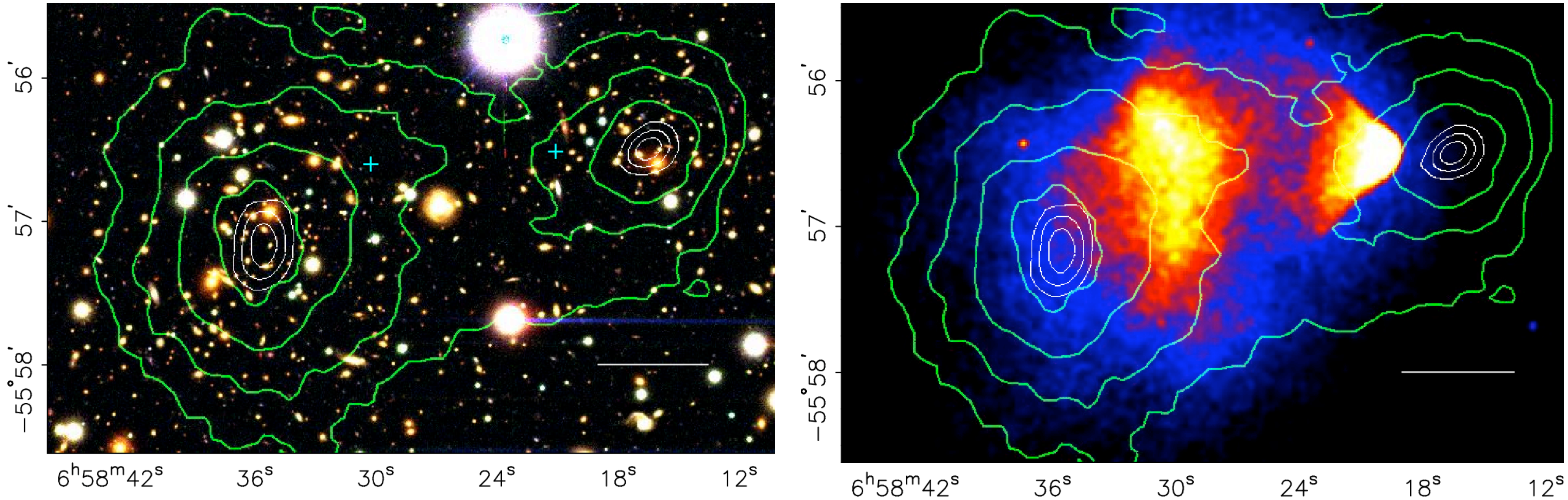
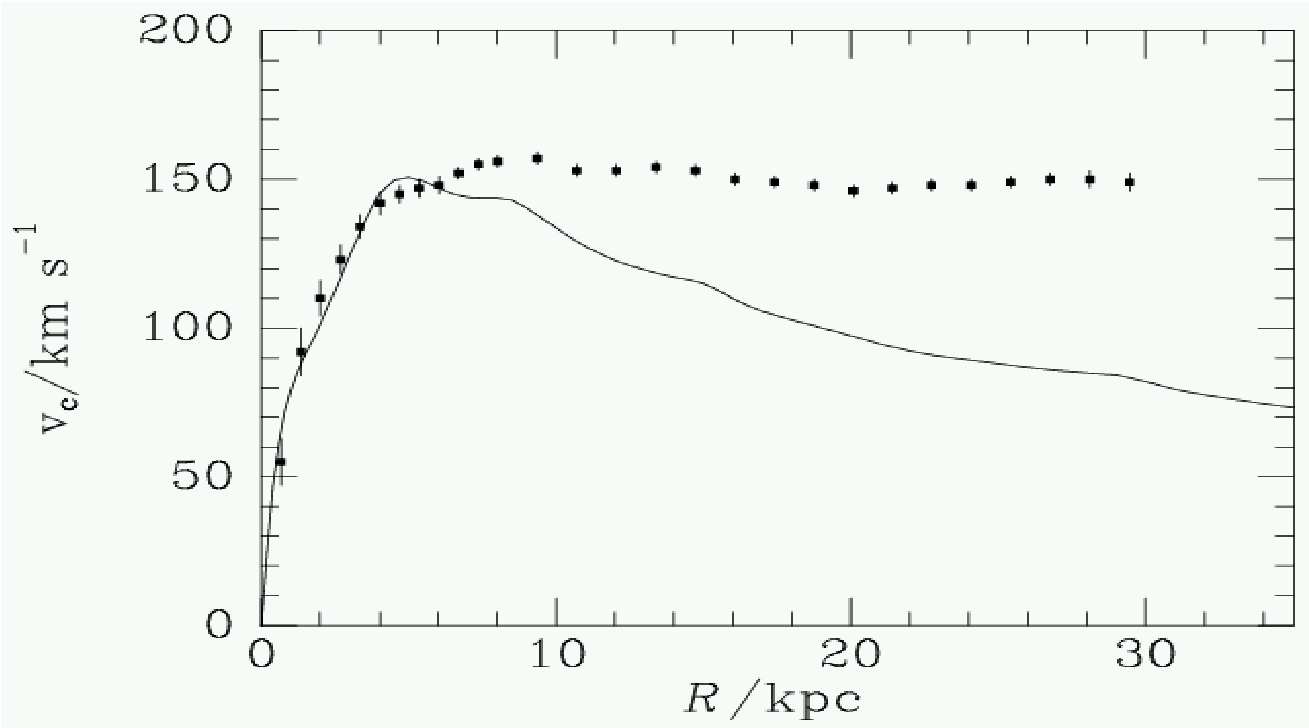
Modified Gravity and the Bullet Cluster



