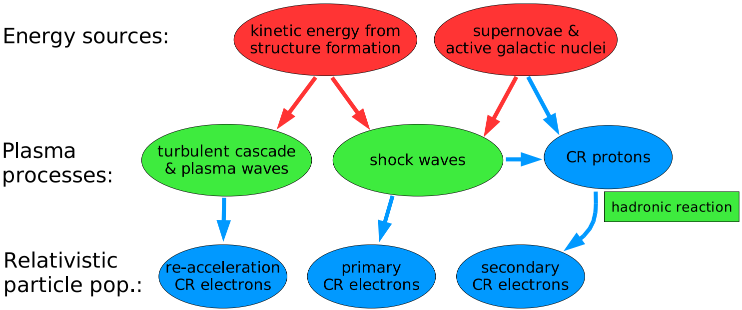

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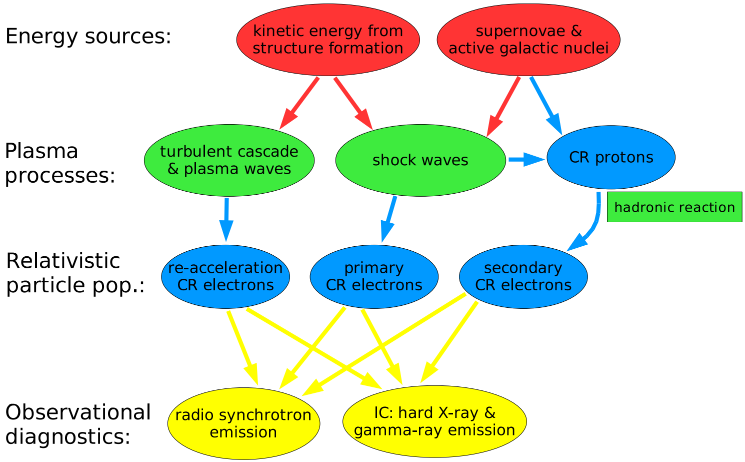

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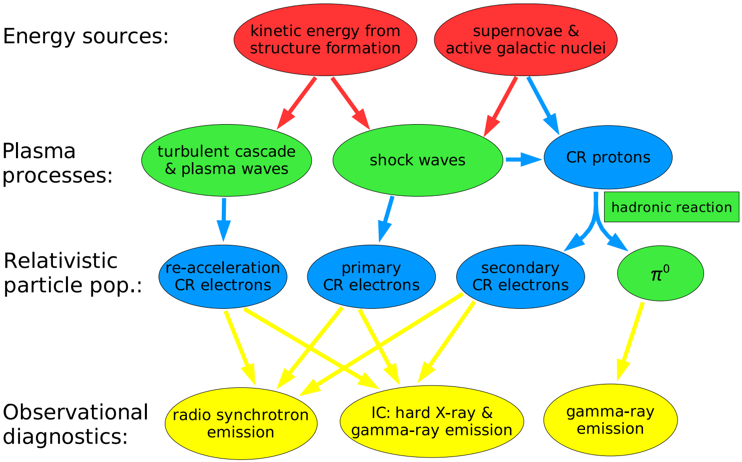
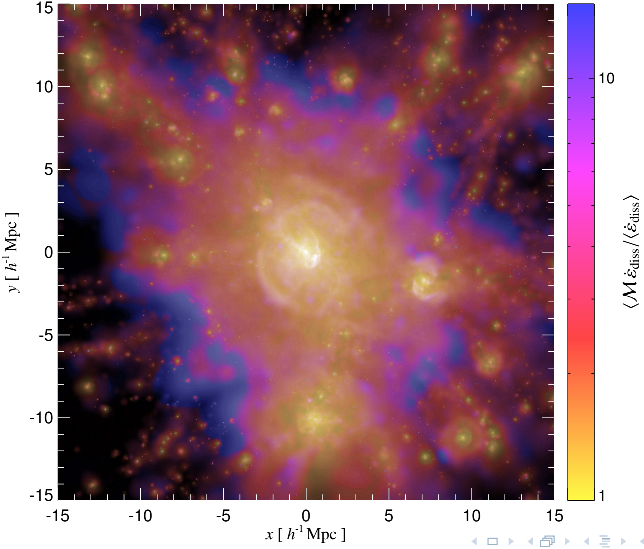
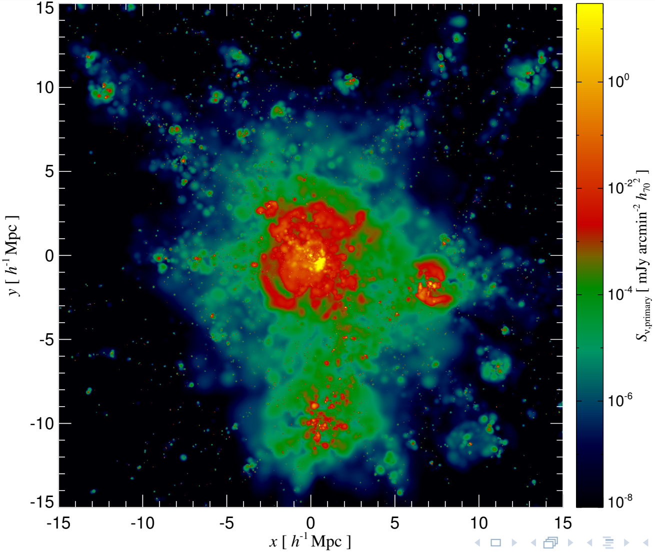


