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# DARK MATTER IN COSMOLOGY

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## ABSTRACT

Problem sets for lectures presented at the INVISIBLES school.

## PROBLEMS

- Problem #1: Define $x = m_\chi c^2/kT$ and show that freeze-out, when the annihilation rate becomes slower than the Hubble expansion rate, occurs at $x \approx 20$. Derive the WIMP "miracle" for weakly interacting cold dark matter:

$$\left(\frac{\Omega_\chi}{0.2}\right) \simeq \frac{x_{FO}}{20}\left(\frac{3.10^{-26}\mathrm{cm}^2}{\langle\sigma_{ann}v\rangle}\right), \qquad (1)$$

where $x_{FO}$ is evaluated at thermal freeze-out and $\sigma_{ann}$ refers to the annihilation cross-section.

- Problem #2: Relic abundance. Estimate the freeze-out temperature for the $p\bar{p}$ annihilation reaction and estimate the relic antiproton density. Compare with the observed antiproton abundance.

- Problem #3: In the case of a neutrino species that decouples relativistically, show that the sum of the neutrino masses cannot exceed 91 eV $(\Omega_\nu h^2)$. Repeat for massive neutrinos for the case of a neutrino species that decouples non-relativistically with annihilation cross section $(<\sigma|v|>\sim 10^{-32}\ \mathrm{cm}^3/\mathrm{s})$ and light mass. Show this leads to an overall freeze-out temperature on the order of $T_{\mathrm{FO}} \sim$ MeV. How much of the dark matter could consist of Standard Model neutrinos? Give two reasons with citations: from direct experiment and from cosmology of structure formation.

- Problem #4 : Asymmetric dark matter. Show that $m_\chi \approx 5m_p$ if the dark matter asymmetry equals the lepton asymmetry.

- Problem #5: Maximum mass of a thermal relic massive particle that interacts electromagnetically. Assume the cross section to be of the form

$$\sigma \sim \frac{m_\chi^2}{(s-m_{Z'}^2)^2+m_{Z'}^4}, \qquad (2)$$

with $s$ the total center of mass energy squared and $Z'$ the mass of the mediator. Show that the maximum mass is 120 TeV.

- Problem #6: Calculate the minimum mass of cold dark matter clumps, set by free-streaming at freeze-out, as a function of particle mass.

- Problem #7: Decaying dark matter plausibly has a decay time $m_{GUT}^4/m_\chi^5$ in natural units (e.g. $H = k^2T^2/m_{pl}c^4$. Show that one can explain such signals as the PAMELA/AMS02 electron/positron flux above $\sim$ 100GeV ($\sim 0.01\mathrm{m}^{-2}\mathrm{s}^{-1}\mathrm{st}^{-1}$) with a decay time of order 10**s and a mass **(specify ranges!) GeV.

## REFERENCES

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