Hot, massive, and awfully complicated

Measuring the mass of the merging cluster 1E0657-56 using strong and weak gravitational lensing

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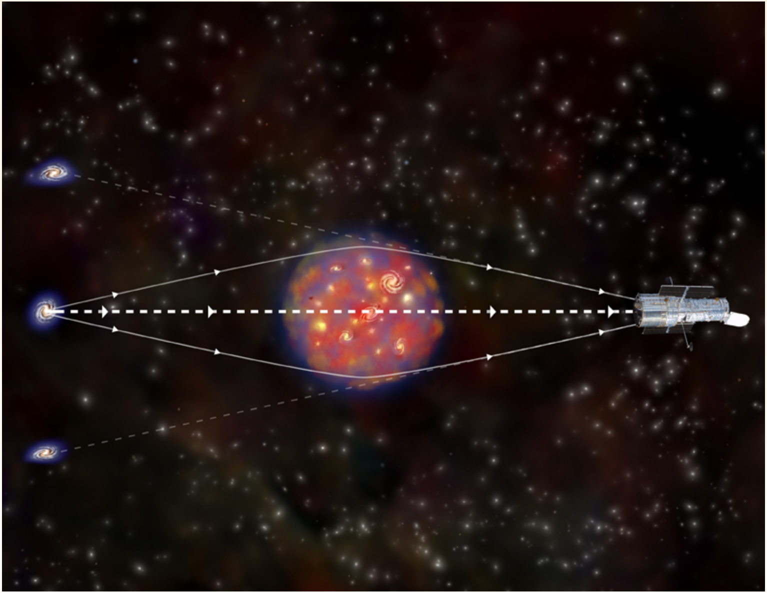
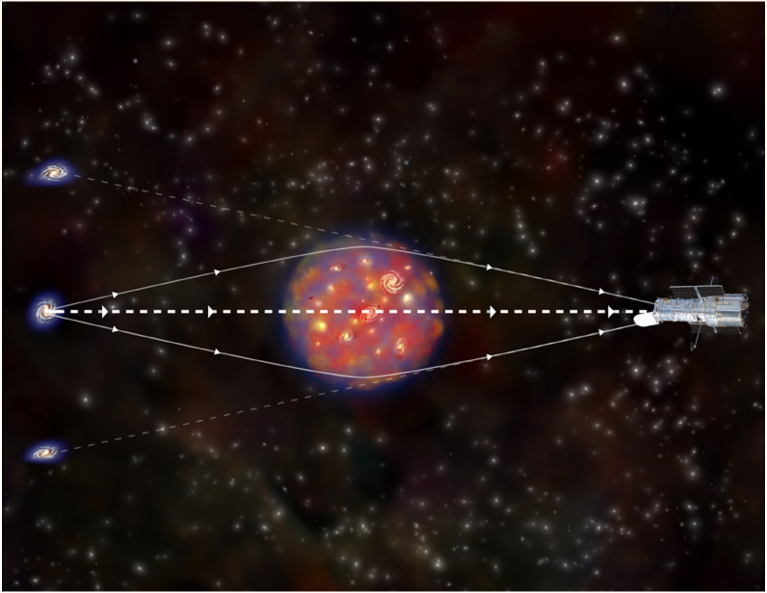
26^{th} September 2006

Clusters are

- ...great tools for cosmology!!
- How to measure cluster mass distribution?
  - X-ray
  - Dynamical methods
  - Gravitational lensing
- One cluster, three methods, same result??!!! In principle yes, in practice....





Strong or weak lensing?

- Strong or weak?
  - Strong lensing sets tight constraints on the mass distribution near θ_{E} and often relies on parametrised models.
  - Weak lensing measures the mass distribution over the entire observed field.
- Problems like mass-sheet degeneracy Bradač et al. (2004) (weak), extending mass measurements to small radii (weak), extending mass measurements to large radii (strong) can all be eliminated by doing:

$\Rightarrow$ Strong AND Weak!!

