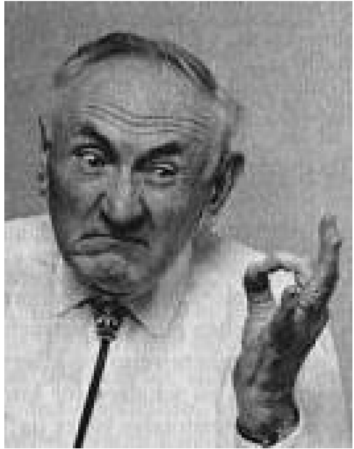


# **Dark Matter and MOND on Galaxy Clusters**

**HuanYuan Shan**

**Dec 1, 2008**

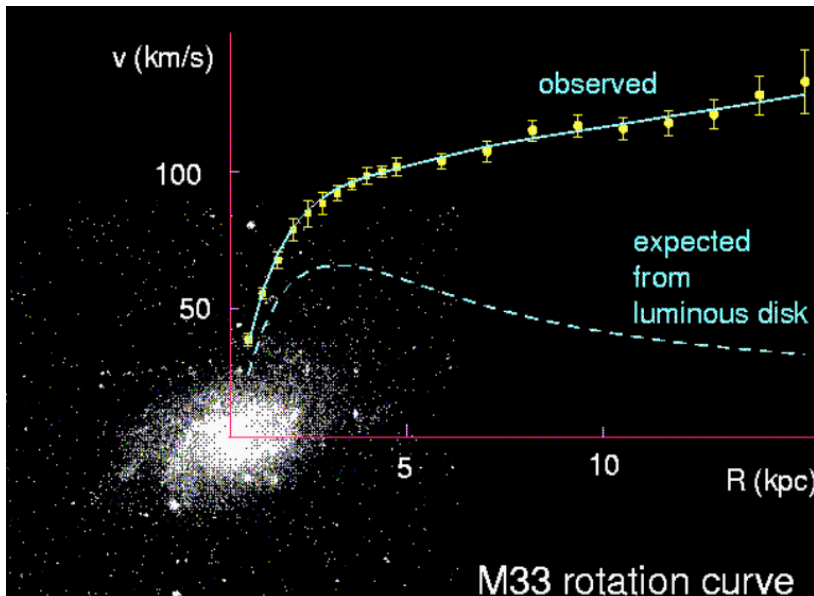
# Dark Matter



Zwicky 1937

# Modified Gravity

- Milgrom 1983 (MOND)
- Beckenstein, 2004 (TeVeS)