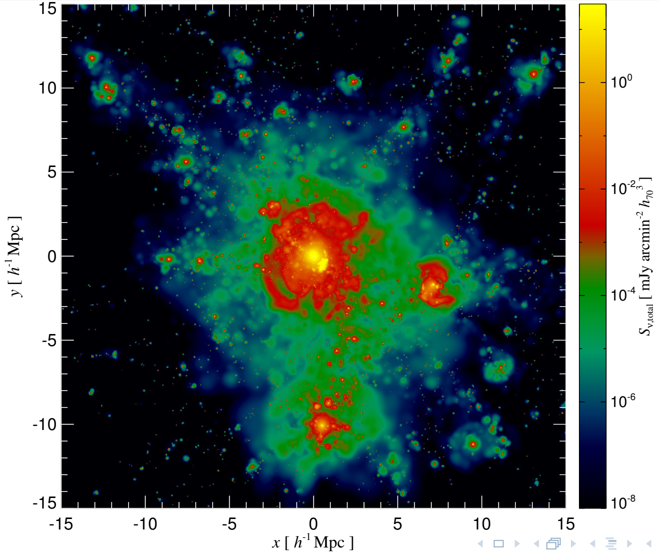
Structure formation shocks



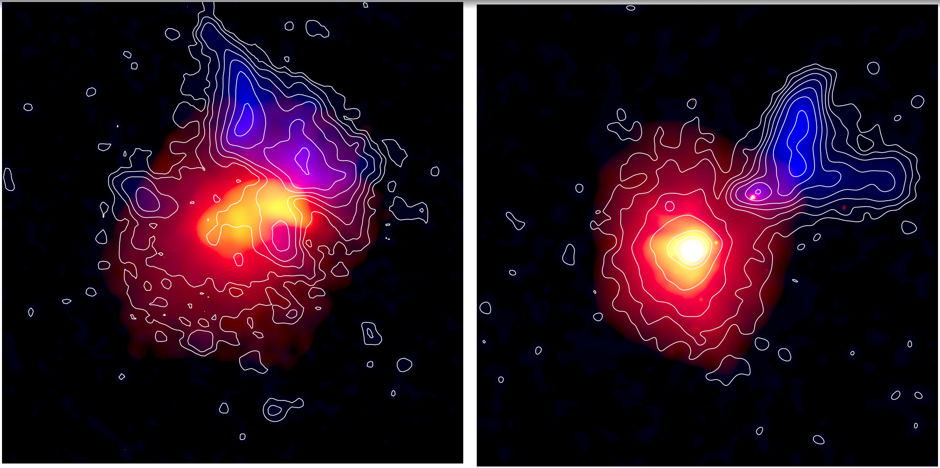
Radio gischt: shock-accelerated CRe



Radio gischt + central hadronic halo = giant radio halo

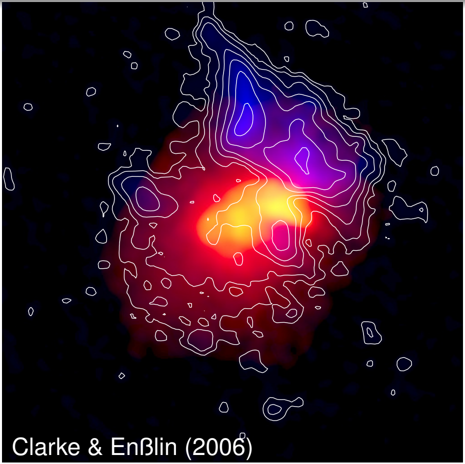


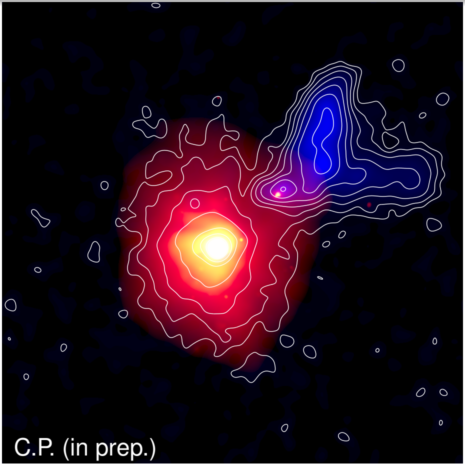
Which one is the simulation/observation of A2256?



