Modified Newtonian Dynamics as an alternative to dark matter: the Bullet Cluster case

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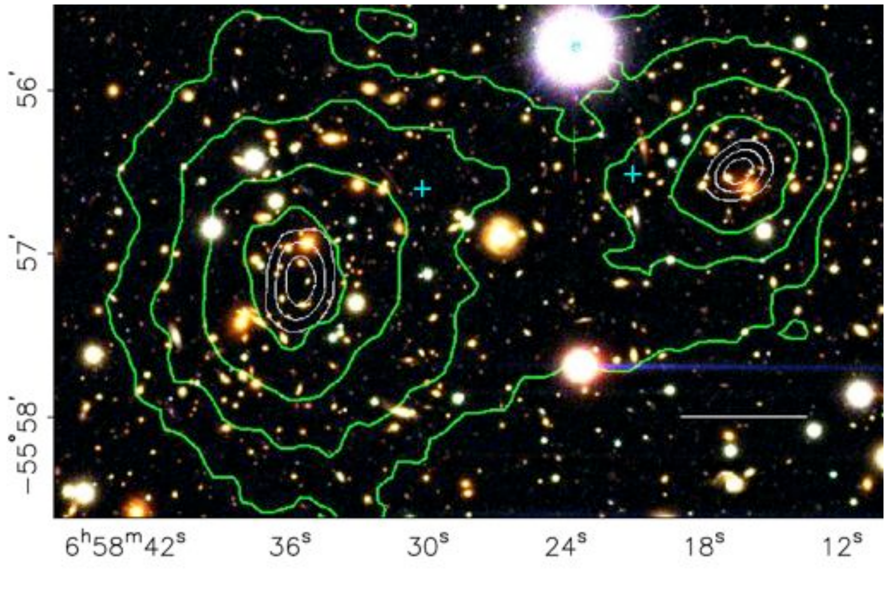
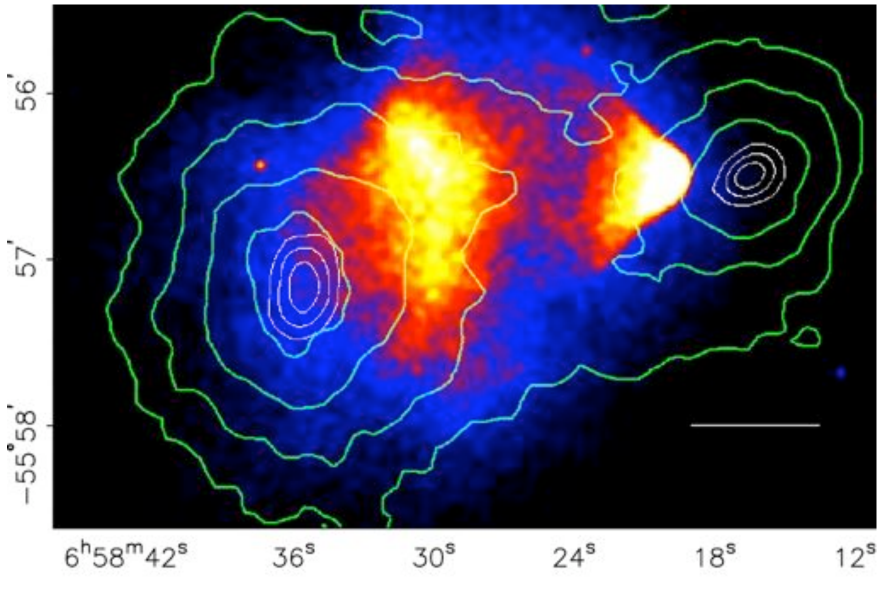
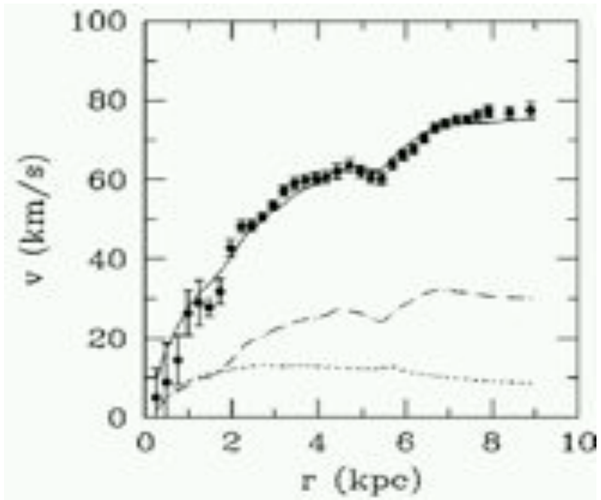