Strong and weak lensing united

- The idea of combining weak and strong lensing not new (e.g. Natarajan and Kneib 1996; Abdelsalam et al. 1998; Kneib et al. 2003; Diego et al. 2005; Cacciato et al. 2005).
- We combine strong and weak lensing constraints in a "non-parametric" fashion (parametrisation as general as possible).
- Need to properly include weak lensing constraints in the vicinity where multiple images form (and the lens is not weak any longer).
- Include redshift information for strong (and weak) lensing sources (helps breaking the mass-sheet degeneracy).
- Bradač et al. (2006) and Bradač et al. (2005).

Strong and weak lensing united

- Following the idea of Bartelmann et al. (1996) we parametrise the lens by considering the values of the potential ψ_k on a regular grid.
- The penalty function includes weak lensing (extended to the cluster centre), strong lensing and regularisation.

$$\chi^2(\psi_k) = \chi^2_\epsilon(\psi_k) + \chi^2_{\mathrm{M}}(\psi_k) + \eta R(\psi_k)\ . \tag{1}$$

- Start from some trial solution, linearise and iteratively solve the equation

$$\frac{\partial}{\partial \psi_k} \chi^2(\psi_k) = 0\ . \tag{2}$$

Outline of the method

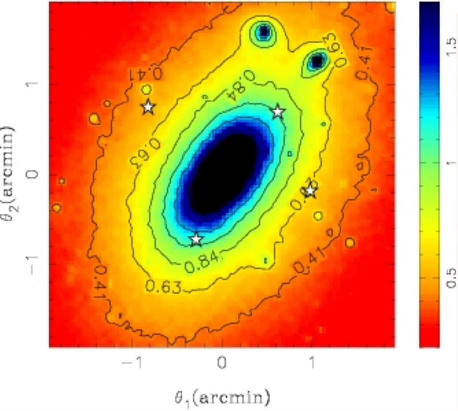
- Start from some trial solution, linearise and iteratively solve the equation

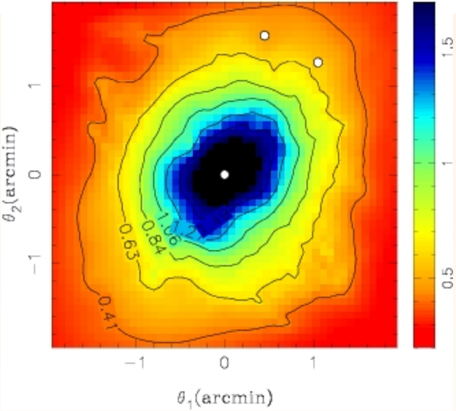
$$\frac{\partial}{\partial \psi_k} \chi^2(\psi_k) = 0 \ . \tag{3}$$

$\Rightarrow$ Trial solution from strong lensing, weak lensing, or set $\kappa_{ij}^{(0)} = 0$, etc.

$\Rightarrow$ $\kappa(\vec{\theta}_i)$, $\gamma(\vec{\theta}_i)$, and $\vec{\alpha}(\vec{\theta}_m)$ are written in terms of ψ_k by using finite differencing methods and bilinear interpolation. Keep all non-linear terms fixed in each iteration step.

Testing of the method - simulations

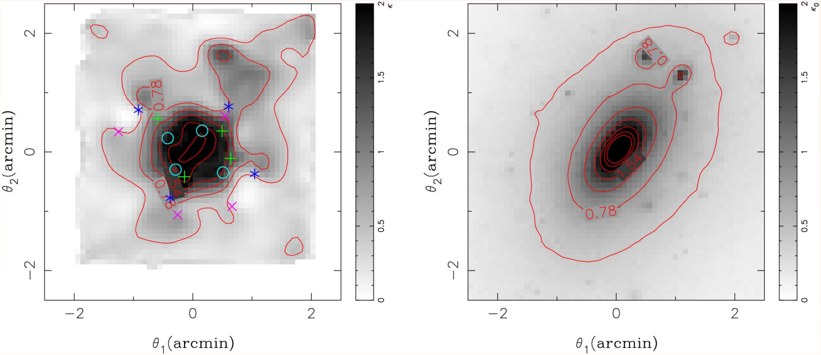




κ from sim. (V. Springel)
$M_\mathrm{t}(< 340\,\mathrm{h}^{-1}\mathrm{kpc}) = 0.99\ 10^{15} M_\odot$
$z_d = 0.4$, $z_\mathrm{s} = 1.76$
3.8×3.8 arcmin^2

