ARISTOTLE UNIVERSITY OF THESSALONIKI

“Standard cosmology at the threshold of change?”
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El Gordo: a massive blow to ΛCDM cosmology

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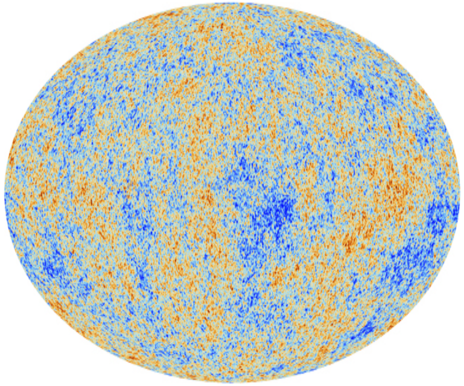
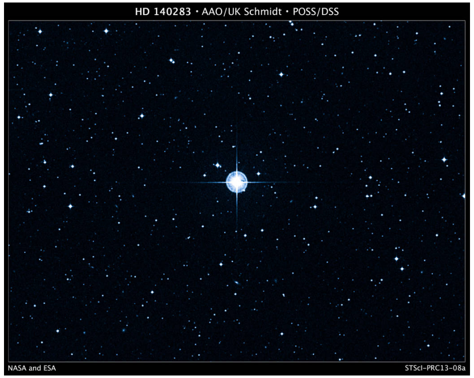
Hierarchical structure formation

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...

1E 0657-56 (The Bullet Cluster)

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

PLCK G287.0+32.9

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

ACT-CL J0102-4915 (El Gordo)

- $z = 0.87$
- Mass $\simeq 2.1 \times 10^{15}\ M_\odot$
- $V_{infall} \simeq 3000$ km/s

SPT-CL J2106-5844

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

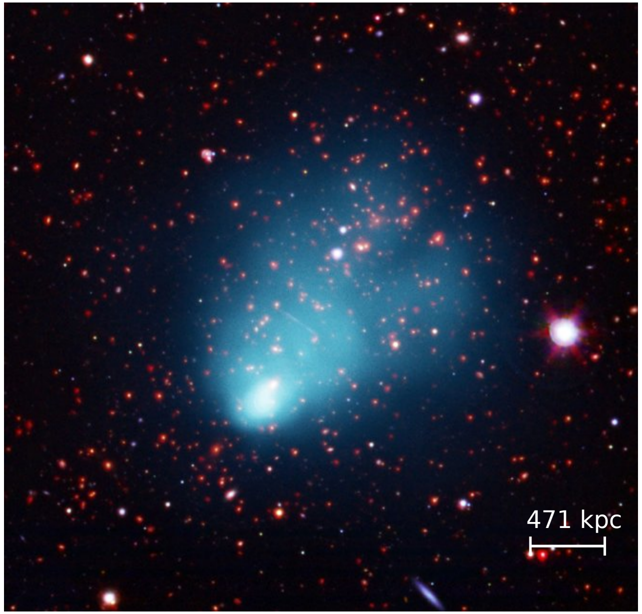
...and more

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...
$M_{El\ Gordo} \simeq 2.13 \times 10^{15}\ M_\odot$ 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 $M_{200} \simeq 2.13 \times 10^{15}$ $M_\odot$ and mass ratio of 1.52 (Kim+ 2021).
- 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.

Outline of the method

CMB → Pre-merger configuration → Detailed observations

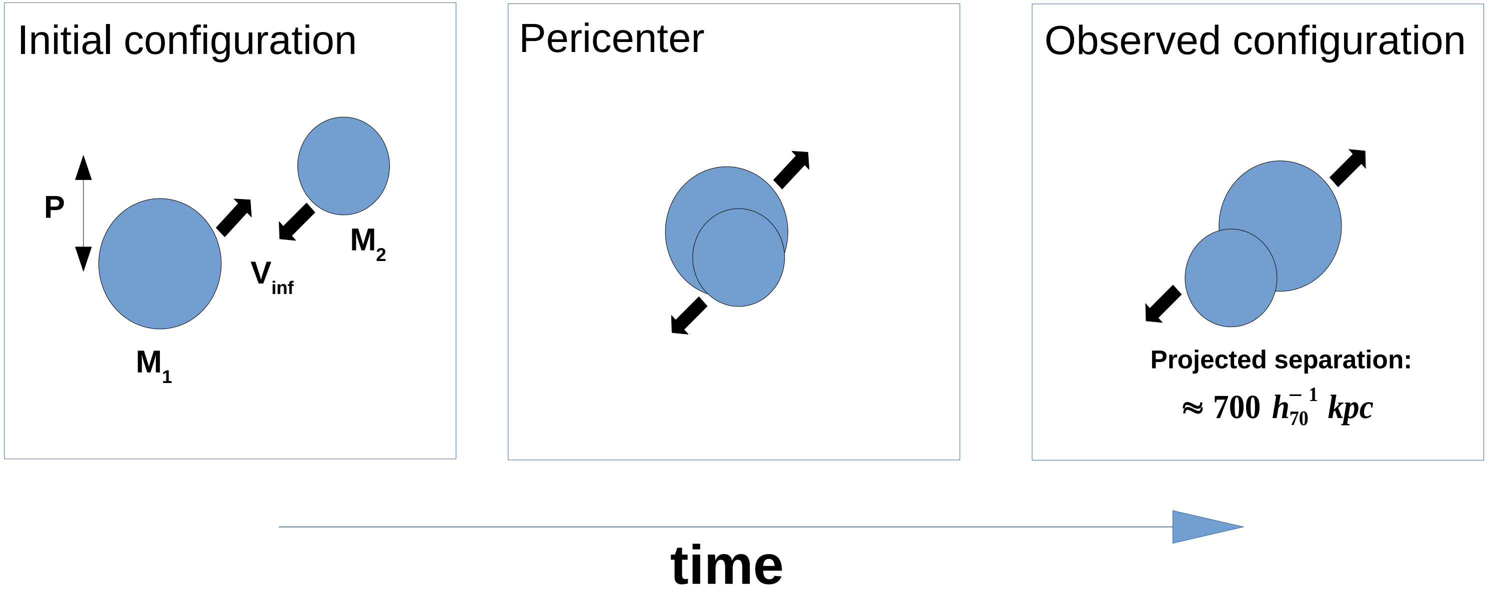
Cosmological *N*-body simulations

(Jubilee simulation, Watson+ 2014)

