Dark Matter

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5/2/08

A Man with a Problem: Fritz Zwicky

(1898-1974)

- Undergraduate thesis under Weyl
- Dissertation under Debye and Scherrer @ETH Zurich(1922)
  - Lived next door to Lenin (morphology?)[3]
- Worked at Caltech with Millikan (1925)
  - "You never had a good idea."[1]
- Language: "Who the Devil," "spherical bastards"[2]
- Invented neutron star to explain supernovae

The Problem

- 1933: Zwicky investigates the Coma galaxy cluster[19]
- Result:

measured rotation + virial theorem

$$\Rightarrow M >> M_{luminous}$$

ISS006E40537

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_{\odot}$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

It gets worse:

- Since Zwicky, much data on various galaxies, including the Milky Way, show spirals spin much faster than Newtonian dynamics, using luminous matter, would predict.

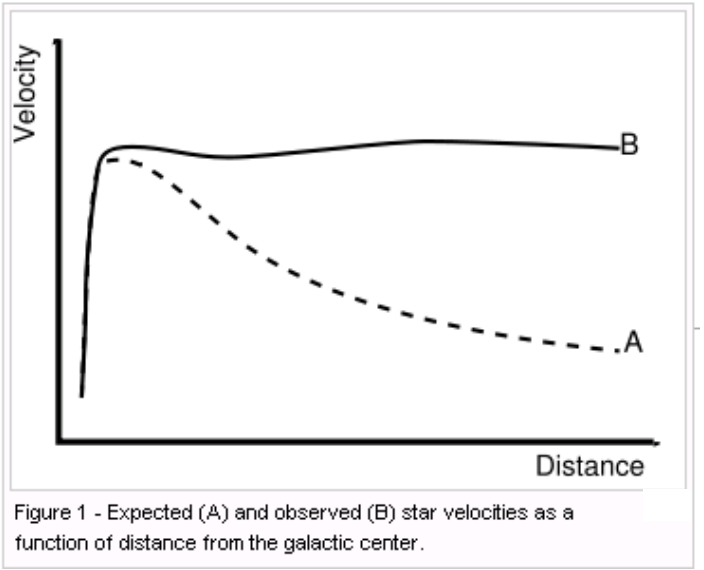


Figure 1 - Expected (A) and observed (B) star velocities as a function of distance from the galactic center.

- Furthermore, our understanding of early nucleosynthesis yields $\Omega_{Baryon} = 0.04$, while kinematics of superclusters imply that $\Omega_{matter} = 0.3$, where Ω is density, normalized to $\Omega = 1$ for a universe that neither expands nor contracts.[8],[18]

Aside: As of 2003, WMAP determined that for the universe, total $\Omega=1.02\pm0.02$[20]

Candidates

- MOND: modified Newtonian dynamics[13],[14]
- HDM: hot dark matter
  - ν[12]
  - Doesn't conform to LSS (large scale structure), so $\Omega_\nu < 0.05$[8],[18]
- Axions
- Possibly: right-handed ν •MiniBooNE
- CDM: cold dark matter
  - WIMPs: weakly interacting massive particles[8]
    - Possibly: neutralino χ (SUSY) •DAMA
    - Possibly: ?
  - MACHOs: massive compact halo objects[8],[15] (only part of Ω_{Baryon})
- Magnetic monopoles, SIMPs, etc.; always negative results

Axions

- Proposed solution to strong CP problem
- Spontaneous Peccei-Quinn symmetry breaking => new Goldstone boson†[10],[11]
- PVLAS: polarization of the vacuum with lasers
  - If axion field exists, polarized photons in a magnetic field could produce axions and annihilate back into photons, slightly rotating the polarization
  - 2006: positive results*[5]
  - 2007: *nevermind - artifact of the detector[6]
- No positive results to date (including CAST[21])