CDM: the cusp problem and the « correlation » problem

- Simulations of clustering CDM halos (e.g. Diemand et al.) predict a central cusp $\rho \propto r^{-\gamma}$, with $\gamma > 1$, observed neither in the MW (e.g. Famaey & Binney 2005), neither in HSB nor in LSB (No present-day satisfactory solution)
- Baryonic Tully-Fisher relation $V_\infty^4 \propto M_{bar}$ (tight->triaxiality of halo?)
- Tidal Dwarf Galaxies with DM? (Gentile et al. **arXiv:0706.1976**)
- What is more: wiggles of rotation curves follow wiggles of baryons in many HSB and in some LSB



Modified Newtonian Dynamics

- Correlation summarized by the MOND formula in galaxies (Milgrom 1983) :

  $\mu\,(|g|/a_0)\,\mathbf{g} = \mathbf{g}_{N\ baryons}$ where $a_0 \sim cH_0$

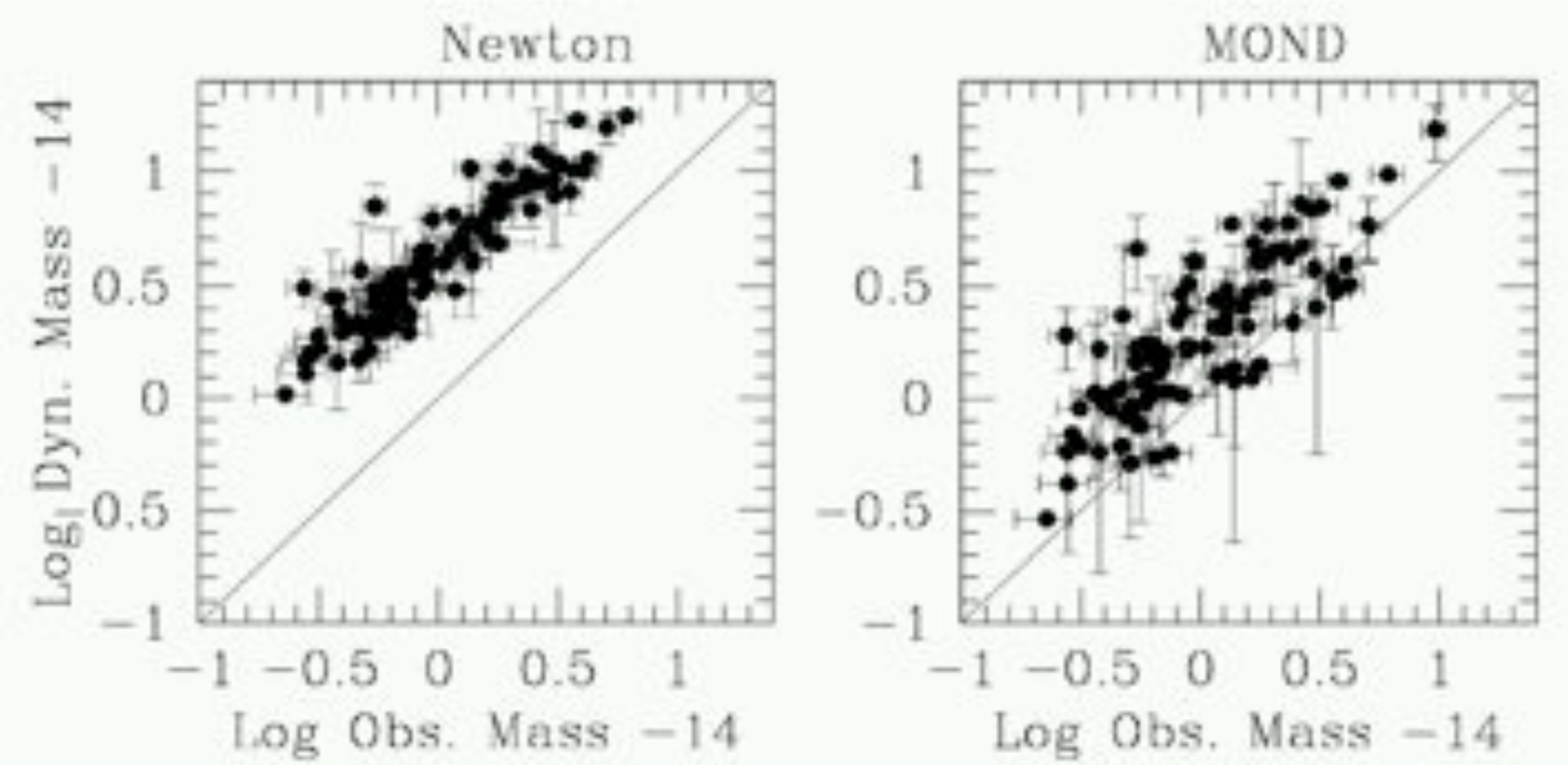
  with $\mu(x) = x$ for $x \ll 1$ (MONDian regime) => $V^2/r \sim 1/r$ => V~cst

