Improving the RHS or LHS of Einstein's Equation

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Einstein's Eq. needs fix to boost acceleration in galaxies/universe

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

Right-handed physicists found easier to add
new energy + new particles ⇒ DE + DM

If you are left-handed, like to Modify $G \Rightarrow G\ e^{2\phi}$…
to achieve similar Not identical effects.

Just an example:
Carroll's modified theory

$$G_{\mu\nu} = 8\pi G e^{-2\psi}\left(T_{\mu\nu}^{(matter)} + T_{\mu\nu}^{(\psi)}\right)$$

Similar to a scalar-tensor theory, but now the scalar is **determined algebraically** by the ordinary matter fields, once we specify the potential $U(\psi)$.

$$\frac{dU}{d\psi} - 4U(\psi) = -T = \rho - 3p¿$$

[Carroll 2006]

Other examples: f(R) gravity, DGP gravity, Bekenstein's TeVeS ...

Rotation Curve & Lensing Data: Deflection by ϕ_{DM} or $\phi_{Tracker}$

$$ds^2 = (1+2\Phi)\, dt^2 - (1-2\Phi)\, (dx^2 + dy^2 + dz^2)$$

- The metric near galaxies is curved by an extra potential

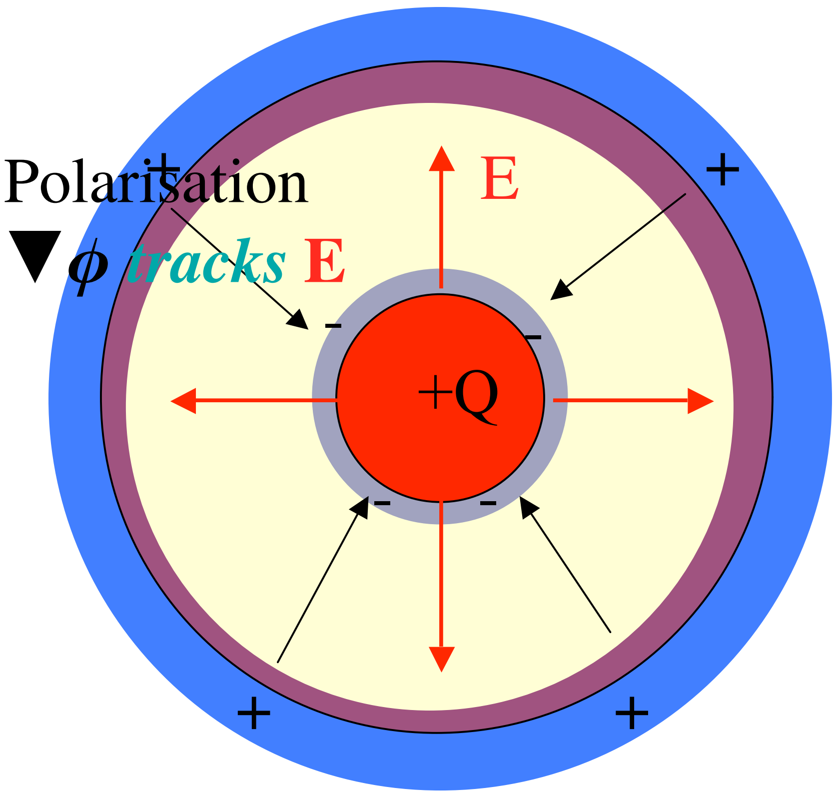
$$\Phi = \Phi_{known} + \phi_{DM} \;\text{-->}\; \Phi_{known} + \phi_{Tracker}$$

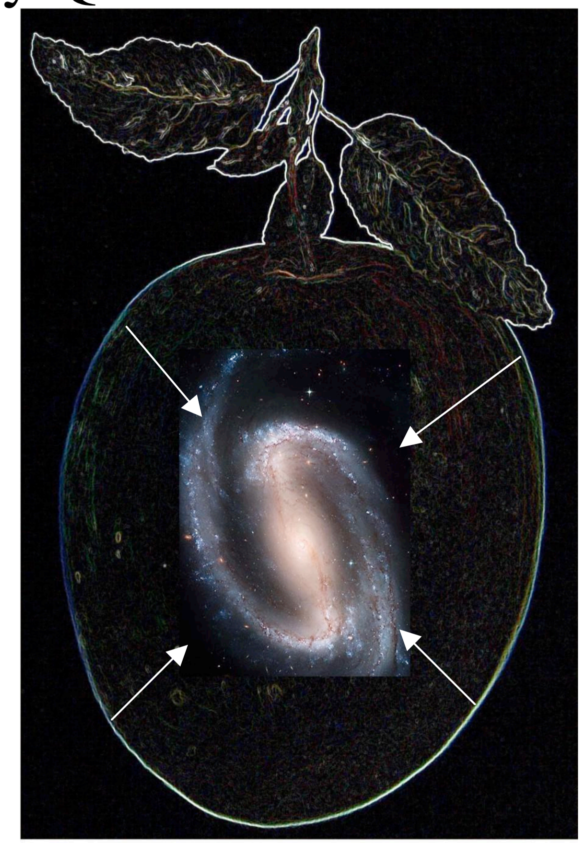
Bekenstein's TeVeS (2004)

- Is it DM gravity or some scalar field tracking known matter with $\nabla\phi_{Tracker} = f(\nabla\Phi_{known})$?

