Connecting neutrinos to everything, via heavy neutral leptons [1]

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Shortcomings of the standard model

The standard model is extremely successful, but leaves us wondering about the origin of:

- ν mass
- cosmological inflation
- dark matter
- matter-antimatter asymmetry

Could we economically tie them all together ?

"Affleck-Dine" Inflation

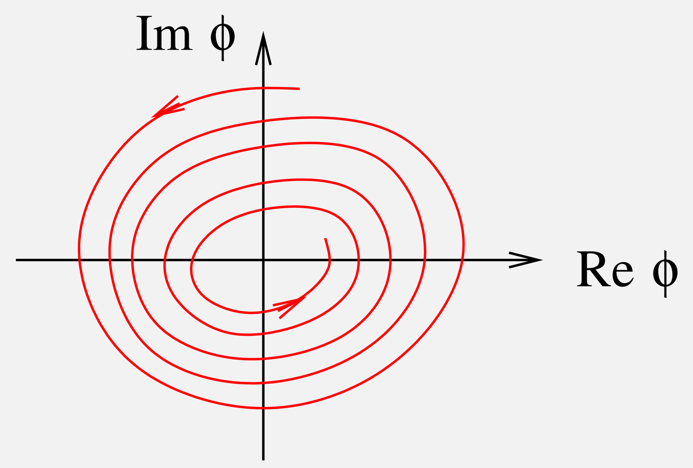
Previously we introduced *Affleck-Dine inflation*, where complex inflaton can produce a particle asymmetry during inflation [2]

$$V = m_\phi^2|\phi|^2 + \lambda|\phi|^4 + i\lambda'(\phi^4 - \phi^{*4})$$

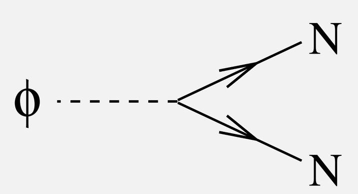
With nonminimal coupling $\xi|\phi|^2 R$ to gravity, this can satisfy Planck constraints on CMB temperature fluctuations.

Nonstandard leptogenesis

Suppose ϕ carries lepton number $L = 2$.



Asymmetry in $\phi - \phi^*$ (lepton number) created *during* inflation, while field bends in complex plane. Transfer it to *heavy neutral leptons* (HNLs)—GeV-scale quasi-Dirac sterile neutrinos, by inflaton decay:

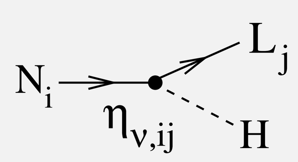


$$\mathscr{L} = g_\phi\, \phi(\bar N_R N_R^c + \bar N_L N_L^c)$$

Lepton asymmetry is transferred to HNLs. They pass it on to the SM, and the dark matter HNL.

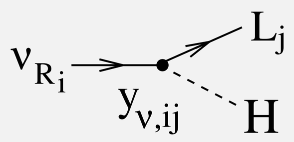
NHLs and neutrinos

HNLs can have mass mixing with νs via Higgs:



$$\Longrightarrow \begin{pmatrix} m_\nu & \eta_\nu^T v & 0 \\ \eta_\nu v & 0 & M_N \\ 0 & M_N & 0 \end{pmatrix} \begin{matrix} \nu_L \\ N_R^c \\ N_L \end{matrix}$$

Minimal flavor violation ansatz: we assume that η_{ij} aligns with the ν Yukawa couplings:

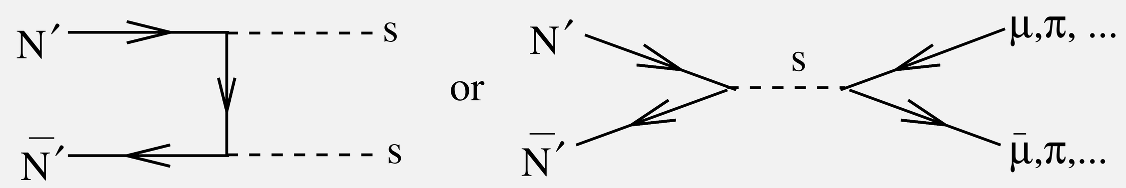


$$= y_{\nu,ij}\bar\nu_{R,i} H L_j, \qquad y_{\nu,ij} = k\,\eta_{\nu,ij}$$

Assume $\nu_{R,i}$ are superheavy, integrate them out to get m_ν. Take 3 HNLs to be degenerate: approximate flavor symmetry, weakly broken by $\eta_{\nu,ij}$. MFV makes theory highly predictive, allows one HNL to be dark matter.