Benoit Famaey (Université Libre de Bruxelles)

General Relativity



- Observe ρ_{bar} in galaxies derive Φ_{bar} $(R|\nabla\Phi_{bar}|)^{1/2} = V_{c\ bar}$ too low in the galactic plane compared to observed V_c

=> DARK MATTER HALO

- Concordance model: Assume GR and Λ to fit supernovae data (the cosmological constant or dark energy density $c^4\Lambda/8\pi G$)

  $$R_{\alpha\beta} - 1/2\, R\, g_{\alpha\beta} + \Lambda g_{\alpha\beta} = (8\pi G/c^4)\, T_{\alpha\beta}$$

- DM non-baryonic ($\Omega_b \approx 0.05$, $\Omega_m \approx 0.3$)

  and cold (CDM) i.e. massive particles

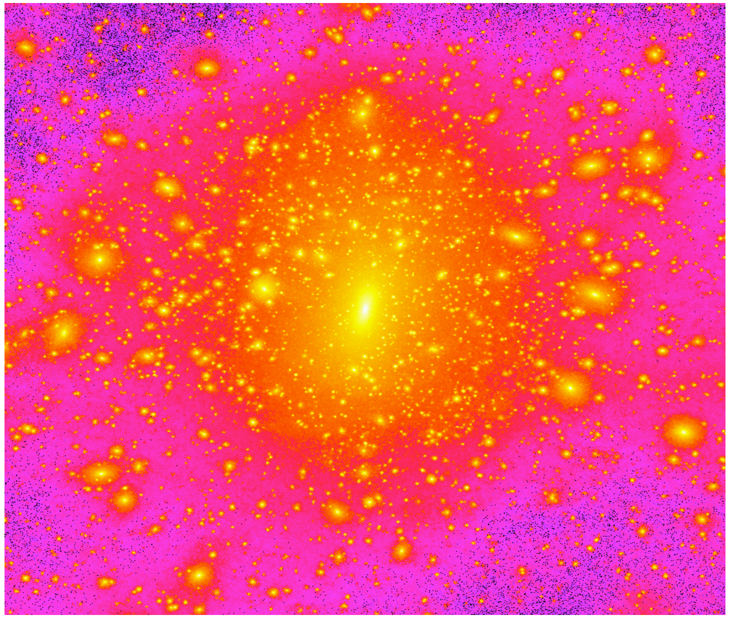
  (e.g. neutralino ~ 1TeV) to grow hierarchical structure

- It cannot be ordinary neutrinos, too light (< 2.2 eV) to form hierarchical structure, too light fermions to have a density comparable to DM densities in galaxies (colder than galaxy clusters). In standard cosmology $\sum m < 0.6$ eV

- However, CDM (necessary in a GR Universe) is not without problems

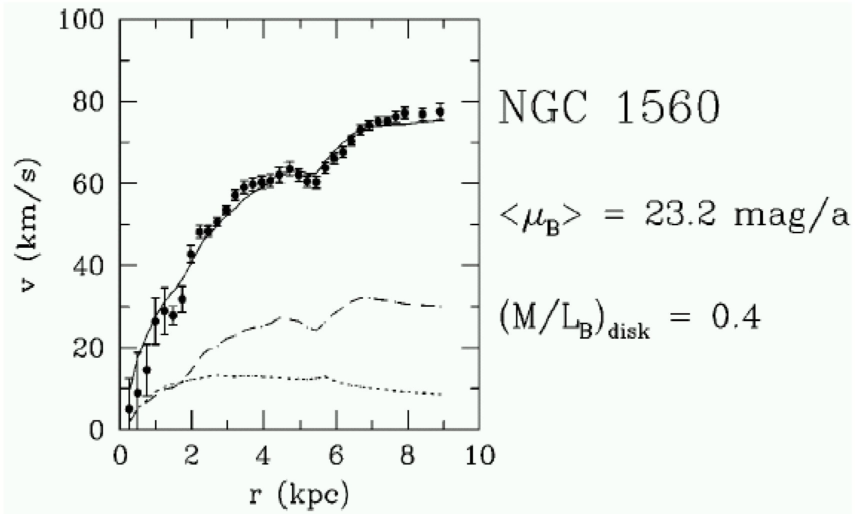
CDM simulations

High resolution simulations of clustering CDM halos (e.g. Diemand et al.)