  $\mu(x) = 1$ for $x \gg 1$ (Newtonian regime)
- Why does it work in CDM and CDM-free galaxies?
- If fundamental: a) fundamental property DM ?

  b) modification of gravity ?

$$\nabla . \left[\, \mu\,(|\nabla\Phi|/a_0)\, \nabla\Phi \right] = 4\,\pi\, G\, \rho$$

- Modifying GR to obtain MOND in static weak-field limit: dynamical 4-vector field $U^\alpha U_\alpha = -1$, with free function in the action playing the role of μ (Bekenstein 2004; Zlosnik, Ferreira & Starkman 2007)

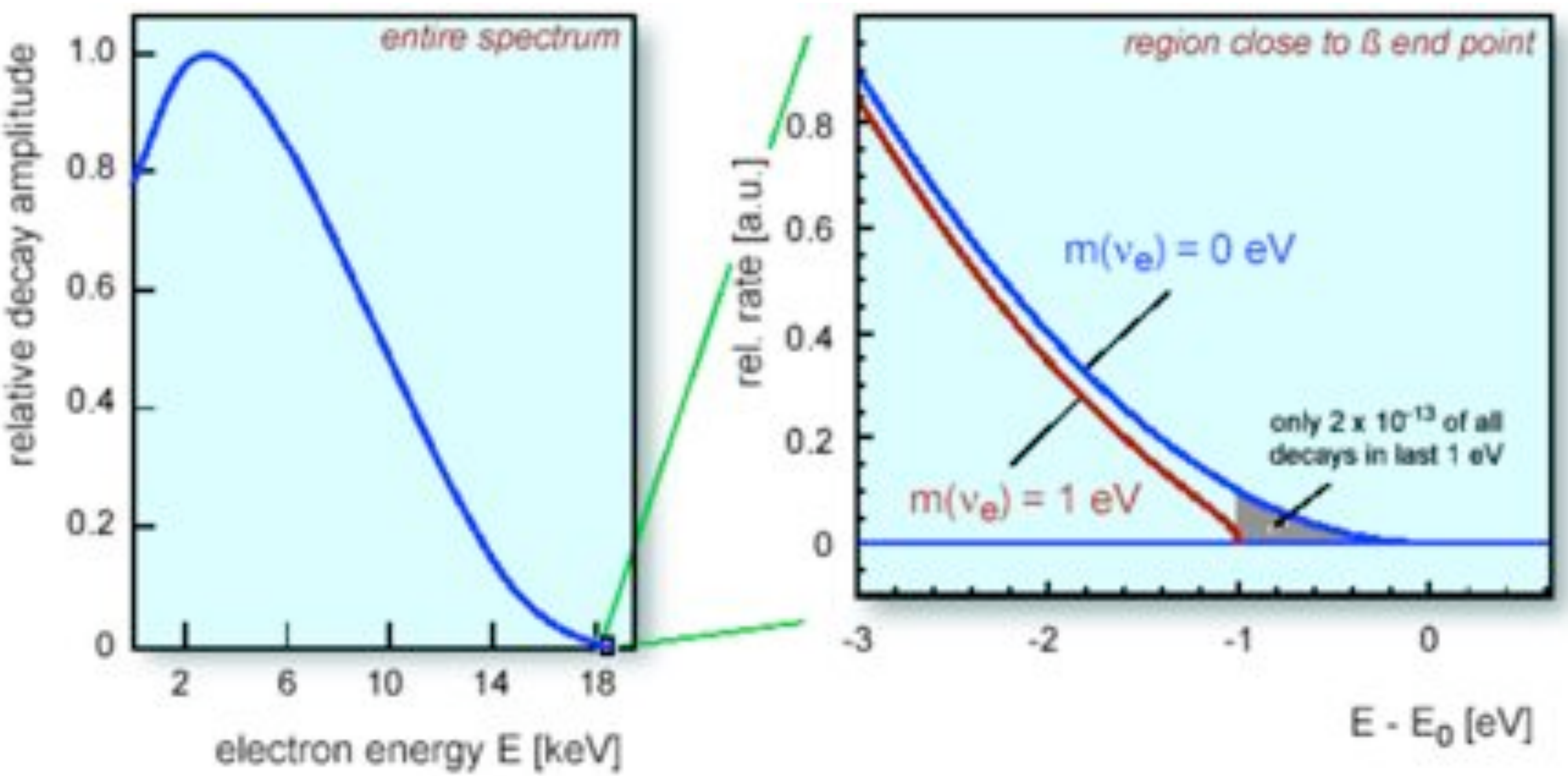


- But… rich clusters of galaxies need dark matter, e.g. ordinary neutrinos of 2eV (Sanders 2003, 2007) and/or dark baryons… 2eV neutrinos also invoked to fit the CMB power spectrum in order not to change the angular-distance relation (Skordis et al. 2006)

  Interestingly $\sum m_\nu \approx 6$eV ($\Omega_\nu \approx 0.12$) excluded in ΛCDM

