Collider and CMB Complementarity: An EFT Approach

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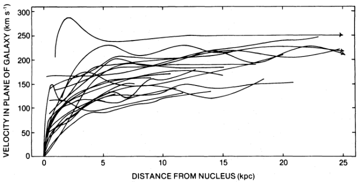
D. Borah, N. Das, S. Jahedi, and B. Thacker

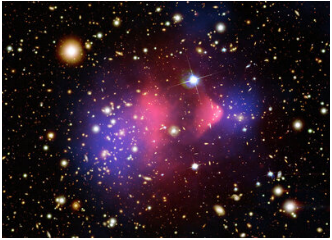
Outline

- New Physics and Where to find it?
- Effective Operators
- Dark Matter Phenomenology
- Cosmological Signatures
- Results and Conclusion

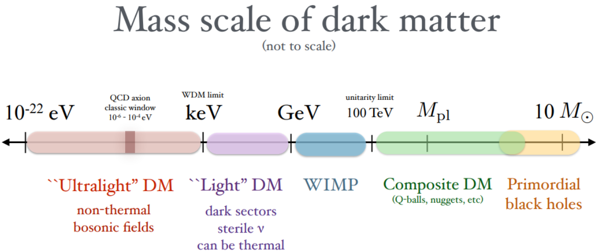
Dark Matter Evidences and Scale



Vera C Rubin et al., Astrophysical Journal

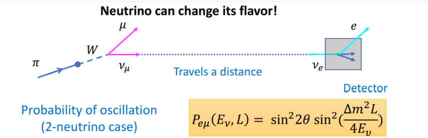


The Bullet Cluster

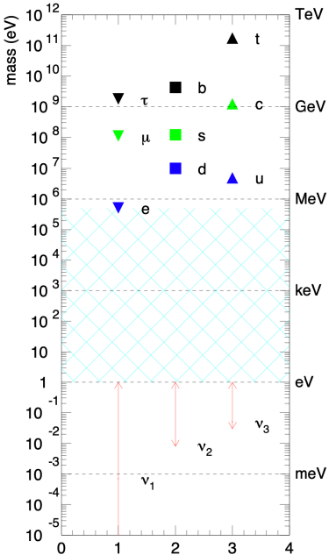


Neutrino Physics

- In the Standard Model:
  - Three flavors of neutrinos
  - Neutrinos are massless
  - Neutrinos interact only weakly



- Beyond the Standard Model:
  - Neutrino oscillations → neutrinos have mass
  - Nature: Dirac or Majorana?



Effective Operators

Setup

- Dark Matter (χ): A Dirac fermion; $\mathcal{G}_{\mathsf{DM}} = \mathbb{Z}_2$
- Right-Handed Neutrinos (ν_R): 3
- EFT Operators:

$$\mathcal{O}_{\rm DM}\mathcal{O}_{\rm SM}, \quad \mathcal{O}_{\rm DM}\mathcal{O}_{\nu_R}, \quad \mathcal{O}_{\rm SM-\nu_R}$$

- Symmetry Requirements:
  - Operators are invariant under $\mathcal{G}_{\mathsf{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$
  - Global lepton number $(\Delta L)_{\rm global} = 0$ is preserved, preventing Majorana mass terms and ensuring the Dirac nature of ν_R.

Effective Operators

Dimension-6 Operators

The operators are of the form:

$$\frac{c_{\chi l}}{\Lambda^2}\mathcal{O}_{\chi l}, \quad \frac{c_{\chi\nu}}{\Lambda^2}\mathcal{O}_{\chi\nu}, \quad \frac{c_{\mathrm{SM}\nu_\mathrm{R}}}{\Lambda^2}\mathcal{O}_{\mathrm{SM}-\nu_\mathrm{R}}$$

where c_{ij} are Wilson coefficients and Λ is the scale of new physics.

