The Dynamics of Merging Clusters: A Monte Carlo Solution Applied to the Bullet and Musket Ball Clusters

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Outline

Why the study of merging cluster are important?

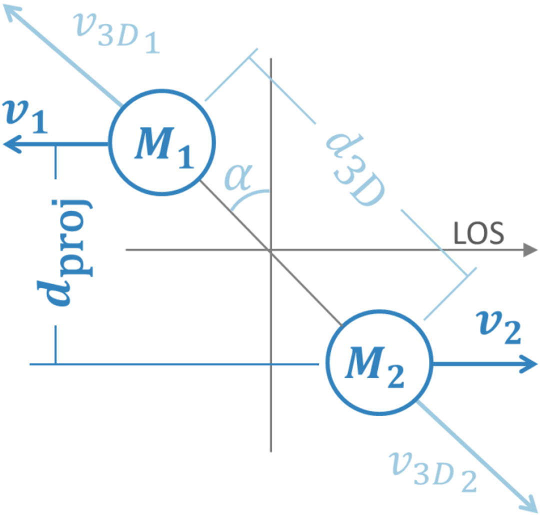
- Merging clusters are important probes to σ_{DM} (e.g. Bullet Cluster) and the large-scale matter-antimatter ratio (e.g. Steigman 08);
- The best constraints come from M/L of the sub-clusters and the offset between the collisionless galaxies and DM; both depends on the merger dynamics (basically the velocity of collision **(1)** and the time since collision **(2)**);
- (1) will affect the the expected momentum transfer between each sub-clusterâs dark matter particles $\rightarrow$ affect the expected dark matter mass transfer from the smaller to the largest sub-cluster $\rightarrow$ affect the expected M/L;
- (2) the galaxy-DM offset depends on the time-since-collision (TSC); initially the offset will increase with TSC (for $\sigma_{DM} > 0$) as the galaxies outrun the DM $\rightarrow$ at later TSC the offset will decrease due to the gravitational attraction (galaxies + DM).

Dissociative mergers

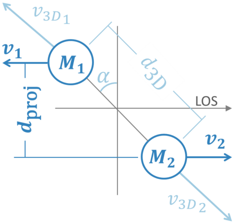
1. are between two sub-clusters of comparable mass;
2. have a small impact parameter;
3. are observed during the short period when the cluster gas is significantly offset from the galaxies and DM;
4. occur mostly transverse to the line-of-sight so that the apparent angular separation of the cluster gas from the galaxies and DM is maximized.

- Only eleven systems confirmed, e.g. 1E 0657-56 (Clowe+06), MACS J0025.4-1222 (Bradac+08), Abell 520 (Mahdavi+07; Okabe & Umetsu 08), Abell 2744 (Merten+11), Abell 2163 (Okabe+11), Musket Ball (Dawson+12) **Abell 1758** (Ragozzine+11).

Merging configuration



Problems



- There is no way to directly observe the main dynamical merger parameters:
  - 3-D relative velocity v_{3D};
  - 3-D separation d_{3D} as function of time;
  - maximum separation d_{max};
  - period between collisions T;
  - time since collision TSC.
- observations are generraly limited to:
  - sub-cluster projected separation d_{proj};
  - the LOS velocity of each cluster v_i from their redshifts;
  - mass M or surface mass density profile.

Problems

- We cannot measure a change in the merger (obviously!);
- It is difficult to constrain the system in an observed state;
- In general, we cannot to constrain the angle α;
- Bullet Cluster: Mach number (X-Ray) $\rightarrow v_{3D} \rightarrow \alpha$ (using too the relative LOS velocities);
- Warning: Springel & Farrar 07 showed that the Mach number only translates to an upper limit on v_{3D} (for the Bullet, they showed that the inferred v_{3D} could be $\sim 2\times$ larger than the real value);
- Other ways from the Mach number: radio relics;

