Gravitational Lensing of the Largest Scales

Maruša Bradač
What is dark matter?

Good question.

How do we answer it?

Gravitational lensing!

Gravitational lensing is fantastic™
Why Clusters of Galaxies

- Because they are cool!!
- Studying empirical properties of dark matter
- Study the very tail of the mass function
- Great laboratory for studying the growth of structure -> dark matter and dark energy
Cluster mass reconstruction methods

* Simply parametrized:

  -> Simple, but limited

  -> Bayesian framework allows simple combinations of datasets and can be used to explore errors and degeneracies between parameters

  -> LENSTOOL Kneib et al. 1993 – Jullo et al. 2007

  -> Natarajan et al. 1998 -> study galaxy properties
Cluster mass reconstruction methods

Strong + Weak Lensing: Cl0024 (Kneib et al. 2003)

With sparsely-sampled WFPC2 pointings, Kneib et al have measured the shear out to 5 Mpc.
A combined weak+strong lensing analysis indicates the density profile falls off like $\rho \propto r^{-n}$ with $n>2.4$.
Found a relatively high concentration parameter: $c \sim 22$
Cluster mass reconstruction methods

Cluster galaxies:

- Mass of a halo that hosts an L* galaxy
- Observations
- Simulations

Natarajan et al. 2009
Cluster mass reconstruction methods

* Grid based

  -> Expect unexpected (the only way to explore merging clusters, maybe discover dark clumps)

  -> Bayesian framework can be implemented, errors can be explored

  -> Can be perfect (see D. Coe)

  -> Combination of observations possible (SL+WL Bradac et al. 2005)

  -> Multi-grid method
Cluster mass reconstruction methods

Jullo et al. 2008
Cluster mass reconstruction methods

- Weak lensing (contours)
- Stellar mass (blue)
- Galaxy density (yellow)
- Hot gas (red)

Massey et al. 2007
Dissecting galaxy clusters
Dark matter profile
RX J1347-1145

- One of the most luminous X-ray clusters known
- Post merger system
The Puzzle of RX J1347-1145

- Discovered by ROSAT, intrinsic bolometric X-ray luminosity

- \( L_{\text{bol}} = 5 \times 10^{45} h^{-2} \text{ergs}^{-1} \) from ASCA observations (Schindler et al. 1997)

- Large discrepancies between different mass estimates
  
  \[ \text{M}_{\text{dyne}} < \text{M}_{\text{strong}} < \text{M}_{\text{weak}} \approx M_X \]  
  a factor of 3 between them.

- \( \text{M}_{\text{s+w}} \approx M_X \) (Bradač et al. 2005a)

- New space based (ACS-HST) data (in addition VLT-FORS multicolour data in UBVRI bands, Ks band from ISAAC).
RX J1347-1145

Bradač et al. 2008
RX J1347-1145

Bradač et al. 2008
Gravitational Lensing of the Largest Scales

RX J1347-1145

Bradač et al. 2008
RX J1347-1145 Mass Estimates

Bradač et al. 2008
Gravitational Lensing of the Largest Scales

Maruša Bradač

Dissecting RX J1347-1145

Bradač et al. 2008

Fitting NFW profile to dark matter

\[ \rho_{DM}(r) = \frac{\rho_{0,DM}}{(r/r_s)^\beta (1 + r/r_s)^{3-\beta}} \]

\[ \beta = 0 \quad c_{200} = 15 \quad r_{200} = 2400 \text{ kpc} \]

\[ \beta = 1 \quad c_{200} = 6 \quad r_{200} = 2200 \text{ kpc} \]
Cluster mass reconstruction methods

Constraints on Inner Slope with observationally motivated prior of $r_{sc} = 100-200$ kpc

Sand et al 2008
Dissecting galaxy clusters

- Great way to probe dark matter profiles
- Analyses underway to include strong+weak+dynamics
- Need large sample of clusters, uniformly analysed
The Nature of Dark Matter
The Bullet Cluster
1E0657-56
The Bullet Cluster 1E0657-56

- One of the hottest and most luminous X-ray clusters known.
- Unique case of a major supersonic cluster merger occurring nearly in the plane of the sky ($i < 15^\circ$, Markevitch et al. 2002).