red/yellow: thermal X-ray emission,
blue/contours: 1.4 GHz radio emission with giant radio halo and relic

Observation – simulation of A2256





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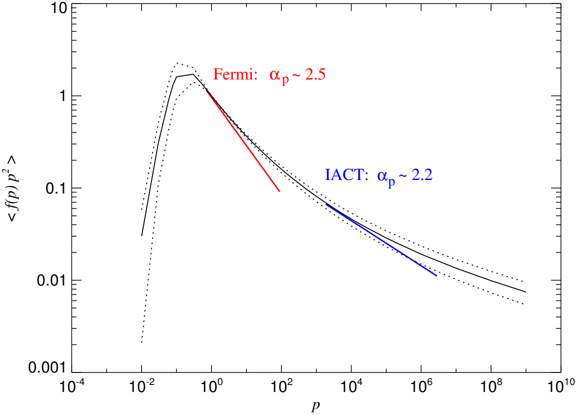
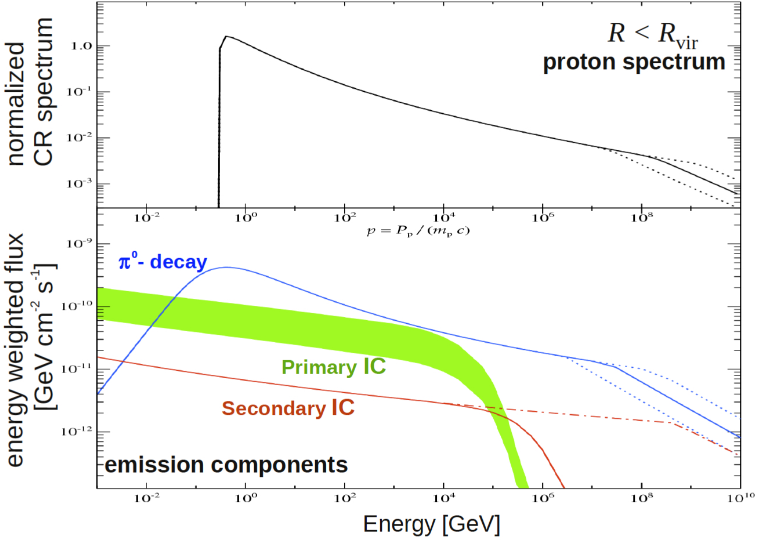
Universal CR spectrum in clusters (Pinzke & C.P. 2010)



Normalized CR spectrum shows universal concave shape $\rightarrow$ governed by hierarchical structure formation and the implied distribution of Mach numbers that a fluid element had to pass through in cosmic history.

CR proton and γ-ray spectra (Pinzke & C.P. 2010)



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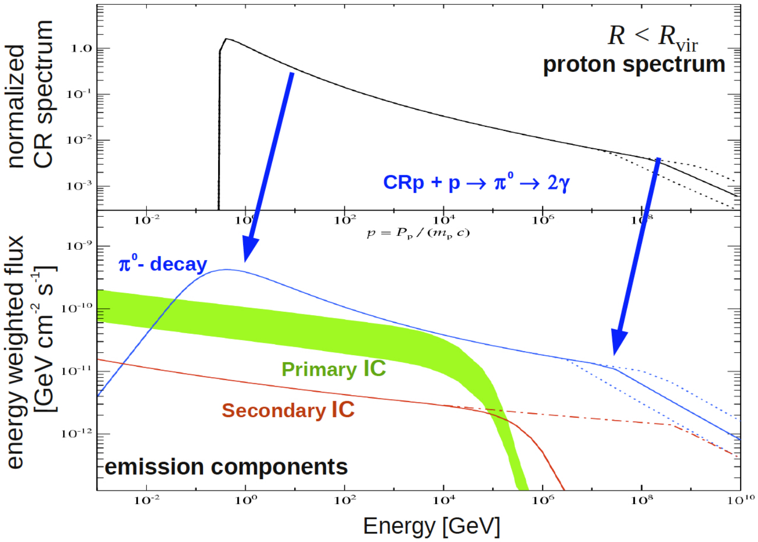