Hydrodynamical simulations

(Zhang+ 2015 simulations)

Hydrodynamical simulations of El Gordo



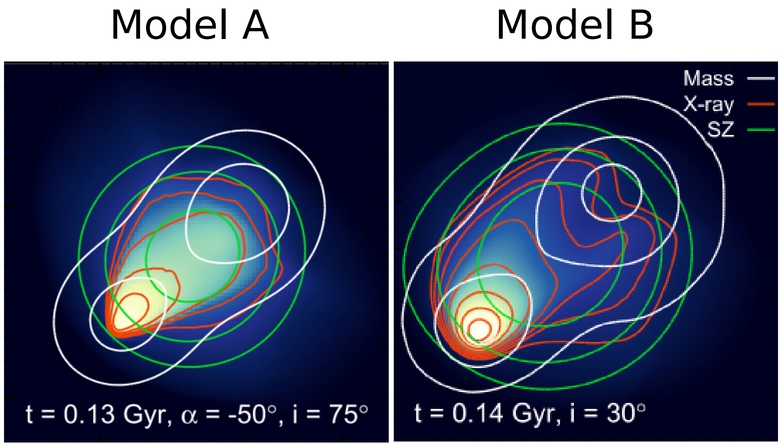
Does it match...?

- $L_X \approx 2 \times 10^{45}\ h_{70}^{-2}\ erg\ s^{-1}$
- 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:

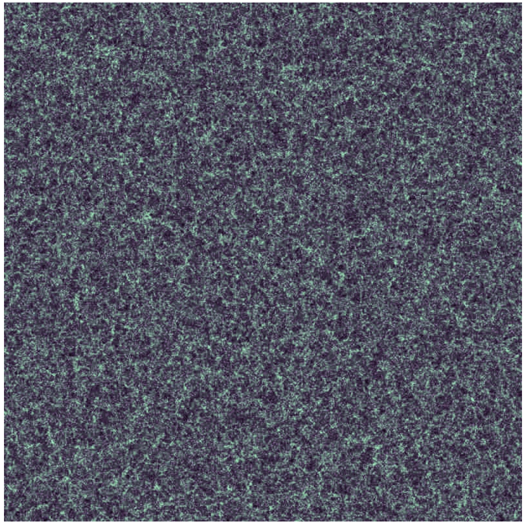
	Model A	Model B
Interaction	extremely energetic head-on collisions	off-centre collisions of two massive clusters
M_{tot}	$1.95 \times 10^{15}\ M_\odot$	$3.19 \times 10^{15}\ M_\odot$
M_{ratio}	2	3.6
V_{infall}	3000 km/s	2500 km/s
Impact parameter	$300\ h_{70}^{-1}$ kpc	$800\ h_{70}^{-1}$ kpc
Two tailed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



X-ray surface brightness, mass surface density, and SZ effect distributions for models A and B. 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).

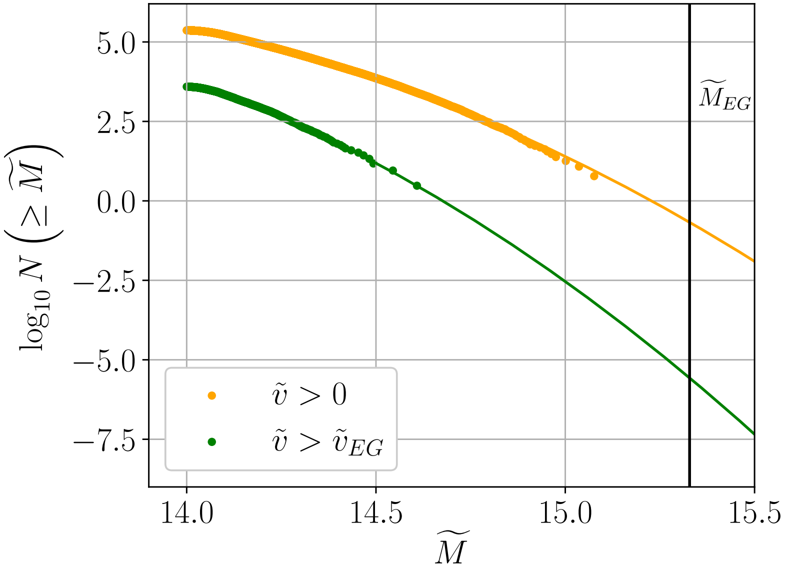


Halo distribution in the Big Jubilee simulation. Source: Jubilee Project

Finding analogues in the cosmological simulation

Conditions to be considered El Gordo analogues:

- Redshift $z = 1$
- Turned around from cosmic expansion $(v \cdot r < 0)$
- Mass ratio ≤ 1.52
- Ratio $\widetilde{v}$ between infall velocity and escape velocity at $2 \cdot R_{200}$: $\widetilde{v} \geq \widetilde{v}_{EG} = 1.88$
- Total virial mass: $M_{200} \geq M_{200,EG} = 2.13 \times 10^{15}\ M_\odot$ $\left(\widetilde{M} \equiv \log_{10}(M_{200}/M_\odot) \geq \widetilde{M}_{EG} = 15.33\right)$