Class	**Name**	$\mathcal{O}_{\mathrm{DM}}$	$\mathcal{O}_{\mathrm{SM}}, \mathcal{O}_{\nu_R}$
DMEFT	$\mathcal{O}_{\chi l}$	$(\overline{\chi}\gamma^\mu\chi), (\overline{\chi}\gamma^\mu\gamma^5\chi)$	$(\overline{L}\gamma_\mu L), (\overline{e_R}\gamma_\mu e_R)$
νDMEFT	$\mathcal{O}_{\chi\nu}$	$(\overline{\chi}\gamma^\mu\chi), (\overline{\chi}\gamma^\mu\gamma^5\chi)$	$(\overline{\nu_R}\gamma_\mu\nu_R)$

Table: Operators involving DM, SM, and ν_R leading to interactions relevant for leptophilic DM phenomenology

Operators for SM-ν_R Interactions

No.	Name	Operator	No.	Name	Operator
1	$\mathcal{O}_{L\nu H}$	$(\bar{L}\nu_R)\tilde{H}(H^\dagger H)$ + h.c.	9	$\mathcal{O}_{d\nu}$	$(\overline{d_R}\gamma^\mu d_R)(\overline{\nu_R}\gamma_\mu \nu_R)$
2	$\mathcal{O}_{H\nu}$	$(\overline{\nu_R}\gamma^\mu \nu_R)(H^\dagger i \overleftrightarrow{D}_\mu H)$	10	$\mathcal{O}_{du\nu e}$	$(\overline{d_R}\gamma^\mu u_R)(\overline{\nu_R}\gamma_\mu e_R)$ + h.c.
3	$\mathcal{O}_{H\nu e}$	$(\overline{\nu_R}\gamma^\mu e_R)(\tilde{H}^\dagger i D_\mu H)$ + h.c.	11	$\mathcal{O}_{L\nu}$	$(\bar{L}\gamma^\mu L)(\overline{\nu_R}\gamma_\mu \nu_R)$
4	$\mathcal{O}_{\nu B}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tilde{H}B^{\mu\nu}$	12	$\mathcal{O}_{Q\nu}$	$(\bar{Q}\gamma^\mu Q)(\overline{\nu_R}\gamma_\mu \nu_R)$
5	$\mathcal{O}_{\nu W}$	$(\bar{L}\sigma_{\mu\nu}\nu_R)\tau^I \tilde{H} W^{I\mu\nu}$	13	$\mathcal{O}_{L\nu Le}$	$(\bar{L}^i \nu_R)\epsilon_{ij}(\bar{L}^j e_R)$ + h.c.
6	$\mathcal{O}_{\nu\nu}$	$(\overline{\nu_R}\gamma^\mu \nu_R)(\overline{\nu_R}\gamma_\mu \nu_R)$	14	$\mathcal{O}_{L\nu Qd}$	$(\bar{L}^i \nu_R)\epsilon_{ij}(\bar{Q}^j d_R)$ + h.c.
7	$\mathcal{O}_{e\nu}$	$(\overline{e_R}\gamma^\mu e_R)(\overline{\nu_R}\gamma_\mu \nu_R)$	15	$\mathcal{O}_{LdQ\nu}$	$(\bar{L}^i d_R)\epsilon_{ij}(\bar{Q}^j \nu_R)$ + h.c.
8	$\mathcal{O}_{u\nu}$	$(\overline{u_R}\gamma^\mu u_R)(\overline{\nu_R}\gamma_\mu \nu_R)$	16	$\mathcal{O}_{Qu\nu L}$	$(\bar{Q}^i u_R)(\overline{\nu_R} L^i)$ + h.c.

Table: Dimension-6 νSMEFT operators. $\Delta L = 0, \Delta B = 0$

DM Relic Abundance and Freeze-Out

- **Thermal Equilibrium and Freeze-Out**
- **Free Parameters:** DM mass (m_χ) and cutoff scale (Λ), with Wilson coefficients $\mathcal{O}(1)$.
- **Boltzmann Equation:**

$$\frac{dY_\chi}{dx} = -1.32\sqrt{g_*}\, M_{\rm pl}\, \frac{m_\chi}{x^2}\, \langle \sigma v \rangle_{2_{\rm DM} \to 2_{\rm SM}} \left({Y_\chi}^2 - Y_{\rm eq}^2 \right)$$

- **Relic Abundance:**

$$\Omega_\chi h^2 \propto 1/\langle \sigma v \rangle \propto \Lambda^4/m_\chi^2$$

- **Effects of New Operators:**
  - New annihilation channels delay freeze-out, reducing relic abundance.
  - $\mathcal{O}_{\chi\nu}$: parameter space shifted upward: increase in annihilation channels.