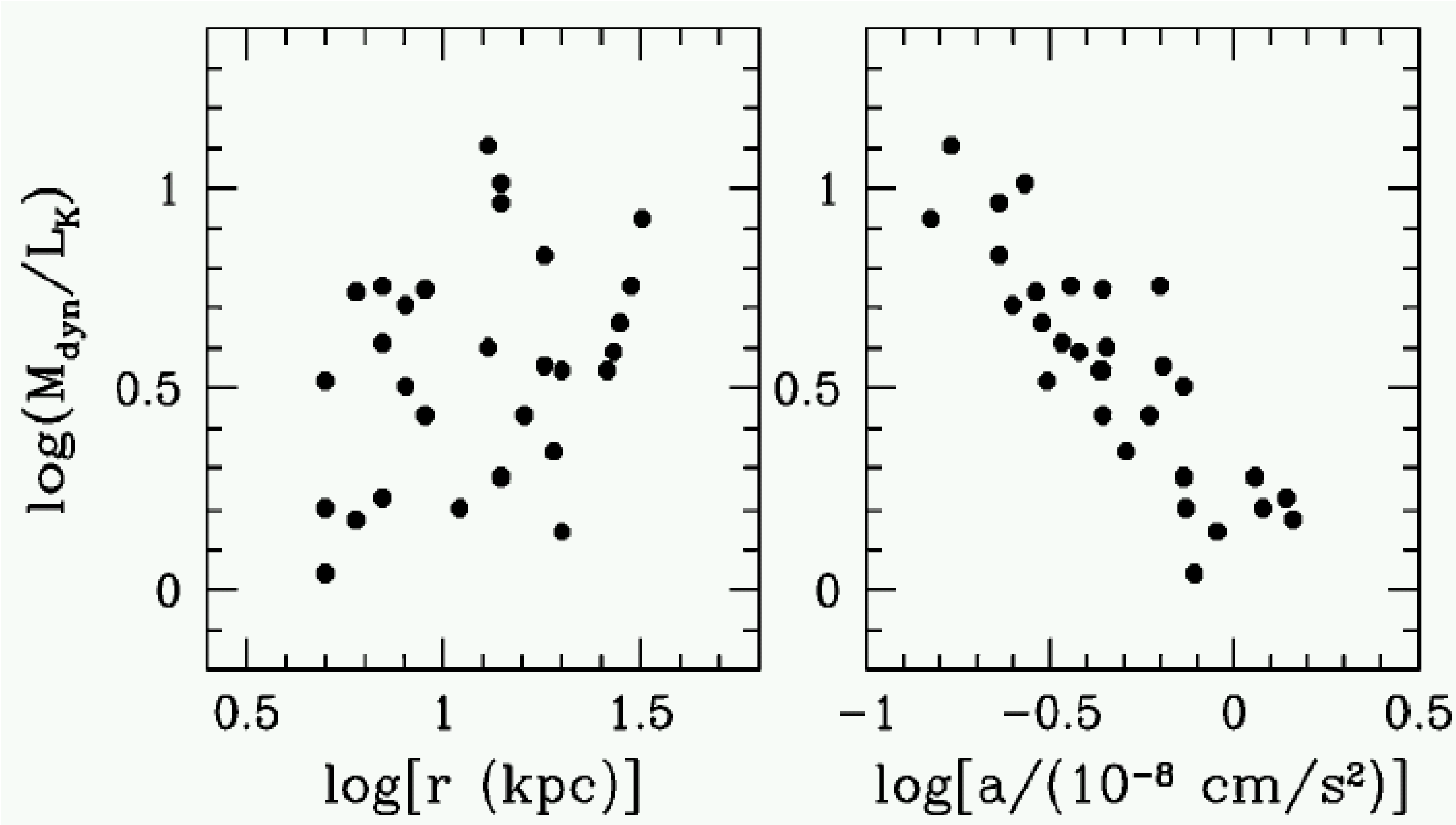
Central **cusp** $\rho \propto r^{-\gamma}$, with $\gamma > 1$

Observed **neither in the Milky Way (see Famaey & Binney 2005) neither in LSB nor in HSB** (No present-day satisfactory solution)



What is more: wiggles of rotation curves follow wiggles of baryons!!

