An SKA and uGMRT perspective of possible discovery of multiple shocks structures and filamentary inroads to massive galaxy clusters

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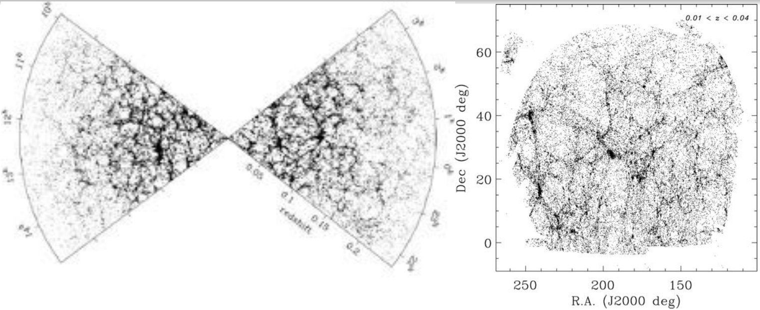
Plan of this talk

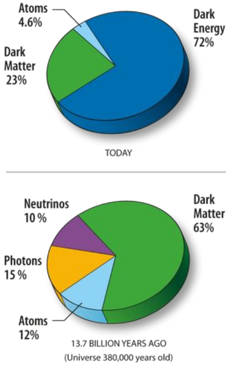
Cosmic web and the structures of the universe (SDSS view)

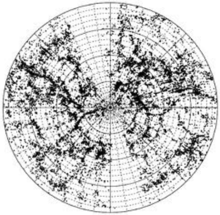


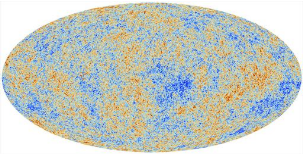
Panel 1: Distribution of Galaxies in RA vs Redshift plot as observed in 2dF survey. **Panel 2:** Galaxy distribution within a sky patch of 100° by 60° and redshift span of 0.01 to 0.04 as seen in SDSS, Blanton et al. (2005)

- Structures are scattered but in a pattern indicating presence of filamentary networks, galaxy groups within the filaments and nodes and higher concentration at the cross roads of filaments forms galaxy clusters
- Component of LSS are: (i) Galaxies (ii) Group of Galaxies (iii) Filaments (iv) Galaxy clusters and (v) Super Clusters

Composition of our universe







Left: Composition of our universe, then and now (Source: [NASA] www.map.gsfc.nasa.gov). **Right:** Above: 6dF image from Anglo Australian Telescope and below: CMB map taken from ESA webpage : http://spaceinimages.esa.int/. Mass fluctuation at the era of CMB was $\sim 10^{-5}$

Initial condition:

- Within isotropic and homogeneous background, cosmic-web structure grows via gravitational instability from the **initial density fluctuations**

Forces in action and physical laws:

- Gravitational pull
- Hubble expansion
- Hydrodynamics & thermodynamics

Effect:

- Matters from rarefied medium accrete to denser medium
- Galaxies and clusters of galaxies formed due to hierarchical clustering of matters
- gas dynamics, heating and cooling etc.

Analytically these structures can't be reproduced from the initial conditions. Its a many body problem and only numerical simulation of millions of particles can give us a broad picture.

So? How the universe can be reconstructed?

The most favourable cosmological model, the cold dark matter (CDM) can be described as a collisionless, non-relativistic fluid. We assumed the representative particle position at certain time t as $\mathbf{x}$ and the particle velocity as $\mathbf{v}$. The coupled equation is thus written as

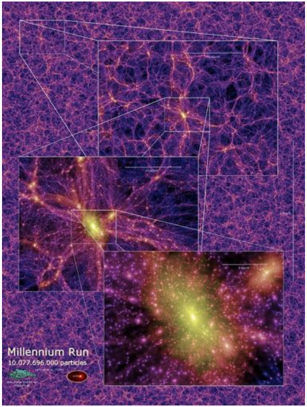
$$\frac{d\mathbf{x}}{dt} = \mathbf{v} \qquad \frac{d\mathbf{v}}{dt} = -\nabla\phi \tag{1}$$