Analogy: Polarisation field in dielectric

tracks E-field of free charge density Q



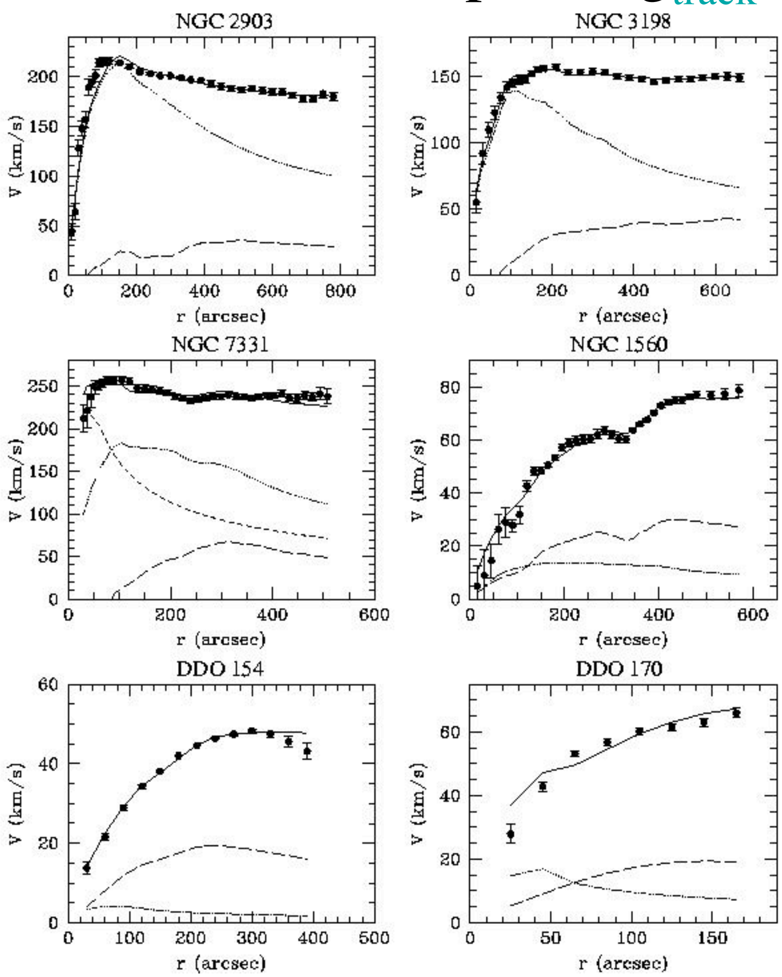


... One Apple ... in the darkness binds them all.

$$\nabla \cdot [\mu \nabla \phi] = 4\pi Q = \nabla \cdot [\varepsilon E]$$

Acceleration tracks known matter

In spirals $g_{track} \sim (a_0 G\, M_{known}/R^2)^{1/2}$ fits



Bruneton, Famaey, Gentile, Nipoti, Zhao (2006)

A Fake Spiral: Light of UGC128 given Rotations of NGC 2403

Tracker field fails to fit (Good !!) DM fits fine (cosmic variance)

