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El Gordo: a massive blow to ΛCDM cosmology

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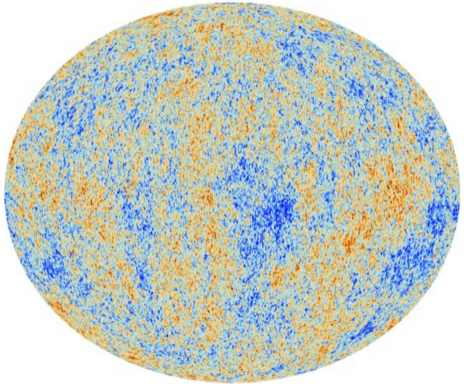
Publication: A massive blow for ΛCDM – the high redshift, mass, and collision velocity of the interacting galaxy cluster El Gordo contradicts concordance cosmology (MNRAS 500, 5249)

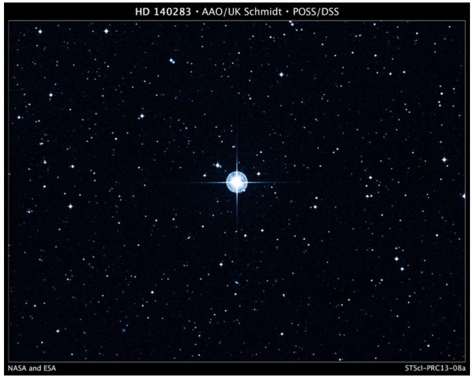
Hierarchical structure formation

Density fluctuations



Cosmic microwave background seen by Planck 2013. Copyright: ESA, Planck Collaboration

Small structures (e.g. stars)



Star HD 140283. Credit: Digitized Sky Survey (DSS), STScI/AURA, Palomar/Caltech, and UKSTU/AAO

Large structures (e.g. galaxies)

Spiral Galaxy M81.Image credit: X-ray: NASA/CXC/SAO; Optical: Detlef Hartmann; Infrared: NASA/JPL-Caltech

The largest structures: galaxy clusters

Galaxy cluster Abell 1689. Credit: NASA, ESA, the Hubble Heritage Team (STScI/AURA), J. Blakeslee (NRC Herzberg Astrophysics Program, Dominion Astrophysical Observatory), and H. Ford (JHU)

If the cosmological model is correct, it should statistically predict when these formed

In recent years, surveys found…

SPT-CL J2106-5844

- z = 1.13
- Mass $\simeq$ 1 x 10^{15} $M_\odot$

ACT-CL J0102-4915 (El Gordo)

- z = 0.87
- Mass $\simeq$ 3 x 10^{15} $M_\odot$
- $V_{infall} \simeq$ 2500 km/s

1E 0657-56 (The Bullet Cluster)

- z = 0.30
- Mass $\simeq$ 2.2 x 10^{14} $M_\odot$
- $V_{infall} \simeq$ 3000 km/s

PLCK G287.0+32.9

- z = 0.39
- Mass $\simeq$ 2 x 10^{15} $M_\odot$

...and more

ΛCDM predicts that galaxy clusters at $z \simeq 1$ should have a maximum mass of $M \simeq 1.7 \times 10^{15}$ $M_\odot$, so objects with a similar mass should be extremely rare.

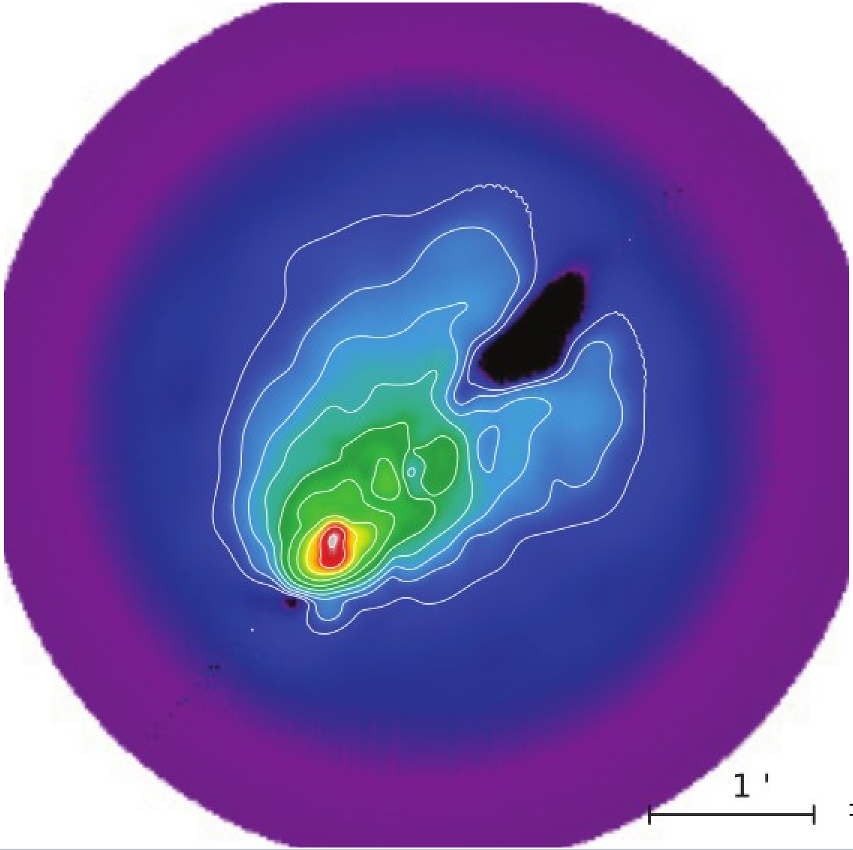
But…
$M_{El\ Gordo} \simeq 3 \times 10^{15}$ $M_\odot$ at z = 0.87!!

El Gordo (ACT-CL J0102-4915)

- Redshift: z = 0.87 (more than 7 billion light years from Earth)
- Two subclusters of total mass $M_{200} \simeq 3 \times 10^{15}\ M_\odot$ and mass ratio of 3.6.
- Infall velocity: $V_{infall} \simeq 2500$ km/s (1.24x its escape velocity)
- Most X-ray luminous, and brightest Sunyaev-Zel'dovich (SZ) effect galaxy cluster at this redshift.
- X-ray emission morphology: single peak and two faint tails.

El Gordo in X-ray light from NASA's Chandra X-ray Observatory in blue, along with optical data from the European Southern Observatory's Very Large Telescope (VLT) in red, green, and blue, and infrared emission from the NASA's Spitzer Space Telescope in red and orange. Credits: X-ray: NASA/CXC/Rutgers/J. Hughes et al; Optical: ESO/VLT & SOAR/Rutgers/F. Menanteau; IR: NASA/JPL/Rutgers/F. Menanteau.

El Gordo (Menanteau+ 2012)

