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**Development of the micrOMEGAs package for calculating  
Dark Matter signals**

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micrOMEGAs is a computer program for calculating dark matter signals. The micrOMEGAs engine is a CalcHEP program for calculating matrix elements of a general model of particle interactions. Thus, you can load your own model of particle interactions with dark matter particles into micrOMEGAs and begin calculating various dark matter signals: the cosmic microwave background density, the direct detection signal, the indirect detection signal, collider constraints, and so on.

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**Main publications (CPC) and steps of development:**

1. MicrOMEGAs: A Program for calculating the relic density in the MSSM. hep-ph/0112278
2. MicrOMEGAs 2.0: A Program to calculate the relic density of dark matter in a generic model hep-ph/0607059
3. Dark matter direct detection rate in a generic model with micrOMEGAs 2.2 arXiv:0803.2360
4. Indirect search for dark matter with micrOMEGAs 2.4 arXiv:1004.1092
5. Collider limits on new physics within micrOMEGAs 4.3 arXiv:1606.03834
6. micrOMEGAs 5.0 : Freeze-in. arXiv:1801.03509
7. micrOMEGAs 6.0: N-component dark matter arXiv:2312.14894

**Cited** > 5000

**Similar packages:** DarkSusy, MadDM

Here we discuss 3 new points:

- 1) Direct detection for DM with electromagnetic interactions.
- 2) Calculation of relic density of sterile neutrino.
- 3) Models with extended cosmology.

## Recasting of Direct Detection experiments

DD experiment: Large underground detector that attempts to detect a nucleus recoil event caused by a collision of DM with a nucleus.

Almost all the models which we considered 20 years ago now are closed by the modern DD experiments, but as a rule, changing the model parameters we can still save the models.

XENON1T(2018)/LZ5T(2025) - Exposure increases 6 times, limit for  $\sigma(DM, N)$  decreases 18 times!

If DM-nucleon collision is presented by a point-like interaction, then we can calculate DM-nucleon amplitude

`nucleonAmplitudes(WINPname, ApSI, ApSD, AnSI, AnSD);`

and compare cross sections with the limits presented by the experiment.

There is a problem if in the model we have an exchange of light mediator with mass less than 100MeV. LZ5T is an experiment where no background (removed by S1/S2 selection) and no events detected. A model is 90% excluded if it predicts  $\log(10) = 2.3$  events. So, for recasting we need an efficiency of registration of recoil energy event.

$$\int p_{eff}(E_r) \frac{dN}{dE}(E_r) dE_r < 2.3 \quad (1)$$

$p_{eff}$  somehow presented in LZ5T publication and we can reproduce their results with reasonable precision

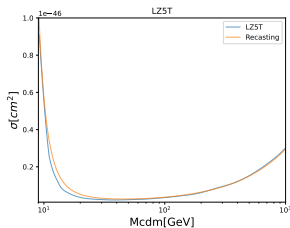


Рис.: Recasting of LZ5T experiment.

# Limits for millicharge and magnetic dipole moment.

We define in Lagrangian millicharge and magnetic dipole interaction

$$\sim X | \sim x | A | 1/2 | DMGeV * (G(p3) * G(m3) - G(m3) * G(p3)) * G5 * i + 2 * milliQ * EE * G(m3)$$

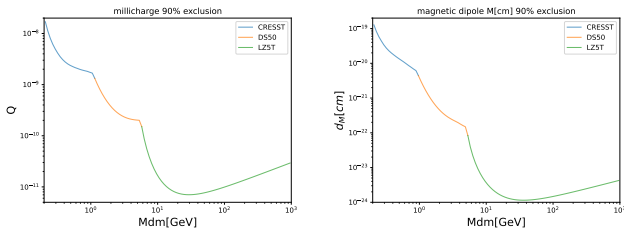


Рис.: Current DD Limits on millicharge and magnetic dipole

**Comment 1:** Millicharge DM with  $Q > 10^{-5}$  should get stuck in rocks under detector

**Comment 2:** In some models DM-SM interaction leads to appearance of dipole and quadruple moment which can increase DD signal.

## Calculation of relic density of sterile neutrino.

The goal was to repeat calculations of relic density of sterile neutrino in case of large lepton number violation in spirit of recent paper arXiv-2507.20659 ( Akita et al). See Wednesday talk of Dmitry Kalashnikov. My care was a technical details of calculation. Dark matter itself has not influence of Universe evolution for  $T > 1\text{MeV}$ . But large lepton asymmetry does. The evolution of Universe is defined by two functions of temperature:  $\rho(T)$  - energy density and  $s(T)$  - entropy density, which define Hubble and time-temperature relation:

$$H = \sqrt{\frac{8\pi\rho}{3M_P^2}} \quad \dot{s} = \frac{ds}{dT} \frac{dT}{dt} = -3Hs \quad (2)$$

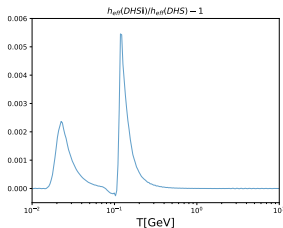
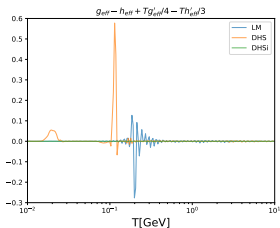
In turn  $\rho$  and  $s$  are defined by effective numbers of degrees of freedom  $g_{eff}(T)$  and  $h_{eff}(T)$

$$\rho(T) = \frac{\pi^2}{30} T^4 g_{eff}(T) \quad s(T) = \frac{2\pi^2}{45} T^3 h_{eff}(T) \quad (3)$$

The entropy conservation *in case of absence of asymmetry* reads

$$0 = g_{eff}(T) - h_{eff}(T) + \frac{1}{4T} g'_{eff}(T) - \frac{1}{3T} h'_{eff}(T) \quad (4)$$

We check it for  $g_{eff}/h_{eff}(T)$  obtained by lattice calculations and see that lattice solution has to be corrected.