Reconstructed κ (ground based quality)
$M_\mathrm{I}(< 340\,\mathrm{h}^{-1}\mathrm{kpc}) = (1.0 \pm 0.1)\ 10^{15} M_\odot$
$N_\mathrm{g} = 210$, z from WL data
$\sigma_\epsilon = 0.2$, $\sigma_\mathrm{err} = 0.1$

Testing of the method - simulations



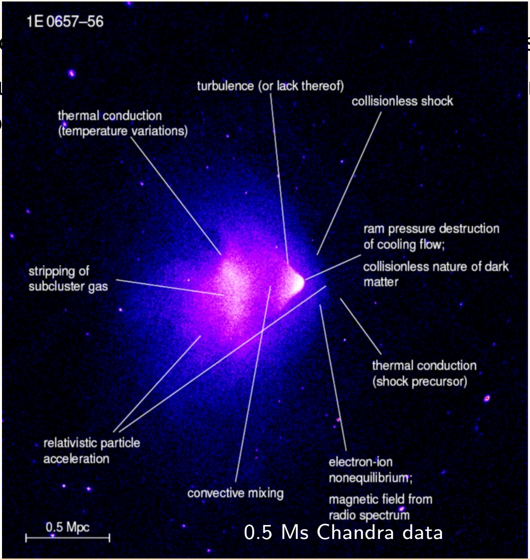
Improvement when using space based data

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).

The bullet cluster 1E0657−56

- One … sters known.
- Uniq … r occurring nearly in the p … 2002).



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 they derived a shock Mach number of 3.2 ± 0.8, which corresponds to a subcluster velocity 4500^{+1100}_{-800}km s^{-1}.
- "How Rare is the Bullet Cluster?" (Hayashi and White 2006). Rare, but not exceptionally.
- The peak of the density of the cluster galaxies is offset from the X-ray halo at 3.4σ significance.
- What does our your grandmother's$^{\mathrm{TM}}$ gravity has to say about the system?

The bullet cluster

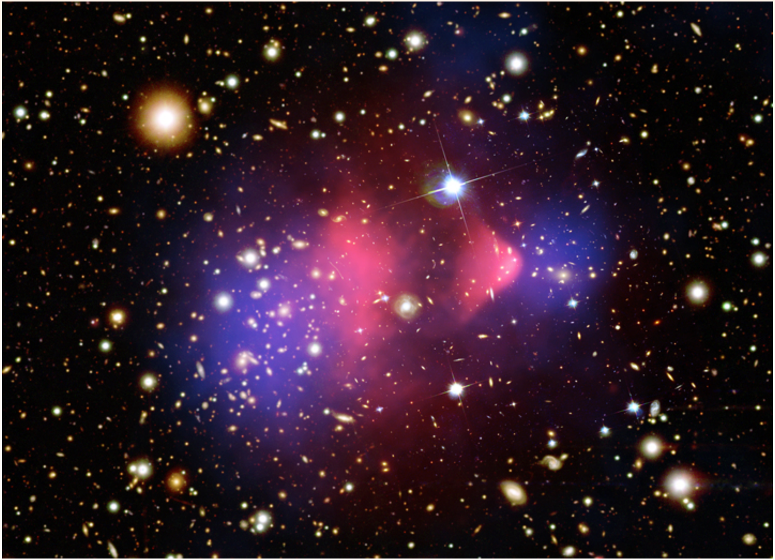
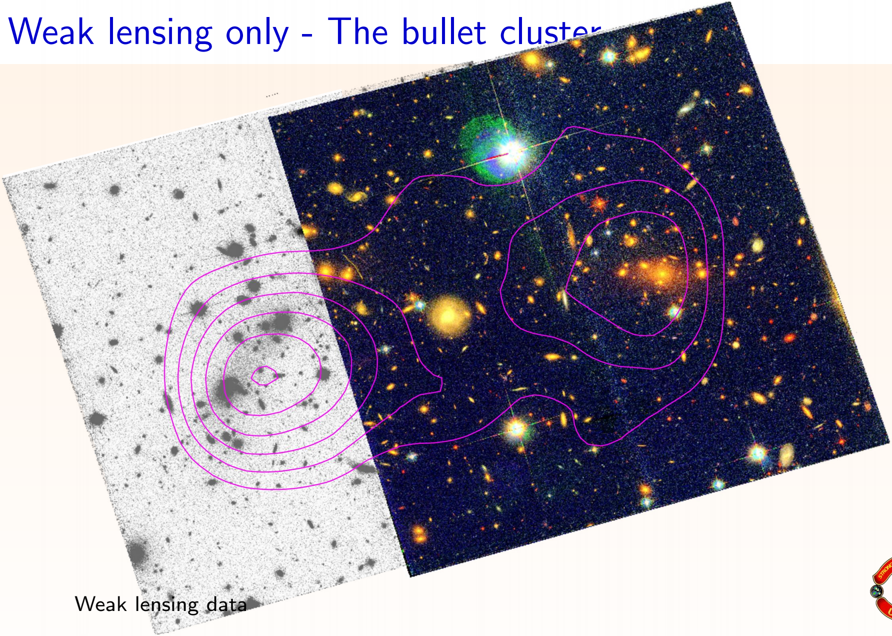