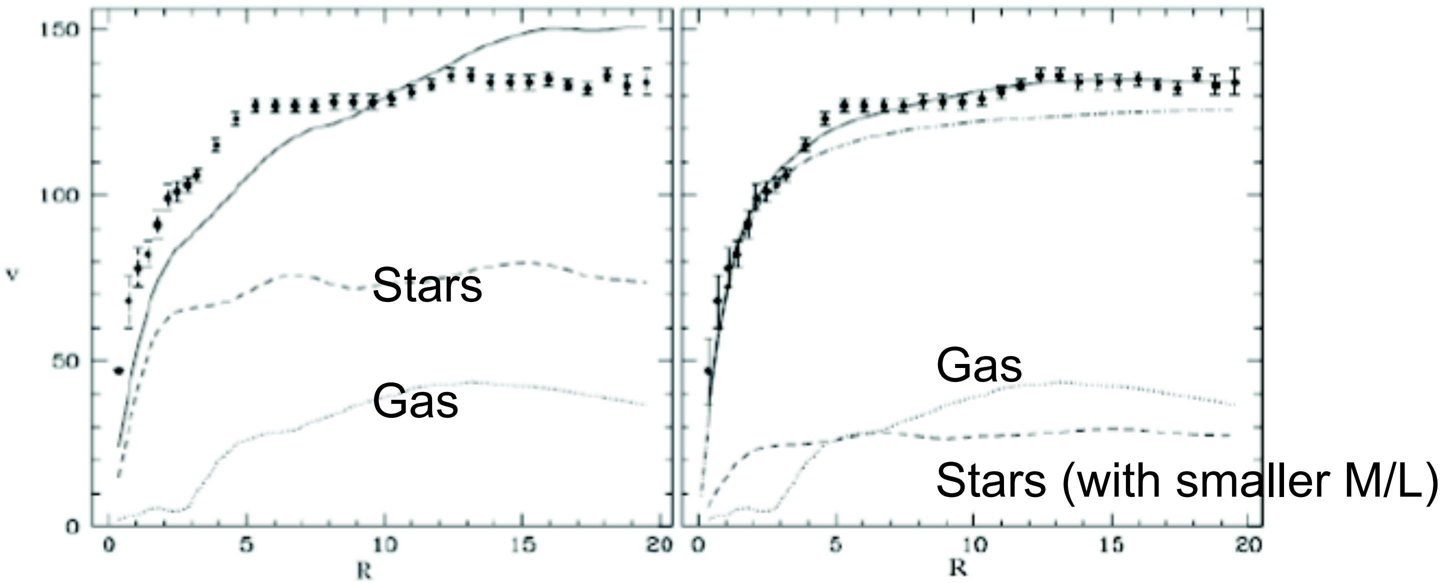
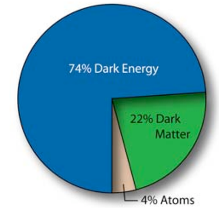
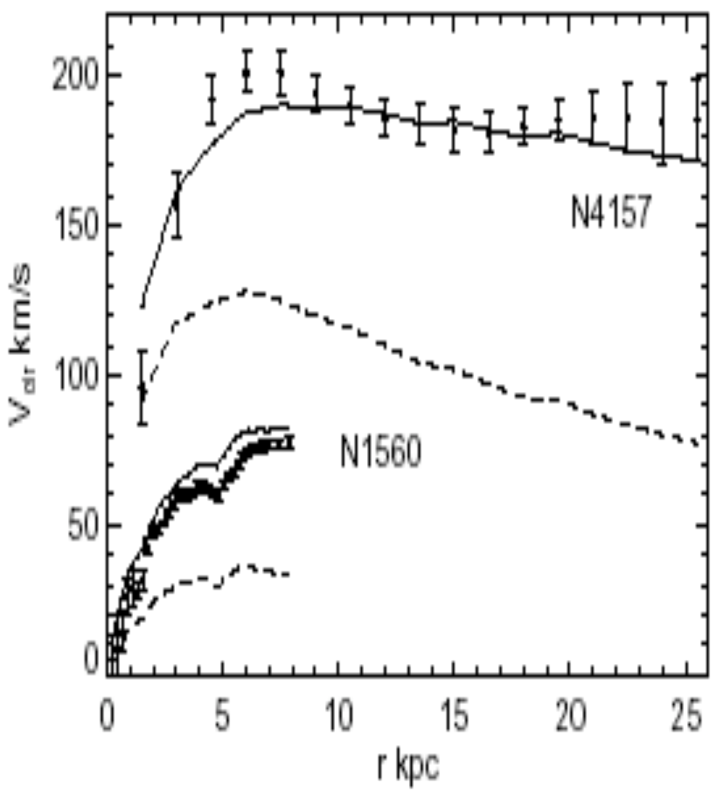


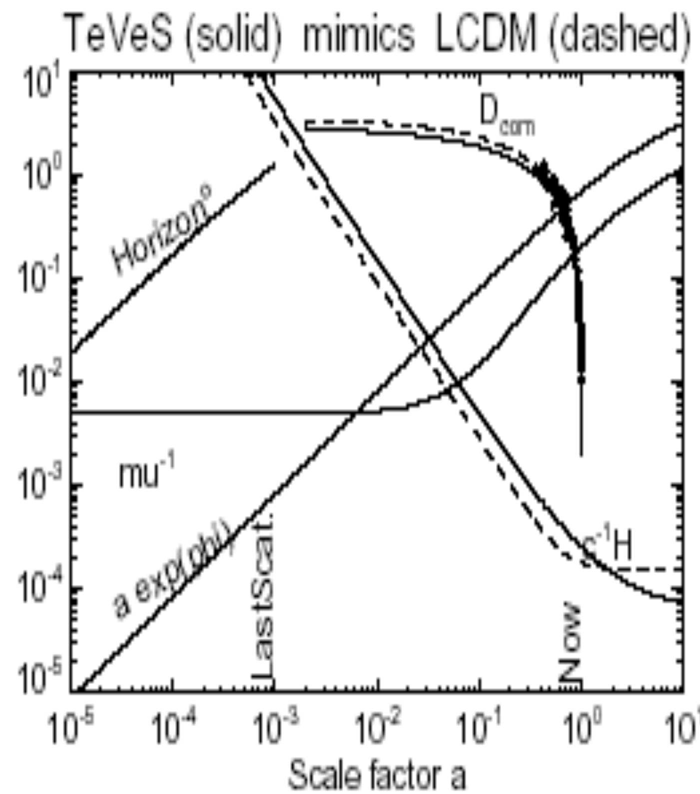
FIGURE 3. Fit of the rotation curves of an hybrid galaxy, obtained using the velocity information for one galaxy (NGC2403) and the photometry – used to compute masses – from another (UGC 128) (data from [15]). MOND (left panel) fails to fit this fake galaxy, which is good. On the other hand, a fit of an isothermal dark-matter halo (right panel) allows so much freedom that an acceptable fit can be found, which is bad. The curves relative to the gas component (dotted line) and stellar disk (dashed line) are also shown. Velocities in km/s, and radius in kpc.