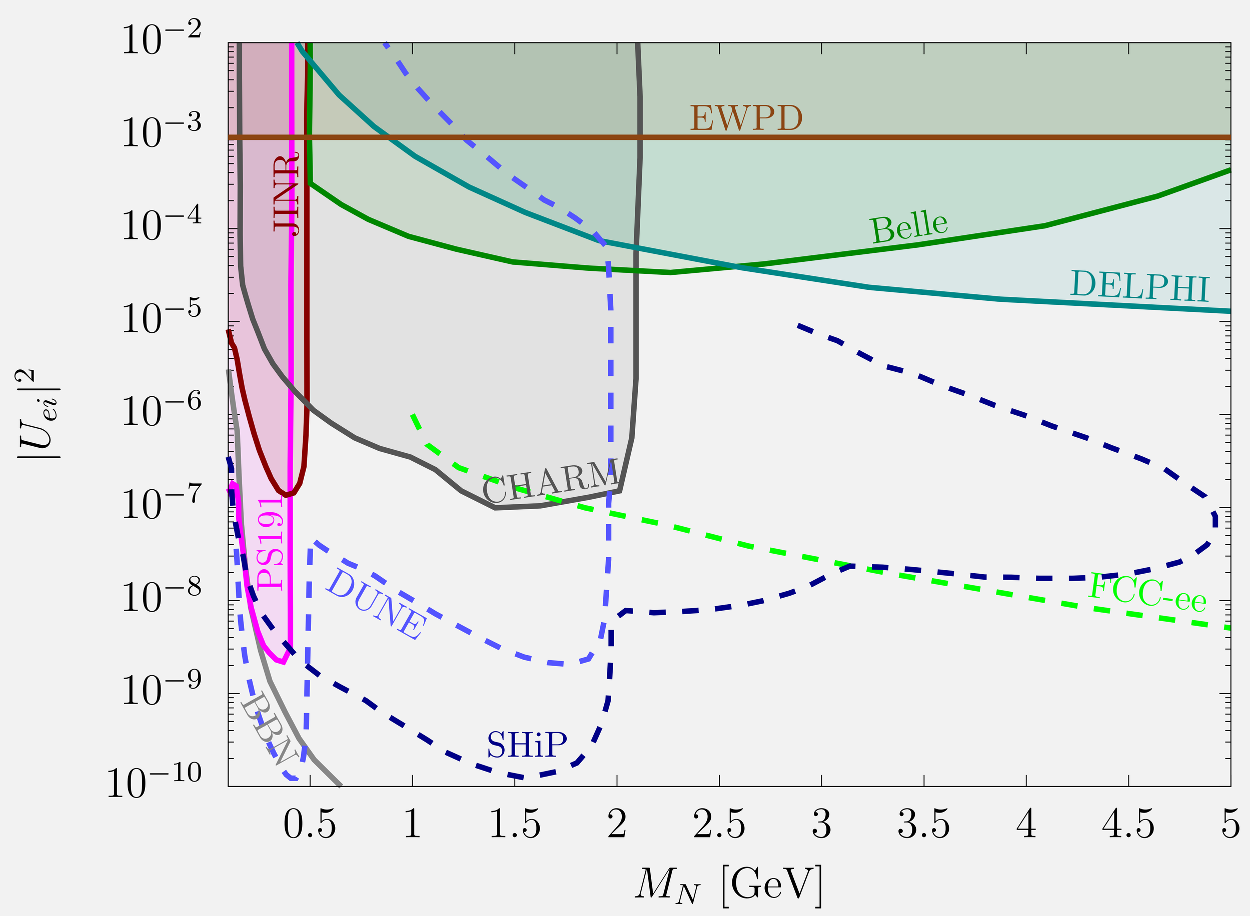
HNL as dark matter

If lightest ν is massless, then $\eta_{\nu,ij}$ has vanishing eigenvalue: gives one HNL (N') that is absolutely stable—DM candidate! But we need new annihilation channel. Add a light singlet scalar s with $g_s\, s\bar N_i N_i + \lambda_{hs} s^2 h^2 + \lambda_s(s^2 - v_s^2)^2$,

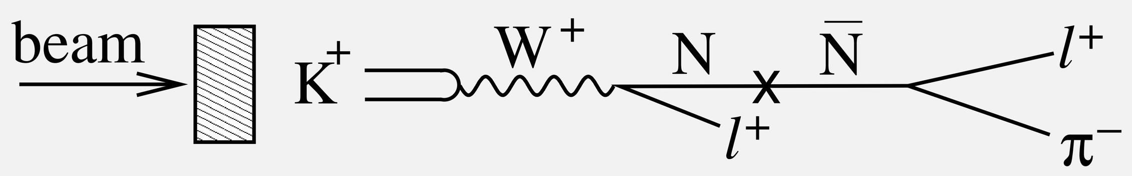


HNL constraints and discovery

If $m_{N_i} < m_s$, beam dump constraints bound HNL mixing $U_{\nu,i}$ with ν's, from $N \to \nu f\bar f$. Otherwise $N \to \nu s$; precision electroweak bounds from PMNS unitarity still give constraint (EWPD).