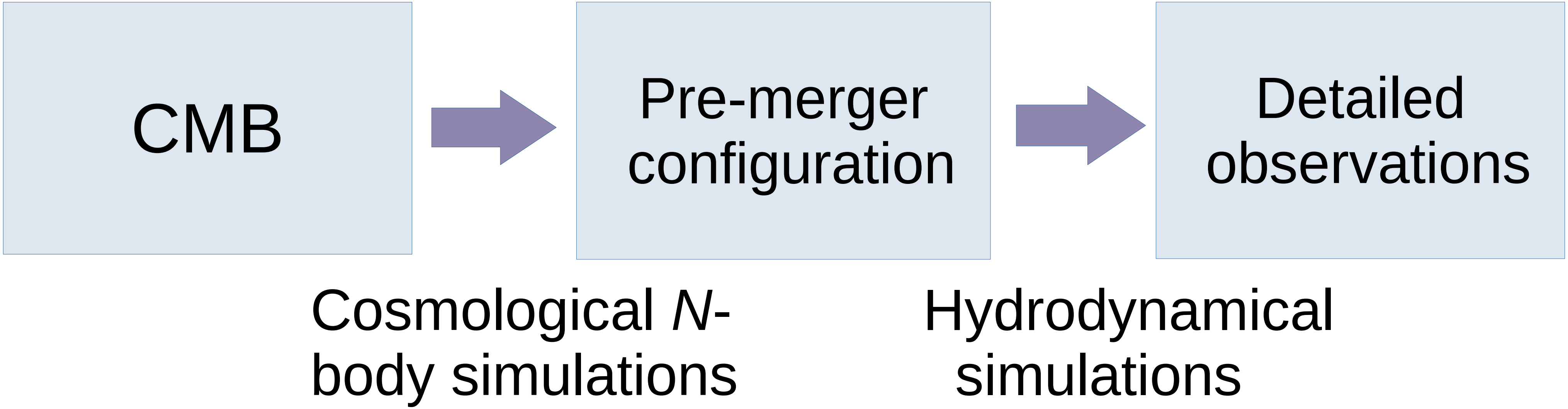


= 471 kpc

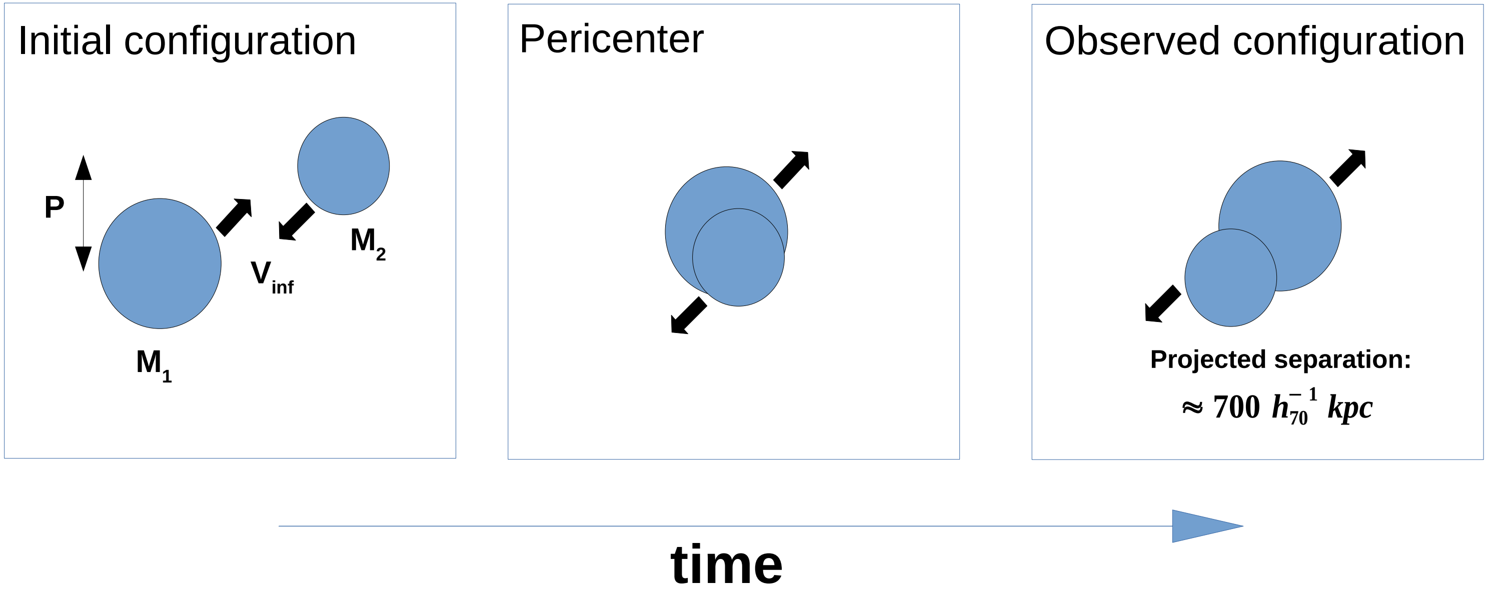
Map of the electron density in the mid-plane of ACT-CL J0102−4915 (El Gordo) from a deprojection of the Chandra image (Menanteau+ 2012, figure 14).

How rare is El Gordo in ΛCDM cosmology?

Outline of the method



Hydrodynamical simulations of El Gordo



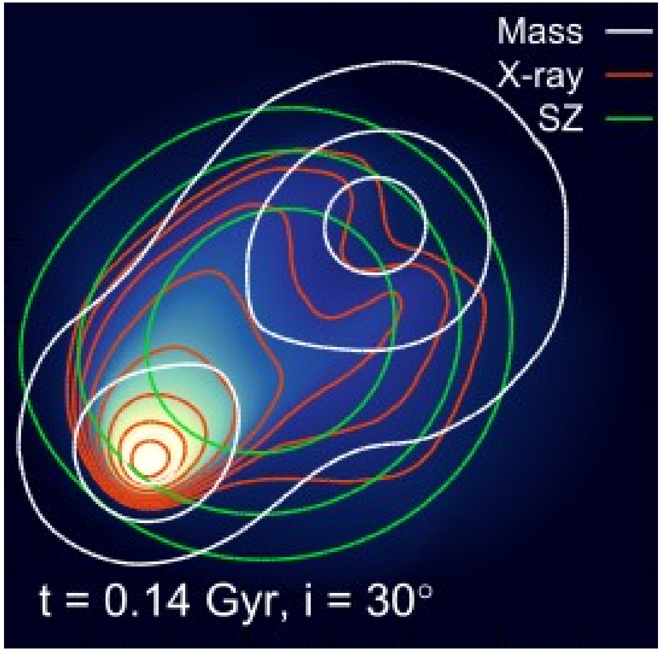
Does it match...?

- $L_X \approx 2 \times 10^{45}\ h_{70}^{-2}\ erg\ s^{-1}$
- Single X-ray peak and two tail morphology
- Observed distance between X-ray and Sunyaev-Zel'dovich centroids.

Hydrodynamical simulation: Zhang et al. 2015

- Zhang et al. 2015 ran 123 simulations for different parameters looking for the best fit to the El Gordo observations.
- Best fits for two different models of the El Gordo interaction:

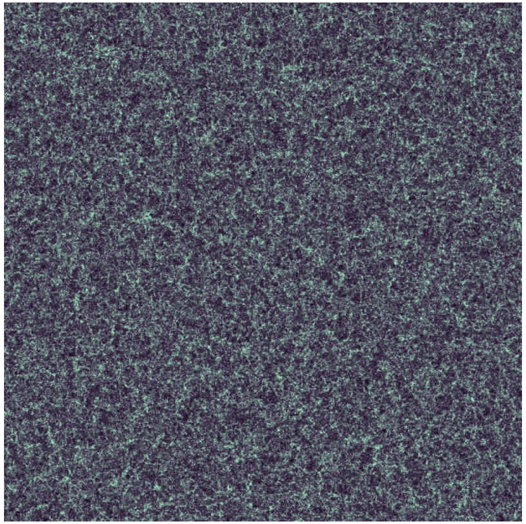
	Model A	Model B
Interaction	extremely energetic head-on collisions	off-centre collisions of two massive clusters
M_{tot}	$1.95 \times 10^{15}\ M_\odot$	$3.19 \times 10^{15}\ M_\odot$
M_{ratio}	2	3.6
V_{infall}	3000 km/s	2500 km/s
Impact parameter	$300\ h_{70}^{-1}$ kpc	$800\ h_{70}^{-1}$ kpc
Two tailed X-ray morphology	No	Yes



X-ray surface brightness, mass surface density, and SZ effect distributions for a merging cluster with the best fit configuration. Snapshot at 0.14 Gyrs after the start of the simulation and viewed under a 30º angle. Simulated using a SPH code. Credit: Zhang et al. 2015.

Cosmological simulation: the Jubilee simulation

- We used the largest $(6\ h^{-1}\ cGpc)^3$ volume box of the Juropa Hubble Volume Simulation (Jubilee) project (Watson+ 2013).
- *N*-body ΛCDM simulation based on the Wilkinson Microwave Anisotropy Probe (WMAP) results: $\Omega_{m,0} = 0.27$, $\Omega_\Lambda = 0.73$, $h = 0.7$, $\sigma_8 = 0.8$, $n_s = 0.96$, $\Omega_{b,0} = 0.044$
- Post-processed with Amiga Halo Finder (AHF) (Gill 2004; Knollmann & Knebe 2009)
- Available at redshifts $z = 0$, $z = 0.509$, $z = 1$, and $z = 6$.
- Particle mass $7.49 \times 10^{10}\ h^{-1}\ M_\odot$
- Lowest mass halo $1.49 \times 10^{12}\ h^{-1}\ M_\odot$ (20 particles, section 2 of Watson+ 2014b).



Halo distribution in the Big Jubilee simulation. Source: Jubilee Project

Initial pair selection

1) Consider only galaxy clusters: require $M_{200} > 3.5 \times 10^{13} M_\odot$

2) Compare pairs with tree-based code (we only compare pairs which can have an encounter within 100x the lifetime of the Universe to reduce computational costs).

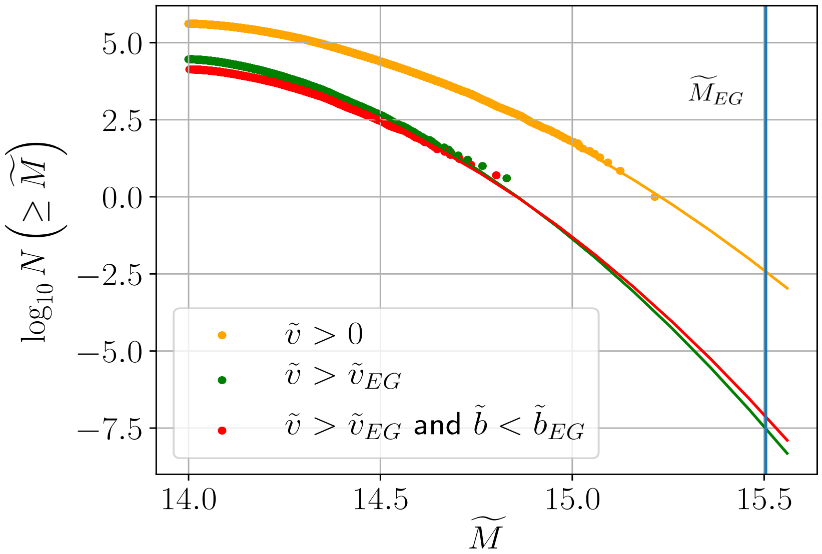
3) Select those which have:

- Turned around from cosmic expansion $(v \cdot r < 0)$
- Mass ratio ≤ 3.6.

