Constrained Simulation of the Bullet Cluster

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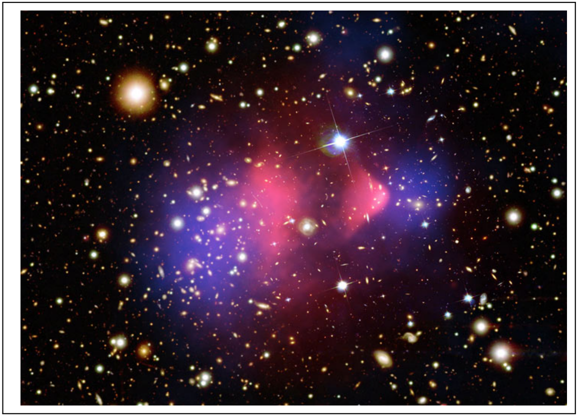
UC Davis: 22-Jan-15

- CSL and Farrar, G., "Constrained Simulation of the Bullet Cluster", ApJ, V787, P144, 2014, arXiv:1312.0959v1.
- CSL and Farrar G.R., "The Bullet Cluster is not a Cosmological Anomaly", Accepted to JCAP, arXiv:1406.6703.

Outline

- Introduction
- Review of Past Simulations
- Our Simulation Strategy
- Mass Lensing Results
- X-ray Flux Results
- Comparison to Past Simulations
- Consistency with ΛCDM
- Need for Non-Thermal Pressure
- Improved modeling of Non-Thermal Pressure
- Magnetic Field and Radio Halo (If time permits)
- Conclusions

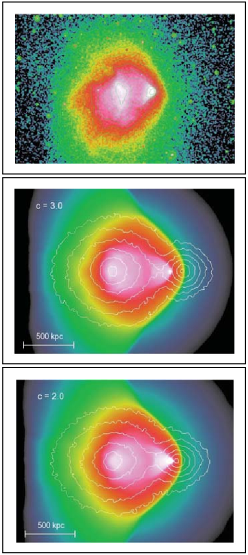
Bullet Cluster Summary



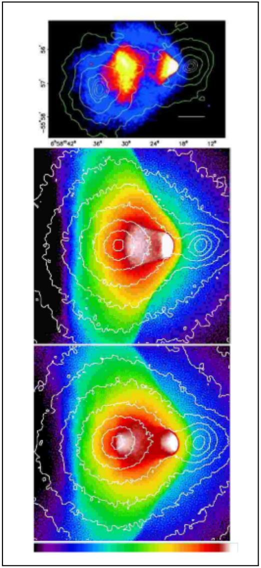
Clowe - 2006

- Ongoing collision of two massive galaxy clusters
- Distance $\approx 1.2\text{Gpc}$ (z = 0.296)
- Combined cluster mass $\approx 10^{15}\text{M}_\odot$
- Considered the best "proof" of the existence of dark matter.

Past Simulation Results



Springel, Farrar
2007 MNRAS



Mastropietro, Burkert
2008 MNRAS

- Top panel - measured data
- Qualitative comparison of shape of X-ray emission.
- Not focused on magnitude of X-ray flux.
- Quantitative focus was on location of mass lensing and X-ray peaks.

Tension with ΛCDM model

Authors	M_{Main}	M_{Bullet}	R_{Initial} (kpc)	V_{Initial} (km/sec)	V_{2500} (km/sec)
Springel and Farrar	1.50E15	1.50E14	3370	2057	2386
Mastropietro and Burkert	7.13E14	1.14E14	5000	3000	3228
Milosavljevic et. al.	1.27E15	2.54E14	4600	0	1546

BULLET CLUSTER: A CHALLENGE TO ΛCDM COSMOLOGY

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ABSTRACT

To quantify how rare the bullet-cluster-like high-velocity merging systems are in the standard Λ cold dark matter (CDM) cosmology, we use a large-volume ($27\ h^{-3}$ Gpc^3) cosmological N-body MICE simulation to calculate the distribution of infall velocities of subclusters around massive main clusters. The infall velocity distribution is given at (1–3)R_{200} of the main cluster (where R_{200} is similar to the virial radius), and thus it gives the distribution of realistic initial velocities of subclusters just before collision. These velocities can be compared with the initial velocities used by the non-cosmological hydrodynamical simulations of 1E0657-56 in the literature. The latest parameter search carried out by Mastropietro & Burkert has shown that an initial velocity of 3000 km s^{-1} at about $2R_{200}$ is required to explain the observed shock velocity, X-ray brightness ratio of the main and subcluster, X-ray morphology of the main cluster, and displacement of the X-ray peaks from the mass peaks. We show that such a high infall velocity at $2R_{200}$ is incompatible with the prediction of a ΛCDM model: the probability of finding 3000 km s^{-1} in (2–3)R_{200} is between 3.3×10^{-11} and 3.6×10^{-9}. A lower velocity, 2000 km s^{-1} at $2R_{200}$, is also rare, and moreover, Mastropietro & Burkert have shown that such a low initial velocity does not reproduce the X-ray brightness ratio of the main and subcluster or morphology of the main cluster. Therefore, we conclude that the existence of 1E0657-56 is incompatible with the prediction of a ΛCDM model, unless a lower infall velocity solution for 1E0657-56 with $\lesssim$1800 km s^{-1} at $2R_{200}$ is found.

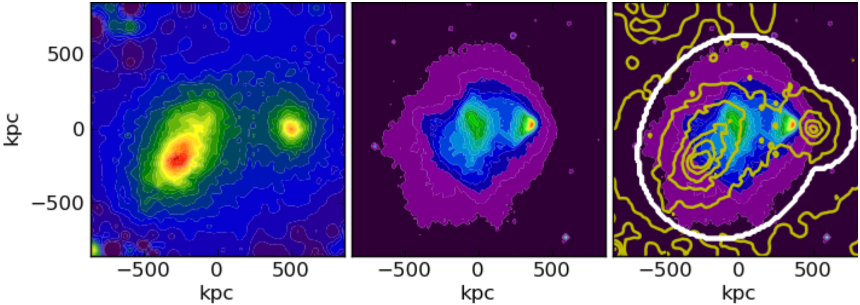
Our Approach - Optimization Using 2D Image Data

- Pixel-by-pixel fit to multiple data sets:

$$\chi^2_{\mathrm{DOF}} = \frac{1}{\mathrm{N_k N_i}} \sum_{\mathrm{Observations=k}}^{\mathrm{N_k}} \sum_{\mathrm{Pixels=i}}^{\mathrm{N_i}} \frac{(\mathrm{Sim_i^k} - \mathrm{Obs_i^k})^2}{(\sigma_\mathrm{i}^\mathrm{k})^2}$$