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 lightcone tomography method

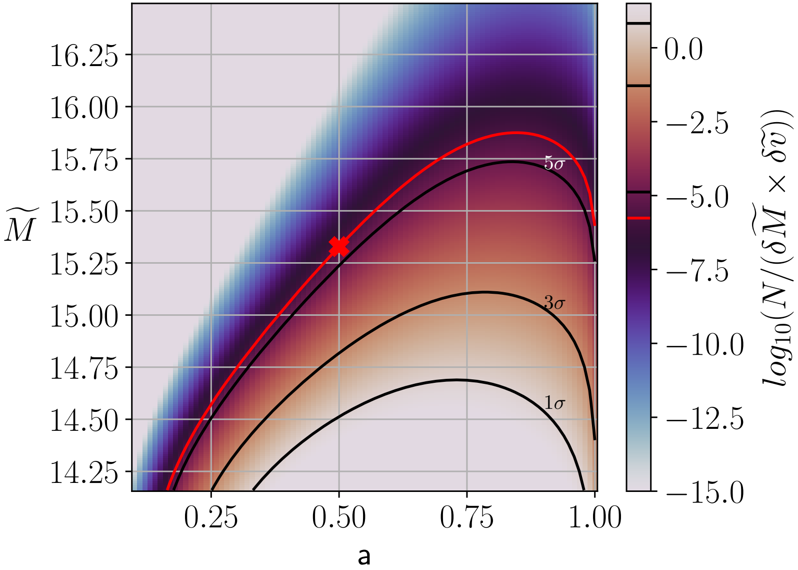
Procedure (consider grid of $\widetilde{M}$ and *a*):

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*



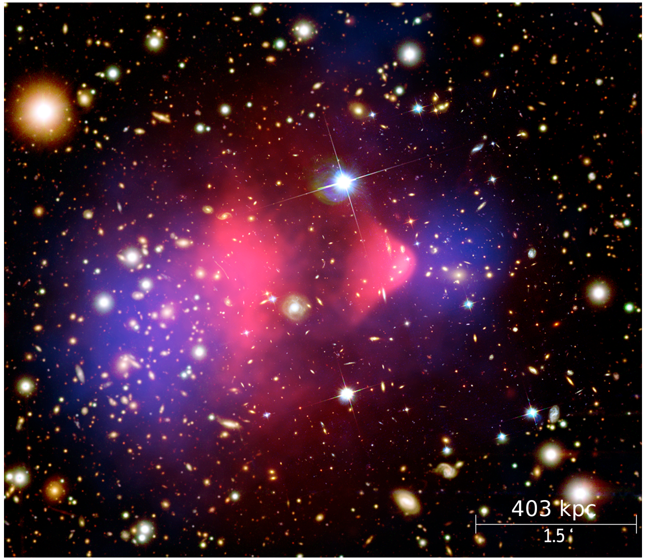
1) The colors and contour lines indicate the expected number of analogues/probability density corresponding to each position in the grid. The point in the grid with the $\widetilde{M}$ and *a* of El Gordo corresponds to 5.38σ ($P = 7.33 \times 10^{-8}$).

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**

- Kraljic & Sarkar (2015): 10% probability of finding a Bullet Cluster analogue in the whole sky (in ΛCDM).

- 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 x 10^{-3} (2.78σ).**



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

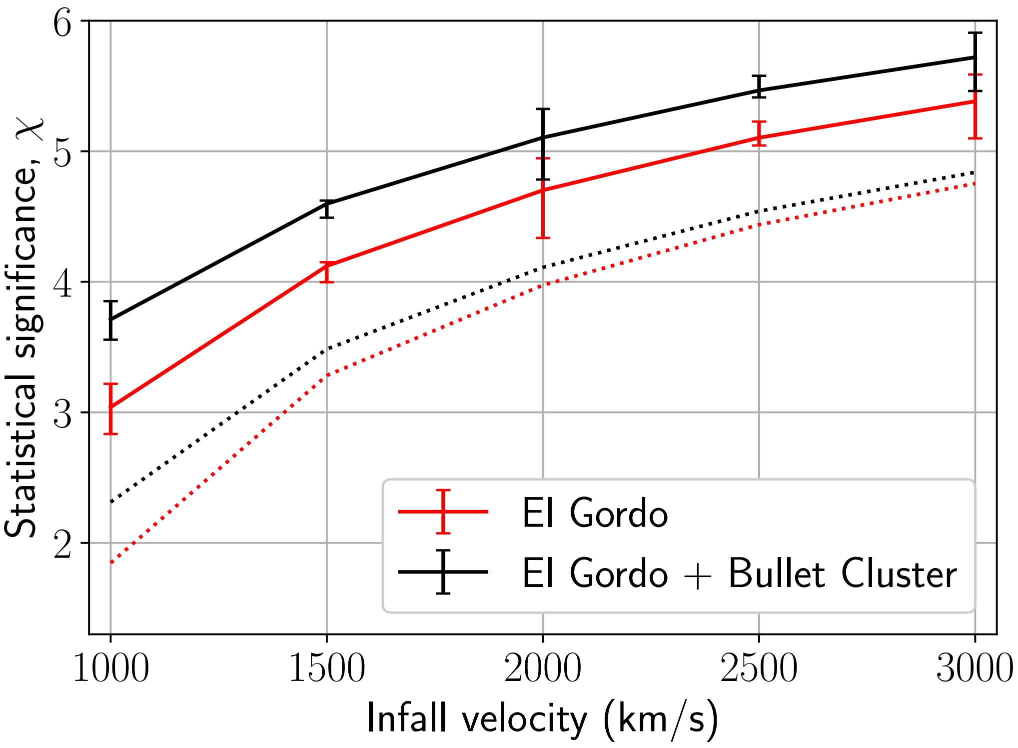
P_{EG}	7.33 x 10^{-8} (5.38σ)
P_{EG+BC}	1.06 x 10^{-8} (5.72σ)

- **We conclude that the ΛCDM model must be rejected at >5σ.**

Can any other cosmological model explain El Gordo?