The baryon-gravity relation



Modification of Newtonian gravity

Suppose $\mathbf{F} = -\nabla\phi$ where

$$\nabla^2\phi_{\mathrm{N}} = 4\pi G\rho \quad \rightarrow \quad \nabla\cdot[\mu(|\nabla\phi|/a_0)\nabla\phi] = 4\pi G\rho$$

where

$$\mu(x) \rightarrow \begin{cases} 1 & \text{for } x \gg 1 \\ x & \text{for } x \ll 1 \end{cases}$$

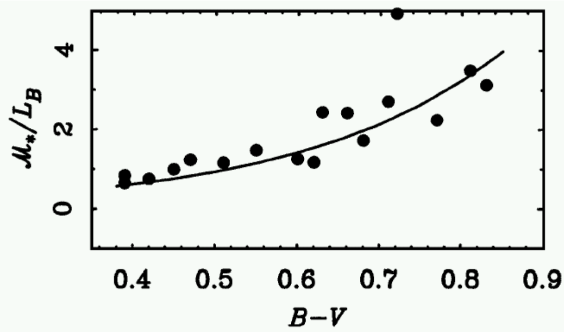
This is the B-M equation (Bekenstein & Milgrom 1984)

Milgrom's formula exact in spherical and cylindrical symmetry and good approximation in a flat axisymmetric disk:

$\boldsymbol{a} = -\nabla\Phi$

$\mu\,(|\nabla\Phi|/a_0)\,\nabla\Phi = \nabla\Phi_N + \nabla \times \mathbf{K}$

- Explains the RC wiggles following the baryons
- Tully-Fisher relation at small *x*: $v^4 = GM_{\text{bar}} a_0$ (small observed scatter)
- Rotation curves of **HSB** (see e.g. Famaey, Gentile, Bruneton, Zhao astro-ph/0611132)
- Rotation curves of **LSB** ($\Sigma \ll a_0/G \Rightarrow g_N \ll a_0$), with high-discrepancy
- Fitted M/L ratios follow predictions of pop. synthesis models



- No discrepancy in giant **ellipticals** (Milgrom & Sanders 2003)
- No discrepancy in nearby **globular clusters**

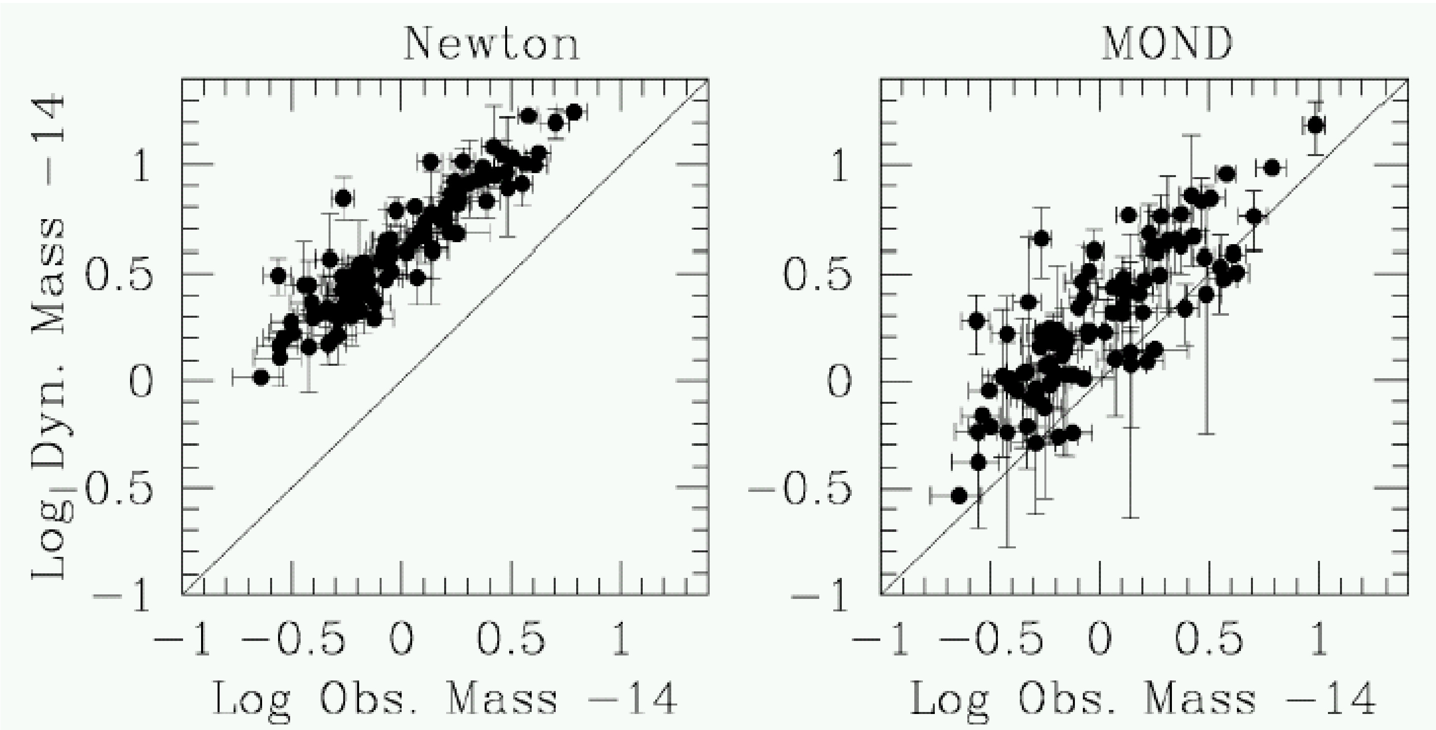
(external field effect, breaks the strong equivalence principle)