# CDM problems

❑ Galaxy scales: Too many small structures

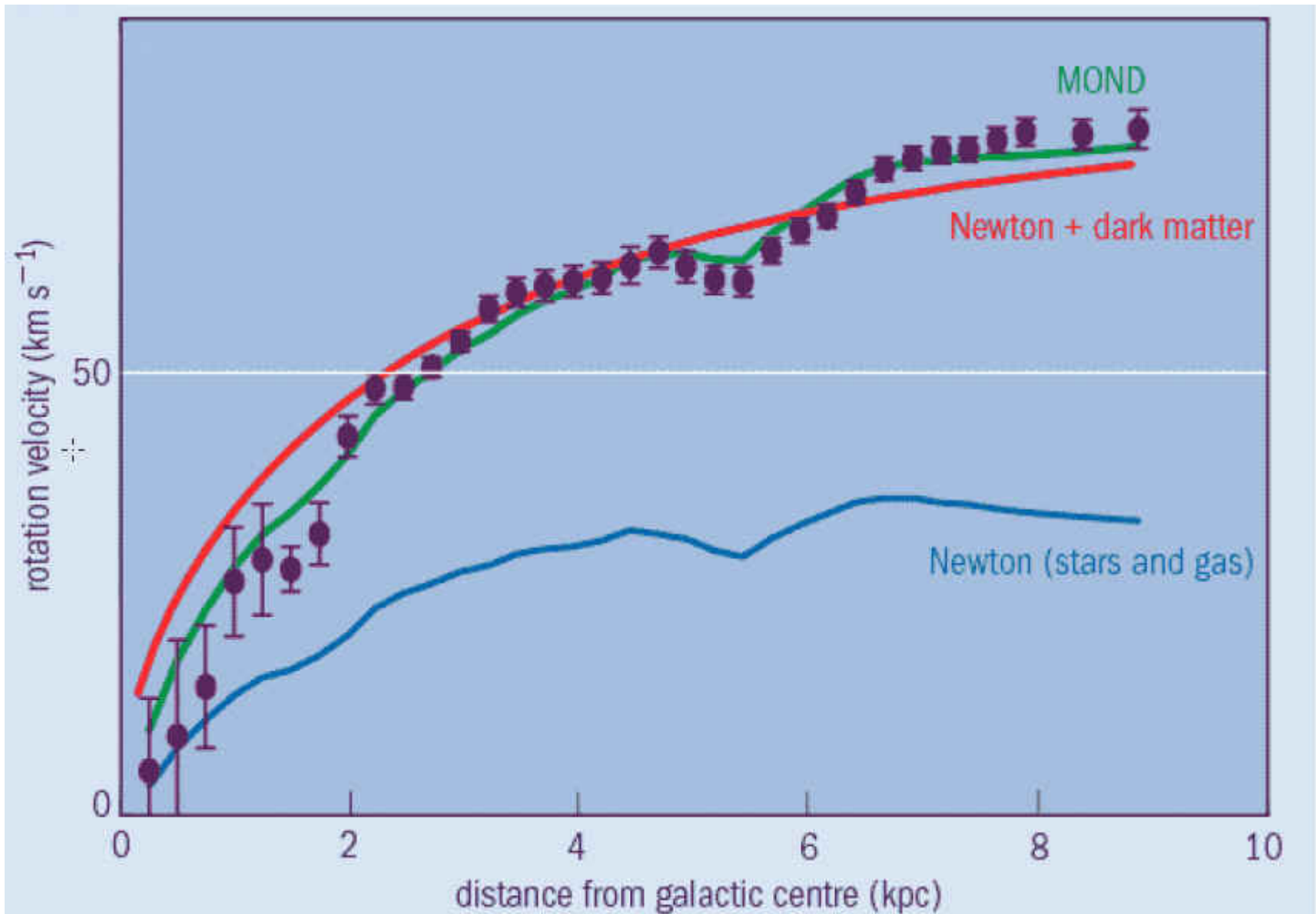
❑ Dark matter halo: cusps and cores

❑ ...

❑ Dark Matter has not been discovered yet.

This means that the presumed existence and distribution of dark matter is highly degenerate with the assumed laws of gravity (**Sanders 2002**).

**MOND** was proposed by **Milgrom in 1983** to explain the flat rotation curve without dark matter.



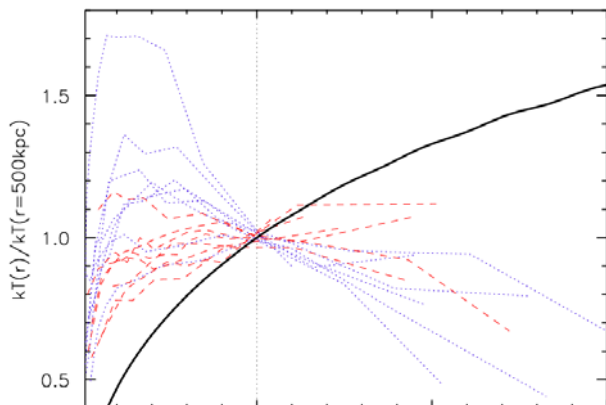
# Modified Newtonian Dynamics

- Gravity becomes stronger than Newtonian in the weak field limit of gravity  $|g| < a_0 = 1.2 \times 10^{-10} \text{ms}^{-2}$ .
- Successes: galactic rotation curves, dynamics of pressure supported systems, the dearth of DM in ellipticals, the Freeman value, the Faber-Jackson and Tully-Fisher relations (**Sanders & McGaugh 2002**).
- Fully covariant - **TeV**S (**Bekenstein 2004**)