- vHDM cosmological model: MOND gravity + sterile neutrinos
- Katz+ 2013 found about one El Gordo analogue in their simulation box using this model.

Possible solutions in ΛCDM



- **Lower mass** – paper demonstrates ≥ 5σ tension for any plausible mass
  - Lower mass reduces X-ray flux (can compensate with higher velocity)
- **Lower velocity** – even V_{infall} = 1500 km s^{-1} presents a very high tension.
- **Larger survey area** – even if we assumed that El Gordo and the Bullet Cluster are the only problematic objects for ΛCDM in the full-sky, tension is still high at plausible V_{infall}.
- **Poisson noise** – mass function based on 15035 pairs. Poisson noise only 8.16 x 10^{-3}

Conclusions

- Model parameters (from Kim+ 2021 and Zhang+ 2015) contradict ΛCDM at 5.38σ.
- Bullet Cluster is in 2.78σ tension (Kraljic & Sarkar 2015)
- Combined tension = 5.72σ
  - Tension >5σ for any plausible mass and collision velocity (ApJ 954, 162)
- Such an extreme collision occurs in νHDM cosmology (Katz+ 2013, Haslbauer+ 2020):
  - Expect 1.16 analogues in the survey region
- Blogs describing papers (MNRAS 500 5249, ApJ 954 162): The Dark Matter Crisis (https://darkmattercrisis.wordpress.com/) and Triton Station (https://tritonstation.com)

Appendix

Early structure formation at other scales

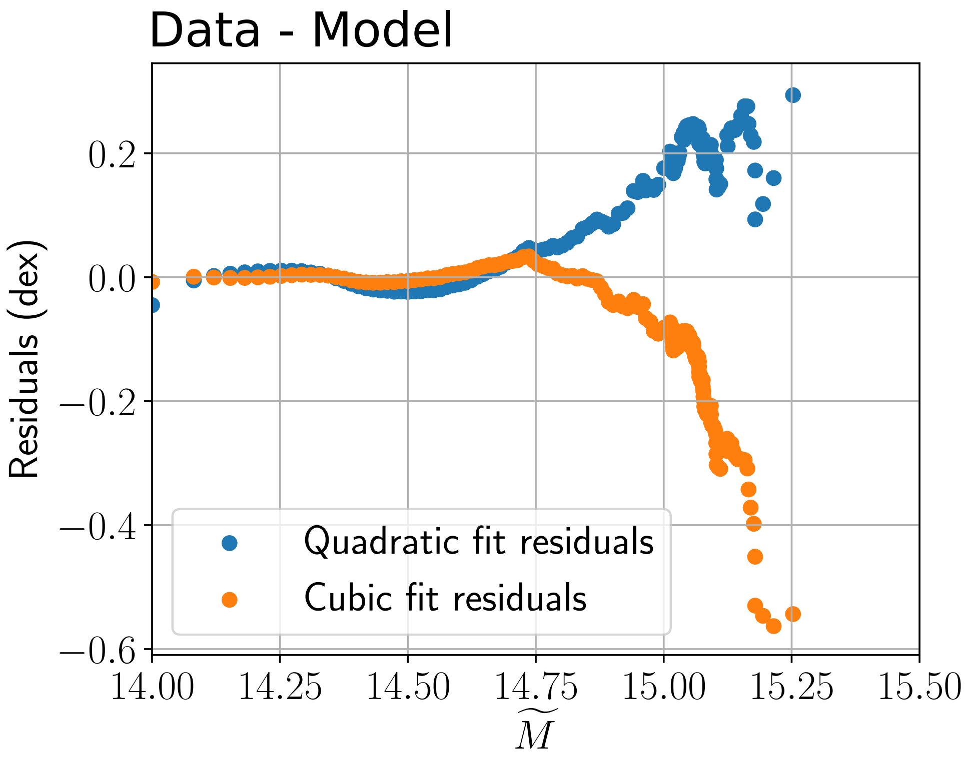
Superclusters:

- 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)