- Using the gas density jump at the shock we derived a shock Mach number of $3.2 \pm 0.8$, which corresponds to a shock velocity $4500 \pm 1000 \text{ kms}^{-1}$

- Subcluster velocity $\sim 2700 \text{ kms}^{-1}$ (Springel & Farrar 2007)
The Bullet Cluster 1E0657-56
Gravitational Lensing
1E0657-56: Strong and Weak Lensing

Total Matter

Gas

Bradač et al. 2009

KISS, July 16 2009
Gravitational Lensing of the Largest Scales

1E0657-56: Strong and Weak Lensing

Only weak lensing

Strong and weak lensing

Clowe, MB et al. 2006

Bradač et al. 2009
1E0657-56: Strong and Weak Lensing

Only weak lensing

Strong and weak lensing

Clowe, MB et al. 2006

Bradač et al. 2009
Dark Matter Properties

* Combining the Chandra data with lensing mass maps -> place an upper bound on the dark matter self-interaction cross section \( \sigma/m < 1 \text{ cm}^2 \text{g}^{-1} = 1.8 \text{barn/GeV} \) (Markevitch et al. 2004).

  -> Significant offset between subcluster X-ray gas core and dark matter peak gives \( \sigma/m < 10 \text{ cm}^2 \text{g}^{-1} \)

  -> Survival of the subcluster dark matter peak during interaction gives \( \sigma/m < 3 \text{ cm}^2 \text{g}^{-1} \)

  -> No loss of mass from subcluster during interaction gives \( \sigma/m < 0.8 \text{ cm}^2 \text{g}^{-1} \)

* \( \sigma/m < 0.7 \text{ cm}^2 \text{g}^{-1} = 1.3 \text{barn/GeV} \) (Randall et al.2008)

* SI dark matter \( \sigma/m < 0.5 - 5 \text{cm}^2 \text{g}^{-1} \) (Dave et al. 2001).
Really Direct Evidence for Dark Matter?

* Adopting MOND gravity:

  -> Angus et al. (2006) - Can fit weak lensing surface mass density predictions with gas+2eV Neutrino model

  -> Still require > 70% of the mass to be hot non-baryonic matter

  -> Incompatible with strong+weak lensing analysis.

  -> Gas mass too low for the subcluster.

* Moffat (2006) - MOG to displace surface mass density peaks away from gas peaks - very unphysical profile.
The Nature of Dark Matter
Really collision-less?
Cosmic Train Wreck A520
A520 – Cosmic "Train Wreck"
A520 – Cosmic "Train Wreck"
The galaxies originally in the dark core could have been ejected through a multiple-body interaction.

Weakly self-interacting dark matter: requiring $3.8 \pm 1.1 \text{ cm}^2\text{g}^{-1}$
(Bullet cluster constraints $\sigma/m < 0.7 \text{ cm}^2\text{g}^{-1} = 1.3\text{barn/GeV}$)
Finding more Bullet-like clusters
Finding more Bullet-like clusters
The Nature of Dark Matter
The “Baby” Bullet Cluster
MACSJ0025-1222
Baby Bullet* Cluster MACSJ0025-1222

Neither baby (daddy!) nor bullet

- F450W WFPC2 5orbits
- F555W ACS 2orbits
- F814W ACS 2orbits
Galaxy Distribution

- Two cluster at the same redshift (0.586±0.001) separated by 600 kpc (projected)

- Velocity separation of the BCG’s radial direction
  \[ \Delta z = 0.0005\pm0.0004 \quad (100\pm80 \text{ km/s}) \]

- Richness / stellar masses of an average massive cluster.