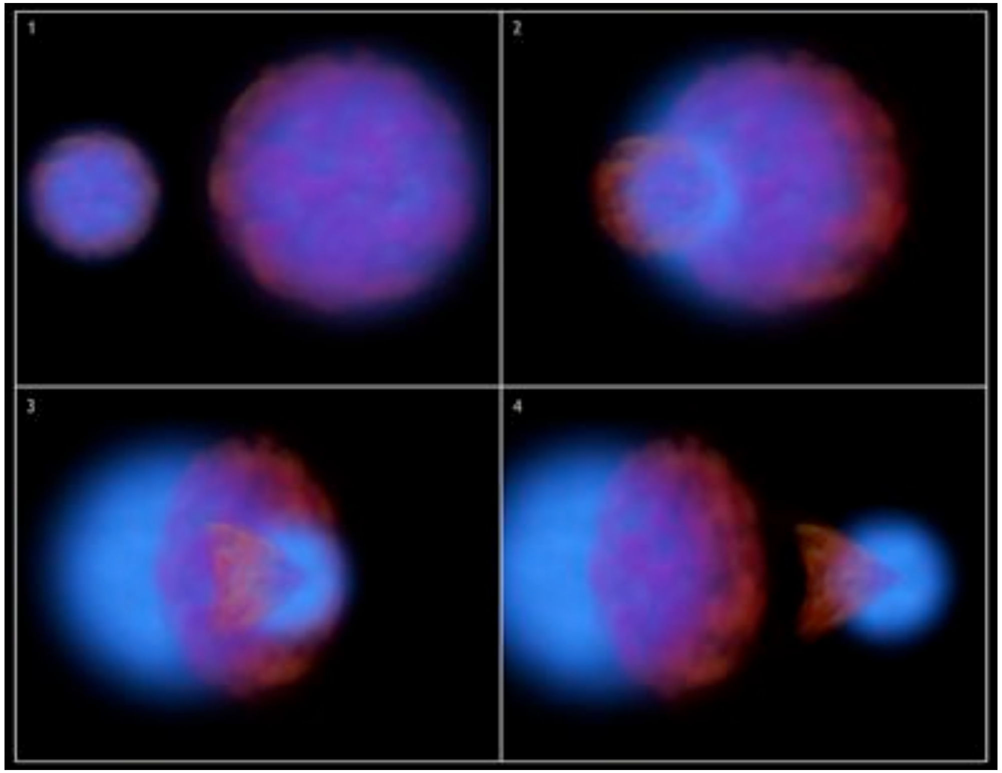
Mass of electron neutrino : KATRIN

β-decay of tritium (^3H) into Helium 3 ion + electron + neutrino:



Which *new* challenge does the bullet cluster pose to MOND?

Merging galaxy cluster (Clowe et al., Bradač et al. 2006) with gas shock speed of 4500 km/s (mass centroids at smaller relative speed): a gigantic lab (1.4 Mpc for main axis) at a distance of 1Gpc (z=0.3), separating the collisionless matter from the gas (10^{13} and 2×10^{13} M_{sun} of gas in the two cluster cores)