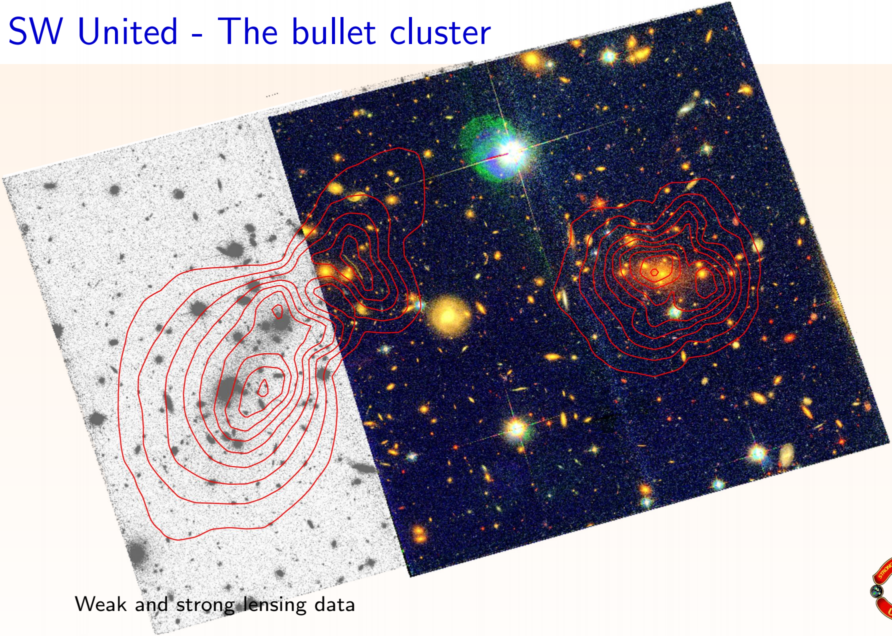
Image: Clowe et al. (2006); Movie: John Wise, KIPAC