  SE(<300kpc): \( 2.7 \times 10^{12} M_\odot \) (3.6 \( \times 10^{12} L_\odot \))

  NW(<300kpc): \( 1.9 \times 10^{12} M_\odot \) (2.5 \( \times 10^{12} L_\odot \))
Gas Distribution

- 38ks Chandra (115ks more to come)
- Gas peak
- Too shallow to see a shock front
Why is Daddy Bullet not a “Bullet”

- The Bullet cluster is a merger of a cool core (low entropy gas) and a non-cool core cluster
- Daddy Bullet is a merger of two non-cool core clusters
- Dynamical information from the shock – still likely
Why is Daddy Bullet not a “Bullet”
Total Mass Distribution
Mass vs. Light

S&W Lensing
K-band Light

Bradač et al. 2008b
Gravitational Lensing of the Largest Scales

Mass vs. Gas

S&W Lensing
X-ray gas

Bradač et al. 2008b
Dissecting MACSJ0025-1222 Into Dark Matter and Baryons

* Significant offset of both sub-cluster peaks from the gas peak

> 4σ
Dark Matter Properties

* Combining the Chandra data with lensing mass maps -> place an upper bound on the dark matter self-interaction cross section \( \sigma/m < 4 \text{ cm}^2\text{g}^{-1} = 8 \text{ barn/GeV.} \)

-> Significant offset between subcluster X-ray gas core and dark matter peak

\[
\tau = \sum \frac{\sigma}{m}
\]

-> Survival of the subcluster (need velocity info)

-> No loss of mass from subcluster

* The Bullet Cluster: \( \sigma/m < 0.7 \text{ cm}^2\text{g}^{-1} = 1.3\text{barn/GeV} \) (Randall et al.2008)
A Mommy Bullet or Daddy Trainwreck?

von der Linden et al. in prep.
Decaying Dark Matter?

- Idea: Use gas-depleted dark matter concentrations in cluster mergers to look for X-ray signatures of radiatively decaying DM

- How: Combine S+W lensing measurements + X-ray flux measurements

- Examples:
  
  -> Sterile neutrinos: Riemer-Sørensen et al. (2007), Boyarsky et al. (2007)

  -> Kaluza-Klein axions: Riemer-Sørensen et al. (2007)
Decaying Dark Matter?

Sterile neutrinos:

Kaluza-Klein axions - lower limit on luminosity, upper limit on $\tau \gtrsim 10^{26}$ s
And now for something completely different.....

Reionization is important!
Using Cosmic Telescopes to Study First Galaxies
High-z Universe
**Lensing is fantastic!**

**Large magnification factors, allows us to get larger number counts (provided the luminosity function is steep)**

**Large areas with observed multiple images – much eased identification; no need for often prohibitive spectroscopy**

**Magnification maps are known to sufficient accuracy to constrain the number counts (and for best cases also individual luminosities)**

**With good mass (hence magnification) map -> errors under control Bradač et al. (2009)**
High-z Universe through 1E0657-56
Not quite yet

Cycle 16 NICMOS -> Cycle 17 WFC3 YAY!!

Deep ACS data: F606W (V, 2340s), F775W (i, 10150s), and F850LP (z, 12700s)

Search for V and i-band dropouts -> z=5-6 population, compare with blank surveys

-> GOODS (v1): V - 5000s, i - 5000s, z - 10660s (320 arcmin$^2$)

-> HUDF: V - 135ks, i - 347ks, z - 347ks (10 arcmin$^2$)
It Works! Galaxies at $z=5-6$

$Z \sim 5$ (V-dropouts)  
$Z \sim 6$ (i-dropouts)  

GOODS, UDF

De-lensed (intrinsic)  
This work (lensed)  
This work (intrinsic)  
Stark et al. (2009)  
Bouwens et al. (2007)  
Beckwith et al. (2006)
Gravitational Lensing of the Largest Scales

Mostra Bradač

DARK MATTER
Most of the universe can't even be bothered to interact with you.

S. Carroll

KISS, July 16 2009