- Local galactic escape speed from the Milky Way

  $v_{\text{esc}} \sim 545$ km/s as observed (Famaey, Bruneton & Zhao astro-ph/0702275)

  for an external field of order $a_0/100 \sim H_0 \cdot 600$ km/s

- Dwarf spheroidals not too bad (large error bars)
- But… clusters of galaxies need dark matter, e.g. neutrinos or the missing baryons… we shall see that the bullet cluster implies that it must be collisionless



Modifying GR?

Bekenstein (2004) proposed a bi-metric multi-field theory with a physical metric that couples with matter fields:

$$g'_{\alpha\beta} = e^{-2\phi}(g_{\alpha\beta} + U_\alpha U_\beta) - e^{2\phi} U_\alpha U_\beta$$

$$S = S_g + S_\phi + S_U + S_m$$

with a dynamical normalized vector field U_α

(pointing in the time-direction for a quasi-static system)

and a k-essence-like scalar field ϕ (with a free function in its lagrangian density depending on $\nabla\phi . \nabla\phi$, and linked to the MOND μ)

=> one can obtain MOND

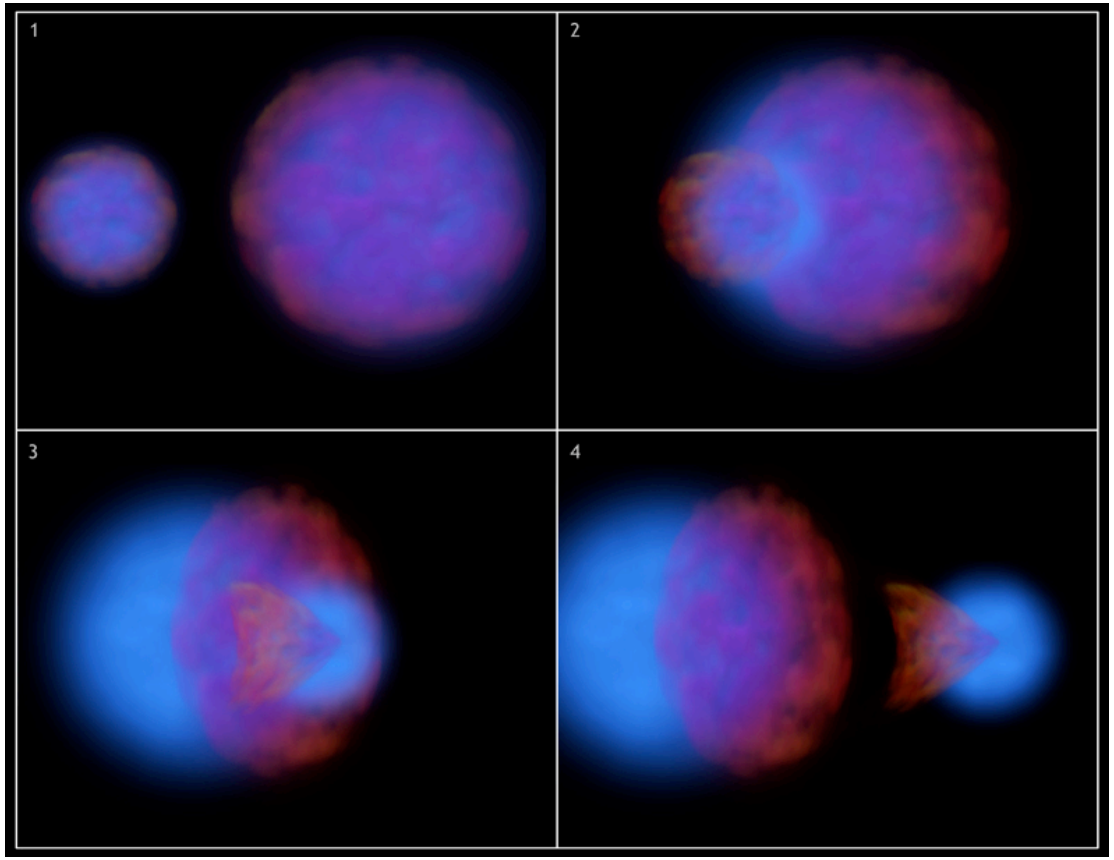
- In a **quasi-static** system with a **weak** gravitational field:
  $g'_{00} = -(1-2\Phi)$ *where* $\Phi \equiv \Phi_N + \phi$
  $g'_{ij} = (1-2\Phi)\,\delta_{ij}$ where $\Phi \equiv \Phi_N + \phi$
  where ϕ **obeys a MOND-like equation**, and plays the role of the dark matter potential (dynamics and lensing are governed by the **same** physical metric *g'*, MOND precisely recovered in spherical symmetry)