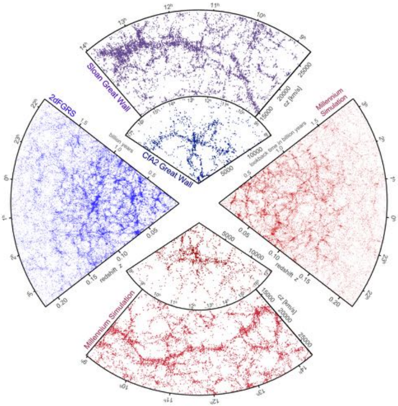
$-\nabla\phi$ describes the gravitational force term in the above equation. A solution to these equations can be found by solving the elliptic Poisson's equation.

$$\nabla^2\phi = 4\pi\rho G \tag{2}$$

where ρ is the density of the dark matter.

Millennium simulation a Dark Matter only universe





Discovery of a unique and spectacular radio ring-like structure around the cluster Abell 3376

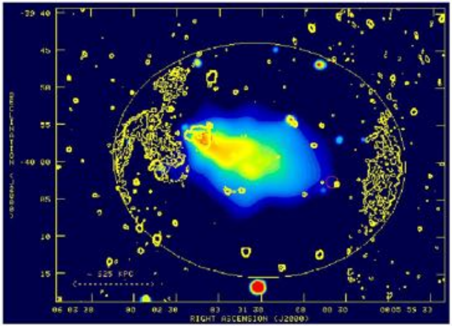


Figure : VLA 1420 MHz radio image [yellow contour] of the cluster Abell 3376 (J. Bagchi, F. Durret, G. B. Lima Neto, S. Paul, Science 314 (2006) 791-794). Colour map showing the XMM X-ray

- Discovery of a unique radio object using VLA
- Broken ring-like radio formation at $\sim$ 1.5 Mpc away from the galaxy-cluster centre.

So, are we missing something in our previous simulations?

Hydro Simulations

The baryonic content of the Universe can typically be described as an ideal fluid. Therefore, to follow the evolution of the fluid, one usually has to solve the set of hydrodynamic equations

Hydro equations:

$$\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t} = -\frac{\nabla P}{\rho} - \nabla\Phi, \tag{3}$$

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\nabla\mathbf{v} = 0 \tag{4}$$

and

$$\frac{\mathrm{d}u}{\mathrm{d}t} = -\frac{P}{\rho}\nabla\cdot\mathbf{v} - \frac{\Lambda(u,\rho)}{\rho}, \tag{5}$$

which are the *Euler equation*, *continuity equation* and the *first law of thermodynamics*, respectively. They are closed by an *equation of state*, relating the pressure P to the internal energy (per unit mass) u. Assuming an ideal, mono atomic gas, this will be

$$P = (\gamma - 1)\rho u \tag{6}$$

A brief description of the hydrodynamic code used

- To study the galaxy group and cluster formation we have used ENZO, a grid-based AMR hydrodynamic + N-body code

Cosmology parameters

- Flat ΛCDM cosmology with $\Omega_m = 0.2743$, $\Omega_b = 0.0458$, $\Omega_\Lambda = 0.7257$, h $=$ 0.702 (E. Komatsu et al., 2009)
- Primordial spectrum normalization $\sigma_8 = 0.816$
- Ideal equation of state for the gas is used with $\gamma = \frac{5}{3}$
- Heating and Radiative Cooling is used from Sarazin & White, 1987

Simulation parameters

- Simulation box size: 128^3 Mpc h^{-1}; root grid 64^3
- 2 static grids and 7 levels of Adaptive Mesh Refinement (AMR)
- Effective resolution: $\sim$15 kpc h^{-1}
- Shock waves as AMR criteria
- Starting redshift is z=60, end redshift z=0

