Comic-Ray Boosted Bremsstrahlung in Direct Direction

Bin Zhu

중앙대학교
CHUNG ANG UNIVERSITY

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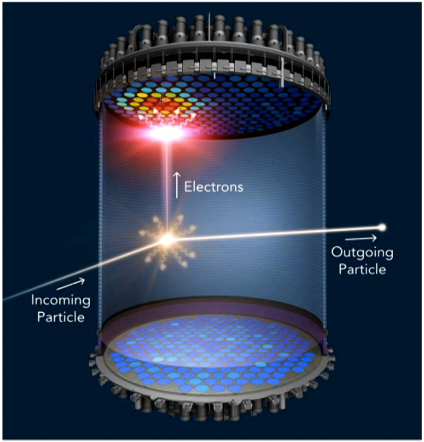
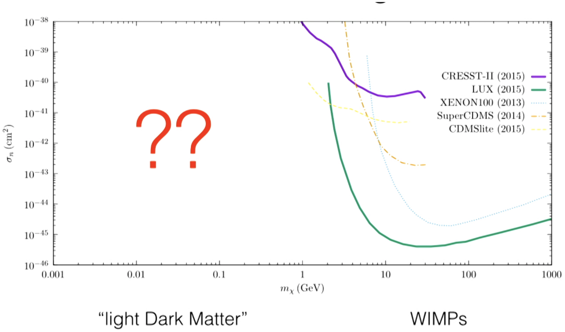
Direct Detection Scheme

Nuclear recoil



The Direct Detection so far ...

Before the experiment started operating we all hoped for great discoveries of WIMP..., But



I bet you heard about these exclusion limit several times!

Nothing but get closer to neutrino floor!

Direct Search Challenges for sub-GeV DM

- Nuclear kinetic recoil energy is

$$E_R = \frac{\mathbf{q}^2}{2m_N} = \frac{\mu_N^2 v^2}{m_N}(1 - \cos\theta_*)$$

- A given recoil, demands a minimum relative velocity

$$v_{\min} = \sqrt{\frac{m_N E_R}{2\mu_N^2}} \simeq \left(\frac{E_R}{0.5\text{keV}}\right)^{1/2} \frac{1\text{GeV}}{m_\chi} \times \begin{cases} 1700\text{km/s} & \text{Xenon} \\ 600\text{km/s} & \text{Oxygen} \end{cases}$$

Kinematical no-go theorem

For sub-GeV DM, there are no particles bound to the Galaxy that could induce a 0.5 keV nuclear recoil on Xenon.

Ways Forward

- Reduce experiment threshold. For example, DM-electron scattering.
- Increase incoming DM kinetic energy. For example, cosmic-ray boosted dark matter
- Novel process to enlarge signal. For example, Bremsstrahlung

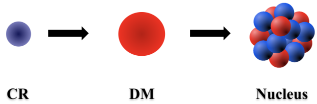
Our Simple proposal: Photon emission in cosmic-ray boosted dark matter

If $(2) + (3)$, what happen? Notice that $(1) + (2)$ equals to Prof. Qinghong Cao, Ran Ding and Qianfei Xiang

Cosmic ray dark matter

see wenyu's talk

- Consider the minimal realization of CRDM



- resulting relativistic dark matter kinetic energy

$$T_\chi = T_\chi^{\max} \frac{1-\cos\theta}{2},$$

$$T_\chi^{\max} = \frac{T_i^2 + 2 m_i T_i}{T_i + (m_i + m_\chi)^2 / (2 m_\chi)}$$

- Maxwell velocity distribution is now replaced by differential flux

$$\frac{d\Phi_\chi}{dT_\chi} = D_{\rm eff} \frac{\rho_\chi}{m_\chi} \sum_i \int_{T_i^{\rm min}} dT_i \frac{d\sigma_{\chi i}}{dT_\chi} \frac{d\Phi_i^{\rm LIS}}{dT_i}$$

Is it good enough?

No! We must consider attenuation process.

How to set limit from existing data for CRDM

Make use of equivalence of event rate.