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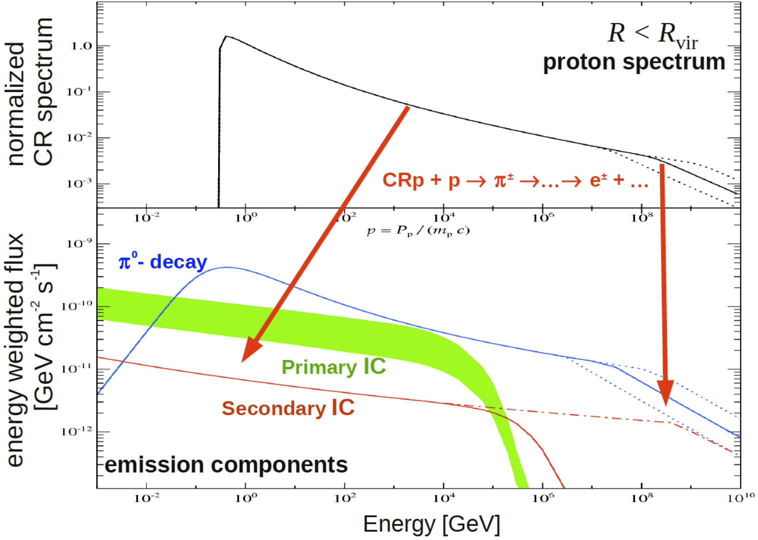
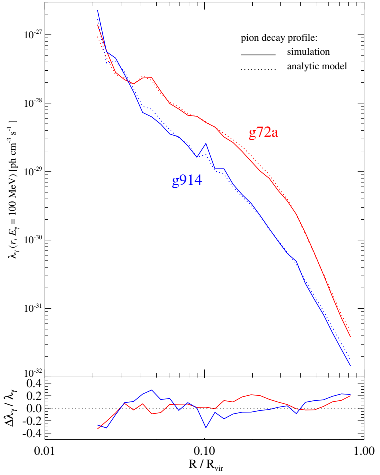
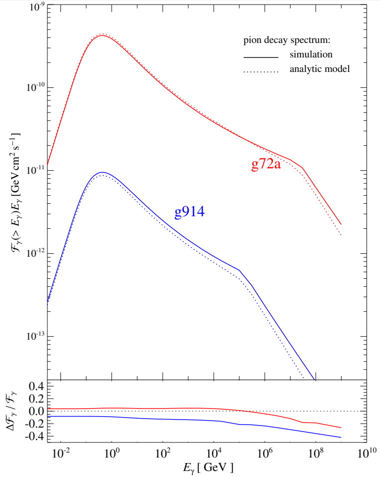


An analytic model for the cluster γ-ray emission

Comparison: simulation vs. analytic model, $M_{\rm vir} \simeq (10^{14}, 10^{15})\,M_\odot$



Spatial γ-ray emission profile



Pion decay spectrum

Constraining CR physics with γ-ray observations

- non-detections constrain $P_{\rm CR}/P_{\rm th} < 1.7\%$ in Coma and Perseus and to $\lesssim 1\%$ in a stacked sample of 50 *Fermi* clusters
- constrains maximum shock acceleration efficiency to $< 50\%$
- hydrostatic cluster masses not significantly biased by CRs: important for cluster cosmology!

Conclusions on non-thermal signatures in clusters

Exploring the memory of structure formation

- primary, shock-accelerated CR electrons resemble current accretion and merging shock waves
- CR protons/hadronically produced CR electrons trace the time integrated non-equilibrium activities of clusters that is modulated by the recent dynamical activities
- *Fermi*, MAGIC, VERITAS non-detections of γ rays from clusters start to limit CR acceleration efficiencies to $< 50\%$ (or tell us about CR transport processes)

$\rightarrow$ Multi-messenger approach from the radio to γ-ray regime!