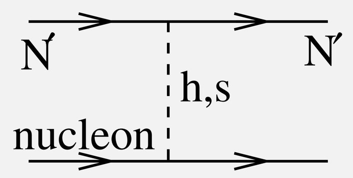


Limits $|\eta_\nu| \lesssim 10^{-3}$. HNLs get small Majorana mass $\delta M \sim \eta_\nu^2 m_\nu \sim 10^{-5}$ eV from light νs $\Longrightarrow$ N-$\bar N$ oscillations observable at SHiP,[3]

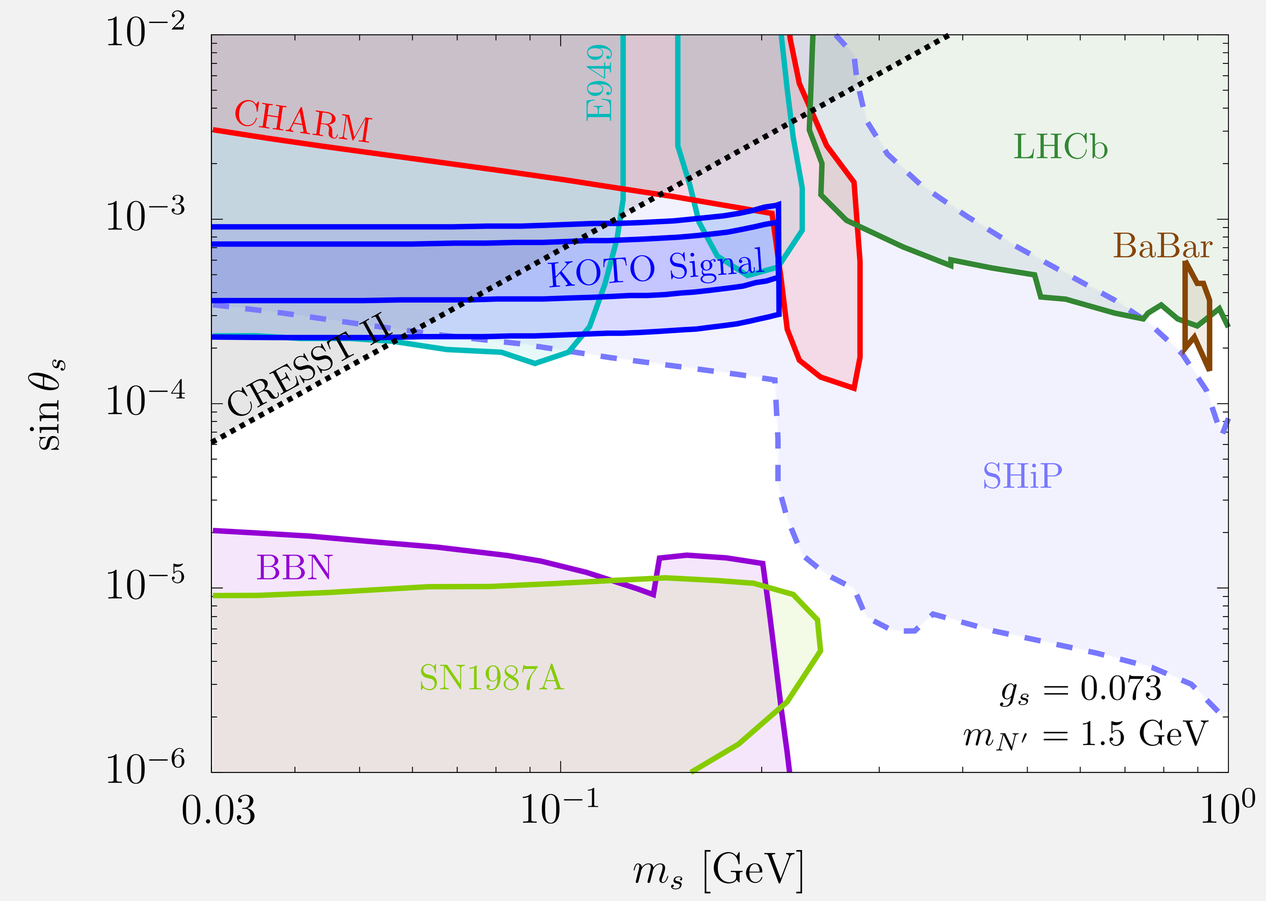


via like-sign leptons.