Relic Allowed Parameter Space

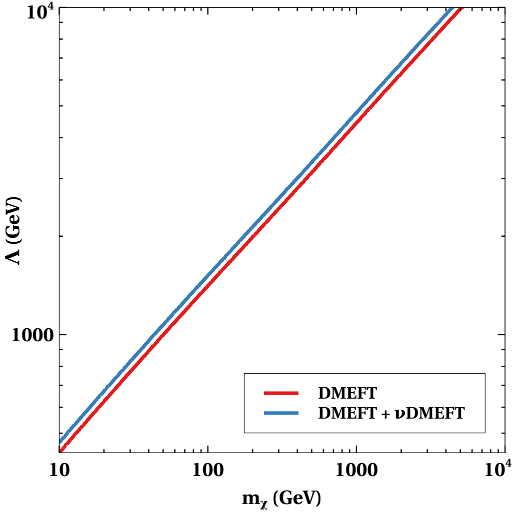


Figure: Relic allowed parameter space in $\Lambda - m_\chi$ plane

Direct Detection

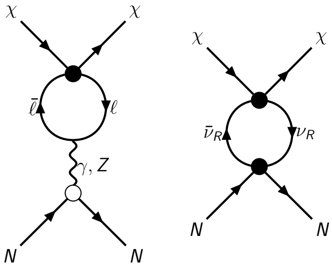


Figure: 1-loop Feynman diagrams from DM-nucleon scattering

The SI DM-nucleon cross-section for the $\mathcal{O}_{\chi\ell}$:

$$\sigma_{\chi N} \approx \frac{\mu_p^2}{9\pi A^2}\left(\frac{\alpha_{\rm em}\mathcal{Z}}{\pi\Lambda^2}\right)^2\left[\ln\left(\frac{\Lambda^2}{\Lambda_{\rm DD}^2}\right)\right]^2$$

Direct Detection

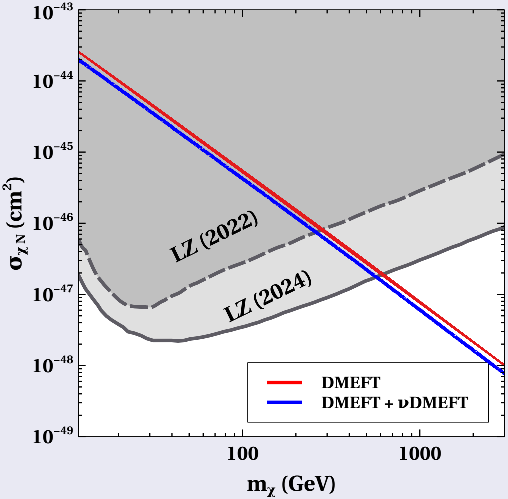


Figure: SI DM-nucleon cross-section for relic density allowed parameter space.

Indirect Search

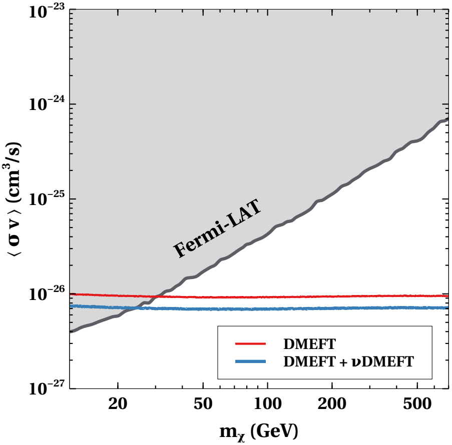


Figure: The shaded region is excluded from combined data analysis of MAGIC Cherenkov telescopes and Fermi-LAT experiment in $\langle \sigma v \rangle_{\chi\chi \to \tau^+\tau^-}$ versus m_χ plane.

Collider Phenomenology

Collider Signatures

- **Mono-X** $+ \not{E}$, where X refers to γ, H, Jet, and Z.
- **Multi-lepton / Multi-Jet** channel: HDSP.

Hadron Colliders

- $\sqrt{\hat{s}}$ unknown. EFT validation questionable for $\sqrt{s} < \Lambda$.
- QCD background.
- Unpolarized beams

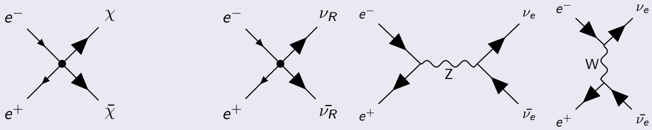
Lepton Colliders

- Known $\sqrt{s}$. EFT applicable for $\sqrt{s} < \Lambda$.
- Less QCD background.
- Initial beam polarization.