- We consider the weak-field static limit i.e. we neglect possible contributions of the spatial part of the vector field due to motion of matter sources (Dodelson & Liguori 2006)

- In the weak-field static limit there is a linear chain
  $\Phi \rightarrow g \rightarrow \alpha \rightarrow \kappa$

- In GR, there is an additional linear relation $\rho \rightarrow \Phi$ so the convergence $\kappa(R)$ directly measures the projected surface density $\Sigma(R)$

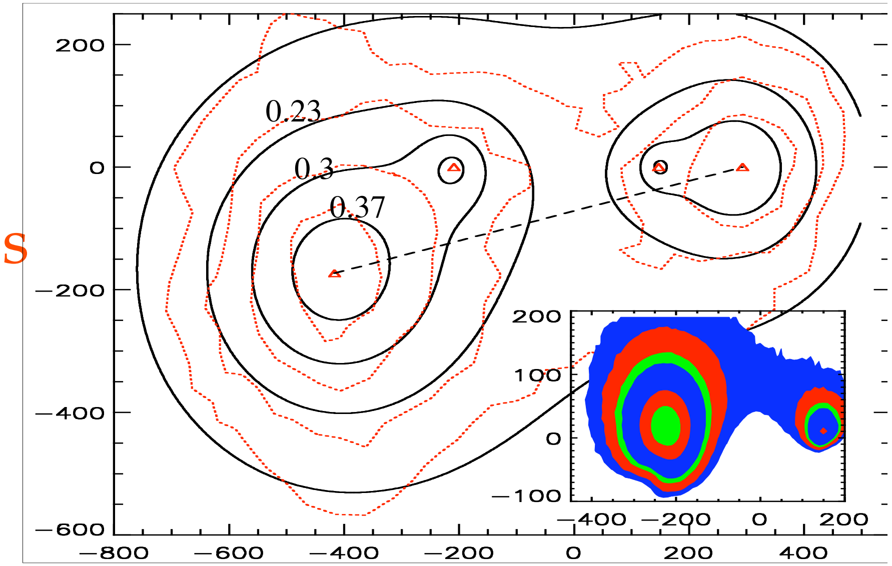
- In non-linear MOND, κ can be non-zero where there is no projected matter (Angus, Famaey & Zhao 2006)