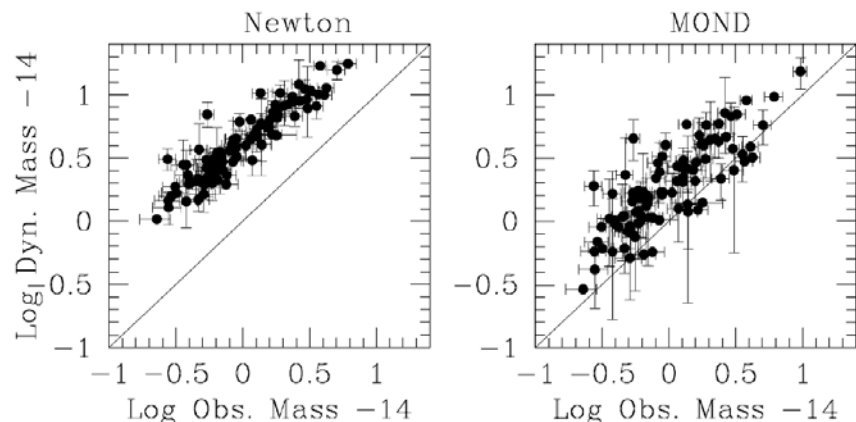
# Problems in clusters

□ Without some non-baryonic matter, **MOND** still cannot explain large radial velocities of the galaxies or the temperature profile of the x-ray emitting gas of galaxy clusters (**Aguirre 2001, Sanders 2003, Pointecouteau & Silk 2005**).

□ DM:baryon ratio of  $>3$ .