- Available data sets (Red data sets used for χ^2_{DOF} calculation)
  - Mass Lensing data (Bradac et.al., 2006)
  - X-ray flux in three energy bins (Chandra)
    - 500 - 2000 eV
    - 2000 - 5000 eV
    - 5000 - 8000 eV
  - Plasma Temperature(Markevitch, Private - 2012)
  - S-Z Effect $\Delta \mathrm{T}$ from SPT (Plagge et.al., 2010)
  - Radio Flux(Liang et.al., 2000)

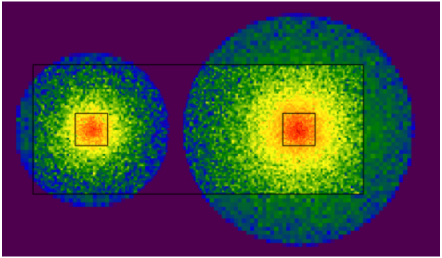
Overview of Principal Data Sets



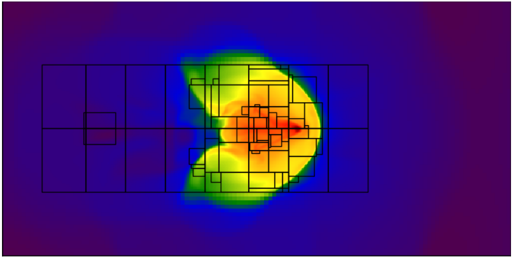
Mass Lensing Data (Bradac et.al., 2006) | X-ray Flux 0.5-2 keV Chandra | Overlay

Only data within the white outline is included in the χ^2_{DOF} calculation

Enzo: Grid-Based Hydro + Particle-Based DM



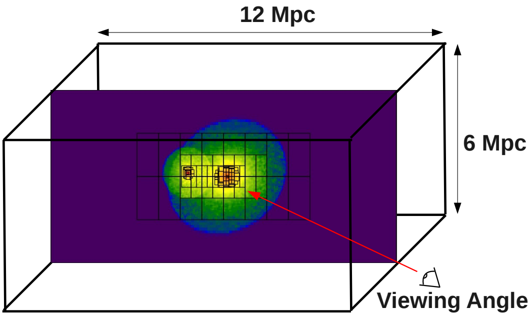
Initial (Spherical) clusters - 3 levels AMR



Time of Best Fit - 5 levels AMR

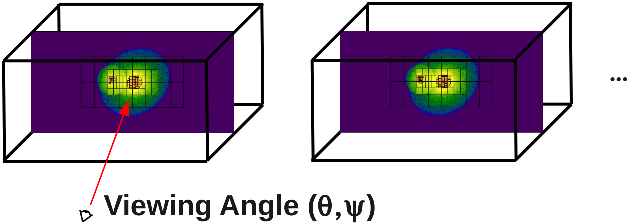
Enzo Simulation Overview

Simulation Volume	12000 x 6000 x 6000	kpc
Coarse Grid	128 x 64 x 64	-
Maximum Number of Refinement Levels	6	-
Minimum Grid Cell Size	2.9	kpc
Total Number of Grid Cells	$\approx 5.0\text{E}6$	-
Maximum Baryon Mass per Grid Cell	2.5E8	$M_\odot$
Number of DM Particles	1.0E7	-



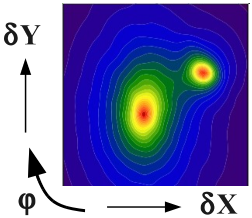
Alignment Optimization for each Set of Initial Conditions

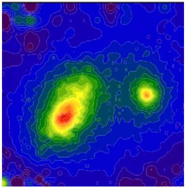
Simulation saved every 0.01 Gy



Viewing Angle (θ,ψ)

Projected Image **Observed Data**



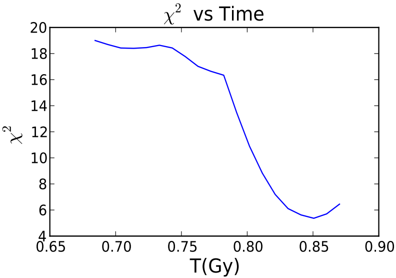


Find
(δX, δY, φ,θ,ψ)
which minimizes
χ^2 at each T

Optimization Cycle

- Assume a set of initial conditions - 34 Parameters
  - DM Halo Sizes and Shapes - 8
  - Baryon Profiles - 14
  - Cluster Orientations - 6
  - Initial Velocities - 2
  - Miscellaneous - 4
    - Magnetic field magnitude
    - Metallicity
    - Viscosity
    - Non-Thermal Pressure
- Run simulation and find best χ^2_{DOF} $\Rightarrow$
- Iterate on initial conditions using Monte-Carlo searches and steepest descent optimizations to minimize χ^2_{DOF}.

- Most simulations run on NASA Pleiades cluster.
- Typical Enzo run - 4 hours wall clock time on 64 cores.
- 32 - 192 runs in parallel.
- > 1000 different initial condition configurations run.



Cluster Generation Procedure

- Choose the cluster mass, concentration, and triaxiality.

$$\rho_{\mathrm{DM}} = \frac{\rho_{\mathrm{DM0}}}{\frac{\mathrm{R}}{\mathrm{R_C}}(1 + \frac{\mathrm{R}}{\mathrm{R_C}})^2}$$

$$\mathrm{R}^2 = \mathrm{x}^2 + \frac{\mathrm{y}^2}{\mathrm{Q}^2} + \frac{\mathrm{z}^2}{\mathrm{P}^2}$$

- Generate a stable dark matter halo using the Schwarzschild procedure (SMILE code from Vasiliev at Rochester).

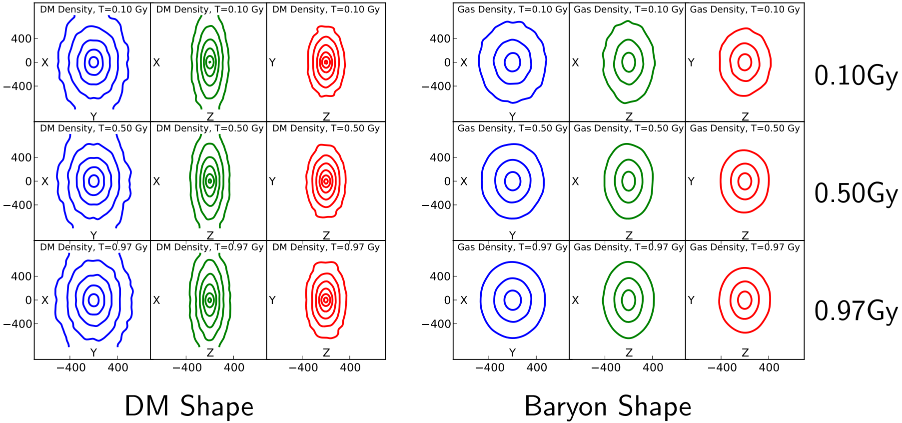
- Choose parameters for the gas density profile.

$$\rho_{\mathrm{G}} = \frac{\rho_{\mathrm{G0}}}{(1 + (\frac{\mathrm{R}}{\mathrm{R_{C1}}})^2)^{\beta 1}(1 + (\frac{\mathrm{R}}{\mathrm{R_{C2}}})^2)^{\beta 2 - \beta 1}(1 + (\frac{\mathrm{R}}{\mathrm{R_{C3}}})^2)^{\beta 3 - \beta 2}}$$

- Calculate temperature to guarantee hydrostatic equilibrium.