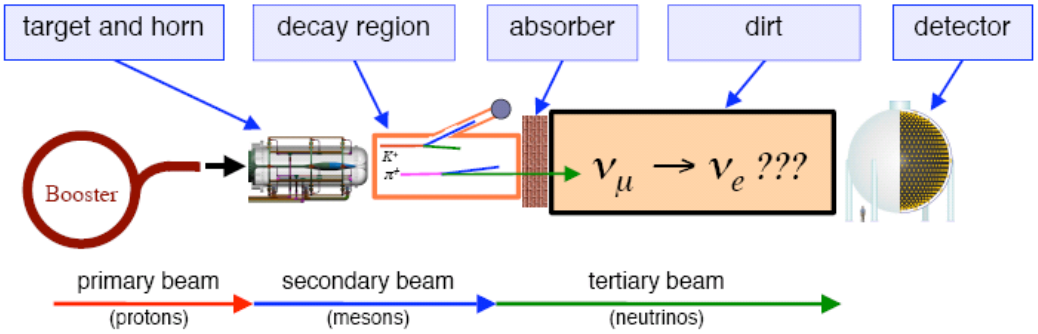
†Technically, vacuum QCD effects break the symmetry, so the axion is a massive pseudo-Goldstone boson

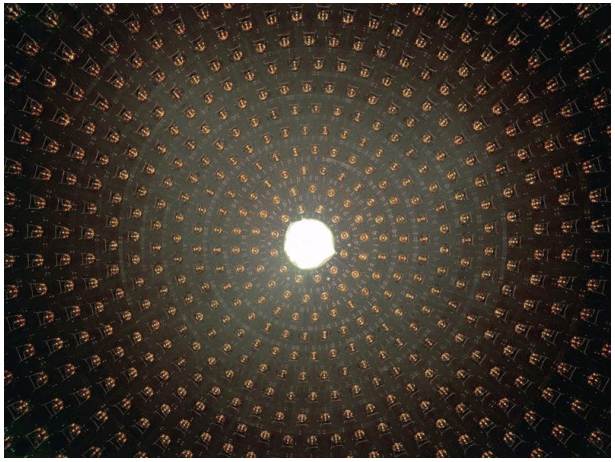
RH Neutrinos

- P violation => No weak interaction
- Why is (LH) neutrino mass so small? Maybe there's a seesaw mechanism, implying very heavy RH neutrinos.
- Existence disputed, multiple theories; currently a hotbed of research:
  - LSND
  - MiniBooNE
  - Cosmology (LSS + WMAP + Lyman α observations)

RH ν Results

- LSND (1997) [16]: Anomalous oscillations => more neutrinos than just three flavors of LH neutrinos
- Cosmology (2006)[9]:
  - Uses CMB, LSS, and spectroscopic data
  - 3 massless, 1 massive case ruled out (99% CL)
  - Allowing massive LH neutrinos, $m_{sterile} < 0.23eV$ at 95% CL ($m_s < 0.42eV$ at 99% CL)
  - Even so, Ω_ν could be as large as 0.1.
- MiniBooNE (2007)[17]:
  - Created to check LSND with higher statistics
  - Preliminarily, have found no evidence for sterile neutrinos

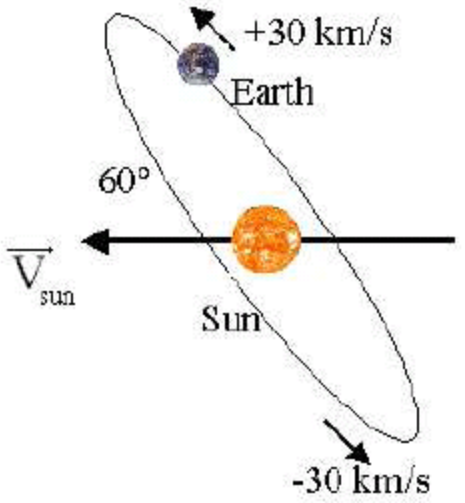




BooNE
BOOSTER NEUTRINO EXPERIMENT

WIMPS: DAMA: Premise[18]

- Annually, the Earth's net velocity within the Milky Way varies sinusoidally due to its orbit around the Sun.