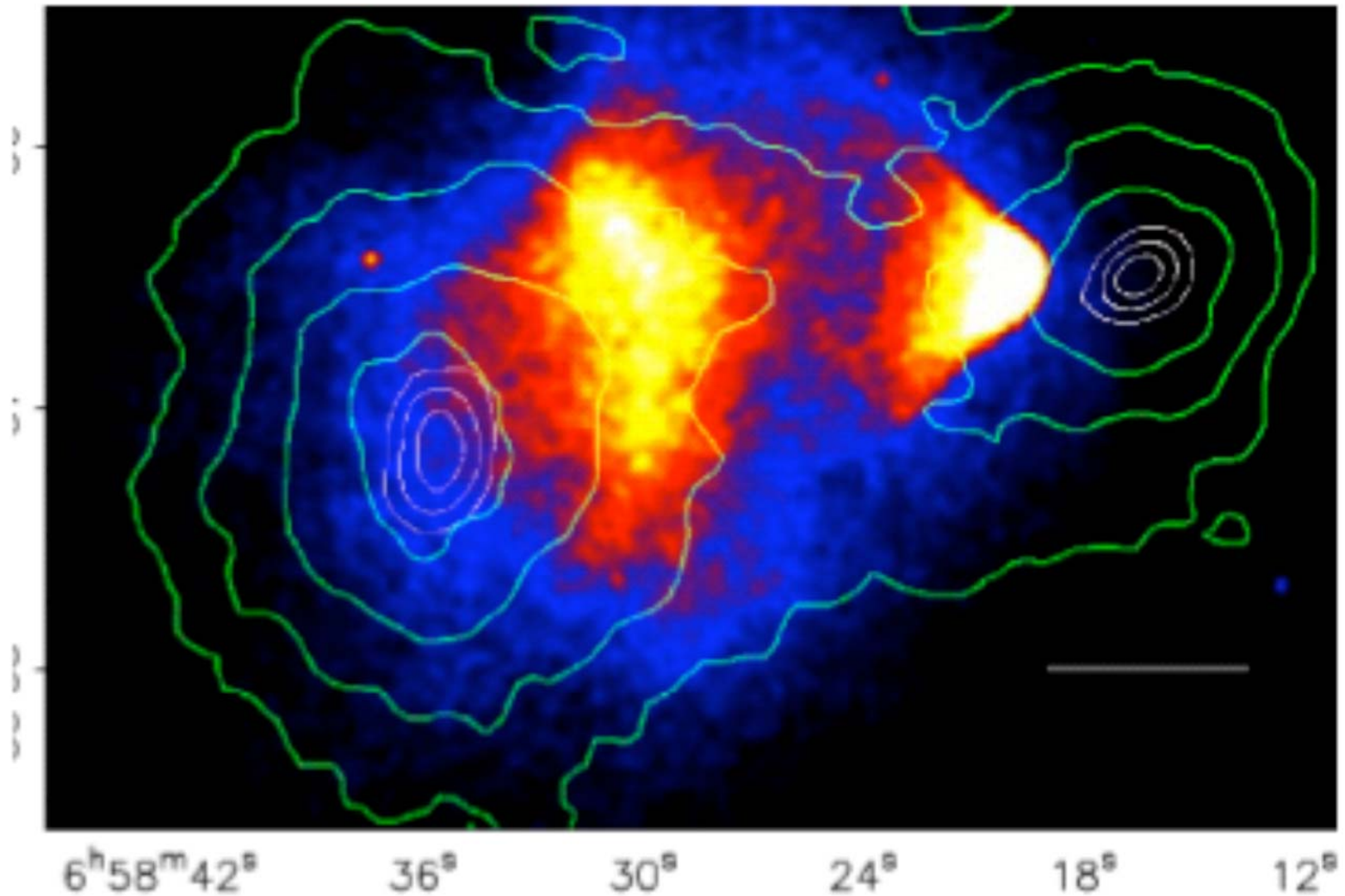


**Pointecouteau & Silk 2005**



**Sanders & McGaugh 2003**

# Bullet cluster—End of **MOND**?

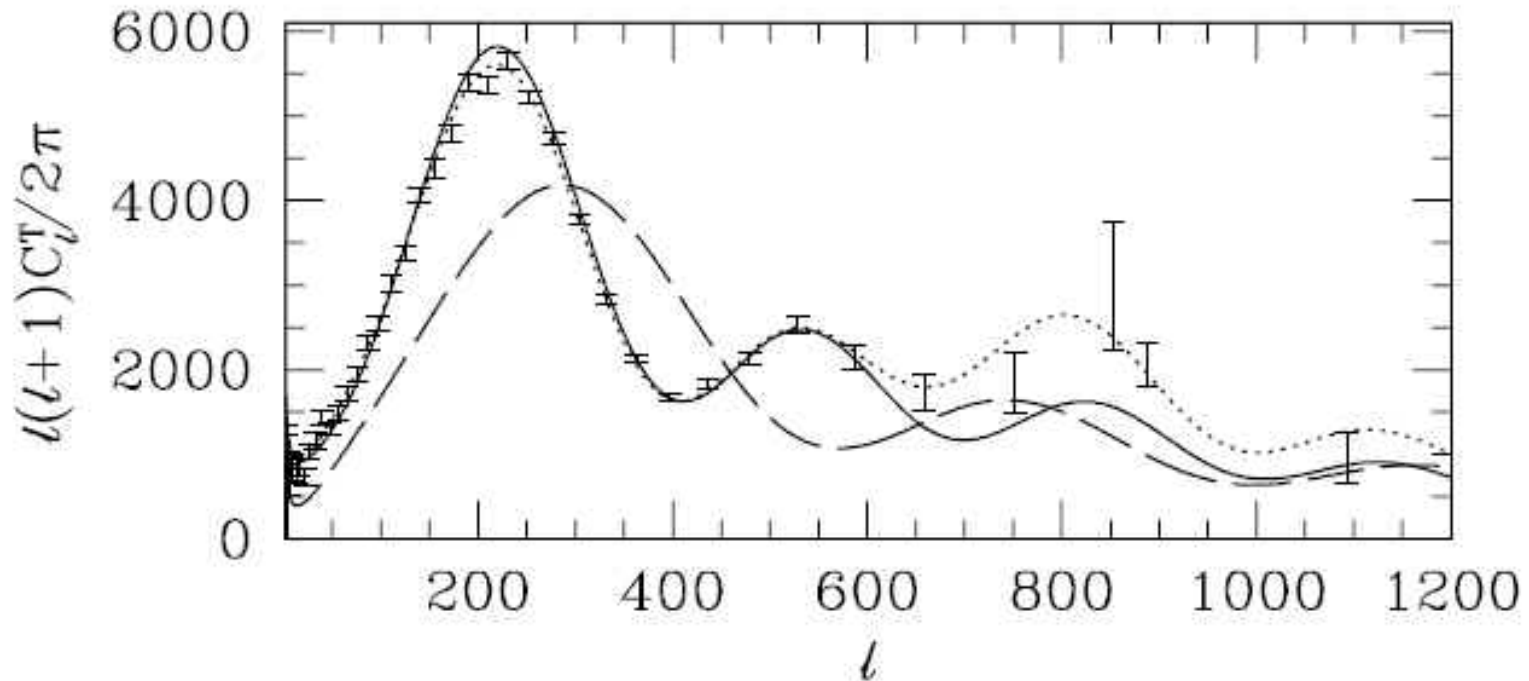


Clowe et al. 2006

**MOND:** Angus, Shan, Zhao & Famaey, 2007

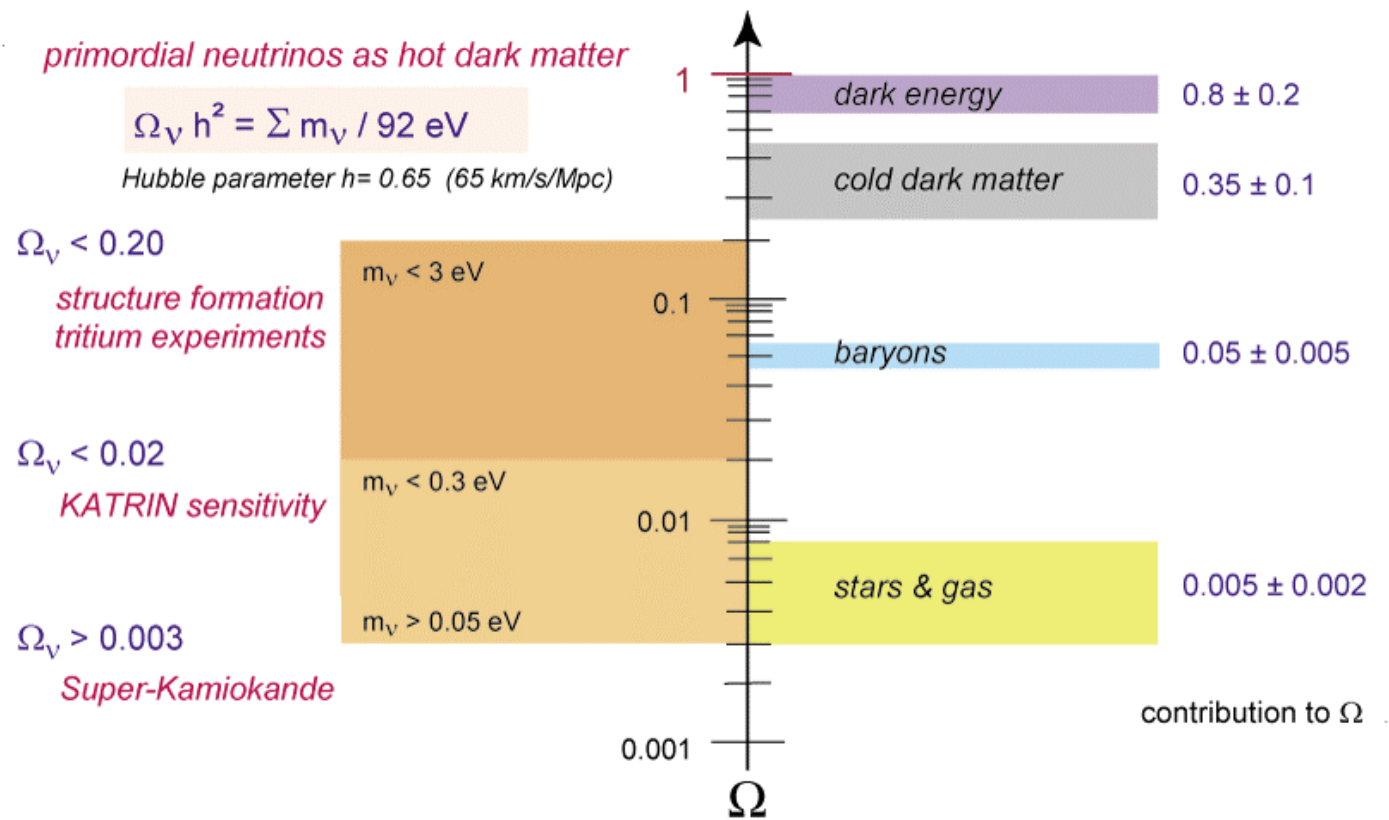
# Implications

- ❑ For **MOND**, the non-baryonic matter has to be hot (HDM) because CDM would cluster on galaxy scales, BBN constrains baryonic contribution -- furthermore, exotic DM would be against the spirit of **MOND** -- **Massive Neutrinos  $\sim 2\text{eV}$** .
- ❑ Only question is how much.  $\Omega_\nu = ?$
- ❑ Consistent with **MOND/TeV**S preliminary fits to the CMB & LSS (**McGaugh 2004, Skordis, Mota, Ferreira & Boehm 2006**).