Angus, Shan, Zhao & Famaey (**ApJ 654 L13**)

- Take parametric logarithmic potential $\Phi(r)$

$$\Phi_i(r) = 1/2\, v_i^2 \ln[1+(r/r_i)^2]$$

- Use Φ_1, Φ_2, Φ_3, Φ_4 for the 4 mass components of the bullet cluster



⇒ Parametric convergence $\kappa(R)$

- χ^2 fitting the 8 parameters on 233 points of the original weak-lensing convergence map

- With $\mu(x) = 1$ (→ GR),or e.g. $\mu(x) = x/(1+x)$, get enclosed M(r):

$$4\pi G M(r) = \int \mu(\,|\nabla\Phi|/a_0\,)\, \partial\Phi/\partial r \; dA$$

- Collisionless:gas ratio within 180kpc of the galaxies and gas centers of the main cluster is 2.4:1 in MOND

  ⇒ if MOND hidden mass = dark baryons

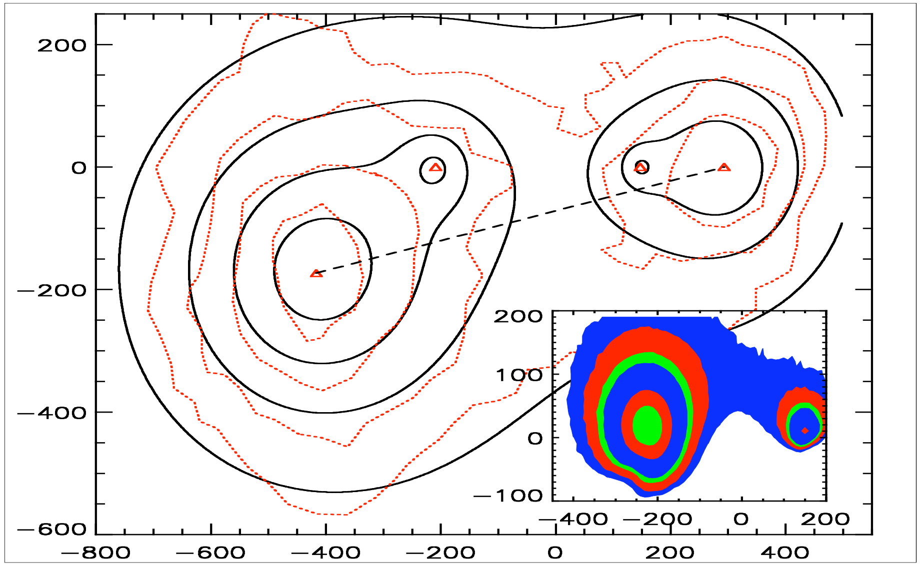
  then they must be in collisionless form (e.g. dense clumps of cold gas)

  Missing baryons still represent ~20% of BBN (depending on the amount in WHIM), while baryonic mass in clusters only ~10% => room for dark baryons