Methods to study the merger dynamics

- Two most prevalent: **the timing argument** and **N-body simulations**;
  - Timing argument (Beers+82; 134 citations): based on the solution to the equations of motion of two gravitational point masses (when $z \rightarrow \infty$, $d_{3D} \rightarrow 0$);
  - N-body simulations have been limited to the Bullet Cluster and have two variants: hydrodynamic and self interacting DM plus collisionless galaxy particles;
- Timing argument is easy to use, but their assumptions result in non-negligible error for dissociative mergers; furthermore it assumes two point mass particles, but this assumption begins to break down as the two sub-clusters overlap and results in divergent solutions near the collision;
- Another weakness: it assumes that the sub-clusters masses are constant since the beginning of the universe (mass accretion history? No! This correction is incompatible with the timing argument method);
- Large covariance between the merger parameters + complexity of the equations of motion: makes the error propagation untenable (a solution is to run few scenarios in order to roughly bound the range of the solutions);
- N-body provides better description, but they are computationally expensive (only Bullet was modelled);

A new method

- Objectives:
  - obtain a solution valid near the collision state;
  - fully estimate the covariance matrix for the merger parameters;
  - be able to analyse a dissociative merger on the order of a day using a typical desktop computer;
- Ingredients: mass of each sub-cluster, redshift of each sub-cluster and projected separation of the sub-clusters.

Model

- Two spherically symmetric NFW halos truncated at r_{200};
- No angular moment;
- v_{max} is the free fall velocity;
- Mass and energy was conserved during the merger;
- $K(t) = \frac{1}{2}\mu v_{3D}(t)^2$
- $V(r) \approx \sum_{i=0}^{N-1}\sum_{j=0}^{N-1}\Phi_1(r'_{ij}+\epsilon)m_{2_{ij}}$ (purely gravitational);
- Null impact parameter (negligible effect);
- Ignores effects of surrounding large scale structure (important $\sim$ 4500 km/s);
- Ignores dynamical friction (more important to slower mergers than the Bullet).

Monte Carlo Analysis

- Starts with the randomly drawing from the PDF of the observables: mass of each subcluster (M_{200}), redshift of each sub-cluster (z_i), projected separation of the sub-clusters (d_{proj});

$$v_{3D_{max}} = \sqrt{-\frac{2}{\mu} V(r = 0)}$$

$$v_i = \left[\frac{(1 + z_i)^2 - 1}{(1 + z_i)^2 + 1} \right] c$$

$$v_{rad}(t_{obs}) = \frac{|v_2 - v_1|}{1 - \frac{v_1 v_2}{c^2}}$$

Monte Carlo Analysis

- α was assumed to be equally probable;
- $PDF(\alpha) = \cos\alpha$

$$v_{3D}(t_{obs}) = \frac{v_{rad}(t_{obs})}{\sin\alpha} \tag{1}$$

$$d_{3D}(t_{obs}) = \frac{d_{proj}(t_{obs})}{\cos\alpha} \tag{2}$$

- if $v_{3D} > v_{3D_{max}}$ merger do not occurs;

Monte Carlo Analysis

$$v_{3D}(t_{col}) = \sqrt{v_{3D}(t_{obs})^2 + \frac{2}{\mu}[V(t_{obs}) - V(t_{col})]} \tag{3}$$

- if $v_{3D} > v_{3D_{max}}$ merger do not occurs;

$$\Delta t = \int_{r_1}^{r_2} \frac{dr}{\sqrt{\frac{2}{\mu}[E - V(r)]}} \tag{4}$$

Monte Carlo Analysis

- Time since collision (TSC);
- Sub-clusters outgoing (TSC_0) or incoming (TSC_1)?
- For TSC_1 is useful to use the time between collisions T:

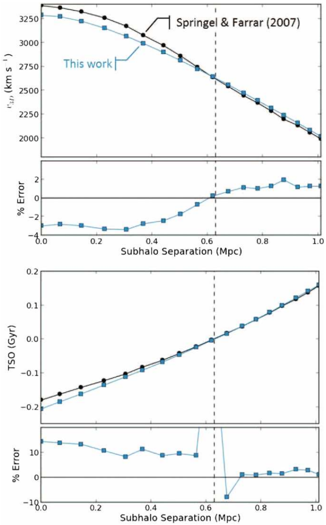
$$T = 2\int_0^{d_{max}} \frac{dr}{\sqrt{\frac{2}{\mu}[E - V(r)]}}$$

$$TSC_1 = T - TSC_0$$

- The majority of the merger time is spent at large separations; observations of the system are more likely near apoapsis than near the collision;
- The probability of each realization is convolved with the prior:

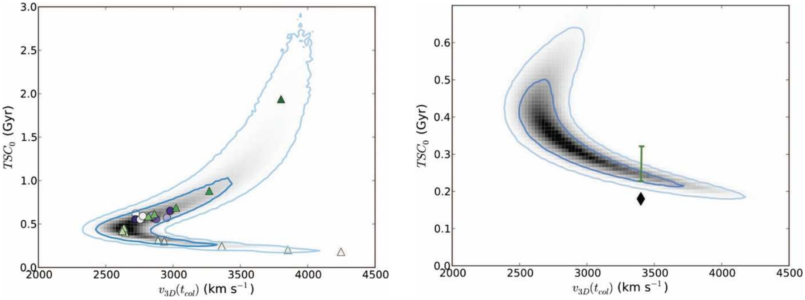
$$PDF(TSC_0) = 2\frac{TSC_0}{T}$$

Comparison with hydrodynamic simulations (Springel & Farrar 07)



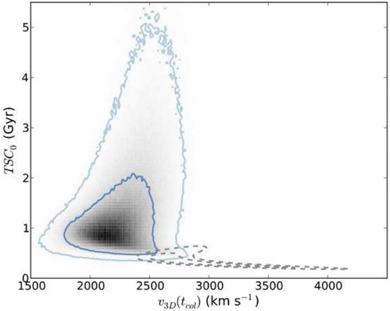
Bullet Cluster dynamics

- PDF was assumed Gaussian;
- 2×10^6 realizations;
- Parameters converge with only 2×10^4 realizations ($\sim$ 6 CPU hours);
- Main results:
  - High degree of covariance between the geometry, velocity and time;
  - Models which disregard the uncertainty in α will fail to capture the true uncertainty in the dynamical parameters;
- Uncertainty in α (dominant source) $\rightarrow$ uncertainty in the geometry, velocity and time parameters (strong correlation);
- A way to measure α: X-ray + redshift (but it overestimate the true v_{3D} for the Bullet $\rightarrow v$ greater than $v_{3D_{max}}$);
- Other priors:
  - observed X-ray shock front;
  - $M_{X-ray} = 2.4 \times M_{lens}$ (due to L and T merger boost, a transient effect);
- Add prior: T boost (duration $\sim 0.4t_{sc}$; entire boost $\sim 1.4t_{sc}$;
- Improves the uncertainty in TSC_0 (180% $\rightarrow$ 67%) and $v_{3D}(t_{col})$ (28% $\rightarrow$ 19%);
- 0% prob. of the Bullet is in the apoapsis and having a returning trajectory.


3.0
2.5
2.0
1.5
1.0
0.5
0.0
TSC_0 (Gyr)
2000
2500
3000
3500
4000
4500
$v_{3D}(t_{col})$ (km s^{-1})
0.6
0.5
0.4
0.3
0.2
0.1
0.0
TSC_0 (Gyr)
2000
2500
3000
3500
4000
4500
$v_{3D}(t_{col})$ (km s^{-1})

Musket Ball dynamics

- Goals: updating analysis and compare its dynamics with the Bullet;
- $3-5\times$ further in time than other confirmed;
- in fact, the Musket is significantly slower and further progressed than the Bullet (at least, $0.8^{+1.2}_{-0.4}$ Gyr more progressed);
- In principle, it could constraint better σ_{DM} since the large offset galaxies-DM (warning: offset will decrease at long time);
- But offset increases as a function of the cluster surface mass density and the collision velocity, both larger in the Bullet;
- SIDM simulations: need for determine when the offset reaches its maximum or which parameters are most important to maximize the offset;
- If the cluster mass and inferred T_{RX} or L_{RX} mass are $\sim$ the same, then $TSC_0 \gtrsim 2t_{sc}$;
- For the Musket, $TSC_0 \gtrsim 1.75$ Gyr (consistent with determination) (not necessary to apply the same prior here).