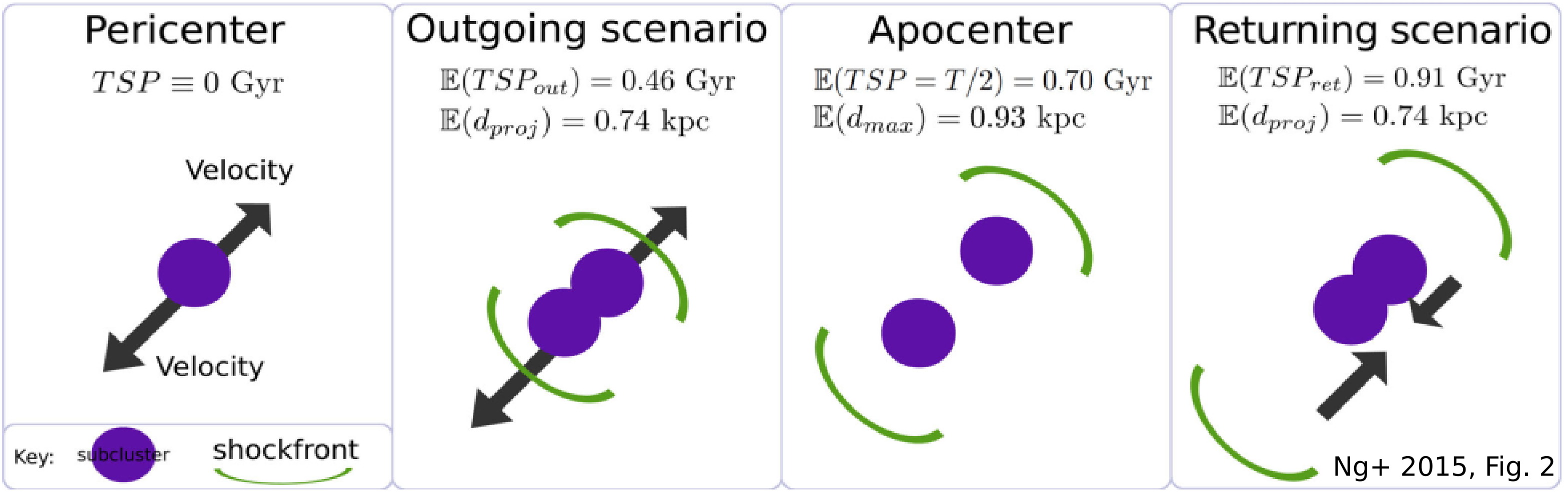
Residuals to analytic mass function



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

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.

Probability of observing El Gordo

- 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 $z = 1$: $N_{Jubilee} \simeq 3.16 \times 10^{-8}$

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

$$P = 1 - \exp\left(-N_{Jubilee}\right) \simeq 3.16 \times 10^{-8}$$ ➡

Solving:

$$1 - \frac{1}{\sqrt{2\pi}} \int_{-X}^{X} \exp\left(-\frac{x^2}{2}\right) dx \equiv P$$ ➡ $$X \simeq 5.5\,\sigma$$

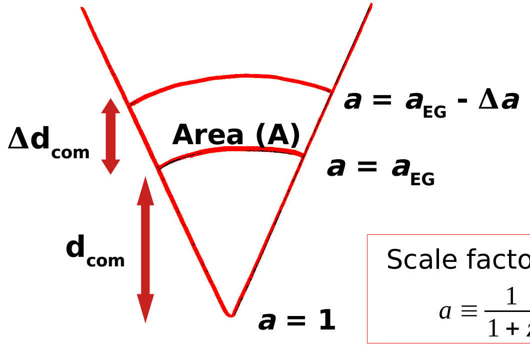
To which probability/number of standard deviations does this correspond to in the El Gordo survey volume?

<u>El Gordo survey volume</u>:

Survey area: A = 755 deg^2 (Menanteau+ 2012)
Survey depth: from $a = a_{EG}$ to $a = a_{EG} - \Delta a$

<u>Effective volume:</u>

$$V_{eff} = A \cdot d_{com}^2 \cdot \Delta\, d_{com}$$



Scale factor :

$$a \equiv \frac{1}{1+z}$$

Statistical analysis: the power-law method

Obtaining Δ*a*:

- 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 $\tilde{M} \geq \tilde{M}_{EG}$ and $\tilde{v} \geq \tilde{v}_{EG}$)