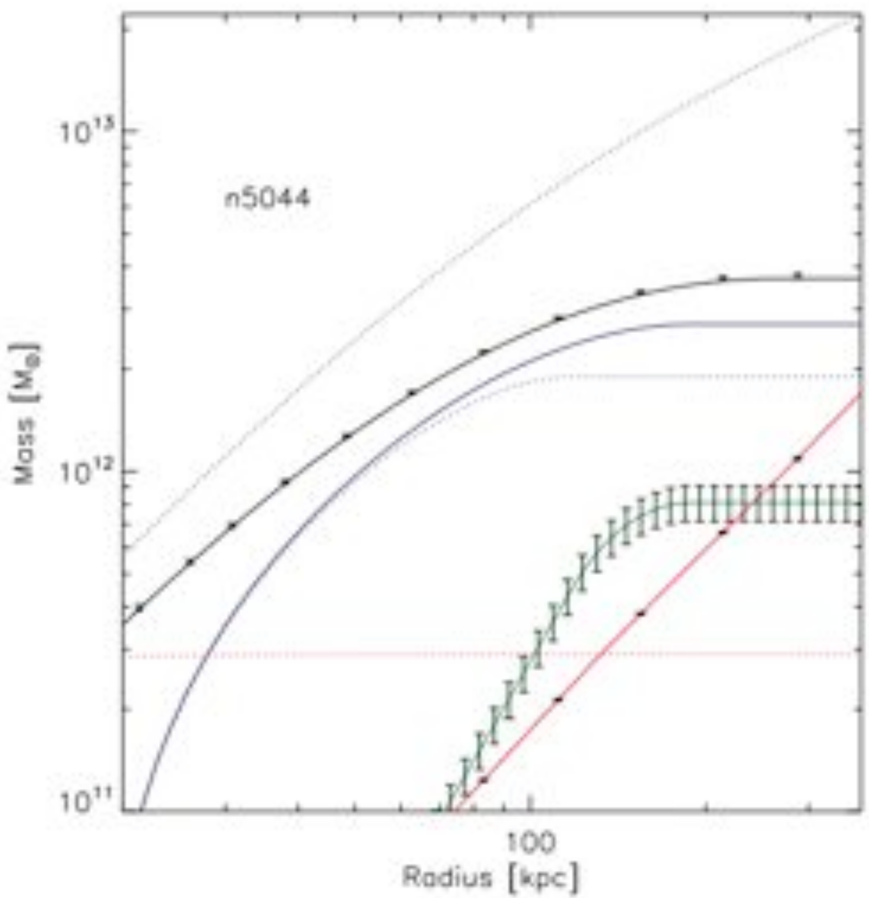
- The densities of the collisionless matter in MOND are compatible with the maximum density of 2eV neutrinos! ($\sim 10^{-3}\ M_{sun}/pc^3$ in the bullet cluster for T=9 keV ~ 10^8 K)

  ⇒ not a new challenge to MOND+neutrinos (but problem from strong-lensing at center of subcluster)

- Problem for 2 eV neutrinos in a 100 kpc central core in rich clusters known from hydrostatic equilibrium since Pointecouteau & Silk (2005)
- Note that our potential-density model yields only the total mass => substract the DM to get the gas BUT, of course, underestimate of the gas mass, especially for the subcluster



Angus, Famaey & Buote 2007
arXiv:0709.0108



- Tremaine-Gunn limit for neutrinos:

  ρ_ν (max) $\propto T^{3/2}$

=> Problem for X-ray emitting groups with T<2 keV

Conclusions

- The bullet cluster weak-lensing in itself is *not* a new challenge to MOND + 2eV ordinary neutrinos
- What about Abell 520? (Mahdavi et al. 2007) Effect of intercluster filaments on gravitational lensing in MOND?
- Looking forward to baby bullets' data
- Low-mass X-ray emitting groups are a tougher challenge:

=> Maybe another fermionic dark particle?
(hot sterile neutrinos with $m_\nu \sim 10eV$?)

=> Maybe dark baryons in the form of e.g.
dense clumps of cold gas, present only in galaxy clusters? (but then, microlensing?)

=> Maybe CDM?… but then one must understand why it does reproduce so precisely the MOND relation for all galaxies…