Finding El Gordo analogues among the selected pairs

Further conditions to be considered El Gordo analogues:

- Redshift $z = 1$
- Ratio $\widetilde{b}$ between impact parameter and total virial radius (R_{200}) : $\widetilde{b} \leq \widetilde{b}_{EG} = 3.42$
- Ratio $\widetilde{v}$ between infall velocity and escape velocity at $2 \cdot R_{200}$: $\widetilde{v} \geq \widetilde{v}_{EG} = 1.24$
- Total virial mass: $M_{200} \geq M_{200,EG} = 3.19 \times 10^{15}$ ($\widetilde{M} \equiv \log_{10}(M_{200}/M_{\odot}) \geq \widetilde{M}_{EG} = 15.50$)



The total mass condition leaves us with no analogous systems in the entire Jubilee volume. We infer the number of El Gordo analogues from a quadratic fit to the cumulative mass distribution function of the selected pairs (in $\log_{10}$ scale): $\log_{10} N(\geq \widetilde{M}) = c_0 + c_1 \widetilde{M} + c_2 \widetilde{M}^2$

Statistical analysis: the power-law method

- Number of analogues with $\widetilde{M} \geq \widetilde{M}_{EG}$ and $\widetilde{v} \geq \widetilde{v}_{EG}$ in the Jubilee volume of (6 h^{-1} cGpc)^3 at z = 1: $N_{Jubilee} \simeq 3.16 \times 10^{-8}$

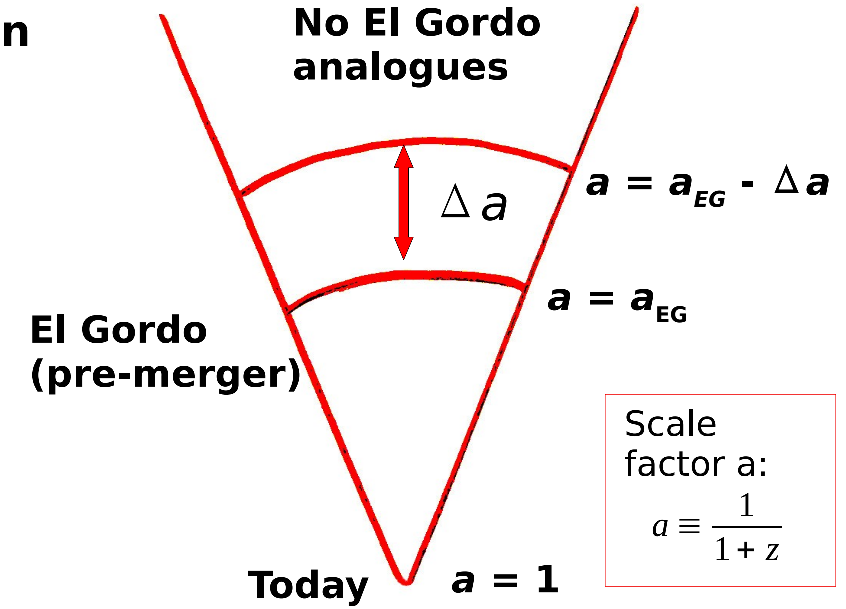
How many analogues does this correspond to in the El Gordo survey volume?

- El Gordo survey volume:

Survey area: A = 755 deg^2 (Menanteau+ 2012)

Survey depth: from $z = z_{EG}$ to z = …?

The effective survey depth is limited by the fact that analogues to El Gordo rapidly become very rare with increasing z.



Scale factor a:
$$a \equiv \frac{1}{1+z}$$

Statistical analysis: the power-law method

Obtaining Δa:

- By estimating the number of El Gordo analogues at z = 1 and at z = 0.509, we infer how the number of analogues increases with the scale factor *a*:

Growth index (k): $n = C\,a^{k} \Rightarrow k \equiv \frac{\Delta \ln n}{\Delta \ln a}$ (with $k = 35.55$ for $\widetilde{M} \geq \widetilde{M}_{EG}$ and $\widetilde{v} \geq \widetilde{v}_{EG}$)

- Number of El Gordo analogues in the observed co-moving volume at $a < a_{EG}$:

$$\int n\, dV_{com} = \int_0^{a_{EG}} n \cdot \frac{dV_{com}}{da}\, da \approx \int_0^{a_{EG}} C\, a^{k} \cdot a^{-2.83}\, da = \frac{C\, a_{EG}^{k+1-2.83}}{k+1-2.83}$$

$$\equiv$$

$$n \cdot \Delta V_{com} = n \cdot \frac{dV_{com}}{da}\, \Delta a = C\, a_{EG}^{k} \cdot a_{EG}^{-2.83} \cdot \Delta a$$

$$\Rightarrow \Delta a = \frac{a_{EG}}{k - 1.83}$$

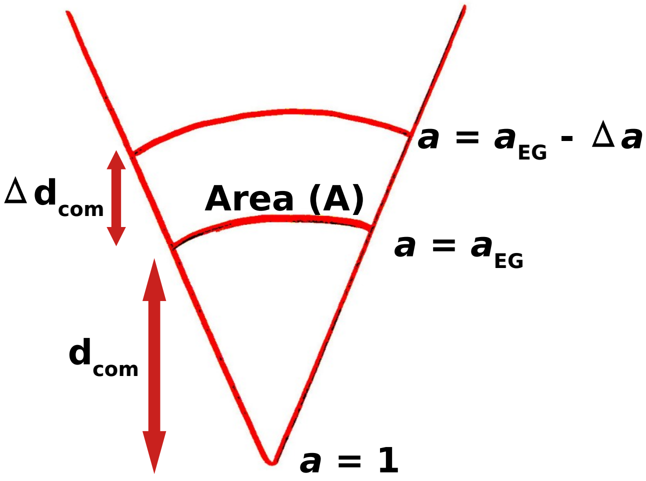
($\Delta a = 0.015$ for $\widetilde{M} \geq \widetilde{M}_{EG}$ and $\widetilde{v} \geq \widetilde{v}_{EG}$)

with: $\frac{dV_{com}}{da} = \frac{cA\, d_{com}^{2}}{a\, H} \propto a^{-2.83}$

Statistical analysis: the power-law method

Obtaining the survey effective volume and the corresponding number of analogues:

- Effective volume: $V_{eff} = A \cdot d_{com}^2 \cdot \Delta d_{com}$
- $V_{eff} = 0.417\ cGpc^3$ for $\widetilde{M} = \widetilde{M}_{EG}$ and $\widetilde{v} \geq \widetilde{v}_{EG}$.
  - ➢ expected number of El Gordo analogues in the survey: $N_{survey} \simeq 2 \times 10^{-11}$



Expressing the result in terms of probability (P) and number of standard deviations (σ):

Solving:

$$P = 1 - \exp\left(-N_{survey}\right) \simeq 2 \times 10^{-11} \Rightarrow 1 - \frac{1}{\sqrt{2\pi}} \int_{-X}^{X} \exp\left(-\frac{x^2}{2}\right) dx \equiv P \Rightarrow X \simeq 6.7\ \sigma$$

Statistical analysis: the lightcone tomography method

Considers the distribution of El Gordo-like pairs along the entire past light-cone, not just at $a \approx a_{EG}$.

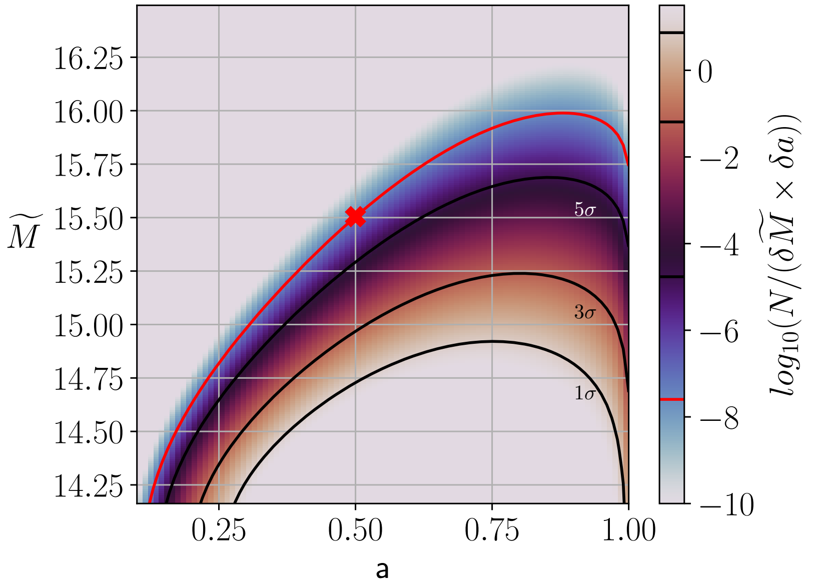
Procedure (consider grid of $\widetilde{M}$ and a):

1) We apply the quadratic fit to the $\log_{10}$ cumulative mass distribution function for $z = 0$, $z = 0.509$, and $z = 1$ in the whole simulation volume.

$$\log_{10} N\left(\geq \widetilde{M}\right) = c_0(a) + c_1(a)\,\widetilde{M} + c_2(a)\,\widetilde{M}^2$$

2) We use a quadratic fit in $\log_{10} a$ to get c_0, c_1 and c_2 at any a

3) We scale this to the survey volume in each pixel in $\widetilde{M}$ and a



The colors and contour lines indicate the expected number of analogues/probability density corresponding to each position in the grid. The point in the grid with the $\widetilde{M}$ and a of El Gordo corresponds to 6.16σ ($P = 7.51 \times 10^{-10}$).

