The Deep Inner Meaning of Hwk. Problem 30.4

- Fixed energy density.
- Same effect as *large* value of cosmological constant.

$$\left[\left(\frac{1}{R}\frac{dR}{dt}\right)^2 - \frac{8}{3}\pi G\left(\frac{u}{c^2}\right)\right]R^2 = -kc^2$$

$$u = \rho_m c^2 + u_{rad} + u_{vac}$$

$$R(t) = R_i e^{t/\tau_i}$$

$$\tau_i = \sqrt{\frac{3c^2}{8\pi G u_{vac}}}$$

- Exponential expansion until universe falls into true lowest energy state.
- Then, *reheating*.
  - Vacuum energy density (latent heat) gets converted back to radiation energy.

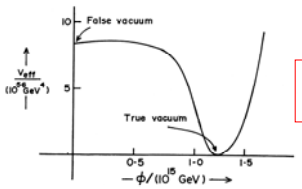
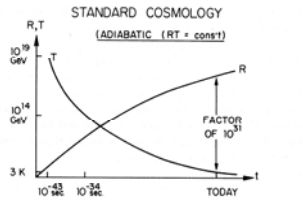
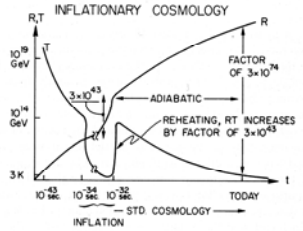


Figure 4 The Coleman-Weinberg potential that was used in the first major revision of the inflationary model.

False vacuum: $u = 10^{98}$ J m^{-3}
➔ heat ➔ particles

"The Ultimate Free Lunch"
Energy density = $u \propto R^0$
Total E $\propto uR^3 \propto R^3$





What *is* Dark Matter?

CO 2nd ed
pp. 896-898
pp. 1232-1233

Candidates

- Cold dark matter
  - "cold" means v << c
  - Leading candidate: Weakly Interacting Massive Particles (WIMPs)
- Hot dark matter
  - "hot" means v ~ c
  - Leading candidate: neutrinos
- Baryonic dark matter
  - Black dwarfs, black holes, failed stars, etc.
  - Massive Compact Halo Objects (MACHOs)
- General Relativity is wrong
  - MOND
  - Other alternate theories of gravity

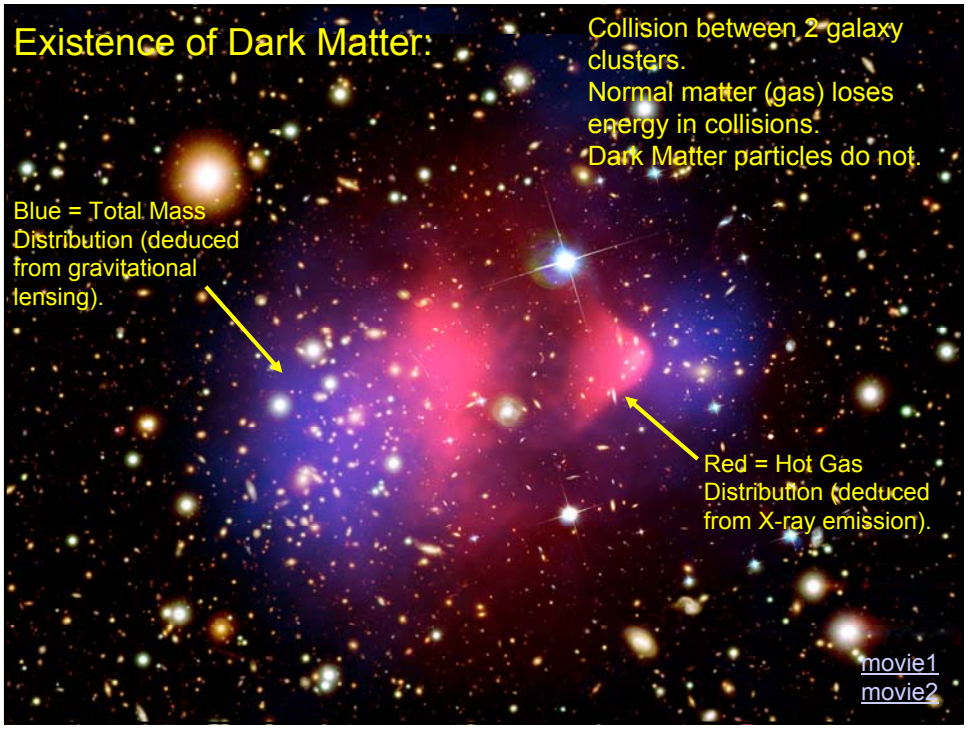
MOdified Newtonian Dynamics (MOND)