Evolution of Baryonic matter

Evolution of thermal shocks

Density, Temperature and X-ray map of LSS

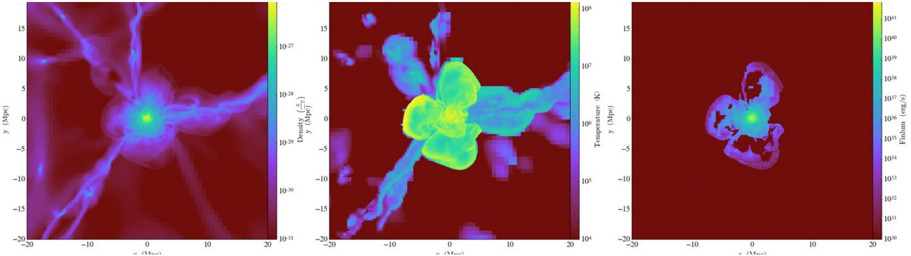
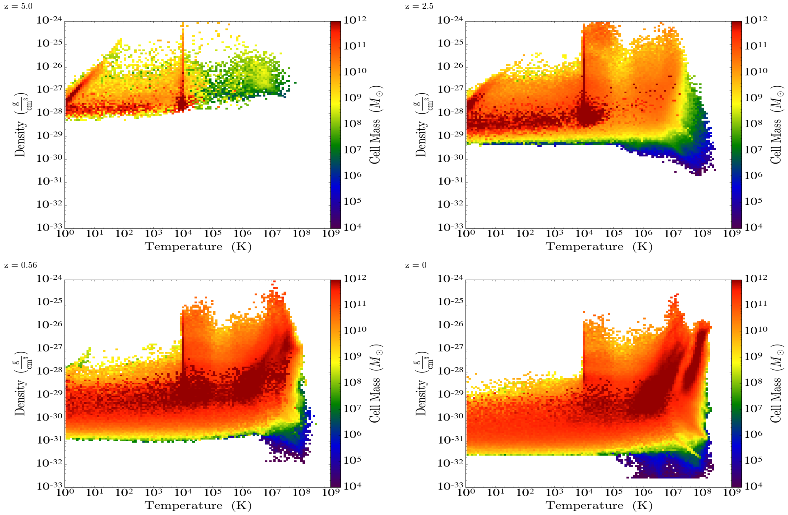


Figure : **Panel 1:** *Density plotted of a 40* $\mathrm{Mpc}^2\ \mathrm{h}^{-1}$ *cosmological simulated area at redshift z=0.06.* **Panel 2:** *Temperature map for the same area.* **Panel 3** *X-ray map of same area.*

Phase plot of density, temperature and CellMass



Evolution of turbulence

Vorticity $\mathbf{w} = \nabla x \mathbf{v} \times$ the maximum eddy size within a grid

- A saturation of magnetisation can be achieved in a fully turbulent medium.
- Fully turbulent medium ensures an equipartition of magnetic energy density $\frac{B^2}{8\pi}$ and the kinetic energy density $\rho\epsilon_{\rm turb}$.
- Mostly solenoidal mode of turbulence is responsible for conversion of kinetic energy to magnetic energy.
- Magnitude of saturated magnetic field is then computed from hydrodynamic parameter and given by $\frac{B_{\rm sat}^2}{8\pi} \propto \rho\epsilon_{\rm turb}$ i.e. $B_{\rm sat} = \sqrt{C_E.4\pi.\rho v_{\rm rms}^2}$ (Subramanian et al. 1998, Iapichino et al. 2012), where, $v_{\rm rms}$ is the local velocity dispersion. The constant of proportionality C_E is at the max 0.05 of the solenoidal turbulence (Miniati et al. 2015).

We have implemented our model of saturated magnetic field on a Coma like cluster and compared our result with real observation of Coma cluster using Faraday rotation measurement.

