THE NATURE OF LIGHT DARK MATTER

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Dark Matter: The evidence

- Dark Matter is required:
- for stability of disks in galaxies (e.g. Ostriker)
- to explain the rotation curves (e.g. Rubin)
- to explain the hot gas distribution in early Hubble type galaxies (e.g. Biermann)
- to explain the motions in groups and clusters (e.g. Zwicky)
- to explain the hot gas containment in groups and clusters (e.g. Ensslin et al.)
- to explain the structure formation
- to explain the flat geometry of the Universe (Spergel et al. 2003, 2007)

70 years: What is dark matter?

Dark Matter: Some history

Sterile neutrinos? Weakly interacting neutrinos - interact with other neutrinos and gravity

- 1930ies: "Dark Matter" first: Oort (1932), Zwicky (1933, 1937), and Swift (1936)
- 1970: Pontecorvo considers sterile neutrinos and introduces the name
- 1982: Olive & Turner consider sterile neutrinos in general terms
- 1994: Dodelson & Widrow show that sterile neutrinos can be dark matter
- 1997: Kusenko & Segre show that sterile neutrinos can explain pulsar kicks
- 2006: Shaposhnikov: The various origins of sterile neutrinos

Proposal

- Lightest supersymmetric particle, very massive: problem small scales
- However: G. Gilmore et al find many small dwarf galaxies, and
  smaller satellites are hindered in formation by ionization
- Sterile neutrinos at $2\,\text{keV} \lesssim m_{DM} \lesssim 20$ keV.
- Right handed neutrinos, very weakly interact with normal left handed neutrinos; otherwise interact only via gravitation
- Lifetime $\tau = 1.3\ 10^{26}\ \text{s} \left(\frac{7\text{keV}}{m_{DM}c^2}\right)^5 \left(\frac{0.8\, 10^{-9}}{\sin^2\theta}\right)$.
- They decay, most importantly: one active neutrino and a photon
- Never in thermodynamic equilibrium, require a chemical potential; probably far subthermal

Background

- They can be produced in the right amount (Dodelson & Widrow 1994; Shi & Fuller 1999; Abazijian *et al.* 2001; Dolgov & Hansen 2002; Abazajian 2006)
- They can explain the baryon asymmetry (Akhmedov *et al.* 1998; Asaka & Shaposhnikov 2005)
- They can explain the lack of power on small scales in Large Scale Structure Formation (Olive & Turner 1982; Abazajian 2006)
- They can explain the inner dark matter distribution and spatial shape in galaxies Belokurov *et al.* 2006; Fellhauer *et al.* 2006)

Lots of recent work by Kevork Abazajian and Mikhail Shaposhnikov

Our recent work

- Pulsar kicks, velocities up to 1000 km/s – see the guitar nebula – (Kusenko 2004)
  range: 2 to 20 keV
- ! Transition from active neutrino to weakly interacting neutrino to prevent scattering: right handed neutrino!
- Early growth of black holes (Munyaneza & Biermann 2005)
  range: 12 - 450 keV: ! Fermion
- Aspen September 2005: Overlap - Eureka!
- From increased secondary ionization molecular Hydrogen formed more abundantly, and so star formation triggered early (Biermann & Kusenko 2007; Stasielak, Biermann & Kusenko 2006) – this removed major obstacle (Yoshida *et al.* 2003) for this known proposal

First star formation

- Sterile neutrinos decay into an active neutrino and a photon (of half the mass in energy)
- After redshift about 40 no absorption anymore, before fraction of ionized atoms (η fraction of photon energy into ionization)
$x_e^{(s)} \sim \frac{0.2}{(1+z)^{3/2}} \left(\frac{\eta}{0.3}\right) \left(\frac{m_s}{7\,\mathrm{keV}}\right)^5 \left(\frac{\sin^2\theta}{0.8\,10^{-9}}\right)$
- Formation of H_2 via H^-
- Level of H_2 above $5\,10^{-4}$ (Tegmark et al. 1997) strong cooling
- Almost an order of magnitude enhancement, with maximum at redshift 80
- Corresponding heating cancels effect for redshifts < 20 (Mapelli, Ripamonti 2006)