- Rotate the cluster to a chosen orientation.

Stability of Typical Cluster with Axis Ratios of (0.35, 0.70)



Dark matter and baryons stable on Gy timescale.

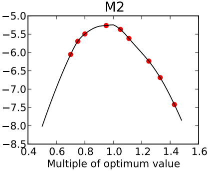
Now for the Results

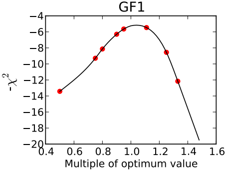
Initial conditions determined from
Mass lensing + 500-2000 eV X-ray flux

Best-Fit Parameter Set

Dark Matter Halo Parameters			
Parameter	Description	Value	Sigma
M_1	Main Cluster Mass (M_{200})	1.91E15	0.20E15
M_2	Bullet Cluster Mass (M_{200})	2.59E14	0.31E14
C_1	Main Cluster Concentration	1.17	0.14
C_2	Bullet Cluster Concentration	5.45	0.70
P_1	Main Cluster Z/X Axis Ratio	0.35	0.05
Q_1	Main Cluster Y/X Axis Ratio	0.68	0.09
P_2	Bullet Cluster Z/X Axis Ratio	0.61	0.08
Q_2	Bullet Cluster Y/X Axis Ratio	0.68	0.10
Gas Profile Parameters			
Parameter	Description	Value	Sigma
GF_1	Main Cluster Gas Fraction	0.19	0.02
GF_2	Bullet Cluster Gas Fraction	0.17	0.02
RC_{11}	Main Cluster Gas Radius1	59.4	7.9
RC_{12}	Bullet Cluster Gas Radius1	19.8	1.9
β_{11}	Main Cluster Exponent1	0.38	0.06
β_{12}	Bullet Cluster Exponent1	0.51	0.07
RC_{21}	Main Cluster Gas Radius2	69.9	11.4
RC_{22}	Bullet Cluster Gas Radius2	47.8	6.4
β_{21}	Main Cluster Exponent2	0.45	0.05
β_{22}	Bullet Cluster Exponent2	0.85	0.14
RC_{31}	Main Cluster Gas Radius3	647	82
RC_{32}	Bullet Cluster Gas Radius3	465	80
β_{31}	Main Cluster Exponent3	0.67	0.05
β_{32}	Bullet Cluster Exponent3	0.50	0.06

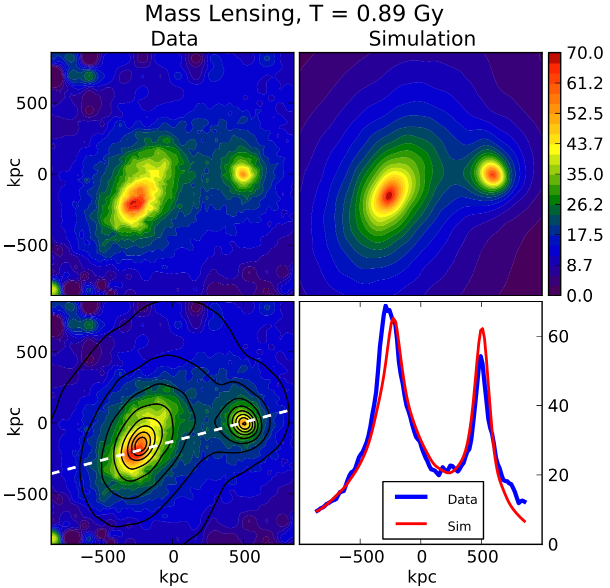
Orbital Geometry Parameters			
Parameter	Description	Value	Sigma
ϕ_1	Main Cluster Euler Angle 1	185	33
θ_1	Main Cluster Euler Angle 2	38.4	5.9
ψ_1	Main Cluster Euler Angle 3	221	30
ϕ_2	Bullet Cluster Euler Angle 1	164	23
θ_2	Bullet Cluster Euler Angle 2	100	14
ψ_2	Bullet Cluster Euler Angle 3	65.0	10
IP	Impact Parameter	256	35
V_{Inc}	Infall Velocity Increment	0.89	0.15
Remaining Parameters			
Parameter	Description	Value	Sigma
Z	Metallicity (Cooling)	0.78	0.10
Mag	Peak Magnetic Field Magnitude	61.0	5.4
f_{ntp}	Non-Thermal Pressure factor	0.52	0.09
Visc	Viscosity	0.12	0.02





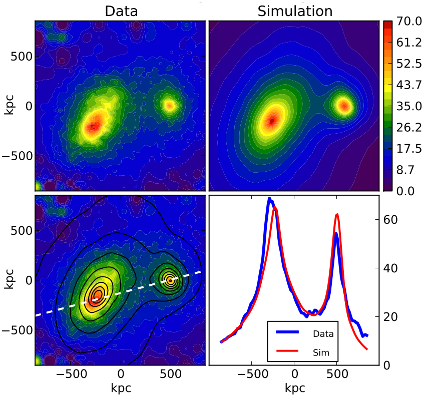
Masses in $M_\odot$, Distances in kpc, Angles in degrees, B in μG

Explanation of Maps



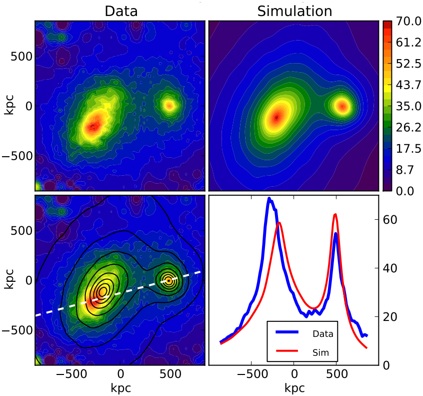
Mass Lensing fit dependence on viewing angle and time

Mass only: $\chi^2_{\mathrm{DOF}} = 1.15$



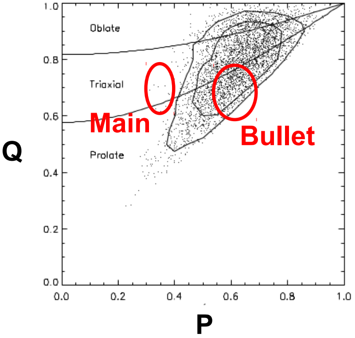
$(\varphi, \theta, \psi, \mathrm{T}) =$
(200, 65.3, 174, 0.88)