Scarpa; http://xxx.lanl.gov/pdf/astro-ph/0601478



Predict cosmic acceleration from fitting acceleration in spirals





Zhao, Skordis, Mota (2006)

Discussions: is non-GR possible?

- Can lensing & structure form?
  - Yes, but subtle difference in CMB amplitudes, a few outliers in strong lensing
  - Readings: Zhao, Bacon, Taylor, Horne **0509590**, Skordis et al. **0505519**, Dodelson et al. **0608602**

- Can give effective DM & DE?
  - Yes, Diaz-Rivera et al **0601153**

- Can predict lensing in non-spherical potential?
  - Yes, Angus et al. **0606216,** Ciotti et al. **0512056**

X-ray Cluster mass-discrepancy

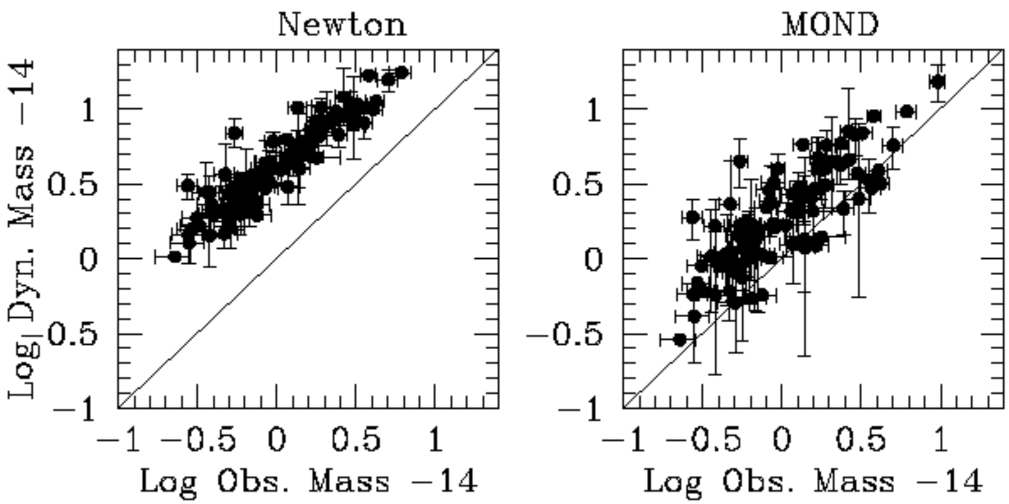
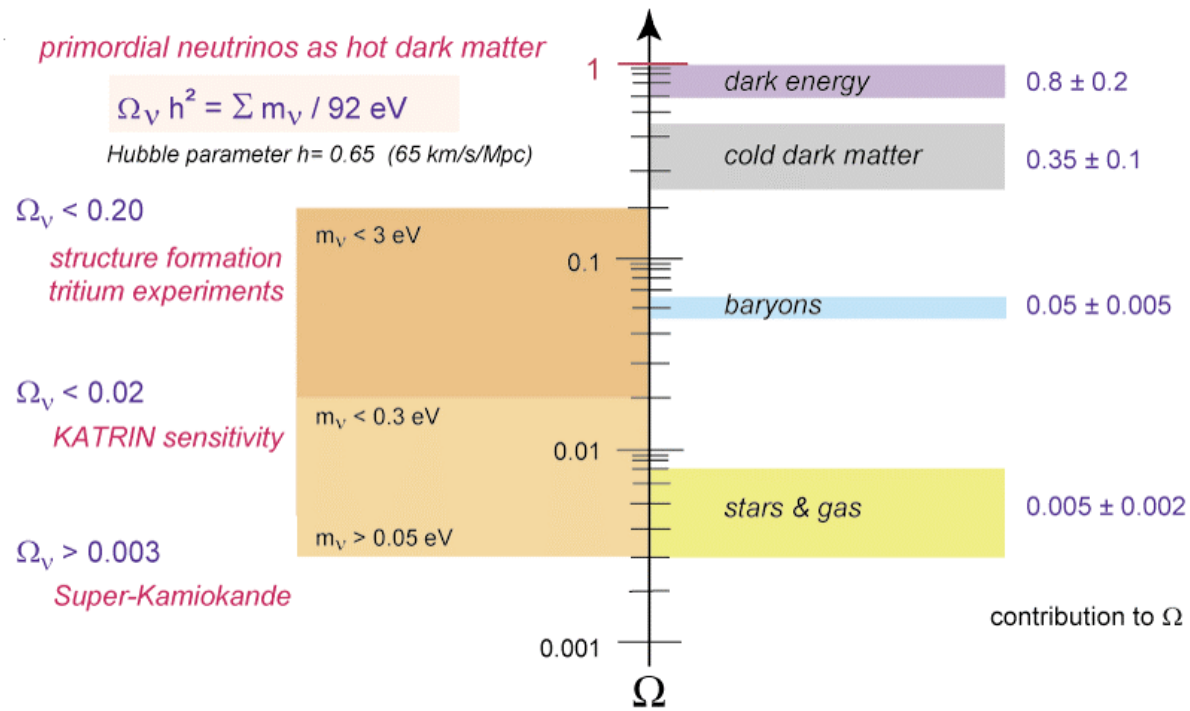


Figure 10: (*Left*) the Newtonian dynamical mass of clusters of galaxies within an observed cutoff radius (r_{out}) vs. the total observable mass in 93 X-ray emitting clusters of galaxies (White et al. 1997). The solid line corresponds to $M_{dyn} = M_{obs}$ (no discrepancy). (*Right*) the MOND dynamical mass within r_{out} vs. the total observable mass for the same X-ray emitting clusters. From Sanders (1999).