- Invented as ad-hoc explanation of flat rotation curves for galaxies

  Suppose that F_{grav} falls off slower than r^{-2}

- Originally not relativistically covariant
  - But there is now a version that does this
- Cannot also explain temperature, density structure of galaxy clusters.
- Dark matter simultaneously explains:
  - Flat rotation curves
  - Gravitational lensing results
  - Structure formation (coming attraction)

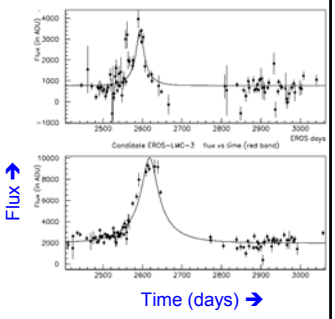
We don't want to trade it in for something that only explains one of these.

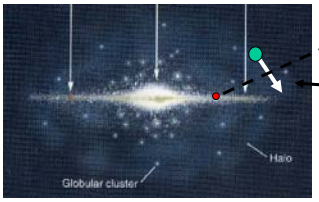


Baryonic Dark Matter

- Candidates include black holes, neutron stars, brown dwarfs, cool white dwarfs, etc.
- Use gravitational lensing to search for MACHOS
  - variability timescale

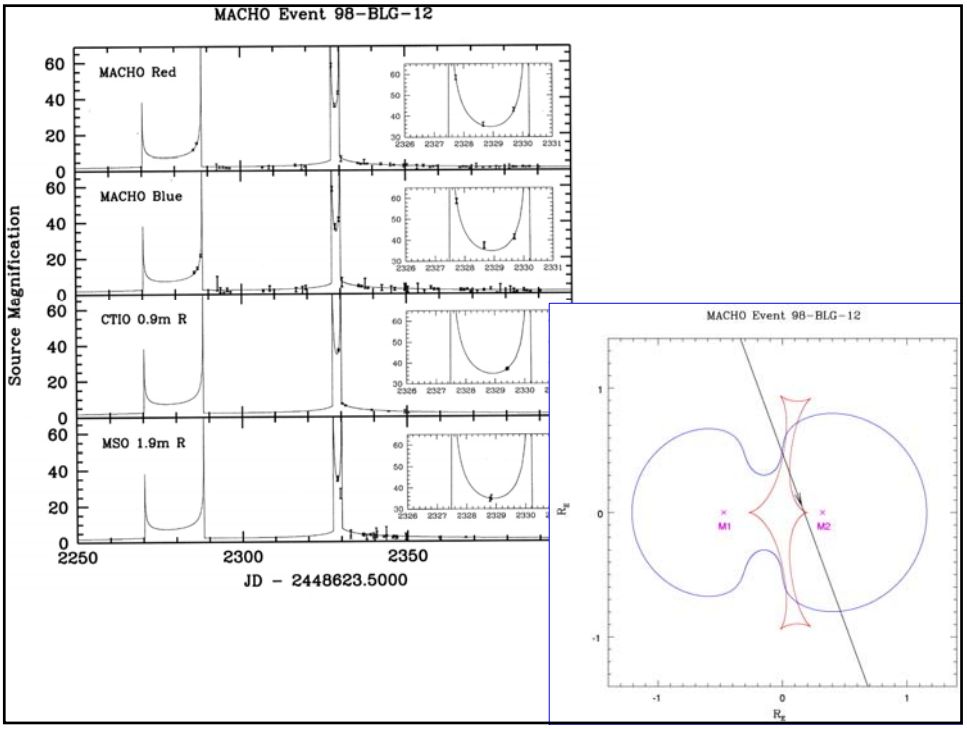
    $t \sim 0.2\ (M/M_{sun})^{1/2}\ (D/10\text{kpc})^{1/2}\ (v/200\ \text{km/s})^{-1}\ \text{yr}$
  - cross section is Einstein radius
  - $\theta_E = (M/M_{sun})^{1/2}\ (D/10\ \text{kpc})^{1/2}$ mas
  - ==> if entire mass of MW is in Machos, still need to observe 10^6 sources to find one microlensed background source at any given time.
- Using LMC, SMC stars as background sources
  - LMC at 50 kpc, but MW halo goes to 200 kpc
- Two major searches
  - MACHO team
  - EROS