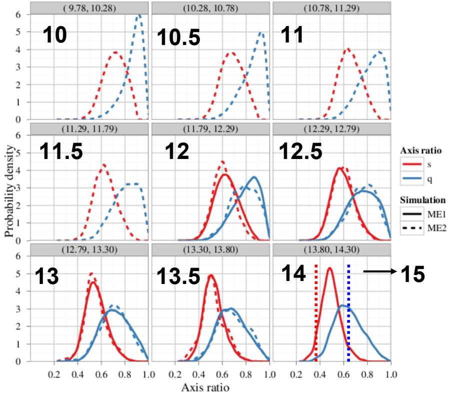
Mass + X-Ray1: $\chi^2_{\mathrm{DOF}} = 3.94$



$(\varphi, \theta, \psi, \mathrm{T}) =$
(199, 61.9, 174, 0.87)

DM Halo Ellipticities Compared to N-body Simulations





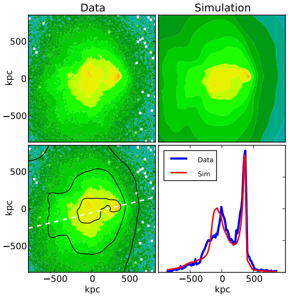
Bailin et.al.(2005) - All masses

Schneider, Frenk, Cole (2012)
More massive → more ellipsoidal.

Both clusters appear typical.

Best Fit Results for X-ray Flux

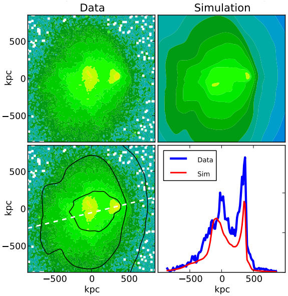
500 - 2000 eV



$$\chi^2_{\mathrm{DOF}} = 5.68$$

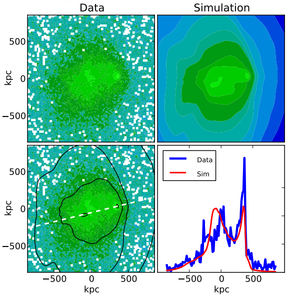
Fit

2000 - 5000 eV



$$\chi^2_{\mathrm{DOF}} = 6.94$$

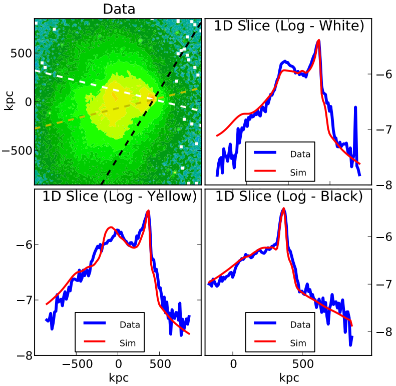
5000 - 8000 eV



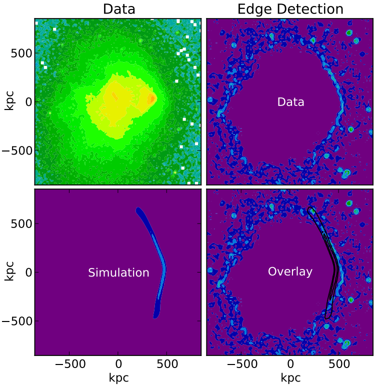
$$\chi^2_{\mathrm{DOF}} = 3.88$$

Prediction

Model fits X-ray flux data over more than two orders of magnitude!



500-2000eV Log scale

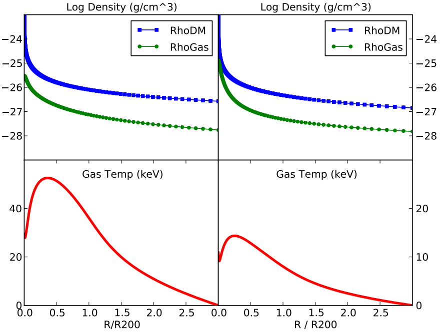


500-2000eV Edge detection

Shape and location of shock front is well captured.

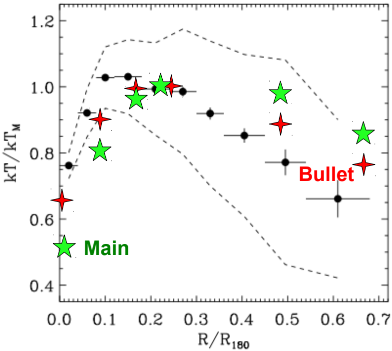
Baryon Profiles

Main Bullet



Baryon profiles

Temperature Profiles

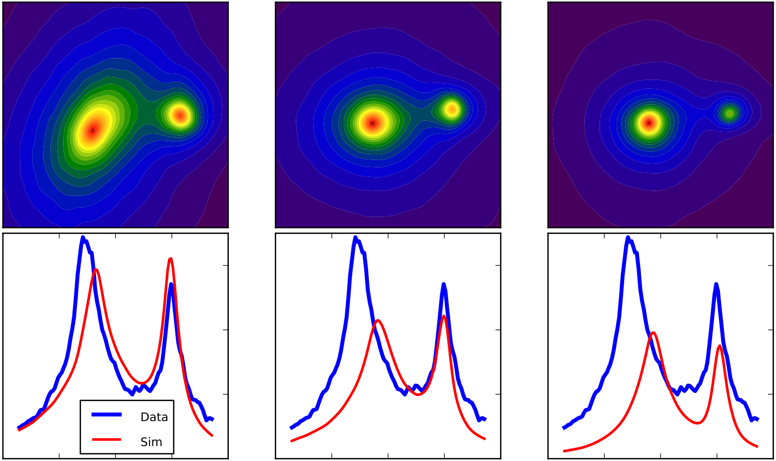


Leccardi, Molendi (2008)

Baryon Fraction

Best-fit values 19±2% and 17±2% - WMAP $\Omega_b/\Omega_m = 16.5 \pm 2.5\%$

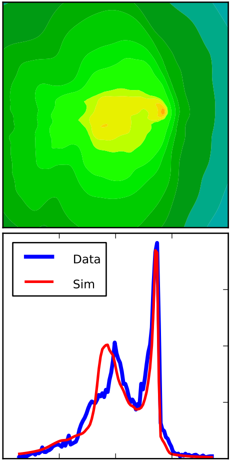
New simulation fit is much better. (Mass lensing)