Weak lensing only - The bullet cluster



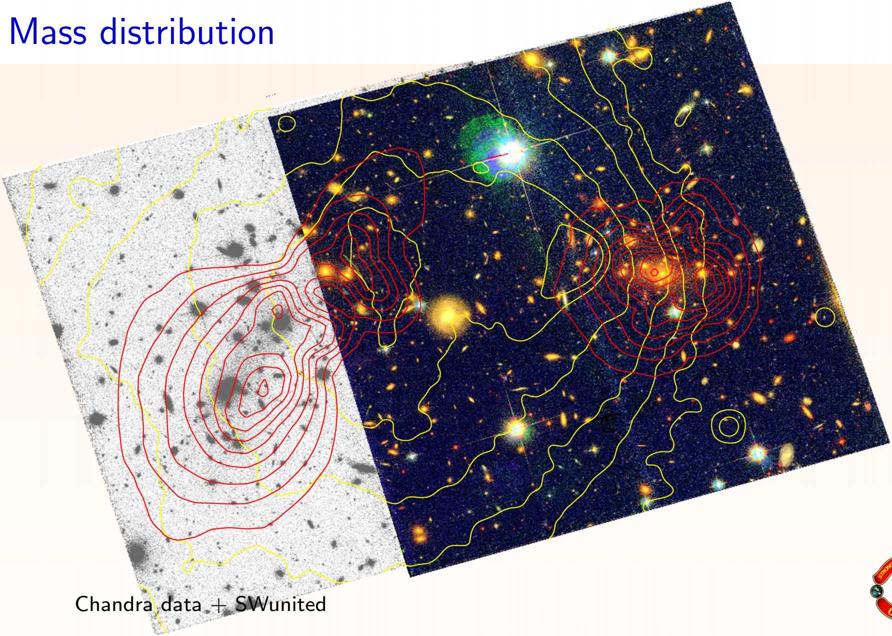
Weak lensing data

SW United - The bullet cluster



Weak and strong lensing data

Mass distribution



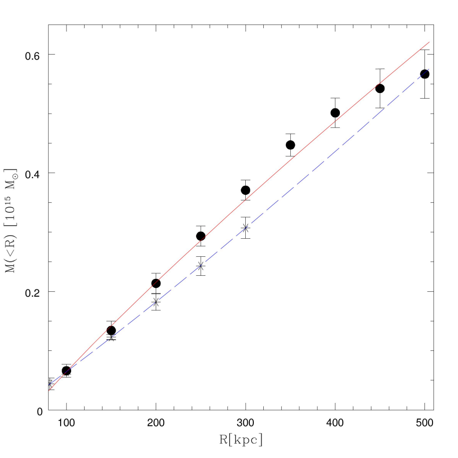
Chandra data + SWunited

Mass distribution - in numbers

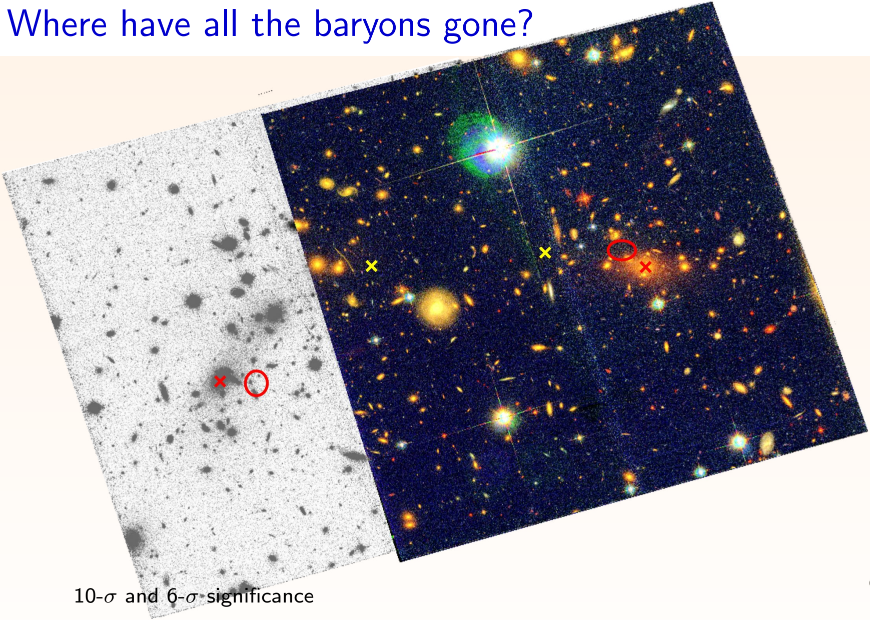
- Only the combination of weak+strong lensing allow us to derive a high-resolution, absolutely calibrated mass map, with no assumptions on the physical properties of the underlying cluster potential.
- Projected, enclosed mass
  $M_{\rm main}(< 250\,\mathrm{kpc}) = (2.8 \pm 0.2) \times 10^{14} M_\odot$
  $M_{\rm sub}(< 250\,\mathrm{kpc}) = (2.3 \pm 0.2) \times 10^{14} M_\odot$
- Assuming an isothermal profile (do you actually believe this assumption?)
  $\sigma_{\rm main} = (1400 \pm 100)\,\mathrm{km\,s^{-1}}$
  $\sigma_{\rm sub} = (1200 \pm 100)\,\mathrm{km\,s^{-1}}$

Mass distribution - profile

- The integrated mass profile (fit $\kappa(r) \propto r^{-n}$, $n_{\rm main} = 1.2$, and $n_{\rm sub} = 0.9$):



Where have all the baryons gone?