Do neutrinos play a role in deep potential? (Sanders & McGaugh, 0204521)

present model-independent range of neutrino mass



What Angus **0609125** did with Bullet Cluster :

- Assume cored potential

$$\Phi_i = \tfrac{1}{2} v_i^2 \ln\left(1 + \frac{r^2}{p_i^2}\right)$$

-Use Φ_1, Φ_2, Φ_3, Φ_4 for the 4 mass components of the bullet cluster centred on the likely positions

⇒Linear chain in any gravity

$\Phi \rightarrow g \rightarrow$ deflection $\rightarrow$ convergence $\kappa \rightarrow$ amplification

⇒χ^2 fit the 8 parameters (v^2_i and p_i) to match our predicted κ-map with Clowe et al. (2006).

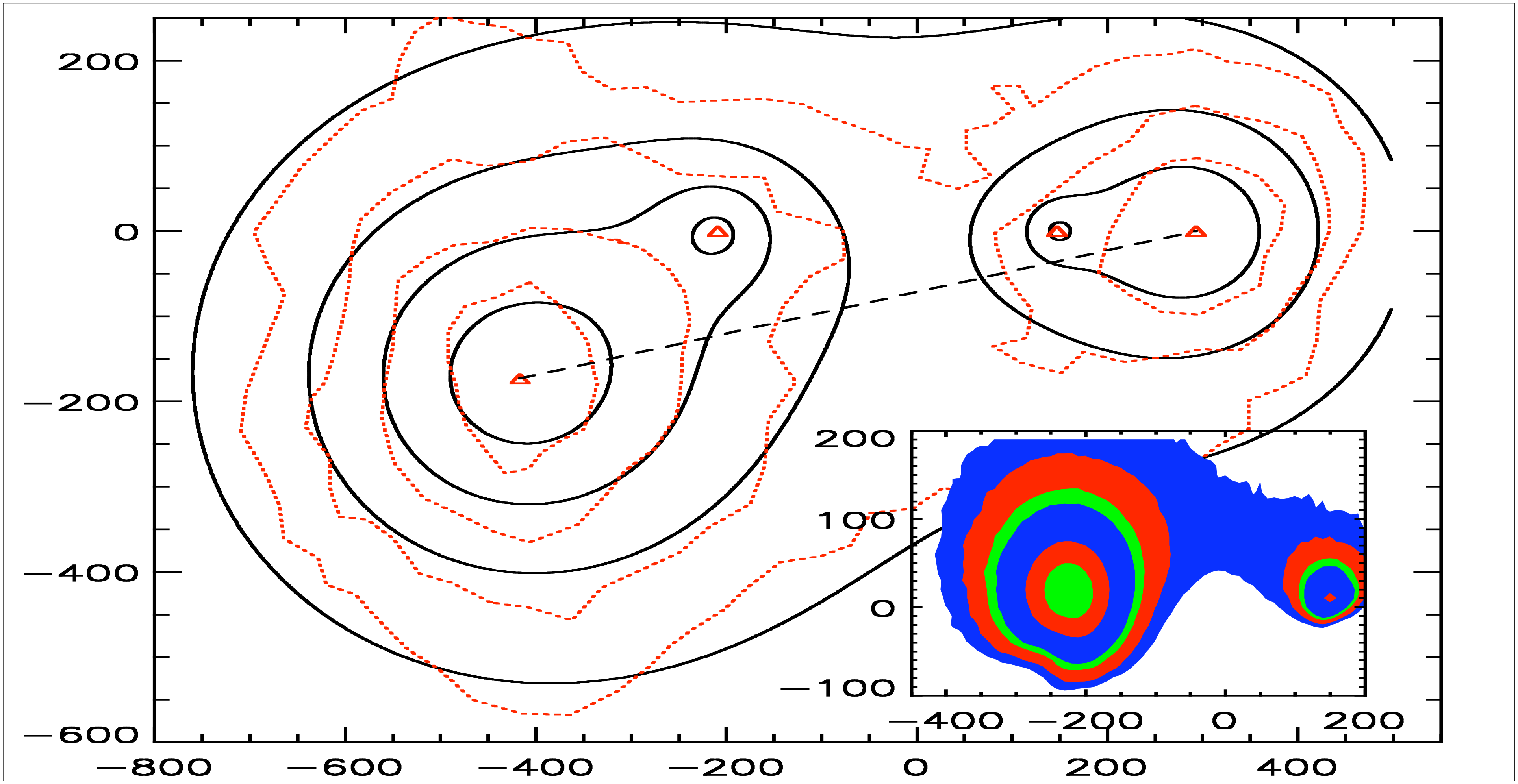
⇒ Gauss said :

$$4\pi\, M(r) = \int (\partial \Phi / \partial r)\, G^{-1}\, dA, \qquad A = 4\pi\, r^2$$