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

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

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

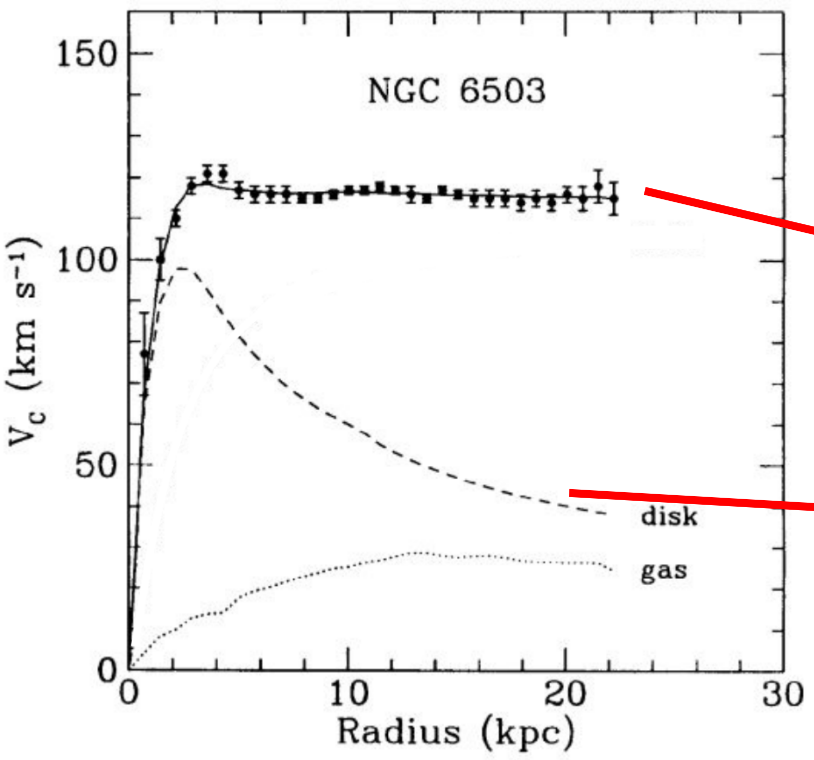
$$\equiv$$

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

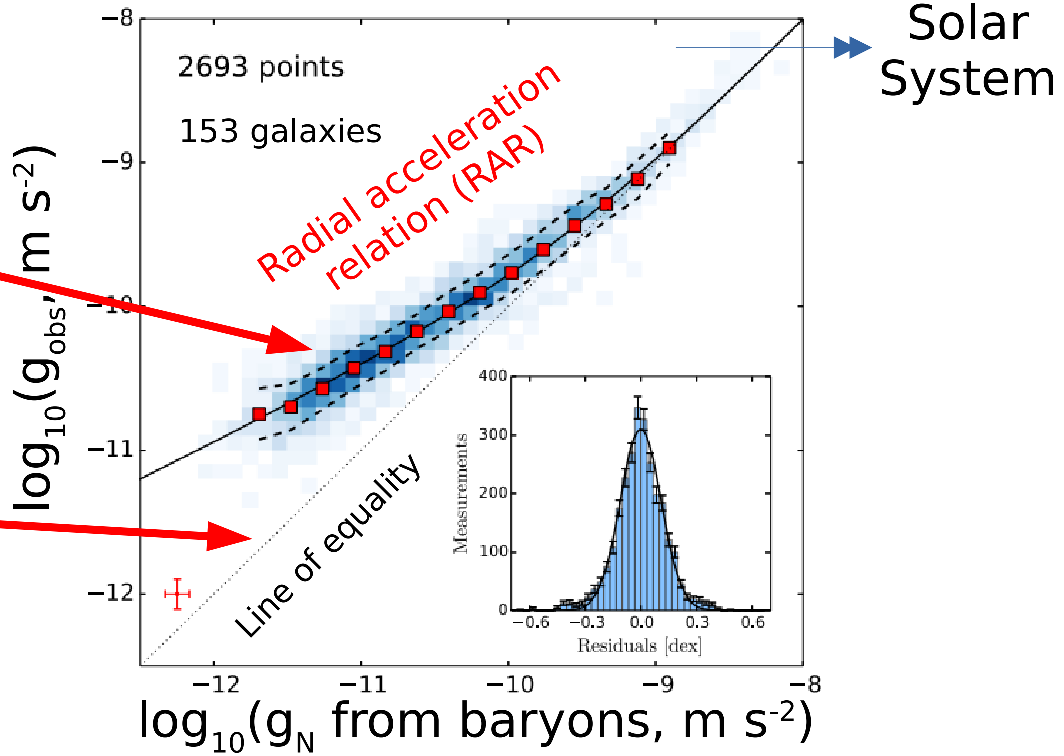
$$\Rightarrow \boxed{\Delta a = \frac{a_{EG}}{k - 1.83}}$$

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

Constraints from galaxies



Freese 2008



McGaugh, Lelli, Schombert 2016

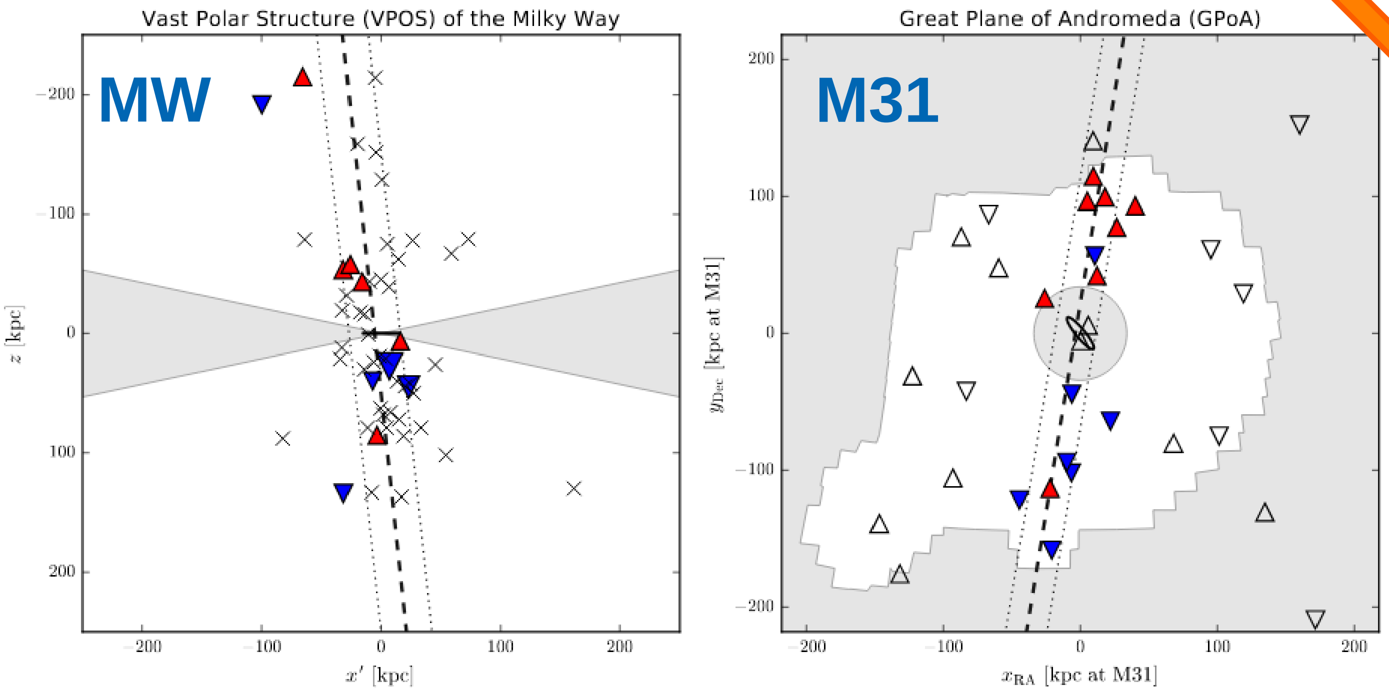
Local Group satellite planes

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)