Large-scale 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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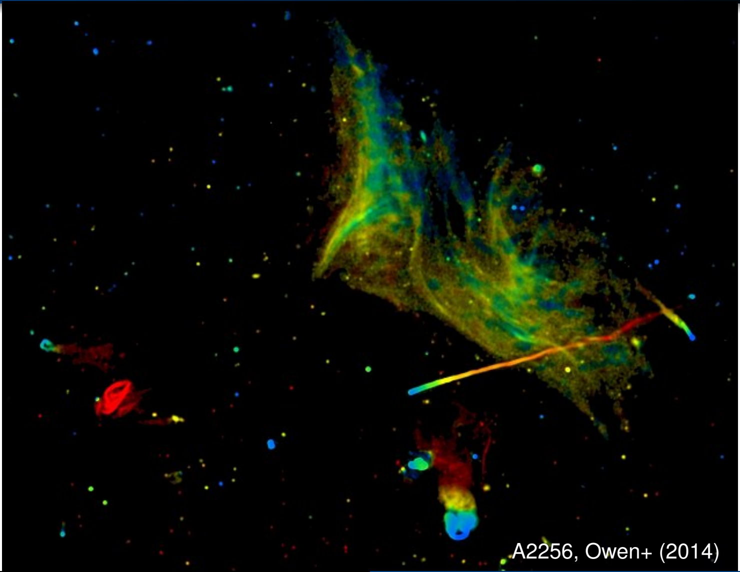
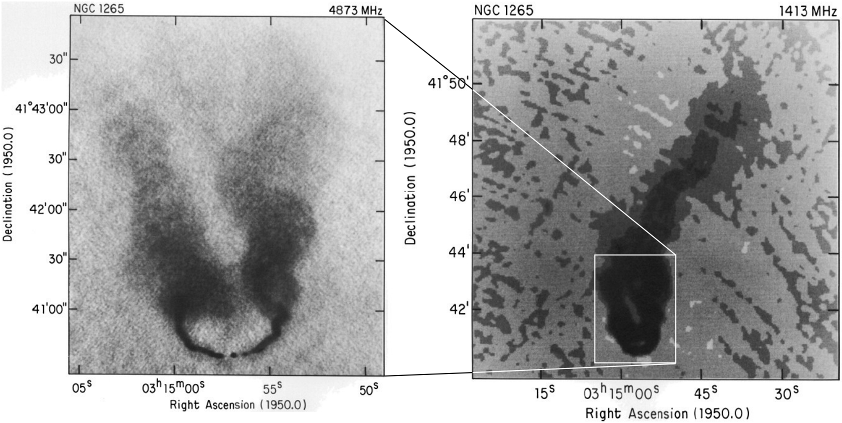
X-rays give limited insight → new complementary tools!

Radio galaxies in merging clusters

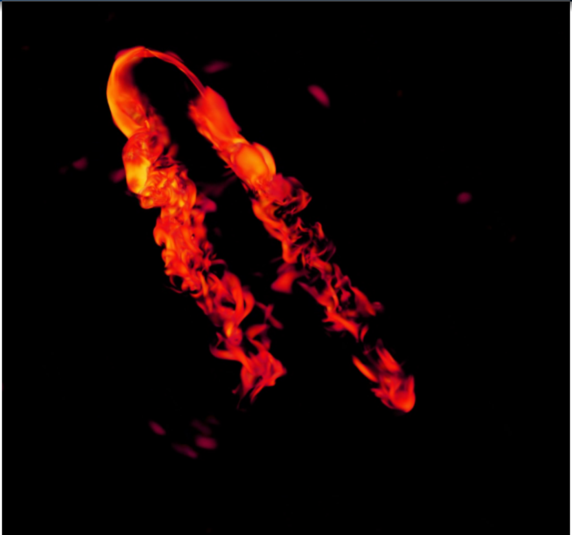


Total synchrotron intensity of NGC 1265



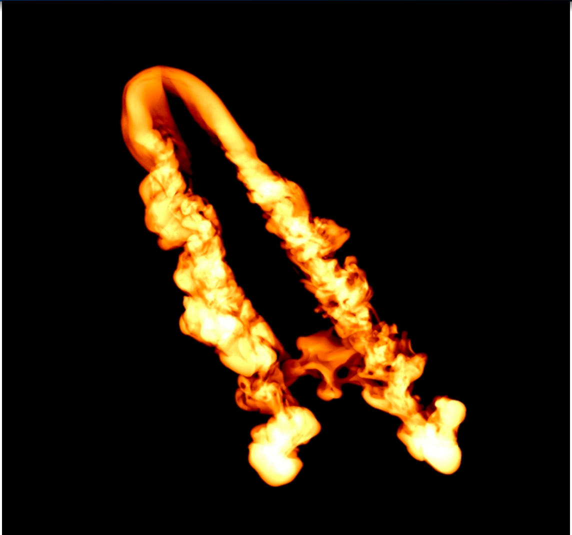
NGC 1265 – a radio galaxy in the Perseus cluster at 4.9 GHz *(left)* and 1.4 GHz *(right)*
O'Dea & Owen (1986)

Bipolar AGN jets in an ICM wind: magnetic field



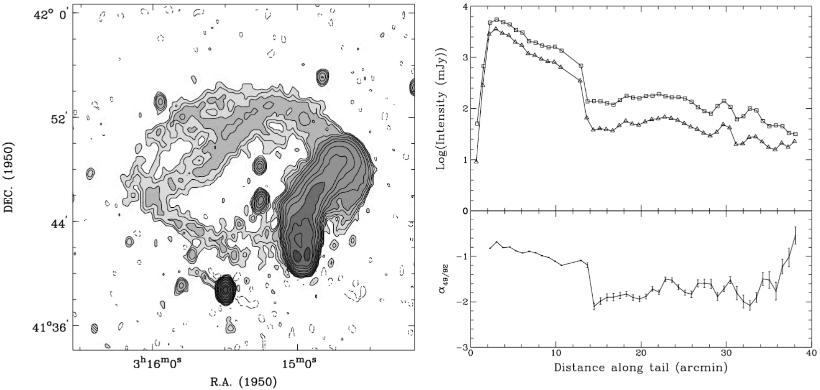
credit: Porter, Mendygral & Jones

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
   $\rightarrow$ *lack of observed strong radio sources in this field*