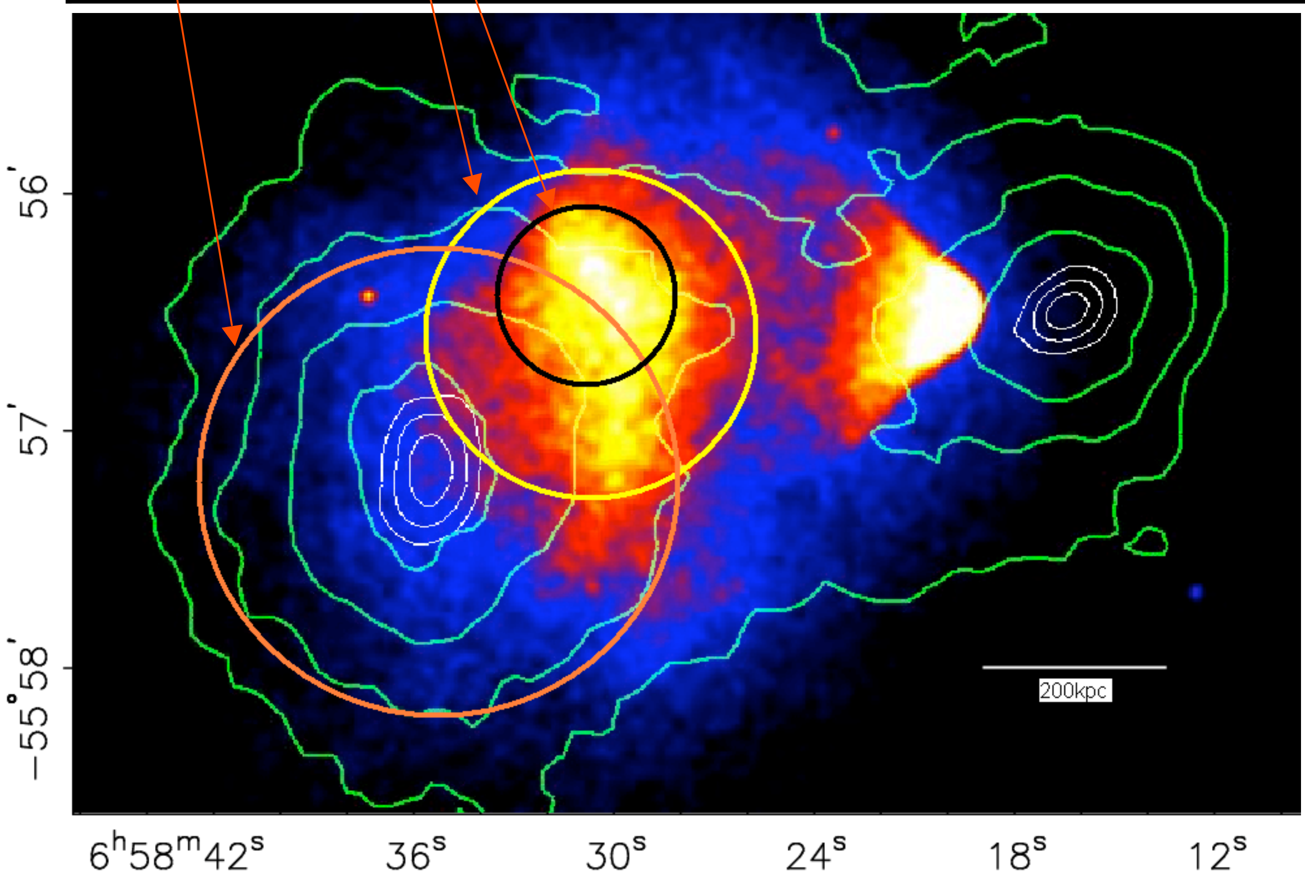
⇒Finally specify gravity: $G_{TeVeS}/G_0 = \mu^{-1} = 1 + (a_0/|\nabla\Phi|)$,

⇒ recover GR: if set $a_0 \rightarrow 0$

Angus Fit to Clowe data



Gravity Theory	Newtonian $\mu=1$	Standard μ $\mu = \frac{x}{\sqrt{1+x^2}}$	Simple μ $\mu = \frac{x}{1+x}$	Value from Clowe et al.
Total M(<250kpc) (10^{13} M_{sun})	10.0	9.0	6.8	28.0!!!
Gas M(<100kpc) Gas M(<180kpc)	1.05 1.97	0.97 1.79	0.74 1.33	0.66 2.0



Central density required by the standard μ function is $\rho=2.6\times10^{-3} M_{sun} pc^{-3}$. Some of this is due to gas.