Combined tension with the Bullet Cluster

- **The Bullet Cluste**r is an interacting cluster at ***z* = 0.3** composed of **two subclusters colliding at 3000 km/s** (needed to reproduce weak lensing and X-ray offset)**.**

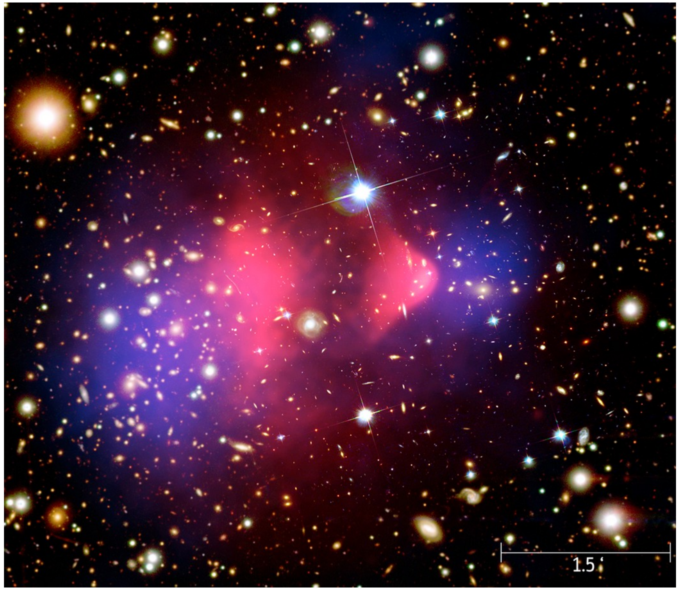
- Kraljic & Sarkar (2015) obtained a 10% probability of finding a Bullet Cluster analogue in the ΛCDM cosmology over the whole sky out to $z = 0.3$.

- The survey in which the Bullet Cluster was found only covered 5.4% of the sky, so **the actual probability of observing a Bullet Cluster-like object is 5.4×10^{-3}, making it a 2.78σ outlier.**

- The probabilities of El Gordo and the Bullet Cluster can be approximately combined as follows:

$$\mathrm{X}^2_{tot} = \mathrm{X}^2_{EG} + \mathrm{X}^2_{BC}$$

$$P = \exp\left(-\mathrm{X}^2_{tot}/2\right)$$



Composite image of the Bullet Cluster. Credit: X-ray (pink): NASA/CXC/CfA/M.Markevitch et al.; Optical (yellow): NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map (blue): NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

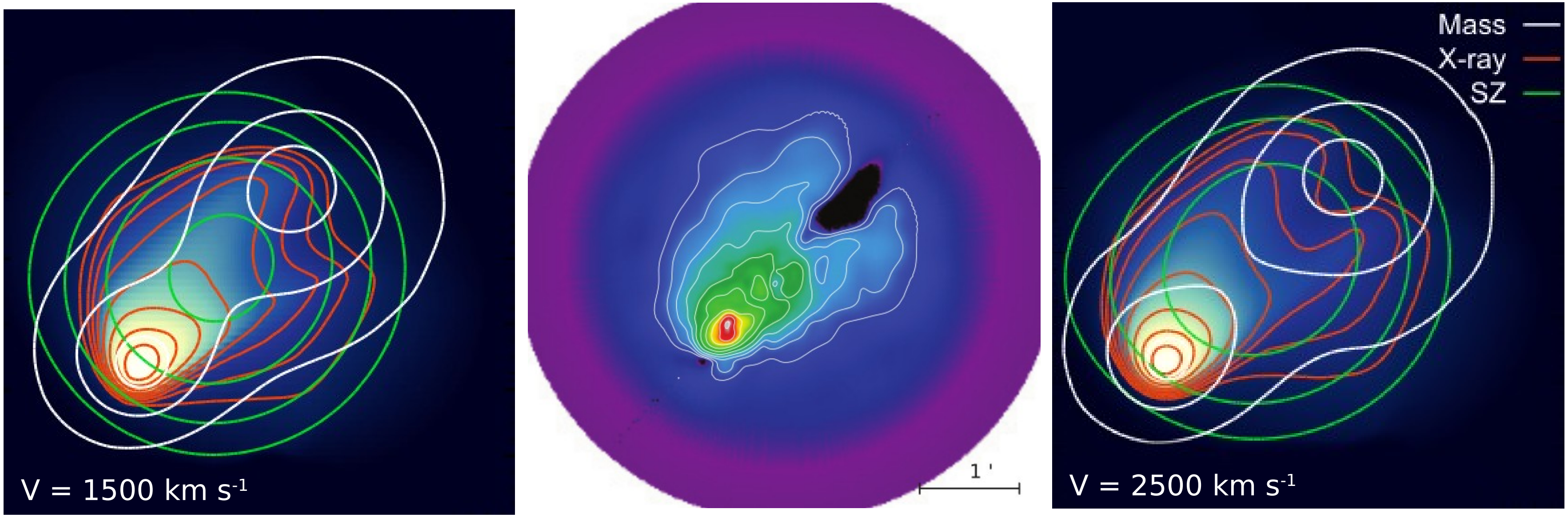
Results

	$\tilde{\upsilon} > 0$		$\tilde{\upsilon} > \tilde{\upsilon}_{EG}$	
	Power-law	Lightcone tomography	Power-law	Lightcone tomography
P_{EG}	4.08×10^{-6} (4.61σ)	1.12×10^{-4} (3.86σ)	2.23×10^{-11} (6.69σ)	7.51×10^{-10} (6.16σ)
P_{EG+BC}	5.13×10^{-7} (5.02σ)	1.20×10^{-5} (4.38σ)	3.98×10^{-12} (6.94σ)	1.24×10^{-10} (6.43σ)
P_{EG+BC} (full sky)	6.09×10^{-5} (4.01σ)	1.36×10^{-3} (3.20σ)	5.04×10^{-10} (6.22σ)	1.55×10^{-8} (5.66σ)

- Consistency between the results of the power-law and lightcone tomography analyses (about 0.5σ difference between the two)
- As results from the lightcone tomography method are more conservative, we choose these as our nominal results.
- **The power-law and lightcone tomography methods agree that the ΛCDM model must be rejected at > 5σ.**
- This threshold is surpassed even in the full sky case, so the detection of no problematic objects in the rest of the sky will not solve the tension.

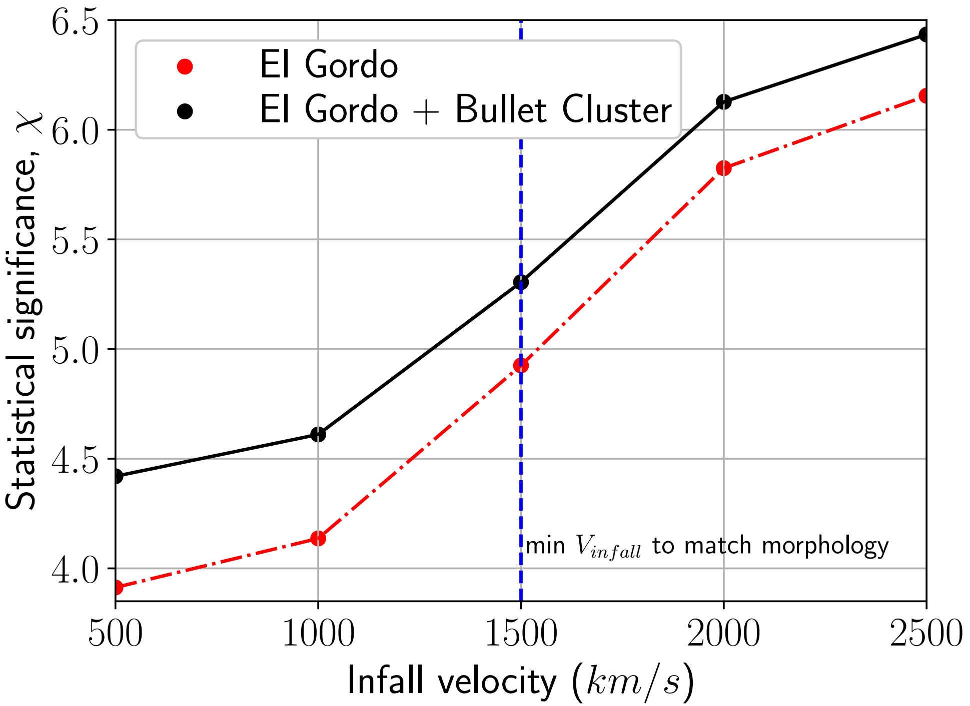
A slower collision?