Our Work Springel Farrar Mastropietro Burkert

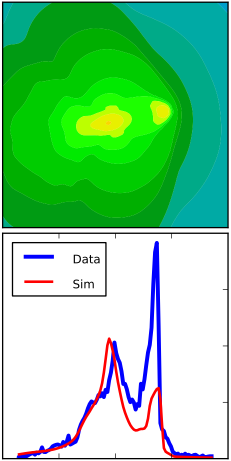
$\chi^2_{\mathrm{DOF}} = 3.94$ $\chi^2_{\mathrm{DOF}} = 13.67$ $\chi^2_{\mathrm{DOF}} = 19.93$

New simulation fit is much better. (X-ray flux 500-2000eV)



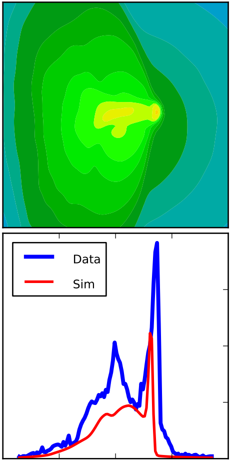
Our Work

$\chi^2_{\mathrm{DOF}} = 3.94$



Springel Farrar

$\chi^2_{\mathrm{DOF}} = 13.67$



Mastropietro Burkert

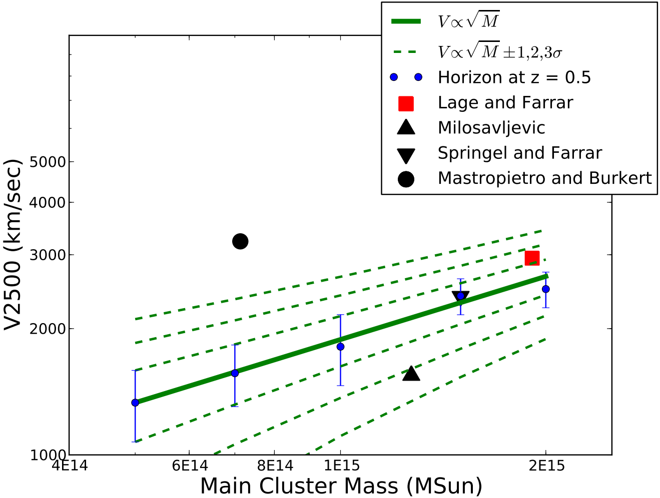
$\chi^2_{\mathrm{DOF}} = 19.93$

Horizon Simulation (Kim et.al. - 2009 ApJ)

- Large N-body cosmological simulation
  - Volume $= (6.592\mathrm{h}^{-1}\mathrm{Gpc})^3$
  - $4120^3 = 6.99\mathrm{E}10$ particles.
  - Using z = 0.5 snapshot (Our simulation begins at z = 0.39)
- Choose halos with masses from $5\mathrm{E}14 - 2\mathrm{E}15\mathrm{M}_\odot$ (Main cluster analogs).
- Choose nearby (within 5 Mpc) halos with masses 6x - 10x smaller (Bullet cluster analogs)
- Extract relative velocity and normalize to separation of 2.5 Mpc.

Authors	$\mathrm{M}_{\mathrm{Main}}$	$\mathrm{M}_{\mathrm{Bullet}}$	$\mathrm{R}_{\mathrm{Initial}}$ (kpc)	$\mathrm{V}_{\mathrm{Initial}}$ (km/sec)	V_{2500} (km/sec)
Lage and Farrar	1.91E15	2.59E14	2800	2799	2943
Springel and Farrar	1.50E15	1.50E14	3370	2057	2386
Mastropietro and Burkert	7.13E14	1.14E14	5000	3000	3228
Milosavljevic et. al.	1.27E15	2.54E14	4600	0	1546

Bullet Simulations Compared to Horizon N-Body



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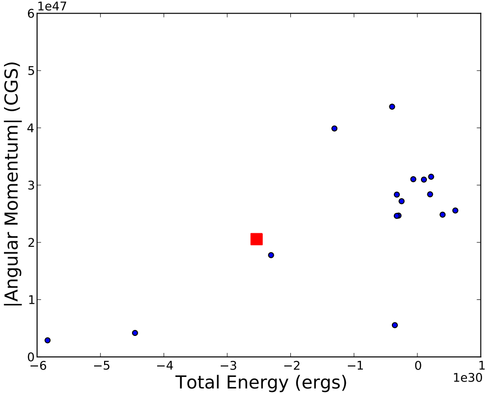
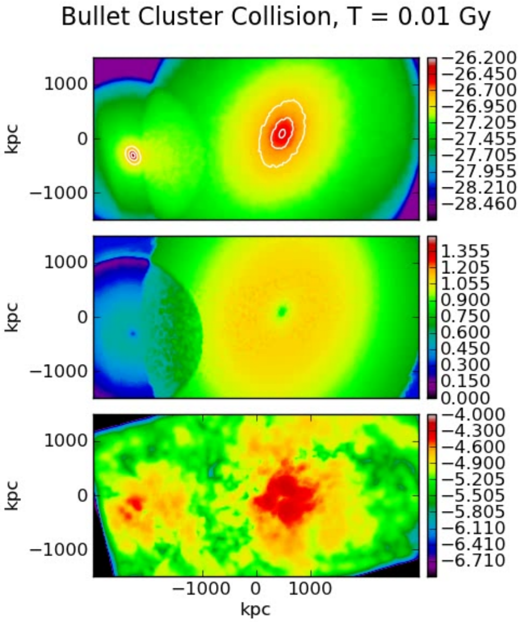
$V = \sqrt{GM_{Main}/R}$ model used - only 7 cluster pairs in $2E15\ M_\odot$ point

Bullet Simulations Compared to Horizon N-Body

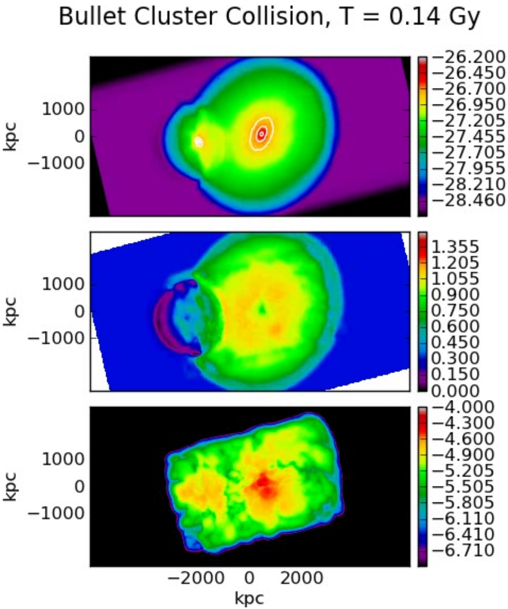


- Blue circles - Horizon clusters which matched our cluster masses $\pm 20\%$ and $< 5\text{Mpc}$ separation.
- Red square - Our best fit.