10-σ and 6-σ significance

Dark matter properties

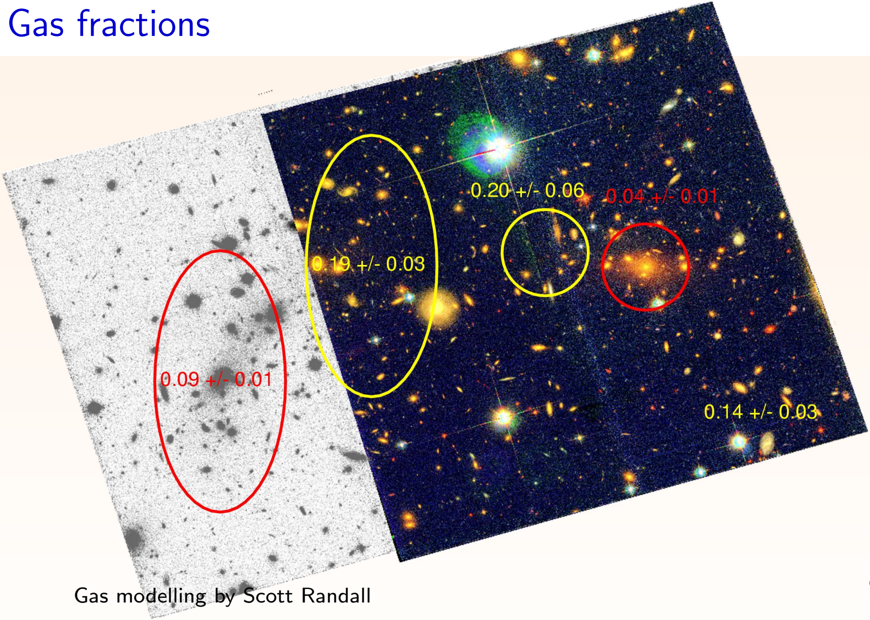
- Combining the Chandra data with lensing mass maps $\Rightarrow$ place an upper bound on the dark matter self-interaction cross section $\sigma/m < 1\mathrm{cm}^2\mathrm{g}^{-1}$ (Markevitch et al. 2004).

$\Rightarrow$ Significant offset between subcluster X-ray gas core and dark matter peak gives $\frac{\sigma}{m} < 10\ \mathrm{cm}^2 g^{-1}$.

$\Rightarrow$ Survival of the subcluster dark matter peak during interaction gives $\frac{\sigma}{m} < 3\ \mathrm{cm}^2 g^{-1}$.

$\Rightarrow$ No loss of mass from subcluster during interaction gives $\frac{\sigma}{m} < 0.8\ \mathrm{cm}^2 g^{-1}$.

Gas fractions



Gas modelling by Scott Randall

Really direct evidence for dark matter?

- Adopting not-your-grandmothers gravity:

⇒ Angus et al. (2006) - Can fit weak lensing kappa contours with gas+2eV Neutrino model

⇒ Moffat (2006) - MOG to displace kappa peaks away from gas peaks - very unphysical profile.

Conclusions

- Only the combination of strong and weak lensing lets us break the mass-sheet degeneracy.
- Very powerful to constrain mass distribution in the cores of the clusters and to reconstruct the critical curves (especially where "standard" parametric modelling fails.
- We have obtained tight constraints on mass-distribution in 1E0657−56 - most of the matter not where most of the baryons are!
- A unique cluster merger system - combining all possible data sets there is a lot to be learned - constraints on DM self interaction cross section, gas physics, cluster dynamics, merger history, ...
- Gravitational lensing is truly golden for this "golden lens".

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