Compare Zhang+ 2015 models at different velocities with observations:



- **Lowest plausible collision velocity: 1500 km/s.**

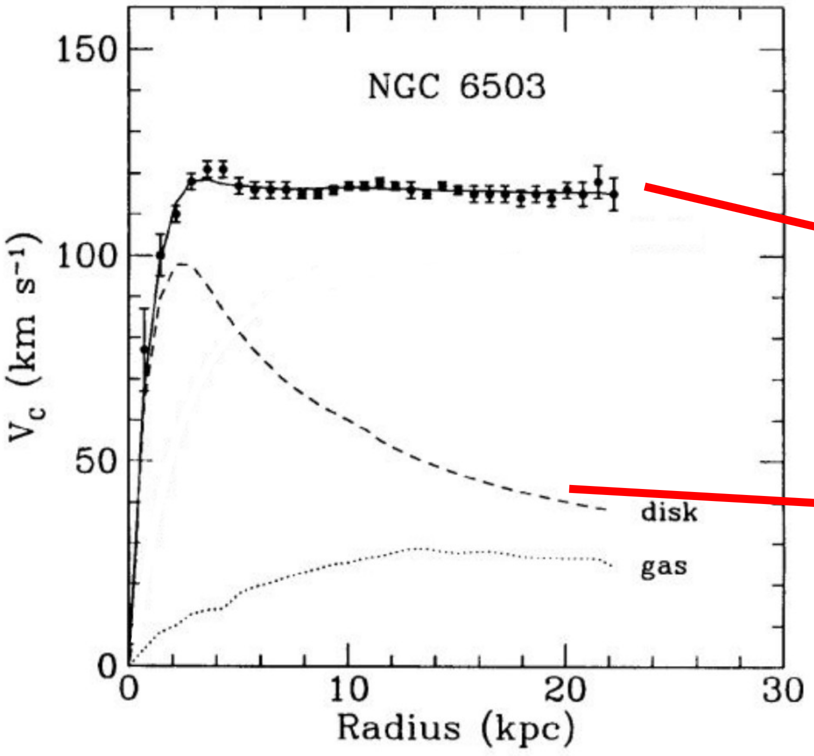
Possible solutions in ΛCDM



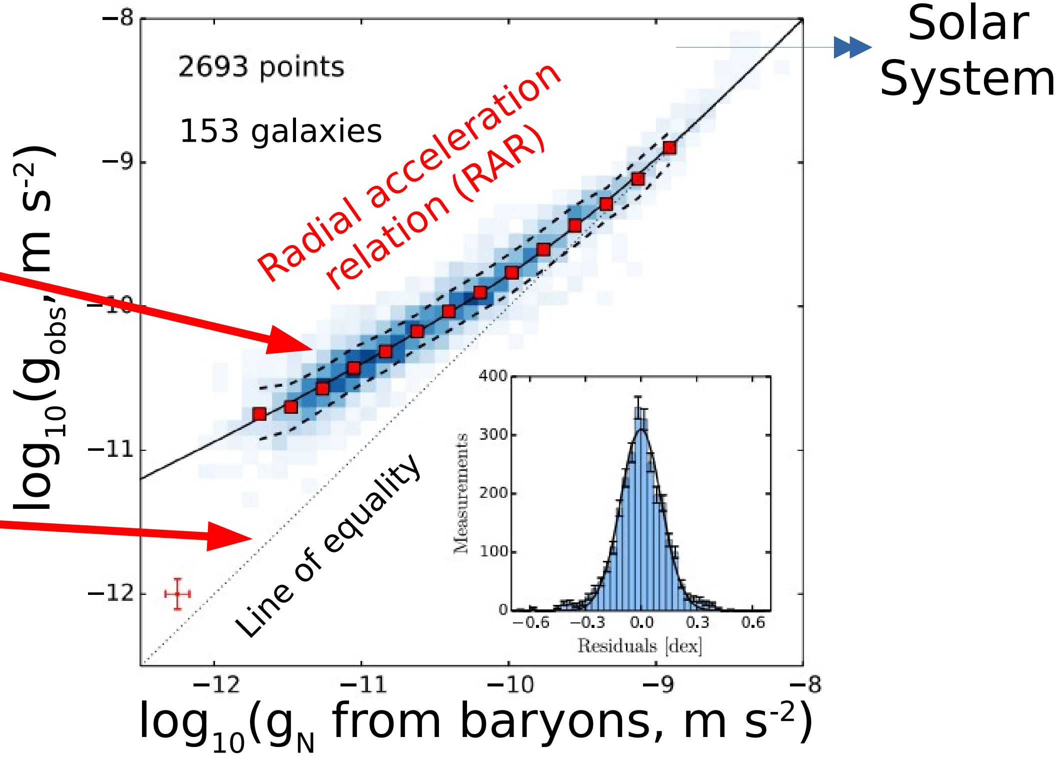
- **Lower velocity** – even V_{infall} = 1500 km s^{-1} presents a very high tension.
- **Lower mass** – paper demonstrates > 5σ tension for any plausible mass (> 1.95×10^{15} h_{70}^{-1} $M_\odot$)
  - Lower mass reduces X-ray flux (can compensate with higher velocity)
  - Mass constrained to (3.13±0.56) x 10^{15} h_{70}^{-1} $M_\odot$ by weak lensing (Jee+ 2014)
- **Poisson noise** – mass function based on 15035 pairs. Poisson noise only 8.16 x 10^{-3}
- **Different mass range for parabolic fits –** paper demonstrates that the results are not greatly affected by this.

How rare is El Gordo in MOND cosmology?

Constraints from galaxies



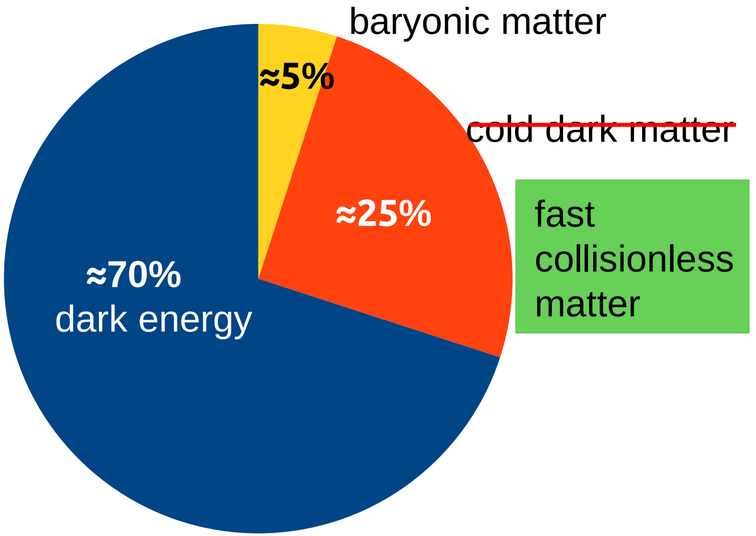
Freese 2008



McGaugh, Lelli, Schombert 2016

Cosmological MOND framework (vHDM): overview

- **Proposed by Angus 2009 (MNRAS, 394, 527)**
- **Cold dark matter (CDM) replaced by**
  fast collisionless matter
  - e.g. 11 eV/c^2 sterile neutrinos (e.g. Angus+2007)
  - same overall mass-energy budget as in ΛCDM
- **Standard background cosmology *a(t)***
  → Nucleosynthesis (BBN)
  - e.g. Skordis 2006 (Phys. Rev. D, 74, 103513)
- **MOND is applied only to density perturbations**
  - e.g. Nusser 2002, Llinares+ 2008, Angus+ 2013, Katz+ 2013, Candlish 2016

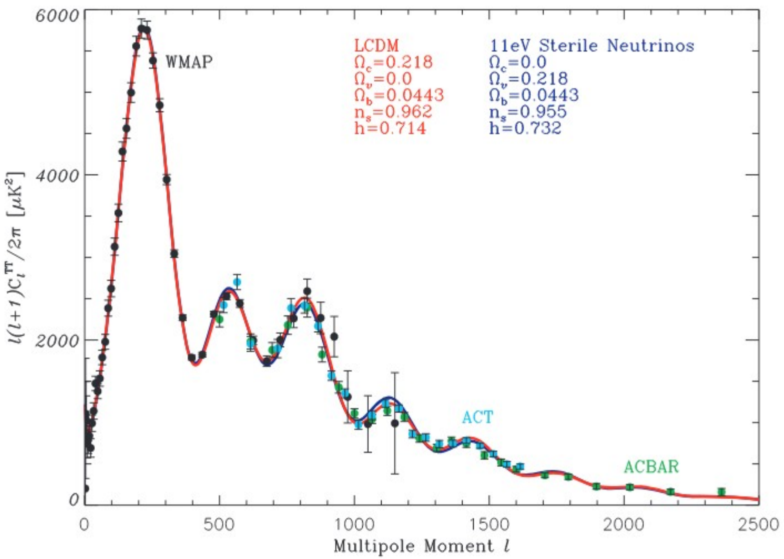


vHDM framework: Impact on CMB

- **Standard expansion and thermal history**
  → same angular diameter distance to CMB
- **MOND is sub-dominant at time of recombination (z = 1100) because g ≈ 20 a_0**
- **Free streaming effects negligible if m_ν > 10 eV/c^2**

  We impose a prior on the physical thermal mass, $m_{\rm sterile}^{\rm thermal} < 10$ eV, when generating parameter chains, to exclude regions of parameter space in which the particles are so massive that their effect on the CMB spectra is identical to that of cold dark matter.