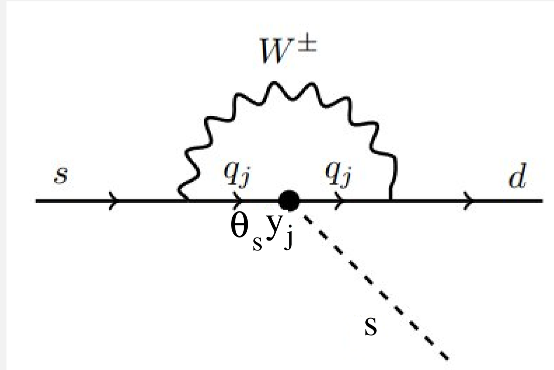
Light scalar and KOTO anomaly



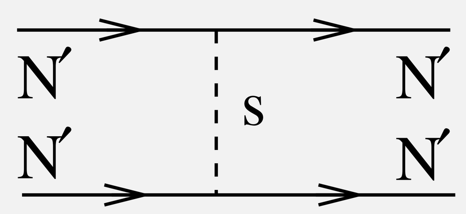
Generic constraints on singlet apply, plus DM direct detection from s exchange:



If $2m_N < m_s$, direct detection constraints are relaxed.

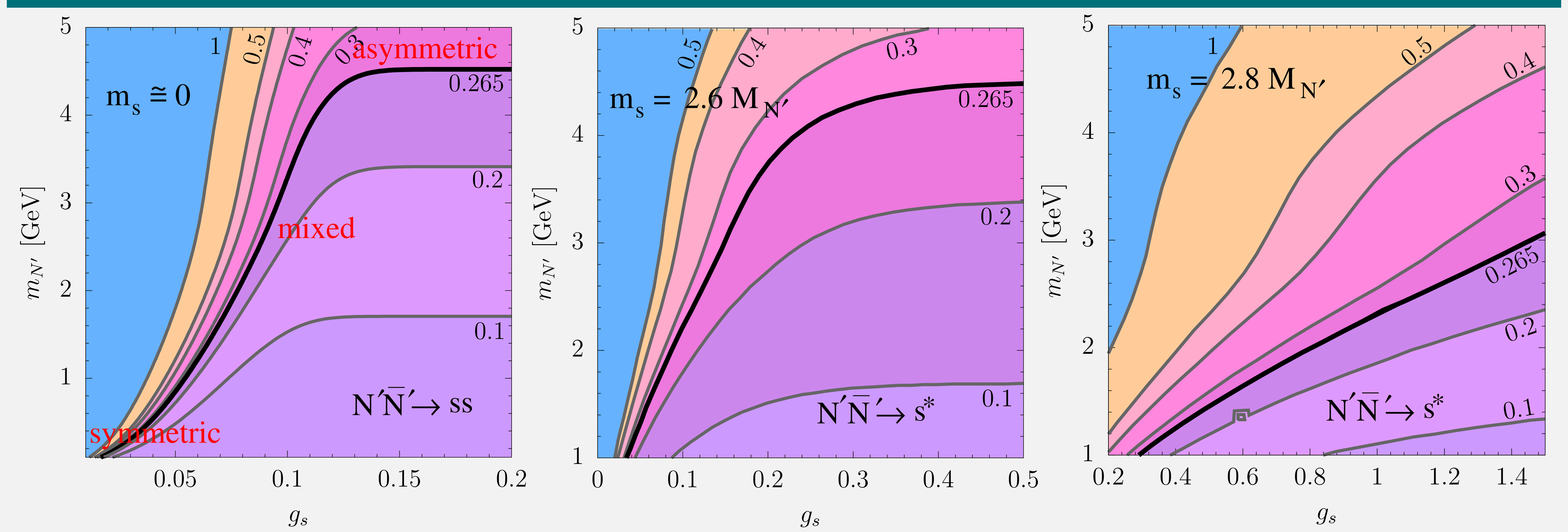


Light singlet can explain KOTO anomalous $K_L \to \pi^0\nu\nu$ signal in blue region above



Singlet could give DM self-interactions, of interest for cosmological structure formation problems

DM Relic Density: asymmetric, symmetric or mixed DM



Contours of Ω_{CDM}. DM can be asymmetric, symmetric or in between. Can be heavier (center, right) or lighter (left) than singlet. **If asymmetric, $m_{DM} \sim 4.5$ GeV, and DM density $\sim$ cosmic ν asymmetry.**

References

[1] J. M. Cline, M. Puel, and T. Toma, "A little theory of everything, with heavy neutral leptons," *JHEP* **05** (2020) 039, arXiv:2001.11505 [hep-ph].

[2] J. M. Cline, M. Puel, and T. Toma, "Affleck-Dine inflation," *Phys. Rev.* **D101** no. 4, (2020) 043014, arXiv:1909.12300 [hep-ph].

[3] J.-L. Tastet and I. Timiryasov, "Dirac vs. Majorana HNLs (and their oscillations) at SHiP," *JHEP* **04** (2020) 005, arXiv:1912.05520 [hep-ph].