Movie of Bullet Cluster Collision



Long Movie of Bullet Cluster Collision



Non-Thermal Pressure

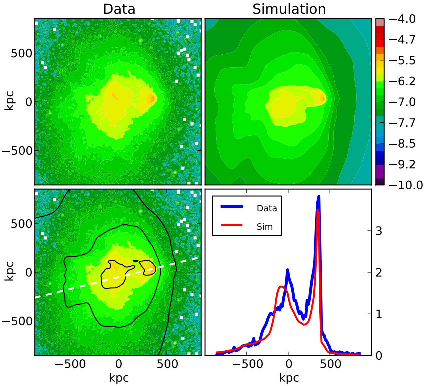
- Non-Thermal Pressure is required to fit S-Z effect measurements.
  - Same amount of NTP fits Markevitch' extracted temperature maps.
  - X-ray flux is minimally impacted.

- We model NTP as a constant multiple of thermal pressure (Bode 2012):

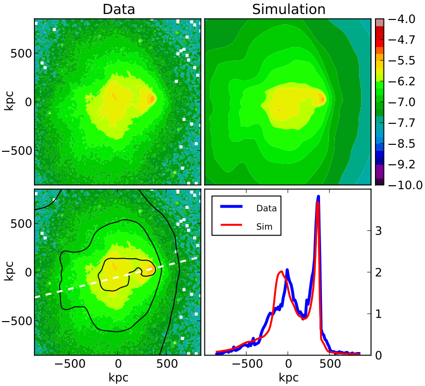
$$P_{tot} = P_{th} + P_{ntp} = P_{th}(1 + \frac{f_{ntp}}{1 - f_{ntp}}) = P_{th}\frac{1}{1 - f_{ntp}}$$

- Future work will focus on a more realistic model, modeling the non-thermal pressure as turbulent fluid motions.

Non-Thermal Pressure has Minimal Impact on X-ray Flux

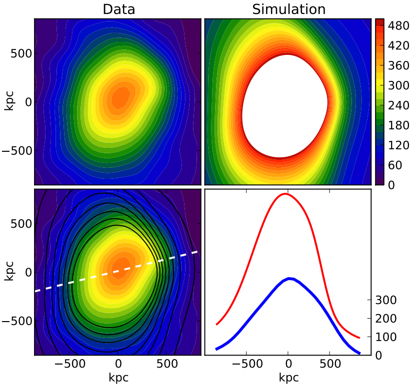


$$f_{ntp} = 0$$

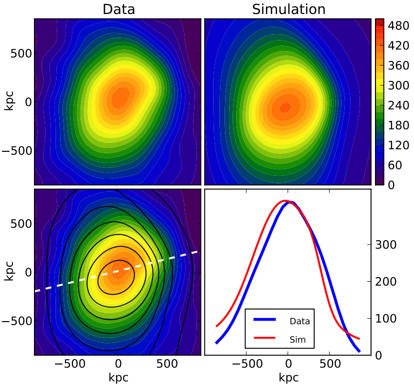


$$f_{ntp} = 0.52$$

Non-Thermal Pressure is Required to Fit S-Z Observations

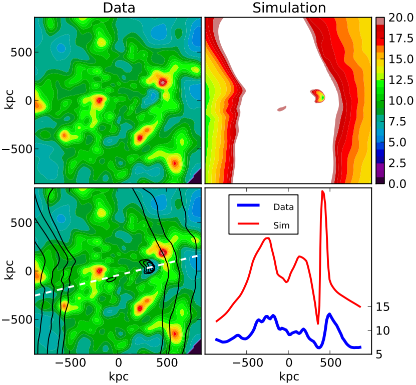


$f_{\mathrm{ntp}} = 0$

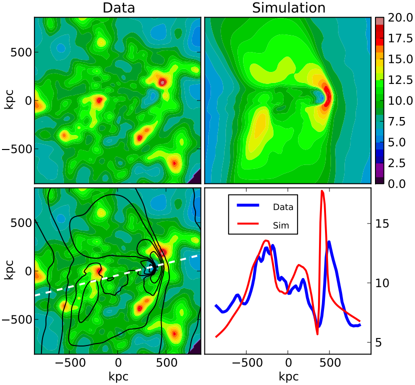


$f_{\mathrm{ntp}} = 0.52$

Same f_{ntp} fits Markevitch Temperature Map



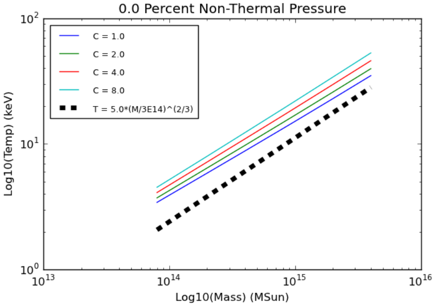
$$f_{ntp} = 0$$

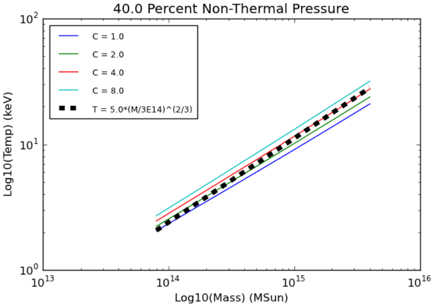


$$f_{ntp} = 0.52$$

Non-Thermal Pressure as turbulent fluid motions

Improved Modeling of Non-Thermal Pressure
Non-Thermal Pressure and Cluster Temperatures





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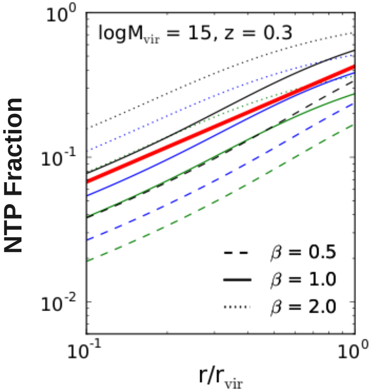
Clusters in hydrostatic equilibrium with just thermal pressure are $\approx 2\text{X}$ too hot.