  Planck Collaboration XIII (2016), section 6.4.3
- **MOND effects become important only at z < 50**



Angus & Diaferio (2011)

νHDM framework can explain:

- **Expansion history *a(t)* → BBN**
- **CMB**
- **Bullet Cluster and 30 virialized clusters (Angus+ 2010, MNRAS, 402, 395)**
- **Galaxy rotation curves**
    - unaffected by neutrinos if $m_\nu < 100$ eV/c^2 (Angus+ 2010)
- **νHDM solves problems with ΛCDM on galaxy scales**
    - plane of satellites with high internal σ around MW (Pawlowski & Kroupa 2020), M31 (Ibata+ 2013, Sohn+ 2020), Centaurus A (Müller+ 2018, 2021)
    - ΛCDM explanations rejected (Pawlowski+ 2014, MNRAS, 442, 2362)
    - other small scale failures (e.g. Kormendy 2010, Peebles & Nusser 2010, Kroupa 2015, Algorry+ 2017).

El Gordo in νHDM cosmology

- Katz+ 2013 (ApJ 772, 10) performed a series of cosmological simulations using the νHDM model to examine the formation of galaxy clusters
- They found about one El Gordo analogue in their simulation volume of $(0.512\ h^{-1}\ \mathrm{cGpc})^3$
  - We found 3.16×10^{-8} analogues in a $(6\ h^{-1}\ \mathrm{cGpc})^3$ box for ΛCDM
- Repeating the power-law analysis for this result, we found that the expected number of analogues in the El Gordo survey volume is 1.16 for νHDM.
  - **νHDM gets the right order of magnitude for the frequency of El Gordo-like objects.**

...but how is it possible that we haven't observed even more El Gordo-like objects at lower redshift?

- νHDM also predicts the existence of large underdensities.
- Keenan+ 2013 observed that our local Universe is immersed in one of these underdensities (the ≈300 Mpc radius KBC void). This explains the lack of observed supermassive clusters at lower *z*.
- The KBC void together with the νHDM model could also explain the Hubble tension (Haslbauer+ 2020).

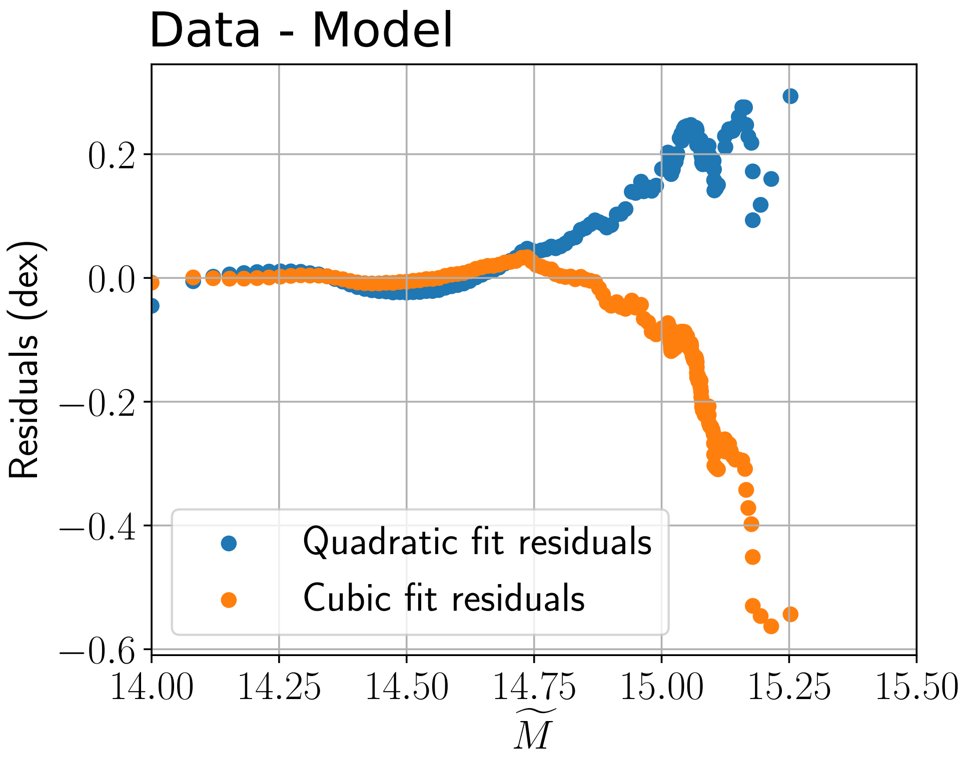
Conclusions

- Pre-merger configuration of El Gordo galaxy cluster collision found by Zhang+ 2015 using hydrodynamical simulations
- Model parameters contradict ΛCDM at 6.16σ based on Jubilee
- Bullet Cluster is in 2.78σ tension (Kraljic & Sarkar 2015)
- Combined tension = 6.43σ
  - Tension > 5σ for any plausible mass (> $1.95 \times 10^{15}\ h_{70}^{-1}\ M_{\odot}$) and collision velocity (> 1500 km/s)
- Such an extreme collision occurs in νHDM cosmology, which is motivated by MOND successes in galaxies (Katz+ 2013):
  - Expect 1.16 analogues in the survey region
- Lack of similar objects at closer distances explained by near-infrared KBC void (Keenan+ 2013), which could also explain H_0 tension (Haslbauer+ 2020).
- Blog describing paper (MNRAS, 500, 5249) on Dark Matter Crisis:

  https://darkmattercrisis.wordpress.com/

Appendix

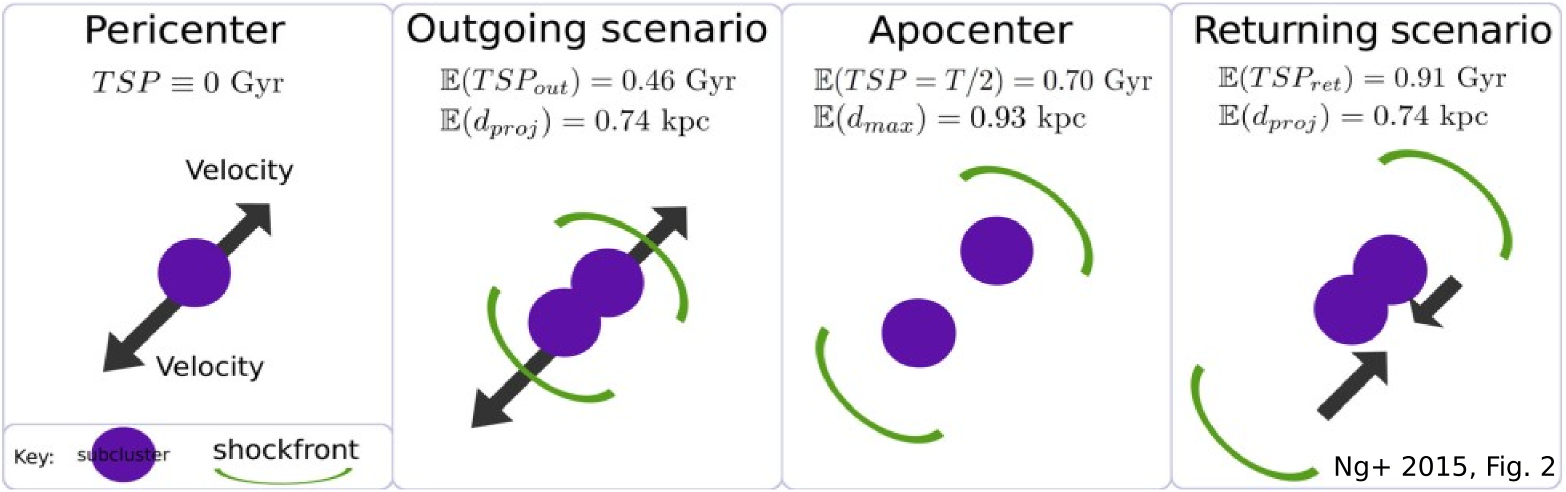
Residuals to analytic mass function



- **Cubic overfits the data, causing errors at high masses.**

El Gordo interaction

- It is generally believed that El Gordo is observed shortly after the first core passage of the subclusters.
- Ng+ 2015 propose a ‘returning scenario’ in which the subclusters would be moving towards, rather than away from each other, post second apocentre.



Ng+ 2015, Fig. 2

Ng+ 2015 estimate V_{infall} = 2400 km/s for the returning scenario too, so our results should be valid regardless of the scenario.

Timescale between pre-merger and observed configuration

- We assume that the pre-merger configuration (z = 1) is before the observed configuration (z = 0.87) by 559 Myr.