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HITS

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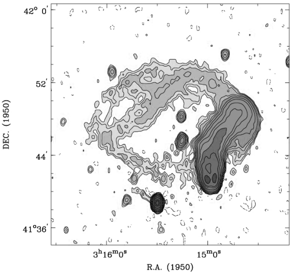
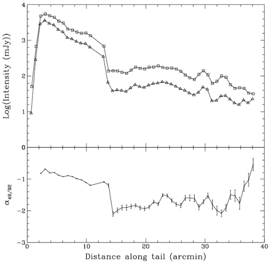
4. ‘radio tail’ outlines ballistic orbit of NGC 1265
   $\rightarrow$ *requires dark object with* $M \gtrsim M_{\mathrm{NGC\ 1265}} \simeq 3 \times 10^{12} M_\odot$ *orbiting the galaxy, no explanation of change of orbit and same challenges regarding electron cooling and re-acceleration*

Requirements for any model of NGC 1265



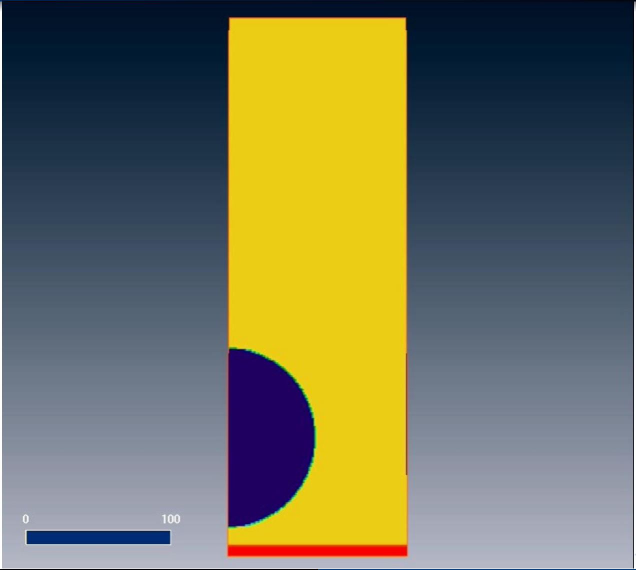


- bright narrow angle tail radio jet: synchrotron cooling
- transition region: change of winding direction and sharp drop in S_ν and α
- coherent properties along the dim radio ring, confined morphology

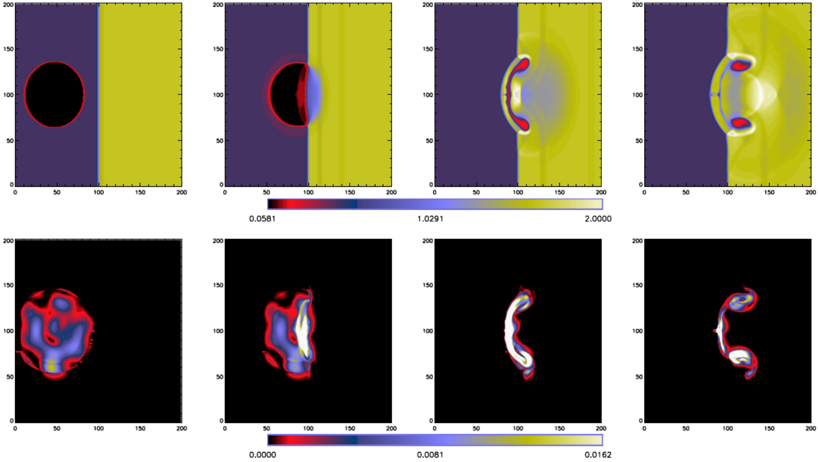
$\rightarrow$ *we are looking at 2 electron populations in projection possibly suggesting 2 different epochs of feedback:*

$\rightarrow$ 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)