DHS - Drees, Hajkarim , Schmitz, 1503.03513

LM - Laine, M. and Meyer, M. 1503.04935

DHSi - improved  $h_{eff}$  solution.

The lepton asymmetry is described via chemical potentials of distribution functions  $f(p, \mu) = \frac{1}{e^{E(p)-\mu} \pm 1}$ .  
 For one degree of freedom

$$n_1 = \frac{1}{2\pi^2} \int_0^\infty p^2 dp f(p, \mu), \quad p_1 = \frac{1}{2\pi^2} \int_0^\infty \frac{p^4}{3e(p)} dp f(p, \mu)$$

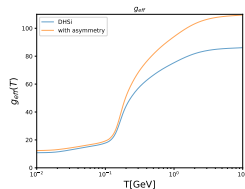
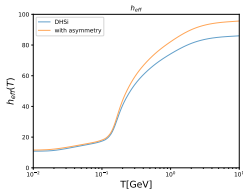
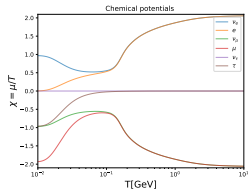
$$e_1 = \frac{1}{2\pi^2} \int_0^\infty e(p) p^2 dp f(p, \mu), \quad s_1 = \frac{\partial p_1}{\partial T} = \frac{e_1 + p_1 - n_1 \mu}{T}$$

Because of detailed balance equation any reaction  $p_1, p_2 \rightarrow p_3, p_4$  we have to have  $\mu_1 + \mu_2 = \mu_3 + \mu_4$ , in particular for particle and anti-particle  $\mu_p = -\mu_{\bar{p}}$ . So, we have 6 chemical potentials for leptons, one for hadrons (to compensate electric charge of leptons), 3 linear equations because of W exchange processes, 3 non-linear equations because of asymmetry

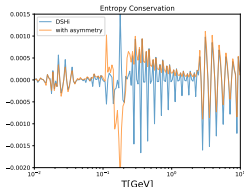
$$L_a/s = (n_a - n_{\bar{a}} + n_{\nu_a} - n_{\bar{\nu}_a})/s \quad a = e, \mu, \tau$$

and one non-linear equation to fix electric charge zero. To calculate entropy density  $s$  we subtract from  $h_{eff}$   $\mu = 0$  lepton contribution and replace it on the current one.

Results: Non-linear equation can be solved by iteration method, moving non-linear parts in the right part of linear equation. But one should decrease step on factor 10. For temperature lattice with 100 elements it takes several seconds. We get solution for chemical potentials which corresponds to Akita paper for  $L_a/s = [0.035, -0.035, 0]$  and solutions for new  $h_{eff}, g_{eff}$



Equation for entropy conservation in case of presence of chemical



potentials reads: 
$$0 = \frac{15}{2\pi^2 T^2} \left( \frac{s}{p+e} \frac{de}{dT} - \frac{ds}{dT} \right)$$

## Other Cosmologies

G.B. Gelmini and P. Gondolo, Neutralino with the right cold dark matter abundance in (almost) any supersymmetric model, Phys. Rev. D 74 (2006) 023510 [hep-ph/0602230]

So, we assume that inflation decays on SM particles with a very small width  $\Gamma_I$ . We also suppose that we know initial energy density of inflatons which leads to Hubble  $H_I$ . Then we'll have a reheating of Universe with subsequent cooling. Now micrOMEGAs is able to solve equation of DM abundance in such models. Solution is split on two parts. First we find SM temperature and inflaton density  $\rho_I$  as a function of scale parameters  $a$ .

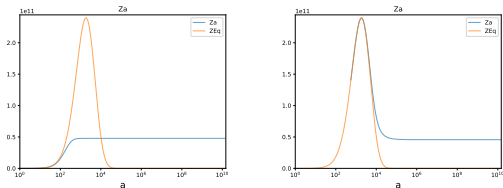
`getInflDecay( $H_I$ ,  $\Gamma_I$ , &Trh, &Tmax, &aEnd)` solves equations

$$\frac{z_I}{da} = -\frac{\Gamma_I}{Ha} z_I, \quad \frac{dz_s}{da} = \frac{4 \Gamma_I s^{1/3}}{3 H T} z_I \quad \text{for } z_I = \rho_I a^3, \quad z_s = s^{4/3} a^4$$

and prepare functions  $Ta(a)$ ,  $\rho_I a(a)$ ,  $\rho_{SM} a(a)$  describe SM and inflaton states for given scale parameter  $a$ .

At next step one can call `darkOmegaInfl(b, Beps, &Tfo, &err)` which returns  $\Omega h^2$  and freeze out temperature (if it exists). It also prepares functions  $Z_a(a)$ ,  $Z_{aEq}(a)$  for current and equilibrium number densities normalized on  $a^3$ .

Below we present freeze in and freeze out -like solutions for  $Z'$  model.



Note that after formation of relic density still we have entropy injection caused by inflaton decay which decreases abundance.