Phase space density arguments of Tremaine & Gunn requires neutrinos of $m_\nu=1.8$eV

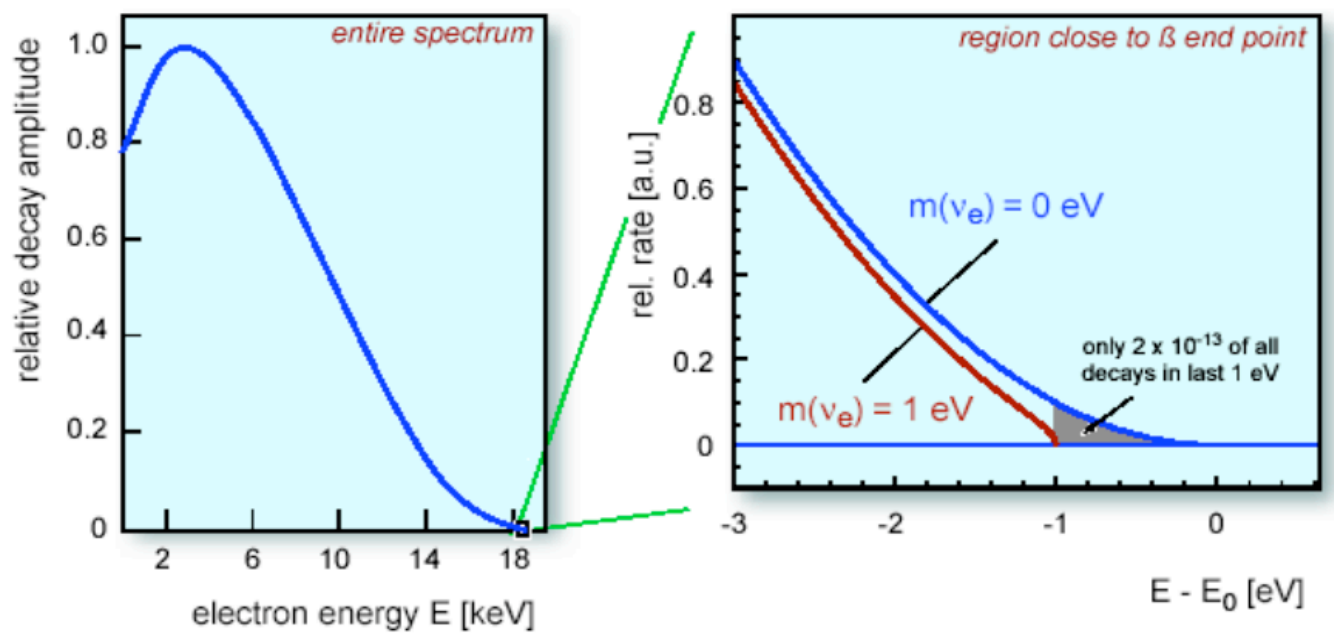
Non-baryon:baryon ratio within 180kpc is 2.4.

Discuss: CAN the bullet prove DM?

- Eventually!
- Even without the harder proof of GR (outside solar system), Angus **0609125**
- Ambiguity of neutrinos
  - to be settled by 2009 (KATRIN experiment)
  - Or go for Galaxy lenses, which probe CDM/WDM more sensitive than clusters.

KATRIN-KArlsruhe TRItium Neutrino Exp

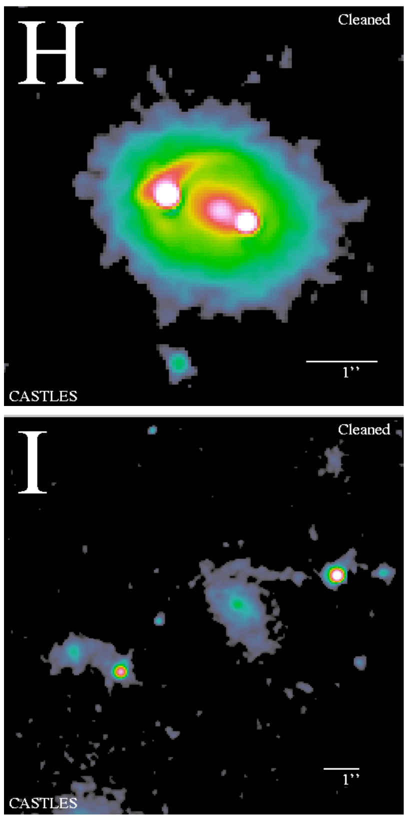
$$^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e + 18.57keV$$



Drop upper limit of neutrino mass from 2.2eV currently to 0.3eV by 2014

Peter Doe's presentation at Neutrino 2006

Do Strong Lensing as usual



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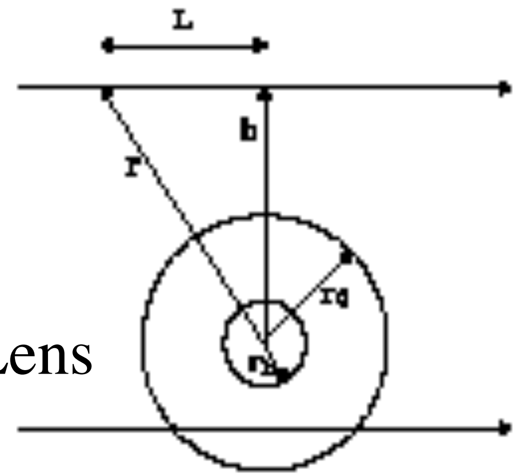