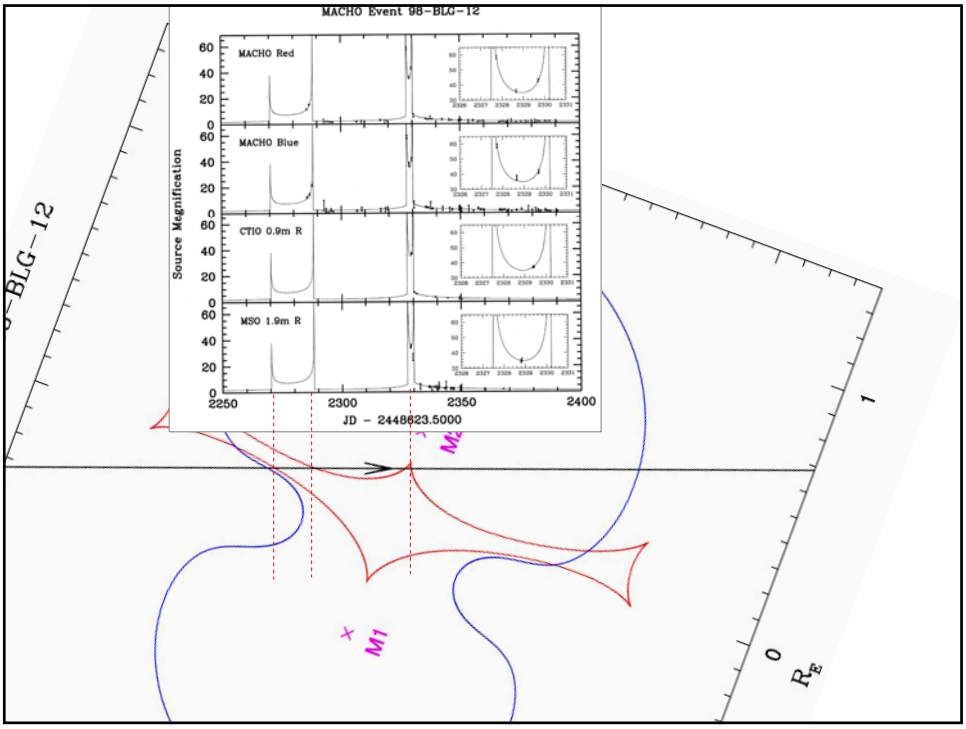




Large Magellanic Cloud

Orbiting MACHO crosses our line-of-sight. Gravitational lensing causes brightening.





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ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Not enough stellar mass Machos in the Galactic halo ⋆

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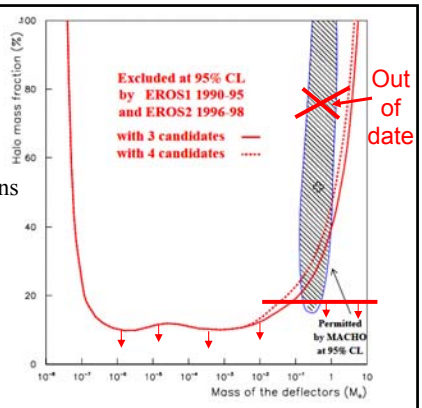
Abstract. We combine new results from the search for microlensing towards the Large Magellanic Cloud (LMC) by EROS2 (Expérience de Recherche d'Objets Sombres) with limits previously reported by EROS1 and EROS2 towards both Magellanic Clouds. The derived upper limit on the abundance of stellar mass MACHOs rules out such objects as an important component of the Galactic halo if their mass is smaller than $1 M_{\odot}$.

Key words: Galaxy: halo – Galaxy: kinematics and dynam-

tion of the Galactic dark matter resides in planet-sized objects (Aubourg et al. 1995; Alcock et al. 1996; Renault et al. 1997; Renault et al. 1998; Alcock et al. 1998).

However a few events were detected with longer timescales. From 6-8 candidate events towards the LMC, the MACHO group estimated an optical depth of order half that required to account for the dynamical mass of the standard spherical dark halo; the typical Einstein radius crossing time of the events, t_E, implied an average mass of about 0.5 $M_{\odot}$ for the lenses (Alcock et al.

- Macho Result:
  - MACHO Project:
    - 5.7 yrs, 11.9 million stars
    - 13-17 microlensed events
    - 2-4 expected from known stellar populations
  - EROS
    - 3 events towards LMC, 1 towards SMC
  - Fraction of MW halo in < 1 M_{sun} dark objects is < 20-40%.
  - Detected objects interpreted as white dwarfs
    - > 10 times more than expected from IMF
    - should be 6-10x more mass in gas than in white dwarfs ==> halo mass budget exceeded.
    - Alternative explanations require much less total mass. (<10% of halo)
      - LMC self-lensing often suggested



- MW halo mostly dark matter, not baryons
  - But massive black holes still possible
    - ~10^5 M_{sun} or so
    - primordial?