- CMB (Skordis et al. 2006) needs a component of HDM, e.g. neutrinos m ~ 2eV (in order not to change the angular-distance relation by having too much acceleration) + good complement to dynamical mass estimated from temperature profiles in galaxy clusters (Aguirre et al. 2001, Sanders 2003, Pointecouteau & Silk 2005)

- The competitor of the ΛCDM model is thus the μHDM model bypassing CDM problems on galaxy scales

The bullet cluster

Merging galaxy cluster at a relative speed of 4700 km/s: 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 $2x10^{13}$ M_{sun} of gas in the two clusters)



Gravitational potential from weak lensing

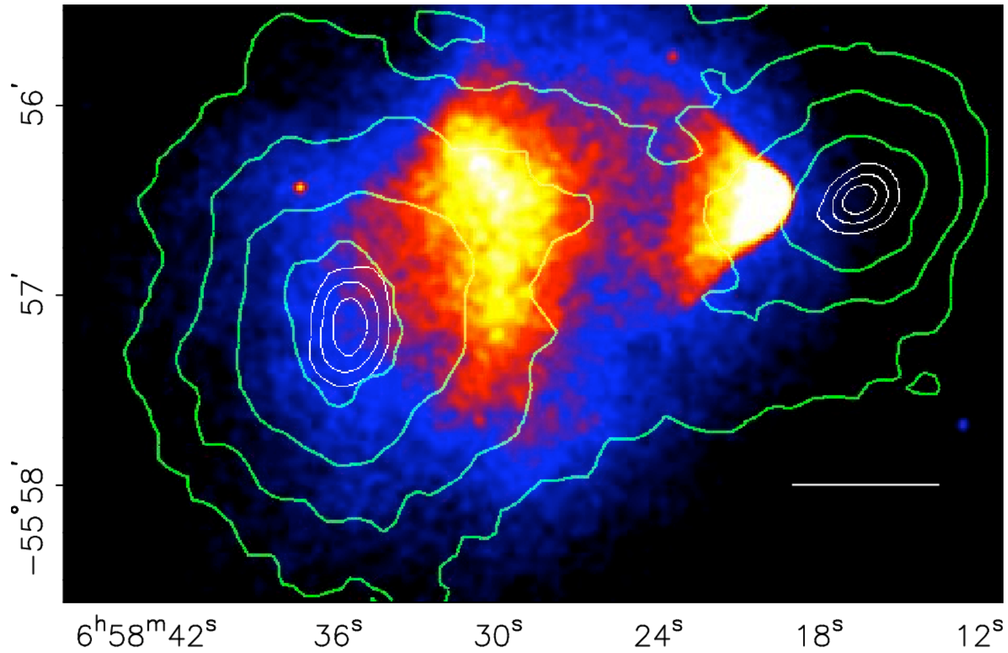
- Weak lensing : deflection of light rays around a gravitational lens causes images of distant galaxies to appear aligned (sheared) along the gradient of the gravitational potential of the lens

  $\Rightarrow$ one can estimate the shear, and the convergence parameter $\kappa(R)$ of the lens = divergence of the bending angle vector in the lens plane $\alpha(R)$

- In any metric gravity theory there is a **linear** chain

  $\Phi \rightarrow \boldsymbol{g} \rightarrow \alpha \rightarrow \kappa$
- 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 gravities, κ can be non-zero where there is no projected matter (Angus, Famaey & Zhao 2006)

Convergence map of the bullet cluster



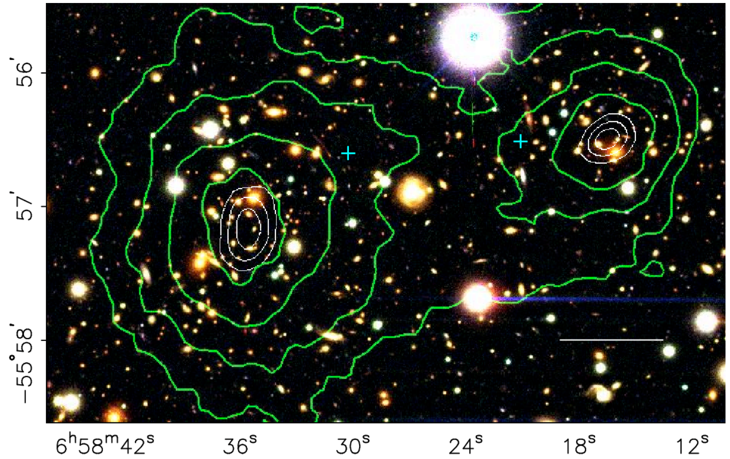
Clowe et al. (2006)

Proof of DM? Proof of CDM??