Tools

FeynRules (LanHEP), MadGraph, Pythia, Delphes, micrOMEGAs

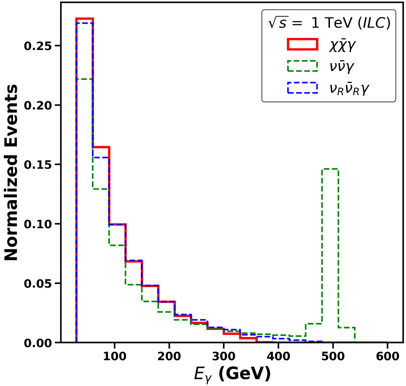
Collider Search: ILC

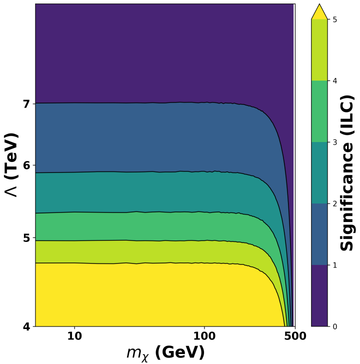


Beam Polarization	Cross-section (fb)		
$\{P_{e^+}, P_{e^-}\}$	$\chi\bar{\chi}\gamma$ (S)	$\nu\bar{\nu}\gamma$ $(B1)$	$\nu_R\bar{\nu}_R\gamma$ $(B2)$
$\{0\%, 0\%\}$	12.34	2450	19.65
$\{+20\%, +80\%\}$	10.38	630	16.50
$\{-20\%, +80\%\}$	14.30	463	22.79
$\{+20\%, -80\%\}$	14.33	5218	22.92
$\{-20\%, -80\%\}$	10.35	3476	16.54

Table: $\sqrt{s} = 1$ TeV and relic satisfied EFT parameters, $m_\chi = 260$ GeV and $\Lambda = 2450$ GeV

Distributions and Significance





Left: E_γ distribution)

Right: Signal Significance

Cosmological Signatures

Key Points

- Light Dirac neutrinos: Contributing to $\Delta N_{\rm eff}$
- Radiation energy density:

$$\rho_r = \rho_\gamma + \rho_{\nu_L} + \rho_{\nu_R} = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right)\rho_\gamma .$$

- SM prediction: $N_{\rm eff}^{\rm SM} = 3.045$. Deviations signal BSM physics.

Current and Future Bounds

- **Planck 2018:** $\Delta N_{\rm eff} \lesssim 0.285$ at 2σ CL.
- **DESI 2024:** $\Delta N_{\rm eff} \lesssim 0.4$ at 2σ CL.
- **CMB-S4 (Future):** $\Delta N_{\rm eff} \sim 0.06$.
- **CMB-HD (Future):** $\Delta N_{\rm eff} \sim 0.014$ (1σ).

Thermal Decoupling of ν_R

$\Delta N_{\rm eff}$

$$\Delta N_{\rm eff} = 0.047 \times 3 \left(\frac{106.75}{g_{*\rho}(T_{\rm dec})} \right)^{4/3},$$

$g_{*\rho}(T_{\rm dec})$ is the relativistic DOF at ν_R decoupling.

Case	**Interactions** ($\bar{f}_{L,R}\gamma^\mu\psi_{L,R}$ **type only)**	**Planck 2018 Limit on Λ**	**DESI 2024 Limit on Λ**
1	All fermions	$\Lambda \lesssim 11.6$ TeV	$\Lambda \lesssim 7.8$ TeV
2	leptons	$\Lambda \lesssim 10$ TeV	$\Lambda \lesssim 6.7$ TeV
3	SM neutrinos	$\Lambda \lesssim 8$ TeV	$\Lambda \lesssim 5.2$ TeV
4	quarks	$\Lambda \lesssim 9.8$ TeV	$\Lambda \lesssim 6.5$ TeV
5	3rd Gen quarks	$\Lambda \lesssim 0.6$ TeV	$\Lambda \lesssim 0.001$ TeV
6	Dark matter (χ)	m_χ dependent	m_χ dependent