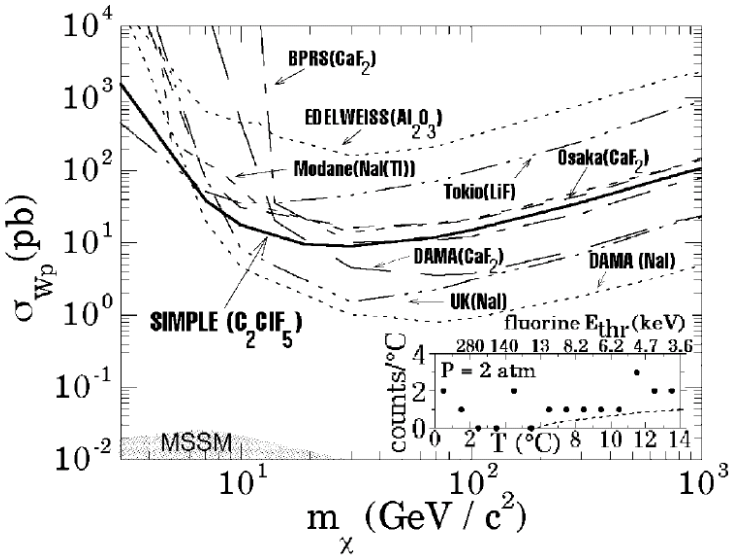
- Therefore, WIMP flux should vary sinusoidally annually (by ~7%), and make a positive signal easy to extract from backgrounds, which are a vast headache for other WIMP searches

DAMA: Experiment

- Low radioactive, highly radiopure NaI(Tl) scintillators, sensitive to nuclear recoil, deep underground in Gran Sasso N.L. in Italy.
- Over 7 years, obtained a signal corresponding exactly to fluctuation cycle due to annual solar orbit (published 2003)
  - Fantastic statistics: 6.3σ CL claimed
  - No possible systematic defects known
- => There is matter bound to our galactic halo that reacts only weakly
- But…

DAMA: Dispute

- All other experiments, which search directly for WIMP-induced nuclear recoils, and subtract off known backgrounds painstakingly, have negative results:
  - CDMS
  - EDELWEISS
  - CRESST
  - SIMPLE[22]



- However, there is phase space in which the positive and negative results are compatible[23].

Reconcilable?

- The (questionably small) compatible phase space will be in the range of forthcoming experiments:
  - CDMS-II[23]
  - CRESST-II[23]
  - DAMA/LIBRA[18]
  - COUPP: Chicago Observatory for Underground Particle Physics[21]
- But…

This Just In:

- 2 weeks ago, DAMA/LIBRA released first results[24]
  - Positive
  - Much more phase space
  - Even higher statistics (combined with NaI): 8.2σ CL
- Equally recently, CDMS-II and XENON10, higher energy-threshold experiments, have released preliminary findings[25]
  - Negative
  - Increased CL
  - More phase space

DAMA Conflict: Current Status

- Phase space now thoroughly overlapping
- Community attitude toward DAMA results:
  - Skeptical
  - Excited
- Possible resolution: mirror matter[25]
  - Interacts only via gravity and "photon-mirror photon kinetic mixing," essentially amounting to a weaker Rutherford scattering
  - only low threshold experiments (i.e., just DAMA) would be sensitive to this kinetic mixing
  - There are specific gravitational lensing structures we expect from mirror matter, and there are cosmological investigations underway to evaluate this possibility

Summary

- Kinematics clearly => much more matter than we see
- Can only be fractionally explained by familiar neutrinos, MACHOs
- Anomalous results from DAMA strongly support WIMPs or mirror matter; contradict everything else
- Otherwise, all explanations becoming less and less likely
  - Axions
  - Sterile Neutrinos
  - WIMPs
- As of yet, no WIMP experiments have reached the phase space of neutralinos, so they are yet to be ruled out or confirmed

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