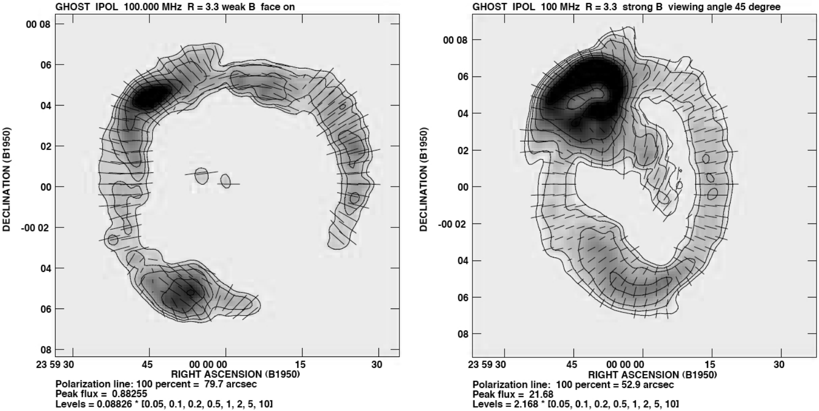


Bubble transformation to vortex ring



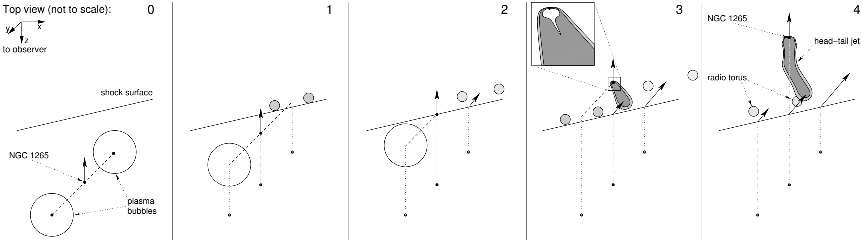
Enßlin & Brüggen (2002): gas density *(top)* and magnetic energy density *(bottom)*

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

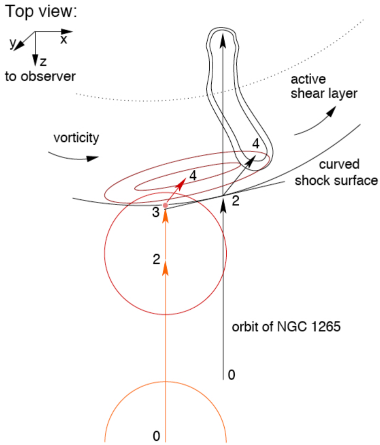


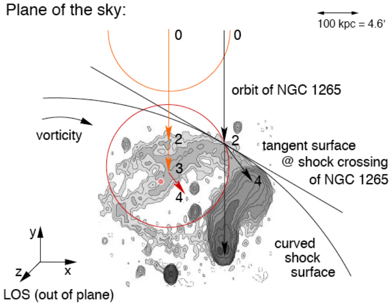
C.P. & Jones (2011)

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 $\parallel$ 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

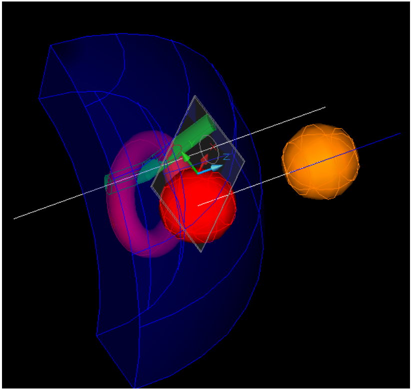




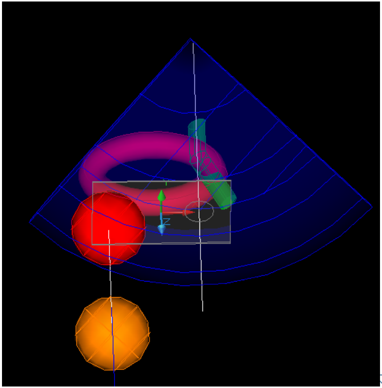
C.P. & Jones (2011)

A 3D model for NGC 1265

3D model:



top view:



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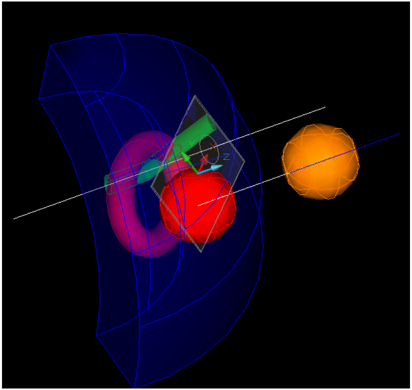
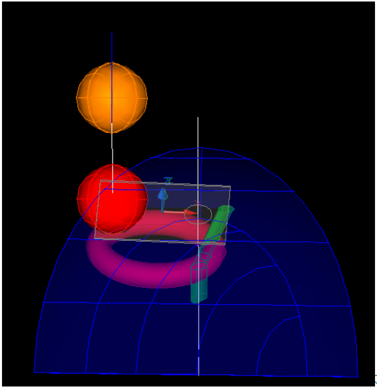


observer's view:



Shock strength and jump conditions

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

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

- assuming pressure equilibrium $\rightarrow$ 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 $\rightarrow$ NGC 1265 on near side of Perseus
  NGC 1265 redshifted w/r to Perseus $\rightarrow$ infalling system
  $\rightarrow$ shock likely the accretion shock
- extrapolating X-ray n- and T-profiles to R_{200} & shock jumps:
  $\rightarrow$ 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)

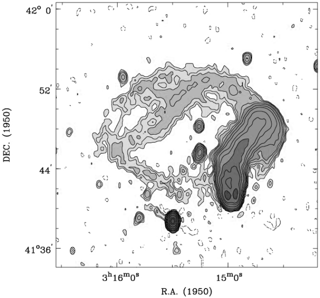
Shear flows and shock curvature

- 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:

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

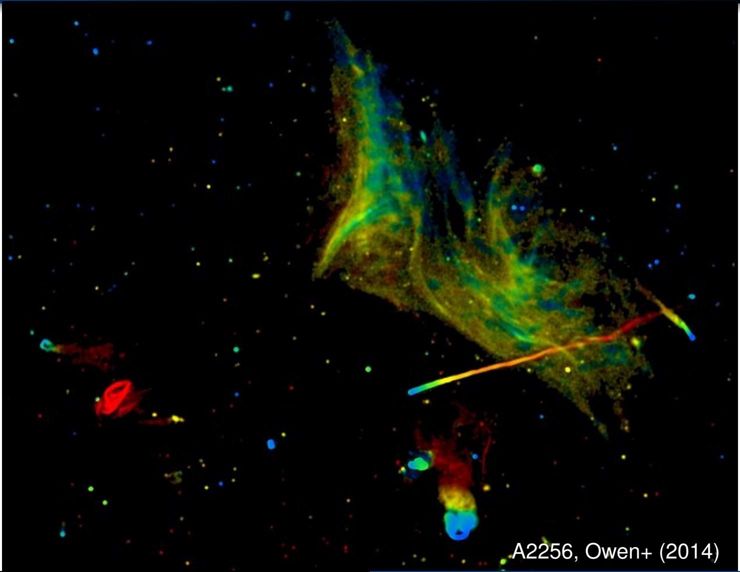
with $kT_2 \simeq 2.4\,\mathrm{keV}$ and $v_\perp \simeq 400\,\mathrm{km/s}$

C.P. & Jones (2011)

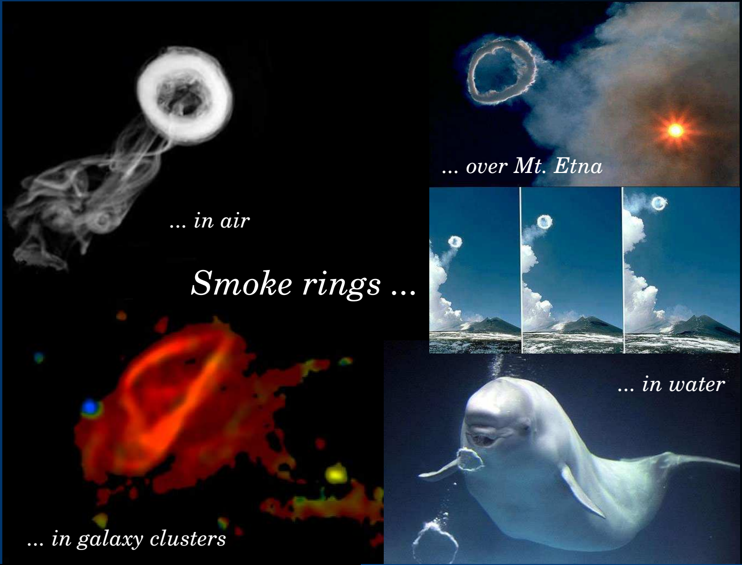


Sijbring & de Bruyn (1998)

Vision and Speculations



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

Cosmic rays in clusters:

- Pfrommer, Enßlin, Springel, Jubelgas, Dolag, *Simulating cosmic rays in clusters of galaxies – I. Effects on the Sunyaev-Zel'dovich effect and the X-ray emission*, 2007, *MNRAS*, 378, 385.
- Pfrommer, Enßlin, Springel, *Simulating cosmic rays in clusters of galaxies – II. A unified scheme for radio halos and relics with predictions of the γ-ray emission*, 2008, *MNRAS*, 385, 1211.
- Pinzke & Pfrommer, *Simulating the gamma-ray emission from galaxy clusters: a universal cosmic ray spectrum and spatial distribution*, 2010, *MNRAS*, 409, 449.

Large-scale shocks:

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