- CRDM's event rate in direct detection

$$R_{\mathrm{CRDM}} = \int_{T_1}^{T_2} dE_T \frac{1}{m_{\mathrm{T}}} \int_{T_\chi^{z,\mathrm{min}}}^{\infty} dT_\chi^z \frac{d\Phi_\chi}{dT_\chi^z} \frac{d\sigma_{\chi T}}{dE_T}$$

- Conventional event rate for WIMP or neutrino can be read in experimental data R_{Exp}
- $R_{\mathrm{CRDM}} = R_{\mathrm{Exp}}$ yields the limit for CRDM.

Fake Calculation of Cosmic ray boosted Bremsstrahlung

- Framework is the same as CRDM.
- Difference is that Bremsstrahlung is three body process rather than two body process

$$R_{\mathrm{CRDM}} = \int d\omega \int_{T_1}^{T_2} dE_T \frac{1}{m_{\mathrm{T}}} \int_{T_\chi^{z,\mathrm{min}}}^{\infty} dT_\chi^z \frac{d\Phi_\chi}{dT_\chi^z} \frac{d\sigma_{\chi T}}{dE_T d\omega}$$

Seems both logic and calculable for us

Before doing that, we should ask what is motivation for Bremsstrahlung

Motivation of Photon Emission

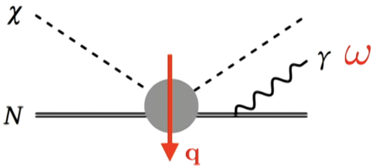


Figure: Inelastic photon emission

- maximal recoil energy of nucleons $4\,(m_\chi/m_N)\,\omega_{\max}$ is much smaller than $\omega_{\max}$. It is kind of absorption process where all the kinetic energy of dark matter is deposited into photon.
- $0.5\ \mathrm{keV}$ photon is never missed. $0.5\ \mathrm{keV}$ nuclear recoil is easily missed.

Real Calculation of Cosmic ray boosted Bremsstrahlung

Step-1: Factorization

- Soft photon limit leads to factorization

$$M = M_{\rm el} \times Ze \left(\frac{p'_N \cdot \epsilon^*}{p'_N \cdot k} - \frac{p_N \cdot \epsilon^*}{p_N \cdot k} \right)$$

- The differential cross section is thus

$$\frac{d\sigma}{dE_T d\omega} = \frac{4Z^2\alpha}{3\pi} \frac{1}{\omega} \frac{E_T}{m_N} \times \frac{d\sigma}{dE_T}$$

Huge suppression from α

Compensated by both large Z^2 and exponentially rising with smaller recoil energy in recoil spectrum

Real Calculation of Cosmic ray boosted Bremsstrahlung

Step-2: Atomic Physics Correction

- Pure quantum field theory description treats cross section scales as $1/\omega$ all the way to lowest energies.
- τ_χ is much smaller than orbital time of eletrons τ_α. Thus atom becomes polarized.

$$\frac{d^2\sigma}{d\omega dE_T} = \frac{4\alpha}{3\pi\omega}\frac{E_T}{m_N}|f(\omega)|^2 \times \frac{d\sigma}{dE_T}$$

$f(\omega)$ is atomic scattering factors

For larger ω, QFT result is recovered

Real Calculation of Cosmic ray boosted Bremsstrahlung

Step-3: Integrates out E_T

- Three-body kinematics is more difficult than two-body process.

$$E_{T,\mathrm{max}\,/\,\mathrm{min}} = \frac{2\mu_N T_\chi \left(-\frac{\omega}{2T_\chi} \pm \sqrt{1-\frac{\omega}{T_\chi}} + 1\right)}{m_N}$$

- Final expression for rate is thus

$$R_{\mathrm{Photon}} = \int d\omega \int_{E_{T,\mathrm{min}}}^{E_{T,\mathrm{max}}} dE_T \frac{1}{m_{\mathrm{T}}} \int_{T_\chi^{z,\mathrm{min}}}^{\infty} dT_\chi^z \frac{d\Phi_\chi}{dT_\chi^z}$$
$$\frac{4\alpha}{3\pi\omega} \frac{E_T}{m_N} |f(\omega)|^2 \times \frac{d\sigma}{dE_T}$$

Final Result and Conclusion

In terms of DarkSUSY and Prof Wenyu, we can set a even stronger limit for sub-GeV DM.

- CRDM actually provides a new method to detect light dark matter
- Combination of photon emission can yield a much stronger limit on MeV dark matter.
- What about Migdal effect?