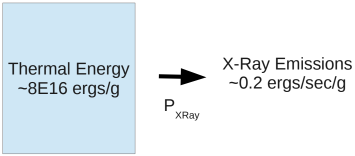
Analytical Model - Shi, Komatsu - 2014



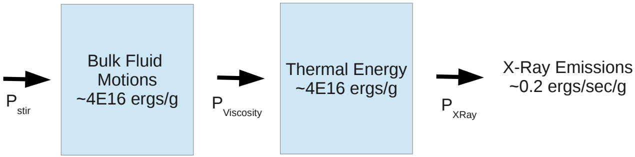
Shi, Komatsu "Analytical model for non-thermal pressure in galaxy clusters", astro-ph:1401.7857v1

Red Line - Battaglia(2012) fitting formula. Other lines - Shi, Komatsu model with varying parameters

Energy Balance Considerations



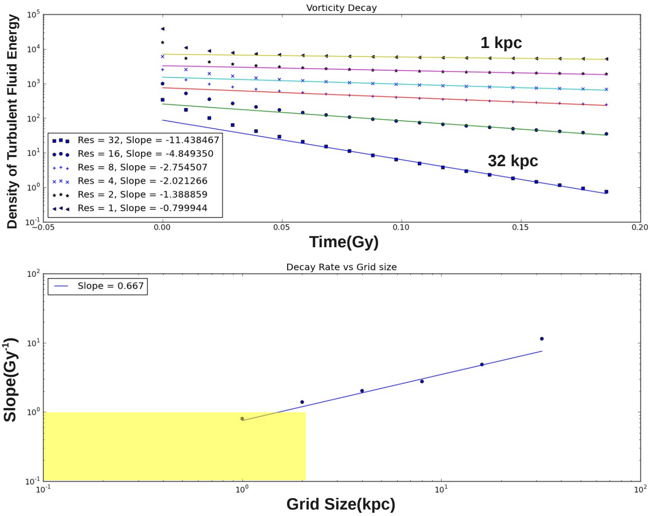
No Non-Thermal Pressure



Non-Thermal Pressure Model

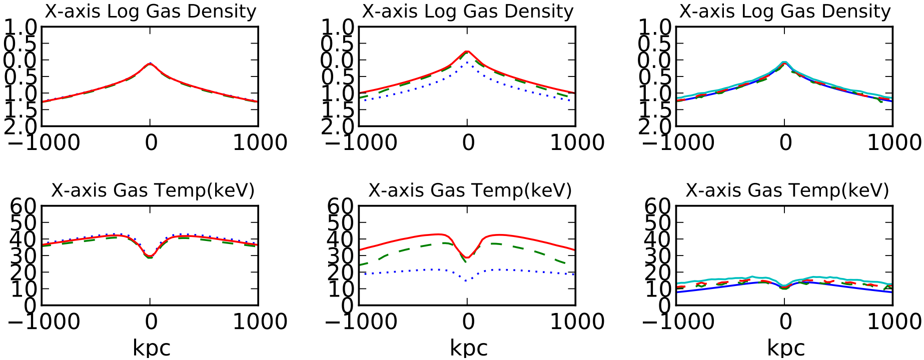
- Residence time of energy reservoirs $\approx 10\mathrm{Gy}$.
- Cannot have $\mathrm{P_{Stir}} >> \mathrm{P_{XRay}}$, otherwise everything just heats up.
- Should not need to stir on a $\approx 1\mathrm{Gy}$ time scale.
- Need to reduce numerical viscosity so $\mathrm{P_{Viscosity}} \approx \mathrm{P_{XRay}}$.

Velocity Decay vs Grid Size



Need decay rate $\lambda \approx 1.0\mathrm{Gy}^{-1} \Rightarrow \mathrm{Grid} \approx 2 - 4\,\mathrm{kpc}.$

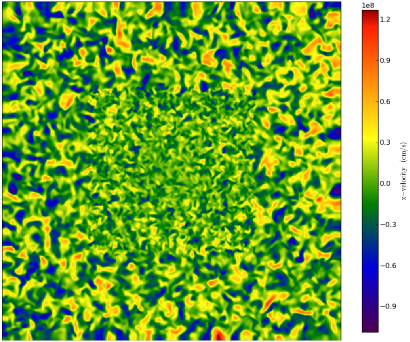
Non-Thermal Pressure with Higher Resolution



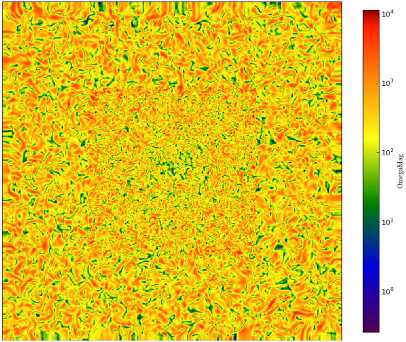
No NTP: $\mathrm{T} = \mathrm{T}_{\mathrm{EQ}}$ No NTP: $\mathrm{T} = 0.5\mathrm{T}_{\mathrm{EQ}}$ NTP: Fluid Turbulence

Left and Center:Blue dot - 0Gy; Green Dash - 0.4Gy; Red - 0.8Gy.
Right:Blue - 0Gy; Green Dash - 0.1Gy; Red - 0.4Gy; Aqua - 0.8Gy.

Velocity Distribution and Vorticity at T = 0.38 Gy



X - Velocity



Squared Magnitude of Vorticity

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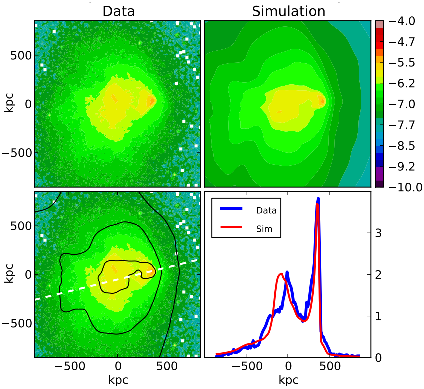
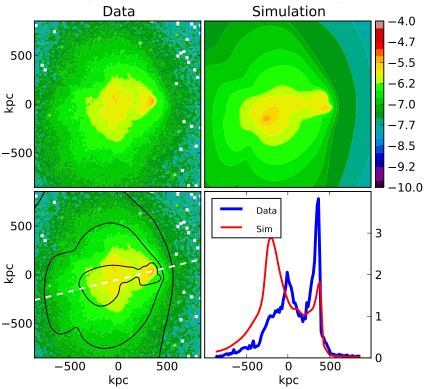
2×512^3 grid - 2 kpc in center 1 Mpc, 4 kpc in outer regions

Compression of magnetic field retards baryon motion.



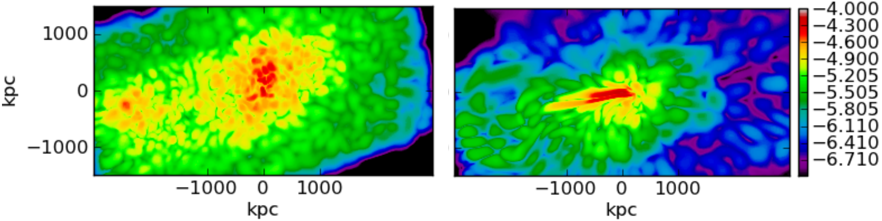
Initial Peak $|\mathrm{B}| = 61\mu\mathrm{G}$.



Initial Peak $|\mathrm{B}| = 0.01\mu\mathrm{G}$.