5
4
3
2
1
0
TSC_0 (Gyr)
1500
2000
2500
3000
3500
4000
$v_{3D}(t_{col})$ (km s^{-1})

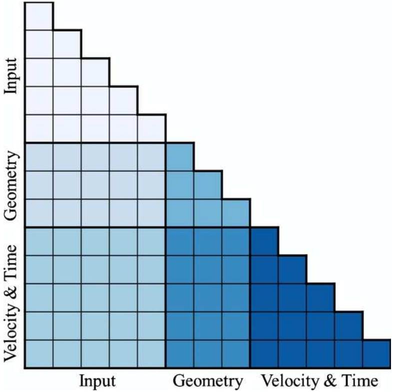
Summary, Conclusions and model improvements

- Addresses the weakness of existing methods:
  - Accurate parameter estimation;
  - Propagation of uncertainty near the collision state.
- Results in $\sim$ 6 CPU hours (SIDM simulation requires $\sim 1 - 10$ million CPU hours);
- Better accuracy compared to N-body simulation;
- Analysis that fail to account the uncertainty for α will underestimate the other uncertainties;
- Priors (ex post facto) can easily be applied to the results of the default priors;
- Musket Ball results are in agreement with previous studies (by same author);

Summary, Conclusions and model improvements

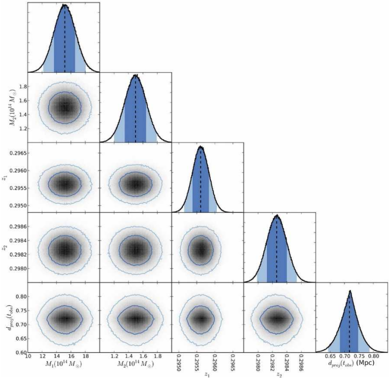
- Open questions:
  - Galaxy evolution;
  - Radio relics;
  - Cluster merger trigger star formation? Quench it? No immediate effect?
- Model improvements:
  - Incorporate sub-cluster mass accretion Physics;
  - Non zero impact parameter;
  - Inclusion of SIDM Physics.

Appendix



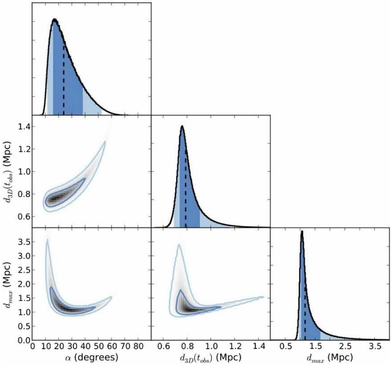
The Input parameters consist of M_{200_1},M_{200_2} , z_1, z_2, and d_{proj}. The calculated Geometry parameters consist of α, d_{3D}, and d_{max}. The calculated Velocity & Time parameters consist of $v_{3D}(t_{obs})$, $v_{3D}(t_{col})$, TSC_0, TSC_1, and T.

Appendix



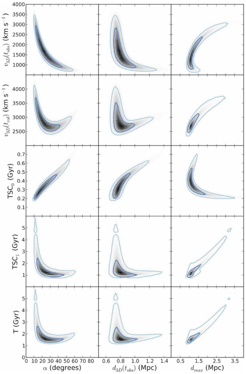
Bullet Cluster marginalized Input vs. Input parameters result plots, for the case including the added temporal prior. Dark and light blue colors correspond to 68% and 95% confidence intervals, respectively. The black dashed line is the bi-weight-statistic location (Beers+982).

Appendix



Bullet Cluster marginalized Geometry vs. Geometry parameters result plots, for the case including the added temporal prior.. Dark and light blue colors correspond to 68% and 95% confidence intervals, respectively. The black dashed line is the bi-weight-statistic location (Beers+82).

Appendix



Bullet Cluster marginalized Geometry vs. Velocity & Time parameters result plots, for the case including the added temporal prior. Dark and light blue colors correspond to 68% and 95% confidence intervals, respectively.