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

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

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**
  - Milgrom 2010

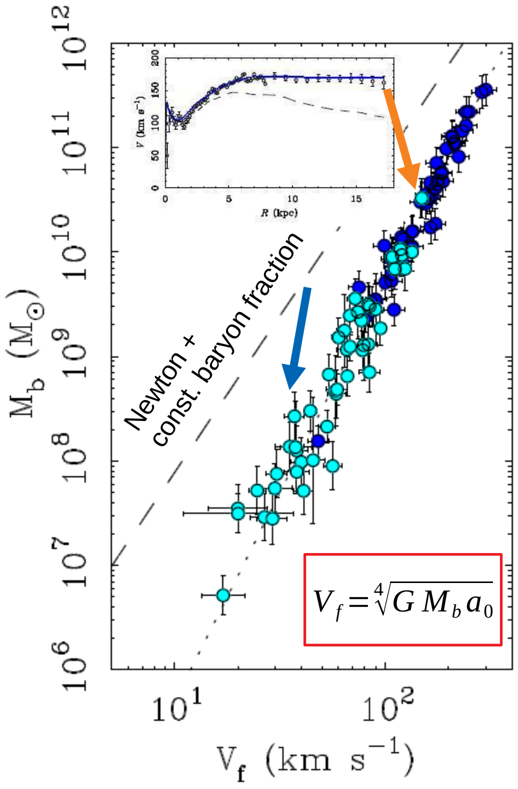
$$L = L_K - L_P = \rho\left(\frac{1}{2}v^2 - \Phi\right) - \frac{1}{8\pi G}\left(2\boldsymbol{g}\cdot\boldsymbol{g}_N - a_0^2 f[g_N]\right)$$

Extremize action

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

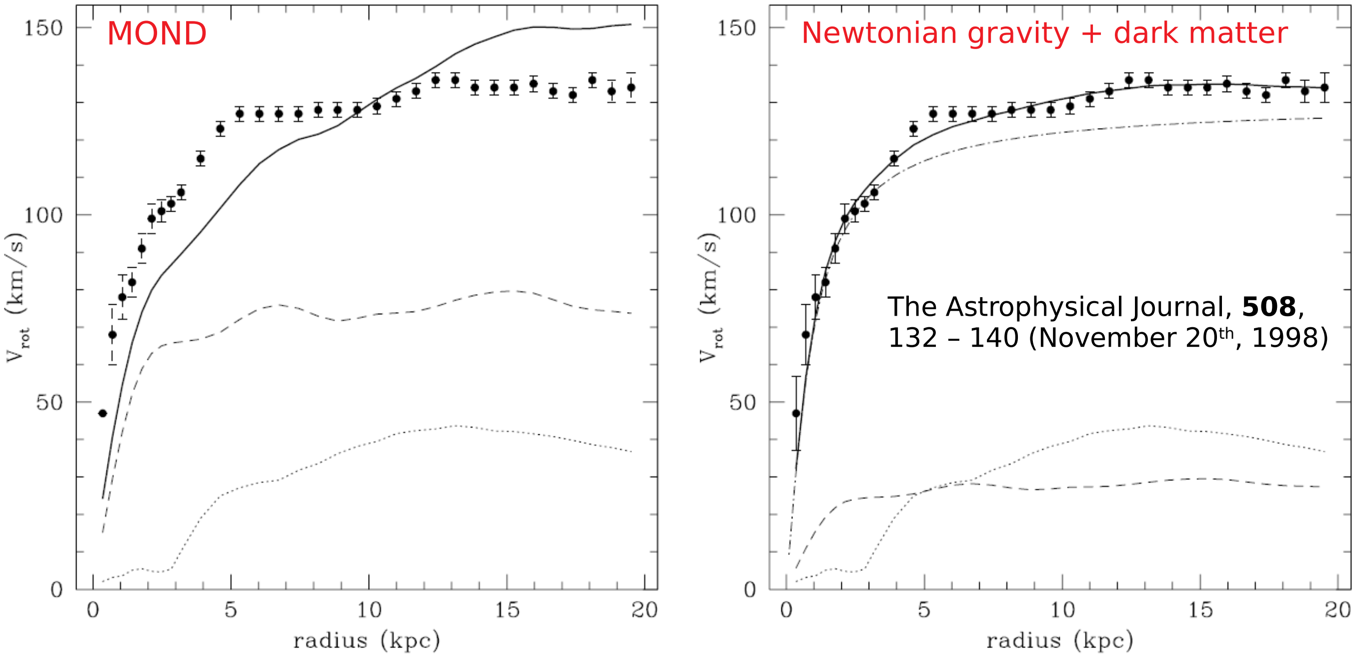
$$\nabla\cdot\boldsymbol{g} = \nabla\cdot\left(\nu\left(\frac{g_N}{a_0}\right)\boldsymbol{g}_N\right), \quad f \Leftrightarrow \nu$$

  - 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)**



Dark matter can fit anything

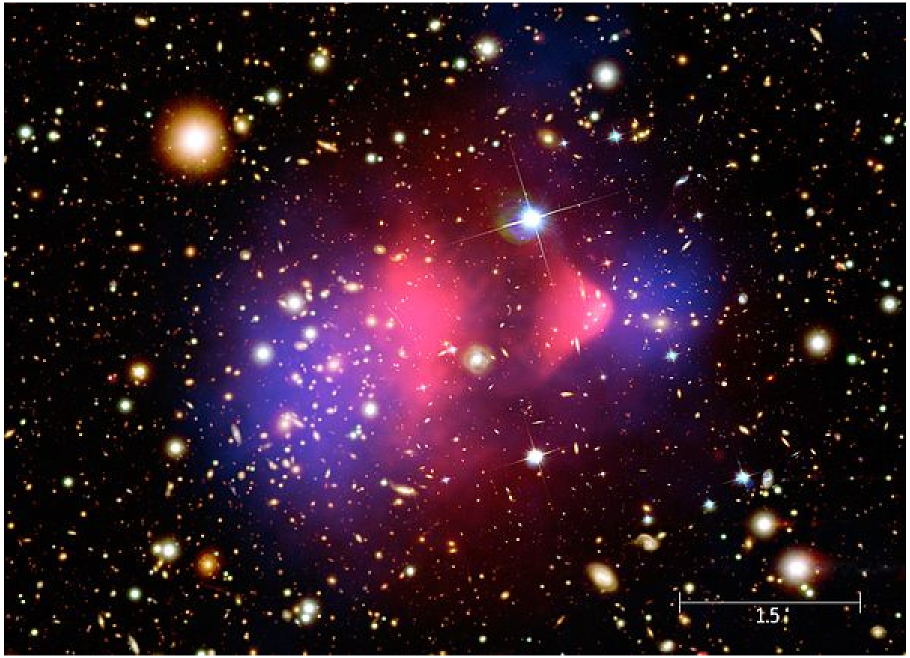
- **Unwary astronomers were given a rotation curve & image and asked to fit the curve**
- **Catch: the image was of the wrong galaxy...**