Angus, Shan, Zhao, Famaey (ApJ 654 L13, astro-ph/0609125)

- 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

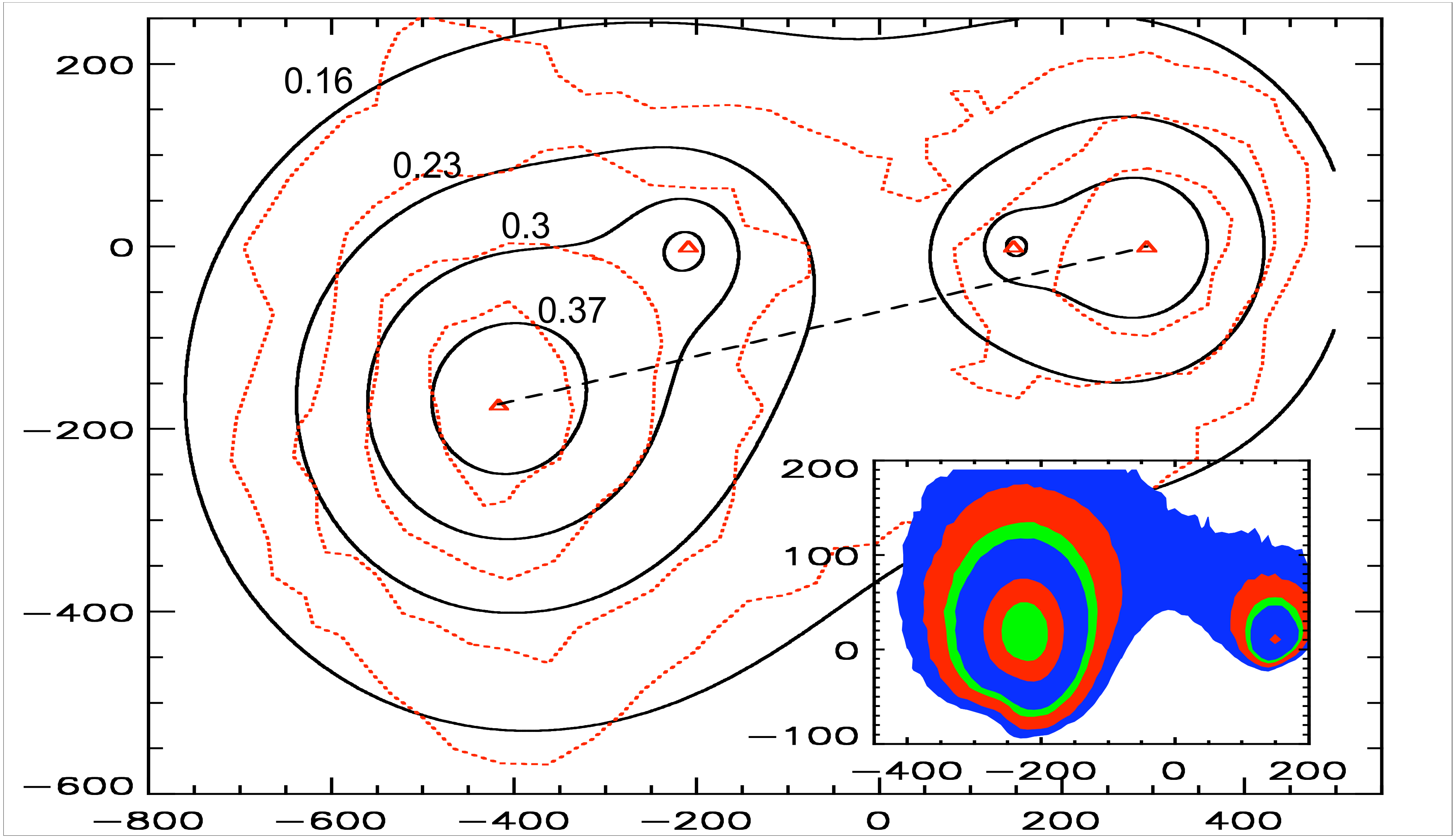
$\Rightarrow$ Parametric convergence $\kappa(R)$

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

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

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

The fit



0.16
0.23
0.3
0.37
200
0
−200
−400
−600
−800
−600
−400
−200
0
200
400
200
100
0
−100
−400
−200
0
200