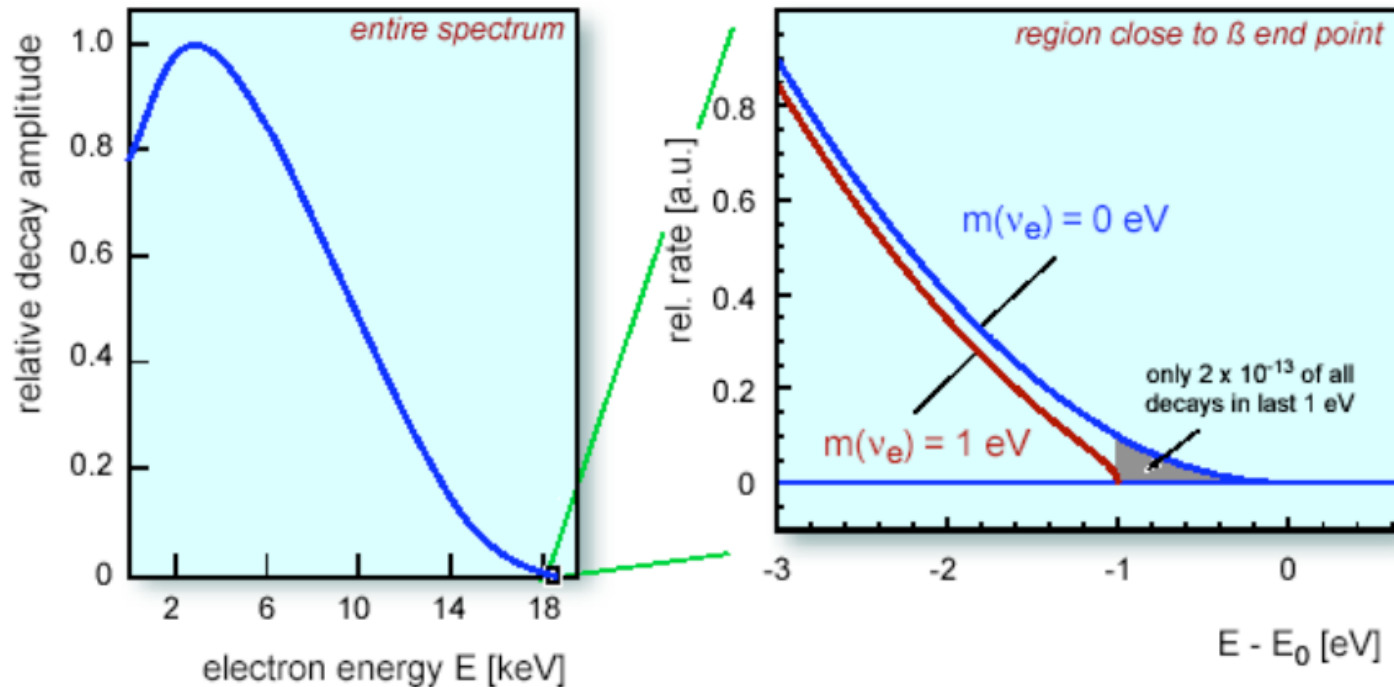
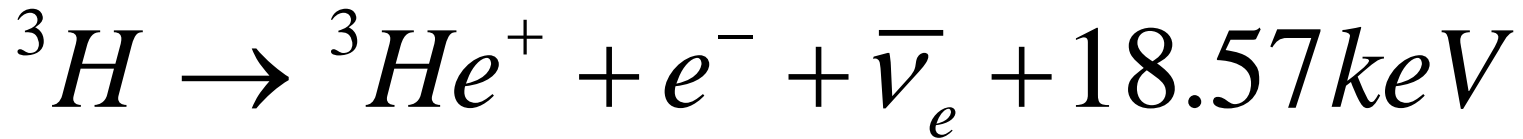


- The angular power spectrum of the CMB for a
  - $\Omega_{\Lambda} = 0.78$  and  $\Omega_{\nu} = 0.17$  and  $\Omega_B = 0.05$  (solid line)
  - MONDian universe, a  $\Omega_{\Lambda} = 0.95$  and  $\Omega_B = 0.05$  (dashed line)
  - MONDian universe (dashed line) and for the CDM model (dotted line). A collection of data points from CMB experiments and Sloan are overplotted. (**Skordis et al. 2006**)


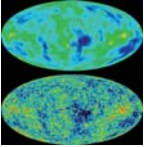
# Present model-independent range of neutrino mass



# KATRIN-KARLSRUHE TRITIUM NEUTRINO EXP



Drop upper limit of neutrino mass from  $2.2\text{eV}$  currently to  $0.3\text{eV}$   
by 2014 **Peter Doe's presentation at Neutrino 2006**

|           |   | Dark Matter | Modified Gravity             |
|-----------|---|-------------|------------------------------|
| Galaxies  |  | Good        | Excellent                    |
| Clusters  |  | Excellent   | Good ( <b>Neutrinos</b> )    |
| Cosmology |  | Excellent   | Good ( <b>TeV</b> <b>S</b> ) |