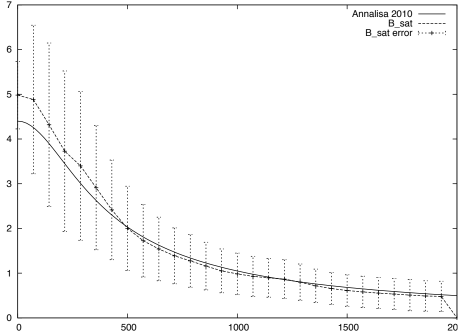


Figure : **Dashed line:** Computed saturated magnetic field from Comma like cluster. **Solid line:** Fitted profile from Faradday rotation observation of Comma Cluster.

Synchrotron Radio Power due to turbulent re-acceleration and Diffusive Shock Acceleration

Synchrotron Radio emission power is given by:

$$\frac{dN_s}{dE_s dt dV} = \frac{\sqrt{3} e^3 B}{h m_e c^2 \, E_s} \int_{m_e}^{E_{\rm max}} dE_e \, F(\frac{E_s}{h\nu_c}) \, \frac{dN_e}{dE_e dV} \qquad (7)$$

where $F(x) = x \int_x^{\infty} K_{5/3}(x')dx'$ is the Synchrotron function, $K_{5/3}$ is the modified Bessel function, and ν_c is the critical frequency of synchrotron emission, $\nu_c = 3\gamma^2 eB/(4\pi m_e c) = 1.6\,(B/1\mu{\rm G})(E_e/10{\rm GeV})^2$ GHz.

For DSA: For a thermally distributed particles after shocks the energy distribution takes up the form $N(E)dE \propto E^{-\delta} dE$ (Drury, 1983). Where, δ is the spectral index of electron energy.

For Turbulent re-acceleration:

$$\left(\frac{dN_e}{dE_e dV}\right)_{\rm inj} = \frac{3 P_A \, c}{4S(E_{\rm max})^{1/2}} \, E_e^{-\delta} \qquad (8)$$

For a Kolmogarov type turbulence δ takes the form $\frac{5}{2}$. (Ke Fang et al. 2015) or DSA spectrum can directly be fed to TRA equation (in prep. Paul et al. 2016).

Predicted magnetic field and radio flux on earth for a beam size of 20" from simulations

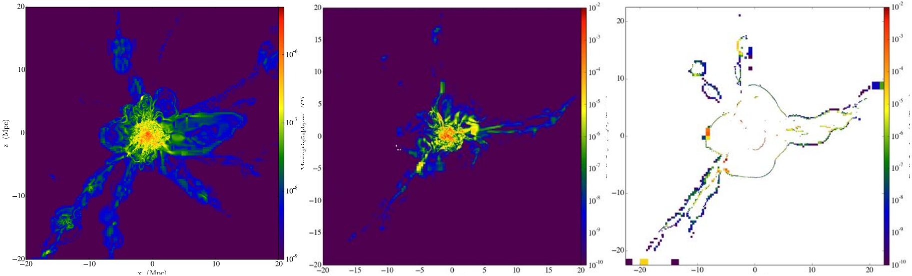


Figure : **Panel 1:** *Computed magnetic field from 40* $\mathrm{Mpc}^2\ \mathrm{h}^{-1}$ *cosmological simulated area at redshift z=0.06.* **Panel 2:** *Computed TRA radio flux for the same area.* **Panel 3:** *Modelled DSA radio flux for the same area [Paul et al. 2016, in prep.].*

X-ray and Radio Luminosity from simulations

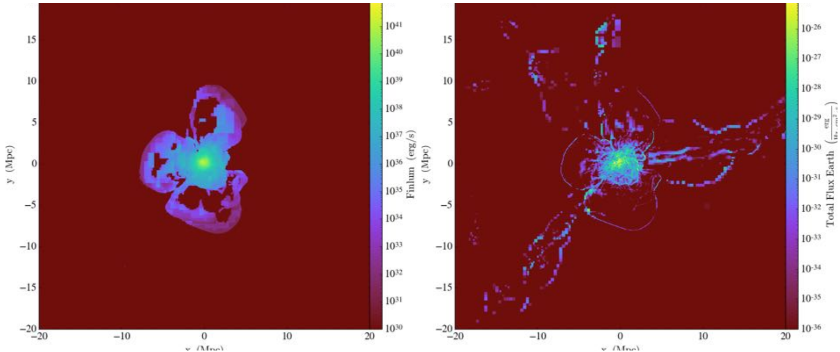


Figure : *Panel 1: Computed X-ray emission from 40* $\mathrm{Mpc}^2\ \mathrm{h}^{-1}$ *cosmological simulated area at redshift z=0.06. Panel 2: Computed DSA+TRA radio flux for the same area. [Paul et al. 2016, in prep.].*