Enclosed mass in MOND

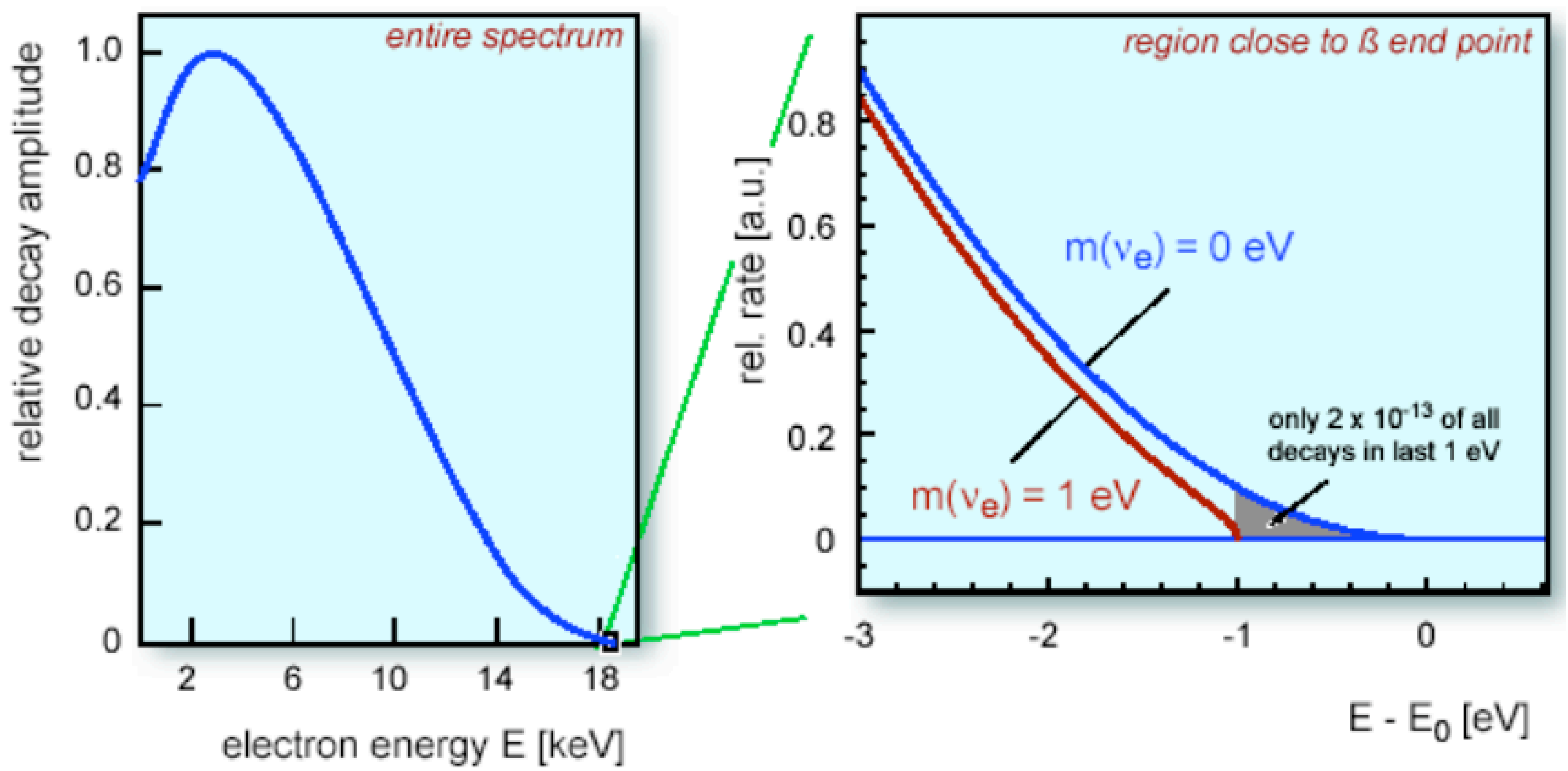
- Collisionless:gas ratio within 180kpc of the galaxy and gas centers of the main cluster is 2.4:1, instead of 1:8 for the ratio of observed collisionless baryons to X-ray gas $\Rightarrow$ proof of DM… but does this exclude MOND?

- The central densities of the collisionless matter in MOND are compatible with the maximum density of 2eV neutrinos! (~ 10^{-3} M_{sun}/pc^3 in clusters)

  => does not exclude μHDM

Mass of electron neutrino

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



Conclusion

- Unseen matter in GR or MOND must be collisionless, but BC doesn't rule out the MOND+neutrinos paradigm (note that this collisionless DM does not HAVE to be neutrinos). Seems somewhat ungainly, but don't forget the baryon-gravity relation in galaxies + velocity of the bullet cluster (Angus & McGaugh in prep.)

- If $m_\nu \sim 2$ eV are discovered (active or sterile), it is a problem in standard cosmology while one could consider it as a succesfull "prediction" of MOND, then there could really be something fundamental about MOND/TeVeS!