The first stars

- Star formation triggered early
- Early magnetic fields from first massive stars – the fastest process – then cosmic ray driven dynamo process in galactic disks, implies by necessity galactic winds
- Reionization from first massive stars at $z > 10$
- Energy input from stellar winds and supernovae
- Chemical enrichment from first massive stars (Wolf Rayet star winds and supernovae)
- First dust
- First Gamma Ray Bursts
- First stellar black holes
- First cosmic rays

Primordial magnetic fields

- Ionization by secondary electron, from ionization:
- The time scale for energy gain (e.g., Jokipii 2004)

$$\tau_A = \frac{4\kappa}{V_A^2} \qquad (1)$$

- Assuming $\frac{B^2/8\pi}{I(k)k} \simeq 1$ and $I(k) \sim k^{-1}$ to just cancel the energy loss by ionization $B(z = 100) < 2\,10^{-8}$ Gauß, corresponding to today

$$B < 4\,10^{-12}\,\text{Gauß}. \qquad (2)$$

- K. Dolag et al. (2002, 2005): $B < (0.2 - 1.) \times 10^{-12}$ Gauß from structure formation simulations: consistent !

Galaxies

- Galaxies merge, and then
- Energy transported out, matter transported in, due to extreme mixing in a merger; akin to accretion disk theory (Lüst 1952)
- Inner dark matter distribution: Powerlaw, Moore 1998, Klypin et al. 2002, Navarro, Frenk, & White 1997
- Consider the low momentum tail of phase space distribution; for keV Fermions degenerate configuration: DARK MATTER STAR
- Suggestion, that Galactic Center Black Hole possibly only fed from dark accretion
- Alternative: direct collapse from supermassive star, or very compact stellar cluster: about $10^6\,M_\odot$

X-ray background

- 2005 - 2007: Boyarsky et al., Riemer-Sørensen, Watson, ...
- What is the upper limit to an invisible emission line at an energy $m_{DM}c^2/2$
- X-ray background: if dark matter, then $m_{DM} < 10$ keV
- Neighboring clusters of galaxies (Virgo, Coma)
- Neighboring galaxies (M31)
- With major effort may be positively detectable with the X-ray satellites Chandra and Newton: Large field high spectral resolution spectroscopy
- Neighboring dwarf ellipticals: Suzaku observations: M. Loewenstein, Kusenko, PLB

Lyman-α forest

- McDonald et al. 2001: forest example; simulations, weak fluctuations in density
- Seljak et al. 2006: WDM power spectrum versus CDM power spectrum
- McDonald et al. 2000: Contamination by metal lines?
- Seljak et al. 2006: SDSS data and high resolution data versus models in CDM (thick lines) and WDM (thin lines)
- Seljak et al. 2006: Discrepancy at high redshift: $m_{DM} > 14$ keV
- Viel et al. 2006: same analysis $m_{DM} > 10$ keV
- Reconciliation with lower mass by subthermal property of particle?

Galaxies

Work of group around G. Gilmore

- Shape of our Galaxy halo: Very spherical: From precessional disruption of incoming dwarf galaxies
- Mass of dwarf spheroidal galaxies
- All data consistent with lower limit to dark matter mass of $5\,10^7\ M_\odot$, for a large range of baryonic mass - direct indication for warm dark matter (or formation history? effect of ionization, heating and cooling of satellite galaxy?)
- Based on Gilmore et al. (2007), and Wyse & Gilmore (2007):

$$m_{DM}\ <\ 4\ \mathrm{keV}\ \mathrm{(AK)}$$

Summary

- Right-handed neutrinos? far subthermal?
- First star formation; first reionization; first magnetic fields; first cosmic rays; first black holes; first ultra high energy cosmic rays
- X-ray line from galaxies, and background
- Pulsar kicks
- Lyman α-forest - consistent for subthermal distribution
- Galactic halo structure; dwarf spheroidal galaxies
- All of these findings can be explained independently. If one concept: sterile neutrino
- $\sim 2 \text{ keV} \lesssim m_s \lesssim \sim 4 \text{ keV}$
- **Critical test X-ray emission line Weakly Interacting Neutrinos**

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