Predicted magnetic field and radio flux on earth for a beam size of 20” from simulations

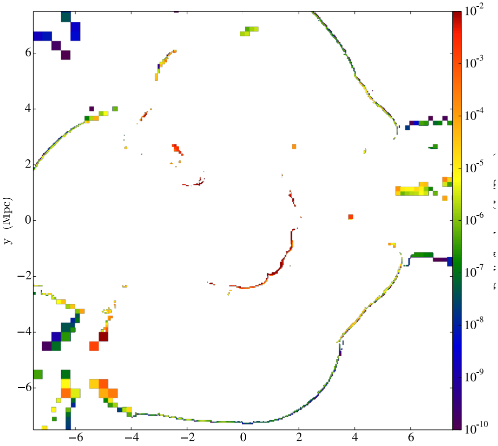


Figure : *Computed DSA radio flux from an object at z=0.06 that will possibly be deteted by SKA [Paul et al. 2016, in prep.].*

- A complete model is given for computing magnetic field and radio emission from DSA and TRA electrons
- Radio emission from filaments gives hope of detection by SKA, mainly the filamentary inroads, groups and the multi-layered virializtion shocks

Thank You !

Inferred from	Ω_b (%) for h_{70}=1
BBN	4.4 ± 0.4
CMB anisotropy	4.6 ± 0.2
Ly_α forest at z>2	>3.5
Observalons at z<2	
Stars	0.26 ± 0.08
HI + HeI + H_2	0.080 ± 0.016
X-ray gas in clusters	0.21 ± 0.06
Ly_α forest	1.34 ± 0.23
Warm + warm-hot OVI	$0.6^{+0.4}_{-0.3}$
Total at z<2	$2.5^{+0.5}_{-0.4}$
Missing baryons at z<2	$2.1^{+0.5}_{-0.4}$

Hydro equations:

The set of hydrodynamical equations for an expanding Universe reads

$$\frac{\partial \mathbf{v}}{\partial t} + \frac{1}{a}(\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{\dot{a}}{a}\mathbf{v} = -\frac{1}{a\rho}\nabla P - \frac{1}{a}\nabla\Phi, \tag{9}$$

$$\frac{\partial \rho}{\partial t} + \frac{3\dot{a}}{a}\rho + \frac{1}{a}\nabla \cdot (\rho\mathbf{v}) = 0 \tag{10}$$

and

$$\frac{\partial}{\partial t}(\rho u) + \frac{1}{a}\mathbf{v} \cdot \nabla(\rho u) = -(\rho u + P)\left(\frac{1}{a}\nabla \cdot \mathbf{v} + 3\frac{\dot{a}}{a}\right) \tag{11}$$

respectively, where the right term in the last equation reflects the expansion in addition to the usual $P\mathrm{d}V$ work.

- Meshes can be refined adaptively during the simulations

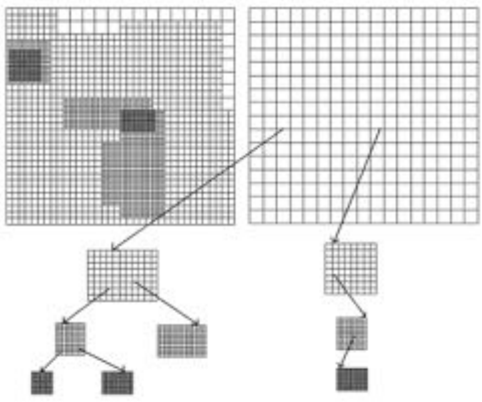


Figure : *AMR schemes*