- In order to have the halos resolved by the AHF they should not be closer than d = R_{200}. For this distance and assuming $\tilde{v}_{EG} = 1.24$, it would take the subclusters about 603 Myr to just reach pericenter.

  - Our approach of looking for the pre-merger configuration at z = 1 is conservative (looking for pairs at higher redshift would have reduced the number of analogues even further).

Early structure formation at other scales

Supervoids:

- The KBC void is a 300 Mpc radius region underdense by ≈30% out to z = 0.07 (Keenan+ 2013, Haslbauer+ 2020)

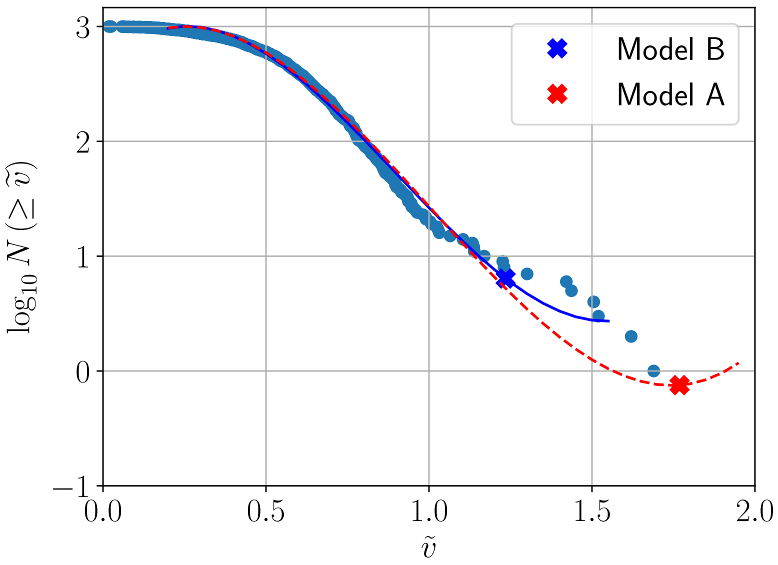
Superclusters:

- Hyperion is a $4.8 \times 10^{15}\ M_\odot$ supercluster at $z = 2.45$ (Cucciati+ 2019)

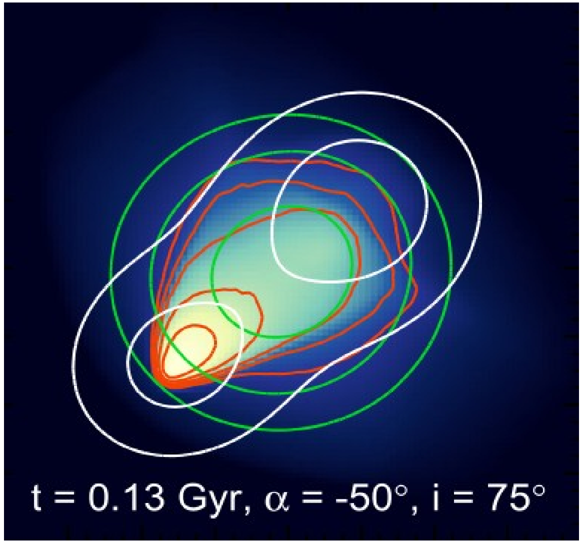
Galaxies:

- J1007+2115 is a quasar containing a SMBH of $1.5 \times 10^{9}\ M_\odot$ at $z = 7.5$ (Yang 2020)

Using a lower mass (Zhang+ 2015 Model A)



The cumulative $\tilde{v}$ distribution for the 1000 most massive candidate El Gordo analogues. The dotted red (solid blue) line shows a cubic fit for Model A (B).

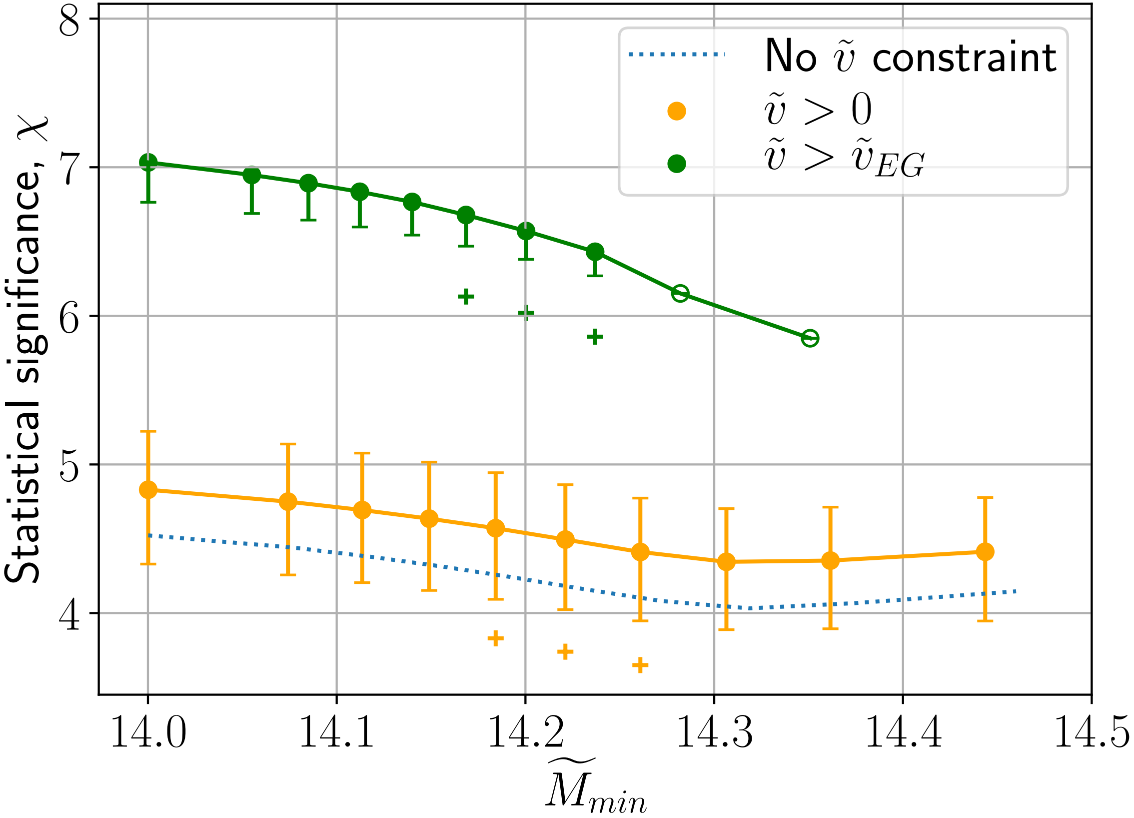


Zhang+ 2015, fig.1. X-ray surface brightness, mass surface density, and SZ effect distributions for a merging cluster with the fiducial model A configuration.

- A higher $\tilde{v}$ is needed, so the model is still problematic (5.14σ tension obtained when repeating the lightcone tomography)
- Two tailed morphology not reproduced in the Zhang+ 2015 simulations

Velocity distribution of cluster pairs

Different mass range for parabolic fits



The statistical significance of the observation of an El Gordo-like object. The circles represent the result of the power-law analysis and the cross-shaped symbols represent the results of the light-cone tomography.

We conclude that the results do not differ that much by choosing a different mass range for the fit

Milgromian dynamics (MOND)

- **Newton gravity/GR developed using Solar System constraints**
- **Developed by M. Milgrom (1983) to address rotation curves without cold dark matter by going beyond Newton**
- **Lagrangian formalism**

$$L = L_K - L_P = \rho\left(\frac{1}{2}v^2 - \Phi\right) - \frac{1}{8\pi G}\left(2\boldsymbol{g}\cdot\boldsymbol{g}_N - a_0^2 f[g_N]\right)$$

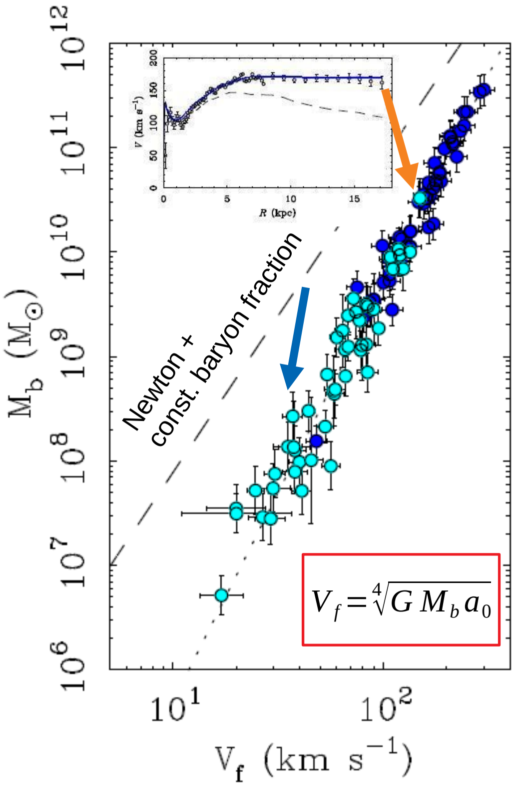
  - Milgrom 2010

Extremize action

- **Non-linear generalization of the Poisson eqn.:**

$$\nabla\cdot\boldsymbol{g} = \nabla\cdot\left(\nu\left(\frac{g_N}{a_0}\right)\boldsymbol{g}_N\right), \quad f \Leftrightarrow \nu$$