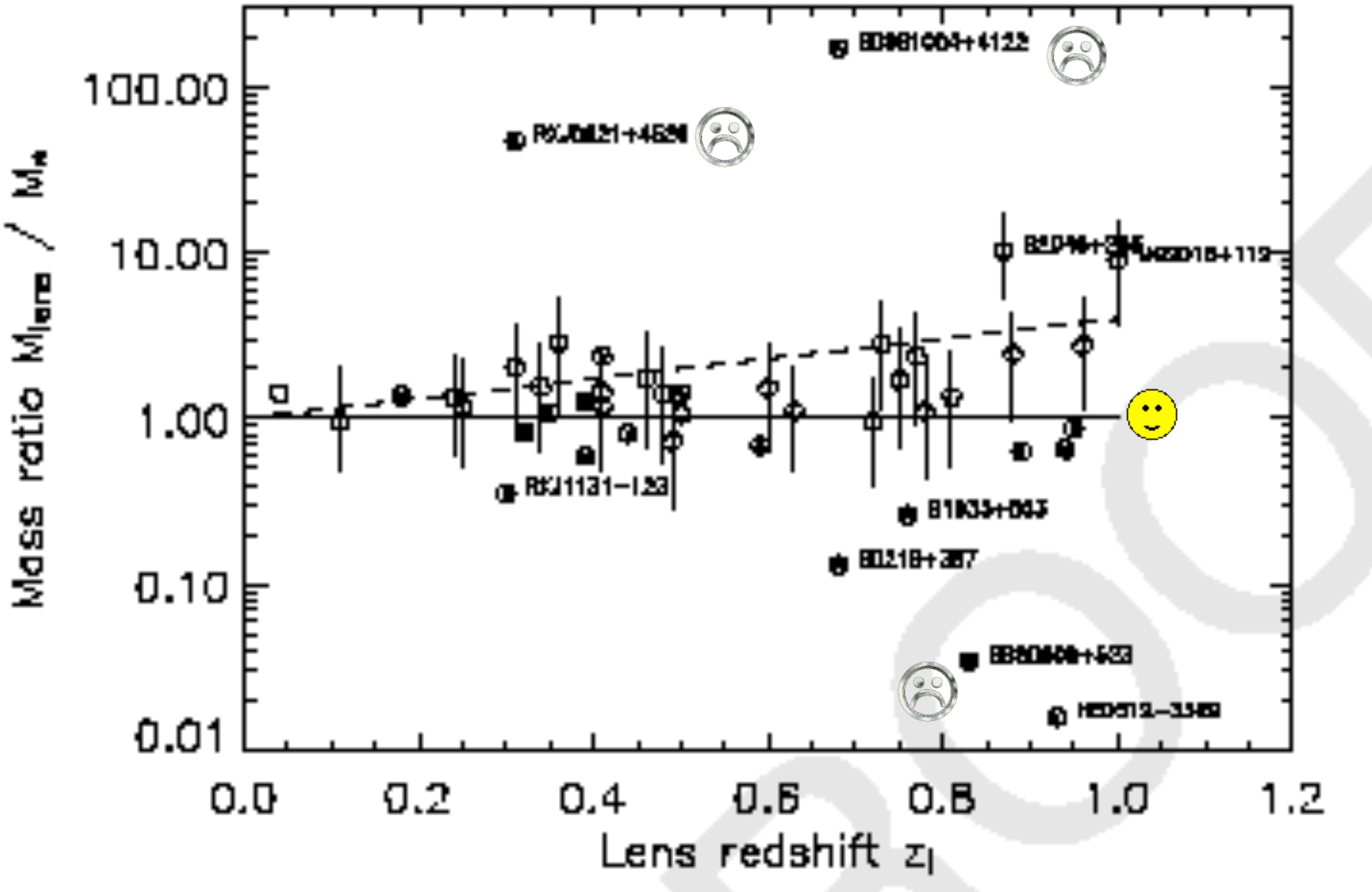
Lens

$$\beta = \theta - \frac{D_{LS}}{D_S}\alpha,$$

$$\alpha(b) = (4/c^2)\int_0^{\infty}(g(r)b/r)dl,$$

No neutrinos in galaxy lens, why see outliers?

Zhao, Bacon, Taylor, Horne (2006,MNRAS)



The Best Place to Find DM?

- Galaxy strong lenses Zhao, Bacon, Taylor, Horne (MNRAS 2006)
  - Outliers exist any baryon-only gravity
  - Robust to assumptions of
    - Gravity theories, Neutrinos and Equilibrium.
    - Non-spherical? Substructure? H0?

- X-ray clusters and bullet:
  - Outliers, but ambiguity due to possible neutrinos
- Rotation curves:
  - Strength of TeVeS, not DM
- Cosmological constant:
  - Neither a challenge to TeVeS nor strength of LCDM