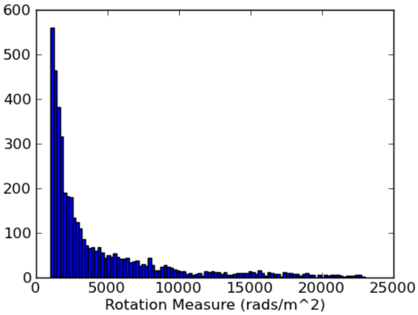
Initial B-Field Generation

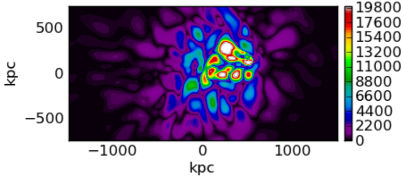
- Using garFields code (Kitaura - MPA)
  - Generate $\hat{\mathrm{B}}(\mathrm{k})$ with Kolmogorov spectrum.
  - Currently exploring impact of maximum coherence length λ
  - Results shown here use $\lambda = 180\mathrm{kpc}$.
- Scale B so that $|\mathrm{B}| \propto \rho_{\mathrm{gas}}^{2/3}$ (Simple collapse model).

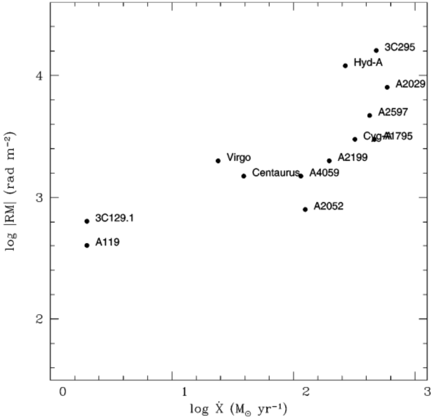


log($|\mathrm{B}|$) near start of simulation. log($|\mathrm{B}|$) at time of best fit.

RM estimates consistent with Carilli and Taylor 2002







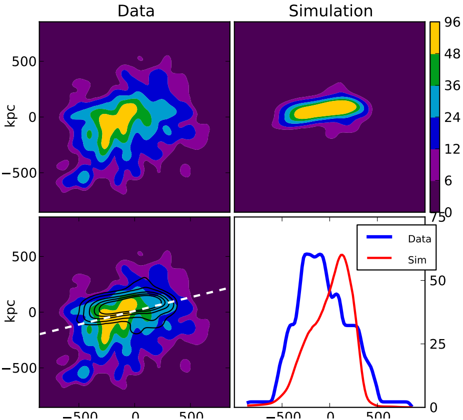
Carilli and Taylor 2002:
Log Max RM vs log Cooling Flow

- Need measurements!

Radio Halo Model

Simple model of synchrotron emission:
Population of relativistic electrons in energy equipartition with B field.

- $N(E) \propto E^{-p}$
- Emission spectrum has $f(\nu) \propto \nu^{-s}$
- $s = \frac{p-1}{2}$
- Best fit value of $p = 3.6 \rightarrow s = 1.3$
- Liang et.al. measured $s = 1.2 - 1.3$.

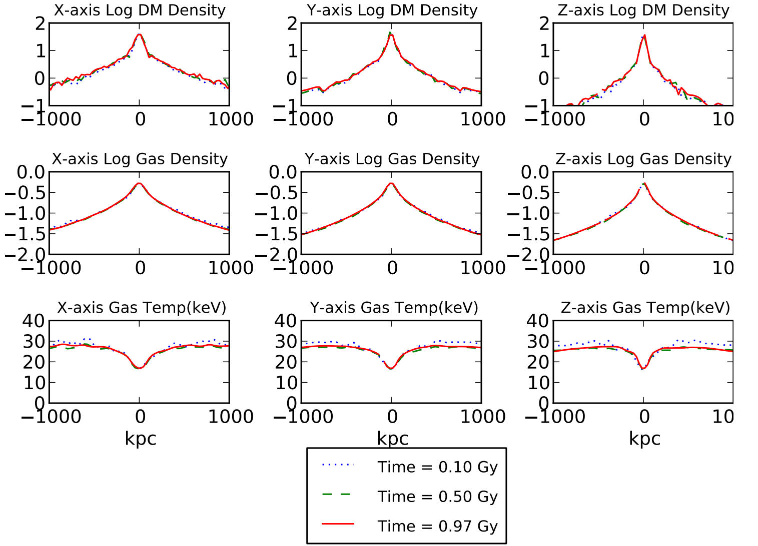


Conclusions

- Combined mass lensing and X-ray fit is very constraining of cluster structure.
- Our fit to the data is quantitatively much better than past simulations.
    - Baryon fraction close to WMAP average, but slightly higher.
    - Inconsistency with $\Lambda\mathrm{CDM}$ has been removed.
- Non-thermal pressure is required to fit S-Z and temperature observations.
    - Future work will include a more sophisticated NTP model.
- Magnetic field improves the simultaneous fit of the mass lensing and X-ray flux data.
    - More study needed on impact of B field.
    - Peak Magnetic field today $|\mathrm{B}| \approx 80\mu\mathrm{G}$.
    - RM consistent with other massive clusters.
    - Magnetic fields required for Mass/X-ray alignment in rough agreement with simple model of radio halos.

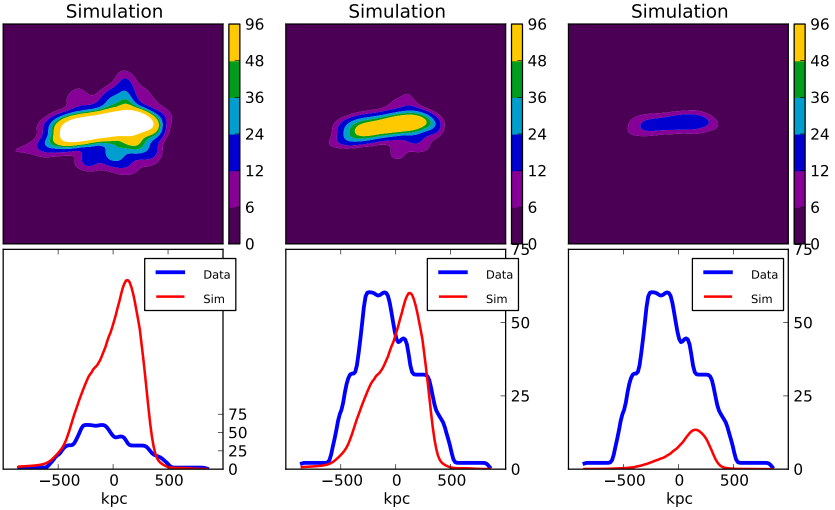
Back-up Slides

Stability of Typical Cluster with Axis Ratios of (0.35, 0.70)



Dark matter and baryons stable on Gy timescale.

Impact of Spectral Index p



p = 3.4

p = 3.6

p = 3.8