Table: ν_R - SM interactions and disallowed values of Λ

Constraints on ν_R Interactions

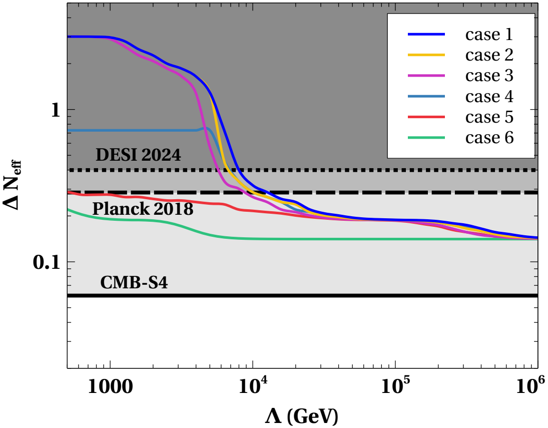
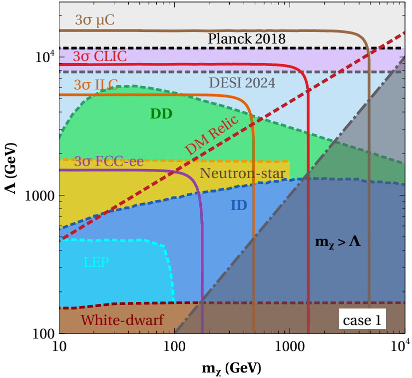
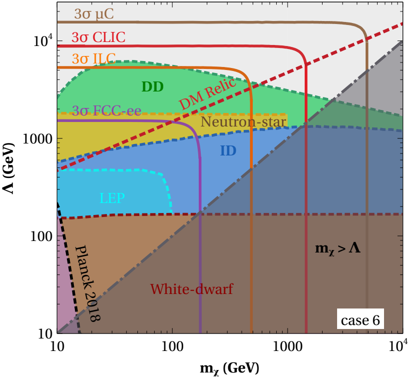


Figure: Variation of $\Delta N_{\rm eff}$ with Λ

Summary Plots





Left: Case 1 (All fermions) **Right:** Case 6 (DM (χ))

$\Lambda - m_\chi$ plane

Conclusion

- We have Studied leptophilic DM with light Dirac neutrinos using an EFT approach.
- νDMEFT / νSMEFT features enhanced $N_{\rm eff}$ measurable by future CMB experiments.
- BSM Discovery prospects explored at future lepton colliders (μC, CLIC, ILC, FCC-ee) and CMB experiments (Planck, DESI).
- Collider sensitivities on Λ ($\sim$ a few tens of TeV) and m_χ ($\sim$ a few TeV).
- Future CMB and Collider experiments can provide complementary searches for BSM Physics through EFT.

Thank You!

Backup: ΔN_{eff} for ν_R Interactions

- **Interaction Rate:**

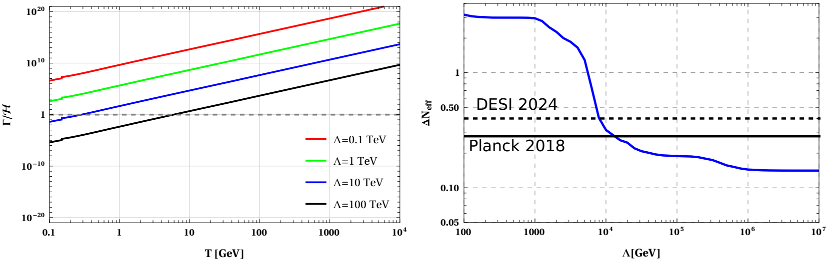
$$\Gamma = \sum_f \frac{n_f^{\mathrm{eq}} n_{\bar{f}}^{\mathrm{eq}}}{n_{\nu_R}^{\mathrm{eq}}} \langle \sigma v \rangle_{f\bar{f} \to \nu_R \bar{\nu}_R}$$

where $f(\bar{f})$: SM fermions and DM

- **Decoupling Temperature:**

$$\Gamma(T_{\mathrm{dec}}) \sim \mathcal{H}(T_{\mathrm{dec}})$$

ν_R decouples when interaction rate falls below Hubble expansion rate.



- **Results:**
  - Left Panel: $\Gamma/\mathcal{H}$ vs T for various Λ
  - Right Panel: ΔN_{eff} vs Λ
  - Planck 2018 excludes $\Lambda \lesssim 11.6$ TeV for $\Delta N_{\text{eff}} > 0.28$
  - DESI 2024 excludes $\Lambda \lesssim 7.8$ TeV

Back Up: Collider Details

Collider Specifications

Maximum reach of various lepton colliders, including $\sqrt{s}$ and beam polarization.

Colliders	$(\sqrt{s}, \mathfrak{L}_{\text{int}})$	**Beam Polarization** $\{P_{e^+}, P_{e^-}\}$
FCC-ee	(365 GeV, 340 fb^{-1})	–
ILC	(1 TeV, 8 ab^{-1})	$\{\pm 20\%, \pm 80\%\}$
CLIC	(3 TeV, 5 ab^{-1})	$\{\pm 0\%, \pm 80\%\}$
μC	(10 TeV, 10 ab^{-1})	–