  - external field effect (EFE, Milgrom 1986)
  - breaks strong equivalence principle (as observed by Chae+ 2020)
- **Milgrom's constant (from RAR):** $a_0 = 1.2\times10^{-10} m/s^2$
- **Asymptotic limits in spherical symmetry:** $g_N \ll a_0:\ g=\sqrt{a_0 g_N}, \quad g_N \gg a_0:\ g=g_N$
- **Relativistic MOND theory where gravitational waves travel at *c* (Skordis & Zlosnik 2019)**



Local Group satellite planes

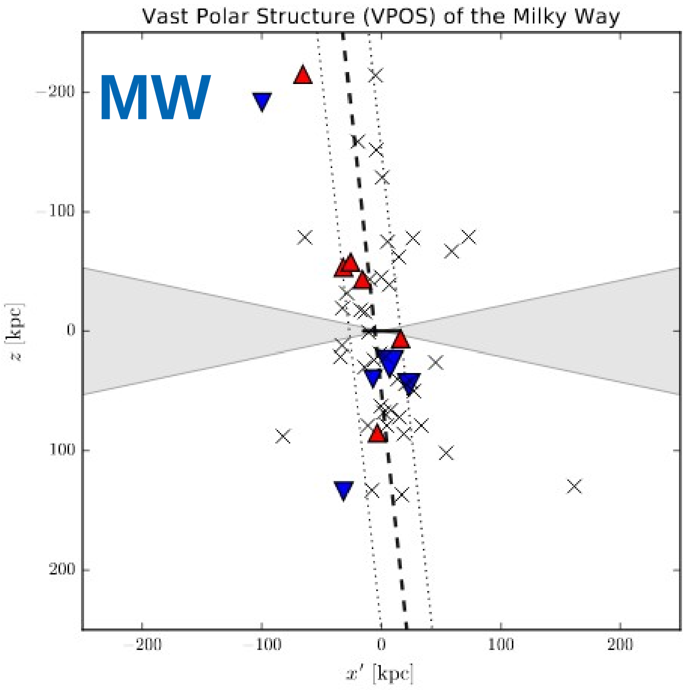
MW satellite galaxies lie within a thin plane (Pawlowski & Kroupa 2013, 2020). Analogous situation for M31 (Ibata+ 2013)

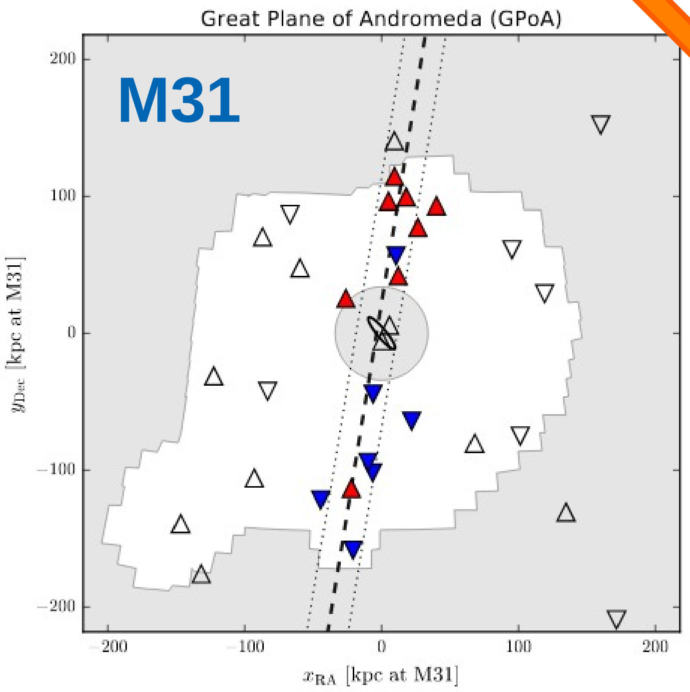
Galaxies observed forming within tidal tails (Mirabel+ 1992)

Satellites were formed from tidal debris. Alternatives not very likely (Pawlowski+ 2014, and references therein)

Should only contain baryons as DM can't cool and form dense tidal tails (Wetzstein+ 2007)

Internal dynamics can't be explained by Newtonian gravity (Kroupa, 2015)



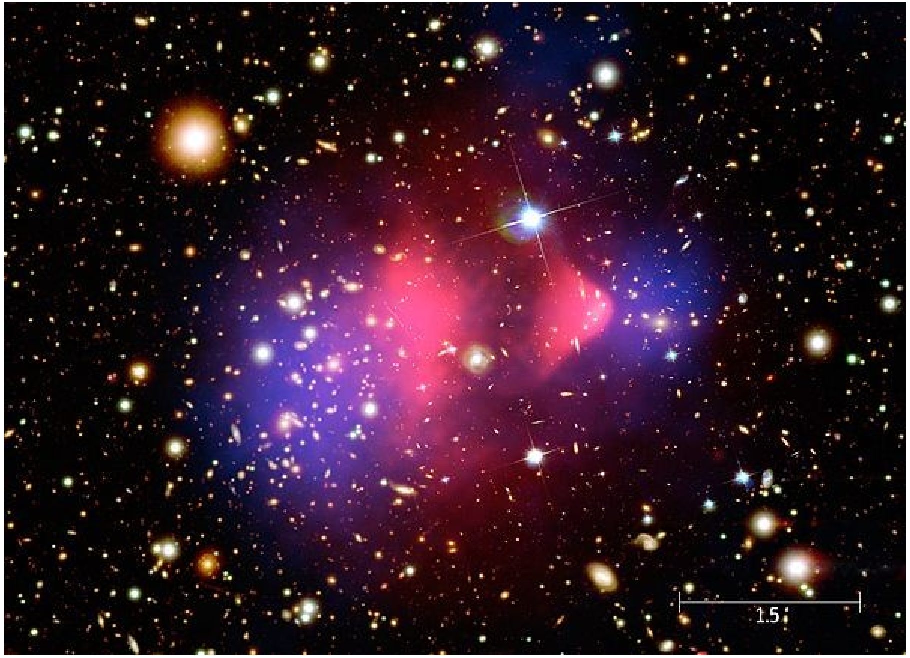


MW and M31 satellite galaxies have high internal velocity dispersions, requiring strong self-gravity (McGaugh & Wolf, 2010; McGaugh & Milgrom 2013)

Astronomical evidence for fast collisionless matter

- **Offset X-ray and weak lensing peaks**
- **$g > a_0$: MOND effects small**

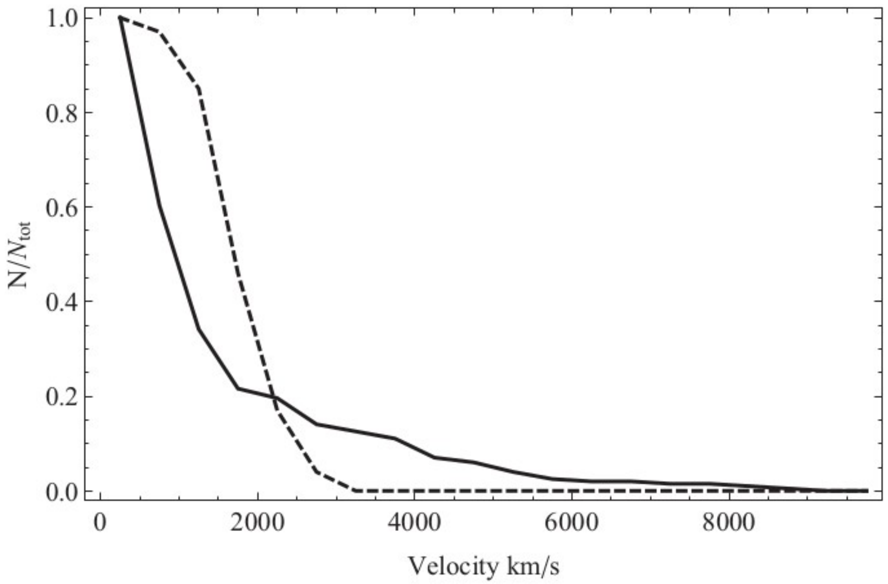
  → Collisionless matter required
- **Tremaine-Gunn limit: $m_\nu > 2$ eV/c^2 (Angus+ 2007, ApJ, 654, L13)**
- **Current constraints imply collisionless particle mass >10 eV/c^2 (strongest limits from CMB)**



Composite image of the Bullet Cluster. Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

El Gordo in νHDM cosmology

- Higher velocities than in ΛCDM, so the Bullet Cluster is not a problematic object in νHDM.
- Higher masses, so it is more plausible to encounter objects like El Gordo.



Katz+ 2013, figure 8. Cumulative distribution function for Bullet Cluster candidates. Candidates from the νHDM model are shown as the solid black line and candidates from the ΛCDM model are shown as the dashed black line.

Dark matter can fit anything

- **Unwary astronomers were given a rotation curve & image and asked to fit the curve**
- **Catch: the image was of the wrong galaxy…**