Astronomical evidence for fast collisionless matter

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

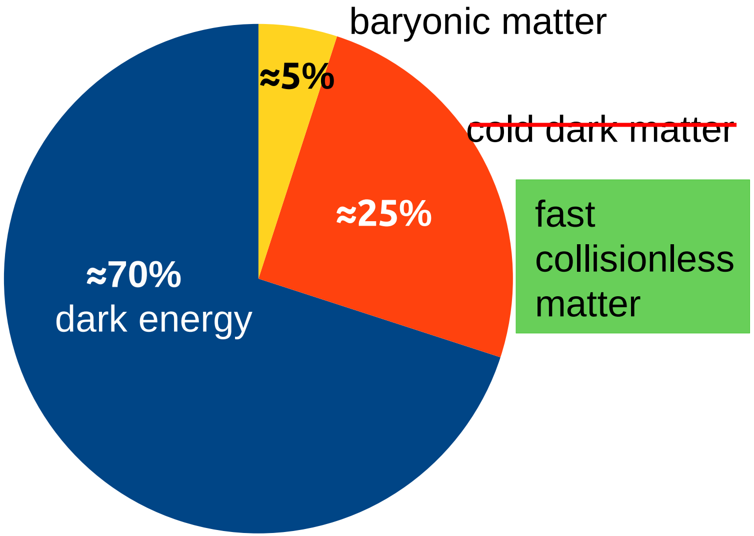
  → Collisionless matter required
- Tremaine-Gunn limit: $m_\nu > 2$ eV/c^2 (Angus+ 2007, ApJ, 654, L13)
- Current constraints imply collisionless particle mass >10 eV/c^2 (strongest limits from CMB)



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.

Cosmological MOND framework (νHDM): 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



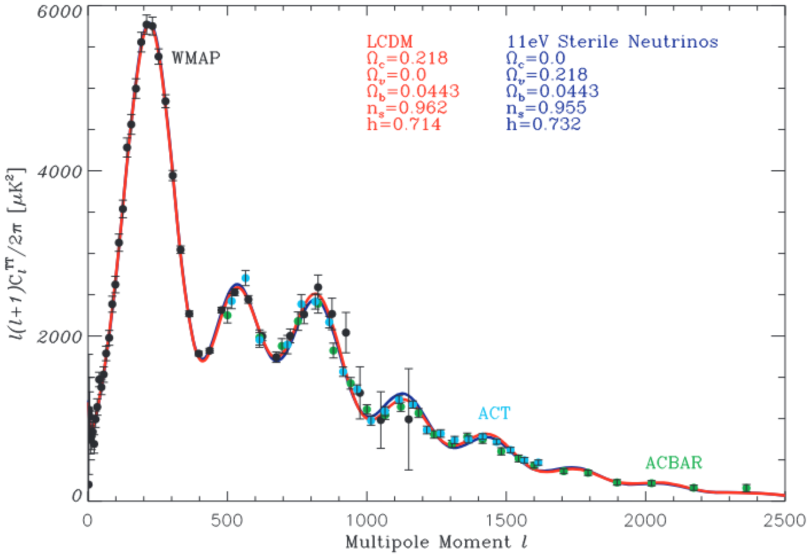
νHDM framework: Impact on CMB

- **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, $m_{\mathrm{sterile}}^{\mathrm{thermal}} < 10$ 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**



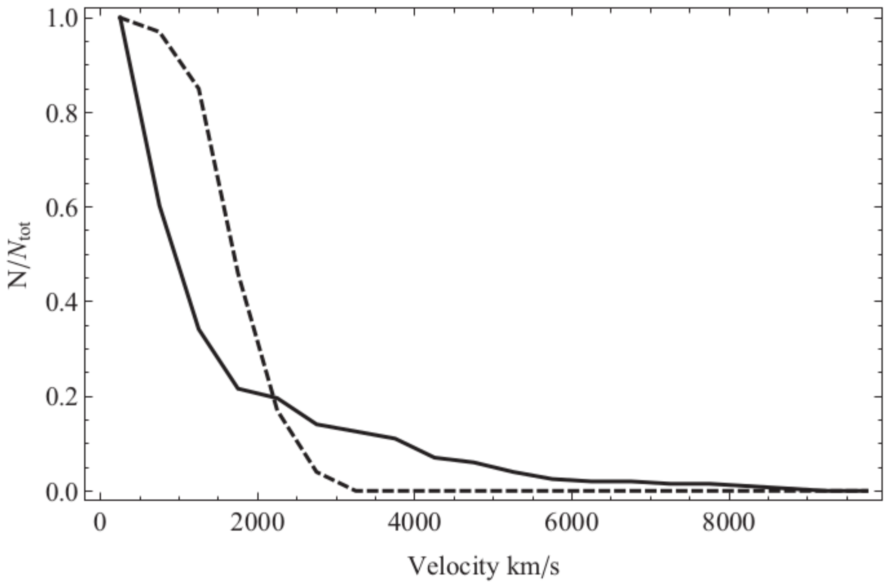
Angus & Diaferio (2011)

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

- 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.